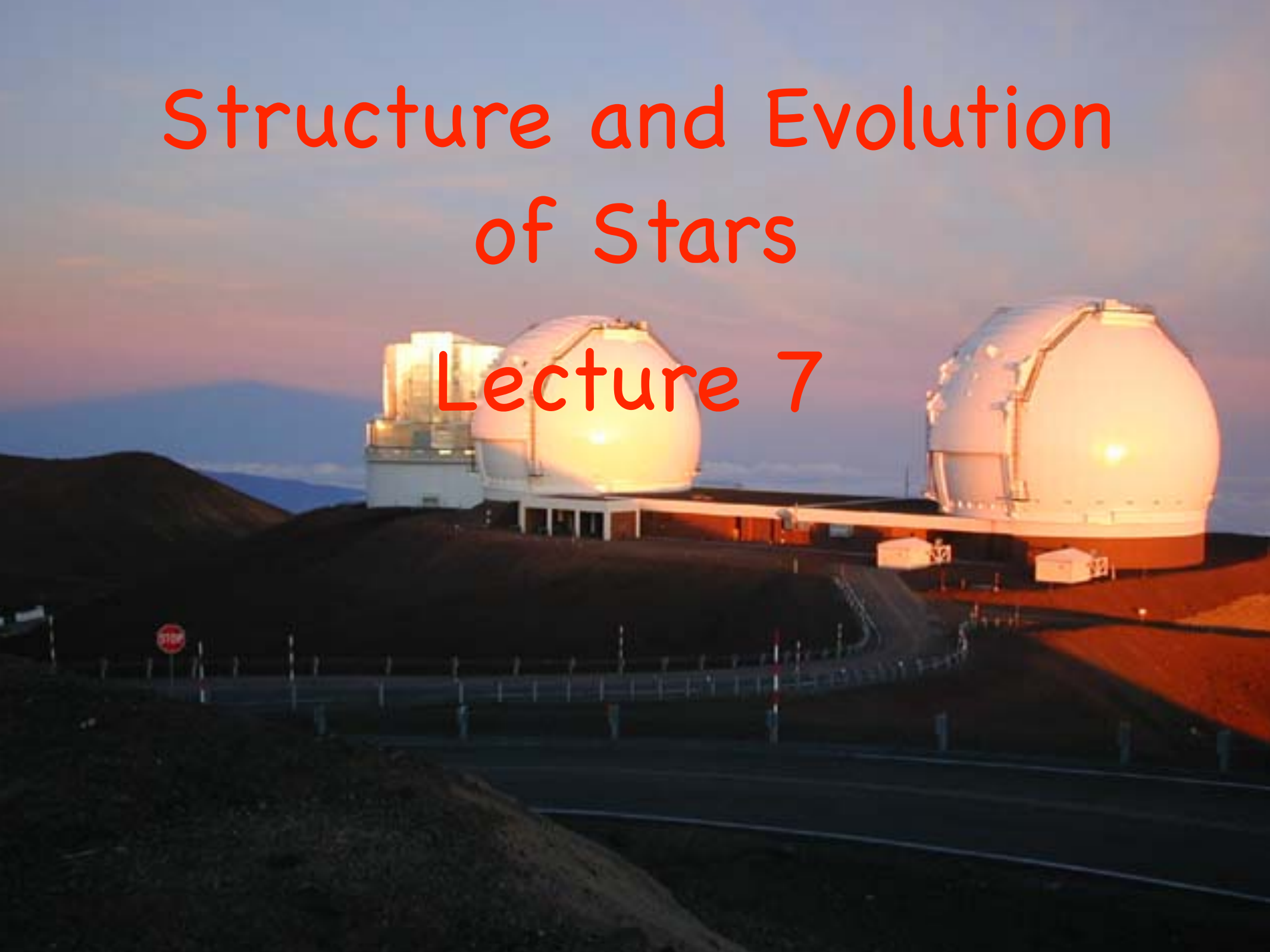
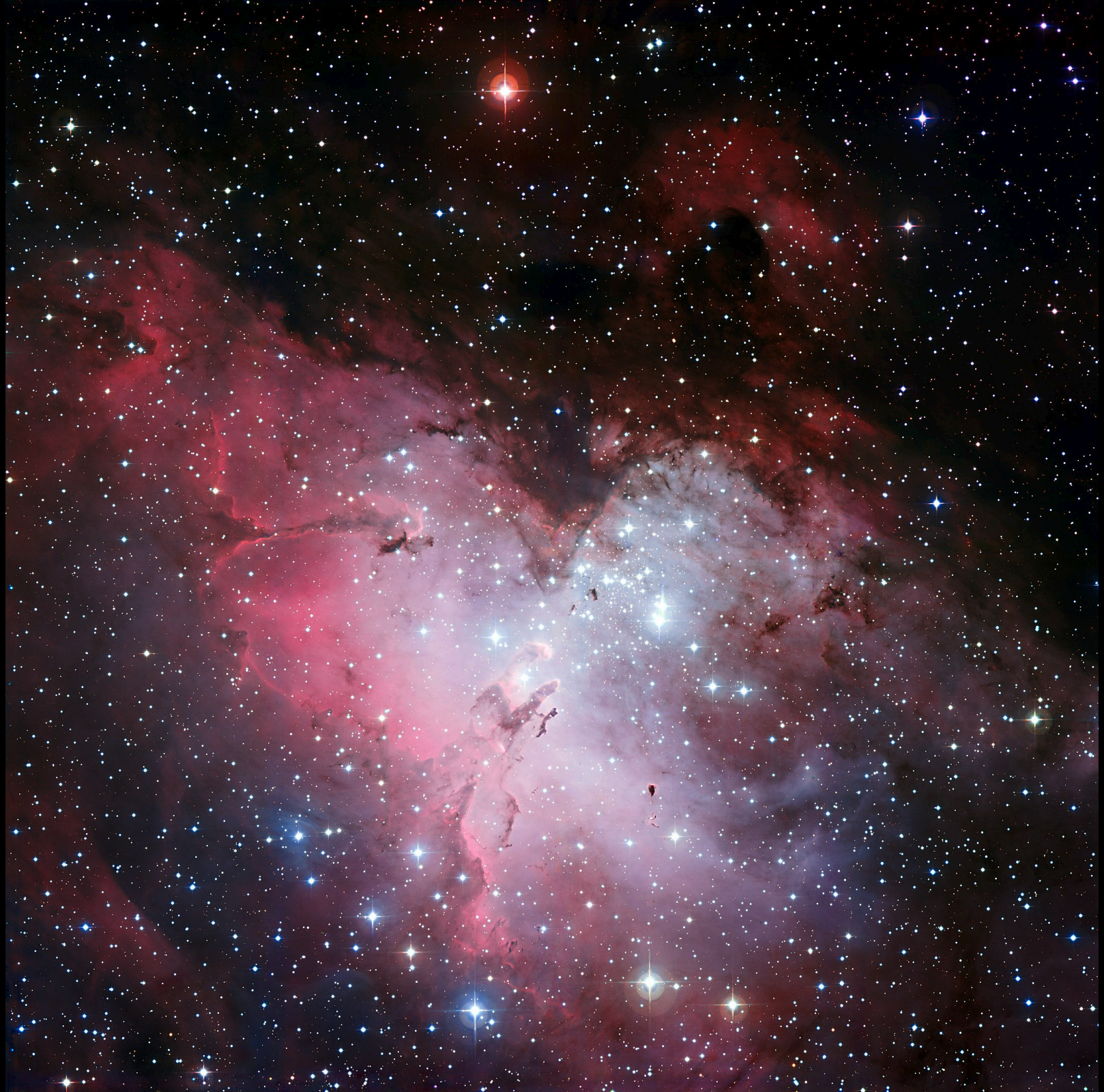
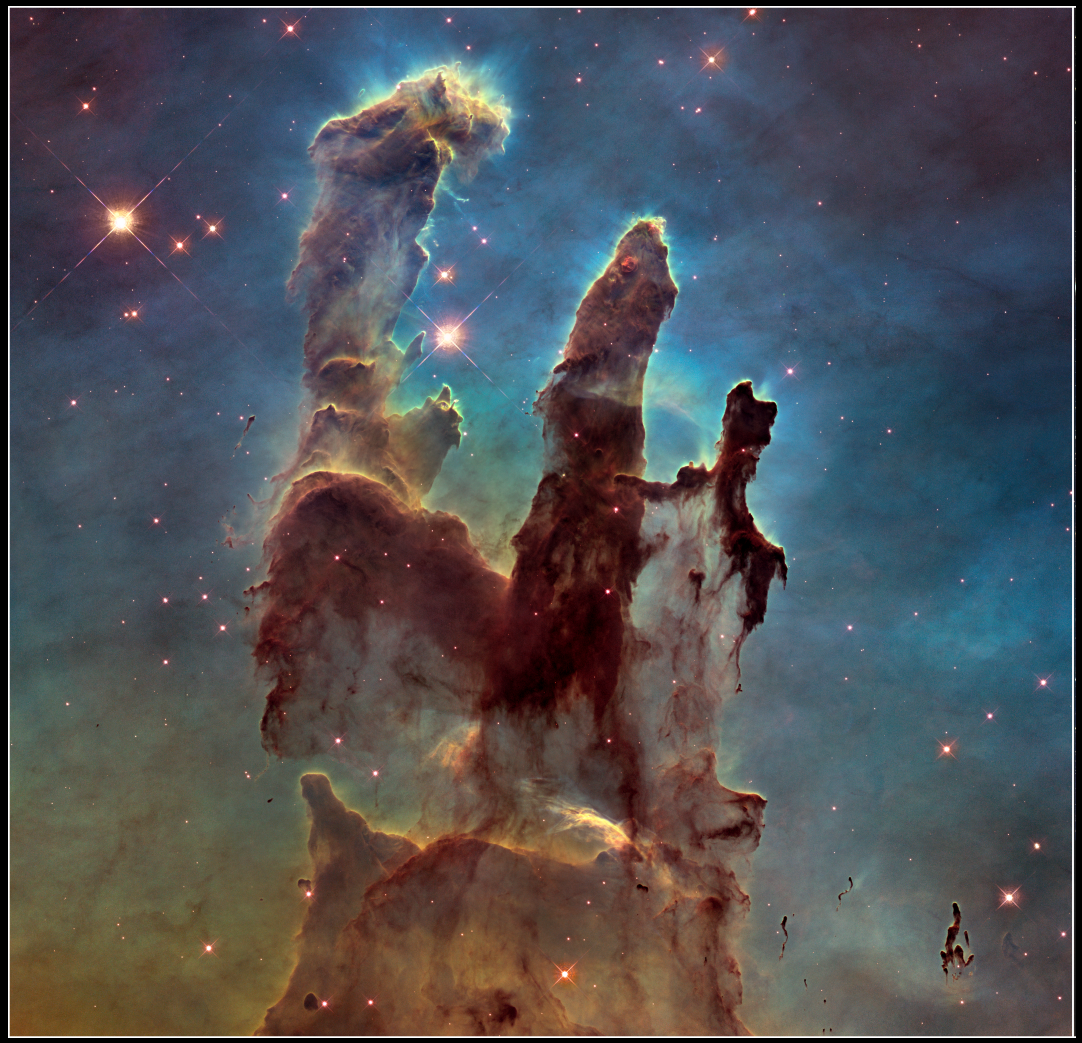
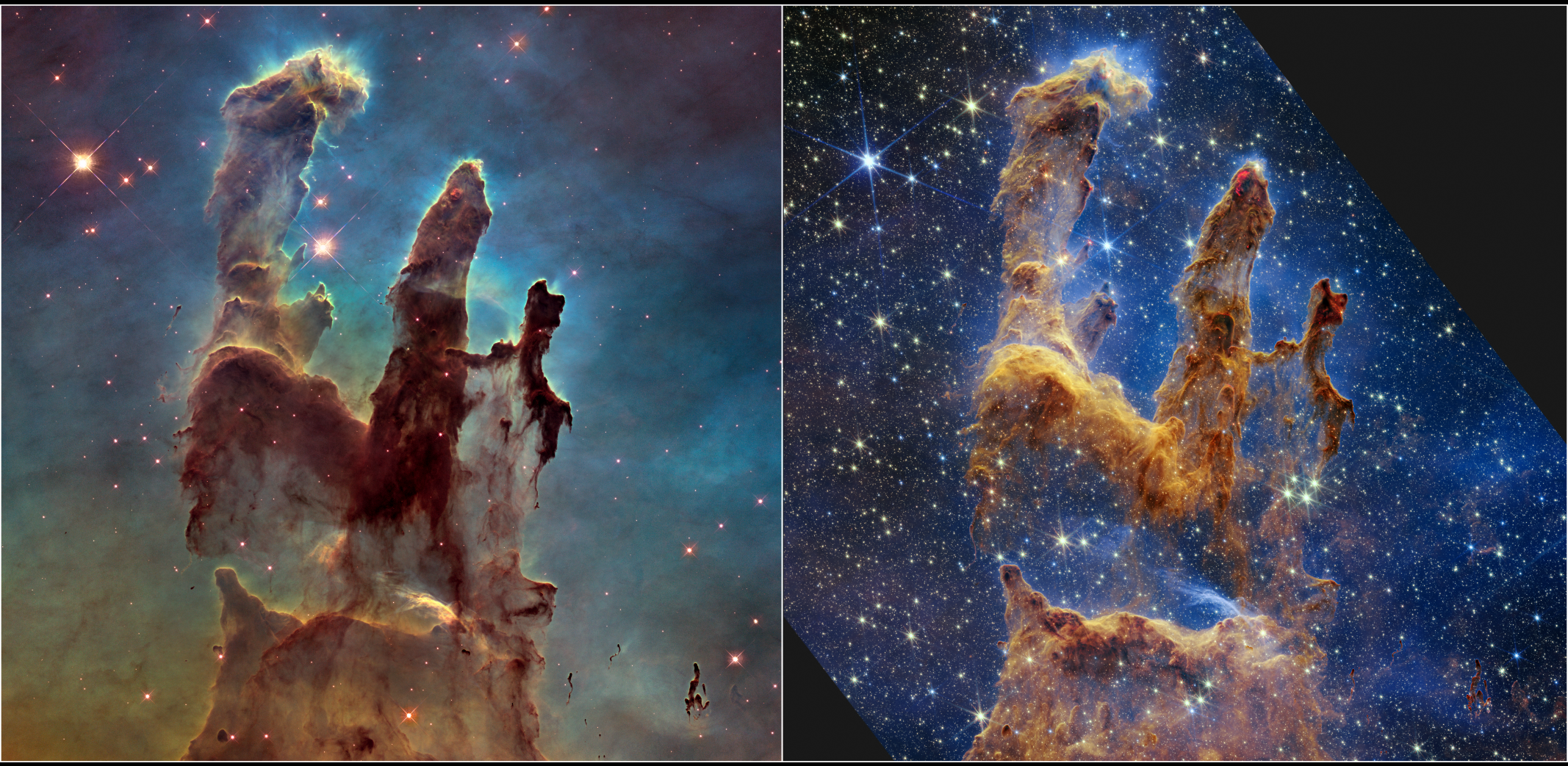
Structure and Evolution of Stars

