Fusion Power Plant
Cost: $50,000 Power: 50000 MW-h

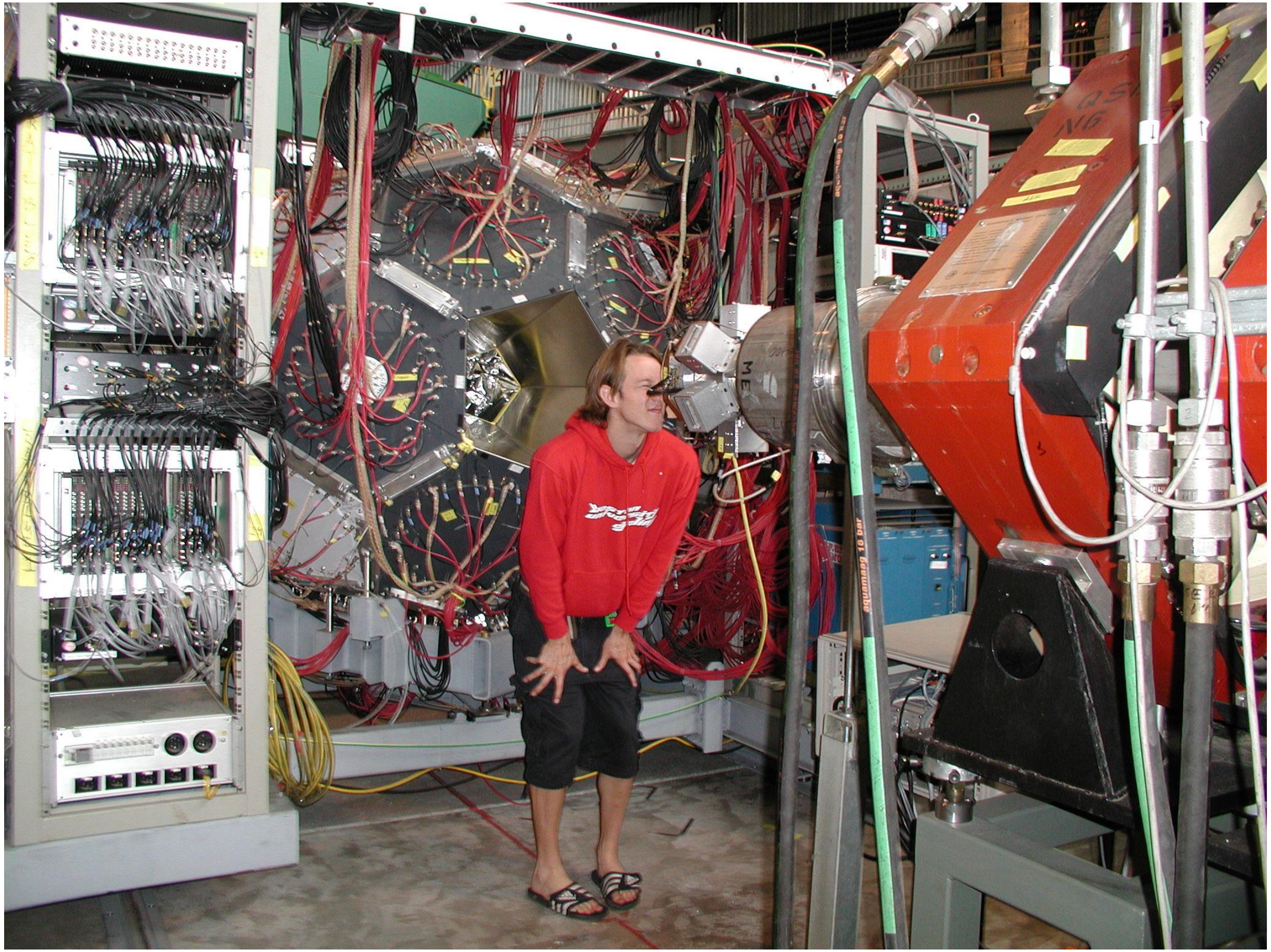
Tapping the same energy the sun uses, Fusion Plants create large amounts of energy with none of the radiation danger of Nuclear Pl
most expens

# Introduction to Fusion (Energy)

Professor Zach Hartwig
MIT Plasma Science and Fusion Center

13 Jun 22

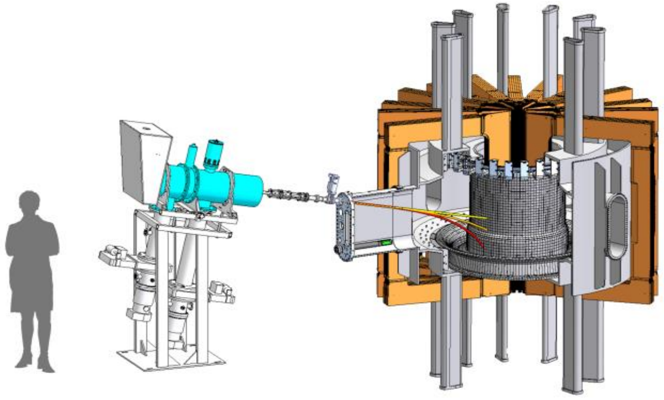
# First, let me introduce myself.
Nothing like an embarrassing photo to kick things off…



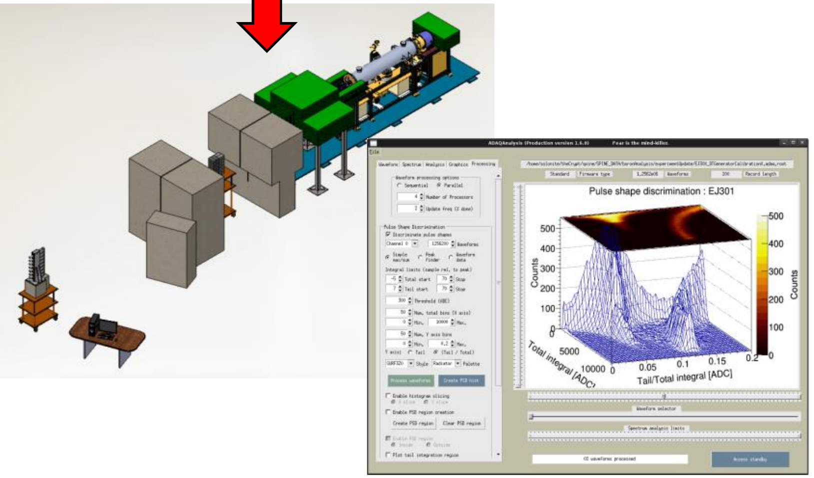
# How did I get here? Some snapshots.
# Note: Not an entirely linear path!

Highest precision measurement of the muon lifetime (2005)

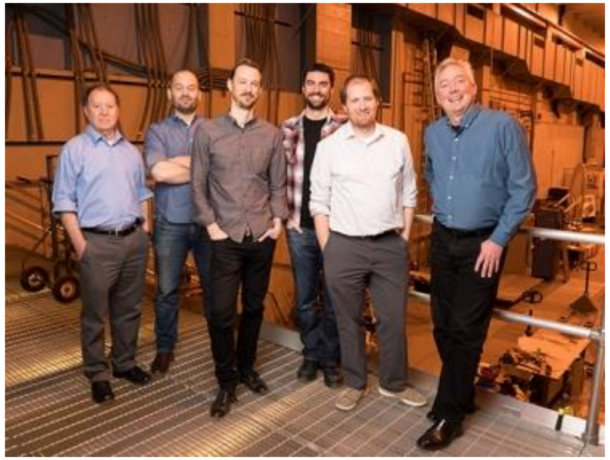
Much needed time away from science: bike racing, traveling, reading (2005-2007)



New in-situ ion beam diagnostic for fusion facing materials (2013)



Nuclear security: Cargo screening and weapons treaty verification (2014-15)

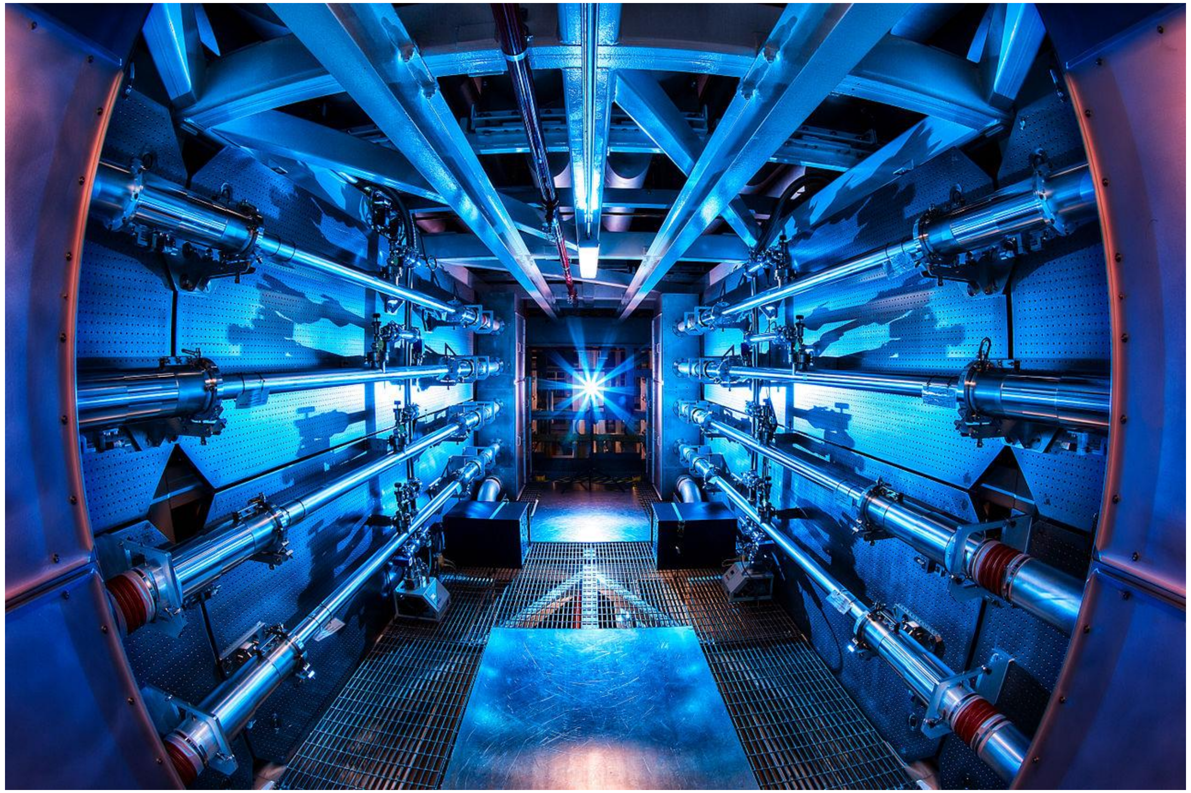


Co-founded Commonwealth Fusion Systems and the SPARC Project (2018)

PI and Project Head of the SPARC Toroidal Field Model Coil Project (2019-21)

It’s an exciting time to talk about fusion energy!

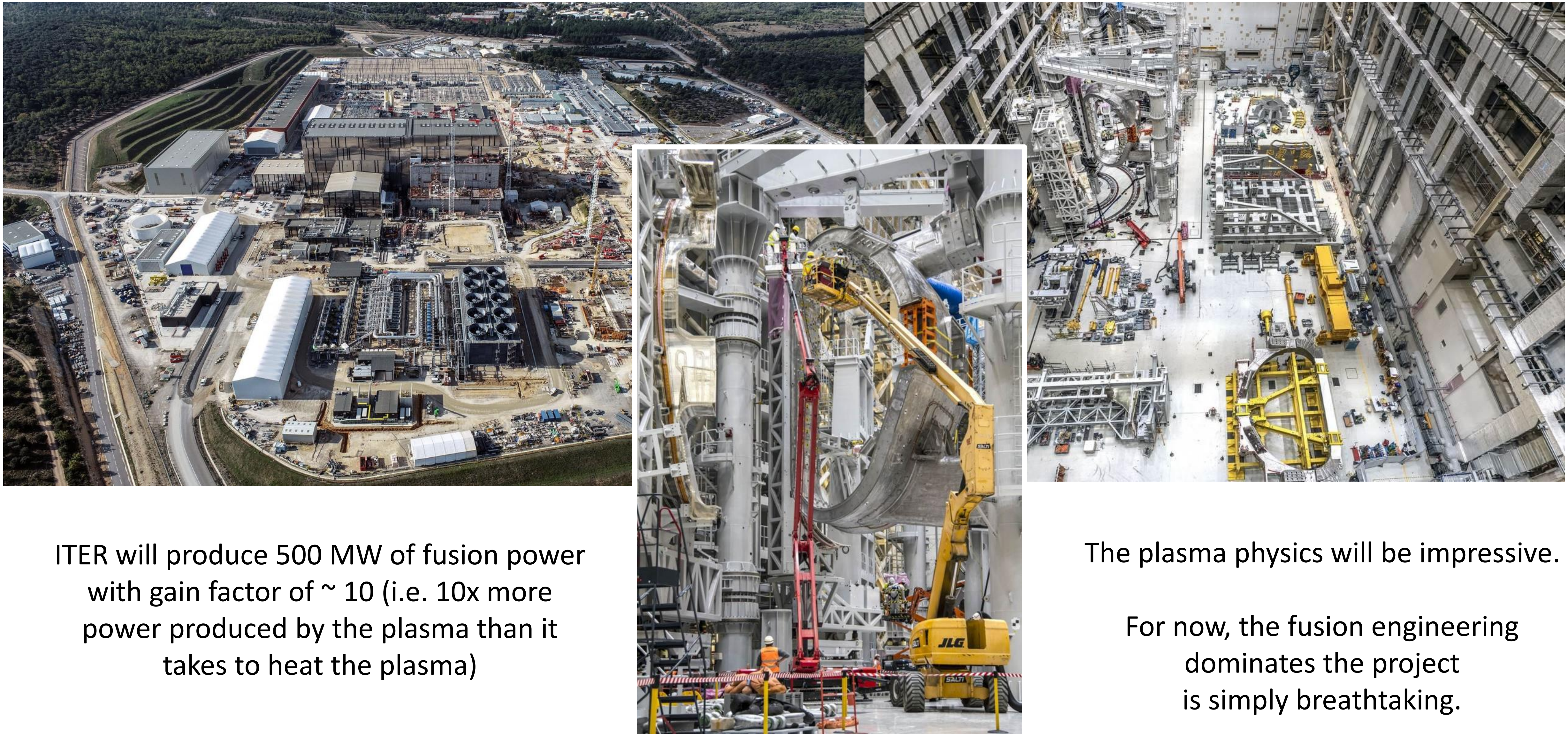
# *It’s an exciting time to talk about fusion energy:*
# The National Ignition Facility at LLNL produced a 1.3 MJ shot



This NIF “shot” produced 10 quadrillion watts (1e16 W) for 100 trillionths of a second (1e-10 s) … don’t blink! (August 2021)

~1.3 MJ of fusion output puts NIF just shy of ignition!
(And a gain factor of ~0.7 depending how you count)

# *It’s an exciting time to talk about fusion energy:* The ITER tokamak is well on its way to construction



ITER will produce 500 MW of fusion power with gain factor of ~ 10 (i.e. 10x more power produced by the plasma than it takes to heat the plasma)

The plasma physics will be impressive.

For now, the fusion engineering dominates the project is simply breathtaking.

# *It's an exciting time to talk about fusion energy:*
# The SPARC Toroidal Field Model Coil achieved 20 tesla at MIT

The TFMC, weighing ~10,000 kg and using almost 300 km of high temperature superconductor, achieved ~20.5 tesla peak field-on-coil in Sep 2021, opening up a new path to fusion energy that seeks to be smaller, sooner, and lower cost

# *It's an exciting time to talk about fusion energy:* Construction of the SPARC site in Devens MA by CFS has begun

**MIT PSFC**

SPARC is racing to be the first net-energy (gain > 1.0) fusion energy experiment. It could produce a gain factor up to 11x and >100 MW of fusion power in a device that is ~70x smaller than the ITER tokamak if successful

# *It’s an exciting time to talk about fusion energy:* A private fusion industry has emerged and is growing

The total private capital in fusion energy start ups is now on the order of $5 billion.

This represents a new private approach (launching off of national government funded foundations in fusion) that didn’t exist 10 years ago.

Work is underway around the world with massive promises made publicly. Succeed or fail, it will certainly be an exciting next few years!

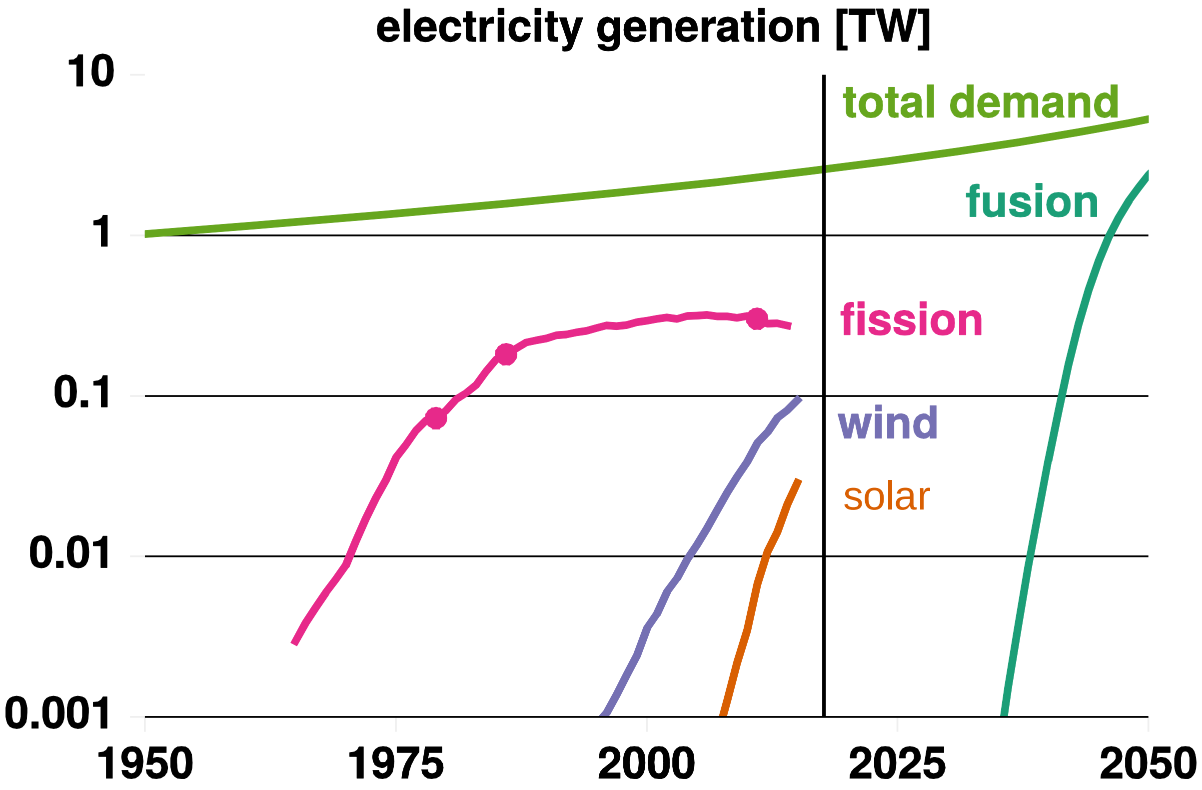
# *It's an exciting time to talk about fusion energy:*
# The world is increasingly desperate for new solutions to climate change

- Historically, energy technologies experience exponential early growth (~1% total energy) and then slow linear growth

- Precedents of new energy sources in 20th century provide insight into potential for fusion energy to contribute

- Fusion scale-up required is compatible with mitigating worst effects of climate change and contributing to mid-century CO2 goals…

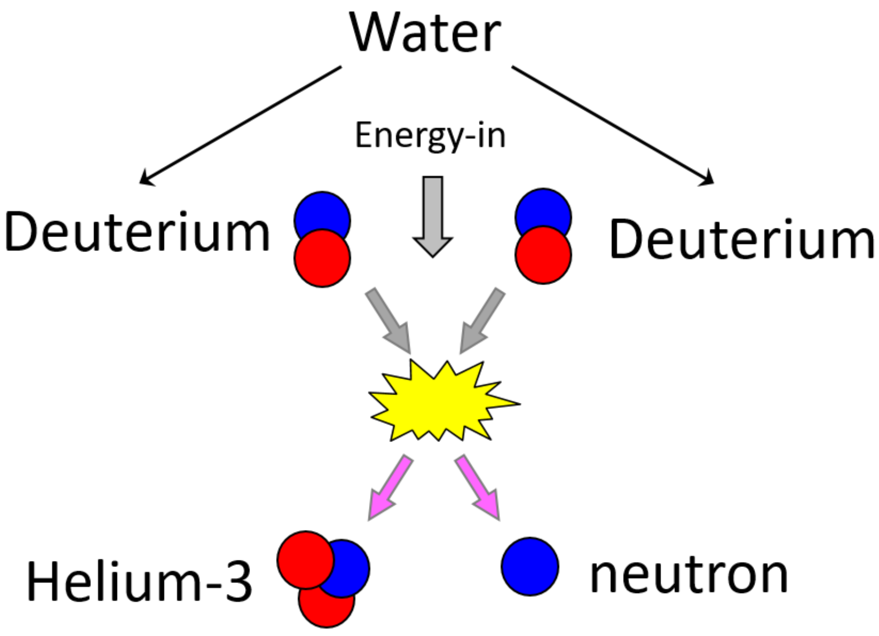
  … but first demonstration must happen by the mid-2030's at the latest if fusion is to help mitigate the worst effects of climate change!



