The r-process of nucleosynthesis: overview of r-process sites

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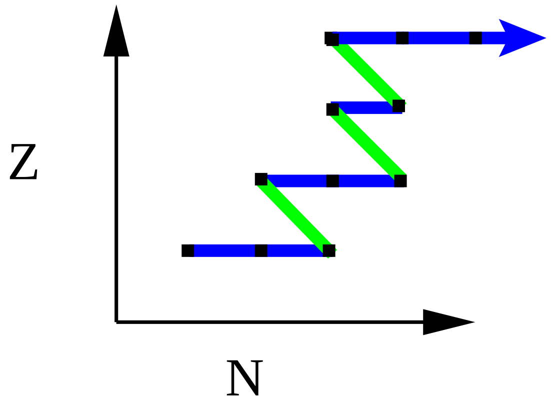
Possible astrophysical sites of the r-process

The r-process elements

e. g. Uranium-238 Z=92, N=146 → 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

Whats the most important criteria you are looking for?

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

How do you get neutrons?

How do you get neutrons?

1. They already exist and just need to be liberated
    - in nuclei
    - in neutron stars
2. You make them through the weak interactions, i.e. conversion of protons into neutrons

How do you judge a site?

How do you judge a site?

- plenty of neutrons
- can populate halo stars
- how often does it occur
- does it match the abundance pattern

Of course, there could be more than one site...

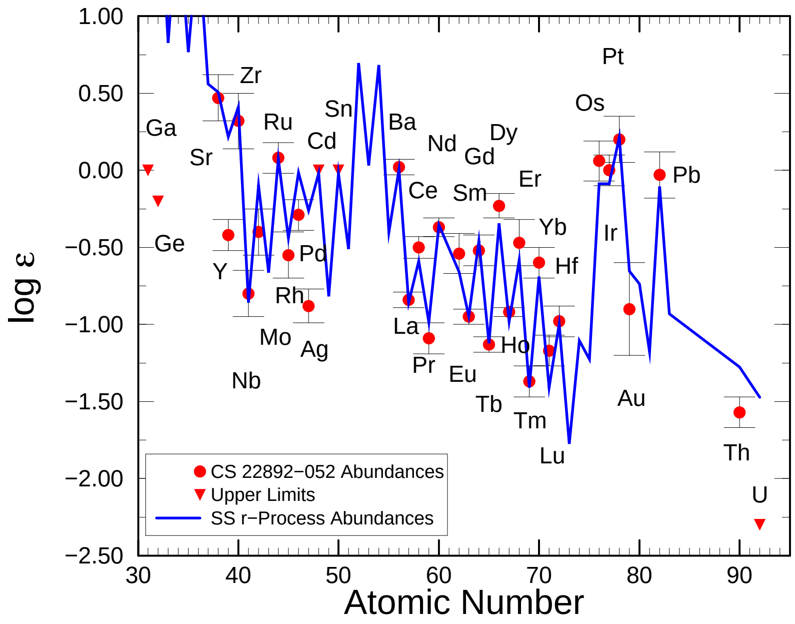
Observational r-process data

Observational Halo Stars:

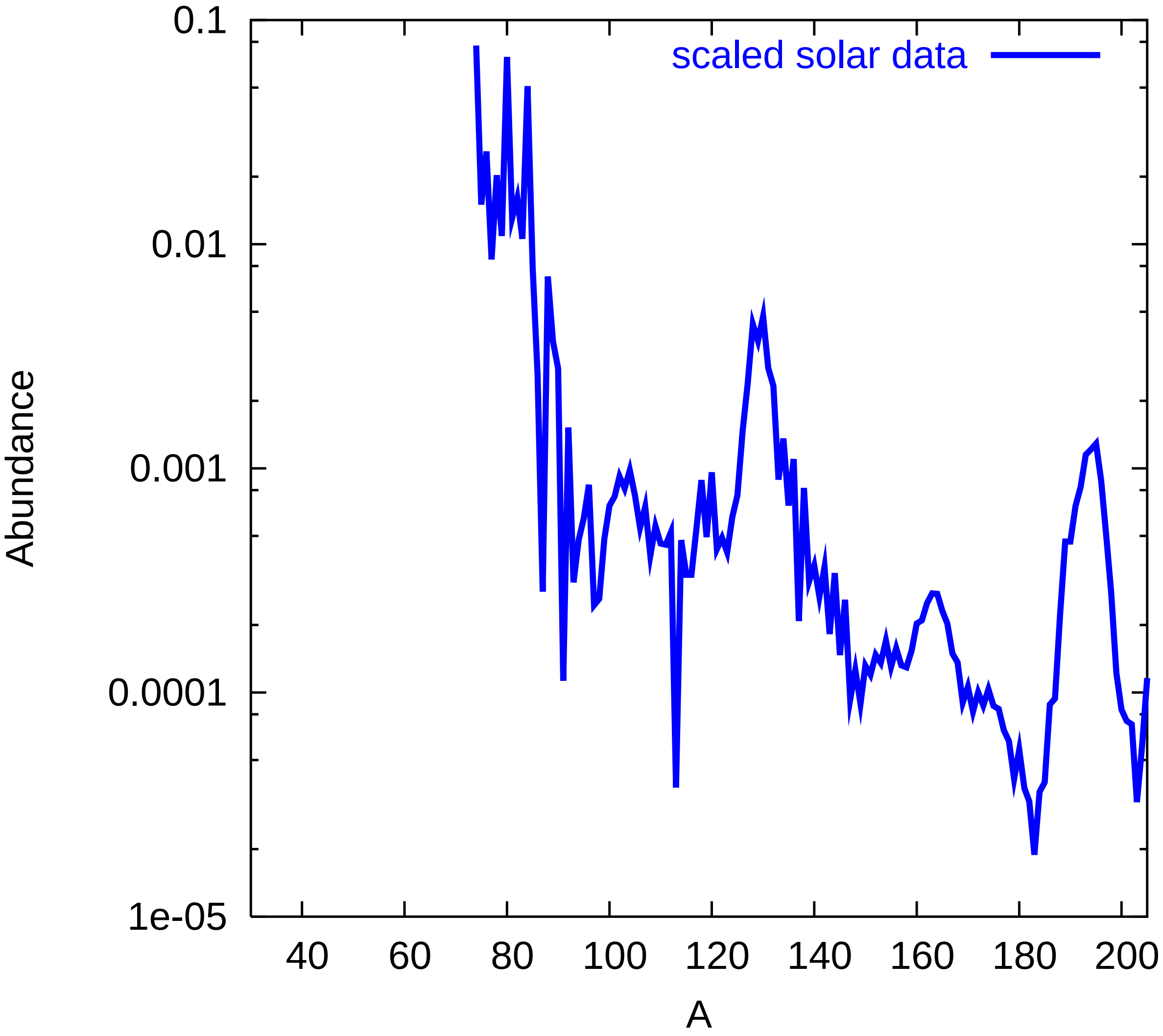
two r-process sites

Figure from Cowan and Sneden (2004)

main r-process and weak r-process or multiple weak



Solar Abundances



What would be your first guess?

