Introduction to Fusion Energy

2021 Intro to Fusion Energy and Plasma Physics Course | June 14, 2021

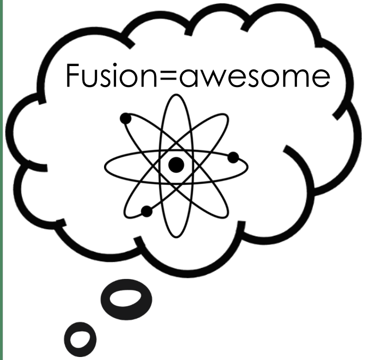
Presented by

Cami Collins

Oak Ridge National Laboratory

My Path in Fusion

5th Grade
1995



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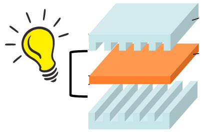
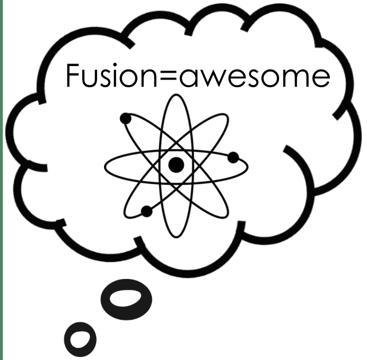


Solid Oxide Fuel Cells (materials)



Solar Physics

Fusion

Nat. Und. Fellowship

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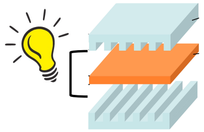

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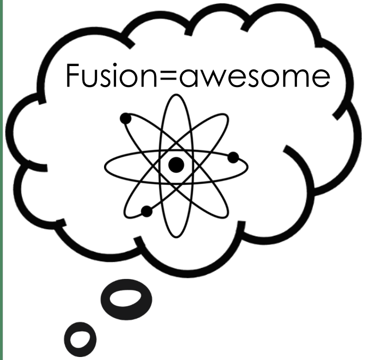

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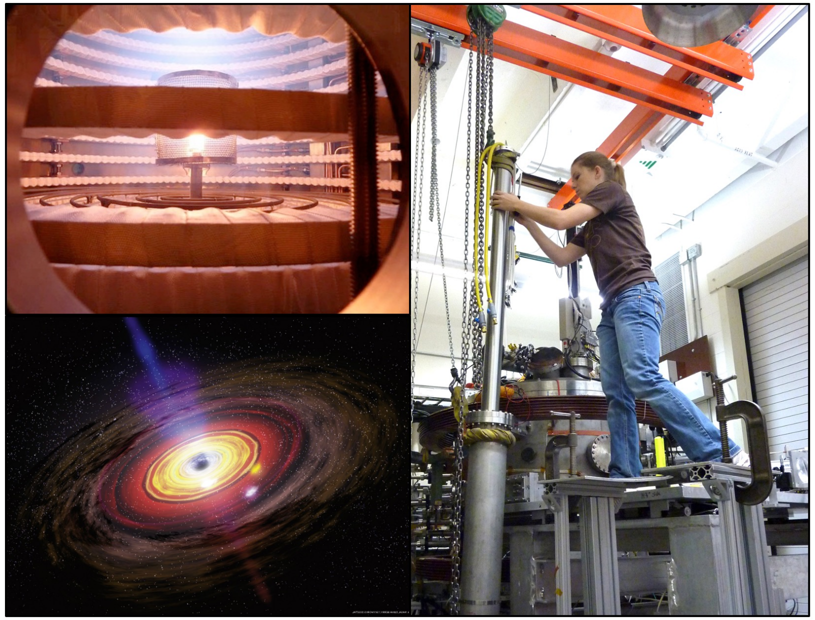

Laboratory Plasma Astrophysics

Fusion Energy Fellowship

Nat. Und. Fellowship

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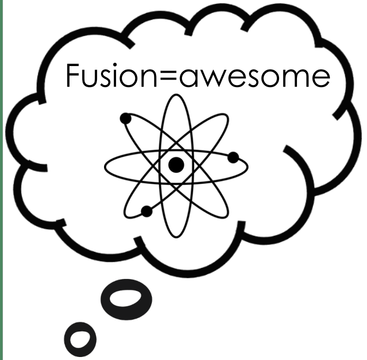
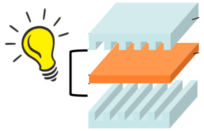
Postdoc 2014-16

Scientist! 2016





Solid Oxide
Fuel Cells
(materials)

Solar
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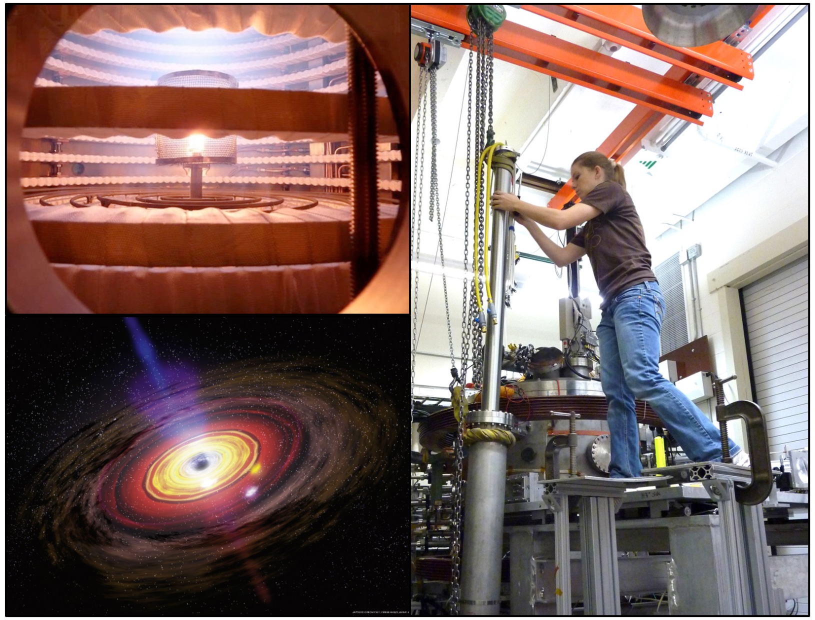

Laboratory Plasma Astrophysics

Fusion Energy Fellowship

My Path in Fusion

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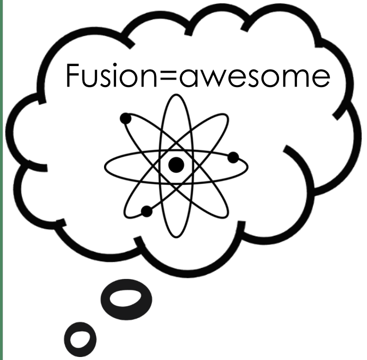

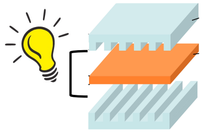

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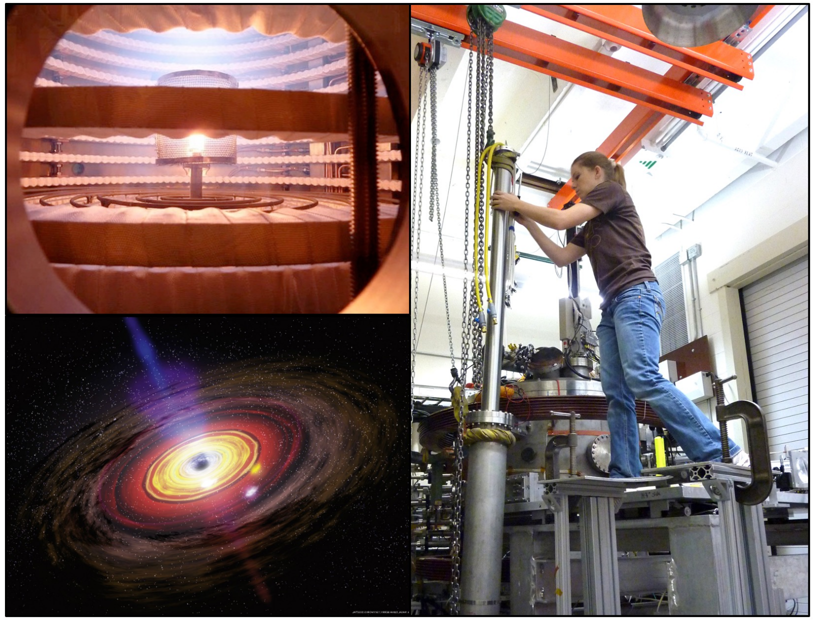

Laboratory Plasma Astrophysics

Fusion Energy Fellowship

My Path in Fusion

5th Grade	Undergrad	Grad	Postdoc	Scientist!	Scientist +
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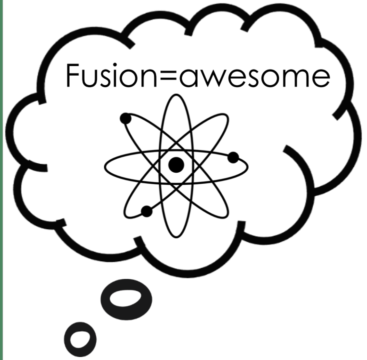

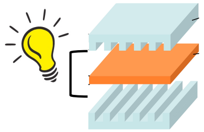

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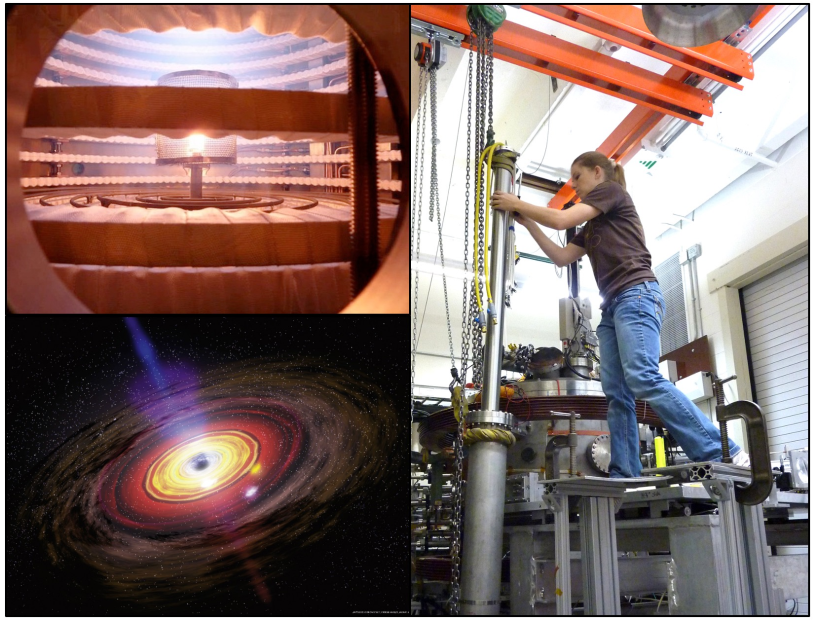


Laboratory Plasma Astrophysics

Fusion Energy Fellowship

Fusion=hard

I want a fusion pilot plant.

(Recent) History of Fusion

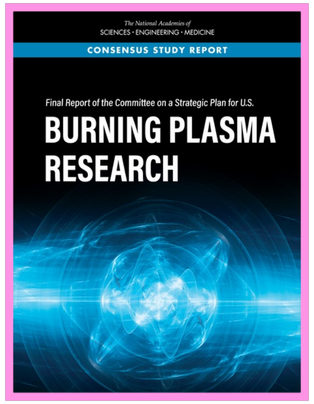
Fusion community comes together – historic success

Strategic Workshops

Community Planning Workshops

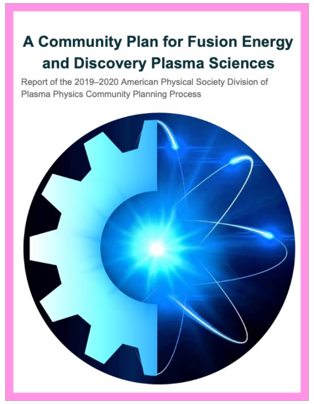
2018 | 2019 | 2020 | 2021

National Academies
Dec 2018



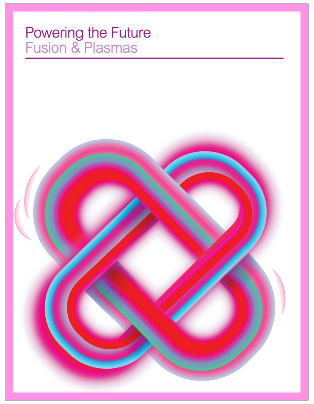
We've advanced a lot - let's make a fusion pilot plant by the 2040's!

APS-DPP-CPP
Mar 2020



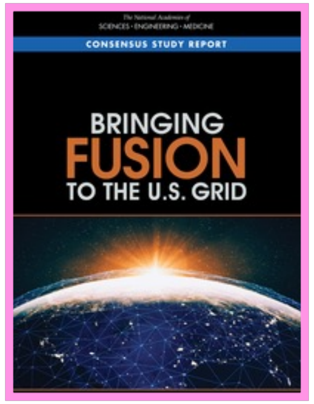
Here's what we need to do!

FESAC
Dec 2020



Hey DOE: do what they said! (but here's how much it costs)

National Academies
Feb 2021

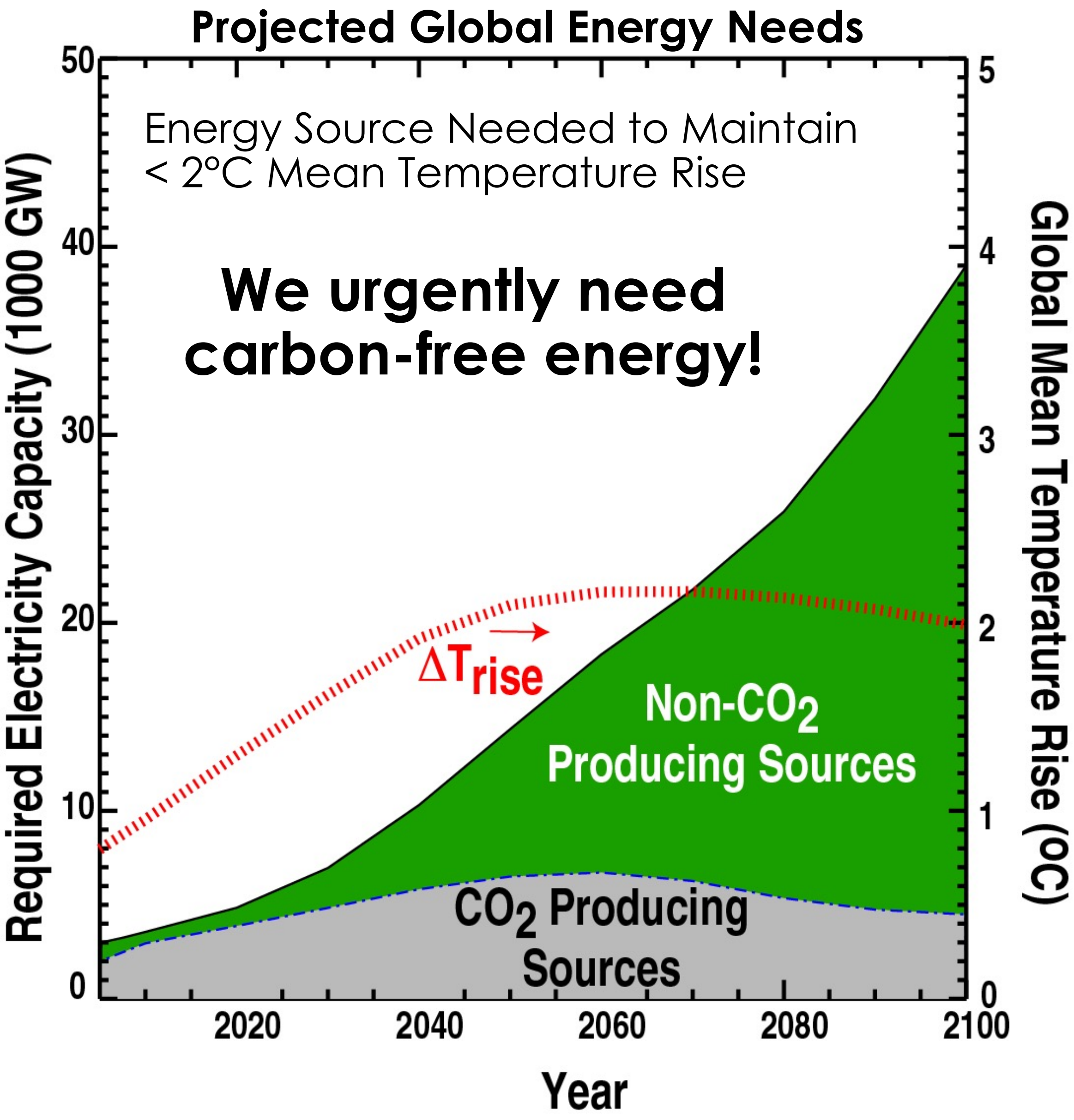


Get going! We need design by 2028, electricity by 2035!

Outline

- Introduction to Needs, Potential, and Conditions for Fusion
- Progress Towards Fusion Energy
- Challenges in Developing in Fusion Energy
- Exciting New Era for Fusion Energy Development

The Future of Our Civilization Depends on Energy



Source: IPCC AMPERE Project, AMPERE-450-FullTech-OPT Scenario

- Projected need for ~ 25,000 GW from non-CO_2 producing sources

25,000 1 GW-e plants !!!

- By 2050, annual global energy investment would need to reach $0.66 T ($23 T cumulative)
  - GDP (2018): US: $21T, China: $14T, UK: $2.9T
  - Global cell phone market: $0.55 T

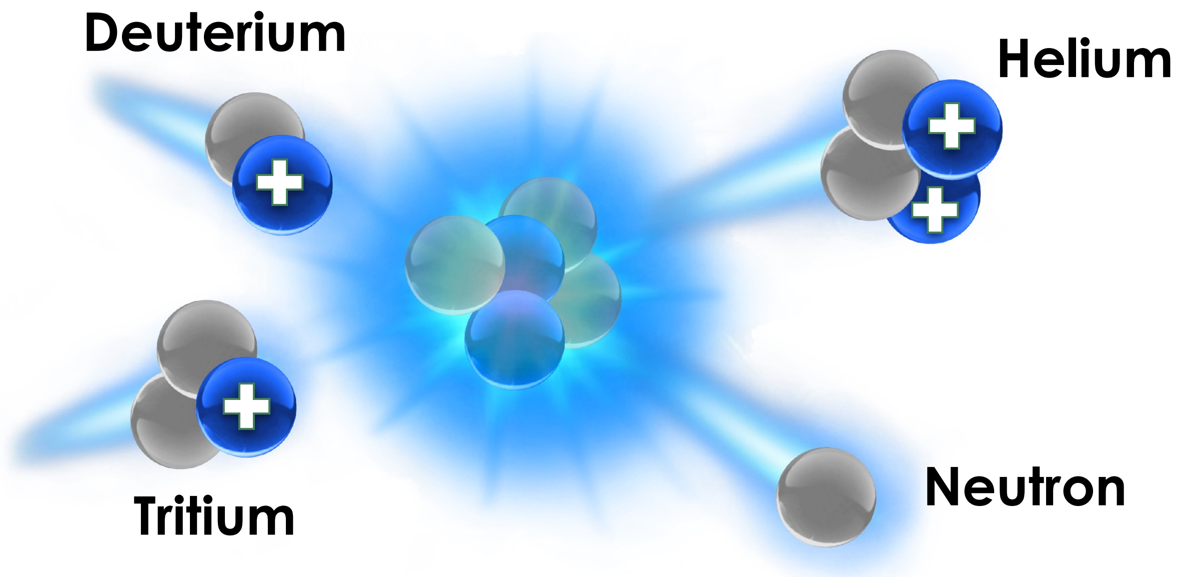
Source: IRENA, Global energy transformation, 2019

Reward of Developing Fusion Energy Is Well Worth the Risk of Investment

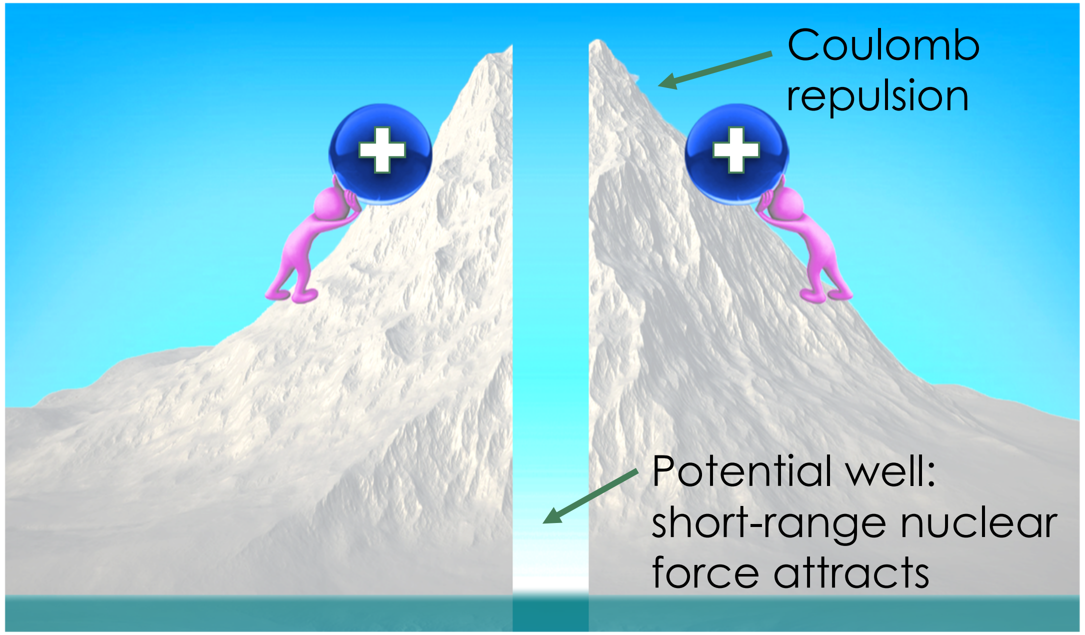
Fuel for thousands of years…

No global warming
No high level nuclear waste
No risk of nuclear accident
Available to all nations
Available on-demand
Minimal land use

Fusion Produces Energy By Combining 2 Nuclei Into 1



To fuse, two positive charges must have enough energy to overcome electric repulsion.



