Basic principles of thermonuclear fusion

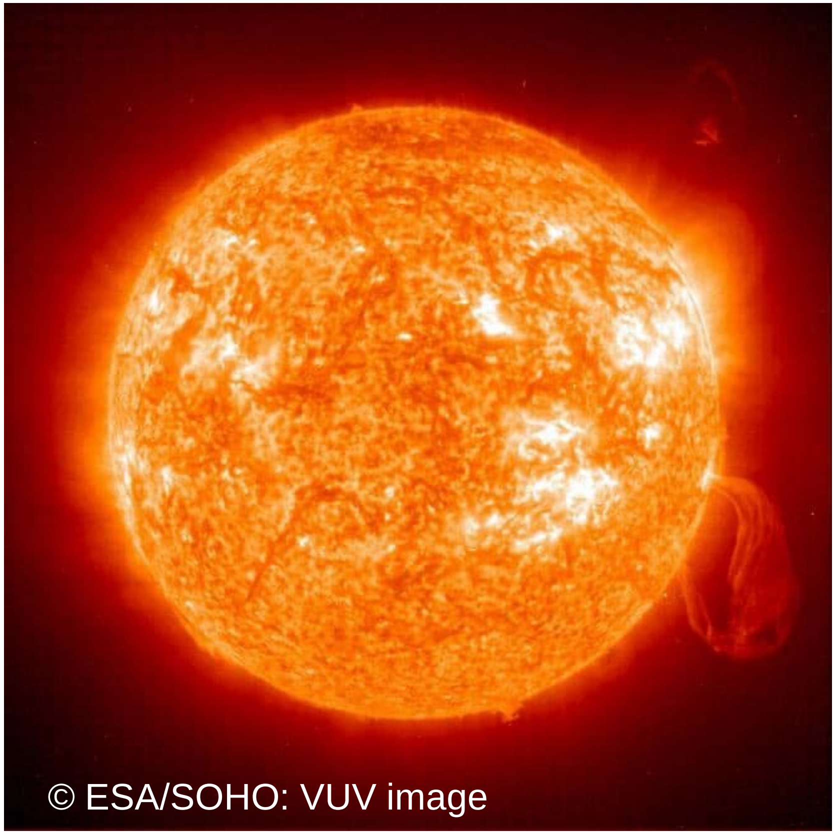
Prof. Dr. Mathias Groth & Dr. Timo Kiviniemi
Aalto University
School of Science, Department of Applied Physics

Outline

- Concept of high-temperature plasmas and nuclear fusion
- Fusion requirements ⇒ Lawson criterion
- Constraints and limitation of burn conditions
- Fusion reactions and fuels

Fusion holds one of the biggest promises of an virtually unlimited energy source

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,e^{+} + 2\,\nu^{+} + 2\,\gamma + 28.6\,MeV$$

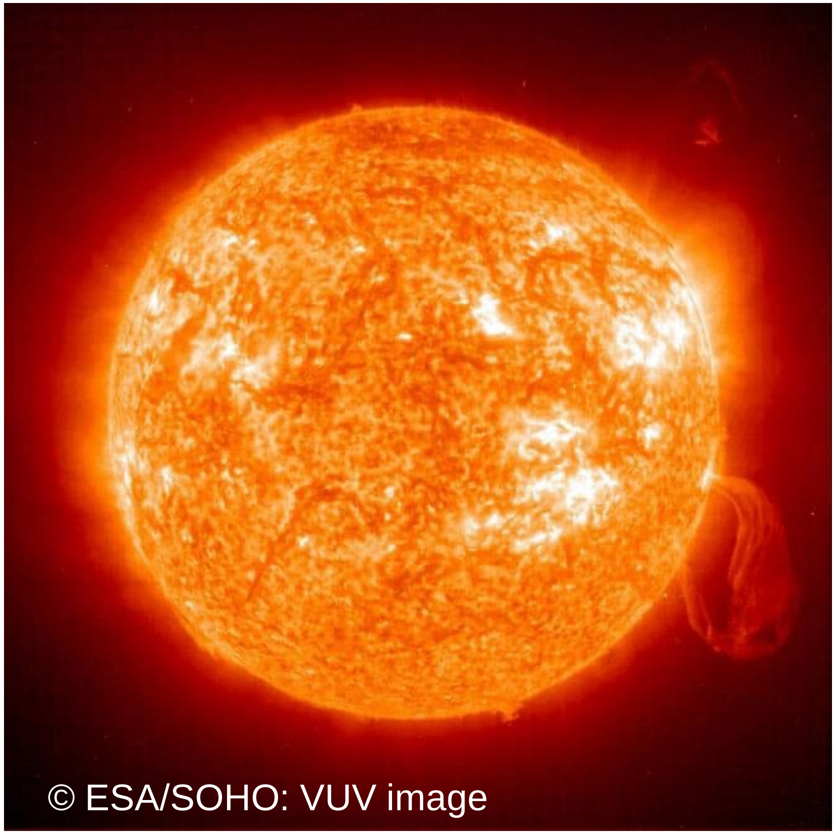


© ESA/SOHO: VUV image

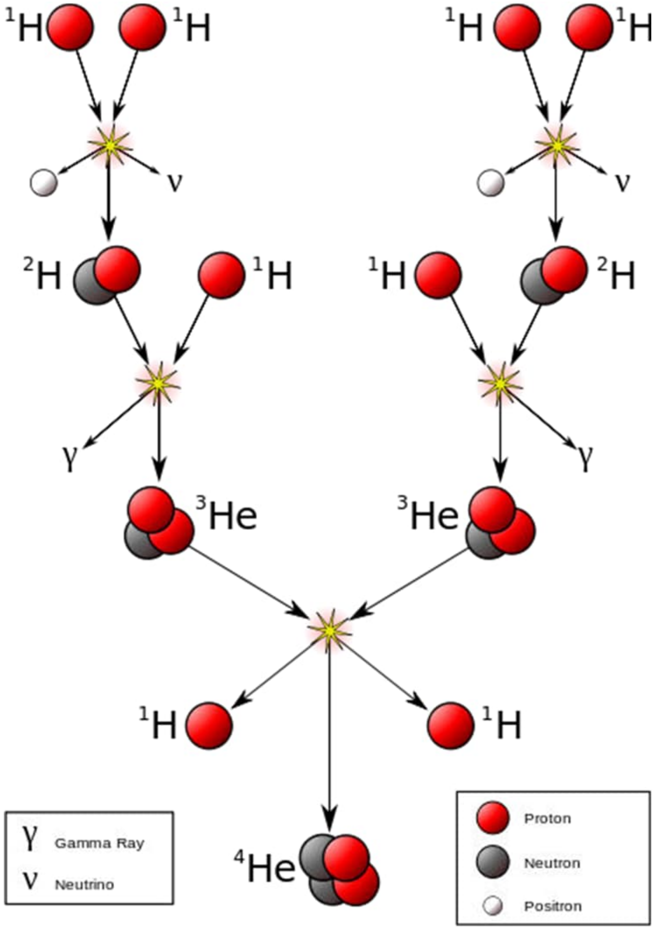
- **Core of the sun produces 380 yottawatts (3.8 x 10^{26} W) via fusion**
- **Merging of hydrogen isotopes to helium**
  - $m \lesssim m_{sun}$: proton-proton chain
  - $m > 1.3\ m_{sun}$: carbon-nitrogen-oxygen-chain (catalytic cycle)

