Nuclear Fusion and Plasma Physics

The basics of thermonuclear fusion

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Lecture 1 - 25 September 2023

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1 Fusion and the world's energy needs (P.P. and F.E. by J.Freidberg, Ch. 1 and 2 - Fusion Physics, IAEA, Ch. 1)

The need for ways to supply energy that are economically and environmentally sustainable represents one of the main issues mankind faces today. Discussing the whole energy issue in general would take an entire course. Nevertheless, it is useful to reflect upon it, even if in a necessarily superficial way, as an introduction to the course, and as a motivation for our efforts. The attached slides remind us of some of the issues, including an overview of the energy options available to meet the demand, including nuclear fusion, and have been used as a basis for our in-class discussion.

2 Nuclear fusion

2.1 Fusion reactions

The 'basic process' is H + H + H + H $\rightarrow$ H^4

1. $D_1^2 + T_1^3 \;\rightarrow\; He_2^4\,(3.5\text{ MeV}) + n_0^1\,(14.1\text{ MeV});\;\; E_{\text{min}} \simeq 4\text{ keV}, \Delta E_f = 17.6\text{ MeV}$
   Note 1: Energy share between α's and n's is dictated by the masses:

$$\left\{ \begin{array}{rcl} \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 & = & \Delta E \\ m_1\mathbf{v}_1 + m_2\mathbf{v}_1 & = & 0 \end{array} \right. \Rightarrow \left\{ \begin{array}{rcl} \frac{1}{2}m_1 v_1^2 & = & \frac{m_2}{m_1+m_2}\Delta E \\ \frac{1}{2}m_2 v_2^2 & = & \frac{m_1}{m_1+m_2}\Delta E \end{array} \right. \Rightarrow \frac{\frac{1}{2}m_1 v_1^2}{\frac{1}{2}m_2 v_2^2} = \frac{m_2}{m_1}$$

2. $$D_1^2 + D_1^2 \begin{array}{lllll} \nearrow 50\% & T_1^3\,(1\text{ MeV}) & + & p_1^1(3\text{ MeV}) & \Delta E_f = 4\text{ MeV} \\ \searrow 50\% & He_2^3\,(0.8\text{ MeV}) & + & n_0^1(2.45\text{ MeV}) & \Delta E_f = 3.2\text{ MeV} \end{array}$$

   $E_{\text{min}} \simeq 10$ keV

3. $D_1^2 + He_2^3 \rightarrow He_2^4\,(3.7\text{ MeV}) + p_1^1(14.5\text{ MeV});\;\; E_{\text{min}} \simeq 30\text{ keV};\;\; \Delta E_f \cong 18.2\text{ MeV}$

Et cetera, with increasing E_{min}; He^3 is a T-decay product, but could also be mined from the surface of the moon.

Note 2: Reaction 3 is the 'cleanest', as it does not produce (fast) neutrons, has no radioactive elements. No neutron irradiation $\Rightarrow$ no activation of structure materials.

Note 3: there is no energy at which a mono-energetic beam can produce more fusion reactions than Coulomb interactions ($\sigma_{\text{Coul}} \geq \sigma_{\text{fus}}\ \forall\ E$). This implies:

- No chance to make fusion energy with beams (thay are scattered before they can fuse).
- We need to deal with a Maxwellian equilibrium generated by Coulomb collisions, like in a gas.
- That is why we speak of *thermonuclear fusion*.

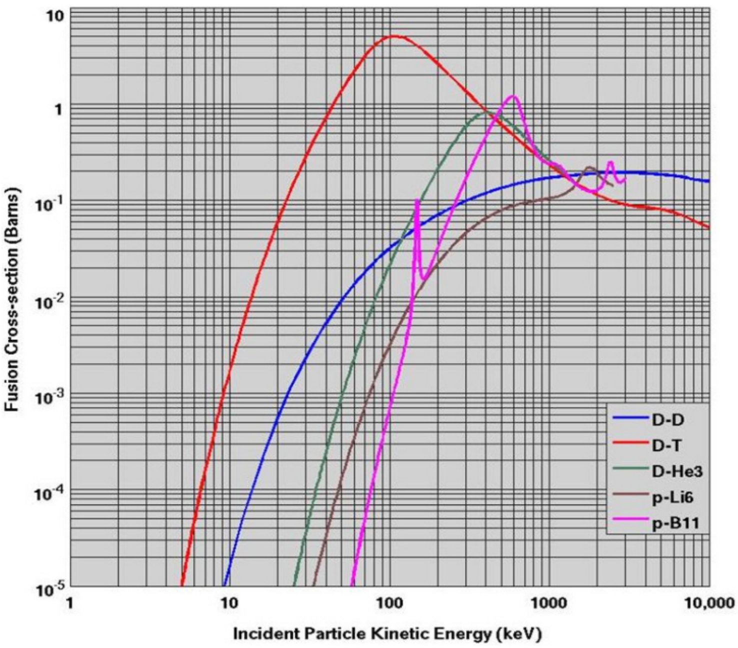

Figure 1: Cross-section dependence upon energy for the most important fusion reactions for use as energy source.

2.2 Sources of fuel for fusion (D-T)

D is $\frac{1}{6700}$ of hydrogenic atoms in oceans i.e. $\sim$ 1.6 g/l $\Rightarrow\sim$ 5 x 10^{16} kg total in oceans. But 1 kg of D-T gives 2.7 x 10^{14}J (or 7.5 x 10^{7} kWh, or the world's need for 1 min) $\Rightarrow$ so the supply is practically unlimited ($\sim 10^{16} \times 10^{14} J$, or $\sim 10^{16}$ x 1 min $= \frac{10^{16}}{60x24x365} \sim 2 \times 10^{10}$ years).

By comparison, 1 kg of coal gives (700 K) 3 x 10^{7} J.

Tritium does not exist in nature, as it is radio-active and relatively short-lived (12.5 years). It can be produced from nuclear reactions with Lithium:
$n_0^1 + Li_3^6 \rightarrow T_1^3 + He_2^4 + 4.8$ MeV (Li^6 is $\sim$ 7% abundant)
$n_0^1 + Li_3^7 \rightarrow T_1^3 + He_2^4 + n_0^1 - 2.5$ MeV (Li^7 is $\sim$ 93% abundant)

As we can see in Fig. 2, the cross section for Li^6 is much larger than for Li^7, so much that we may not even need to use artificially Li^6 - enriched Lithium. But we need to have low-energy neutrons, i.e. to moderate them (from 14MeV down to thermal) before they interact with Lithium.
The second thing to note is that, if we need to multiply neutrons before we breed T (and we do need to do it, as we must guarantee one new T for each fusion reaction), we must do it while the neutrons are still at high energy, for example using reactions with Lead or Beryllium.
So, the logical sequence is to first use neutron-multipliers, then moderate the neutrons, and finally, breed Tritium.

Li is in the earth crust, and also in ocean waters ($\sim$ 0.17 g/m^3 ; for comparison, Uranium is

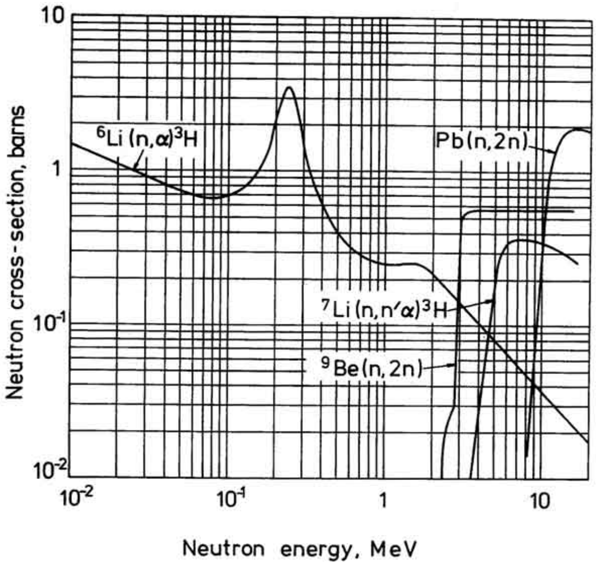

Figure 2: Cross-section for neutron reactions for n-multiplication and Tritium breeding.

0.003 g/m^3).

As we will see, in practice T is generated 'in situ', in a blanket containing Lithium that surrounds the plasma reactor. To compare the 'feasibility' of the different reactions, one should consider not just the minimum energy, but also the reaction rate as a function of energy, which stems from the concept of **cross-section**. This will also allow us to calculate the conditions for fusion energy production.

2.3 Fusion as a collisional process (P.P. and F.E. by J.Freidberg, Ch. 3)

Note 1: we focus only on DT reactions.

Fusion reaction rate (# of fusion reactions per unit volume per unit time)

$$R_{DT}(v) = n_D(n_T\sigma_{DT}(v)v) \quad \left(\frac{1}{\mathrm{m^3 s}}\right) \quad \text{for velocity v}$$

Fusion power density for velocity v (or corresponding energy) = $R_{DT}(v)\Delta E_f$ =

$$= \overbrace{(n_D n_T \sigma_{DT}(v)v)}^{\#\text{ of reactions/s/volume}} \times \underbrace{(\Delta E_f)}_{\text{energy of one reaction}} \quad \left(\frac{\mathrm{W}}{\mathrm{m^3}}\right)$$

ΔE_f is the energy released in one reaction (for DT, ΔE_f = 17.6 MeV).

Note 2: this quantity, as R_{DT}(v), is velocity (or energy) dependent, so it does not represent a global property of a plasma. We must perform an average over the distribution function.

Fusion power density = $n_D n_T \langle\sigma v\rangle_{DT}\Delta E_f = \frac{1}{4}n_e^2\langle\sigma v\rangle_{DT}\Delta E_f$

Note 3: we can assume that $n_D \simeq n_T \simeq \frac{1}{2}n_e$, where n_α is assumed to be negligible. Otherwise, $\sum Z_j n_j = n_D + n_T + 2n_\alpha = n_e$.

Note 4: the symbol $\langle\ \rangle_{DT}$ indicates an average over the D and T distributions (σ depends on v, so it cannot be taken out of the integral defining the average). Formally:

$$R_{DT} = n_D n_T \langle \sigma v \rangle_{DT} = \iint d\mathbf{v}_D d\mathbf{v}_T f_D(\mathbf{v}_D) f_T(\mathbf{v}_T) \sigma_{DT}(|\mathbf{v}_D - \mathbf{v}_T|)(|\mathbf{v}_D - \mathbf{v}_T|)$$

Note 5: v is in fact the relative velocity: $(|\mathbf{v}_D - \mathbf{v}_T|)$

For two Maxwellian distributions with the same temperature ($T_D = T_T = T$), we have:

$$\langle \sigma v \rangle_{DT} = \left(\frac{m_r}{2\pi T}\right)^{3/2} \int_0^\infty 4\pi v^3 \exp\Big(-\frac{m_r v^2}{2T}\Big) \sigma_{DT}(v) dv$$

where m_r is the reduced mass $m_r = \frac{m_D m_T}{m_D + m_T}$. This is represented as a function of temperature in Fig. 3.

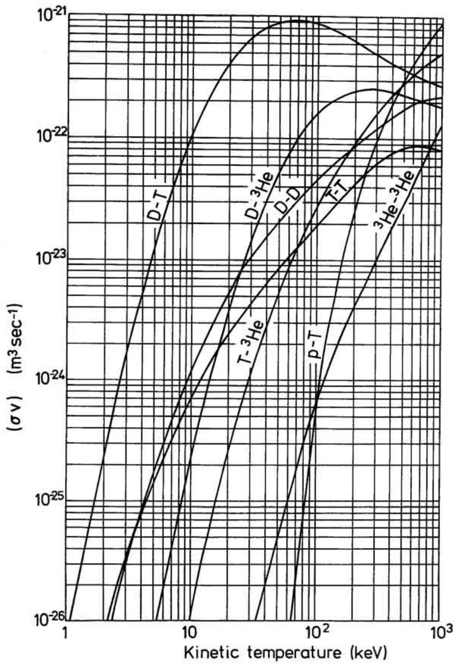

Figure 3: Fusion $\langle \sigma v \rangle_{DT}$ as a function of the plasma temperature.

Note 6: the maximum of $\langle \sigma v \rangle_{DT} vs.T$ is around 60 keV (it was around 100 keV for the mono-energetic case, as it can be seen in Fig. 1).
Note 7: at T = 9 keV the curve is at 10% of its maximum, while to be at 10% of the max. for the mono-energetic case we need to be at 35 keV.

2.3.1 Numerical example to evaluate if fusion can be obtained in a reasonable size reactor

We want a D-T fusion reactor with $P_{\text{fusion}} \sim 1$ GW (note: $P_{\text{fusion}} \neq P_{\text{electric}}$): what volume do we need?

In magnetic fusion we can take $n_e \sim 5 \times 10^{20}\text{m}^{-3}$; $\langle \sigma v \rangle_{DT} \sim 4 \times 10^{-22} \frac{\text{m}^3}{\text{s}}$ (for T $\sim$ 20 keV)

volume =

$$\frac{P_{\text{fusion}}}{n_D n_T \langle \sigma v \rangle_{DT} \Delta E_f} =$$

$$\frac{10^9 \text{J/s}}{\frac{1}{4}(5 \times 10^{20})^2 \text{m}^{-6} \times 4 \times 10^{-22} \text{m}^3/\text{s} \times 17.6 \times 10^6 \text{eV} \times 1.6 \times 10^{-19} \text{J/eV}} \cong 14\text{m}^3 (\text{reasonable})$$

Note 8: characteristic (thermal) velocity of ions is $v_{th_i} = \sqrt{\frac{T_i}{m_i}}$. Assuming T_i = 20 keV for a Deuterium ion,

$$\sqrt{\frac{T_i}{m_i}} = \sqrt{\frac{20 \times 10^3 \text{eV} \times 1.6 \times 10^{-19} \text{J/eV}}{3.3 \times 10^{-27} \text{kg}}} \simeq 10^6 \text{m/s}$$

For 1 m (reactor dimension) we have $\Delta t = \frac{1\text{m}}{10^6 \text{m/s}} = 1\mu\text{s} \rightarrow$ we need a confinement scheme!

2.4 Power balance in fusion (P.P. and F.E. by J.Freidberg, Ch. 4)

We need (at least) a power produced by fusion reactions that exceeds the losses from the plasma. This 'starting point' is called "break-even", at which the fusion power coincides with the input power.

Break-even: $\frac{\text{fusion power}}{\text{input power}} = \frac{P_f}{P_{in}} = 1$

We know that $\frac{P_f}{\text{volume}} = \frac{1}{4} n_e^2 \langle \sigma v \rangle_{DT} \Delta E_f$ $\qquad (\Delta E_f = 17.6 \text{ MeV})$

and that in steady-state, $P_{in} = P_l - P_\alpha$, where P_l = lost power (as plasma heating = losses).

We have two kinds of losses:

1. **direct losses** from plasma, described by a characteristic time over which energy is 'transported' outside the plasma by conduction and convection, defined by: $\frac{P_{dl}}{\text{volume}} = \frac{\text{energy/volume}}{\tau_E} = \frac{3 n_e T}{\tau_E}$ (defines τ_E)

   Note 1: the average energy is $\frac{3}{2}T$ for both ions and electrons (assumed at the same temperature T), so the total energy per unit of volume is 3nT.

   τ_E = 'energy confinement time'.

2. **radiation** due to acceleration (deceleration) of electrons in the field of ions ('bremsstrahlung').

   $$\frac{P_b}{\text{volume}} = A \sum_{\text{species } j} Z_j^2 n_j n_e (T_e|_{\text{keV}})^{1/2} = A n_e (T_e|_{\text{keV}})^{1/2} \sum_j n_j Z_j^2, \qquad A \simeq 5 \times 10^{-37} \text{Wm}^3$$

   where $T_e|_{\text{keV}}$ is the numerical value of the temperature expressed in keV (the physical units of T_e are already included in A).

We can write $\sum_j n_j Z_j^2 = n_e Z_{\text{eff}}$ with $Z_{\text{eff}} = \frac{\sum_j n_j Z_j^2}{n_e}$ where Z_j = charge number

Therefore, we obtain that $\frac{P_b}{\text{volume}} \simeq A n_e^2 Z_{\text{eff}} T_e^{1/2}$

Note 2: as shown in Fig. 4, P_b is in the form of X-rays, which are not re-absorbed by the plasma since the plasma is transparent to these wavelengths. Also, the X-rays go through the metal walls and are therefore lost from the plasma region.

