Nucleosynthesis processes in the Universe: from Big-Bang to stars

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Outline

Lecture 1: Introduction to nuclear astrophysics

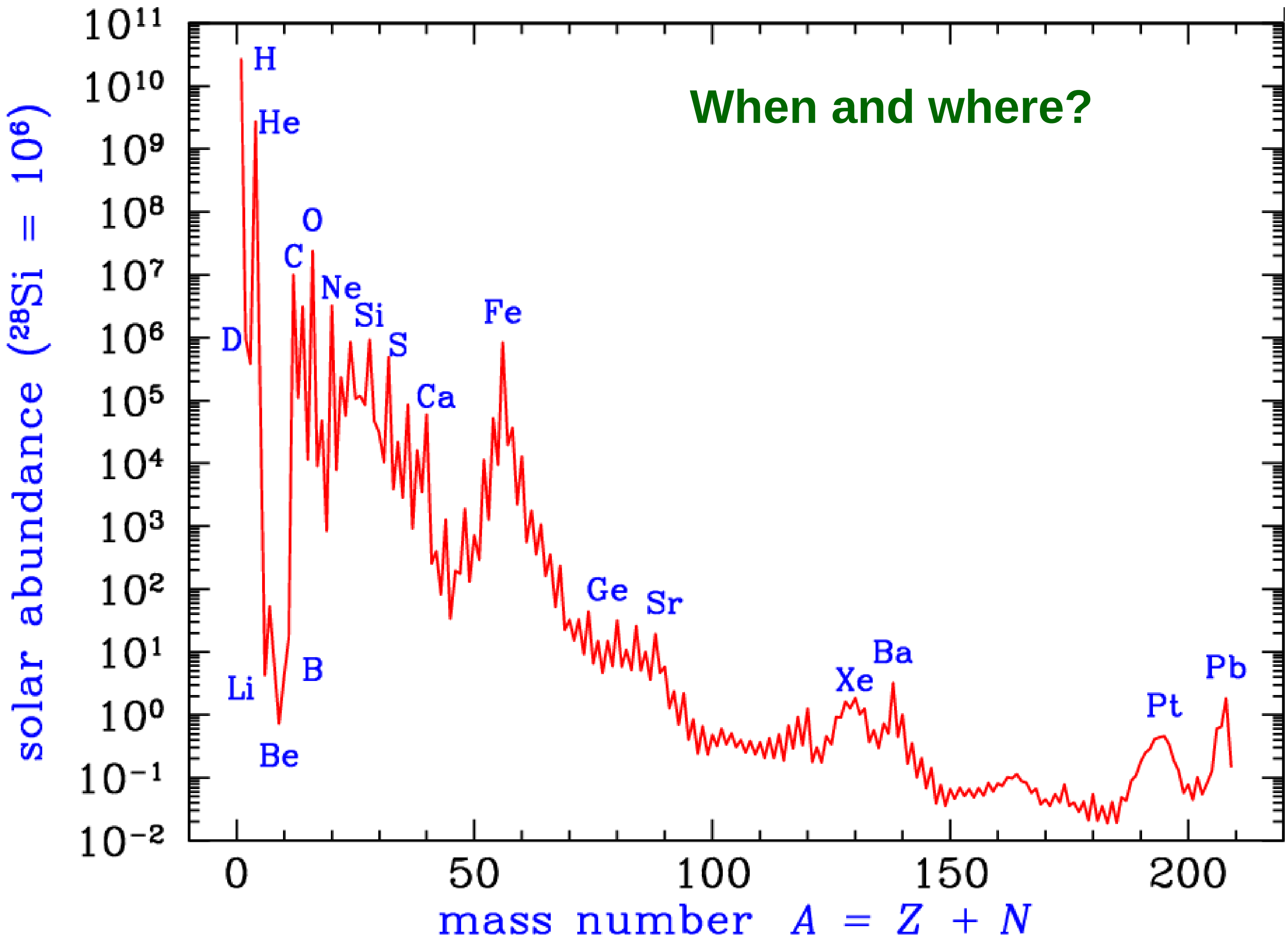
Lecture 2: Nucleosynthesis processes in the Universe

1. A little bit of history
2. Big-Bang nucleosynthesis
3. Cosmic ray nucleosynthesis
4. Stellar nucleosynthesis
   - Hydrogen burning: p-p chains and CNO cycles
   - Helium burning
   - Advanced burning stages: C, Ne, O and Si burning
   - Explosive nucleosynthesis
   - Nucleosynthesis beyond iron: *s*- and *r*-process
5. Back to the Hertzsprung-Russel diagram

Lecture 3: Cross-sections and thermonuclear reaction rates

Lecture 4: Experimental approaches in nuclear astrophysics

1. A little bit of history



Important dates

- 1920 – Aston: mass of the helium atom is slightly less than four times the mass of the hydrogen
- 1928 – Eddington: suggests that Aston's discovery would explain the energy generation in Sun
- 1928 – Gamow, Condon & Gourney: 1st calculation of the quantum tunneling probability
- 1929 – Atkinson & Houtermans: suggest that Gamow's results may explain energy generation

- 1932 – Cockcroft & Walton: 1st induced nuclear reaction $^{7}Li(p,\alpha)\alpha$ → pp chain
- 1934 – Lauritsen & Crane: 10 min radioactivity produced $^{12}C(p,\gamma)^{13}N$ → CNO cycle

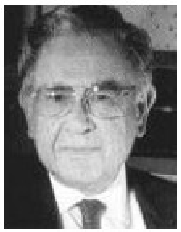
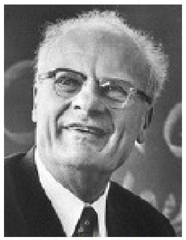
- 1936 – Atkinson, Bethe & Critchfield: p+p reactions give correct energy generation in Sun
- 1936 – von Weizsaker & Bethe: energy generation in stars produced via the CNO cycle

- 1957 – Burbridge, Burbridge, Fowler & Hoyle
- 1957 – Cameron

} **Overview of nucleosynthesis processes**

- 1968 – 1st detection of neutrinos emitted by the Sun core
- 1969 – 1st detection of ^{26}Al γ-ray decay in the Milky Way
- 1987 – γ-ray detection of ^{56}Co and ^{57}Co decays in supernova SN 1987A
- 2013 – observational evidences of heavy nuclei nucleosynthesis in the coalescence of a binary system of two neutron stars (GRB 130603B)
- 2017 – Observational confirmation of heavy nuclei nucleosynthesis in a binary neutron star merger (GW 170817)

Primordial nucleosynthesis

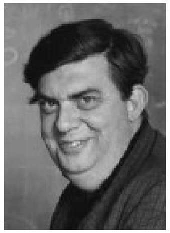




Alpher Bethe Gamow
(“α β γ”)

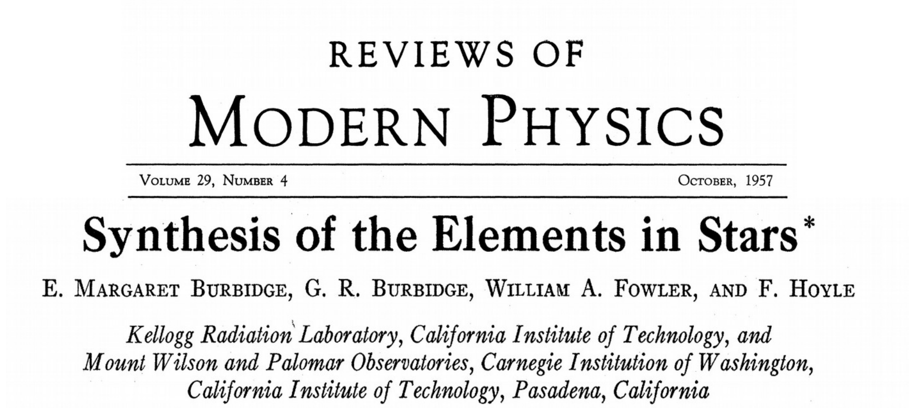
« All the elements were formed just after Big-Bang »
Phys. Rev. 73. (1948) 803

Almost true for D, He and a part of ^{7}Li
BUT no stable isotopes with A = 5 and A = 8
(mass gap)

Stellar nucleosynthesis

Burbridge Burbridge Fowler Hoyle
(B^2FH)


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

« All elements are synthesized in stars through various processes »
Rev. Mod. Phys. 29 (1957) 547

B^2FH heritage

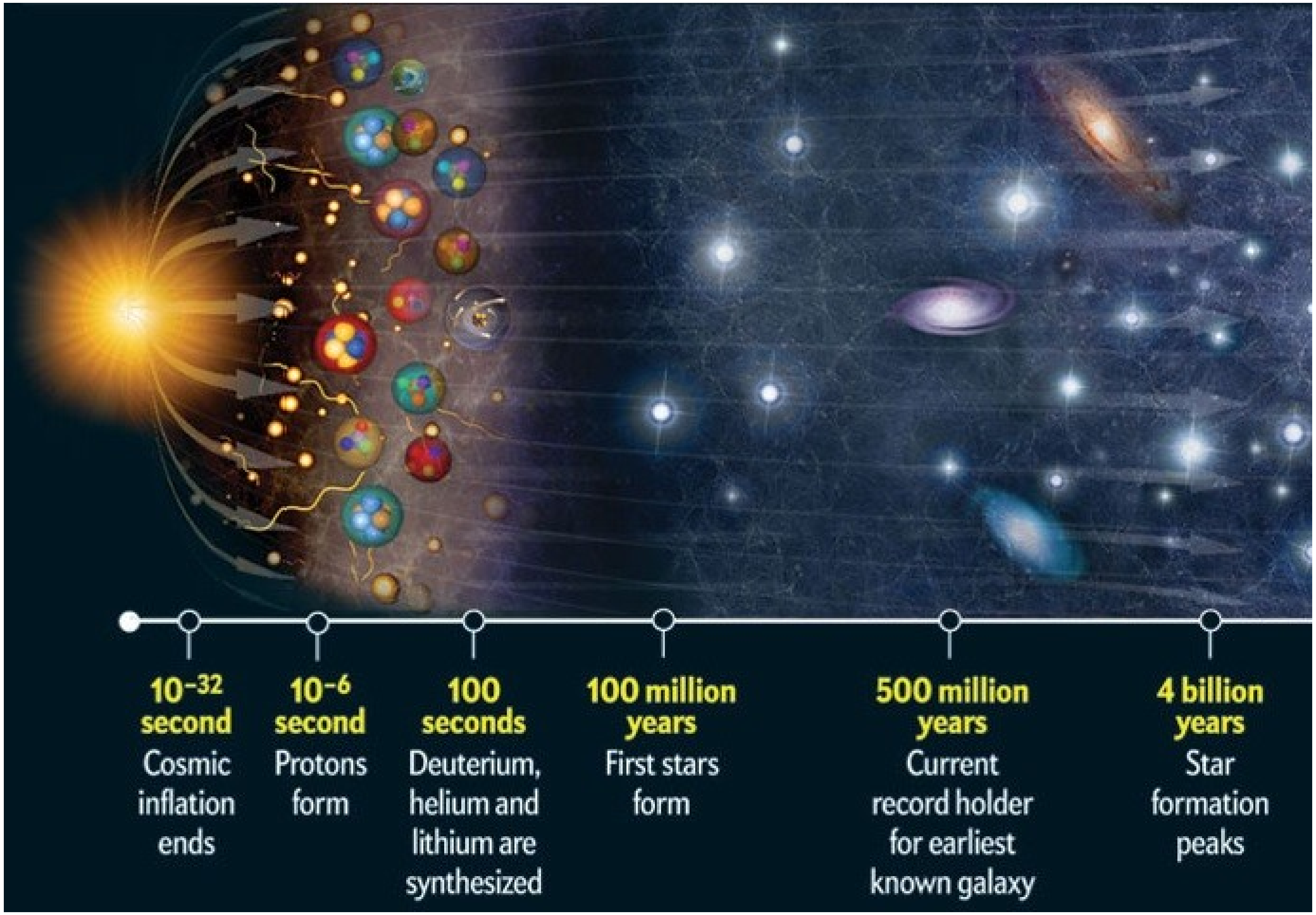
Identified nucleosynthesis processes

- Primordial (Big-Bang) nucleosynthesis
- Hydrogen and Helium burning
- “e” process (iron peak)
- “x” process (LiBeB; “x” for unknown)
- “r” process (rapid neutron capture)
- “s” process (slow neutron capture)
- “p” process (proton rich)

Today

- “x” is identified as non-thermal nucleosynthesis (cosmic rays)
- Additional burning stages identified: C, Ne, O, Si

2. Big Bang nucleosynthesis



Observational pillars for Big-Bang model

- The expansion of the Universe

  Galaxies move away from each other and from us according to Hubble's law: $V = H_0 \times D$, where $H_0 \approx 70$ km/s/Mpc is the Hubble "constant"

- The Cosmic Microwave Background radiation (CMB)

  Black body radiation at 2.7 K corresponding to the redshifted spectrum emitted when the Universe became transparent (Penzias & Wilson, 1965)

- Primordial nucleosynthesis (BBN) of light elements

  BBN reproduces the observed primordial abundances over a range of nine orders of magnitudes!

Nucleosynthesis (1)

- For T > 10 GK, the energy density is dominated by radiation (photons and neutrinos), and all weak, strong and electromagnetic processes established a thermal equilibrium

- $n \leftrightarrow p$ equilibrium driven by weak interactions:

  (1): $\nu_e + n \leftrightarrow e^- + p$ (2): $\bar{\nu}_e + p \leftrightarrow e^+ + n$ (3): $n \leftrightarrow p + e^- + \bar{\nu}_e$

$$\frac{N_n}{N_p} = e^{-Q_{np}/kT}$$

$$Q_{np} = 1.29 MeV$$

- Equilibrium as long as the weak reaction rate [(1) + (2)] are faster than the expansion rate, hence breaks out when:

$$\Gamma_{n \leftrightarrow p} \sim H(t)$$

Γ: reaction rates

- Decoupling and freezeout $t \approx 10$ s after Big-Bang when $T \approx 3$ GK and $N_n/N_p \approx 1/6$

Nucleosynthesis (2)

- After freezeout the dominant weak interaction is the decay of free neutrons to protons

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- Neutrons decay until T is low enough so that:

$$n + p \rightarrow D + \gamma$$

becomes faster than deuterium photodisintegration

$$\gamma + D \rightarrow n + p$$

- This occurs at $t \approx 200$ s (3 min) when $T \approx 0.9$ GK and $N_n/N_p \approx 1/7$

- Nucleosynthesis starts to produce essentially ^{4}He together with traces of D, ^{3}He, ^{7}Li, …

$N_n/N_p \approx 1/7 = 2/14$ → X(^{4}He) ≈ 4 / (4 + 12) ≈ 0.25

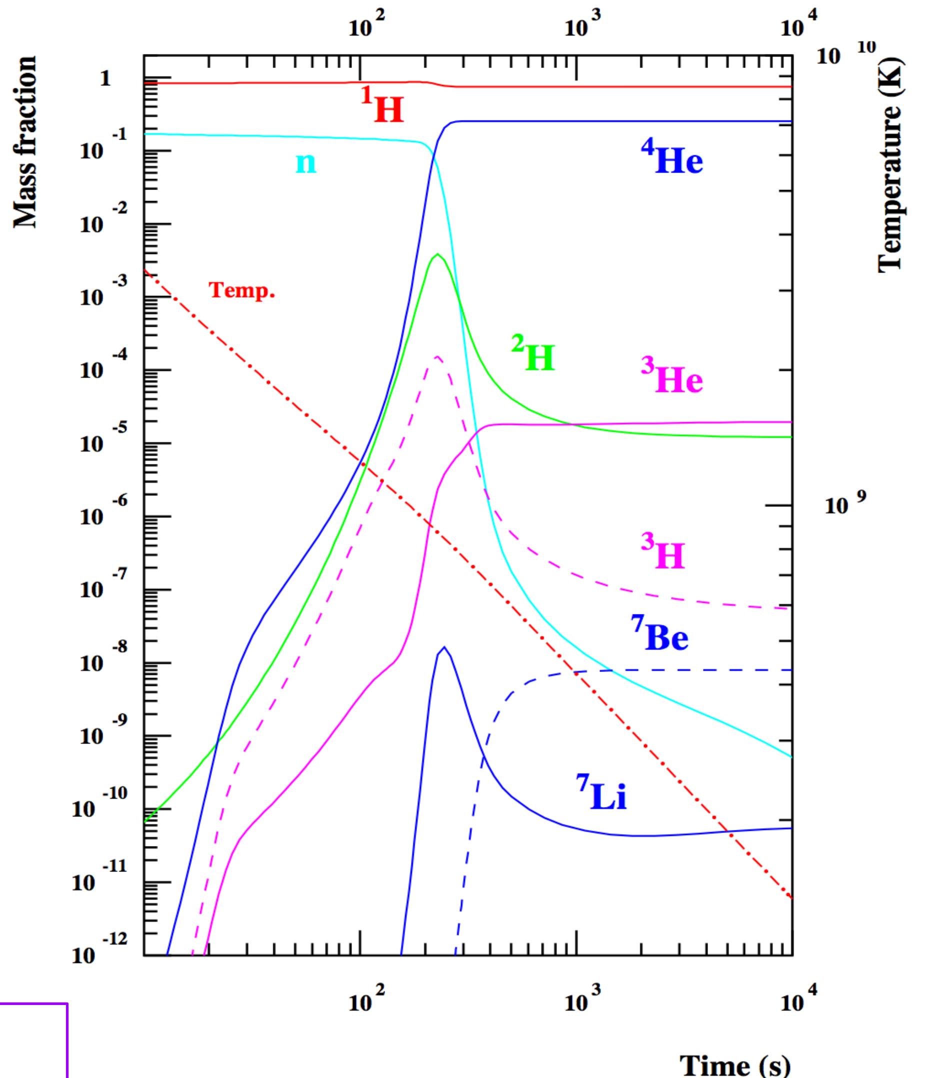
The canonical BBN reaction network

- Standard BBN: no convection, no mixing, no diffusion, known physics
- The 12 reactions of standard BBN:

theory
- $n \leftrightarrow p$ and τ_n = 880 (4) s
- $p + n \rightarrow D + \gamma$

experiments
- $D + p \rightarrow {}^3He + \gamma$
- $D + D \rightarrow {}^3He + n$
- $D + D \rightarrow T + p$
- $T + D \rightarrow {}^4He + n$
- $T + {}^4He \rightarrow {}^7Li + \gamma$
- ${}^3He + n \rightarrow p + T$
- ${}^3He + D \rightarrow p + {}^4He$
- ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
- ${}^7Li + p \rightarrow {}^4He + {}^4He$
- ${}^7Be + n \rightarrow {}^7Li + p$

$\Omega_b h^2$ from WMAP



Number of baryons per photon: $\eta \equiv n_b/n_\gamma$

Baryonic density of the Universe: $\Omega_b h^2 = 3.65\times10^7\ \eta$

Predictions vs observations

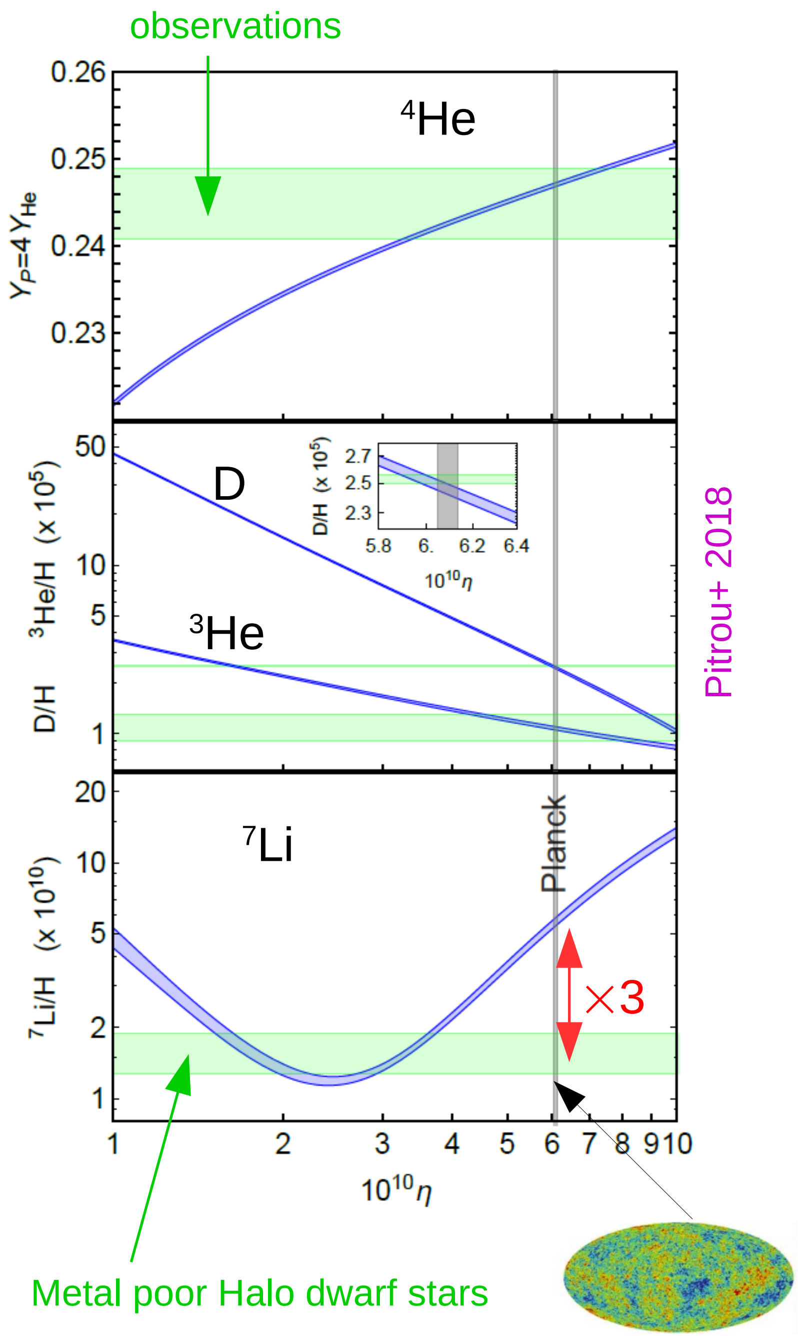
Observations from a set of primitive objects when the Universe was young

- D observations: in remote cosmological clouds (i.e. at high redshift) on the line of sight of quasars
  D/H = $(2.527 \pm 0.030) \times 10^{-5}$

- ^{4}He observations: in H II (ionized H) regions of blue compact galaxies
  ^{4}He/H = 0.2449 ± 0.0040

- ^{3}He observations: in HII regions of *our* Galaxy
  ^{3}He/H = $(1.1 \pm 0.2) \times 10^{-5}$

- ^{7}Li observations: at the surface of low metallicity stars in the halo of our Galaxy
  ^{7}Li/H = $1.58^{+0.35}_{-0.28} \times 10^{-10}$



Solutions to the ^{7}Li problem?

Several possibilities are considered

- Astrophysical solution
- Nuclear physics solution
- Physics beyond the standard model

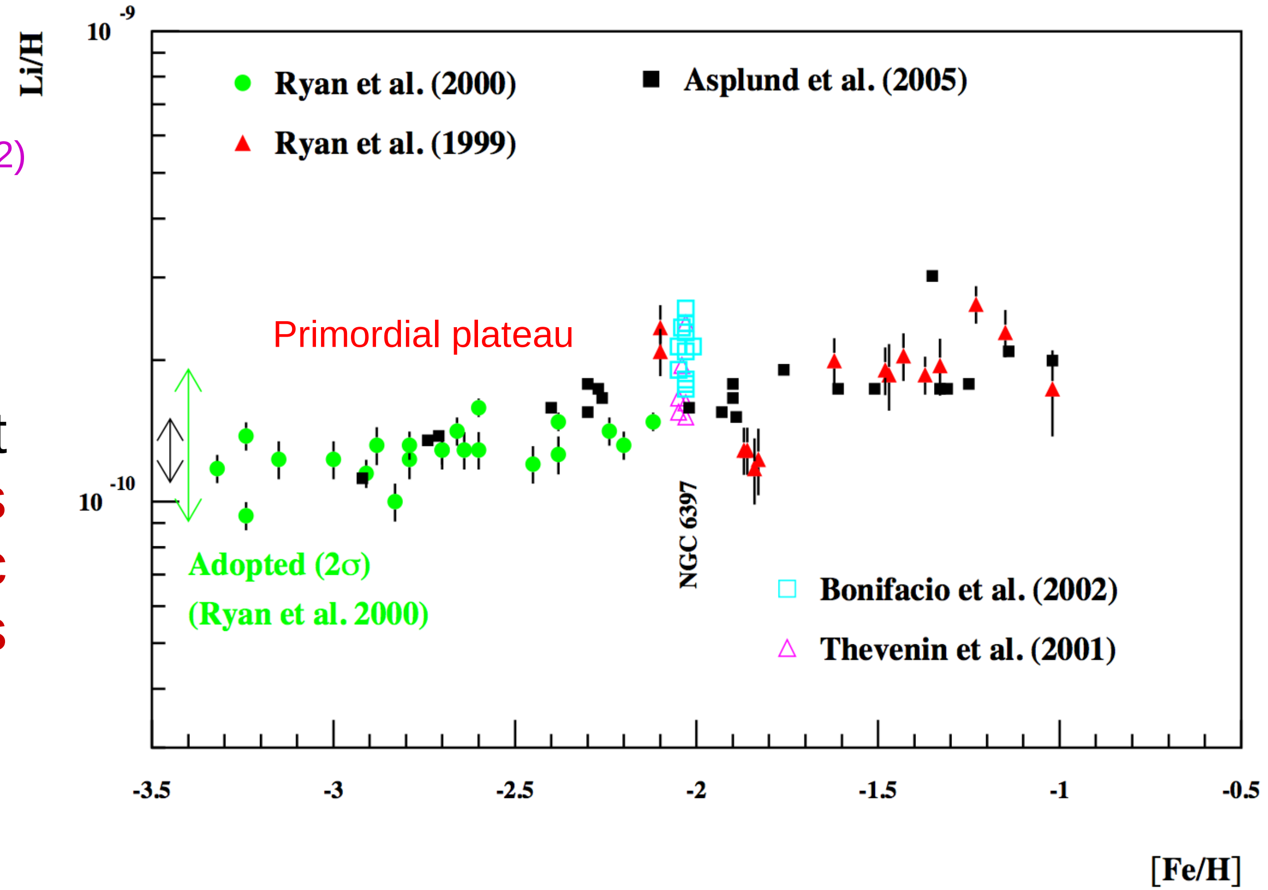
^{7}Li abundances

Primordial ^{7}Li abundance measured in old metal poor halo dwarf stars

Spite plateau (Spite & Spite, 1982)

- Li/H ≈ 1.12 x 10^{-10}
- Very low dispersion

Spite plateau indicates that the bulk of the lithium is unrelated to galactic nucleosynthesis processes and thus is primordial



How reliable is Li abundance determination?

