From Nuclei to stars: The nucleosynthesis processes at work in Universe: from Big-Bang to stars

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Plan of lecture II

I. Little bit of history

II. Big-Bang nucleosynthesis

III. Cosmic ray nucleosynthesis

IV. Stellar nucleosynthesis
- Hydrogen burning: p-p chains and CNO cycles
- Helium burning
- Advanced burning stages: C-, Ne, O and Si burning
- Explosive burning in Core Collapse Supernovae
- Explosive nucleosynthesis
- Nucleosynthesis beyond iron: s- and r-process

Text books

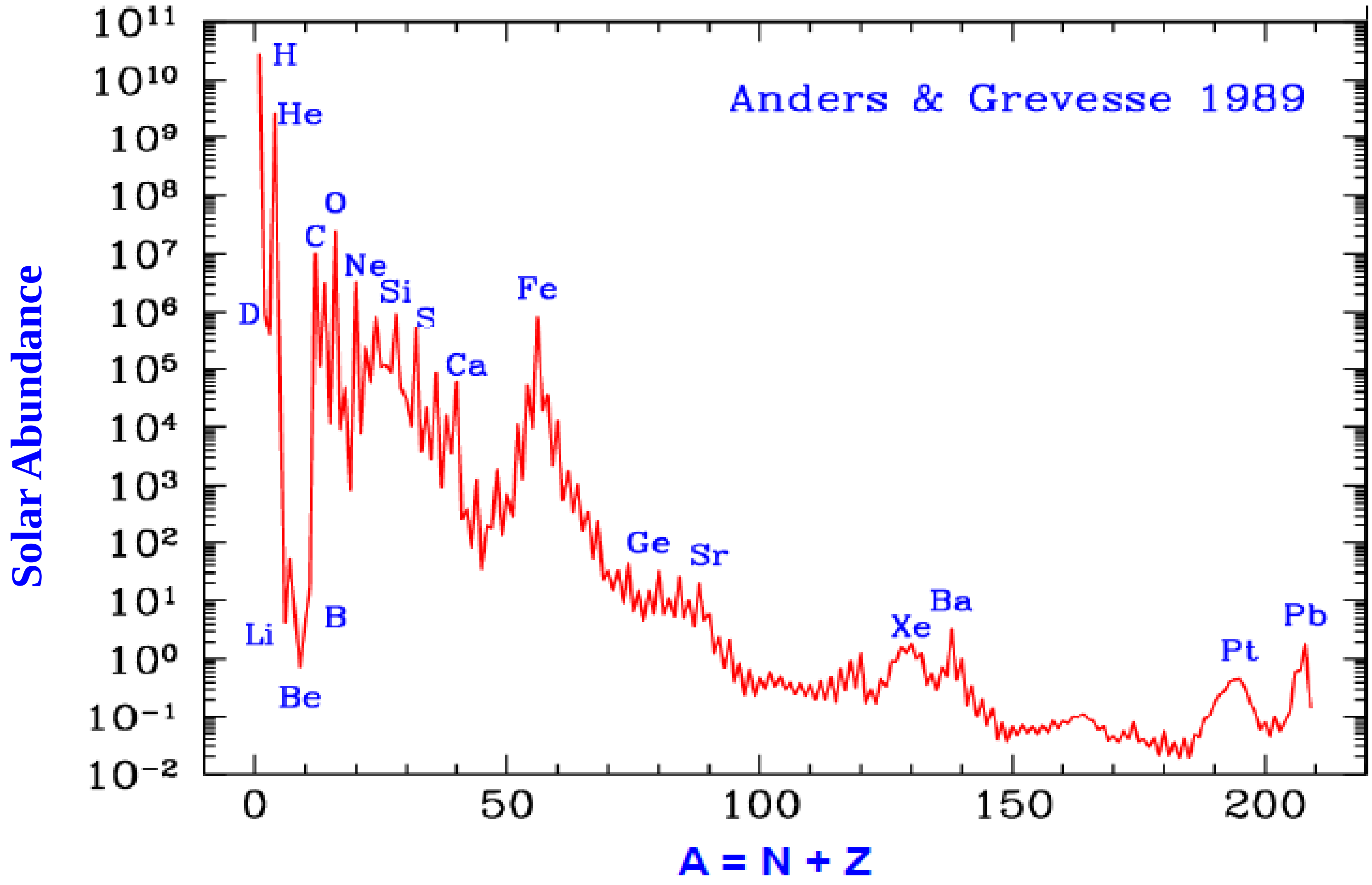
- **Cauldrons in the Cosmos**, Nuclear Astrophysics ,
  Claus E. Rolfs and William S.Rodney
  The University of Chicago Press, 1988
  ISBN 0-226-72456-5

- **Principles of Stellar Evolution and Nucleosynthesis**,
  Donald D. Clayton, The University of Chicago Press ,1968
  ISBN 0-226-10953-4

- **Supernovae and Nucleosynthesis** – An investigation of the History of Matter, from the Big-Bang to the Present.
  David Arnett

Nucleosynthesis : When and where?

Abundance curve of the elements:

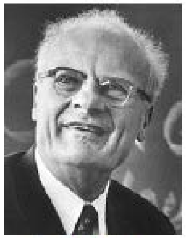


Little bit of history: Important dates

- 1920 Eddington suggests that the energy of the stars result from nuclear fusion
- 1928 Gamow : discovery of quantum tunneling, which demonstrates the non-zero probability of nuclear reactions in stars
- 1938 Bethe, Critchfield & von Weizsaecker : discovery of pp chain and CNO cycle
- 1951–1953 Öpik, Salpeter and Hoyle : discovery of He burning mechanism
- 1957 Burbidge, Burbidge, Fowler & Hoyle (B^2FH) give an overview of nucleosynthesis processes in the Stars
- 1968 Davis et al. : 1st detection of neutrinos emitted in Sun core
- 1987 γ radioactivity detection of ^{56}Co and ^{57}Co in supernova SN 1987A
- 2013 Observational evidence of heavy nuclei nucleosynthesis in the coalescence of a binary system of two neutron stars (GRB 130603B)
- **2017 (August)** observational confirmation of heavy nuclei nucleosynthesis in a binary neutron star mergers (GW170817)

Little bit of history: Nucleosynthesis processes

Primordial Nucleosynthesis


Alpher **Bethe** **Gamow**

("α β γ")

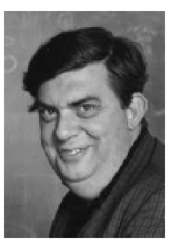
"All the elements were formed just after Big-Bang"

Phys. Rev. 73. (1948) 803

→ Almost right for D, He, a part of ^{7}Li

But: Mass gap A=5& A=8 (unbound nuclei)

Stellar Nucleosynthesis

Burbridge Burbridge Fowler Hoyle

(B2FH)

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

<u>B2FH epoch:</u>

- Primordial (Big-Bang) nucleosynthesis
- H burning & He 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 : no fundamental changes, "x" → identified as non-thermal nucleosynthesis and C,Ne, O, Si burning phases added to the list above.

Big-Bang Nucleosynthesis

Three observational pillars of Big-Bang Model:

- **The expansion of the Universe**

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

- **Cosmic Microwave Background radiation (CMB)**

→ A black body radiation at 2.7 K corresponding to the redshifted spectrum emitted when the universe became transparent (Penzias & Wilson in 1965)

- **Primordial nucleosynthesis (BBN) of light elements**

→ BBN reproduces the observed primordial abundances over a range of nine order of magnitudes

Big-Bang nucleosynthesis: Nucleosynthesis (1)

- At T> 10^{10} K, the particles present: photons, e-,e+, ν, anti-ν, p, n

Equilibrium p ↔ n : $N_n/N_p=\exp(-Q_{np}/kT)$; Q_{np} = 1.29 MeV

$$\nu_e + n \leftrightarrow e^- + p \qquad \bar{\nu}_e + p \leftrightarrow e^+ + n$$

Equilibrium as long as the weak reaction rate is faster than the expansion rate: $\Gamma_{n\leftrightarrow p} >> H(t)$

Equilibrium breaks out when :

$\Gamma_{n\leftrightarrow p} < H(t)$ at T≈ 10^{10}K

Then N_n/N_p ↘ 0.13 due to free neutron β decay

Neutrons decay until T is low enough for :

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

becomes faster then deuterium photodisintegration

$$D+\gamma \rightarrow n+p \quad (Q = -2.2\ \mathrm{MeV})$$

Then, $t = 3$ mn, $T \approx 10^9$ K and N_n has decrased to $N_n/N_p \approx 0.1$

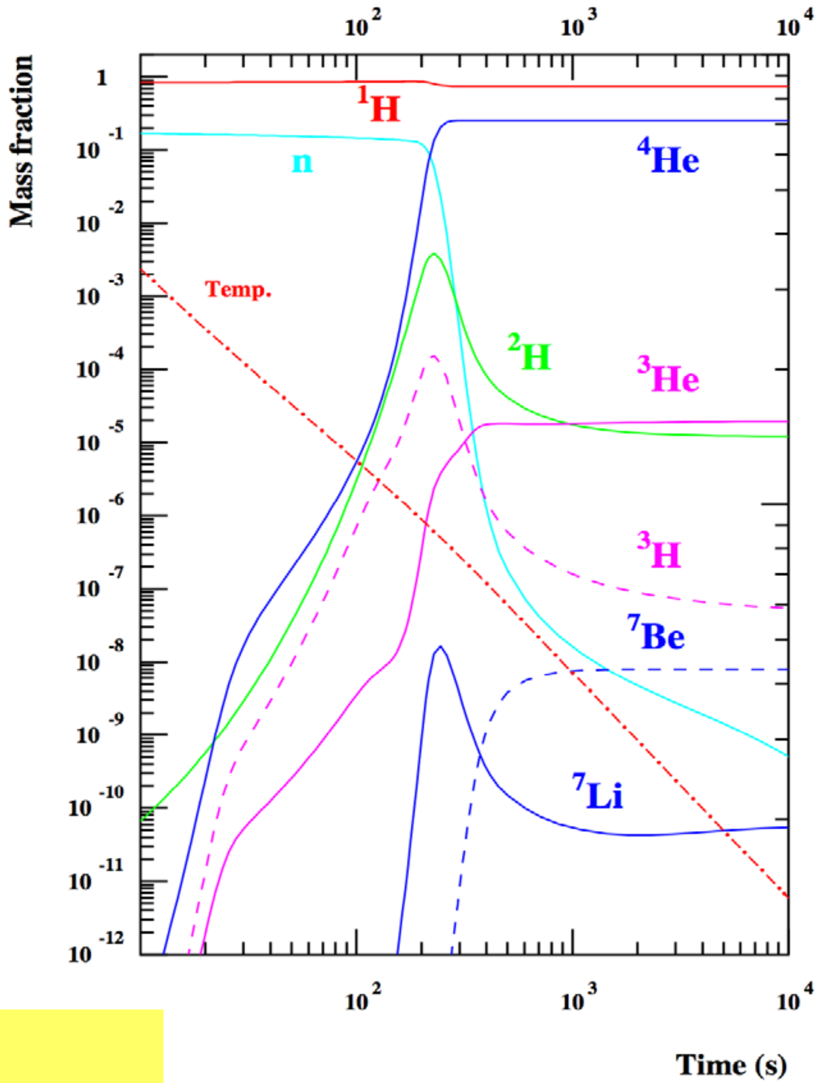
Nucleosynthesis starts to produce essentially ^4He together with traces of D, ^3He, ^7Li, ….

Big-Bang nucleosynthesis: The canonical BBN reaction network

The 12 reactions of standard BBN:

- $n \leftrightarrow p$ with $\tau_n = 880 \pm 4\ s$
- $p + n \rightarrow D + \gamma$
- $D + p \rightarrow {}^3He + \gamma$
- $D + D \rightarrow {}^3He + n$
- $D + D \rightarrow T + p$
- $T + D \rightarrow {}^4He + n$
- $T + {}^4He \rightarrow {}^7Li + \gamma$
- ${}^3He + n \rightarrow p + T$
- ${}^3He + D \rightarrow p + {}^4He$
- ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
- ${}^7Li + p \rightarrow {}^4He + {}^4He$
- ${}^7Be + n \rightarrow {}^7Li + p$

$\Omega_b h^2$=WMAP



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

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

Big-Bang nucleosynthesis: Observations versus predictions

Observations: From a set of the most primitive astrophysical objects with the lowest metallicity

- **D observations** in clouds (cold objects) at high redshift on the line of sight of distant quasars

$D/H=(2.53\pm0.40)\times10^{-5}$

- **^{4}He observations** in HII (ionized H) regions of blue compact galaxies

$Y_p=0.2561\pm0.0108$

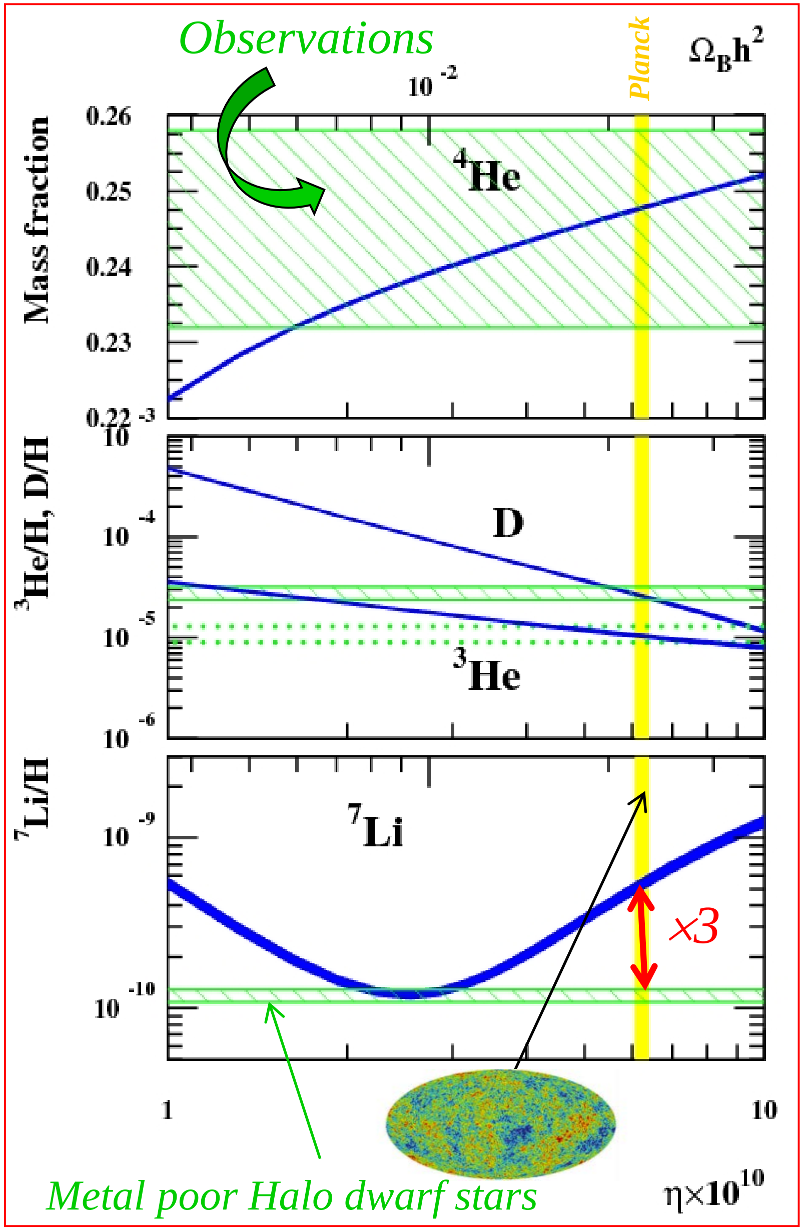
- **^{3}He observations** in HII regions of our Galaxy

$^3He/H=(1.1\pm0.2)\times10^{-5}$

- **^{7}Li observations** at the surface of metal poor Halo dwarf stars

$^7Li/H=(1.58\pm0.31)\times10^{-10}$ =1/3 predicted ^{7}Li

→ The ^{7}Li cosmological problem



What are the possible solutions to ^{7}Li problem?

→ Astrophysical solution?

→ Nuclear physics solution?

→ Physics beyond standard model?

Big-Bang nucleosynthesis: The astrophysical solution (I) to ^{7}Li ?

