



Credit: Getty images/NASA

# Introduction to Fusion

Prof. Bhuvana Srinivasan

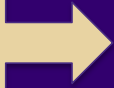
2026 SULI, 1 June 2026

UNIVERSITY *of* WASHINGTON

# My path to a career in plasma physics



Middle/high school  
fascination with things  
that move fast



# My path to a career in plasma physics



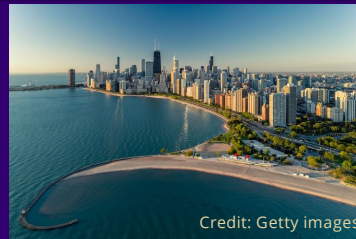
Middle/high school  
fascination with things  
that move fast



## ILLINOIS TECH

Armour College of Engineering

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



Credit: Getty images

# My path to a career in plasma physics



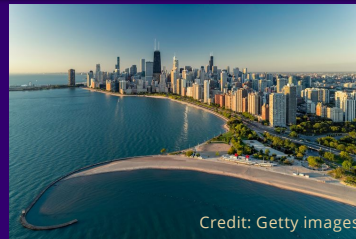
Middle/high school fascination with things that move fast



## ILLINOIS TECH

Armour College of Engineering

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



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!



# My path to a career in plasma physics



Middle/high school fascination with things that move fast



## ILLINOIS TECH

Armour College of Engineering

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




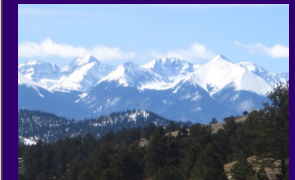
After some industry experience, wanted to go to grad school to research something exciting – going to the Moon is cool, but going to the next star is even cooler! Fusion propulsion? Bonus: fusion to solve terrestrial energy problems!



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



Professor? No way! To  More plasma, more mountains!



# My path to a career in plasma physics



Middle/high school fascination with things that move fast



## ILLINOIS TECH

Armour College of Engineering

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



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!



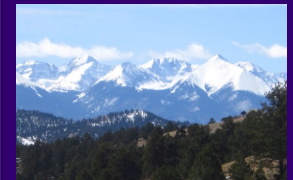
Plasma physics and mountains?! UW (Seattle) it is for grad school!



Hmm, Professor? Started as an Assistant Professor at Virginia Tech in Aerospace and Ocean Engineering



Professor? No way! To Los Alamos National Laboratory More plasma, more mountains!



# My path to a career in plasma physics



Middle/high school fascination with things that move fast



## ILLINOIS TECH

Armour College of Engineering

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



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!

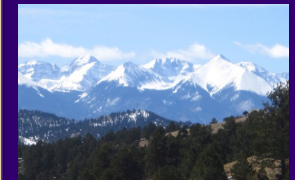


Made my way back to the University of Washington as a professor after 13+ years. More plasmas, more mountains!

Hmm, Professor? Started as an Assistant Professor at Virginia Tech in Aerospace and Ocean Engineering



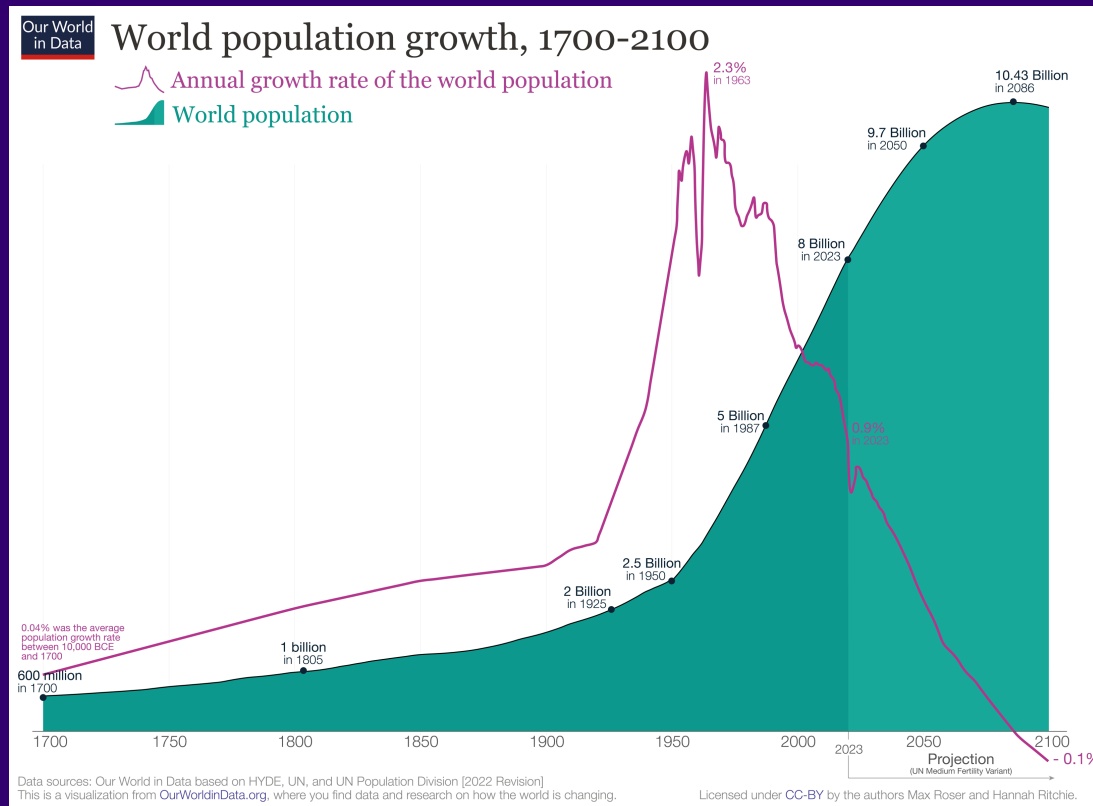
Professor? No way! To  More plasma, more mountains!



# 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

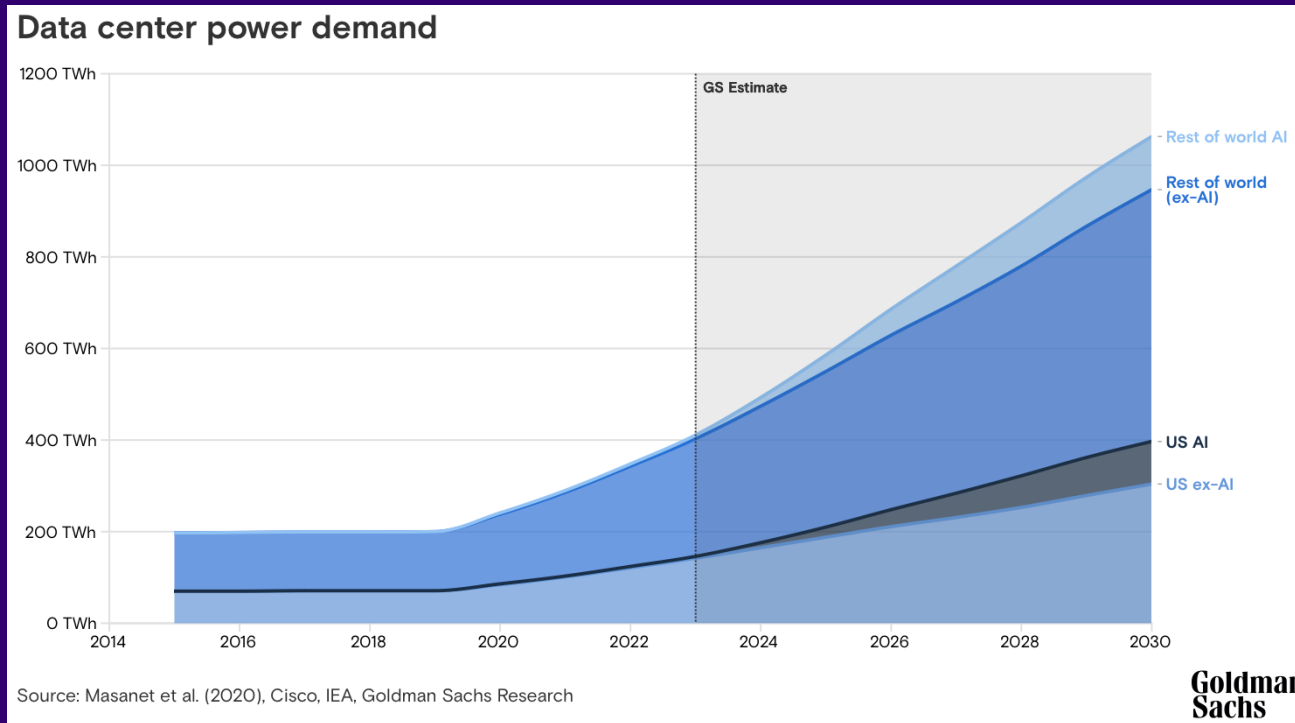


- “Global electric vehicles sales, solar and battery installations hit record highs in 2022. However, renewables are only partly meeting growing energy demand rather than replacing fossil fuels in the energy mix. Fossil fuels are still growing in absolute terms.
- Energy related CO2 emissions are still hitting record highs”

**“Limiting global warming to 1.5 degrees Celsius has gone from highly unlikely in 2023 to no longer possible in 2025.”**

**Ref: DNV’s Energy Transition Outlook**

# AI is about to make the problem worse



- “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 165% by 2030.”
- “US data center power demand is forecast to more than double to 66 GW in 2027 from 31 GW in 2025”
- “Along the way, carbon dioxide emissions of data centers may more than double between 2022 and 2030.”

## Existing energy sources have serious disadvantages

Energy sources	Advantages	Disadvantages
<b>Coal</b>	<ul style="list-style-type: none"> <li>1.1 trillion tonnes of coal reserves</li> </ul>	<ul style="list-style-type: none"> <li>Burns dirty, health hazards</li> <li>1 lb of coal emits 2+ lbs of CO<sub>2</sub></li> <li>~ 133 year supply</li> </ul>
<b>Oil</b>	<ul style="list-style-type: none"> <li>1.7 trillion barrels</li> </ul>	<ul style="list-style-type: none"> <li>Large source of methane → 25x global warming potential of CO<sub>2</sub></li> <li>VOC emissions, air pollution, soil pollution</li> <li>~ 50 year supply</li> </ul>
<b>Natural Gas</b>	<ul style="list-style-type: none"> <li>6 trillion barrels (of oil equivalent)</li> </ul>	<ul style="list-style-type: none"> <li>Similar to oil</li> <li>~ 86 year supply</li> </ul>
<b>Hydroelectric</b>	<ul style="list-style-type: none"> <li>Clean</li> </ul>	<ul style="list-style-type: none"> <li>Geographically limited</li> <li>Dam construction impact to habitats</li> </ul>
<b>Wind</b>	<ul style="list-style-type: none"> <li>Clean</li> </ul>	<ul style="list-style-type: none"> <li>Geographically limited</li> <li>Huge number of windmills required for large scale</li> </ul>
<b>Solar</b>	<ul style="list-style-type: none"> <li>Clean</li> </ul>	<ul style="list-style-type: none"> <li>Geographically limited</li> <li>Huge number of solar cells required for large scale</li> </ul>
<b>Fission</b>	<ul style="list-style-type: none"> <li>Clean</li> </ul>	<ul style="list-style-type: none"> <li>Waste disposal challenging</li> <li>Safety concerns</li> </ul>

# The case for fusion is stronger than ever



Credit: ESA

Limitless fuel  
~  $5 \times 10^{13}$  tons  
in earth's  
oceans

Equitable  
access to  
fusion fuel

Clean, no  
 $\text{CO}_2$  or other  
emissions



Credit: AMWatch

Complements  
renewables with  
large-scale energy  
production



Credit: Getty Images

**Fusion**

Safe, no  
possibility of  
meltdown-  
like scenarios

Compatible  
with existing  
power grid



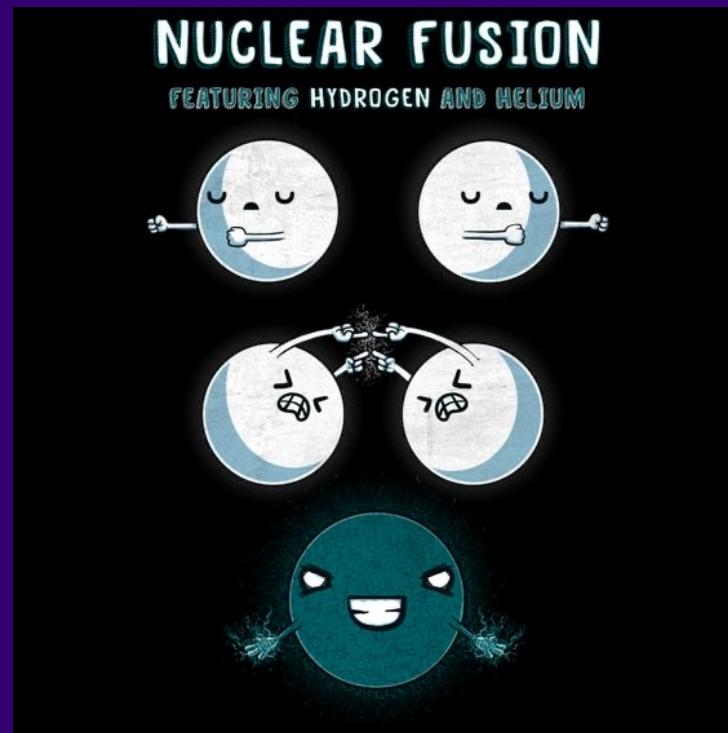
Credit: Getty Images

Does not  
work yet!

