Supernova Nucleosynthesis: The Role of Neutrinos

Gail McLaughlin

North Carolina State University

Question: How do neutrino oscillations, sterile neutrinos and ambient conditions impact the nucleosynthesis in extreme astrophysical environments such as supernova and gamma ray bursts?

The R-process

One of the major unsolved problems in nuclear astrophysics is where the rapid neutron capture elements (e.g. Uranium, Thorium) are made. In particular, are they made in supernovae?

A short history:

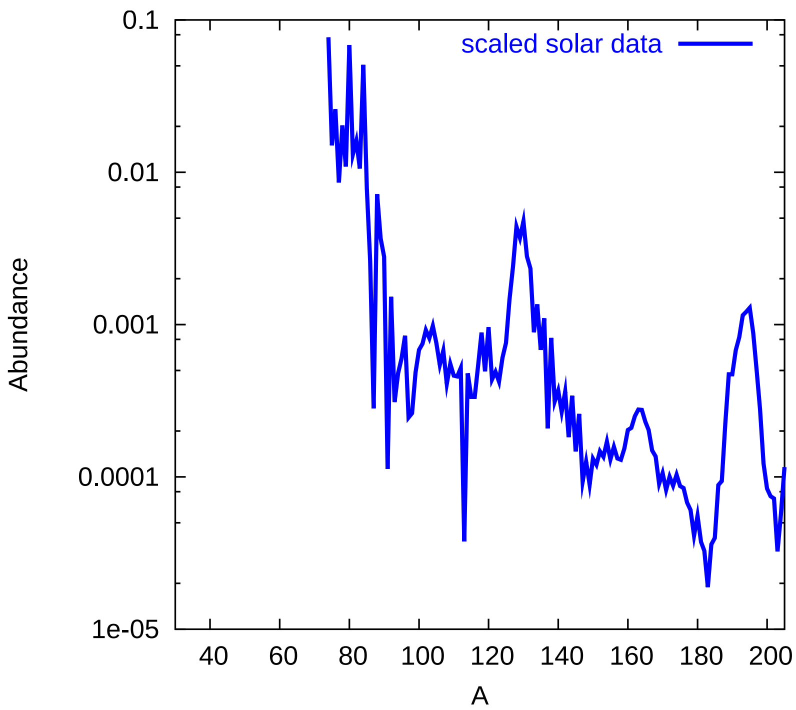
- 1957 - It was understood that half the heavy elements were made by rapid neutron capture
- 1990's Calculations of r-process nucleosynthesis were done in supernovae and these elements were produced in a primary process

  Meyer et al 1992, Woosley et al 1994,Takahashi et al 1994
- late 90's more physics was included and the calculations began to fail

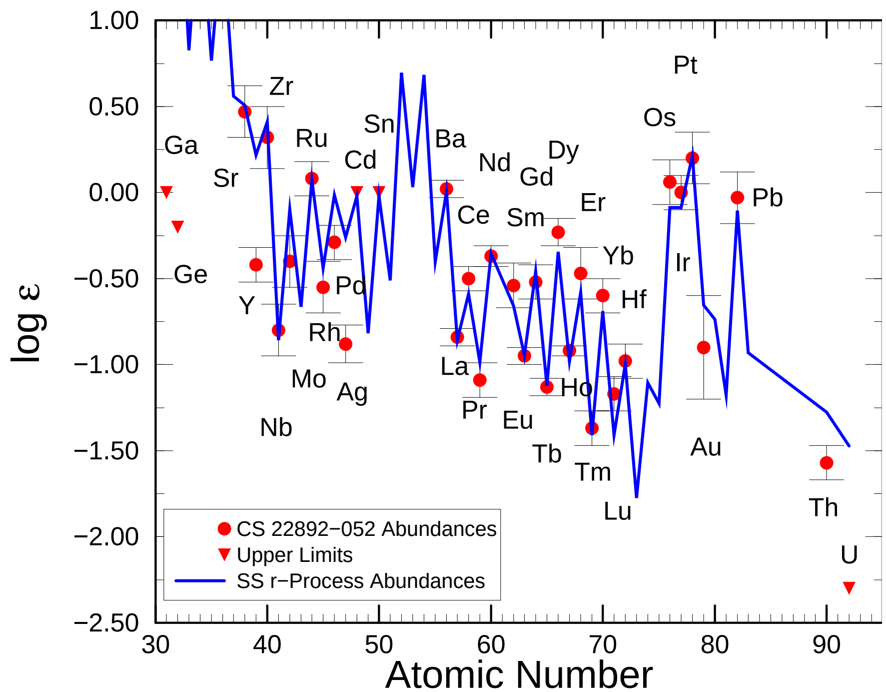
But... data suggests that supernova are a good site.

The r-process

These are plots of the measured abundances of r-process elements.

