Nucleosynthesis from Compact Object Mergers

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- General remarks about nucleosynthesis
- Nuclei produced from ejection of tidal tails
- Nuclei produced from accretion disk winds
- Remarks

Nucleosynthesis from compact object mergers

Two types of environments

- ejection from tidal tails
- accretion disk “wind’

Three primary types of nucleosynthesis

- r-process
- p-process
- ^{56}Ni and other iron group nuclei

Different merger configurations

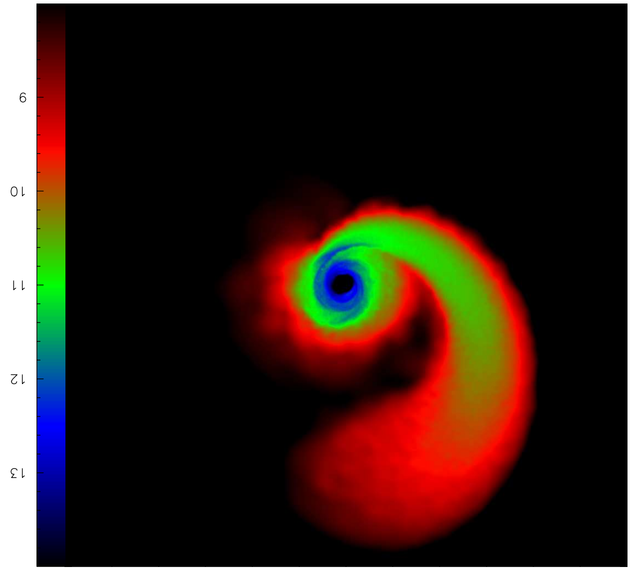


figure from Korobkin 2012

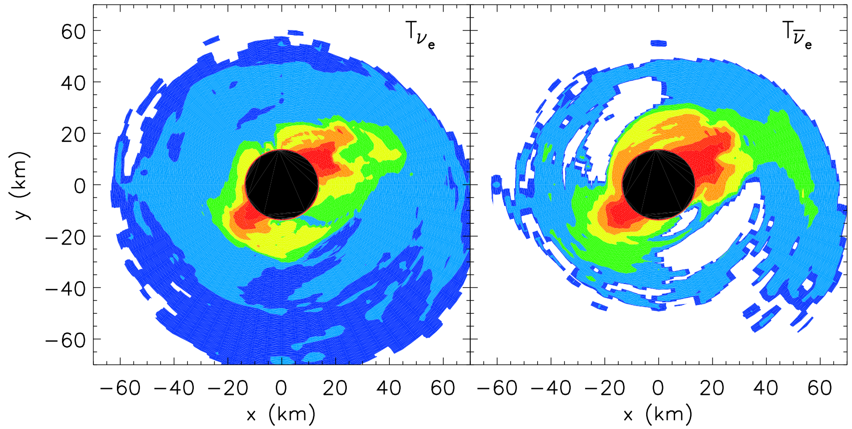


figure from Surman 2008

Material can be ejected from tidal tails, off the edges of the disk or in a wind off of the disk.

A couple of questions

Ejected material from mergers will certainly make some nuclei.

1. How much stuff is ejected?

2. What sort of nuclei are made?

How much stuff?

Estimates depend on the hydrodynamic + thermodynamic + neutrino calculation, but some recent estimates:

1. winds: $\sim 2 \times 10^{-3} M_\odot$ Wanajo and Janka 2011
   $10^{-4} M_\odot$ Dessart et al 2009

2. tidal tail ejection: 10^{-2} to $10^{-3}\, M_\odot$ Goriely et al 2011
   $7.6 \times 10^{-3}\, M_\odot$ to $3.9 \times 10^{-2}\, M_\odot$ Korobkin 2012

3. thermonuclear winds: up to $10^{-1} M_\odot$ Metzger

Hot ejection: winds

Characteristics

- entropy per baryon, s/k is at least 20 or higher
- weak rates significant, i.e. e^+, e^-, ν_e, $\bar{\nu}_e$ capture on n,p
- neutron to proton ratio determined by all the weak rates
- practical place to look for this: above trapped neutrino surfaces $T \sim 3 - 6\,\mathrm{MeV}$

Cold ejection: tidal tails

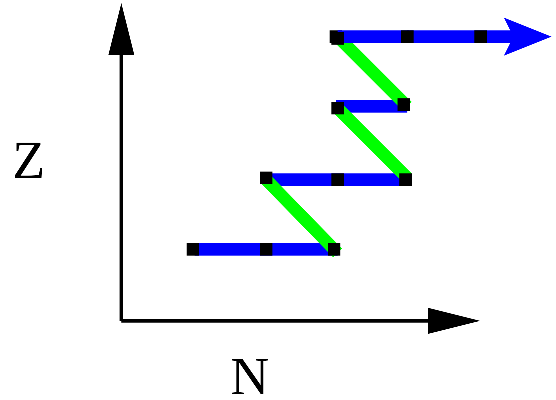
- entropy per baryon, s/k is usually less than 20
- nucleosynthesis calculations typically commence at $10^{10}K$
- weak rates not so crucial (pauli blocking, few νs)
- material retains neutron richness from original neutron star
- practical place to look for this: tidal ejection, ejection from edges

We are looking for the r-process elements

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

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

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



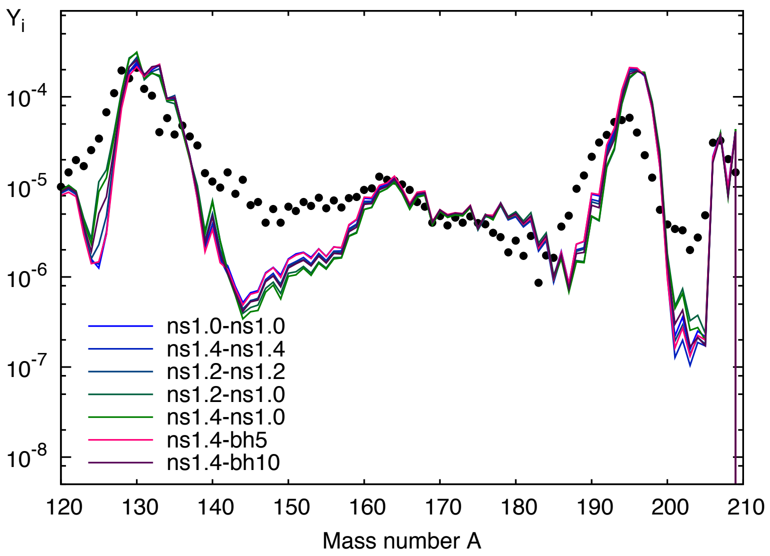
rapid neutron capture as compared with beta decay

At what temperatures does this happen?

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

Cold Ejection and Fission Cycling

Fission cycling

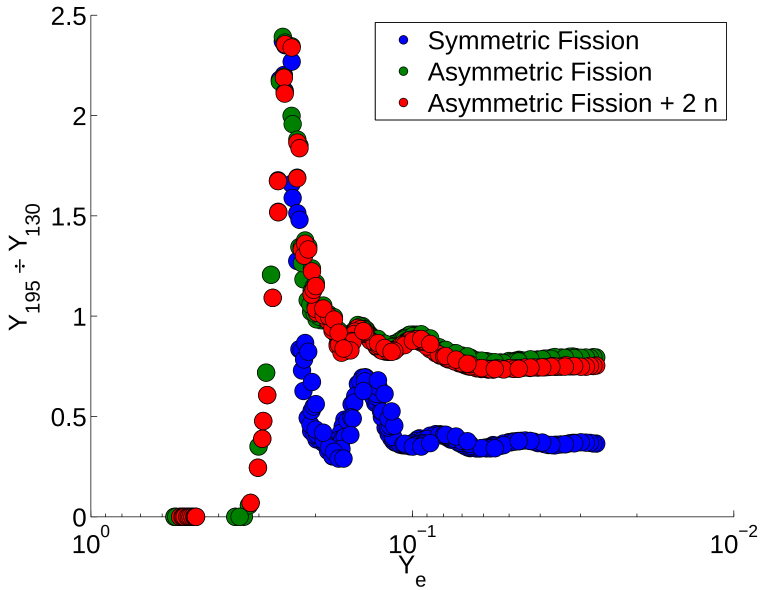


Korobkin et al

- cold ejection has low Y_e
- many neutrons
- fission cycling
- consistent peak ratio

Cold Ejection and Fission Cycling

Fission cycling



Beun et al 2008

- cold ejection has low Y_e
- many neutrons
- fission cycling
- consistent peak ratio

Neutrinos in wind outflows

A strong neutrino flux of all flavors comes from the disk

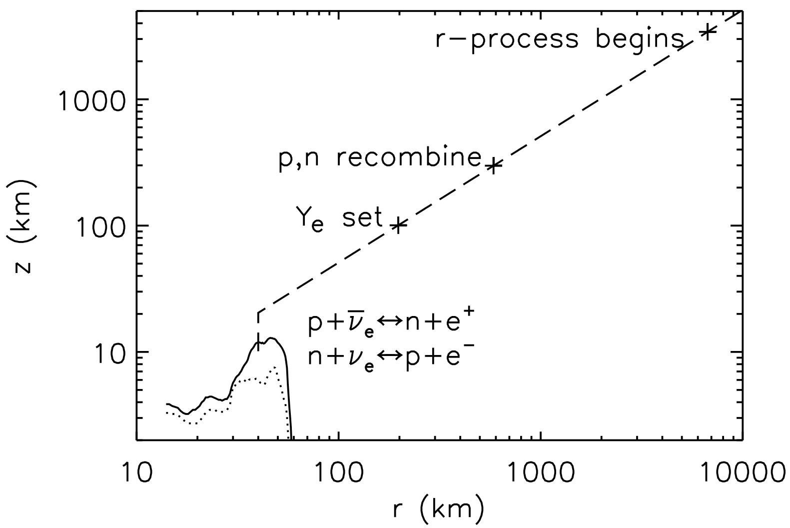
Electron type neutrinos are influential in determining numbers of neutrons and protons in winds above the disk.

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

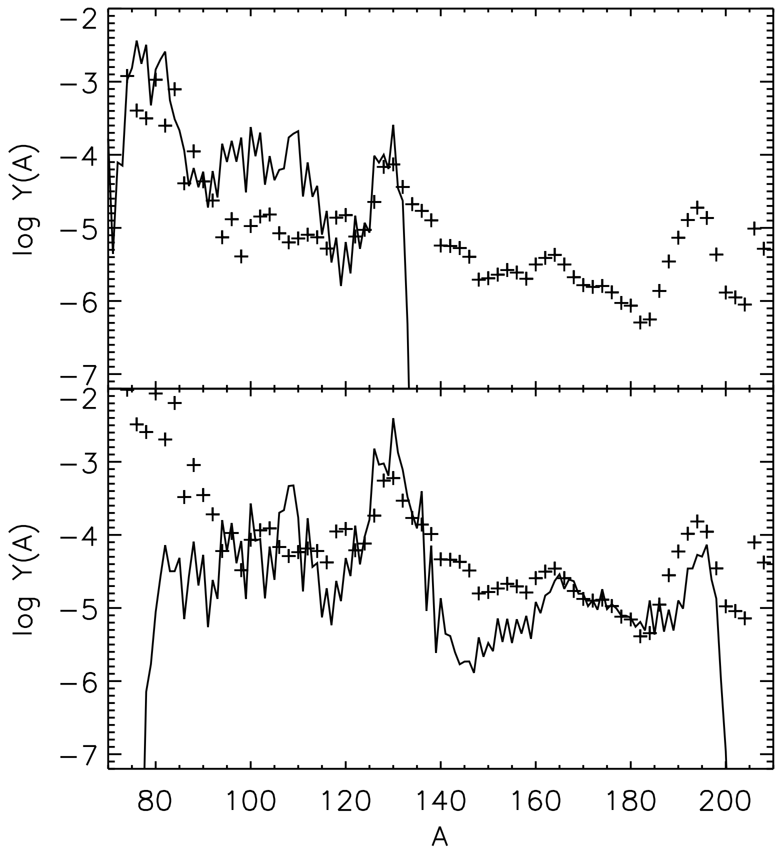
Neutrinos and antineutrinos can also capture on nuclei.

Simple model of wind nucleosynthesis

Black Hole Neutron Star Merger



Schematic of events in outflow

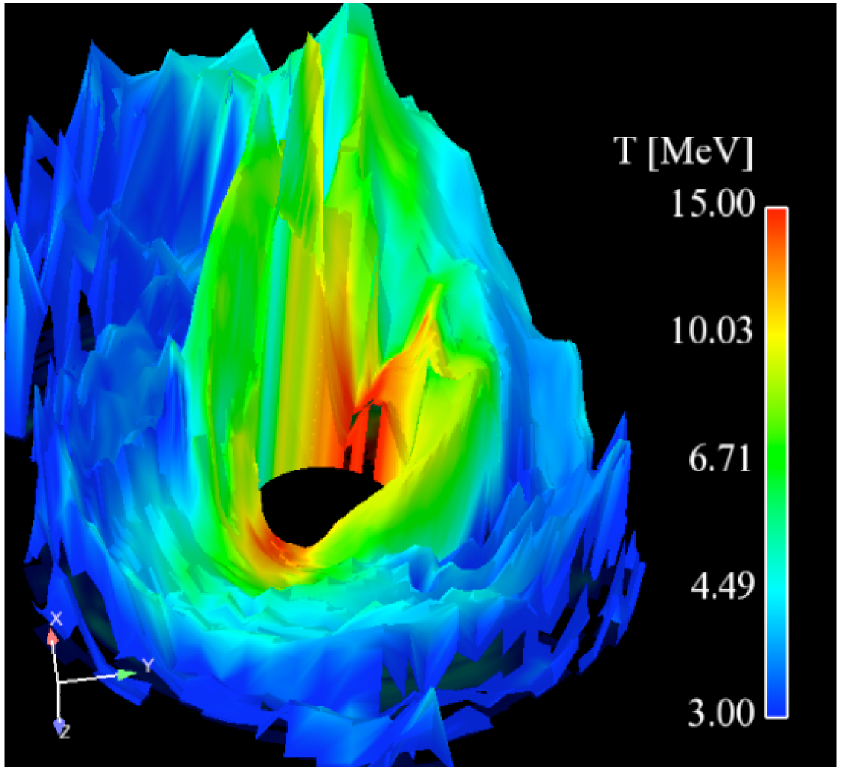


R-process occurs in the wind, but simplified emission surface of neutrinos

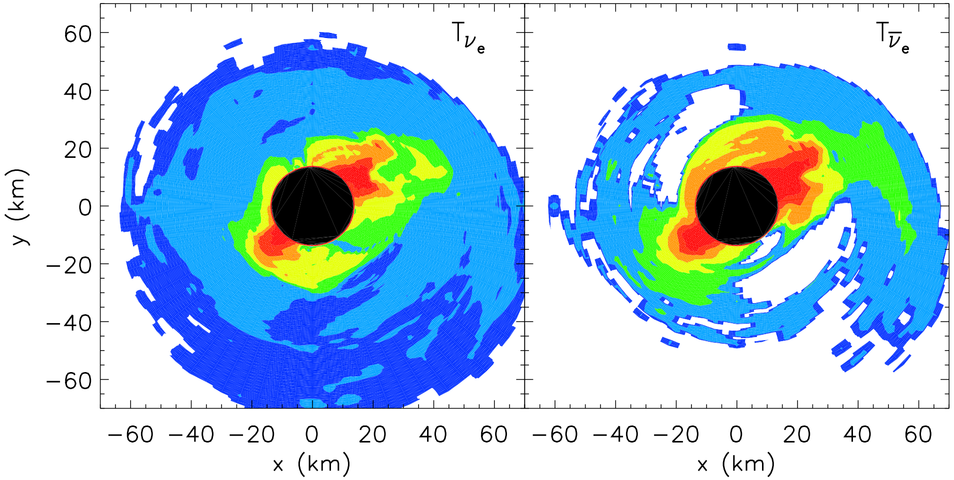
Surman et al. 2008

Hot ejection

Accretion Disk ν_e temperatures



Caballero et al



Surman et al 2008

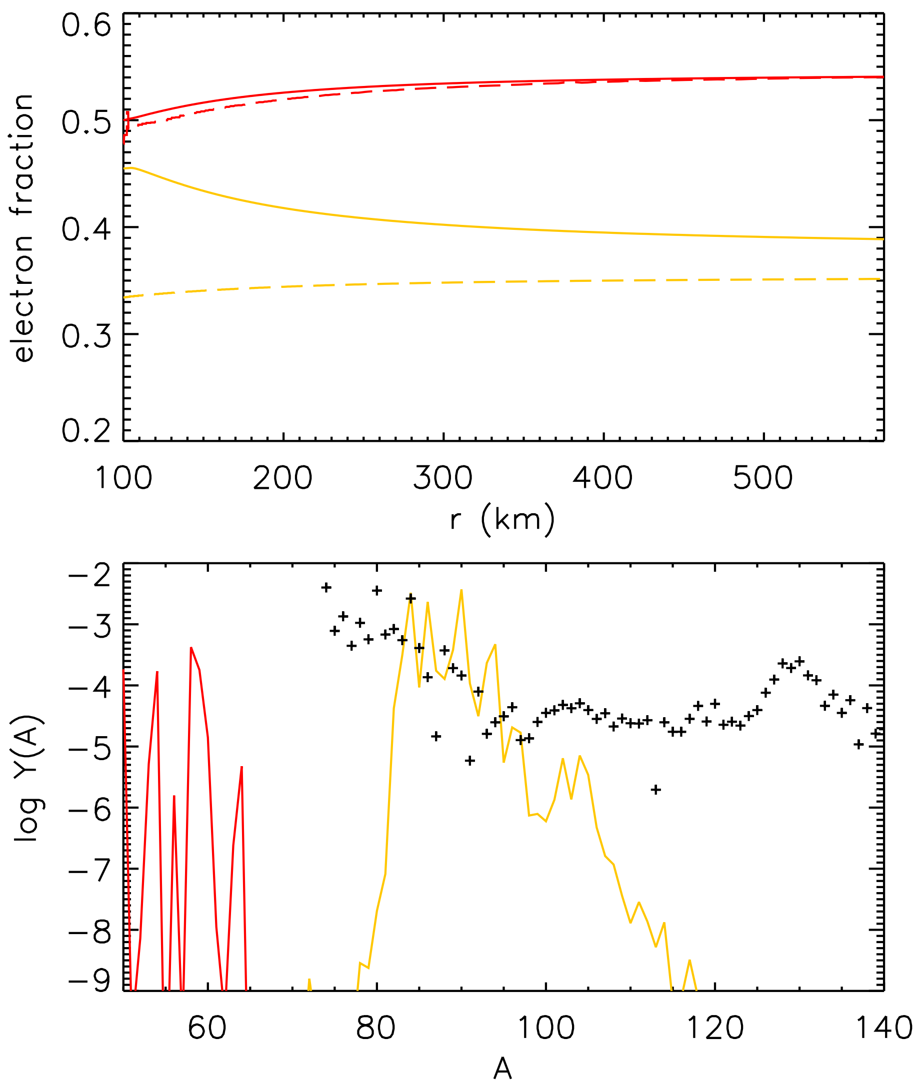
ν general relativistic effects - high entropy trajectory

Iron group elements

- yellow - No GR
- red - ν GR, no rot., a $= 0$

Stellar wind type trajectory with $s/k = 40$, $\beta = 2$

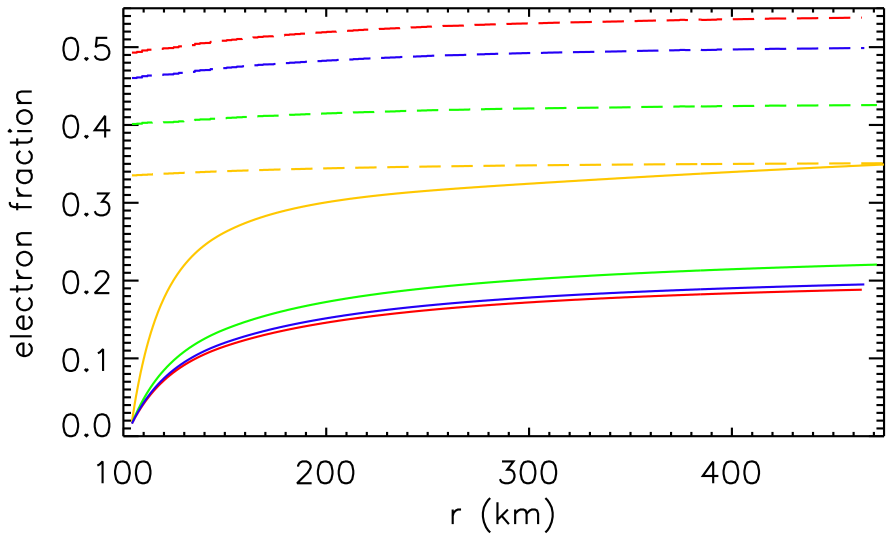
Caballero et al 2011

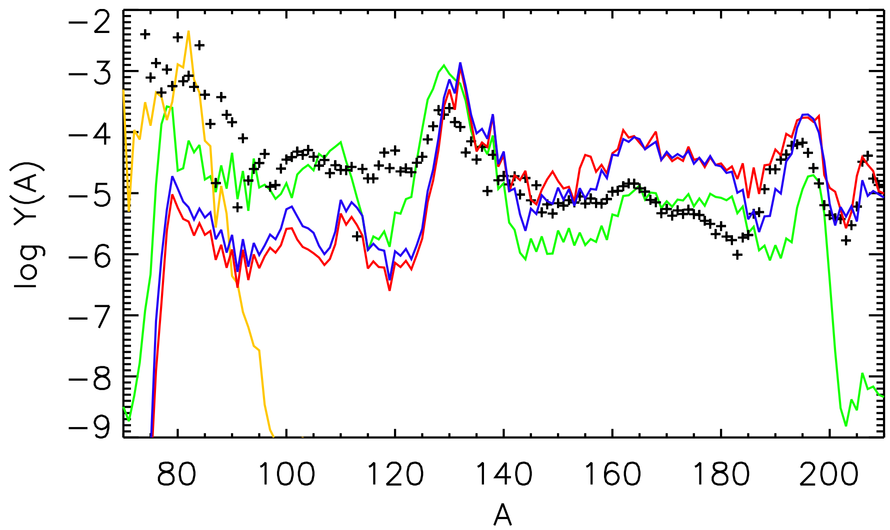


ν general relativistic effects

low entropy fast trajectories

- yellow - No GR, flat disk
- red - ν GR, no rot., a $=$ 0
- blue - ν GR, rot., a$=$0
- green - ν GR, rot., a$=$0.6



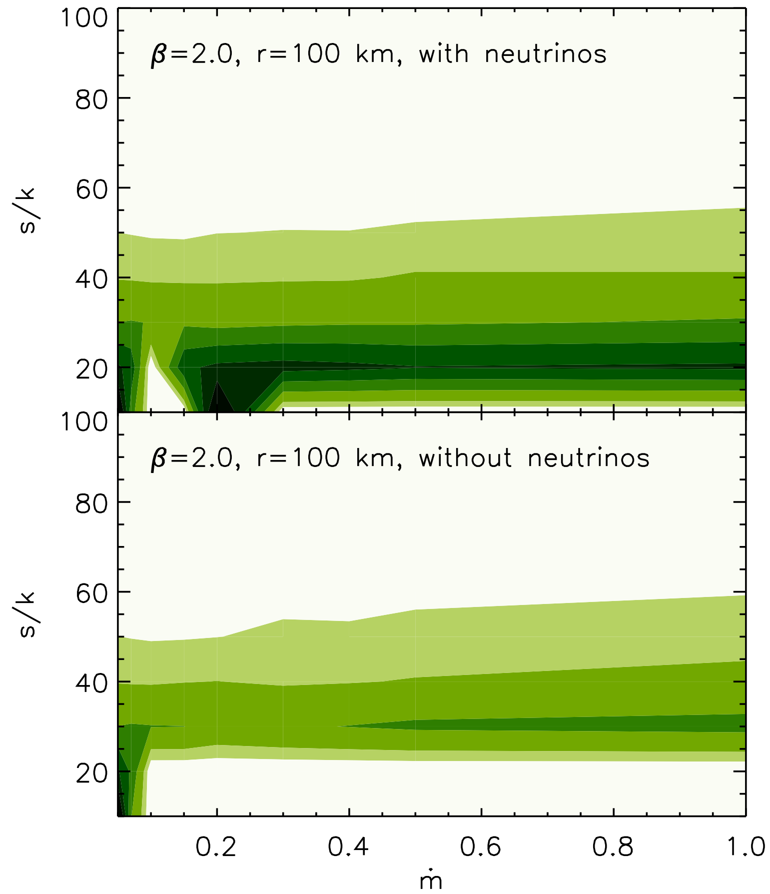


Neutrino wind type trajectory with s/k $=$ 20, t $=$ 5ms.

Caballero et al 2011

Expect behavior similar to collapsar type disks: Nickel - 56

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



Surman et al 2010

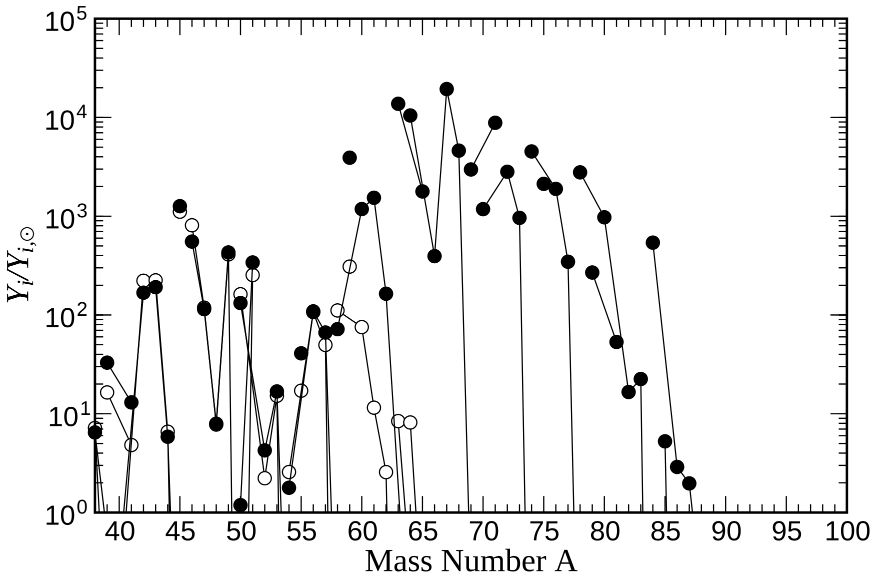
Expect behavior similar to collapsar type disks:

Neutrinos enhanced light p-nucleosynthesis

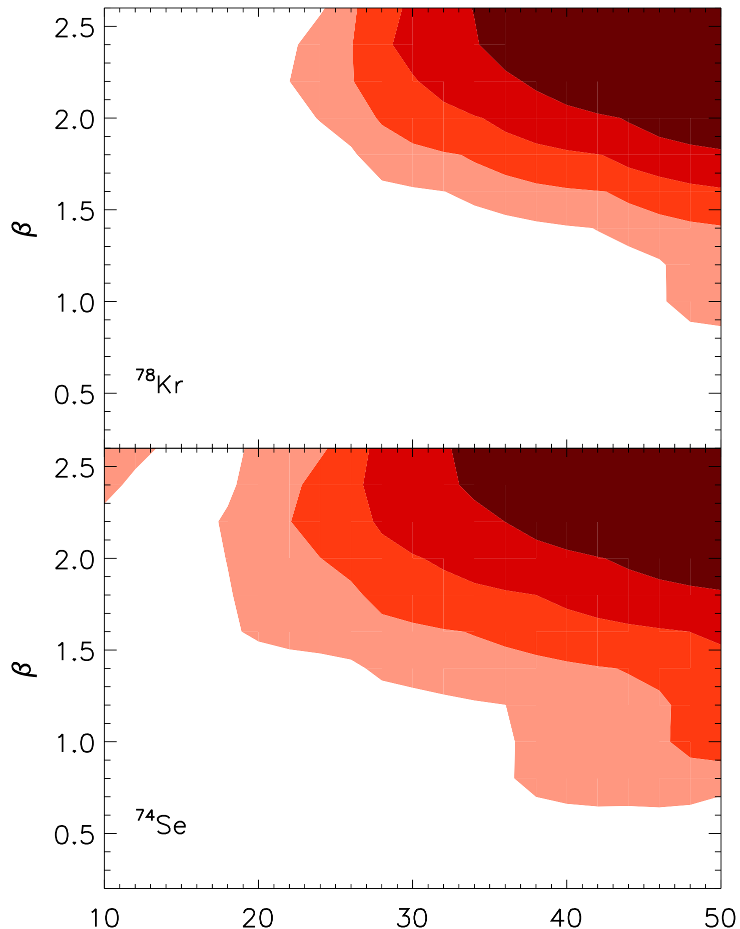
Thought to occur in supernovae and in accretion disk outflows

ν-p process

p-rich nuclei



Frohlich et al 2007, Kizivat et al 2010



Implications of Nucleosynthesis from compact object mergers

Three primary types of nucleosynthesis

1. r-process - tidal tails, maybe ν winds
2. p-process - ν winds
3. $^{56}\mathrm{Ni}$ and other iron group nuclei - ν winds

Implications of r-process from compact object mergers

Potentially one can make a lot of r-process

1. 10^{-1} $M_\odot$ to 10^{-3} $M_\odot$ per merger

2. together with a Galactic merger rates 10^{-4} yr^{-1}

3. makes 10^5 $M_\odot$ to 10^3 $M_\odot$ over 10^{10} years

4. amount of Galactic r-process mass with $A > 100$ is $\sim 10^4$ $M_\odot$

5. making a significant amount of r-process (if not overproduction)

Implications of r-process from compact object mergers

r-process is seen in halo stars

1. if this comes from mergers they must evolve quickly
2. ejecta must become more mixed in ISM than predicted Qian 2000

Most robust mechanism for producing the r-process is tidal tails

1. fission cycling
2. consistent abundance pattern
3. good because the pattern in halo stars is the same as in the solar system
4. bad if you don't get the right pattern

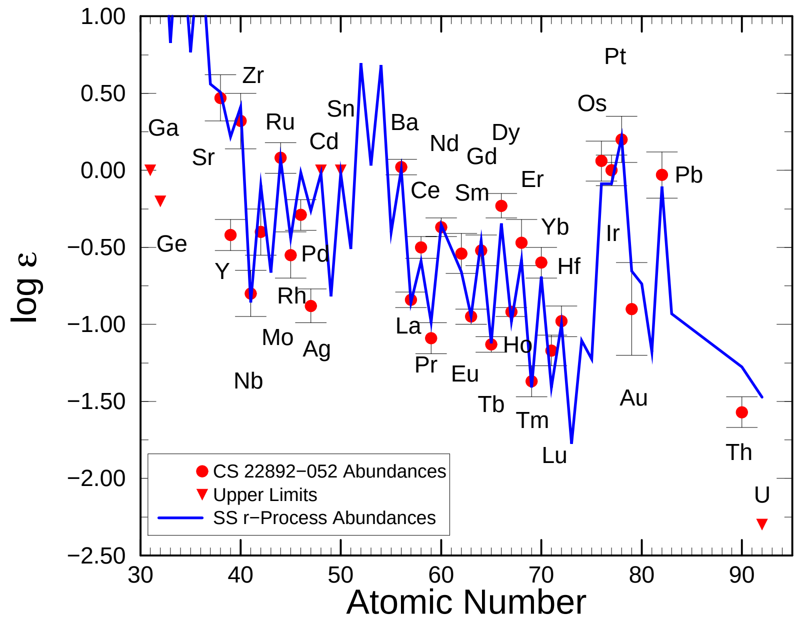
Halo star data:

Consistent main r-process pattern that looks solar

What does this suggest?

Two r-process sites?

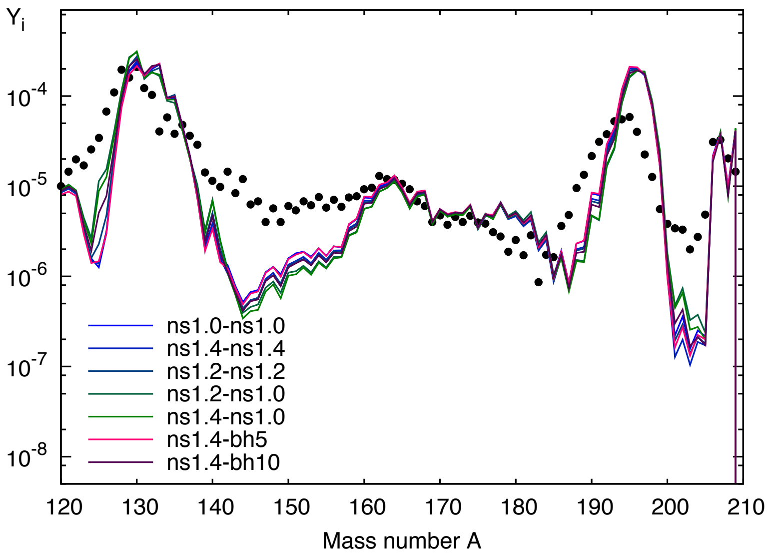
Figure from Cowan and Sneden (2004)



Mergers must evolve quickly or there are two r-process sites that produce exactly the same pattern.

Lets revisit a merger pattern

Fission cycling



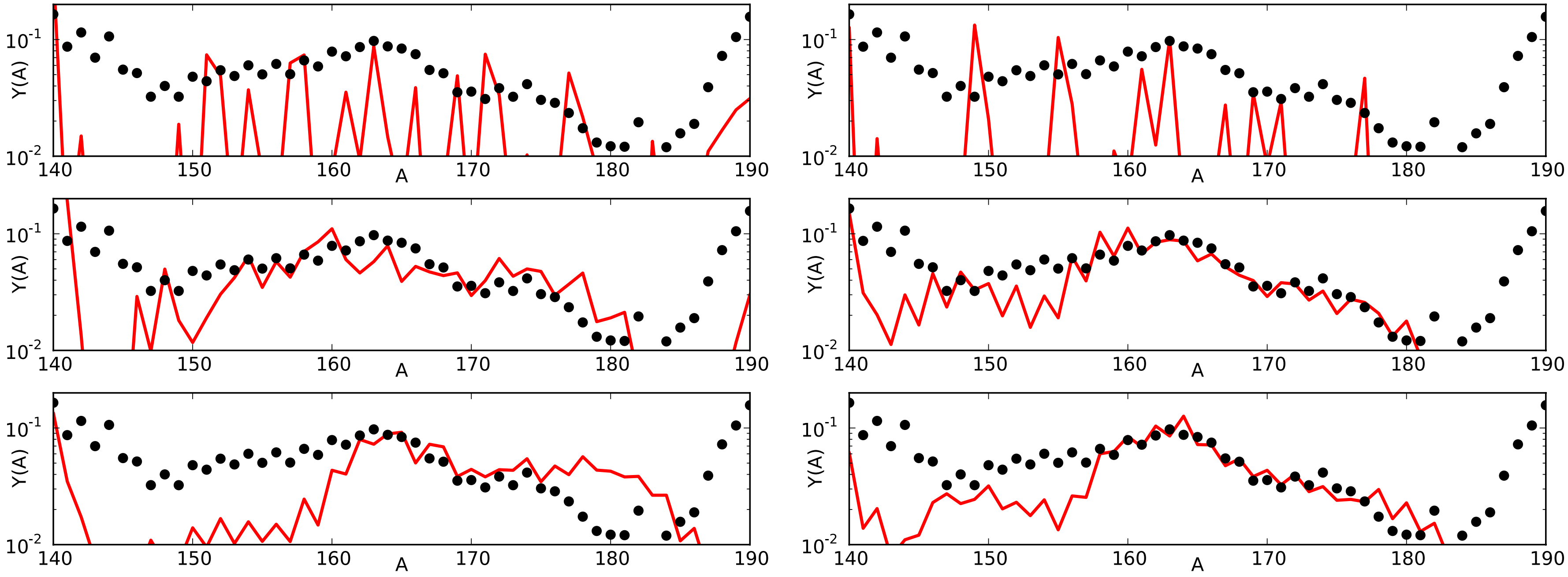
Korobkin et al

- has main peaks
- has a rare earth peak
- big hole before the rare earth peak

Why is the material on the sides of the rare earth peak tilted?

Watching the rare earth region form

(n, γ), (γ, n) equilibrium should persist to very low neutron to seed ratio or there is too much late time neutron capture



(a) (b)

Mumpower et al 2012

Reconciling the solar system pattern with mergers

Option 1

- outflow with very slowly declining temperature or low neutron density
- hard with tidal tails

Option 2

- arrange fission products so they fill in the whole
- not an aesthetically pleasing solution

Option 3: Mergers are not the primary source of the r-process

Conclusions

- Mergers make r-process through tidal tails
- Mergers make additional nuclei through winds - likely nickel
- Merger r-process abundance patterns have features of excess neutron capture
- More effort is needed to see if mergers can evolve quickly enough for halo stars
- Unless you don't make all the r-process material in the solar system this way
- But then this limits the amount that can be ejected from mergers