The sun shines 3.85e33 erg/s = 3.85e26 Watts for at least ~4.5 bio years

1. H – burning reactions PART 1
2. Introduction to reaction rates

… and its all nuclear physics:

- 1905 Einstein finds $E=mc^2$
- 1920 Aston measures mass defect of helium (!= 4p's)
- 1920 Nuclear Astrophysics is born with Sir Arthur Eddington remarks in his presidential address to the British Association for the Advancement of Science:

> "Certain physical investigations in the past year make it probable to my mind that some portion of sub-atomic energy is actually set free in the stars … If only five percent of a star's mass consists initially of hydrogen atoms which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy"

> "If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulllment our dream of controlling this latent power for the well-being of the human race|or for its suicide."

… continued history of understanding of energy generation in the sun

1928 G. Gamov: Tunnel Effect

1938 H. A. Bethe and C. L. Critchfield:
"The formation of deuterons
by proton combination"

1938/1939 H. A. Bethe
C. F. Weizaecker
} CNO Cycle

H. Bethe in Michigan

The p-p chains

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

Fusion of hydrogen (^1H) 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 ppI chain is the only possible sequence of reactions. (all other reaction sequences require the presence of catalyst nuclei)

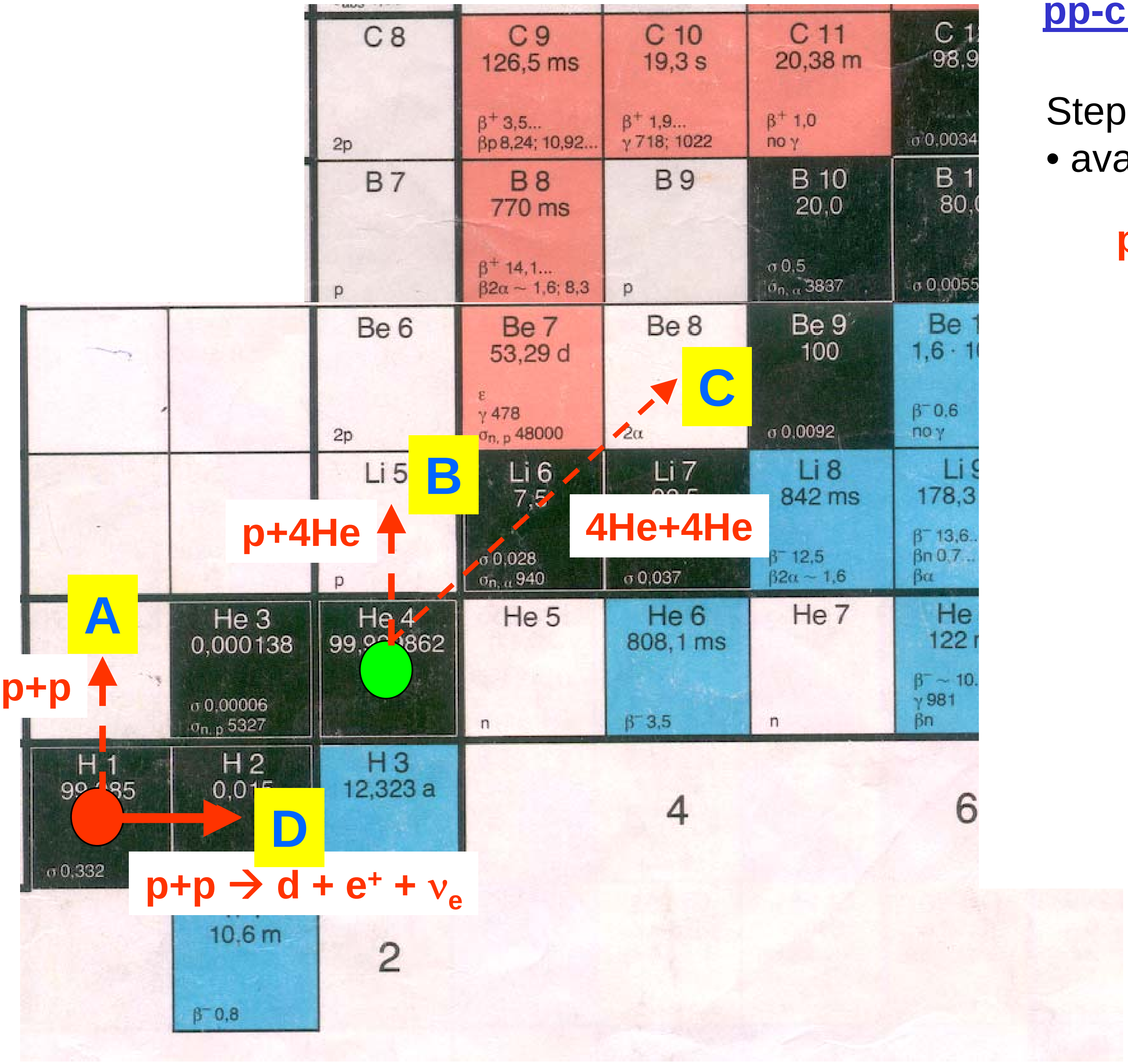
3- or 4-body reactions are too unlikely – chain has to proceed by steps of 2-body reactions or decays.

