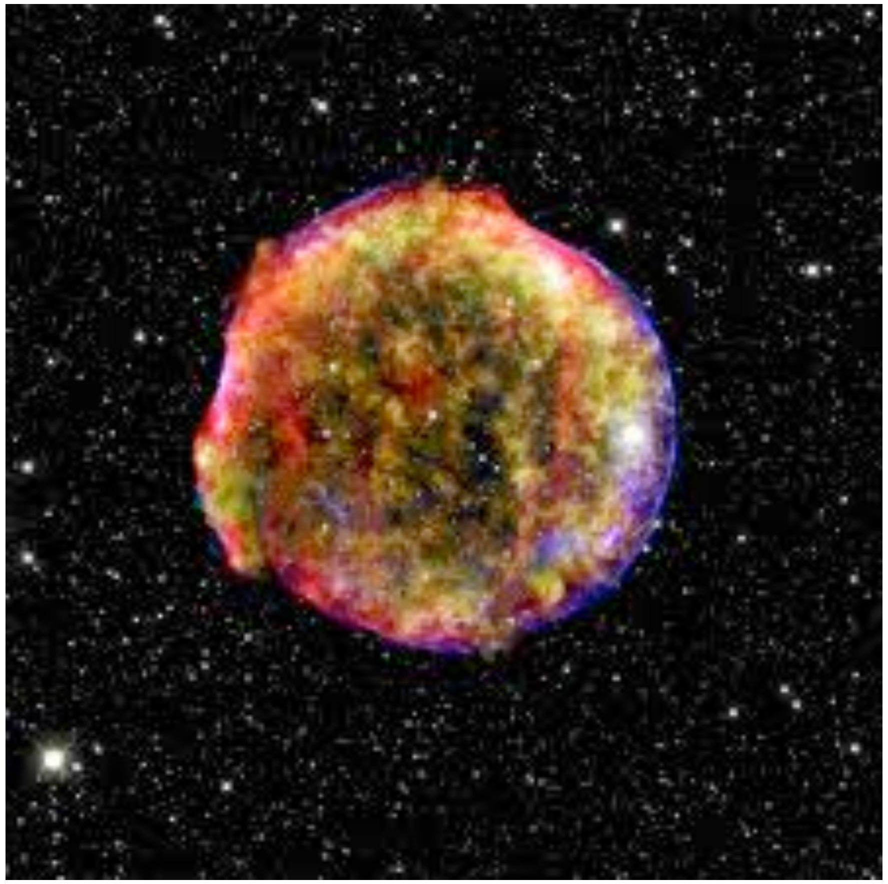
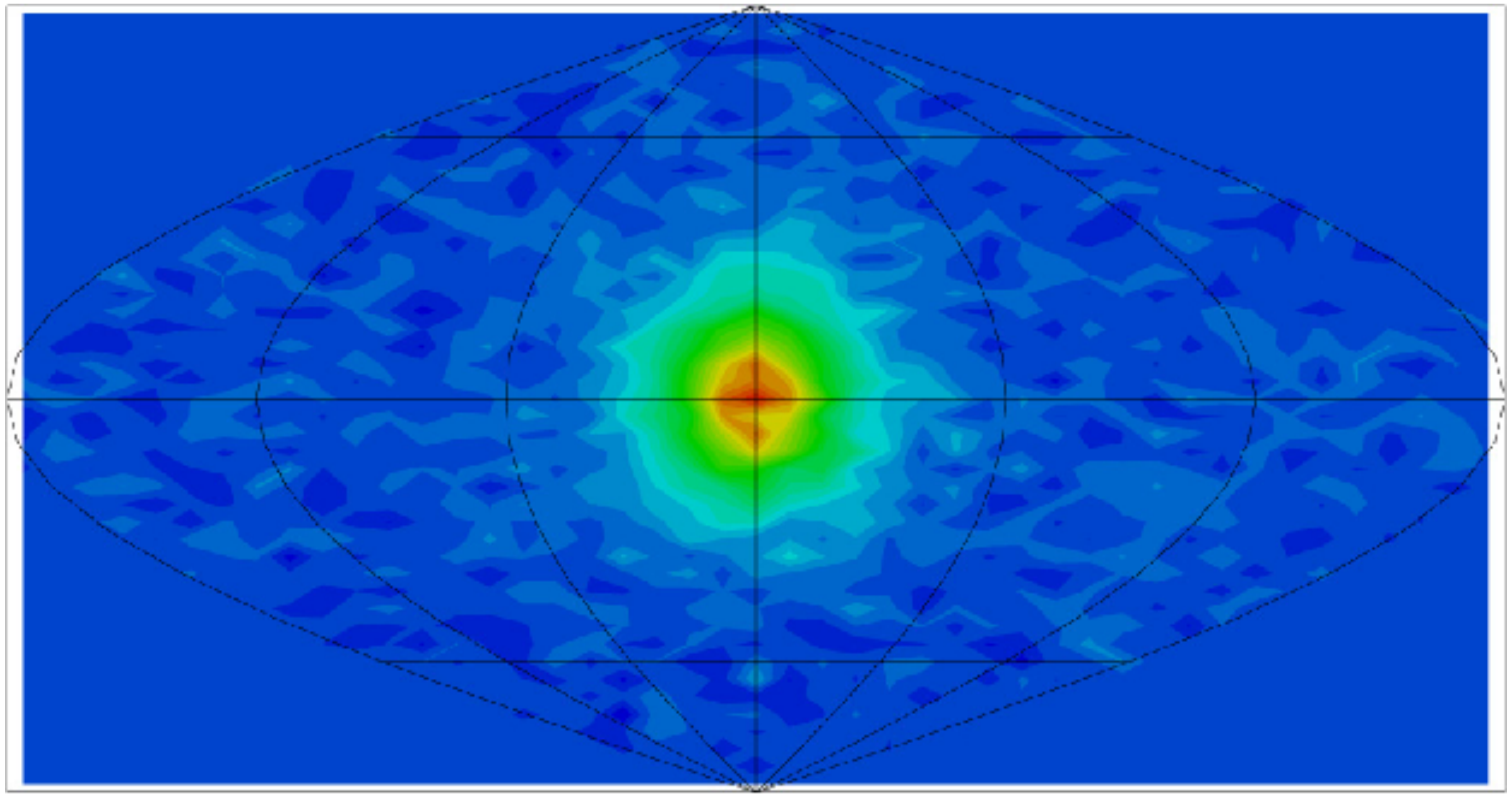
Lecture 6: "Stellar nucleosynthesis and origin of elements"

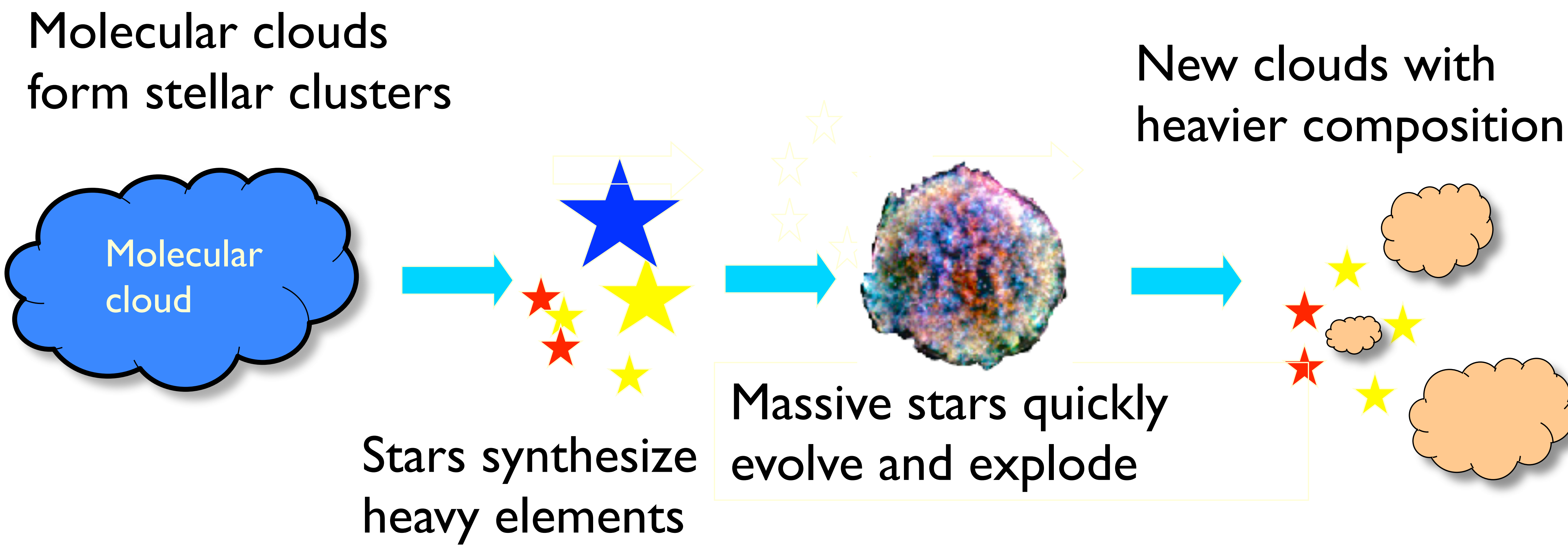




Outline

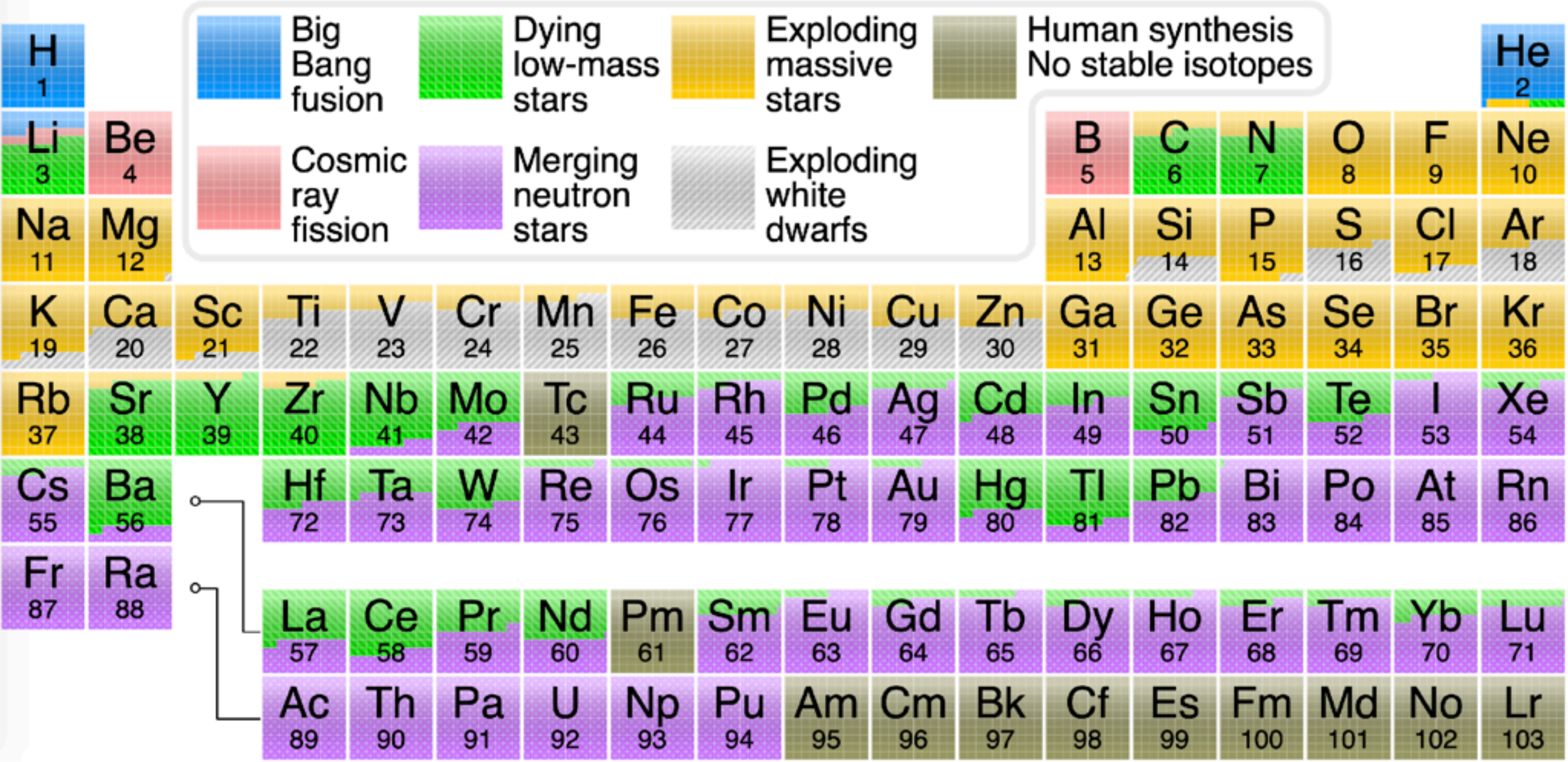
- Origin of elements: observational clues
- Stellar nucleosynthesis
- Stellar evolution

Life cycle of matter in space



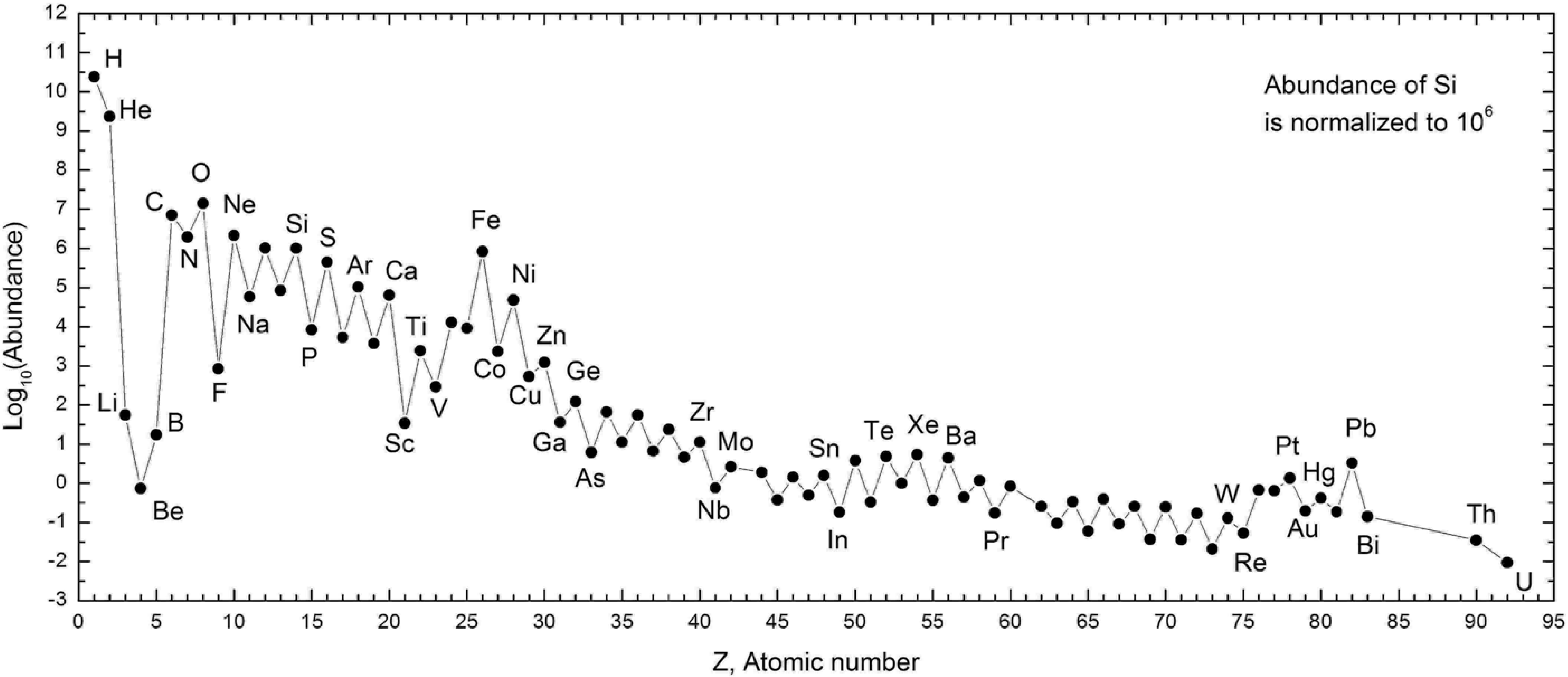
- Gravity vs pressure support (T, B-fields, turbulence, etc.)
- Stars: gravity vs fusion ($E = \Delta mc^2$)
- Nucleosynthesis: new generation of stars with higher metalicity
- Release: stellar winds and (super)nova explosion

Periodic table: astrophysical sources



- H, D, He: Big Bang
- Li (except ^{7}Li), Be, B: spallation of CNO elements by cosmic rays
- Nuclear fusion till ^{56}Fe and capture processes for heavier elements

