The r-process of nucleosynthesis: overview of current status

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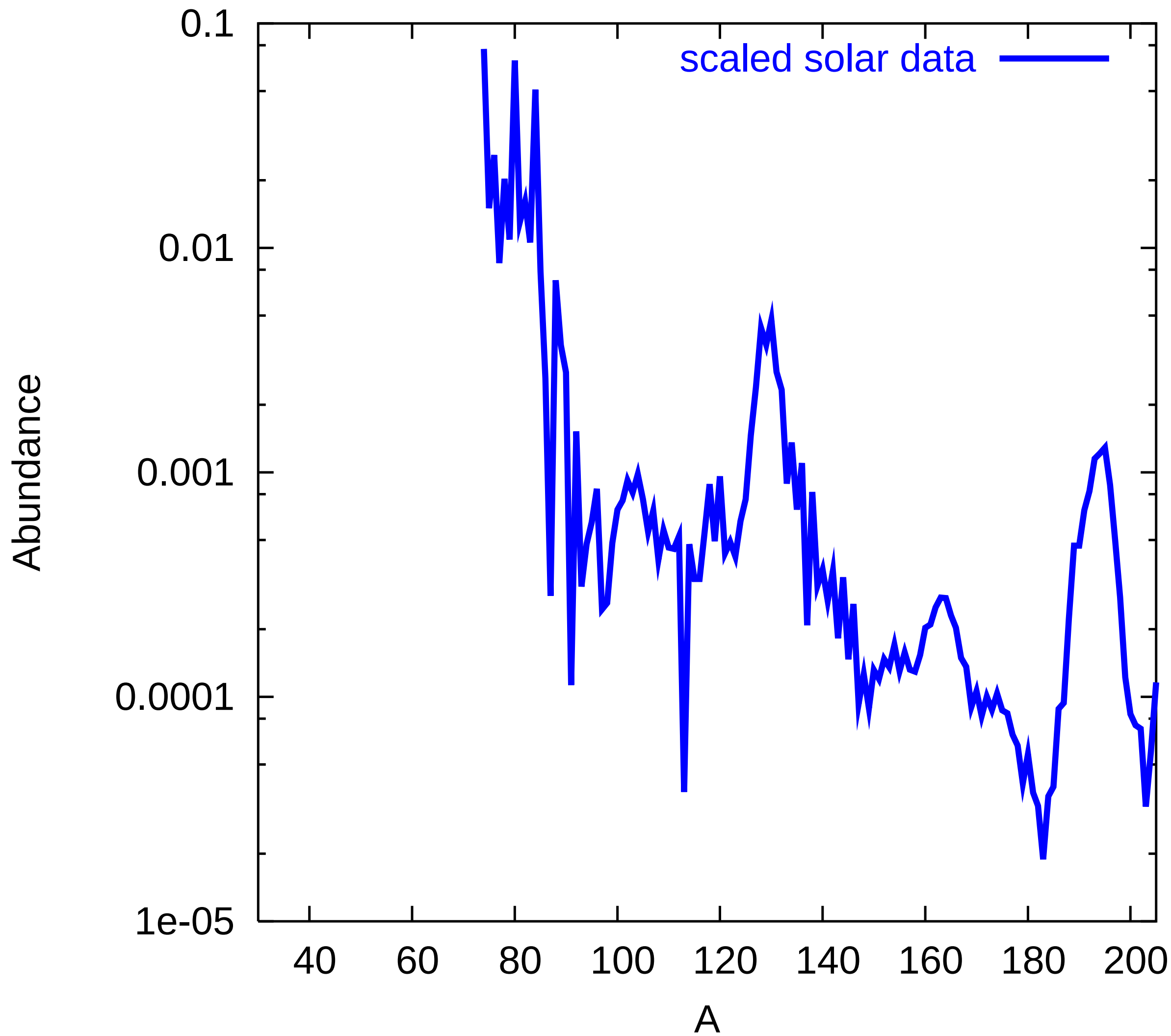
The popular press says that the gold and platinum in wedding bands is made in neutron star mergers

Why? Do you agree?

Solar Abundances



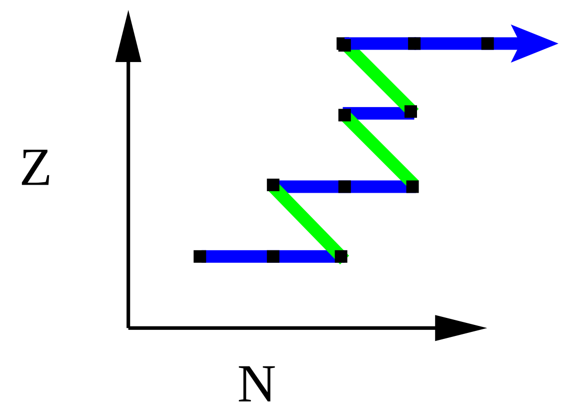
Where are gold and platinum on this plot? (Gold Z=79, A=197, Platinum Z=78, A=194,195 196, 198)

The r-process elements

e. g. Gold Z=79, N=197 $\rightarrow$ 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

Possible astrophysical sites of the r-process

What do you think?

Whats the most important criteria you are looking for?

Whats the most important criteria you are looking for?

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
- can you see a signal from r-process elements

Could there be more than one site?

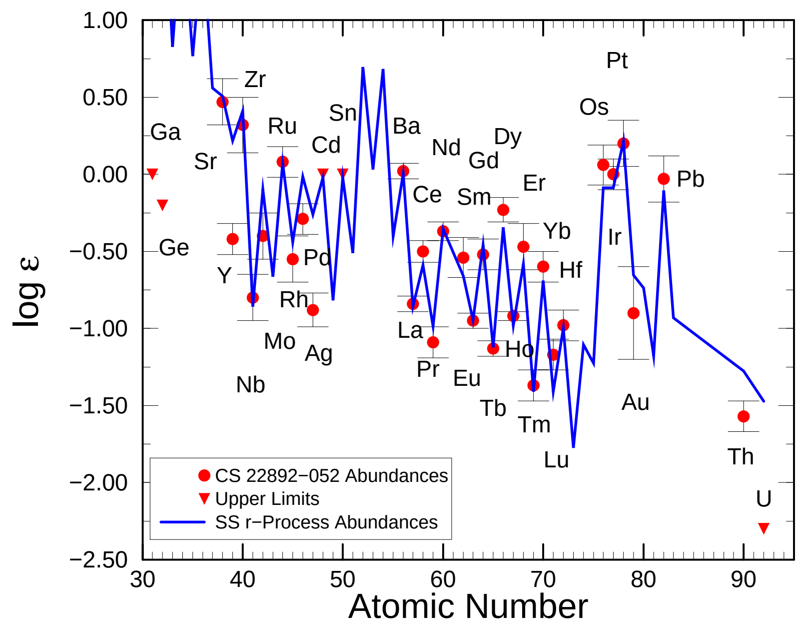
Observational r-process data

Observational Halo Stars:

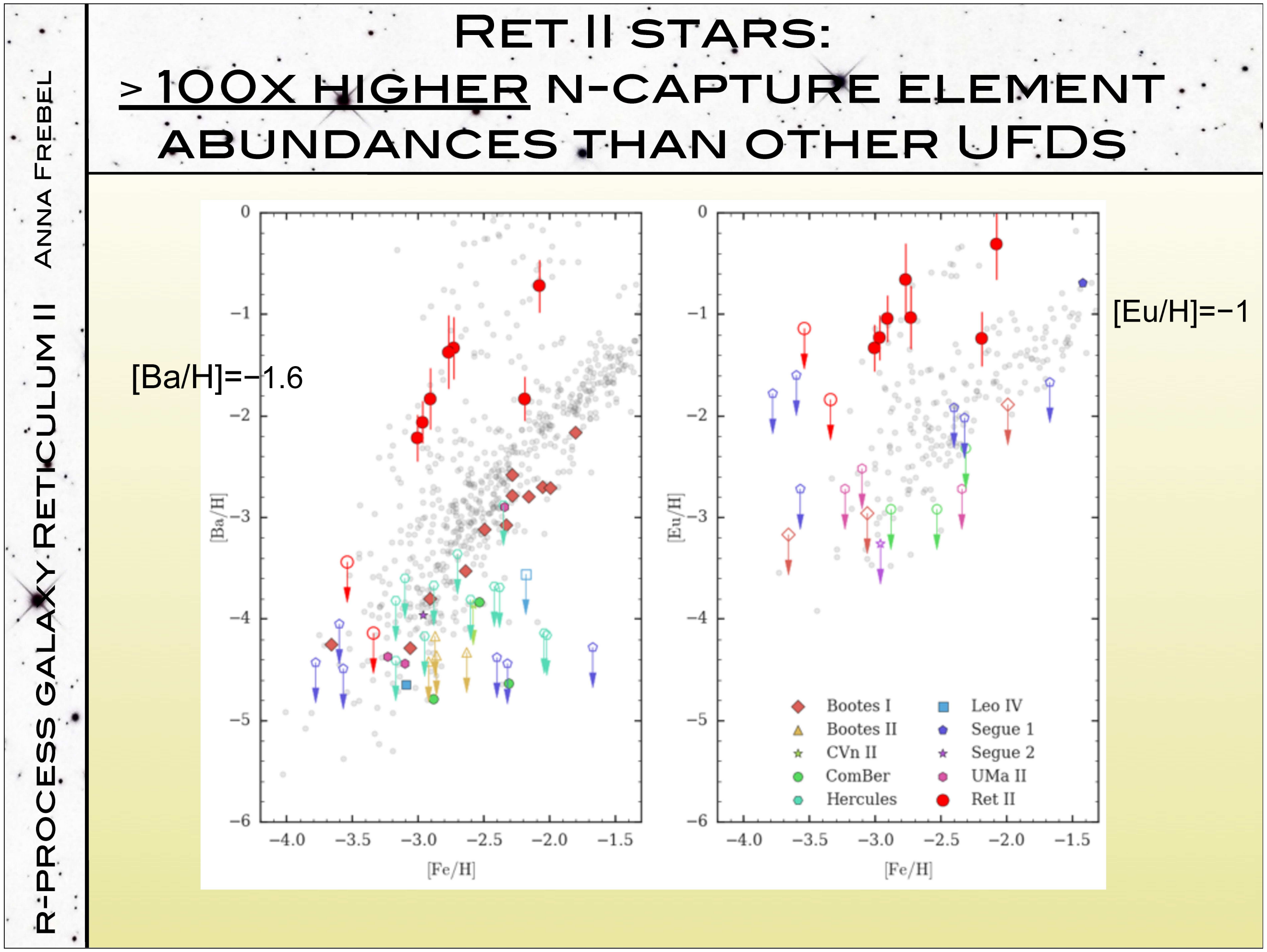
- two r-process sites

  Figure from Cowan and Sneden (2004)