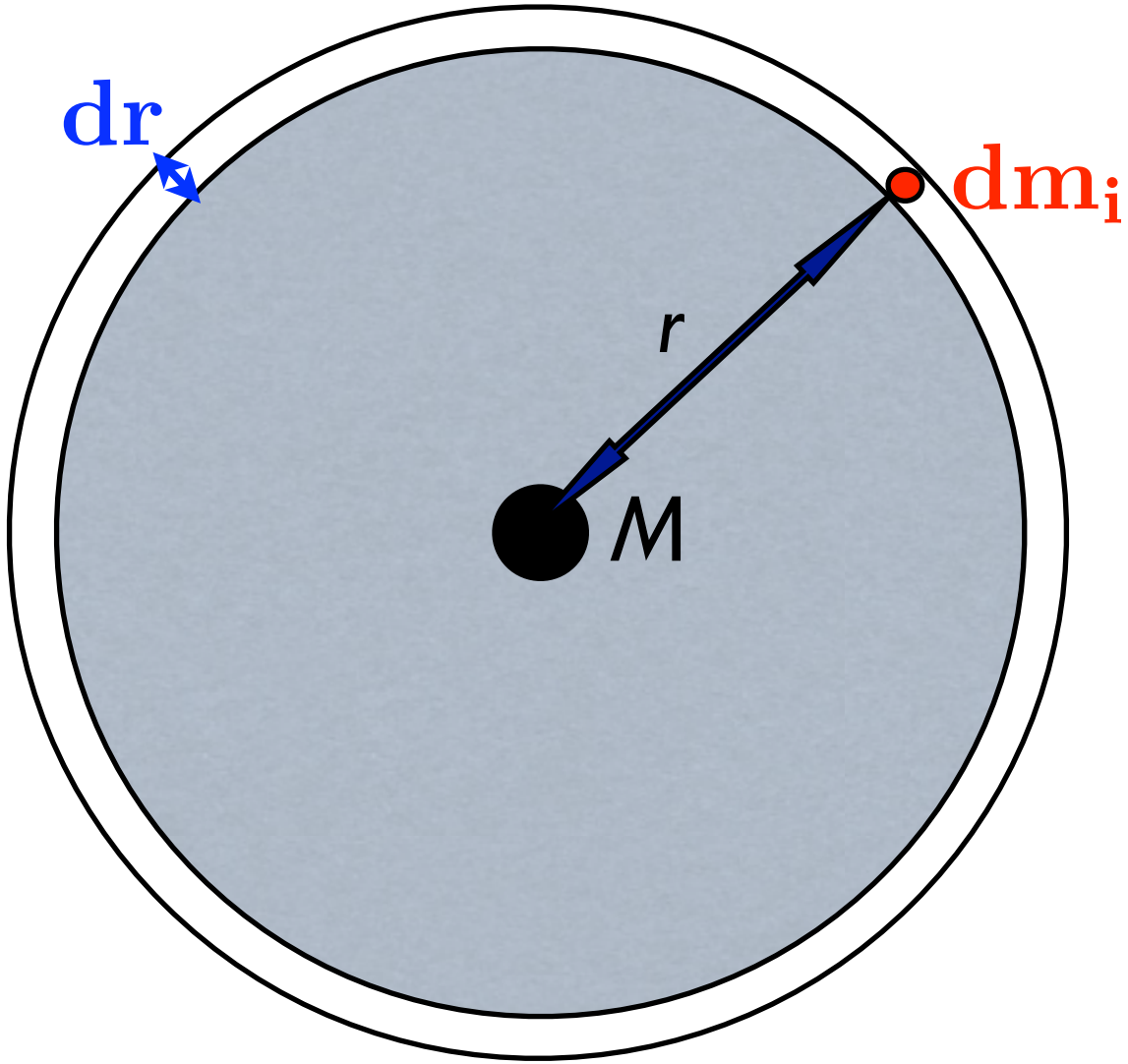
Lecture 7





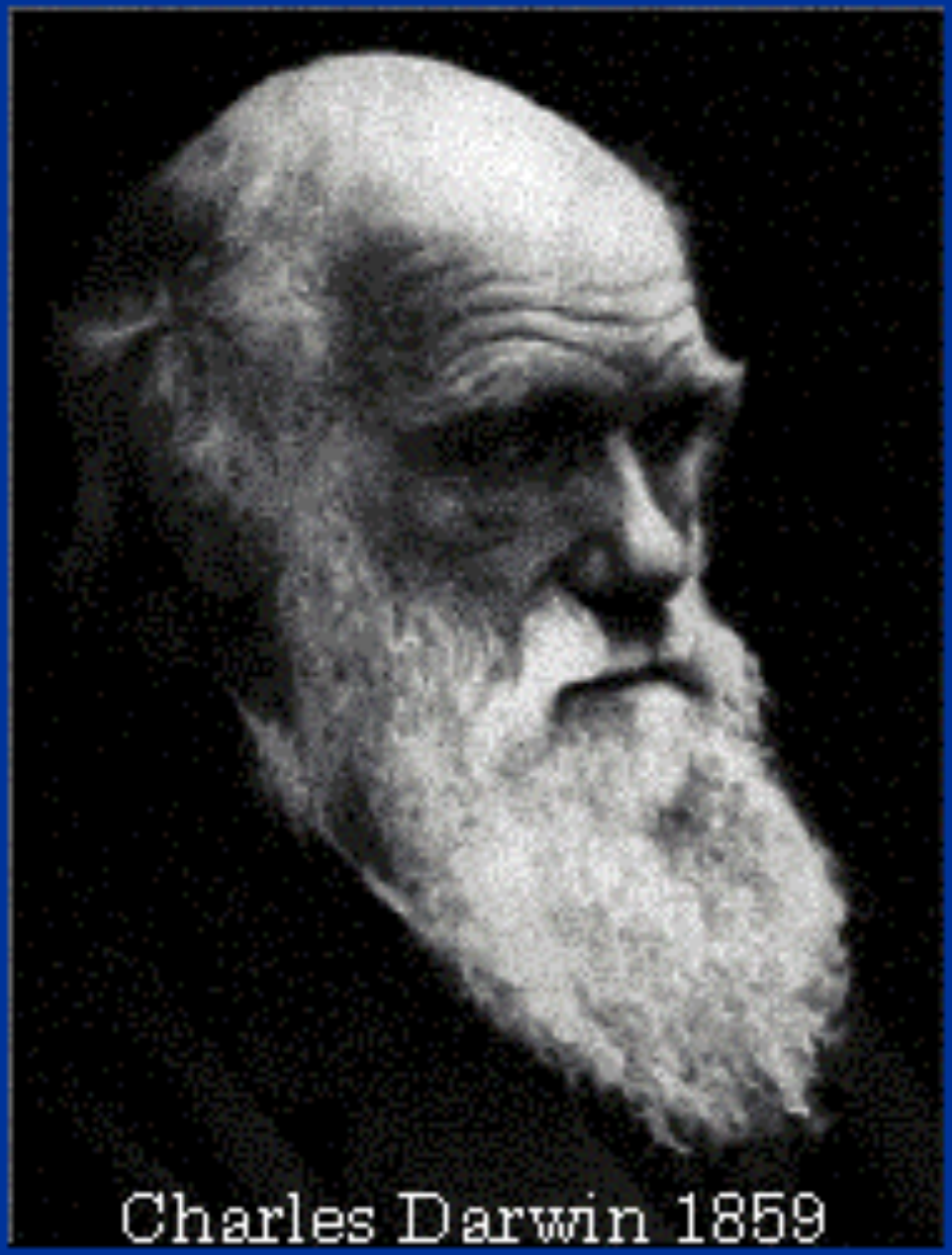





dr
dm_i
r
M

the earth, were limited. Already toward the end of the 17th century, Newton and others calculated the cooling rate of a hot metallic earth and arrived at an answer of about 50,000 years (Dalrymple 1991. p. 28). However, such a high estimate was in direct contradiction to the theologians' claim that the earth was created by God about 6000 years earlier. John Lightfoot, Vice-Chancellor of the University of Cambridge, first published his calculations of the age of the earth in 1644, thus anticipating Bishop Ussher's famous statement made in 1650. Guided by a careful interpretation of Mosaic chronology, he succeeded in working out the date of the creation of the earth exactly. According to Dr. Lightfoot: 'The earth was created on October 26, 4004 BC, at nine o'clock in the morning in Mesopotamia, according to the Julian calender'. (Dalrymple 1991, p. 14). On the other hand, the Scottish