Solar abundances of elements

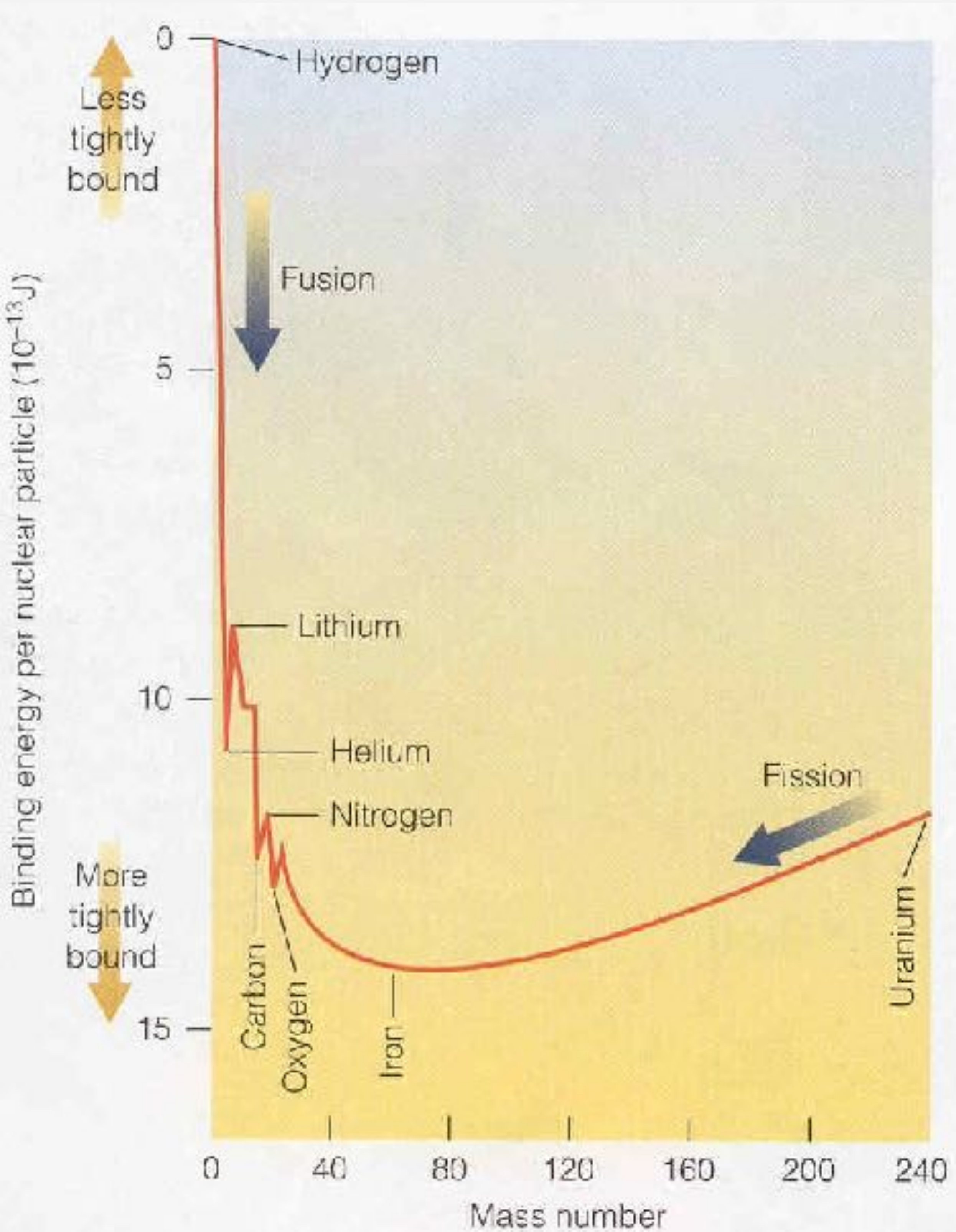


- General decrease in abundance with atomic number:
  - Negative anomaly at Li, Be, B (not stable)
  - Sawtooth pattern (even > odd; Oddo-Harkins rule [1914])
  - Positive anomaly at Fe and Ni

Nuclear shell model

- Nuclear shell model: Pauli exclusion principle to describe energy levels (ΔE_{ul} > MeV)
- *n*, *ℓ*, spin-orbit interaction
- Shells for p and n are independent
- A greater stability when p or n–shells are filled (“magic nuclei”)
- Doubly magic nuclei are particularly stable (Z=2, 8, 20, 28, 50, 82): ^{4}He, ^{16}O, ^{40}Ca, iron,…

The Curve of Nucleon Binding Energy



From our text: Horizons, by Seeds

- If you keep adding protons to a nucleus?
  - Coulomb repulsion continues to increase
    - new proton feels repulsion from all other protons
  - Strong force attraction reaches limit
    - new proton can't feel attraction from protons on far side of a big nucleus
- Gain energy only up to point where Coulomb repulsion outweighs strong force attraction.
- Most "stable" nucleus is ^{56}Fe (26 protons, 30 neutrons, 56 total)
- Release energy by fusion of light nuclei to make heaver ones– up to ^{56}Fe
- Release energy by fission of heavy nuclei to make lighter ones – down to ^{56}Fe

Nucleosynthesis via nuclear reactions

$$^{A1}_{Z1}A + ^{A2}_{Z2}B \Rightarrow ^{A3}_{Z3}C + ^{A4}_{Z4}D$$

Conservation laws:

$$\begin{cases} A1 + A2 = A3 + A4 & \text{(mass numbers)} \\ Z1 + Z2 = Z3 + Z4 & \text{(atomic numbers)} \end{cases}$$

Energy of a reaction:

$$Q = [\underbrace{(m_A + m_B)}_{\text{initial}} - \underbrace{(m_C + m_D)}_{\text{final}}]c^2$$

$Q > 0$: exothermic process

$Q < 0$: endothermic process

Origin of elements' theory

- All elements are from Big Bang, static nuclear abundances (Alpher, Bethe, Gamow 1948)

- B^2FH paper in 1957 (Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle):

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

George Gamow

(1904 –1968)

Margaret Burbidge

(1919 – 2020)

Hydrogen Burning

- Eddington, 1920's: H ⇒ He in stars

- Coulomb repulsion ⇒ barrier ⇒ Sun is too cold

- Proton tunneling via barrier

- No reactions for H & He gas:

$^{1}H + {}^{1}H \Rightarrow {}^{2}He$ (unstable) $\Rightarrow {}^{1}H + {}^{1}H$

$^{1}H + {}^{4}He \Rightarrow {}^{5}Li$ (unstable) $\Rightarrow {}^{1}H + {}^{4}He$

$^{4}He + {}^{4}He \Rightarrow {}^{8}Be$ (unstable) $\Rightarrow {}^{4}He + {}^{4}He$

Arthur Eddington

1882 – 1944

Hydrogen Burning

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

The Formation of Deuterons by Proton Combination

H. A. BETHE, *Cornell University, Ithaca, N. Y.*

AND

C. L. CRITCHFIELD, *George Washington University, Washington, D. C.*

(Received June 23, 1938)

Hans Bethe

(1906 – 2005)

Charles Critchfield

(1910 – 1994)

- Hans Bethe and Charles L. Critchfield (1938):
- Beta-plus decay of p to n in ^{2}He via weak interaction
- Two-stage process:
    1. $^{1}H + {}^{1}H \Rightarrow {}^{2}He + \gamma$
    2. $^{2}He \Rightarrow {}^{2}D + e^{+} + \nu_{e} + 0.42$ MeV (extremely slow)
- Half-life of p in the Sun's core before reaction: $\sim 10^{9}$ years

Proton-proton (PP) chain

- Converts 4 ^{1}H to ^{4}He:

1. $^{1}H + ^{1}H \Rightarrow ^{2}D + e^{+} + \nu_e$ (0.42 MeV)

2. $^{1}H + ^{2}D \Rightarrow ^{3}He + \gamma$ (5.49 MeV)

- 4 pathways to ^{4}He

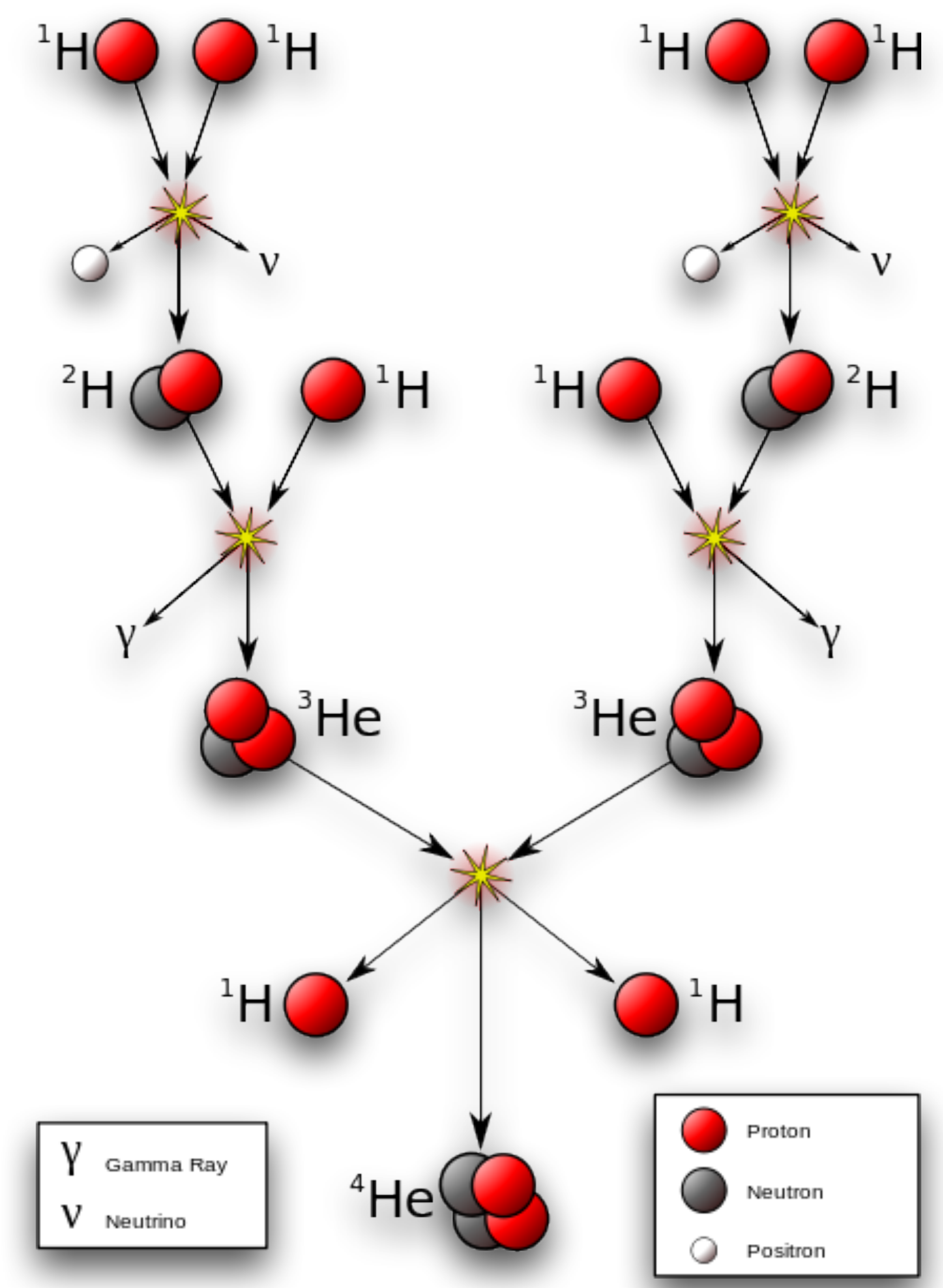
- Proton-Proton cycle I (requires $T > 4 \times 10^{6}$ K):

3. $^{3}He + ^{3}He \Rightarrow ^{4}He + 2\ ^{1}H$ (12.86 MeV)

Total energy production:

$Q_{PP\text{-}I} = 26.22$ MeV

PP-I chain



1H
1H
1H
1H
ν
ν
2H
1H
1H
2H
γ
γ
3He
3He
1H
1H
4He
γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron

Proton-proton (PP) chain

- PP-II cycle ($T \sim 14 - 23 \times 10^6$ K)
- Continues after PP-I cycle:

$^3He + ^4He \Rightarrow ^7Be + \gamma$

$^7Be + e^- \Rightarrow ^7Li + \nu_e$

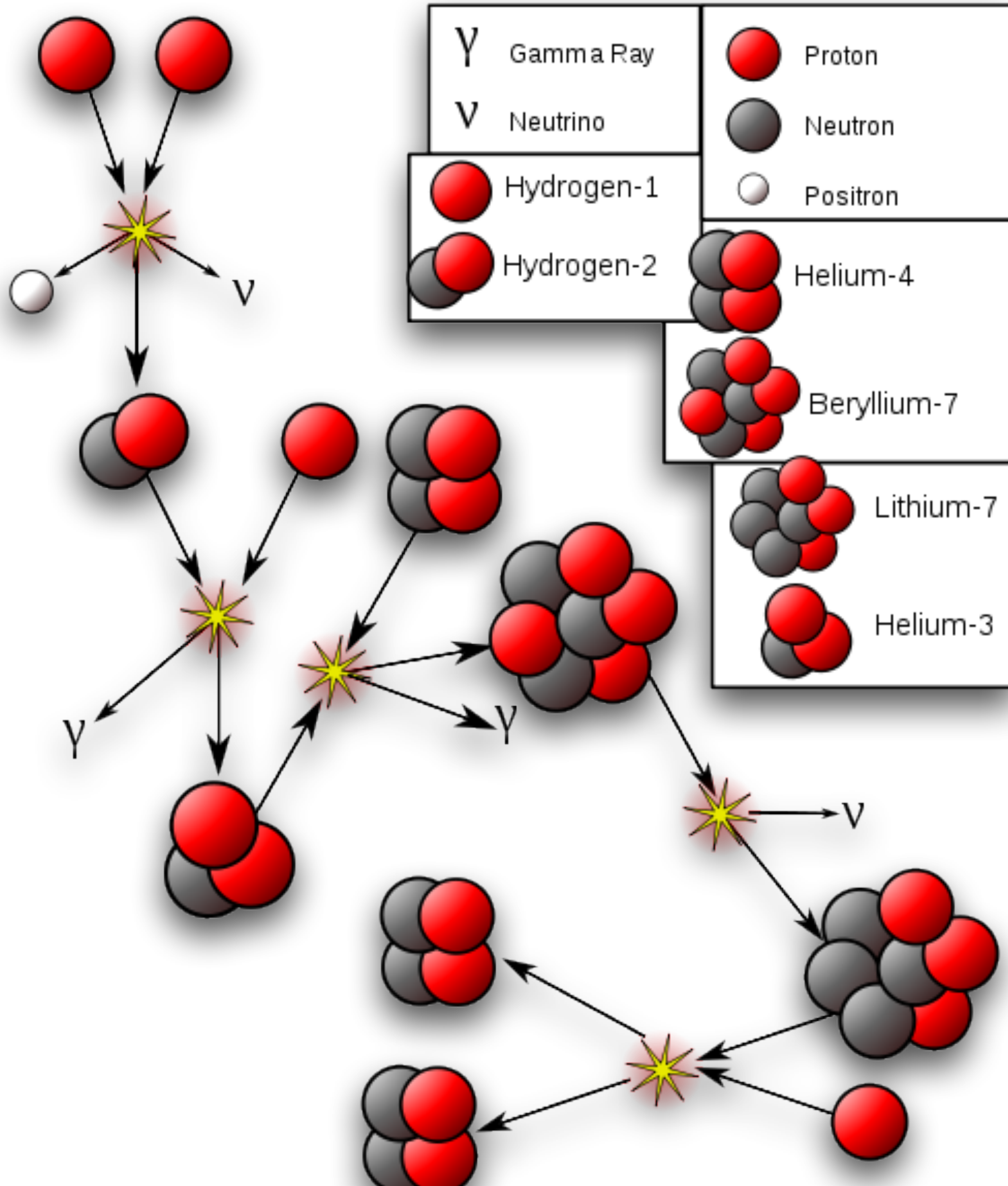
$^7Li + ^1H \Rightarrow 2\ ^4He$

Energy production:

$Q_{pp\text{-}II} = Q_{pp\text{-}I} + 0.813$ MeV

- Sun's core: Efficiency of PP-I ~ 86 %, PP-II ~ 14 %

PP-II chain

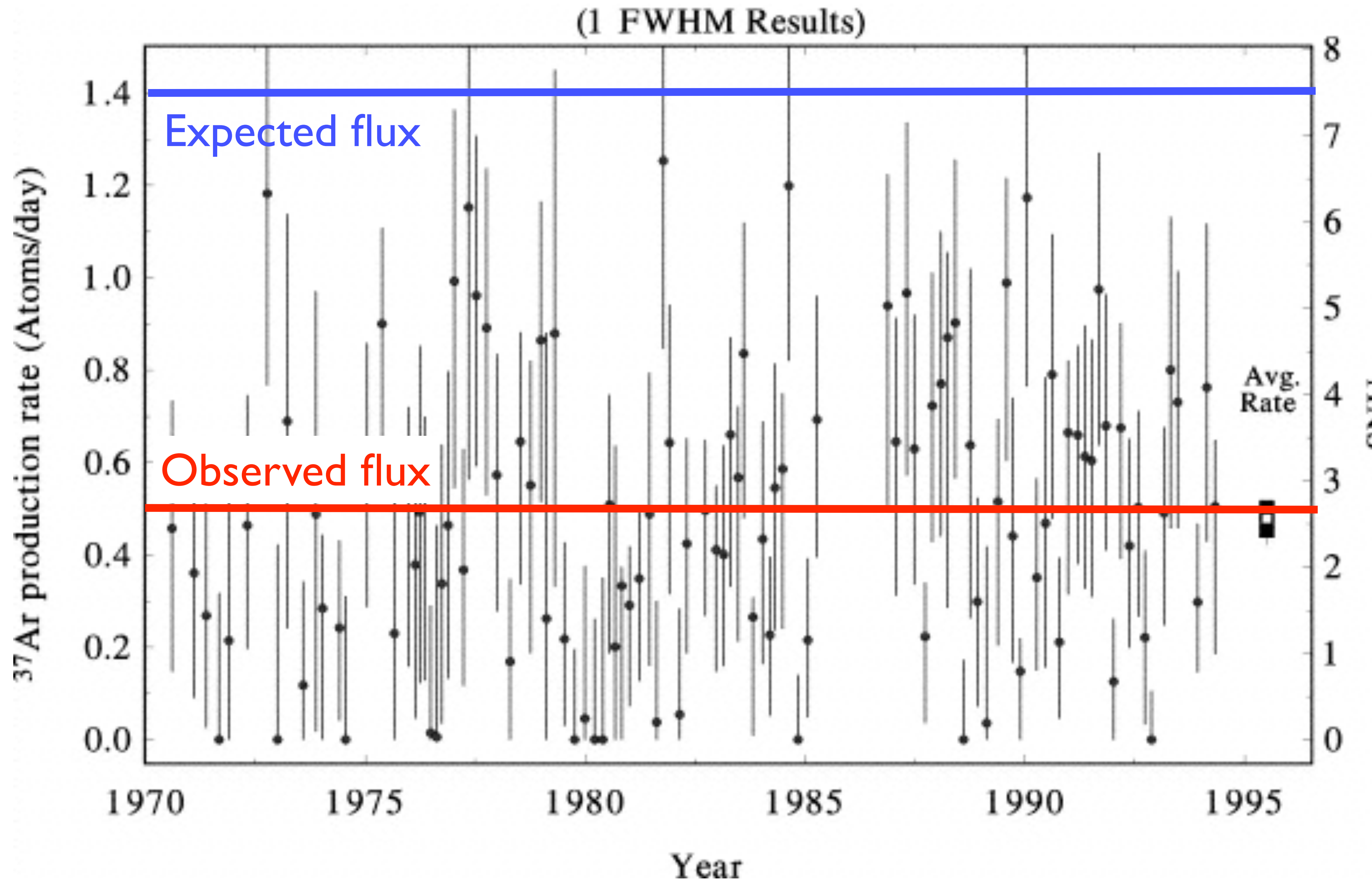


γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron
Hydrogen-1
Hydrogen-2
Helium-4
Beryllium-7
Lithium-7
Helium-3
ν
γ
γ
ν

Direct detections of solar neutrinos

- R. Davis, Jr. and J. Bahcall (>1969)
- Homestake Gold mine (South Dakota), 1.5 km depth
- Shielding from cosmic rays
- A cistern with 600 tons of perchloroethylene C_2Cl_4
- $\nu_e + {}^{37}Cl \Rightarrow {}^{37}Ar + e^-$ (barrier of ~0.8 MeV)
- ^{37}Ar is radioactive and can be counted
- Cadence: once per few weeks

Direct detections of solar neutrinos



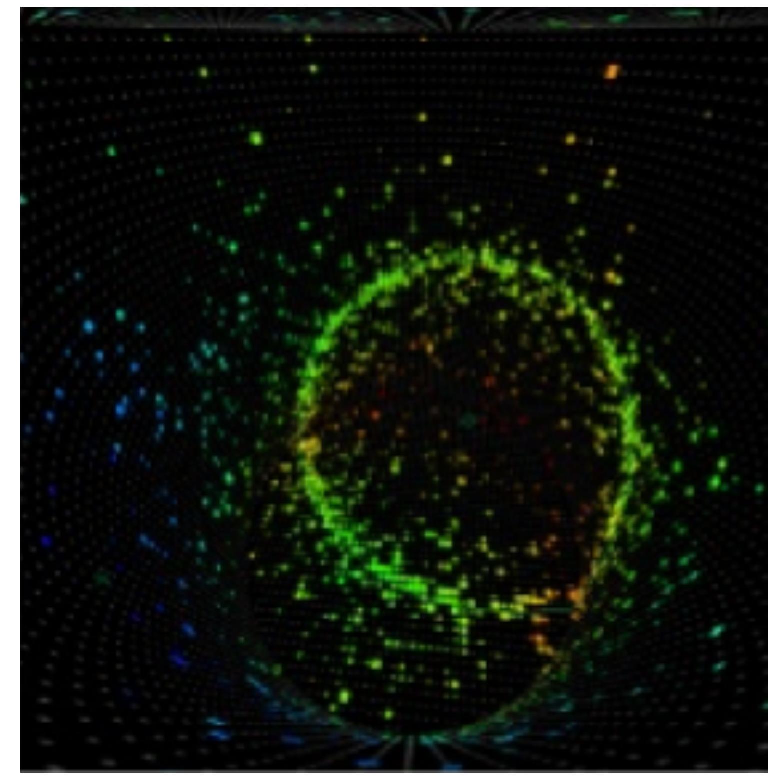
- ~1/3 of predicted flux detected
- Neutrinos have non-zero mass ⇒ neutrino flavor "oscillation" on their way to Earth (predicted by B. Pontecorvo in 1957)

Direct detections of solar neutrinos

- ν + water ⇒ relativistic e^- ⇒ Cherenkov radiation cone

- Super-Kamiokande (>1982): 1km depth, Mozumi mine,

Japan



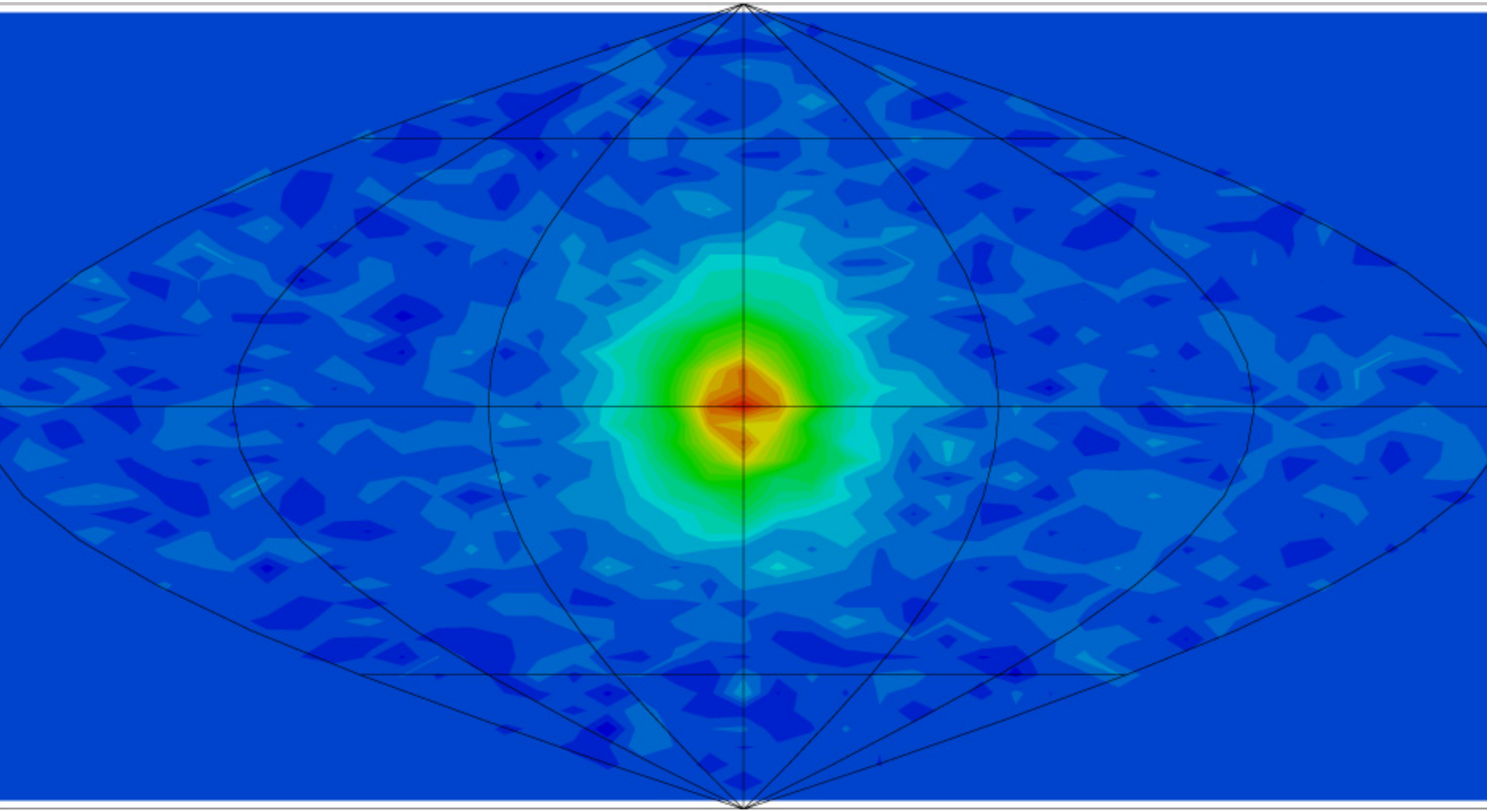
- 50 000 tons of ultra-pure H_2O

- ~ 12 000 photo-detectors: real time obs.

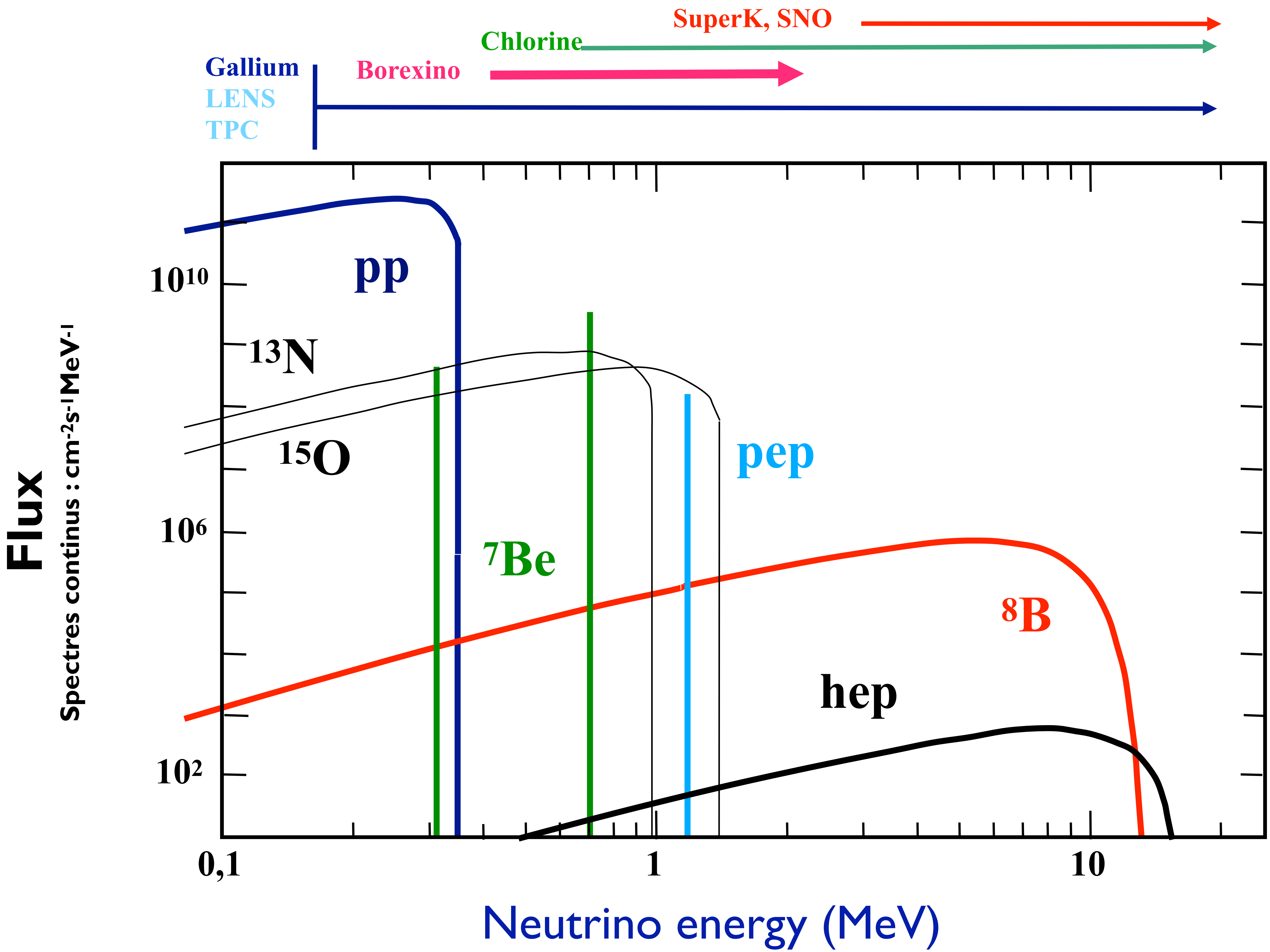
- Timing and charge: flavor and direction of ν

- Also energy distribution of ν

Direct image of the Sun's core



Direct detections of solar neutrinos



CNO Cycle

Carl Friedrich von Weizsäcker

(1912 – 2007)

- Bethe–Weizsäcker cycle (1938-39)
- Operates in stars with $M > 1.3\ M_{Sun}$
- $T > 15 \times 10^6$ K, dominates at 17×10^6 K
- Catalytic cycle via C, N, O isotopes:

$$4\,{}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + Q_{CNO}$$

Total energy production:

$Q_{CNO} = 26.73$ MeV

Hans Bethe

(1906 – 2005)

CNO Cycle-I

1. $^{12}C + ^{1}H \Rightarrow ^{13}N + \gamma + 1.95$ MeV

2. $^{13}N \Rightarrow ^{13}C + e^{+} + \nu_e + 1.20$ MeV (half-life 10 min)

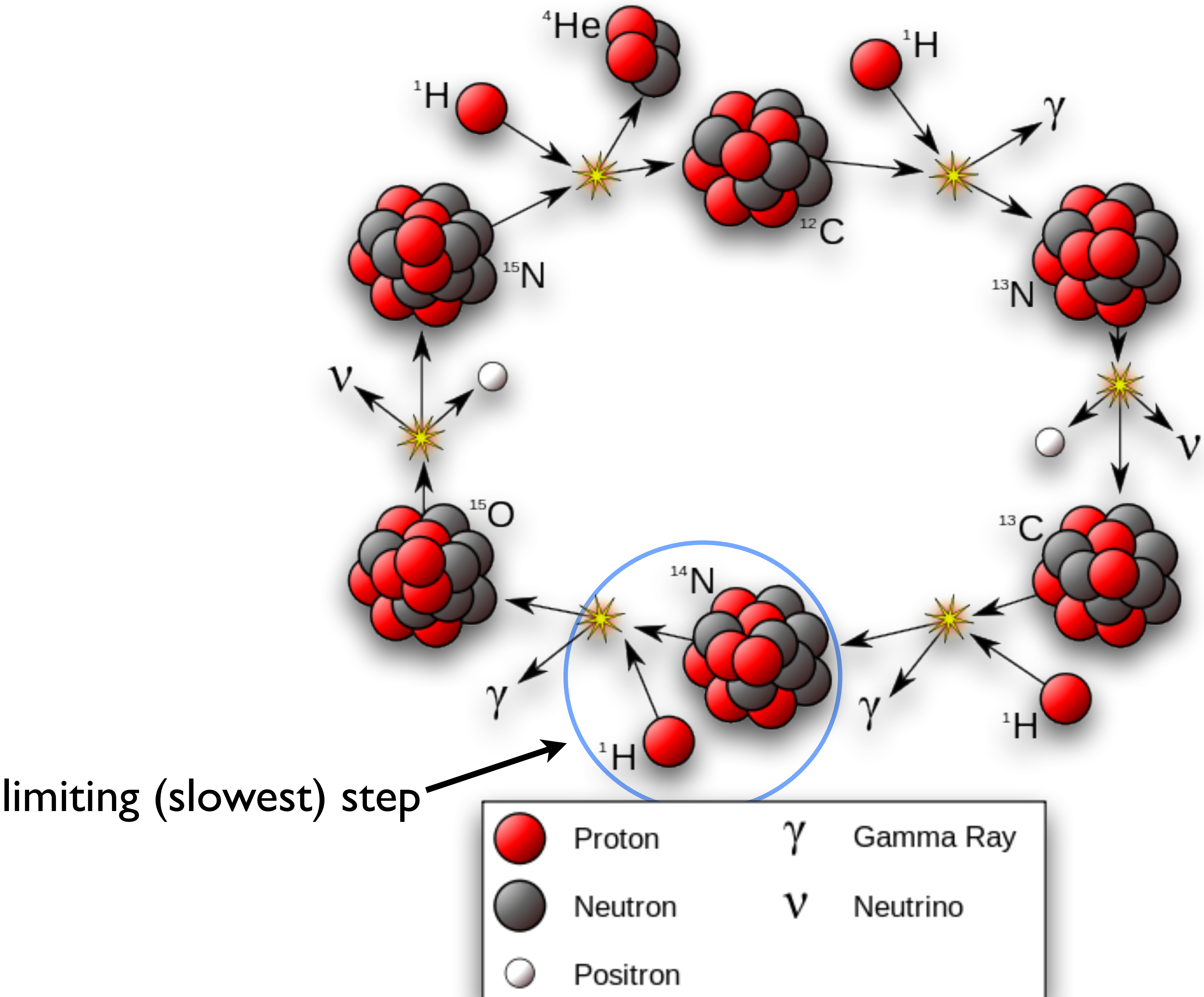
3. $^{13}C + ^{1}H \Rightarrow ^{14}N + \gamma + 7.54$ MeV