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

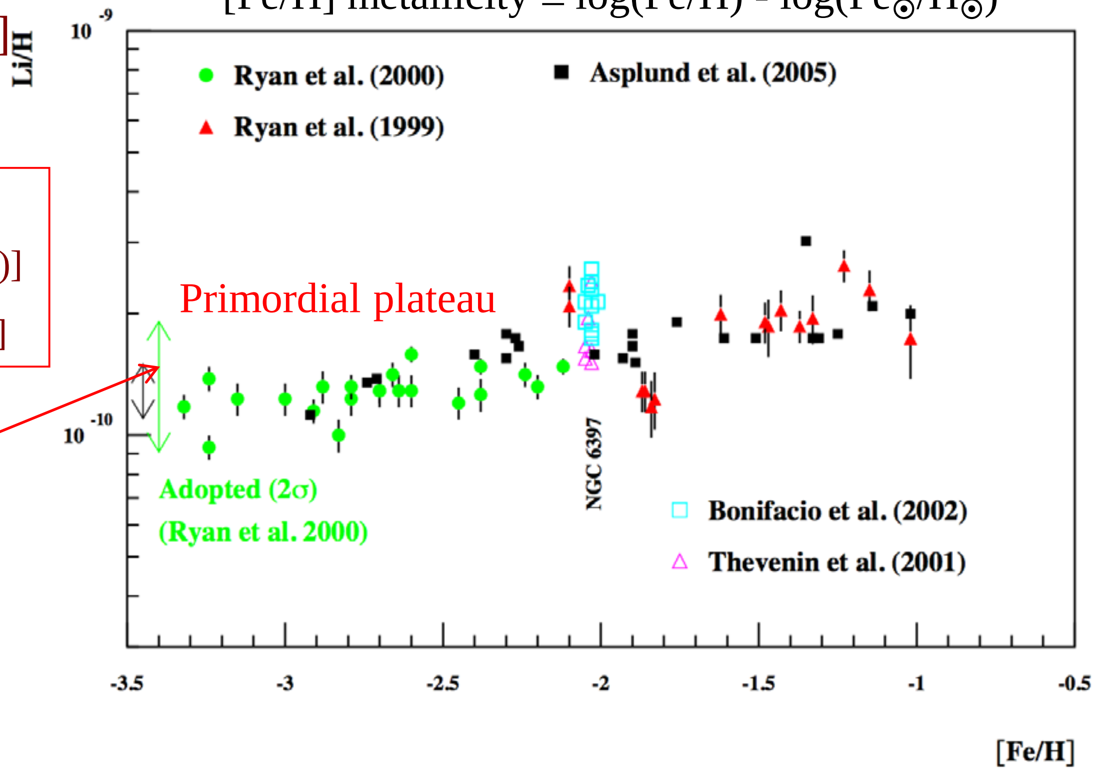
Spite plateau:

Li/H versus [Fe/H] (time)

Li/H ≈1.12 10^{-10} [Spite & Spite, 1982]

$0.9 \leftrightarrow 1.9 \times 10^{-10}$	[Ryan et al. (2000)]
$\approx 1.3 \leftrightarrow 2.3 \times 10^{-10}$	[Charbonnel et al (2005)]
$\approx 1.1 \leftrightarrow 1.5 \times 10^{-10}$	[Asplund et al. (2006)]

[Fe/H] metallicity ≡ log(Fe/H) - log(Fe$_\odot$/H$_\odot$)



• Very low dispersion

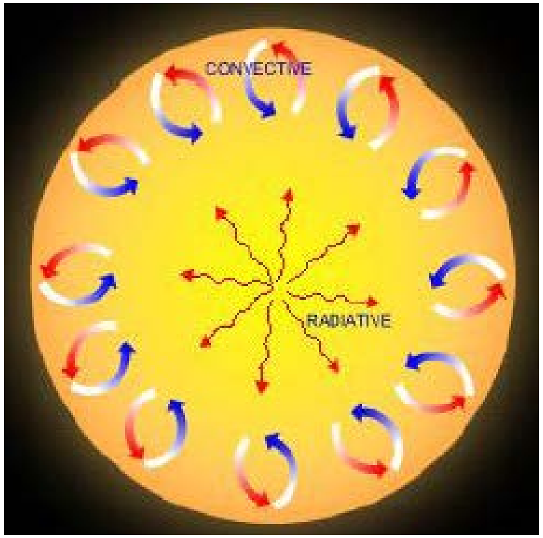
- Reliable primordial abundance?

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

Big-Bang nucleosynthesis: The astrophysical solution (II) to ^{7}Li ?

→ Depletion of the atmospheric ^{7}Li due to rotationally induced mixing and/ diffusion?

- Lithium easily burned in stars (low binding energy):
  $T \geq 2.5\times10^6$ K $\Rightarrow$ $^7\mathrm{Li}+p\rightarrow 2\,^4\mathrm{He}$



- Destroyed by convection
  - Deeper mixing of surface material → ^{7}Li burning

- **But not enough and not uniformity!**
  - Metal poor halo stars have shallower convective zones than in solar metallicity stars
  - Different stars have different convective zones
  - Should see larger scatter around "plateau"

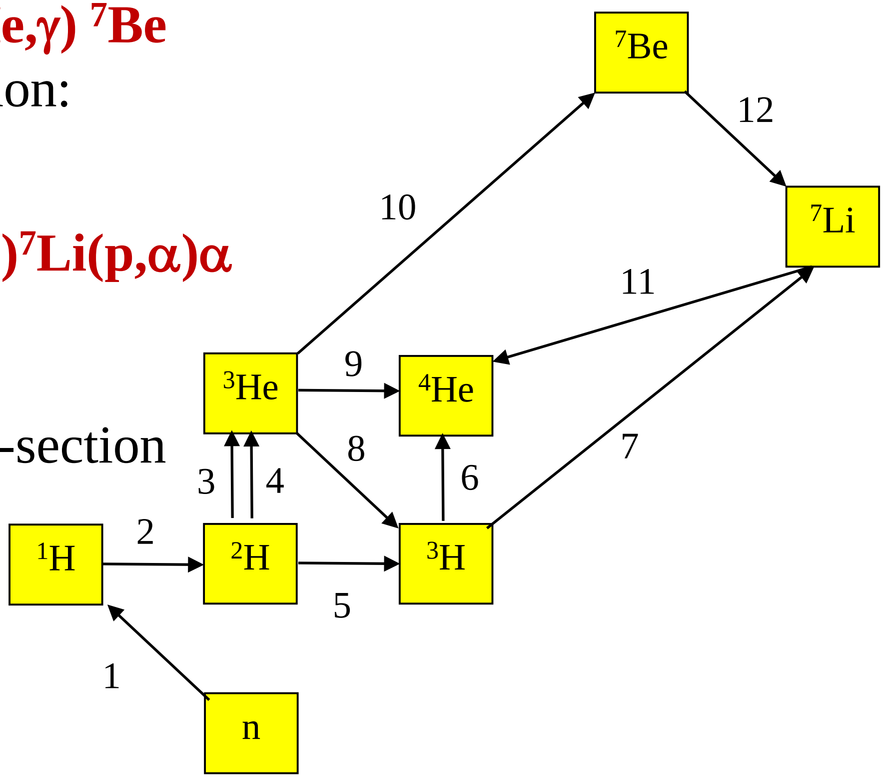
Big-Bang nucleosynthesis: Nuclear solution to ^{7}Li problem?

- **^{7}Li** production via **EC decay of ^{7}Be at high η** :

- 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 cross-section well known :
  1% uncertainty
  → ^{7}Li(p,α)α : 6% uncertatinty on the cross-section

- Secondary destruction reactions:
  ^{7}Be+d, **^{7}Be+^{3}He**, **^{7}Be+^{4}He**, ...
  → All experimentally studied these last years & none is responsible of the ^{7}Li deficit



The solution to the ^{7}Li problem has very likely to be found outside nuclear physics

Big-Bang nucleosynthesis: Physics beyond standard model?

→ Decays of heavier meta-stable (100-1000s) particles that inject additional neutrons which could increase the rates of ^{7}Be+n

[Jedamzik (2004,2006), Kawasaki et al. (2005), Ellis et al. (2005)]

→ Existence of mirror universe in which neutrons can oscillate to our world ⇒ effective late time neutron injection which induces an increase of the ^{7}Be destruction by ^{7}Be+n [Coc et al. 2013]

Big-Bang nucleosynthesis: Summary

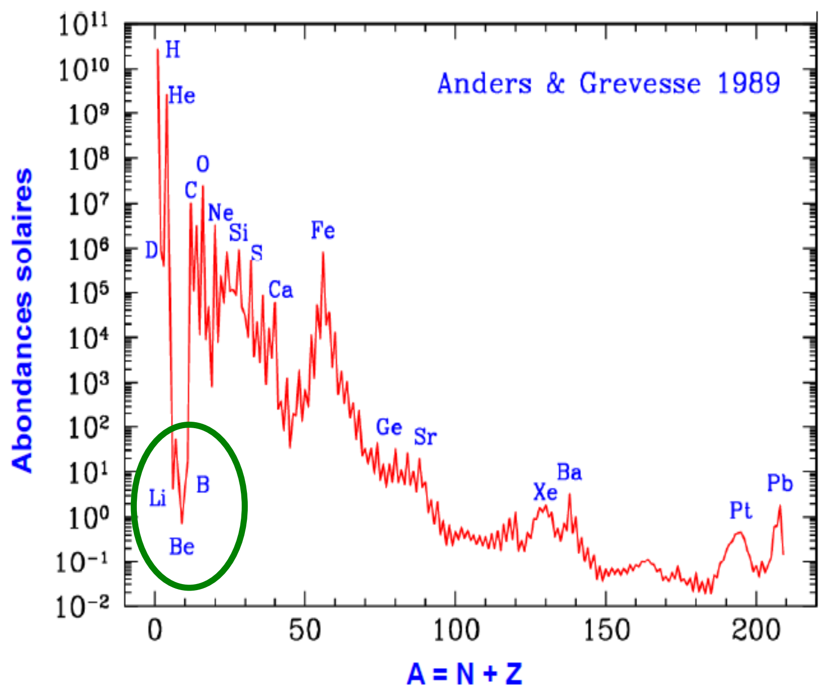
BBN produced **H, D, He** & part of **Li** only. The nucleosynthesis of heavier element is prevented by:

- coulomb barriers (see next course) of elements with higher atomic numbers
- the lack of stable isotopes of mass numbers **5** and **8**
- the decreasing density of matter as the universe expends

BBN details => see cosmology course

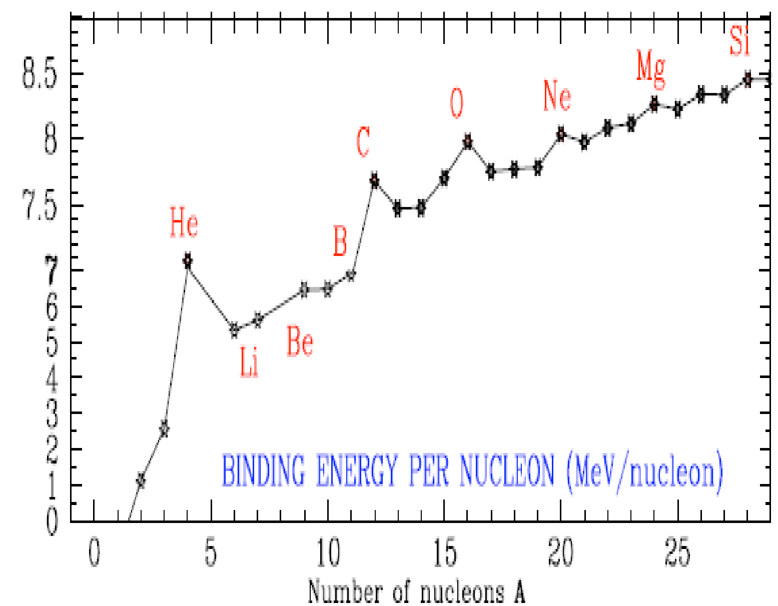
Cosmic-ray Nucleosynthesis

Cosmic ray nucleosynthesis: The LiBeB story



➢ ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B are fragile enough to be destroyed in stellar interiors

⇒ Not in stars



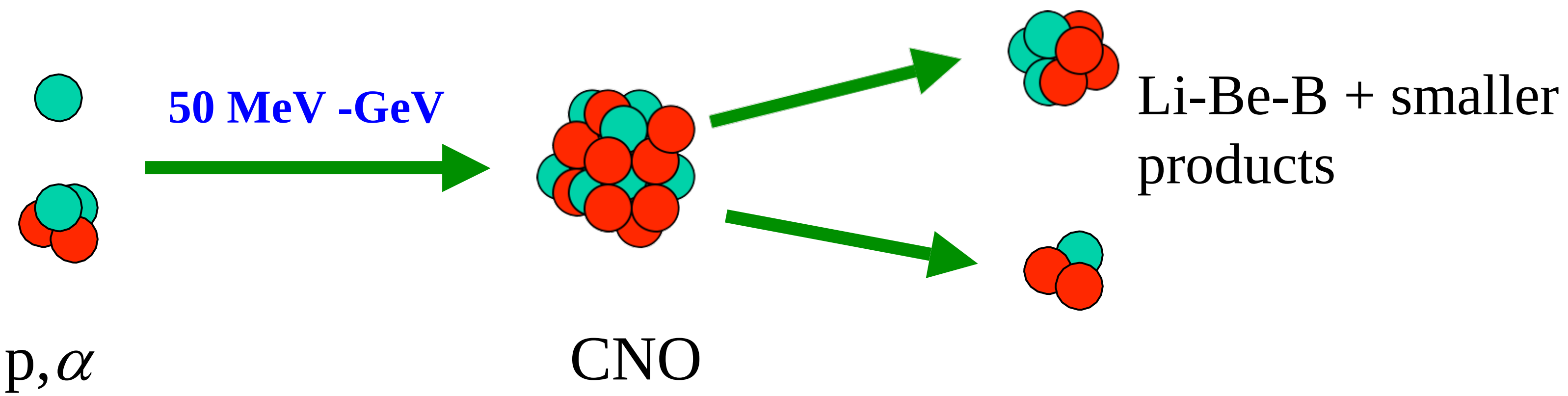
➢ BBN model: 10 order magnitudes differences between ^{7}Li and ^{10}B

⇒ Light elements not from BBN

Cosmic ray nucleosynthesis: The LiBeB story

- **Must come from galactic processes: Cosmic ray nucleosynthesis**

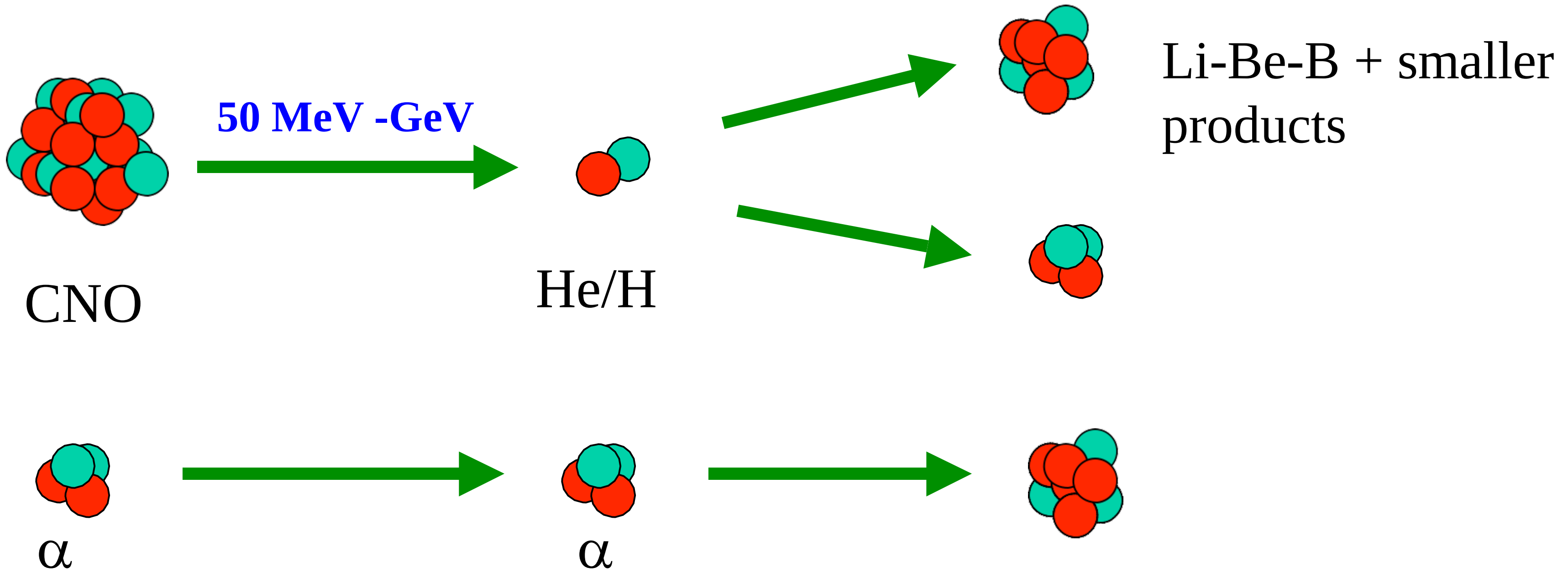
  → Spallation



- Cosmic ray particles with high energy (50 MeV – GeV) interact with CNO in ISM to produce light elements
- This is a *metallicity dependent* "secondary" process – it depends on the amount of CNO in the ISM

Cosmic ray nucleosynthesis: The LiBeB story

→ Inverse Spallation



•C,N,O,H accelerated by supernovae reacts with interstellar H & He, breaks apart

Stellar Nucleosynthesis: Hydrostatic (quiescent) stellar burning

Little Reminder

To achieve life as a star for a protostar $\rightarrow$ equilibrium is needed

1- gravity pulls gas and dust inward

the core

$\Downarrow$

2- T(core) ↗

3- ρ(core) ↗

$\Downarrow$

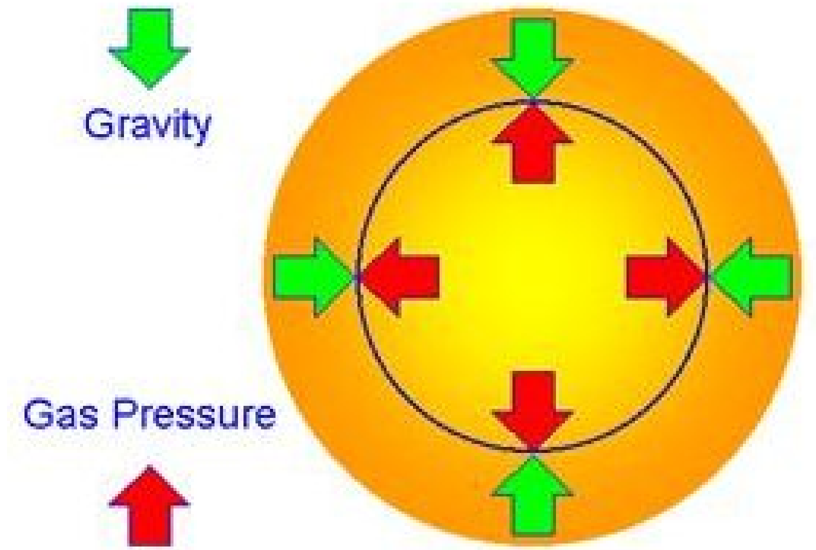
4- gas pressure ↗ $\rightarrow$ resists the

collapse of the nebulae

5- when gas pressure (T,ρ)= gravity

$\Downarrow$

equilibrium $\rightarrow$ accretion stops

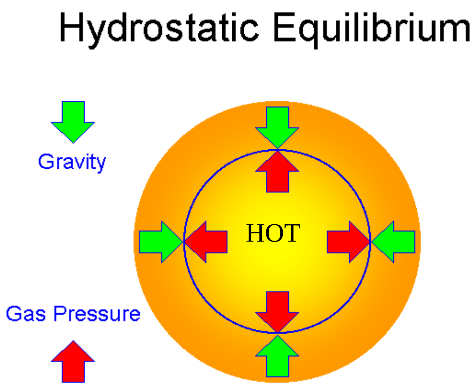


Option 1: if T not high enough $\longrightarrow$ the protostar ends up a brown dwarf