# What is fusion?

# “Fusion” typically denotes the process of combining two light (i.e. low-Z) nuclei into a heavier nucleus

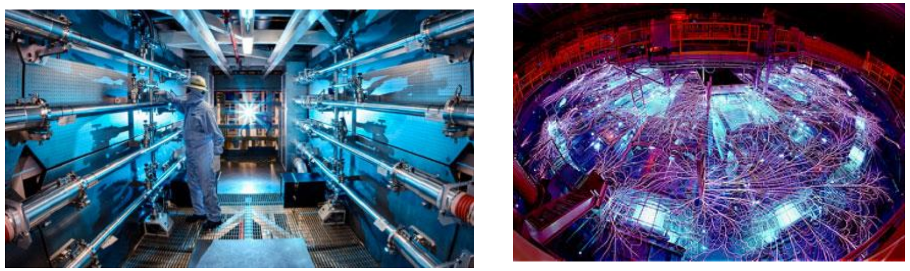
Fusion is a fundamental process that combines two nuclei, often releasing enormous energy
Its immense potential has driven research for almost 60 years…



**10 to ∞ times the Energy-in**

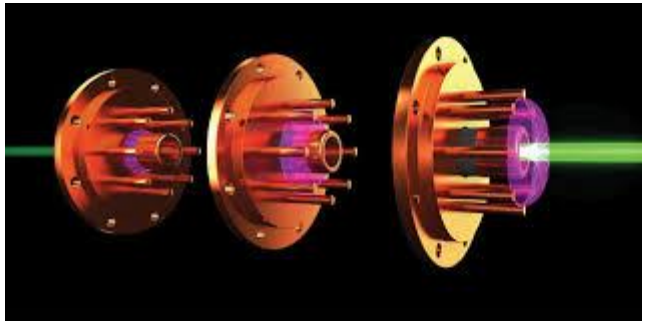
# There are many different uses of fusion in science and engineering …

## Stockpile stewardship



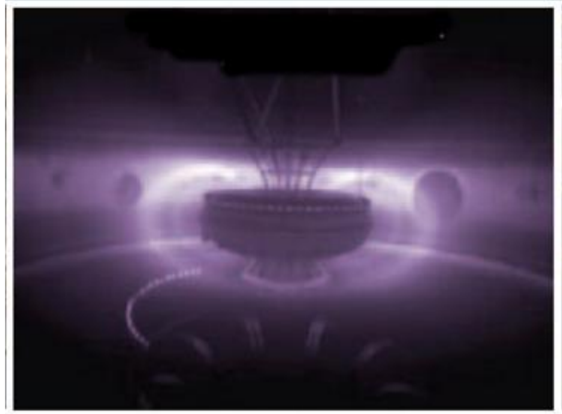
The National Ignition Facility (LLNL) and Z-Machine (SNL) replicate conditions of nuclear weapons (and stellar and planetary cores)

## Nuclear security



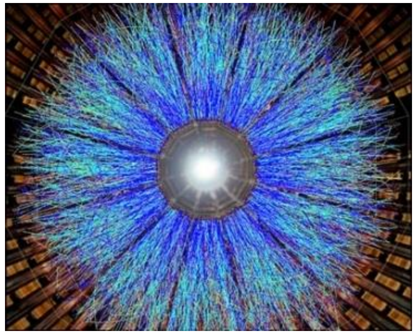
The dense plasma focus (LLNL) is an ultrafast high-fluence DD and DT neutron source

## Planetary / Space science



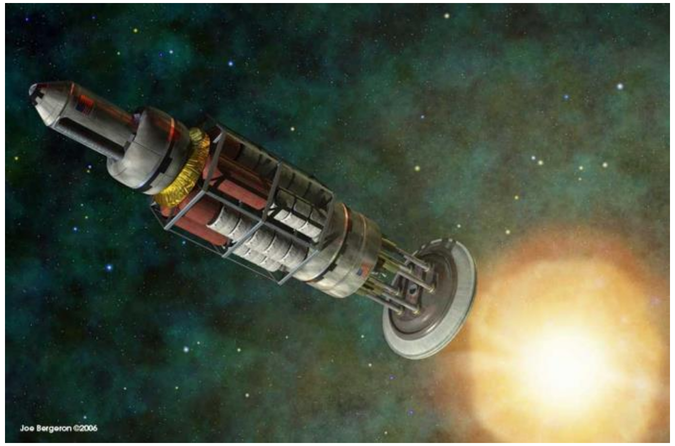
The levitated dipole experiment (MIT) created planetary like magnetic fields

## Cosmology



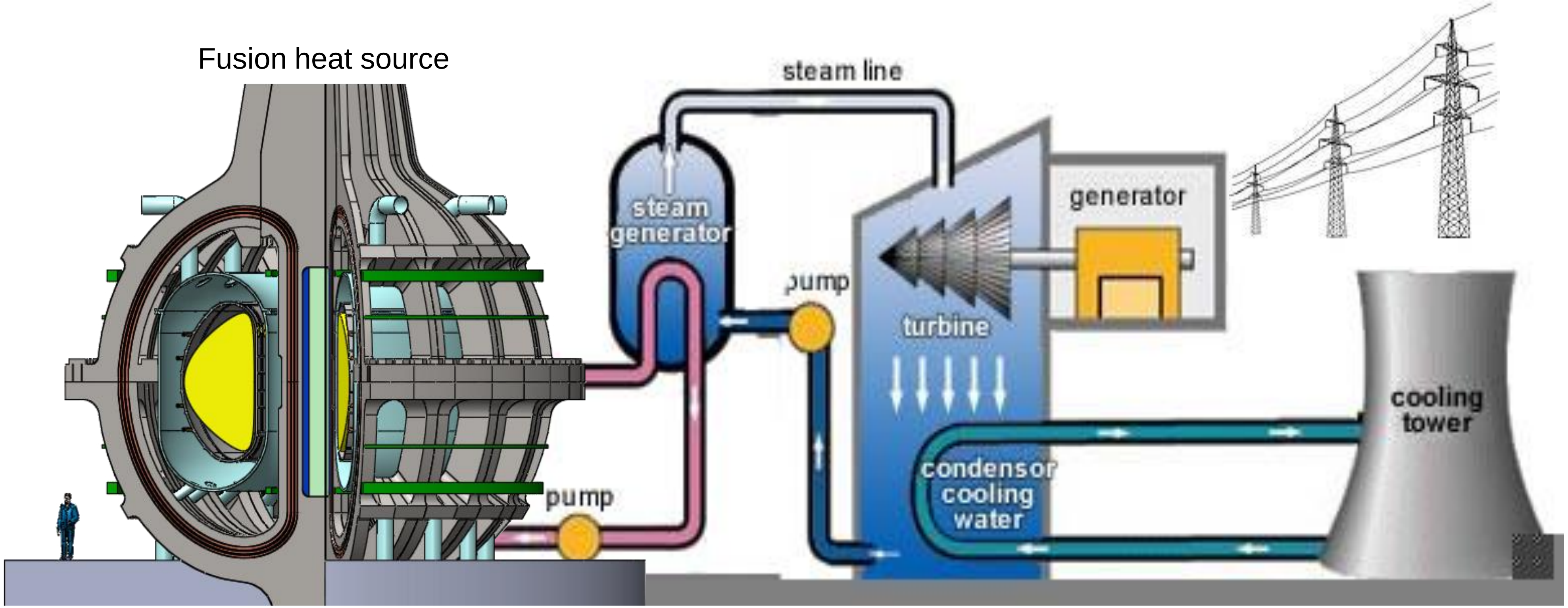
RHIC (BNL) creates the conditions of the early universe (quark gluon plasma)

## Space propulsion (maybe…)



Fusion rockets and nuclear weapons propulsion!

# … but I want to talk about fusion energy today.



Looks like any other power system, except the source of heat is fusion

# You should be able to speak knowledgeably about fusion energy!

There are so many topics that we could cover today; however, I'd like to focus this introductory lecture on two objectives:

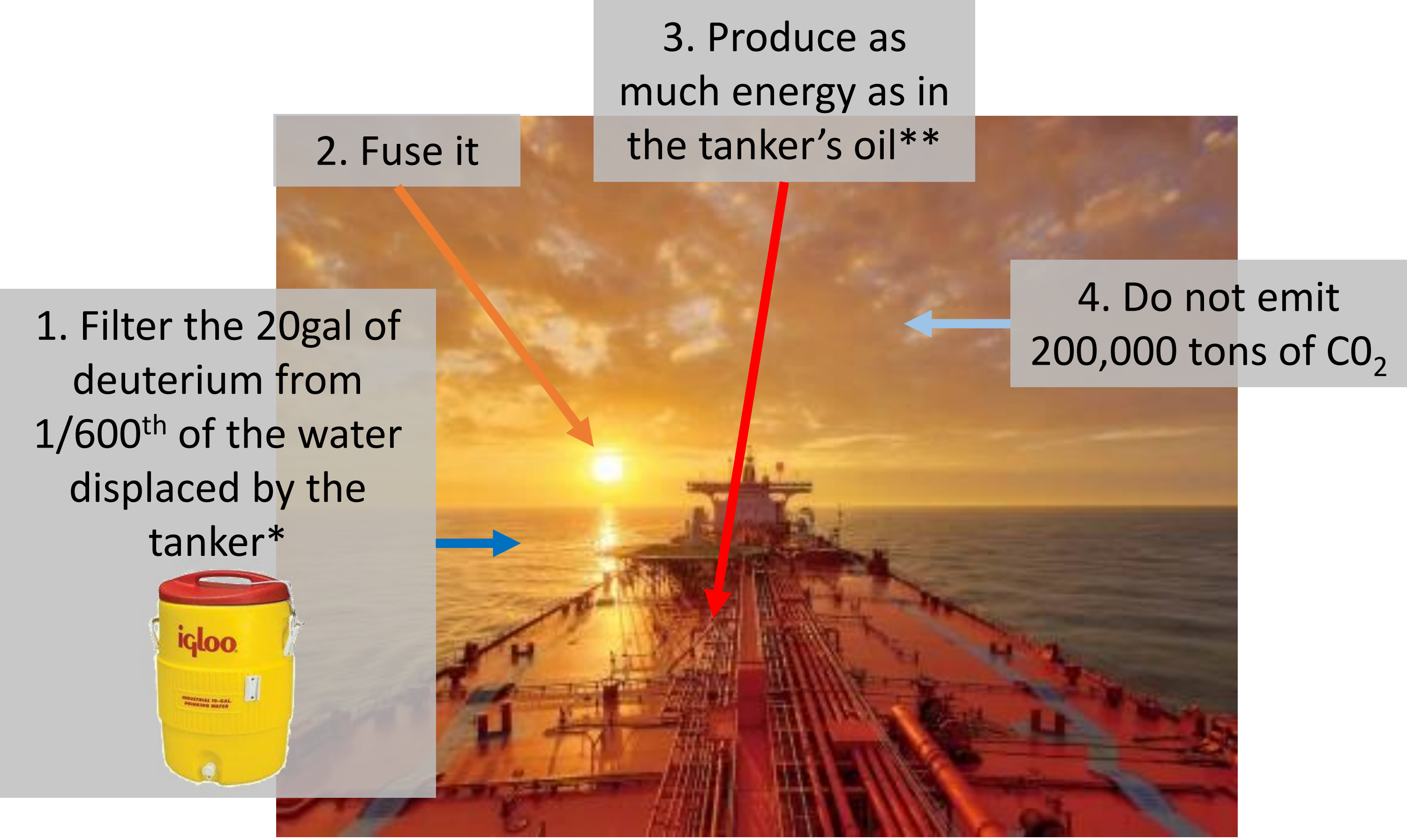
- *Primary:* Understand the basic technical foundation of fusion energy
- *Secondary:* Ensure that you can answer questions such as:
  - *"Why do we spend so much money on fusion energy research?"*
  - *"Where does the energy come from in fusion?"*
  - *"What is the fuel in a fusion energy power plant?"*
  - *"We can't we just use cold fusion? That's a thing, right?"*
  - *"I read about this fusion company in Time … are they for real?"*
  - *"Isn't most fusion research focused on nuclear weapons?"*
  - *"What's the most realistic approach to achieving fusion energy?"*

# Why fusion energy?

# Fusion has some key advantages over other energy sources

**Advantages of fusion over fossil fuels**:

- No carbon, SOx/NOx, particulate emissions
- Inexhaustible fuel supply
  - Thousands to millions of years
- Fuels equally accessible to all
- No large scale extraction or transport of fuels



1. Filter the 20gal of deuterium from 1/600th of the water displaced by the tanker*

2. Fuse it

3. Produce as much energy as in the tanker's oil**

4. Do not emit 200,000 tons of C0$_2$

*Or buy it for $200k

** $750M value

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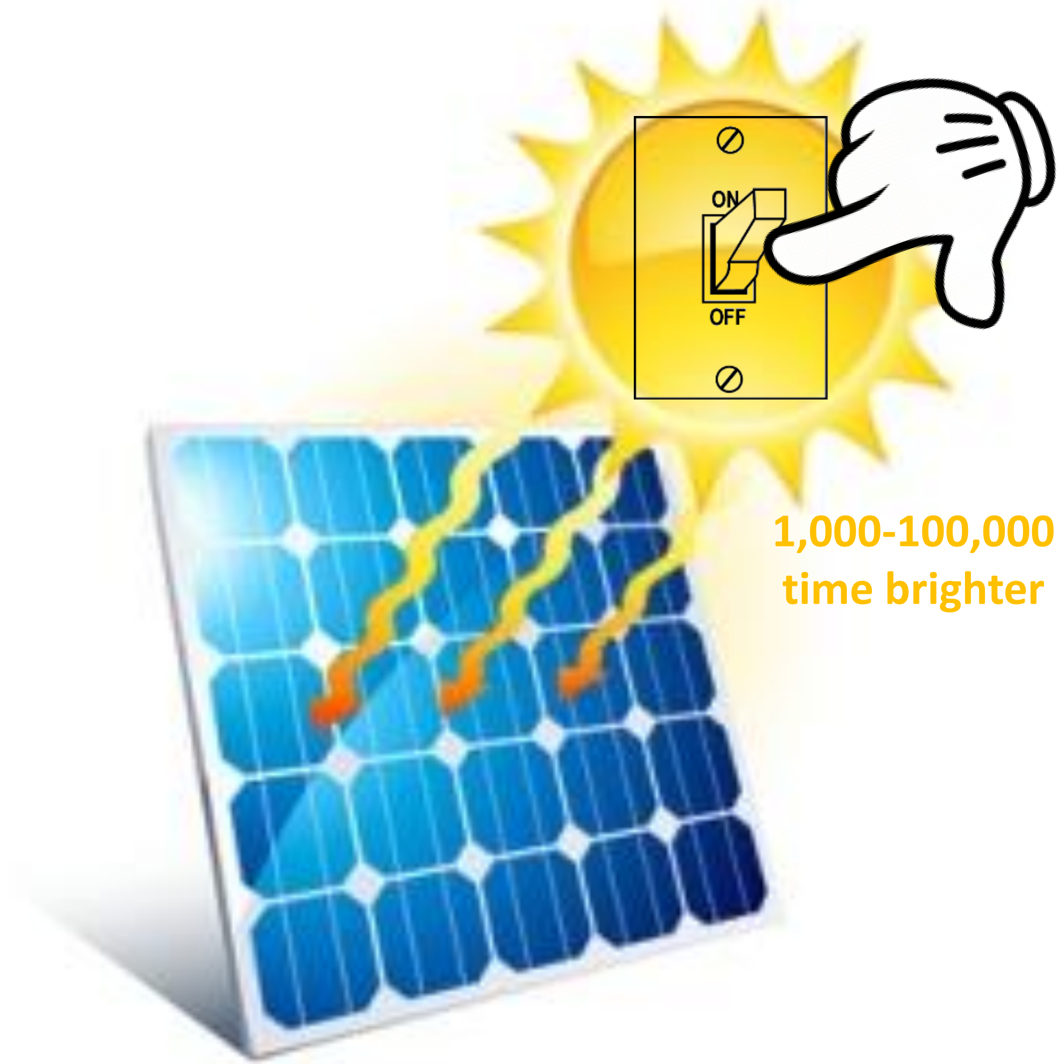
**Advantages of fusion over other renewables:**

- High power density land use
- High power density materials use
- On when it is wanted
- Site where it is needed
- Plugs into established grids



1,000-100,000 time brighter

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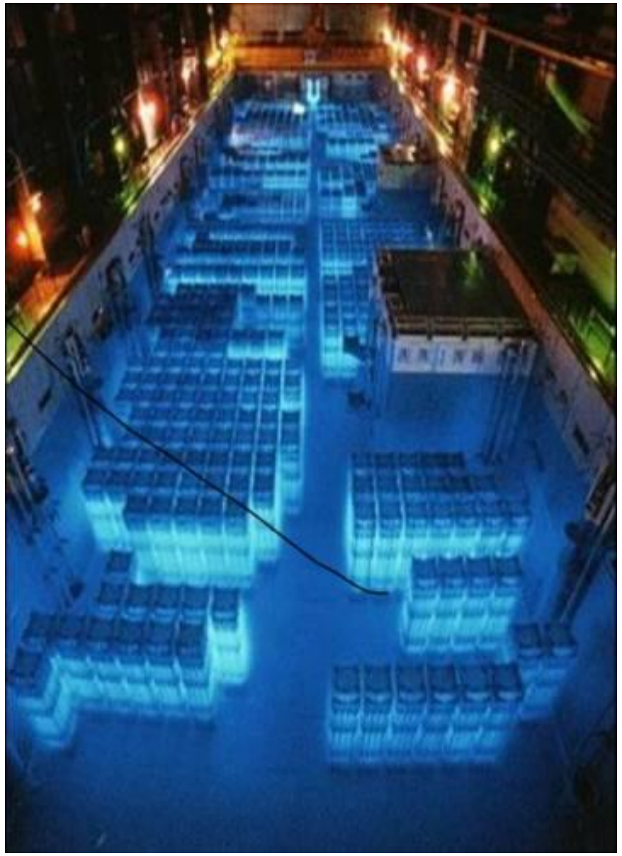
**Advantages of fusion over nuclear fission energy**:
- No chain reaction = no possibility of a melt down
- No long-lived nuclear waste for deep storage
  - Lower level activation of components
- Low proliferation risk
  - No need for fissile material (*e.g.* U, Pu)
  - Non-fusion clandestine use highly infeasible

**Fusion fuel cycle:**
Helium is the waste

Release to environment

**Fission fuel cycle:**
Transuranics are the waste



Actively cool for 5 years
Store for 10,000 years

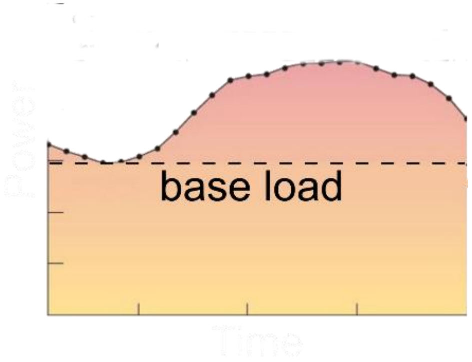
# The advantages of fusion energy are compelling …

Low carbon

Inexhaustible fuel

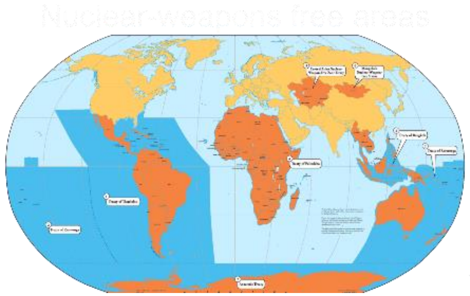
Deployable

Highly complementary

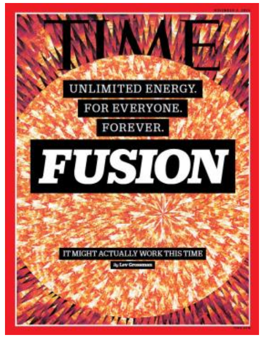


Load-following energy

Intrinsically safe



Zero fissile materials



Civilization-scale energy

"Unlimited energy
for everyone forever"

# … the disadvantages are obvious.

(It doesn’t work … yet!)

# How can I evaluate fusion energy?

# Fusion has some key advantages over other energy sources

Fusion is a fundamental process that combines two nuclei and releases energy. Its immense potential has driven research for 60 years…

**Advantages of fusion over fossil fuels**:

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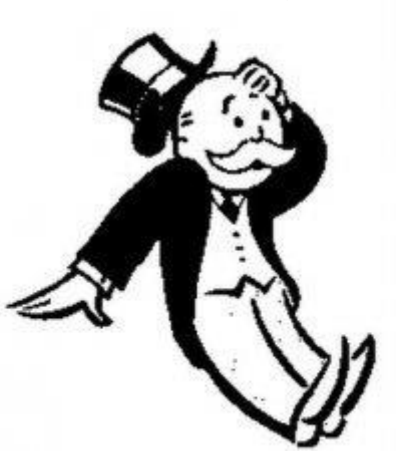
# The term “fusion energy” describes a basic physical process for producing energy; the complications come from the approach!

- Fusion is a fundamental process that combines two nuclei and releases energy. Its immense potential has driven research for 60 years…

- …but there are so many approaches to fusion energy that it can be extremely difficult to distinguish “winners” from “long-shots” from “losers”.
    - This is true of the layperson, interested reader, investor, students, and even fusion scientist themselves!



# The term “fusion energy” describes a basic physical process for producing energy; the complications come from the approach!

- Fusion is a fundamental process that combines two nuclei and releases energy. Its immense potential has driven research for 60 years…
- …but there are so many approaches to fusion energy that it can be extremely difficult to distinguish “winners” from “long-shots” from “losers”.
  - This is true of the layperson, interested reader, investor, students, and even fusion scientist themselves!
- The primary purpose of this talk is to give you tools to think critically about fusion energy, it’s opportunities and challenges

# We'll develop 3 rules as answers to 3 key questions – exploring the relevant physics as we go – and then put them to use.

