Radioactivity

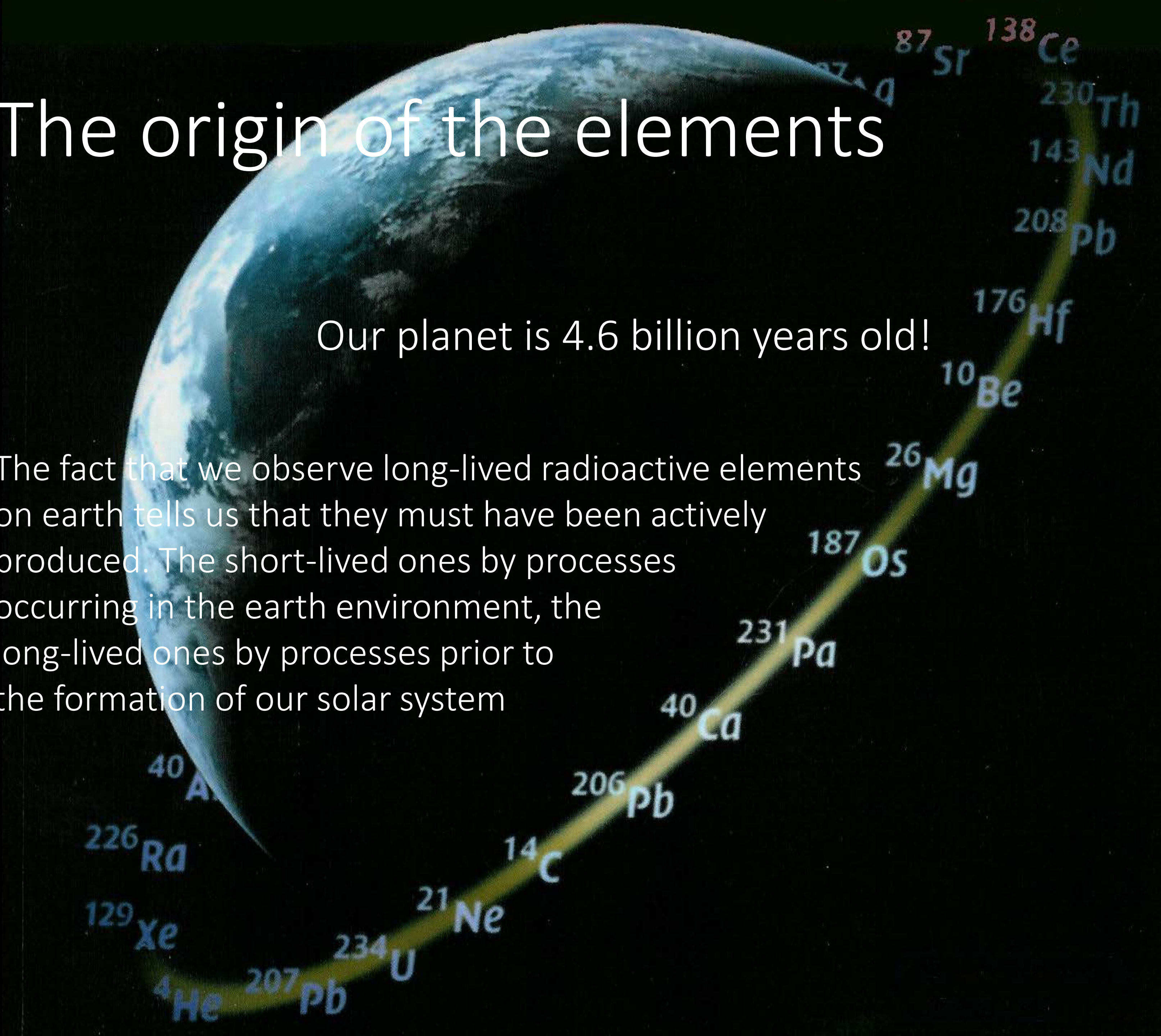
Lecture 9

The Origin of Radioactivity

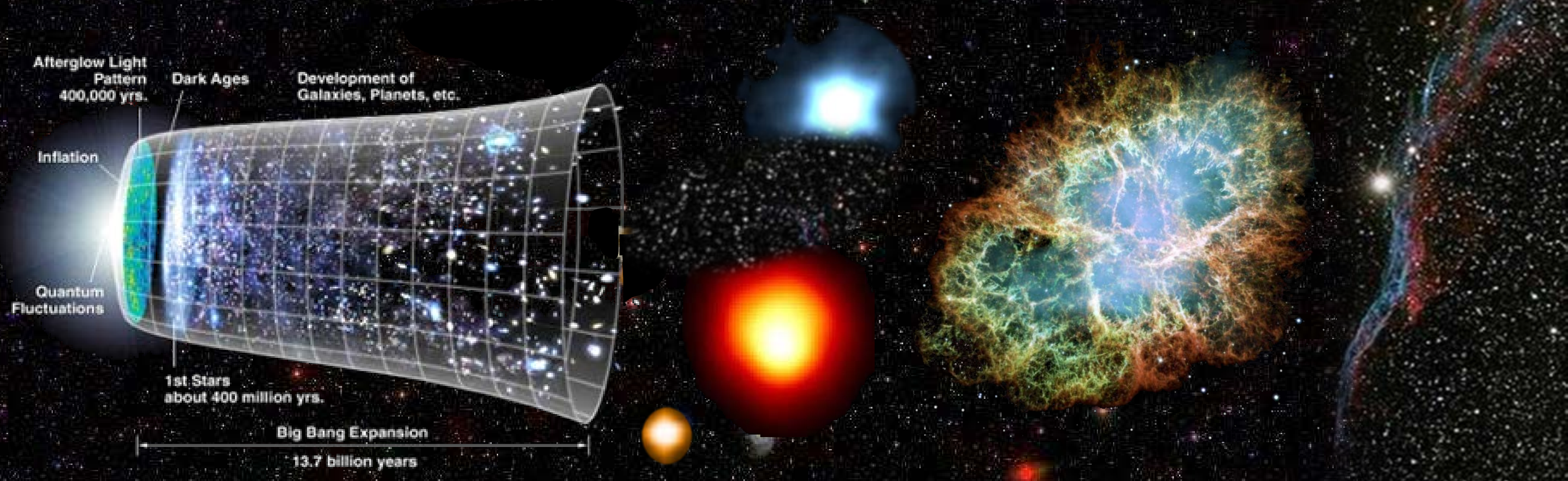
The origin of the elements

Our planet is 4.6 billion years old!

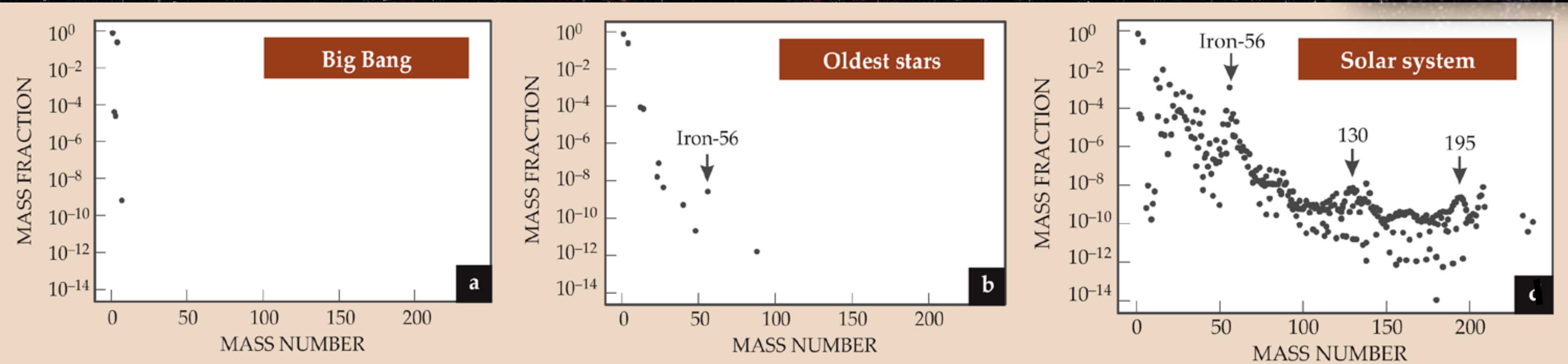
The fact that we observe long-lived radioactive elements on earth tells us that they must have been actively produced. The short-lived ones by processes occurring in the earth environment, the long-lived ones by processes prior to the formation of our solar system



