Neutrinos and Neutrons in the r-process

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Neutrino Astrophysics

- What are the fundamental properties of neutrinos?
- What do they do in astrophysical environments?
- What do neutrinos in a core collapse supernova do?
- What do neutrinos in a black hole accretion disk do?

Nuclear Astrophysics

- What is the origin of the elements?
- Where are the heaviest elements made?
- What elements are made in compact object mergers/ stellar explosions?

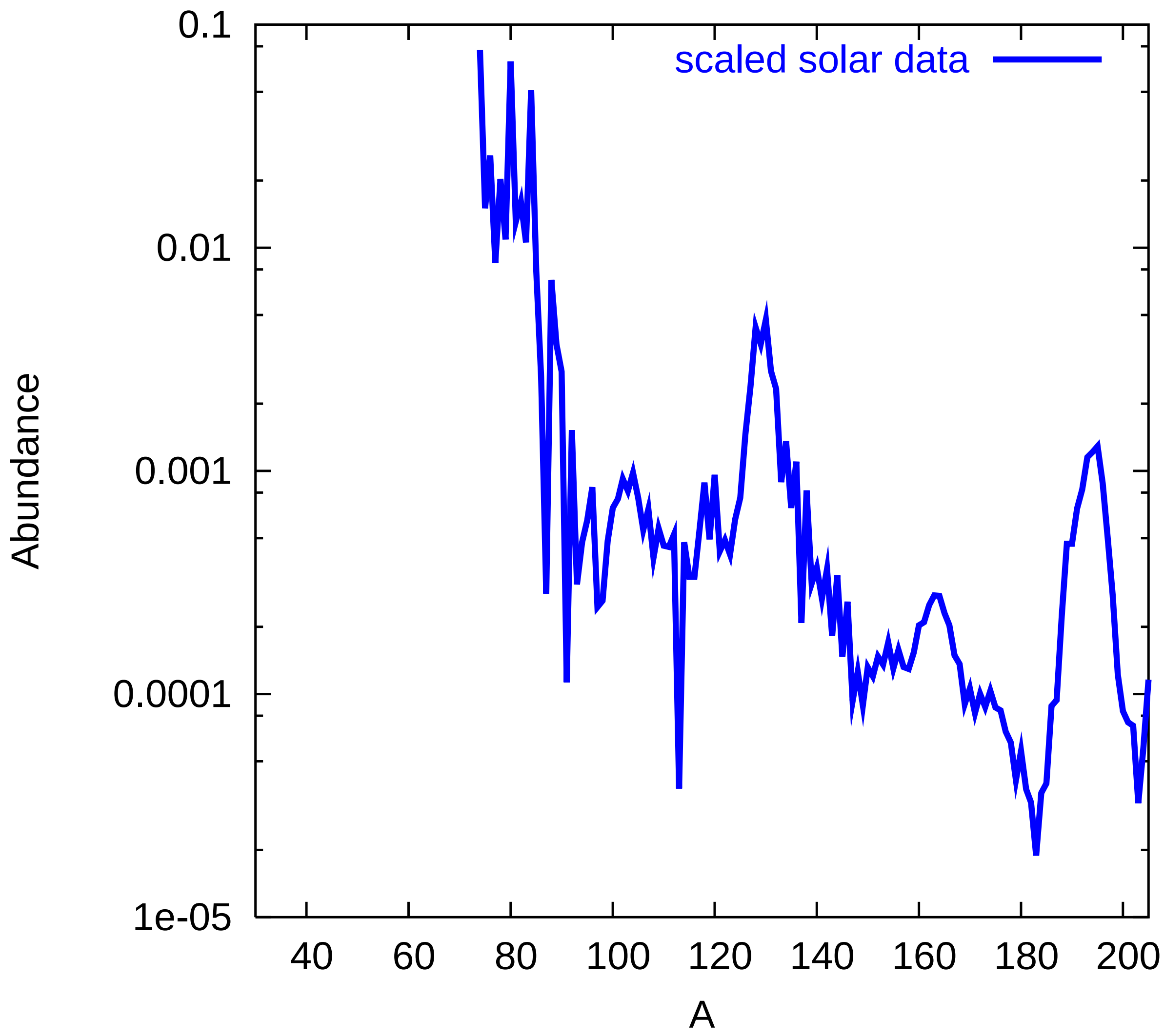
Where is uranium made?

Uranium is an r-process element . . .

From where do the heaviest elements come?

- Elements beyond the iron peak in three main categories
  - r-process
  - s-process
  - p-process
- examples of r-process elements
  - Europium
  - Platinum
  - Uranium
  - Thorium

Solar Abundances

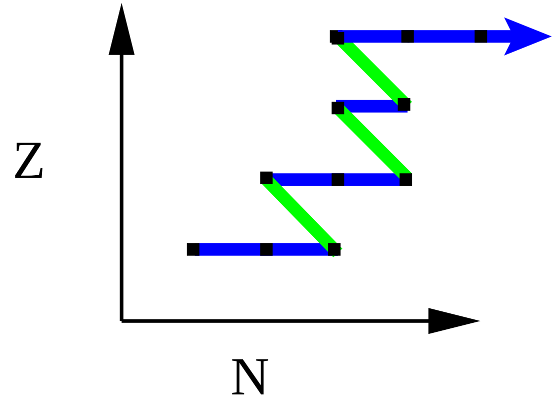


The r-process elements

e. g. Uranium-238 Z=92, N=146 $\longrightarrow$ 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

At what temperatures does this happen?

$(n,\gamma)\,(\gamma,n)$ equilibrium at $T \approx 10^9$K

What astrophysical sites have a lot of neutrons *and* eject material?

- neutron star mergers/ neutron star - black hole mergers
- "wind" close to the center of a core-collapse supernova

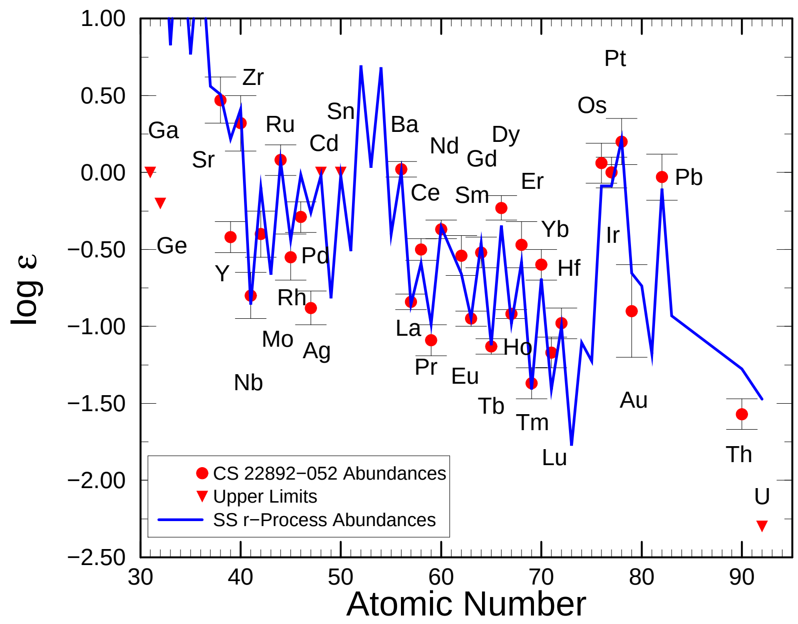
Two kinds of r-process data: Observational and Meteoritic

Meteoritic: Isotopic measurements of r-process nuclei: two r-process sites?

Wasserburg, Busso and Gallino (1996)

Observational Halo Stars: two r-process sites?

