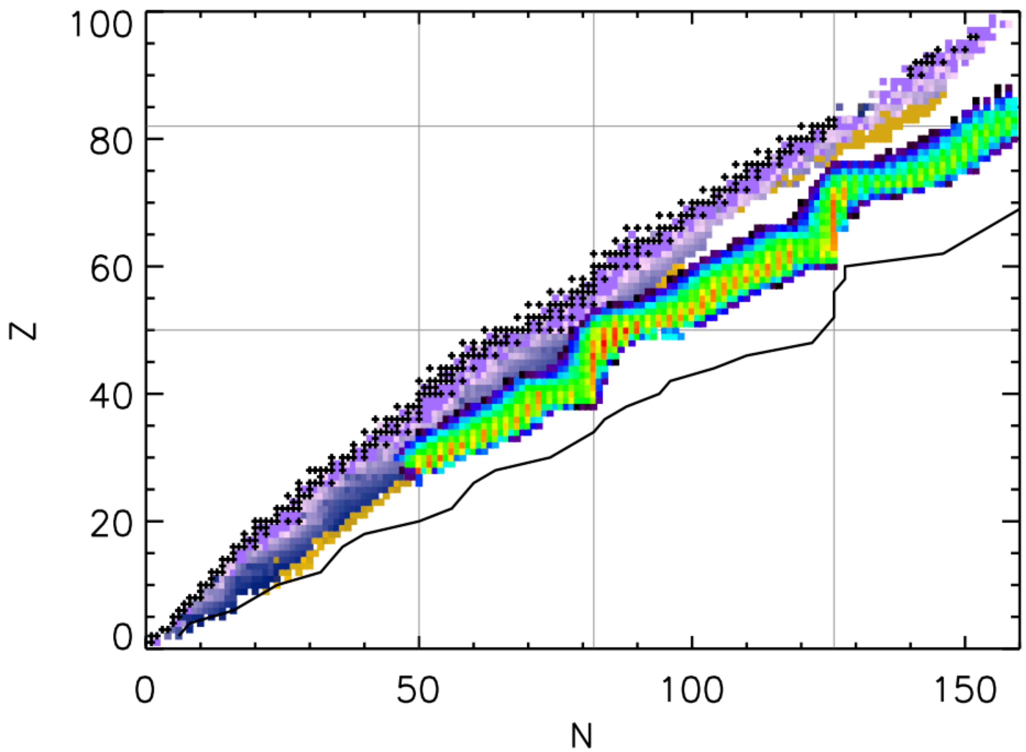
neutrino interactions and heavy element nucleosynthesis



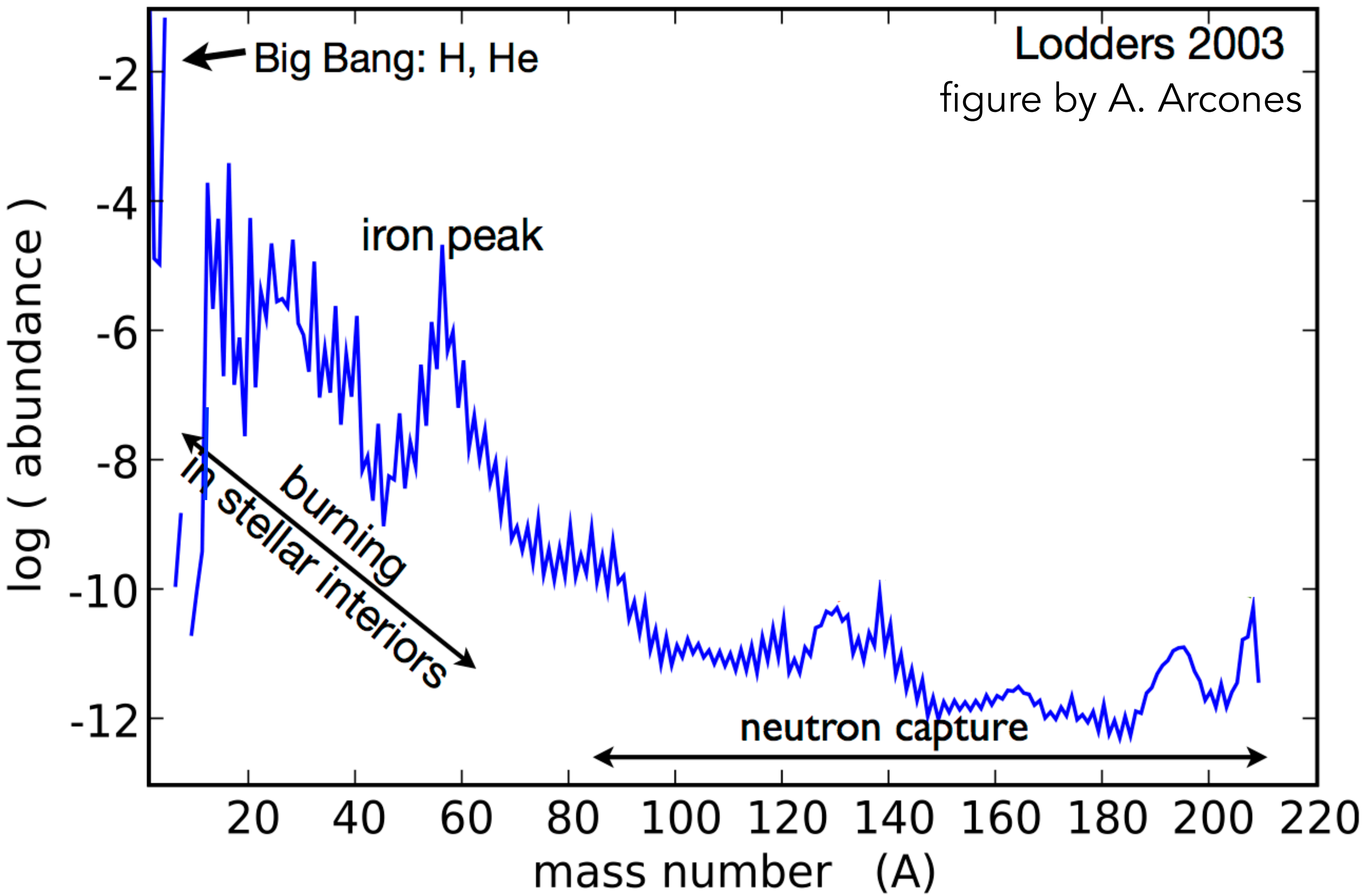
Rebecca Surman
University of Notre Dame

INT 15-2a
Neutrino Astrophysics and Fundamental Properties
1-26 June 2015

UNIVERSITY OF NOTRE DAME College of Science

JINA

solar system abundances



solar system abundances of heavy nuclei

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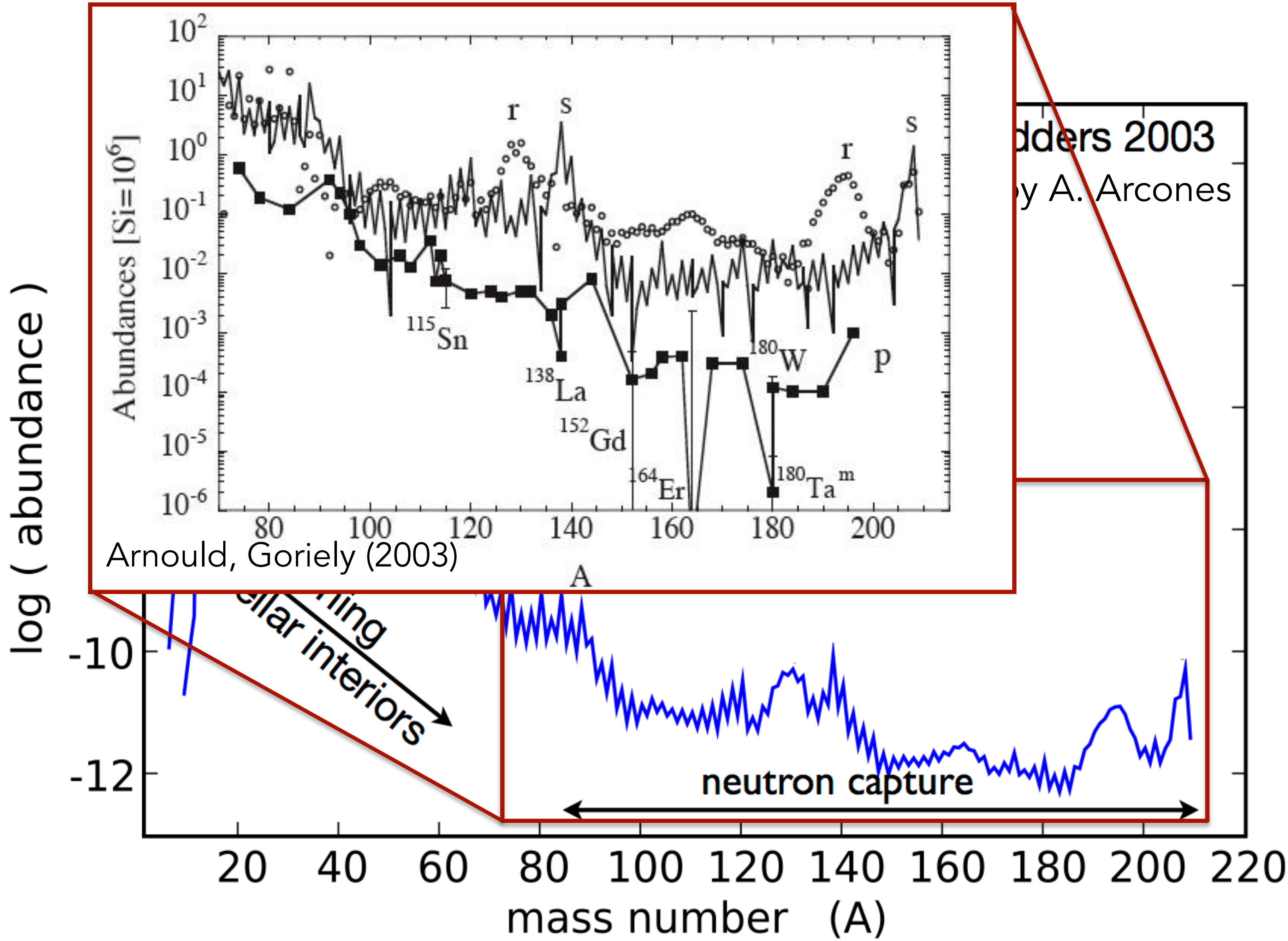

