[Transcript] Lex Fridman Podcast / #353 – Dennis Whyte: Nuclear Fusion and the Future of Energy

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nuclear physicist at MIT and the director
of the MIT Plasma Science and Fusion Center.
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makes me realize all the things I'm subscribed to
that actually add value to my life.
For example, it shows Audible and Netflix,
maybe Spotify, I'm trying to think.
Things I pay for every single month
and things that add a huge amount of value to my life.
And in that list are a bunch of subscriptions
that I don't need, that I completely forgot.
Or actually I aspired to use, but I end up not using.
And then you kind of have to confront yourself
with the reality of the fact that you plan
to use a service and you don't use it
and why pay a huge amount of money every month,
every year to use it.
And so it's really nice to kind of have
an introspective analysis of your life.
Reflect and start anew.
I'm a big believer that habits every single day
can make a huge amount of progress in your growth,
in your learning, in your development,
in that same way.

Paying for stuff every single day, every week,
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in their respective disciplines.
The list is ridiculous.
Chris Hadfield will write Carlos Santana,
Garrick Esparva, Daniel Negrano, Neil Gaiman,
Martin Scorsese.
I would love to talk to Martin Scorsese on this podcast.
I think he's probably, if not the,
he's one of the greatest directors of all time,
but also just a really interesting mind,
a really unique mind, a really unique cinematographer,
director, producer, storyteller, visionary,
has created some of the greatest movies ever.
But I think a podcast is a totally different thing
than a Masterclass.
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The best teachers are the ones that have reached the top
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a service I use to track biological data.
They have a bunch of plans,
most include blood tests that give you information
to make decisions about your health.
Like John Mayer said, your body is a wonderland.
It's a source of a lot of signal, a lot of data.
It's obvious to me that in the 21st century,
maybe the 22nd century,
we're going to create systems for the collection
of that data and then use machine learning
to analyze that data in order to understand
what is going on outside and what you should do next.
That means recommendations about lifestyle,
about health, about everything.
Career advice, relationship advice.
Yeah, you should get blood data
that then help you understand what your dating life
should be like.
This is obvious to the future.
And then also if you can get data from the brain,
the electrical, the mechanical,
the chemical signals from the brain,
high resolution, regular collection of that data
all inside an app and make predictions based on that
and what you should do with your life.
Because otherwise, just like I am right now,
you would be deeply lost.
Deeply lost in the turmoil of the human condition,
services like Insight Tracker can at least give you
a little bit of hope.
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in the description.
And now, dear friends, here's Dennis White.
["Dennis White"]
Let's start with a big question.
What is nuclear fusion?
It's the underlying process that powers the universe.
So as the name implies, it fuses together
or brings together two different elements,
technically nuclei, that come together.

And if you can push them together close enough
that you can trigger essentially a reaction,
what happens is that the element typically changes.
So this means that you change from one element
to another, the chemical element to another.
Underlying what this means is that you change
the nuclear structure, this rearrangement
through equals MC squared releases large amounts of energy.
So fusion is the fusing together of lighter elements
and to heavier elements.
And when you go through it, you say, oh, look,
so here were the initial elements, typically hydrogen.
And they had a particular mass, rest mass,
which means just the mass with no kinetic energy.
And when you look at the product afterwards,
it has less rest mass.
And so you go, well, how is that possible?
Because you have to keep mass, but mass and energy
are the same thing, which is what equals MC squared
means.
And the conversion of this comes into kinetic energy,
namely energy that you can use in some way.
And that's what happens in the center of stars.
So fusion is literally the reason life
is viable in the universe.
So fusion is happening in our sun.
And what are the elements?
The elements are hydrogen that are coming together.
It goes through a process, which is probably
gets a little bit too detailed.
But it's a somewhat complex, catalyzed process
that happens in the center of stars.
But in the end, stars are big balls of hydrogen,
which is the lightest.
It's the simplest element, the lightest element,
the most abundant element.
Most of the universe is hydrogen.
And it's essentially a sequence through which these processes
occur that you end up with helium.
So those are the primary things.
And the reason for this is because helium
has features as a nucleus, like the interior part of the atom,
that is extremely stable.

And the reason for this is helium has two protons
and two neutrons.
These are the things that make up nuclei,
that make up all of us, along with electrons.
And because it has two pairs, it's extremely stable.
And for this reason, when you convert the hydrogen
into helium, it just wants to stay helium.
And it wants to release kinetic energy.
So stars are basically conversion engines
of hydrogen into helium.
And this also tells you why you love fusion.
I mean, because our sun will last 10 billion years
approximately.
That's how long the fuel will last.
But to do that kind of conversion,
you have to have extremely high temperatures.
It is one of the criteria for doing this.
But it's the easiest one to understand.
Why is this, it's because effectively what this requires
is that these hydrogen ions, which is really
the bare nucleus, so they have a positive charge,
everything has a positive charge of those ones,
is that to get them to trigger this reaction,
they must approach within distances
which are like the size of the nucleus itself.
Because the nature, in fact, what it's really using
is something called the strong nuclear force.
There's four fundamental forces in the universe.
This is the strongest one.
But it has a strange property is that it,
while it's the strongest force by far,
it only has impact over distances
which are the size of a nucleus.
So to get, let's put that into, what does that mean?
It's a millionth of a billionth of a meter, okay?
Incredibly small distances.
But because the distances are small
and the particles have charge,
they want to push strongly apart.
Namely, they have repulsion that wants to push them apart.
So it turns, when you go through the math of this,
the average velocity or energy of the particles
must be very high to have any significant probability

of the reactions happening.
And so the center of our sun
is at about 20 million degrees Celsius.
And on Earth, this means it's one of the first things
we teach, you know, entering graduate students,
you can do a quick, you can do a quick,
basically power balance and you can determine
that on Earth, it requires a minimum temperature
of about 50 million degrees Celsius on Earth.
To perform fusion.
To get enough fusion that you would be able
to make, get energy gain out of it.
So you can trigger fusion reactions at lower energy,
but they become almost vanishingly small
at lower temperatures than that.
First of all, let me just link around some crazy ideas.
So one, the strong force,
just stepping out and looking at all the physics.
Is it weird to you that there's these forces
and they're very particular,
like it operates at a very small distance
and then gravity operates at a very large distance
and they're all very specific.
And the standard model describes
three of those forces extremely well.
And there's-
And this is one of them.
Yeah, this is one of them.
And it's just all kind of works out.
There's a big part of you that's, you know, an engineer.
Did you step back and almost look at the philosophy of physics?
So it's interesting, because as a scientist,
I see the universe through that lens
of essentially the interesting things that we do
are through the forces that get used around those.
And everything works because of that.
Richard Feynman had, I don't know if you ever had Richard Feynman.
It's a little bit of a tangent, but-
He's never been on the podcast.
He's never been on the podcast.
He was unfortunately passed away,
but one of like a hero to almost all physicists.
And a part of it was because of what you said.

He kind of looked through a different lens at these,
where typically look like very dry,
like equations and relationships.
And he kind of, I think he brought out the wonder of it
in some sense, right, for those.
He posited what would be,
if you could write down a single,
not even really a sentence, but a single concept
that was the most important thing scientifically
that we knew about, that in other words,
you had only one thing that you could transmit
like a future or past generation.
It was very interesting.
It was, so it's not what you think.
It wasn't like, oh, strong nuclear force
or fusion or something like this.
And it's very profound, which was,
he was that the reason that matter operates the way
that it does is because all matter is made up
of individual particles that interact
to each other through forces.
That was it.
So just-
Atomic theory, basically.
Yeah.
Which is like, wow, that's like so simple,
but it's not so simple.
It's because like, who thinks about atoms
that they're made out of?
Like, this is a good question I give to my students.
How many atoms are in your body?
Like almost no students can answer this.
But to me, that's like a fundamental thing.
By the way, it's about 10 to the 28.
10 to the 28.
So that's a trillion, million trillion trillion
or something like that.
Yes.
So one thing is to think about the number
and the other is to start to really ponder the fact.
That it all holds together.
Yeah, it all holds together and you're actually that.
You're more that than you are anything else.

Yes, exactly.
Yeah.
No, I mean, there are people who do study such things
of the fact that if you look at the, for example,
the ratios between those fundamental forces,
people have figured out, oh, if this ratio was different
by some factor, like a factor of two or something,
I was like, oh, this would all like not work.
And I look, you look at the sun, right?
It's like, so it turns out that there are key reactions
that if they had slightly lower probability,
no star would ever ignite.
And then life wouldn't be possible.
It does seem like the universe set things up for us
that it's possible to do some cool things,
but it's challenging.
So they keeps it fun for us.
Yeah, yeah, that's the way I look at it.
I mean, the, you know, the multiverse model
is an interesting one because they're, you know,
quantum scientists who look at and figure,
I was like, oh, it's like, oh yeah.
Like quantum science perhaps tells us
that there are almost an infinite, you know,
variety of other universes,
but the way that it works probably is,
it's almost like a form of natural selection.
It's like, well, the universes that didn't have
the correct or interesting relationships
between these forces, nothing happens in them.
So almost by definition,
the fact that we're having this conversation
means that we're in one of the interesting ones by default.
Yeah, one of the somewhat interesting,
but there's probably super interesting ones
where I tend to think of humans as incredible creatures.
Our brain is an incredible computing device,
but I think we're also extremely cognitively limited.
I can imagine alien civilizations
that are much, much, much, much more intelligent
in ways we can't even comprehend
in terms of their ability to construct models of the world,
to do physics, to do physics and mathematics.

I would see it in a slightly different way.
It's actually, it's because we have creatures
that live with us on the earth that have cognition, right,
that understand and move through their environment,
but they actually see things in a way,
or they sense things in a way
which is so fundamentally different.
It's really hard.
Like, it's the problem is the translation,
not necessarily intelligence,
so it's the perception of the world.
So I have a dog, and when I go out and I see my dog,
like smelling things, there's a realization that I have
that he sees or senses the world in a way that I can never,
like I can't understand it
because I can't translate my way to this.
We get little glimpses of this as humans, though, by the way,
because there are some parts of it,
for example, optical information which comes from light,
is that now, because we've developed the technology,
we can actually see things, you know, I've had,
I get this, you know, as one of my areas of research
is spectroscopy.
So this means the study of light, you know,
and I get this quote unquote,
see things or representations of them from, you know,
the far infrared all the way to like hard, hard X-rays,
which is several orders of magnitude of the light intensity,
but our own human eyes, like see a teeny, teeny little sliver
of this, so that even like bees, for example,
see a different place than we do.
So I don't, I think if you think of,
there's already other intelligences like around us
in a way, in a limited way,
because of the way they can communicate,
but that's like, those are already baffling,
in many ways, yeah.
If we just focus in on the senses,
there's already a lot of diversity,
but there's probably things we're not even considering
as possibilities.
For example, whatever the consciousness is,
could actually be a door into understanding

some physical phenomena we're not,
haven't even begun understanding.
So just like you said, spectroscopy,
there could be a similar kind of spectrum
for consciousness that we're just like,
we're like these dumb descendants of apes,
like walking around, it sure feels like something
to experience the color red, but like we don't have,
it's the same as in the ancient times,
you experienced physics, you experienced light.
It's like, oh, it's bright, and you know.
Yeah, yeah.
And you could start kind of semi-religious kind of
explanations.
We might actually experience this faster than we thought,
because we might be building another kind of intelligence.
Yeah.
And that that intelligence will explain to us
how silly we are.
There was an email thread going around the professors
in my department already of,
so what is it going to look like to figure out
if students have actually written their term papers
or it's chat, the-
Chat GPT.
Chat GPT.
It was, so as usual, as we tend to be empiricists
in my field, so of course they were in there
like trying to figure out if it could answer like questions
for a qualifying exam to get into the PhD program at MIT,
which was, they didn't do that well at that point,
but of course this is just the beginning of it.
So if you have some interesting ones to go for.
Eventually both the students and the professors
will be replaced by Chat GPT.
Yeah.
And we'll sit on the beach.
I really recommend, I don't know if you've ever seen them,
it's called The Day the Universe Changed.
This is James Burke.
He's a science historian based in the UK.
He had a fairly famous series on public television
called Connections, I think it was that,

but the one that I really enjoyed
was The Day the Universe Changed.
And the reason for the title of it was that,
he says, the universe is what we know and perceive of it.
So when there's a fundamental insight
as to something new, the universe for us changes.
Of course, the universe from an objective point of view
is the same as it was before, but for us it has changed.
So he walks through these moments of perception
in the history of humanity that changed what we were, right?
And so as I was thinking about coming to discuss this,
people see fusion, oh, it's still far away,
or we've been, it's been slow progress.
It's like, when my godmother was born,
like people had no idea how stars worked.
So you talk about like that day, that insight,
the universe change is like, oh, this is the,
I mean, and they still didn't understand all the parts of it,
but they basically got it.
It was like, oh, because of the understanding
of these processes, it's like we unveiled the reason
that there can be life in the universe.
That's probably one of those days,
the universe changed, right?
And that was in the 1930s.
It seems like technology is developing faster and faster
and faster.
I tend to think just like with JGPT,
I think this year might be extremely interesting,
just with how rapid and how profitable the efforts
in artificial intelligence are,
that just stuff will happen where our whole world
is transformed like this, and there's a shock,
and then the next day you kind of go on
and you adjust immediately.
You probably won't have a similar kind of thing
with nuclear fusion, with energy,
because there's probably going to be an opening ceremony
and stuff, and announcement that take months,
but with digital technology,
you can just have a immediate transformation of society,
and then it'll be this gasp, and then you kind of adjust,
like we always do, and then you don't even remember,

just like with the internet and so on,
how the days work before.
And how it worked before, right?
I mean, fusion will be, because it's energy,
its nature is that it will be, and anything
that has to do with energy use
tends to be a slower transition,
but they're the most, I would argue,
some of the most profound transitions that we make.
I mean, the reason that we can live like this
and sit in this building and have this podcast
and people around the world at its heart is energy use,
and it's intense energy use that came from the evolution
of starting to use intense energies
at the beginning of the Industrial Revolution up to now.
It's like, it's a bedrock, actually, of all of these,
but it doesn't tend to come overnight.
Yeah, and some of the most important,
some of the most amazing technologies,
one we don't notice, because we take it for granted,
because it enables this whole thing.
Yeah, exactly, which is energy,
which is amazing for how fundamental it is
to our society and way of life
is a very poorly understood concept, actually,
just even energy itself.
People confuse energy sources with energy storage,
with energy transmission.
These are different physical phenomena,
which are very important.
So for example, you buy an electric car,
and you go, oh, good, I have an emission-free car.
And, ah, but it's like, so why do you say that?
Well, it's because if I draw the circle around the car,
I have electricity, and it doesn't emit anything.
Okay, but you plug that into a grid
where you follow that wire back,
there could be a coal power plant or a gas power plant
at the end of that.
Oh, really?
I mean, so this isn't like carbon-free?
Oh, and it's not their fault, it's just, you know,
they don't, like the car isn't a source of energy.

The underlying source of energy
was the combustion of the fuel back somewhere.
Plus, there's also a story of how the raw materials
are mined, in which parts of the world,
with sort of basic respect
or deep disrespect of human rights
that happens in that money.
So the whole supply chain, there's a story there
that is deeper than just the particular electric car
with the circle around it.
And the physics or the science of it, too,
is the energy use that it takes to do that digging up,
which is also important and all that.
Yeah, anyway, so we wandered away from fusion,
but yes, but it's very important, actually,
in the context of this, just because, you know,
those of us who work in fusion
and these other kinds of sort of disruptive energy
technologies, it's interesting.
I do think about, like, what is it going to mean
to society to have an energy source that is like this,
that would be like fusion, you know,
which has such completely different characteristics.
For example, you know, free unlimited access to the fuel,
but it has technology implications.
So what does this mean geopolitically?
What does it mean for how we distribute wealth
within our society?
It's very difficult to know, but probably profound.
Yeah.
We're going to have to find another reason to start wars
instead of resources.
We've done a pretty good job of that
over the course of our history.
So we talked about the forces of physics
and again, sticking to the philosophical
before we get to the specific technical stuff.
E equals MC squared, you mentioned.
How amazing is that to you?
That energy and mass are the same.
And what does that have to do with nuclear fusion?
So it has to do with everything we do.
It's the fact that energy and mass are equivalent

to each other.
They're just, the way we usually comment to it
is that they're just energy, just in different forms.
Can you intuitively understand that?
Yes, but it takes a long time.
I haven't for all about usually,
often I teach the introductory class
for incoming nuclear engineers.
And so we put this up as an equation
and we go through many iterations of using this,
how you derive it, how you use it and so forth.
And then usually in the final exam,
I would basically take all the equations
that I've used before and I flip it around.
I basically, instead of thinking about energy
is equal to mass, it's sort of mass is equal to energy.
And I ask the question in a different way
and usually about half the students don't get it.
It takes a while to get that intuition.
Yeah, so in the end, it's interesting
is that this is actually the source of all free energy
because that energy that we're talking about
is kinetic energy if it can be transformed from mass.
So it turns out even though we used equals MC squared,
this was burning coal and burning gas
and burning wood is actually still equals MC squared.
The problem is that you would never know this
because the relative change in the mass
is incredibly small.
By the way, which comes back to fusion
which is that equals MC squared.
Okay, so what does this mean?
It tells you that the amount of energy
that is liberated in a particular reaction
when you change mass has to,
because C squared is that the speed of light squared.
It's a large number.
It's a very large number and it's totally constant
everywhere in the universe, which is another weird thing.
Which is another weird thing and in all rest frames
and actually the relativity stuff gets more difficult
conceptually even until you get through.
Anyway, so you go to that and what that tells you

is that it's the relative change in the mass.
We'll tell you about the relative amount of energy
that's liberated and this is what makes fusion
and you asked about fusion as well too.
This is what makes them extraordinary.
It's because the relative change in the mass
is very large as compared to what you get
like in a chemical reaction.
In fact, it's about 10 million times larger.
And that is at the heart of why you use something like fusion.
It's because that is a fundamental of nature.
Like you can't beat that.
So whatever you do, if you're thinking about,
and why do I care about this?
Well, because mass is like the fuel, right?
So this means gathering the resources
that it takes to gather a fuel, to hold it together,
to deal with it, the environmental impact it would have.
And fusion will always have 20 million times
the amount of energy released per reaction
that you get of those.
So this is why we consider it the ultimate,
like environmentally friendly energy sources
because of that.
So is it correct to think of mass broadly
as a kind of storage of energy?
Yes.
You mentioned it's environmentally friendly.
So nuclear fusion is a source of energy.
It's cheap, clean, safe.
So easy access to fuel and virtual element of supply,
no production of greenhouse gases,
little radioactive waste produced allegedly.
Can you sort of elaborate why it's cheap, clean and safe?
I'll start with the easiest one, cheap.
It is not cheap yet
because it hasn't been made at a commercial scale.
Mine flies when you're having fun, but yes.
Yeah, yeah.
But yes, not yet.
We'll talk about it.
Actually, we'll come back to that
because this is cheaper

or a more technically correct term
that it's economically interesting
is really the primary challenge actually,
a fusion at this point.
But I think we can get back to that.
So what were the other ones you said?
So cheap, actually when we're talking about cheap,
we're thinking like asymptotically,
like if you take it forward several hundred years,
that's sort of because of how much availability
there is of resources to use.
Of the fuel.
Yeah, of the fuel.
We should separate those two.
The fuel is already cheap.
It's basically free, right?
What do you mean by basically free?
So if we were to be using fusion fuel sources
to power your, and it's like,
that's all we had was fusion power plants around
and we were doing it,
the fuel costs per person are something like 10 cents a year.
It's free, okay.
This is why it's hard to,
in some ways I think it's hard to understand fusion
because people see this and go,
oh, if the fuel is free,
this means the energy source is free
because we're used to energy sources like this.
So we, you know, we spend resources and drill
to get that gas or oil or we chop wood
or we make coal, we find coal or these things, right?
So fusion, this is what makes fusion.
And it's also, it's not an intermittent renewable energy
source like wind and solar.
So it's like, but this is, this makes it hard to understand.
So if you're saying the fuel is free,
why isn't the, like why isn't the energy source free?
And it's because of the necessary technologies
which must be applied to basically recreate the conditions
which are in stars, in the center of stars in fact.
So there's only one natural place in the universe
that fusion energy occurs, that's in the center of stars.

