Outline: Hydrogen burning

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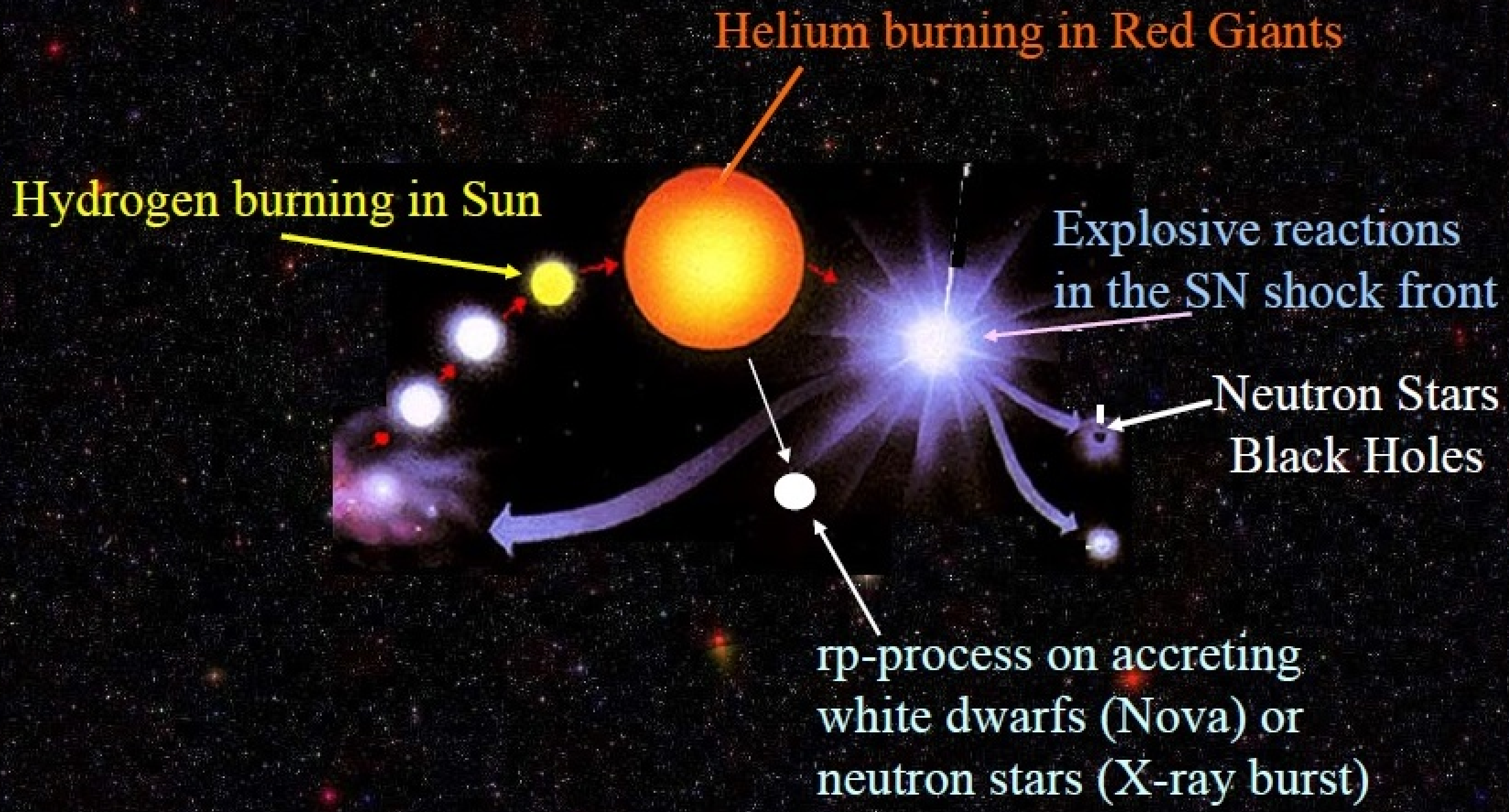
Kernphysik Skript

1. Sun properties
2. p-p chains
3. neutrino emission



Helium burning in Red Giants

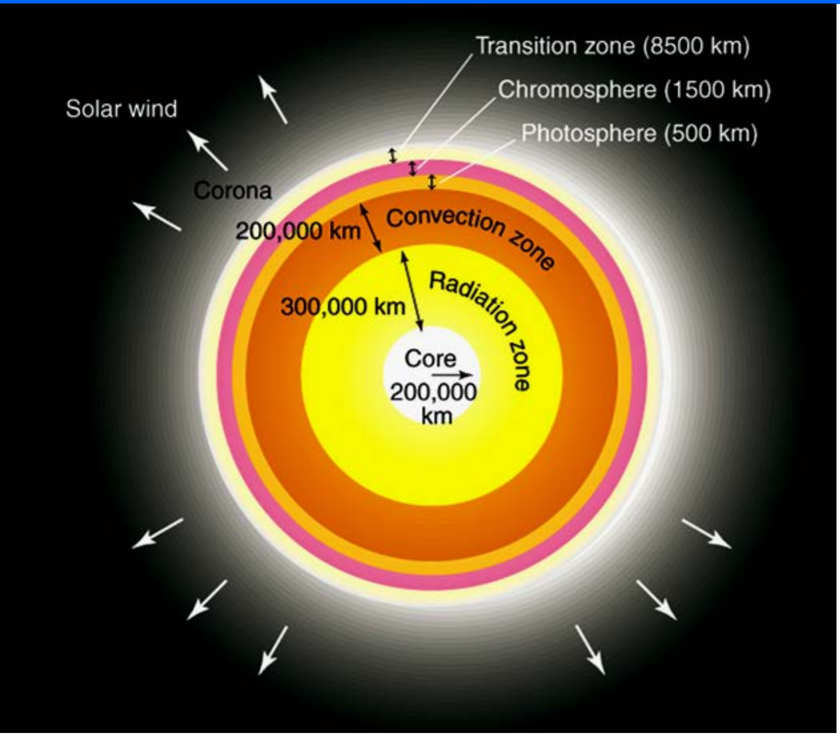
Hydrogen burning in Sun

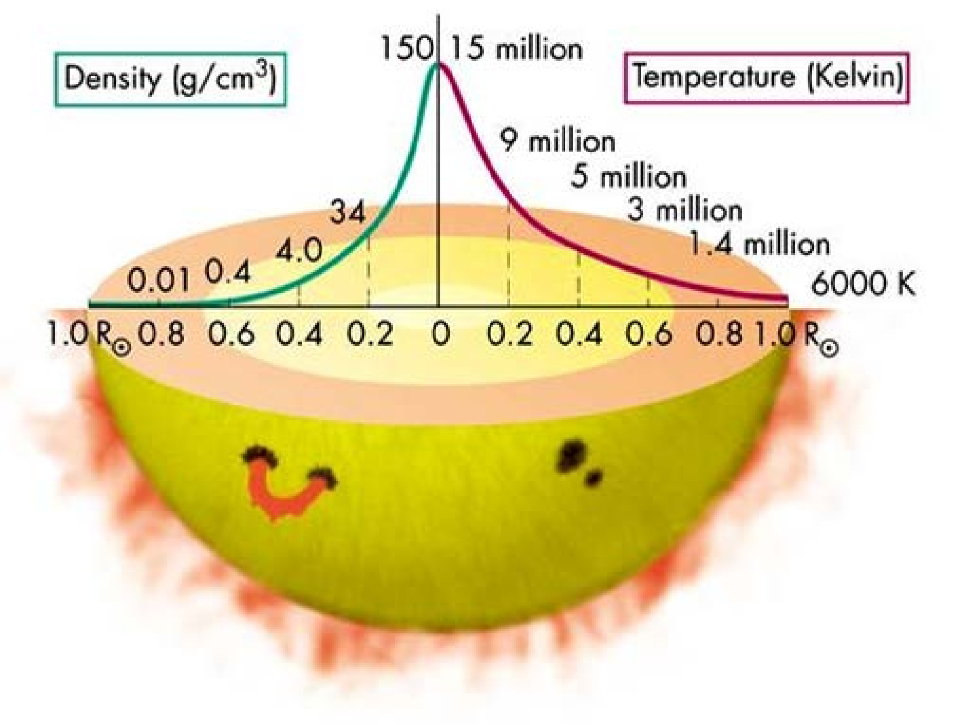
Explosive reactions
in the SN shock front

Neutron Stars
Black Holes

rp-process on accreting
white dwarfs (Nova) or
neutron stars (X-ray burst)