solar system abundances of heavy nuclei

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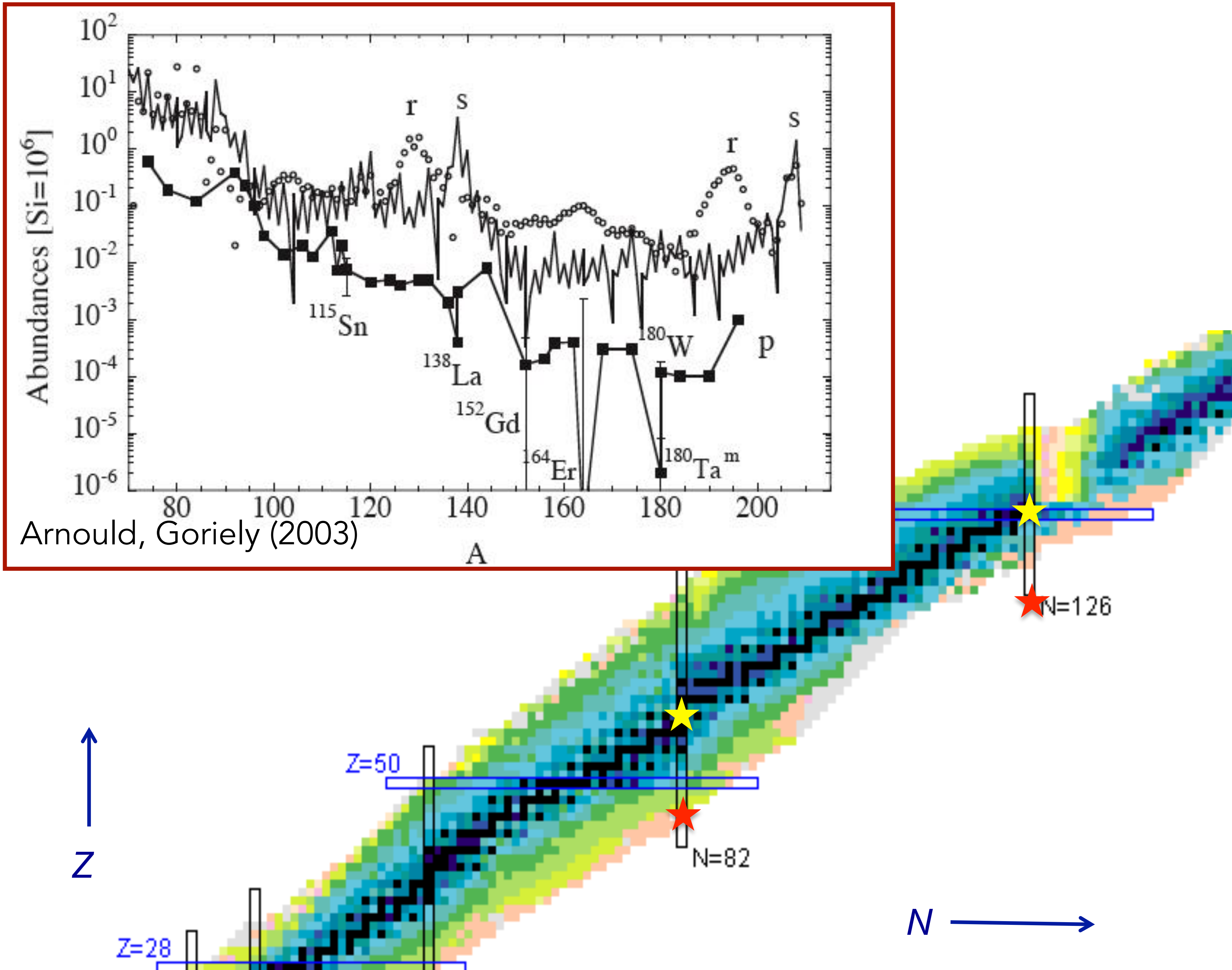

solar system abundances of heavy nuclei

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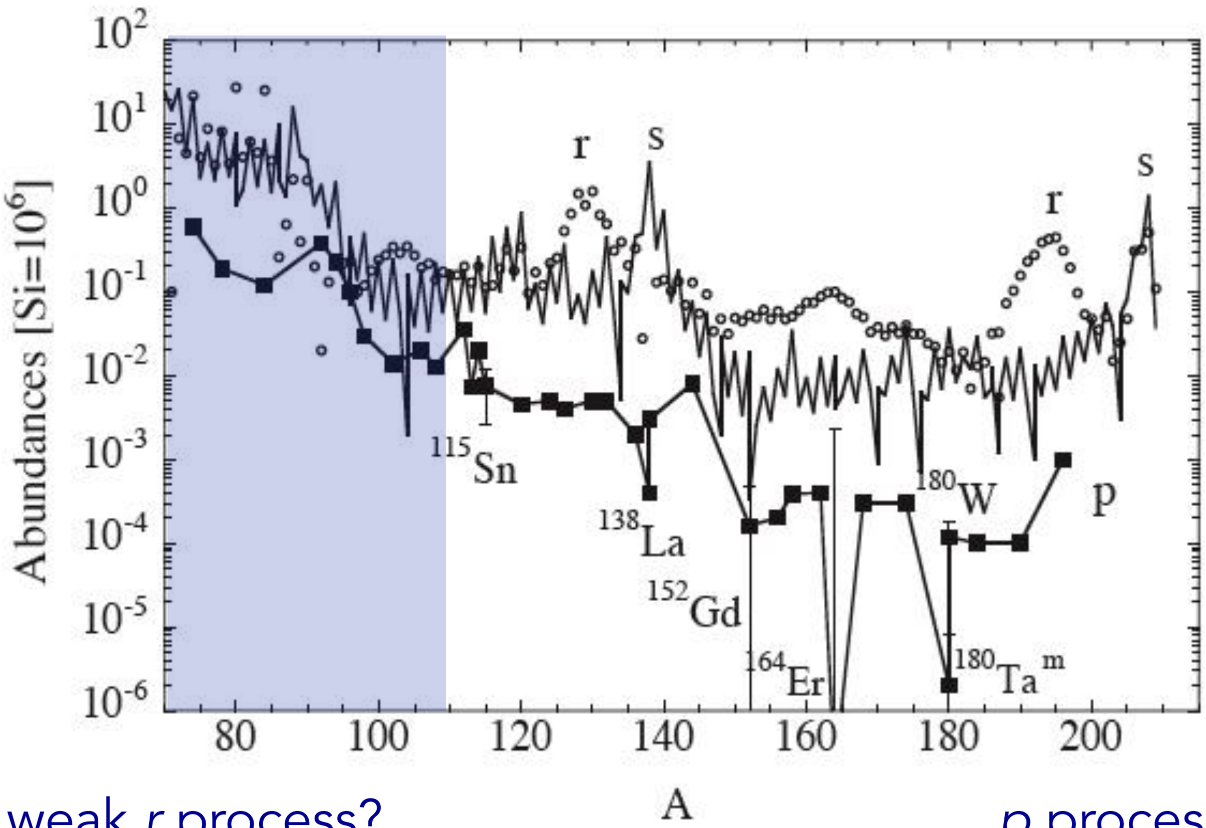

s process:
slow neutron capture
AGB stars

r process:
rapid neutron capture
site unknown

weak *r* process?
weak *s* process?
LEPP?
ν*p* process?

p process:
(γ,n) reactions on
preexisting heavy nuclei

ν process:
^{7}Li, ^{11}B, ^{19}F, ^{138}La, ^{180}Ta, etc.

solar system abundances of heavy nuclei

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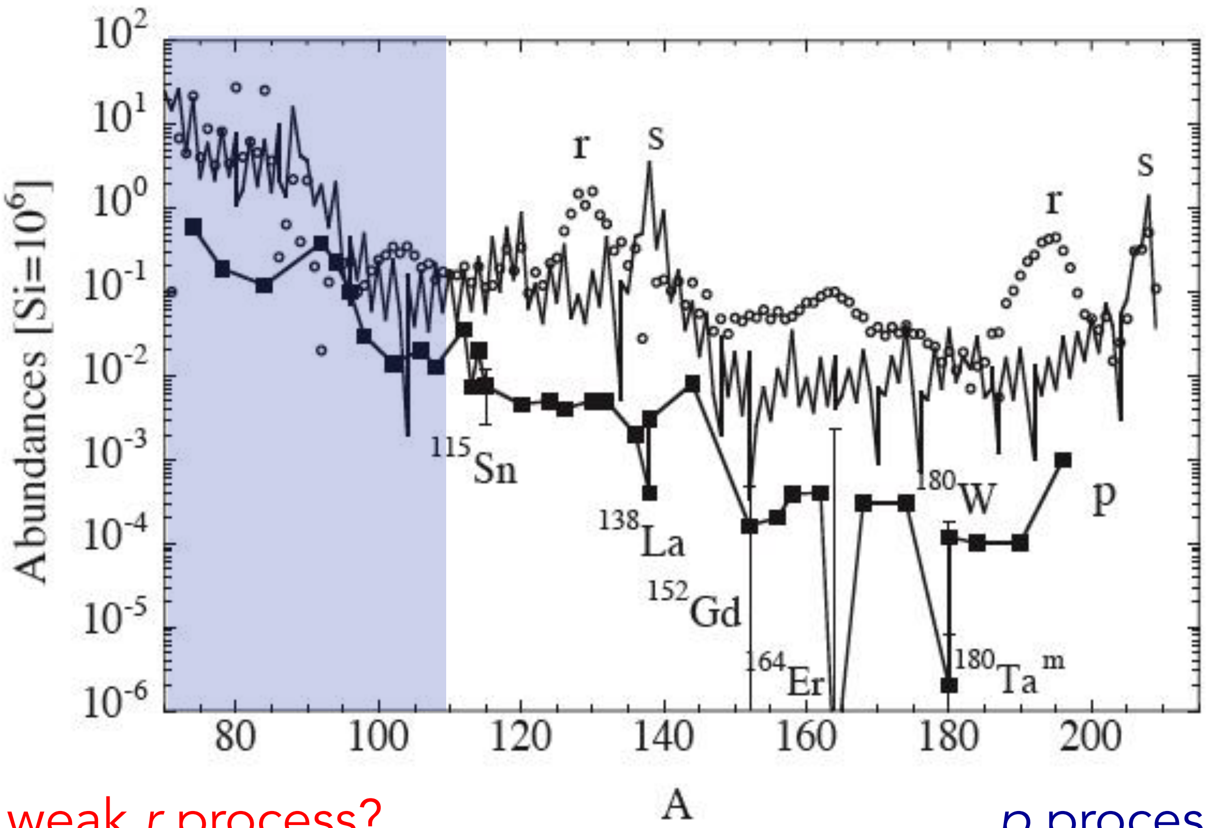

