The role of neutrinos in the formation of heavy elements

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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 compact object merger 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?

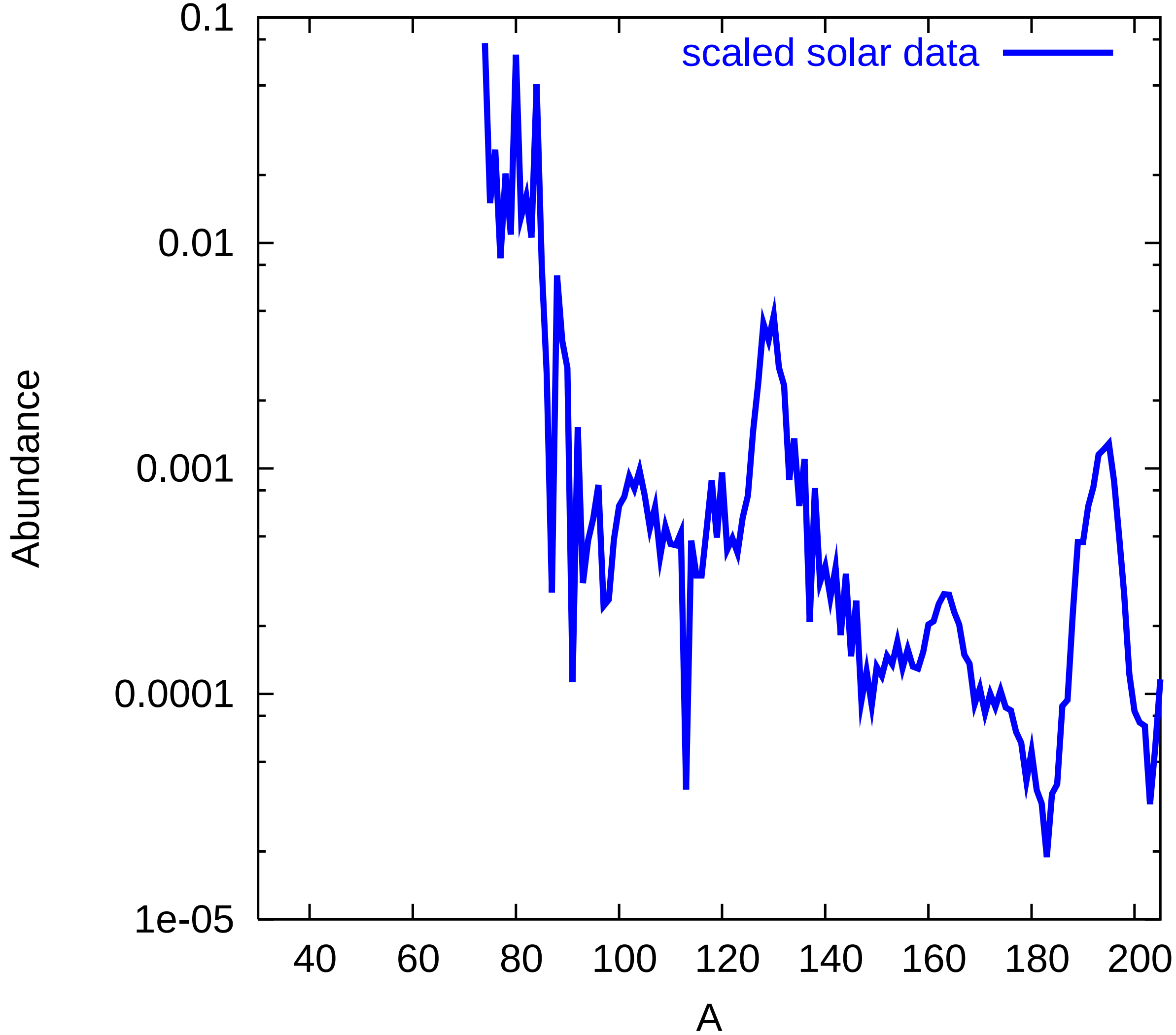
Where is uranium made?

Uranium is an r-process element . . .

Nucleosynthesis: In particular, 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

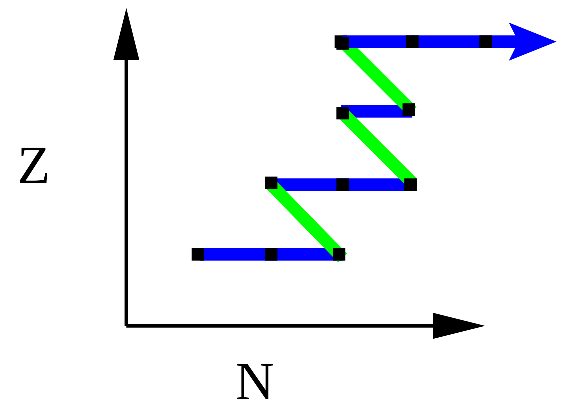


The r-process elements

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

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

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



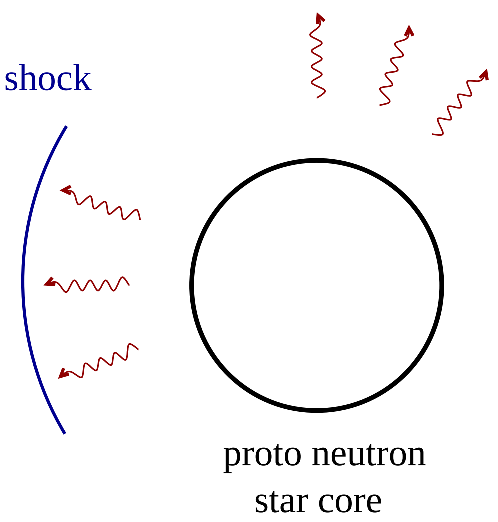
rapid neutron capture as compared with beta decay

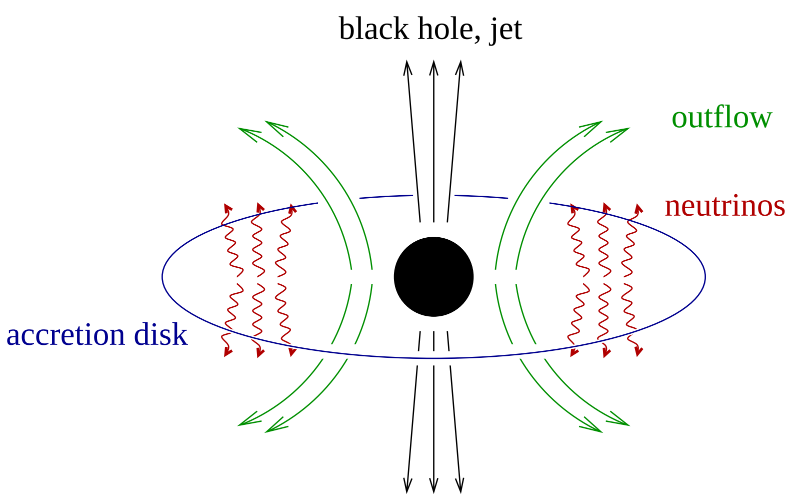
At what temperatures does this happen?

