Jim Truran

Lecture II: Advanced Stellar Evolution and Nucleosynthesis

- **Stellar Evolution as a Function of Mass**
  - **low mass stars, planetary nebulae, and white dwarfs**
  - **massive stars, supernovae, and neutron stars**
  - **nucleosynthesis of elements past iron via neutron captures**

Summer School in Nuclear Physics
Laurence Berkeley National Laboratory

June 6-10, 2005

Nuclear Reactions and Energy Generation

Proton-Proton Hydrogen Burning Reactions

The pp-chains

pp-1:	$^{1}H(p,e^{+}\nu)^{2}H$	
	$^{2}H(p,\gamma)^{3}He$	
	$^{3}He(^{3}He,2p)^{4}He$	84.7%
pp-2:	$^{3}He(\alpha,\gamma)^{7}Be$	13.8%
	$^{7}Be(e^{-},\nu)^{7}Li$	13.78%
	$^{7}Li(p,\alpha)^{4}He$	
pp-3:	$^{7}Be(p,\gamma)^{8}B$	0.02%
	$^{8}B(\beta^{+}\nu)2^{4}He$	

fusion of $4\,^{1}H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

Nuclear Reactions and Energy Generation

Network for the pp-chain I

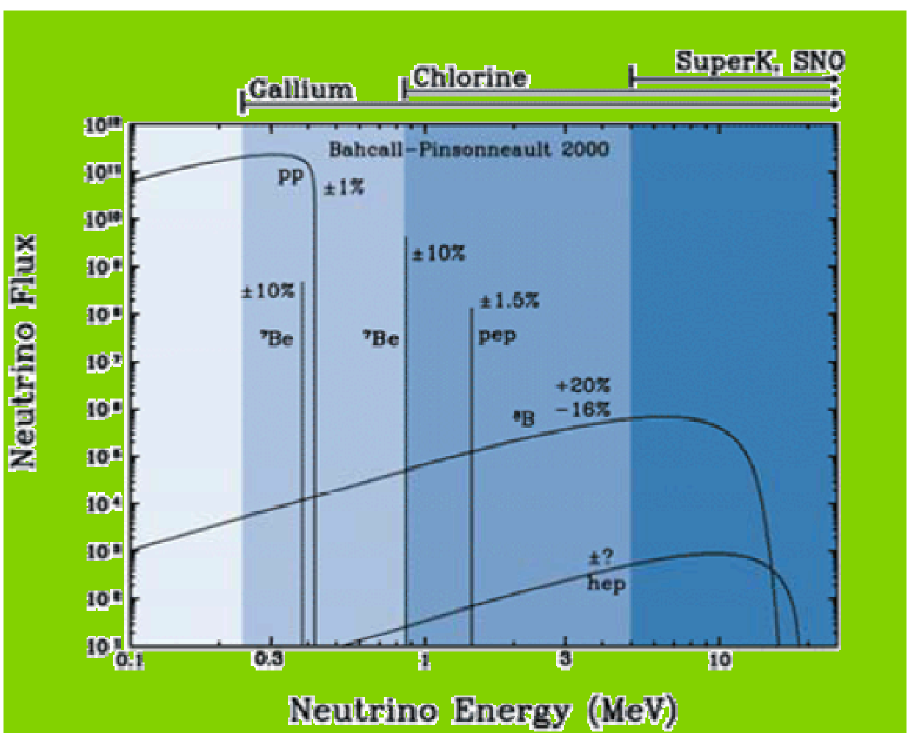
$$\frac{d^1H}{dt} = -2\cdot\frac{1}{2}\cdot Y_{^1H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^1H(p,e^-\nu)} + 2\cdot\frac{1}{2}\cdot Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)}$$

$$\frac{d^2H}{dt} = -Y_{^2H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^2H(p,\gamma)} + \frac{1}{2}\cdot Y_{^1H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^1H(p,e^-\nu)}$$

$$\frac{d^3He}{dt} = -2\cdot\frac{1}{2}Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)} + Y_{^2H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^2H(p,\gamma)}$$

$$\frac{d^4He}{dt} = \frac{1}{2}Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)}$$

Calculated Solar Neutrino Fluxes

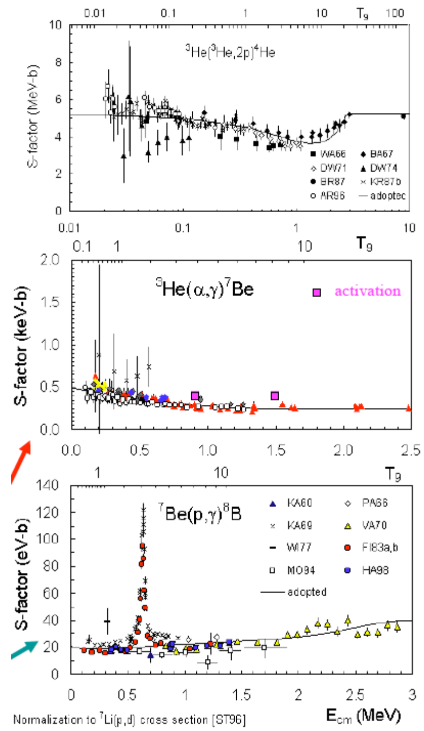


S(E) Factors for Critical Rates for Solar Neutrinos

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

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

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



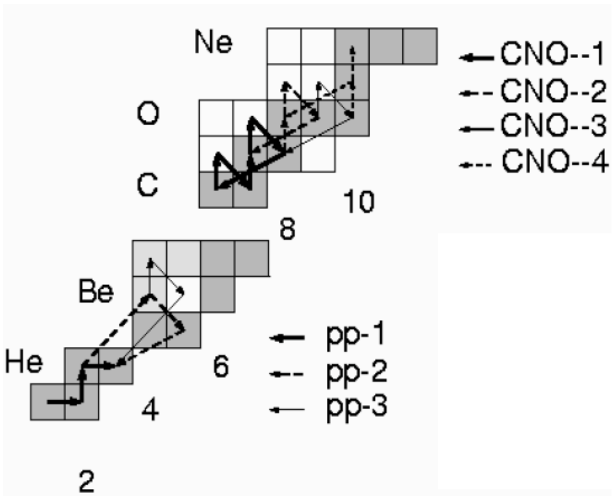
Nuclear Reactions and Energy Generation

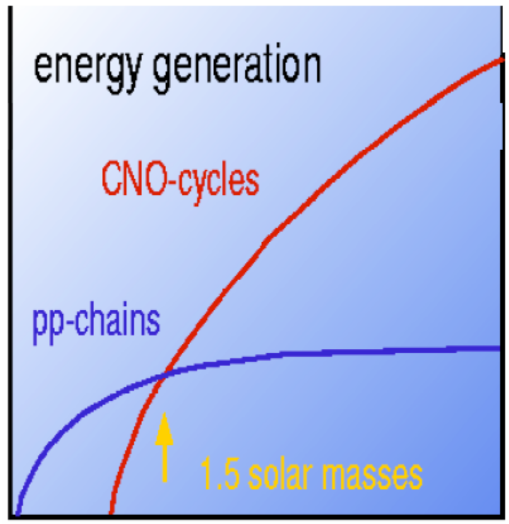
Reactions in the CNO cycles

CNO-1:	$^{12}C(p,\gamma)^{13}N$	$S_{12C(p,\gamma)}$=3 10^{-3} MeV-barn
	$^{13}N(\beta+\nu)^{13}C$	
	$^{13}C(p,\gamma)^{14}N$	
	$^{14}N(p,\gamma)^{15}O$	$S_{14N(p,\gamma)}$=2 10^{-3} MeV-barn
	$^{15}O(\beta+\nu)^{15}N$	
	$^{15}N(p,\alpha)^{12}C$	$S_{15N(p,\alpha)}$=1 10^{+2} MeV-barn
CNO-2:	$^{15}N(p,\gamma)^{16}O$	$S_{15N(p,\gamma)}$=5 10^{-2} MeV-barn
	$^{16}O(p,\gamma)^{17}F$	
	$^{17}F(\beta^{+}\nu)^{17}O$	
	$^{17}O(p,\alpha)^{14}N$	
CNO-3:	$^{17}O(p,\gamma)^{18}F$	
	$^{18}F(\beta^{+}\nu)^{18}O$	
	$^{18}O(p,\alpha)^{15}N$ $\Rightarrow$ CNO-4	