Figure from Cowan and Sneden (2004)

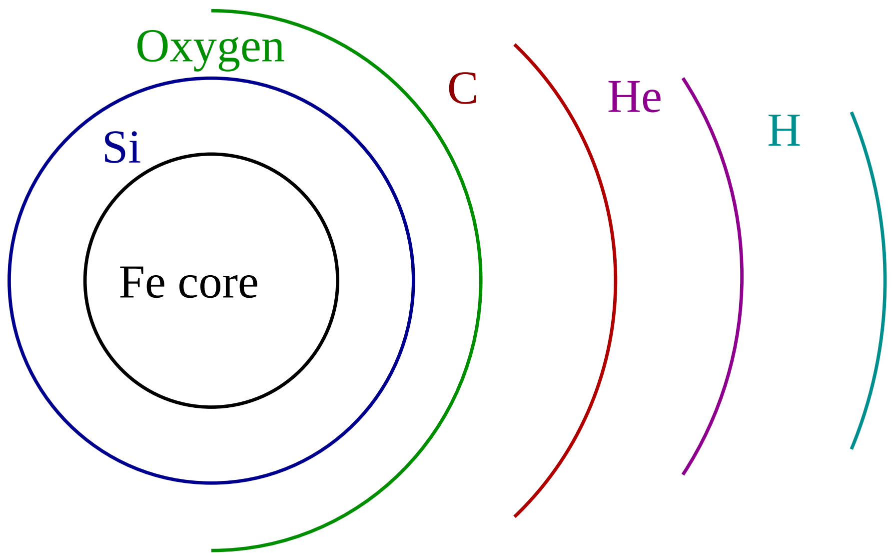


What do the data suggest?

Supernovae are favored over neutron star mergers Argast et al 2004

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

Supernova Explosion!

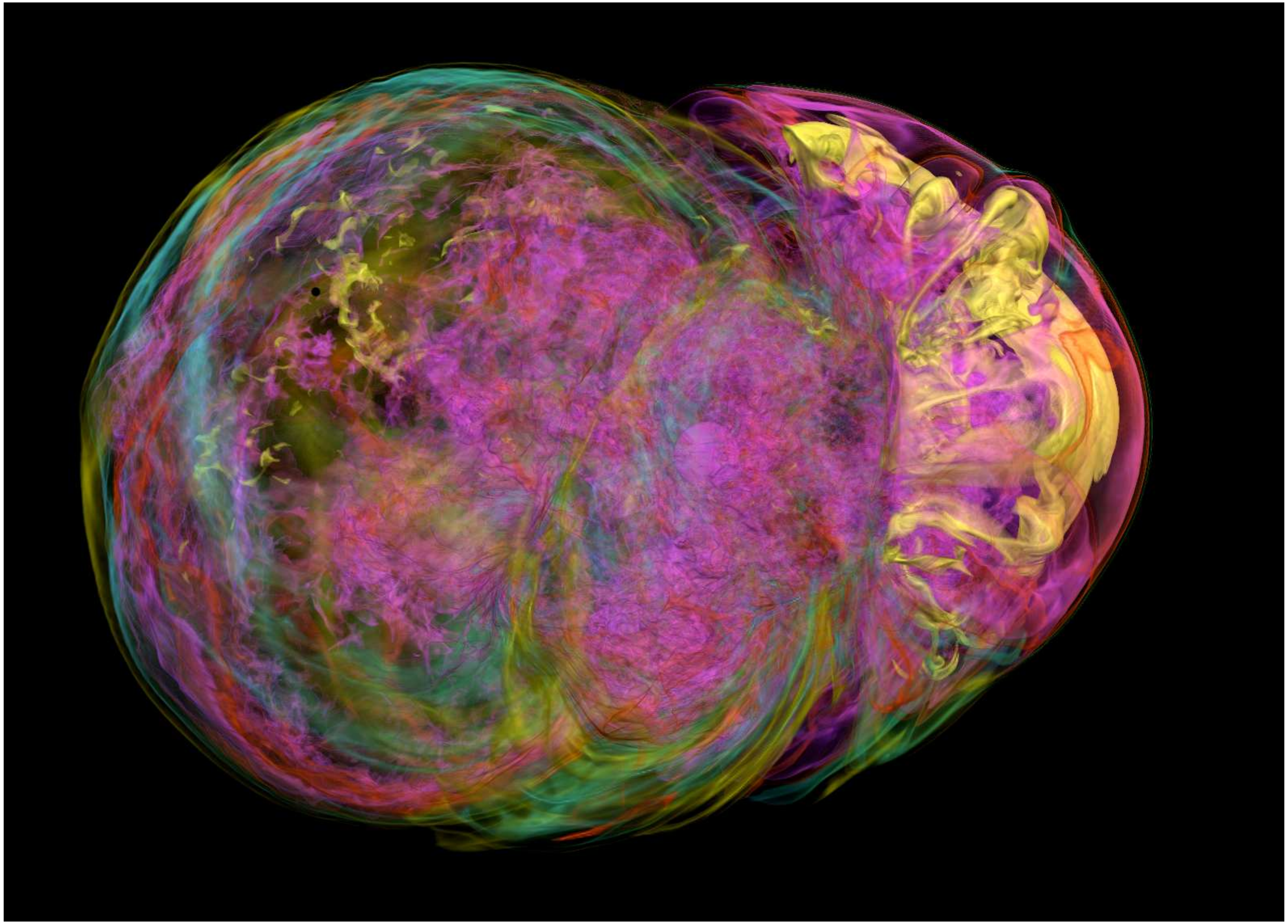
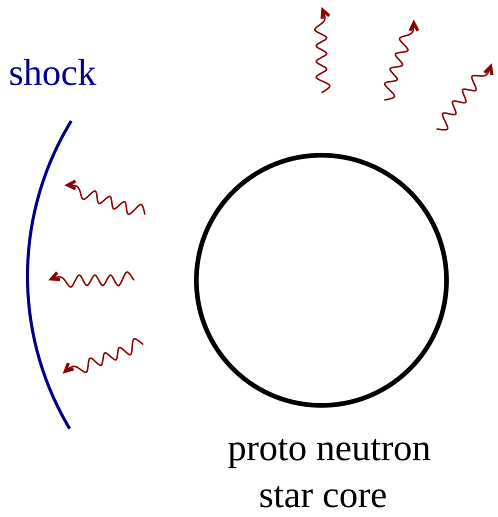
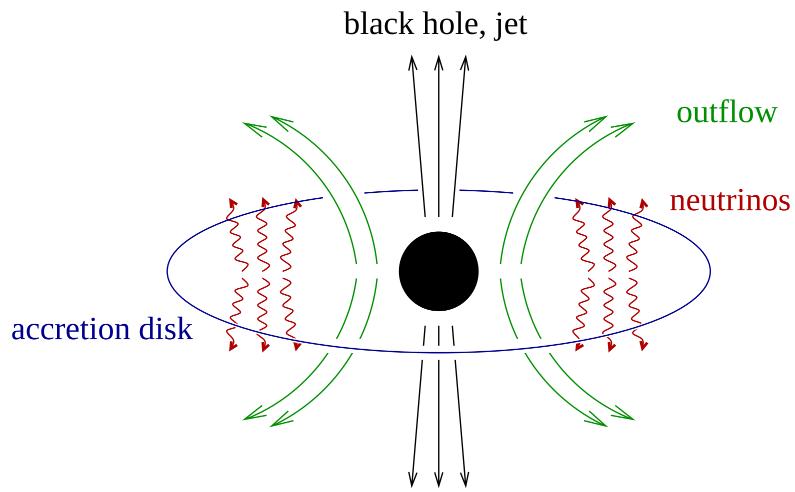


Figure from John Blondin

Explosions of Massive Stars: What's happening at the Center?