→ Systematic errors in the extraction of Li abundances due to the used atmosphere models?

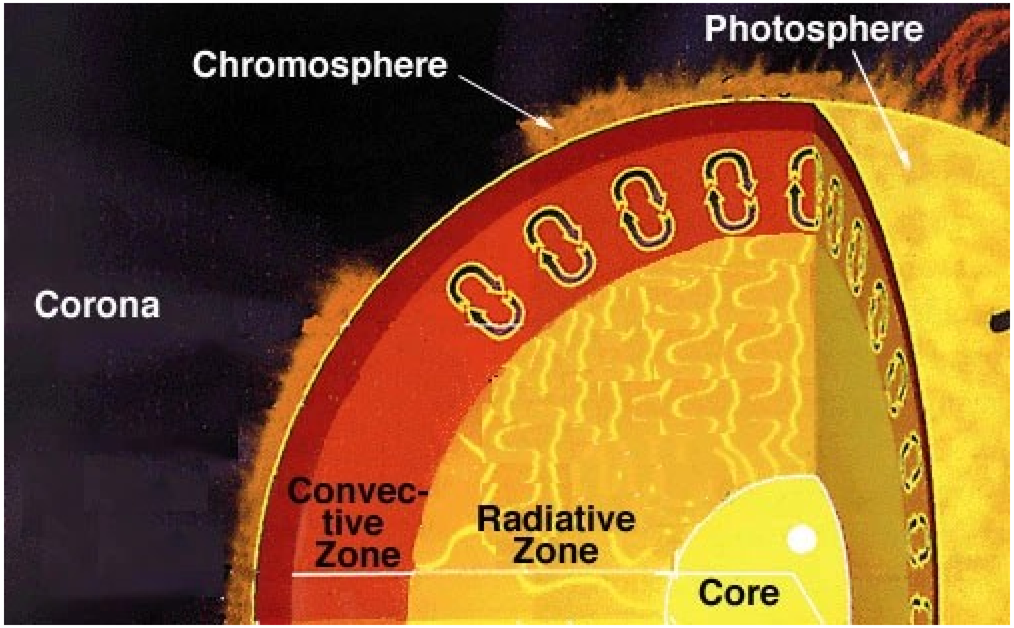
→ unlikely Asplund and Lind 2010

^{7}Li stellar destruction?

Could atmospheric ^{7}Li be depleted by rotationally induced mixing and/or diffusion?

- Lithium easily burned in stars (low binding energy)
  → ^{7}Li(p,α)α for T > 2.5 MK

- Convection brings surface material to deeper layers
  → lithium burning



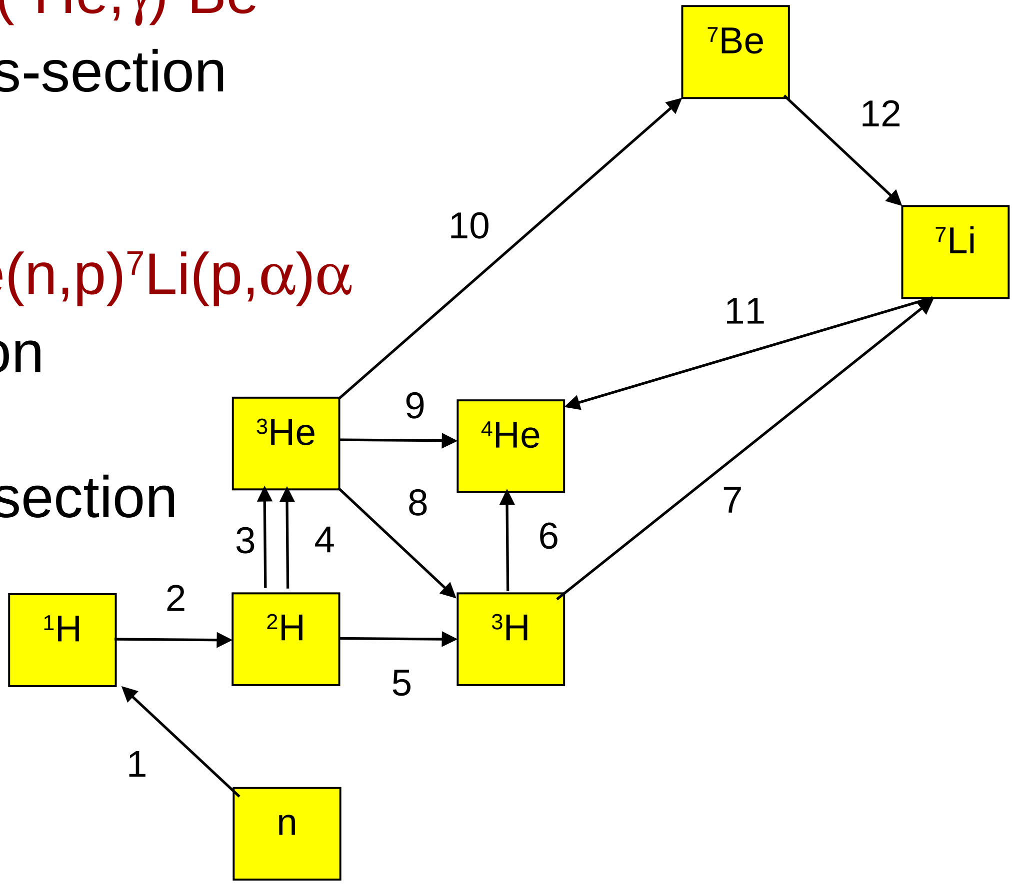
Not enough and not uniform ^{7}Li destruction

- Metal poor halo stars have shallower convective zones than in solar metallicity stars
- Stars of different masses have different convective zone size
  → larger scatter around ^{7}Li plateau should be observed

Nuclear solution to ^{7}Li problem?

Any additional ^{7}Be destruction would alleviate the ^{7}Li problem

- ^{7}Li produced by ^{7}Be decay (EC) at high $\Omega_b h^2$
- Main ^{7}Be production mechanism: ^{3}He(^{4}He,γ)^{7}Be
  → Various measurements of the cross-section
  10% uncertainty
- Main ^{7}Be destruction mechanism: ^{7}Be(n,p)^{7}Li(p,α)α
  → ^{7}Be(n,p)^{7}Li well known cross-section
  1% uncertainty
  → ^{7}Li(p,α)α 6% uncertainty on cross-section
- Secondary destruction mechanisms
  ^{7}Be+d, ^{7}Be+^{3}He, ^{7}Be+^{4}He….
  → all experimentally studied, and none can alleviate the ^{7}Li problem



Nuclear physics is very unlikely to solve the ^{7}Li problem

Physics beyond the standard model?

Idea: late time neutron injection

- enhance ^{7}Be destruction by ^{7}Be(**n**,p)^{7}Li(p,α)α reactions
- Alleviate the Li problem at the expense of deuterium overproduction

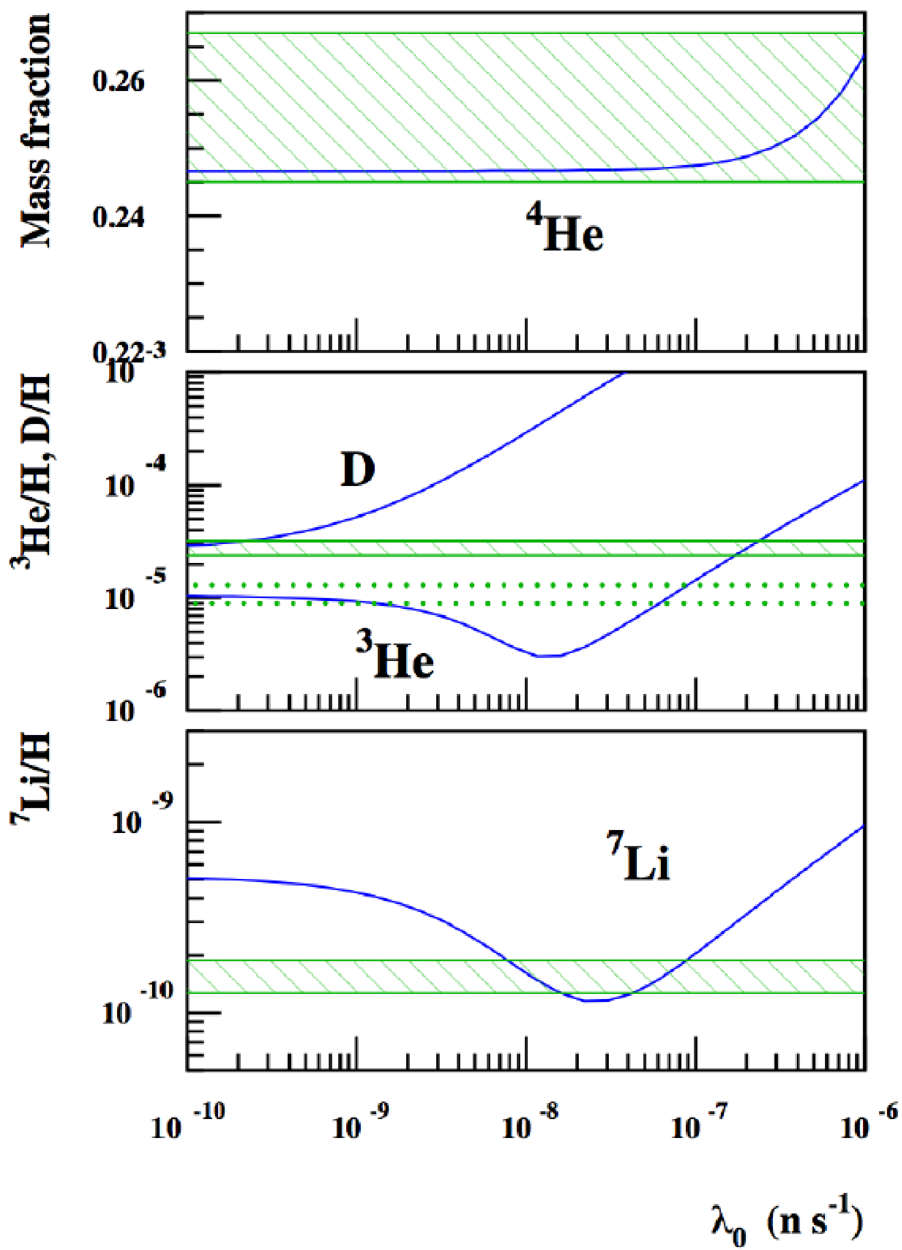
Two examples among many….

- Decays of heavier meta-stable (100 – 1000 s) particles that inject additional neutrons

  (Jedamzik (2004, 2006), Kawasaki+ (2005), Ellis+ (2005))

- Existence of a mirror universe in which neutrons can oscillate to our world (Coc+ 2013)

  → effective late time neutron injection



Summary

- Big-Bang Nucleosynthesis (BBN) produces, between 3 min and 20 min, **H**, **D**, **He** and part of **Li**

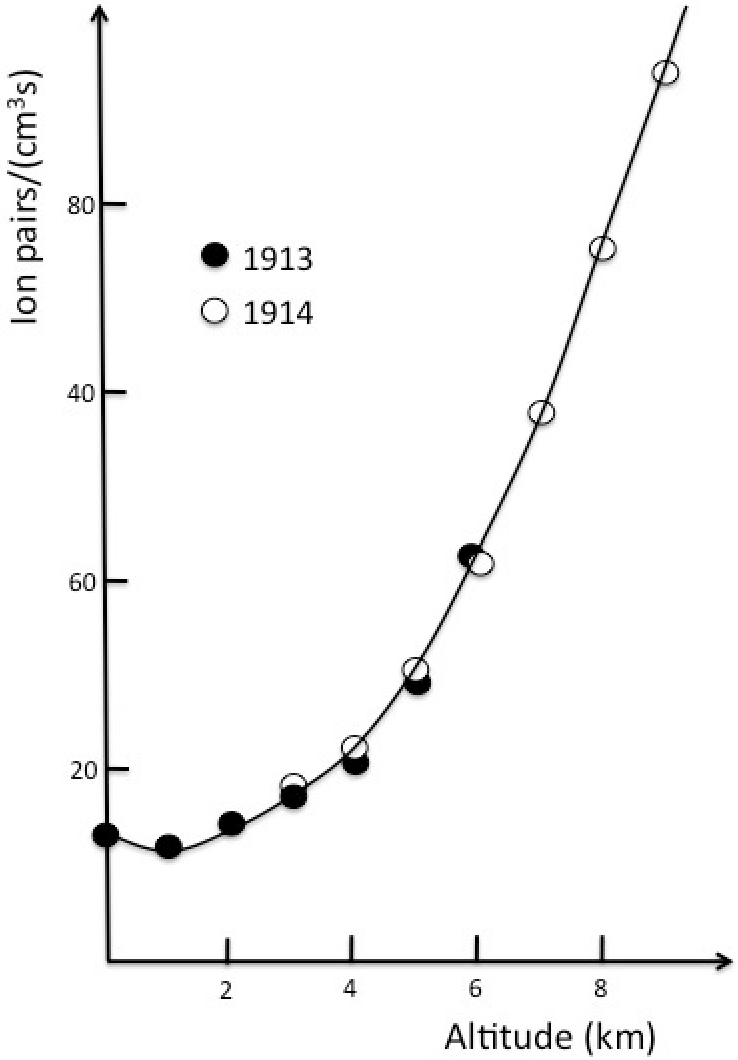
- Heavier elements nucleosynthesis is prevented because:
  - Larger Coulomb barriers for elements with higher atomic numbers (see next Lecture)
  - Lack of isotope of mass number A = 5 and A = 8
  - Decreasing matter density as the Universe expands

Further reading…

- C. Pitrou, A. Coc, P. Uzan & E. Vangioni, *Physics Reports* (2018)
- NPAC, cosmology course

3. Cosmic rays nucleosynthesis

Hess (center) lands after his balloon flight in 1912



Ionization as a funtion of altitude (Hess)

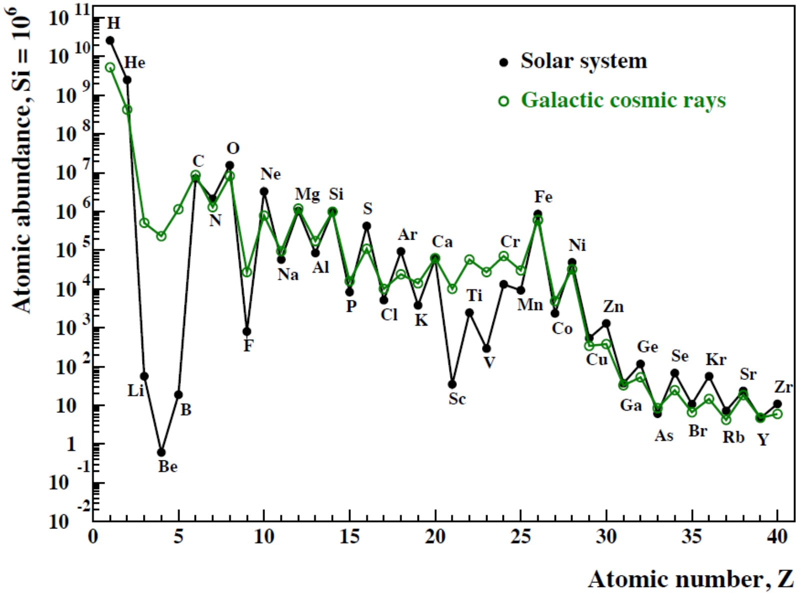
What is the origin of LiBeB isotopes?

What are the processes producing ^{6,7}Li, ^{9}Be and ^{10,11}B?

- Big-Bang Nucleosynthesis
  - significant amount of ^{7}Li
  - ^{6}Li, ^{9}Be and ^{10,11}B abundances predicted from BBN are at least 3 orders of magnitude below the abundances measured in metal-poor stars

- Stellar nucleosynthesis
  - Light elements are fragile enough (relatively low binding energy per nucleon) to be destroyed in stars during quiescent burning
  - ^{7}Li in classical novae (explosive), AGB (?)
  - ^{7}Li, ^{11}B by ν-induced spallation reactions

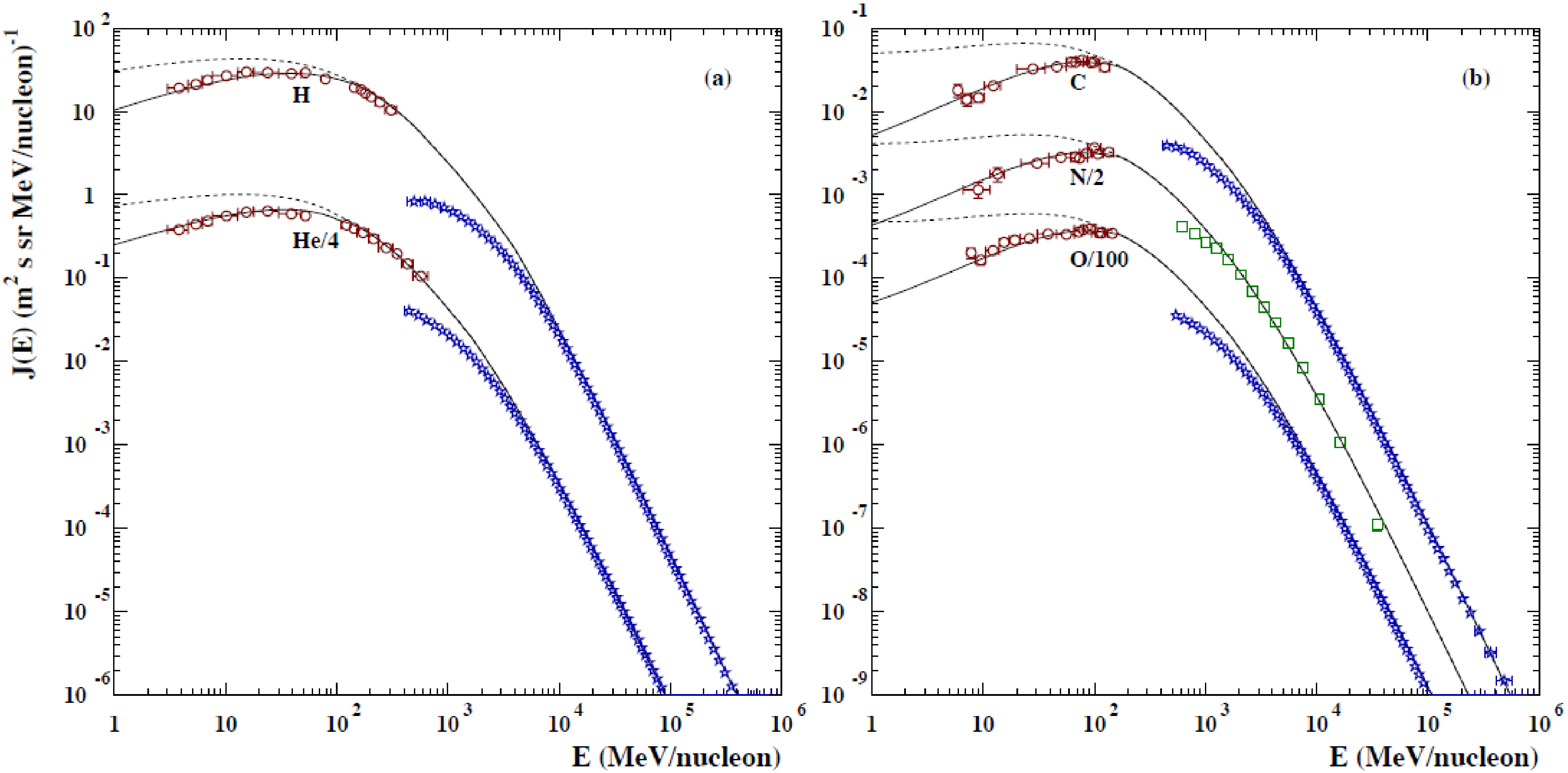
- Galactic Cosmic Rays (GCR)
  - Similar abundances than solar system with notable exception for LiBeB!!



Cosmic rays properties

Composition: H (90 %), He (9 %), C, N, O, …. e- (1 %)

Cosmic rays are not in thermodynamic equilibrium → power law spectrum

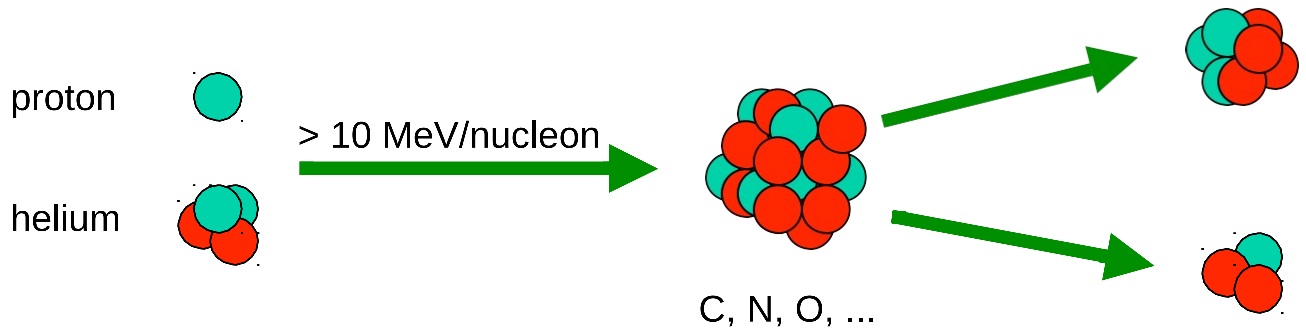


Data from *Voyager 1* probe (red circles), AMS-02 experiment (blue stars) and HEAO-3-C2 (green squares)

Spallogenic nucleosynthesis

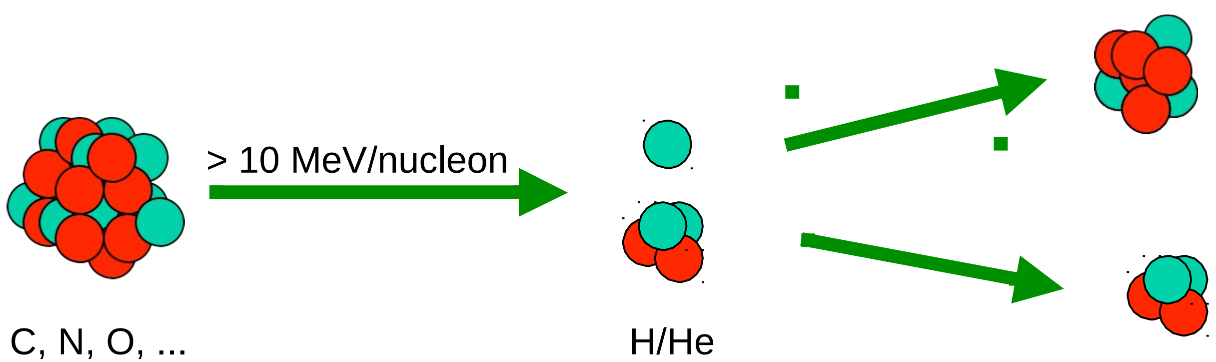
Non thermal nucleosynthesis induced by cosmic rays

Spallation: "heavy" nucleus (C, N, O, …) emits lighter fragments (Li, Be, B, …) as a result of a collision with a high-energy particle (H, He)