Fusion holds one of the biggest promises of an virtually unlimited energy source

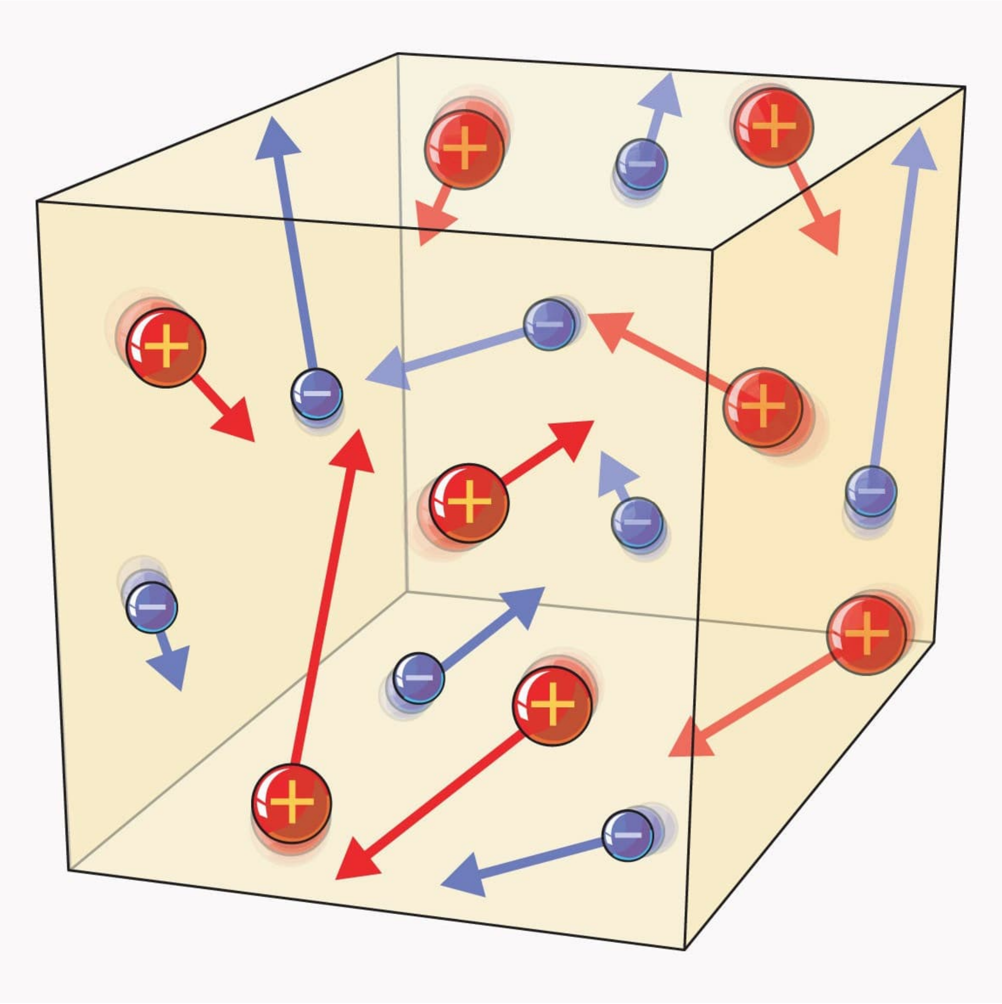
$$4\,{}^{1}_{1}H \;\rightarrow {}^{4}_{2}He + 2\,e^{+} + 2\,\nu^{+} + \;2\,\gamma + 28.6\,MeV$$



© ESA/SOHO: VUV image



At fusion-relevant temperatures, a plasma exists of unbounded ions and electrons



http://www.efda.org

- **Plasmas are (electro-statically) neutral**
- **Plasmas need to be confined to remain hot**
- **Merging of hydrogen isotopes to helium**
  - Gravity
  - Inertia
  - Magnetic fields

Man-made, sustained fusion on Earth has not yet been achieved, but it is within reach

- **ITER is the first plasma magnetically-confined fusion device to achieve excess fusion power**

- **The National Ignition Facility is the first plasma inertially-confined fusion device to achieve excess fusion power**

A wide range of reactants may be used besides hydrogen isotopes

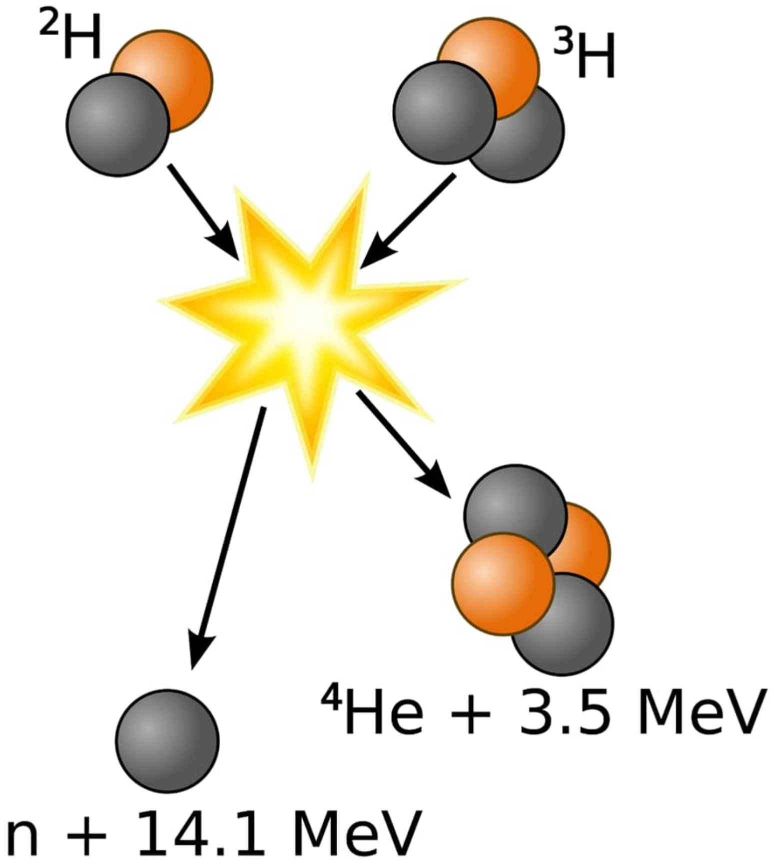
D+T	^{4}He (3.5 MeV) + n (14.1 MeV)
D+D	50%: T (1.01 MeV) + p (3.02 MeV)
	50%: ^{3}He (0.82 MeV) + n (2.45 MeV)
D+^{3}He	^{4}He (3.6 MeV) + p (14.7 MeV)
T+T	^{4}He + 2n + 11.3 MeV
^{3}He+^{3}He	^{4}He + 2p
^{3}He+T	51%: ^{4}He + p + n + 12.1 MeV
	43%: ^{4}He (4.8 MeV) + D (9.5 MeV)
	6%: ^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV)
D+^{6}Li	2 ^{4}He + 22.4 MeV
^{3}He+^{6}Li	2 ^{4}He + p + 16.9 MeV
p+^{11}B	3 ^{4}He (1.7 MeV) + 8.7 MeV

Kikuchi et al., Fusion Physics (2012) www-pub.iaea.org/MTCD/Publications/PDF/Pub1562_web.pdf

Presemo quiz #1

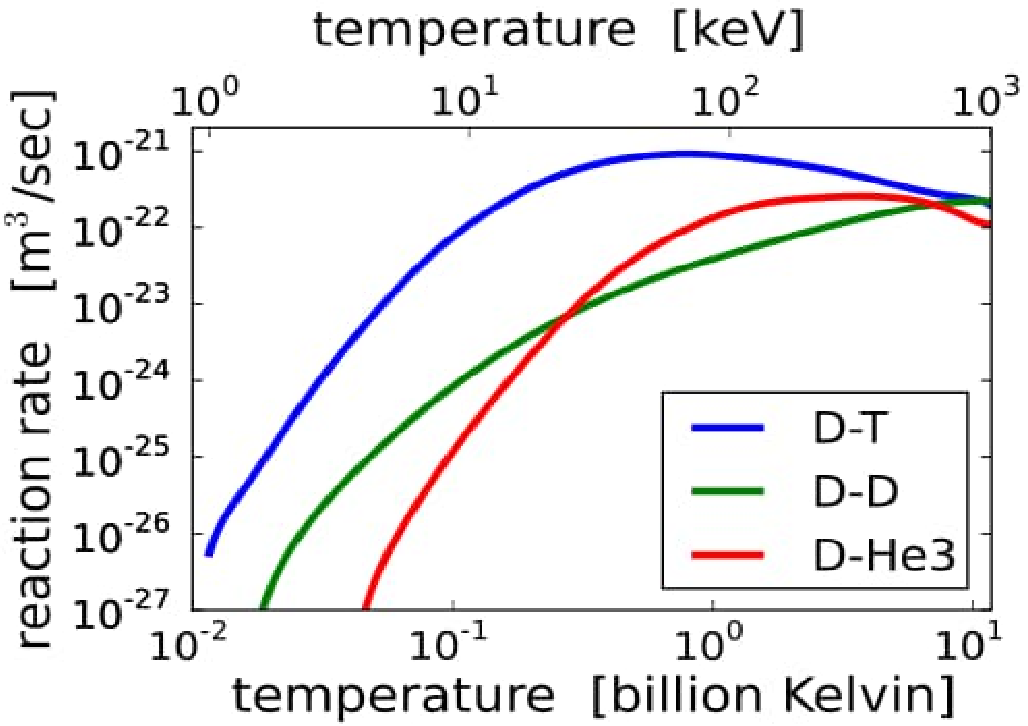
https://presemo.aalto.fi/fet/

Deuterium-tritium reaction is favored since it has the highest reaction rate at the lowest temperature



- $\Delta E_{D\text{-}T \rightarrow 4He}$ **= 17.6 MeV**
- **Energy in neutrons (~80%) for energy production (e.g., heating of blanket, also tritium production)**
- **^{4}He (fast α particles) for internal, self-sustained heating of the fusion process**

