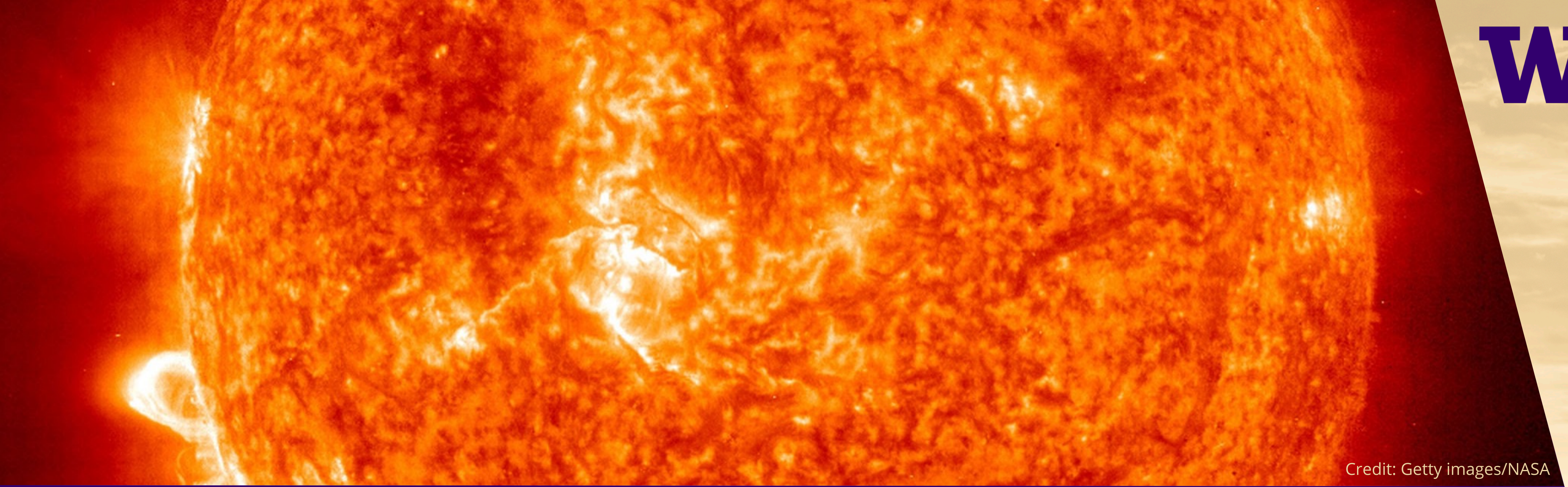

Credit: Getty images/NASA

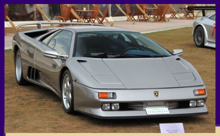
Introduction to Fusion

Prof. Bhuvana Srinivasan

2024 SULI, 10 June 2024

UNIVERSITY of WASHINGTON

My path to a career in plasma physics



Middle/high school fascination with things that move fast

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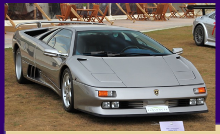

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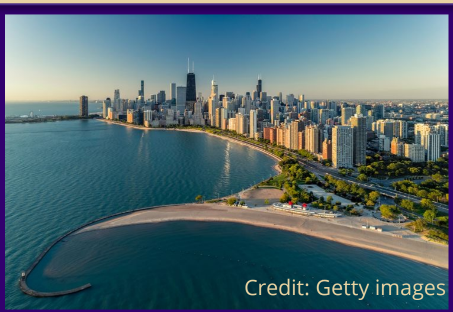
ILLINOIS TECH

Armour College of Engineering

Moved to the US to study aerospace and mechanical engineering. Chicago seemed like a fun city from TV ☺



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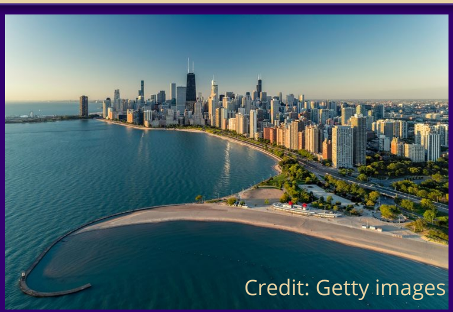

Credit: Getty images

After some industry experience, wanted to go to grad school to research something exciting – going to the Moon is cool, but going to the next star is even cooler! Fusion propulsion? Bonus: fusion to solve terrestrial energy problems!

Plasma physics and mountains?! UW (Seattle) it is for grad school!

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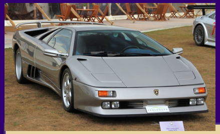

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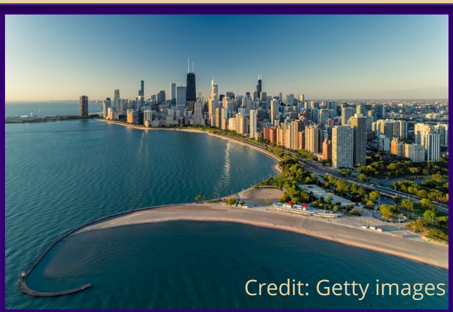

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More plasma, more mountains!

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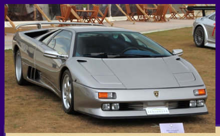

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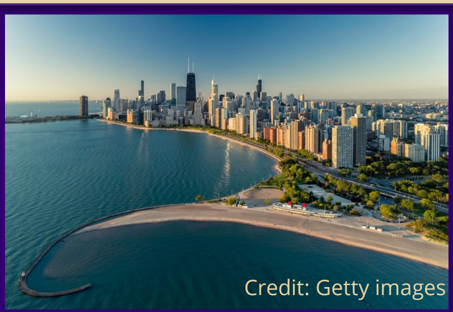

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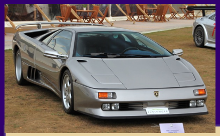

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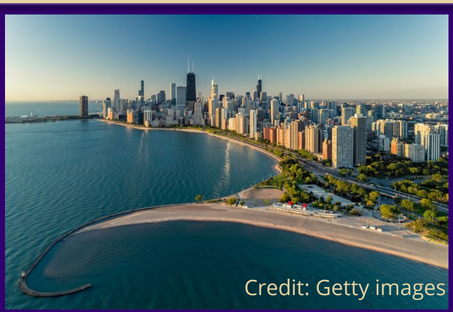

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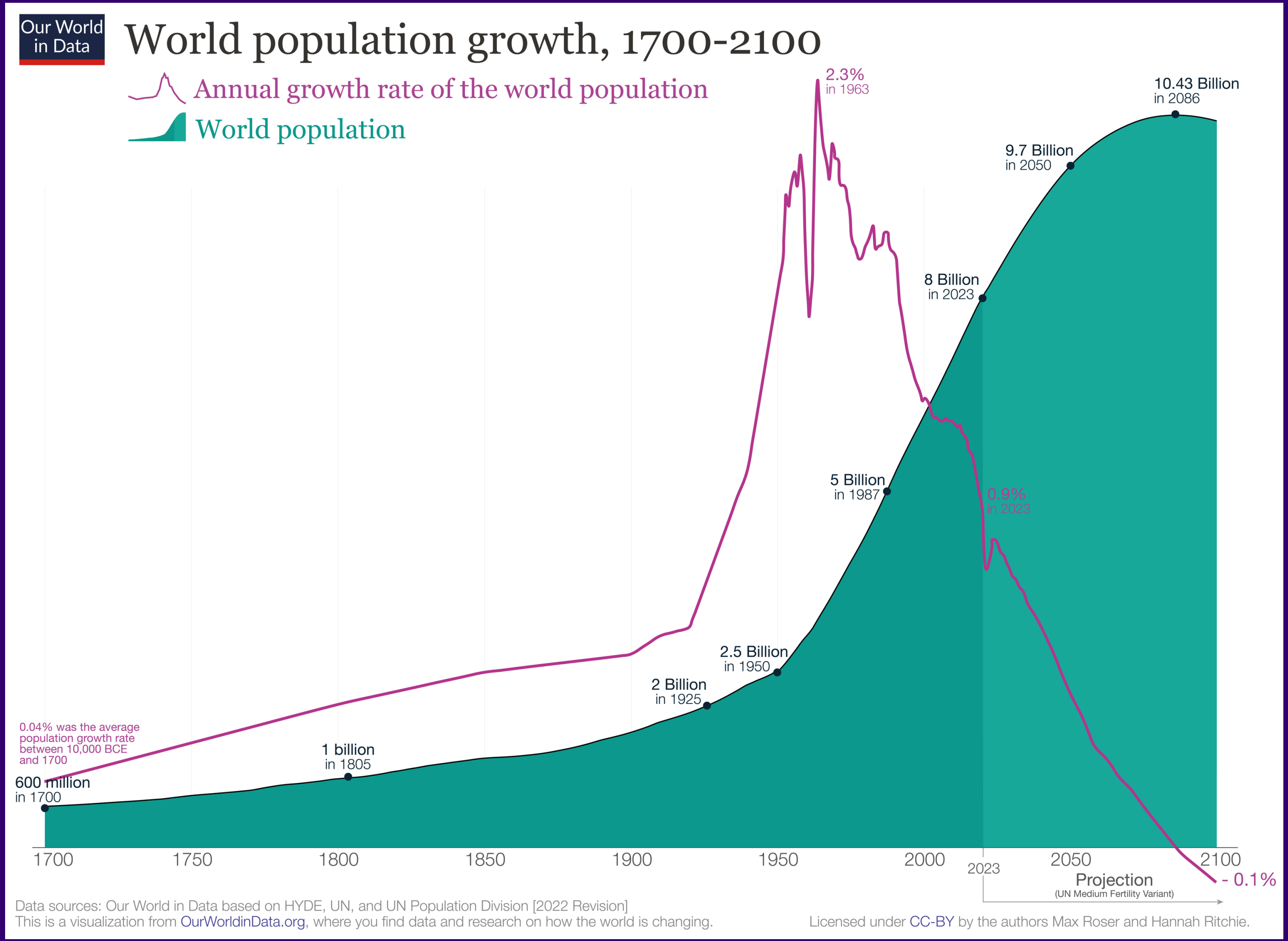
VIRGINIA TECH™

Made my way back to the University of Washington as a professor after 13+ years. More plasmas, more mountains!

Outline

- **The case for fusion**
- What is fusion?
- Metrics to evaluate fusion energy
- Brief history of fusion and some pioneers
- Fusion concepts: steady-state vs pulsed
- Progress in fusion

The world's population is projected to grow and with it come rising energy demands


World population growth, 1700-2100

Data sources: Our World in Data based on HYDE, UN, and UN Population Division [2022 Revision]
This is a visualization from OurWorldinData.org, where you find data and research on how the world is changing.

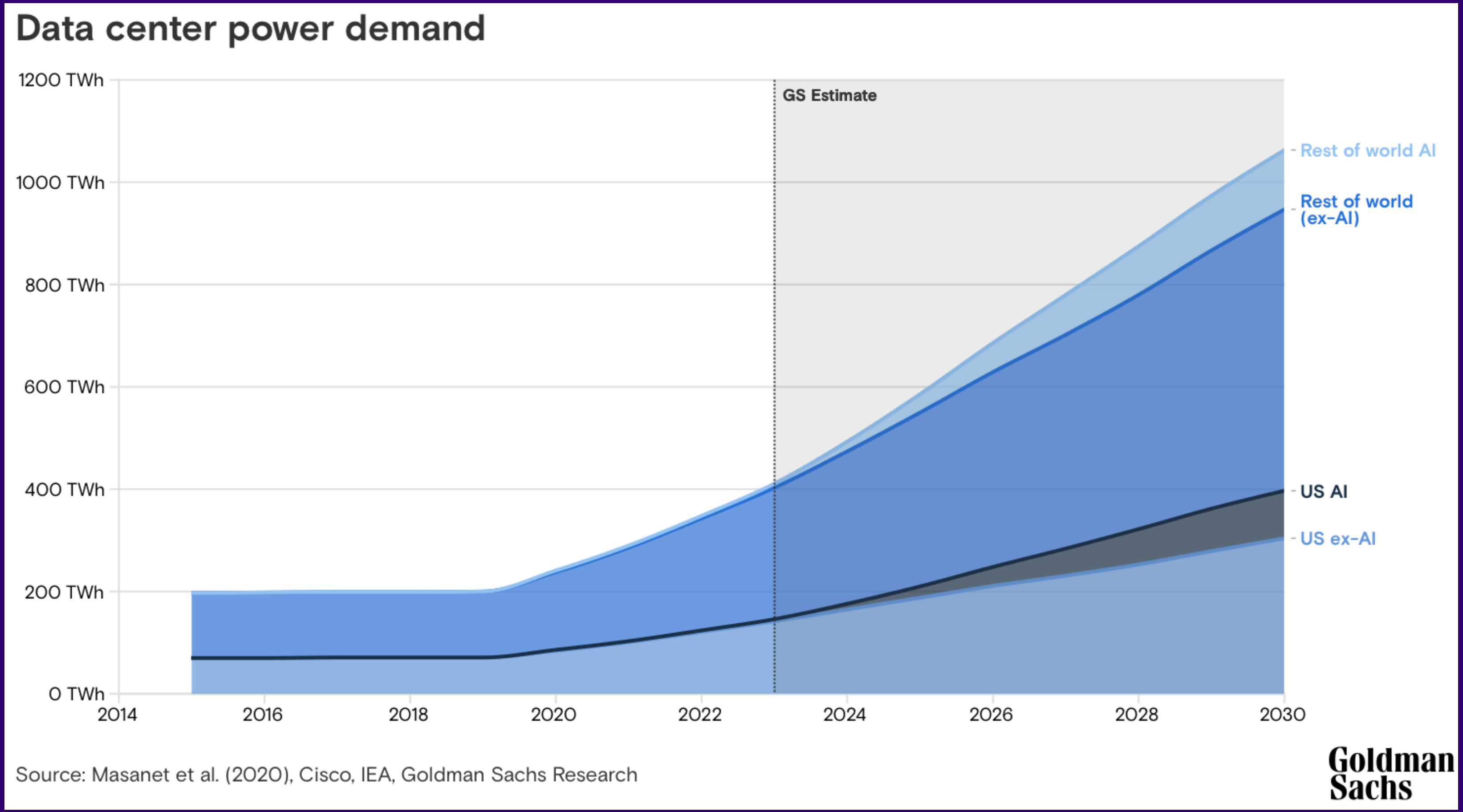
Licensed under CC-BY by the authors Max Roser and Hannah Ritchie.

- "Global electric vehicles sales, solar and battery installations hit record highs in 2022. However, renewables are only partly meeting growing energy demand rather than replacing fossil fuels in the energy mix. Fossil fuels are still growing in absolute terms.
- Energy related CO2 emissions are still hitting record highs and are only likely to peak in 2024, which is effectively the point at which the global energy transition begins."

"Limiting global warming to 1.5°C warming is less likely than ever."

Ref: DNV's Energy Transition Outlook

AI is about to make the problem worse



Source: Masanet et al. (2020), Cisco, IEA, Goldman Sachs Research

- “On average, a ChatGPT query needs nearly 10 times as much electricity to process as a Google search.”
- “Goldman Sachs Research estimates that data center power demand will grow 160% by 2030.”
- “Along the way, the carbon dioxide emissions of data centers may more than double between 2022 and 2030.”

Existing energy sources have serious disadvantages

Energy sources	Advantages	Disadvantages
Coal	- 1.06 trillion tonnes of coal reserves	- Burns dirty, health hazards - 1 lb of coal emits 2+ lbs of CO_2 - ~ 132 year supply
Oil	- 1.6 trillion barrels	- Large source of methane → 25x global warming potential of CO_2 - VOC emissions, air pollution, soil pollution - ~ 47 year supply
Natural Gas	- 1.06 trillion barrels (of oil equivalent)	- Similar to oil - ~ 52 year supply
Hydroelectric	- Clean	- Geographically limited - Dam construction impact to habitats
Wind	- Clean	- Geographically limited - Huge number of windmills required for large scale
Solar	- Clean	- Geographically limited - Huge number of solar cells required for large scale
Fission	- Clean	- Waste disposal challenging - Safety concerns

The case for fusion is stronger than ever

Credit: ESA

Limitless fuel ~ 5×10^{13} tons in earth's oceans

Complements renewables with large-scale energy production

Credit: Getty images

Equitable access to fusion fuel

Fusion

Compatible with existing power grid

Credit: Getty images

Low Carbon

Credit: AMWatch

Clean, no CO_2 or other emissions

Safe, no possibility of meltdown-like scenarios

Does not work yet!

Outline

- The case for fusion
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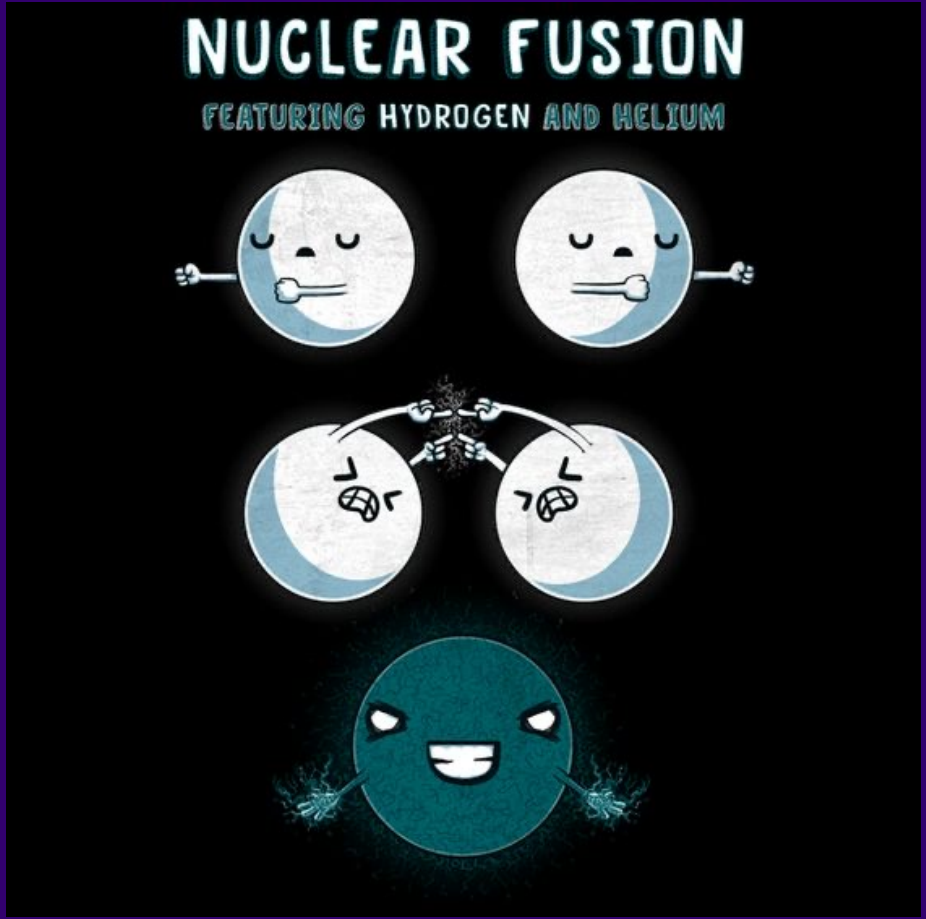
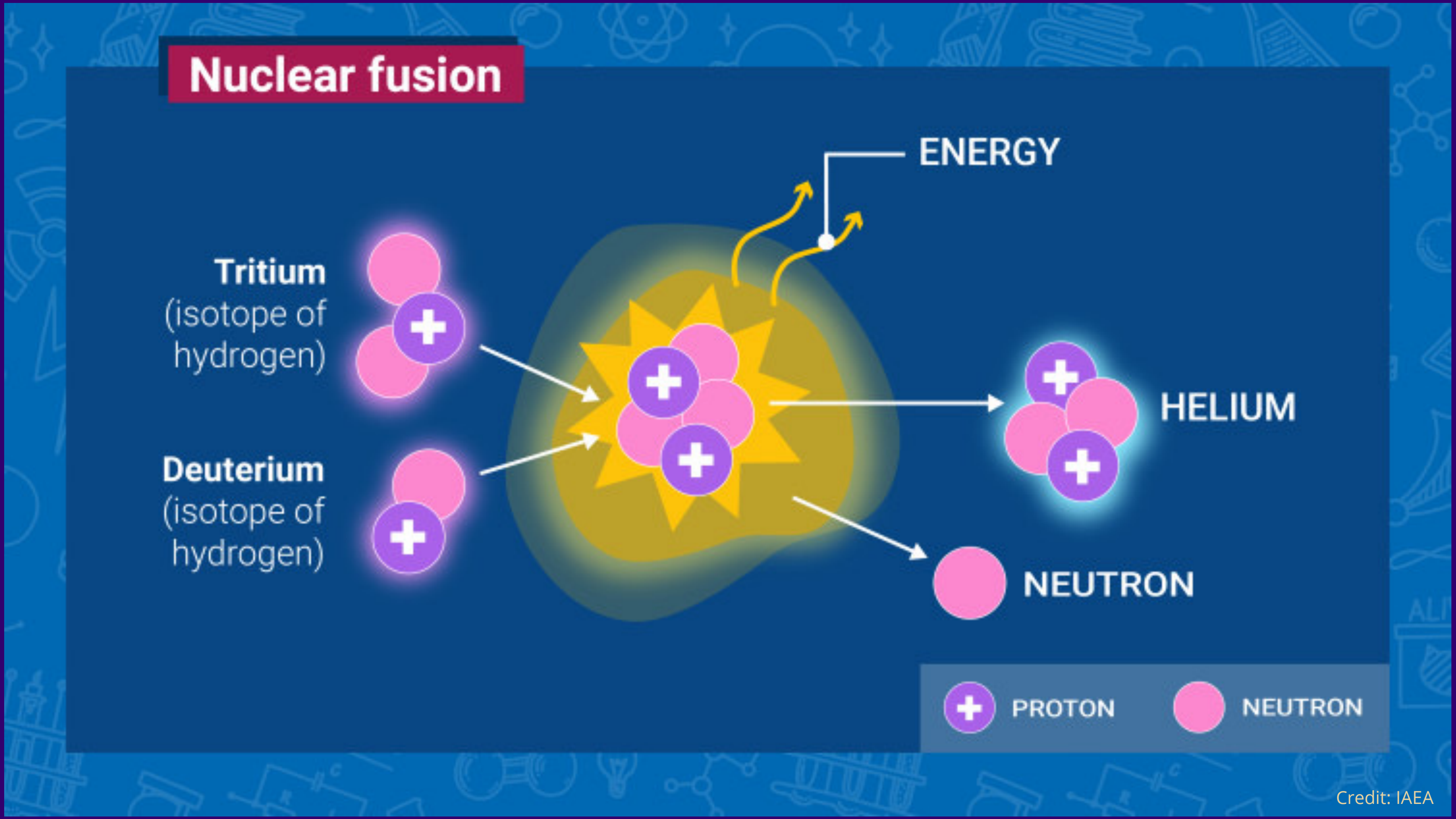
OK, so why don't we have fusion yet? Because fusion is hard! Let's start with what is fusion



