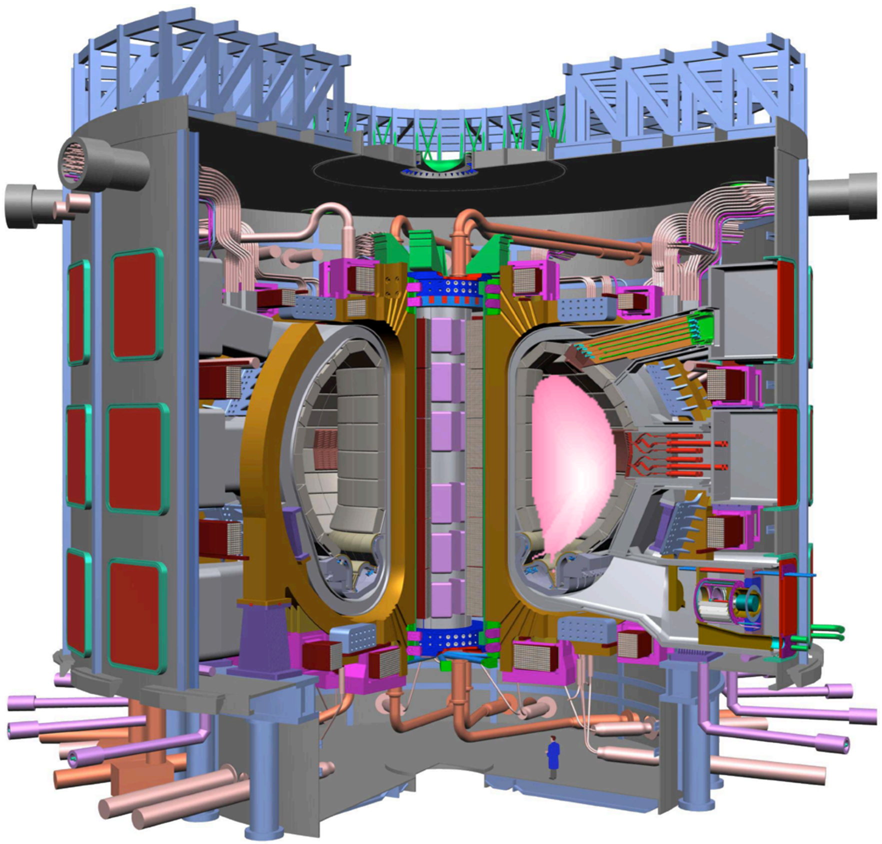
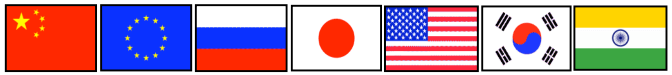
ITER

First Sustained Burning Plasma. Starts in 2018 - 2020.

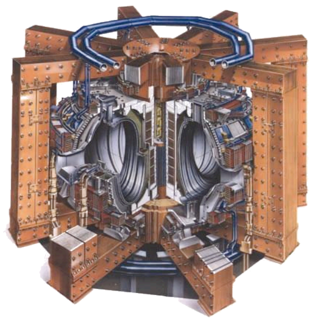


BASIC PARAMETERS.
Plasma Major Radius 6.2m
Plasma Minor Radius 2.0m
Plasma Current 15.0MA
Toroidal Field on Axis 5.3T
Fusion Power 500MW
Burn Flat Top >400s
Power Amplification Q>10

Cost is > 8 Billion Euro.



JET



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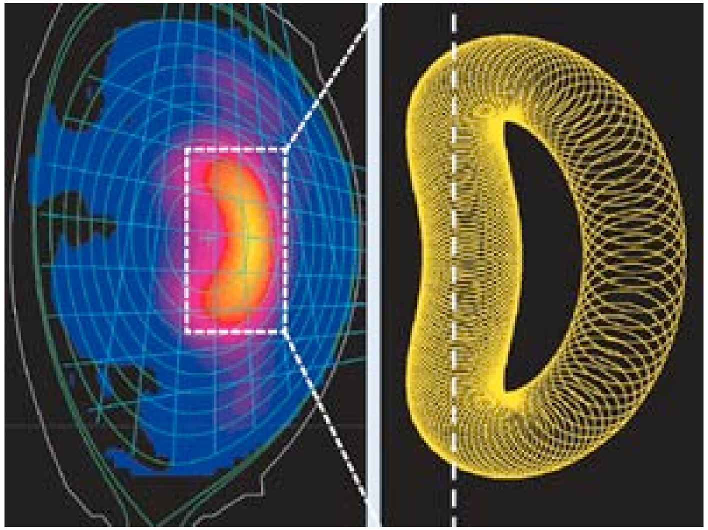
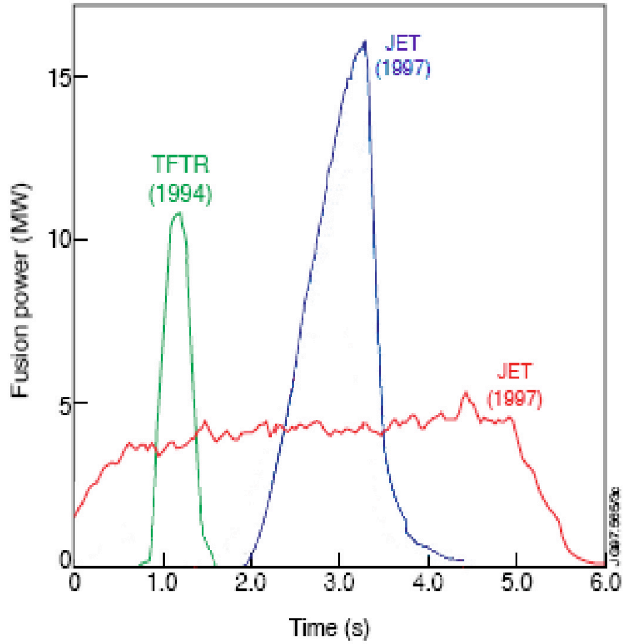
Science and Engineering Challenges for Fusion: Large - Compact

Steve Cowley -- Culham, Imperial

Rob Akkers, Brian Lloyd, Colin Roach, Steve Lisgo and MAST team.





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1920 The British Association

Arthur Stanley Eddington -- delivered the presidential address.

One of the many questions he addressed is:

Where does the energy radiated by the stars/sun come from?

F. W. Aston had measured the masses of elements and shown:

$M_{hydrogen} = 1.008$ and $M_{helium} = 4.0$

"F. W. Aston's experiments seem to leave no room for doubt that all the elements (nuclei) are constituted out of hydrogen atoms bound together with negative electrons".

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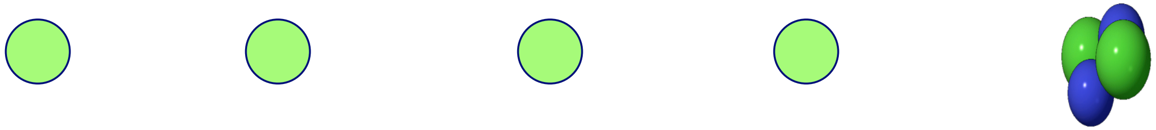
Fusion and the Sun

Eddington assumed that the sun puts four hydrogens together to make helium.:

H + H + H + H → He



Mass difference is energy by Einstein's relation $E= mc^2$. Thus:

1.008 kilograms of hydrogen → 1 kilogram of Helium + 7.5×10^{14} J of Energy.

That will supply you with all your energy needs for about 10,000 years.

Eddington estimated the sun's life expectancy to be 15 billion years from the mass and the radiated power -- quite close.

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Fusion

One possible solution for a long term energy supply is Fusion

"This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped".
Arthur Stanley Eddington 1920.

I will try to explain the scientific challenge and why we are finally at the point of generating Fusion burning plasmas -- the gateway to energy production.