- 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
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Compact object mergers

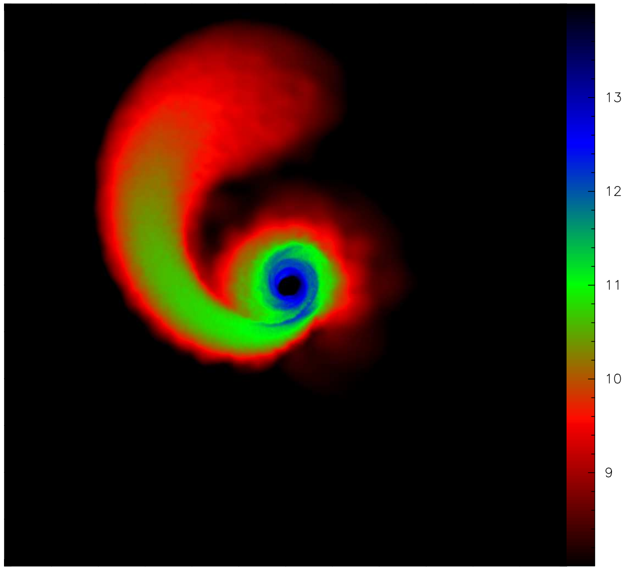


figure from Korobkin 2012

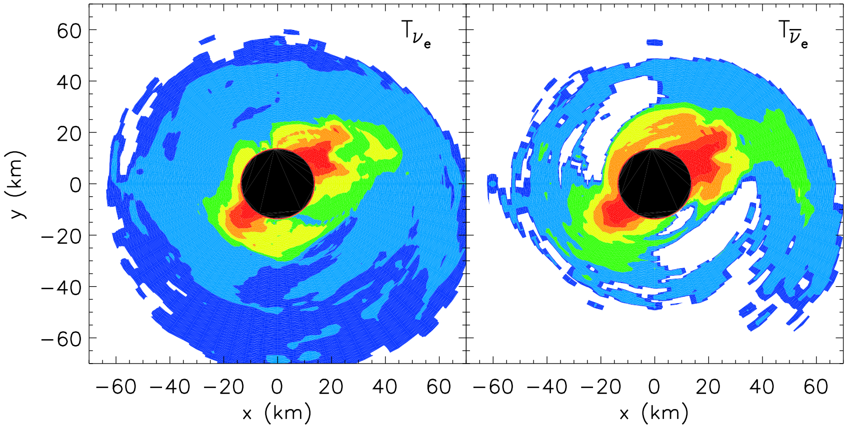


figure from Surman 2008

Mergers have many signals

- Gravitation wave signal, primary target of next generation detectors
- Prime candidate for short duration gamma ray bursts
- Huge emission of neutrinos, but hard to detect
- optical signal powered by radioactive decay of newly formed elements
- chemical evolution, elements produced in mergers, later observed in stars

Interesting from a nucleosynthetic point of view, but also for many other reasons

Evolution of neutron star merger

- Insprial driven by gravitational wave emission
- Until last moments of inspiral, neutron stars may essentially be treated as cold neutron stars
- merger results in formation of a shocked extremely rapidly spinning hypermassive neutron star
- later formation of a disk around a black hole
- Models under development!

Types of mass ejection

- Dynamical ejection
  - material tidally ejected from tails
  - matter ejected through collisional region
- Winds
  - accretion disk
  - hypermassive neutron star
- Outflows from viscous heating

What happens to all this ejecta from a nucleosynthesis perspective?