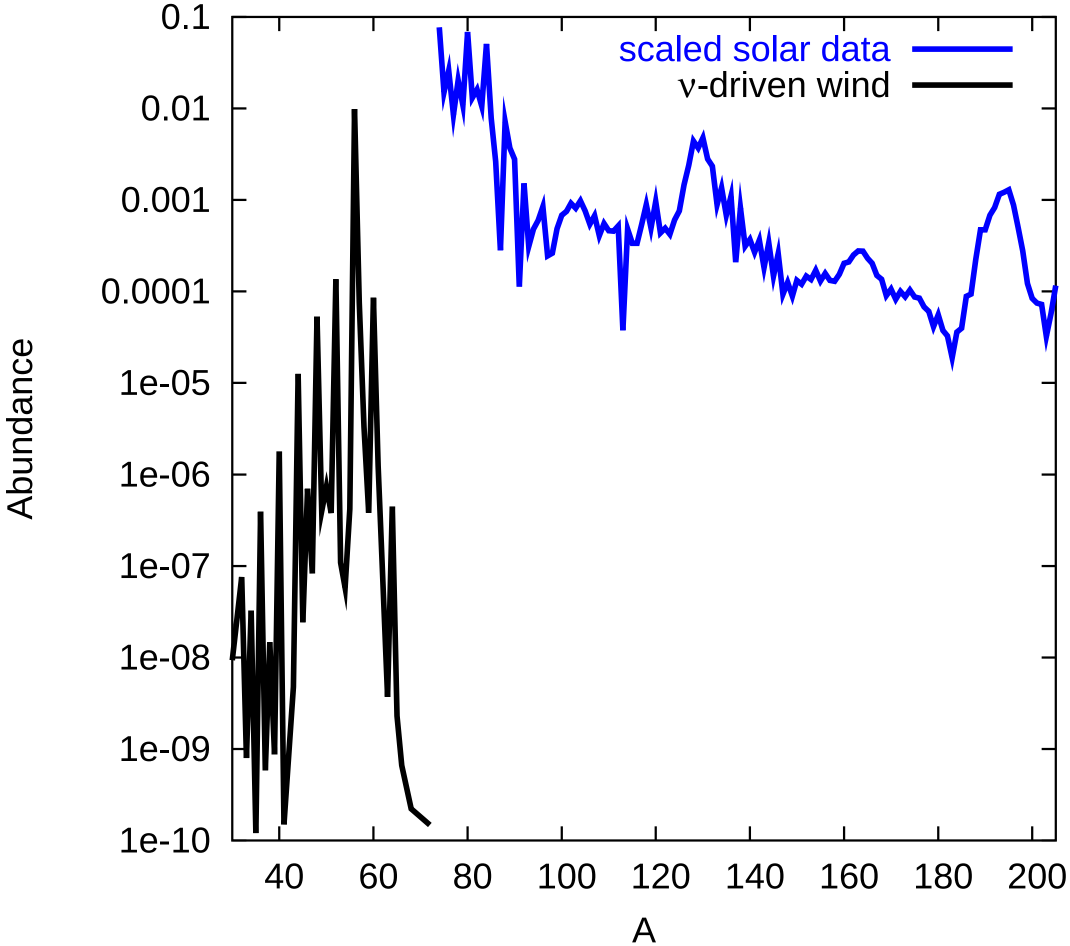


Abundance vs. Mass Number, Solar system



Abundance vs. Atomic Number, from Cowan and Sneden 2004

Sample Calculation:



What happened?

All the left over neutrons get turned into protons by

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

And the protons become incorporated into $^4\mathrm{He}$

It's a disaster for the r-process!

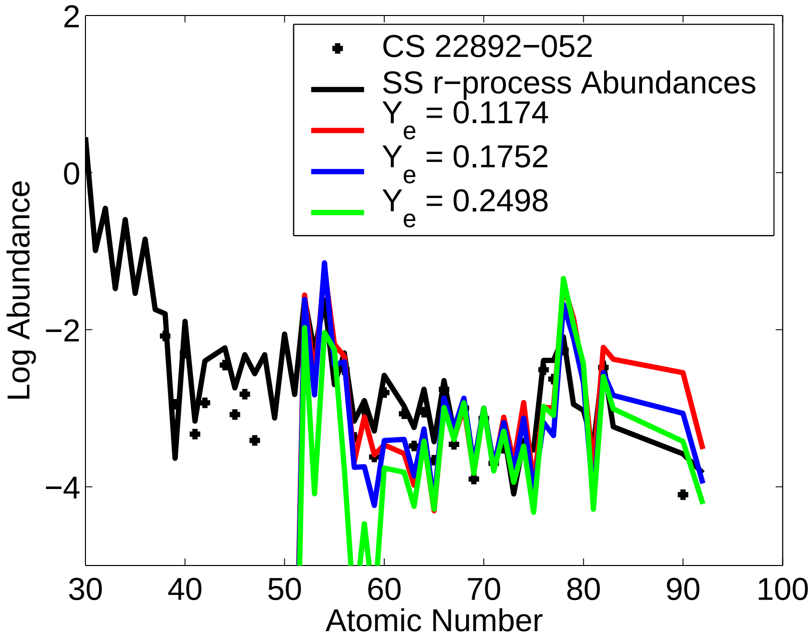
What would fix the problem?

Suggestions....

- Create a faster outflow Hoffman et al 1997
- Create more entropy Takahashi et al 1994
- A larger ratio of neutrons to protons

These are not free parameters. The first two have been shown to reproduce the full spectrum of r-process elements, lets try the last one.