$(n,\gamma)\,(\gamma,n)$ 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





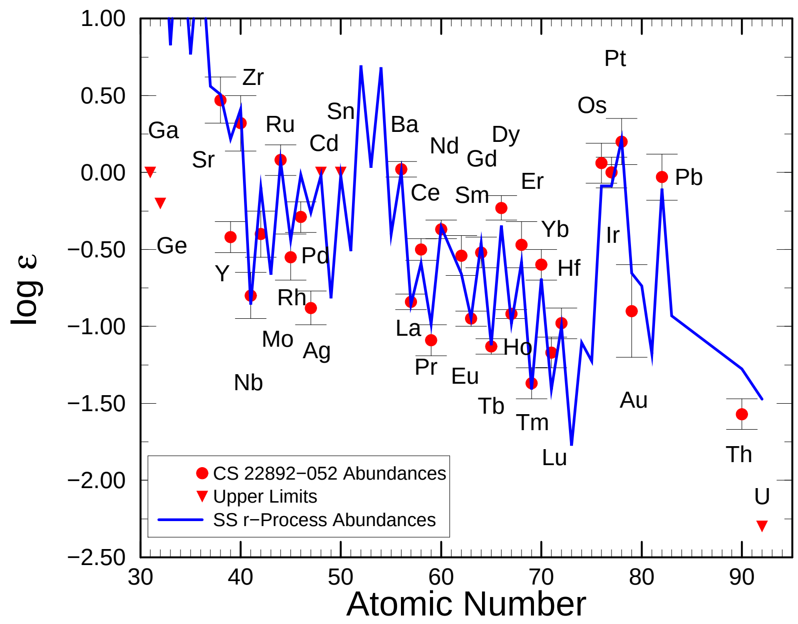
Two kinds of r-process data: Observational and Meteoritic

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)

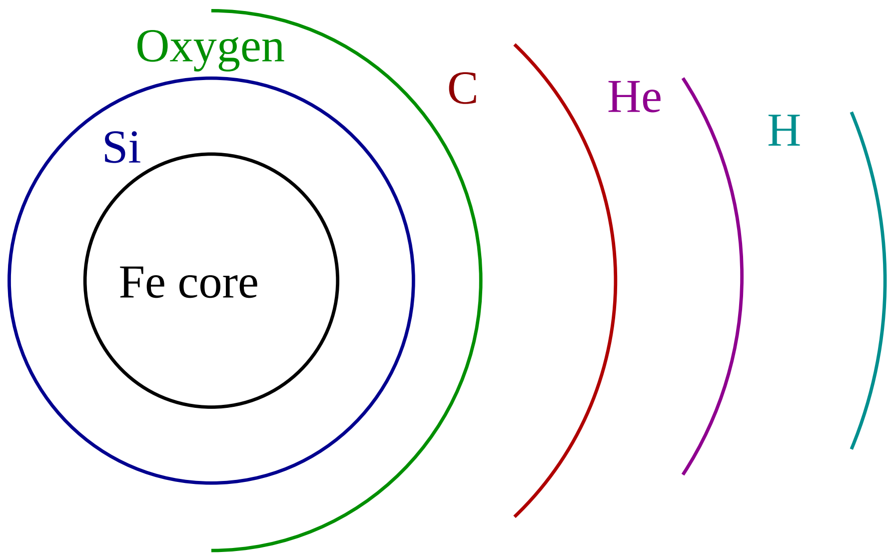


What do the data suggest?

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!