Hydrostatic stellar nucleosynthesis : Hydrogen burning

Option 2: if T high enough $\longrightarrow$ "nuclear burning" takes place

when $T \sim 10 - 15 \times 10^6$ K and $\rho \sim 10^2$ gcm^{-3}



HYDROGEN BURNING (1st equilibrium) → a star is born

$$^4H \rightarrow \underbrace{^4He}_{ash} + 2\beta^+ + 2\nu + \underbrace{26.73\ \text{MeV}}_{energy\ source}$$

$$Q = 4(\Delta m)1H - (\Delta m)4He \approx 26.73\text{MeV}$$

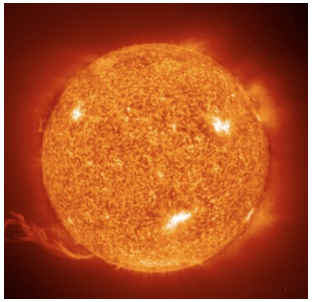
gravitational collapse is halted $\Rightarrow$ star undergoes phase of *hydrostatic equilibrium*

MAIN SEQUENCE STARS

Minimum mass required for hydrogen burning to ignite $M \sim 0.1\ M_\odot$

Hydrostatic stellar nucleosynthesis : Hydrogen burning

- Not simultaneous reaction of 4p (too small probability), but proton-proton chains and CNO cycle



<u>proton-proton (pp) chain</u>

Sun (T=15.6 MK),
Core of main-sequence stars(T=8-55 MK)
Burning shell of AGB stars (T=45-140 MK)

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

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

$^{3}He + {}^{3}He \rightarrow \alpha + 2p$ **pp1**

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

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ → $^{7}Li + p \rightarrow \alpha + \alpha$ **pp2**

$^{7}Be + p \rightarrow {}^{8}B + \gamma$ → $^{8}Be \rightarrow 2\alpha + e^{+} + \nu_e$ **pp3**

- Neutrinos provide direct evidence that nuclear reaction occurs

Hydrostatic stellar nucleosynthesis : Hydrogen burning

<u>pp1 chain</u>

- Succession of 3 reactions that produce almost **90%** of Sun's energy

- **p+p** (Q=1.44 MeV) is a week interaction
  → the cross-section σ is ~ 20 order of magnitudes smaller than σ associated with nuclear interaction
  ⇒ **the slowest reaction**
  → it can not be measured
  → theoretically determined

- All subsequent reactions involve electromagnetic and nuclear forces
  ⇒ **much faster**

- **^{2}H+p→^{3}He+γ** (Q=5.49 MeV) has been measured in LUNA laboratory (lecture IV)

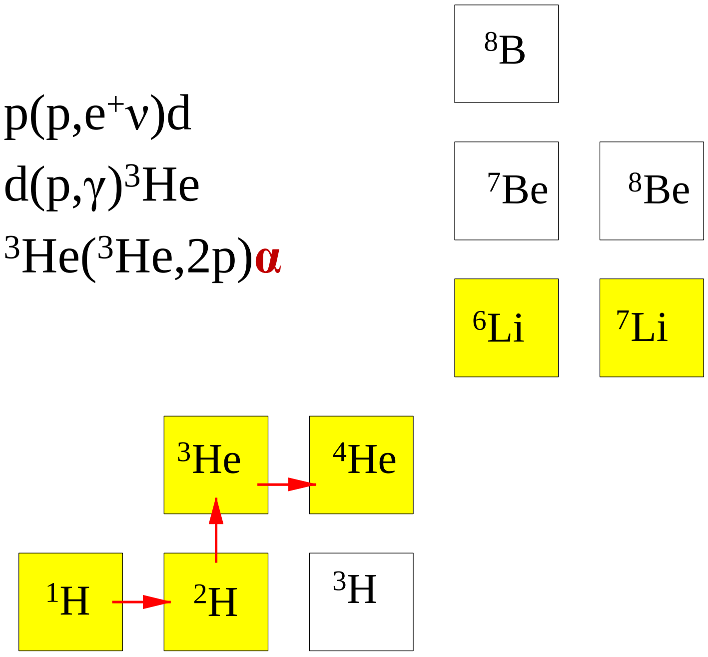
- First p+p neutrino detection (BOREXINO) in 2014

pp1 chain

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

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

$^3He(^3He,2p)\alpha$



pp1 chain

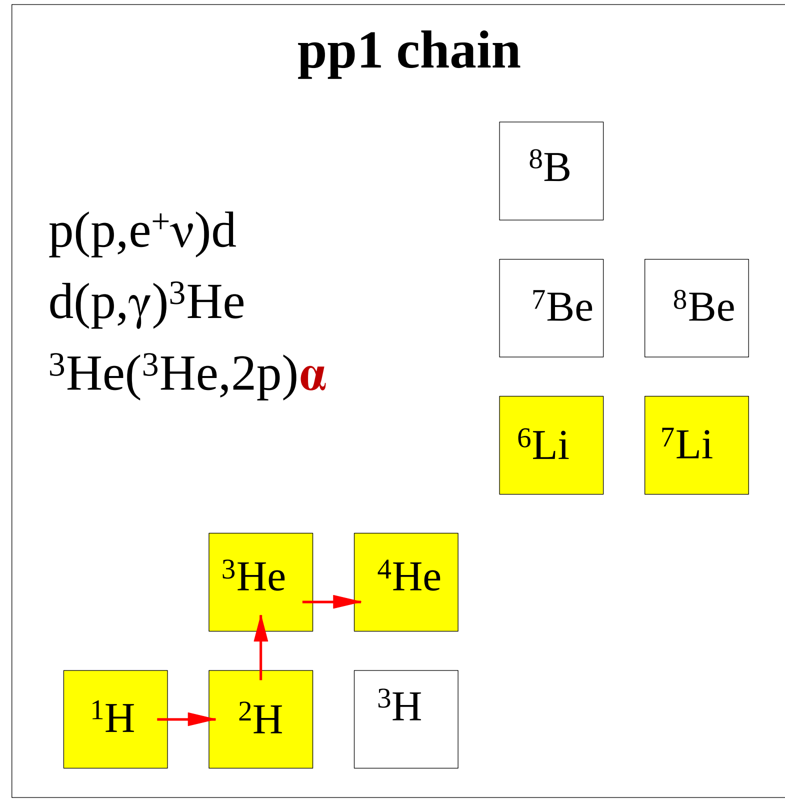
- $^{3}\text{He} + \text{p} \rightarrow {}^{4}\text{Li} \rightarrow {}^{3}\text{He} + \text{p}$ ($\tau = 10^{-22}$ s)
- $^{3}\text{He} + \text{d}$ negligible given the low N_d
- $\mathbf{^{3}He + {}^{3}He \rightarrow \alpha + 2p}$ (Q=12.86 MeV)

$\rightarrow$ third reaction of the pp1 chain

$\rightarrow$ Has been measured in LUNA (lecture IV)

if $N_\alpha >> N_{3He}$, $^{3}\text{He} + \alpha \rightarrow {}^{7}\text{Be} + \gamma$

$\Rightarrow$ pp2 and pp3 chains



Hydrostatic stellar nucleosynthesis : Hydrogen burning

pp2 chain

- ^{7}Be decays by electron capture and its lifetime depends on its charge state

$\Rightarrow$ if ^{7}Be has all of the orbital electrons removed, the decay rate $\rightarrow 0$

- In center of stars, ^{7}Be almost completely ionized but immersed in a sea of free electrons $\Rightarrow$ the e$^-$ capture rate ($\lambda=1/\tau$) depends on the electron density n_e and T.

The stellar lifetime is given by:

$$\boxed{\tau_s(^7Be) = 7.06\times10^8 \frac{T_6^{1/2}}{\rho(1+X_H)}}$$

pp2 chain

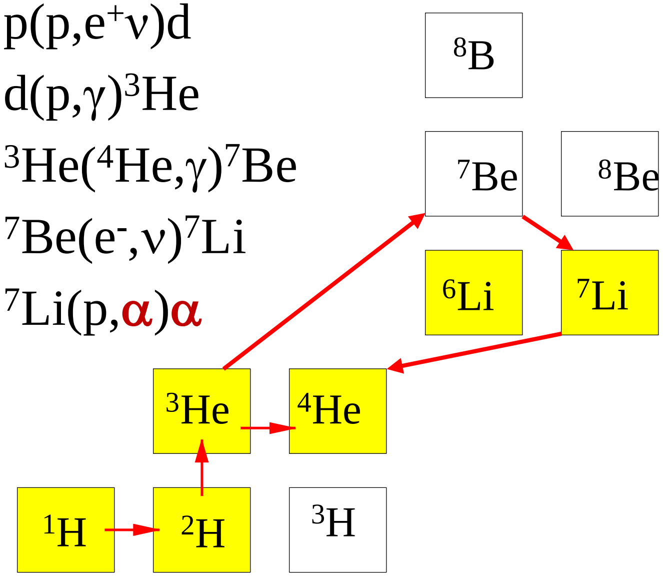
p(p,e$^+\nu$)d

d(p,γ)^{3}He

^{3}He(^{4}He,γ)^{7}Be

^{7}Be(e$^-$,ν)^{7}Li

^{7}Li(p,α)α



Ex: In the sun's core T_6=15, ρ=100 g cm^{-3}, X_H=0.5 $\rightarrow$ $\tau_s(^7Be)$= 140 d

- But the probability that ^{7}Be atoms are only partially ionized is non-zero

$\Rightarrow$ $\lambda_{tot}=\lambda_c+\lambda_K$ (λ_c: decay rate due to continuum free electrons, λ_K: K-capture rate)

$\Rightarrow$ $\tau_{sun}(^7Be)$= **120 d=0.33 y** [$\tau_e(^7Be)$= **77d** on earth]

Hydrostatic stellar nucleosynthesis : Hydrogen burning

pp3 chain

- The enhanced $\tau_s(^7Be)$ in stars increases the probability of its destruction via $^7Be(p,\gamma)^8Be$ when T is increasing

- For sun's conditions: T=15MK
  $\tau_s(^7Be) = 0.33$ y $<< \tau_H(^7Be) = 150$ y
  $\rightarrow$ 99.89% of the time, ^7Be proceeds through e- capture & only 0.11% through proton capture

- The reaction $^7Be(p,\gamma)^8Be$ is faster for **T > 25 MK**
  $\Rightarrow$ **pp3 chain**

- ^8B neutrinos discovered at Homestake [0.02%] in 1968
  (solar ν problem)

- Super-Kamiokande/SNO experiments (neutrino oscillations)

pp3 chain

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

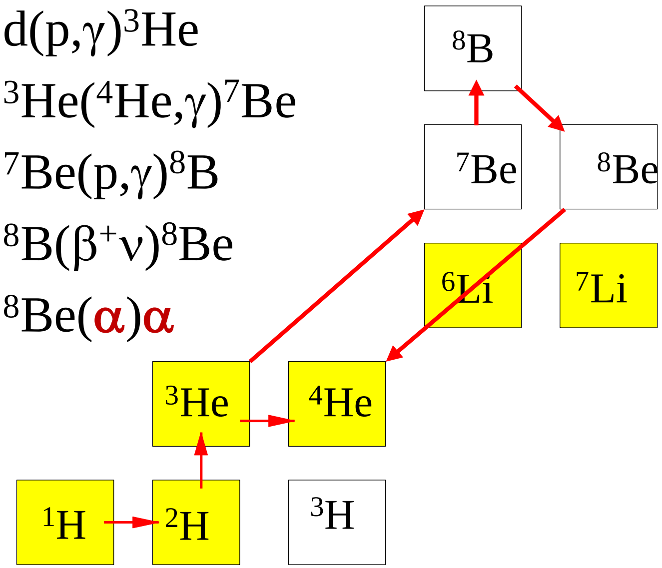
$d(p,\gamma)^3He$

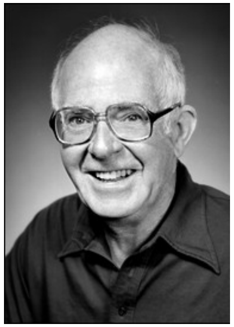
$^3He(^4He,\gamma)^7Be$

$^7Be(p,\gamma)^8B$

$^8B(\beta^+\nu)^8Be$

$^8Be(\alpha)\alpha$

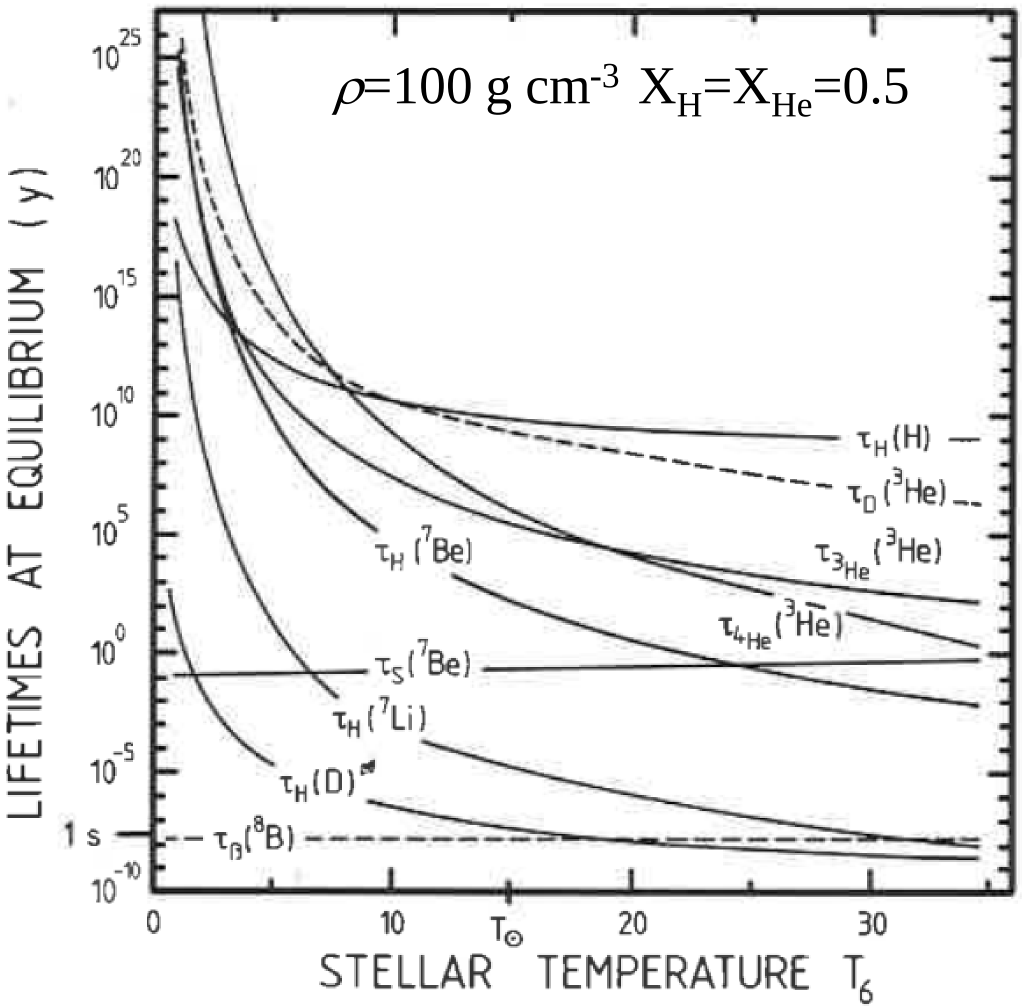




Ray Davis (1914-2006)
Nobel Prize 2002

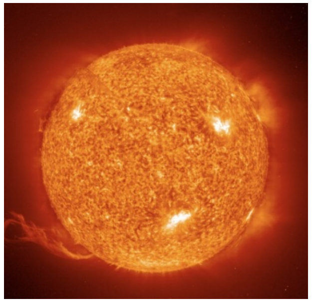
pp chains: Capture & decay lifetimes as function of stellar temperature

(see later in lecture III)



Hydrostatic stellar nucleosynthesis : Hydrogen burning

The reactions of p-p chain in the sun



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

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

86% 14%

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

$^3He(\alpha,\gamma)^7Be$

99.89% 0.11%

$^7Be(e^-,\nu_e)^7Li$

$^7Li(p,\alpha)^4He$

$^7Be(p,\gamma)\,^8B$

$^8B(e^+\nu_e)8Be^*$

$^8Be^*(\alpha)^4He$

pp1 pp2 pp3

pp1-chain:

$$\overline{E}_\nu(p+p) = 0.26MeV$$

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

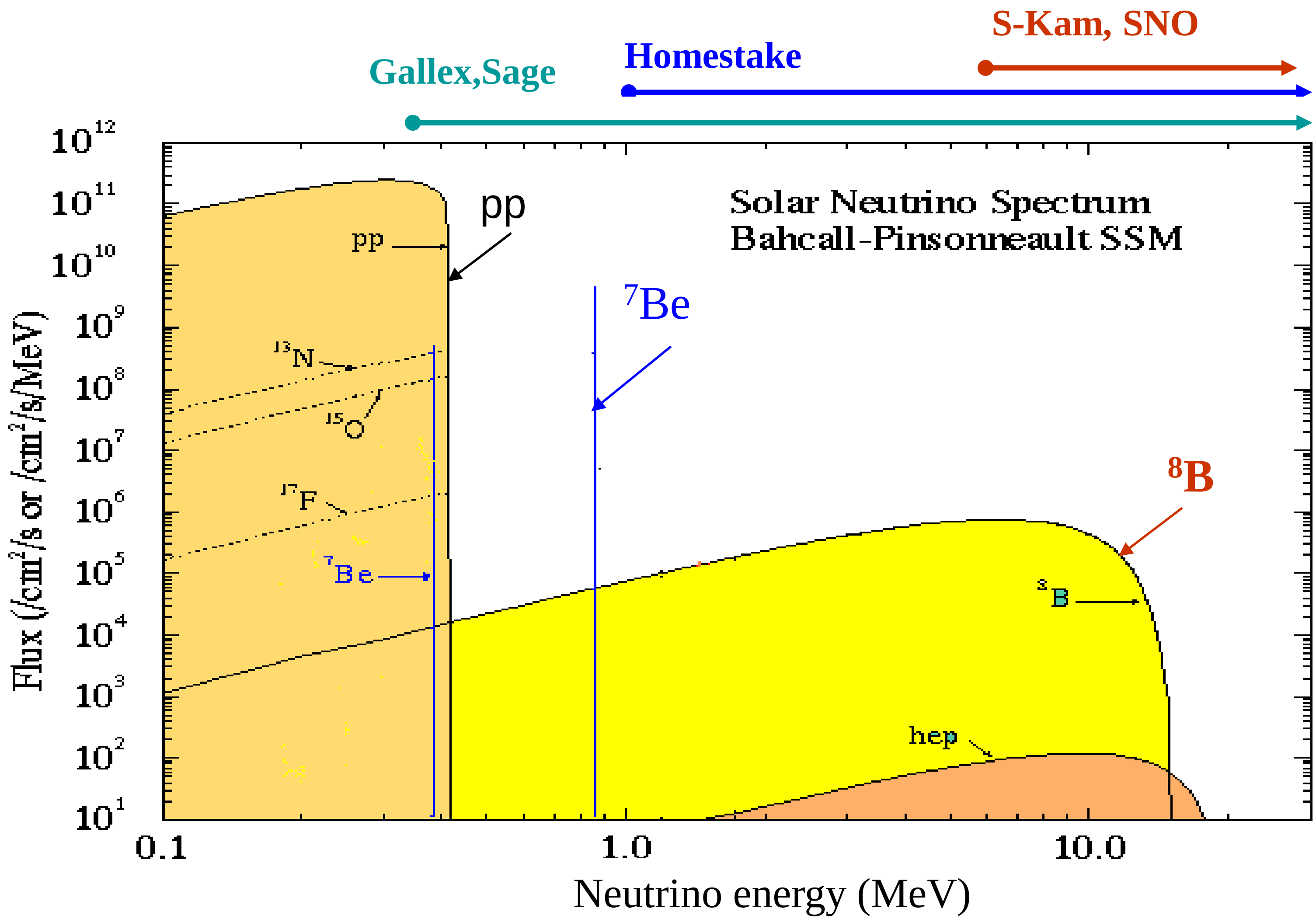
$$= 26.20MeV$$

pp2-chain: $\overline{E}_\nu(^7Be) = 0.81MeV, Q_{eff} = Q - 2\overline{E}_\nu(p+p) - \overline{E}_\nu(^7Be) = 25.66MeV$

pp3-chain: $\overline{E}_\nu(^8B) = 7.30MeV, Q_{eff} = Q - 2\overline{E}_\nu(p+p) - \overline{E}_\nu(^8B) = 19.17MeV$