Increasing the n/p ratio: Fission Cycling



This works well, but only produces the heavier r-process elements Beun et al 2006

Fission Cycling: Neutron capture builds elements that are so heavy they fission. The daughter products capture neutrons themselves, creating a cycle.

Data: Halo Star and Meteoritic

Both types of data suggest two separate types of events e.g. Argast et al

Event type (1) Operates on a core collapse supernova timescale and occurs early in the evolution of the Galaxy (just like supernova) and makes the heavier elements

Event type (2) Operates on a neutron star merger timescale and may begin later in the evolution of the Galaxy. Makes primarily the lighter r-process elements

It looks like increasing the neutron to proton ratio in SN works well as event type (1).

But how can you increase n/p?

Neutrinos set the neutron-to-proton ratio

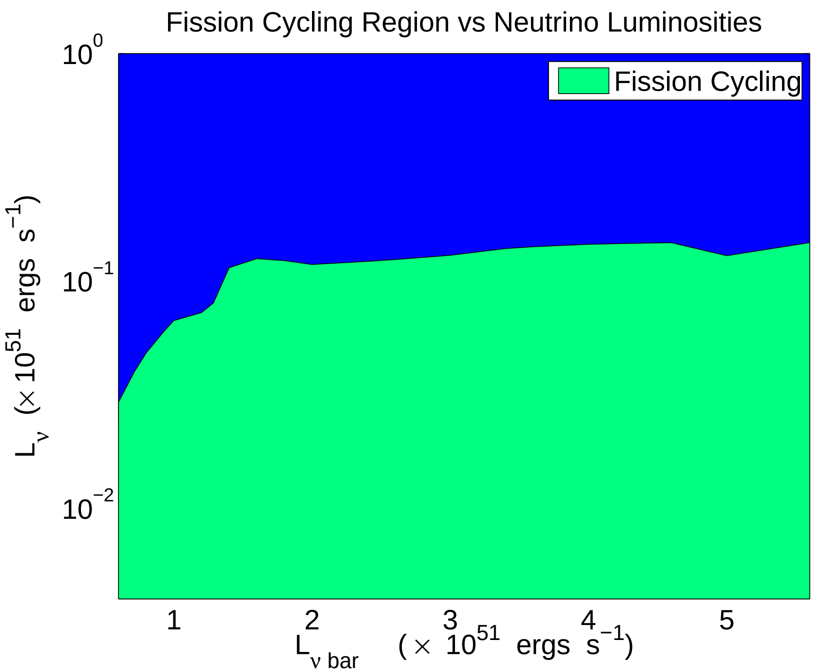
Just above the Neutrino Sphere is the ν-driven wind.

- νs impart energy to small amounts of material on the core
- The ν flux is so high the n/p ratio is set by
- neutrino capture $\nu_e + n \rightarrow p + e^-$
- and antineutrino capture $\bar{\nu}_e + p \rightarrow n + e^+$

If ν_e's have less energy than the $\bar{\nu}_e$s the there will be more neutrons than protons.

Lowering the Flux of Electron Neutrinos

Thought Experiment: reduce the flux of ν_es



Plot shows where fission cycling is occurring

Beun et al 2006

But, if you are going to reduce the flux of neutrinos, its better to do it at a point in the outflow after energy deposition but before element synthesis. Sounds like a resonance...

What about Neutrino Oscillations?

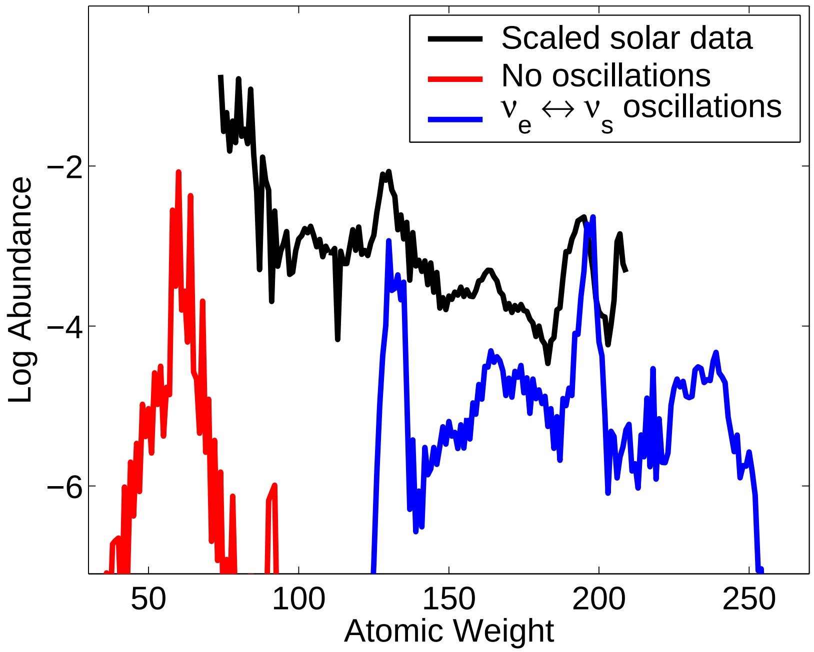
Active-Active neutrino oscillations typically drive material around the proto-neutron star less neutron rich because $\langle E_{\nu_e} \rangle < \langle E_{\nu_\mu} \rangle = \langle E_{\nu_\tau} \rangle$