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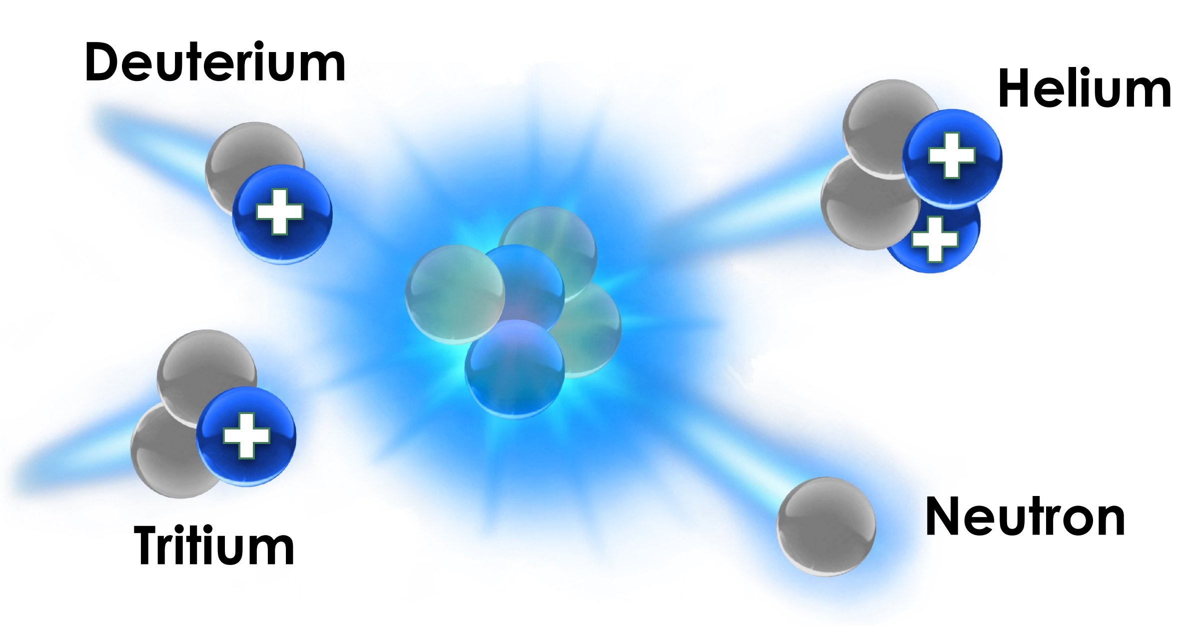

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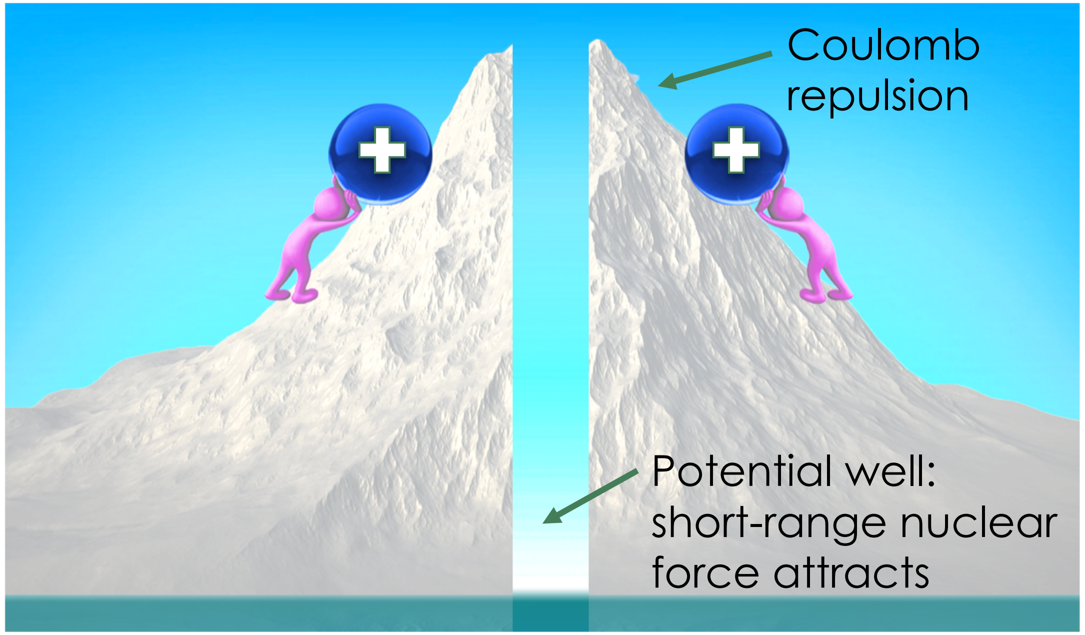

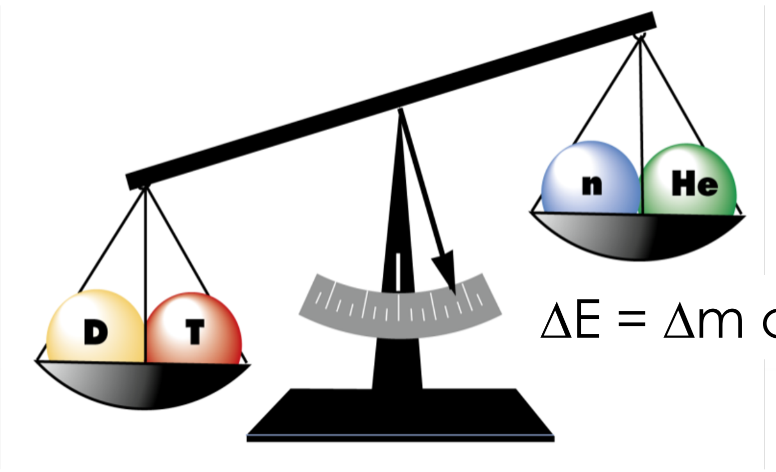

- The fused nucleus is in a lower energy state than its isolated components
  - The total mass of the product is less than the sum of the masses of the separate particles
  - Energy released depends on binding energy

Fusion Creates a LOT of Energy

To produce 1000 megawatts electricity for 1 day (enough for a major city)

Coal Plant		**D-T Fusion Plant**
 *18 million Lb coal* **80** **railroad cars**	**Fuel Consumed**	*1.0 Lb D_2* *1.5 Lb T_2* **3** **water bottles** 

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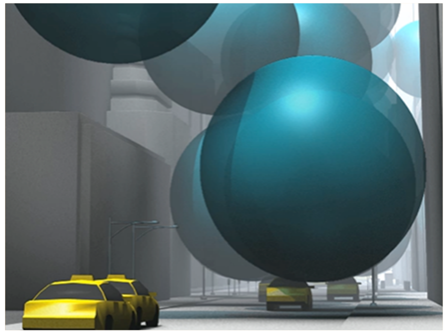
	Coal Plant		D-T Fusion Plant	
	*18 million Lb coal* **80 railroad cars**	**Fuel Consumed**	*1.0 Lb D_2 1.5 Lb T_2* **3 water bottles**	
	*61 million Lb greenhouse gases* **28,000 33 foot spheres**	**Waste Produced**	*2.0 Lb helium* **400 balloons**	

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Coal Plant

18 million Lb coal

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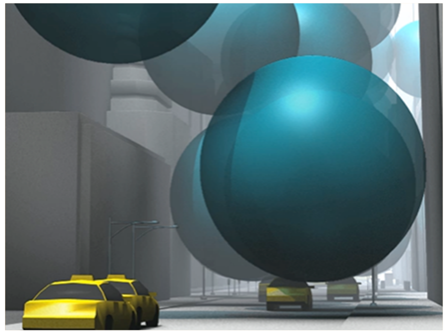
railroad cars



61 million Lb greenhouse gases

28,000
33 foot spheres

It takes a forest of
15 million trees
(~536 square mile area)
to absorb this much waste gas!

Fusion Creates a LOT of Energy

To produce 1000 megawatts electricity for 1 day (enough for a major city)

Energy Density Comparison

DT Fusion: **339** GJ/g DT

Fission: **82** GJ/g U-235

Methane: **20** kJ/g CH_4

Fusion is a million times larger!

D-T Fusion Plant

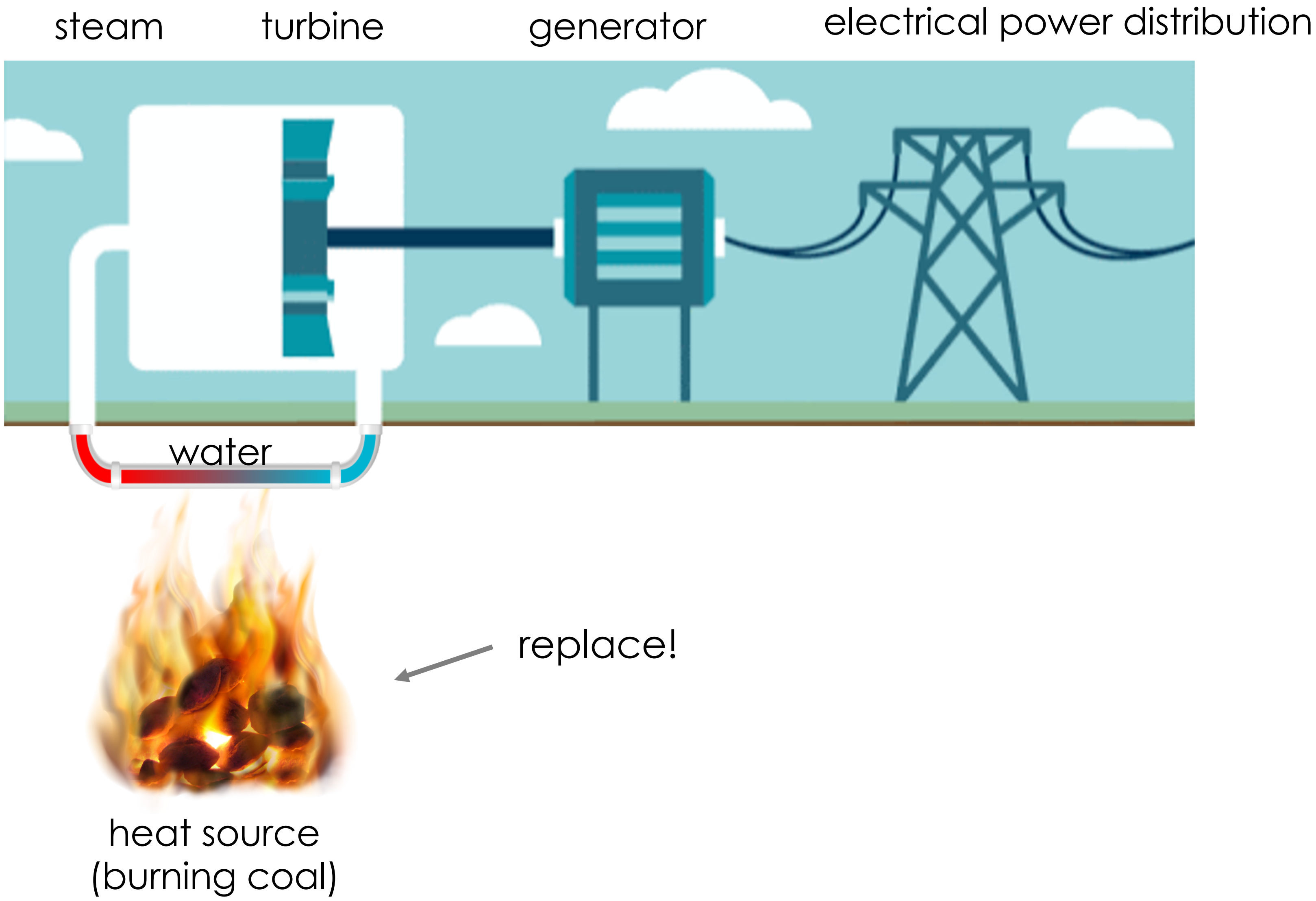
1.0 Lb D_2
1.5 Lb T_2

3
water bottles

2.0 Lb helium

400
balloons

Awesome! How Do We Make A Fusion Power Plant?



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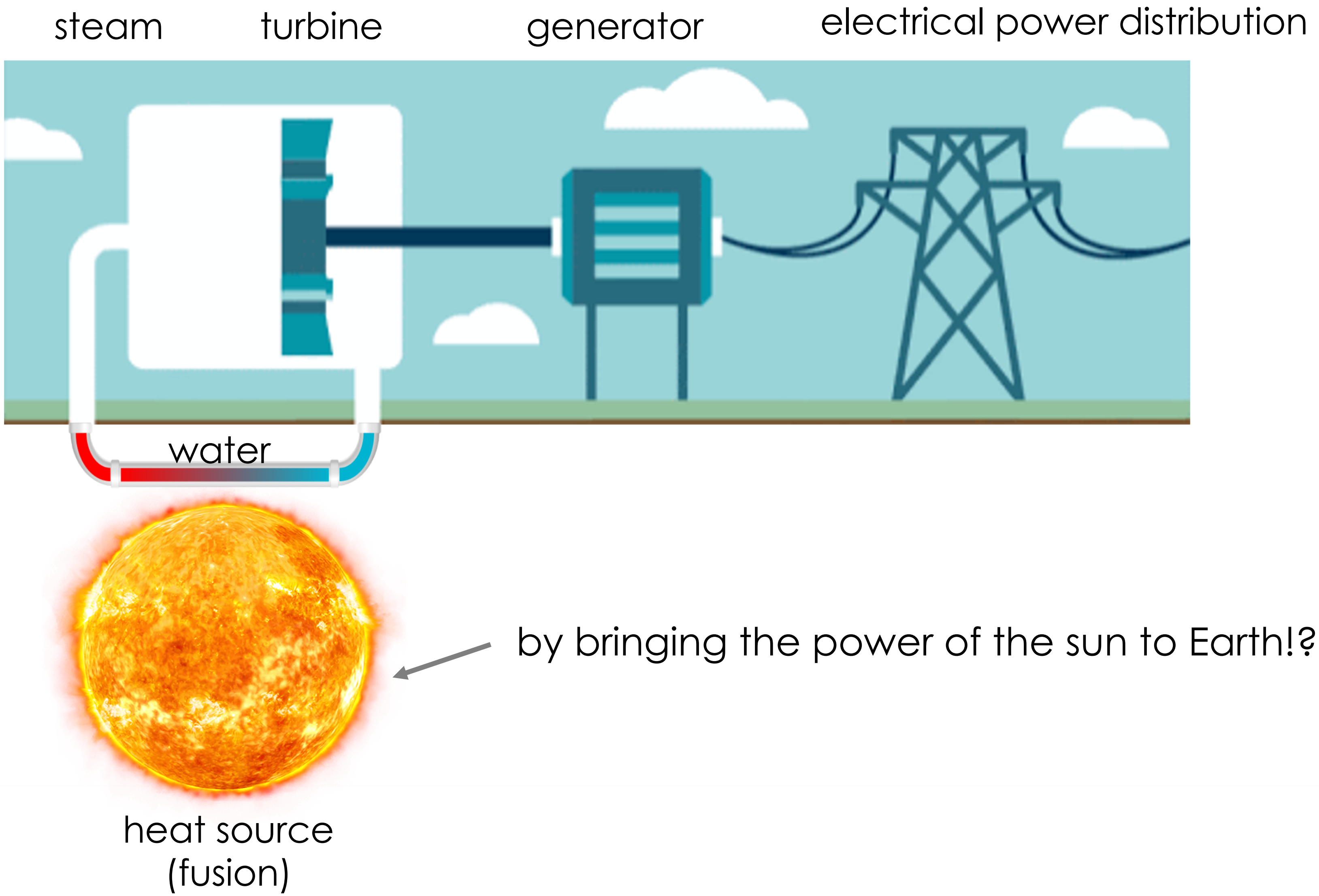
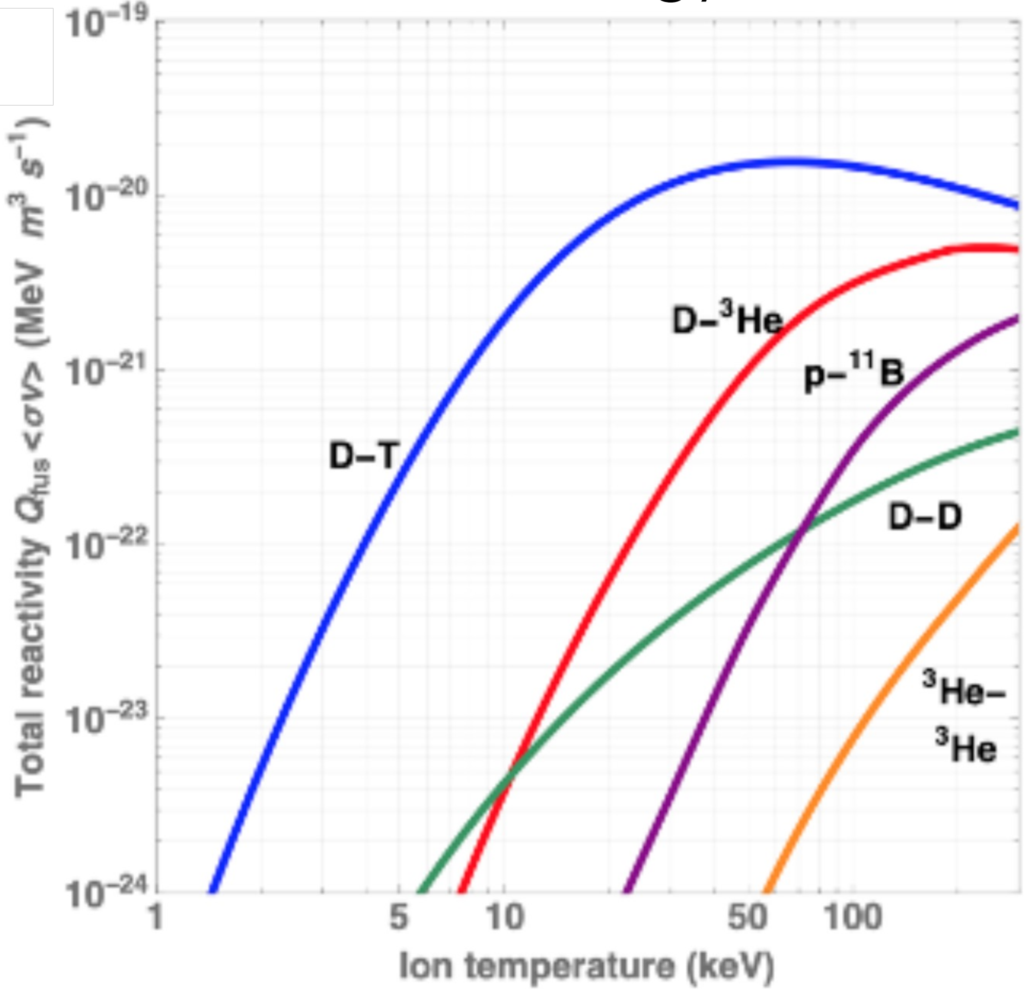


by bringing the power of the sun to Earth!?

Deuterium-Tritium Fusion is the Main Focus of Research

Reaction cross section
times total energy released



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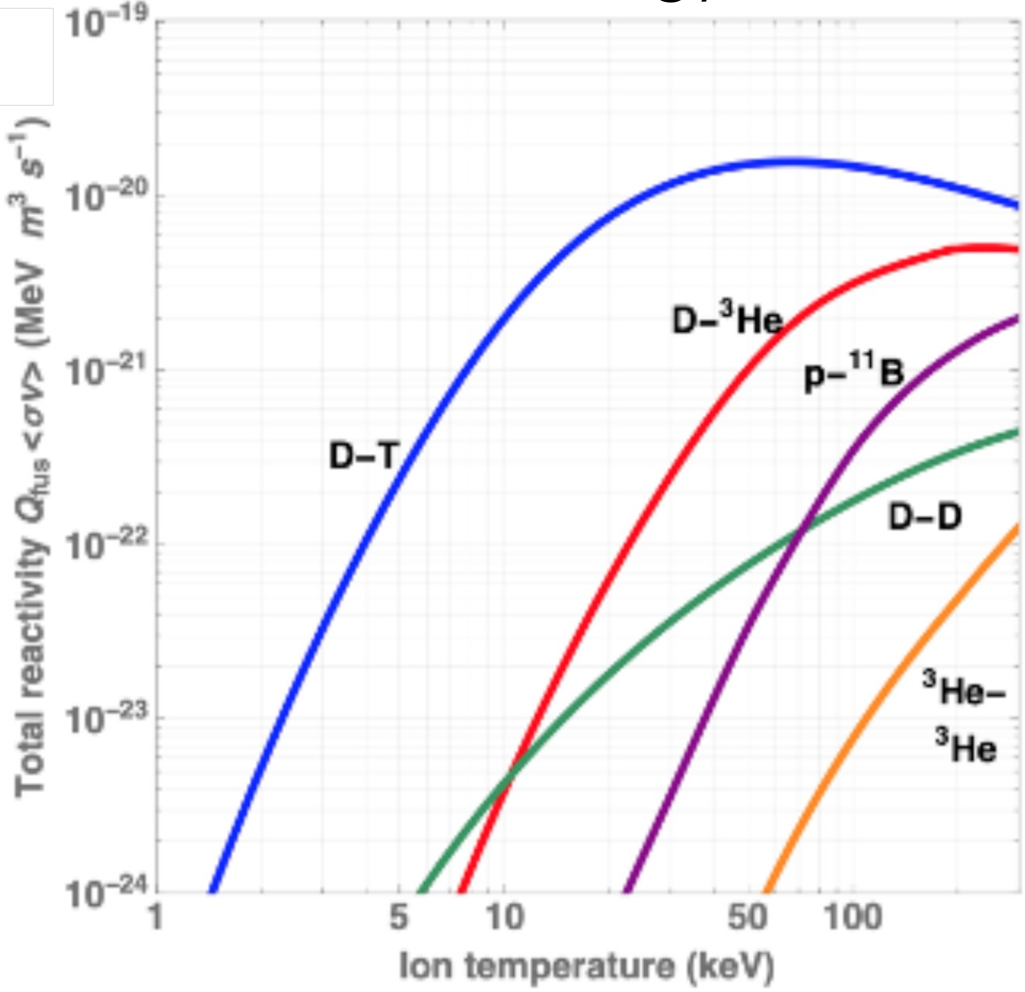
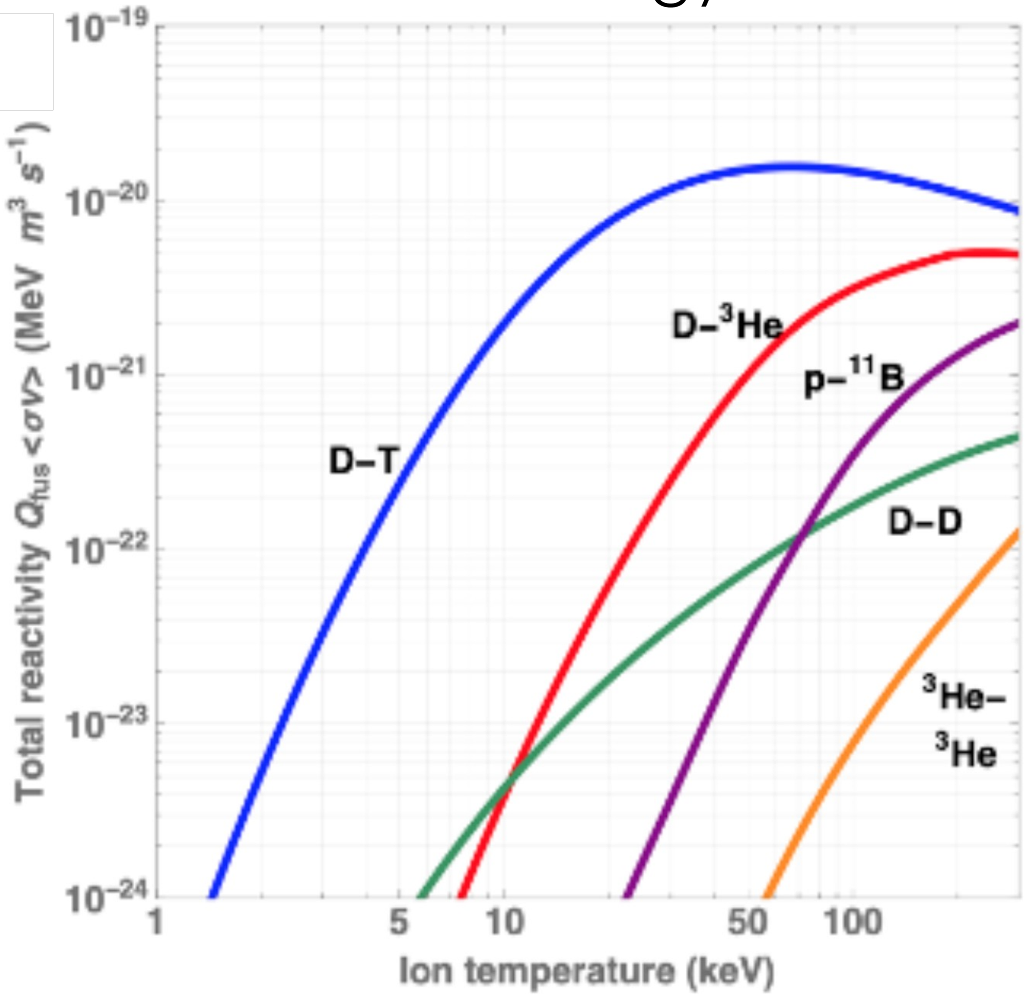


- First thing to note, this is hot!
  - electron-Volt (eV):
    energy imparted to an electron by passing through a potential of 1 V
  - 1 eV ~ 11,600 K
  - fusion reactors must achieve temperatures *at least* **10x hotter than the Sun**!