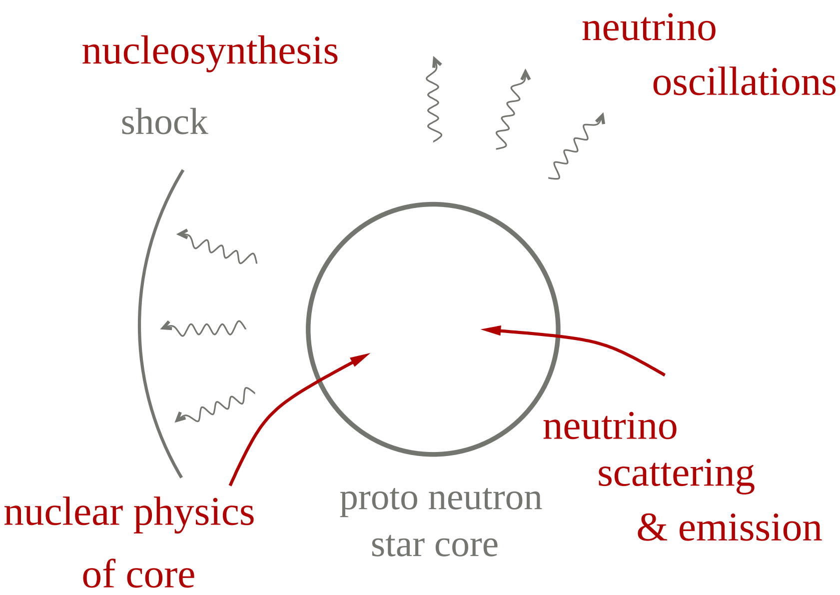


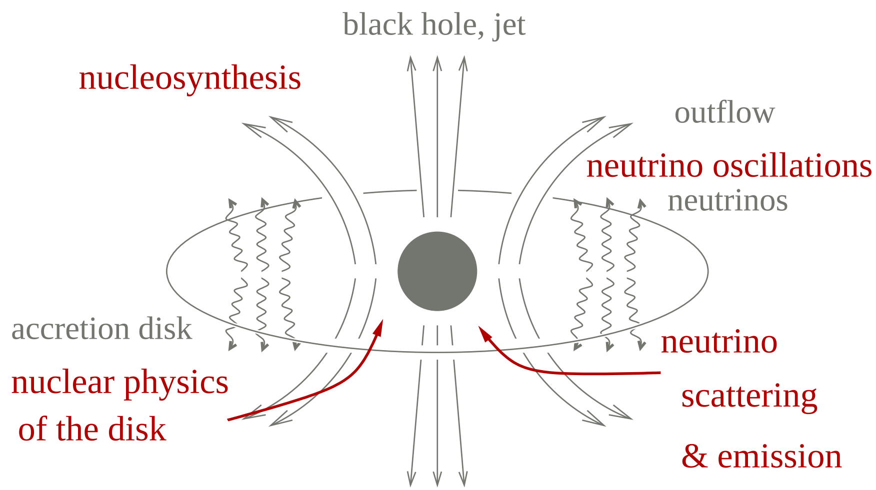


Standard core core collapse SN

Long duration gamma ray burst from core collapse SN or compact object merger

Explosions of Massive Stars: Where is the nuclear-neutrino physics?





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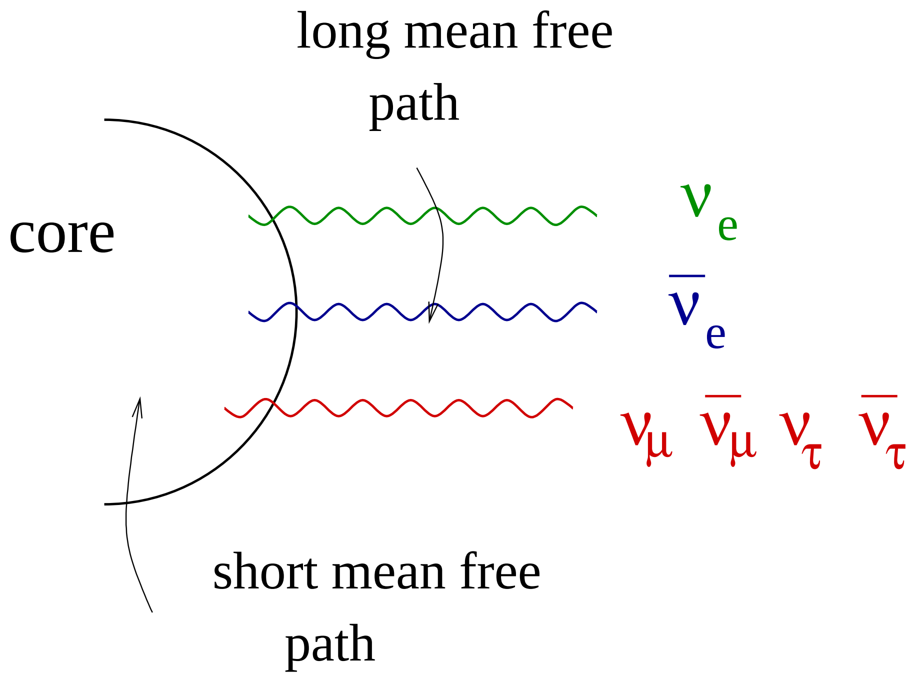
Neutrinos from Standard Supernovae

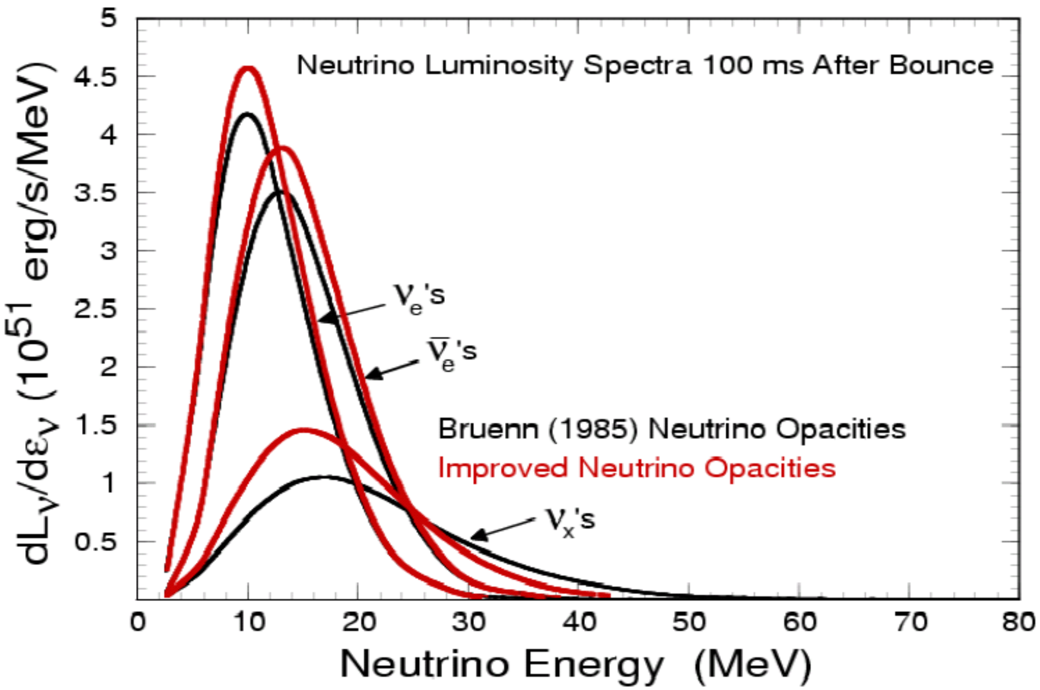
All types of neutrinos are trapped in the core. At the surface they escape and travel through the outerlayers of the SN, then to earth.