Credit: neatoshop.com

Fusion combines 2 nuclei, typically isotopes of hydrogen, to produce energy



Credit: IAEA

What are some viable fusion reactions?

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.52\ \mathrm{MeV}) + \mathrm{n}\ (14.06\ \mathrm{MeV})$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.02\ \mathrm{MeV})$$

$$\rightarrow {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV})$$

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He}\ (3.6\ \mathrm{MeV}) + p\ (14.7\ \mathrm{MeV})$$

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\ {}^{3}\mathrm{He} + 8.7\ \mathrm{MeV}$$

These are the only fusion fuels that are theoretically feasible for energy and propulsion!

Remember that 1 eV = 1.6 x 10^{-19} J

What are some viable fusion reactions?

$$
\begin{aligned}
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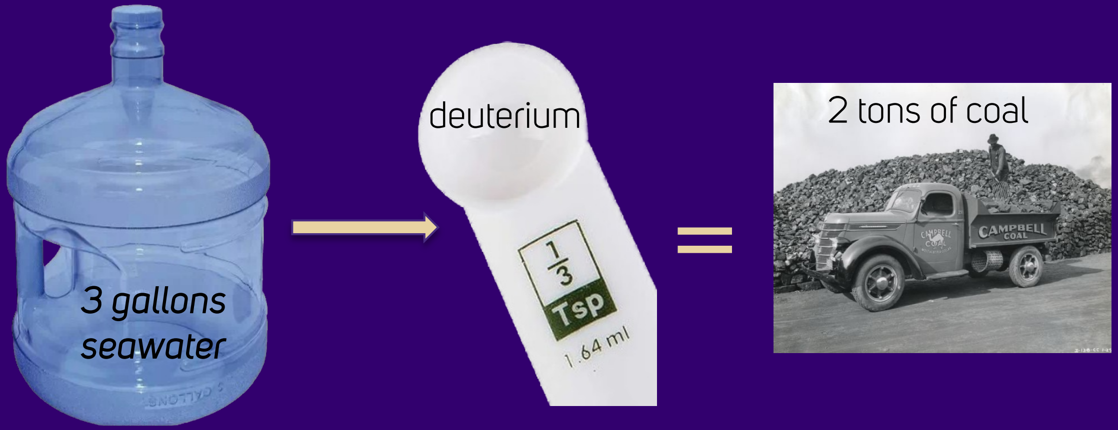
These are the only fusion fuels that are theoretically feasible for energy and propulsion!

Note these reactions are aneutronic and highly desirable, but more challenging, we'll see why.

Remember that 1 eV = 1.6 x 10^{-19} J

Where can we find deuterium and tritium?

There is plenty of deuterium in the earth's oceans



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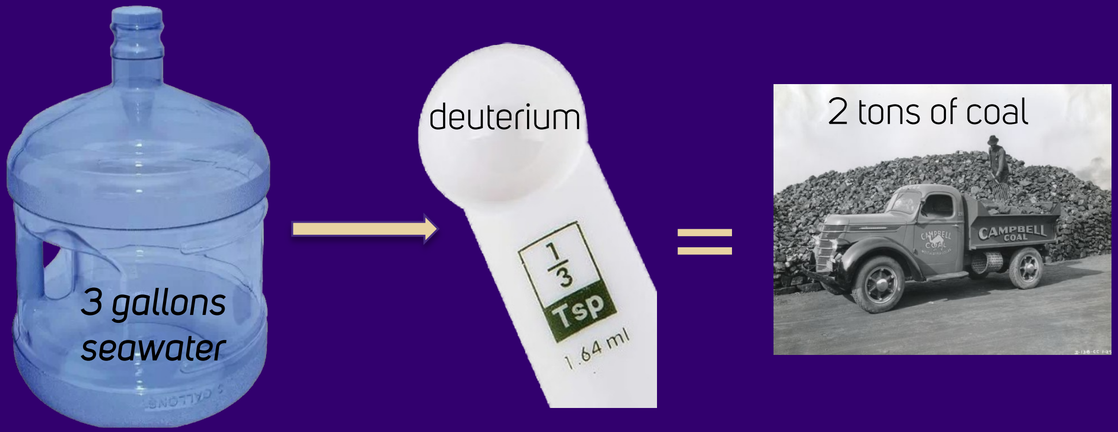

Tritium would need to be "bred" in the fusion reactor → lithium blankets

$$\mathrm{n} + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + \mathrm{T}$$

Earth has abundant lithium on land and in the ocean to last perpetually as far as human timescales are concerned

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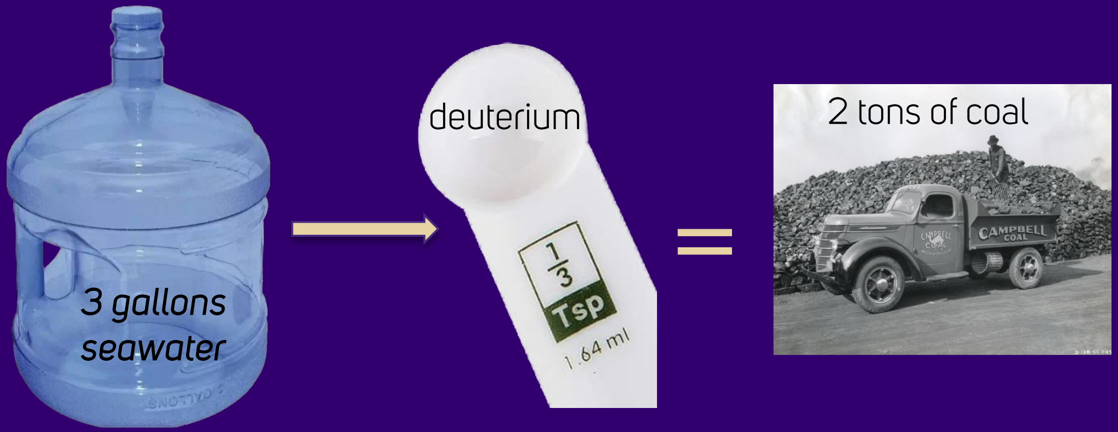

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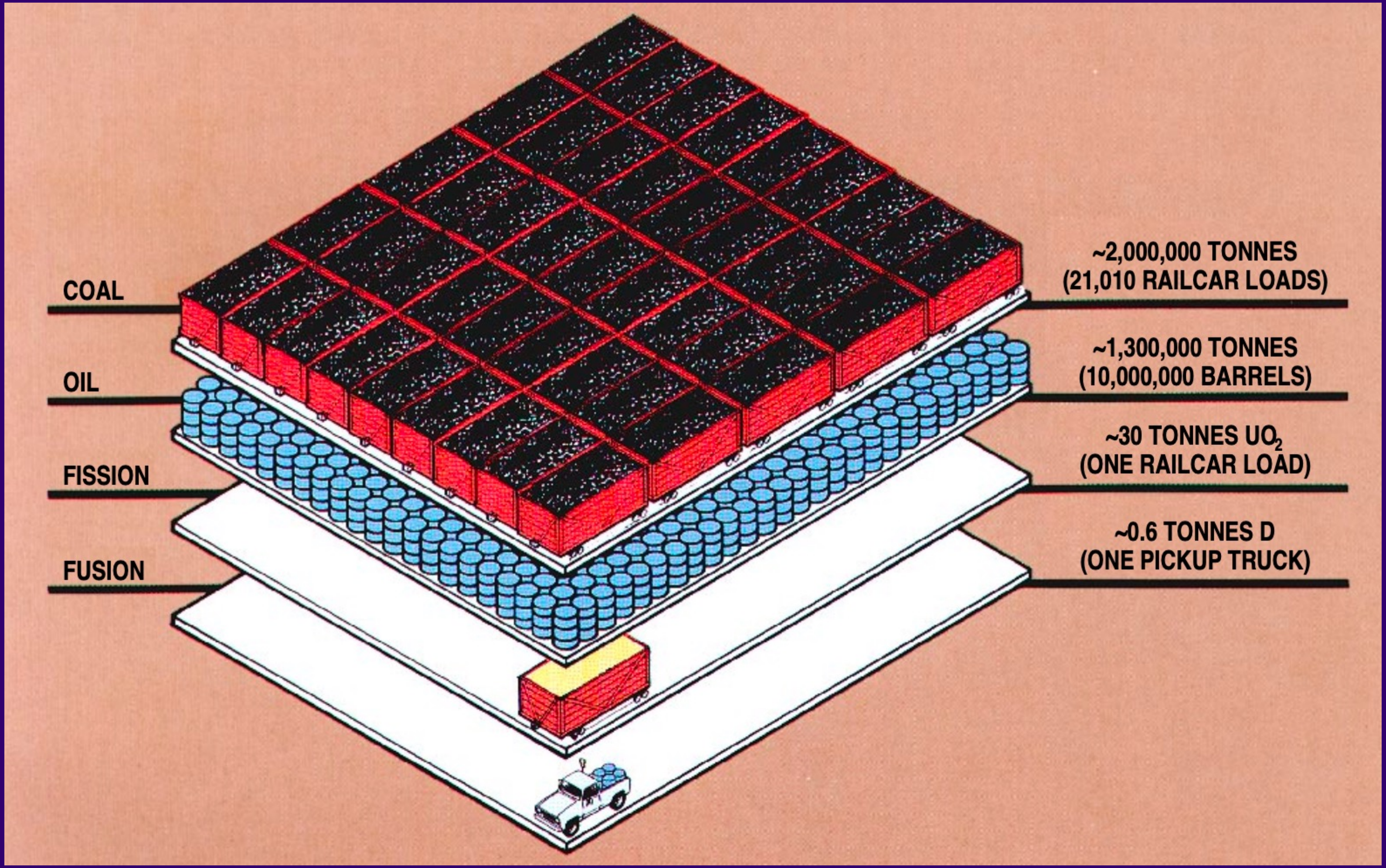
^{3}He does not exist naturally on earth, but does on the moon → mine the moon?

Credit: GA and San Diego Schools

How does fusion fuel compare to other energy fuels?



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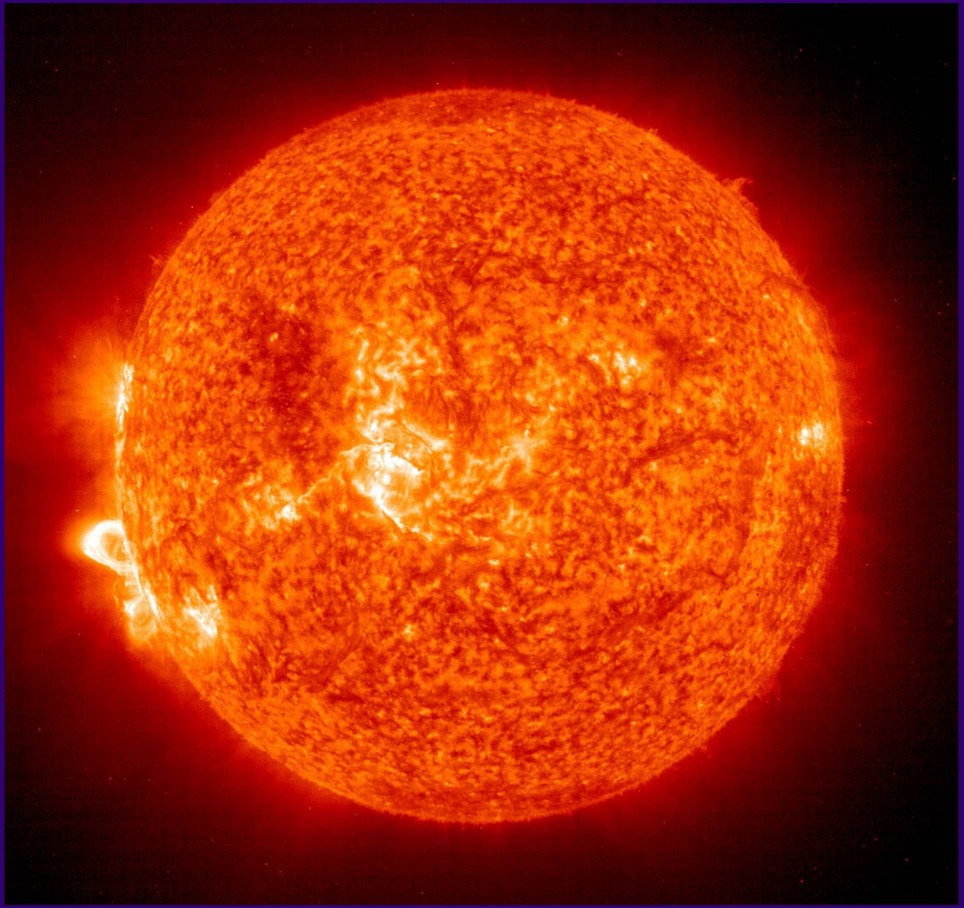
All matter in our universe came from fusion reactions so why is the list of viable reactions for energy so short?



- Most matter was born from gravitational confinement of plasma in stars
- Fusion reactions occurring over billions of years fused hydrogen before fusing heavier elements
- Plasma pressure balanced with gravity
- **A bit challenging for us earthlings to apply gravitational confinement!**

All matter in our universe came from fusion reactions so why is the list of viable reactions for energy so short?

We will learn about 3 concepts here to understand if a fusion reaction produces enough energy and has high probability:

1. Coulomb forces versus nuclear forces
2. Gamow peak
3. Cross-sections for the different reactions

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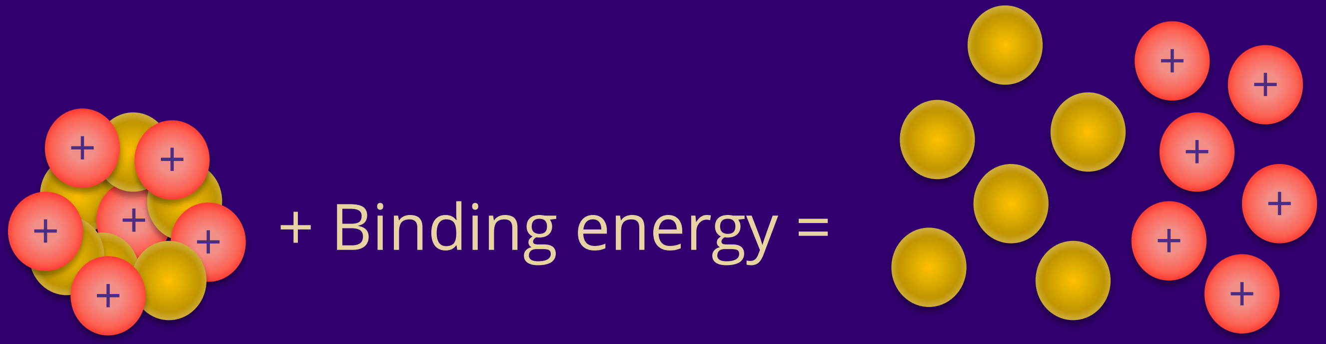
Let’s start with the nuclear binding energy



+ Binding energy =

Nucleus

Nucleons

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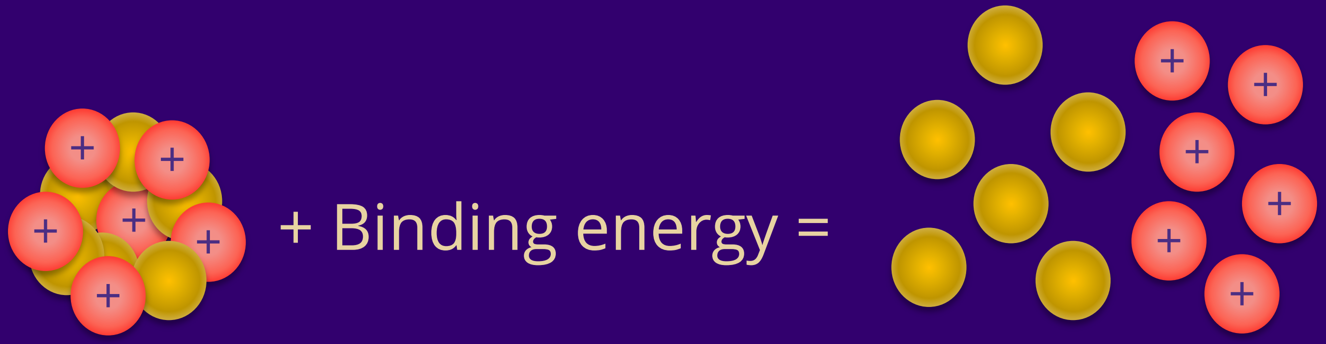

Nucleus

Nucleons

Protons and neutrons, i.e. nucleons, held together in nucleus by strong nuclear force

The mass of individual nucleons > mass of the nucleus

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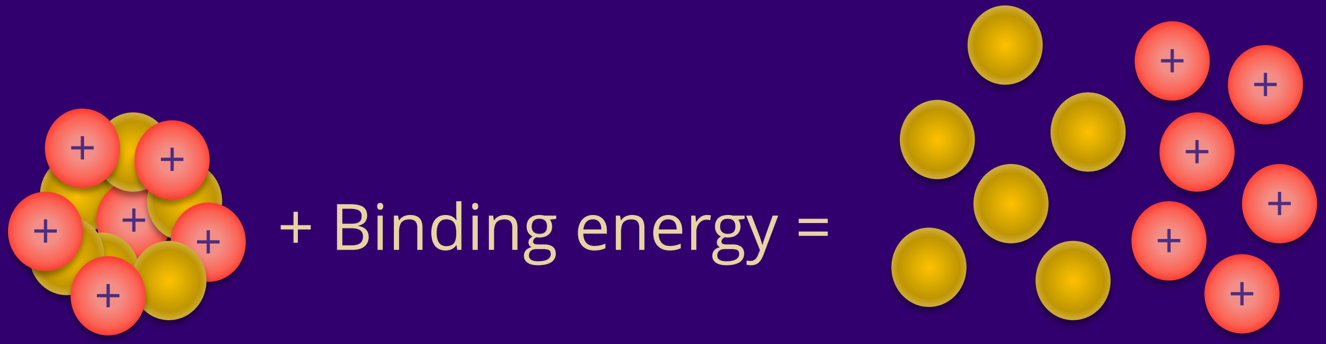
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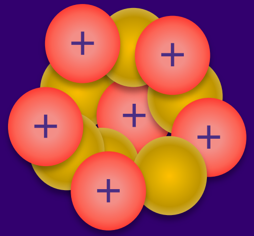

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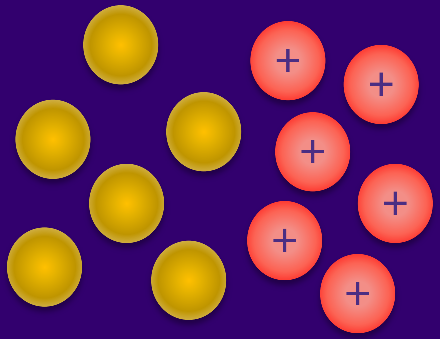

Nucleus

Nucleons

Attractive strong nuclear force holds protons and neutrons together in a nucleus. Binding energy needed to pull them apart.