→*Matter is a plasma at these temperatures*

Deuterium-Tritium Fusion is the Main Focus of Research

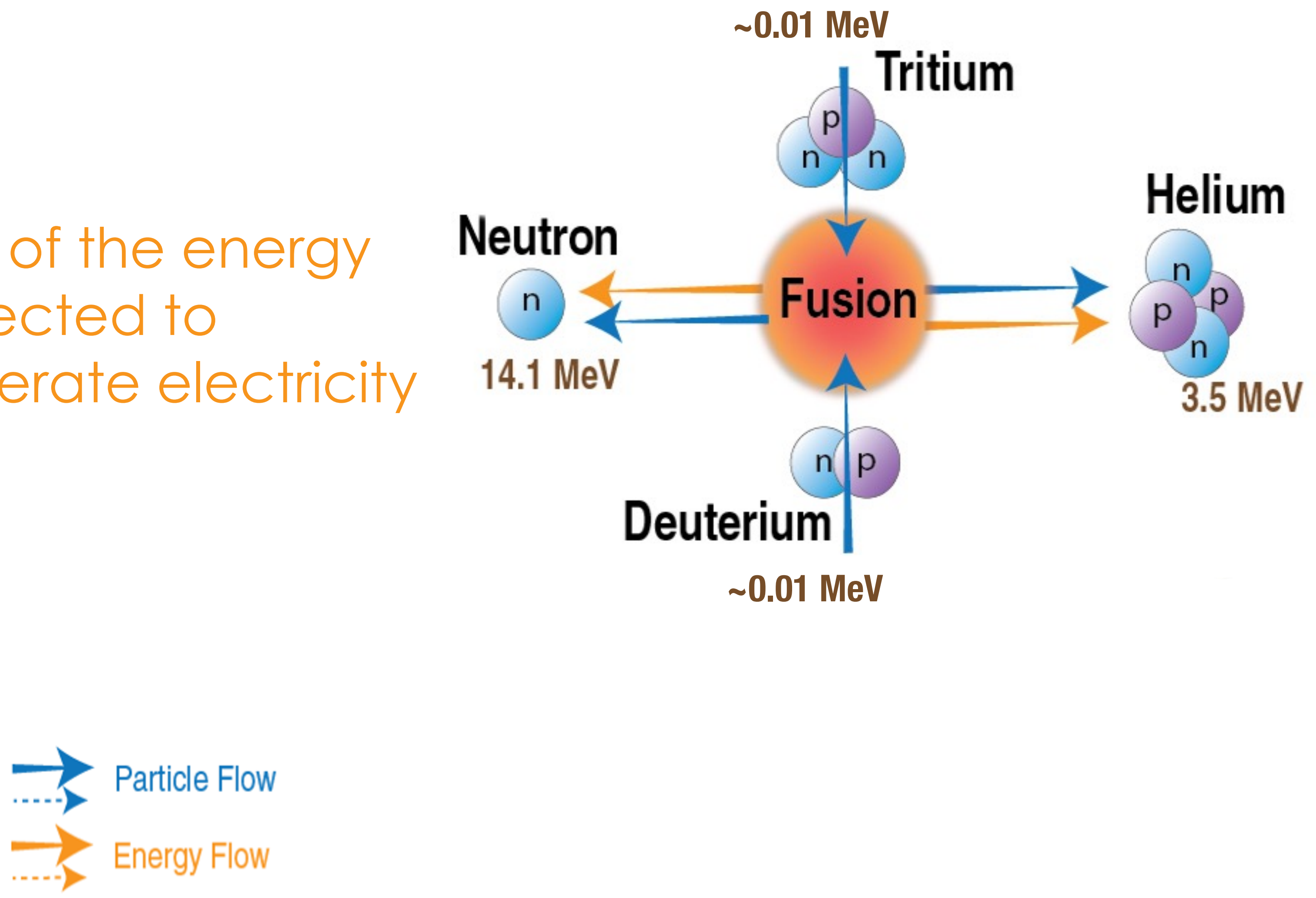
Reaction cross section times total energy released



- D-T is the "easiest"
- Fuel cycles like D-D, D-^{3}He, p-^{11}B
  - Produce less neutrons, reduces the requirement for neutron-tolerant materials in a fusion pilot plant
  - Removes need for tritium breeding
  - BUT require higher temperatures than D-T, require novel surface energy removal technology and configurations

DT Fusion Fundamentals

80% of the energy collected to generate electricity



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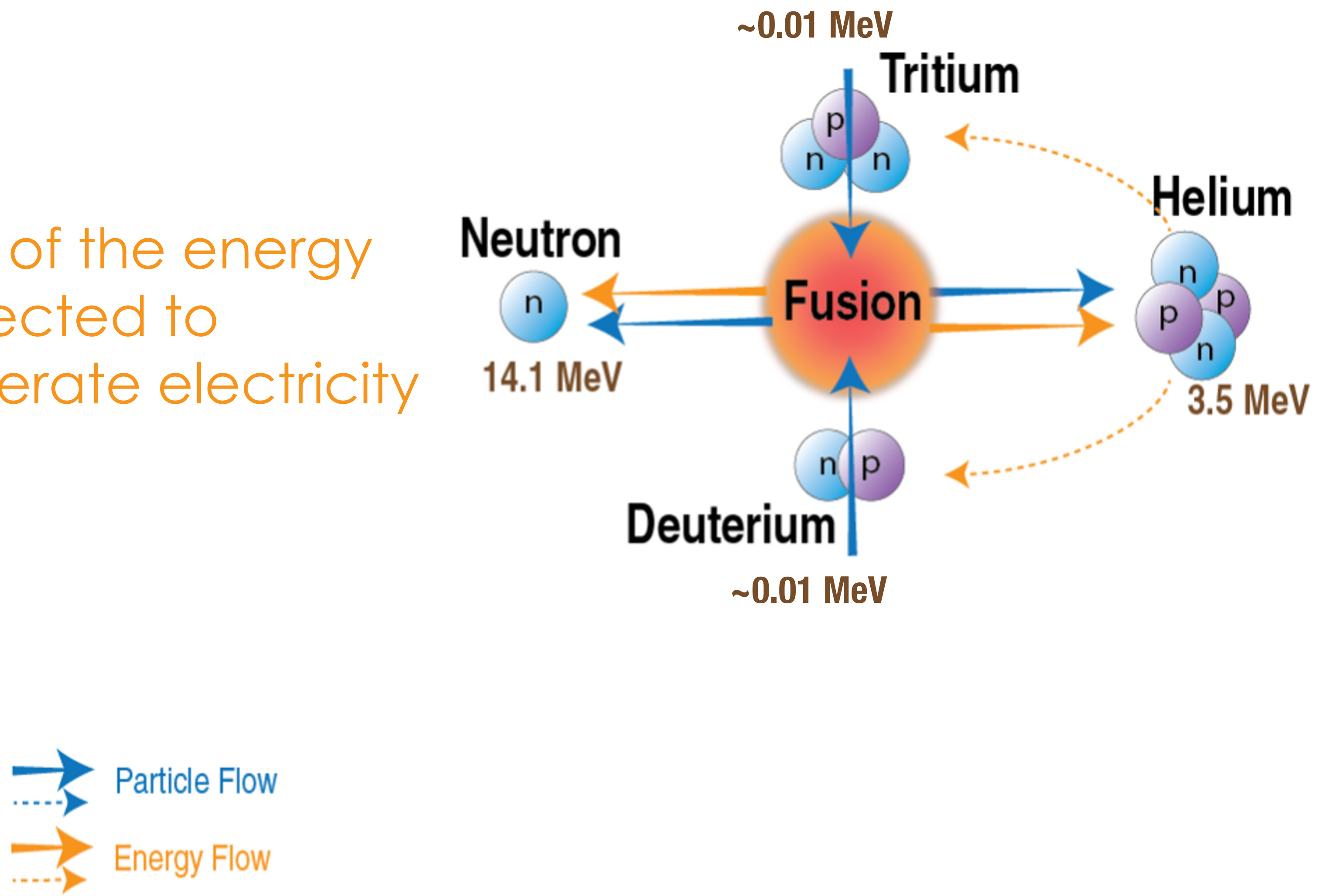
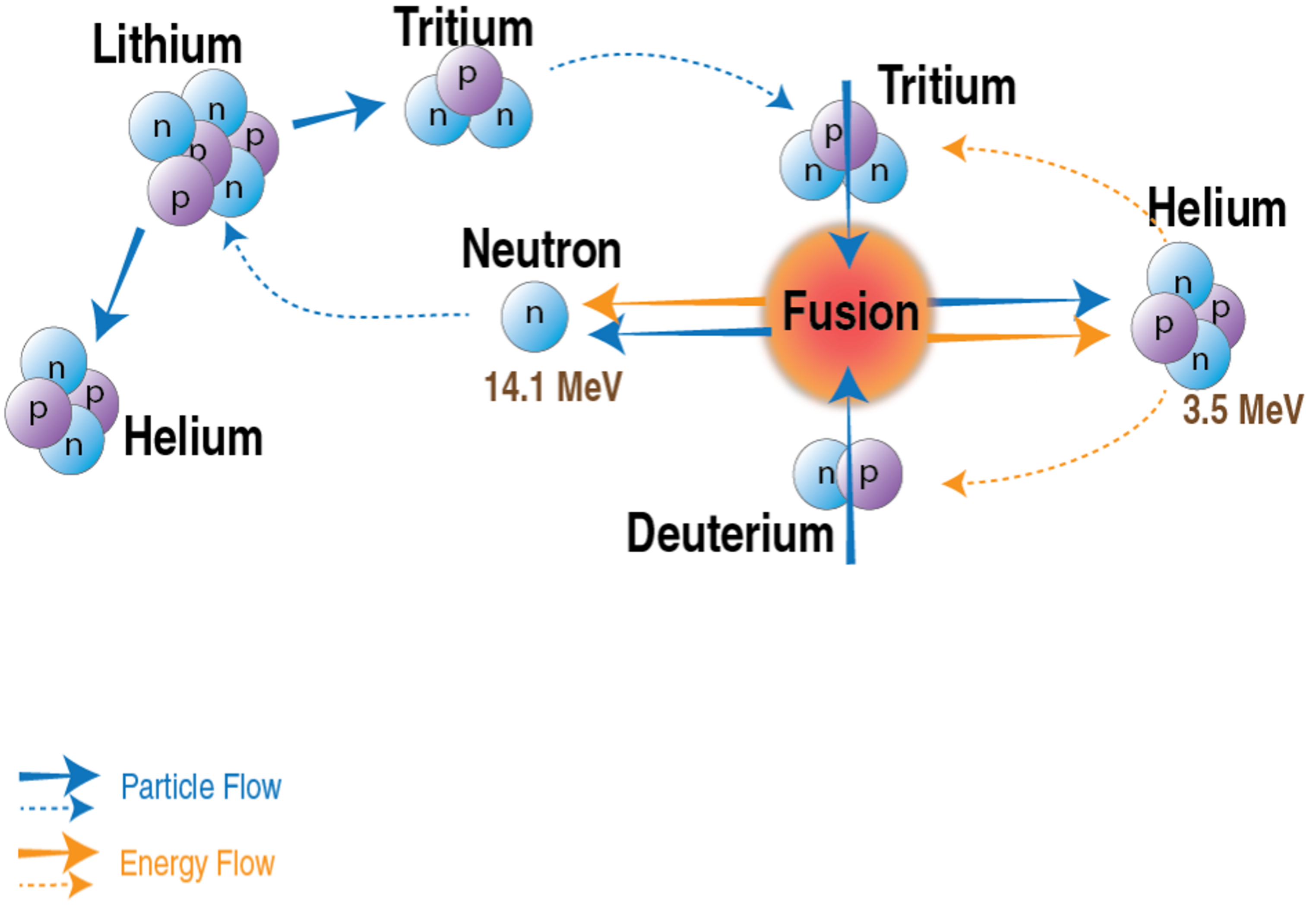


alpha particle heating:

20% of the energy stays to sustain the reaction

DT Fusion Fundamentals

Fusion reactor would need to "breed" tritium



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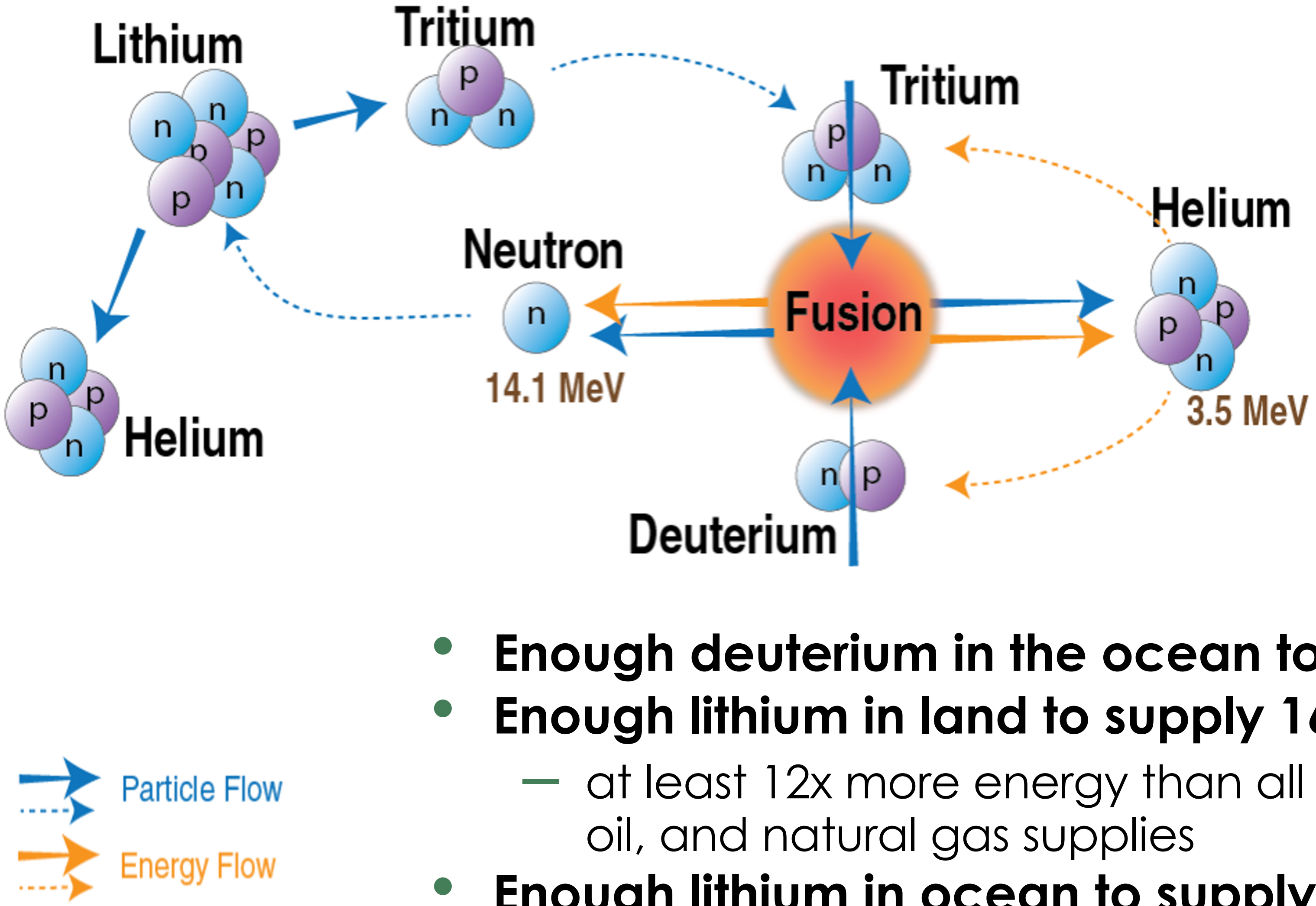

- **Enough deuterium in the ocean to supply 60 billion years**
- **Enough lithium in land to supply 16k years**
  - at least 12x more energy than all uranium, thorium, coal, oil, and natural gas supplies
- **Enough lithium in ocean to supply 30 million years**

Outline

- Introduction to Needs, Potential, and Conditions for Fusion
- **Progress Towards Fusion Energy**
- Challenges in Developing in Fusion Energy
- Exciting New Era for Fusion Energy Development

There Are a Lot of Fusion Concepts Out There

(rough map)

- Steady-state
  - Magnetic Confinement
    - Tokamak
    - Stellarator
    - Spheromak, FRC, RFP
    - Mirrors/GDT
  - Electrostatic Confinement
    - Fusor
    - Penning trap
    - Polywell
- Pulsed
  - Magnetized
    - Z, θ Pinches
    - Solid-liner MTF
    - Mag LIF
    - General Fusion
    - Helion
    - Hyper Jet
    - Plasma Focus
  - Inertial Confinement
    - Indirect Drive (NIF)
    - Direct Drive (LLE, NRL)
    - Heavy-ion-beam driven (LBNL)
    - Fast/shock ignition
    - Magnetized ICF

(yes, tokamak, others could be 'pulsed')

→ Increasing Density

There Are a Lot of Fusion Concepts Out There

Steady-state

Magnetic Confinement

Elec
Con

Tokamak
Stellarator
Spheromak, FRC, RFP
Mirrors/GDT

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P

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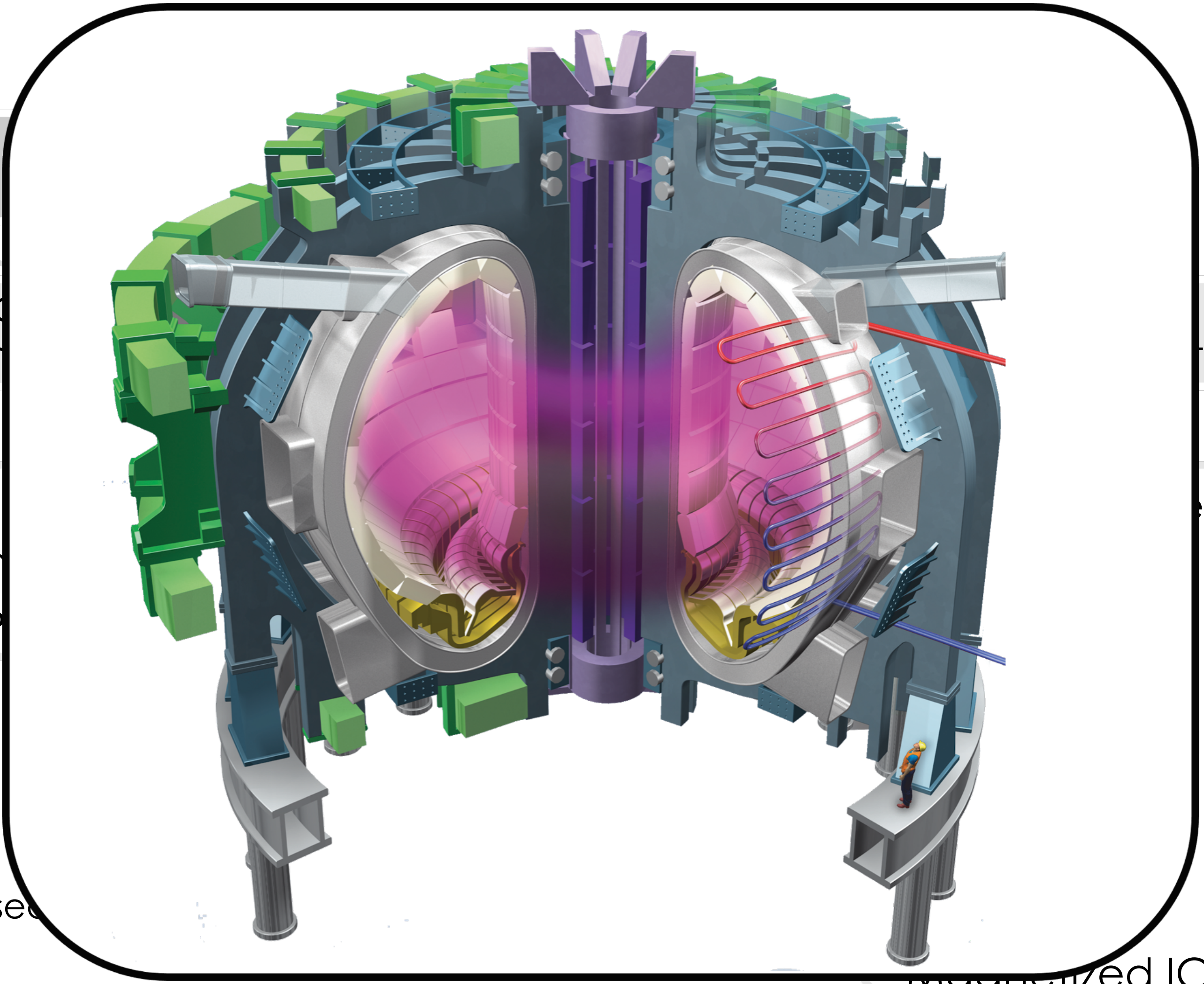
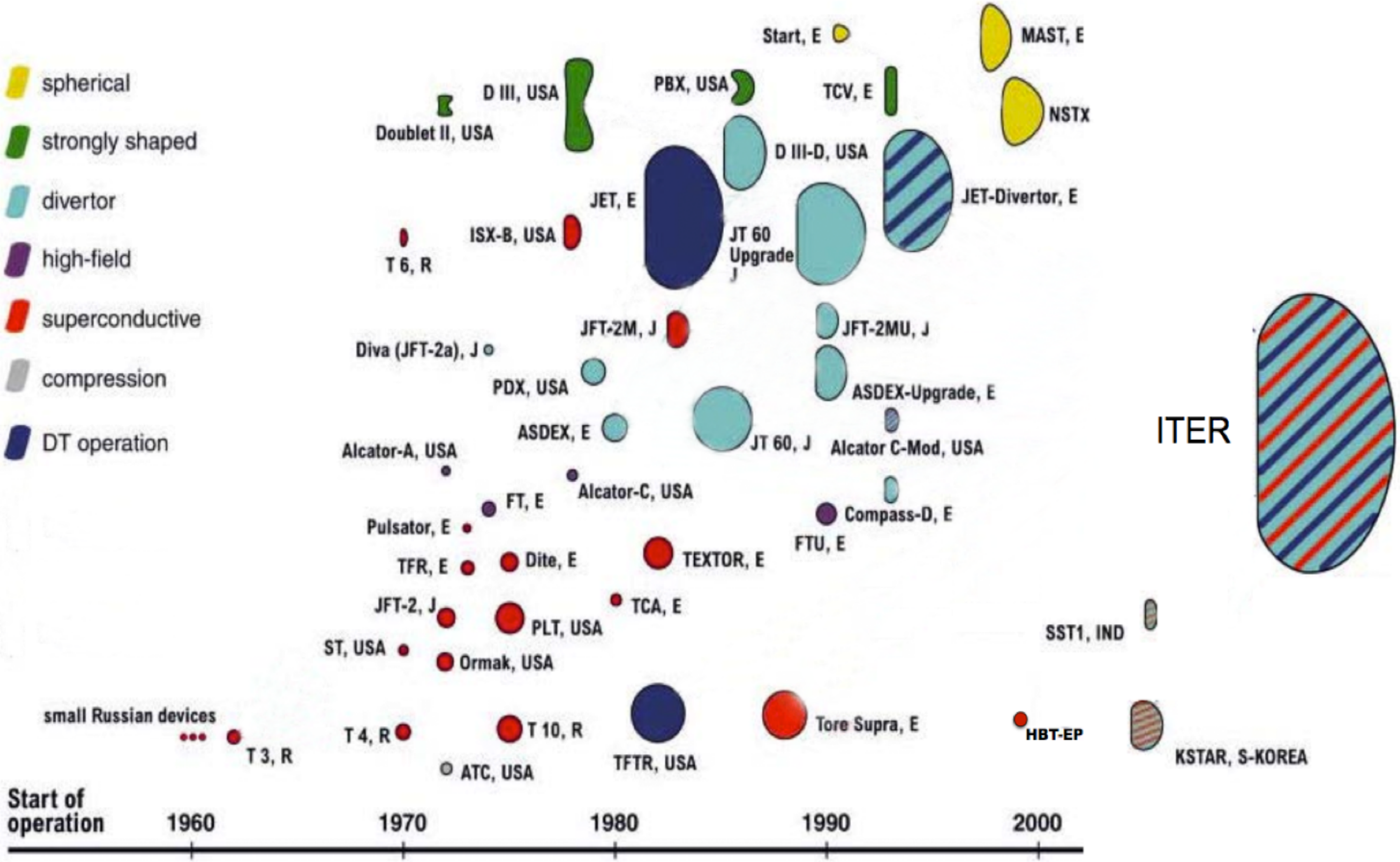


Magnetized ICF

(yes, tokamak, others could be 'pulse

Increasing Density

Tokamaks Have Been The Best Performing – We've Built Over 200 Tokamaks in All of Time!



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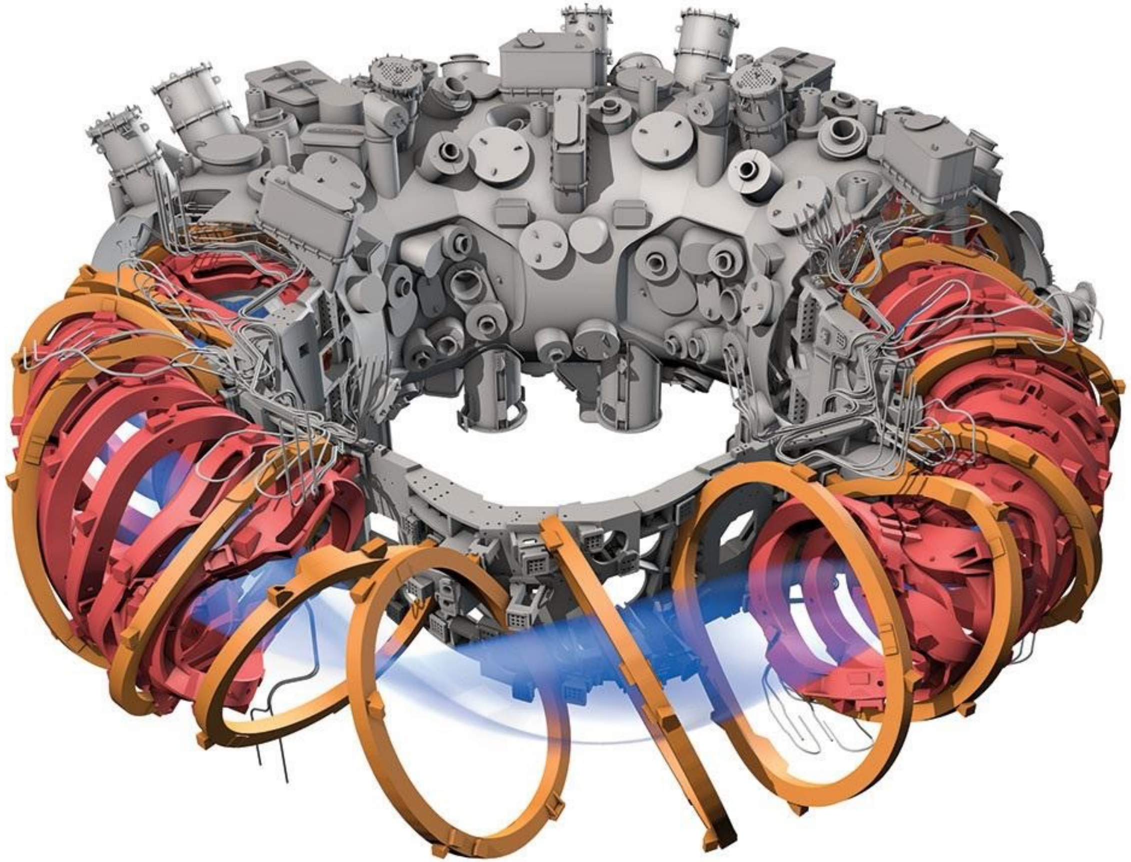

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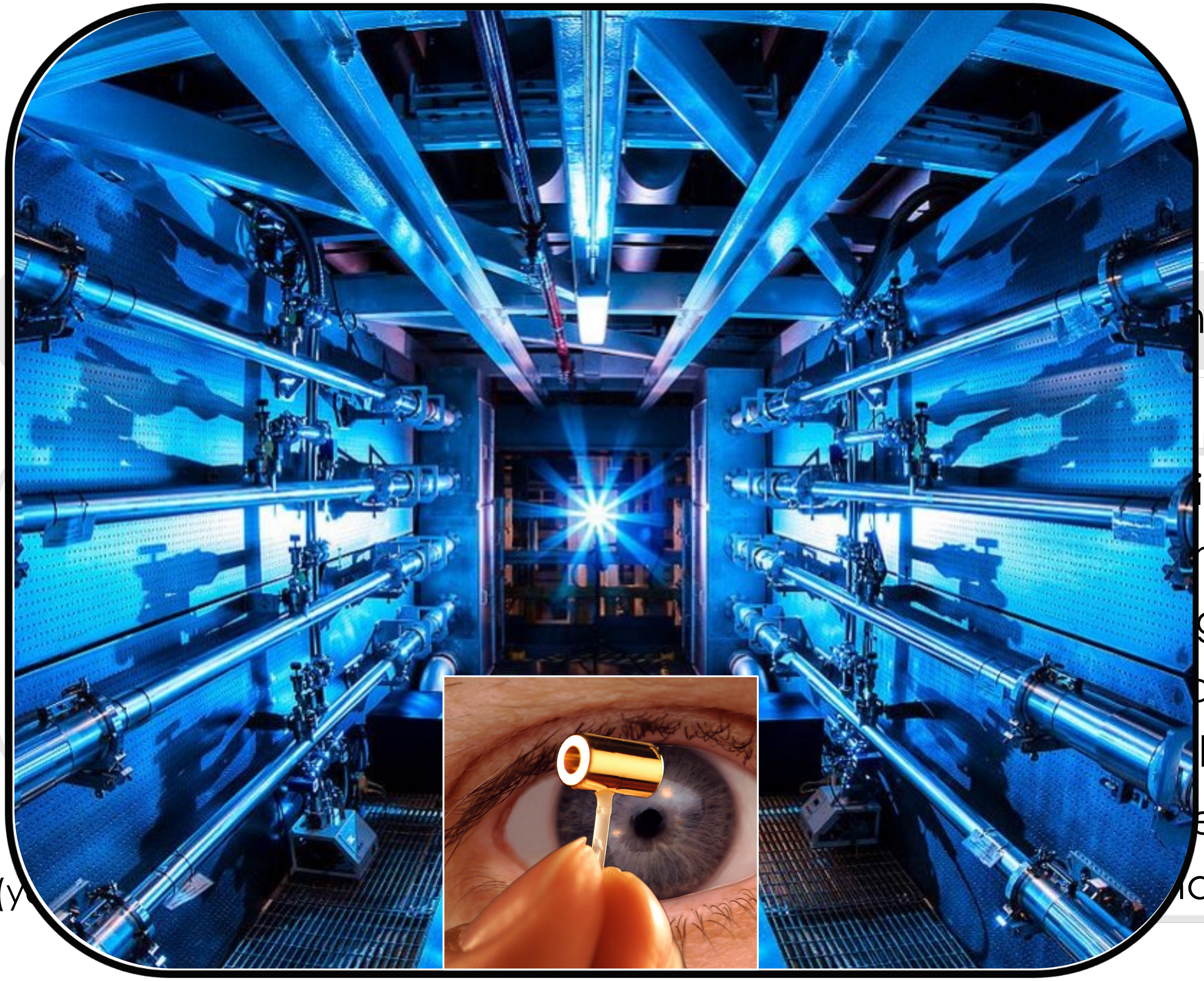