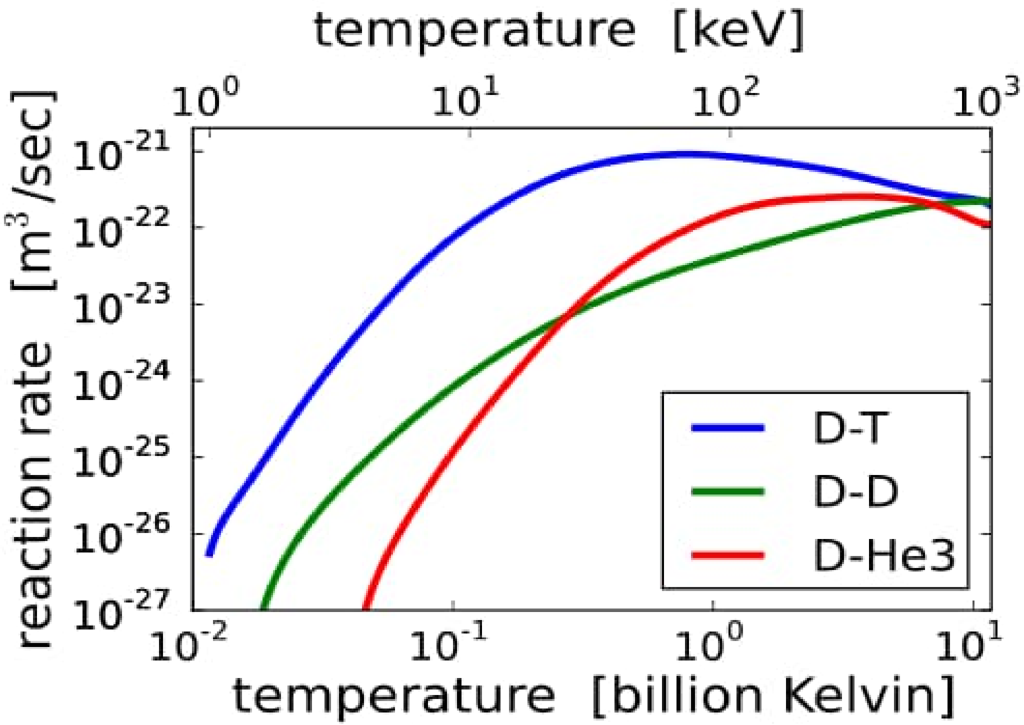
Deuterium-tritium reaction is favored since it has the highest reaction rate at the lowest temperature



- **Reactant nuclei have to overcome electrostatic repulsion ⇒ heating to increase thermal velocity**
- **Reaction rates strongly depend on temperature, have a maximum**

http://en.wikipedia.org

Deuterium-tritium reaction is favored since it has the highest reaction rate at the lowest temperature



- **At (engineering feasible) 10 keV, D-T reaction three orders of magnitude higher than D-D**

$$<\sigma v>_{DT} \approx 3.68 \times 10^{-12} T^{-2/3} \exp(-19.94 T^{-1/3})\ cm^3\ s^{-1}$$ T in keV

$$<\sigma v>_{DD} \approx 2.33 \times 10^{-14} T^{-2/3} \exp(-18.76 T^{-1/3})\ cm^3\ s^{-1}$$

http://en.wikipedia.org

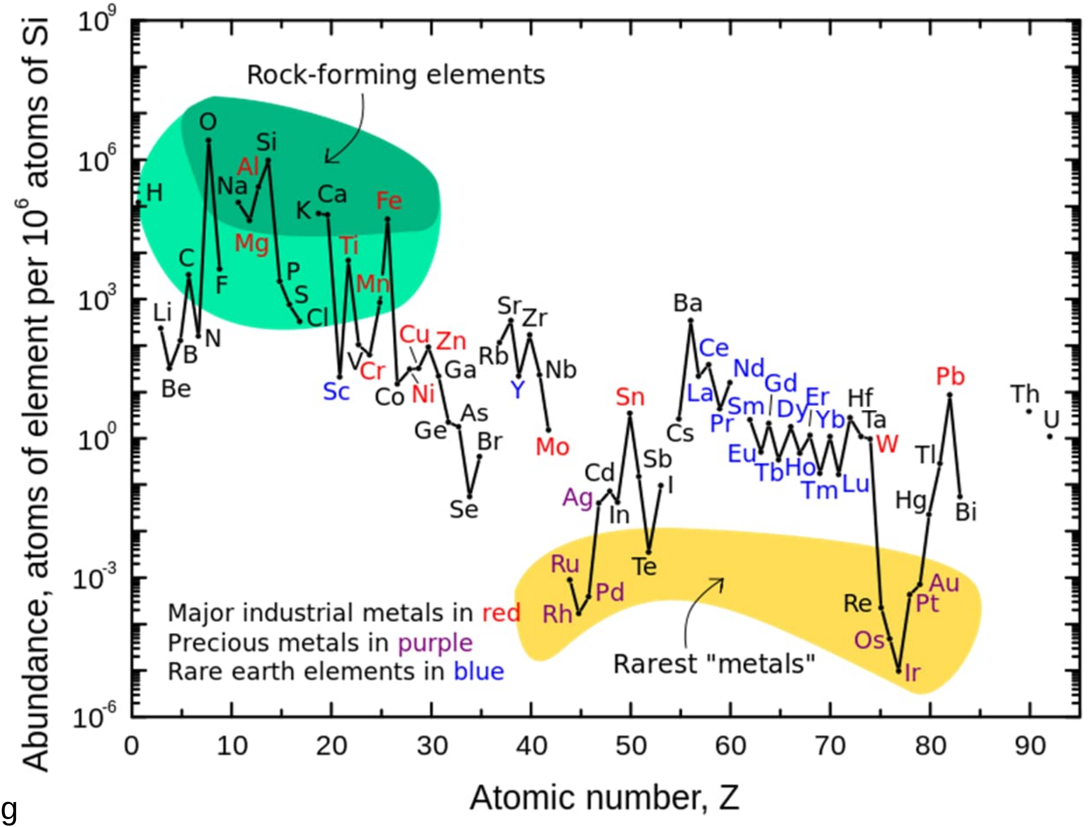
Video: from where does the fusion fuel come?

- **Video about fusion fuel (https://youtu.be/vDAZsPkTkMM) (from 1.45s – 3.57s)**
- **Where do you get Tritium?**
- **How much fuel do you need for average European family‘s demand for electrical energy for entire year?**

Video: from where does the fusion fuel come?

- **Where do you get Tritium?**

⇒ **Lithium abundant in natural rock everywhere on Earth**



http://en.wikipedia.org

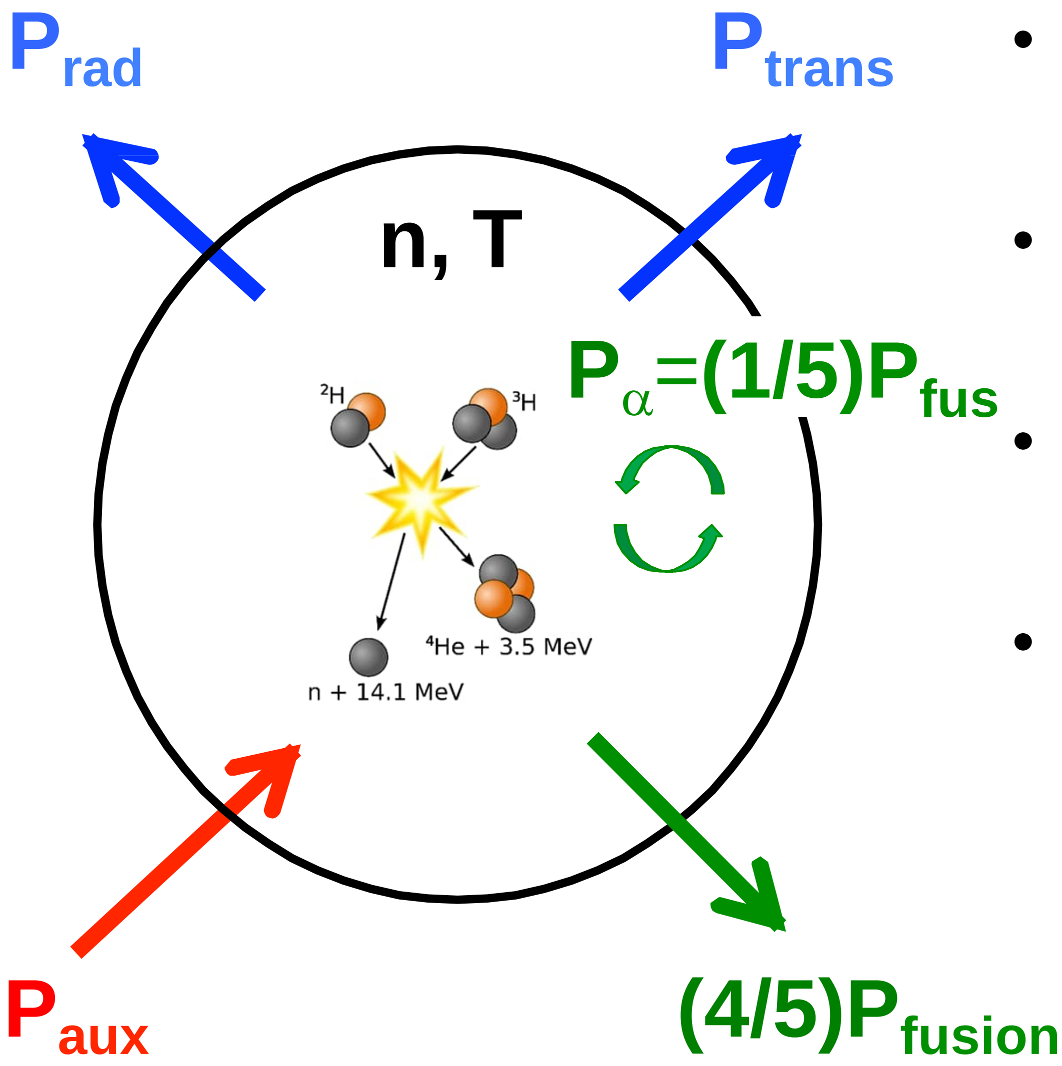
Video: from where does the fusion fuel come?