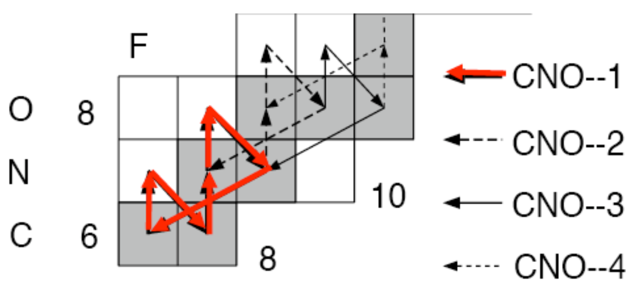
Nuclear Reactions and Energy Generation

Hydrogen Burning Phase of Stellar Evolution

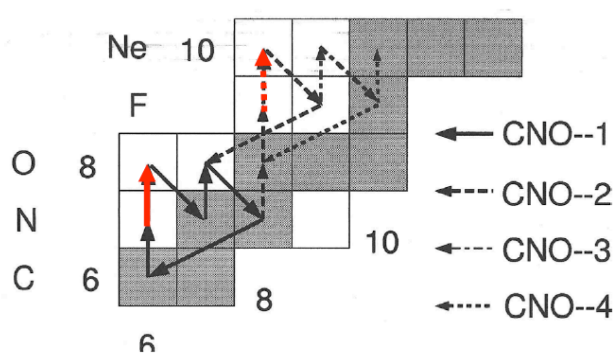




CNO Burning as a Function of Temperature



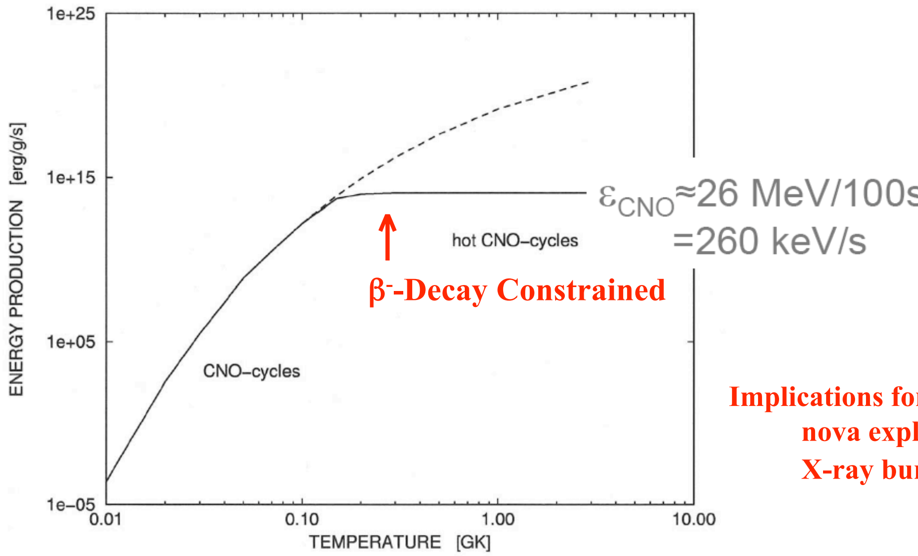
'Normal' CNO Cycle Burning



'Hot' CNO Cycle Burning (T > 80 million K)

CNO Burning as a Function of Temperature

Impact on energy generation

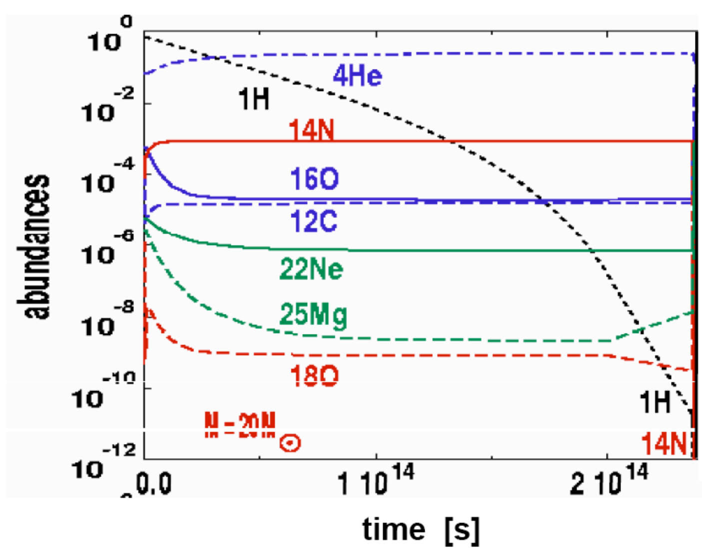


Implications for:

nova explosions

X-ray bursts

CNO Hydrogen Burning in a 20 $M_{\odot}$ Star



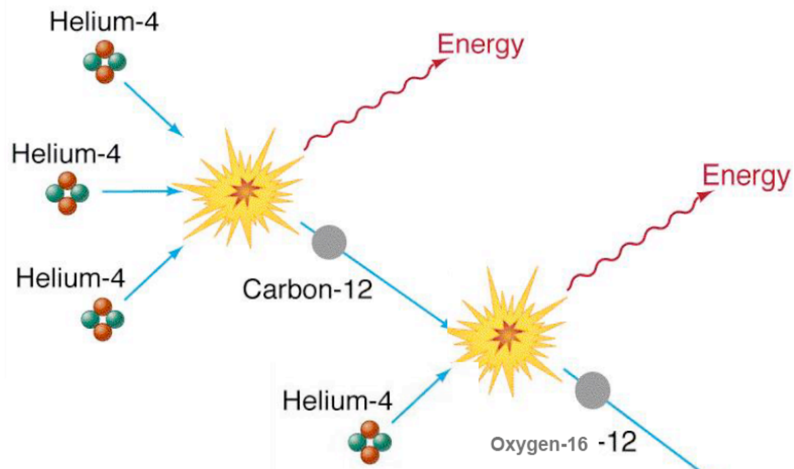
Conversion of the initial

- ^{1}H to ^{4}He
- ^{12}C, ^{16}O to ^{14}N

$^{14}N(p,\gamma)^{15}O$ is the slowest rate in the CN cycle.

Helium Burning: ^{12}C and ^{16}O Synthesis

Critical Reactions in He-burning

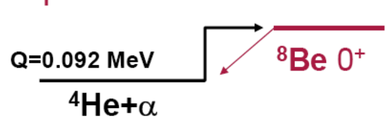


Energy source in stellar He burning
Energy release determined by associated reaction rates

Helium Burning Reactions in Stars

The ($\alpha\alpha\alpha$) Reaction as two step process

first step!