LiBeB emitted at much lower energy than incident H/He

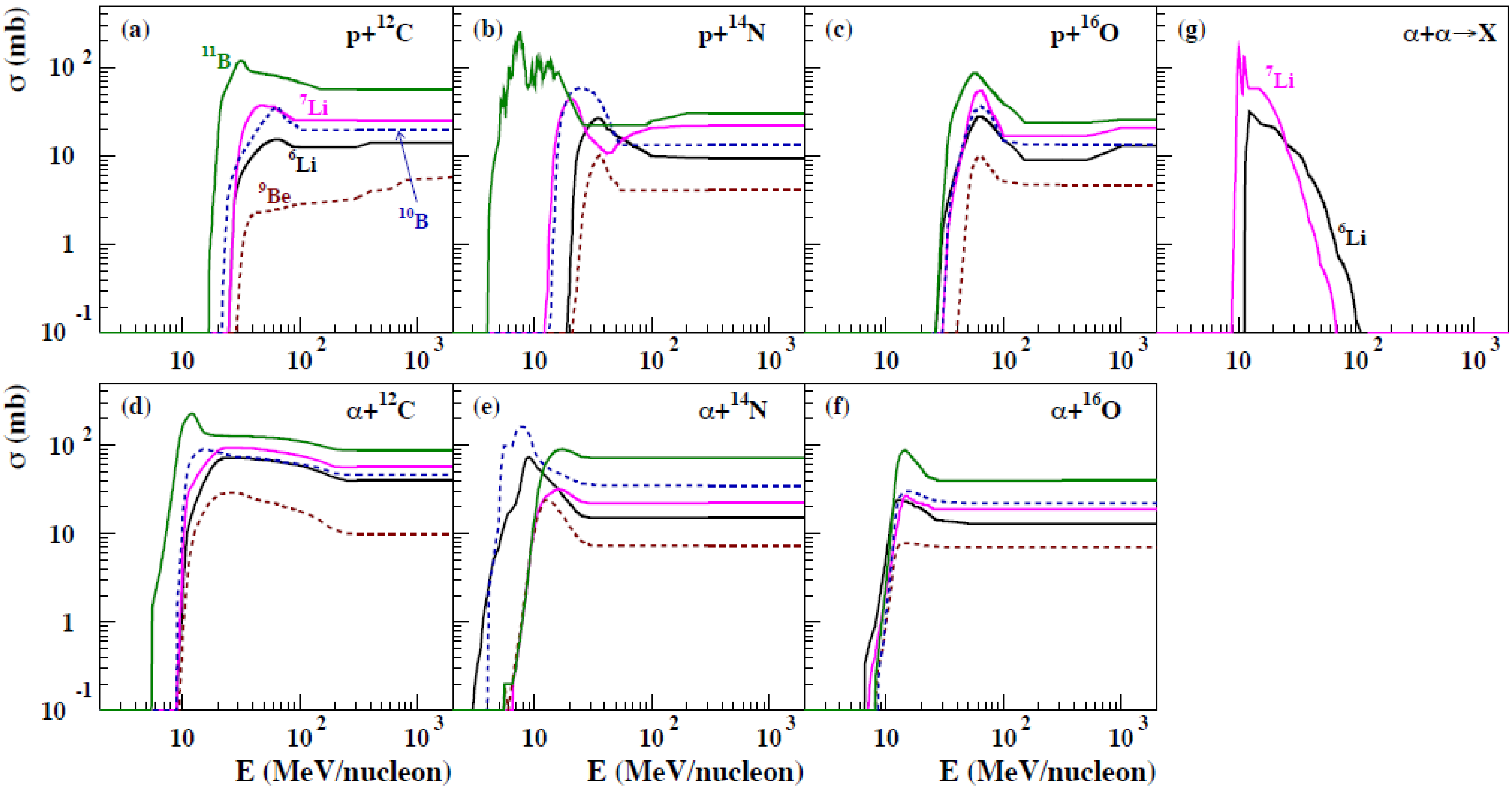
Inverse spallation: heavy nucleus impinges light nucleus



LiBeB emitted at about same energy per nucleon as incident C, N, O, …

→ must slow down to rest (small survival probability)

Spallation cross-sections



- The decreasing sequence of B, Li and Be matches the B, Li and Be GCR abundances
- $\alpha + \alpha$ reactions important for production of ^{6,7}Li isotopes

Summary

Galactic Cosmic Rays play a major role in the production of the LiBeB elements

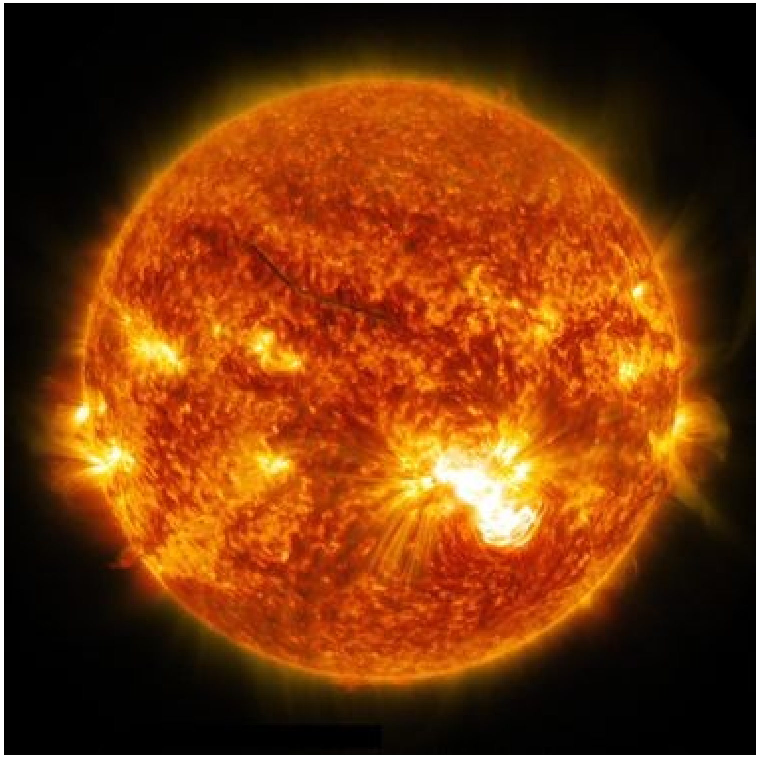
	BBN	GCR	ν in core-collapse supernovae	Low-mass stars
^{6}Li		100 %		
^{7}Li	12 %	18 %	< 20 %	50 – 70 %
^{9}Be		100 %		
^{10}B		100 %		
^{11}B		70 %	30 %	

Further reading…

- V. Tatischeff & S. Gabici, *Annual Reviews* (2018)
- N. Prantzos, *Astronomy & Astrophysics* 542, A67 (2012)

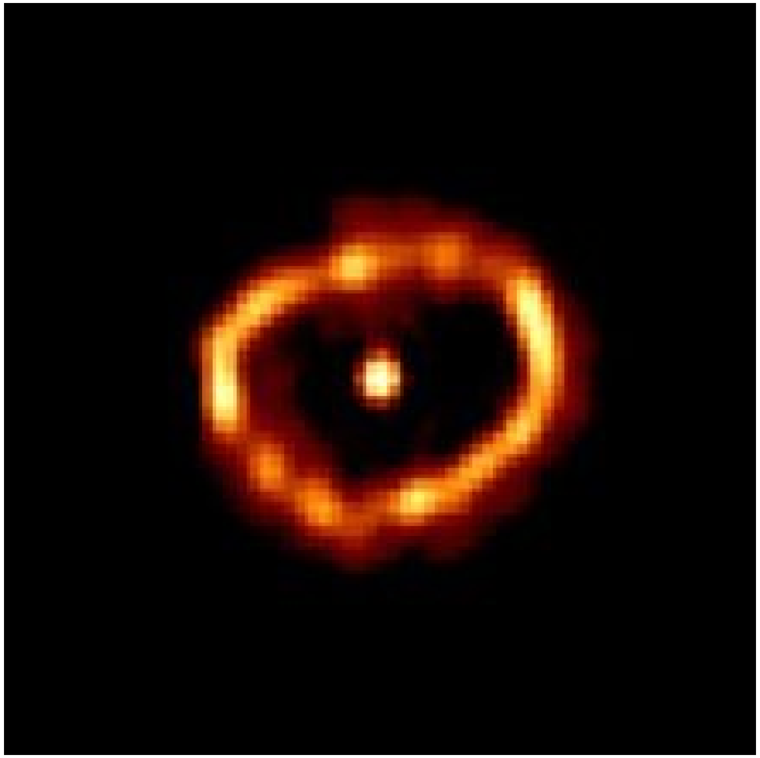
4. Stellar nucleosynthesis

Quiescent (hydrostatic)
stellar burning



Sun, Solar Dynamics Observatory

Explosive
stellar burning



Classical nova, Nova Cygni 1992, HST

4.1 Quiescent hydrogen burning

- Where does it take place?
  - Core of main-sequence stars (8 – 55 MK)
  - Core of the Sun (15.6 MK)
  - Burning shell in AGB stars (45 – 100 MK)

- How does it work?
  - $4p \rightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_e \quad (Q = 26.73 \text{ MeV})$

    ${}^{4}\mathrm{He}$ → ashes; Q → energy source
  - Probability for the simultaneous interaction of 4 protons far too small → reactions sequence

- Who & when?
  - Bethe & Critchfield (1938) } pp chain
  - von Weizsaecker (1938) } pp chain
  - Bethe (1939) → CNO cycle

Hans Bethe (1906 – 2005)

The proton – proton (pp) chains

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

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

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

pp1

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

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

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

pp2

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

$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + \mathrm{e}^+ + \nu_e$$

$${}^8\mathrm{Be}^* \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

pp3

Note: neutrinos provide direct evidence that nuclear reactions occur (see later)

The pp1 chain (1)

- Succesion of 3 reactions producing almost 90 % of Sun's energy

- First reaction: $p + p \rightarrow d + e^+ + \nu$ (Q = 1.44 MeV)

  → strong + weak interactions

  → cross-section is about 20 orders of magnitude smaller than for nuclear (strong) interaction!!

  → cannot be measured

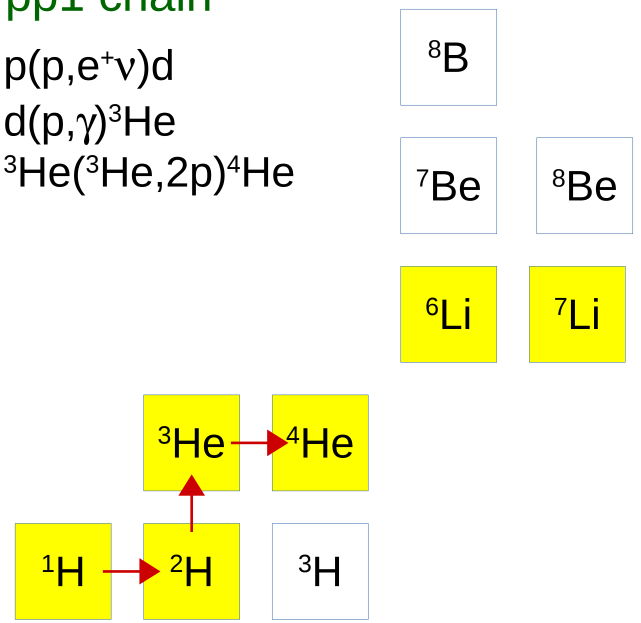
  → can be calculated

pp1 chain

$p(p,e^+\nu)d$

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

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



- All subsequent reactions involve nuclear and electromagnetic interactions

  → much faster

- Second reaction: $p + d \rightarrow {}^3He + \gamma$ (Q = 5.49 MeV)

  → many measurements since 1962, including one at LUNA in 2002 (see lecture 4)

The pp1 chain (2)

- Deuterium abundance in the core of the Sun
  - Temporal evolution of deuterium = production [p(p,e$^+\nu$)d] – destruction [d(p,γ)^{3}He]

$$\frac{dN_d}{dt} = \frac{N_H^2}{2} \langle \sigma v \rangle_{p(p,e^+\nu)} - N_H N_d \langle \sigma v \rangle_{d(p,\gamma)}$$

  - At equilibium:

$$\left(\frac{N_d}{N_H}\right)_e = \frac{\langle \sigma v \rangle_{p(p,e^+\nu)}}{2 \langle \sigma v \rangle_{d(p,\gamma)}}$$

For T = 15.6 MK (Sun)

$$\langle \sigma v \rangle_{p(p,e^+\nu)} = 1.5 \times 10^{-43} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\langle \sigma v \rangle_{d(p,\gamma)} = 2.0 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\left(\frac{N_d}{N_H}\right)_e = 7.5 \times 10^{-18}$$

Solar D/H ≈ 2x10^{-5}
→ D from BBN

- Lifetime of a proton and a deuterium in the core of the Sun

we consider ρ_c = 150 g cm^{-3} and $X_H \sim X_{He} \sim 0.5$ → N_H = 4.5 10^{25} cm^{-3}

$$\tau_H = \frac{1}{N_H \langle \sigma v \rangle_{p(p,e^+\nu)}} = 4.7 \times 10^9 \ \mathrm{yr} \qquad \tau_d = \frac{1}{N_H \langle \sigma v \rangle_{d(p,\gamma)}} = 1.1 \ \mathrm{s}$$

The pp1 chain (3)

Possible reactions for ^{3}He burning

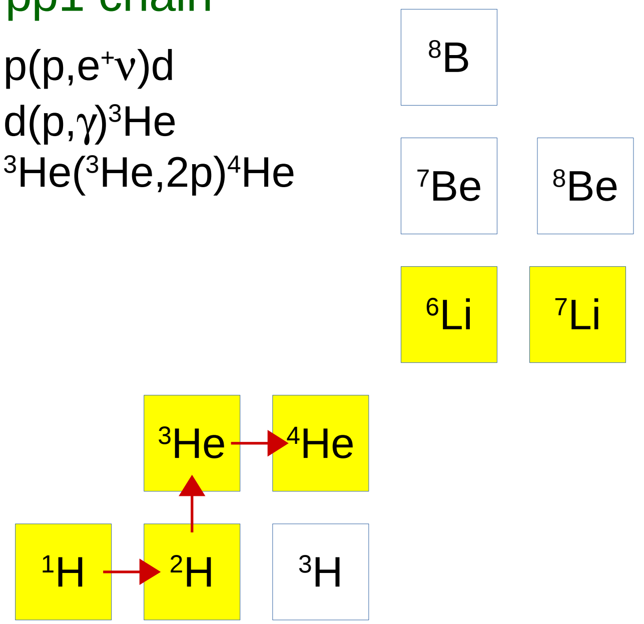
Reaction	Q (MeV)	*S*(0) (keV b)
$^3He(d,\gamma)^5Li(p)^4He$	16.39	~0.3
$^3He(d,p)^4He$	18.35	6240
$^3He(^3He,\gamma)^6Be(2p)^4He$	11.50	~0.8
$^3He(^3He,2p)^4He$	12.86	**5320 (80)**
$^3He(^4He,\gamma)^7Be$	1.59	**0.57 (4)**

pp1 chain

$p(p,e^+\nu)d$

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

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

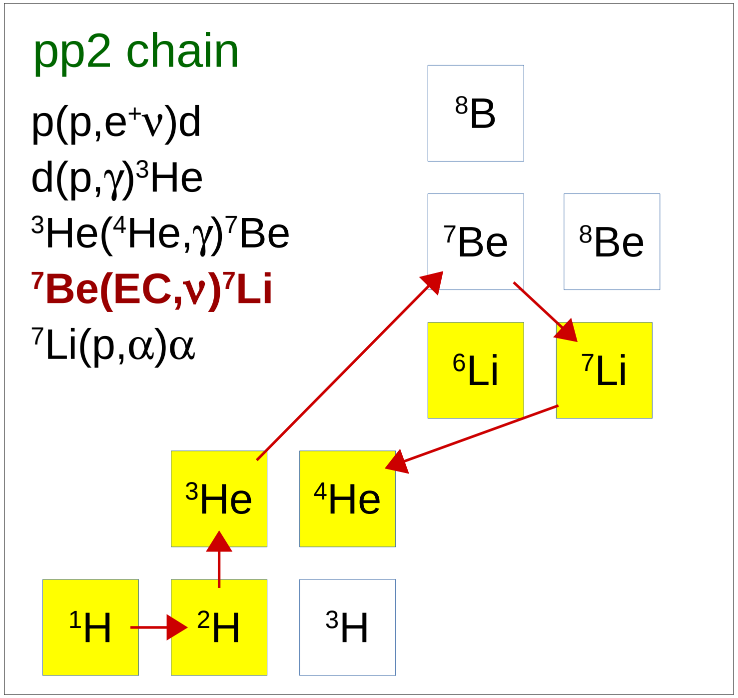


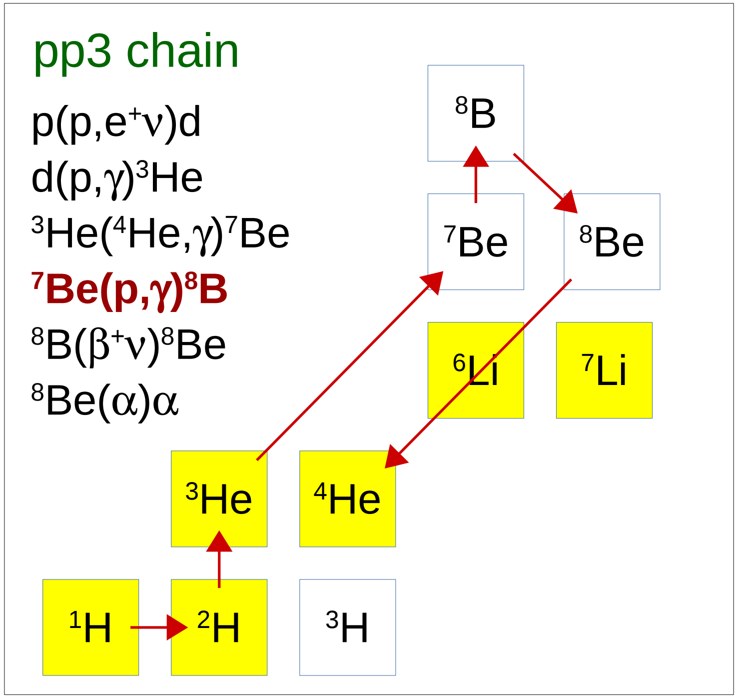
- $^3He + p \rightarrow {}^4Li \rightarrow {}^3He + p$ ($\tau = 10^{-22}$ s)
- ^{3}He + d negligible given the low deuterium abundance
- $^3He + {}^3He \rightarrow 2p + {}^4He$ (Q = 12.86 MeV) → Third reaction of the pp1 chain
  → has been measured in LUNA (see lecture 4)

- If N(^{4}He) >> N(^{3}He) [factor > 10^4] then $^3He(^4He,\gamma)^7Be$ is activated
  → pp2 & pp3 chains

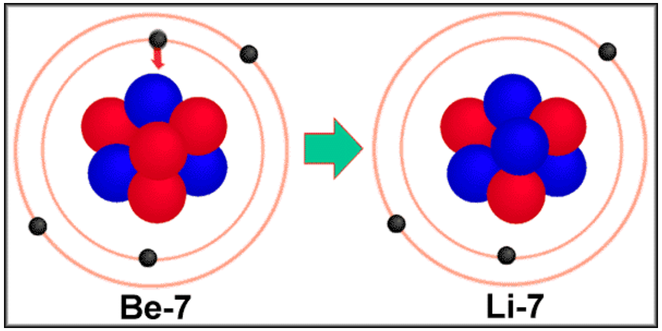
The pp2 and pp3 chains

^{7}Be destruction: competition between electronic capture (EC) and proton capture



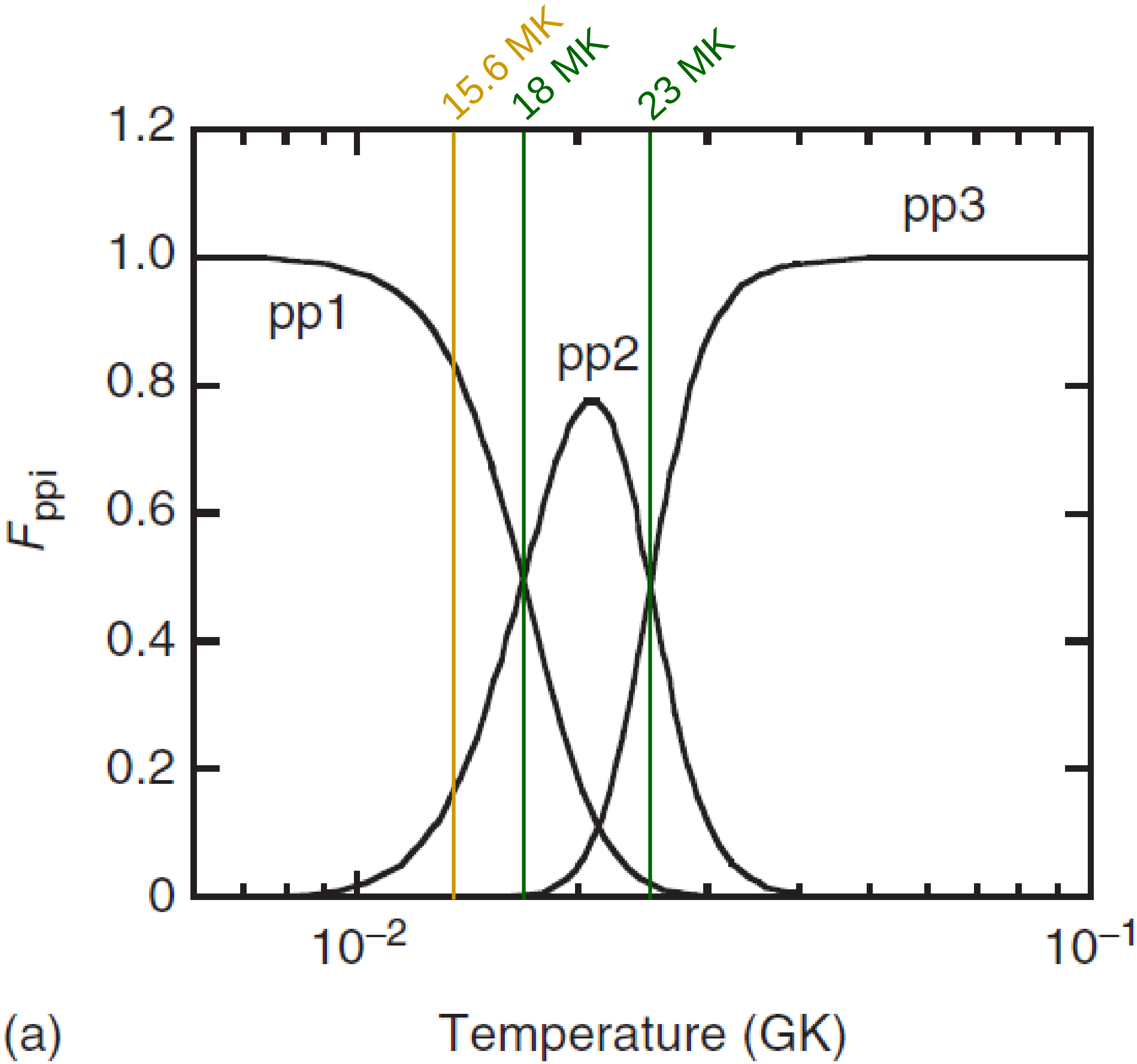


- ^{7}Be decays by EC and its lifetime depends on its charge state
- In stars, ^{7}Be fully ionized and then capture free electrons, so τ depends on n_e and T. In the Sun's core $\tau_s = 1.6\ \tau_{lab} = 120$ days



- The ^{7}Be(p,γ)^{8}B reaction is faster than ^{7}Be EC for $T > 25$ MK → pp3 chain

Relative contribution of the 3 pp chains



- T < 18 MK
  → pp1 chain
- 18 MK < T < 23 MK
  → pp2 chain
- T > 23 MK
  → pp3 chain
- Sun (T = 15.6 MK)
  → pp1 (84 %) + pp2 (14 %)

The pp chains in the Sun

$$p + p \rightarrow d + e^+ + \nu_e \; [0.26 \text{ MeV}]$$ (99.75 %)

$$p + e^- + p \rightarrow d + \nu_e \; [1.44 \text{ MeV}]$$ (0.25 %)

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

86 % → pp1:

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

14 %:

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

99.89 % → pp2:

$$^7\text{Be} + \text{e}^- \rightarrow {}^7\text{Li} + \nu_e \; [0.86 \text{ MeV}]$$

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

0.11 % → pp3:

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

$$^8\text{B} \rightarrow {}^8\text{Be}^* + \text{e}^+ + \nu_e \; [6.80 \text{ MeV}]$$

$$^8\text{Be}^* \rightarrow {}^4\text{He} + {}^4\text{He}$$

The effective energy given to the Sun is smaller than Q = 26.73 MeV because of the escape of the neutrinos

pp2 $Q_{eff} = Q - \overline{E}_\nu(p+p) - \overline{E}_\nu(^7\text{Be}) = 25.61 \text{ MeV}$

pp1 $Q_{eff} = Q - 2\overline{E}_\nu(p+p) = 26.20 \text{ MeV}$

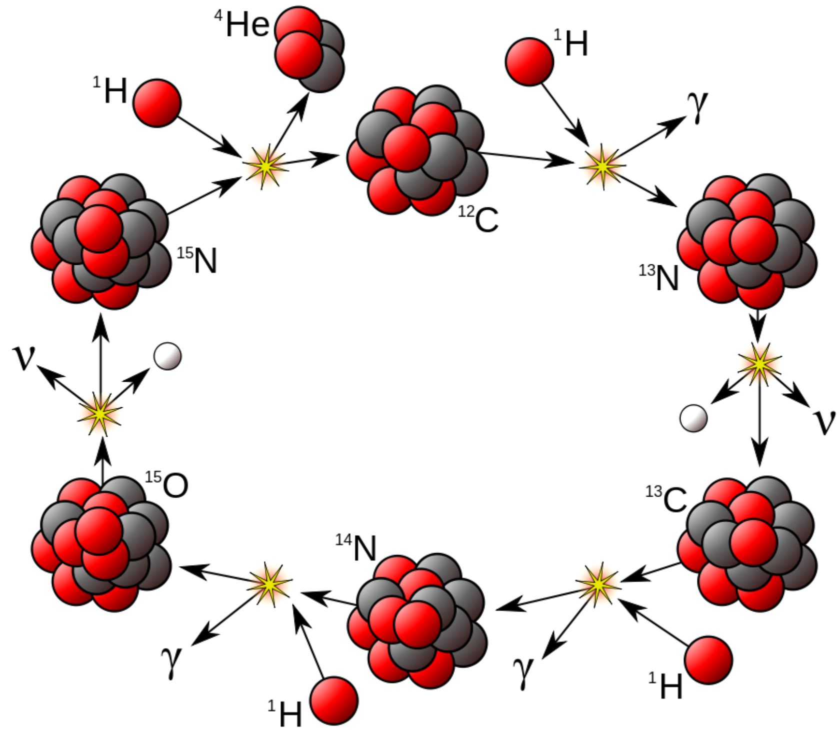
pp3 $Q_{eff} = Q - \overline{E}_\nu(p+p) - \overline{E}_\nu(^8\text{B}) = 19.67 \text{ MeV}$

