

The sun shines 3.85×10^{33} erg/s = 3.85×10^{26} 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 ($\neq 4p$'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 fulfillment 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 pp chain is the only possible sequence of reactions.
(all other reaction sequences require the presence of catalyst nuclei)

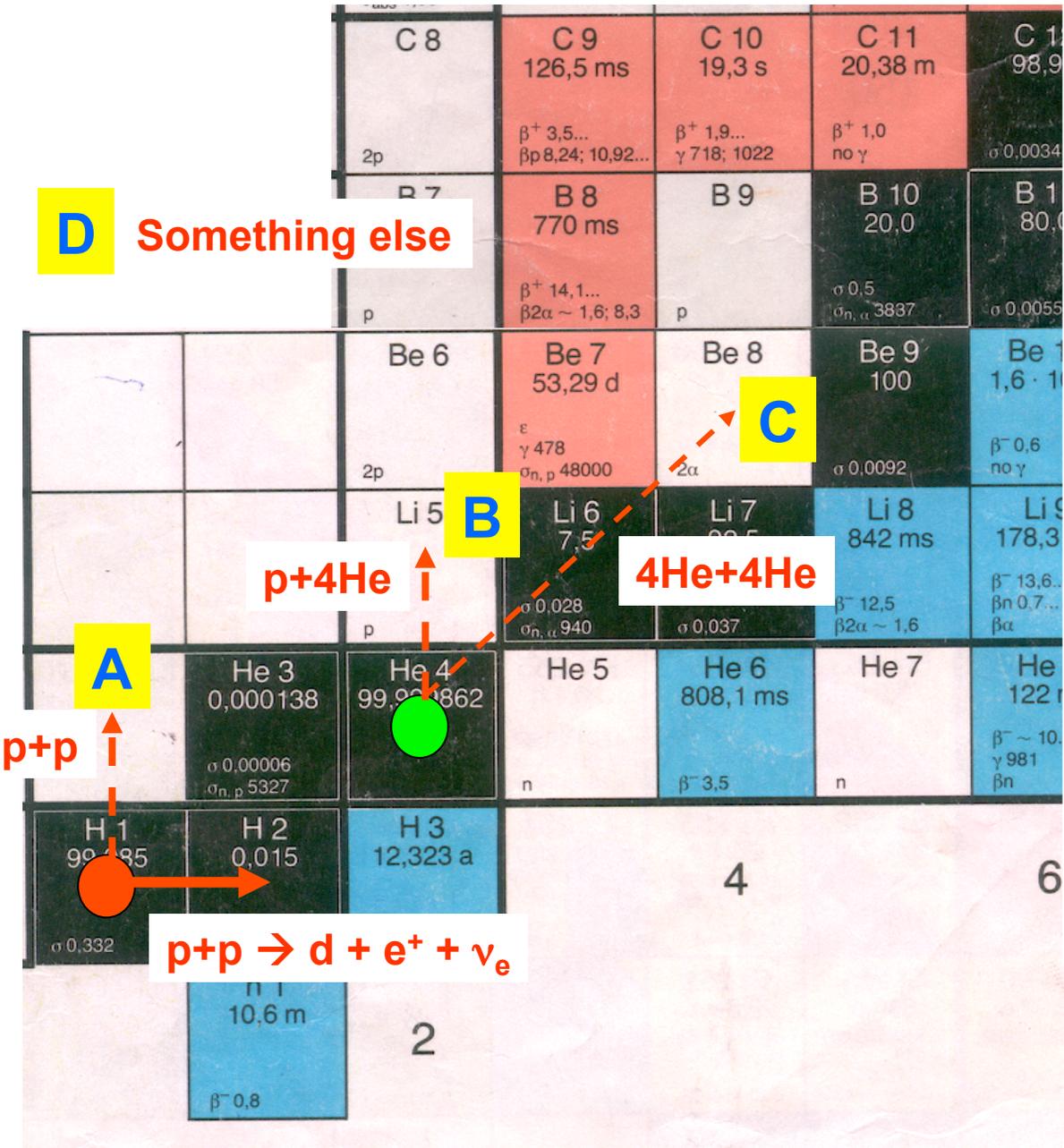
3- or 4-body reactions are too unlikely – chain has to proceed by steps of 2-body reactions or decays.