# Outline

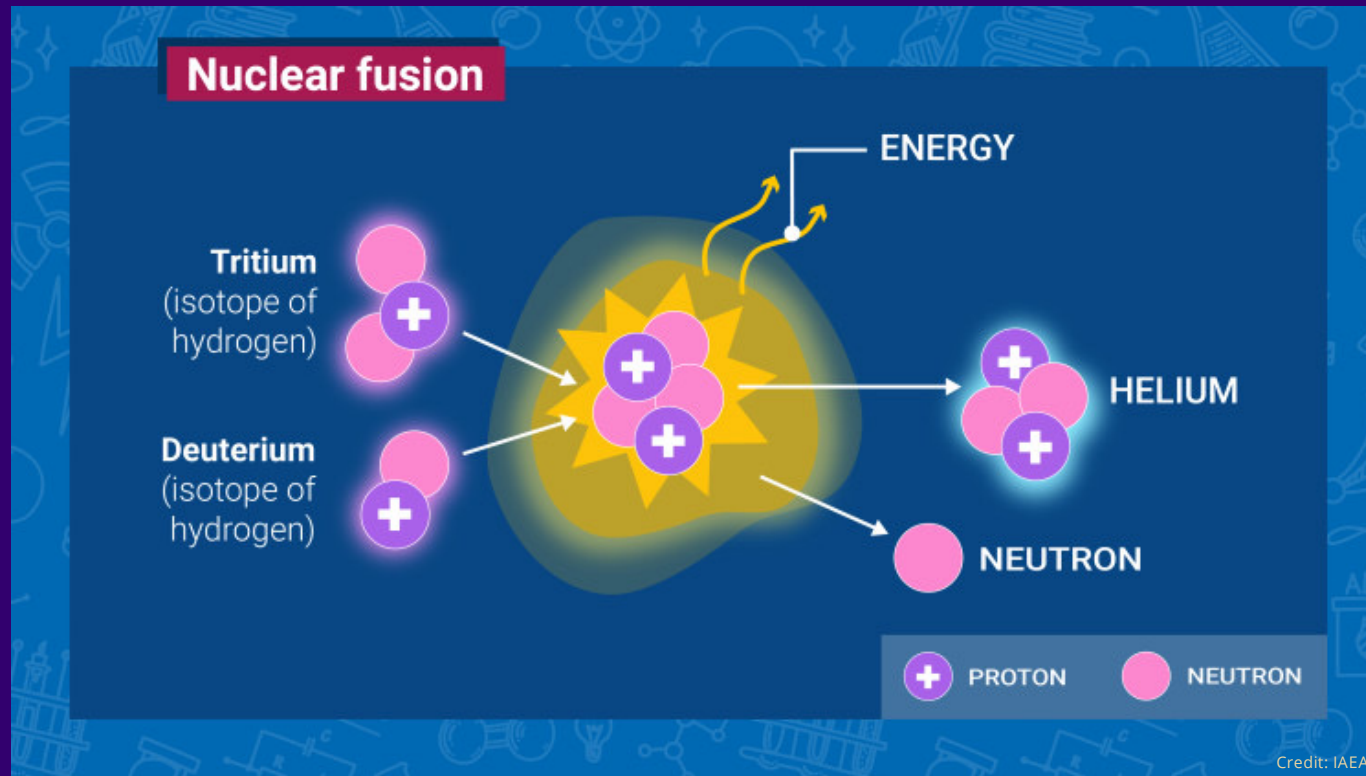
- The case for fusion
- **What is fusion?**
- Metrics to evaluate fusion energy
- Brief history of fusion and some pioneers
- Fusion concepts: steady-state vs pulsed
- Progress in fusion

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

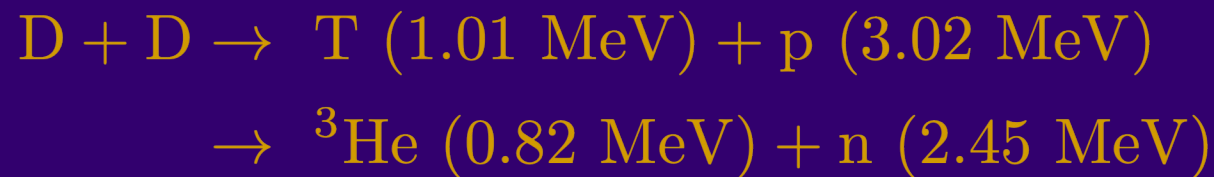


Credit: neatoshop.com

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



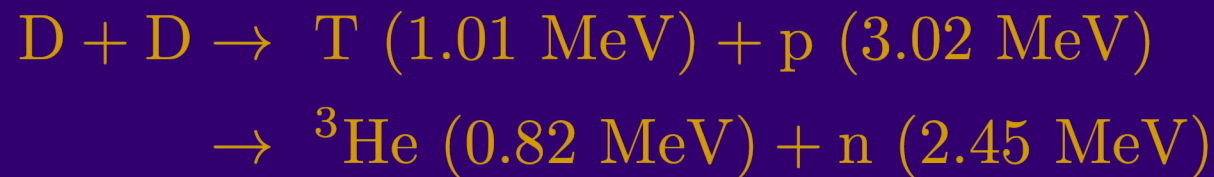
## What are some viable fusion reactions?



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

Remember that  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

## What are some viable fusion reactions?



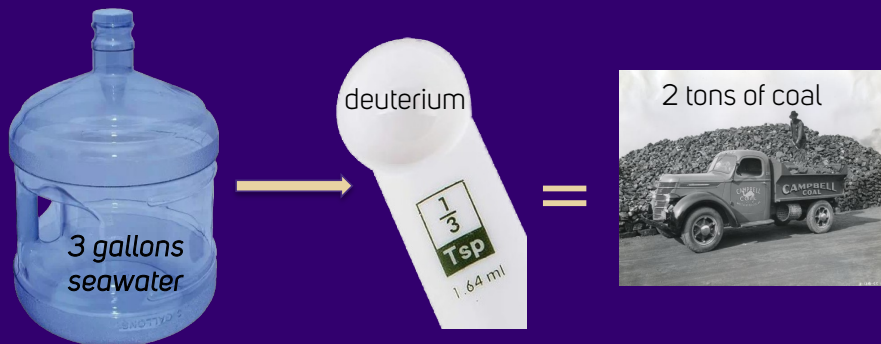
These are the only fusion fuels that are theoretically feasible for energy and propulsion!

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

Remember that  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

# Where can we find deuterium and tritium?

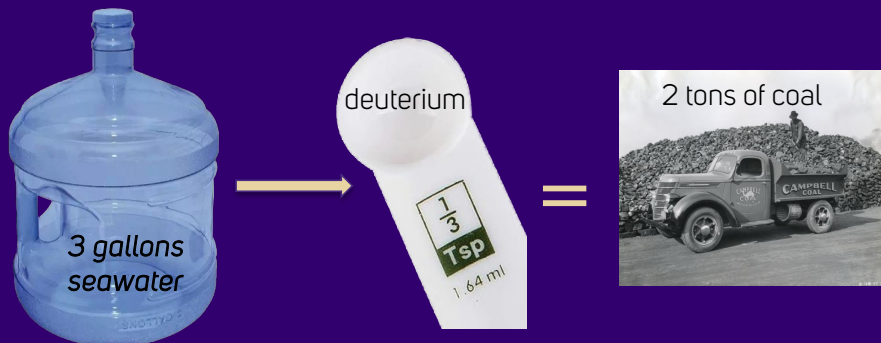
There is plenty of deuterium in the earth's oceans



Credit: GA and San Diego Schools

# Where can we find deuterium and tritium?

There is plenty of deuterium in the earth's oceans



Tritium would need to be "bred" in the fusion reactor  $\rightarrow$  lithium blankets

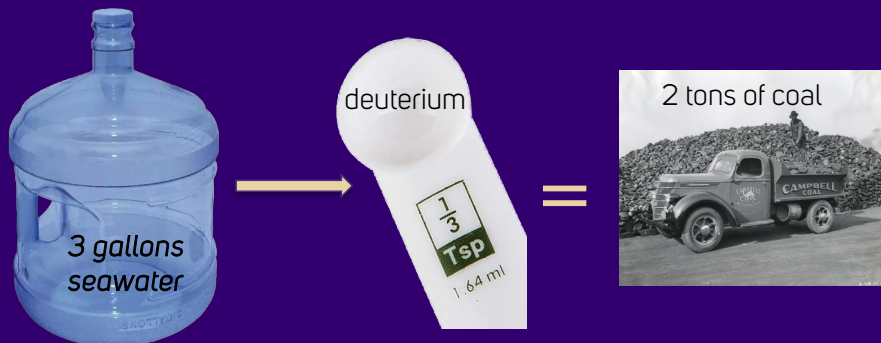


Earth has abundant lithium on land and in the ocean to last perpetually as far as human timescales are concerned

Credit: GA and San Diego Schools

## Where can we find deuterium and tritium?

There is plenty of deuterium in the earth's oceans



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

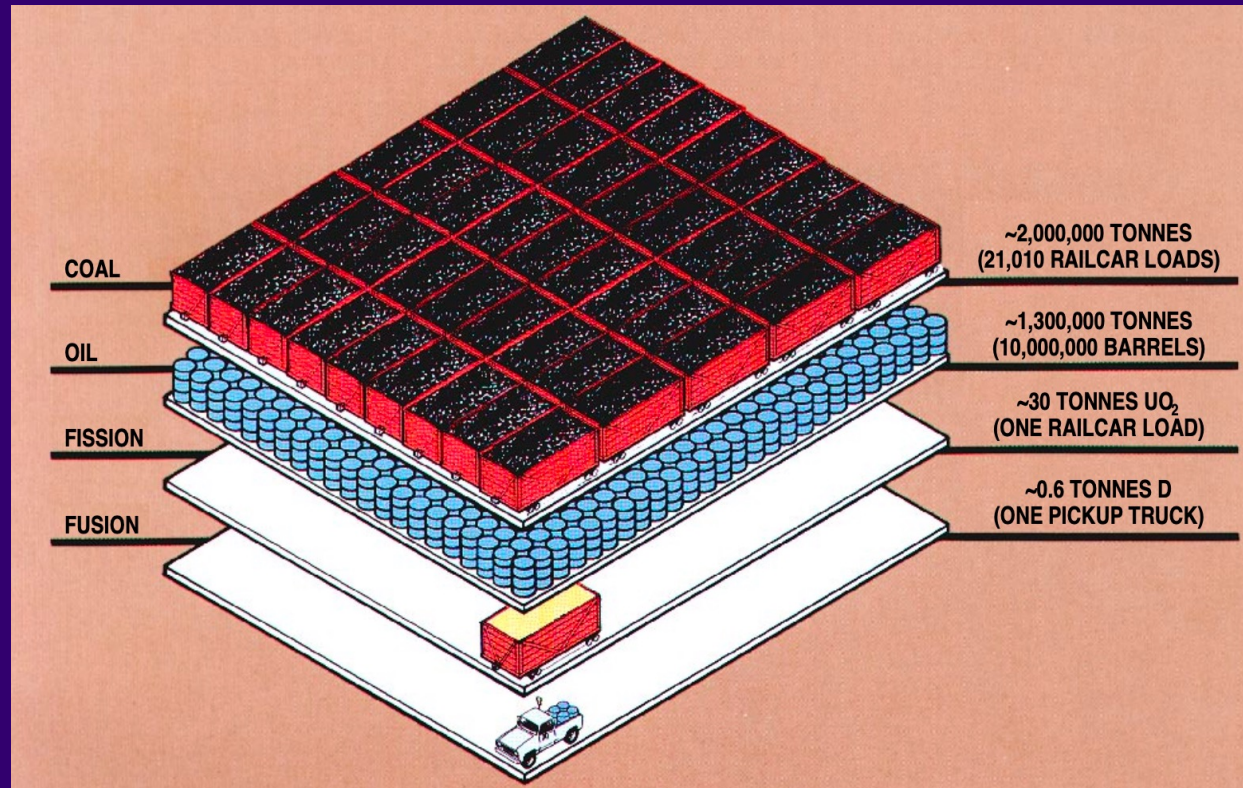


Earth has abundant lithium on land and in the ocean to last perpetually as far as human timescales are concerned

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

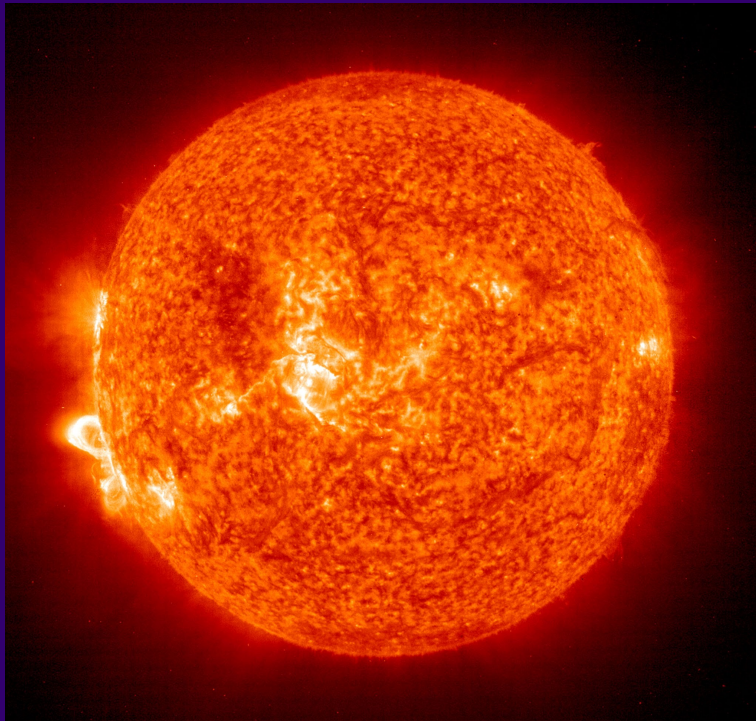
Credit: GA and San Diego Schools

# How does fusion fuel compare to other energy fuels?



Credit: GA and San Diego Schools

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:

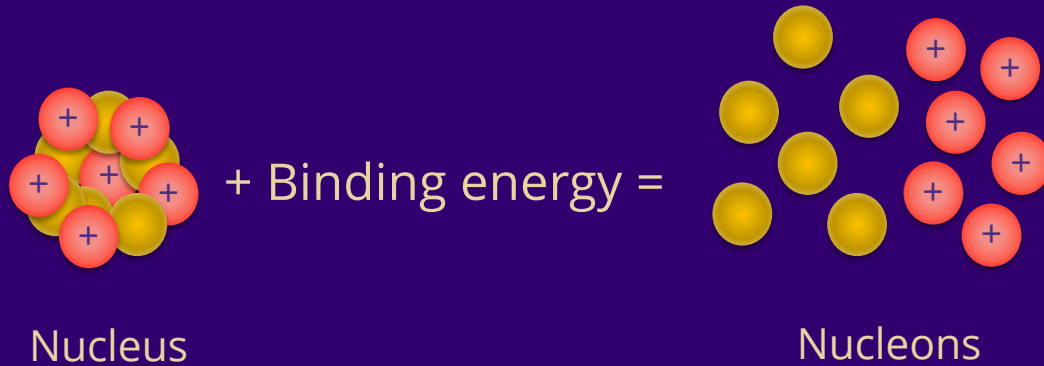
1. Coulomb forces versus nuclear forces
2. Gamow peak
3. Cross-sections for the different reactions

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

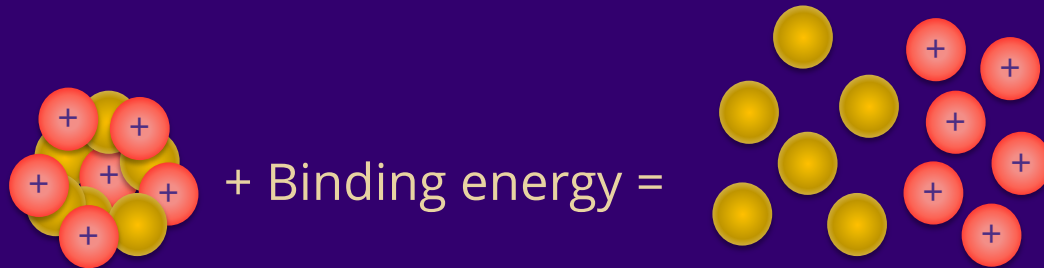
We will learn about 3 concepts here to understand if a fusion reaction produces enough energy and has high probability:

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

# Let's start with the nuclear binding energy



## Let's start with the nuclear binding energy



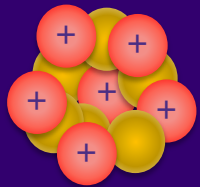
Nucleus

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

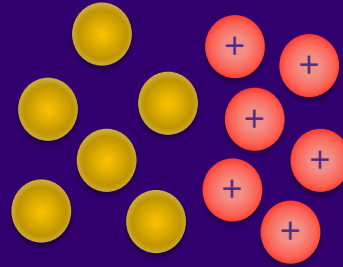
Nucleons

The mass of individual  
nucleons > mass of  
the nucleus

## Let's start with the nuclear binding energy



+ Binding energy =



Nucleus

Nucleons

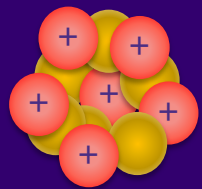
Protons and neutrons,  
i.e. nucleons, held  
together in nucleus by  
strong nuclear force

The mass of individual  
nucleons > mass of  
the nucleus

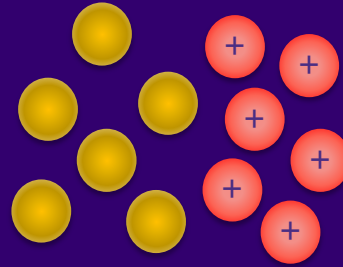
$$E = mc^2$$

$$\Delta E = \Delta mc^2$$

## Let's start with the nuclear binding energy



+ Binding energy =



Nucleus

Nucleons

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

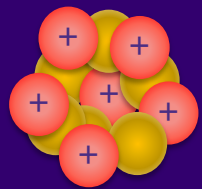
Protons and neutrons, i.e. nucleons, held together in nucleus by strong nuclear force

The mass of individual nucleons > mass of the nucleus

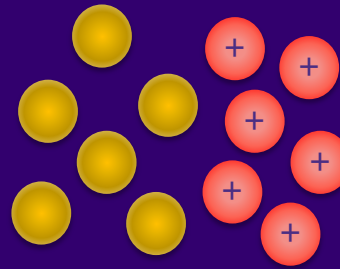
$$E = mc^2$$

$$\Delta E = \Delta mc^2$$

## Let's start with the nuclear binding energy



+ Binding energy =



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

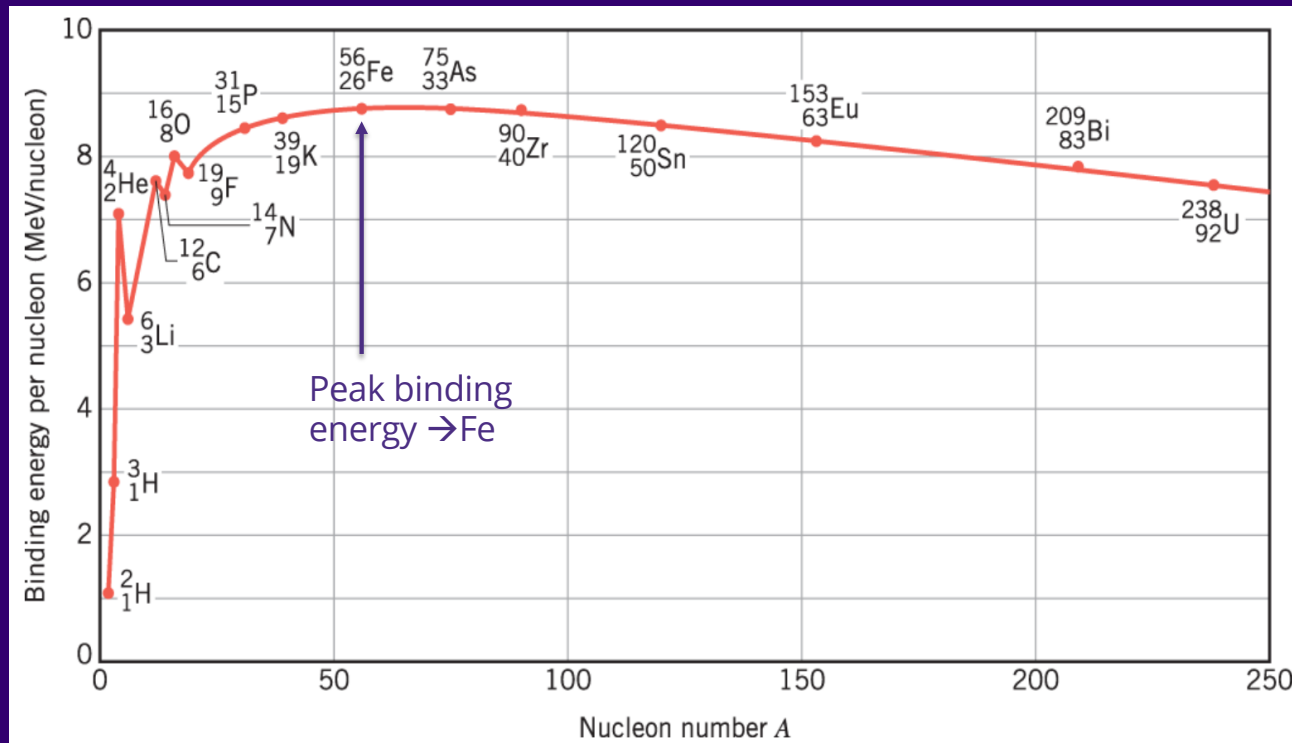
$$E = mc^2$$

$$\Delta E = \Delta mc^2$$

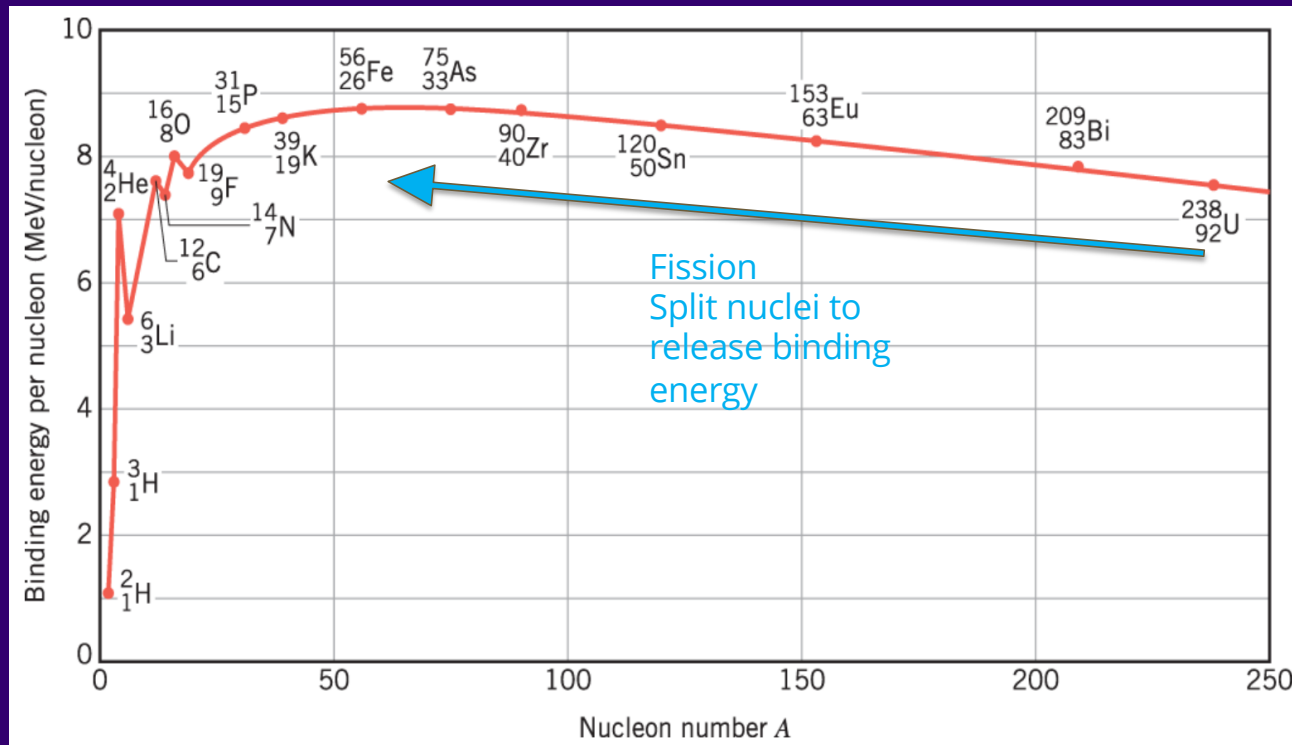
**Attractive strong nuclear force** holds protons and neutrons together in a nucleus. Binding energy needed to pull them apart.

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

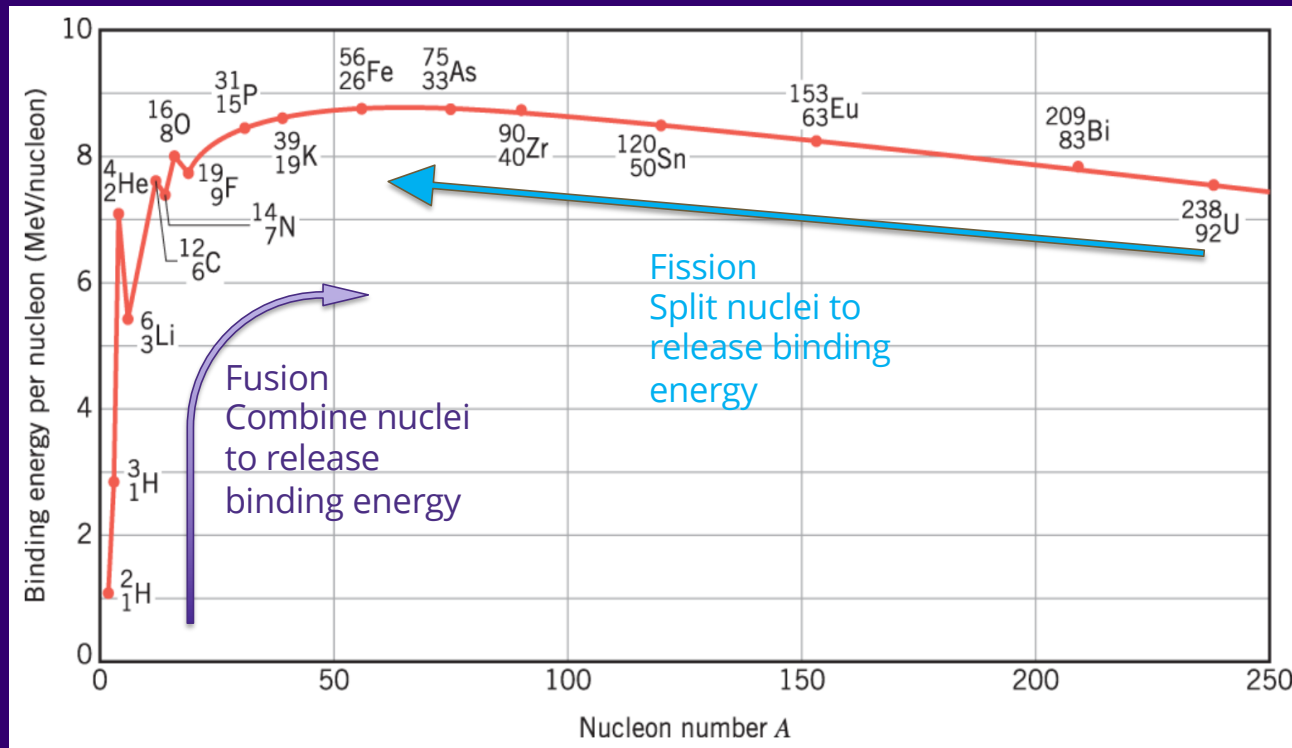
The nuclear binding energy released per nucleon in fission versus fusion access different sides of the periodic table



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



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



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



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

- Note that an atom  $\sim 1$  Angstrom  $\sim 10^{-10}$  m
- Attractive nuclear forces  $\sim 10^{-15}$  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



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

- Note that an atom  $\sim 1$  Angstrom  $\sim 10^{-10}$  m
- Attractive nuclear forces  $\sim 10^{-15}$  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

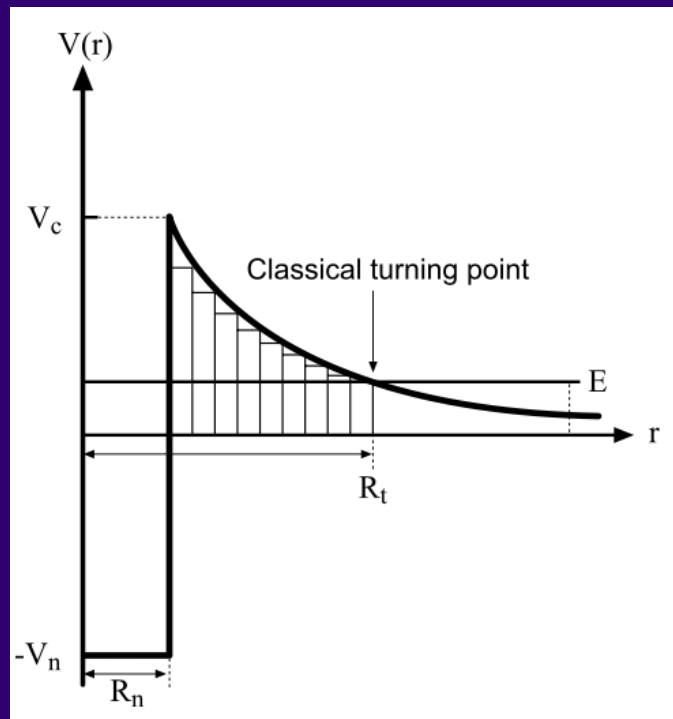
- This input energy must be practically achievable  $\rightarrow$  rules out most fusion reactions in the periodic table

