Overview of Fusion Parameter Space

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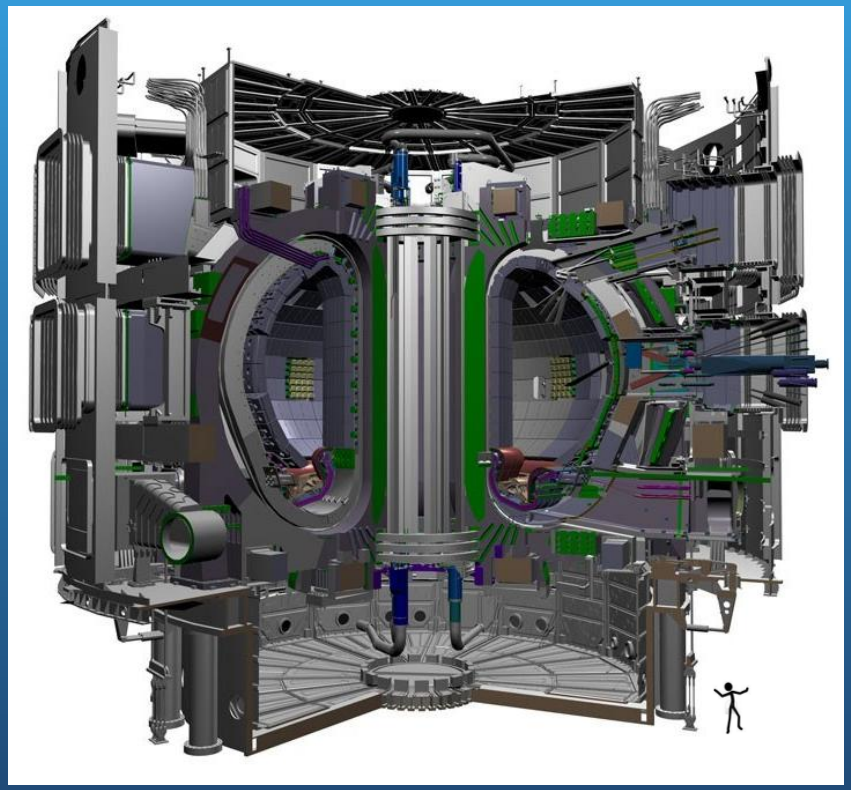
Summary of talk

- Introduction to fusion based on my personal opinions formed by working a few years on the subject
- Cost of development is biggest obstacle to fusion energy
- Looking at parameter space as constrained by Mother Nature reveals a mostly unexplored region where cost should be less
- ARPA-E funding could seed game-changing experiments that finally make fusion for energy more than just a dream for the future

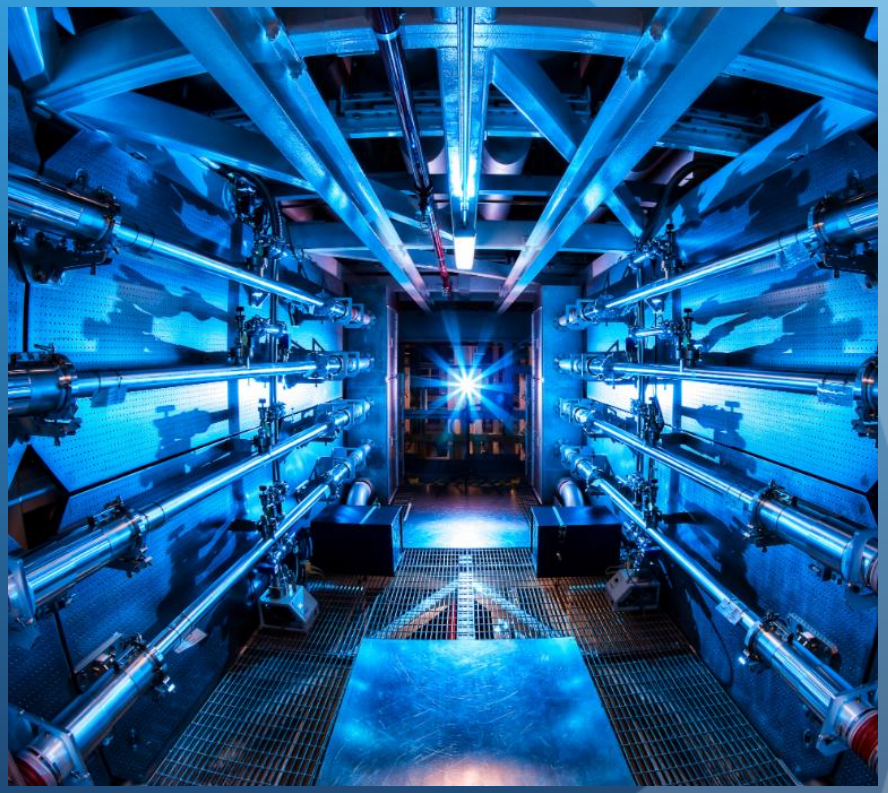
Conventional Magnetic and Inertial Fusion: Good Science