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

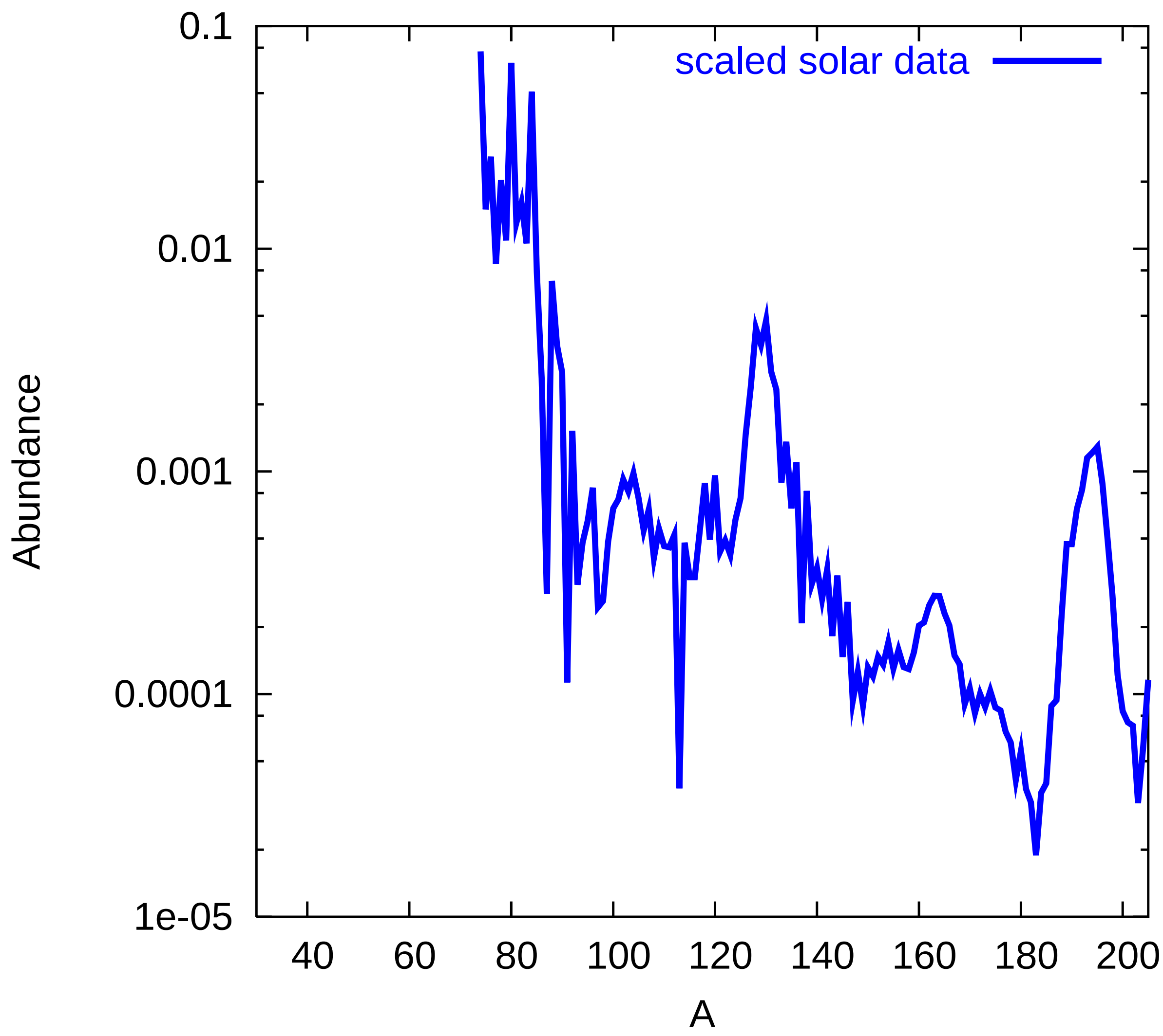


r-process elements in a dwarf galaxy

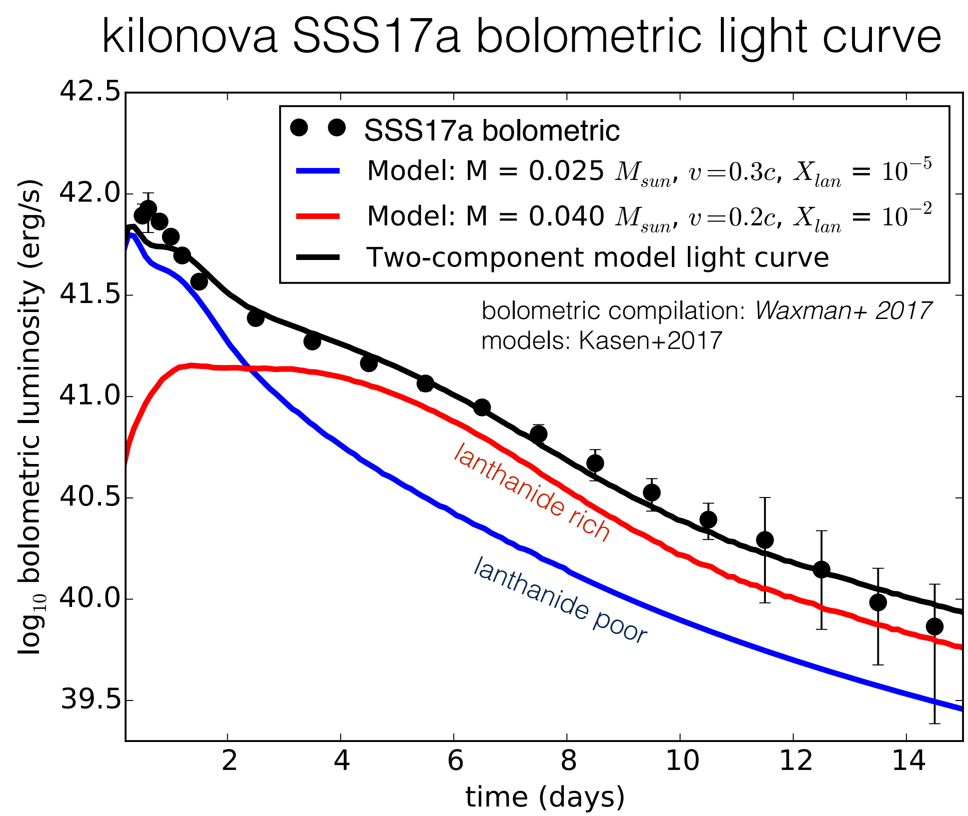


One galaxy of ten has r-process elements Slide credit: Anna Frebel

Solar Abundances

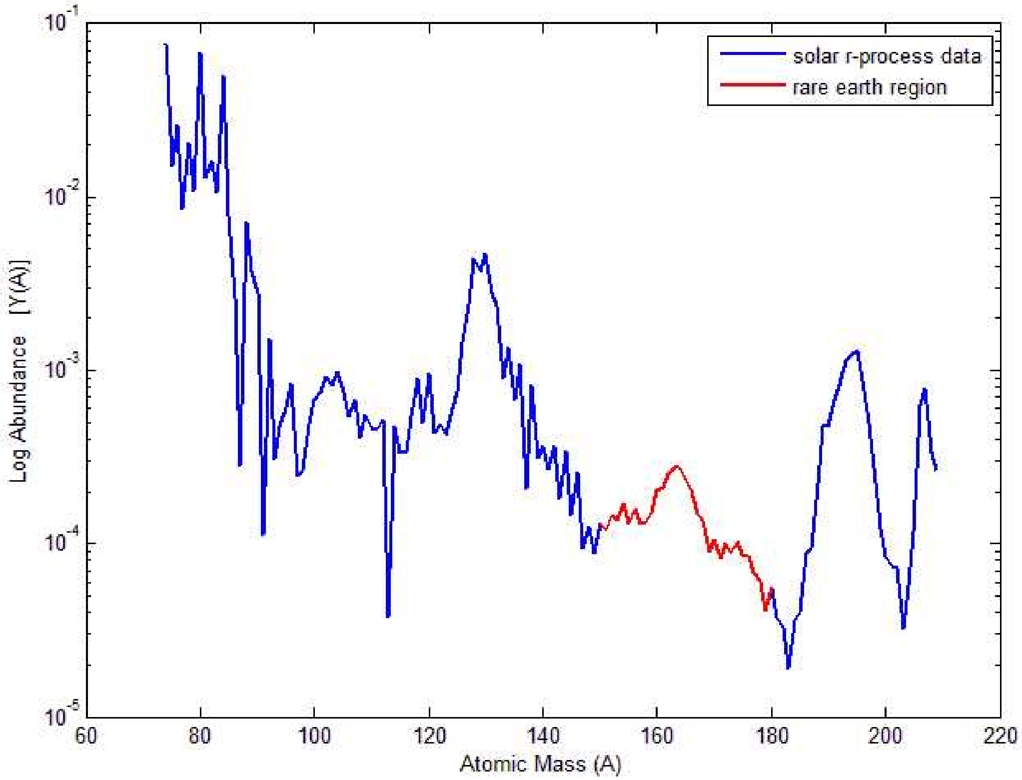


Electromagnetic counterpart to neutron star merger



Lanthanides are a cource of considerable opacity Slide credit: Dan Kasan

Where are the lanthanides?



If lanthanides are required to fit the electromagnetic counterpart, then at least the rare earth elements were synthesized in this merger.

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
- Tidal ejection of neutron rich matter in neutron star mergers
- shocked ejecta from merger
- accretion disk outflows from mergers

Possible astrophysical sites of the r-process

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Compact object mergers

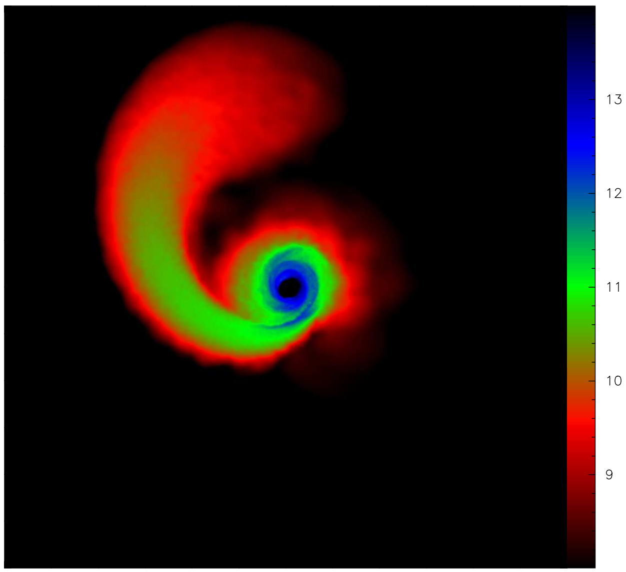


figure from Korobkin 2012

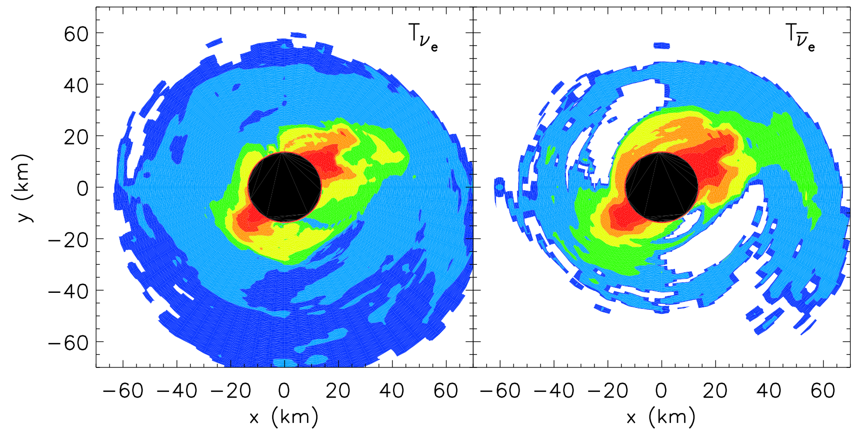


figure from Surman 2008

Mergers have many signals

- Gravitation wave signal, now observed!
- 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

