



# Fusion on Earth

**A quintessential scientific pursuit  
with a big commercial goal**

An Exploration with

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# Story of Energy in few easy vignettes

The story of civilization closely follows the advancement and sophistication of our abilities to convert one form of energy into another

Convert chemical energy in the natural gas to heat- and make our delectable Darjeeling

**Exothermic reactions**

Convert chemical energy in gasoline to kinetic energy and drive to Pune

**Latent Energy**

Most spectacular conversions take place in Heavens

Nuclear fusion has been producing heat and light for billions of years

Bringing Heavens to Earth defines the quest of a Fusion scientist-

Our challenge is not just to do fusion but to do it so efficiently and so well that

**we can sell the energy at a profit**

**Commercially Viable**

**Fusion**

**is our pressing mandate!**

Fuel= Any substance that has latent energy

# Energy Bounty of the Earth

## Current Account

### Sun Light

source of all renewables - plants (animals), windmills, solar cells/thermal- different but short time scales;

perpetually renewable.

**Low energy density**

## Savings Account

### Stored Past Sunlight

All Fossils- end products of highly complex processing-the renewal periods ~10- 100M

Non-renewable.

**Much higher energy density**

## Patrimony 1

Fissionable Heavy elements Uranium and Thorium

generated in extreme conditions the cosmic dust from which our solar system was formed.

This is a huge endowment.

**Millions time more energy density\*\***

## Patrimony 2:

### Deuterium

A gift from the baby universe

utterly enormous energy content for nuclear fusion.

**Even higher energy density\*\*\***

Both Patrimonies, generous as they are, are non-renewable (?)

**Behold: nuclear Energy is the ultimate source of all energy that we will ever use!**



## A Broad-Brush History of Energy- **The Anthropropic Take Over**

- Much of its history, mankind subsisted on Current Income.
- Industrial revolution, however, was fueled by the savings account
  - Vast storehouse of energy, accumulated over 100 million years, was spent in a few centuries -20-21 the most profligate
- The dawn of nuclear age began with dipping into Patrimony 1-- Nuclear Fission went online in the late fifties
  - ~10% of the world's electricity- safe and well-understood technology- Fission stagnated in the last few decades
- Baby steps were taken towards Dipping into Patrimony 2 in the middle of twentieth century- Not a technology yet as fission and fossils are!





## Dipping into Patrimony 2

### Nuclear Fusion

#### Energy via Controlled Thermonuclear Program

Extremely High Energy Density  
The fatal attraction of Fusion

Creating a Sun on Earth\*

\*An inspiring metaphor

- A few grams of D-T has more *latent nuclear energy* than the *latent chemical energy* in a truck load of coal
- This principal supplier of visible energy in the universe, however, is so hard to replicate on earth despite ready availability of fusion fuel and all the **anthropic resourcefulness**.

Scientific Needs and Challenge:

- An extremely energetic (high temperature **T**) collection of nuclei with sufficiently large density (**n**) confined together for a sufficiently long time (**tau**).
- The figure of merit for such a plasma of nuclei and electrons  $L = (nT)^* \tau$
- $L$  is what we must chase!!

For a solar plasma tau is essentially infinite

# Magnetic Field to the Rescue

recruit the strong force of the  
magnetic fields on charged  
nucleons/ electrons

Magnetic Bottle



Heating a dense plasma to high temperatures is, by no means, easy

But it is **confining** a hot plasmas into a limited region **away from material walls** that really constitutes both the excitement and formidable challenge of controlled thermo-nuclear fusion.