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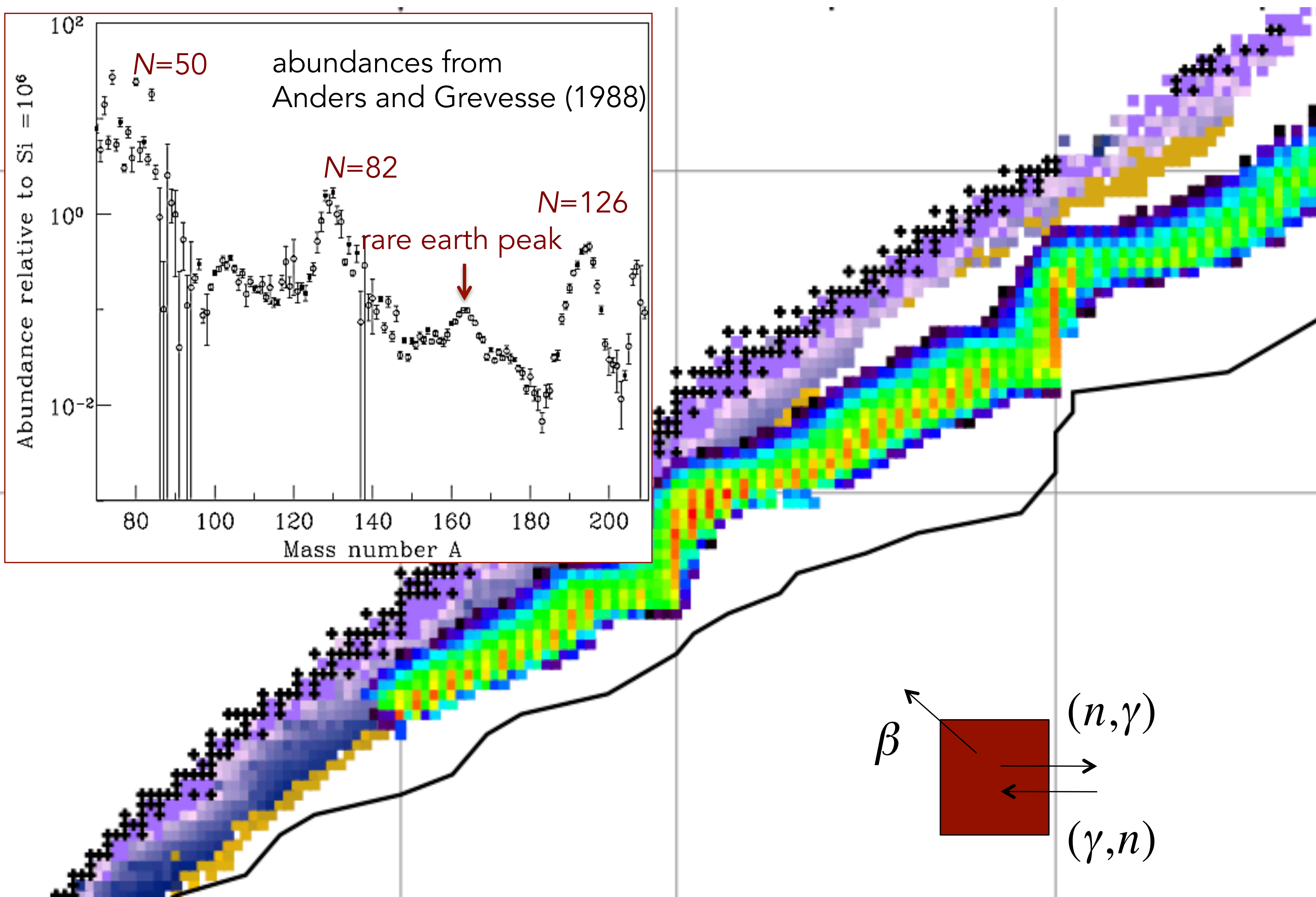
r-process nucleosynthesis



observations of *r*-process elements

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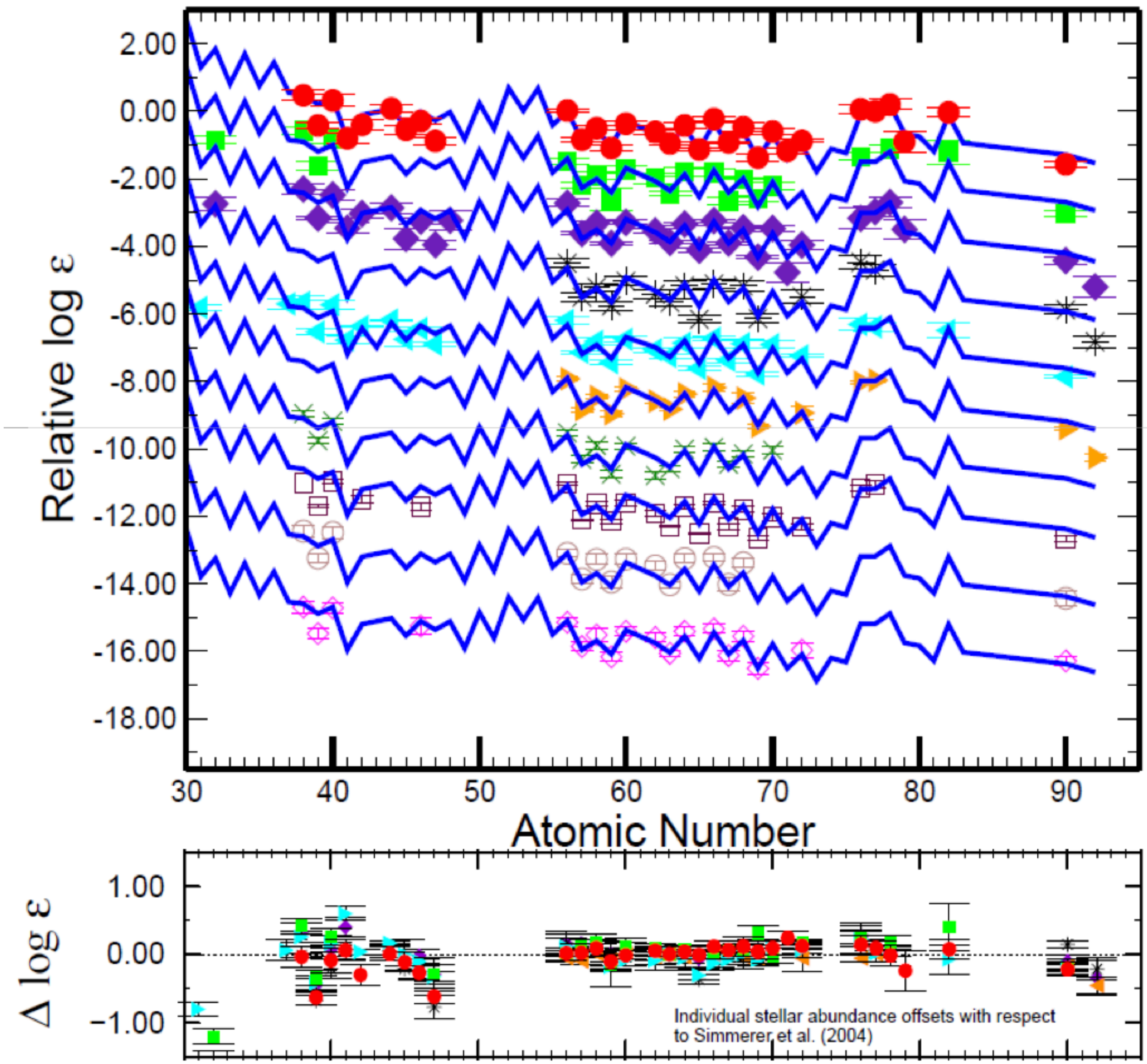
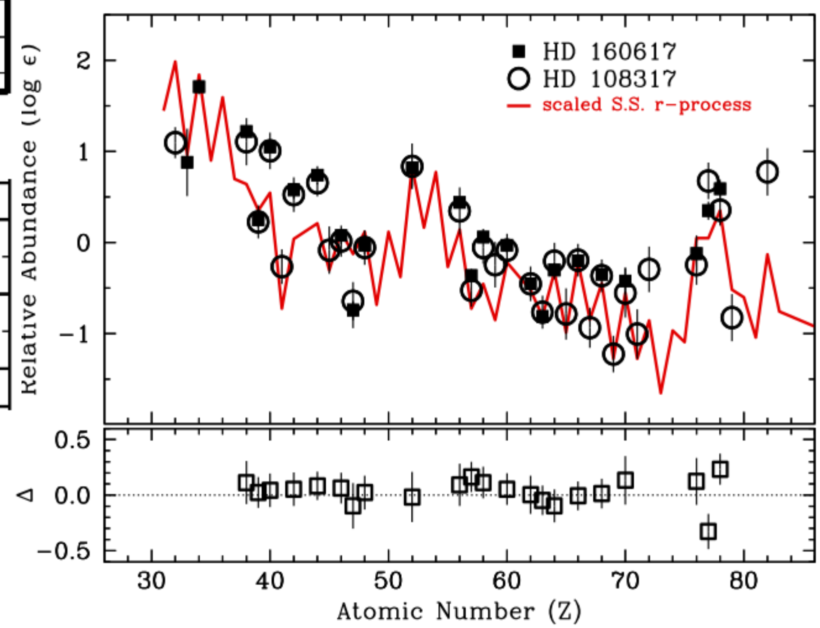
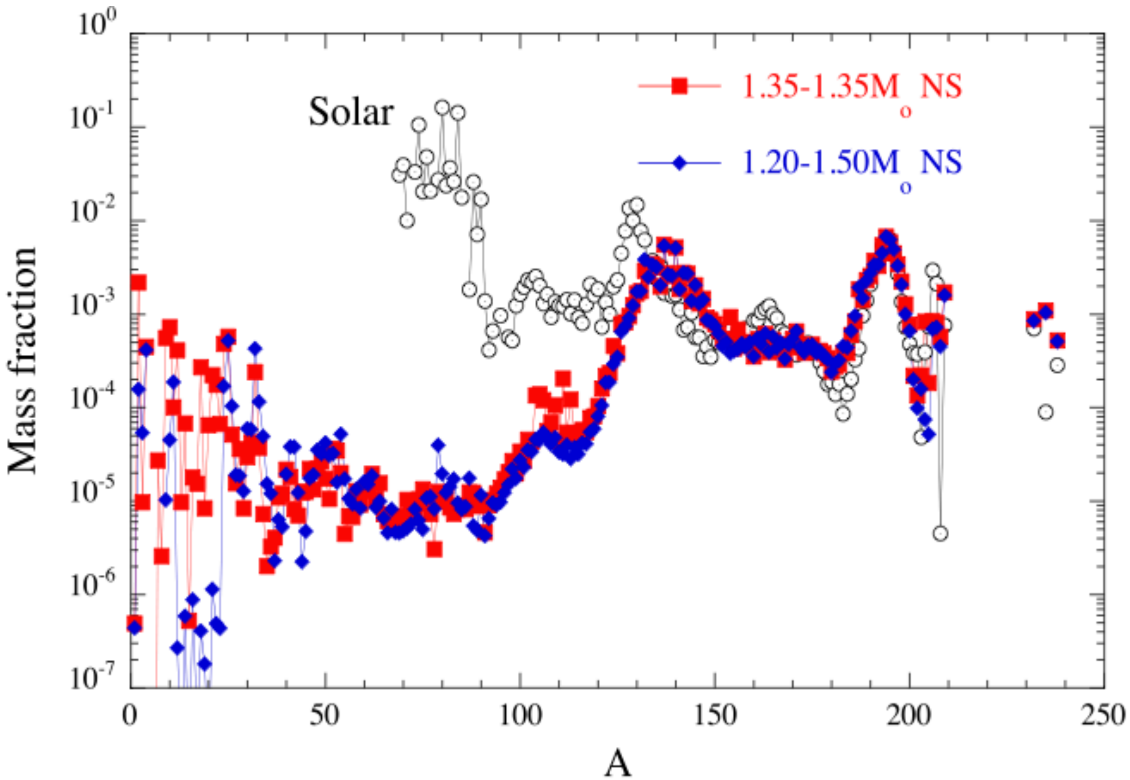