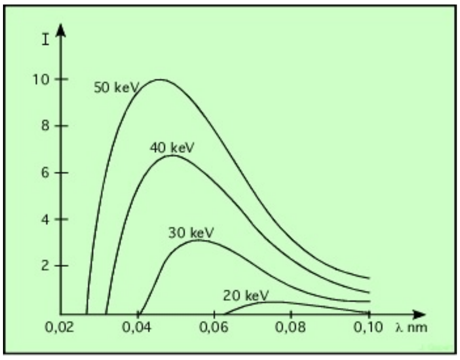

Figure 4: Emission spectrum for bremsstrahlung radiation for different plasma temperatures.

Note 3: as the emission spectrum depends on T_e, a measurement of it provides information on the electron temperature.

Note 4: Z_{eff} is the parameter that describes such emission. In pure D-T (only H-species) plasma $Z_{\text{eff}} = 1$.

The total lost power can therefore be written as:

$$\boxed{\frac{P_l}{\text{volume}} \simeq \frac{P_{dl}}{\text{volume}} + \frac{P_b}{\text{volume}} = \frac{3 n_e T_e}{\tau_E} + A n_e^2 Z_{\text{eff}} T_e^{1/2}}$$

Note 5: radiation due to acceleration around magnetic field lines, cyclotron emission, can be significant (P_{cycl}/volume $\simeq$ const $\times$ $\text{n}_\text{e}\text{T}_\text{e}\text{B}^2$). $P_{cycl} \propto n_e$ as it is not a binary collisional effect, and $f_{cycl} \propto B$ ($\omega = n\Omega_{ce}, n = 1, 2, \ldots$). P_{cycl} is very large, but it does not constitute a loss, as it is mostly reabsorbed by the plasma or it is reflected (at least most of it) by the conducting vessel walls. In fact, the small fraction that does come out is used as a diagnostic tool, to get information on n_e and T_e for example.

2.4.1 The Lawson criterion

The power losses per unit of volume are thus given by:

$$\frac{P_l}{\text{volume}} = \frac{3 n_e T}{\tau_E} + A n_e^2 Z_{\text{eff}} T^{1/2} \qquad (T_e = T_i = T)$$

The ratio between the fusion power and the input power is then:

$$\frac{P_f}{P_{in}} = \frac{P_f}{P_l - P_\alpha} \cong \frac{P_f}{\frac{3n_eT}{\tau_E} + An_e^2 Z_{\text{eff}} T^{1/2} - P_\alpha} = \frac{\frac{1}{4}n_e^2\langle\sigma v\rangle_{DT}\Delta E_f}{\frac{3n_eT}{\tau_E} + An_e^2 Z_{\text{eff}} T^{1/2} - \frac{1}{4}n_e^2\langle\sigma v\rangle_{DT}\Delta E_\alpha}$$

$\Delta E_\alpha = 3.5$ MeV is the energy associated with the α-particle issued by the fusion reaction. To achieve break-even or do better ($P_f/P_{in} \geq 1$):

$$n_e\tau_E(\langle\sigma v\rangle_{DT}\Delta E_f) \geq 12T + 4An_e\tau_E Z_{\text{eff}} T^{1/2} - n_e\tau_E(\langle\sigma v\rangle_{DT}\Delta E_\alpha)$$

or

$$n_e\tau_E(\langle\sigma v\rangle_{DT}(\Delta E_f + \Delta E_\alpha) - 4AZ_{\text{eff}} T^{1/2}) \geq 12T \quad \Rightarrow \quad n_e\tau_E \geq \frac{12T}{\frac{6}{5}\langle\sigma v\rangle_{DT}\Delta E_f - 4AZ_{\text{eff}} T^{1/2}}$$

considering

$$\Delta E_f + \Delta E_\alpha \cong \left(1 + \frac{1}{5}\right)\Delta E_f \cong \frac{6}{5}\Delta E_f$$

When can we neglect the bremsstrahlung term? This corresponds to verifying when the following relation is verified:

$$\frac{6}{5}\langle\sigma v\rangle_{DT}\Delta E_f \gg 4AZ_{\text{eff}} T^{1/2} \quad \xrightarrow{(Z_{eff}=1)} \quad \frac{6}{5}\langle\sigma v\rangle_{DT}\Delta E_f \gg 4AT^{1/2}$$

where we have assumed $Z_{\text{eff}} = 1$ for simplicity. The approximate form of $\langle\sigma v\rangle_{DT}$ in the range 10-20 keV is $\langle\sigma v\rangle_{DT} \simeq 1.1 \times 10^{-24}(T|_{\text{keV}})^2 \text{m}^3/\text{s}$. This gives:

$$\frac{6}{5}1.1 \times 10^{-24} T|_{\text{keV}}^2 \text{m}^3/\text{s} \times 17.6 \times 10^6 \times 1.6 \times 10^{-19}\text{J} \gg 4 \times 5 \times 10^{-37} T|_{\text{keV}}^{1/2}\text{Wm}^3$$

$$T|_{\text{keV}}^{3/2} \gg 0.5 \quad \Rightarrow \quad T|_{\text{keV}} \gg 0.5^{2/3} \simeq 0.7$$

So for $T \gg 1$ keV we can neglect the bremsstrahlung contribution.(For Z not much larger than 1)

Note 6: we consider here the steady-state power balance. Otherwise, we would need to include, as an effective 'loss' (or utilization of input power) the variation of the plasma energy $\frac{\text{d}}{\text{dt}}(3\text{nT})$.

Coming back to the steady-state break-even (or better) condition, assuming $\frac{P_l}{\text{volume}} \simeq \frac{3n_eT}{\tau_E}$, we have:

$$n_e\tau_E\left\{\frac{6/5\langle\sigma v\rangle_{DT}\Delta E_f}{12T}\right\} = n_e\tau_E\left\{\frac{\langle\sigma v\rangle_{DT}\Delta E_f}{10T}\right\} \geq 1$$

We can indicate $\frac{\langle\sigma v\rangle_{DT}\Delta E_f}{10T} = \text{f(T)}$ and thus

$$\boxed{n_e\tau_e \geq \frac{1}{\text{f(T)}}} \qquad \text{(Lawson Criterion)}$$

This is expressed in graphical form in Fig. 5.

Typically, we need $\left\{\begin{array}{rcl} n_e\tau_E & \geq & 10^{20}\text{m}^{-3}\text{s} \\ T & \geq & 10 \text{ keV} \end{array}\right.$

Two approaches (will be discussed later):

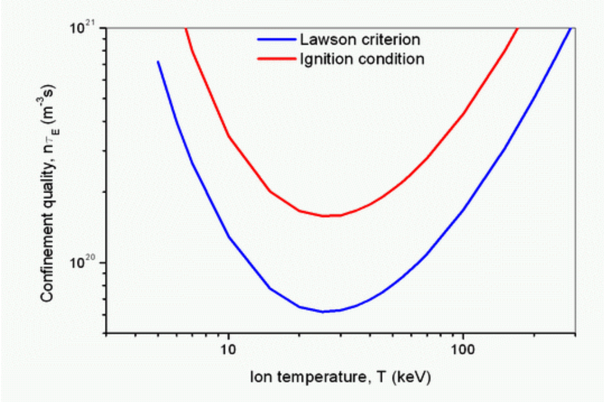

Figure 5: The conditions for break-even (Lawson Criterion) and ignition in a D-T plasma.

- large n_e ($\sim 10^{31}\mathrm{m}^{-3}$) , small τ_E ($\sim 10^{-11}$s): 'inertial' confinement
- small n_e ($\sim 10^{20}\mathrm{m}^{-3}$), large τ_E ($\sim$ 1s): 'magnetic' confinement

Beyond break-even: Naturally, in reality the break-even condition is not at all sufficient to make a reactor. We must have $\frac{P_f}{P_{in}} \gg 1$, for two reasons:

- In D-T reactions, the neutron energy escapes the plasma (and is used to produce heat, then electricity), while the α energy can (and should) remain in the plasma.
- The conversion efficiency of the fusion power into electricity, and of electricity into plasma heating power are significantly less than 100%

2.4.2 Ignition and burning plasma regime

If we do not want to rely on external power to maintain fusion reactivity ($P_{in} = 0$), we have to consider an equilibrium between the α-particle power and the losses.

$$\frac{P_\alpha}{P_l} \geq 1 \Rightarrow \frac{1}{4}n_e^2\langle\sigma v\rangle_{DT}\Delta E_\alpha \geq \frac{3n_eT}{\tau_E}$$

Analogously to the break-even condition, this can be written as

$$n_e\tau_E \geq \frac{12T}{\langle\sigma v\rangle_{DT}\Delta E_\alpha}, \quad \text{or} \quad n_e\tau_E \geq \frac{6}{f(T)}, \quad \text{or} \quad n_e\tau_E T \geq \frac{6T}{f(T)}$$

Graphically (see also Figure 5):

Note 1: if we consider bremsstrahlung radiation as an irreducible (the only one!) energy loss, we must have for ignition that $P_\alpha \geq P_b$:

$$\frac{P_\alpha}{P_b} = \frac{1/4\langle\sigma v\rangle_{DT}E_\alpha n^2}{An^2 Z_{\mathrm{eff}}(T_e|_{\mathrm{keV}})^{1/2}} \geq 1$$

Using the values of $\langle\sigma v\rangle_{DT}$, this gives $T \geq 4.4\ keV$. This is known as the '*ideal ignition temperature*'.

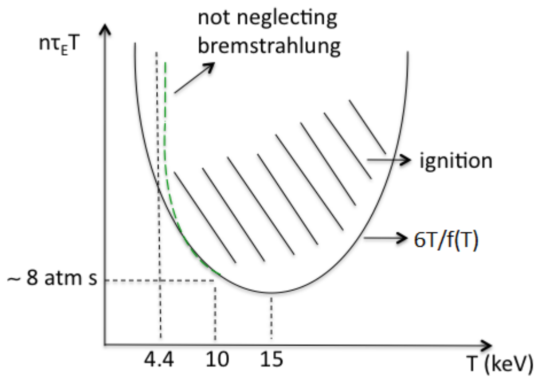

Figure 6: Ignition condition in terms of the fusion triple-product.

Looking at Fig. 6, we can identify the minimum (or easiest) ignition conditions:

$$\begin{cases} T_{\text{min}} & \simeq & 15 \text{ keV} \\ (n\tau_E T) & \simeq & 8 \text{ atm s} \end{cases} \qquad \text{(nT is plasma pressure)}$$

In practice, a reactor can (and, most likely, will) operate above break-even but below ignition, so that its 'burn' can be controlled and the conditions to be reached are not as tough as for ignition. This intermediate situation is described by the fusion gain factor, Q.

2.4.3 Physics fusion gain factor Q

$$Q \equiv \frac{P_{\text{fusion out}} - P_{in}}{P_{in}}$$

$P_{\text{fusion out}}$ = fusion power that comes out from a reactor. P_{in} = external heating power. The difference $P_{\text{fusion out}} - P_{in}$ corresponds to the net power coming out from the tokamak.

Steady-state: $P_{\text{fusion out}} = P_{\text{neutrons}} + P_{\text{losses}} = P_{\text{neutrons}} + P_{\text{heating}}$

$$= P_{\text{neutrons}} + P_\alpha + P_{\text{in}}$$

$$= P_f + P_{\text{in}}$$

$$\Rightarrow Q = \frac{P_{\text{fusion out}} - P_{\text{in}}}{P_{\text{in}}} = \frac{P_f + P_{\text{in}} - P_{\text{in}}}{P_{\text{in}}} = \frac{P_f}{P_{\text{in}}}$$

Here $P_{heating}$ is the effective power that can be used to heat the plasma, namely the injected power P_{in} and the α particle power P_α.

Note 2: Ignition: $Q \to \infty$; Break-even: Q = 1

This can be written as $Q = 5\frac{nT\tau_E}{(nT\tau_E)_{\text{ignition}} - nT\tau_E}$ (not demonstrated here) and plotted as a function of $n\tau_E T$

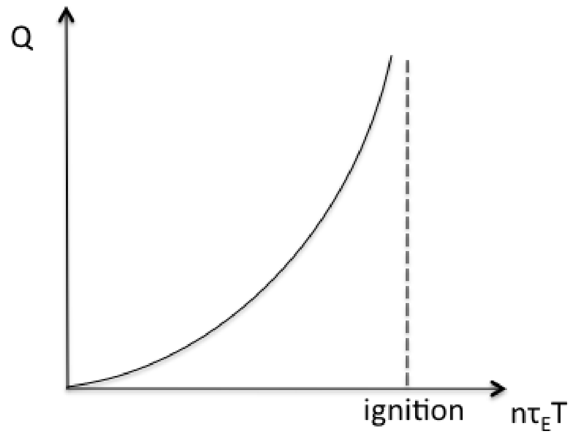

Figure 7: Qualitative behaviour of plasma fusion gain factor as a function of the fusion triple-product.

Note 3: Fraction of α-particle heating $f_\alpha = \frac{P_\alpha}{P_{\text{heating}}} = \frac{P_\alpha}{P_\alpha + P_{\text{in}}}$

$f_\alpha \cong \frac{Q}{Q+5}$; $f_\alpha \geq \frac{1}{2} \Leftrightarrow Q \geq 5$ (burning plasma)

$(Q = \frac{P_f}{P_{\text{in}}} \cong \frac{5P_\alpha}{P_{\text{heating}} - P_\alpha} = \frac{5}{\frac{1}{f\alpha} - 1} = \frac{5f_\alpha}{1-f_\alpha} \Rightarrow (1 - f_\alpha)Q = 5f_\alpha \Rightarrow f_\alpha(5 + Q) = Q)$

2.4.4 Finite conversion efficiency

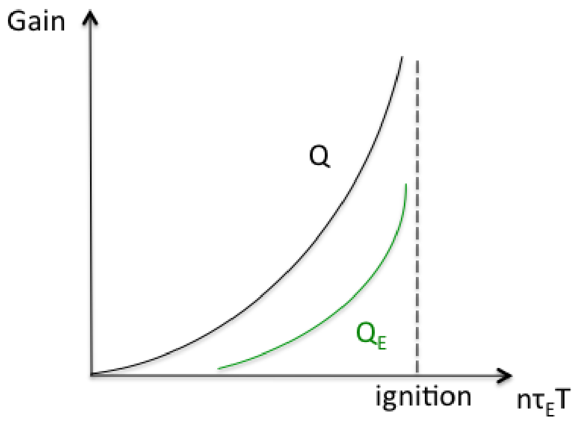

Figure 8: Qualitative behaviour of plasma fusion gain factor and engineering gain factor for increasing values of fusion triple-product.

Engineering gain factor $Q_E = \frac{\text{net electric power out}}{\text{net electric power in}} = \frac{P^{(E)}_{\text{out}} - P^{(E)}_{\text{in}}}{P^{(E)}_{\text{in}}}$

Typically, $P^{(E)}_{\text{in}} = \frac{P_{\text{in}}}{\eta_e}$, as $P_{\text{in}} = P^{(E)}_{\text{in}} \times \eta_e$, where η_e = efficiency of power source (ex.

generator of microwaves); a reasonable number is $\eta_e \sim 70\%$.

The power out is converted into electricity at a finite efficiency, η_t (a reasonable number is $\eta_t \sim 40\%$).

$\Rightarrow P_{\text{out}}^{(E)} = \eta_t[P_f + P_{\text{in}}]$

Note: We neglect the power not absorbed by the plasma (included in η_e) and rejected.