Pulsed

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Inertial Confinement

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Indirect Drive (NIF)

Direct Drive (LLE, NRL)

Heavy-ion-beam driven (LBNL)

Fast/shock ignition

Magnetized ICF

(y

Increasing Density

The Triple Product is a Fundamental Figure of Merit

- Self-sustaining fusion reaction requires high fusion gain

$$Q = \frac{P_{fusion}}{P_{heat}}$$

- Triple product (Lawson criterion): energy released in fusion products must exceed the sum of the energy applied to heat

$$nT\tau_E > 2\text{x}10^{21}\ \text{m}^{-3}\text{-keV-s}$$ (for Q=10)

Density
(enough particles)
n~2-3x10^{20} *ions/m*^{3}

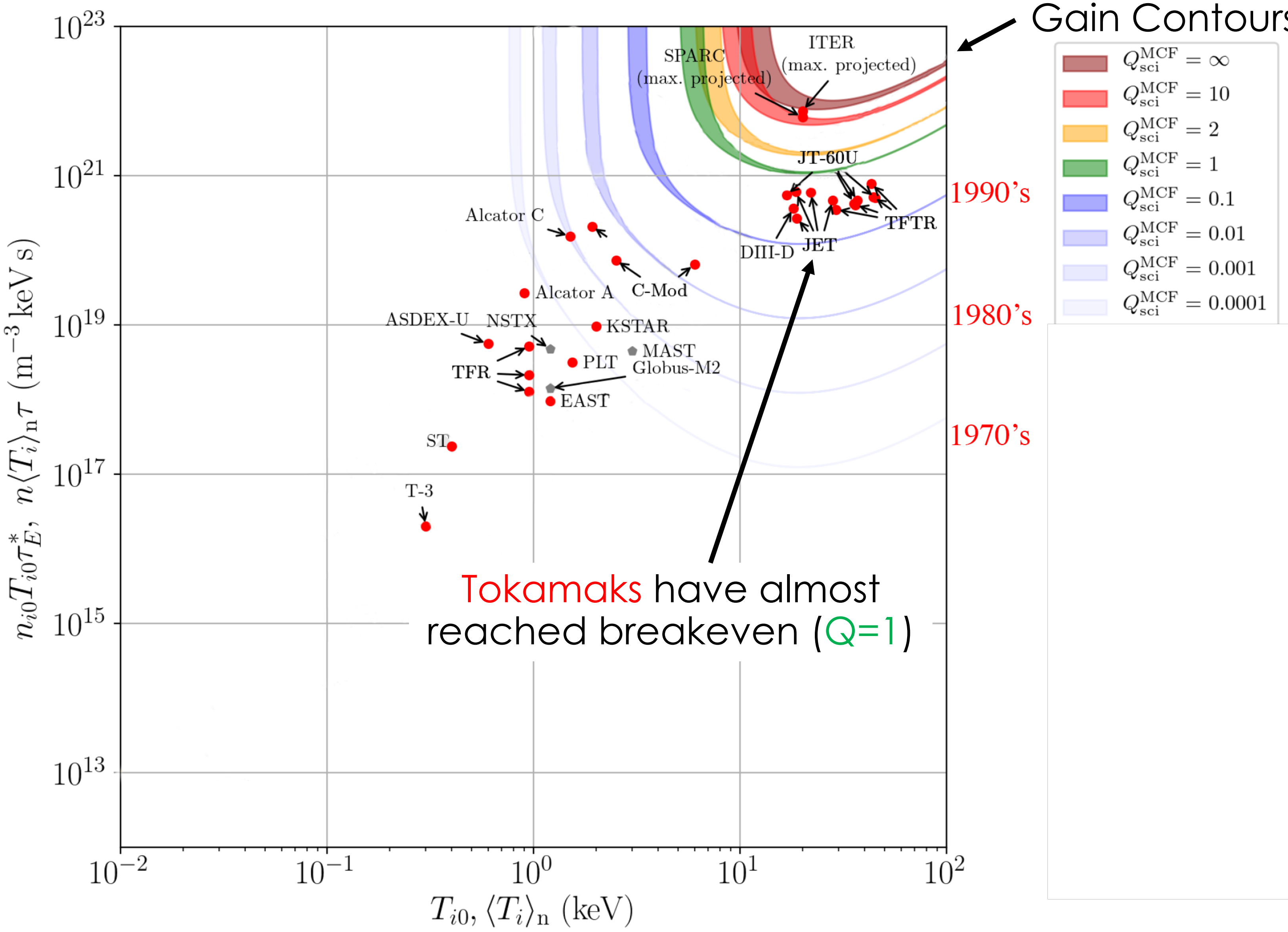
Temperature
(enough energy)
T~100-200 *million K*

Confinement
(enough time to collide)
τ_E ~1-2 *seconds*

Triple Product Progress

Gain Contours

Triple Product

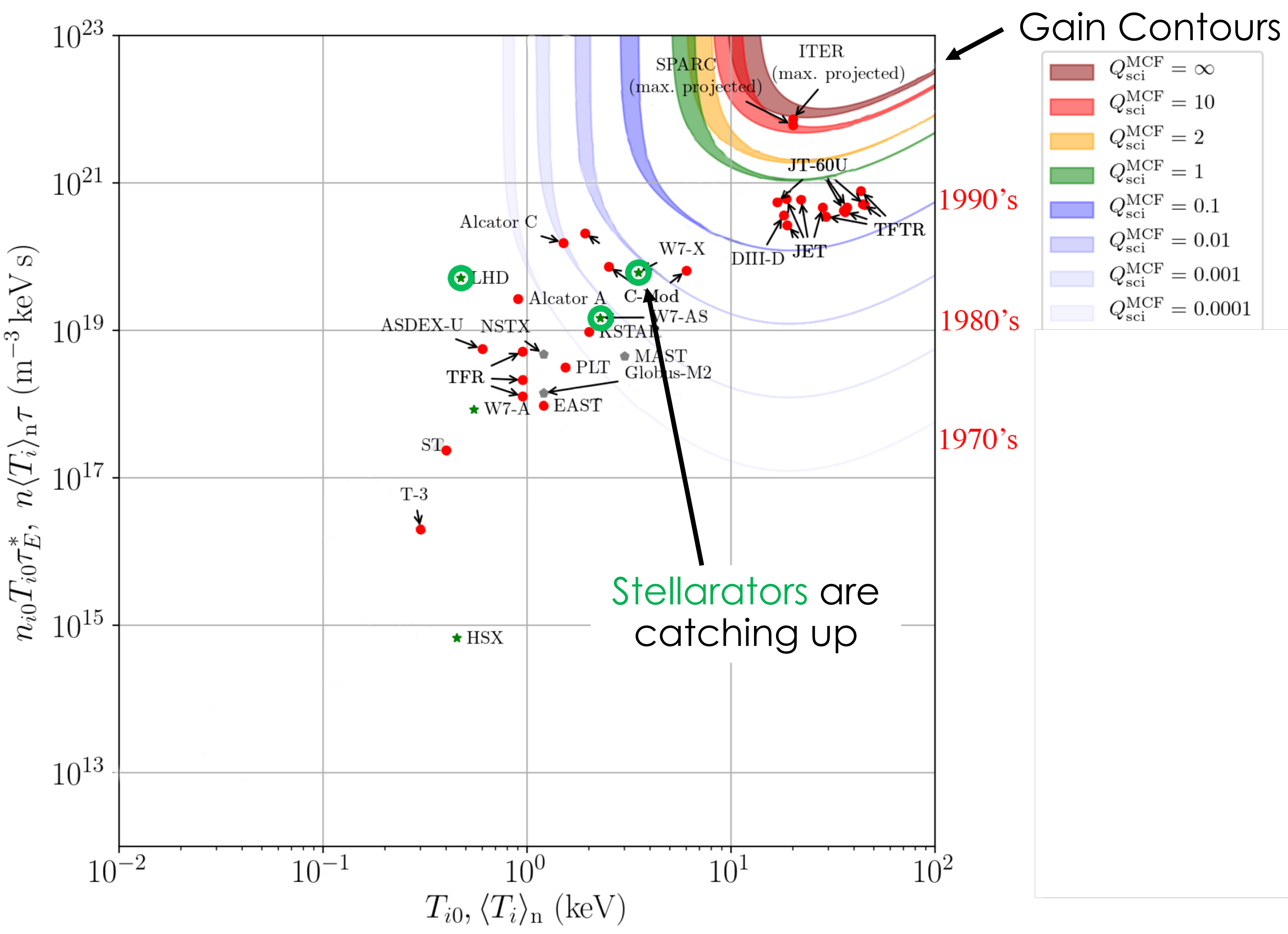


Ion Temperature

[Wurzel, preprint arxiv.org/abs/2105.10954]

Triple Product Progress

Triple Product



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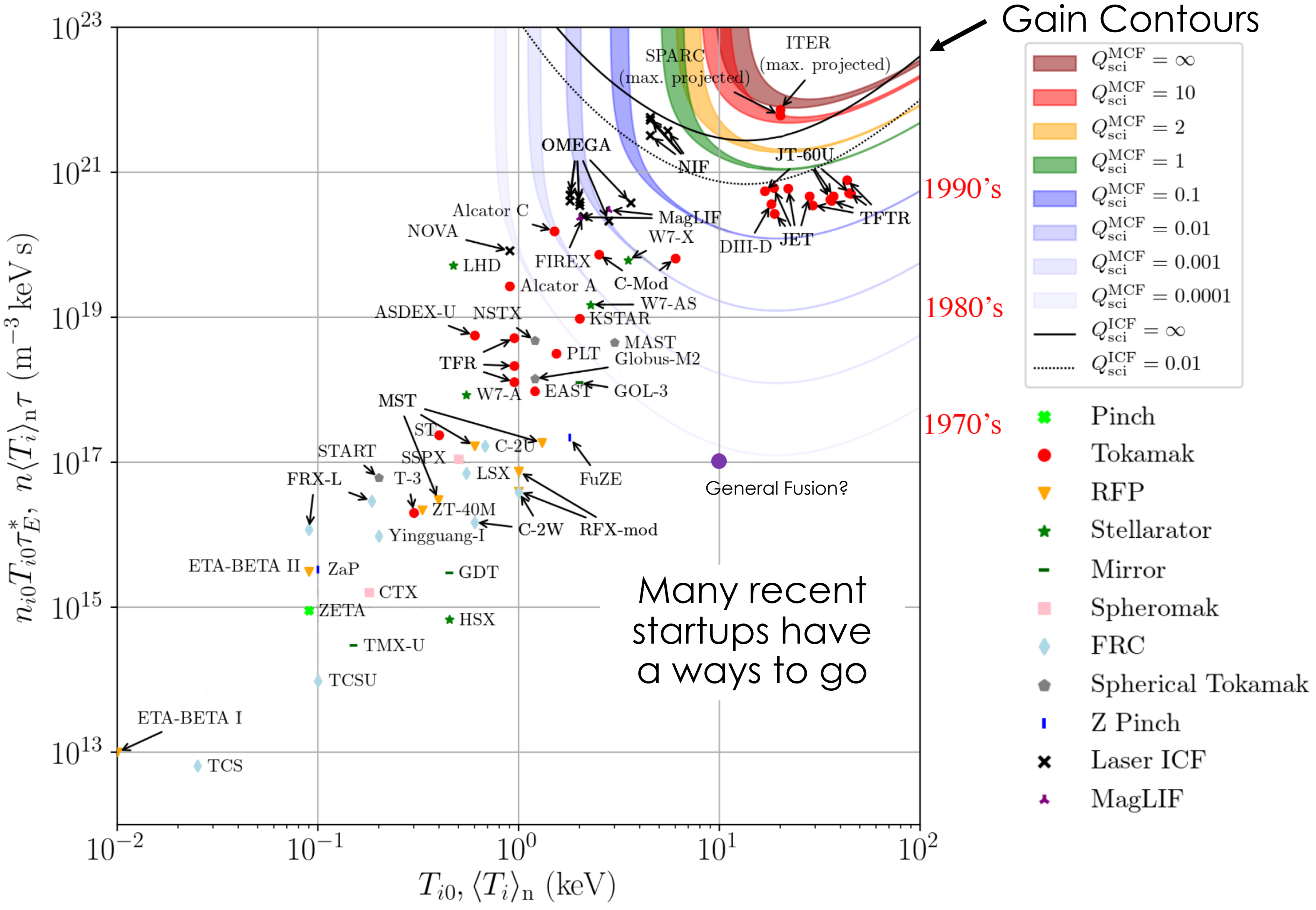
Triple Product Progress

Triple Product



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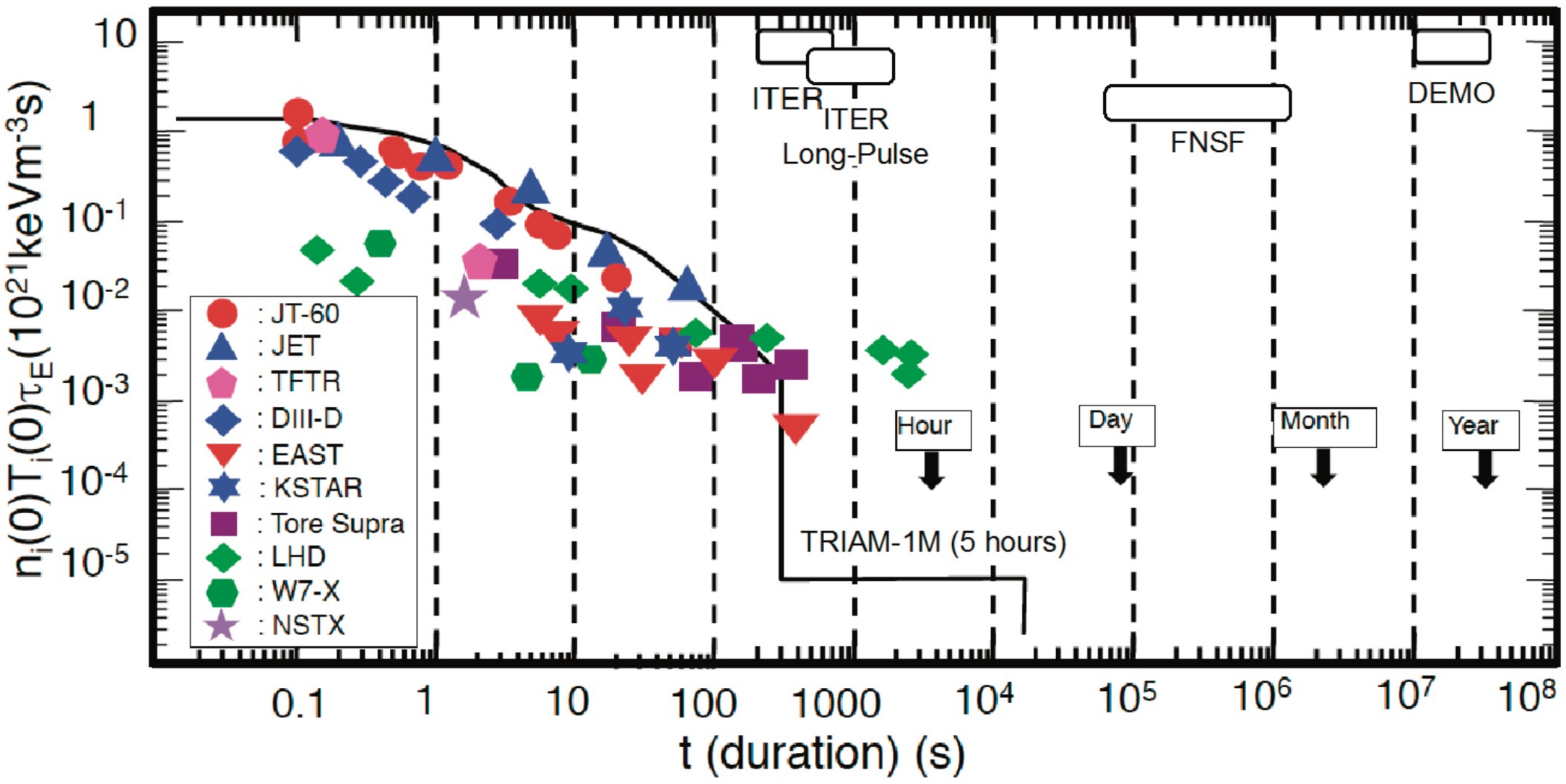
But Making Electricity Is More Than Just Triple Product

Fusion Triple Product vs. Plasma Duration

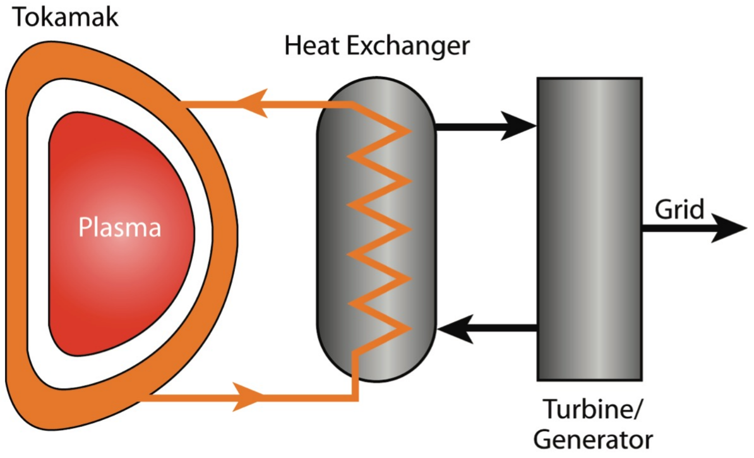


Significant progress is needed to demonstrate high gain AND long-duration (or high rep rate?) to be relevant for cost-effective, uninterrupted fusion power production

Why Steady-State?

Power Plant Optimization Motivates Steady-State Tokamak Operation

- **Efficient conversion of heat to electricity requires a constant heat source**
  - Lifetime of heat exchangers limited if temperature deviates by more than a few degrees
  - Time without fusion power between tokamak pulses is too long (>100 s) for a thermal reservoir to be practical
  - Probability of unscheduled outage must be very small ➔ high reliability needed



133-09/jy

2009 APS Meeting/TCL/2009

[Tim Luce, APS 2009]

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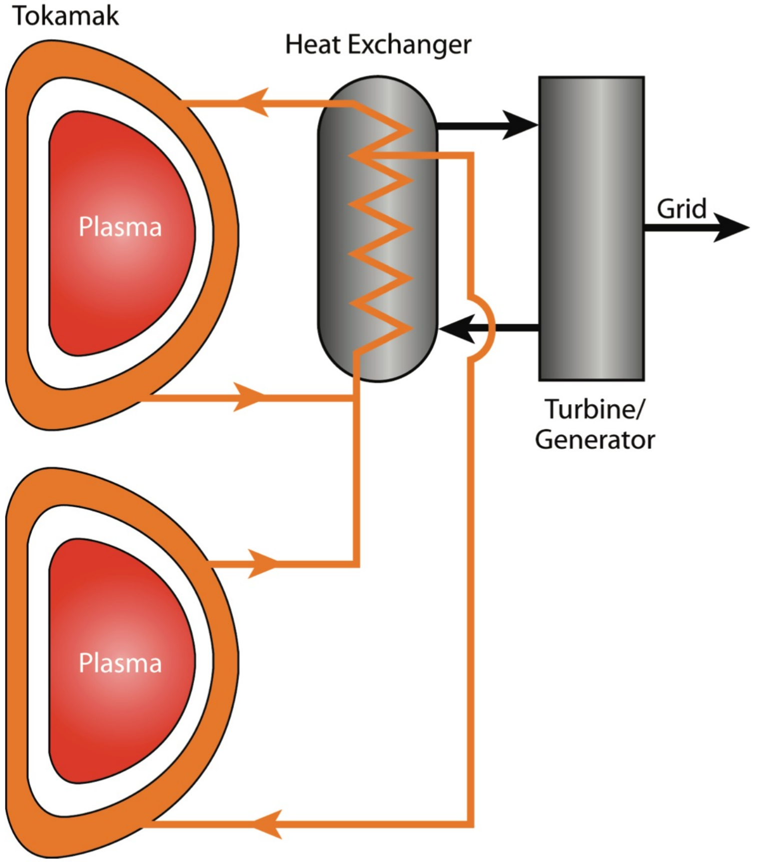
- **Pulsed tokamaks can be used in pairs to yield constant heat source ➔ capital cost increases for fixed power**



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[Tim Luce, APS 2009]

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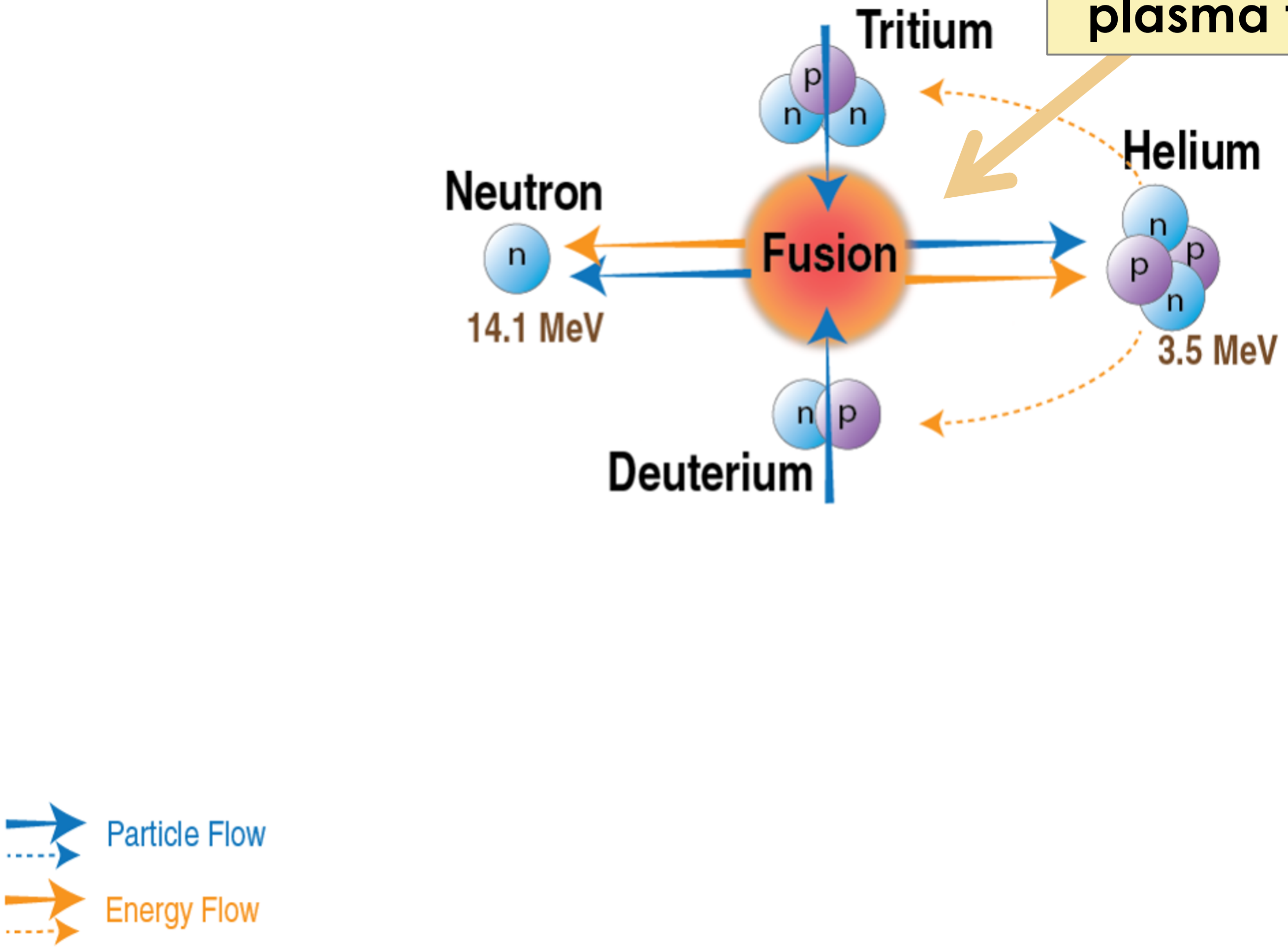
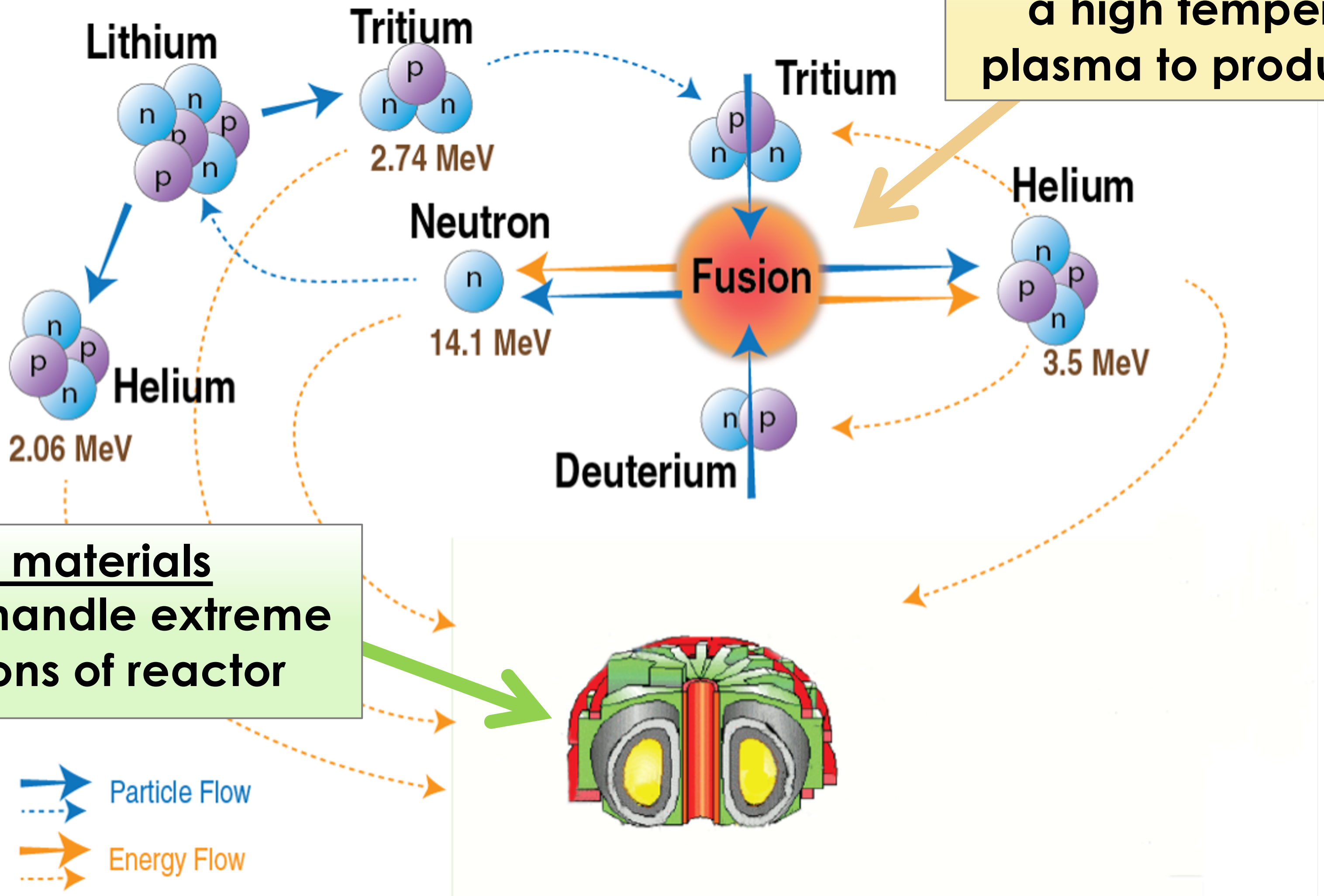
Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges

<u>Control, sustain, and predict</u>
a high temperature "burning" plasma to produce neutrons/heat



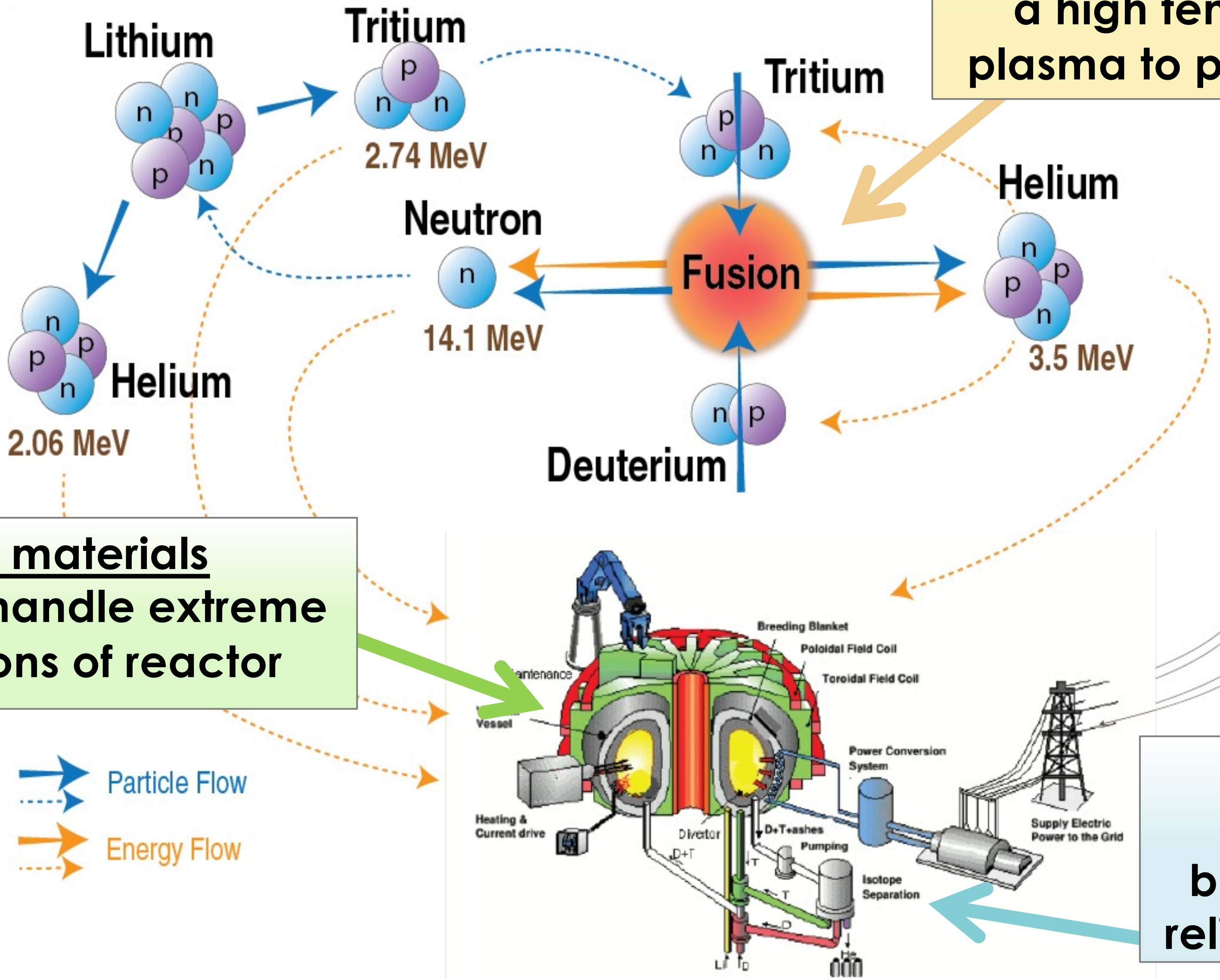
Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges

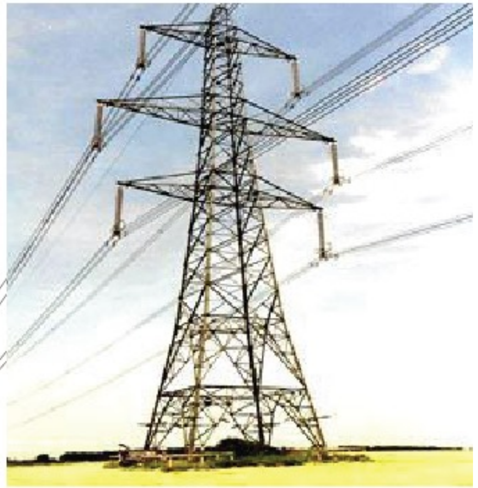
<u>Control, sustain, and predict</u>
a high temperature "burning" plasma to produce neutrons/heat



<u>Find materials</u>
that can handle extreme conditions of reactor

Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges





Control, sustain, and predict
a high temperature "burning" plasma to produce neutrons/heat

Find materials
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Harness fusion power
by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges

<u>Control, sustain, and predict</u>
a high temperature “burning” plasma to produce neutrons/heat

Much of fusion research has been focused on this ‘first’ step,
so I’ll go into a bit more of an overview here (tokamak-centered).

But achieving fusion energy is **critically dependent on finding the integrated solution to all challenges**:
significant, urgent research is needed here
(more to come in materials, fuel cycle talks in this course)

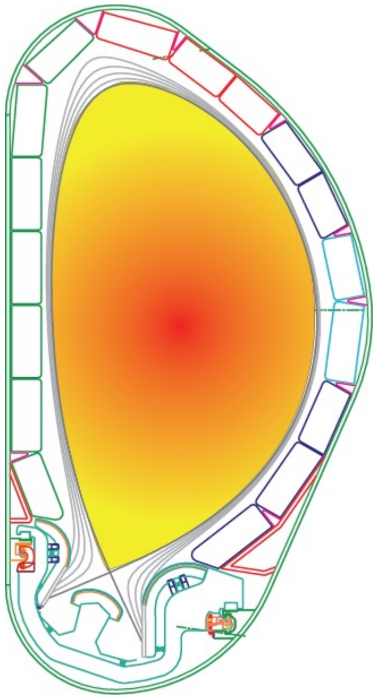
<u>Find materials</u>
that can handle extreme conditions of reactor

<u>Harness fusion power</u>
by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

Integrated Research Necessary to Produce and Optimize Burning Plasmas

Control, sustain, and predict

Harness fusion power



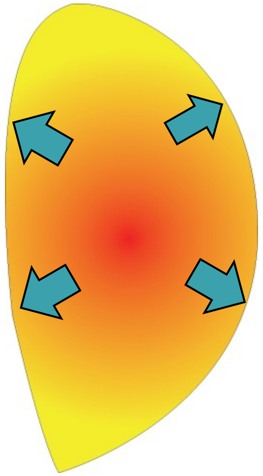
Find materials

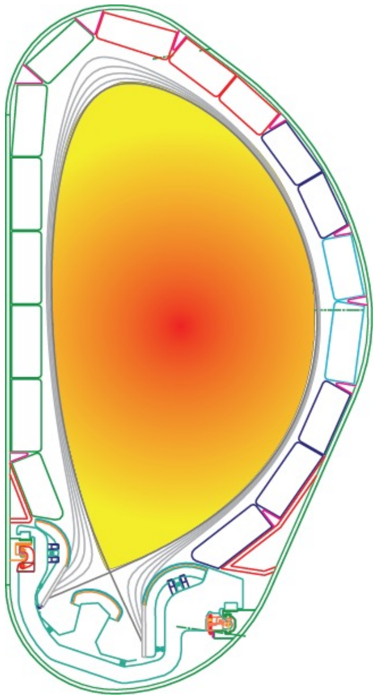
Integrated Research Necessary to Produce and Optimize Burning Plasmas

Control, sustain, and predict

Harness fusion power

- **Core**:
  - Generate heat/neutrons from fusion reactions
  - Contain energy as long as possible
  - Produce optimize state w/ weak control





Find materials

Integrated Research Necessary to Produce and Optimize Burning Plasmas

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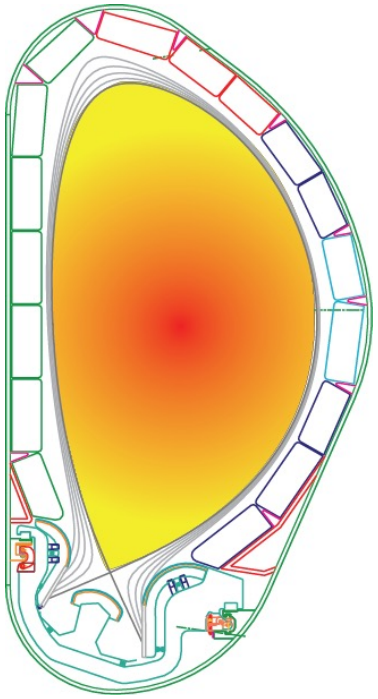

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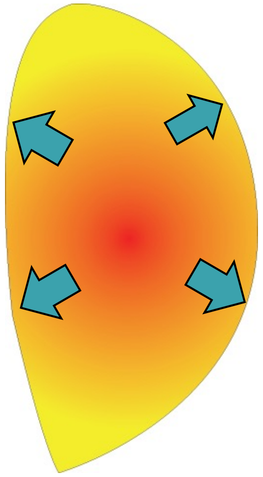
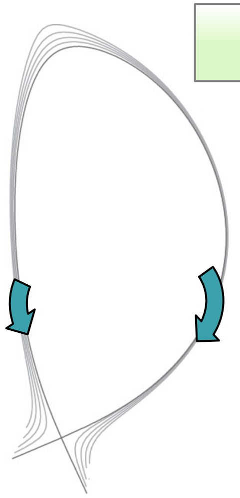


Find materials

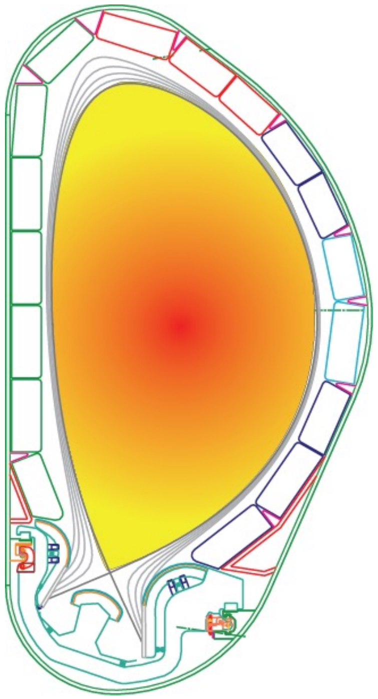


- **Edge/Scrape-Off Layer:**
  - Mediate core and divertor coupling
  - Minimize effect of transients
  - Screen impurities

Integrated Research Necessary to Produce and Optimize Burning Plasmas

Control, sustain, and predict

Harness fusion power



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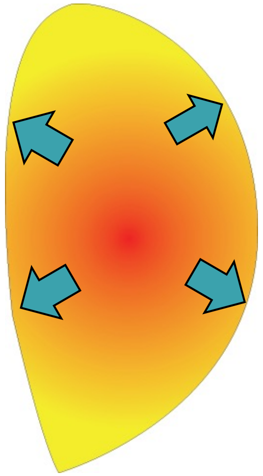

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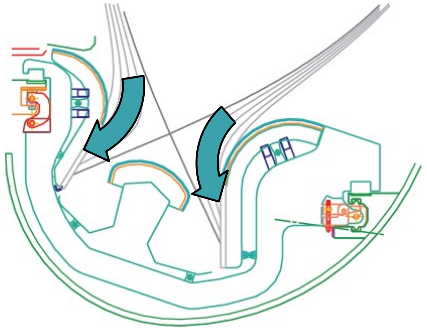

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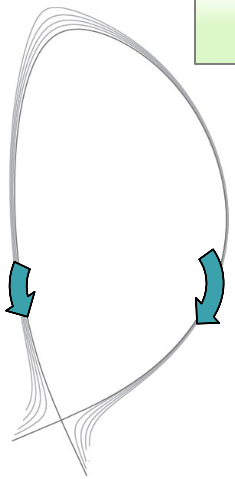
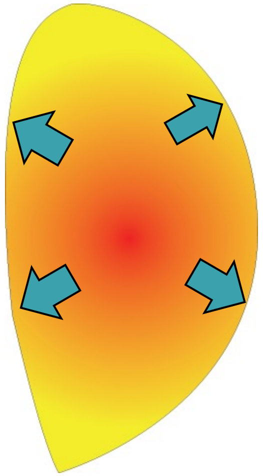


- **Divertor:**
  - Dissipate heat
  - Shield eroded materials from core
  - Exhaust helium "ash"

Integrated Research Necessary to Produce and Optimize Burning Plasmas

Control, sustain, and predict



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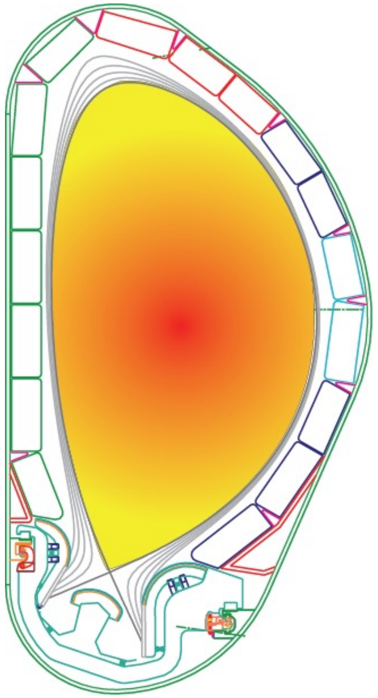
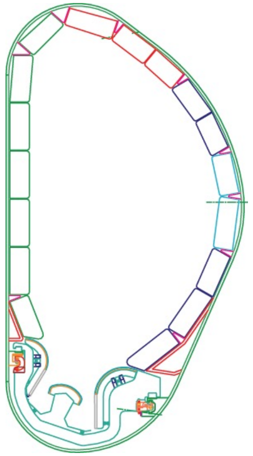
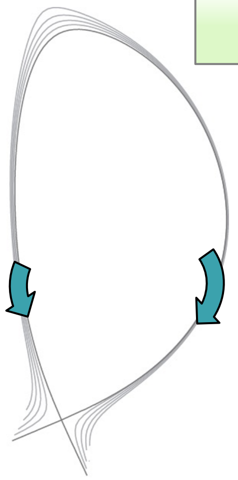


Harness fusion power



- **Blanket:**
  - Breed tritium
  - Extract heat
  - Shield magnets from neutrons

Find materials



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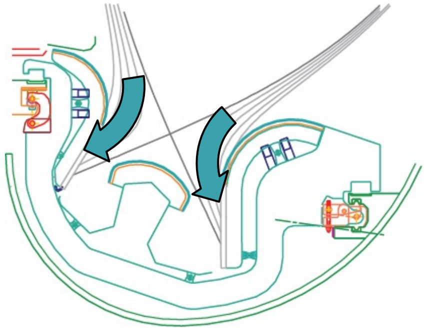

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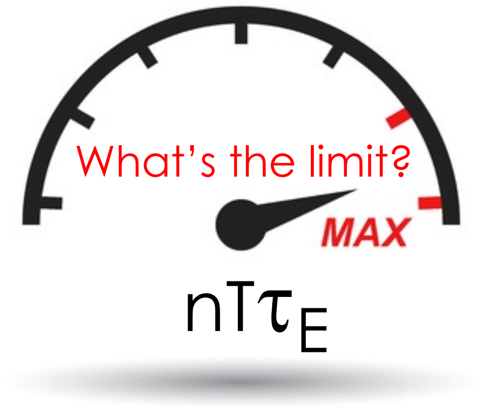
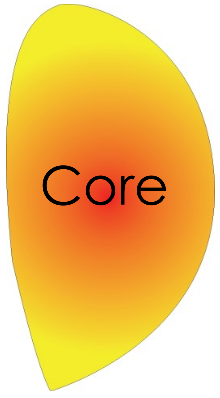
Some General Considerations About Burning Plasma Access

- Physics of turbulent transport and large scale MHD instabilities constrain pressure and temperature gradients





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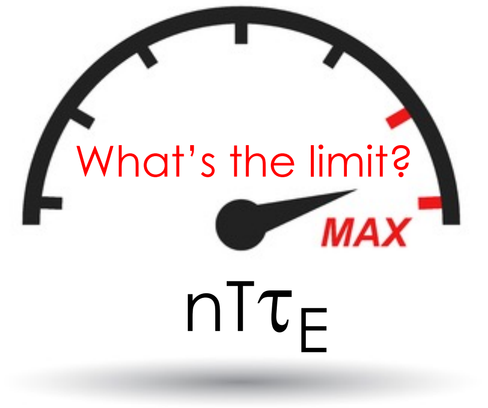

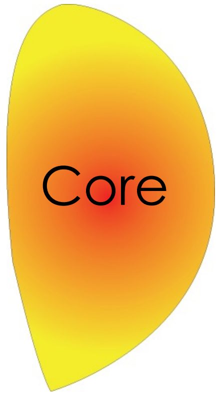

Maximum pressure limited by plasma stability:

$$\beta = n\,T \,/\, (B^2/2\mu_o) < \beta_{limit}$$

magnetic field

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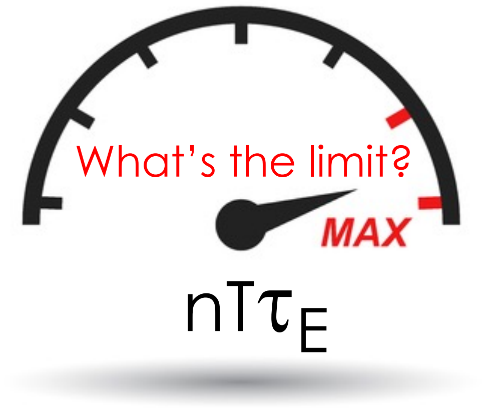

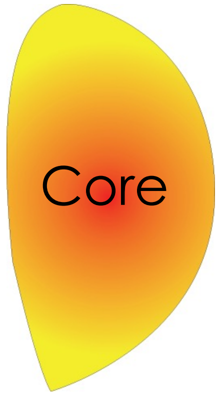

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$$\beta = n\,T \,/\, (B^2 / 2\mu_o) < \beta_{limit}$$

magnetic field

Global energy loss time scale:

$$\tau_E \sim a^2 / \chi$$

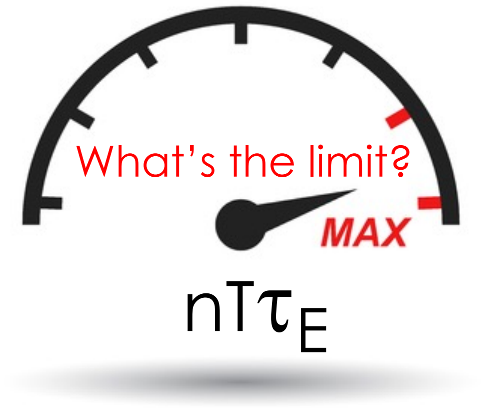
minor radius   plasma transport coefficient

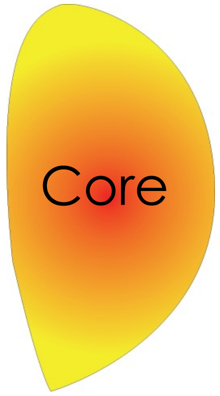
Leading order plasma physics term in transport scalings is plasma current (I_p):

$$\chi \sim 1 / I_p$$

Some General Considerations About Burning Plasma Access

- Physics of turbulent transport and large scale MHD instabilities constrain pressure and temperature gradients





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$$\tau_E \sim a^2 /\chi$$

minor radius

plasma transport coefficient

Leading order plasma physics term in transport scalings is plasma current (I_p):

$$\chi \sim 1 \,/\, I_p$$

Combining all these:

$$n\,T\,\tau_E \sim \beta\, I_p\, (a\,B)^2$$

Rewrite with normalized beta

$$\beta_N = \beta \,/\, (I_p \,/\, a\,B)$$

Hence,

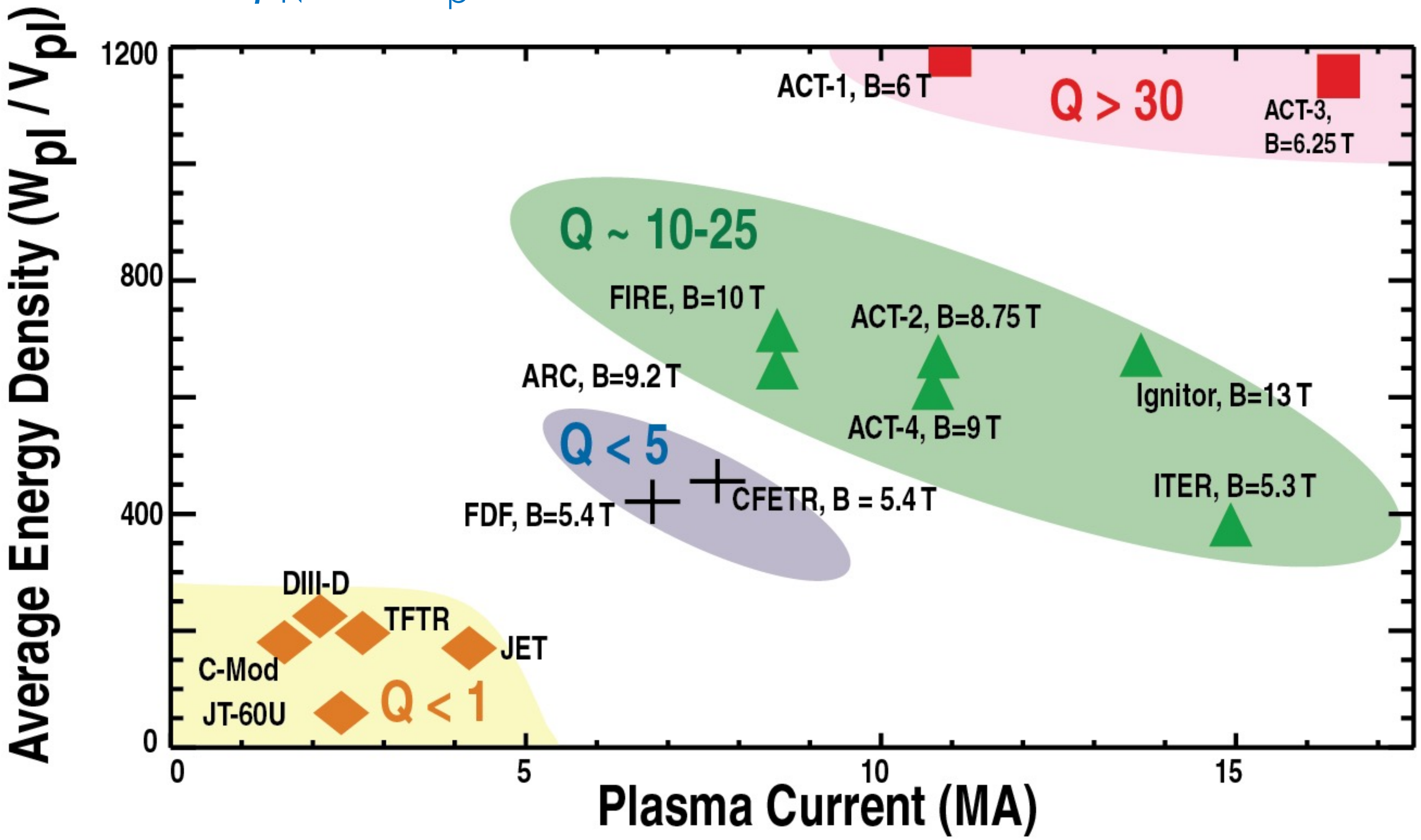
$$\boxed{n\,T\,\tau_E \sim \beta_N\, I_p^2\, a\,B}$$

(β_N is limited by plasma stability)

Burning Plasmas Designs Typically Have I_p > 8 MA, B_T > 5 T and High Thermal Energy Density

- Design approach: Adopt physics and technology limits for β_N, I_p, and B; Adjust device size for desired n T τ_E

→ β_N > 2; I_p ~ 8-15 MA; B ~ 5-9 T; a ~ 1-5 m



What Makes a Burning Plasma Unique?