- **How much fuel do you need for average European family‘s demand for electrical energy for entire year?**

⇒ **2 litres of water + 250g of rock**

Criteria for self-sustain fusion

What temperatures, densities, and confinement (times) are required for fusion?



P_{rad}

P_{trans}

n, T

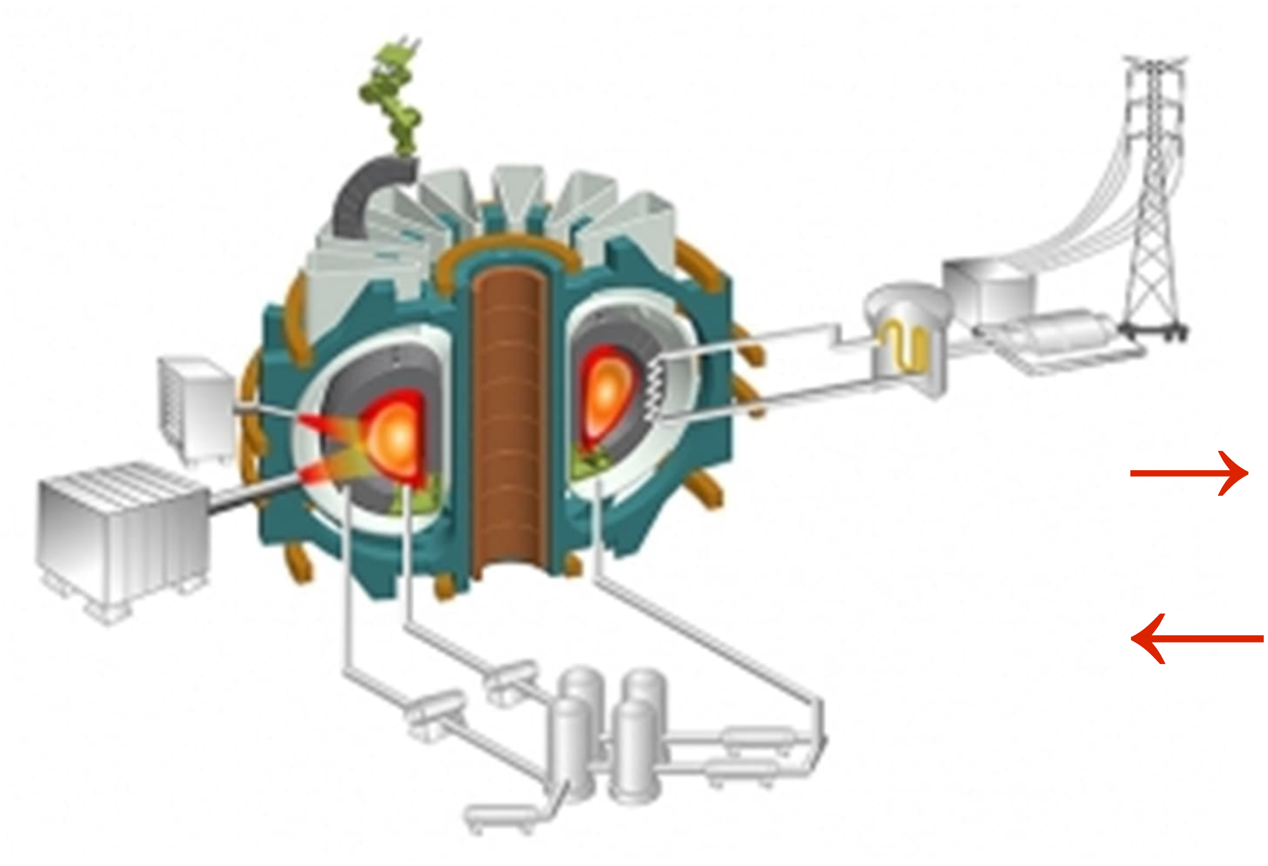
$P_{\alpha}=(1/5)P_{fus}$

P_{aux}

$(4/5)P_{fusion}$

- Internal heating via fusion α's (> 1 MeV)
- Fusion power in neutrons
- Radiative and transport losses
- Up to self-sustained burn, auxiliary heating required ⇒ fraction of P_{fusion}

Energy gain factor determines the technological efficiency of fusion energy: $Q \equiv P_{fusion} / P_{aux}$



→ **Electricity (Q >> 1)**

← **Electricity (Q < 1)**

Lawson criterion ($Q \rightarrow \infty$)

An energy gain Q>1 gives scientific breakeven, but other engineering constraints must be met

- **“Engineering” breakeven takes into account:**
  - Only a fraction (1-f_{ch}) of fusion energy goes to blanket
  - Cooling fluid of blanket drives steam turbines with efficiency η_{elec}= 35-40 %
  - Fraction f_{recirc} of P_{elec} recirculated back into the heaters
  - η_{heat} is the efficiency that power supplied to the heating systems is turned into heat in the fuel

$$\Rightarrow P_{heat} = (1-f_{ch})\, \eta_{elec}\, f_{recirc}\, \eta_{heat}\, P_{fus}$$

What temperatures, densities, and confinement (times) are required for fusion?

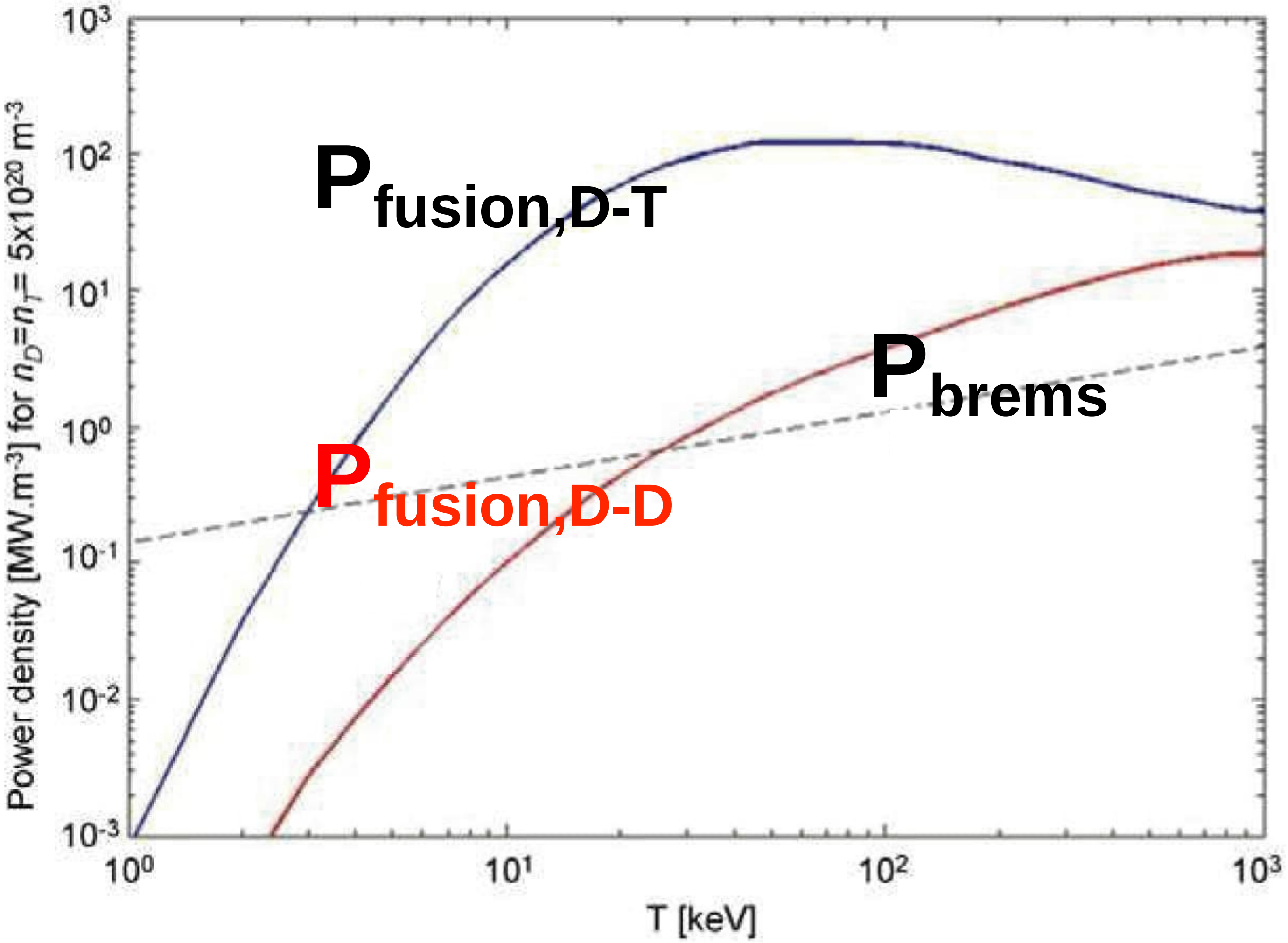
- **Ignition condition:** $Q \equiv P_{fusion} / P_{aux} >> 1 \Rightarrow Q \to \infty$
  - Q=1 break-even
- **50-50 mix of D-T total fusion power:** $P_{fusion} = 5P_{\alpha} = 5n_X n_Y <\sigma v> E_{\alpha} V_P$
- **Net heating power:** $P_{heat} = P_{aux} + P_{\alpha} - P_{brems}$