# 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

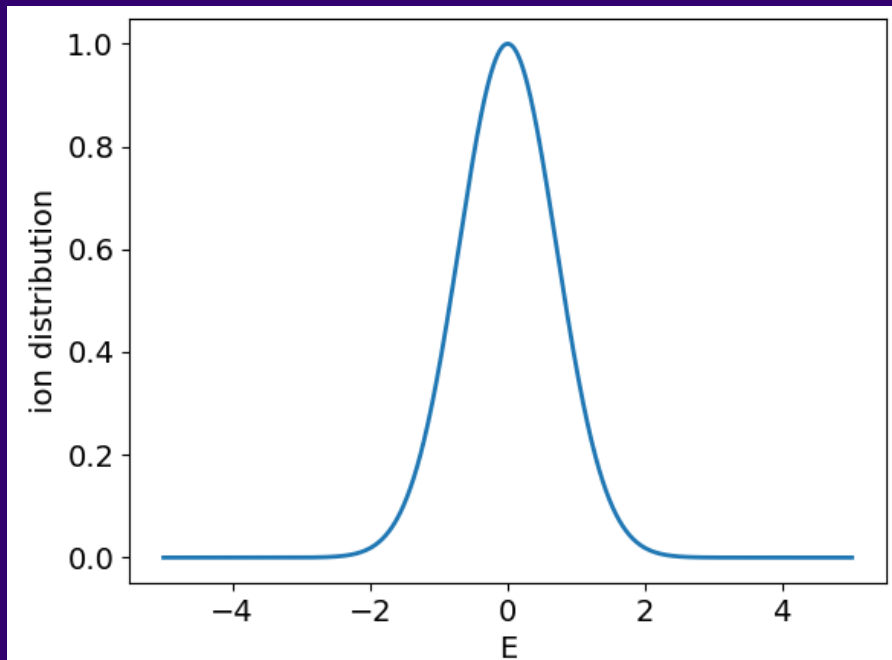
Quantum mechanics shows that there is a finite probability for an ion to penetrate the Coulomb barrier



Credit: José, Stellar Explosions (2016)

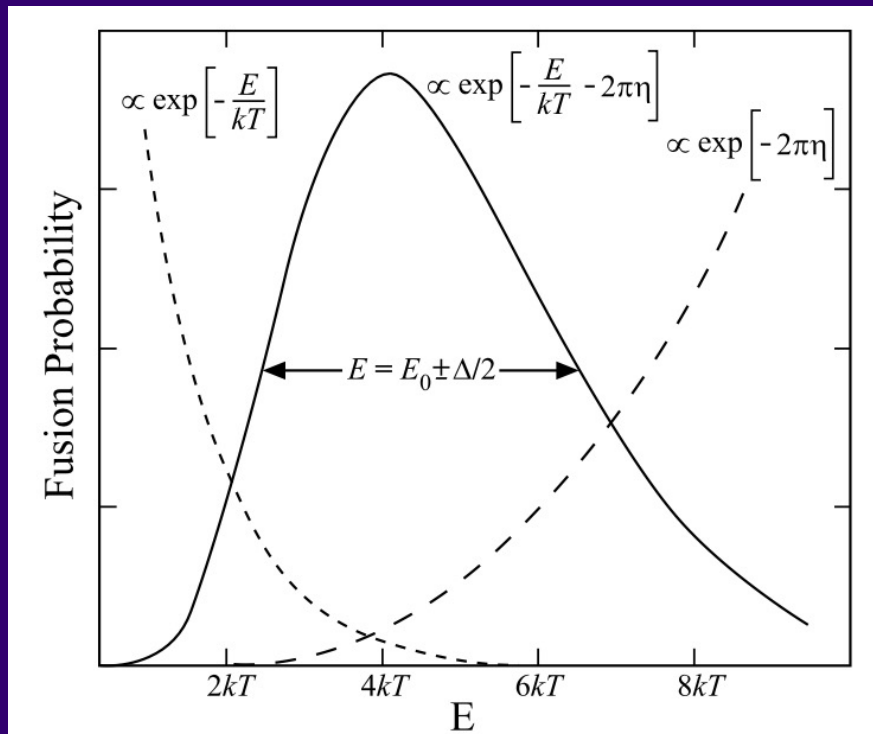
- Quantum tunneling through which the ions penetrate the Coulomb barrier [Gamow (1928)]
- Penetration probability comes from the time-dependent Schrödinger equation, i.e. the wave equation
- This probability is given by an exponential, known as the Gamow factor

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  $\rightarrow$  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:

1. Coulomb forces versus nuclear forces
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,  $\sigma$ , 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,  $\sigma$ , is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity,  $v$ , between the colliding ions

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

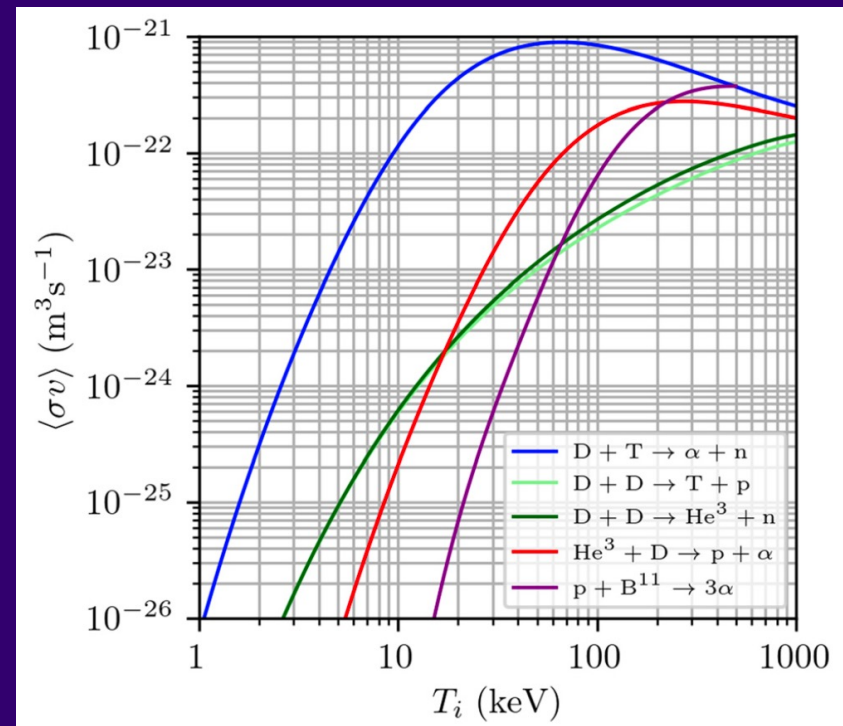
## Each fusion reaction has a collision cross-section that is a function of energy

- A collision cross-section,  $\sigma$ , 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  $\langle \sigma v \rangle$  which is a function of temperature, comes from the Gamow peak we just discussed

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

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

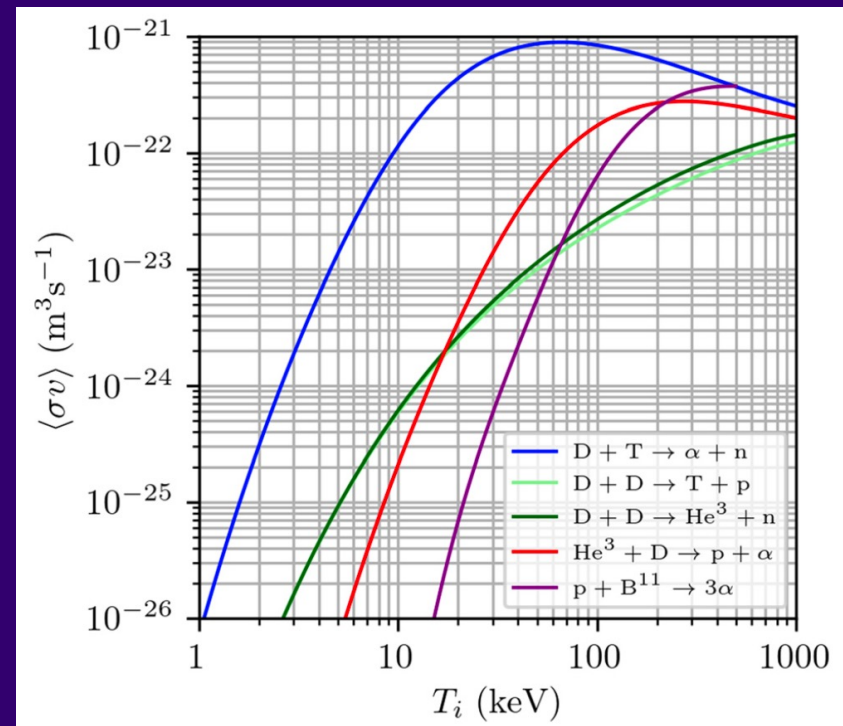
- A collision cross-section,  $\sigma$ , is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity,  $v$ , between the colliding ions
- Want to maximize the fusion reaction rate, given by  $\langle \sigma v \rangle$  which is a function of temperature, comes from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

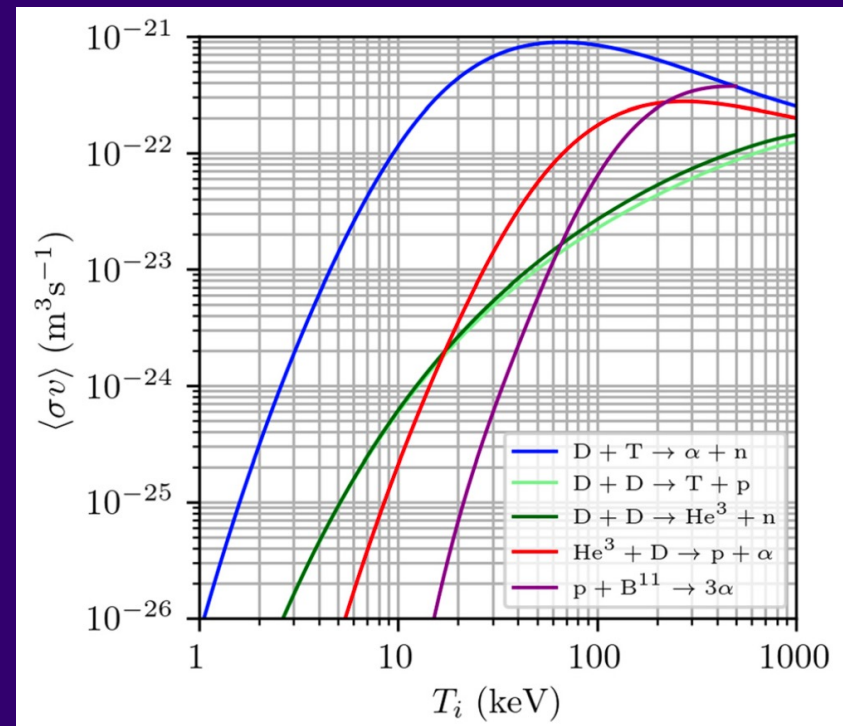
- A collision cross-section,  $\sigma$ , is the effective area “seen” by colliding ions
- Each Coulomb collision has a relative velocity,  $v$ , between the colliding ions
- Want to maximize the fusion reaction rate, given by  $\langle \sigma v \rangle$  which is a function of temperature, comes from the Gamow peak we just discussed
- Too low of a cross-section also eliminates many fusion reactions for energy
- Note that the D-T reaction has the highest reaction rate and at the lowest temperature  $\sim 175$  million degrees!



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,  $\sigma$ , 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  $\langle \sigma v \rangle$  which is a function of temperature, comes from the Gamow peak we just discussed
- Too low of a cross-section also eliminates many fusion reactions for energy
- Note that the D-T reaction has the highest reaction rate and at the lowest temperature  $\sim 175$  million degrees!
- The energy at the core of the sun  $\sim 15$  million degrees

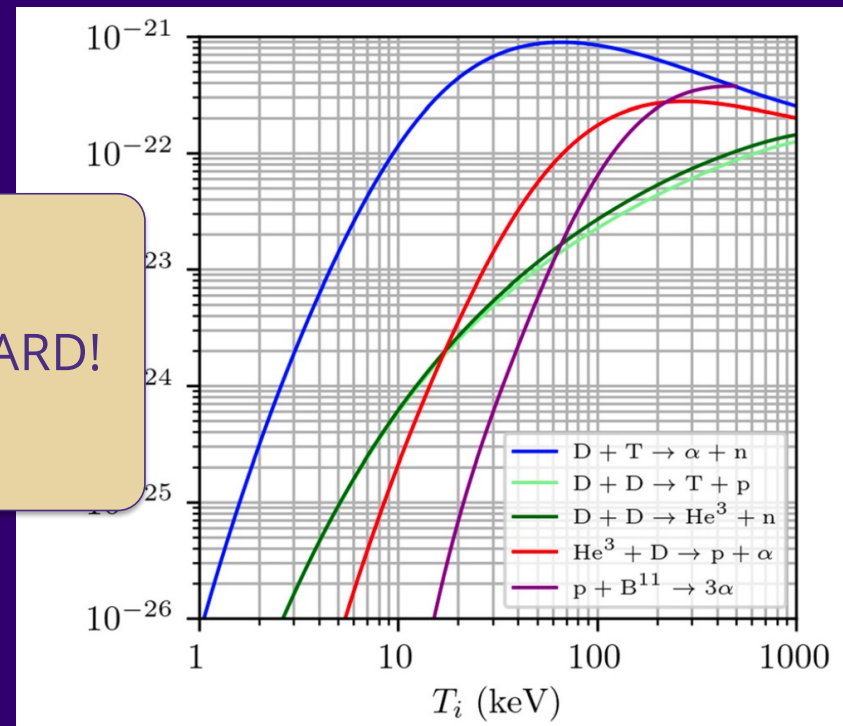


Credit: Wurzel and Hsu, Phys. Plasmas (2022)

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

- A collision cross-section,  $\sigma$ , 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 rate given by  $\langle \sigma v \rangle$  which is a function of temperature, comes from the Maxwell-Boltzmann distribution we just discussed
- Too low of a cross-section also means many fusion reactions for energy
- Note that the D-T reaction has the highest reaction rate and at the **lowest temperature ~ 175 million degrees!**
- The energy at the **core of the sun ~ 15 million degrees**

FUSION IS HARD!