	Fusion Gain	α-Heating Fraction	Scientific Frontier
	$Q = \frac{P_{fusion}}{P_{heat}}$	$f_\alpha = \frac{P_\alpha}{P_\alpha + P_{heat}}$	
Scientific Breakeven	Q = 1	17%	Alpha confinement

plasma transitions from endothermic to exothermic

Endothermic

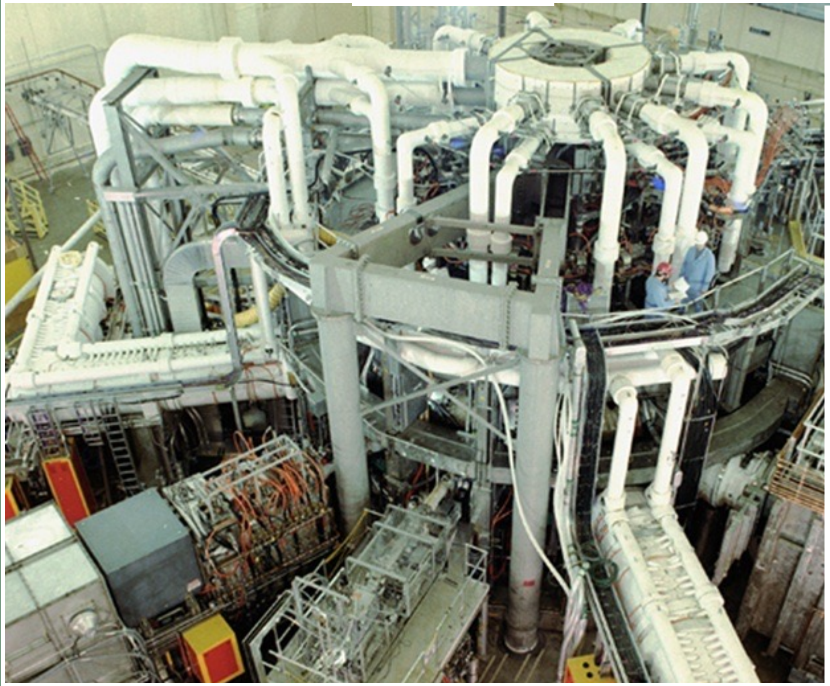
Exothermic

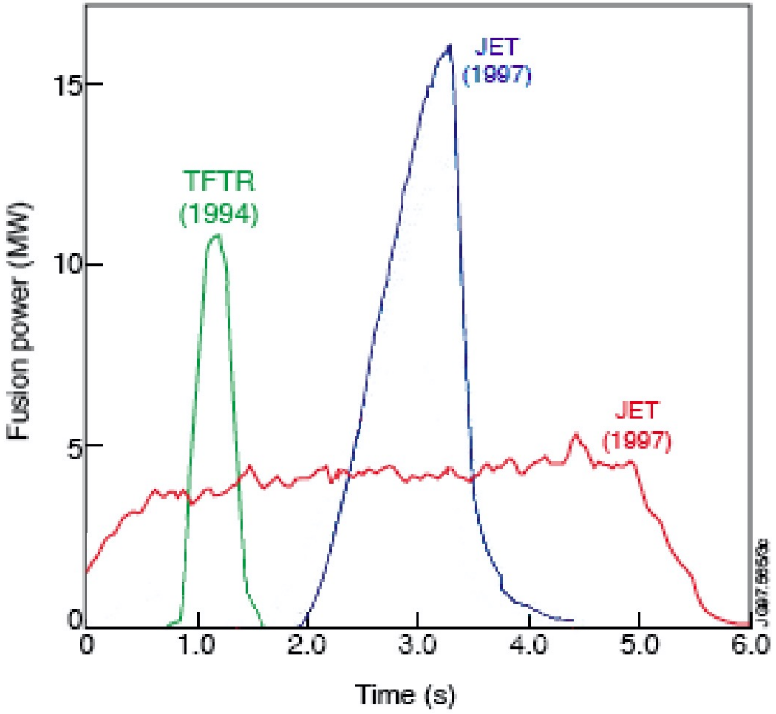
Highly non-linear behavior can result

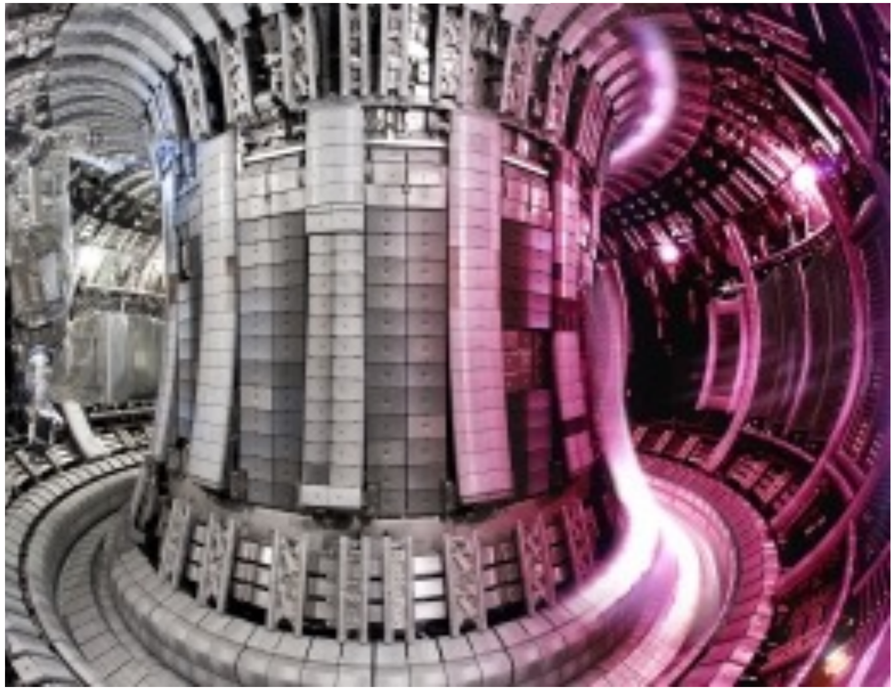
Alpha Particle Heating has Been Observed in D-T Experiments on JET and TFTR at Q < 1

TFTR

JET

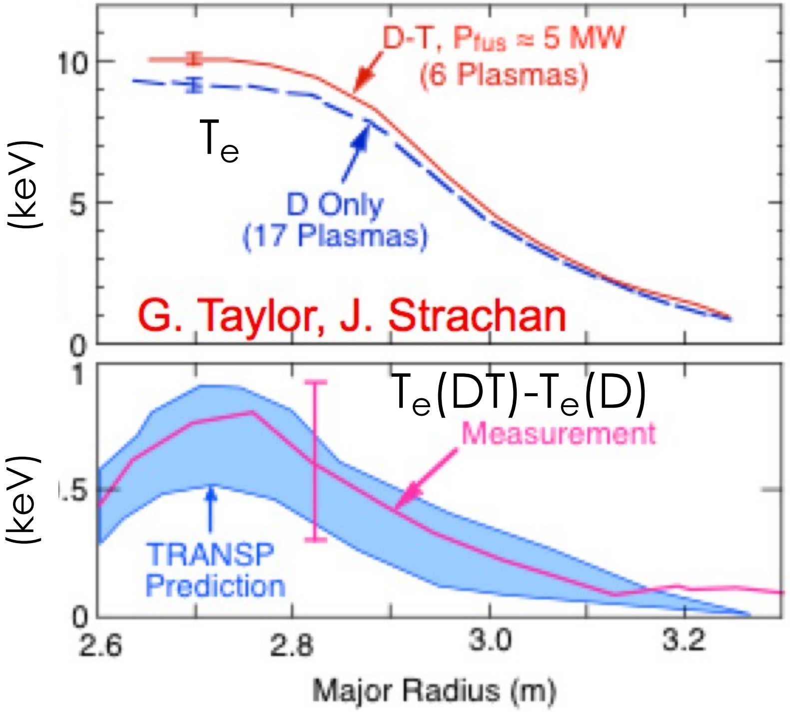


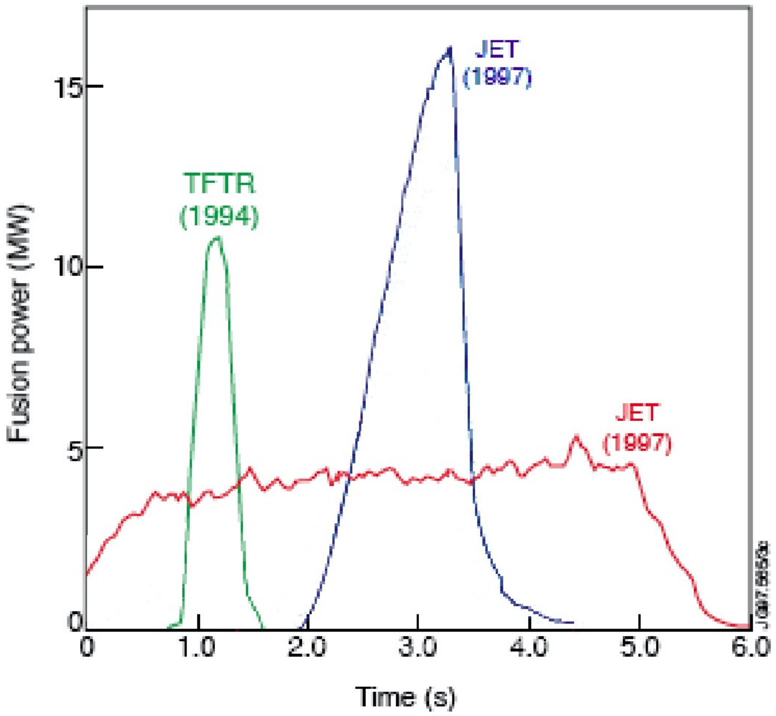




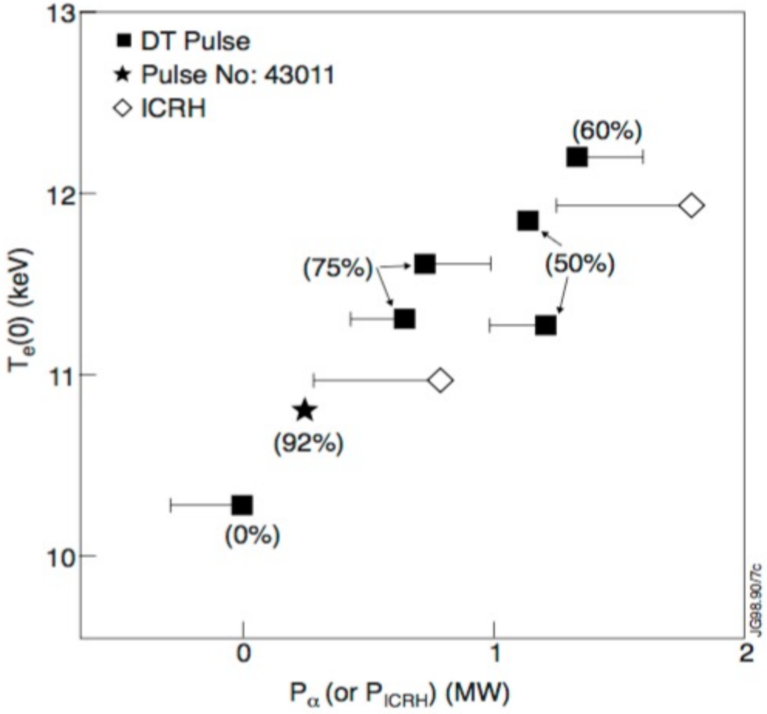
Alpha Particle Heating has Been Observed in D-T Experiments on JET and TFTR at Q < 1

TFTR





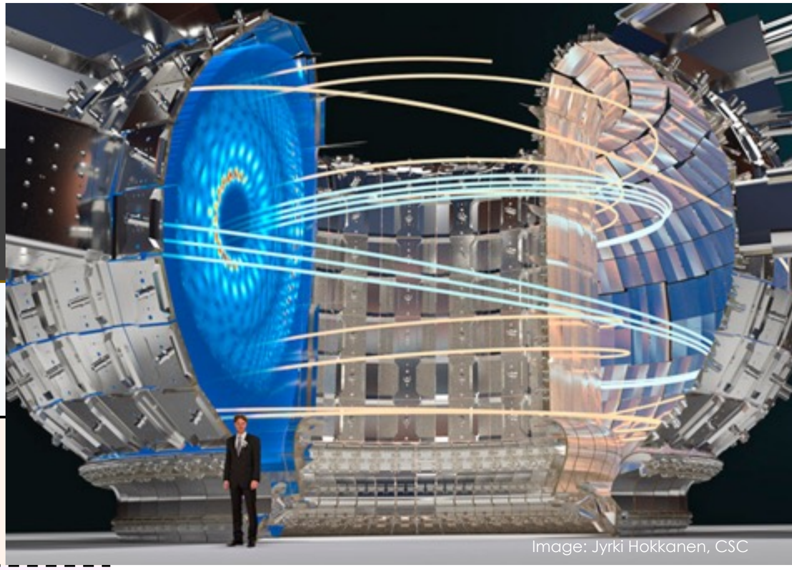
JET



- In both cases, results were consistent with expectations….But, Q << 1
- What happens as fusion power becomes dominant?

What Makes a Burning Plasma Unique?

Energetic particles interacting with Alfvén Eigenmode instability in ITER



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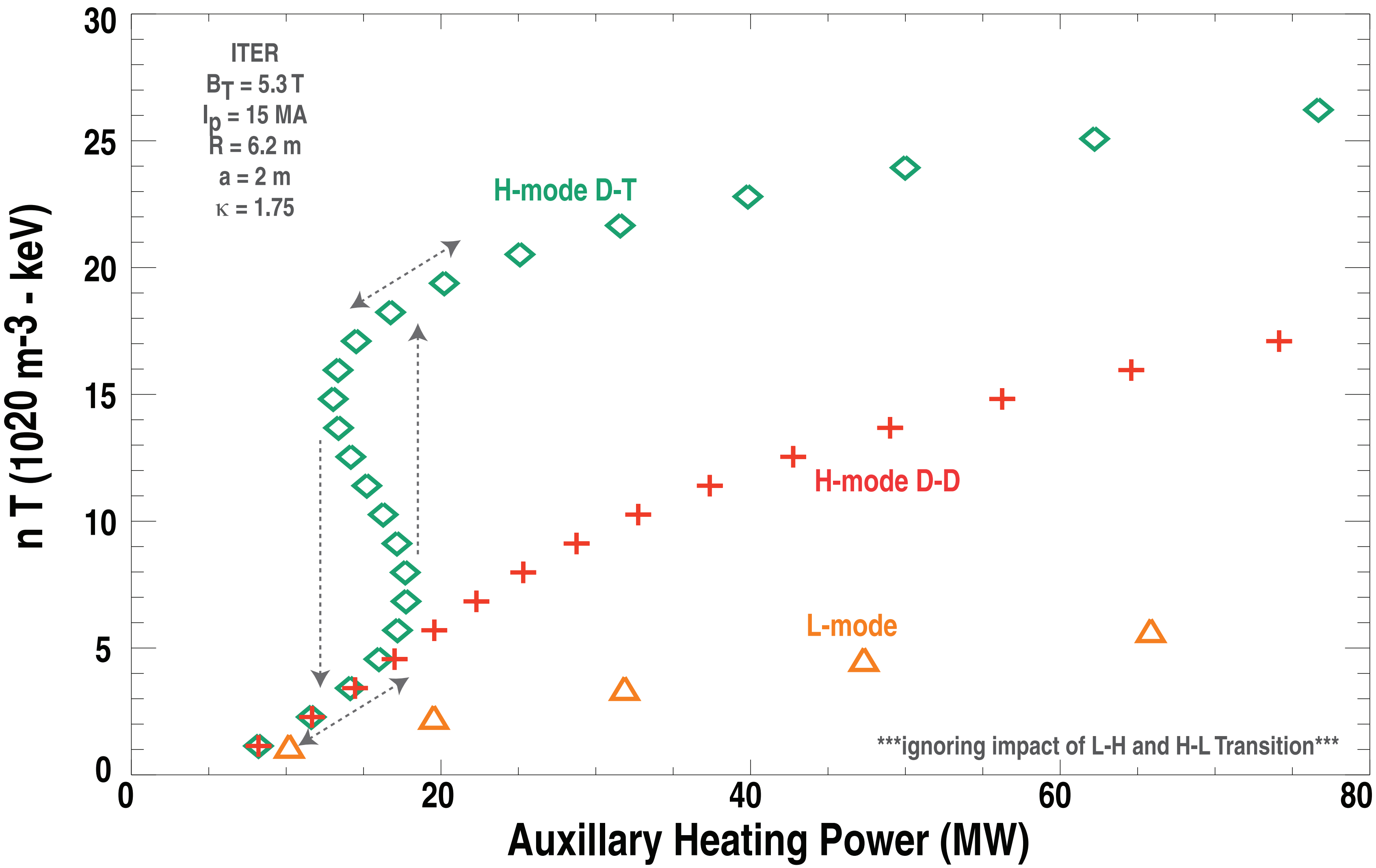
	$Q = \frac{P_{fusion}}{P_{heat}}$	$f_\alpha = \frac{P_\alpha}{P_\alpha + P_{heat}}$	
Scientific Breakeven	Q = 1	17%	Alpha confinement
Burning Plasma Regime	Q = 5	50%	Alpha heating; Alpha effects on energetic particle instabilities
	Q = 10	67%	Strong alpha heating; Non-linear coupling effects
	Q = 20	80%	Burn Control; potentially strong non-linear coupling
	Q = ∞	100%	Ignition

ITER's research goal

Presence of Alpha Heating Leads to Non-Linear Response of Plasma Energy to Applied Heating



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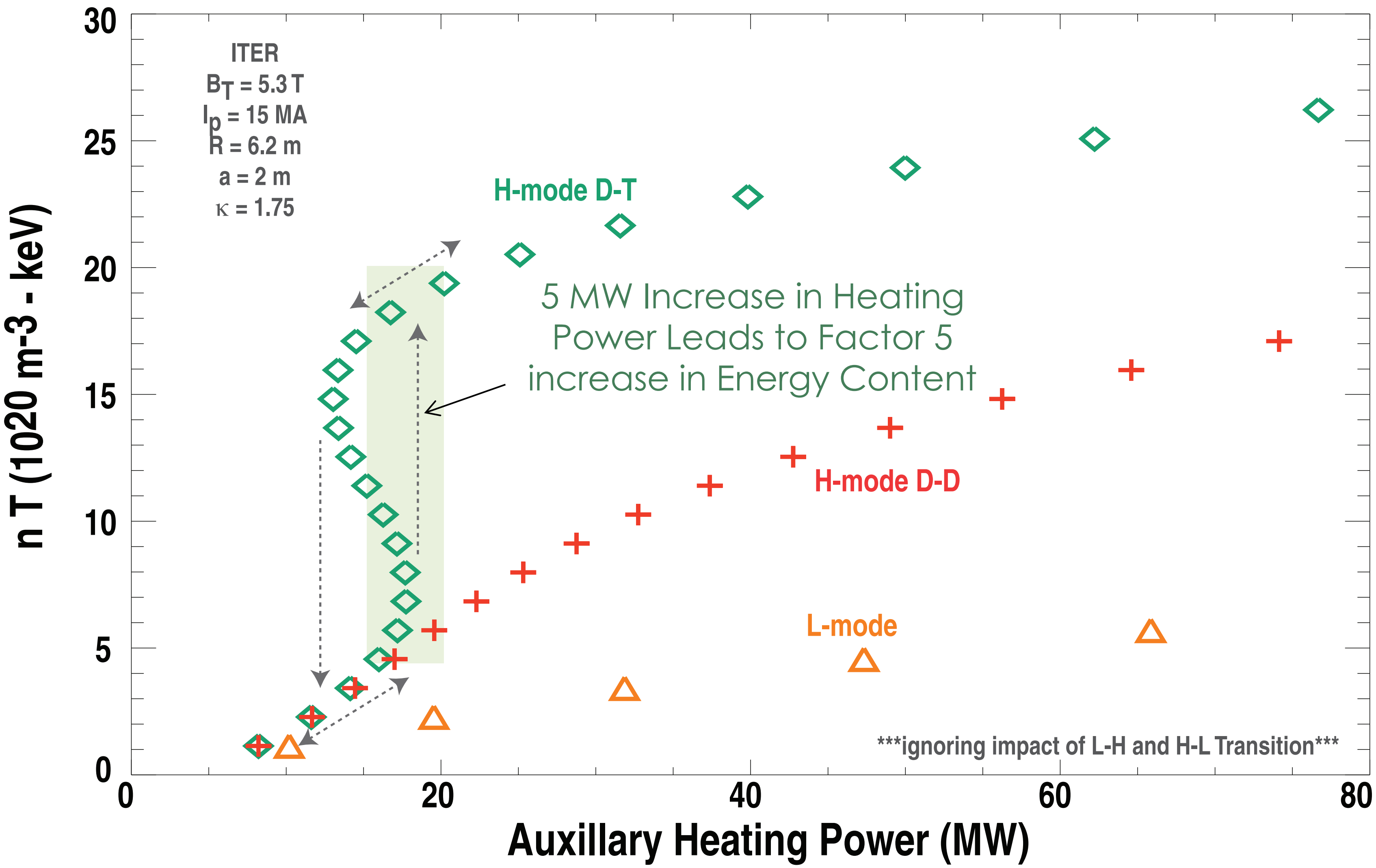
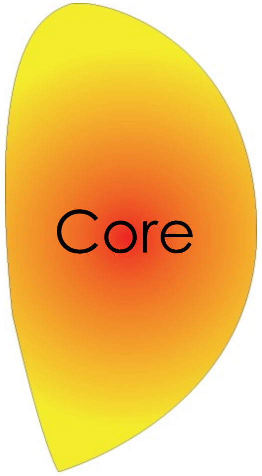


In a burning plasma, increase in plasma temperature → more alpha production → further increase temperature

Burning Plasma Access Will Enable Frontier Research in the Physics of Fusion Plasma Cores



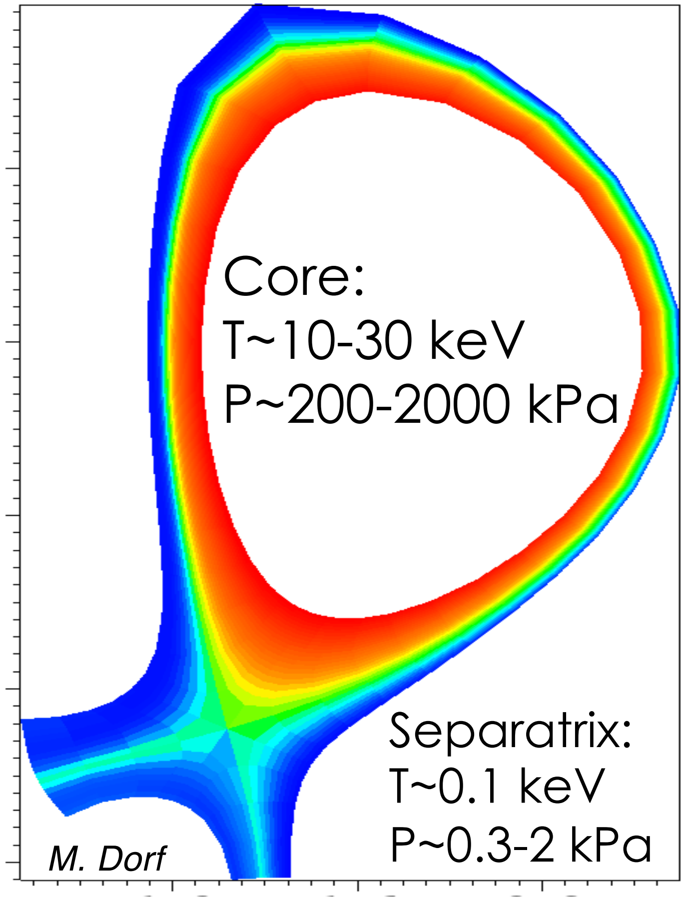
<u>Core physics enabled by burning plasmas</u>

- Alpha particle physics
  - Will alpha particles heat as expected in high Q plasmas?
  - Will non-linear coupling to instabilities cause significant losses?
  - Will new, unexpected phenomena emerge at high alpha power?