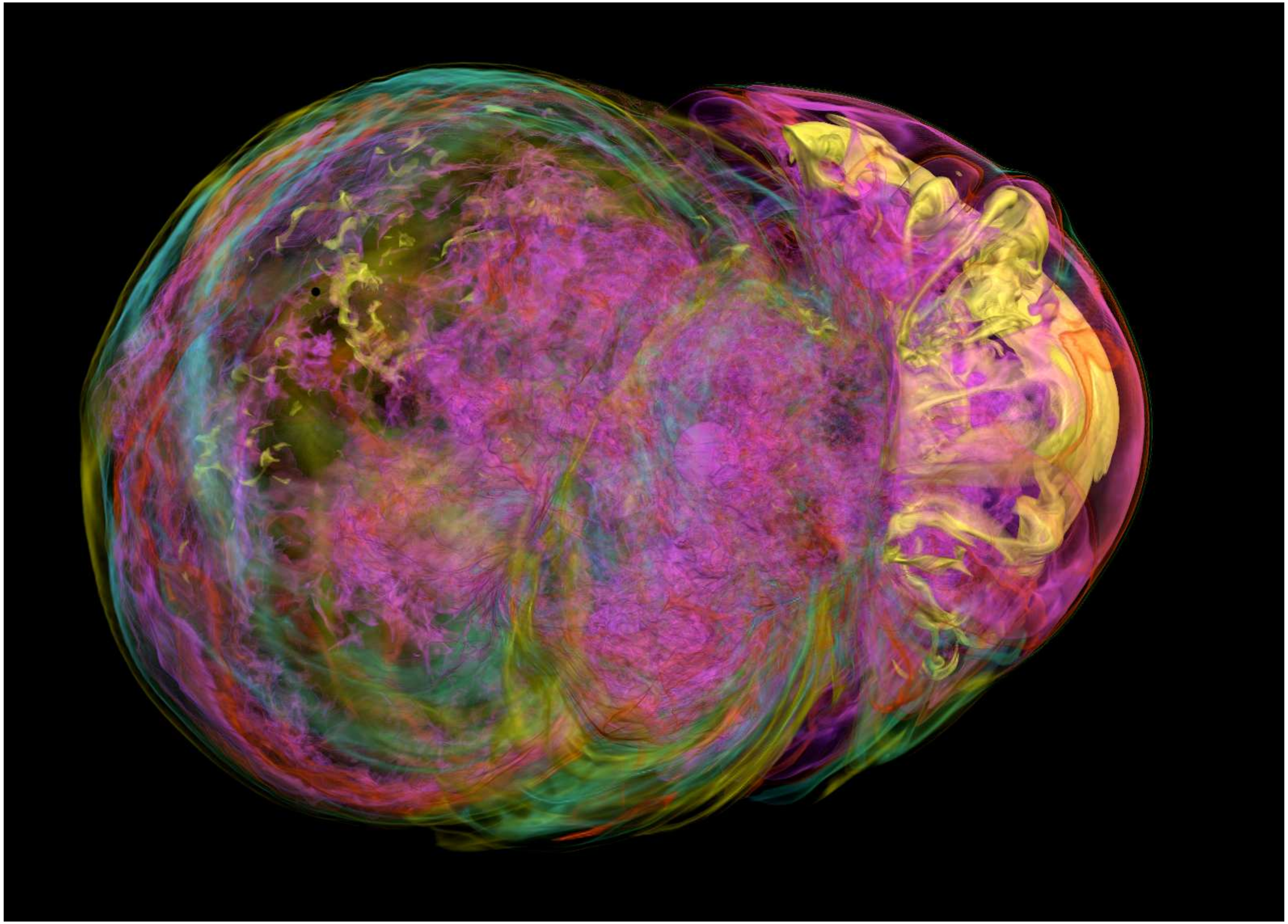
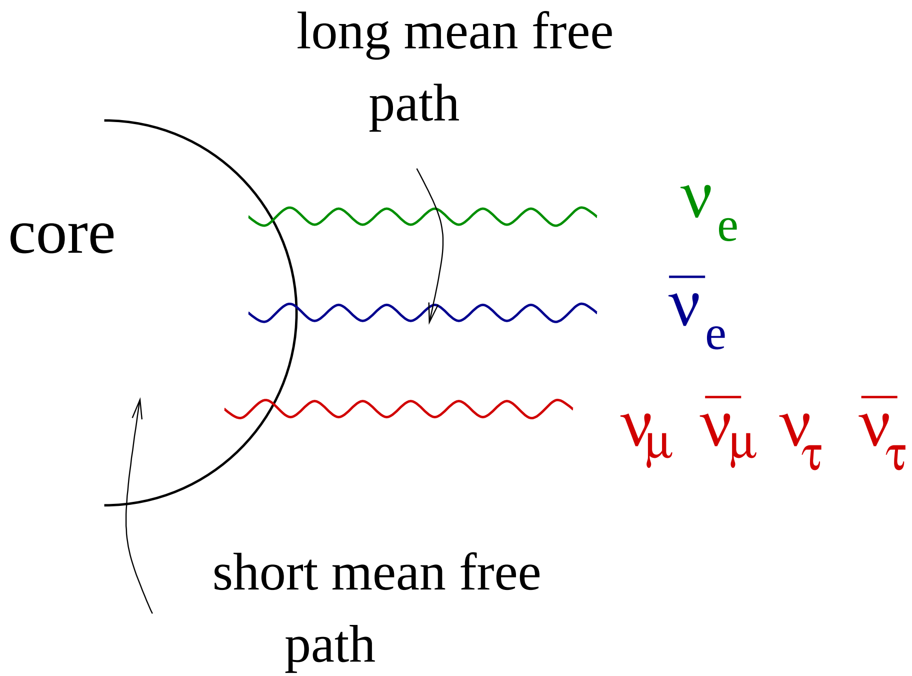


Figure from John Blondin

Neutrinos from Core Collapse Supernovae

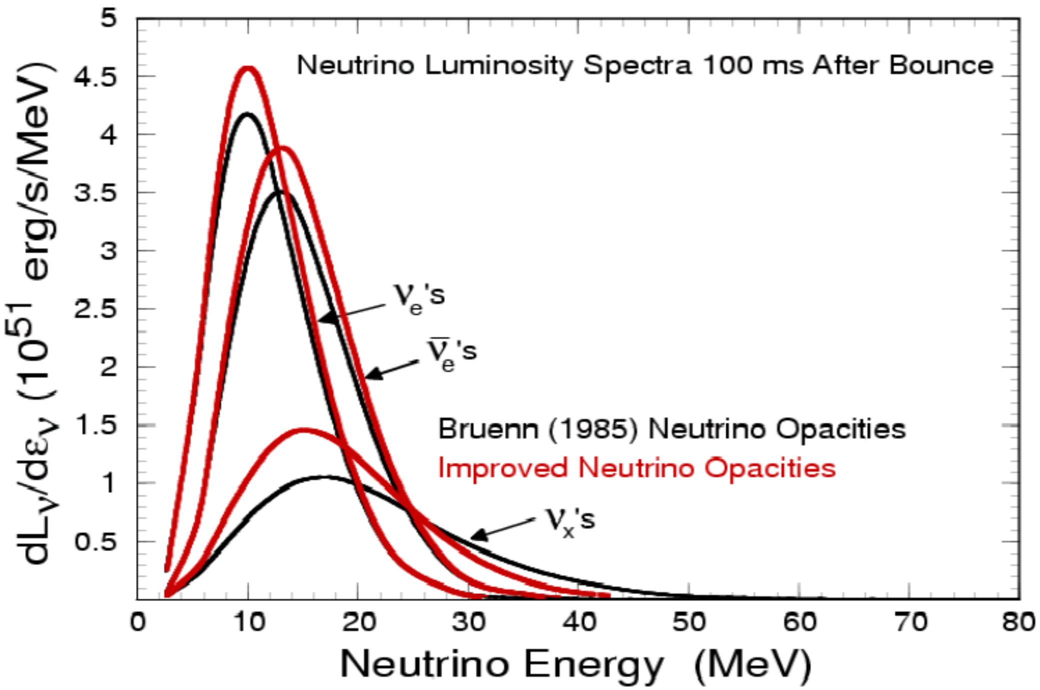
99% of the gravitational binding energy of the core is released in neutrinos. All types of neutrinos are trapped in the core. At the surface of the core they escape and travel through the outerlayers of the SN, then to earth.



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

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

Predictions of the spectral shape are different, too.