Cowan et al (2011)



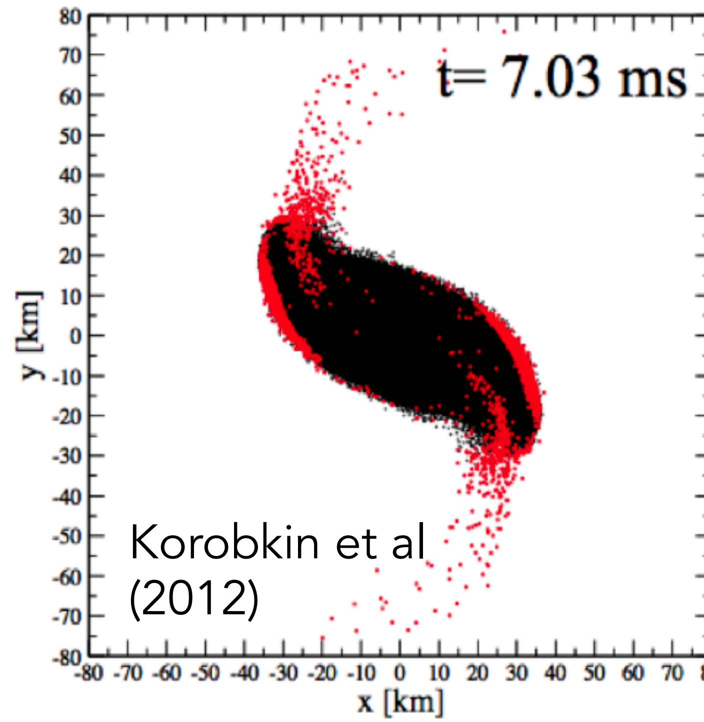
Roederer & Lawler (2012)

r-process astrophysical site: compact object mergers?



Goriely et al (2012)

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

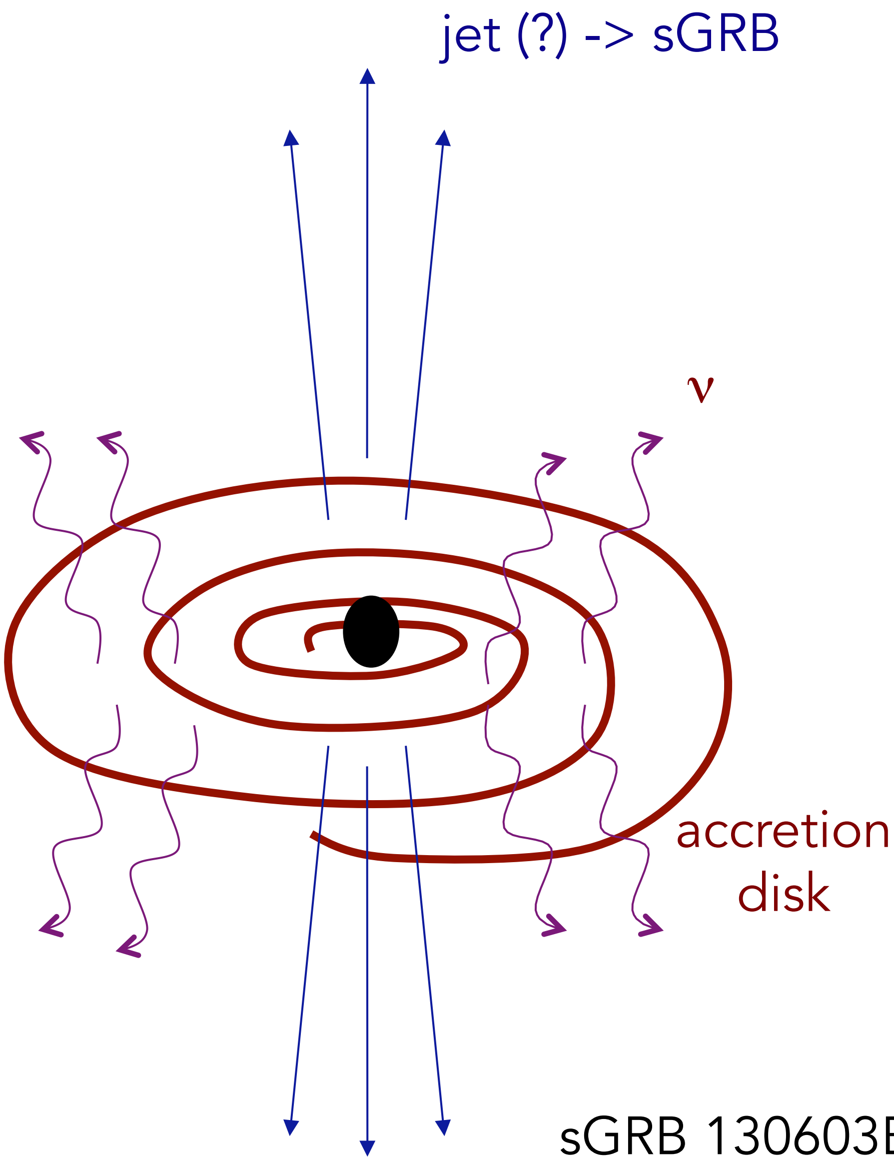


Korobkin et al (2012)