- ITER: world's largest Tokamak under construction in France



Cost over $20 billion

- NIF: world's largest laser operating at LLNL



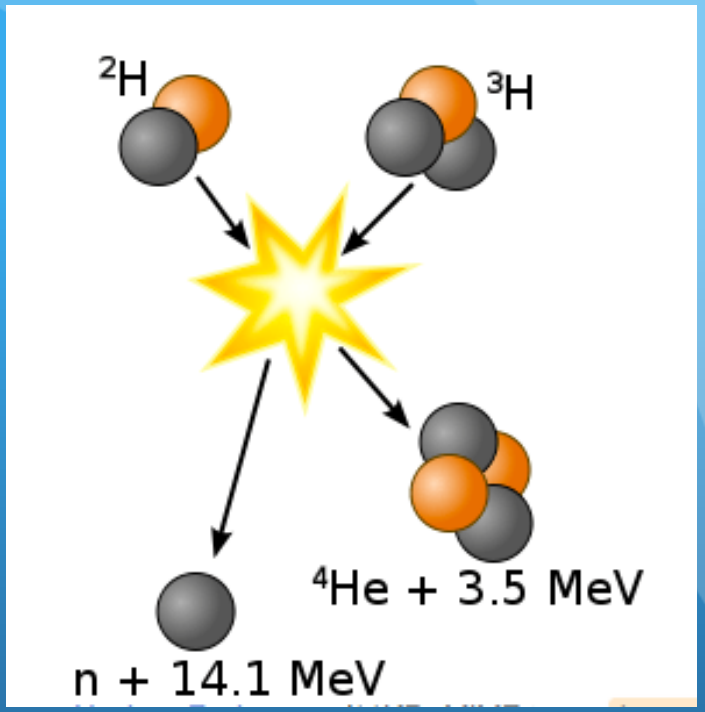
Cost over $4 billion

Problem: Cost of Development

- Facilities to produce fusion energy gain cost $billions
- One consequence is slow pace of scientific progress to date (ITER to operate after 2020)
- More important consequence appears when fusion reaches the development phase of a new technology and many prototype reactors to do trial and error solutions to material problems, operational reliability and safety, licensing issues, etc.
- Following remarks will show why a basically unexplored approach called magnetized target fusion (or magneto-inertial fusion) should avoid the underlying problem of large facility cost.

Fusion basics

- Overcoming Coulomb repulsion requires about 10 keV temperature (110 million degrees Kelvin)
- Density, n, of interacting particles determines power generation, P, given fusion energy, E_f per reaction
- ONLY density can be changed by much!!



$$n_D = n_T = n/2$$

$$P_f = 1/4 \langle sv \rangle n^2 E_f$$

Density and known temperature determine ideal gas pressure = 2nkT

Density (ions/cm3)	Gas Pressure (atmospheres)
10^{14} - 10^{15} tokamaks; stellarators	3 -30
Yield strength steel	≈$3x10^{4}$
≈10^{20} magnetized target (tbd)	≈$3x10^{6}$
10^{25} inertial fusion target	$3x10^{11}$

Main points

- Range of numbers is impressively large
- The density for fusion with “targets” involves large pressures that will explode