The CNO cycle (1)

- In population I stars (second, third… generation of stars), the elements C, N and O serve as catalysts of the transformation:

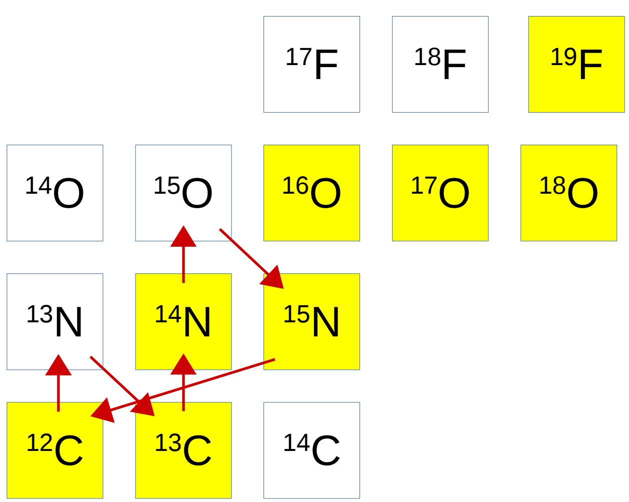
$$4p \rightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{e} \quad (Q = 26.73\ \mathrm{MeV})$$

- There are four sets of reactions converting H to He → 4 CNO cycles
  → we will focus on the CNO-1 cycle



CNO-1

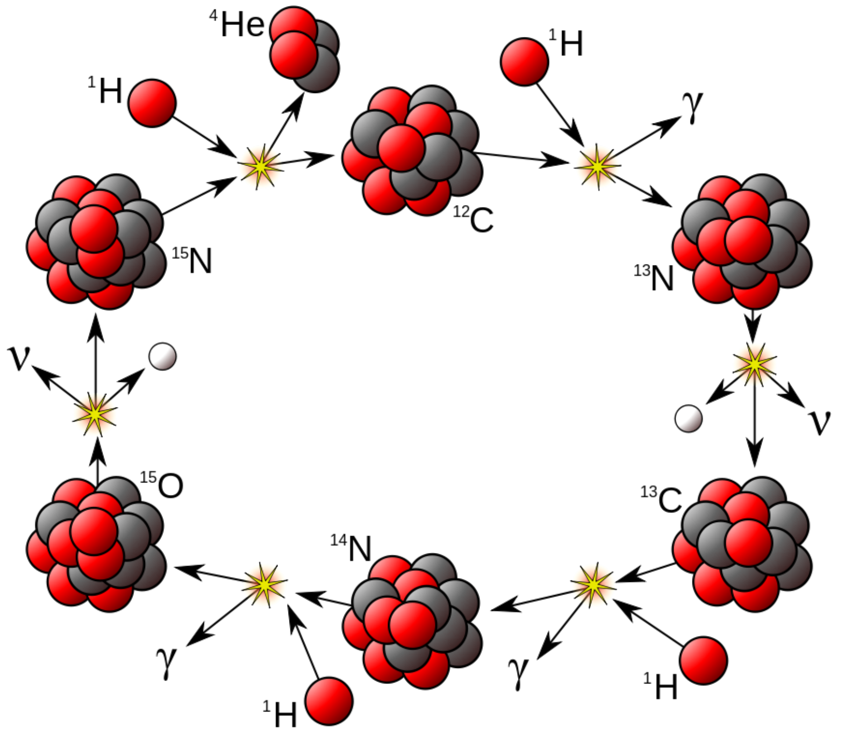
$^{12}C(p,\gamma)^{13}N$
$^{13}N(\beta^{+}\nu)^{13}C$
$^{13}C(p,\gamma)^{14}N$
$^{14}N(p,\gamma)^{15}O$
$^{15}O(\beta^{+}\nu)^{15}N$
$^{15}N(p,\alpha)^{12}C$



$T_{1/2}(^{13}N) = 9.965$ min
$T_{1/2}(^{15}O) = 122.24$ s
$T_{1/2}(^{17}F) = 64.49$ s
$T_{1/2}(^{18}F) = 109.77$ min

The CNO cycle (2)

- The slowest reaction $^{14}N(p,\gamma)^{15}O$ of the CNO cycle fixes:
  - the energy production rate $\epsilon \propto Q_{CNO}/\tau_{CNO}$
  - the cycle duration
    - $\tau_{CNO} = \tau_p(^{12}\mathrm{C}) + \tau_p(^{13}\mathrm{C}) + \tau_p(^{14}\mathrm{N}) + \tau_p(^{15}\mathrm{N}) \cong \tau_p(^{14}\mathrm{N})$
    - For ρ_c = 100 g.cm^{-3}, X_H = 0.5 and T_c = 60 MK → $\tau(^{12}C)$ = 6.1×10^9 yr, $\tau(^{13}C)$ = 1.1×10^9 yr, $\tau(^{14}N)$ = 2.1×10^{12} yr, $\tau(^{15}N)$ = 1.0×10^8 yr



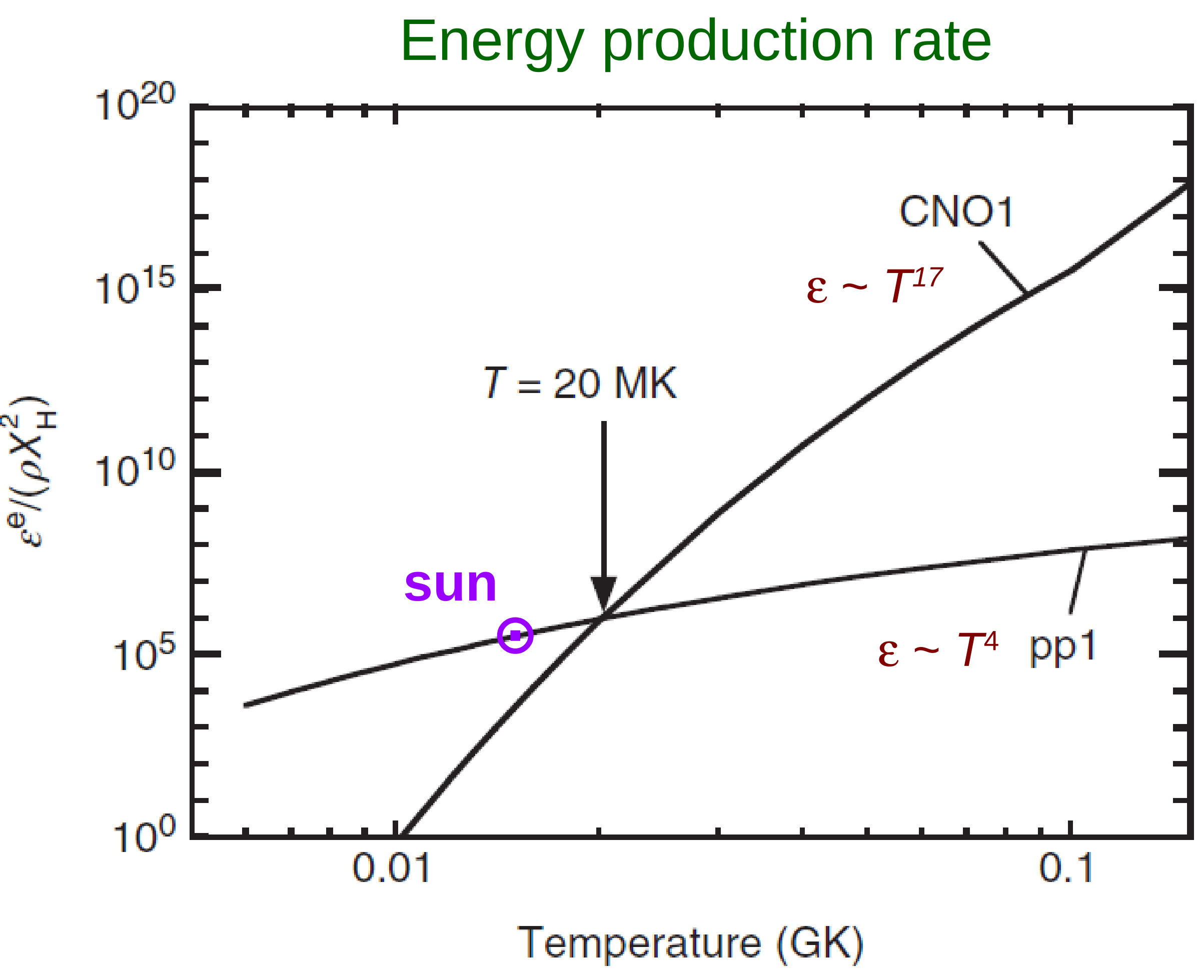
- The $^{14}N(p,\gamma)^{15}O$ reaction has been measured directly by the LUNA collaboration (see lecture 4)

  → impact on the age of Globular Clusters (turn-off age; see lecture 1)

  (Imbriani+, A&A, 2013)

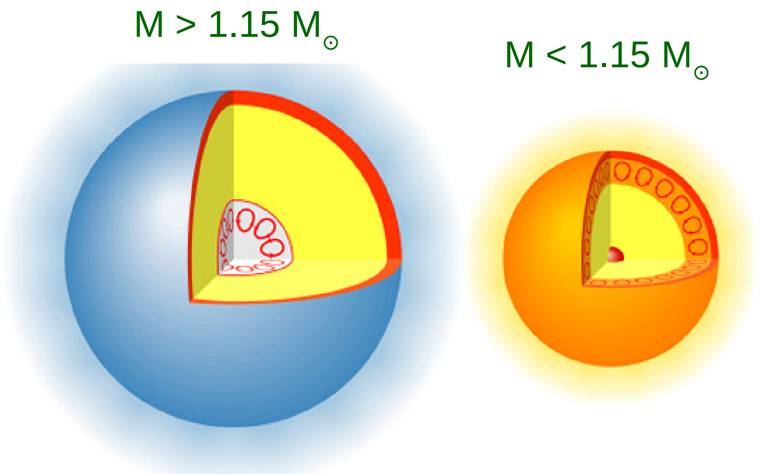
- CNO cycle in AGB stars is the main source of ^{13}C and ^{14}N in the Universe

The CNO cycle (3)

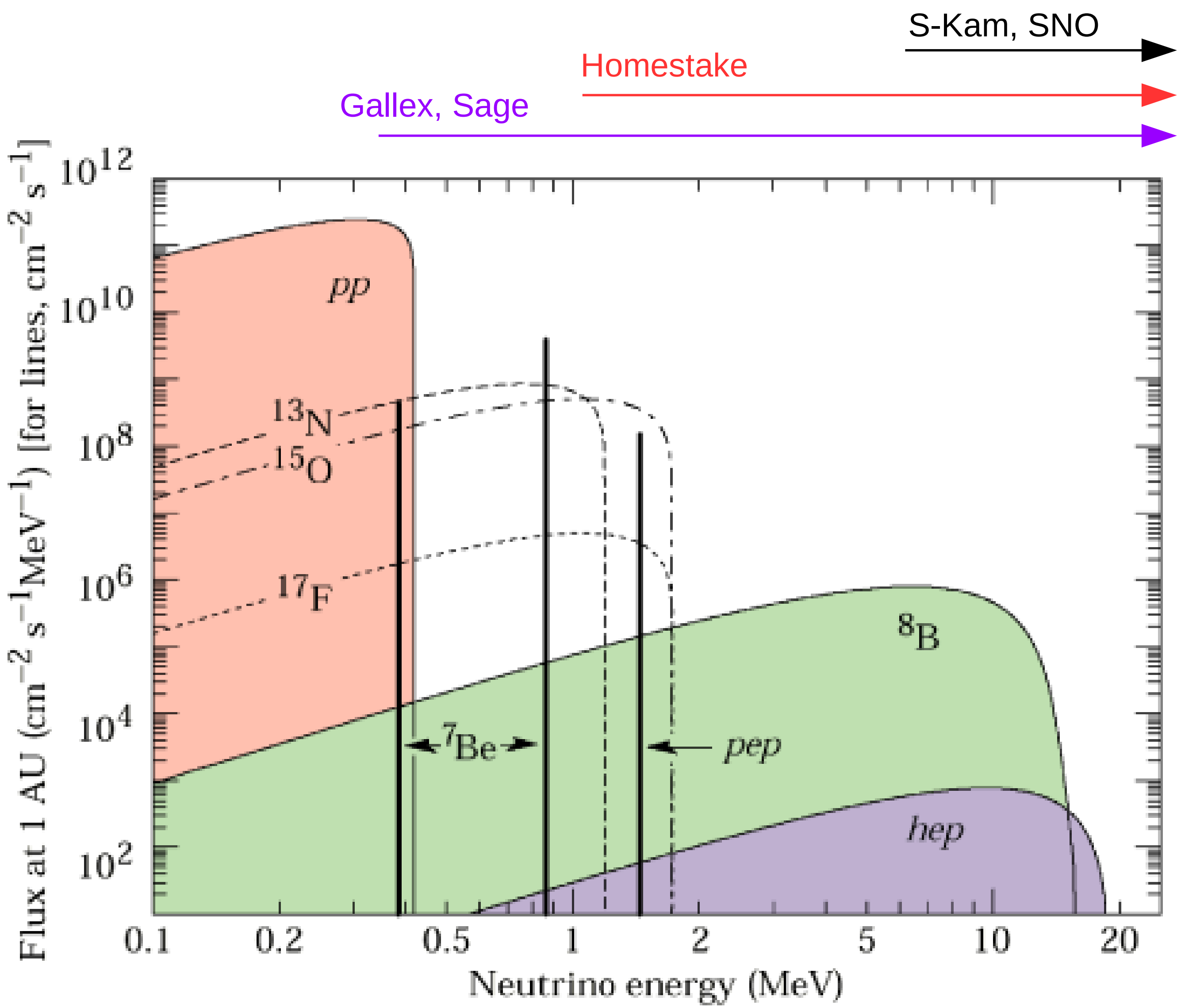


- CNO cycle has a steeper temperature dependence than pp chain (see lecture 3)
- pp1 chain dominates in low mass stars (~ $M_{\odot}$), while CNO cycles dominates for higher mass stars (few $M_{\odot}$)
- Above T = 20 MK, CNO1 faster than pp1

  → change in stellar structure at 1.15 $M_{\odot}$, e.g. different radiative / convective zones



The solar neutrino spectrum



The detection of solar neutrinos (1)

The pioneering experiment (1964- 2001) of R. Davis (Nobel price in 2002) and J. Bahcall

- 680 tons of perchloroethylene (C_2Cl_4) in the Homestake gold mine (1.5 km deep)

- $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar$ ($T_{1/2}$ = 35 days) + e^-

- Production of ^{37}Ar: ~0.5 atom per day

- Radiochemical separation: extraction of the ^{37}Ar nuclei every 100 days, counting (EC → Auger electrons) in a gas detector

- Result: 2.56 ± 0.16 (stat) ± 0.16 (sys) **SNU**
  → 30 % of the expected signal

- Solar model (Bahcall 2004): 8.5 ± 0.18 SNU

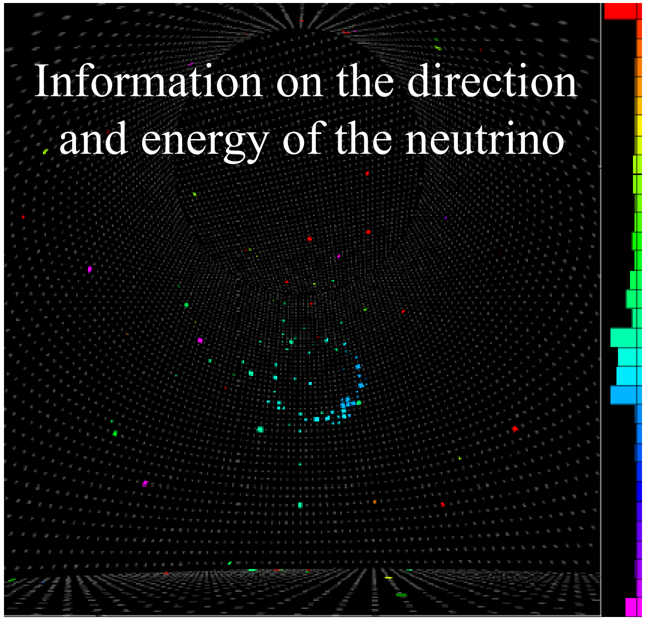
1 SNU (Solor Neutrino Unit) = 10^{-36} capture per second and target atom

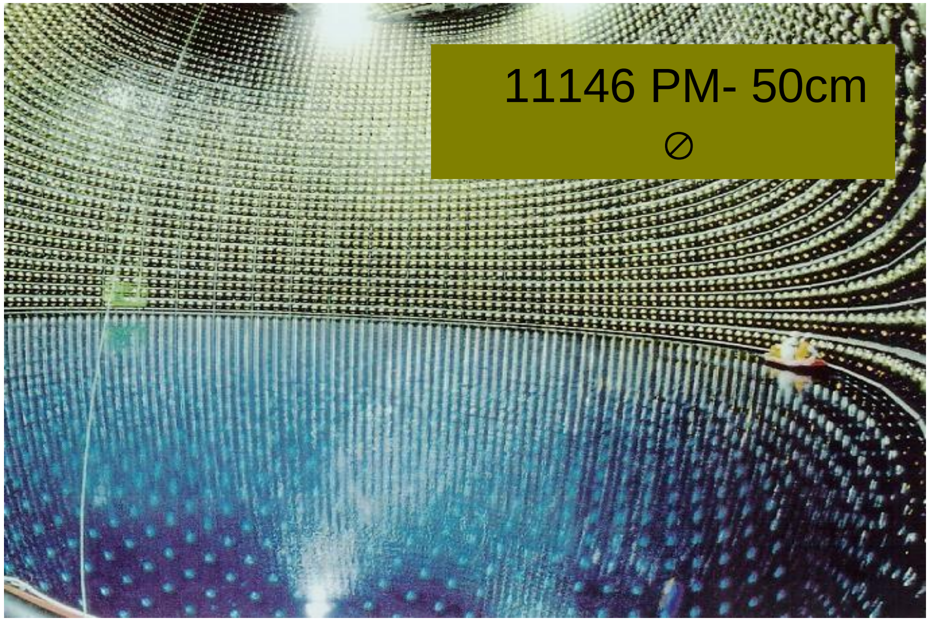
The detection of solar neutrinos (2)

- Radiochemical experiments with gallium: SAGE and GALLEX
  - Reaction: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge$ ($T_{1/2}$ = 11.4 d) + e^- (threshold E_ν = 0.23 MeV)

    → sensitive to pp neutrinos
  - Results: 40 % of the expected signal

- Real-time detection of (mostly) e- neutrinos: Kamiokande (700 tons of water, 1983 – 1996), Super-Kamiokande (50 kt, 1996 –)
  - Reaction: $\nu_e + e^- \rightarrow \nu_e + e^-$ (emission of Cherenkov light)
  - Results: 40 % of the expected signal





Solution to the solar neutrino problem

Possible origin of the deficit

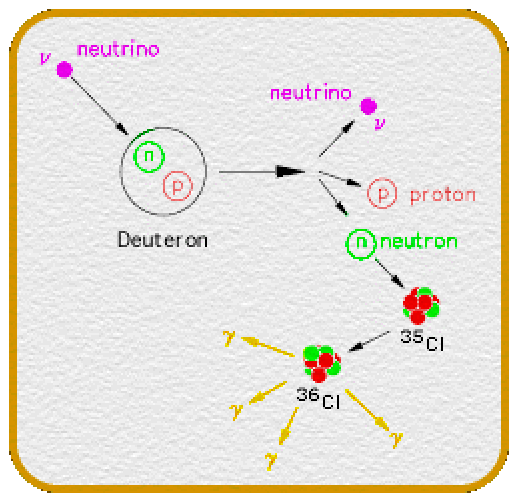
- Problem with the standard solar model? (3% of error on T_c → a factor of 2 in N_ν)
- Problem with the nuclear data? ^{7}Be(p,γ)^{8}B cross-section
- New physics of neutrino → oscillation $\nu_e \rightarrow \nu_\mu, \nu_\tau$?

SNO: Sudbury Neutrino Observatory

- 1100 tons of **D**$_2$O (99.9%)
- Sensitive to the three neutrino flavors

  $\rightarrow \nu_x + d \rightarrow p + n + \nu_x$ (neutral current)

  (Bellerive+, NPB, 2016)



- Results: ϕ_{NC} = 5.21 ± 0.27 (stat) ± 0.39 (sys) SNU in agreement with $\phi_{SSM} = 5.05^{+1.01}_{-0.81}$ SNU

4.2 Quiescent helium burning

- Where does it take place?
  - Core of horizontal branch stars (100 – 400 MK)
  - Burning shell in AGB stars (45 – 100 MK)

- Main nucleosynthesis products

  ^{4}He transformed in ^{12}C and ^{16}O for stars of more than ~ 0.5 $M_{\odot}$

- How does it work?

  Mainly three reactions:
    - $\alpha + \alpha + \alpha \rightarrow {}^{12}$C $\quad$ Q = 7.3 MeV
    - ^{12}C$(\alpha,\gamma)^{16}$O $\quad$ Q = 7.2 MeV
    - ^{16}O$(\alpha,\gamma)^{20}$Ne $\quad$ Q = 4.7 MeV

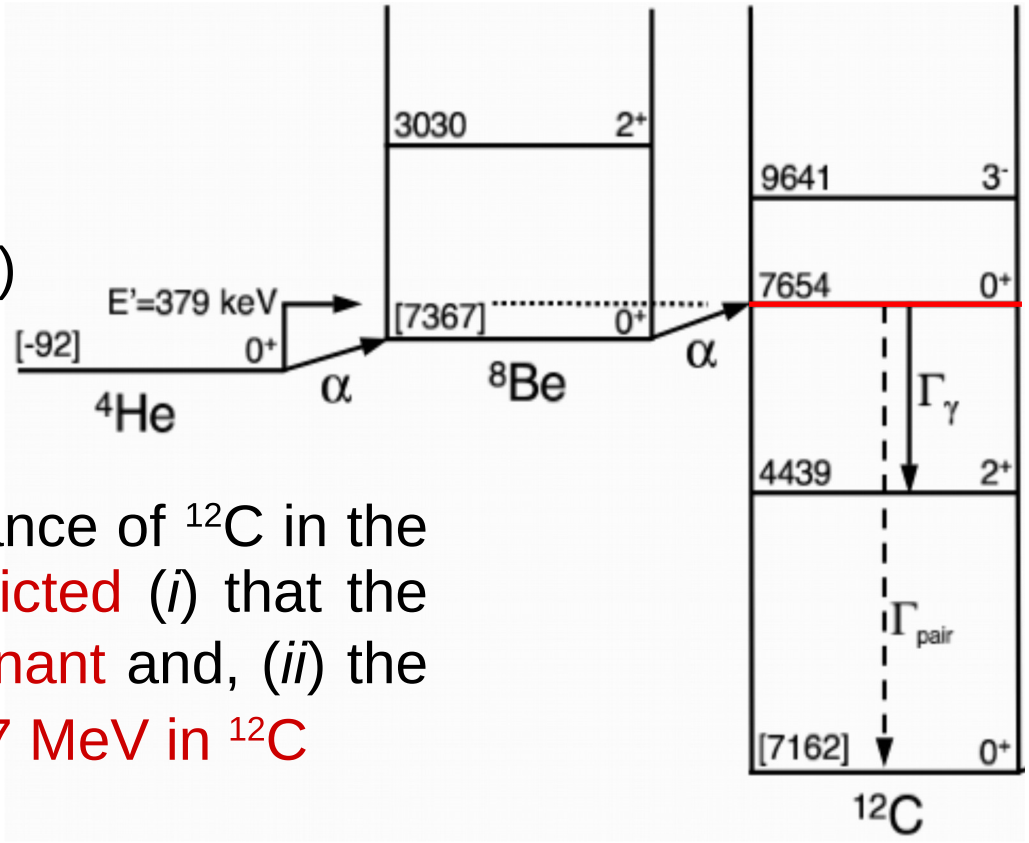
Fred Hoyle (1915 – 2001)

- Who & when?
  - Triple alpha process: Öpik (1951), Salpeter (1952)
  - The "Hoyle" state in ^{12}C: Hoyle (1953)

The triple alpha process

How are synthesized elements heavier than ^{4}He, given that there are no stable isotopes for mass A = 5 (p+α) and A = 8 (α+α)?