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

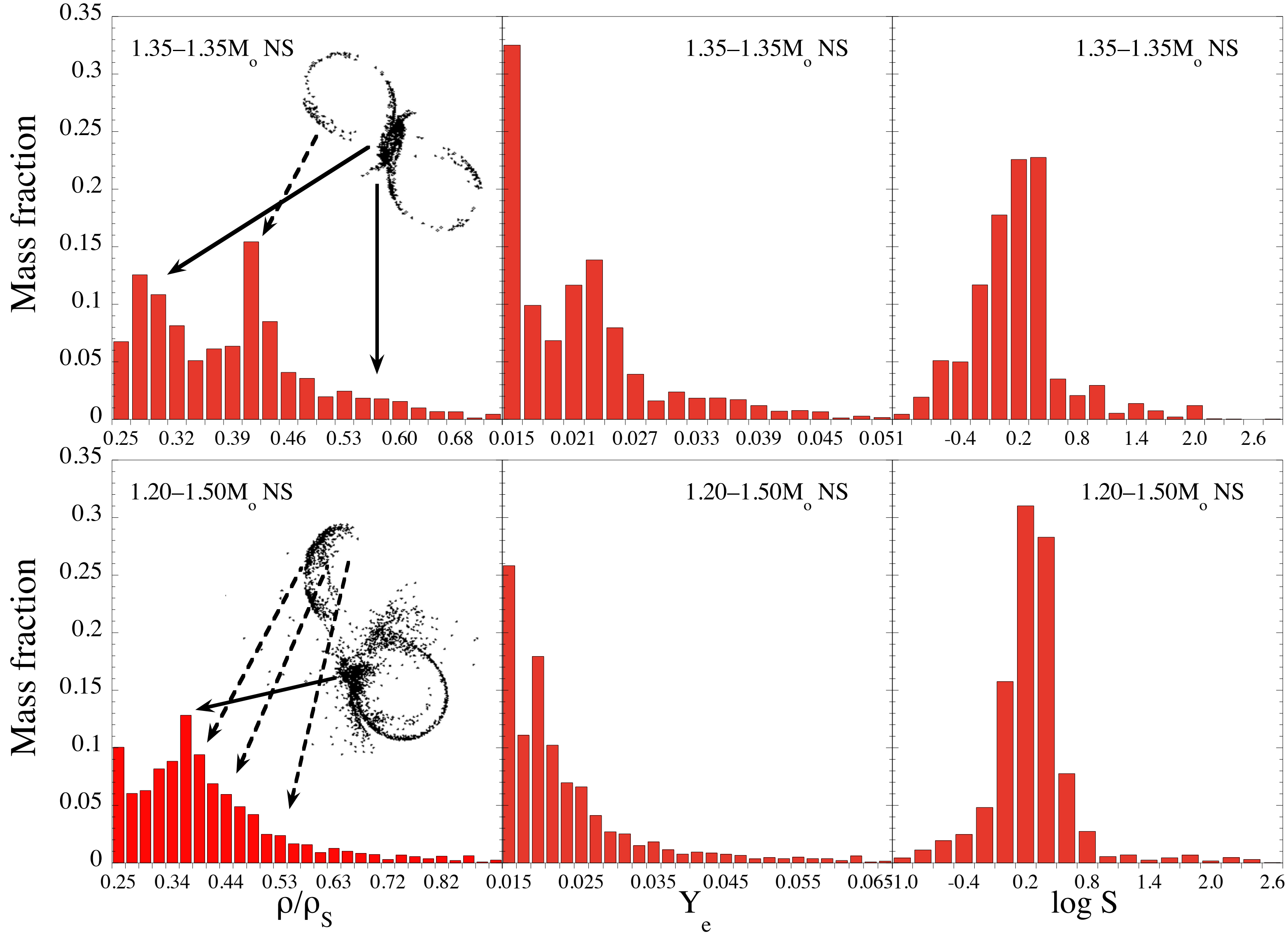
$$Y_e = \frac{n}{p + n} \tag{1}$$

Want this to be low.

neutron stars start with low Y_e.

Of the types of outflow we have considered (dynamical, wind) , 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

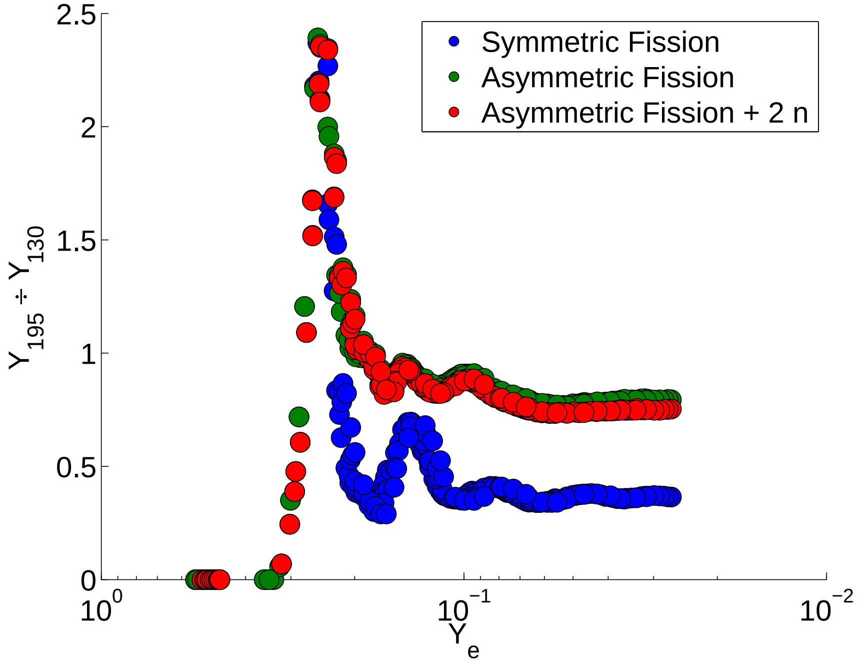
Halo star data suggest that abundance pattern in 2nd & 3rd peak region is "robust". Abundance pattern below 2nd peak shows variations between different stars.

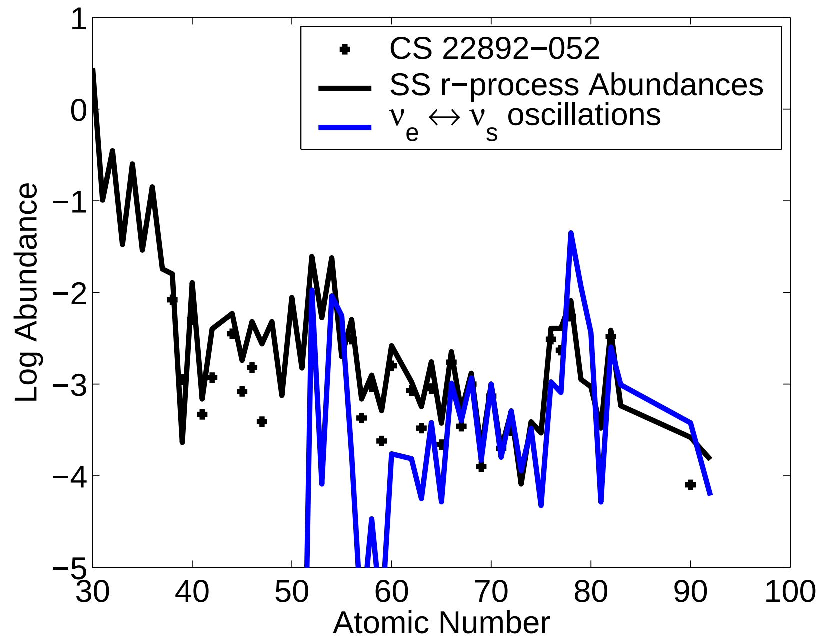
Need robust mechanism for populating 2nd & 3rd peaks.