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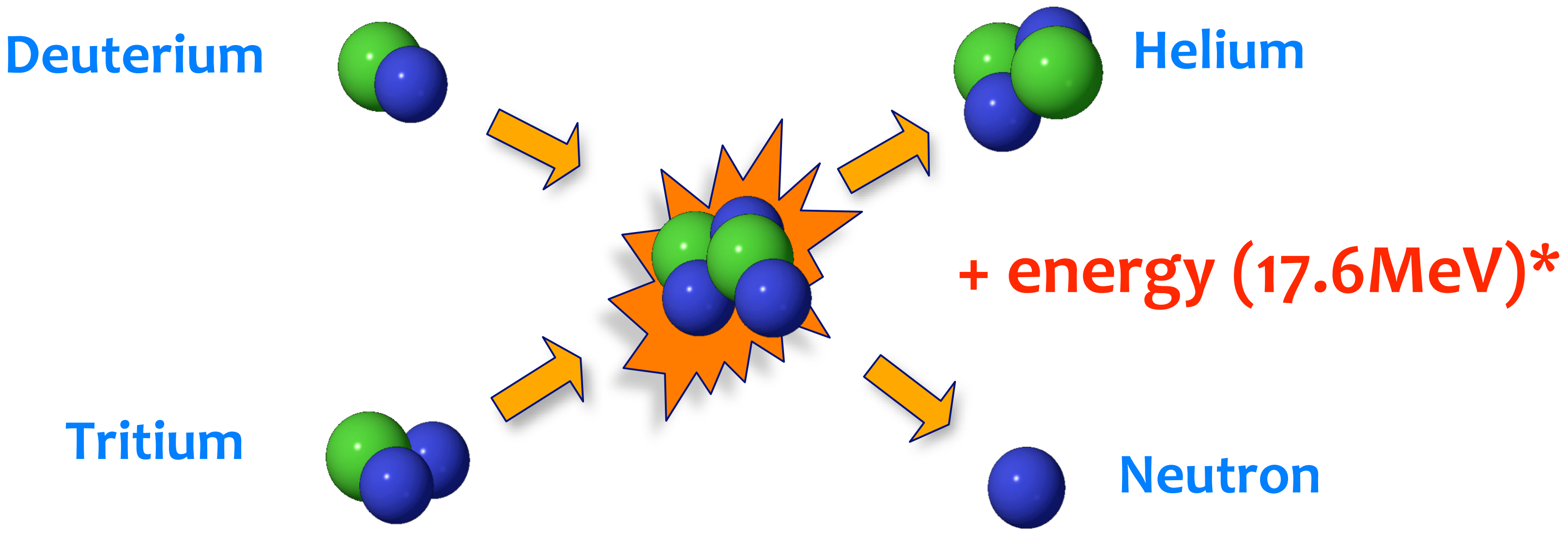
Which Fusion?



Tritium is bred from lithium using the neutron

$Li^6 + n \rightarrow He^4 + T$

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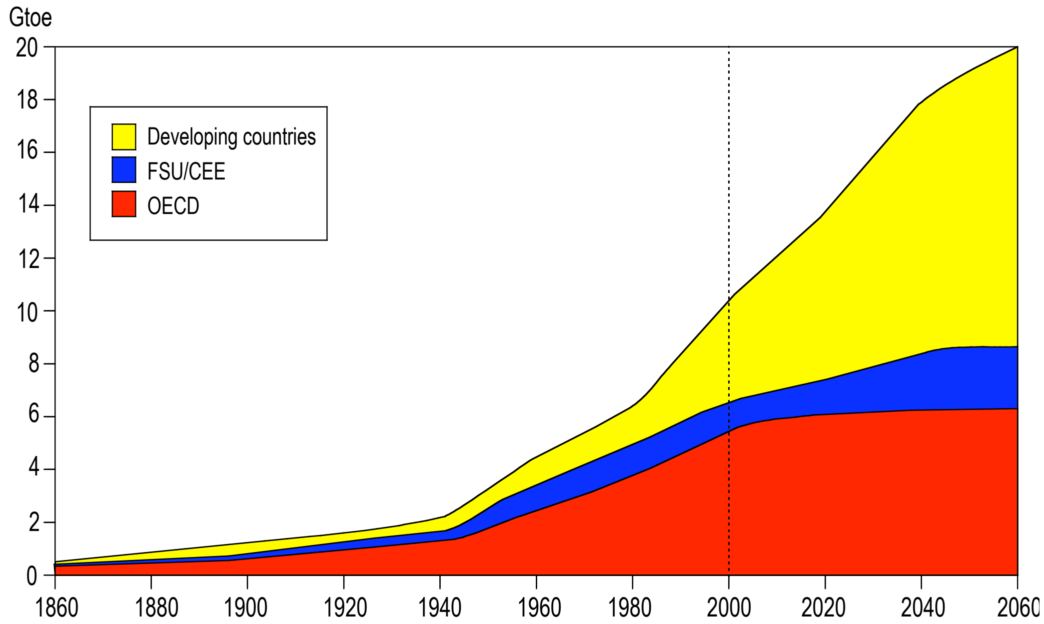
Predicted Energy Growth



Source: World Energy Council, World Bank.
The graph for the period 2000-2060 shows a scenario of future energy consumption based on current trends.

This assumes no increase in OECD energy consumption (efficiency improvement balances growth)

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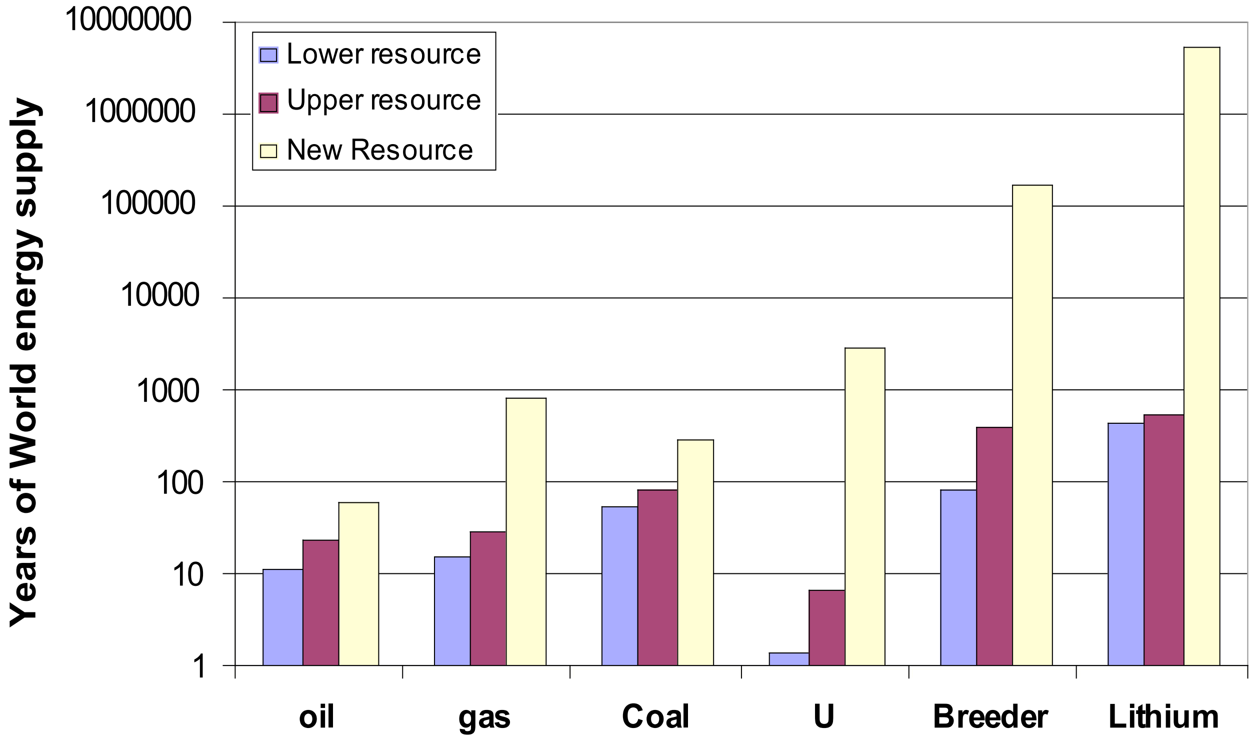
Ultimate Fuel Resource for Different Energy Systems



Large resources in coal, fission breeder and fusion. Solar provides a large resource as well.