The effective energy given to the star is < Q=26.73 MeV because of the escape of the neutrinos

The solar neutrino problem



- SSM: "Standard" Solar Model

The solar neutrino problem: detection of solar neutrinos (1)

- The pioneering experiment of Ray Davis (1968-2001) & J.N. Bahcall

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

$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}$ ($T_{1/2}$ = 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) in a gas detector

Result: 2.56 ± 0.16 (stat) ± 0.16 (syst) SNU ⇒ 30% of the expected signal

Solar model (Bahcall 2004): 8.5 ± 0.18 SNU

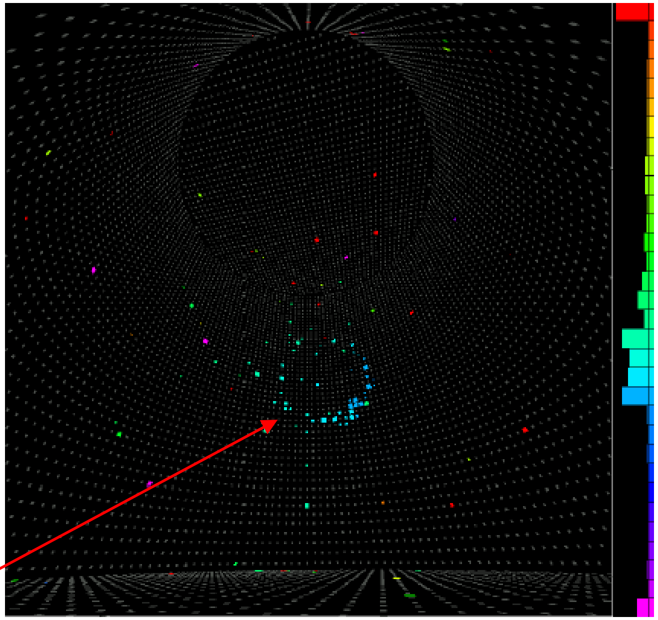
1 SNU (Solar Neutrino Unit) = 10^{-36} capture per second and target atom

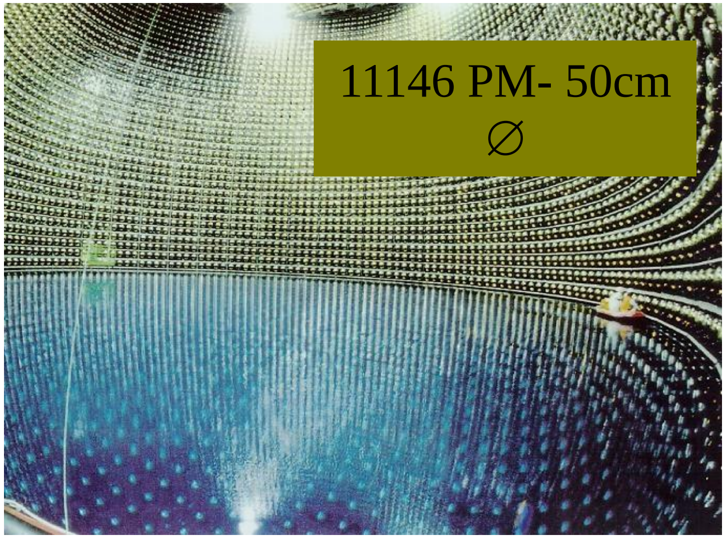
The solar neutrino problem: detection of solar neutrinos (2)

- 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)

→ Result: 40% of the expected signal

- Real-time detection of (mostly) **e^- neutrinos**: **Kamiokande** (700 t of water, 1983 - 1996), **Super-Kamiokande** (50 kt, 1996 → M. Koshiba Nobel price in 2002) $\nu_e + e^- \rightarrow e^- + \nu_e$ ⇒ **Cherenkov light**





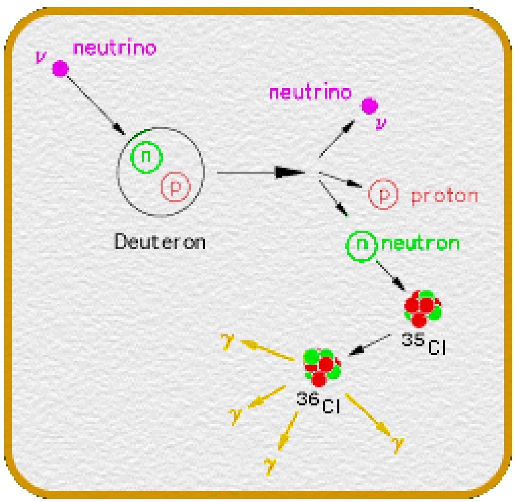
Result: $2.44 \pm 0.102(\text{stat}) \pm 0.08\ (\text{syst}) \times 10^6\ cm^{-2}s^{-1}$ ⇒ 42% of the expected signal

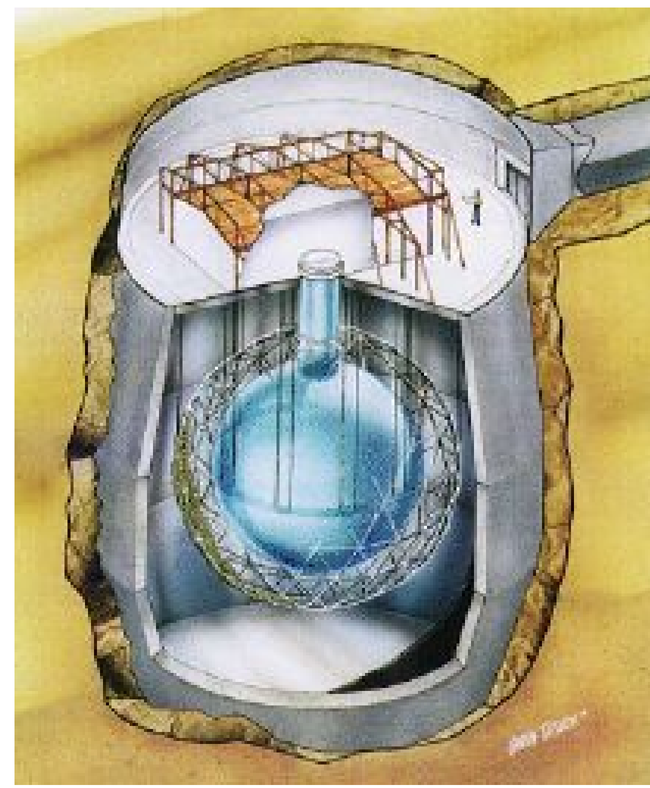
Solar model (Bahcall 2004):

$5.8 \pm 1.3 \times 10^6\ cm^{-2}s^{-1}$

The solar neutrino problem: The solution

- Origin of the deficit: problem with the nuclear data: $^{7}\mathbf{Be(p,\gamma)^{8}B}$?, or new physics of the neutrino = **oscillation $\nu_e \rightarrow \nu_\mu , \nu_\tau$** ?
- Sudbury Neutrino Observatory (SNO): 1100 tons of $\mathbf{D}_2O$ (99.9%) sensitive to the 3 neutrino flavours $\nu_x + d \rightarrow p + n + \nu_x$ (neutral current)





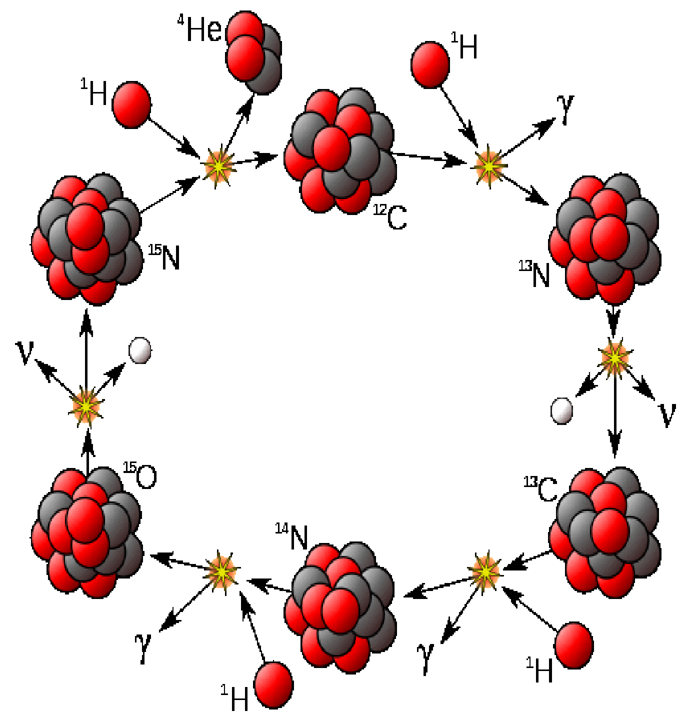
$\phi_{CN} = 5.21 \pm 0.27\,(\mathrm{stat}) \pm 0.389\,(\mathrm{syst}) \times 10^6\,\mathrm{cm^{-2}s^{-1}}$

in agreement with $\phi_{SSM} = 5.05^{+1.01}_{-0.81} \times 10^6\,\mathrm{cm^{-2}s^{-1}}$

Hydrostatic stellar nucleosynthesis : Hydrogen burning

The CNO cycle

- In population I stars (second-or third-generation stars), the elements C, N and O can serve as catalysts of the transformation $4p \rightarrow {}^4He + 2e^+ + 2\nu$ (Q = 26.73 MeV)



CNO-1 cycle

$^{12}C(p,\gamma)^{13}N$

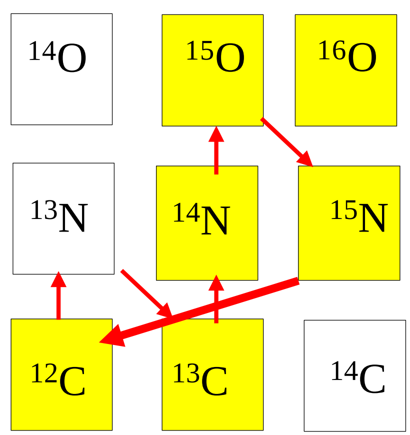
$^{13}N(\beta^+\nu)^{13}C$

$^{13}C(p,\gamma)^{14}N$

$^{14}N(p,\gamma)^{15}O$

$^{15}O(\beta^+\nu)^{15}N$

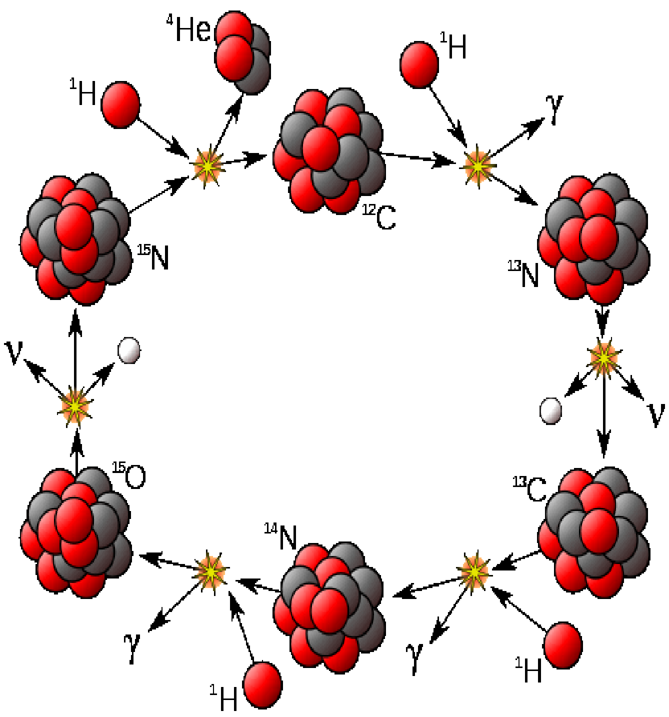
$^{15}N(p,\alpha)^{12}C$



- If the cycle starts with ^{12}C, it ends with $^{12}C \Rightarrow {}^{12}C$ is a catalyst & only hydrogen is consumed

The CNO cycle

- The rate of energy production in the CNO cycle $\boldsymbol{\varepsilon \propto Q_{CNO} / \tau_{CNO}}$ as well as the cycle duration is governed by the **slowest** reaction **$^{14}N(p,\gamma)^{15}O$: τ_{CNO}** $= \tau_p(^{12}C) + \tau_p(^{13}C) + \tau_p(^{14}N) + \tau_p(^{15}N) \cong$ **$\tau_p(^{14}N)$** **(**$\tau_{\beta+}(^{13}N) = 14$ min & $\tau_{\beta+}(^{15}O) = 2.9$ min (being negligible)



Ex: for ρ=100 g/cm-3, X_H=0.5 & T=60 MK

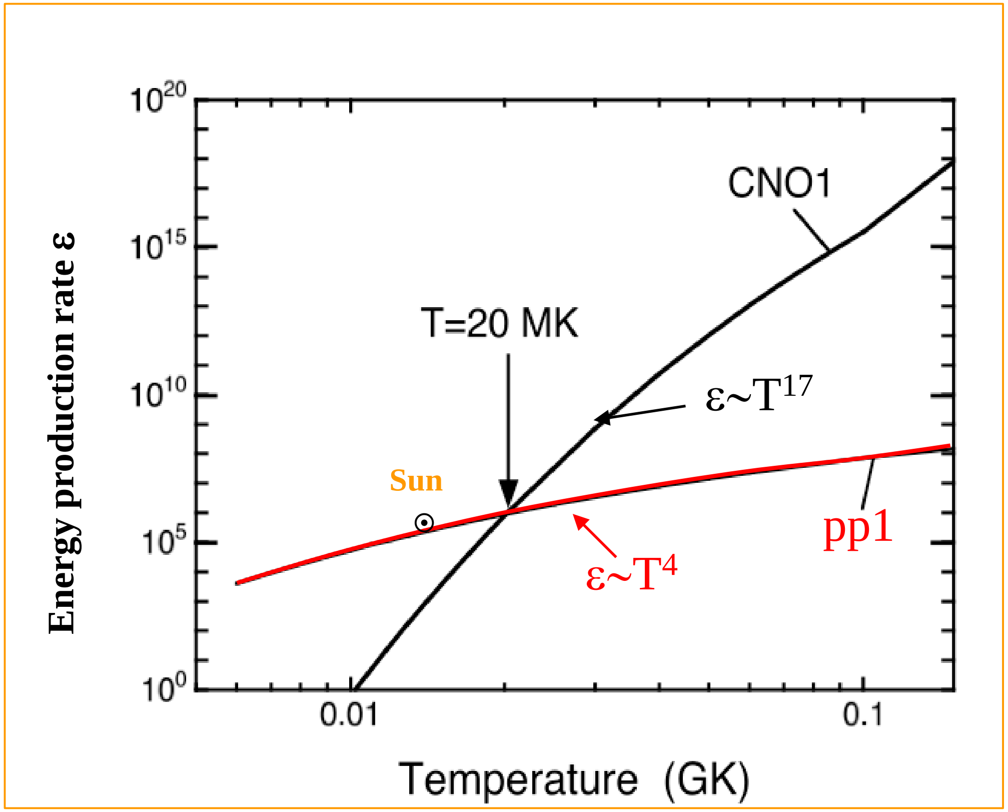
$\tau_p(^{12}C)=6.1\times10^9$ y; $\tau_p(^{13}C)=1.1\times10^9$ y: **$\tau_p(^{14}N)=2.1\times10^{12}$ y** ; $\tau_p(^{15}N)=1.0\times10^8$ y

- $^{14}N(p,\gamma)^{15}O$ has been measured by LUNA (lecture IV)

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

The CNO cycle

CNO : steeper temperature–dependence than pp chain (see later in lecture III)
⇒ pp chain dominates in low–mass main–sequence stars (~ $M_\odot$) and CNO cycle dominates in higher–mass stars (few $M_\odot$)



- T>20 MK: CNO1 faster than pp1
- $M \geq 1.5\ M_\odot \Rightarrow T_6 > 30$

⇓

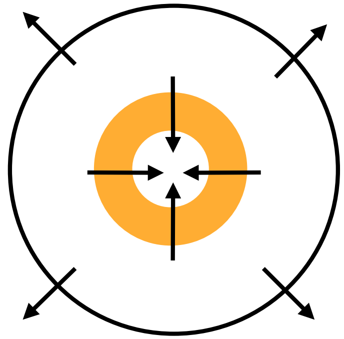
CNO cycle
(also depends on CNO abundance)