$\Rightarrow \mathrm{Q}_E = \frac{\eta_t(P_f+P_{\text{in}})-P_{\text{in}}/\eta_e}{P_{\text{in}}/\eta_e} = \frac{\eta_e\eta_t(P_f+P_{\text{in}})-P_{\text{in}}}{P_{\text{in}}}$

Define $\eta = \eta_e\eta_t$

$\Rightarrow \mathrm{Q}_E = \frac{\eta[P_f+P_{in}]-P_{\text{in}}}{P_{\text{in}}} = \eta\frac{P_f}{P_{\text{in}}} - (1-\eta) = \eta\mathrm{Q} - (1-\eta)$

Ex.: $\eta_e \simeq 70\%$; $\eta_t \simeq 40\% \Rightarrow \eta \simeq 28\%$ and $\mathrm{Q}_E \simeq 0.28\mathrm{Q} - 0.72$

$\mathrm{Q}_E = 10 \Leftrightarrow \mathrm{Q} \cong 40$; $\mathrm{Q}_E = 2 \Leftrightarrow \mathrm{Q} \simeq 10$

Nuclear Fusion and Plasma Physics

Lecture 1

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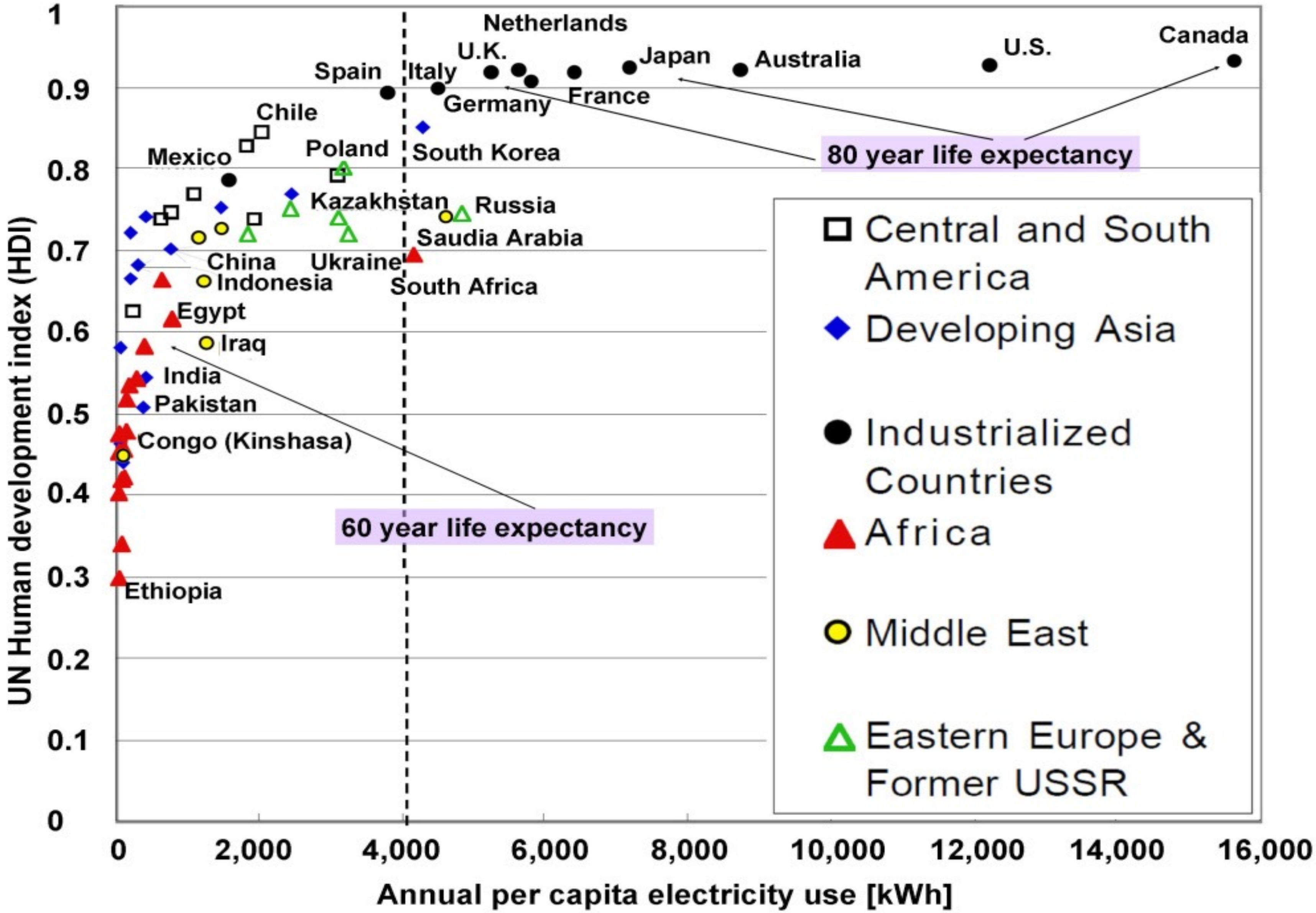
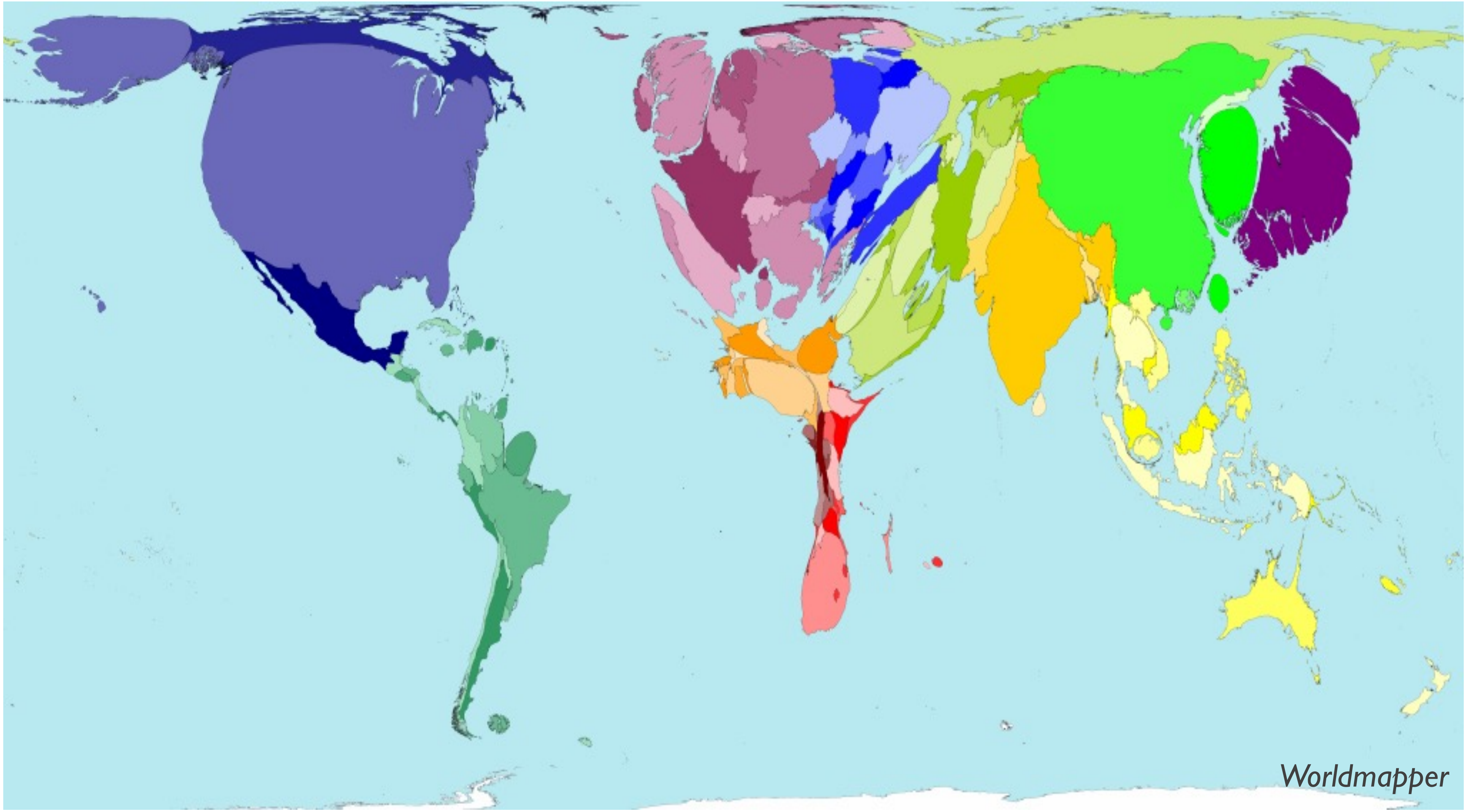
Swiss Plasma Center

Energy and human development

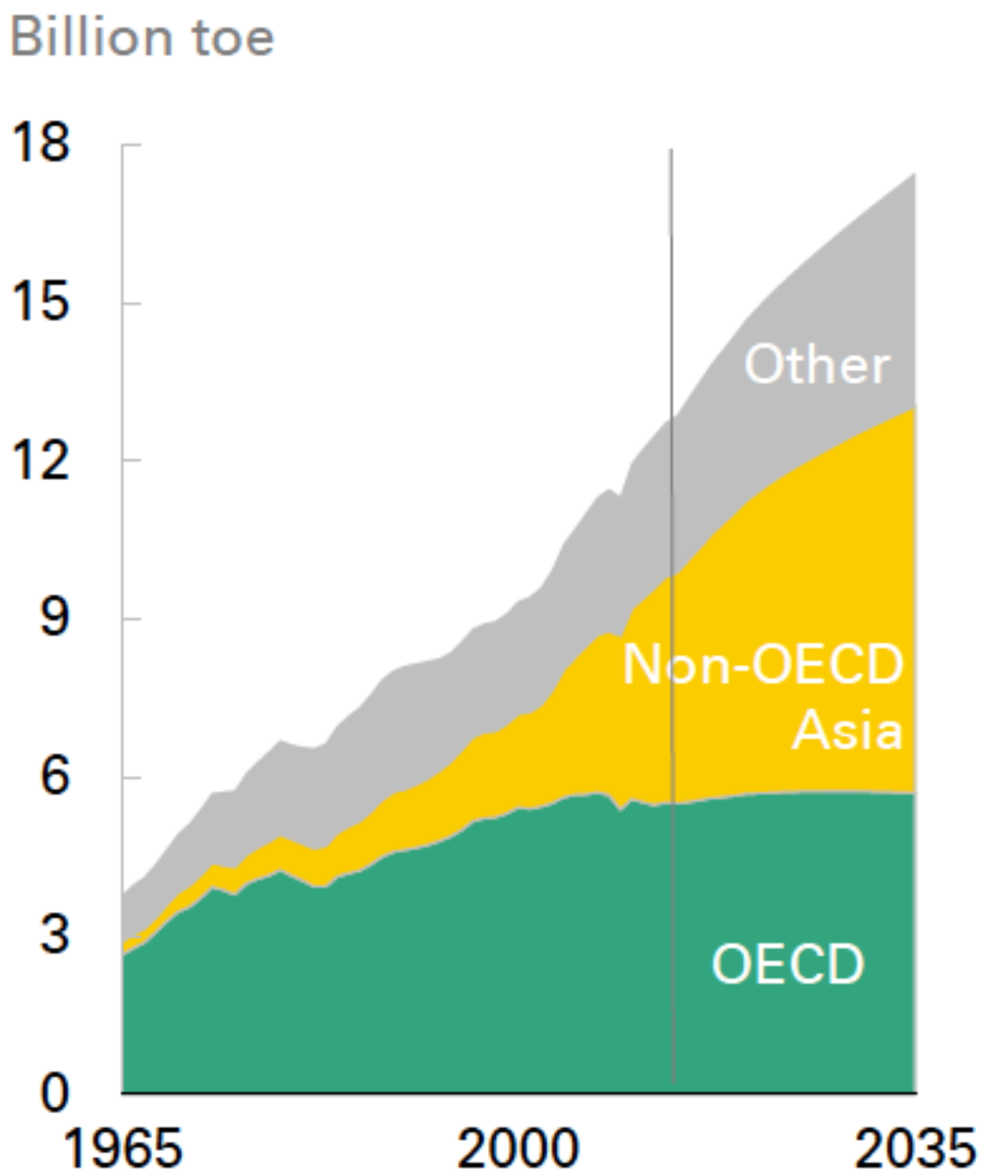


PASTERNAK, A., US Department of Energy Report UCRL-ID- 140773, LLNL , Livermore, CA (2000) 38.

Present unequal distribution of energy consumption



Evolution of distribution of energy consumption



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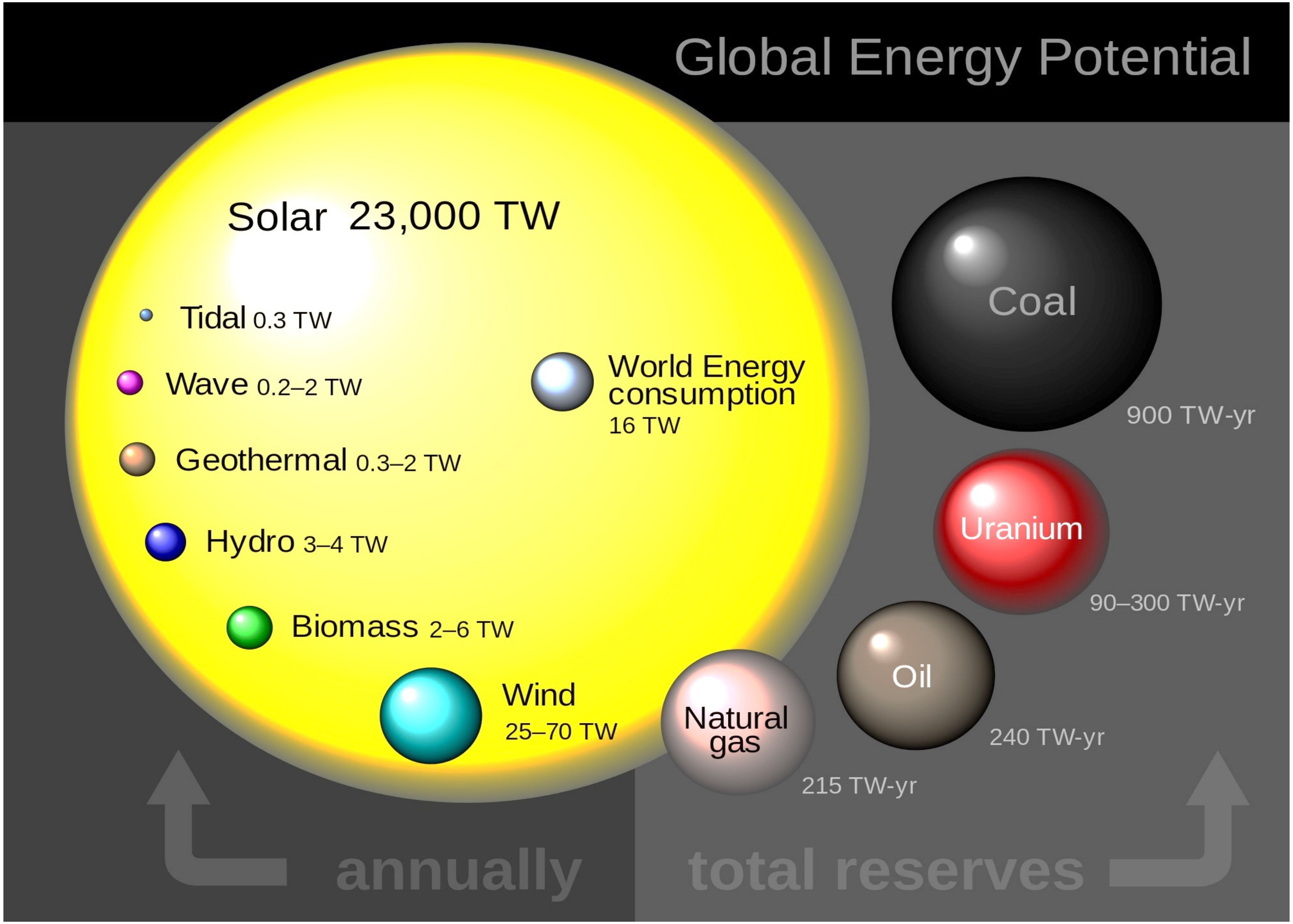
SUSTAINABLE DEVELOPMENT GOALS

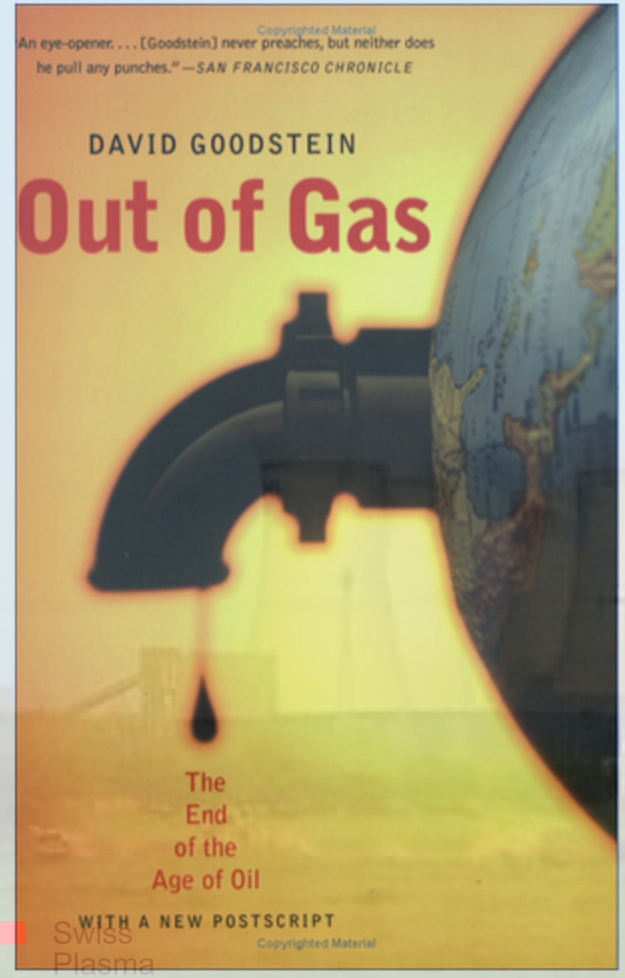
Discussion of today's energy options
Global view of energy fluxes