Source: WEC, BP, USGS, WNA

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Is Fusion Possible?

For plasma at 10-20Kev temperatures (100-200MºC) D-T fusion power density is approximated by:

$$\mathcal{P}_{Fusion} = 0.08P^2 \; (MWm^{-3})$$

Plasma pressure in atmospheres

We need >1MWm^{-3} for a economic system -- need a few Atmospheres of plasma pressure. Can we hold it with a magnetic field?

Magnetic pressure = $P_{Magnetic} \sim 4 B^2$ (atmospheres)

Magnetic Field in Tesla

Figure of merit $\beta = P/P_{Magnetic}$

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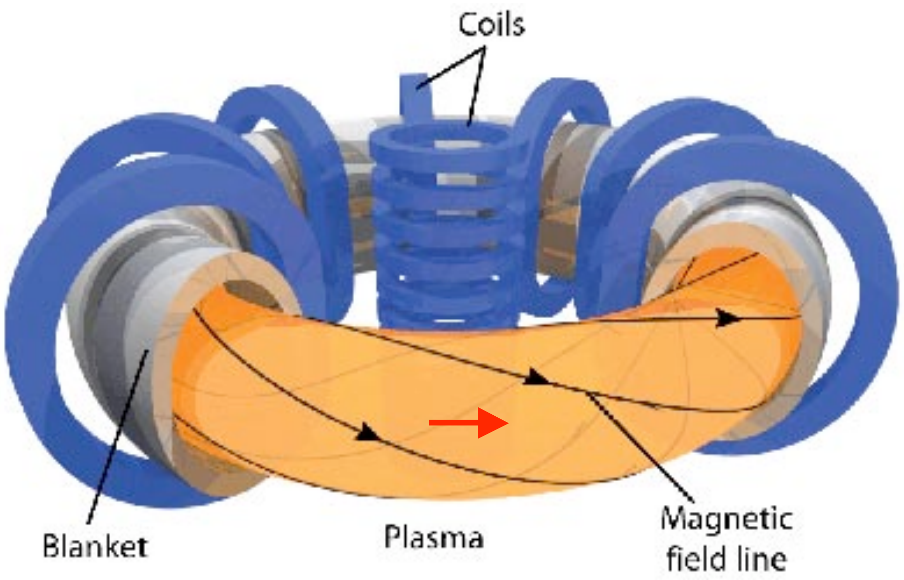
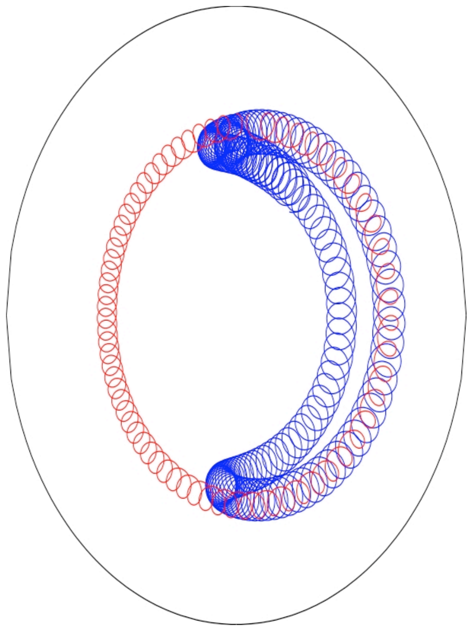
How do you hold something at 100 million degrees?
The Magnetic Bottle.

At these temperatures gas ➔ plasma

electrons and ions move independently





Projected particle orbits

Charged Particles stay inside plasma

Current

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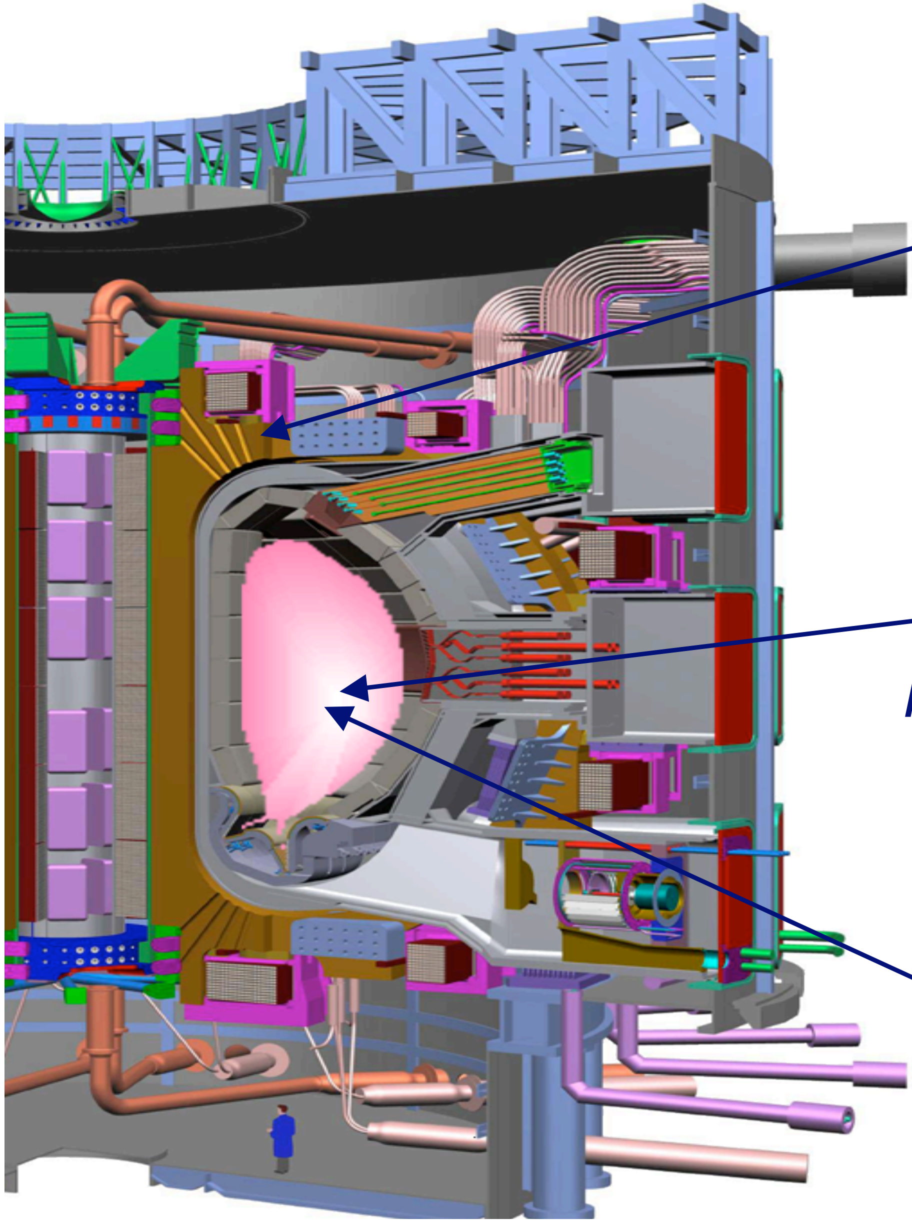
Fusion Force Balance in ITER