Energy gain requires adequate energy confinement time "Lawson" condition

- Energy confinement time τ_E is whatever characteristic time results in the loss of energy from the hot fuel

$$P_f = 1/4 < \sigma v > n^2 E_f$$

$$P_f > nT / t_E$$

$$n t_E > (T / E_f)(1/ < \sigma v >)$$

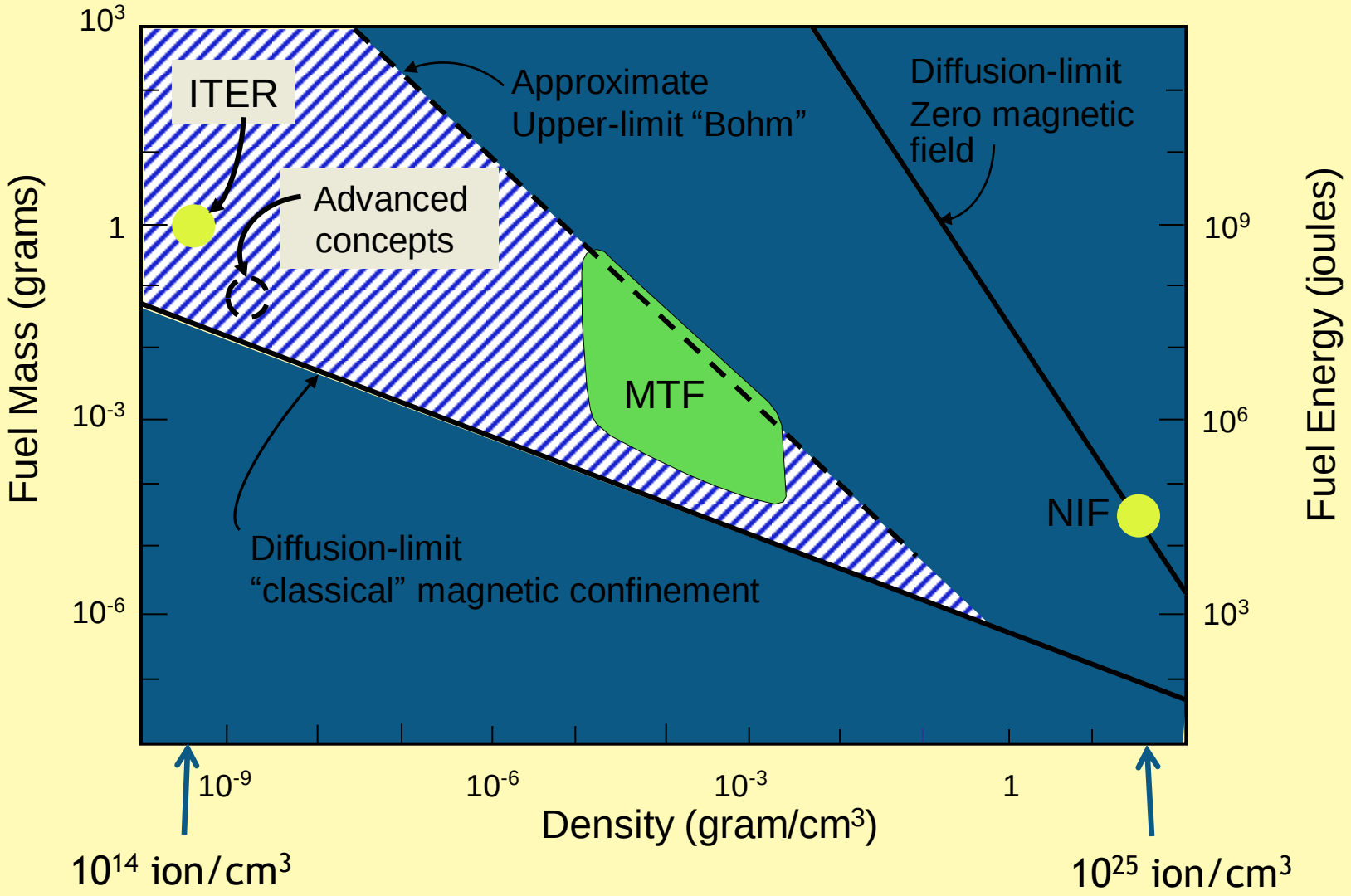
Knowledge of energy diffusivity | gives estimate of size to meet Lawson

$$t_E = \frac{R^2}{c\ (n, T, B)}$$

- Diffusivity has lower bound of "classical" given by Spitzer, and various other theoretical and experimental guidelines
- With known radius, we can compute volume, mass of fuel, energy of fuel, power, etc.
- Of course there are devils in the details.
  See Lindemuth & Siemon, Am. J. Phys. 77, 407(2009).

