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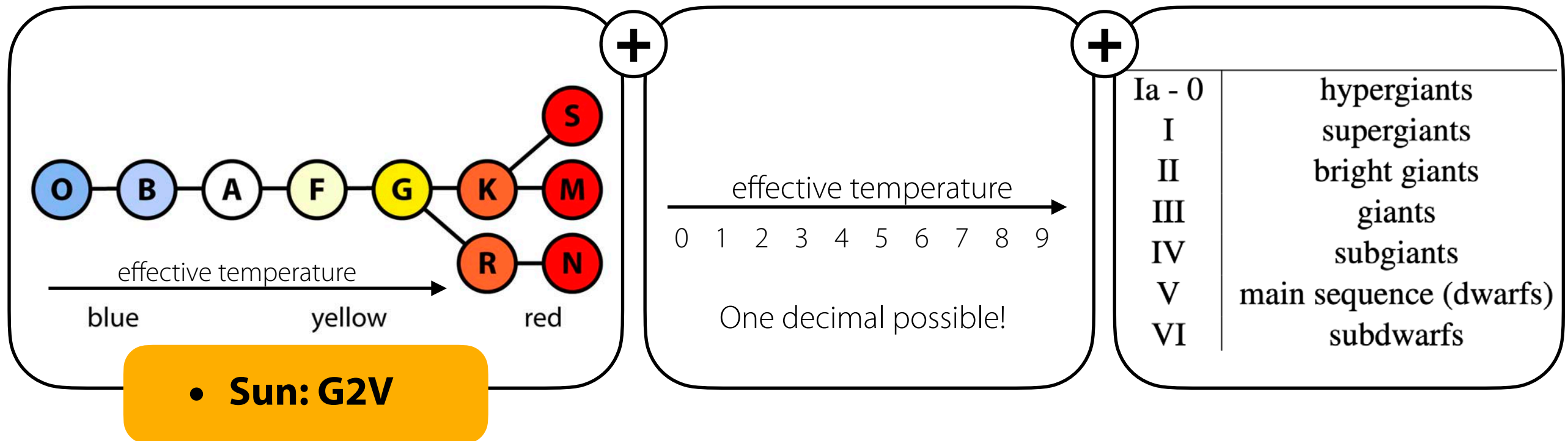
Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2025

Recap

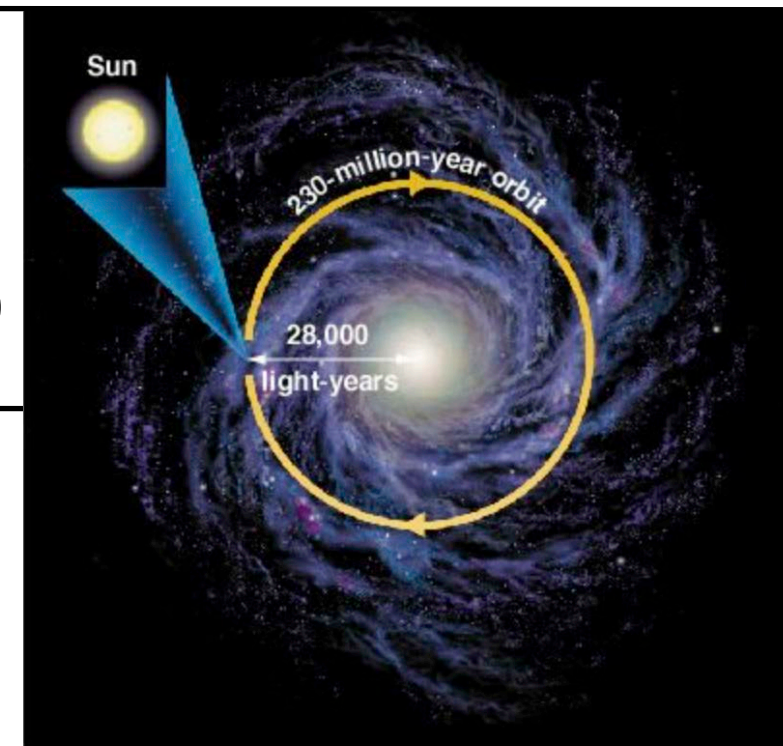
Spectral classification and stellar populations

- Harvard spectral classification /Morgan–Keenan system



- Population I:** “recent” stars, high metallicity
- Population II:** old stars, low metallicity
- Population III:** first stars in the universe (very low metal content)

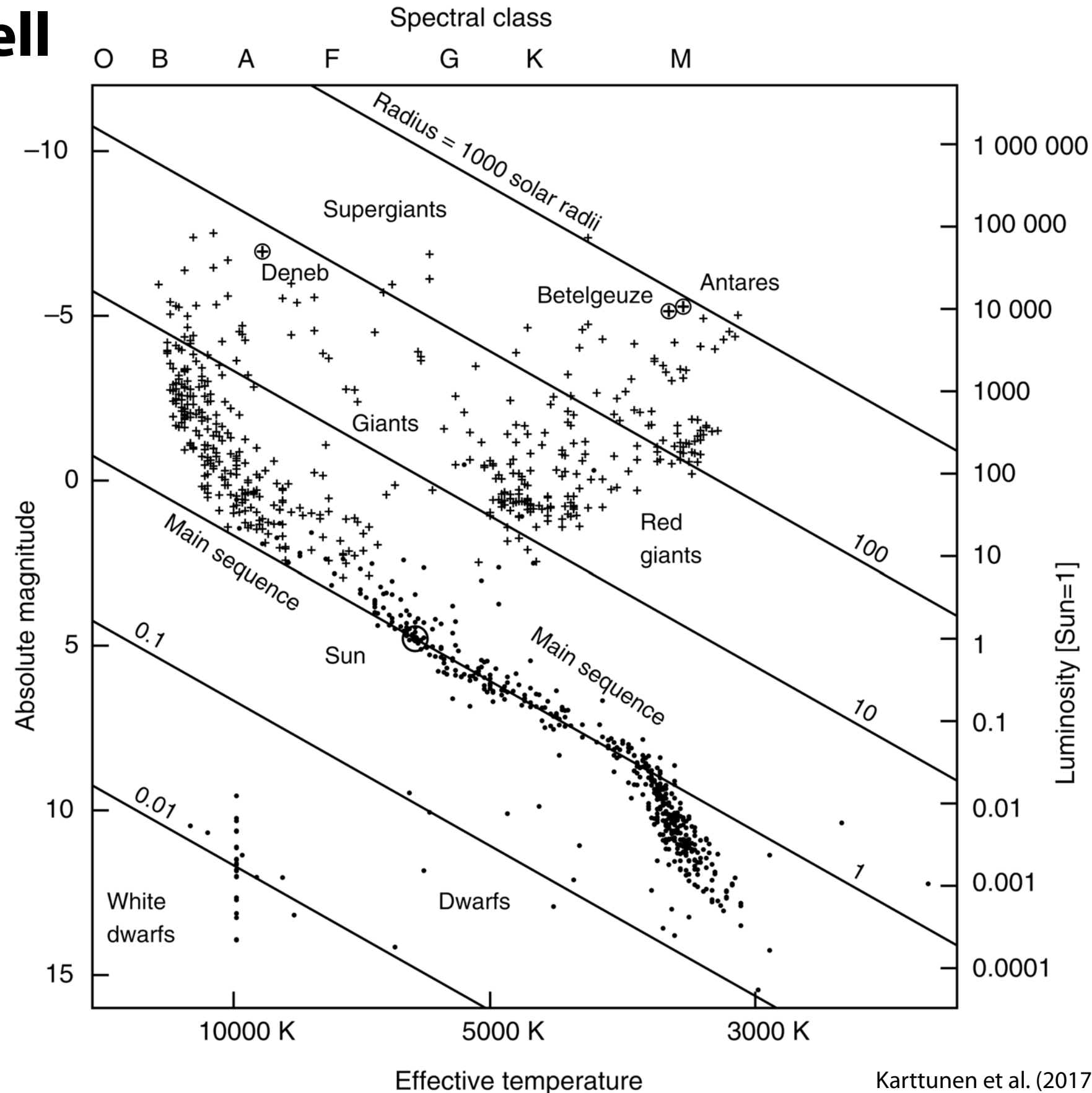
- Total number of stars in the Milky Way only known roughly:
100 - 400 billion stars



Recap

Hertzsprung-Russell diagram

- Stars clearly not distributed randomly
 - Connections between
 - T_{eff} /Spectral class
 - Luminosity/absolute brightness
 - Radius
- ➔ Constraints for models of structure and evolution of stars

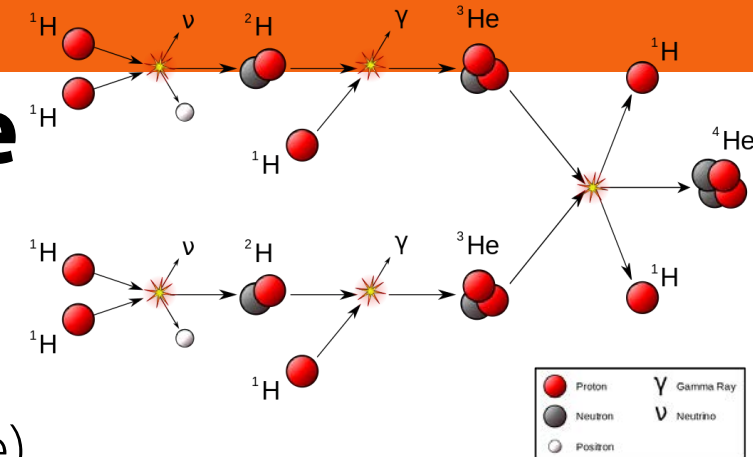


Physical stellar parameters

Lifetime of the Sun on the main sequence

- In solar interior: Thermonuclear fusion (here pp chain)
- 4 hydrogen nuclei (protons) $\rightarrow$ 1 helium nucleus (alpha particle)
- Mass difference $\Delta m = 4 m_p - m_\alpha > 0$ corresponds then to released energy

$$\Delta E = \Delta m c^2$$



- **Energy released per fusion reaction:**

$$E_{\text{FUS}} \sim 4.3 \times 10^{-12} \text{ Ws}$$

Solar luminosity

$$L_{\odot} \sim 3.9 \times 10^{26} \text{ W}$$

- Fusion reactions (pp) in the Sun per second: $N_{\text{FUS}} \sim L_{\odot} / E_{\text{FUS}} \sim \underline{10^{38} \text{ s}^{-1}}$

