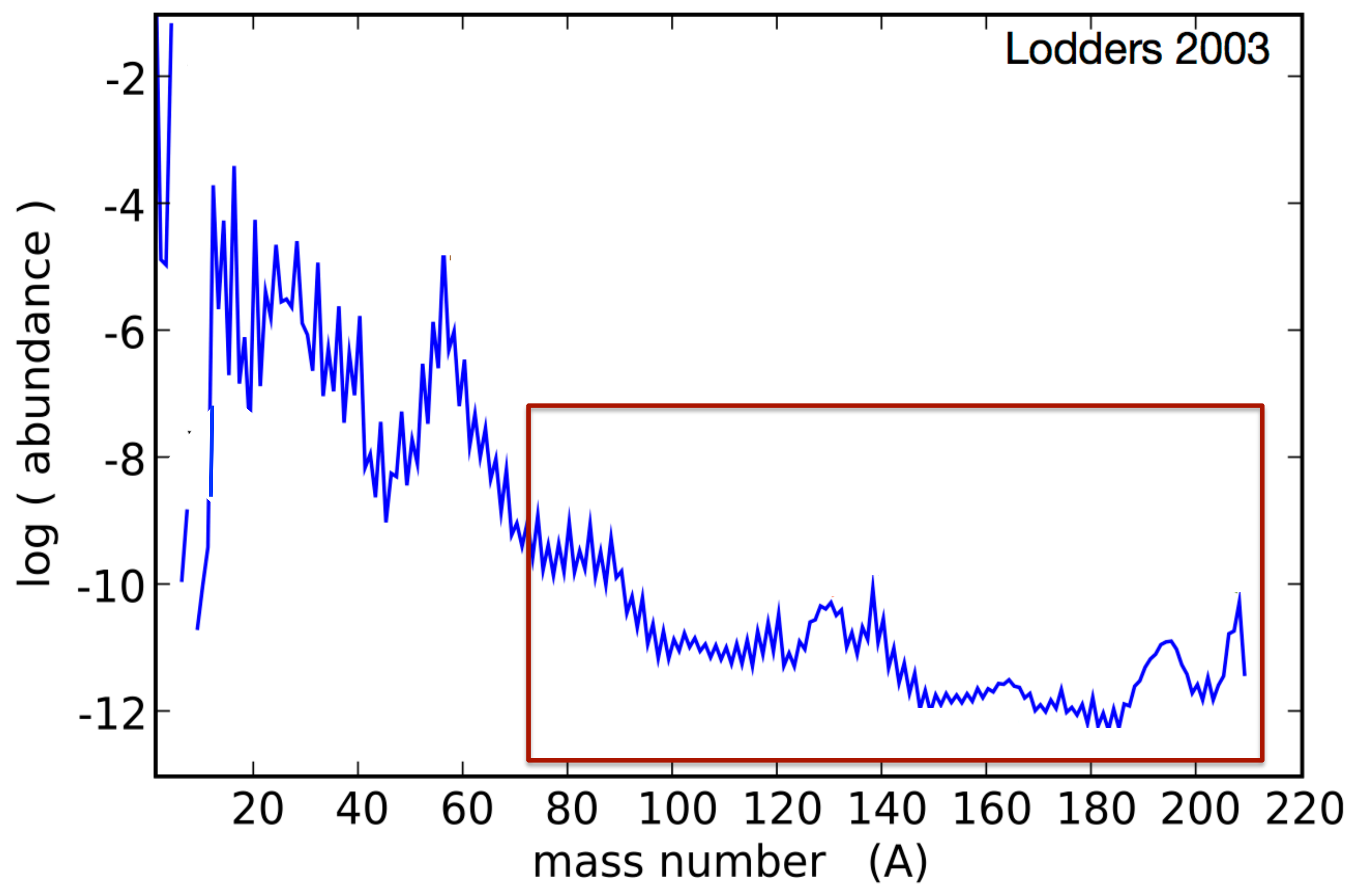
r-process nucleosynthesis in AD-BH outflows

Rebecca Surman
Union College

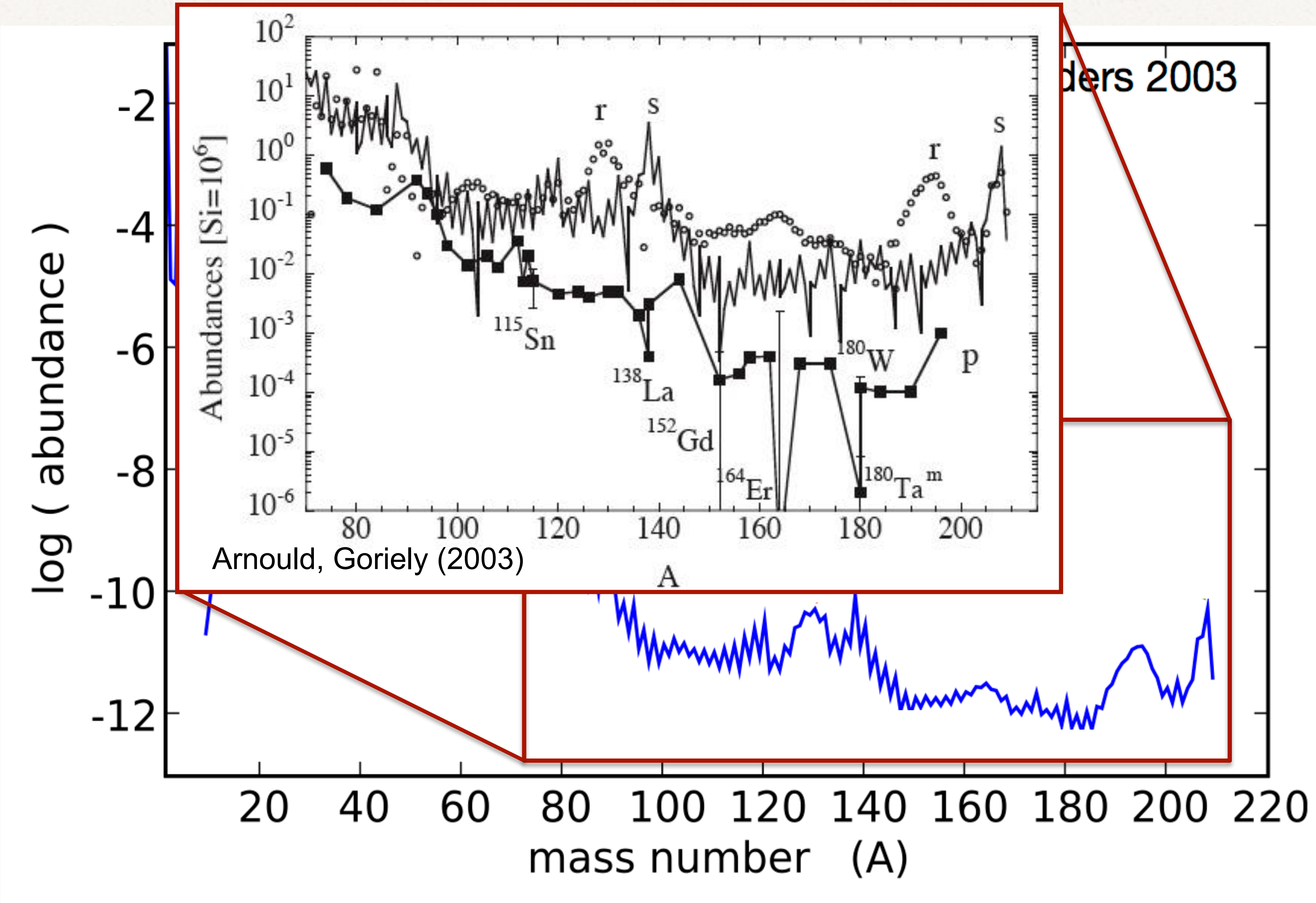
Workshop on SNe and GRBs
Yukawa Institute, Kyoto, Japan
12 November 2013

solar system abundances



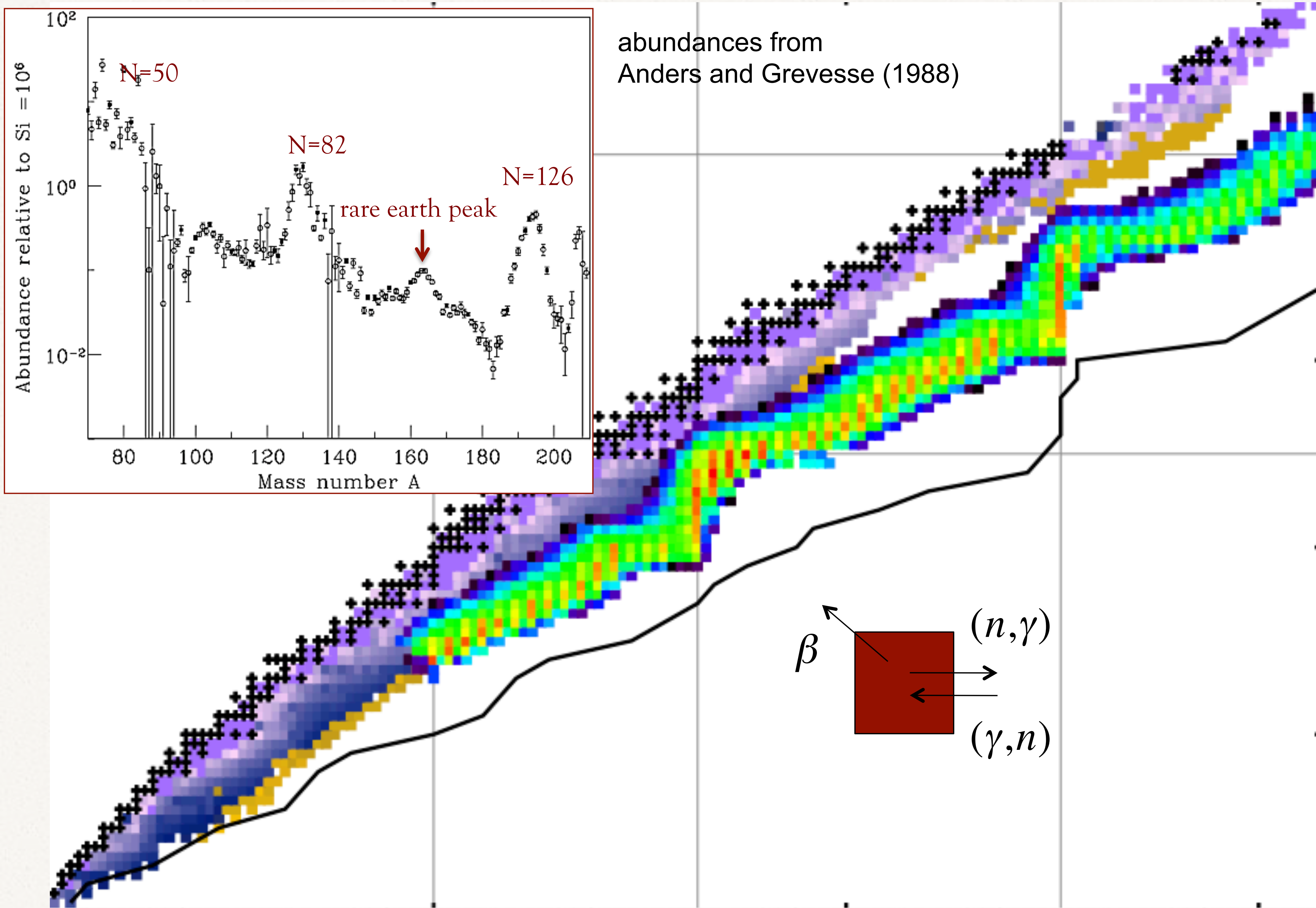
plot courtesy A. Arcones

solar system abundances



Arnould, Goriely (2003)

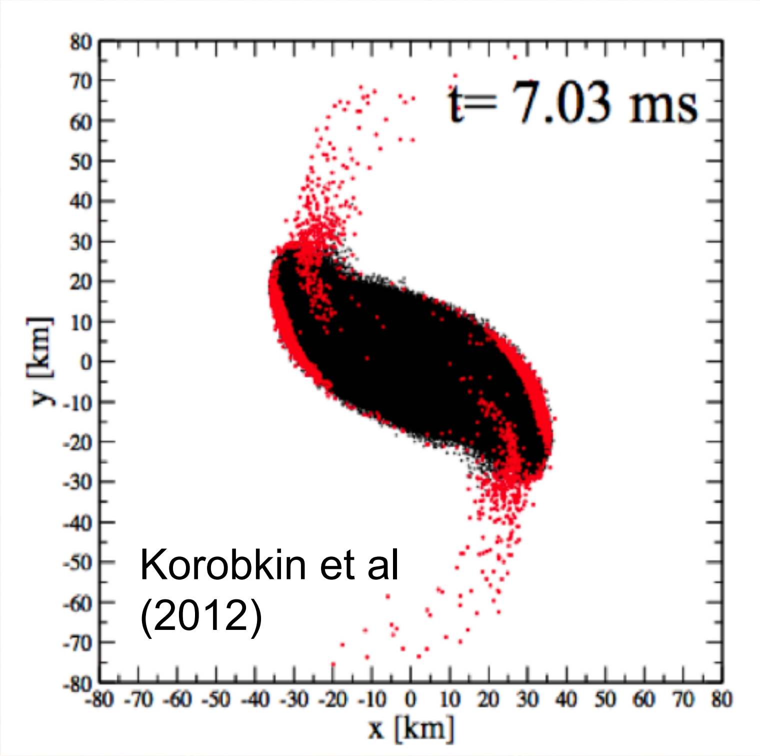
r-process nucleosynthesis

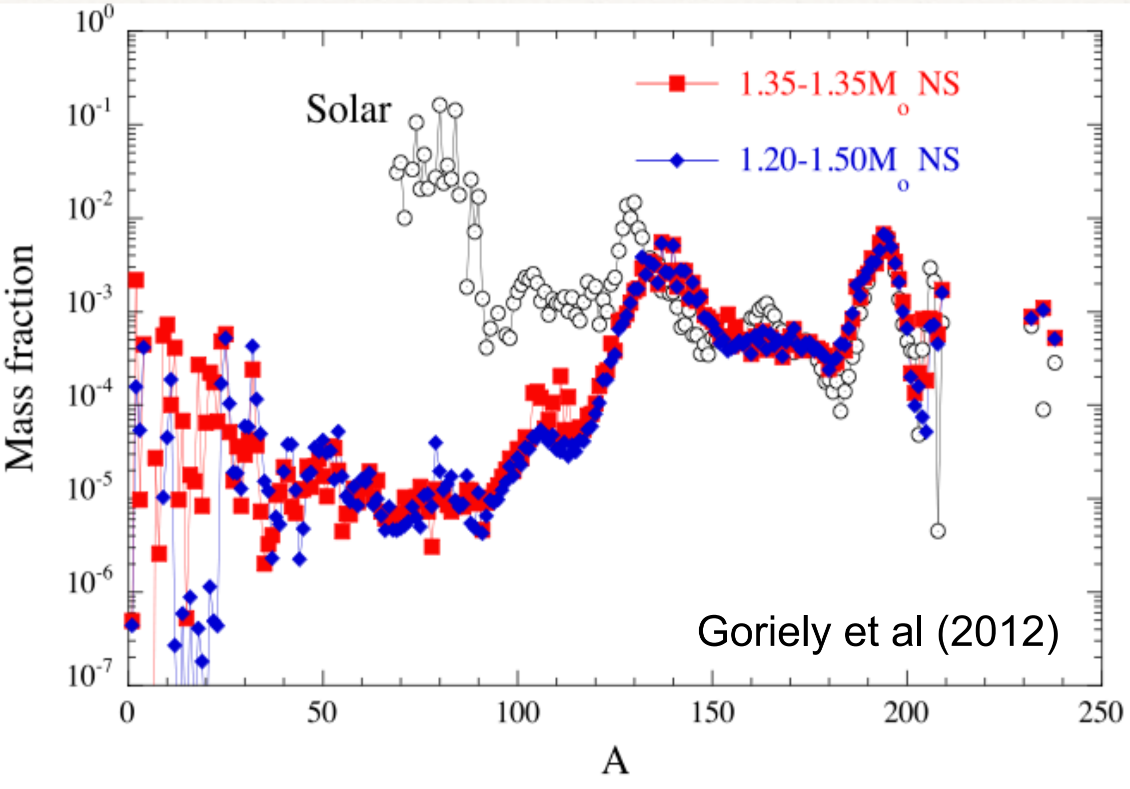


abundances from
Anders and Grevesse (1988)

r-process site: mergers?

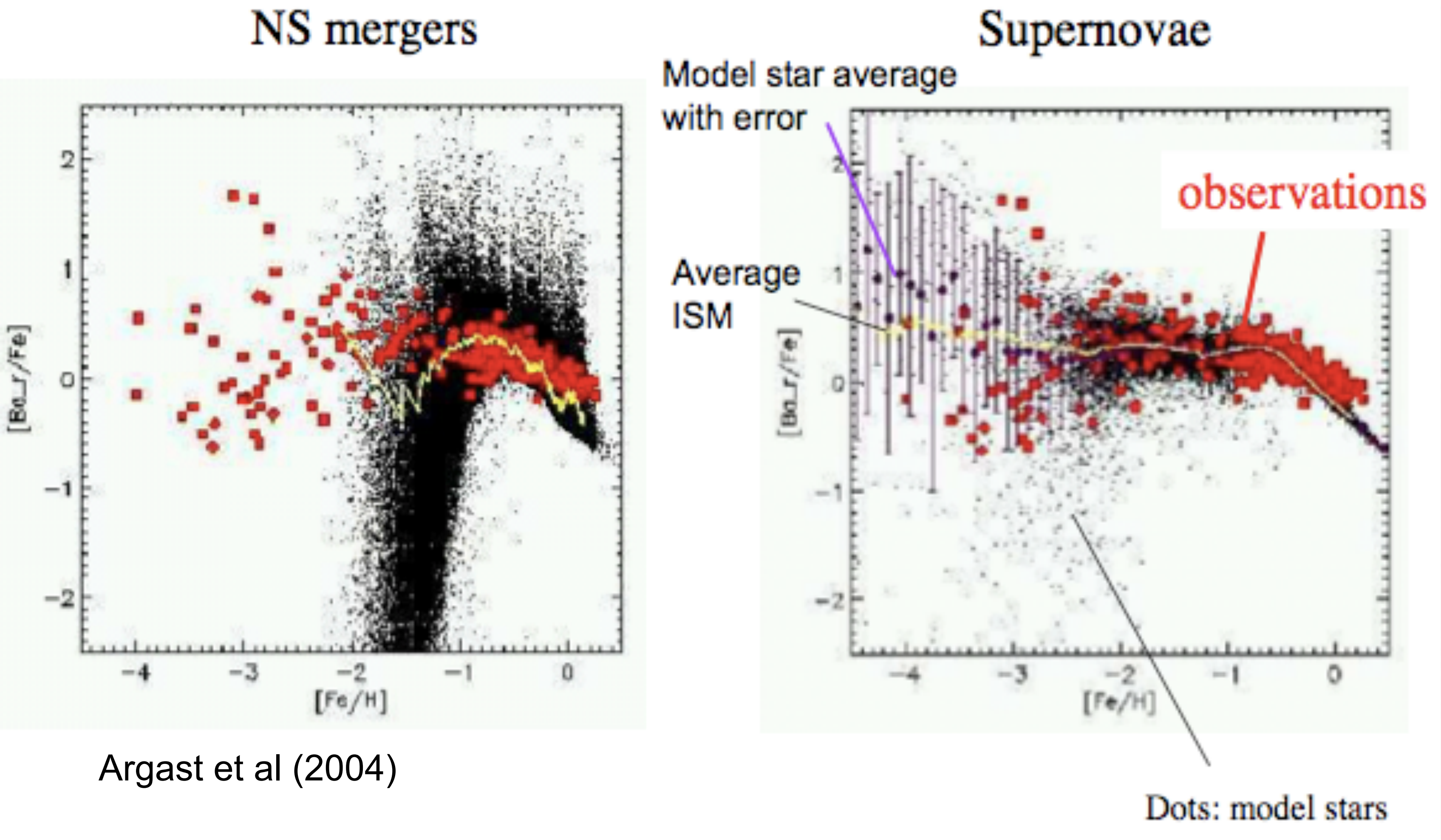
neutron star-neutron star or black hole-neutron star mergers


Korobkin et al (2012)


Goriely et al (2012)

e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Rosswog (2005), Wanajo & Ishimaru (2006), Oechslin et al (2007), Metzger et al (2010), Roberts et al (2011), Goriely et al (2012), Korobkin et al (2012), Tanaka & Hotokezaka (2013), S. Wanajo talk

r-process site: mergers?