Protons and neutrons, i.e. nucleons, held together in nucleus by strong nuclear force

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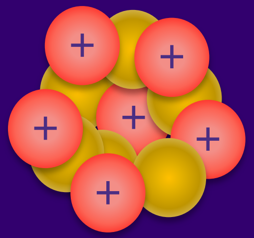

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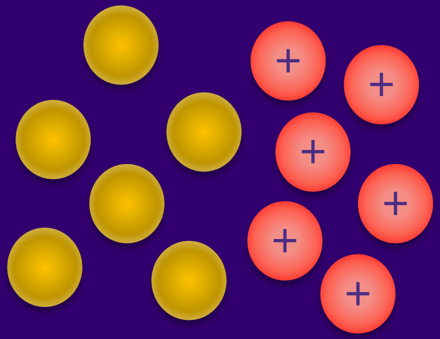

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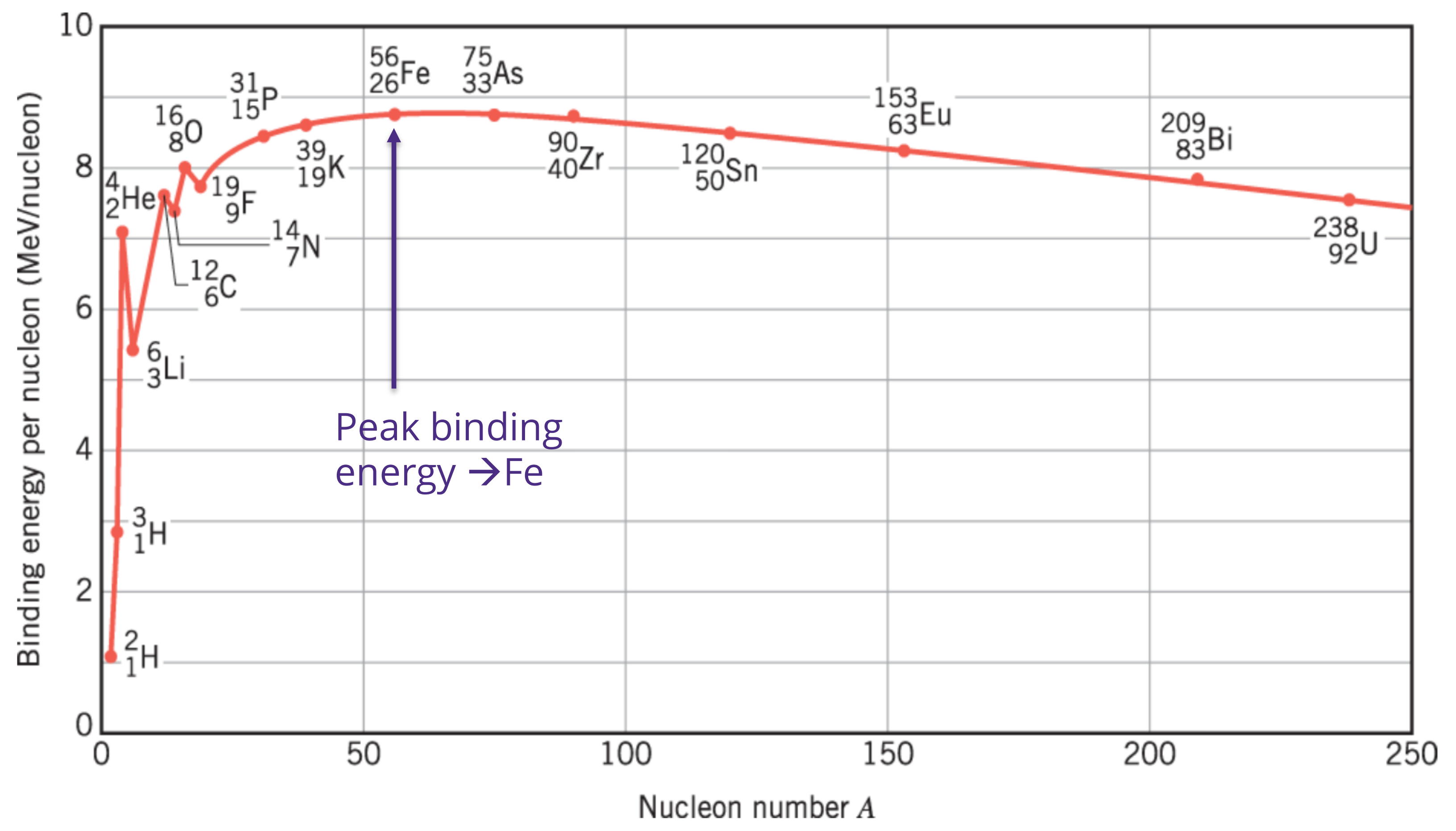
Attractive strong nuclear force holds protons and neutrons together in a nucleus. Binding energy needed to pull them apart.

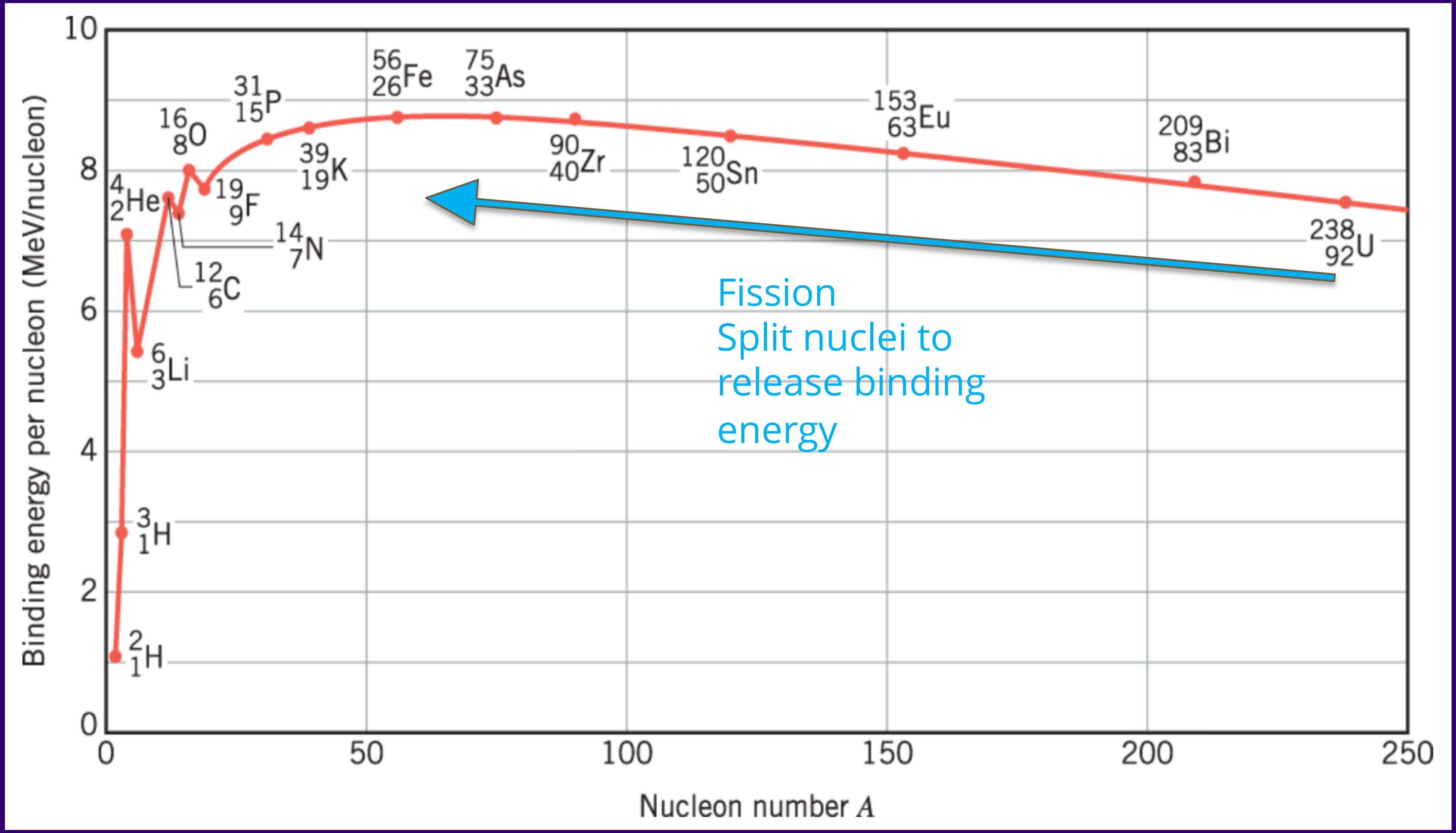
The binding energy of the nucleus is directly related to the amount of energy released in a fusion reaction or in a fission reaction

The nuclear binding energy released per nucleon in fission versus fusion access different sides of the periodic table



Peak binding energy →Fe

The nuclear binding energy released per nucleon in fission versus fusion access different sides of the periodic table



Fission
Split nuclei to release binding energy

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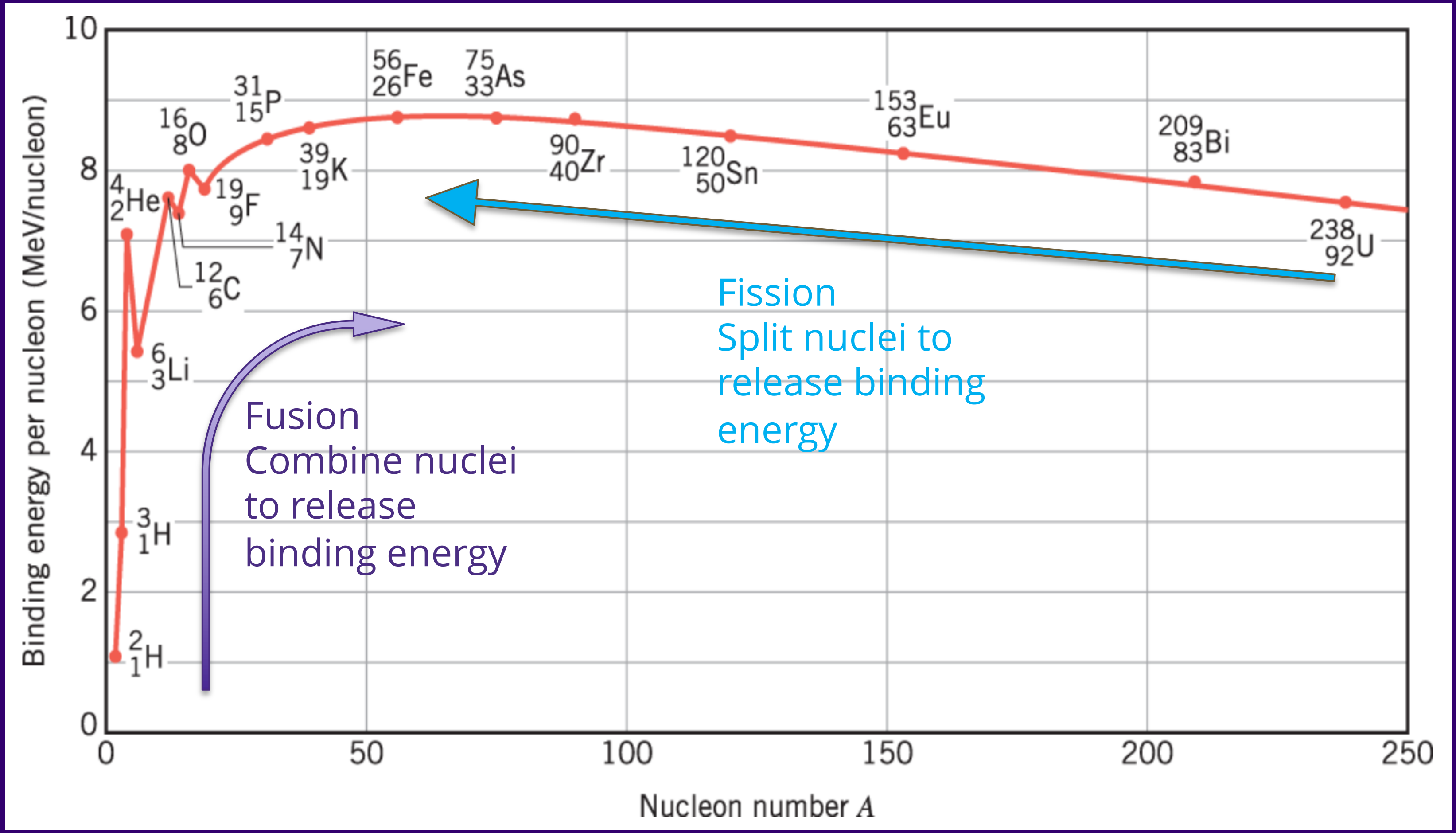
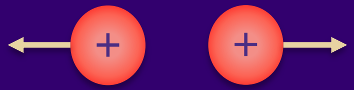


Fusion
Combine nuclei to release binding energy

Fission
Split nuclei to release binding energy

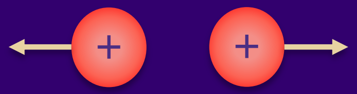
Remember that like charges repel – Coulomb forces provide a challenge to overcome



$$F \propto \frac{q_1 q_2}{r^2} \qquad U \propto \frac{q_1 q_2}{r}$$

- Note that an atom ~ 1 Angstrom ~ 10^{-10} m
- Attractive nuclear forces ~ 10^{-15} m
- For larger distances, need to overcome long-range repulsive Coulomb forces before attractive strong nuclear forces dominate
- Requires input energy to ions to overcome the Coulomb barrier

Remember that like charges repel – Coulomb forces provide a challenge to overcome



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- For larger distances, need to overcome long-range repulsive Coulomb forces before attractive strong nuclear forces dominate
- Requires input energy to ions to overcome the Coulomb barrier

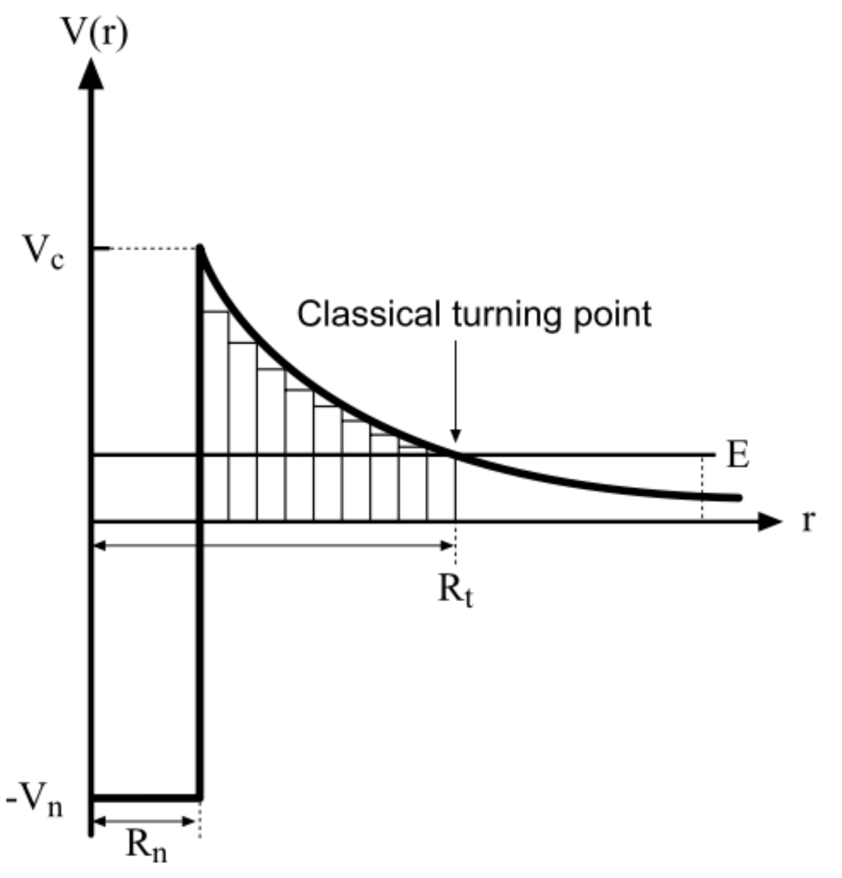
- This input energy must be practically achievable → rules out most fusion reactions in the periodic table

All matter in our universe came from fusion reactions so why is the list of viable reactions for energy so short?