Physical stellar parameters

Lifetime of the Sun on the main sequence

- Mass “lost” via fusion per second

$$\Delta M = N_{\text{FUS}} \times 4 m_p \sim 6.7 \times 10^{11} \text{ kg/s} \quad (m_p: \text{proton mass})$$

- Solar mass $M_{\odot} = 2 \times 10^{30} \text{ kg}$
- Solar lifetime if **all mass** is “used” at constant rate via $\text{H} \rightarrow \text{He}$ fusion (pp chain)
- $\tau = M_{\odot} / \Delta M = 2 \times 10^{30} \text{ kg} / 6.7 \times 10^{11} \text{ kg/s} = 3 \times 10^{18} \text{ s} = 9 \times 10^{10} \text{ yr}$

➔ **90 billion year**

➔ **Older than the universe???**

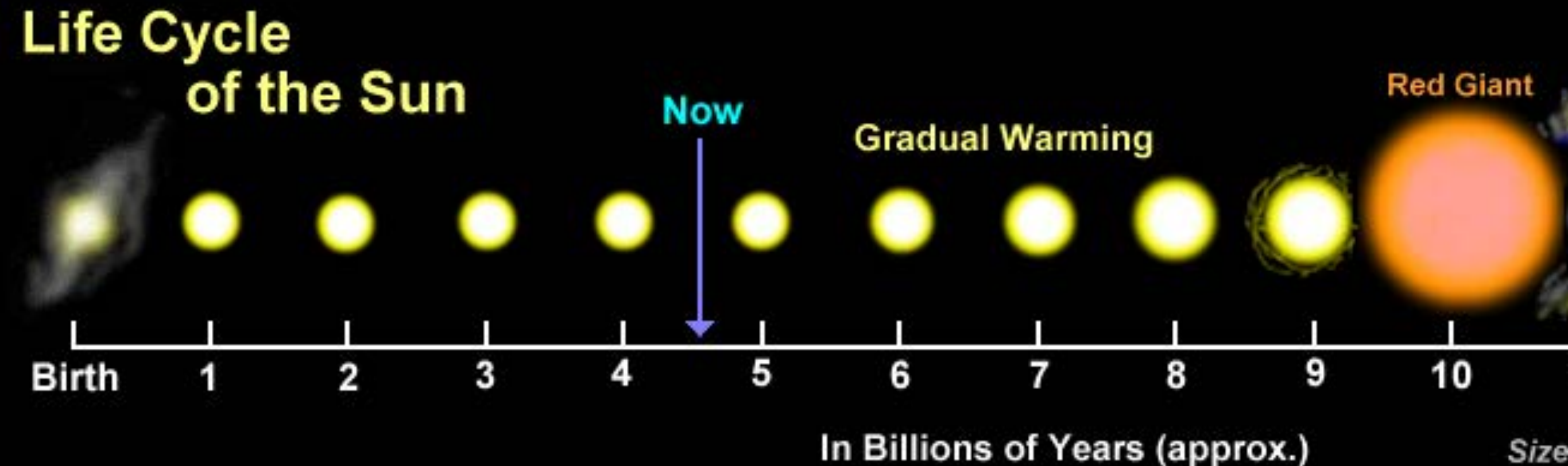
Based on detailed stellar evolution models:

Sun's lifetime ~ 10¹⁰ yr!

- ➔ Corresponds to 10% of solar mass.
- ➔ Explanation: H-He fusion only in solar core (and also not constant rate)
- ➔ More detailed evolution models needed.

Physical stellar parameters

Lifetime of the Sun on the main sequence



Based on detailed stellar evolution models:

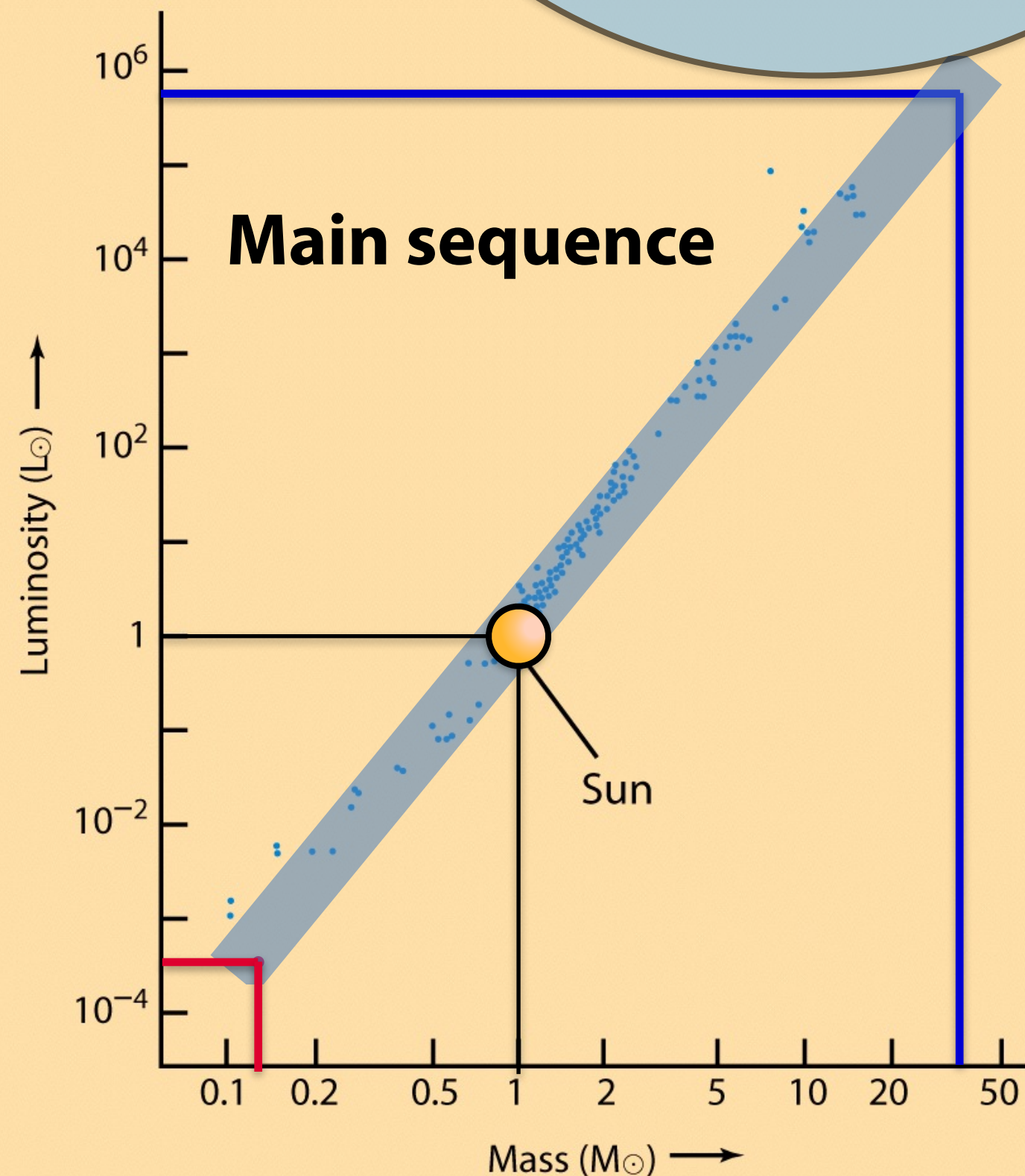
Sun's lifetime ~ 10^{10} yr!

- ➡ Corresponds to 10% of solar mass.
- ➡ Explanation: H-He fusion only in solar core (and also not constant rate)
- ➡ More detailed evolution models needed.

Fundamental parameters

Lifetime on main sequence

$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}} \right)^{3.5}$$



- Energy set free by fusion
- Stellar **mass** sets absolute limit
- **Luminosity** gives energy loss rate

- Simplifying assumption for an *order of magnitude estimate*:
Energy conversion via fusion with constant rate set at constant luminosity

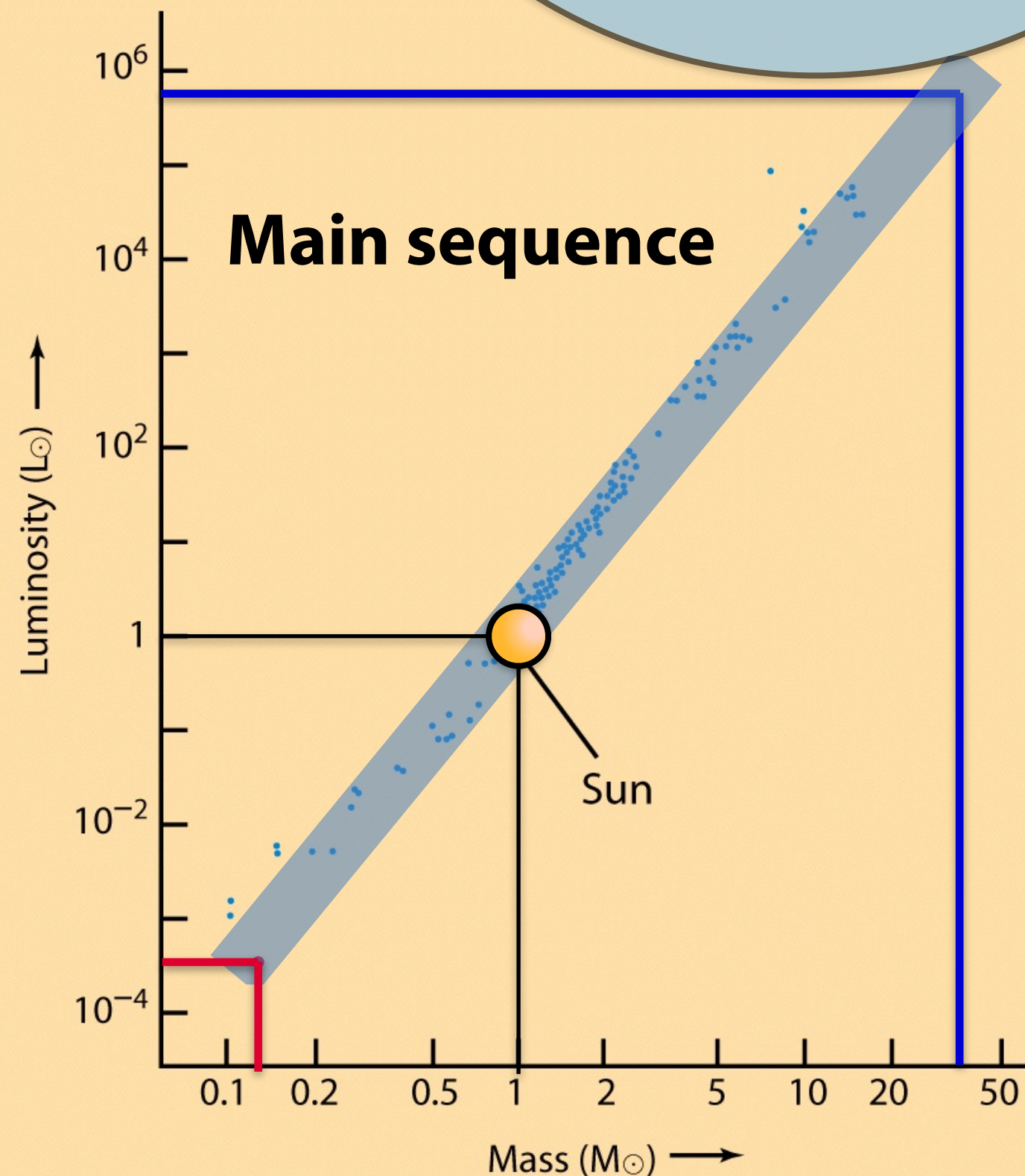
➡ Max. time at “constant burn”

$$\tau \propto M / L = M^{n-1}$$

Fundamental parameters

Lifetime on main sequence

$$\tau \propto M / L$$



- Energy set free by fusion
 - Stellar **mass** sets absolute limit
 - **Luminosity** gives energy loss rate
- ➔ Max. time at “constant burn” M / L