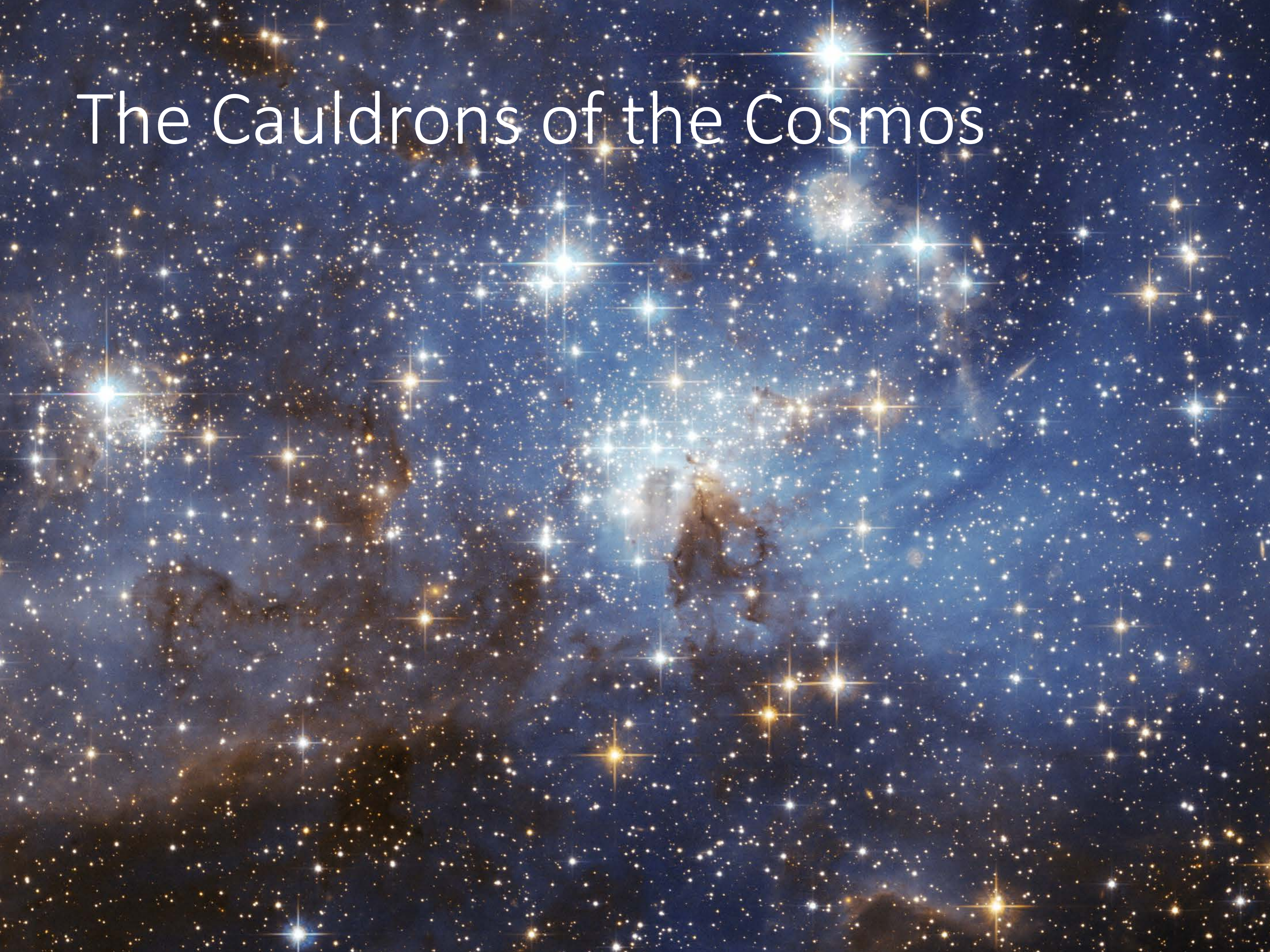
Galactic Chemical Evolution



Observational evidence points to a gradual build-up of the heavy elements in the cauldrons of stars and stellar explosions from the initial H, He seed after the Big Bang 13.6 billion years ago!

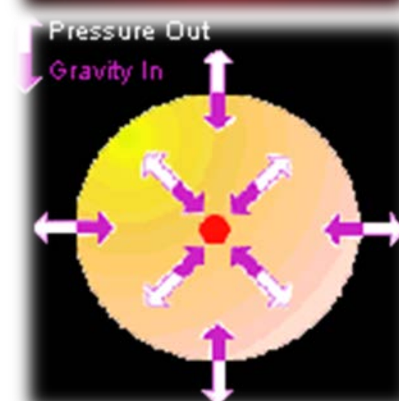


The Cauldrons of the Cosmos



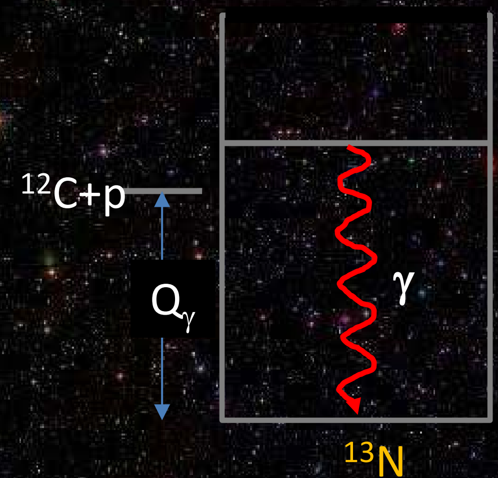
Nucleosynthesis in Stars

- Nucleosynthesis emerges from a balance between gravitation and nuclear energy.
- Star contracts gradually under gravitation releasing energy that heats its interior.
- If sufficient temperature has been reached nuclear fusion reactions set in, release energy that generates heat and internal pressure balancing the gravitational contraction until the nuclear fuel is exhausted.
- Gravitational contraction sets in again raising the temperature towards next burning stage on the ashes of the preceding nucleosynthesis event.



Nuclear Reactions in Stars

- generate energy
- create new isotopes and elements



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

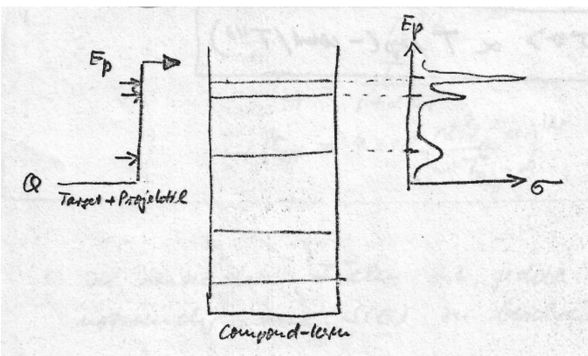
Generates energy that corresponds to the mass difference between $^{12}C+^{1}H$ and ^{13}N

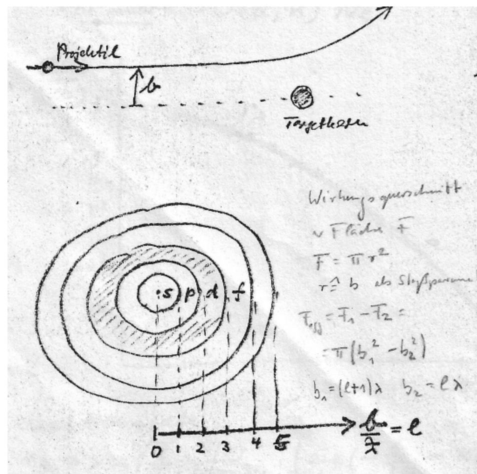
^{13}N is a radioactive isotope with $T_{1/2}$=10m

reaction probability ⇒ σ: reaction cross section (in unit barns=$10^{-24}cm^2$)

Reaction Components

Rutherford scattering misses the nucleus, it is only based on electromagnetic interaction between the charged projectile and target nucleus. In case of nuclear reactions, the projectile and target nucleus merge (fusion), forming a highly excited compound nucleus that decays into all energetically possible decay channels, including γ decay to the ground state.





$$\sigma^2 \propto area\ F \quad \sigma_{\max} = F = \pi \cdot r^2$$

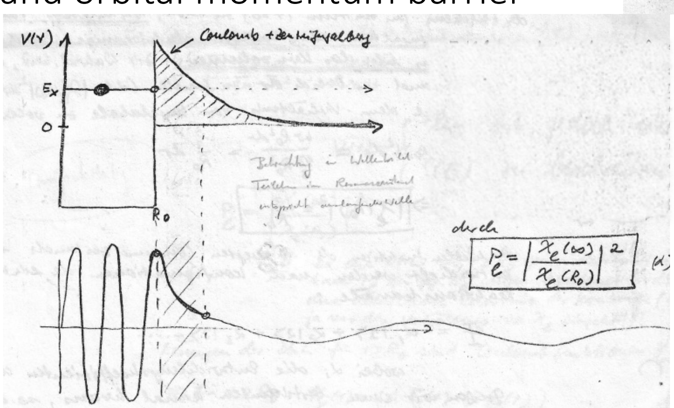
$$r_{nucleus} = r_0 \cdot A^{1/3}; \quad r_0 = 1.25\, fm = 1.25 \cdot 10^{-13}\, cm$$

$$r_{^{12}C} = 1.25\, fm \cdot 12^{1/3} = 2.86\, fm = 2.86 \cdot 10^{-13}\, cm$$

$$F_{^{12}C} = \pi \cdot r_{^{12}C}^2 = 25.68\, fm^2 = 2.57 \cdot 10^{-25}\, cm^2$$

$$unit: 1\, barn = 10^{-24}\, cm^2 \quad \sigma_{\max} = 0.257\, barn$$

Tunnel probability through Coulomb and orbital momentum barrier



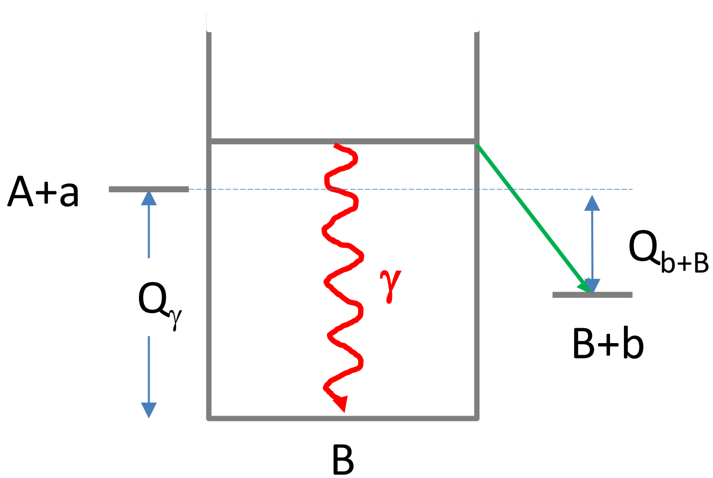
angular momentum ℓ dependence
Depends on momentum parameter