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

Measuring the Supernova Neutrino Signal

Why? Neutrinos are our window deep into the core of the Supernova



Roughly the range is

- $\langle E_{\nu_\mu} \rangle = \langle E_{\bar{\nu}_\mu} \rangle = \langle E_{\nu_\tau} \rangle = \langle E_{\bar{\nu}_\tau} \rangle = 16 - 25\,\mathrm{MeV}$
- $\langle E_{\bar{\nu}_e} \rangle = 12 - 18\,\mathrm{MeV}$
- $\langle E_{\nu_e} \rangle = 8 - 13\,\mathrm{MeV}$

Predictions of the spectral shape are different, too.

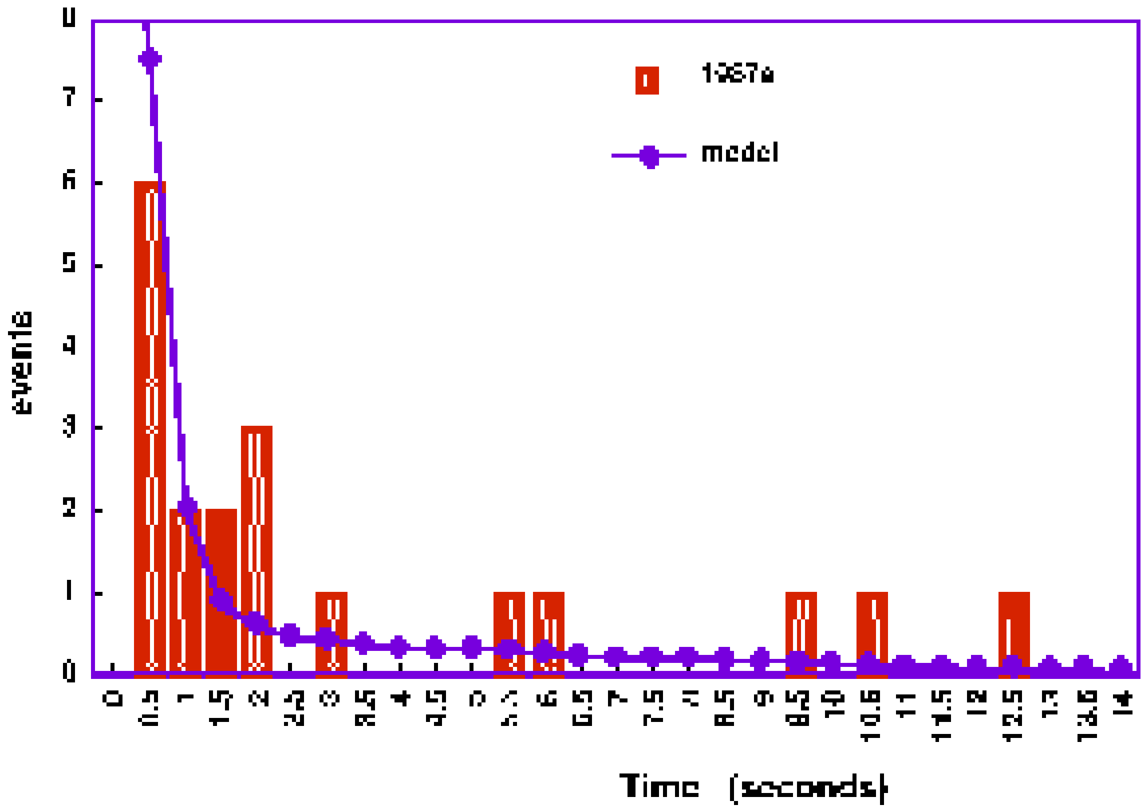
Supernova Neutrinos

Most neutrinos emitted during the first ~ 10 sec

Galactic supernovae estimated to occur ~ 1 every 30 years

Supernova neutrinos detected from SN1987a:

~ 20 events observed in Kamiokande and IMB.



Returning to the uranium problem

We want to examine a supernova “wind” near the core

We want to know if it has a lot of neutrons . . .

The weak interaction

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

- beta decay $n \rightarrow p + e^- + \bar{\nu}_e$
- electron (neutrino) capture $e^- + p \leftrightarrow n + \nu_e$
- positron (antineutrino) capture $e^+ + n \leftrightarrow p + \bar{\nu}_e$

A few words about neutrinos . . .

They come in three flavors: ν_e, ν_μ, ν_τ and have associated charged leptons e, μ, τ

The neutrinos have 10s of MeV energies, not enough to make muons or taus, so only the electron type change charge.

The weak interaction

So does the material have more protons or neutrons?

- electron (neutrino) capture $e^- + p \leftrightarrow n + \nu_e$
- positron (antineutrino) capture $e^+ + n \leftrightarrow p + \bar{\nu}_e$

Electons and positrons are in equilibrium with the rest of the matter, the neutrinos are not.

i.e. the electrons are positrons are cooling as material moves away from the core, but the neutrino temperatures are fixed.

At some point the neutrino and antineutrino reactions begin to dominate

The weak interaction

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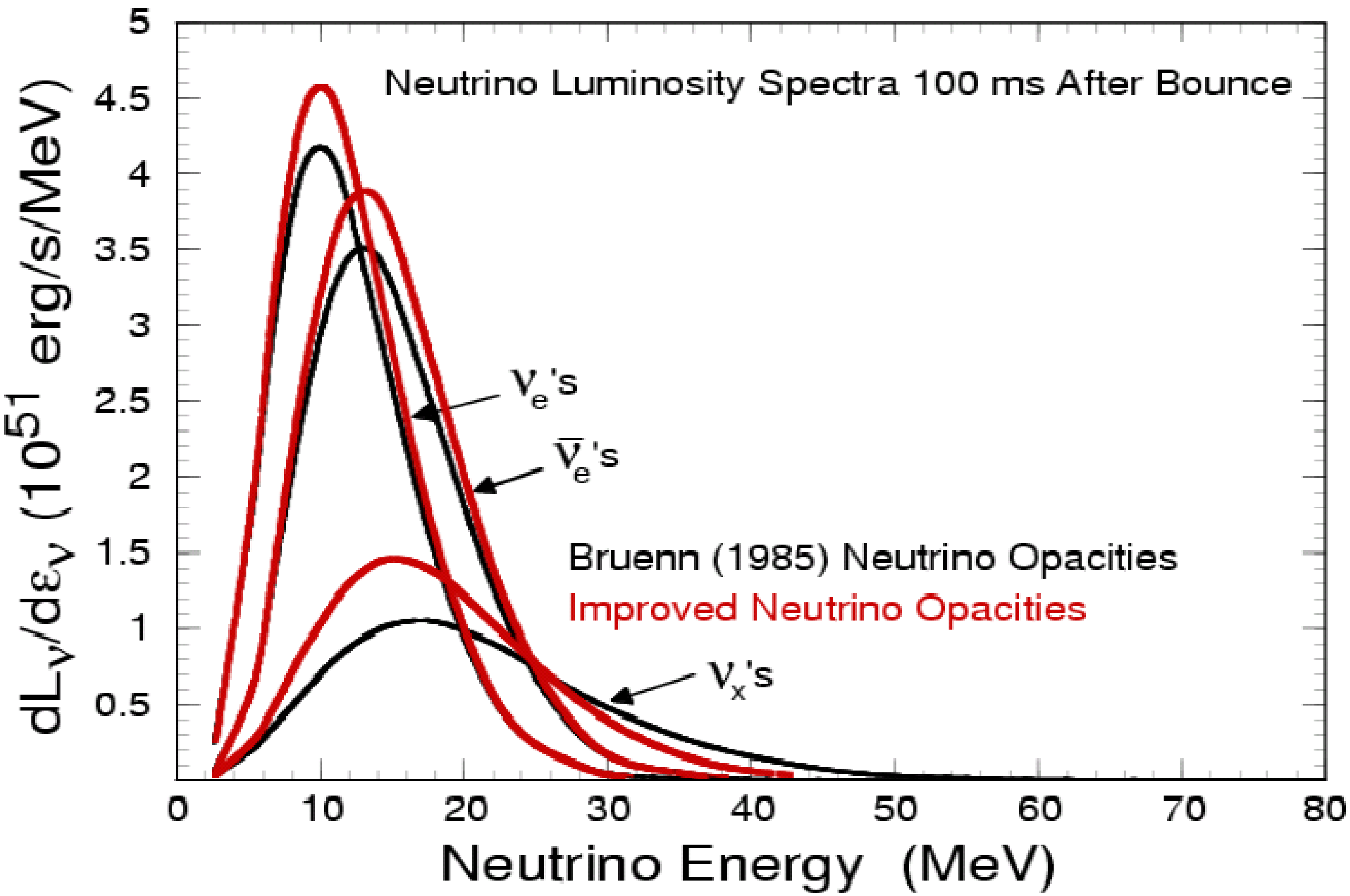