The Age of the Sun: 4.6 Billion Yr

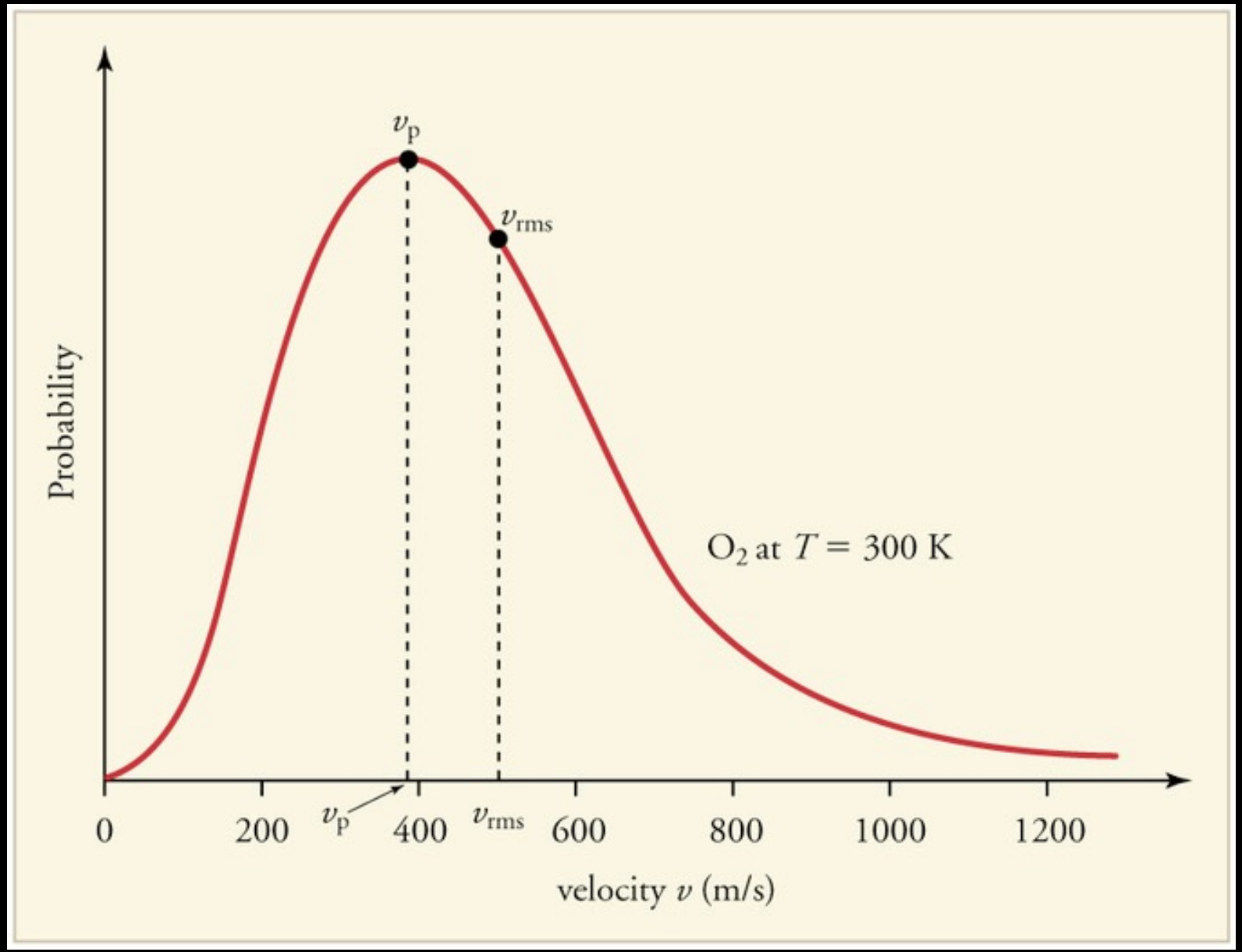


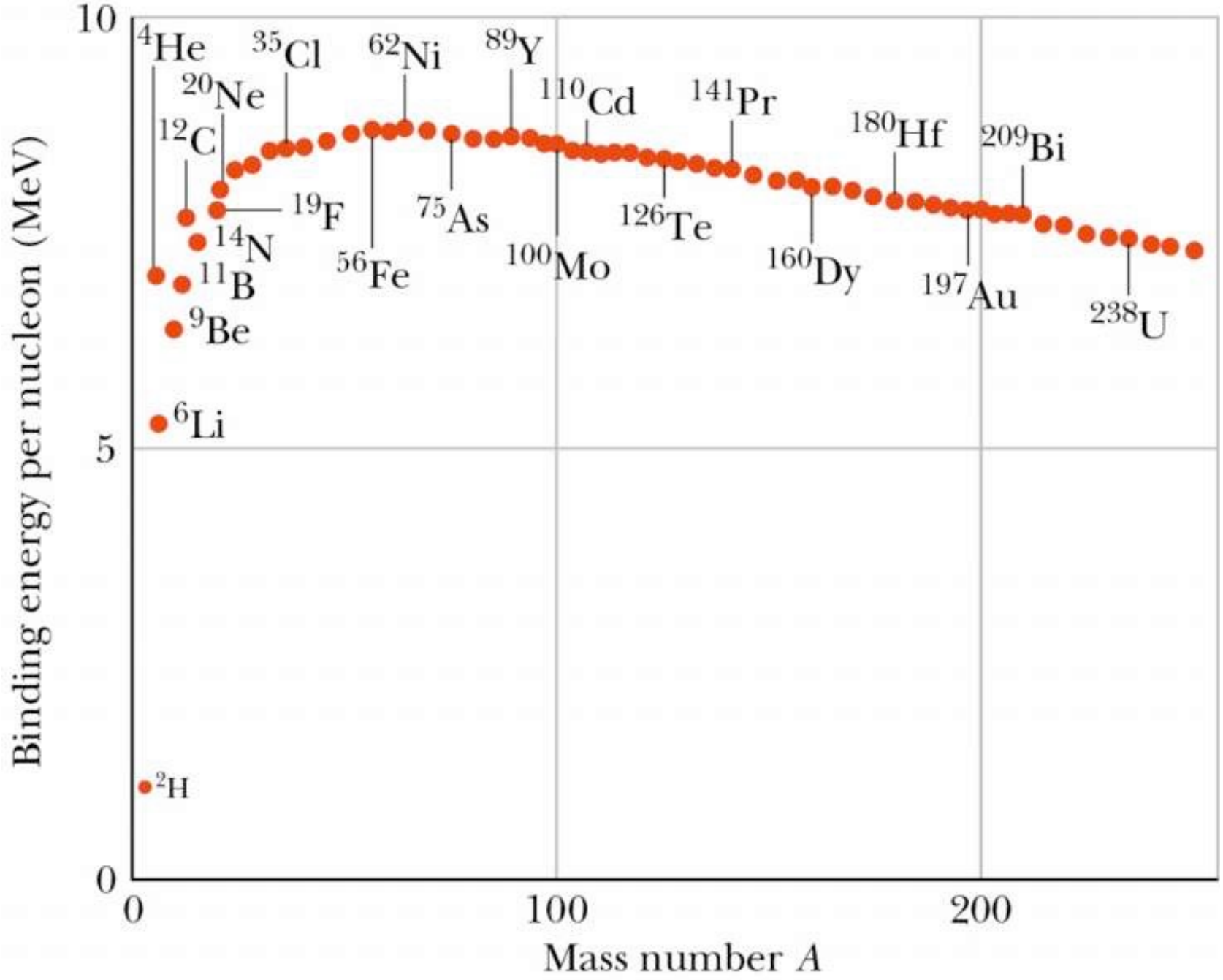
Charles Darwin 1859

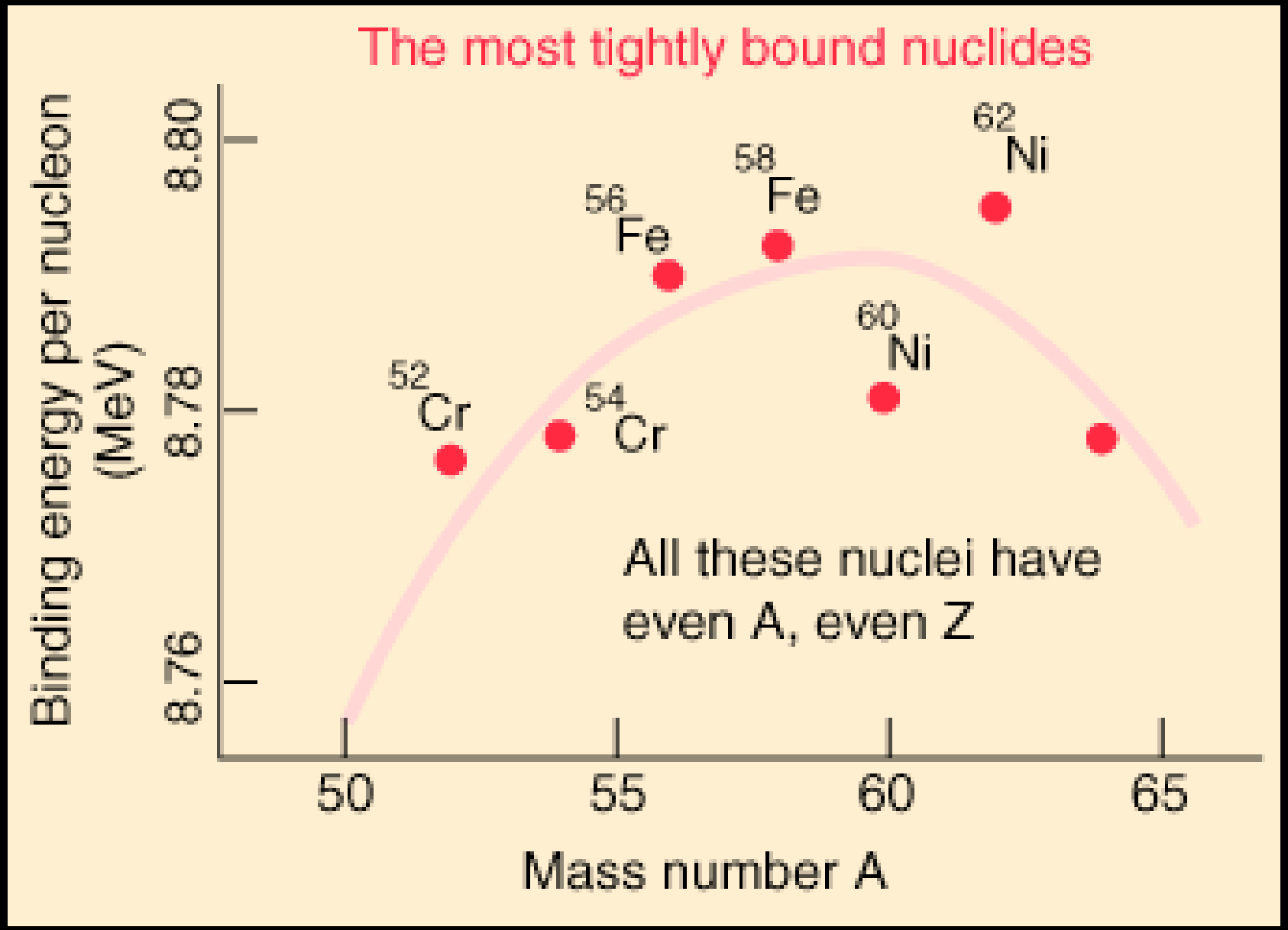
Lord Kelvin 1862

$\geq$ 0.3 billion yr

$\sim$ 0.03 billion yr


v_p
v_{rms}
Probability
O_2 at $T = 300$ K
0
200
v_p
400
v_{rms}
600
800
1000
1200
velocity v (m/s)


10
5
0
0
100
200
Binding energy per nucleon (MeV)
Mass number A
^{4}He
^{35}Cl
^{62}Ni
^{89}Y
^{20}Ne
^{110}Cd
^{141}Pr
^{180}Hf
^{209}Bi
^{12}C
^{19}F
^{75}As
^{126}Te
^{14}N
^{56}Fe
^{100}Mo
^{160}Dy
^{197}Au
^{11}B
^{238}U
^{9}Be
^{6}Li
^{2}H


The most tightly bound nuclides
Binding energy per nucleon (MeV)
8.80
8.78
8.76
62 Ni
58 Fe
56 Fe
60 Ni
52 Cr
54 Cr
All these nuclei have even A, even Z
50
55
60
65
Mass number A

