Basic principle of thermonuclear fusion

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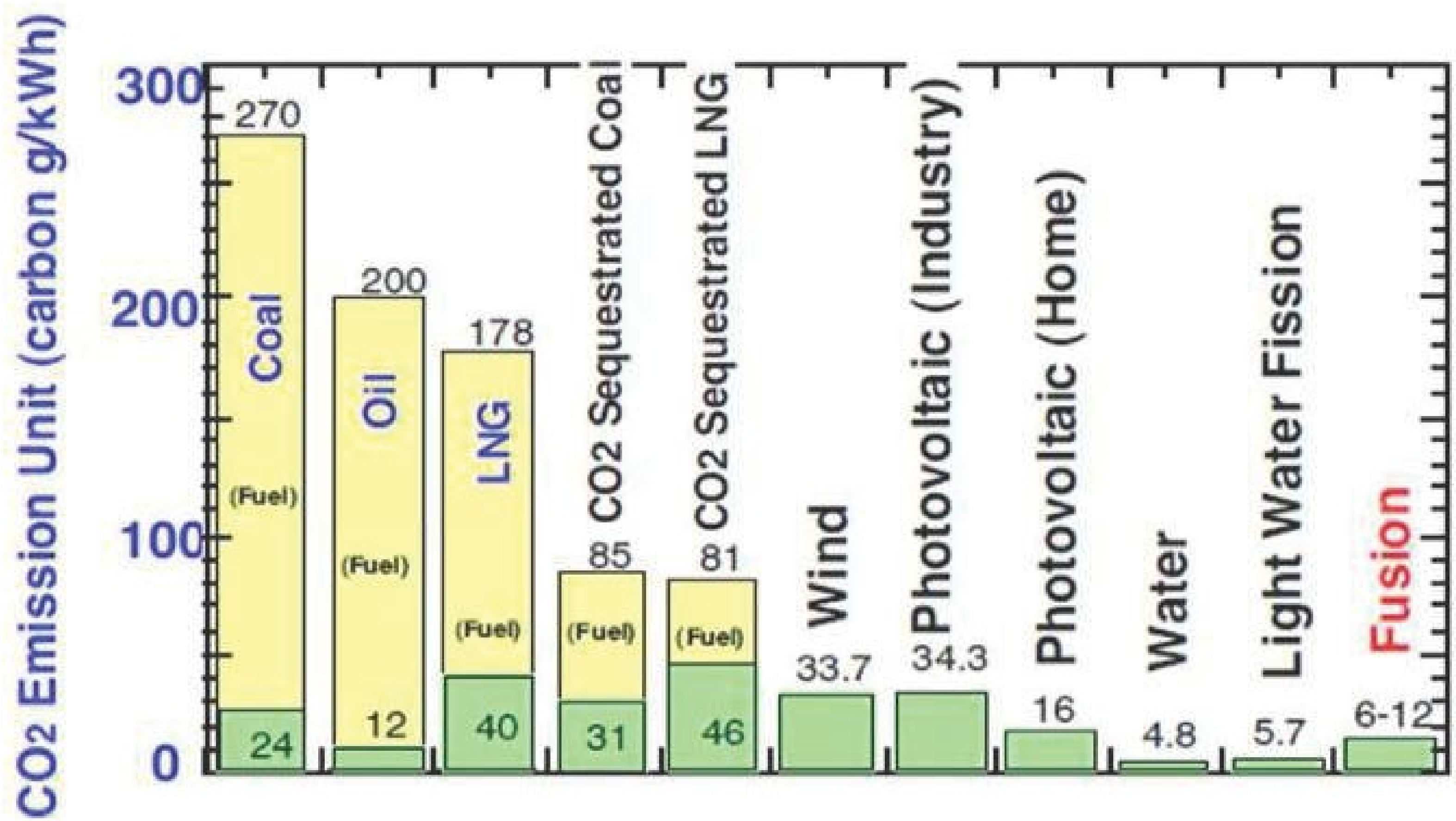
CO_2 emissions of fusion/fission (last lecture)

CO_2 exhaust of power reactors in their entire life cycle



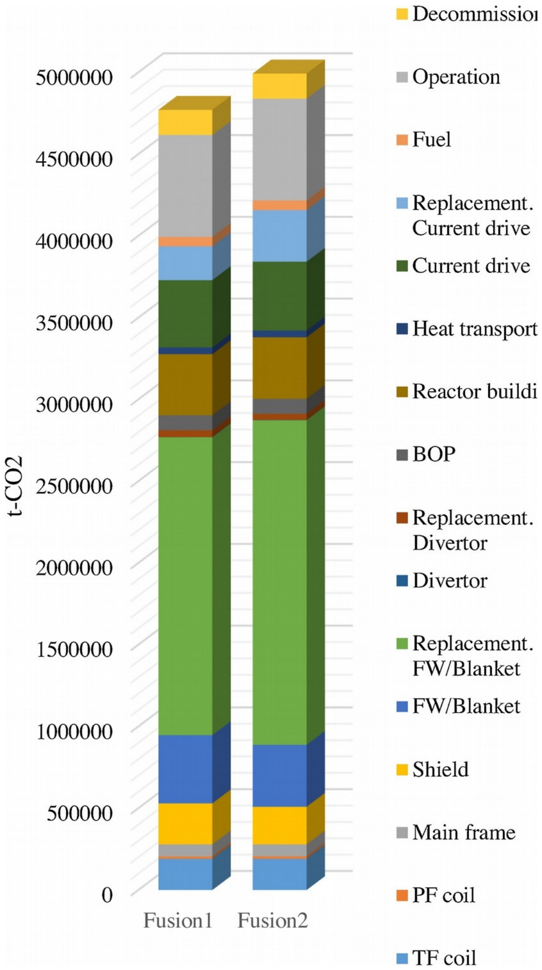
Kikuchi, Proc. 18th World Energy Conference 2001

CO_2 emissions of fusion/fission (last lecture)

Where do CO_2 emissions of fusion come from?

(fusion 6-12 vs e.g. fission 5.7 and coal 270 carbon g/kWh)

- **Most CO_2 emissions from fusion reactors are from materials (according to Tokimatsu et al NF2000)**
- **CO_2 emissions from (ITER-like) reactor construction account for almost 60-70% of the total, with the rest coming from reactor operation**
- **The emissions depend much on reactor type (size etc)**

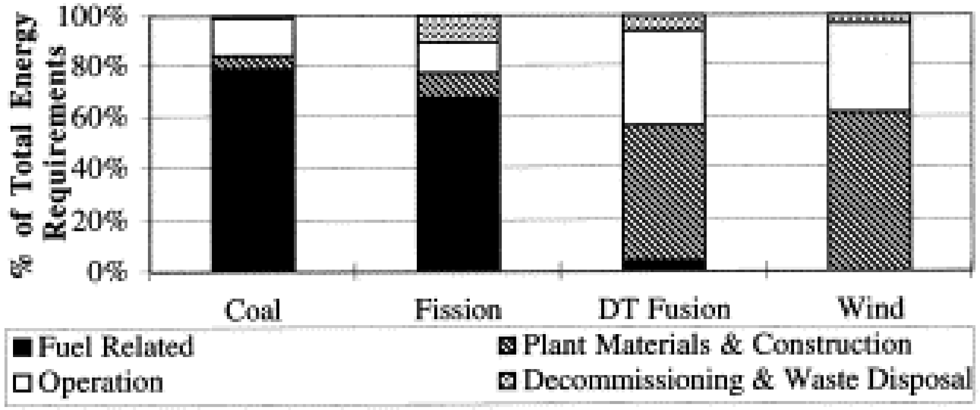


Life cycle total CO_2 emission for two different DEMO designs. Kobori et al Fusion Engineering and Design 2016

CO_2 emissions of fusion/fission (last lecture)

Fusion vs. fission

- **In fission, the processes for mining and refining uranium and making reactor fuel all require large amounts of energy.**
- **Nuclear power plants also have large amounts of metal and concrete, which require large amounts of energy to manufacture.**
- **In fission, emissions are mostly fuel related while in fusion plants material related**