4. $\underline{^{14}N + ^{1}H \Rightarrow ^{15}O + \gamma + 7.35 \text{ MeV (limiting step)}}$

5. $^{15}O \Rightarrow ^{15}N + e^{+} + \nu_e + 1.73$ MeV (half-life 2 min)

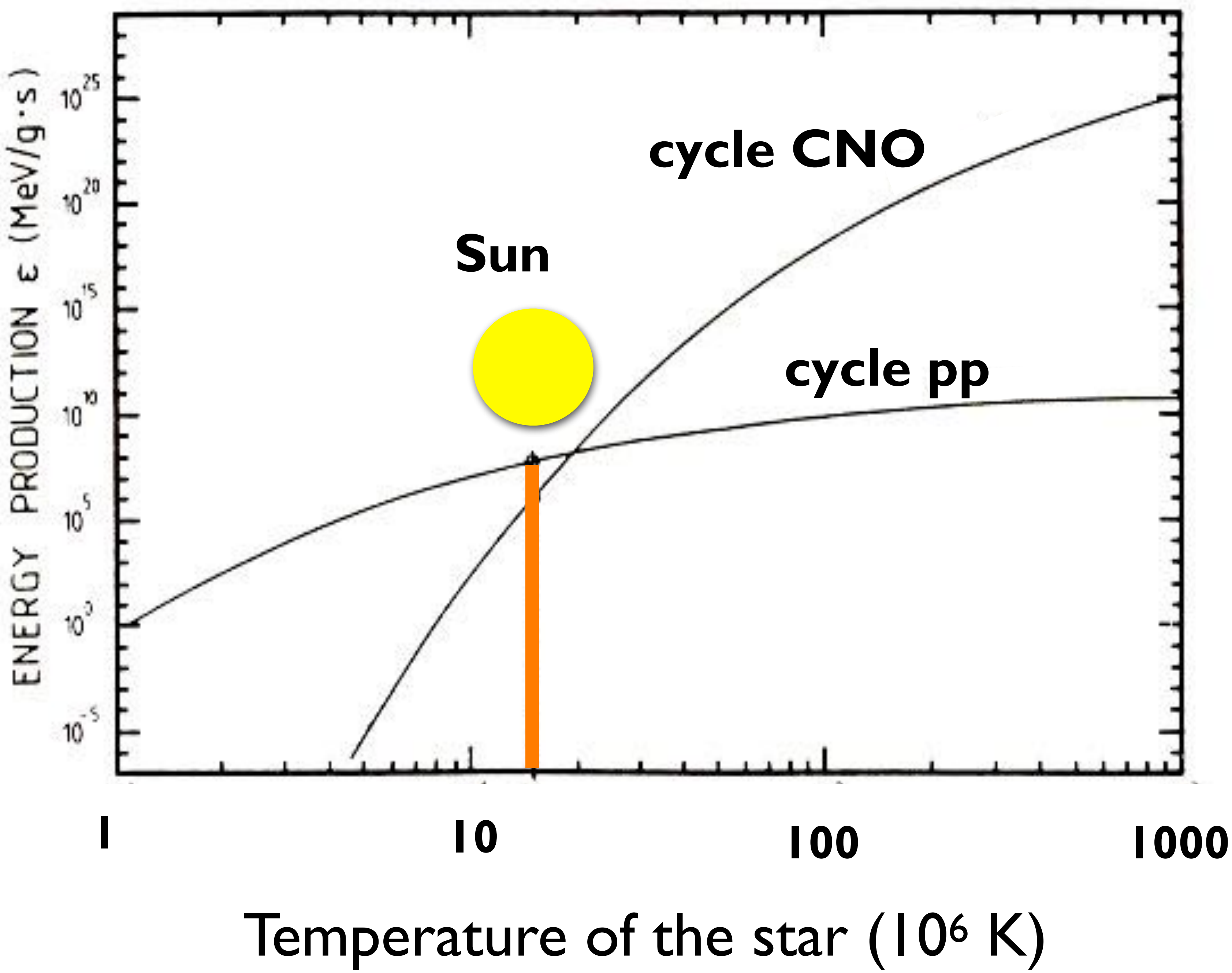
6. $^{15}N + ^{1}H \Rightarrow ^{12}C + ^{4}He + 4.96$ MeV

CNO Cycle



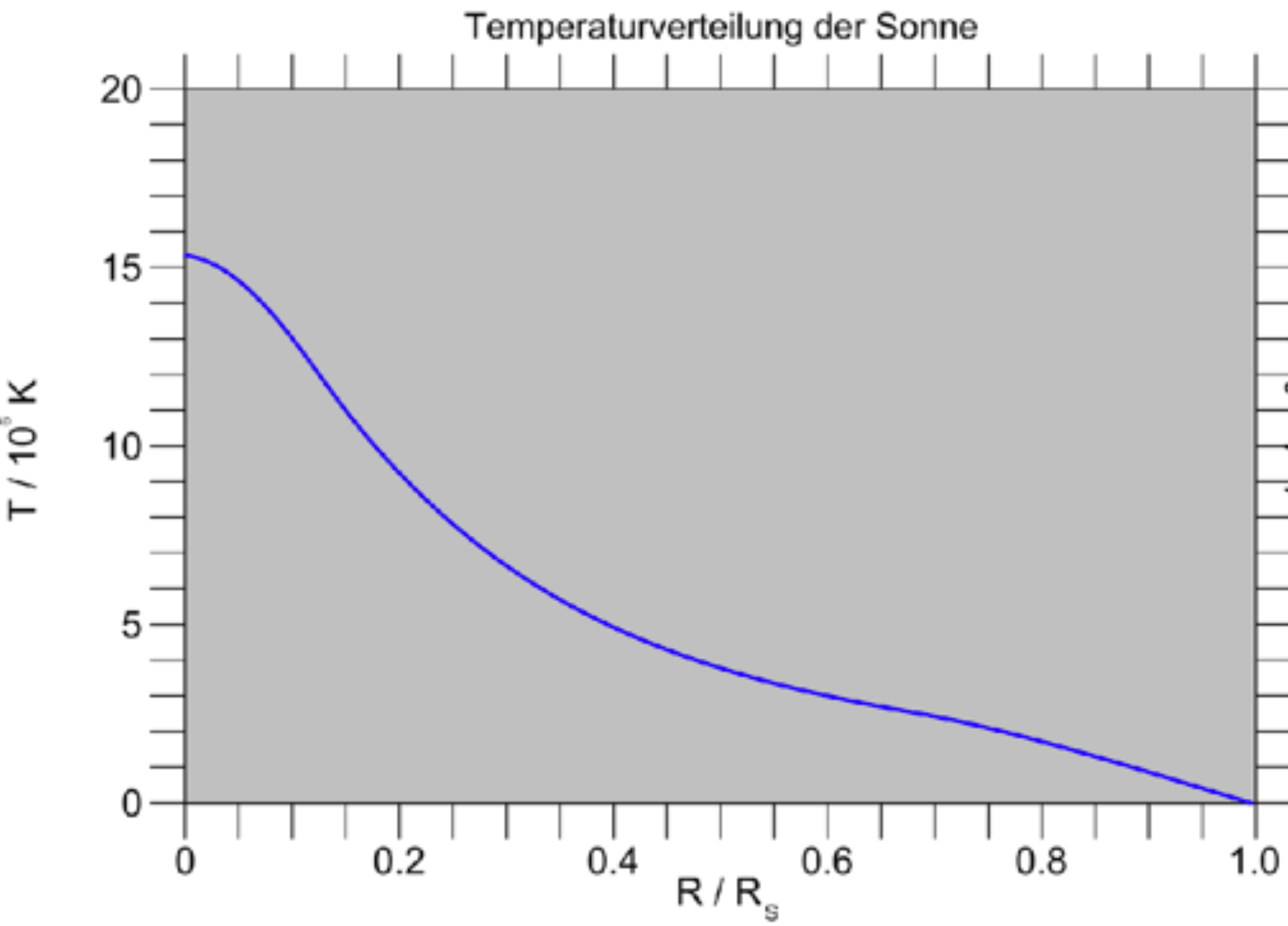
⁴He
¹H
¹H
γ
¹²C
¹⁵N
¹³N
ν
ν
¹⁵O
¹³C
¹⁴N
γ
γ
¹H
¹H
limiting (slowest) step
Proton
γ Gamma Ray
Neutron
ν Neutrino
Positron

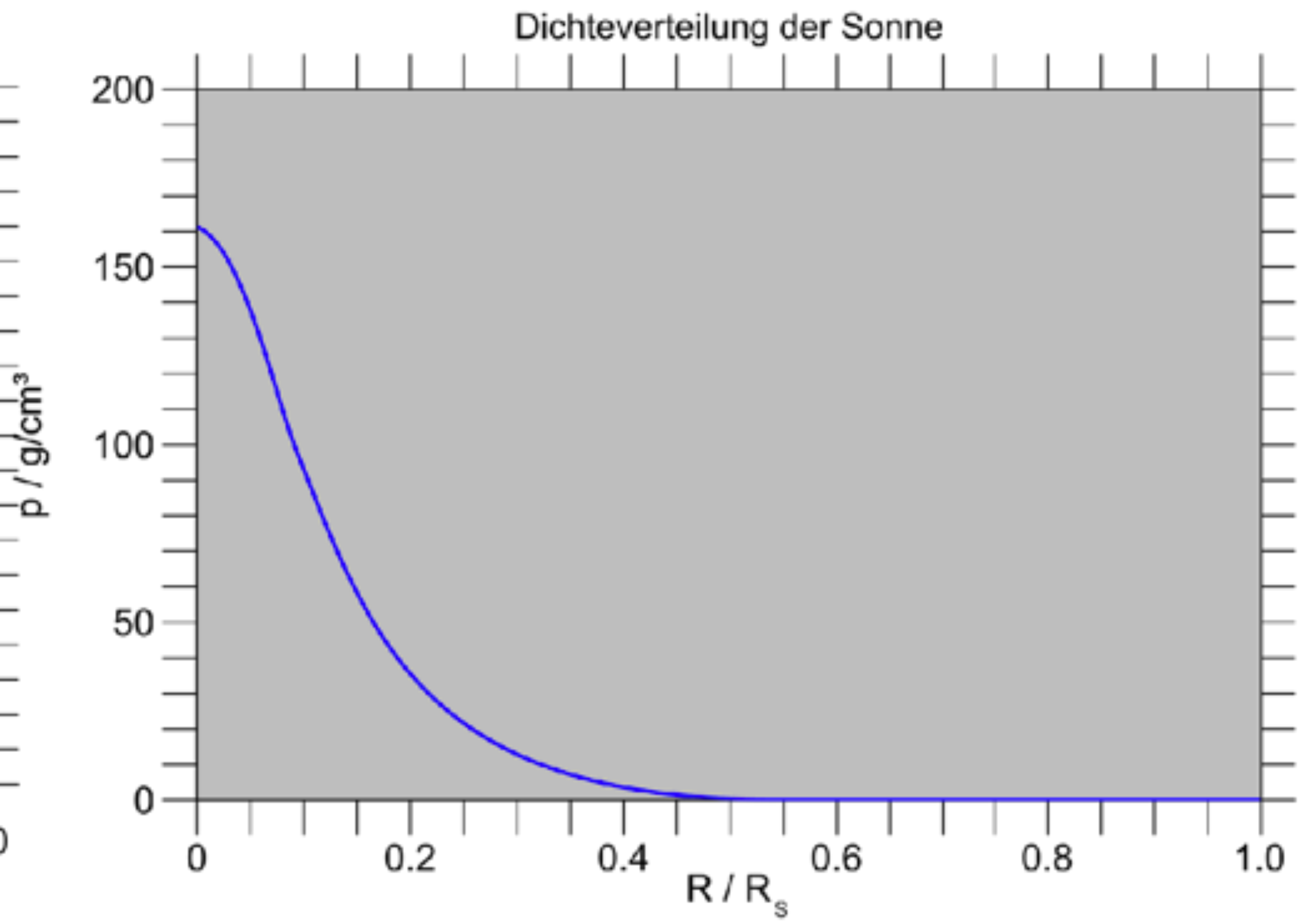
Sun: CNO-I cycle vs PP-chains



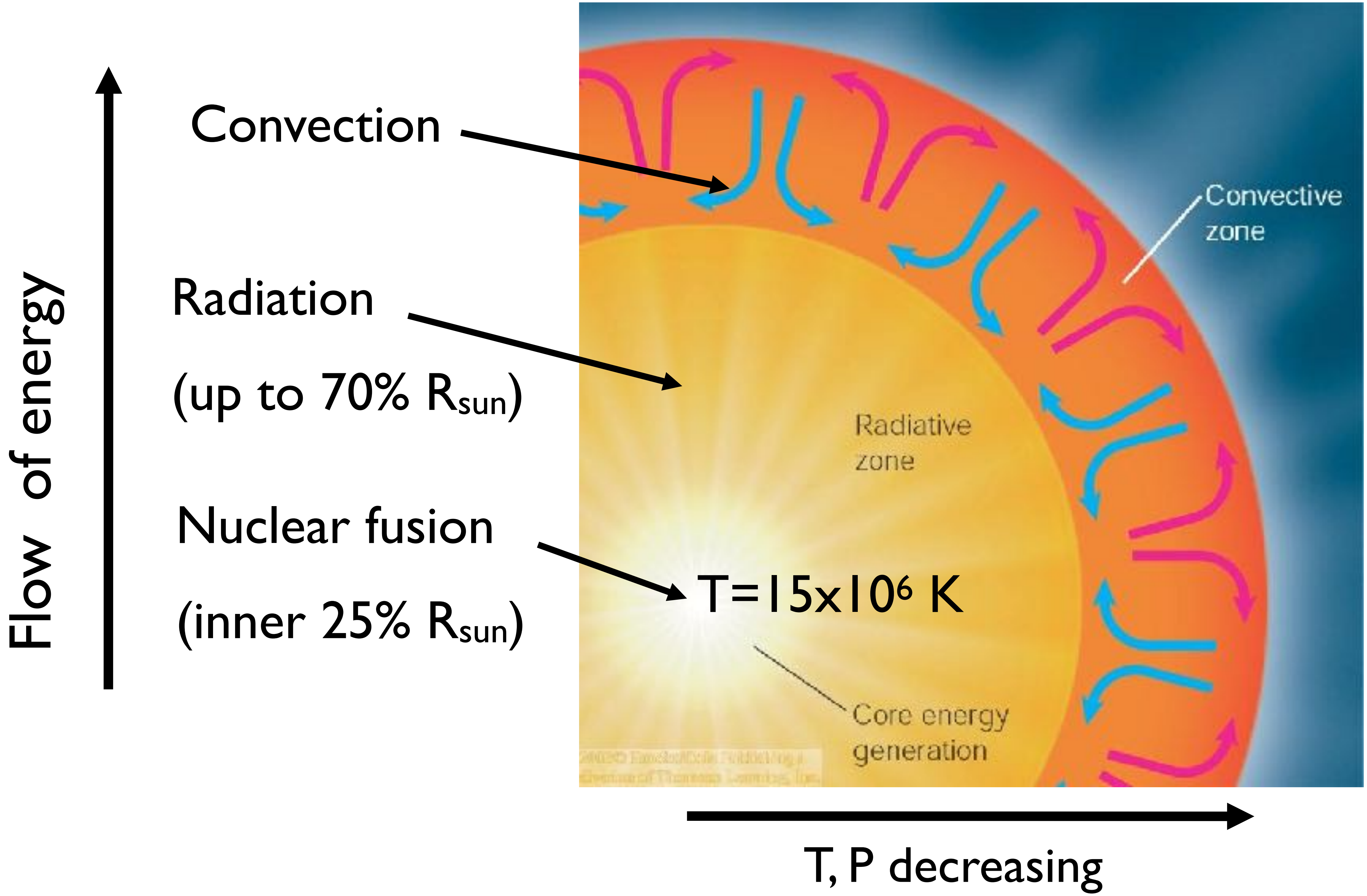
- PP-chain: >98% ^{4}He (10^{38} events/s using 4×10^{38} protons/s)
- CNO cycles: 1.7% ^{4}He