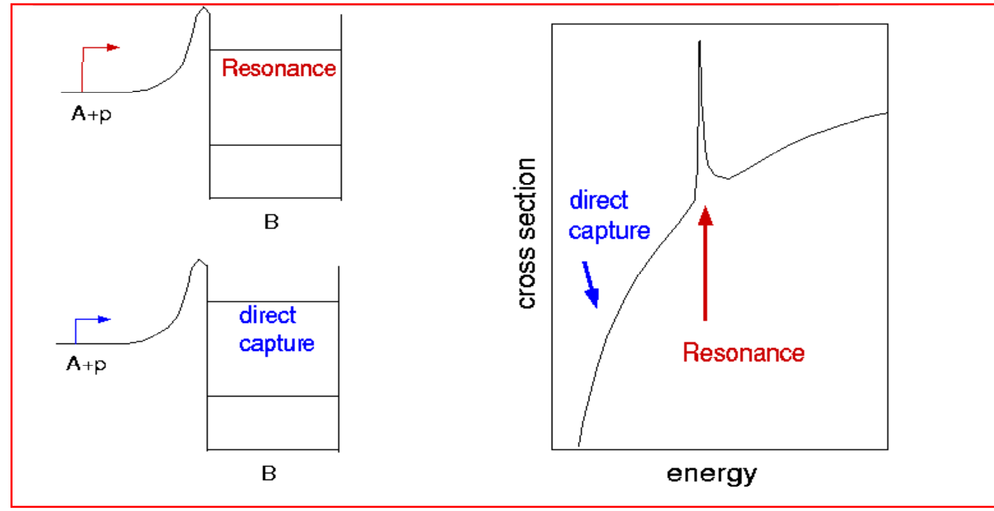
$$\sigma_{\ell,\max} = F_\ell = \pi\left(b_1^2 - b_2^2\right) \quad b_1 = (\ell + 1) \cdot \bar{\lambda} \quad b_2 = \ell \cdot \bar{\lambda}$$

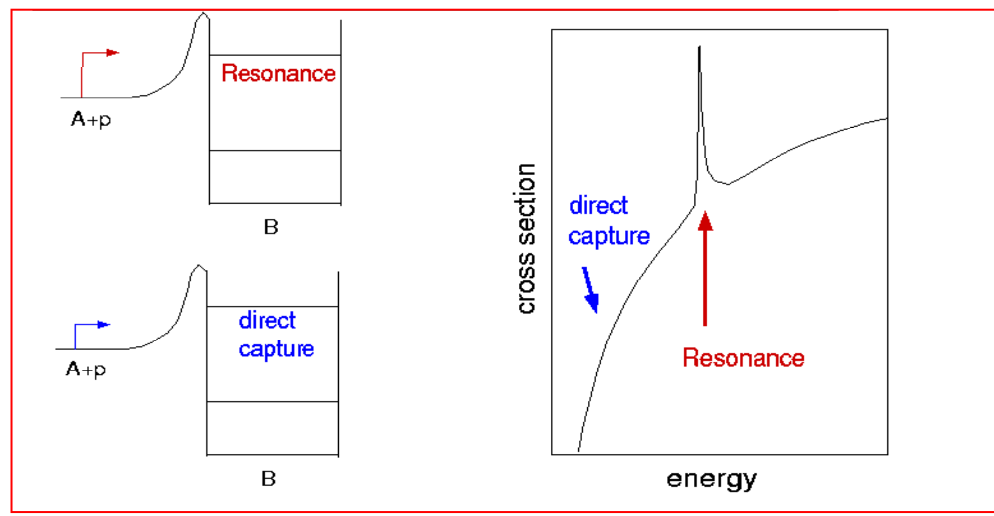
$$\sigma_{\ell,\max} = \pi\left((\ell+1)^2 - \ell^2\right) \cdot \bar{\lambda}^2 = (2l+1) \cdot \pi \cdot \bar{\lambda}^2$$

$$\sigma = \sigma_{\max} \cdot P_\ell(Z_1 Z_2) \cdot \left\langle \phi_f \middle| H_{interaction} \middle| \phi_i \right\rangle$$

Reaction probabilities







Reaction probabilities are determined by quantum-mechanical effects:

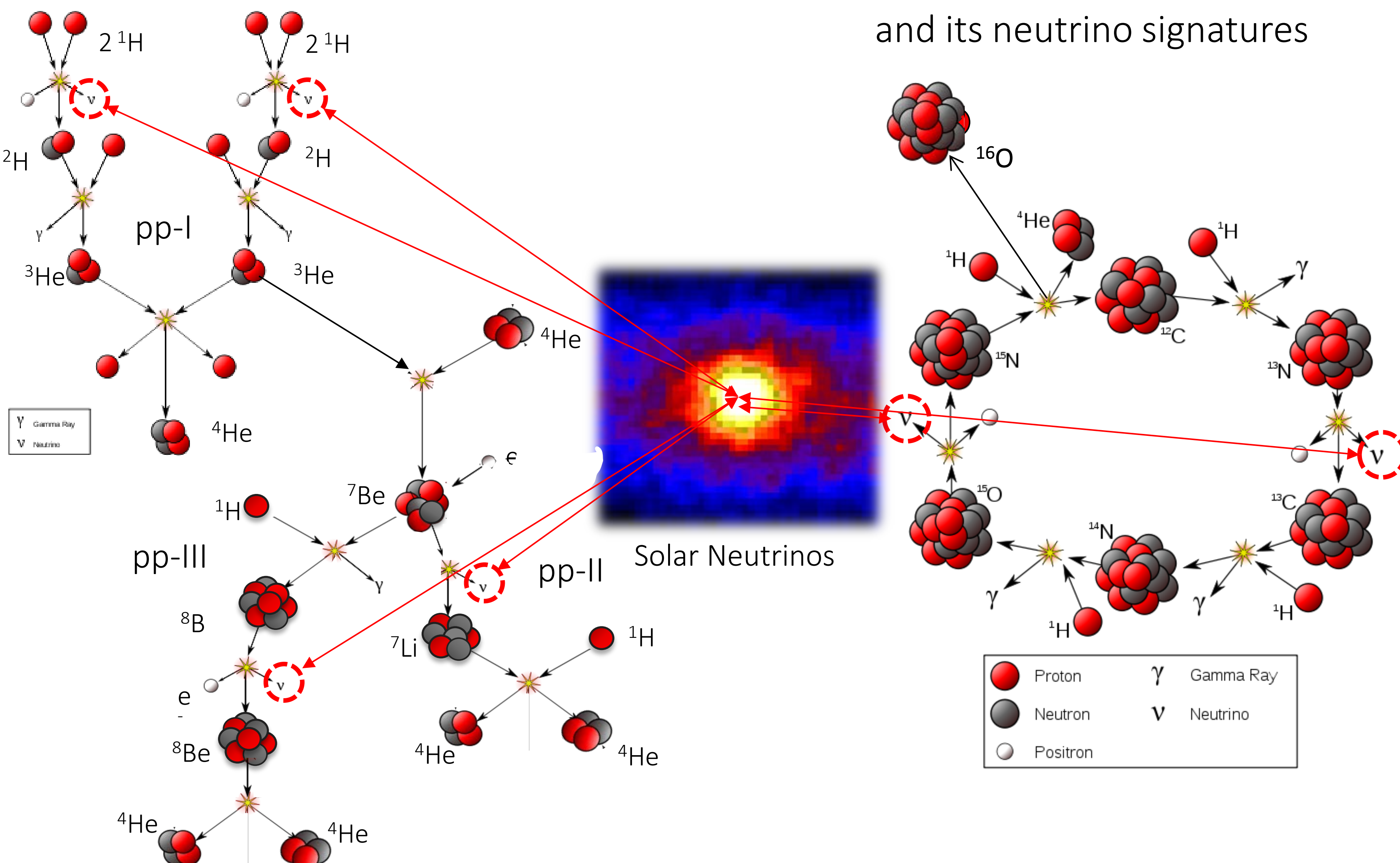
1. Tunnel probability through barriers

2. Fusion probability through overlap of particle wave functions

3. Population of excited states in the so-called compound nucleus (intermediary state)

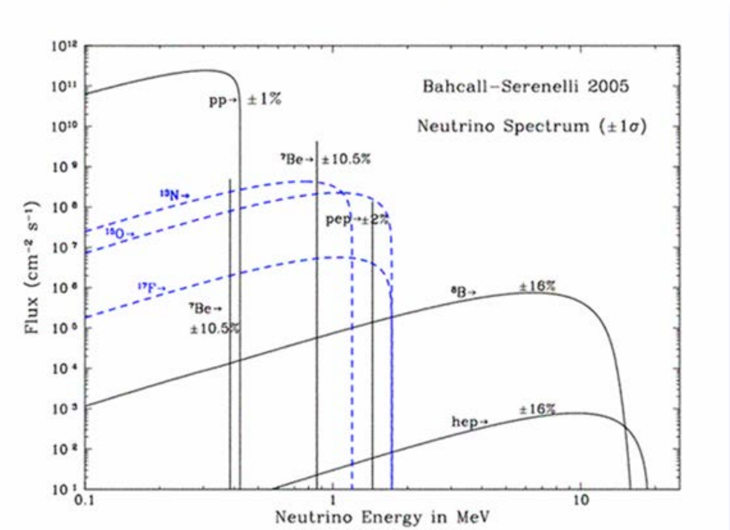
Hydrogen burning in stars

and its neutrino signatures

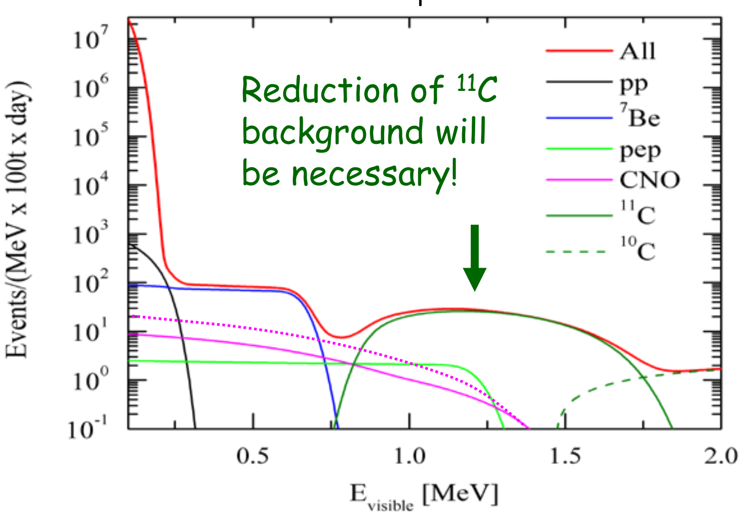


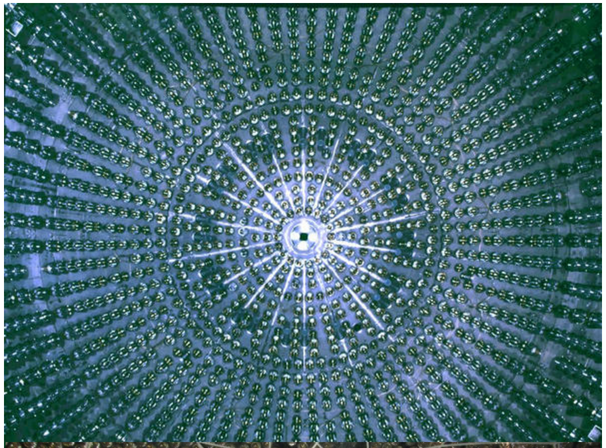
Looking for radioactivities in solar core

By studying the neutrino signals signalizing the radioactive decay associated with p+p ($^2He \Rightarrow ^2H$), ^7Be, ^8B, ^{13}N, ^{15}O, ^{17}F



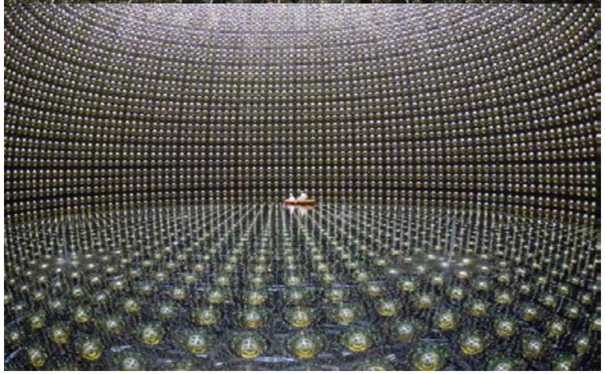
Neutrino Spectrum





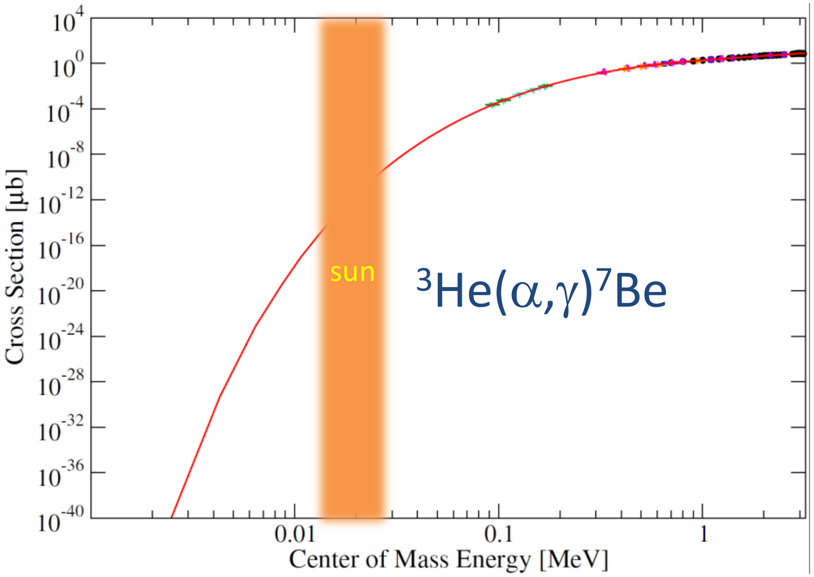
BOREXINO at Gran Sasso, Italy Liquid-Scintillator detector

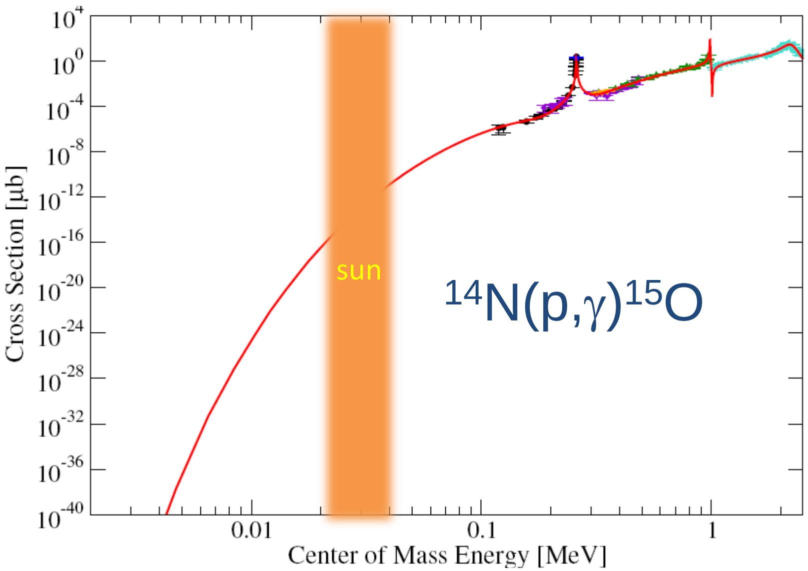
SNO at Sudbury Mine, Canada Heavy-Water D_2O detector