Spectral class O6

$R = 18 R_{\odot}, T_{\text{eff}} = 38\,000\text{ K}, M = 40 M_{\odot}$

➔ $L = 520\,000 L_{\odot}$

➔ Compared to Sun

$$M[M_{\odot}]/L[L_{\odot}] = 40 / 520\,000 = 8 \cdot 10^{-5}$$

➔ 13000 shorter time

Red dwarf star

$R = 0.1 R_{\odot}, T_{\text{eff}} = 2885\text{ K}, M = 0.12 M_{\odot}$

➔ $L = 6 \cdot 10^{-4} L_{\odot}$

➔ Compared to Sun

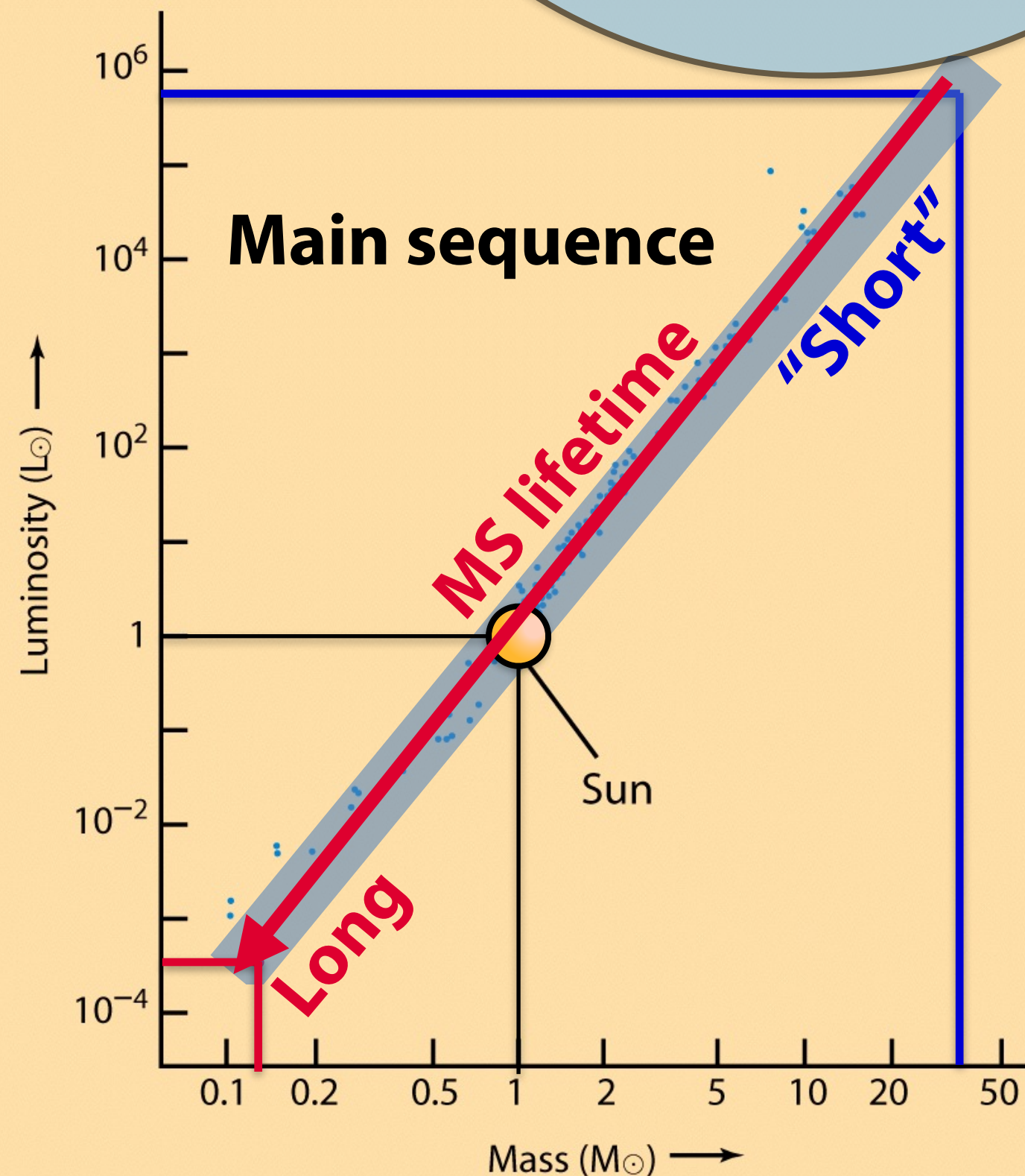
$$M[M_{\odot}]/L[L_{\odot}] = 0.12 / 6 \cdot 10^{-4} = 200$$

➔ 200 times longer

Fundamental parameters

Lifetime on main sequence

$$\tau \propto M / L$$



- Lifetime of Sun on main sequence on the order of 10^{10} yr

Spectral class O6

- ➡ $\tau \sim 8 \cdot 10^{-5} \cdot 10^{10} \text{ yr} \sim 800\,000 \text{ yr}$
- ➡ "Only" less than 1 million years.

Red dwarf star

- ➡ $\tau \sim 200 \cdot 10^{10} \text{ yr} \sim 2 \cdot 10^{12} \text{ yr}$
- ➡ 2000 billion years
- ➡ Age of universe "only" ~ 14 billion years!

Evolutionary Time Scales

Overview

- **Time scales are a fundamentally important in physics as they highlight which physical process is important in which context.**
 - ➡ **Allows to focus on what is important and derive “lean” and yet accurate models.**
- **Changes in a star** occur on different time scales at different evolutionary phases.
 - Most important:
 - Nuclear time scale t_n
 - Thermal time scale t_t
 - Dynamical or freefall time scale t_d .
 - Usually: $t_d \ll t_t \ll t_n$

Evolutionary Time Scales

Nuclear Time Scale

- **Definition:** time in which a star radiates away all the energy that can be released by nuclear reactions
- **Estimate** (as already done for the Sun) for **hydrogen burning**
 - Time in which all available hydrogen is turned into helium.
 - Theoretical considerations / evolutionary model calculations:
 - ➡ ~10 % of total mass of hydrogen in a star can be consumed before other, more rapid evolutionary mechanisms set in.
 - ➡ Of these 10% a mass fraction 0.7 % is turned into energy in

$$t_n \approx \frac{0.007 \times 0.1 M c^2}{L}$$

- For the Sun:

$$t_n \approx \frac{M/M_\odot}{L/L_\odot} \times 10^{10} \text{ a}$$

- Remember: Mass-luminosity relation with high exponent

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot} \right)^n$$

- ➡ $M = 30 M_\odot : t_n \sim 2 \text{ million yr}$

Evolutionary Time Scales

Thermal Time Scale

- **Definition:** time in which a star would radiate away all its thermal energy if the nuclear energy production were suddenly turned off
- **Estimate:** time it takes for **radiation from the centre to reach the surface.**

- Virial theorem: $\langle T \rangle = -\frac{1}{2} \langle U \rangle$

T: total kinetic energy of the system
U: potential energy of the system.

➡ Kinetic energy of the thermal motion of the gas particles equals half of the potential energy.

$$t_t \approx \frac{0.5 GM^2/R}{L}$$

G: constant of gravity
R: stellar radius

$$\approx \frac{(M/M_\odot)^2}{(R/R_\odot)(L/L_\odot)} \times 2 \times 10^7 \text{ a.}$$

- For the Sun: $t_t \sim 20 \text{ million yrs} \sim 1/500 t_n$ (nuclear time scale)

Evolutionary Time Scales

Dynamical Time Scale

- **Definition:** the time it would take a star to collapse if the pressure supporting it against gravity were suddenly removed.
- **Estimate:** time for a particle to **fall freely from the stellar surface to the centre**
 - Equals half of period given by Kepler's third law with stellar radius R corresponding to semimajor axis of the orbit:

$$t_d = \frac{2\pi}{2} \sqrt{\frac{(R/2)^3}{GM}} \approx \sqrt{\frac{R^3}{GM}}$$

- Shortest time scale of the three!
- For the Sun: $t_d \sim 30\text{min}$

Evolutionary Time Scales

Stellar lifetimes

Dynamical
Time scale
 t_d

Nuclear
time scale
Hydrogen
burning
 t_n

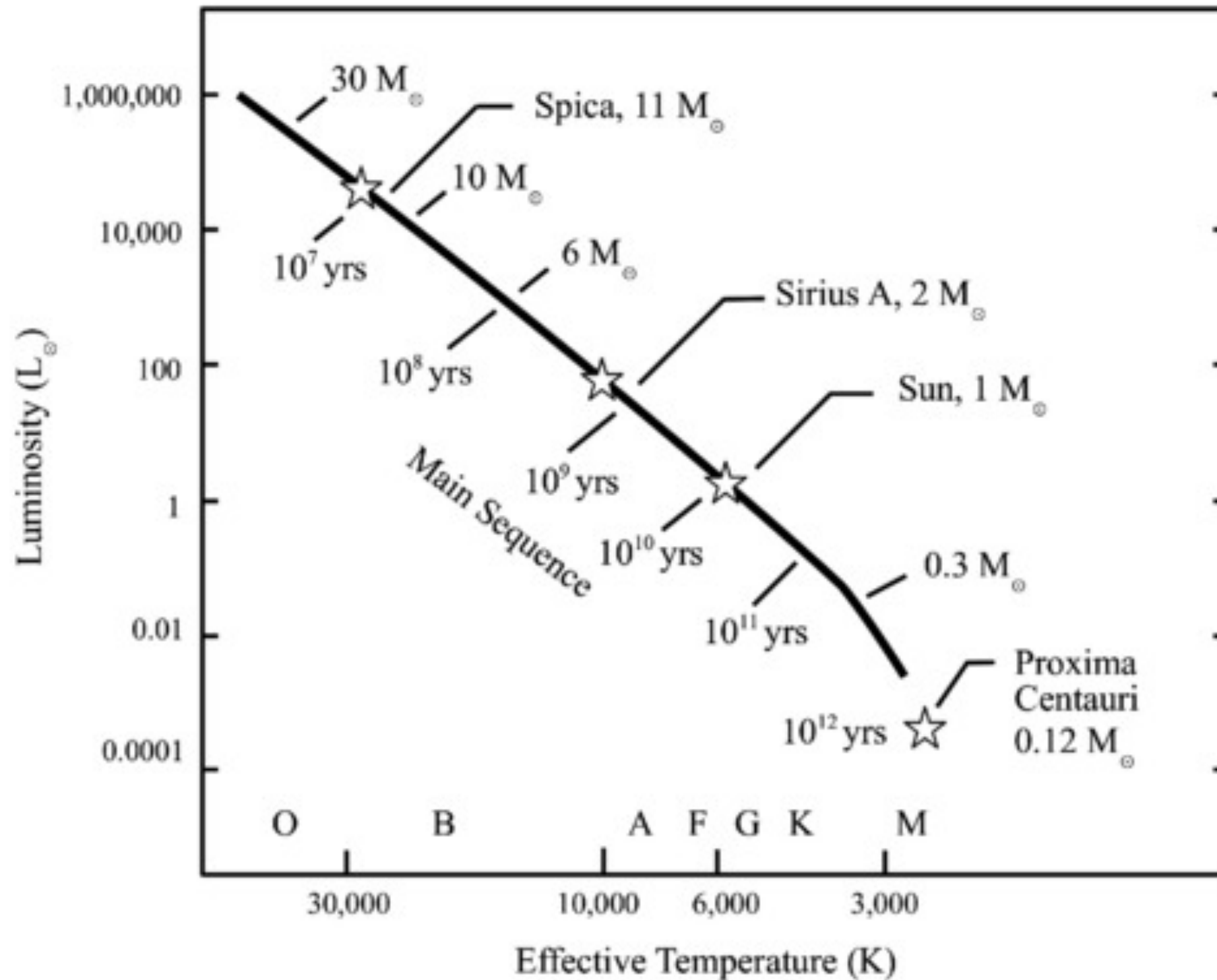
Nuclear
time scale
He burning etc
 $t_{n'}$

Stellar lifetimes (unit 10^6 years)

Mass [$M_\odot$]	Spectral type on the main sequence	Contraction to main sequence	Main sequence	Main sequence to red giant	Red giant
30	O5	0.02	4.9	0.55	0.3
15	B0	0.06	10	1.7	2
9	B2	0.2	22	0.2	5
5	B5	0.6	68	2	20
3	A0	3	240	9	80
1.5	F2	20	2000	280	
1.0	G2	50	10,000	680	
0.5	M0	200	30,000		
0.1	M7	500	10^7		

Note: Contraction of a much larger cloud from which the star forms.

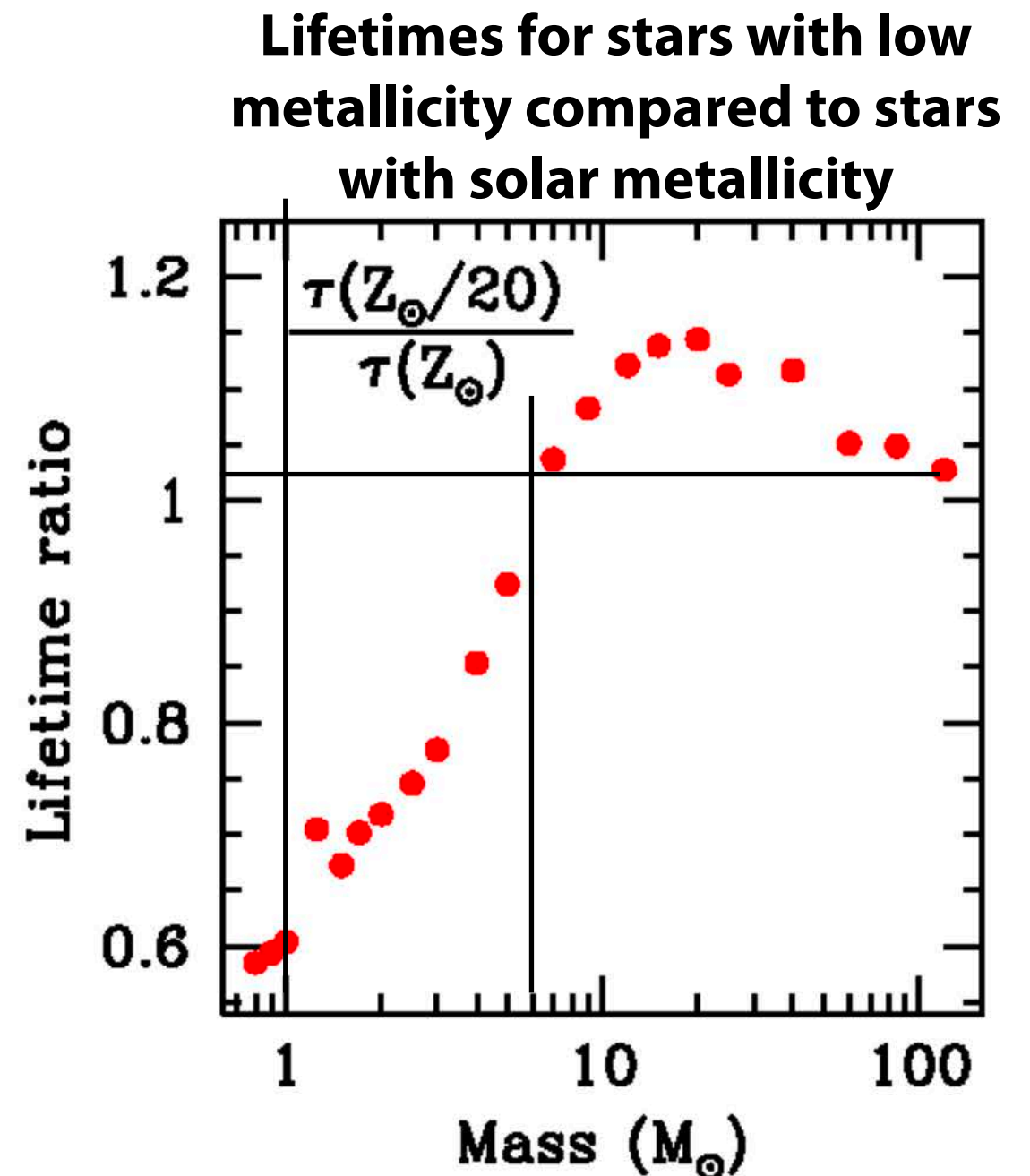
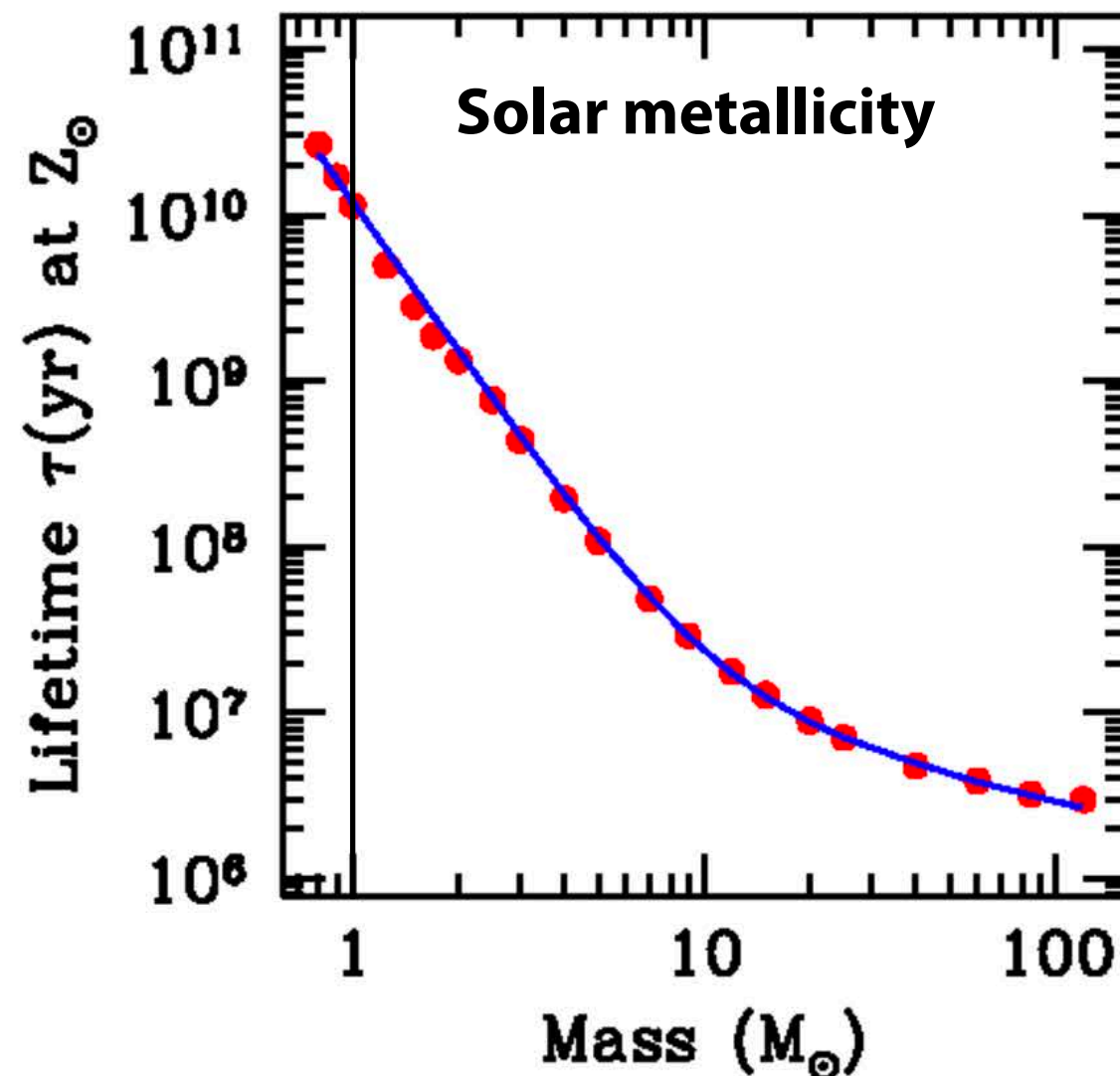
Stellar lifetimes