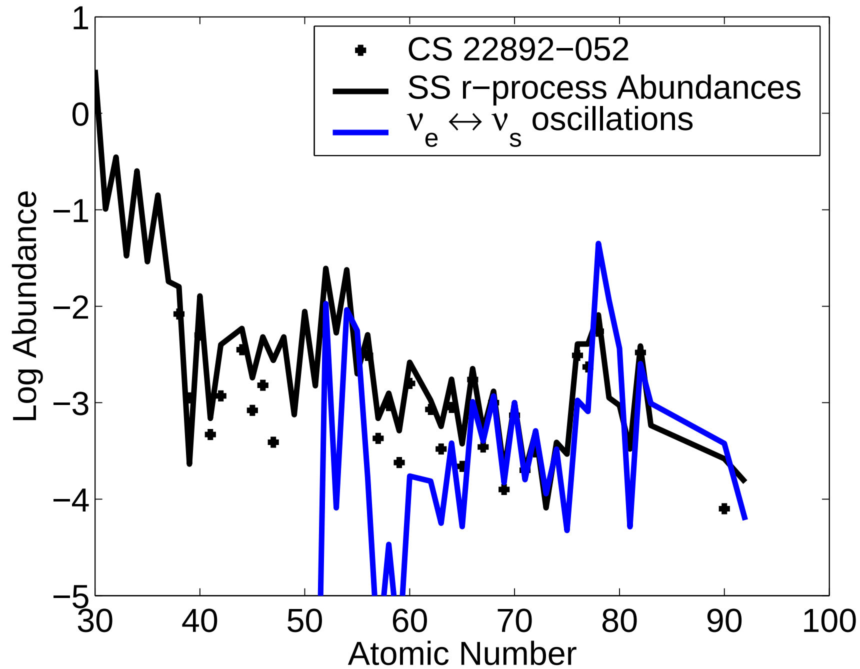
Qian et al 1993

But, what about sterile neutrinos? Motivation for additional 'sterile' species of neutrino comes from LSND.

What would an extra neutrino mean for the r-process?

Sterile Neutrinos

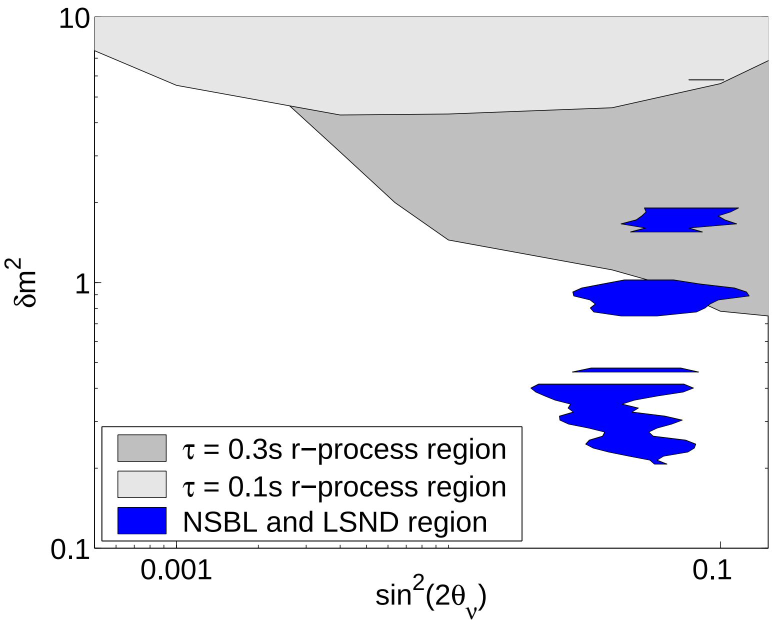




$\delta \mathrm{m}^2 = 2\,\mathrm{eV}^2$, $\sin^2 2\theta = 10^{-2}$, $\mathsf{s} = 100$, $\tau = 0.3\,\mathrm{s}$ Beun et al 2006

Conclusion of this exercise: To solve the problem of r-process in supernova, it looks like one can use a sterile neutrino or find something that does what a sterile neutrino does (reduce the n/p ratio at the right time).

r-Process/ MiniBooNE Sterile Neutrino



Gray: r-process ν_s

Blue: from Sorel et al.

Cautionary notes: (1) Could be more than one species of sterile neutrino, (2) neutrino background terms should be included in calculation

see work by Fetter et al 2004, Fuller and Patel 2000, Yuksel and Balantekin 2005, Duan and Fuller 2006

(3) ambient conditions (entropy, timescale) may evolve as hydrodynamic models become more mature.

But if there is no sterile neutrino, then what?