We will learn about 3 concepts here to understand if a fusion reaction produces enough energy and has high probability:

1. Coulomb forces versus nuclear forces
2. **Gamow peak**
3. Cross-sections for the different reactions

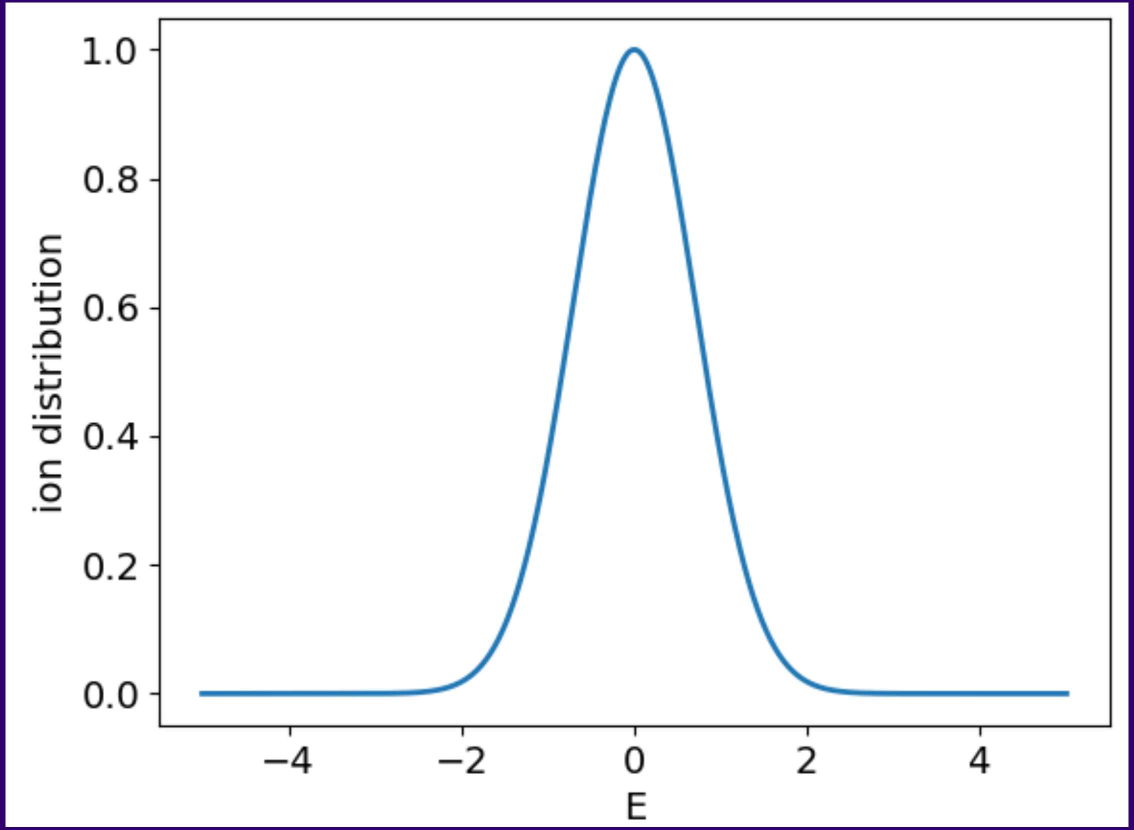
Quantum mechanics shows that there is a finite probability for an ion to penetrate the Coulomb barrier



Credit: José, Stellar Explosions (2016)

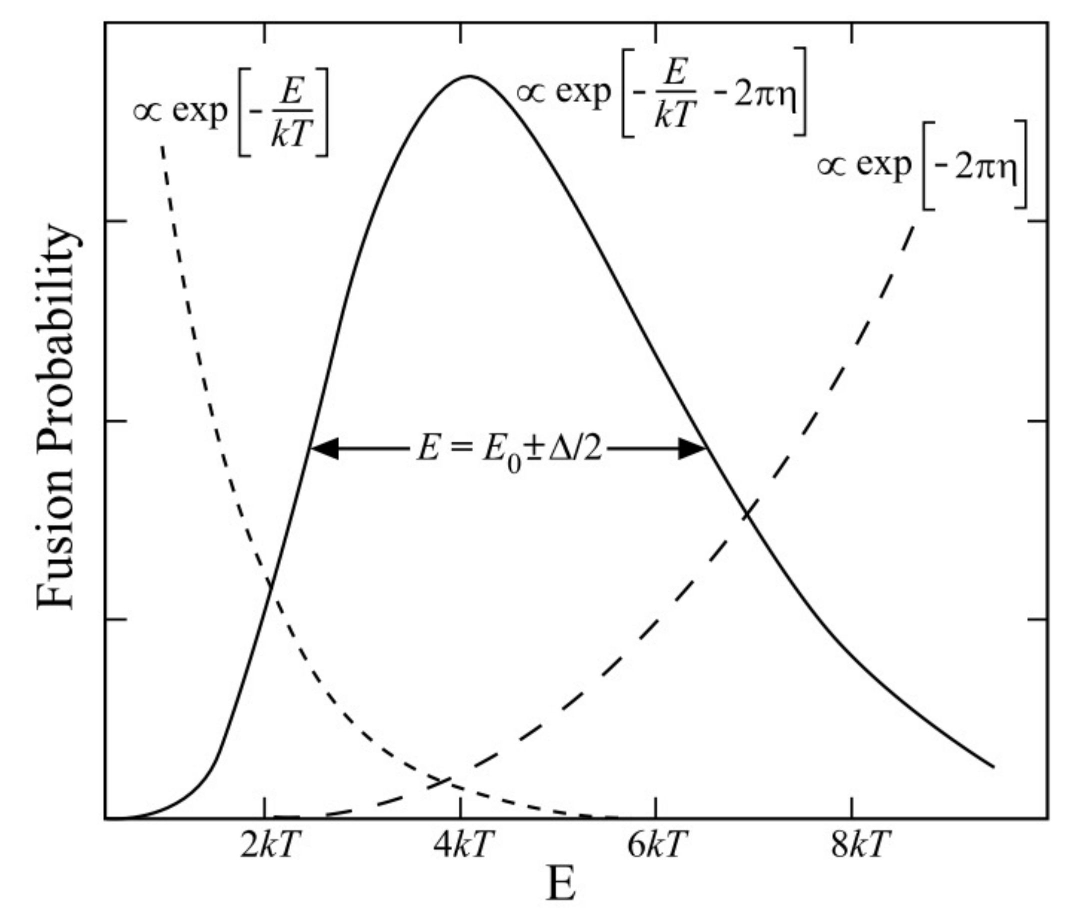
- Quantum tunneling through which the ions penetrate the Coulomb barrier [Gamow (1928)]
- Penetration probability comes from the time-dependent Schrödinger equation, i.e. the wave equation
- This probability is given by an exponential, known as the Gamow factor

Quantum mechanics shows that there is a finite probability for an ion to penetrate the Coulomb barrier



- Most plasma is assumed to be distributed as a Gaussian with respect to energies, specifically a Maxwellian distribution
- This Maxwellian distribution is also given by an exponential function

Quantum mechanics shows that there is a finite probability for an ion to penetrate the Coulomb barrier



Credit: José, Stellar Explosions (2016)

- The product of the two exponentials: the Maxwellian distribution and the tunneling probability → provides the Gamow peak
- Specifies the energy range at which a specific nuclear reaction occurs for a given temperature
- This leads us to the third topic: Reaction rates

All matter in our universe came from fusion reactions so why is the list of viable reactions for energy so short?

We will learn about 3 concepts here to understand if a fusion reaction produces enough energy and has high probability:

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2. Gamow peak
3. **Cross-sections for the different reactions**

Each fusion reaction has a collision cross-section that is a function of energy

- A collision cross-section, $\boldsymbol{\sigma}$, is the effective area “seen” by colliding ions

Credit: Wurzel and Hsu, Phys. Plasmas (2022)

Each fusion reaction has a collision cross-section that is a function of energy

- A collision cross-section, $\boldsymbol{\sigma}$, is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity, $\mathbf{v}$, between the colliding ions

Credit: Wurzel and Hsu, Phys. Plasmas (2022)

Each fusion reaction has a collision cross-section that is a function of energy

- A collision cross-section, $\boldsymbol{\sigma}$, is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity, **v**, between the colliding ions
- Want to maximize the fusion reaction rate, given by $< \boldsymbol{\sigma}\ \mathbf{v} >$ which is a function of temperature , comes from the Gamow peak we just discussed

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Each fusion reaction has a collision cross-section that is a function of energy

- A collision cross-section, $\boldsymbol{\sigma}$, is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity, **v**, between the colliding ions
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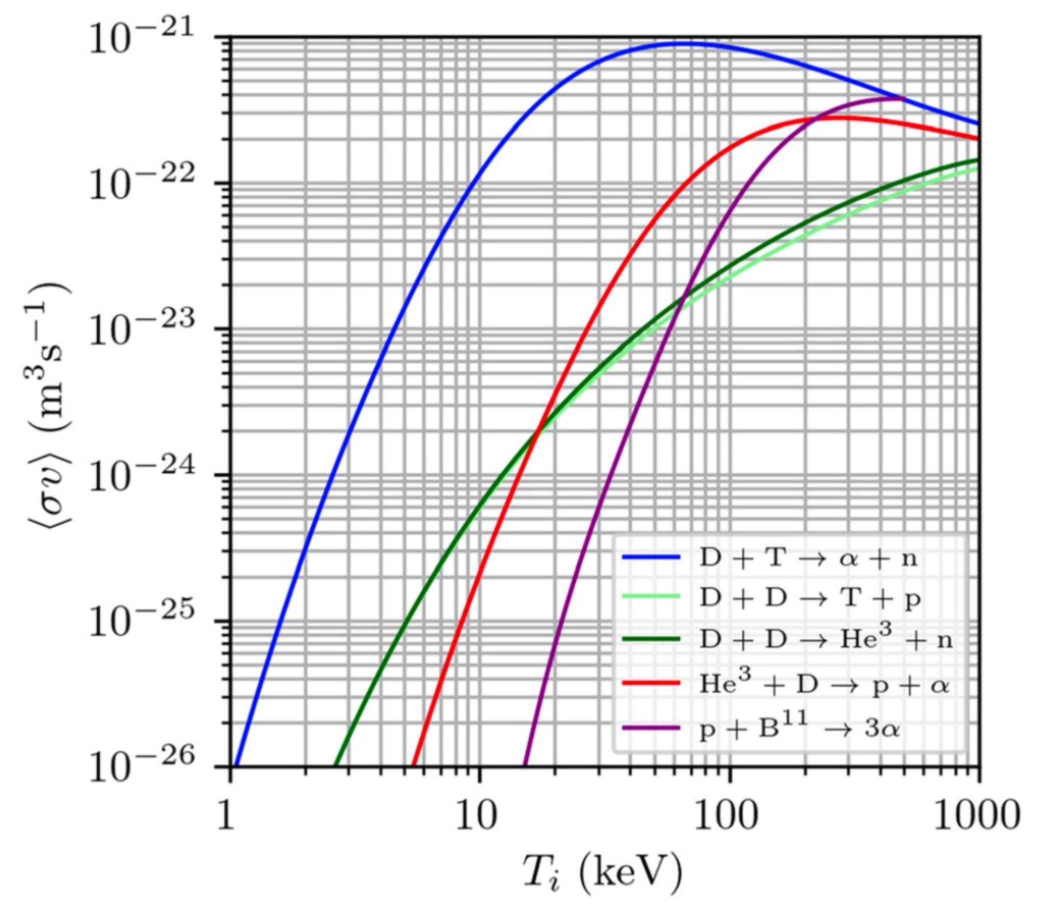
- Too low of a cross-section also eliminates many fusion reactions for energy



Credit: Wurzel and Hsu, Phys. Plasmas (2022)

Each fusion reaction has a collision cross-section that is a function of energy

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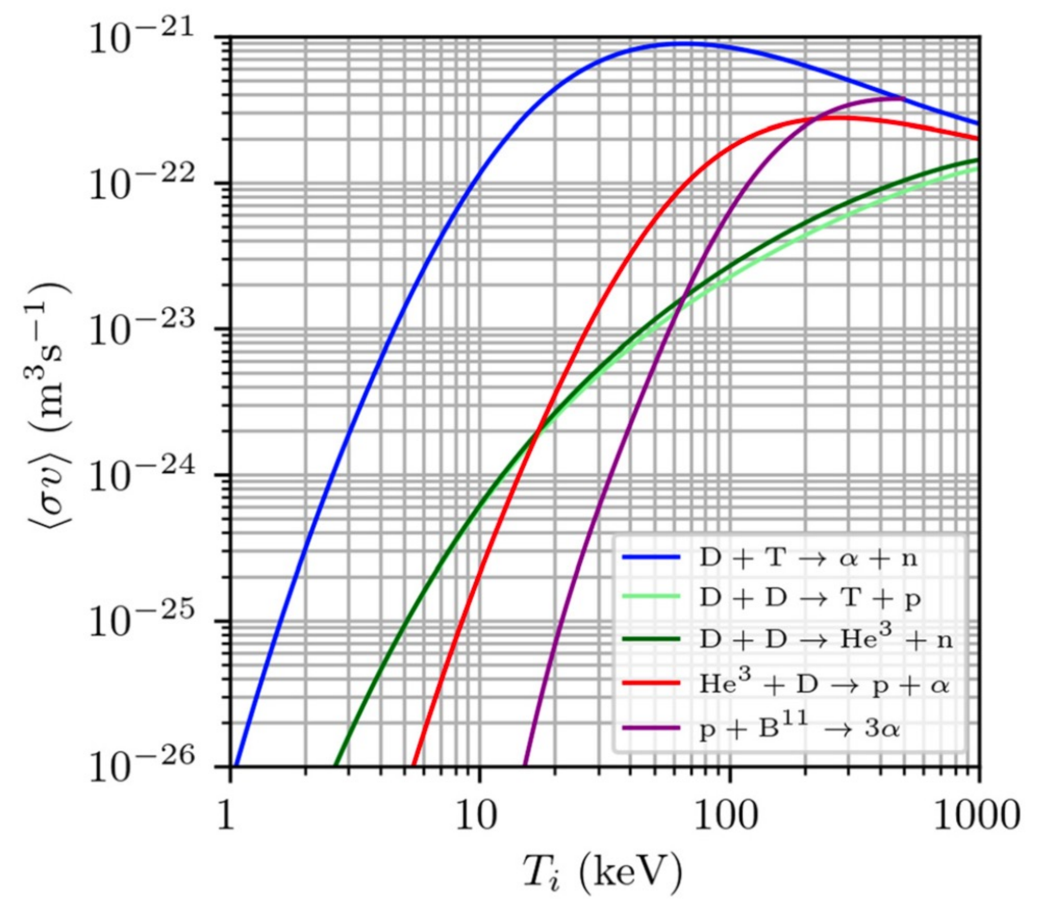

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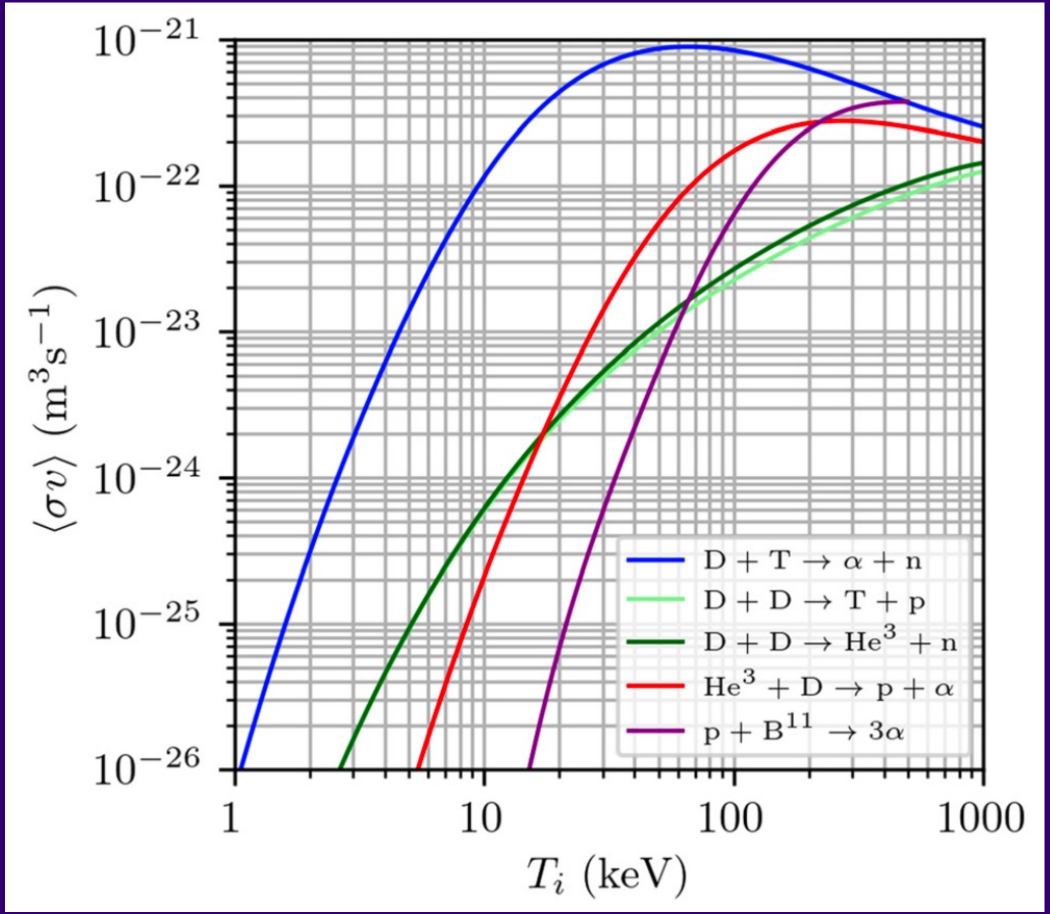

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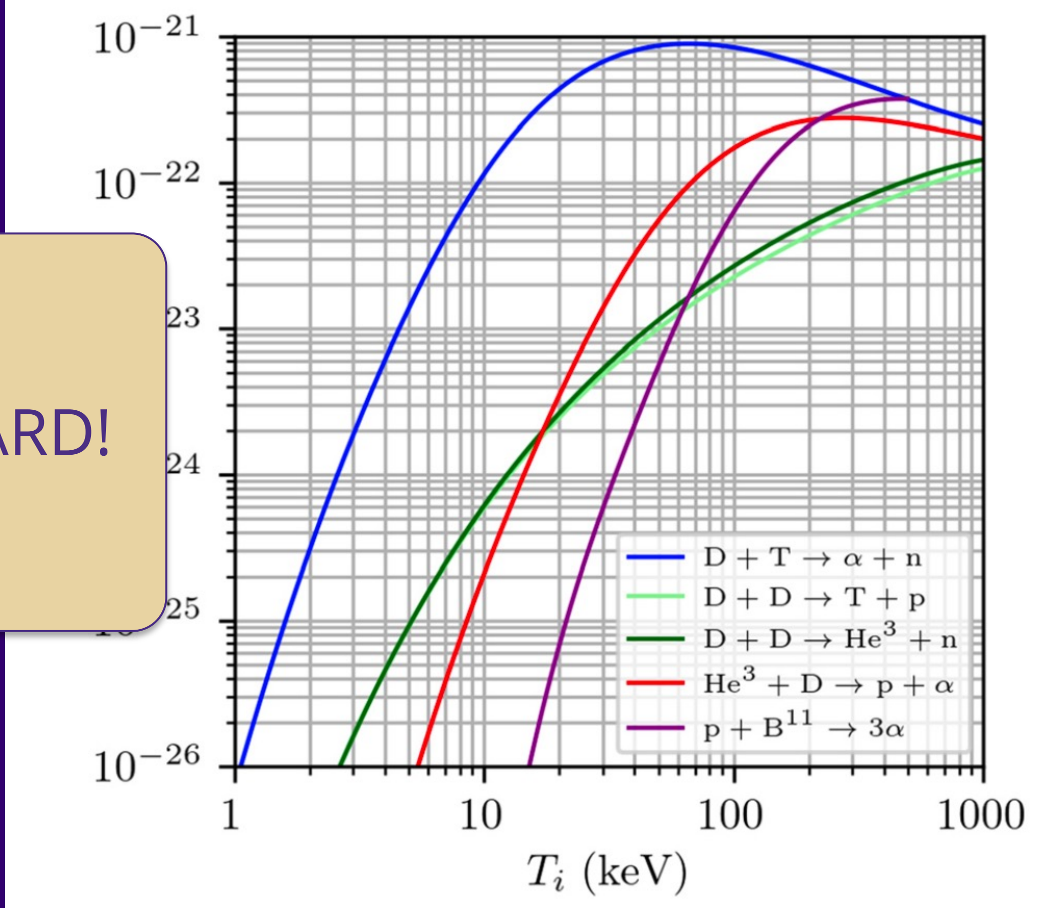
FUSION IS HARD!



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Outline

- The case for fusion
- What is fusion?
- **Metrics to evaluate fusion energy**
- Brief history of fusion and some pioneers
- Fusion concepts: steady-state vs pulsed
- Progress in fusion

Fusion energy is evaluated using key metrics

We will discuss some key metrics by which fusion energy is evaluated for feasibility:

1. Breakeven
2. Ignition
3. The Lawson criteria
4. The fusion triple product
5. Fusion gain, Q

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The energy from fusion needs to balance energy in and radiation losses (and any other losses that may exist).

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$$\begin{aligned}
\mathrm{D} + \mathrm{T} \rightarrow\ & {}^4\mathrm{He}\ (3.52\ \mathrm{MeV}) + \mathrm{n}\ (14.06\ \mathrm{MeV}) \\
\mathrm{D} + \mathrm{D} \rightarrow\ & \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.02\ \mathrm{MeV}) \\
\rightarrow\ & {}^3\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}\ (2.45\ \mathrm{MeV}) \\
\mathrm{D} + {}^3\mathrm{He} \rightarrow\ & {}^4\mathrm{He}\ (3.6\ \mathrm{MeV}) + p\ (14.7\ \mathrm{MeV}) \\
\mathrm{p} + {}^{11}\mathrm{B} \rightarrow\ & 3\ {}^3\mathrm{He} + 8.7\ \mathrm{MeV}
\end{aligned}$$

Remember the reactions we talked about. There is energy associated with the ^{4}He (α-particle) product → **alpha particle heating** is very important for the success of fusion.

