Nucleosynthesis from Black Hole Accretion Disks

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Three Relevant Nucleosynthesis Processes

Explosive Burning

- e. g. shock moves through outer layers of star
- pre-exiting nuclei recombine to form new nuclei

Winds

- start with free neutrons and protons near hot part of object
- material flows away from the hot part and cools
- as it cools free neutrons and protons recombine into nuclei

Ejection of Cold Neutron Rich matter

- might occur, e.g. from edges in in-spiraling neutron stars
- neutron captures, beta decays make heavy elements

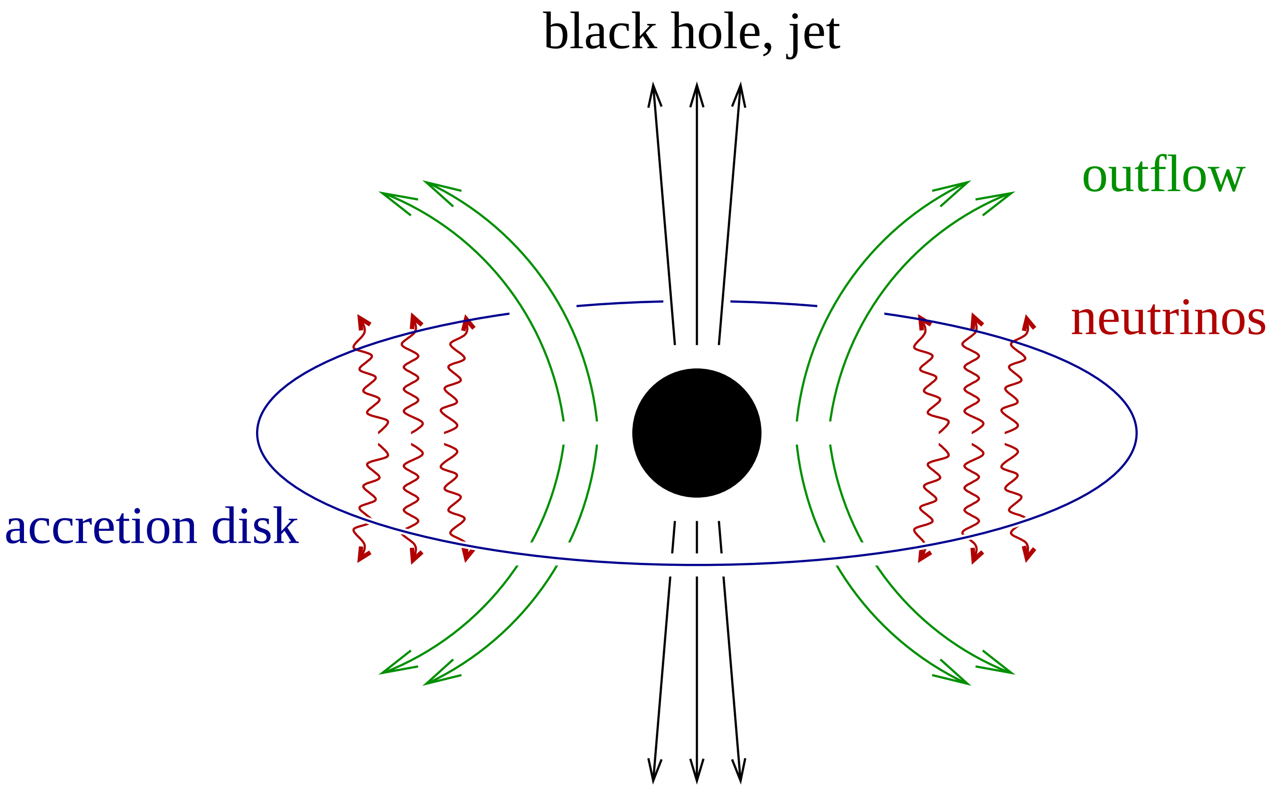
Which nucleosynthesis process is appropriate?