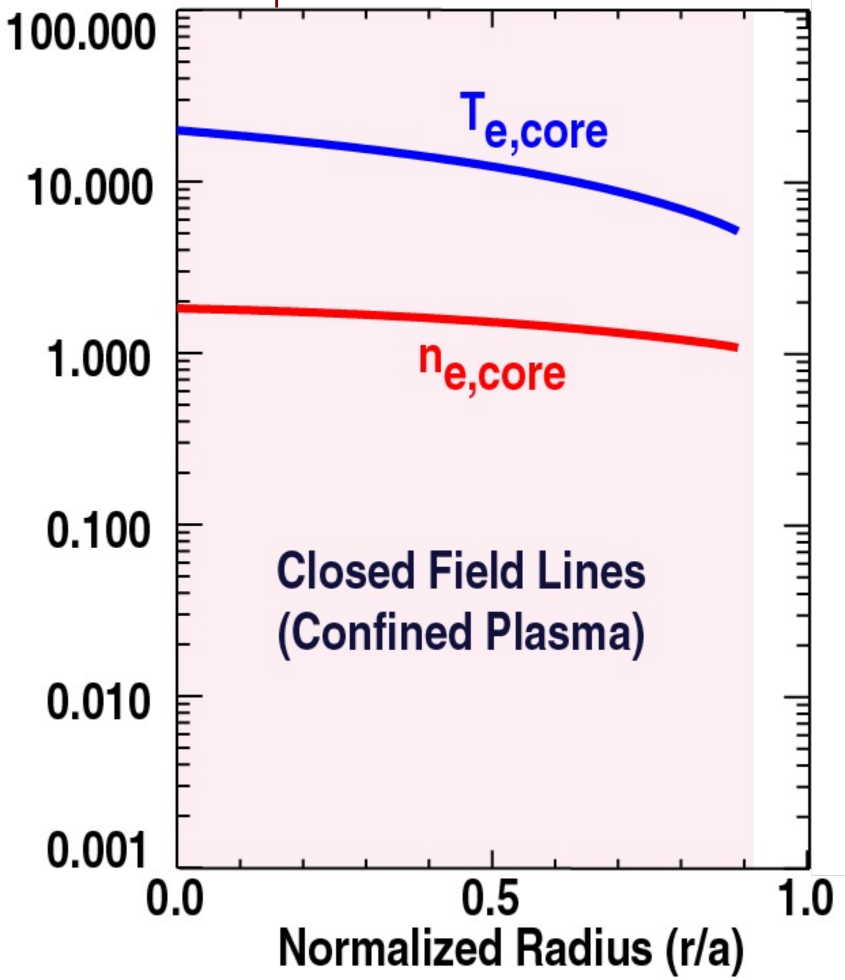
- Energy & Particle transport:
  - How will burning-plasma-specific conditions (smaller ρ^*, electron heating, low rotation) affect confinement at high Q?
  - Will helium ash be transported efficiently to edge for exhaust?

- Self-organization and plasma control
  - Will the plasma self organize to an optimal state for confinement & stability?
  - If not, how effective will control tools be in producing optimized state?

Fundamental Challenge: Fusion Conditions in Core Compatible with Edge/Materials



Radial Profile of Density and Temperature in Plasma Core



- Need high core nT for fusion

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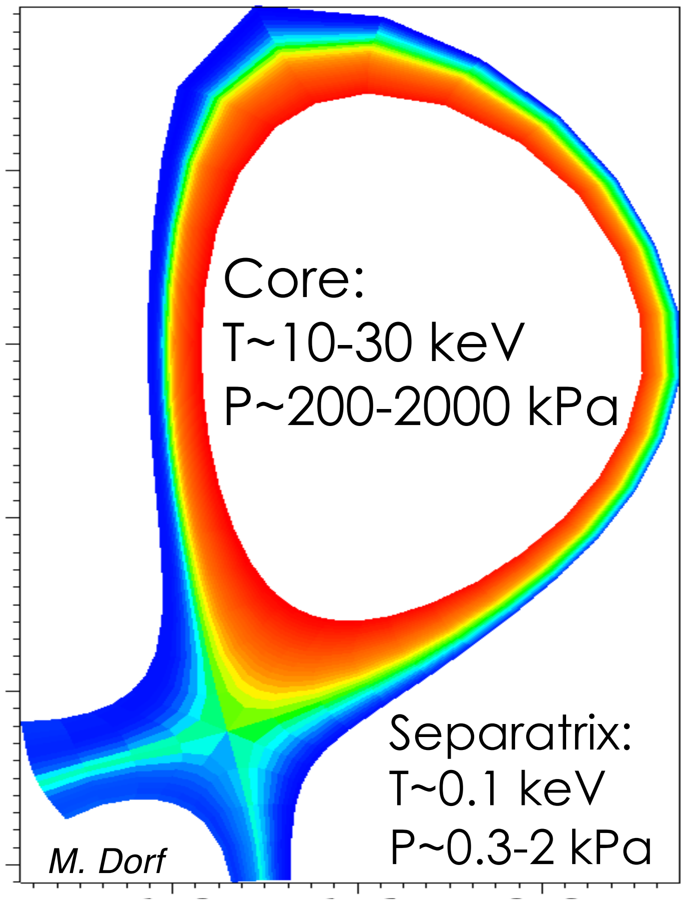

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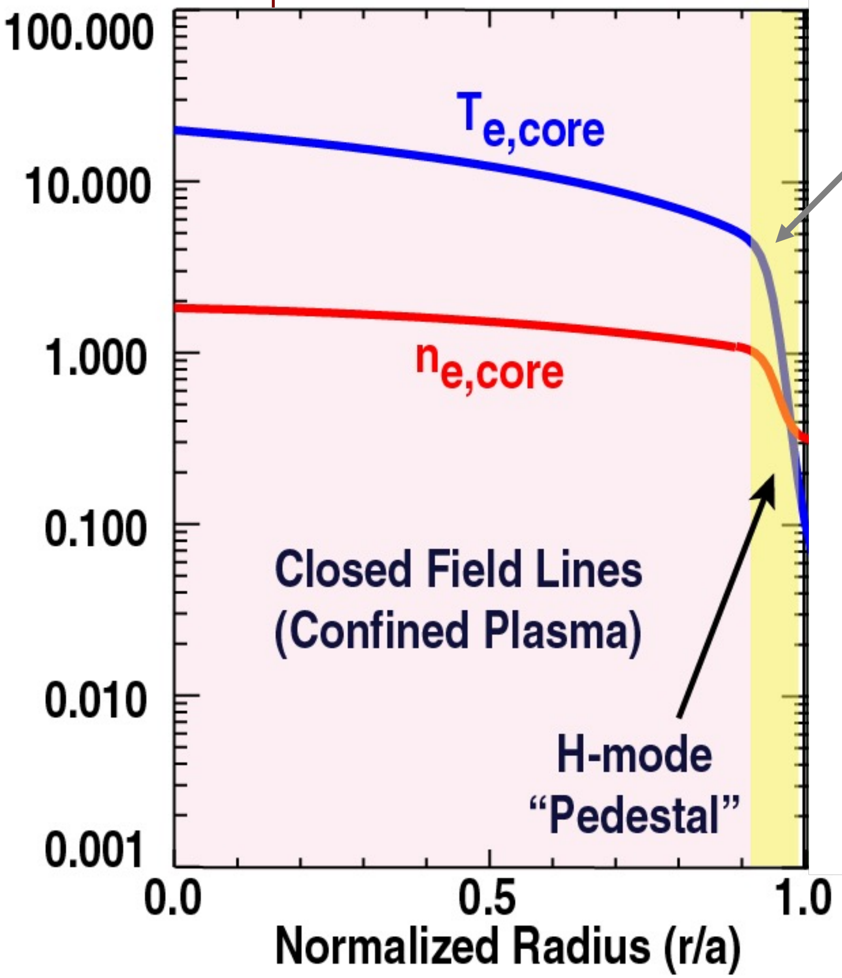
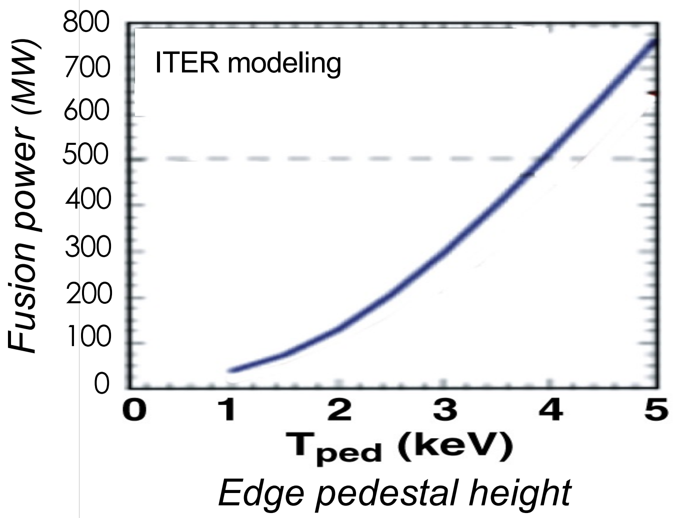


- Need high core nT for fusion
  →need high pedestal height
  →(of course) it's limited by stability



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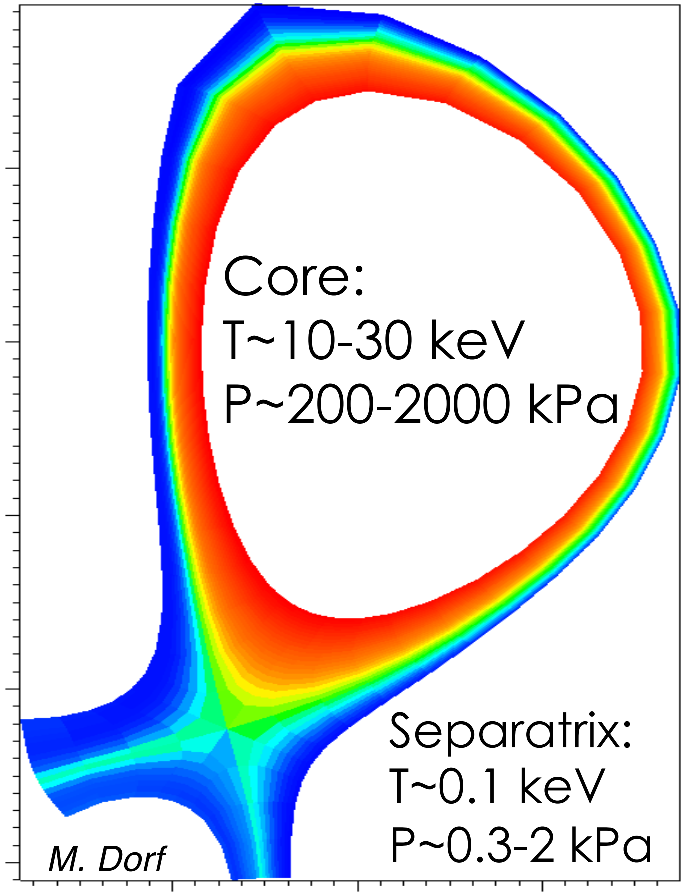
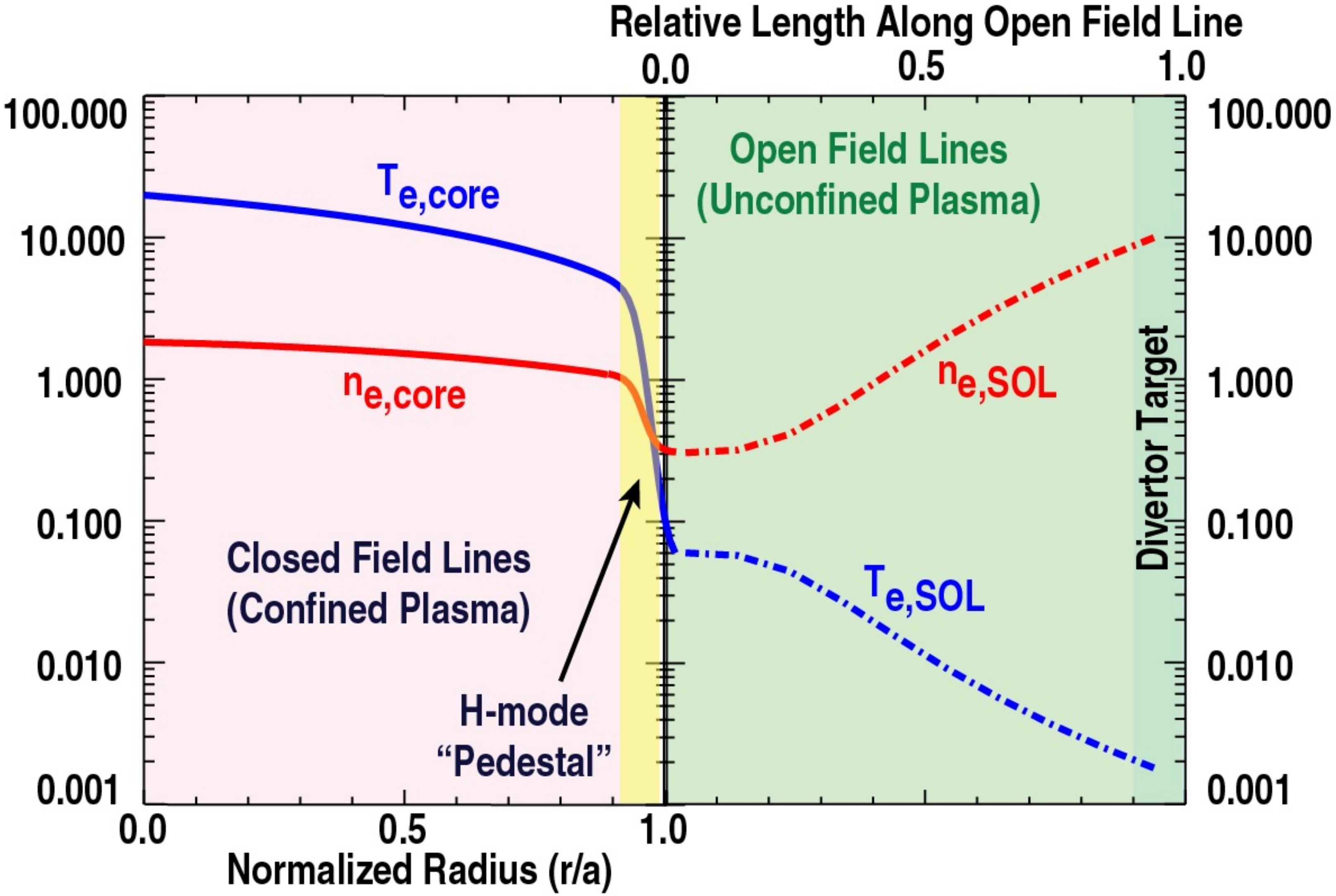


Materials:
T~0.0001 keV



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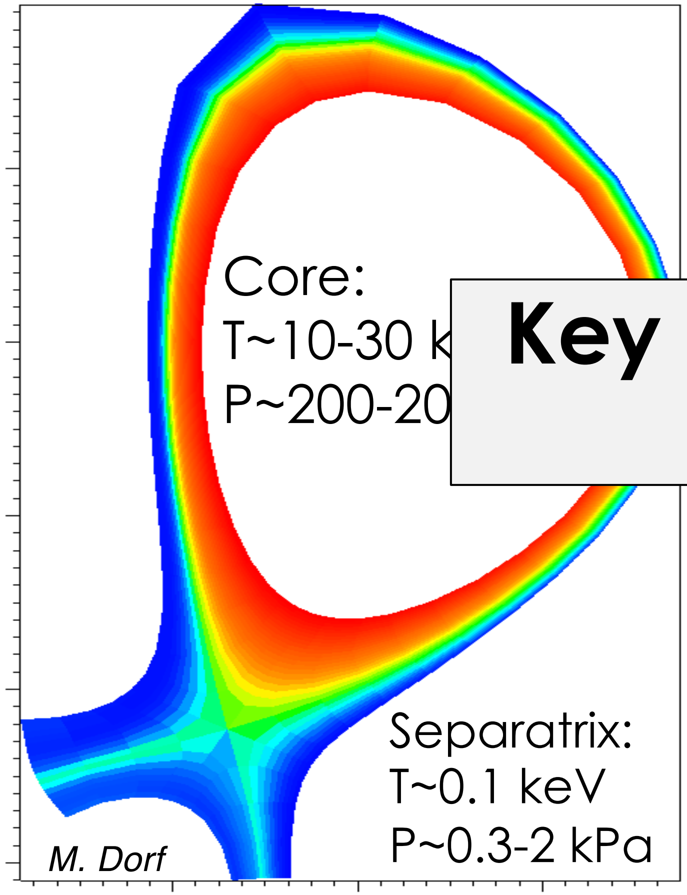

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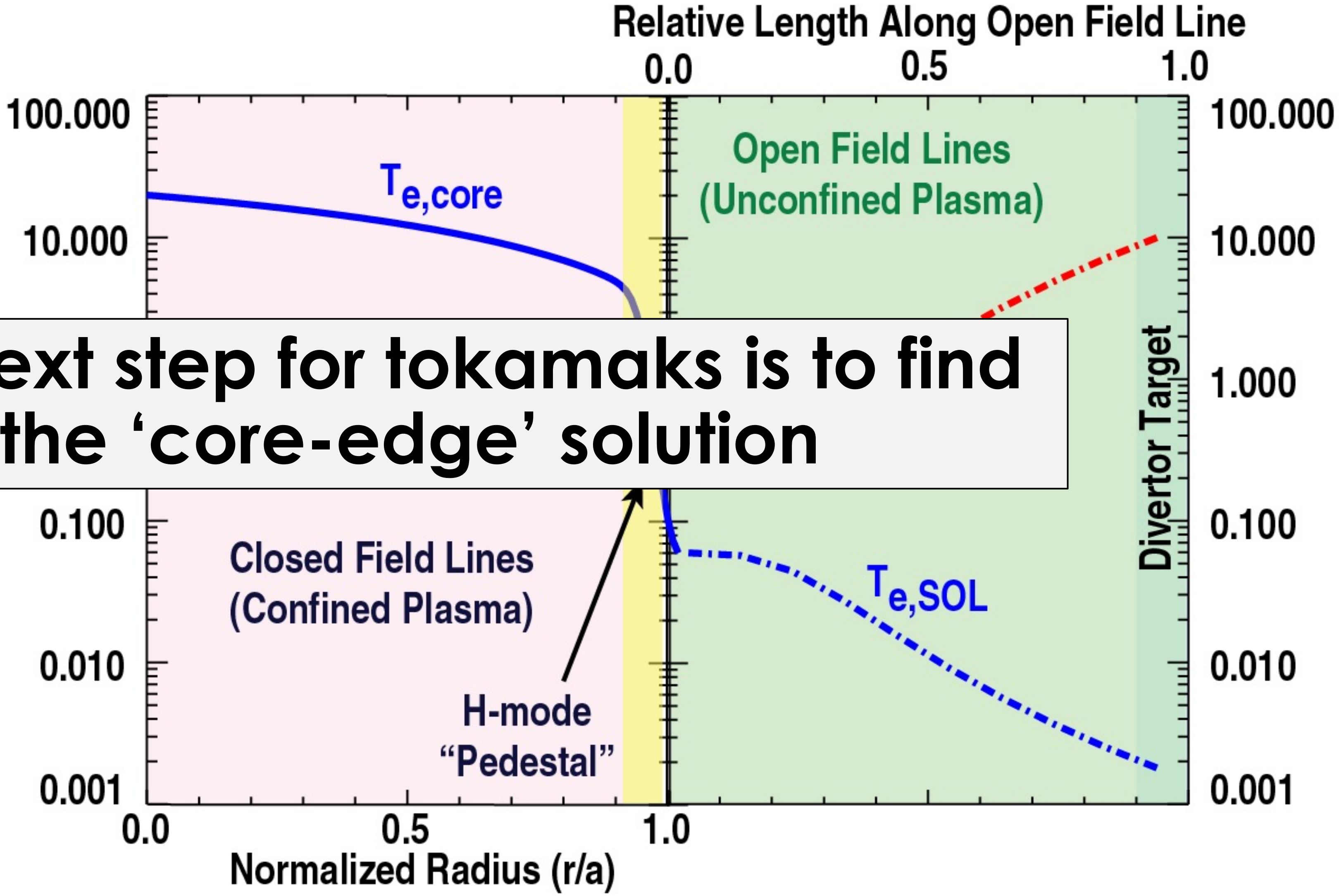
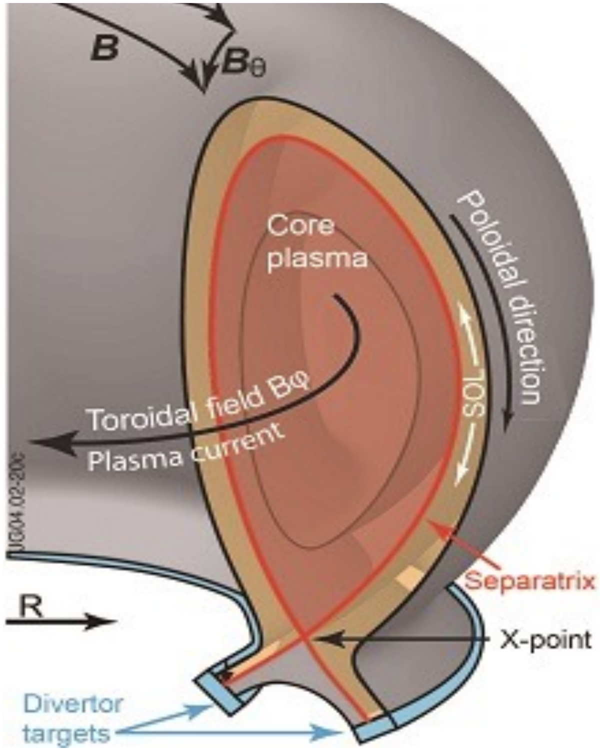


Key next step for tokamaks is to find the 'core-edge' solution

Handling the Power Flowing Out of the Plasma is a Serious Challenge

- Best tokamak performance found when hot particles escaping main plasma are channeled to a separate region
  - Region known as the divertor
- Heat fluxes on material surface can exceed those of a rocket nozzle
  - > 10 MW/m^2
- Long time-scale operation (> 30 s) only possible with effective mitigation measures and excellent surface cooling



Handling the Power Flowing Out of the Plasma is a Serious Challenge

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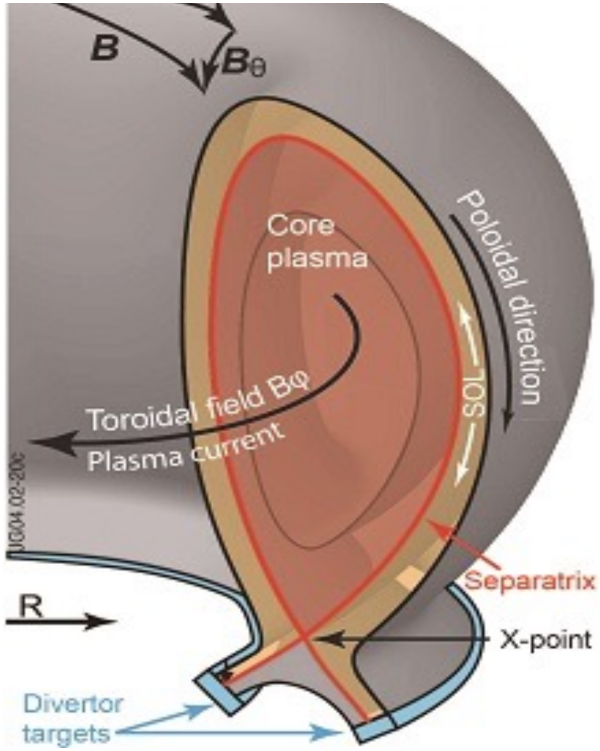
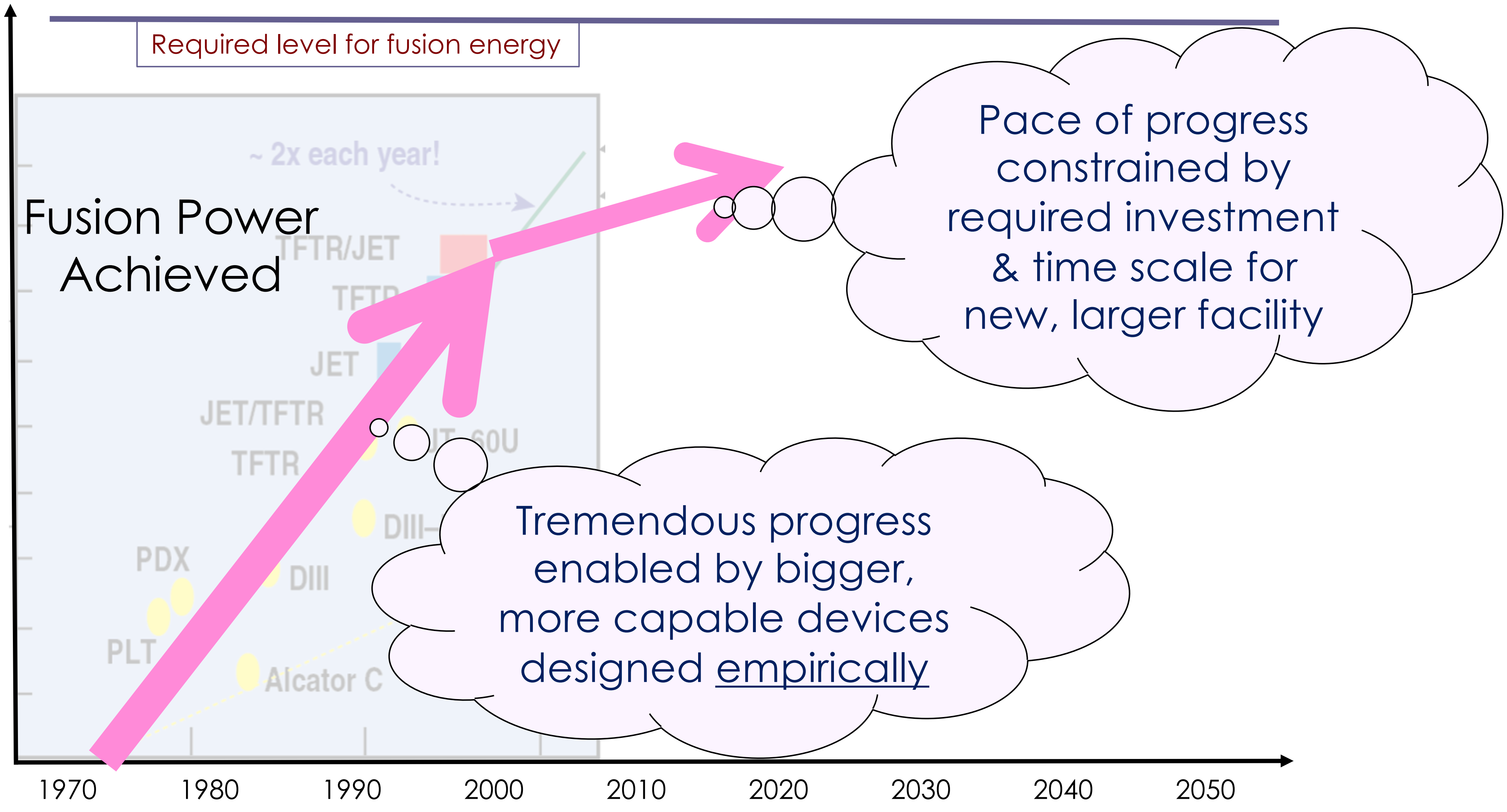
Fusion=hard