Stellar lifetimes

Impact of metallicity

- Metallicity (chemical composition) of a star influences its evolution (time scales)
- For $Z = 0.05 Z_{\odot}$ (lower metallicity):
- $M < 6 M_{\odot}$: lifetimes get shorter
- $M > 6 M_{\odot}$: lifetimes get longer



Stellar lifetimes

Type	Mass	Temp.	Luminosity	Life time [10^6 yr]	Occurrence
O	50	40 000 K	100 000	10	0.00001 %
B	10	20 000 K	1000	100	0.1 %
A	2	8500 K	20	1 000	0.7 %
F	1.5	6500 K	4	3 000	2 %
G	1	5700 K	1	10 000	3.5 %
K	0.8	4500 K	0.2	50 000	8 %
M	0.3	3200 K	0.01	200 000	80 %

- **Main sequence stars** with same mass have typically similar radius, luminosity and temperature (only small slow changes during the time of the main seq. and chemical composition)
- **Low mass stars by far most abundant!**

Stellar lifetimes

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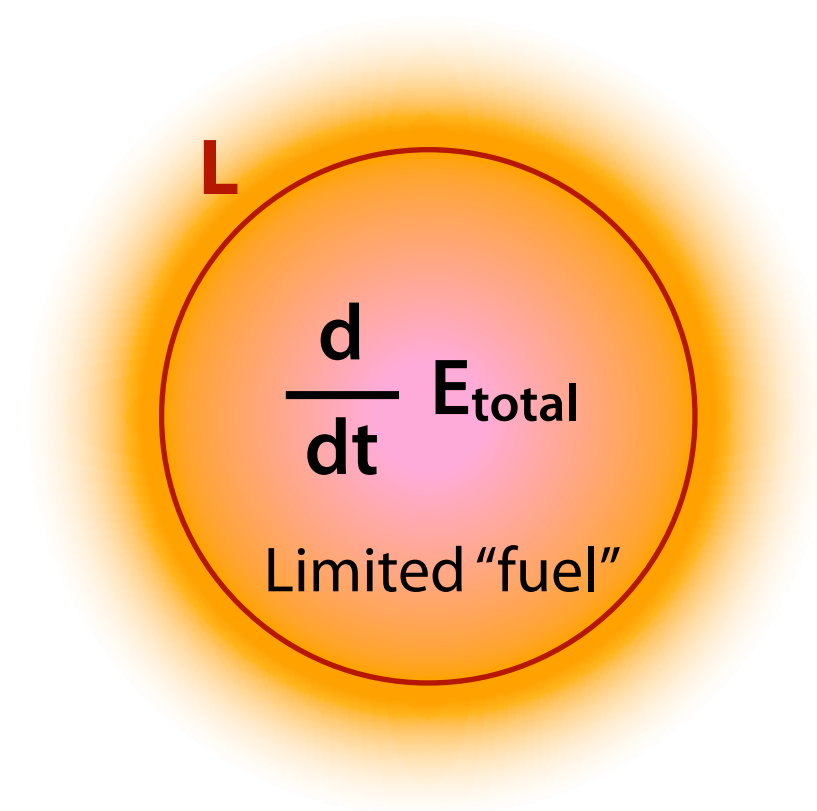
- NOTE: This is the total lifetime of the main series (these stars are not older than the universe)
- No K or M-type dwarf has left the main sequence yet!

Stellar interior

Overview

- Stars radiate (luminosity)
 - **Conservation of energy** (whole system)
 - ➡ Total energy of a star decreases with time
 - ➡ How is the required energy set free?
 - ➡ How is the energy transported to the surface?
- The physical properties of interior structure determined by

• Temperature T • Pressure P • Chemical composition μ	Equation of state Opacity
--	--
- Gradients d/dr decisive for energy transport and in return the stratification
- Stellar structure due to **balance** and will change as function of time



Energy reservoirs

Overview

- There are different **energy reservoirs** available:
 - Potential energy E_p (all mass elements of a star).
 - Thermal energy E_t (kinetic energy of all particles)
 - Nuclear energy E_n (set free by nuclear reactions, e.g., fusion)
 - *Chemical energy (set free during chemical reactions, atoms combining, typically insignificant under stellar conditions)*
- **Total energy** $E_{\text{total}} = E_n + E_t + E_p$
 - ➡ Decreases as a star emits energy as radiation at the surface.
 - ➡ Resulting luminosity of a star = temporal change of the star's energy content:

$$L = - \frac{d}{dt} E_{\text{total}}$$

Remember

- Dynamical time scale t_d
- Thermal time scale t_t
- Nuclear time scale t_n

Energy reservoirs

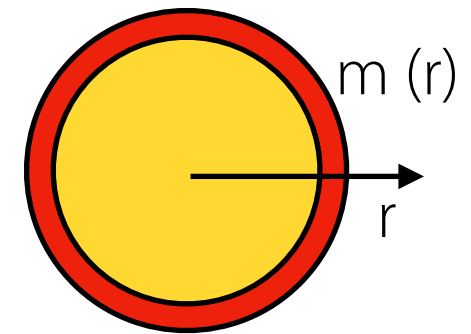
Gravitational potential

- **Gravitational potential energy** for a system of two particles:
- **Contraction:** masses closer together
 ➡ potential energy becomes more negative.

$$U = -\frac{Gm_1m_2}{r}$$

- Instead now integration over thin shells of thickness dr

$$U = -G \int_0^R \frac{m(r)4\pi r^2 \rho}{r} dr = -\frac{3GM^2}{5R}$$



- Apply **virial theorem**:
 total energy = 1/2 (time-averaged) potential energy

$$E_{\text{total}} = \frac{3GM^2}{10R} = \frac{3}{5} \frac{GM^2}{R}$$

- **Virial theorem:** relates the average total kinetic and average potential energy of a gravitationally bound system and thus to internal thermodynamical quantities (e.g, temperature, pressure, density)

$$\langle T \rangle = -\frac{1}{2} \langle U \rangle \longrightarrow \frac{1}{2} v^2 = \frac{3}{2} \frac{k_B T}{m_p} = \frac{3}{5} \frac{GM}{R}$$

T : total kinetic energy of the system U : potential energy of the system.

M : stellar mass R : stellar radius

v : particle velocity T : temperature

G : Newton's constant

k_B : Boltzmann constant

m_p : proton mass

Energy reservoirs

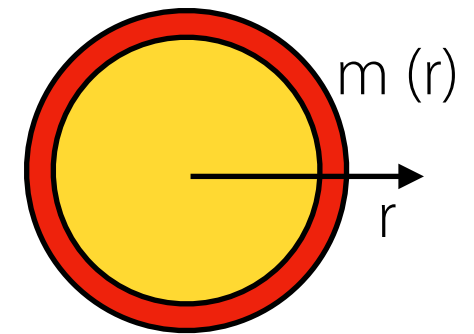
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- Apply **virial theorem:**
 total energy = 1/2 (time-averaged) potential energy ➡

$$E_{\text{total}} = \frac{3GM^2}{10R}$$

- **Example: Contraction of the Sun at current luminosity**

$$t \approx \frac{E_{\text{total}}}{L_{\odot}} \approx \frac{1.1 \cdot 10^{41} \text{ J}}{3.84 \cdot 10^{26} \text{ W}} \approx 2.9 \cdot 10^{14} \text{ s} \approx \mathbf{9 \cdot 10^6 \text{ yr}} \quad (\text{Very simplified estimate!})$$

- Proposed as energy source for the Sun by Kelvin and Helmholtz in late 19th century
(before fusion was known)
- **Dismissed** due to clear geological and biological indications of much higher age

Energy reservoirs

Chemical energy

- Chemical reactions: based on interactions of orbital electrons in atoms.
 - Typical energy differences between atomic orbitals $\Delta E \sim 10$ eV.

- **Example:** Assume the Sun is pure hydrogen

➡ Total number of H atoms in the Sun:
$$n = \frac{M_{Sun}}{m_H} = \frac{1.99 \times 10^{30}}{1.67 \times 10^{-27}} = 1.19 \times 10^{57}$$

- Assume all atoms release $\Delta E \sim 10$ eV each due to chemical reactions

➡ Total released chemical energy: $\approx 10^{58} \text{ eV} = 10^{39} \text{ J}$

➡ **How long could the Sun radiate at current luminosity?**

$$t \approx \frac{E_{chem}}{L_{\odot}} \approx \frac{10^{39} \text{ J}}{3.84 \times 10^{26} \text{ W}} \approx 10^5 \text{ yr}$$

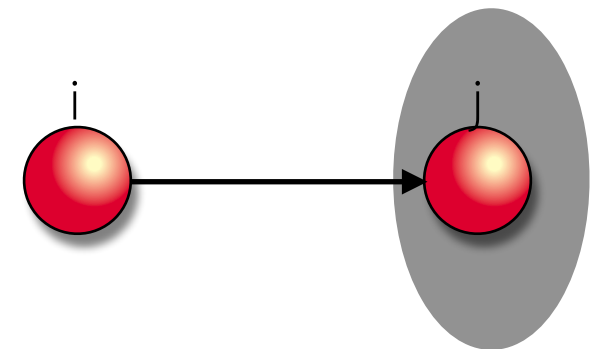
- ➡ Purely based on chemical energy: only 100,000 years
(~100 times less than for the gravitational potential energy)
- ➡ Obviously not a viable energy source.

$$L = - \frac{d}{dt} E_{total}$$

Energy reservoirs

Nuclear energy

- **Wanted: Energy production rate as a function of temperature, density, chemical composition**
- Needed:
 1. What is the probability of a certain type of reaction to occur?
 - ➡ Cross-section and number densities of reactants!
 - ➡ Reaction rates
 2. How much energy is released in each reaction?
- Energy production rate must be related to the rate $r_{i,j}$ of collisions between two particles (i,j)
 - Amount of energy released per unit mass if each reaction releases an energy Λ :



$$\epsilon_{ij} = \left(\frac{\Lambda}{\rho} \right) r_{ij}$$

ρ : mass density

Energy reservoirs

Nuclear energy — Reaction rates

- Rate proportional to number of i-j pairs in the volume.

