The r-process of nucleosynthesis: weak interactions

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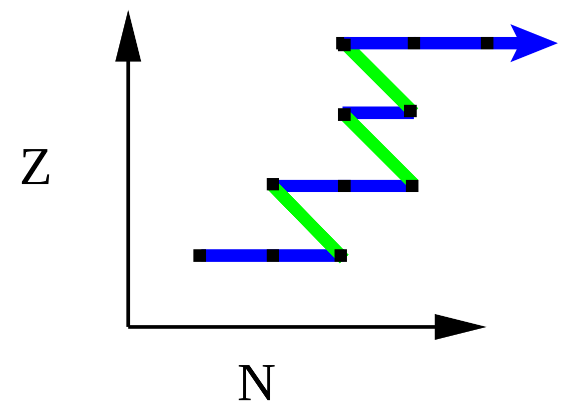
What makes the neutrons?

e. g. Uranium-238 Z=92, N=146 $\rightarrow$ need lots of neutrons

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$



rapid neutron capture as compared with beta decay

Electron Fraction

In order to get the r-process nuclei, prefer a lot of neutrons

$$Y_e = \frac{p}{p+n} \tag{1}$$

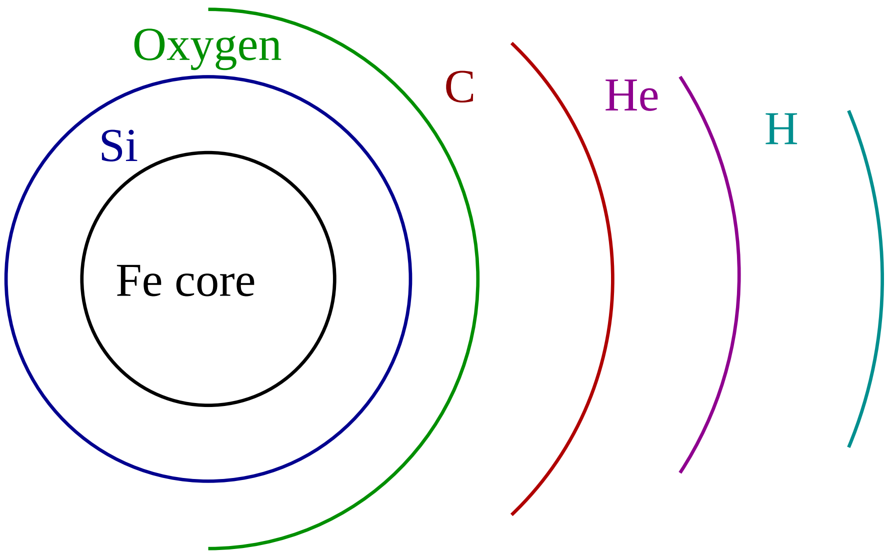
Want this to be low.

Possible astrophysical sites of the r-process

- Neutrino driven wind of the supernovae
- Jets from core collapse supernovae
- Accretion disks from core collapse supernovae
- ONeMg supernovae
- low entropy outflows from supernovae
- He Shell of core collapse supernovae
- Supernova with sterile neutrinos
- Tidal ejection of neutron rich matter in neutron star mergers
- shocked ejecta from merger
- accretion disk outflows from mergers