Electron Fraction

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

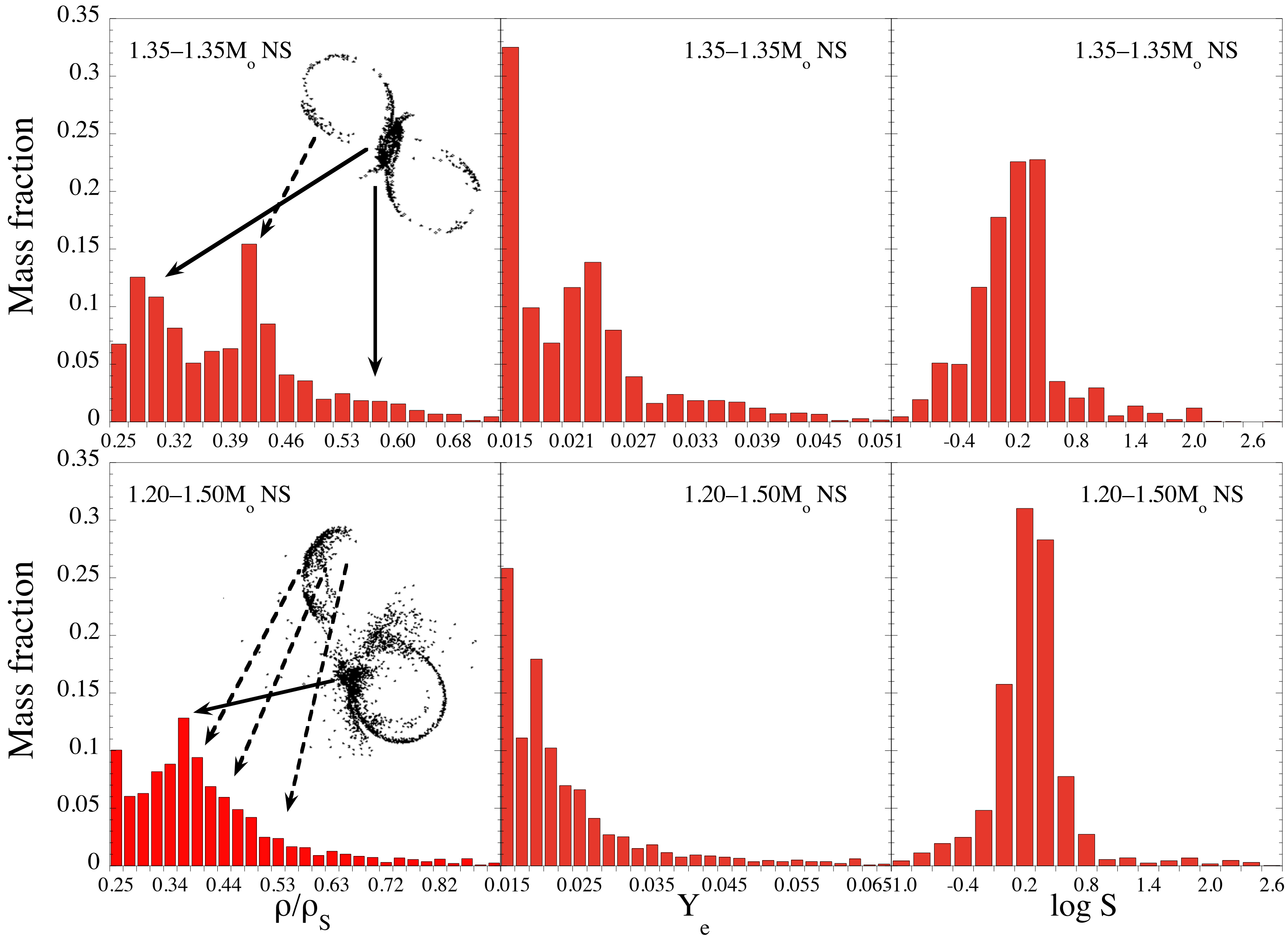
$$Y_e = \frac{n}{p+n} \tag{1}$$

Want this to be low.

neutron stars start with low Y_e.

Of the types of outflow we have considered (dynamical, wind, viscous heating driven), which has lowest Y_e?

Dynamically ejected material from newtonian calculation



Goriely et al 2011

Y_e is so low you could have fission cycling!

Why fission cycling is a good thing

Basic observation

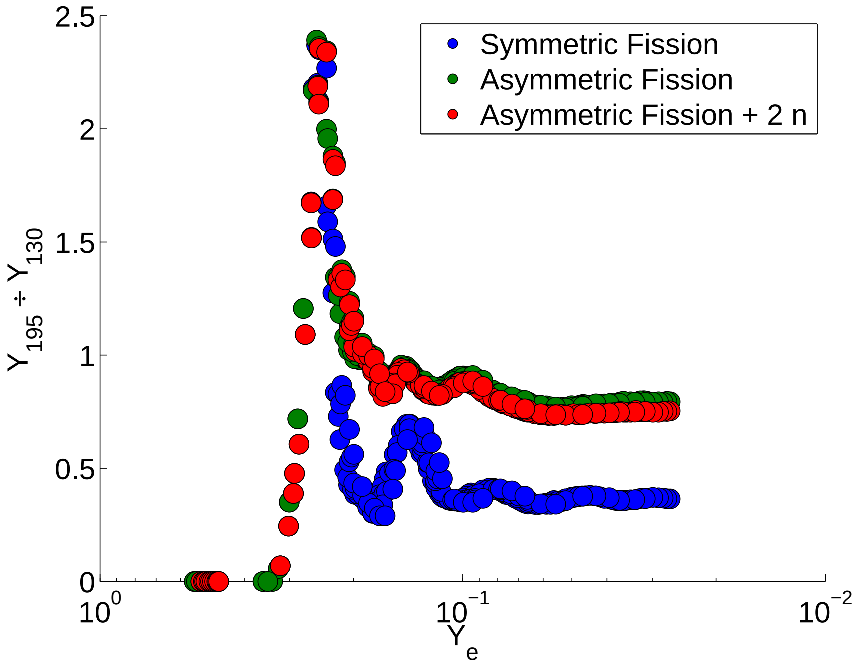
Halo star data suggest that abundance pattern in 2nd & 3rd peak region is "robust". Abundance pattern below 2nd peak shows variations between different stars.

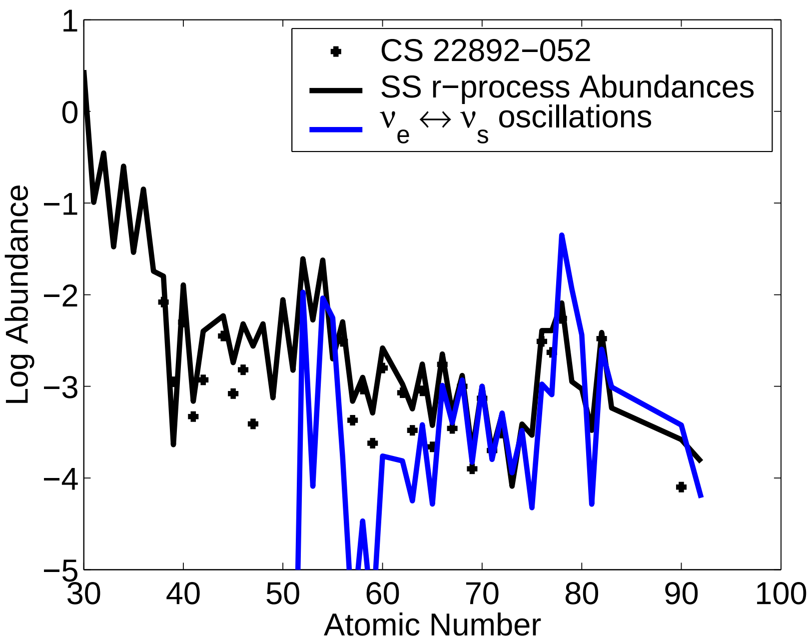
Need robust mechanism for populating 2nd & 3rd peaks.

Fission Cycling?

Note: Data show rare earth/3rd peak stable, few data in 2nd peak region. Generally assumed that 2nd/3rd also stable.