cold/mildly heated prompt ejecta

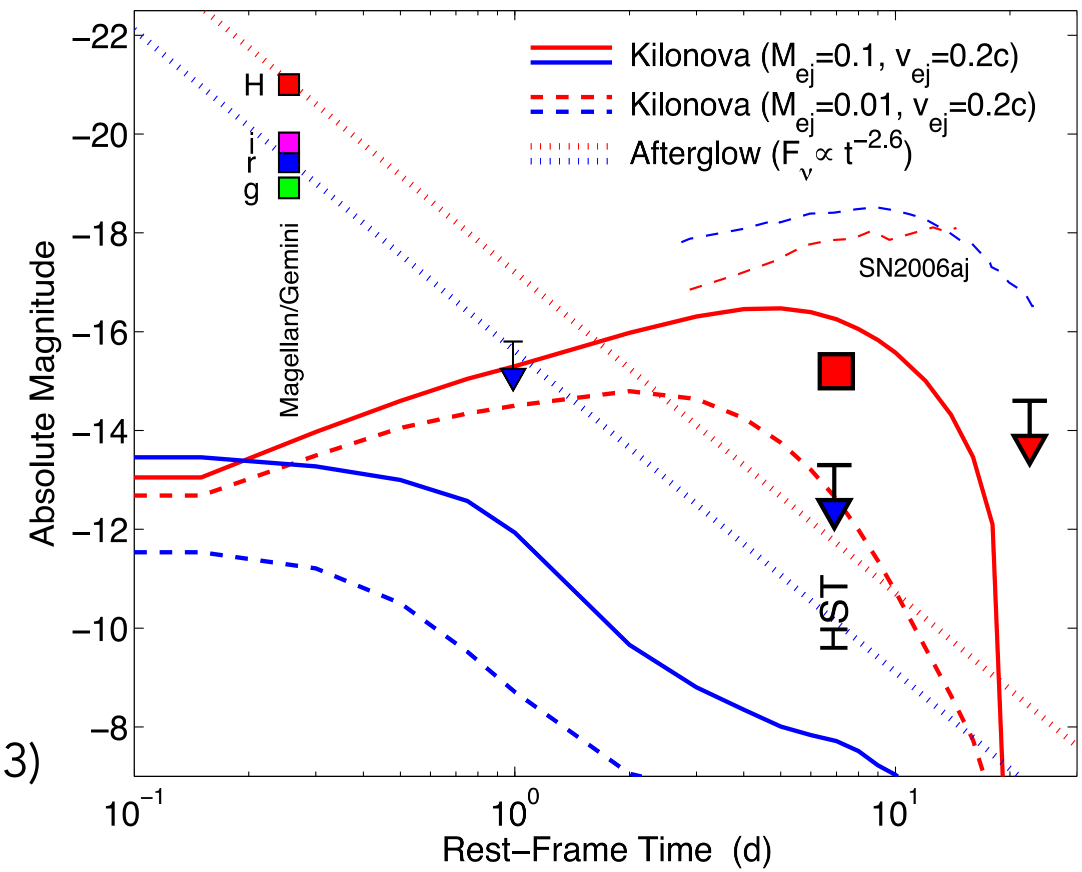
e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Argast et al (2004), Wanajo & Ishimaru (2006), Oechslin et al (2007), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012), Rosswog el at (2013), Wanajo et al (2014), Just et al (2014), etc., etc.

r-process astrophysical site: compact object mergers?

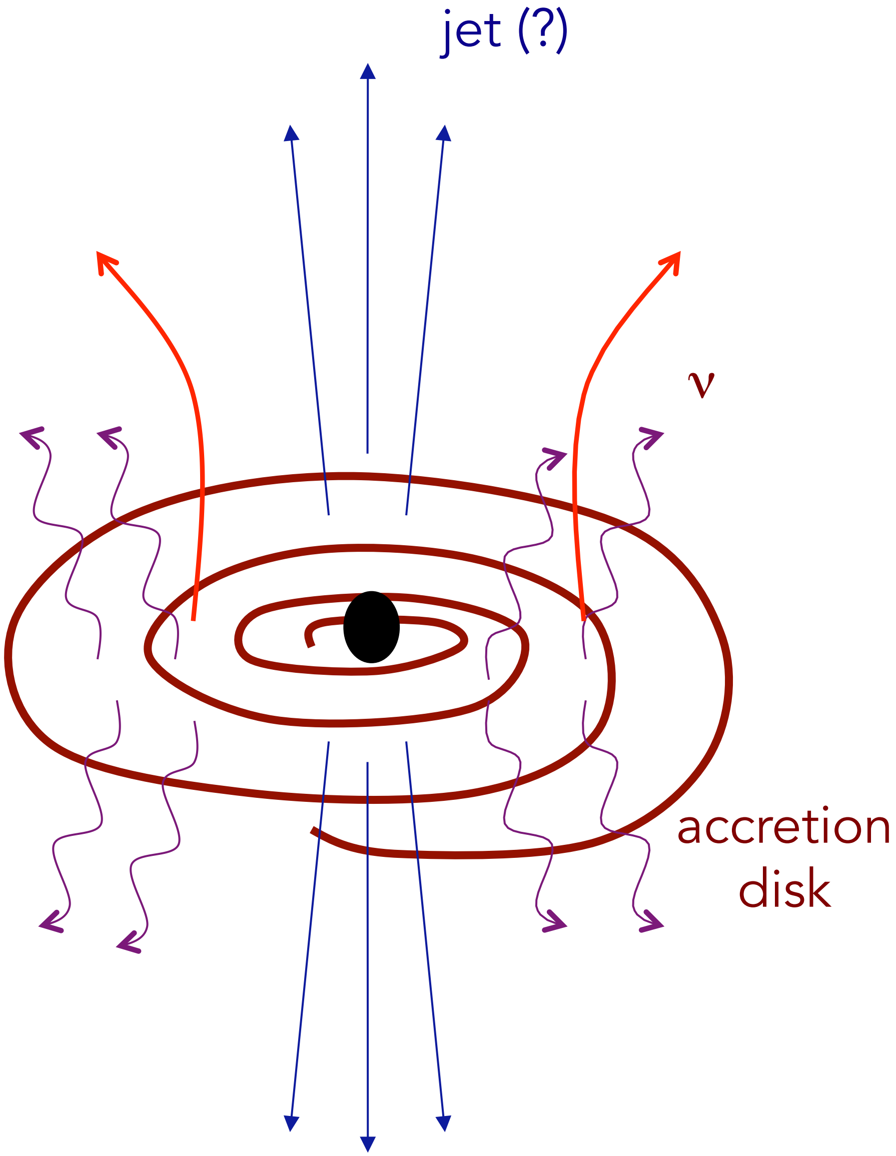


sGRB 130603B
Berger et al (2013)

r-process 'kilonova'/'macronova'
e.g., Li & Paczynski (1998), Metzger et al (2010), Barnes & Kasen (2013)

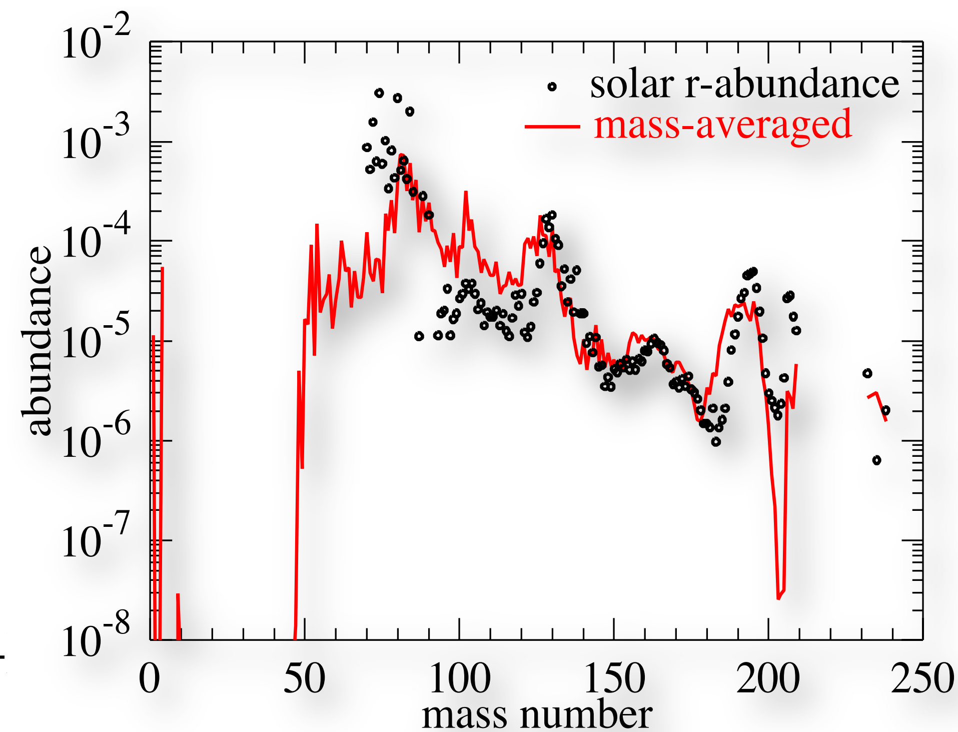


r-process astrophysical site: compact object mergers?



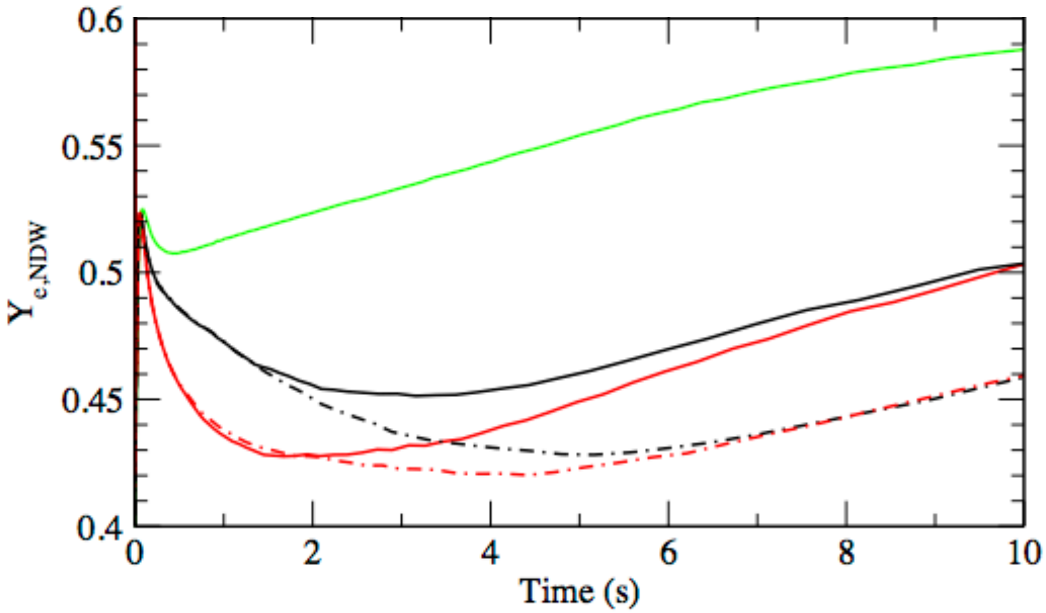
accretion disk outflows

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), Metzger et al (2011), Wanajo & Janka (2012), Perego et al (2014), Just et al (2014), Wanajo et al (2014)