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

# 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,  $Q$

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. Ignition
3. The Lawson criteria
4. The fusion triple product
5. Fusion gain, Q

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

# Fusion energy is evaluated using key metrics

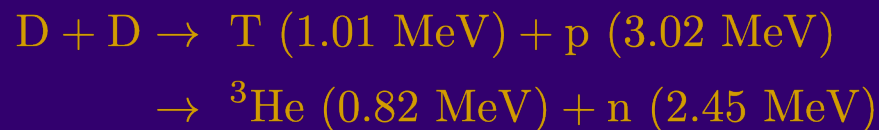
We will discuss some key metrics by which fusion energy is evaluated for feasibility:

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. The Lawson criteria
4. The fusion triple product
5. Fusion gain, Q

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. The Lawson criteria
4. The fusion triple product
5. Fusion gain, Q



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

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. The fusion triple product
5. Fusion gain, Q

# The Lawson criteria evaluates conditions for breakeven

- Lawson criteria is the product

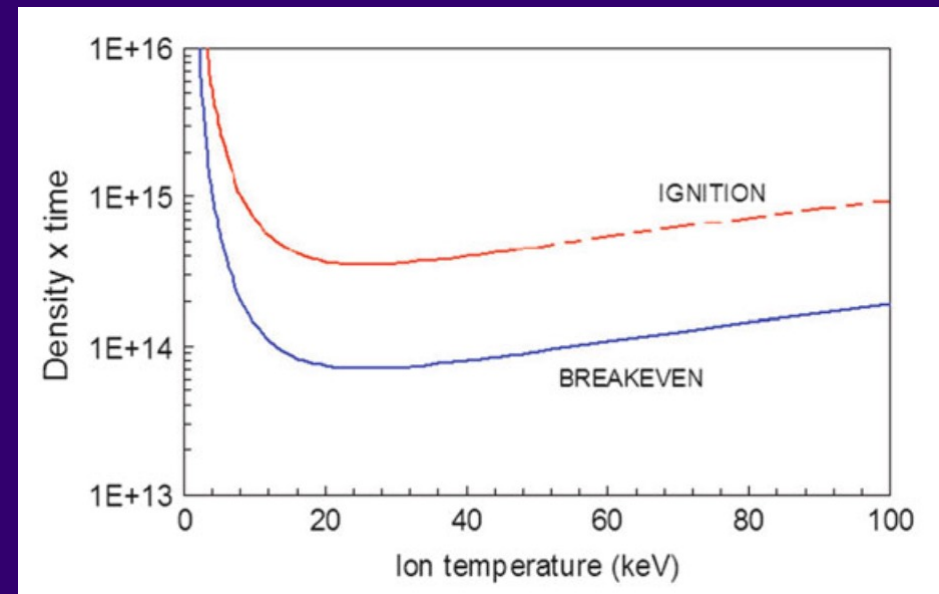
$$n \tau_E$$

**Density x Energy Confinement Time**

- For D-T reactions:

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

- 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



# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. **The fusion triple product:** evaluates conditions for breakeven considering temperature
5. Fusion gain, Q

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. **The fusion triple product:** evaluates conditions for breakeven considering temperature
5. Fusion gain, Q

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.

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. **The fusion triple product:** evaluates conditions for breakeven considering temperature
5. **Fusion gain, Q:** Is the measure of a self-sustaining fusion reaction, like an efficiency

## Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. **The fusion triple product:** evaluates conditions for breakeven considering temperature
5. **Fusion gain, Q:** Is the measure of a self-sustaining fusion reaction, like an efficiency

$$Q = \frac{\text{Energy output from fusion}}{\text{Energy input}}$$

# Fusion energy is evaluated using key metrics

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

1. **Breakeven:** Fusion energy produced = energy into the plasma + losses
2. **Ignition:**  $\alpha$ -particle ( $^4\text{He}$ ) heating maintains plasma temperature without further energy in
3. **The Lawson criteria:** evaluates conditions for breakeven
4. **The fusion triple product:** evaluates conditions for breakeven considering temperature
5. **Fusion gain, Q:** Is the measure of a self-sustaining fusion reaction, like an efficiency

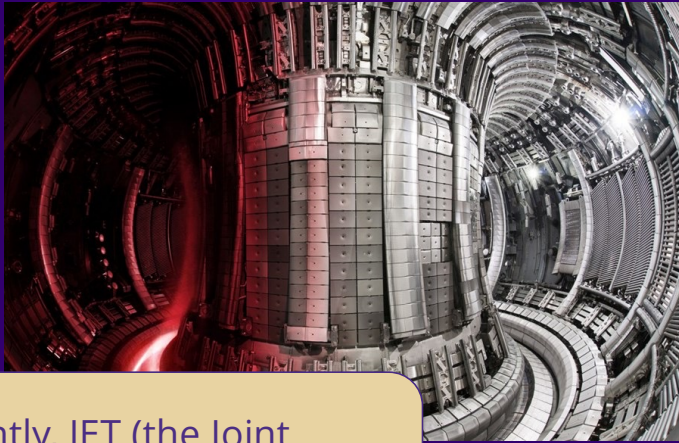
$$Q = \frac{\text{Energy output from fusion}}{\text{Energy input}}$$

- $Q = 1$  is scientific breakeven
- $Q \approx 5$  for burning plasma where  $\alpha$ -heating provides self-heating
- $Q = \infty$  ignition  $\rightarrow$  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?



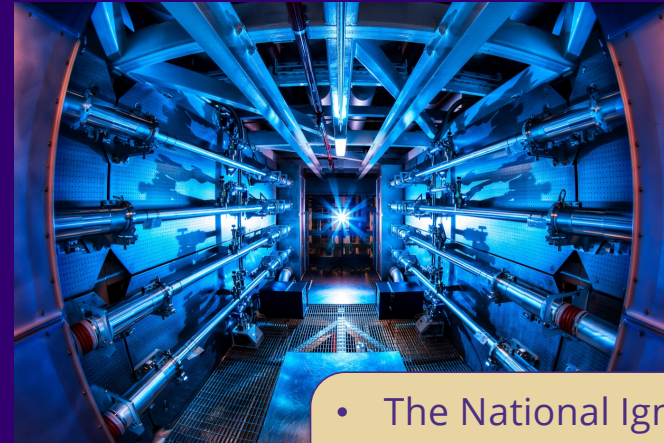
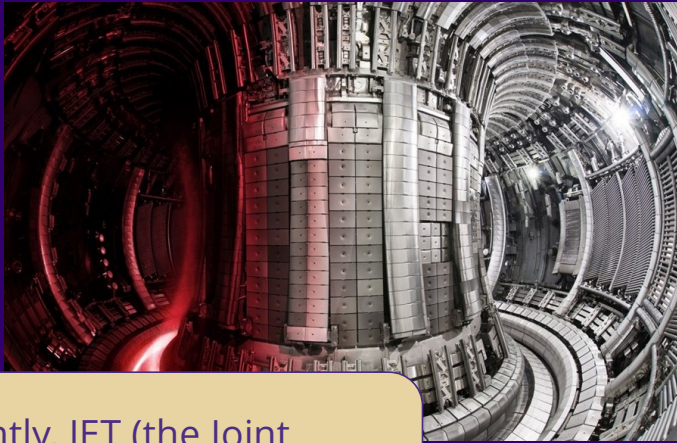
# Have any fusion concepts achieved scientific breakeven?



- Until recently, JET (the Joint European Torus) held the record since 1997 for  $Q=0.67$
- 22 MJ of heat released in 1997
- 59 MJ of heat released in 2022
- 69 MJ of heat released in 2024

An average US home uses 100 MJ per day

# Have any fusion concepts achieved scientific breakeven?

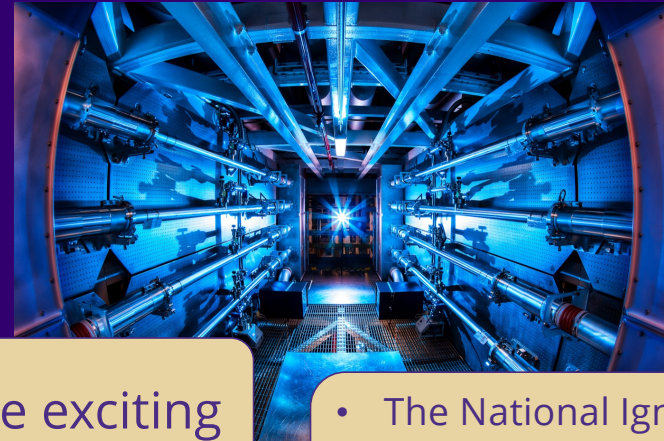
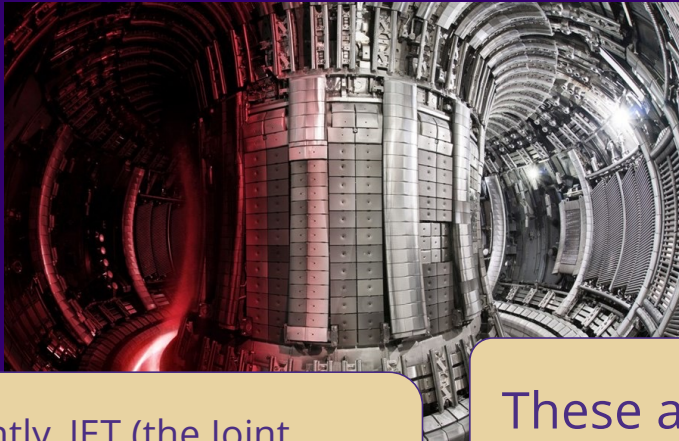


- Until recently, JET (the Joint European Torus) held the record since 1997 for  $Q=0.67$
- 22 MJ of heat released in 1997
- 59 MJ of heat released in 2022
- 69 MJ of heat released in 2024

An average US home uses 100 MJ per day

- The National Ignition Facility (NIF) holds the record for highest  $Q = 4$
- 1.35 MJ of energy in 2021
- 3.15 MJ of energy in 2022
- 5.2 MJ of energy in 2024
- 8.6 MJ of energy in 2025

# Have any fusion concepts achieved scientific breakeven?



- Until recently, JET (the Joint European Torus) held the record since 1997 for  $Q=0.67$
- 22 MJ of heat released in 1997
- 59 MJ of heat released in 2022
- 69 MJ of heat released in 2024

These are exciting times to work in fusion!

An average US home uses 100 MJ per day

- The National Ignition Facility (NIF) holds the record for highest  $Q = 4$
- 1.35 MJ of energy in 2021
- 3.15 MJ of energy in 2022
- 5.2 MJ of energy in 2024
- 8.6 MJ of energy in 2025

# Outline

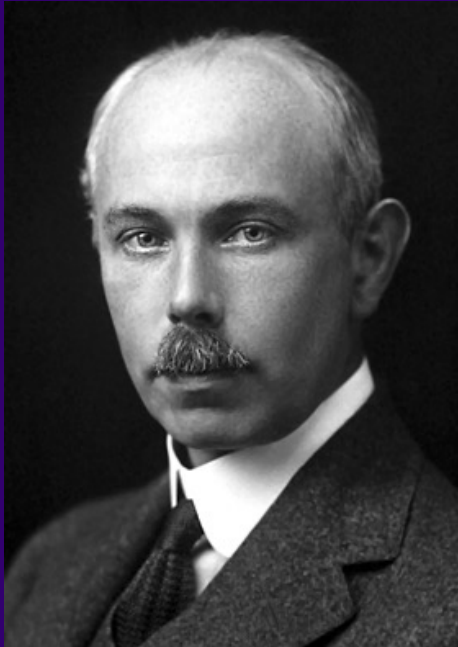
- The case for fusion
- What is fusion?
- Metrics to evaluate fusion energy
- **Brief history of fusion and some pioneers**
- Fusion concepts: steady-state vs pulsed
- Progress in fusion

## Brief history of fusion, starting with the earliest pioneers



- **Arthur Eddington** was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- **Cecilia Payne**, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- **Cecilia Payne**, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.

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.

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- Cecilia Payne, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.
- **George Gamow**, in 1928, introduced quantum tunneling

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- Cecilia Payne, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.
- George Gamow, in 1928, introduced quantum tunneling
- **Mark Oliphant**, in 1933, first demonstrated neutrons from fusion

## Brief history of fusion, starting with the earliest pioneers



- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, “The Internal Constitution of the Stars” (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- Cecilia Payne, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.
- George Gamow, in 1928, introduced quantum tunneling
- Mark Oliphant, in 1933, first demonstrated neutrons from fusion
- **Hans Bethe**, in 1939, showed that beta decay and quantum tunneling in the sun’s core may convert one of the protons to a neutron, producing deuterium

## Brief history of fusion, starting with the earliest pioneers



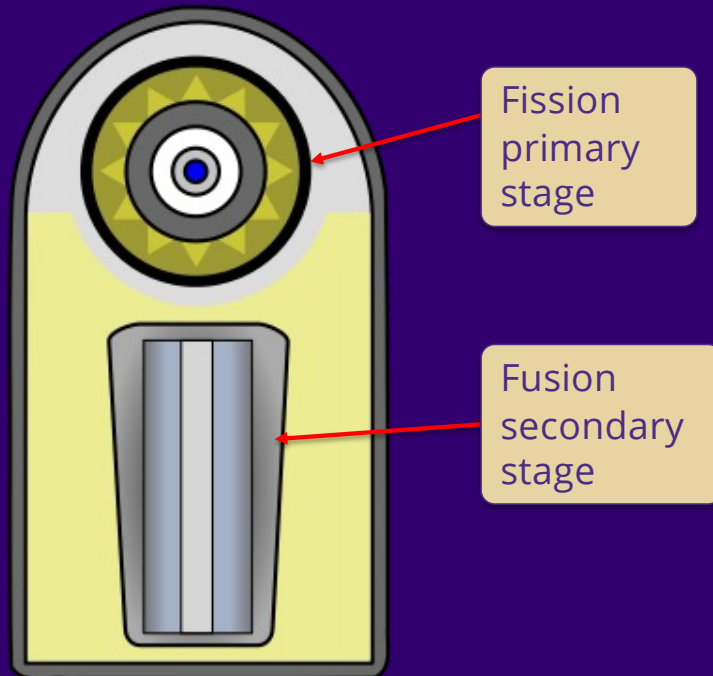
- Arthur Eddington was the first to speculate that stellar energy was due to nuclear fusion of hydrogen into helium, "The Internal Constitution of the Stars" (1920)
- Francis Aston had recently shown (1907) that the masses:

$$m_{\text{helium}} = (0.8\%) (4) m_{\text{hydrogen}}$$

- Cecilia Payne, in 1925, published her doctoral thesis showing that hydrogen is the primary constituent in stars and the most abundant element in the universe.
- George Gamow, in 1928, introduced quantum tunneling
- Mark Oliphant, in 1933, first demonstrated
- **Hans Bethe**, in 1939, showed that beta decay and quantum tunneling in the sun's core may convert one proton into a neutron, producing deuterium

The recent ARPA-E BETHE program funding "Breakthroughs in THERmonuclear fusion" named after Hans Bethe

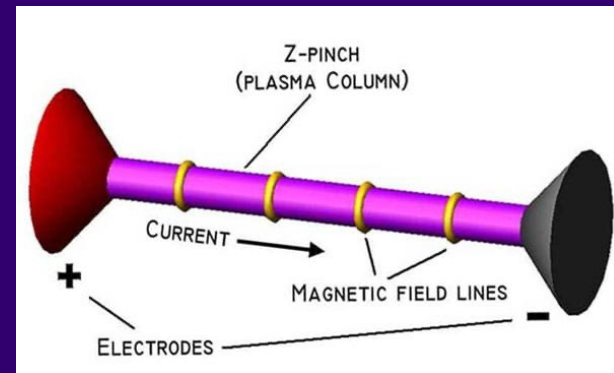
# H-bomb in the 1950s showed that nuclear fusion does work if controlling it isn't a requirement