Is this how the sun shines

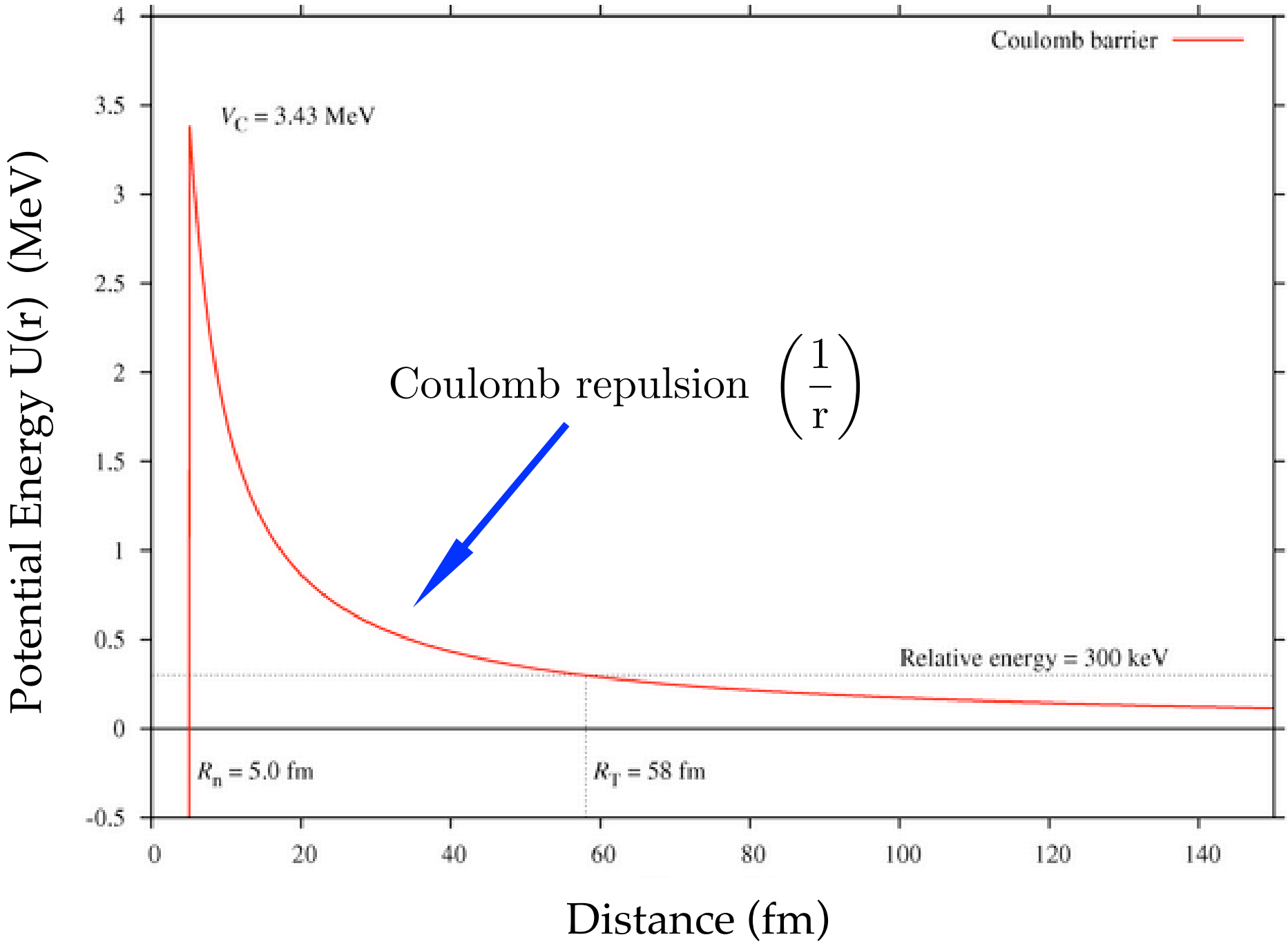
H. A. Bethe

W. A. Fowler

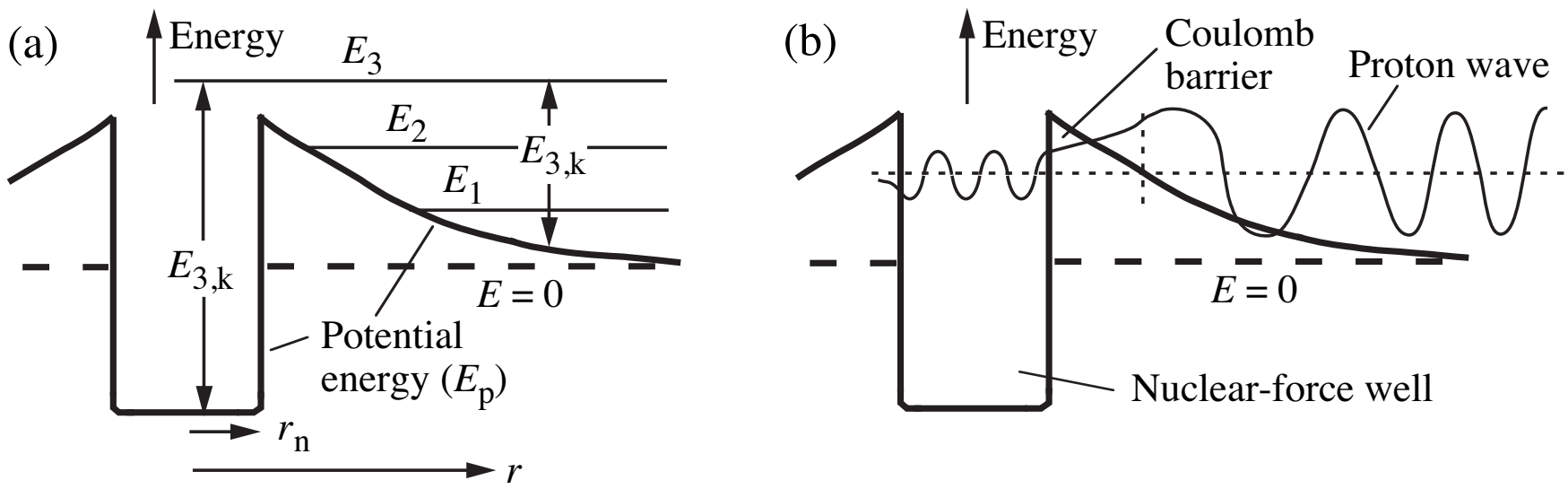
Basic theory: 1939

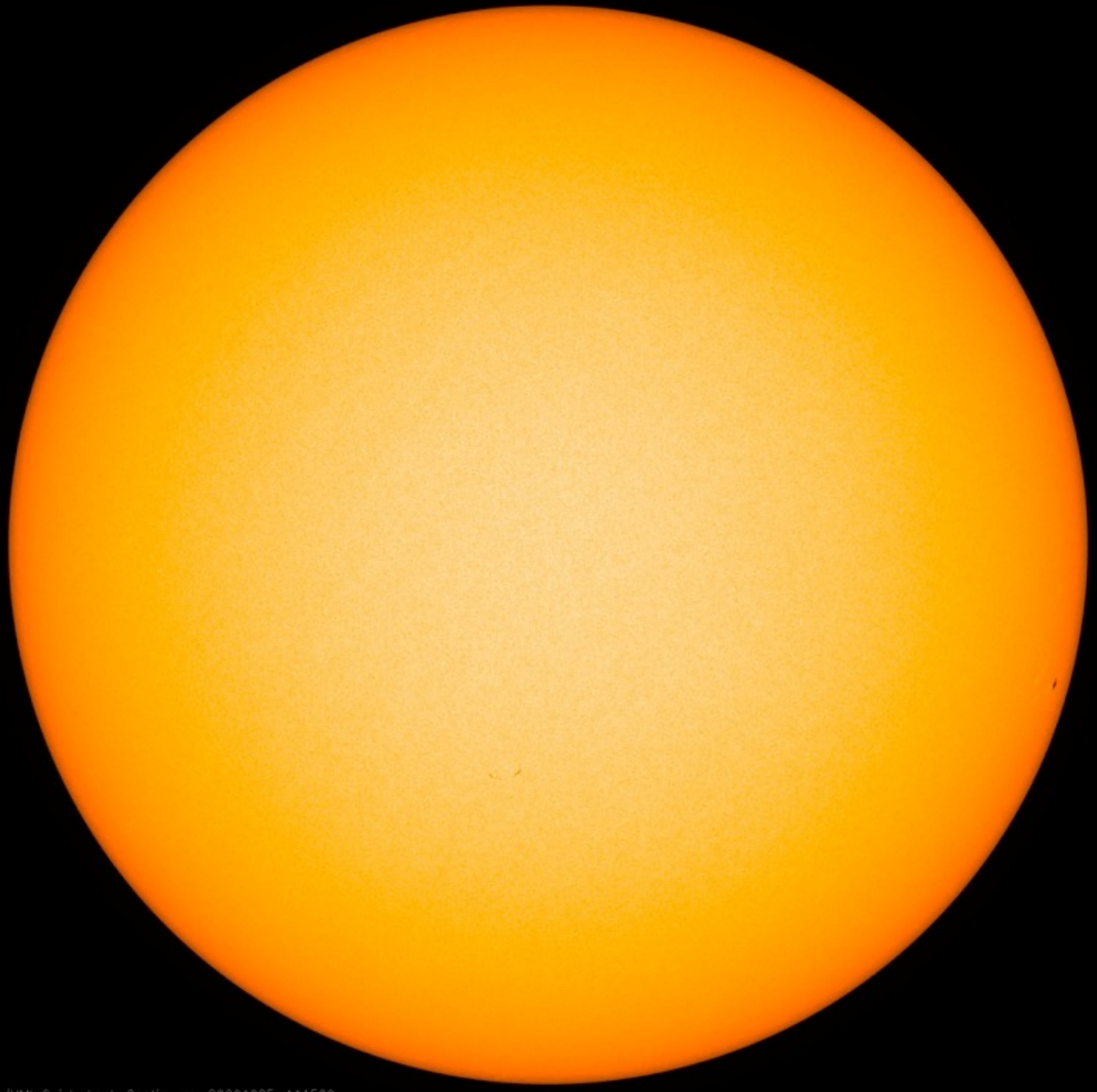
Experiments: 1950's

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + \sim 25\ \mathrm{MeV}$$


Potential Energy U(r) (MeV)
Distance (fm)
Coulomb barrier
V_C = 3.43 MeV
Coulomb repulsion $\left(\frac{1}{r}\right)$
Relative energy = 300 keV
R_n = 5.0 fm
R_T = 58 fm
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
20
40
60
80
100
120
140