NS mergers

Supernovae

Model star average with error

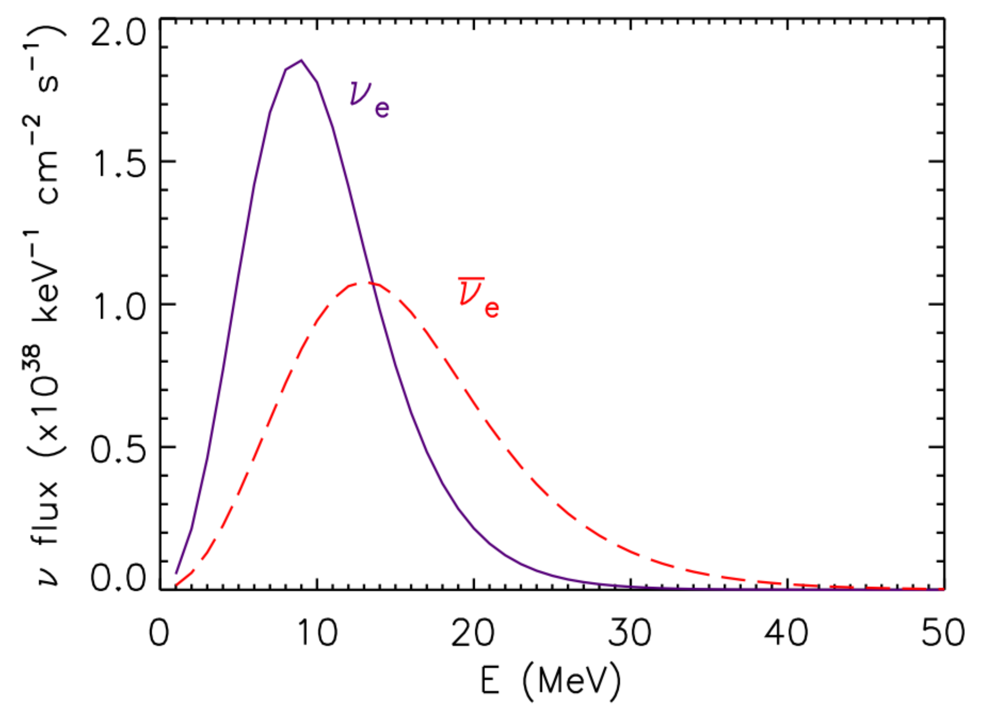
Average ISM

observations

Dots: model stars

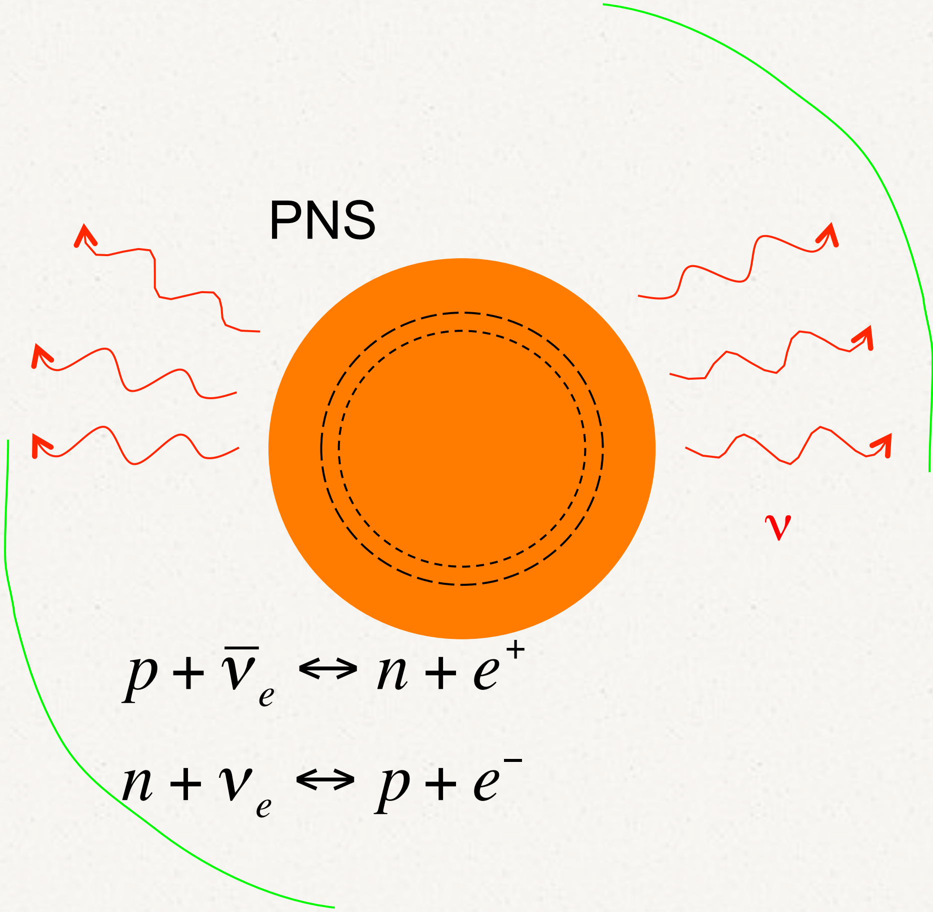
Argast et al (2004)

r-process site: supernovae?



late-time ν fluxes from Keil et al (2003)

supernova neutrino-driven wind

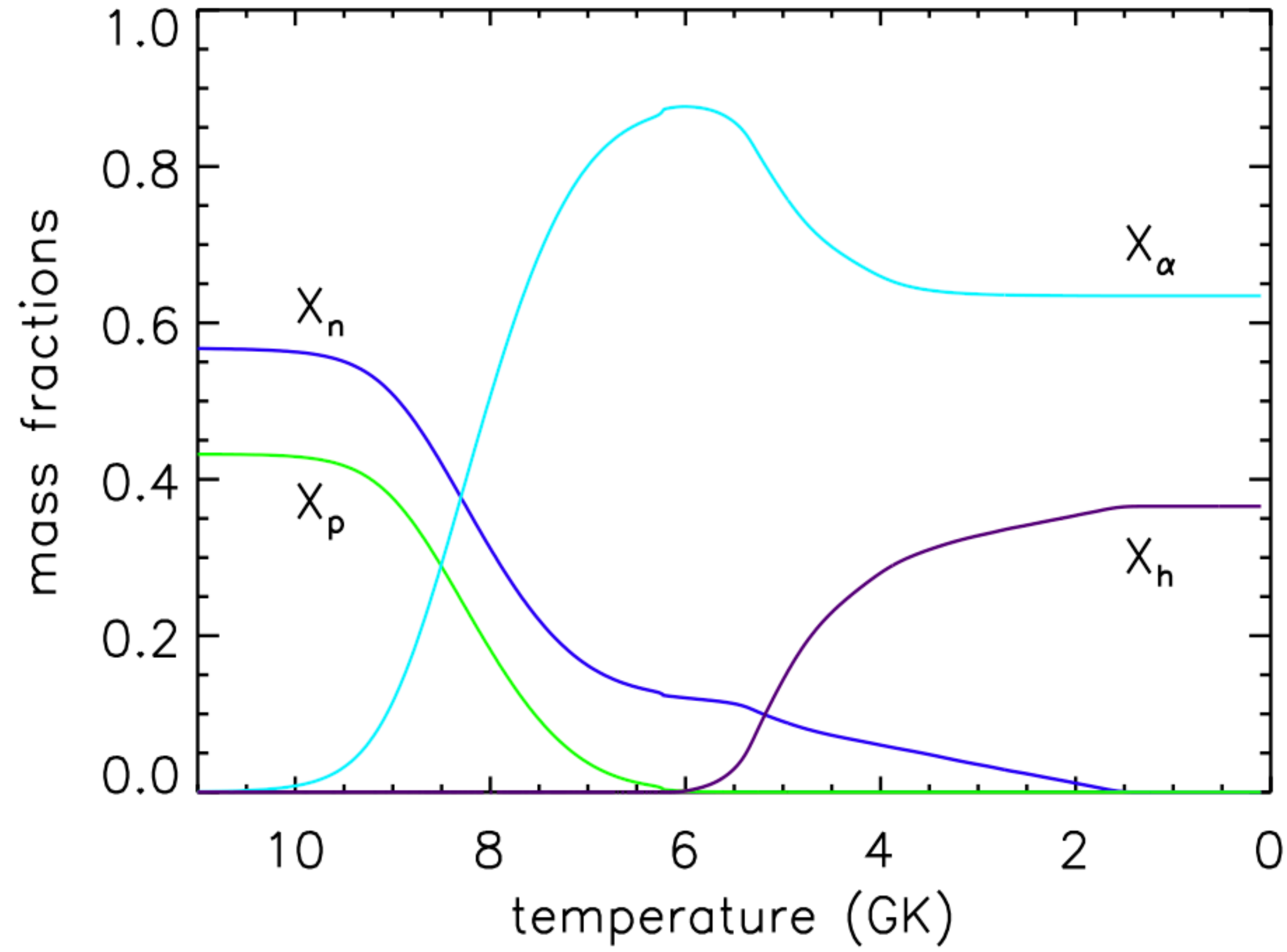


$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

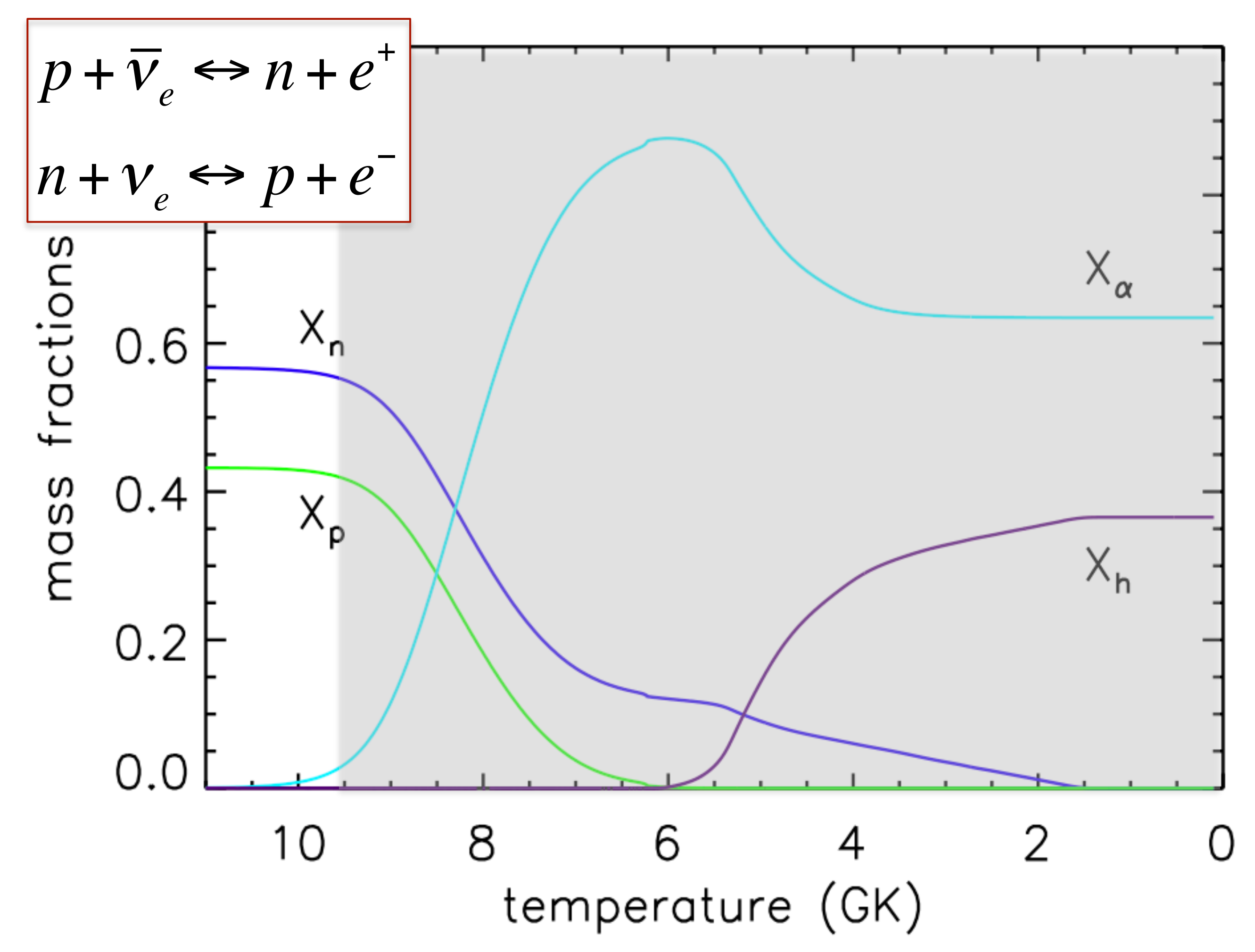
$$n + \nu_e \leftrightarrow p + e^-$$

e.g., Meyer et al (1992), Woosley et al (1994), Takahashi et al (1994), Witti et al (1994), Fuller & Meyer (1995), McLaughlin et al (1996), Meyer et al (1998), Qian & Woosley (1996), Hoffman et al (1997), Cardall & Fuller (1997), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), Huedepohl et al (2010), Fischer et al (2010), Roberts & Reddy (2012), etc., etc.