Properties of the Sun

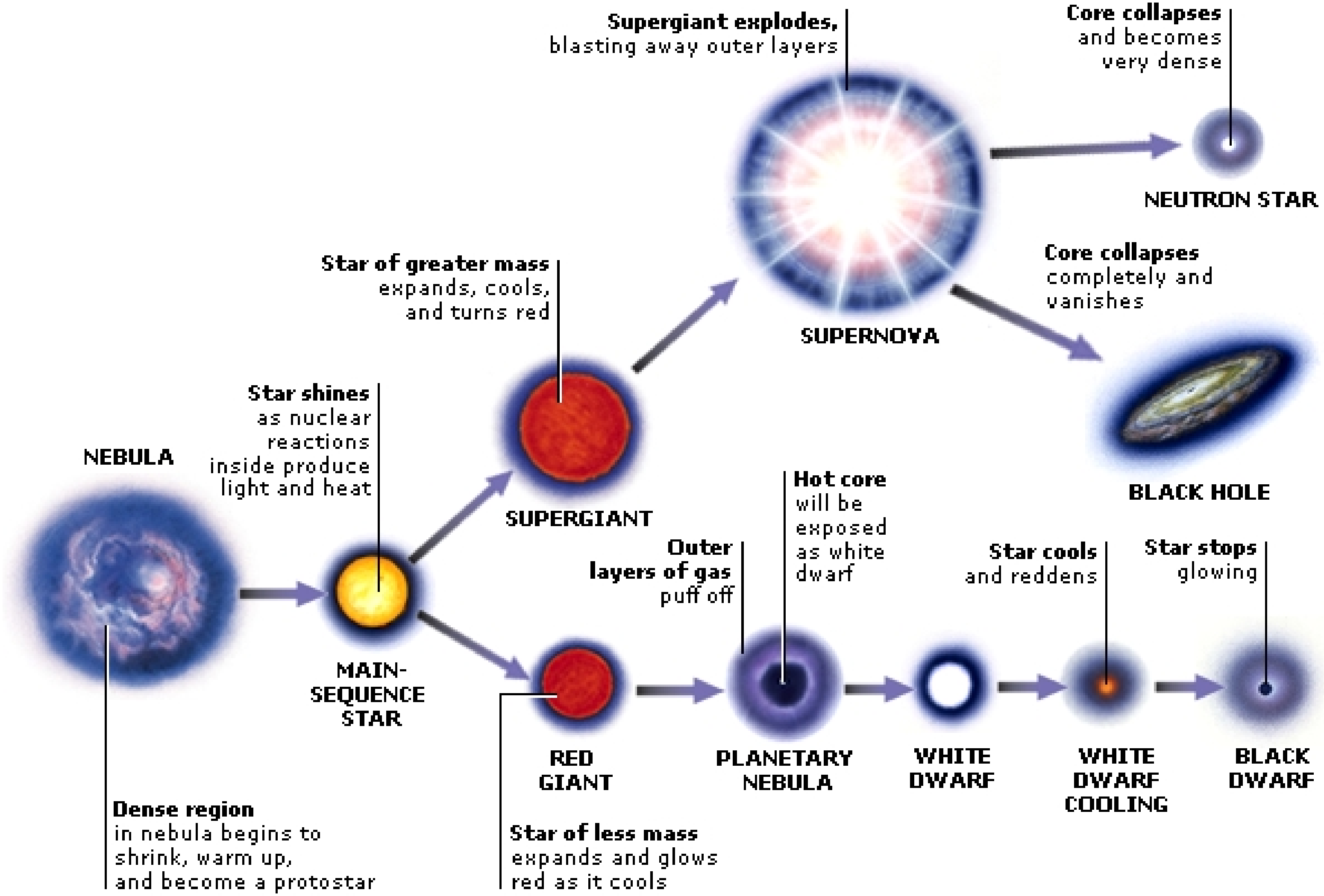


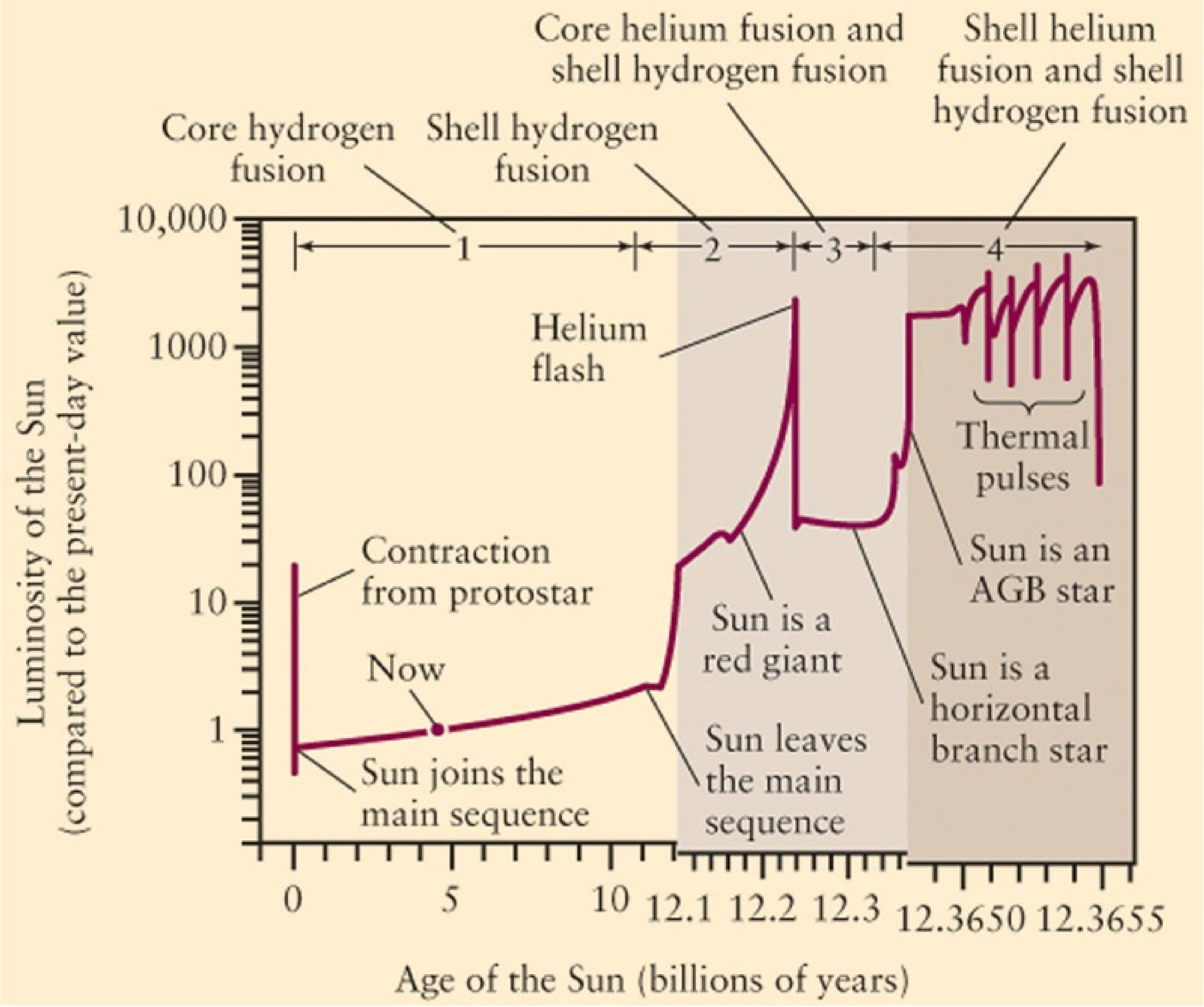


Radius: $7 \cdot 10^8$ m
Mass: $2 \cdot 10^{39}$ kg
Density: 1.4 g/cm^3

Luminosity: ~ $4 \cdot 10^{26}$ W

Hydrogen	73.46%
Helium	24.85%
Oxygen	0.77%
Carbon	0.29%
Iron	0.16%
Neon	0.12%
Nitrogen	0.09%


Supergiant explodes,
blasting away outer layers
Core collapses
and becomes
very dense
NEUTRON STAR
SUPERNOVA
Core collapses
completely and
vanishes
Star of greater mass
expands, cools,
and turns red
BLACK HOLE
Star shines
as nuclear
reactions
inside produce
light and heat
NEBULA
SUPERGIANT
Hot core
will be
exposed
as white
dwarf
Outer
layers of gas
puff off
Star cools
and reddens
Star stops
glowing
MAIN-
SEQUENCE
STAR
RED
GIANT
PLANETARY
NEBULA
WHITE
DWARF
WHITE
DWARF
COOLING
BLACK
DWARF
Dense region
in nebula begins to
shrink, warm up,
and become a protostar
Star of less mass
expands and glows
red as it cools


Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
Core hydrogen fusion
Shell hydrogen fusion
1
2
3
4
10,000
1000
100
10
1
Helium flash
Contraction from protostar
Now
Sun joins the main sequence
Sun is a red giant
Sun leaves the main sequence
Thermal pulses
Sun is an AGB star
Sun is a horizontal branch star
Luminosity of the Sun (compared to the present-day value)
0
5
10
12.1
12.2
12.3
12.3650
12.3655
Age of the Sun (billions of years)

Why does the star expand and become a red giant?