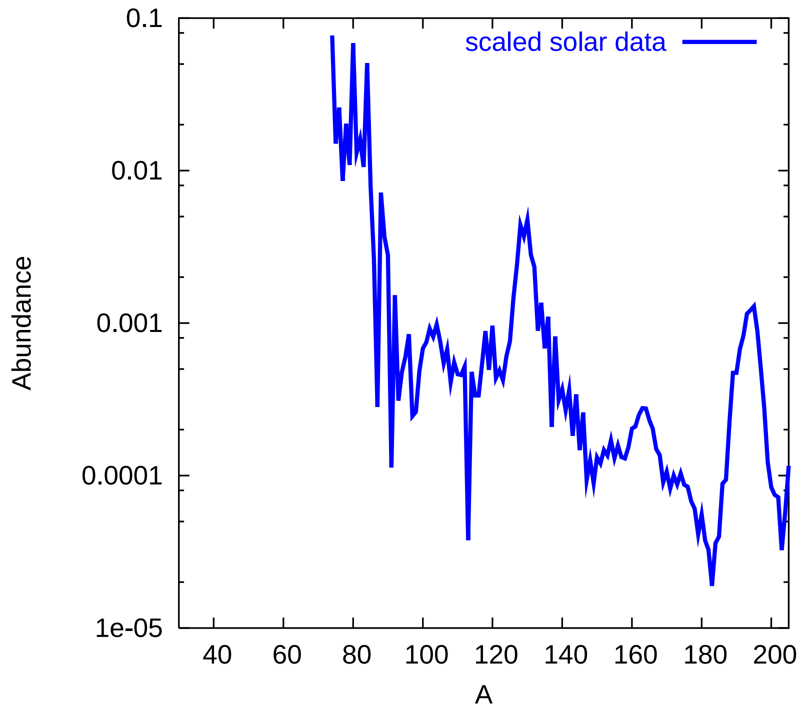
Let's try a network calculation

Reaction network calculation contains $\sim$ 3000 elements and isotopes

Takes as input temperature, density profiles . . .

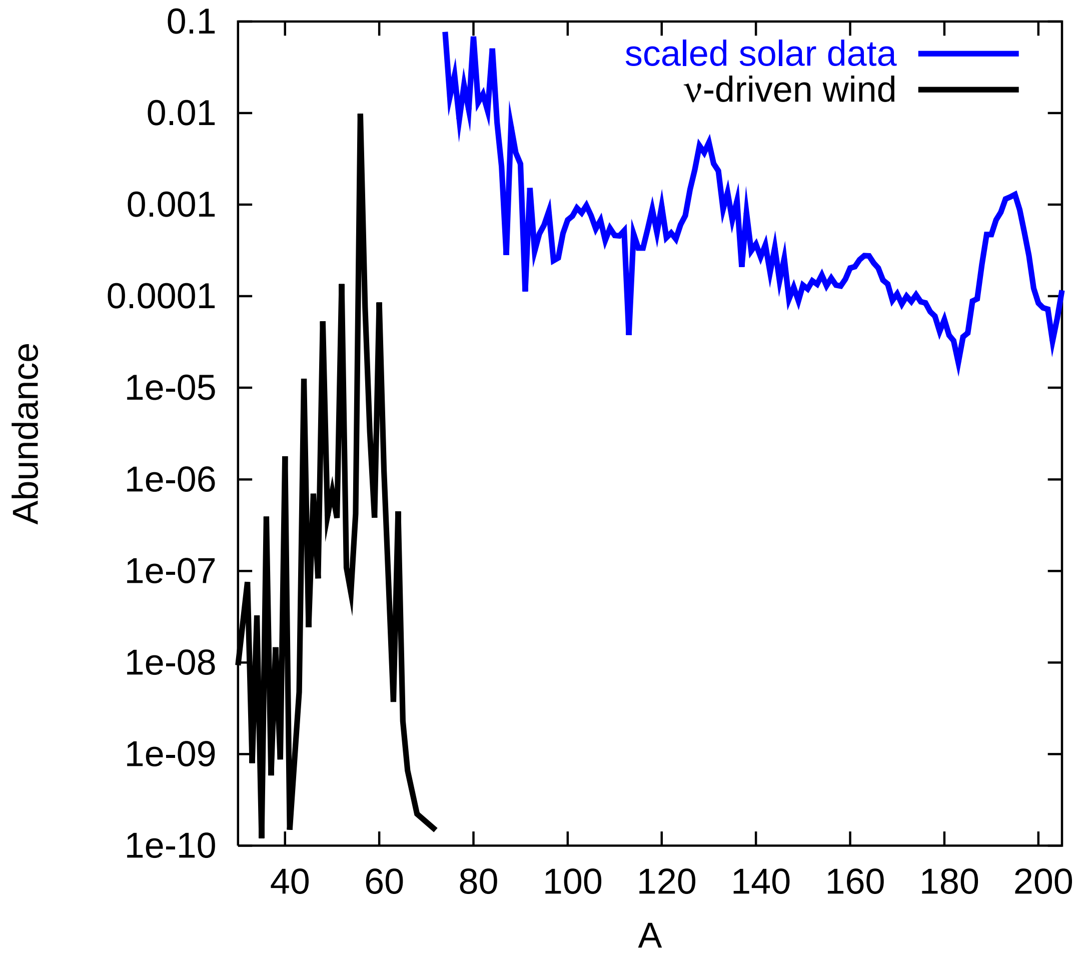
Outputs an abundance pattern . . .

Recall that we want to match the data . . .



Core Collapse Supernovae: Nucleosynthesis in the Traditional Neutrino Driven Wind

Hoped for r-process site



What happened?