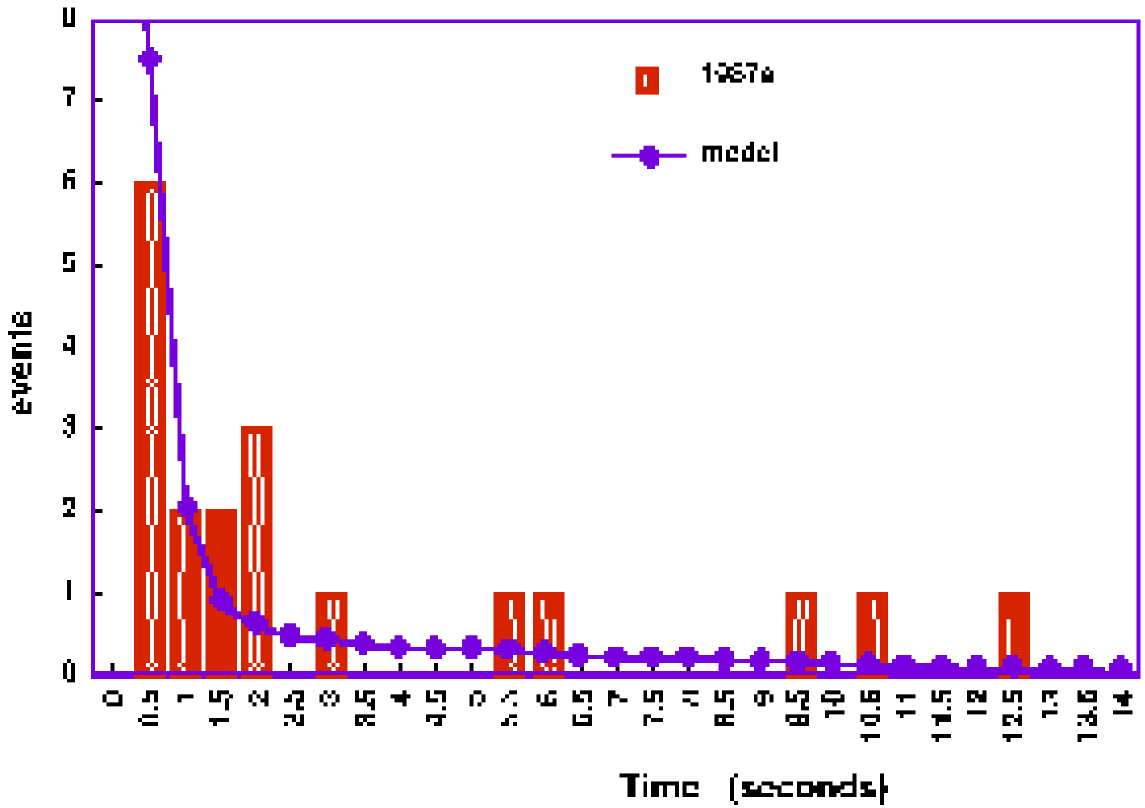
Supernova Neutrinos

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

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

So does the material have more protons or neutrons?

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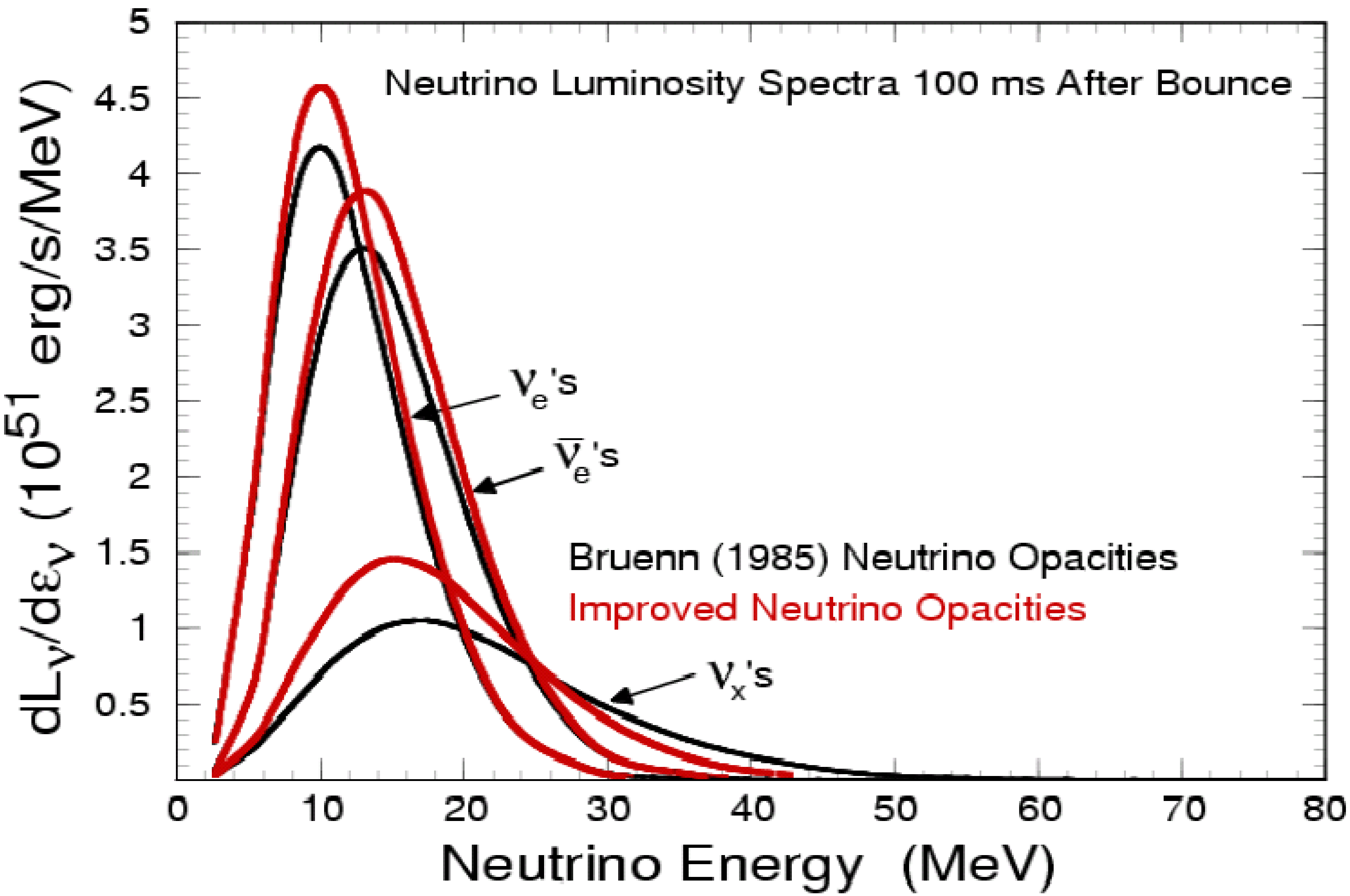


