NUCLEAR FUSION

PRINCIPLES AND PROGRESS

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Habilitationskolloquium

“black board with many formulas blending into a nuclear fusion reactor”
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OUTLINE

I. Motivation

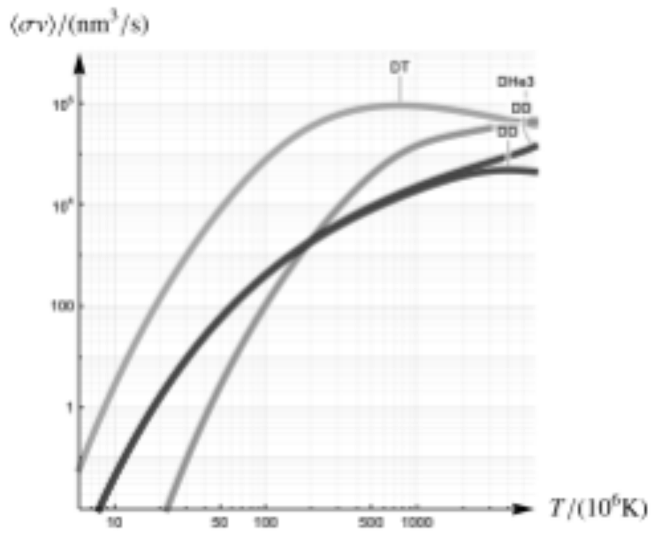
II. Fundamental principles

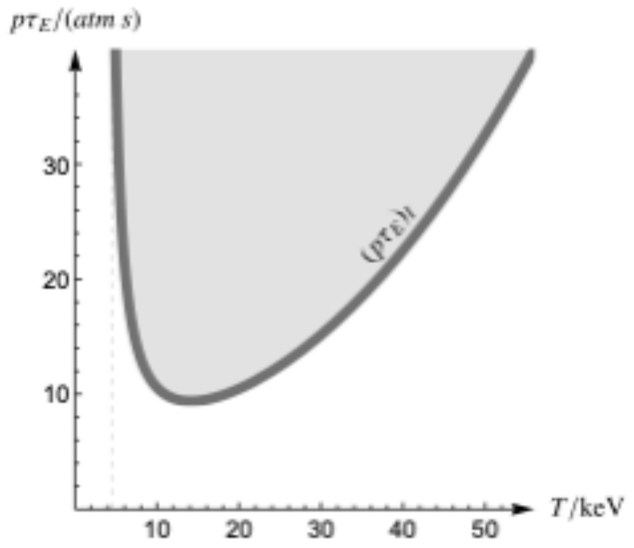
nuclear reactions,

electrostatic repulsion,

reaction rates,

plasma, …





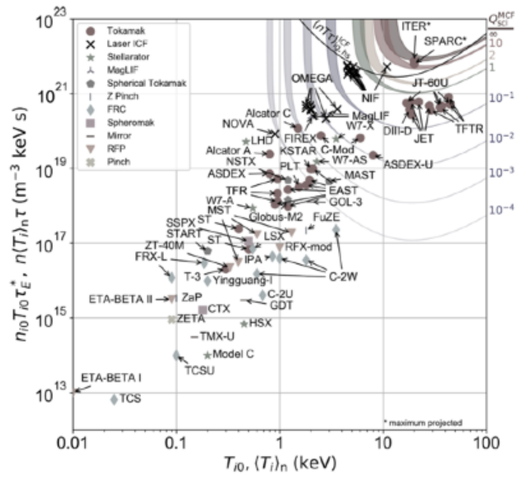
III. Technical implementation

Lawson criterium,

ignition,

confinement,

fuel self-sufficiency, …



IV. Summary

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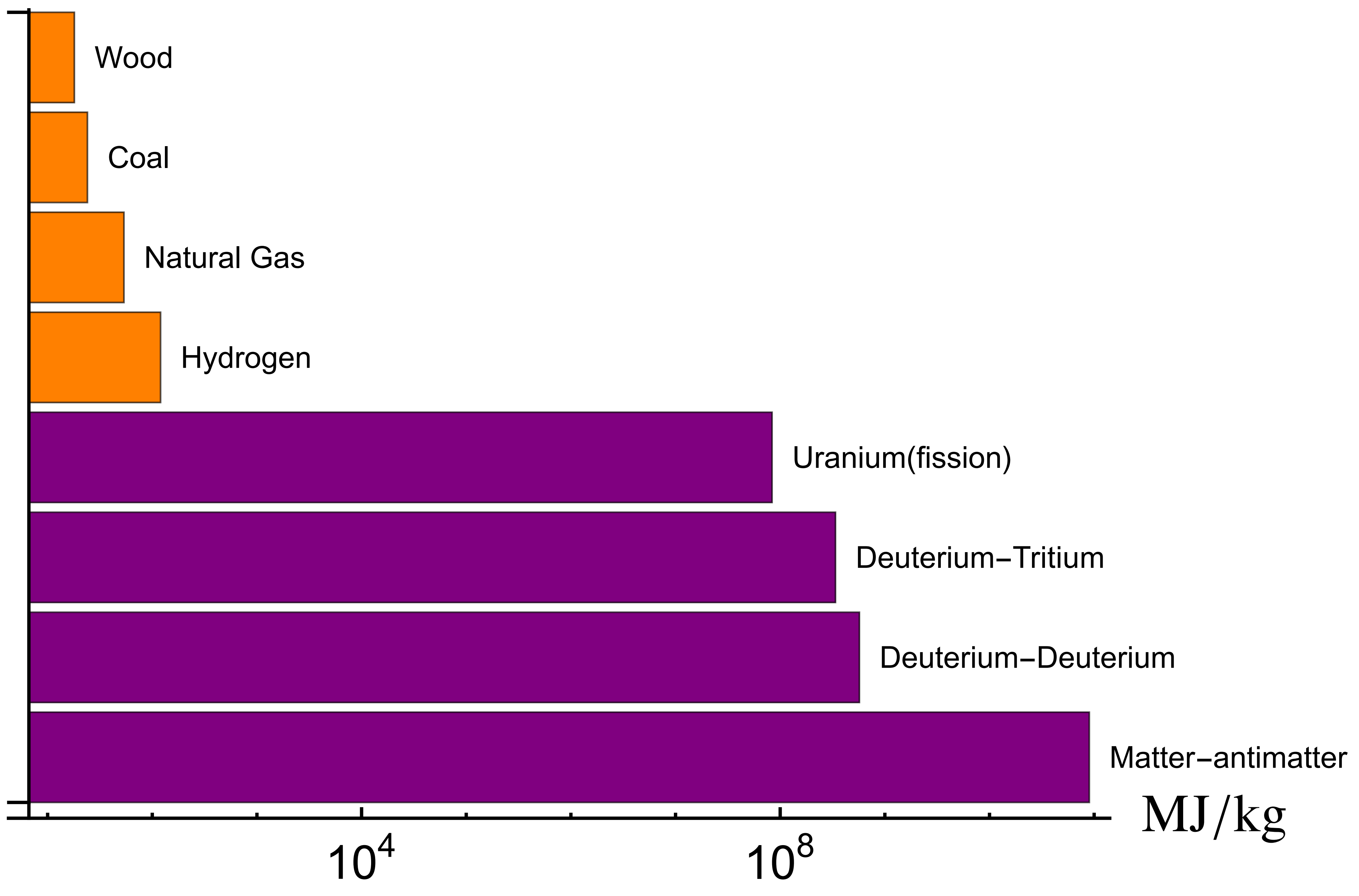
MOTIVATION

Electricity production

	known since	availability	impact on nature
fossil fuels	~1880s	flexible (60-900y)	CO^2 pollution
natural	~1900s	local	areal changes
renewable	~1890s	stochastic	areal changes
nuclear fission	~1950s	flexible (200y+)	nuclear waste
nuclear fusion	?	flexible(?)	~ 0(?)