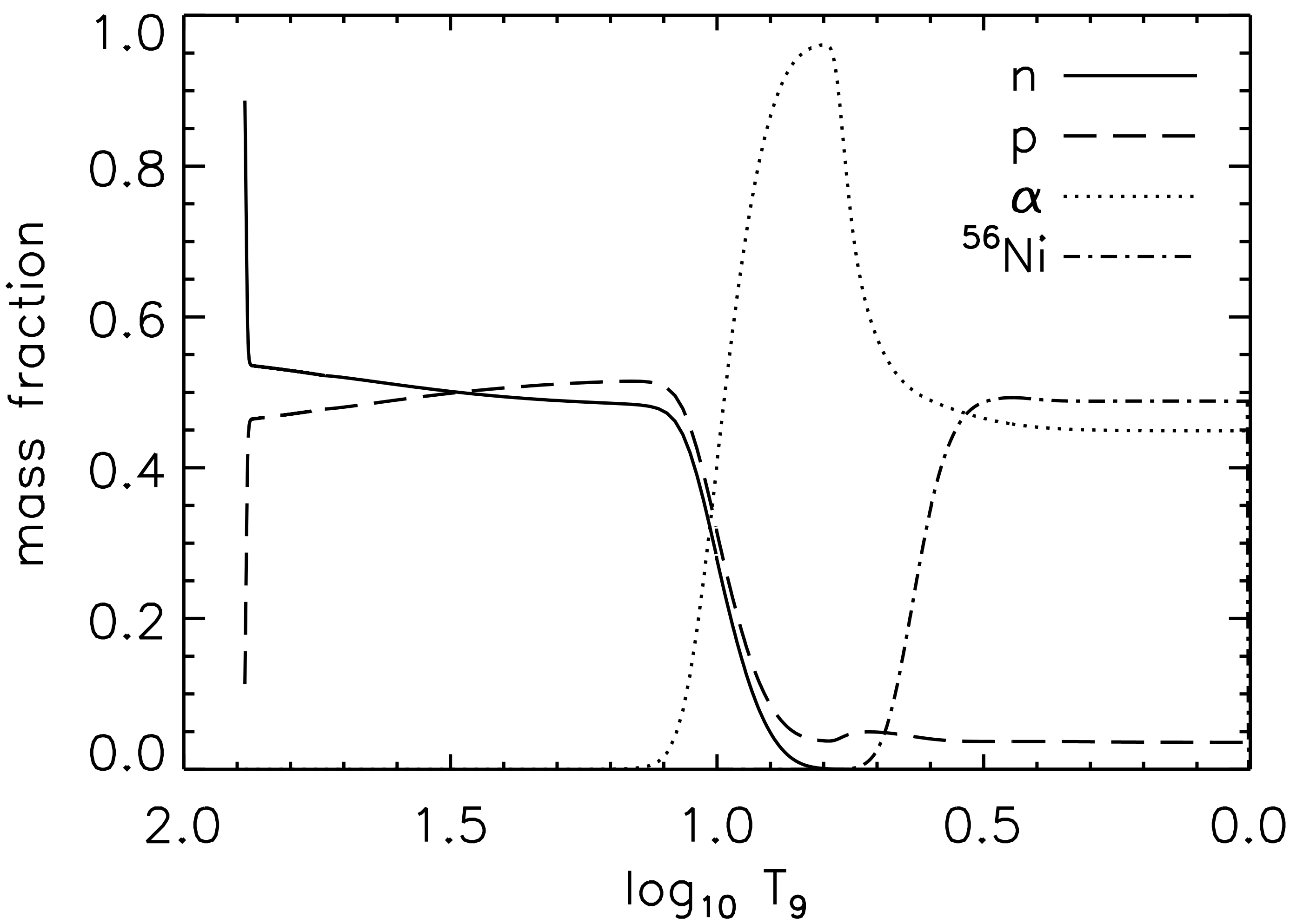
Not enough entropy

$E_{\bar{\nu}_e}$s too low

Most current simulations don't work!

Nucleosynthesis in Hot Outflows

n,p $\rightarrow {}^4\mathrm{He} \rightarrow$ iron peak nuclei $\rightarrow$ heavier nuclei



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,

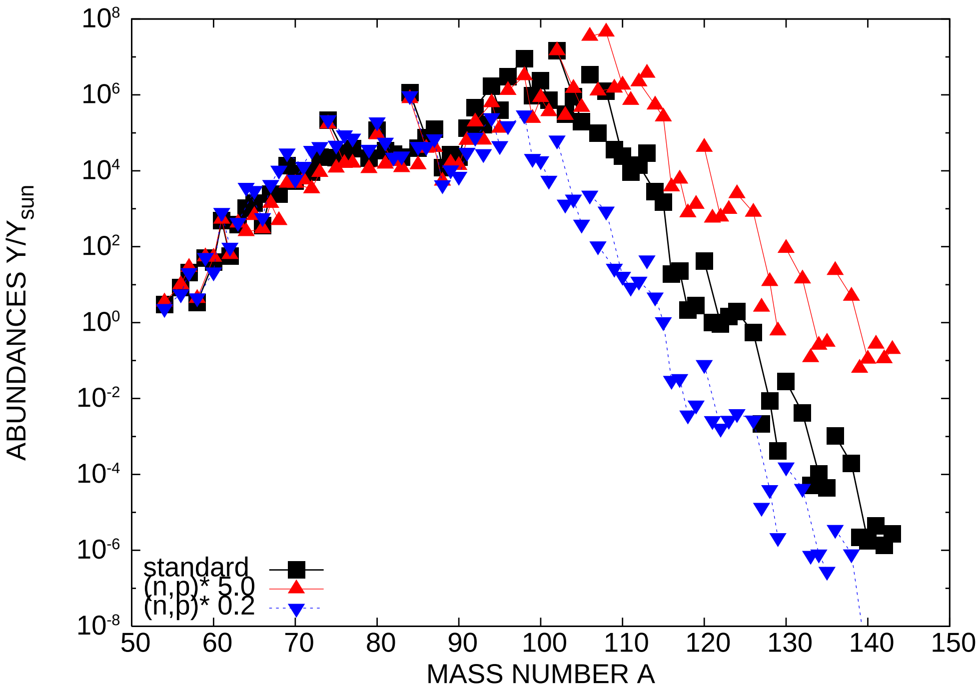
Electron fraction is set by the weak interactions:

$\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$

What about $\bar{\nu}_e + p \rightarrow n + e^+$ on left over protons?

Neutrino induced processes in proton rich winds in core collapse supernova

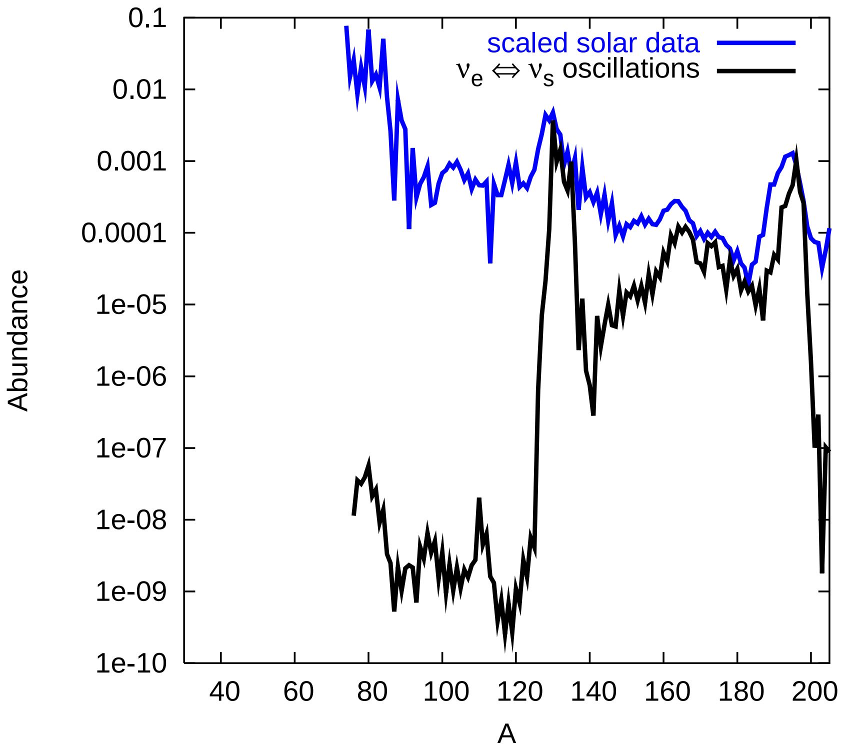
Antineutrino capture on left over protons produces p process elements



Frohlich et al 2011

But what about the r-process?