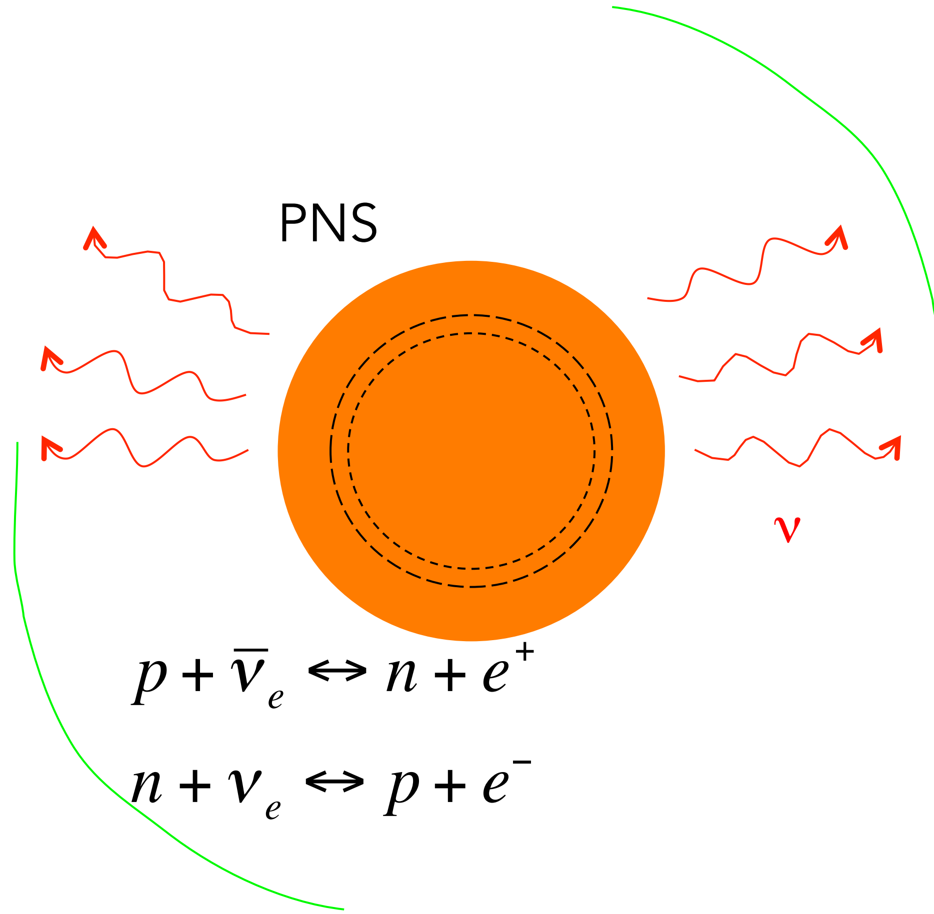


Wanajo et al (2014

r-process astrophysical site: core-collapse supernovae?



Roberts, Reddy & Shen (2012)



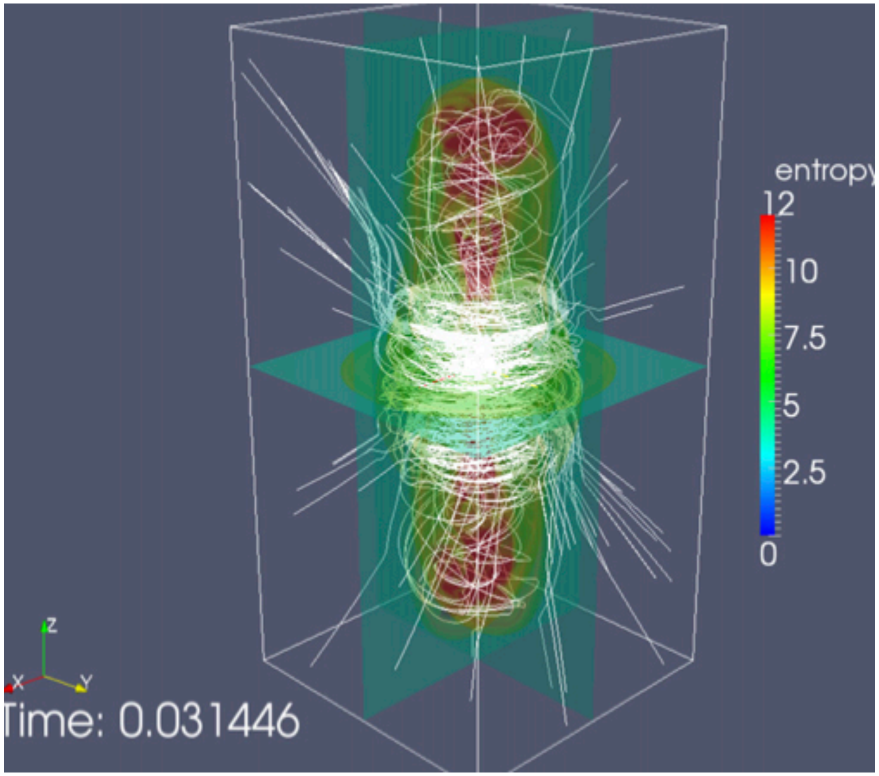
supernova neutrino-driven wind

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), Horowitz et al (2012), Wanajo (2013), Martinez-Pinedo et al (2014)

r-process astrophysical site: core-collapse supernovae?

neutron-rich MHD jets

e.g., Cameron (2003), Kotake et al (2004), Nishimura et al (2006), Fujimoto et al (2008), Winteler et al (2012), Mösta et al (2014), etc.



Winteler et al (2012)

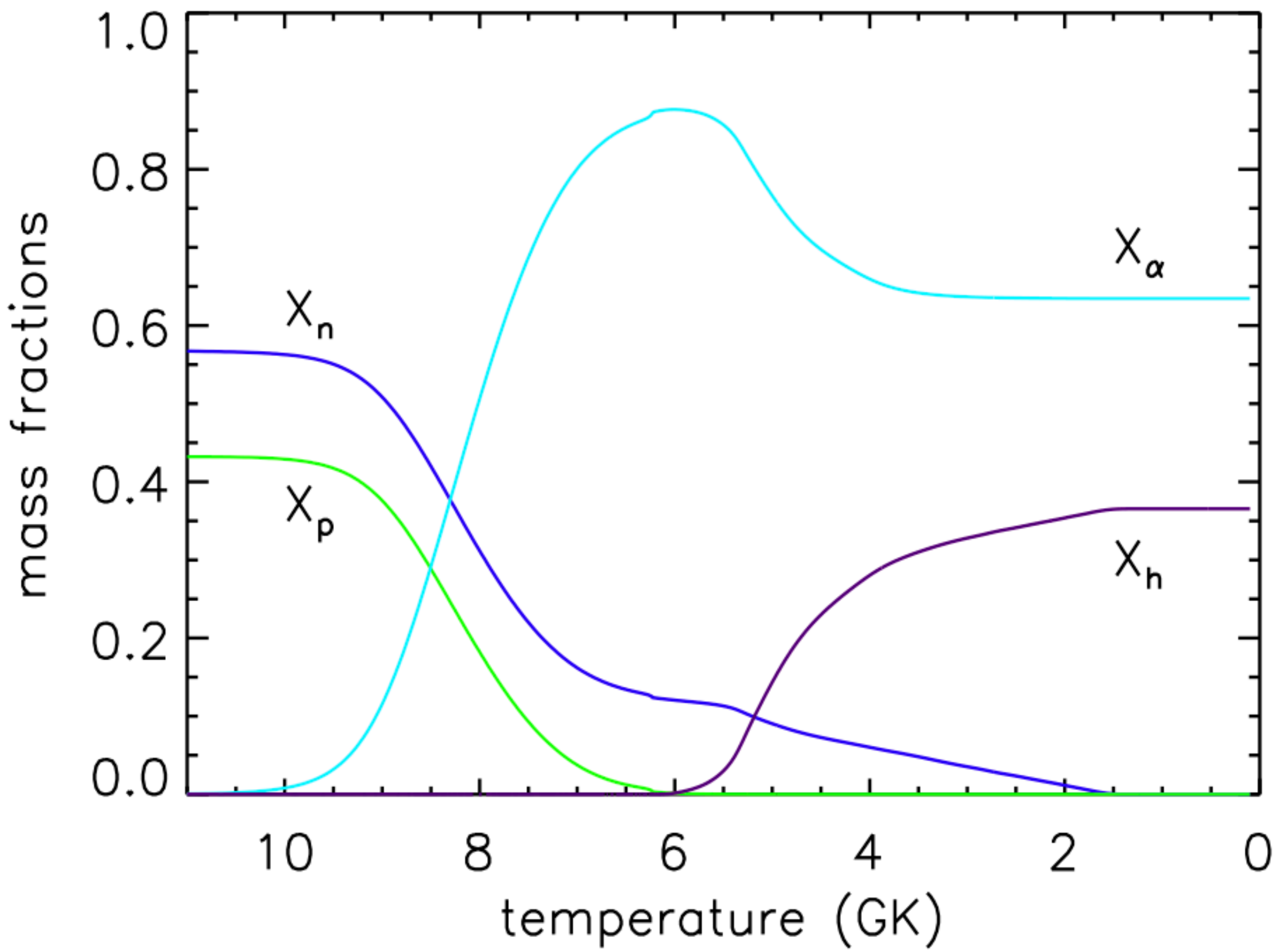
collapsars/lGRBs

e.g., Beloborodov (2003), Nagataki et al (2003), Surman & McLaughlin (2005), 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), Malkus et al (2012), Nakamura et al (2013), etc.