$T_{1/2}(^{8}Be) = 9.7\cdot 10^{-17}$ s
Γ_{α}=6.8 eV
pure α cluster configuration

fast capture $\Rightarrow$ equilibrium between capture and decay

Interaction time: $t \approx \frac{2R_{\alpha}}{v_{\alpha}} = \frac{2\cdot 1.3\cdot A^{1/3}}{\sqrt{\frac{2E_{\alpha}^{cm}}{\mu}}} \approx \frac{4.17\ fm}{3.8\cdot 10^{24}\ fm/s} \approx 10^{-24}\ s << \tau(^{8}Be)$

Application of Saha Equation
For calculating ^{8}Be equilibrium: $N(^{8}Be) = N_{\alpha}^{2}\cdot\hbar^{3}\cdot\left(\frac{2\pi}{\mu\cdot kT}\right)^{3/2}\cdot e^{\left(-\frac{Q}{kT}\right)}$

Helium Burning Reactions in Stars

Example for ^{8}Be equilibrium abundance:

Case of typical He-burning: T=0.1GK $\Rightarrow$ T_9=0.1; $\rho=10^5$ g/cm^3

$$N\left({}^{8}Be\right)=6\cdot10^{-35}\cdot N_\alpha^2\cdot T_9^{-3/2}\cdot e^{\left(-\frac{1.068}{T_9}\right)}$$

$$N\left({}^{8}Be\right)\approx 4.4\cdot10^{-38}\cdot N_\alpha^2$$

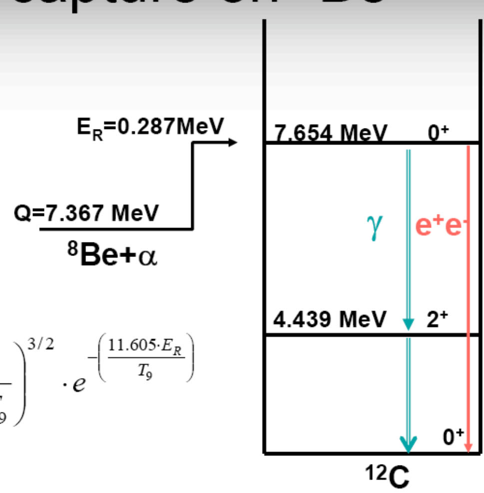
$$N=\rho\cdot N_A\cdot\frac{X_i}{A_i}\quad\Rightarrow\quad\frac{X\left({}^{8}Be\right)}{X_\alpha^2}\approx1.3\cdot10^{-9}$$

~ one ^{8}Be nucleus
for 10^9 α particles

Helium Burning Reactions in Stars

Resonant capture on ^{8}Be

The Hoyle resonance!



$$N_A\langle\sigma v\rangle=1.54\cdot10^{11}\cdot\omega\gamma\cdot\left(\frac{1}{\mu\cdot T_9}\right)^{3/2}\cdot e^{-\left(\frac{11.605\cdot E_R}{T_9}\right)}$$

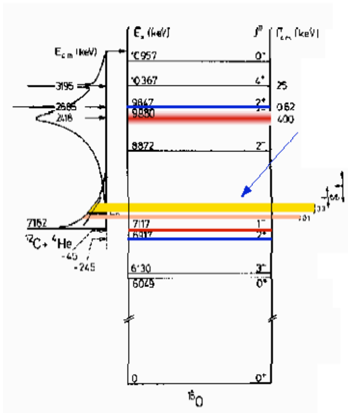
$$\omega\gamma=(2J+1)\cdot\frac{\Gamma_{in}\cdot\Gamma_{out}}{\Gamma_{tot}}$$

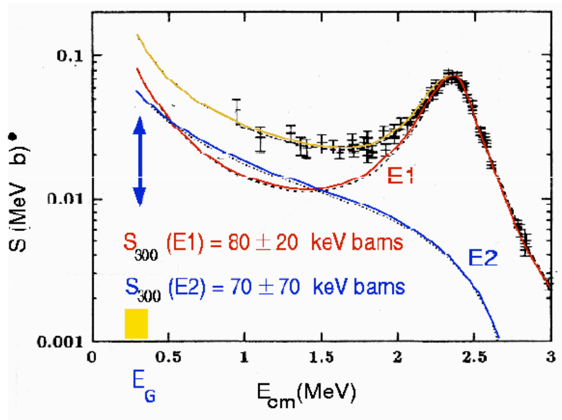
Decay by sequential E2 γ transitions
or internal e$^+$ e$^-$ pair conversion

Helium Burning Reactions in Stars

$^{12}C(\alpha,\gamma)^{16}O$, the Holy Grail

Level and Interference Structure

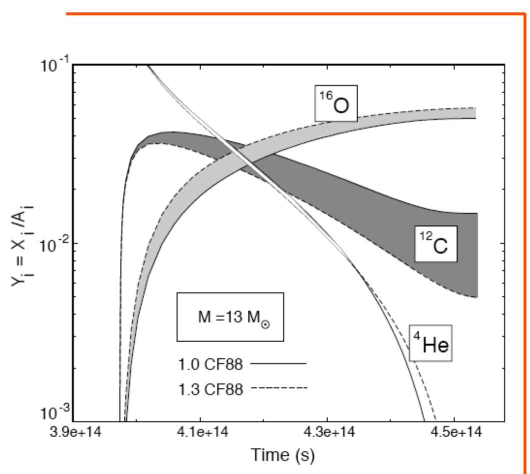




Uncertainty in low energy extrapolation

Helium Burning Reactions in Stars

Consequences of $^{12}C(\alpha,\gamma)^{16}O$

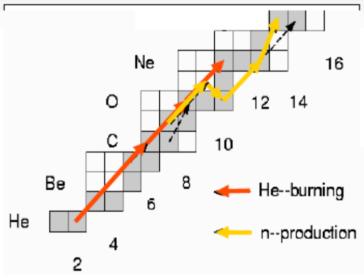


- Late Stellar Evolution
  determines Carbon and/or Oxygen phase
- Type Ia Supernova
  central carbon burning of C/O white dwarf
- Type II Supernova
  shock-front nucleosynthesis in C and He shells of pre-supernova star

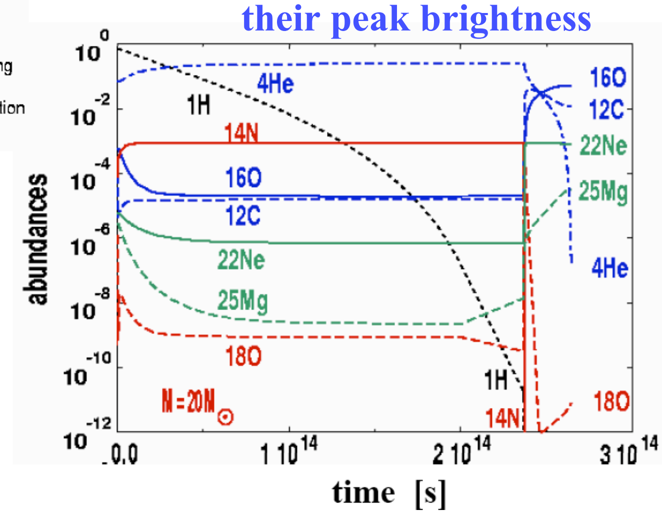
^{12}C synthesis in red giant stars in incomplete helium burned regions