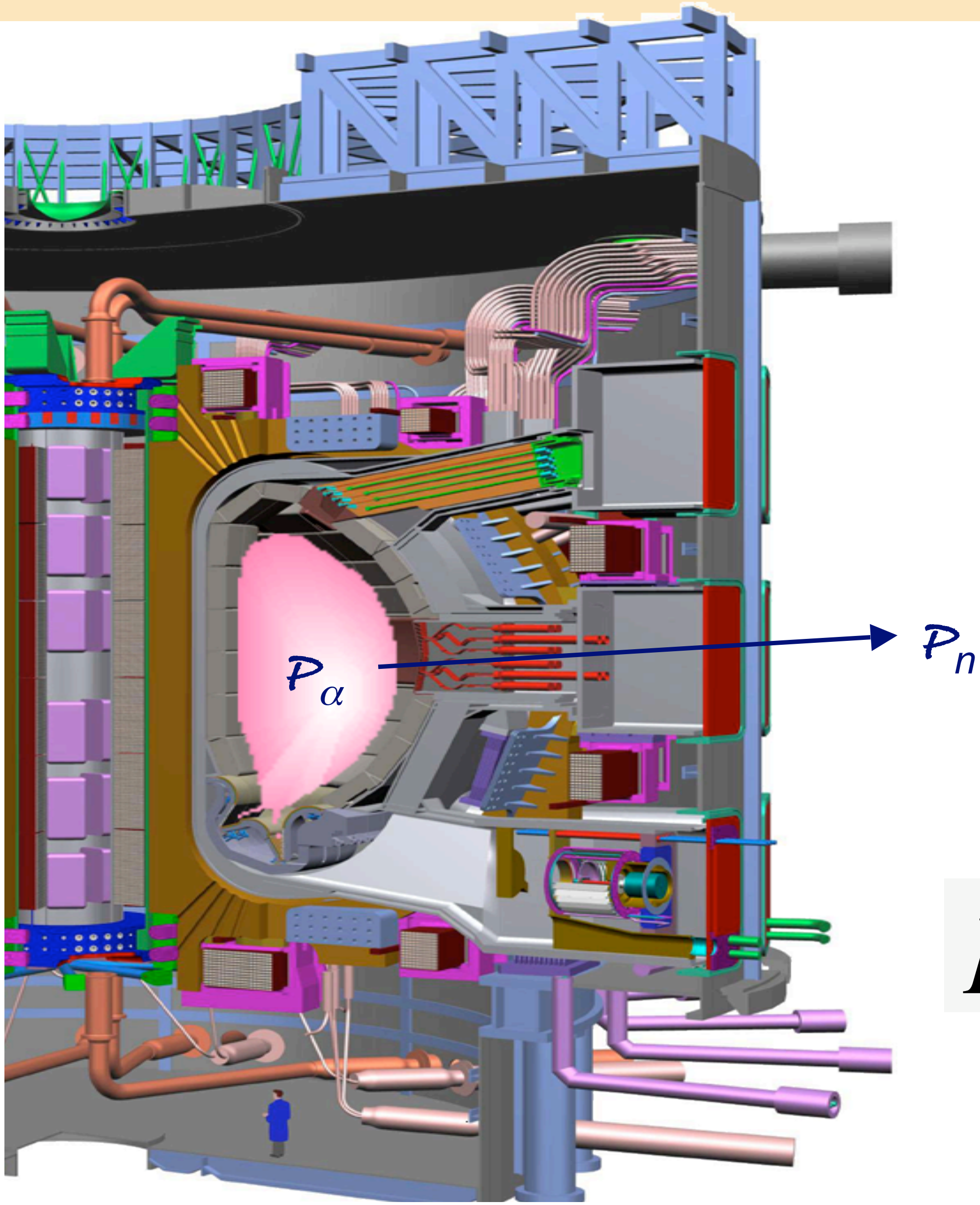
Superconducting Coils
central B field 5.2 Tesla
$P_{magnetic}$ *~ 100 atmospheres*

Central Temperature >20keV
P =Plasma Pressure ~7 atmospheres

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV

Fusion Energy Balance in ITER



'Baseline Performance'

Power in alphas captured by Plasma $\mathcal{P}_\alpha$ ~ 100MW.

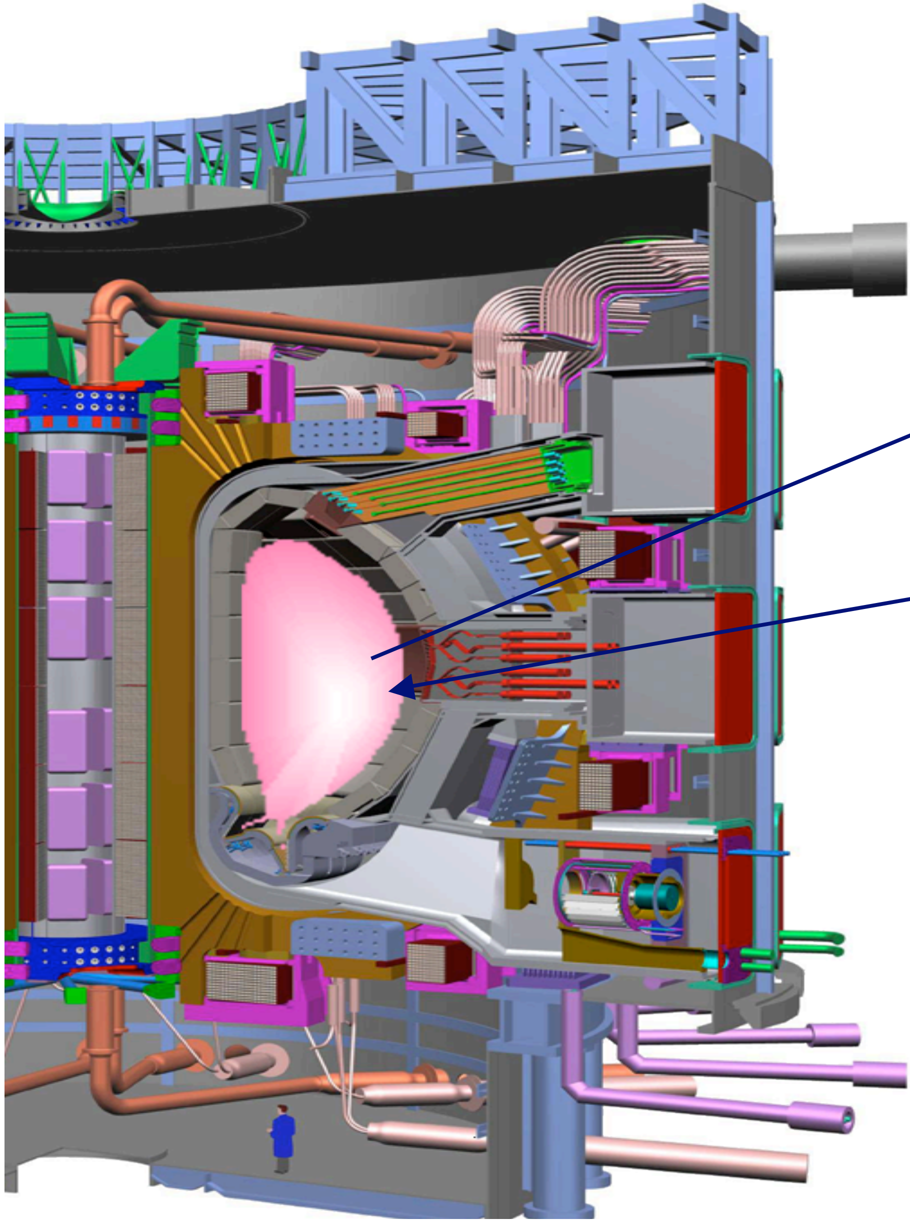
Power in neutrons escaping Plasma $\mathcal{P}_n$ ~ 400MW.

$\mathcal{P}_n + \mathcal{P}_\alpha = \mathcal{P}_{Fusion}$

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV

Fusion Energy Balance in ITER



Turbulent Plasma Energy Loss

$$\mathcal{P}_{loss} = \frac{0.15P}{\tau_E}(MWm^{-3})$$

Confinement Time

External Plasma heating

$\mathcal{P}_{Heat}$~50MW

Energy Balance

$$\frac{\mathcal{P}_{Fusion}}{5} + \mathcal{P}_{Heat} = \mathcal{P}_{loss} \sim 0.15\frac{P}{\tau_E}$$

Energy Gain > 10

Why so Big?