primary heavy element nucleosynthesis



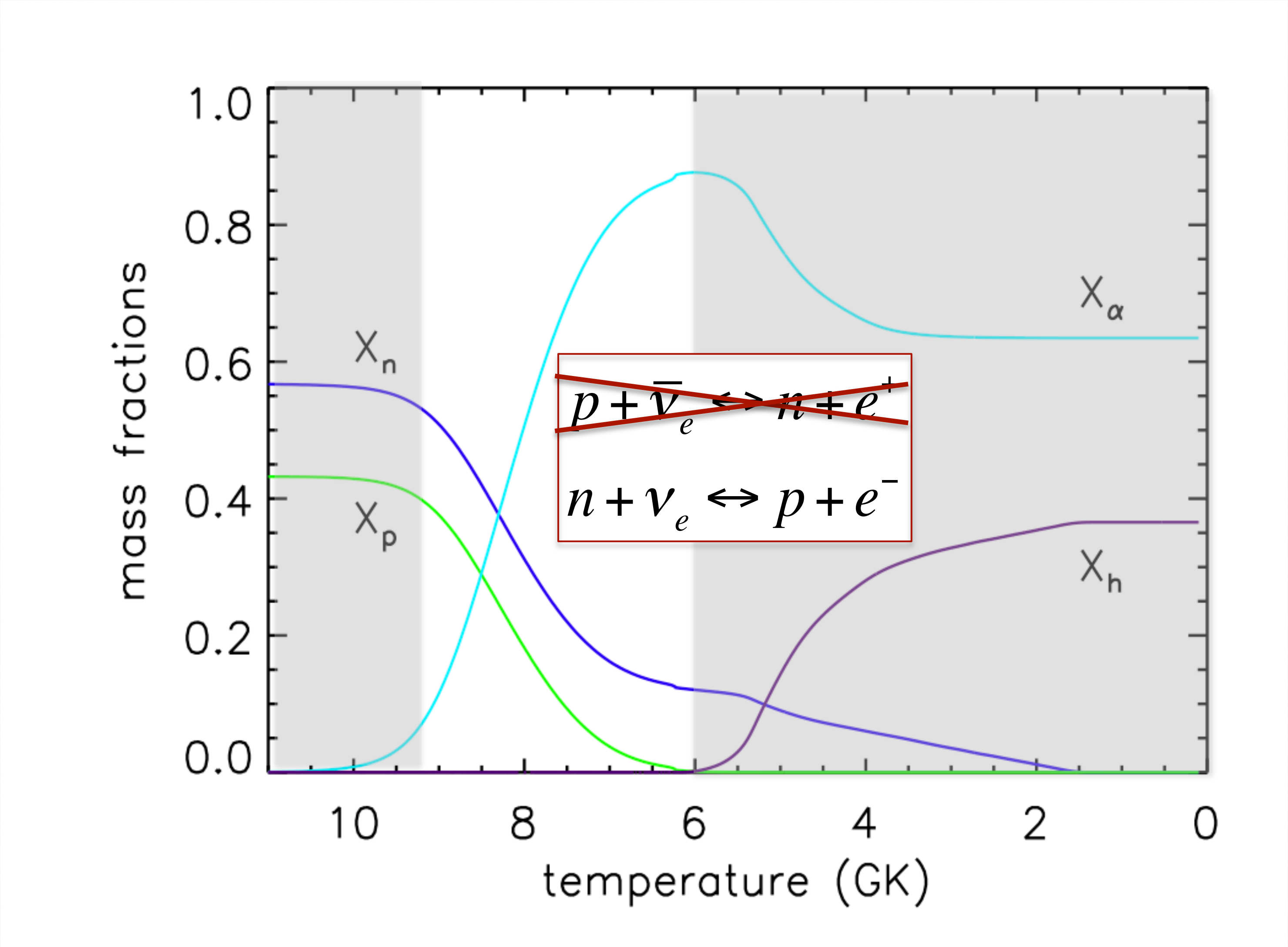
neutrinos and primary nucleosynthesis



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

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

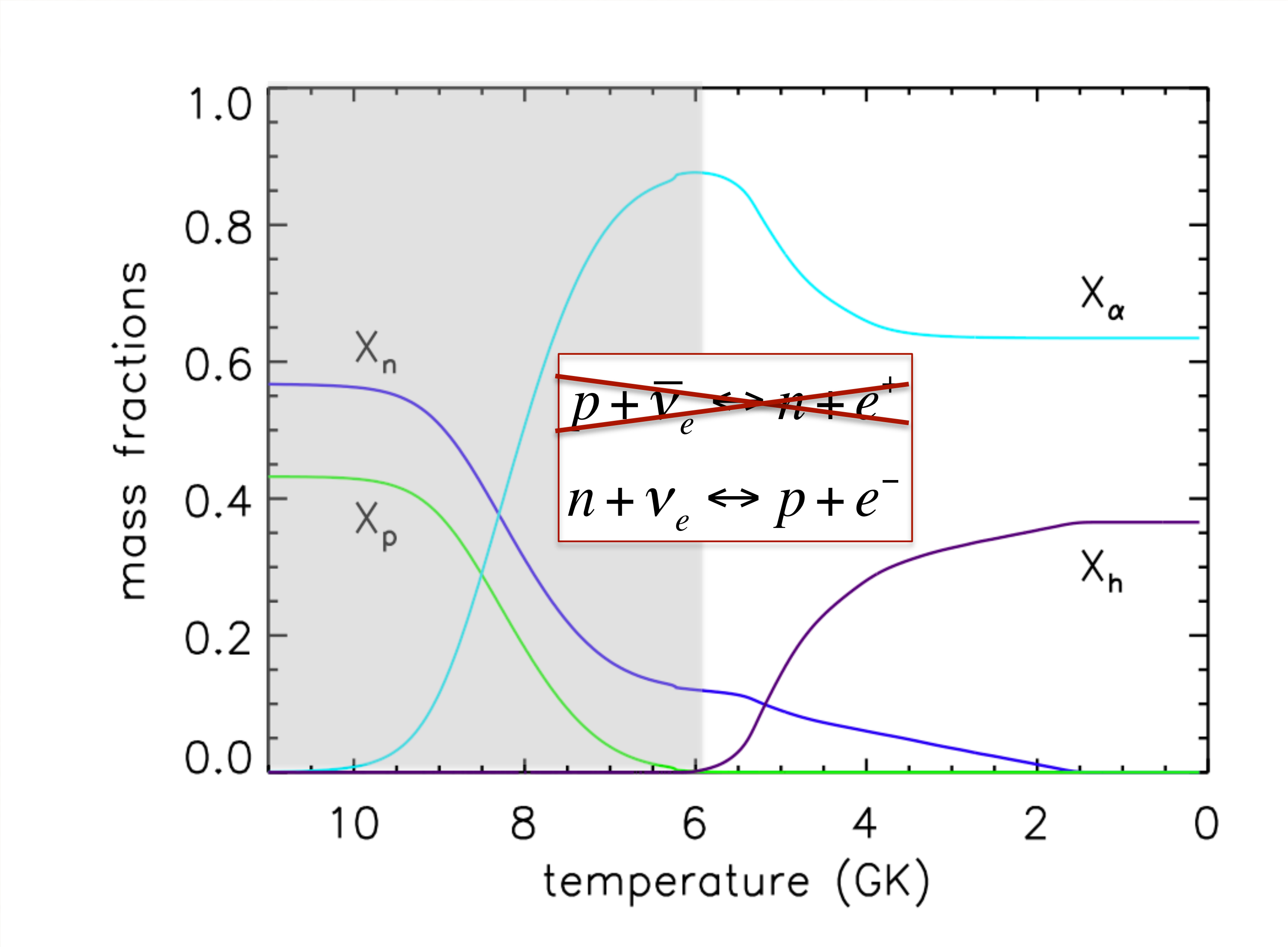
neutrinos and primary nucleosynthesis



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

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

neutrinos and primary nucleosynthesis



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

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

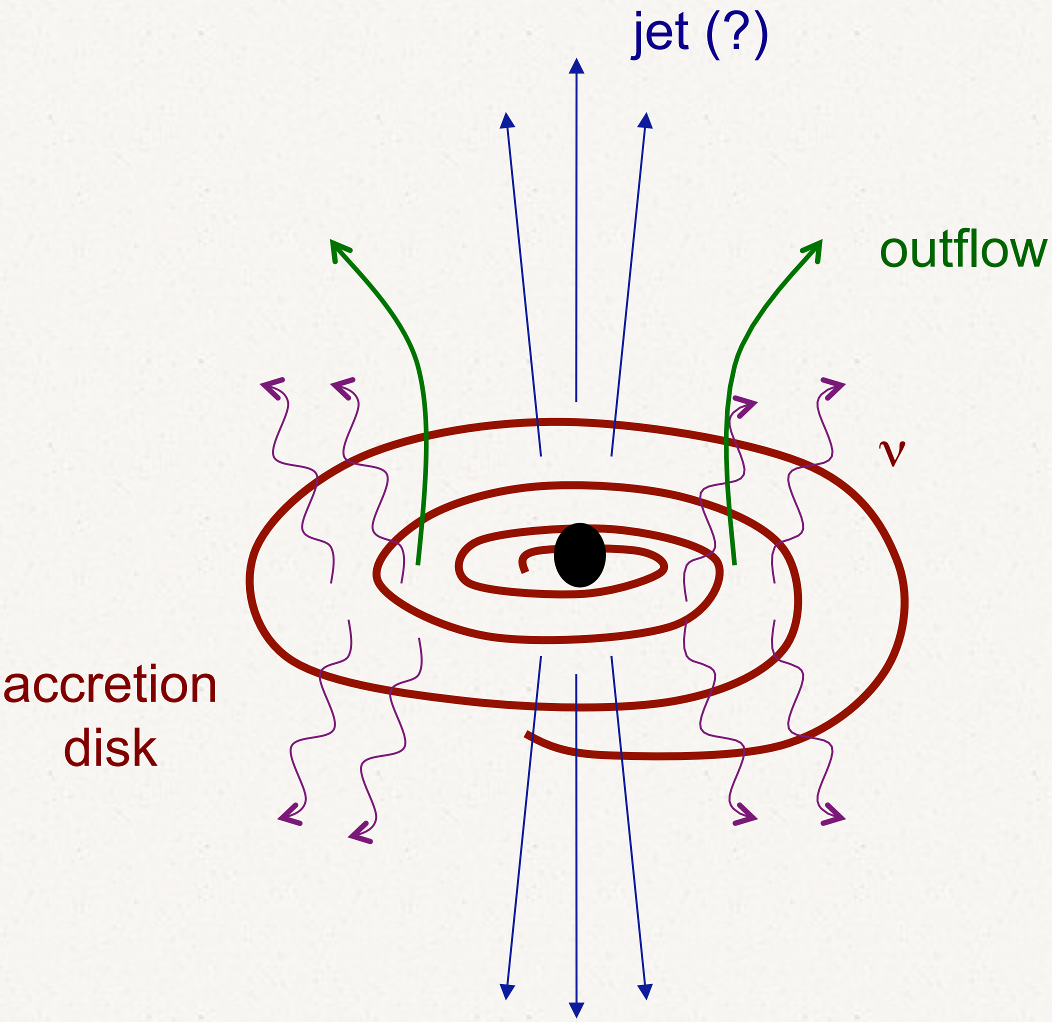
r-process astrophysical site: status

Compact object mergers have plenty of neutrons, but do not evolve on short enough timescales to explain the halo star data

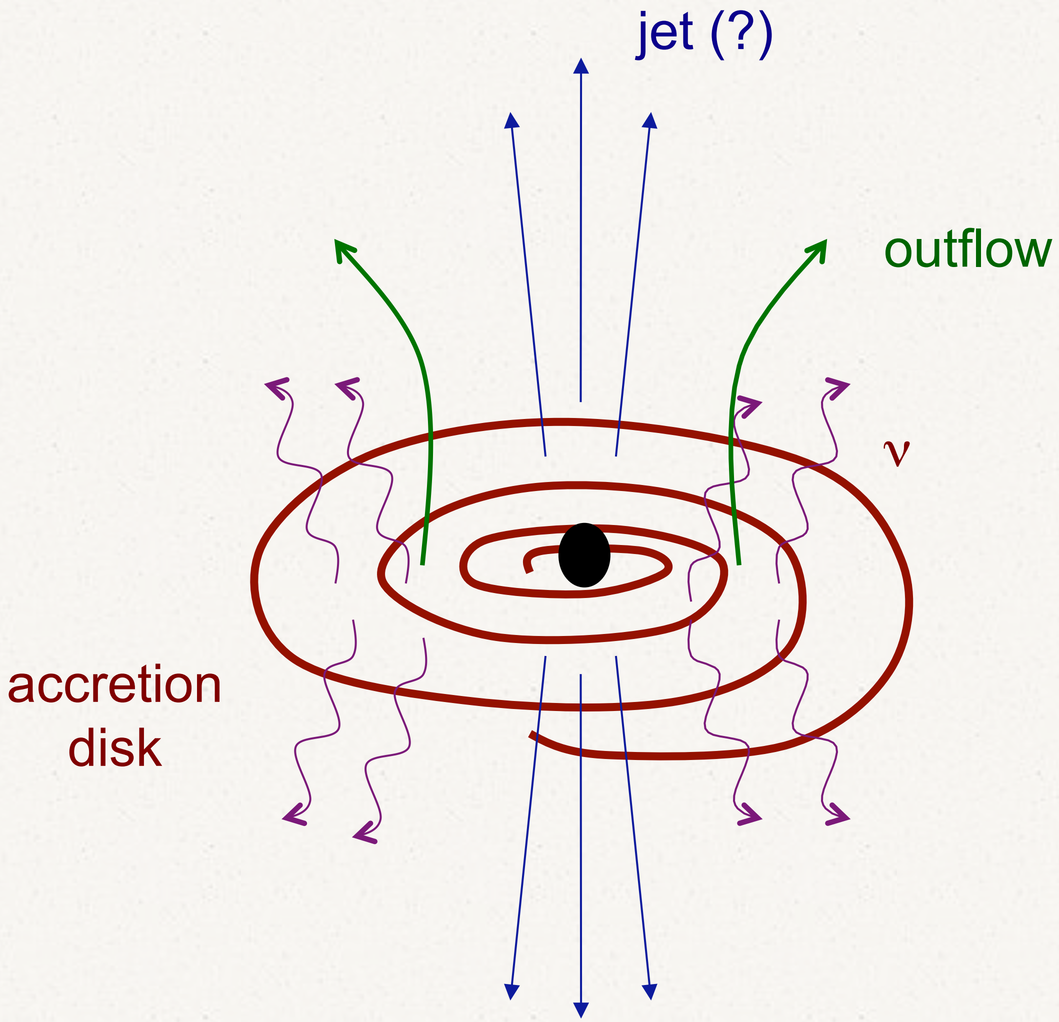
Core-collapse supernovae evolve on the correct timescale to explain the halo star data, but may not produce enough neutrons

(but see talk by N. Nishimura for an alternate SNe site...)

black hole accretion disks (AD-BHs)



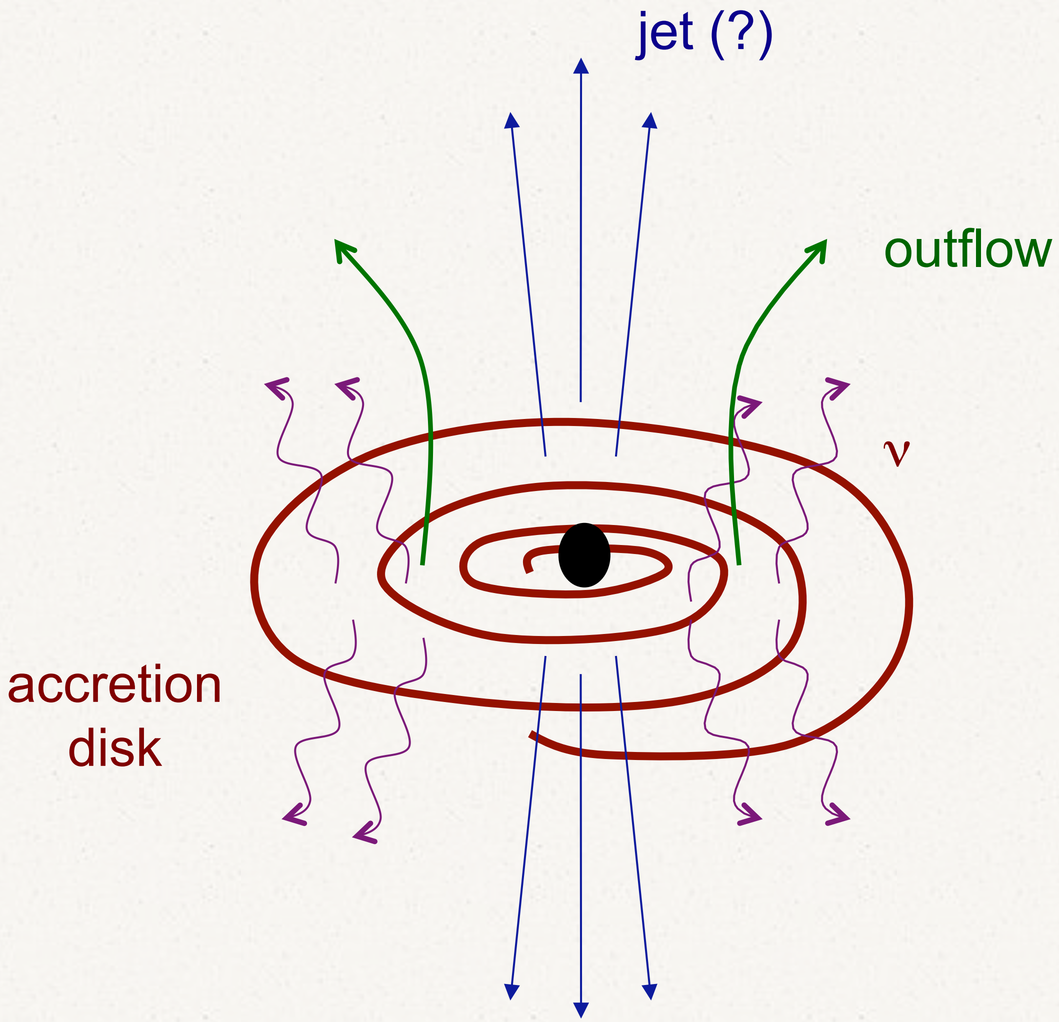
black hole accretion disks (AD-BHs)



GRB jet/explosive nucleosynthesis

e.g., Beloborodov (2003), Nagataki et al (2003), Nagataki et al (2006), Fryer et al (2006), Fujimoto et al (2007), Fujimoto et al (2008), Tominaga (2009), Maeda & Tominaga (2009), Nomoto et al (2010), Horiuchi et al (2012), Shibata & Tominaga (2012), Nakamura et al (2013)

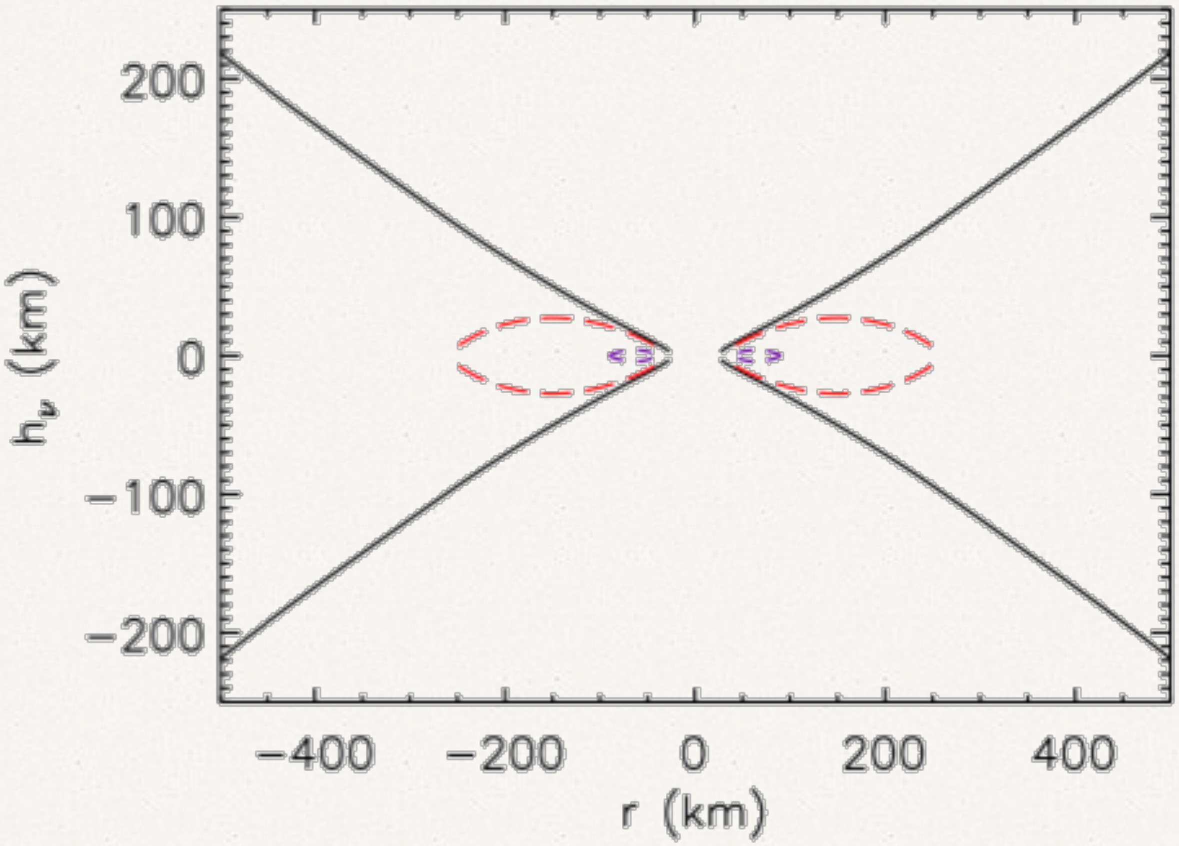
black hole accretion disks (AD-BHs)



