Nuclear Astrophysics:
Lecture 1

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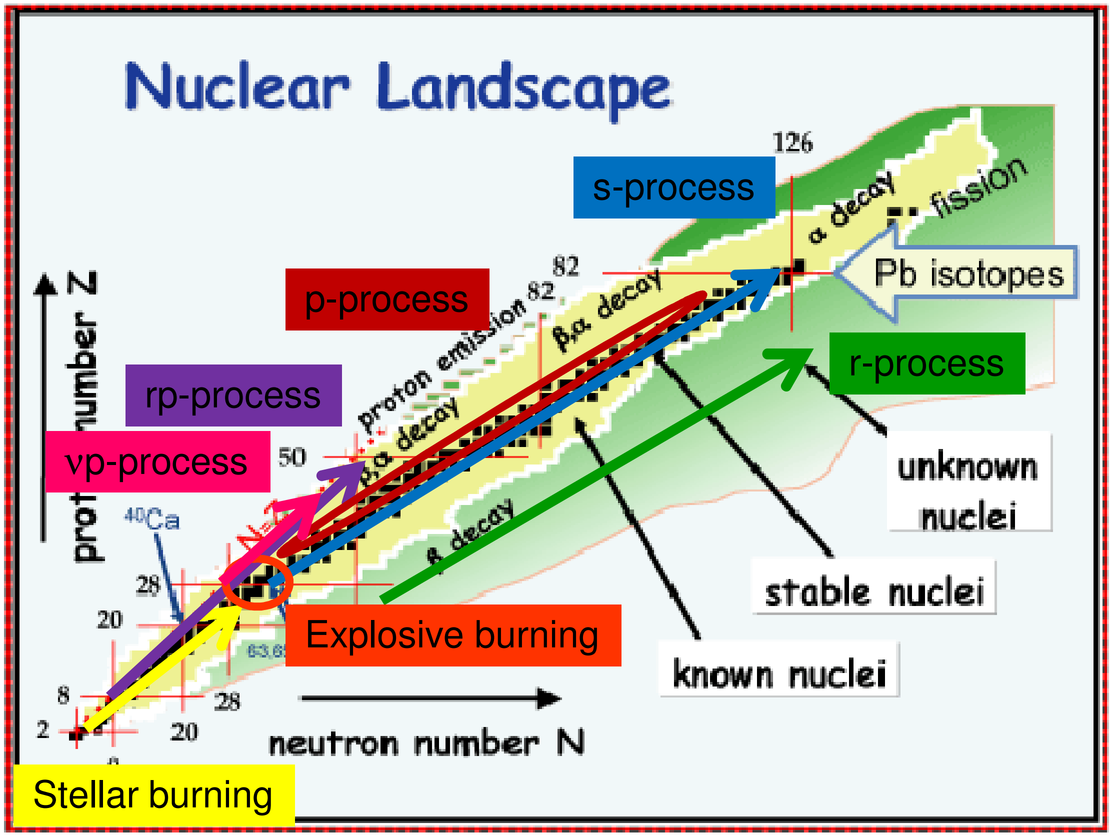
Lecture plan

- Lecture 1
    - Solar system abundances
    - A tiny little bit of BBN
    - Hydrostatic nuclear burning
    - Thermonuclear reaction rates

- Lecture 2
    - Explosive nuclear burning
    - Heavy element synthesis
    - Spectroscopy and metal-poor stars

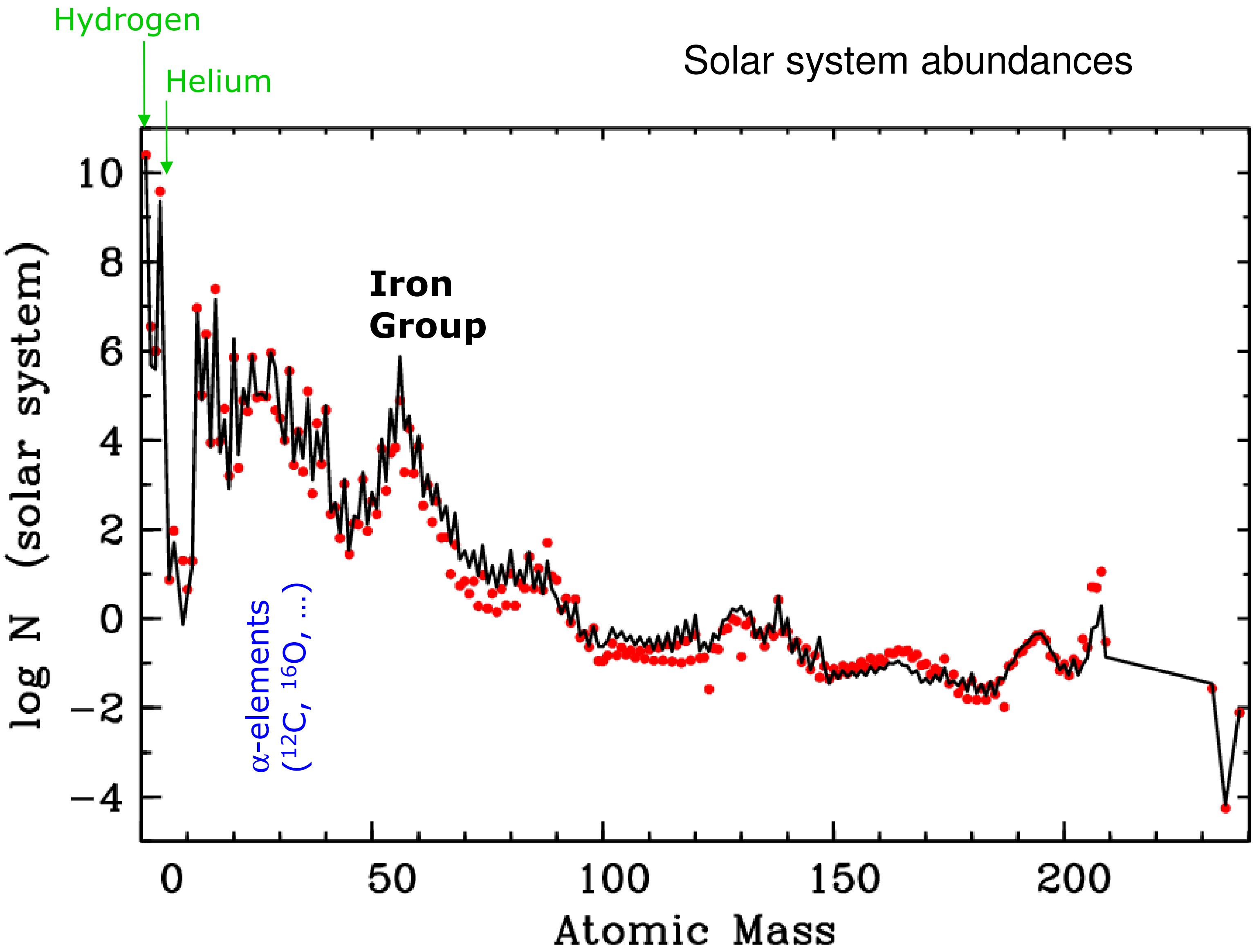
Origin of elements



Astrophysical sites:

- Stellar evolution of low-mass and massive stars
- AGB stars (main s-process)
- core He-burning of massive stars (weak s-process)
- Supernovae
- Core-collapse supernovae
- Core-collapse supernovae
- Neutrino-driven winds in SNe?
- NS mergers
- X-ray bursts

Origin of elements



Big Bang Nucleosynthesis (BBN)

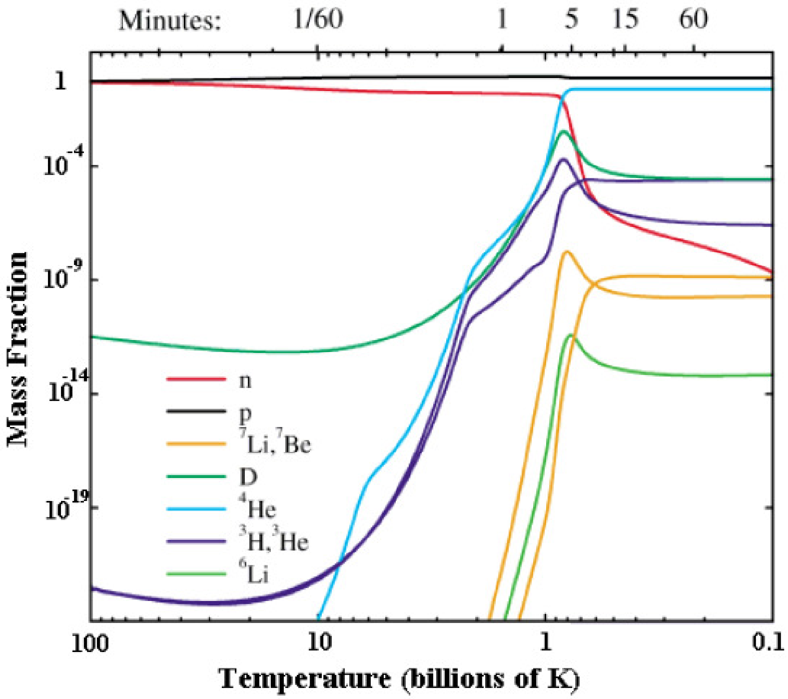
- After t ~ 180 s nuclear reactions begin to occur in earnest.
- There are essentially just 11 reactions.
- The most important 7 are:

$$
\begin{gathered}
n+p \Rightarrow D+\gamma \\
D+p \Rightarrow {}^{3}He+\gamma \\
D+D \Rightarrow {}^{3}He+n \\
D+D \Rightarrow {}^{3}H+p \\
{}^{3}H+p \Leftrightarrow {}^{3}He+n \\
D+{}^{3}H \Rightarrow {}^{4}He+n \\
D+{}^{3}He \Rightarrow {}^{4}He+p
\end{gathered}
$$

- The other 4 reactions that occur are:

$$
\begin{gathered}
{}^{4}He+{}^{3}H \Rightarrow {}^{7}Li+\gamma \\
{}^{4}He+{}^{3}He \Rightarrow {}^{7}Li+\gamma \\
{}^{7}Be+n \Rightarrow {}^{7}Li+p \\
{}^{7}Li+n \Rightarrow 2\,{}^{4}He
\end{gathered}
$$

Big Bang Nucleosynthesis (BBN)

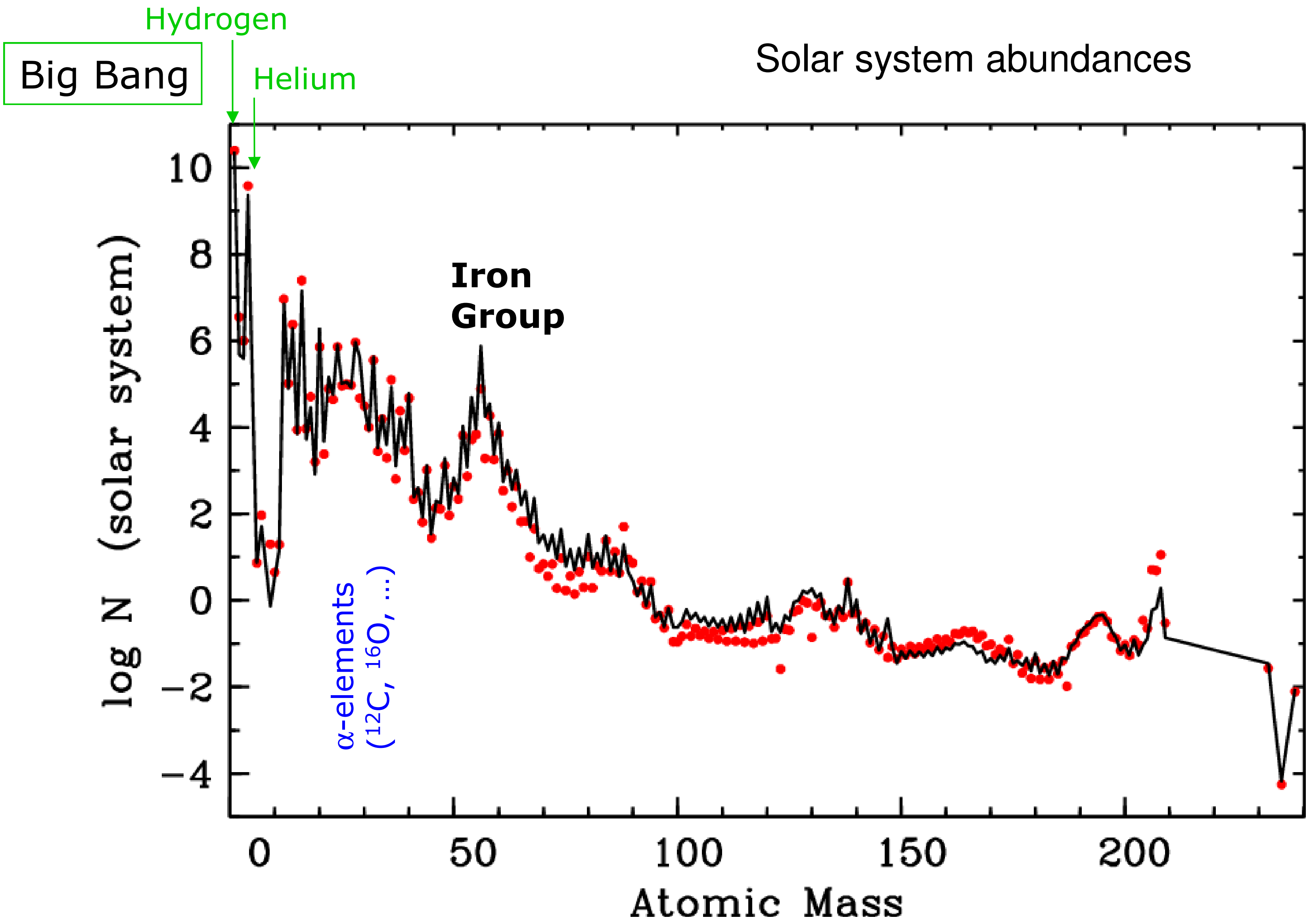


- After t ~ 15 minutes, BBN is over
- What is produced are lots of leftover free protons, ^{4}He and trace amounts of D, ^{3}H + ^{3}He, and ^{7}Li + ^{7}Be.