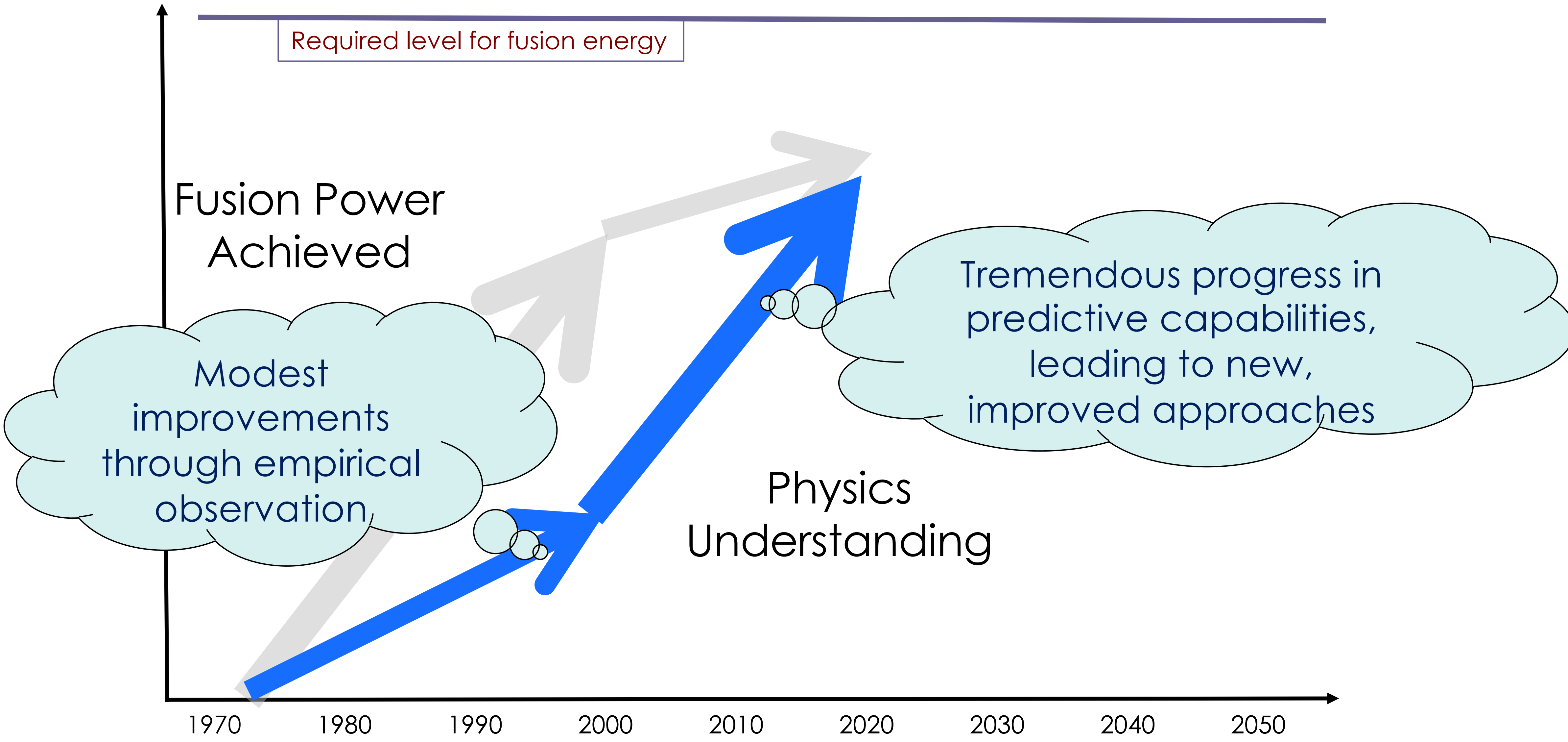
Outline

- Introduction to Needs, Potential, and Conditions for Fusion
- Progress Towards Fusion Energy
- Challenges in Developing in Fusion Energy
- **Exciting New Era for Fusion Energy Development**

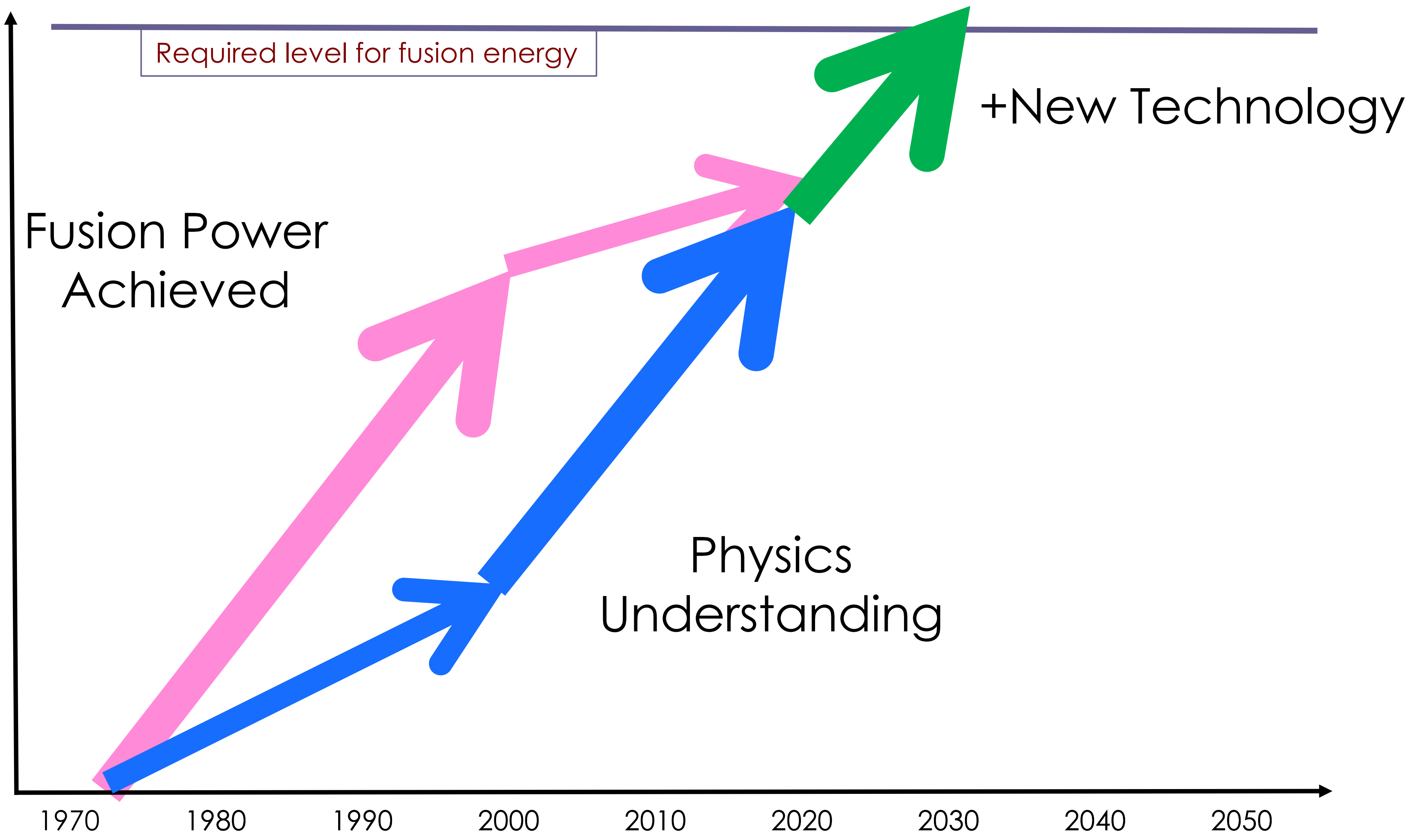
Early Rapid Progress Fueled by Ability to Increase Facility Size ...Until a Limit was Reached



Lull in Progress Towards Fusion Energy Goal Accompanied by Tremendous Advances in Physics Understanding

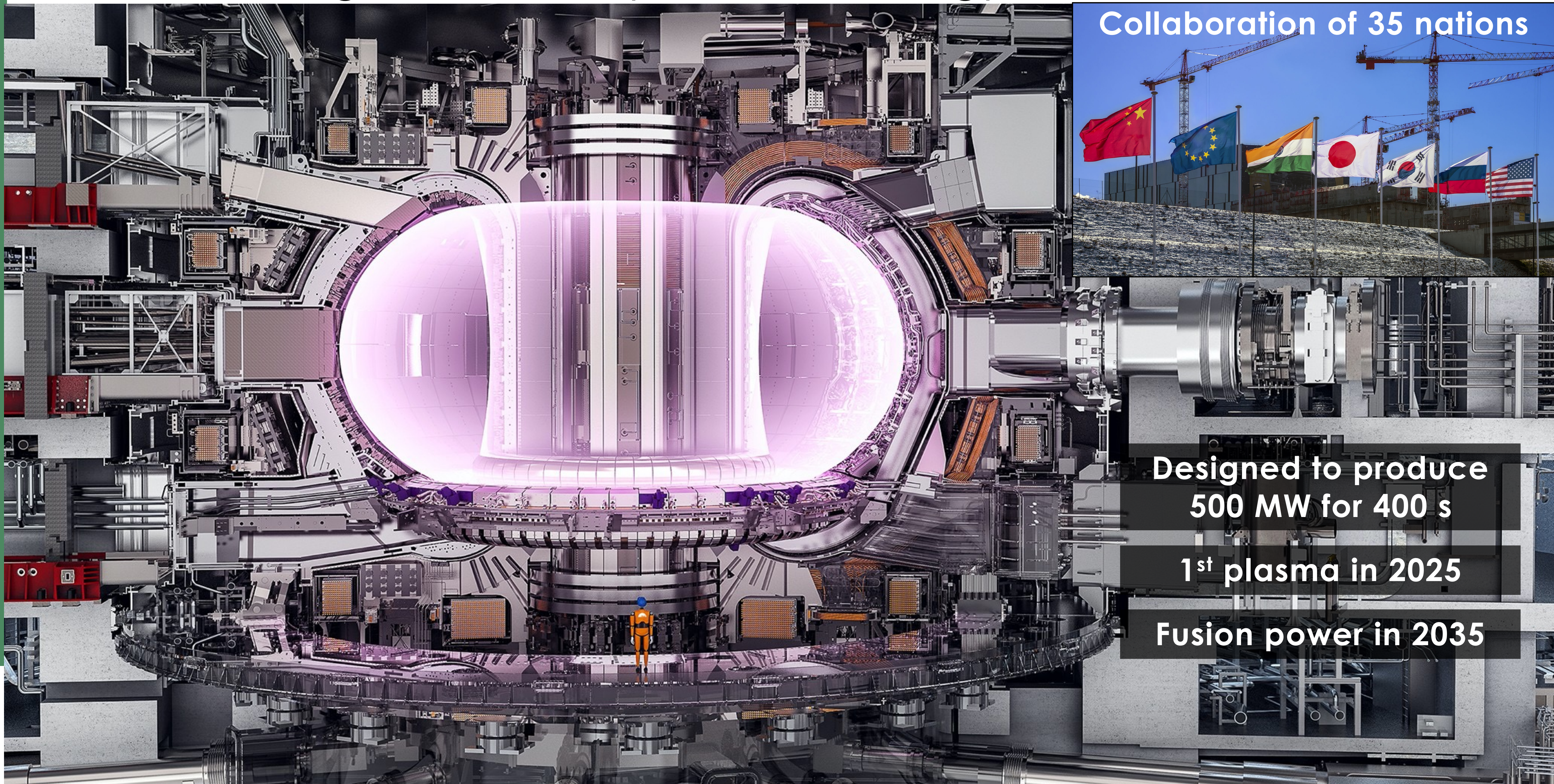


Can We Leverage New Capabilities to Accelerate the Timeline?



ITER is on the Horizon

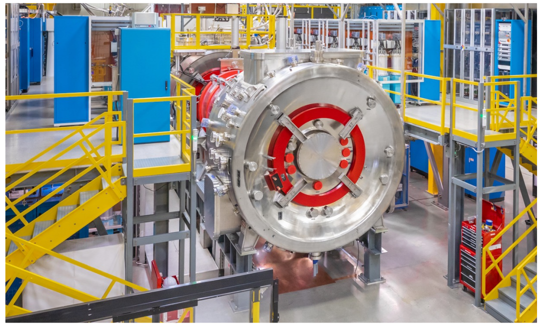
ITER – A International Partnership to Demonstrate the Scientific and Technological Feasibility of Fusion Energy

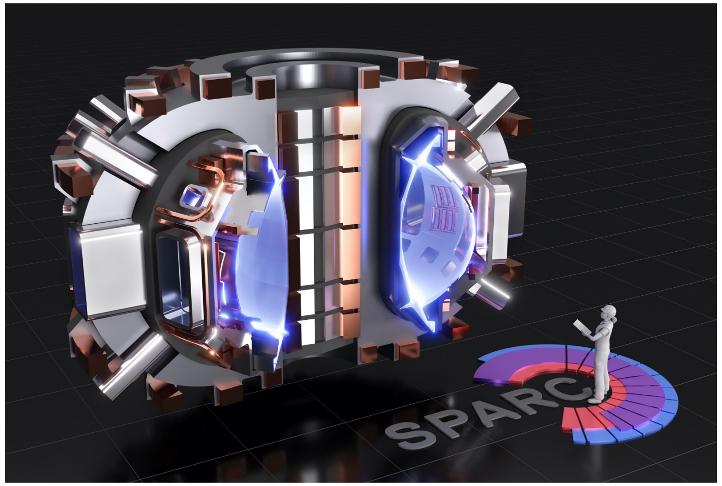


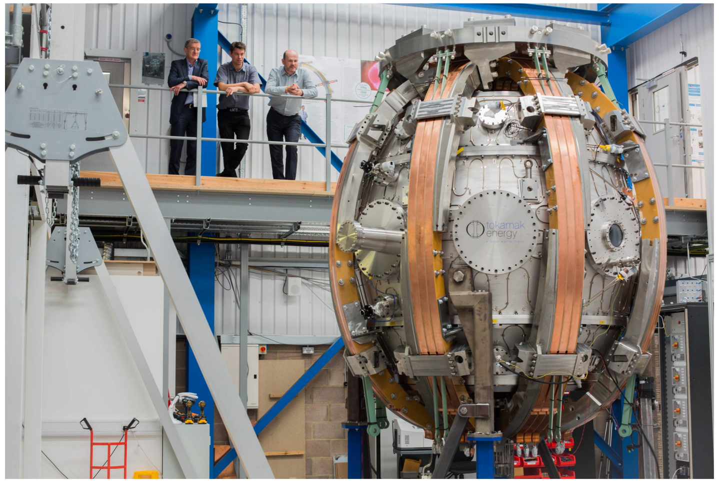
Recent Years Have Seen A Significant Increase in Investment and Interest in Fusion Energy by the Private Sector

- $2B of investment in last 5 years
- Leveraging DOE programs through cost-share programs
- Have established industry trade group to promote common interests

Helion Energy
COMMONWEALTH FUSION SYSTEMS
generalfusion
tae TECHNOLOGIES
fuse
tokamak energy a faster way to fusion
CTFusion
HYPERJET FUSION CORP
MIFTI
COMPACT FUSION SYSTEMS
LPP FUSION
PROTON SCIENTIFIC
HORNE TECHNOLOGIES
first light
AGNI FUSION ENERGY
PrincetonSATELLITE SYSTEMS
EMC2
RENAISSANCE FUSION
FUSION INDUSTRY ASSOCIATION
HelicitySpace







"Creating a Sun on Earth" is a Grand Challenge for the 21st Century

National Academy of Engineering listed Fusion Energy among 14 Grand Challenges for Engineering in the 21st Century

http://www.engineeringchallenges.org/challenges.aspx

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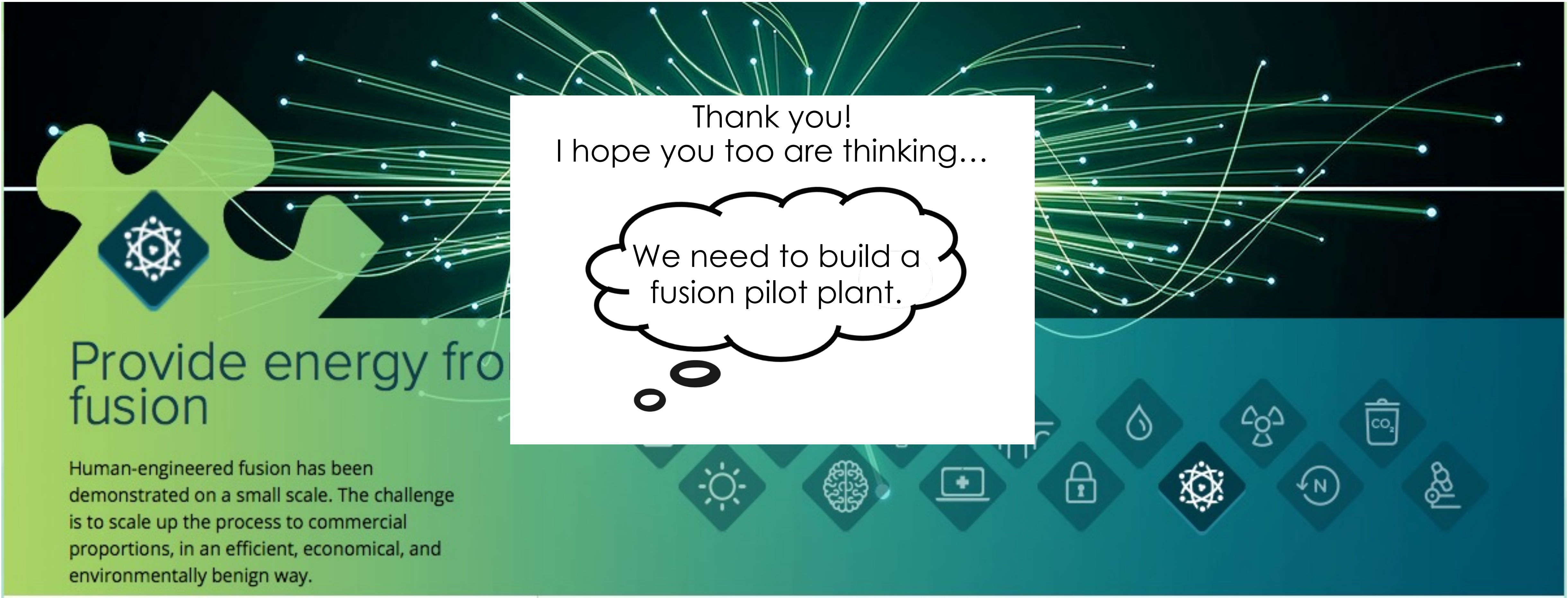


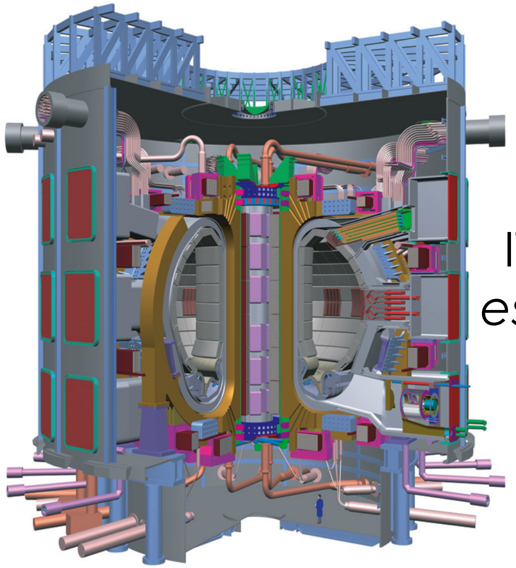
Thank you!
I hope you too are thinking…

We need to build a fusion pilot plant.

http://www.engineeringchallenges.org/challenges.aspx

Extra Slides

Fusion is Expensive? Cost in Perspective



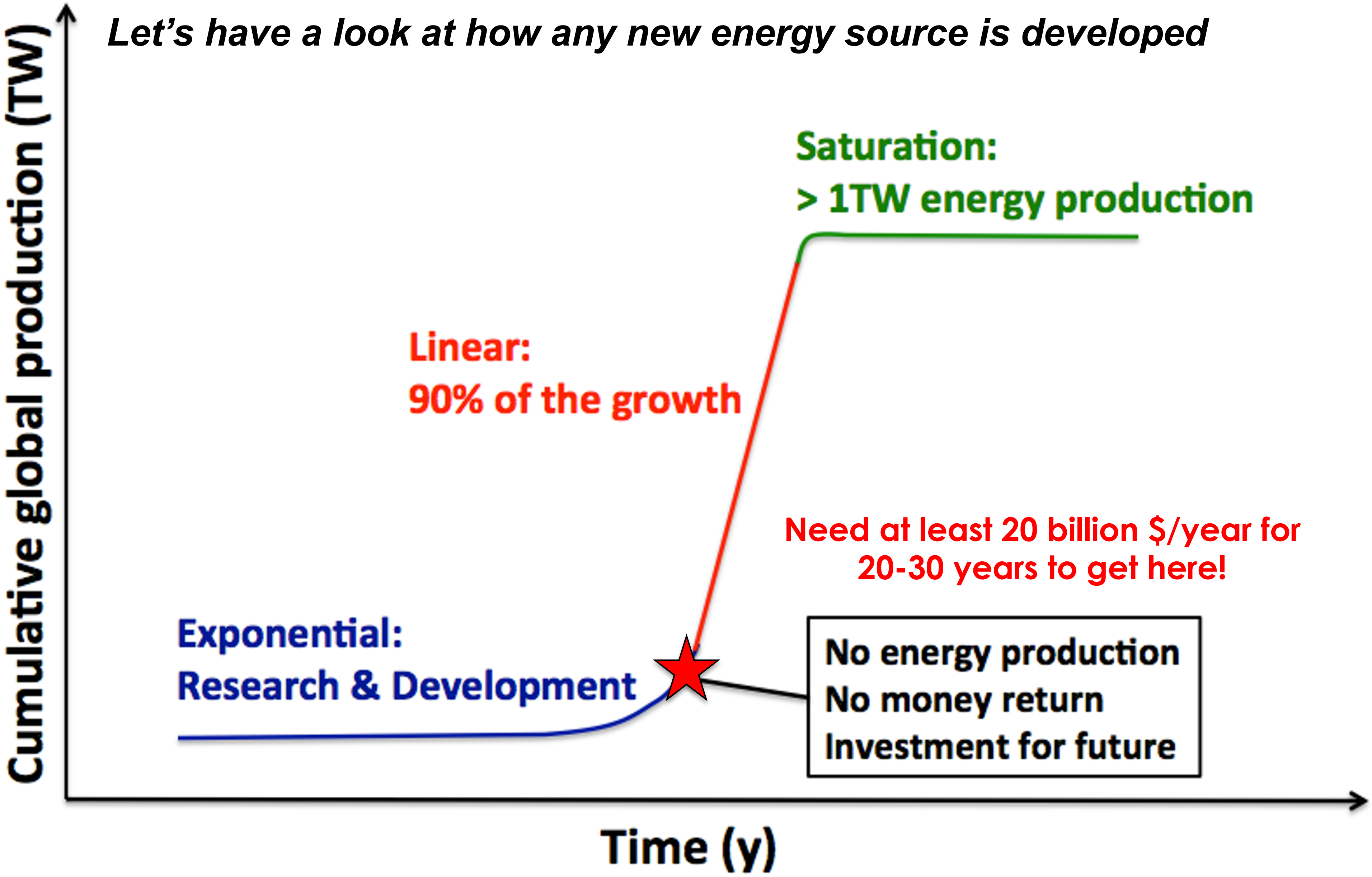
ITER construction cost *estimated* EUR 17 billion

single CVN-78-class aircraft carrier: $9.8 billion

single B-2 Spirit: $737 million

In total, the F-22 Raptor cost $79.2 billion to develop

Why is Fusion Taking So Long to Achieve?



World Investment Needed to Reach EXPONENTIAL GROWTH Phase of Energy Sources