Hydrostatic stellar nucleosynthesis : Helium burning

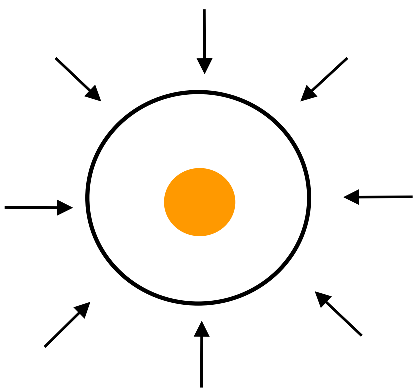
H exhausted in core
isothermal He core
contraction sets in

temperature increases

H-burning shell



$R \sim 10\text{-}100\ R_i \Rightarrow T_s \sim 3\text{-}4\text{x}10^3$ K



RED GIANT STARS
First step in old age

contracting core
expanding envelope

when $T \sim 10^8$ K and $\rho \sim 10^3$ gcm^{-3} (minimum mass $\sim 0.5\ M_\odot$)

HELIUM BURNING (2nd equilibrium)

Hydrostatic stellar nucleosynthesis : Helium burning

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

$T_C = (1\text{-}\ 4) \times 10^{8}$ K

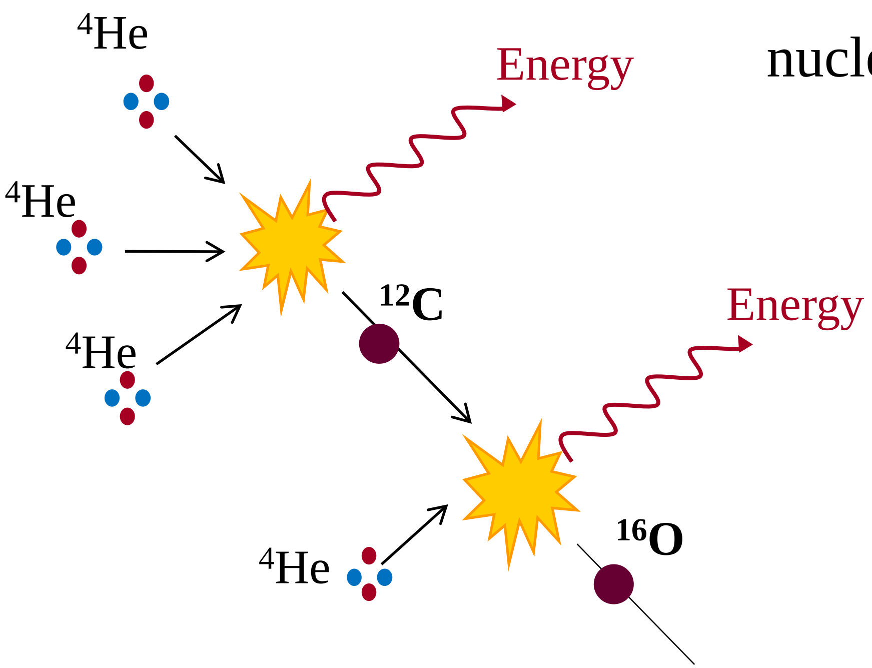
Main reactions:

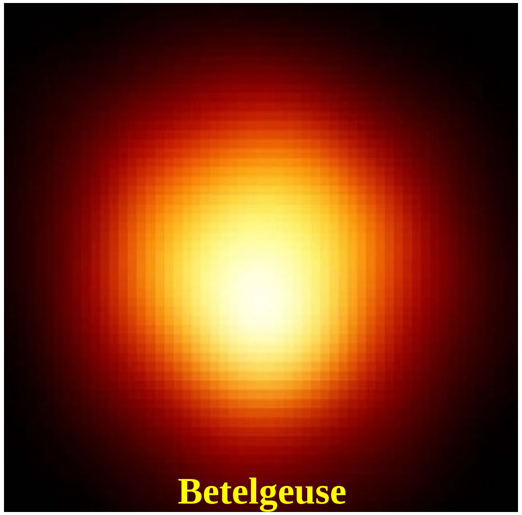
Triple a process : $3\alpha \rightarrow {}^{12}C$ Q=7.3 MeV

$^{12}C(\alpha,\gamma)^{16}O$ Q=7.2 MeV

$^{16}O(\alpha,\gamma)^{20}Ne$ Q=4.7 MeV

nuclear burning ashes energy source





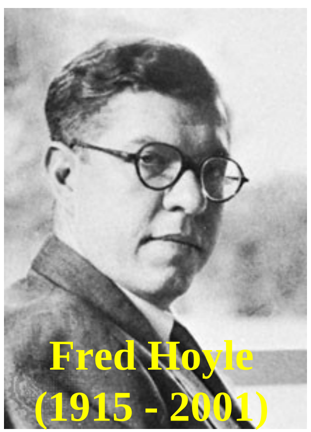
The triple α-process:

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

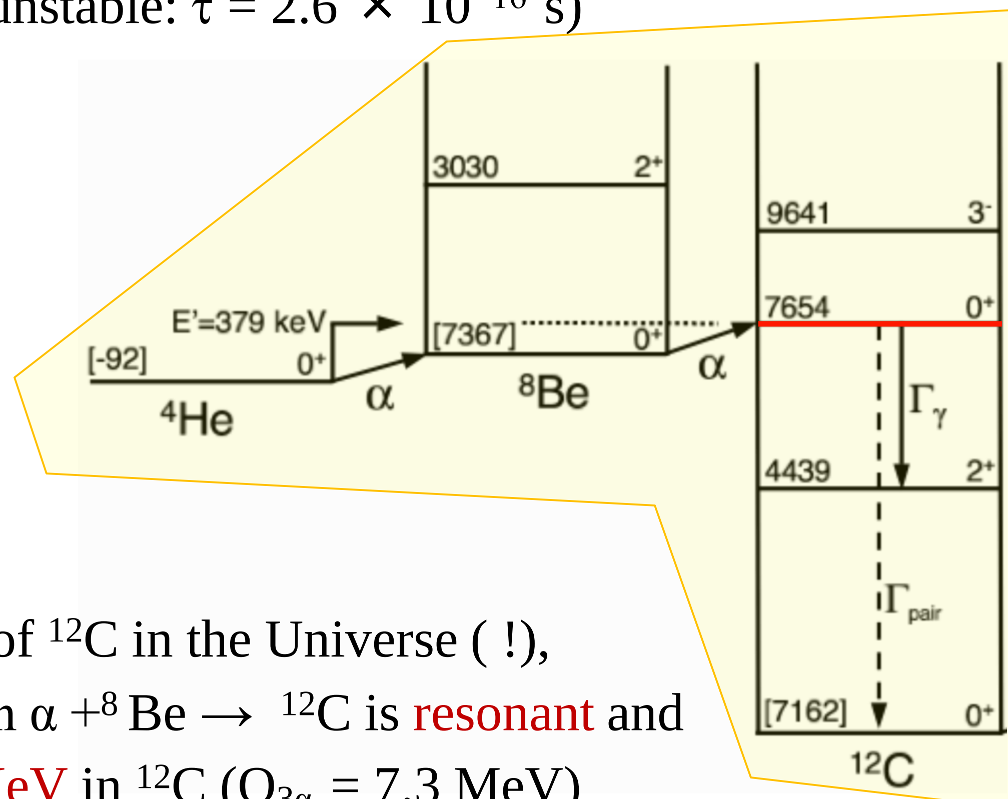
•Fusion of 3α in ^{12}C in 2 steps:

$\alpha + \alpha \rightarrow {}^8\mathrm{Be}$ Q=-92 keV   (^{8}Be is unstable: $\tau = 2.6 \times 10^{-16}$ s)

then $\alpha + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^*$ Q=-288 keV



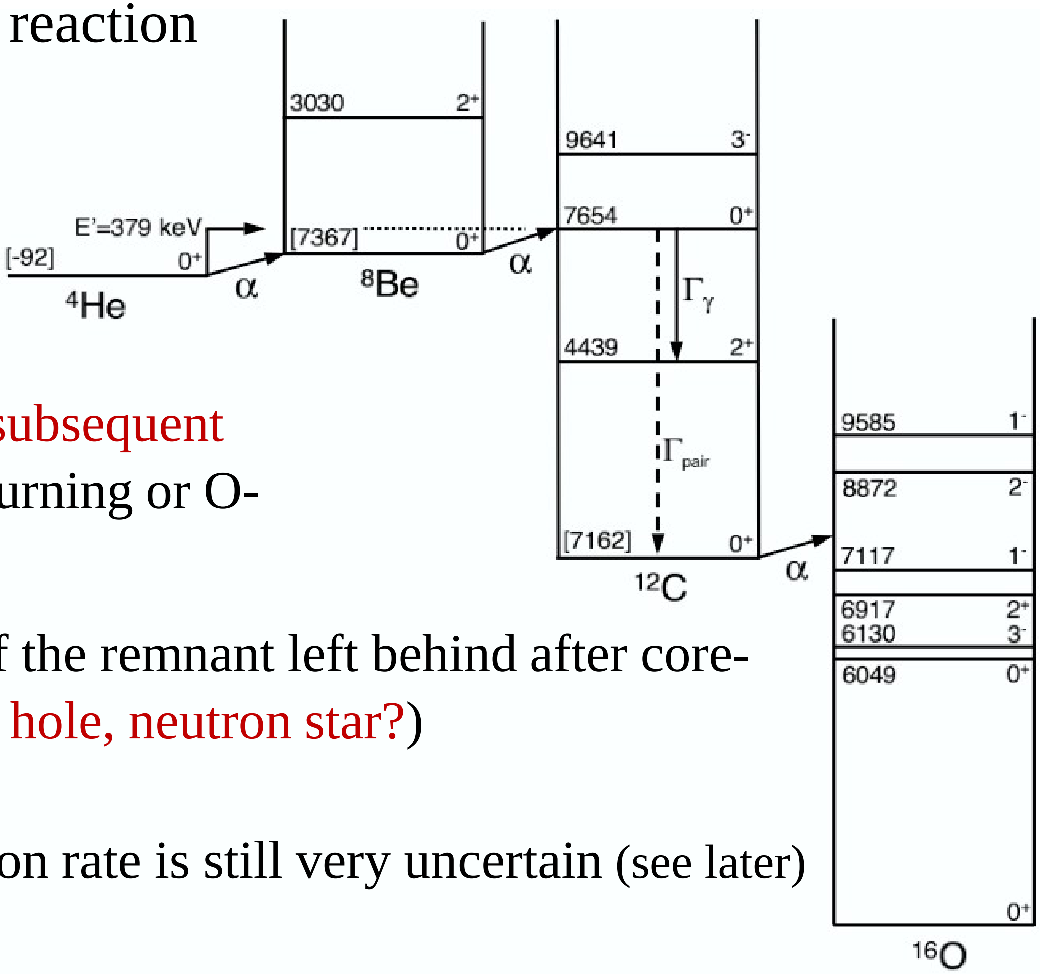
Fred Hoyle (1915 - 2001)



- In view of the significant abundance of ^{12}C in the Universe (!), Hoyle (1953) predicted that the reaction $\alpha + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C}$ is resonant and the existence of a $J^\pi = 0^+$ state at 7.7 MeV in ^{12}C ($Q_{3\alpha}$ = 7.3 MeV)

- Experimental verification in 1953 and 1957

$^{12}C+\alpha \rightarrow ^{16}O+\gamma$ $\rightarrow$ slow, crucial reaction



- The rate of this reaction determines the $^{12}C/^{16}O$ ratio at the end of the helium burning phase (solar abundance $(C/O)_{\odot} = 0.5$).
- $^{12}C/^{16}O$ ratio has impact on the the subsequent burning stages in massive stars (C-burning or O-burning?)
- $^{12}C/^{16}O$ ratio influences the nature of the remnant left behind after core-collapse supernova explosion (black hole, neutron star?)
- Various measurements but the reaction rate is still very uncertain (see later)

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

- reaction rate << rate of $^{12}C(\alpha,\gamma)^{16}O$) for $T<3\times10^{8}$ K $\Rightarrow$ survival of ^{16}O at the end of helium burning

Hydrostatic stellar nucleosynthesis: Helium burning

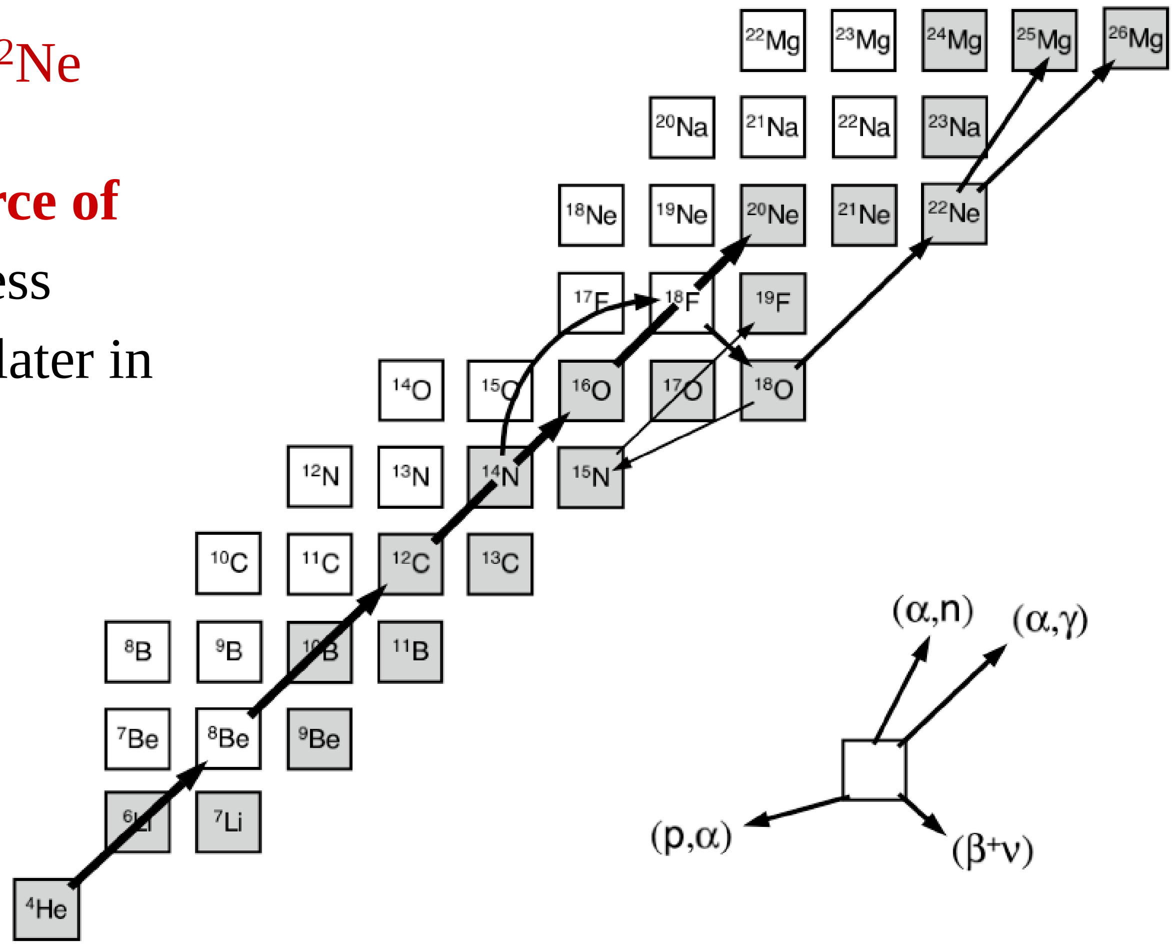
<u>Other reactions</u>:

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

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

+ $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ = main **source of neutrons** of the weak s-process ("slow" neutron capture, see later in this lecture)

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



Hydrostatic stellar nucleosynthesis: Advanced burning stages (I)

He exhausted in the core $\rightarrow$ mainly of ^{12}C & ^{16}O in the core $\rightarrow$ gravitational contraction $\rightarrow$ increase of T. When $T \sim (5\text{-}9)\times 10^{8}$ K and $\rho > 2.\ 10^{5}$ gcm^{-3} ($M \geq 8\ M_{\odot}$)

Carbon burning

Major reaction sequences:

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

$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ Q=2.24 MeV

$^{12}C + ^{12}C \rightarrow ^{23}Mg + n$ Q=-2.62 MeV

+several secondary reactions

Composition at the end of burning:

Mainly ^{20}**Ne** with some $^{21,22}Ne$, ^{23}Na, $^{24,25,26}Mg$, $^{26,27}Al$

and ^{16}**O**: still present in quantities comparable with ^{20}Ne (not burning … yet)

Hydrostatic stellar nucleosynthesis: Advanced burning stages (II)

- After C burning, when $T \sim (1\text{-}2)\times10^9$ K and $\rho \sim 10^6$ gcm^{-3} ($M \geq 11\ M_\odot$)

➡ **Neon burning**

Why would neon burn before oxygen ???