Depends on the circumstances:

Nucleosynthesis from object is composed of one of these (explosive burning, winds, ejection of neutron rich matter) or some combination or none

This talk is about calculations of nucleosynthesis from winds

Black Hole Accretion Disks



What matters for the wind nucleosynthesis

- neutron to proton ratio
- entropy
- timescale of outflow

How charged current weak interactions determine the nucleosynthesis

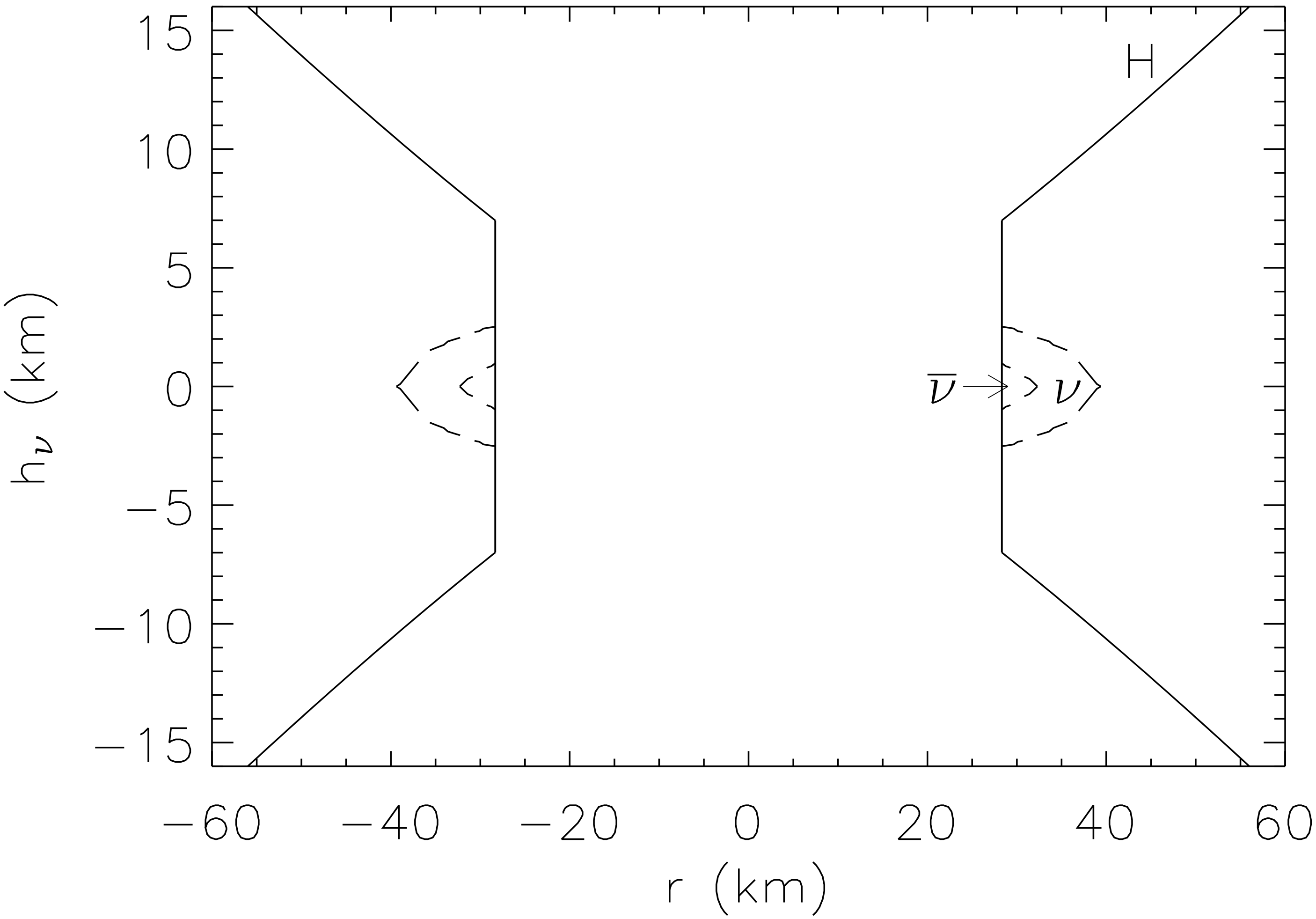
$$e^- + p \leftrightarrow n + \nu_e$$

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

$+$ capture on nuclei

$+$ beta decay

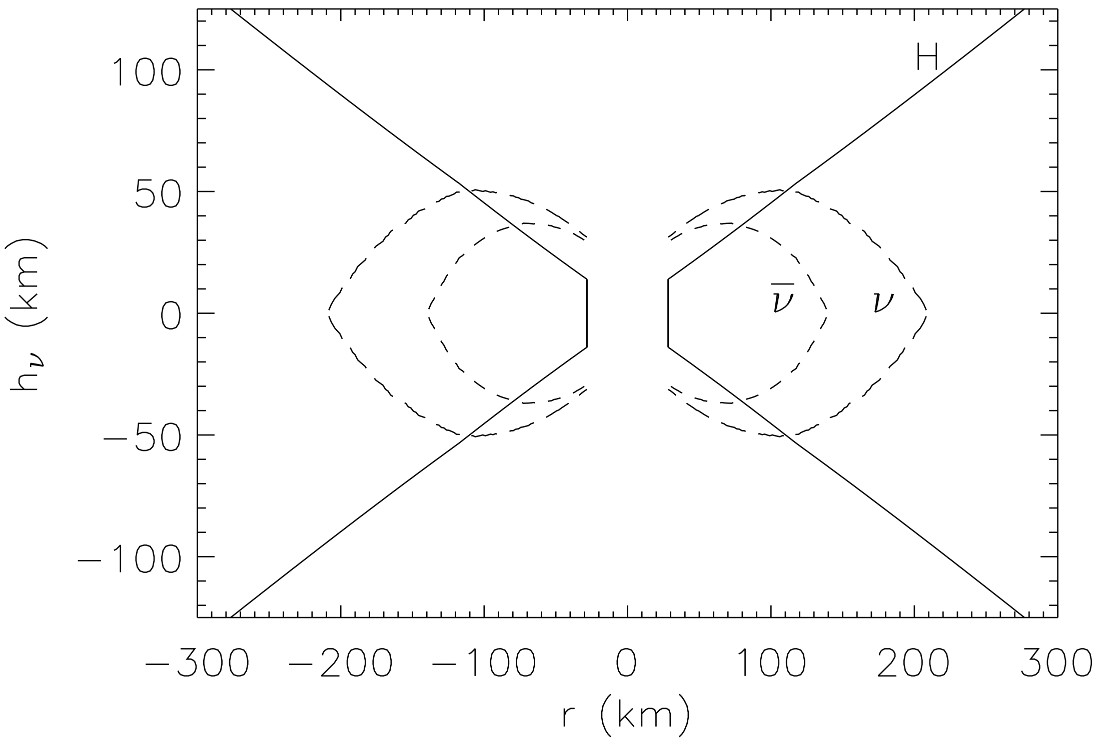
The accretion disk neutrino surface:



$\dot{M} = 1\mathrm{M}_\odot/\mathrm{s}$, $\mathrm{a} = 0$, neutrino physics built on a DPN (2002) model

Surman and McLaughlin 2003

Electron Neutrino and Antineutrino Surfaces:



For $\dot{M} = 10\,\mathrm{M}_\odot/\,\mathrm{s}$, a = 0 DPN

Depending on the model we find $T_{\nu_e} = 2.5$ MeV to 4.5 MeV and $T_{\bar{\nu}_e} = 3.6$ MeV to 5.1 MeV

How neutrinos determine the nucleosynthesis

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

$+$ capture on nuclei

$\dot{M} = 0.1\mathrm{M}_\odot/\mathrm{s}, a = 0 \rightarrow$ some neutrinos, ν_es from inverse beta decay are a correction to e^+e^- capture and create a more proton rich environment - nickel, p-process

$\dot{M} = 1\mathrm{M}_\odot/\mathrm{s}, a = 0 \rightarrow$ more neutrinos, $\nu_e s$ from trapped region overwhelm $\bar{\nu}_e$s which have a smaller trapped region and create a *very* proton rich environment