**Such bottles can never be perfect-they are always leaky**

**The very laws of physics militate against such bottles**

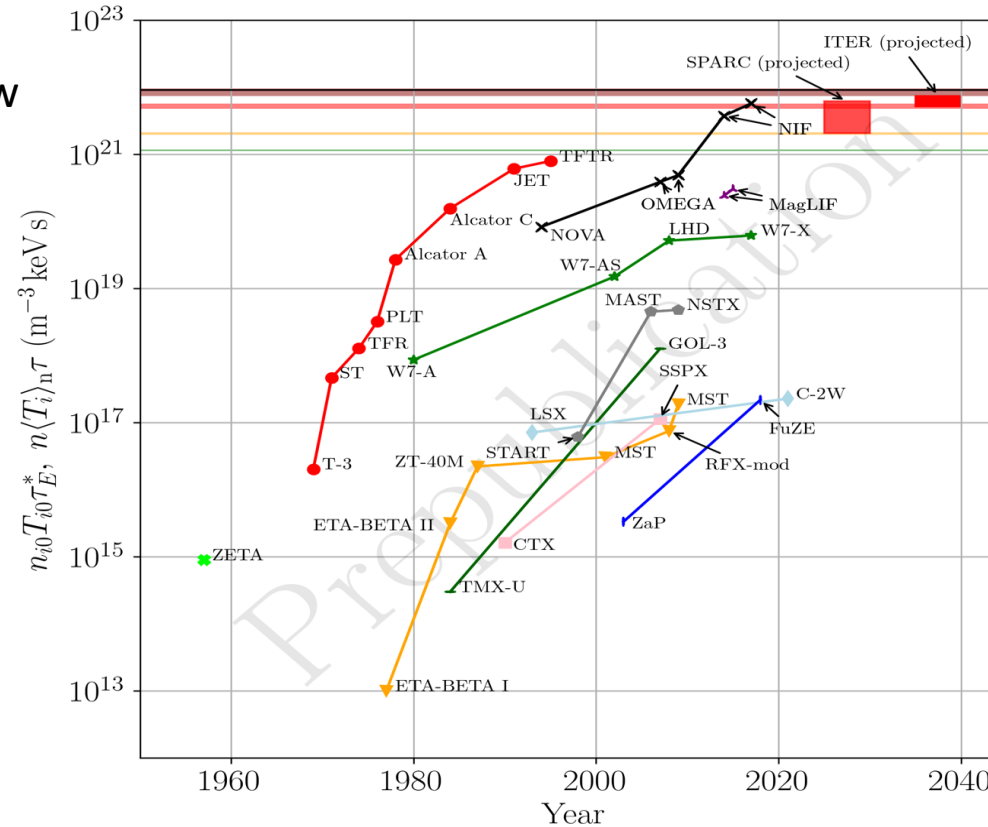
The story of controlled fusion is the story of trying a whole variety of magnetic bottles- always driven by special understanding of physics, and often by partial success- improving those that seem to work, discarding those that do not seem to – **And Coming back to discarded ones with a new understanding of physics and HOPE**

**The Tokamak line has been the most successful yet**

Hark, the fusion landscape of today is populated with EVERY Magnetic bottle ever conceived