Evolution Past Hydrogen Burning

Abundance evolution in stellar core

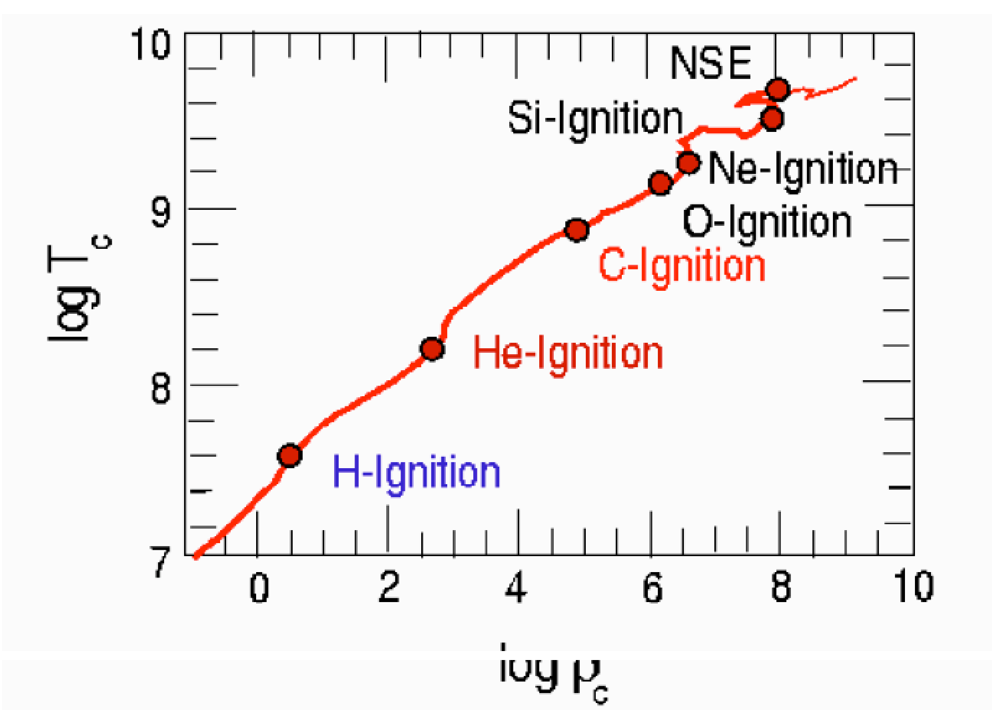


* ^{22}Ne levels in SNe Ia progenitors impacts their peak brightness

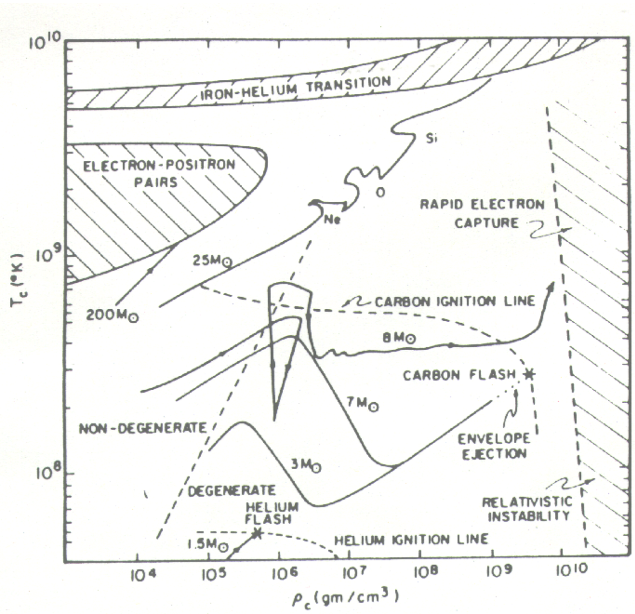


Decline of ^{4}He (time-scale)
increase in ^{12}C, ^{16}O
$\Rightarrow$equilibrium ^{12}C/^{16}O
Rapid decline in ^{14}N.

Core Temperature and Density Evolution in Stars

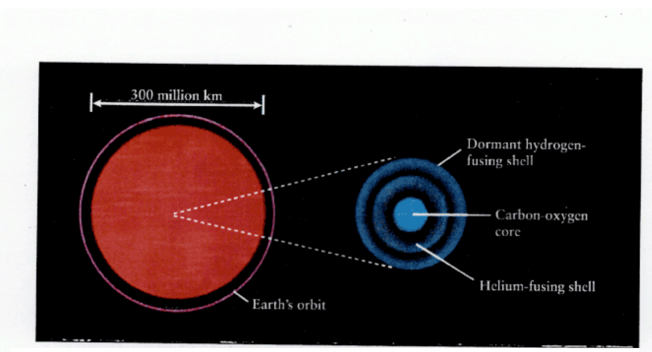


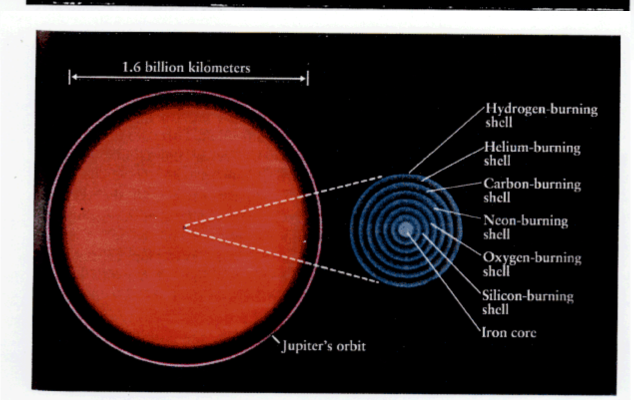
Distinguishing Low Mass and Massive Star Behaviors



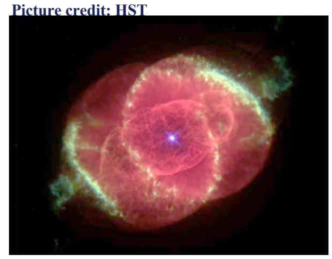
- **The Virial Theorem predicts a dependence $T \propto M^{2/3}\rho^{1/3}$ of core temperature on density for an ideal gas law.**
- **Equality of gas pressure and degeneracy pressure yields $T \propto \rho^{2/3}$.**
- **The critical issue is whether the temperature is sufficient to ignite the H, He, C, or O fuel prior to reaching degeneracy.**