Density and temperature in the Sun



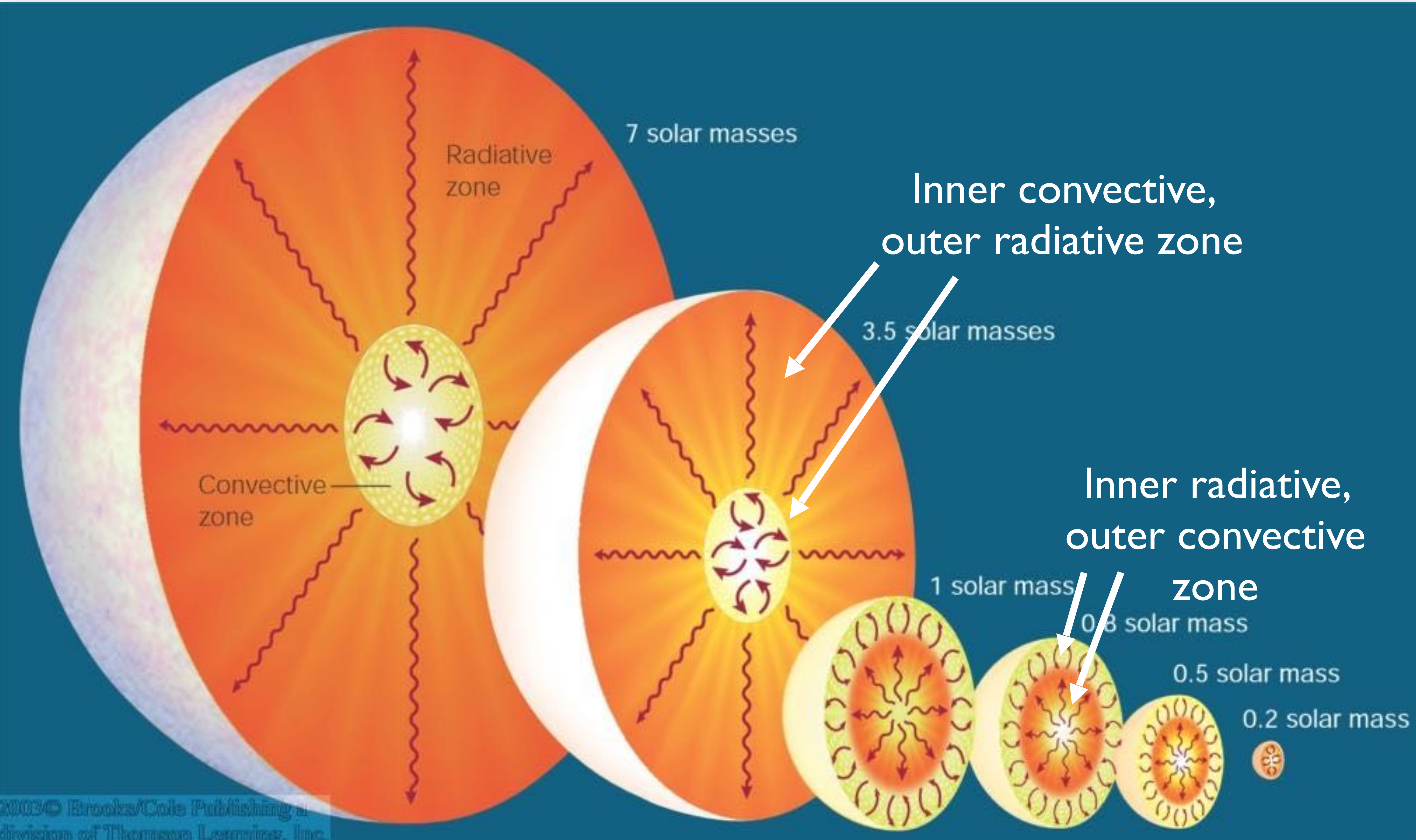


Sun's internal structure: P vs G



- Energy: ~ 3.86 10^{26} W (10^{11} megatons of TNT / s)
- Energy density: ~0.0002 W/cm^3

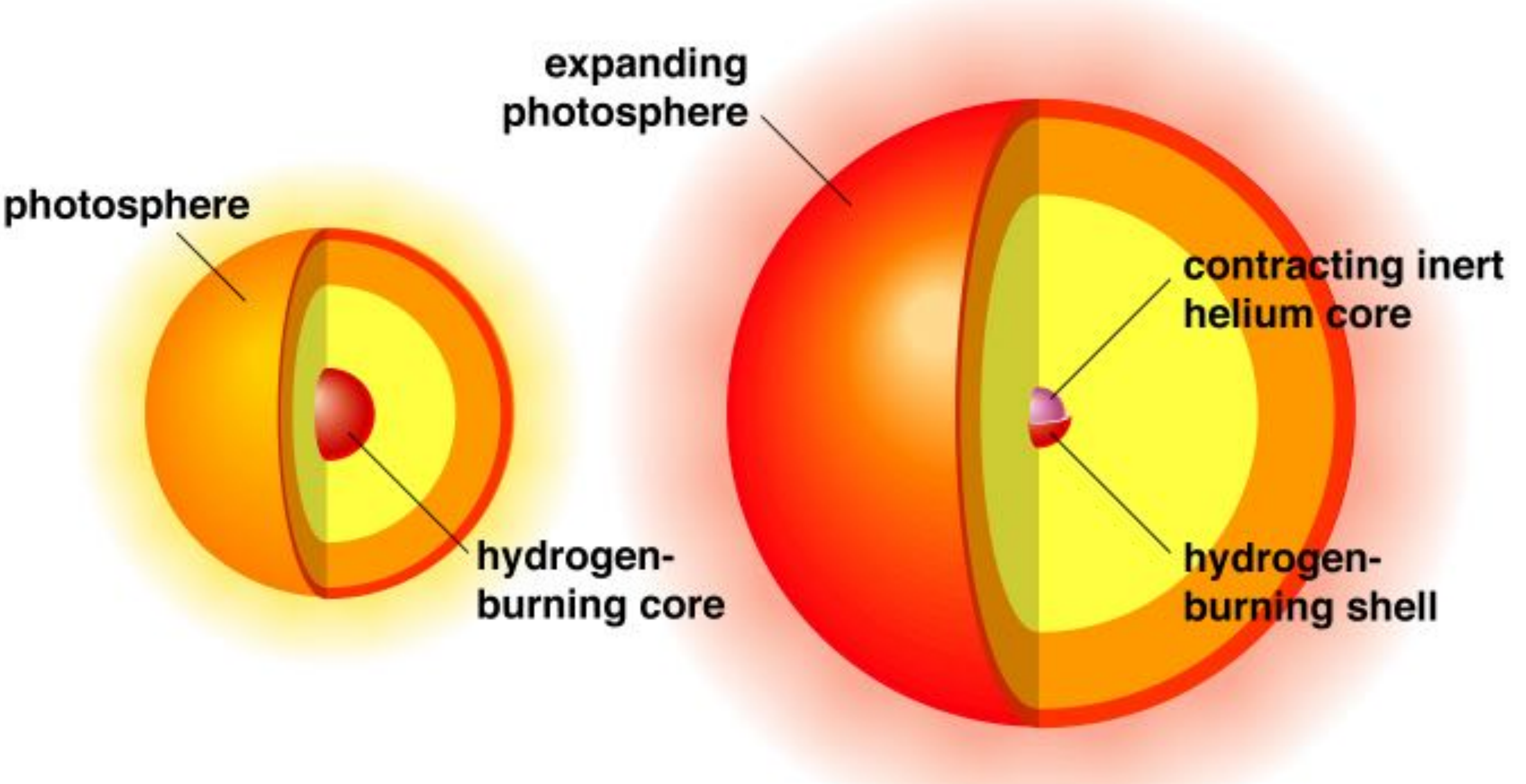
Structure of various stars



CNO cycle dominant

PP chain dominant

Sun after ~9.3 Gyr: red giant



- He-core volume shrinks ⇒ Fusion rate increases
- T increases ⇒ H-shell puffs up ⇒ red giant (~1 Gyr)
- End fusion products: He, C, O

Triple-alpha process (He burning)

Fred Hoyle

(1915 – 2001)

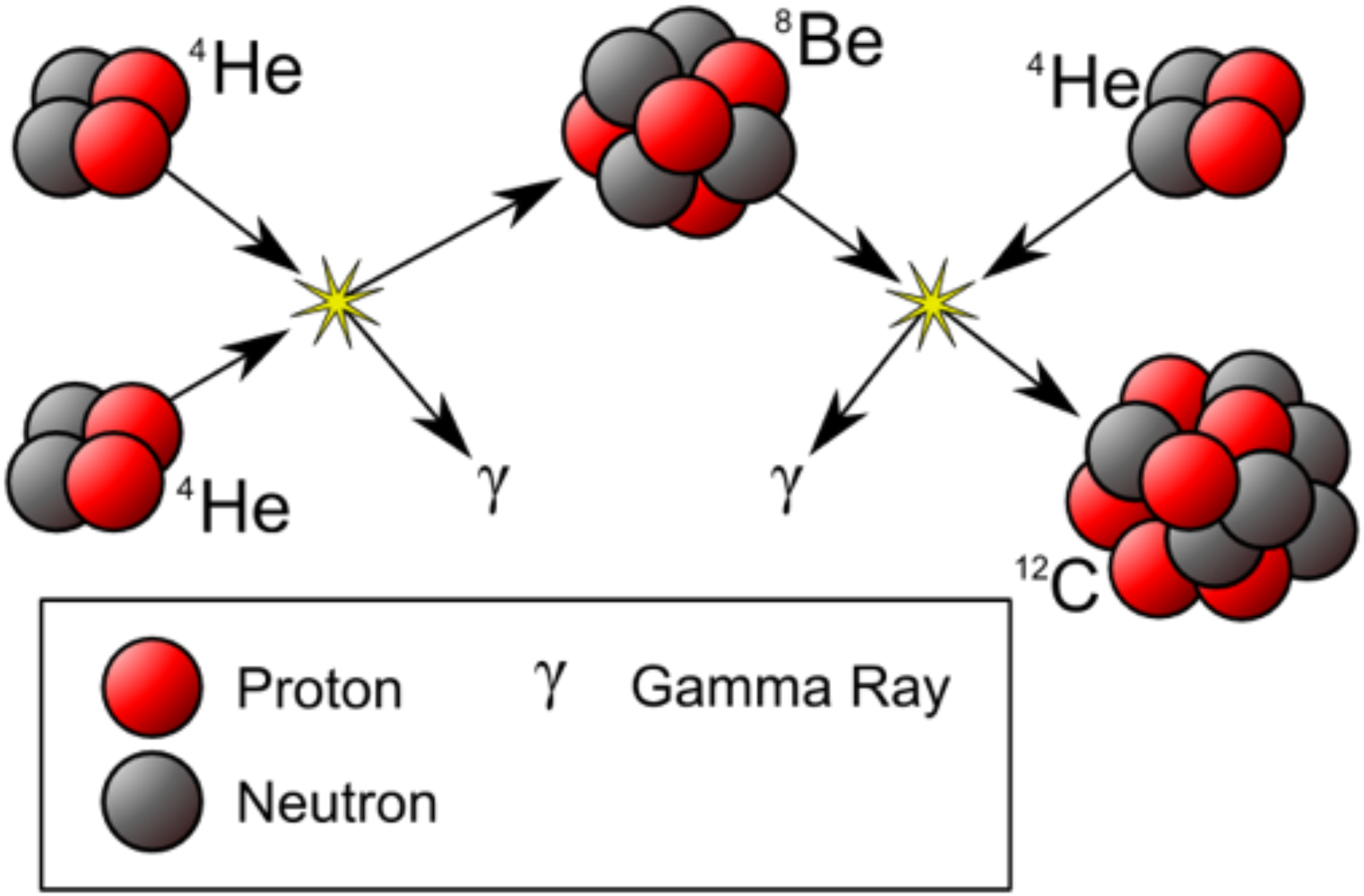
- ^{12}C is abundant ⇒ ^{12}C forms from 3 x ^{4}He (F. Hoyle)
- Higher-mass stars than Sun
- T ~ 100 x 10^{6} K:

1. $^{4}He + ^{4}He \Rightarrow ^{8}Be$ (–0.0918 MeV), extremely unstable
2. $^{8}Be + ^{4}He \Rightarrow ^{12}C + 2\gamma$ (+7.367 MeV)
3. $^{12}C + ^{4}He \Rightarrow ^{16}O + \gamma$ (+7.162 MeV)

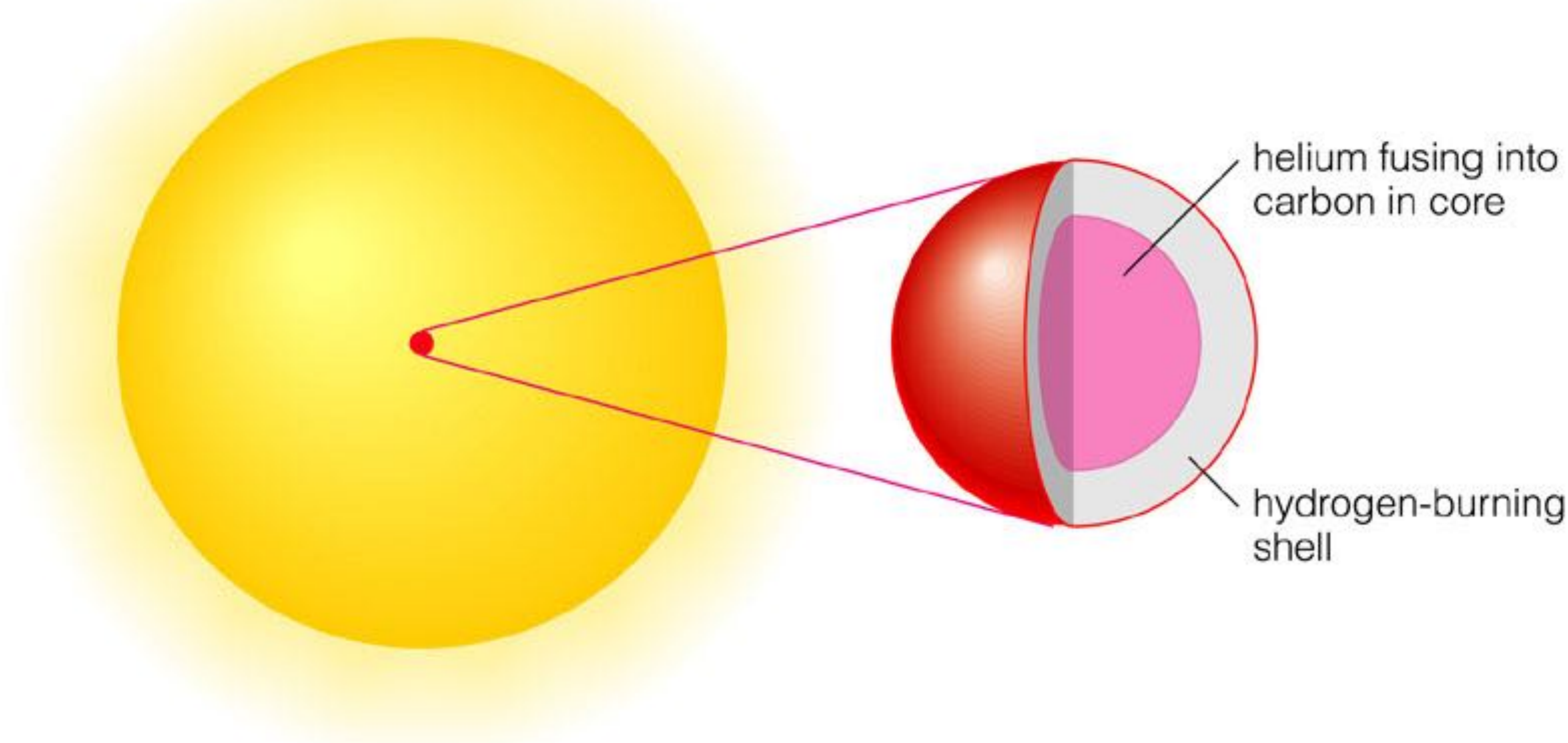
Energy production for ^{12}C:

Q_{3He} = 7.275 MeV

Helium burning (triple-alpha process)