➡ Reaction rate per second and cm³ :

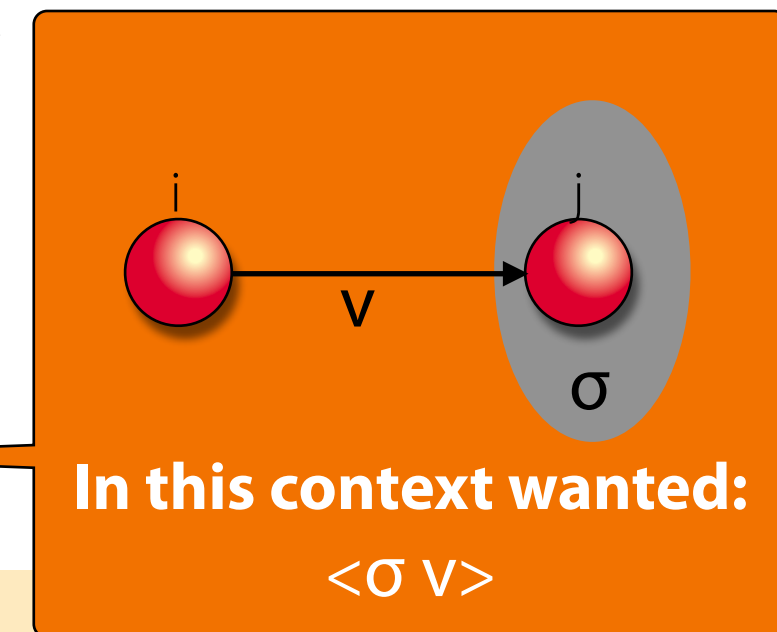
$$r_{ij} = \sigma v n_i n_j$$

v: relative velocity between particles

σ : **cross-section**

- Interaction between particles of same species:
divide rate by 2:

$$r_{ij} = \frac{1}{1+\delta_{ij}} n_i n_j \sigma v = \frac{1}{1+\delta_{ij}} \frac{X_i \rho}{A_i m_u} \frac{X_j \rho}{A_j m_u} \sigma v$$



- Number density n_i :** number of particles per cm³

$$n_i = \frac{N_i}{V} = \frac{X_i \rho}{m_i}$$

$$m_i \approx A_i \cdot m_u$$

- Abundance of species i:

$$Y_i = \frac{X_i}{A_i}$$

Particles=nuclei of species i

N_i : Absolute number of particles of species i

V: Volume

ρ : mass density (g/cm³)

m_i : mass of nucleus of species i

X_i : fraction of total mass of gas consisting of particle type i

A_i : atomic weight

m_u : atomic mass unit

Use cgs units...

Energy reservoirs

Nuclear energy — recap: fusion

- **Coulomb barrier** due to electric charges of particles

$$U_c = \frac{1}{4\pi\epsilon_0} \frac{Z_i Z_j e^2}{d}$$

(Coulomb potential energy)

- Particle energy needed for reaction to become possible:

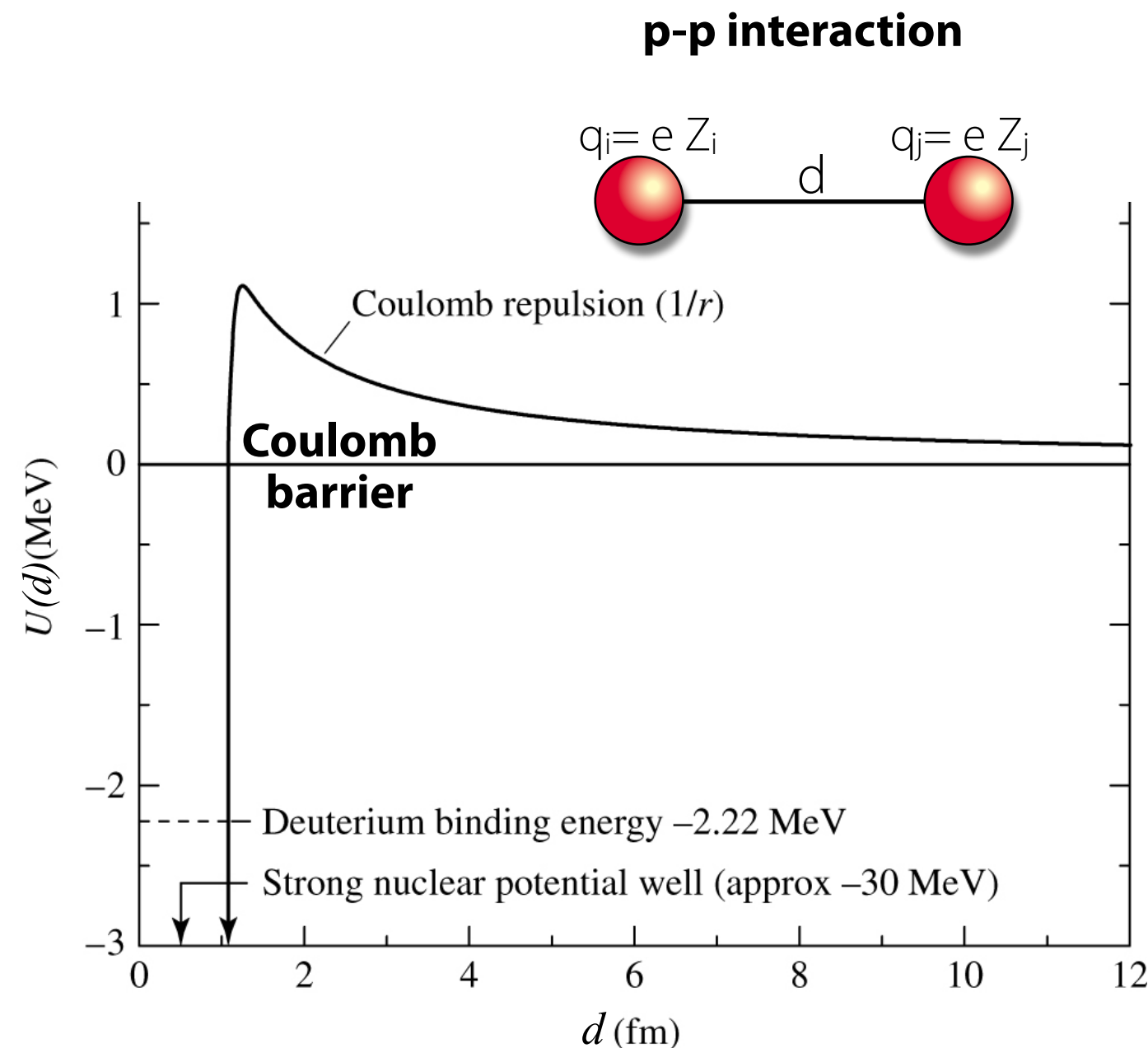
$$E = 3/2 kT \geq U_c$$

- Equivalently: Required particle velocity :

$$v \gg \sqrt{3kT/(2m)}$$

Mean thermal velocity

- Quantummechanical **tunneling**
“through” Coulomb barrier!



Energy reservoirs

Nuclear energy — recap: fusion

- Coulomb barrier** due to electric charges

$$U_C = \frac{1}{4\pi\epsilon_0} \frac{Z_i Z_j e^2}{d}$$

(Coulomb potential energy)

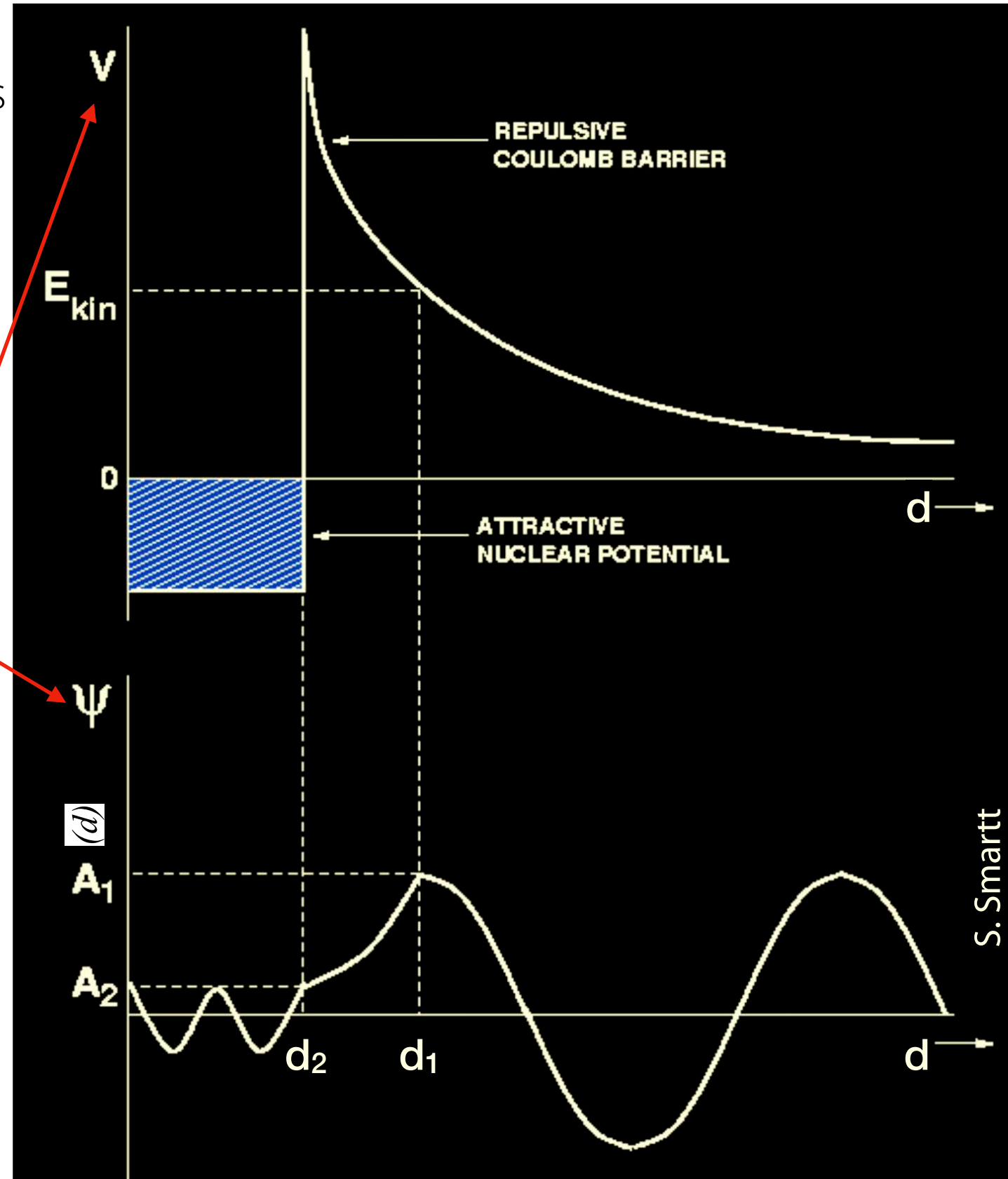
Penetration probability $\propto e^{\frac{-\pi Z_i Z_j e^2}{\epsilon_0 h v}}$

(Gamow)

- Quantummechanical **tunneling** "through" Coulomb barrier!