# Spectacular Gain in the triple product $nT\tau_E$ .

Faster than Moore's law



ITER/CFS are bland extrapolations

The nT tau revolution upto 2000 has slowed down

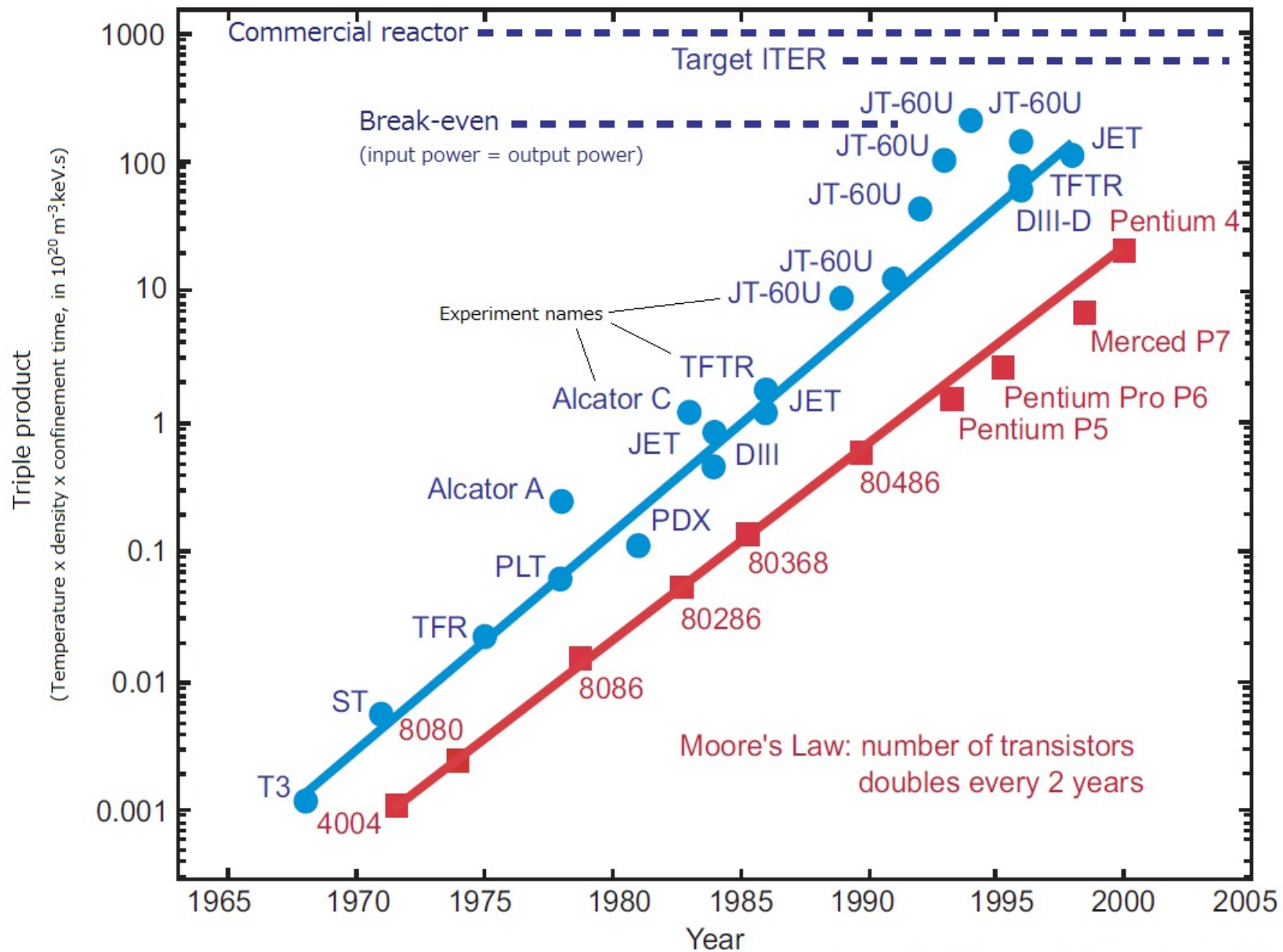
A big idea needed for another big boost

\*Tokamak central temperatures are much much higher than the solar interior



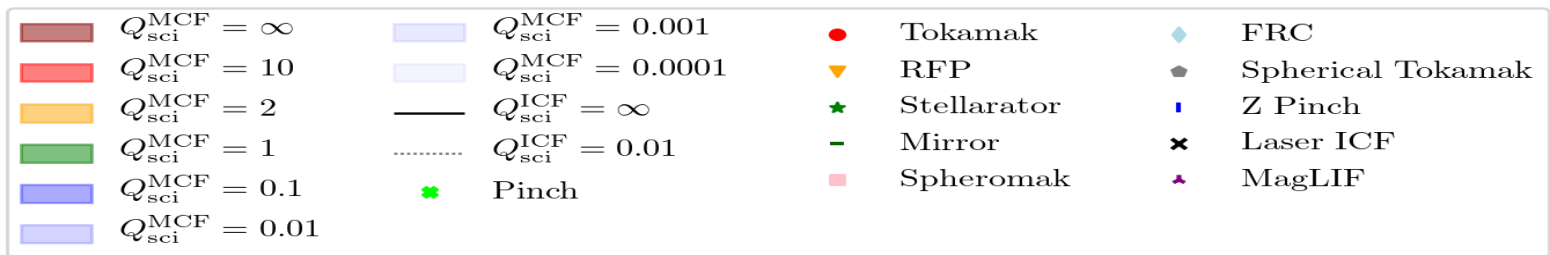
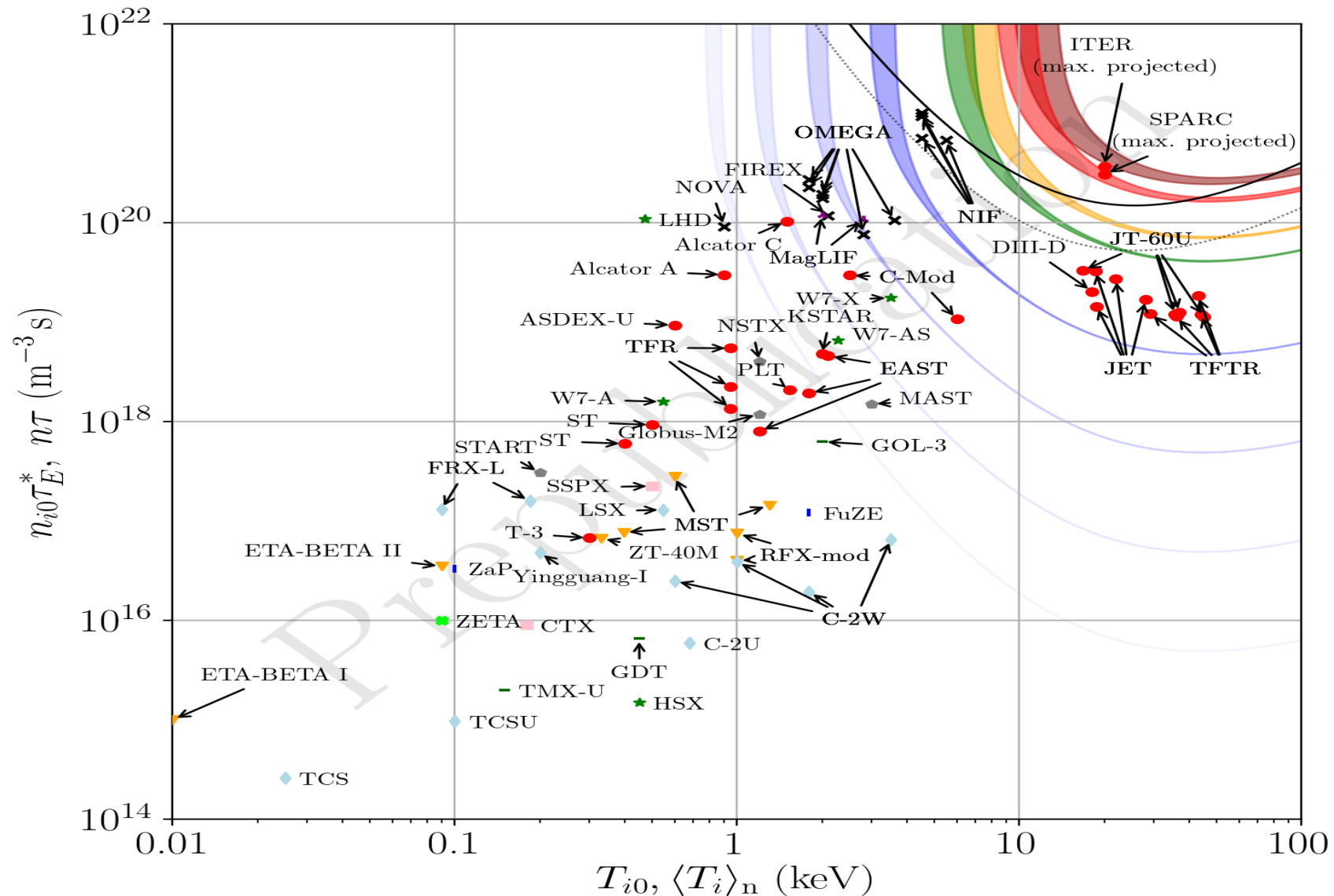
n T Tau