- 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

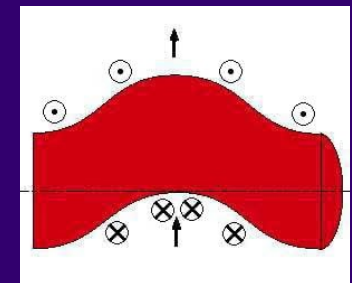
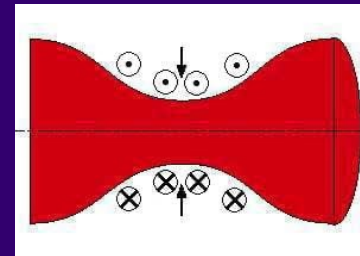
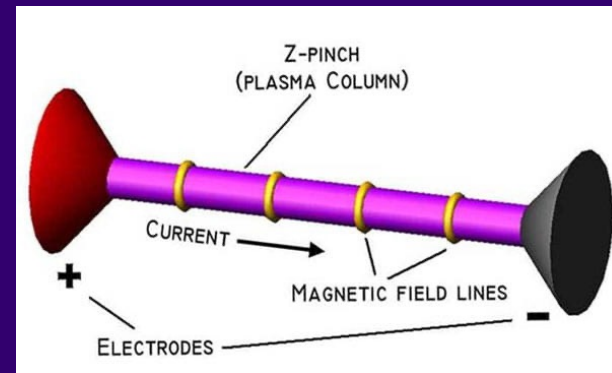
## The first fusion reactor was a Z-pinch, patented in 1946

- 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



## 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
- 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, now has private funding



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

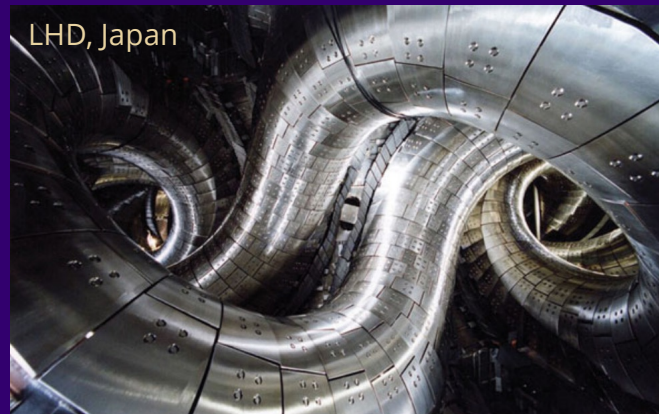
- Lyman Spitzer was unaware of the Zpinch work and created the stellarator
- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially

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

- Lyman Spitzer was unaware of the Zpinch work and created the stellarator
- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially
- Complicated 3-D magnetic fields, breakthroughs in theory, optimized magnets → substantial private and public funding!
- Complex engineering to achieve 3-D field structure

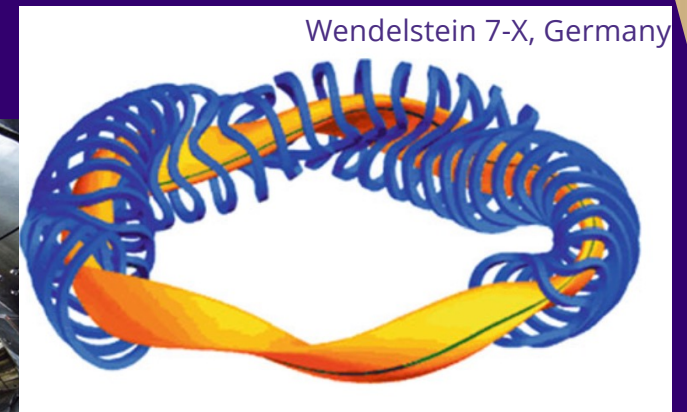
## The next concept that came about was the stellarator, also magnetic confinement fusion

- Lyman Spitzer was unaware of the Zpinch work and created the stellarator
- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially
- Complicated 3-D magnetic fields, breakthroughs in theory, optimized magnets → substantial private and public funding!
- Complex engineering to achieve 3-D field structure



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

- Lyman Spitzer was unaware of the Zpinch work and created the stellarator
- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially
- Complicated 3-D magnetic fields, breakthroughs in theory, optimized magnets → substantial private and public funding!
- Complex engineering to achieve 3-D field structure



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

- Lyman Spitzer was unaware of the Zpinch work and created the stellarator
- This ultimately led to the creation of PPPL
- Steady-state device, evolved substantially
- Interest resumed in recent years
- Complicated 3-D magnetic fields, breakthroughs in theory, optimized magnets → substantial private and public funding!
- Complex engineering to achieve 3-D field structure



MAX PLANCK INSTITUTE  
FOR PLASMA PHYSICS



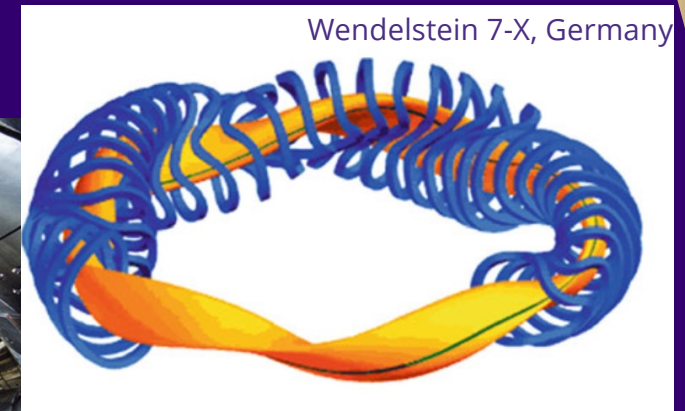
WISCONSIN  
UNIVERSITY OF WISCONSIN-MADISON



UNIVERSITY of WASHINGTON



LHD, Japan

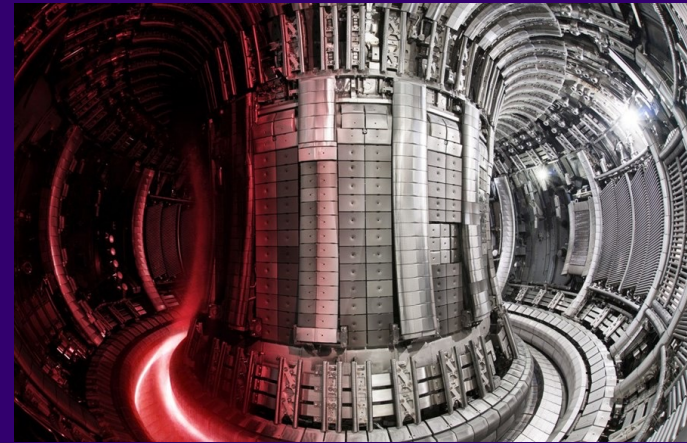


Wendelstein 7-X, Germany

Bhuvana Srinivasan

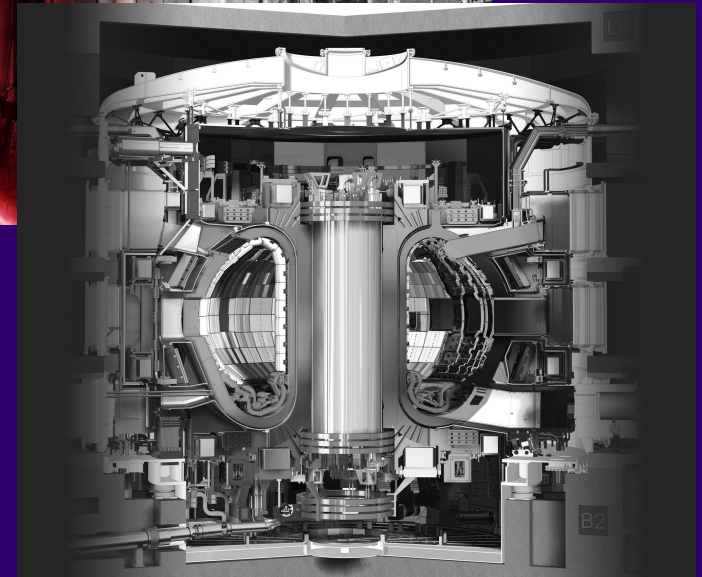
# Tokamaks emerged in the 1950s in the USSR, most funded and developed magnetic confinement fusion device

- 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



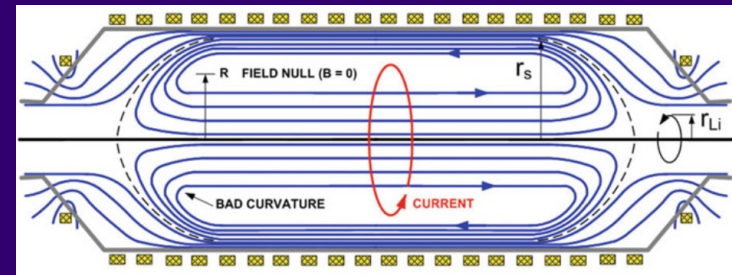
# Tokamaks emerged in the 1950s in the USSR, most funded and developed magnetic confinement fusion device

- 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
  
- 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,  $Q \sim 10$**
- Expected to produce 500 MW of fusion power, but focus is still research not powerplant



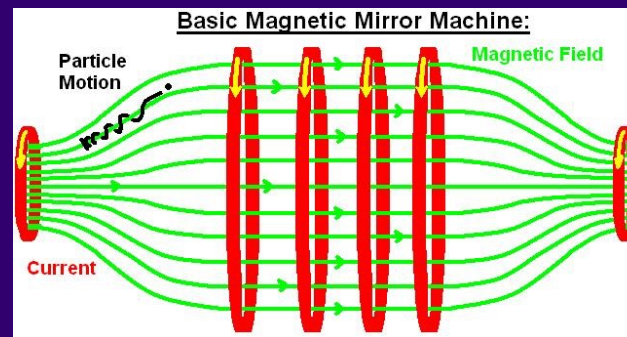
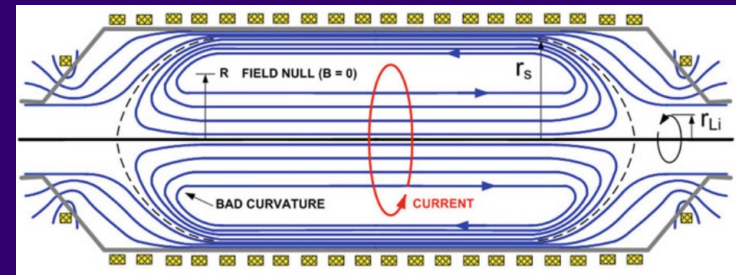
A number of other magnetic confinement fusion pulsed devices exist that have had a history of limited funding, but...

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



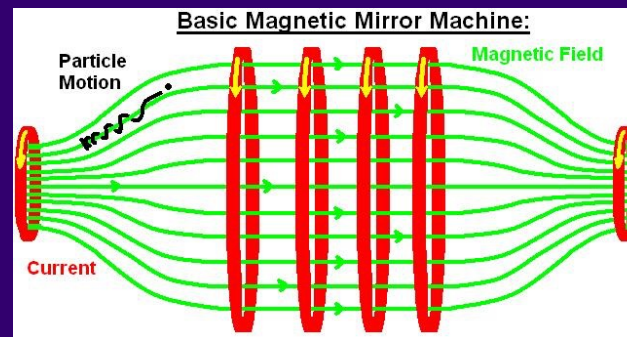
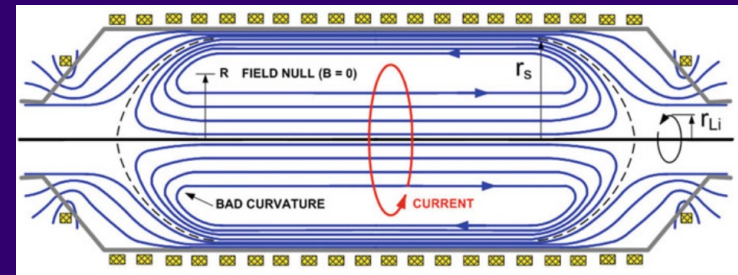
A number of other magnetic confinement fusion pulsed devices exist that have had a history of limited funding, but...

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



# 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



Bhuvana Srinivasan

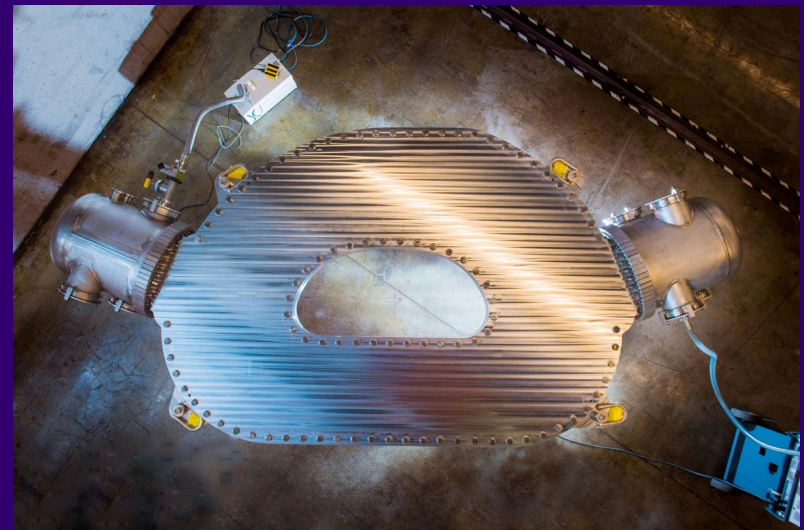


# A number of other magnetic confinement fusion pulsed devices exist that have had a history of limited funding, but...

- Private investment is changing the story dramatically
- Field-reversed configurations
- Magnetic mirrors
- Spheromaks
- And others
- Recent advances in magnet technology, high-temperature superconductors, have a transformative effect on the field of MCF

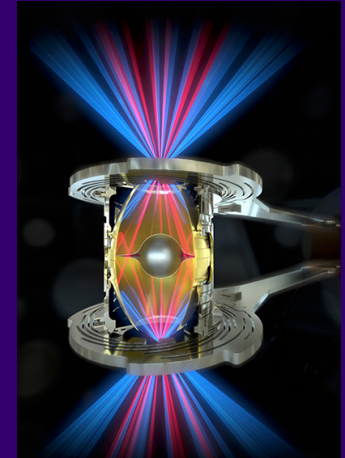


Commonwealth Fusion Systems



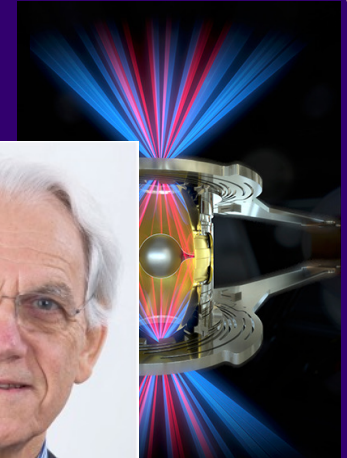
# Inertial confinement fusion was motivated by the stockpile stewardship program