Core Collapse Supernovae: Nucleosynthesis in non-Traditional Neutrino Driven Winds



Active Sterile ν oscillations

Beun et al 2007

Other ideas:

- magnetic fields
- 3-D calculations
- compact object mergers

Compact Object Mergers:

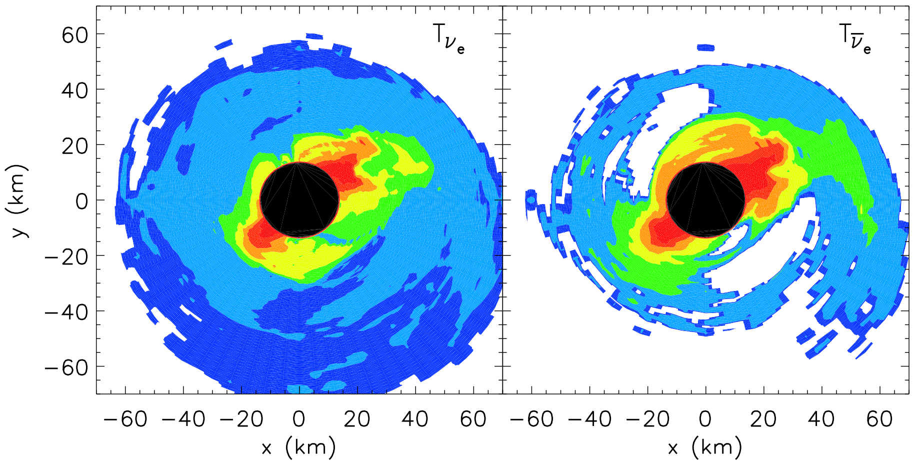
Can they make the r-process?

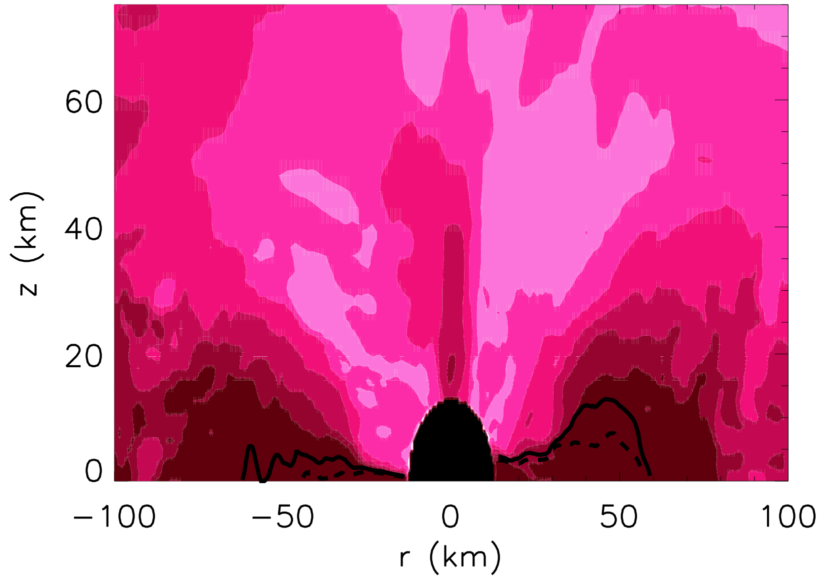
- two neutrons stars spiral together
- or: a black hole and a neutron star spiral together
- a disk is formed
- some material is ejected from tails
- some material is blown off in a neutrino wind

Examine: neutrino wind from the disk

Neutrino Surfaces

Black Hole Neutron Star Merger





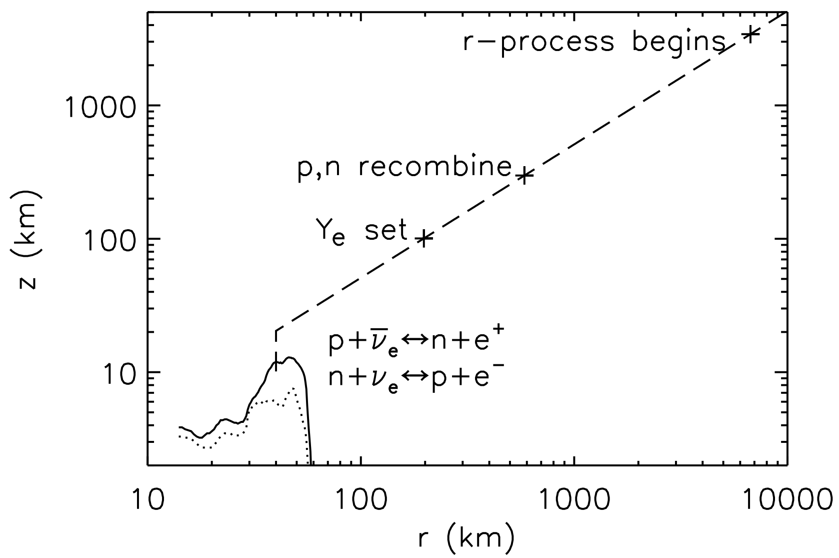
Accretion disk in neutrinos

Side view shows neutrino surfaces

Surman et al. 2008

Accretion Flow Nucleosynthesis

Black Hole Neutron Star Merger



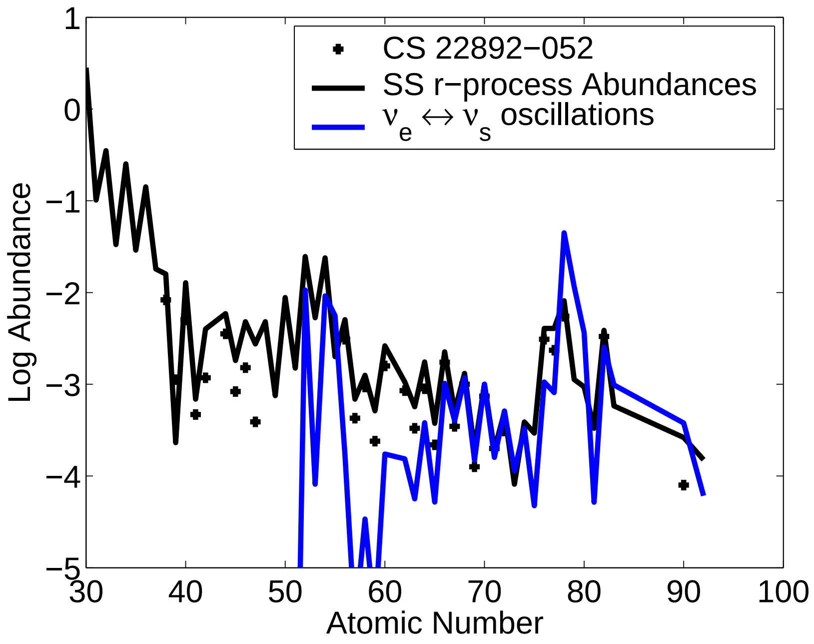
Hypothetical schematic of events in outflow

Do you get to the r-process stage in this environment?