SUPER-KAMIOKANDE at Kamioka, Japan Water-Cherenkov detector

Cross sections



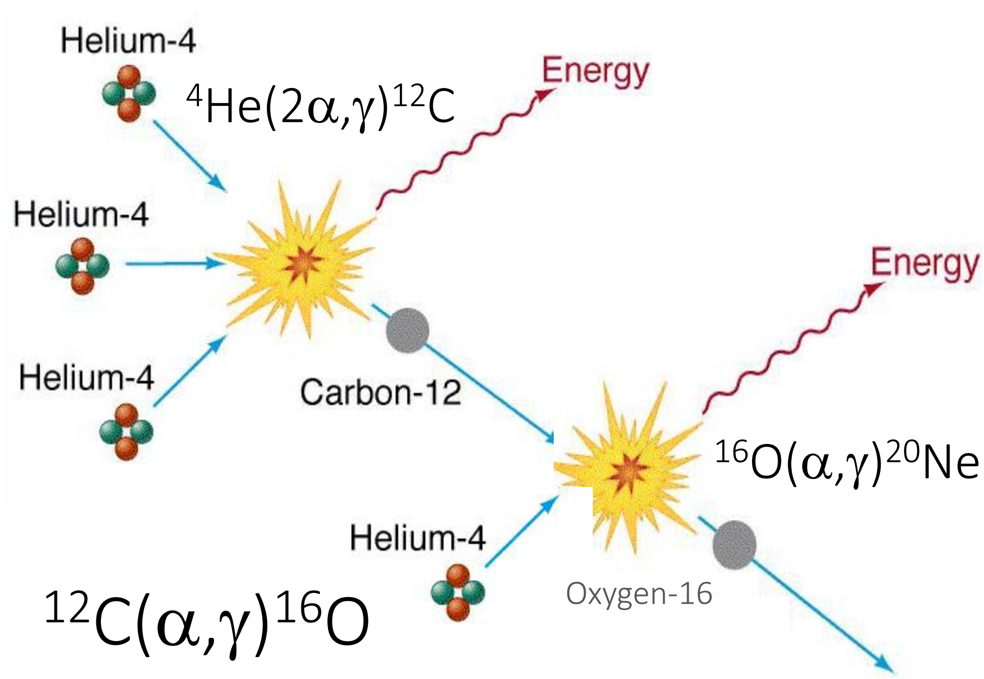


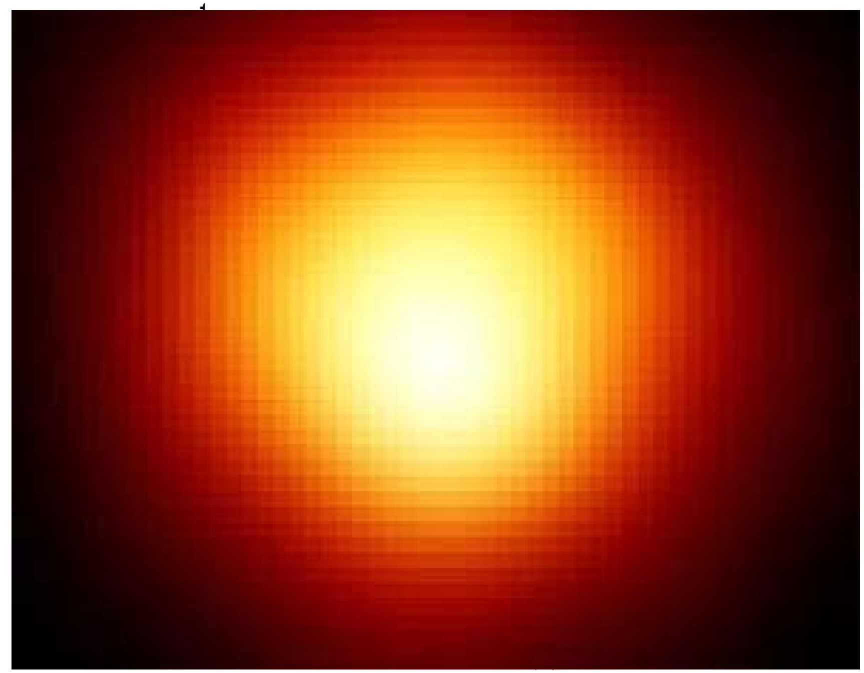
Decreasing probability $\lambda \sim \sigma$ of reaction with energy, increasing time τ for reaction to take place!

$$\lambda(T) \cong \frac{1}{\tau(T)} = \frac{\ln 2}{T_{1/2}(T)} \qquad \tau = \frac{T_{1/2}(T)}{\ln 2} \cong \frac{1}{\lambda(T)}$$

A temperature dependent lifetime and reaction rate. As lower the cross section, as longer an element lives, determines the elemental abundances emerging in stellar burning processes.

Nucleosynthesis in He burning





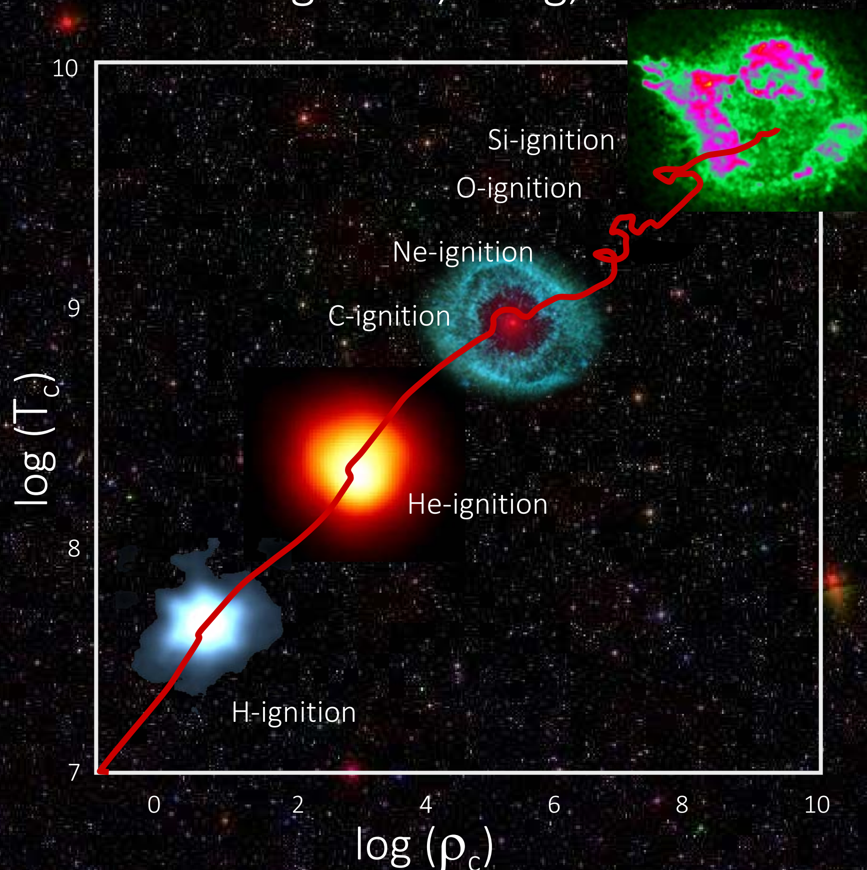
The reactions determines the $^{12}C/^{16}O$ ratio in our universe! It also defines the late stellar evolution of massive stars, determines white dwarf matter, the ignition of supernovae type Ia, the standard candle for cosmological predictions.

Nuclear Burning in Stars

Hydrogen Burning: ^{4}He, ^{14}N

Helium Burning: ^{12}C, ^{16}O, ^{22}Ne, n, s-nuclei

Carbon Burning: ^{20}Ne, ^{24}Mg,

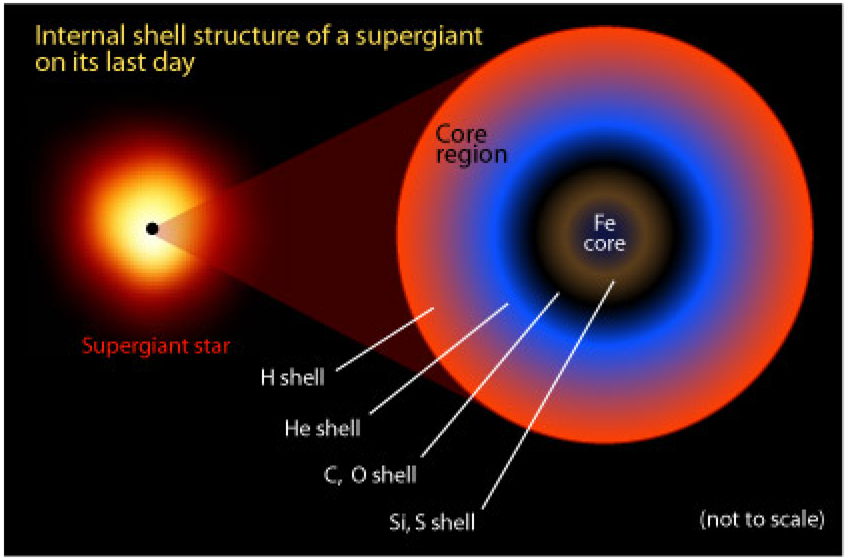


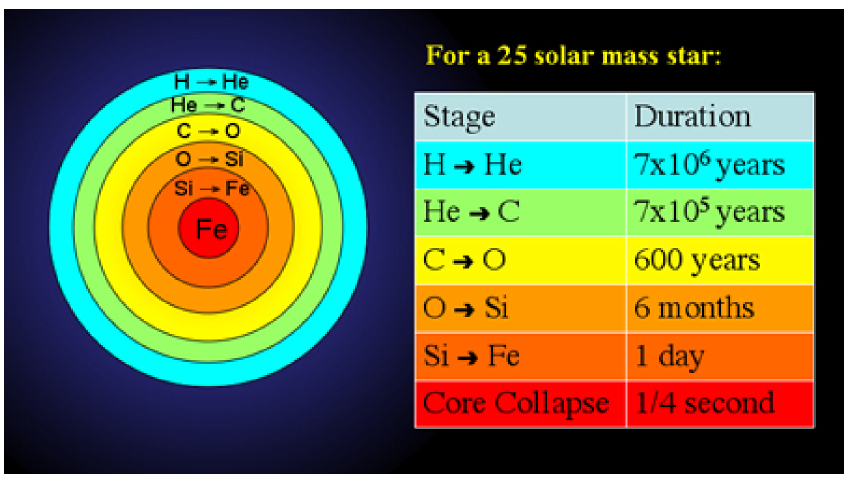
is characterized by low energy reaction sequences:

- pp-chains,
- CNO cycles
- He-burning
- Carbon fusion

producing energy for maintaining stability, and provide seed for subsequent explosion!