Energy density[1]



[1] International Energy Agency (IEA), Department of Energy (DOE), Nuclear Energy Agency (NEA)

MOTIVATION

Nuclear fusion in "action"

1. stars
   - gravity: high density, temperature $T \sim 10^7\,\mathrm{K}$
   - ${}^1_1\mathrm{H} + {}^1_1\mathrm{H} \to {}^2_1\mathrm{H} + e^+ + \nu \qquad \Delta E = 0.42\,\mathrm{MeV}$
   - CNO and tripple-alpha processes — fine-tuning[1]
2. fission/fusion weapons
   - fission stage: high density, temperature $T \sim 10^8\,\mathrm{K}$
   - fusion stage: deuterium-tritium reaction

fission weapons $\leftrightsquigarrow$ ***commercial reactors =*** $\mathcal{O}(10y)$

… can one de-weaponise fusion? [2]

[1] Adams, Phys. Rept. 807 (2019) 1; Lähde et al. Eur.Phys.J.A 56 (2020) 3
[2] Dittmar, Energy 37 (2012) 35-40

II. FUNDAMENTAL PRINCIPLES

Power balance

electrostatic repulsion

Ignition

Lawson criterion

…

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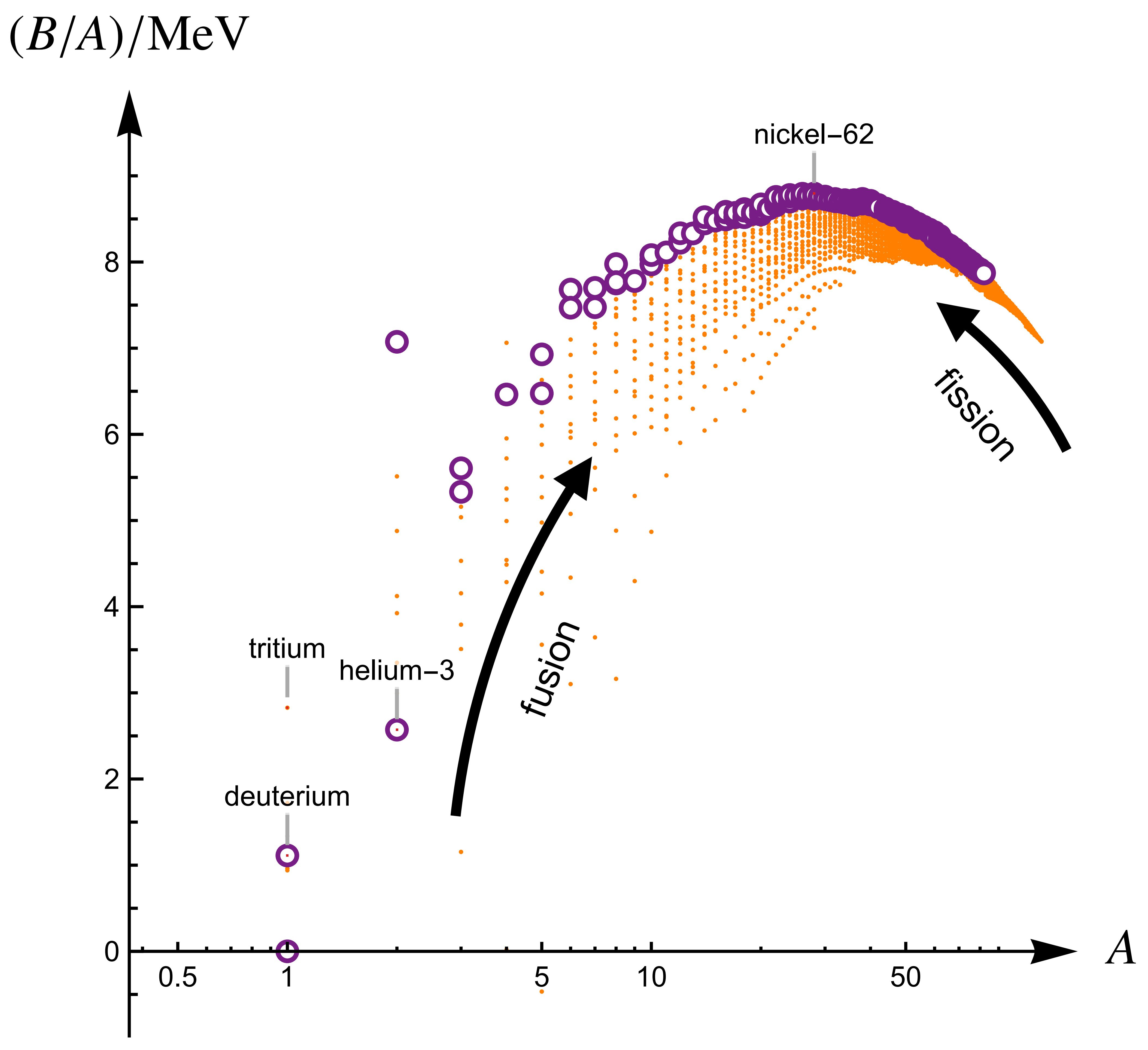
BASIC PRINCIPLE

Nuclear fusion

- $X(B_X) + Y(B_Y) \to Z(B_Z)$
- Excess in energy $\Delta E = B_Z - B_Y - B_X > 0$ for small A
- Example[1]:

$$\underbrace{{}^2_1\mathrm{H}}_{B=2.2\,\mathrm{MeV}} + \underbrace{{}^2_1\mathrm{H}}_{B=2.2\,\mathrm{MeV}} \to \underbrace{{}^3_2\mathrm{He}}_{B=7.8\,\mathrm{MeV}} + {}^1\mathrm{n} \quad (\Delta E = 3.3\ \mathrm{MeV})$$



Strong(short-) vs. EM(long-range) force

[1] https://periodictable.com/Isotopes/010.20/index.p.dm.html

COULOMB BARRIER

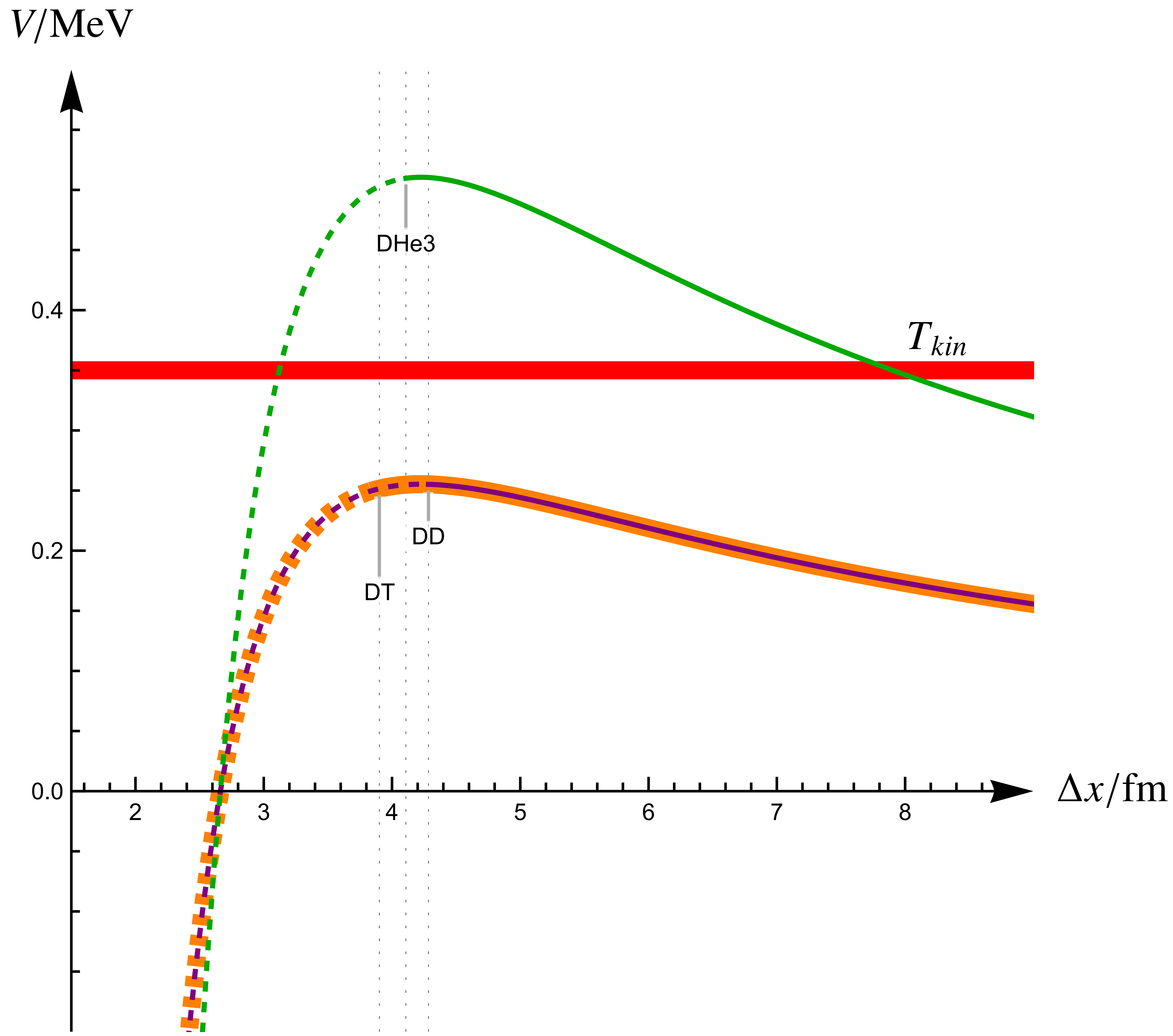
Reactants are charged!