Developing "The Rules" for assessing fusion energy concepts:

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

*Part 1* : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
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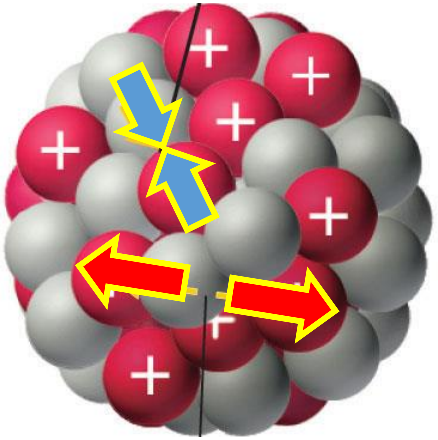
# Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy

- Protons and neutrons are held together in the nucleus by the **strong nuclear force**, which overcomes **Coulomb repulsion**

**Strong nuclear force**

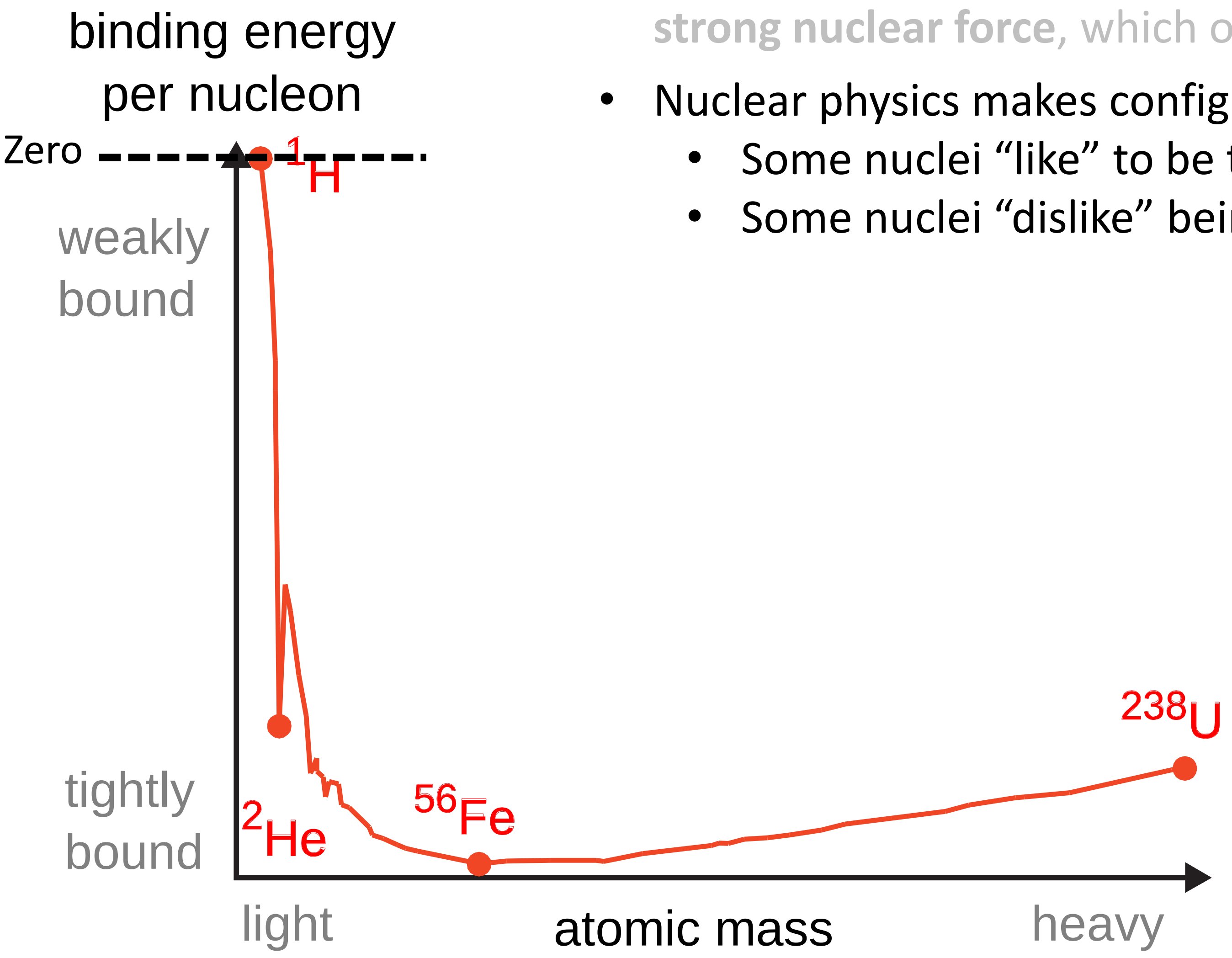
**n↔n n↔p p↔p**



**Coulomb repulsion**

**p↔p**

# Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy



- Protons and neutrons are held together in the nucleus by the **strong nuclear force**, which overcomes **Coulomb repulsion**
- Nuclear physics makes configurations of protons and neutrons different:
  - Some nuclei “like” to be together and require less “binding energy”
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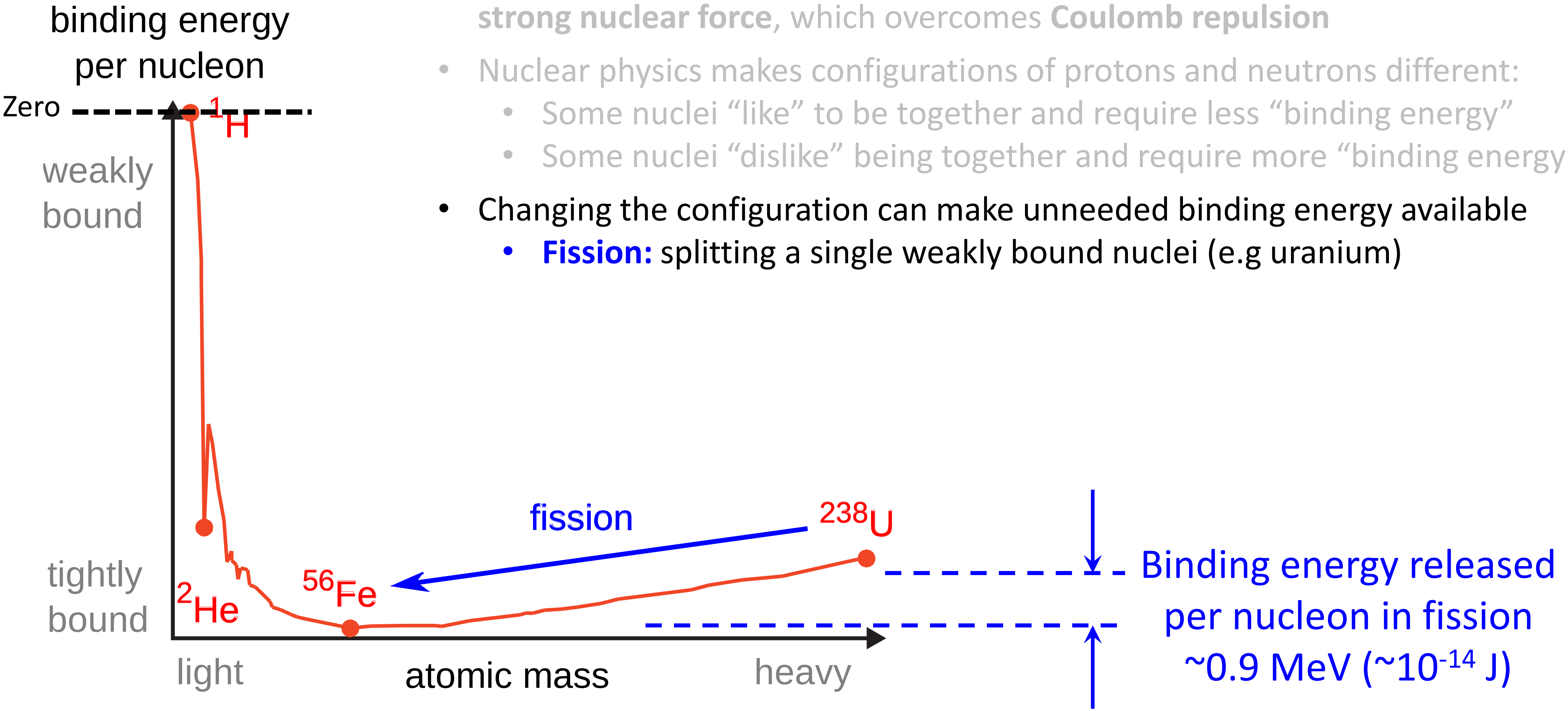
- Changing the configuration can make unneeded binding energy available
  - **Fission:** splitting a single weakly bound nuclei (e.g uranium)



Binding energy released per nucleon in fission ~0.9 MeV (~$10^{-14}$ J)

# Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy

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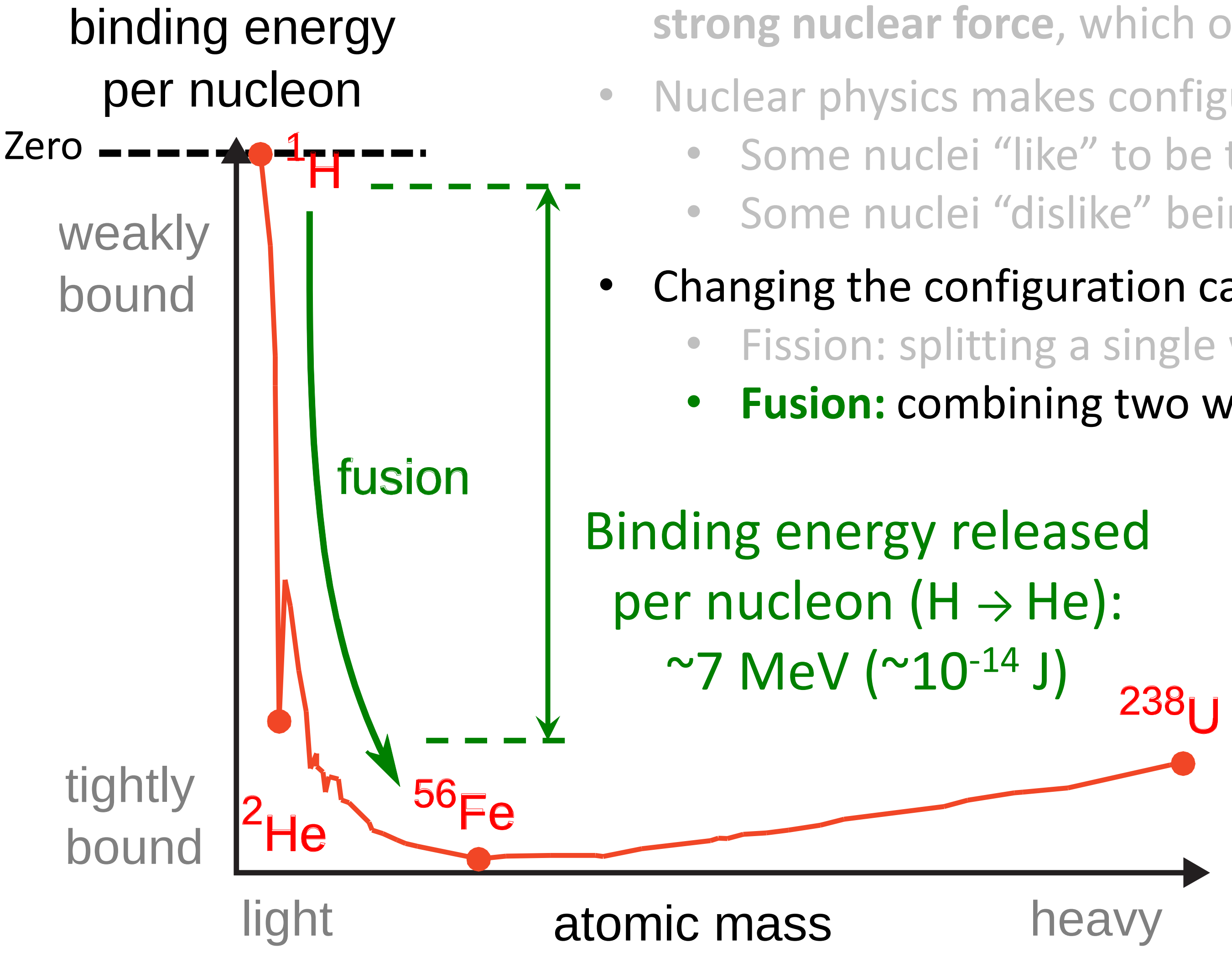
- Changing the configuration can make unneeded binding energy available
  - Fission: splitting a single weakly bound nuclei (*e.g* uranium)
  - **Fusion:** combining two weakly bound nuclei (*e.g.* hydrogen into helium)



Binding energy released per nucleon (H → He): ~7 MeV (~$10^{-14}$ J)

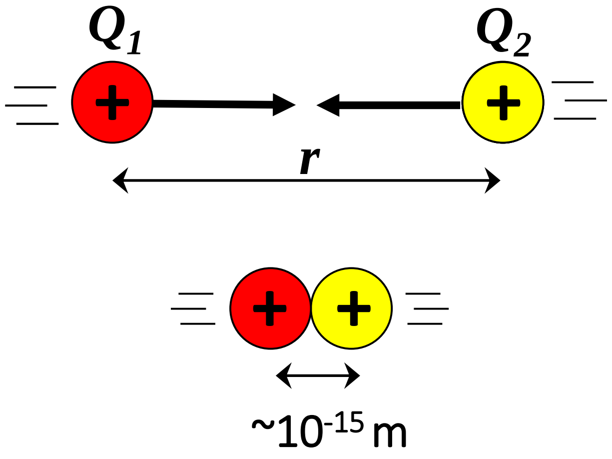
# Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

## Reaction energetics

**Input energy:**

The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$



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## Reaction energetics

**Input energy:**

The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

**Output energy:**

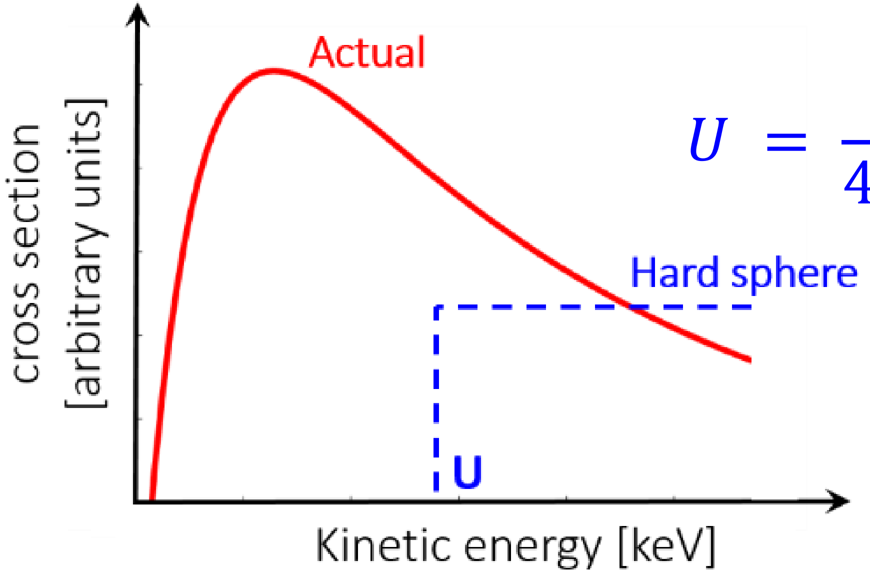
Energy released from reaction must not only be net positive but sufficiently large enough

# Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

## Reaction probability

**Fusion reaction cross section**

The probability that two nuclei will fuse must be sufficiently high. Probability is not simple but governed by quantum and nuclear physics



$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

# Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

## Reaction energetics

## Reaction probability

**The ideal fusion fuel will have:**

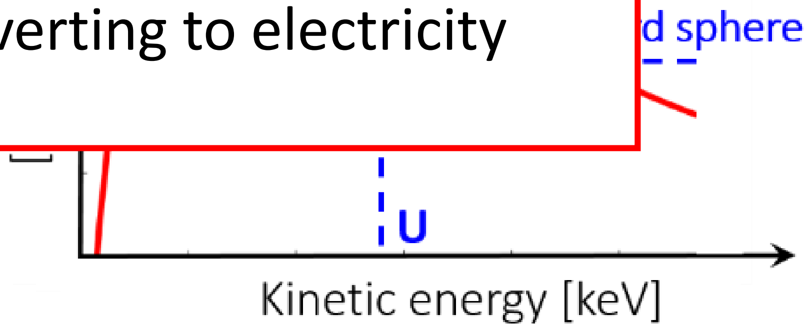
1. Low input energy to induce a fusion reaction
    - Technologically easier to achieve
    - Economically requires less input energy
2. A high probability of fusion
3. High output energy for converting to electricity

use must

simple

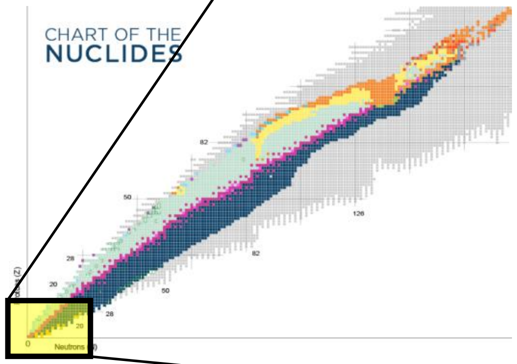
ar physics

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$



# Let’s take a closer look at combining nuclides and assess what combinations might be attractive for fusion fuels

**MIT PSFC**



🟩 **Theoretically feasible**
🟨 **Borderline**
🟥 **Not feasible**

Neglect:

- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion

Input nucleus 2

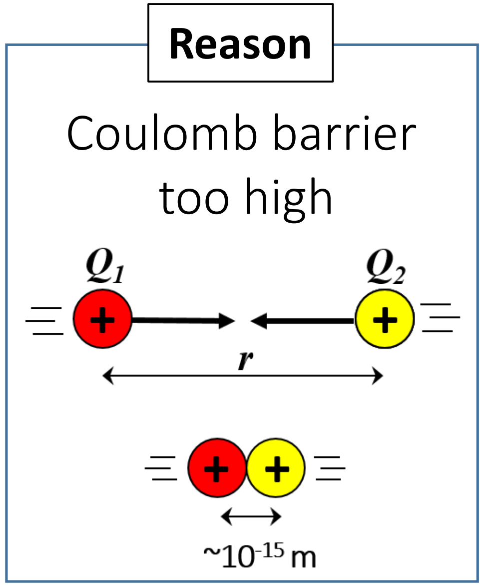
Input nucleus 1

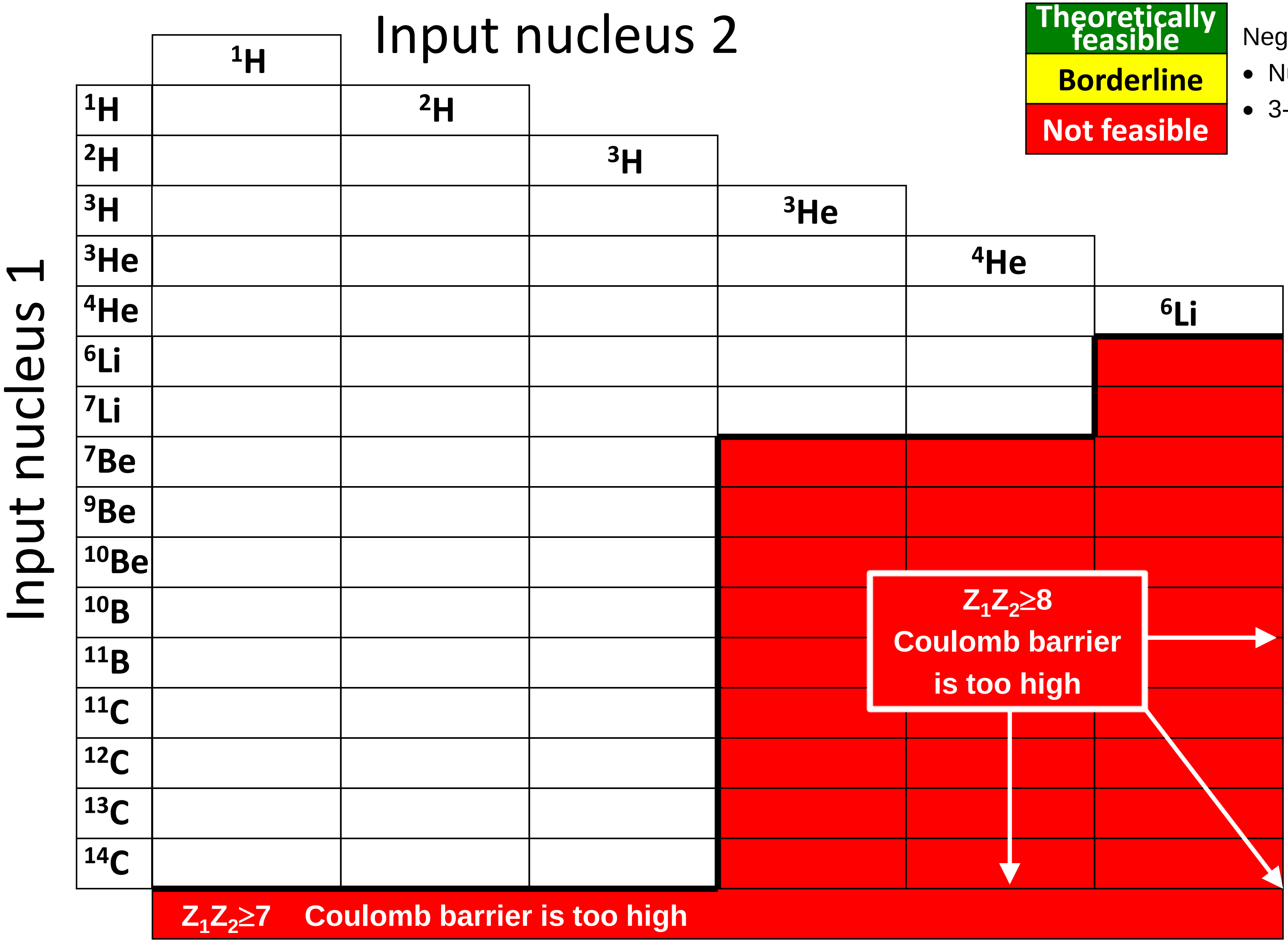
| | **$^{1}$H** | **$^{2}$H** | **$^{3}$H** | **$^{3}$He** | **$^{4}$He** | **$^{6}$Li** |
|---|---|---|---|---|---|---|
| **$^{1}$H** | | | | | | |
| **$^{2}$H** | | | | | | |
| **$^{3}$H** | | | | | | |
| **$^{3}$He** | | | | | | |
| **$^{4}$He** | | | | | | |
| **$^{6}$Li** | | | | | | |
| **$^{7}$Li** | | | | | | |
| **$^{7}$Be** | | | | | | |
| **$^{9}$Be** | | | | | | |
| **$^{10}$Be** | | | | | | |
| **$^{10}$B** | | | | | | |
| **$^{11}$B** | | | | | | |
| **$^{11}$C** | | | | | | |
| **$^{12}$C** | | | | | | |
| **$^{13}$C** | | | | | | |
| **$^{14}$C** | | | | | | |

# The fusion reaction energy and probability dramatically restrict viable fusion fuels

**Reason**

Coulomb barrier too high





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Input nucleus 1

| | $^{1}$H | $^{2}$H | $^{3}$H | $^{3}$He | $^{4}$He | $^{6}$Li |
|---|---|---|---|---|---|---|
| $^{1}$H | | | | | | |
| $^{2}$H | | | | | | |
| $^{3}$H | | | | | | |
| $^{3}$He | | | | | | |
| $^{4}$He | | | | | | |
| $^{6}$Li | | | | | | 🟥 |
| $^{7}$Li | | | | | | 🟥 |
| $^{7}$Be | | | | 🟥 | 🟥 | 🟥 |
| $^{9}$Be | | | | 🟥 | 🟥 | 🟥 |
| $^{10}$Be | | | | 🟥 | 🟥 | 🟥 |
| $^{10}$B | | | | 🟥 | 🟥 | 🟥 |
| $^{11}$B | | | | 🟥 | 🟥 | 🟥 |
| $^{11}$C | | | | 🟥 | 🟥 | 🟥 |
| $^{12}$C | | | | 🟥 | 🟥 | 🟥 |
| $^{13}$C | | | | 🟥 | 🟥 | 🟥 |
| $^{14}$C | | | | 🟥 | 🟥 | 🟥 |