He-burning via helium flash



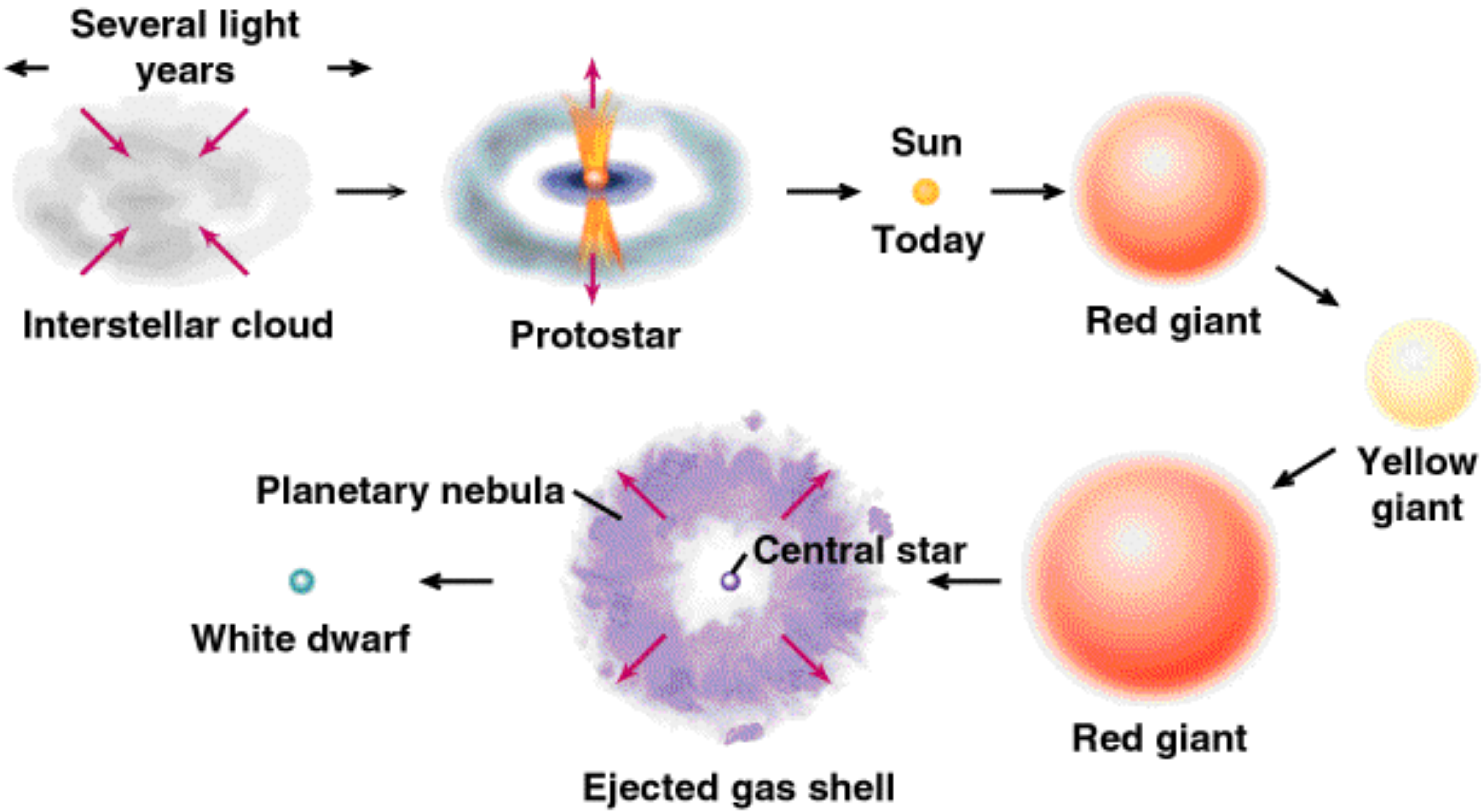
- e- degeneracy pressure in the He core (no T-dependence) ⇒ Triple-alpha processes begin without core expansion ⇒ Runaway reaction (He flash) ⇒ ~ 60 – 80% He is burned within minutes (energy ~ 10^{11} L_{Sun})
- Released energy ⇒ degeneracy lift and core expansion

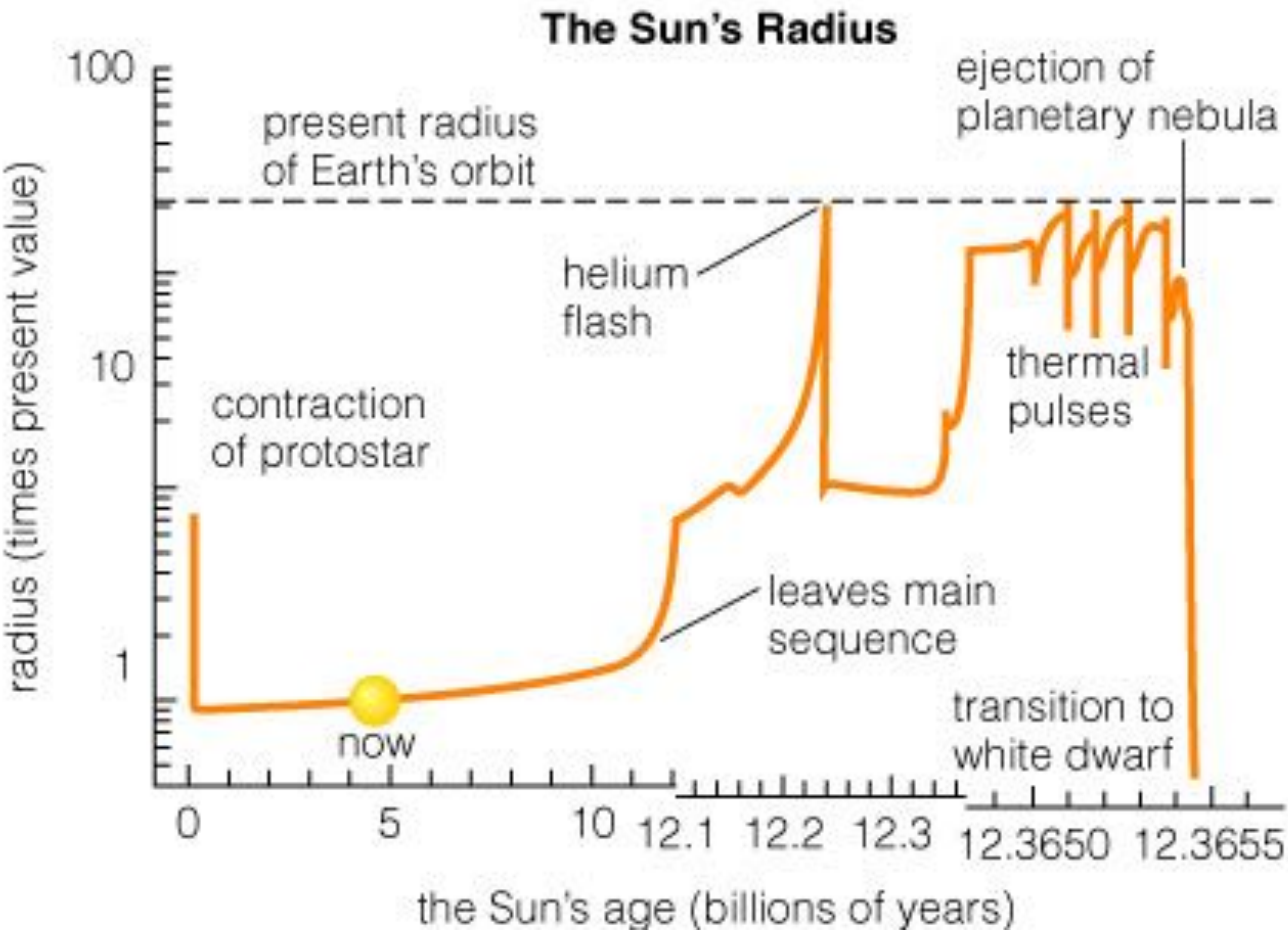
Alpha processes (minor): ^{20}Ne – ^{56}Ni

- Require higher T and densities as for triple-alpha process

$$
\begin{aligned}
{}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma & E &= 4.73\ \mathrm{MeV} \\
{}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{24}_{12}\mathrm{Mg} + \gamma & E &= 9.32\ \mathrm{MeV} \\
{}^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{28}_{14}\mathrm{Si} + \gamma & E &= 9.98\ \mathrm{MeV} \\
{}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{32}_{16}\mathrm{S} + \gamma & E &= 6.95\ \mathrm{MeV} \\
{}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{36}_{18}\mathrm{Ar} + \gamma & E &= 6.64\ \mathrm{MeV} \\
{}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{40}_{20}\mathrm{Ca} + \gamma & E &= 7.04\ \mathrm{MeV} \\
{}^{40}_{20}\mathrm{Ca} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{44}_{22}\mathrm{Ti} + \gamma & E &= 5.13\ \mathrm{MeV} \\
{}^{44}_{22}\mathrm{Ti} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{48}_{24}\mathrm{Cr} + \gamma & E &= 7.70\ \mathrm{MeV} \\
{}^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{52}_{26}\mathrm{Fe} + \gamma & E &= 7.94\ \mathrm{MeV} \\
{}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{56}_{28}\mathrm{Ni} + \gamma & E &= 8.00\ \mathrm{MeV}
\end{aligned}
$$

Life of a Sun-like star: ~12 Gyr

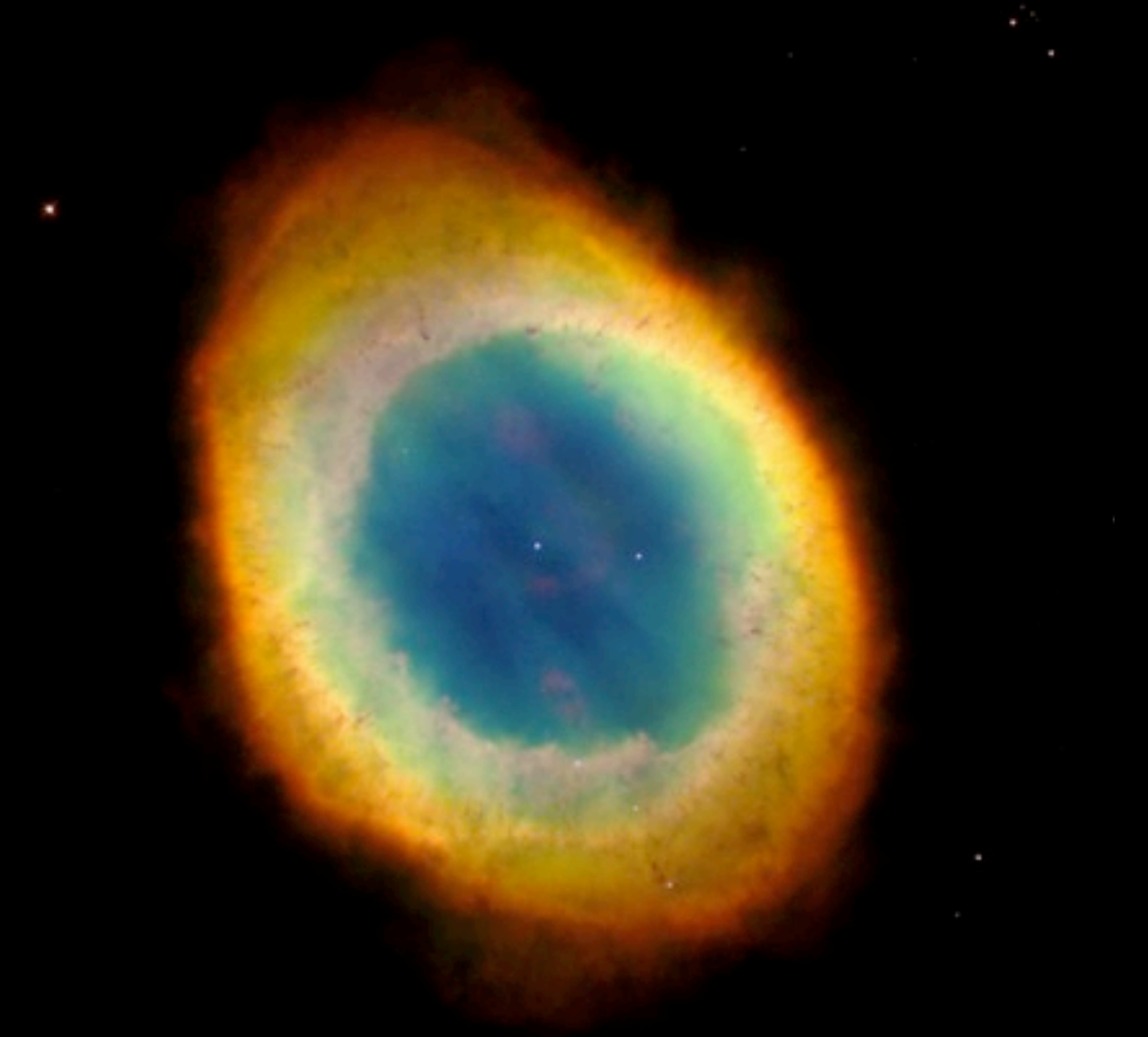



The Sun's Radius
100
10
1
radius (times present value)
present radius
of Earth's orbit
ejection of
planetary nebula
helium
flash
thermal
pulses
contraction
of protostar
leaves main
sequence
transition to
white dwarf
now
0
5
10
12.1
12.2
12.3
12.3650
12.3655
the Sun's age (billions of years)

Beautiful death of a Sun-like star

Cat's Eye nebula

Ring nebula



- 97% of all stars will end as a white dwarf
- Electron-degenerate C and O gas
- Chandrasekhar (1930): maximum mass 1.44 Msun

Carbon burning

- Stars more massive than 8–9 M_{sun}
- T > 500 x 10^6 K, density > 3 x 10^6 g/cm^3:

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He \quad + 4.617 \text{ MeV}$$

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{23}_{11}Na + {}^{1}_{1}H \quad + 2.241 \text{ MeV}$$

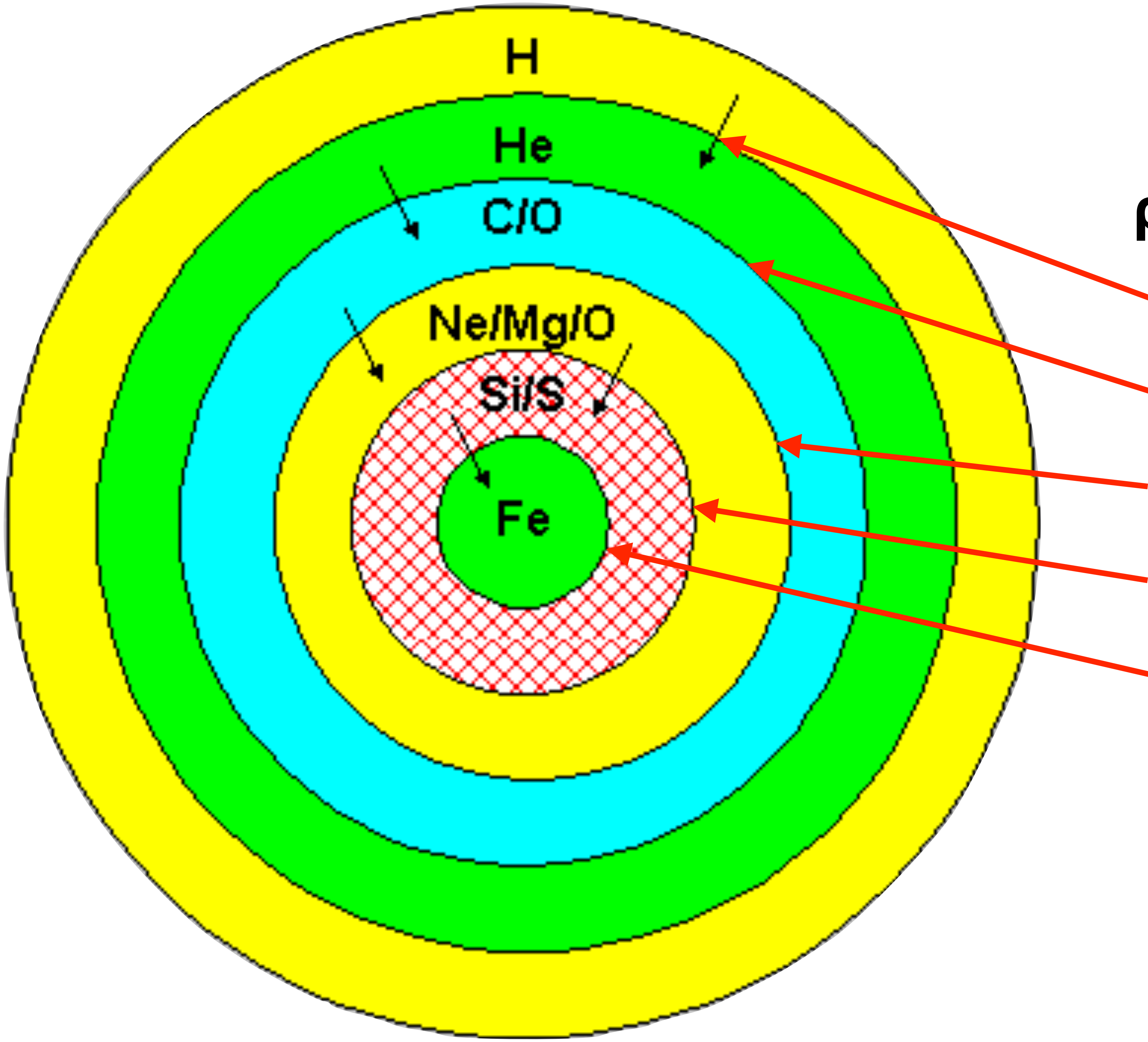
$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{23}_{12}Mg + n \quad - 2.599 \text{ MeV}$$

Alternatively:

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{24}_{12}Mg + \gamma \quad + 13.933 \text{ MeV}$$ (improbable)

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{16}_{8}O + 2\,{}^{4}_{2}He \quad - 0.113 \text{ MeV}$$

Massive stars: "onion skin layers"



ρ (g cm^{-3})	T (10^8 K)
10^2	0.2
10^4	1
10^5	6
10^6	20
10^7	30

- Fusion stops at ^{56}Fe $\Rightarrow$ Core is supported by degeneracy pressure
- Heavier elements are forged by capture processes

Nucleosynthesis in a 15 M_{Sun} star

Fused	Products	Time
H	^{4}He	10^{7} yrs.
^{4}He	^{12}C	Few X 10^{6} yrs
^{12}C	^{16}O, ^{20}Ne, ^{24}Mg, ^{4}He	1000 yrs.
^{20}Ne +	^{16}O, ^{24}Mg	Few yrs.
^{16}O	^{28}Si, ^{32}S	One year
^{28}Si +	^{56}Fe	Days
^{56}Fe	Neutrons	< 1 second