Answer:

Temperatures are sufficiently high to initiate **photodisintegration** of ^{20}Ne

$$\left.\begin{array}{l} ^{20}\text{Ne}+\gamma \rightarrow {}^{16}\text{O} + \alpha \ (Q=-4.73\ \text{MeV}) \\ ^{16}\text{O}+\alpha \rightarrow {}^{20}\text{Ne} + \gamma \end{array}\right\} \text{ equilibrium is established}$$

this is followed by (using the released helium)

$$^{20}\text{Ne}+\alpha \rightarrow {}^{24}\text{Mg} + \gamma \quad (Q=9.31\text{MeV})$$

so net production of nuclear energy : $\boxed{2\ {}^{20}\text{Ne} \rightarrow {}^{16}\text{O} + {}^{24}\text{Mg}+4.58\ \text{MeV}}$

- Main nuclear ash **^{16}O** with some ^{24}Mg

Hydrostatic stellar nucleosynthesis: Advanced burning stages (III)

After Ne burning, the core contracts further until $T \sim (2\text{-}3)\times10^9$ K and $\rho \sim 3\times10^6$ g.cm^{-3}

($M \geq 11\ M_\odot$)

➡ **Oxygen burning**

Major reaction sequences:

$$^{16}O + ^{16}O \rightarrow\ ^{32}S^* \rightarrow\ ^{31}S + n \quad Q=1.45\ \text{MeV}$$

$$\rightarrow\ ^{31}P + p \quad Q=7.68\ \text{MeV}$$

$$\rightarrow\ ^{30}P + d \quad Q=-2.41\ \text{MeV}$$

$$\rightarrow\ ^{28}Si + \alpha \quad Q=9.59\ \text{MeV}$$

+ recapture of n,p,d,α

Main nuclear ashes:

^{28}Si and to a somewhat lesser extent ^{32}S

Hydrostatic stellar nucleosynthesis: Advanced burning stages (IV)

After O burning, the core contracts until $T \sim (3\text{-}4)\times10^9$ K and $\rho \sim 3\times10^7$ g.cm^{-3}

($M \geq$ 11 $M_\odot$)

➡ Silicon burning

- Starts with ^{28}Si photodesintegration: $^{28}Si(\gamma,\alpha)^{24}Mg(\gamma,\alpha)^{20}Ne(\gamma,\alpha)\ldots$
- Photodesintegration rearrangements: destruction of less tightly bound species and capture of released p, n, α to synthesize more tightly bound species
- Many reactions achieve nuclear statistical equilibrium (NSE)

  $\rightarrow$ NSE is established when both, photodisintegration rates of the type:

  $(Z,N) + \gamma \rightarrow (Z\text{-}1,N) + p$; $(Z,N) + \gamma \rightarrow (Z,N\text{-}1) + n$; $(Z,N) + \gamma \rightarrow (Z\text{-}2,N\text{-}2) + \alpha$

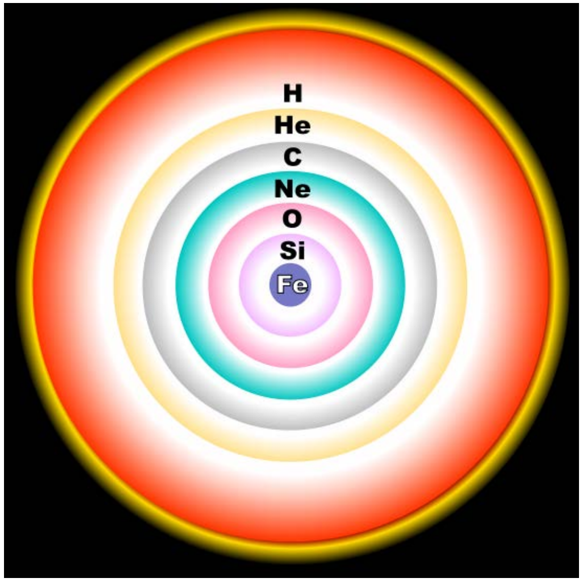
  and capture reactions of type: $(Z,N) + p \rightarrow (Z+1,N) + \gamma$; $(Z,N) + n \rightarrow (Z,N+1) + \gamma$;

  $(Z,N) + \alpha \rightarrow (Z+2,N+2) + \gamma$ are fast

- equilibrium drives nuclei towards A=56 : most stable nuclei (higher binding energy)
- synthesis of nuclei from Si to Zn ("iron peak" elements Ti to Zn)
- Main ash is ^{56}**Fe** $\rightarrow$ formation of an iron core

Hydrostatic stellar nucleosynthesis: Advanced burning stages

After ^{28}Si burning (Melting), the star core is mainly made of iron. The final stage of a massive star has an onion-ring structure like



→ **PRE-SUPERNOVA STARS**

- Further reactions become endothermic
- Stars can no longer convert mass into energy via nuclear fusion!

  ⇒ final gravitational collapse

  ⇒ **SUPERNOVA EXPLOSION**

  (Core-collapse Supernova or Supernova type II)

  ⇒ remnant: neutron star or black hole

SN remnant Cassiopeia A

Chandra X-ray Observatory image

Note: Burning also takes place in thin regions (burning shells) at the interface of different composional layers

Hydrostatic stellar nucleosynthesis: 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

Back to the HR diagram: Main sequence and Red Giant Branch

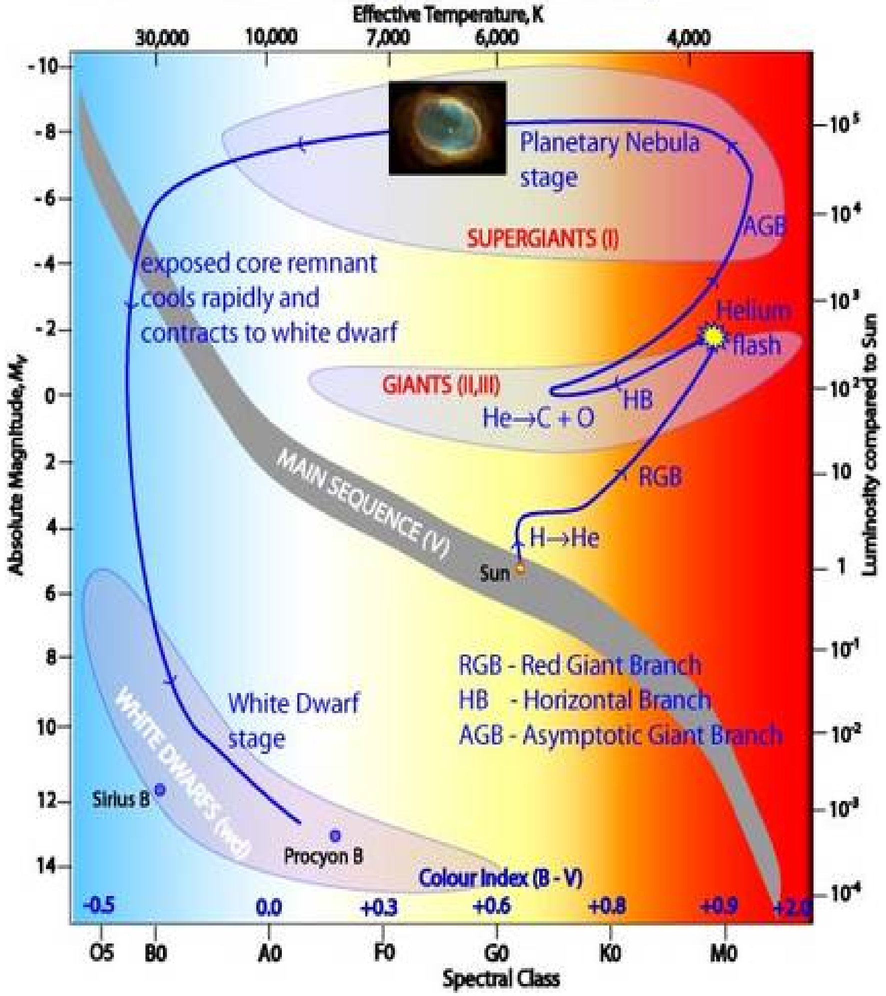
➢H–burning core ≡ main sequence
and H–burning shell ≡ red giant branch (If $M_{star} \geq 10 M_{\odot}$ → red supergiant)

➢ H–burning core leads to He core:

M_c ↗ core contracts, **T_c ↗**, **P↗**
⇒ He inert core surrounded by H–burning shell ⇒ expansion and cooling of the envelope
($R_{\odot} \rightarrow 50\ R_{\odot}$ ~ Mercury)

➢ subgiant phase (horizontal in HR diagram : **R ↗**, **$T_e$ff ↘** and L ≈ cst)

➢ red giant phase (vertical in HR diagram : L ↗at T_{eff} ↘)



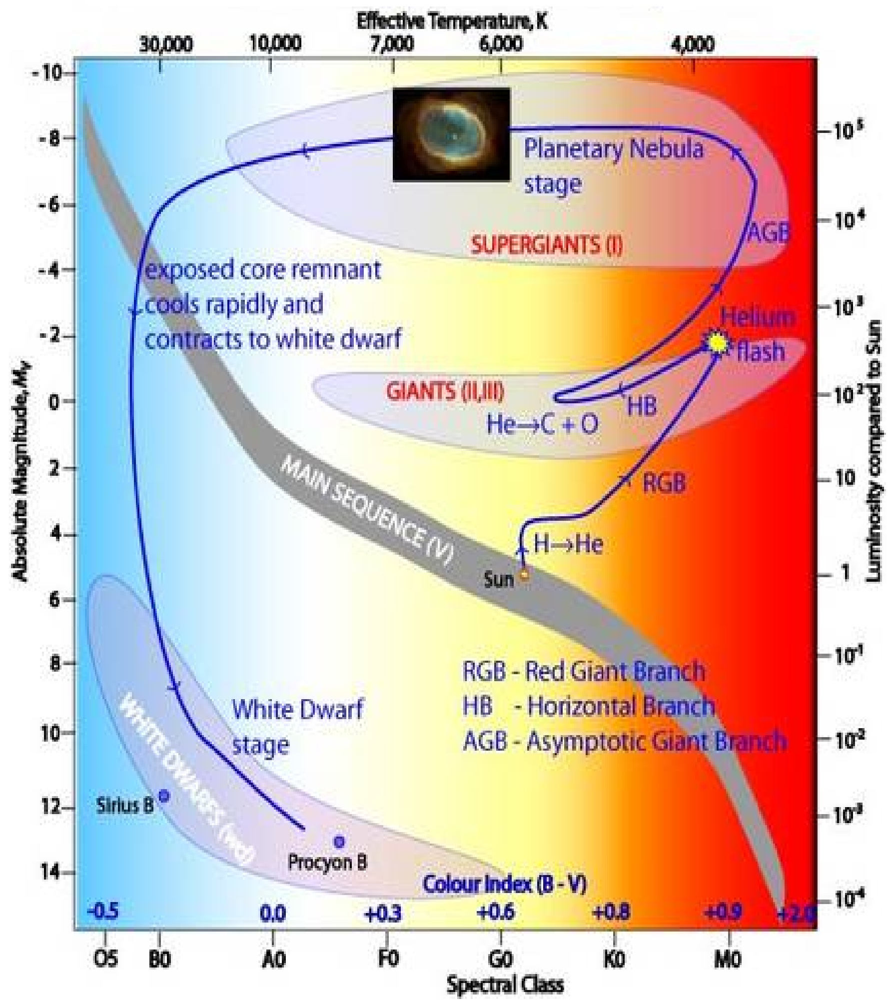
Back to the HR diagram: Stars of the horizontal branch (I)

- Ignition of the He core at $T_C \sim 10^8$ K $\Rightarrow$ core contraction stops

- In low-mass stars (0.7-2 $M_\odot$) the electron gas in the centre is partially degenerate $\Rightarrow$ helium flash

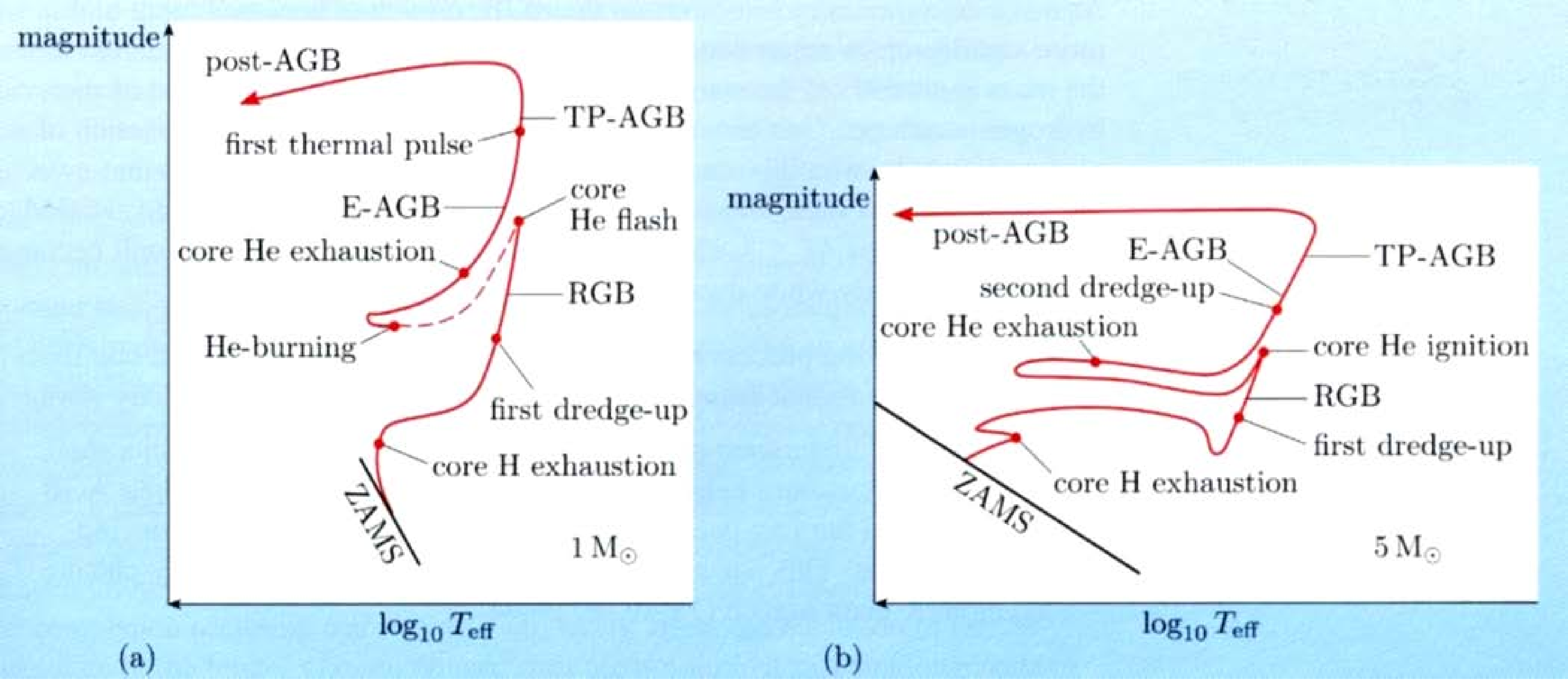
$\Rightarrow$ Release during a few seconds of $10^{10}\ L_\odot$ in L_{nuc}! But invisible from the surface

$\Rightarrow$ Expansion and cooling of the core result in the contraction and heating of the envelope



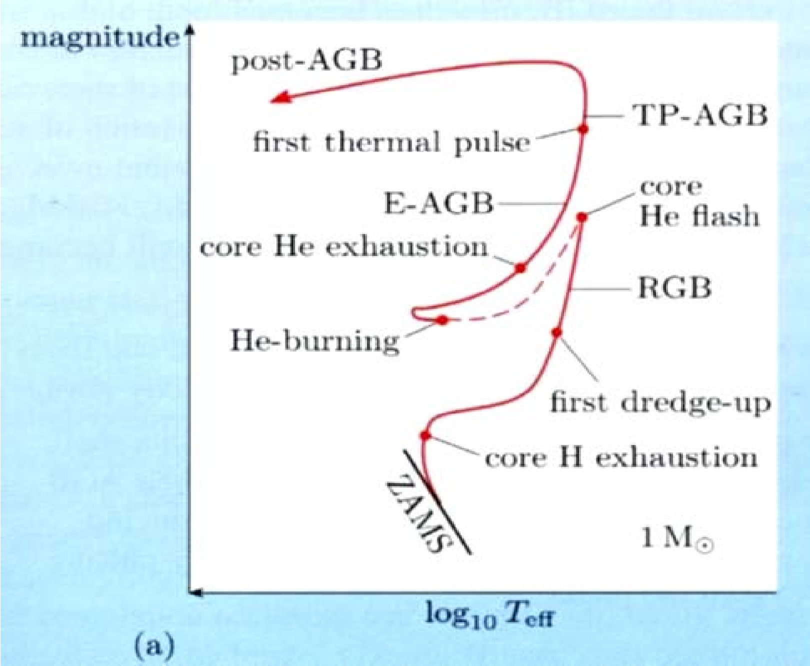
Stars of the horizontal branch (II)

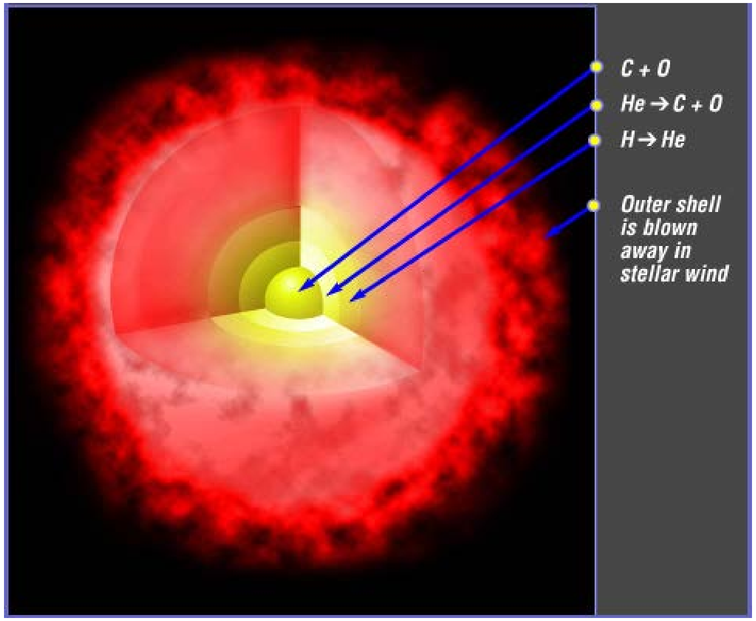
- Quiet ignition of the He core (convective) for intermediate-mass stars (2-10 $M_{\odot}$)