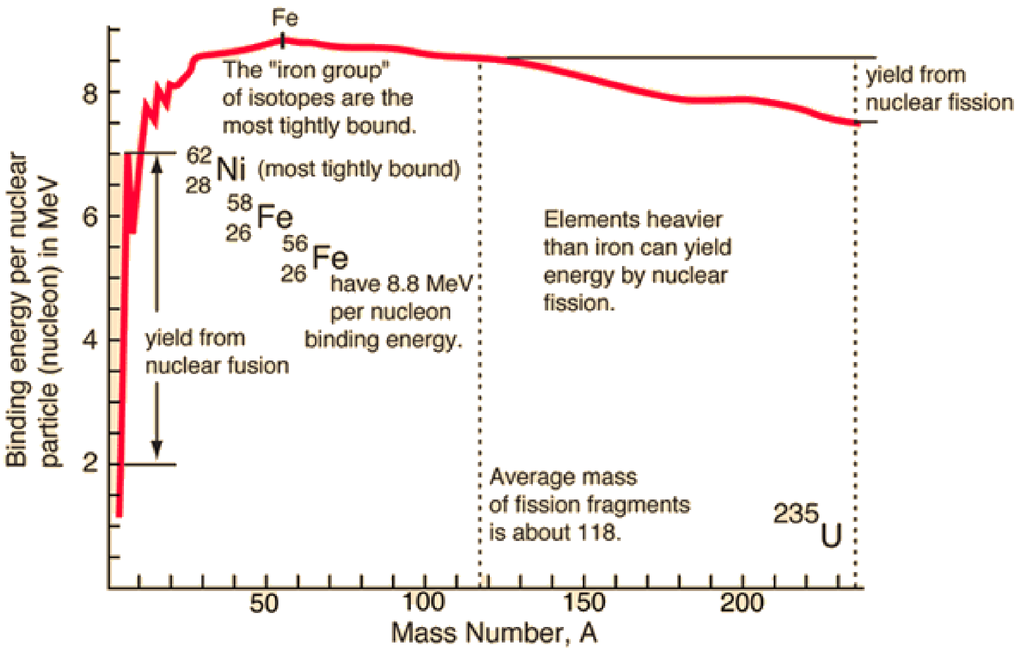
Core Collapse Supernovae

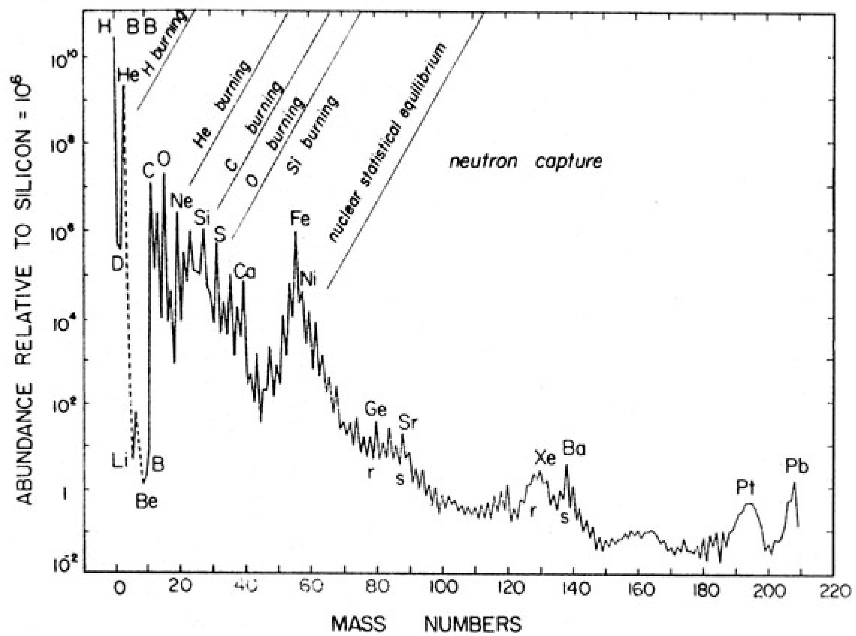




Stage	Duration
H → He	$7x10^6$ years
He → C	$7x10^5$ years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

How are the heavy elements made?

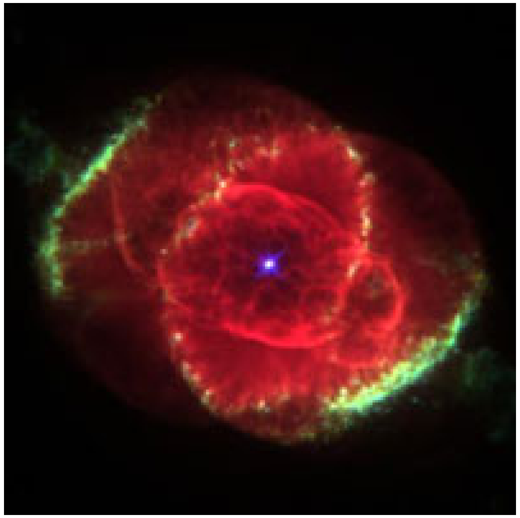




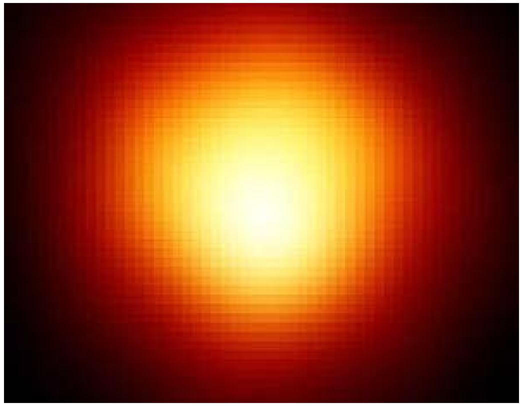
Coulomb barrier handicaps fusion of high Z-nuclei, binding energy conditions are Elements above Fe are primarily produced by neutron capture processes as secondary reaction products since first neutrons have to be produced. Because the neutron production has a limited probability the heavy elements have a substantial lower abundance than the light ones as primary reaction products!

Neutron production in stars

Two neutron sources associated with different environments in stars:

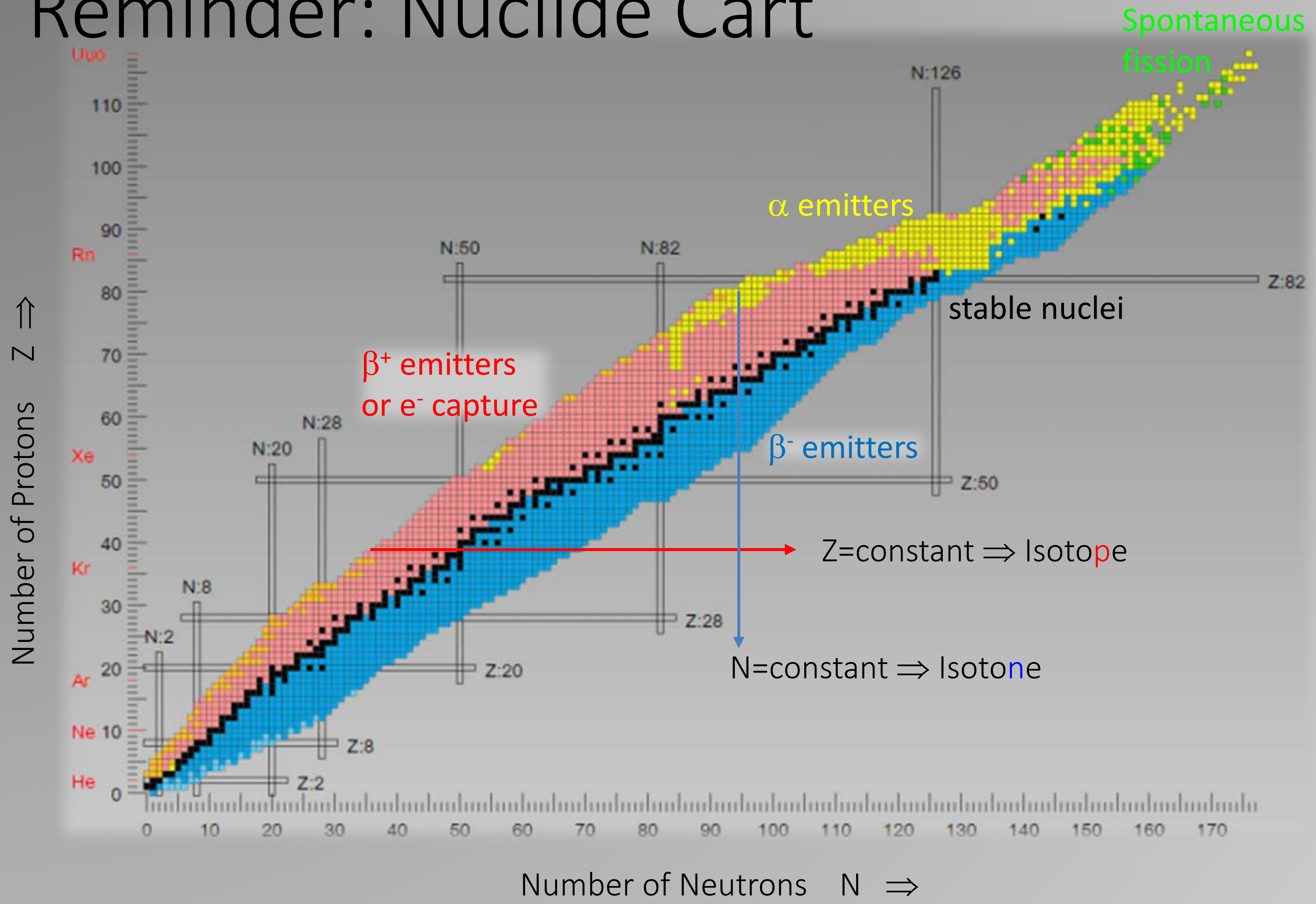


- AGB stars intershell mixing: $^{13}C(\alpha,n)$
- AGB stars helium flash: $^{22}Ne(\alpha,n)$