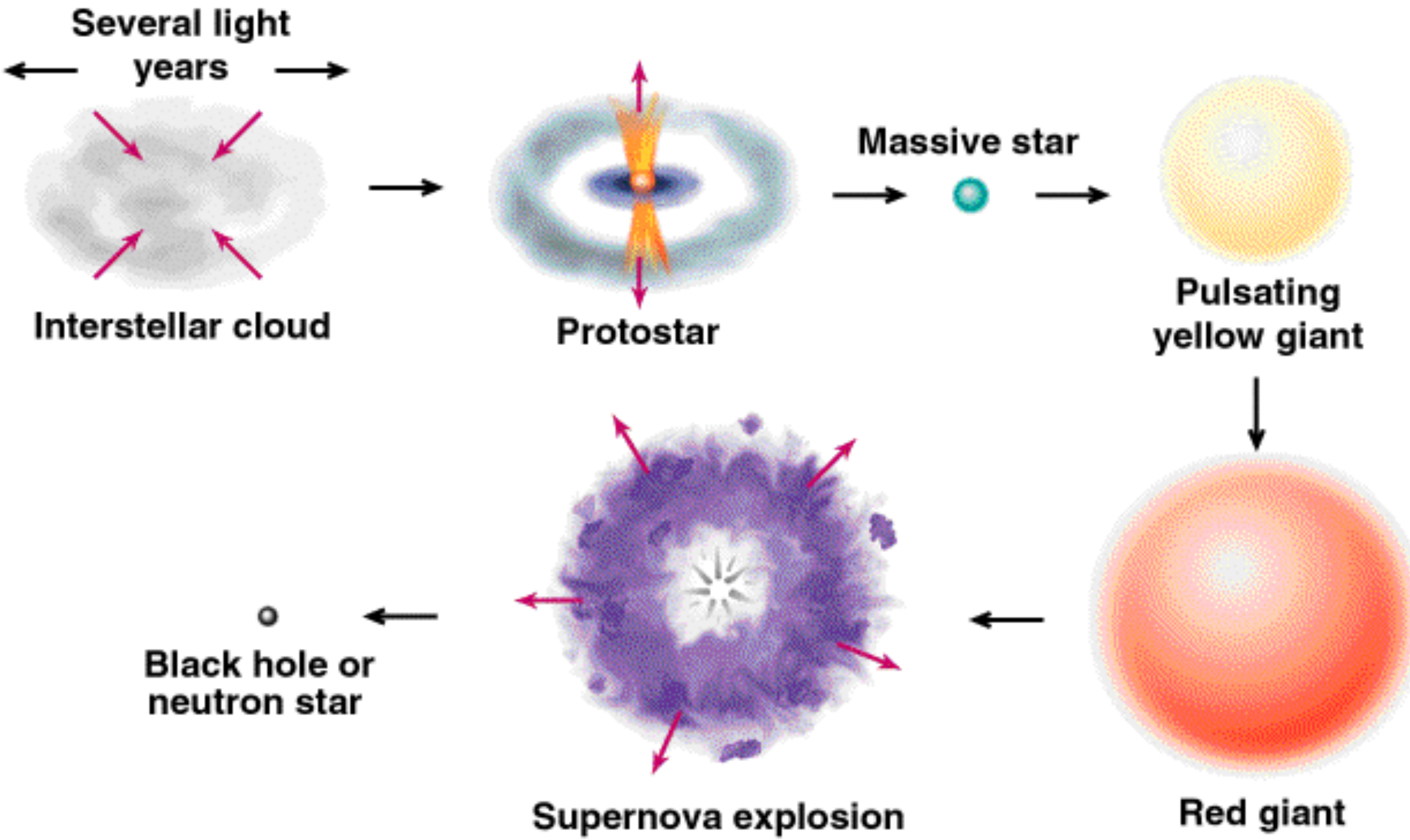
Life of (rock) stars: shine bright, die young

- Mass of "fuel" / Rate of consumption
- Lifetime ~ M / L ~ $M^{-2.5}$

Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)
25	35,000	80,000	3
15	30,000	10,000	15
3	11,000	60	500
1.5	7000	5	3000
1.0 (Sun)	6000	1	10,000
0.75	5000	0.5	15,000
0.50	4000	0.03	200,000

Table 12-2
Discovering the Universe, Eighth Edition

Life of a massive star: ~1-100 Myr



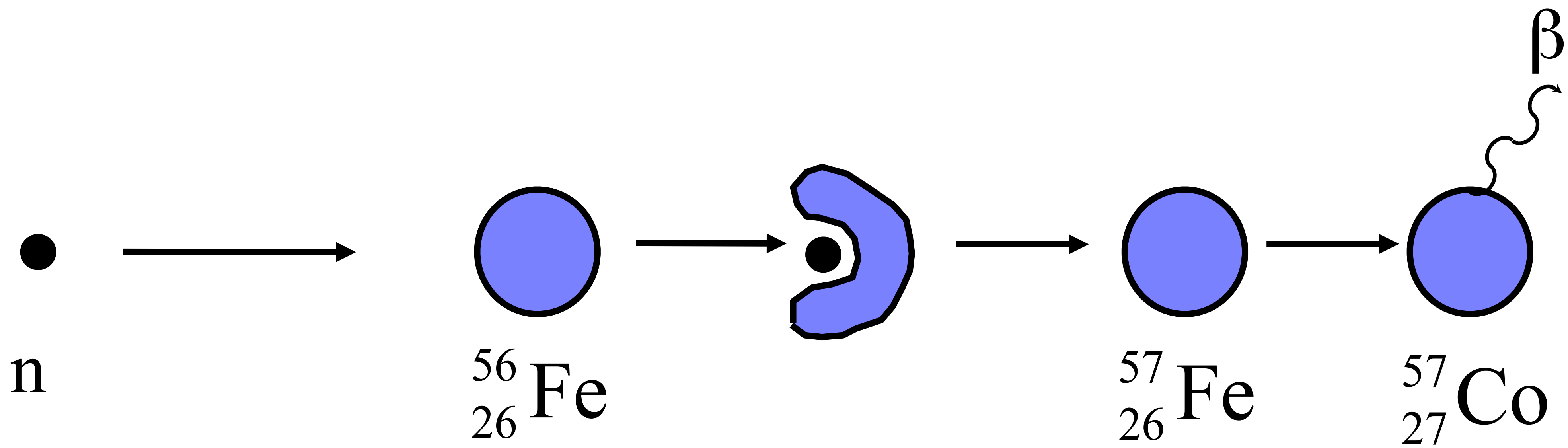
Massive, >8-10M_{Sun} stars

- Inert Fe-core collapses when $M_{core} > 1.44M_{Sun}$:

  $^{56}Fe + \gamma \Rightarrow 14\ ^4He + \nu$ (<1 s)

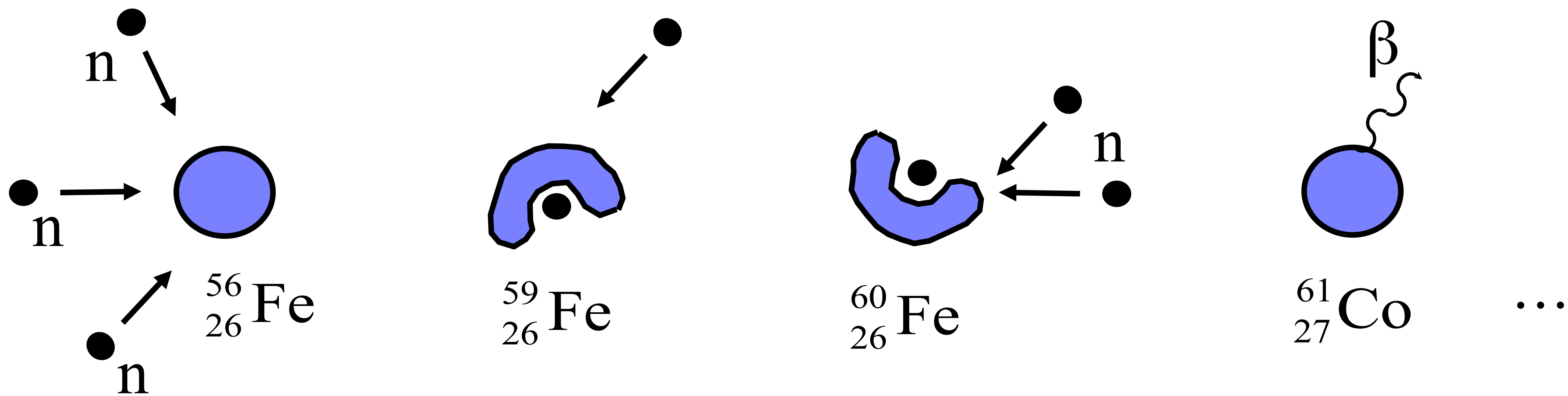
- Implosion of outer core: V up to ~25% speed of light
- Inner core heating above 10^{11} K: $^4He + 2e^- \Rightarrow 4n + \nu$ (~10 s)
- Collapse is halted by neutron degeneracy pressure
- Supernova explosion ⇒ creation of heavy elements
- Collapse with $M_{core} < 4M_{Sun}$: neutron star
- Collapse with $M_{core} > 4M_{Sun}$: black hole

s-process: slow neutron capture



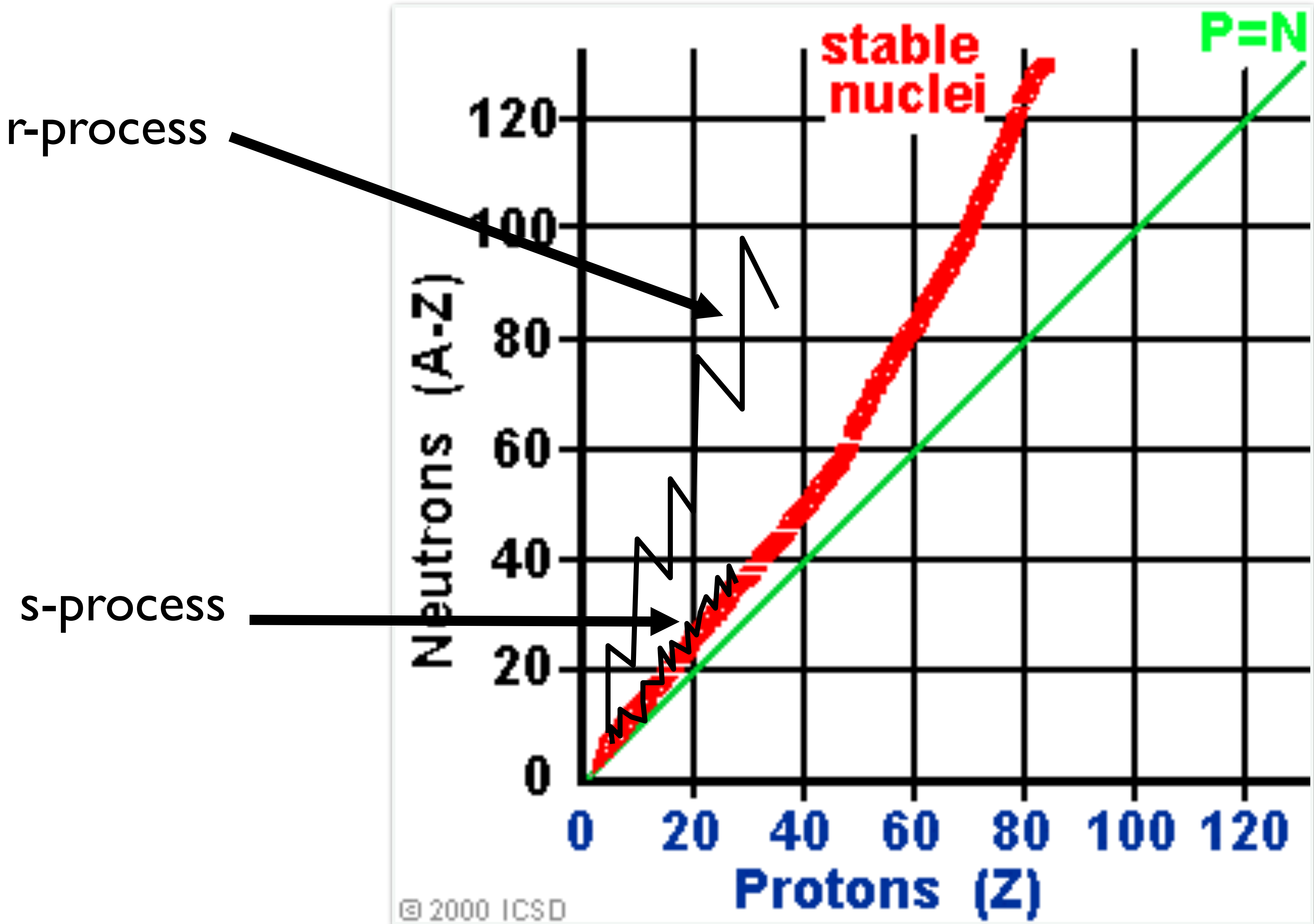
- Neutron capture
- β-minus decay of n to p
- Slow neutron capture compared to β-decay
- ~ 50% of stable isotopes after ^{56}Fe

r-process: rapid neutron capture

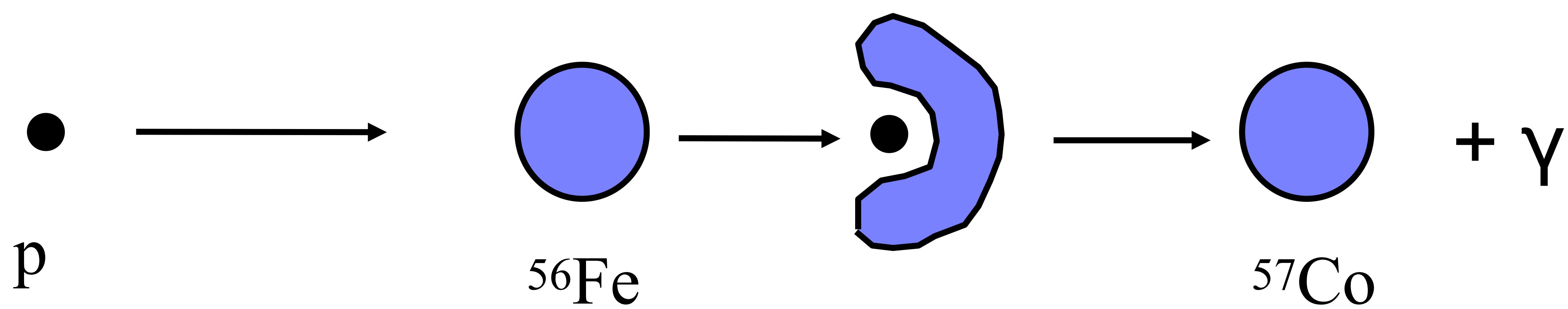


- Requires high neutron flux: core-collapse supernovae
- Rapid neutron capture compared to β-decay
- ~50% of neutron-rich nuclei after ^{56}Fe

Neutron capture processes



p-process: proton capture



- B^{2}FH paper (wrong conditions), still poorly understood
- Free protons captured by heavy nuclei
- Proton-rich isotopes (from Se to Hg)
- Coulomb repulsion

Neutron stars

- Proposed by W. Baade and F. Zwicky (1934): neutron degenerate core
- Mass ~ 2 Msun
- Radius ~ 12 km
- Density ~ 5×10^{14} g/cm^3
- Magnetic fields ~ 2×10^{11} Gauss
- Structure: superconducting fluid + iron crust (~1 m)
- Fast rotation and ~10^8 Tesla magnetic fields ⇒ synchrotron "beams"

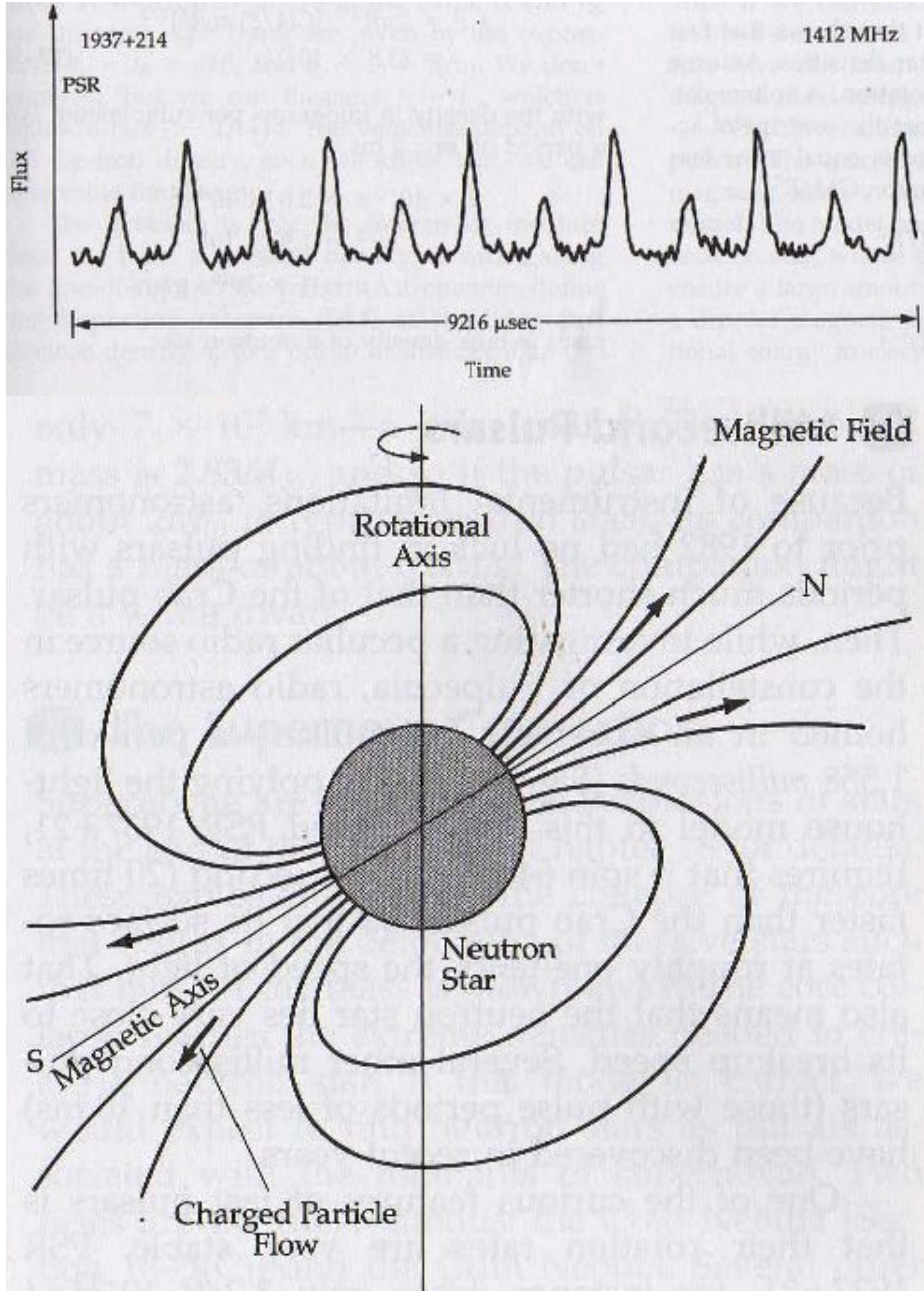
Observational evidence: pulsars and binaries