So that's going to bring a price to it
depending on the cost and, sorry, the size
and complexity of the technology
that's needed to recreate those things.
And we'll talk about the details of the technologies
and which parts might be expensive today
and which parts might be expensive in two or three years.
Exactly.
It will have a revolution, I'm certain of it.
So about clean, so clean is at its heart,
what it does is converts, it basically converts hydrogen
into, it's heavier forms of hydrogen,
the most predominant one that we use on Earth
and converts it into helium and some other products
but primarily helium is the product that's left behind.
So helium, safe, inert, gas, you know.
In fact, that's actually what our sun is doing
is eventually going to extinguish itself
because it'll just make so much helium
that it doesn't do that.
So in that sense, clean because there's no emissions
of carbon or pollutants that come directly
from the combustion of the fuel itself.
And safe.
Safe, yeah.
We're talking about very high temperatures.
Yeah, so this is also the counterintuitive thing.
So I told you temperatures which like 50 million degrees
or it actually tends to be more like about 100 million degrees
is really what we aim for.
So how can 100 million degrees be safe?
And it's safe because it is,
this is so much hotter than anything on Earth
where everything on Earth is at around
300 Kelvin, you know, it's around a few tens of degrees Celsius.
And what this means is that in order to get a medium
to those temperatures, you have to completely isolate it
from anything to do with terrestrial environment.
It can have no contact like with anything on Earth basically.
So this means what we, this is the technology
that I just described is it fundamentally what it does
is it takes this fuel and it isolates it
from any terrestrial conditions so that it has no idea

it's on Earth.
It's not touching any object that's at room temperature.
Including the walls of the containment.
Even the completing the walls of the containment building
or containment device or even air or anything like this.
So it's that part that makes it safe
and there's actually another aspect to it.
But that fundamental part makes it so safe.
And in the main lines approach to fusion is also
that it's very hot, but there's very, very few particles
at any time in the thing that would be the power plant.
The actually the more correct way to do it is you say
there's very few particles per unit volume.
So in a cubic centimeter and cubic meters and that.
So we can do this.
So right now we're, although we don't think of air really
as there's atoms floating around us and there's a density
because if I wave my hand I can feel the air pushing
against my face.
That means we're in a fluid or a gas which is around us.
That has a particular number of atoms per cubic meter.
So it's what this actually turns out to be 10 to the 25th.
So this is one with 25 zeros behind it per cubic meter.
So we can figure out like cubic meters about like this.
The volume of this table, like the whole volume mistake.
Okay, very good.
So like fusion, there's a few of those.
So fusion like the mainstream one of fusion
like what we're working on at MIT will have 100,000 times
less particles per unit volume than that.
So this is very interesting
because it's extraordinarily hot 100 million degrees
but it's very tenuous.
And what matters from the engineering and safety point
of view is the amount of energy which is stored
per unit volume because this tells you about the scenarios
and that's what you worry about.
Cause when those kinds of energies are released suddenly
it's like what would be the consequences, right?
So the consequences of this are essentially zero
because that's less energy content than boiling water.
Because of the low density.
Because of the low density.

So if you take water is at about 100 million
to a billion times more dense
than this.
So even though it's at much lower temperature
it's actually still it has more energy content.
So for this reason, one of the ways that I explain this
is that if you imagine a power plant
that's like powering Cambridge, Massachusetts
like if you were to, which you wouldn't do this directly
but if you went like this on it
it actually extinguishes the fusion
because it gets too cold immediately.
Yeah, so that's the other one.
And the other part is that it does not
and because it works by staying hot
rather than a chain reaction
it can't run out of control.
That's the other part of it.
So by the way, this is what very much distinguishes it
from fission.
It's not a process that can run away from you
cause it's basically thermally stable.
What is thermally stable in me here?
That means is that you want to run it
at the optimization in temperature
such that if it deviates away from that temperature
the reactivity gets lower.
And the reason for this is because it's hard
to keep the reactivity going.
Like it's a very hard fire to keep going basically.
Also it doesn't run away from you.
It can't run away from you.
How difficult is the control there to keep it at that?
It varies from concept to concept
but in generally it's fairly easy to do that.
And the easiest thing, it can't physically run away
from you because the other part of it
is that there's just at any given time
there's a very, very small amount of fuel
available to fuse it anyway.
So this means that that's always intrinsically limited
to this.
So even if the power consumption of the device goes up

it just kind of burns itself out immediately.
So you are just to take another tangent on a tangent.
You're the director of MIT's Plasma Science
and Fusion Center.
We'll talk about, maybe you can mention
some interesting aspects of the history of the center
in the broader history of MIT
and maybe broader history of science and engineering
in the history of human civilization.
But also just the link on the safety aspect.
How do you prevent some of the amazing reactors
that you're designing?
How do you prevent from destroying
all of human civilization in the process?
What's the safety protocols?
Fusion is interesting because it's not really directly
weaponizable because what I mean by that
is that you have to work very hard to make these
conditions in which you can get energy gain from fusion.
And this means that when we design these devices
with respect to application in the energy field
is that they, while they will,
because they're producing large amounts of power
and they will have hot things inside of them
this means that they have like a level of industrial hazard
which is very similar to what you would have
like a chemical processing plant or anything like that
and any kind of energy plant actually has these as well too.
But the underlying underneath it core technology
like can't be directly used in a nefarious way
because of the power that's being emitted.
It just basically, well, if you try to do those things
typically it just stops working.
So the safety concerns have to do with just regular things
that like equipment, malfunctioning,
melting of equipment, all this kind of stuff
that has nothing to do with fusion necessarily.
I mean, usually what we worry about is the viability
because in the end we build pretty complex objects
to realize these requirements.
And so what we try really hard to do
is like not damage those components
but those are things which are internal

to the fusion device.
And this is not something that you would consider
about like it would, as you say, destroy human civilization
because that release of energy is just inherently limited
because of the fusion process.
So it doesn't say that there's zero,
so you asked about the other feature that it's safe.
So it is, the process itself is intrinsically safe
but because it's a complex technology
you still have to take into consideration
aspects of the safety.
So it produces ionizing radiation instantaneously.
So you have to take care of this
which means that you shield it.
You think of like your dental x-rays
or treatments for cancer and things like this.
We always shield ourselves from this.
So we get the beneficial effects
but we minimize the harmful effects of those.
So there are all those aspects of it as well too.
So we'll return to MIT's Plasma Science a few years later
but let us linger on the destruction of human civilization
which brings us to the topic of nuclear fission.
What is that?
So the process that is inside nuclear weapons
and current nuclear power plants.
So it relies on the same underlying physical principle
but it's exactly the opposite of which actually the names
imply fusion means bringing things together,
fission means splitting things apart.
So fission requires the heaviest instead of the lightest
and the most unstable versus the most stable elements.
So this tends to be uranium or plutonium,
primarily uranium.
So take uranium.
So uranium 235 is one of the heaviest unstable elements
and what happens is that this is,
and fission is triggered by the fact
that one of these subatomic particles,
the neutron which has no electric charge
basically gets in proximity enough to this
and triggers an instability effectively inside of this.
What is teedering on the border of instability

and basically splits it apart.
And that's the fission, right?
The fissioning.
And so when that happens because the products that are,
and roughly splits in two, but it's not even that,
it's actually more complex,
it splits into this whole array of lighter elements
and nuclei and when that happens,
there's less rest mass left than the original one.
So it's actually the same.
So it's again, it's rearrangement
of the strong nuclear force
that's happening, but that's the source of the energy.
And so in the end, it's like,
so this is a famous graph that we show everybody is basically,
it turns out every element that exists
in the periodic table,
all the things that make up everything have a,
remember you asked a good question.
It was like, so should we think of mass
as being the same as stored energy?
Yes.
So you can make a plot that basically shows
the relative amount of stored energy
and all of the elements that are stable
and make up basically the world in the universe.
And it turns out that this one has a maximum amount
of stability or storage at iron.
So it's kind of in the middle of the periodic table
because this goes from, it's roughly that.
And so what that means is that if you take something heavier
than iron, like uranium,
which is more than twice as heavy than that,
and you split apart, if you somehow just magically,
you just split apart its constituents
and you get something that's lighter,
that will, because it moves to a more stable energy state,
it releases kinetic energy.
That's the energy that we use.
Kinetic energy meaning the movement of things.
So it's actually an energy you can do something with.
And fusion sits on the other side of that
because it's also moving towards iron,

but it has to do it through fusion together.
So this leads to some pretty profound differences.
As I said, they have some underlying physics
or science proximity to each other,
but they're literally the opposite.
So fusion, why is this?
It actually goes in the practical implications of it,
which is that fission can happen at room temperature.
It's because there's this neutron has no electric charge
and therefore it's literally room temperature neutrons
that actually trigger the reaction.
So this means in order to establish what's going on with it,
and it works by chain reaction,
is that you can do this at room temperature.
So Enrico Fermi did this like on a university campus,
University of Chicago campus,
the first sustained chain reaction was done
underneath a squash court with a big blocks of graphite.
It was still, don't get me wrong,
an incredible human achievement, right?
But that's, and then you think about fusion,
I have to build a contraption of some kind
that's going to get to a hundred million degrees.
Okay, wow, that's a big difference.
The other one is about the chain reaction,
that namely fission works by the fact
that when that fission occurs,
it actually produces free neutrons.
Free neutrons, particularly if they get slowed down
to room temperature, trigger,
can trigger other fission reactions
if there's other uranium nearby or fissometers.
So this means that the way that it releases energy
is that you set this up in a very careful way
such that every, on average, every reaction that happens
exactly releases enough neutrons and slows down
that they actually make another reaction, one, exactly one.
And this means is that because each reaction releases
a fixed amount of energy, you do this and then in time,
this looks like just a constant power output.
So that's how our fission power plan works.
And so there's control of the chain reactions
is extremely difficult and extremely important for.

It's very important.
And when you intentionally design it,
that it creates more than one fission reaction
per starting reaction, that it exponentiates away.
Which is what a nuclear weapon is.
Yeah, so how does an atomic weapon work?
How does a hydrogen bomb work, asking for a friend?
Yeah, so at what you do is you very quickly put together
enough of these materials that can undergo fission
with room temperature neutrons
and you put them together fast enough
that what happens is that this process
can essentially grow mathematically like very fast.
And so this releases large amounts of energy.
So that's the underlying reason that it works.
So you've heard of a fusion weapon.
So this is interesting is that it is,
but it's dislike fusion energy in the sense
that what happens is that you're using fusion reactions
but it's simply, it increases the gain actually
of the weapon rather than, it's not a pure,
at its heart it's still a fission weapon.
You're just using fusion reactions
as a sort of intermediate catalyst basically
to get even more energy out of it.
But it's not directly applicable
to be used in energy source.
Does it terrify you just again to step back
at the philosophical that humans have been able
to use physics and engineering to create
such powerful weapons?
I wouldn't say terrify.
I mean, we should be, this is the progress of human.
Every time that we've gotten access,
you talk again, the day the universe changed,
those really changed when we got access
to new kinds of energy sources.
But every time you get access,
and typically what this meant was you get access
to more intense energy, right?
That's, and that's what that was.
And so the ability to move from burning wood
to using coal to using gasoline and petrol,

and then finally to use this is that both the potency
and the consequences are elevated around those things.
It's just like you said, the way that fusion,
nuclear fusion would change the world,
I don't think unless we think really deeply
we'll be able to anticipate some of the things we can create.
There's going to be a lot of amazing stuff,
but then that amazing stuff is gonna enable
more amazing stuff and more, unfortunately,
or depending on how you see it, more powerful weapons.
Well, yeah, but see, that's the thing.
Fusion breaks that trend in the following way.
So one of them, so fusion doesn't work on a chain reaction.
There's no chain reaction, zero.
So this means it cannot physically
exponentiate away on you, because it works,
and actually this is why star, by the way,
we know this already, it's why stars are so stable,
why most stars and suns are so stable.
It's because they are regulated
through their own temperature and their heating.
Because what's happening is not that
there's some probability of this exponentiating away,
is that the energy that's being released by fusion
basically is keeping the fire hot.
And these tend to be, and when it comes down
to thermodynamics and things like this,
there's a reason, for example,
it's pretty easy to keep of constant temperature,
like in an oven and things like this.
It's the same thing in fusion.
So this is actually one of the features
that I would argue fusion breaks the trend of this,
is that it has more energy intensity
than fusion on paper, but it actually does not have
the consequences of control and sort of rapid release
of the energy, because it's actually,
the physical system just doesn't want to do that.
We're gonna have to look elsewhere
for the weapons with which we fight World War III.
Fair enough.
So what is plasma that you may or may have not mentioned?
You mentioned ions and electrons and so on.

So what is plasma?
What is the role of plasma in nuclear fusion?
So plasma is a phase of matter or state of matter.
So unfortunately our schools don't,
it's like, I'm not sure why this is the case,
but all children learn the three phases of matter, right?
So, and what does this mean?
So we'll take like waters and examples.
So if it's cold, it's ice, it's in a solid phase, right?
And then if you heat it up,
it's the temperature that typically depends,
sets the phase, although it's not only temperature.
So you heat it up and you go to a liquid
and obviously it changes its physical properties
because you can pour it and so forth, right?
And then if you heat this up enough,
it turns into a gas and a gas behaves differently
because there's a very sudden change
in the density, actually that's what's happening.
So it changes by about a factor of 10,000 in density
from the liquid phase into when you make it into steam
at atmospheric pressure, all very good.
Except the problem is they forgot,
like what happens if you just keep elevating the temperature?
You don't wanna give kids ideas.
They're gonna start experimenting
and they're gonna start heating up the gas.
It's good to start doing it anyway.
So you, it turns out that once you get above,
it's approximately five or 10,000 degrees Celsius,
then you hit a new phase of matter.
And actually that's the phase of matter
that is for all, pretty much all the temperatures
that are above that as well too.
And so what does that mean?
So it actually changes phase.
So it's a different state of matter.
And the reason that it becomes a different state of matter
is that it's hot enough that what happens is
that the atoms that make up, remember,
go back to Feynman, right?
Everything's made up of these individual things,
these atoms, but atoms can actually themselves be,

which are made of nuclei,
which contain the positive particles in the neutrons.
And then the electrons, which are very, very light,
very much less mass than the nucleus,
and that's around this.
This is what makes up an atom.
So a plasma is what happens when you start pulling away
enough of those electrons that they're free from the ion.
So all the atoms that make us up in this water
and all that, the electrons are in tightly bound states
and basically they're extremely stable.
Once you're at about 5,000 or 10,000 degrees,
you start pulling off the electrons.
And what this means is that now the medium that is there,
its constituent particles mostly have net charge on them.
So why does that matter?
It's because now this means that the particles can interact
through their electric charge.
In some sense, they were when it was in the atom as well too,
but now that they're free particles,
this means that they start,
it fundamentally changes the behavior.
It doesn't behave like a gas.
It doesn't behave like a solid or liquid.
It behaves like a plasma, right?
And so why is it disappointing
that we don't speak about this?
It's because 99% of the universe is in the plasma state.
It's called stars.
And in fact, our own sun at the center of the sun
is what clearly a plasma,
but actually the surface of the sun,
which is around 5,500 Celsius is also a plasma
because it's hot enough that is that.
In fact, the things that you see,
sometimes you see these pictures
from the surface of the sun, amazing,
like satellite photographs of like those big arms of things
and of light coming off of the surface of the sun
and solar flares, those are plasmas.
What are some interesting ways
that this force data matters different than gas?
Let's go to how a gas works, right?

So the reason a gas,
and it goes back to Feynman's brilliant sense saying
that this is the most important concept.
The reason actually solid liquid and gas phases work
is because the nature of the interaction
between the atoms changes.
And so in a gas, you can think of this as being this room
and the things, although you can't see them,
is that the molecules are flying around,
but then with some frequency,
they basically bounce into each other.
And when they bounce into each other,
they exchange momentum and energy around on this.
And so it turns out that the probability
and the distances and the scattering
of those of what they do,
it's those interactions that set the,
about how a gas behaves.
So what do you mean by this?
Well, so for example,
if I take an imaginary test particle of some kind,
like I spray something into the air
that's got a particular color,
in fact, you can do it in liquids as well too,
like how it gradually will disperse away from you.
This is fundamentally set
because of the way that those particles are bouncing
into each other.
The probabilities of those particles bouncing.
The rate that they go at
and the distance that they go at and so forth.
So this was figured out by Einstein and others
at the beginning of the Brownian motion,
all these kinds of things.
These were set up at the beginning of the last century
and it was really like this great revelation.
Wow, this is why matter behaves the way that it does.
Like, wow.
So, but it's really like,
and also in liquids and in solids,
like what really matters is how you're interacting
with your nearest neighbor.
So you think about that one,

the gas particles are basically going around
until they actually hit into each other though,
they don't really exchange information.
And it's the same in a liquid,
you're kind of beside each other,
but you can kind of move around in a solid,
you're literally like stuck beside your neighbor,
you can't move like that.
Plasmas are weird in the sense is that it's not like that.
So it's because the particles have electric charge,
this means that they can push against each other
without actually being in close proximity to each other.
It's not, that's not an infinitely true statement,
which we go together, it's a little bit more technical,
but basically this means that you can start having action
or exchange of information at a distance.
And that's in fact the definition of a plasma
that it says, these have a technical name,
it's called a Coulomb collision,
it just means that it's dictated by this force,
which is being pushed between the charged particles,
is that the definition of a plasma is a medium
in which the collective behavior is dominated
by these collisions at a distance.
So you can imagine, then this starts to give you
some strange behaviors,
which I could quickly talk about like for example,
one of the most counterintuitive ones is
as plasmas get more hot, as they get higher in temperature,
then the collisions happen less frequently, like what?
That doesn't make any sense.
When particles go faster,
you think they would collide more often,
but because the particles are interacting,
they're interacting through their electric field,
when they're going faster, they actually spend less time
in the influential field of each other,
and so they talk to each other less,
and in an energy and momentum exchange point of view.
It's just one of the counterintuitive aspects of plasmas.
Which is probably very relevant for nuclear fusion.
Yes, exactly.
So if I can try to summarize

what a nuclear fusion reactor is supposed to do,
so you have what, a couple of elements,
what are usually the elements?
Usually deuterium and tritium,
which are the heavy forms of hydrogen.
Hydrogen, you have those and you start heating it,
and then as you start heating it,
I forgot the temperature you said,
but it becomes plasma.
No, first it becomes.
Oh, first it becomes plasma, so it's a gas,
and then it turns into a plasma at about 10,000 degrees.
And then so you have a bunch of electrons and ions
flying around, and then you keep heating the thing.
And I guess as you heat the thing,
the ions hit each other rarer and rarer?
Yes.
So, oh man, that's not fun.
So you have to keep heating it,
such that you have to keep hitting it
until the probability of them colliding
becomes reasonably high.
And also on top of that, and sorry to interrupt,
you have to prevent them
from hitting the walls of the reactor somehow.
So you asked about the definitions
of the requirements for fusion.
So the most famous one or some sense
the most intuitive one is the temperature.
And the reason for that is that you can make
many, many kinds of plasmas
that have zero fusion going on in them.
And the reason for this is that the average,
so you can make a plasma at around 10,000.
In fact, if you come, by the way,
you're welcome to come to our laboratory at the PSFC.
I can show you a demonstration of a plasma
that you can see with your eyes
and sit at about 10,000 degrees.
And you can put your hand up beside it and all this.
And it's like, and nothing, there's zero fusion going on.
So you have, sorry, what was the temperature
of the plasma?

10,000 degrees?
You can stick your hand in?
Well, you can't stick your hand into it,
but there's a glass tube.
You can basically see this with your bare eye.
And you can put your hand on the glass tube
because it's-
What's the color?
It's purple.
It's purple, yeah.
It's purple.
It is kind of beautiful.
Yeah, plasmas are actually quite astonishing
sometimes in their beauty.
Actually, one of the most amazing forms of plasma
is lightning, by the way,
which is instantaneous form of plasma that exists on Earth,
but immediately goes away
because everything else around it's at room temperature.
That's fascinating.
Yeah, so there's different requirements in this.
So making a plasma takes about this,
but at 10,000 degrees, even at a million degrees,
there's almost no probability
of the fusion reactions occurring.
And this is because while the charged particles
can hit into each other,
if you go back to the very beginning of this,
remember I said, oh, these charged particles
have to get to within distances
which are like this size of a nucleus
because of the strong nuclear force.
Well, unfortunately, as the particles get closer,
the repulsion that comes from the charge,
the Coulomb force,
increases like the inverse distance squared.
So as they get closer,
they're pushing harder and harder apart.
So then it gets a little bit more exotic,
which maybe you will like though,
that it turns out that people understood this
at the beginning of the age
of after Rutherford discovered the nucleus.

It's like, oh, yeah, it's like,
how are we going to, how's this gonna work, right?
Because how do you get anything within these distances?
It's like, inquire, extraordinary energy.
And it does.
And in fact, when you look at those energies,
they're very, very high.
But it turns out quantum physics comes to the rescue
because the particles aren't actually just particles.
They're also waves.
This is the point of quantum, right?
You can treat them both as waves and as particles.
And it turns out if you get,
if they get in close enough proximity to each other,
then the particle pops through basically this energy barrier
through an effect called quantum tunneling,
which is really just the transposition of the fact
that it's a wave so that it has a finite probability of this.
By the way, you talk about like,
do you have a hard time like conceptualizing this?
These are, this is one of them.
Quantum tunneling is one of them.
This is like throwing a ping-pong ball
like at a piece of paper.
And then every like, you know,
100 of them just like magically show up
on the other side of the paper
without seemingly breaking the paper.
I mean, to use a physical analogy.
And that phenomena as important is critical
for the function of nuclear fusion.
Yes, for all kinds of fusion.
So this is the reason why stars can work as well too.
Like the stars would have to be much,
much hotter actually to be able to.
In fact, it's not clear that they would actually ignite,
in fact, without this effect.
And so we get to that.
So this is why there's another requirement.
It's not, so you must make a plasma,
but you also must get it very hot
in order for the reactions
to have a significant probability to actually fuse.

And it actually falls effectively almost to zero
for lower temperatures as well too.
So there's some nice equation
that gets you to 50 million degrees
or like the order you said,
practically speaking 100 million.
So it's a really simple equation.
It's the ideal gas law basically, almost always.
In the end, you've got a certain number of particles,
of these fusion particles in the plasma state.
They're in the plasma state.
There's a certain number of particles.
And if the confinement is perfect,
if you put in a certain content of energy,
then basically eventually they just,
they come up in a temperature
and they become, they go up to high temperature.
This turns out to be, by the way, extraordinarily small
amounts of energy.
And you go, what?
It's like I'm getting something to like 100 million degrees.
That's going to take the biggest flame burner
that I've ever seen.
No.
And the reason for this is it goes back
to the energy content of this.
So yeah, you have to get it to high average energy,
but there's very, very few particles.
There's low density.
How do you get it to be low density in a reactor?
So the way that you do this is primarily, again,
this is not exactly true in all kinds of fusion,
but in the primary one that we work on magnetic fusion,
this is all happening in a hard vacuum.
So it's like it's happening in outer space.
So basically you've gotten rid of all the other particles,
except for these specialized particles.
So you add them one at a time.
No, actually it's even easier than that.
You connect a gas valve and you basically leak gas into it.
In a controlled fashion.
Yeah, yeah.
Well, this is beautiful.

It's a gas cylinder.
How do you get it from hitting the walls?
Yeah.
So now you've touched on the other necessary requirements.
So it turns out it's not just temperature that's required.
You must also confine it.
So what does this mean?
Confine it.
And there's two types of confinement, as you mentioned.
You mentioned the magnetic one.
Magnetic one, and there's one called inertial as well too.
But the general principle actually has nothing to do with,
in particular, with what the technology is
that you use to confine it.
It's because this goes back to the fact
that the requirement in this is high temperature
and thermal content.
So it's like building a fire, man.
And what this means is that if you,
when you release the energy into this,
or apply heat to this,
if it just instantly leaks out,
it can never get hot, right?
So if you're familiar with this,
it's like you've got something that you're trying
to apply heat to,
but you're just throwing the heat away very quickly.
This is why we insulate homes, by the way,
and things like this, right?
It's like you don't want the heat that's coming
into this room to just immediately leave,
because you'll just start consuming infinite amounts
of heat to try to keep it hot.
So in the end, this is one of the requirements.
And it actually has a name.
We call the energy confinement time.
So this means if you release a certain amount of energy
into this fuel, kind of how long,
you sit there and you look at your watch,
how long does it take for this energy
to like leave the system?
So you could imagine that in this room,
that these heaters are putting energy

into the air in this room,
and you waited for a day,
but all the heat have gone to outside
if I open up the windows.
Oh, that's energy confinement time, okay?
So it's the same concept as that.
So this is an important one.
So all fusion must have confinement.
There's another more esoteric reason for this,
which is that people often confuse temperature and energy.
So what do I mean by that?
So this is literally a temperature,
which means that it is a system
in which all the particles,
every particle has high kinetic energy
and is actually in a fully relaxed state,
namely that entropy has been maximized.
I think it's a little bit more technical,
but this means that basically it is a thermal system.
So it's like the air in this room,
it's like the water, it's the water in this.
These all have temperatures,
but it means that there's a distribution of those energies
because the particles have collided so much that it's there.
So this is distinguished from having high energy particles,
like what we have in like particle accelerators
like CERN and so forth.
Those are high kinetic energy, but it's not a temperature.
So it actually doesn't count as confinement.
So we go through all of those.
You have temperature and then the other requirement,
not too surprising is actually that there has to be
enough density of the fuel.
Enough, but not too much.
Enough, but not too much, yes.
And so in the end, the way that there's a fancy name for it,
it's called the Lawson Criterion
because it was formulated by a scientist
in the United Kingdom about 1956 or 1957.
And this was essentially the realization,
oh, this is what it's going to take,
regardless of the confinement method.
These are, this is the basic,

what it is actually power balance is just says,
oh, there's a certain amount of heat coming in,
which is coming from the fusion reaction itself,
because the fusion reaction heats the fuel
versus how fast you would lose it.
And it basically summarized,
it's summarized by those three parameters,
which is fairly simple.
So temperature and then the reason we say 100 million degrees
is because almost always in,
for this kind of fusion, deuterium, tritium fusion,
the minimum in the density and the confinement time product
is at about 100 million.
So you almost always design your device around that minimum.
And then you try to get it contained well enough
and you try to get enough density.
So that temperature thing sounds crazy, right?
That's what we've actually achieved in the laboratory.
Like our experiment here at MIT,
when it ran its optimum configuration,
it was at 100 million degrees.
But it wasn't actually the product of the density
in the confinement time wasn't sufficient
that we were at a place
that we were getting high net energy gain,
but it was making fusion reactions.
So this is the sequence that you go through,
make a plasma, then you get it hot enough.
And when you get it hot enough,
the fusion reactions start happening so rapidly
that it's overcoming the rate
that which is leaking heat to the outside world.
And at some point it just becomes like a star.
Like a sun and our own, our own sun and a star
doesn't have anything plugged into it.
It's just keeping itself hot
through its own fusion reactions.
In the end, that's really close
to what a fusion power plant would look like.
What does it visually look like?
Does it look like, like you said, like purple plasma?
You know.
Yeah, actually it's invisible to the eye

because it's so hot that it's basically emitting light
in frequencies that we can't detect.
It's literal, it's invisible.
In fact, light goes through it,
visible light goes through it so easy
that if you were to look at it,
what you would see in our own particular configuration,
what we make is in the end is a donut shaped,
it's a vacuum vessel to keep the air out of it.
And when you turn on the plasma,
it gets so hot that most of it just disappears
in the visible spectrum.
You can't see anything.
And there's very, very cold plasma,
which is between 10 and 100,000 degrees,
which is out in the very periphery of it, which is kind of,
so the very cold plasma is allowed to interact
with the, kind of has to interact with something
eventually at the boundary of the vacuum vessel.
And this kind of makes a little halo around it.
And it glows this beautiful purple light, basically.
And these are, that's the,
that's what weakened sense in the human spectrum.
I remember reading on a subreddit called shower thoughts,
which people should check out.
It's just fascinating philosophical ideas
that strike you while you're in the shower.
And one of them was,
it's lucky that fire, when it burns,
communicates that it's hot using visible light.
Otherwise, humans would be screwed.
I don't know if there's a deep, profound truth to that,
but nevertheless, I did find it on shower thoughts,
subreddit.
You have, this goes off in a bit of, you're right.
This is actually, it's interesting,
because as a scientist,
you also think about evolutionary functions
and how we got, like, why do we have the senses that we do?
It's an interesting question, right?
Like, why can bees see in the ultraviolet and we can't?
Then you go, well, it's natural selection.
For some reason, this wasn't really

particularly important to us, right?
Why can't we see in the infrared and other things can?
It's like, mm-hmm, mm-hmm.
It's a fascinating question, right?
Obviously, there's some advantage
that you have there that isn't there,
and even color distinguishing, right?
Of something safe to eat, whatever it would be.
I'll actually go back to this,
because it's something that I tell all of my students
when I'm teaching ionizing radiation
and radiological safety.
Whatever you say, there's a cultural concern
or that when people hear the word radiation,
like, what does this mean?
It literally just means light is what it means, right?
But it's light in different parts of the spectrum, right?
And so it turns out, besides the visible light
that we can see here, we are immersed
in almost the totality of the electromagnetic spectrum.
There is visible light, there's infrared light,
there is microwaves going around,
as that's how our cell phone works.
You can't, it's way past our detection capability.
But also higher energy ones,
which have to do with ultraviolet light,
how you get a sunburn,
and even X-rays and things like this at small levels
are continually being, like from the concrete
and the walls of this hotel,
there's X-rays hitting our body continuously.
I can bring out, we can go down to the lab at MIT
and bring out a detector and show you.
Every single room will have these.
By our body, you mean the 10 to the 28 atoms?
Yeah, the 10 to the 28 atoms,
and they're coming in and they're interacting
with those things.
And those, particularly the ones where the light
is at higher average energy per light particle,
those are the ones that can possibly have an effect
on human health.
So we have, it's interesting,

humans and all animals have evolved on Earth
where we're immersed in that all the time.
There's natural source of radiation all the time,
yet we have zero ability to detect it, like zero.
Yeah, and our ability,
cognitive ability to filter it all out and not give it down.
It would probably overwhelm us, actually,
if we could see all of it.
But my main point is it goes back to your thing
about fire and self-protection.
If these ionizing radiation was such a critical aspect
of the health of organisms on Earth,
we would almost certainly have evolved methods
to detect it, and we have none.
And the physical world that's all around is just incredible.
You're blowing my mind, Dr. Dennis White.
Okay, so you have experience with magnetic confinement.
You have experience with inertial confinement.
Most of your work has been a magnetic confinement.
But let's sort of talk about the sexy, recent thing
for a bit of a time.
There's been a breakthrough in the news
that laser-based inertial confinement was used
by DOE's National Ignition Facility
at the Lawrence Livermore National Laboratory.
Can you explain this breakthrough
that happened in December?
Yeah, so it goes to the set of criteria
that I talked about before about getting high energy gain.
So in the end, what are we after infusion
is that we basically assemble this plasma fuel in some way
and we provide it a starting amount of energy,
think of lighting the fire.
And what you want to do is get back significant excess gain
from the fact that the fusion is releasing the energy.
So it's the equivalent of we wanna have a match,
a small match, light a fire,
and then the fire keeps us hot.
It's very much like that.
So as I said, we've made many of the,
and what I mean by we,
it's like the fusion community has pursued aspects of this
through a variety of different confinement methodologies.

Is that the key part about what happens,
what was the threshold we had never gotten over before
was that if you only consider the plasma fuel,
not the total engineering system,
but just the plasma fuel itself,
we had not gotten to the point yet
where basically the size of the match
was smaller than the amount of energy
that we got from the fusion.
Is there a good term for when the output
is greater than the input?
Yes, yes, there is.
Well, there's several special definitions of this.
So one of them is that if you, like in a fire,
if you light a match and you have it there,
and it's an infinitesimal amount of energy
compared to what you're getting out of the fire,
we call this ignition, which makes sense, right?
This is like what our own son is as well too.
So that was not ignition in that sense as well too.
So what we call this is scientific,
what the one that I just talked about,
which is for some instance,
when I get enough fusion energy released
compared to the size of the match,
we call this scientific break-even.
Break-even.
Break-even.
And it's because you've gotten past the fact
that this is unity now at this point.
What does fusion gain or as using the notation Q
from the people who reviewed the spark talk-a-mock
before using just the same kind of term?
Yeah, actually, so that is, sorry,
the technical term is Q, capital Q.
Oh, so people actually use Q.
We actually use capital Q.
Or some days it's called Q.
Q is taken.
Q sub P or something like this.
Okay, so this is,
which means what it means is that it's in the plasma.
So all we're considering is the energy balance

or a gain that comes from the plasma itself.
We're not considering the technologies
which are around it, which are providing
the containment and so forth.
So why the excitement?
And so, well, because for one reason,
it's a rather simple threshold to get over,
to understand that you're getting more energy out
from the fusion, even a theoretical sense
than you were from the starting match.
Do you mean conceptually simple?
It's conceptually simple that you get past one,
that everyone under, like when you're less than one,
that's much less interesting than getting past one.
So that's a really big threshold.
You started to get energy gain, yeah.
To get past.
But it's really, it really is a scientific threshold
because what QP actually denotes
is the relative amount of self-heating
that's happening in the plasma.
So what I mean by this is that in the end,
in these systems, and what you want is something
that where the relative amount of heating,
which is keeping the fuel hot,
is dominated by from the fusion reactions themselves.
And so it becomes, it's sort of like thinking
like a bonfire is a lot more interesting physically
than just holding a blow torch to a wet log, right?
There's a lot more dynamics,
it's a lot more self-evolved and so forth.
And what we're excited as as scientists
is that it's clear that in that experiment,
that they actually got to a point
where the fusion reactions themselves
were actually altering the state of the plasma.
It's like, wow.
I mean, we'd seen it in glimpses before
in magnetic confinement at relatively small levels,
but apparently it seems like in this experiment,
it's likely to be a dominant, dominated by self-heating.
That's a very important, that's a very-
So that makes it a self-sustaining type of thing.

It's more self-sustaining,
it's more self-referential system in a sense.
And it sort of self-evolves in a way.
Again, it's not that it's going to evolve
to a dangerous state,
it's just that we want to see what happens
when the fusion is the dominant heating source.
And we'll talk about that,
but there's also another element,
which is the inertial confinement,
laser-based inertial confinement,
it's kind of a little bit of an underdog.
I guess so a lot of the broad nuclear fusion communities
have been focused on magnetic confinement.
Can you explain just how laser-based inertial confinement
works so it says 192 laser beams
were aligned on a deuterium-tradium-dt target
smaller than a P.
Yes.
This is like-
Maybe, actually, yeah.
Okay, well, it depends,
not all P's are made the same.
But this is like throwing a perfect strike
in baseball from a pitch.
This is like a journalist wrote this, I think.
This is like, oh no, it's not a journalist,
it's DOE wrote.
Yeah, yeah, it could be, we try to use all these analogies.
This is like throwing a perfect strike
in baseball from a pitcher's mount 350 miles away
from the plate.
There you go.
Department of Energy.
The United States Department of Energy wrote this.
Okay.
Can you explain what the laser's-
What actually happens?
Actually, there's usually mass confusion about this.
So what's going on in this form of it?
So the fuel is delivered in a discrete,
the fusion fuel, the deuterium-tradium,
is in a discrete spherical,

it's more like a BB, let's call it a BB.
So it's a small one.
And all the fuel that you're gonna try to burn
is basically there, okay?
And it's about that size.
So how are you going to get,
and it's literally, it's like at 20 degrees
above absolute zero,
because the deuterium and tridium are kept
in a liquid and solid state.
Oh wow, so the fuel is injected not as a gas as a solid.
It's actually, and these are particular experiments
like an introduce one of these targets once per day
approximately, something like that.
Cause it's very, it's very,
it's a kind of amazing technology actually that,
I know some of the people that worked on this
back in the day is they actually make these things
at a BB size of this frozen fuel,
it's actually at cryogenic temperatures.
And they're almost like smooth to the atom level.
I mean, they're amazing pieces of technology.
So what you do in the end is think,
what you have is a spherical assembly of this fuel,
like a ball, and what is the purpose of the lasers?
The purpose of the lasers is to provide optical energy
to the very outside of this.
And what happens is the, that energy is absorbed
because it's in the solid phase of matter.
So it's absorbed really in the surface.
And then what happens is that when it's absorbed
in something called the ablator, what does that mean?
It means it goes instantly from the solid phase
to the gas phase.
So it becomes like a rocket engine.
And, but you hit it like very uniformly.
So all, there's like rocket engines coming off the surface.
Think of like an asteroid almost,
where there's like rockets coming off all this thing.
So what does that do?
Well, what does a rocket do?
It actually pushes by Newton's laws, right?
It pushes the other thing on the other side of it,

equal and opposite reaction.
It pushes it in.
So what it does is that the lasers actually don't heat.
This is what was confusing.
People think the lasers, oh, we're gonna get it
to a hundred million degrees.
In fact, you want the exact opposite of this.
What you want to do is get essentially a rocket
going out like this.
And then what happens is that the sphere like,
and this is happening in a billionth of a second
or lasts actually, this rapidly, that force,
like so rapidly compresses the fuel,
that what happens is that you're squeezing down on it
and it's like, what was the...
See, BB, that's bad, actually BB.
I should have started with a basketball.
Goes from like a basketball down to something like this.
And a billionth of a second.
And when that happens, I mean, scale that in your mind.
So when that happens, and this comes from,
almost from classical physics,
so there's some quantum in it as well too.
But basically, if you can do this like very uniformly
and so-called adiabatically,
like you're not actually heating the fuel,
what happens is you get adiabatic compression
such that the very center of this thing
all of a sudden just spikes up in temperature
because it's actually done so fast.
So why is it called inertial fusion?
It's because you're doing this on such fast time scales
that the inertia of the hot fuel basically is still finite
so it can't like push itself apart
before the fusion happens.
Oh wow, so how do you make it so fast?
This is why you use lasers
because you're applying this energy
in very, very short periods of time,
like under a fraction of a billionth of a second.
And so basically that, and then the force
which is coming from this comes from the energy
of the lasers, which is basically the rocket action

which does the compression.
So is the force, is the inward facing force,
is that increasing the temperature?
No, you wanna keep the fuel cold
and then just literally just ideally compress it.
And then in something which is at the very center
of that compressed sphere
because you've compressed it so rapidly,
the laws of physics basically require
for it to increase in temperature.
So the change in temperature.
The effect is like if you know the thing,
so adiabatic cooling we're actually fairly familiar with.
If you take a spray can, right, and you push the button,
when it rapidly expands, it cools.
This is the nature of a lot of cooling technology
we use actually.
Well, the opposite is true
that if you would take all of those particles
and jam them together very fast back in,
they wanna heat up and that's what happens.
And then what happens is you basically have this
very cold compressed set of fusion fuel
and at the center of this,
it goes to this 100 million degrees Celsius.
And so if it gets to that 100 million degrees Celsius,
the fusion fuel starts to burn.
And when that fusion fuel starts to burn,
it wants to heat up the other cold fuel around it
and it just basically propagates out so fast
that what you would do, ideally,
you would actually burn in a fusion sense
most of the fuel that's in the pellet.
So this was very exciting because what they had done
was it's clear that they propagated this,
they got this, what they call a hotspot.
And in fact, that this heating can propagate it
out into the fuel.
And that's the science behind inertial fusion.
So the idea behind a reactor is based on this
kind of inertial confinement
is that you would what have a new BB every like...
10 times a second or something like this.

And then there's some kind of...
So there's a incredible device that you kind of implied
that kind of has to create one of those BBs that did so.
So you have to make the BBs very fast.
There's reports on this, but about what does it mean?
The starting point is can you make this gain?
So this was a scientific achievement primarily.
And the rest is just engineering.
No, no, no, the rest is incredibly complicated engineering.
Well, in fact, there's still physics hurdles to overcome.
So where does this come from?
And it's actually because if you want to make
an energy source out of this,
this had a gain of around 1.5,
that namely the fusion energy was approximately,
was 1.5 times the laser input energy.
This is a fairly significant threshold.
However, from the science of what I just told you
is that there's two fundamental efficiencies
which come into it, which really come from physics really.
One of them is hydrodynamic efficiency.
What I mean by this is that it's a rocket.
So it just has a fundamental efficiency built into it,
which comes out to orders of like 10%.
So this means is that your ability to do work
on the system is just limited by that, okay?
And then the other one is the efficiency
of laser systems themselves,
which if the wall plug efficiency is 10%,
you've done spectacularly.
Well, in fact, the wall plug efficiency
of the ones using that experiments are like more like 1%, right?
So when you go through all of this,
the approximate place that you're ordering this
is for a fusion power plant would be a gain of 100, not 1.5.
So you still, and hopefully we see experiments
that keep climbing up towards higher and higher gain,
but then the whole fusion power plant
is a totally different thing.
So it's not one BB and one laser pulse per day.
It's like five or 10 times per second.
Like, like that, right?
So you're doing it there.

And then comes the other aspect.
So it's making the targets, delivering them,
being able to repeatedly get them to burn.
And then we haven't even talked about like,
how do you then get the fusion energy out?
Which is mainly because these things
are basically micro implosions which are occurring.
So this energy is coming out to some medium on the outside
that you've got to figure out
how to extract the energy out of this thing.
How do you convert that energy to electricity?
So in the end, you have to basically convert it
into heat in some way.
So in the end, what fusion makes mostly
is like very energetic particles from the fusion reaction.
So you have to slow those down in some way
and then make heat out of it.
So basically the conversion of the kinetic energy
of the particles into heating some engineered material
that's on the outside of this.
And that's, from a physics perspective,
is a somewhat solved problem,
but from an engineering is still quite open.
Physics, I can draw the,
I can show you all the equations
that tell you about how it slows down
and converts kinetic energy into heat.
And then what that heat means, you know,
you can write out like an ideal thermal cycle,
like a Carnot cycle.
So the physics of that, yeah, great.
The integrated engineering of this is a whole other thing.
I'll ask you to maybe talk about the difference
between an initial magnetic,
but first we'll talk about magnetic,
but let me just linger on this breakthrough.
You know, it's nice to have exciting things,
but in a deep human sense,
there's no competition in science and engineering.
Or like you said, we were broad.
First of all, we are a humanity all together.
And you talk about this,
it's a bunch of countries collaborating.

It's really exciting.
There's a nuclear fusion community broadly.
But then there's also MIT.
There's colors and logos, and it's exciting.
And you have friends and colleagues here
that work extremely hard and done some incredible stuff.
Is there some sort of,
how do you feel seeing somebody else get a breakthrough
in using a different technology?
Is that exciting?
Is this the competitive fire?
Get-
All of the above.
I mean, I mean-
The ignition-
I saw just to wave the flag a little bit.
So MIT was a central player in this accomplishment.
Interesting, I'd say it showed some of our two best traits.
So one of them was that the,
like, how do you know that this happened?
This measurement, right?
So one of the ways to do this is if I told you,
is that in the DT fusion,
what it actually, the product that comes out is helium,
what we call an alpha, but it's helium,
and a free neutron, right?
So the neutron contains 80% of the energy
released by the fusion reaction.
And it also, because it lacks a charge,
it basically tends to just escape and go flying out.
So this is what we would use eventually for.
That's mostly what fusion energy would be.
But so what my colleagues, my scientific colleagues
at the Plasma Science and Fusion Center built
were extraordinary measurement tools
of being able to see the exact details
of not only the number of neutrons that were coming out,
but actually what energy that they're at.
And by looking at that configuration,
it reveals enormous, I'm not gonna scoop them
because they need to publish the paper,
but it reveals enormous amounts of scientific information
about what's happening in that process

that I just described.
So exciting, I mean, and I have colleagues there
that have worked like 30 years on this for that moment.
Of course you're excited for them, right?
And there's one of those, like there is nothing,
it's hard to describe to people who aren't,
it's almost addicting to be a scientist
when you get to be at the forefront of research
of anything, like when you see like an actual discovery
of some kind and you're looking at it,
particularly when you're the person who did it, right?
And you go, no human being has ever seen this
or understood this.
It's like, it's pretty thrilling, right?
So even in proxy, it's incredibly thrilling to see this.
It's not, I don't wanna say it's rivalry or jealousy.
It's like, I can tell you already, fusion is really hard.
So anything that keeps pushing the needle forward
is a good thing, but we also have to be realistic
about what it means to making a fusion energy system.
That's the-
And then, but that's the fun, I mean,
these are the still the early steps,
you maybe can say the early leaps.
Yeah.
So let's talk about the magnetic confinement.
Yeah.
What is, how does magnetic confinement work?
What's the talk of Mac?
Yeah, how does it all work?
So go back to that.
So why inertial confinement works
on the same principle that a star works.
So like, what is the confinement mechanism in the star
is gravity because it's own inertia
of the something the size of the sun
basically pushes a literally a force by gravity
against the center.
So the center is very, very hot, 20 million degrees.
And literally outside the sun,
it's essentially zero because it's vacuum of space.
How the hell does that do that?
It does that by, and it's out of,

like why doesn't it just leak all of its heat?
It doesn't leak its heat because it all is held together
by the fact that it can't escape because of its own gravity.
So this is why the fusion happens in the center of the star.
Like we think of the surface of the sun as being hot.
That's the coldest part of the star.
So if our own sun, this is about in 5,500 degrees,
a beautiful symmetry by the way is like,
so how do we know all this?
Cause we can't of course see directly
into the interior of the sun by knowing the volume
and the temperature of the surface of the sun.
You know exactly how much power it's putting out.
And by this, you know that this is coming
from fusion reactions occurring at exactly the same rate
in the middle of the sun.
Is it possible as a small tangent to build
an inertial confinement system like the sun?
Is it possible to create a sun?
It is of course possible to make a sun,
although he's doing to have stars,
but it is not impossible on earth
because for the simple reason that it takes,
the gravitational force is extremely weak.
And so it takes something like the size of a star
to make fusion occur in the center.
Well, I didn't mean on earth.
I mean, if you had to build like a second sun,
how'd you do it?
You can't, there's not enough hydrogen around.
So the limiting factor is the just the hydrogen.
Yeah, I mean, the forces that an energy
that it takes to assemble that is just mind boggling.
All right, so we will do that.
To be continued.
Yeah, to be continued.
So what are we doing it with?
So in the one that I just described, it's like you say,
so you have to replace this with some force
which is better than that.
And so what I mean by that, it's stronger than that.
So what I talked about the laser fusion,
this is coming from the force,

which is enormous compared to gravity, like,
from the rocket action of pushing it together.
So in magnetic confinement, we use another force of nature,
which is the electromagnetic force.
And that's very orders and orders of magnitude stronger
than the gravitational force.
And the key force that matters here
is that if you have a charged particle,
that namely it's a particle that has an electric,
net electric charge, and it's in the proximity
of a magnetic field, then there is a force
which is exerted on that particle.
So it's called the Lorentz force
for those who are keeping track.
So that is the force that we use
to replace physical containment.
So, and so this again,
how do you hold something at 100 million degrees?
It's impossible in a physical container.
This is not like, you know,
it's not less plastic bottle holding in this liquid
or a gas chamber.
What you're doing is you're using,
you're immersing the fuel in a magnetic field
that basically exerts a force at a distance.
This comes back again to again,
like why plazas are so strange.
It's the same thing here.
And if it's immersed in this magnetic field,
you're not actually physically touching it,
but you're making a force go onto it.
So that's the inherent feature of magnetic confinement.
And then magnetic confinement devices are like a tokamak
are basically configurations
which exploit the features of that magnetic containment.
There's several features to it.
One is that the stronger the strength
of the magnetic field, the stronger the force.
And for this reason is that
if you increase the strength of magnetic fields,
this means that the containment,
because namely the force which you're pushing against it
is more effective.

And the other feature is that there is no force.
So for those who remember magnetic fields,
what are these things?
They're also invisible.
But if you think of a permanent magnets
or your fridge magnet, there are field lines
which we actually designate as arrows
which are going around.
You sometimes see this in school
when you have the iron filings on a thing
and you see the directions of the magnetic field lines
or when you use a compass.
So that's telling you in the world
because we're living in an immersed magnetic field
made by the earth,
which is that very low intensity magnetic field.
It's strong enough we can actually see what direction is.
So this is the arrow that the magnetic field is pointing.
And it's always pointing north and for us is that,
so an interesting feature of this force
is that there is no force
along the direction of the magnetic field.
There's only force in the directions orthogonal
to the magnetic field.
So this by the way is a huge deal
in a whole other discipline of plasma physics
which is like the study of like our near atmosphere.
So the study of Aurora Borealis,
what's happening in the near atmosphere,
what happens when solar flares hit the magnetic field.
In fact, remember I said fusion is the reason
that life is responsible in the universe.
We could also argue so is magnetic confinement
because the charged particles which are being emitted
from the galaxy and from our own star
would be very, very damaging on earth.
So we get two layers of protection.
One is the atmosphere itself,
but the other one is the magnetic field
which just surrounds the earth
and basically traps these charged particles
so they can't get away.
It's the same deal.

How do you create a strong magnetic field?
Yeah, so.
With a giant magnet.
Giant magnet, yeah.
So it's basically true.
Engineering is awesome.
There's essentially two ways to create a magnet.
So one of them is that we're familiar
with like fridge magnets and so forth.
These are so-called permanent magnets.
And what it means is that within these,
the atoms arrange in a particular way
that it produces the electrons
basically arrange in a particular way
that it produces a permanent magnetic field
that is set by the material.
So those have a fundamental limitation
how strong they can be.
And they also tend to have this like circular shape like this.
So we don't typically use those.
So what we use are so-called electromagnets.
And what is this?
It's like, so the other way to make a magnetic field
also go back to your elementary school physics
or science class is that you take a nail
and you wrap a copper wire around it
and connect it to a battery.
Then it can pick up iron filings.
This is an electromagnet.
And it's simplest what it is, it's an electric current
which is going in a pattern around and around and around.
And what this does is it produces a magnetic field
which goes through it by the laws of electromagnetism.
So that's how we make the magnetic field
in these configurations.
And the key there is that it's not limited
by the magnetic property of the material.
The magnetic field amplitude is set
by the amount of, the geometry of this thing
and the amount of electric current that you're putting through.
And the more electric current that you put through
the more magnetic field that you get.
The closest one that people maybe see

is one of my, one of my favorite skits actually
was Super Dave Osborn on, it's probably past you.
It was like in a show called Bazaar.
Super Dave Osborn, which is a great comedian cult.
He was a stunt man.
And one of his tricks was that he was,
he gets into a car and then one of those things
in the junk yard comes down, you know,
and picks up the car and then puts it into the crusher.
This is his stunt, which is pretty hilarious.
Anyway, but that thing that picks him up,
like how does that work?
That's actually not a permanent magnet.
It's an electrical magnet.
And so you can turn, by turning off and on the power supply,
it turns off and on the magnetic field.
So this means you can pick it up
and then when you switch it off,
the magnetic field goes away and the car drops, okay?
So that's what it looks like.
Speaking of giant magnets,
MIT and Commonwealth Fusion Systems, CFS,
built a very large, high temperature,
superconducting electromagnet
that was ramped up to a field strength of 20 Tesla,
the most powerful magnetic field of its kind
ever created on Earth.
Because I enjoy this kind of thing.
Can you please tell me about this magnet?
Yeah, sure.
Oh, it was, it's fun, yeah.
There's a lot to parse there.
So maybe, so we already explained an electromagnet,
which in general is what you do is you take electric current
and you force it to follow a pattern of some kind,
typically like a circular pattern,
around and around and around and around.
It goes the more time, the more current
and the more times it goes around,
the stronger the magnetic field that you make, okay?
And as I pointed out,
it's like really important in magnetic confinement
because it is the force that's produced by that magnet.

In fact, technically it goes like the magnetic field squared
because it's a pressure,
which is actually being exerted on the plasma
to keep it contained.
Just so we know for magnetic confinement,
what is usually the geometry of the magnet?
What are we supposed to imagine?
Yeah, so the geometry is typically that,
typically is what you do is you want to produce
a magnetic field that loops back on itself.
And the reason for this was,
goes down to the nature of the force that I described,
which is that there's no containment or force
along the direction of the magnetic field.
So here's a magnetic field.
In fact, what it's more technically
or more graphically what it's doing
is that when the plasma is here,
here's plasma particles here, here's a magnetic field.
What it does is it forces all those,
because of this Lorenz force,
it makes all of those charged particles
execute circular orbits around the magnetic field.
And they go around like this,
but they stream freely along the magnetic field line.
So this is why the nature of the containment
is that if you can get that circle smaller and smaller,
it stays further away from earth, temperature materials.
That's why the confinement gets better.
But the problem is that because it free streams along,
so we just have a long straight magnetic field,
okay, it'll just keep leaking out the ends like really fast.
So you get rid of the ends.
So you basically loop it back around.
So what these look like are typically donut shaped
or more technically toroidal shaped,
but donut shaped things where this collection
of magnetic fields loops back on itself.
And it also for reasons which are more complicated
to explain basically it also twists,
that also twists slowly around
in this direction as well too.
So that's what it looks like.

That's what the plasma looks like
because that's what the fuel looks like.
So then this means is that the electromagnets
are configured in such a way
that it produces the desired magnetic fields around this.
So they-
How precise does this have to be?
You were probably listening to our conversation
with some of my colleagues yesterday.
So it's actually, it depends on the configuration
about how you're doing it.
The configuration of the plasma.
The configuration of the electromagnets
and about how you're achieving this requirement.
It's fairly precise,
but it doesn't have to be in particularly
in something like a tokamak.
What we do is we produce planar coils
which is mean they're flat and we situate them.
So if you think of a circle like this,
what does it produce?
If you put current through it,
it produces a magnetic field
which goes through the circle like this.
So if you align many of them like this, this, this, this,
there's things online.
You can go see the picture.
You keep arranging these around in a circle itself.
This forces the magnetic field lines
to basically just keep executing around like this.
So you tend to align.
That one tends to, while it requires good confine
or good alignment, it's not like insane alignment
because you're actually exploiting the symmetry
of the situation to help it.
There's another kind of configuration of magnetic,
of this kind of magnetic confinement called a stellarator
which is, we have these names for historic reasons.
Which is different than a tokamak.
It's different than a tokamak
but actually works on the same physical principle
that namely, in the end, it produces a plasma
which loops in magnetic fields

which loop back on themselves as well.
But in that case, the totality, basically,
the totality of the confining magnetic field
is produced by external three-dimensional magnets.
So they're twisted.
And it turns out the precision of those
is more stringent, yeah.
So our tokamaks by far more popular
for research and development currently than stellarators.
Of the concepts which are there, the tokamak
is by far the most mature
in terms of its breadth of performance
and thinking about how it would be applied
in a fusion energy system.
And the history of this was that many,
in fact, you asked what, if we go back
to the history of the plasma science and fusion center,
the history of fusion is that people,
scientists had started to work on this in the 1950s.
It was all hush-hush and cold war and all that kind of stuff.
And they realized, holy cow, this is really hard.
Like we actually don't really know what we're doing
in this, because everything was at low temperatures.
They couldn't get confinement.
It was interesting.
And then they declassified it.
And this is one of the few places
that the West and the Soviet Union
actually collaborated on was a science.
Even during the Cold War.
Even during the middle of the Cold War.
It was really, and this actually perpetuates
all the way to now for, we can talk about the project
that that is sort of captured in now.
But, and the reason they declassified it
was because like everything like kind of like
sucked basically, you know,
about trying to make this confinement
in high temperature plasma.
And then the Russians, then the Soviets, right,
came along with this device called a Tokamak,
which is a Russian acronym, which basically means
magnetic coils arranged in the shape of a donut.

And, and they said, holy, holy cow.
Like everyone was stuck at like a meager,
like half a million degrees or half a million degrees,
which is like in fusion terms of zero, basically.
And then they come along and they say,
oh, we've actually achieved a temperature 20 times higher
than everybody else.
And it's actually started to make fusion reactions.
And everyone just go, oh, you know, no way.
It's just hype from the, it's like, there's no way.
Cause we've failed at this.
It's a great story in the history of fusion is that then,
but they insisted and said, no, look,
you can see this from our data.
It's like, this thing is really hot.
And it seems to be working.
This is, you know, late 1960s.
And there was a, there was a team that went
from the United Kingdom's fusion development lab
and they brought this very fancy,
amazing new technology called a laser.
And they use this laser and they shot the laser beam
like through the plasma.
And by looking at the scattered light that came from the,
they go, that basically the scattered light
gets more broadened in its spectrum if it gets hotter.
So you could, you could exactly tell the temperature of this.
And even though you're not physically touching the plasma,
it's like, holy cow, you're right.
It is like, it is 10 million degrees.
And so this was one of those explosions of like,
everyone in the world then wanted to build a tokamak
because it was clearly like, wow, this is like so far ahead
of everything else that we tried before.
So that actually has a part of the story to MIT
in the Plasma Science and Fusion Center was,
why is there a strong fusion and a major fusion program at MIT?
It was because we were host
to the Francis Bitter Magnet Laboratory,
which is also the National Highfield Magnet Laboratory.
Well, you can see where this goes, right?
From this, you know, we're kind of telling the stories
backwards almost, but, you know, the, the,

the advent of a tokamak along with the fact
that you could make very strong magnetic fields
with the technology that had been developed at that laboratory.
That was the origins of sort of pushing together the physics
of the, of the plasma containment and the magnet technology
and put them together in a way that I would say is, you know,
a very typical MIT success story, right?
We don't do just, just pure science or pure technology.
We sort of set up this intersection between them.
And there were several pioneers that of my, of the,
of people at MIT, like Bruno Kopp,
who's a professor in the physics department,
and Ron Parker, who was a professor in electrical engineering
and nuclear engineering.
It's like even the makeup of the people, right?
His that got this blends of science and engineering in them.
And that's actually was the origin
of the Plasma Science and Fusion Center was,
was doing those things.
So anyway, so back to this.
So why, so yes, tokamaks have been,
have achieved the highest in magnetic fusion by far,
like the best amounts of these conditions
that I talked about.
And in fact, pushed right up to the point
where they were near QP of one.
They just didn't quite get over one.
So can we actually just linger on the,
on the collaboration across different nations?
Just maybe looking at the philosophical aspect of this.
Even in the Cold War,
there's something hopeful to me besides the energy
that these giant international projects
are a really powerful way to ease
some of the geopolitical tension,
even military conflict across nations.
There's a war in Ukraine and Russia.
There's a brewing tension and conflict with China.
Just the world is still seeking military conflict,
cold or hot.
What can you say about sort of the lessons
of the 20th century and these giant projects
in their ability to ease some of this tension?

So it's a great question.
So as I said, there was a reason,
because it was so hard,
that was one of the reasons they declassified it.
And actually they started working together
in some sense on it as well too.
And I think it was really,
there was, you know,
a heuristic or altruistic aspect to this.
It's like, this is something that could change,
you know, the future of humanity and its nature
and its relationship with energy.
Isn't this something that we should work on together, right?
And that went along in those ones.
And in particularly,
that any kind of place where you can actually have
an open exchange of people
who are sort of at the intellectual frontiers
of your society, this is a good thing, right?
Of being able to collaborate.
I've had the, I mean, I have had an amazing career.
I've worked with people from,
it's like hard to throw a dart at a country on the map
and not hit a country of people
that I've been able to work with.
How amazing is that?
And even just getting small numbers of people
to bridge the cultural and societal divides
is a very important thing.
Even when it's a very tiny fraction
of the overall populations,
it can be held up as an example of that.
But it's interesting that if you look at,
then that continued collaboration,
which continues to this day,
is that this actually played a major role, in fact,
in East-West relations or like Soviet-West relations,
is that back in the Reagan-Gorbachev days,
which of course were interesting in themselves
of all kinds of changes happening in both sides, right?
And, but still like a desire to push down
the stockpile of nuclear weapons and all that,
within that context,

there was a fairly significant historic event
that at one of the Reagan-Gorbachev summits
is that they had really, they didn't get there.
Like they couldn't figure out how to bargain
to the point of some part of the treaty
anymore, the details of it anymore.
But they needed some kind of a symbol, almost to say,
but we're still gonna keep working
towards something that's important for all of us.
What did they pick?
A fusion project.
And that was in the mid-1980s and actually,
then after, so they basically signed an agreement
that they would move forward to like literally collaborate
on a project whose idea would be to show
large net energy gain in fusion's commercial viability
and work together on that.
And very soon after that, Japan joined
as did the European Union.
And now that project, it evolved over a long period of time
and had some interesting political ramifications to it.
But in the end, this actually also had South Korea,
India and China join as well too.
So you're talking about a major fraction of,
and now Russia, of course, instead of the Soviet Union.
And actually that coalition is holding together
despite the obvious political turmoil
that's going around on all those things.
And that's a project called ETER,
which is under construction in the South of France
right now.
Can you actually look at it before we turn
to the giant magnet and maybe even talk about Spark
and the stuff going to all amazing stuff going on at MIT.
What is ETER?
What is this international nuclear fusion mega project
being built in the South of France?
So it's scientific purpose is a worthy one
that it's essentially in any fusion device,
the thing that you want to see is more and more
relative amounts of self-heating.
And this is something that had not been seen,
although we had made fusion reactions

and we'd seen small amounts of the self-heating,
we never got to it.
This actually goes to this QP business, okay?
The goal of ETER, and it shifted around
a little bit historically, but fairly quickly became
we want to get to a large amount of self-heating.
So this is why it has a,
its primary feature is to get to QP of around 10.
And through this, this is a way to study
this plasma that has more higher levels
of self-determination around on it.
But it also has another feature which was,
let's produce fusion power at a relevant scale.
And actually they're linked together,
which actually makes sense to you think about is that,
because the fusion power is the heating source itself,
this means that they're linked together.
And so ETER makes, is projected to make
about 500 million watts of fusion power.
So this is a significant amount,
like this is what you would use, you know,
for powering cities.
So it's not just the research,
they're really, it is the development
of really trying to achieve scale here.
So self-heating and scale.
Yeah, yes.
So this meant then too,
is the development of an industrial base
that can actually produce the technologies,
like the electromagnets and so forth.
And to do it with, it is a tokamak,
it is one of these, yes.
But very interesting,
it also revealed limitations of this as well too.
Like what?
Well, it is, it's interesting is that,
it is clearly a, on paper,
and in fact, in in practice as well too,
the world, you know, and very different political systems,
and you consider at least geopolitical
or economic rivals or whatever you want to use.
Like working towards a common cause,

and one that we all think is worthy is very like,
okay, that's very satisfying.
But it's also interesting to see the limitations of this.
It's because, well, you've got seven,
you know, chefs in the kitchen.
So what is this meant in terms of the speed of the project
and the ability to govern it and so forth?
It's just been a challenge, honestly, around this.
And this is, I mean, it's very hard technically,
what's occurring.
But when you also introduce such levels of,
I mean, this isn't just me saying it,
there's like GAO reports from the U.S. government
and so forth, it's hard to like, steer all of this around.
And what that's tended to do is make it,
it's not the fastest decision-making process.
You know, my own personal view of it was,
it was interesting, because you asked me,
you said about the magnet and common fusion systems.
It was, I worked most of my career on ETER
because when I came into the field in the early 1990s,
when I completed my PhD and started to work,
this was one of the most, like you can't imagine
being more excited about something,
like we're going to change the world with this project,
we're going to do these things.
And we just like pour it like an entire generation
and afterwards as well too is just poured their imagination
and their creativity about making this thing work.
Very good.
But also at some point though, when, you know,
when it got to being another five years of delay
or a decade of delay, you start asking yourself,
well, is this what I want to do?
Right, am I going to wait for this?
So it was a part of me starting to ask questions
with my students.
I was like, is there another way that we can get
to this extremely worthwhile goal,
but maybe it's not that pathway.
And the other part that was clearly frustrating to me
because I'm an advocate of fusion.
You asked me about was I, you know,

I was like, well, it's laser fusion
or inertial fusion or magnetic fusion.
I just want fusion energy, okay?
Because I think it's so important to the world is that,
but the other thing, if that's the case, then why do we have
only one attempt at it on the entire planet,
which was Eater.
It's like, that makes no sense to me, right?
We should have multiple attempts at this
with different levels of whatever you want to think about,
a technical, schedule, scientific risk
which are incorporated in them.
And that's going to give us a better chance
of actually getting to the goal line.
With that spirit, you're leading MIT's effort
to design Spark, a compact, high field,
DT burning Tachemac.
How does it work?
What is it?
What's the motivation?
What's the design?
What are the ideas behind it?
At its heart, it's exactly the same concept as Eater.
So it's basically a configuration of electromagnets.
It's arranged in the shape of a donut.
And within that, we will do the same thing
that happens in all the other Tachemacs
and including an Eater and in this one.
Is it namely you put in gas, make it into a plasma,
you heat it up, it gets to about 100 million degrees.
The differentiator in Spark is that
we use the actual deuterium tritium fuel.
And because of the access to very high magnetic fields,
it's in a very compact space.
It's very, very small.
What do I mean by small?
So it's 40 times smaller in volume than Eater.
But it uses exactly the same physical principles.
So this comes from the high magnetic field.
So in the end, why does this matter?
What it does is it does those things
and it should get to the point
where it's producing over 100 million watts of fusion power.

But remember, it's 40 times smaller.
So Eater was 500 megawatts.
Technically, our design is around 150 megawatts.
So it's only about a factor of three difference
despite being 40 times smaller.
And we see QP large order of 10 or something like this.
At that state is very important scientifically
because this is basically matches what Eater is looking to do.
The plasma is dominated by its own heating.
It's very, very important.
And it does that for about 10 seconds.
And the reason it's for 10 seconds is that
in terms of that, that basically allows everything to settle
in terms of the fusion in the plasma equilibrium,
everything is nice and settled.
So you know, you have seen the physical state
at which you would expect a power plant
to operate basically for magnetic fusion.
Like, wow, right?
But it's more than that.
And it's more than that,
it's because about who's building it
and why and how it's being financed.
So that scientific pathway was made possible
by the fact that we had access to a next generation
of magnet technology.
So to explain this real quick, why do we call it,
you said it in the words, a superconducting magnet.
What does this mean?
Superconducting magnet means that the materials
which are in the electromagnet have no electrical resistance.
Therefore, when the electric current is put into it,
the current goes around unimpeded.
So it could basically keep going around
and around, you know, technically for infinity.
And what that mean are for eternity.
And what that means is that the,
when you energize these large electromagnets,
they're using basically zero electrical power
to maintain them.
Whereas if you would do this in a normal wire, like copper,
you basically make an enormous toaster oven
that's consuming enormous amounts of power

and getting hot, which is a problem.
That was the technical breakthrough
that was realized by myself and at the time,
my students and postdocs and colleagues at MIT
was that we saw the advent of this new,
this new superconducting material,
which would allow us to access much higher magnetic fields.
It's basically a next generation of the technology.
And it was quite disruptive to fusion,
that namely what it would allow that if we could,
if we could get to this point
where we can make the round 20 Tesla,
we knew by the rules of Tokimax that this is going to be,
is going to allow us to vastly shrink
like the sizes of these devices.
So it wouldn't take, although it's a worthy goal,
it wouldn't take a seven nation international,
you know, treaty basically to build it.
You could build it with a company and a university.
So same kind of design,
but now using the superconducting magnets.
Yeah. And if, in fact, if you look at,
it's like it's, if you just expand the size of it,
they're like, they look almost identical to each other
because it's based on the,
and actually that comes for a reason, by the way,
is that it also looks like a bigger version of the Tokimax
that we ran at MIT for 20 years,
where we established the scientific benefits,
in fact, of these higher magnetic fields.
So that's the pathway that runs.
So we say, so what does this mean?
The context is different because it was made,
because it's primarily being made
by a private sector company spun out of MIT
because the way that it raised money
and the purpose of the entity which is there
is to make commercial fusion power plants,
not just to make a scientific experiment.
This is actually why we have,
it's why we have a partnership, right?
Is that our purpose at MIT is not to commercialize directly,
but boy, do we want to advance the technology

in the science that comes along this,
and that's the reason we're sort of doing it together.
So it's MIT and Commonwealth fusion systems.
So what's interesting to say about financing,
and this seems like from a scientific perspective,
maybe not an interesting topic,
but it's perhaps an extremely interesting topic.
I mean, you can just look at the tension
between SpaceX and NASA, for example.
It's just clear that there's different financing mechanisms
that actually significantly accelerate
the development of science and engineering.
It's great that you brought that up.
We use several historic analogs,
and one of them is around SpaceX,
which is an appropriate one because space,
putting things into orbit has a minimum size to it,
and integrated technological complexity,
and budget, and things like this.
So our point when we were talking
about starting a fusion commercialization company,
people look at you like,
isn't this still really just a science experiment?
But one of the things that we pointed to was SpaceX,
they say, well, tell me 25 years ago,
how many people would have voted that the leading entity
on the planet to put things into orbit?
It's a private company.
People would have thought you were not so, right?
It's like, and what is interesting about SpaceX
is that it proved it's more than actually just financing.
It's really the purpose of the organization.
So the purpose of a gut,
and I'm not against public finance or anything like that,
but the purpose of a public entity like NASA,
correctly speaks to the political,
because the cost comes from the political assembly
that is there, and I guess from us eventually as well too,
but its purpose wasn't about making a commercial product.
It's about fundamental discovery and so forth,
which is all really great.
It's like, why did SpaceX,
it's interesting, why did SpaceX succeed so well

is because the idea was it's like the focus
that comes in the idea that you're going to relentlessly
like reduce cost and increase efficiency
is a drive that comes from the commercial aspect of it, right?
And this also then changes the people in the teams,
which are doing it as well too.
And in fact, trickles throughout the whole thing
because the purpose isn't,
while you're advancing things,
like it's really good that we can put things
in orbit a lot more cheaply, like it advances science,
which is an interesting synergy, right?
And it's the same thing that we think
is going to happen in fusion,
that namely this is a bootstrap effect
that actually that when you start to push yourself
to think about near-term commercialization,
it allows the science to get in hand faster,
which then allows the commercialization to go faster
and up we go.
By the way, we've seen this also in another,
like again, you have to watch out with analogies
because they only can go so far,
but like biotech is another one.
Like you look at the human genome project,
which was, it's sort of like,
to me, that's like mapping the human genome
is like that we can make net energy from fusion.
Like it's one of those like in your drawer that you go,
this is a significant achievement by humanity,
right in the century.
And there's the human genome project,
fully government funded.
It's going to take 20, 25 years
because we basically know the technology.
We're just going to be really diligent,
keep going to, to, to, to.
And then all of a sudden, what comes along?
Disruptive technology, right?
You can sequence, you know, shock on sequencing
and computer, you know, recognition patterns.
And basically, oh, I can do this a hundred times faster.
Like, wow, right?

So that's really the, you know,
to me that the story about why we started,
why we launched Comma Fusion Systems
was more than just about another source of funding,
which it is a different source of funding
because it comes, it's also a different purpose,
which is very important.
But there's also something about a mechanism
that creates culture.
So giving power to like a young student, ambitious student
to have a tremendous impact on the progress
of nuclear fusion creates a culture
that actually makes progress more aggressively.
Like, like you said, when seven nations collaborate,
it gives more incentive to the bureaucracy
to slow things down, to kind of have,
let's have first have a discussion
and certainly don't give voice
to the young ambitious minds
that are really pushing stuff forward.
And there's something about like the private sector
that rewards, encourages, inspires young minds
to say in the most beautiful of ways,
FU to the, to the boss and to say like,
we'll make it faster, we'll make it simpler,
we'll make it better, we'll make it cheaper.
And sometimes that brashness doesn't bear out.
You know, that's an aspect
that you just take a different risk profile as well too.
But you're right, it's this, you know, of the,
I mean, it was interesting, our own trajectory
at the, at the fusion center was like,
we were pushed into this place by necessity as well too.
Because I told you, we have, and we had operated
for a long time, a Tokamak at, on the MIT campus,
achieve these world records like a hundred million degree
plasma and stuff like, wow, this is fantastic.
But, you know, somewhat ironically I have to say is
that it was like, oh, but we're not,
this isn't the future of fusion anymore.
Like we're not, we're just going to stop
with small projects because it's too small, right?
So we should need, we need to really move

on to these much bigger projects
because that's really the future of fusion.
And so it was defunded and this basically put at risk,
like, like we were going to essentially lose MIT
in the ecosystem, really a fusion,
both from the research, but also clearly important
from the educational part of it.
So we, you know, we pushed back against this,
we got a lifeline, we were able to go,
and it was in this, it was in this time scale
that we basically came up with this idea.
It's like, we should do this.
And in the end, it was all of those,
the people who were in the C level of the company
were all literally students who got caught in that.
They were PhD students at the time.
So you talk about enabling another generation.
It's like, yeah, there we go, right?
So Spark gave a lifeline.
A lifeline gave fuel to the future of MIT
that it continues.
But it's way more than that.
It wasn't just about like surviving
for the sake of surviving.
It was like, in the end for me, it became like this,
I remember the moment,
you talk about these moments as a scientist
and we were just like, we were working so hard
about figuring out like, does this really,
with this really work, like in this, it's complex.
Like, does the magnet work?
Does the interaction with the plasma work?
Does all these things work?
And it was just the grind, push, push, push, push.
And I remember the moment,
because I was sitting in my office in Brookline
and there was just like, I read like,
and I was in, I don't know, whatever,
the 20 or 40th slide or something into it.
And it was sort of that moment,
like it just came together.
And I like, I couldn't even sit down.
Cause all it was just like, my wife was like,

why are you walking around the apartment like this?
Like, I just couldn't, she, I said, it's going to work.
Like it's going to work.
Like, that moment of realization is like, kind of amazing.
But it also brings the responsibility
of making it work as well.
Yeah, how do you make it work?
So you mean like that magic realization
that you can have this, this modern magnet technology
and you can actually like,
why do we need to work with Eater?
We can do it here.
Yeah, yeah.
But it's interesting that Eater is,
that one of the reasons that we started
with a group of six of us at MIT,
and then once we got some funding
through the establishment of the company,
it became a slightly larger.
But in the end, we had a rather small team.
Like this was like a team of order of like 20 to 25 people
design Spark in like about two years, right?
How does that happen?
Well, we're clever, but you have to give Eater,
it's due here as well too.
That again, this is an aspect always of the bootstrap up.
Like I go back to the human genome project.
So modern day genomics would not be possible
without the underlying basis that came from setting that up.
It had to be there.
It had to be curiosity driven public program
is the same with Eater.
But we, because we had the tools
that were there to understand Eater,
we also had the tools to understand Spark.
So we, we parlayed those in an extremely powerful way
to be able to tell us about what was going to happen.
So these things are never simple, right?
It's like, people look at this go,
oh, this means we should like,
should we really have a public based program about fusion
or should we have it all in the private?
It's like, no, the answer is neither way

because in all these complex technologies,
you have to keep pushing on all the fronts
to actually get it there.
So, you know, the natural question
when people hear breakthrough with the,
with the inertial confinement,
with the magnetic confinement is,
so when will we have commercial
Yeah.
Reactive power plants that are actually producing electricity.
What's your sense looking out into the future?
When do you think you can envision a future
where we have actual electricity
coming from nuclear fusion?
Partly driven by us, but in other places as well too.
So there's the advent, what's, you know,
what's so different now than three or four years ago,
like we launched around four years ago.
What's so different now is,
is the advent of a very nascent,
but seemingly robust like commercial fusion, you know,
endeavor.
So it's not just Commonwealth fusion systems.
There's something like 20 plus, you know, companies.
There's a sector now.
There's a sector.
They actually, they actually have something called
the fusion industry association,
which is if your viewers want to go see this,
this describes the difference.
And they've got this plethora of approaches.
Like I haven't even described all the approaches.
I've basically described the mainline approaches,
you know, and they're all at varying degrees
of technical and scientific maturity
with very huge different, you know,
balances between them.
But what they share is that because they're going out
and finding, getting funding from the private sector
is that their stated goals are about getting fusion
into place so that both it meets the investor's demands,
which are interesting, right?
And the time scales of that.

But also it's like, well, there's gonna, and why?
It's because it's easy.
There's gonna, there's this enormous push driver
about getting carbon-free energy sources out into the market.
And whoever figures those out is going to be both very,
it's gonna be very important geopolitically,
but also economically as well too.
So it's a different kind of bat, I guess,
or a different kind of gamble that you're taking with fusion.
But it's so disruptive that it's like,
there's essentially a class of investors and teams
that are ready to go after it as well too.
So what do they share in this?
They typically share getting after fusion on a time scale
so that could it have any relevance
towards climate change, battling climate change?
And I would say this is difficult,
but it's fairly easy because it's math.
So what you do is you actually go to some target,
like 2050 or 2060, something like this,
and say, I wanna be blank percent
of the world's market of electricity or something like that.
And we know historically what it takes to evolve
and distribute these kinds of technologies
because every technology takes some period of time,
it's so-called S-curve, it's basically,
everything follows a logarithmic curve,
exponential type curve, it's a straight line of log plot.
And like you look at wind, solar, fission,
they all follow the same thing.
So it's easy, you take that curve and you go,
that's slope and you work backwards.
And you go, if you don't start in the early 2030s,
like it's not gonna have a significant impact by that time.
So all of them share this idea.
And in fact, it's not just the companies now,
the US federal government has a program
that was started last year that said,
we should be looking to try to get like the first,
and what I mean by like, what does it mean to start,
that you've got something that's putting electricity
on the grid, a pilot, what we call it.
And if that can get started like in the early 2030s,

the idea of ramping it up makes sense, that's math, right?
So that's the ambition, then the question is,
and actually this is different
because the government program,
and they vary around in this.
So for example, the United Kingdom's government idea
was to get the first one on by 2040.
And China has ambitions probably in the middle 2030s,
or maybe a little bit later.
And Europe, continental Europe is,
it's a little bit, I'm not exactly sure where it is,
but it's like later, it's like 2050 or 2060,
because it's mostly linked to the Eater timeline as well too.
The fusion companies, which makes sense,
it's like, of course they've got the most aggressive timelines.
It's like, we're gonna map the human genome
faster as well too, right?
So it's interesting about where we are.
And I think, we're not all the way there,
but my intuition tells me we're probably gonna have
a couple of cracks at it actually on that timeline.
So this is where we have to be careful though,
you say commercial fusion, what does that mean?
Commercial fusion to me means that you actually
have a known quantity about what it costs,
what it costs to build and what it costs to operate,
the reliability of putting energy on the grid.
That's commercial fusion.
So it turns out that that's not necessarily exactly
the first fusion devices that put electricity on the grid,
because you got it, there's a learning curve
to get better and better at it.
But that's probably, I would suspect the biggest hurdle
is to get to the first one.
The work I've done, the work I continue to do
with autonomous vehicles and semi-autonomous vehicles.
There's an interesting parallel there where a bunch
of companies announced a deadline for themselves
in 2020, 2021, 2022.
And only a small subset of those companies
have actually really pushed that forward.
There's Google with Waymo or Alphabet, rather.
And then there's Tesla with semi-autonomous driving

in their autopilot full-cell driving mode.
And those are different approaches.
So Tesla is achieving much, much higher scale,
but sort of the quality of the drive is semi-autonomous, right?
I don't know if there's a metaphor and analogy here.
And then there's Waymo that's focusing
on very specific cities, but achieving real full autonomy
with actual passengers, but the scale isn't much smaller.
So I wonder, like just like you said,
there'll be these kinds of similar kind
of really hard pushes.
Absolutely.
So actually this is what I,
it's why I'm encouraged about fusion.
So fusion's still hard, let's let everyone be clear,
because the science underneath it
of achieving the right conditions for the plasma
basically is a yardstick that you have to put up
against all of them.
What's encouraging that I see in this,
and it's actually what happens when you sort of
let loose the creativity of this is,
maybe I'll go back to first principles.
So fusion is also a fairly strange,
so if you think about building a coal,
like burning wood and coal and gas
is actually not that much different from each other,
because they're kind of about the same physical conditions
and you get the fuel and you light into that.
Fusion is very, remember I told you
that there's this condition of the temperature,
which is kind of universal,
but if you take the density of the fuel
between magnetic fusion and inertial fusion,
they're different by about a factor of 10 billion.
So this, and the density of fuel really matters.
That actually sort of,
and this means the energy confinement time
is also different by a factor of 10 billion as well too,
because it's the product of those two.
So one's really dense and short lived,
and the other one's really long lived
and actually under dense as well too.

So what that means is that the way to get the underlying
physical state is so different
among these different approaches,
what it lends itself to is,
does this mean that eventual commercial products
will actually fill different needs in the energy system?
So it sort of goes to your comment about,
I have to suspect this because anything that is high tech
and is like a really important thing in our economy
tends to never find its way as one, only one manifestation,
like look at transportation as well too.
We have scooters, Vespas,
Overland trucks, cars, electric cars,
of course we have these because they meet different demands in it.
So what's interesting that I find fascinating now
is that we have infusion, it's going to look like that,
that probably there's the,
while the near term focuses on electricity production,
there might even be different kinds of markets
that actually make sense in some places, less than others,
it comes to trade offs,
because we haven't really talked about the engineering yet,
but the engineering really matters,
like to the operation of the device.
And so it could be that I suspect what we'll end up with
is several different configurations
which have different features
which are trade offs basically in the energy market.
What do you see as the major engineering
or general hurdles that are in the way?
Yeah.
So the first one is just the cost of building a single unit.
So fusion has, and it's actually interesting
you talked about the different models that you have.
So fusion has one of its interesting limitations
is that it's very hard,
almost at some point it becomes physically impossible
to actually make small power units.
Like a kilowatt, 1,000 Watts,
which is like a personal home,
like this is about 1,000 Watts
or your personal use of electricity is about like 1,000 Watts.

This is basically impossible
for a single unit to do this.
So like you're not gonna have a fusion power plant
like as your furnace in or your electric heater in your home.
And the reason for this comes from the fact
that fusion relies on it being,
it's not just that it's very hot,
is that the fusion power is the heating source
to keep it hot.
So if you go too small,
it basically just cannot keep it hot.
That's, so it's interesting is that this,
so this is one of the hard parts.
So this means that the individual units,
and it varies from concept to concept,
but the National Academy's report that came out last year
sort of put the benchmark as being
like probably the minimum size
looks like around 50 million Watts of electricity,
which is like enough for like a meat,
like a small to mid-sized city actually.
So that's sort of like a scale challenge.
And in fact, it's one of the reasons
why in Commonwealth and in other private sector ones,
like they try to push this down actually
of trying to get to these smaller units,
just cause it reduces the cost of it.
Then probably obviously,
I would say it's an obvious one
like achieving the fusion state itself
and high gain is a hard one,
what we already talked about.
What kind of hurdle, what kind of challenges is that?
That's achieving the right temperature density
and energy confinement time in the fuel itself,
in the plasma itself.
And so some of the configurations
which are being chosen are actually,
I have quite a ways to go in fact, I've seen those,
but what their consideration is,
oh yes, but by our particular configuration,
the engineering simplicity confers
like an economic advantage,

even if we're behind in sort of a science sense,
okay, which is fine.
This is also what you get when you get
an explosion in the private sector,
that you basically are distributing risks in different ways,
right, which makes sense, all of that good.
So what I would say is that the next hurdle
to really overcome is about making that electricity.
So like we need to see a unit or several units,
like put using fusion in some way
to put a meaningful amount of energy on the grid,
because this starts giving us real answers
as to like what this is going to look like.
The full end-to-end.
The full end-to-end thing.
So Commonwealth's goal is that,
I'll let this comment to Commonwealth
because I'll take some, I guess some credit for this,
is that the origins of Commonwealth were in fact
in examining that.
Like we could see this new technology coming forward,
this new superconducting material,
and the origins of our thought process
were really around designing effectively
the pilot plant or the commercial unit.
It's called ARC,
which is actually the step forward after Spark.
And that was the origins of it.
So all the things that were other parts of the plant,
like Spark and the magnet,
were actually all informed totally by building
something that's going to put net electricity on the grid.
And the timing of that, we still hope,
is actually the early 2030s.
So Spark is the design of the Takamak
and ARC is the actual full end-to-end thing.
Is like a thing that actually puts that energy on the grid.
So Spark is named intentionally,
that it's like, it's on for a short period of time.
And it doesn't have a, it has, yeah, you know,
it's the spark of the fusion, you know, revolution
or something like that, I guess we could call it.
Yeah, so those are,

so those are sort of the programmatic challenges
of doing that.
And, you know, it's interesting,
you asked about, you talked about SpaceX,
so what has evolved even in the last year or so
was in fact in March of 2022,
the White House announced that it was going to start
a program that kind of looks like a SpaceX analogy,
that namely, wow, we've got these things
in the private sector, we should leverage
the private sector and the advantages of what they obtain.
But also with the things, like this is going to be hard
and it's going to take quite a bit of financing.
So why don't we set up a program
where we don't really get in the way
of the private sector fusion companies,
but we help them finance these difficult things,
which is how SpaceX basically became successful
through the COTS program, fantastic, right?
And that's evolving as well too.
So like the fusion ecosystem is almost unrecognizable
from where it was like five years ago around those things.
How important is it for the heads of the companies
that are working on nuclear fusion to have a Twitter account
and to be quite, you said you don't use Twitter.
I don't use Twitter.
I mean, there is some element to,
and I don't think this should be discounted,
whatever you think about, failures like Jeff Bezos
with Blue Origin or Elon Musk with SpaceX.
There is a science communication to put it in nice terms
that's kind of required to really educate the public
and get everybody excited and sell the sexiness of it.
I mean, just even the videos of SpaceX,
just being able to kind of get everybody excited
about going out to space once again.
I mean, there's all kinds of different ways of doing that,
but I guess what the companies do well
is to advertise themselves, to really sell themselves.
It is, yeah.
Well, actually, I feel like one of the reasons
on this podcast and so I don't have an official role
in the company.

And one of the reasons for this was also that
it's interesting because when you come from,
like you're running a company, it makes sense
that they're promoting their own product
and their own vision, which totally makes sense.
But there's also a very important role for academics
who have knowledge about what's going on,
but are sufficiently distant from it
that they're not fully only self-motivated
just by their own projects or so forth.
And for me, this is, I mean, we see particularly
the problems of the distrust in technology
and then honestly in the scientific community as well too.
It will be one of the greatest tragedies, I would say,
that if we go through all of this
and almost pull off what looks like a miracle,
like technologic and scientific-wise,
which is to make a fusion power plant
and then nobody wants to use it
because they feel that they don't trust the people
who are doing it or the technology.
So we have to get so far out ahead of this.
Like, so I give lots of public lectures
or things like this of accessing a larger range of people.
We're not trying to hide anything.
You can come and see, you know,
come do tours of our laboratory.
In fact, I wanna set those up virtually as well too.
You might look at our Plasma Science
and Fusion Center YouTube channel.
So we are reaching out through those media.
And it's really important that we do those things.
But it's also then realizing,
setting up the realistic expectations
of what we need to do.
You know, we're not there.
Like, we don't have commercial fusion devices yet.
And you ask, like, what are the challenges?
I'm not gonna get into any deep technical, you know,
questions of what the challenges are.
But it is the pathway,
not just to make fusion work technically,
but to make it economically competitive and viable.

So that's actually used out in the private sector
is a non-trivial task.
And it's because of the newness of it.
Like, we're simultaneously trying to evolve the technology
and make it economically viable at the same time.
Those are two difficult coupled tasks.
So my own research and my own drive right now
is that fantastic combo of fusion systems is set up.
We have a commercialization unit of that particular kind,
which is gonna drive forward a tokamak.
In fact, I was just, there's discussions
or there's dialogues going on around the world
with other kinds of ones.
Like, stellar radars, which prefer different kinds
of challenges and economic advantages.
But what we have to, I know what we have to have.
What we have to have is a new generation
of integrated scientists, technologists, and engineers
that understand, like, how, what needs to get done
to get all the way to the goal line.
Because we don't have them now.
So like a multi-disciplinary.
Yeah, exactly.
What's required, I mean, you've spoken about,
you said that fusion is, quote, the most multi-disciplinary
field you can imagine.
Yes, yeah.
Why is that?
What are the differences?
Well, because most of our discussion
that we've had so far is really like a physics discussion,
really, so which don't neglect physics
is at the origin of this.
But already we touched on plasma physics
and nuclear physics, which are basically two, you know,
somewhat overlapping independent disciplines.
Then when it comes to the engineering,
it's almost everything.
So why is this?
Well, let's build an electromagnet together, okay?
What is this gonna take?
It's gonna take, it's basically electrical engineering,
computer engineering, so you understand

what goes together, what happens.
Computational engineering to model
this very complex integrated thing.
Materials engineering, because you're pushing materials
to their limit with respect to stress and so forth.
Takes cryogenic engineering, which is sort of a sub-discipline
but cooling things to extremely low temperatures.
There's probably some kind of chemistry thing in there too.
Well, actually, yeah, which tends to show up in the materials.
And that's just one of the sub-components of it.
Like almost everything gets hit in this, right?
So you're, and you're also in a very integrated environment
because in the end, all these things,
while you isolate them from each other in a physics sense,
in an engineering sense, they all have to work
like seamlessly together.
So it's one of those, I mean, in my own career,
I've basically done atomic physics, spectroscopy,
you know, plasma physics, iron etching.
So this includes material science,
something called MHD, Magnetohydrodynamics,
and now all the way through,
it's like, I'm not even sure
how many different careers I've had.
It's also, by the way, this is also
a recruiting stage for young scientists
thinking to come in.
My comment to science is if you're bored in fusion,
you're not paying attention
because there's always something interesting to go and do.
So that's a really important part of what we're doing,
which isn't new in fusion actually,
and in fact is in the roots of what we've done at MIT.
But holy cow, the proximity of possibility
of commercial fusion is the new thing.
So my catchphrase is, you may be wondering,
why weren't we doing all these things?
Why weren't we pushing towards economic fusion
and new materials and new methods of heat extraction
and so forth, because everybody knew fusion
was 40 years away, and now it's four years away.
There is a history, like you said, 40, 30,
whatever, that kind of old joke.

There's a history of fusion projects
that are characterized by cost overruns and delays.
How do you avoid this?
How do you minimize the chance of this?
You have to build great teams, is one of them.
It tends to be that the smaller the,
there's sort of an, I'm not an expert in this,
but I've seen this enough integrated.
Is there an equation?
Yeah, well there's almost,
I've seen this from enough teams.
Like I've seen also the futility of lone geniuses
trying to solve everything by themselves, like no.
But also organizations that have 10,000 people in them
is just not, doesn't lend itself at all to innovation.
So, like one of our original sponsors
and a good friend, Vinod Kosla,
I don't know if you've ever talked to Vinod Kosla,
he's a venture, he's got fantastic ideas
about like the right sizes of teams
and things that really innovate, right?
And there is an optimum place in there
is that you get enough cross-discipline and ideas,
but it doesn't become so overly bureaucratic
that you can't execute on it.
So, one of the ways,
and this was one of the challenges of Fusion,
is that everything was leading towards,
like I have to like enormously large teams
just to execute because of the scale of the project.
The fact that now through both technology
and argue financing innovation,
we're driving to the point where it's smaller,
focused teams about doing those things.
So that's one way to make it faster.
The other way to make it faster is modularize the problem
or parse the problem.
So this is the other difficulty in Fusion,
is that you tend to look at this as like,
oh, it's really just about making the plasma
into this state here that you get this energy gain.
No, because in the end,
if you can parse out the different problems of making that

and then make it as separate as possible
from extracting the energy
and then converting it into electricity,
the more separate those are,
the better they are because you get parallel paths
that basically mitigate risk.
This is not new in Fusion, by the way,
and this is the way that we attack
most complex technological,
integrated technological challenges.
Have you been any chance seen some of the application
of artificial intelligence, reinforcement learning?
A deep mind has a nice paper, has a nice effort
on basically using reinforcement learning
for a learned control algorithm
for controlling nuclear fusion.
Do you find those kinds of,
I guess you throw under the umbrella
of computational modeling,
do you find those interesting, promising directions?
They're all interesting.
So when people, I'll pull back,
maybe a natural question is like,
why is it different in Fusion?
Like there's a long history to Fusion, right?
It was going on for, like I told you,
like stories from the late 1960s,
like what's different now, right?
So I think from the technology point of view,
there's two massive things which are different.
So one of them, I'll be parochial,
it's the advent of this new superconducting materials
because the most mature ways that we understand
about how we're gonna get to Fusion power plants
are magnetic fusion.
And by the fact that you've got access
to something which like changes the economic equation
by an over-in-order magnitude is just a totally,
and that wasn't that long ago,
it was only September of 2021
that we actually demonstrated the technology.
That changes the prospects there.
And the other one is computing

and it's across the whole spectrum.
It's not just in control of the Fusion device.
It's actually, we actually use machine learning
and things like this in the design of the magnet itself.
It's an incredibly complex design space.
So you use those tools.
The simulation of the plasma itself is actually,
we're at a totally different place than we were
because of those things.
So those are the two big drivers that I see actually
that make it different.
And actually, and it's interesting,
both those things self-enforce about what you asked about
before, like how do you avoid delays and things?
Well, it's by having smaller teams
that can actually execute on those.
But now you can do this
because the new magnets make the devices all smaller.
And the computing means your human effectiveness
about exploring the optimization space is way better.
It's like they're all interlinked to each other.
Plus the modularization, like you said,
and it's everything just kind of works together
to make smaller teams more effective, move faster.
And it's actually,
and it's through that learned experience,
I mean, you know, of the things that I'm the most proud of
about what came out.
In fact, the origins of thinking about how we would use
the high temperature superconducting magnets
came out of my design class at MIT.
And in the design class,
like one of the features that I kept,
I mean, it was interesting, I actually learned,
I really learned along with the students about this,
but like this insistence on the features,
like we can't have so many coupled
integrated hard technology developments.
Like we have to separate these somehow.
So we worked and worked and worked at this.
And in fact, that's what really, in my opinion,
the greatest advantage of the arc design,
and when a, you know,

and built into the Commonwealth fusion system idea
is like to parse out the problems.
Like how can we attack these in parallel?
Yeah, and so it really comes to a,
we talked about philosophy.
It's like a design philosophy.
Like how do you attack these kinds of problems?
And, you know, you do it like that.
And also like you mentioned offline,
that there's a power to, you know,
as part of a class to design a nuclear fusion power plan.
Well, then make it a reality.
And it's hard to imagine a more powerful force
than like 15 MIT PhD students,
like working together towards solving a problem.
And what I always, in fact,
we just, we recently just taught the most recent,
you know, I say, I teach it.
I mean, I guide it actually.
The most recent version of this,
where they actually designed, you know,
based on this National Academy's report,
they actually designed like a pilot plant
that has basis and similarities to what we had done before.
But, you know, I kept wanting to like push the envelope
and where they are.
It's like the creativity and the energy
that they bring to these things is kind of like,
it keeps me going, like I'm not gonna retire anytime soon.
When I keep seeing that kind of dedication
and it's wonderful around on that.
It almost, not to overuse a,
or to paraphrase something, right?
Which is that, you know, the famous quote by Margaret Mead.
You know, never doubt that a small group of dedicated,
you know, persons will change the world.
Indeed, it's the only thing that ever has.
I mean, that's just such a powerful and inspiring thing
for an individual.
Find the right team, be part of that.
And then you yourself, your passion,
your efforts could actually make a big change.
Yeah, a big impact.

I gotta ask you, so it's,
it's a whole another different conversation
I'm sure to have, but nuclear power is it currently stands.
So using a fission is extremely safe,
despite public perception.
It is the safest actually.
So that's a whole nother conversation,
but almost like a human bureaucratic physics,
engineering question of what lessons do you draw
from the catastrophic events where they,
the populace did fail.
So Chernobyl and Three Mile Island.
Chernobyl, what lessons do you draw?
She's Three Mile Island wasn't really a disaster
because nothing escaped from the thing,
but Chernobyl and Fukushima have been, you know,
had obvious consequences in the populations
and they live nearby.
What lesson do you draw from those
that you can carry forward to fusion?
Now I know there's, you can say that you're not gonna
have the same kind of issues, but it's possible
that the same folks also said there's not gonna be,
have those same kind of issues.
We humans, the human factor,
we haven't talked about that one quite as much,
but it's still there.
So to be clear, it's not,
so fusion has the intrinsic safety with respect to,
it can't run away, those are physics bases.
Technology and engineering bases of running a complex,
again, anything that makes large amounts of power
and heats things up is got intrinsic safety in it.
And by the fact that we actually produce
very energetic particles,
this doesn't mean that there's no radiation involved
in ionizing radiation to be more accurate.
Infusion, it's just that it's in a very different order
of magnitude, basically.
So what are the lessons in fusion?
So one of them is make sure that you're looking
at aspects of the holistic, environmental,
and societal footprint that the technology will have.

As technologists, we tend not to focus on these,
and particularly in early stages of development.
Like we just want something that works, right?
But if we come with just something that works,
but doesn't actually satisfy the societal demands
for safety and for disposal,
I mean, we will have materials
that we have to dispose of out of fusion.
Just this is, but there's technological questions
about what that looks like.
So will this look like something that you have to put
in the ground for a hundred years or five years?
Like, and the consequences of those are both economic
and societal acceptance and so forth,
but don't bury those.
Like bring these up front, talk to people about them,
and make people realize that you're actually,
the way I would look at it is that you're making fusion
more economically attractive
by making it more societally acceptable as well, too.
And then realize is that,
I think there's a few interesting boundaries, basically.
So one of them, or speaking of boundaries,
that successful fusion devices,
I'm pretty sure will require that you don't have
to have an evacuation plan for anybody who lives
at the site boundary.
So this has implications for what we build
from a fusion engineering point of view,
but it has major implications for where you can site
fusion devices, right?
So in many ways, it becomes more like,
well, we have fences around industrial heat sources
and things like this, for reason, right?
For personal safety, it looks more like that, right?
It's not quite as simple as that,
but that's what it should look like.
And in fact, we have research projects going on right now
at MIT that are trying to push the technologies
to make it more look like that.
I think that those are key.
And then in the end, as I said,
so Chernobyl is physically impossible,

actually, in a fusion system.
From a physics perspective.
From a physics perspective,
you can't run away like it did at Chernobyl,
which was basically human error,
that of letting the reactors run out of control,
essentially.
Human error can still happen,
nuclear fusion-based reactors.
But in that one, if human error occurs,
then it just stops, and this is done.
And all of those things,
this is the requirement of us as technologists
and developers of this technology
to not ignore that dimension, in fact, of the design.
And that's why, me personally,
I'm actually pouring myself more and more into that area
because this is going to be,
I actually really think it is an aspect
of the economic viability of fusion
because it clearly differentiates ourselves
and also sets us up to be about what we want fusion to be.
Is that, again, on paper,
fusion can supply all of our energy, like all of it.
So this means I want it to be really environmentally benign,
but this takes engineering ingenuity, basically, to do that.
Let me ask you some wild out there questions.
Sure.
So for-
We've been talking too much, you know?
It's a-
Simple, practical things in everyday life.
No, only revolutionizing the entire energy infrastructure
of human civilization.
Yes.
But, so cold fusion, this idea, this dream,
this interesting physical goals seem to be impossible,
but perhaps it's possible.
Do you think it is possible?
Do you think down the line,
so we're in the far distance it's possible to achieve fusion
at a low temperature?
It's very, very, very unlikely.

And this comes from-
So this would require a pretty fundamental shift
in our understanding of physics, as we know it now.
And we know a heck of a lot
about how nuclear reactions occur.
By the way, what's interesting is that there's-
They actually have a different name for it.
They call it leaner, like low energy nuclear reactions.
But we do have low energy nuclear reactions.
We know these, it's because these come from
particularly the weak force, nuclear force.
And so it's, at this point, as a scientist,
you always keep yourself open because,
but you also demand proof, right?
And that's the thing.
It almost requires a breakthrough
on the theoretical physics side.
So some deeper understanding about quantum mechanics.
So the quantum tunneling, some weird-
Yeah, and people have looked at that,
but even like something like quantum tunneling
has a limit as to what it can actually do.
So there are people who are genuine,
that really want to see it,
but it sort of goes to the extort.
I mean, we know fusion happens at these high energies,
like when we know it's extremely accurate,
and I can show you a plot that shows that
as you go to lower, lower energy,
it basically becomes immeasurable.
So if you're going down this other pathway,
it means there's really a very different
physical mechanism involved.
So all I would say is that I actually poke in my head
once in a while to see what's going on in that area.
And as scientists, we should always try
to make ourselves open.
But in this one, it's like,
but show me something that I can measure
and that it's repeatable,
and then it's going to take more extraordinary effort.
And to date, this has not met that threshold,
in my opinion.

So even more so than just mentioning,
or in that question, thinking about people
that are claiming to have achieved co-fusion,
I'm more thinking even about people
who are studying black holes,
and they're basically trying to understand
the function of theoretical physicists.
They're doing the long haul,
trying to investigate like,
okay, what is happening at the singularity?
What is this kind of holographic projections on a plate?
These weird freaking things that are out there
in the universe, and somehow accidentally,
they start to figure out something weird.
Weird, yeah.
And then all of a sudden-
There's weirdness all over the place already, yeah.
Somehow that weirdness will,
I think on a timescale probably of 100 years or so,
that weirdness will open.
It just seems like nuclear fusion and black holes
and all of this, they're next to our neighbors
a little bit too much for like, you'll find something.
Interesting.
Well, let me tell you a story about this.
Yes.
Okay, it's a real story, okay.
So there are really, really clever scientists
in the end of the late 1800s in the world.
You talk about like James Kirk Maxwell,
and you talk about Lord Kelvin,
and you talk about Lawrence actually,
who named after these other ones,
and on and on and on, and like Faraday,
and they discovered electromagnetism, holy cow,
and it's like, they figure out all these things,
and yet there were these weird things going on
that you couldn't quite figure out.
It's like, what the heck is going on with this, right?
Maybe we teach this all the time in physics classes, right?
So what was going on?
Well, there's just a few kind of things unchecked,
but basically we're at the end of discovery

because we figured out how everything works,
because we've got basically Newtonian mechanics,
and we've got Maxwell's equations,
which describe basically how matter gets pushed around
and how electromagnetism works, holy cow, what a feat.
But there were these few nagging things,
like for instance, there's certain kinds of rocks
that for some reason, like if you put
a photographic plate around it,
it gets burned or it gets an image on it.
Like, well, where's the electromagnetism in that?
There's no electromagnetic properties of this rock.
Oh yeah, and the other thing too,
is that if I take this wonderful classical derivation
of something that is hot,
about how it releases radiation,
everything looks fantastic, perfect match.
Oh, until I get to high frequencies of the light,
and then it basically just, the whole thing falls apart.
In fact, it gives a physical explanation,
which is total nonsense.
It tells you that every object should basically
be producing an infinite amount of heat.
And by the way, here's the sun,
and we can look at the sun,
and we can figure out it's made out of hydrogen.
And Lord Kelvin actually made a very famous calculation
who was basically one of the founders of thermodynamics.
So you look at the hydrogen,
hydrogen has a certain energy content,
that you know the latent heat, basically, of hydrogen.
We know the mass of the sun
because we knew the size of it,
and he conclusively proved that basically,
there could only, the sun could only make net energy
for about two or 3,000 years.
So therefore, all this nonsense about like deep,
because clearly the sun can only last
for two or 3,000 years.
If you think about the, and this is basically
the chemical energy content of hydrogen,
and what comes along in one decade,
basically, one guy sitting in a postal office,

you know, in Switzerland,
figures out that all these, you know, Einstein, of course,
which was like figured out all this,
like took these seemingly unconnected things,
and it's like, boom, there it is.
This is what, it wasn't just him,
but it was like, there's quantum physics,
like this explains this other disaster.
And then there's this other guy,
my hero Ernst Rutherford, experimentalist,
did the most extraordinary experiment,
which is like, which was that, okay,
they had these funny rocks, they emitted these particles.
They, in fact, they called them alpha particles,
alpha, just A in the alphabet, right?
Because it was the first thing that they discovered.
And what were they doing?
So they were taking these alpha particles,
and by the way, I do this to all my students,
because it's a demonstration of what you should be
as a good scientist.
So he took these alpha things,
and he was a classically trained physicist,
knew everything about momentum scattering
and so forth and like that.
And he took this, and these alpha,
which clearly were some kind of energy,
but they couldn't quite figure out what it was.
So he said, let's try to figure that,
we'll actually use this to try to probe the nature of matter.
So he took this, took these alpha particles,
and a very, very thin gold foil.
And so what you wanted to see was that
as they were going through,
the way that they would scatter based on classical,
in fact, the Coulomb collision,
based on classical mechanics,
this will tell me, reveal something
about what the nature of the charge distribution is
in matter, because they didn't know,
like where the hell is this stuff coming from?
Even though they'd solved that electromagnetism,
they didn't know like what made up charges.

Okay, very interesting.
Through it goes, do, do, do, do, do.
And so what did you set up?
So it turns out in these experiments,
what you did was, because if these,
these so-called alphas,
which actually now we know something else,
as they go through, they would deflect,
how much they deflect tells you
how strong an electric field they saw.
So you put detectors,
because if you put, if you put like a piece of glass
in front of this, what will happen
is that when the alpha particle hits,
it literally gives a little boop,
a little boop of light like this.
It scintillates, a little blue flash.
So he would train his students or postdocs
or whatever the heck they were at the time.
You have to train yourself,
because you have to put yourself in the dark
for like hours to get your eyes adjusted.
And then they would start the experiment
and they would sit there and literally count the things.
And they could see this pattern developing,
which was revealing about what was going on.
But there was also another part of the experiment,
which was that it's like, here's the alphas,
here's the source, they're going this,
they could tell they were going in one direction only,
basically, they're going in this direction.
And you put all these over here,
because you want to see how they deflect and bend through it.
But you put a control in the experiment,
but you basically put glass part of glass plates back here,
because obviously everything should just deflect,
but nothing should bounce back.
So it's a control in the experiment.
But what did they see?
They saw things bouncing back, like what the hell?
Like that fit no model of any idea, right?
But Rutherford like refused to like ignore
what was a clear, like they validated it.