Fusion: figure-of-merit (the 'triple product')  
doubles every 1.8 years



All machines

n T tau



# Fusion on Earth- Government versus Private- Contrasting Prioritizations

**Government: Most research, till now, was in govt. labs or govt. sponsored labs**

- Dedicated to Understanding the science and technology of fusion
- lip service was paid to commercialization, it was, by no reckoning, the compelling goal.
- What really drove fusion research was the fundamental goal of demonstrating that fusion, ``in principle'', is possible; cost and time spent did not enter the equation- the sheer grandeur of replicating on earth what stars do in the Heavens.
- It is my firm belief that this awe/wonder will stir folks to pursue fusion to the very successful end.
- The Govt research that has brought us near what is called scientific breakeven ( $Q_{sc} = 1$ ).
- It is my equal firm belief that the next synthetic stage, fueled by a combination of

**steady plus path breaking innovations in fusion science and technology  
plus  
entry of more and more highly innovative private companies**

*will be qualitatively different.*

*Riding on the shoulders of the Govt sponsored research, and relentlessly pushed by the profit-motive, vision and dynamism of the private sector, the fusion enterprise has, finally, come of age.*





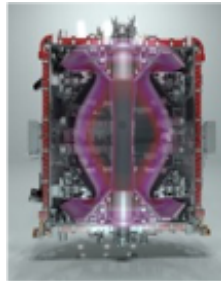
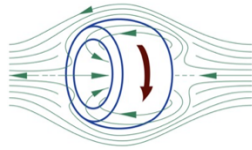
# The Fusion Market-Place - Government and Private –let Hundred Flowers Bloom

all contenders claim relative advantages in a possible fusion energy economy

Lower magnetic field systems- simpler, cheaper

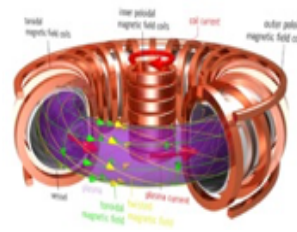
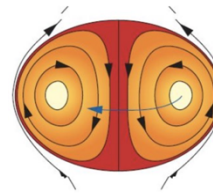
## FRC (1)