Potential barrier




SDO/HMI Quick-Look Continuum: 20201025_111500

June 24-29 2018 Assergi, L'Aquila, Italy

Nuclei in the Cosmos XV

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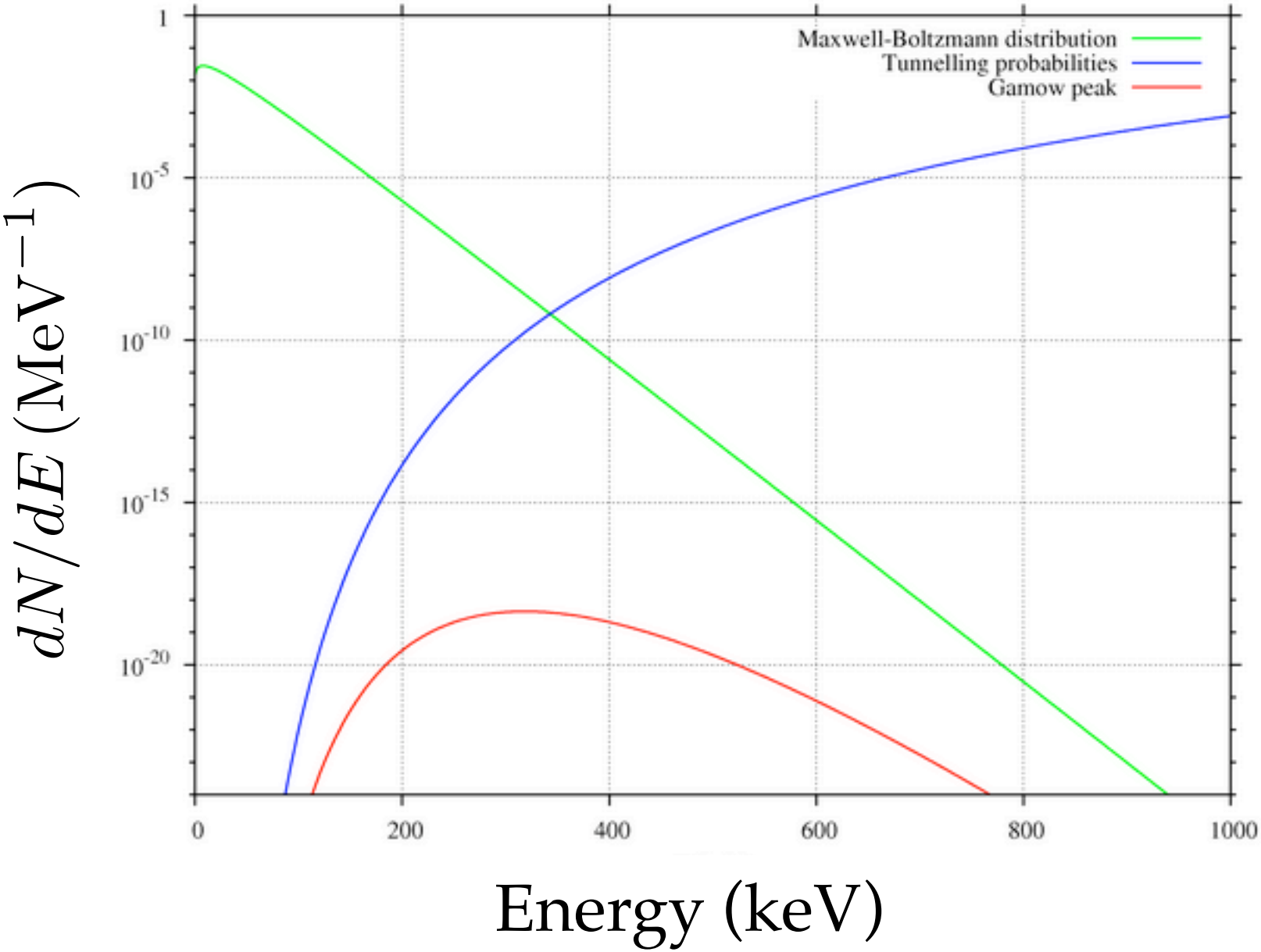
conference main site.

Topics

- Cosmology and big bang nucleosynthesis
- Stellar contributions to the chemical evolution, hydrostatic and explosive nucleosynthesis
- Neutrino and nucleus interaction in the cosmos
- Physics of nuclei far from stability
- Synthesis of heavy elements
- Direct observation of nucleosynthesis in stars
- Study of extra terrestrial materials
- Nucleosynthesis in extreme environments
- Techniques, tools and facilities for nuclear astrophysics
- Nuclear data for astrophysical applications
- Special topic: particle astrophysics and rare events in cosmos


Maxwell-Boltzmann distribution
Tunnelling probabilities
Gamow peak
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
0
200
400
600
800
1000
$dN/dE\ (\mathrm{MeV}^{-1})$
Energy (keV)

$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu_e$$

$$^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$

69% 31%

$$^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H}$$

(PP I)

$$^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$$

99.7% 0.3%

$$^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu_e$$

$$^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \rightarrow 2\,{}^{4}_{2}\mathrm{He}$$

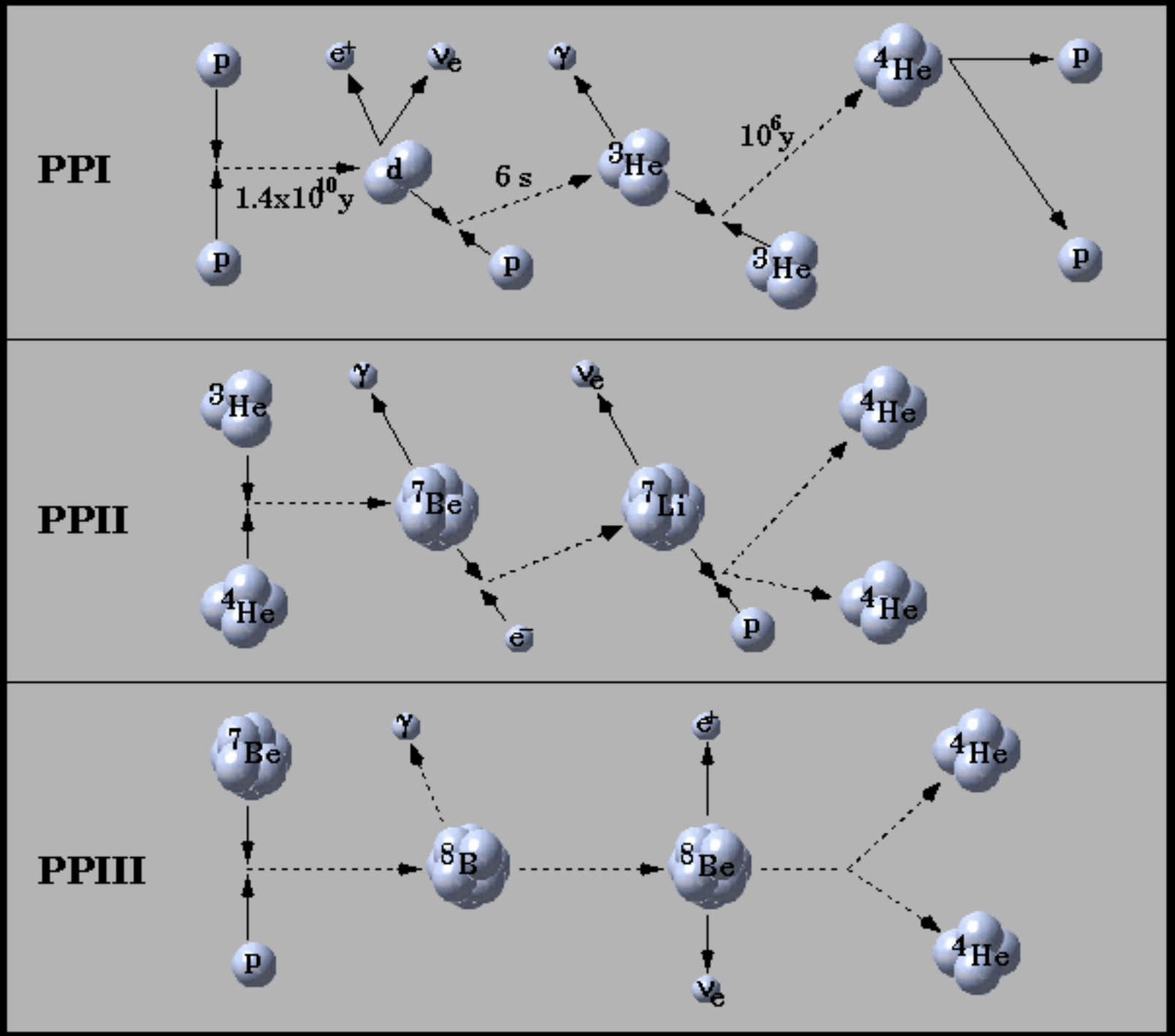
(PP II)

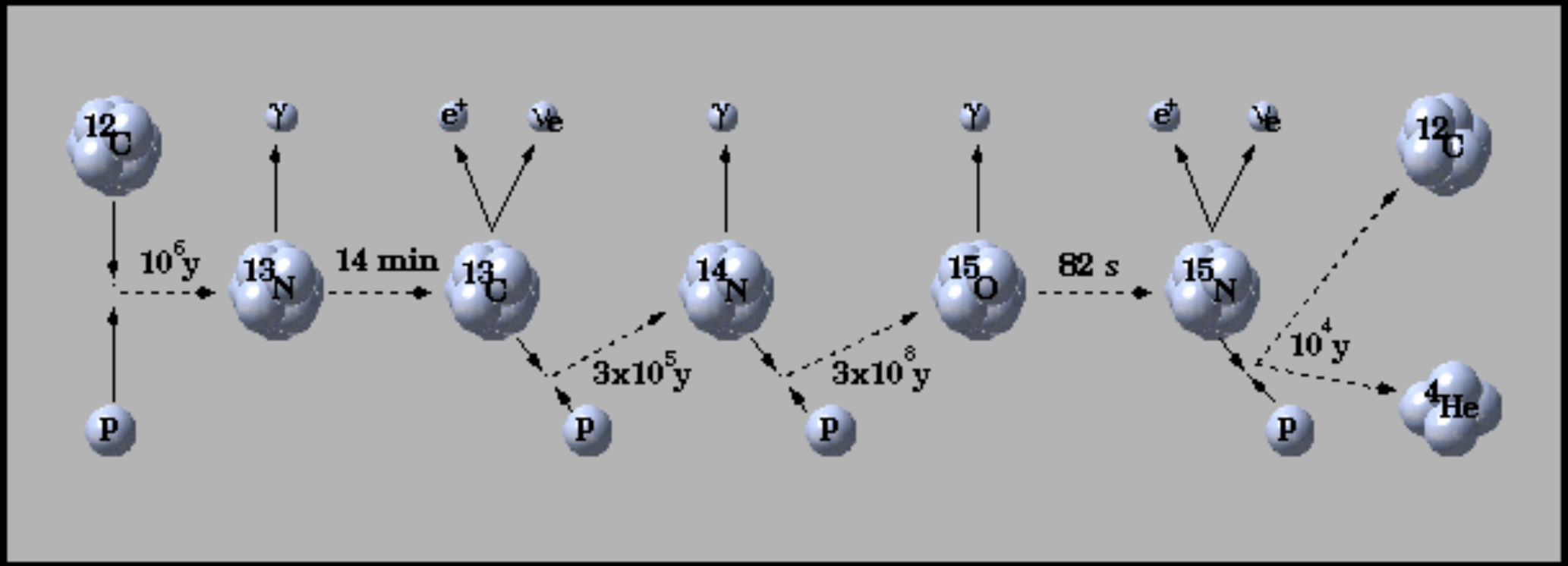
$$^{7}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$$