Fission Cycling in the r-process



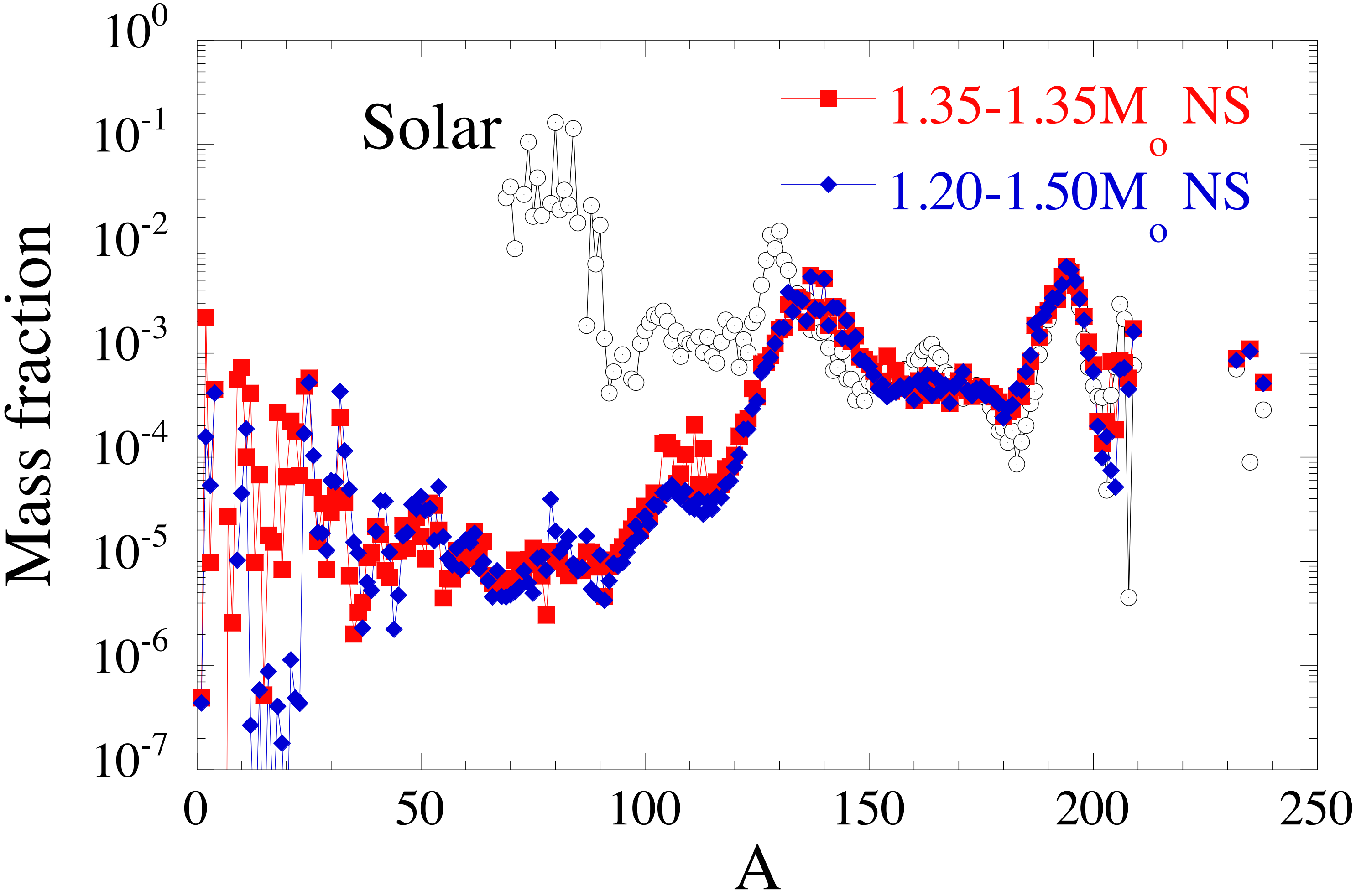


abundance in 3rd/2nd peak as a fct of decreasing Y_e

Very little data on the relevant fission rates and daughter products

Beun, GCM et al 2006, Beun, GCM et al 2008

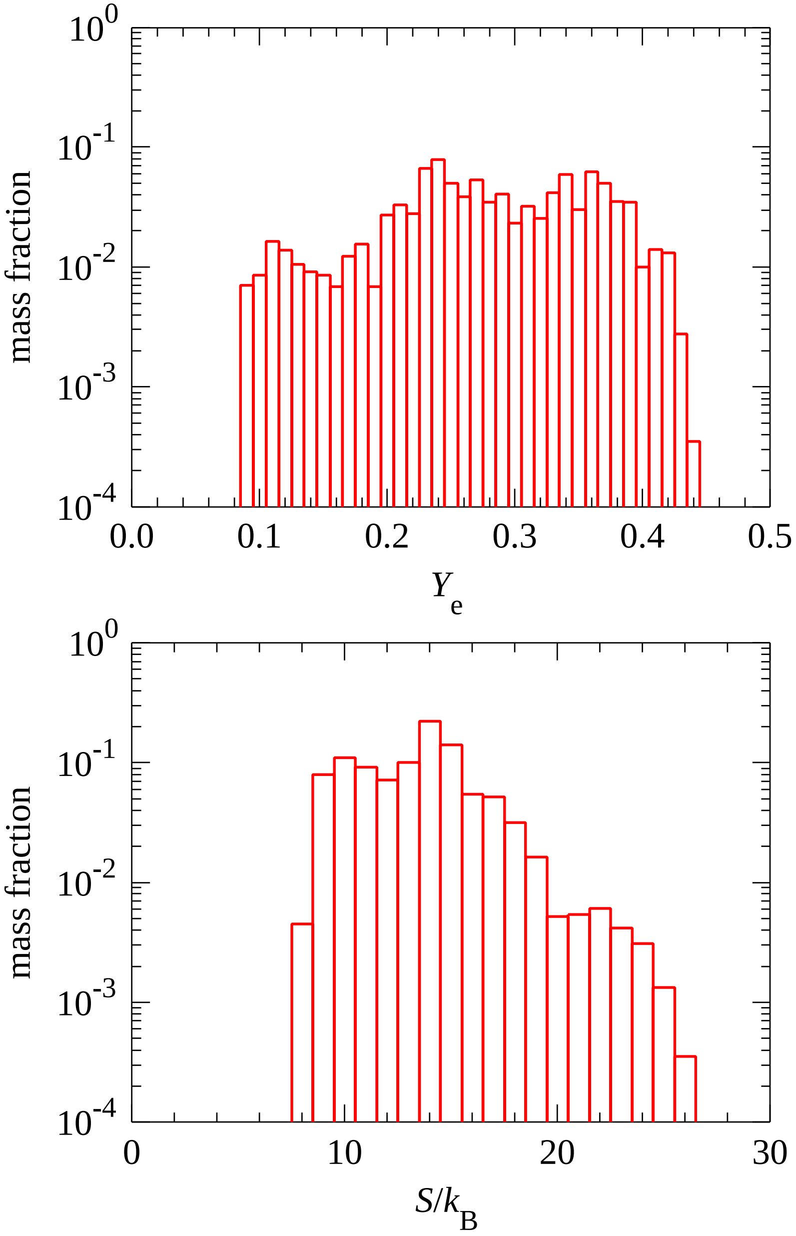
Dynamically Ejected Material from Newtonian Calculation



Goriely et al 2011

Where is the evidence that there is fission cycling going on?

What about calculations where neutrinos are included?



What has happened to the Y_e? Why?

Fig. from Wanajo et al 2014

How much stuff?

Estimates depend on the hydrodynamics & thermodynamics & neutrino transport. Recent estimates:

- winds: $\sim 2 \times 10^{-3} M_\odot$ Wanajo and Janka 2011
- tidal tail ejection: 10^{-2} to 10^{-3} $M_\odot$ Goriely et al 2011, Korobkin et al 2012

Need to make $\sim 10^{-2} M_\odot$ to account for all r-process material in Galaxy.