Stellar and Supernova Nucleosynthesis





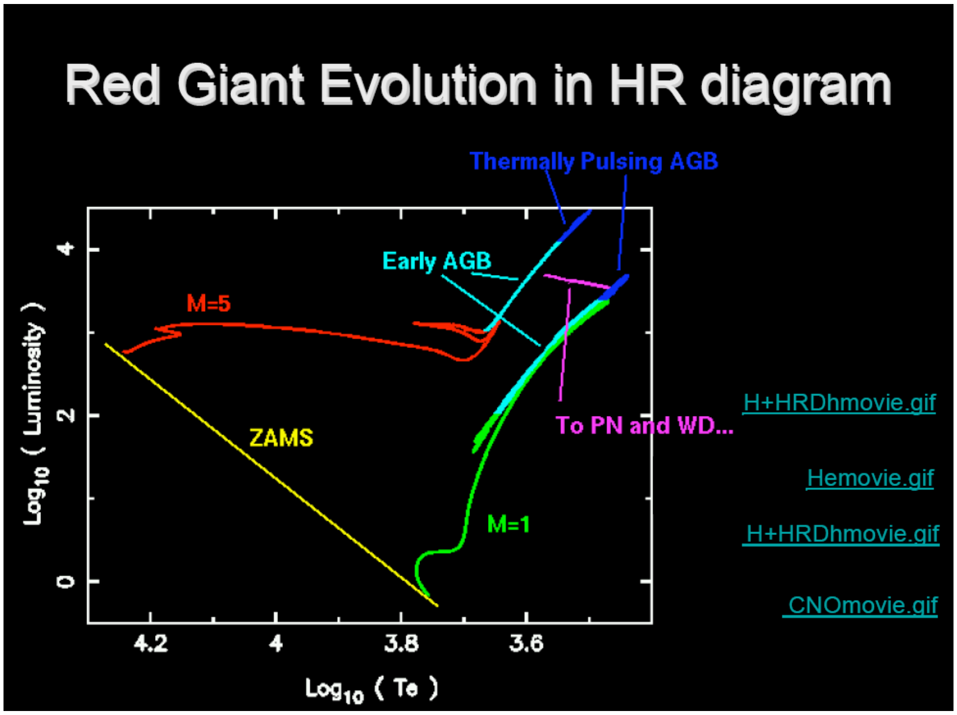
Picture credit: HST



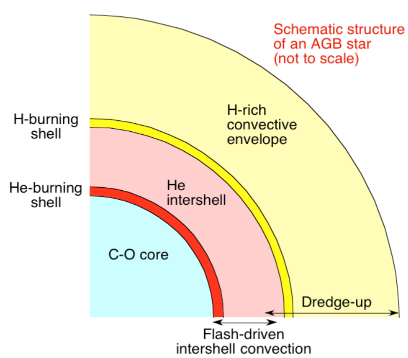
AGB Star - Planetary Nebula

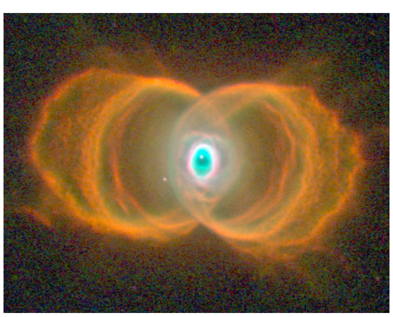
Massive Star - SNII

Evolution of Intermediate Mass (AGB) Stars



Nucleosynthesis in Red Giant Stars





- Asymptotic giant stars are an advanced stage of evolution of all low mass stars $1 < M_* < 10\ M_\odot$

- Thermal pulses in their helium burning shells provide an environment for the production of both ^{12}C and many isotopes of heavy nuclei (s-process products) .

- Incomplete helium burning leaves the He intershell ^{12}C rich and results in the limit in the formation of a "carbon star."

- These products are returned to the interstellar gas via winds and planetary nebula ejection.

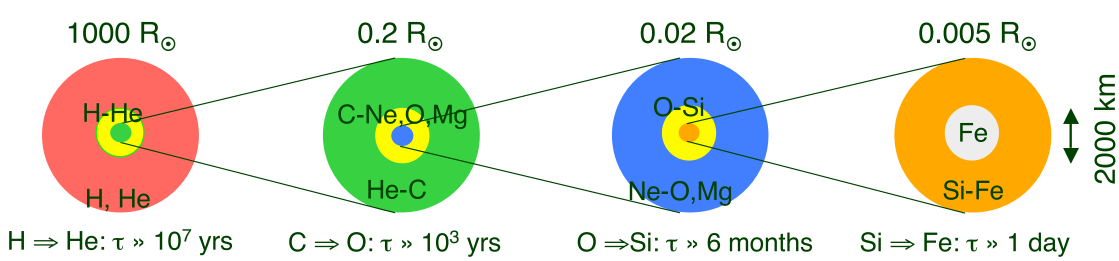
Heavy Ion Reactions: Advanced Burning Stages

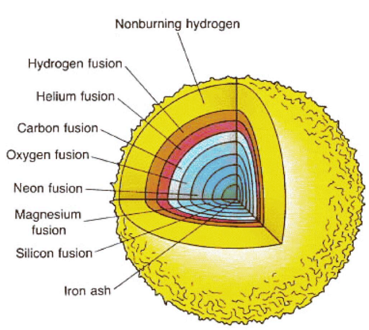
- **Subsequent to helium burning, stars more massive than 10 M are sufficiently hot to continue thermonuclear burning. The next stages are:**
  - **Carbon burning, proceeding via $^{12}C + ^{12}C$**
  - **Neon burning, initiated via ^{20}Ne photodisintegration**
  - **Oxygen burning, proceeding via $^{16}O + ^{16}O$**

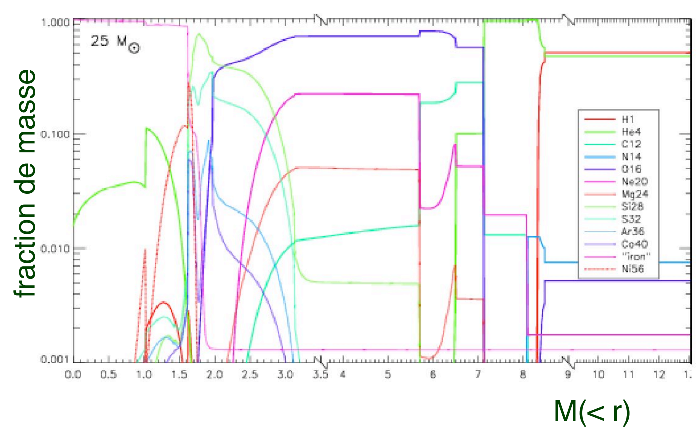
- **The final stage of energy generation involves the conversion of ^{28}Si to iron-peak nuclei, in what is known as silicon burning -or the "equilibrium" process.**

- **These stages leave in their wake a layered compositional structure, with an iron core that is on the verge of collapse in the absence of further nuclear fuel.**

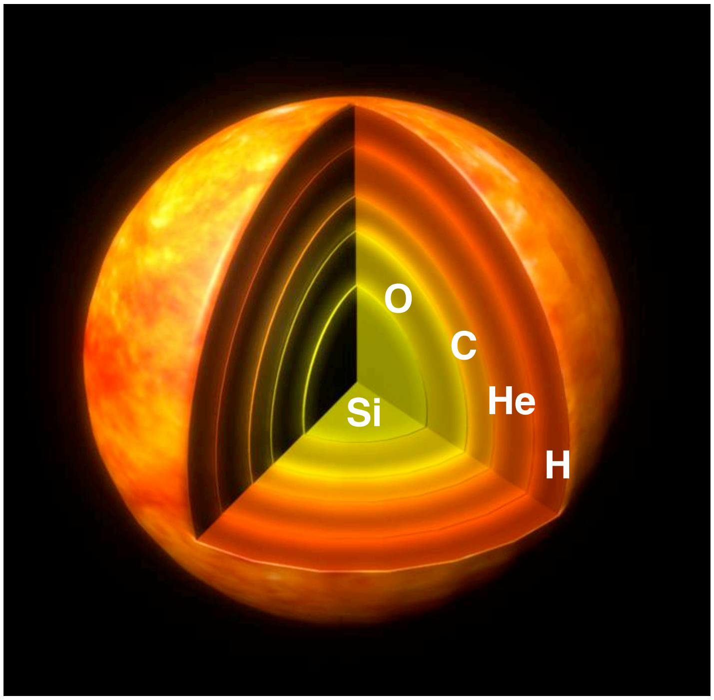
Composition pre-supernova : $M = 25\ M_\odot$