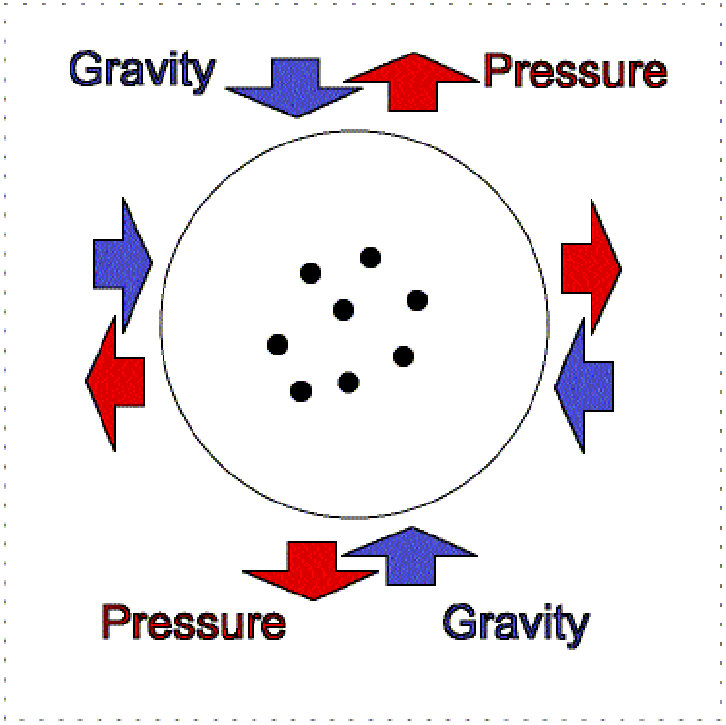
- essentially every neutron ended up in ^{4}He.

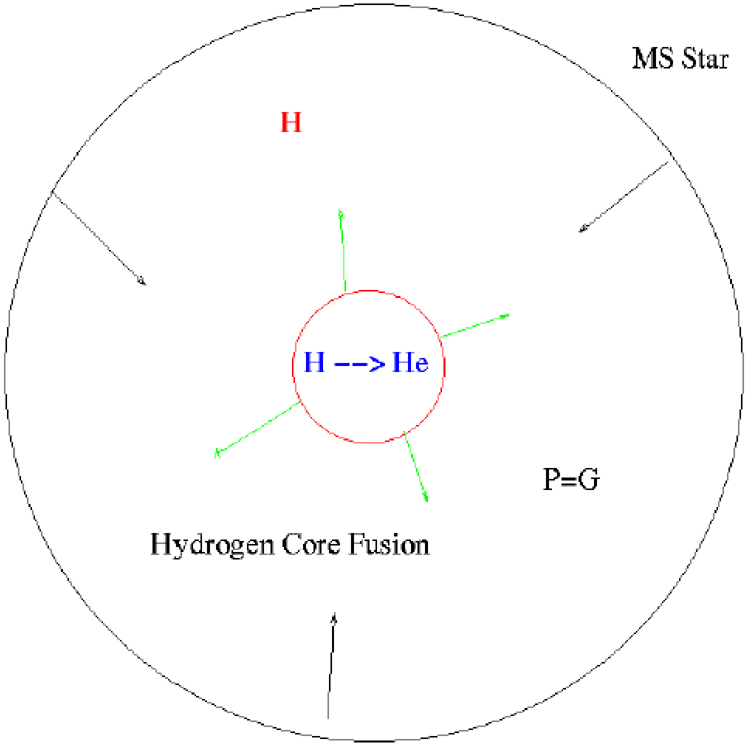
- The first stars were born with this composition!

Origin of elements



Stars (structure and evolution)

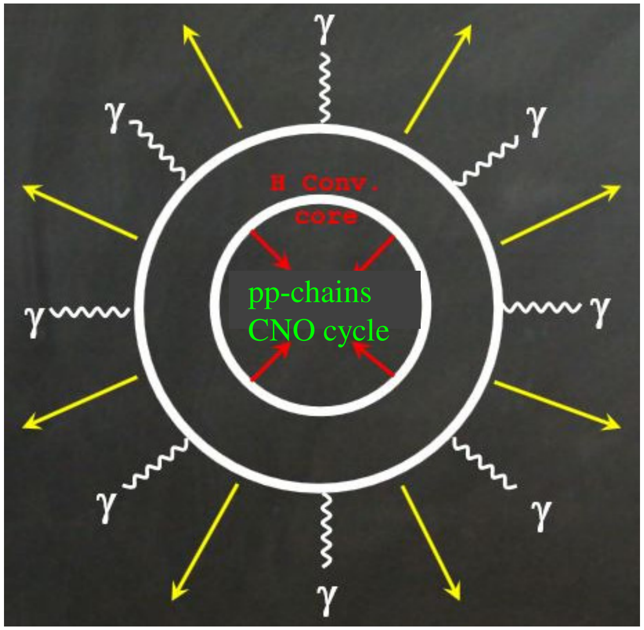




Not to scale!

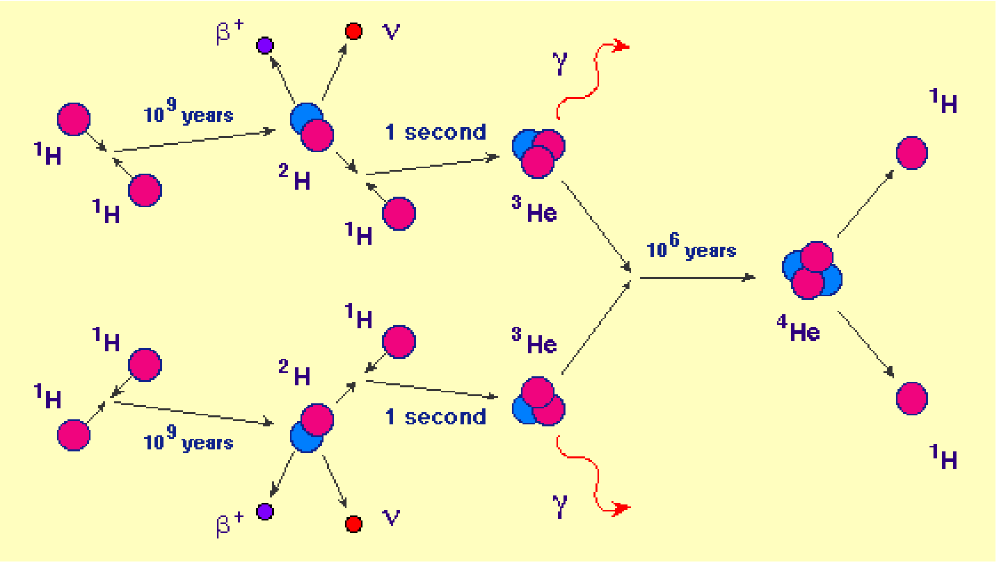
H-burning

- Typical temperature: 10^7 K
- Net reaction: $4\ p \rightarrow {}^4He$
  - Fuel: hydrogen
  - Main product: helium
  - Bottle neck: $p + p \rightarrow d + e^+ + v_e$ (Q-value: 0.42 MeV)
  - Lower mass stars: pp-chains
  - Higher mass stars: CNO cycle



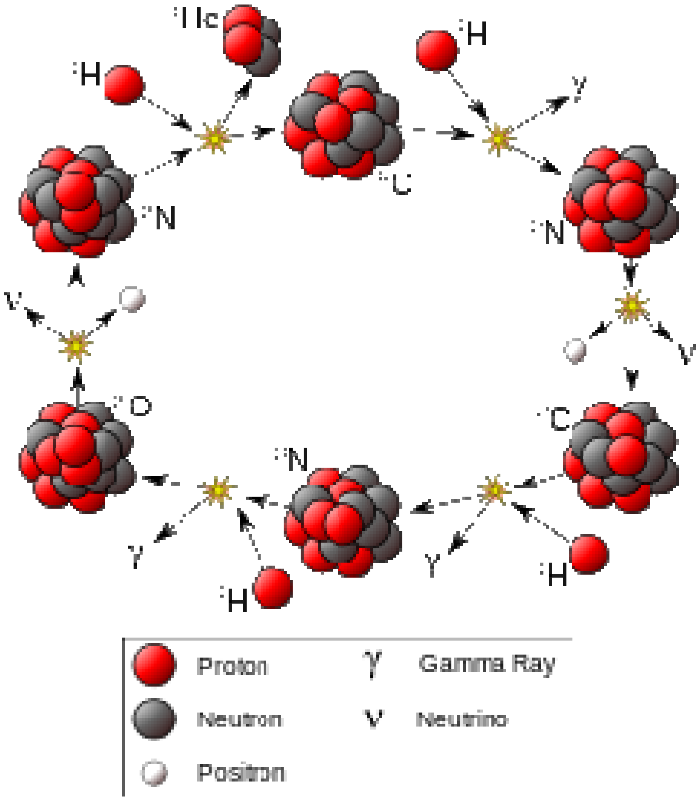
- Duration:
  12 billion (our Sun) to 10 million ($25M_{sun}$ star)