- Fusion of 3α in ^{12}C in two steps
  - α + α ↔ ^{8}Be Q = -92 keV
    (^{8}Be is unstable τ = 9.7×10^{-17} s)
  - α + ^{8}Be → ^{12}C*



- In view of the significant abundance of ^{12}C in the Universe (!), Hoyle (1953) predicted (*i*) that the reaction α + ^{8}Be → ^{12}C* is resonant and, (*ii*) the existence of a J$^\pi$ = 0$^+$ state at 7.7 MeV in ^{12}C

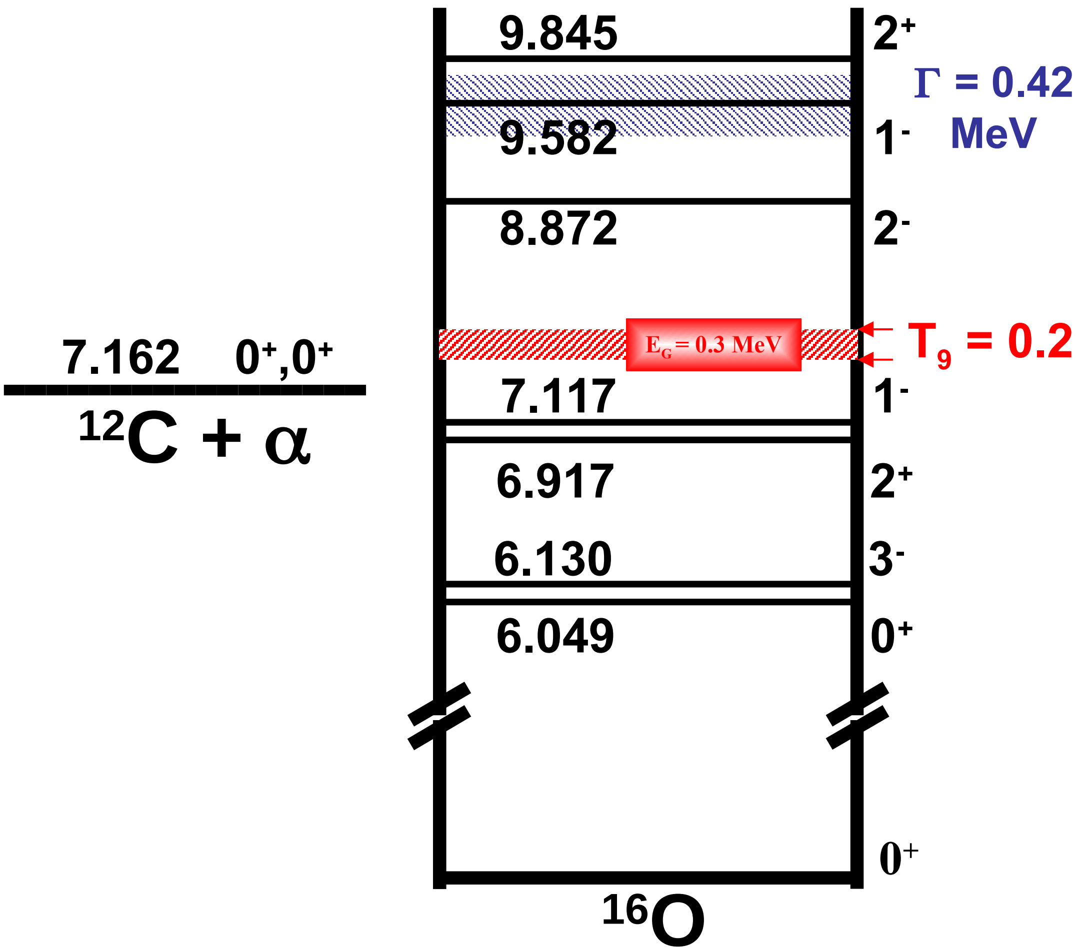
- Experimental verification in 1953 and 1957

The $^{12}C(\alpha,\gamma)^{16}O$ reaction

Slow and crucial reaction → Holy Grail in nuclear astrophysics

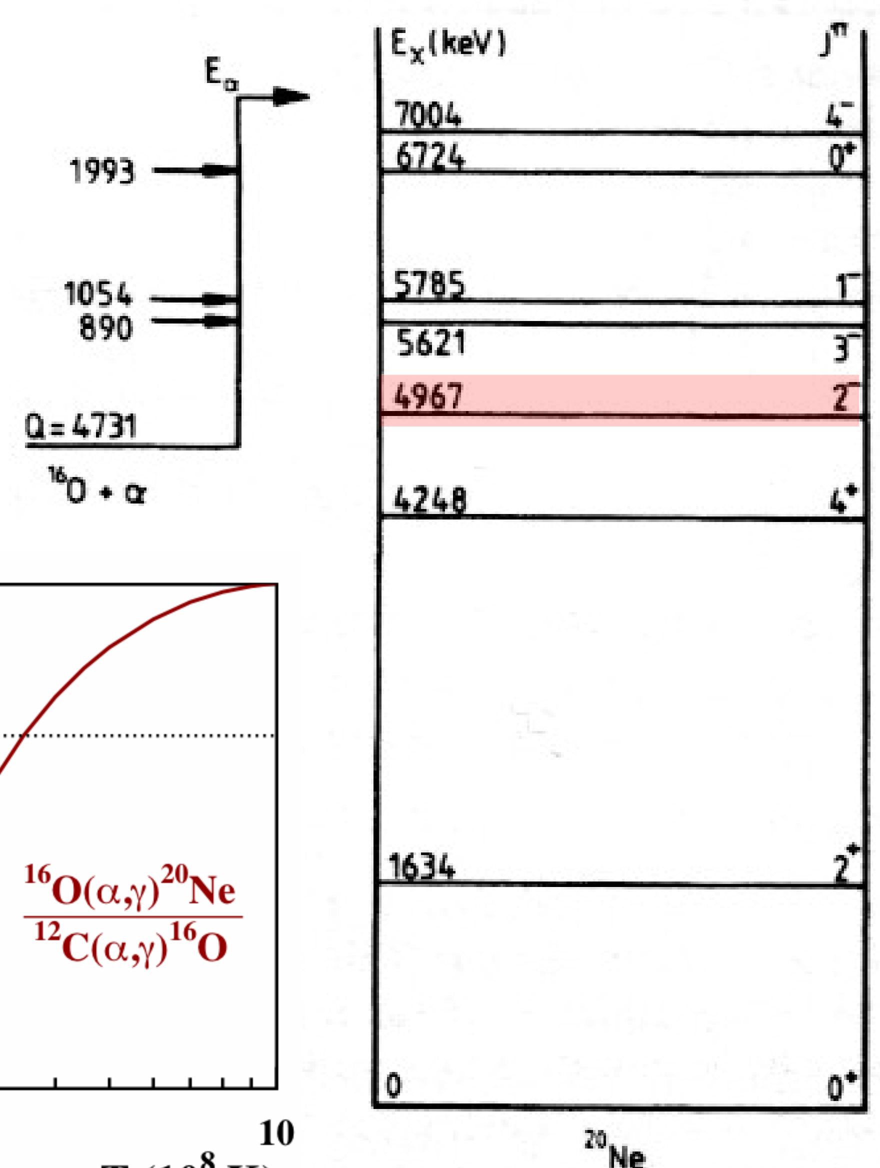
- The rate of this reaction determines the $^{12}C/^{16}O$ ratio at the end of the helium burning phase, and thus the subsequent burning stages in massive stars
- $^{12}C/^{16}O$ influences the nature of the remnant (neutron star? Black hole?) left after a core-collapse supernova
- A difficult case: contribution from a broad state, two sub-threshold resonances and the direct capture process.
- Cross-section at 300 keV

  → $\sigma \approx 10^{-17}$ b! (can't be measured, less than 1 event per year)



The $^{16}O(\alpha,\gamma)^{20}Ne$ reaction

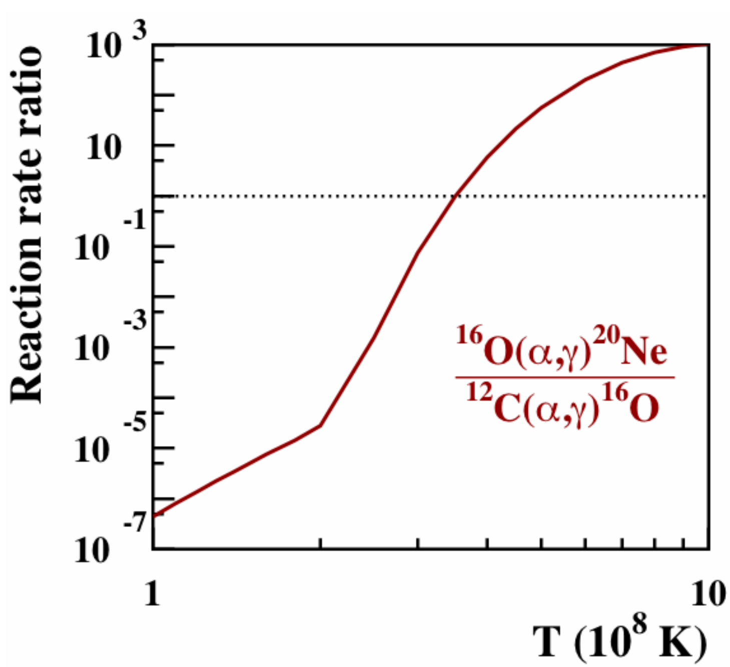
- Very slow reaction because no resonant state in the energy range of interest 5.0 MeV < $E_x(^{20}Ne)$ < 5.2 MeV (the $J^\pi = 2^-$ state at E_x = 4967 keV being of non-natural parity)



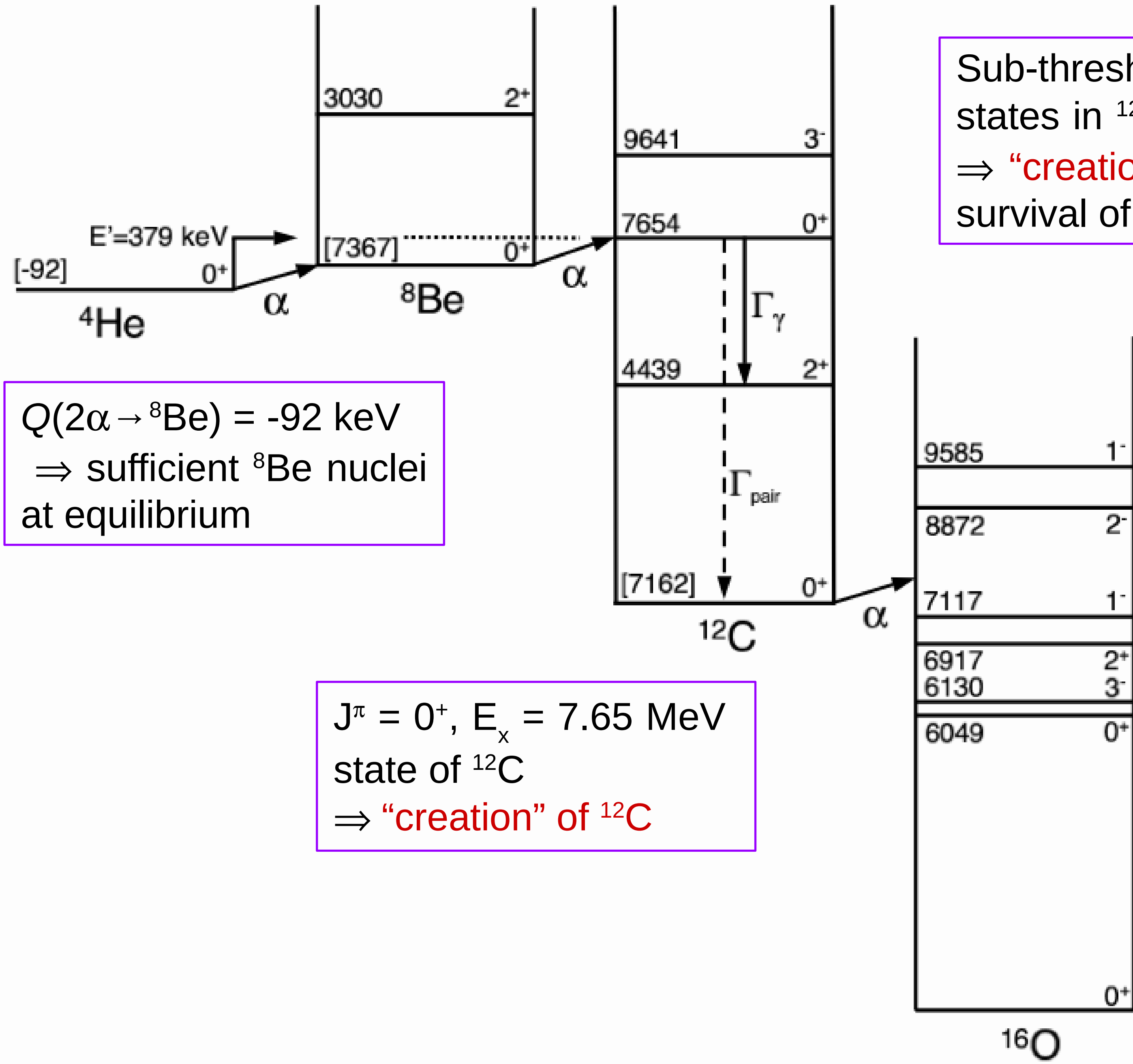
- Reaction rate << rate of $^{12}C(\alpha,\gamma)^{16}O$ for T < 0.3 GK

  ⇒ end of the helium burning phase in stellar cores

  ⇒ survival of ^{16}O



How insignificant we are!



Sub-threshold 1^- and 2^+ states in $^{12}C + \alpha \rightarrow {}^{16}O$
$\Rightarrow$ "creation" of ^{16}O but survival of ^{12}C

$Q(2\alpha \rightarrow {}^8Be) = -92$ keV
$\Rightarrow$ sufficient ^8Be nuclei at equilibrium

$J^\pi = 0^+$, $E_x = 7.65$ MeV state of ^{12}C
$\Rightarrow$ "creation" of ^{12}C

^{20}Ne state at 4.97 MeV of non-natural parity (2^-)
$\Rightarrow$ survival of ^{16}O

Other reactions

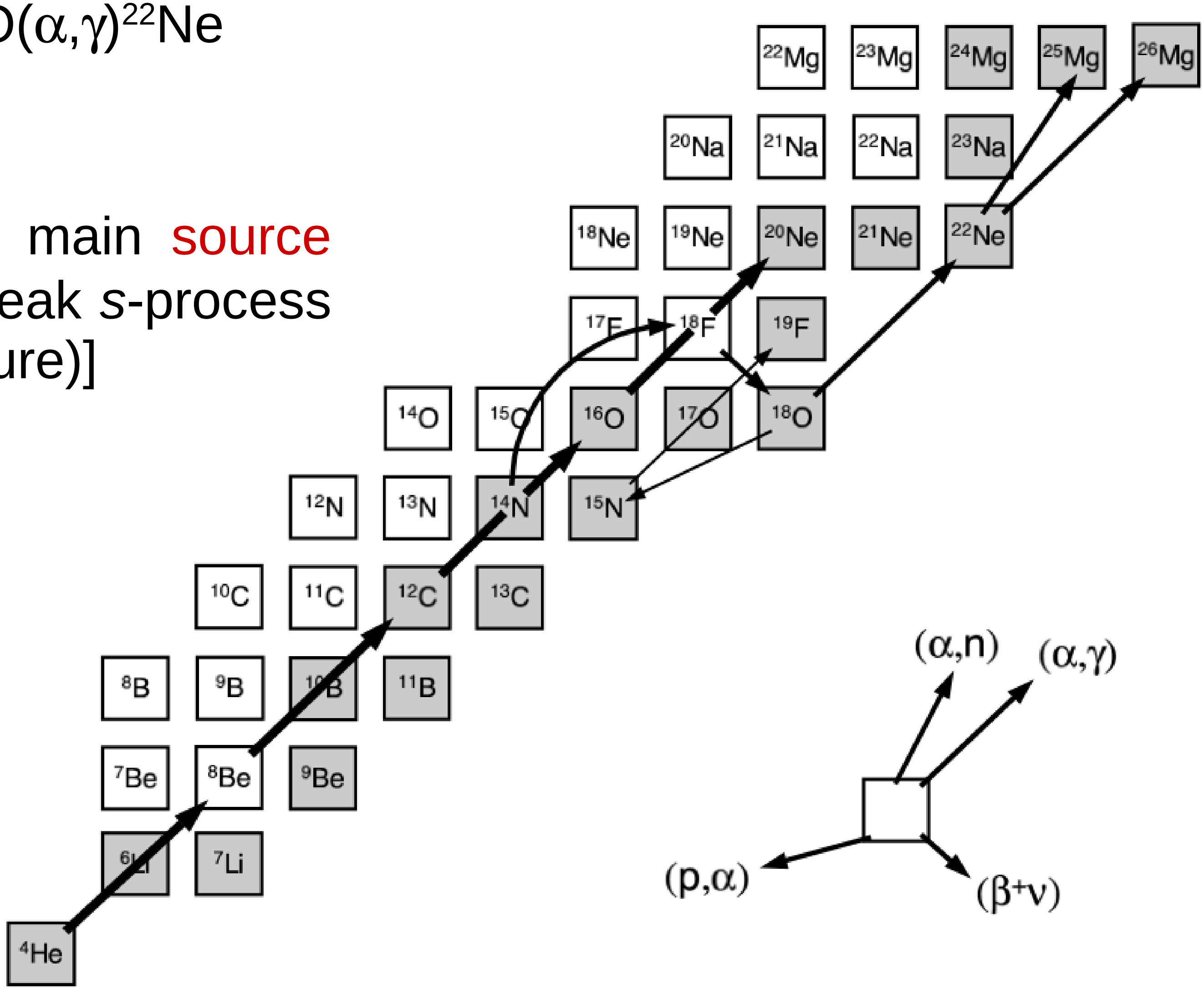
- ^{14}N is the main "ash" from the CNO cycle, and accounts for 1-2% of the mass of the fusion core at the end of H burning (pop I stars)

  → $^{14}\mathbf{N}(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$

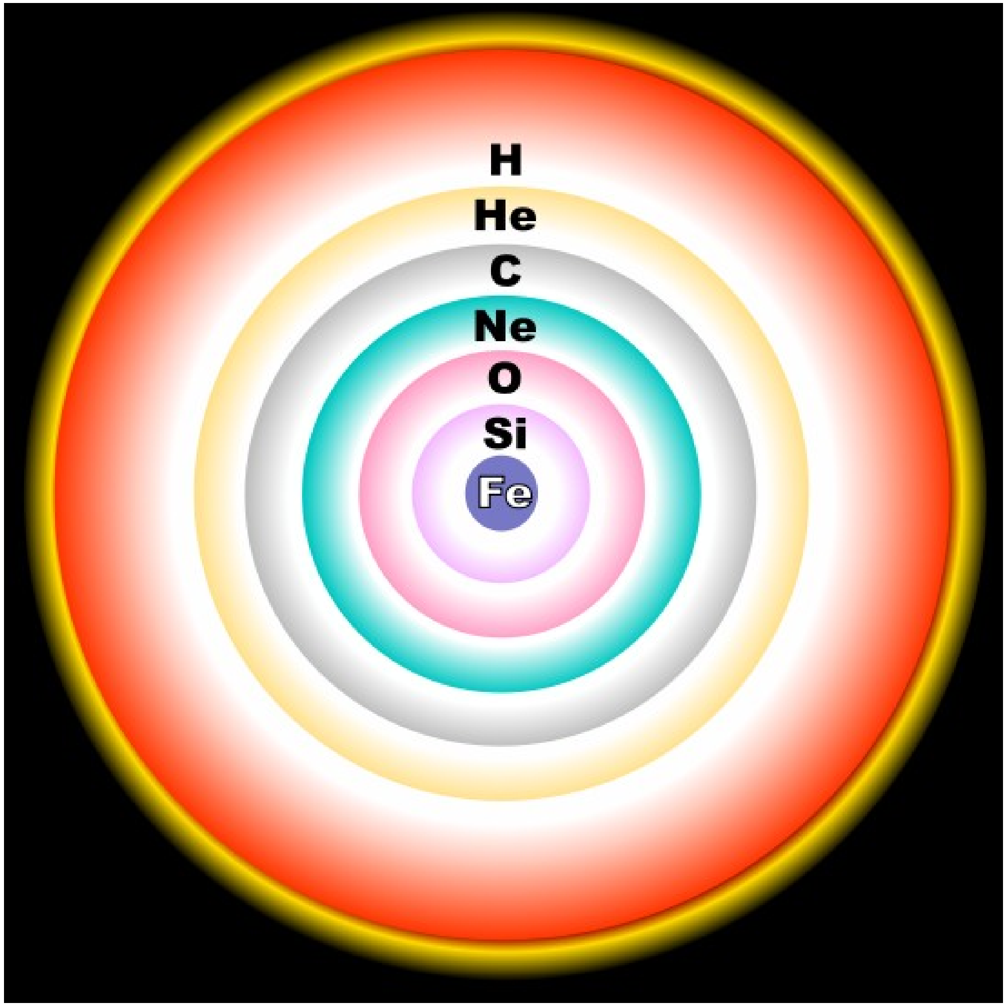
  followed by

  → $^{22}Ne(\alpha,\mathbf{n})^{25}Mg$ [= main source of neutrons of the weak *s*-process ("slow" neutron capture)]

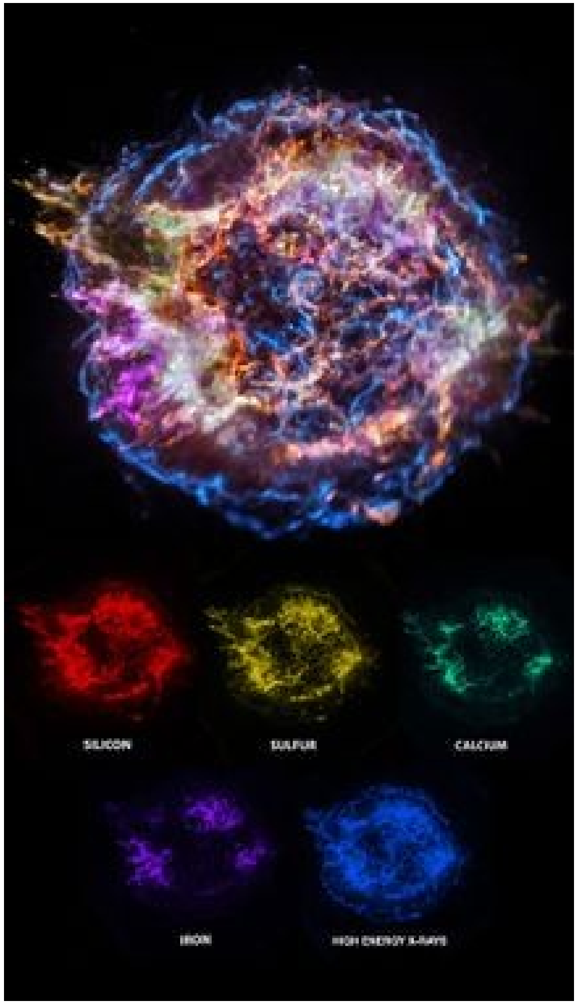
- Helium burning is the main source of ^{12}C, ^{16}O, ^{18}O and ^{22}Ne in the Universe



4.3 Advanced nuclear burning phases



Schematic diagram of the “onion-skin” structure of a pre-supernova



Chandra X-ray observatory image of the SN remnant Cassiopeia A

Carbon burning

- When?
  - He exhausted in the stellar core → mainly ^{12}C and ^{16}O ashes → gravitational contraction → increase of temperature
  - $T_c \sim (5 - 9) \times 10^8$ K and $\rho > 2 \times 10^5$ g cm^{-3} for $M \geq 8\ M_\odot$

- Major reaction sequences

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha \qquad (Q = 4.62\ \text{MeV})$$ dominates by far

$$\rightarrow {}^{23}Na + p \qquad (Q = 2.24\ \text{MeV})$$

$$\rightarrow {}^{23}Mg + n \qquad (Q = -2.62\ \text{MeV})$$

+ several seconday reactions..