$$= P_{aux} + n_X n_Y <\sigma v> E_{\alpha} V_p - C_B T^{1/2} n_e^2 V_P$$

⇒ **50-50 mix of D-T:**

$$P_{heat} = P_{aux} + 1/4\, n_e^2 <\sigma v> E_{\alpha} V_P - C_B T^{1/2} n_e^2 V_P$$

Fusion power must exceed radiative (and thermal conductive-convective) losses: Lawson criterion



Energy leaks continuously out of the plasma ⇒ needs to be compensated by additional heating

- **Total kinetic energy in plasma:**

$$W_P = 3\, n_e\, k_B\, T\, V_P$$

- **Heating power is consumed to raise W_P and to compensate (transport) losses:**

$$P_{heat} = dW_P / dt + P_{trans}$$

⇒ **Energy confinement time:**

$$\tau_E = W_P / (P_{heat} - dW_P / dt)$$

⇒ **(Time-dependent) power balance:**

$$n_e^2 \langle \sigma v \rangle\, E_\alpha \frac{(Q+5)}{4Q} - C_B T^{\frac{1}{2}} n_e^2 = \frac{3 n_e k_B T}{\tau_E} + \frac{d}{dt}(3 n_e k_B T)$$

Energy leaks continuously out of the plasma ⇒ needs to be compensated by additional heating

Overleaf →

$$n_e^2\langle\sigma v\rangle\, E_\alpha\, \frac{(Q+5)}{4Q} - C_B T^{\frac{1}{2}} n_e^2 = \frac{3n_e k_B T}{\tau_E} + \frac{d}{dt}(3n_e k_B T)$$

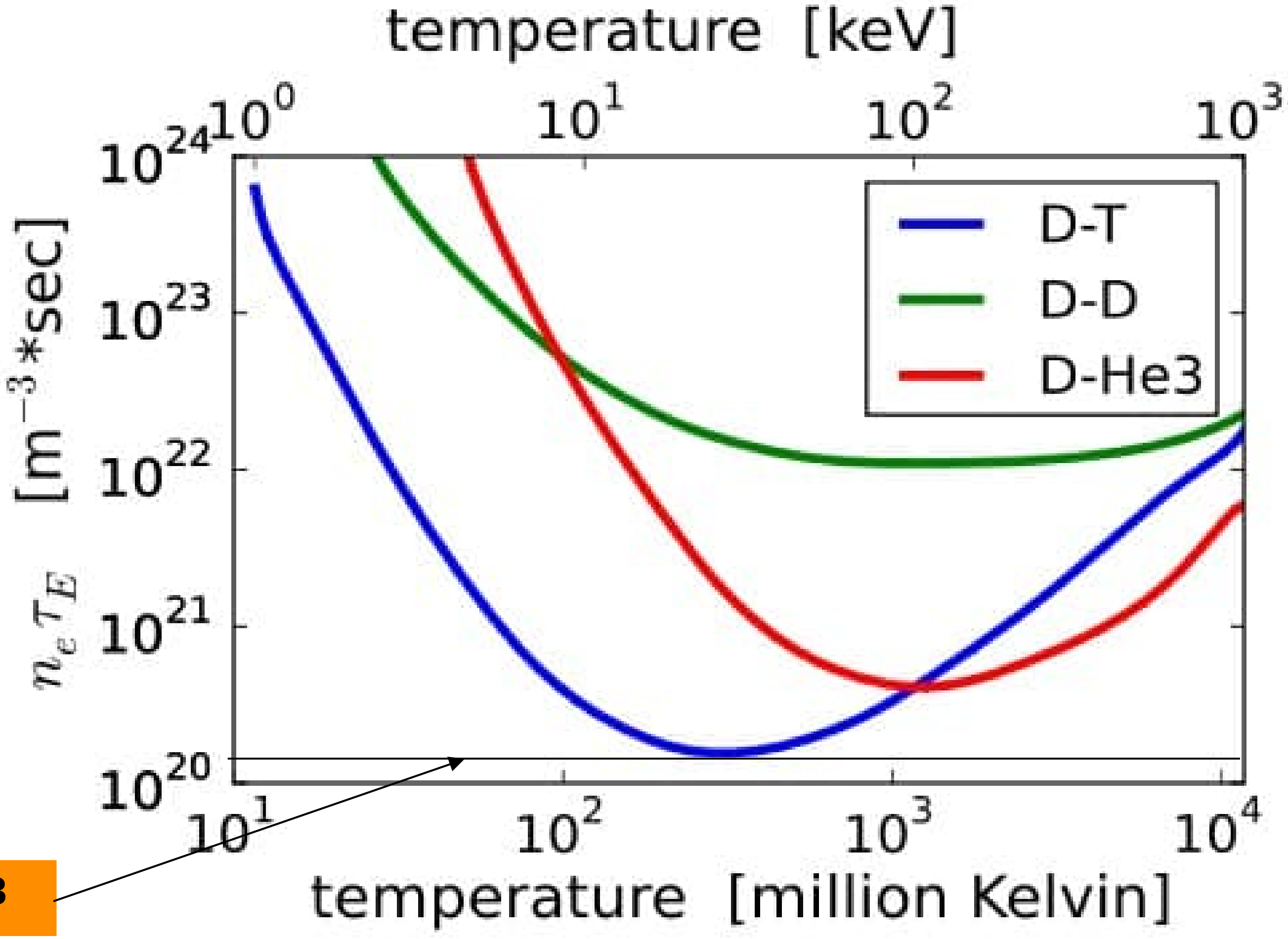
- **Steady-state (d/dt=0):** $P_{heat} = P_{aux} + \frac{1}{4} n_e^2 <\sigma v> E_\alpha V_p - C_B T^{\frac{1}{2}} n_e^2 V_P$

- **Break-even (Q = 1):** $$n_e\tau_E = \frac{3k_B T}{\frac{3}{2}\langle\sigma v\rangle\, E_\alpha - C_B T^{\frac{1}{2}}}$$

⇒ For 50-50 D-T, min. $n_e\tau_E$ at T = 25 keV ⇒ $n_e\tau_E \geq 10^{20}$ s m^{-3}