**$Z_1Z_2\geq8$ Coulomb barrier is too high**

**$Z_1Z_2\geq7$ Coulomb barrier is too high**

- 🟩 **Theoretically feasible**
- 🟨 **Borderline**
- 🟥 **Not feasible**

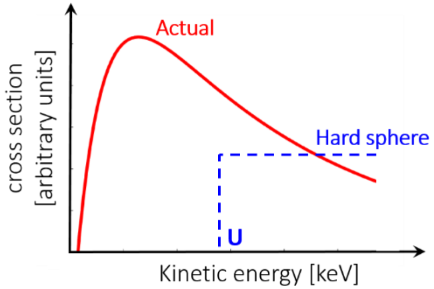
Neglect:

- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion

# The fusion reaction energy and probability dramatically restrict viable fusion fuels

**Reason**

Cross section too low



🟩 **Theoretically feasible**
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Neglect:

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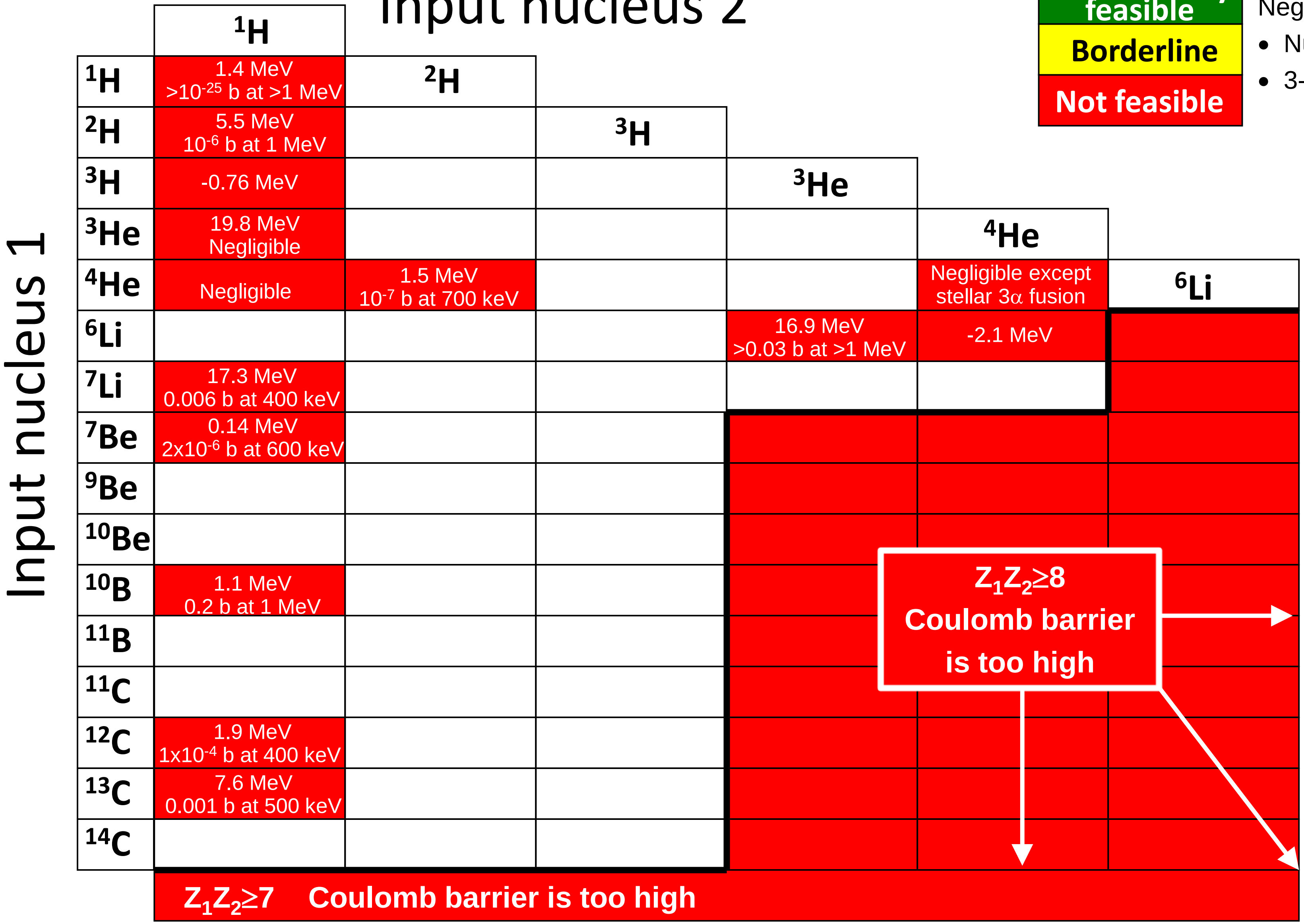
## Input nucleus 2



Input nucleus 1

| | **$^{1}$H** | | | | | |
|---|---|---|---|---|---|---|
| **$^{1}$H** | 🟥 1.4 MeV<br>>$10^{-25}$ b at >1 MeV | **$^{2}$H** | | | | |
| **$^{2}$H** | 🟥 5.5 MeV<br>$10^{-6}$ b at 1 MeV | | **$^{3}$H** | | | |
| **$^{3}$H** | 🟥 -0.76 MeV | | | **$^{3}$He** | | |
| **$^{3}$He** | 🟥 19.8 MeV<br>Negligible | | | | **$^{4}$He** | |
| **$^{4}$He** | 🟥 Negligible | 🟥 1.5 MeV<br>$10^{-7}$ b at 700 keV | | | 🟥 Negligible except stellar 3$\alpha$ fusion | **$^{6}$Li** |
| **$^{6}$Li** | | | | 🟥 16.9 MeV<br>>0.03 b at >1 MeV | 🟥 -2.1 MeV | 🟥 |
| **$^{7}$Li** | 🟥 17.3 MeV<br>0.006 b at 400 keV | | | | | 🟥 |
| **$^{7}$Be** | 🟥 0.14 MeV<br>2x$10^{-6}$ b at 600 keV | | | 🟥 | 🟥 | 🟥 |
| **$^{9}$Be** | | | | 🟥 | 🟥 | 🟥 |
| **$^{10}$Be** | | | | 🟥 | 🟥 | 🟥 |
| **$^{10}$B** | 🟥 1.1 MeV<br>0.2 b at 1 MeV | | | 🟥 | 🟥 | 🟥 |
| **$^{11}$B** | | | | 🟥 | 🟥 | 🟥 |
| **$^{11}$C** | | | | 🟥 | 🟥 | 🟥 |
| **$^{12}$C** | 🟥 1.9 MeV<br>1x$10^{-4}$ b at 400 keV | | | 🟥 | 🟥 | 🟥 |
| **$^{13}$C** | 🟥 7.6 MeV<br>0.001 b at 500 keV | | | 🟥 | 🟥 | 🟥 |
| **$^{14}$C** | | | | 🟥 | 🟥 | 🟥 |

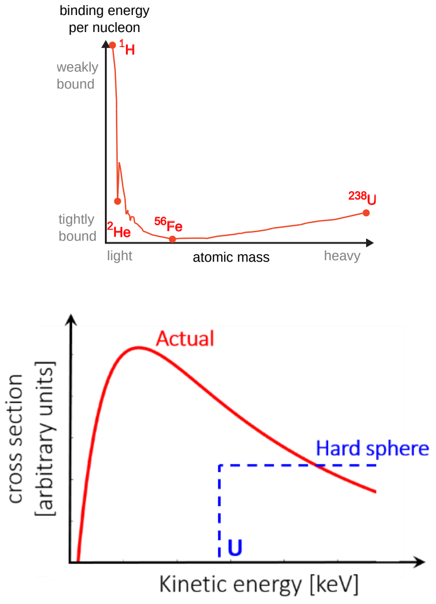
**$Z_1Z_2\geq8$ Coulomb barrier is too high**

**$Z_1Z_2\geq7$ Coulomb barrier is too high**

# The fusion reaction energy and probability dramatically restrict viable fusion fuels

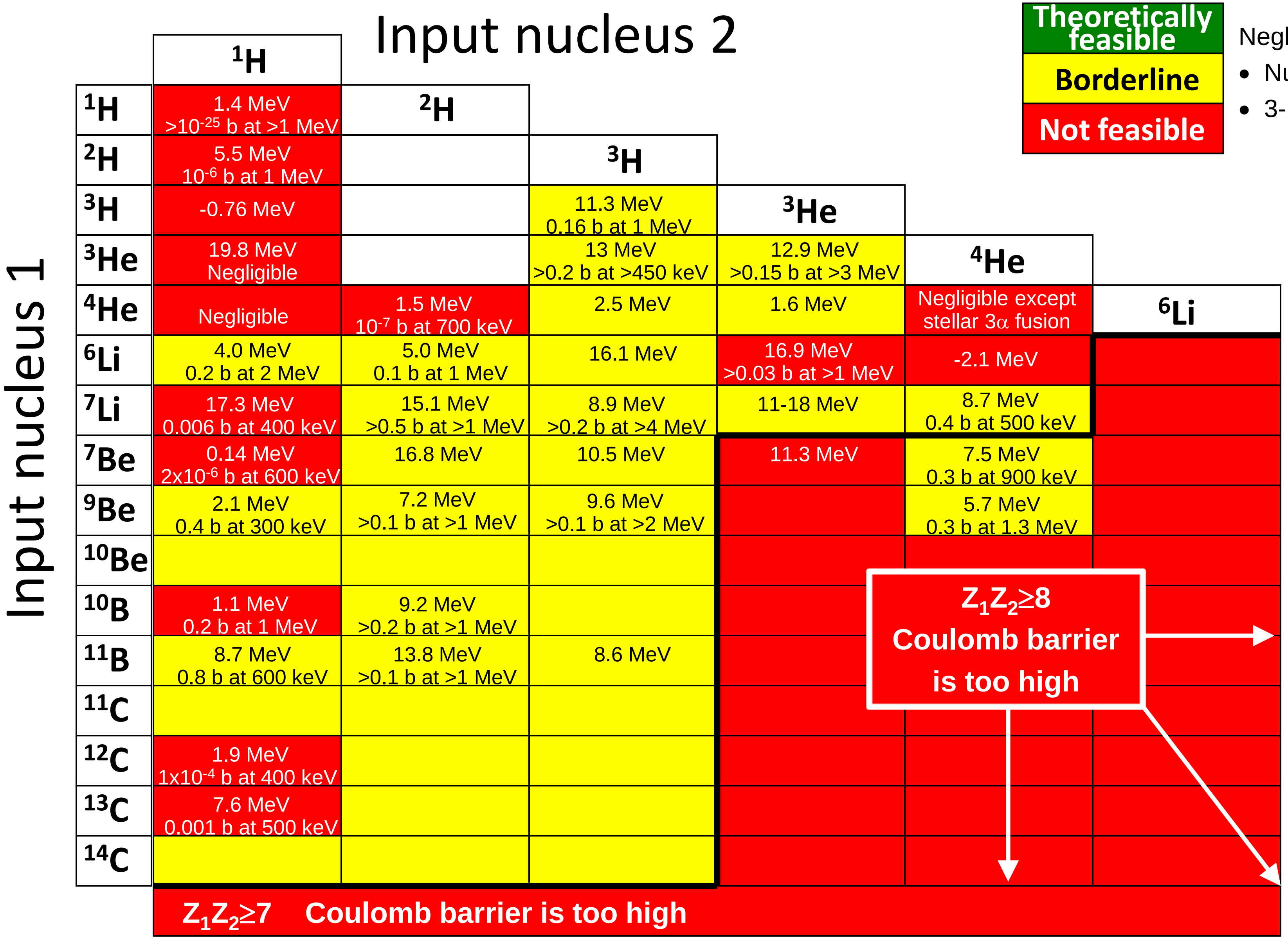
**Reason**

Energy out + cross section are weak



| | |
|---|---|
| 🟩 | **Theoretically feasible** |
| 🟨 | **Borderline** |
| 🟥 | **Not feasible** |

Neglect:
- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion



Input nucleus 2

Input nucleus 1

| | $^{1}$H | $^{2}$H | $^{3}$H | $^{3}$He | $^{4}$He | $^{6}$Li |
|---|---|---|---|---|---|---|
| $^{1}$H | 🟥 1.4 MeV<br>$>10^{-25}$ b at >1 MeV | | | | | |
| $^{2}$H | 🟥 5.5 MeV<br>$10^{-6}$ b at 1 MeV | | | | | |
| $^{3}$H | 🟥 -0.76 MeV | | 🟨 11.3 MeV<br>0.16 b at 1 MeV | | | |
| $^{3}$He | 🟥 19.8 MeV<br>Negligible | | 🟨 13 MeV<br>>0.2 b at >450 keV | 🟨 12.9 MeV<br>>0.15 b at >3 MeV | | |
| $^{4}$He | 🟥 Negligible | 🟥 1.5 MeV<br>$10^{-7}$ b at 700 keV | 🟨 2.5 MeV | 🟨 1.6 MeV | 🟥 Negligible except stellar 3α fusion | |
| $^{6}$Li | 🟨 4.0 MeV<br>0.2 b at 2 MeV | 🟨 5.0 MeV<br>0.1 b at 1 MeV | 🟨 16.1 MeV | 🟥 16.9 MeV<br>>0.03 b at >1 MeV | 🟥 -2.1 MeV | 🟥 |
| $^{7}$Li | 🟥 17.3 MeV<br>0.006 b at 400 keV | 🟨 15.1 MeV<br>>0.5 b at >1 MeV | 🟨 8.9 MeV<br>>0.2 b at >4 MeV | 🟨 11-18 MeV | 🟨 8.7 MeV<br>0.4 b at 500 keV | 🟥 |
| $^{7}$Be | 🟥 0.14 MeV<br>$2x10^{-6}$ b at 600 keV | 🟨 16.8 MeV | 🟨 10.5 MeV | 🟥 11.3 MeV | 🟨 7.5 MeV<br>0.3 b at 900 keV | 🟥 |
| $^{9}$Be | 🟨 2.1 MeV<br>0.4 b at 300 keV | 🟨 7.2 MeV<br>>0.1 b at >1 MeV | 🟨 9.6 MeV<br>>0.1 b at >2 MeV | 🟥 | 🟨 5.7 MeV<br>0.3 b at 1.3 MeV | 🟥 |
| $^{10}$Be | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{10}$B | 🟥 1.1 MeV<br>0.2 b at 1 MeV | 🟨 9.2 MeV<br>>0.2 b at >1 MeV | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{11}$B | 🟨 8.7 MeV<br>0.8 b at 600 keV | 🟨 13.8 MeV<br>>0.1 b at >1 MeV | 🟨 8.6 MeV | 🟥 | 🟥 | 🟥 |
| $^{11}$C | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{12}$C | 🟥 1.9 MeV<br>$1x10^{-4}$ b at 400 keV | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{13}$C | 🟥 7.6 MeV<br>0.001 b at 500 keV | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{14}$C | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |

**$Z_1Z_2 \geq 8$ Coulomb barrier is too high**

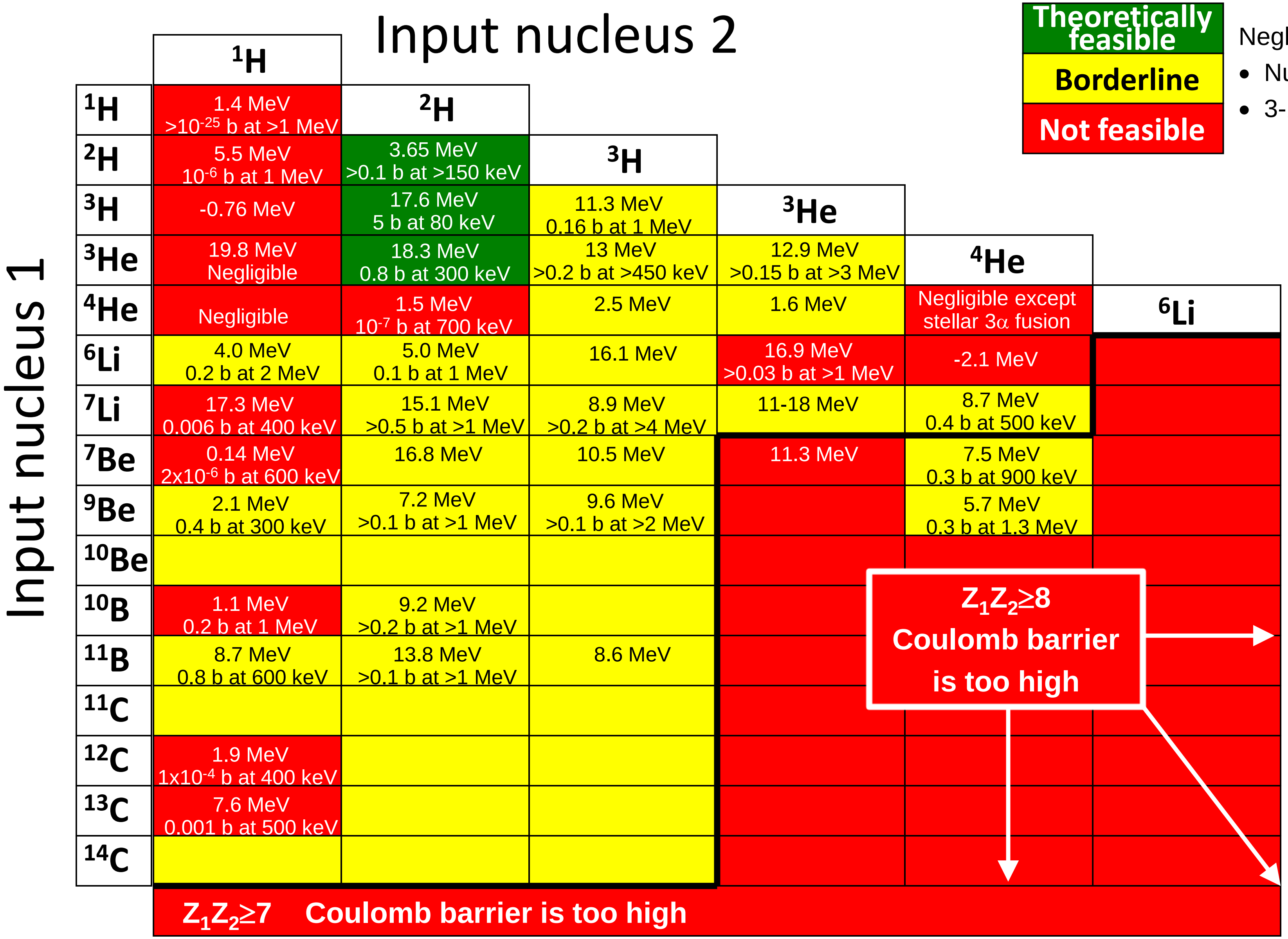
**$Z_1Z_2 \geq 7$ Coulomb barrier is too high**

# The fusion reaction energy and probability dramatically restrict viable fusion fuels: only ~0.2% of all known isotopes even approach viability!