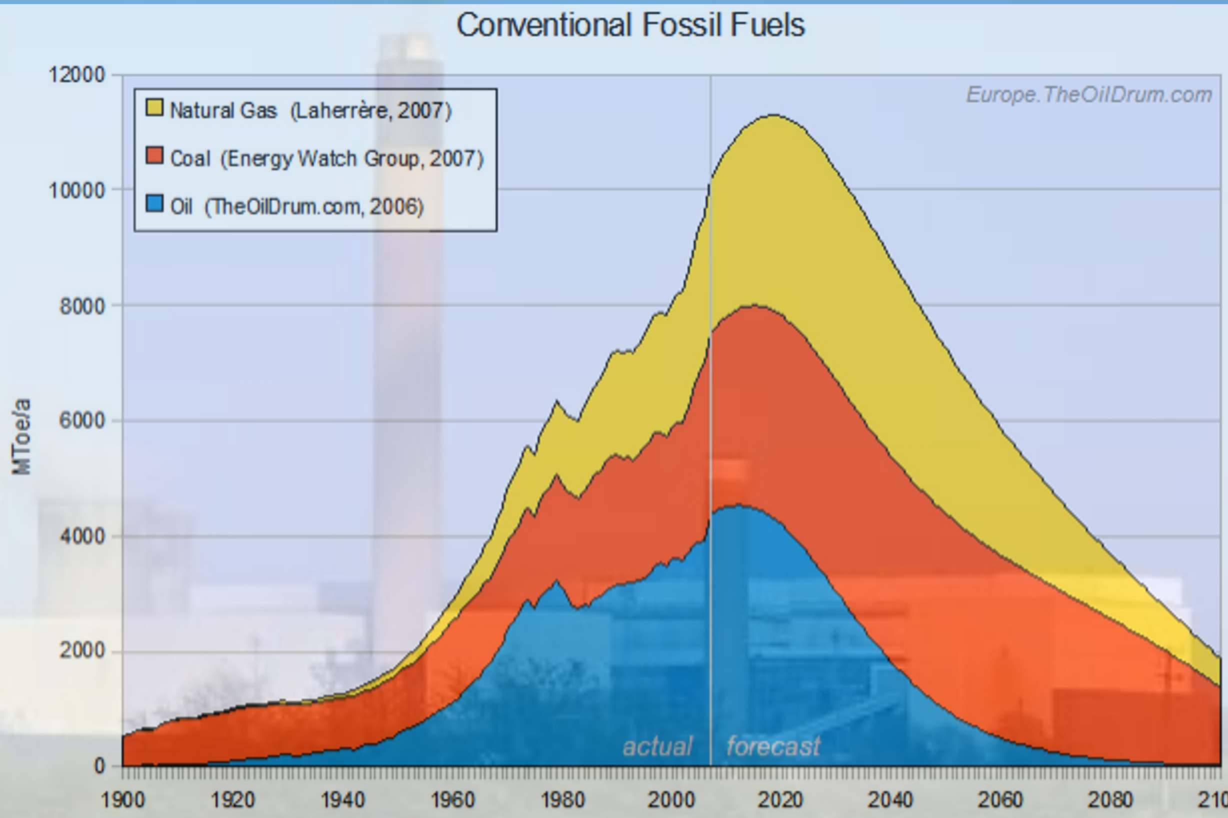


Perez et al., 2009, "A Fundamental Look At Energy Reserves For The Planet"

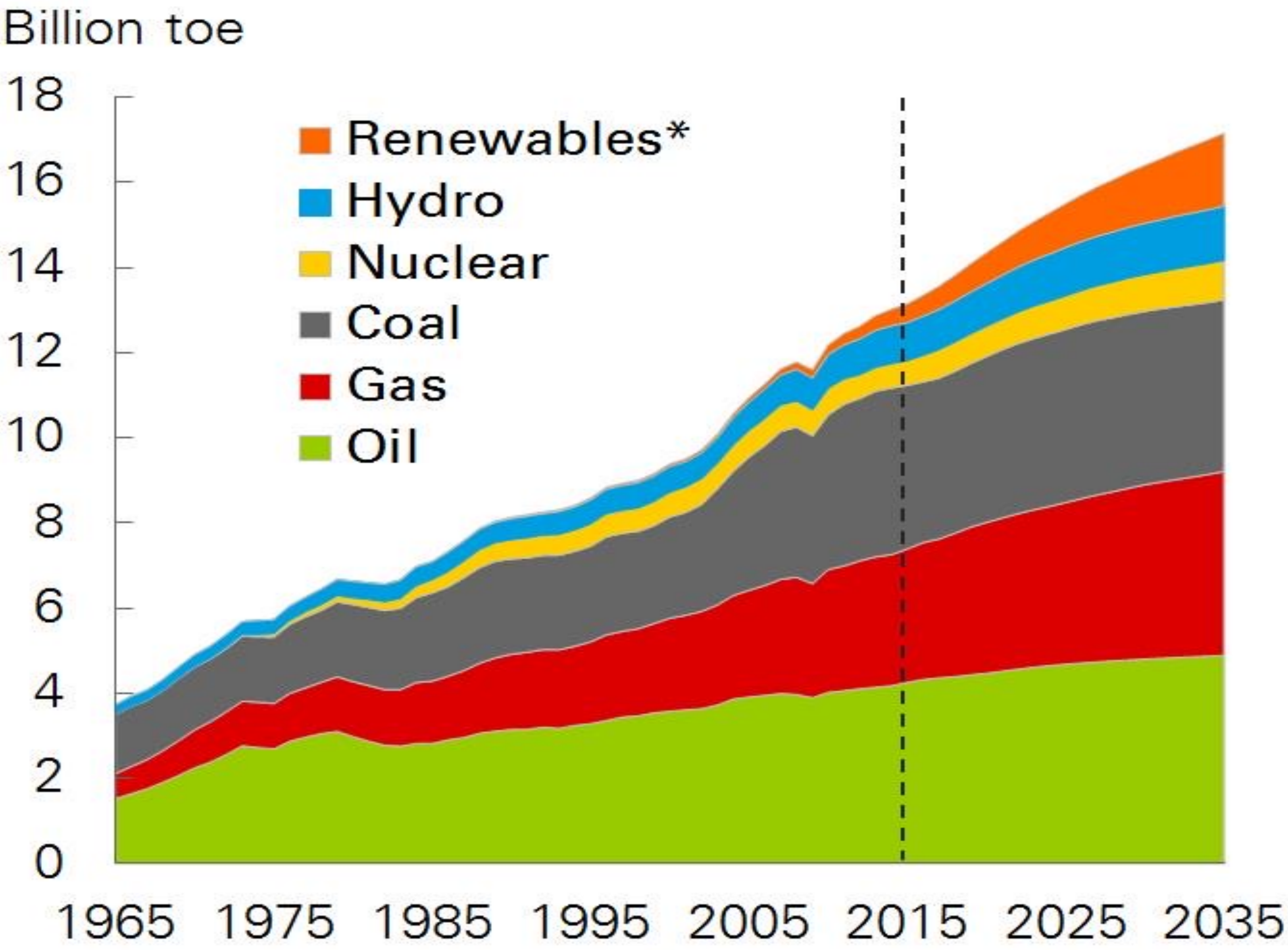
Reliance on fossil fuels

Fossil Fuels have been produced from decayed plant and animal matter over millions of years, cannot be re-formed in time





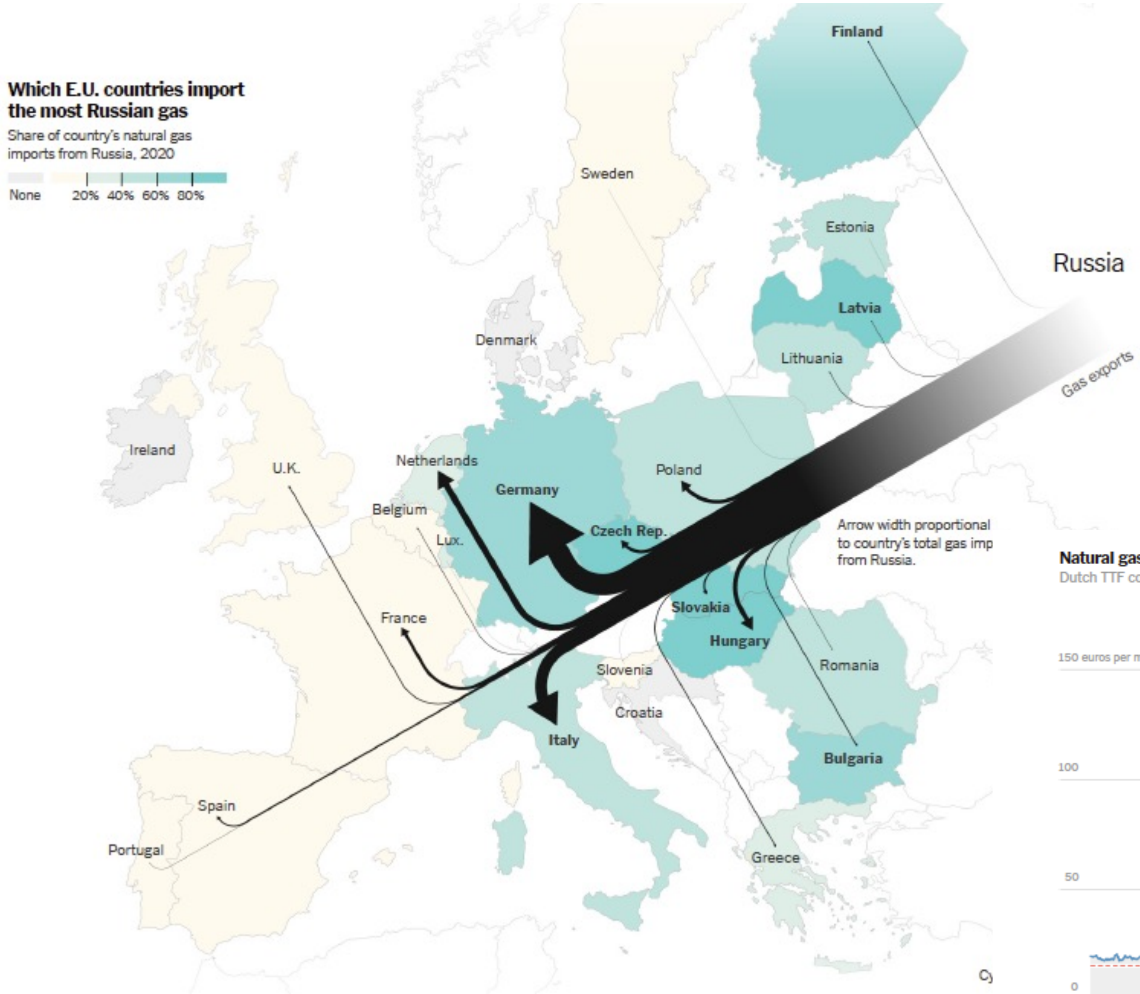
Primary energy consumption by fuel

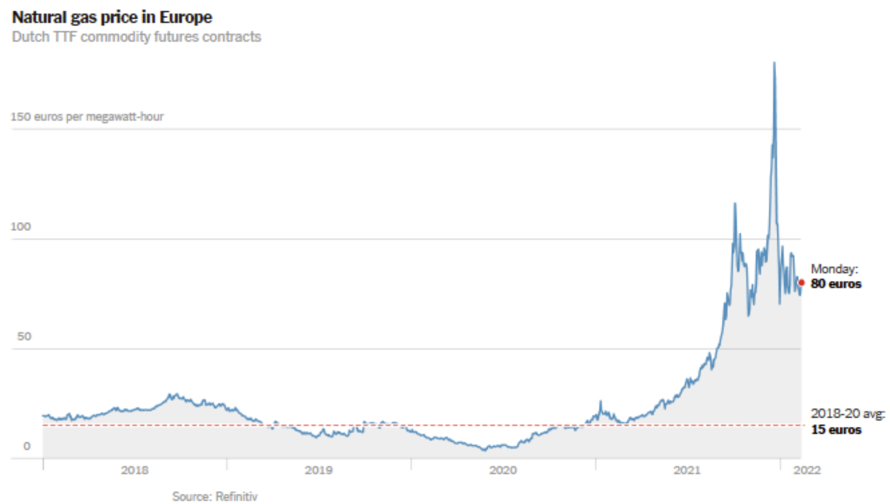


*Renewables includes wind, solar, geothermal, biomass, and biofuels

Urgency of alternates development

Geopolitical issues





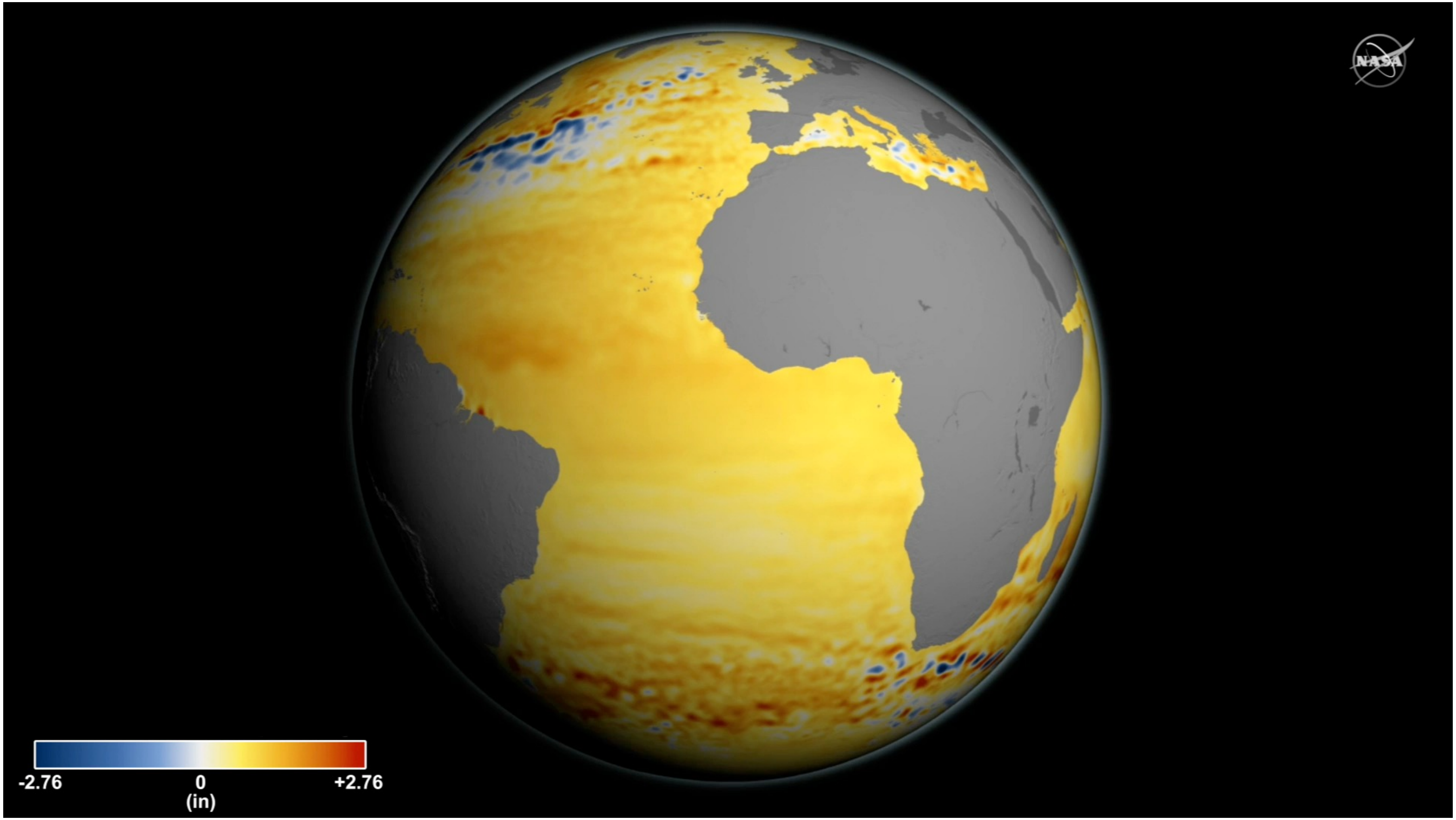
The New York Times

ENERGY & ENVIRONMENT | How a Ukraine Conflict Could Reshape Europe's Reliance on Russia