He shells in low metallicity SNe

e.g., Epstein et al (1988), Nadyozhin & Panov (2008), Banerjee et al (2011)

primary nucleosynthesis

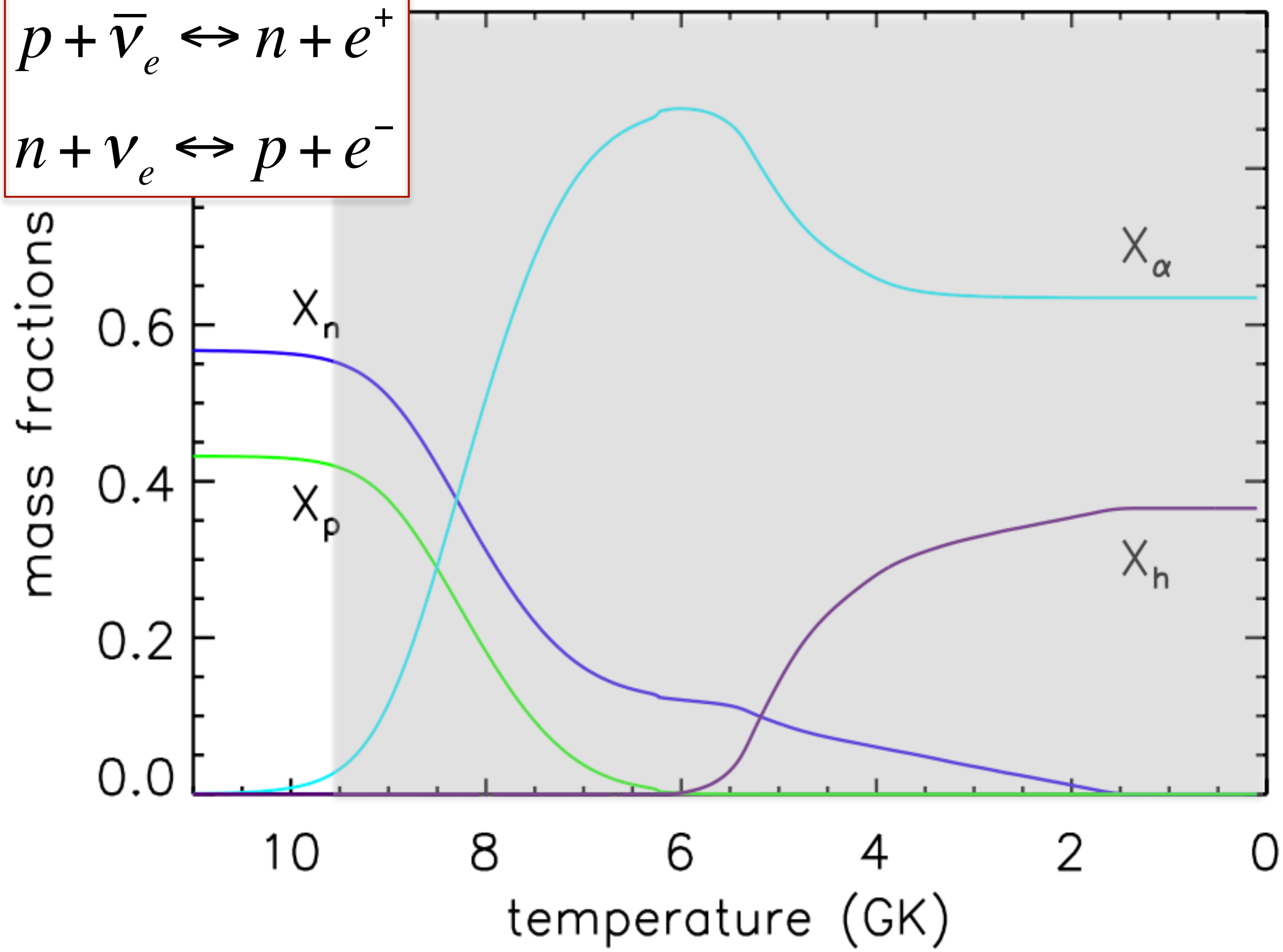


neutrinos and primary nucleosynthesis

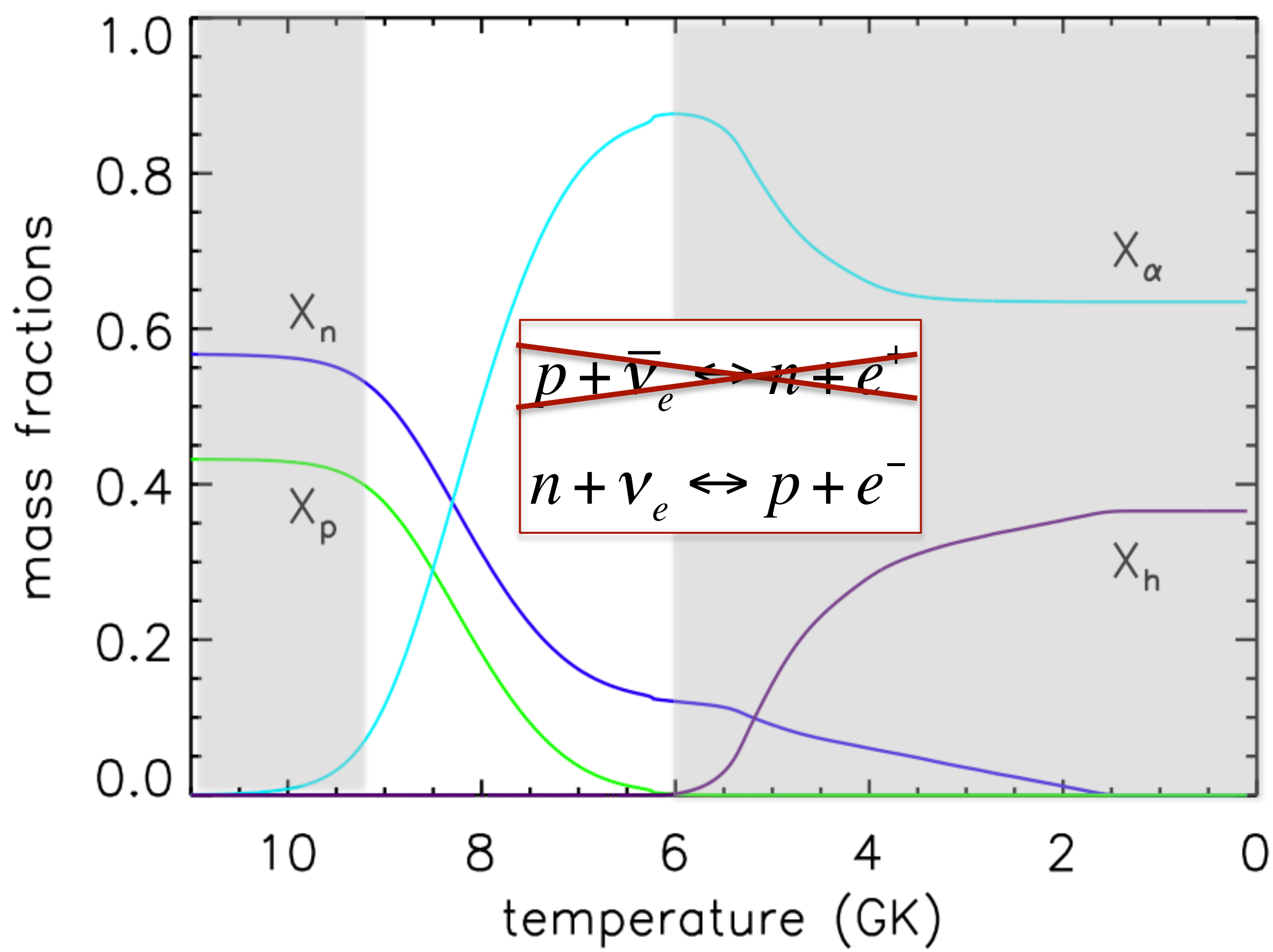
R Surman
Notre Dame
INT 15-2a

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

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



neutrinos and primary nucleosynthesis



'alpha effect'

Fuller and Meyer (1995)

neutrinos and primary nucleosynthesis

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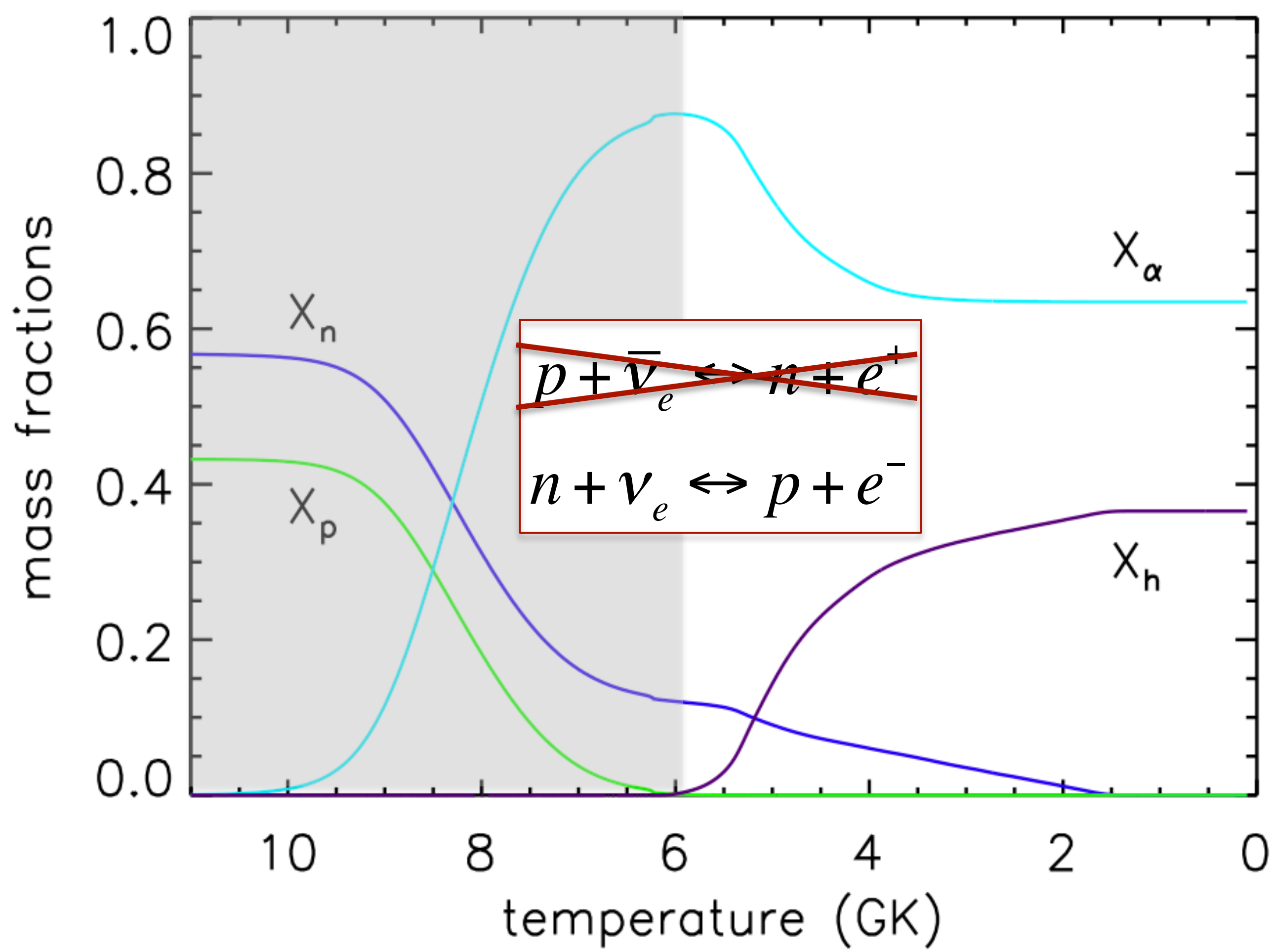