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



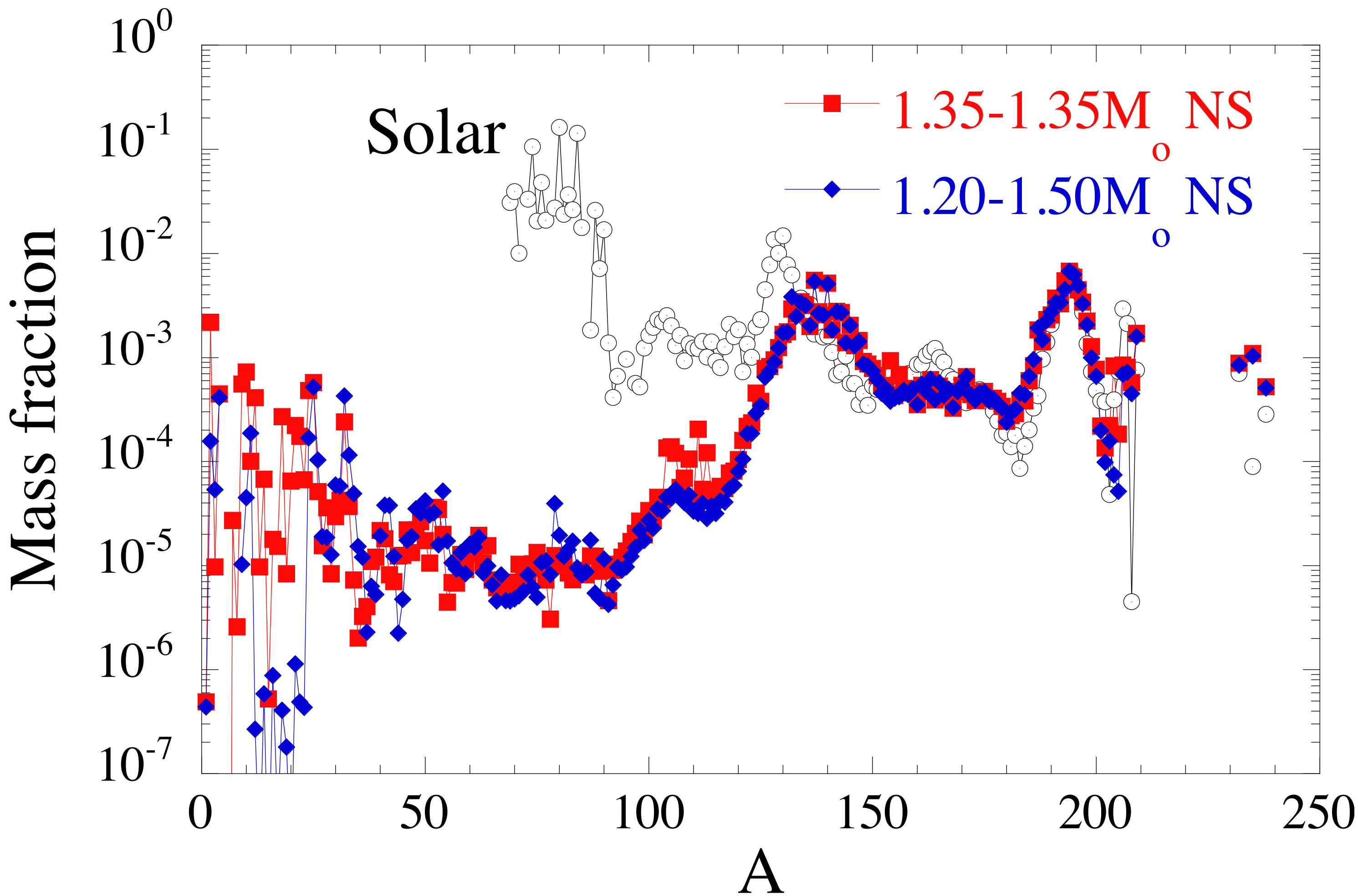


abundance in 3rd/2nd peak as a fct of decreasing Y_e

Very little data on the relevant fission rates and daughter products

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

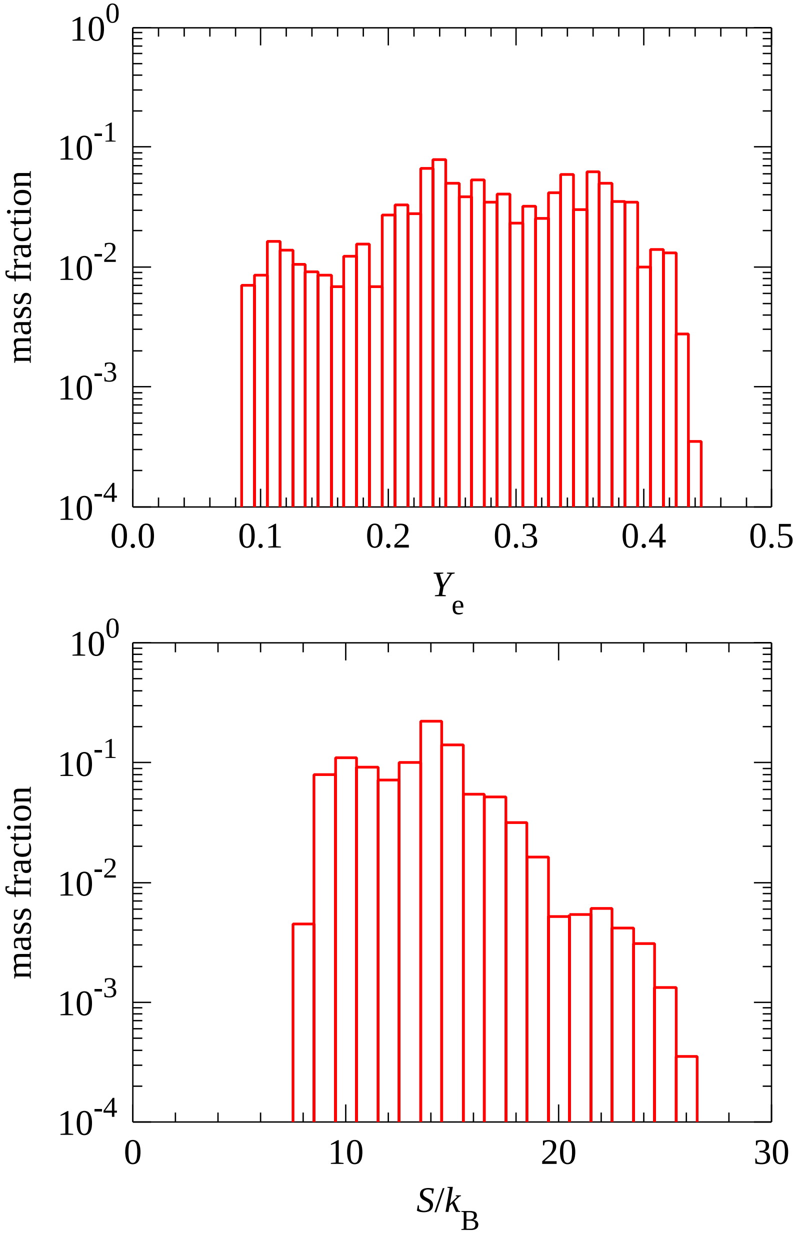
Dynamically Ejected Material from Newtonian Calculation



Goriely et al 2011

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

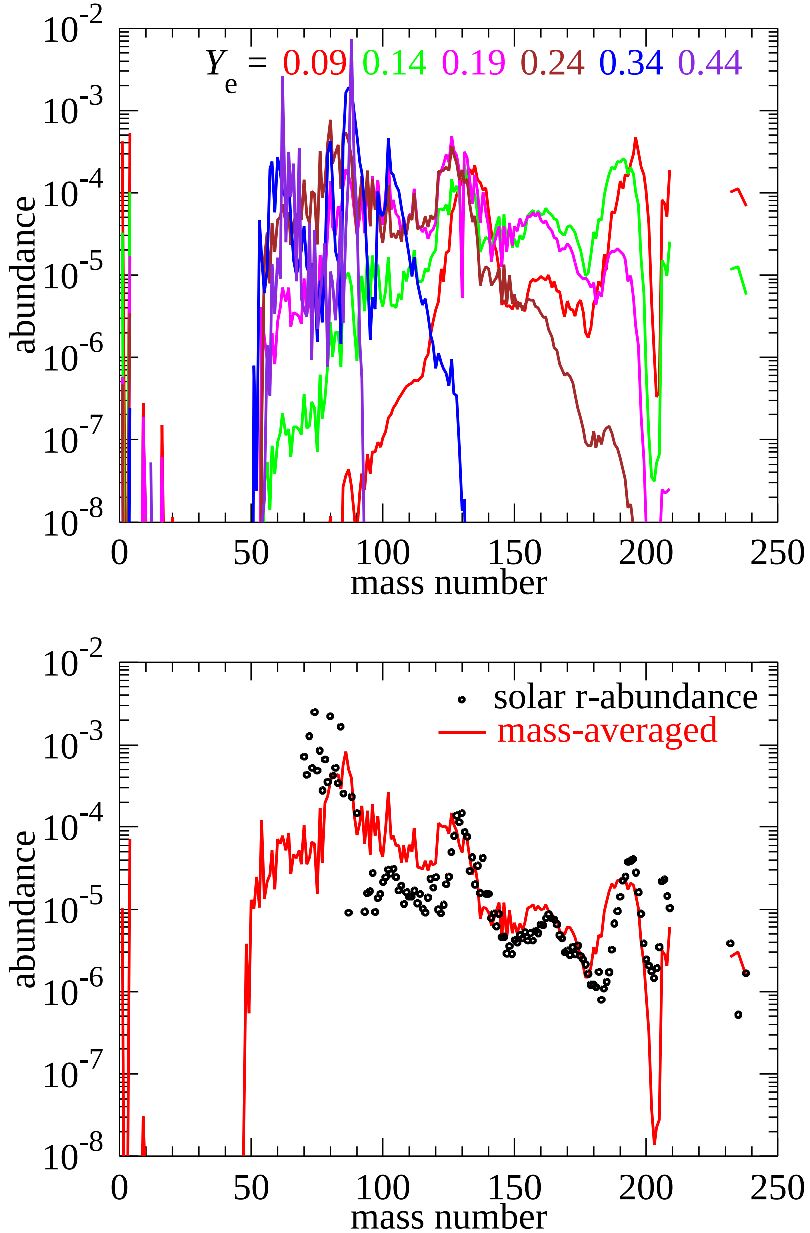
What about calculations where neutrinos are included?



What has happened to the Y_e? Why?