Urgency of alternates development

Environmental impact (CO_2 and global warming)

The effects of climate change

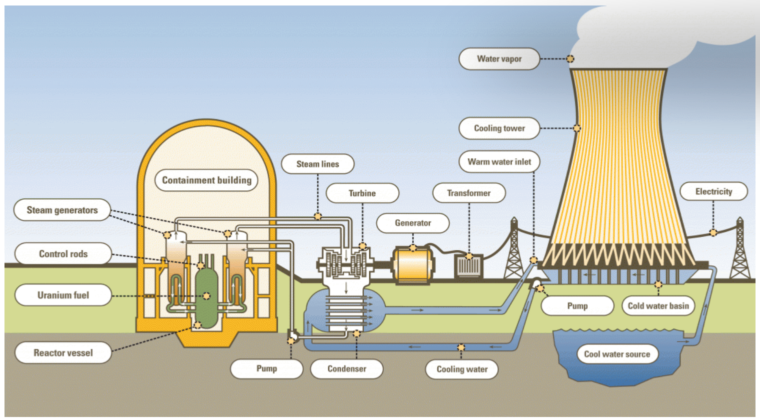


Discussion of today’s energy options

Fossil
- Coal
- Natural gas
- Oil

Renewables
- Hydro-electric
- Wind
- Solar

Nuclear fission



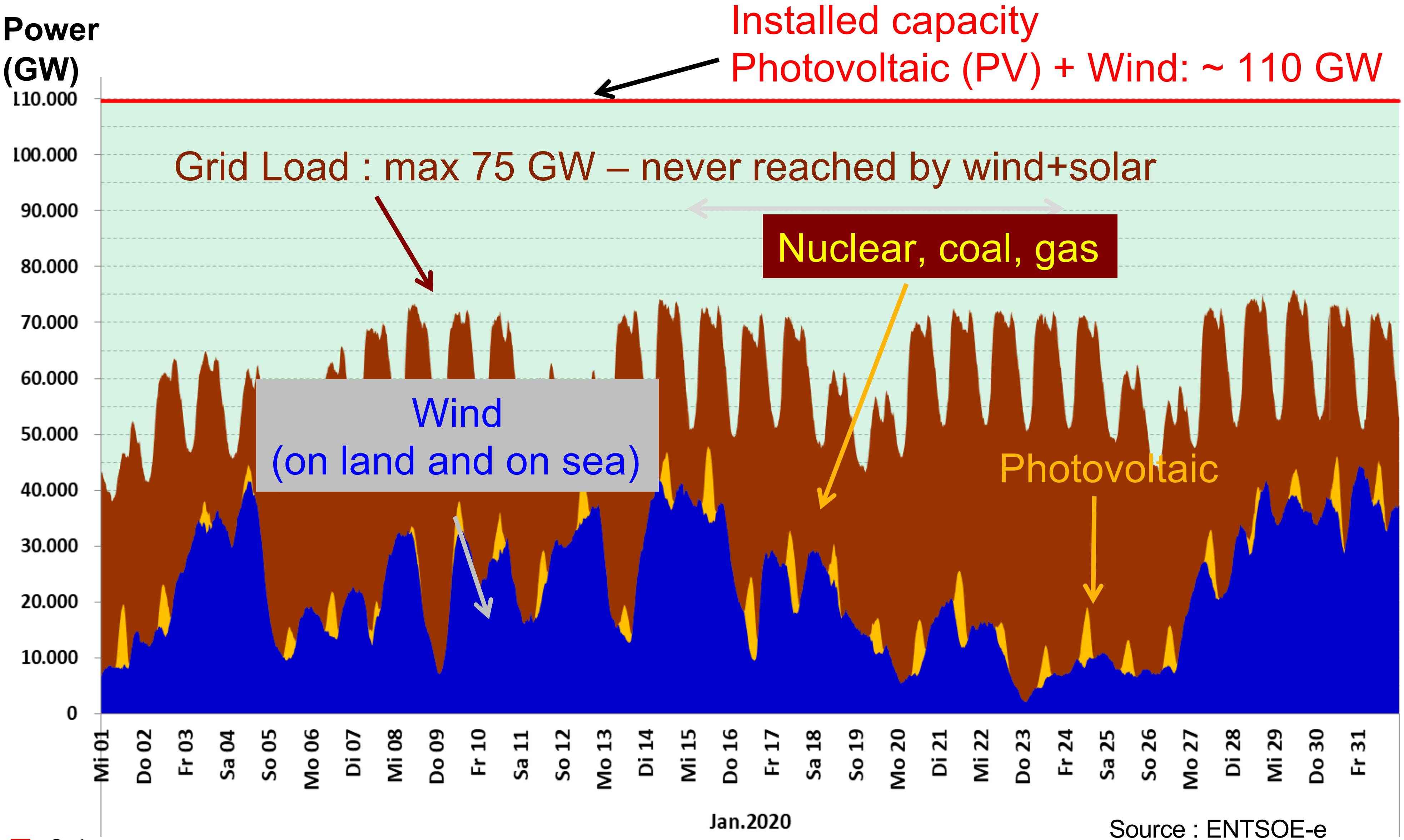
Discussion of today's energy options

Why not only renewables ?

Renewables
- Hydro-electric
- Wind
- Solar

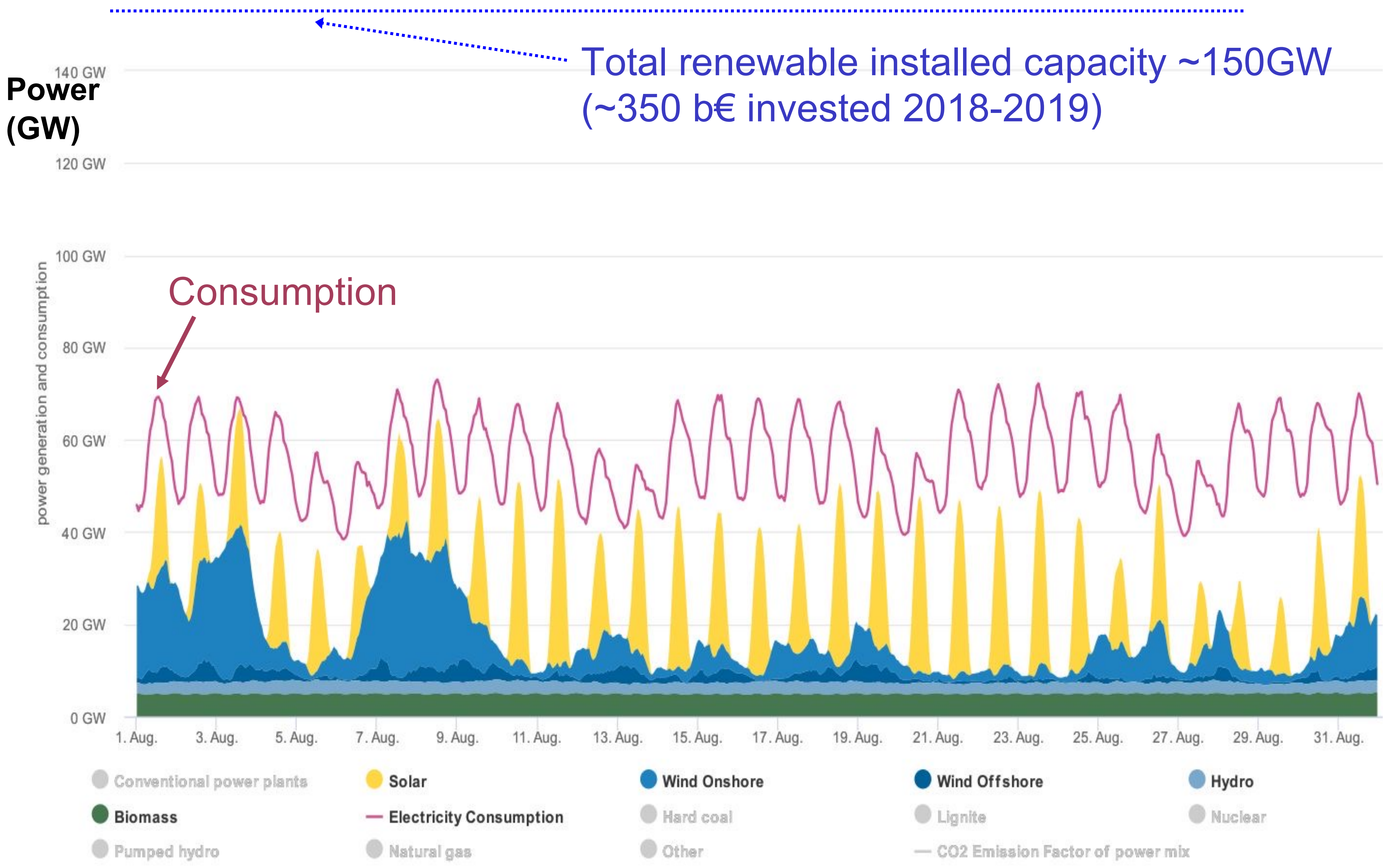
The example of Germany

Electricity production in January 2020



Source : ENTSOE-e

The example of Germany - August '23



Agora Energiewende; C

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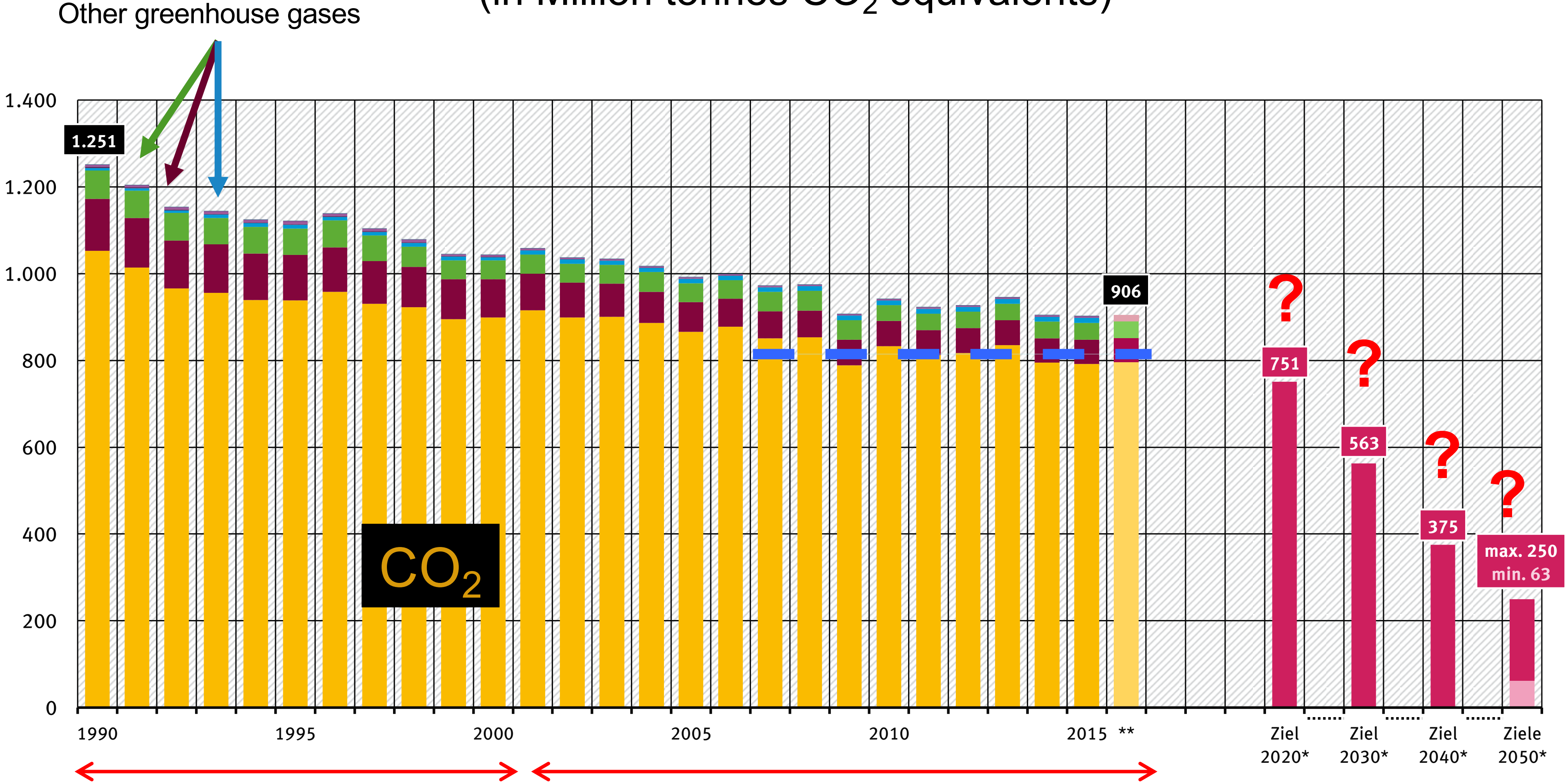
The example of Germany

Evolution Total GHG emissions in Germany since 1990

(in Million tonnes CO_2 equivalents)



20% reduction due to end of DDR

(source : Umweltbundesamt 2017)

Energiewende up to now
Essentially constant CO_2 over last ~10 years

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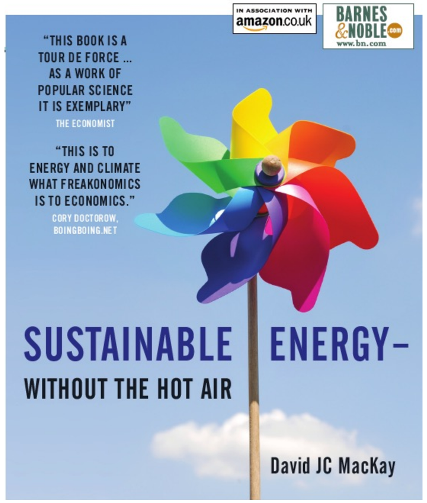
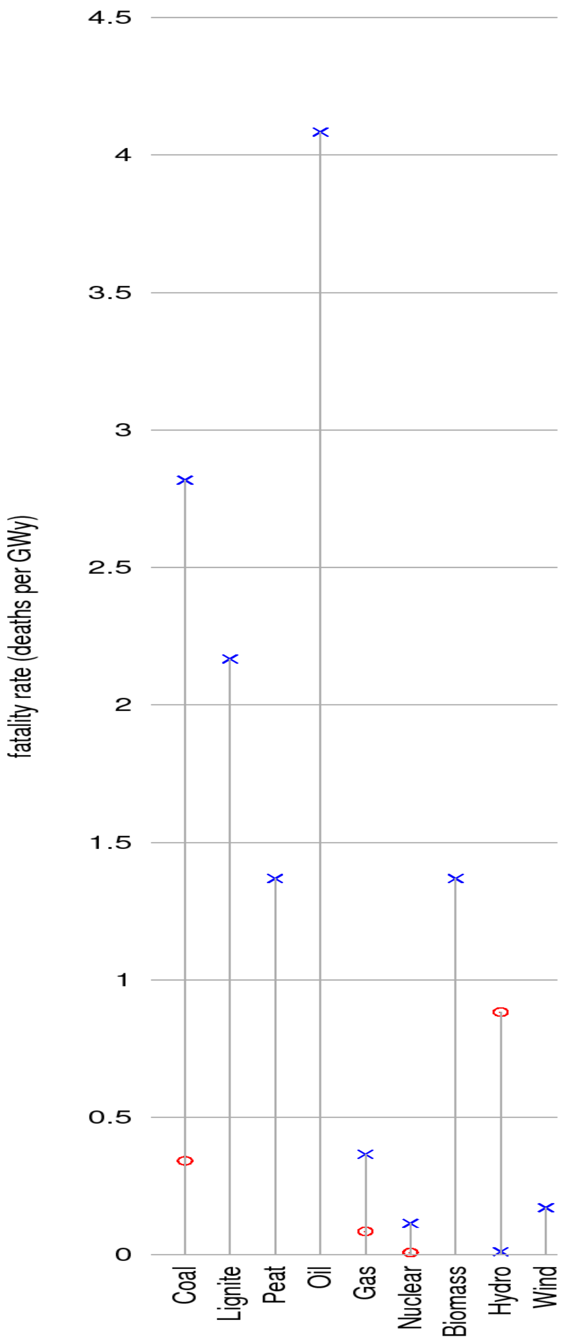
Discussion of today's energy options