The D-T reaction requires the lowest product of density and confinement time

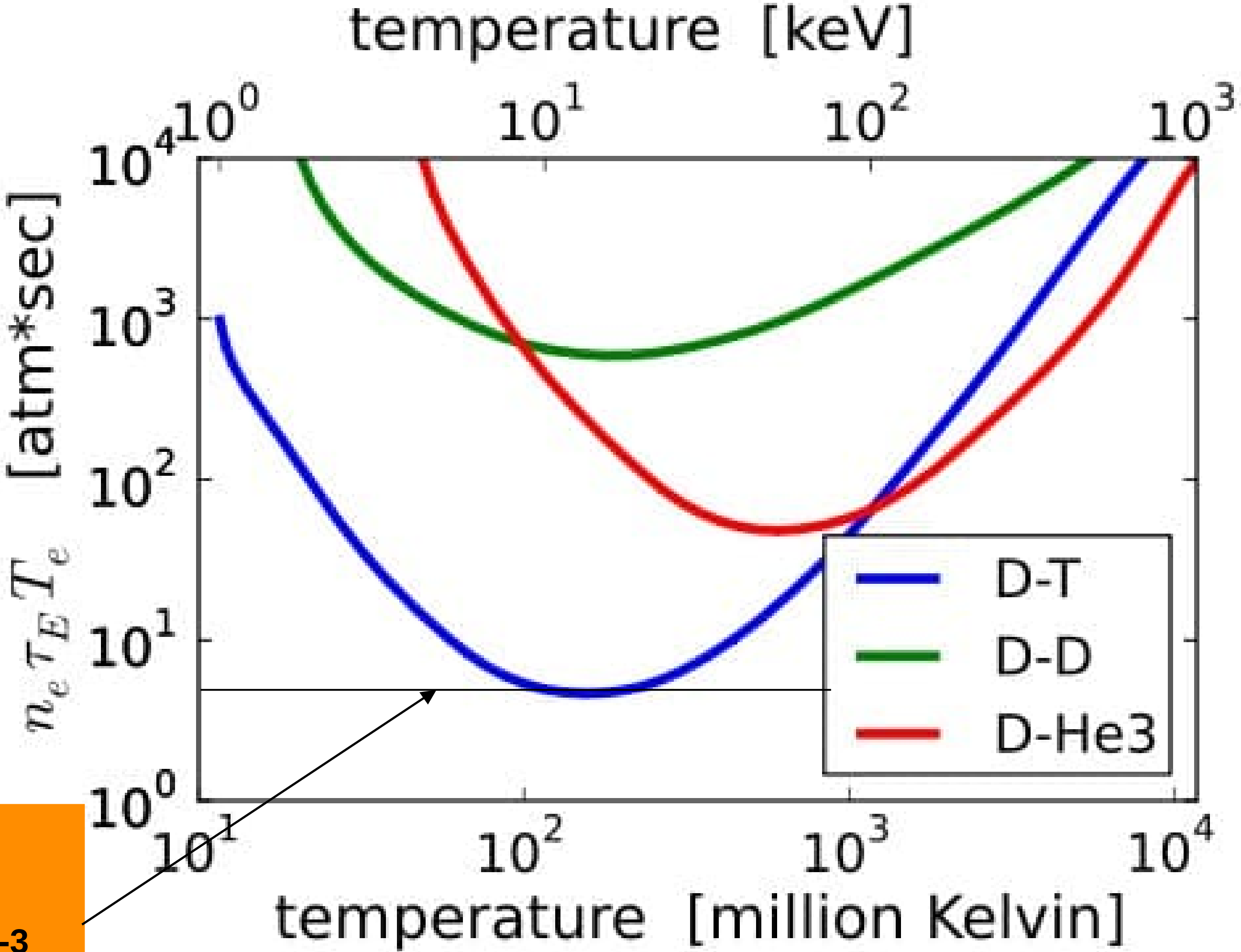
$\langle\sigma v\rangle$ = const.



$n_e\tau_E \geq 10^{20}$ s m^{-3}

Allowing for a temperature-dependent reaction rate, the Lawson criterion becomes a triple product

$<\sigma v> \propto T^2$



$n_e\tau_E T \geq$

1.5×10^{21} keV s m^{-3}

Requirements for ignition are more stringent than for break-even

Power balance, steady-state

$$n_e\tau_E = \frac{3k_BT}{\langle\sigma v\rangle E_\alpha\left(\frac{Q+5}{4Q}\right) - C_BT^{\frac{1}{2}}}$$

- **Ignition (Paux = 0, Q → ∞):**

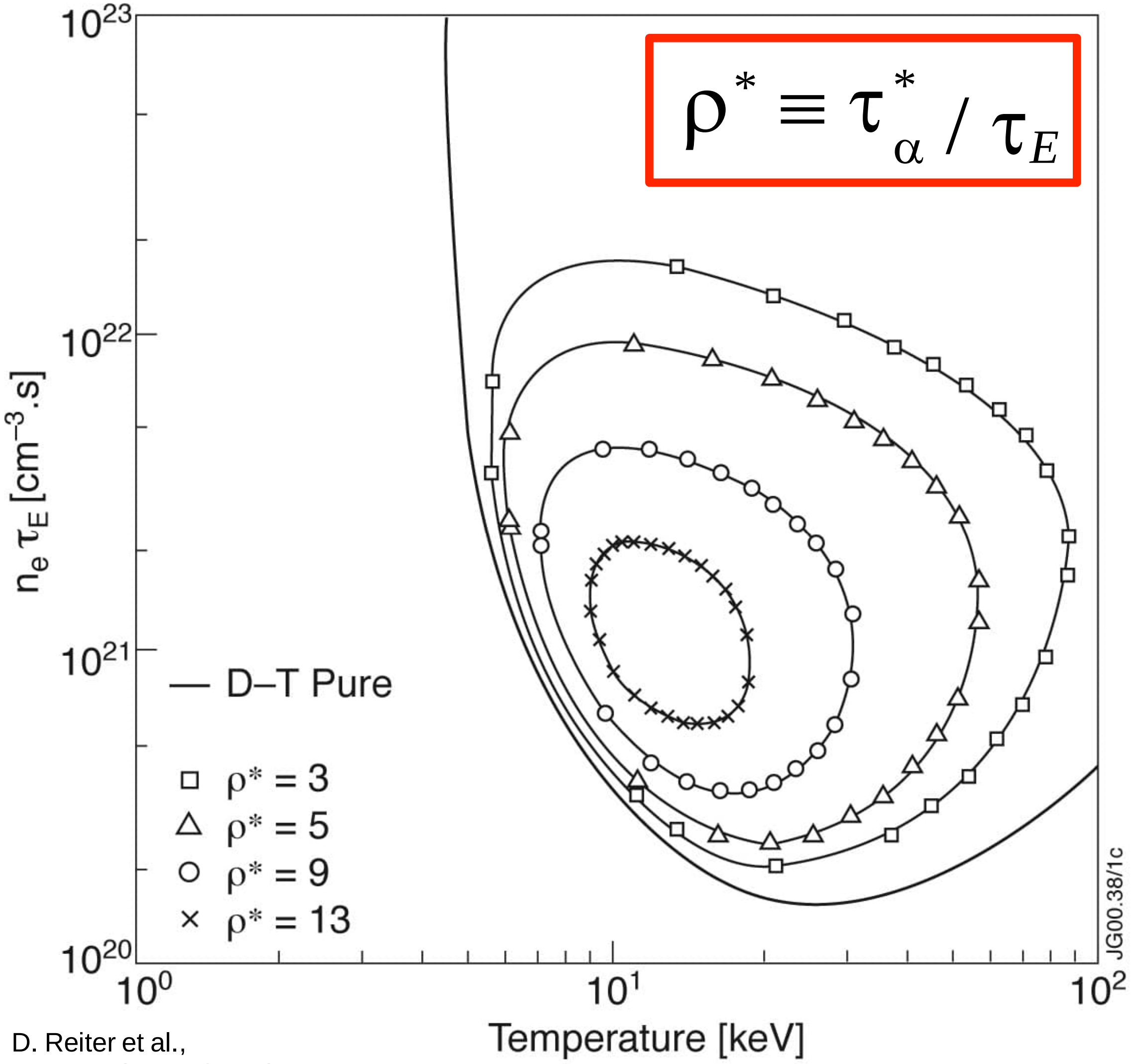
$$n_e\tau_E = \frac{3k_BT}{\frac{1}{4}\langle\sigma v\rangle E_\alpha - C_BT^{\frac{1}{2}}}$$

⇒ For 50-50 D-T, min. $n_e\tau_E$ at T = 25 keV ⇒ $n_e\tau_E \geq 1.5\ 10^{20}$ s m^{-3}

Limitations and uncertainties of the Lawson criterion values

- Original Lawson criterion did not take into account P_α heating, nor helium ash, and intrinsic and extrinsic impurities
- τ_E is function of n and T (and device parameters); determined experimentally ⇒ approach to ignition
- Conversion efficiencies of input power sources and output thermal energy to electric energy: ~30%
- Profiles of n and T, peaking in the center, lead to increase in minimum triple product
- Lawson criterion for inertial confinement (IC) system takes on a slightly different form ⇒ to be discuss together with IC systems