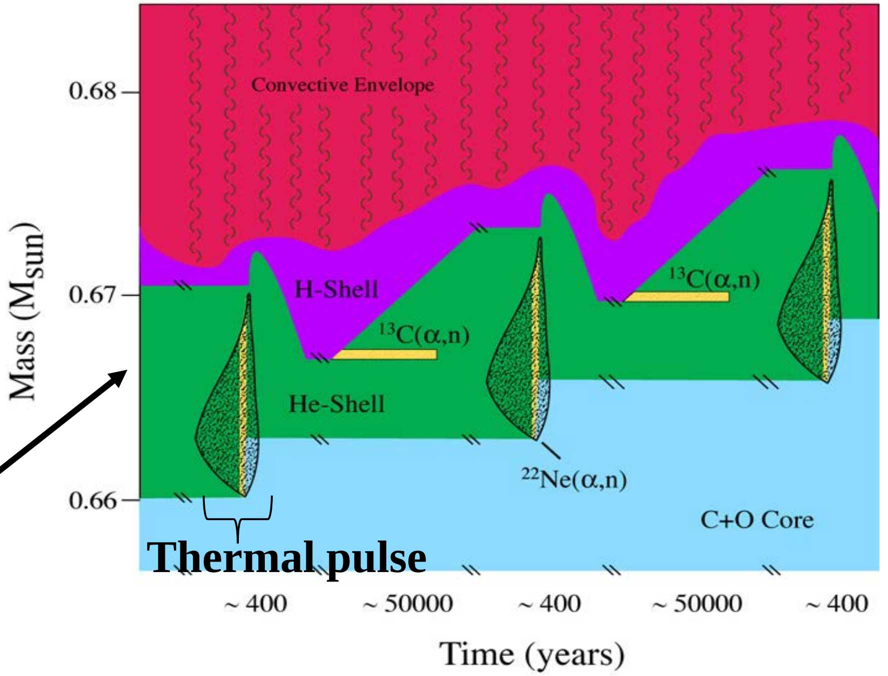


Back to the HR diagram: AGB (Assymptotic Giant Branch) stars

- Asymptotic giant branch. E-AGB = early AGB
- H-burning ashes are brought to the surface by convection







Mixing of ashes from H and He burning.
Site of the s process (see later)

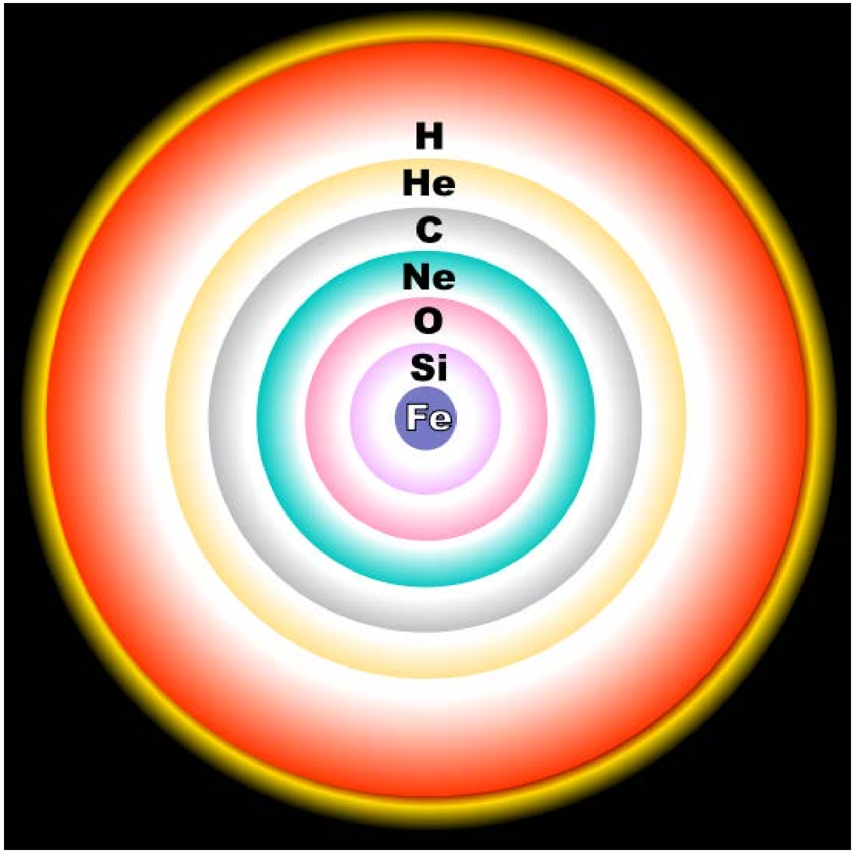
Evolution of a solar-type star

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

Stellar Nucleosynthesis:
Explosive stellar burning

Explosive stellar burning: Core-collapse supernova

Remember: "Onion Shell" Structure of Massive Star: Instant Before Core Collapse



- no other nuclear energy source is available to core
- core is in NSE, with $T=10^{10}$ K and $\rho=10^{10}$ g/cm^3
- grows in mass; when it reaches 1.4 times solar mass, electron degeneracy pressure is unable to counteract gravity…
- rapid heating and compression of the matter enhance the collapse by 2 processes :

  - photodisintegration (many ways), exemple:

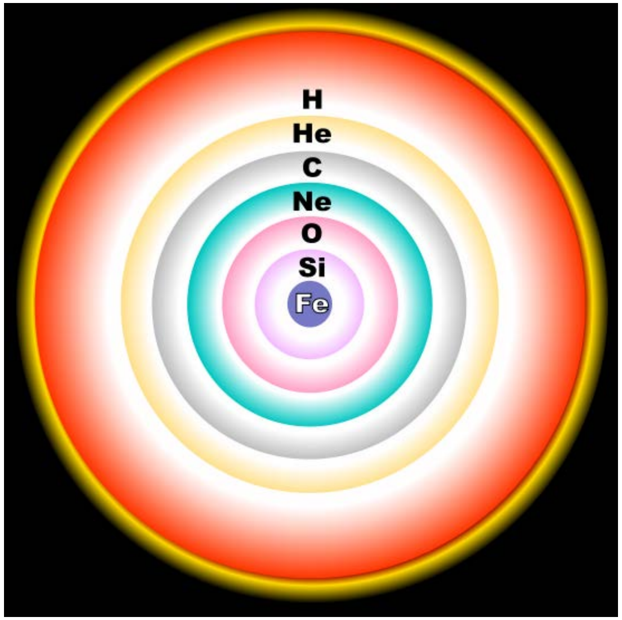
    $\gamma+{}^{56}Fe \rightarrow 13\ {}^{4}He+4n$

  - electron capture on nuclei: ${}^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-1}N + \nu_e$

- when $\rho=10^{14}$ g/cm^3: nuclei and nucleons feel short-range nuclear force [repulsive at very short distance] $\rightarrow$ inner part of core rebounds, producing an outward **moving shock wave…**

Explosive stellar burning: Core-collapse supernova

Explosive burning: → Shock moving through "Onion" Layers



Explosive Si burning:

➢ outgoing shock wave heats inner ^{28}Si layer of star to high T and ρ ; matter approaches NSE: composition entirely determined by values of T, ρ, and neutron excess η

- at T=6 GK, NSE is quickly established
- complete conversion of ^{28}Si to ^{56}Ni ["complete explosive silicon burning"]

Explosive O burning: ➢ next layer reached by shock is composed of ^{16}O

➢at T=3.8 GK, ^{16}O fuel is depleted via ^{16}O+^{16}O, ^{16}O(γ,α)^{12}C, etc., giving rise to two clusters in the mass regions of Si and Fe with more material in the Si region

➢Most abundant nuclides: ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca ("α-element") and some iron peak species

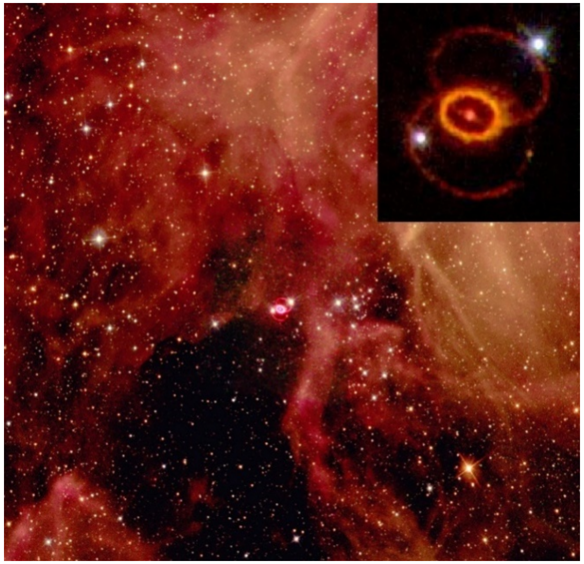
Explosive NeC burning: ➢ next layer reached by shock is composed of ^{16}O,^{20}Ne, ^{12}C

➢ at T=2.5 GK, ^{20}Ne & ^{12}C burn explosively

➢ Production of the radio-isotope ^{26}Al via ^{24}Mg(n,γ)^{25}Mg(p,γ)^{26}Al (γ-ray astronomy)

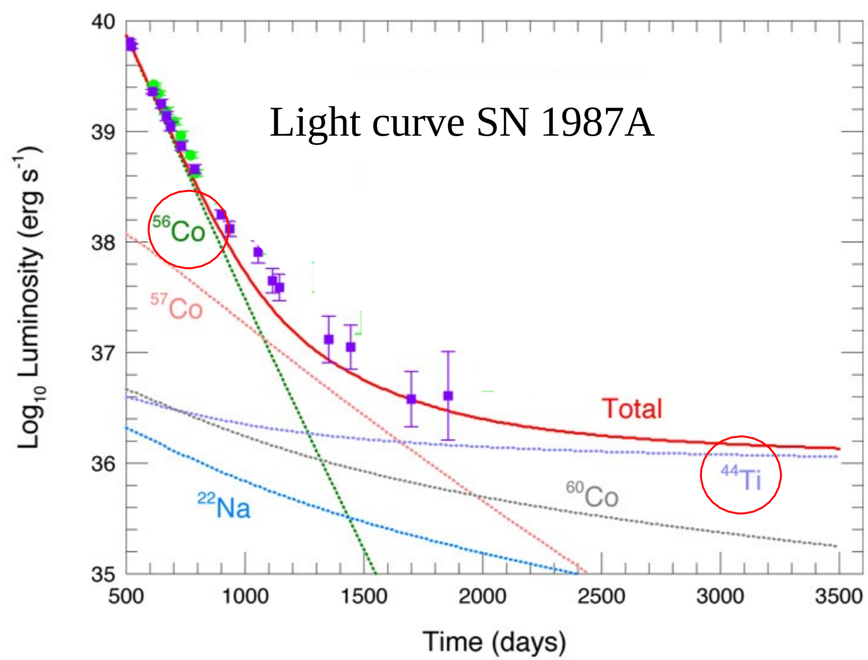
Explosive stellar burning: Core-Collapse Supernova observations

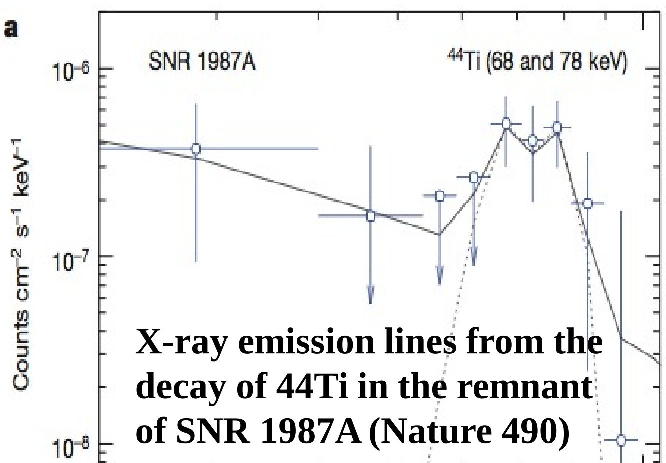
- The brightest objects in the universe $\rightarrow$ Luminosity : ~$10^{9\text{-}10}$ L_{sun}



Supernova SN1987A

h^p://cococubed.asu.edu/images/V44_co60





X-ray emission lines from the decay of 44Ti in the remnant of SNR 1987A (Nature 490)

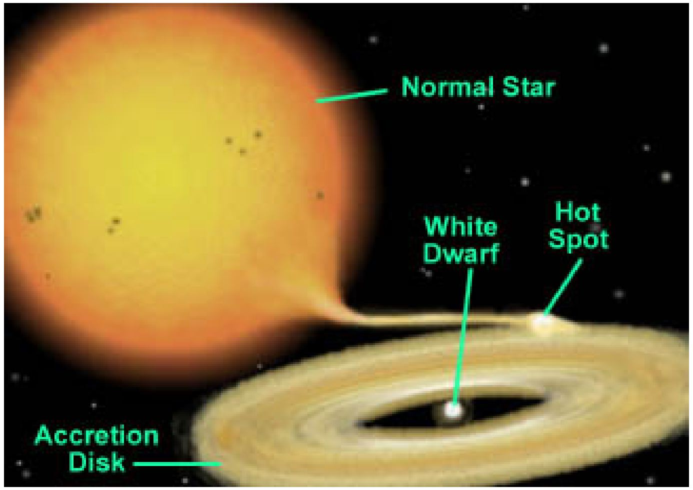
$$^{56}\mathrm{Ni} \xrightarrow{T_{1/2}=6.1\ \mathrm{d}} {}^{56}\mathrm{Co} \xrightarrow{T_{1/2}=77.3\ \mathrm{d}} {}^{56}\mathrm{Fe}\ \text{(stable)}$$

SN1987A: $m(^{56}\mathrm{Ni})=0.07\pm0.01\ M_{s\odot}$

Explosive stellar burning: NOVAE

NOVAE = sudden increase in star's luminosity ($L \sim 10^4 - 10^6\ L_i$ and $t \sim 1$ h–1 d)

Binary system: White Dwarf + accreting normal star (e.g. SUN)



H-rich mass transfer from companion to WD

⬇

temperature and density increase
on WD's surface

thermonuclear runaway $\Rightarrow$ cataclysmic explosion

(p,γ) reactions on proton-rich nuclei

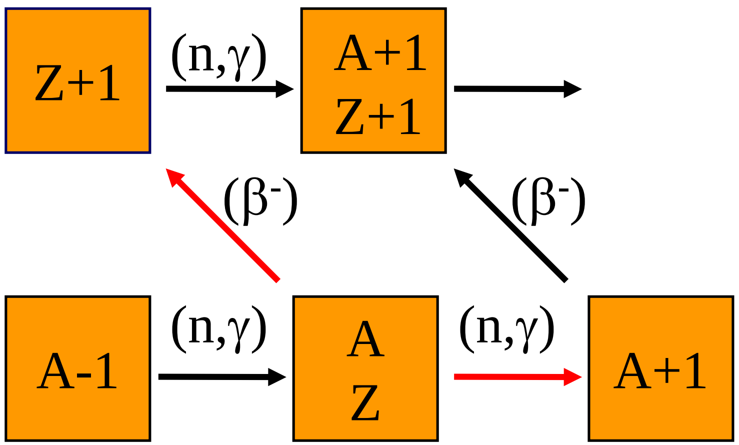
$T > 10^8$ K
$\rho > 10^3$ g cm^{-3}

➡ nucleosynthesis up to A ~ 40 mass region

Nucleosynthesis beyond Fe

Nucleosynthesis beyond Fe

- start with Fe *seeds*
- Elements heavier than Fe can not be synthesized by fusion reactions, their formation is explained by neutrons capture reactions
- Z change $\rightarrow$ β decay



DEFINE:

mean lifetime of nuclei A
against destruction by neutron capture

$$\tau_n(X) = \frac{1}{N_n < \sigma v >}$$

if $\tau_n > \tau_\beta$ $\Rightarrow$ unstable nucleus decays
if $\tau_n < \tau_\beta$ $\Rightarrow$ neutron capture

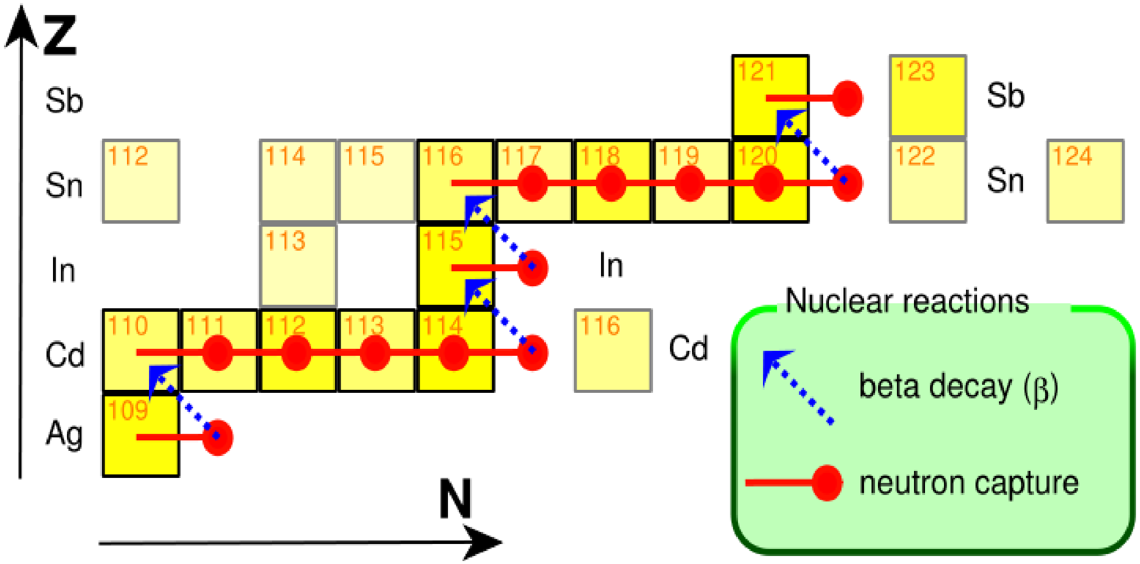
τ_β = beta-decay lifetime
(seconds $\rightarrow$ years)

Nucleosynthesis beyond Fe: s-process

s-process (s = slow neutron capture process)

unstable nucleus decays before capturing another neutron

$$\tau_\beta \ll \tau_n \quad \Leftrightarrow \quad N_n \sim 10^8 \text{ n/cm}^3$$