A politically incorrect view

Human deaths per energy





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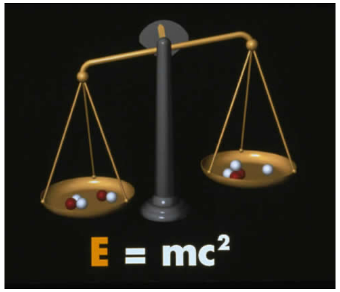
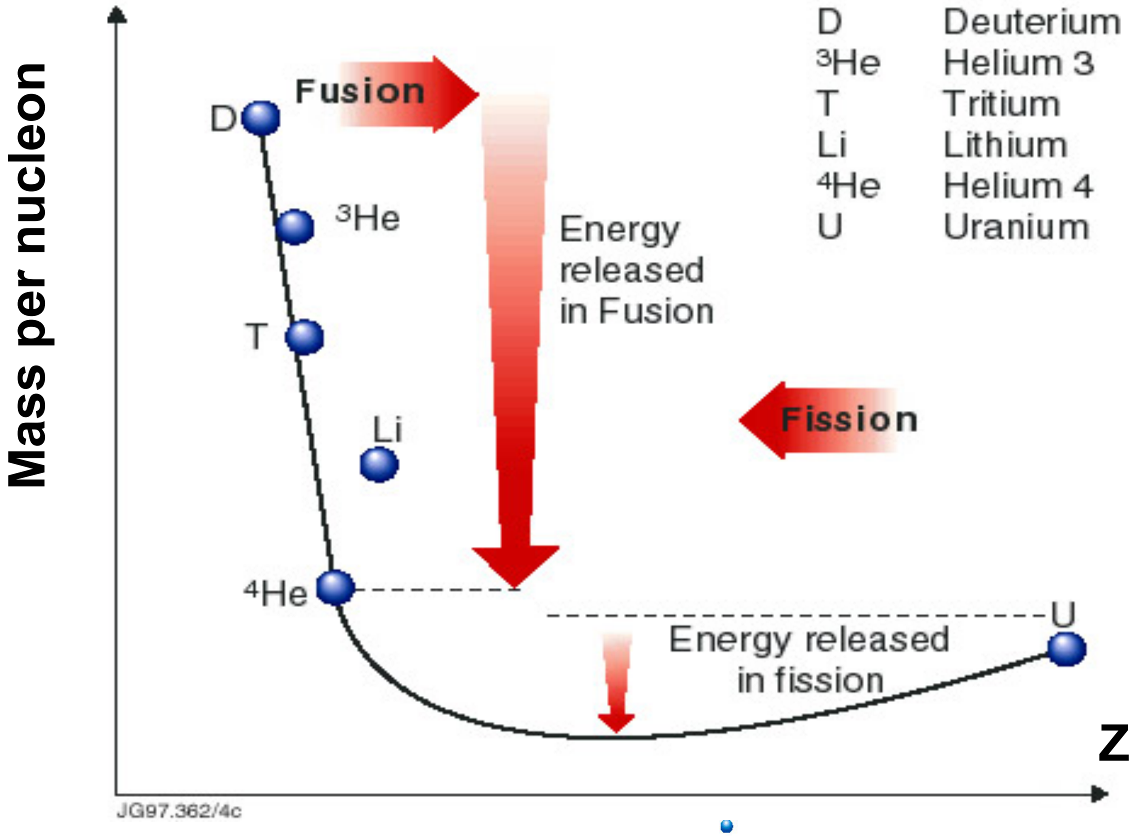
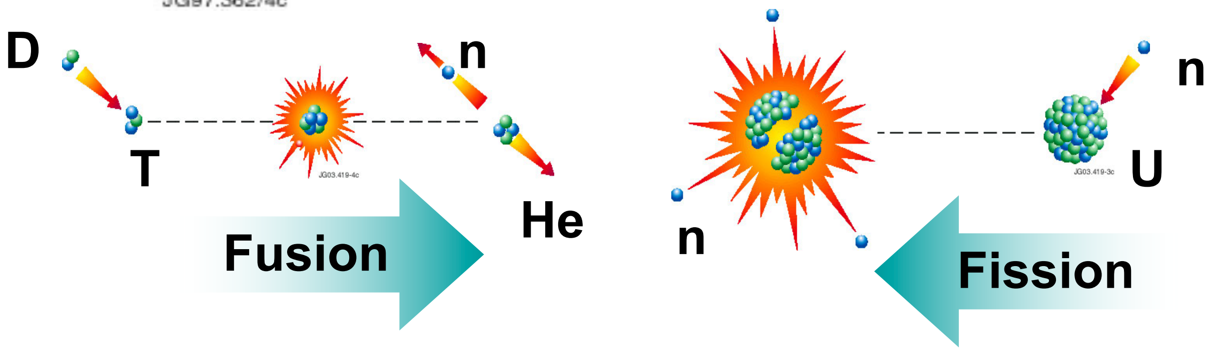
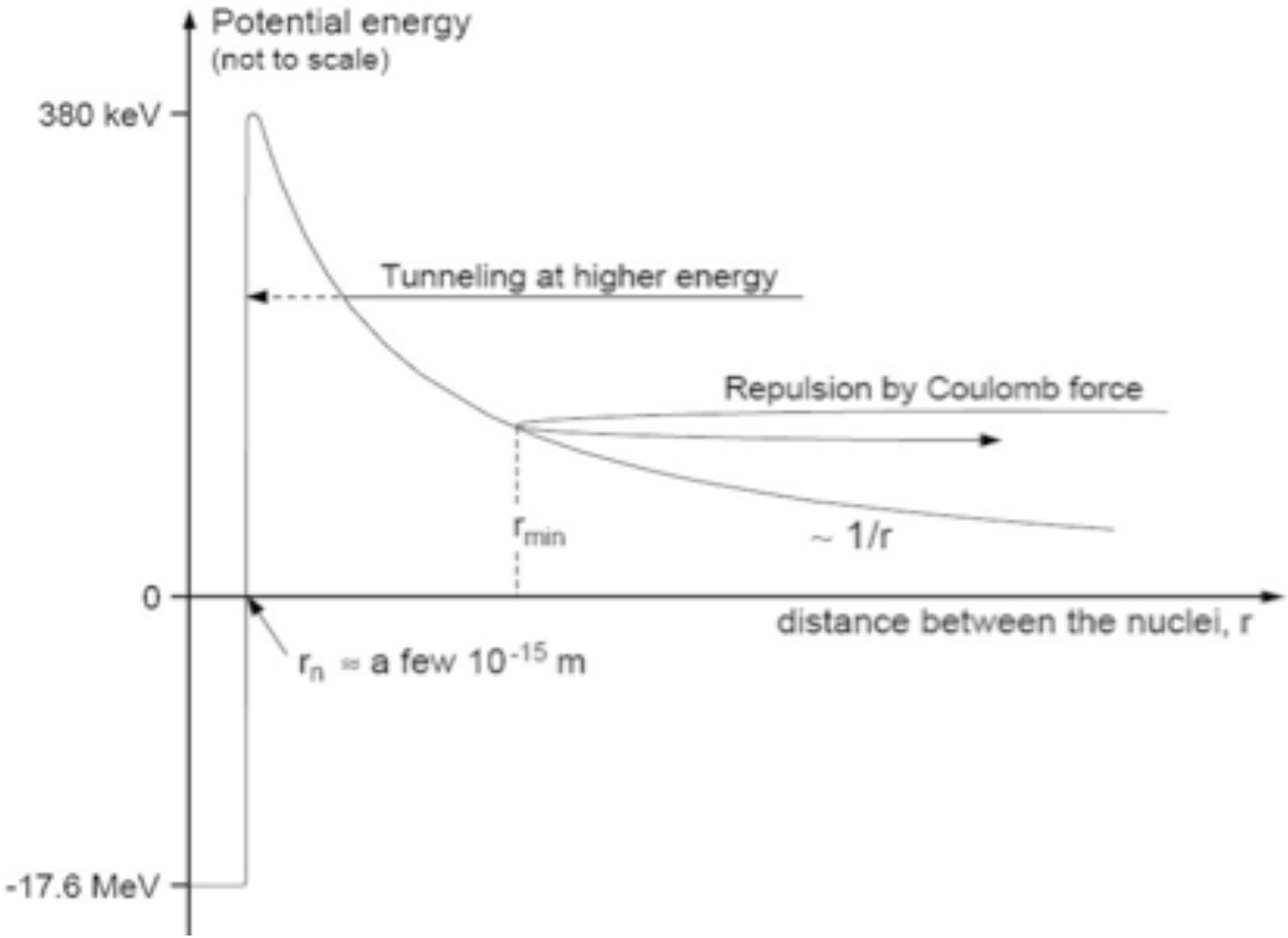
A solution in the nucleus ? Fusion vs. fission