**MIT PSFC**

- 🟩 **Theoretically feasible**
- 🟨 **Borderline**
- 🟥 **Not feasible**

Neglect:
- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion



## Input nucleus 2

| Input nucleus 1 | $^{1}$H | $^{2}$H | $^{3}$H | $^{3}$He | $^{4}$He | $^{6}$Li |
|---|---|---|---|---|---|---|
| $^{1}$H | 🟥 1.4 MeV<br>$>10^{-25}$ b at >1 MeV | | | | | |
| $^{2}$H | 🟥 5.5 MeV<br>$10^{-6}$ b at 1 MeV | 🟩 3.65 MeV<br>>0.1 b at >150 keV | | | | |
| $^{3}$H | 🟥 -0.76 MeV | 🟩 17.6 MeV<br>5 b at 80 keV | 🟨 11.3 MeV<br>0.16 b at 1 MeV | | | |
| $^{3}$He | 🟥 19.8 MeV<br>Negligible | 🟩 18.3 MeV<br>0.8 b at 300 keV | 🟨 13 MeV<br>>0.2 b at >450 keV | 🟨 12.9 MeV<br>>0.15 b at >3 MeV | | |
| $^{4}$He | 🟥 Negligible | 🟥 1.5 MeV<br>$10^{-7}$ b at 700 keV | 🟨 2.5 MeV | 🟨 1.6 MeV | 🟥 Negligible except stellar 3α fusion | |
| $^{6}$Li | 🟨 4.0 MeV<br>0.2 b at 2 MeV | 🟨 5.0 MeV<br>0.1 b at 1 MeV | 🟨 16.1 MeV | 🟥 16.9 MeV<br>>0.03 b at >1 MeV | 🟥 -2.1 MeV | 🟥 |
| $^{7}$Li | 🟥 17.3 MeV<br>0.006 b at 400 keV | 🟨 15.1 MeV<br>>0.5 b at >1 MeV | 🟨 8.9 MeV<br>>0.2 b at >4 MeV | 🟨 11-18 MeV | 🟨 8.7 MeV<br>0.4 b at 500 keV | 🟥 |
| $^{7}$Be | 🟥 0.14 MeV<br>$2\times10^{-6}$ b at 600 keV | 🟨 16.8 MeV | 🟨 10.5 MeV | 🟥 11.3 MeV | 🟨 7.5 MeV<br>0.3 b at 900 keV | 🟥 |
| $^{9}$Be | 🟨 2.1 MeV<br>0.4 b at 300 keV | 🟨 7.2 MeV<br>>0.1 b at >1 MeV | 🟨 9.6 MeV<br>>0.1 b at >2 MeV | 🟥 | 🟨 5.7 MeV<br>0.3 b at 1.3 MeV | 🟥 |
| $^{10}$Be | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{10}$B | 🟥 1.1 MeV<br>0.2 b at 1 MeV | 🟨 9.2 MeV<br>>0.2 b at >1 MeV | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{11}$B | 🟨 8.7 MeV<br>0.8 b at 600 keV | 🟨 13.8 MeV<br>>0.1 b at >1 MeV | 🟨 8.6 MeV | 🟥 | 🟥 | 🟥 |
| $^{11}$C | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{12}$C | 🟥 1.9 MeV<br>$1\times10^{-4}$ b at 400 keV | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{13}$C | 🟥 7.6 MeV<br>0.001 b at 500 keV | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |
| $^{14}$C | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 |

**$Z_1Z_2\geq8$ Coulomb barrier is too high**

**$Z_1Z_2\geq7$ Coulomb barrier is too high**

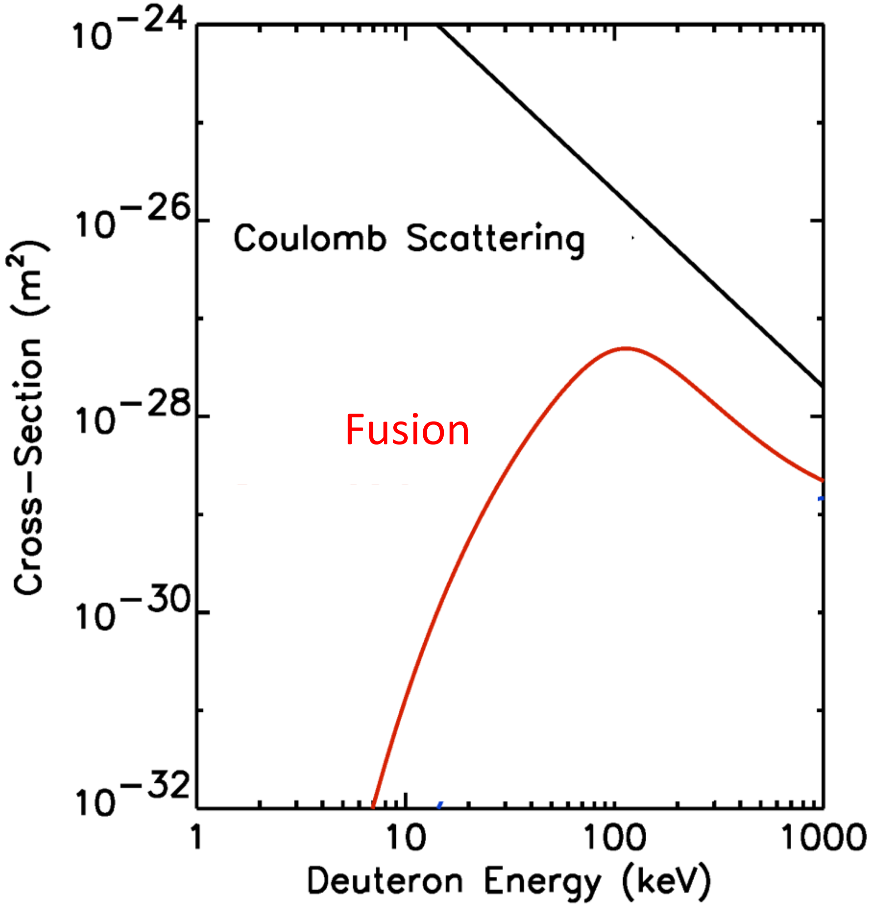
# Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy.

| Fuel (Input) | Exhaust (output) | Energy gain (MeV) | Cross section (barn) |
|---|---|---|---|
| D + T | $^{4}He + n$ | 17.6 | 5.0 @ 80 keV |
| D + D | T + p (50%)<br>$^{3}He + n$ (50%) | 3.7 | 0.1 @ 150 keV |
| $D + {}^{3}He$ | $^{4}He + p$ | 18.3 | 0.8 @ 300 keV |
| $p + {}^{11}B$ | $3\ {}^{4}He$ | 8.7 | 0.8 @ 600 keV |

# Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

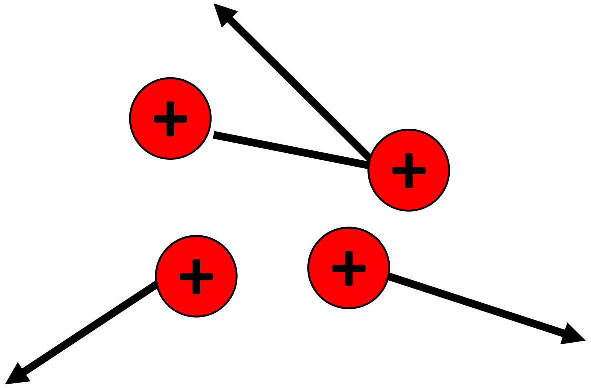
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

The bane of fusion energy

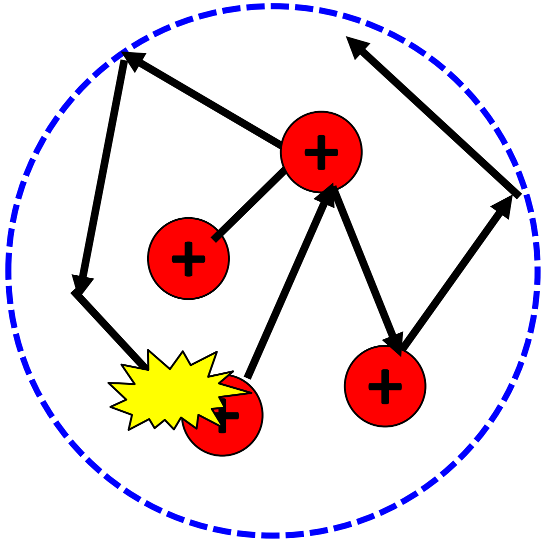


# Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions
- Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this "confinement".



**No confinement:**
- Particles scatter and are lost
- No fusion occurs



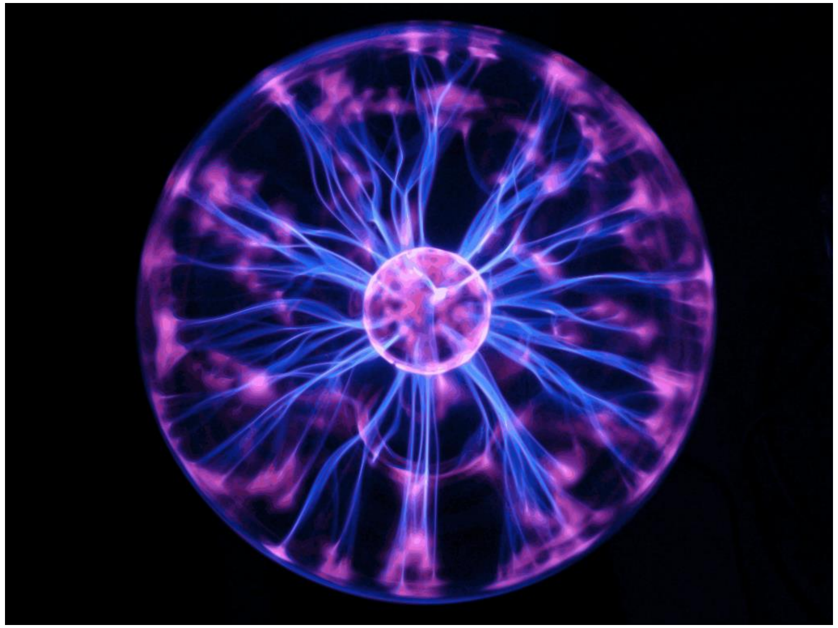
**Ideal confinement**
- Who cares if particles scatter?
- Fusion occurs eventually

# Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

- Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this “confinement”.

- Confinement of particles at these energies creates the conditions of a plasma
    - Ionized gas (“fluids” of electrons and ions)
    - Dominated by collective behavior
    - Energy of the system is best described as a temperature



# Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required temperature

| Rank | Fuel (Input) | Exhaust (output) | Energy gain (MeV) | Peak reactivity [$m^{-3}$ $s^{-1}$] | Temperature [K / C / F] |
|---|---|---|---|---|---|
| 1 | D + T | $^4$He + n | 17.6 | 1x10$^{-18}$ @ 15 keV | **175,000,000** |
| 2 | D + D | T + p (50%)<br>$^3$He + n (50%) | 3.7 | 1x10$^{-20}$ @ 20 keV | **232,000,000** |
| 3 | D + $^3$He | $^4$He + p | 18.3 | 2x10$^{-20}$ @ 50 keV | **580,000,000** |
| 4 | p + $^{11}$B | 3 $^4$He | 8.7 | 3x10$^{-21}$ @ 150 keV | **1,740,000,000** |

**Primary condition:** the required temperature must be practically achievable

- This turns out to be so important as to determine the ranking

# Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy

| Rank | Fuel (Input) | Exhaust (output) | Energy gain (MeV) | Peak reactivity [$m^{-3}$ $s^{-1}$] |
|---|---|---|---|---|
| 1 | D + T | $^4$He + n | 17.6 | $1 \times 10^{-18}$ @ 15 keV |
| 2 | D + D | T + p (50%)<br>$^3$He + n (50%) | 3.7 | $1 \times 10^{-20}$ @ 20 keV |
| 3 | D + $^3$He | $^4$He + p | 18.3 | $2 \times 10^{-20}$ @ 50 keV |
| 4 | p + $^{11}$B | 3 $^4$He | 8.7 | $3 \times 10^{-21}$ @ 150 keV |

**Primary condition:** the required temperature must be practically achievable

- This turns out to be so important as to determine the ranking

**Secondary condition:** the reactivity and energy gain must be large

- These conditions are necessary but not sufficient

# Q1: What are the viable fusion fuels and how do they affect the approach?

**Rule 1**

Fuel choice fundamentally sets the difficulty of any approach to fusion energy

*D-T fuel is the easiest by far.*
*D-D and D-$^{3}$He increasingly difficulty.*
*p-$^{11}$B possibly infeasible; other fuels are not viable.*

**Questions you should ask:**

*"What fusion fuel are they using? Do they acknowledge difficulties?"*
*"How do they propose conversion to electricity?"*
*"How mature and demonstrated is this technology?"*

*Part 1* : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

*Part 2* : MIT's accelerated pathway to demonstrate net fusion energy

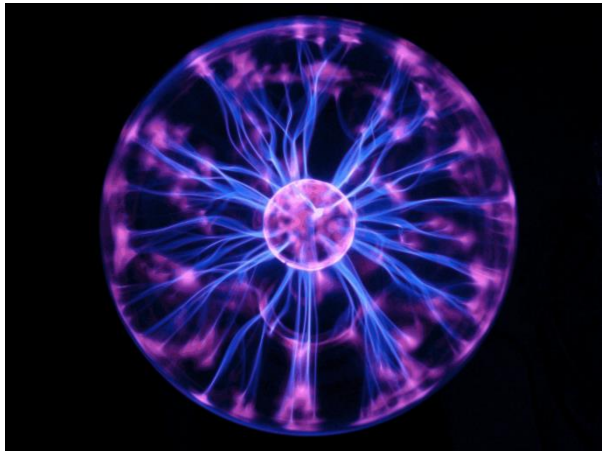
# The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release)

Wood density

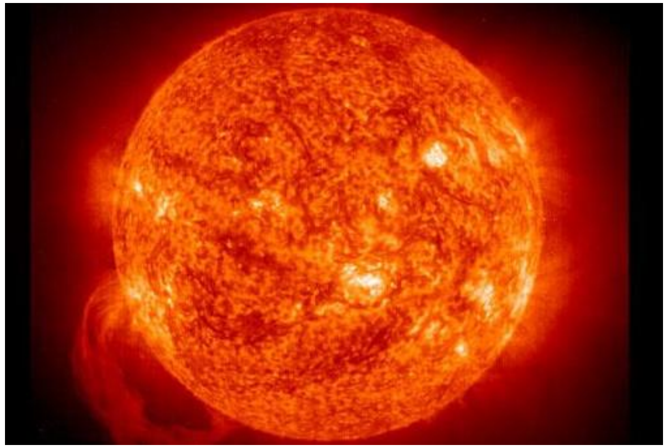
Wood temperature

Energy confinement

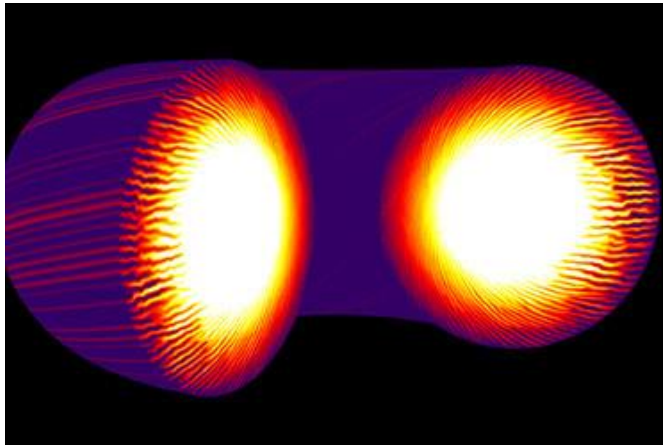
# The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release)



Plasma density



Plasma temperature

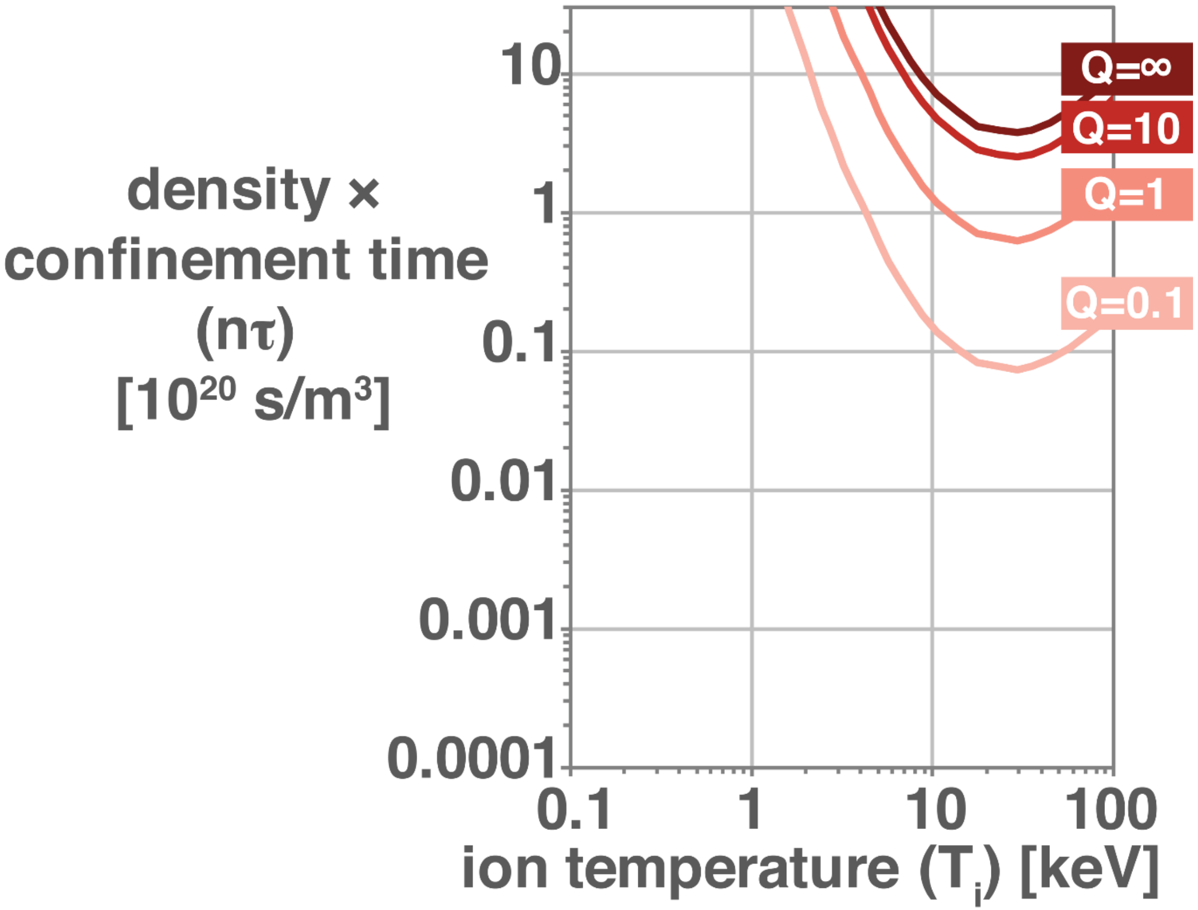


Energy confinement

$$n \times T \times \tau_E$$

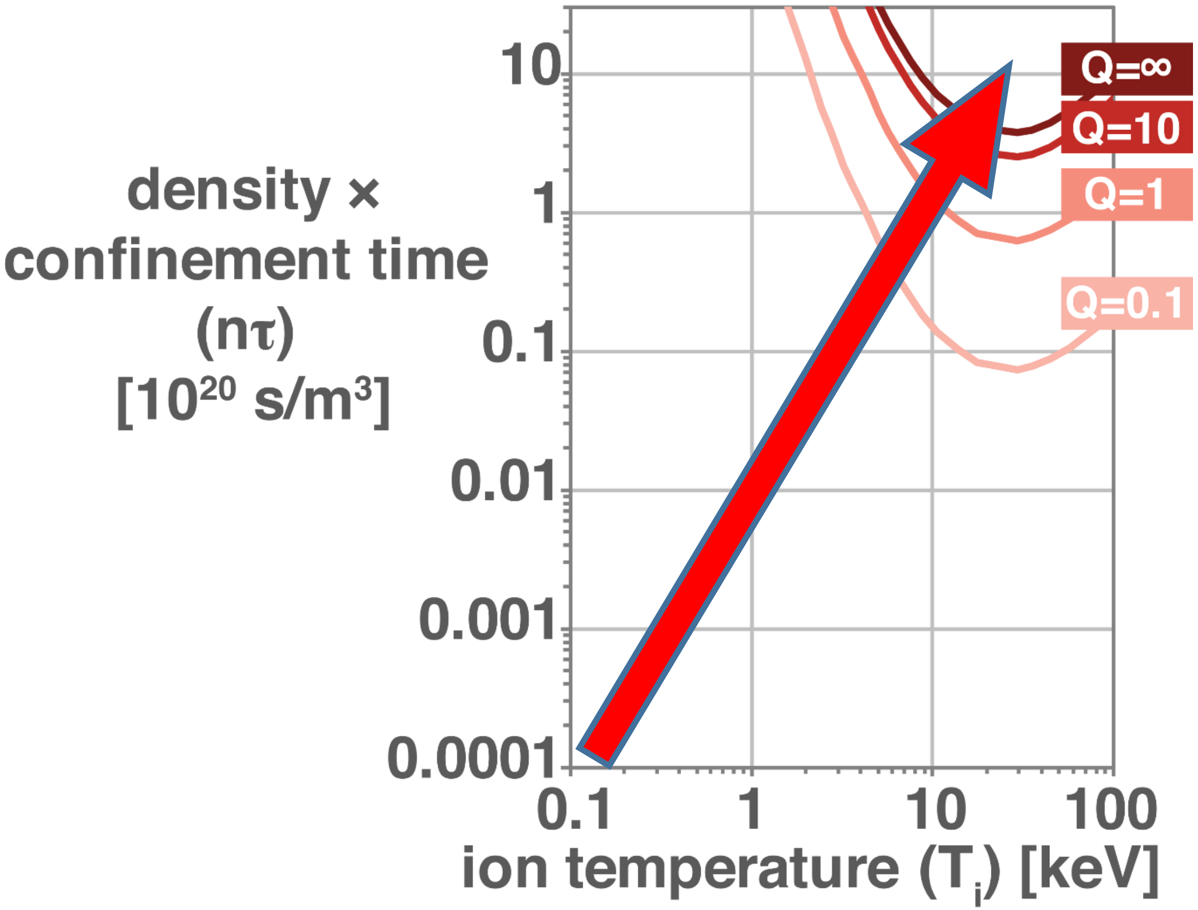
The three things required for fusion energy … known since 1955!

# Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions



$$Q = \frac{Fusion\ energy\ output}{Energy\ input}$$

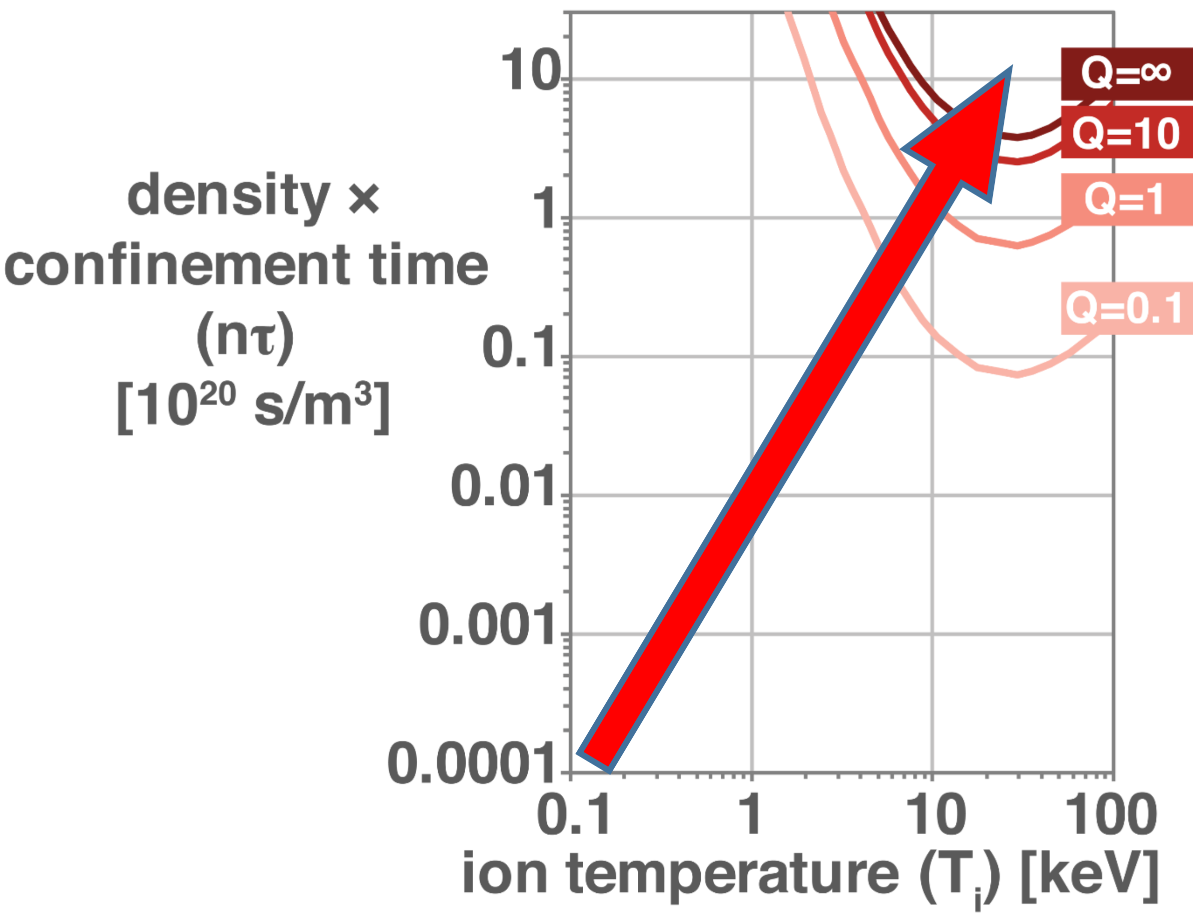
# Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions



Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years …

# Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

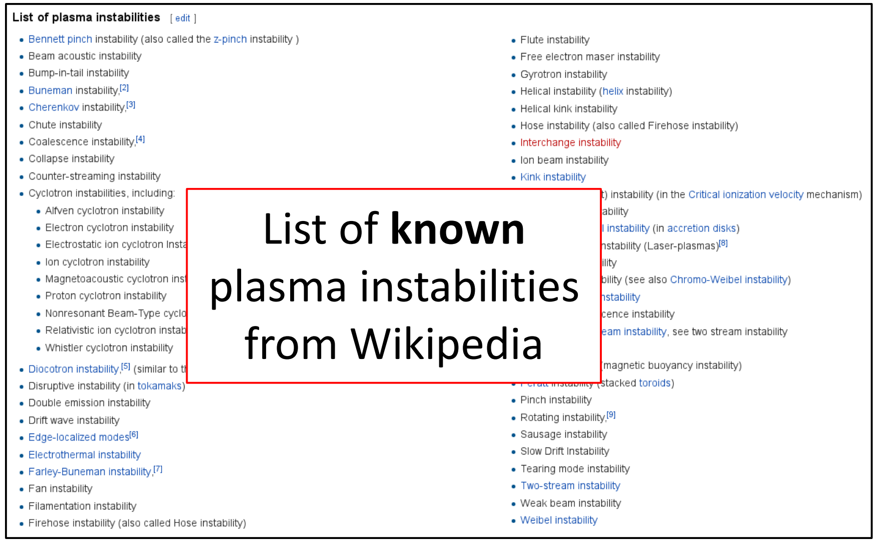
Be **very** wary of extrapolation
in this space …



Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years …

This turns out to be enormously difficult

- Moving orders of magnitude in dimensional, absolute parameters
- Unknown unknowns (plasma instabilities) wait to destroy your fusion energy dreams

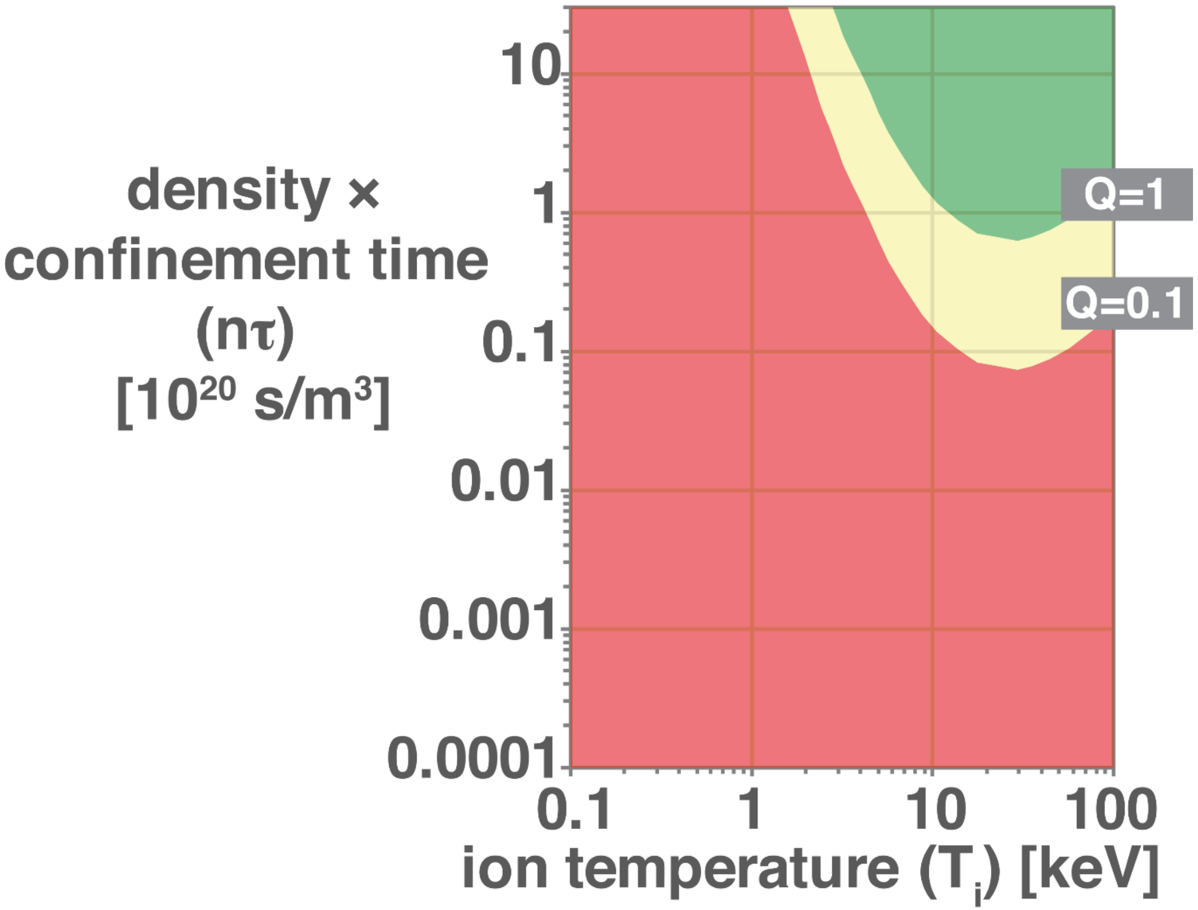


**List of plasma instabilities** [ edit ]

- Bennett pinch instability (also called the z-pinch instability )
- Beam acoustic instability
- Bump-in-tail instability
- Buneman instability,[2]
- Cherenkov instability,[3]
- Chute instability
- Coalescence instability,[4]
- Collapse instability
- Counter-streaming instability
- Cyclotron instabilities, including:
  - Alfven cyclotron instability
  - Electron cyclotron instability
  - Electrostatic ion cyclotron Insta
  - Ion cyclotron instability
  - Magnetoacoustic cyclotron inst
  - Proton cyclotron instability
  - Nonresonant Beam-Type cyclo
  - Relativistic ion cyclotron instab
  - Whistler cyclotron instability
- Diocotron instability,[5] (similar to t
- Disruptive instability (in tokamaks)
- Double emission instability
- Drift wave instability
- Edge-localized modes[6]
- Electrothermal instability
- Farley-Buneman instability,[7]
- Fan instability
- Filamentation instability
- Firehose instability (also called Hose instability)
- Flute instability
- Free electron maser instability
- Gyrotron instability
- Helical instability (helix instability)
- Helical kink instability
- Hose instability (also called Firehose instability)
- Interchange instability
- Ion beam instability
- Kink instability
- t) instability (in the Critical ionization velocity mechanism)
- ability
- l instability (in accretion disks)
- nstability (Laser-plasmas)[8]
- ility
- bility (see also Chromo-Weibel instability)
- nstability
- cence instability
- eam instability, see two stream instability
- (magnetic buoyancy instability)
- instability (stacked toroids)
- Pinch instability
- Rotating instability,[9]
- Sausage instability
- Slow Drift Instability
- Tearing mode instability
- Two-stream instability
- Weak beam instability
- Weibel instability

List of **known** plasma instabilities from Wikipedia

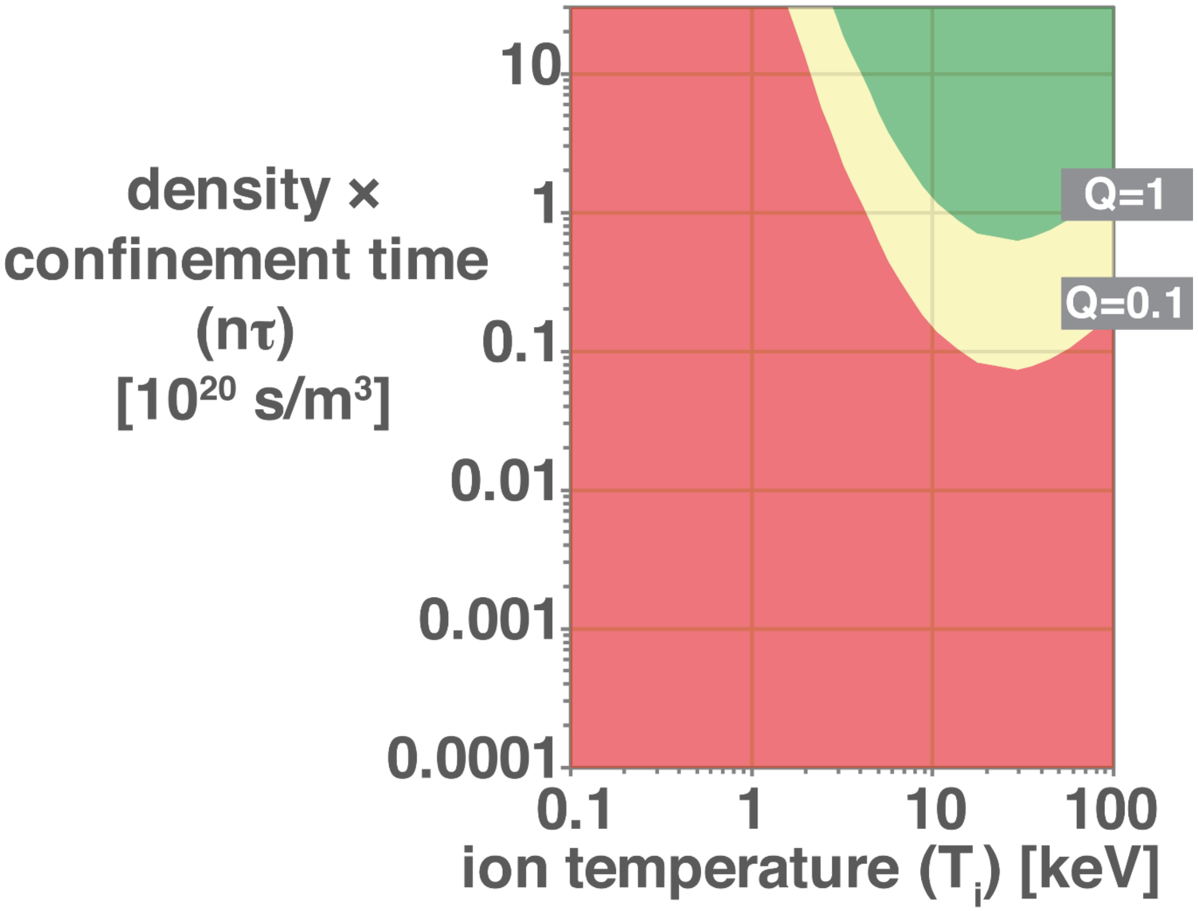
# Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

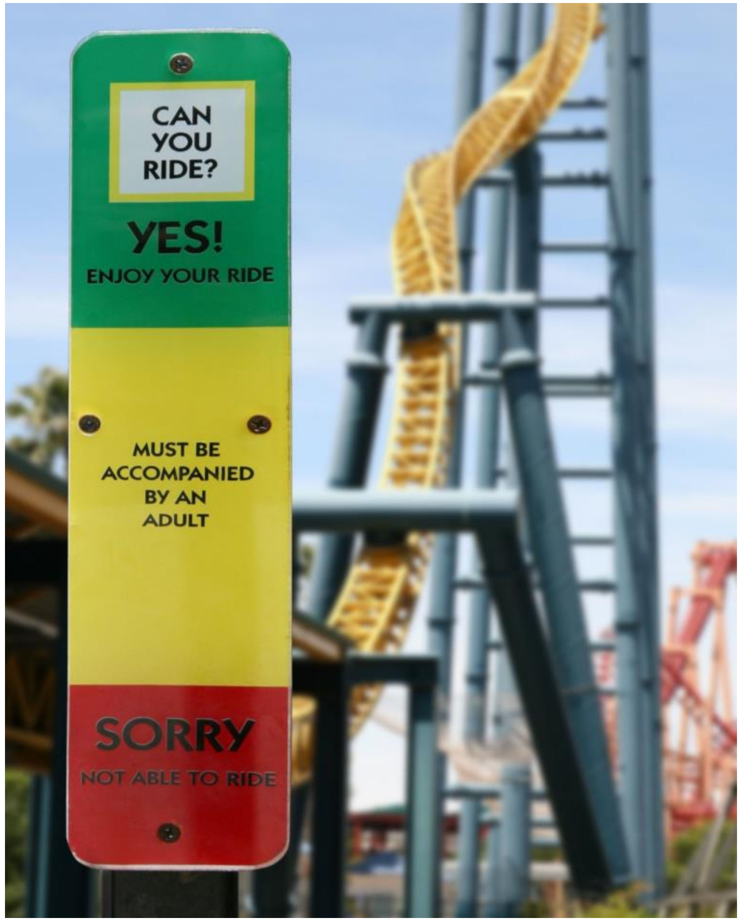


What does this mean for fusion energy concepts?

Let's make a simple analogy…

# Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions





Fusion Energy: The Ride!

# Q2: What are the physical conditions required to achieve net fusion energy?

**Rule 2**

Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

*T and* $n\tau_E$ *giving* $\sim Q \geq 0.1$ *is ready for fusion energy.*
*T and* $n\tau_E$ *giving* $\sim Q \leq 0.1$ *is a physics experiment.*

**Questions you should ask:**

*“What is the plasma pressure? The ion temperature? The confinement time?”*
*“What Q values (energy gain) are achieved on present machines?”*
*“Is the plasma magnetohydrodynamically (MHD) stable?”*
*“What problems with turbulence are they encountering?”*

*Part 1* : Developing "The Rules" for assessing fusion energy concepts

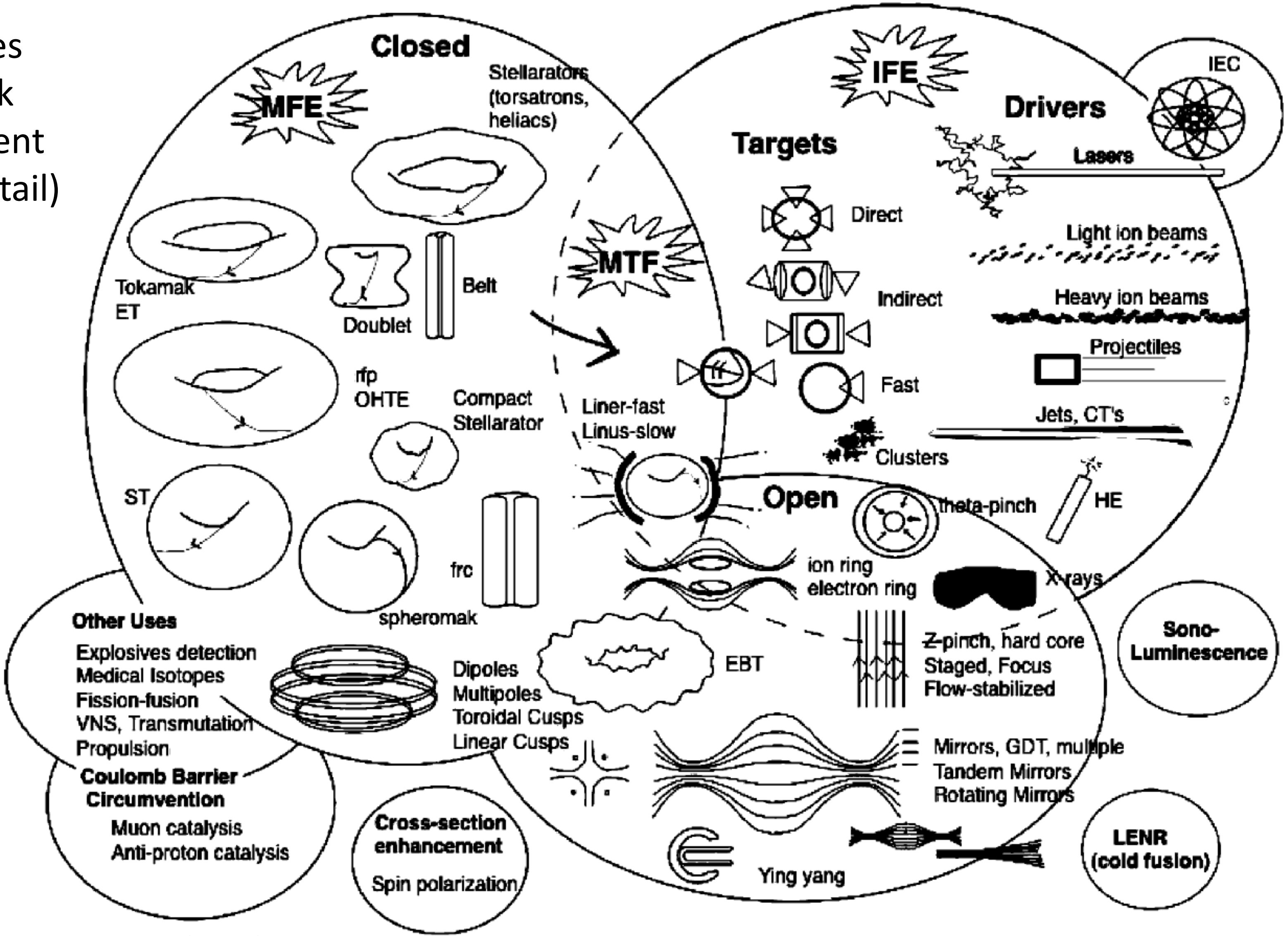
- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

*Part 2* : MIT's accelerated pathway to demonstrate net fusion energy

# There are a surprisingly large number of ways to attempt fusion energy. In short: we've tried just about everything to get n, T, and $\tau_E$ up!

**MIT PSFC**

(There are 12 slides in the posted deck going into 12 different concepts in more detail)



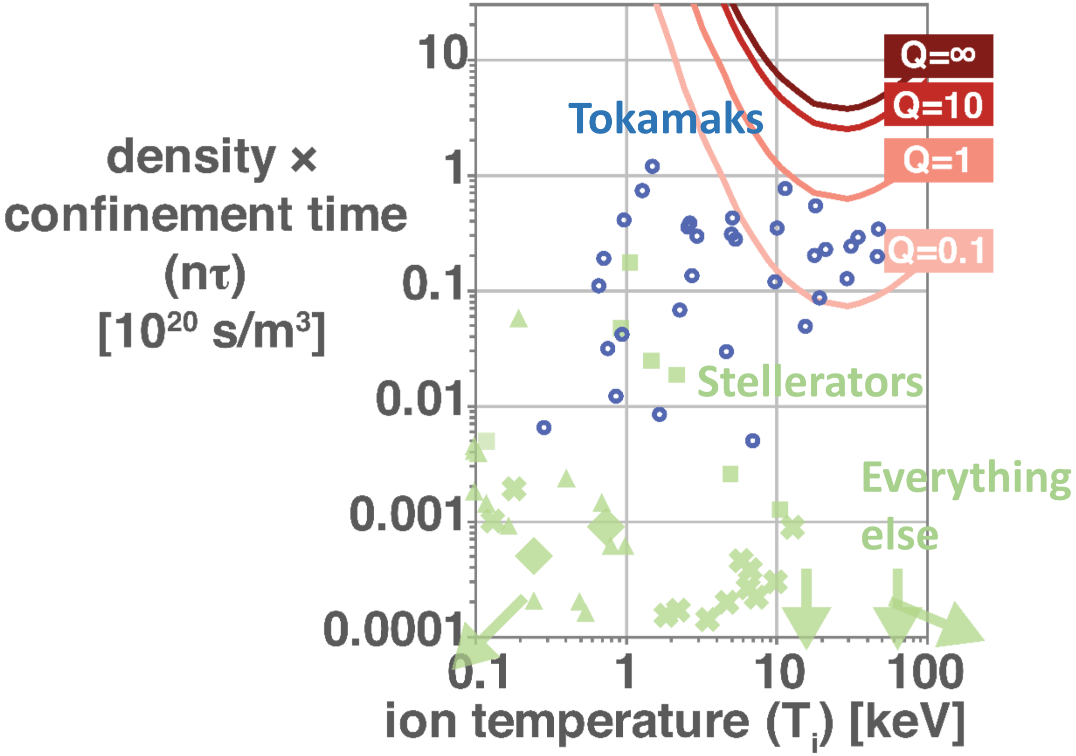
[1] S. Woodruff, *Journal of Fusion Energy,* **23** (2004) 27-40.

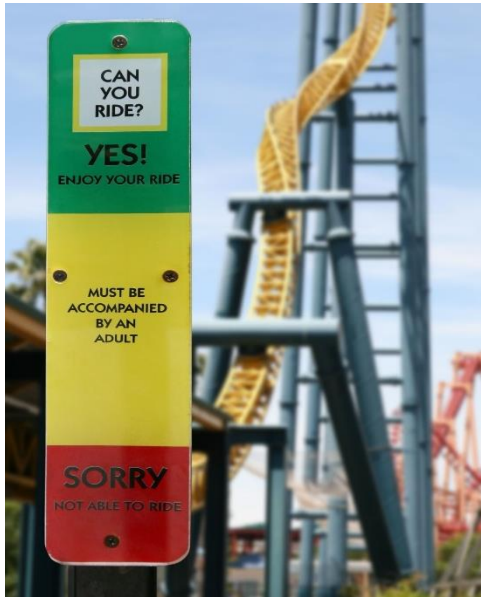
# The tokamak outperforms by far all other fusion energy concepts in nTtE, justifying its claim as the leading contender for fusion energy

**MIT PSFC**

Only the tokamak has demonstrated the proximity to Q > 1

- Maximum achieved $nT\tau_E$ gave Q ~ 0.7 (JET, UK, 1997)
- Not quite there yet (still requires adult supervision to ride…)





# Q3: What fusion energy approaches exist and how should they be evaluated?

## Rule 3

Many approaches to fusion energy have been/are being tried;
only the tokamak has demonstrated energy-ready performance.