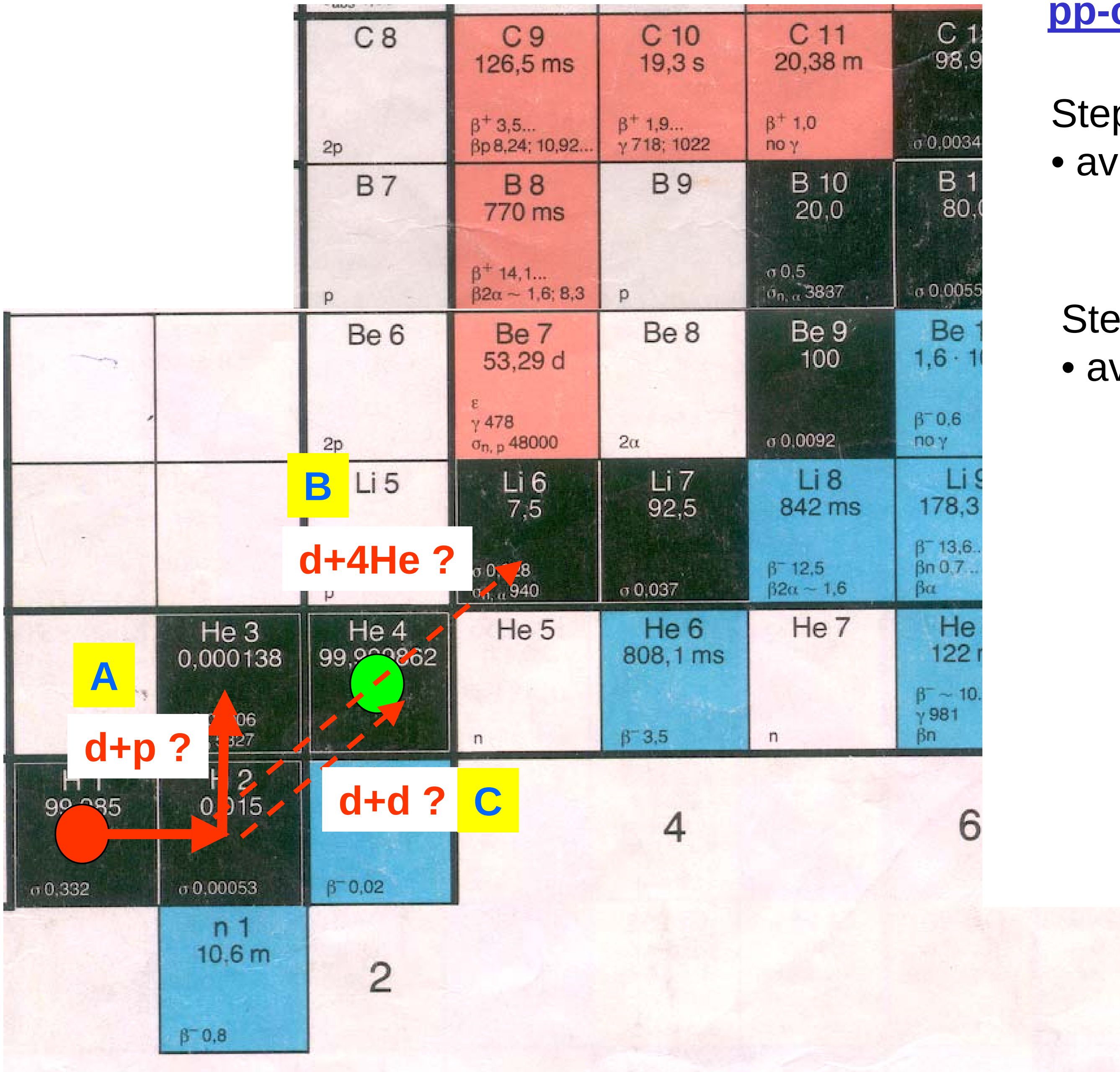
pp-chains: 1H → 4He

Step 1:

- available: ^1H, some ^4He

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





pp-chains: 1H → 4He

Step 1:

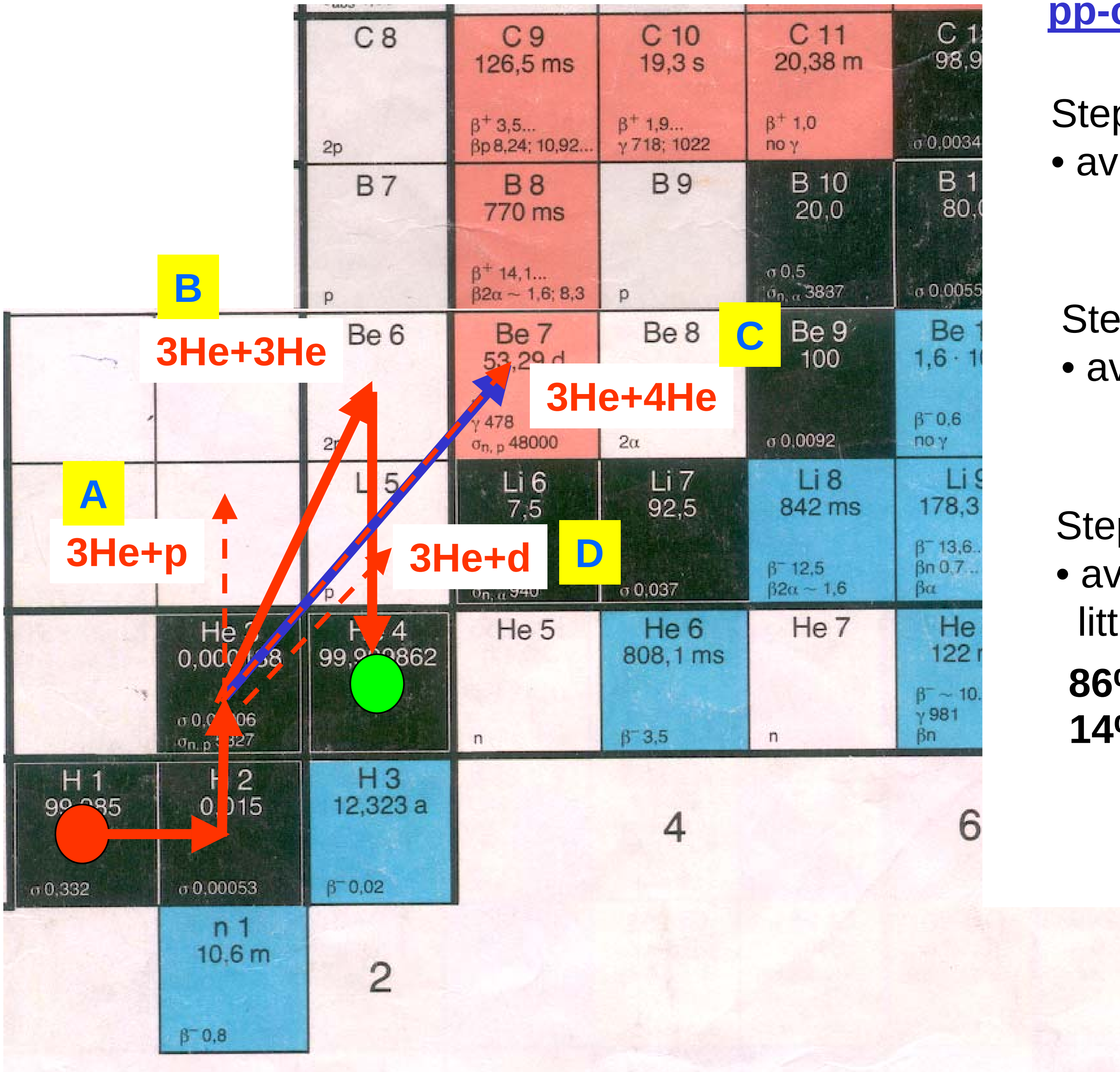
- available: ^{1}H, some ^{4}He

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

Step 2:

- available: p, some d, ^{4}He

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



pp-chains: 1H → 4He

Step 1:

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

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

Step 2:

- available: p, some d,^{4}He

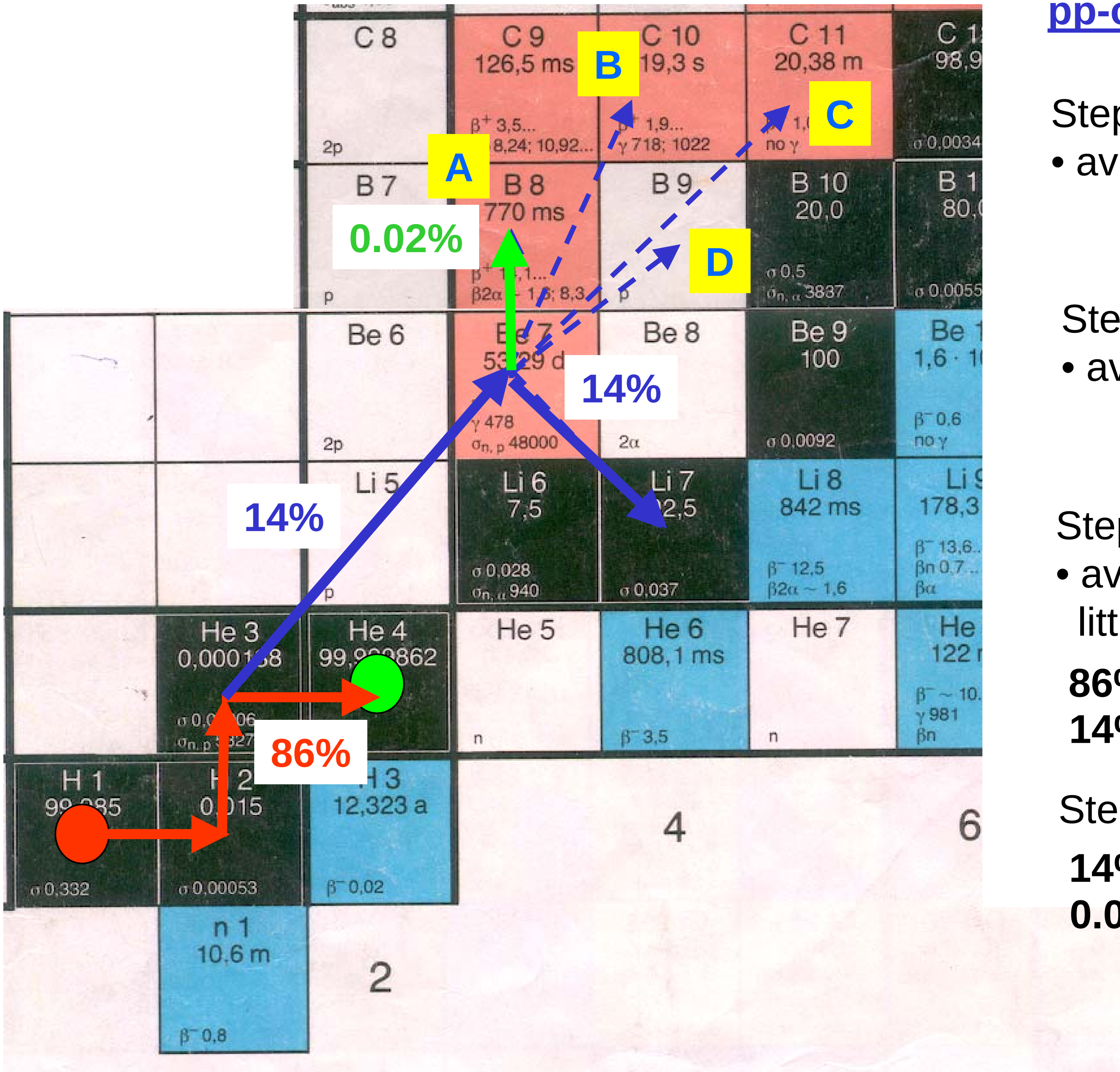
$$d+p \rightarrow 3He$$

Step 3:

- available: p, some 3He,4He little d (rapid destruction)

86% 3He+3He → 2p + 4He

14% 3He+4He → 7Be



pp-chains: 1H → 4He

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

Step 2:

- available: p, some d,^{4}He

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Step 3:

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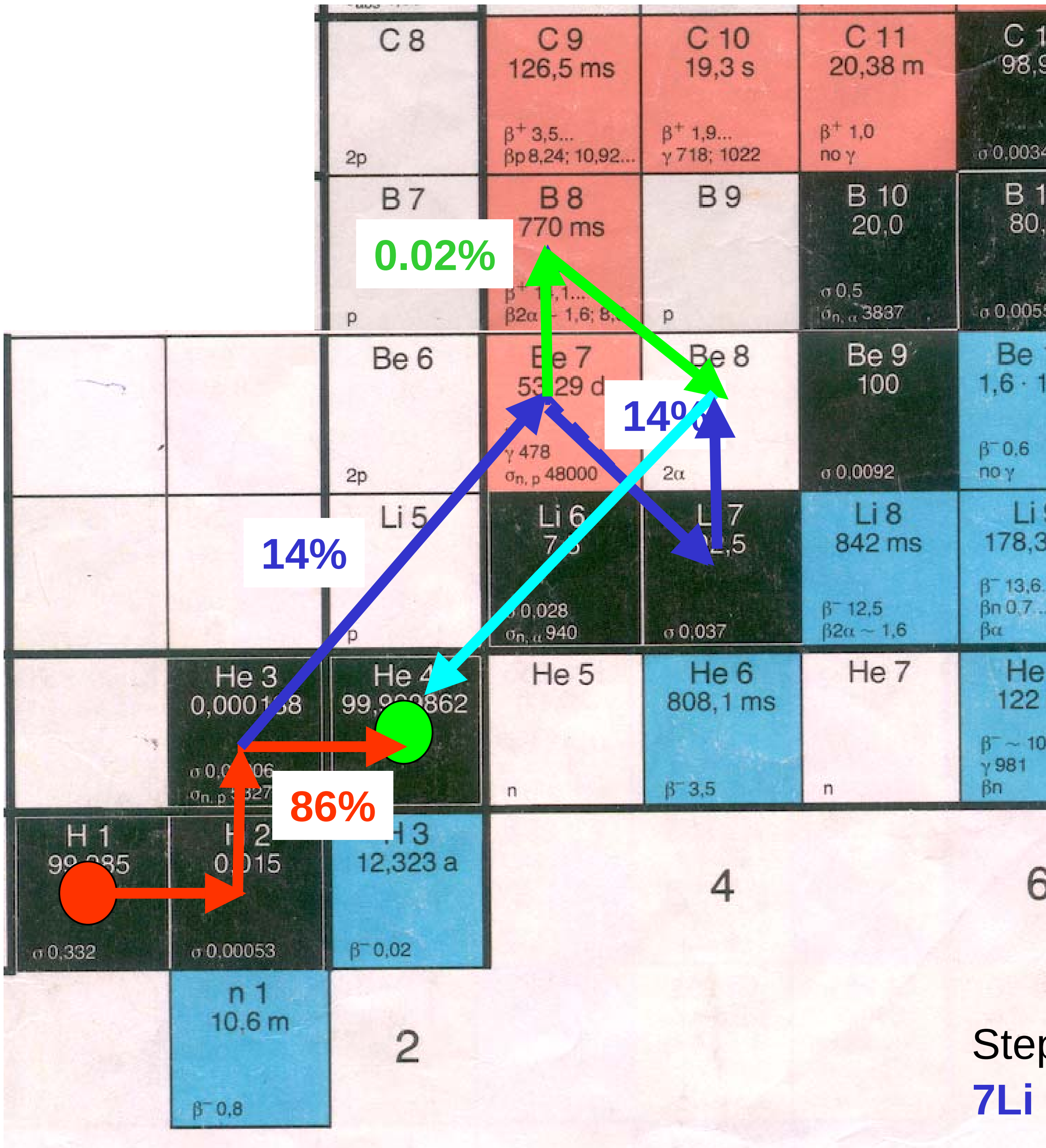
86% 3He+3He → 2p + 4He
14% 3He+4He → 7Be

Step 4:

14% $7Be + e^- \rightarrow 7Li + \nu_e$
0.02% 7Be + p → 8B



pp-chains: 1H → 4He

Step 1:

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

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

Step 2:

- available: p, some d,^{4}He

d+p → 3He

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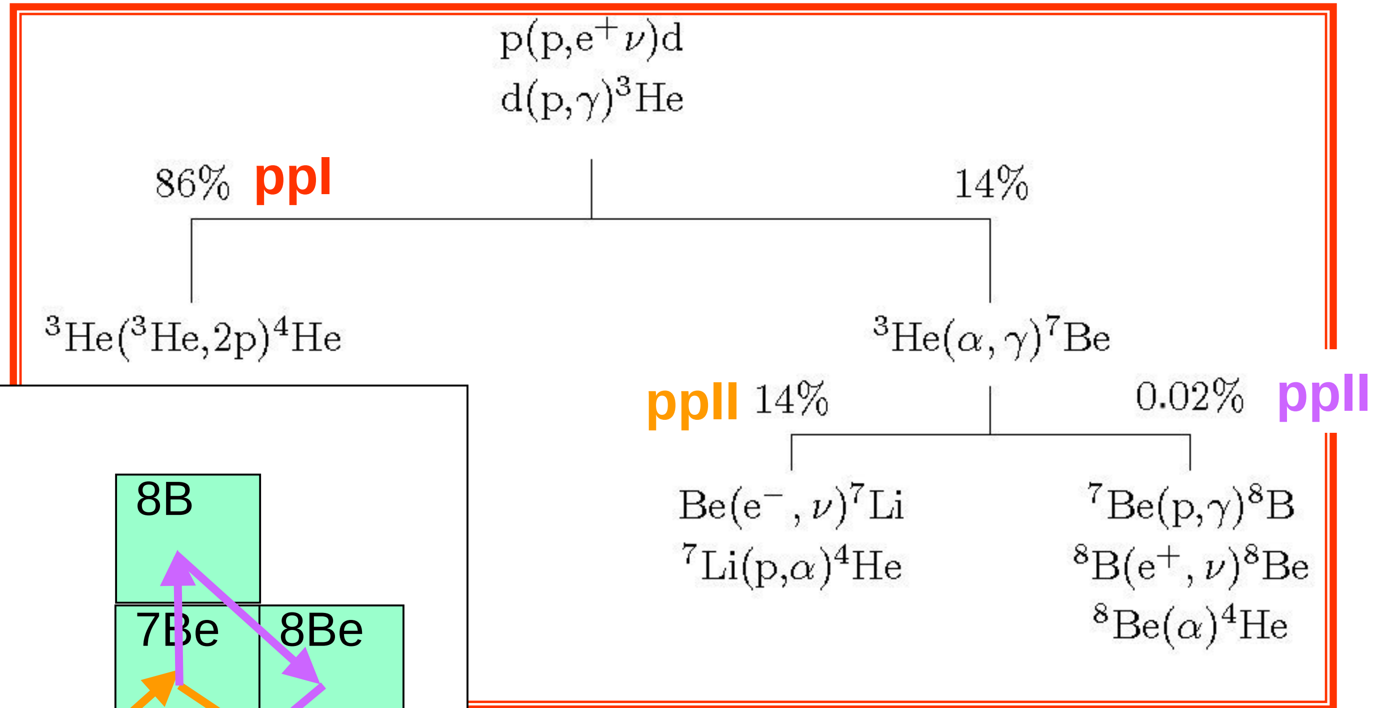
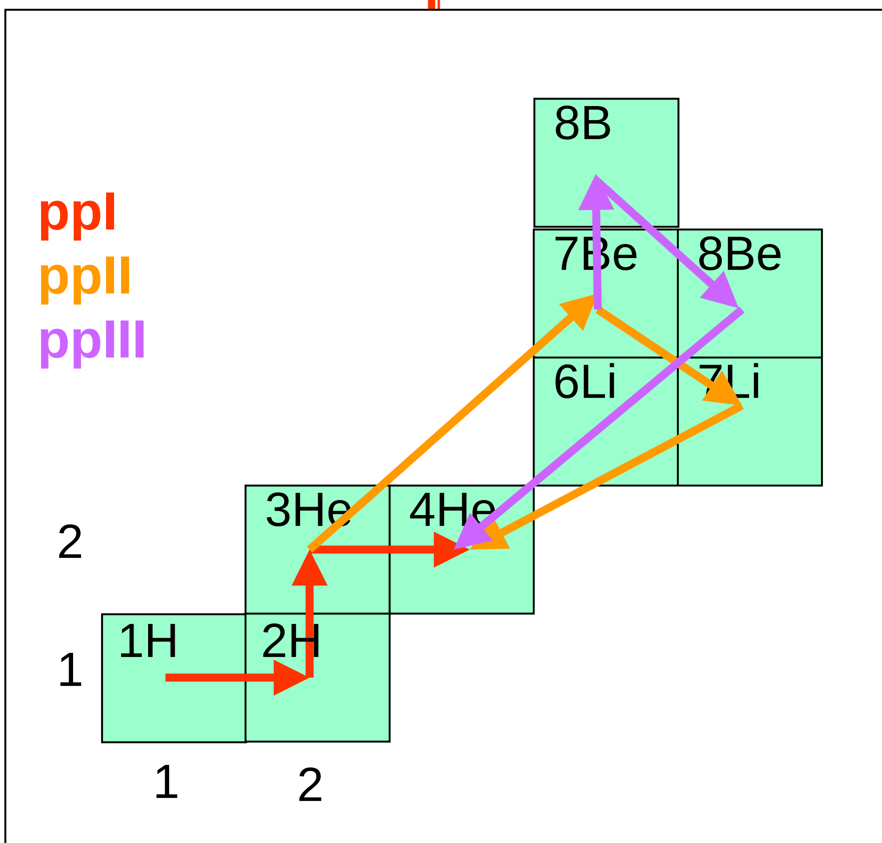
14% $7Be + e^- \rightarrow 7Li + \nu_e$
0.02% 7Be + p → 8B