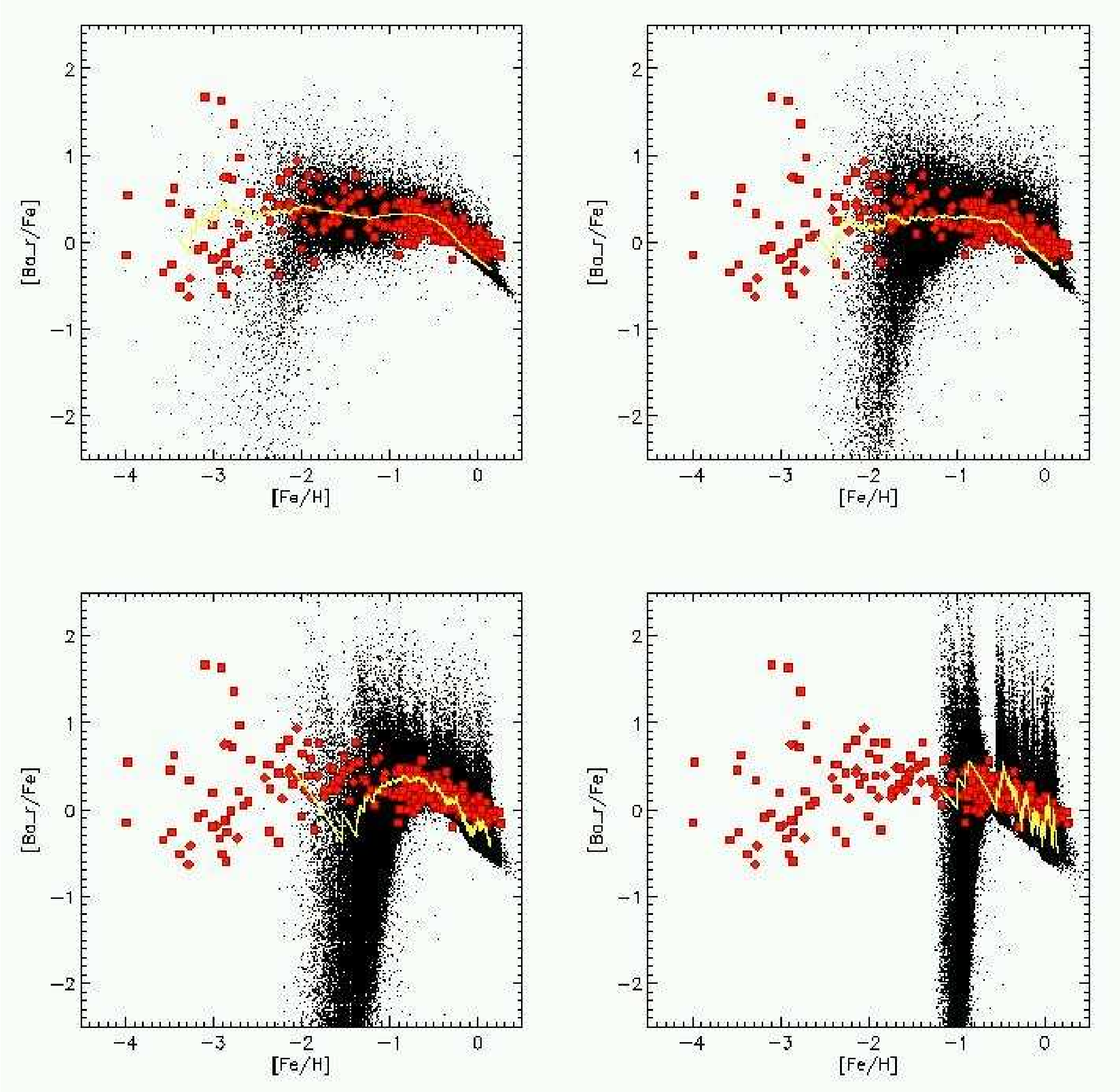
Does it match the halo stars?

Unresolved issues:

Mergers evolve slowly, $\tau_{\mathrm{coales}} \approx 10^{6-8}$ years. Not clear how to populate halo stars

Mergers are rare, suggesting there should be more scatter in the amount of r-process material in halo stars than is seen.

Does it match the halo stars?



Argast et al 2004

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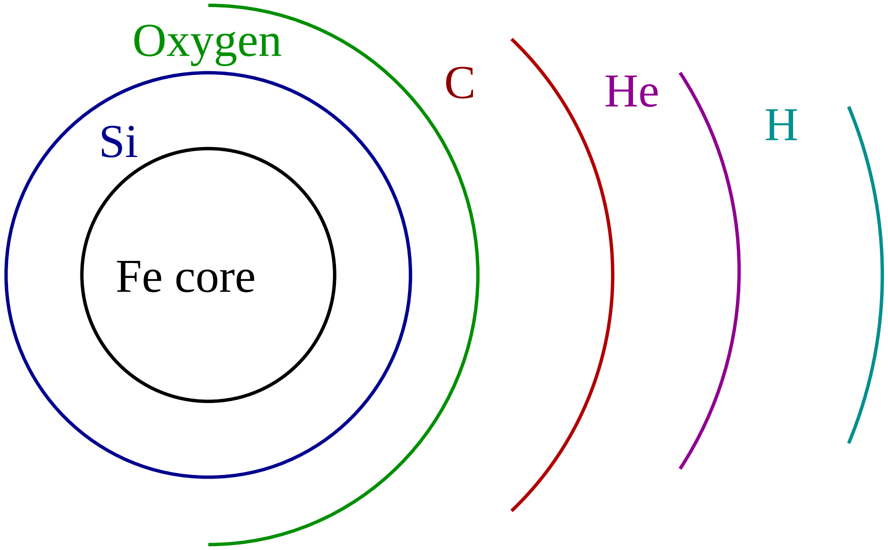
Core Collapse Supernovae