Other options for the r-process

- New beyond the Standard Model physics will be important
- New physics will come from the hydrodynamics community

  Groups such as Janka's, Mezzacappa's, Burrows', e.g. SASI instability, Acoustic Heating

- Neutron Star Mergers Ruffert and Janka, Thielemann
- Gamma Ray Bursts

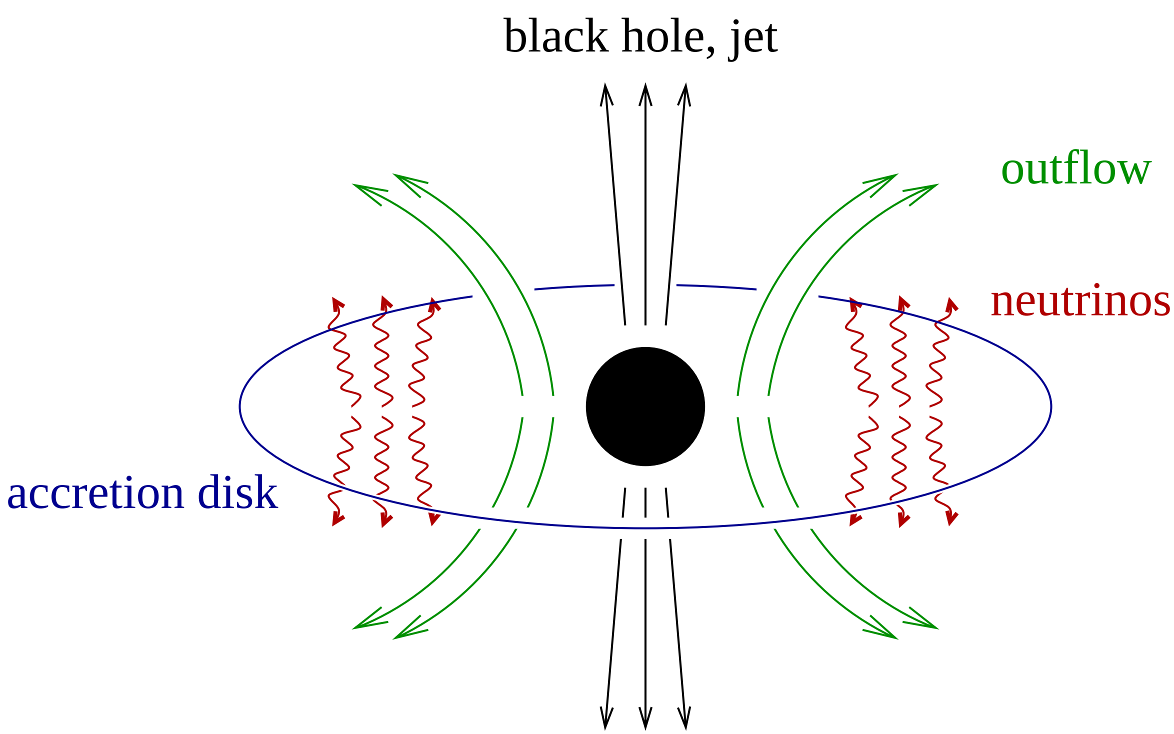
We don't know much about the nucleosynthesis in gamma ray bursts, because we are only starting to understand these objects

Long duration bursts are thought to come from an "exotic" type of supernova, that creates a black hole surrounded by an accretion disk