Lawson criterion becomes more stringent when considering D-T dilution due to helium ash



$$\rho^* \equiv \tau^*_\alpha / \tau_E$$

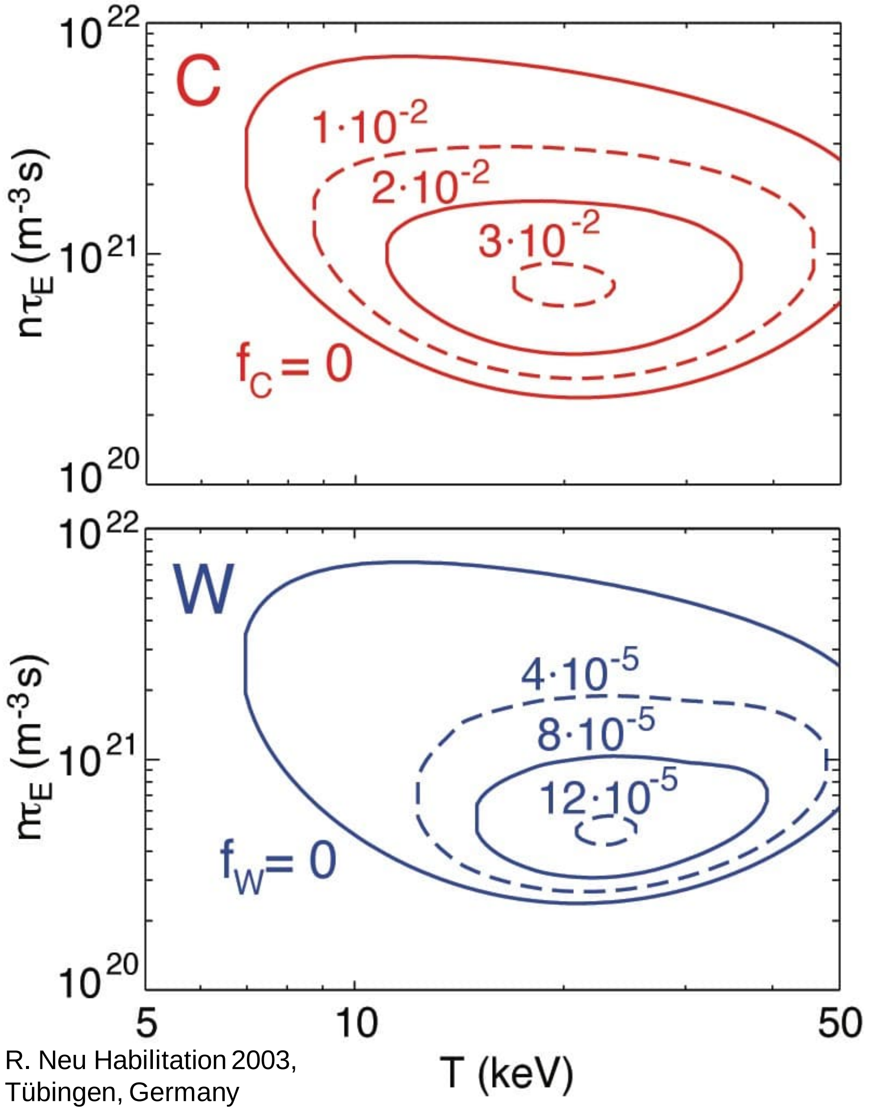
D. Reiter et al.,
Nucl. Fusion **30** (1990) 2141.

- **D-T fusion α's = 3.5 MeV ⇒ become thermal He^{2+} at <10 keV**

⇒ Dilution of D-T

⇒ Accumulation of He^{2+} in the center may quench fusion process

Lawson criterion becomes EVEN more stringent when considering impurities



R. Neu Habilitation 2003,
Tübingen, Germany

$$\rho^* = 5,$$

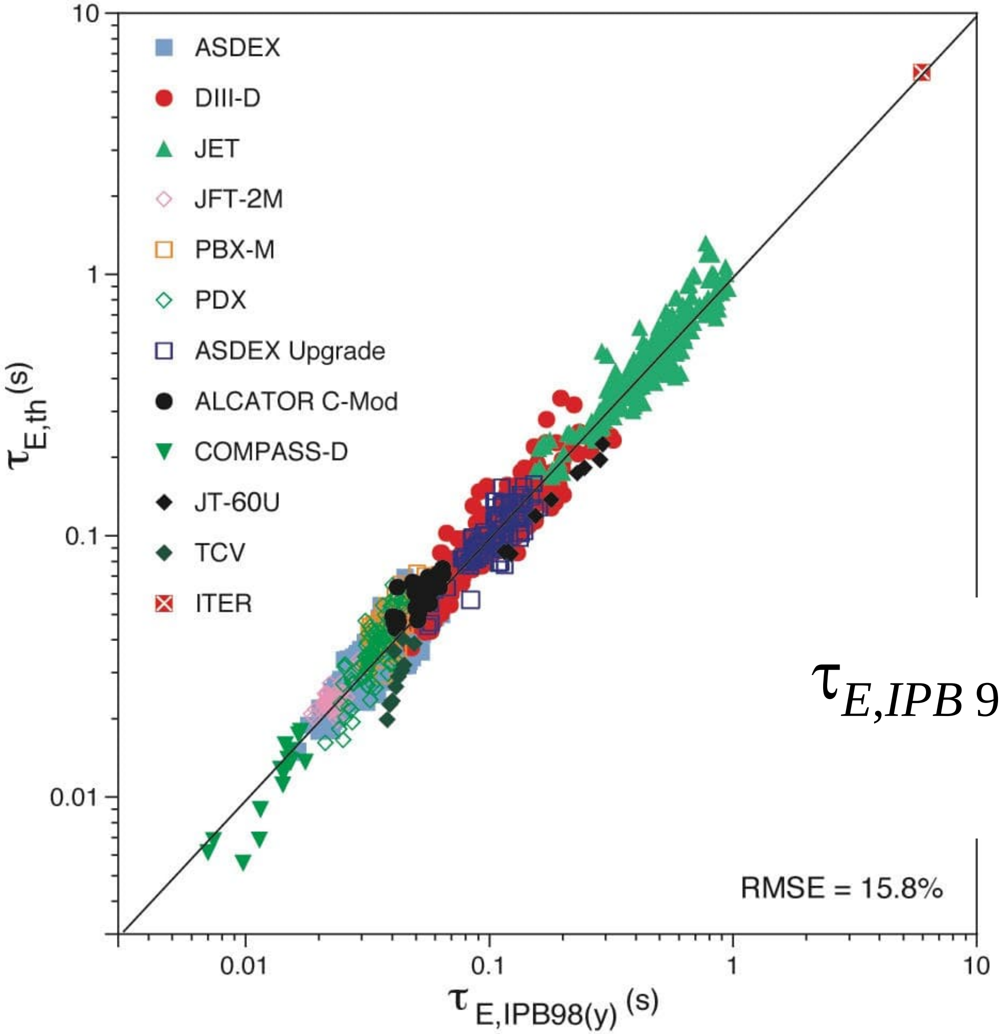
C (Z=6), W (Z = 74)

$$P_{brems} \sim Z^2)$$

- **Additional dilution and radiative losses due to impurities ⇒ upper limit of $n\tau_E$**

⇒ Only very small concentrations of high-Z impurities, such as W, can be tolerated (< $5\text{x}10^{-5}$)

Energy confinement time depends on many plasma and device parameters



ITER Physics Basis, Nucl. Fusion **39** (1999) 2175.

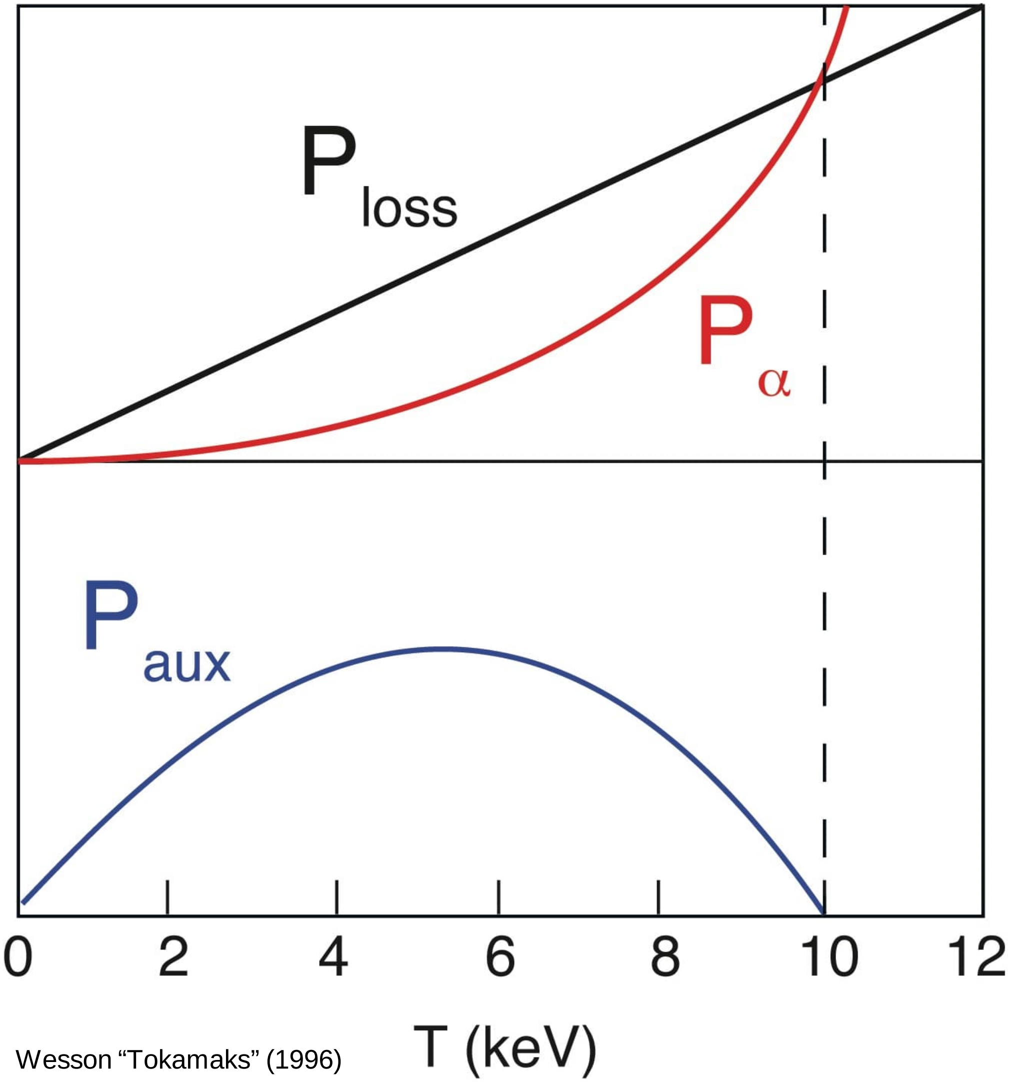
- **Confinement times of close to 1 s have been achieved in tokamaks**