Core Collapse Supernovae

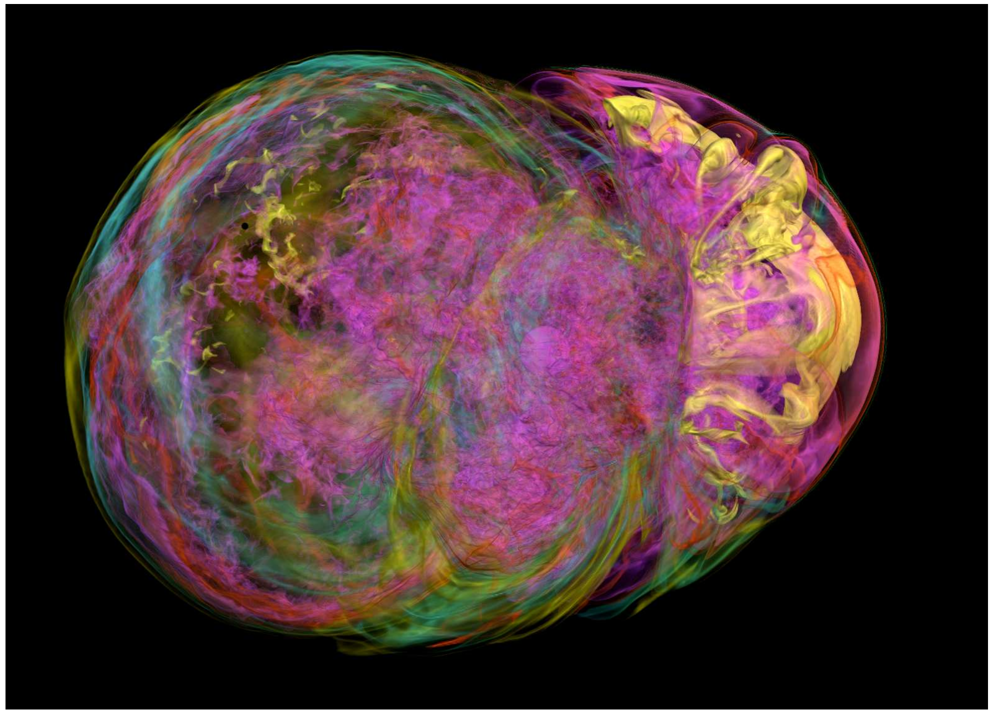
end of the life of a massive star



- core unstable
  $M_{core} \sim 1.5 M_{sun}$
- collapse to nuclear density
- core bounce
- shock produced
- shock stalls
- neutrinos diffuse out of core, may energize shock

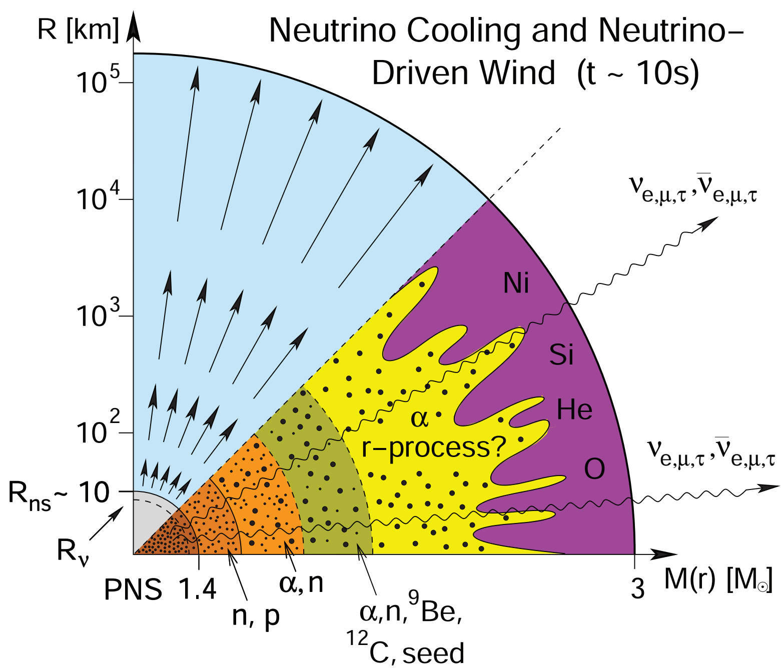
Re-energizing the stalled shock

Neutrinos heat the material below the stalled shock, helping along the two or three dimensional shock instabilities.



From Blondin et al.

Nucleosynthesis in core collapse winds



How much stuff?

$$10^{-6}\text{-}10^{-4}\,M_\odot$$

Need (to account for all r-process material):