V (potential energy)

Wave function



Energy reservoirs

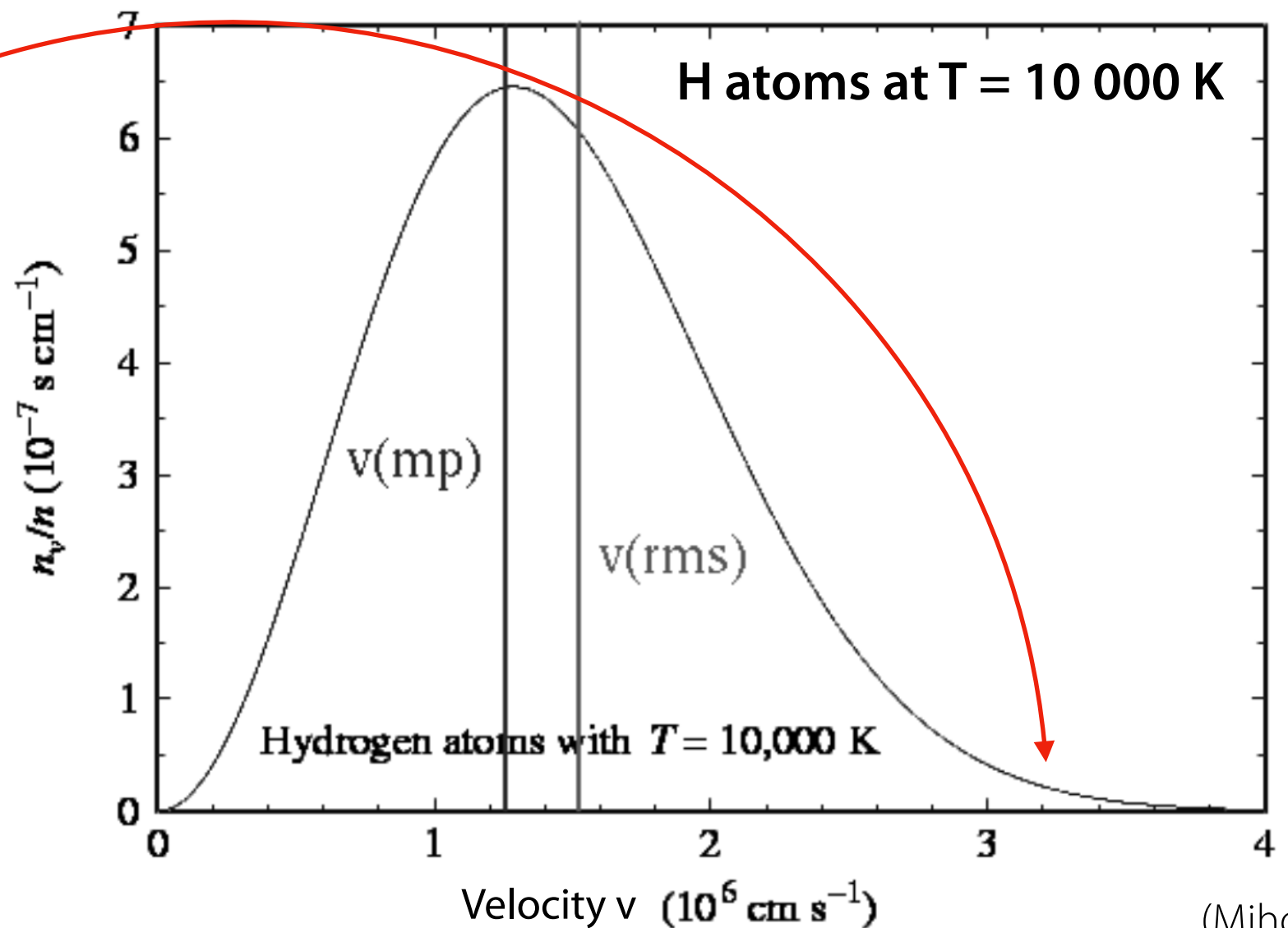
Nuclear energy — recap: fusion

- Distribution of particle velocities: **Maxwellian** velocity distribution

$$P(v) dv = 4\pi \left[\frac{\mu}{2\pi kT} \right]^{3/2} e^{-\mu v^2/(2kT)} v^2 dv$$

reduced mass $\mu = m_1 m_2 / (m_1 + m_2)$

- Note the high-velocity tail!



(Mihos)

Energy reservoirs

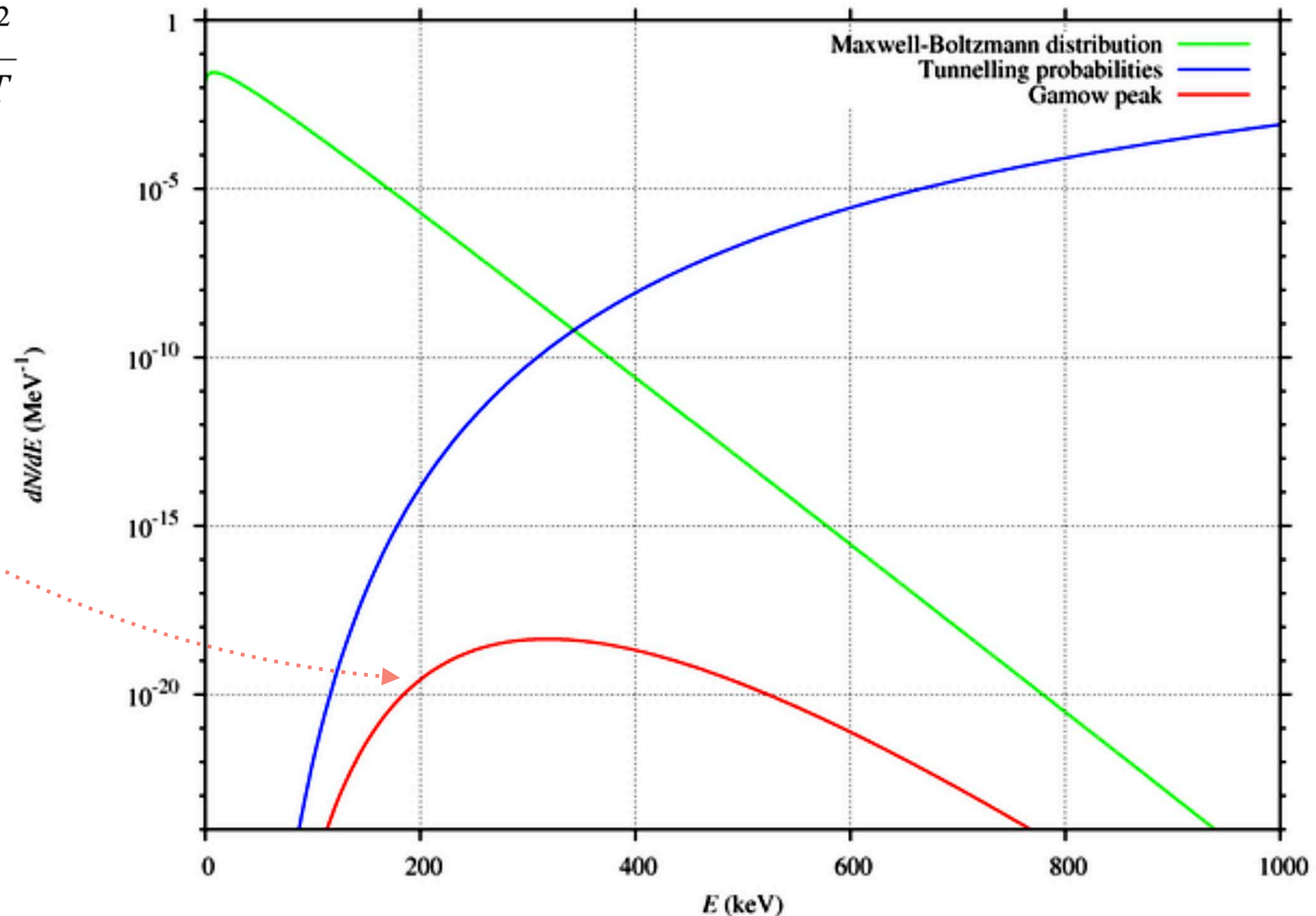
Nuclear energy — recap: fusion

- Combining tail of velocity distribution and tunnelling probability

➡ Probability that this reaction occurs

$$\propto e^{\frac{-\pi Z_i Z_j e^2}{\epsilon_0 h v}} e^{-\frac{mv^2}{2kT}}$$

➡ Gamow peak



Energy reservoirs

Nuclear energy — Reaction rates

- **Conclusion:** Reaction rates depend on
 - Number of reactants (expressed as **chemical composition and mass density**)
 - **Temperature** (via cross-section, reaction probability)
- For simplicity: Approximate reaction rates as **power laws**

$$r_{ij} \approx r_0 X_i X_j \rho^{1+\alpha} T^\beta$$

$$\Rightarrow \text{Energy production rate } \epsilon_{ij} = \left(\frac{\Lambda}{\rho} \right) r_{ij} \approx \epsilon_0 X_i X_j \rho^\alpha T^\beta$$

- Parameter **α** : Depends on details of reaction (how many reactants are involved)
 - For two-body interactions (i.e. p+p collisions), $\alpha \sim 1$
- Parameter **β** : Temperature dependence
 - $\Rightarrow$ Fusion reactions known to very sensitively dependent on temperature
 - $\Rightarrow \beta$ can have a wide range of values