⇒ Next-step devices are expected to reach 8 s, due to larger size (R)

$$\tau_{E,IPB\,98(y)} \propto I^{0.97} B^{0.08} P^{-0.63}\, n^{0.41}$$

$$x\, M^{0.02}\, R^{1.93}\, \varepsilon^{0.23}\, \kappa^{0.67}$$

Approach to ignition depends on actual values and gradients of T and τ_E



Wesson “Tokamaks” (1996)

- **Max. P_{aux} required at ~5 keV ⇒ P_α starts to dominate for T > 5 keV**
- **At T ≈ 10 keV, ignition reach ⇒ $P_{aux} \rightarrow 0$**
- **P_α non-linear with T ⇒ unstable equilibrium**
- **Lack of experimental data**

D-T reaction has the highest power density at lowest temperature, but produces (too) many fast neutrons

Fuel	$<\sigma v>/T^2$	Neutro-nicity	E_{fus} [MeV]	Power density [$Wm^{-3}\ kPa^{-2}$]
D-T	$1.24x10^{-24}$	0.80	17.6	34
D-D	$1.28x10^{-26}$	0.66	12.5	0.5
D-^{3}He	$2.24x10^{-26}$	~0.05	18.3	0.43
p-^{11}B	$3.01x10^{-27}$	~0.001	8.7	0.014

- **Fast neutrons + high neutronicity (fraction of fusion energy released in neutrons) lead to radiation damage and plant safety issues**

Fusion of D-D is significantly more beneficial than D-T

D+D	50%: T (1.01 MeV) + p (3.02 MeV)
	50%: ^{3}He (0.82 MeV) + n (2.45 MeV)
D+^{3}He	^{4}He (3.6 MeV) + p (14.7 MeV)
p+^{11}B	3 ^{4}He (1.7 MeV) + 8.7 MeV

- **D-D does not require control of fuel mix**
- **D-D reaction results in 1 MeV tritons ⇒ self-heating + additional D-T burn**
- **Advanced fuels (^{3}He, ^{11}B) low neutronicity, but requires significantly higher densities, temperatures, and confinement (higher triple products)**

Presemo quiz #2

https://presemo.aalto.fi/fet/

D-D reaction results in 1 MeV tritons ⇒ self-heating + additional D-T burn

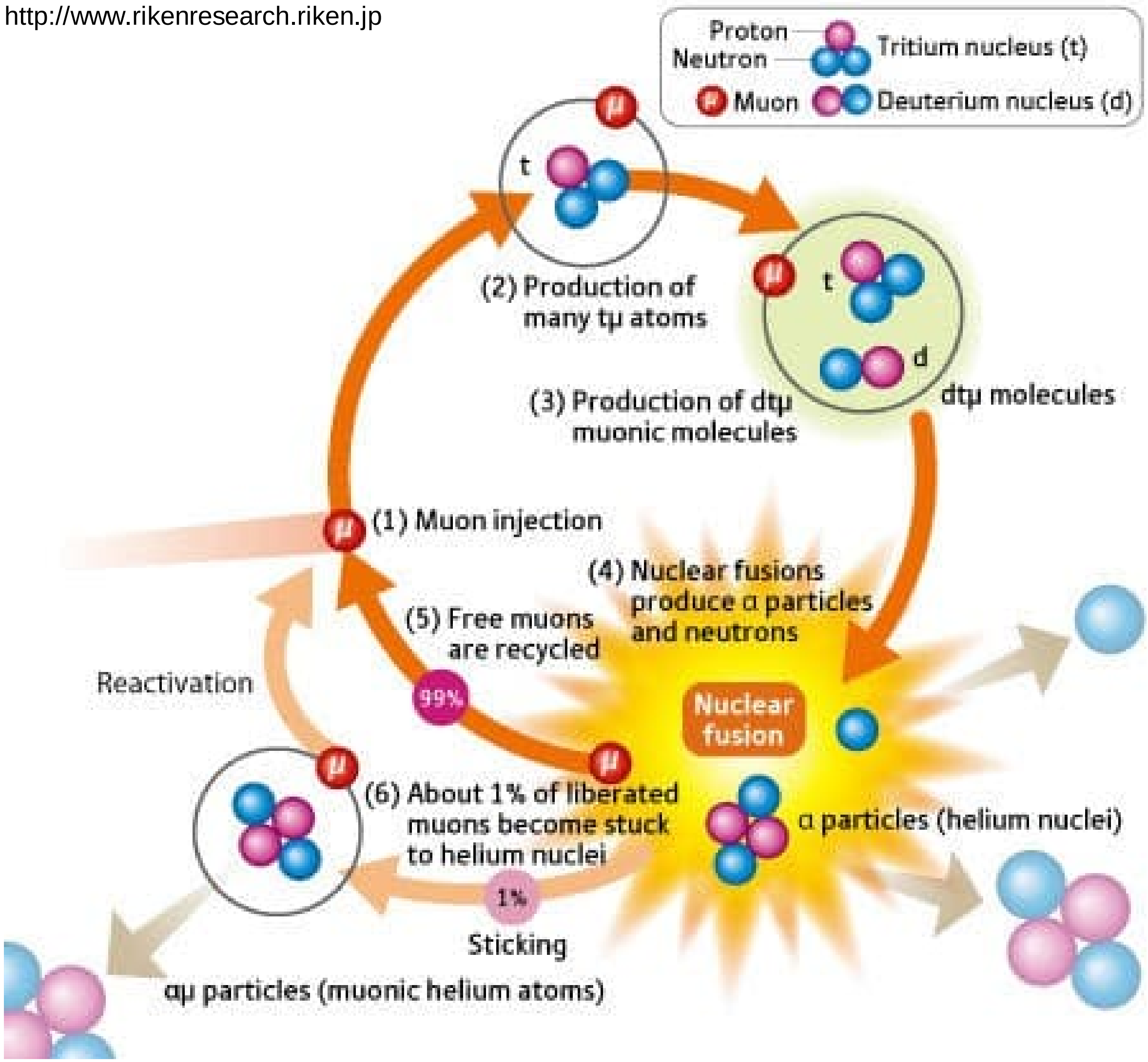
- **Deuterium may be distilled from any form of water ⇒ widely available, harmless, and virtually inexhaustible (33 mg in each liter/kg of water)**
- **Tritium is an unstable radioactive isotope ⇒ half-life of 12.3 yr (beta decay):** $T \rightarrow {}^{3}He + e^{-} + \nu$
- **Tritium currently being produced externally in fission plants (CANDU reactors)**
- **In future plants, breeding of tritium by nuclear reactions (https://www.youtube.com/watch?v=v5hOIjDsuJs, 3 min 16 s) of fusion neutrons with Li:**

$$n + {}^{6}Li \rightarrow {}^{4}He + T \qquad +4.8\,\mathrm{MeV}$$

$$n + {}^{7}Li \rightarrow {}^{4}He + T + n \quad -2.5\,\mathrm{MeV}$$

Replacing an electron with a muon permits fusion at significantly lower (room) temperatures

http://www.rikenresearch.riken.jp



- **Creating muons requires energies >> fusion output**
- **Limited muon cycle due to sticking to α-particles**
- **Muons have a short life time**

Summary

- **A high-temperature plasma at sufficient confinement is required to achieve fusion conditions**
  - Magnetic, inertial and gravitational systems
- **Break-even and ignition conditions are described by the Lawson criterion**
  - Self-heating has to exceed radiative and transport losses
  - Presence of helium and impurities significantly limits the operational space
- **Fusion of deuterium-tritium is currently favored:** highest cross-section (power density) at lowest temperature
  - Fuel is abundantly available, though D-D reaction more favorable for future devices