………Turbulence

without turbulence machine size ~ 20- 50cm

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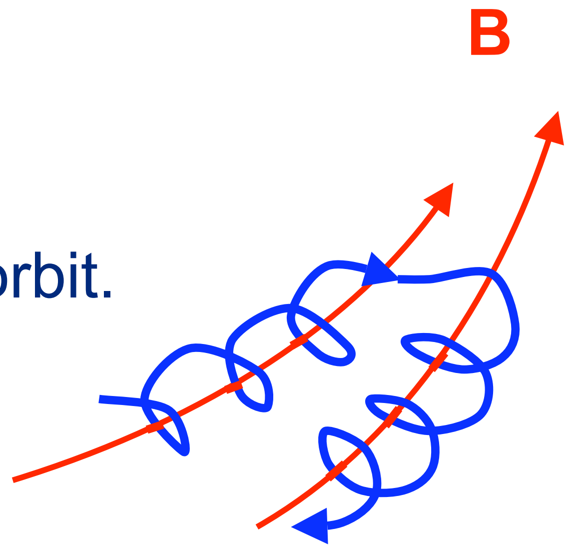
Classical Transport.

Spitzer. 1951.

Ion orbit.



Random walk:
Step = ρ, larmor/cyclotron radius.
Decorrelation rate = ν = collision rate
Radius of plasma = *a*.

$$\tau_E \sim \frac{a^2}{\nu\rho^2}$$

Collisions are rare and classical confinement can be very good.
Spitzer only needed *a* = 20cm, (τ_E>4s) for IGNITION.
Can't be right. Observed transport is much larger.

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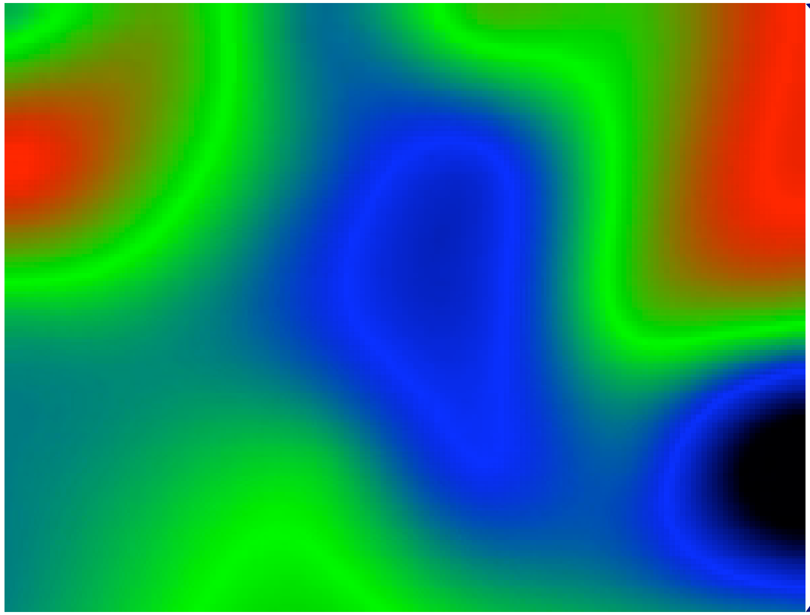
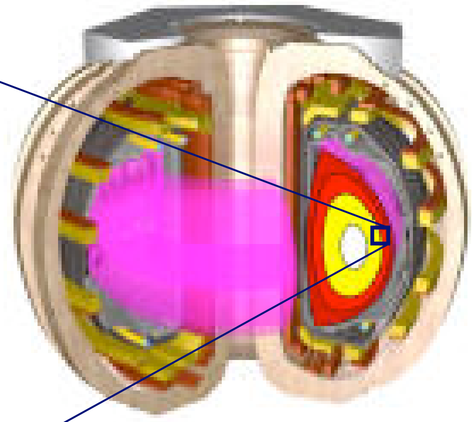
Turbulence Imaging, Beam Emission Spectroscopy

Ray Fonck and George McKee

~ 4cm



Density fluctuations



DIII-D in San-Diego

Plasma is 1m across

Eddies are small

compared to the device

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Gyro-kinetic simulation.

DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

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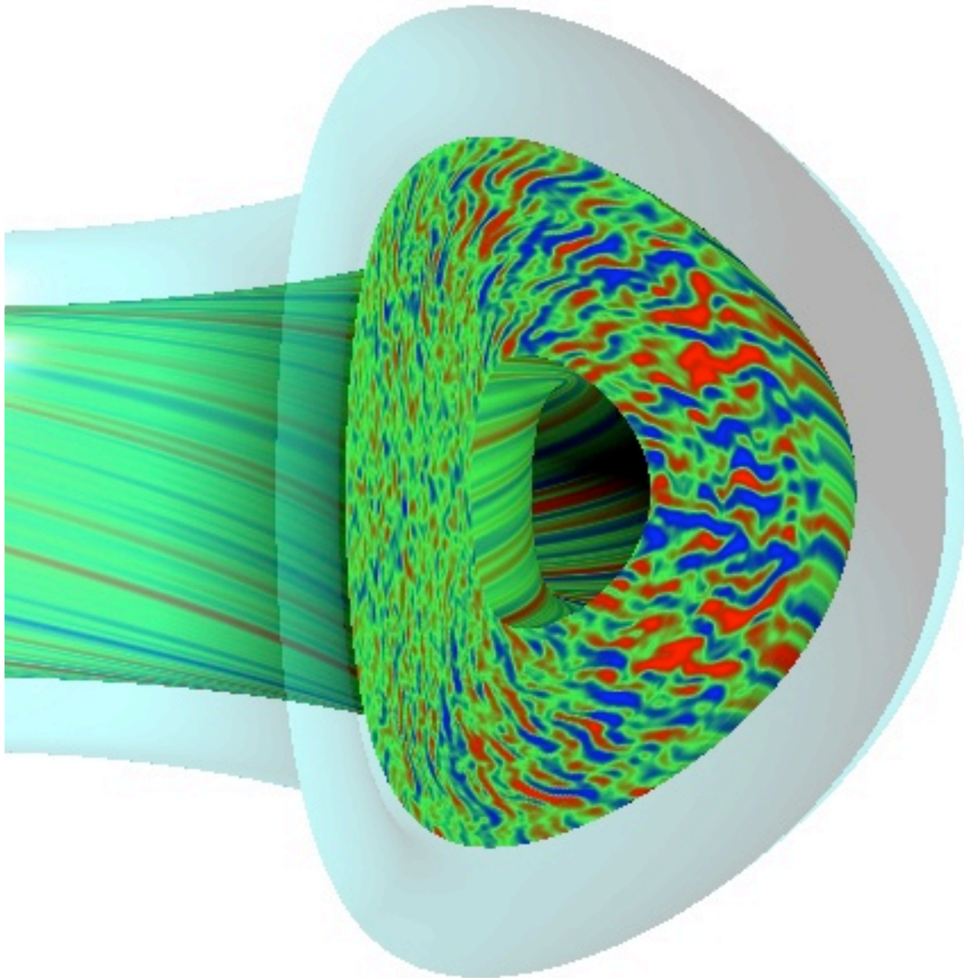
GYRO code simulations by Jeff Candy and Ron Waltz GA

Energy Confinement -- Random walk of heat/particles.



L = typical machine size

Δ= radial eddy size ∝ Ion larmor Radius ρ_i = random step.

N = number of steps to random walk out of plasma

$$L \sim \sqrt{N}\rho_i$$

$$\rightarrow N = (\frac{L}{\rho_i})^2$$

For ITER N ~ 10^6.