Tri Alpha Energy, Helion

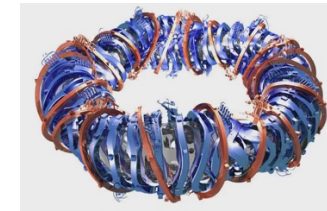
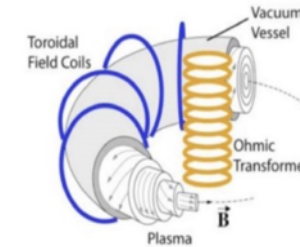


## Spheromak (2)

CT Fusion



## Toroidal Pinch (3)



## Spherical Tokamak (4)

STEP -UKAEA  
Tokamak Energy

## Tokamak (5)

ITER-EU  
CFS

## Stellarator (6)

Type One Energy  
Renaissance Fusion

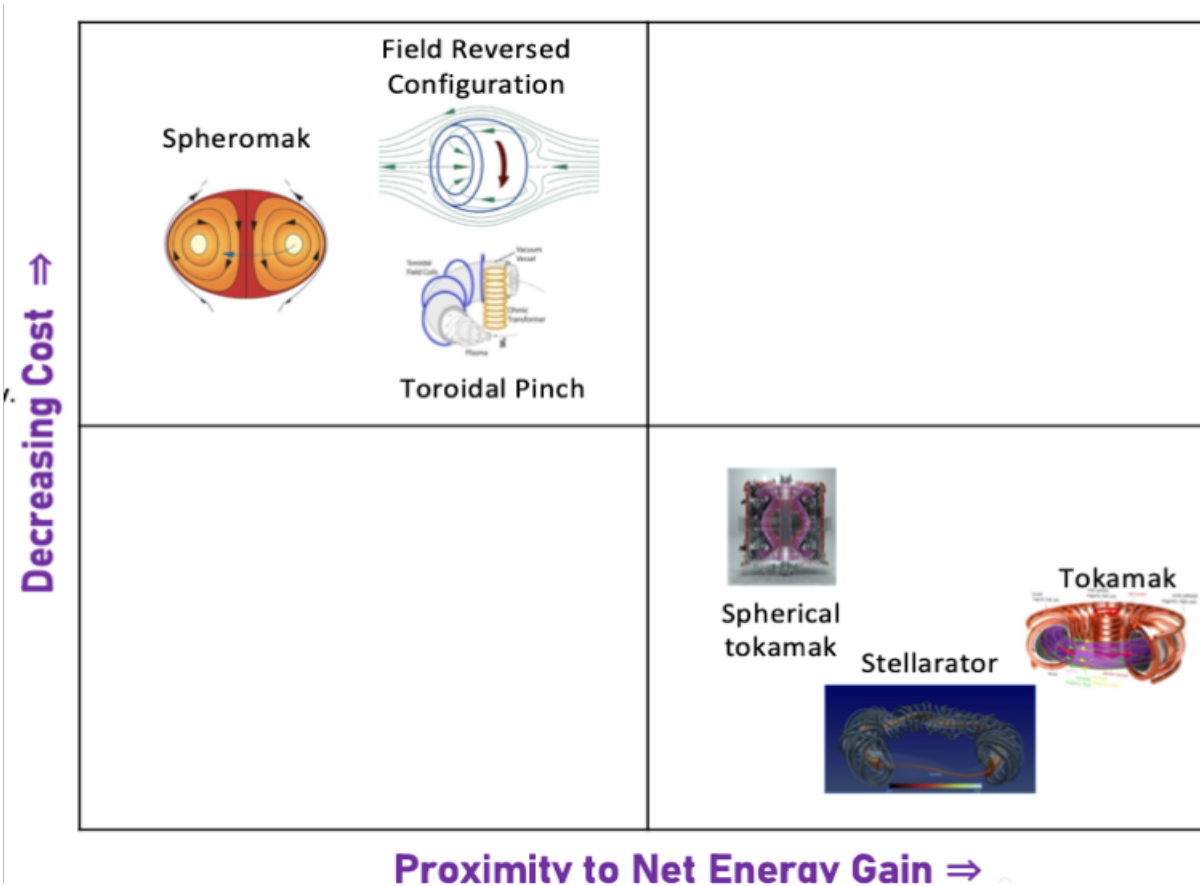
Much larger magnetic fields, complex, expensive