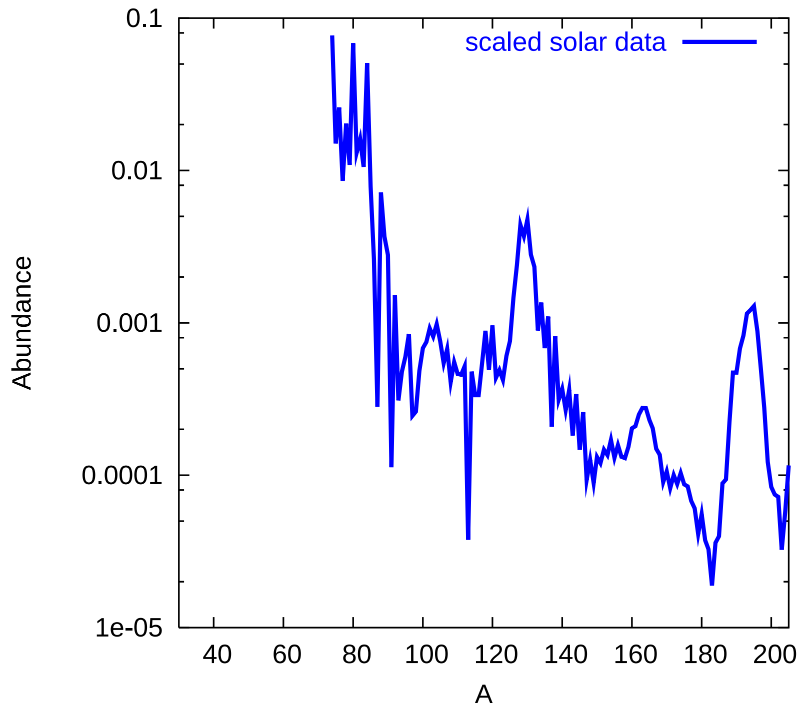
Let's try a network calculation

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

Takes as input temperature, density profiles ...

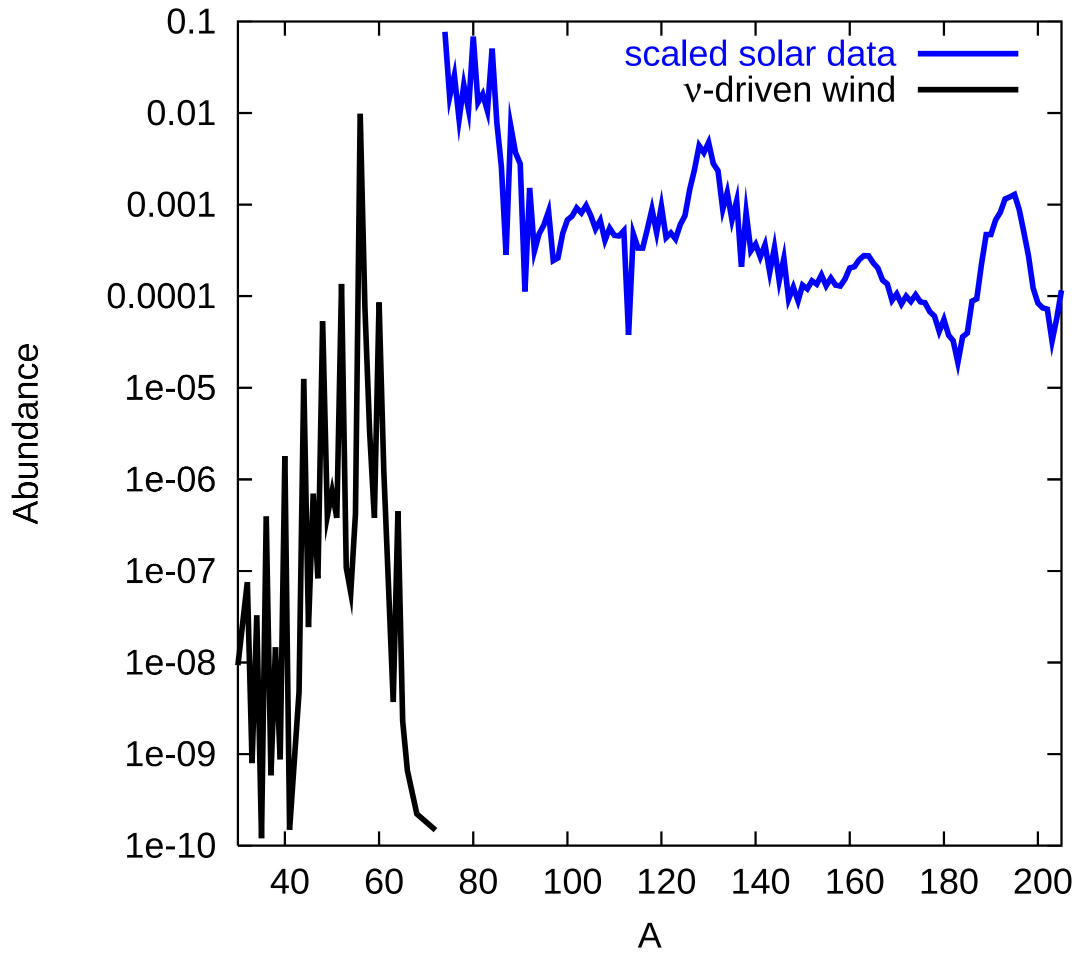
Outputs an abundance pattern ...

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?