Final product is ^4He

pp-chains: 1H → 4He

Step 1:

- available: ^1H , some ^4He



pp-chains: 1H → 4He

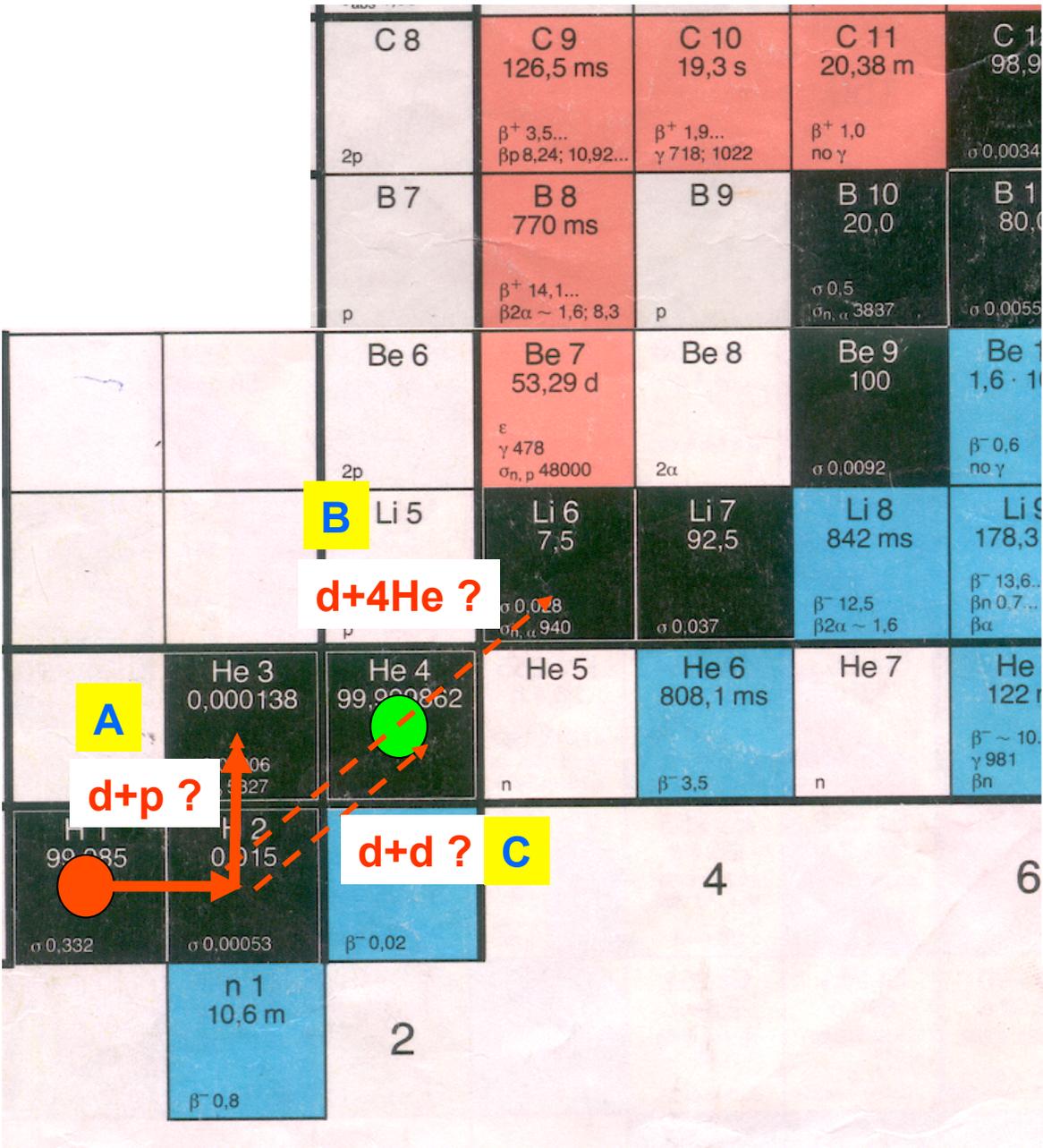
Step 1:

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



Step 2:

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



pp-chains: 1H → 4He

Step 1:

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



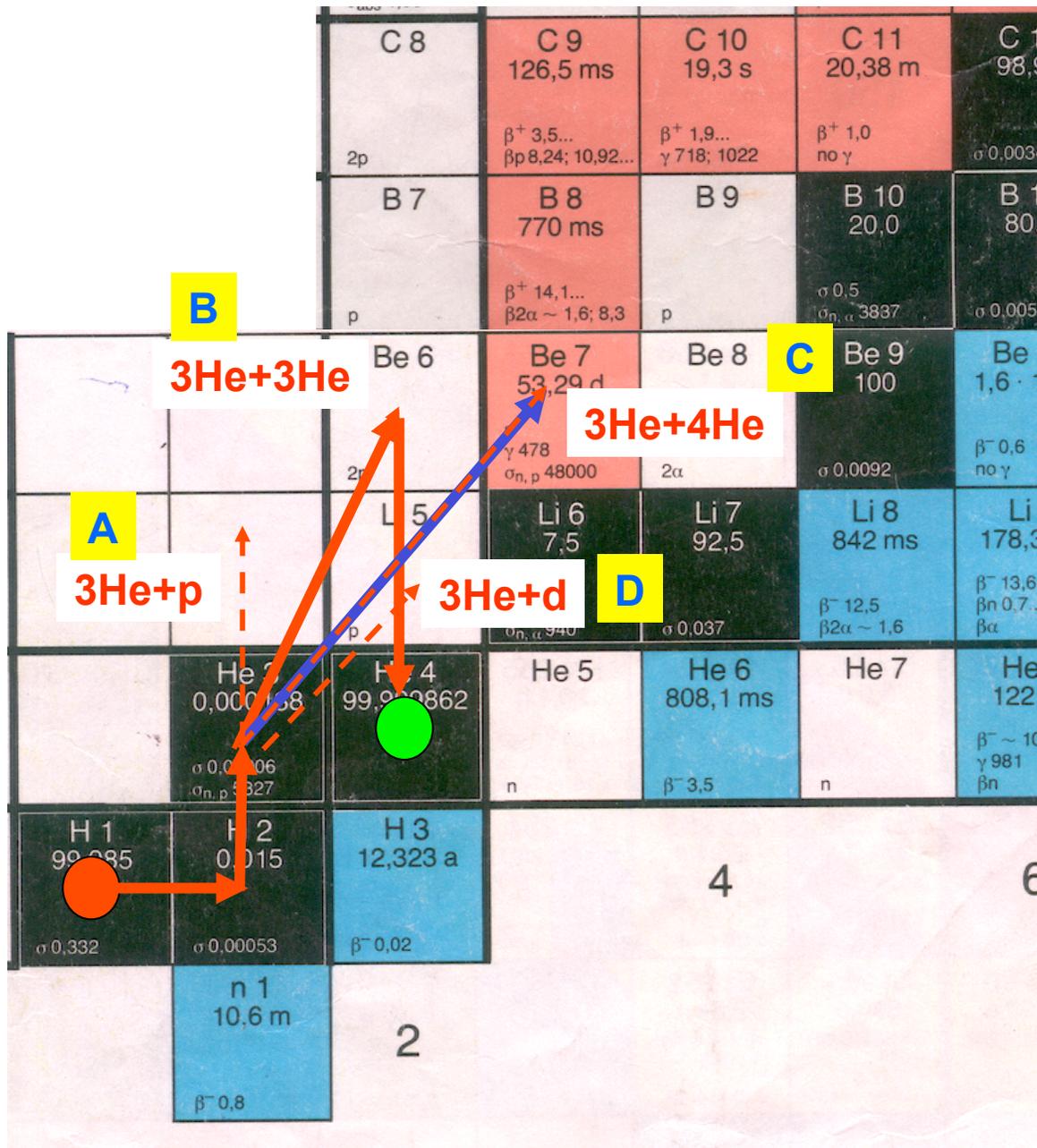
Step 2:

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



Step 3:

- available: p, some ${}^3\text{He}$, ${}^4\text{He}$
little d (rapid destruction)



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

Step 1:

- available: 1H , some 4He



Step 2:

- available: p , some $d, 4\text{He}$

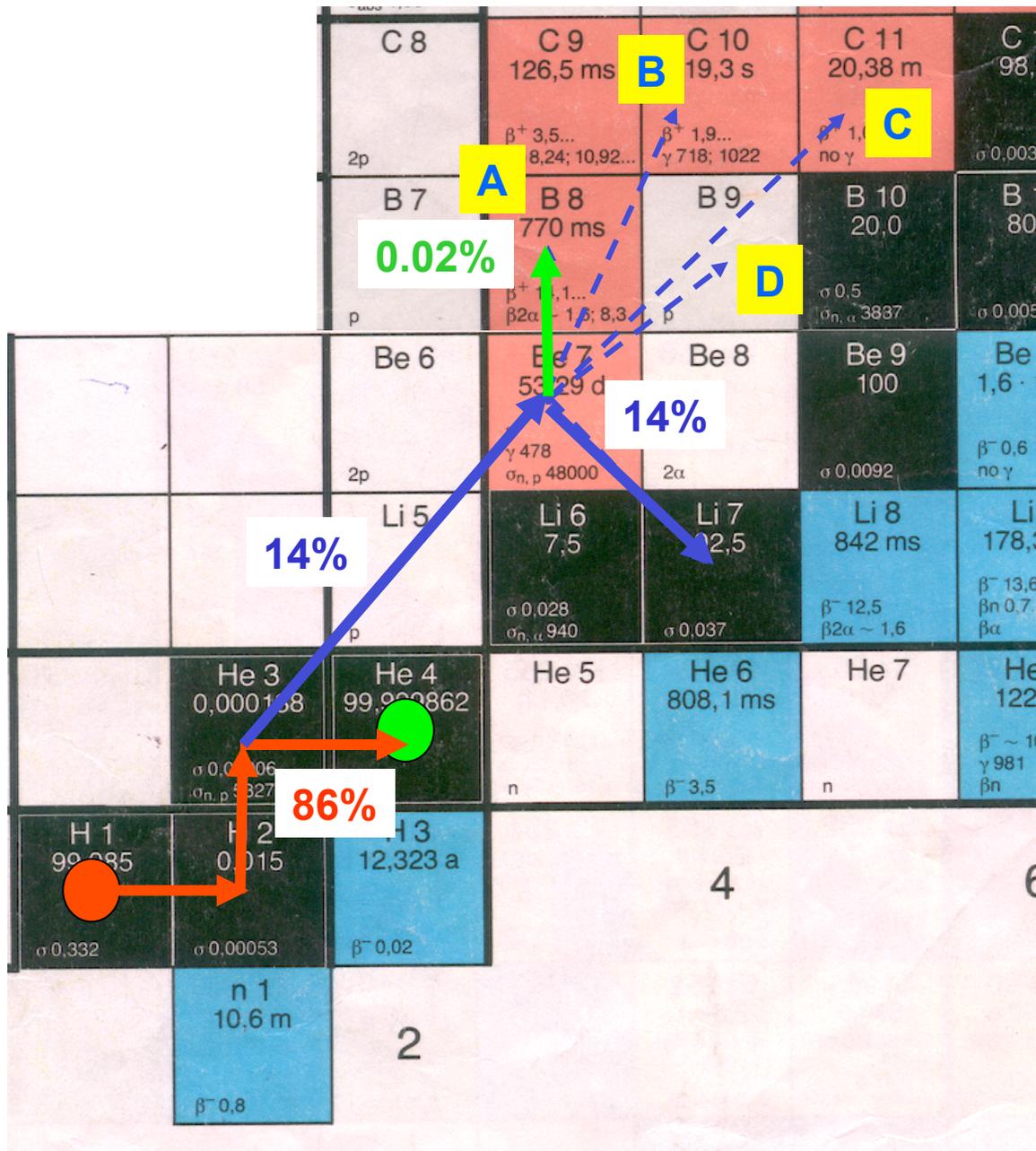


Step 3:

- available: p , some $3\text{He}, 4\text{He}$
little d (rapid destruction)



Step 4:



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

Step 1:

- available: 1H , some 4He



Step 2:

- available: p , some $d, 4\text{He}$



Step 3:

- available: p , some $3\text{He}, 4\text{He}$
little d (rapid destruction)