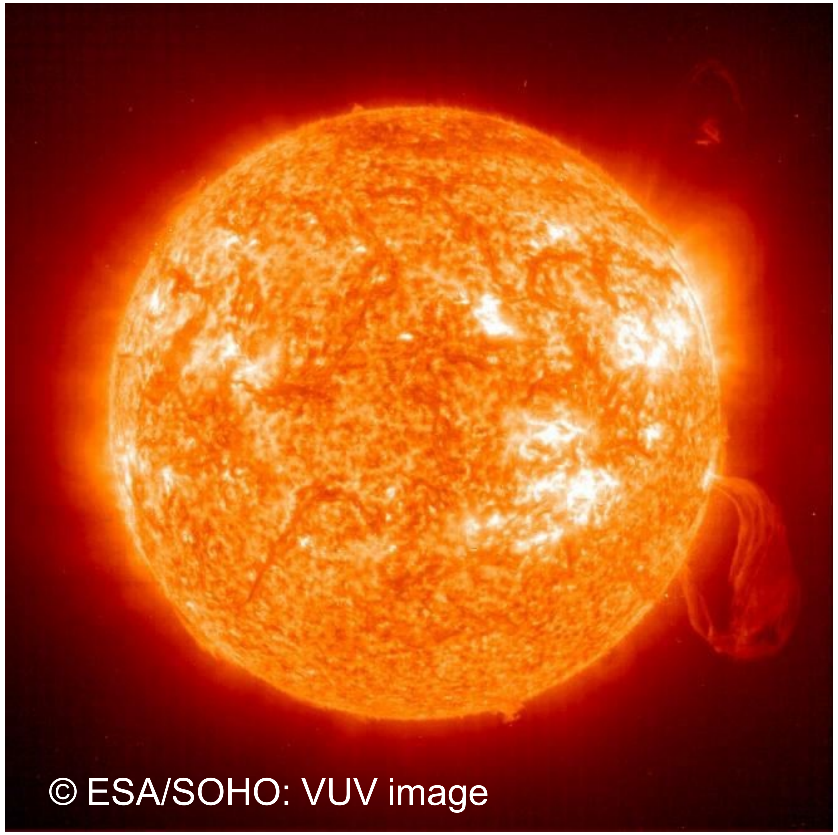
Proportional energy requirements for different energy sources. White et al Fusion Engineering and Design 2000

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

$$4\ {}^1_1H \rightarrow {}^4_2He + 2e^+ + 2v^+ + 2\gamma$$
$$+26.8MeV$$



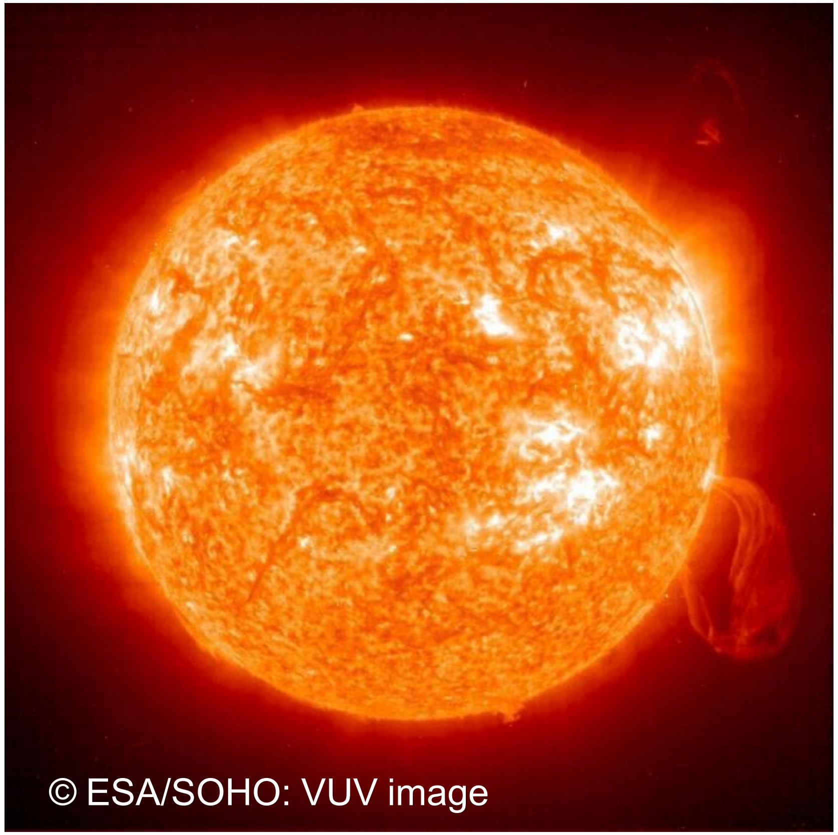
– **Core of the sunproduces 380 yottawatts (3.8 x 10^{26} W) via fusion**

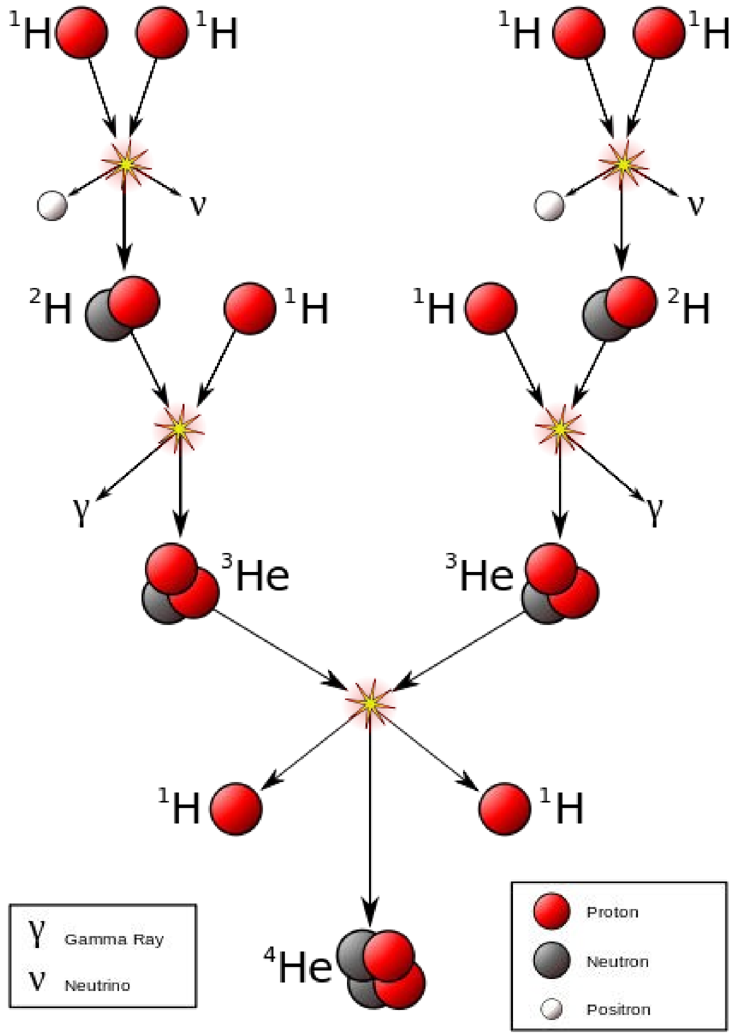
– **Merging of hydrogen isotopes to helium**

- $m \lesssim m_{sun}$: proton-proton chain
- $m > 1.3\ m_{sun}$: carbon-nitrogen-oxygen-chain (catalytic cycle)

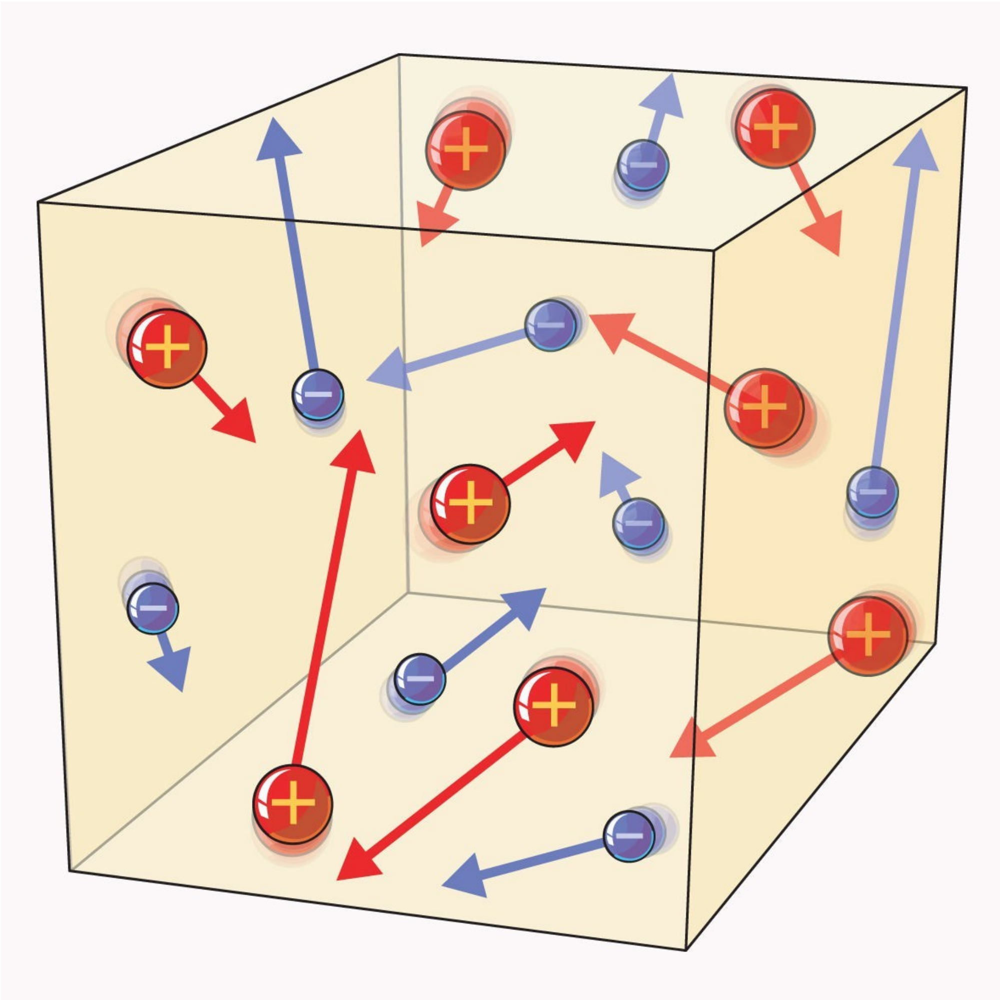
Fusion holds one of the biggest promises of an virtually unlimited energy source

