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# Astrophysical reactions with halo nuclei

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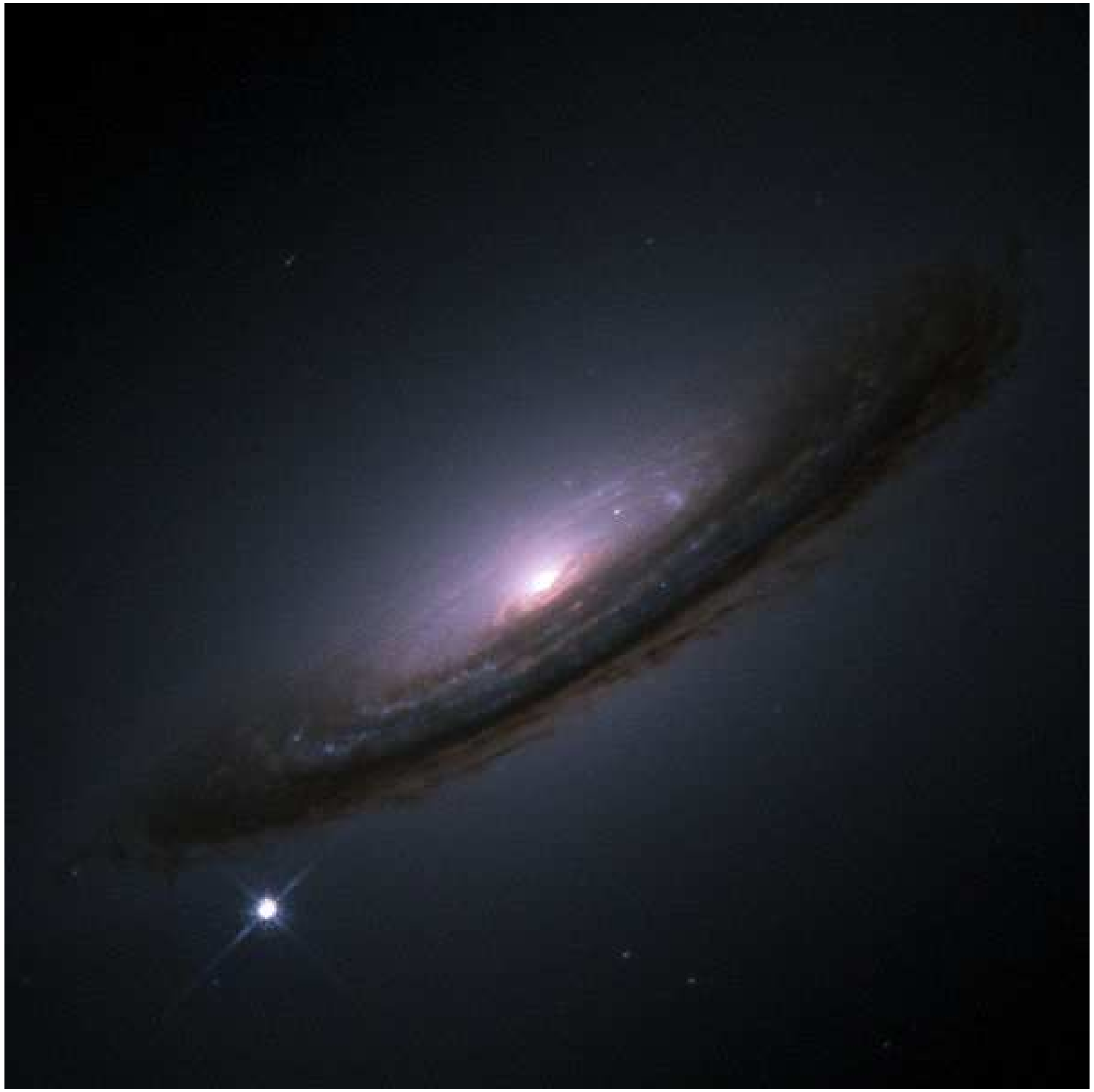
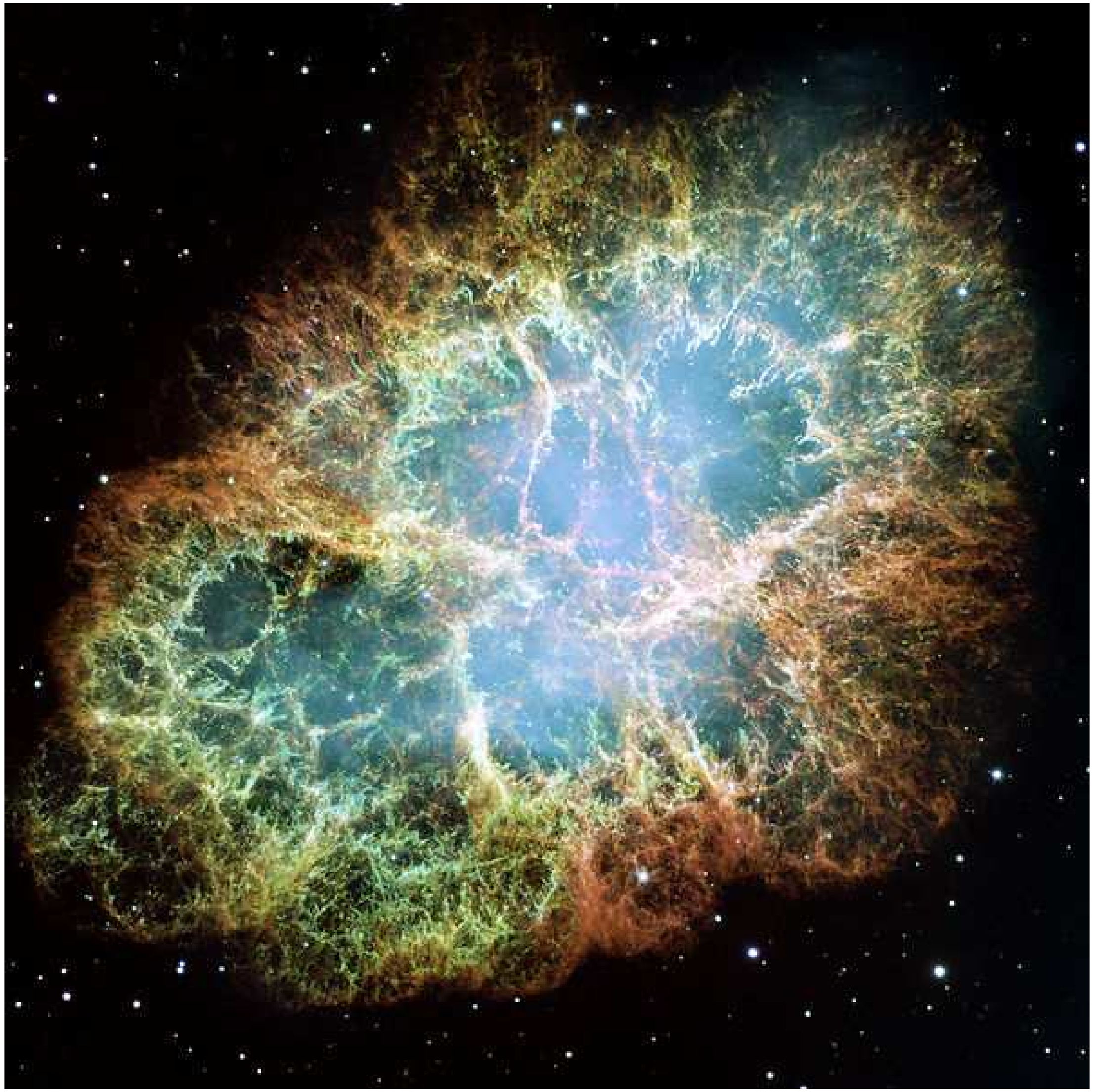
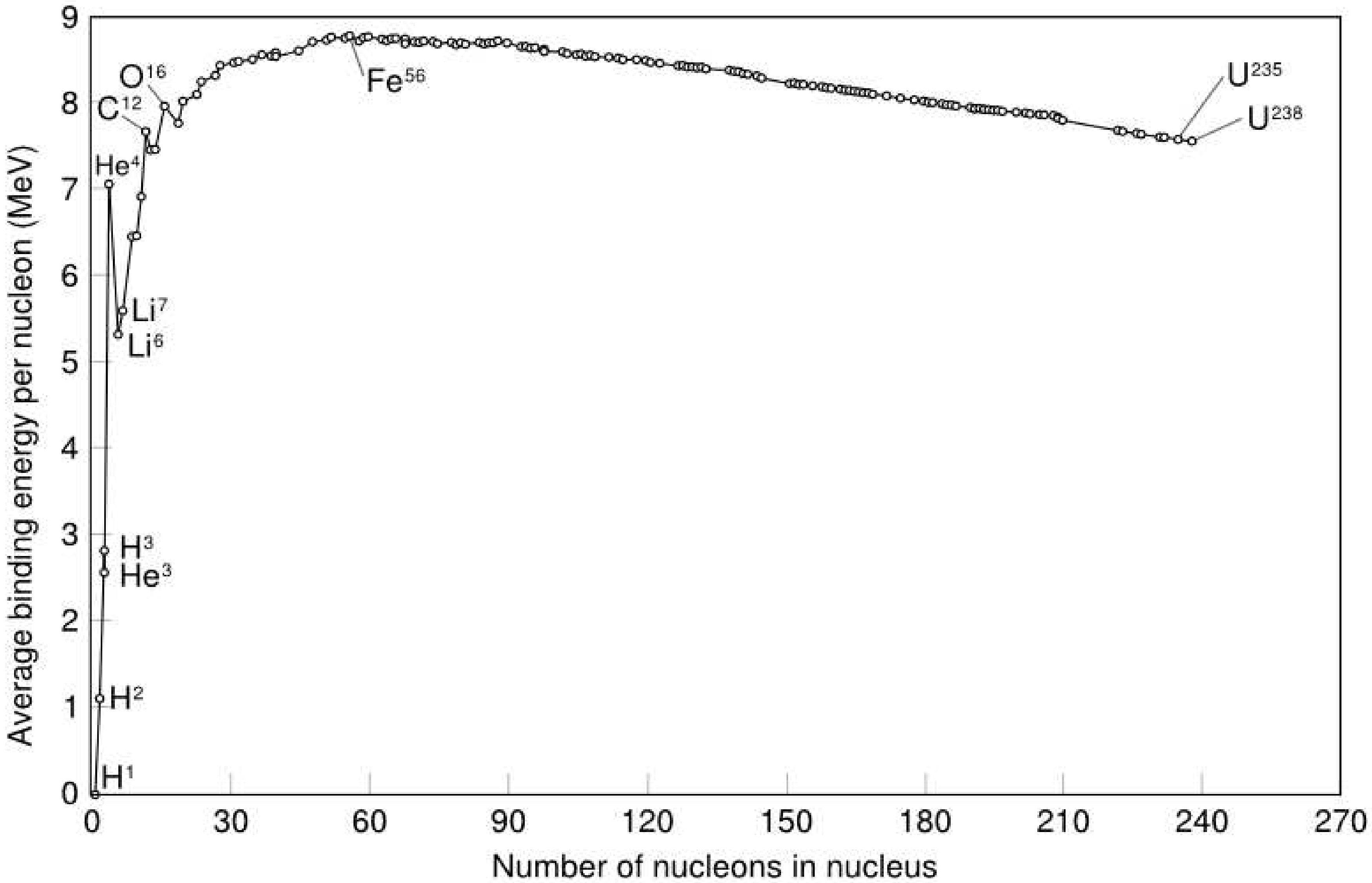
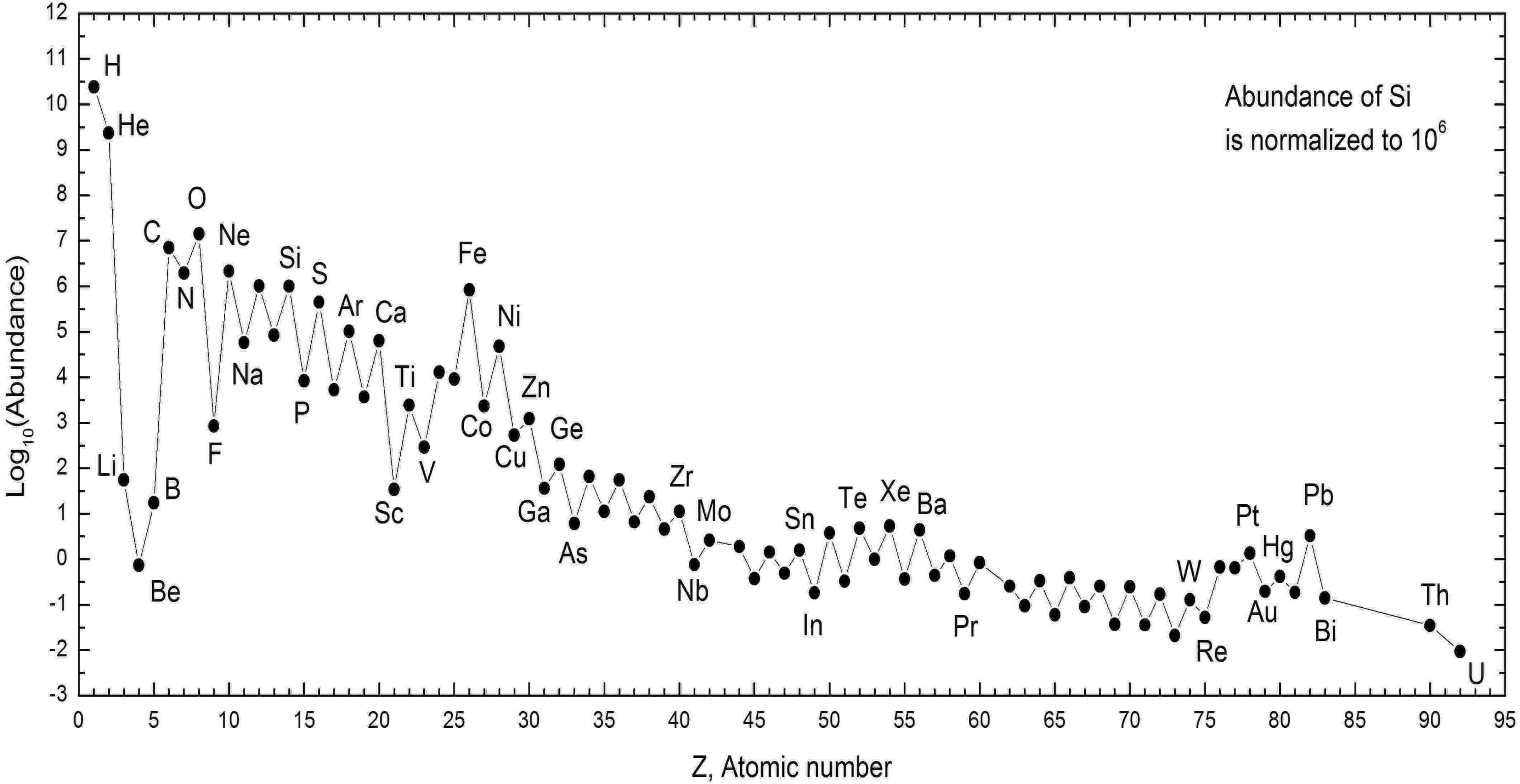


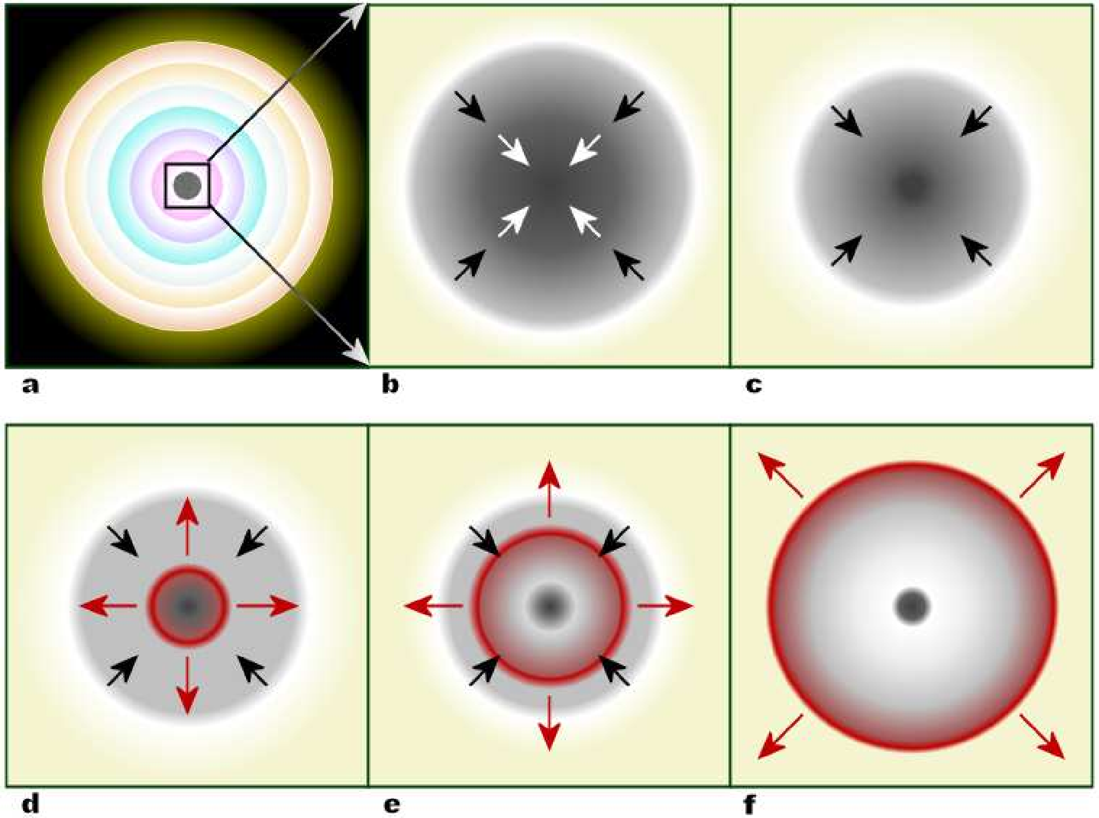
## *Crab Nebula, the remnant of SN 1054 core-collapse supernova*





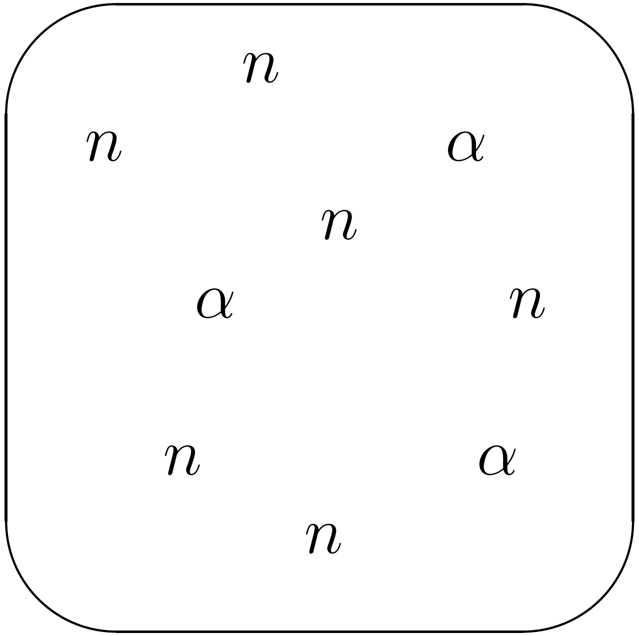
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
210
240
270
H1
H2
H3
He3
He4
Li6
Li7
C12
O16
Fe56
U235
U238


Log10(Abundance)
Z, Atomic number
Abundance of Si
is normalized to 10^6
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au
Hg
Pb
Bi
Th
U




$$e^- + p \rightarrow n + \nu_e$$

$$\gamma\text{'s} + \text{Fe's} \rightarrow \alpha\text{'s} + n\text{'s}$$




$$T \sim 0.1 \text{ MeV}$$

$$\text{neutron density} \sim 10^{20} - 10^{30} \text{ cm}^{-3}$$

- seeds are reassembled from $\alpha$-particles and neutrons
- heavy elements are built by rapid neutron capture (r-process)

The systems $n+\alpha$ and $\alpha+\alpha$ (and also $n+n$) are unbound. The nucleosynthesis

$$\alpha\text{-particles} + \text{neutrons} \longrightarrow \text{metals}$$

proceeds largely via three-body reactions,

$$\alpha+\alpha+\alpha \longrightarrow {}^{12}\text{C}+\gamma\,,$$

$$\alpha+\alpha+n \longrightarrow {}^{9}\text{Be}+\gamma\,,$$

$$\alpha+n+n \longrightarrow {}^{6}\text{He}+\gamma\,.$$

Another possibility: a neutron-recoil four-body reaction,

$$\alpha+\alpha+n+n \longrightarrow {}^{9}\text{Be}+n\,.$$

Amplitude:

$$\underline{(\alpha\alpha n)} + \underline{\gamma} \longleftarrow \underline{\alpha + \alpha + n}$$

$$M_{fi} = \langle f | \langle 1_{\vec{k}\lambda} | \vec{d}\vec{E} | 0 \rangle | i \rangle$$

Probability:

$$dw_{fi} = \frac{2\pi}{\hbar^2} \left| M_{fi} \right|^2 \frac{d\nu}{dE}$$

$$w_{fi}^{(\mathrm{em})} = \frac{4}{3}(2\pi)^2 \frac{\omega}{\lambda^2} \frac{|\langle f | \vec{d} | i \rangle|^2}{\hbar c} \; ,$$

Amplitude:

$$\underline{(\alpha\alpha n)} + \underline{n} \longleftarrow \underline{\alpha + \alpha + n} + \underline{n}$$

$$M_{fi} = \int d^3r \, \langle f | \frac{e^{-i\mathbf{p}'\cdot\mathbf{r}}}{\sqrt{V}} W \frac{e^{+i\mathbf{p}\cdot\mathbf{r}}}{\sqrt{V}} | i \rangle$$

$$\frac{4\pi\hbar^2 a_{nn}}{m} \delta(\mathbf{r}_{nn}) \leftarrow \text{LO EFT}$$

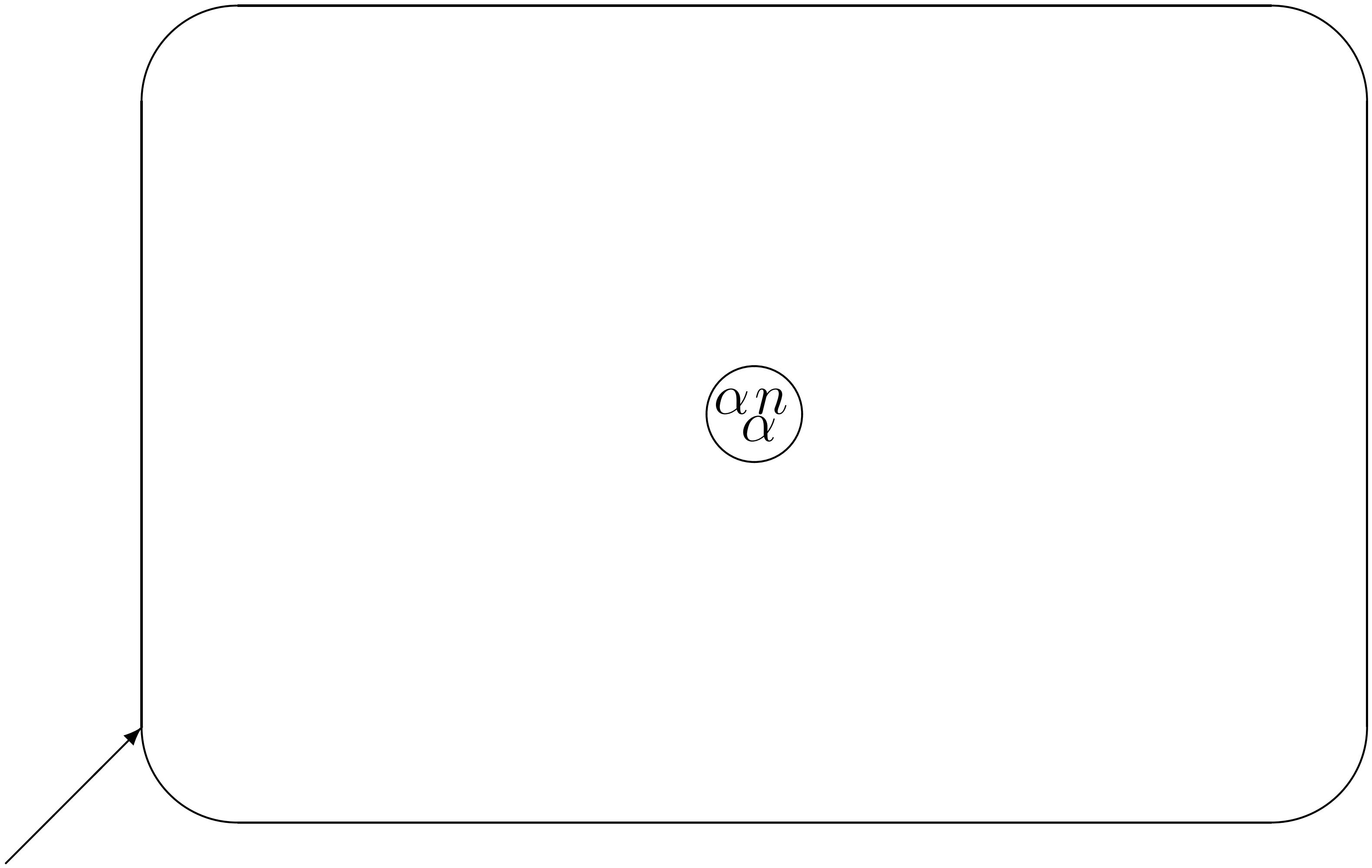
Probability:

$$w_{fi} = n_n a_{nn}^2 v \int d\Omega_q \left| \langle f | e^{i\mathbf{q}\mathbf{r}_n} | i \rangle \right|^2$$

$$M_{fi} = \langle \text{bound state} | O | \text{continuum state} \rangle$$

Methods with no need to build continuum state wave-functions:

- Lorentz Integral Transform (Trento)
- Bounding box




$\Psi_{\alpha\alpha n} = 0$ on the border: spectrum becomes discrete

The transition probability

$$w_{fi} = n_n a_{nn}^2 v F_{fi}$$

$$F_{fi} = \int d\Omega_q \left| \langle f | e^{i\mathbf{q}\mathbf{r}_n} | i \rangle \right|^2$$

depends on the box. However, the strength

$$\frac{dw}{dE} = n_n a_{nn}^2 v \frac{dF}{dE}$$

where

$$\frac{dF}{dE} = \frac{1}{\Delta E} \sum_{E_i \in E \pm \Delta E/2} F_{fi} \ .$$

is box independent.