Because of higher Coulomb barrier He burning requires much higher temperatures
→ drastic change in central temperature
→ star has to readjust to a new configuration

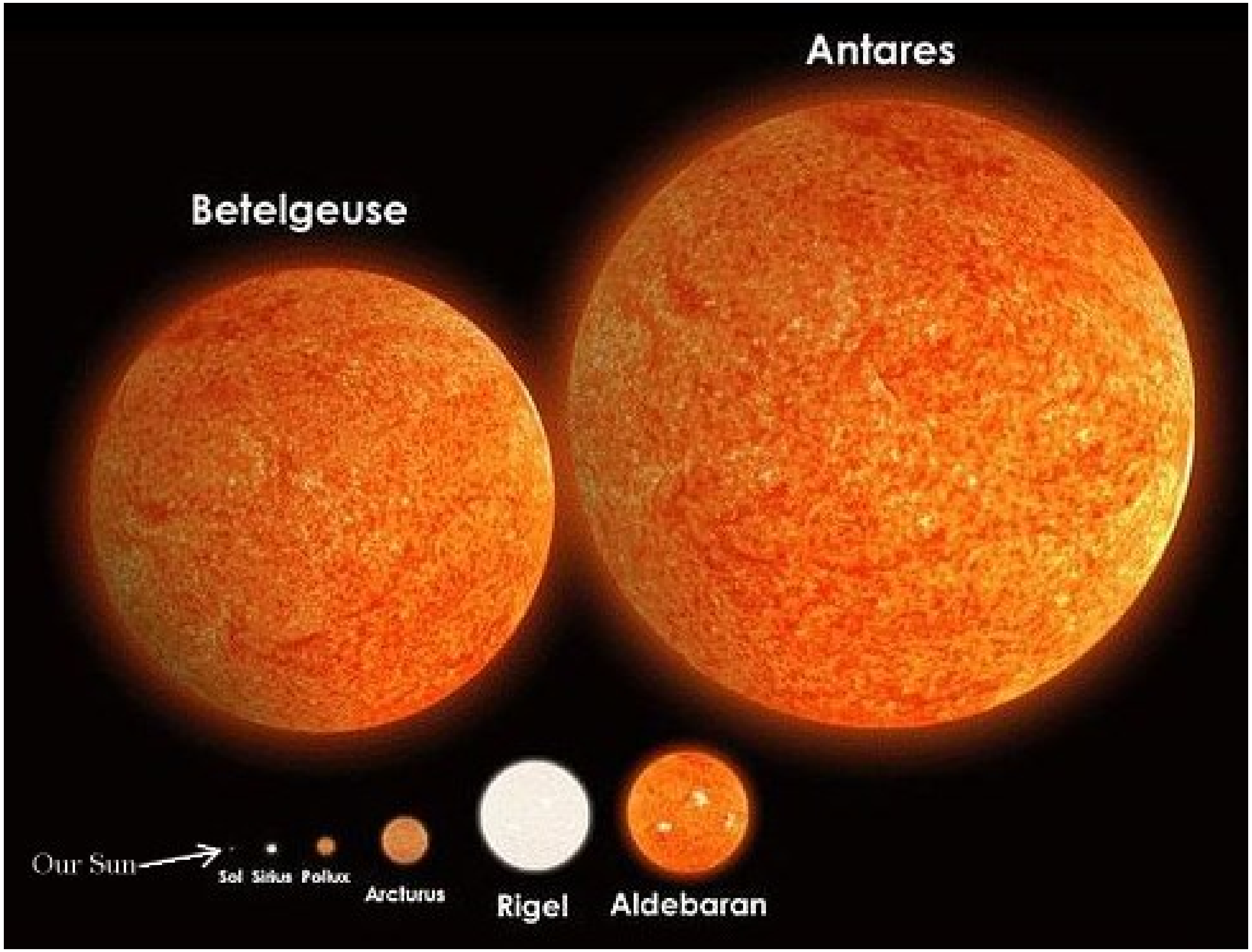
Qualitative argument:

- need about the same Luminosity – similar temperature gradient dT/dr
- now much higher T_c – need larger star for same dT/dr

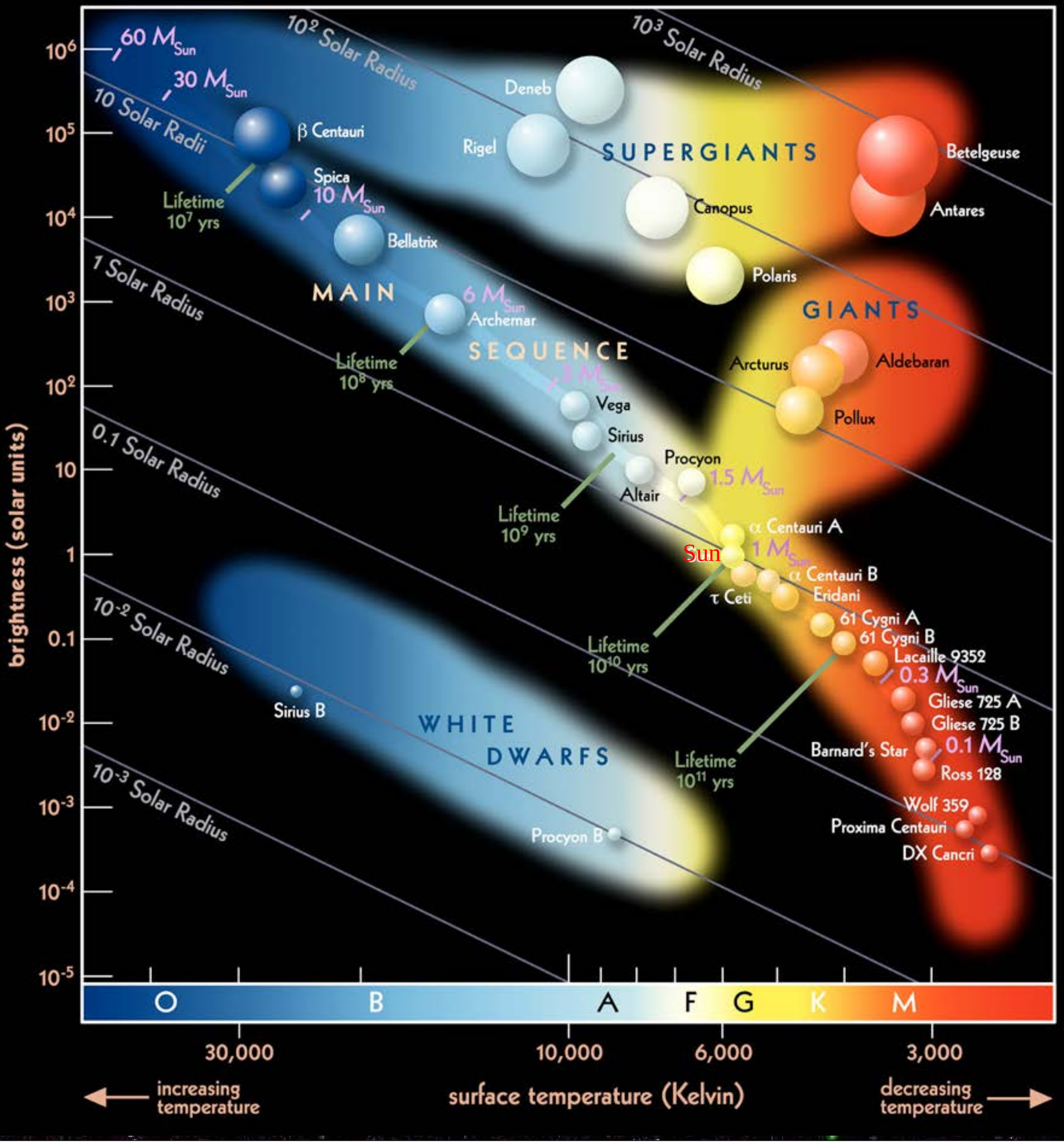
Lower mass stars become red giants during shell H-burning

If the sun becomes a red giant in about 5 Bio years, it will almost fill the orbit of Mars