# Where are these various contenders Located Cost versus proximity to breakeven

## The Fusion Quandary

Stratups opt for smaller magnetic field- cheaper systems

But they are orders of magnitude below tokamaks  
In  $nT\tau_E$

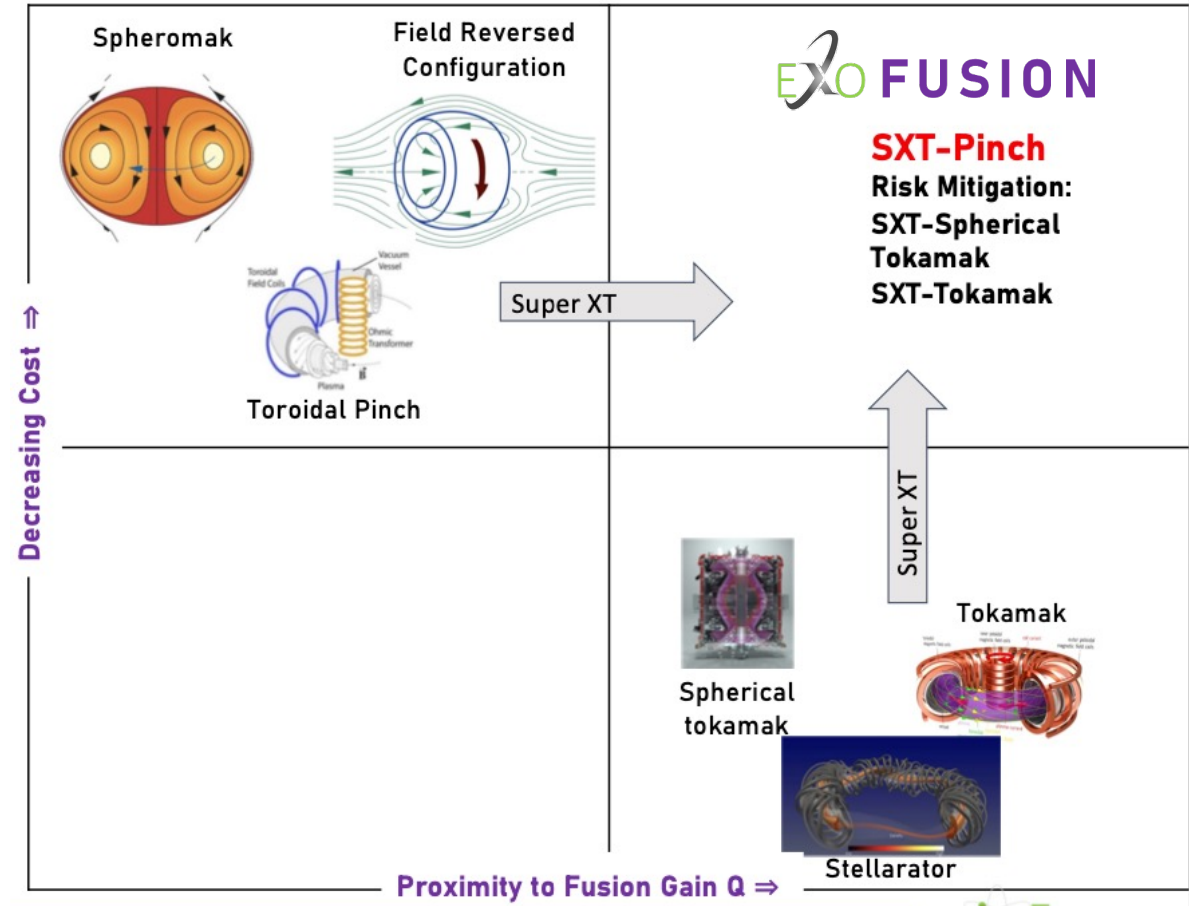


Already at the threshold of breakeven

??  
Strong magnetic fields too expensive- great for research and giving proof of principle

Magnetic field Cost: Magnitude, complexity, and the size of the device  
A smaller device with comparable performance is road to Heaven

# Where do we want them to be



Commercially viable regime

CVF

**CVF Reactor** - "small" size, low magnetic field (possibly with a simple structure) device  
with the maximum possible energy confinement time ( $\tau_E$ )