Nuclear Astrophysics: Perspective

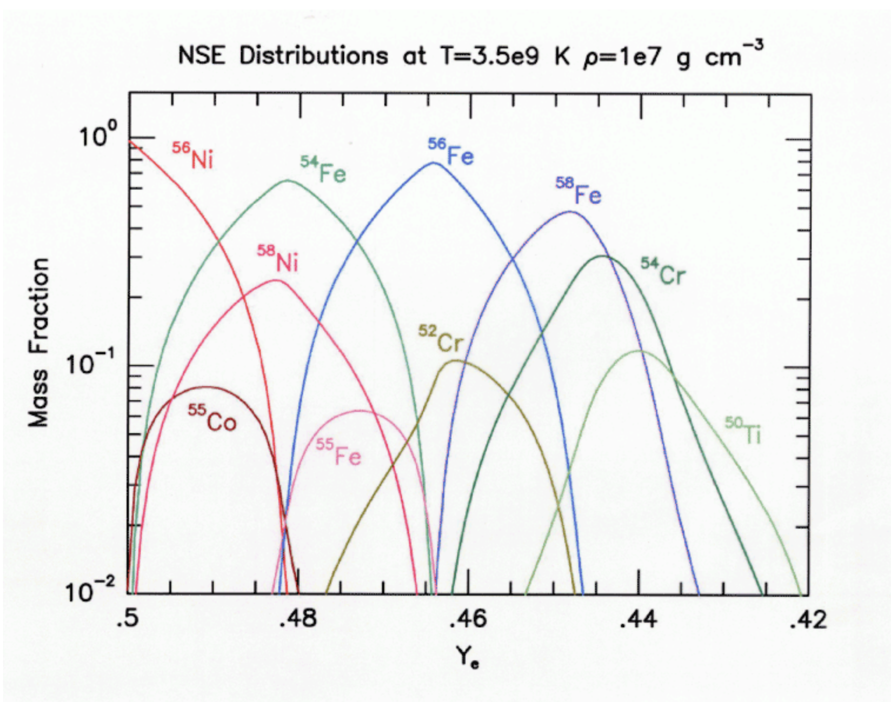


Onion-like structure of a presupernova star several million years after its birth:

mass: 10 ... 10^2 $M_\odot$
radius: 50 ... 10^3 $R_\odot$

- shells of different composition are separated by active thermonuclear burning shells
- core Si-burning leads to formation of central iron core

Nuclear Statistical Equilibrium Conditions

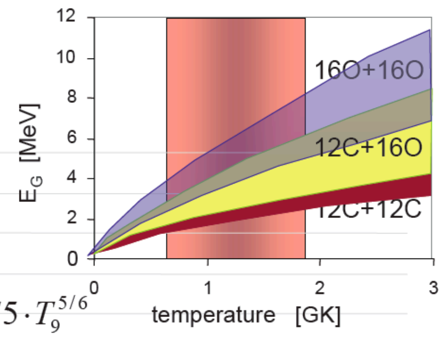


Heavy Ion Reactions: Advanced Burning Stages

The Gamow window for heavy ion reactions

$$E_G = 0.122 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^2\right)^{1/3} \; [MeV]$$

$$\Delta E_G = 0.236 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^5\right)^{1/6} \; [MeV]$$



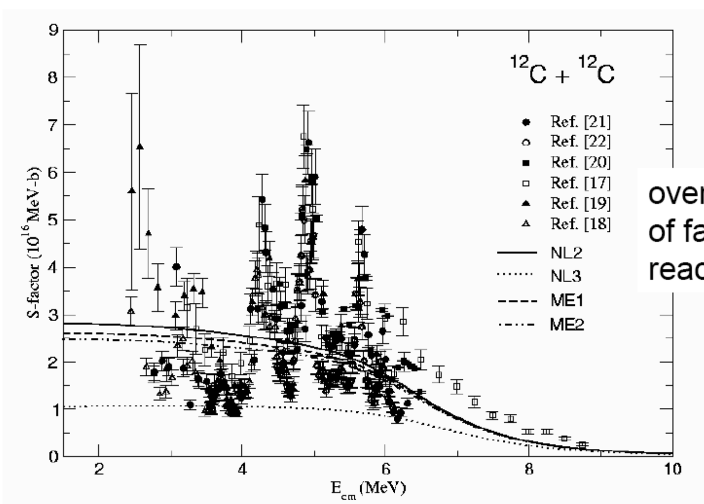
$$^{12}C{+}^{12}C: \quad E_G = 2.42 \cdot T_9^{2/3} \pm 0.75 \cdot T_9^{5/6}$$

$$^{16}O{+}^{12}C: \quad E_G = 3.06 \cdot T_9^{2/3} \pm 0.86 \cdot T_9^{5/6}$$

$$^{16}O{+}^{16}O: \quad E_G = 3.90 \cdot T_9^{2/3} \pm 1.34 \cdot T_9^{5/6}$$

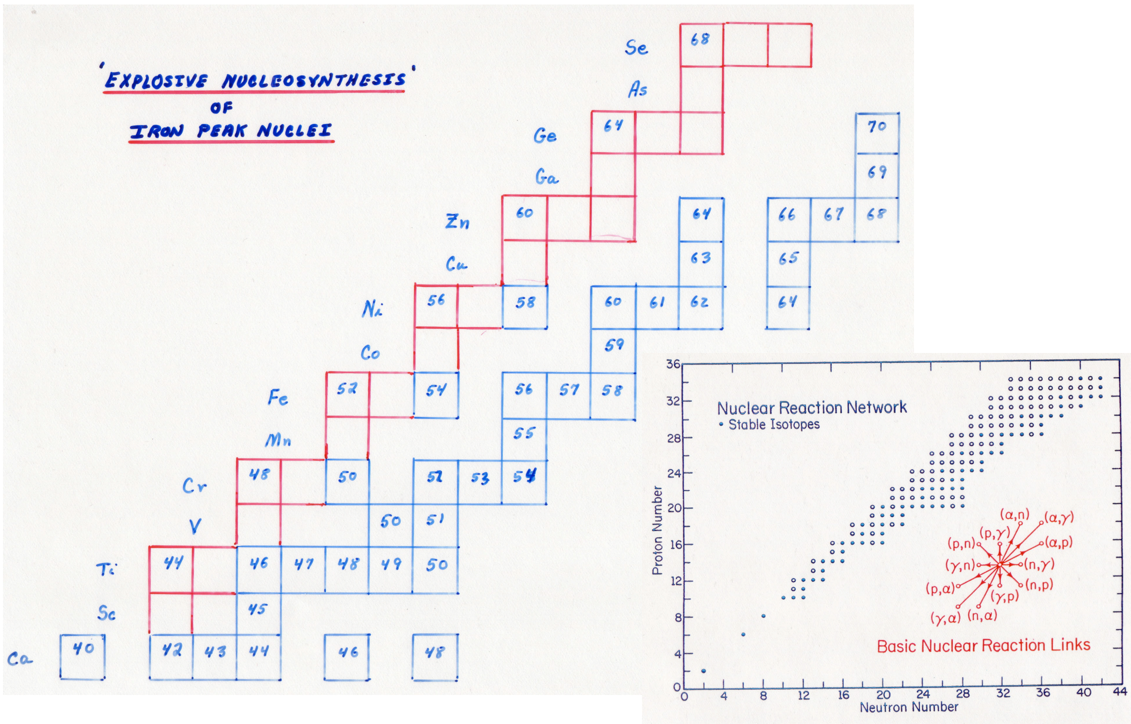
Heavy Ion Reactions: Advanced Burning Stages

S-factor extrapolations for different nuclear models

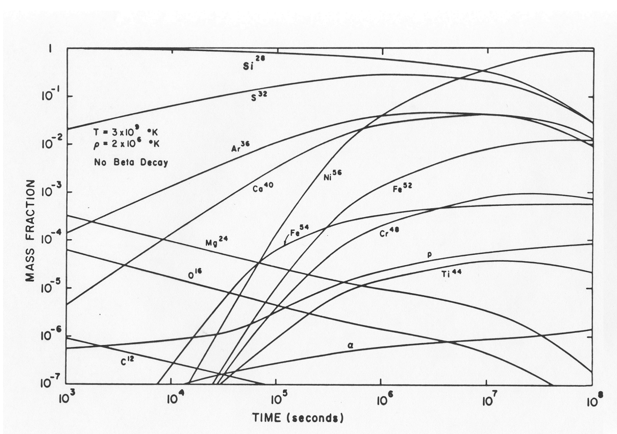


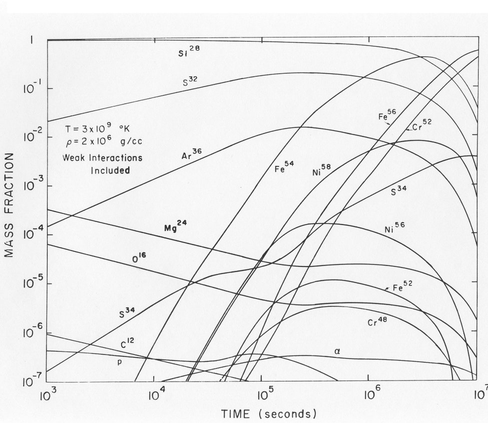
overall uncertainty of factor 2-5 in the reaction rate