AD-BH outflow nucleosynthesis

e.g., Pruet, Thompson, & Hoffman (2004), Surman & McLaughlin (2004), Arai et al (2004), Fujimoto et al (2004), Surman, McLaughlin, & Hix (2006), Barzilay & Levinson (2008), Metzger, Thompson, & Quataert (2008), Kizivat et al (2010), Wanajo & Janka (2012)

black hole accretion disk neutrino emission



positron captures dominate in merger disks, so

$$f_{\bar{\nu}_e} > f_{\nu_e}$$

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

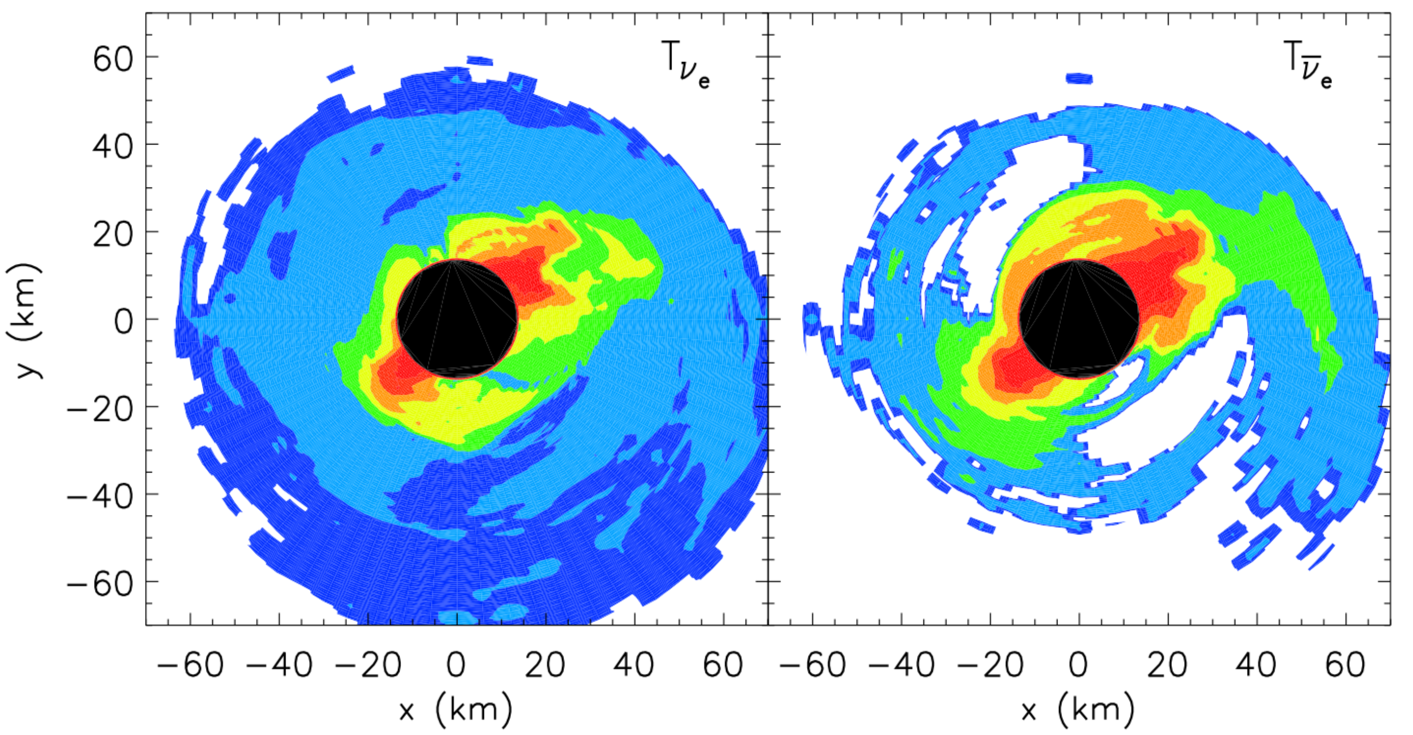
$$\boxed{p + e^-} \leftrightarrow n + \nu_e$$

electron captures dominate in collapsar disks, so

$$f_{\nu_e} > f_{\bar{\nu}_e}$$

Disk models from Chen and Beloborodov (2008), neutrino calculation from Surman and McLaughlin

nucleosynthesis from a merger black hole accretion disk



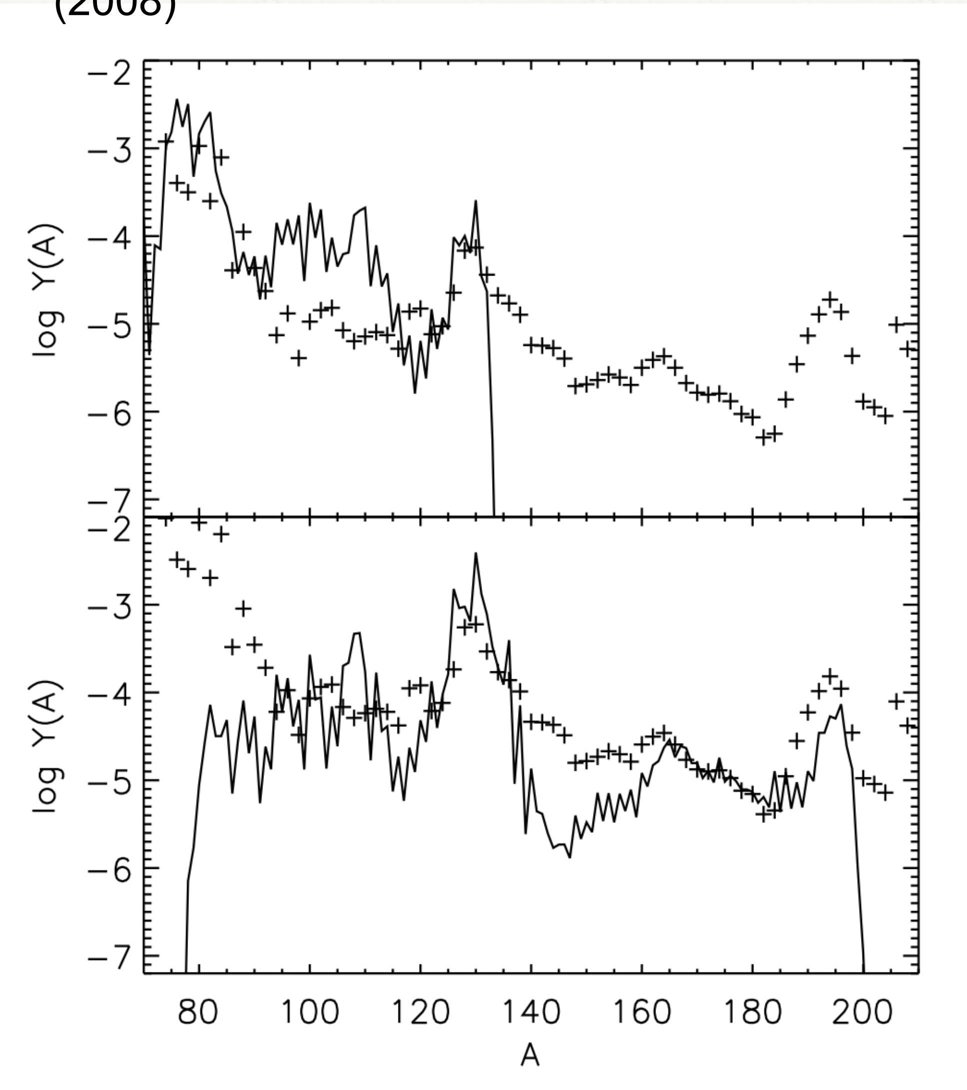
Surman, McLaughlin, Ruffert, Janka, Hix (2008)

nucleosynthesis from a merger black hole accretion disk

Assume an adiabatic wind with

$$v = v_\infty \left(1 - \frac{R_0}{r}\right)^\beta$$

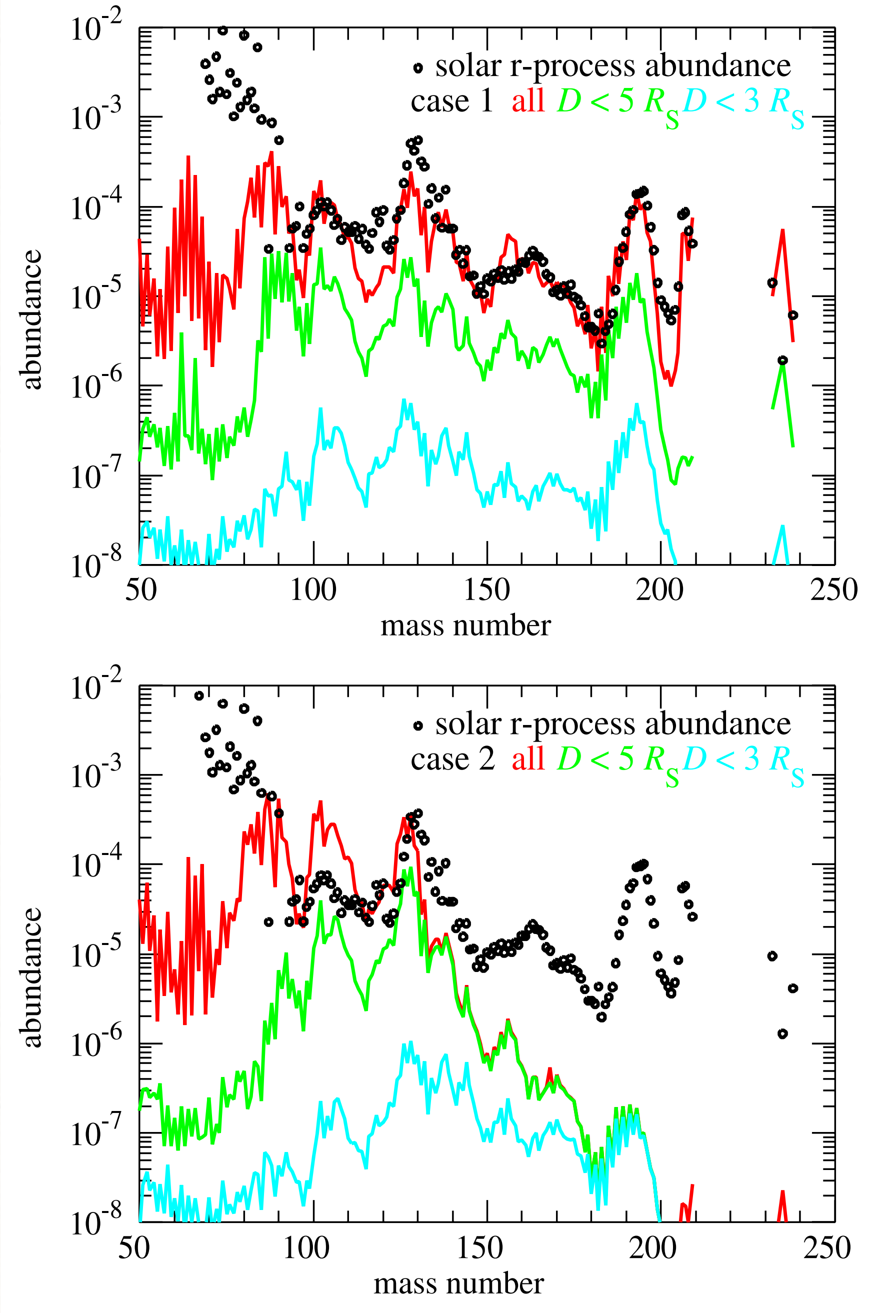
Surman, McLaughlin, Ruffert, Janka, Hix (2008)



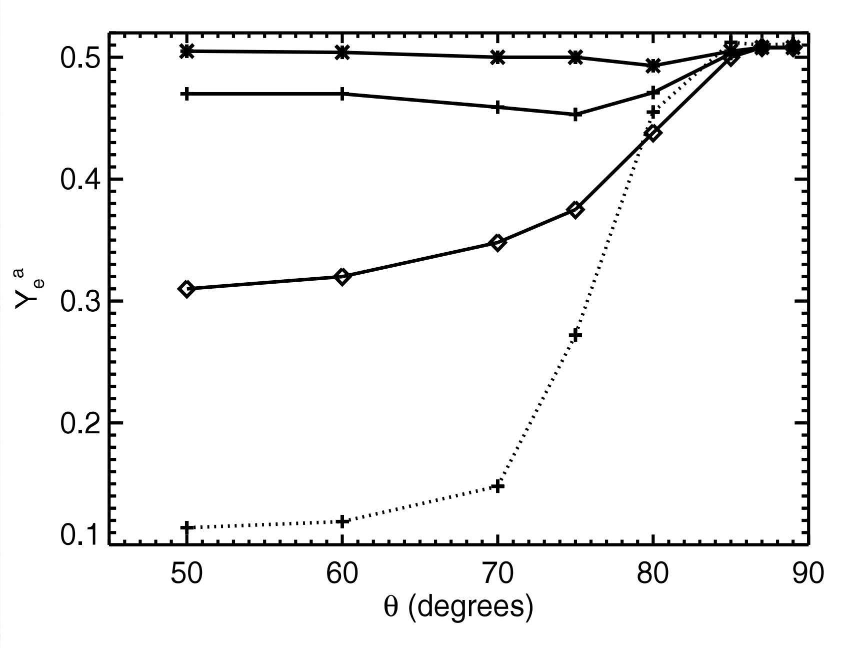
low *s/k*,
fast acceleration

high *s/k*,
slower acceleration

nucleosynthesis from a merger black hole accretion disk

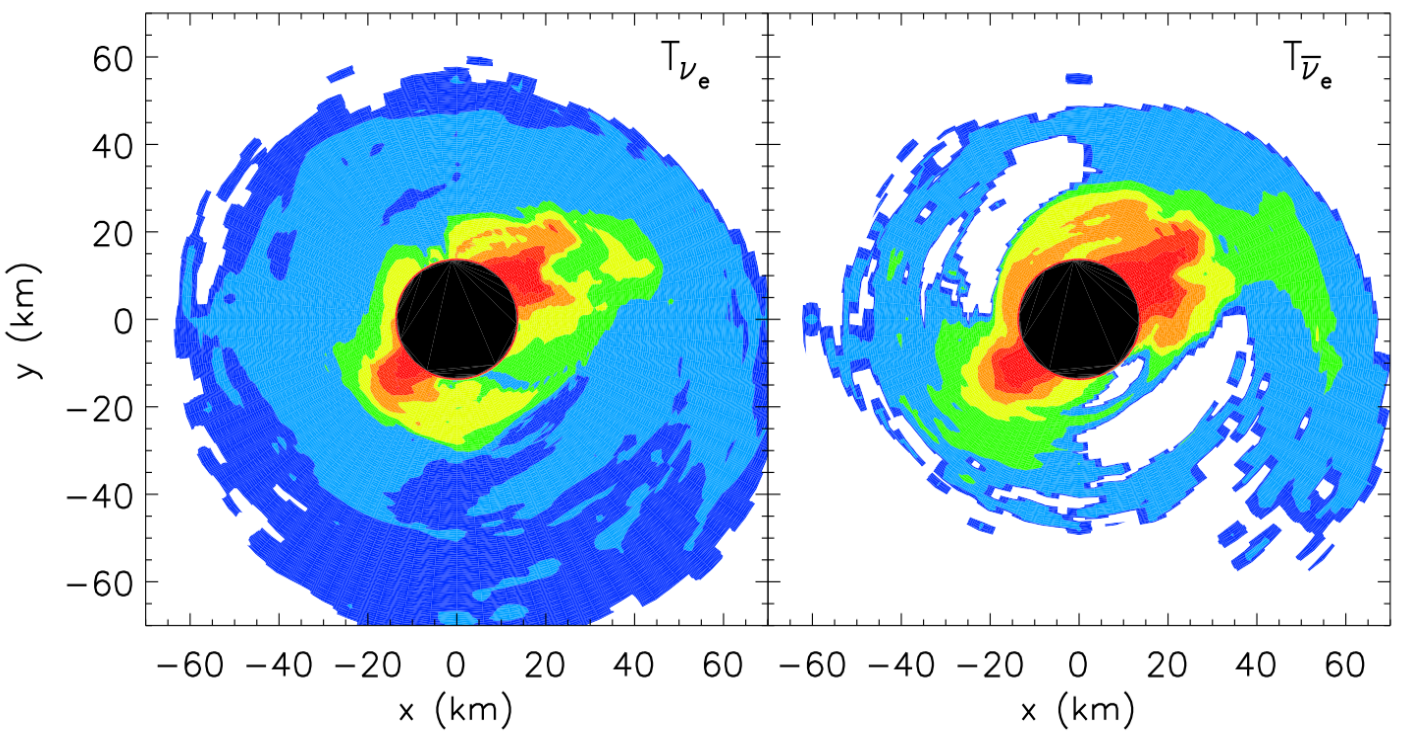


Wanajo, Janka (2012)



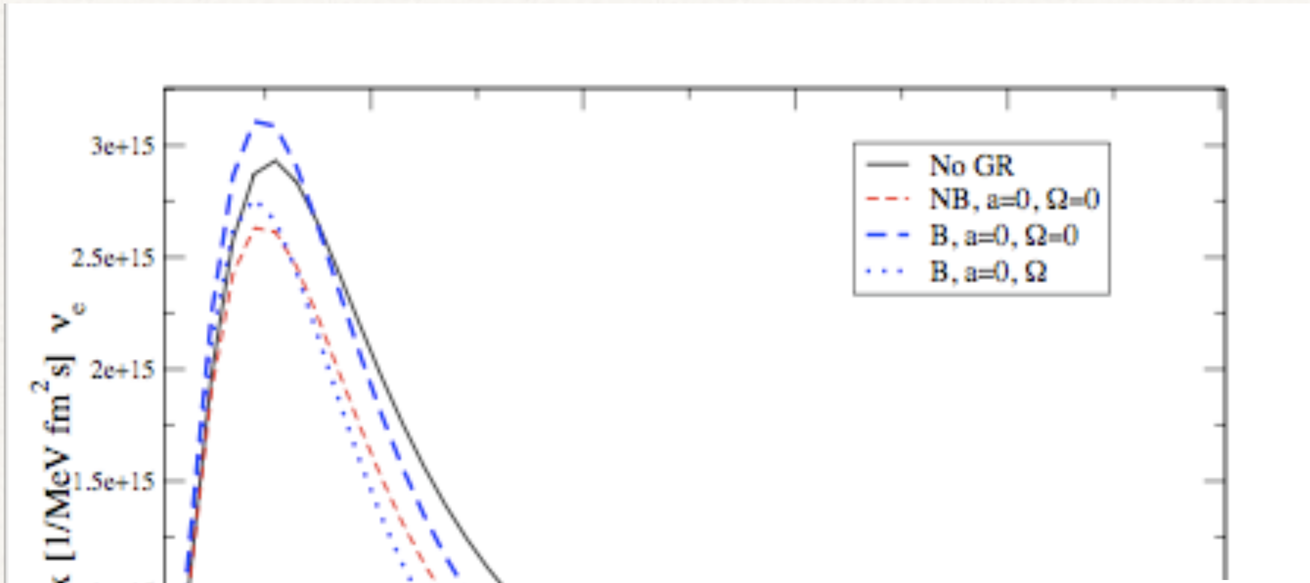
Metzger et al (2008)

nucleosynthesis from a merger black hole accretion disk



Surman, McLaughlin, Ruffert, Janka, Hix (2008)