H-burning

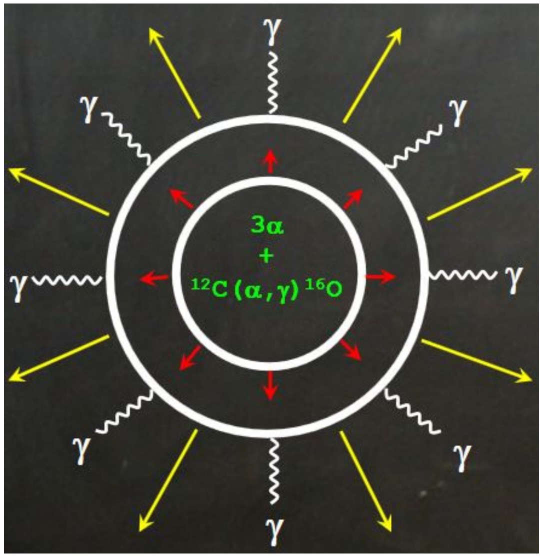


pp-chain

CNO-cycle

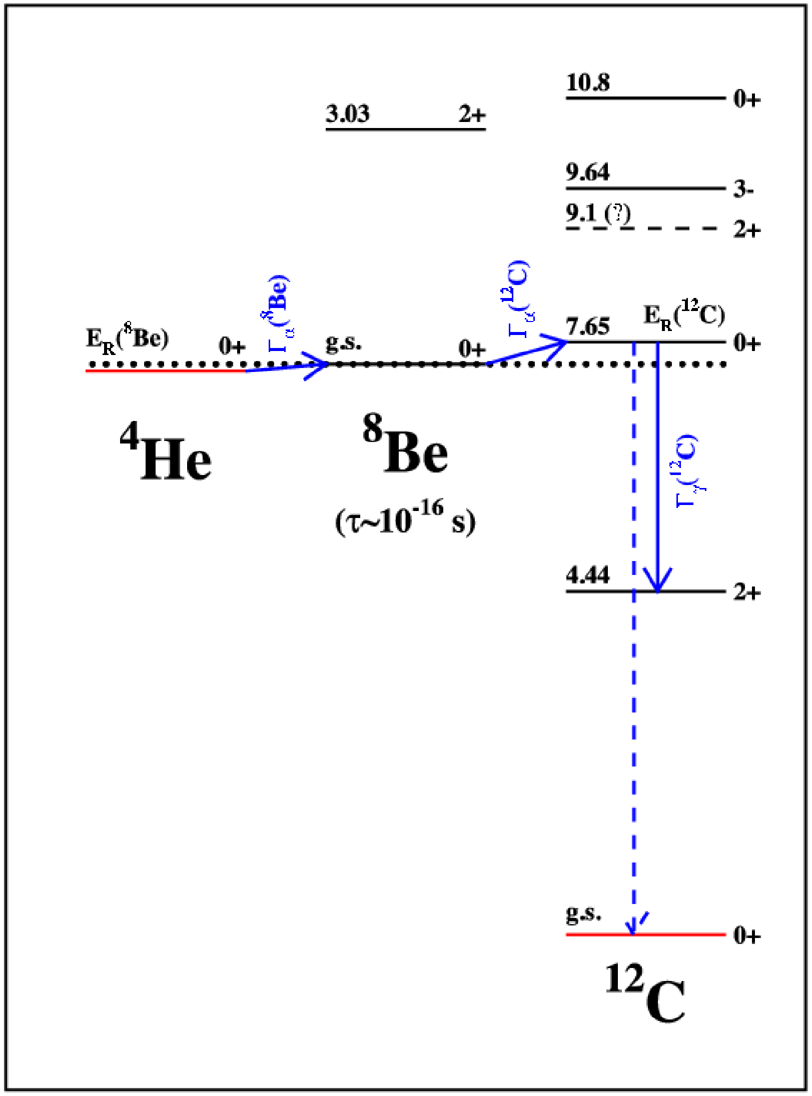


He-burning

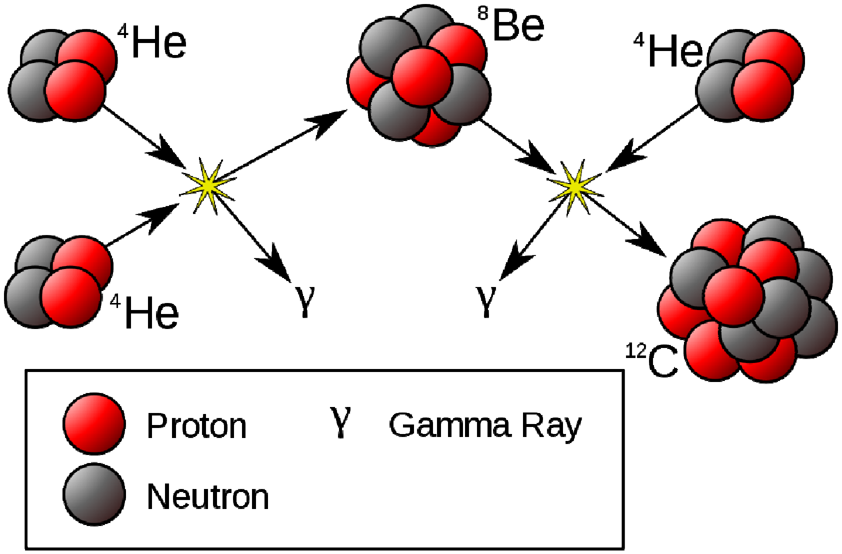


- Typical conditions:
  - Temperature: (1-2) 10^8 K
  - Density: a few 10^2 – 10^4 g/cm^3
- Net reaction: ^{4}He (2α, γ) ^{12}C
  - Fuel: helium
  - Main products: carbon, oxygen
  - ^{4}He + ^{4}He $\leftrightarrow$ ^{8}Be + γ
    ^{8}Be + ^{4}He $\leftrightarrow$ ^{12}C + γ
  - And ^{12}C + ^{4}He → ^{16}O + γ
  - Difficulty: lifetime of ^{8}Be ~ 10^{-16} s
    → Hoyle state (resonance in ^{12}C at E=7.68 MeV)
  - Other products: ^{21,22}Ne, ^{25,26}Mg, ^{36}S, ^{37}Cl, ^{40}K, ^{40}Ar
  - ^{14}N (α,γ) ^{18}F (e^+,ν) ^{18}O (α,γ) ^{22}Ne (α,n) ^{25}Mg

He-burning

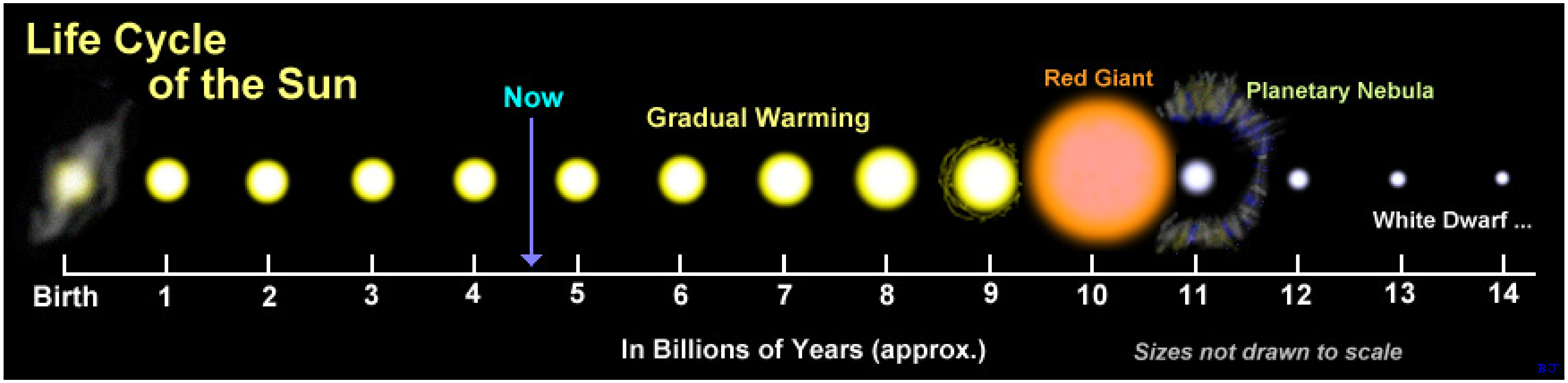


Ekström+2010



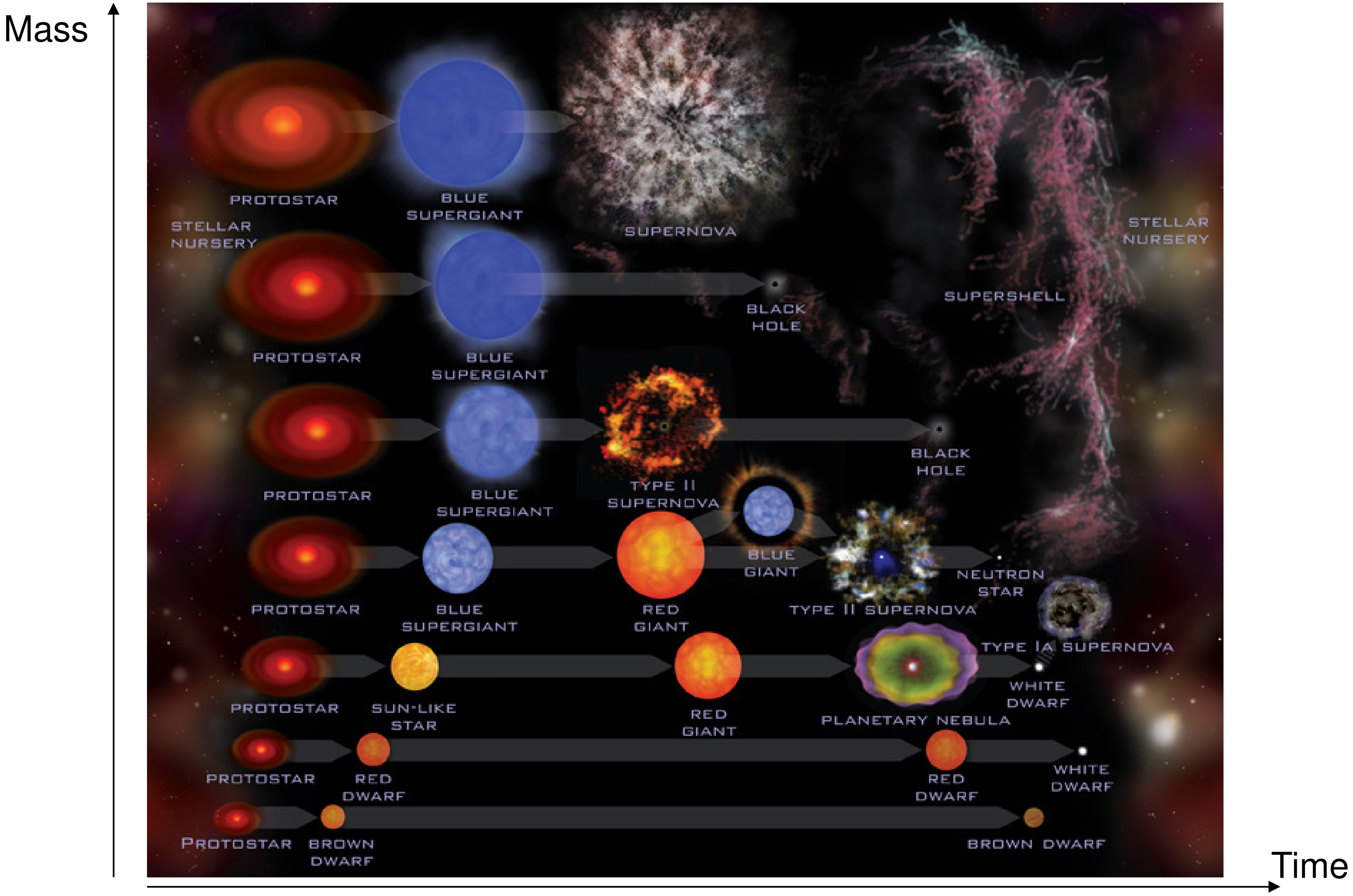
Low-mass stars

- End their life after He-burning
- Eg the Sun



- If WD is in a binary system → type Ia supernova

Stellar lifetimes



C-burning

- Typical conditions:
  - Temperature: (6-8) 10^8 K
  - Density: 10^5 g/cm^3

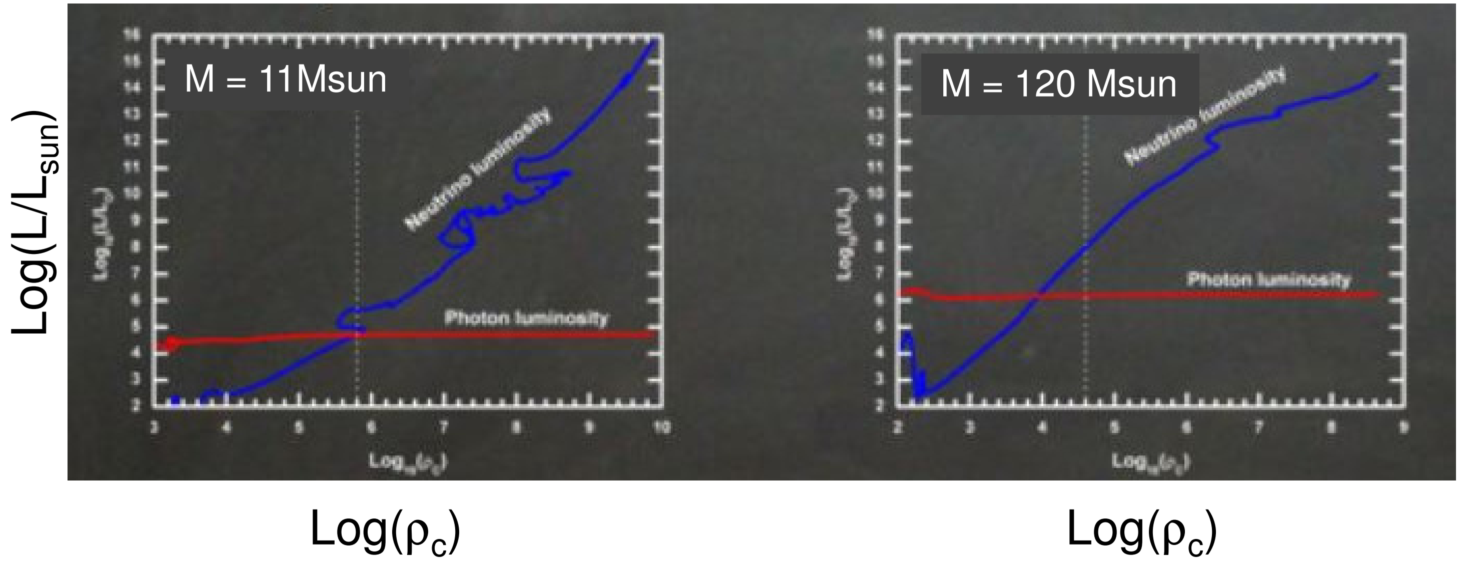
- Net reaction: $^{12}C + ^{12}C$
  - Fuel: carbon
  - Main products: neon, magnesium, oxygen
  - $^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$ (Q=4.62 MeV)
    $^{12}C + ^{12}C \rightarrow p + ^{23}Na$ (Q=2.24 MeV)
  - Other reactions: $^{23}Na + p \rightarrow \alpha + ^{20}Ne$
    $^{20}Ne + \alpha \rightarrow ^{24}Mg$
  - $^{12}C + \alpha \rightarrow ^{16}O + \gamma$ (Q=4.73 MeV)