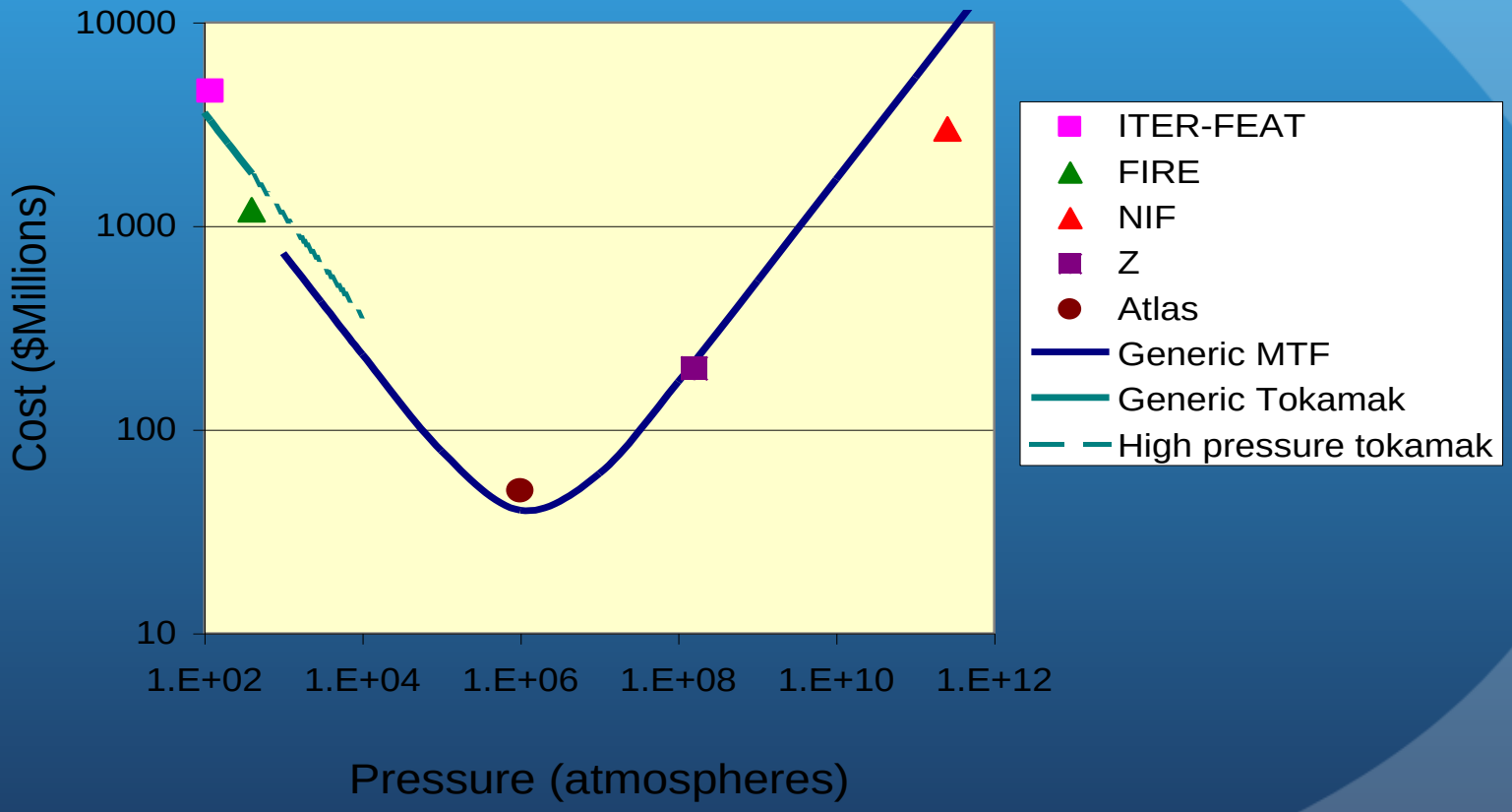
Compact torus; T = 10 keV; Fusion gain~3; Poloidal beta =1

Required DT Fuel Mass



Cost of fusion facilities

Ballpark estimate for cost = $30/Joule E_{plasma} + $30/MW P_{heat}



Conclusions

- The broad brush perspective just painted suggests that the cost of development implied by high facility cost is most likely prohibitive unless we look for fusion systems with density intermediate between conventional magnetic or inertial
- ARPA-E could restore interest in energy generation based on fusion by directing attention to new directions and funding a few carefully chosen experiments to demonstrate a viable pathway towards affordable fusion energy

Road sign for the direction needed

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