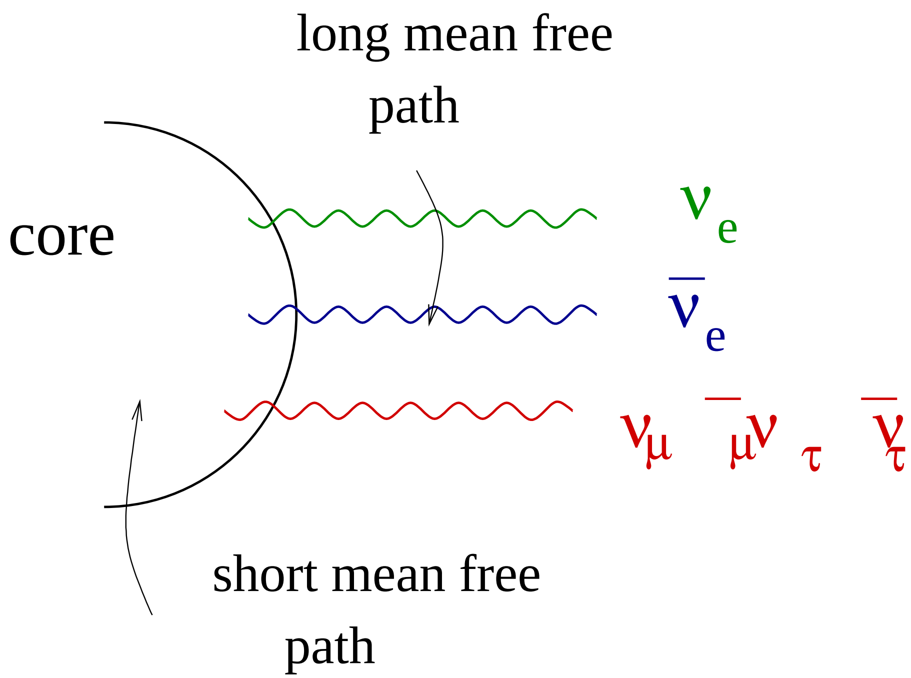
$$10^{-6}\,M_\odot$$

Core collapse supernovae evolve "quickly"

No problem with finding r-process elements in halo stars

Neutrinos from Standard Supernovae

All types of neutrinos are trapped in the core. At the surface they escape and travel through the outerlayers of the SN, then to earth.



The Neutrino Sphere, near the surface of the proto-neutron star is where the neutrinos decouple. This is where the neutrino energies are determined.

large uncertainty in spectra:

- $\langle E_{\nu_\mu} \rangle = \langle E_{\bar{\nu}_\mu} \rangle = \langle E_{\nu_\tau} \rangle = \langle E_{\bar{\nu}_\tau} \rangle = 20 - 30\,\mathrm{MeV}$
- $\langle E_{\bar{\nu}_e} \rangle = 13 - 19\,\mathrm{MeV}$
- $\langle E_{\nu_e} \rangle = 8 - 13\,\mathrm{MeV}$

The weak interaction

The only way to convert protons to neutrons and vice-versa

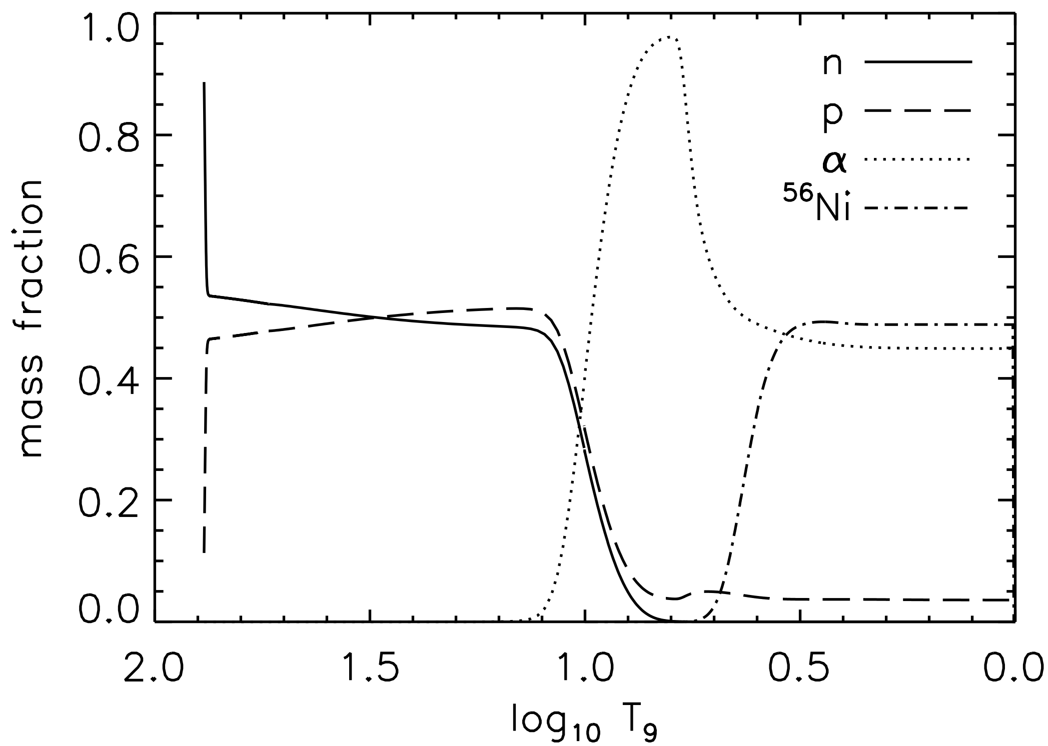
- beta decay $n \to p + e^- + \bar{\nu}_e$
- electron (neutrino) capture $e^- + p \leftrightarrow n + \nu_e$
- positron (antineutrino) capture $e^+ + n \leftrightarrow p + \bar{\nu}_e$
- neutrino capture on nuclei
  $\nu_e + A(Z,N) \leftrightarrow A(Z+1,N-1) + e^-$
- neutrino capture on nuclei
  $\bar{\nu}_e + A(Z,N) \leftrightarrow A(Z-1,N+1) + e^+$

Nucleosynthesis in hot outflows

What matters?