general relativistic effects on the neutrino spectra



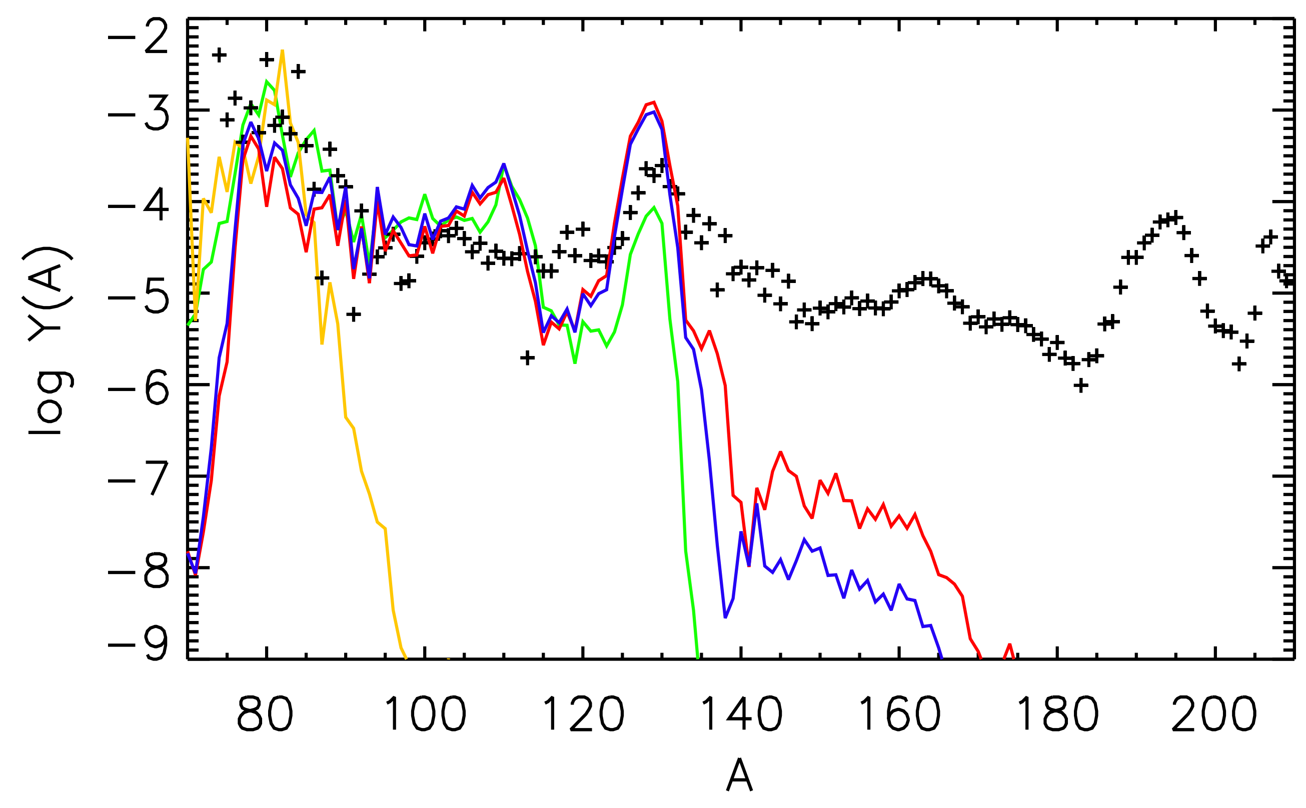
no GR

redshift, bending

+ rotation

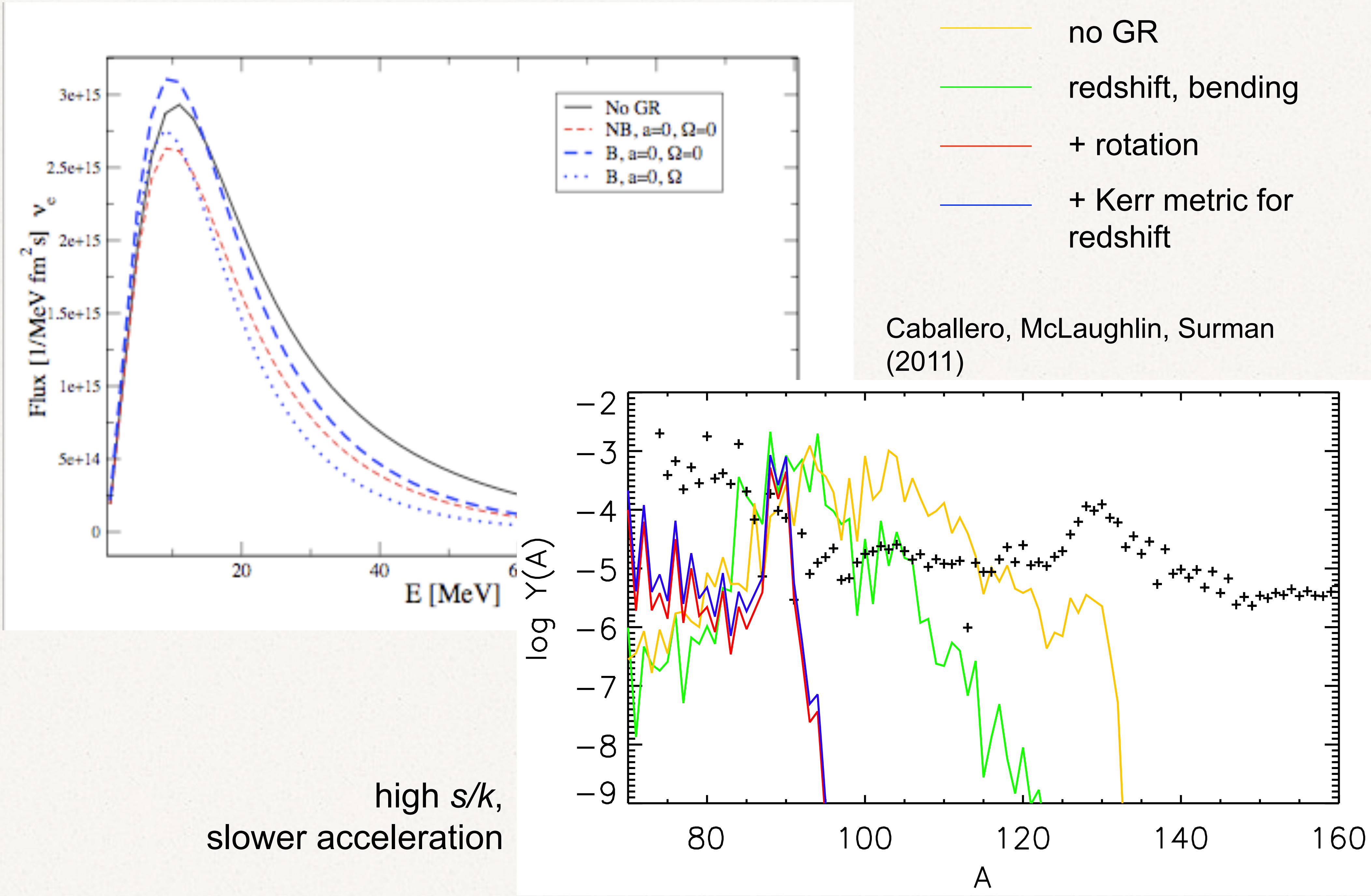
+ Kerr metric for redshift

Caballero, McLaughlin, Surman (2011)



low *s/k*,
fast acceleration

general relativistic effects on the neutrino spectra

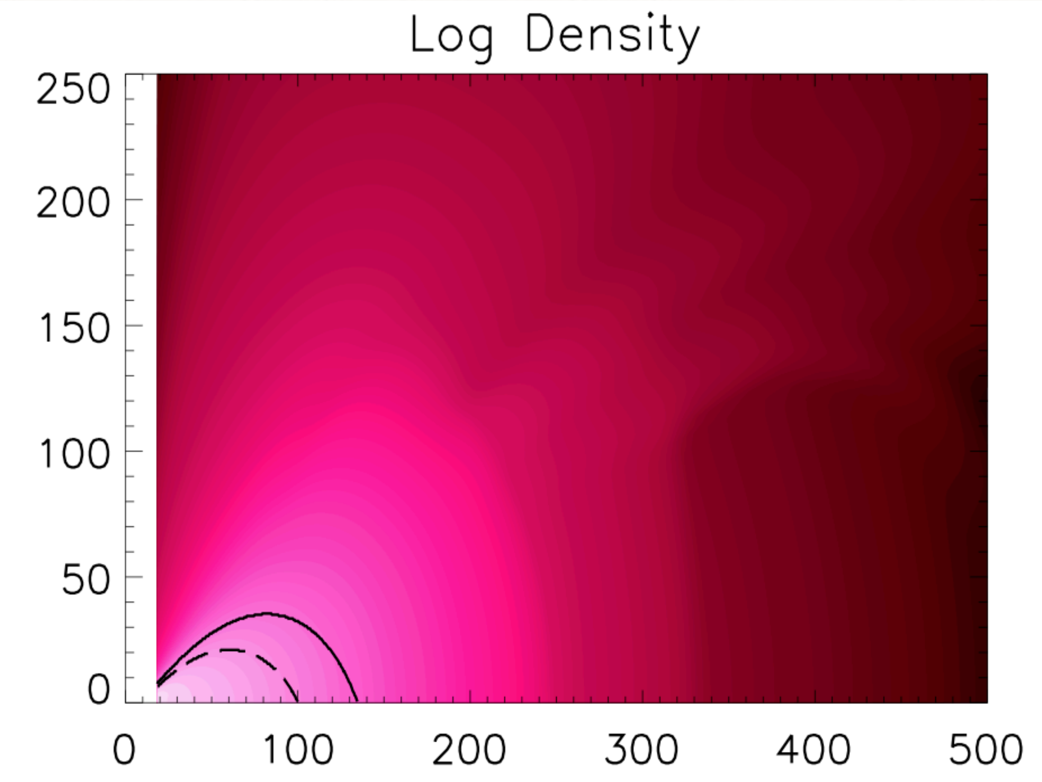


—	no GR
—	redshift, bending
—	+ rotation
—	+ Kerr metric for redshift

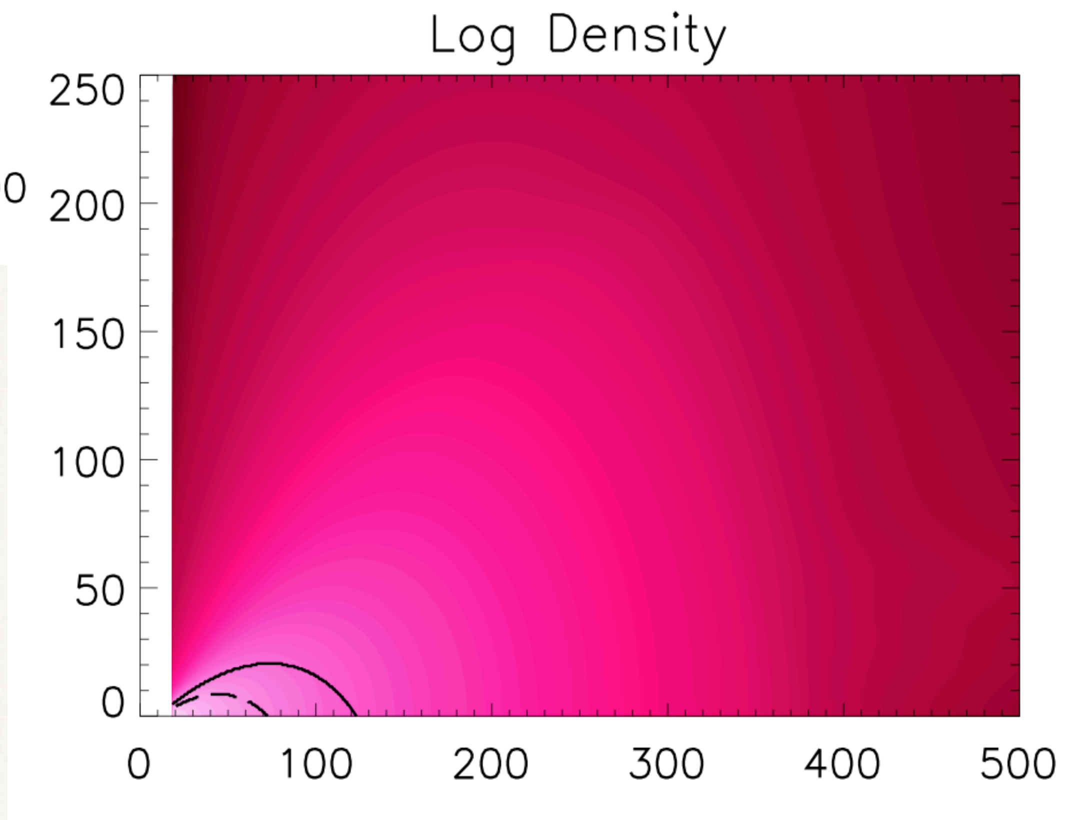
Caballero, McLaughlin, Surman (2011)

high *s/k*,
slower acceleration

nucleosynthesis from a time-dependent merger disk



t = 20 ms



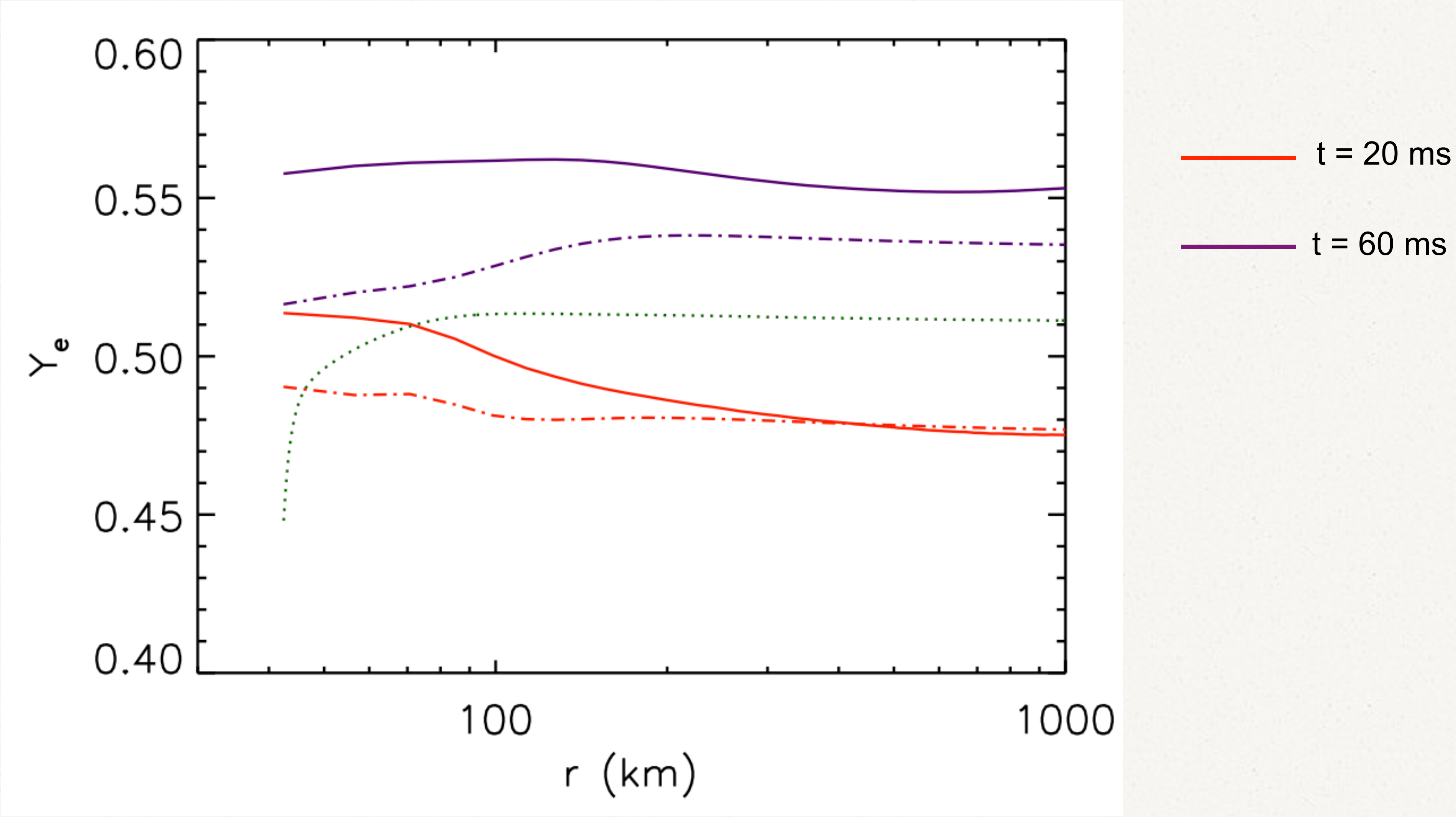
t = 60 ms

Disk model from Just and Janka

Neutrino decoupling surface calculation by L. Caballero

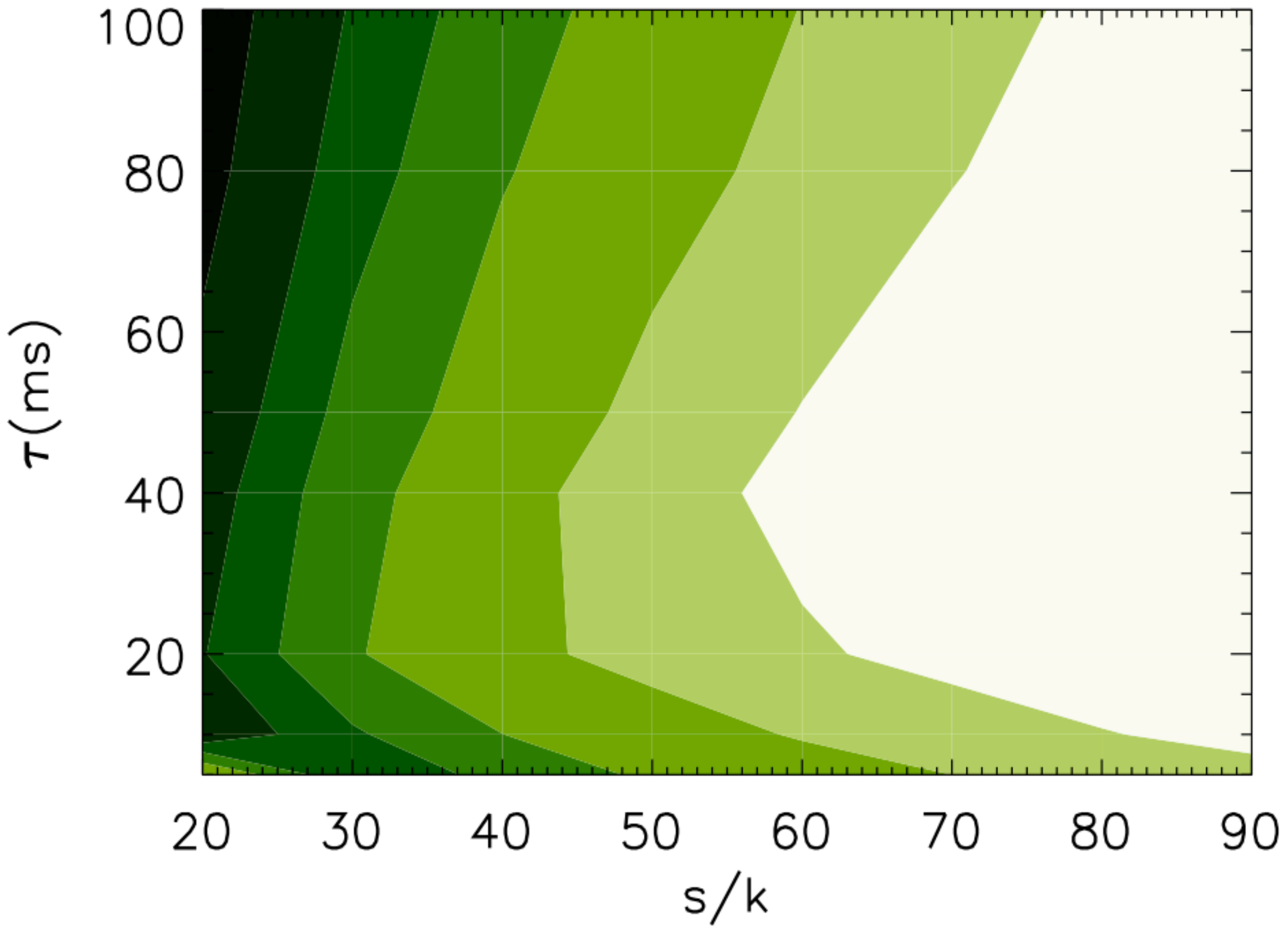
nucleosynthesis from a time-dependent merger disk