- 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



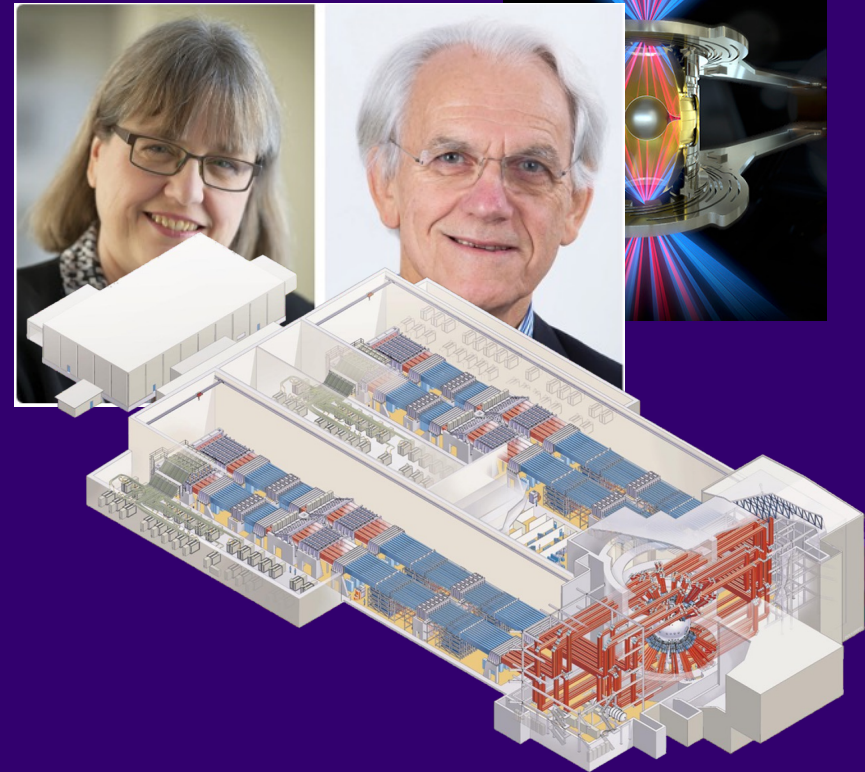
# Inertial confinement fusion was motivated by the stockpile stewardship program

- 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
- Donna Strickland and Gérard Mourou invented chirp pulse amplification (Nobel prize) which was transformative for future laser facilities



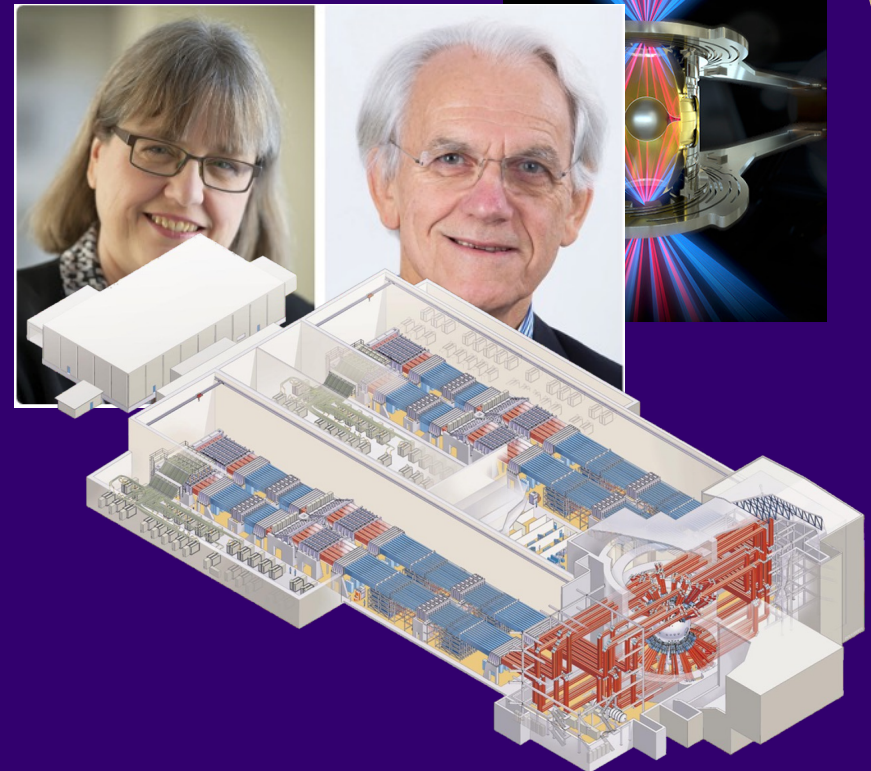
# Inertial confinement fusion was motivated by the stockpile stewardship program

- 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
- Donna Strickland and Gérard Mourou invented chirp pulse amplification (Nobel prize) which was transformative for future laser facilities
- NIF was the first to achieve fusion ignition,  $Q=4$  with 8.6 MJ of fusion energy



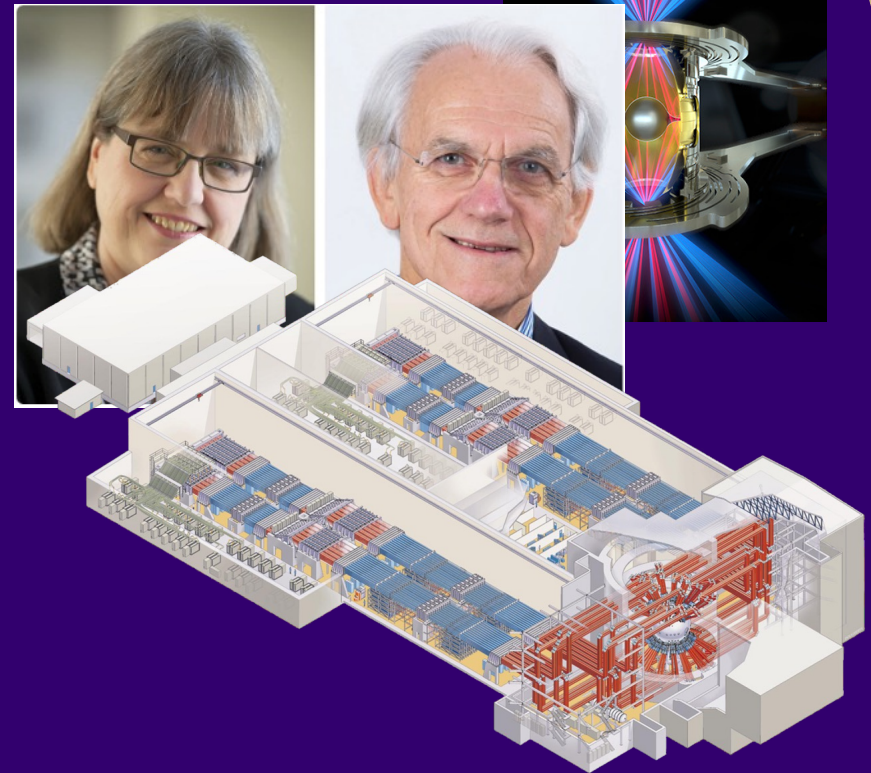
# Inertial confinement fusion was motivated by the stockpile stewardship program

- 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
- Donna Strickland and Gérard Mourou invented chirp pulse amplification (Nobel prize) which was transformative for future laser facilities
- NIF was the first to achieve fusion ignition,  $Q=4$  with 8.6 MJ of fusion energy
- NIF's primary goal is still stockpile stewardship
- Very challenging to achieve inertial fusion energy with NIF's lasers, only 2-3 shots per day



# Inertial confinement fusion was motivated by the stockpile stewardship program

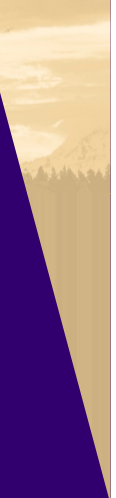
- Lasers providing energy directly or indirectly, through x-rays, to target to compress it to fusion conditions
- The Nova laser was built in the 1980s, but lost energy before hitting the fuel
- Donna Strickland and Gérard Mourou invented chirp pulse amplification (Nobel prize) which was transformative for future laser facilities
- NIF was the first to achieve fusion ignition,  $Q=4$  with 8.6 MJ of fusion energy
- NIF's primary goal is still stockpile stewardship
- Very challenging to achieve inertial fusion energy with NIF's lasers, only 2-3 shots per day
- US DOE recently funded inertial fusion energy hubs
- Number of private ventures exploring different variations of laser-driven fusion, including laser technology



Bhuvana Srinivasan

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

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches

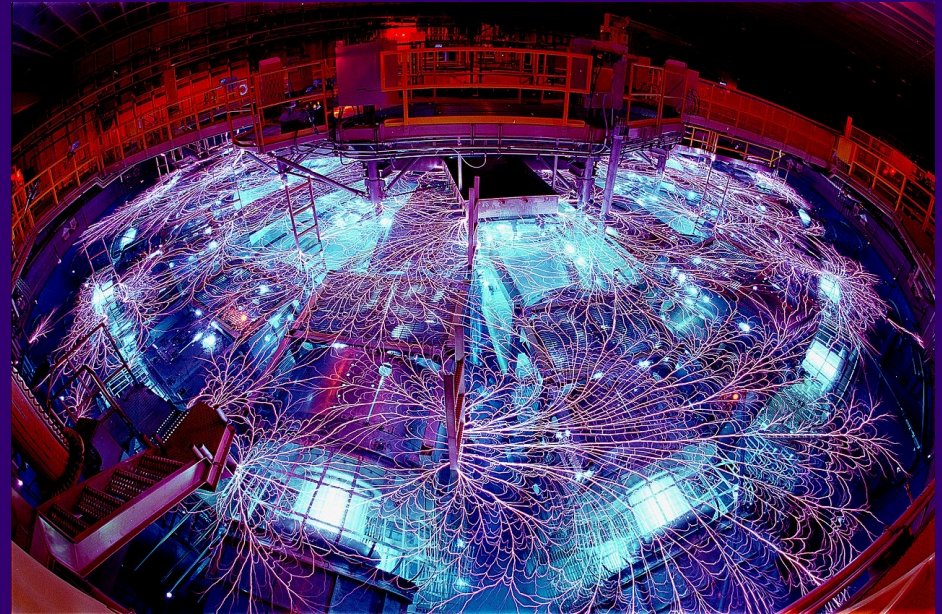


# Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches
- Cylindrical configuration typically

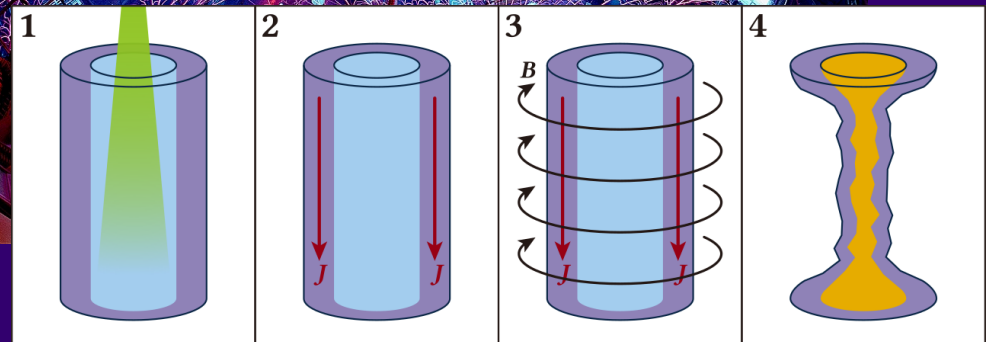
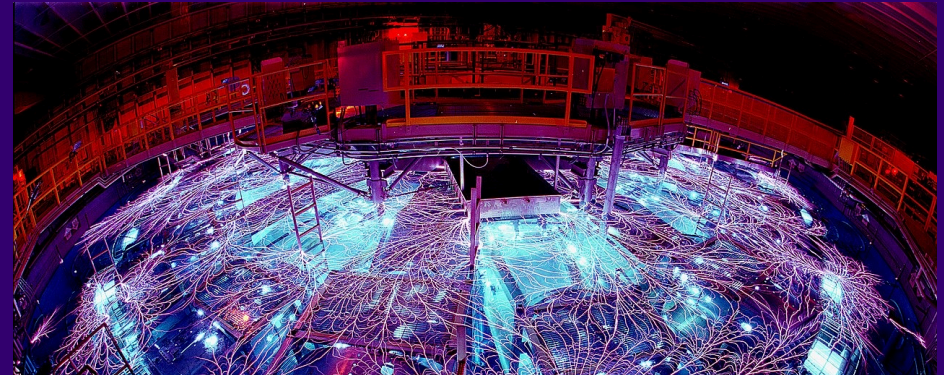
# Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches
- Cylindrical configuration typically
- Sandia's Z-machine existed in some form since the 1980s and reached its present form in the 1990s, presently ~ 18 MAmps of current



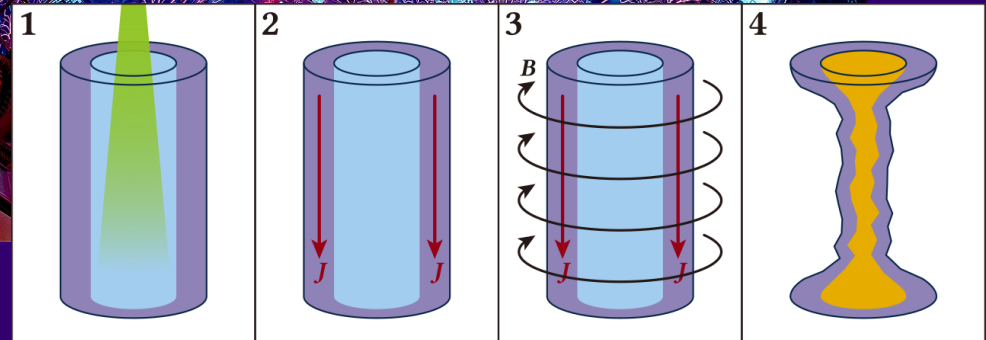
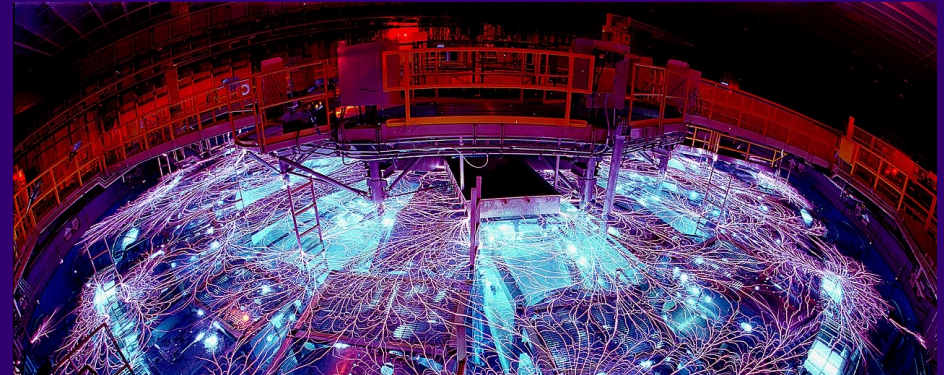
# Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches
- Cylindrical configuration typically
- Sandia's Z-machine existed in some form since the 1980s and reached its present form in the 1990s, presently ~ 18 MAmps of current
- **MagLIF (Magnetized Liner Inertial Fusion)** generates fusion energy by driving currents in a thin liner (e.g. aluminum can) to compress D-T fusion fuel target