Red Giants

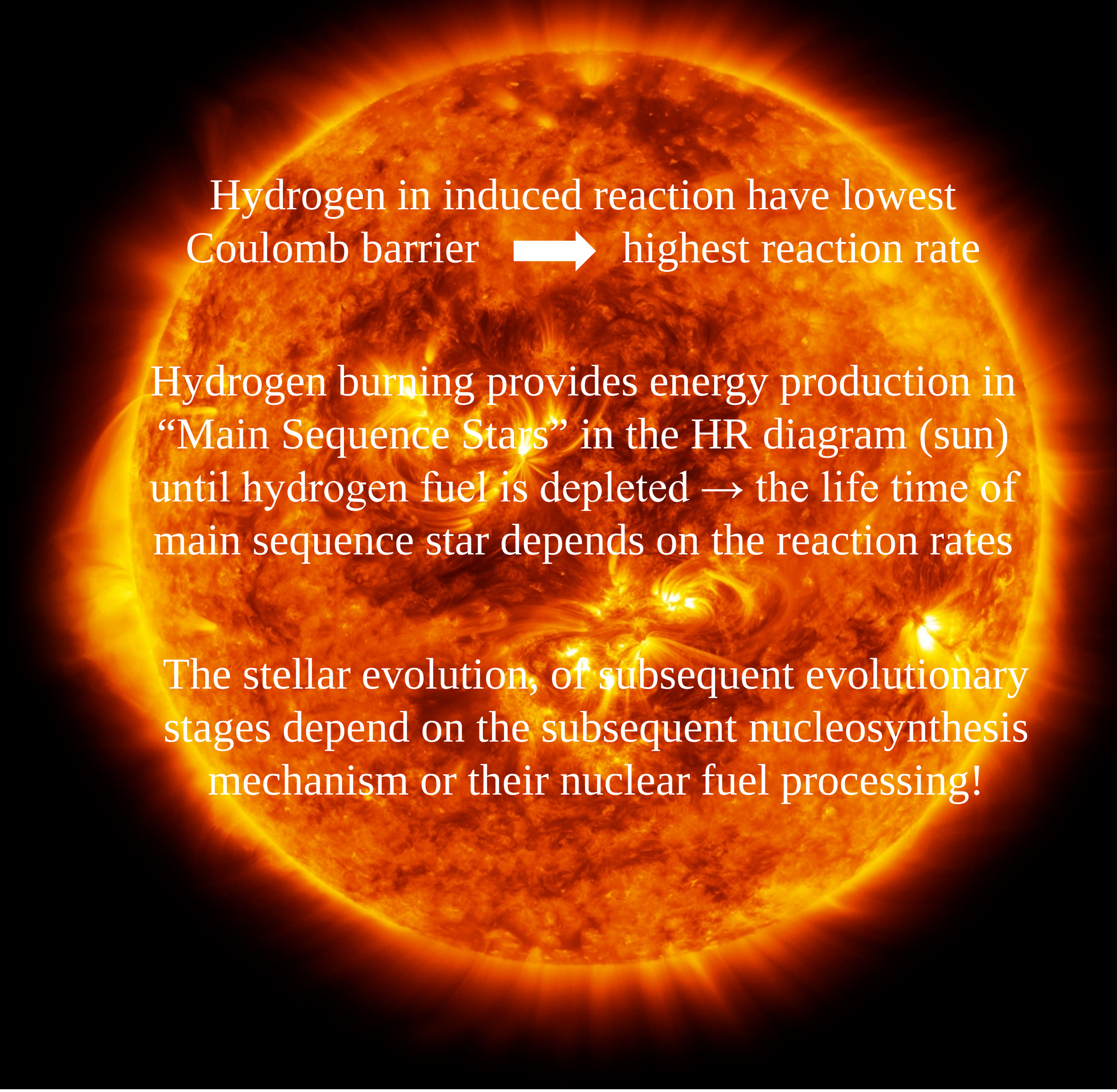

Antares
Betelgeuse
Our Sun
Sol
Sirius
Pollux
Arcturus
Rigel
Aldebaran

Hertzsprung Russell Diagram



Main Sequence Stars are identified as stars in their hydrogen burning stage. As more massive the star is as larger its size, its energy production (temperature) and its luminosity

Hydrogen burning in stars



Hydrogen in induced reaction have lowest Coulomb barrier → highest reaction rate

Hydrogen burning provides energy production in “Main Sequence Stars” in the HR diagram (sun) until hydrogen fuel is depleted → the life time of main sequence star depends on the reaction rates

The stellar evolution, of subsequent evolutionary stages depend on the subsequent nucleosynthesis mechanism or their nuclear fuel processing!

The p-p chains

As a star forms density and temperature (heat source?) increase in its center

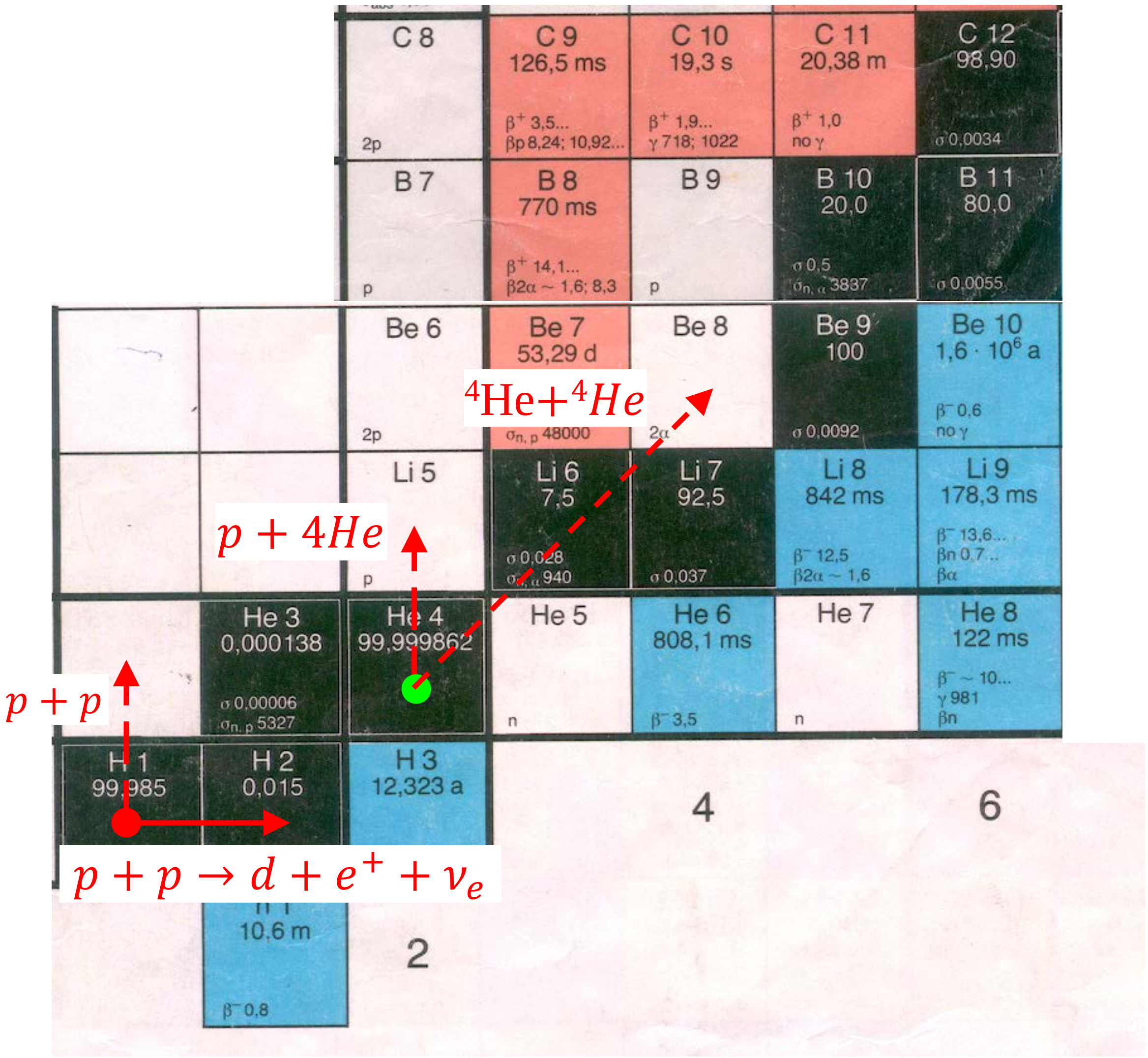
Fusion of hydrogen (^{1}H) is the first long term nuclear energy source that can ignite.
Why?

With only hydrogen available (for example in a first generation star right after it´s formation) the p-p chain is the only possible sequence of reactions.
(all other reaction sequences require the presence of catalyst nuclei)

3- or 4-body reactions are too unlikely – chain has to proceed by steps of 2-body reactions or decays.