Step 5:

7Li + p → 8Be
$8B \rightarrow e^+ + \nu_e + 8Be$
} 2 x 4He

Summary pp-chains:





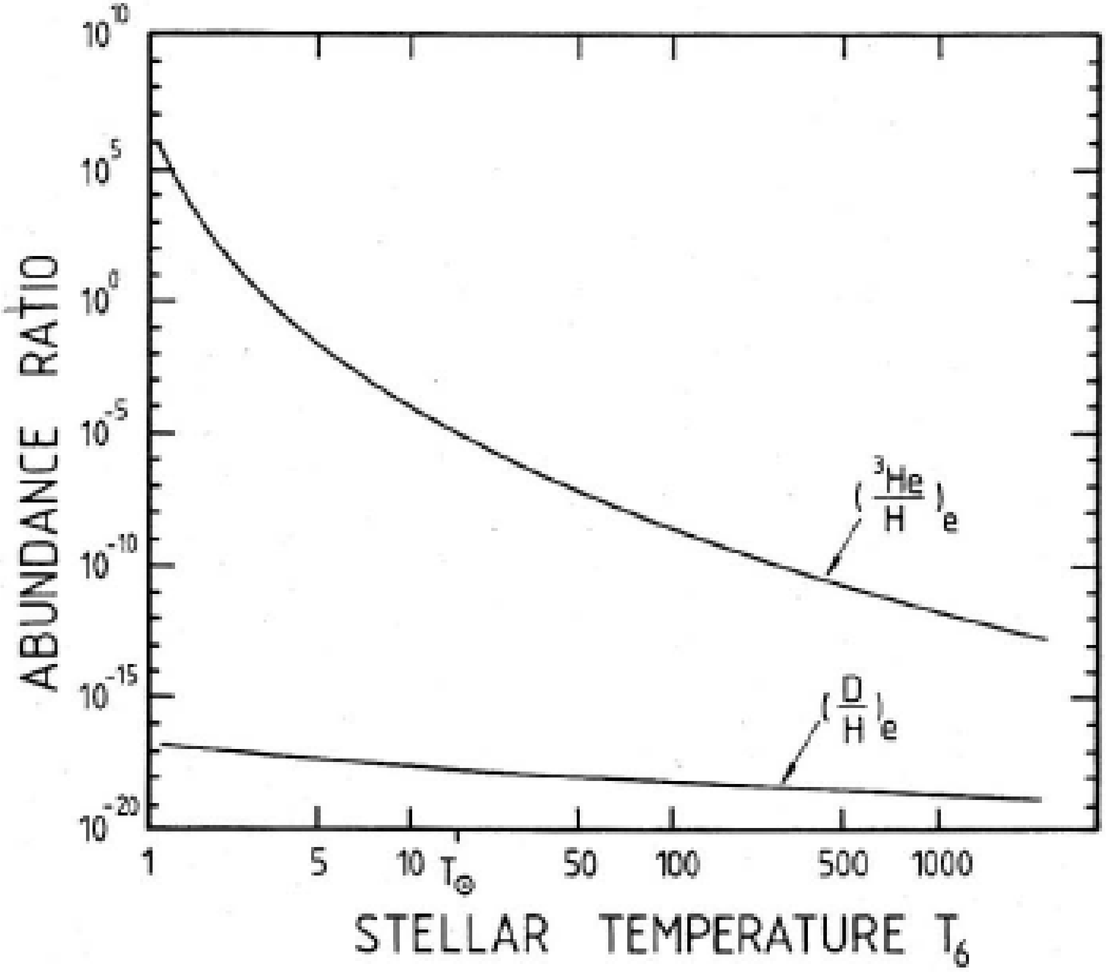
Why do additional pp chains matter ?

p+p dominates timescale BUT

ppI produces 1/2 ^{4}He per p+p reaction

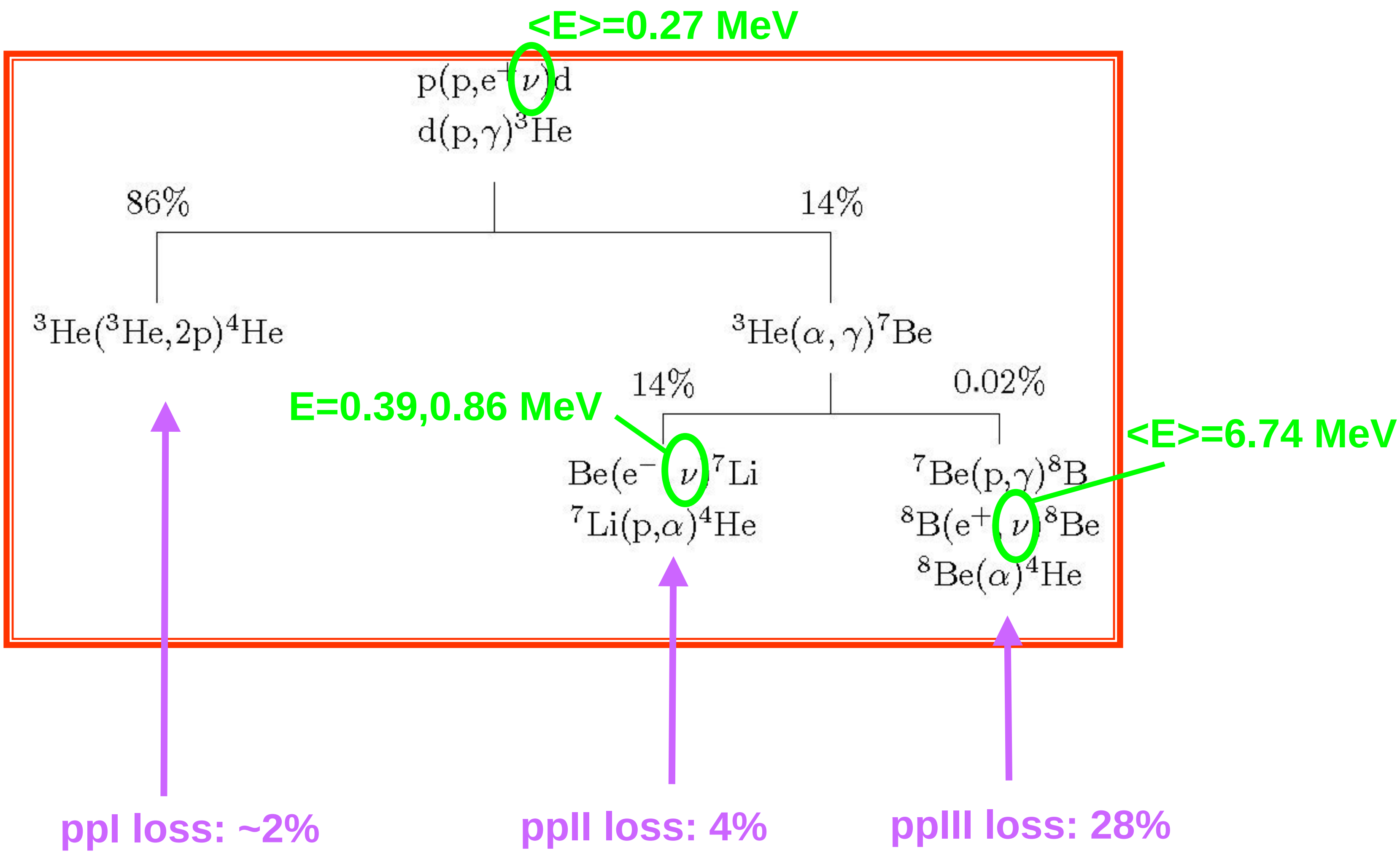
ppII or III produces 1 ^{4}He per p+p reaction

→ **increase burning rate**



ABUNDANCE RATIO
10^10
10^5
10^0
10^-5
10^-10
10^-15
10^-20
(³He/H)e
(D/H)e
1
5
10
T⊙
50
100
500
1000
STELLAR TEMPERATURE T6

Neutrino emission



note: <E>/Q=
0.27/26.73 = 1%

Total loss: 2.3%

2 neutrino energies from 7Be electron capture ?

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