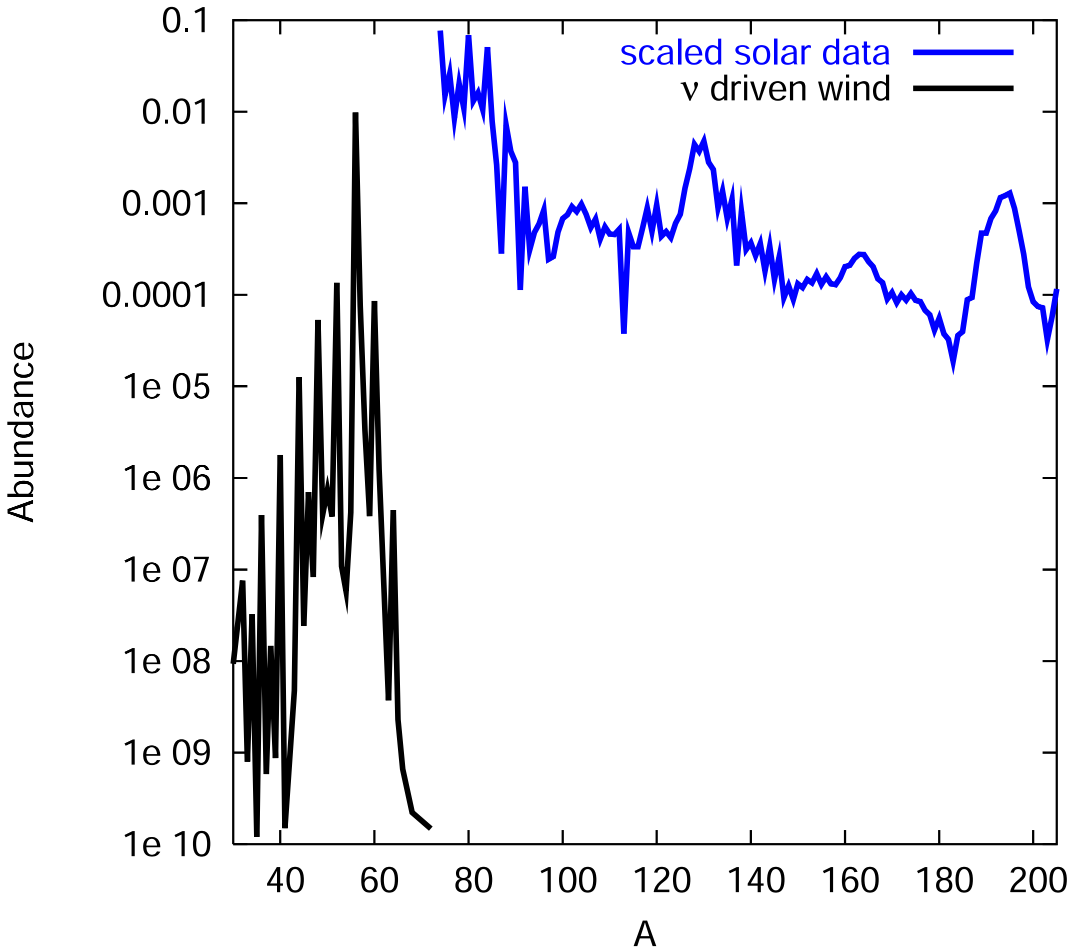
- outflow timescale, milliseconds to seconds
- entropy $s \sim 20$ to $s \sim 400$
- electron fraction, $Y_e = \frac{\mathrm{p}}{\mathrm{n+p}}$, $Y_e \sim 0.1$ to 0.6,

Nucleosynthesis in hot outflows: an example



Core Collapse Supernovae: Nucleosynthesis in the Traditional Neutrino Driven Wind

Hoped for r-process an site



What happened?

Entropy too high for outflow timescale (or vice versa)

Supernovae vs. mergers

Core collapse supernovae have the right evolution time scale, but it is difficult to make enough neutrons.

Compact object mergers have plenty of neutrons, but it is not obvious that they have the required evolution time scales.