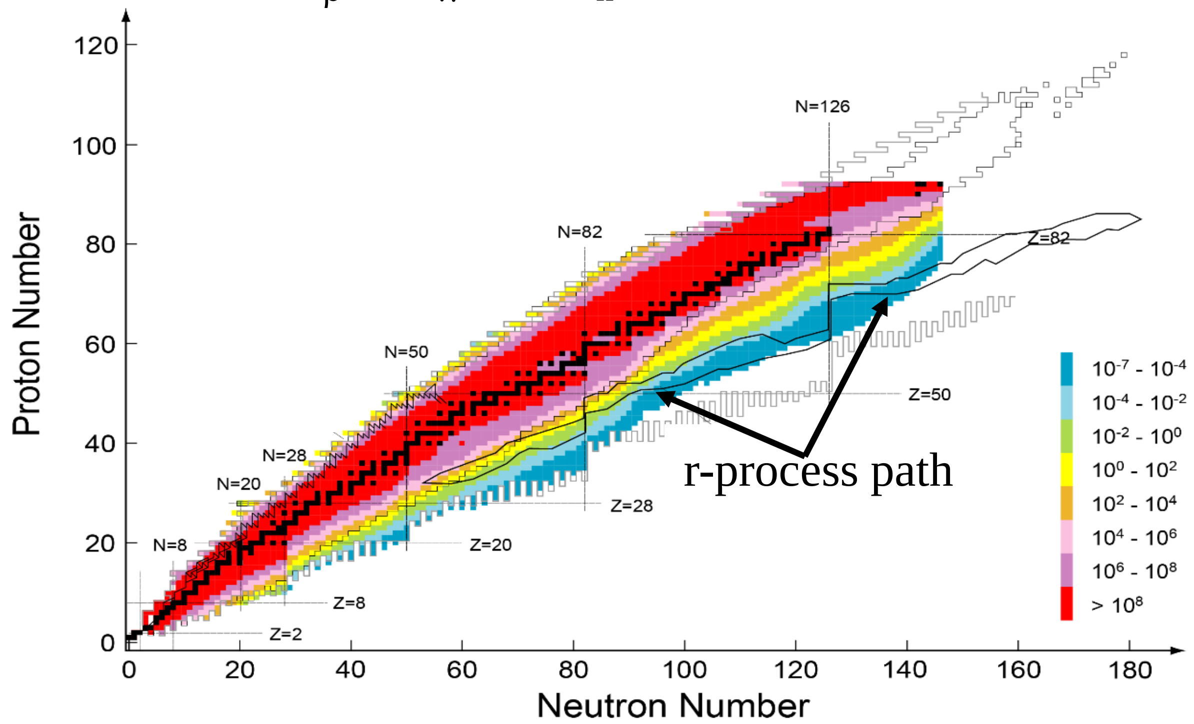
- synthesis path along valley of β– stability up to ^{209}Bi (long time scale ~ 10^4 years)
- neutron source: $^{13}C(\alpha,n)^{16}O$ and/or $^{22}Ne(\alpha,n)^{25}Mg$
- quiescent scenarios: AGB stars (low and intermediate mass $M<8\,M_\odot$ or massive stars $M\geq8M_\odot$)

Nucleosynthesis beyond Fe: r-process

r-process (r = rapid neutron capture)

unstable nucleus captures another neutron before decaying

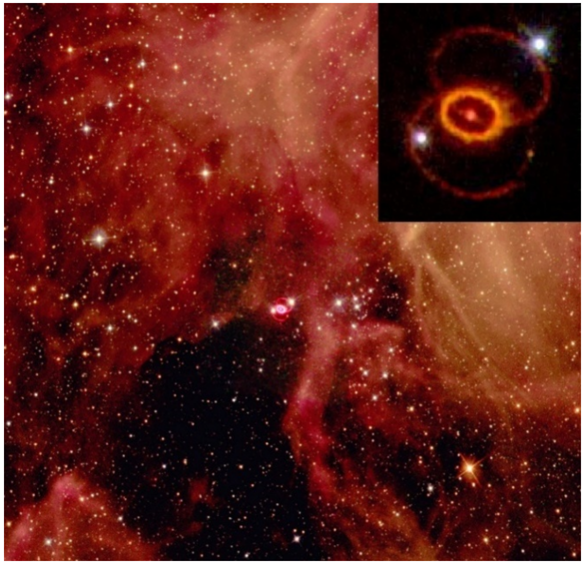
$$\tau_\beta >> \tau_n \Leftrightarrow N_n >> 10^{20}\ n/cm^3$$



synthesis path far from valley of β –stability (short timescale ~ seconds)

- synthesis of n-rich nuclei
- unknown nuclear properties
- explosive scenarios but where?

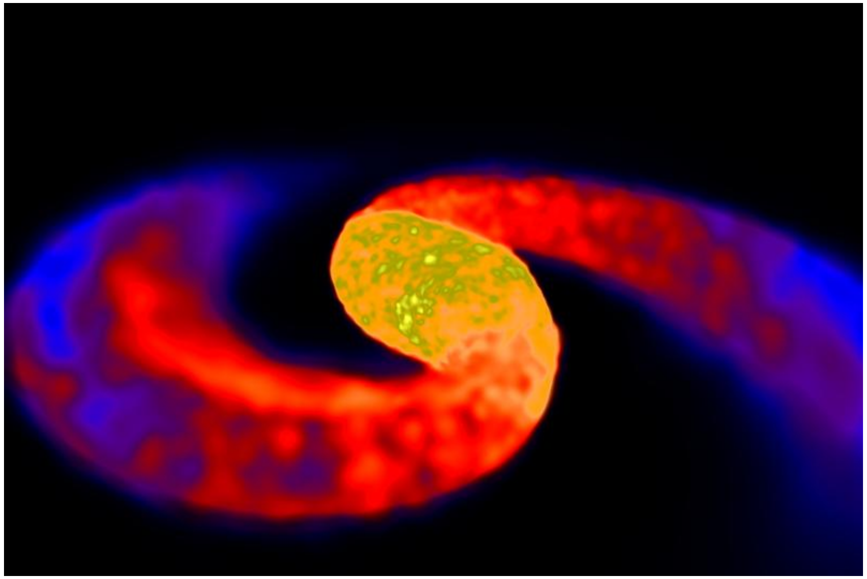
r-process: Astrophysical sites?



Supernova SN1987A

Core-collapse supernova?

- Neutrino-winds from protoneutron stars, …

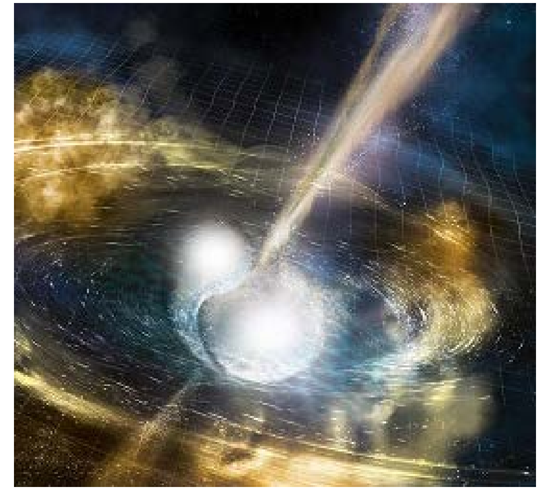


Neutron star mergers ?

- Mergers are expected to eject around 0.01 $M_\odot$ of very neutron rich-material
- Sources of gravitational waves
- Observational signature: electromagnetic emission from radioactive decay of r-process nuclei
  $\rightarrow$ **kilonova**

r-process: Neutron star mergers

- **17/08/2017** → gravitational waves were detected from neutron star mergers, **GW170817**, by LIGO/VIRGO.



- An optical transient source, Swope Supernova Survey 17a (SSS17a), was subsequently identified as the counterpart of this event in the galaxy NGC4993 at ~ 40 Mpc distance

First day

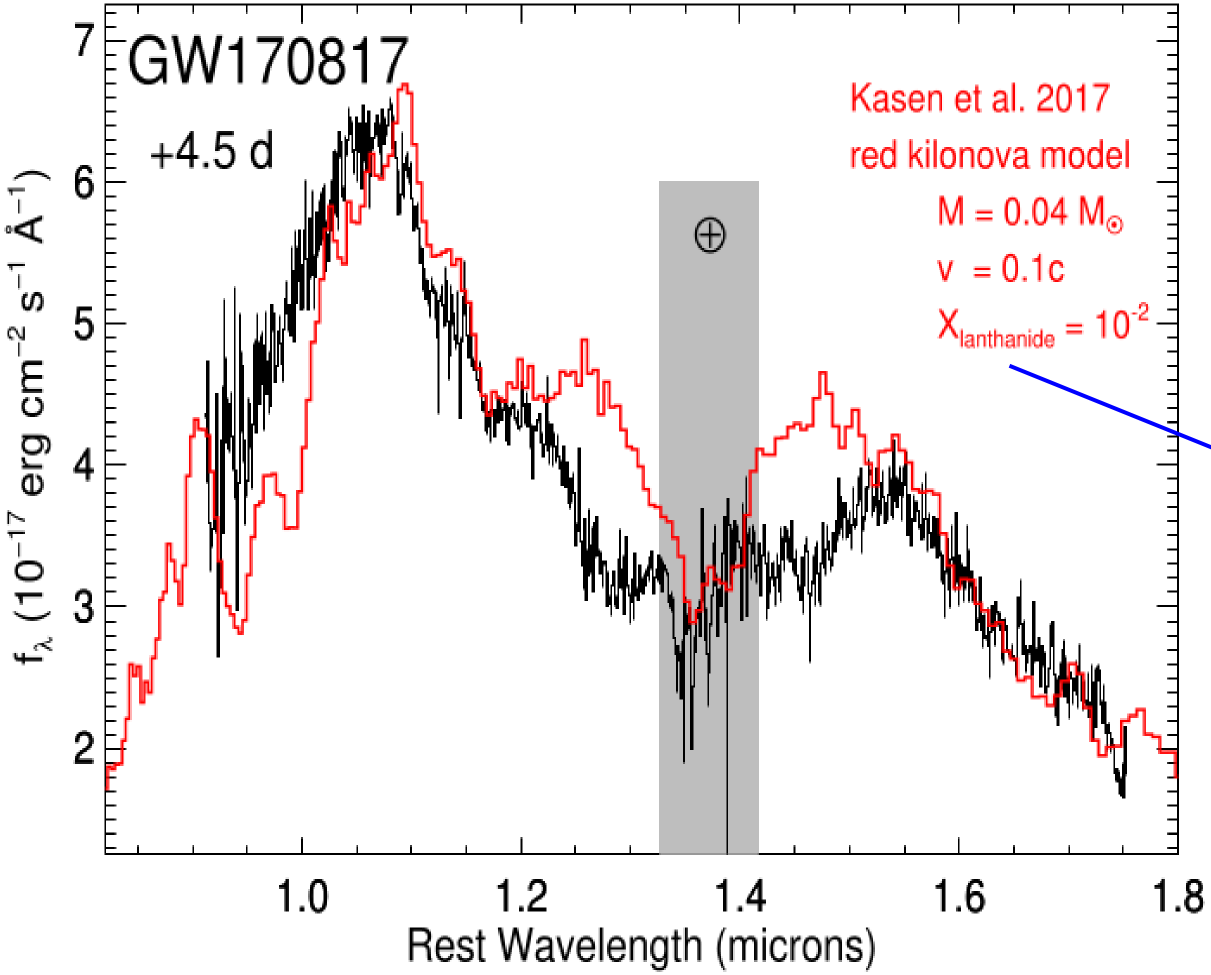
- Bright & Blue

4 days later

- Fade & red

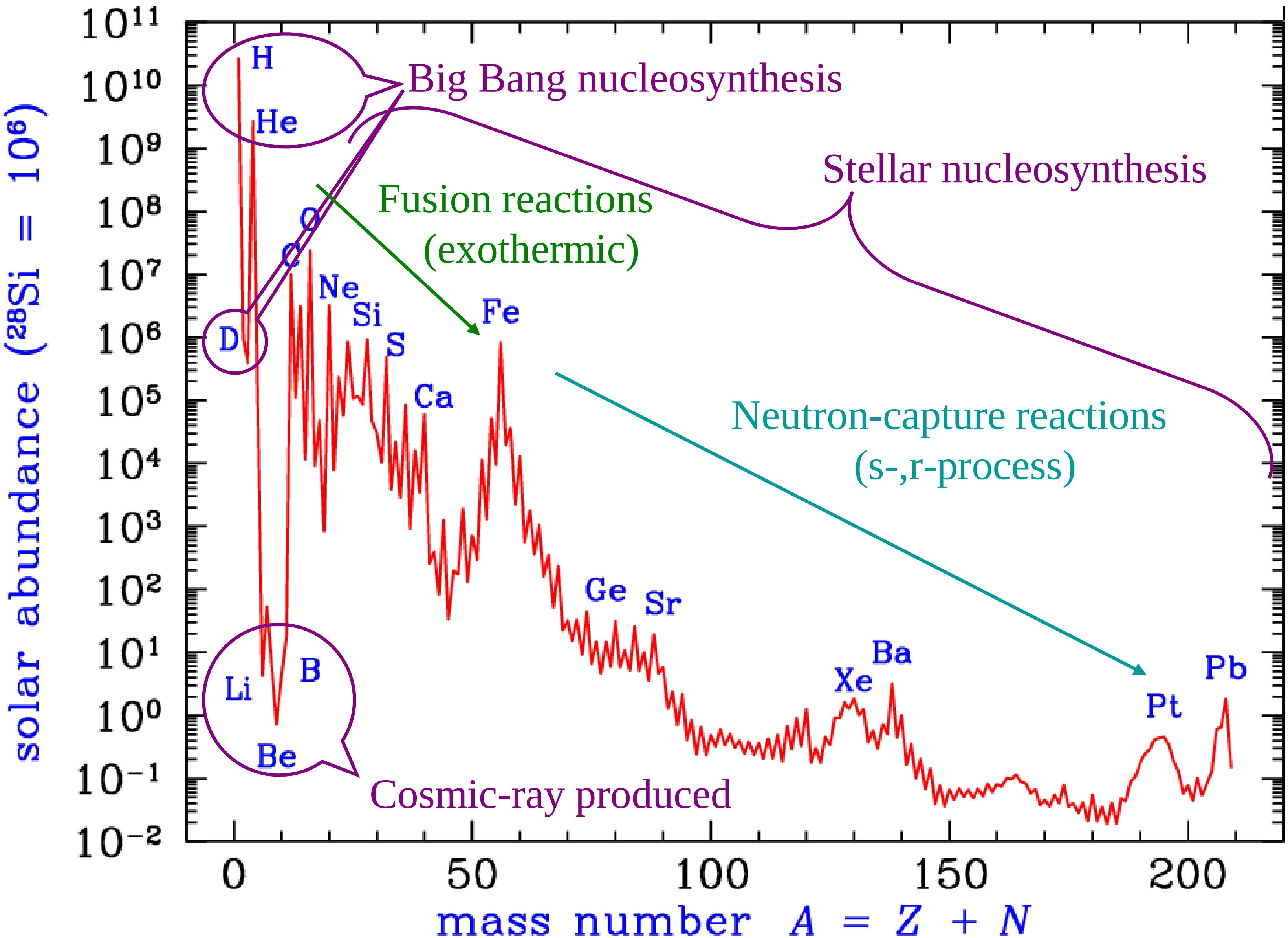
These observations show that the **heaviest r-process elements** were produced in neutron star mergers

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

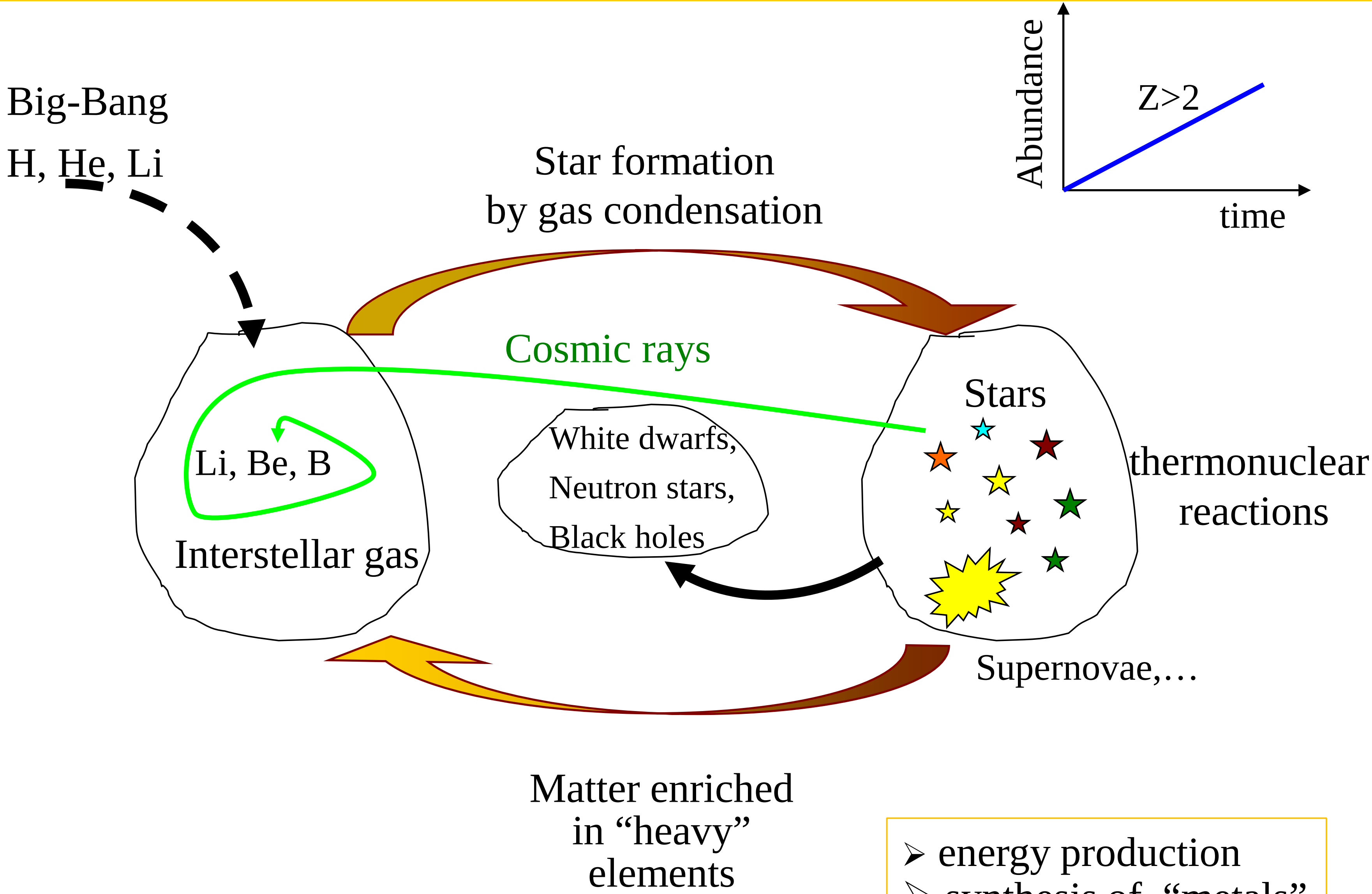


r-process heavy elements

The origin of elements: Summary



Summary: Big-Bang & star life cycle



- energy production
- synthesis of “metals”