- Electrostatic repulsion

1. deuterium-deuterium $^2_1\mathrm{H} + ^2_1\mathrm{H} \rightarrow ^3_2\mathrm{He} + ^1\mathrm{n} + 3.3\ \mathrm{MeV}$
2. deuterium-deuterium $^2_1\mathrm{H} + ^2_1\mathrm{H} \rightarrow ^3_1\mathrm{H} + ^1_1\mathrm{H} + 4.0\ \mathrm{MeV}$
3. deuterium-tritium $^2_1\mathrm{H} + ^3_1\mathrm{H} \rightarrow ^4_2\mathrm{He} + ^1\mathrm{n} + 17.6\ \mathrm{MeV}$
4. deuterium-helium3 $^2_1\mathrm{H} + ^3_2\mathrm{He} \rightarrow ^4_2\mathrm{He} + ^1_1\mathrm{H} + 18.3\ \mathrm{MeV}$

- Tunnelling: larger distances (lower temperature)

… through WKB[1]



[1] Liu et al. Phys Rev C 104, 044614 (2021);
[2] Bosch/Hale 1992 Nucl. Fusion 32 611

REACTION RATES

Reactants do not have fixed momentum

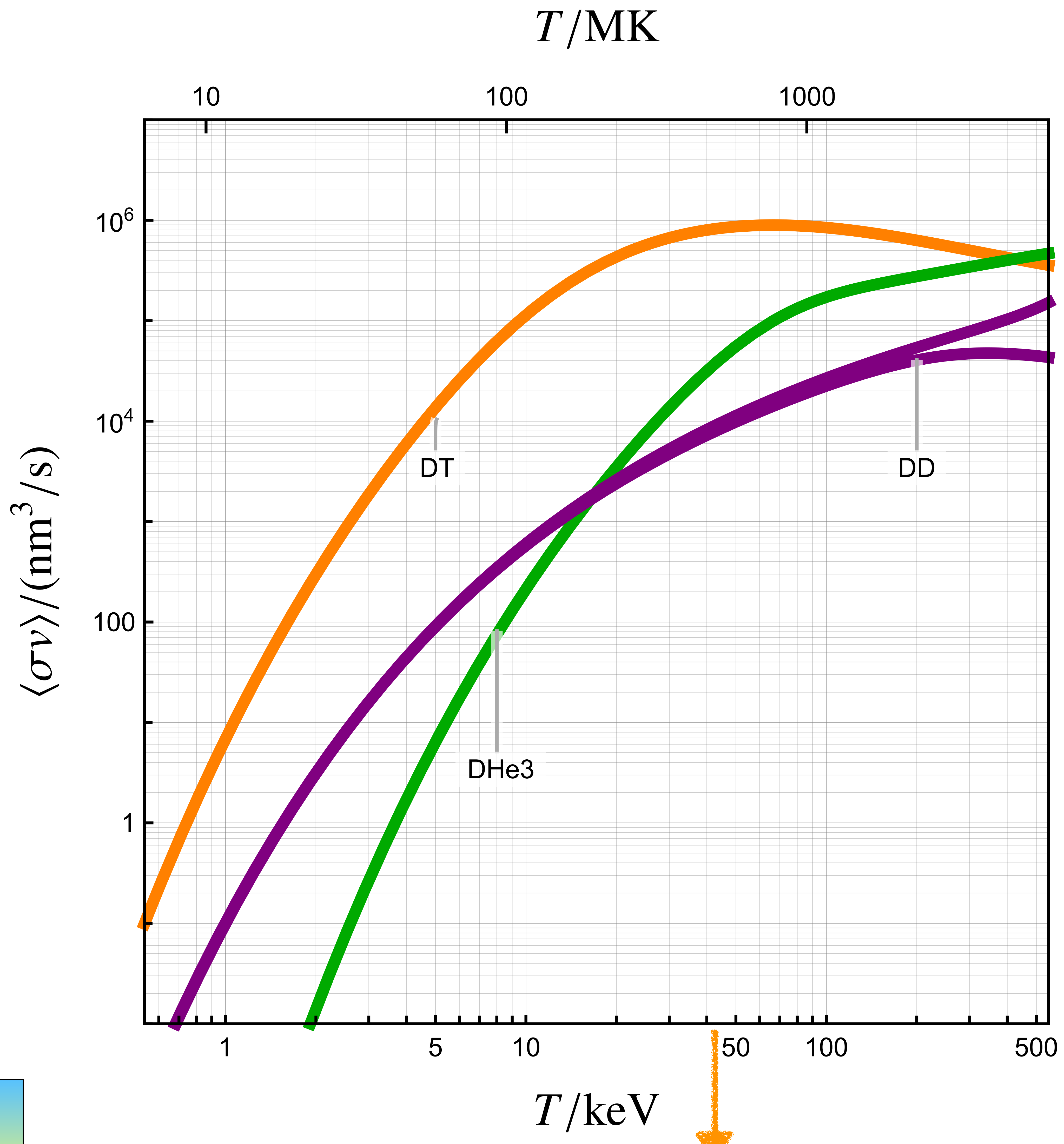
- Maxwell-averaged cross section $\langle \sigma v \rangle$

  ➡ reaction rate $n_1 n_2 \langle \sigma v \rangle$
- R-matrix parametrisation[1] (see also NCSM[2], NLEFT[3]…)

1. deuterium-deuterium ${}^2_1\mathrm{H} + {}^2_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + {}^1\mathrm{n} + 3.3\ \mathrm{MeV}$
2. deuterium-deuterium ${}^2_1\mathrm{H} + {}^2_1\mathrm{H} \rightarrow {}^3_1\mathrm{H} + {}^1_1\mathrm{H} + 4.0\ \mathrm{MeV}$
3. deuterium-tritium ${}^2_1\mathrm{H} + {}^3_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + {}^1\mathrm{n} + 17.6\ \mathrm{MeV}$
4. deuterium-helium3 ${}^2_1\mathrm{H} + {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + 18.3\ \mathrm{MeV}$

➡ most favourable* reaction deuterium-tritium (DT)

energy density ($\sim 4 \cdot 10^8\ \mathrm{MJ/kg}$)
orders of magnitude higher than chemical (eV)



$E_T \sim 100\,\mathrm{keV} \gg E_{ionization} \sim 10\,\mathrm{eV}$
Fusion fuel is completely ionized: **Plasma**

[1] Bosch/Hale 1992 Nucl. Fusion 32 611
[2] Navrátil/Quaglioni *Phys.Rev.Lett.* 108 (2012) 042503; Hupin/Quaglioni/Navrátil Nature Comm. 10 351 (2019)
[3] PRL 115, 122301 (2015); DD scattering in progress.. Meyer et al.

III.TECHNICAL REALISATION

Confinement

Stability

Self-efficiency

Tokamak/Stellarator

…

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PLASMA EQUILIBRIUM

SOURCES OF ENERGY

- **External heating** (ohmic, microwaves):

$$S_h$$

- **Fusion reaction** $\mathrm{DT} \to \alpha(3.5\,\mathrm{MeV}) + \mathrm{n}(14.1\,\mathrm{MeV})$

neutrons: large mean free path ➔ reactor output

alpha: small mean free path $\mathcal{O}(1\,\mathrm{mm})$ ➔ plasma reheating

$$S_\alpha = E_\alpha \frac{n_\alpha^2}{4}\langle \sigma v \rangle = E_\alpha \frac{\langle \sigma v \rangle}{16} \frac{p^2}{T^2}$$

SINKS OF ENERGY

- **Bremsstrahlung** (dominantly electrons)

$$S_B = C_B n^2 T^{1/2} = \frac{C_B}{4} \frac{p^2}{T^{3/2}}$$

- Fluid dynamics of plasma (steady state):

➡ **Heat conduction**: $S_d = \nabla(\kappa \nabla T)$. Empirically,

$$S_d = \frac{2}{3} \frac{p}{\tau_E}$$

… relaxation time τ_E.