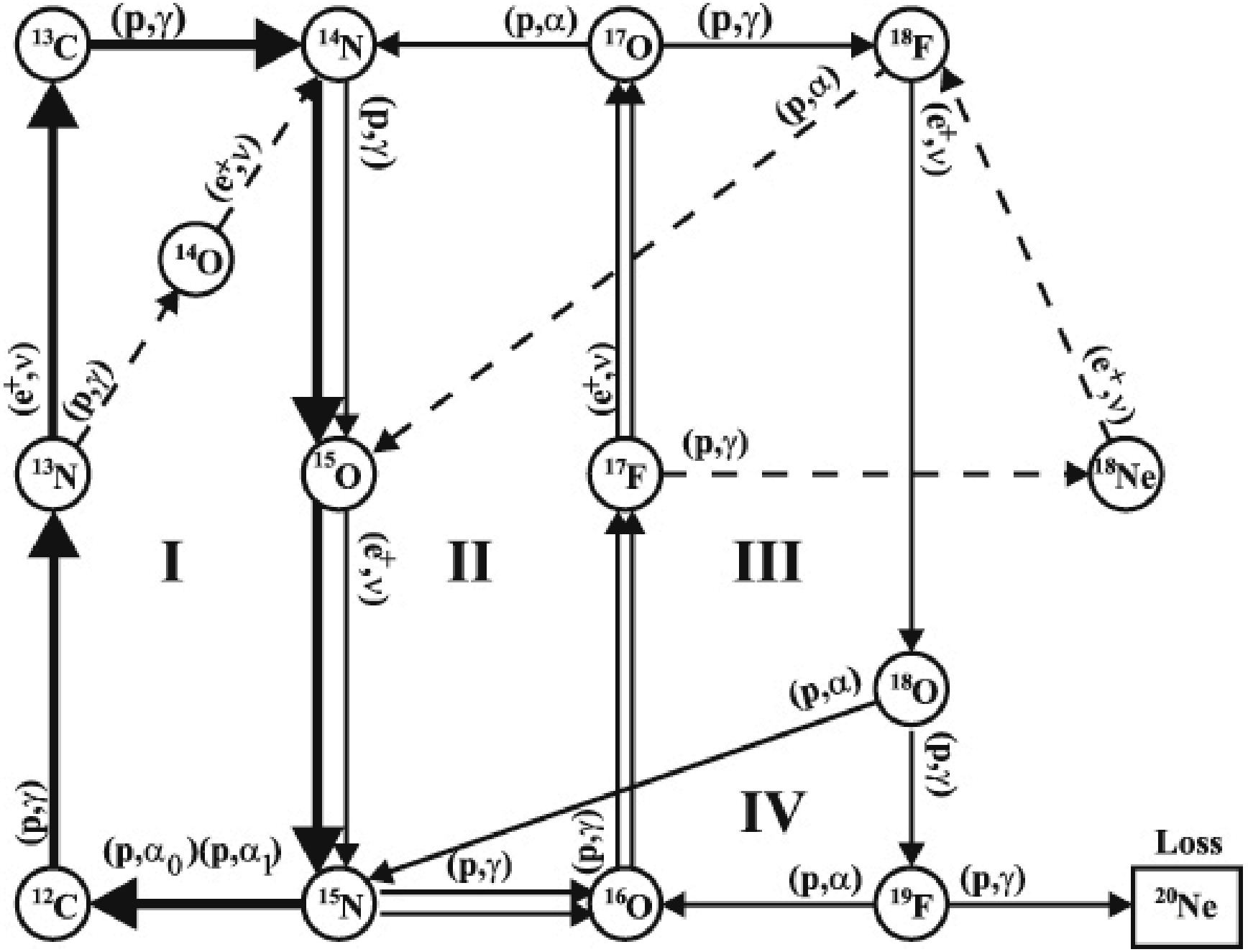
$$^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^{+} + \nu_e$$

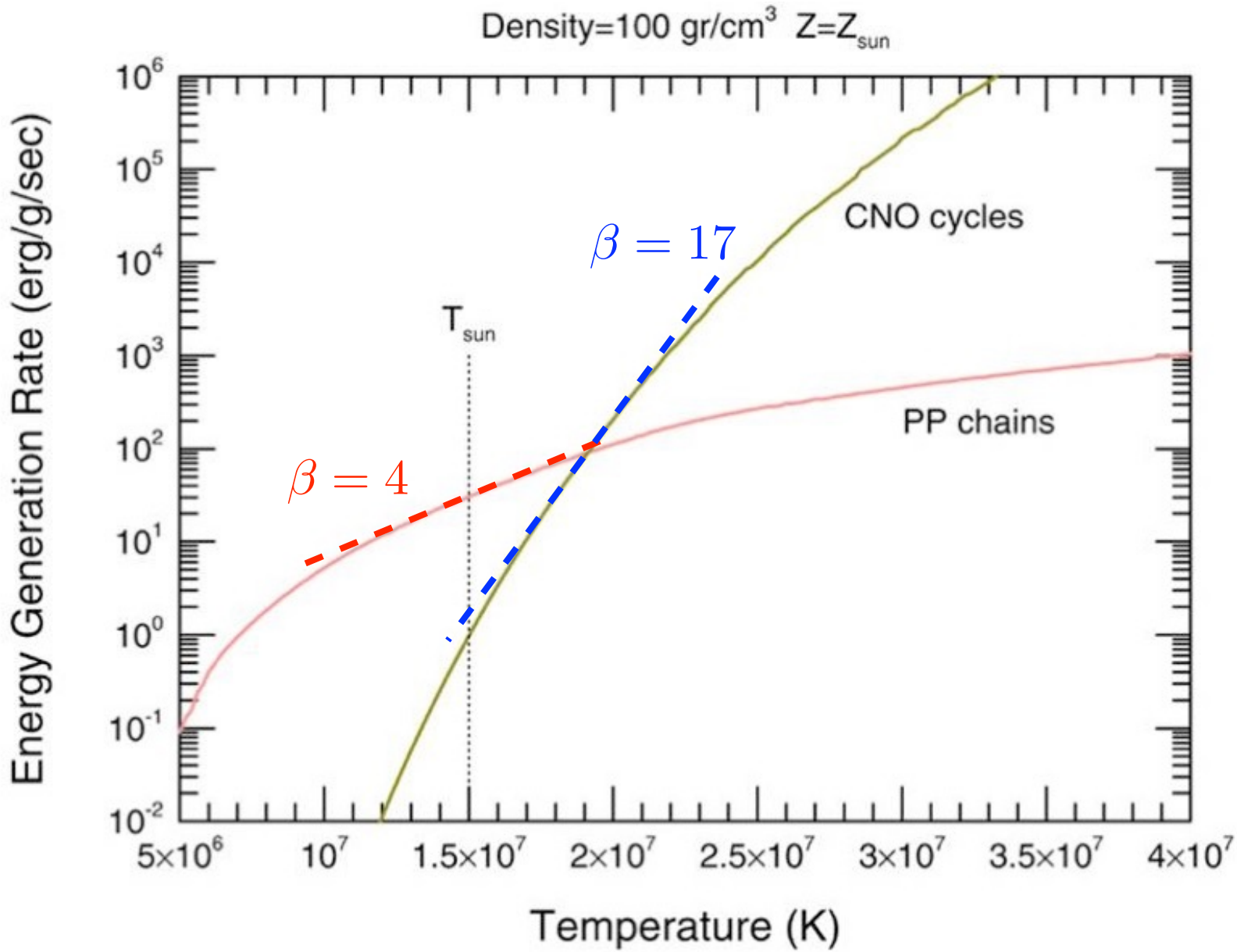
$$^{8}_{4}\mathrm{Be} \rightarrow 2\,{}^{4}_{2}\mathrm{He}$$

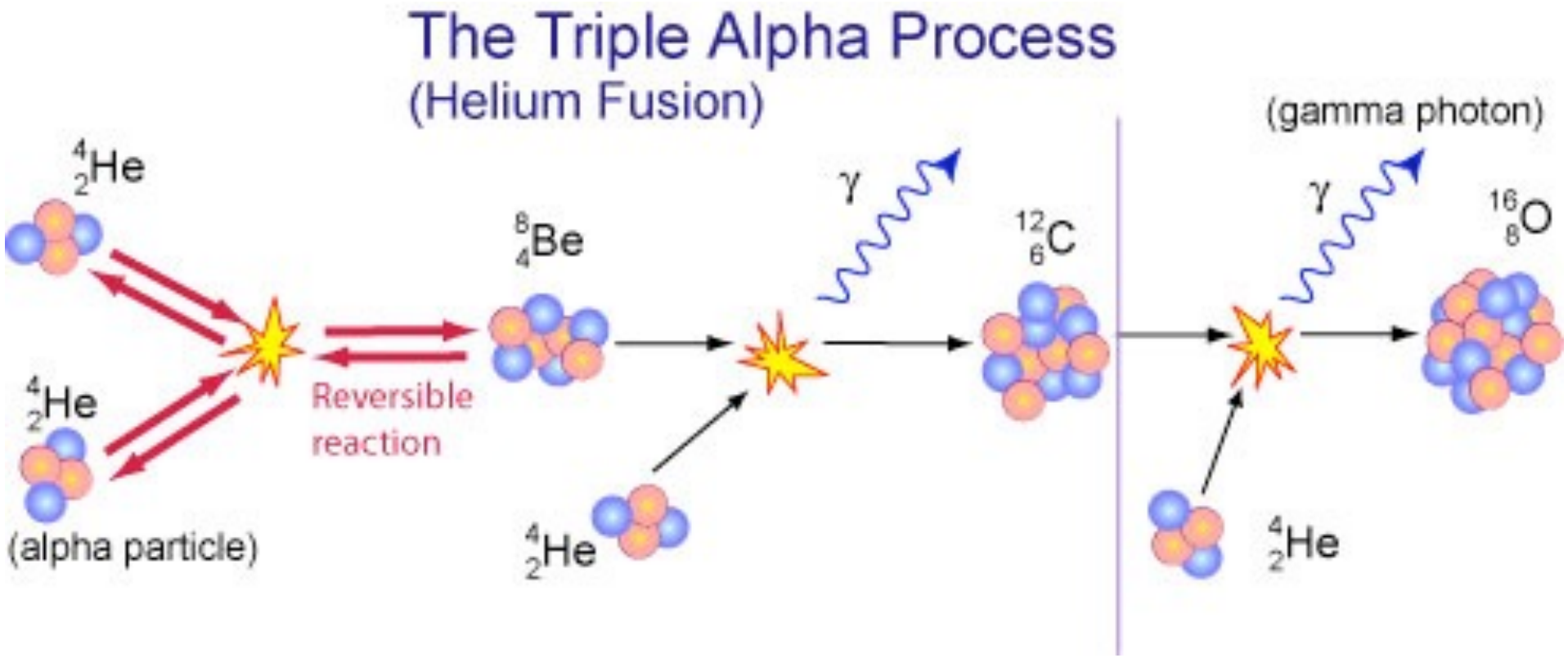
(PP III)


PPI
p
p
1.4x10^10 y
d
e+
νe
p
6 s
γ
3He
3He
10^6 y
4He
p
p
PPII
3He
4He
γ
7Be
e−
νe
7Li
p
4He
4He
PPIII
7Be
p
γ
8B
e+
νe
8Be
4He
4He


12C
γ
e+
νe
γ
γ
e+
νe
12C
10^6 y
13N
14 min
13C
14N
15O
82 s
15N
3x10^5 y
3x10^8 y
10^4 y
p
p
p
p
4He