end of the life of a massive star



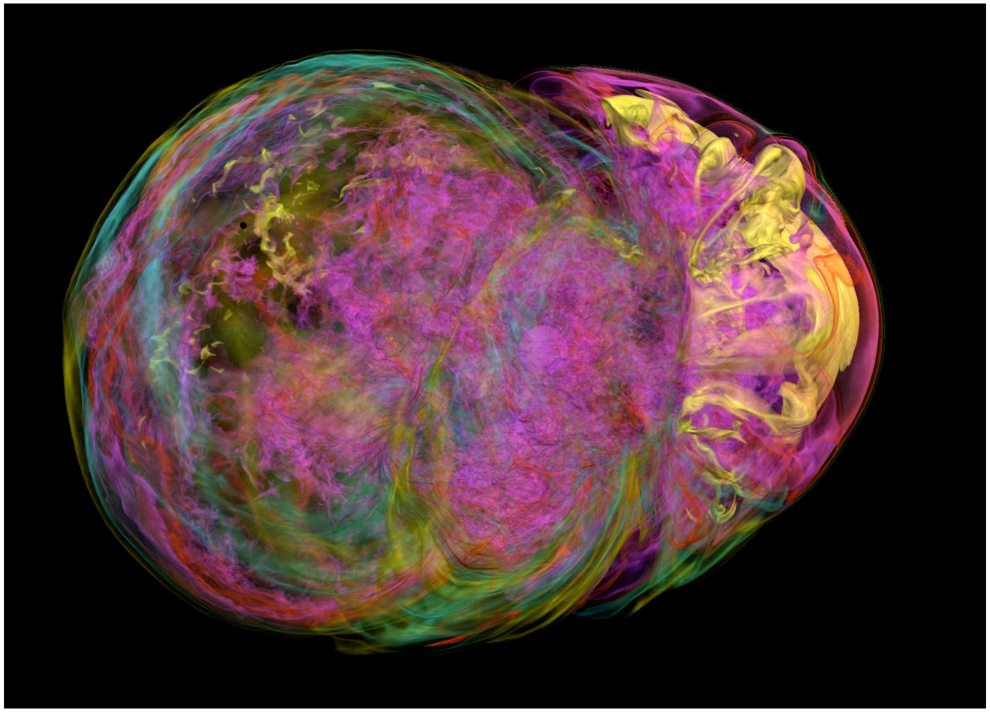
- core unstable

  $M_{core} \sim 1.5 M_{sun}$

- collapse to nuclear density
- core bounce
- shock produced
- shock stalls
- neutrinos diffuse out of core, may energize shock

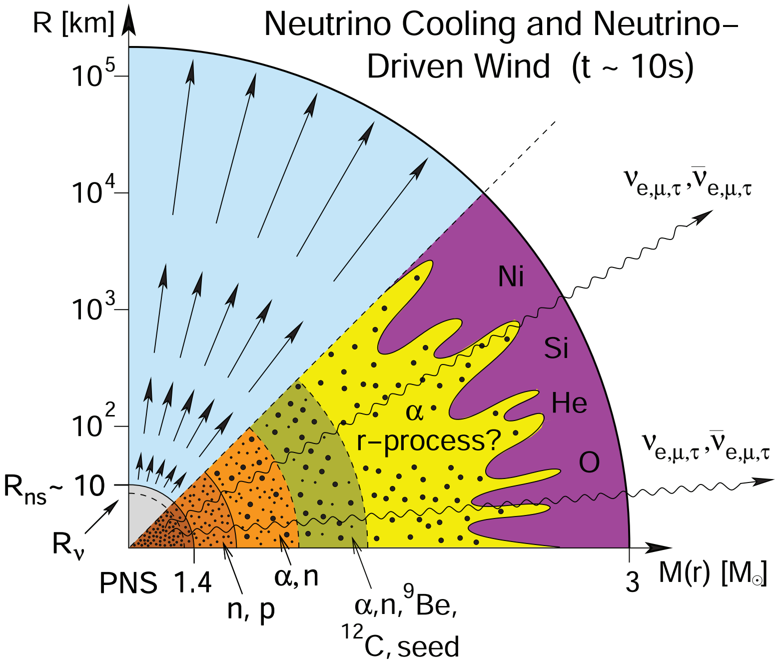
Re-energizing the stalled shock

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):

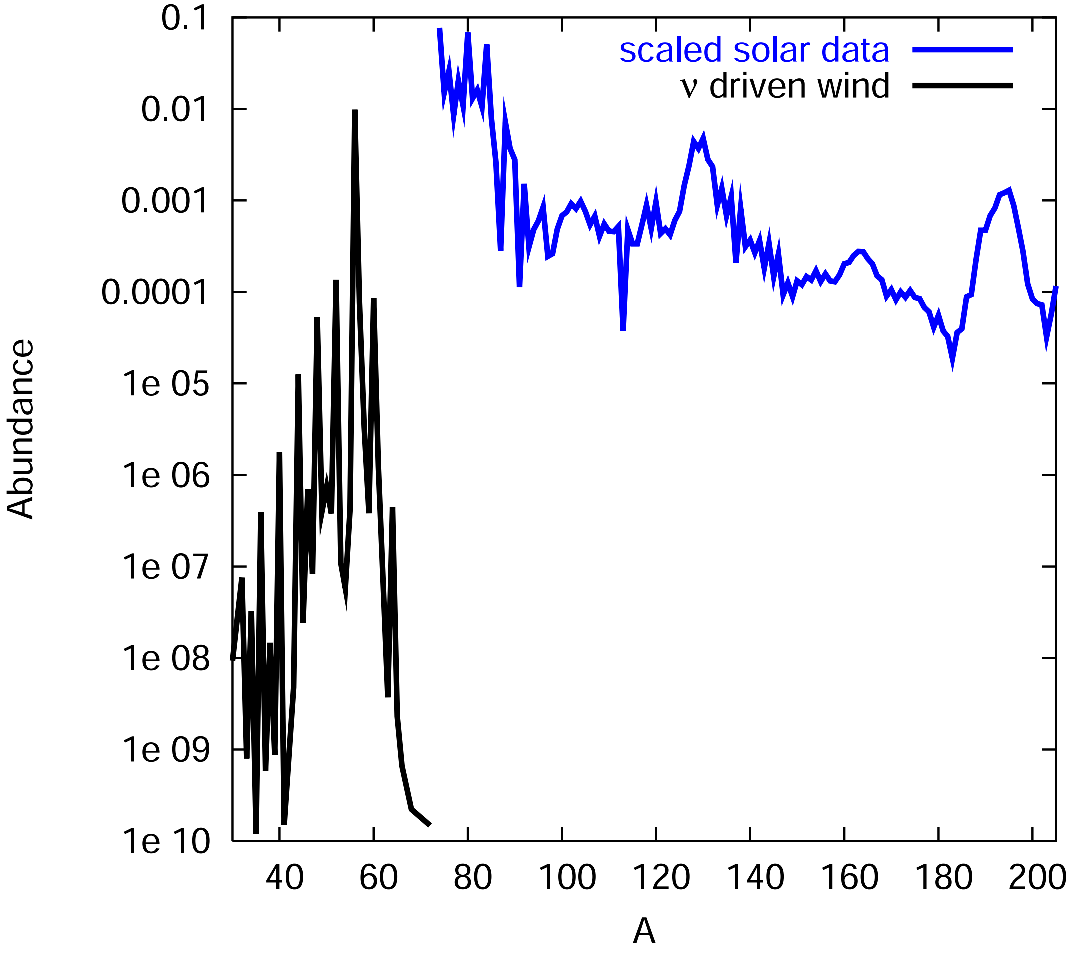
$$10^{-6}\,M_\odot$$

Core collapse supernovae evolve “quickly”

No problem with finding r-process elements in halo stars

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 difficult to get the required evolution time scale.