➡ Corrections: volume expansion/convection/micro-turbulences/temperature profile/…

POWER BALANCE RELATION[1]

$$\frac{E_\alpha \langle \sigma v \rangle}{16} \frac{p^2}{T^2} + S_h = \frac{C_B}{4} \frac{p^2}{T^{3/2}} + \frac{3}{2} \frac{p}{\tau_E} \qquad \left[\frac{W}{m^3}\right]$$

[1] Lawson (1957). *Proceedings of the Physical Society* B70, 6

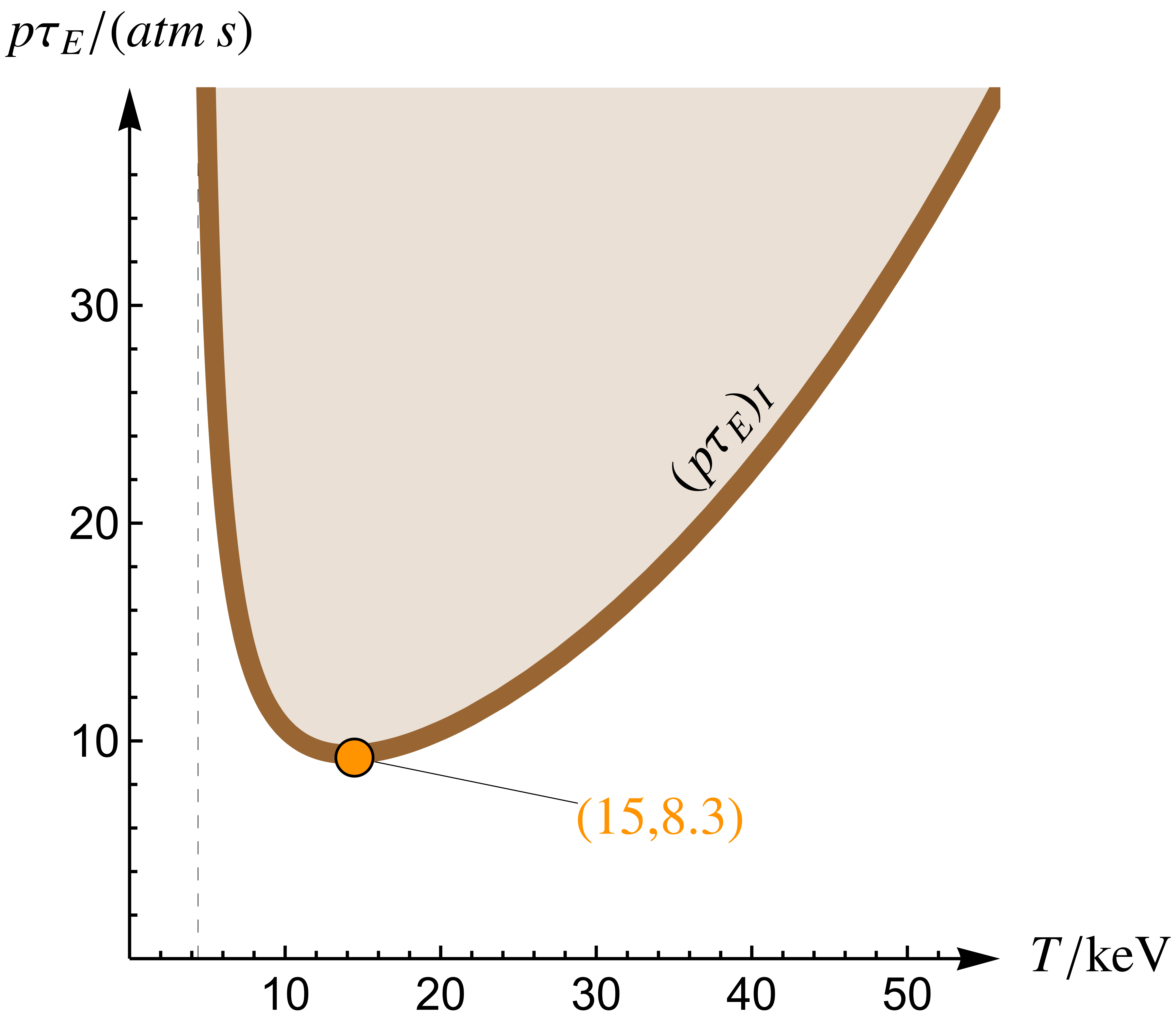
IGNITION

Ignition $(S_\alpha = S_B + S_\kappa)$

- Lawson parameter $(p\tau_E)_I = \dfrac{K_\kappa T^2}{K_\alpha \langle \sigma v \rangle - K_B T^{1/2}}$

… high-T solution — stable equilibrium

… low-T solution — unstable equilibrium → burn control



[1] Lawson (1957). *Proceedings of the Physical Society* B70, 6

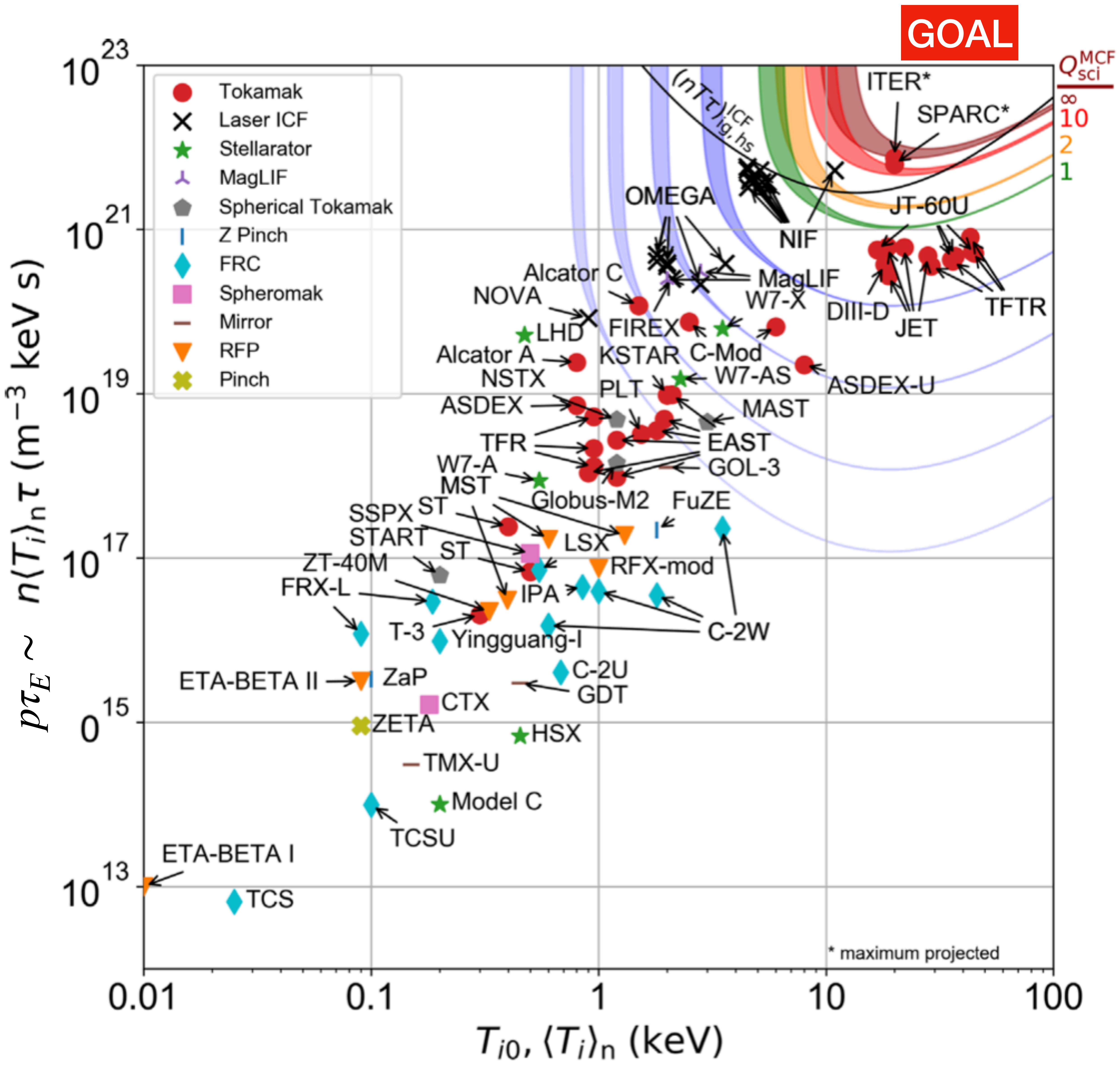
IGNITION

Ignition $(S_\alpha = S_B + S_\kappa)$

- Lawson parameter $(p\tau_E)_I = \dfrac{K_\kappa T^2}{K_\alpha \langle \sigma v \rangle - K_B T^{1/2}}$
- External heating $S_h > 0$ can reduce $(p\tau_E)_{min}$ (reducing gain)

World progress

- Operating and proposed (*) facilities



[FIG] Wurzel et al. Phys. Plasmas 29, 062103 (2022)

[1] Lawson (1957). *Proceedings of the Physical Society* B70, 6

PLASMA CONFINEMENT

Overcoming Coulomb-barrier requires $T \sim 10^8 K$

No materials can withstand such temperatures

Fuel-Plasma needs to be confined/controlled[1]

Prospective ansätze:

1. **ICF Inertial Confinement Fusion (Laser, Ion-beam, …)**

Laser induced shock waves in small pellets $\mathcal{O}(1\,\mathrm{mm})$. Experiments since 1970s.