collapsar model: Woosley and MacFadyen

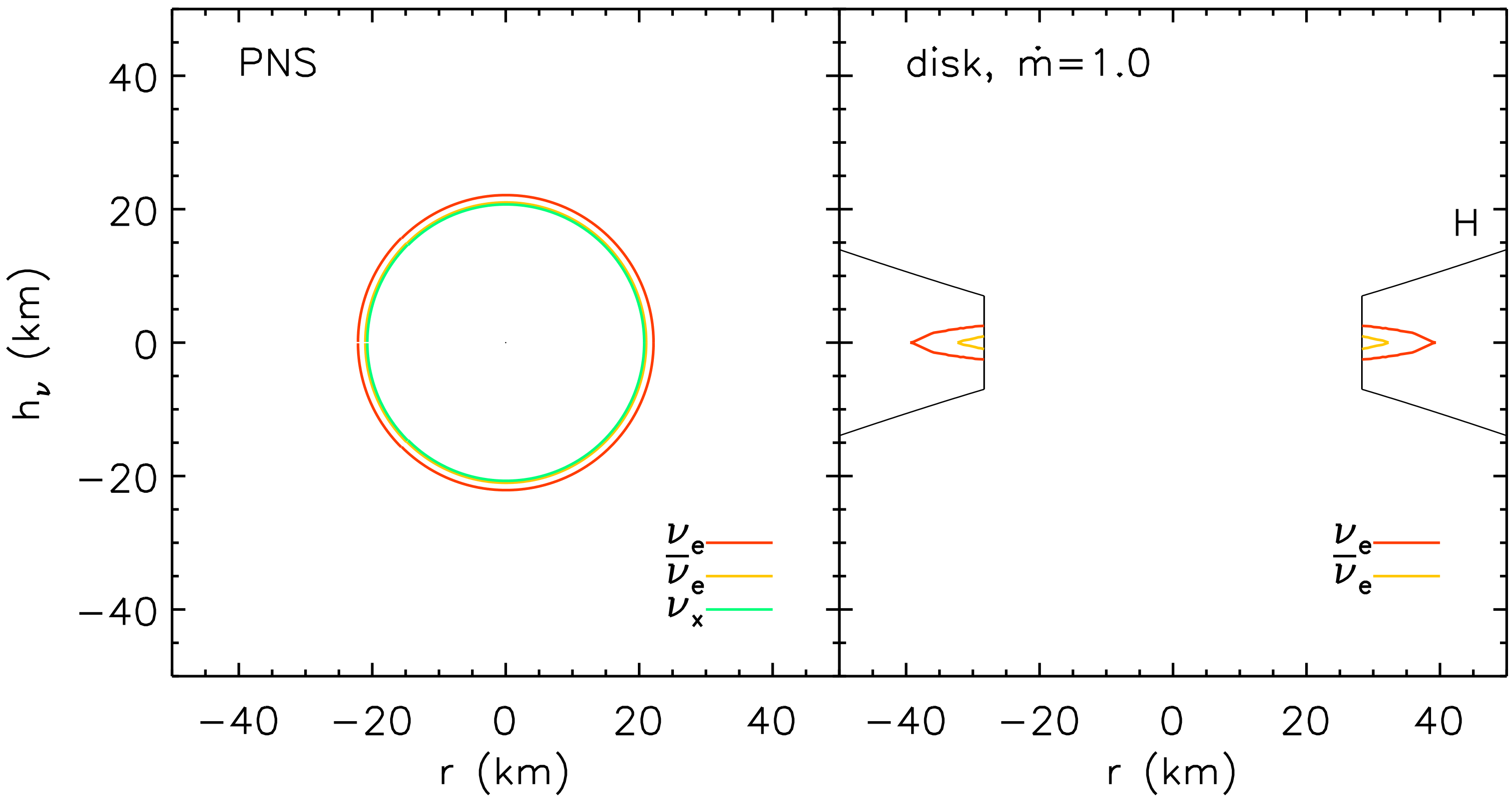
Black Hole Accretion Disks

These exotic supernovae may form accretion disks surrounding black holes, instead of the canonical proto-neutron star. Some of these may have jets which form GRBs.



- material spirals to toward the black hole
- it is ejected by the disk, nucleosynthesis

Comparison of proto-neutron star and accretion disk neutrino surfaces



In the disk electron neutrinos and antineutrinos have similar energies to the protoneutron star. Although few muon and tau neutrinos are produced unlike in the traditional supernova. Neutrinos in Disks: Surman at el 2003, upcoming work by Hungerford, Cardall

Nucleosynthesis depends on the neutrinos

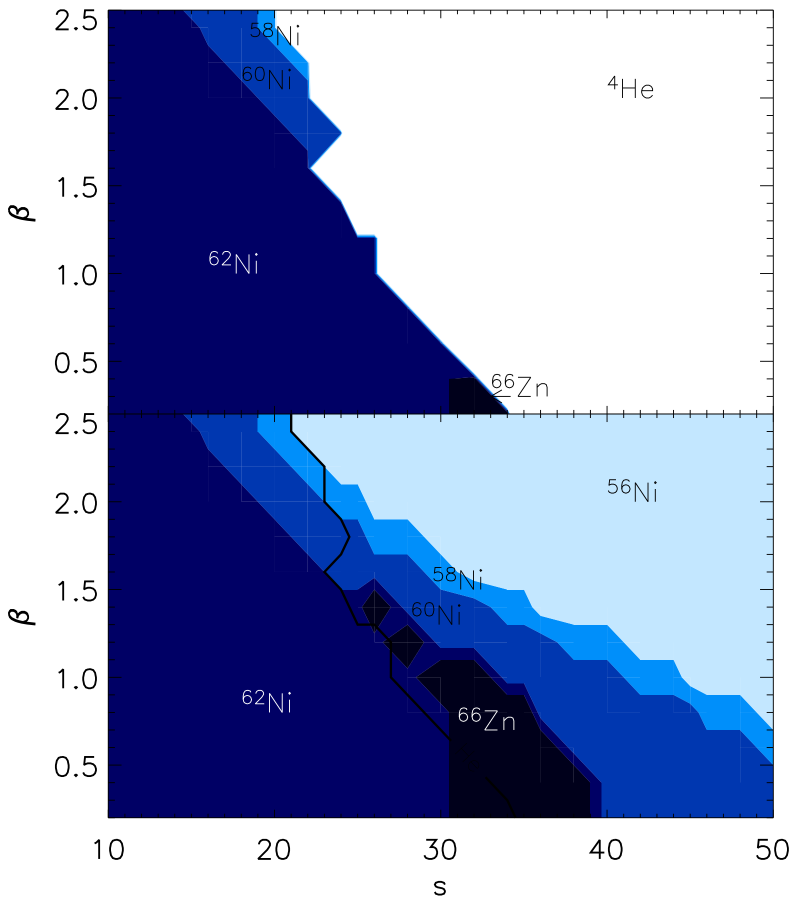
Again $\nu_e + n \longrightarrow p + e^-$ and $\bar{\nu}_e + p \longrightarrow n + e^-$ are important in determining the neutron-to-proton ratio.