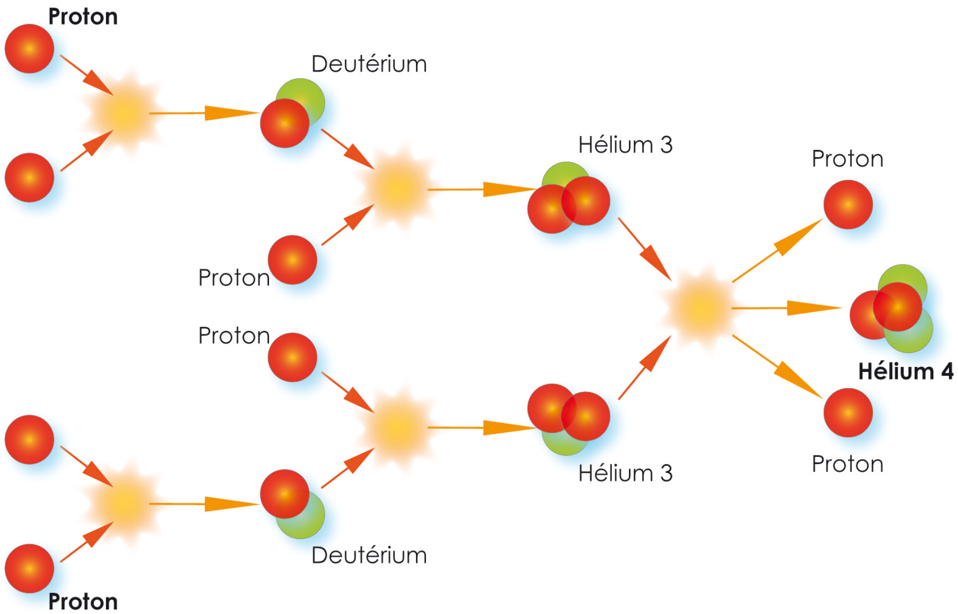
Large energies are required for fusion

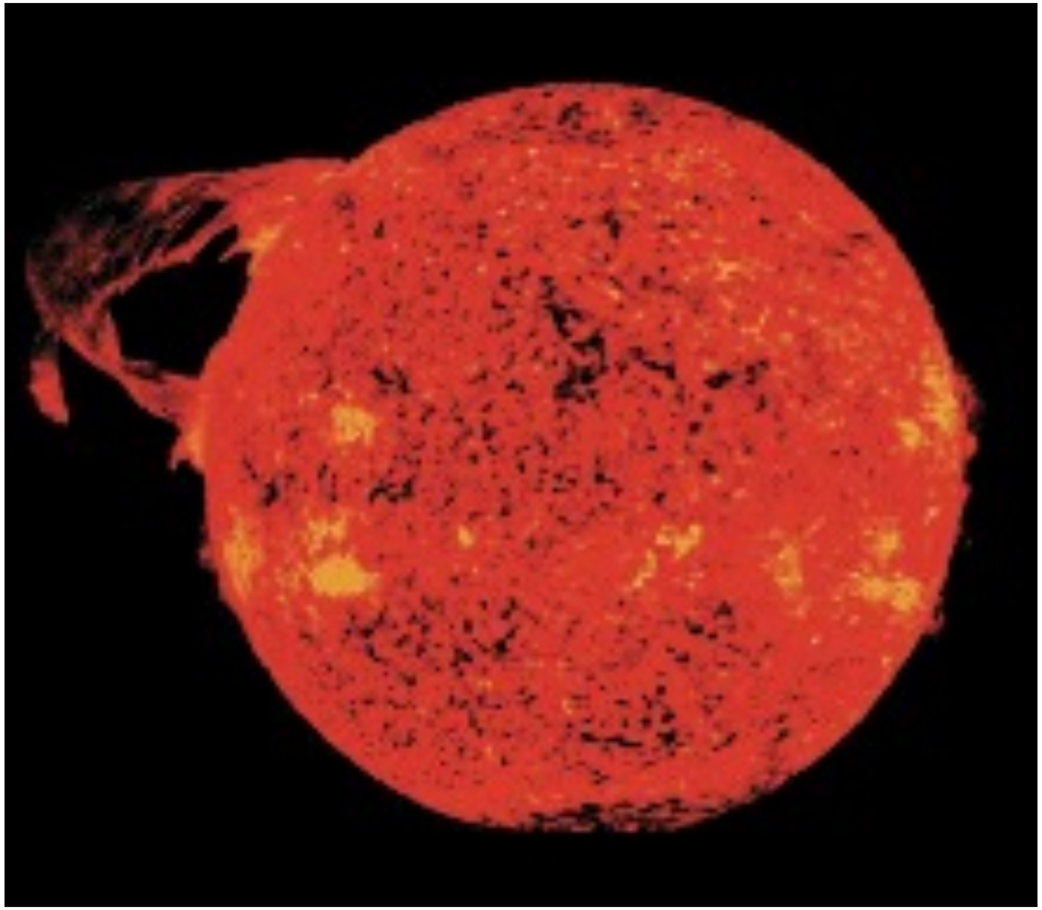


At such large energies matter is in the form of **plasma**

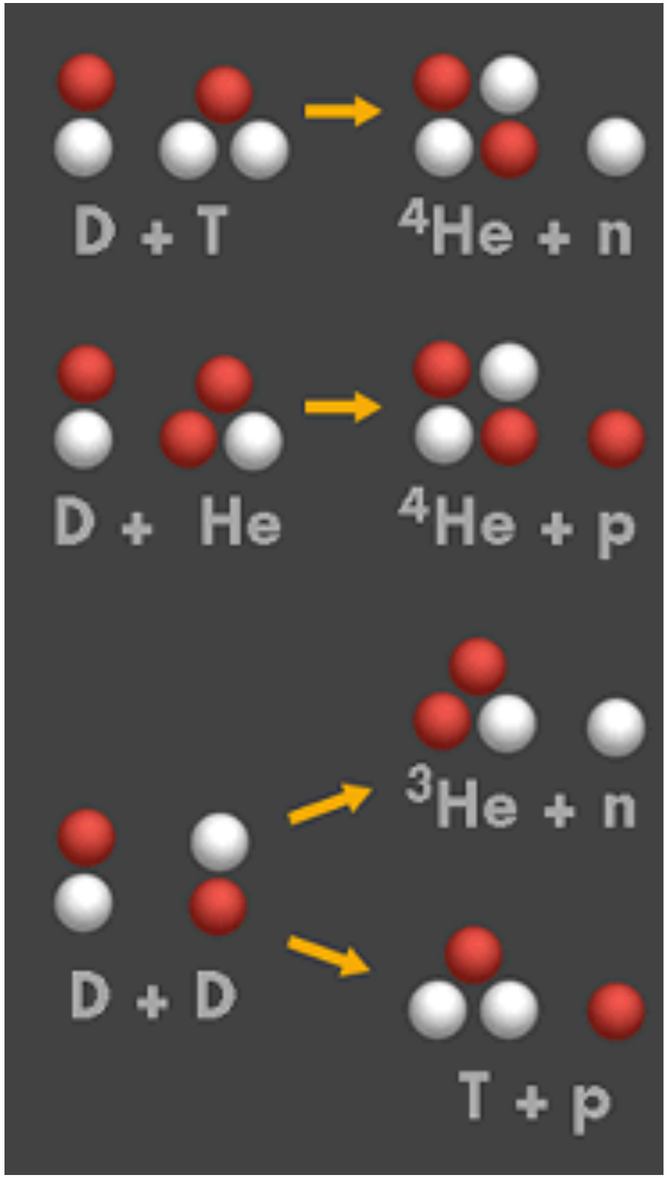
Examples of plasmas

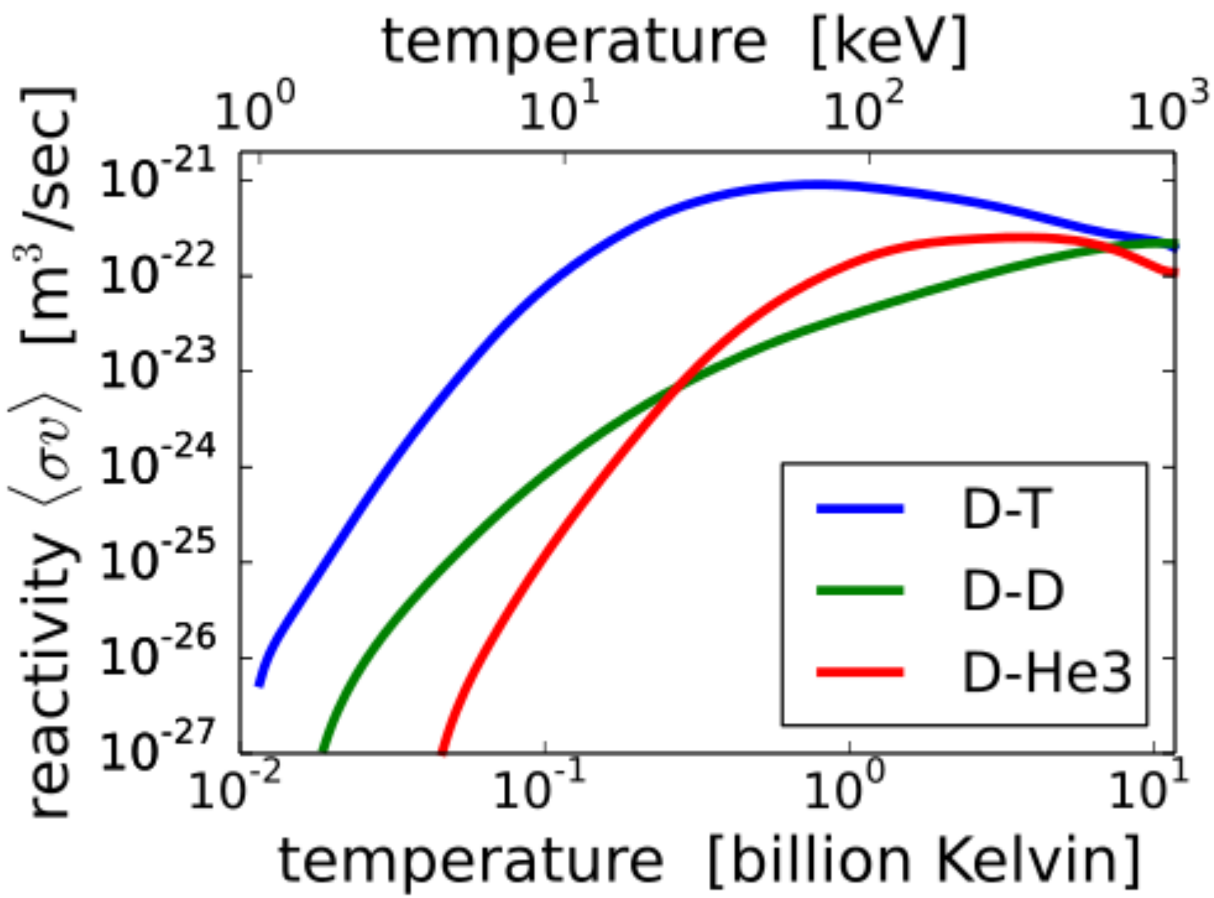
Fusion powers the sun and all the stars



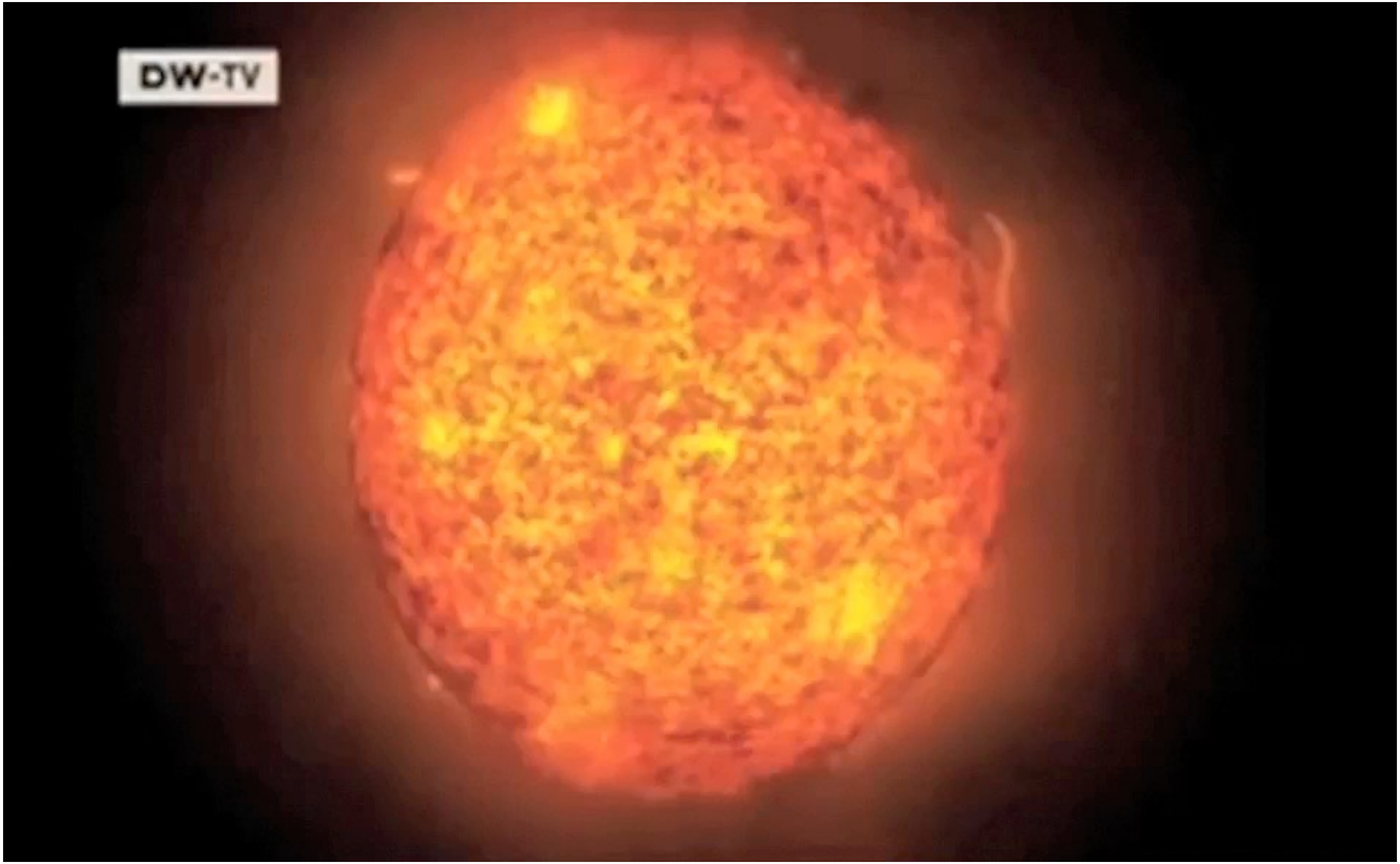


Fusion reactions and cross-sections

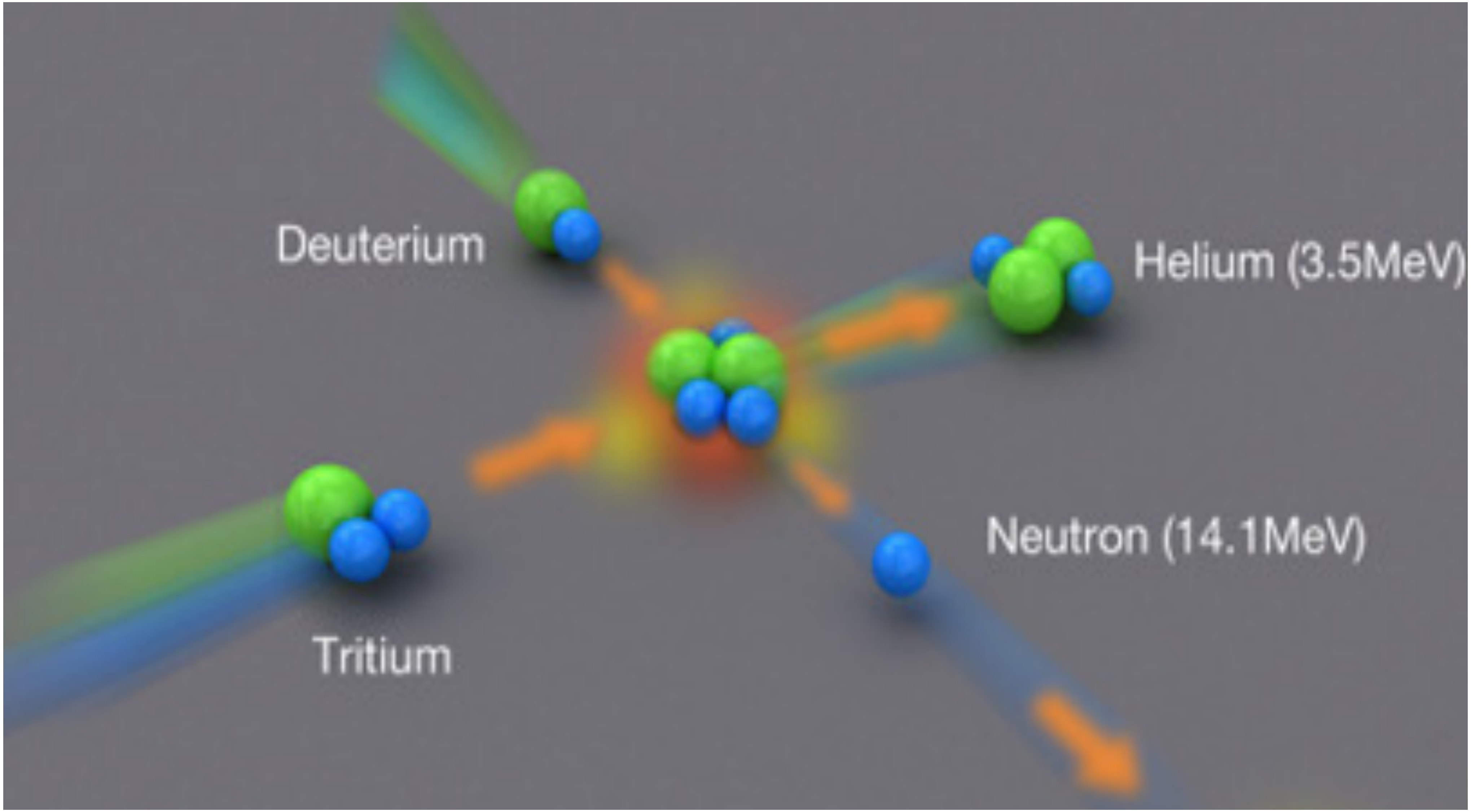




The fusion challenge



The D-T reaction



Sources of fuel for D-T reaction

D is 1/6700 of hydrogenic atoms in oceans, i.e. 1.6g/l

T does not exist in nature, as is radioactive and short-lived (12.5y)

But can be produced from Lithium

$n_0^1 + Li_3^6 \rightarrow T_1^3 + He_2^4 + 4.8MeV$

(Li_3^6 is ~7%)

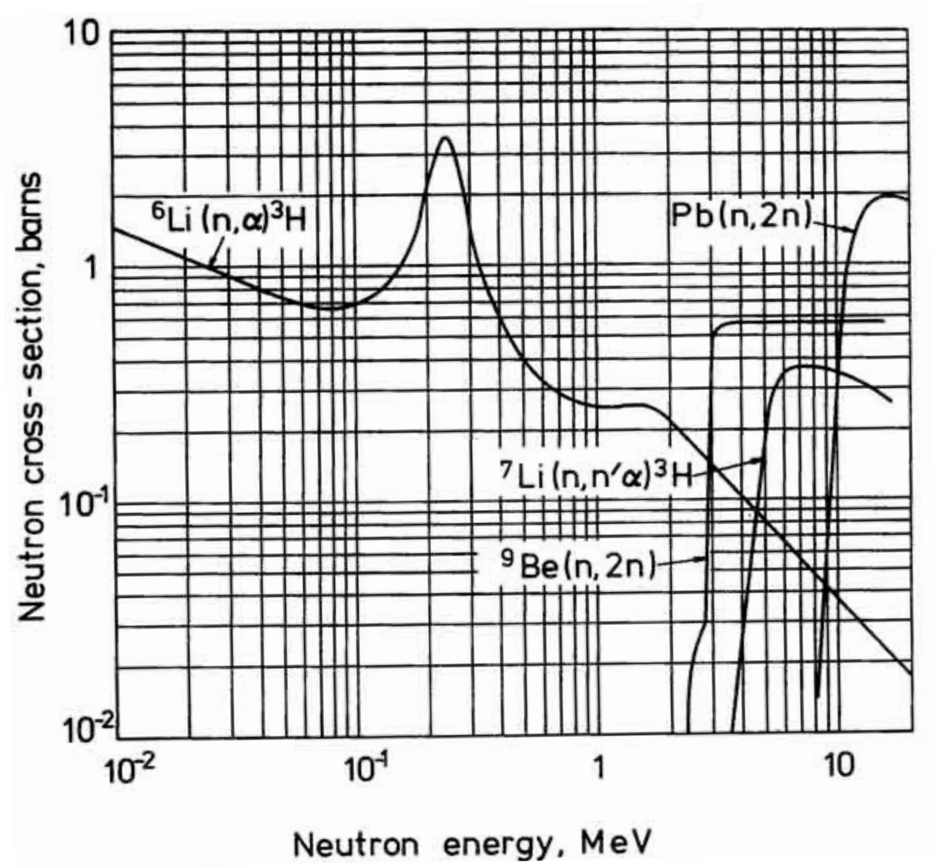
$n_0^1 + Li_3^7 \rightarrow T_1^3 + He_2^4 + n_0^1 - 2.5MeV$

(Li_3^7 is ~93%)

Note that the Li^6 cross section is much larger for low energies

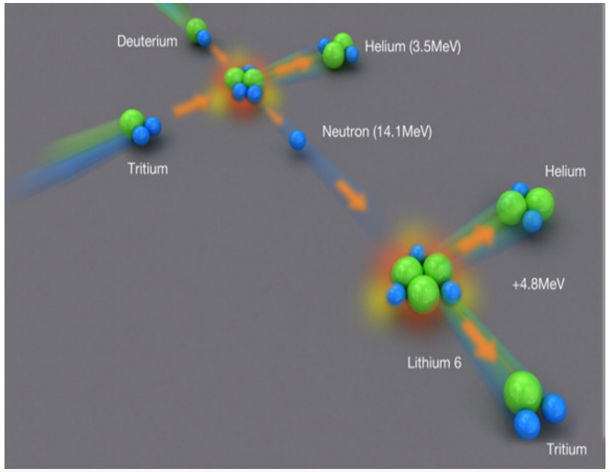
moderate neutrons first

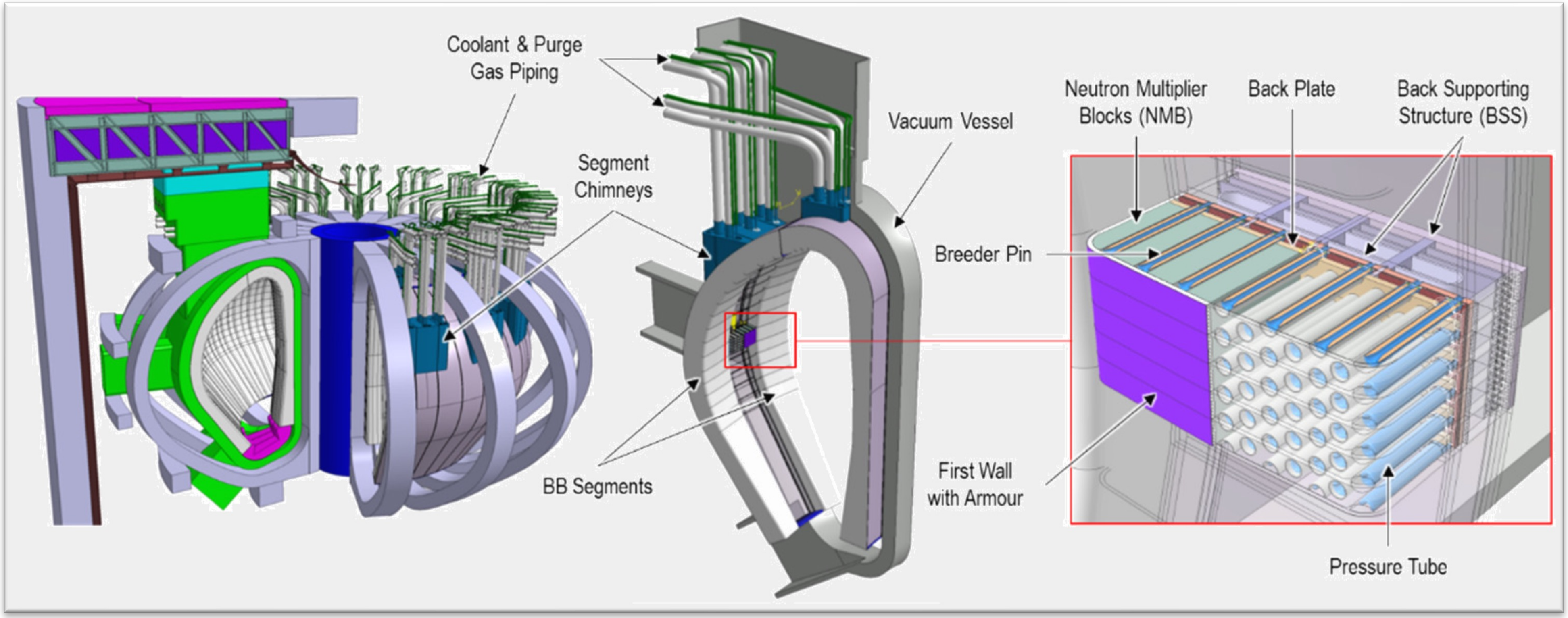
Neutron multiplication is needed, and is possible above ~3MeV with Pb or Be