Fig. from Wanajo et al 2014

The abundance pattern when neutrinos are included



Have these elements been fission cycled? Why or why not?

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.

It looks promising, where are we?

Electromagnetic observations of a NSM suggest that rare earths are made in mergers

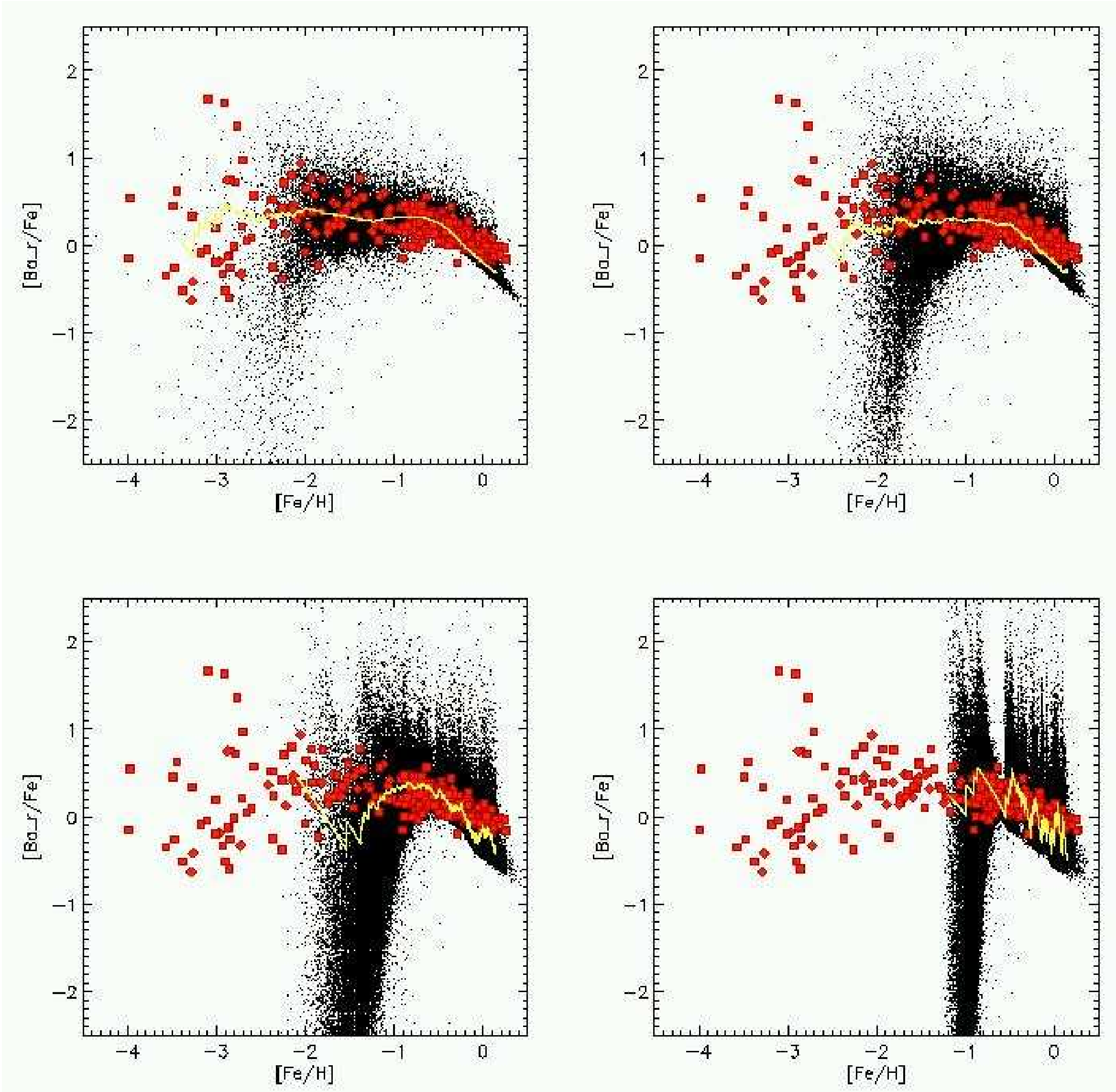
Dwarf galaxy observations suggest a rare event the produces rare earths

Unresolved issues:

We lack evidence for fission cycling in mergers

We lack evidence for elements heavier than the rare earths from mergers

Does it match the halo stars?



Argast et al 2004

So what do you think?

Does the gold and platinum in your wedding band come from neutron star mergers?

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
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What role can nuclear physics play?

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Nuclear physics plays an important role in understanding the r-process pattern

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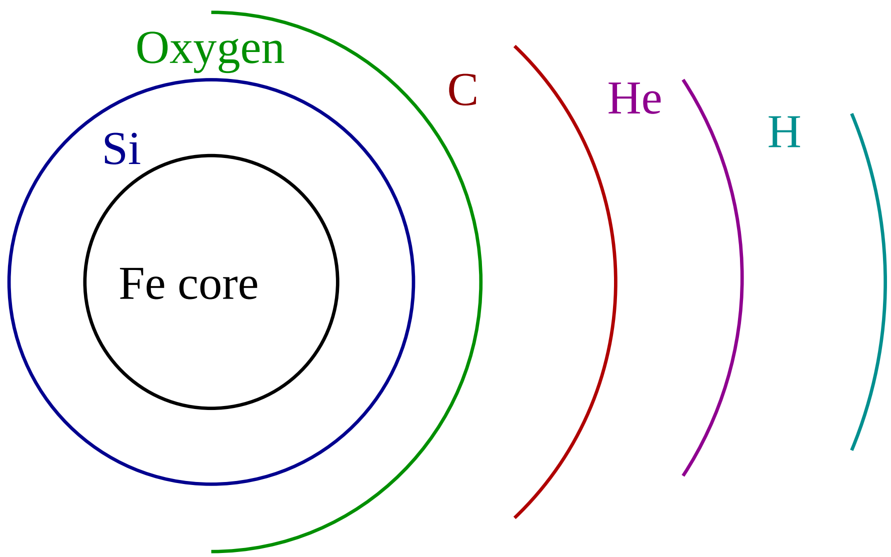
Core Collapse Supernovae

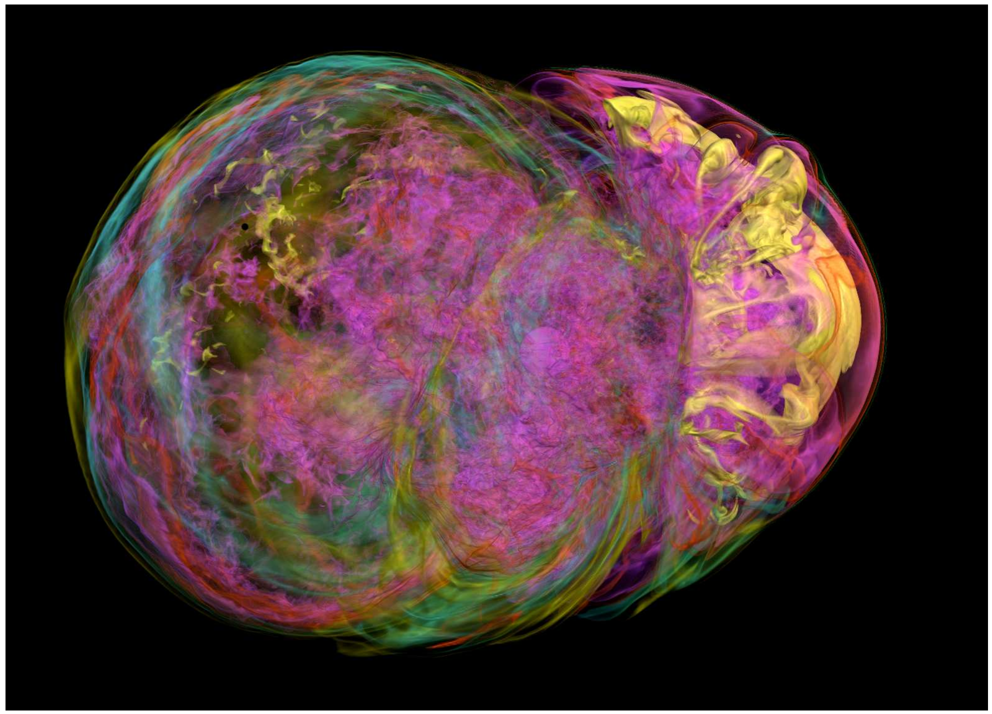
end of the life of a massive star



- 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

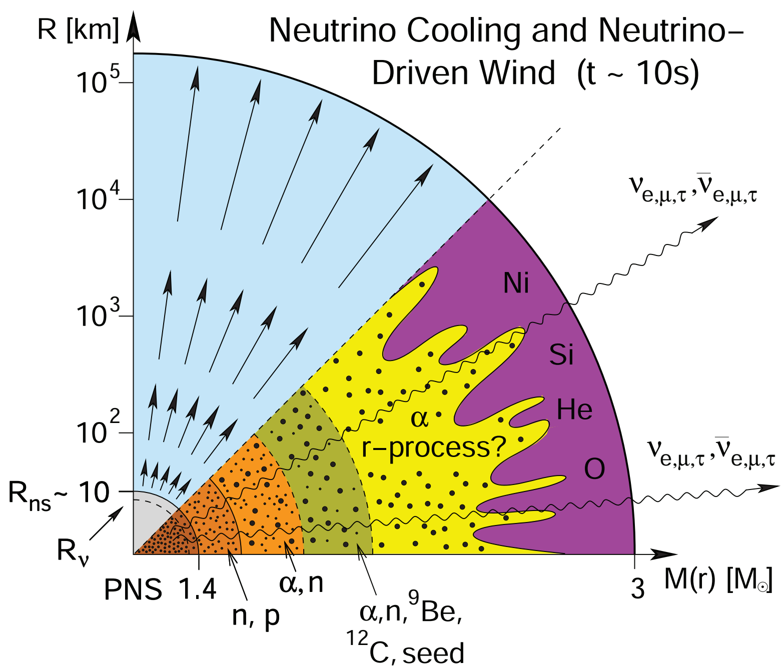
Re-energizing the stalled shock

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):

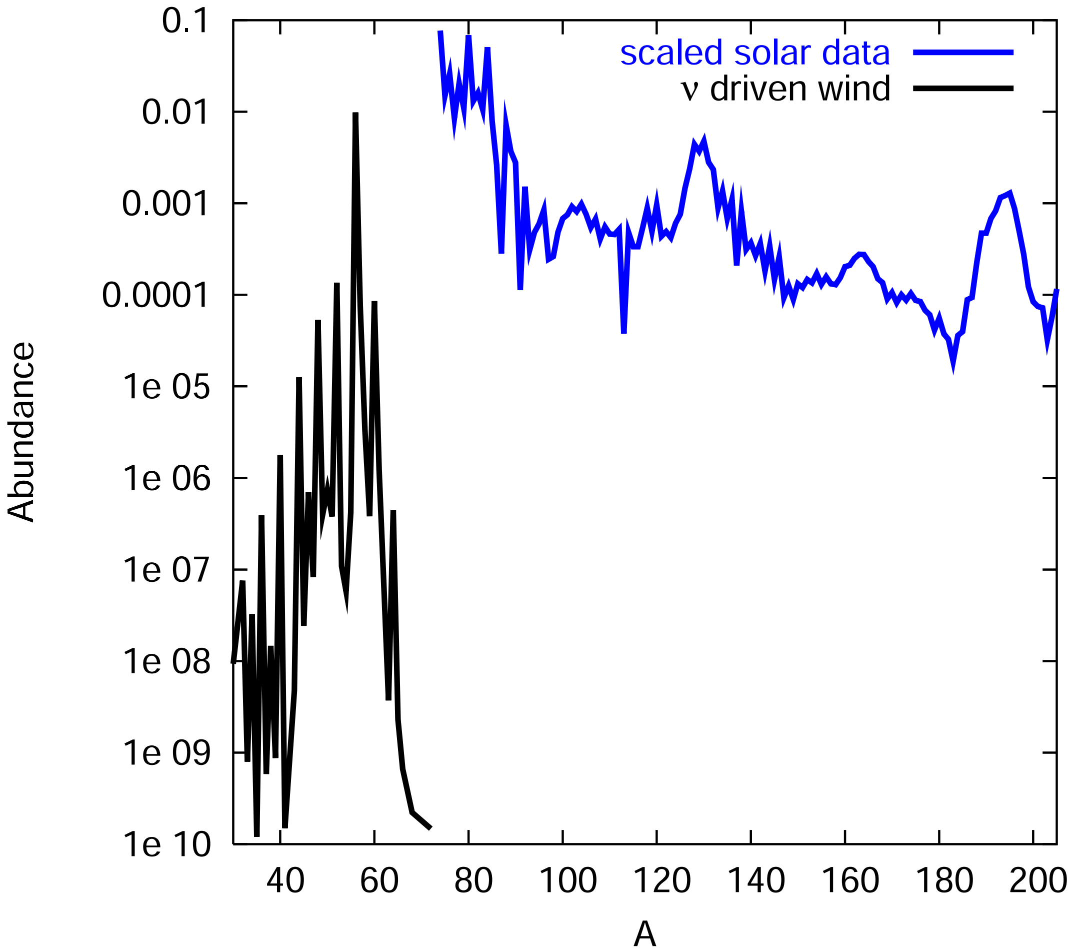
$$10^{-6}\,M_\odot$$

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



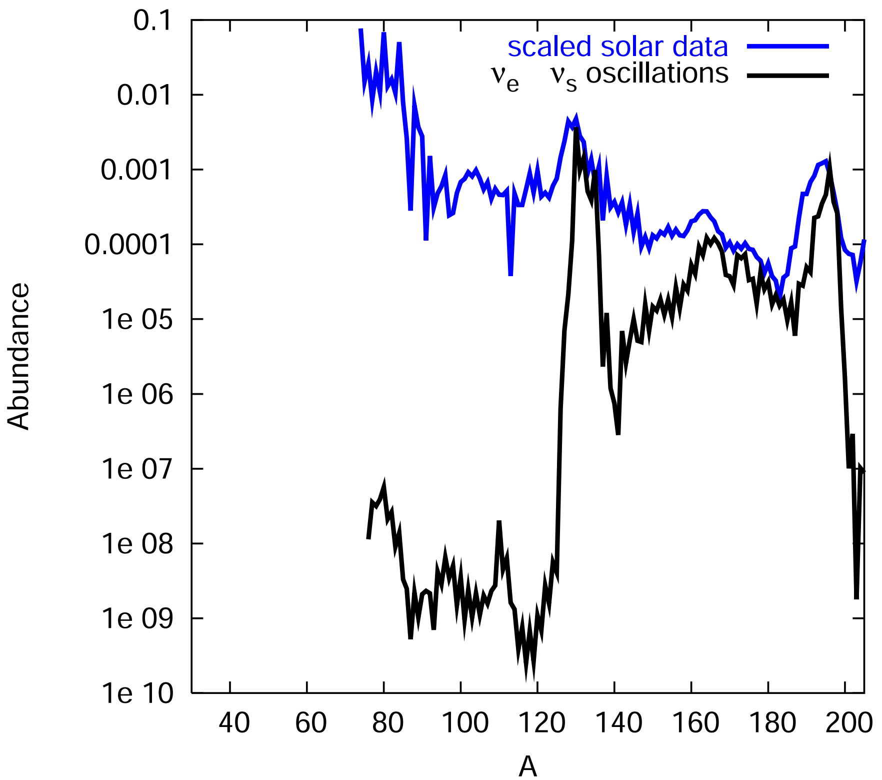
What happened?

Entropy too high for outflow timescale (or vice versa)

Possible astrophysical sites of the r-process

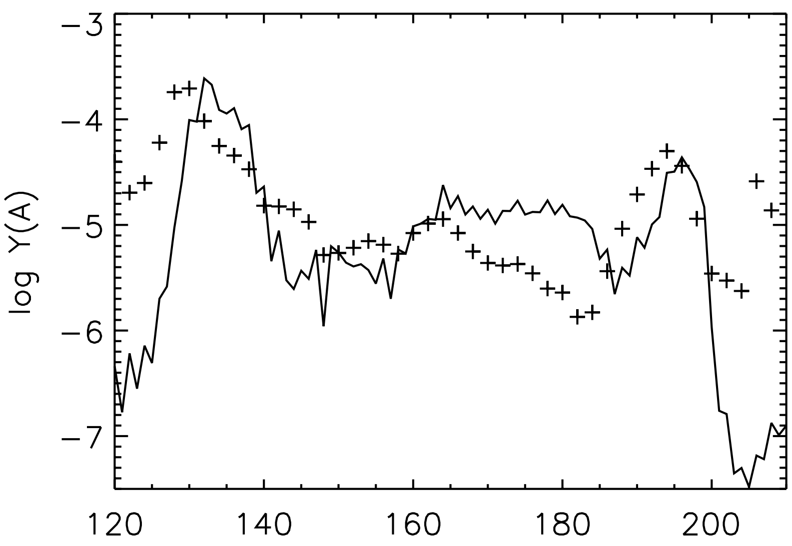
- Neutrino Driven Wind of the Supernovae
- Jets from Core Collapse Supernovae
- Accretion Disks from Core Collapse Supernova
- ONeMg Supernovae
- low entropy or fast outflows from supernovae
- He Shell of core collapse supernovae
- Supernova with sterile neutrinos
- Tidal ejection of neutron rich matter in neutron star mergers
- shocked ejecta from merger
- accretion disk outflows from mergers

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



Active Sterile ν oscillations

Beun et al 2007



Two component outflows

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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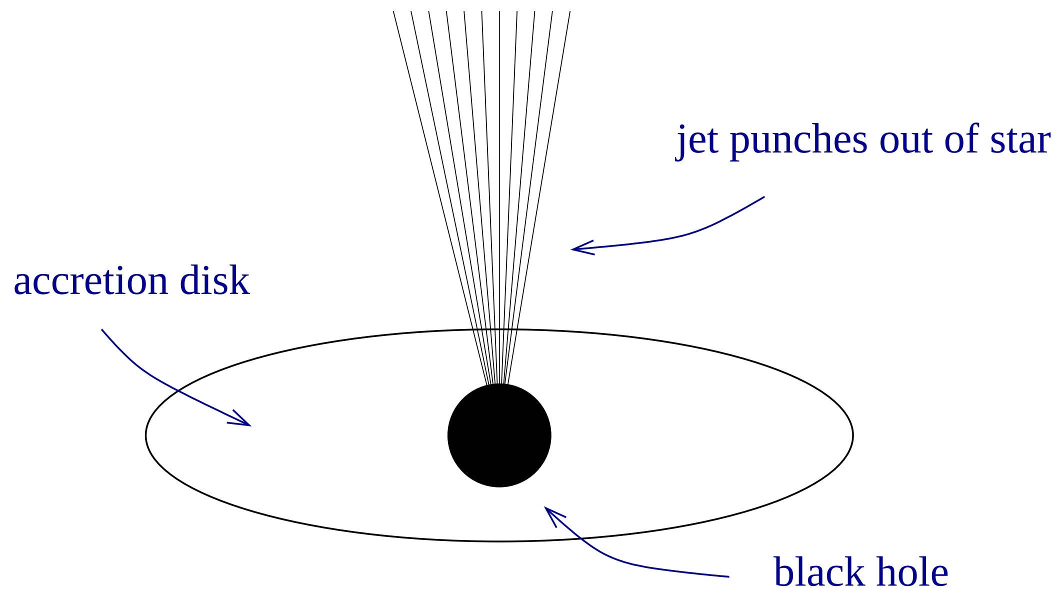
Collapsar/Hypernovae Model of Long Duration Gamma Ray Bursts

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

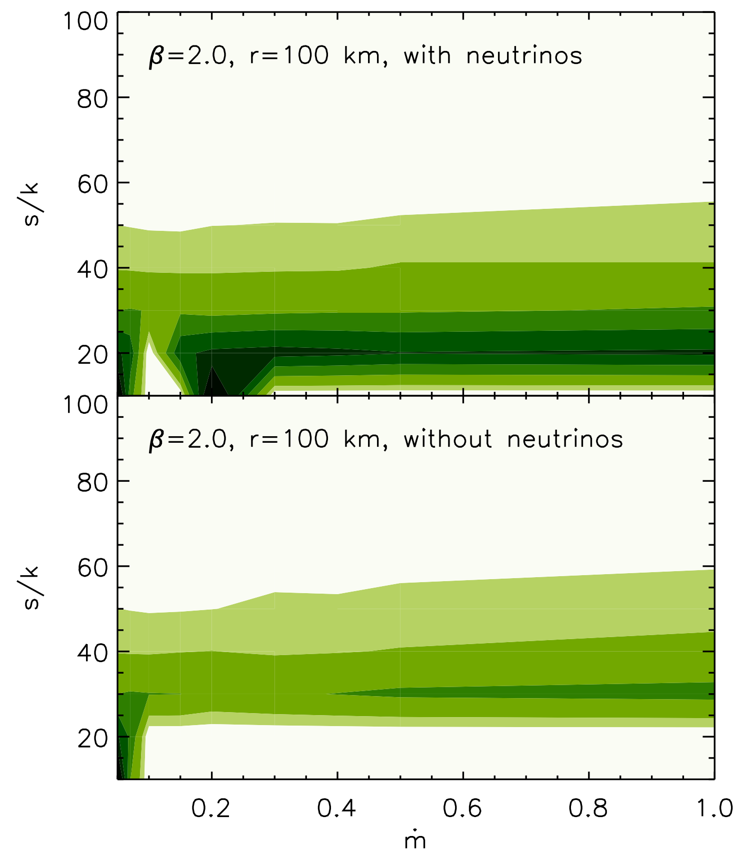


Neutrinos from the disk may provide some of the energy required to power the jet. Neutrinos also provide some of the energy for a wind that comes from the surface of the disk.

Collapsar type disk wind nucleosynthesis

Neutrino oscillations not included: Nickel - 56

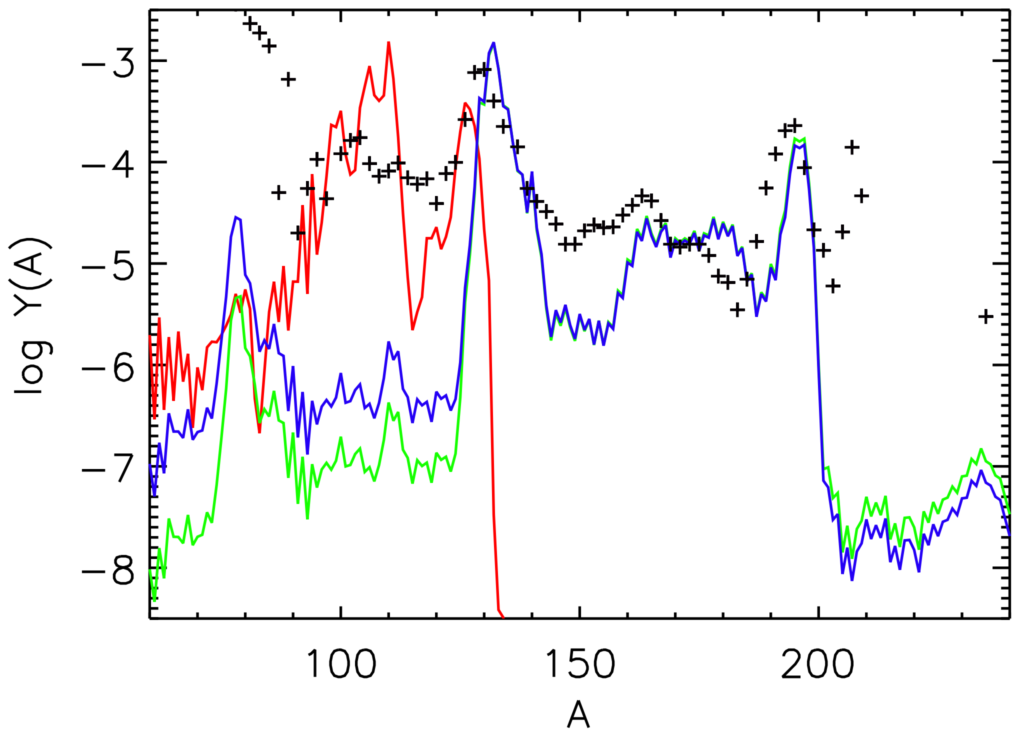
n,p $\rightarrow^4$ He $\rightarrow$ iron peak nuclei $\rightarrow$ heavier nuclei



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 dynamicl timescale can enable to 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?

- Neutrino driven wind of the supernovae
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