*The tokamak (*$nT\tau_E$ *giving Q ~ 0.65 ) leads by a lot.*
*Stellarators come next and will be interesting to watch.*
*All others a very distant (factor of* $10^4 - 10^6$*) third.*

**Questions to ask:**

*"Has this approach been tried before? Why was it previously abandoned?"*
*"How far in* $nT\ \tau_E$ *are they extrapolating to show energy-relevance?"*
*"How do they propose achieving a* $10^4$ *to* $10^6$ *needed* $nT\ \tau_E$ *improvement?"*
*"What cost and time were historically required to make* $nT\tau_E$ *improvement?*

# The Rules for assessing fusion energy approaches

**Rule 1**

Fuel choice fundamentally sets the difficulty of any approach to fusion energy.

**Rule 2**

Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

**Rule 3**

Many approaches to fusion energy have been/are being tried; only the tokamak has demonstrated energy-ready performance.

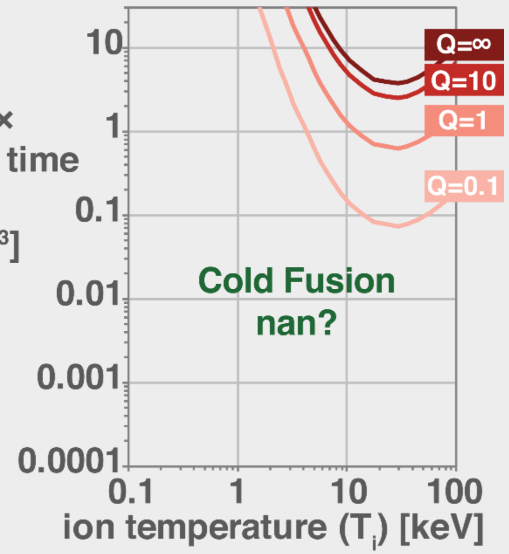
# Backup

# Cold fusion (alias: Low energy nuclear reactions or “LENR”) can be described by no known physical model and has never achieved verified power production

**Confinement basis**
- Cold Fusion / LENR

**Active experiments:**
- Surprisingly numerous, “eCAT”

**Key lessons learned:**
- If it’s too good to be true, then it almost certainly is.



- Cold fusion purports to use some process to create fusion energy conditions at room temperature
  - First “discovered” by Pons and Fleischmann in 1989
- Proposed processes cannot be rectified with any known model of physics
  - Rapidly and continually debunked
  - Zero independent validation by critics
  - Initial Pons and Fleischmann debunking done by MIT
- Considered a *pathological science*: research that continues in an enthusiastic minority long after scientific consensus establishes it as false

Boston Herald

25 Cents Monday May 1, 1989

MIT bombshell knocks fusion ‘breakthrough’ cold

# Gravitational force confines plasma and create the conditions necessary for sustained generation of fusion energy in the stars

**Confinement basis**

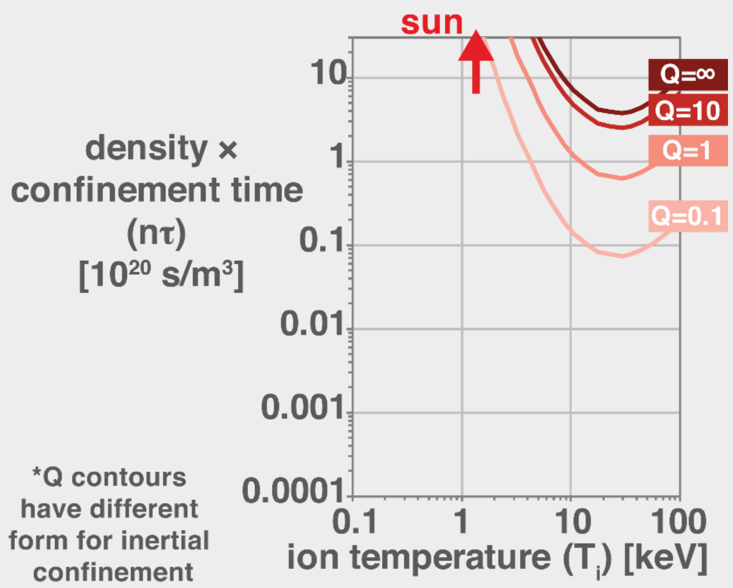
- Gravity

**Active experiments**

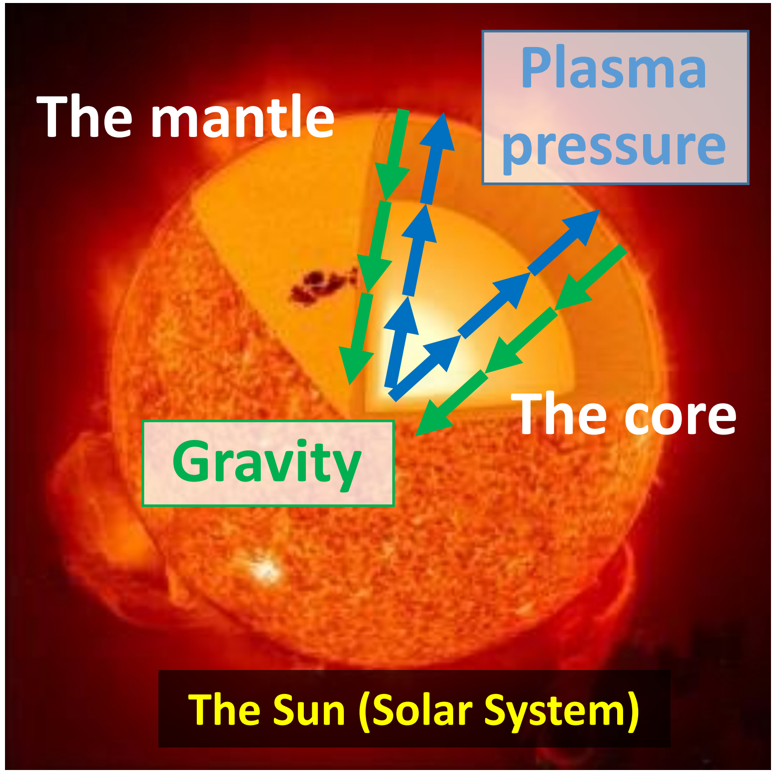
- See: The universe

**Key lessons learned**

- Conditions required for net energy fusion are allowed by this universe, but need different confinement mechanism



- Stars initially fuse hydrogen but progress to fusing heavier elements
- Energy release from fusion reactions generates **tiny** power densities but over **massive** volume:
  - 0.27 W/m³ average power density (about your average compost pile)
  - ~$10^{27}$ m³ (absolute volume)
- Stars exist balance plasma pressure with gravity
  - Not likely to be replicated on Earth in the near term



# Hydrogen bombs create fusion initiated by fission bombs, but resulting blast is unacceptable and infeasible for energy production.

**Confinement basis:**

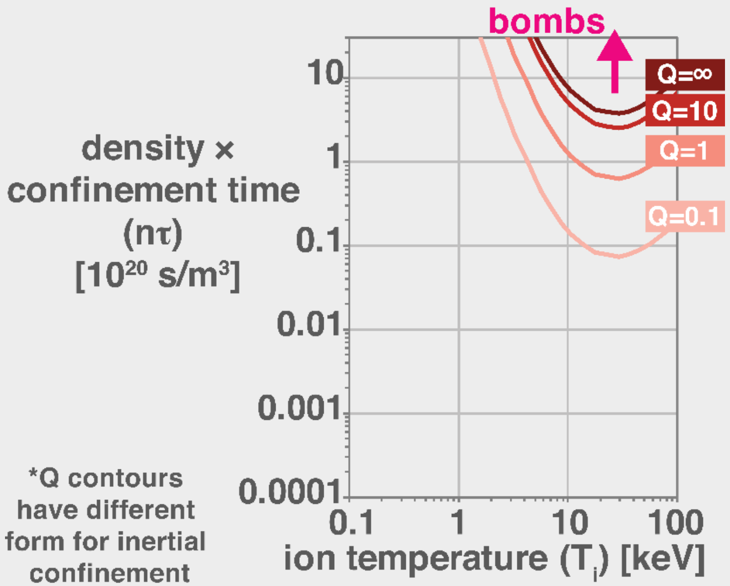
- Inertia with implosion driven by fission bomb

**Active experiments:**

- Weapon-industrial complex

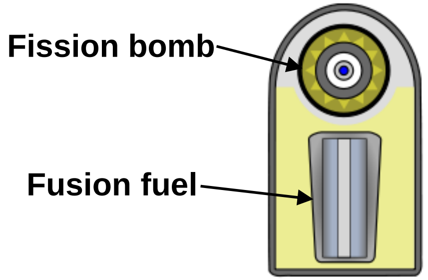
**Key lessons learned:**

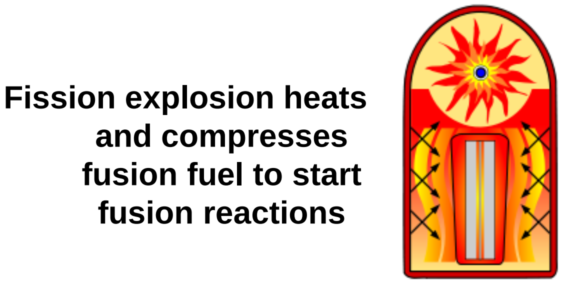
- To date, only successful fusion net gain on Earth but not great for energy…



*Q contours have different form for inertial confinement

- Fission bomb is ignited next to fusion fuel
  - Resulting X-rays rapidly heat and compress fuel to fusion conditions prior to destruction
  - Fusion boosts the fission explosion energy by 1000x
- Important to note: that fusion explosion *requires* fission explosion first
- Not a good power source!





# Inertial confinement fusion (mini-bombs) has demonstrated impressive physics performance but has very unfavorable technological scaling to fusion energy.

**Confinement basis:**

- Inertia with implosion driven by lasers

**Active experiments:**

- NIF,Omega (US), Laser Mégajoule (FR)

**Key lessons learned:**

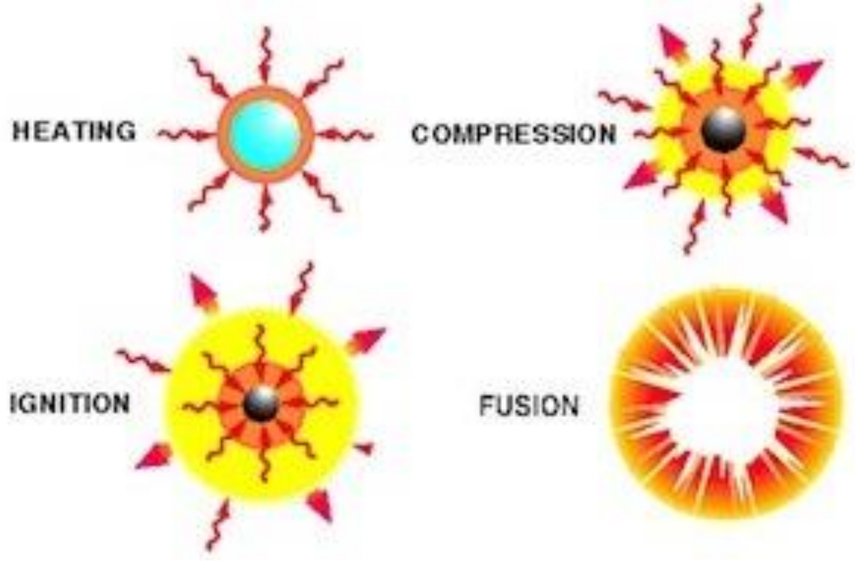
- Capable of high performance but at very low rep rate and gain

Lawson criterion has different form for inertial confinement. Apples-to-apples comparison to magnetic confinement through Q for NIF:

$$Q = \frac{E_{\text{fusion}}}{E_{\text{driver-on-target}}} = \frac{17\text{ kJ}}{150\text{ kJ}} \approx 0.1$$

Hurricane, O. A., et al. *Nature* 506.7488 (2014): 343-348.

- Instead of using a bomb, use something else that is powerful and fast
  - Lasers: NIF, achieved near-breakeven
- Gives insight into how bombs work which is the primary purpose of the R&D
- Impressive performance but scaling to reactor looks difficult:
  - *Maintenance:* Significant machine components destroyed each implosion
  - *Rep rate:* present ~1/day (max); need ~1/s (need 100 000 scale-up)
  - *Efficiency:* 0.7% of NIF wall plug power makes it to the fusion fuel target



National Ignition Facility (LLNL)

# Particle accelerators can easily achieve necessary conditions for fusion, but high Coulomb cross section compared to fusion cross section leads to tiny gain .

**Confinement basis:**

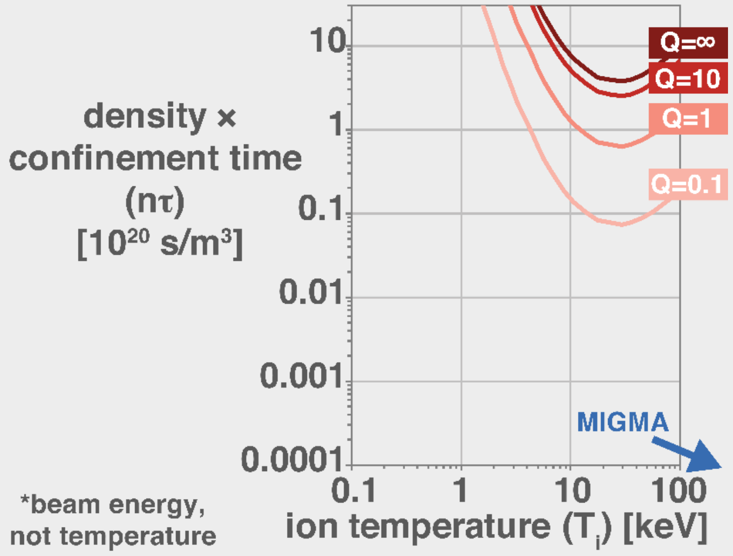
- Accelerating with electric fields

**Active experiments:**

- Any accelerator with E ≥ 10 keV

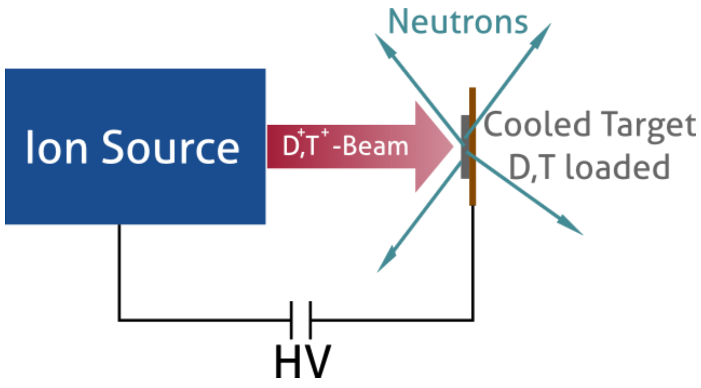
**Key lessons learned:**

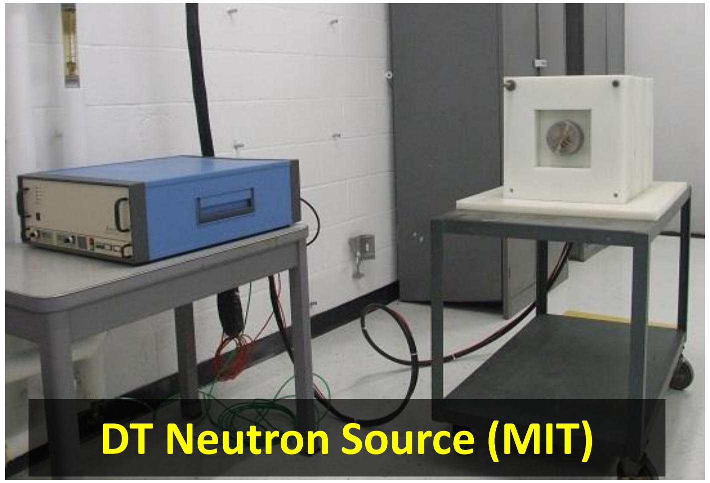
- Coulomb collisions and instabilities reduce gain to unacceptable levels



*beam energy, not temperature

- Fire beam of high energy particles into other particles
  - Easy to build a compact 100 keV beam
  - Can fuse anything from standard DT fuel (neutron source) to heavy ions (RHIC) depending on beam energy
- But…Coulomb cross section is ~100,000x too large
  - Beam ions slows down before fusion dominates
  - Beam requires more energy than it makes from fusion
- Good for neutron source, but low gain precludes energy generation




DT Neutron Source (MIT)

# Electrostatic potential wells (fusors) can be used to accelerate and confine ions, but several loss mechanisms limit plasma performance

**Confinement basis:**

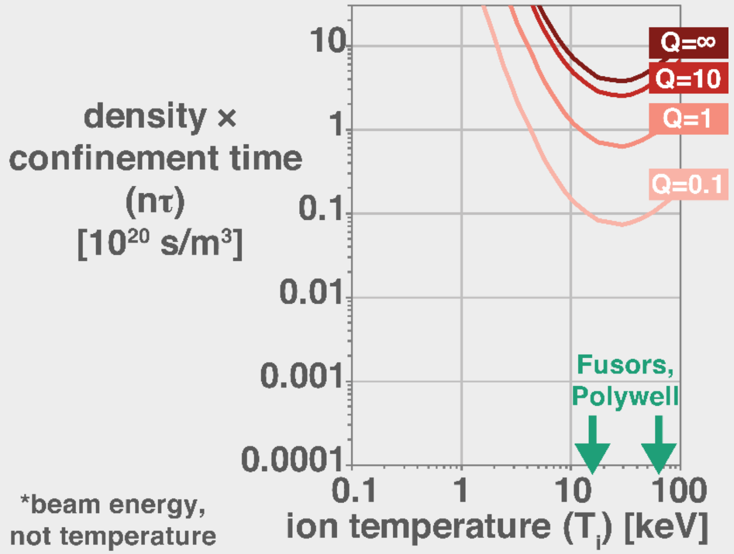
- Electric fields

**Active experiments:**

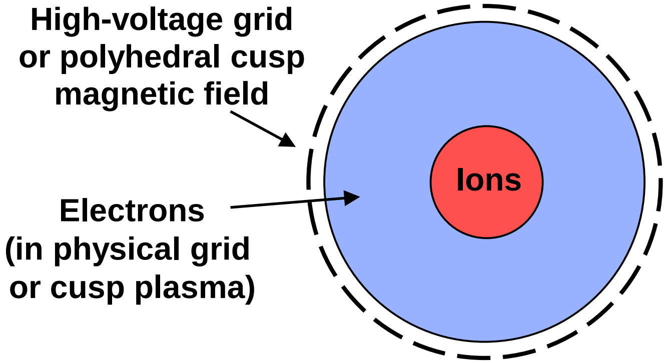
- Hobbyists, university students

**Key lessons learned:**

- Simple devices, good for teaching tools but too many loss mechanisms for net power production



- A spherical ion accelerator with a potential well to collide ions against each other in the center
  - Physical high-voltage grid or a “virtual cathode” made of electrons
- Multiple mechanisms slow or eject the ions before *enough* fusion happens for net gain[1]
  - Coulomb collisions
  - Particle losses
  - Conduction losses
  - Bremsstrahlung
- While orders of magnitude from energy gain, can be effective simple neutron sources



**Plasma in a fusor (hobbyist’s garage)**

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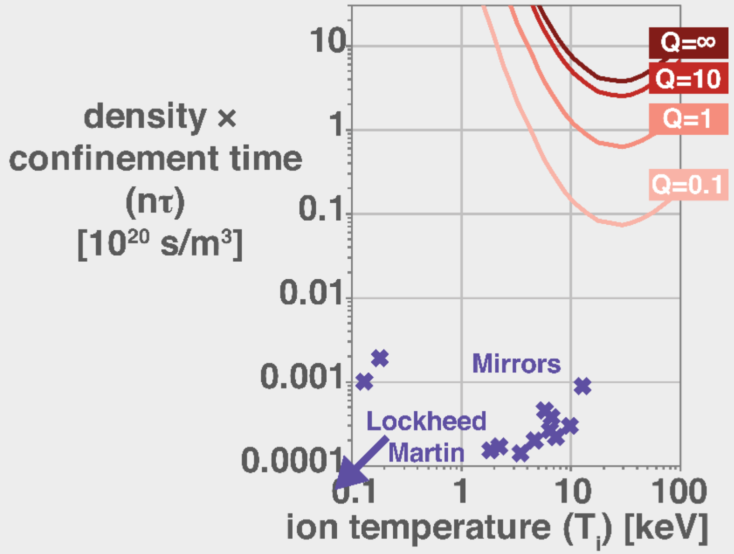
[1] Rider, Todd H. "A general critique of inertial-electrostatic confinement fusion systems." *Physics of Plasmas (1994-present)* 2.6 (1995): 1853-1872.

# Magnetic mirrors use a magnetic field to confine plasma in 2 dimensions and then unsuccessfully try to plug the losses along the magnetic field.

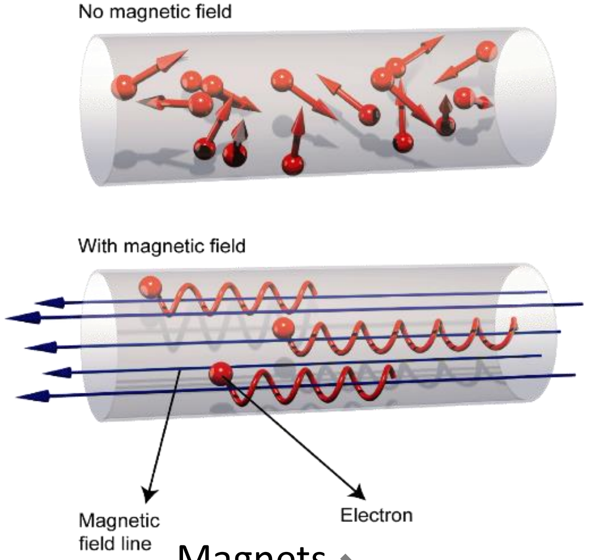
**Confinement basis:**
- Magnetic fields (crimped)

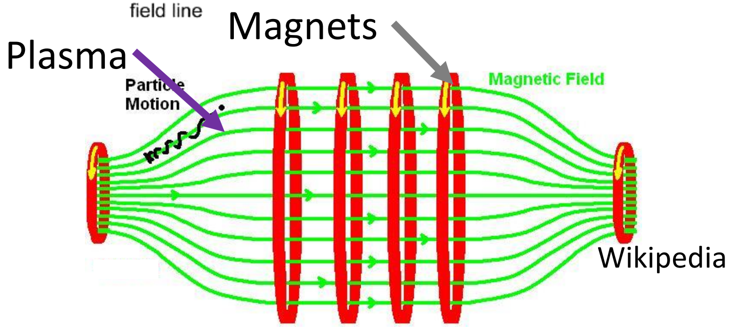
**Active experiments:**
- Gamma-T (Japan), Gas Dynamic Trap (Russia), Lockheed Martin Co.