- Composition at the end of core carbon burning
  - Mainly ^{20}Ne with some $^{21,22}Ne$, ^{23}Na, $^{24,25,26}Mg$ and $^{26,27}Al$
  - ^{16}O not burning yet…. → amount comparable with ^{20}Ne

Neon burning

- When?
  - After carbon burning → mainly ^{20}Ne ashes → the core further contracts → increase of temperature
  - $T_c \sim (1-2) \times 10^9$ K and $\rho \sim 10^6$ g cm^{-3} for $M \geq 11\ M_\odot$

- Major reaction sequences

  Temperatures are high enough to initiate photodisintegration processes

  $$\gamma + {}^{20}\text{Ne} \rightarrow {}^{16}\text{O} + \alpha \qquad (Q = -4.73\ \text{MeV})$$

  $${}^{16}\text{O} + \alpha \rightarrow {}^{20}\text{Ne} + \gamma$$

  } Equilibrium establishes

  followed by e.g. the ^{20}Ne$(\alpha,\gamma)^{24}$Mg$(\alpha,\gamma)^{28}$Si sequence

- Composition at the end of core neon burning
  - Mainly ^{16}O with some ^{24}Mg and ^{28}Si

Oxygen burning

- When?
  - After neon burning the core further contracts
  - $T_c \sim (2 - 3) \times 10^9$ K and $\rho \sim 3\ 10^6$ g cm^{-3} for M ≥ 11 $M_\odot$

- Major reaction sequences

$$^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow ^{31}S + n \qquad (Q = 1.45 \text{ MeV})$$
$$\rightarrow ^{31}P + p \qquad (Q = 7.68 \text{ MeV})$$
$$\rightarrow ^{30}P + d \qquad (Q = -2.41 \text{ MeV})$$
$$\rightarrow ^{28}Si + \alpha \qquad (Q = -2.41 \text{ MeV})$$

+ recapture of n, p, d and α-particles

- Composition at the end of oxygen burning
  - The most abundant nuclides are ^{28}Si and ^{32}S

Silicon burning

- When?
  - After oxygen burning the core further contracts and the temperature incresases
  - $T_c \sim (2.8 – 4.1) \times 10^9$ K and $\rho \sim 3\ 10^7$ g cm^{-3} for M ≥ 11 $M_\odot$

- Photodisintegration
  - Starts with ^{28}Si: ^{28}Si(γ,α)^{24}Mg(γ,α)^{20}Ne(γ,α)…
  - Photodisintegration rearrangement: destruction of less tightly bound species and capture of released n, p, α-particles to synthesize more tightly bound species

- Nuclear Statistical Equilibrium (NSE) is achieved for many reactions
  - NSE = both photodisintegration and capture rates are fast

$$\gamma + (Z,N) \rightleftharpoons p + (Z-1,N) \qquad \gamma + (Z,N) \rightleftharpoons n + (Z,N-1) \qquad \gamma + (Z,N) \rightleftharpoons \alpha + (Z-2,N-2)$$

  - Equilibrium drives towards A = 56 → most stable nuclide (higher binding energy)

- Synthesis of nuclei from Si to Zn (“iron peak” elements Ti to Zn)
- Composition at the end of silicon burning: ^{56}Fe → formation of an iron core

Summary

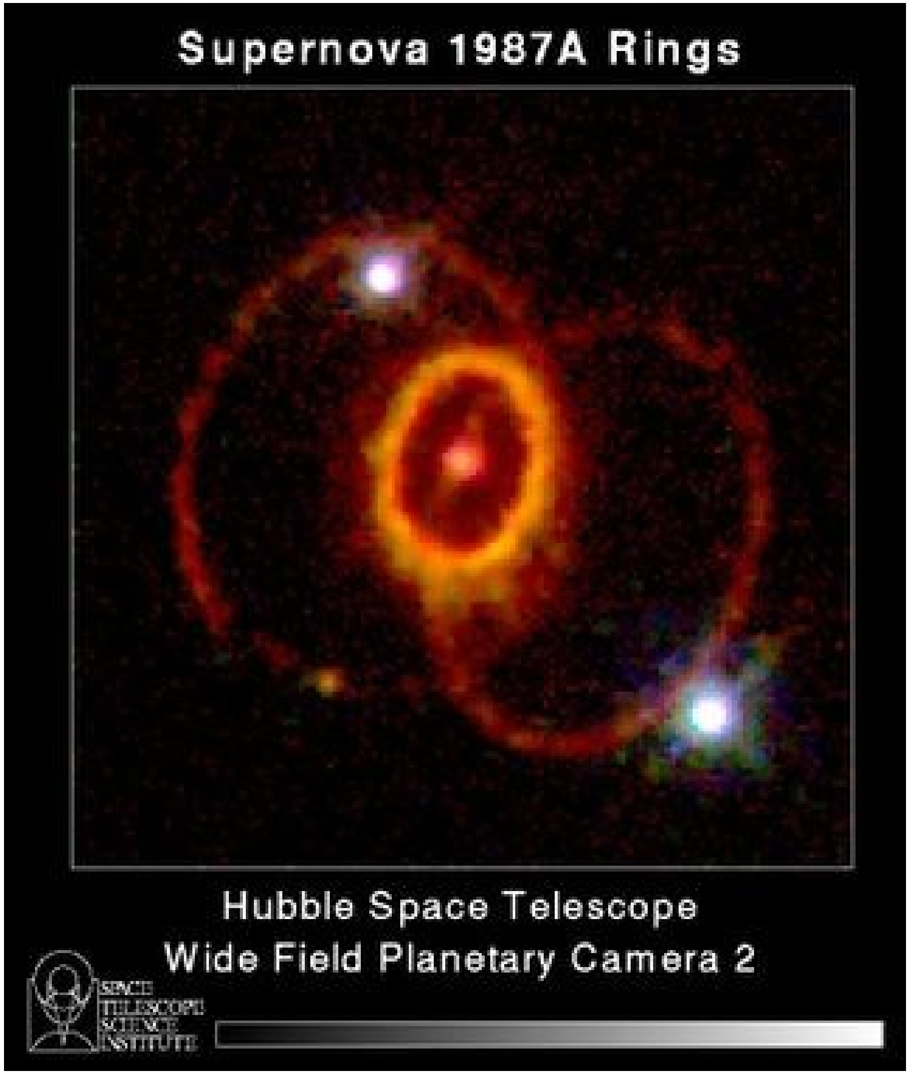
Stellar mass ($M_\odot$)	Stage reached
< 0.08	no thermonuclear fusion
0.1 -0.5	H burning
0.5 - 8	He burning
8 - 11	C burning
> 11	all stages

Evolution stages of a 25 $M_\odot$ star

Stage reached	Timescale	T_{core} (10^9 K)	Density (g cm^{-3})
H burning	7×10^6 y	0.06	5
He burning	5×10^5 y	0.23	7×10^2
C/O burning	600 y / 6 months	0.93 – 2.3	2×10^5 – 1×10^7
Si melting	1 d	4.1	3×10^7
Explosive burning	0.1 – 1 s	1.2 - 7	varies

4.4 Explosive nucleosynthesis

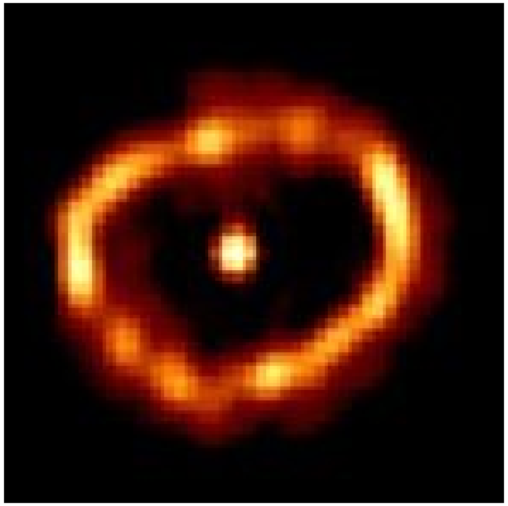
Massive stars



Binary systems

Type Ia supernova

G299 (Chandra X-ray observatory)

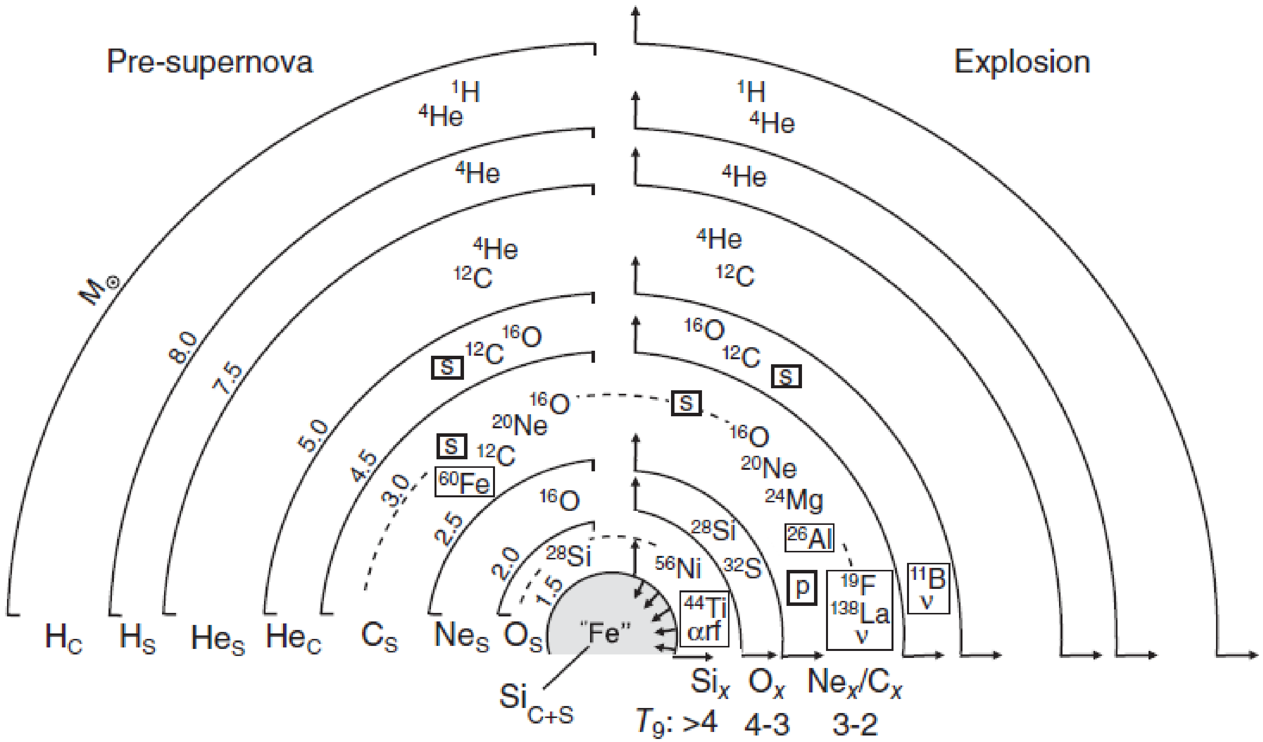


Classical nova

Nova Cygni 1992 (HST)

Core collapse supernova (1)

"Onion shell" structure of massive stars



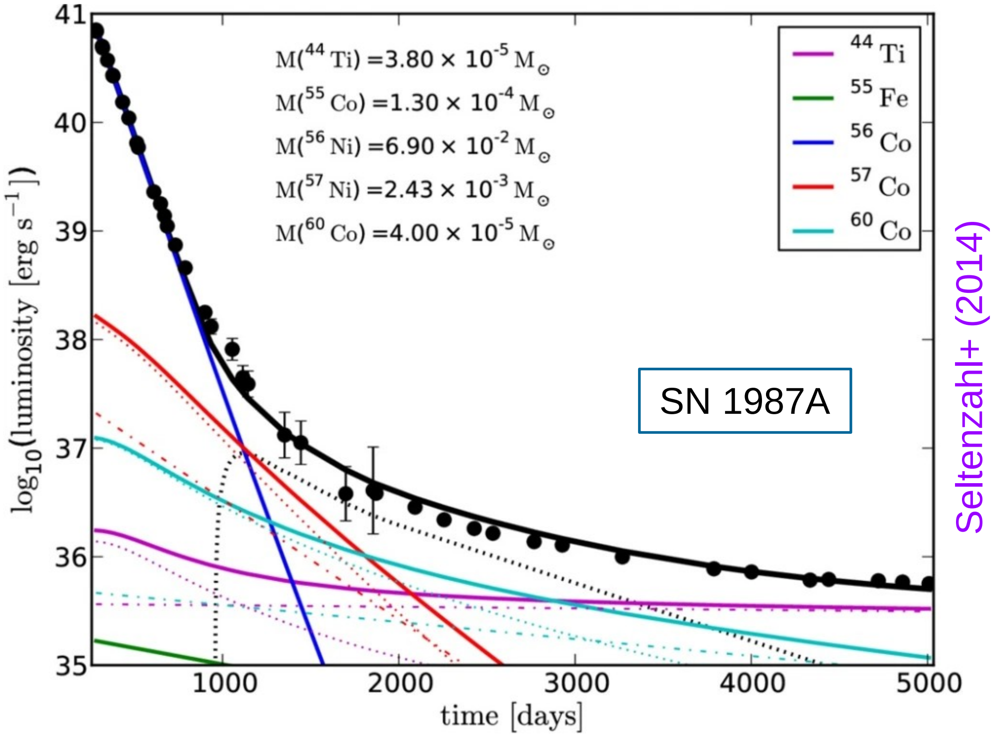
Explosion:

- Core in NSE, grows in mass until ~ 1.4 $M_\odot$, electron degeneracy pressure unable to counteract gravity...
- Collapse starts, enhanced by photodisintegration (e.g. $\gamma + {}^{56}Fe \rightarrow 13\ {}^4He + 4n$) and electron capture ($e^- + (Z,N) \rightarrow \nu_e + (Z-1,N+1)$)
- When $\rho \sim 10^{14}$ g/cm^3 nuclei feel short-range nuclear force → inner part of core rebounds → outward moving shock

Explosive nucleosynthesis: induced by neutrinos and outward moving shock (mainly in Si, O and Ne/C layers)

Core collapse supernova (2)

Light curve powered by radioactive decay



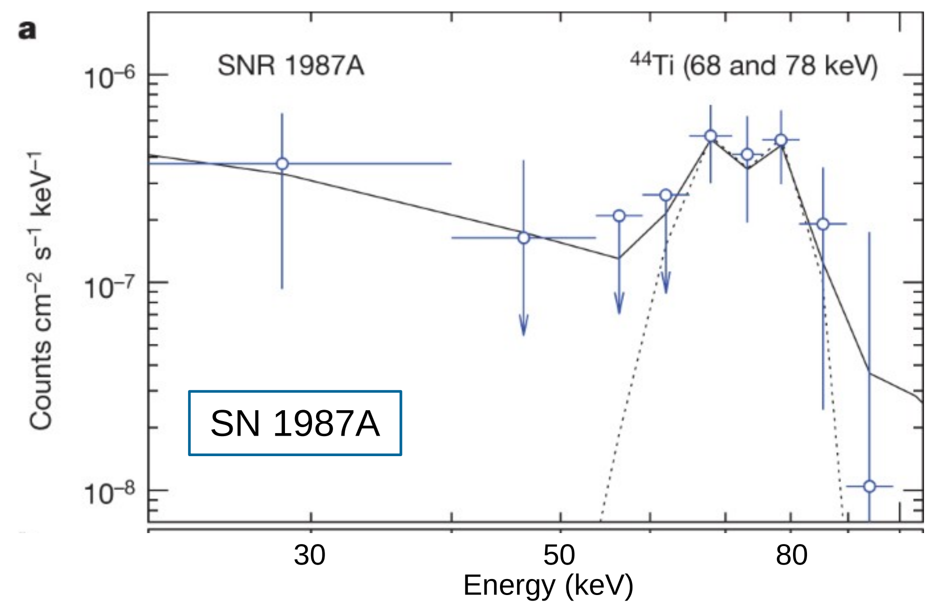
^{56}Ni → ^{56}Co → ^{56}Fe (stable)

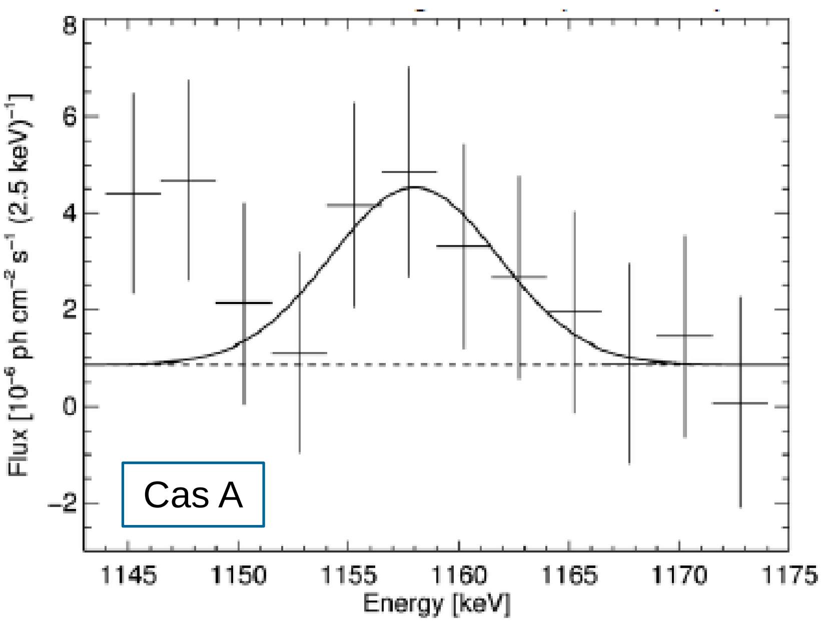
($T_{1/2}$ = 6.1 d) ($T_{1/2}$ = 77.3 d)

^{44}Ti → ^{44}Sc → ^{44}Ca (stable)

($T_{1/2}$ = 60 yr) ($T_{1/2}$ = 3.97 h)

^{44}Ti observations from SN remants

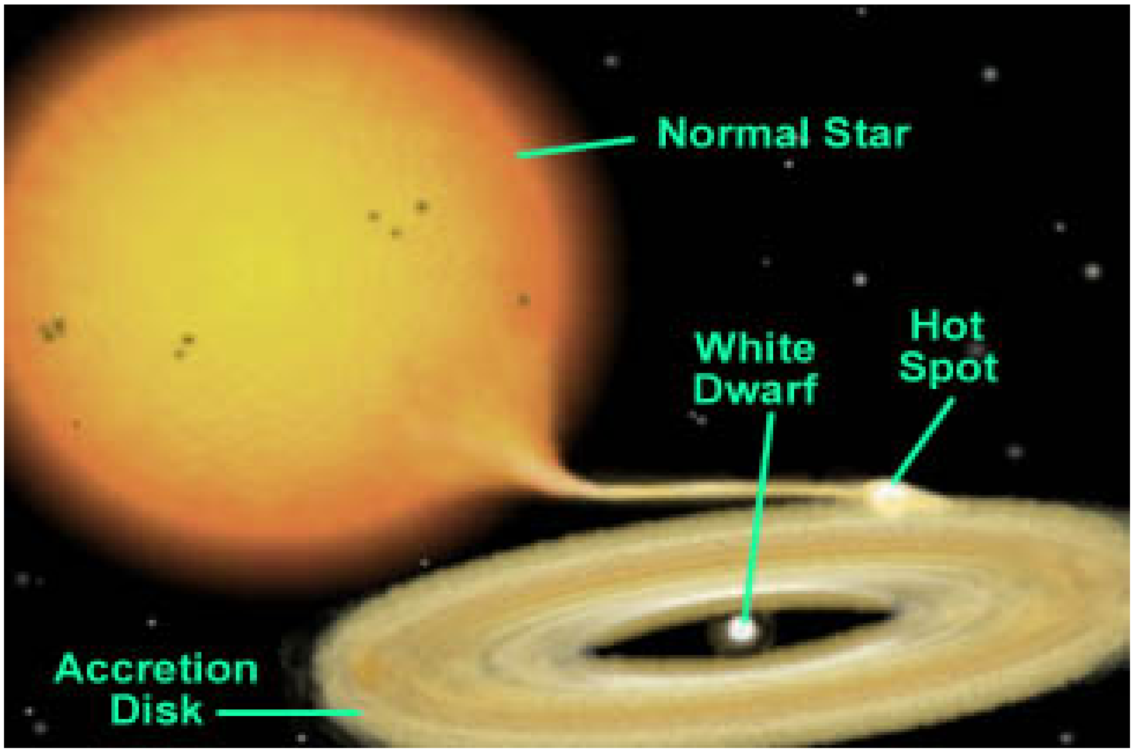




Classical novae (1)

Sudden increase in star's luminosity (L ~ 10^4 – 10^6 L_i, and t ~ 1h – 1d)

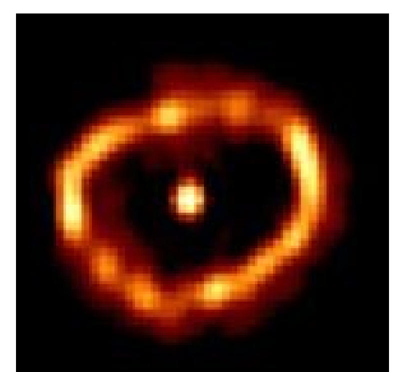
Final evolution of a close binary system



- H-rich material transfer from normal star to white dwarf (WD)
- T and ρ increase at surface of WD
- Start and thermonuclear runaway (T ≈ 50 – 300 MK)

  → cataclysmic explosion
- Ejection of part of the accreted material

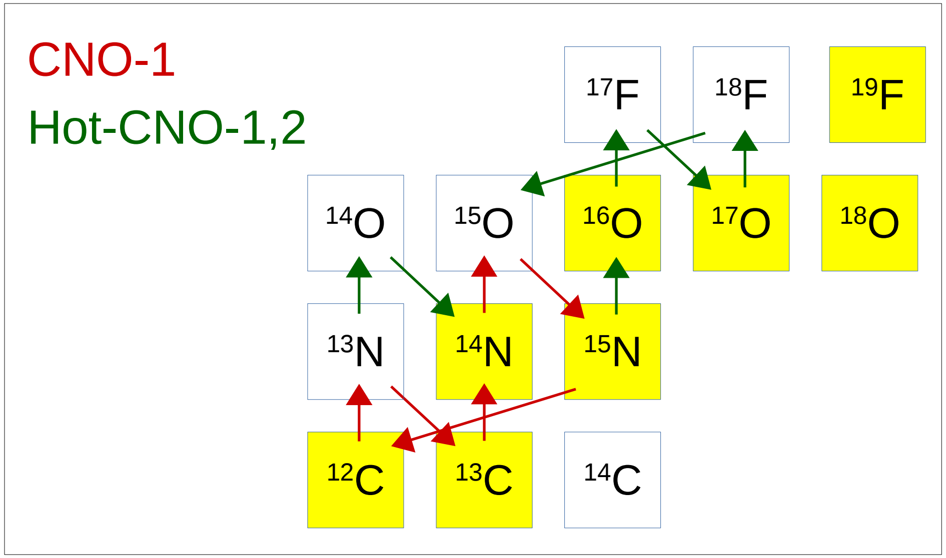
	novae	ccSN
M_{ej} ($M_{\odot}$)	~ 10^{-5}	~ 10
f (yr^{-1} $galaxy^{-1}$)	~ 30	~ 10^{-2}
L ($L_{\odot}$)	~ 10^5	~ 10^{11}
Nucleosynthesis	^{13}C, ^{15}N, ^{17}O	~ all



Classical novae (2)

Shell ejection

The energy release from the β+-decays (^{13}N, ^{14}O, ^{15}O, ^{17}F) throughout the envelope helps to eject the material from the WD



$T_{1/2}(^{13}N)$ = 9.965 min
$T_{1/2}(^{15}O)$ = 122.24 s
$T_{1/2}(^{17}F)$ = 64.49 s
$T_{1/2}(^{18}F)$ = 109.77 min

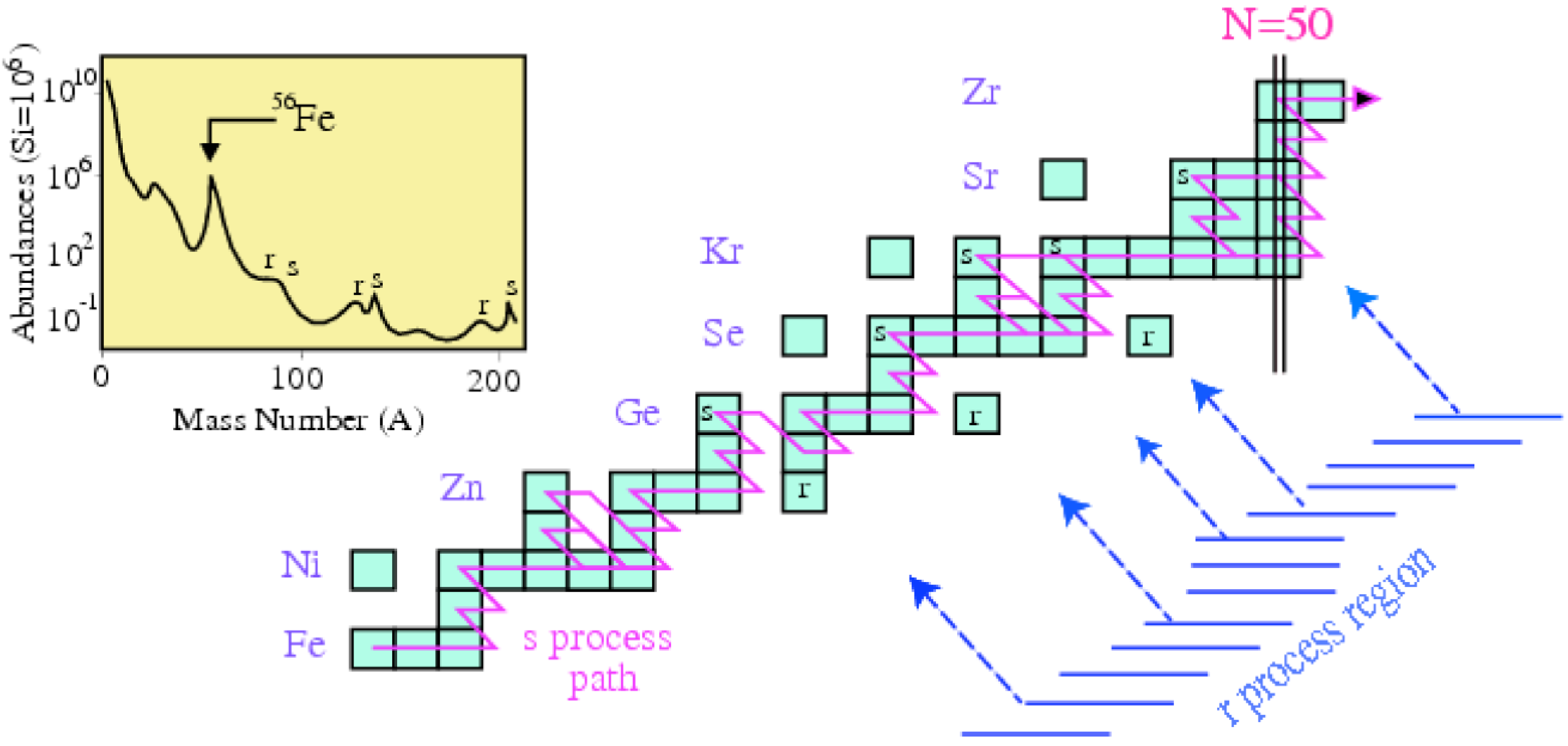
End-point of nucleosynthesis: A ~ 40 (Ca)

- T_{peak} ~ 300 – 400 MK
- (p,γ) reactions on the proton-rich side
- Coulomb barrier too high to overcome for $A \geq 40$

Nucleosynthesis of γ-ray emitters

- ^{18}F ($T_{1/2}$=110 min); 511 keV
- ^{22}Na ($T_{1/2}$=2.6 yr); 1275 keV
- ^{26}Al ($T_{1/2}$=0.7 Myr); 1809 keV