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The Lawson criteria evaluates conditions for breakeven

- Lawson criteria is the product

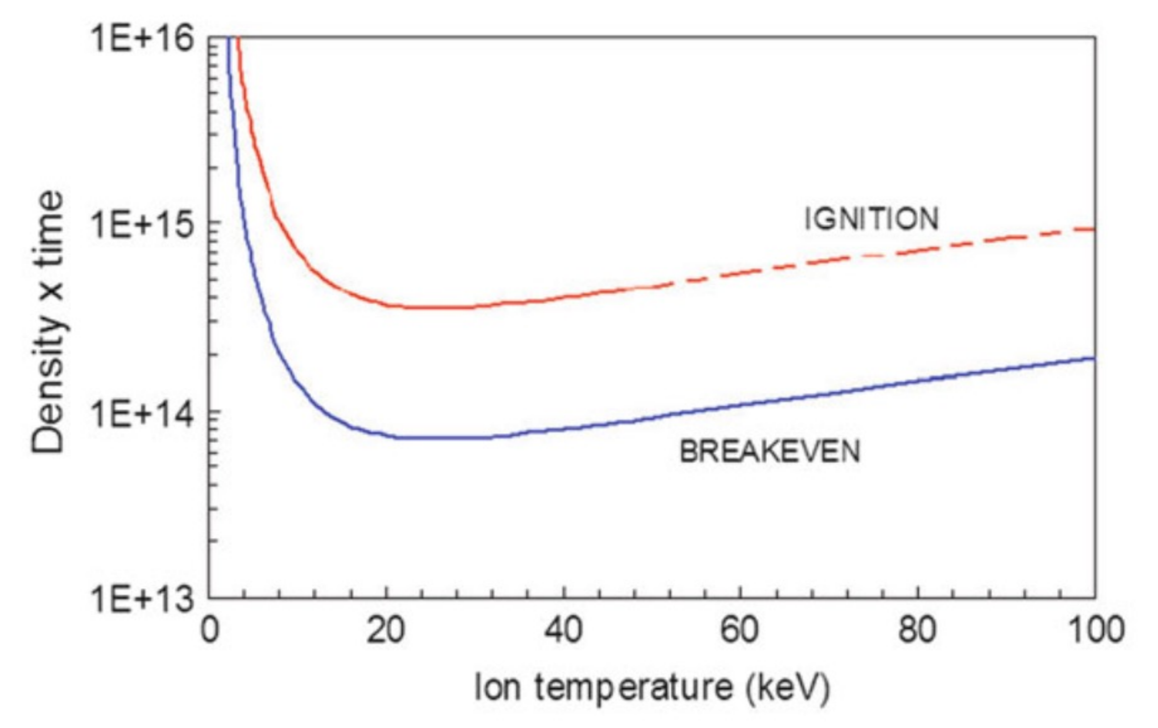
$$n\ \tau_E$$

Density x Energy Confinement Time

- For D-T reactions:

$$n\ \tau_E \geq 1.49 \times 10^{20} \mathrm{s/m}^3$$

- There are two distinct operating conditions for fusion:
  - > Steady-state: confining plasma at a certain density for sufficiently long times
  - > Pulsed: achieving very high density at sufficiently short confinement times



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For D-T fusion:

$$n\ T\ \tau_E \geq 2.76 \times 10^{21}\ \text{keV s/m}^3$$

For magnetic confinement concepts, where plasma pressure is considered for stability, density and temperature can vary widely. So the triple product includes temperature.

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- Q = 1 is scientific breakeven
- $Q \approx 5$ for burning plasma where $\boldsymbol{\alpha}$-heating provides self-heating
- $Q = \infty$ ignition → self-heating removes need for external heating
- Engineering breakeven: wall-plug efficiency
- Commercial breakeven: cost efficiency (necessary to compete with coal)

Have any fusion concepts achieved scientific breakeven?

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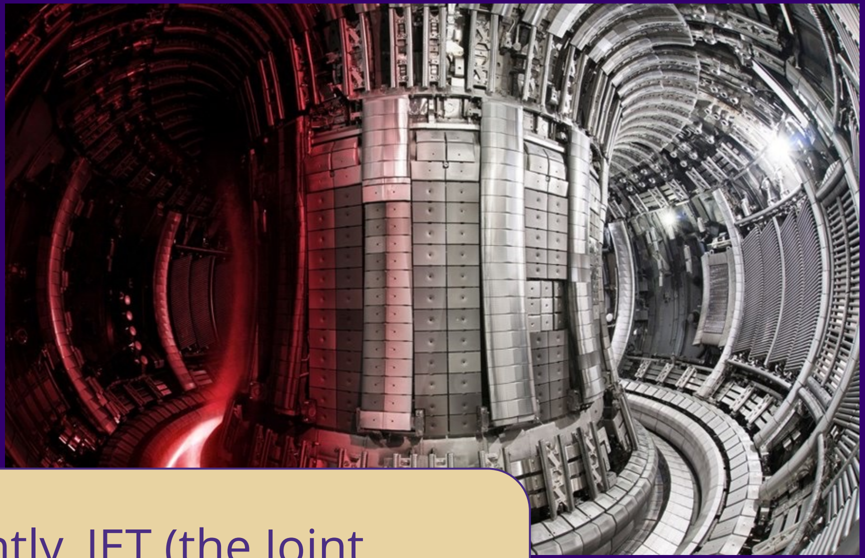

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- 22 MJ of heat released in 1997
- 59 MJ of heat released in 2022
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An average US home uses 100 MJ per day

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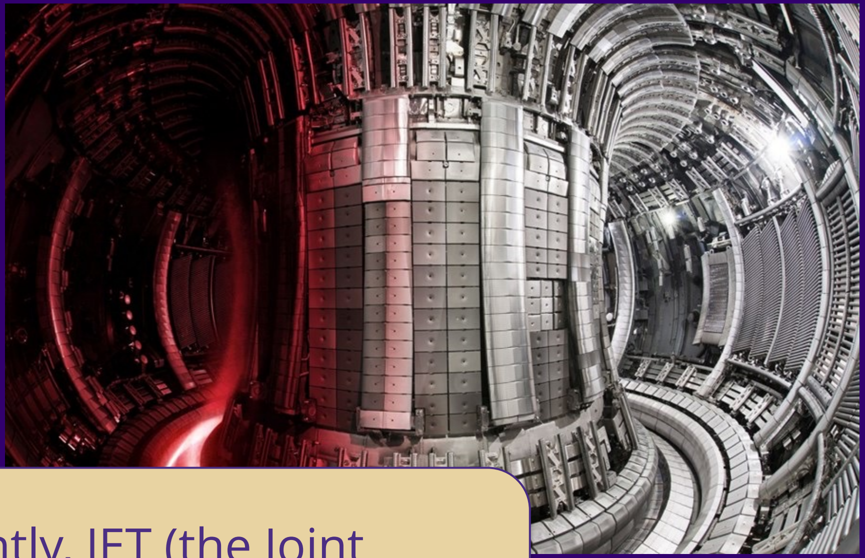

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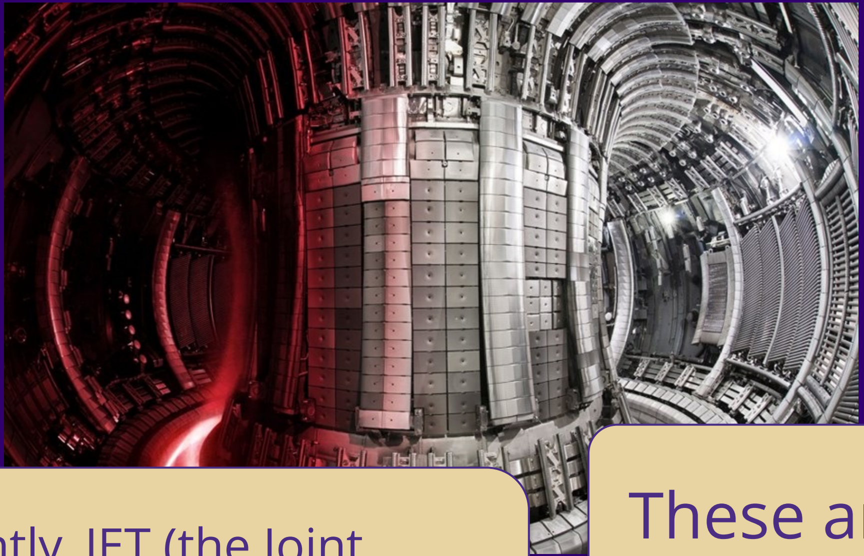

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These are exciting times to work in fusion!

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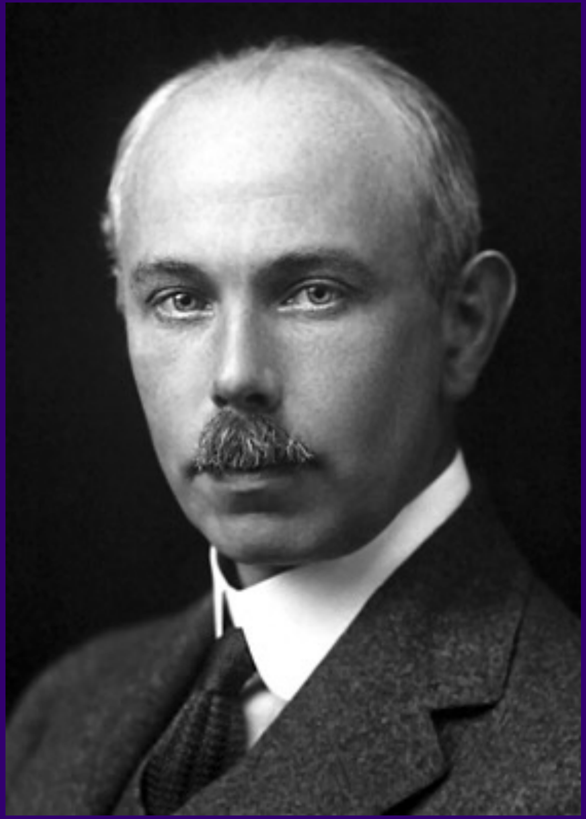

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Her thesis was discredited at the time by Henry Russell who later published a paper in 1929 agreeing with her. Yet Russell is the one who is primarily credited for this.

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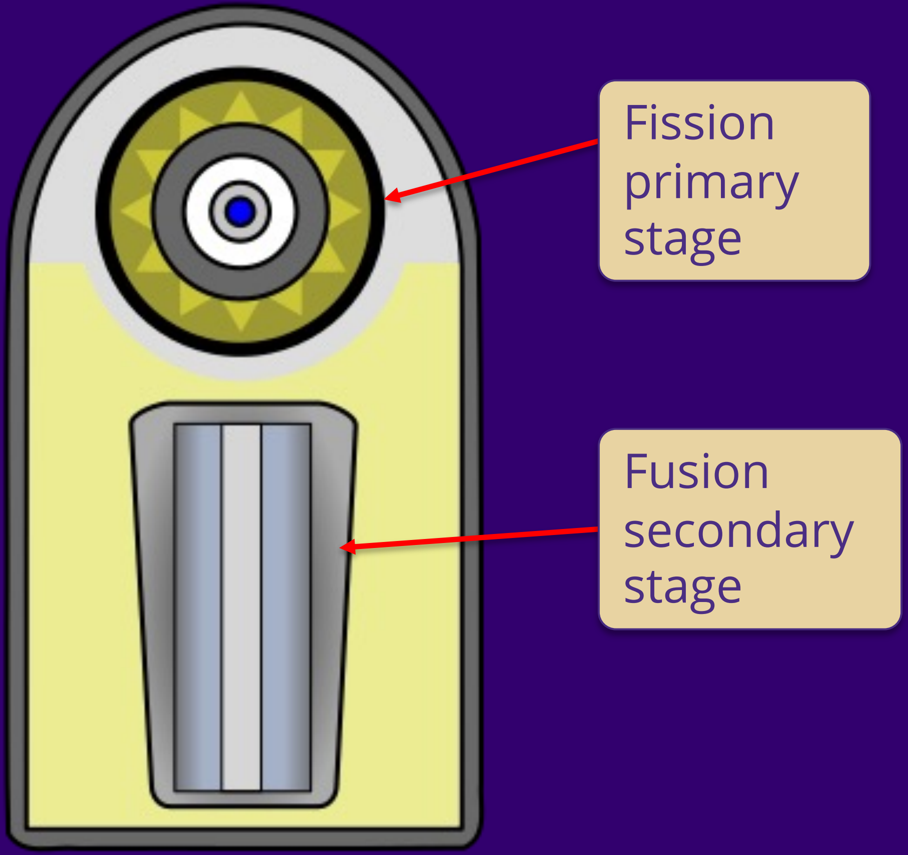
The recent ARPA-E BETHE program funding “Breakthroughs in THErmonuclear fusion” named after Hans Bethe

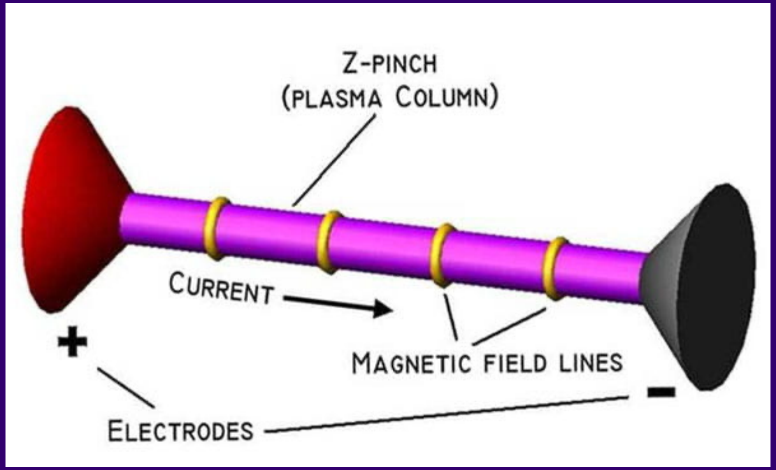
H-bomb in the 1950s showed that nuclear fusion does work if controlling it isn't a requirement



- First full-scale tests in the US in 1952
- Requires X-rays from fission reactions to heat, compress, and ignite fusion fuel
- Fission explosion is required for fusion explosion to occur
- Goal is to avoid the disadvantages of fission, so this is not pursued in earnest for fusion energy

The first fusion reactor was a Z-pinch, patented in 1946

- Plasma column with axial current flowing through it
- As with a current-carrying wire, a theta (azimuthal) magnetic field is generated
- The magnetic pressure could compress the plasma potentially achieving the Lawson criteria i.e. magnetic confinement fusion



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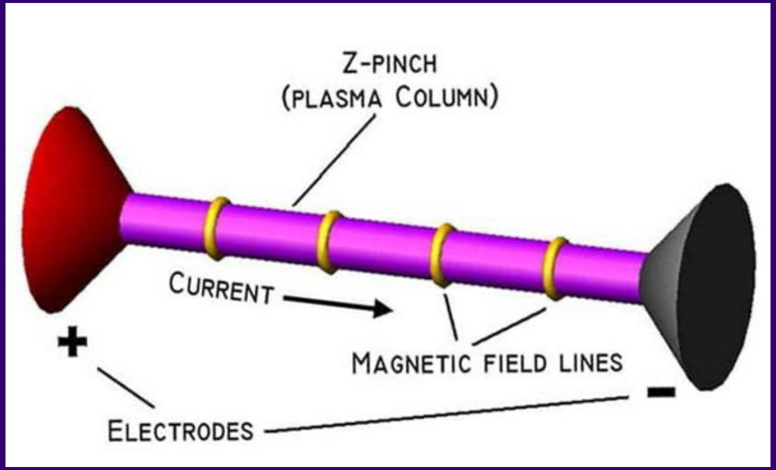
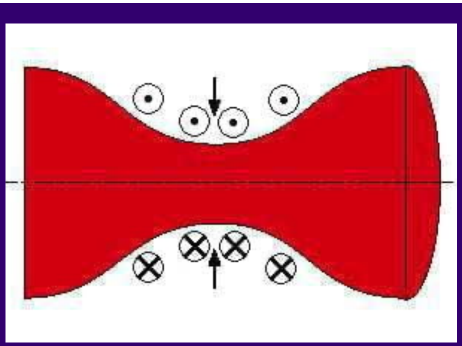
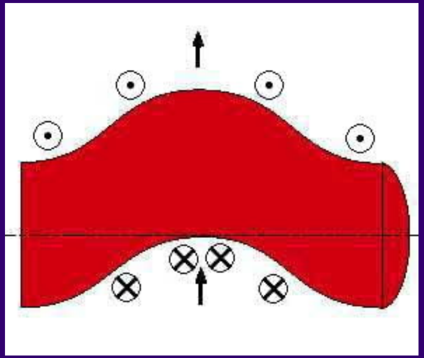
- Other concepts were prioritized due to susceptibility to plasma instabilities
- However, the last 3 decades have shown that there are stabilization techniques such as shear-flow stabilization that can make this a viable concept for fusion energy
- Provides a simple, elegant concept for fusion
- Pulsed device, lots of private funding







ZAP ENERGY

Bhuvana Srinivasan

The next concept that came about was the stellarator, also magnetic confinement fusion

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- Complex engineering to achieve 3-D field structure

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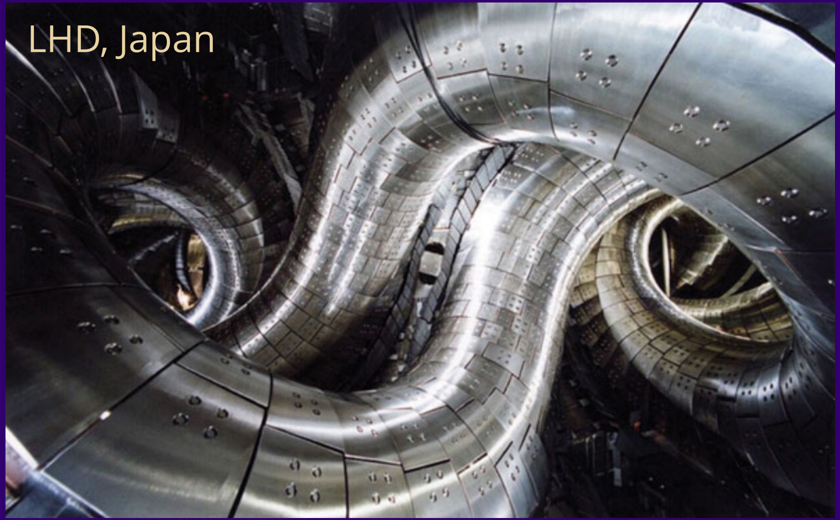

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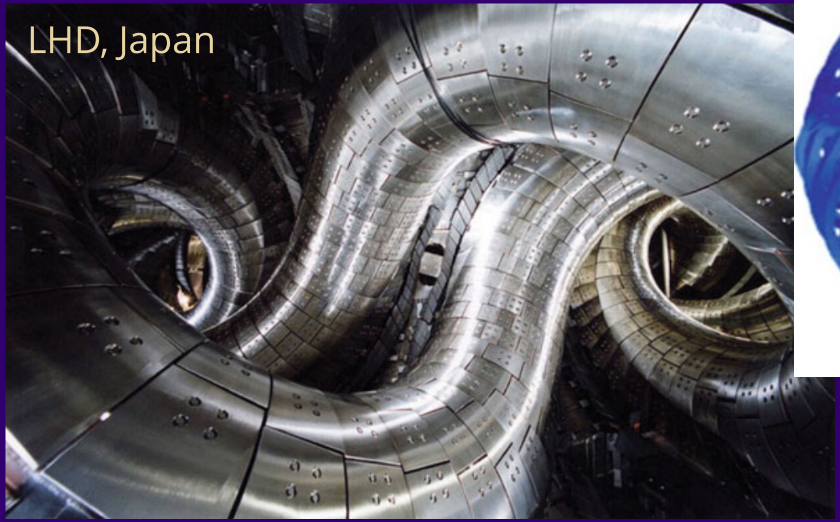
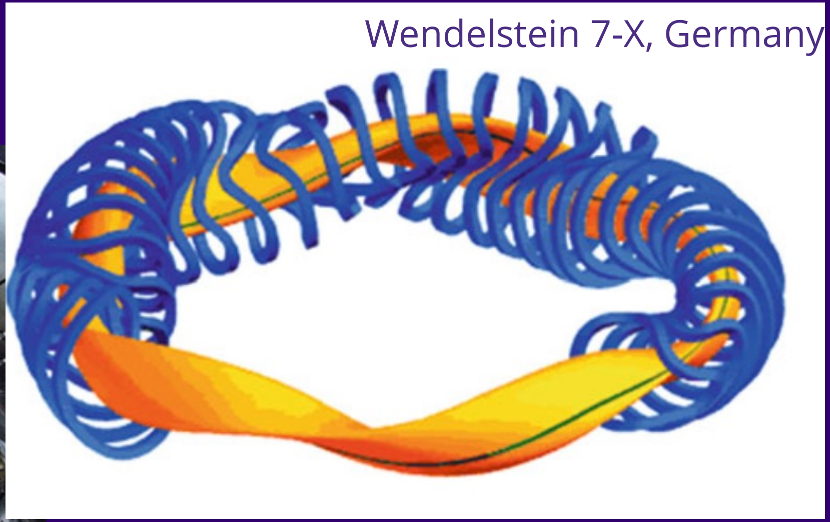


LHD, Japan



Wendelstein 7-X, Germany

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- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially
- Interest resumed in recent years

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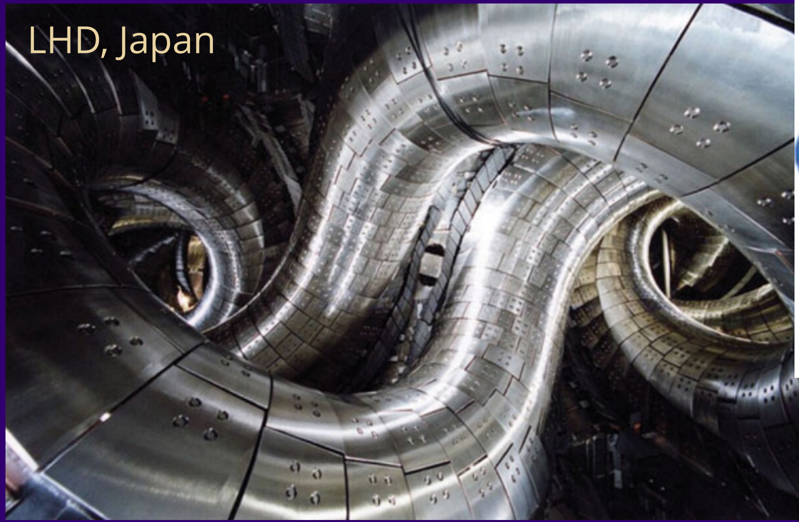
PPPL

MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

RENAISSANCE
FUSION

TYPE ONE ENERGY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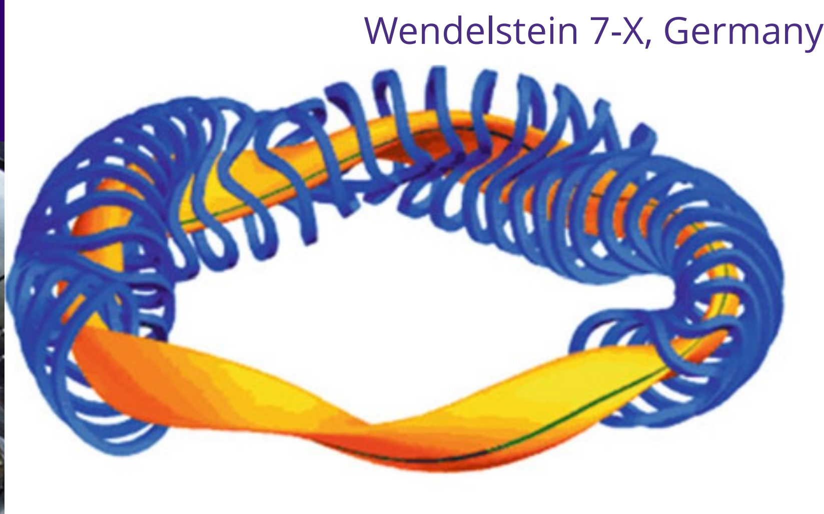
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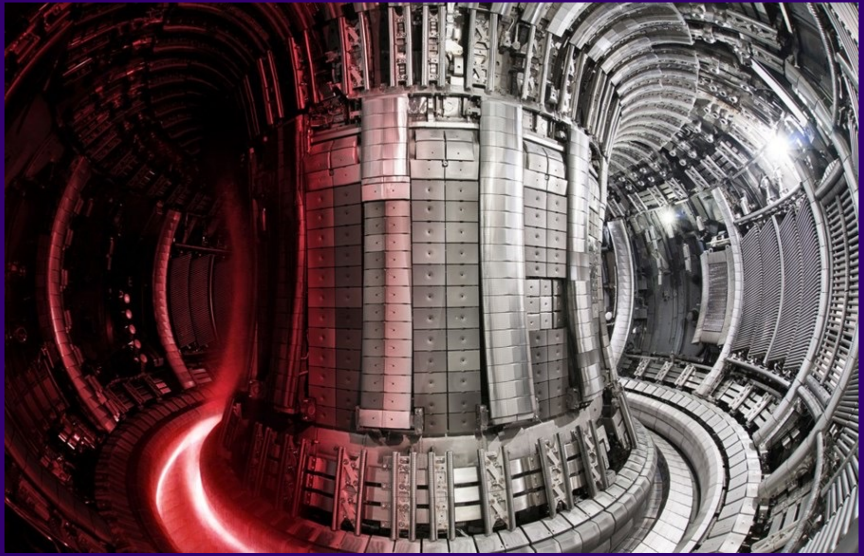
Tokamaks emerged in the 1950s in the USSR, most funded and developed magnetic confinement fusion device

- Toroidal chamber requiring simple geometry external field coils to confine the donut shaped plasma
- Steady-state device
- Hundreds of tokamaks built across the world
- TFTR at PPPL reached Q = 0.3 and JET in the UK reached Q = 0.67 in the 1990s
- KSTAR (Korea) records for longest duration (102s) and 48s at a temperature of 100 million deg in 2024



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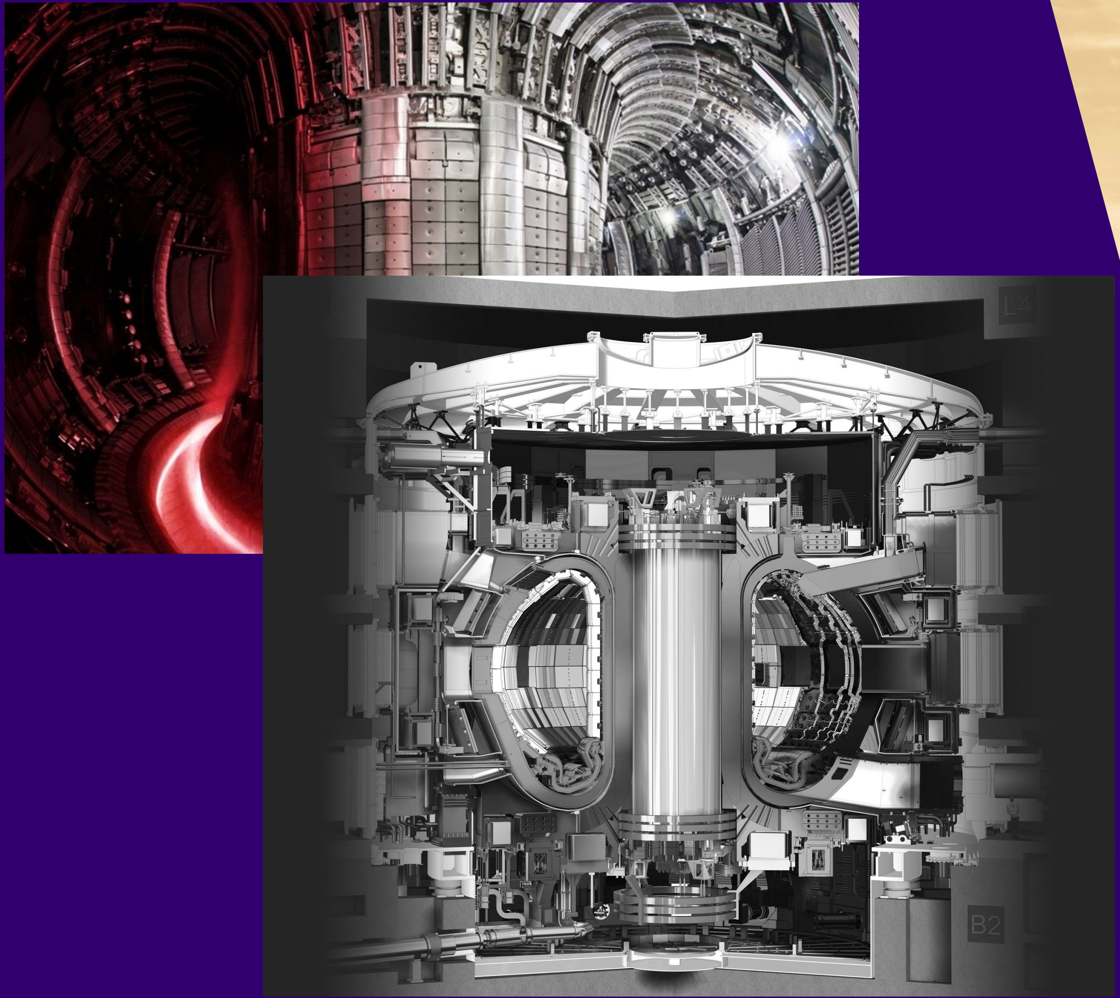
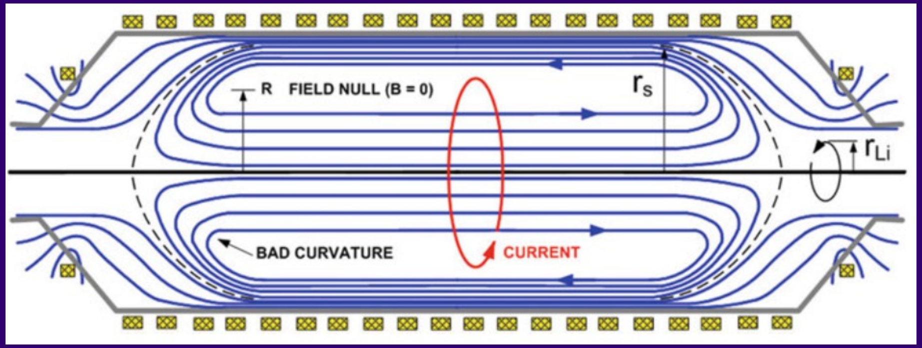
- ITER, being built in southern France, will be the world’s largest tokamak, multiple countries involved
- ITER’s goal is to reach a burning plasma regime, Q~10
- Expected to produce 500 MW of fusion power, but focus is still research not powerplant



A number of other magnetic confinement fusion pulsed devices exist that have had a history of limited funding, but…

- Private investment is changing the story dramatically
- Field-reversed configurations
- Magnetic mirrors
- Spheromaks
- And others



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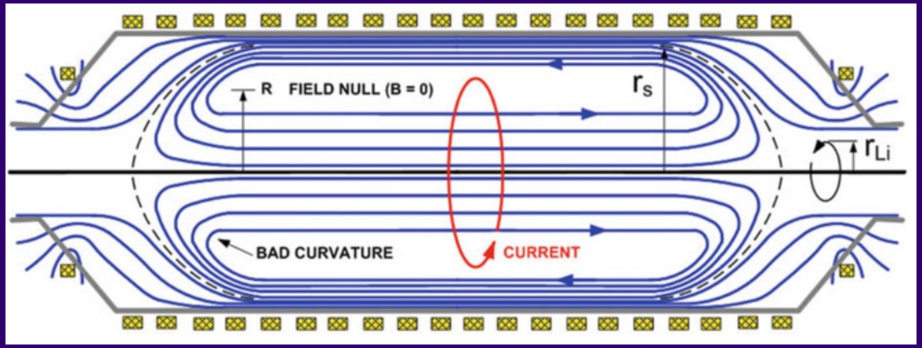

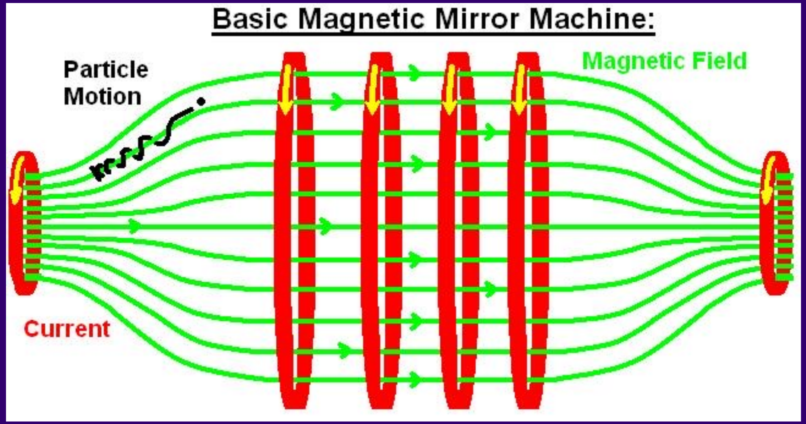

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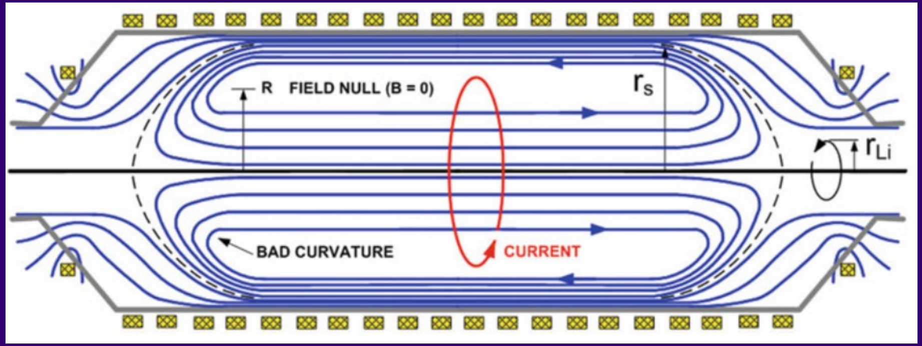

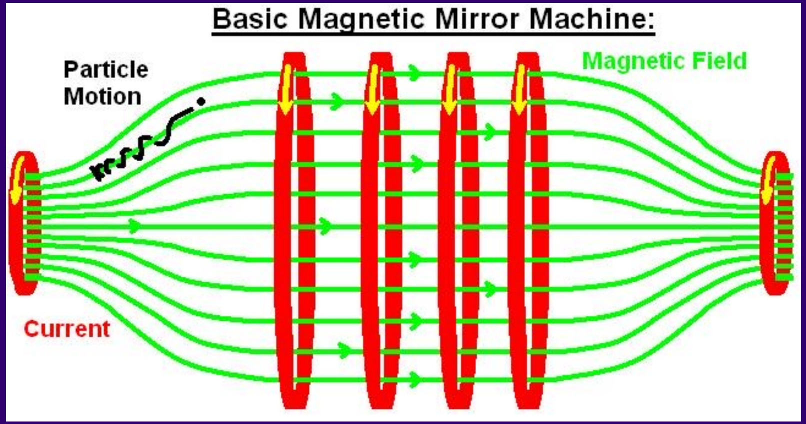

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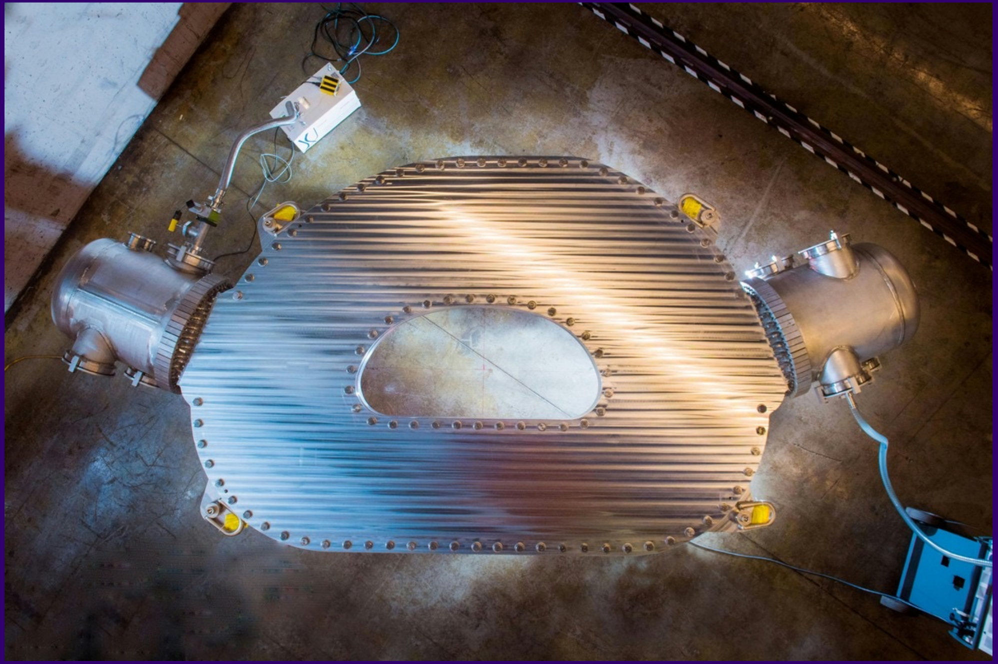
- And others
- Recent advances in magnet technology, high-temperature superconductors, have a transformative effect on the field of MCF

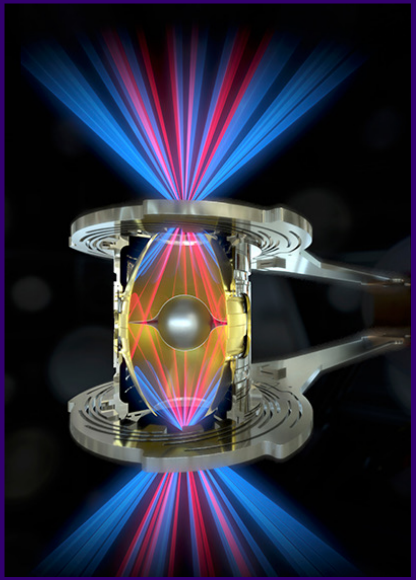


Massachusetts Institute of Technology

Commonwealth Fusion Systems

Inertial confinement fusion was motivated by the stockpile stewardship program

- Lasers providing energy directly or indirectly, through x-rays, to target to compress it to fusion conditions
- The Nova laser was built in the 1980s, but lost energy before hitting the fuel