Neutrino-losses

- At temperatures above ~10^9 K: pair-production

$$\gamma \leftrightarrow e^+ + e^- \leftrightarrow \nu_e + \bar{\nu}_e$$

- Luminosity of photons and neutrinos



Ne-burning

- Typical conditions:
  - Temperature: (1-2) 10^9 K
  - Density: 10^6 g/cm^3

- Reactions:
  - Fuel: neon
  - Main products: oxygen, silicon
  - ^{20}Ne (γ,α) ^{16}O
  - Other reactions:

^{20}Ne (α,γ) ^{24}Mg (α,γ) ^{28}Si (α,γ) ^{32}S

^{21}Ne (α,n) ^{24}Mg (n,γ) ^{25}Mg (α,n) ^{28}Si

^{23}Na (α,p) ^{25}Mg (α,n) ^{28}Si

^{25}Mg(p,γ) ^{25}Al

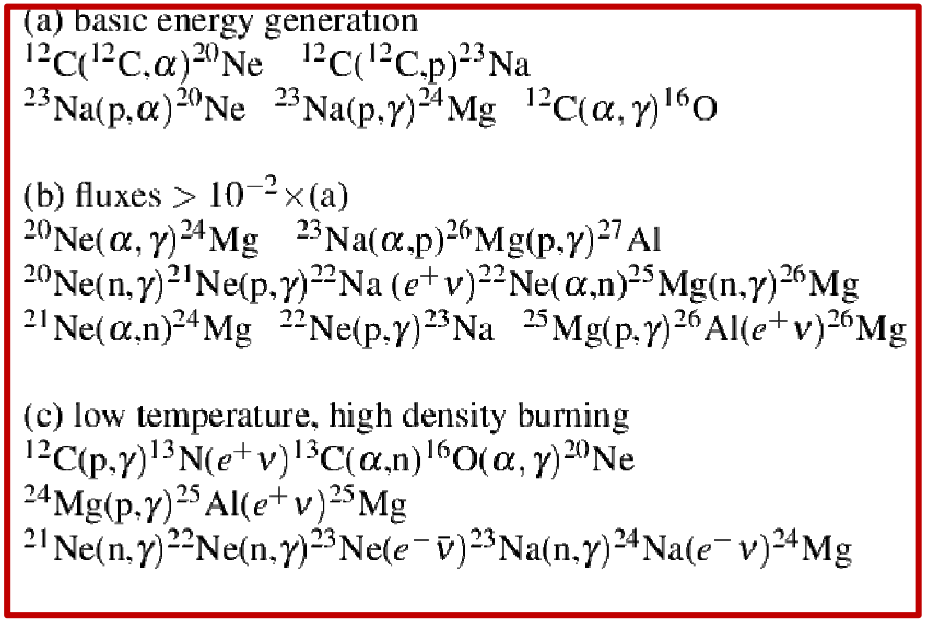
^{23}Na (p,α) ^{20}Ne

O-burning

- Typical conditions:
  - Temperature: (1.5-2.2) 10^9 K
  - Density: 10^7 g/cm^3

- Reaction:
  - Fuel: oxygen
  - Main products: silicon
  - $^{16}O + {}^{16}O \rightarrow p + {}^{31}P$ (Q=7.676 MeV)
    $^{16}O + {}^{16}O \rightarrow \alpha + {}^{28}Si$ (Q=9.593 MeV)
    $^{16}O + {}^{16}O \rightarrow n + {}^{31}S$ (Q=1.459 MeV)
  - Other reactions: $^{31}P\ (p,\alpha)\ {}^{28}Si$
    $^{33}S\ (e^-,\nu_e)\ {}^{33}P$
    $^{35}Cl\ (e^-,\nu_e)\ {}^{35}P$

C-, Ne-, O-burning reactions (details)


(a) basic energy generation

$^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$ $^{12}\mathrm{C}(^{12}\mathrm{C},\mathrm{p})^{23}\mathrm{Na}$

$^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ $^{23}\mathrm{Na}(\mathrm{p},\gamma)^{24}\mathrm{Mg}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

(b) fluxes $> 10^{-2}\times$(a)

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$ $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}$

$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\mathrm{p},\gamma)^{22}\mathrm{Na}\ (e^{+}\nu)^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}$

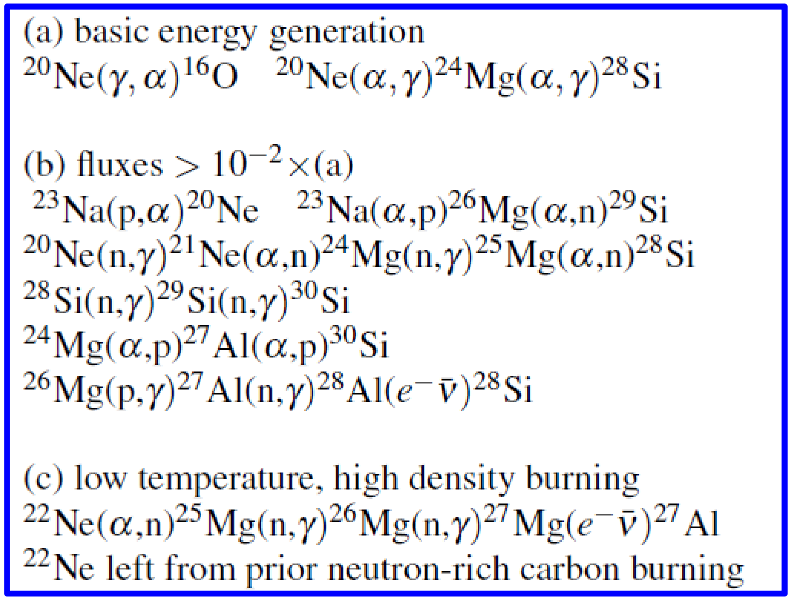
$^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}$ $^{22}\mathrm{Ne}(\mathrm{p},\gamma)^{23}\mathrm{Na}$ $^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}(e^{+}\nu)^{26}\mathrm{Mg}$

(c) low temperature, high density burning

$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

$^{24}\mathrm{Mg}(\mathrm{p},\gamma)^{25}\mathrm{Al}(e^{+}\nu)^{25}\mathrm{Mg}$

$^{21}\mathrm{Ne}(\mathrm{n},\gamma)^{22}\mathrm{Ne}(\mathrm{n},\gamma)^{23}\mathrm{Ne}(e^{-}\bar{\nu})^{23}\mathrm{Na}(\mathrm{n},\gamma)^{24}\mathrm{Na}(e^{-}\nu)^{24}\mathrm{Mg}$


(a) basic energy generation

$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

(b) fluxes $> 10^{-2}\times$(a)

$^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}(\alpha,\mathrm{n})^{29}\mathrm{Si}$

$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}(\mathrm{n},\gamma)^{25}\mathrm{Mg}(\alpha,\mathrm{n})^{28}\mathrm{Si}$

$^{28}\mathrm{Si}(\mathrm{n},\gamma)^{29}\mathrm{Si}(\mathrm{n},\gamma)^{30}\mathrm{Si}$

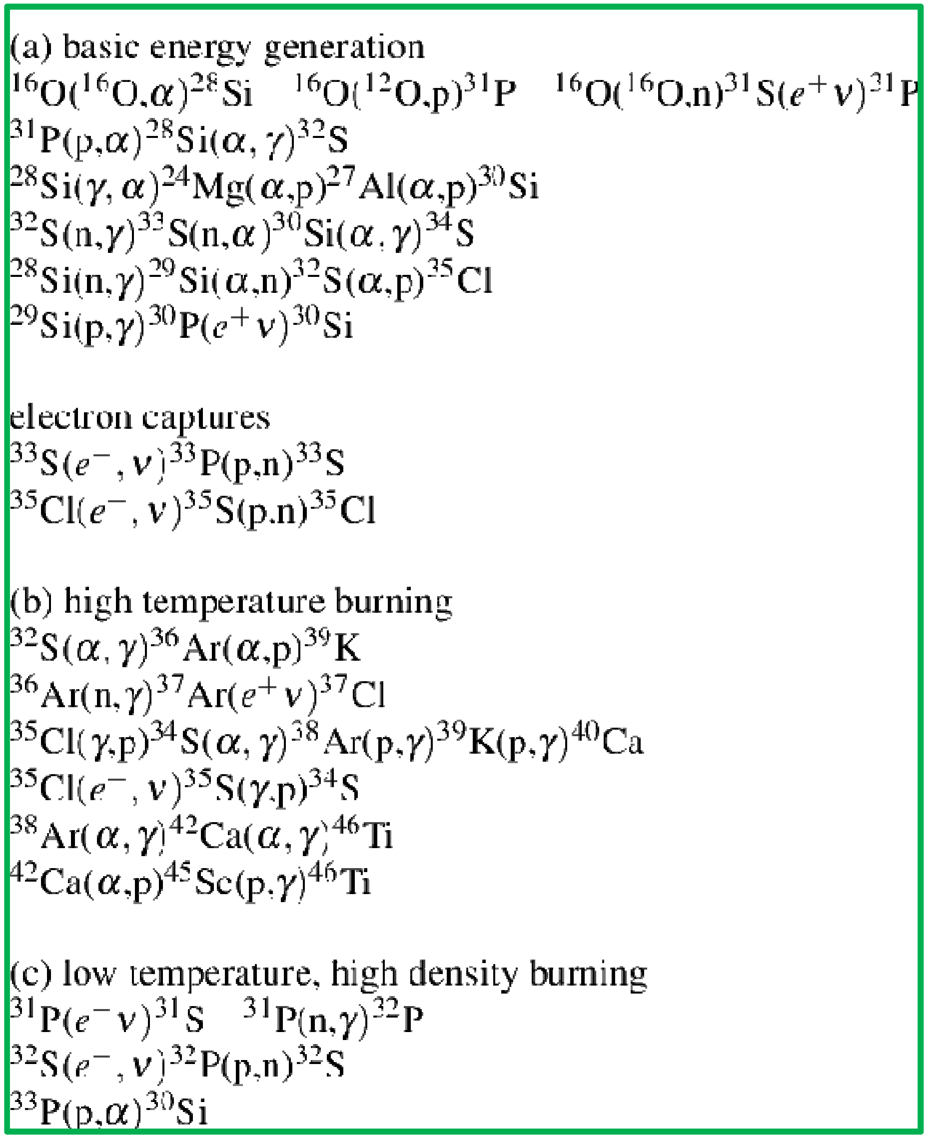
$^{24}\mathrm{Mg}(\alpha,\mathrm{p})^{27}\mathrm{Al}(\alpha,\mathrm{p})^{30}\mathrm{Si}$

$^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}(\mathrm{n},\gamma)^{28}\mathrm{Al}(e^{-}\bar{\nu})^{28}\mathrm{Si}$

(c) low temperature, high density burning

$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}(\mathrm{n},\gamma)^{27}\mathrm{Mg}(e^{-}\bar{\nu})^{27}\mathrm{Al}$

$^{22}\mathrm{Ne}$ left from prior neutron-rich carbon burning


(a) basic energy generation

$^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$ $^{16}\mathrm{O}(^{12}\mathrm{O},\mathrm{p})^{31}\mathrm{P}$ $^{16}\mathrm{O}(^{16}\mathrm{O},\mathrm{n})^{31}\mathrm{S}(e^{+}\nu)^{31}\mathrm{P}$

$^{31}\mathrm{P}(\mathrm{p},\alpha)^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}$

$^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}(\alpha,\mathrm{p})^{27}\mathrm{Al}(\alpha,\mathrm{p})^{30}\mathrm{Si}$

$^{32}\mathrm{S}(\mathrm{n},\gamma)^{33}\mathrm{S}(\mathrm{n},\alpha)^{30}\mathrm{Si}(\alpha,\gamma)^{34}\mathrm{S}$