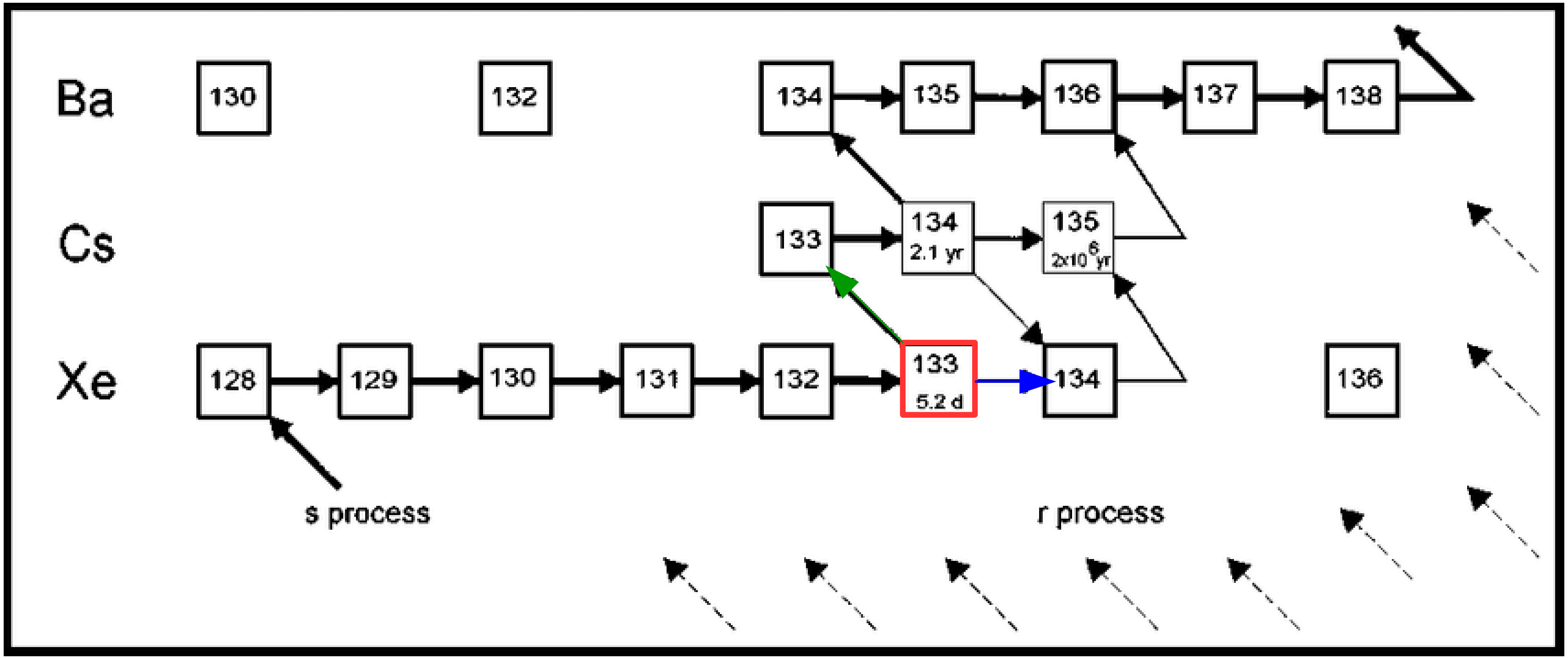
4.5 Nucleosynthesis beyond iron



Elements heavier than iron can't be synthesized by fusion reactions

Neutron capture reactions

- Radiative neutron captures [(n,γ) reactions] in competition with β⁻ decay
- Processus starts with Fe seeds

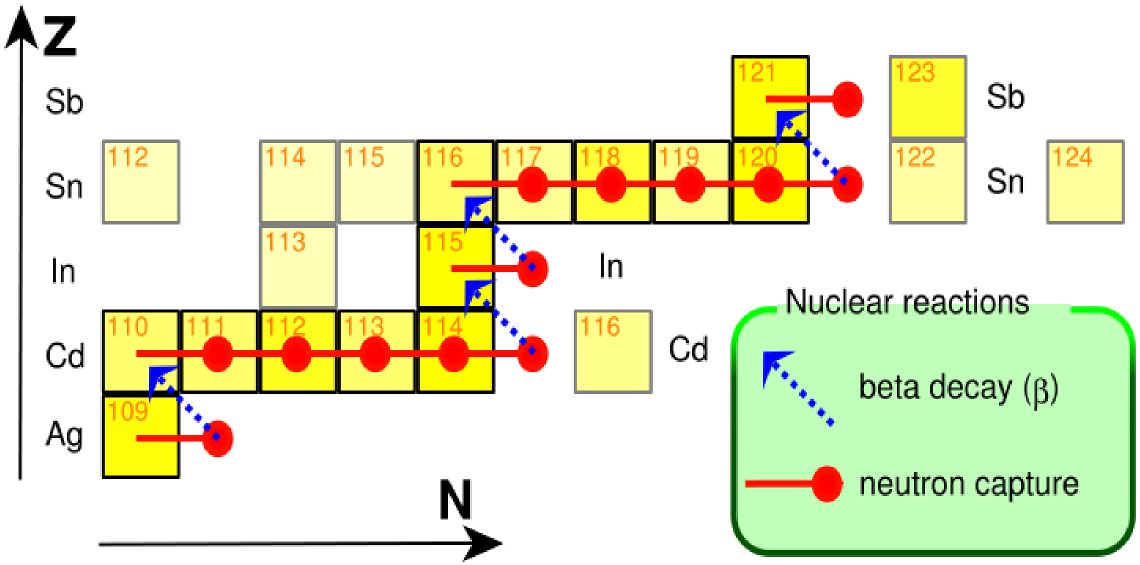


- Mean lifetime for neutron capture $\tau_n = \frac{1}{N_n \langle \sigma v \rangle}$ to be compared to β^-–decay lifetime τ_β (from seconds to years)
- If $\tau_n > \tau_\beta$ → unstable nuclide decays
  if $\tau_n < \tau_\beta$ → neutron capture

s-process: "slow"
r-process: "rapid"

s-process

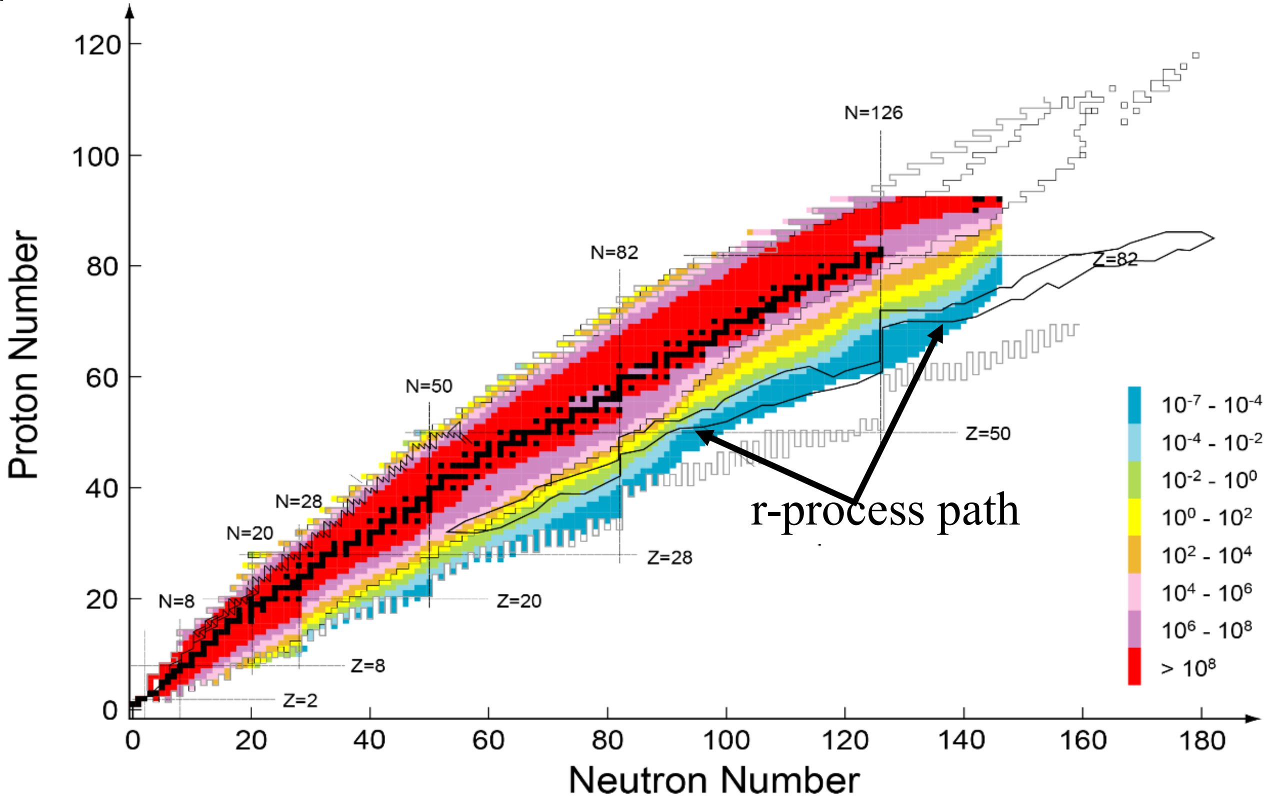
- Slow neutron capture process
  - Unstable nucleus decays before capturing another neutron
  - $\tau_n >> \tau_\beta \quad \Leftrightarrow \quad N_n \sim 10^8$ n/cm^3



- Nucleosynthesis: path along the valley of β^- stability up to ^{209}Bi (long time scale ~ 10^4 yr)
- Neutron source: ^{13}C(α,n)^{16}O and/or ^{22}Ne(α,n)^{25}Mg
- Quiescent scenarios:
  - AGB stars; main *s*-process; "Ba/Pb" peaks
  - Massive stars; weak *s*-process; "Sr-Y" peak

r-process

- Rapid neutron capture process
  - Unstable nucleus captures neutron before decaying
  - $\tau_n << \tau_\beta \quad \Leftrightarrow \quad N_n >> 10^{22}$ n/cm^3



- Nucleosynthesis: path far from the valley of β^- stability (short time scale ~ seconds)
- Explosive scenarios: but where?

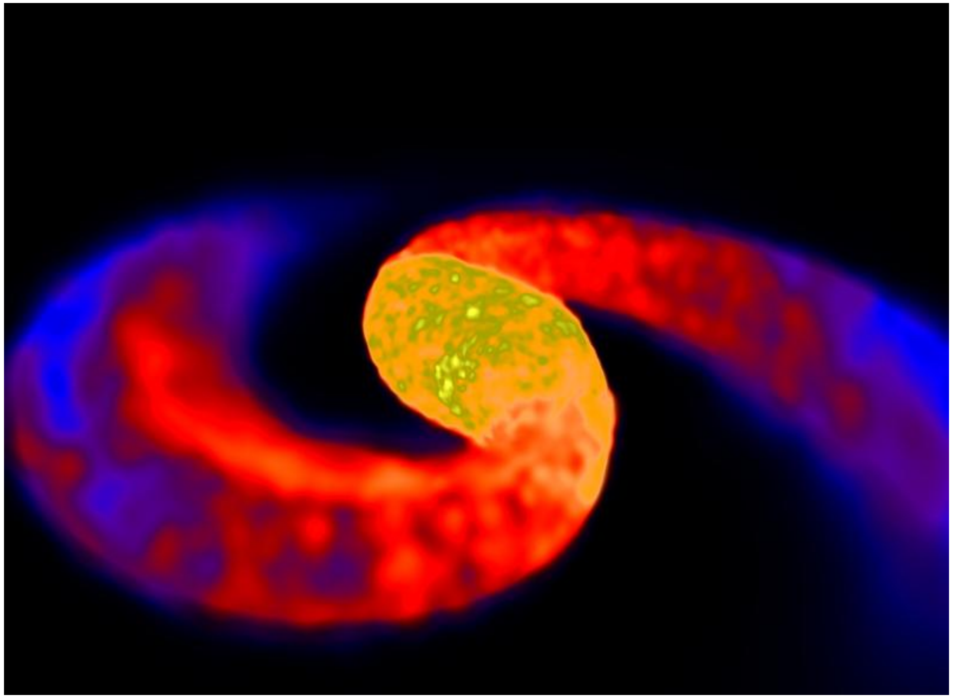
Astrophysical site for *r*-process?

Core-collapse Supernovae?

Supernova SN1987A

- Dynamical ejecta of prompt explosions (of O-Ne-Mg cores)
- Neutrino-driven wind from proto-neutron stars
- ...

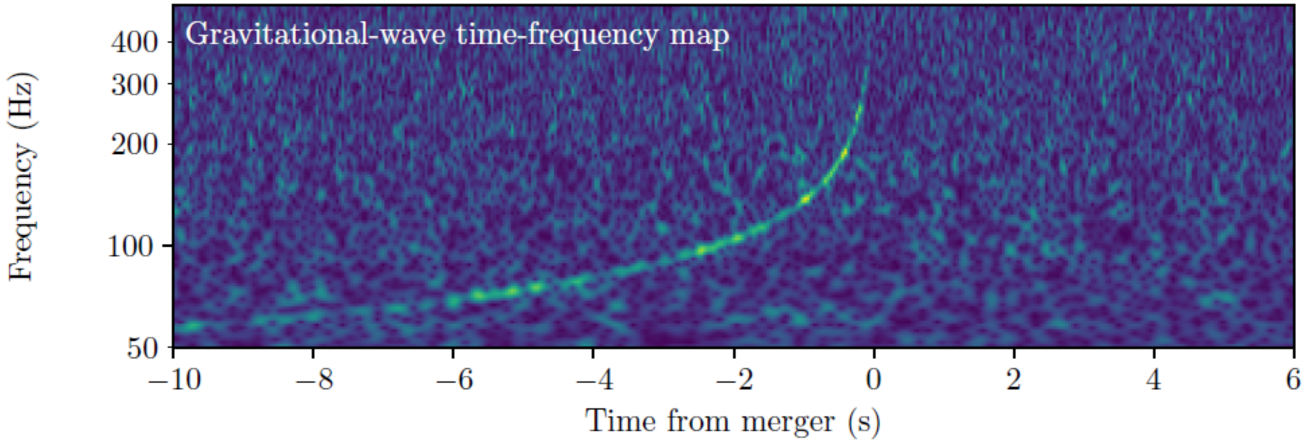
Neutron star merger?



- Mergers are expected to eject ~ 0.01 $M_\odot$ of very neutron-rich material
- Sources of gravitational waves
- Electromagnetic emission from radioactive decay of *r*-process nuclei → **kilonova**

Neutron star merger GW170817

- Gravitational waves from neutron star merger detected by LIGO/VIRGO



Two neutron stars of 0.86 $M_\odot$ and 2.26 $M_\odot$

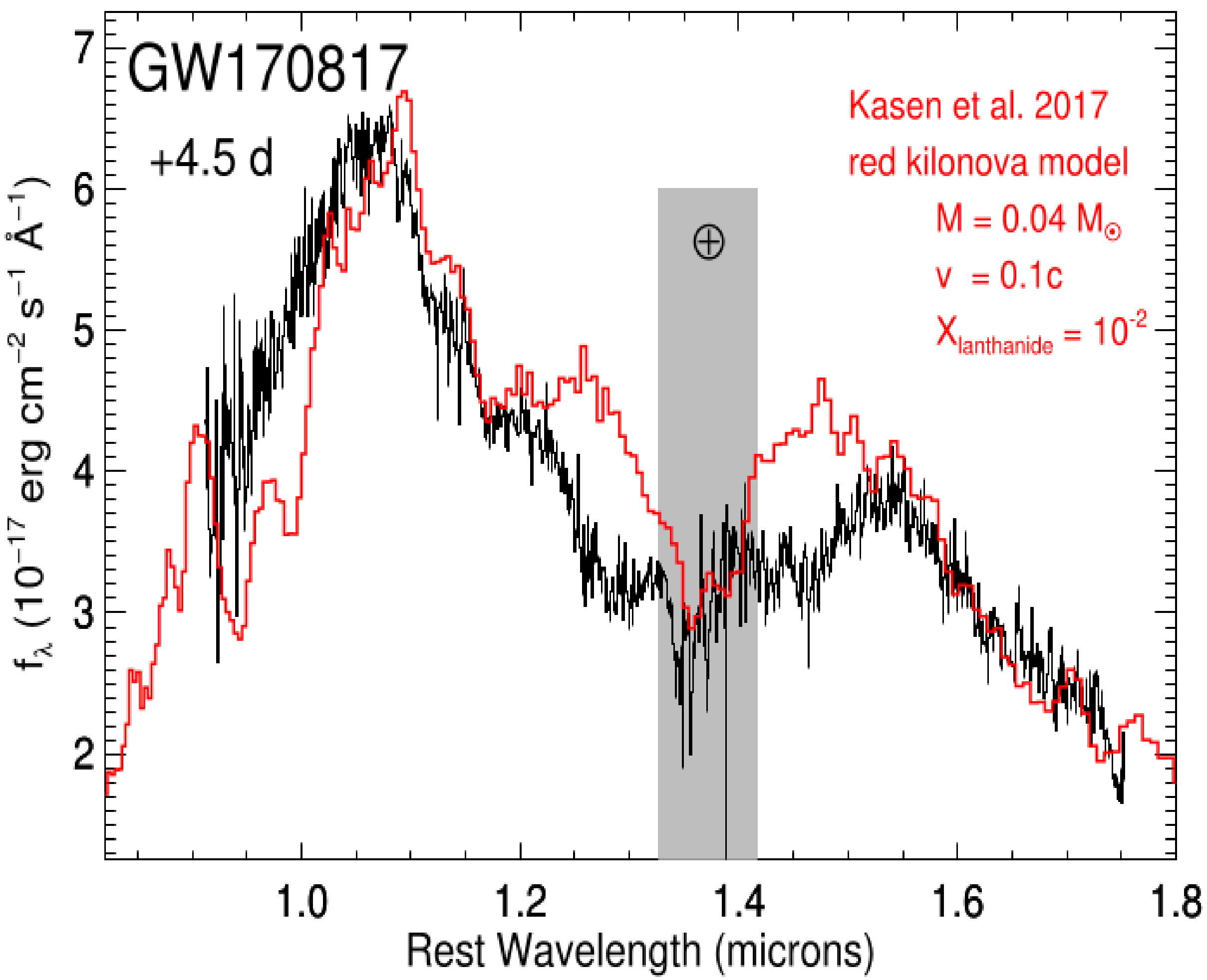
- Optical transient source counterpart SSS17a (Swope Supernova Survey)

Counterpart in galaxy NGC4993 at ~ 40 Mpc

- First day
  → blue and bright
- Four days later
  → red and fainter

Near-infrared emission

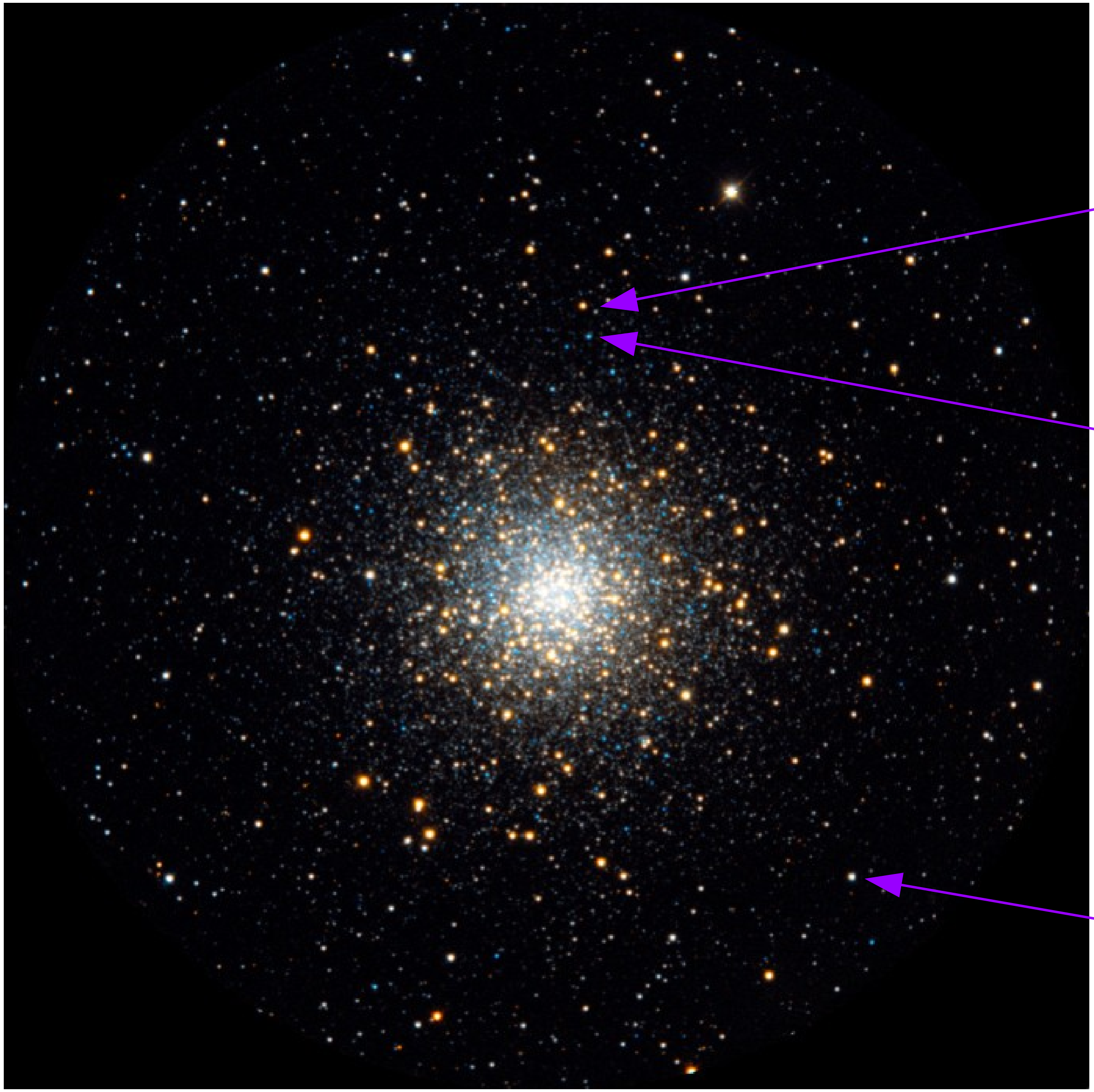
Comparison of the measured near-infrared spectrum counterpart of the binary neutron star merger GW170817 with a "red" kilonova model



- The two bumps in the near infrared spectrum is a signature of very heavy elements
- Effect of opacity induced by lanthanide elements
- Lanthanides (~ 1%)

  → ***r*-process**

5. Back to the HR diagram



Globular cluster M10

Red giant star:
H → He shell burning via the CNO cycle

Horizontal branch star:
He → C, O core burning + H → He shell burning

Main sequence star:
H → He core burning via the pp chains

Red giant stars (1)

- Stars of mass 0.5 – 10 $M_\odot$ (if $M \geq 10\ M_\odot$ → red supergiants)
- Inert He core (no energy source) surrounded by a H burning shell

- From the Virial theorem

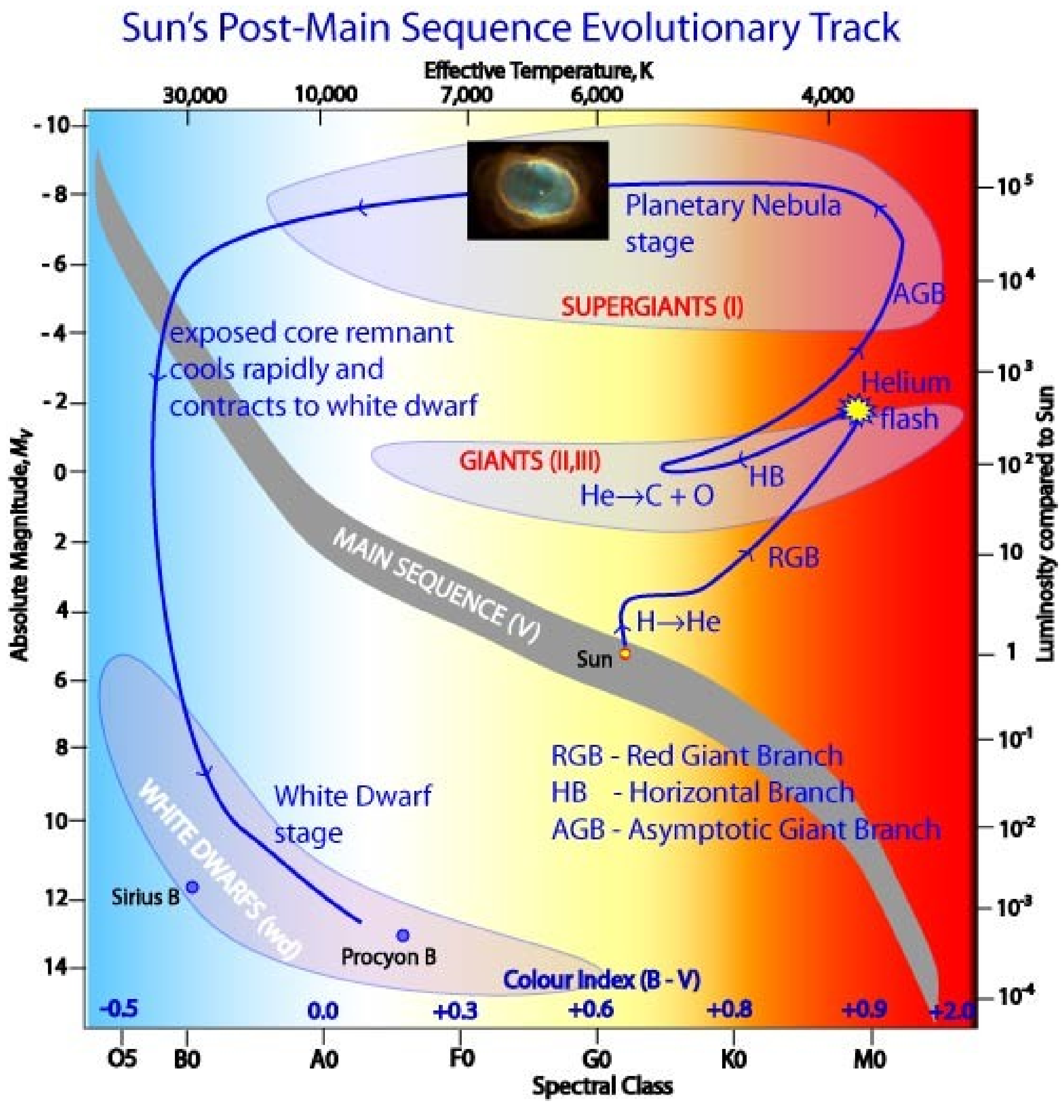
$$E = K + \Omega = \Omega/2 = -K$$

If E ~ cst, Ω and K also

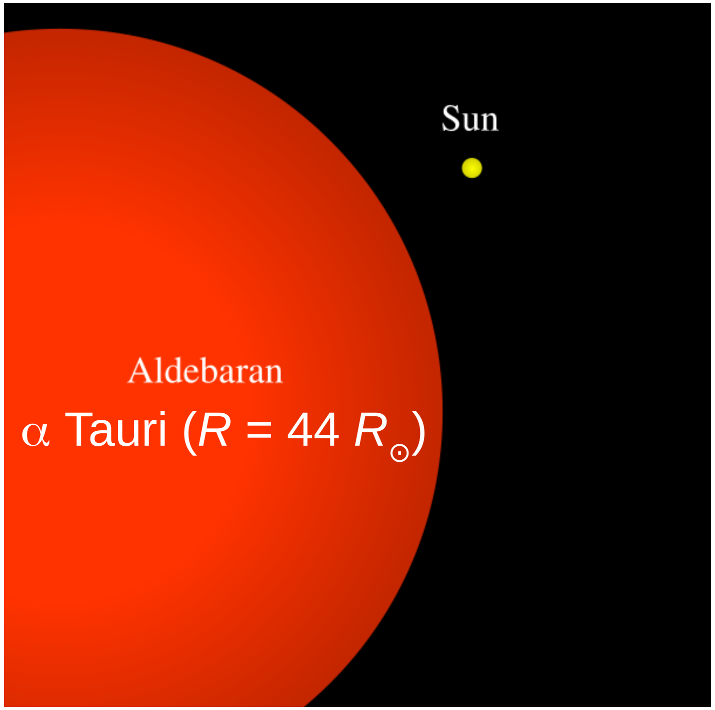
→ contraction of the core must be accompagnied by expansion of the envelope (Ω ~ cte) up to 50 $R_\odot$ (~ Mercury)