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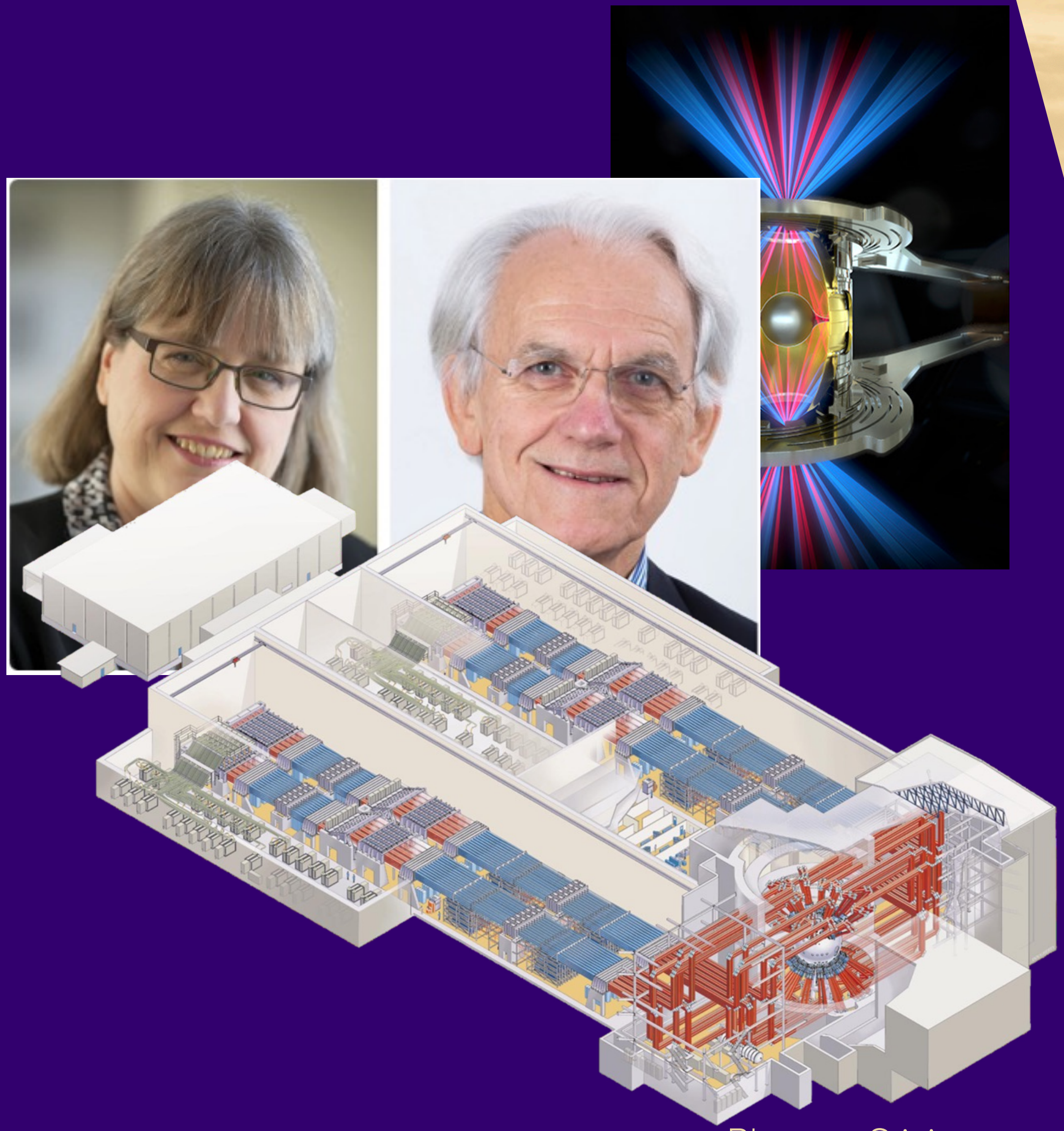

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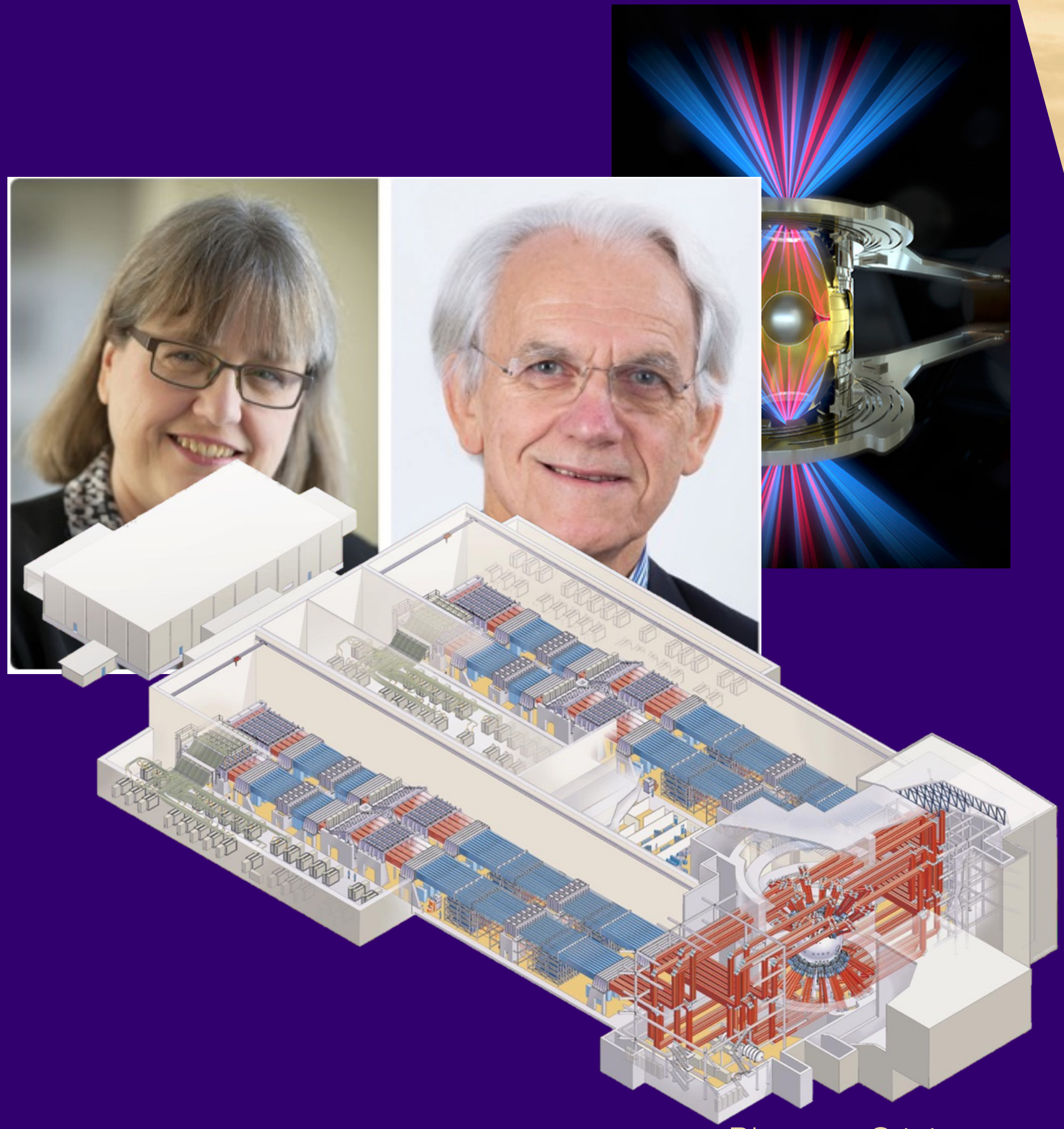

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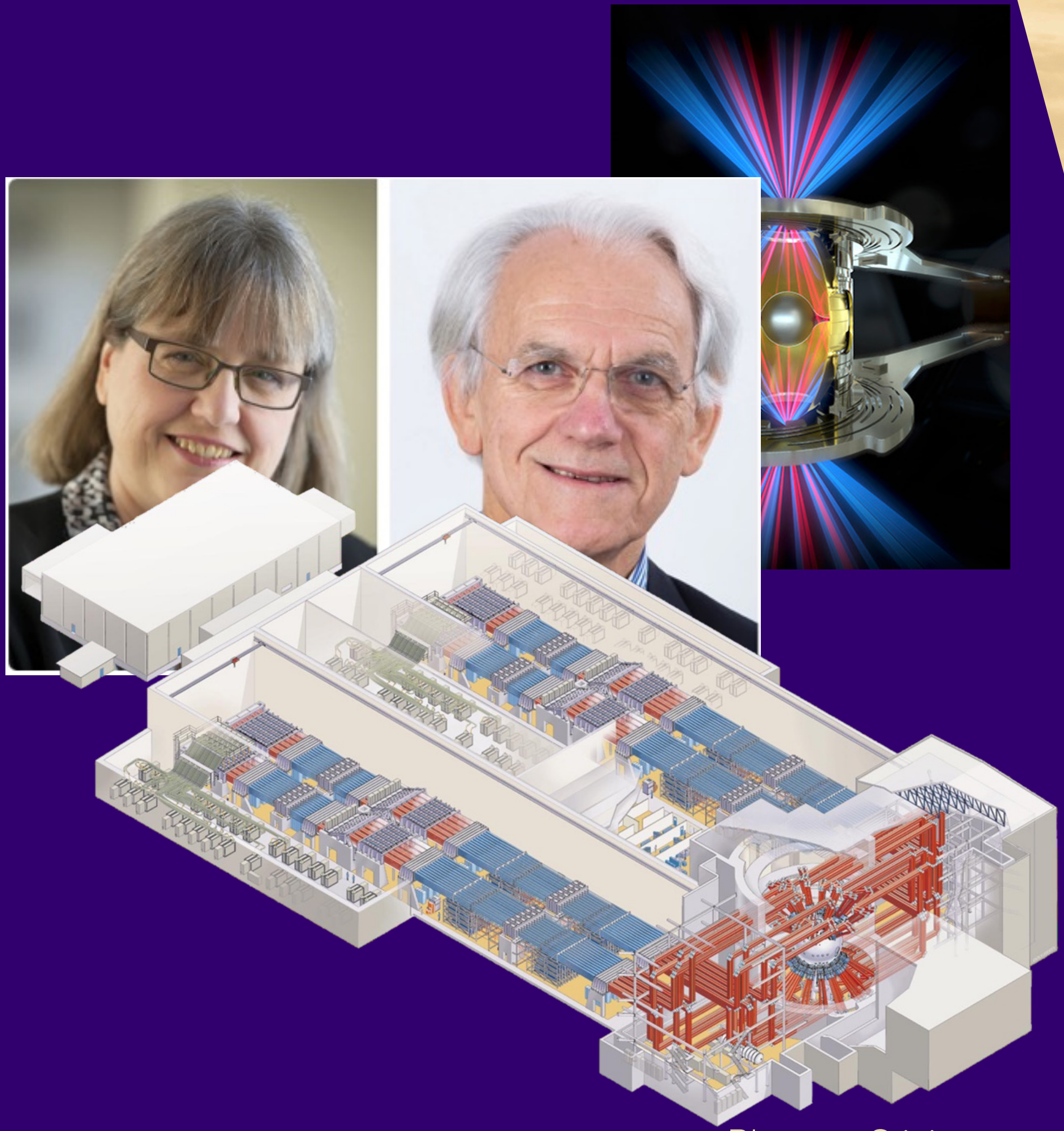
- US DOE recently funded inertial fusion energy hubs
- Number of private ventures exploring different variations of laser-driven fusion, including laser technology



Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

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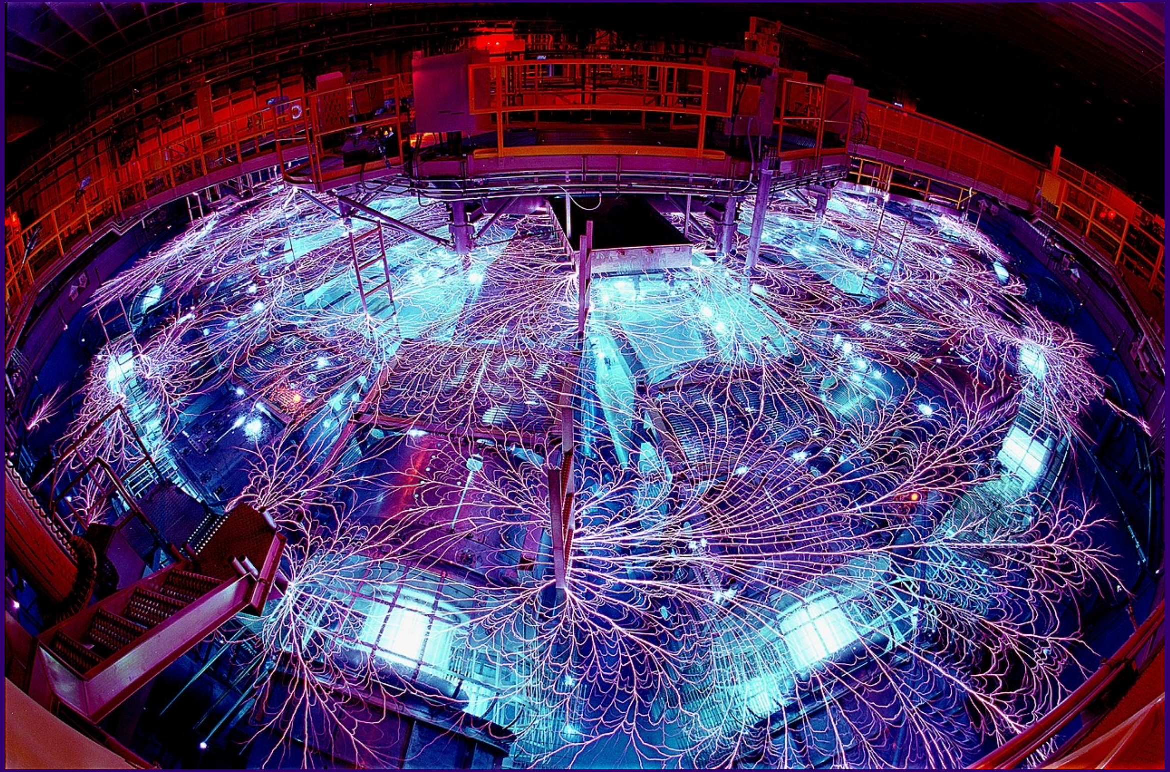

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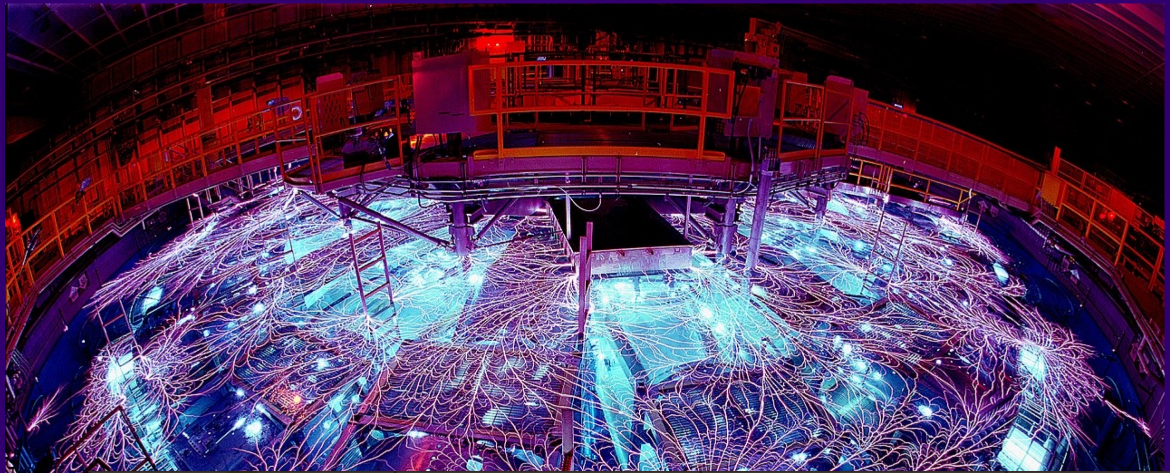

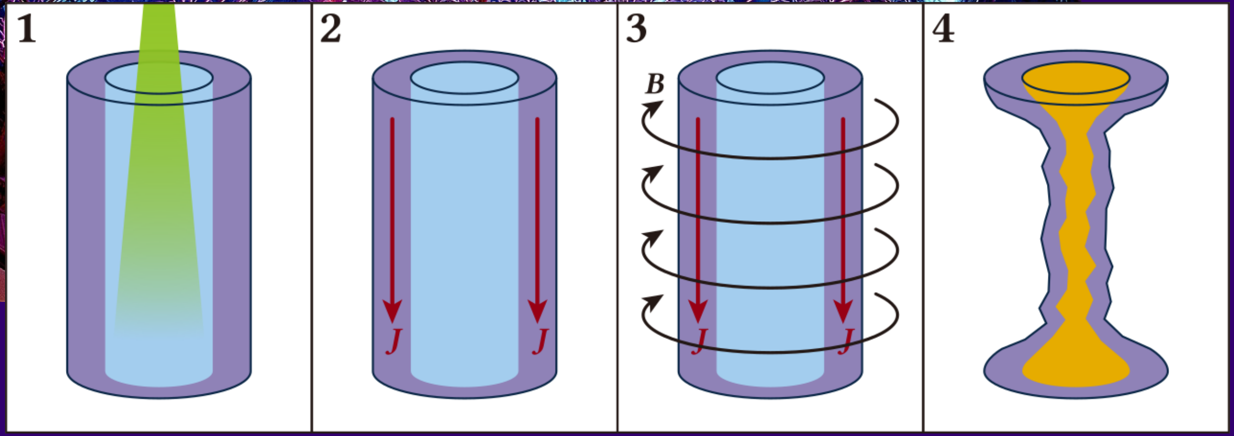

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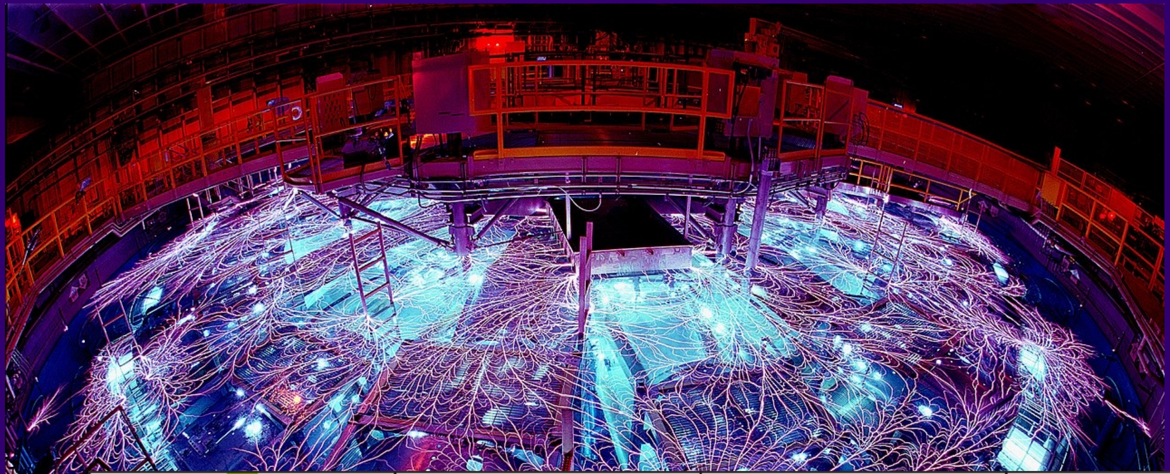