$^{28}\mathrm{Si}(\mathrm{n},\gamma)^{29}\mathrm{Si}(\alpha,\mathrm{n})^{32}\mathrm{S}(\alpha,\mathrm{p})^{35}\mathrm{Cl}$

$^{29}\mathrm{Si}(\mathrm{p},\gamma)^{30}\mathrm{P}(e^{+}\nu)^{30}\mathrm{Si}$

electron captures

$^{33}\mathrm{S}(e^{-},\nu)^{33}\mathrm{P}(\mathrm{p},\mathrm{n})^{33}\mathrm{S}$

$^{35}\mathrm{Cl}(e^{-},\nu)^{35}\mathrm{S}(\mathrm{p},\mathrm{n})^{35}\mathrm{Cl}$

(b) high temperature burning

$^{32}\mathrm{S}(\alpha,\gamma)^{36}\mathrm{Ar}(\alpha,\mathrm{p})^{39}\mathrm{K}$

$^{36}\mathrm{Ar}(\mathrm{n},\gamma)^{37}\mathrm{Ar}(e^{+}\nu)^{37}\mathrm{Cl}$

$^{35}\mathrm{Cl}(\gamma,\mathrm{p})^{34}\mathrm{S}(\alpha,\gamma)^{38}\mathrm{Ar}(\mathrm{p},\gamma)^{39}\mathrm{K}(\mathrm{p},\gamma)^{40}\mathrm{Ca}$

$^{35}\mathrm{Cl}(e^{-},\nu)^{35}\mathrm{S}(\gamma,\mathrm{p})^{34}\mathrm{S}$

$^{38}\mathrm{Ar}(\alpha,\gamma)^{42}\mathrm{Ca}(\alpha,\gamma)^{46}\mathrm{Ti}$

$^{42}\mathrm{Ca}(\alpha,\mathrm{p})^{45}\mathrm{Sc}(\mathrm{p},\gamma)^{46}\mathrm{Ti}$

(c) low temperature, high density burning

$^{31}\mathrm{P}(e^{-}\nu)^{31}\mathrm{S}$ $^{31}\mathrm{P}(\mathrm{n},\gamma)^{32}\mathrm{P}$

$^{32}\mathrm{S}(e^{-},\nu)^{32}\mathrm{P}(\mathrm{p},\mathrm{n})^{32}\mathrm{S}$

$^{33}\mathrm{P}(\mathrm{p},\alpha)^{30}\mathrm{Si}$

Thielemann+2010

Si-burning

- Typical temperature: (3-4) 10^9 K
- Net reaction: $^{28}Si + ^{28}Si$
  - Fuel: silicon
  - Main products: Fe-group elements (A = 50-60 nuclei)
  - Other reactions: $^{28}Si + \gamma \rightarrow p + ^{27}Al$
    $^{28}Si + \gamma \rightarrow \alpha + ^{24}Mg$
    $^{28}Si + \gamma \rightarrow n + ^{27}Si$
- Balance between forward and reverse reactions for increasing number of processes: $a + b \leftrightarrow c + d$
  → Nuclear statistical equilibrium (NSE)

Nuclear Statistical Equilibrium (NSE)

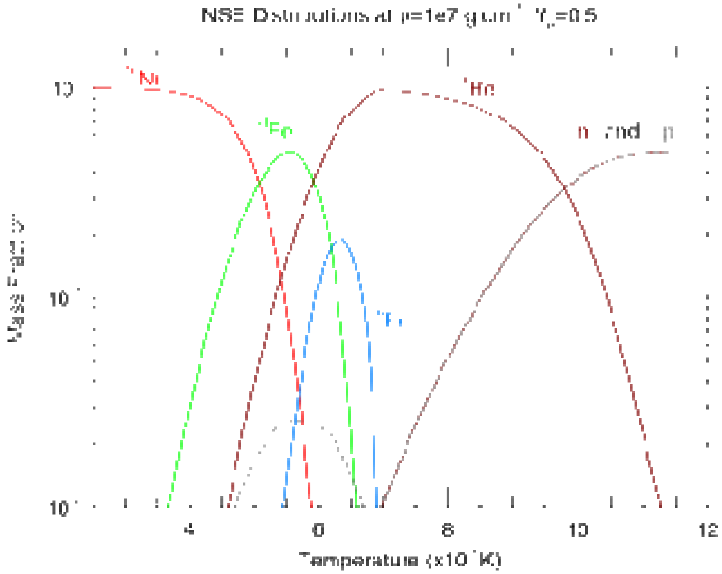
- Chemical equilibrium (for species i):

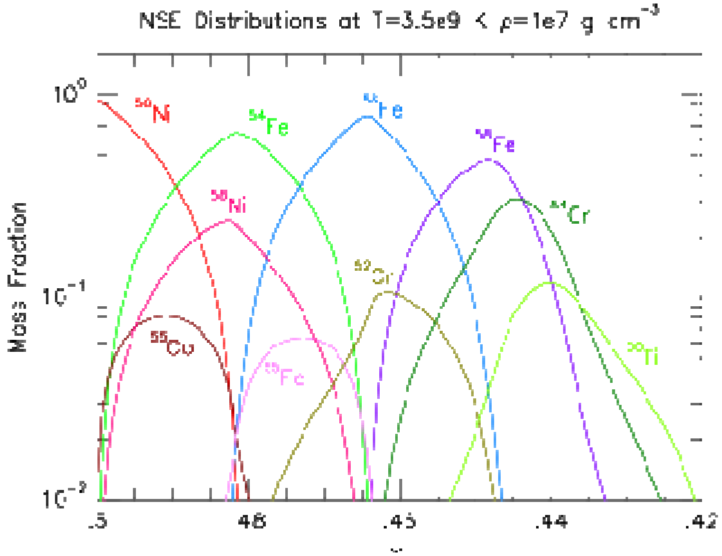
$$Z_i\,\mu_p + N_i\,\mu_n = \mu_i$$

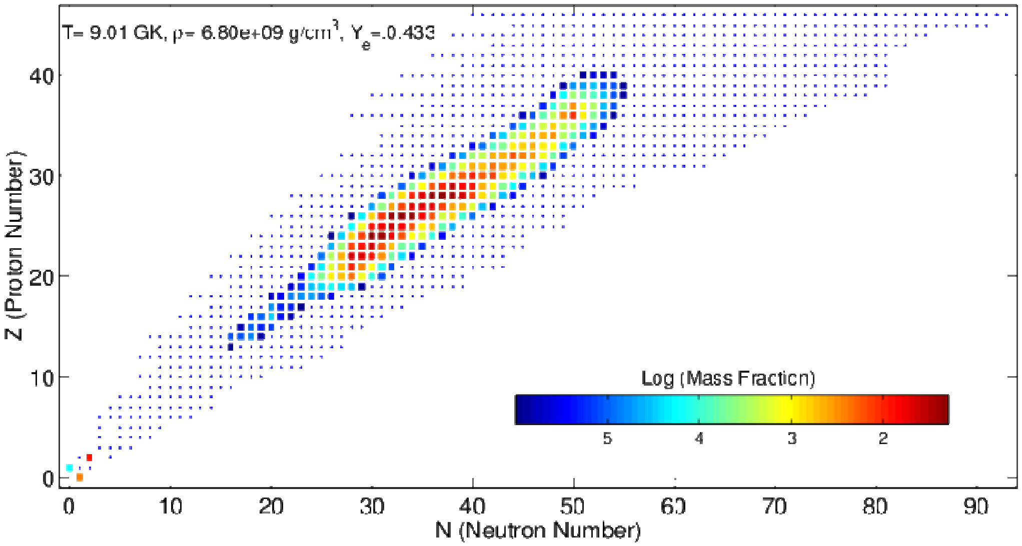
- Abundances given by:

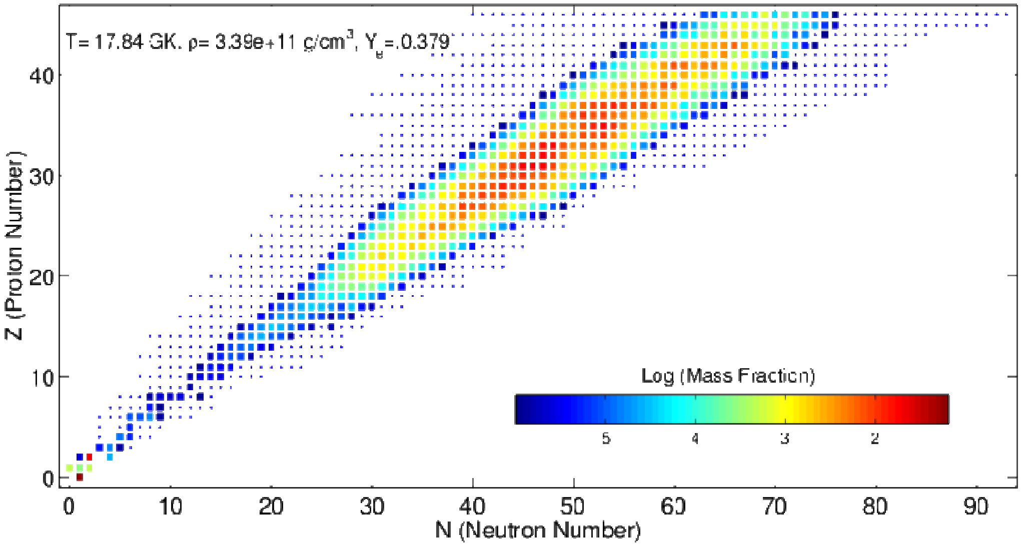
$$Y(Z,N) = G_{Z,N}\,(\rho\,N_A)^{A-1}\,\left(A^{2/3}/2^A\right)\left(\frac{2\pi h}{m_n kT}\right)^{3/2(A-1)}\,Y_n^N\,Y_p^Z\,e^{B_{Z,N}/kT}$$

Nuclear Statistical Equilibrium (NSE)









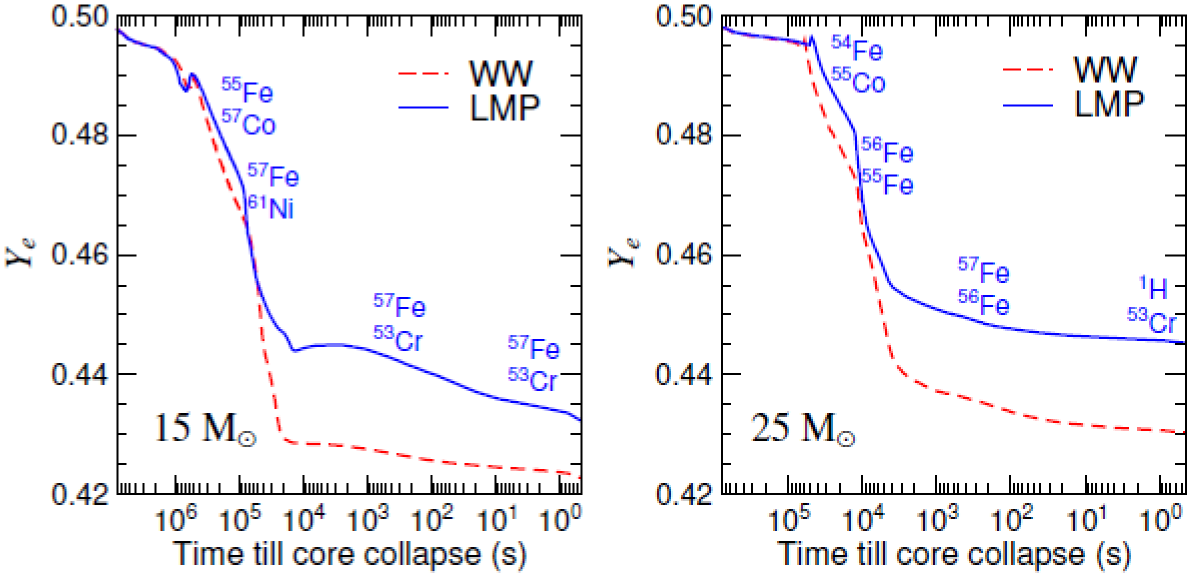
Weak Interactions

- Become relevant in later burning stages
- Lead to neutronization
- Electron captures:

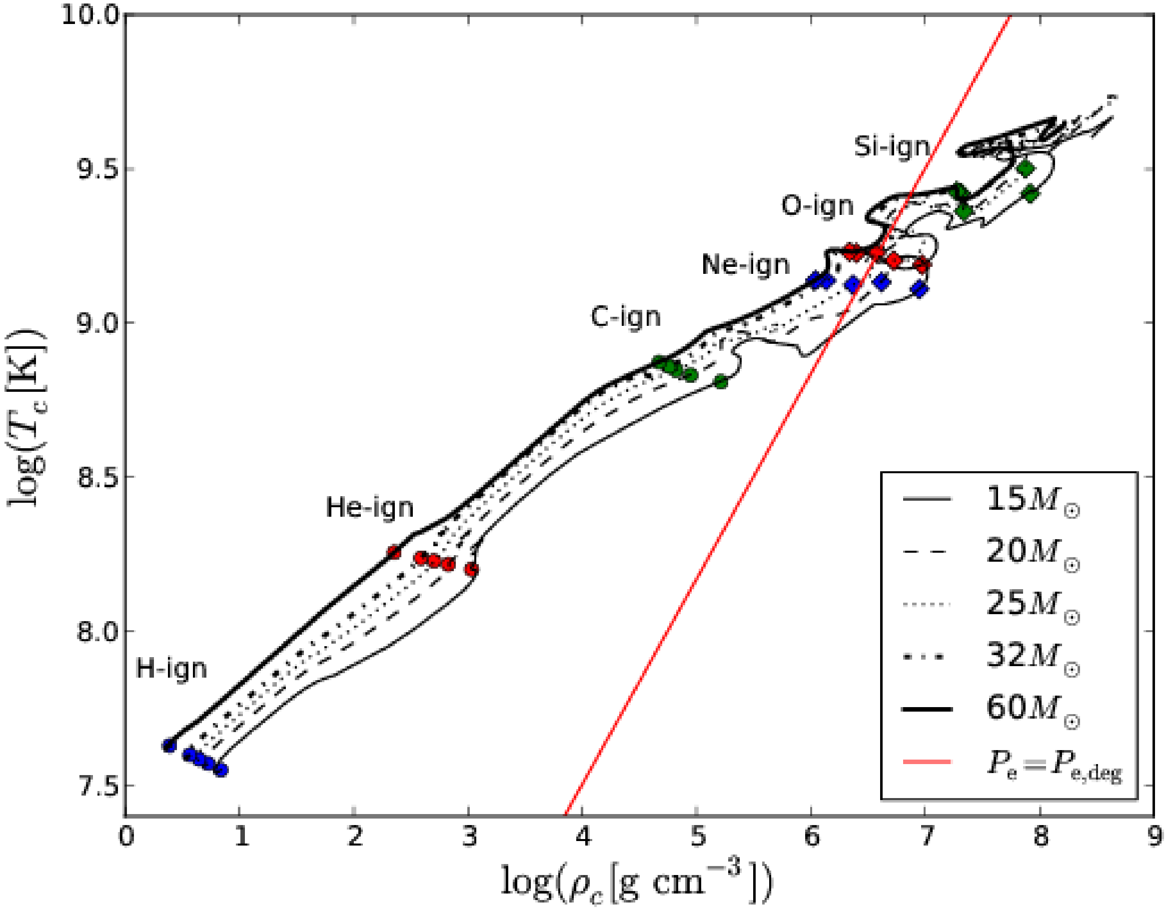
$$p + e^- \rightarrow \nu_e + n \quad \text{or} \quad \mathrm{p}(e^-, \nu_e)\mathrm{n}$$
$$(A,Z) + e^- \rightarrow \nu_e + (A, Z-1) \quad \text{or} \quad {}^{A}\mathrm{Z}(e^-, \nu_e)^{A}\mathrm{Z\text{-}1}$$

$$E_F(\rho Y_e = 10^7\,\mathrm{gcm}^{-3}) = 0.75\ \mathrm{MeV}$$
$$E_F(\rho Y_e = 10^9\,\mathrm{gcm}^{-3}) = 4.70\ \mathrm{MeV}$$

- Electron fraction:

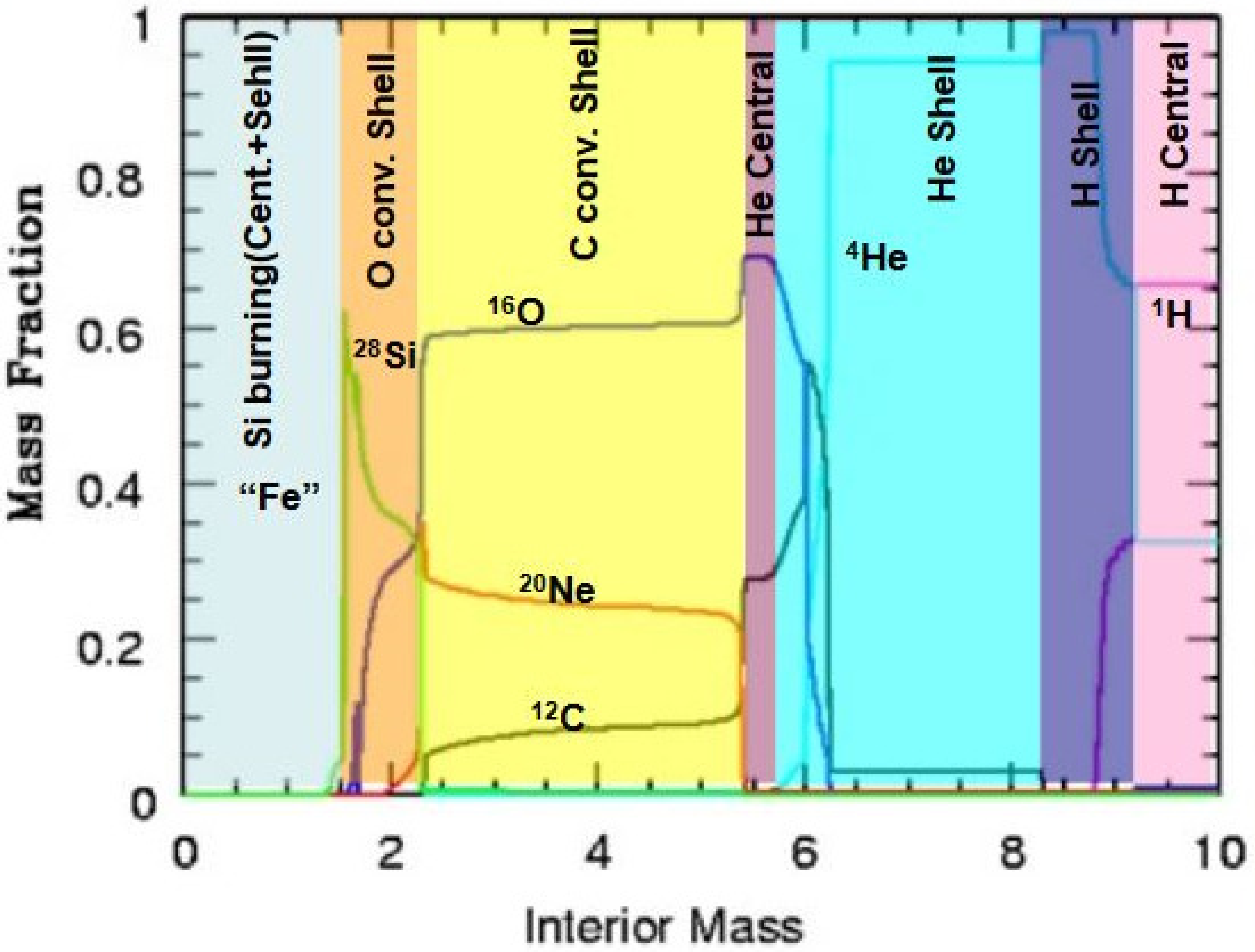


Central evolution

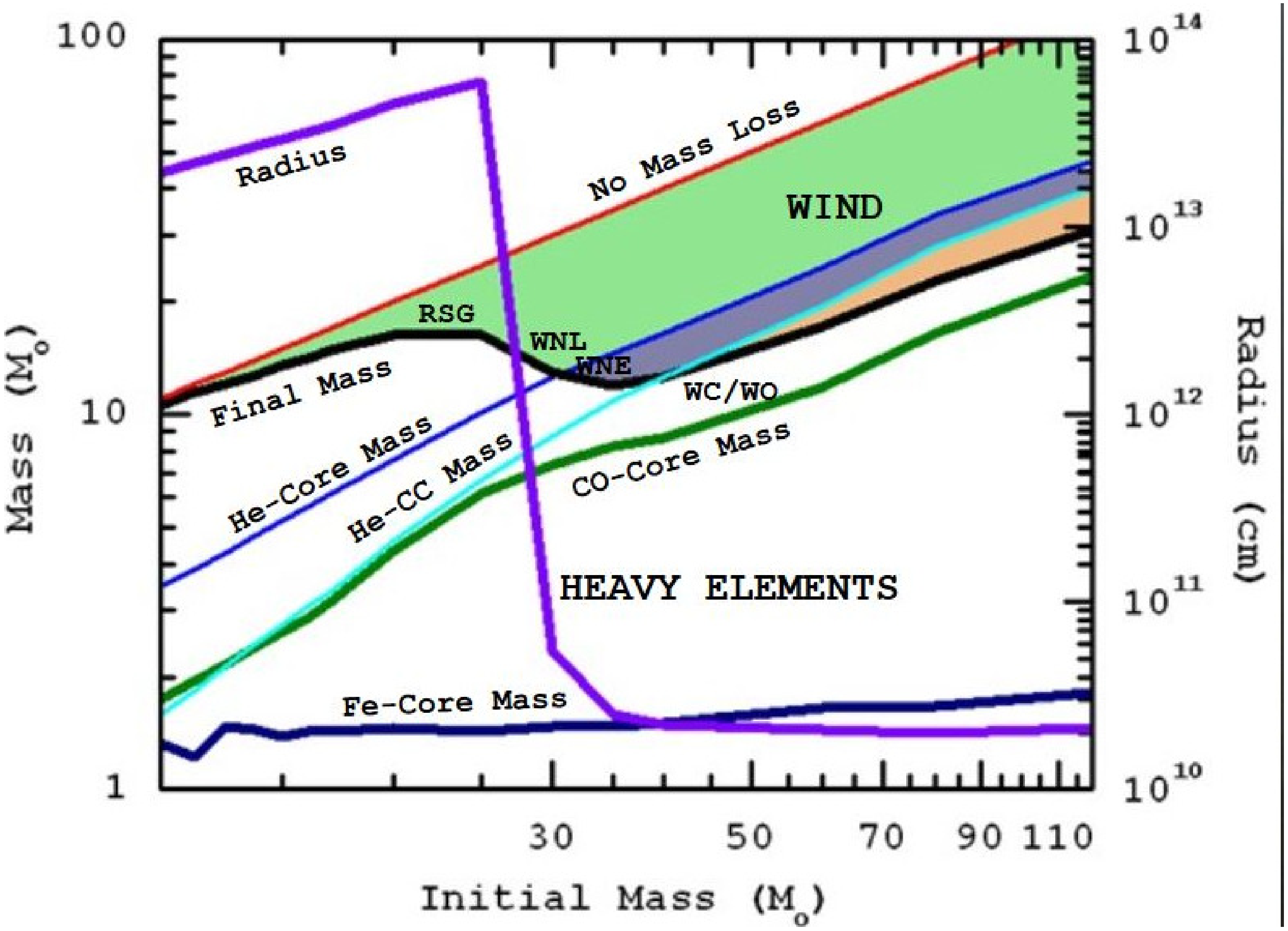


Pre-supernova stage

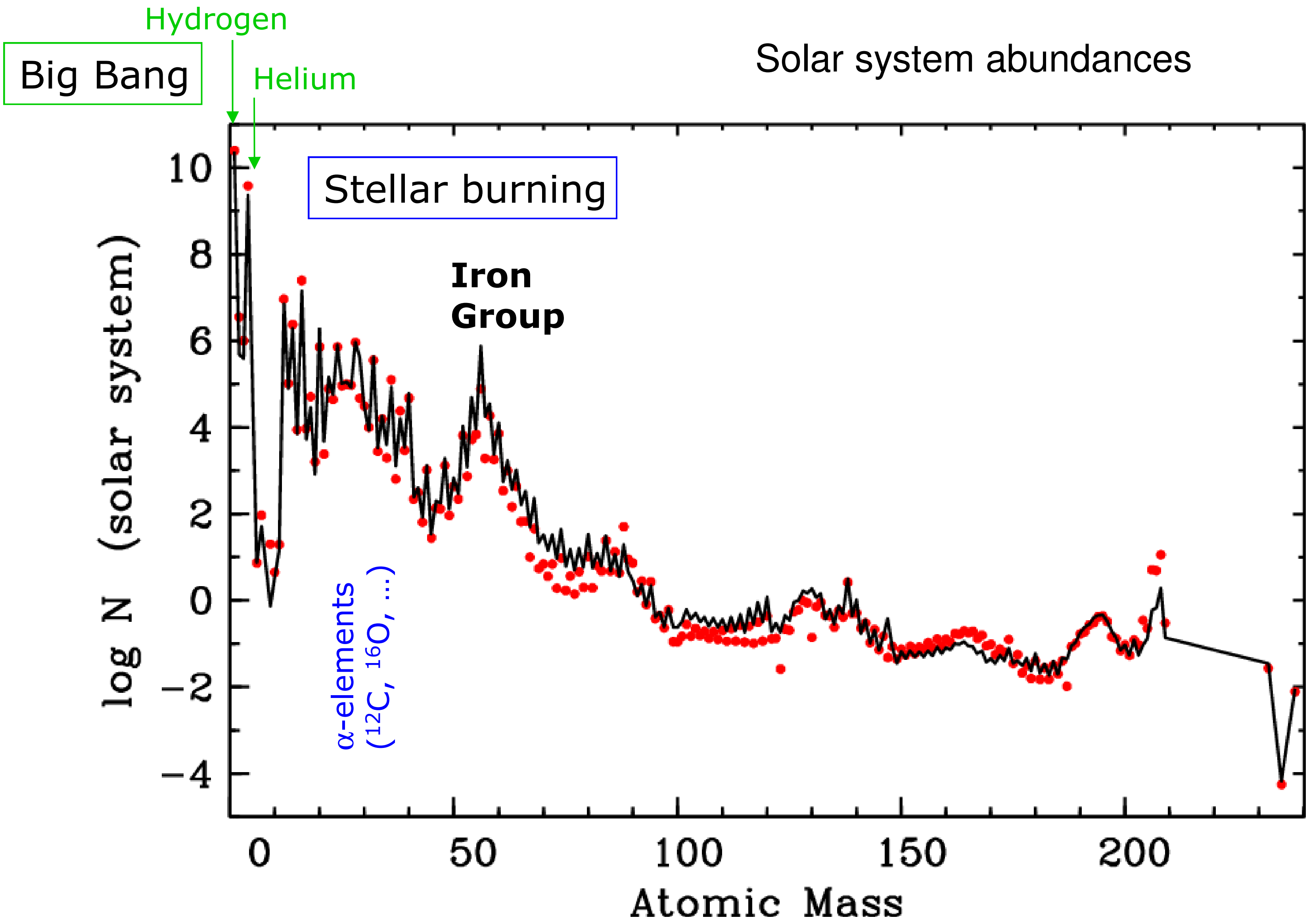
Composition



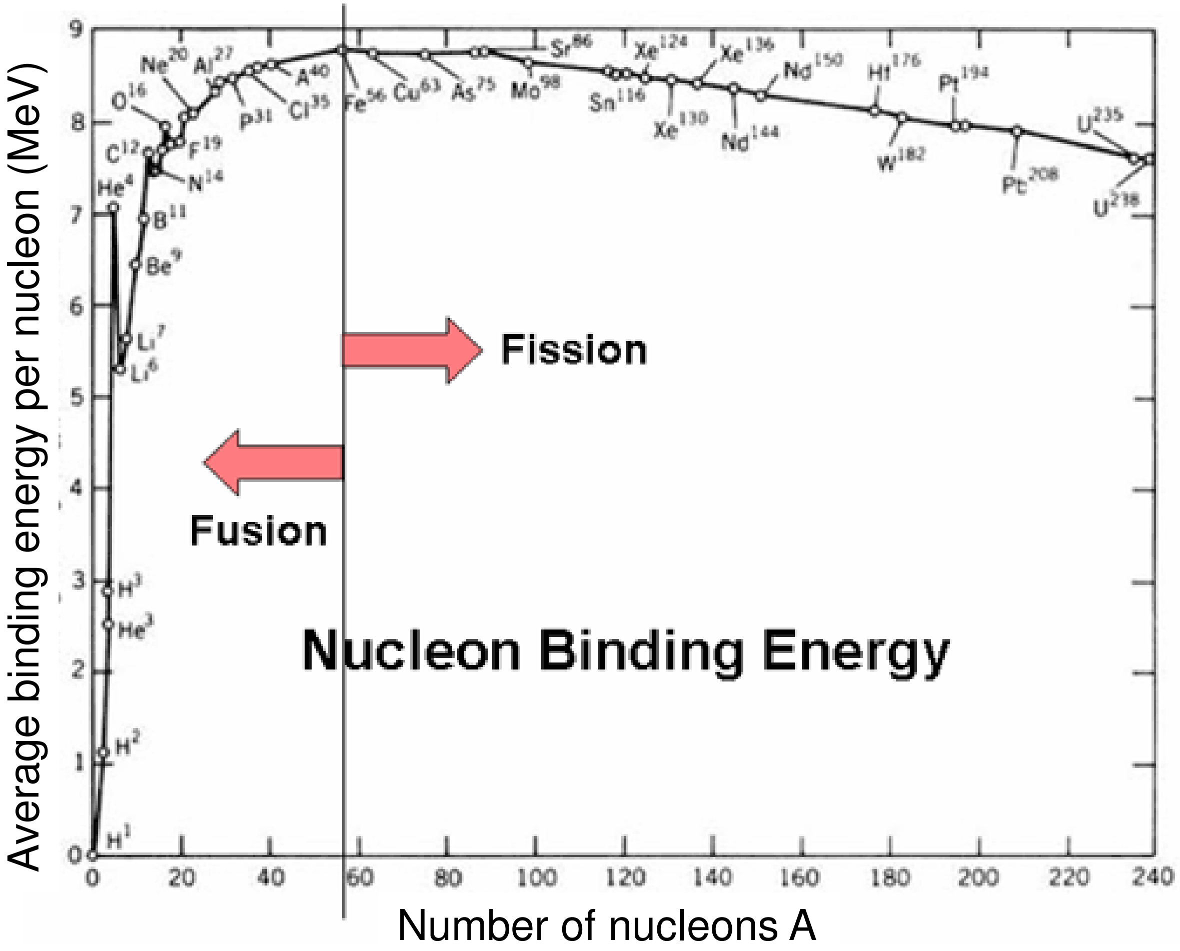
Pre-supernova stage



Origin of elements



Nuclear binding energy

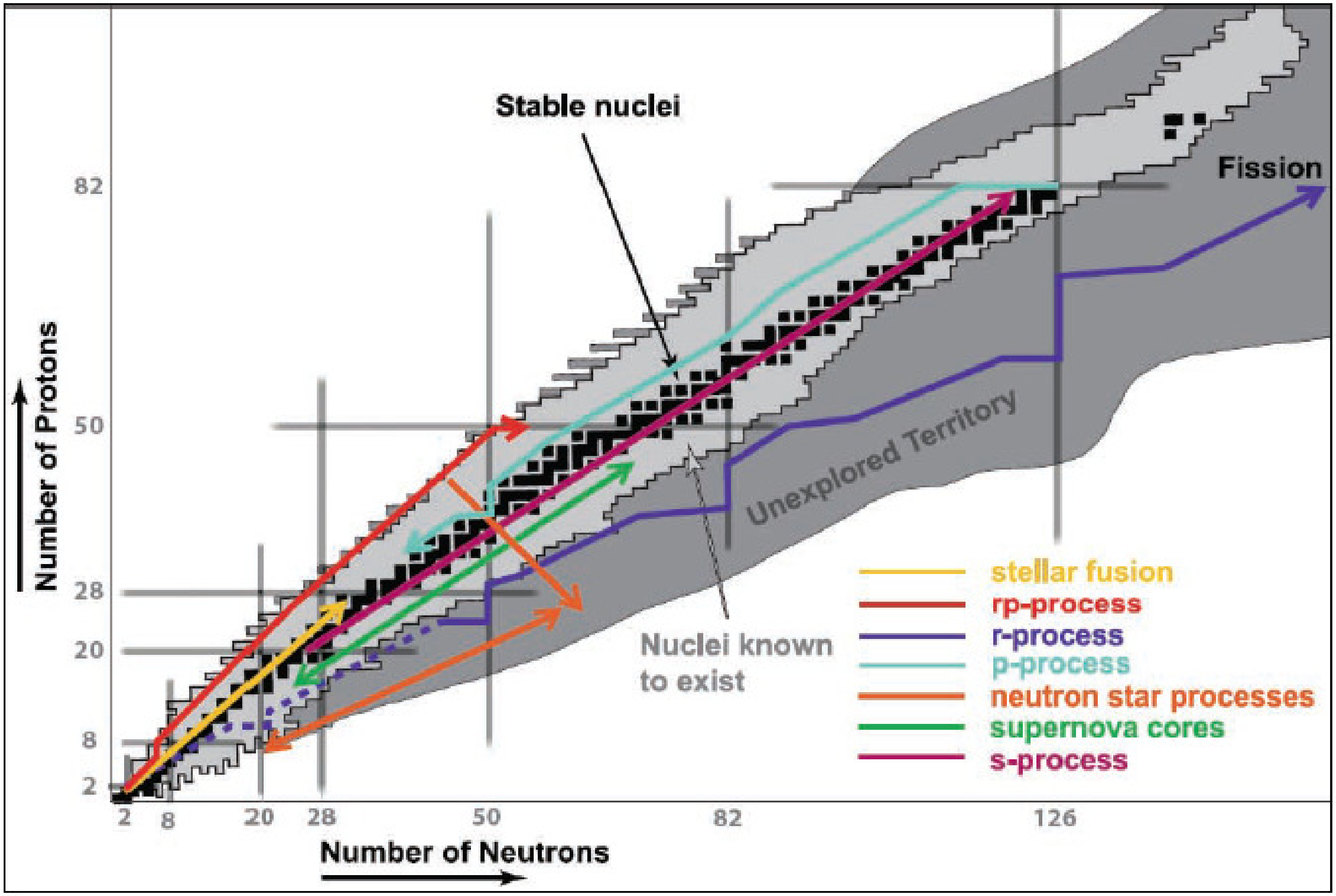


H → He → C → O → …. → Fe

Nuclear fusion in stellar cores

Need mechanisms other than charged-particle fusion:
E.g. neutrons, photons, neutrinos

Origin of elements



How are nuclei made? Where? Through what processes?

Nuclear physics

- Need to know the relevant nuclear physics:
  - Properties of nuclei (mass, half-life, spin, levels, etc)
  - Properties of reactions between nuclei (and leptons, photons)

Reaction rates

Consider:

- n_i: number density of particles of type i $\quad$ cm^{-3}
- n_j: number density of particles of type j $\quad$ cm^{-3}
- σ: cross section (effective area for reaction) $\quad$ cm^{2}

- Reactions per time per volume
  = relative flux of particles i $\quad$ cm^{-3} cm s^{-1}
  × number of particles j $\quad$ cm^{-3}
  × cross section $\quad$ cm^{2}
  $r = n_i \, v \, n_j \, \sigma(v)$ $\quad$ cm^{-3} s^{-1}

Reaction rates

- Previously: particles i move at constant v
- For constant relative velocity between particles i and j

→ reacts / vol / time: $r_{i;j} = \int \sigma \cdot |\vec{v}_i - \vec{v}_j| dn_i dn_j$

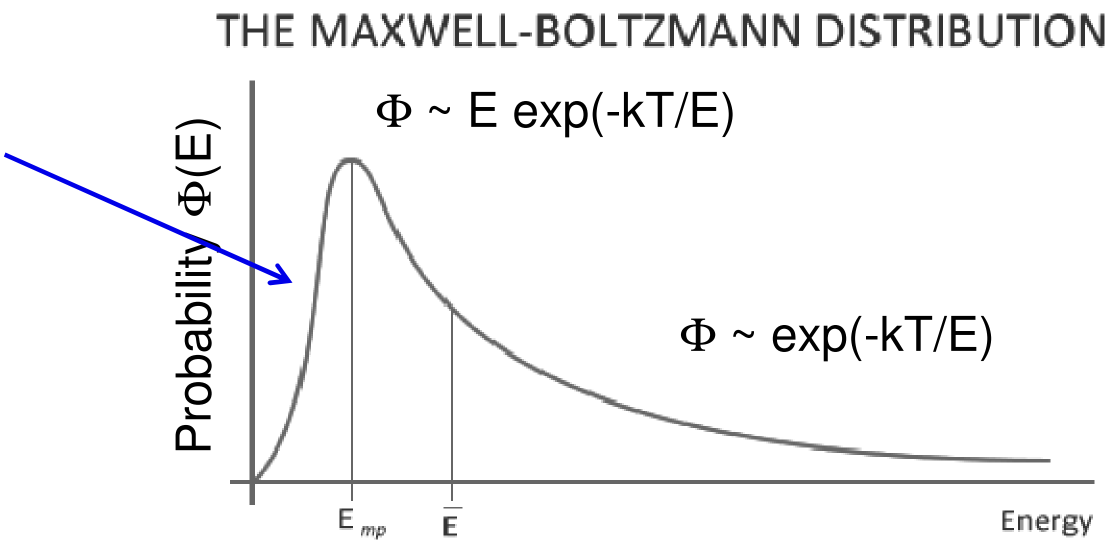
- General: projectiles and targets follow velocity distribution

$$r_{i;j} = n_i n_j \int \sigma(|\vec{v}_i - \vec{v}_j|)|\vec{v}_i - \vec{v}_j|\phi(\vec{v}_i)\phi(\vec{v}_j)d^3v_i d^3v_j$$