We want: n,p $\longrightarrow \mathrm{He}$, n

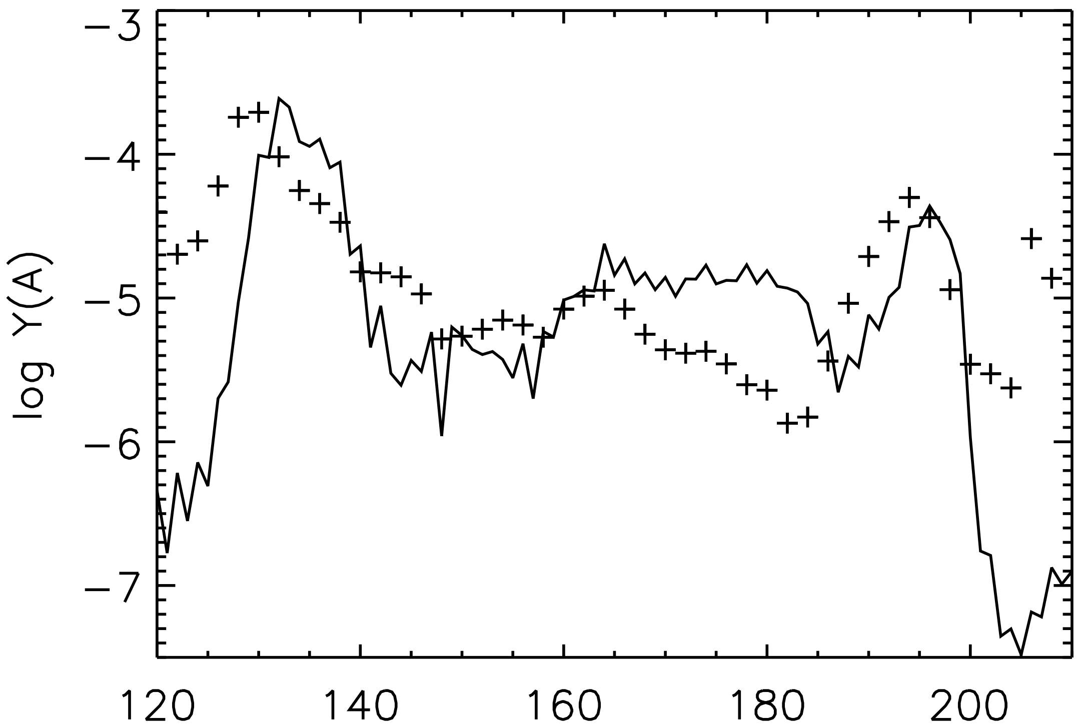
He, n $\longrightarrow$ Ni, n

Ni, n $\longrightarrow$ uranium

but neutrons got turned into protons in the He stage

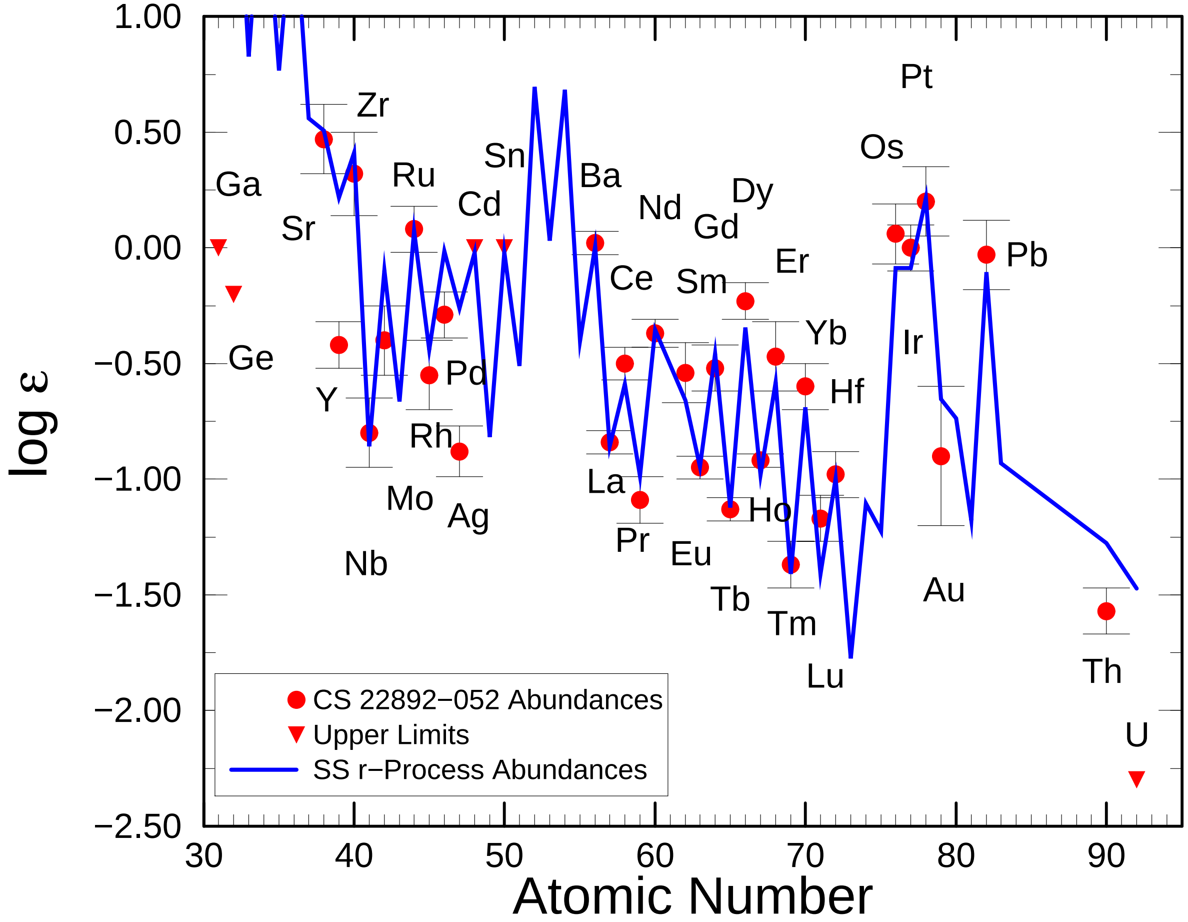
How do we fix it?

Try improvements in the model for the wind . . .



Better but finely tuned . . .

Fine tuning is not consistent with halo star data



What about neutron star-neutron star mergers or neutron star-black hole mergers?

Picture of a merger in neutrinos

- Neutron star and black hole spiral in
- Create an accretion disk around a black hole