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- Jets from Core Collapse Supernovae
- Accretion Disks from Core Collapse Supernova
- ONeMg Supernovae
- low entropy or fast outflows from supernovae
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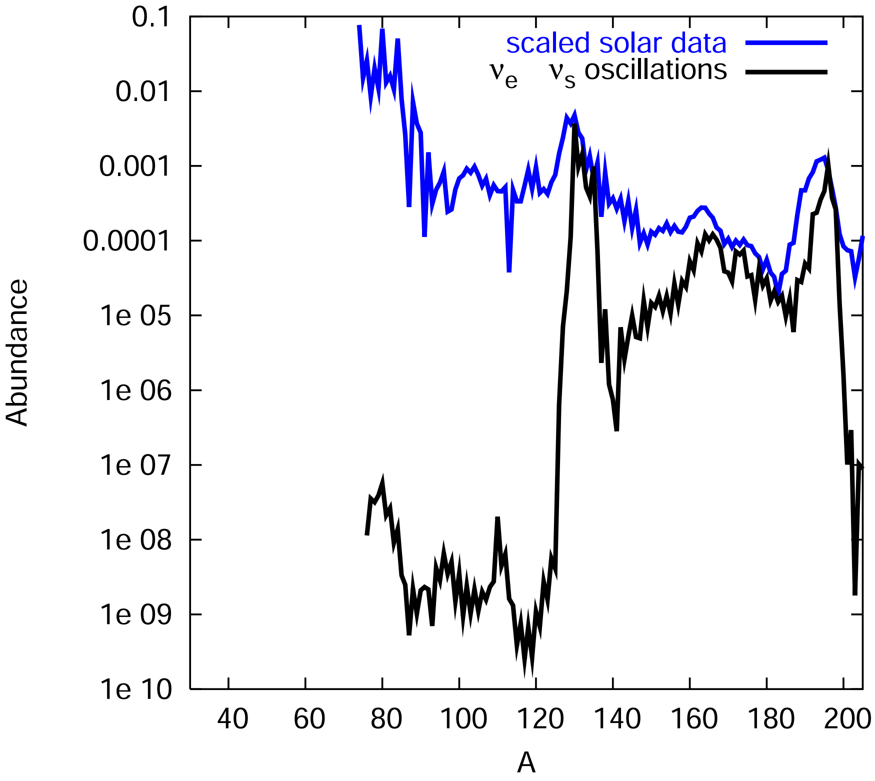
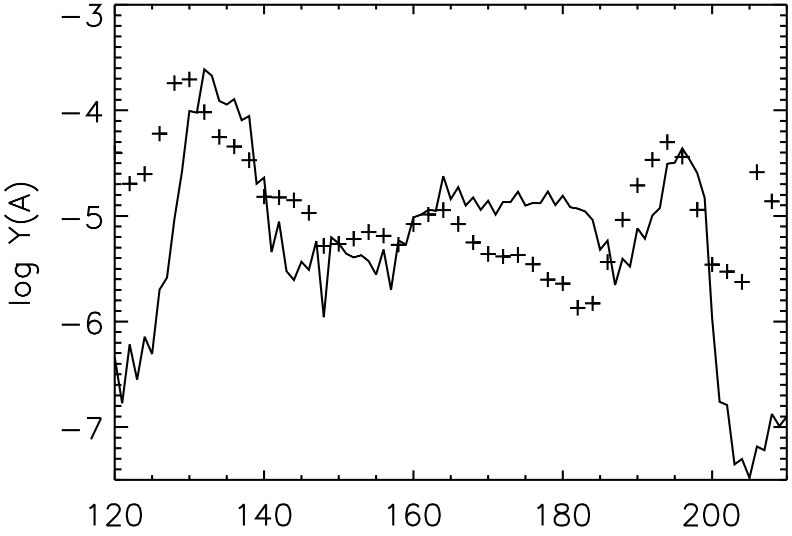
Core Collapse Supernovae: Nucleosynthesis in non-Traditional Neutrino Driven Winds





Active Sterile ν oscillations

Two component outflows

Beun et al 2007

Fig from R. Surman

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He shell r-process nucleosynthesis

$$^4\mathrm{He}(\nu, \nu\; n)^3\mathrm{He} \quad \mathrm{or} \quad ^4\mathrm{He}(\nu_e, e\; n)^3\mathrm{H} \tag{2}$$

$$^3\mathrm{He}(n, p)^3\mathrm{H} \tag{3}$$

$$^3\mathrm{H}(^3\mathrm{H}, 2n)^4\mathrm{He} \tag{4}$$

Neutrons are then available for capture on pre-existing nuclei.

Neutron density then depends strongly on the temperature of the neutrinos. It could be as high as 10^{19} per cm^3 for $T_{\nu_\mu} \approx 8$ MeV.

Neutron density is not high enough for a traditional r-process. Instead get a part s-process/ part r-process pattern. But... requires a higher energy ν_μ flux than is currently predicted

Example of a secondary r-process

Doesn't look like early r-process site

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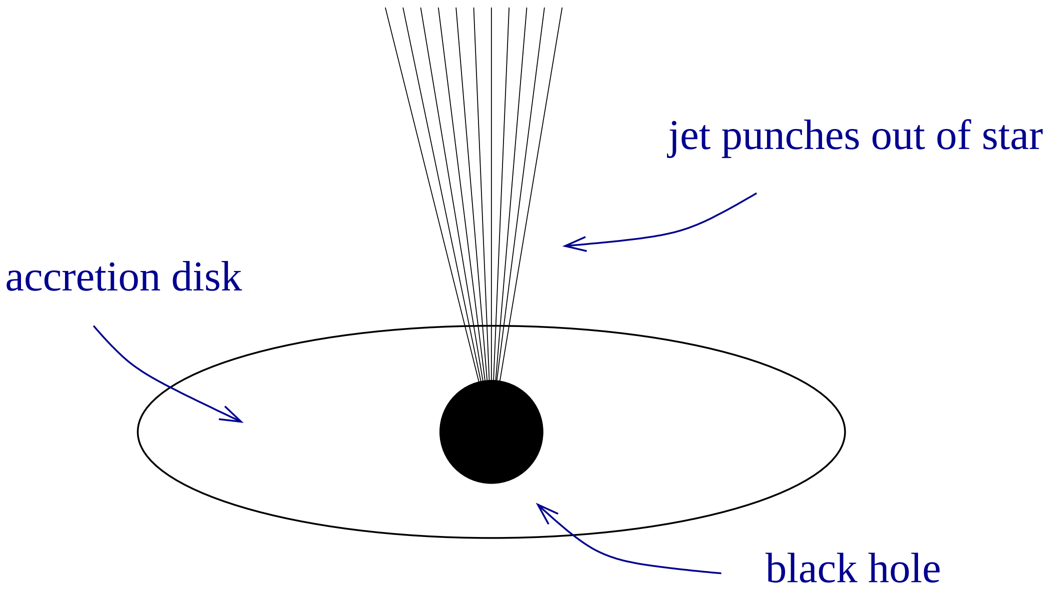
Collapsar/Hypernovae Model of Long Duration Gamma Ray Bursts