[+] Only a small portion needs to be heated up.

[+] Plasma self-heating, mean free path of ${}^4_2\mathrm{He}$: $\mathcal{O}(0.01\,\mathrm{mm})$

[+] Gain: 3.15/2.05 (2022NIF[2])

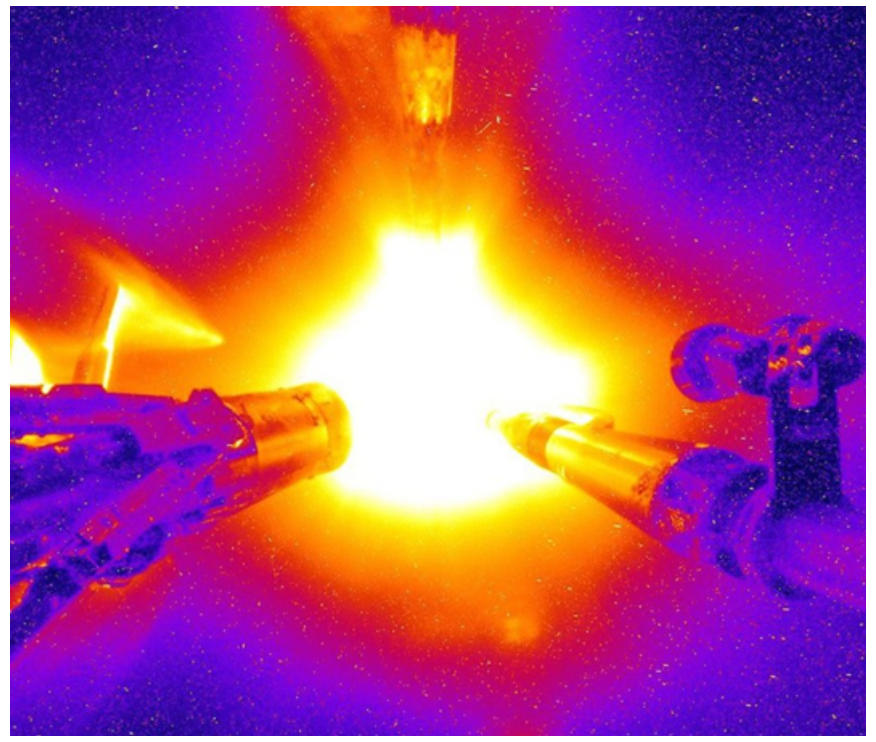
[−] Confinement time $\mathcal{O}(20\,\mathrm{ns})$

[−] Blows apart in the process

… **How to make a continuous process and collect energy?**

Nova Laser Bay

Target



NIF "Big Foot" deuterium-tritium (DT) implosion

[1] Lawson 1957 Proc. Phys. Soc. B 70 6
[2] Abu-Shawareb Phys. Rev. Lett. 129, 075001 (2022);

PLASMA CONFINEMENT

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Prospective ansätze:

2. MCF Magnetic Confinement Fusion (Tokamak, Stellarator, …)

Locally quasi-neutral, high-conductivity (~40x copper) Plasma. Charged particles in the Plasma move along the B-field lines

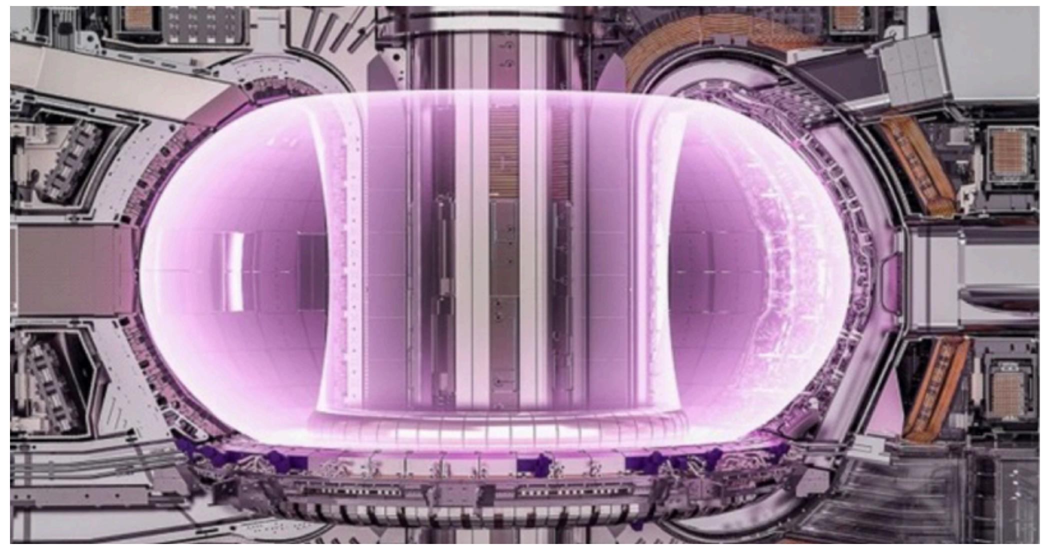
[+] Sustained self-heated plasma conditions $\mathcal{O}(10\,\mathrm{min})$[2]

[+] Semi-realistic reactor designs exist (Energy conversion..)

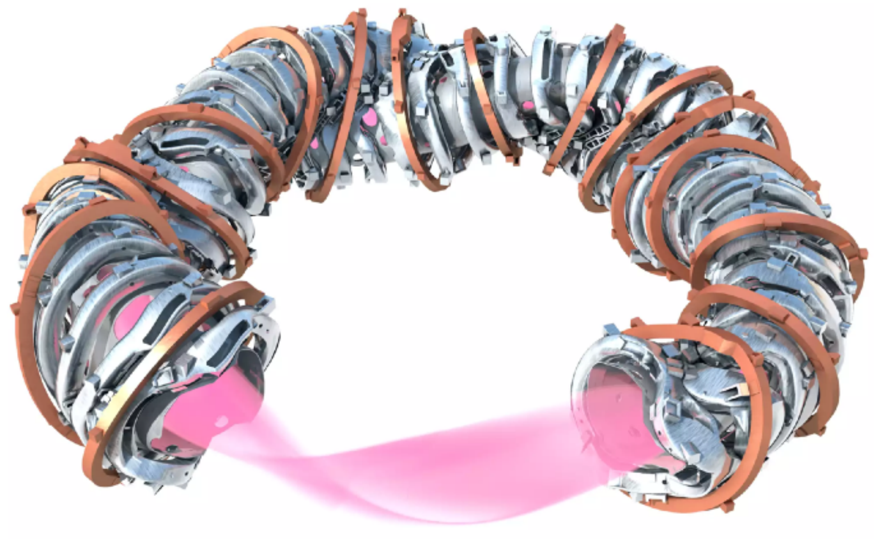
[–] Complex configuration (shielding, …)