Final product is ^{4}He

pp-chains



pp-chains: ^{1}H ⟶ ^{4}He

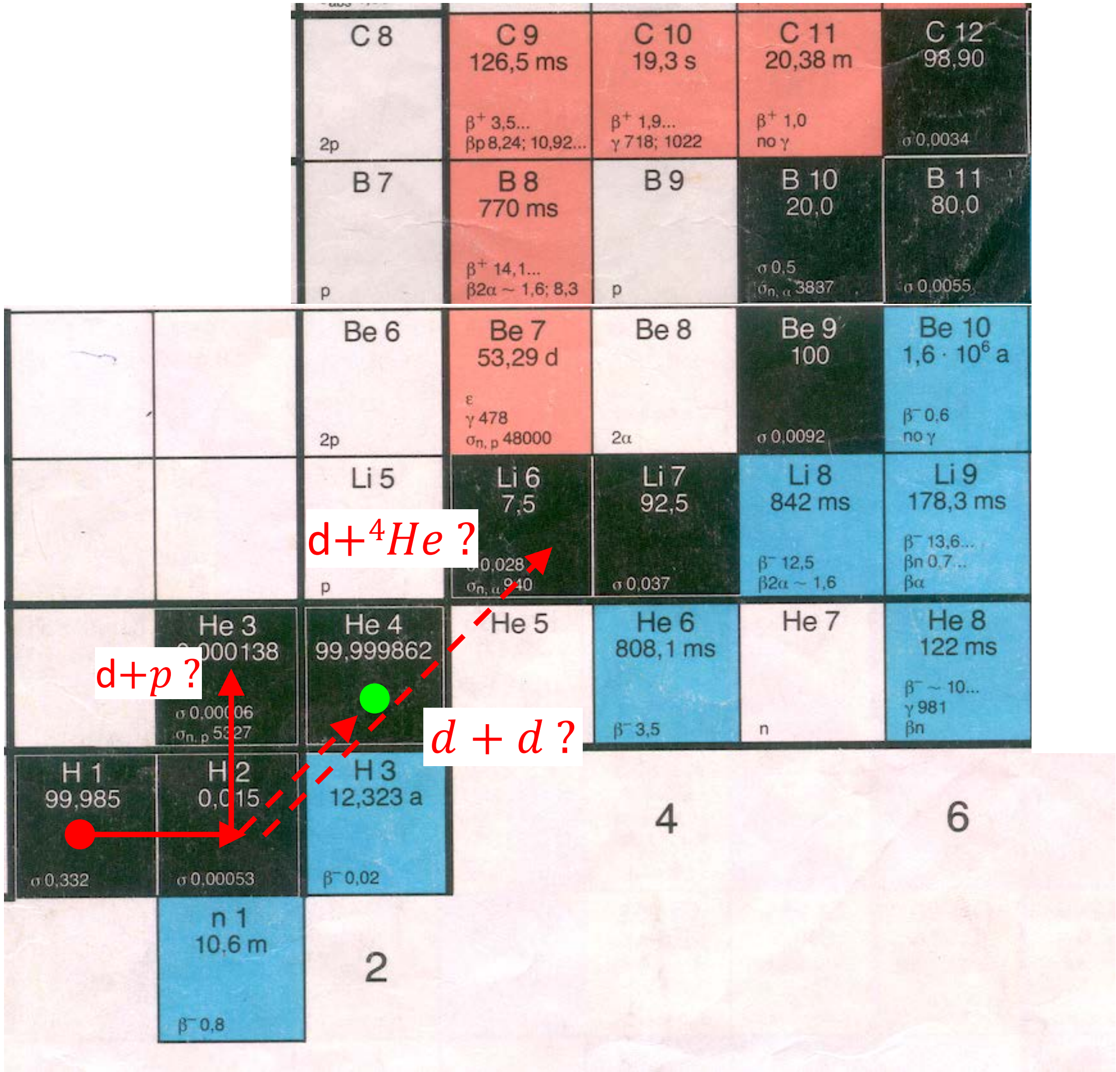
step 1:

- available: ^{1}H, some ^{4}He

$p + p \rightarrow d + e^+ + \nu_e$

- no atoms exist in nature with an A = 5 or 8

pp-chains



pp-chains: ^{1}H ⟶ ^{4}He

step 1:

- available: ^{1}H, some ^{4}He

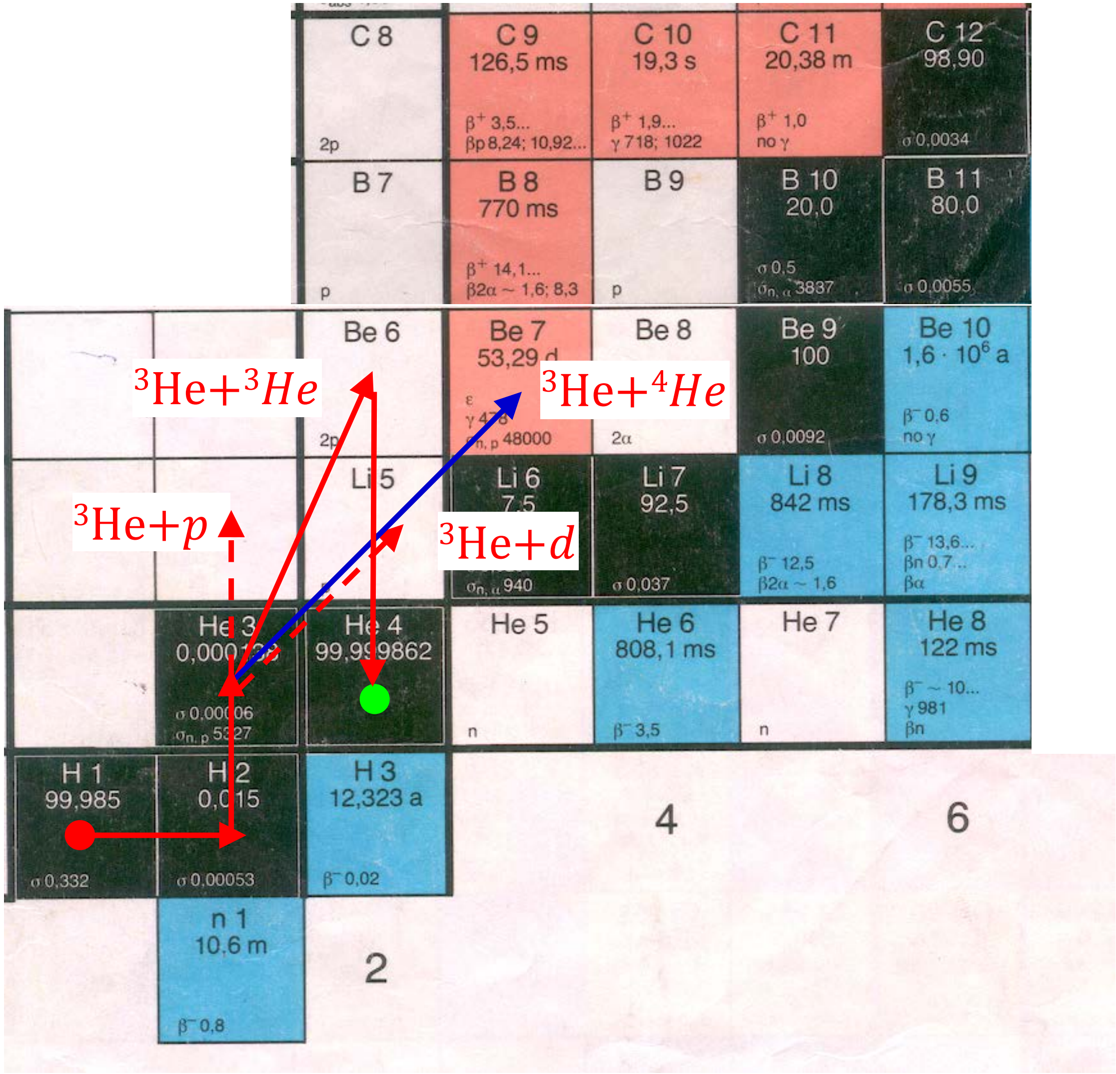
$$p + p \rightarrow d + e^+ + \nu_e$$

step 2:

- available: ^{1}H, some d, ^{4}He

$$\mathrm{d} + p \rightarrow {}^3He$$

pp-chains



pp-chains: ^{1}H ⟶ ^{4}He

step 1:

- available: ^{1}H, some ^{4}He

$p + p \rightarrow d + e^+ + \nu_e$

step 2:

- available: ^{1}H, some d, ^{4}He

$d + p \rightarrow {}^3He$

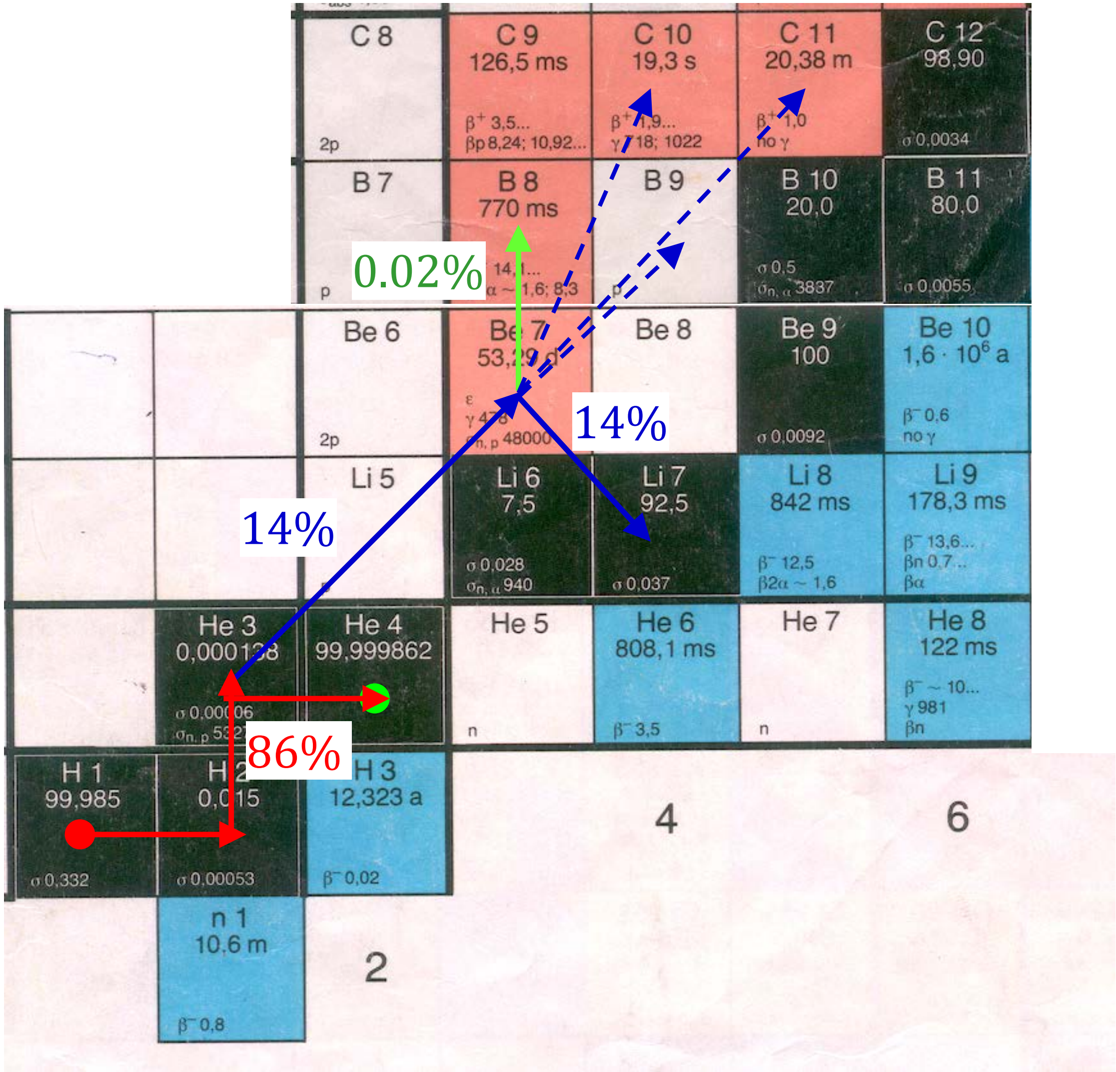
step 3:

- available: ^{1}H, some ^{3}He, ^{4}He
  little d (rapid destruction)

86% $^3He + 3He \rightarrow 2p + 4He$

14% $^3He + 4He \rightarrow {}^7Be$

pp-chains



pp-chains: ^{1}H ⟶ ^{4}He

step 1:

- available: ^{1}H, some ^{4}He

$p + p \rightarrow d + e^+ + \nu_e$

step 2:

- available: ^{1}H, some d, ^{4}He

$d + p \rightarrow {}^3He$

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86% $^3He + 3He \rightarrow 2p + 4He$

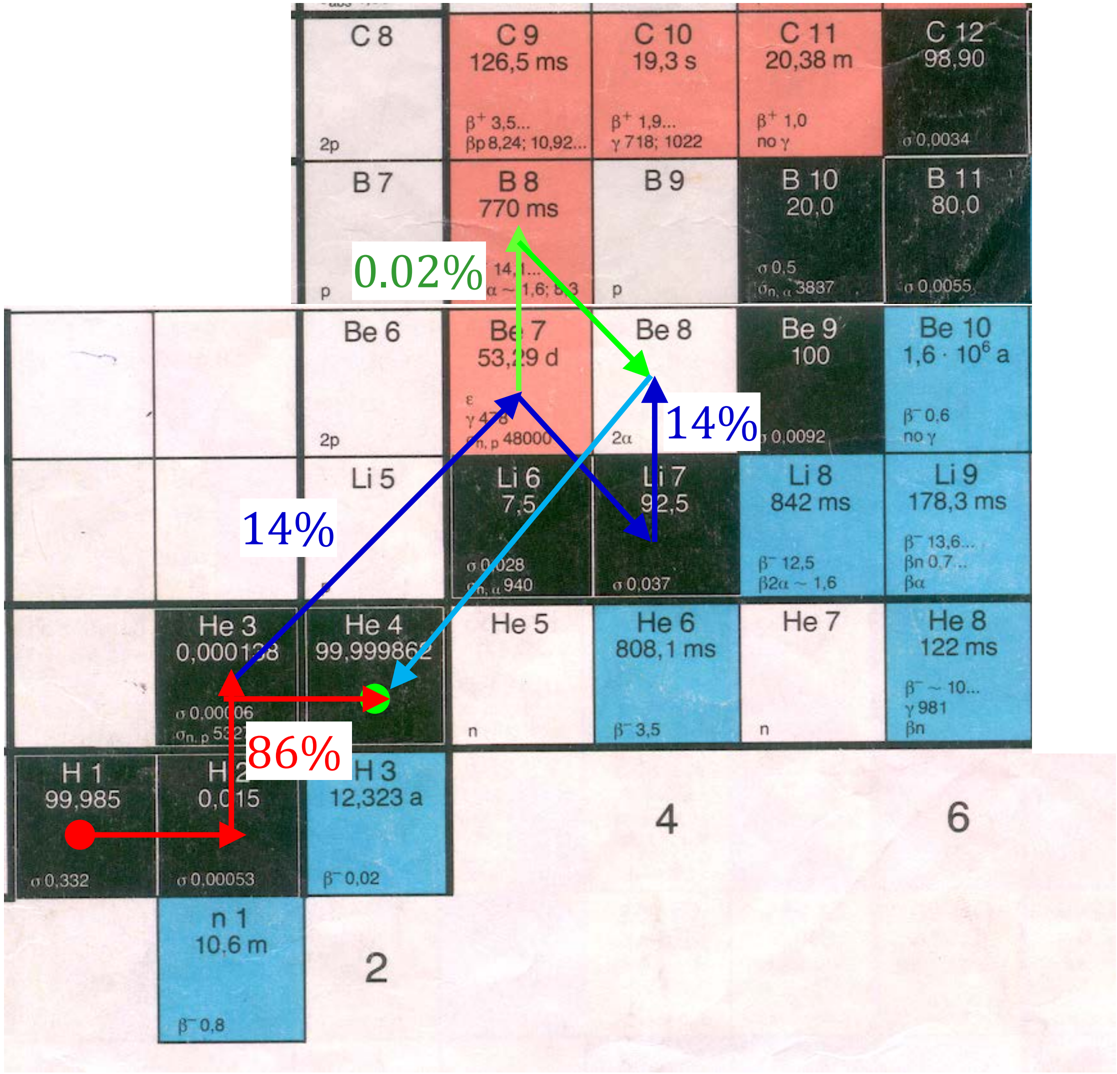
14% $^3He + 4He \rightarrow {}^7Be$

step 4:

14% $^7Be + e^- \rightarrow {}^7Li + \nu_e$

0.02% $^7Be + p \rightarrow {}^8B$

pp-chains



pp-chains: $^{1}\text{H} \longrightarrow {}^{4}\text{He}$

step 1:

- available: ^{1}H, some ^{4}He

$$p + p \rightarrow d + e^{+} + \nu_e$$

step 2:

- available: ^{1}H, some d, ^{4}He

$$\mathrm{d} + p \rightarrow {}^{3}He$$

step 3:

- available: ^{1}H, some ^{3}He, ^{4}He
  little d (rapid destruction)

86% $^{3}He + 3He \rightarrow 2p + 4He$

14% $^{3}He + 4He \rightarrow {}^{7}Be$

step 4:

14% $^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

0.02% $^{7}Be + p \rightarrow {}^{8}B$

step 5:

$$\left.\begin{array}{l} {}^{7}Li + p \rightarrow {}^{8}Be \\ {}^{8}B \rightarrow e^{+} + \nu_e + {}^{8}Be \end{array}\right\} 2 * {}^{4}He$$

Summary pp-chain

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86% | 14%

pp-I Q_{eff}= 26.20 MeV

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

pp-II Q_{eff}= 25.66 MeV — 99.7% | 0.3% — **pp-III** Q_{eff}= 19.17 MeV

pp-II:

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\ {}^4He$

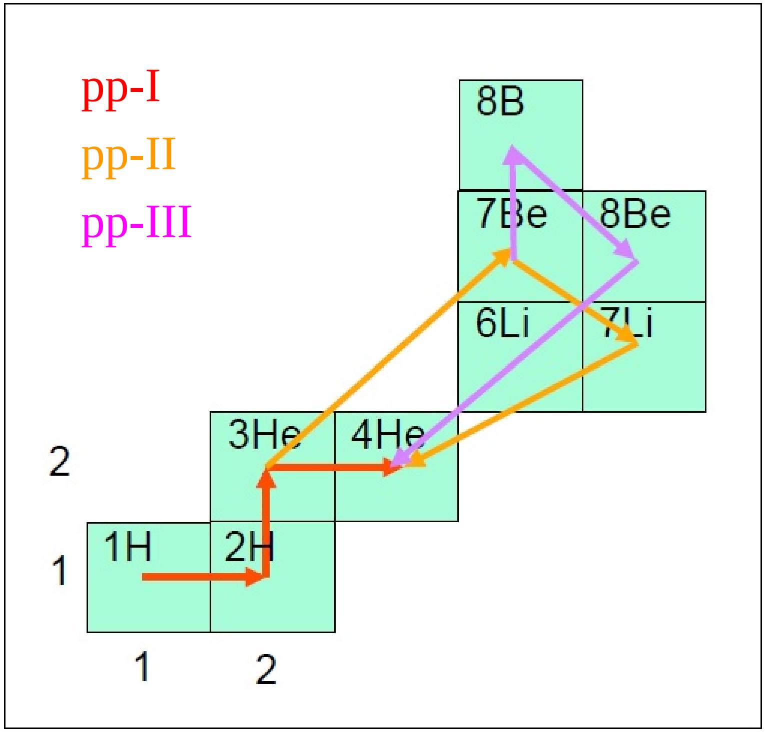
pp-III:

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

$2\ {}^4He$



net result: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + Q_{eff}$

Why do additional pp-chains matter?

p+p dominates timescale BUT
pp-I produces 50% ^{4}He per p+p reaction
pp-II or III produces 1 ^{4}He per p+p reaction

→ increase burning rate

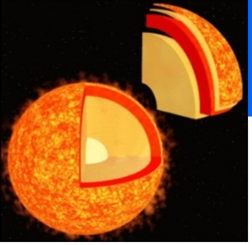
Solar fusion: the pp-chain

	uncertainty in reaction rate		branching
pp-1:	5%	${}^{1}H(p,e^{+}\nu)\,{}^{2}H$	
	5%	${}^{2}H(p,\gamma)\,{}^{2}He$	
	7%	${}^{3}He\left({}^{3}He,2p\right)\,{}^{4}He$	84.7%
pp-2	3%	${}^{3}He(\alpha,\gamma)\,{}^{7}Be$	13.8%
		${}^{7}Be(e^{-},\nu)\,{}^{7}Li$	13.78%
	13%	${}^{7}Li(p,\alpha)\,{}^{4}He$	
pp-3	5-10%	${}^{7}Be(p,\gamma)\,{}^{8}B$	0.02%
		${}^{8}B(e^{+},\nu)2\,{}^{4}He$	

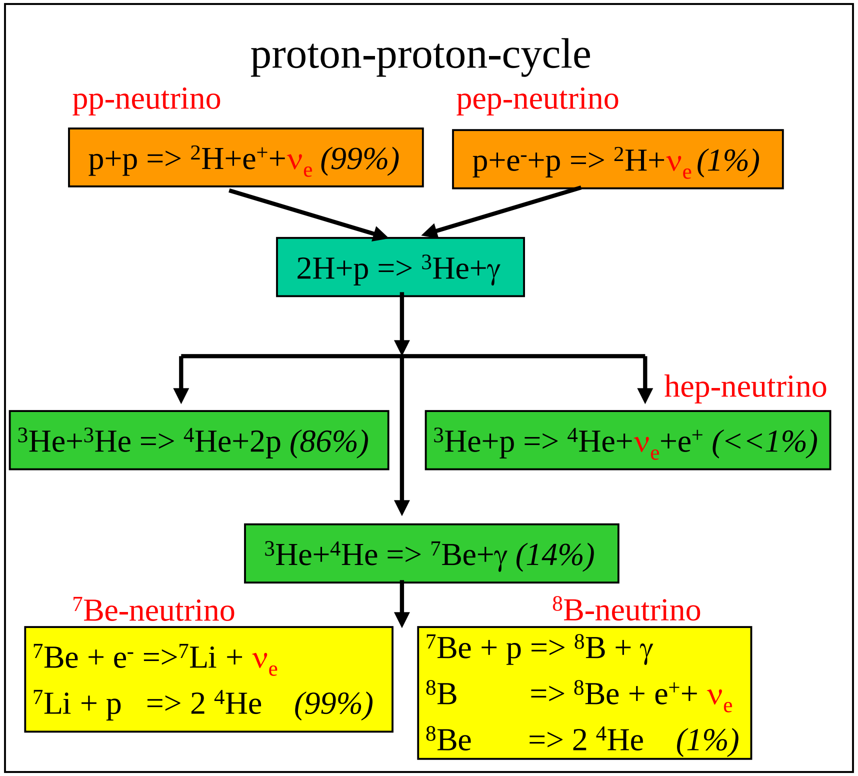
only ν most experiments measure

fusion of 26.7 MeV energy released

Neutrinos from the sun



$$4\ \text{protons} \rightarrow \text{He-nucleus} + 2e^{+} + 2\nu + 26\,MeV$$



proton-proton-cycle

pp-neutrino

$p+p => {}^{2}H+e^{+}+\nu_e$ *(99%)*

pep-neutrino

$p+e^{-}+p => {}^{2}H+\nu_e$ *(1%)*

$2H+p => {}^{3}He+\gamma$

${}^{3}He+{}^{3}He => {}^{4}He+2p$ *(86%)*

hep-neutrino

${}^{3}He+p => {}^{4}He+\nu_e+e^{+}$ *(<<1%)*

${}^{3}He+{}^{4}He => {}^{7}Be+\gamma$ *(14%)*

^{7}Be-neutrino

${}^{7}Be + e^{-} => {}^{7}Li + \nu_e$

${}^{7}Li + p \quad => 2\ {}^{4}He$ *(99%)*

^{8}B-neutrino

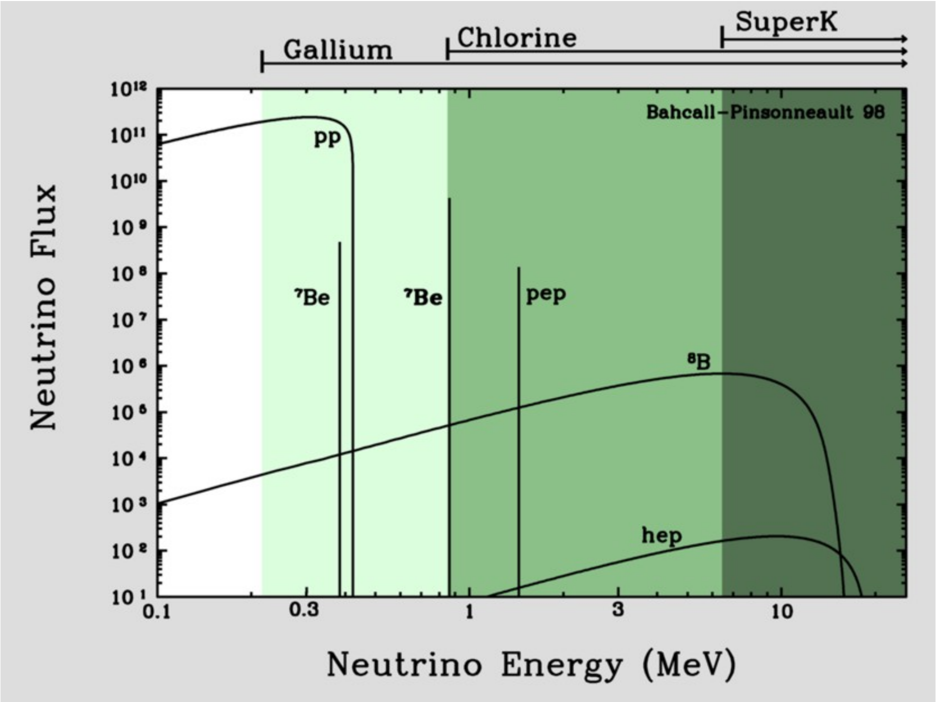
${}^{7}Be + p => {}^{8}B + \gamma$

${}^{8}B \quad => {}^{8}Be + e^{+} + \nu_e$

${}^{8}Be \quad => 2\ {}^{4}He$ *(1%)*

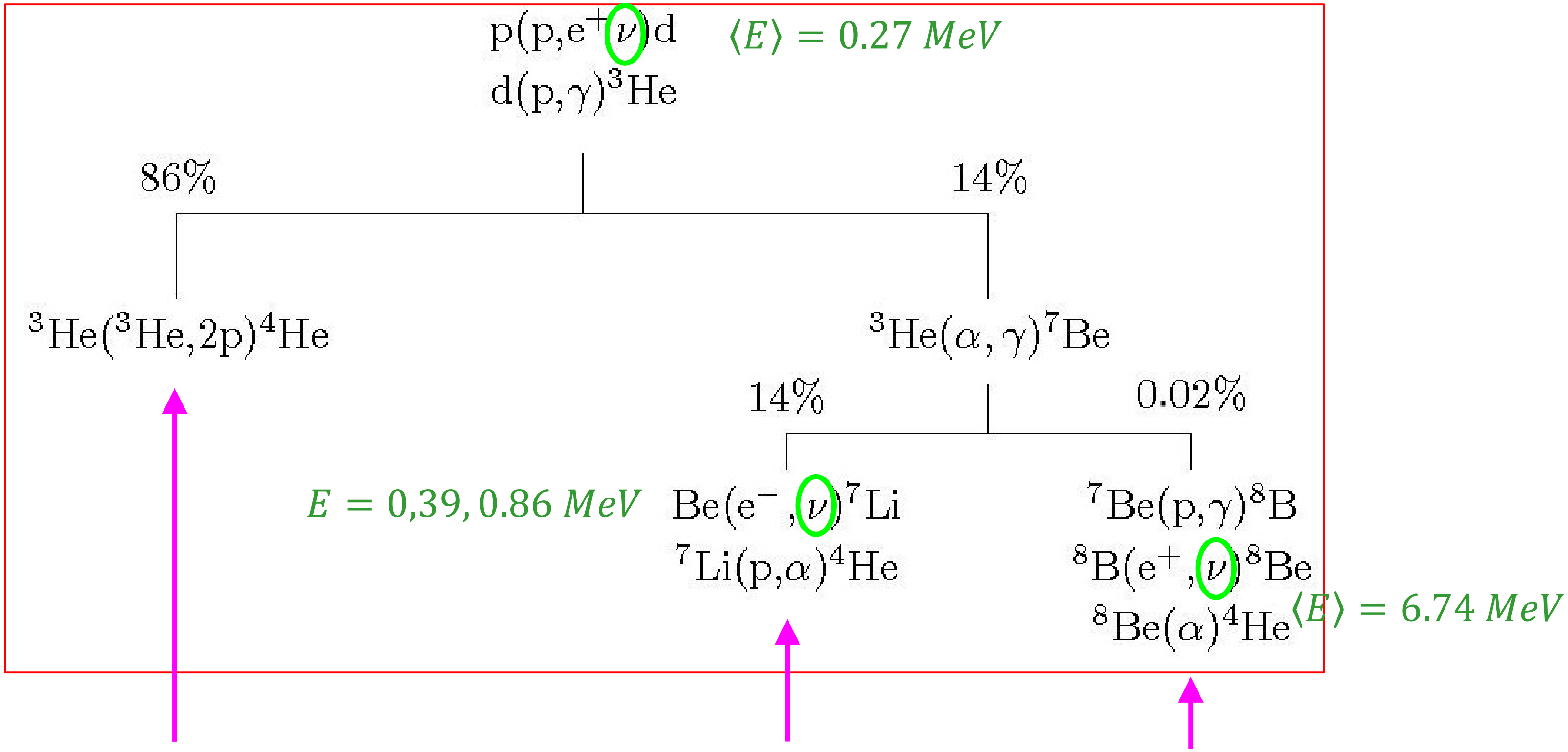
- Known: total emitted energy
- Known: energy per fusion process