Similarly for the electromagnetic transition,

$$\frac{dw^{(E1)}}{dE} = \frac{(4\pi)^3}{9}\omega\frac{e^2}{\hbar c}\left(\frac{R}{\lambda}\right)^2 \frac{dF^{(E1)}}{dE}$$

with the (reduced) electromagnetic strength function

$$\frac{dF^{(E1)}}{dE} = \frac{1}{\Delta E} \sum_{E_i \in E \pm \Delta E/2} \frac{B_{fi}^{(E1)}}{e^2 R^2} \ ,$$

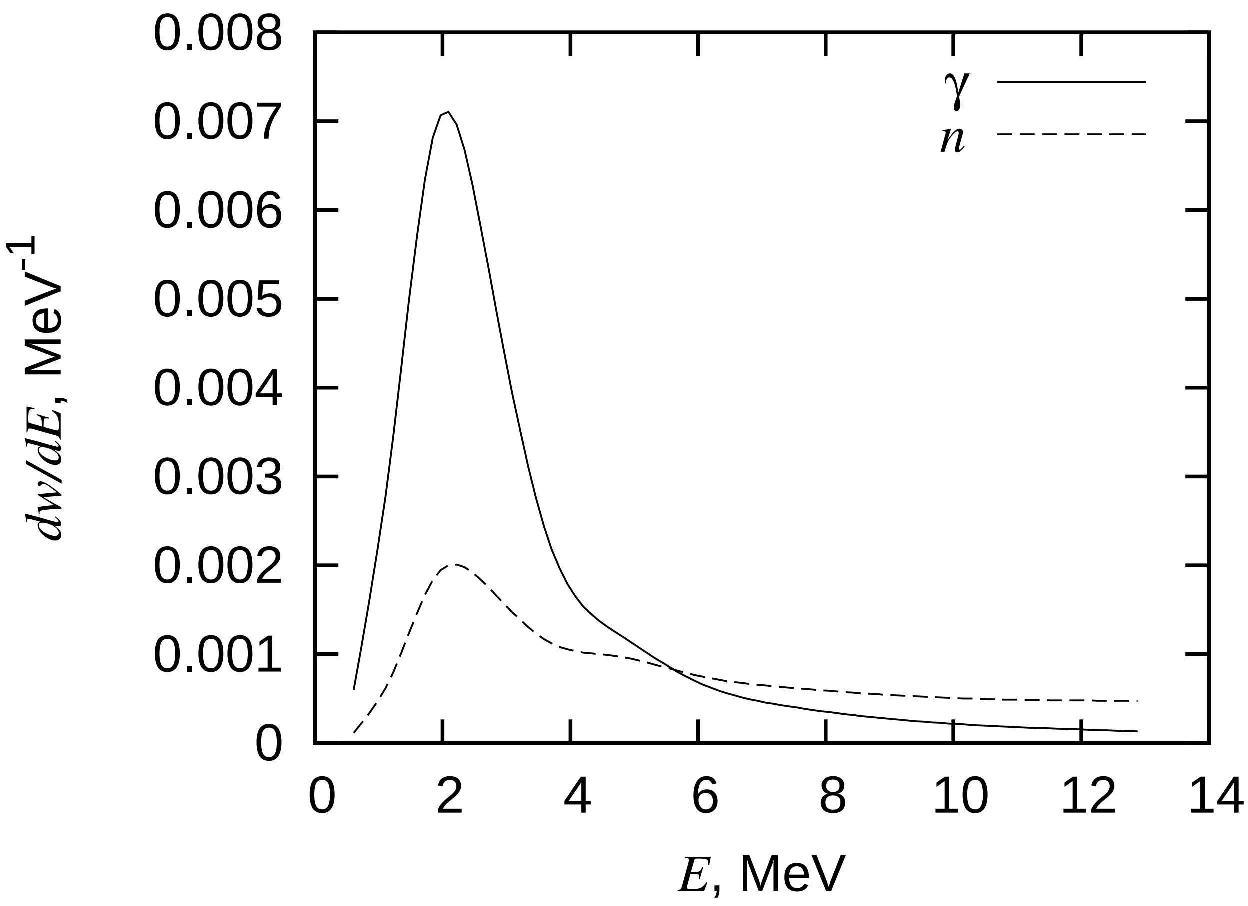



Figure 1: Electromagnetic (reduced dipole) and neutron-recoil strength functions for the $5/2^+$ channel in the $\alpha + \alpha + n$ system.

$$\frac{w_{fi}^{(n)}}{w_{fi}^{(E1)}} \sim (n_n a_{nn}^3) \frac{\left(\frac{v}{c}\right)}{\left(\frac{R}{\lambda}\right)^2} \frac{\lambda}{a_{nn}} \sim 10^5 (n_n a_{nn}^3) \; ,$$

$$n_n \sim 10^{-5} a_{nn}^{-3} \sim 10^{30} \mathrm{cm}^{-3} \; ,$$

Boltzmann distribution:

$$P_i = \frac{e^{\frac{-E_i}{T}}}{Z} \; , \; Z \equiv \sum_i e^{\frac{-E_i}{T}} \; ,$$