[–] Stability, Plasma discharges, Turbulences

[–] Fuel self-sufficiency



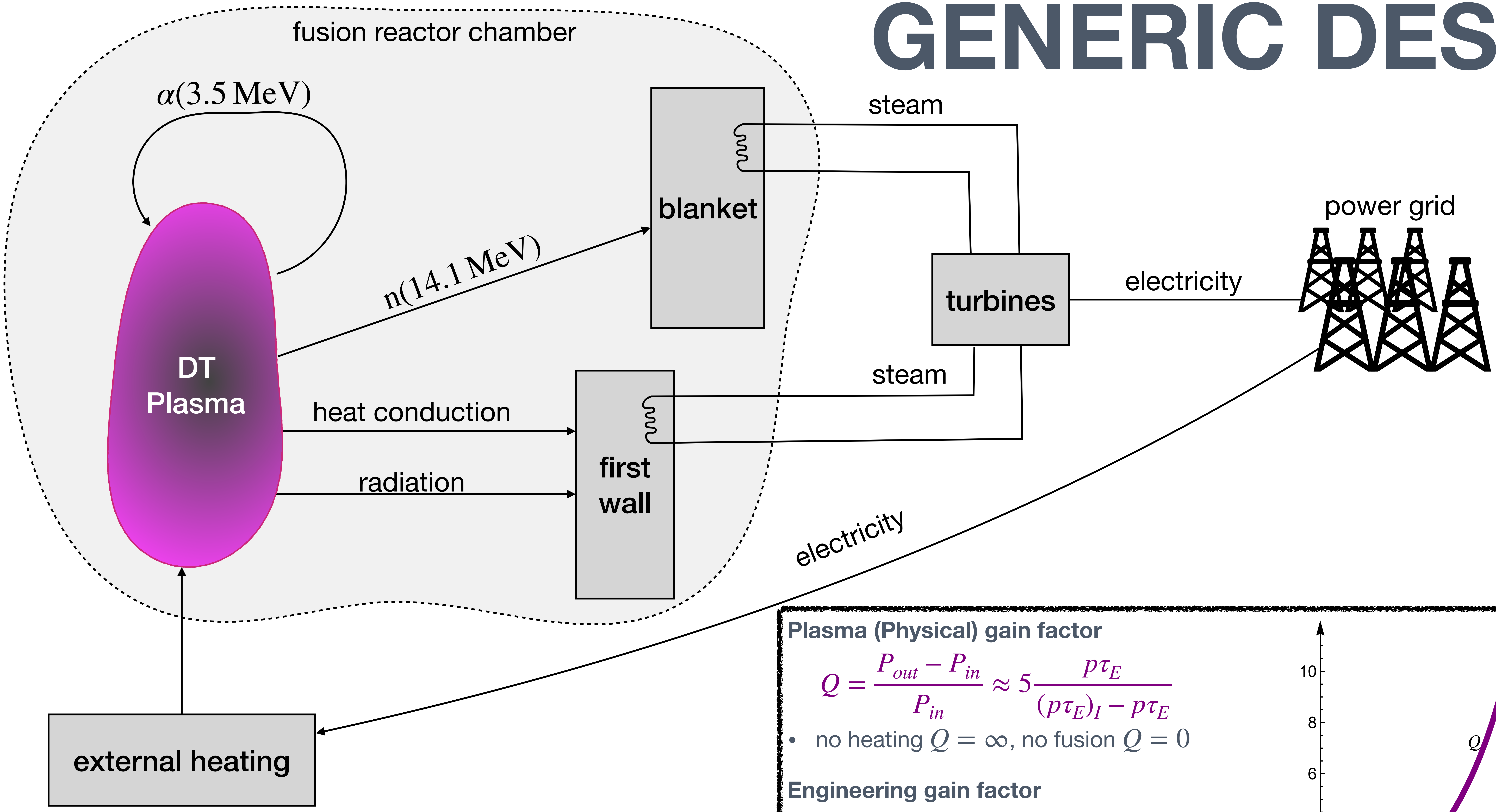
ITER (Tokamak)



Wendelstein7-X (Stellarator)

[1] Lawson 1957 Proc. Phys. Soc. B 70 6
[2] http://east.ipp.ac.cn/; https://www.ipp.mpg.de/5322229/01_23

GENERIC DESIGN



Plasma (Physical) gain factor

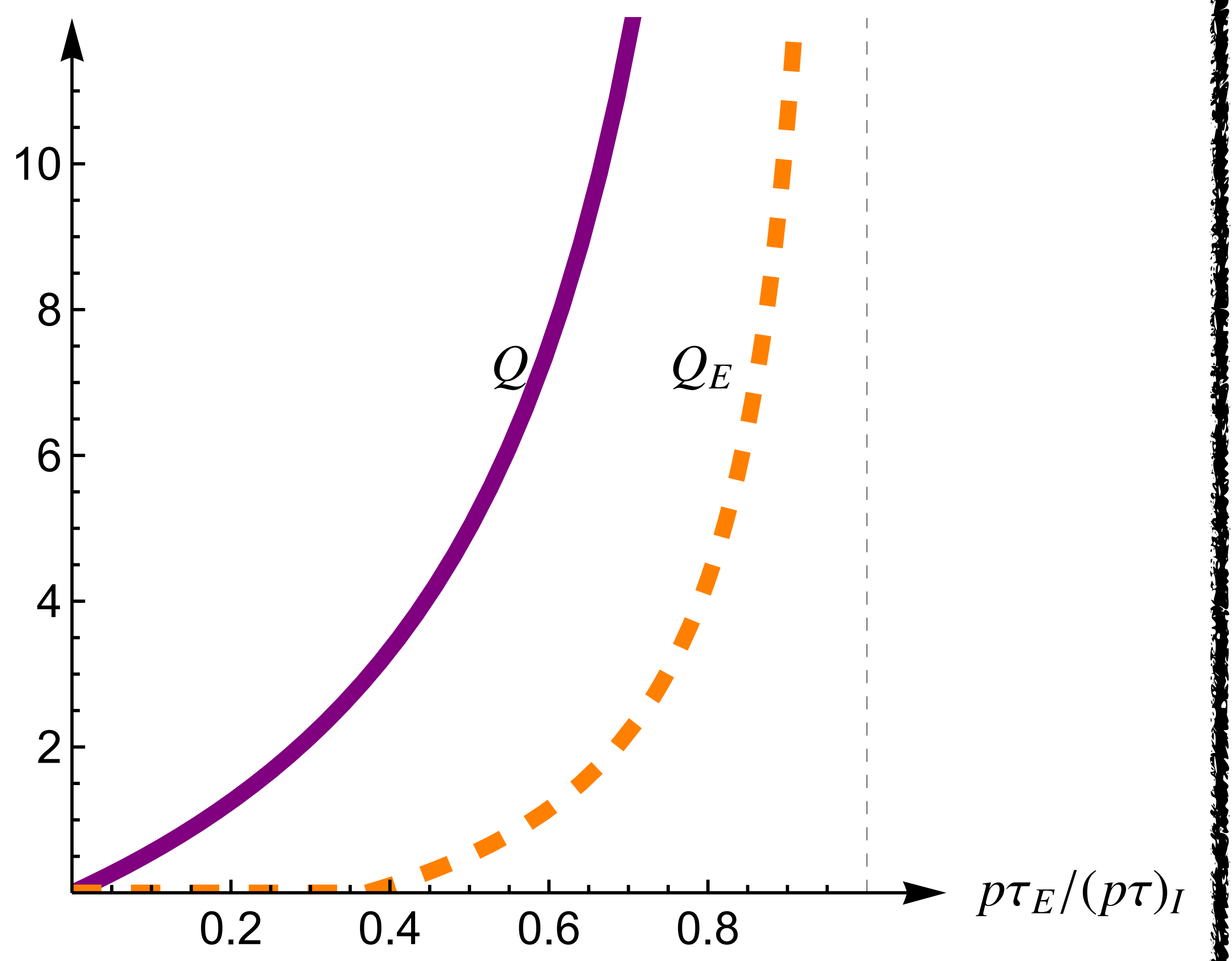
$$Q = \frac{P_{out} - P_{in}}{P_{in}} \approx 5\frac{p\tau_E}{(p\tau_E)_I - p\tau_E}$$

- no heating $Q = \infty$, no fusion $Q = 0$

Engineering gain factor

$$Q_E = \frac{P^{el}_{out} - P^{el}_{in}}{P^{el}_{in}} \approx 2\frac{p\tau_E - 0.37(p\tau_E)_I}{(p\tau_E)_I - p\tau_E}$$

- Depends on efficiency (absorption, heating, …)
- “Break-even” Q=0



FUEL SELF-SUFFICIENCY

- Good news:

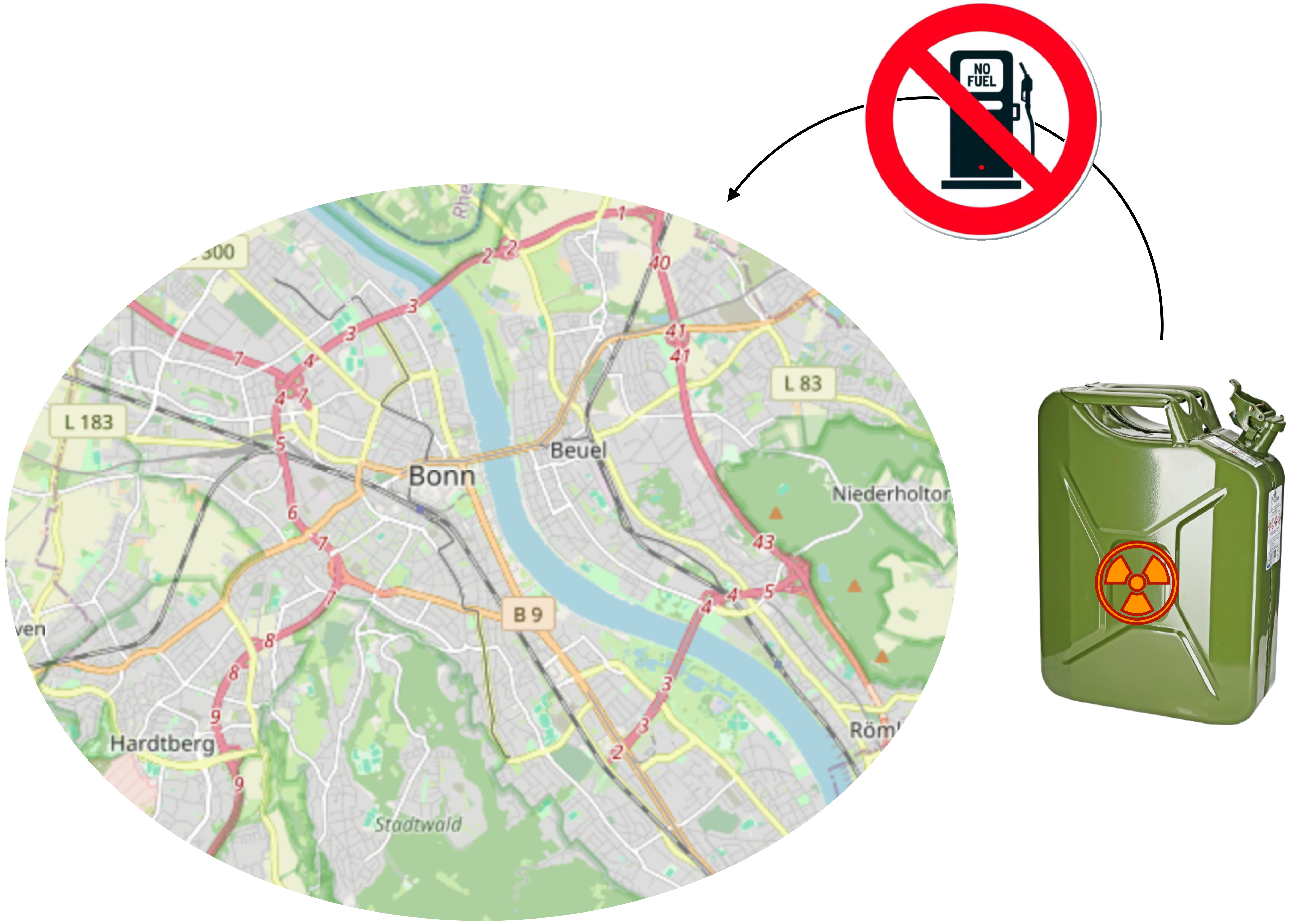
DT fusion has large energy density ($\approx 4 \cdot 10^8\,\mathrm{MJ/kg}$)

$$\frac{\text{Consumption(Bonn)}}{\text{year}} \sim 16\,\mathrm{kg} \quad \text{Tritium}$$

- Bad news:

$$\frac{\text{Tritium}}{\text{Earth}} \sim 20\,\mathrm{kg}$$

➡ Concept for Tritium breeding is needed …



TRITIUM BREEDING

Typical concept: **breeding in a lithium blanket**

$$^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} + 4.78\,\mathrm{MeV}$$

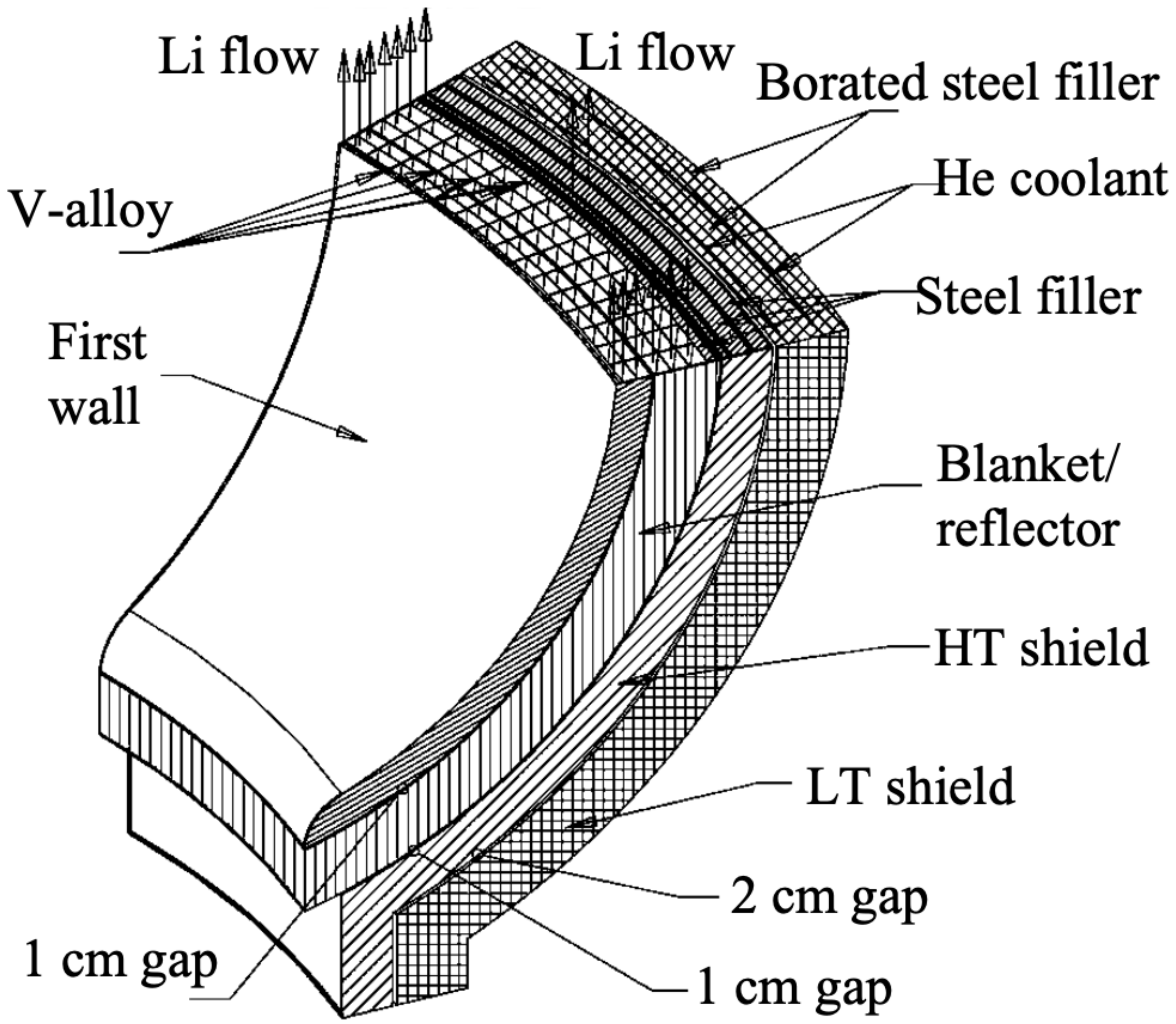
$$^{7}_{3}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} + \mathrm{n} - 2.7\,\mathrm{MeV}$$

Technological challenges[1]

- $1\ \mathrm{m}$ thick layer around $1000\ \mathrm{m}^3$ volume
- Neutrons need to be slowed down for efficiency
- complex configuration
- high demand on materials

…

- Essential experiments @ITER (20??), @DEMO (2???)