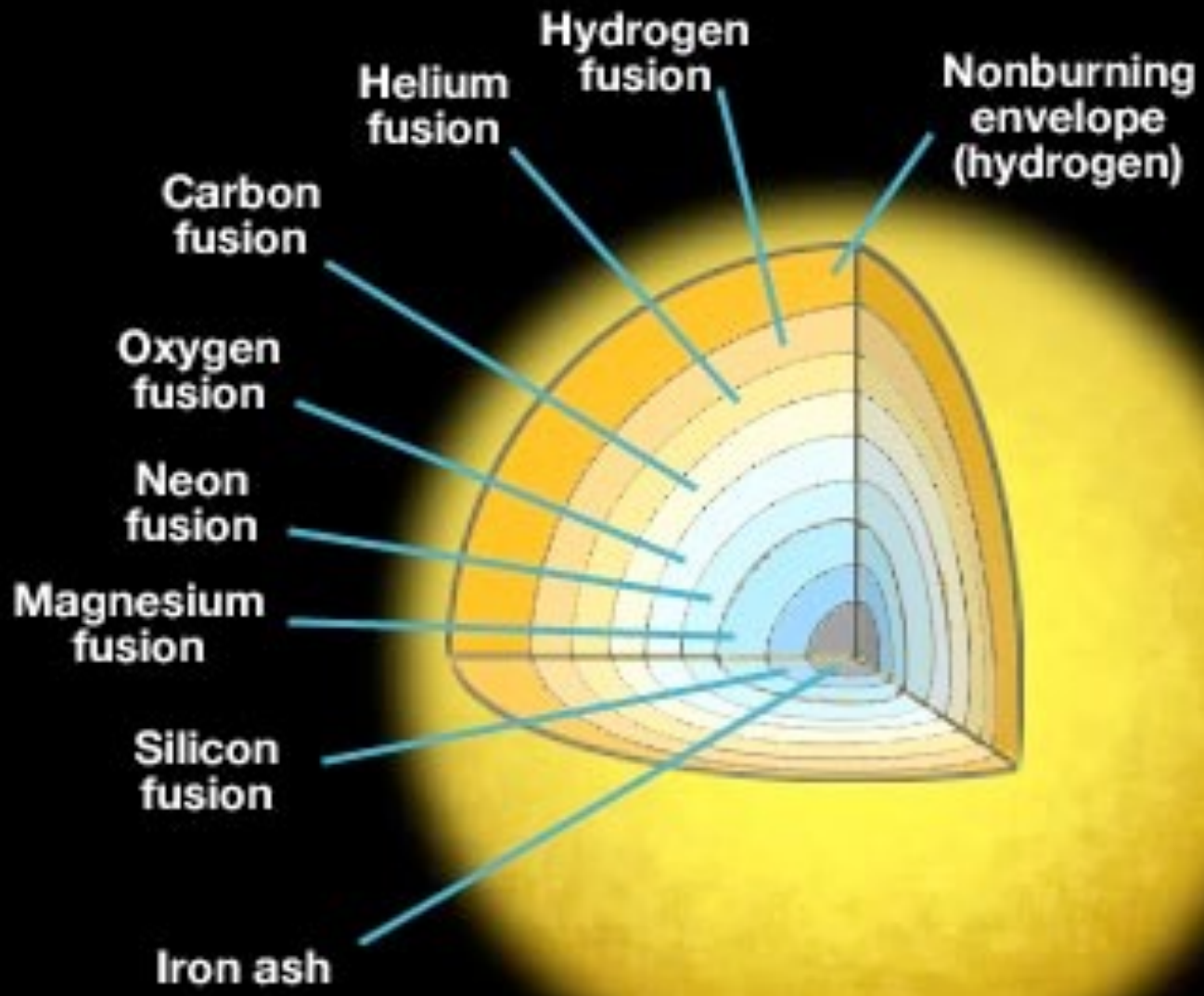

^{13}C
(p,γ)
^{14}N
(p,α)
^{17}O
(p,γ)
^{18}F
(p,γ)
(e$^+$,ν)
(p,α)
^{14}O
(e$^+$,ν)
(e$^+$,ν)
(p,γ)
(e$^+$,ν)
^{13}N
(p,γ)
^{15}O
^{17}F
(p,γ)
^{18}Ne
(e$^+$,ν)
I
II
III
(p,α)
^{18}O
(p,γ)
IV
(p,γ)
(p,α$_0$)(p,α$_1$)
(p,γ)
(p,γ)
Loss
^{12}C
^{15}N
^{16}O
(p,α)
^{19}F
(p,γ)
^{20}Ne

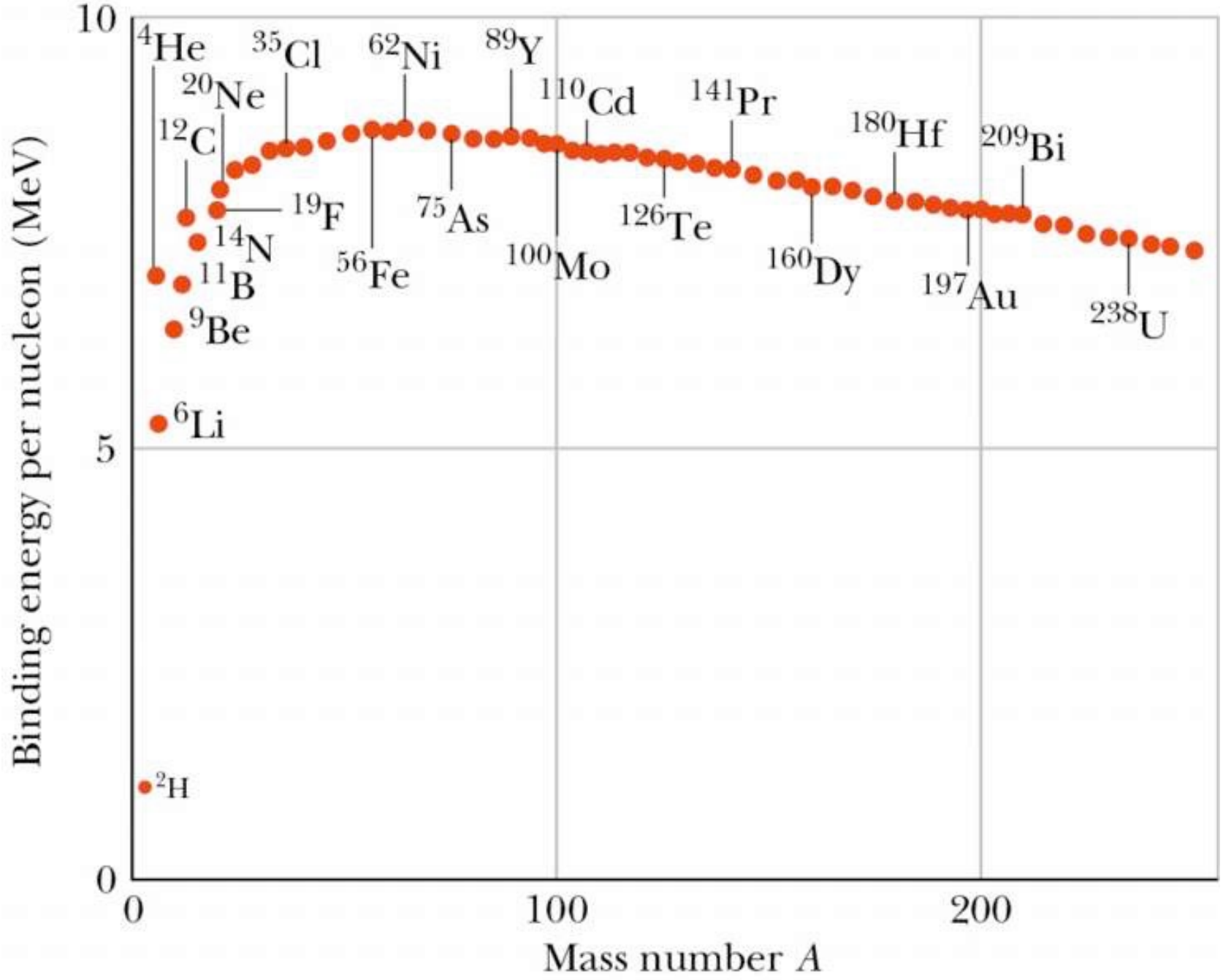

Density=100 gr/cm^3 Z=Z$_{sun}$
Energy Generation Rate (erg/g/sec)
Temperature (K)
CNO cycles
PP chains
$\beta = 17$
$\beta = 4$
T$_{sun}$
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
5×10^6
10^7
1.5×10^7
2×10^7
2.5×10^7
3×10^7
3.5×10^7
4×10^7

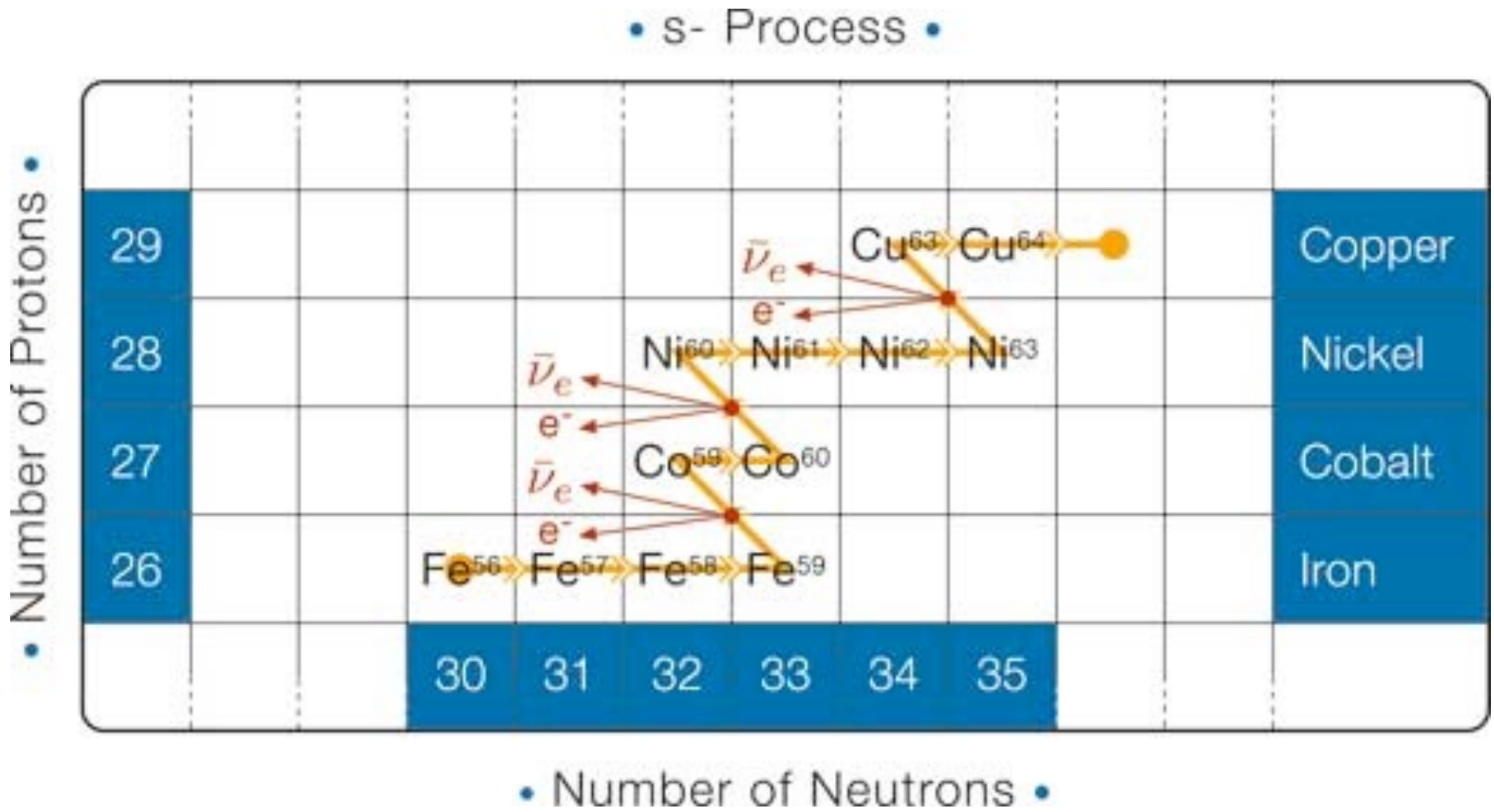

The Triple Alpha Process
(Helium Fusion)
(gamma photon)
$^{4}_{2}He$
$^{4}_{2}He$
(alpha particle)
Reversible reaction
$^{8}_{4}Be$
$^{4}_{2}He$
γ
$^{12}_{6}C$
γ
$^{16}_{8}O$
$^{4}_{2}He$