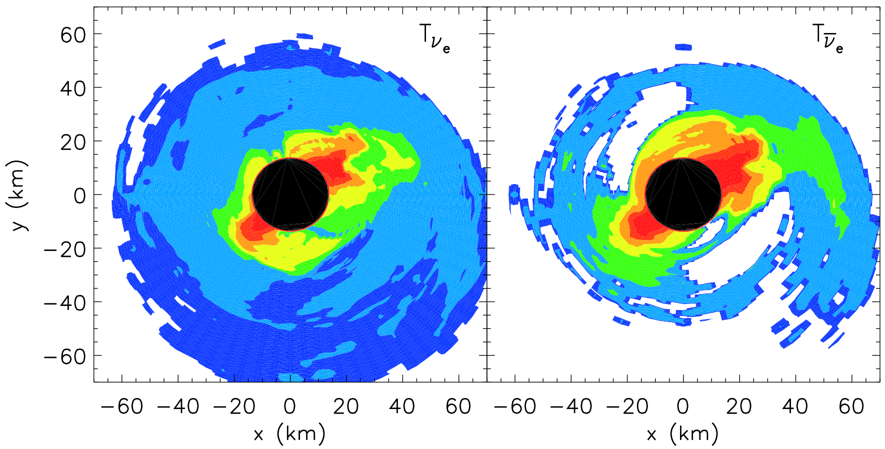
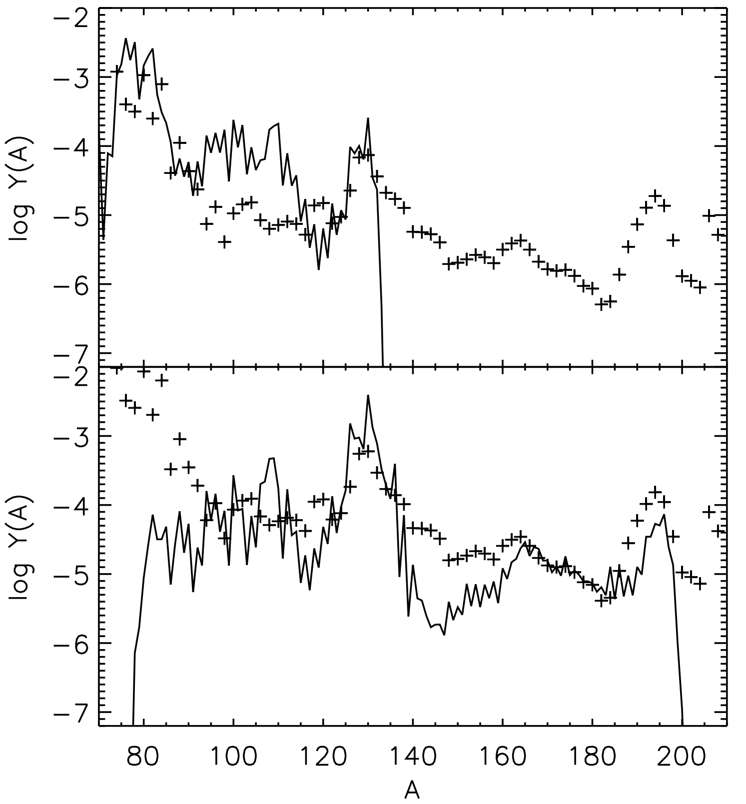


figure from Caballero et al 2009

The electron antineutrinos have higher temperature than the neutrinos.

Mergers very consistently produce a r-process

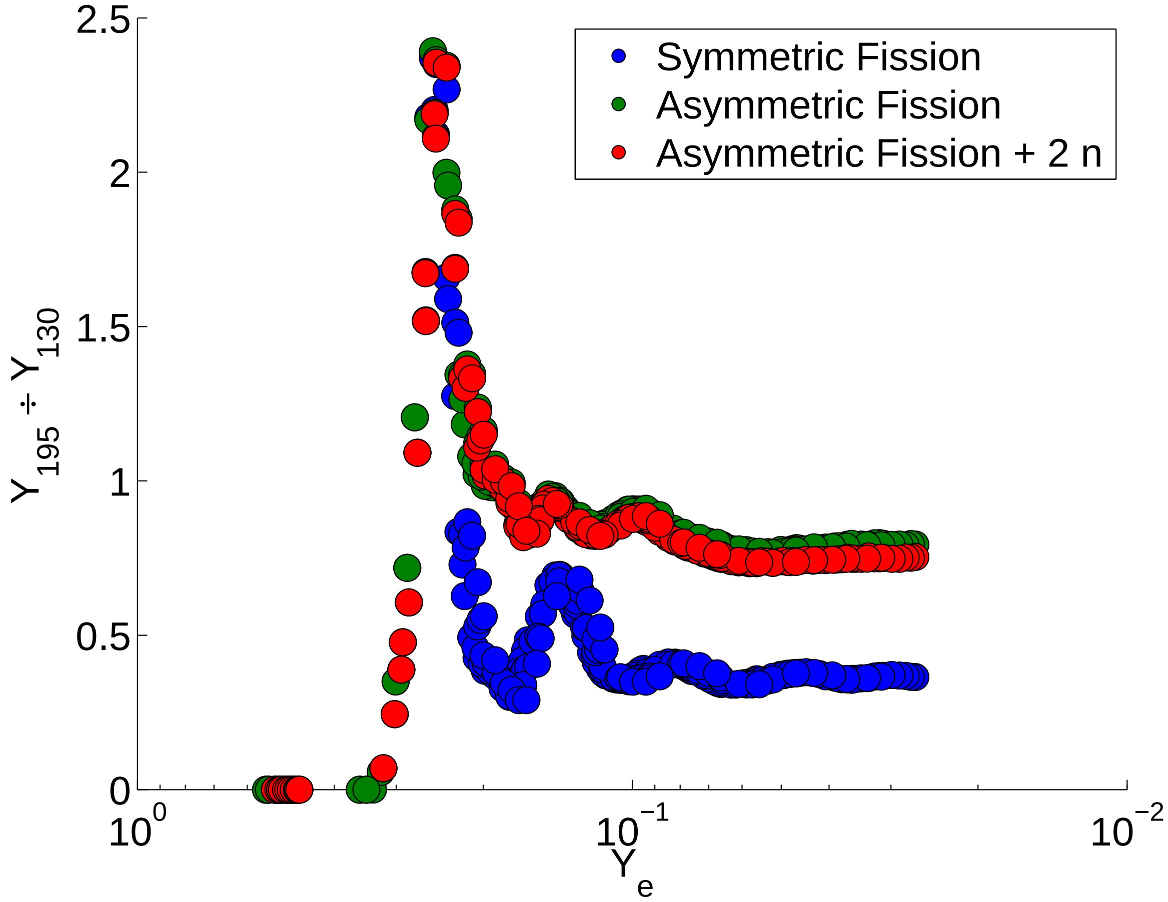


But, this doesn't explain how the elements got into the halo stars

What type of environment the data the best?

Similar pattern in old halo stars suggests fission cycling . . .

Fission cycling requires an *extremely* neutron rich environment.



Not found in current models of supernovae or neutron star mergers.