Reaction rate:

$$\langle \alpha\alpha n \rangle = \sum_i \frac{e^{\frac{-E_i}{T}}}{Z} w_{fi} = \int_0^\infty dE \frac{e^{\frac{-E}{T}}}{Z} \frac{dw}{dE}$$

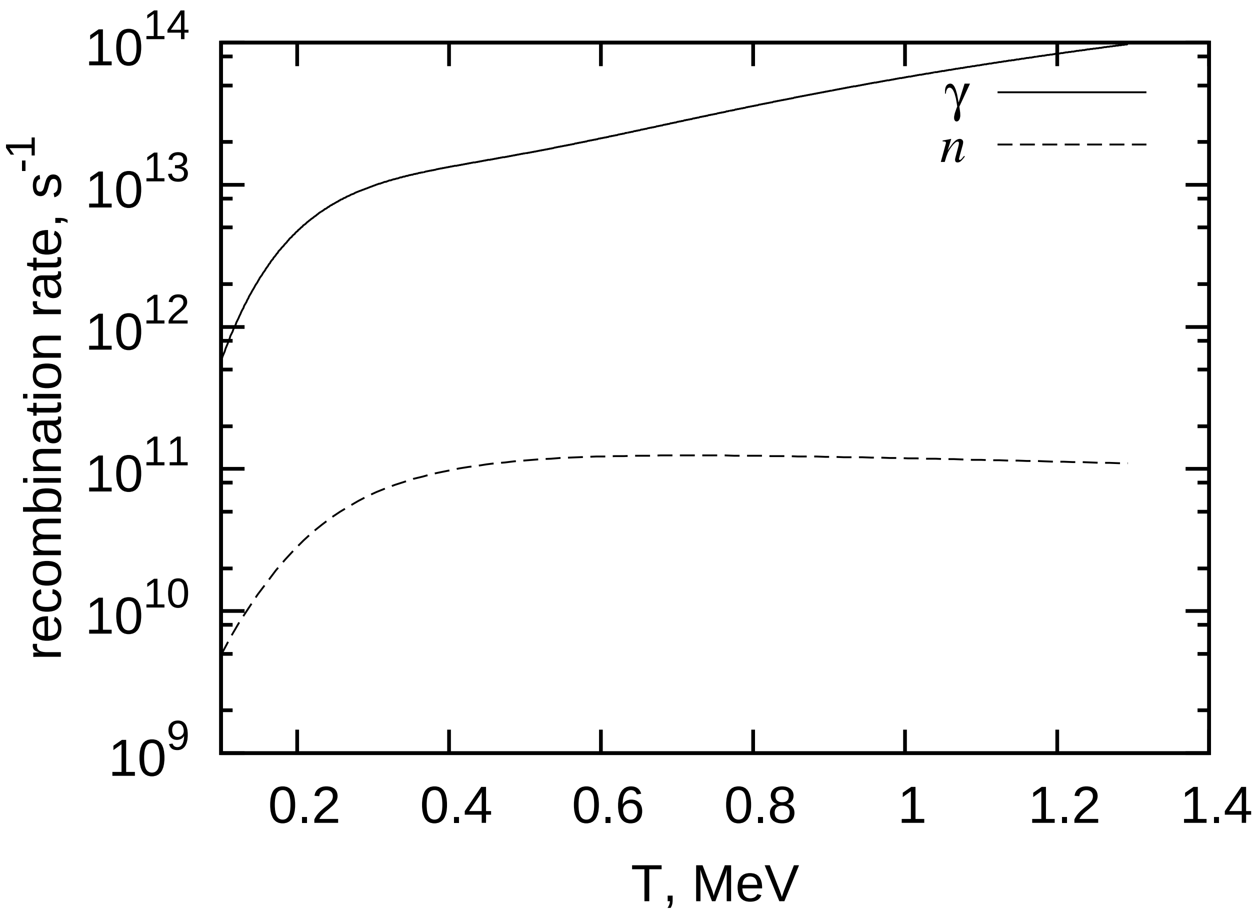



Figure 2: Boltzmann averaged nuclear and electromagnetic rates for the $\alpha\alpha n \rightarrow^9$ Be recombination.

- Halos are astronomically important
- The bounding box boundary condition is a useful tool to calculate
  - Positions and widths of resonances
  - Strength functions
  - Reaction rates
- At higher neutron densities the “neutron-recoil recombination” can potentially contribute to rebuilding the seeds for the r-process.