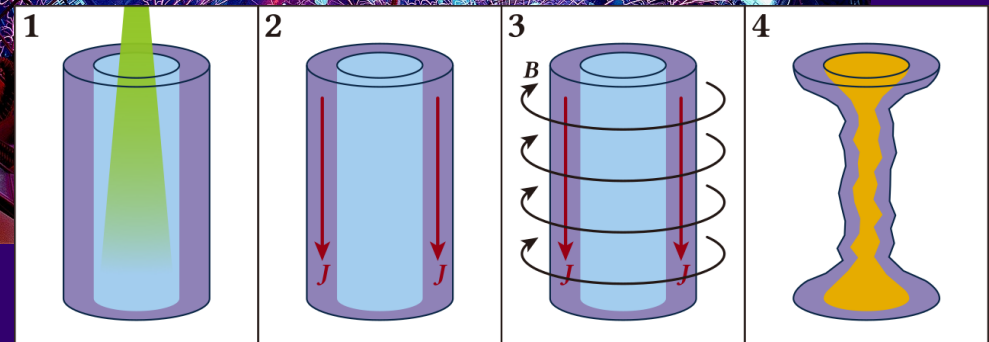
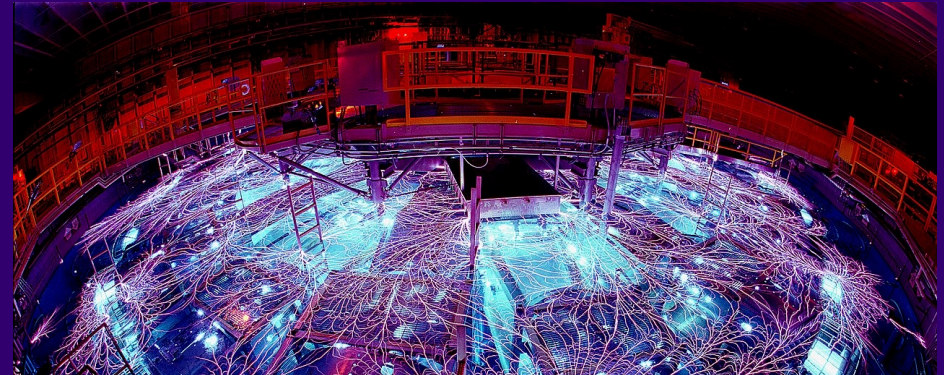
# Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches
- Cylindrical configuration typically
- Sandia's Z-machine existed in some form since the 1980s and reached its present form in the 1990s, presently ~ 18 MAmps of current
- MagLIF (Magnetized Liner Inertial Fusion) generates fusion energy by driving currents in a thin liner (e.g. aluminum can) to compress D-T fusion fuel target
- Other variations of MIF exist with different drivers (e.g. plasma jets) and different targets (e.g. FRCs)

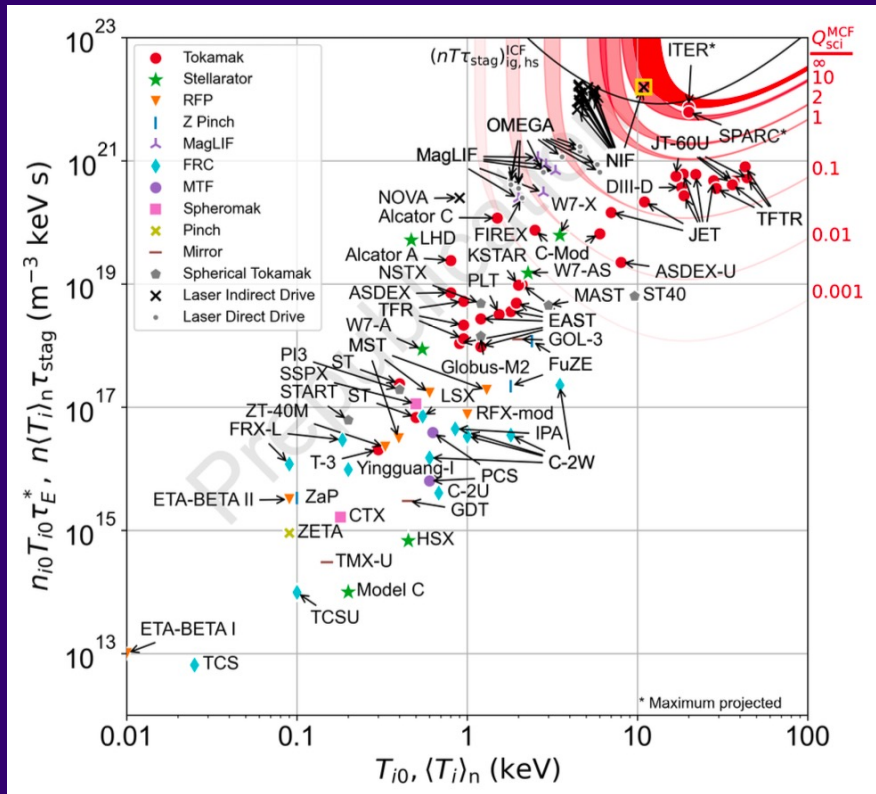


# Magneto-inertial fusion uses magnetic fields to rapidly compress and heat plasma

- Uses pulsed-power, fast discharge of large capacitors, to rapidly create and implode Z-pinches
- Cylindrical configuration typically
- Sandia's Z-machine existed in some form since the 1980s and reached its present form in the 1990s, presently ~ 18 MAmps of current
- MagLIF (Magnetized Liner Inertial Fusion) generates fusion energy by driving currents in a thin liner (e.g. aluminum can) to compress D-T fusion fuel target
- Other variations of MIF exist with different drivers (e.g. plasma jets) and different targets (e.g. FRCs)
- **Public and private efforts for stockpile stewardship and fusion energy**

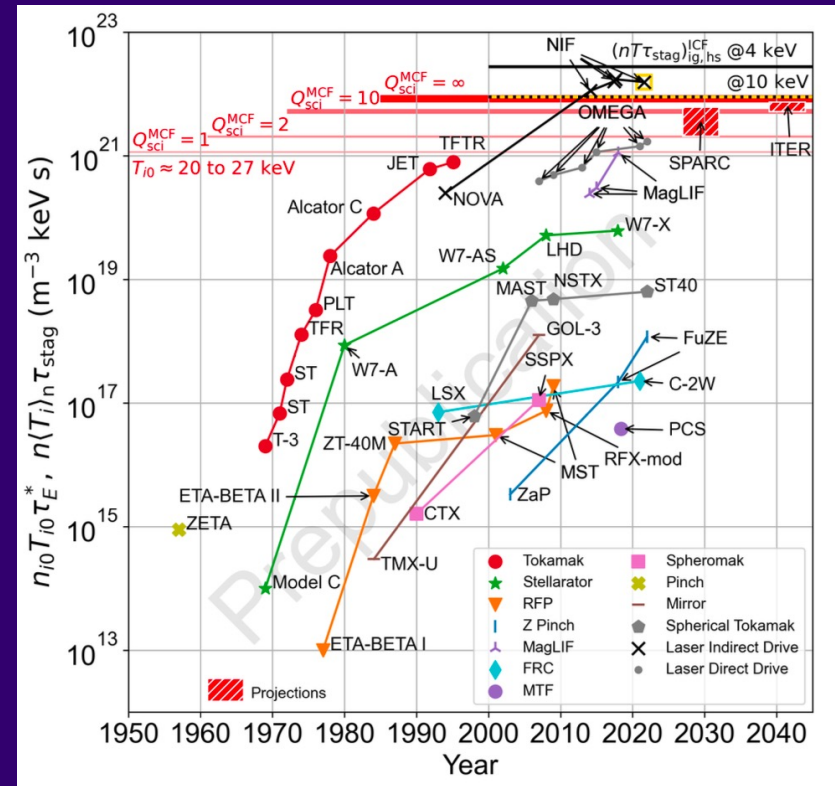
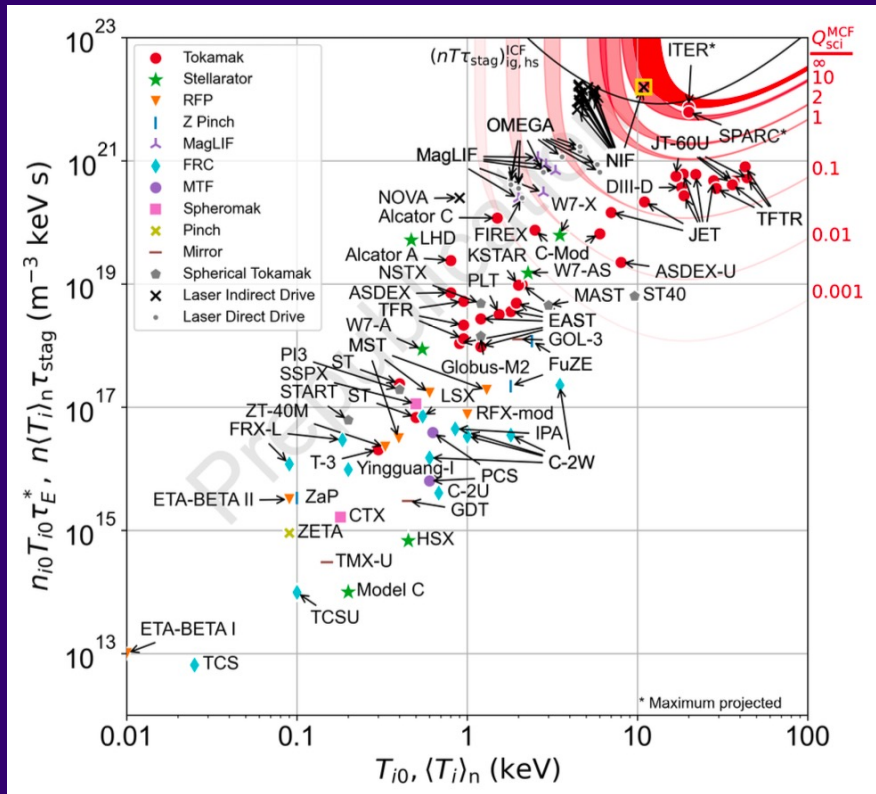


# Progress in fusion energy summarized by fusion triple product vs temperature and vs year for various experiments



Credit: Wurzel and Hsu, Phys. Plasmas (2025)

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



Credit: Wurzel and Hsu, Phys. Plasmas (2025)

There is over \$8 billion in private investment in fusion with 80% of the investment in the US, this is unprecedented!

AVALANCHE Commonwealth Fusion Systems FOCUSED

Fusion Industry Association

fuse generalfusion HELION

INERTIA PACIFIC FUSION Proxima Fusion

tae TYPE ONE ENERGY XCIMER

ZAP

HELICITY SPACE

MOORE TECHNOLOGIES

LaserFusionX

LIBERTY FUSION

LONGVIEW FUSION

LPP FUSION

MARITIME FUSION

MIFTI Fusion

nearstar

NOVATRON

nT-tao Compact Fusion Power

PRANOS FUSION ENERGY

RENAISSANCE FUSION

STELLAREX

TERRA FUSION

TIBBAR PLASMA technologies

EX-Fusion

first light

GAUSS FUSION

KYOTO FUSIONEERING

MarvelFusion

OPENSTAR

REALTA FUSION

SHINE

THEA ENERGY

Tokamak Energy

acceleron

anubal FUSION

BLUE LASER FUSION

FIREFLY FUSION

GenF

Helical Fusion

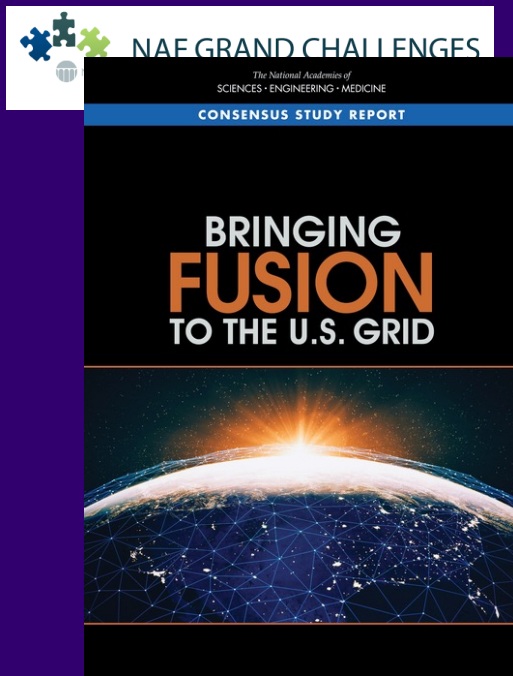
# National commitment to fusion energy is stronger than ever



- One of 14 NAE Grand Challenges in the 21<sup>st</sup> century:  
**Provide energy from fusion**

# National commitment to fusion energy is stronger than ever

W



- One of 14 NAE Grand Challenges in the 21<sup>st</sup> century: **Provide energy from fusion**
- NASEM report on Bringing Fusion to the US Grid: US public and private sector should **produce net electricity in a fusion plant in the US by 2035-2040**

# National commitment to fusion energy is stronger than ever



- One of 14 NAE Grand Challenges in the 21<sup>st</sup> century: **Provide energy from fusion**
- NASEM report on Bringing Fusion to the US Grid: US public and private sector should **produce net electricity in a fusion plant in the US by 2035-2040**
- 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”**

# National commitment to fusion energy is stronger than ever



- One of 14 NAE Grand Challenges in the 21<sup>st</sup> century: **Provide energy from fusion**
- NASEM report on Bringing Fusion to the US Grid: US public and private sector should **produce net electricity in a fusion plant in the US by 2035-2040**
- 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”
- 2025 DOE Fusion Science and Technology Roadmap
  1. Key Actions to deliver public infrastructure that supports the fusion private sector scale-up in the 2030s

# National commitment to fusion energy is stronger than ever

- One of 14 NAE Grand Challenges in the 21<sup>st</sup> century: **Provide energy from fusion**

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

...ing Fusion to the US Grid: US  
...r should **produce net electricity in**  
...by 2035-2040

... Strategy:  
... technology gaps to a  
...nt fusion pilot plant  
... sustainable, equitable  
... deployment  
... external partnerships"

- 2025 DOE Fusion Science and Technology Roadmap
  1. **Key Actions to deliver public infrastructure that supports the fusion private sector scale-up in the 2030s**



# 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 MS or PhD in plasma physics and fusion energy!
- Interested in a **graduate certificate in fusion engineering** for fusion industry? Reach out to us!