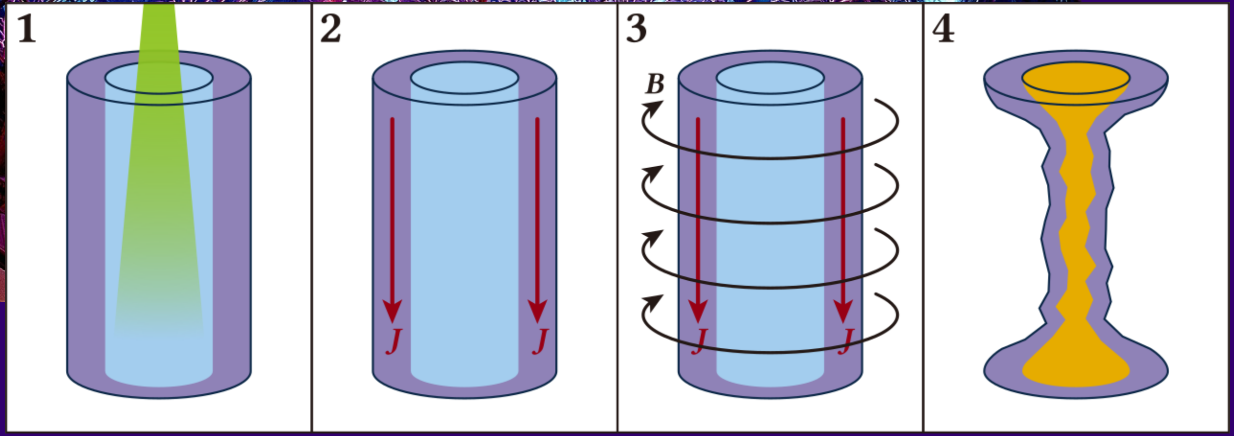

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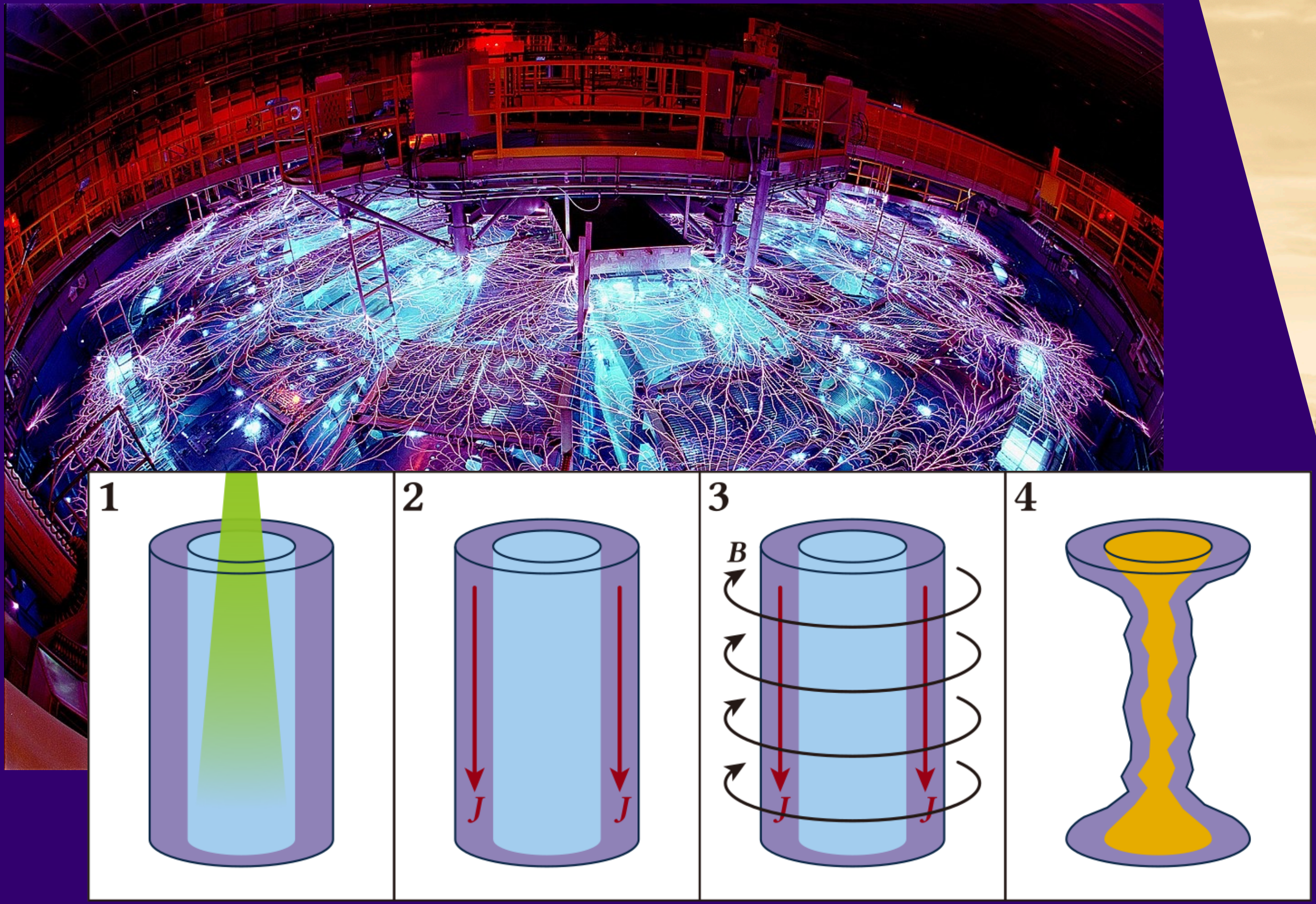
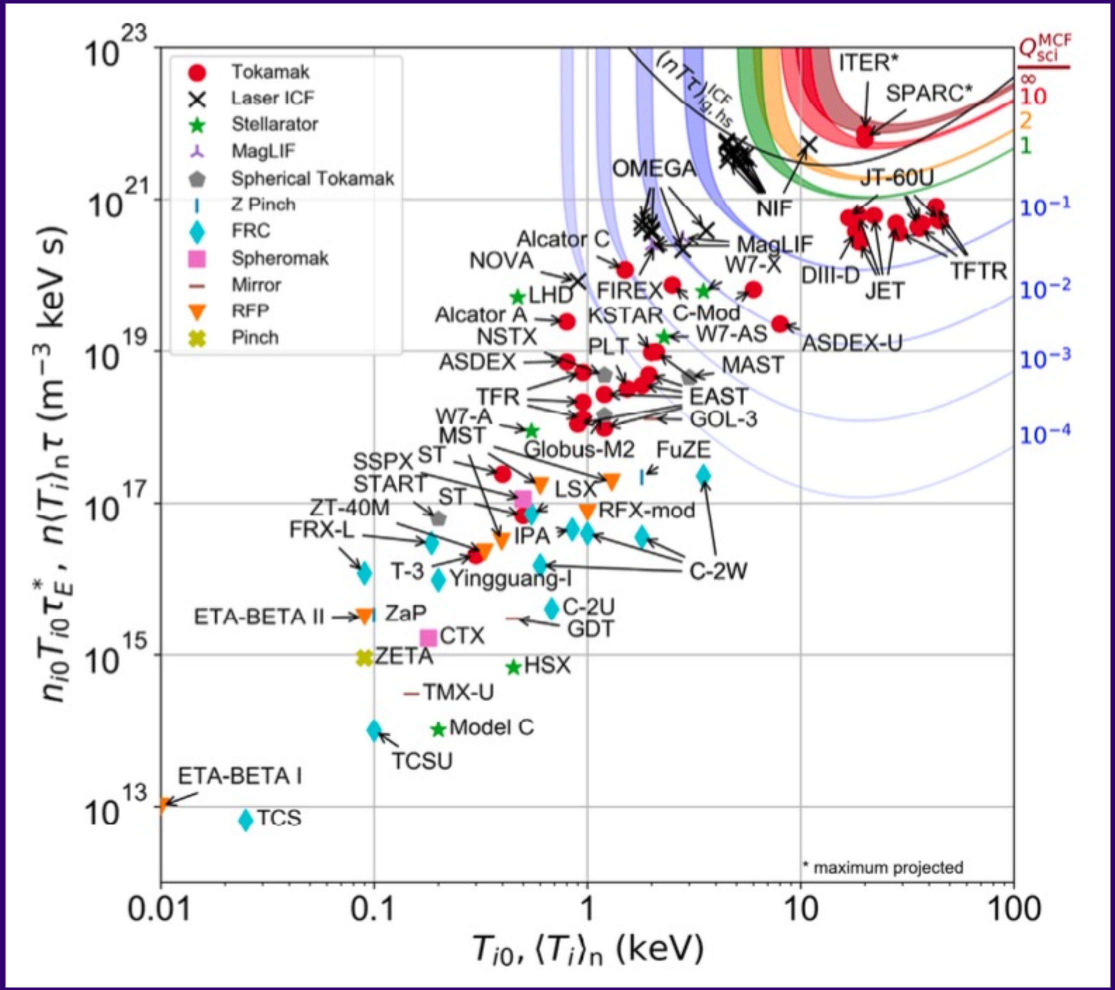
- Public and private efforts for stockpile stewardship and fusion energy



Progress in fusion energy summarized by fusion triple product vs temperature and vs year for various experiments



Credit: Wurzel and Hsu, Phys. Plasmas (2022)

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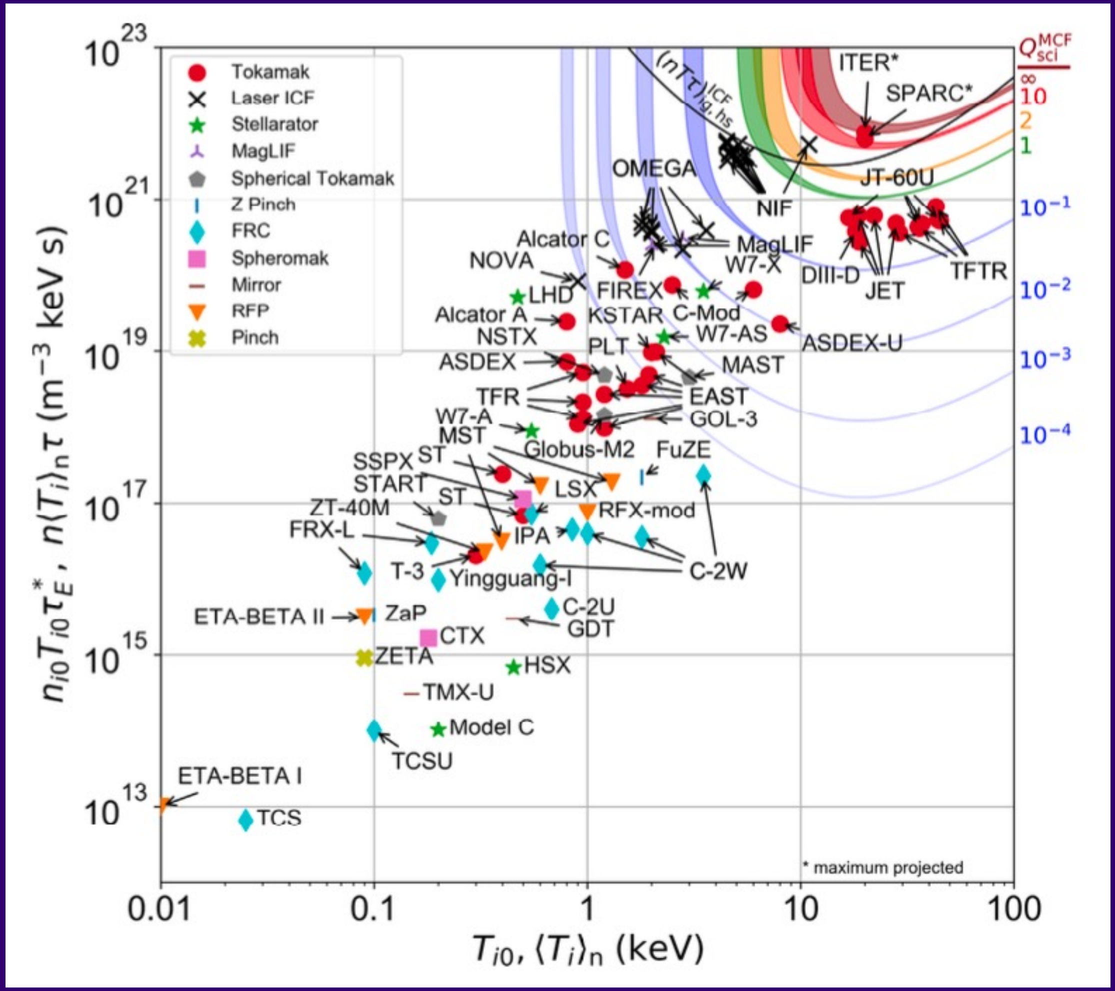

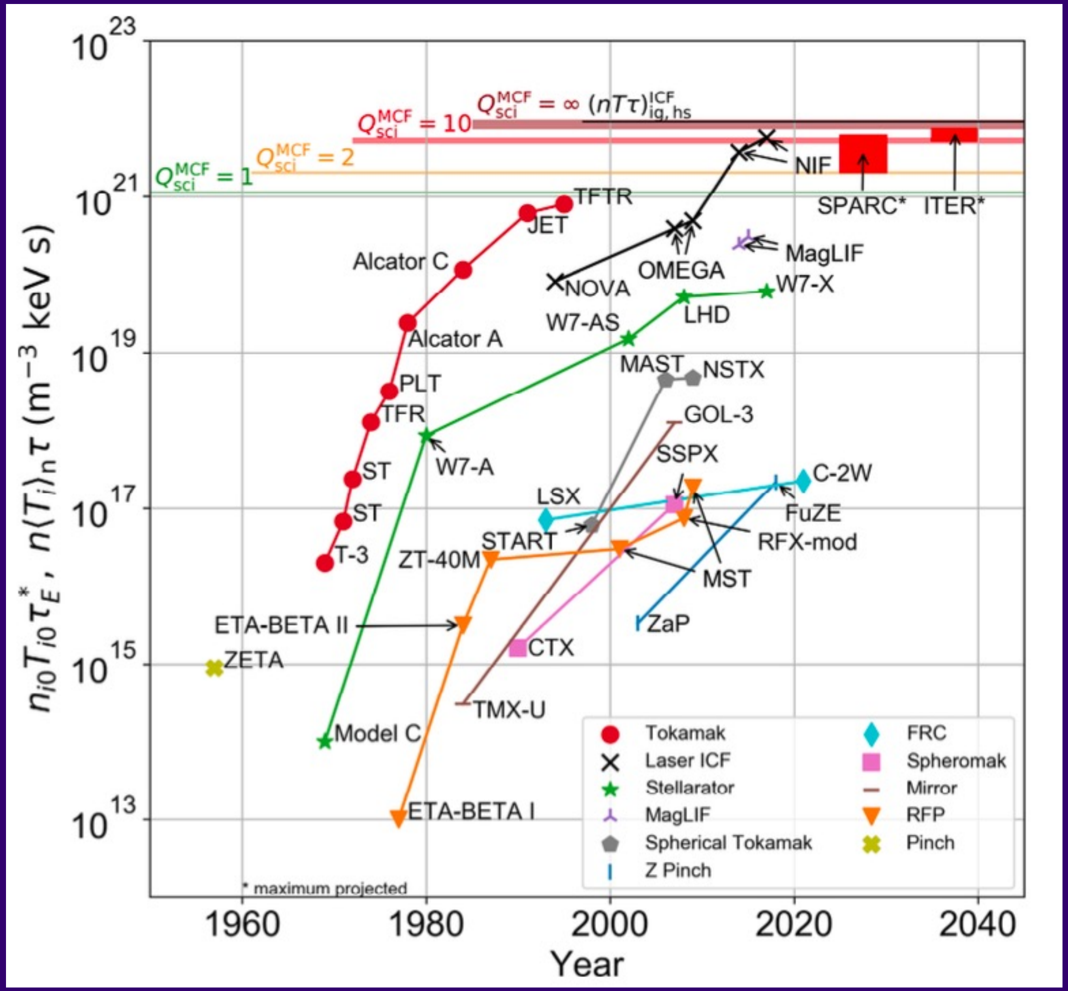

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There is over $6 billion in private investment in fusion with 80% of the investment in the US, this is unprecedented!

Fusion Industry Association

National commitment to fusion energy is stronger than ever

NAE GRAND CHALLENGES FOR ENGINEERING
NATIONAL ACADEMY OF ENGINEERING

- One of 14 NAE Grand Challenges in the 21st century: Provide energy from fusion

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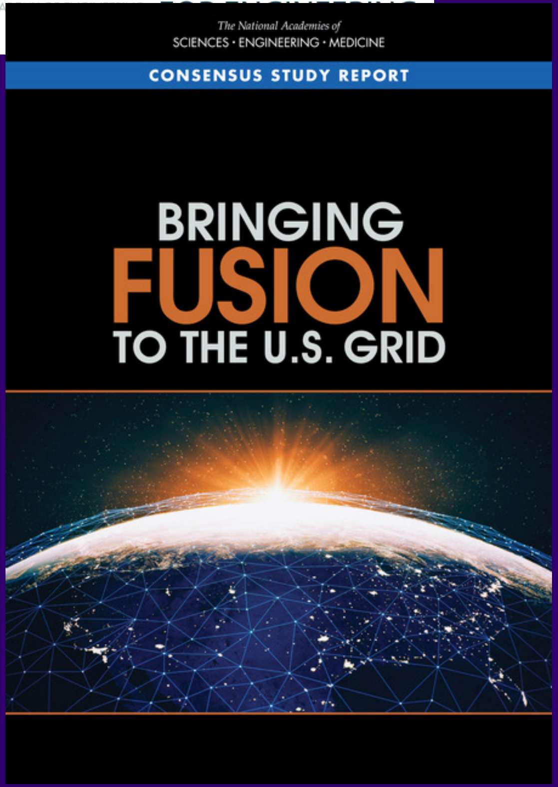
NAE GRAND CHALLENGES



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CONSENSUS STUDY REPORT

BRINGING
FUSION
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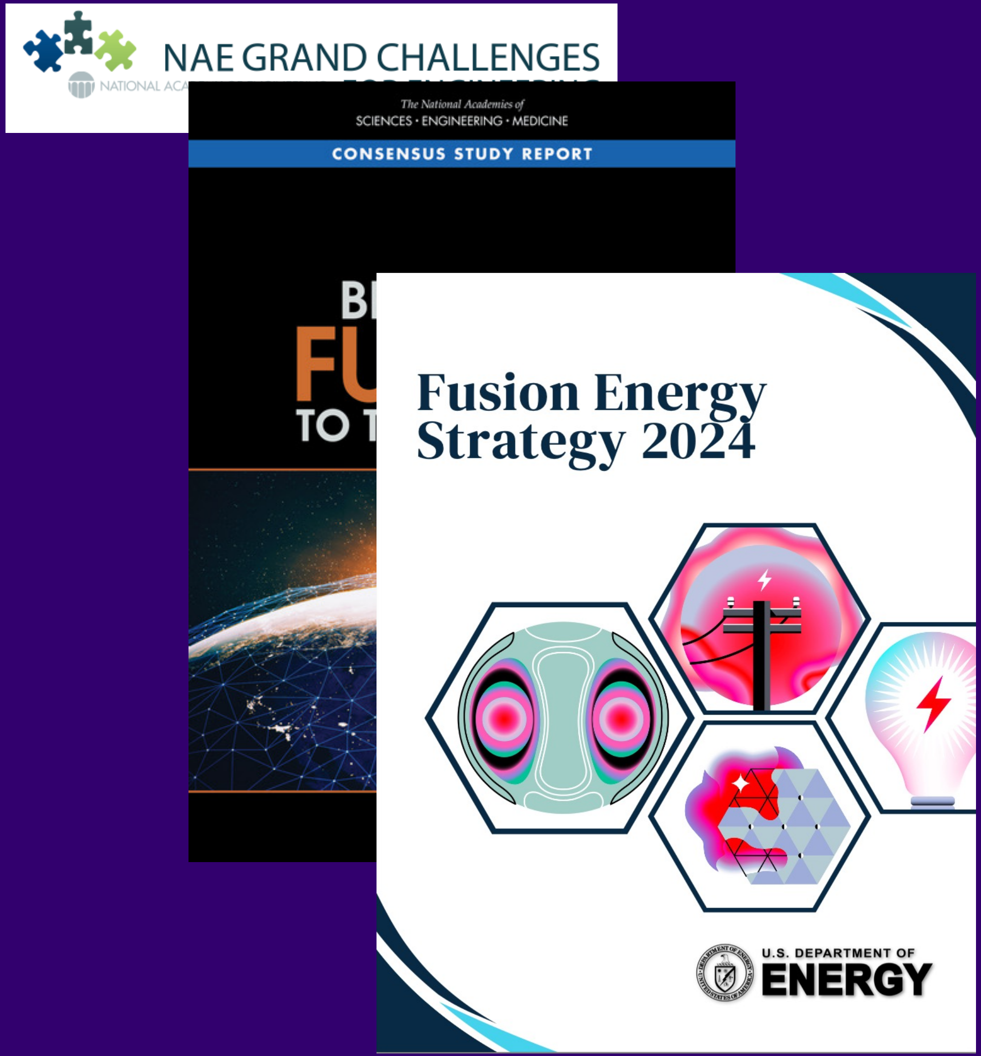

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Fusion Energy Strategy 2024

U.S. DEPARTMENT OF ENERGY

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- 2024 DOE Fusion Energy Strategy:
  1. “Close science and technology gaps to a commercially relevant fusion pilot plant
  2. Prepare the path to sustainable, equitable commercial fusion deployment
  3. Build and leverage external partnerships”

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With the unprecedented private investment and the national commitment to fusion energy, there is no better time than now to work in fusion!

Univ. of Washington has a long history of contributions to fusion

- Fusion energy research at the UW at least since the 1980s in the nuclear engineering department
- This was absorbed into the aeronautics and astronautics department
- Long standing history in fusion, significant experiments originated for innovative confinement concepts
- Research relevant to magnetic, inertial, and magneto-inertial fusion with a long history of theoretical, computational, and experimental contributions to plasma physics
- Multiple fusion startups spun out of the UW
- Consider the UW for a PhD in plasma physics and fusion energy!