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu^{+} + 2\gamma$$
$$+26.8MeV$$





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



http://www.efda.org

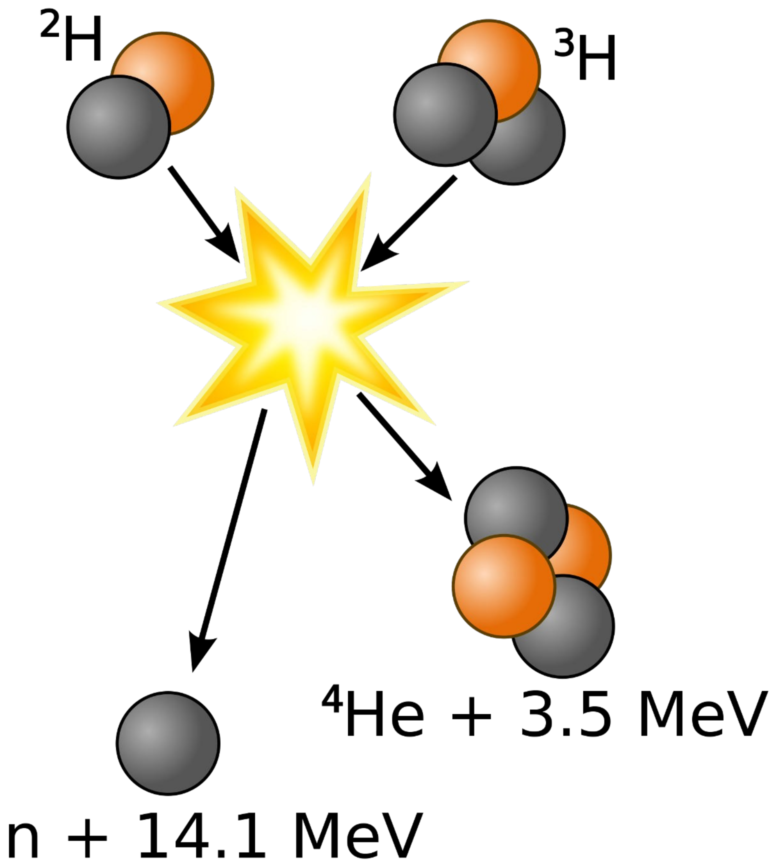
- **Plasmas are (electrostatically) neutral**
- **Plasmas need to be confined to remain hot**
  - Gravity
  - Inertia
  - Magnetic fields

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	^{4}He (1.7 MeV) + ^{3}He (2.3 MeV)
^{3}He+^{6}Li	2 ^{4}He + p + 16.9 MeV
p+^{11}B	3 ^{4}He (1.7 MeV) + 8.7 MeV

Ref

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



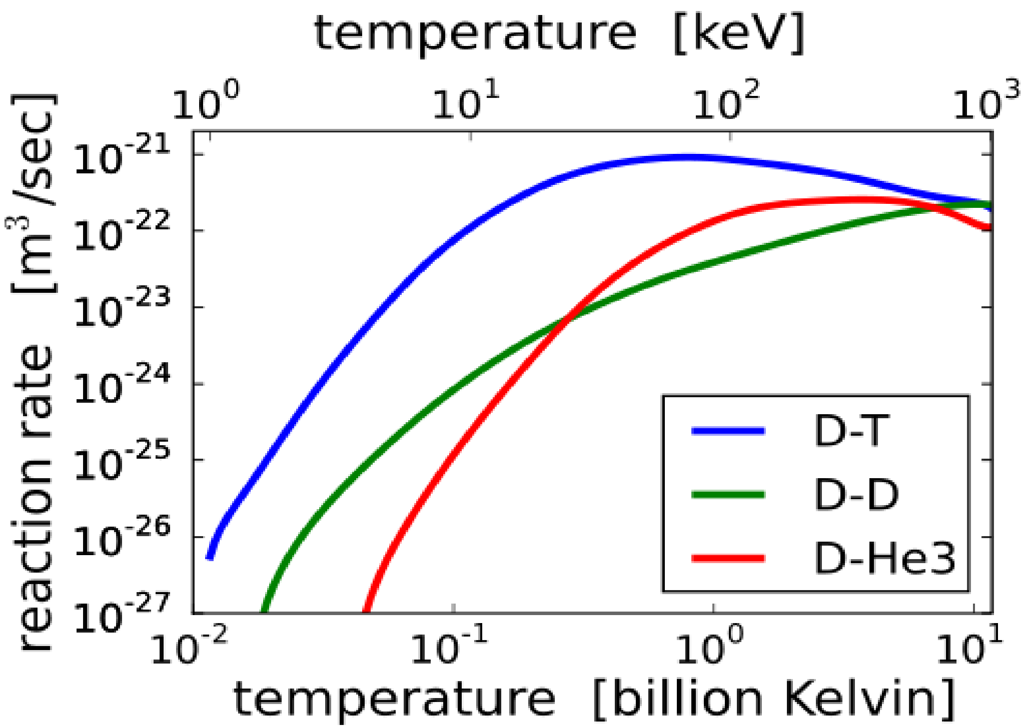
- $\Delta E_{D\text{-}T \rightarrow 4He}$ = 17.6 MeV

- **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

Reaction rates strongly depend on temperature

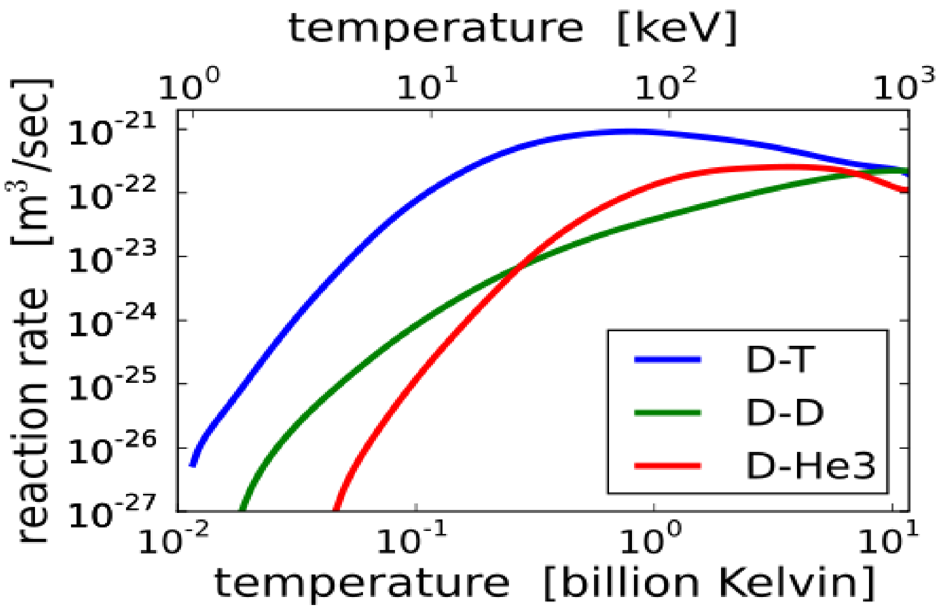


- **Reactant nuclei have to overcome electrostatic repulsion ⇒ heating to increase thermal velocity**

⇒ Reaction rates have a maximum

http://en.wikipedia.org

Deuterium-tritium reaction 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**

$$\langle \sigma v \rangle_{DT} \approx 3.68 \times 10^{-12} T^{-2/3} \exp(-19.94 T^{-1/3})\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

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

Here, temperature is in keV

http://en.wikipedia.org

Video: Where do you get fusion fuel?