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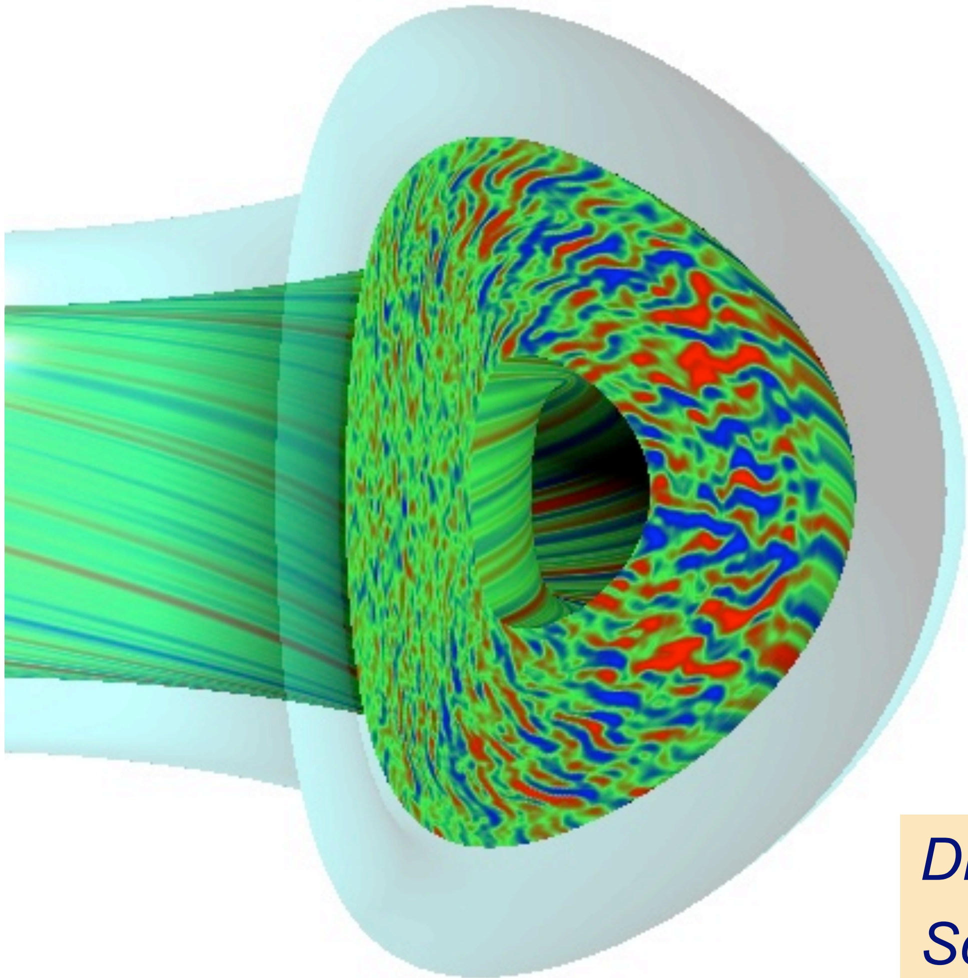
Energy Confinement -- Random walk of heat/particles.



Eddy turnover time =

$$\tau_{eddy} = (\frac{L}{v_{thi}})$$

$$\tau_E \sim N\tau_{eddy} \sim (\frac{L^3}{\rho_i^2 v_{thi}})$$

$$\propto L^3 B^2 T^{-1}$$

Dramatic scaling with size!
Scaling approximately agrees with data BUT geometry dependant.

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Why so Big? Physics and Cost of Electricity.

Almost no external heating: $\mathcal{P}_\alpha = \frac{\mathcal{P}_{Fusion}}{5} \sim 0.01 P^2 > \mathcal{P}_{loss} \sim 0.18 \frac{P}{\tau_E}$

$$\rightarrow P\tau_E > 20$$

Detailed design analysis shows plasma radius greater than ~2m (B ~ 5 tesla) will ignite.

Capital Cost: $\propto L^{2-3}$ *Power Output:* $\propto P^2 L^3$

Detailed design analysis shows cost of electricity is reasonable (5-15 c/kWh) at GW level power station

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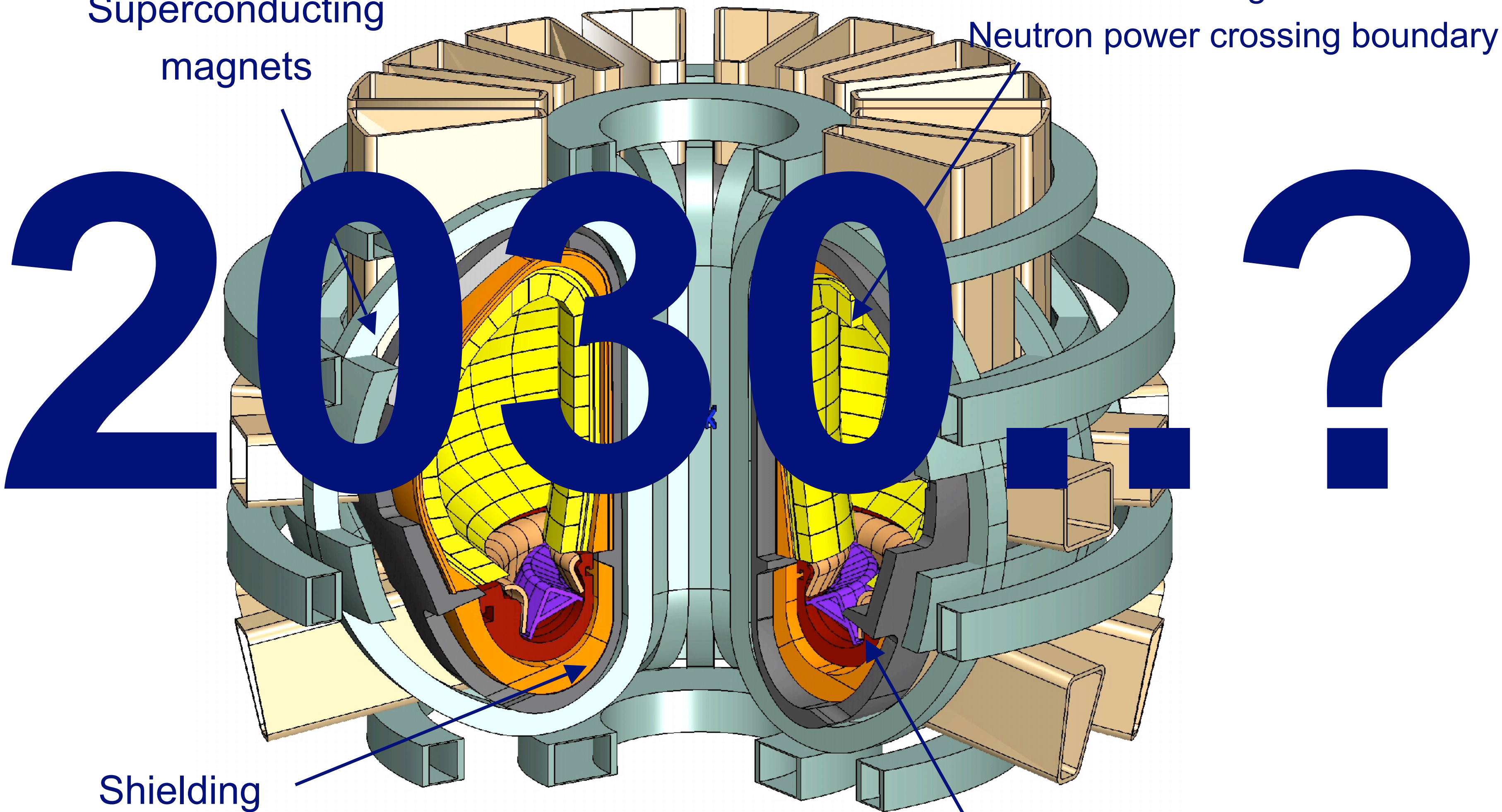
Fusion Power is Possible.

EU Power Plant.



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MAST - Compact Fusion -- why?

MAST -- fusion performance in a compact device at modest cost. Why?

- *Lower capital cost -- development easier.*
- *Higher efficiency -- larger $\beta = P/(4B^2)$.*
- *Rotationally enhanced confinement.*
- *Innovate improved REACTOR designs.*

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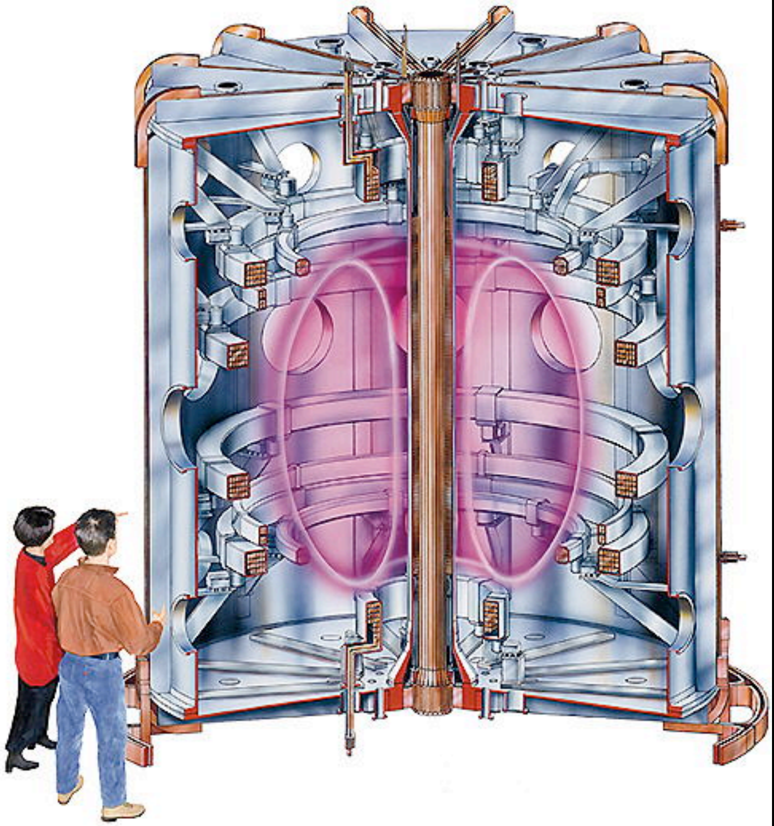
MAST - Compact Fusion



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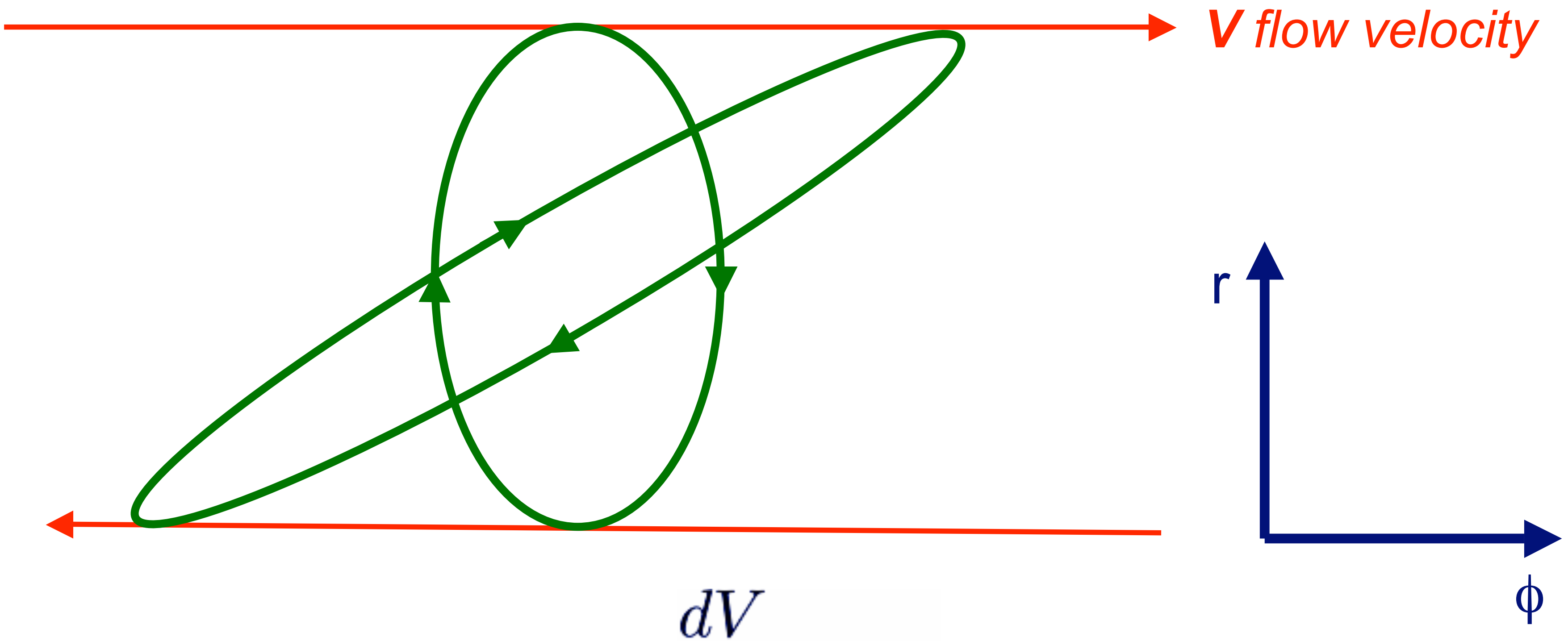
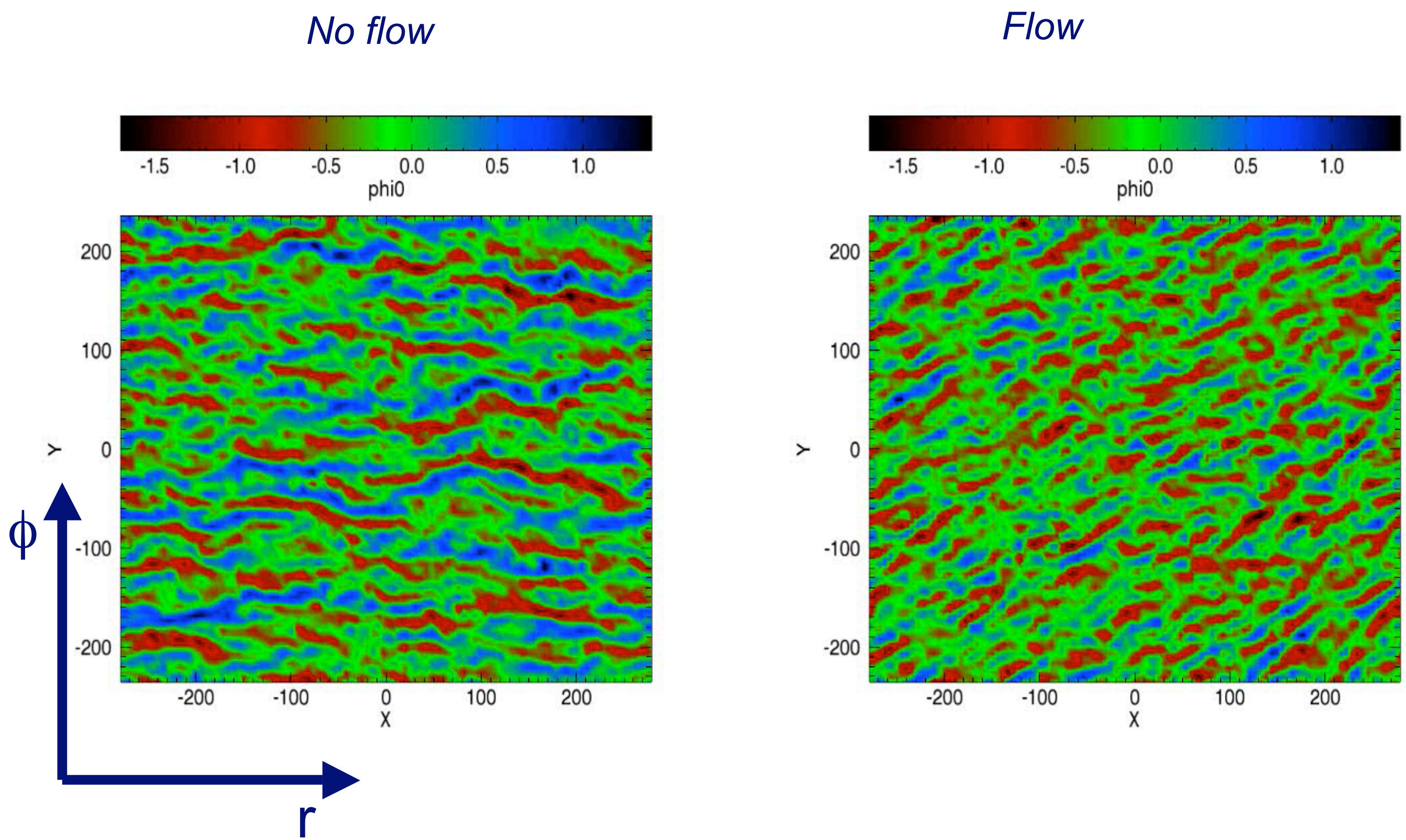
Shear Flow Stabilization