- Failed Supernova
- Too much rotation for real collapse & bounce

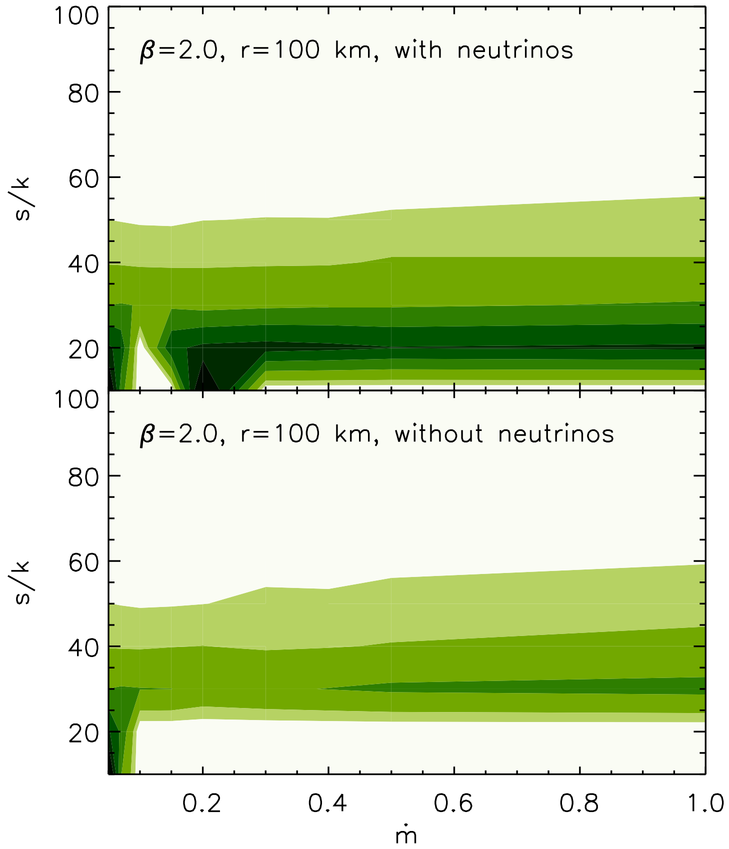


Neutrinos from the disk may provide some of the energy required to power the jet. Neutrinos also provide some of the energy for a wind that comes from the surface of the disk.

Collapsar type disk wind nucleosynthesis

Neutrino oscillations not included: Nickel - 56

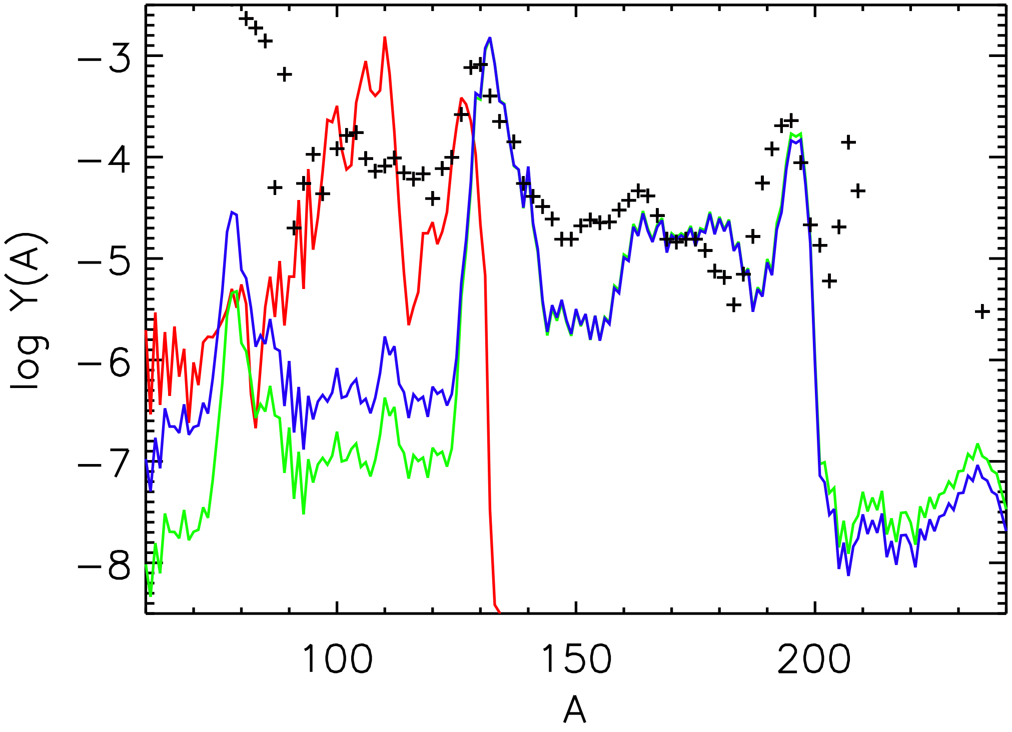
n,p $\rightarrow {}^4\mathrm{He}$ $\rightarrow$ iron peak nuclei $\rightarrow$ heavier nuclei



Surman et al 2010

Accretion disk nucleosynthesis

Neutrino oscillations have been included: r-process



red - no oscillations, blue - oscillations figure from Malkus et al, 2012

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Shocked Surface Layers of O-Ne-Mg Cores

- stars around 8 - 12 $M_\odot$ develop O-Ne-Mg cores before undergoing collapse
- density above core falls off more drastically
- SN models explore much more easily than Fe cor SN
- this material is struck by shock then follows adiabatic expansion
- rapid expansion
- this fast dynamical timescale can enable the r-process
- required entropy entropy per baryon is about 100k
- not all models get this

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Jets from Supernovae

- jets driven by interaction with magetic fields eject material
- very fast outflow timescale
- little time for heating
- produces neutron rich ejecta with large neutron to seed ratio
- models in very early stage of development

What do you think?

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