➢ number of created neutrinos per sec!
on earth: 66 billions ν per ($cm^2 \cdot s^1$)



Solar neutrino energy spectrum

Neutrino emission



$p(p,e^+\nu)d$ $\langle E \rangle = 0.27\ MeV$

$d(p,\gamma)^3He$

86%

14%

$^3He(^3He,2p)^4He$

$^3He(\alpha,\gamma)^7Be$

14%

0.02%

$E = 0{,}39, 0.86\ MeV$ $Be(e^-,\nu)^7Li$

$^7Li(p,\alpha)^4He$

$^7Be(p,\gamma)^8B$

$^8B(e^+,\nu)^8Be$

$^8Be(\alpha)^4He$ $\langle E \rangle = 6.74\ MeV$

pp-I loss: ~2%

pp-II loss: 4%

pp-III loss: 28%

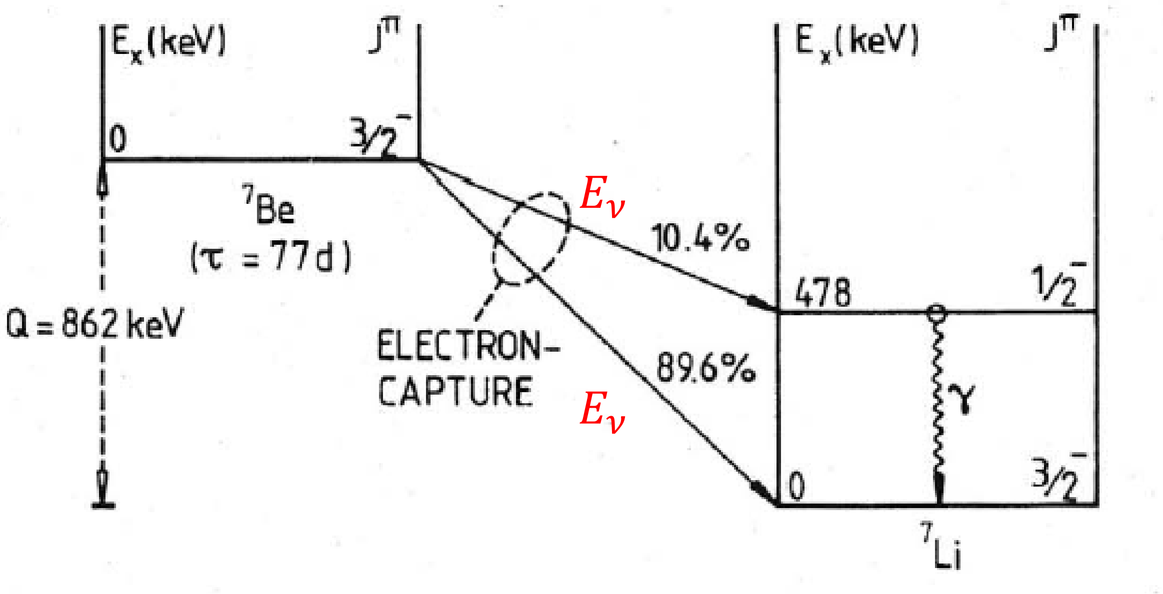
note: <E>/Q = 0,27/26.73 = **1%**

total loss: 2.3%

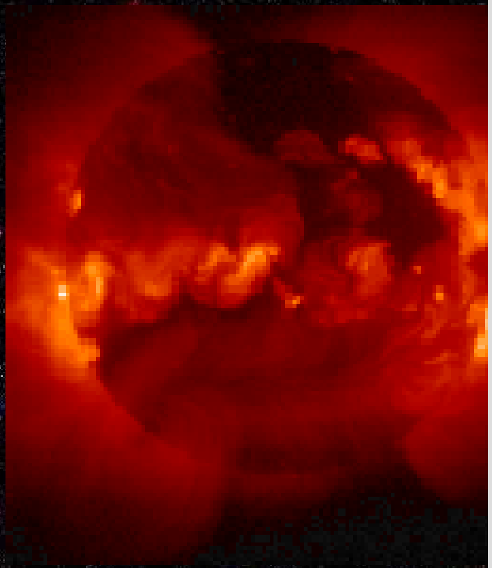
Neutrino emission

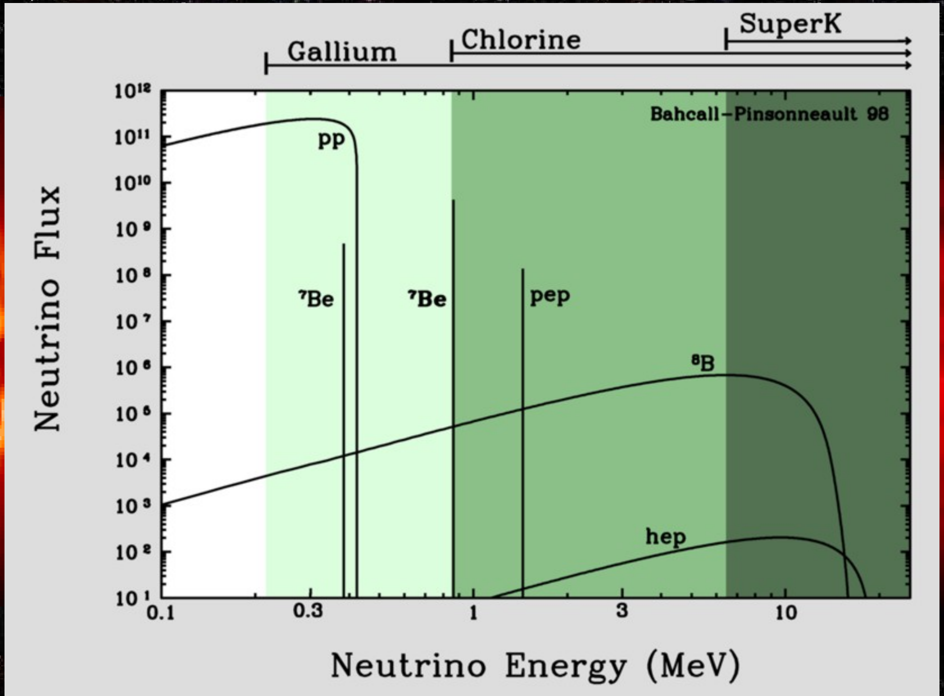
2 neutrino energies from ^{7}Be electron capture?

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

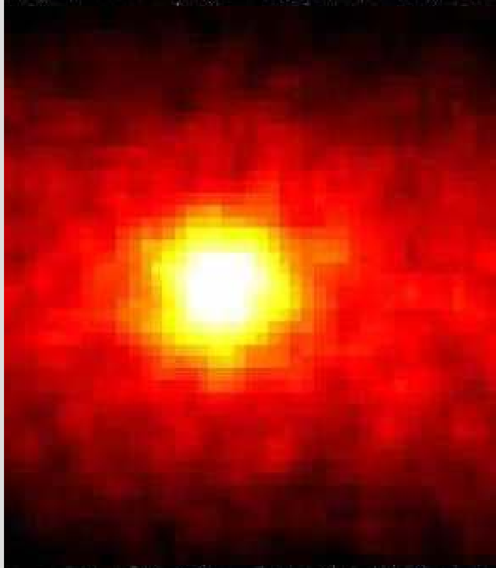


Solar Neutrino Production





Solar neutrino energy spectrum



Neutrinos as signature for probing the solar core