Lithium is in earth crust and in ocean water (0.15g/m^3)

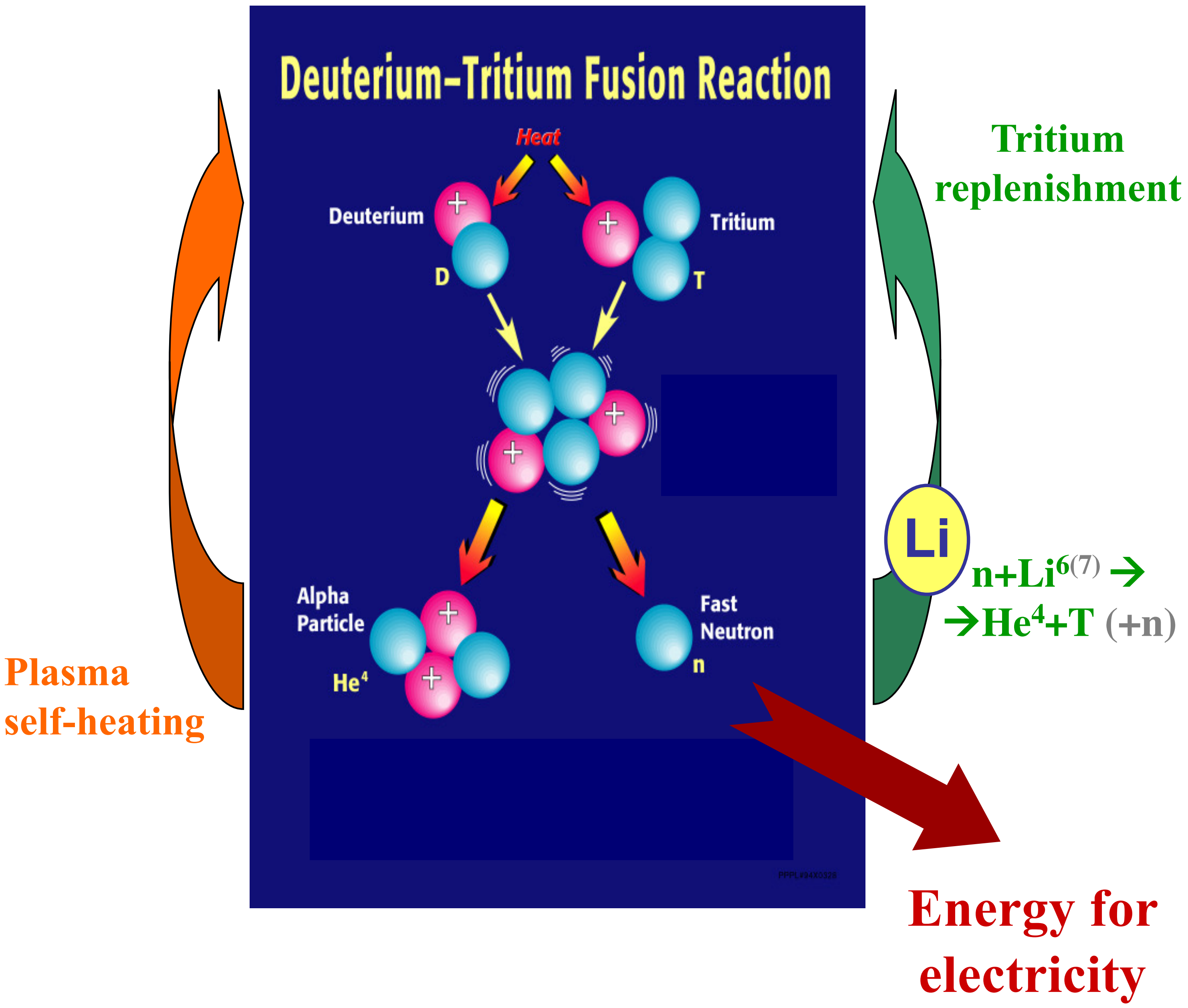
Tritium breeding





The D-T fusion reaction

$$D+T \rightarrow {}^{4}He\,(3.5MeV) + n(14MeV)$$



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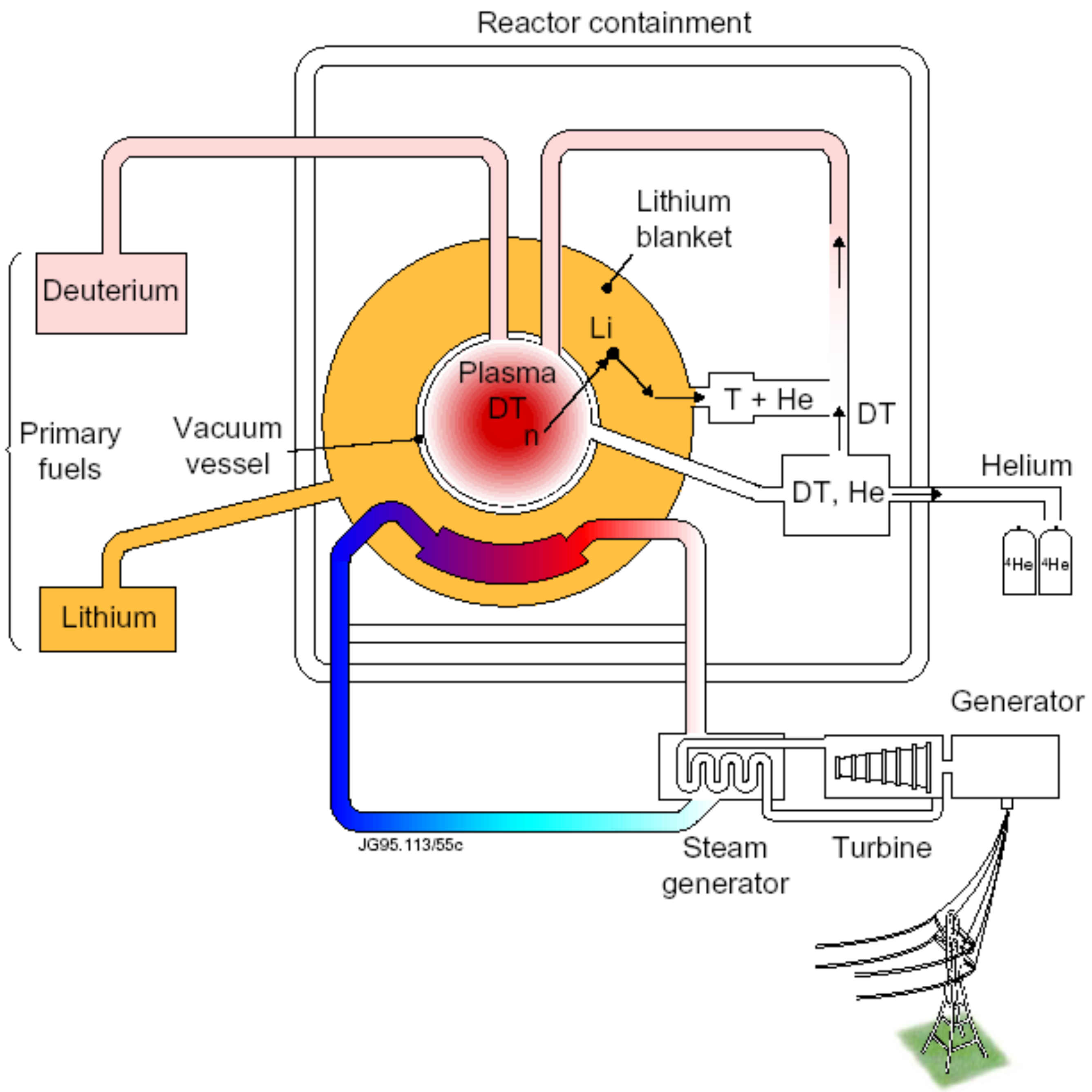
Schematic of a fusion power plant



Advantages of fusion energy

High energy density fuel

Fuel	Specific Energy (MJ/kg)
Water, 100m-high dam	0.001
Coal, oil, food	30-50
Fission (U-235)	85’000’000
Fusion (D-T)	**350’000’000**

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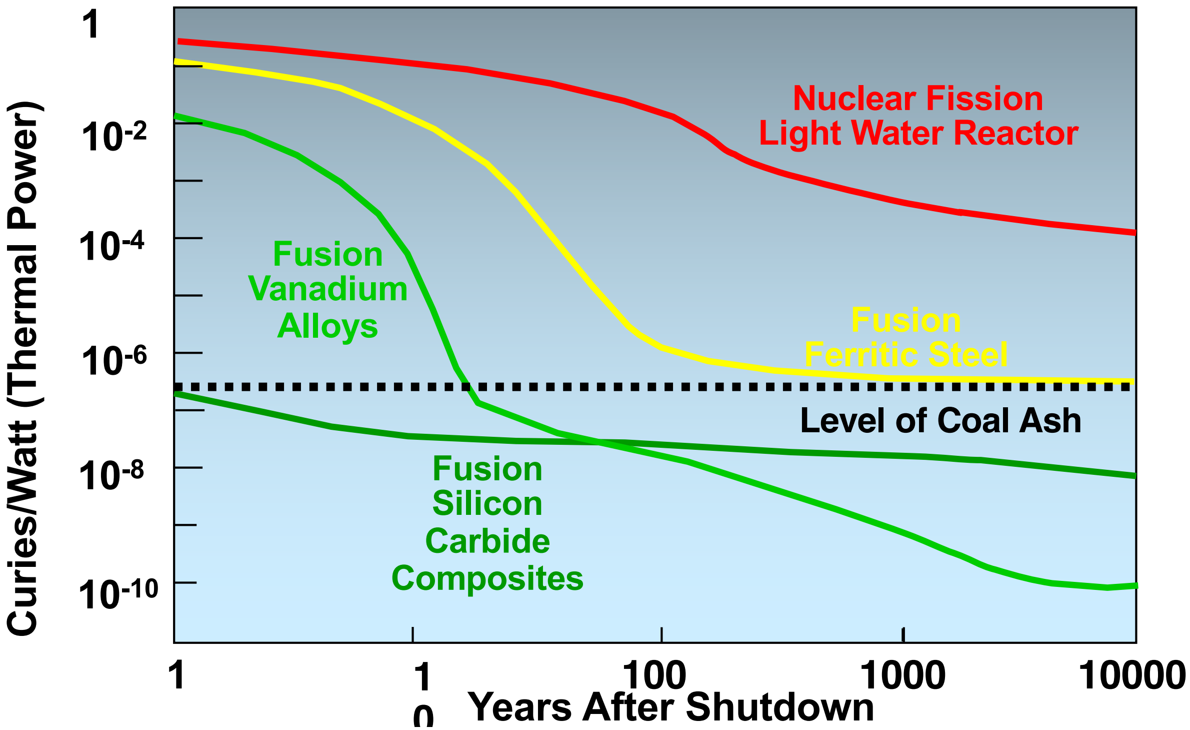
Advantages of fusion energy

High energy density fuel

Practically inhestaustible fuel

Environmental

- No CO_2 emission
- No high-level radioactive wastes



Advantages of fusion energy

High energy density fuel

Practically inhestaustible fuel

Environmental

- No CO_2 emission
- No high-level radioactive wastes

No risk of nuclear accidents

- Only ~1g of fuel in reactor
- No chain reactions

No generation of weapons material

Geographically concentrated, not subject to wheather variations

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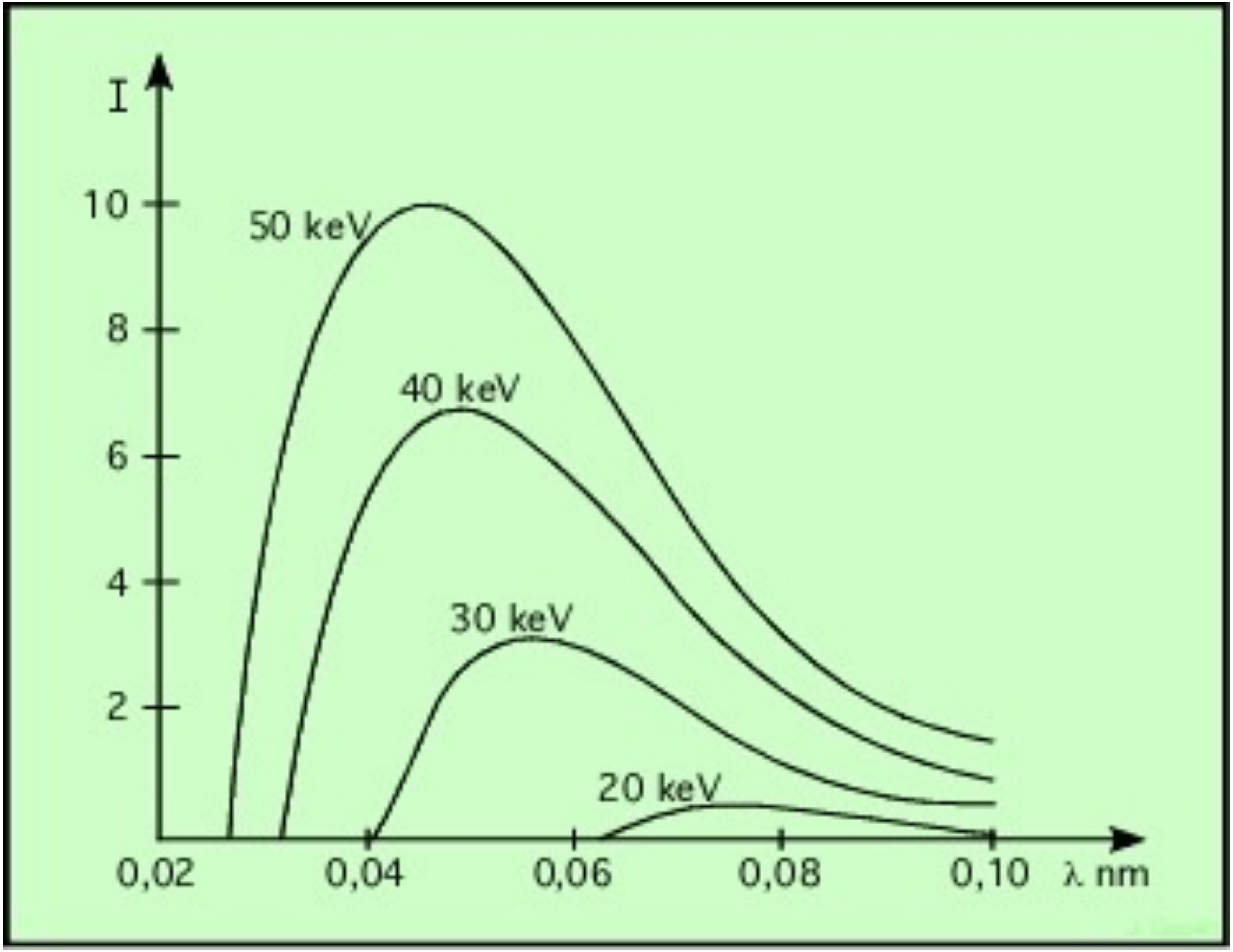
Bremsstrahlung radiation spectrum



Fusion <σv> vs. plasma temperature