Integral depends on type of particles and distribution

Maxwell-Boltzmann distribution

- Nuclei in astrophysical plasma are not mono-energetic
- They obey MB distribution



$\Phi \sim E$

$\Phi \sim E \exp(-kT/E)$

$\Phi \sim \exp(-kT/E)$

$E_{mp} = kT$

Reaction rates

- Use center-of-mass coordinates, carry out integration, and remember that $\int \phi(\vec{V}) d^3V = 1$

  reaction rate becomes $r_{i;j} = n_i n_j \langle \sigma v \rangle_{i;j}$

  with the thermonuclear cross section <σv>

$$\langle \sigma v \rangle (T) = \left(\frac{8}{\mu \pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E) \, \exp(-E/kT) dE$$

  - Only depends on temperature
  - If we know σ (E), we can get <σv>

Astrophysical S-factor

- Use known energy dependence of $\sigma(E)$
- For charged particles: $\sigma(E)$ is proportional to:
  - Coulomb barrier penetration ~exp(-E ^{½})
  - Nuclear size ~1/E
- All other energy dependencies are lumped together into astrophysical S-factor S(E)
- Why?
  - For non-resonant reactions: S(E) is slowly varying

→ better to work with S(E) if extrapolations are needed

Astrophysical S-factor

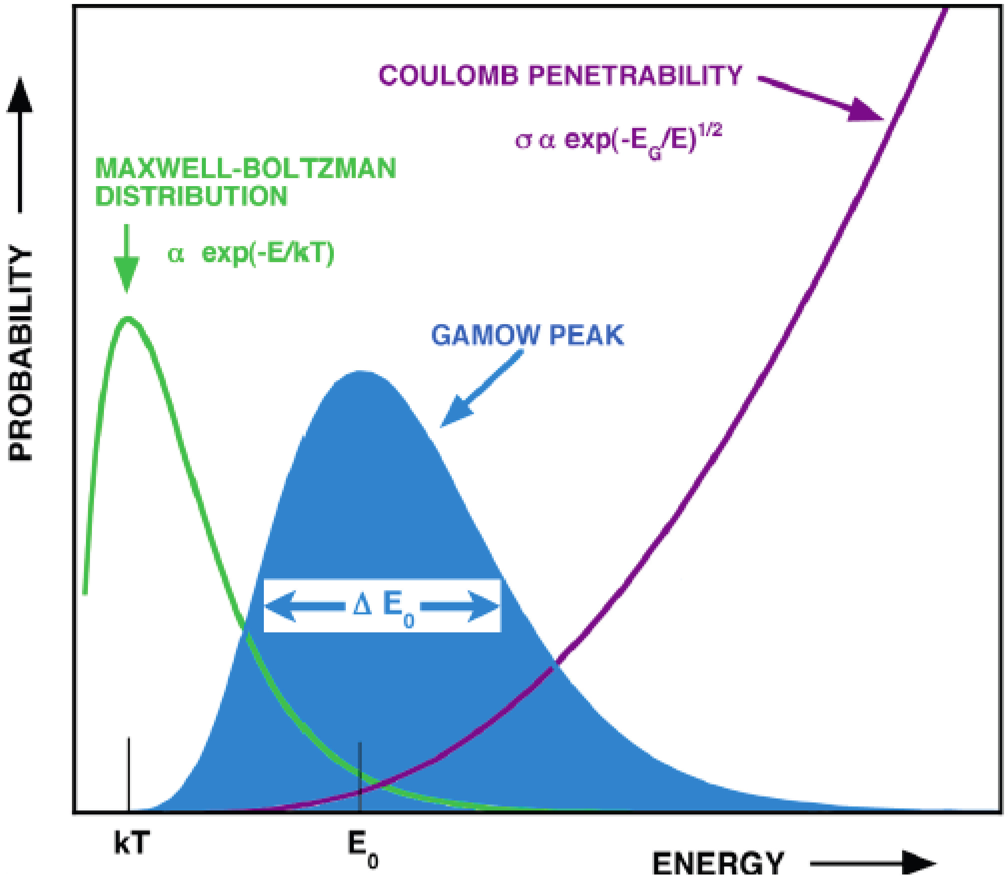
- Cross section σ = $E^{-1} \times \exp(-E^{½}) \times S(E)$

- Reaction rate becomes

$$\begin{aligned}\langle \sigma v \rangle &= \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E)\ \exp(-E/kT)dE \\ &= \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E)\ \exp(-bE^{-1/2})\ \exp(-E/kT)dE.\end{aligned}$$

  - S(E) is slowly varying with E, so integral is dominated by the two exponentials

Gamow peak



Most effective stellar energy

Nuclear reaction networks

- Turn number of reactions per volume and time into differential equation,
  for a reaction $i(j,o)m$

$$r_{i;j} = \frac{1}{1+\delta_{ij}} n_i n_j \langle \sigma v \rangle \longrightarrow \begin{array}{l} (\frac{\partial n_i}{\partial t})_\rho = (\frac{\partial n_j}{\partial t})_\rho = -r_{i;j} \\ (\frac{\partial n_o}{\partial t})_\rho = (\frac{\partial n_m}{\partial t})_\rho = +r_{i;j} \end{array}$$

- Total rate of change of number density:

$$\dot{n}_i = (\frac{\partial n_i}{\partial t})_\rho + n_i \frac{\dot{\rho}}{\rho}$$

  - Includes changes due to density change (we are not interested in those)

Abundances, mass fractions

- Matter density ρ (g cm^{-3})
- Number density n depends on matter density

- Can we separate dependence on matter density?

→ Define abundance $Y = n / \rho N_A$

- Units of abundance: mole g^{-1}

- Mass fraction $X_i = A_i Y_i$ with normalized sum

Nuclear reaction networks

- Use abundance $Y_i = \frac{n_i}{\rho N_A}$ $\dot{Y}_i = \frac{\dot{n}_i}{\rho N_A} - \frac{n_i}{\rho N_A}\frac{\dot{\rho}}{\rho}$
- Derivative becomes:

$$\dot{Y}_i = \frac{1}{\rho N_A}(\frac{\partial n_i}{\partial t})_\rho = -\frac{r_{i;j}}{\rho N_A} = -\frac{1}{1+\delta_{ij}}\rho N_A \langle\sigma v\rangle_{i;j} Y_i Y_j$$

- For decays (and reactions with photons and leptons):
  - “decay rate” λ
  - Derivate becomes $\dot{Y}_i = -\lambda_i Y_i$

Inverse reactions

- Many reactions are the inverse of an other reaction
- Forward and inverse reactions are linked by time reversal invariance

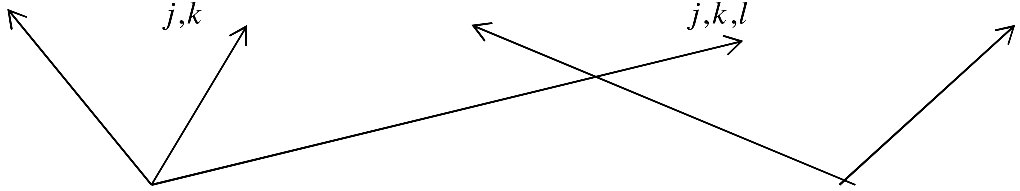
- For reaction i(j,o)m the thermonuclear cross section depends on
  - Q-value (energy difference between products and reactants)
  - Partition functions (Energy weighted density of states)

$$\langle\sigma v\rangle_{i;j,o} = \frac{1+\delta_{ij}}{1+\delta_{om}} \frac{G_m g_o}{G_i g_j} (\frac{\mu_{om}}{\mu_{ij}})^{3/2} \ \exp(-Q_{o,j}/kT) \, \langle\sigma v\rangle_{m;o,j}$$

Nuclear reaction networks

- Set of coupled differential equations

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{jk} \rho N_A \langle \sigma v \rangle_{jk} Y_j Y_k + \sum_{j,k,l} N^i_{jkl} \rho^2 N_A^2 \langle \sigma v \rangle_{jkl} Y_j Y_k Y_l$$



Specify number of particles created or destroyed; take into account reactions between the same (indistinguishable) species

Thermonuclear cross section

Y .. Abundance
λ …decay rate

Nuclear reaction networks

- Set of coupled differential equations

$$\dot{Y}_i = \underbrace{\sum_j N^i_j \lambda_j Y_j}_{} + \underbrace{\sum_{j,k} N^i_{jk} \rho N_A \langle \sigma\, v \rangle_{jk} Y_j Y_k}_{} + \underbrace{\sum_{j,k,l} N^i_{jkl} \rho^2 N_A^2 \langle \sigma\, v \rangle_{jkl} Y_j Y_k Y_l}_{}$$

  - Decays, photodisintegrations, reactions with leptons (e^-,e^+, ν)
  - Two-particle reactions
  - Three-particle reactions (e.g. triple-α reaction)

  - Right-hand side is sum of all reactions either creating or destroying species i
  - Group into 1-body, 2-body, and 3-body reactions programming reasons

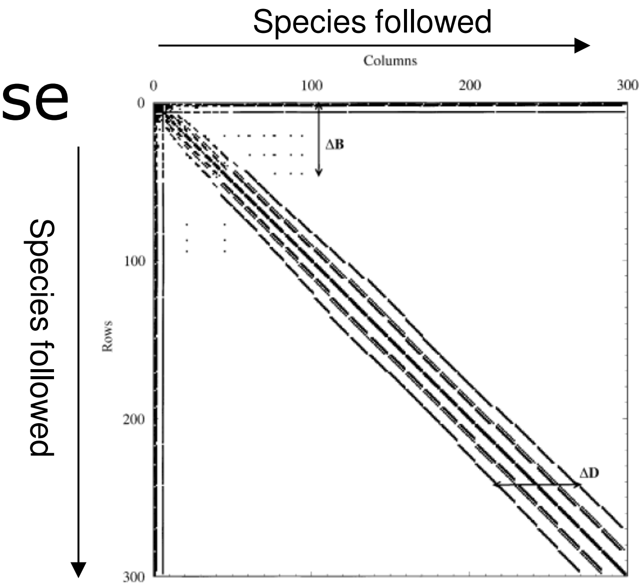
Nuclear reaction networks

- Set of coupled differential equations

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{jk} \rho N_A \langle \sigma v \rangle_{jk} Y_j Y_k + \sum_{j,k,l} N^i_{jkl} \rho^2 N_A^2 \langle \sigma v \rangle_{jkl} Y_j Y_k Y_l$$

- One equation for each species followed
    - ~2000 for supernova nucleosynthesis
    - ~6000 for r-process nucleosynthesis

- Matrix for system of DE is sparse
    - Use special solvers and matrix storage format



How to Model Nucleosynthesis

In principle: need 3D hydro in order to follow convection, mixing, explosion

Problems:

- Coupling of hydro to reaction networks (nucleosynthesis, energy generation)
- Explosions

Compromise:

- (1D) hydro with reduced energy generation network
- Mixing length theory, convection criteria
- Parameterized explosions (mass cut and/or explosion energy as free parameters)

Nevertheless: mostly reliable nucleosynthesis expected (except for nuclides dependent on explosion mechanism)

Implementation of Networks

- Fully coupled
    - Energy feedback + abundances

- Operator splitting
    - Reduced network for energy generation
    - Abundances in full network (mixing, convection)

- Post-processing
    - Reduced network for energy generation
    - Other abundances from post-processing

Explosive burning

- Similar to hydrostatic burning, but
  - Shorter timescales
  - Higher temperatures

- H-burning:
  - Hot CNO-cycle (pp-chains are too slow), where $^{13}N(\beta)$ becomes $^{13}N(p,\gamma)$
- He-burning:
  - N-rich isotopes ^{15}O, ^{18}O, ^{19}F, ^{21}Ne
- C- and Ne-burning:
  - Simultaneously occurring

Explosive burning

- O-burning:
  - Quasi-equilibrium (regions of equilibrium, connected by individual reactions)
- Si-burning:
  - Complete destruction of silicon
  - Details depend on peak temperature and density:
    - Complete Si-burning
    - Incomplete Si-burning (p-rich)
    - Incomplete Si-burning (α-rich)

Explosive burning