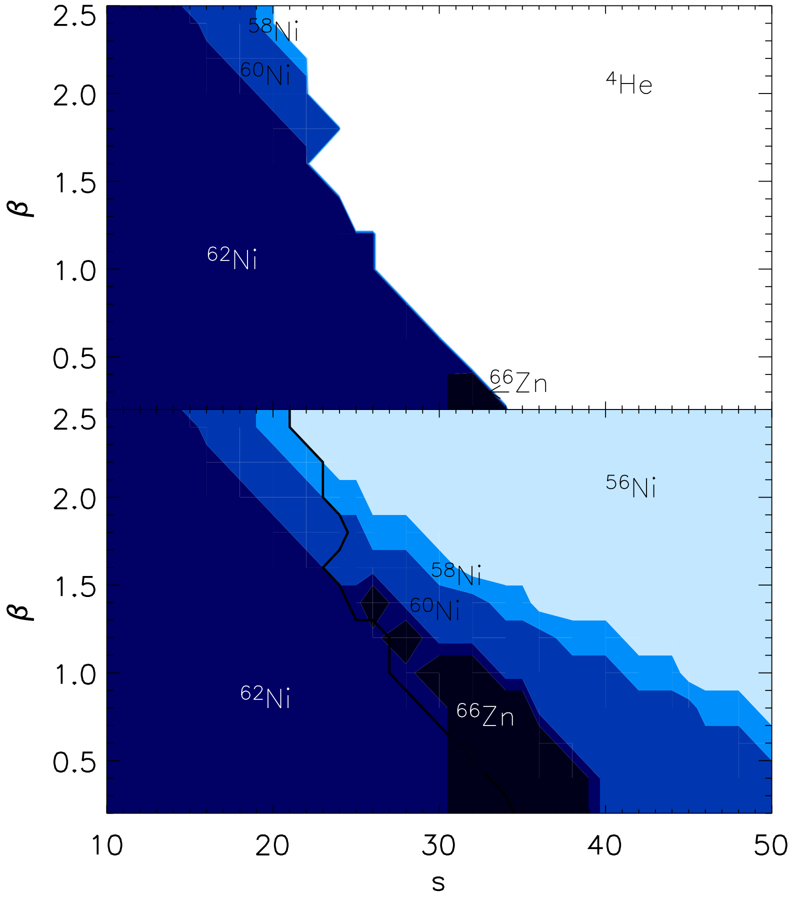
$\dot{M} = 10\mathrm{M}_\odot/\mathrm{s}, a = 0 \rightarrow$ lots of neutrinos, $T_{\bar{\nu}_e}$ from trapped region is higher than T_{ν_e} creates lots of neutrons - the r-process!

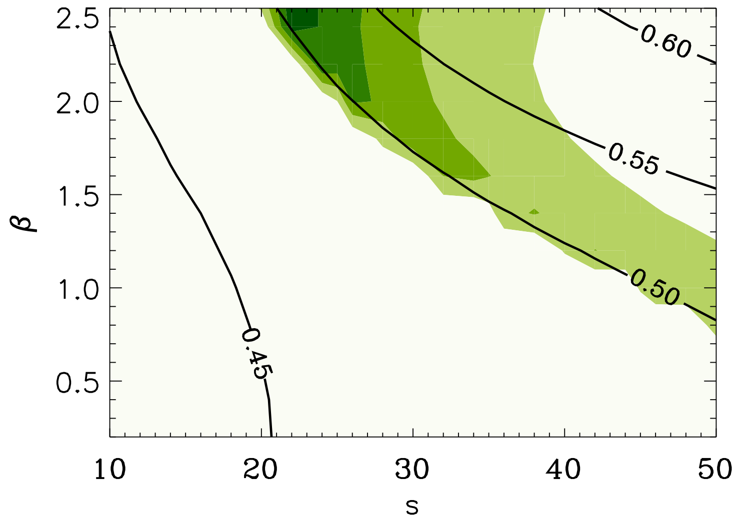
More details on the nucleosynthesis

What else matters?

- Entropy per baryon: in the disk it is $S/B \sim 10$, heating presumably brings it to somewhere between 10 and 50, e.g. Pruet, Thompson, Hoffman (2004)
- Outflow velocity and acceleration, we parametrize
  $v = v_\infty(1 - R_0/R)^\beta$ with $\beta \rightarrow 0.2\,\mathrm{to}\,2.5$,
  $v_\infty = (1-3) \times 10^4 \mathrm{km\,s^{-1}}$,
  flow first vertical, then radial
- Starting position on the disk, because of the influence of the neutrinos

Nucleosynthesis from 0.1 $\mathrm{M}_\odot/\,\mathrm{s}$, a $=$ 0 disks:





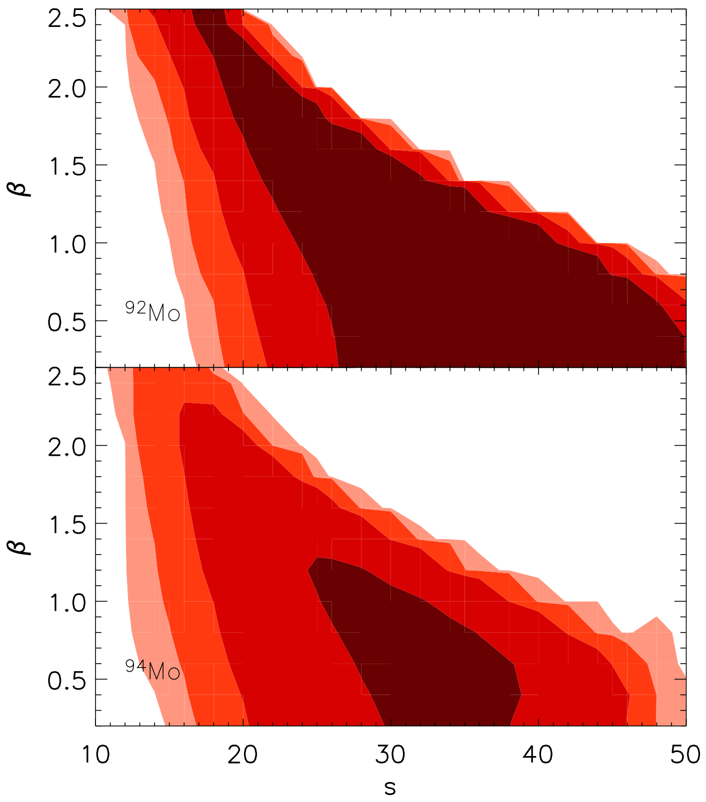
Y_e (lines), Nickel-56 (green)

Surman et al 2006

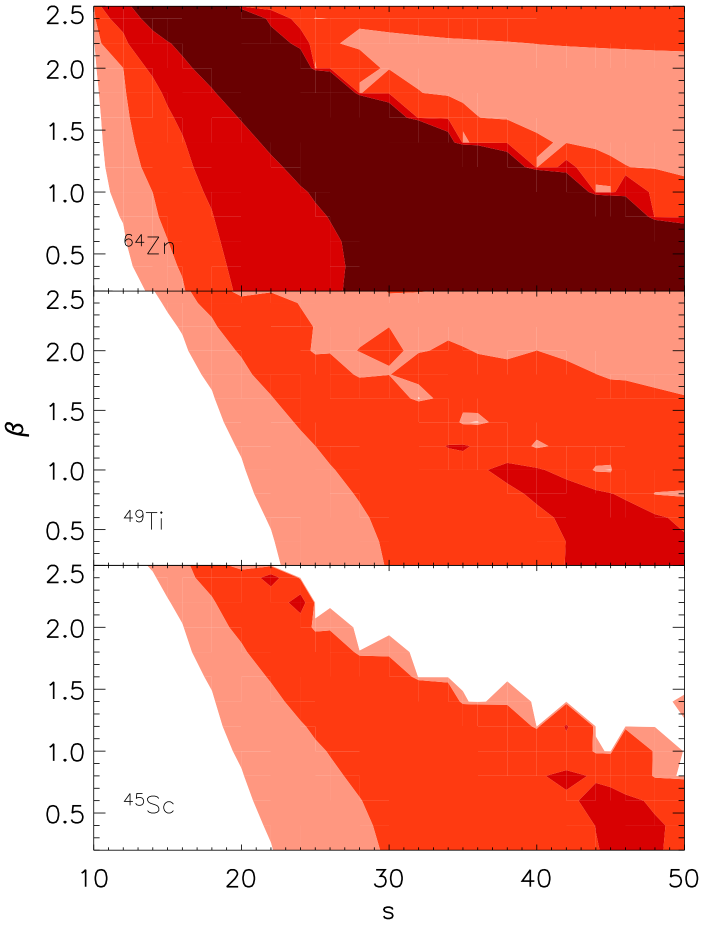
Maximum mass fraction (upper),

excluding Helium (lower)

Overproduction factors for 0.1 $M_\odot/s$:



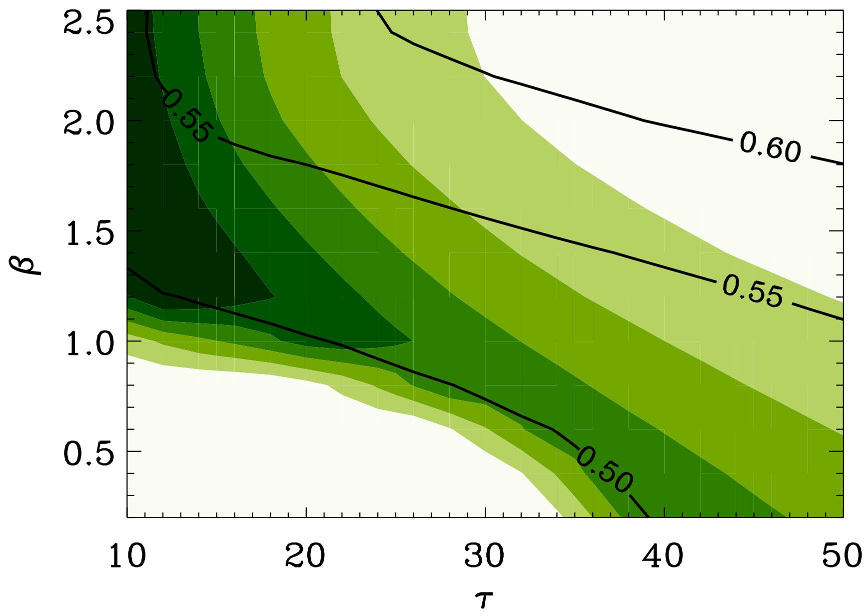
^{92}Mo,^{94}Mo



Zinc-64,Titanium-49,
Scandium-45

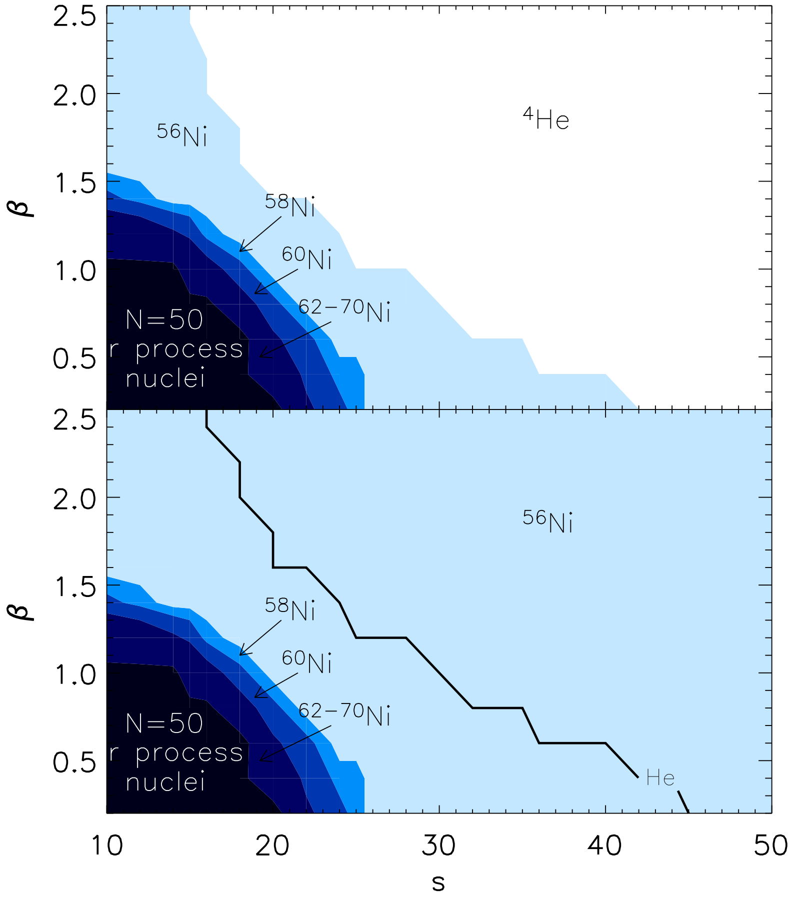
Pruet et al 2003, Surman et al 2006

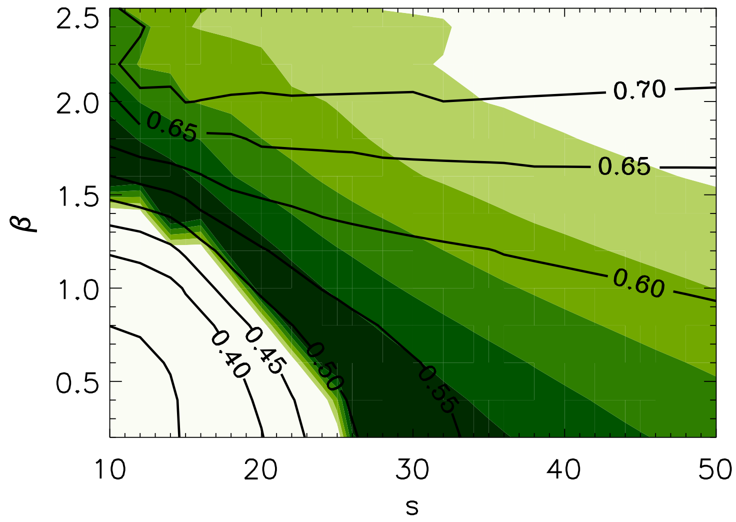
Compare Nickel-56 from a similar disk:



$\dot{M} = 0.1\ \mathrm{M}_{\odot}/\,\mathrm{s}$, a = 0.95

Nucleosynthesis from 1.0 $\mathrm{M}_\odot/\,\mathrm{s}$ disks:





Y_e (lines), Nickel-56 (green)

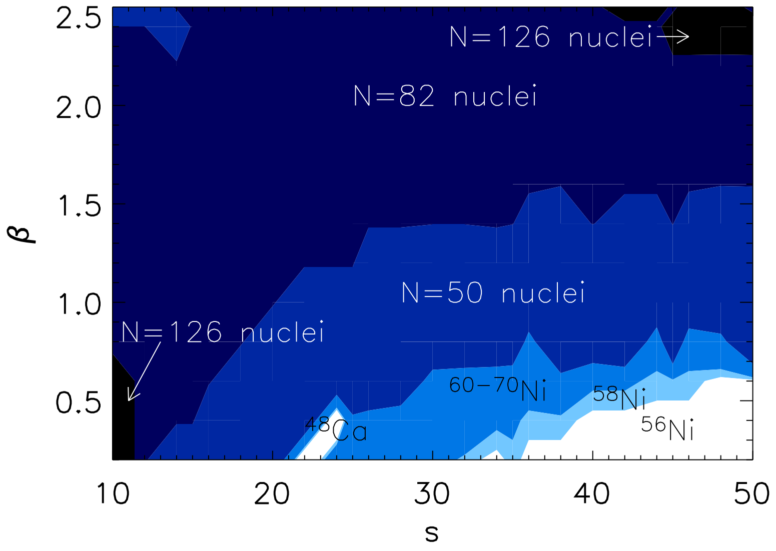
Surman et al 2005

Maximum mass fraction (upper),

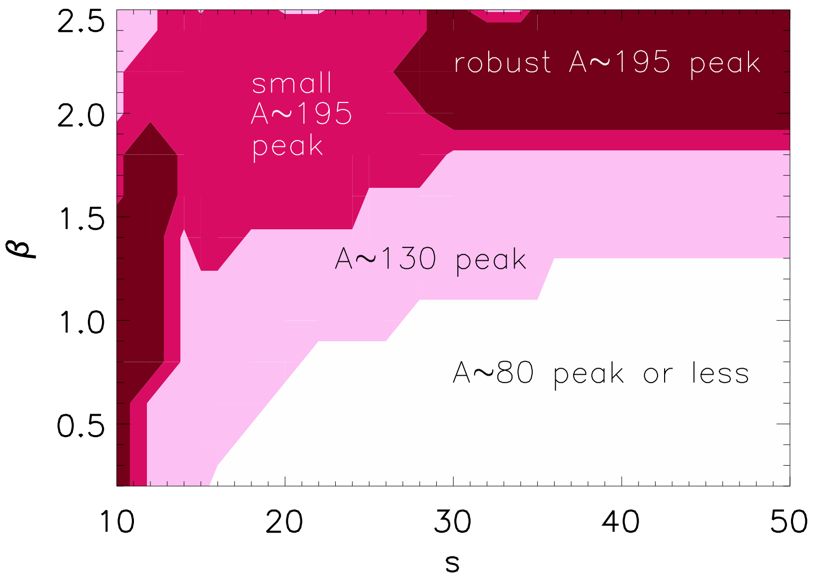
excluding Helium (lower)

Nucleosynthesis from high accretion rate disks:

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



Nuclear species with the largest mass fraction



r-process peaks

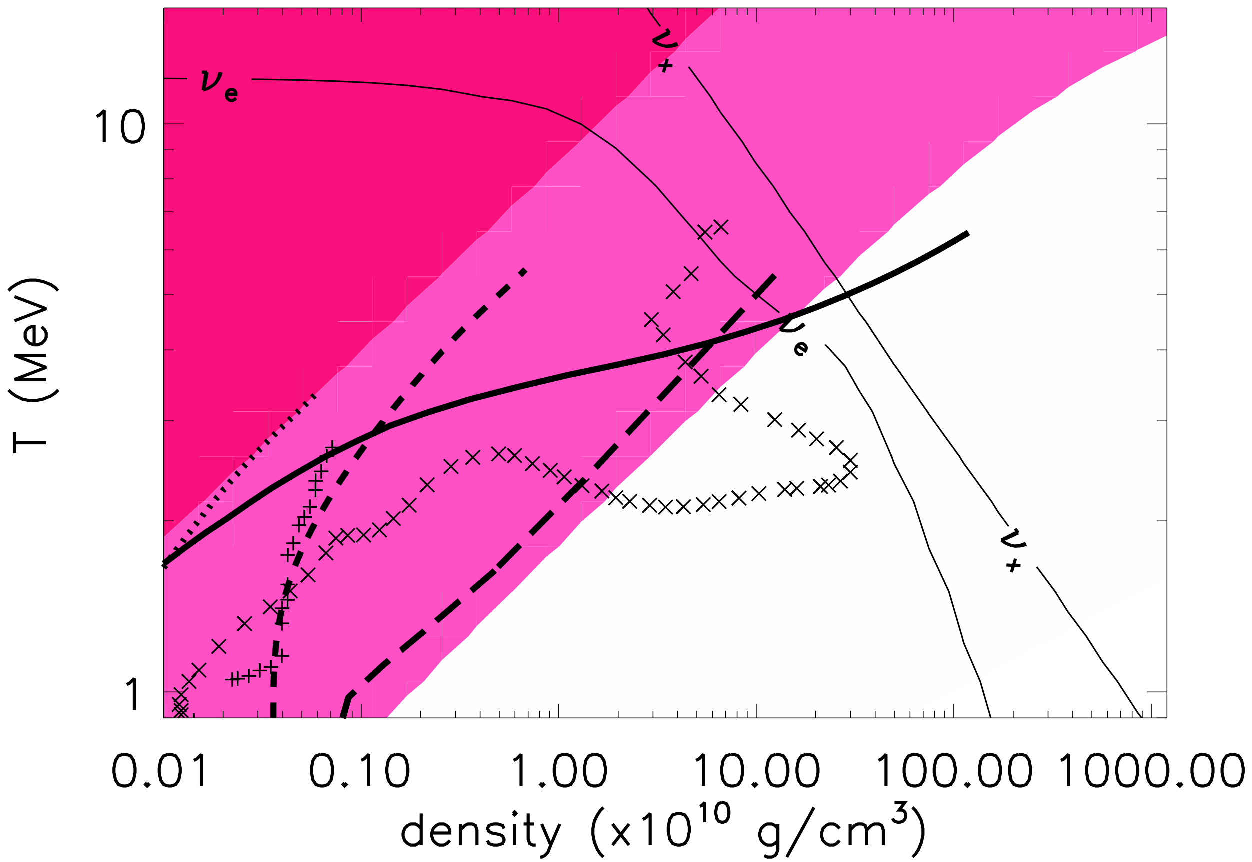
$\bar{\nu}_e + p \longrightarrow e^- + n$ produces many neutrons.

McLaughlin and Surman 2004, Surman et al 2005

The calculations:

- Start with disk temperatures and densities from somebody else's one dimensional steady state model: Popham, Woosley, Fryer 1999 or DiMatteo, Perna and Narayan 2002, or Chen and Belobodorov 2006
- recalculate the electron fraction and neutrino physics in the disk, build vertically assuming hydrostatic equilibrium → determine neutrino decoupling temperatures
- use parameters of entropy and outflow timescale to build temperature and density trajectories for the outflow
- calculate the ν_e and $\bar{\nu}_e$ flux in the outflow using the already calculated neutrino spectra
- trajectories through the reaction network

Looking at some of the underlying disk models



dashed lines: various steady state disk models that we are using

crosses: dynamical collapsar-type models

Wish list:

Trajectories in the wind:

- first choice: self consistent wind calculation
- second choice: Lagrangian trajectory from a dynamical model

Disk models with “real” neutrino transport

- first choice: disk with real neutrino transport and a self consistent calculation of Y_e in the disk

Conclusions

- In a disk wind on the order of 0.1 $M_\odot$ / s disks (roughly “collapsar” type)it is likely that Nickel-56 is made, but not guaranteed.
- In a disk wind from 1.0 $M_\odot$ / s disks (roughly “collapsar” or NS merger type) a lot of Nickel-56 is probably made
- But 1.0 $M_\odot$ / s disks can have highly variable nucleosynthesis patterns depending on details of disk models
- In a hotter disk e.g. 10 $M_\odot$ / s, a $=$ 0, (NS merger type?) not much nickel but can make an r-process
- “collapsar” type disk, a number of rare nuclei, e.g. 92Mo, 64Zn have large overproduction factors.
- Future: examine more self -consistent disks, examine dynamical models, improve by calculations, e.g. add neutrino oscillations