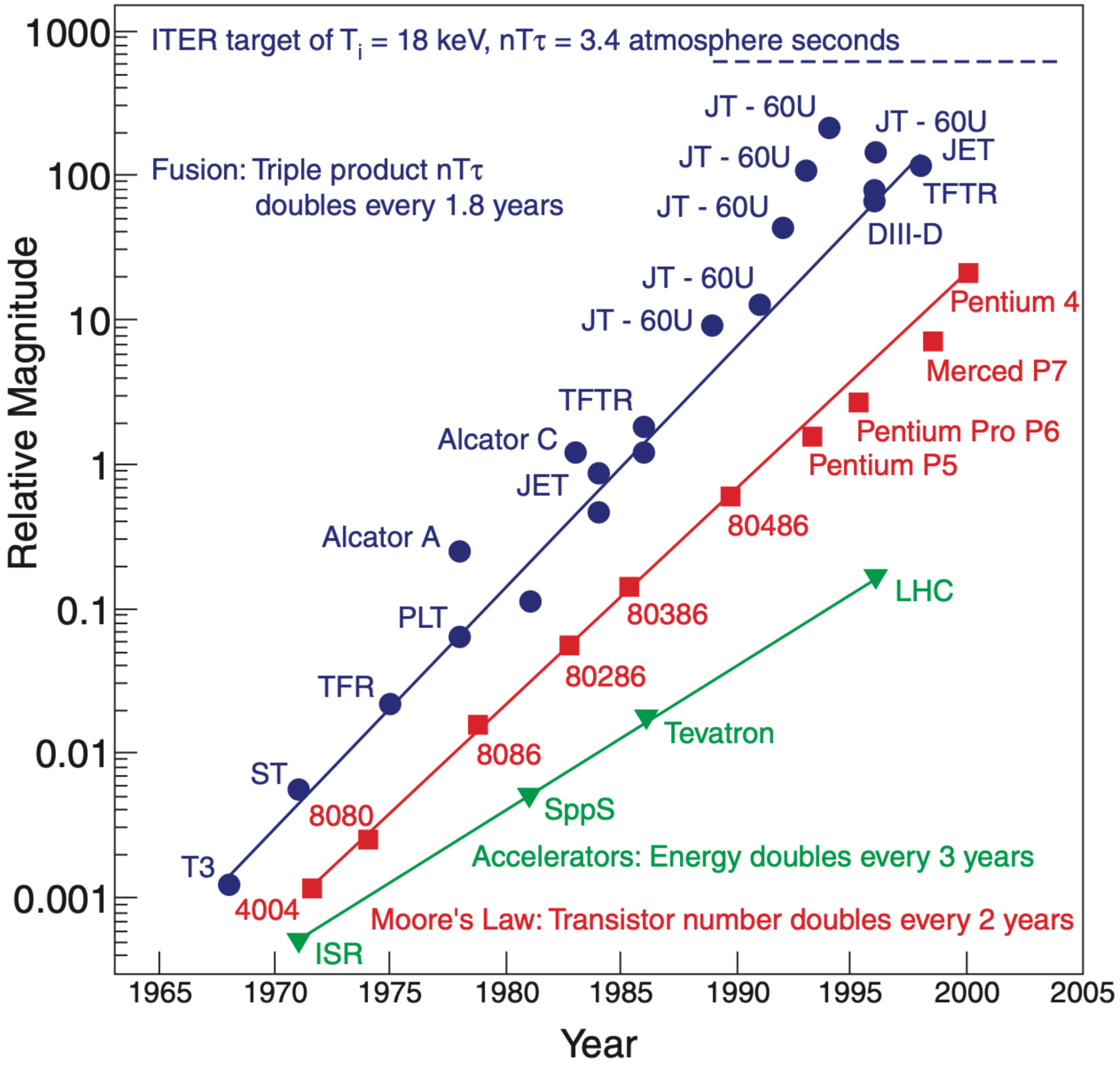
[FIG] Raffray et al. / Journal of Nuclear Materials 307–311 (2002) 21–30
[1] Rubel, Journal of Fusion Energy (2019) 38:315–329; Dittmar, Energy 37 (2012) 35-40

SUMMARY

NUCLEAR FUSION — ASTONISHINGLY SIMPLE & ASTONISHINGLY COMPLEX

Progress

- Basic design well understood
- Many test reactor facilities $\mathcal{O}(100)$
- Confinement time records, e.g., $t_C = 480\,\mathrm{s}$ @ Wendelstein7-X
- Net (plasma) energy gain, e.g., $Q \sim 3/2$ @NIF



[FIG] Webster, “Fusion: Power for the future”, Physics Education 38, 135 (2003)

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- Confinement time records, e.g., $t_C = 480\,\mathrm{s}$ @ Wendelstein7-X
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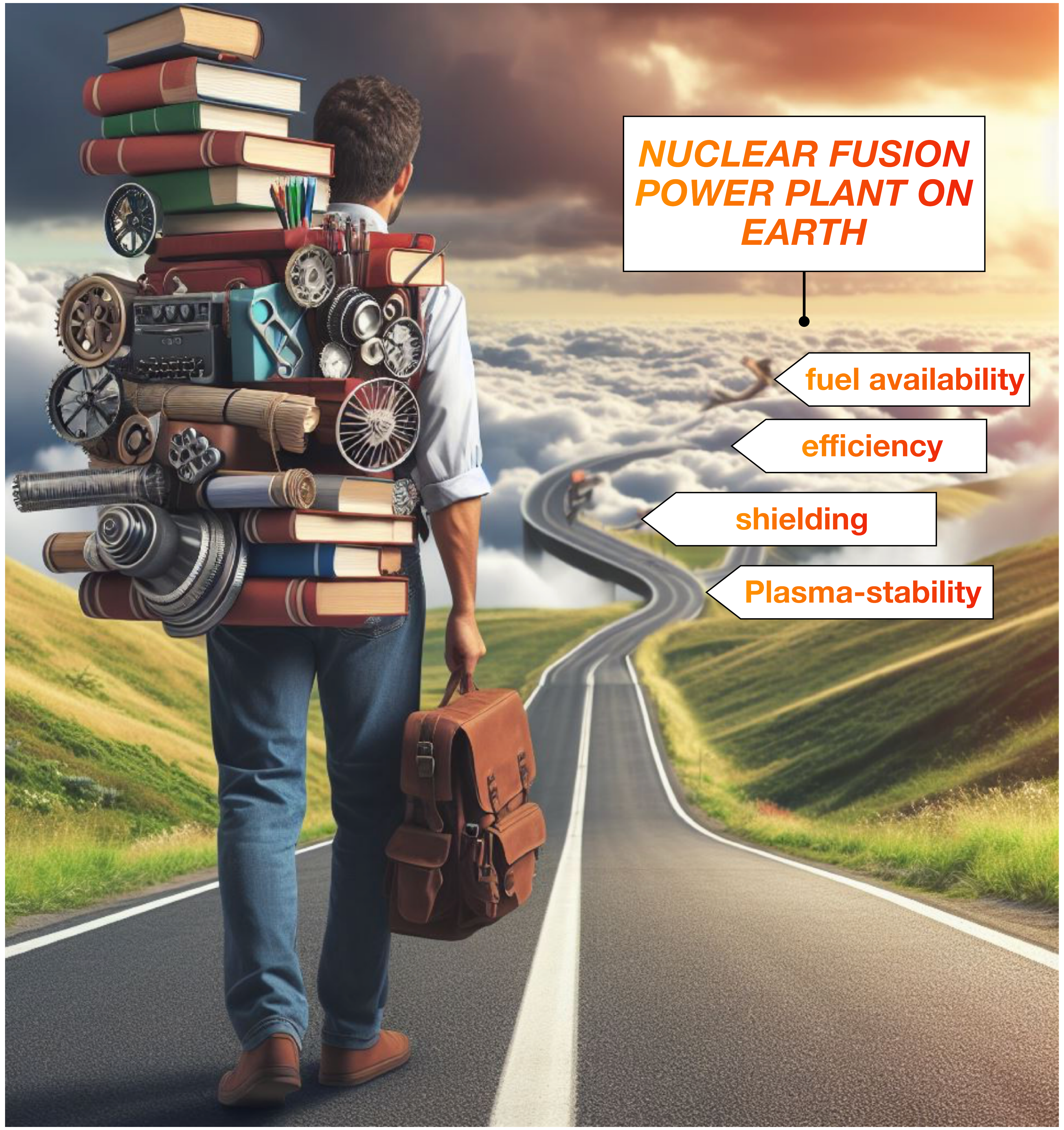
Challenges

- Plasma stability
- Net (engineering) gain $Q_E \sim 0$

  … efficient thermal-electric conversion
- Shielding vs. very high energy, flux neutrons

  … radioactive waste $T_{1/2} \sim \mathcal{O}(10\mathrm{y})$
- Tritium-breeding concept very theoretical:

  … experiments/design updates will take decades



A mechanical engineer with many books in his backpack walking a very windy road
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