^{56}Ni Production in Explosive Nucleosynthesis



Silicon Burning with and w/o Weak Interactions





Synthesis of Nuclei Beyond Iron

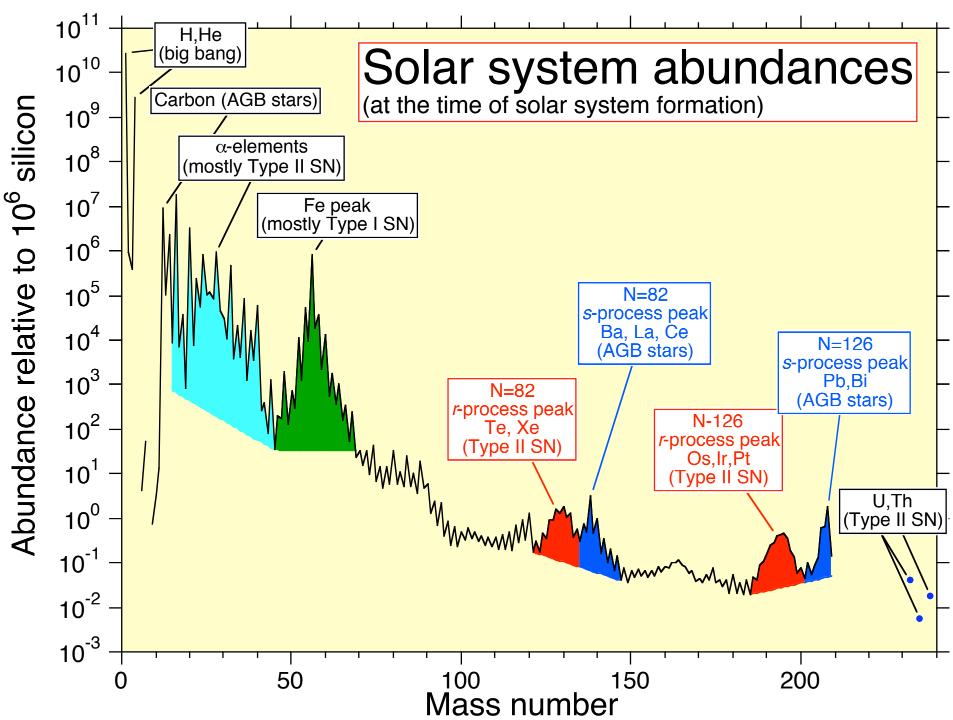
- **Nuclei heavier than iron (A > 60) are understood to be formed in neutron capture processes.**

- **The helium shells of red giant stars (≈ 1-10) provide the s-process environment, with the $^{13}C(\alpha,n)^{16}O$ reaction providing neutrons.**

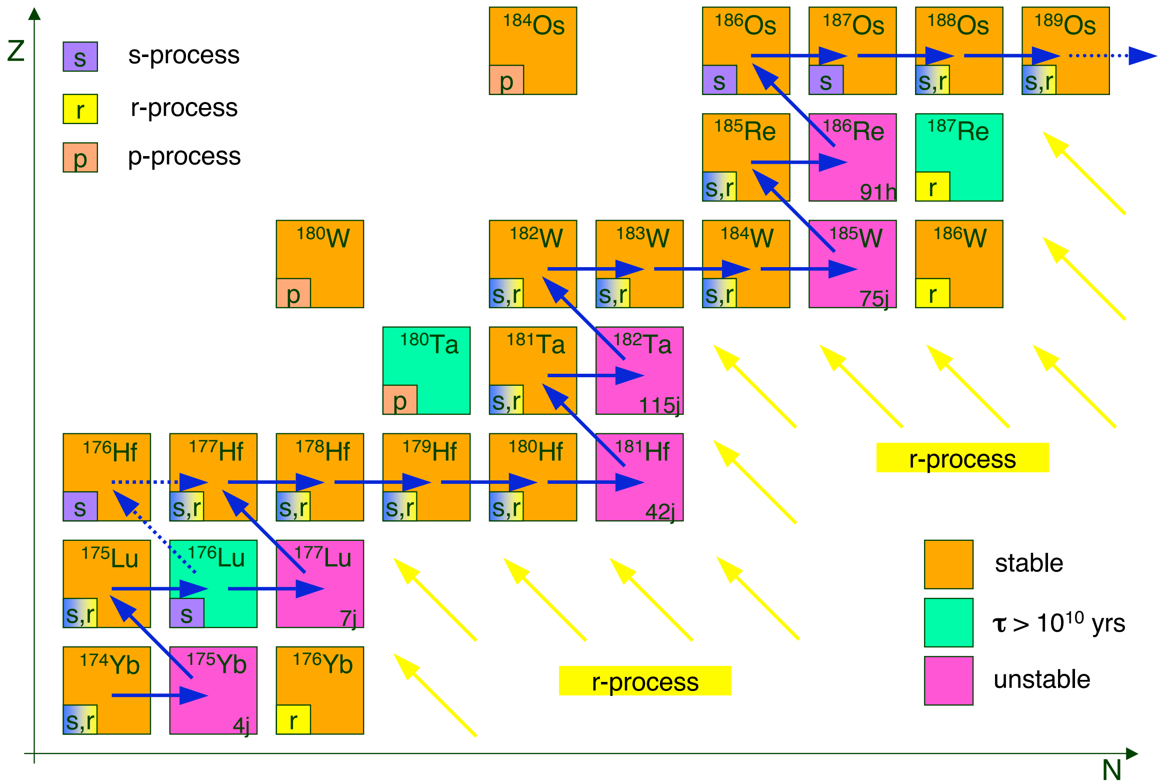
- **Supernovae II provide the setting for the r-process.**

- **Note the different production timescales for the two neutron capture processes – 10^9 verses 10^8 years.**

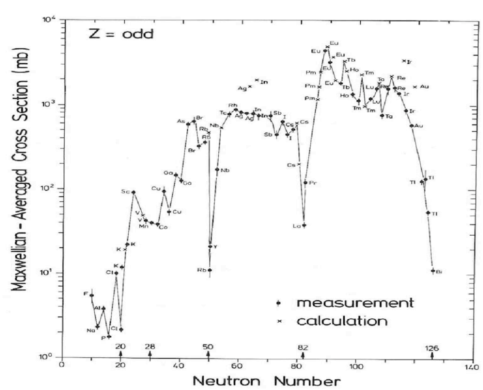
Cosmic Abundances

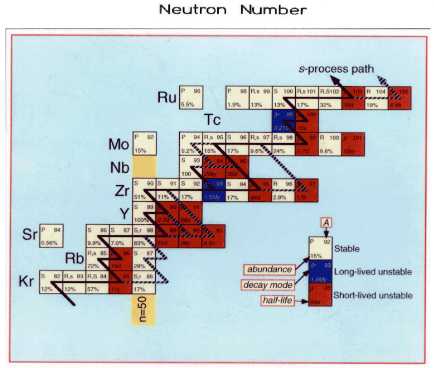


« s » Process



s-Process/r-Process in Solar System Matter



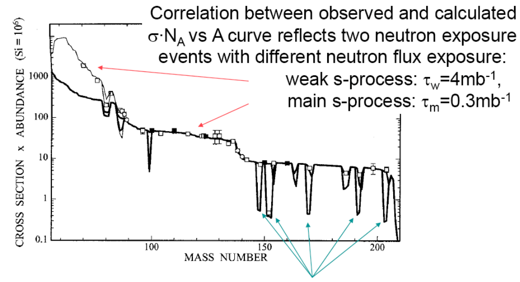


The classical s-process model

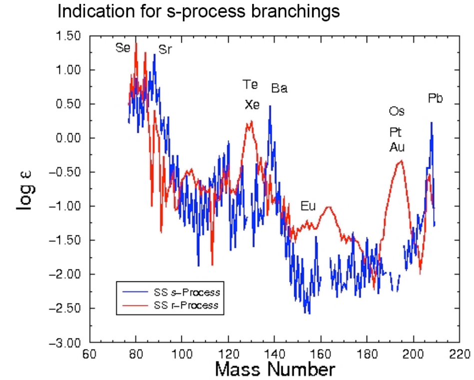
Correlation between observed and calculated $\sigma \cdot N_A$ vs A curve reflects two neutron exposure events with different neutron flux exposure:

weak s-process: τ_w=4mb^{-1},

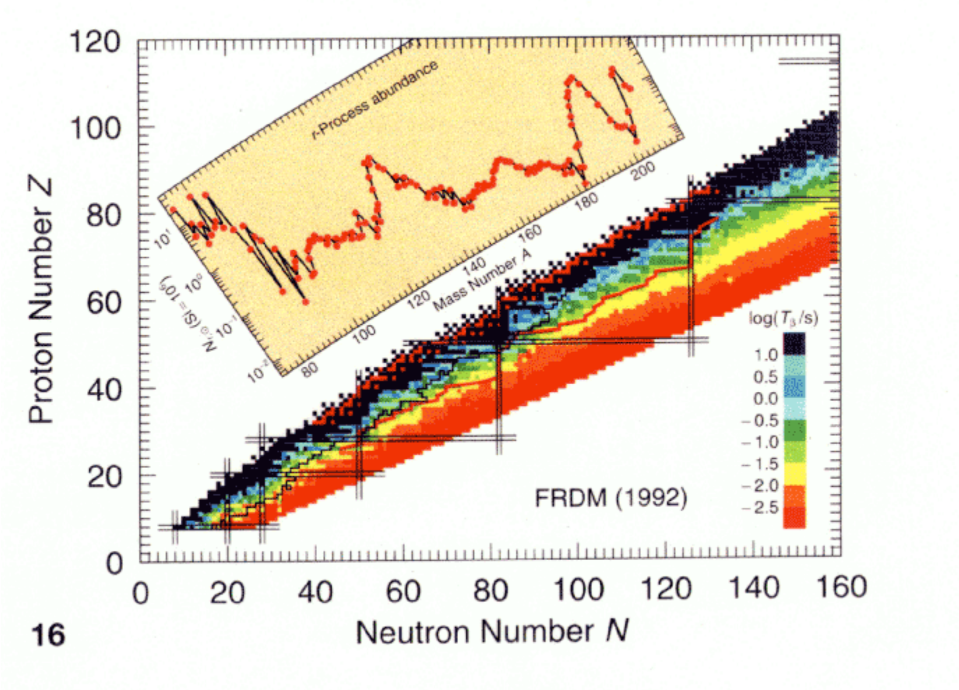
main s-process: τ_m=0.3mb^{-1}



Indication for s-process branchings

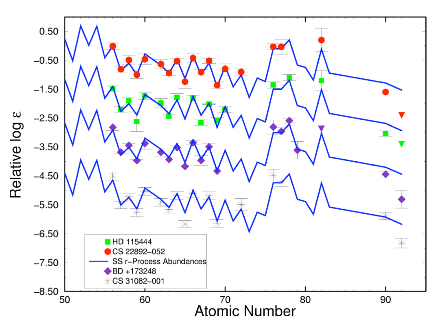


r-Process Neutron Capture Path

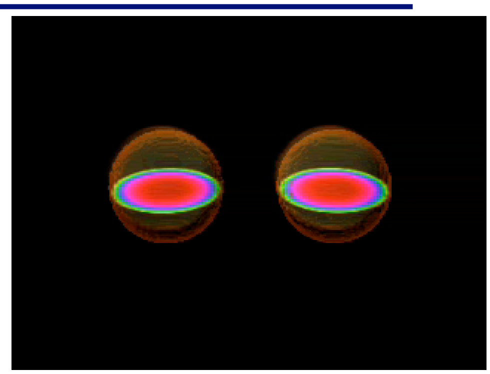


r-Process Nucleosynthesis: Theory

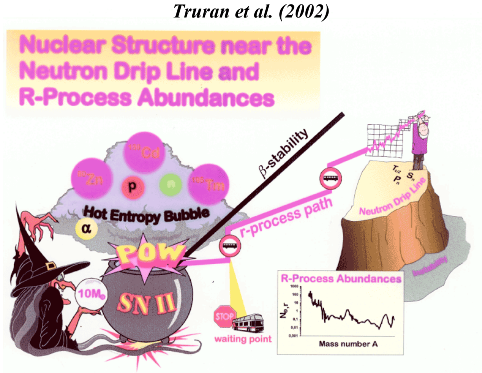
r–Process Abundances in Halo Stars



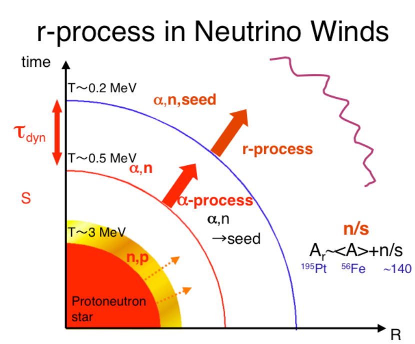
Truran et al. (2002)



Courtesy: Alan Calder, UChicago



Courtesy: K.-L. Kratz, Mainz

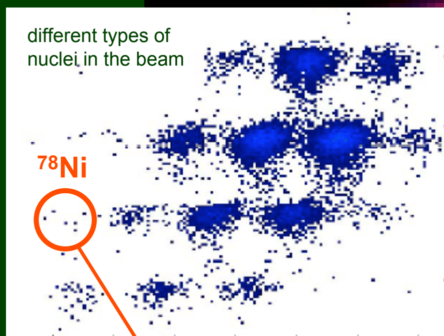


Courtesy: Kaori Otsuki, UChicago

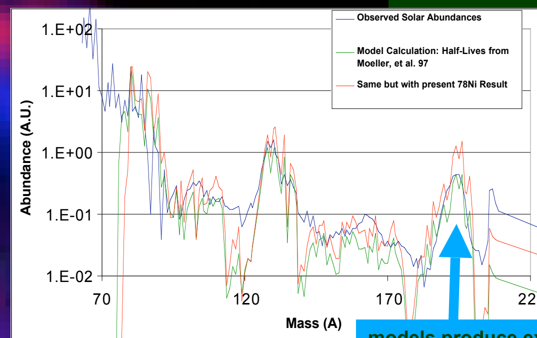
H. Schatz

Doubly magic nucleus accelerates synthesis of heavy elements

Particle identification in rare isotope beam from NSCL at Michigan State University



Model calculation for synthesis of heavy elements during the r-process in supernova explosions



models produce excess of heavy elements with new shorter 78Ni half-life

Measured half-life of ^{78}Ni with 11 events
This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

→ the synthesis of heavy elements in the r-process proceeds faster than previously assumed

→ a step towards the answer of the open question of the origin of the heavy elements in the cosmos

Result: 110^{+100}_{-60} ms

P. Hosmer et al. accepted in PRL