neutrino-only equilibrium electron fractions



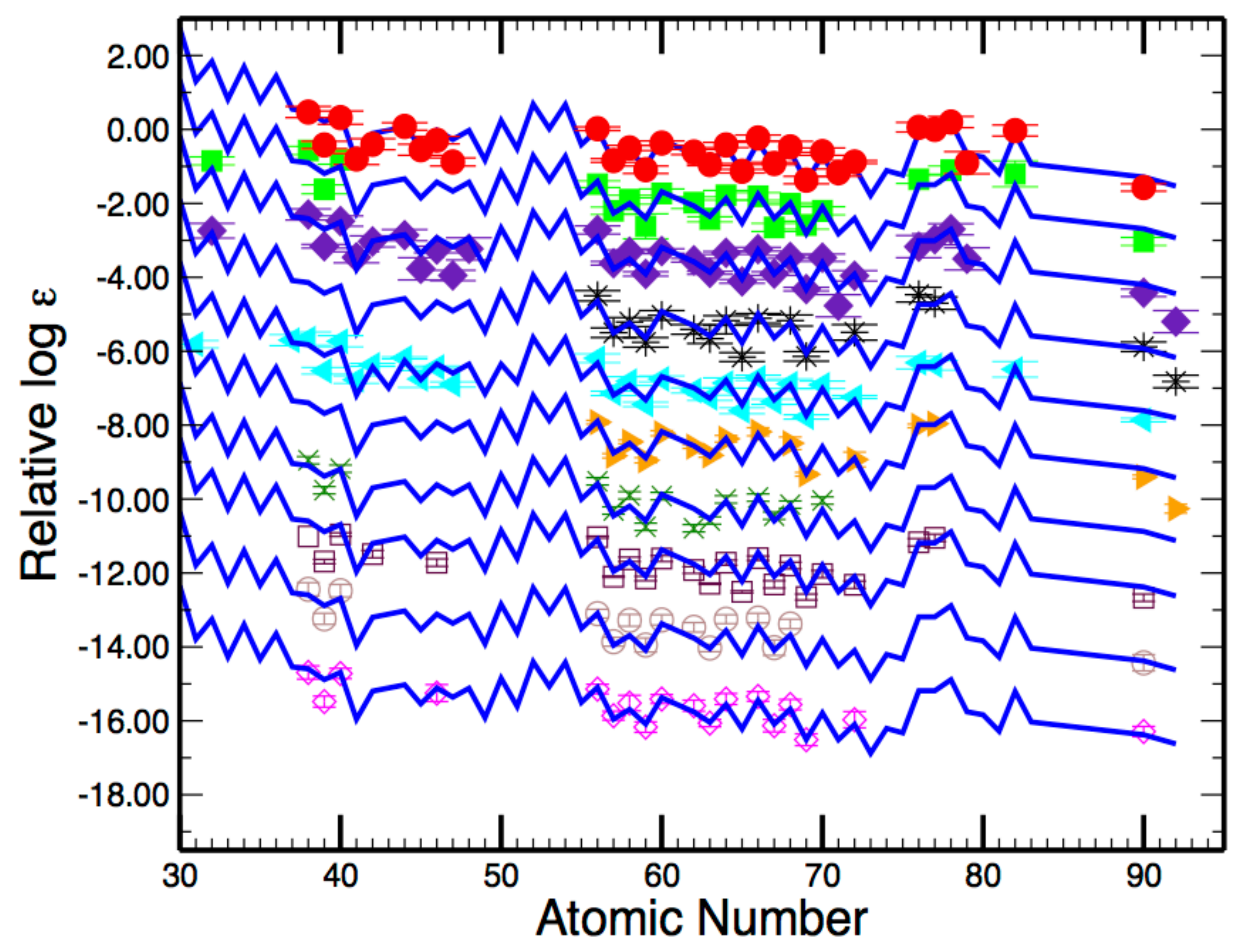
Surman, Caballero, McLaughlin, Just, Janka, submitted (2013)

nucleosynthesis from a time-dependent merger disk: ^{56}Ni



Surman, Caballero, McLaughlin, Just, Janka, submitted (2013)

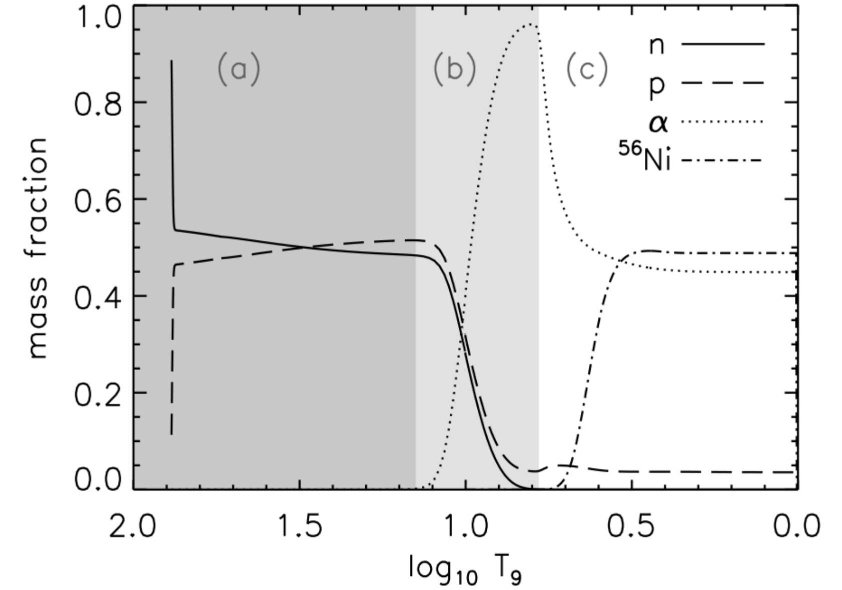
r-process in the oldest stars?

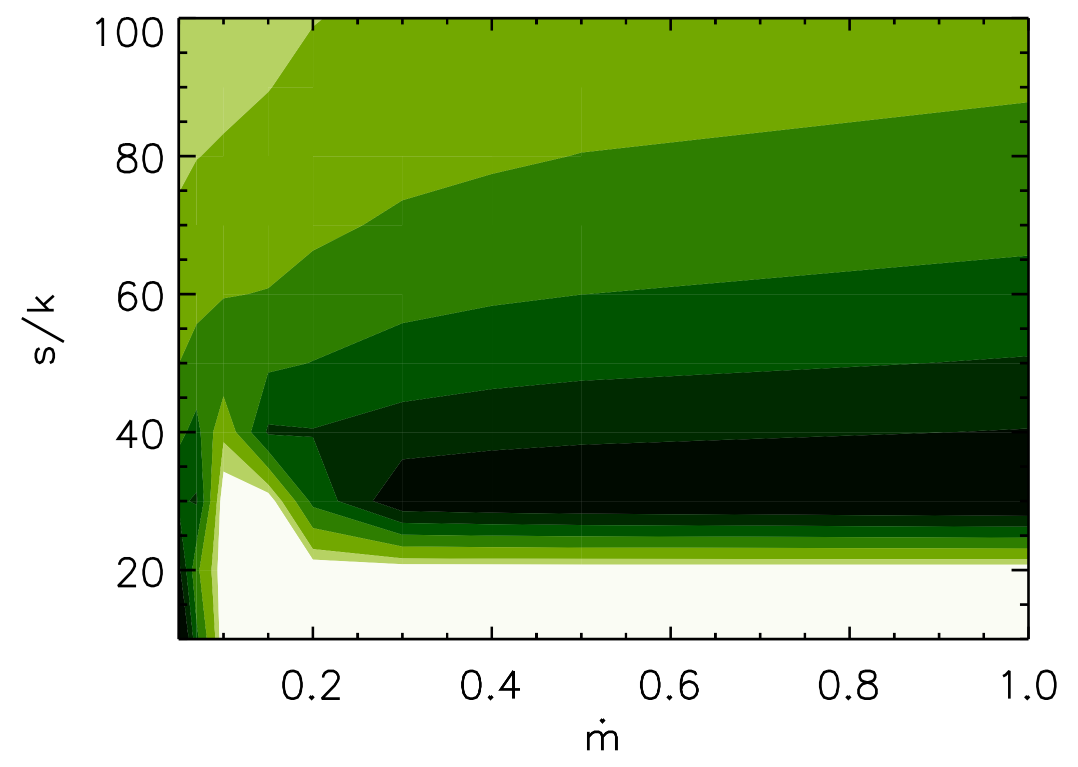


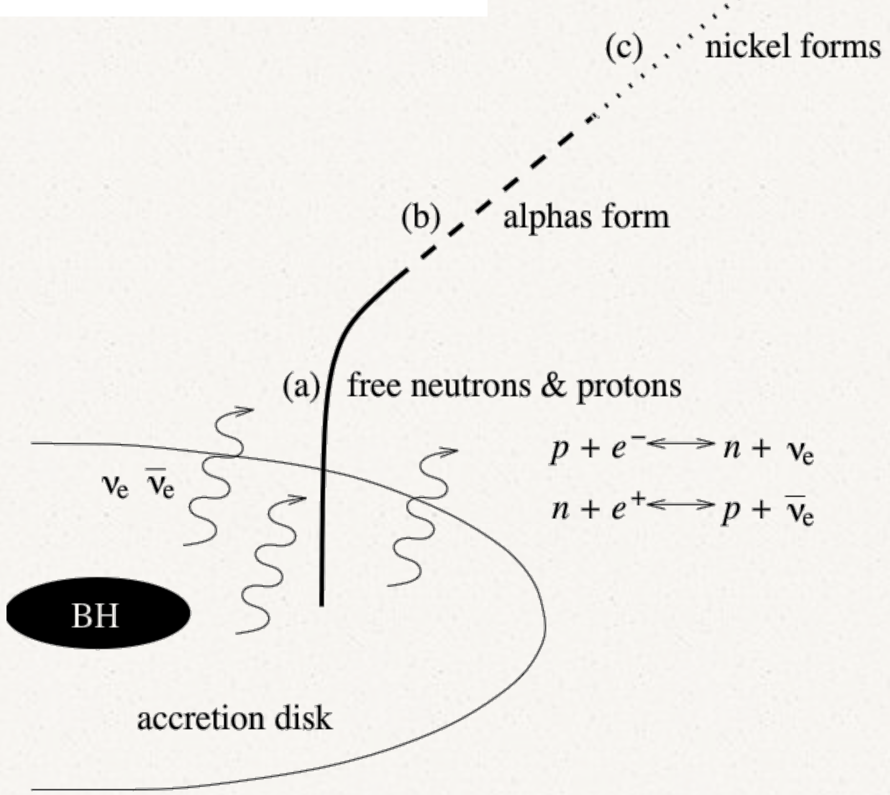
Cowan et al (2011)

nucleosynthesis from lower accretion rate/collapsar disks: ^{56}Ni

Surman, McLaughlin, Sabbatino (2011)





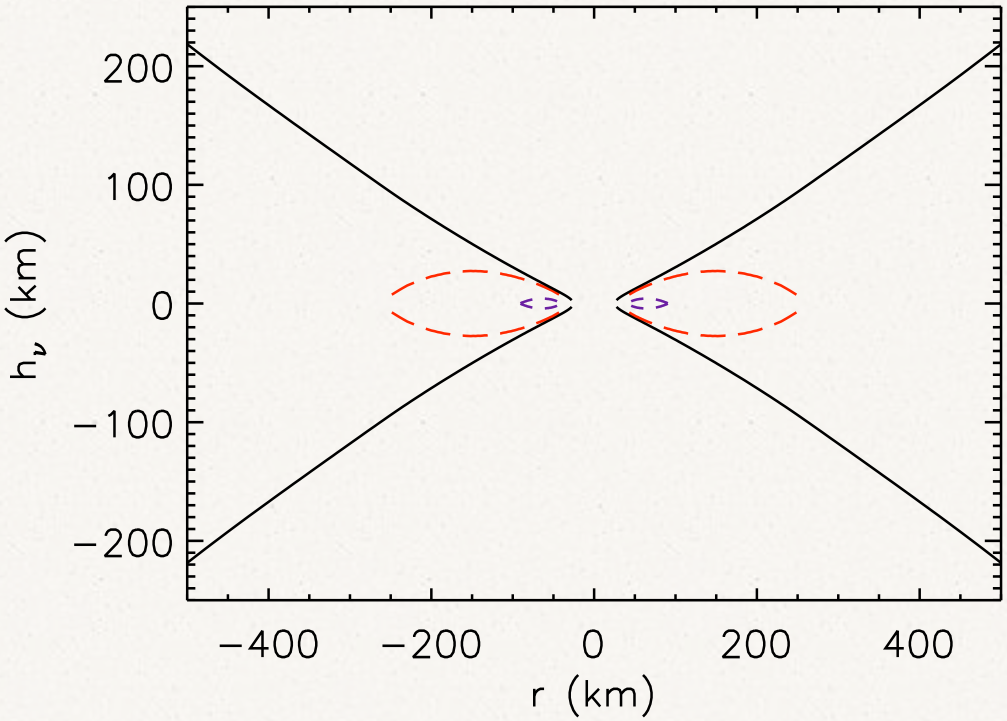


collapsar disk with trapped neutrinos and antineutrinos

Neutrino emission similar to a protoneutron star (PNS) in a typical core-collapse event, except:

- primarily ν_e and $\bar{\nu}_e$ (vs. all flavors in a PNS)
- emission surfaces not spherical
- ν_e emission surface much larger than that for $\bar{\nu}_e$

As a result, antineutrino emission can dominate over neutrino emission close to the disk, but neutrino emission can dominate farther out



neutrino oscillations

Two flavor mixing in matter with a high neutrino flux:

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} V_e + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e - V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

θ	mixing angle
δm^2	mass difference squared
E	neutrino energy
V_e	effective potential due to matter
V_ν	neutrino self interaction potentials

neutrino oscillations

Two flavor mixing in matter with a high neutrino flux:

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} V_e + \cancel{V_\nu^a} - \frac{\delta m^2}{4E}\cos(2\theta) & \cancel{V_\nu^b} + \frac{\delta m^2}{4E}\sin(2\theta) \\ \cancel{V_\nu^b} + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e - \cancel{V_\nu^a} + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

θ	mixing angle
δm^2	mass difference squared
E	neutrino energy
V_e	effective potential due to matter
V_ν	neutrino self interaction potentials

MSW flavor transition: $V_e \approx \frac{\delta m^2}{4E}\cos(2\theta)$

neutrino oscillations

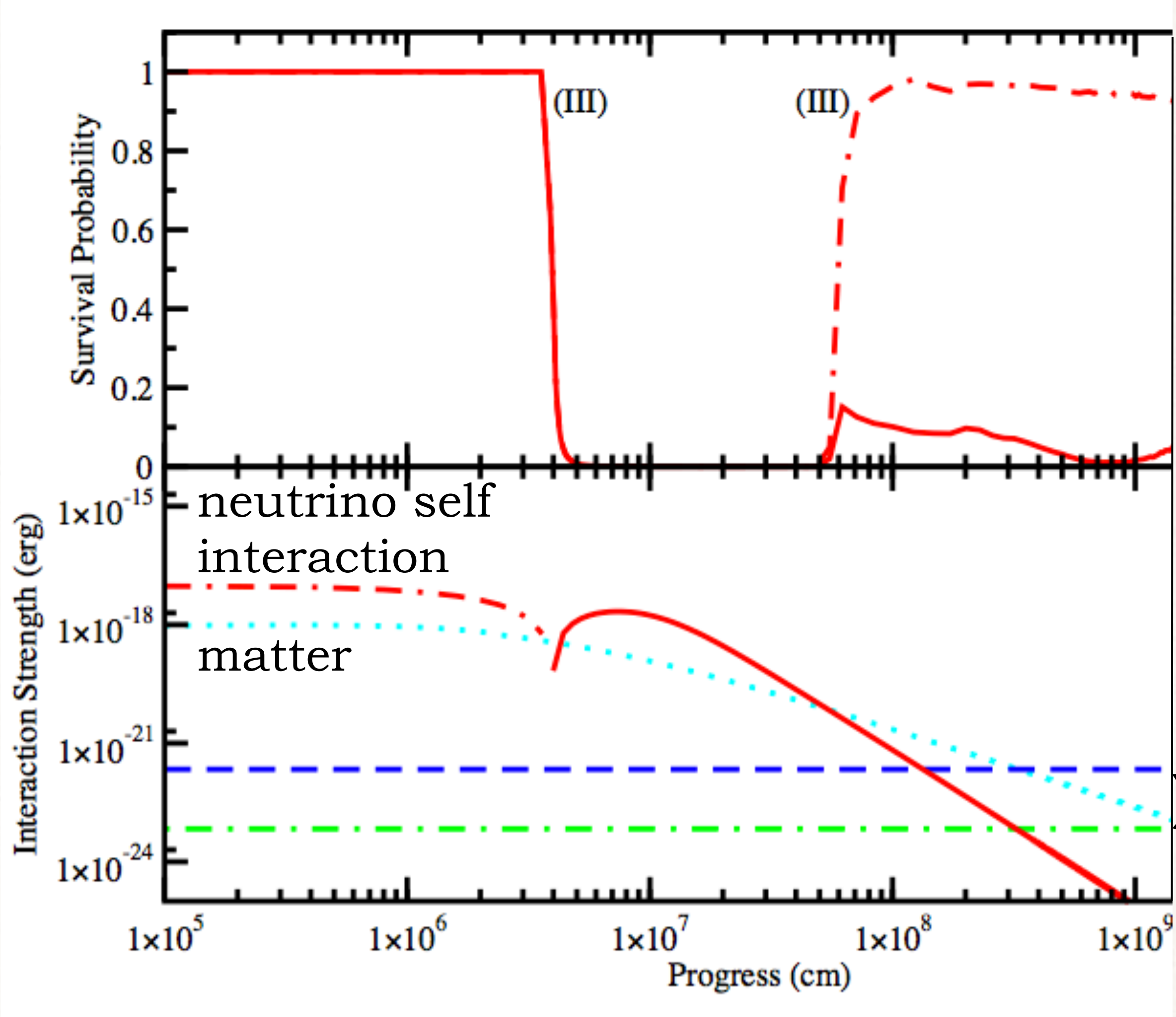
Two flavor mixing in matter with a high neutrino flux:

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} \xcancel{V_e} + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -\xcancel{V_e} - V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

θ	mixing angle
δm^2	mass difference squared
E	neutrino energy
V_e	effective potential due to matter
V_ν	neutrino self interaction potentials

Collective flavor transformation: $V_\nu \approx \frac{\delta m^2}{4E}\cos(2\theta)$

black hole accretion disk neutrino oscillations

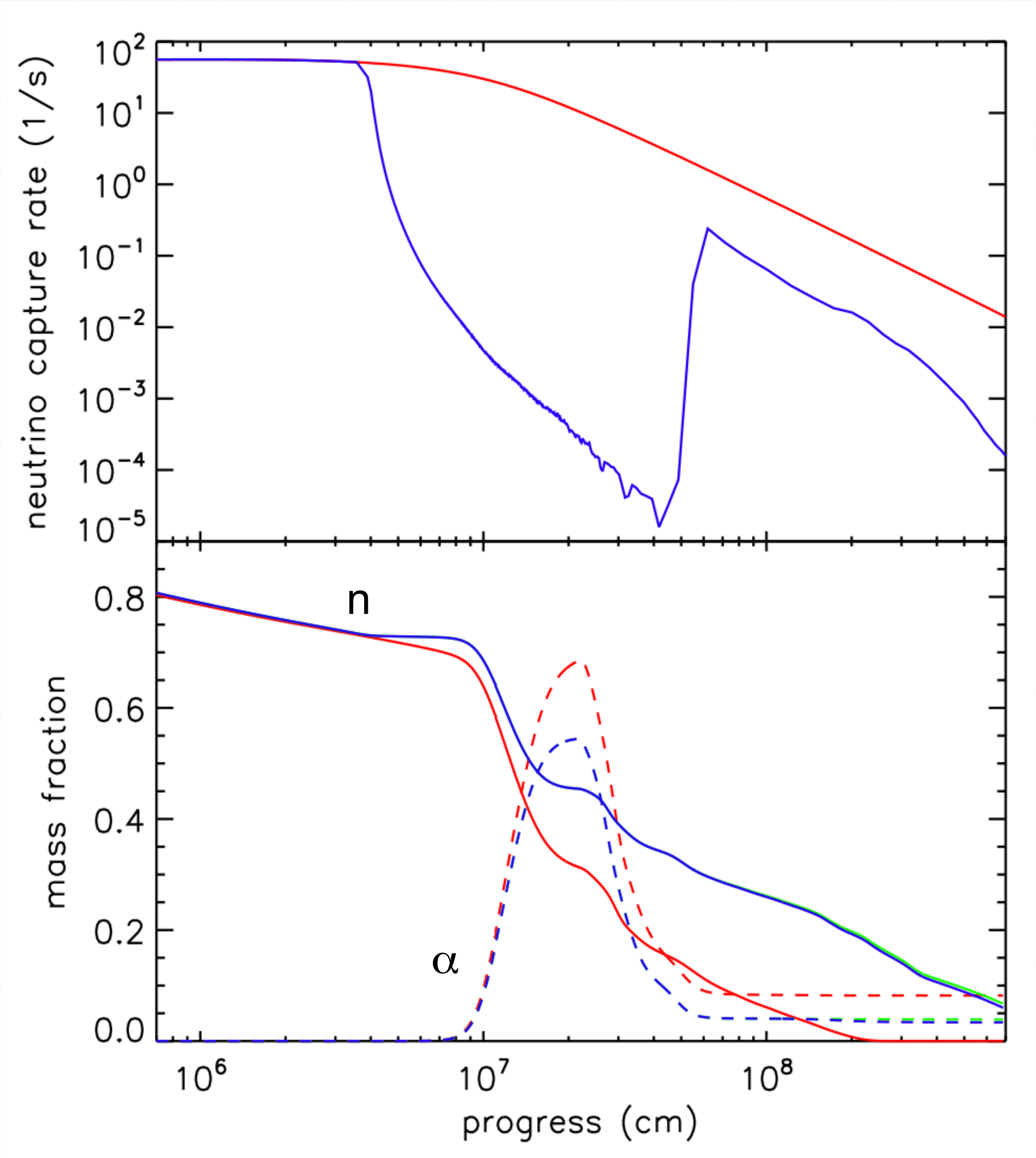


Malkus, McLaughlin, Kneller, Surman (2012)

vacuum terms

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} \boxed{V_e + V_\nu^a} - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & \boxed{-V_e - V_\nu^a} + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

AD-BH neutrino oscillations: consequences for nucleosynthesis

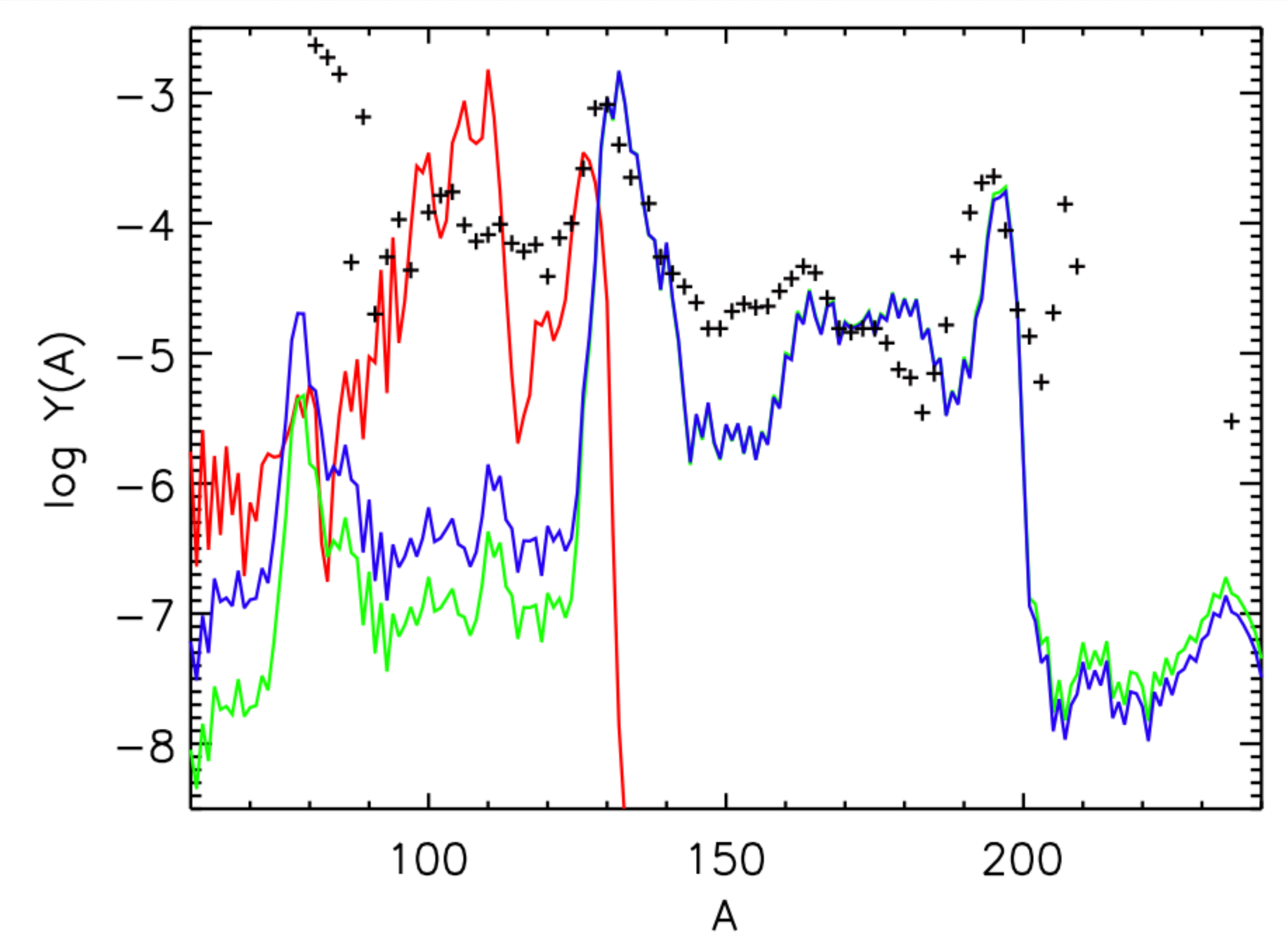


— no oscillations

— single angle ν oscillation calculation

Malkus, McLaughlin, Kneller, Surman (2012)

AD-BH neutrino oscillations: consequences for nucleosynthesis



no oscillations

single angle ν
oscillation
calculation

Malkus, McLaughlin, Kneller, Surman (2012)

summary (I)

Neutrinos play a key role in heavy element synthesis in GRB black hole accretion disk outflows. Neutrinos can:

- set the initial neutron-to-proton ratio
- determine free nucleon availability for capture after seed formation

A careful treatment of the neutrino physics – including oscillations and general relativistic effects – is therefore essential to accurately predict nucleosynthetic outcomes in this environment

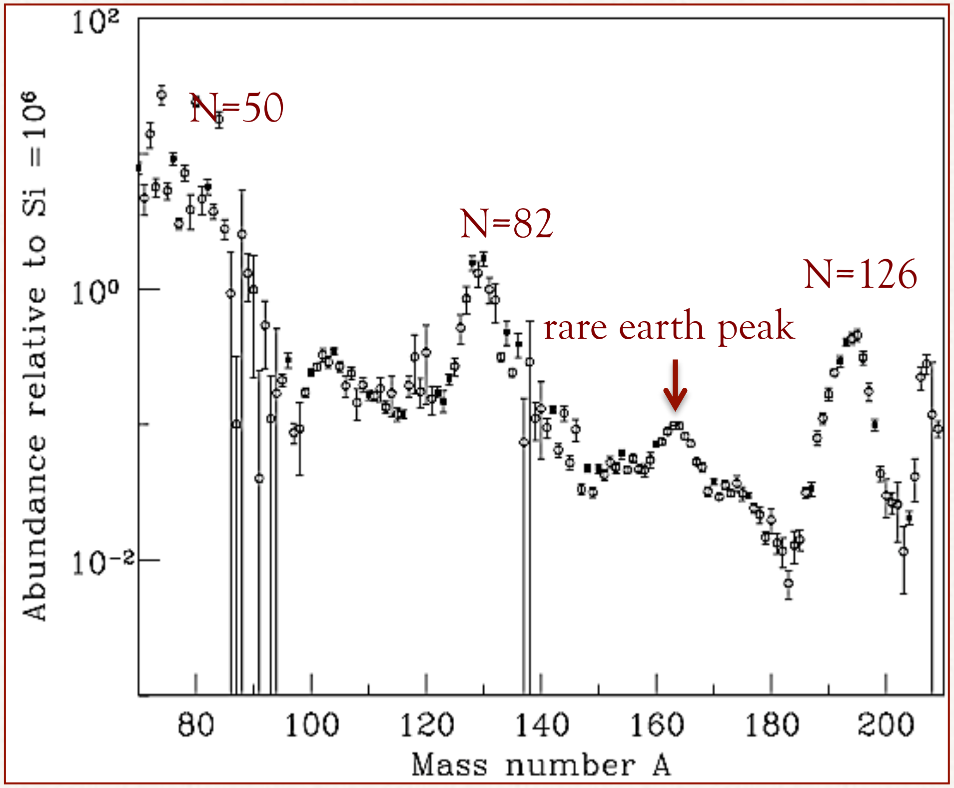
r-process astrophysical site: a new approach?

With the next generation of radioactive beam facilities + theoretical efforts to develop improved models, we will know the nuclear physics properties of nuclei populated in the late stages of the r-process

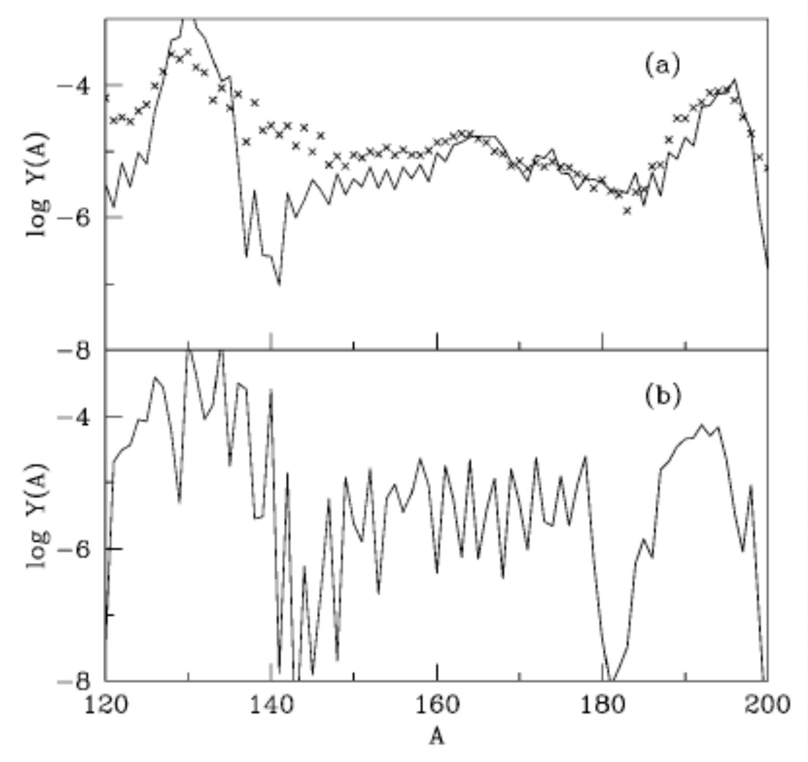
With the current and planned stellar surveys + follow-up spectroscopy, we will know the r-process abundance pattern (and all of its variations) in unprecedented detail

➡ we can use these details to get at the hydrodynamic conditions that must have existed during the late stage of the r-process

example: the rare earth peak

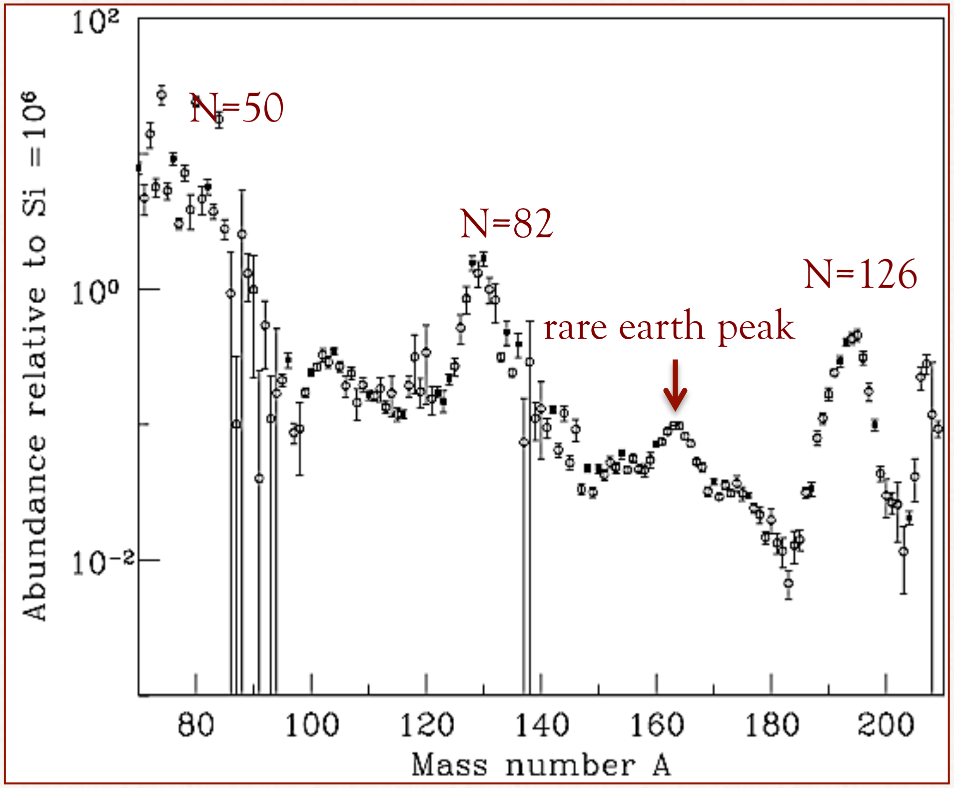


- Forms at the late stages of the r-process, during freezeout from (n,γ)-(γ,n) equilibrium



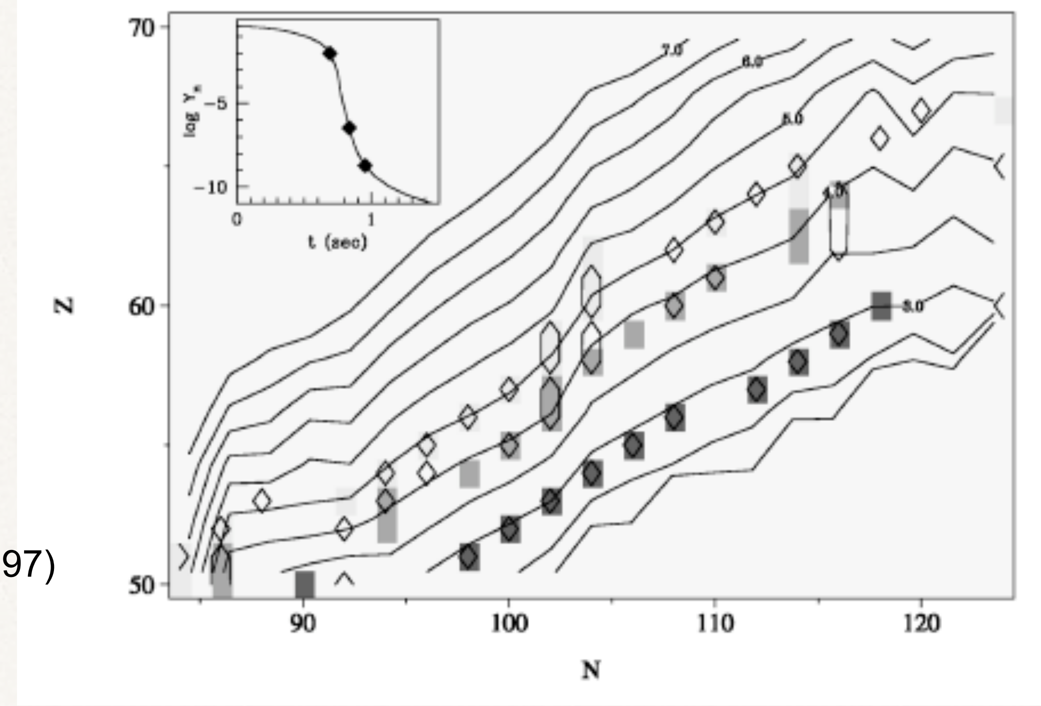
Surman, Engel, Bennett, Meyer (1997)

example: the rare earth peak



- Forms at the late stages of the r-process, during freezeout from (n,γ)-(γ,n) equilibrium