And he sat down and based on classical physics,
he made the most extraordinary discovery,
which was the nucleus, which is a very,
very strange discovery.
What I mean by that, because what he could figure out
from this is that in order for these particles
to bounce back and hit this plate,
they were hitting something that must be heavier than them.
And that basically something like 99.999% of the mass
of the matter that was in this gold foil
was in something that contained
about one trillionth of the volume of it.
And that's called the nucleus.
And until, and you talk about, so how revealing is this?
It's like, this totally changes your idea of the universe
because a nucleus is a very unintuitive,
non-intuitive thing.
It's like, why is all the mass in something
that is like zero, like it basically is the realization
that matter is empty.
It's all empty space.
And that changes everything.
And it changes everything.
Until you had that, like you had steam engines,
by the way, you had telegraph wires,
you had all those things.
But that realization, like opened up,
those two realization opened up everything,
like lasers, all these things about the modern world
of what we use them.
And that set it up.
So all I would point out is that there's a story already
that sometimes there's these nagging things
at the edge of science that, you know,
we seem, we pat ourselves on the back
and we think we got everything under control.
And of course, by the way,
that was the origin of also that,
that it, think about this, that was 1908.
It took like another 20 some years
before people put that together with,
that's the process that's powering stars.
Is the rearrangement of those nuclei, not atoms.

That's why Kelvin wasn't wrong.
He just, he was working with the wrong assumptions, right?
So fast forward to today, like what would this mean?
Right?
Well, there's a couple of things like this
that sit out there in physics.
And I'll point out one of them, which is very interesting.
We don't know what the hell makes up 90% of the mass
in the universe.
So the, you know, the search for dark matter, right?
What is it?
We still haven't discovered it.
90% of the mass of the universe is undetectable.
Like what?
And then, you know, and dark energy in the, again,
black holes are the window into this.
Well, I mean, sometimes black holes
are way better understood than those things as well too.
So all it tells us is that we shouldn't have hubris
about the ideas that we understand everything.
And when we, you know, who knows what the next
major intellectual insight will be
about how the universe, you know, functions.
And actually, I think Rutherford is the one
who's attributed at least that quote,
that physics is the only real science,
everything else is stamp collecting, right?
So there's-
I'm sorry, he's my hero,
but I'll slightly disagree with that, yes.
Well, no, if it's a stamp collecting,
that's very important too.
But, you know, you have to have humility
about the kind of disciplines that make progress
at every stage in science.
Yeah, exactly.
Physics did make a huge amount of progress
in the 20th century,
but it's possible that other disciplines start to step in.
Yeah, but Rutherford couldn't imagine,
like mapping the human genome
because we didn't even know about DNA.
Yeah, or computers really.

Or computers.
He probably didn't think deeply about computation.
Like, is it, here's a wild one,
what if like the next great revelation to humanity
about the universe is not done by the human mind?
That seems increasingly more likely.
And then you start to ask deep questions
about what is the purpose of science?
For example, if AI system will design
a nuclear fusion reactor better than humans do,
but we don't quite understand how it works,
and the AI can't, we know that it works.
We could test it very thoroughly,
but we don't know exactly what the control mechanism is.
Maybe what the chemistry, the physics is.
AI can't quite explain it.
They just can't.
It's impenetrable to our consciousness, basically.
Trying to hold it all together.
And then, okay, so now we're living in that world
where many of the biggest discoveries
are made by AI systems.
Yeah.
As if we weren't going big.
Yeah, I say, you know, it's, again,
as a point out, like when my godmother was born,
like, none of this was in front of us, right?
It's like, we live in an amazing time.
It's like, right, like my grandfather, you know,
plowed, you know, fields with a horse.
I get to work on designing fusion reactors.
Yeah. Yeah.
Pretty amazing time.
But still there's humans.
So we'll see, we'll see if that's around 100 years.
Maybe it'll be cyborgs and robots.
I think we're pretty resilient, actually.
Yeah, I know.
That's one lesson from life is it finds a way.
Let me ask you a bigger question as if those
weren't big enough.
Let's look out, maybe a few hundred years,
maybe a few thousand years out.

There's something called the Kardashev Scale.
It's a method of measuring civilization's level
of technological advancement based on the amount
of energy it's able to use.
So type one civilization, and this might be given
all your work is not no longer a scale
that makes, quite makes sense, but it very much focuses
on the source of fusion, natural source of fusion,
which is for us, the sun.
And type one civilizations are able to leverage,
sort of collect all the energy that hits earth.
And then type two civilizations are the ones
that are able to leverage the entirety of the energy
that comes from the sun by maybe building something
like a Dyson sphere.
So when will we reach type one status?
As get to the level, which we're, I think, maybe a few
orders of magnitude away from currently.
And in general, do you think about this kind of stuff?
Is where energy is so fundamental to this,
like of life on earth, but also the expansion
of life into the universe?
Oh yeah, so one of the fun, you know, on a weekend
when I sat down and figured out what would it mean
for interstellar travel, like to have a DT fusion.
In fact, one of the, I talked about my design class,
one of my design classes was how you use
essentially a special configuration of a fusion device
for not only traveling to, but colonizing Mars.
So, because what would we,
you talk about energy use being at the heart
of civilizations, like, so what if you want to go
to Mars not to just visit it, but actually,
like leave people there and make it something happen
and these massive amounts of energy.
So what would that look like and it actually transforms
how you're thinking about doing that as well too.
Oh yeah, so we do those kinds of fun.
And actually it was a fairly, you know,
quasi-realistic actually scenario.
Do you think it'll be nuclear fusion
that powers the civilization of Mars?
Well, what we considered was something,

so it turns out that there's thorium,
which is a heavy element.
So it's a so-called fertile element
that we know, we still know fairly little
about the geology of Mars in a deep sense.
And we know that there's a lot of this
on the surface of Mars.
So one of the things we considered was what would happen
that it's basically a combination of a fusion device
that actually makes fuel from the thorium.
But the underlying energy one was fission itself as well too.
So this is one of the examples of being,
trying to be clever right around those things.
Or what is it, you know, this also means
is like interstellar travel.
It's like, oh yeah, that looks almost like impossible
basically from an energy balance point of view.
It's just because like the energy required
to, that you have to transport to get there.
Almost the only things that would work are DT fusion
and basically annihilation.
It's like Star Trek, right?
That's what it is.
So your sense is that interstellar travel
will require fusion power.
Oh, it's almost even impossible
with fusion power actually.
It's so hard.
It's so hard because you have to carry the fuel with you.
And the rocket equation tells you
about how much fuel you use to take.
So what you end up with is like,
how long does it take to go to these places?
And it's like staggering, you know, periods of time.
So I tend to believe that there's alien civilizations
dispersed all throughout universe.
Yeah, but we might be totally isolated from them.
So you think we're not, there's none in this galaxy.
So like, I guess, and the question I also have
is what kind of, do you think they have nuclear fusion?
It's like, is it all, is the physics all the same?
Yeah, oh, the physics is all the same.
Yeah, right.

So this is the, and this is the Fermi paradox.
Like, where the hell is everybody in the universe?
Sorry.
Well, there's some so, you know,
the scariest one of those is that I would point out
that there's been, you know, there's, you know,
order of many tens of millions of species
on the planet Earth.
And only one ever got to the point of sophisticated tool use
that we could actually start essentially leveraging
the power of what's in nature to our own will.
Does this mean that basically this means,
so almost, look, there is almost certainly life
or DNA equivalents or whatever would be somewhere.
I mean, just because you just need a soup
and you need energy and you get organics
and whatever the equivalent of amino acids are.
But, you know, most of the life on Earth has been that,
those are still amazing, but it's still,
like, it's not very interesting.
Are we actually the accident of history?
This is a very interesting one.
It's super rare.
Super rare.
And then, of course, the other part is that also,
just the other scary part of it,
which if you look at the fairy paradoxes,
good, good, we got to this point.
How long has it been in humans?
So humans, Homo sapiens has been around for whatever,
100,000 years, 200,000 years on Earth.
Our ability in that timeline to actually make an imprint
on the universe by emitting radio waves
or by modifying nature in a significant way
has only been for about 100 of those 100,000 years.
And, you know, are we, it's a good question.
So is it by definition, by the fact
that when you are able to reach that level
of being able to manipulate nature and, for example,
discover, you know, discover like fission
or other, or burning fossil fuels and all this,
is that what it says, oh, you're doomed,
because by definition, any species that gets the point

that can modify their environment like that,
they'll actually push themselves, you know, past,
that's one of the most depressing scenarios
that I can imagine.
Yeah, so the...
So basically, we will never line up in time
because you get this little teeny window in time
over where civilization might occur
and you can never see it because you never,
these sort of like scatter like fireflies
around the galaxy and you never, yeah.
It goes up, it goes up, it goes up, it goes up
and then explodes, it destroys itself
because of the exponential.
And when we say destroy ourselves,
all we'd have to do is that we basically go,
if humans are all left and we're still living
on the planet and, but all we have to do
is go to the technology of like, you know, 1800.
And we're invisible in the universe again.
So it was, when I listened to the,
I thought I wanted to talk about this as well too
because it comes from, well, it comes from a science point
even actually of what it means.
But also to me, it's like another compelling driver
of telling us, it's like, why we should try
really hard not to screw this up.
Like we're in this unique place
of our ability to discover and make it.
And I just don't want to give up
about thinking that we can get through.
Yeah, I tend to see that there is some kind
of game theoretic force, like with the mutually shared
destruction that ultimately in each human being,
there's a desire to survive and a willingness
to cooperate, to have compassion for each other
in order to survive.
And I think that, I mean, maybe not in humans,
but I can imagine a nearly infinite number of species
in which that overpowers any technological
investment that can destroy or rewind the species.
So I think if humans fail, I hope they don't.
I see a lot of evidence for them not,

but it seems like somebody will survive.
And there you start to ask questions
about why we haven't met yet.
Maybe it's just space is large.
Oh, spaces, it's, I think in logarithms
and I can't even fathom space.
This is extraordinary, right?
Yeah. It's extraordinarily large.
I mean, there's so many places on earth.
I just recently visited Paris for the first time.
And there's so many other places I haven't visited.
There's so many other places.
Well, I like to, you know, it's interesting
that we have this fascination with alien life.
We have what is essentially alien life on earth already.
Like you think about the organisms that develop
around deep sea, like thermal vents.
One of my favorite books of all time from Stephen Jay Gould.
If you've never read that book, it kind of blows your mind.
It's about the Cambrian explosion of life.
And it's like, oh, you look at these things.
And it's like, the chance of us existing as a species,
like the genetic diversity was larger back then.
You know, this is about 500 million years ago
or something like that.
It is a mind-altering trip
of thinking about our place in the universe,
I have to say.
Plus the mind itself is a kind of alien
with almost a mystery to ourselves.
We still don't understand it.
The very mechanism that helps us explore the world
is still a mystery.
So that, like understanding that will also unlock,
quite possibly unlock our ability to understand the world
and maybe build machines that help us understand the world,
build tools that help us understand the world.
I mean, it already has.
I mean, our ability to understand the world
is ridiculous almost, Ashley.
And post the bottom on TikTok.
It's almost unbelievable
where we've gotten all this too.

So what advice would you give to young folks
or folks of all ages who are lost in this world,
looking for a way, looking for a career
that they can be proud of
or looking to have a life they can be proud of?
Yeah.
Oh, the first thing I would say is don't give up.
I get to see multiple sides of this.
And, you know, there seems to be a level of despair
in a young generation.
It's like, you know, it's almost like the multi-Python skit.
Like, I'm not dead yet, right?
I mean, like we're not there.
We're in a place that, you know,
don't say the world's gonna end in 300 days or something.
It's not, okay?
And what we mean by this is that we have a robust society
that's figured out how to do like amazing things
and we're gonna keep doing amazing things.
But that shouldn't be complacency about what our future is.
And the future for their children as well too.
And in the end, I mean, it's a very,
it's a staggering legacy to think of what we've built up
primarily by basically using carbon fuels.
Like people almost tend to think of this
as an evil thing that we've done.
I think it's an amazing thing that we've done.
But we owe it to ourselves and to this thing that we've built.
I mean, we're talking about the end of the world.
Is this nonsense?
What it is is it's the end of this kind of lifestyle
and civilization at this scale
and the ability to execute on these kinds of things
that we are talking about today.
Like we are extraordinarily privileged.
We are in a place where it's almost unfathomable
compared to most of the misery
that humans have lived in for our history.
So don't give up about this, okay?
But also roll up your sleeves
and let's get going at solving and getting real solutions
to the problems that are in front of us,
which are significant, you know?

It's, I would argue, most of them are linked to
what we use in energy, but it's not just that.
It's around all the aspects of like, what does it mean?
Like, what does it mean to have a distributed energy source
that lifts billions of people out of poverty?
You know, particularly outside of like the Western nations,
right?
That seems to me a pretty compelling, you know,
moral goal for all of us.
But particularly for this upcoming, you know, generation.
And then the other part is that we've got
possible solutions in front of us, apply your talents
in a way that you're passionate about
and is gonna make a difference.
And that's only possible with optimism, hope, and hard work.
Yeah.
What, easy question.
Certainly easier than nuclear fusion.
What's the meaning of life?
Why are we here?
42.
Is it 42?
No, no.
We already discussed about the beauty of physics,
that there's almost a desire to ask a why question
about why the parameters have these values.
Yeah.
It's very tempting, yeah.
It's an interesting hole to go down as a scientist
because we're a part of what people have a hard time,
people who aren't scientists have a hard time understanding
what scientists do to themselves.
And a great scientist does a very non-intuitive
or non-human thing.
What we do is we train ourselves to doubt ourselves,
like hell, like that's a great scientist.
We doubt everything we see,
we doubt everything that we think
because we basically try to turn off the belief valve,
that humans just naturally have.
So when it comes to these things,
like I can make my own comments to this as like personally,
you see these things about the ratios of life

and I made a comment where I said,
well, some part of my brain that just goes,
yeah, well, yeah,
because we're the only interesting multiverse
because by definition, it has to look like this.
But there's, I have to say, there's other times,
I can say in the history of the whole
of what has happened over the last 10 years,
there have been some pretty weird coincidences,
like coincidences that like you look at it and just go,
is that really a coincidence?
That is something like pushing us towards these things.
And it's a natural, it's a human instinct
because since the beginnings of humanity,
we've always assigned human motivation and needs
to these somewhat empirical observations.
And in some sense, the stories,
before we understand the real explanations,
the stories, the myths serve as a good approximation
for the thing that we're yet to understand.
And in that sense, you said the antithesis
to sort of scientific doubt is having a faith
in these stories, they're almost silly
when looked at from a scientific perspective,
but just even the feelings of it seems that love
is a fundamental fabric of human condition.
And what the hell's that?
Why are we so connected to each other?
Again, as a physicist I go,
it's this is a repeatable thing that's due to a set
of synapses that fire in a particular pattern
and all this, that's kind of like,
okay, man, what a drag that is to think of it this way.
And you can have an evolutionary biology explanation,
but there's still a magic to it.
I mean, I see scientists, some of my colleagues,
do this as well too, like what is spirituality
compared to science and so forth, my own feeling in this
is that as a scientist,
because I've had the pleasure of being able
to both understand what my predecessors did,
but I also had the privilege
of being able to discover things as a scientist.

And I see that and just in just the range
of our conversations, that is my, in a weird way,
it's the awe that comes from looking at that.
That is, if you're not in awe of the universe and nature,
you haven't been paying attention.
I mean, my own personal feeling is that I feel,
if I go snorkeling on a coral reef,
I feel more awe than I could ever feel like in a church.
You kind of notice some kind of magic there.
There's something about the way the whole
darn thing holds together
that just sort of escapes your imagination.
And that's to me, this thing of,
and then we have different words,
we call them holistic or spiritual,
the way that it all hangs together.
In fact, one of the interesting,
you asked about like what I think about,
one of the craziest things that I think
that how does it hold together is like our society.
Like how does, what?
Like how, because there's no way,
like you just think of the United States,
there's 330 million people kind of working like this engine
about going towards making all these things happen.
But there's like no one in charge of this, really.
How the heck does this happen?
It's kind of like, it's, so these things,
these are the kinds of things mathematically
and organization-wise that I think of
just because they're sort of, they're awe-inspiring.
And there's different ideas that we come up together
and we share them and then there's teams of people
that share different ideas and those ideas compete.
Like there was, the ideas themselves are these kinds
of different organisms and ultimately,
somehow we build bridges and nuclear reactors.
And do those things.
Well, I have to give a shout out to my daughter,
by the way, who's interested.
She's an applied math major and she's amazing at math.
And over the break, she was showing me,
she's doing research and it's basically about how ideas

and ethos are transmitted within a society.
So she's building an applied math model
that is explaining like, she was showing me
and this, like this simulation, she goes,
oh, look, look at this.
And I said, oh, oh, that's like how political parties
like evolve, right?
And even though it was a rather, you know,
quote unquote simple mathematical model,
it wasn't really, it's like, oh, wow.
Well, maybe she has a chance to derive mathematically
the answer to the, what's the meaning of life.
There we go.
And maybe it is indeed 42.
Well, Dennis, thank you so much for just doing,
creating tools, creating systems, exploring this idea.
That's one of the most amazing magical ideas
in all of human endeavor, which is nuclear fusion.
I mean, that's so interesting.
You know, it's almost like my,
one of my lifelong goals is like to make it,
it's like, it's not magic.
It's like, it's boring as all heck.
And this means we're using it everywhere, right?
Yeah.
And the magic is then built on top of it.
Well, thank you for everything you do.
Thank you for talking to me as a huge honor.
This was a fascinating and amazing conversation.
Thank you.
Thanks for listening to this conversation with Dennis White.
To support this podcast,
please check out our sponsors in the description.
And now let me leave you with some words from Albert Einstein.
There are two ways to live your life.
One is as though nothing is a miracle.
The other is though everything's a miracle.
Thank you for listening.
I hope to see you next time.
I hope to see you next time.