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20 March 2008

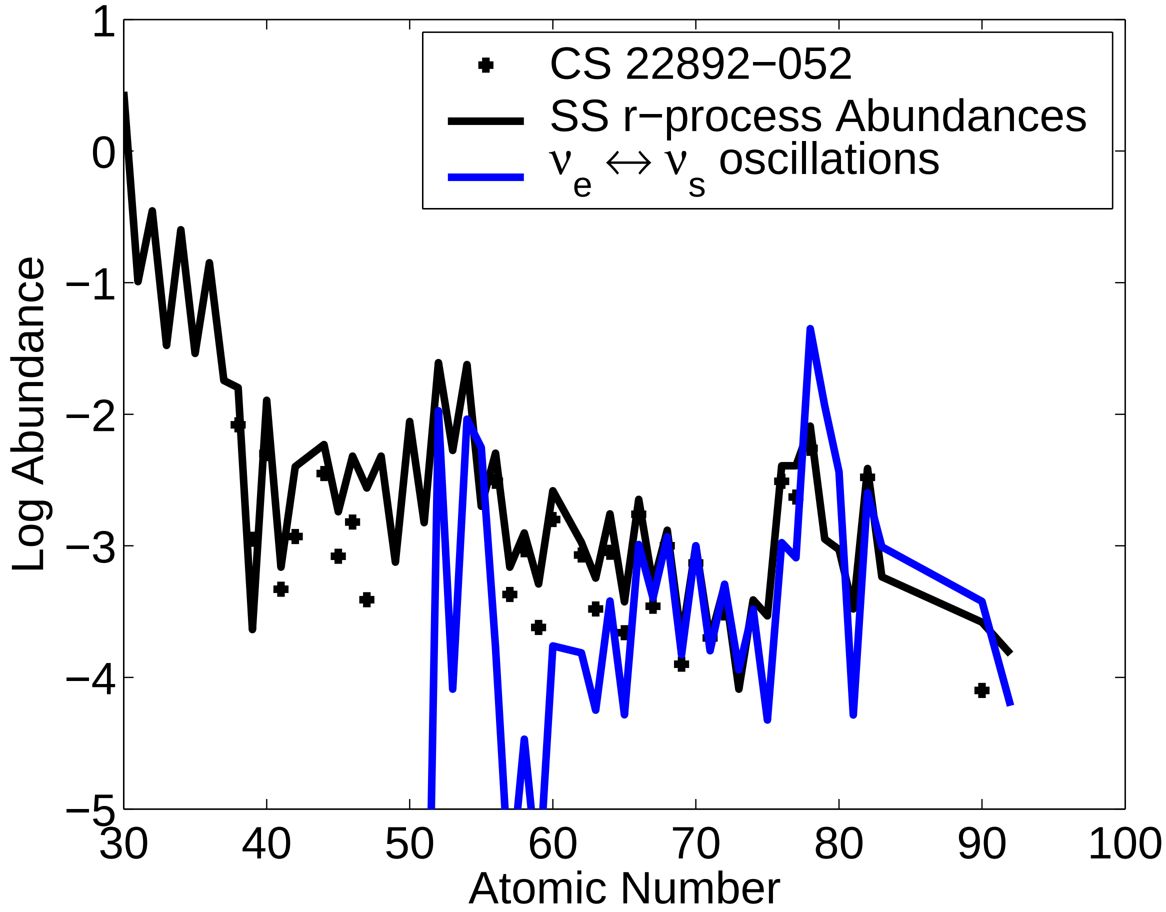
Heavyweight Contender

Supernova explosions at the ends of stars' lives produce most of the elements heavier than iron. But theorists have had trouble cooking up models of supernovae that make the heaviest elements in their observed abundances. A theoretical study in the March *Physical Review C* shows that a process involving fission--nuclei falling apart--could fit into the complicated story of heavy element synthesis. The new model is

Punchstock

J. Beun et al "Fission Cycling in a Supernova r-process", Phys. Rev **C77** 035804 (2008)

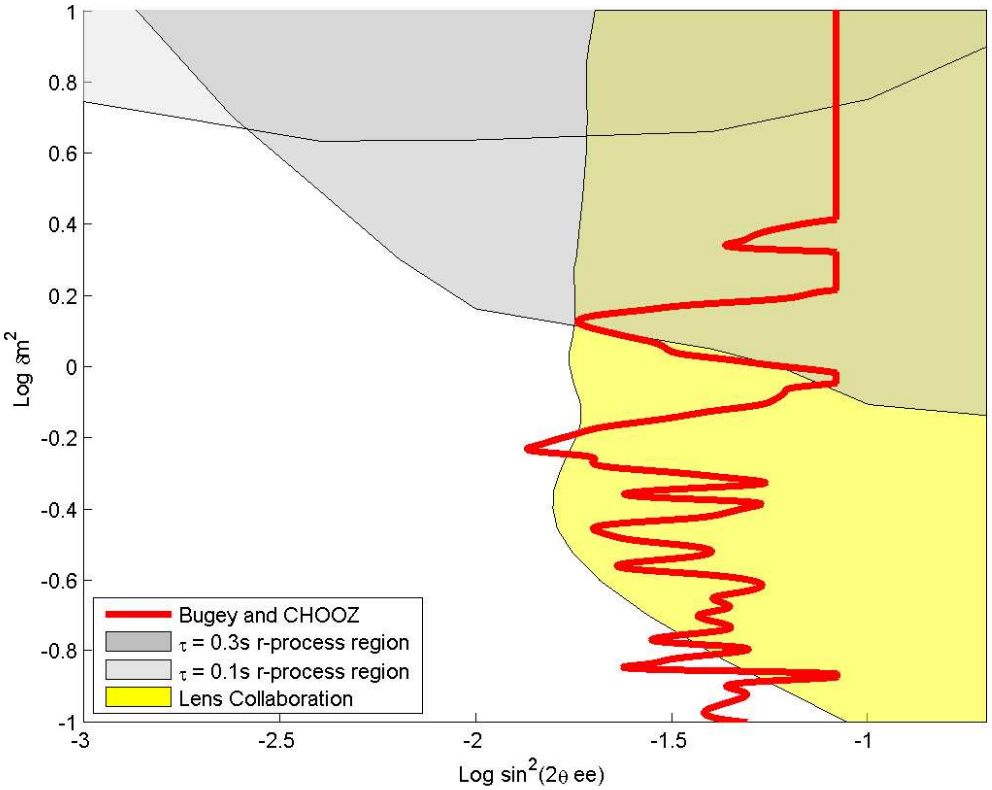
Let's try it . . .



Get robust results without fine tuning . . .

How to make such a neutron rich environment?

Oscillations with sterile neutrinos $\nu_e \leftrightarrow \nu_s$.



Conclusions

- We still don't know where uranium is made
- Data is suggestive of core collapse supernovae
- But theory calcuations don't quite work
- Compact object mergers make lots of uranium
- But its hard then to explain the halo star data
- Or we could go beyond the standard model and consider new particles
- Stay tuned ...