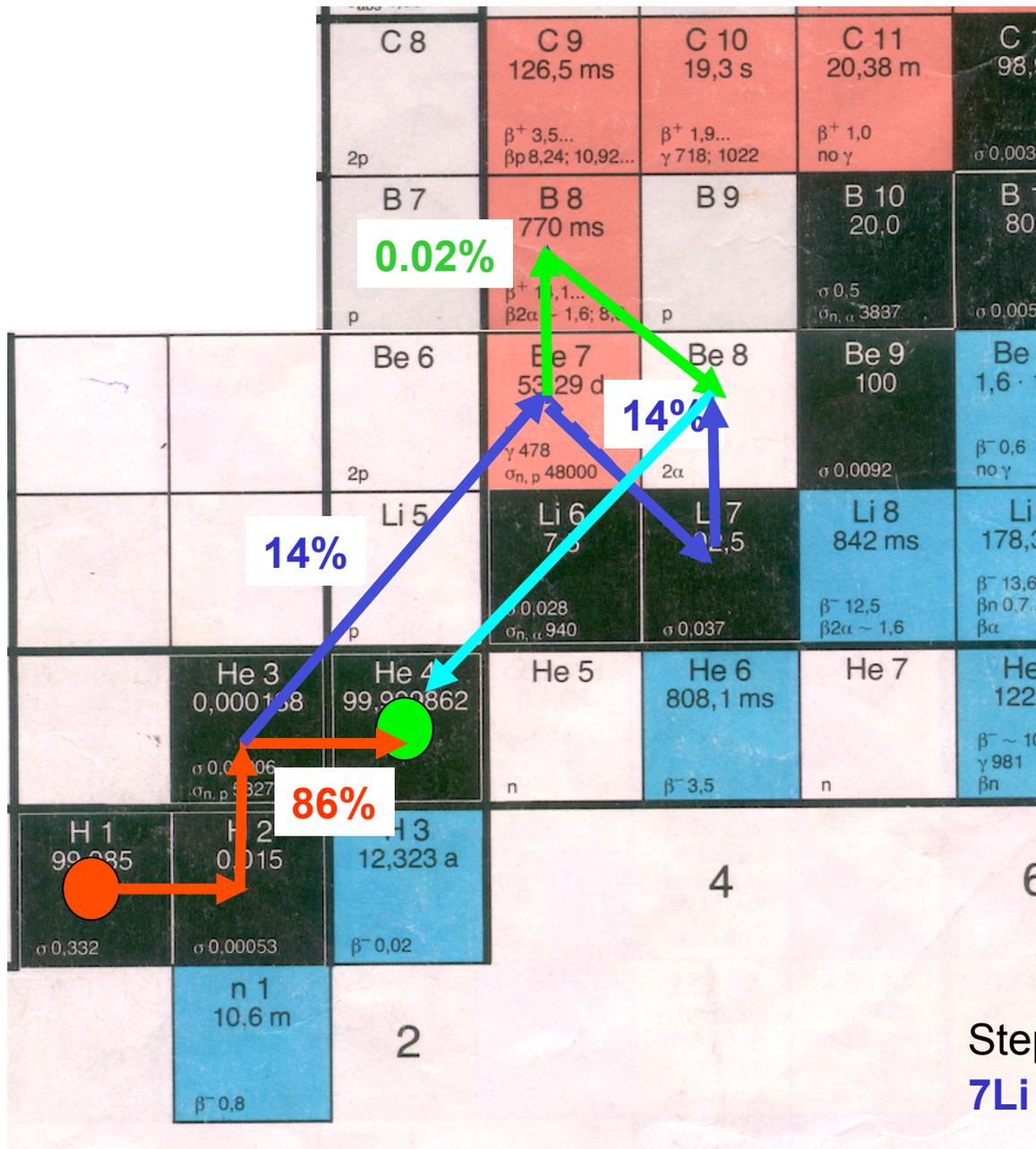
Step 4:



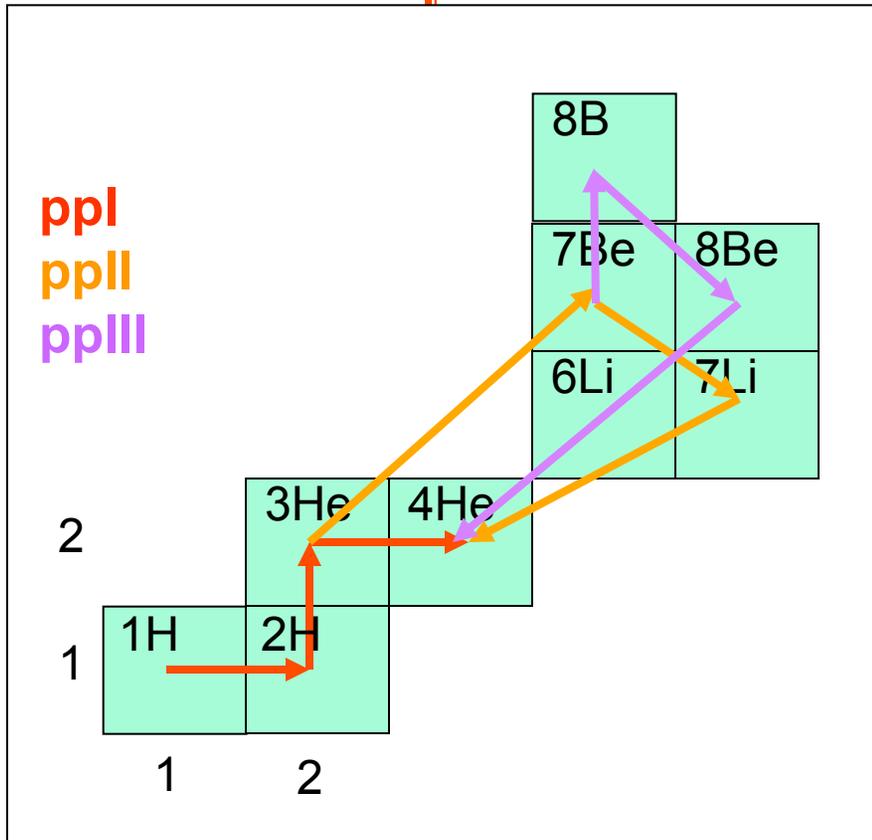
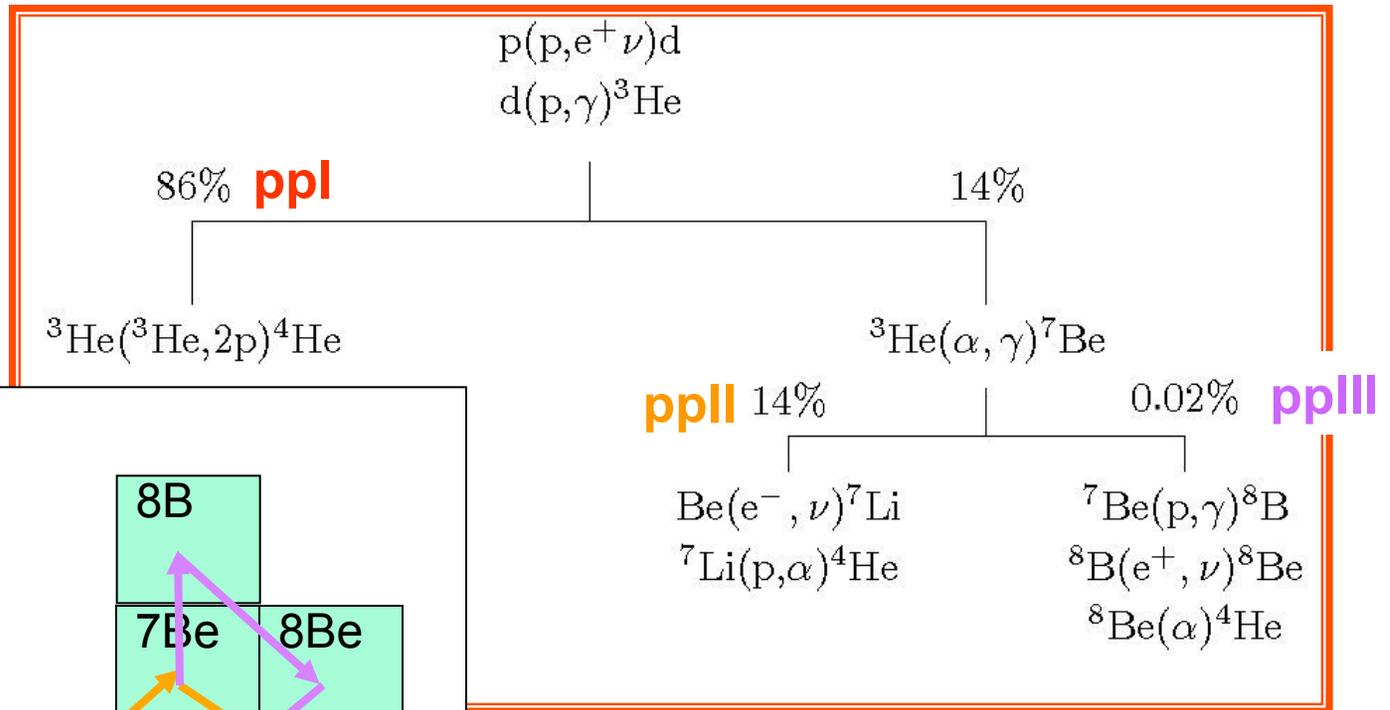
Step 5:



} 2 x 4He



Summary pp-chains:



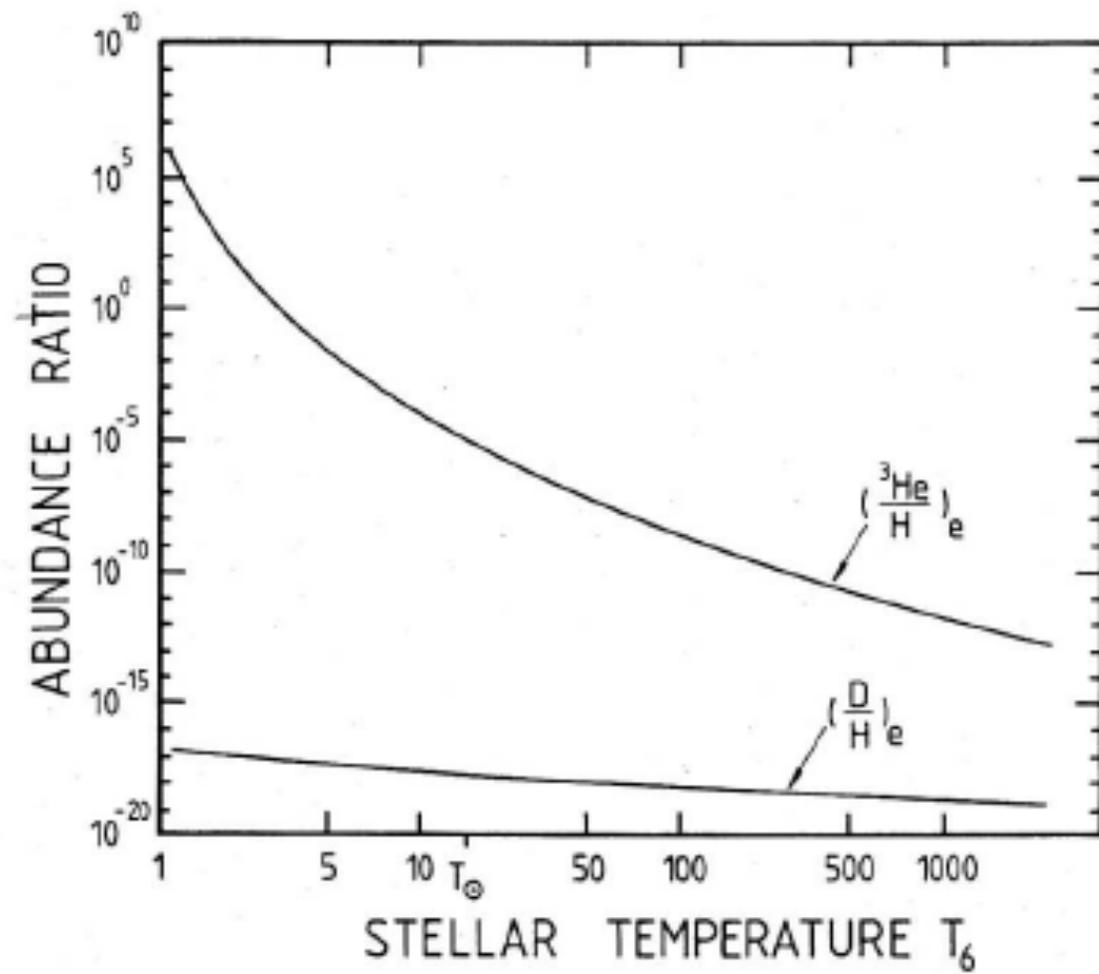
Why do additional pp chains matter ?

p+p dominates timescale BUT

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

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

→ **increase burning rate**



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