# How do we get there-

## In principle

Figure of Merit:  $F = n T \tau_E = (n T) \tau_E = (P) \tau_E$  P=Pressure

For a given B, maximize  $P \tau_E$

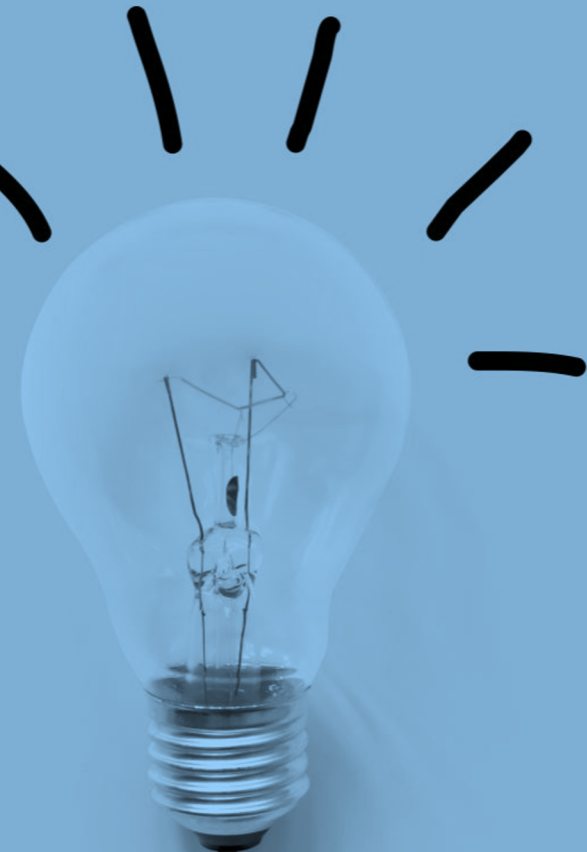
From totally elementary physics ( of fusion), For a given B,  $(n T) = P$  is fully constrained, it cannot go beyond  $P_{max}$ - Otherwise fast instabilities set in and plasma is “ lost”

After all the engineering is done , the only way F can be increased is by increasing  $\tau_E$

The confinement time  $\tau_E$  is set by what is called turbulent transport ( loss of heat)

Suppress processes that cause turbulent transport and march to CVF

*Confinement is the key*



# Boosting Confinement – the new Frontier – Twenty first century physics (TFP)

TFP=Deeper theoretical analysis in conjunction with State-of-the-Art simulations

There are yet unexplored regimes of higher confinement -  
we can simulate them

We can also devise well- defined pathways through which these regimes can be accessed in experiments- it is possible to identify the knobs that control entry into these regimes.

*Some such regimes have, at least partially, been reached in experiments, possibly, through trial and error.* But TFP can help us understand why and how of these experiments.

One of the most exciting routes to high confinement is via redesigning the relatively cold edge of the magnetic bottle so that it works to improve the core confinement (where fusion reactions are taking place)

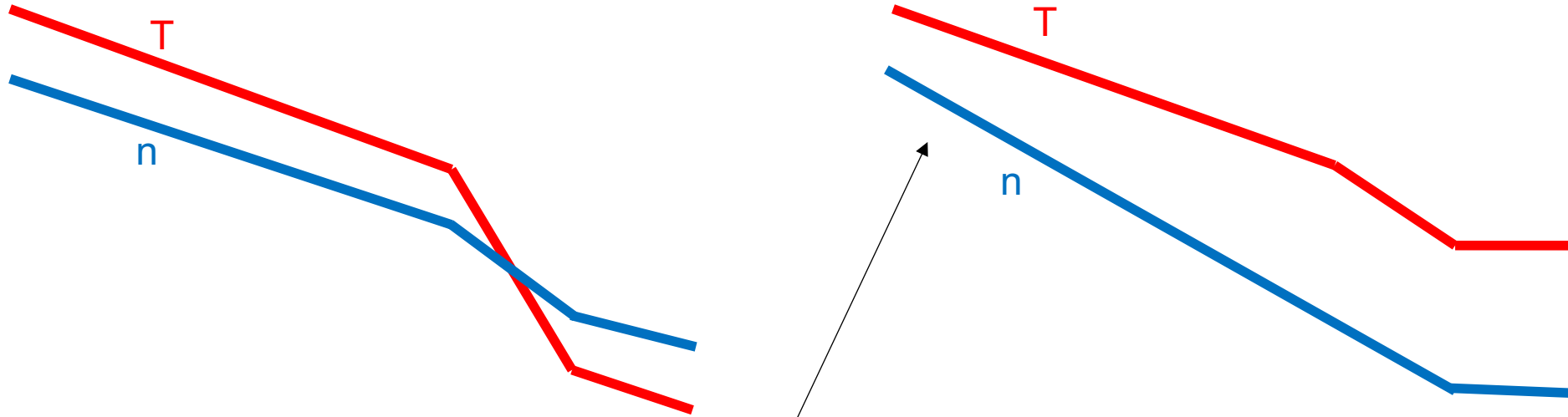
This is where ExoFusion contributes most fundamentally to Commercially Viable Fusion

Our concept is called the Super XT divertor- we were the inventor of the highly successful Super X divertor

Though born of advanced physics, it requires tremendous engineering and technology ideas that we have been systematically developing with many patents ( provisionally filed)

**Confinement Doubles    =>    Size Halves    => cost down by a factor 5-8**

# Energy Confinement- forever the key issue



## Conventional:

Challenges of steep T gradients: ETGs, MTM, ITG/TEM, etc., etc.