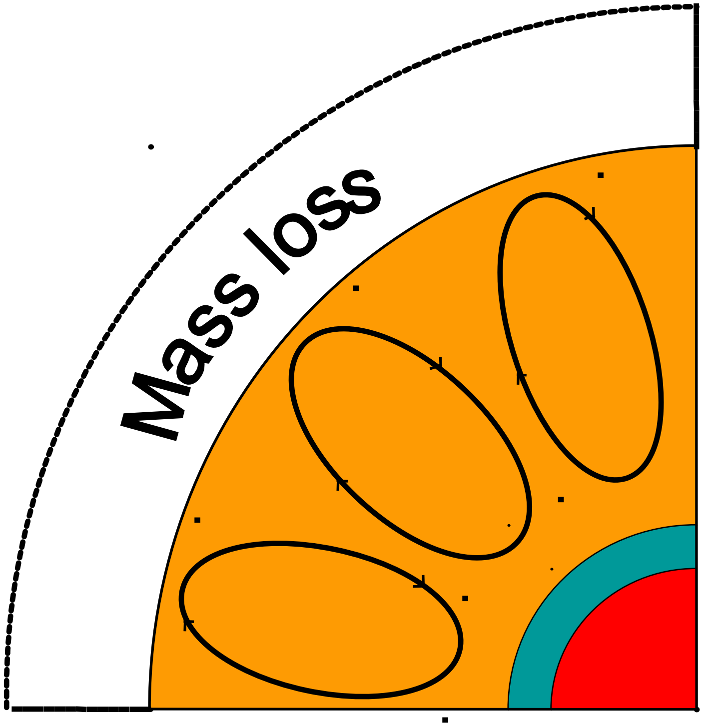
→ core heating must result in cooling of the envelope (K ~ cte) → T_{eff} decreases

$\rightarrow L = 4\pi R^2 \sigma_s T_{eff}^4$ increases



Red giant stars (2)





- Decrease of T_{eff} → recombination in stellar atmosphere → increase of opacity → radiative transport less efficient → convection settles in envelope
- Ashes of H-shell burning – ^{13}C, ^{14}N – are transported to the surface
  → first "dredge-up"
  → high $^{13}C/^{12}C$ and $^{14}N/^{12}C$ isotopic ratios observed in absorption spectra of red giant stars

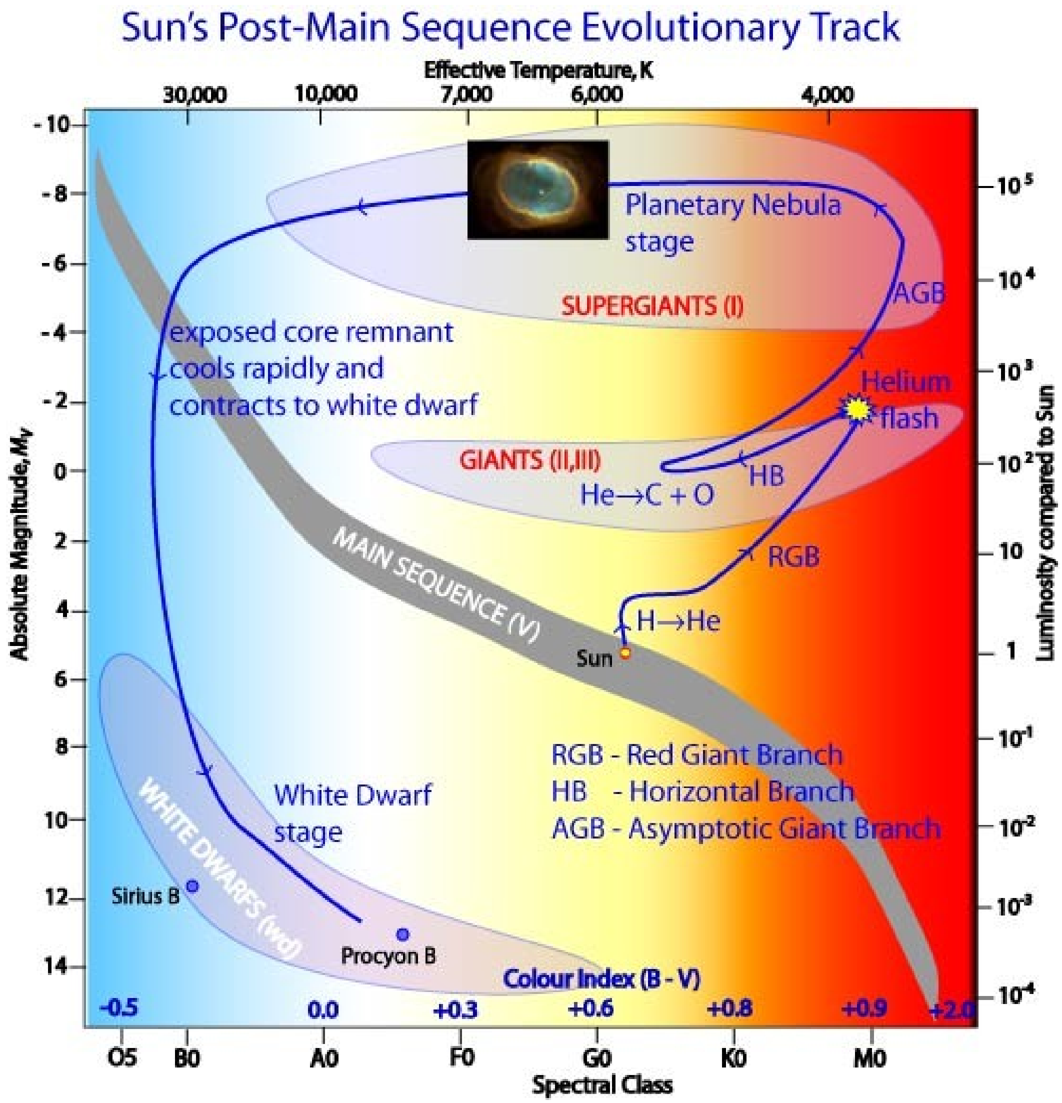
Stars of the horizontal branch (1)

Ignition of the He core at T_c ~ 100 MK → core contraction stops

- In low-mass stars (0.7 – 2 $M_\odot$) the electron gas in the core is partially degenerated → helium flash

  → release during a few seconds of 10^{10} $L_\odot$ in L_{nuc}! but invisible from the surface

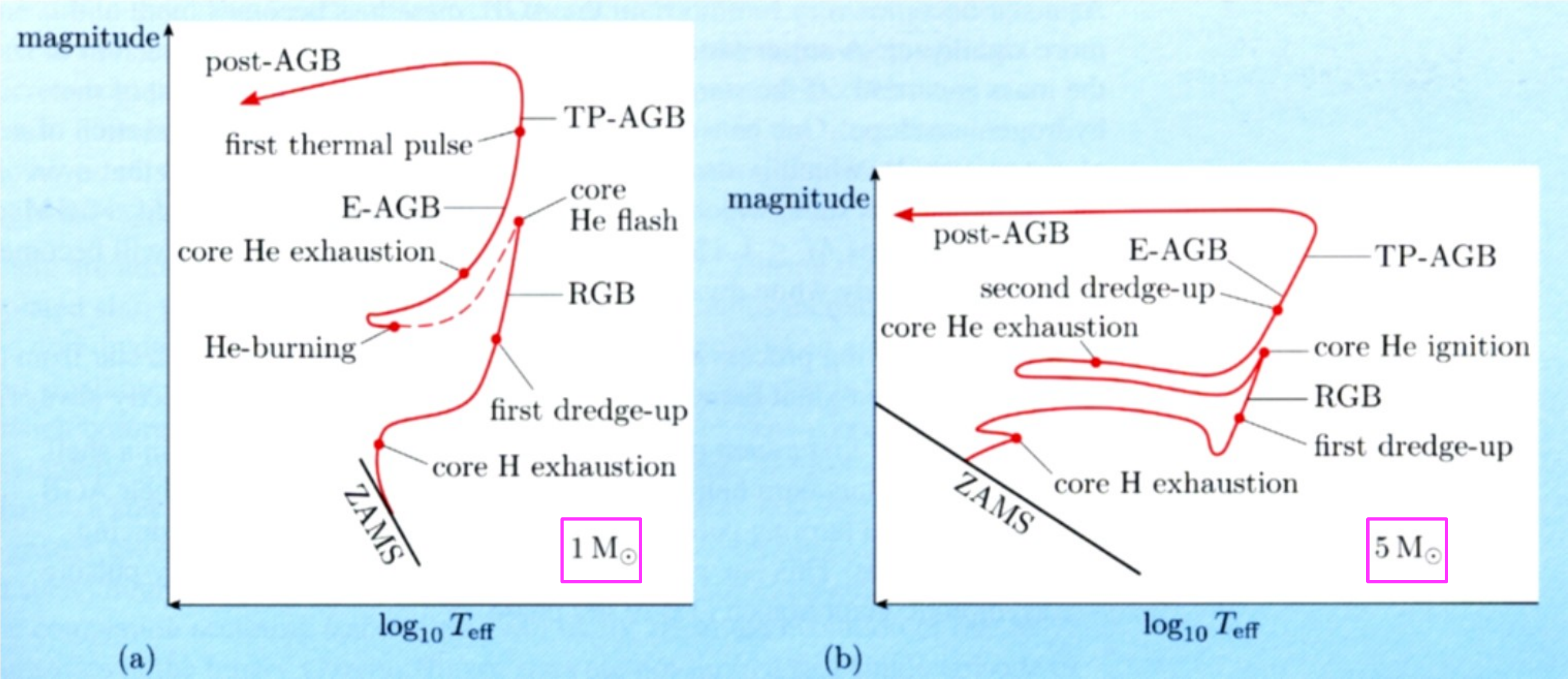
  → expansion and cooling of the core result in the contraction and heating of the envelope



Stars of the horizontal branch (2)

Ignition of the He core at T_c ~ 100 MK → core contraction stops

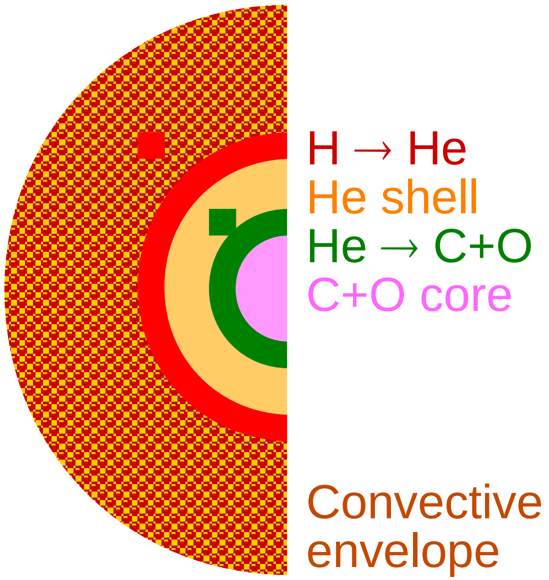
- Quiet ignition of the He core (convective) for intermediate-mass stars (2 – 10 $M_\odot$)



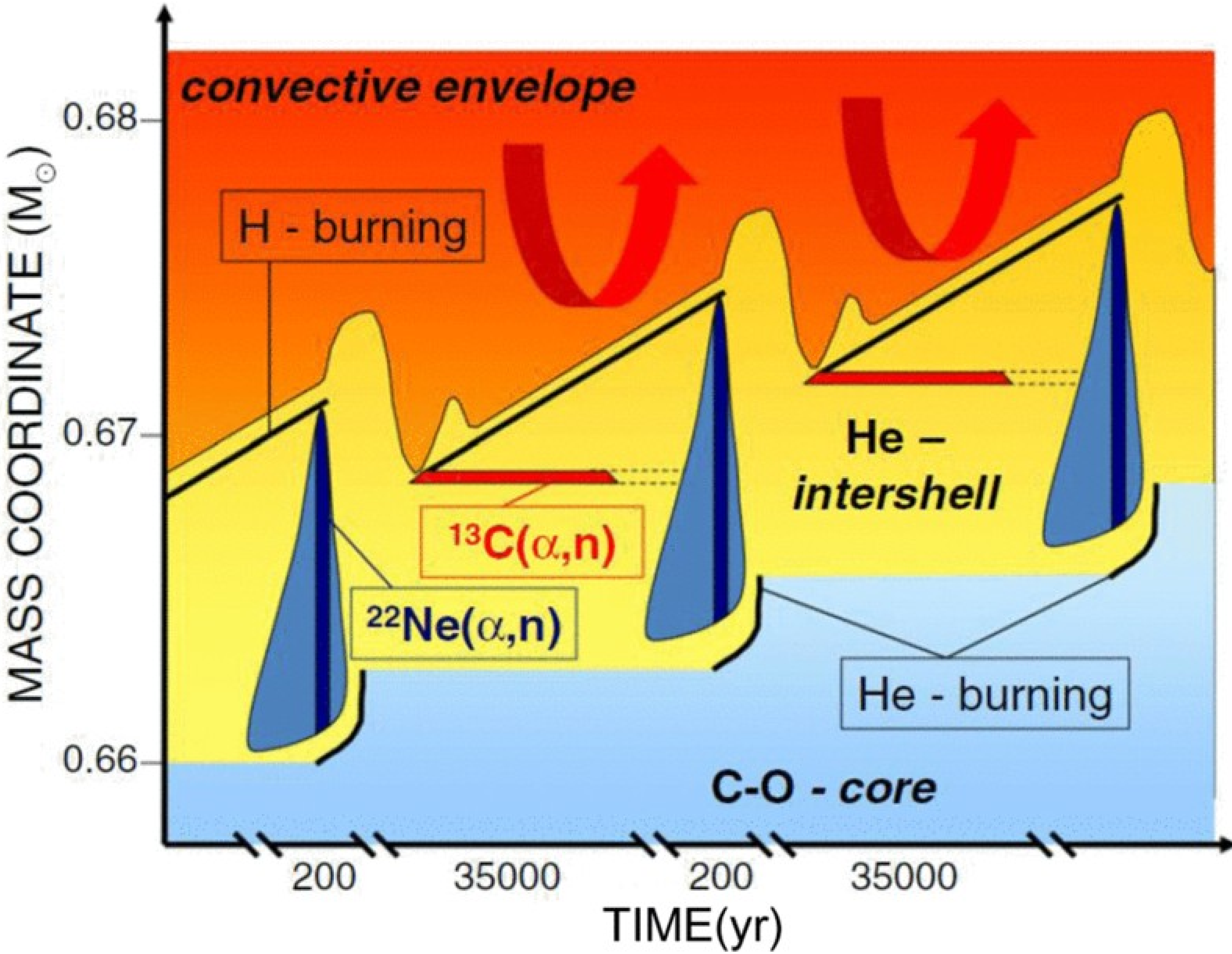
AGB stars

- Asymptotic Giant Branch (AGB); E-AGB = early AGB
  - Inert C/O core (no energy source) left after He core burning
  - He burning shell + H burning shell
  - Convective envelope → second "dredge-up" (H-burning ashes are brought to the surface by convection)

- As for red giant phase, radius is increasing….. up to 200 $R_\odot$ (~ Earth)!



TP-AGB stars (Thermal Pulses)



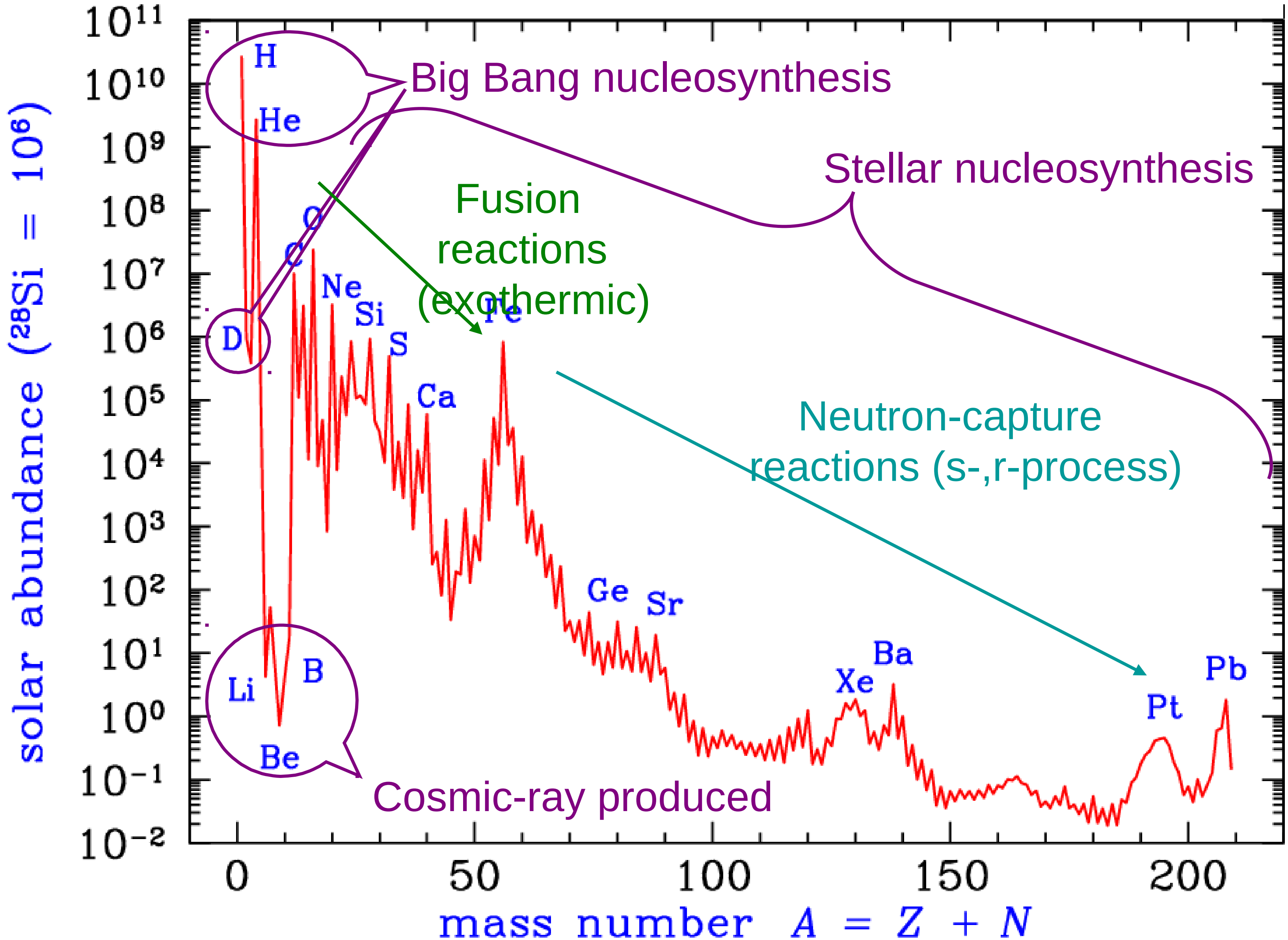
- Mixing of ashes from H and He burning
- Site of the main *s*-process

Evolution of a solar-type star

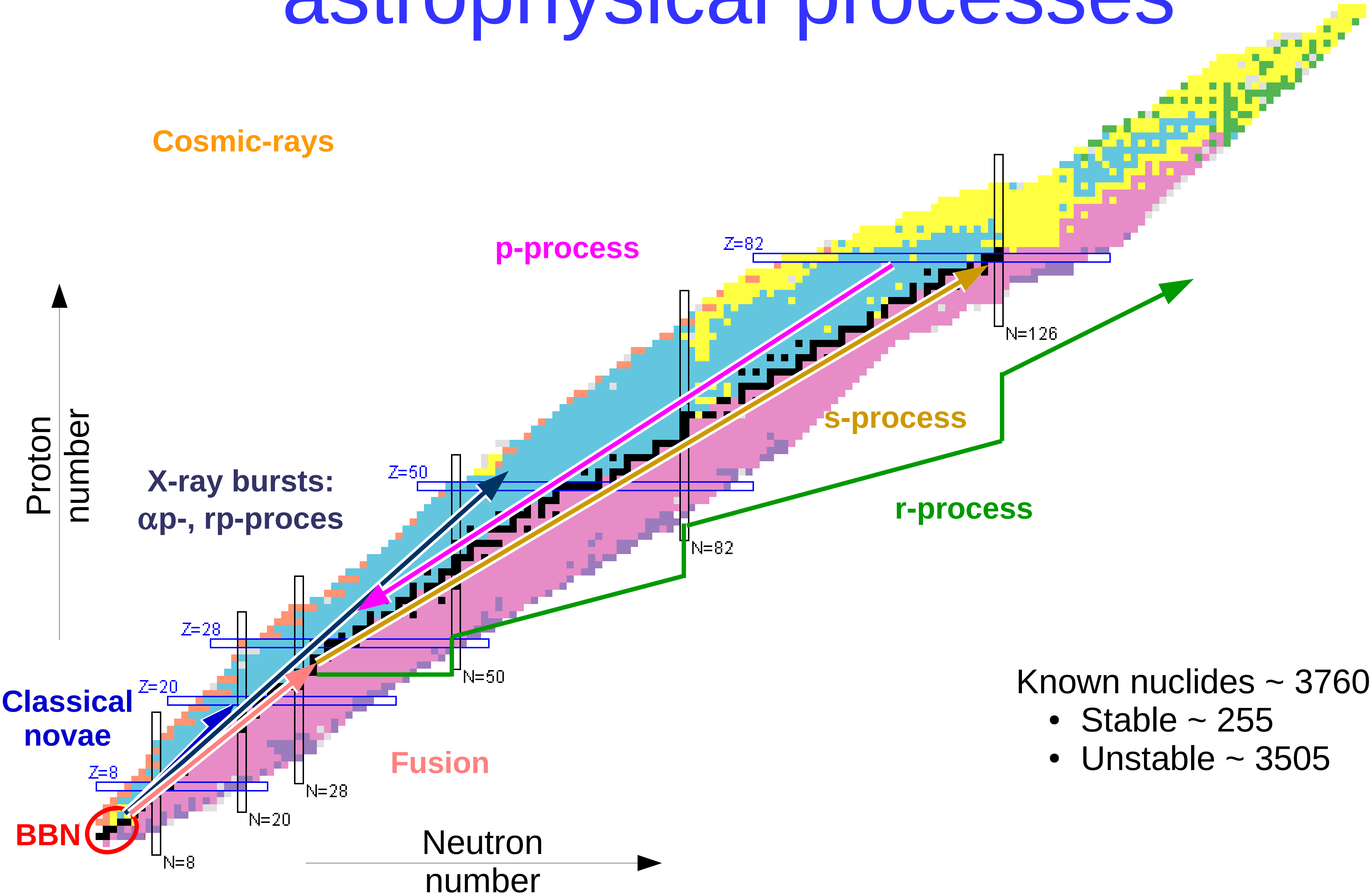
Time until the next stage (year)	T_C **(MK)**	T_{eff} **(K)**	ρ_C **(g cm^{-3})**	**Radius ($R_\odot$)**	**Stellar stage**
10^{10}	15	6000	10^2	1	Main sequence
10^8	50	4000	10^4	3	Subgiant
10^5	100	4000	10^5	50	Helium flash
5×10^7	200	5000	10^4	10	Horizontal branch
10^4	250	4000	10^5	200	AGB
10^5	300	100 000	10^7	0.01	Compact star enriched in C, O (planetary nebula)
-	100	50 000	10^7	0.01	White dwarf

Summary

Abundance curve and processes



Nuclear landscape and astrophysical processes



Known nuclides ~ 3760

- Stable ~ 255
- Unstable ~ 3505

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