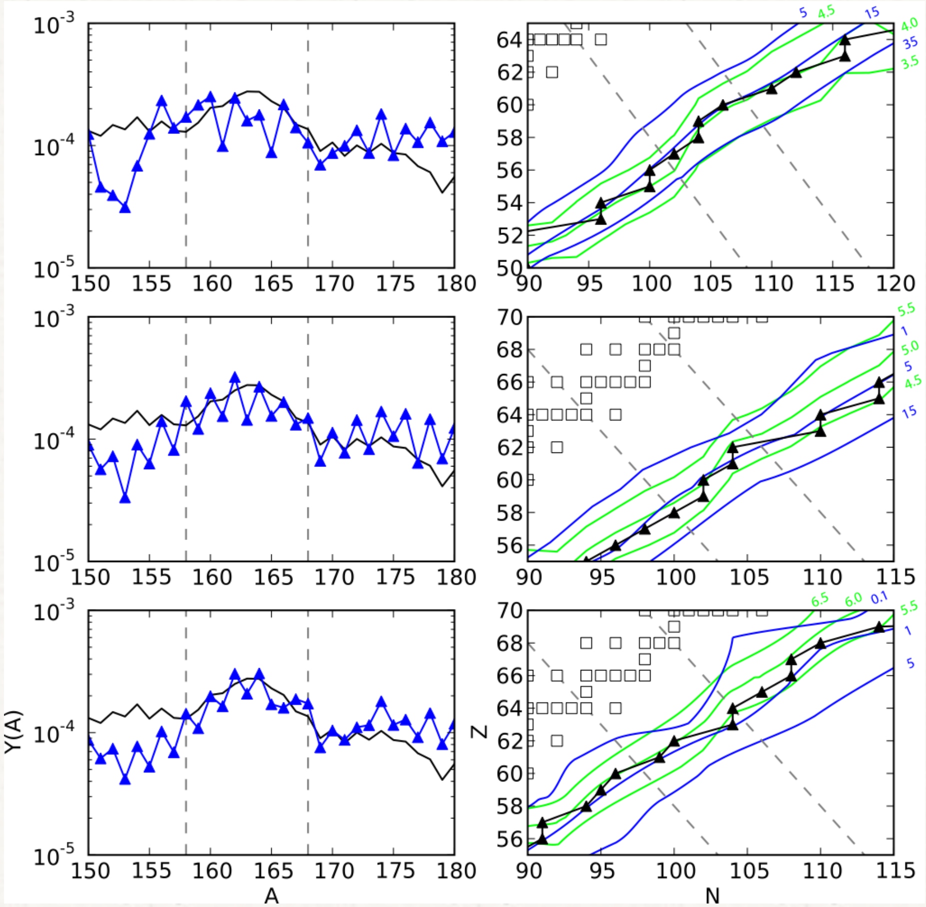
- The formation mechanism is sensitive to both the astrophysical conditions of the late phase of the r-process and the nuclear physics of the nuclei populated at this time



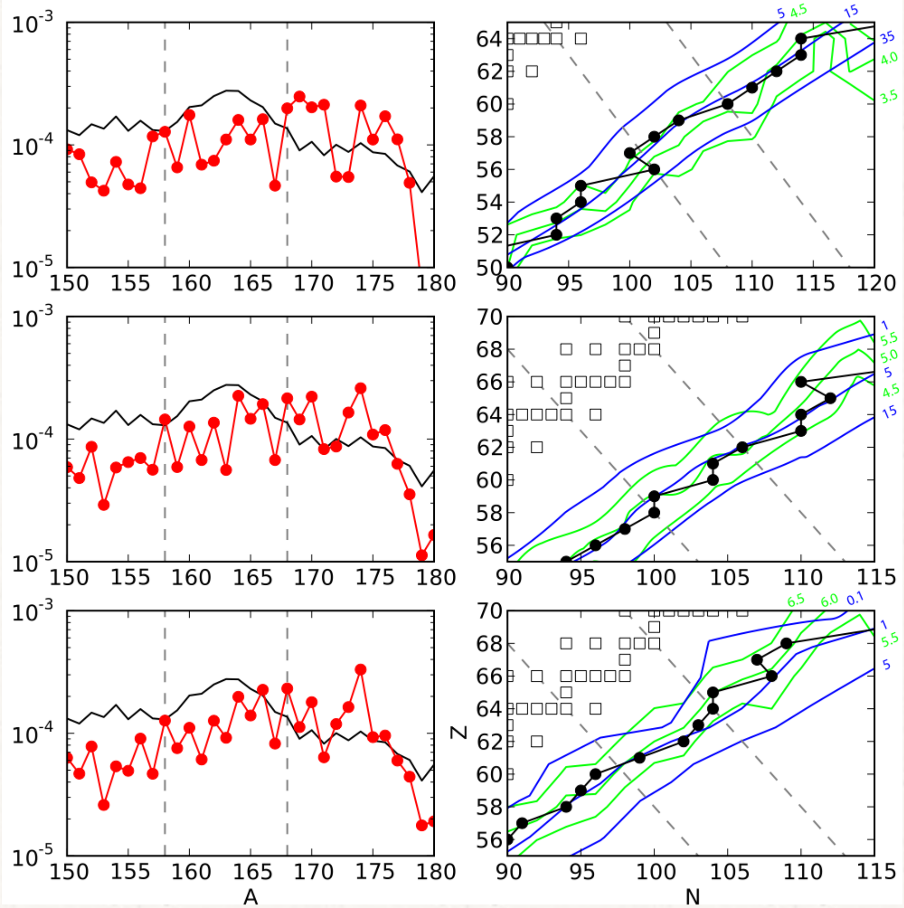
Surman, Engel, Bennett, Meyer (1997)

rare earth peak formation: nuclear data uncertainties

FRDM

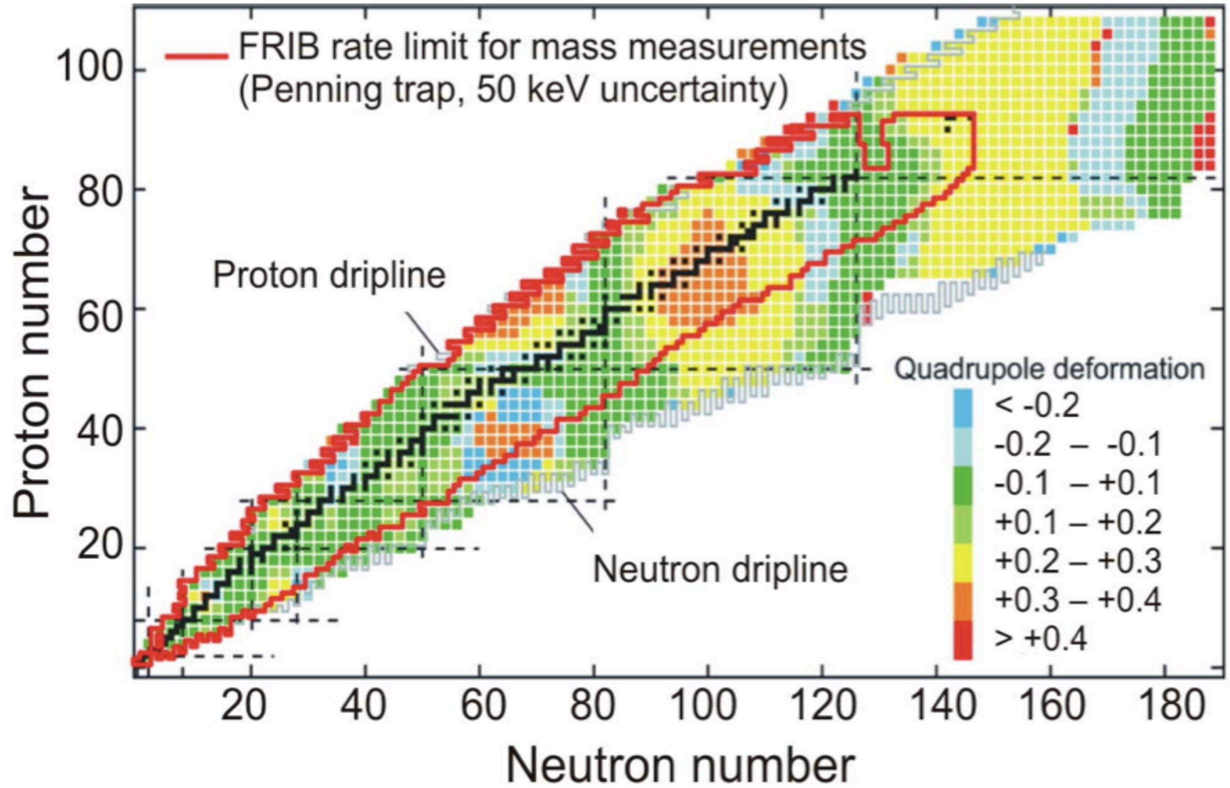


HFB-21



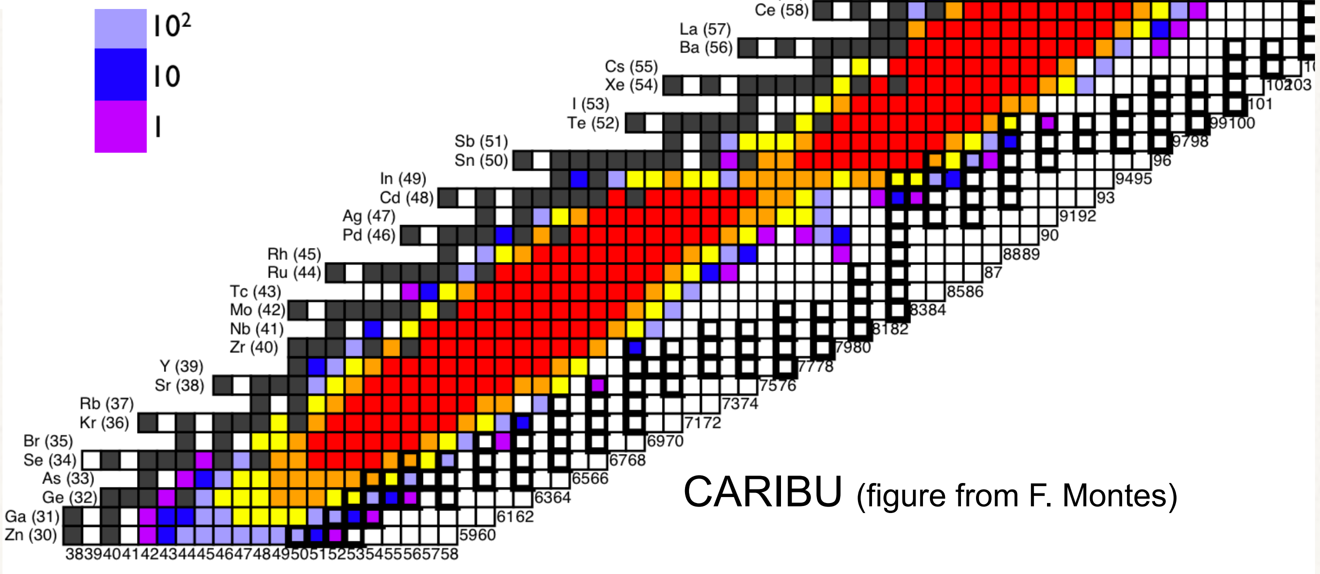
Mumpower, McLaughlin, Surman, PRC (2012)

experimental prospects



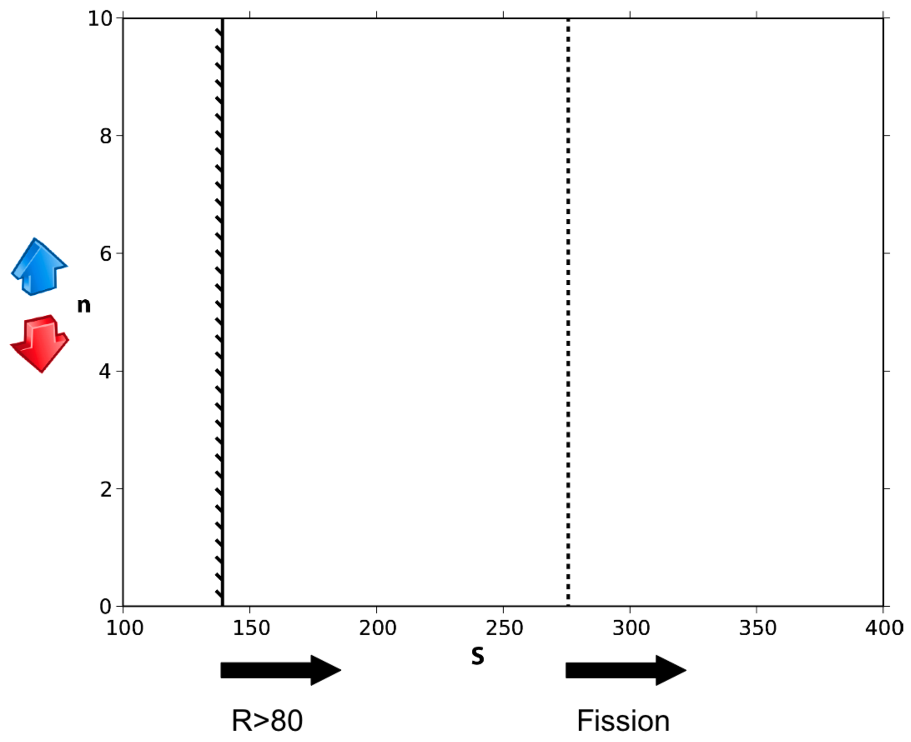
FRIB (figure from G. Bollen)

+ RIKEN + ARIEL + FAIR



CARIBU (figure from F. Montes)

using the rare earth peak to constrain r-process conditions



Mumpower, McLaughlin, Surman, ApJ (2012)

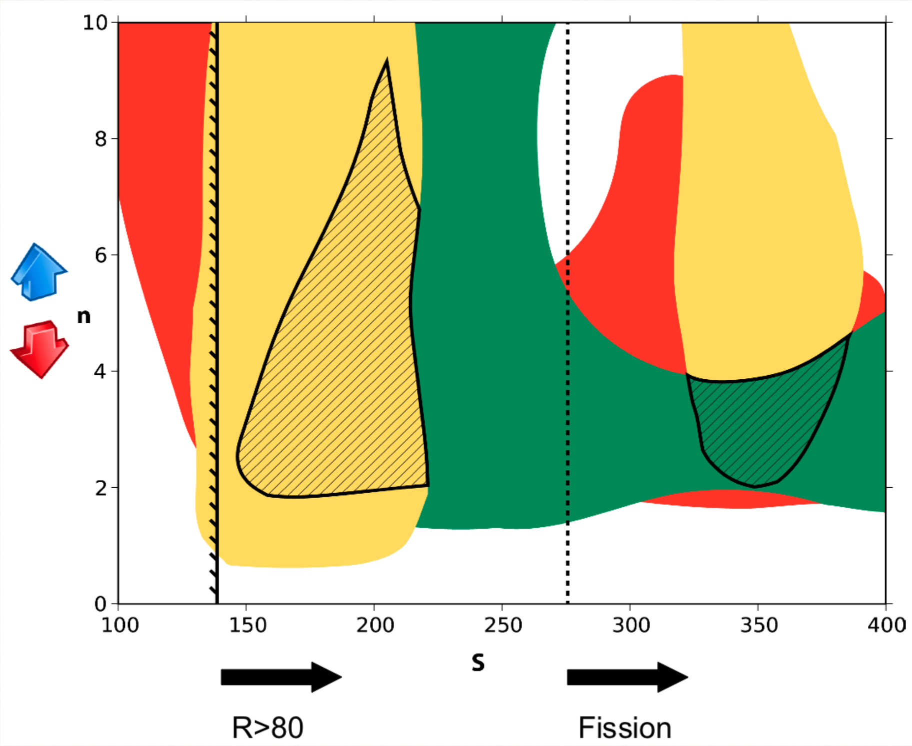
Parameterized wind based on Meyer (2002):

$$\rho(t) = \rho_1 e^{-3t/\tau} + \rho_2 \left(\frac{\Delta}{\Delta + t} \right)^n$$

with τ=80 ms, Y_e=0.3, FRDM masses

Vary 50<*s/k*<400, 0<*n*<10

using the rare earth peak to constrain r-process conditions



🟥 match with rare earth region

🟨 match with ratio of the A~195 main peak to rare earth peak

🟩 minimal late time neutron capture

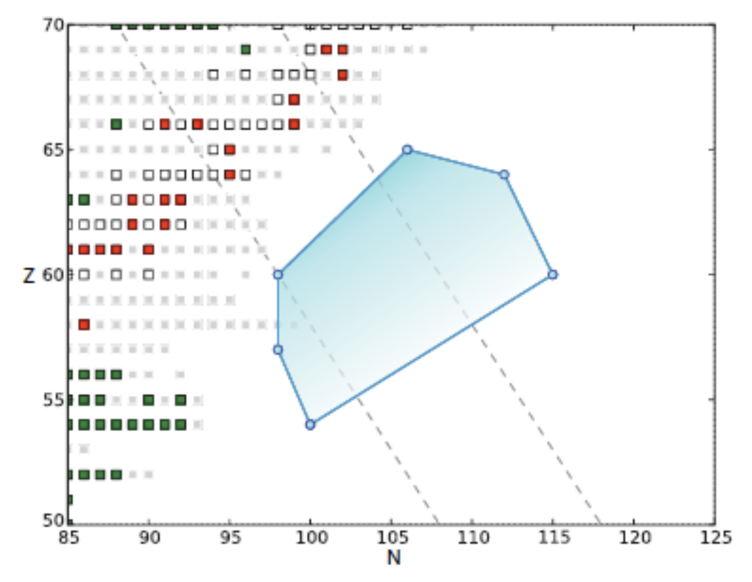
Mumpower, McLaughlin, Surman, ApJ (2012)

summary (II)

The rare earth peak offers unique insight into the nuclear physics and the astrophysics of the r-process. Its formation seems to require:

a deformation maximum in the rare earth region

the ‘right amount’ of neutron capture at late times in the r-process



Once the nuclear physics uncertainties are clarified by experiments at the next generation of radioactive beam facilities, the rare earth peak will become an even more powerful probe of the r-process astrophysical environment.