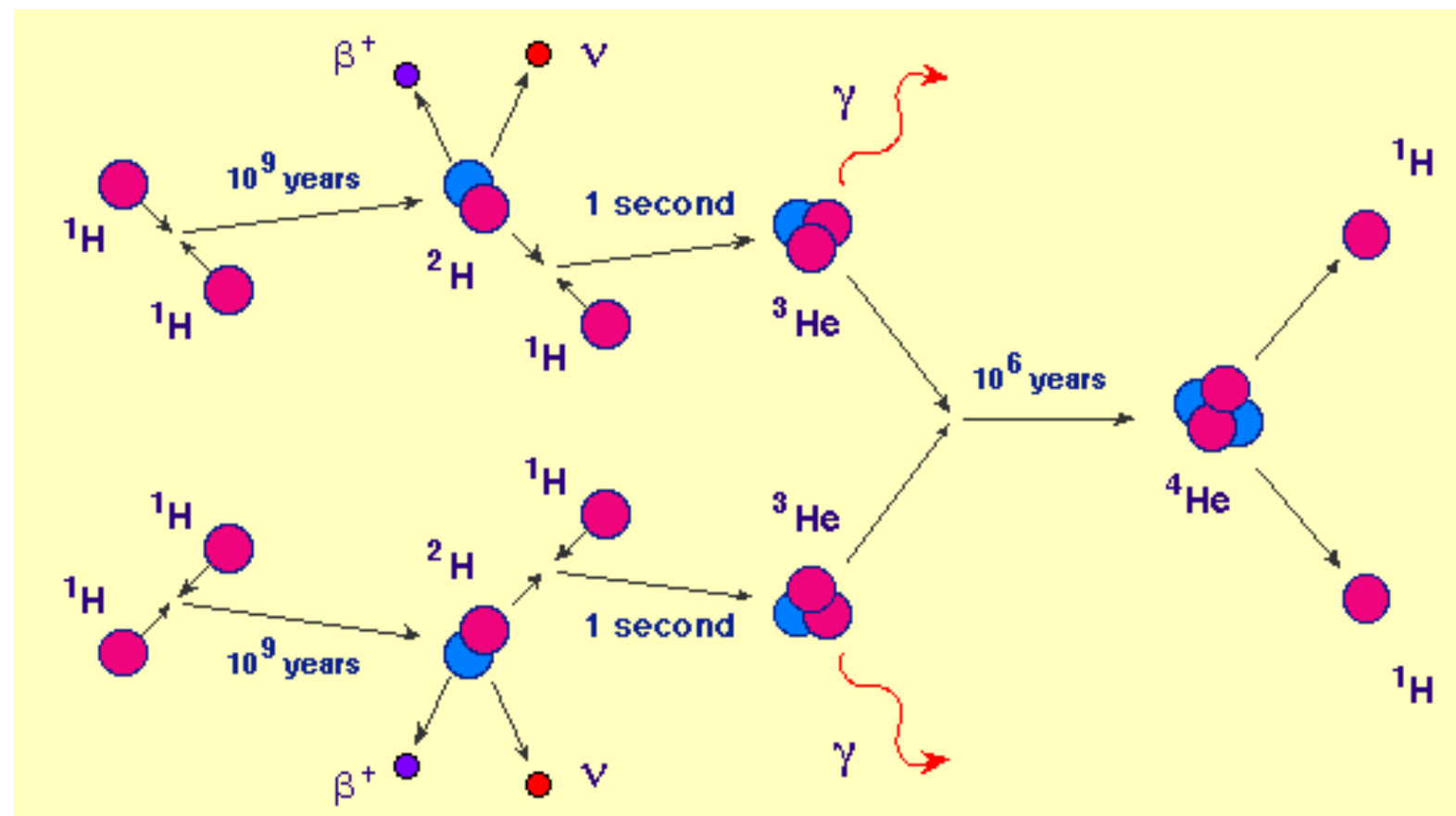
Energy reservoirs

Nuclear energy — Hydrogen burning

- Different fusion reactions with different chains, branches, steps
- Individual reactions reaction rates (and a reaction being relevant) depends on the local plasma properties such as temperature, density, and abundance of the required reactants
 - Will change as function of radius from centre to surface
- **Example:** Hydrogen burning in the Sun (and solar-like stars):
 - Mostly pp chain with three different branches with different relative occurrence

- **PP1 in the Sun:**

Step 1	${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu_e$	10^9 yr
Step 2	${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$	$\sim 1 \text{ s}$
Step 3	${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2 {}^1_1\text{H}$	10^6 yr



Energy reservoirs

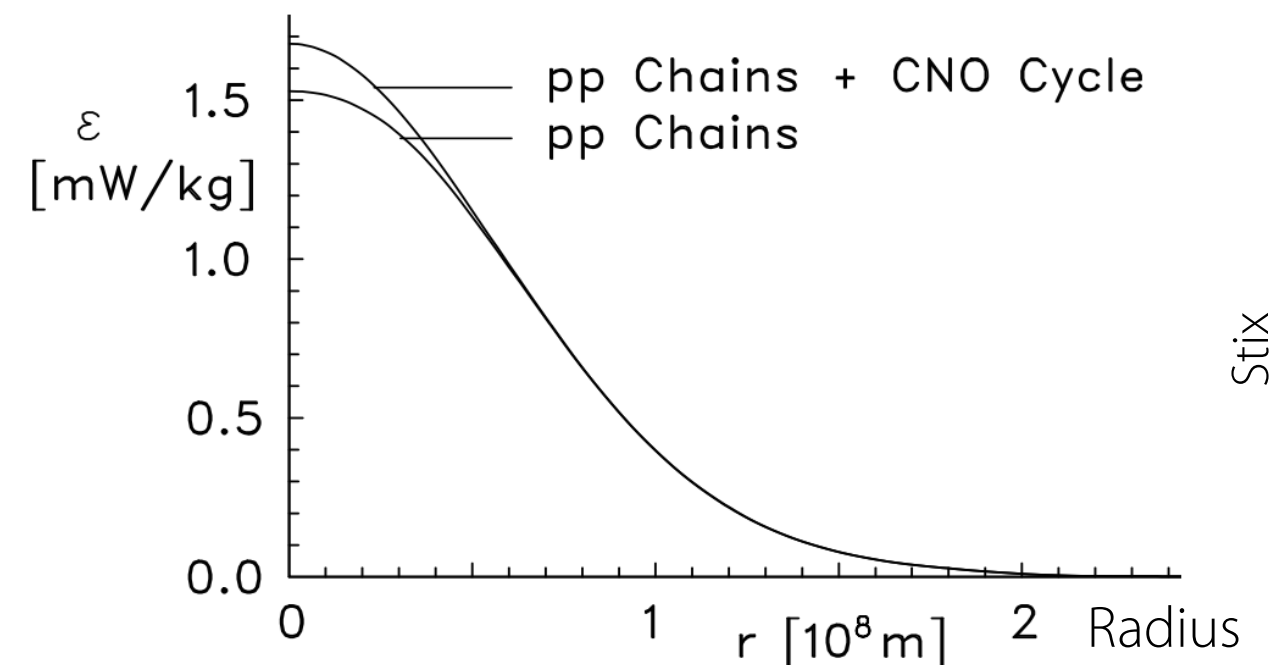
Nuclear energy — Hydrogen burning

PP1	PP2	PP3	CNO
${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu_e$ ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$ ${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2{}^1_1\text{H}$	${}^3_2\text{He} + {}^4_2\text{He} \rightarrow {}^7_4\text{Be} + \gamma$ ${}^7_4\text{Be} + e^- \rightarrow {}^7_3\text{Li} + \nu_e$ ${}^7_3\text{Li} + {}^1_1\text{H} \rightarrow 2{}^4_2\text{He}$	${}^7_4\text{Be} + {}^1_1\text{H} \rightarrow {}^8_5\text{B} + \gamma$ ${}^8_5\text{B} \rightarrow {}^8_4\text{Be} + e^+ + \nu_e$ ${}^8_4\text{Be} \rightarrow 2{}^4_2\text{He}$	${}^{12}_6\text{C} + {}^1_1\text{H} \rightarrow {}^{13}_7\text{N} + \gamma$ ${}^{13}_7\text{N} \rightarrow {}^{13}_6\text{C} + e^+ + \nu_e$ ${}^{13}_6\text{C} + {}^1_1\text{H} \rightarrow {}^{14}_7\text{N} + \gamma$ ${}^{14}_7\text{N} + {}^1_1\text{H} \rightarrow {}^{15}_8\text{O} + \gamma$ ${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + e^+ + \nu_e$ ${}^{15}_7\text{N} + {}^1_1\text{H} \rightarrow {}^{12}_6\text{C} + {}^4_2\text{He}$
69 %	31 %	<0.3%	
$T < 1.4 \cdot 10^7 \text{ K}$	$T > 1.4 \cdot 10^7 \text{ K}$	$T > 3 \cdot 10^7 \text{ K}$	

Relative occurrence in the Sun. **PP1 dominates in the current Sun.**

Temperature at which this branch dominates

- Overall nuclear energy production rate ε , either in total or by fusion chain derived as sum over all involved reactions



Energy reservoirs

Nuclear energy — Hydrogen burning

PP1	PP2	PP3	CNO
${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu_e$ ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$ ${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2{}^1_1\text{H}$	${}^3_2\text{He} + {}^4_2\text{He} \rightarrow {}^7_4\text{Be} + \gamma$ ${}^7_4\text{Be} + e^- \rightarrow {}^7_3\text{Li} + \nu_e$ ${}^7_3\text{Li} + {}^1_1\text{H} \rightarrow 2{}^4_2\text{He}$	${}^7_4\text{Be} + {}^1_1\text{H} \rightarrow {}^8_5\text{B} + \gamma$ ${}^8_5\text{B} \rightarrow {}^8_4\text{Be} + e^+ + \nu_e$ ${}^8_4\text{Be} \rightarrow 2{}^4_2\text{He}$	${}^{12}_6\text{C} + {}^1_1\text{H} \rightarrow {}^{13}_7\text{N} + \gamma$ ${}^{13}_7\text{N} \rightarrow {}^{13}_6\text{C} + e^+ + \nu_e$ ${}^{13}_6\text{C} + {}^1_1\text{H} \rightarrow {}^{14}_7\text{N} + \gamma$ ${}^{14}_7\text{N} + {}^1_1\text{H} \rightarrow {}^{15}_8\text{O} + \gamma$ ${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + e^+ + \nu_e$ ${}^{15}_7\text{N} + {}^1_1\text{H} \rightarrow {}^{12}_6\text{C} + {}^4_2\text{He}$
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