**Key lessons learned:**
- Any open field lines lead to unacceptable losses

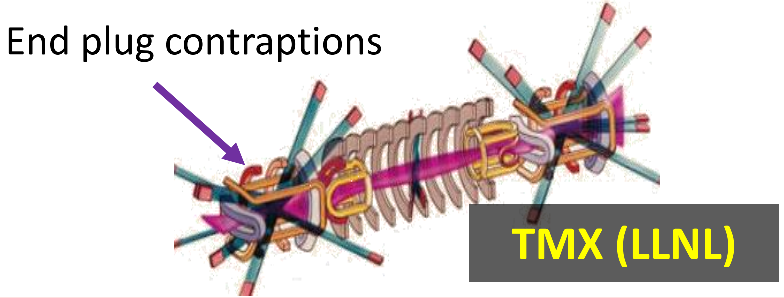


- Charged particles spiral around magnetic field lines
  - But confinement is only in 2D
  - Some particles always leak out the ends
- Many different configurations tried to plug the ends of the "mirror"
  - Large $1B-class experiments
  - Losses always dominate fusion unless the mirror is very long
- Conclusion: A net-energy device is unrealizably long (~km) still a good fusion neutron source





Wikipedia



# Pinches or magnetized targets use magnetic fields to rapidly compress the plasma before it leaks energy, but this creates instabilities.

**Confinement basis:**

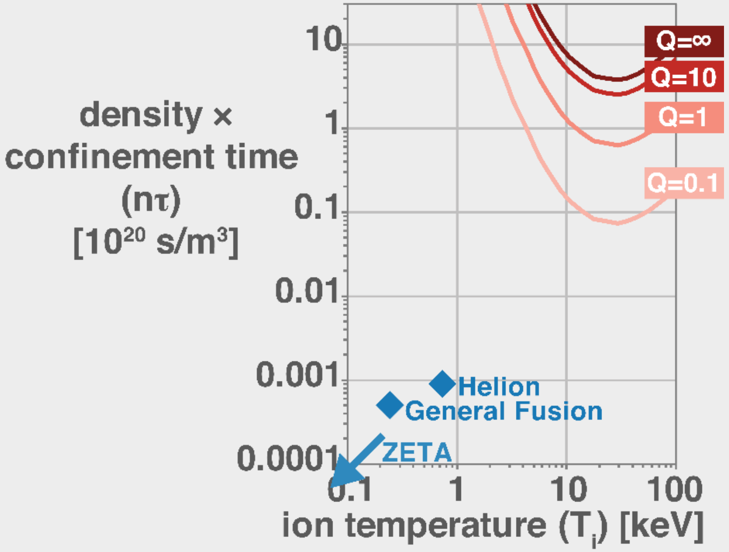
- Magnetic fields (squeezed)

**Active experiments:**

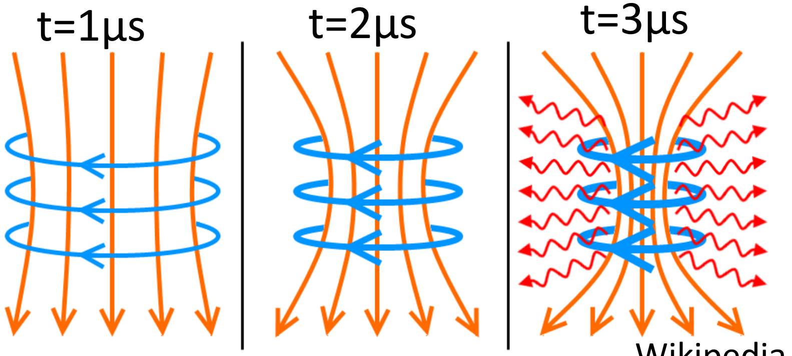
- Z-machine (SNL), Dense Plasma Focus (LLNL), ZaP (U. Wash), LPP co., General Fusion Co., Helion Co.

**Key lessons learned:**

- Instabilities are critically important



- Very quickly compress the plasma and heat it by rapidly changing magnetic field
- Many different configurations have been tried at many different scales
  - Requires large pulsed power systems
  - Often with sacrificial conductors surrounding plasma
- Large instabilities and plasma cooling occur before net-energy conditions are reached
  - Useful as a high-power X-ray or neutron source or particle accelerator



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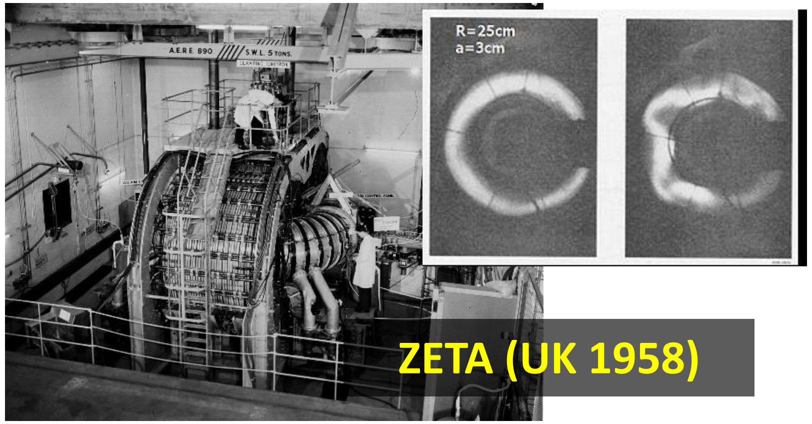
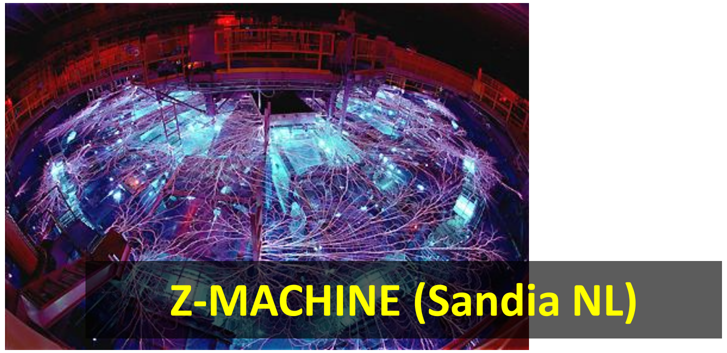


ZETA (UK 1958)



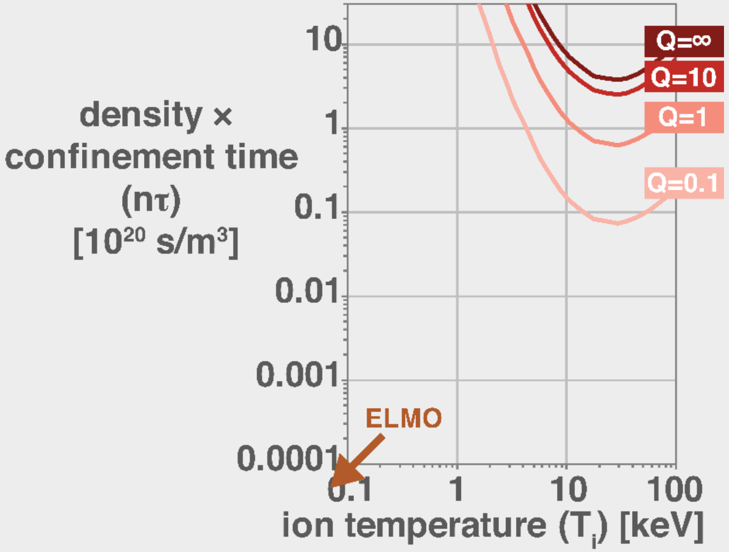
Z-MACHINE (Sandia NL)

# A torus of mirrors or cusps eliminates end losses by turning the system onto itself but with the toroidal shape come new instabilities.

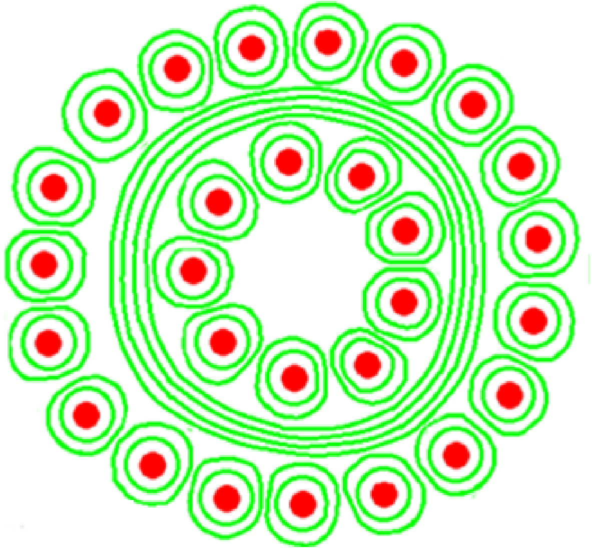
**Confinement basis:**
- Magnetic fields (bumpy)

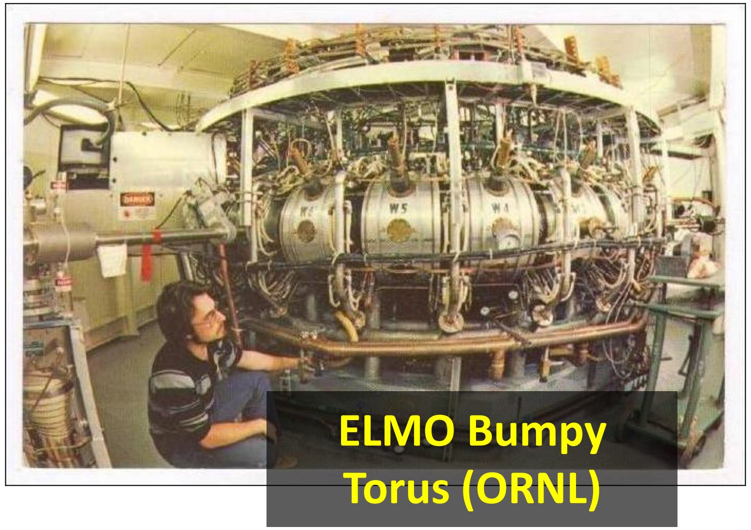
**Active experiments:**
- None anymore

**Key lessons learned:**
- Symmetries are important



- Instead of plugging the mirror end losses, feed them into another mirror
  - Ad infinitum = A torus
- Tried with many geometry variations in the 1970s and 1980s in large programs
  - ORNL: ELMO bumpy torus
  - UC California: TORMAC
  - NASA: Bumpy torus
- But breaking the symmetry created additional instabilities in the plasma
  - Limited the temperatures and ruined confinement
  - Interesting plasma physics!





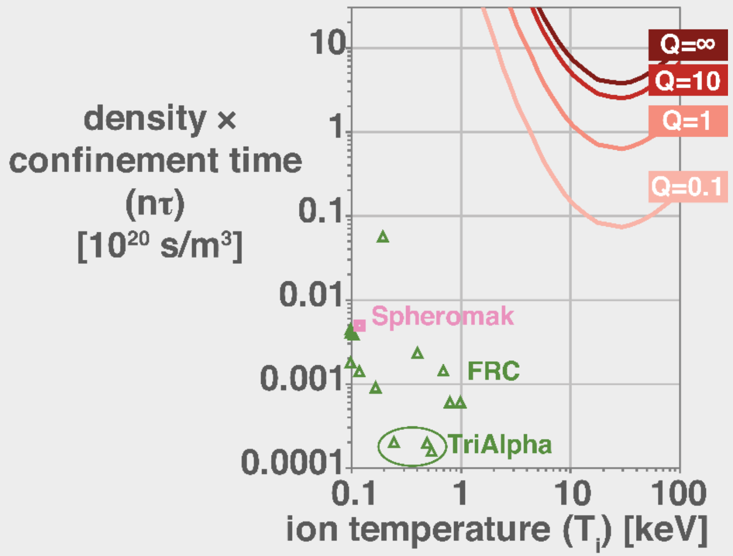
ELMO Bumpy Torus (ORNL)

# Field-reverse configurations, spheromaks etc. use the plasma to create helical fields in the torus, increasing confinement at the expense of stability.

**Confinement basis:**
- Magnetic fields (self-twisted)

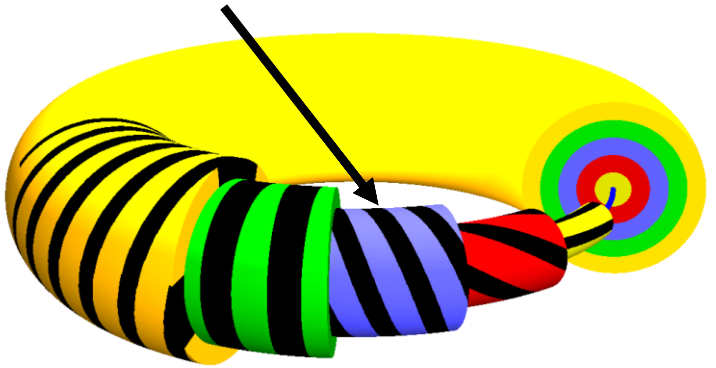
**Active experiments:**
- Tri-alpha Energy Co., RFX (EU), MST (U. Wisc.), Dynomak Co.

**Key lessons learned:**
- A helical magnetic field gives good confinement and sometimes stability, but relying on the plasma alone is difficult



- Instead of torus of many mirrors, make a torus with the magnetic field spiraling in a helix
  - Increases the stability
- Plasma can create these field shapes though “self-organization”
  - Transient effects limited to milliseconds
  - Studied widely over a long period
- Very rich plasma physics but very difficult to control and confinement still lacking
  - Have not yet reach energy-relevant confinement or temperatures

Magnetic field is helical shaped



Reverse Field Pinch

RFX-Mod (Italy)

# Stellarators use external magnets to create the helical fields and are approaching fusion relevant conditions.

**Confinement basis:**

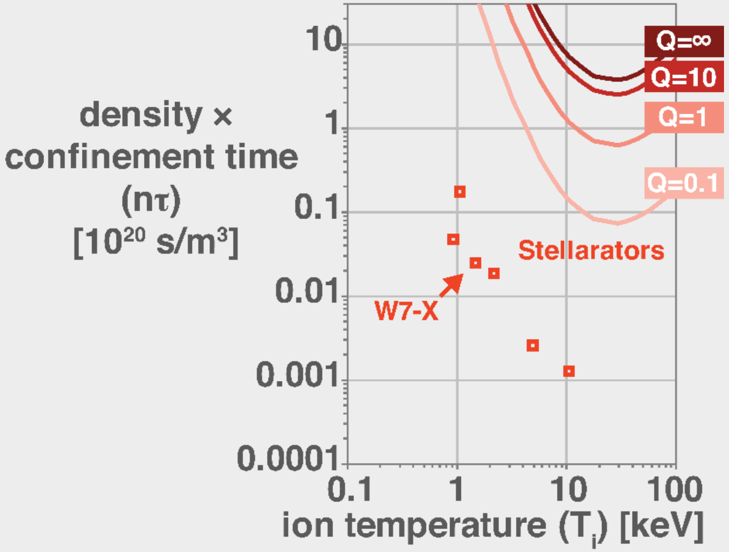
- Magnetic fields (twisted by external coils)

**Active experiments:**

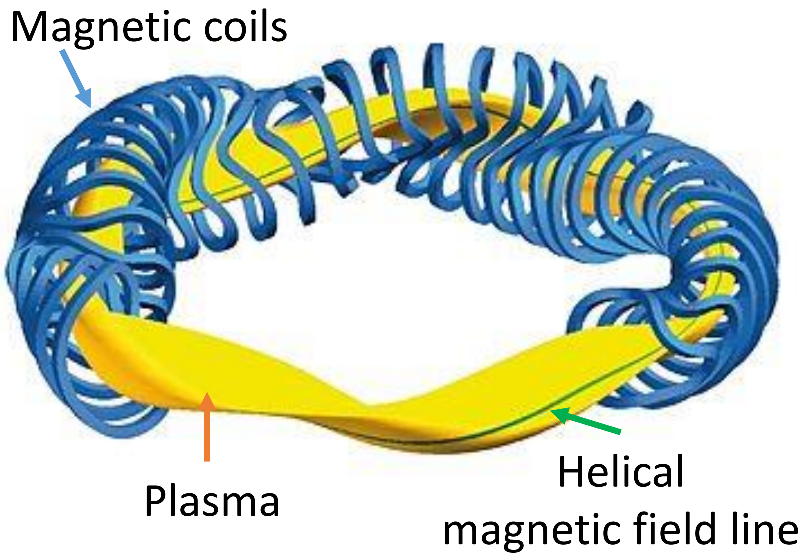
- LHD (Japan), W7-X (Germany), HSX (U. Wisc.)

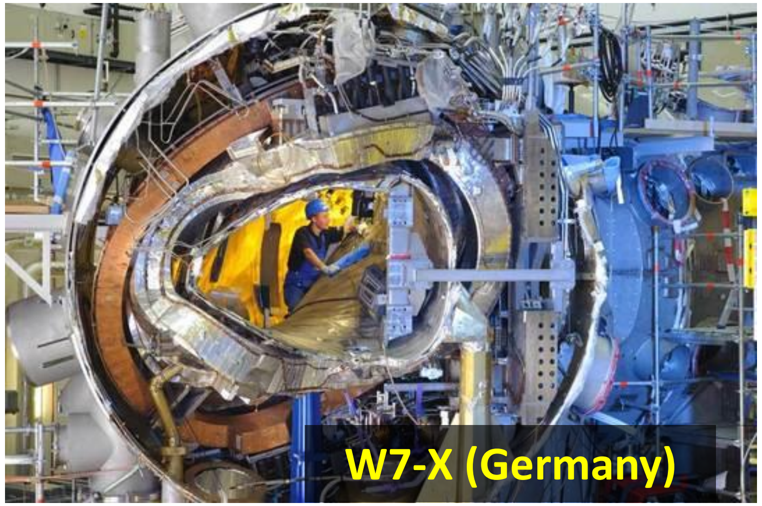
**Key lessons learned:**

- Good plasma performance but tough engineering



- Use many external magnetic coils to create precisely the desired magnetic field shape
  - Stable and steady-state
- Requires highly optimized field shapes and magnets to obtain best performance
  - One of the original fusion concepts
  - Ongoing work world-wide
- Higher performance but with complex engineering to create the exact right 3D shapes
  - Makes an expensive reactor





# Tokamaks use the plasma and simple external coils to generate the helical magnetic field. They have performed the best.

**Confinement basis:**

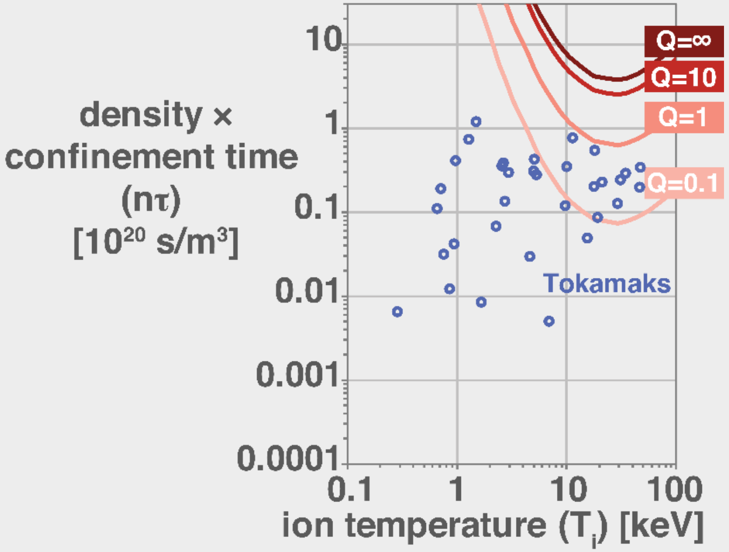
- Magnetic fields (twisted by external coils and plasma)

**Active experiments:**

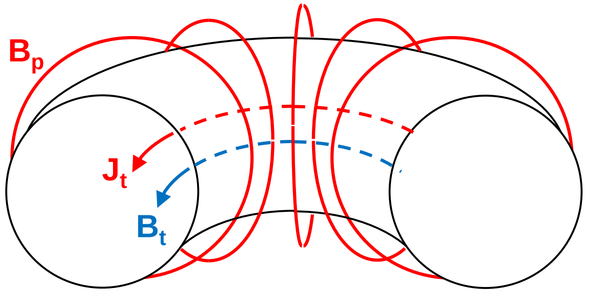
- JET, ASDEX-U, DIII-D (33 worldwide)

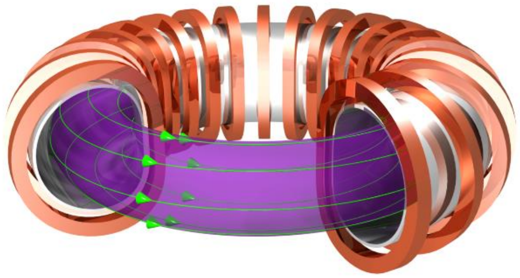
**Key lessons learned:**

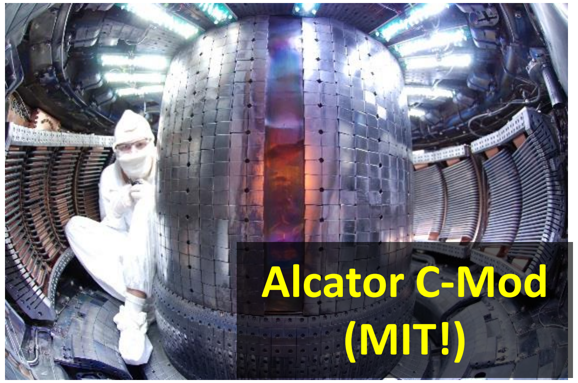
- Most promising candidate for fusion energy



- Simplify the magnets by carrying toroidal current in the plasma to create a slightly helical field
  - Good stability and can be made steady-state
  - Symmetry provides good confinement
- High initial performance led to lots of research for the past 50 years,
  - ~170 devices built (6 at MIT)
  - Extensive physics understanding
  - Technologies well developed
  - Only devices to make significant fusion energy (17MW Q~0.65)
- Consensus among world plasma physics community is that tokamaks will be able to generate net energy







Alcator C-Mod (MIT!)