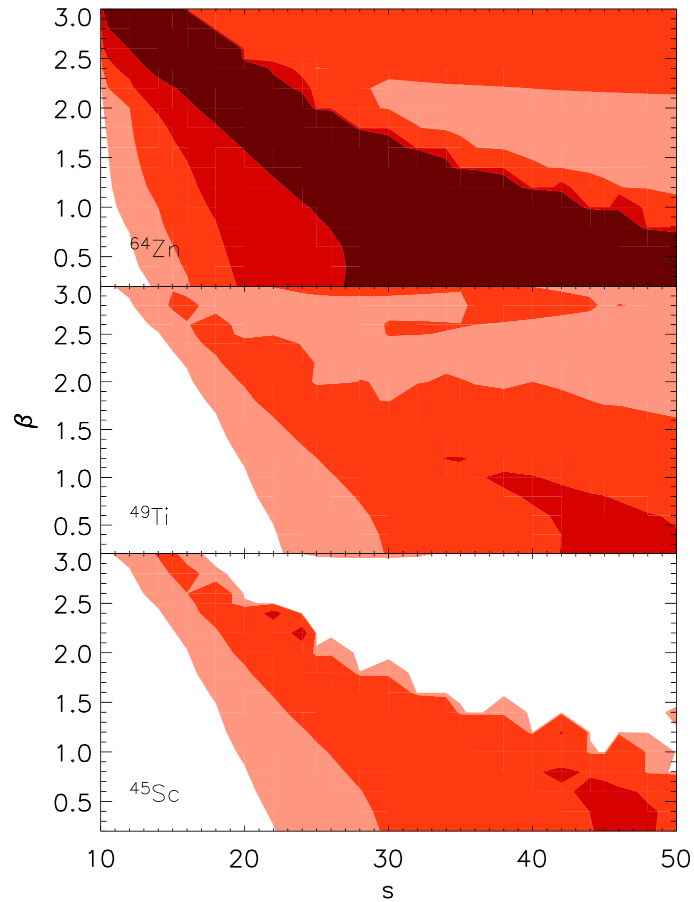
High accretion rate disks $\longrightarrow$ hotter $\longrightarrow$ more neutrinos $\longrightarrow$ strong influence from νs

Low accretion rate disks $\longrightarrow$ cooler,$\longrightarrow$ less neutrinos $\longrightarrow$ moderate of the neutrinos

Nucleosynthesis from slowly accreting disks:

$$\dot{M} = 0.1\, M_{\odot} /\, \mathrm{s}$$



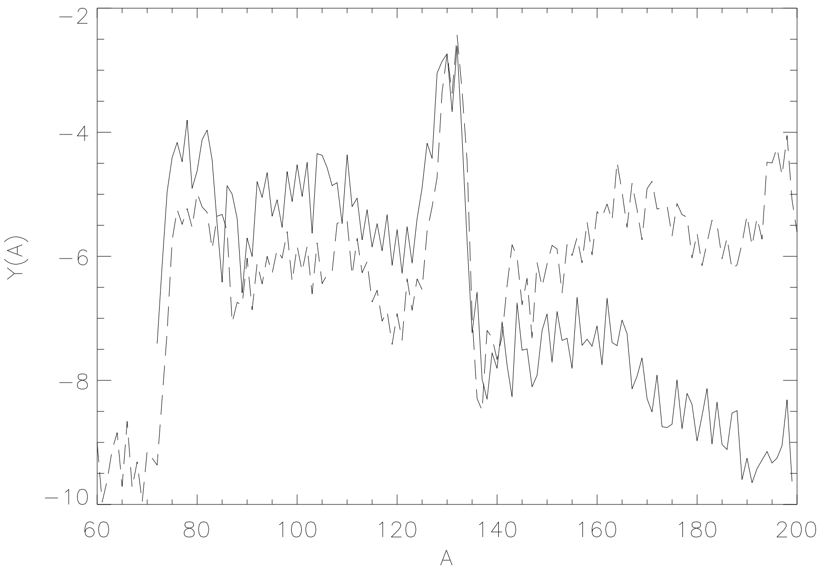


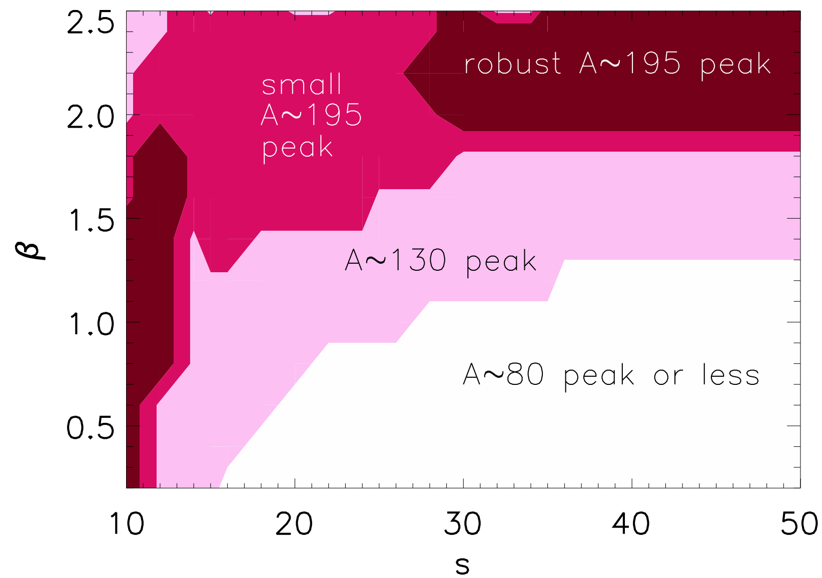
Maximum mass fraction (upper), *excluding Helium* (lower)