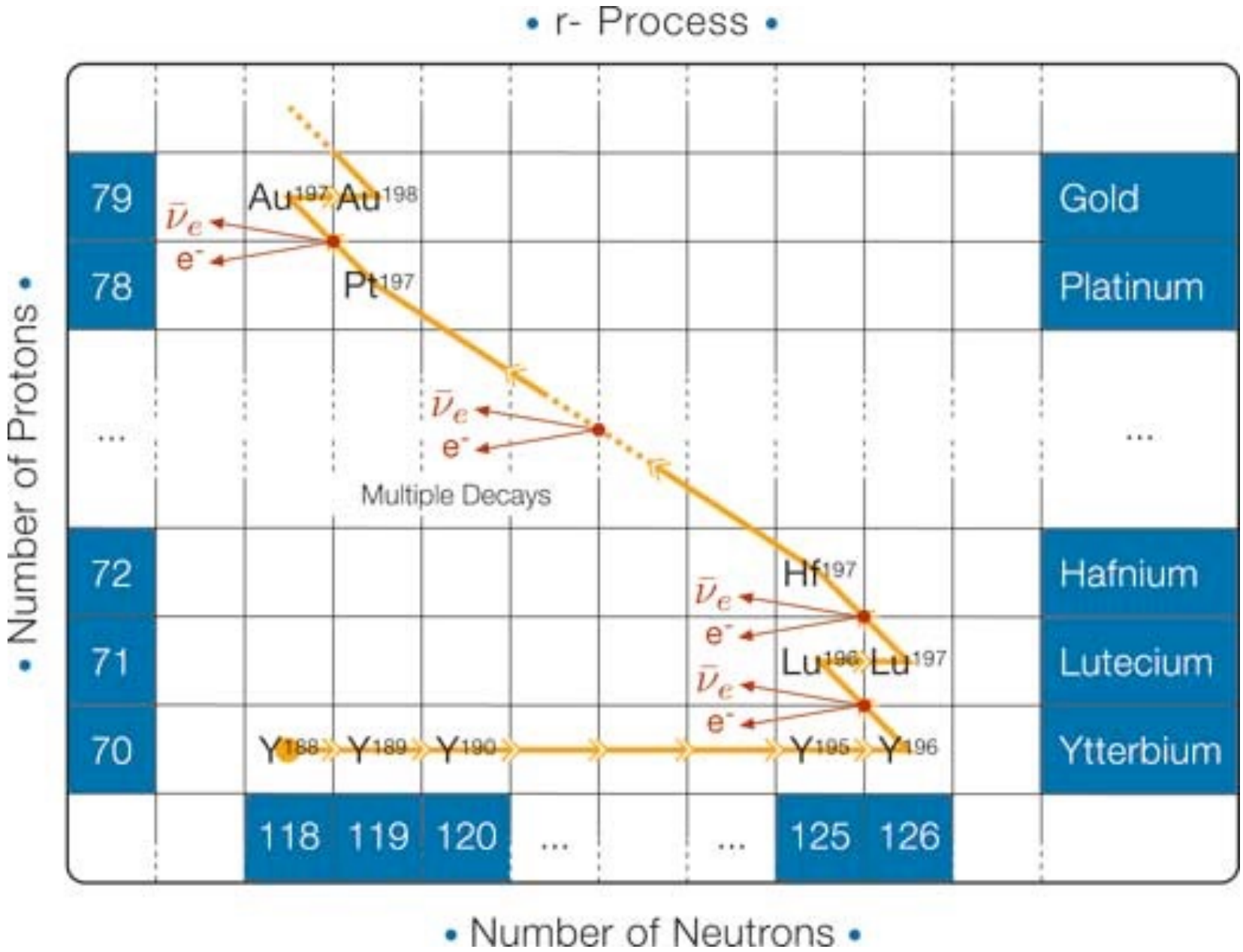
$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{16}\mathrm{O} + 2\,{}^{4}\mathrm{He} \\
&\rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \\
&\rightarrow {}^{23}\mathrm{Na} + p^{+} \\
&\rightarrow {}^{23}\mathrm{Mg} + n \\
&\rightarrow {}^{24}\mathrm{Mg} + \gamma
\end{aligned}
$$

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{24}\mathrm{Mg} + 2^{4}\mathrm{He} \\
&\rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He} \\
&\rightarrow {}^{31}\mathrm{P} + p^{+} \\
&\rightarrow {}^{31}\mathrm{S} + n \\
&\rightarrow {}^{32}\mathrm{S} + \gamma
\end{aligned}
$$

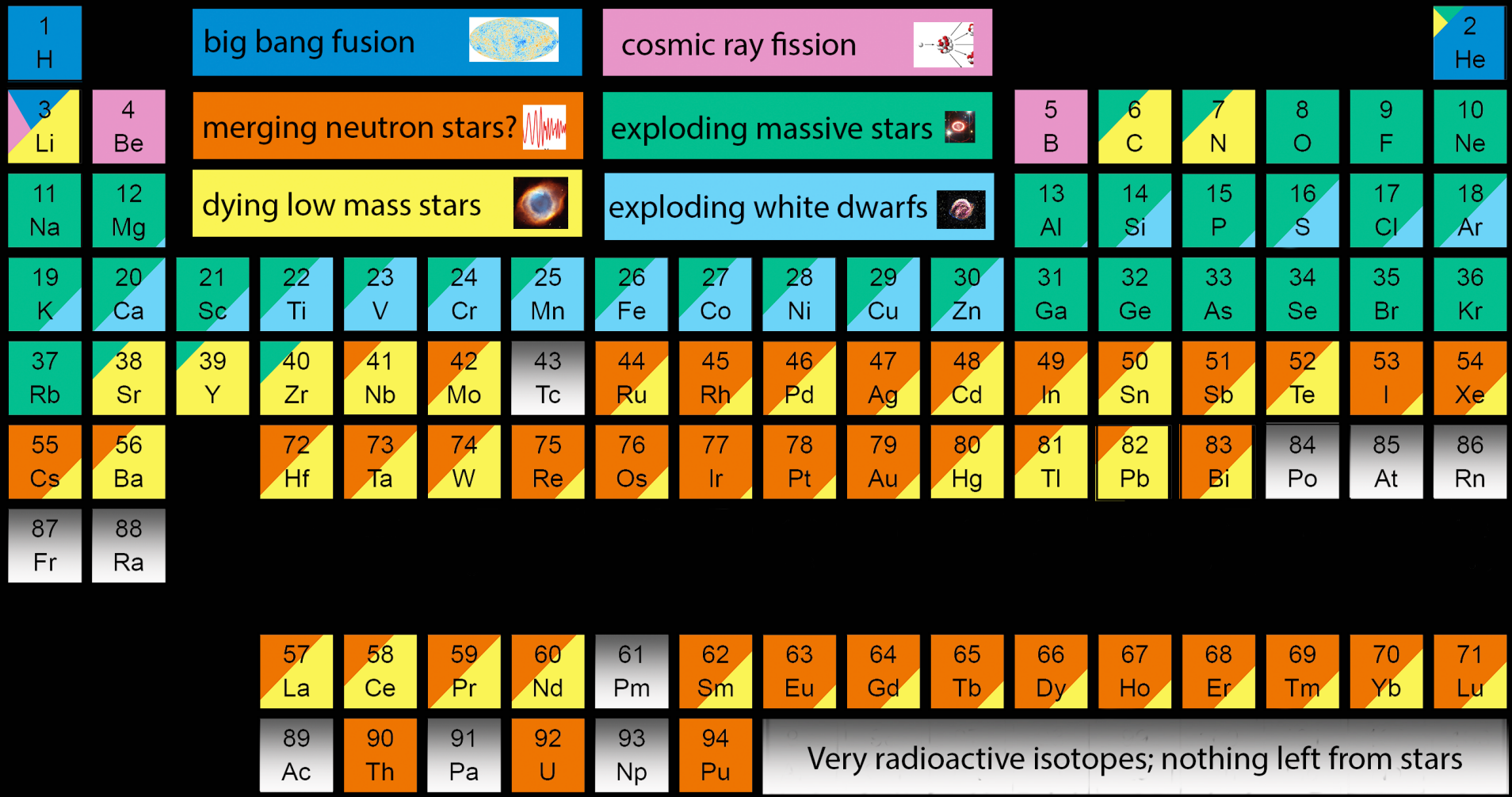

Hydrogen fusion
Helium fusion
Nonburning envelope (hydrogen)
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash


10
5
0
0
100
200
Binding energy per nucleon (MeV)
Mass number A
^{4}He
^{35}Cl
^{62}Ni
^{89}Y
^{20}Ne
^{110}Cd
^{141}Pr
^{180}Hf
^{209}Bi
^{12}C
^{19}F
^{75}As
^{126}Te
^{14}N
^{56}Fe
^{100}Mo
^{160}Dy
^{197}Au
^{11}B
^{238}U
^{9}Be
^{6}Li
^{2}H


• s- Process •
• Number of Protons •
29
28
27
26
30
31
32
33
34
35
Copper
Nickel
Cobalt
Iron
Cu63 Cu64
Ni60 Ni61 Ni62 Ni63
Co59 Co60
Fe56 Fe57 Fe58 Fe59
$\bar{\nu}_e$
e-
• Number of Neutrons •


• r- Process •
• Number of Protons •
• Number of Neutrons •
79
78
72
71
70
Gold
Platinum
Hafnium
Lutecium
Ytterbium
Au197
Au198
Pt197
Hf197
Lu196
Lu197
Y188
Y189
Y190
Y195
Y196
$\bar{\nu}_e$
e-
Multiple Decays
118
119
120
125
126

The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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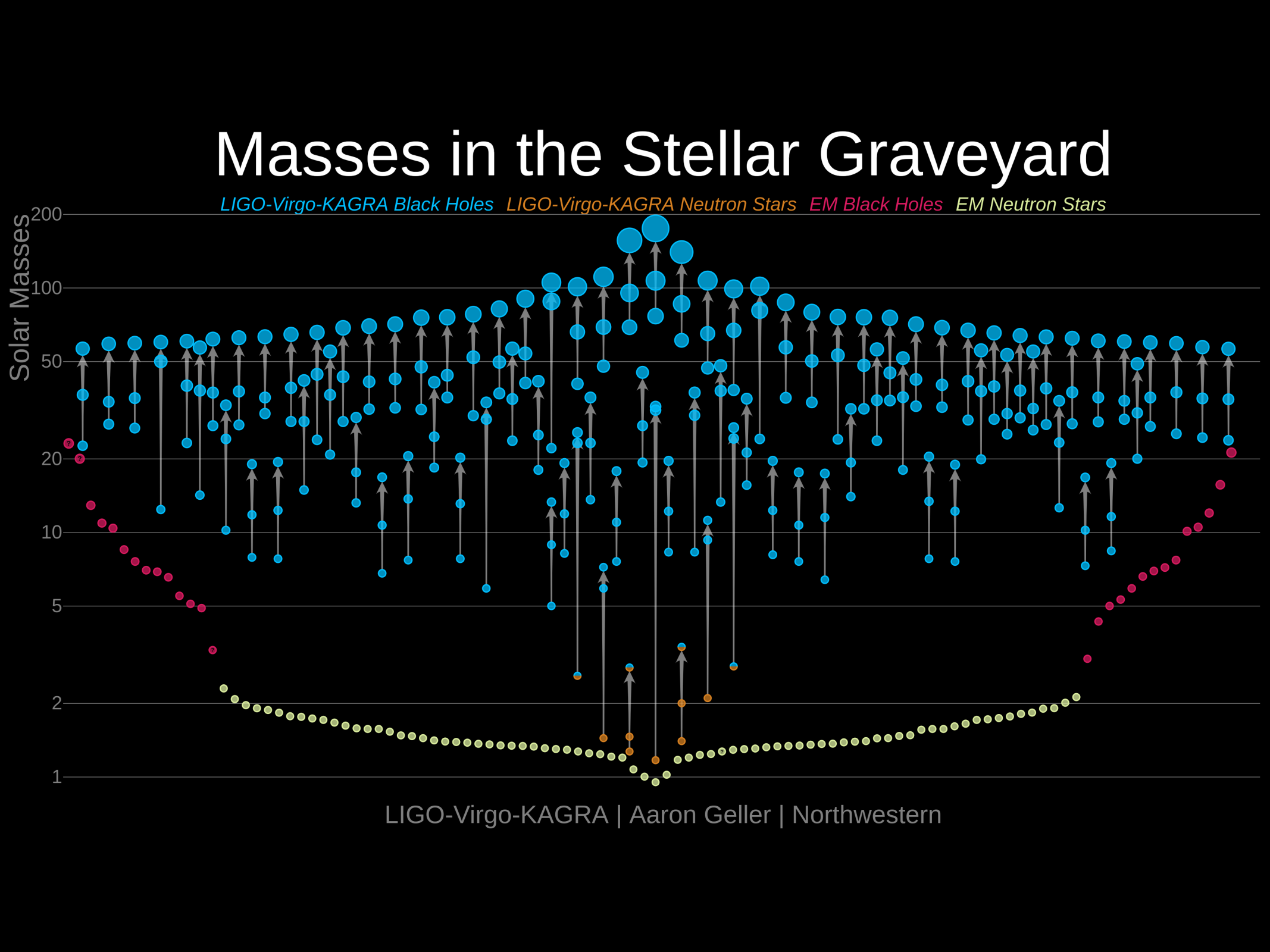
Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern