Neutrinos and Nucleosynthesis from Gamma Ray Bursts

Gail McLaughlin

North Carolina State

Outline

1. Gamma ray bursts
2. Gamma ray burst neutrinos
3. Nucleosynthesis from gamma ray bursts

Gamma Ray Bursts

- characteristics
  - few second bursts of $\sim$ MeV photons, isotropic on the sky
  - $10^{51} - 10^{54}$ erg if isotropic, but beamed to a few %
  - Two classes: Long ($>$ 0.2s) and short ($<$ 0.2s) Kouvelietou et al 1993
- Long Bursts - afterglows
  - x-ray, radio, optical counterparts, 3 hours-days, months after γs
  - SN bumps in a couple of light curves e.g. Stanek et al 2003
  - Asssociation with Type Ib/c supernovae
- Long Bursts - Association with host galaxies

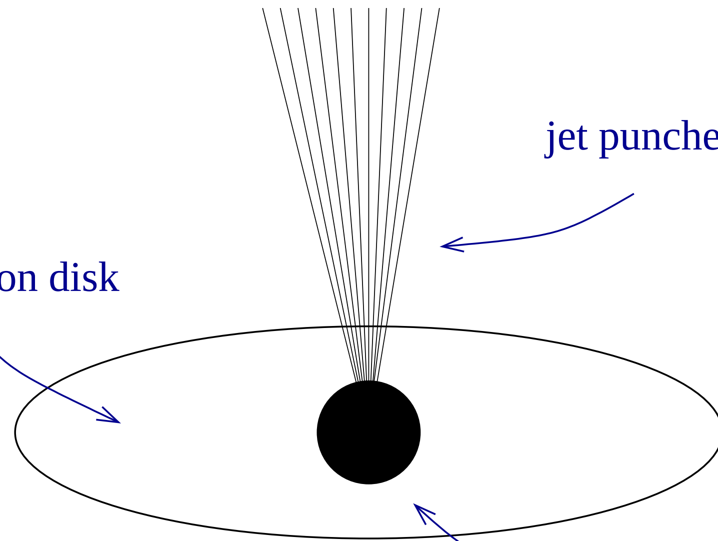
What astrophysical sites?

Long Bursts - Rare type of Core Collapse SN

Short Bursts - Neutron Star Mergers?

Collapsar/Hypernovae Model

- Failed Supernova
- Too much rotation for real collapse & bounce
- Create an accretion disk around a black hole

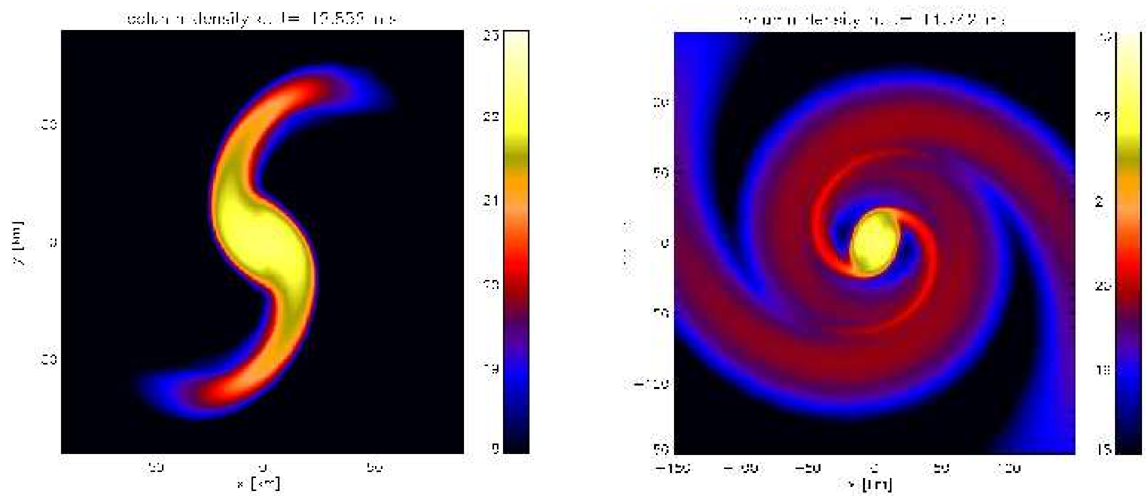


What provides the energy which drives the jet? The neutrinos! (at least in part)

Woosley 1993, MacFadyen and Woosley 1999

Neutron Star Merger Models

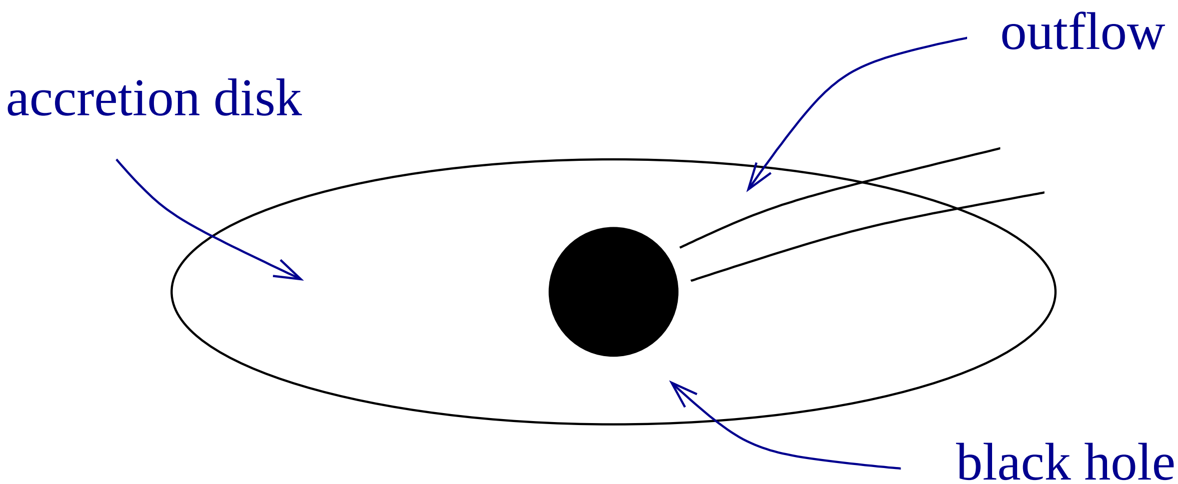
- Two neutron stars spiral in
- Create an accretion disk around a black hole



pictures from Rosswog 2002

What provides the energy which drives the jet? The neutrinos! (at least in part)

GRB accretion disk



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

Disk Models needed:

Popham, Woosley & Fryer 1999 DiMatteo, Perna & Narayan 2002

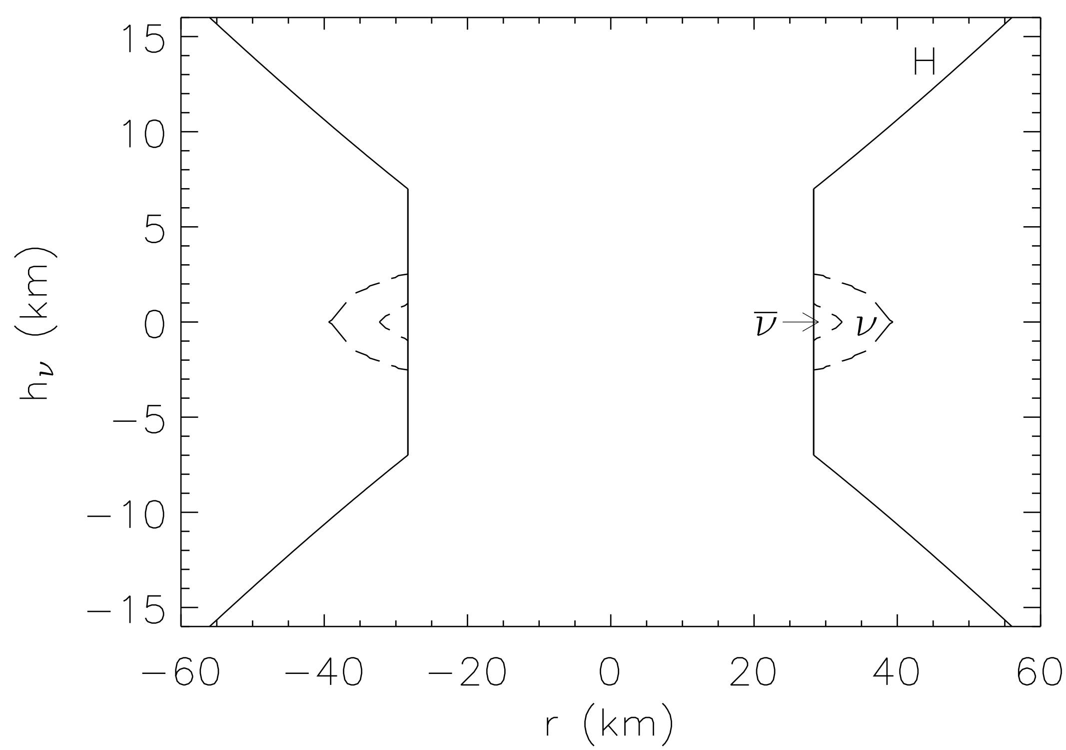
Charge changing neutrino interactions in the disk

Neutrino production and neutrino absorption:

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

- These aren't the neutrinos you might detect, but they might power the jet
- And affect the nucleosynthesis
- In high accretion rate and/or spin parameter disks, neutrinos become trapped
- Need to follow a mass element as it spirals into the disk and then gets ejected to understand the neutrino spectra

Neutrino and Antineutrino Surfaces:



Surman and McLaughlin 2003

For $\dot{M} = 1\,\mathrm{M}_\odot/\,\mathrm{s}$, a = 0 DPN

Trapped region grows rapidly as $\dot{M}$ increases

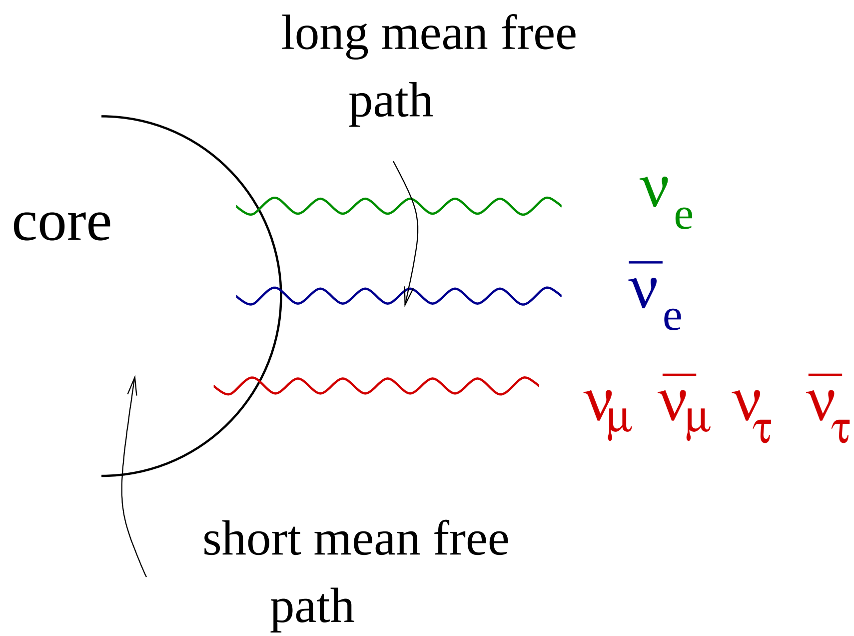
Small antineutrino surface, larger neutrino surface

Above surface $\nu_e + n \rightarrow e^+ + p$ faster than $\bar{\nu}_e + p \rightarrow e^- + n$

Surman and McLaughlin 2003

Comparison: Supernova Neutrinos

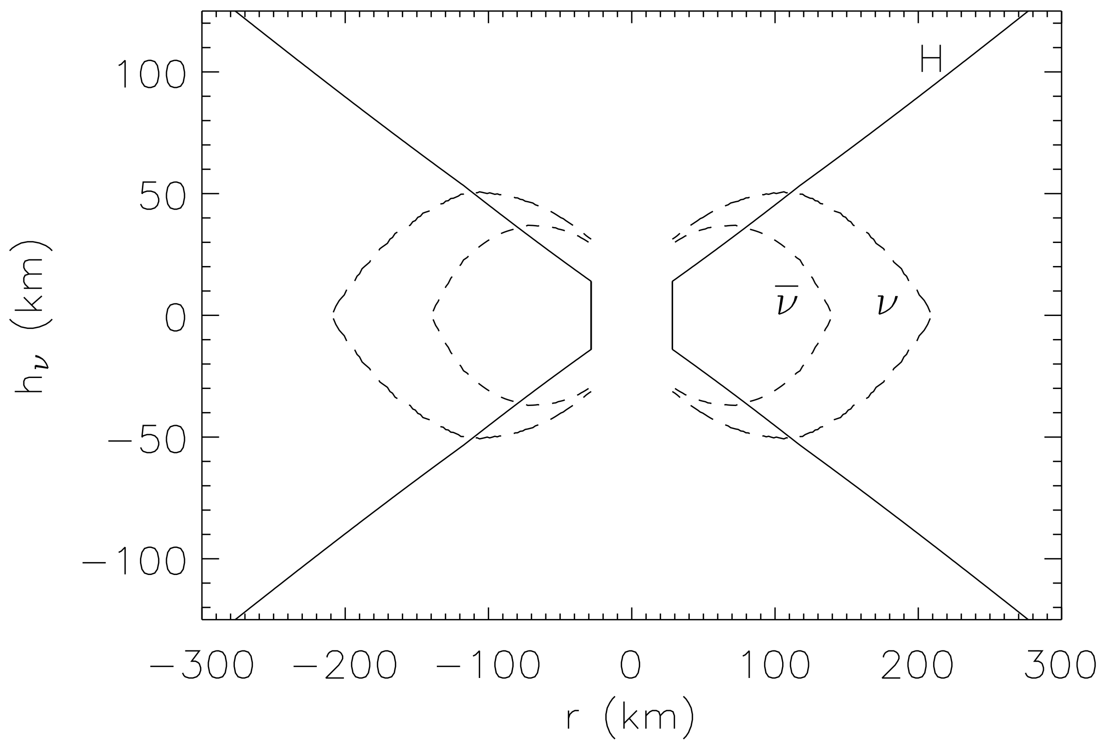
All types of neutrinos emanate from the core.



SN Neutrino spectra determined by surface of last scattering in SN core

$$T_{\nu_\mu}, T_{\bar{\nu}_\mu}, T_{\nu_\tau}, T_{\bar{\nu}_\tau} >> T_{\bar{\nu}_e} >> T_{\nu_e}$$

Neutrino and Antineutrino Surfaces:



For $\dot{M} = 10\,\mathrm{M}_\odot/\,\mathrm{s}$, a = 0 DPN
Large neutrino and antineutrino surfaces. $T_{\bar{\nu}_e} > T_{\nu_e}$
Above surface $\bar{\nu}_e + p \rightarrow e^- + n$ faster than $\nu_e + n \rightarrow e^+ + p$
Surman and McLaughlin 2003

A few numbers:

Temperatures at the surface of neutrino spheres:

- $T_{\nu_e} = 2.5\,\mathrm{MeV}$ to $T_{\nu_e} = 4.5\,\mathrm{MeV}$
- $T_{\bar{\nu}_e} = 3.6\,\mathrm{MeV}$ to $T_{\bar{\nu}_e} = 5.1\,\mathrm{MeV}$

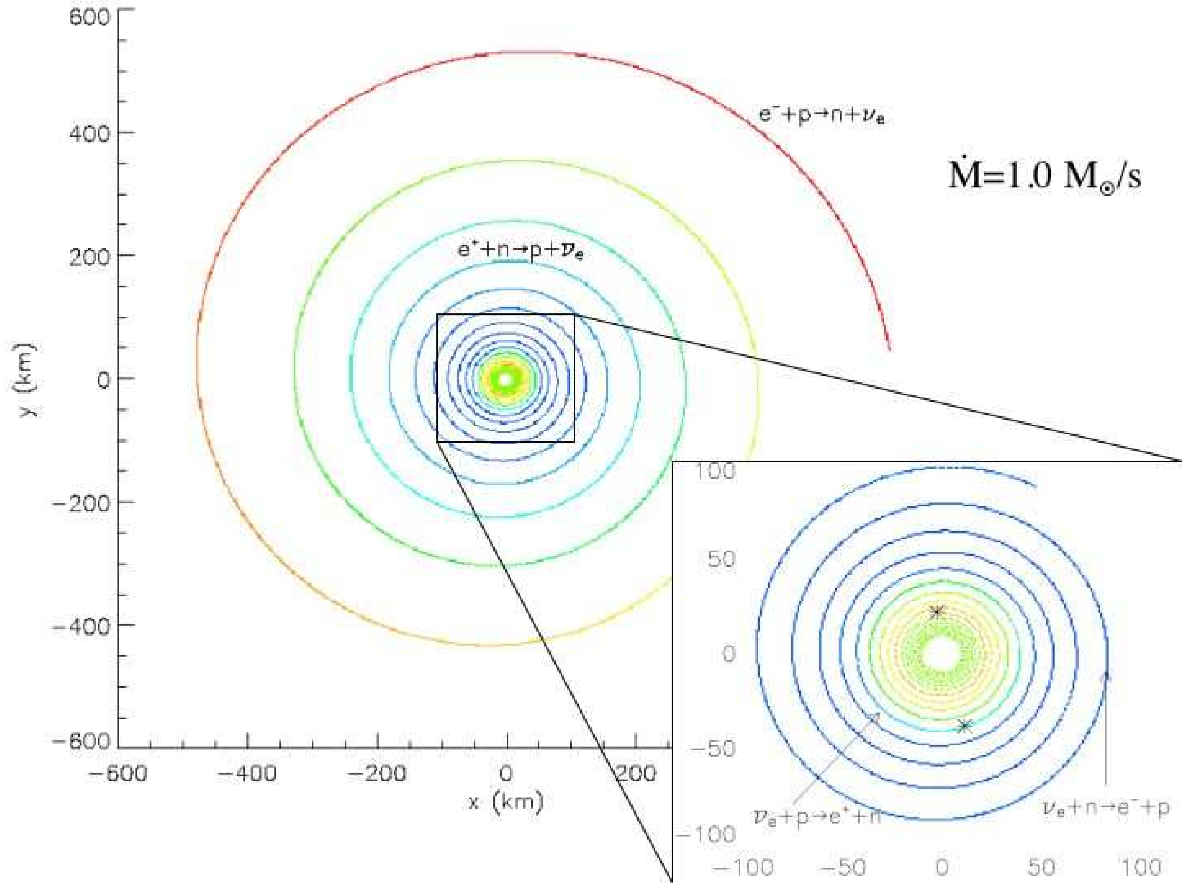
Density at the center of disks:

- $\rho = 10^{10}\,\mathrm{g\,cm^3}$ to $\rho = 10^{12}\,\mathrm{g\,cm^3}$

Temperature at the centers of the disks:

- $T \sim 10\,\mathrm{MeV}$ to $T \sim 1\,\mathrm{MeV}$

Following a mass element in the disk:



Surman and McLaughlin (2003)

Nucleosynthesis in the disk outflow:

What might we find?

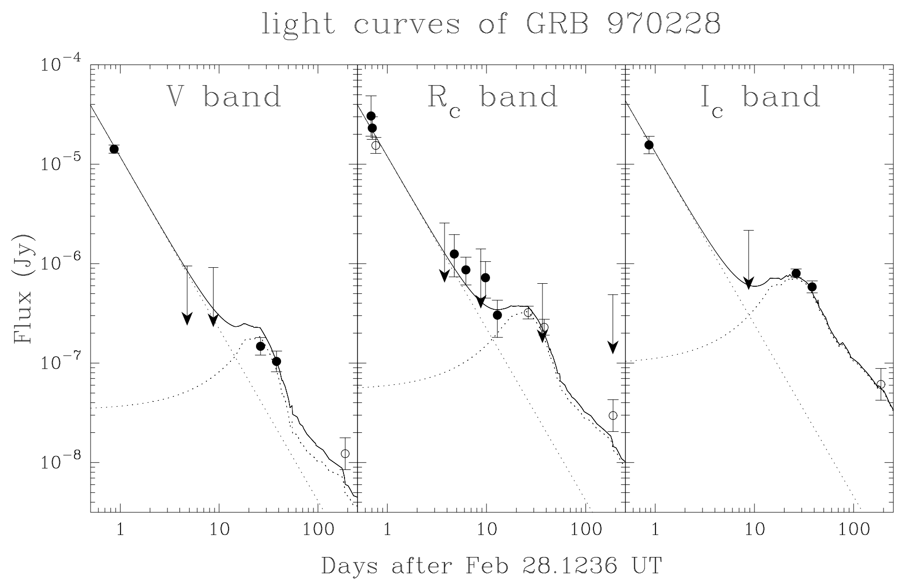
- Nickel-56
- r-process nuclei
- light p-process
- other rare nuclei
- D, Li, Be, B

Some definitions:

- Mass fraction X_j - fraction of total mass in a given nuclear species, j
- Overproduction factor $O = \frac{M_{wind}}{M_{ejecta}} \frac{X_j}{X_{\odot,j}}$, use $\frac{M_{wind}}{M_{ejecta}} \sim 0.1$
- Electron fraction $Y_e = 1/(1 + n/p)$.

Nickel in the Outflow from GRB accretion disks

Supernova light curve bumps are seen in the afterglow light curves of some GRBS



Galama et al 1999

About $\sim 0.5 M_\odot$ Nickel-56 is required for these bumps Woosley and Heger 2003

It could come from the disk outflow MacFadyen 2003, MacFadyen and Woosley 1999

or it could come from explosive burning Maeda and Nomoto 1004

Nucleosynthesis in the disk outflow:

What matters? The same things as in the Supernova...

- Entropy per baryon: in the disk it is $S/B \sim 10$, heating presumably brings it to somewhere between 10-40, e.g. Pruet, Thompson, Hoffman (2004)
- Outflow velocity and acceleration, we parameterize $v = v_\infty (1 - R_0/R)^\beta$ with $\beta = 0.2 - 2.5$, $v_\infty = (1-3) \times 10^4 \mathrm{km\,s^{-1}}$, flow first vertical, then radial
- New for GRBs - Starting position on the disk
- The neutrinos! i.e. the accretion rate and spin parameter of the disk

Studying the nucleosynthesis:

We'll study outflow from three types of disks:

- slowly accreting disks - $\dot{M} = 0.1\,\mathrm{M}_\odot\,/\,\mathrm{s}$: predicted by collapsar model: long burst GRBs
- moderately accreting disks $\dot{M} = 1\,\mathrm{M}_\odot\,/\,\mathrm{s}$: predicted by neutron star merger models: short burst GRBs
- high accretion rate disks $\dot{M} = 10\,\mathrm{M}_\odot\,/\,\mathrm{s}$: predicted by neutron star merger models: short burst grbs

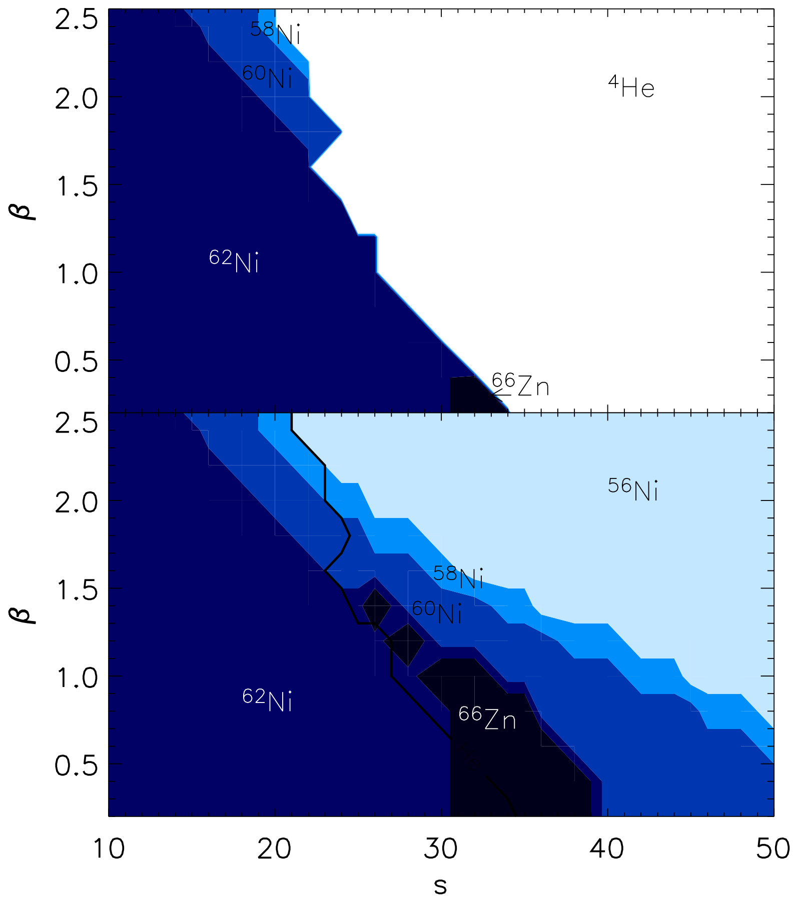
Rate for long duration GRBS: 10^{-3} lower than core collapse supernova

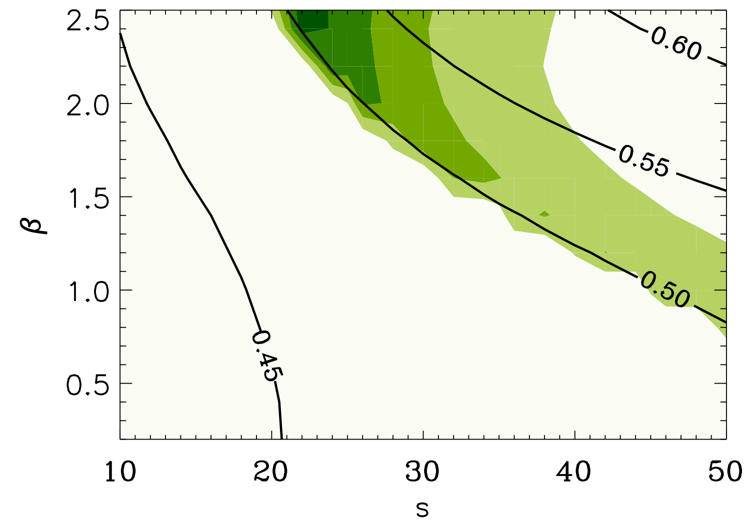
Are there core collapse events that make disk winds but not bursts?

Same question for neutron star mergers..

Nucleosynthesis from slowly accreting disks:

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





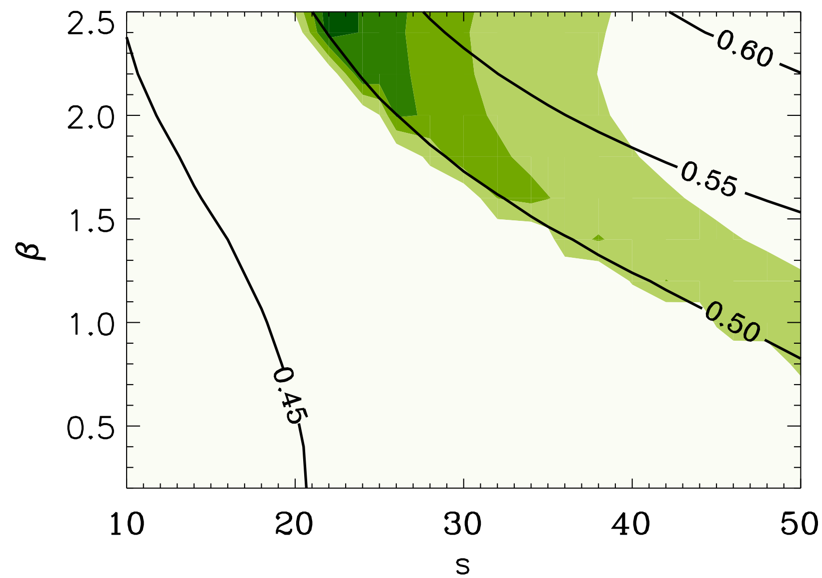
Y_e (lines), Nickel-56 (green)

Surman, McLaughlin, Hix 2005

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

Influence of the Neutrinos

It can be seen in the electron fraction contours:

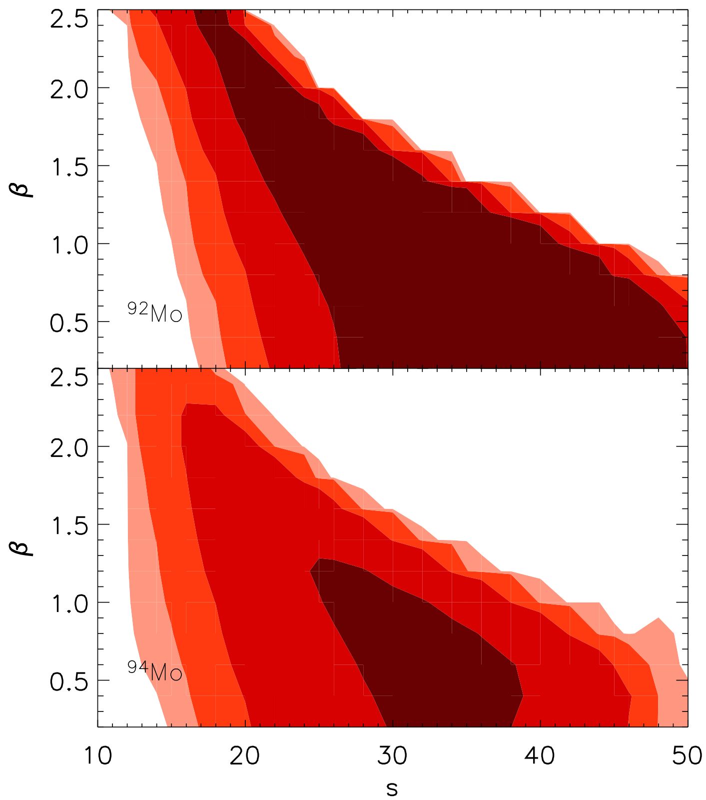


Vertical contours would be no influence from the neutrinos

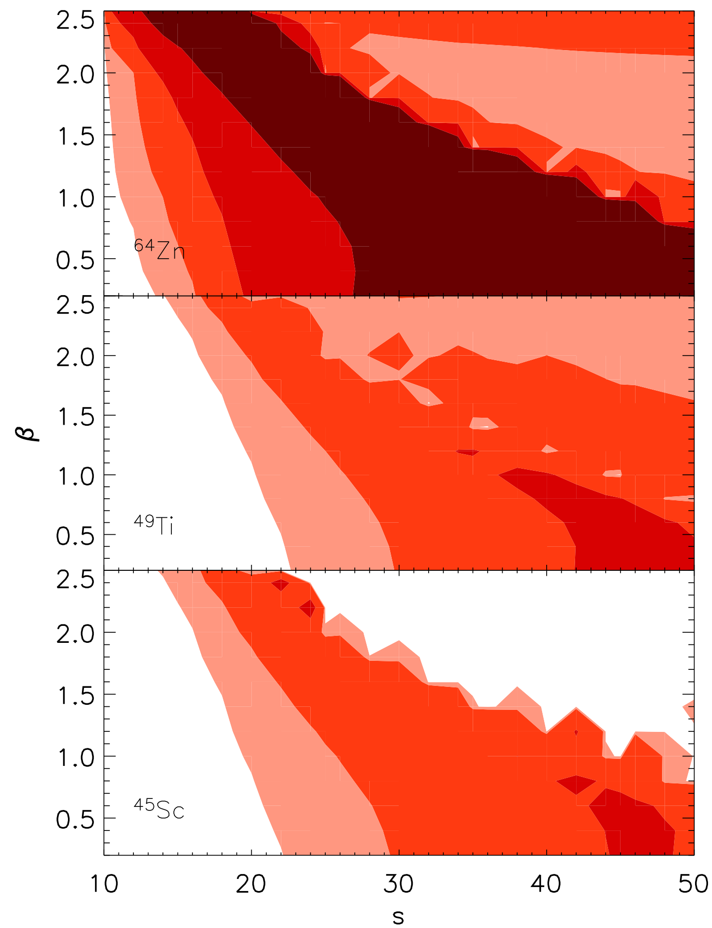
Horizontal contours would be maximal influence of the neutrinos

In this case ν_e from inverse beta decay interact with neutrons in the outflow through $\nu_e + n \rightarrow p + e^-$ to make the material more proton rich.

Overproduction factors for slowly accreting disks:



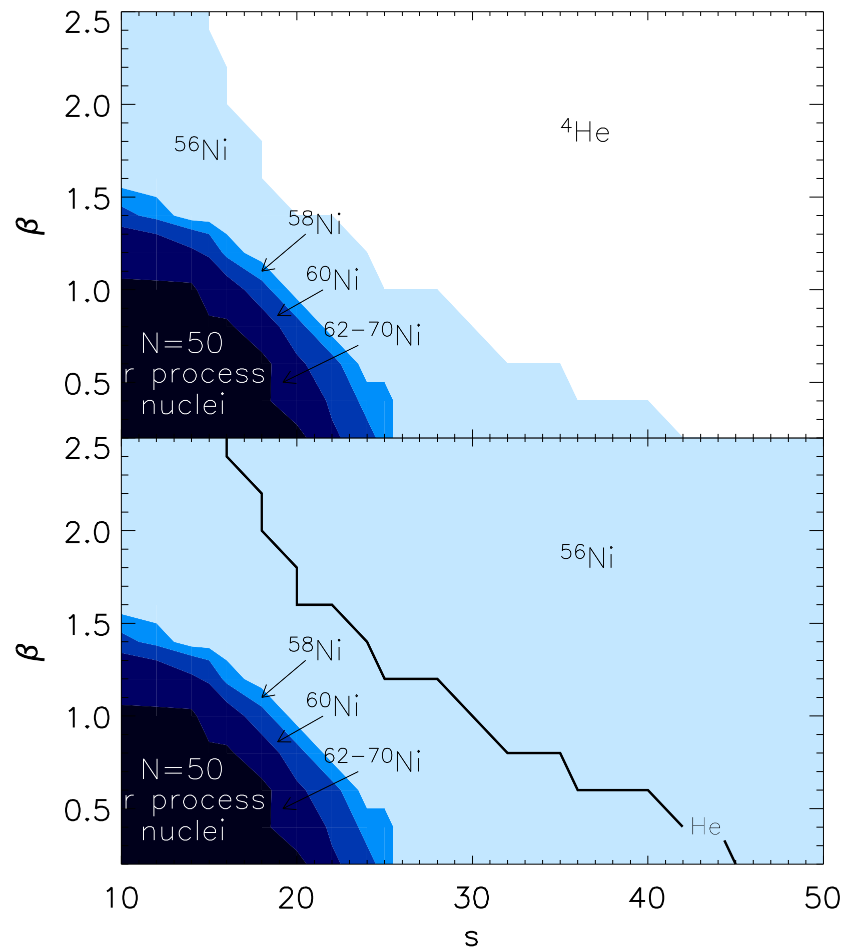
^{92}Mo, ^{94}Mo



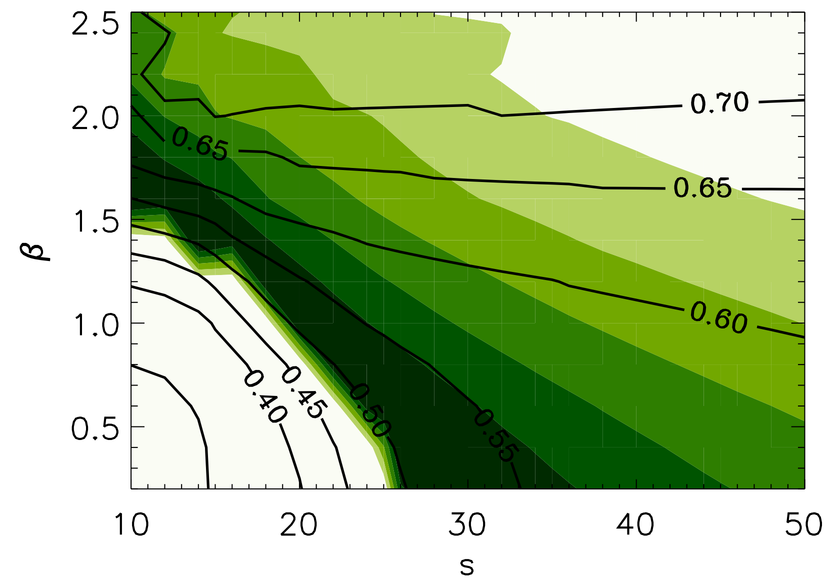
Zinc-64, Titanium-49, Scandium-45

Pruet, Surman, McLaughlin 2003, Surman, McLaughlin, Hix 2005

Nucleosynthesis from moderate accretion rate disks: $\dot{M} = 1\,M_{\odot}/\,\mathrm{s}$



Maximum mass fraction

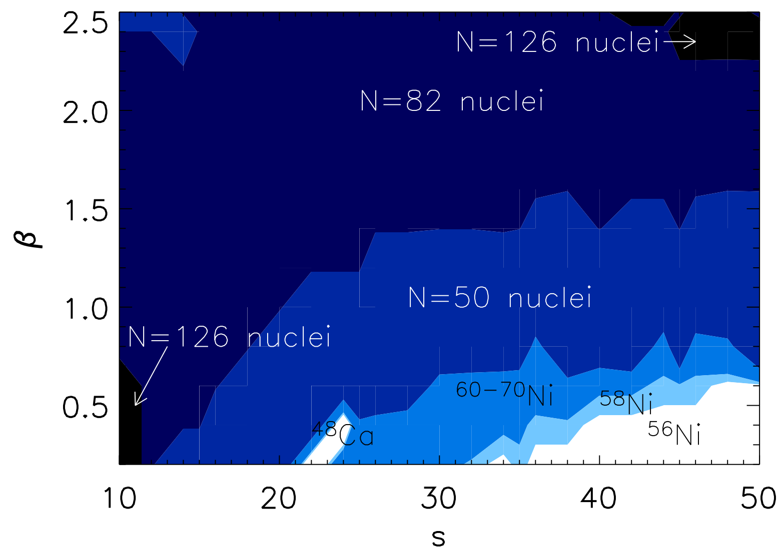


Y_e (lines), Nickel-56 (green)

Surman, McLaughlin, Hix 2005

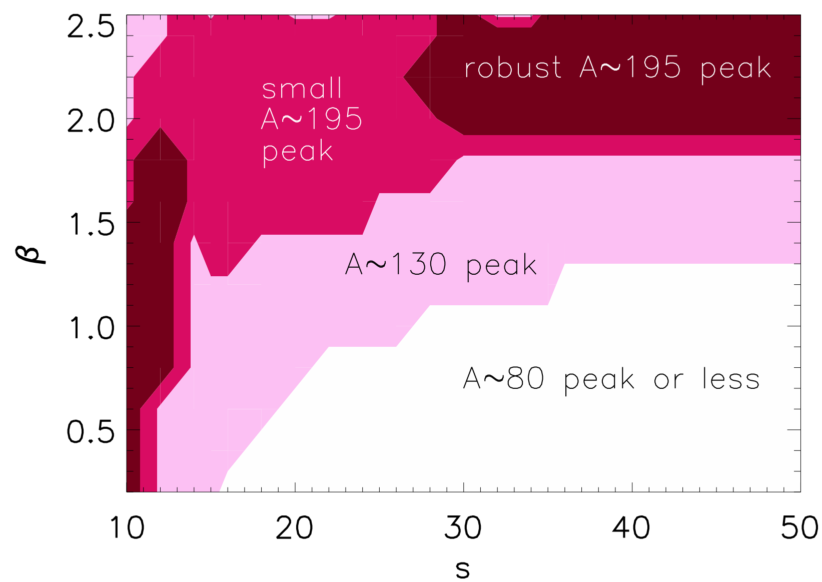
Nucleosynthesis from high accretion rate disks:

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



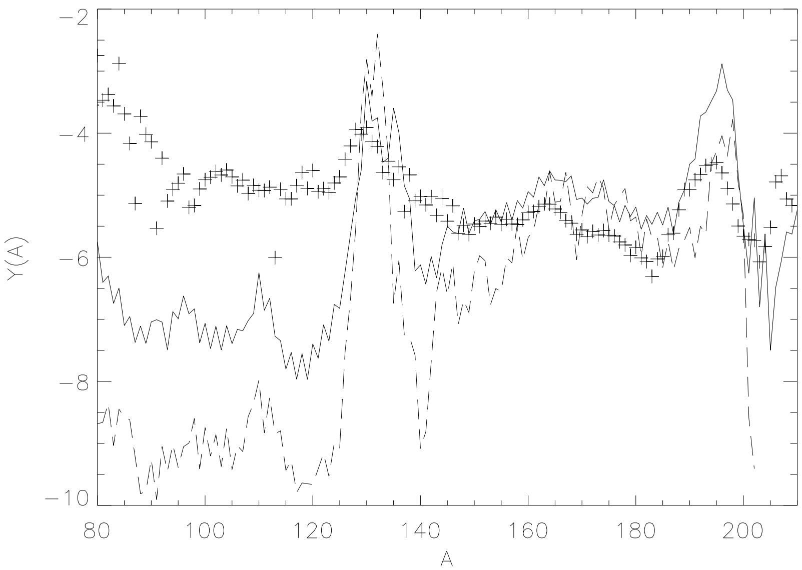
Nuclear species with the largest mass fraction

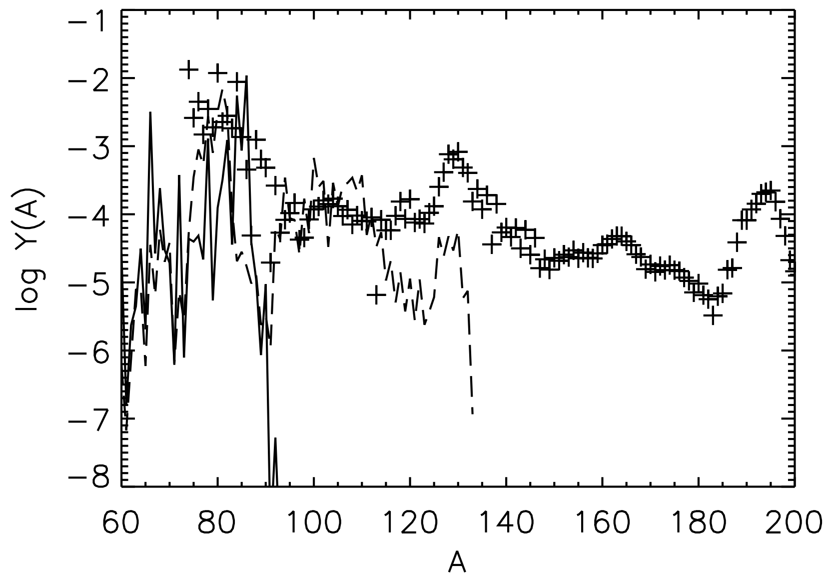
McLaughlin and Surman 2004, Surman, McLaughlin and Hix 2005



r-process peaks

A couple of r-process scenarios: $\dot{M} = 10\, M_\odot /\, \mathrm{s}$





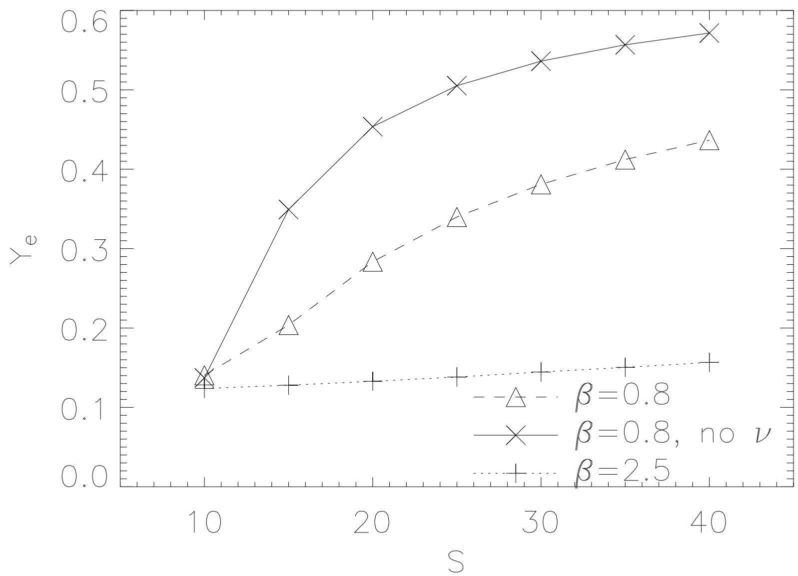
Fast acceleration or low entropy

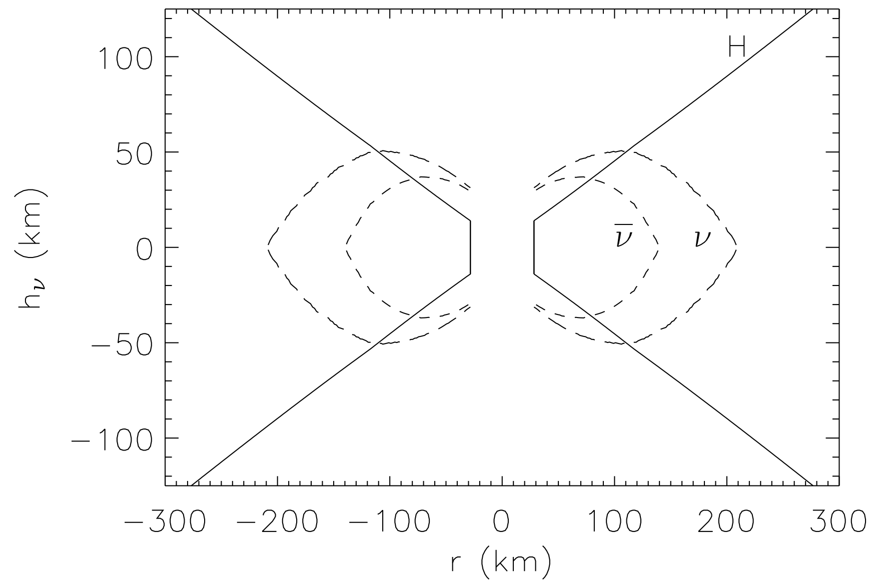
moderate entropy, acceleration

DPN $\dot{M} = 10.0\, \mathrm{M}_\odot/\mathrm{s}$, $\alpha = 0.1$, $a = 0$, $v_\infty = 3 \times 10^4 \mathrm{km/s}$

Why the r-process?

Again, check out the electron fractions





Y_e for different accelerations

Neutrino surface, again

DPN $\dot{M} = 10.0\,\mathrm{M}_\odot/\mathrm{s}$, $\alpha = 0.1$, $a = 0$, $v_\infty = 3 \times 10^4 \mathrm{km/s}$

A slow outflow or a low entropy creates neutron rich environment!

Two kinds of r-process data: Observational and Meteoritic

Meteoritic: Isotopic measurements of r-process nuclei:

two r-process sites?

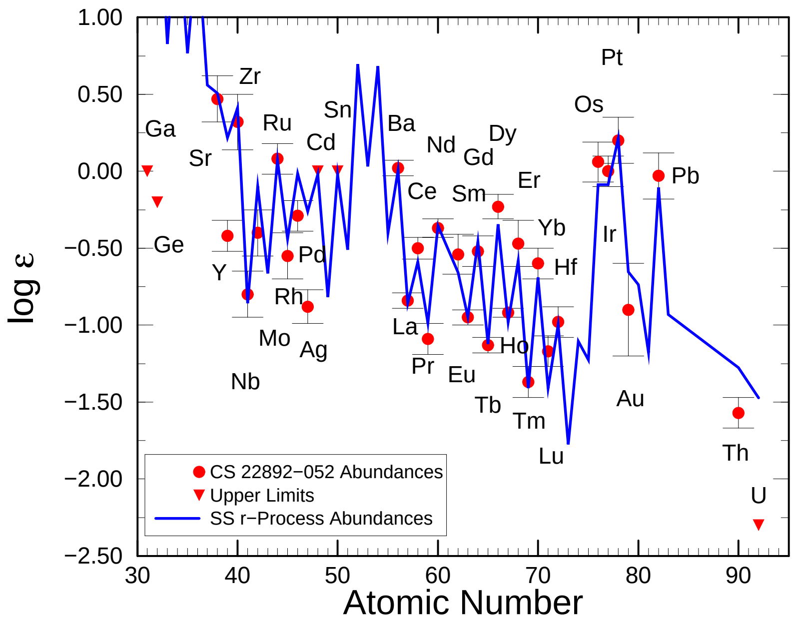
Wasserburg, Busso and Gallino (1996)

Y.-Z. Qian

Observational Metal Poor Halo Stars:

two r-process sites?

Figure from Cowan and Sneden (2004)



Implications of r-process data

Data implications (see work by Y.-Z. Qian)

Halo stars - good agreement with solar system abundances above 130 peak suggests an event that operates early

Meteorites- isotopic analysis - event that makes the A=195 peak occurs often

Meteorites - isotopic analysis - event that makes light r-process nuclei occurs less often

Implications for GRBS :

(1) Collapsar model does not at present make an r-process
(2) Neutron Star Mergers models could make the light r-process

Summary

- Some nucleosynthesis comes from gamma ray bursts
- Possibly also from accretion disk outflow without bursts
- It could be an r-process
- It could be Nickel-56
- It could be $^{92}\mathrm{Mo}$

But how will we know?

- Galactic Chemical Evolution
- Emission lines in X-ray afterglows
- Improved calculations

Outlook

We need to better understand...

- neutrino diffusion in the disk
- neutrino oscillations driven by neutrino-neutrino scattering
- the outflow from the disk
- the disk itself, black hole spin parameter