Stabilized when Stretching rate ~$\frac{dV}{dr} = \gamma_E$ *> Eddy turnover rate (~growth rate)*

Some Moving Blobs of Tokamak Turbulence



Φ contours on outboard midplane: γ_E=0 and γ_E=0.02~0.5γ_{max}

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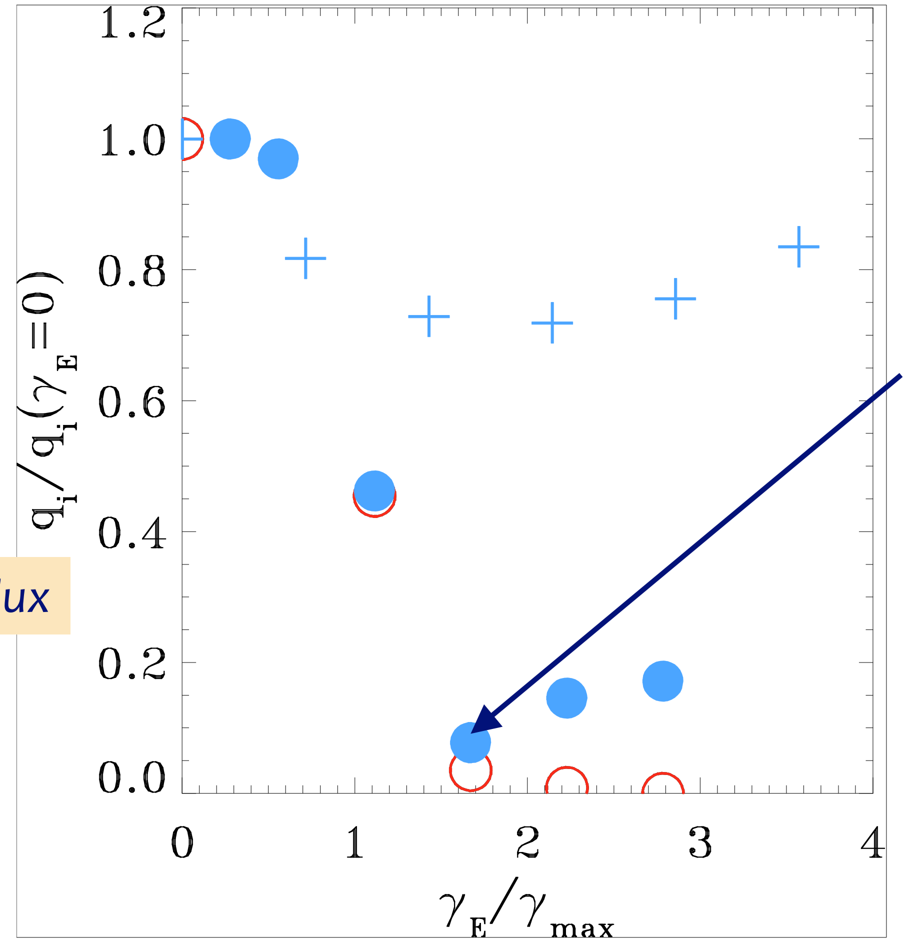
Heat Flux Flow: Shear "Suppression"

Roach et. al. 2009



Heat Flux

Shearing Rate

[1] Kinsey et al, Phys Plasmas **12** (2005)

- no linear drive (~spherical, GS2)
- with linear drive (~spherical, GS2)
- with linear drive (~JET, GKW)

Optimum shearing rate

Suppresses heat loss by factor >10

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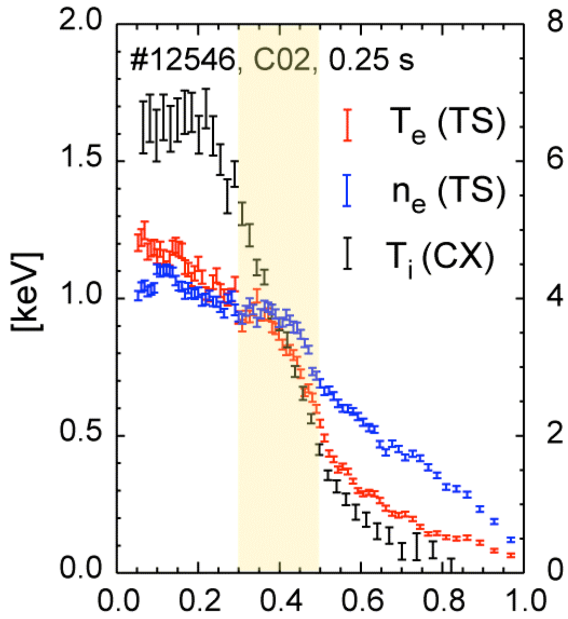
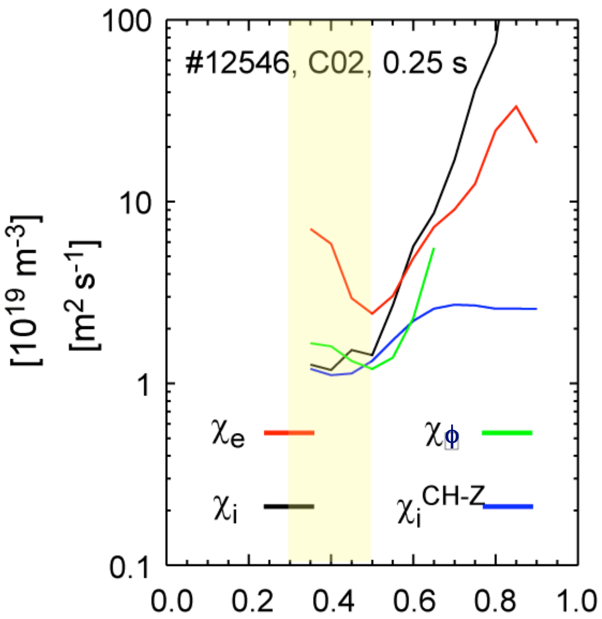
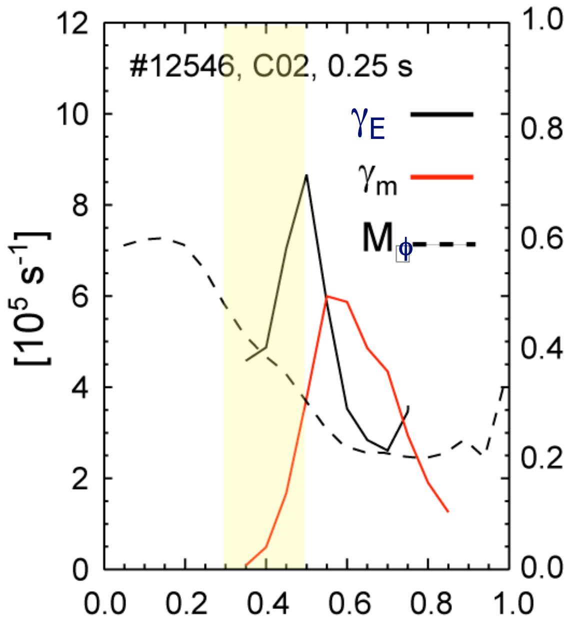
Rotationally Enhanced Confinement.



Radius



Radius



Radius

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Register for our PhD event on 25 November

www.culhamphd.org.uk/

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UKAEA Fusion
Working with Europe

Fusion Soon.

- *Pretty certain we can now do fusion at large scale.*

  We must get a fusion reactor online in the UK by 2040.
- *It requires considerable investment -- political will is vital.*
- *Fusion at compact scale is more speculative -- but……*

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