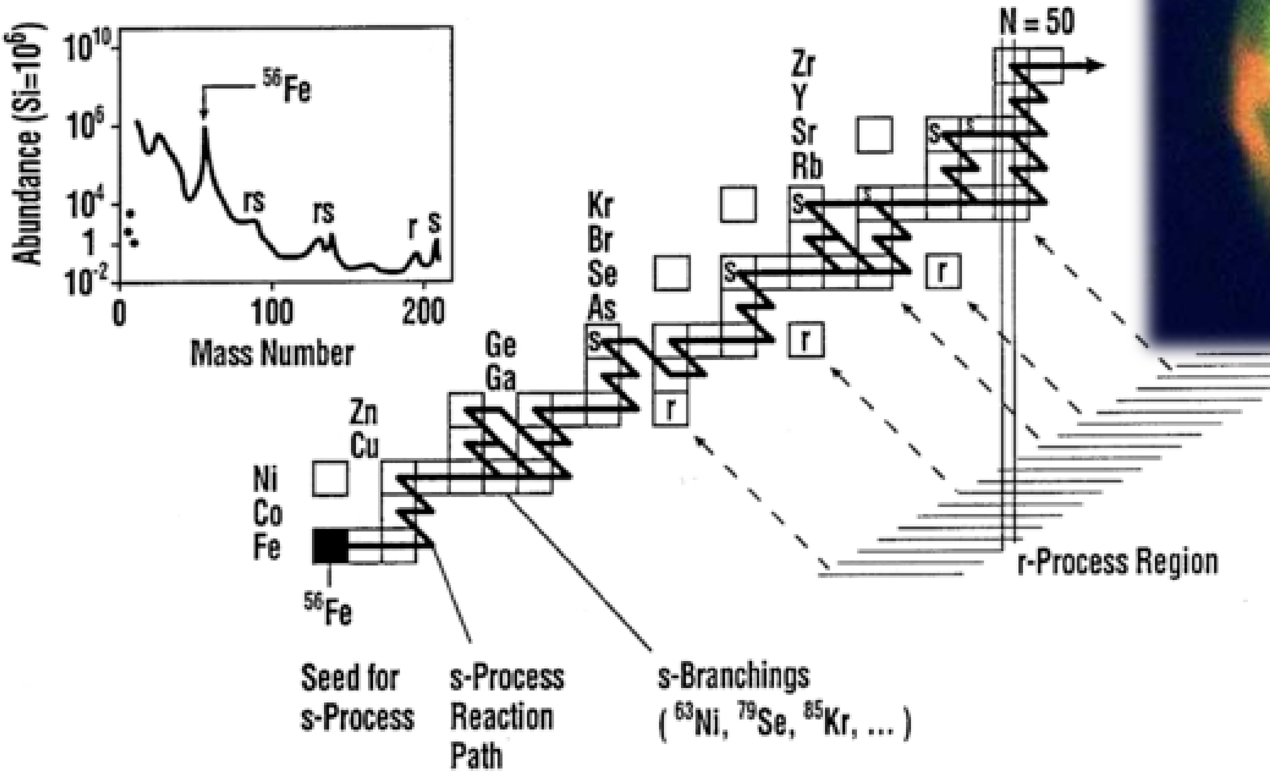


- RGB stars helium core burning: $^{22}Ne(\alpha,n)$
- RGB stars carbon core burning: $^{12}C(^{12}C,n)$

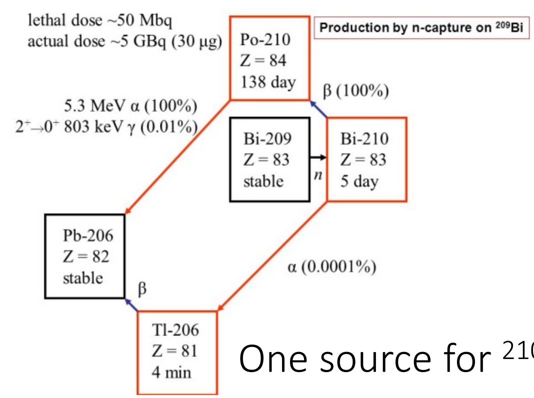
Reminder: Nuclide Cart



The slow neutron capture process or s-process



May produce several radioactive isotopes in the Pb, Bi range as the s-process terminator !



One source for ^{210}Po

Building up heavy elements along the line of stability, each radioactive isotope produced decays back to lien of stability!

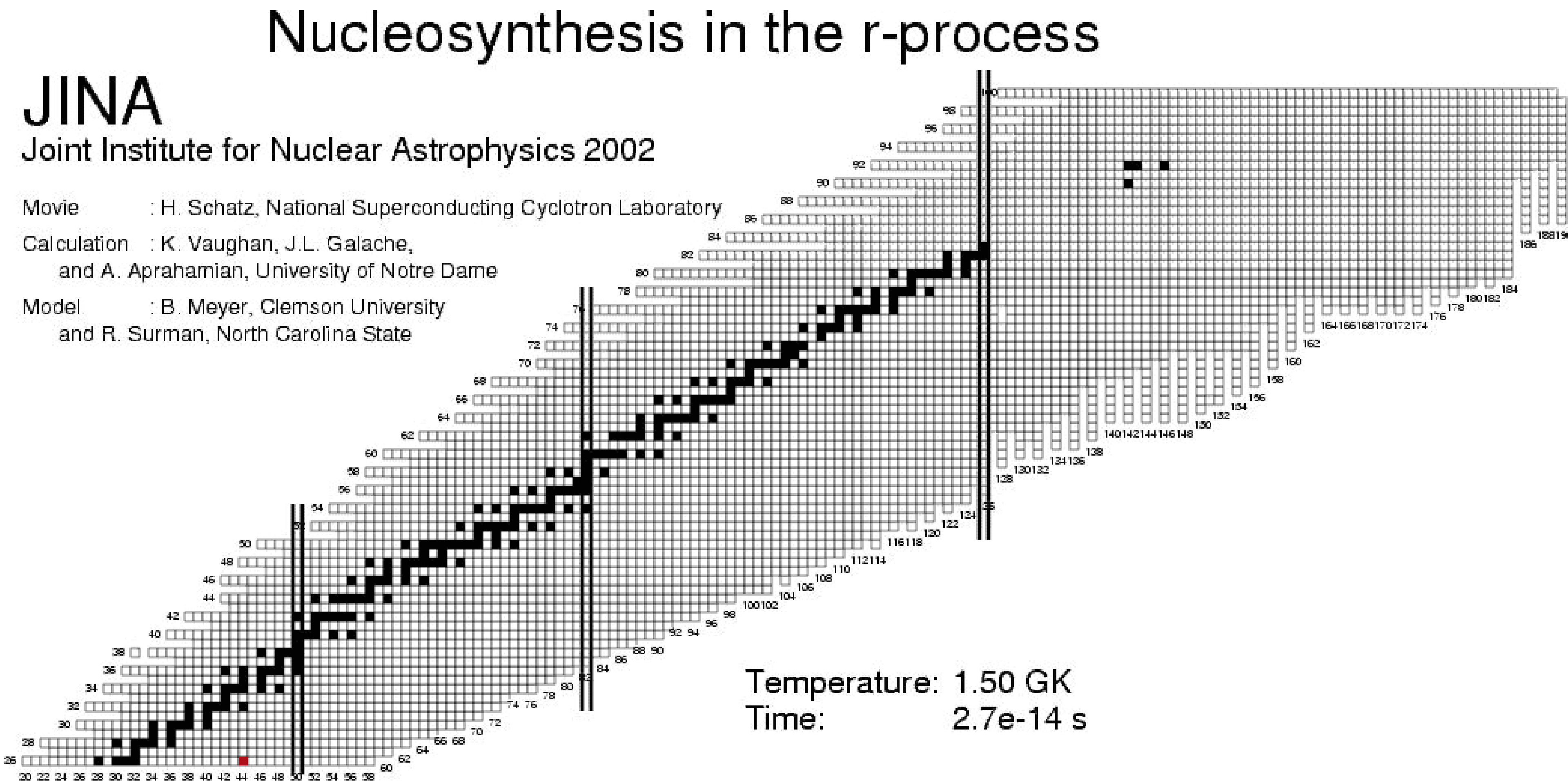
The rapid neutron capture process or r-process

The r-process requires an extremely high flux of neutrons $\approx 10^{22}$ neutrons /$cm^2 \cdot$sec, the most powerful reactors on earth can only produce less than a billionth of this flux, but may reach that fluence level after 30 years of operation. A fission bomb explosion may reach neutron flux comparable to r-process conditions.