Produces lots of some elements that have had an unknown origin

Nucleosynthesis from high accretion rate disks:

$$\dot{M} = 10\, M_\odot / \, \mathrm{s}$$





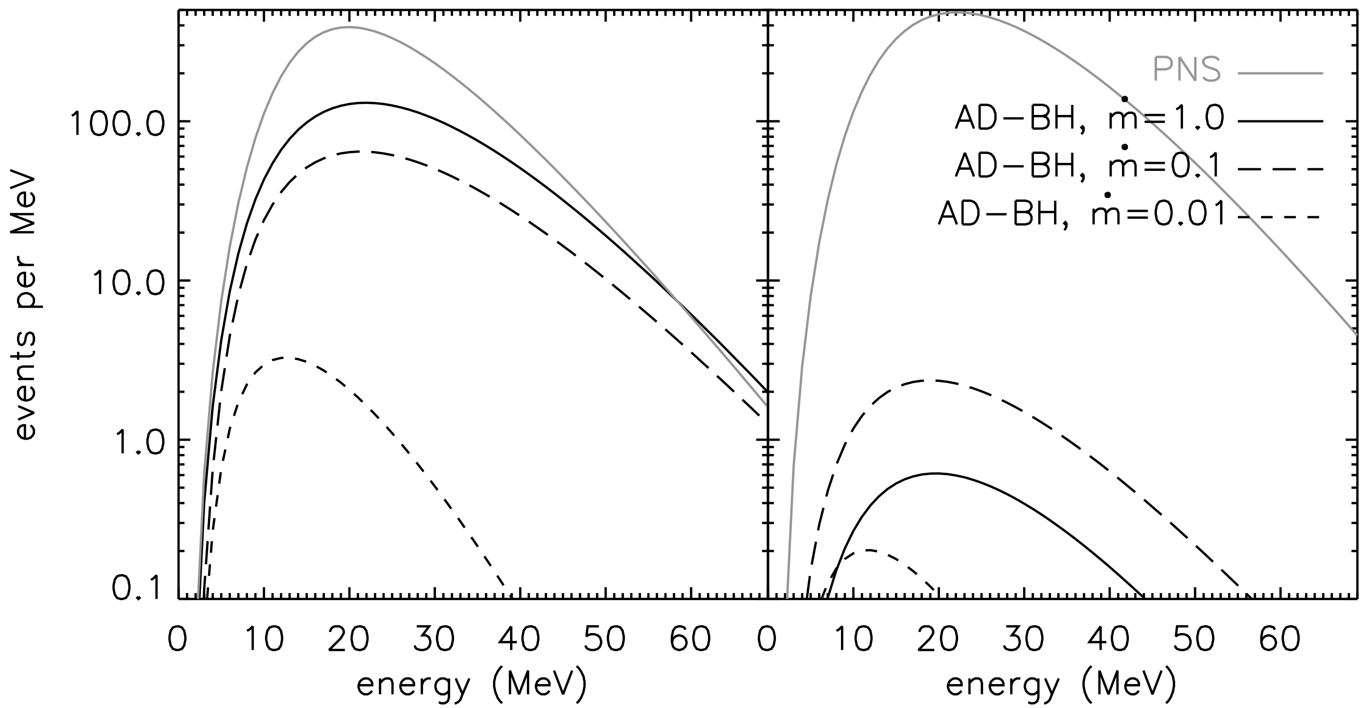
Makes primarily light r-process elements

r-process peaks

Perhaps rapidly accretion disks are a candidate for event type (2) which makes the light r-process: such disks may also be associated with neutrino star mergers.

Surman et al 2005

If a neutrino emitting accretion disk formed in the Galaxy, we may detect the neutrinos!



$\bar{\nu}_e + p$ events in SuperK for two oscillation scenarios and 3 accretion disks

Event rate must be scaled by $(M/M_\odot)$ where M is the amount of material processed by the disk $\rightarrow$ time the disk is in existence is important. McLaughlin and Surman 2006

Conclusions

- Making the r-process in supernovae is problematic
- sterile neutrinos will help
- or perhaps we need some other physics
- or new site, such as black-hole accretion disks
- Black hole accretion disks produce large neutrino fluxes
- which create an r-process
- and/or Nickel-56
- The neutrinos from a black hole accretion disk in the Galaxy may be observable
- Next time we see SN neutrinos, we should try to determine if they came from a traditional supernova or a disk

Rates in SuperKamiokande

In comparison with supernova (PNS), neutrinos arrive on a different timescale, and with a different NC to CC ratio

Rates:

- Regular supernova ~ 7000 events, 10 seconds
- Accretion Disk of $\dot{M} = 1 M/M_\odot$, 2800 events, 1 second
- Accretion Disk of $\dot{M} = 0.1 M/M_\odot$, 1400 events, 10 seconds
- Accretion Disk of $\dot{M} = 0.01 M/M_\odot$, 50 events, 100 seconds

Times and rates should be scaled by $M/M_\odot$ where M is the amount of material processed by the accretion disk.