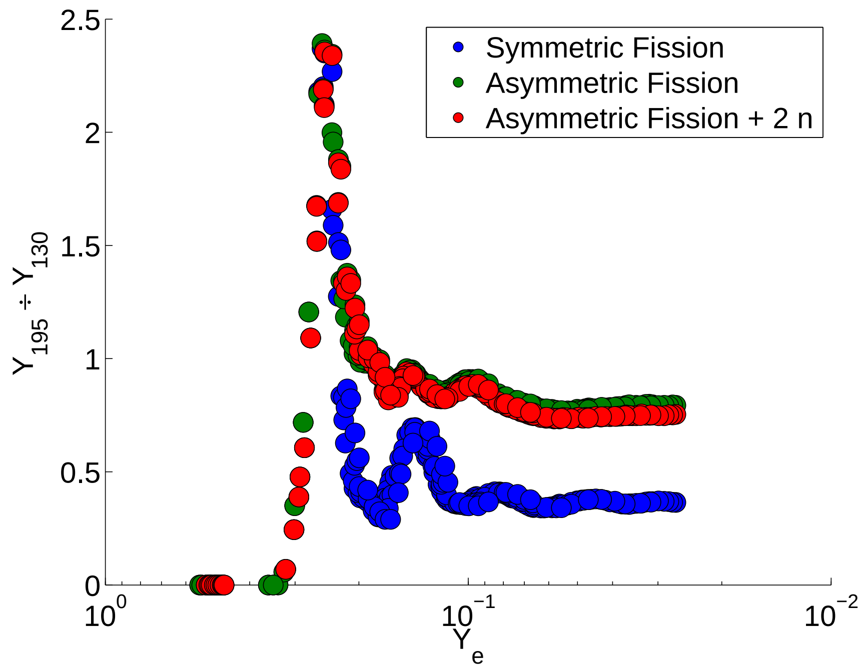
Uncertainties

- Astrophysical Environment
- Equation of state
- Neutrino Properties/Oscillations
- β-decay rates
- nuclear masses/capture rates
- fission rates/daughter products

Fission Cycling in the r-process



astrophysical data hints at fission cycling

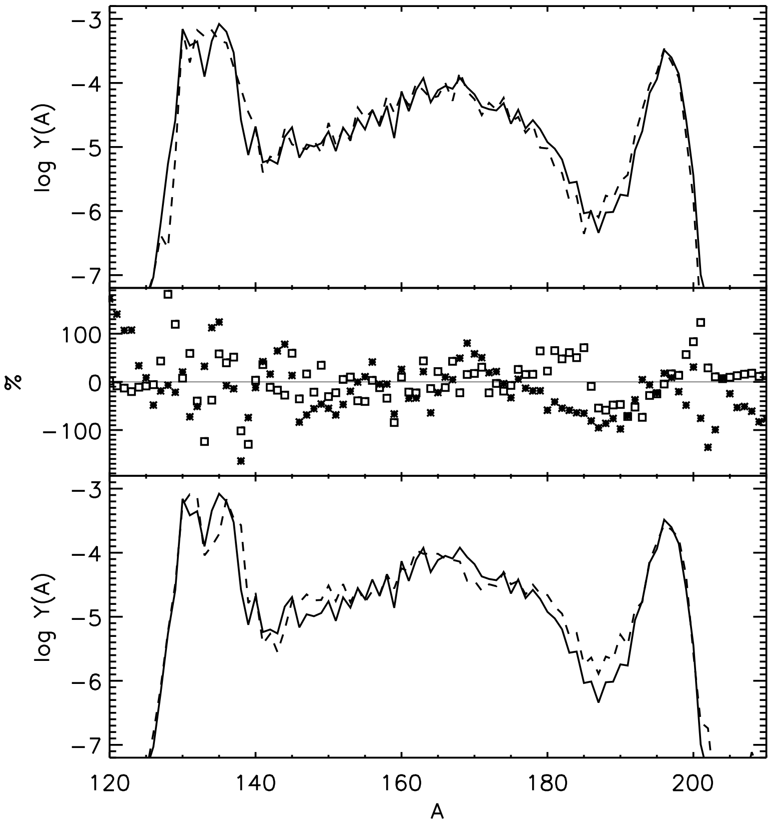


fission cycling requires many neutrons

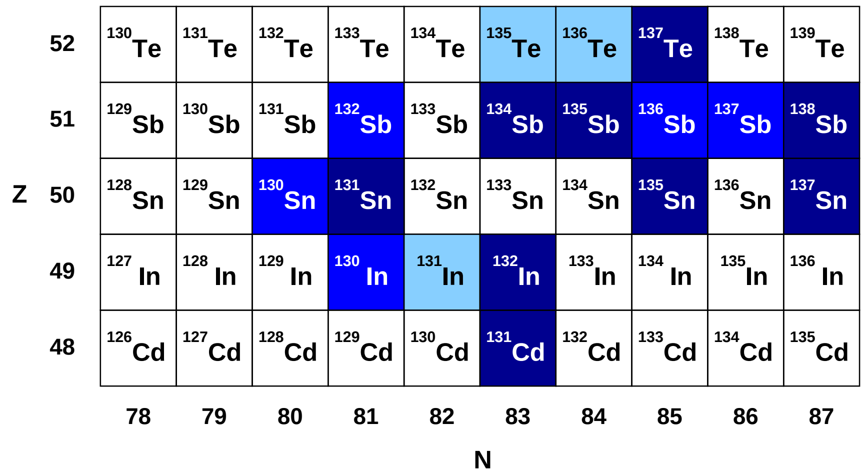
Very little data on the relevant fission rates and daughter products

Beun et al 2006, Beun et al 2008

Neutron Capture rates on the A=130 peak



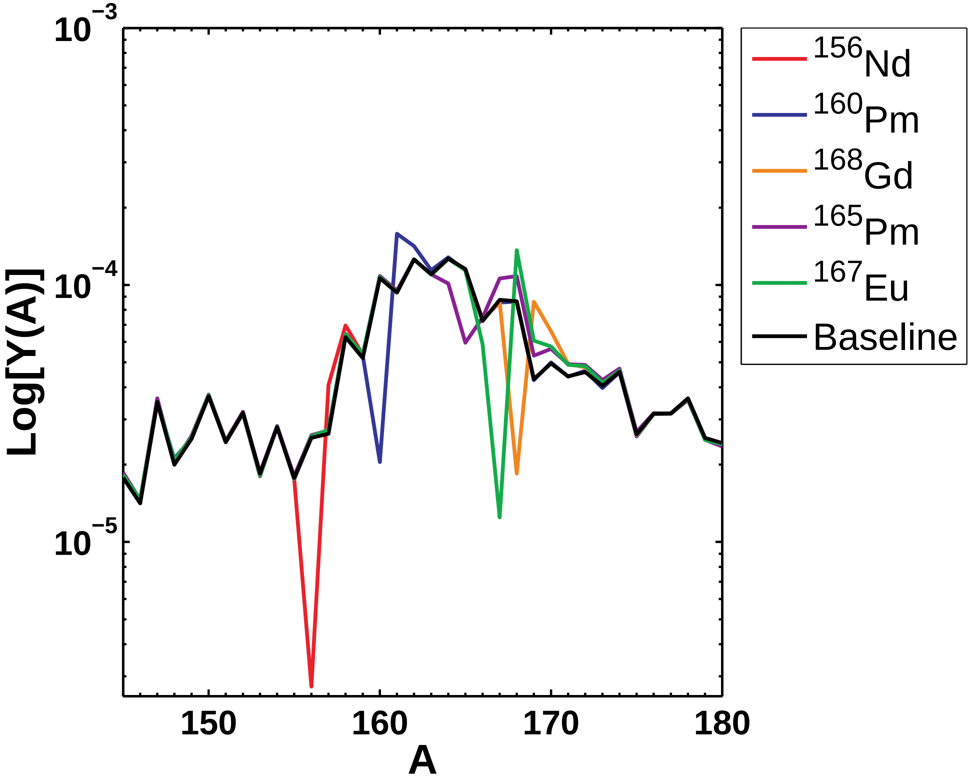
Change the mass model (bottom) or vary the capture rates (top)



Nuclei in the 130 peak with neutron capture rates that effect a 5% or more change in the abundance distribution

Surman et al 2008

Neutron capture rates and the rare earth peak



Mumpower et al in prep 2011

Rare earth peak forms from combination of beta decay and neutron capture Surman and Engel 1997

Neutron capture rates together with astrophysical conditions determine the rare earth peak. Entering precision era of abundance measurements $\longrightarrow$ need better data and better analysis of astrophysical conditions.

Summary

- Supernova may be the site of the r-process (or not)
- Neutrinos play an important role in determining the type of elements formed in supernovae and compact object mergers
- Neutron capture as well as beta decay are important for future understanding the r-process
- Improvements in our understanding of nuclear physics will allow better constraints on the site of the r-process