J. Bell Burnell

(1943, 79 years)

- Discovered by J. Bell Burnell & A. Hewish in 1967
- Extremely regular radio signals (ms–s)
- LGM-1 (now PSR 1919+21)
- Synchrotron beam passing LOS
- Binaries: dynamic masses (direct or via acc. disk)

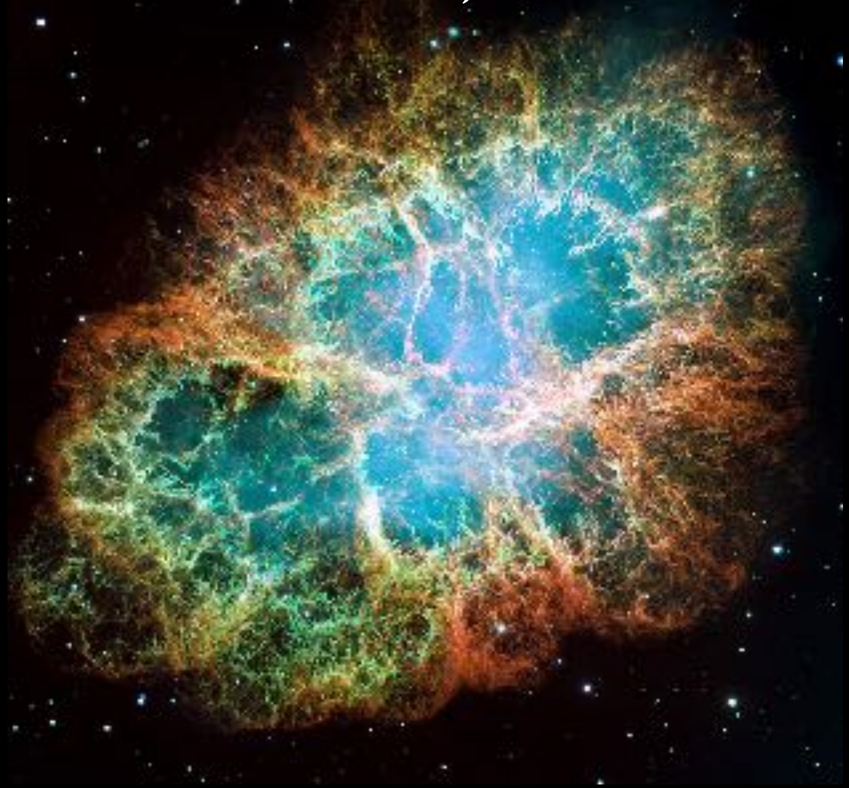
Observational evidence: pulsars



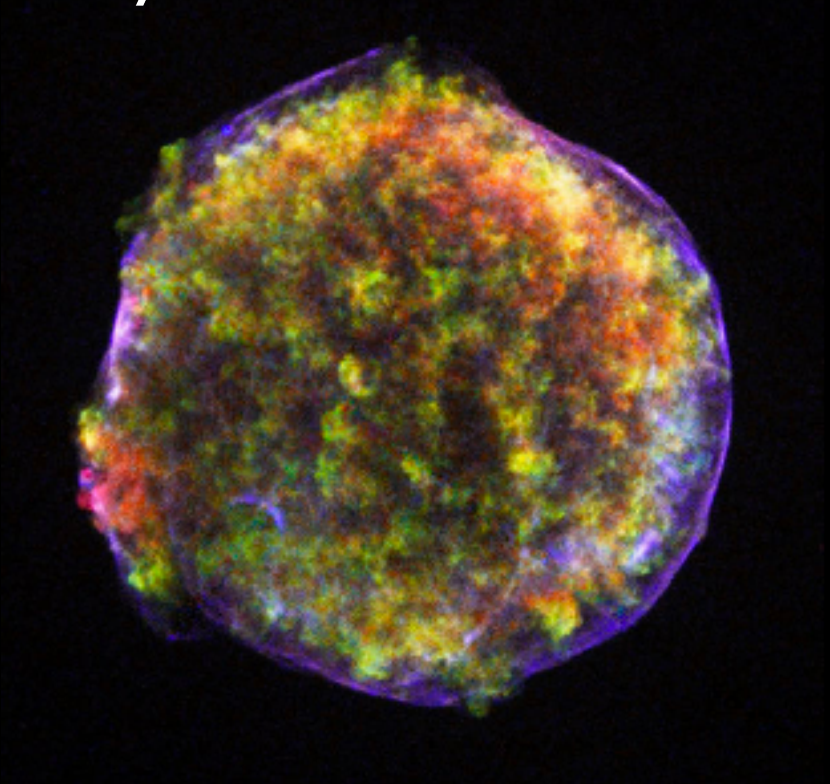
Beautiful death of massive stars

Vela SN, ~4000 BC

Crab nebula, 1054



Tycho Brahe SN, 1572

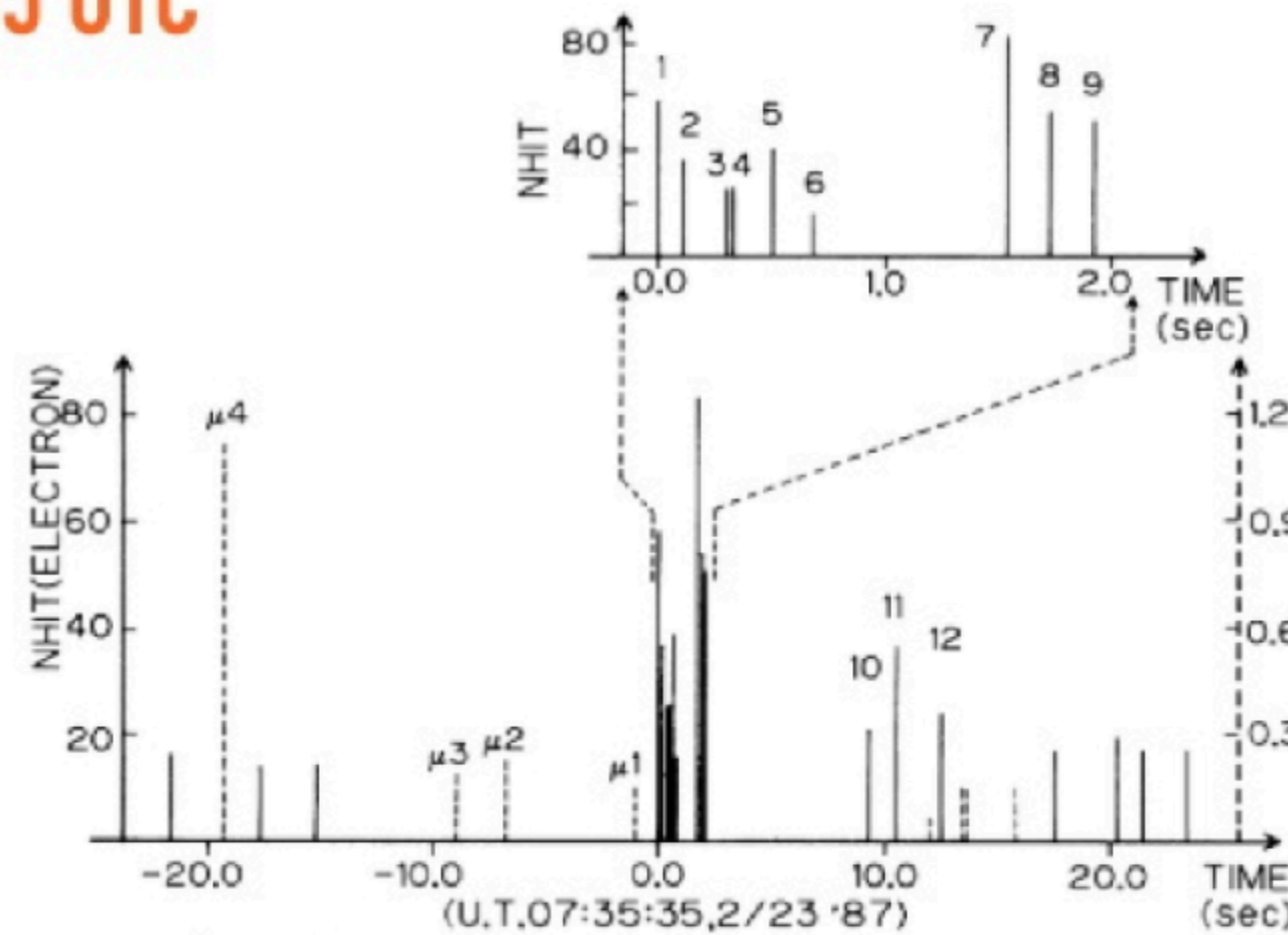


Kepler SN, 1604

…Can also be recorded via neutrinos!

SN 1987A (Large Magellanic Cloud), Kamiokande II

A neutrino burst was detected on 23 Feb. 1987, 7:35:35 UTC

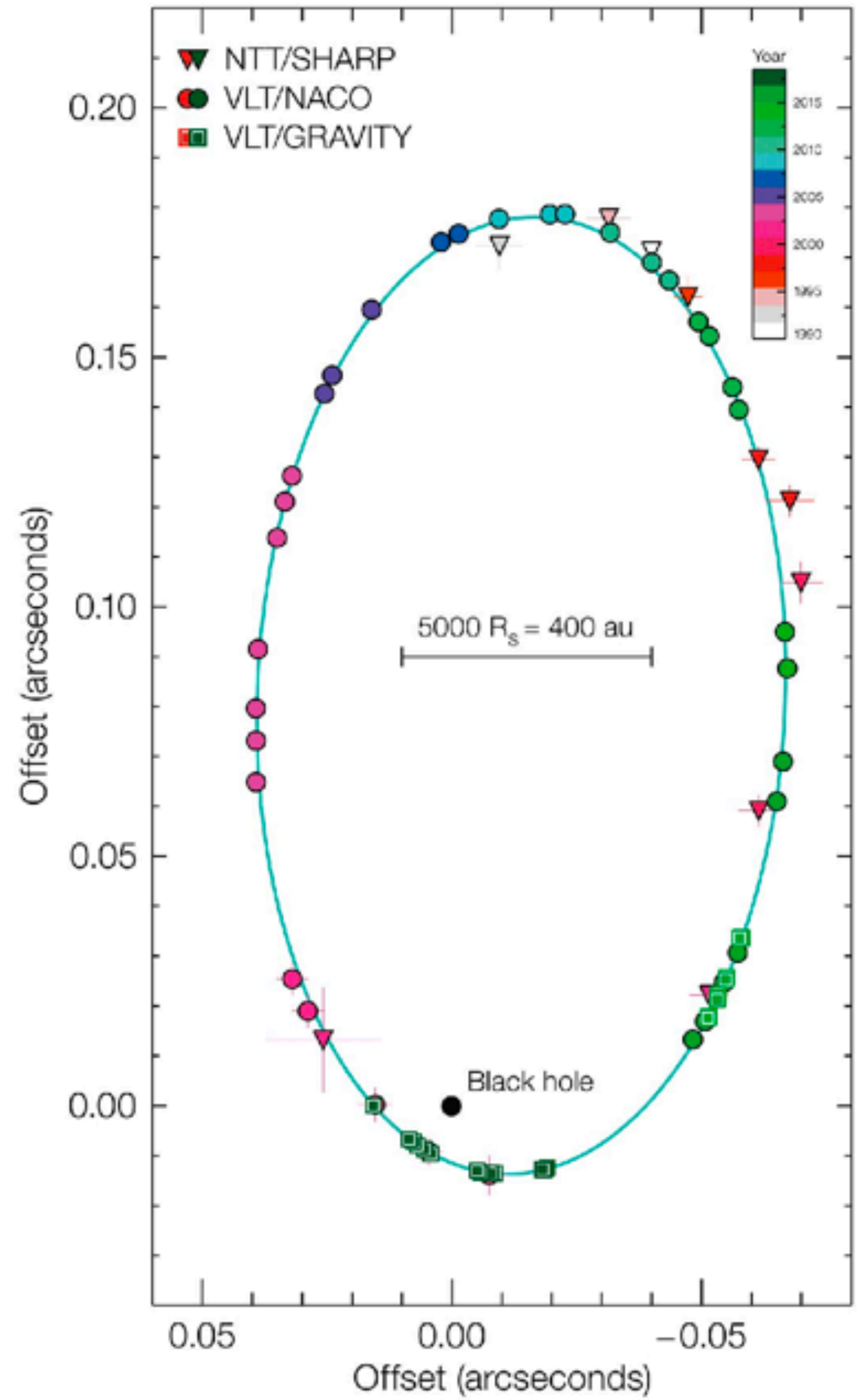


Black holes (BHs)

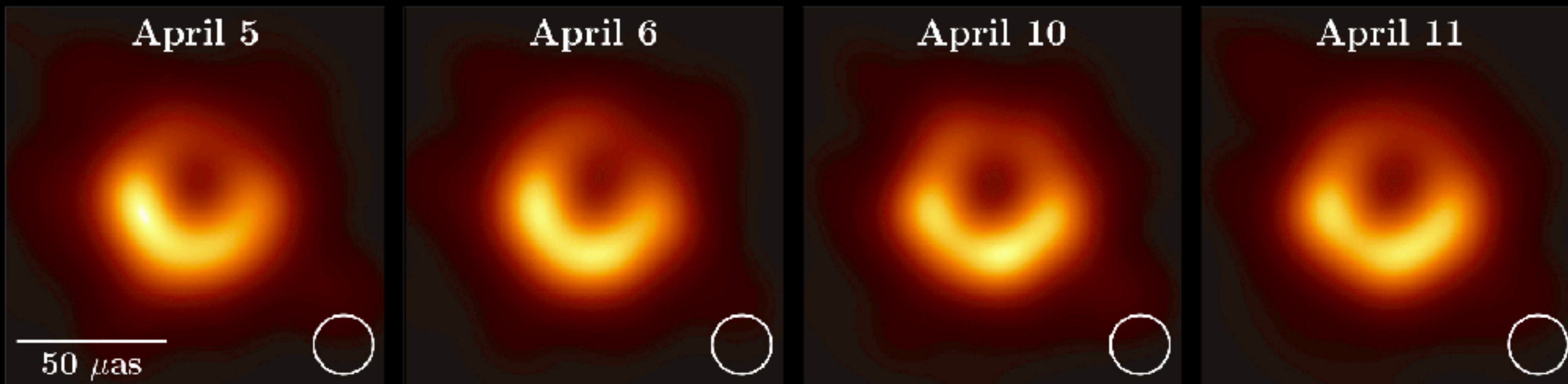
- Neutron star equation of state suggests that neutron degeneracy cannot provide sufficient support for $M_{core} > 4$ Msun
- Then nothing can halt collapse and neutron core collapses to a point mass
- Models imply that stars with $M_* > 20$ Msun likely produce BHs
- Amount of mass loss is uncertain and so models are not definitive
- Singularity – cannot be described with laws of physics
- Event Horizon (V_{escape} = speed of light c): $R_S = 2GM/c^2$ (Schwarzschild radius)
- If one could compress Sun to a BH, it would have R_S = 3 km

Black hole in the Galactic center

- S2 nearby star orbiting Sgr A* BH: min separation is 120 au, period ~ 16 years
- Accurate astrometry and distance
- Precession of orbit matches Gen. Relativity (Schwarzschild precession)
- Supermassive BH of ~ 4 x 10^6 M_{Sun}
- Nobel prize For A. Ghez and R. Genzel in 2020



First image of event horizon around M87* BH



- Event Horizon Telescope: Radio-interferometry with very long baselines
- Supermassive BH in massive elliptical galaxy M87 (16.4 Mpc)
- $M \sim 6.5 \times 10^9\ M_{sun}$
- $R_S \sim 120$ au

Literature

- B^2HF paper (1953)
- ed. B. Bederson (1999), "More Things in Heaven and Earth", Springer
- Ch. Iliadis (2007), "Nuclear Physics of Stars"