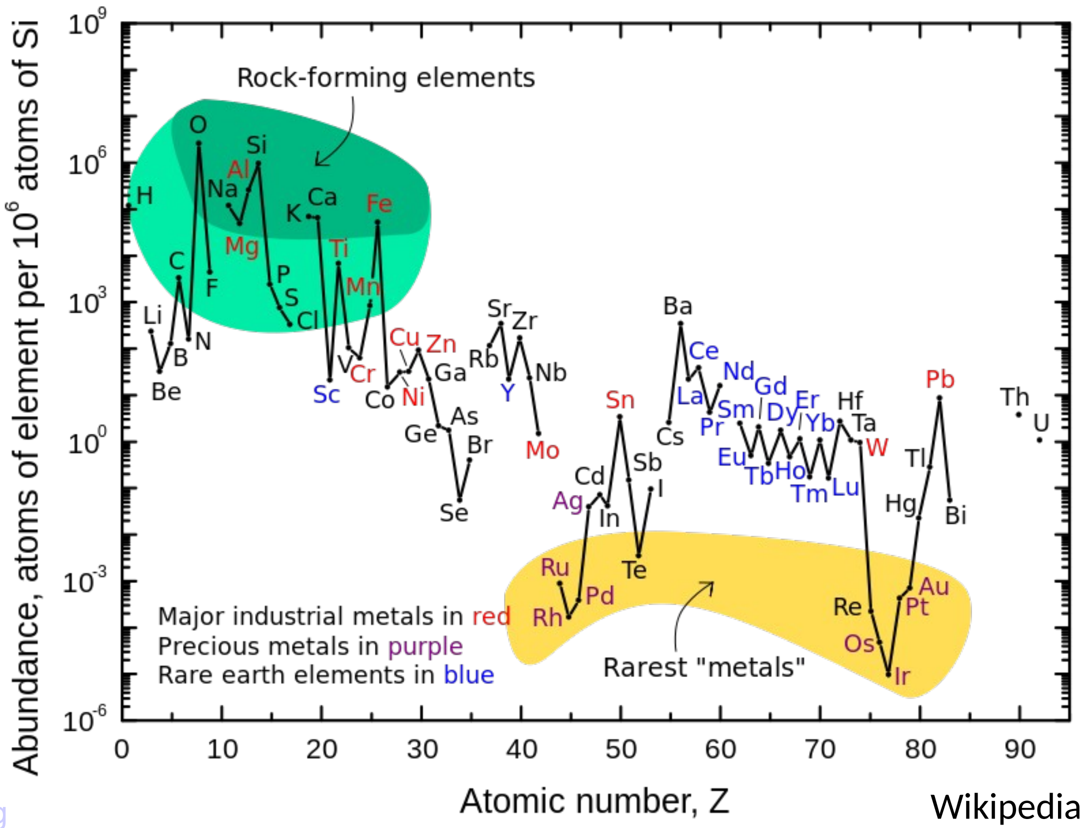
- Video about fusion fuel **(from 1.45s – 3.57s)**
- **Where do you get Tritium?**
- **How much fuel do you need for average European family‘s demand for electrical energy for entire year?**

http://en.wikipedia.org

Video: Where do you get fusion fuel?

- **Where do you get Tritium? A: from Lithium which is abundant in natural rock everywhere on Earth**
- **How much fuel do you need for average European family's demand for electrical energy for entire year?**

A: 2 litres of water + 250g of rock

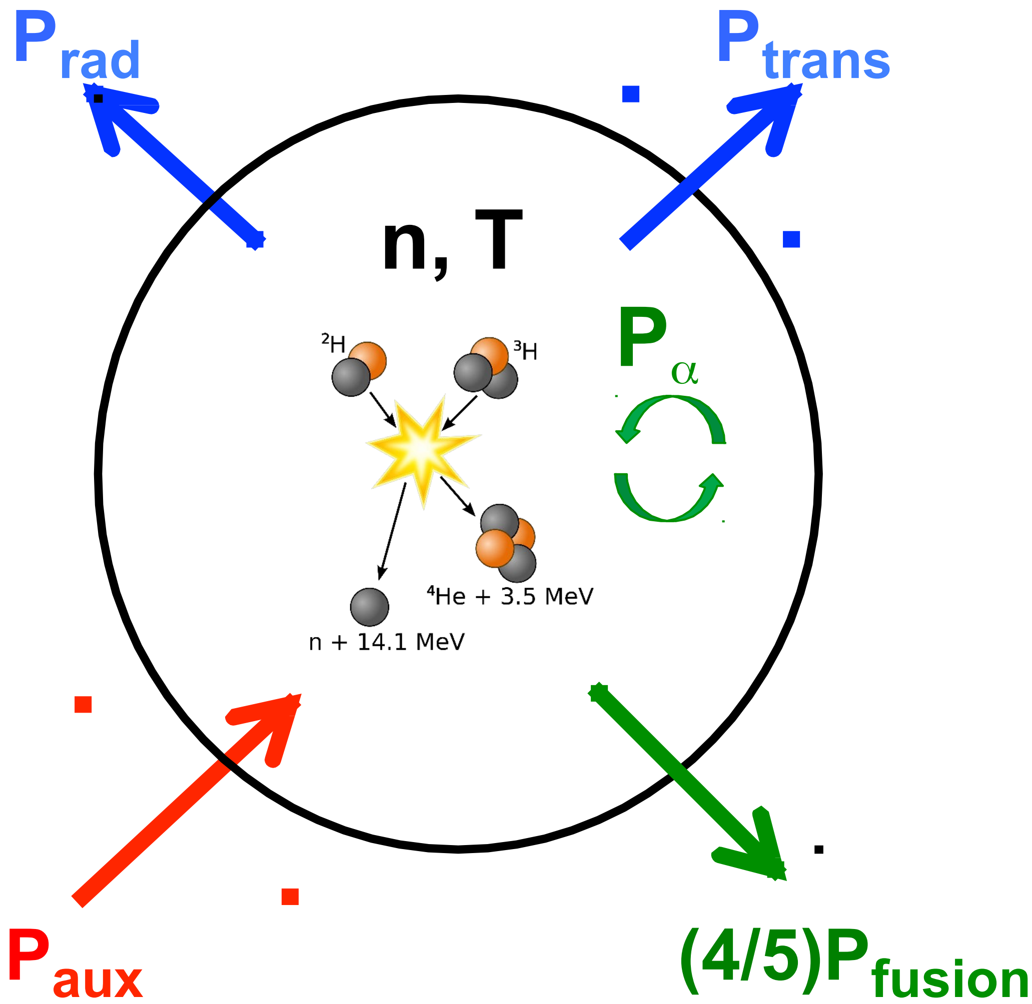


http://en.wikipedia.org

Wikipedia

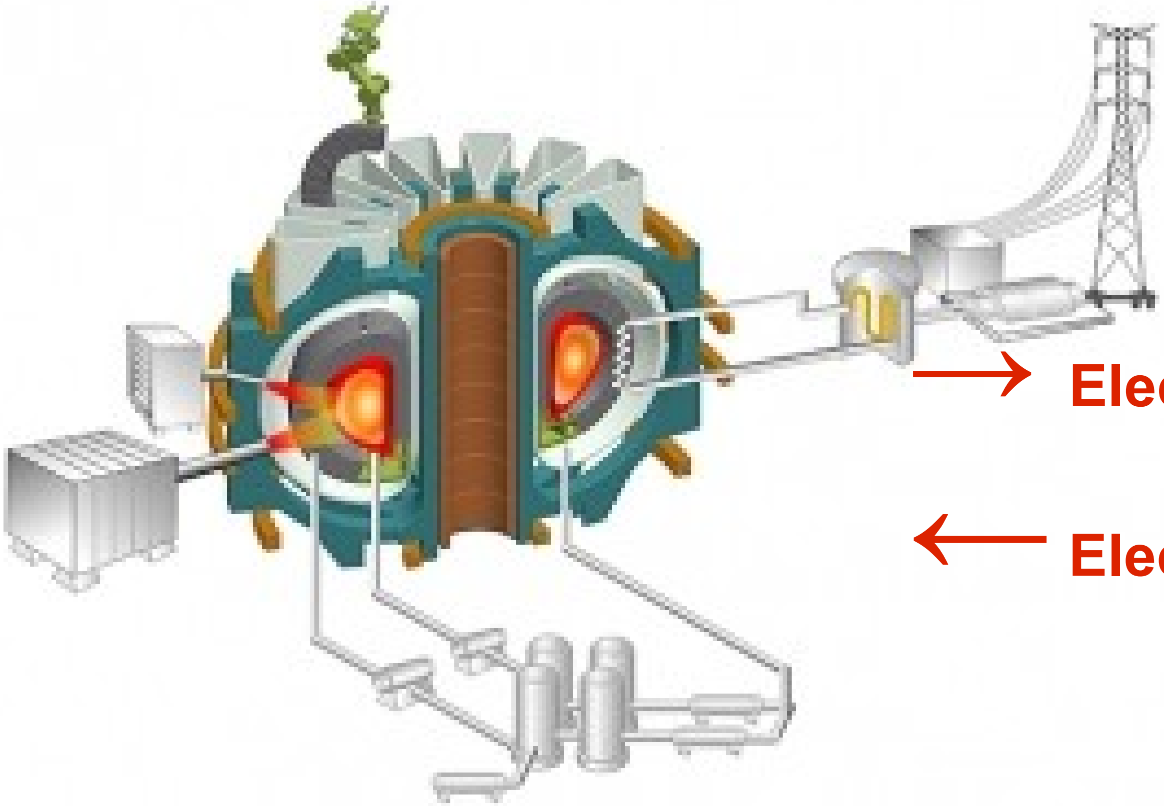
Criteria for fusion energy

What temperatures, densities, and confinement (times) are required for 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 $Q \equiv P_{fusion} / P_{aux}$



→ Electricity (Q >> 1)

← Electricity (Q < 1)

Lawson criterium ($Q \rightarrow \infty$)

Energy gain Q>1 gives scientific breakeven but...

"Engineering" breakeven: takes into account that

1) only a fraction $(1-f_{ch})$ of fusion energy goes to blanket

2) cooling fluid of blanket drives steam turbines with efficiency η_{elec} = 35-40 %

3) fraction f_{recirc} of P_{elec} recirculated back into the heaters

4) η_{heat} is the efficiency that power supplied to the heating systems is turned into heat in the fuel

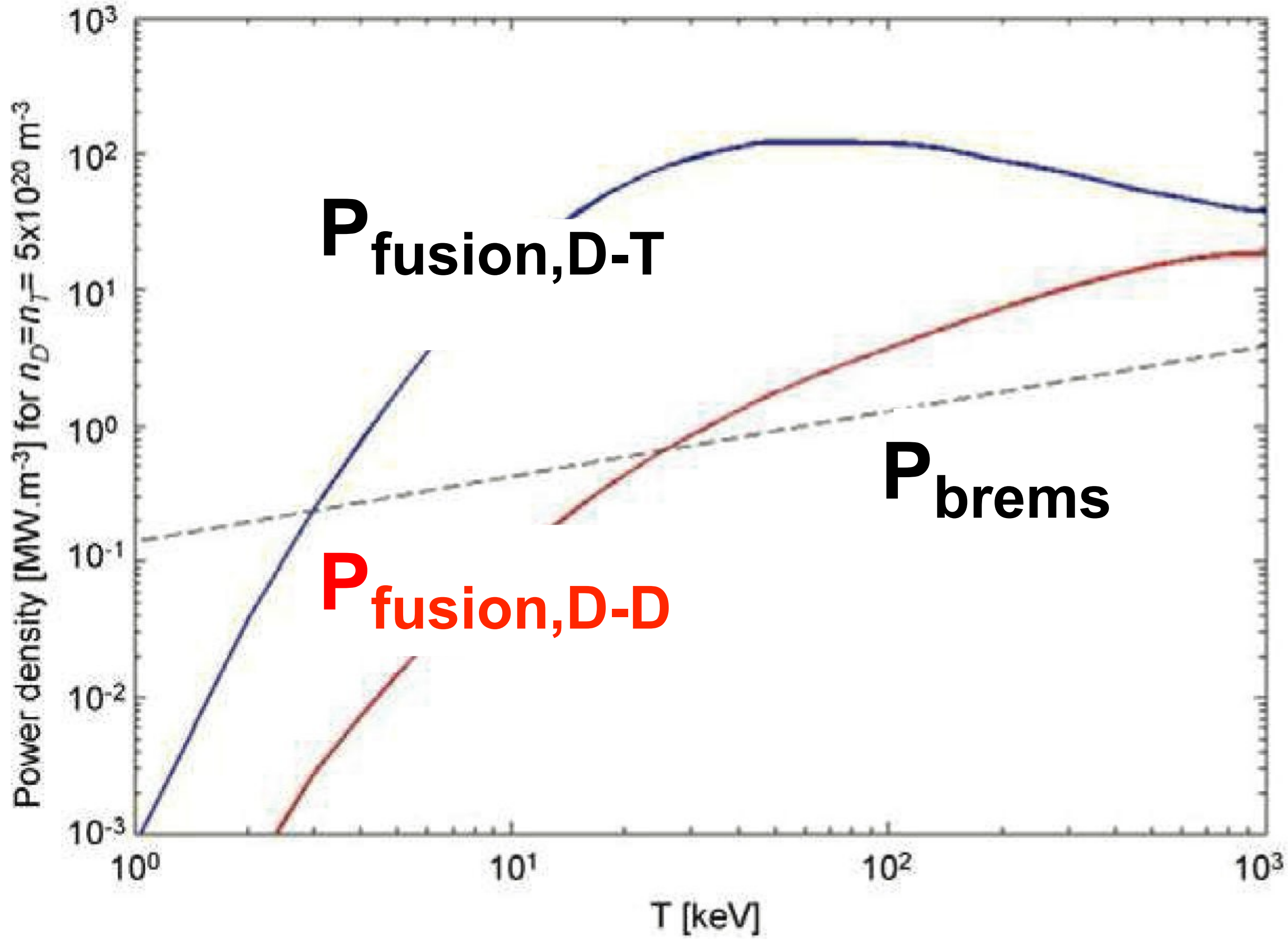
$$P_{heat} = (1-f_{ch})\,\eta_{elec}\,f_{recirc}\,\eta_{heat}\,P_{fus}$$

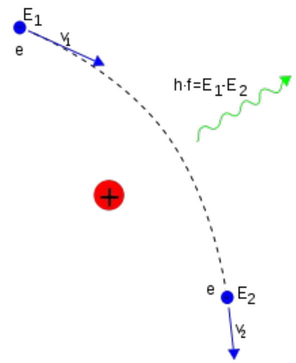
What temperatures, densities, and confinement times are required for fusion?

- **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:** $$P_{fusion} = 5P_{\alpha} = 5n_X n_Y \langle \sigma v \rangle E_{\alpha} V_p$$
- **Net heating power:** $$P_{heat} = P_{aux} + P_{\alpha} - P_{brems}$$ $$= P_{aux} + n_X n_Y \langle \sigma v \rangle E_{\alpha} V_p - C_B T^{1/2} n_e^2 V_p$$

$\Rightarrow$ **50-50 mix of D-T:** $$P_{heat} = P_{aux} + \frac{1}{4} n_e^2 \langle \sigma v \rangle E_{\alpha} V_p - C_B T^{1/2} n_e^2 V_p$$

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:** $$\tau_E \equiv W_p / (P_{heat} - dW_p / dt)$$

⇒ **(Time-dependent) power balance (using $Q \equiv P_{fusion} / P_{aux}$ and equation for P_{heat} shown earlier)**

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

For a 50-50 mix of D-T, the product of density and energy confinement time must exceed 10^{20} s m^{-3}

Overleaf ➔

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

- **Steady-state: (d/dt=0)**

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

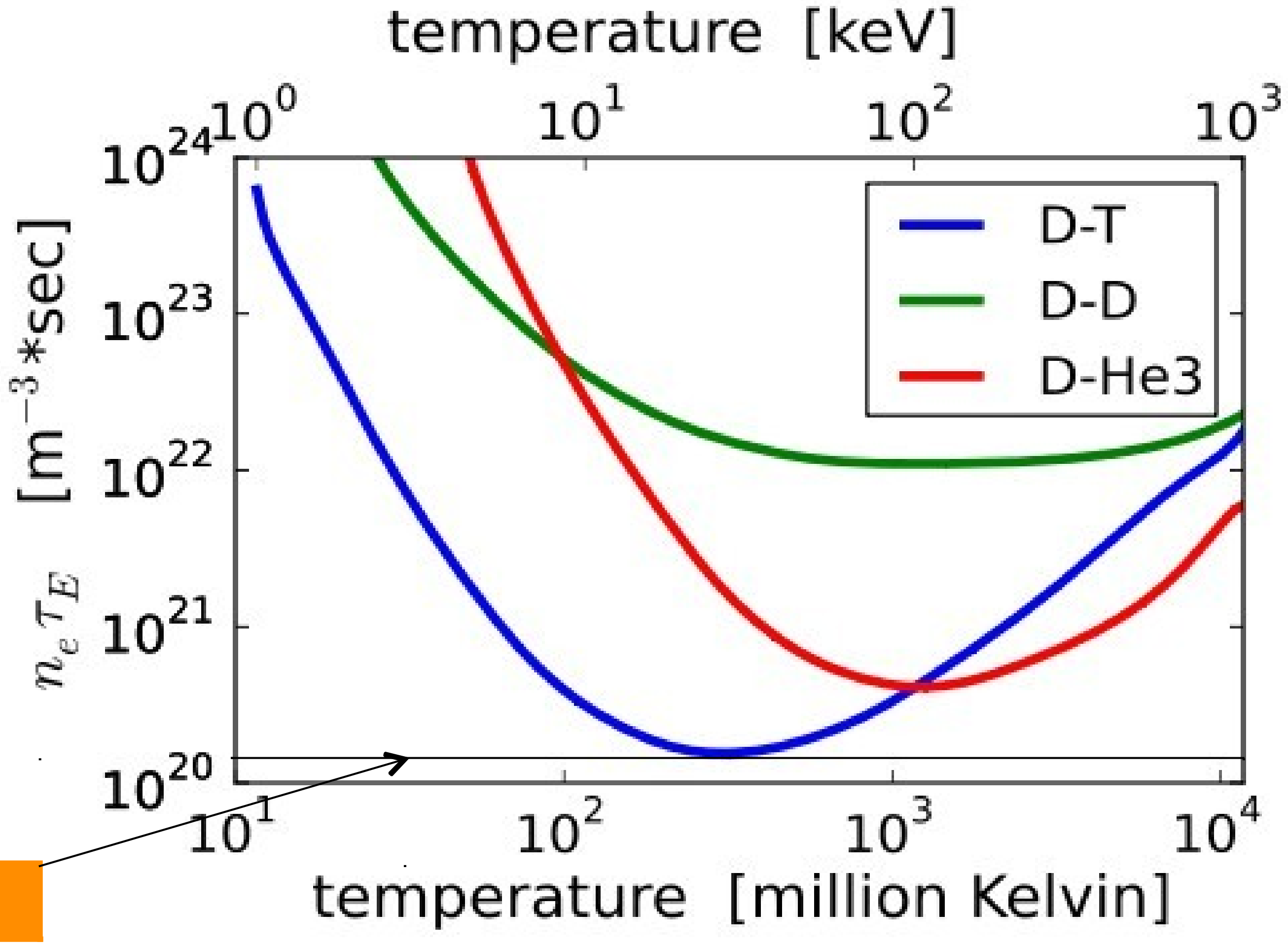
- **Break-even (Q = 1):**

$$n_e \tau_E = \frac{3 k_B T}{\frac{3}{2} \langle \sigma v \rangle E_\alpha - C_B T^{1/2}}$$

⇒ **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

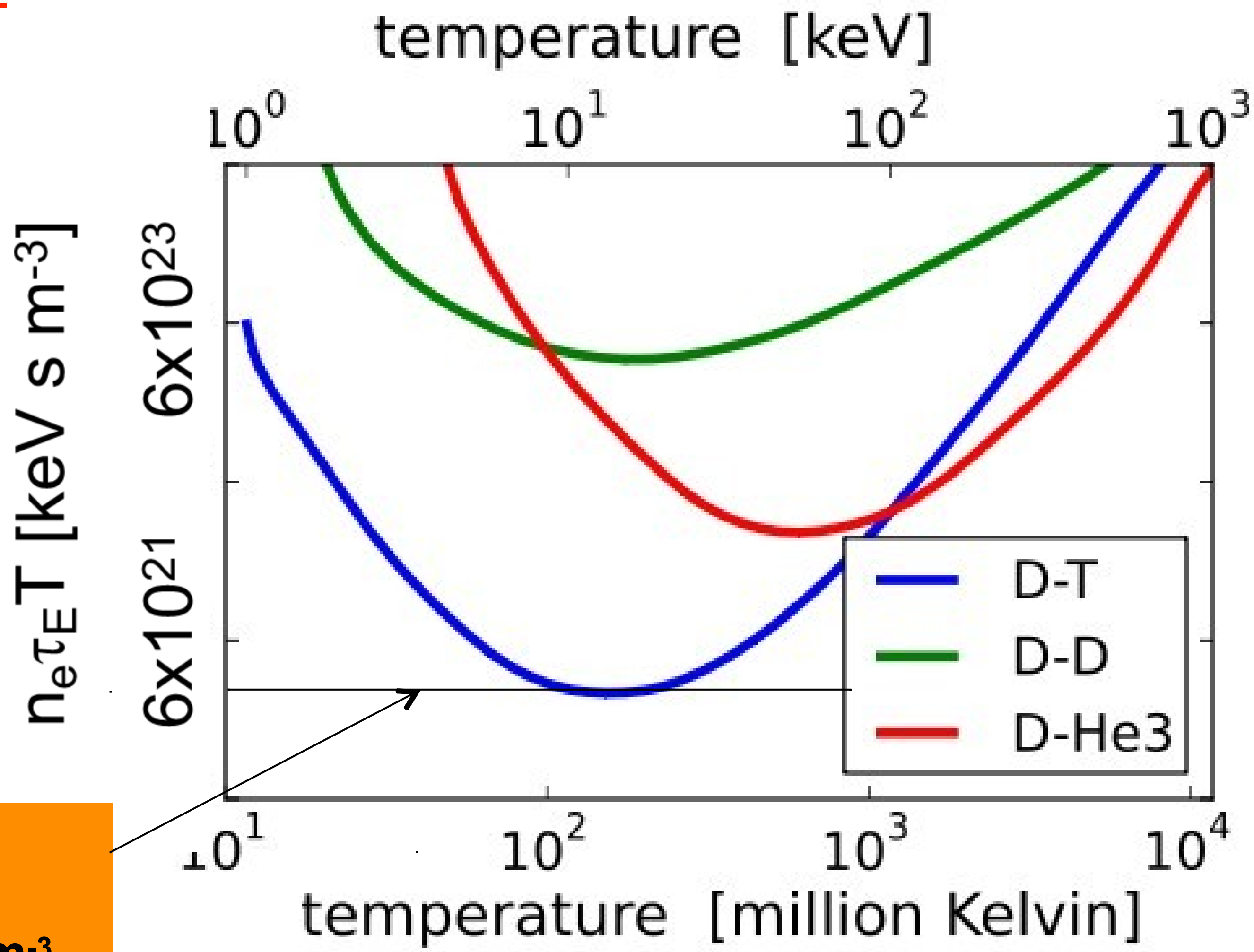
<σv> = const.



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

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

$\langle\sigma v\rangle \propto T^2$



$n_e\tau_E T \geq$

1.5×10^{21} keV s m^{-3}

Requirements for ignition are more stringent than for break-even

Power balance, steady-state

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

- **Ignition (P_{aux} = 0, Q →∞):**

$$n_e \tau_E = \frac{3 k_B T}{\frac{1}{4} \langle \sigma v \rangle E_\alpha - C_B T^{1/2}}$$

⇒ For 50-50 D-T, a minimum product of $n_e \tau_E$ at T = 25 keV
⇒ $n_e \tau_E \geq 1.5 \times 10^{20}$ 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**

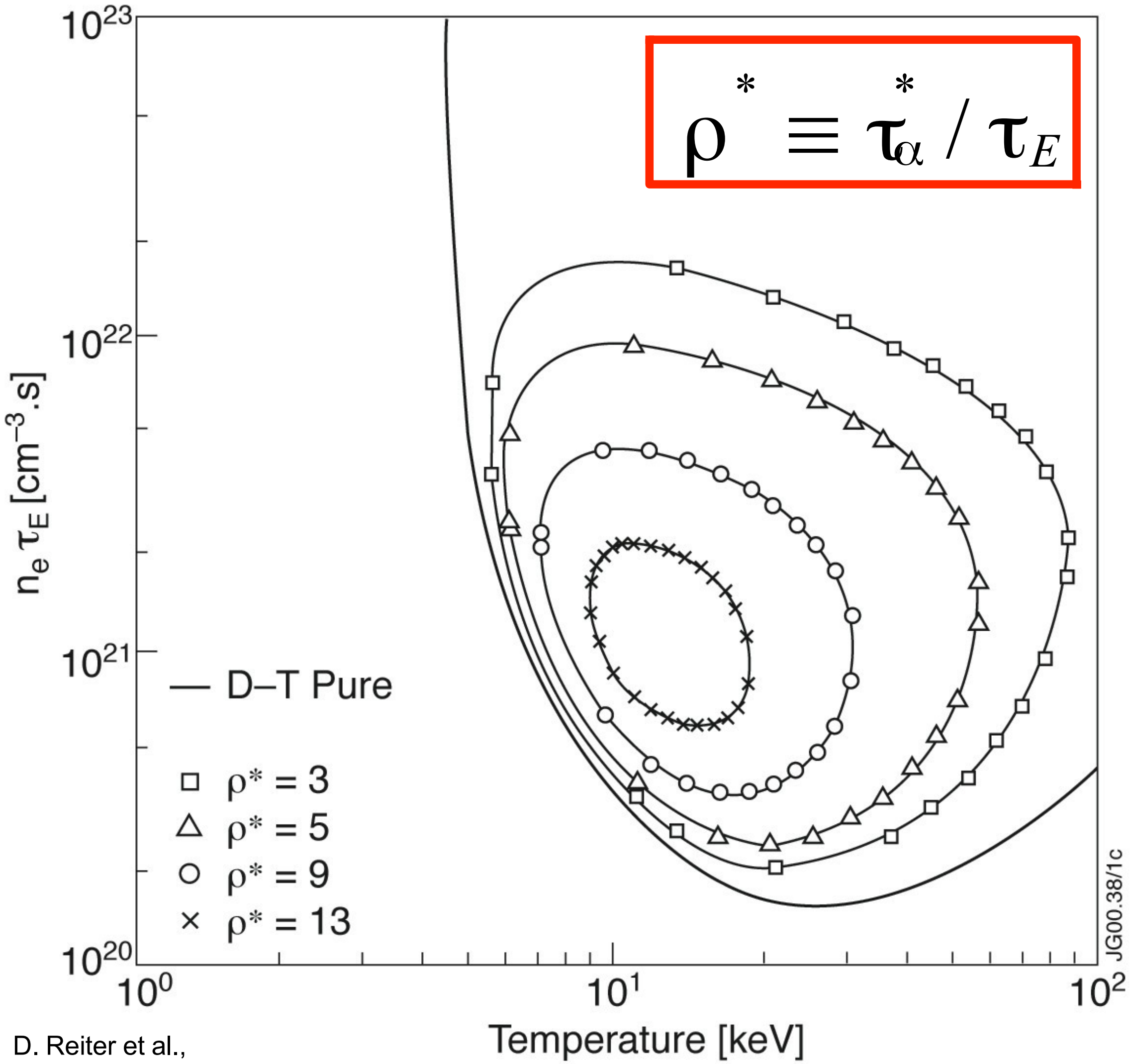
- **τ_E is function of n and T (and device parameters); determined experimentally ⇒ approach to ignition**

- **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



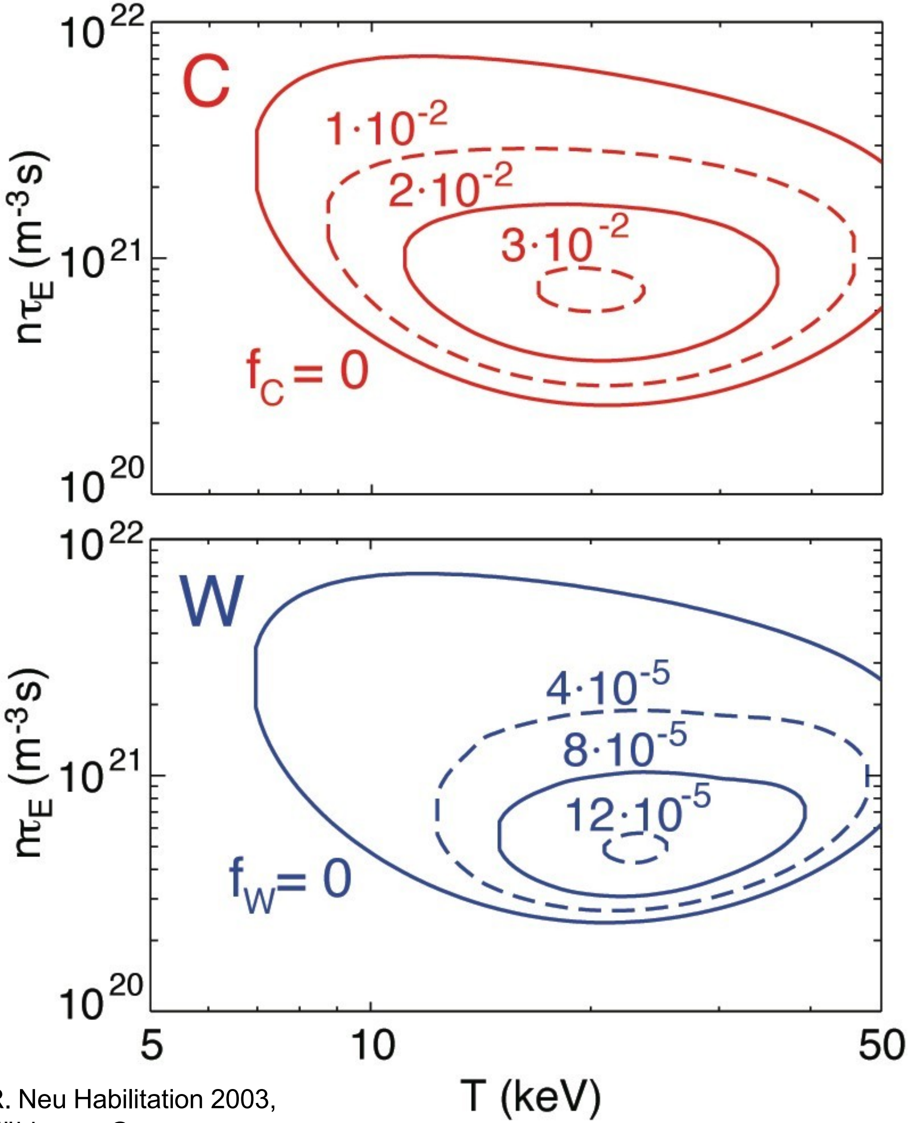
D. Reiter et al.,
Nucl. Fusion **30** (1990) 2141.

- 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



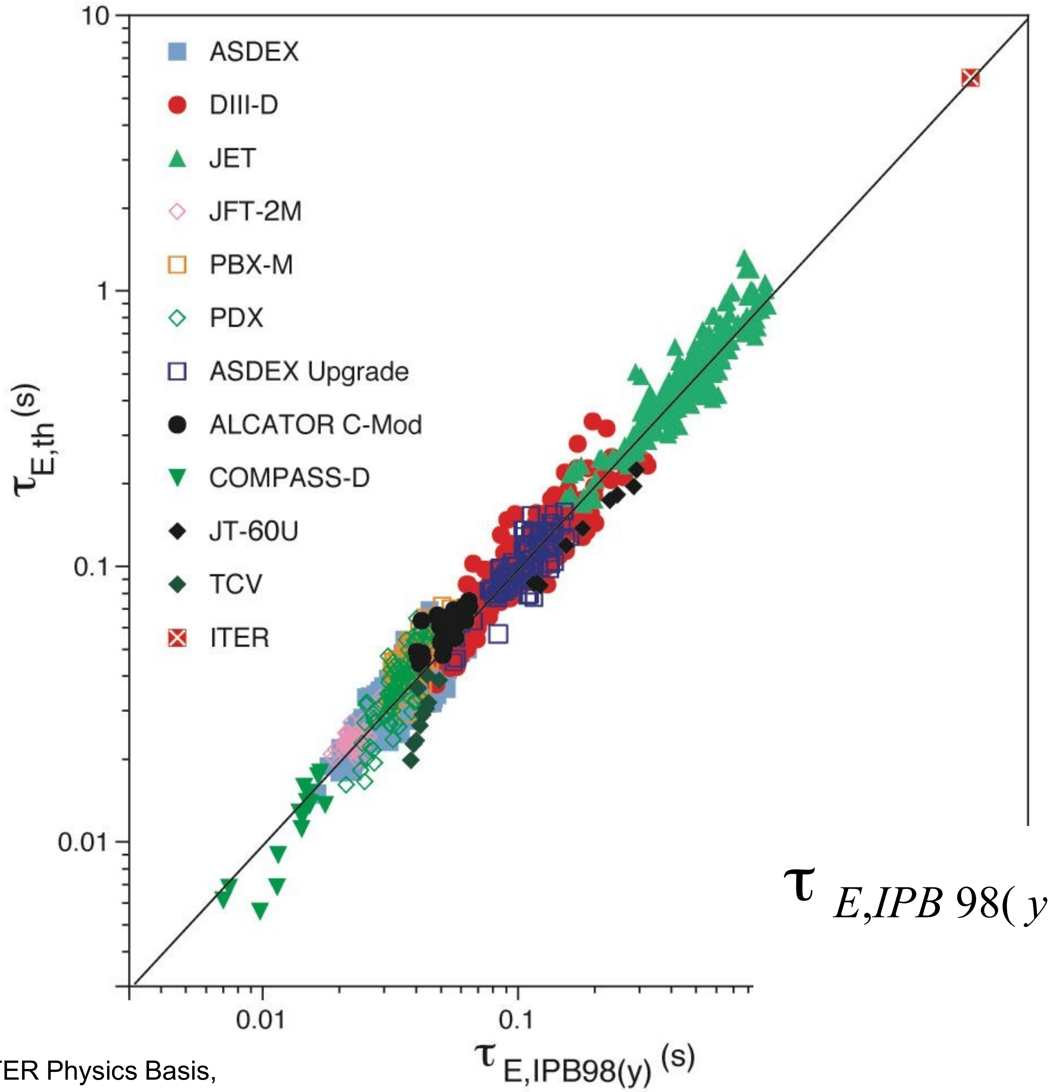
R. Neu Habilitation 2003, Tübingen, Germany

$\rho^* = 5$,
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 (< $5x10^{-5}$)**

Energy confinement time depends on many plasma and device parameters



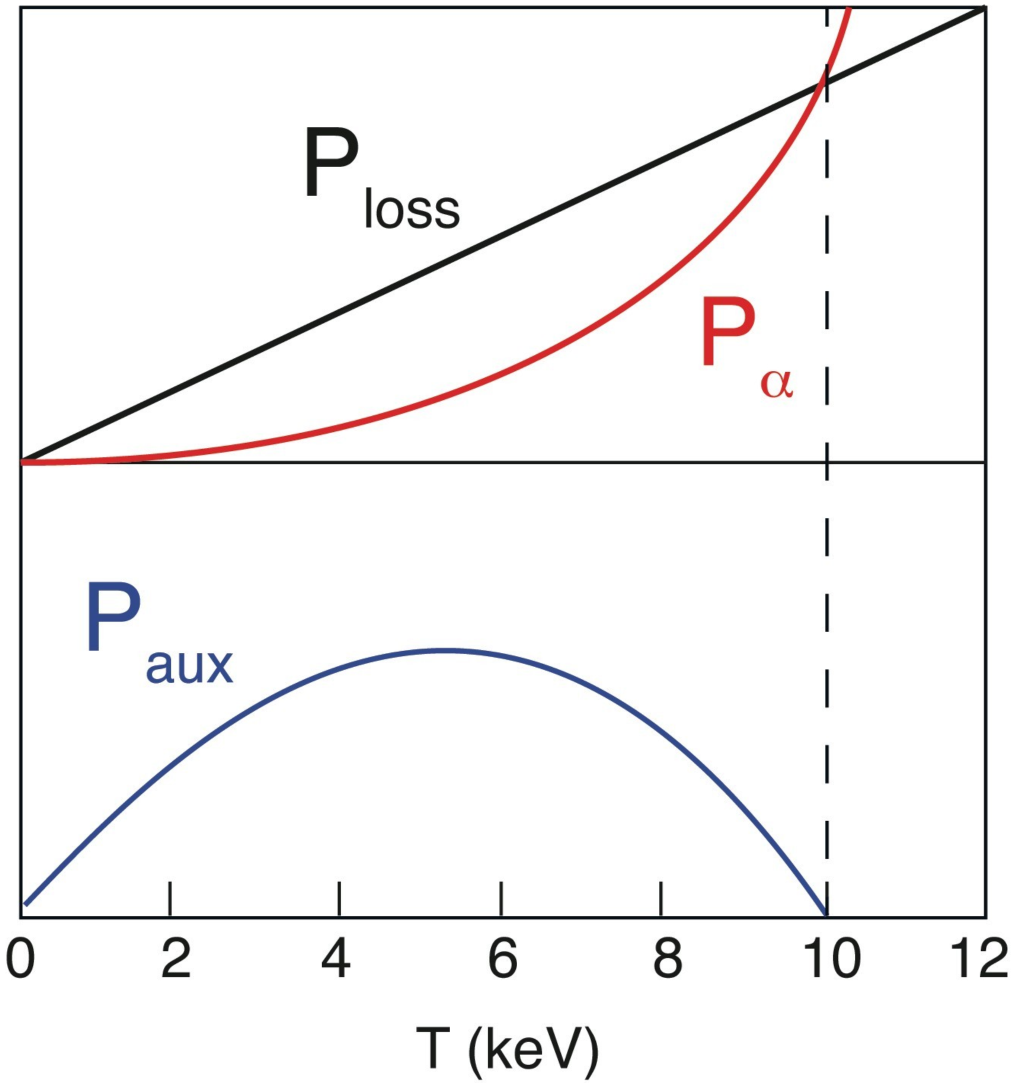
ITER Physics Basis,
Nucl. Fusion **39** (1999) 2175.

- **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)**

$$\tau_{E,IPB98(y)} \propto I^{0.97} B^{0.08} P^{-0.63} n^{0.41} \times M^{0.20} R^{1.93} \varepsilon^{0.23} \kappa^{0.67}$$

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	$\langle \sigma v \rangle / T^2$	Neutro-nicity	E_{fus} [MeV]	Power density [$Wm^{-3}\ kPa^{-2}$]
D-T	1.24×10^{-24}	0.80	17.6	34
D-D	1.28×10^{-26}	0.66	12.5	0.5
D-^{3}He	2.24×10^{-26}	~0.05	18.3	0.43
p-^{11}Be	3.01×10^{-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)**

Deuterium and tritium are abundantly available

- **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):**

$$T \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$$

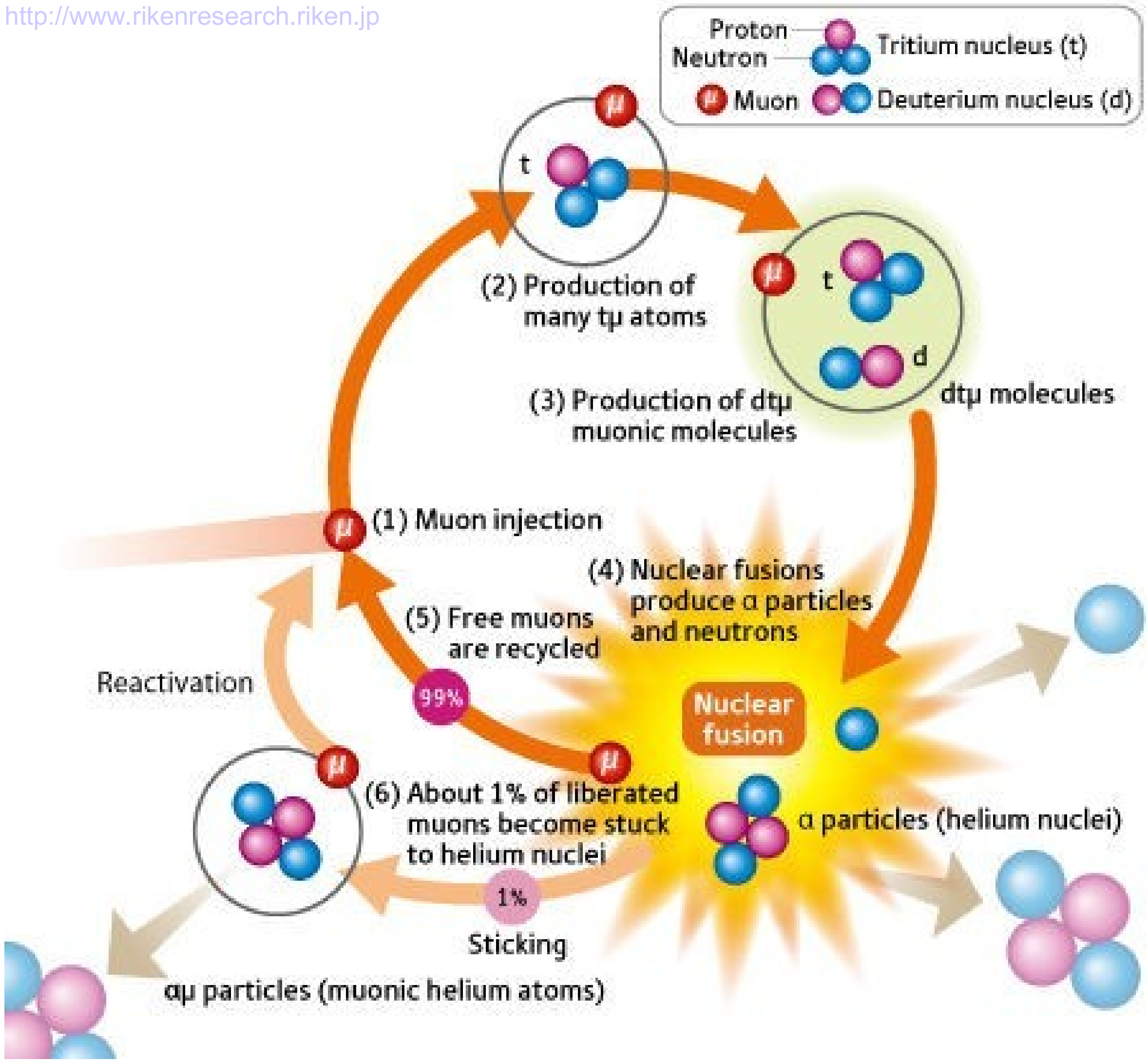
- **Tritium currently being produced externally in fission plants (CANDU reactors)**

- **In future plants, breeding of tritium by nuclear reaction (video: 3min 16s) of fusion neutrons with Li:**

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

$$n + {}^{7}Li \rightarrow {}^{4}He + T + n \qquad - 2.5\ \text{MeV}$$

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



- 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