We have a lot of experience with these

They'll cause ENORMOUSLY less transport if the profiles looked like this instead

## Super-XT divertor:

Much easier to reach fusion T in core: If the SOL is ~ 2 keV, a pedestal at ~ 4 keV is trivial

L-mode core sufficient even in small device

Any improved core confinement is bonus (in fact steeper density gradients will help!)

# The Super-X Divertor- forerunner to the Super-XT

The Super-X divertor, invented by my group at Texas, was a major breakthrough.

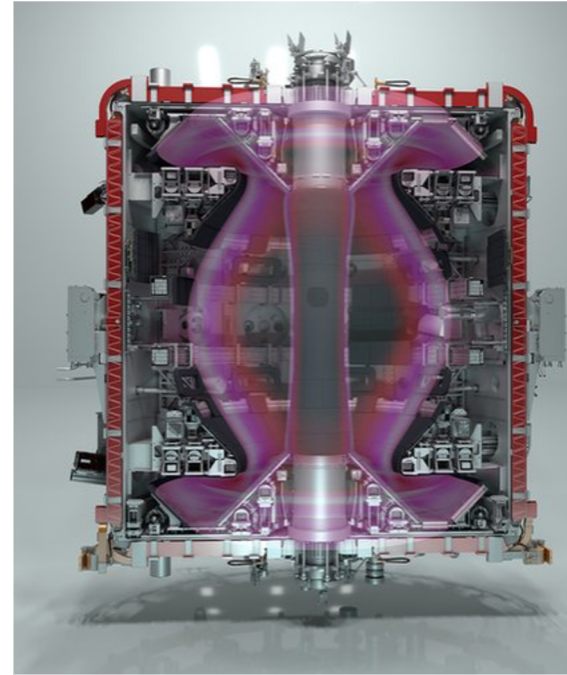
The U.K. gov't flagship experiment was upgraded to test it - £50-100 million Spectacular experimental verification in 2021

But the Super-X operates in the conventional mode (cold edge).

Exo-Fusion has patents pending on crucial, non-obvious modifications of the Super-X divertor so it will become the uniquely successful configuration for a “low recycling divertor” (hot edge).

The Super-XT (XT for eXtreme Temperature) allows an enormous boost to magnetic concepts it is connected to

## Super-X Divertor UK experiment



“I think the Super-X Divertor is a big step forwards. A huge step forwards”  
*Prof. Ray Orbach, Secy in charge of DOE science*

“The Super-X Divertor could certainly enable the high-power devices that the Texas group want... It will be the model of the kind of divertor that we will have on any demo reactor.”

—Sir Steve Cowley, then director of the UK Atomic Energy Agency fusion program, now director of the largest U.S. fusion lab (Princeton Plasma Physics Laboratory).

Quotes in Nature, the most prestigious physics journal in the world



# Taking Stock

- Though the highway to the destination -commercially viable fusion- is partially constructed (through scientifically brilliant, sustained and dogged research), we still have miles to build
- Soon we will have  $Q_{sci} = 1$ , the first grand step in the grand pursuit- fusion on earth. But much work still needs to be done to ensure that the star on earth, we create, does not remain just a prize museum ornament.
- Confinement must be boosted for both set of contenders:
  - 1) currently cheaper but low confinement systems –essential period!
  - 2) currently moderate/good confinement systems => smaller and lower magnetic fields => reduce cost.
- Fortunately, there are ideas and inventions driven by recent advances in Physics and incorporation of newer technologies, that could grow into a well-defined program for boosting confinement to needed levels.
- With the literal formation of the united community of Government Researchers, private companies and the private-public partnerships, the fusion enterprise will surely graduate from scientific breakeven to a regime of commercial viability.

# A Quintessential Scientific Quest

- It will be unwise to declare Fusion to be an Engineering and development program only
- Without periodic scientific injection of new ideas , CVF may remain distant
- Boosting Confinement today, new Fuels tomorrow, neutron Free fusion day after- This will keep scientists busy for a while