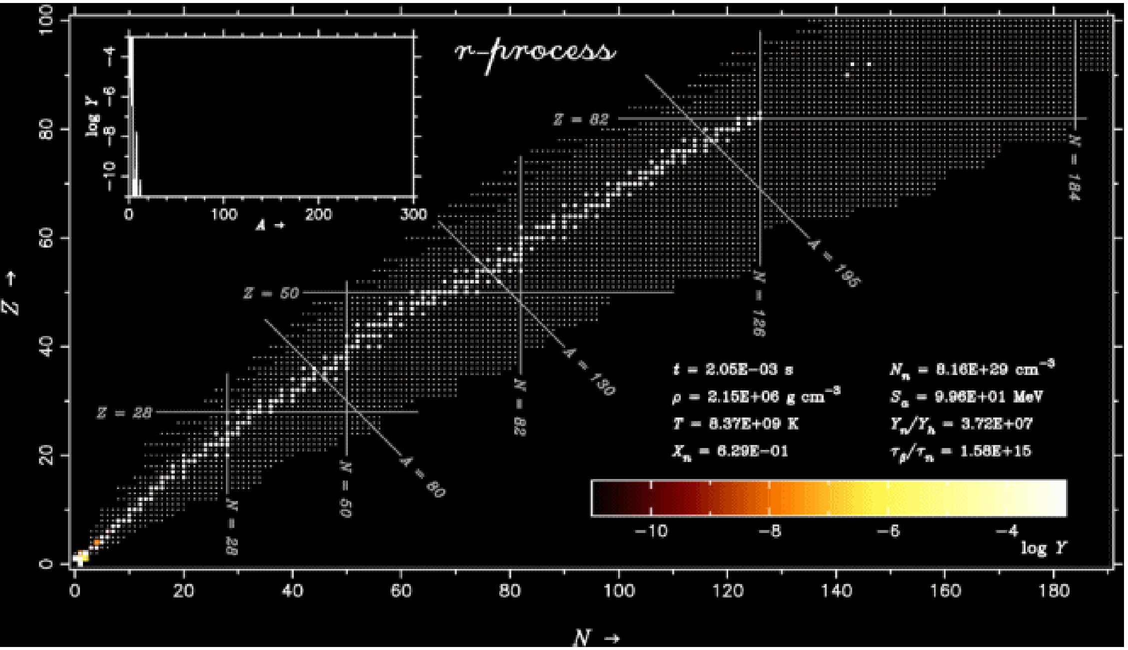
There are are two potential sites for the r-process, the emerging shock-front of a core collapse supernovae and the collision of two neutrons stars, called neutron star mergers.

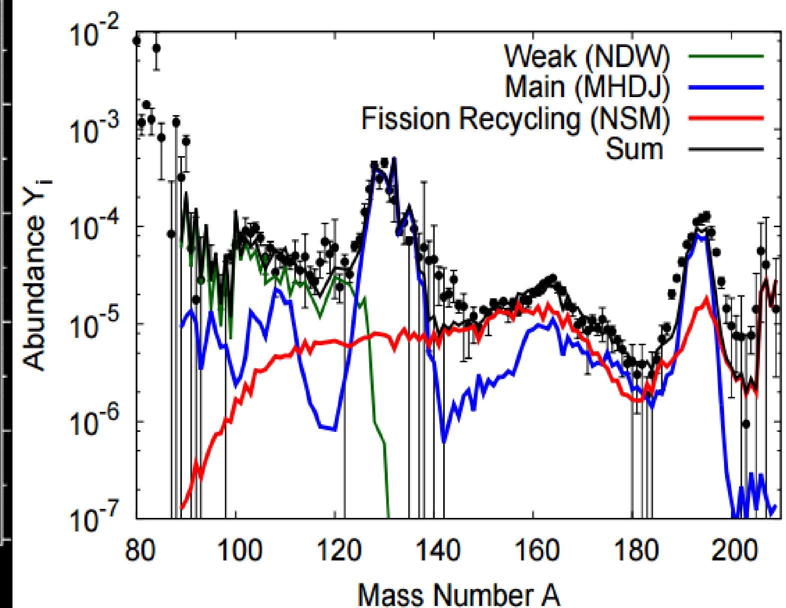
The r-process path

in the nuclide chart



The r-process abundances



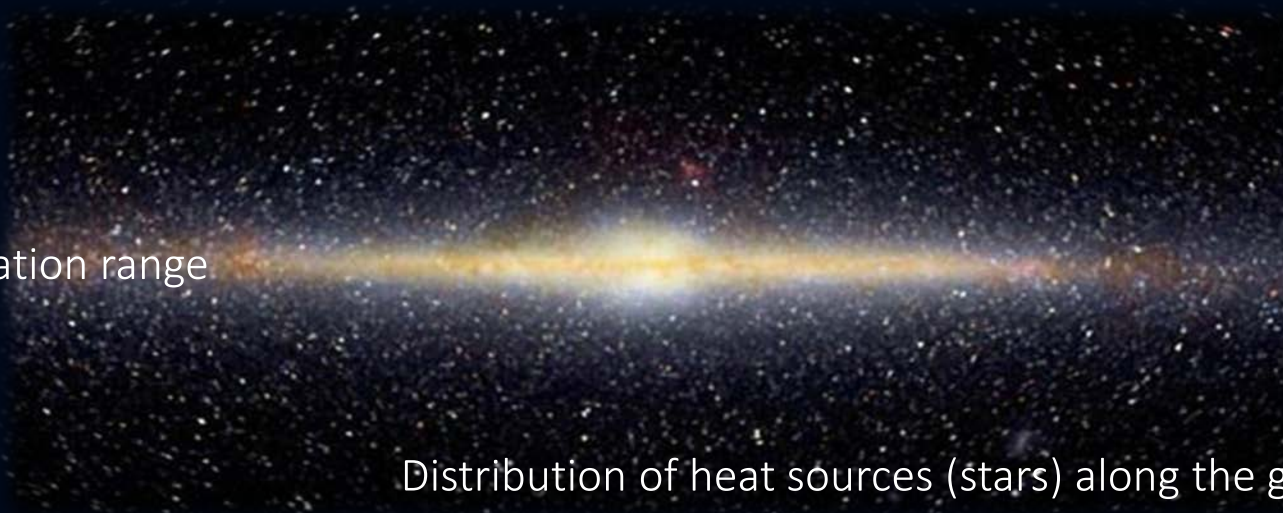


r-process path reaches far above the range of exiting nuclei into the range of super-heavy nuclei with masses near A~300 , well above Uranium (A=235,238). These super-heavy elements fission and cycle the material back into the mass A=100-200 range.

Assumption today is that weak r-process is associated with core collapse supernova explosions and main r-process is associated with merging neutron star explosions. In both cases the radioactive r-process material is ejected into interstellar space.

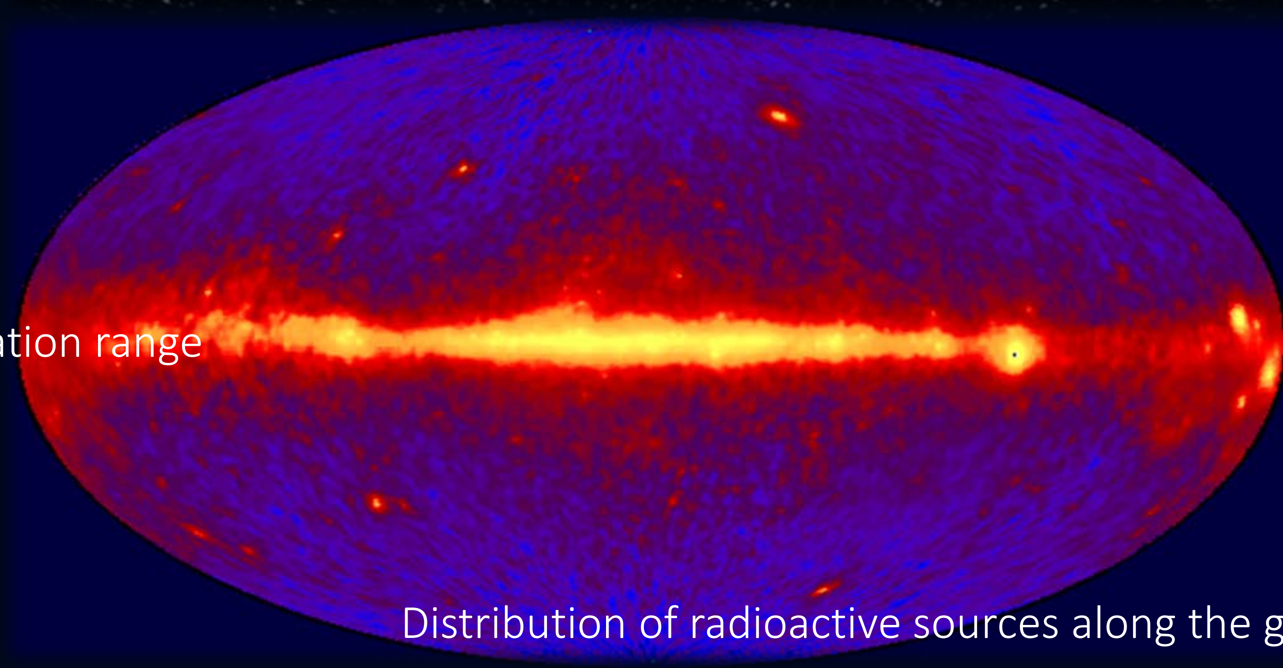
Our Radioactive Galaxy

Infrared radiation range



Distribution of heat sources (stars) along the galactic plane

Gamma radiation range



Distribution of radioactive sources along the galactic plane

Interstellar Dust

Formed condensation points for meteorites and asteroids though collision and accretion