neutrino-driven wind conditions

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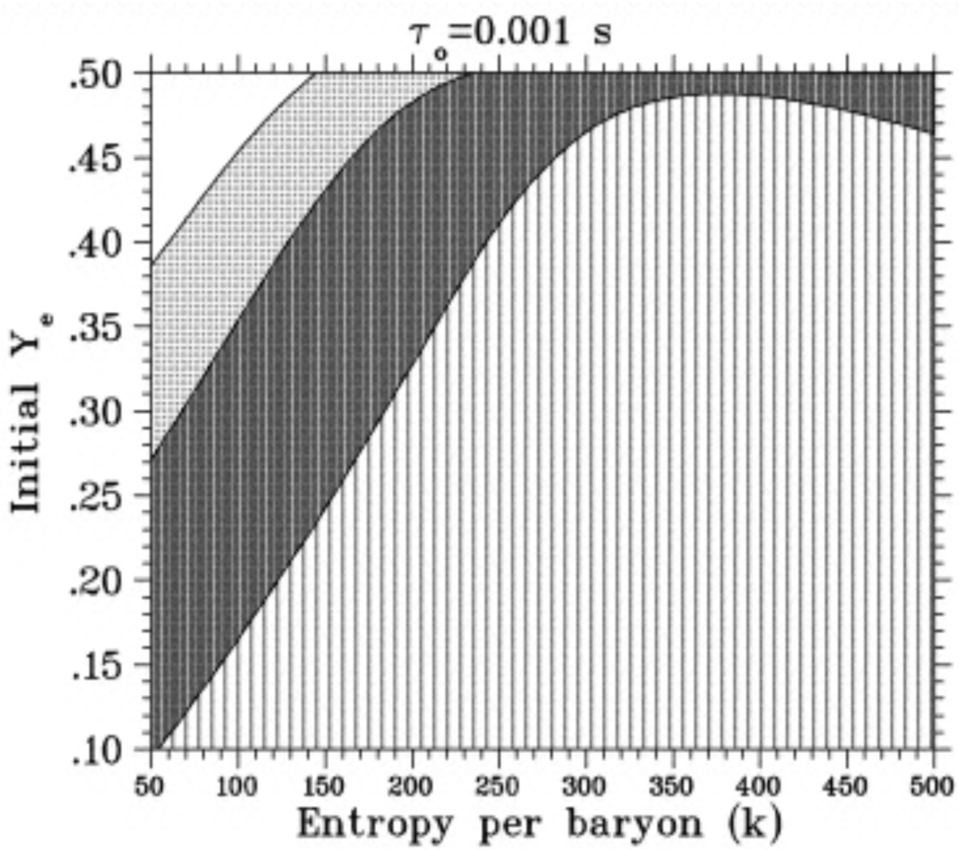
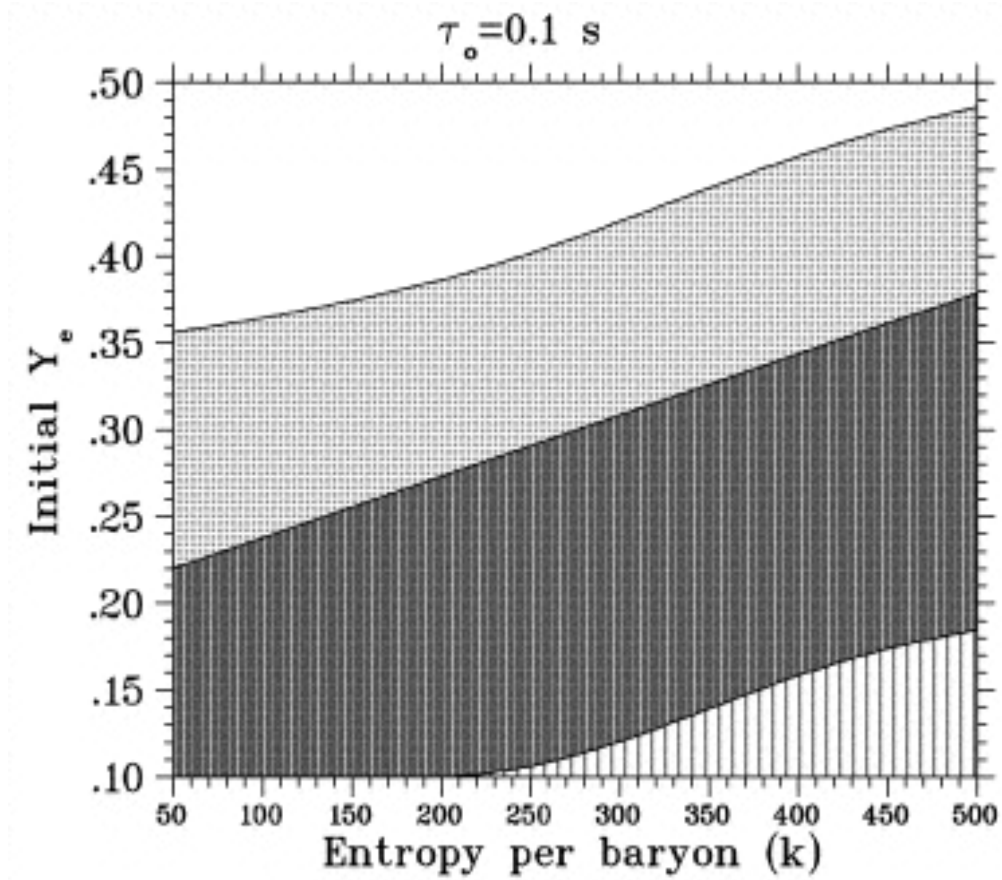
Key quantities:

electron fraction Y_e
entropy s/k
dynamic timescale τ

} neutron to seed ratio R





Meyer and Brown (1997)

supernova neutrino-driven wind conditions

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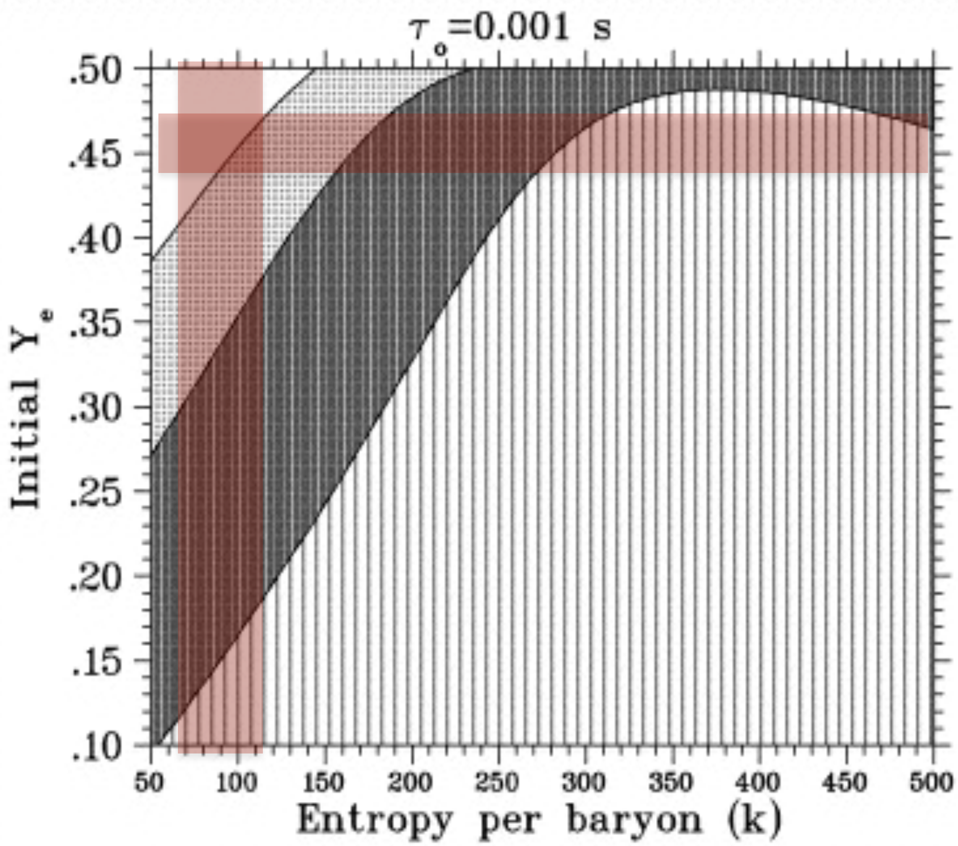
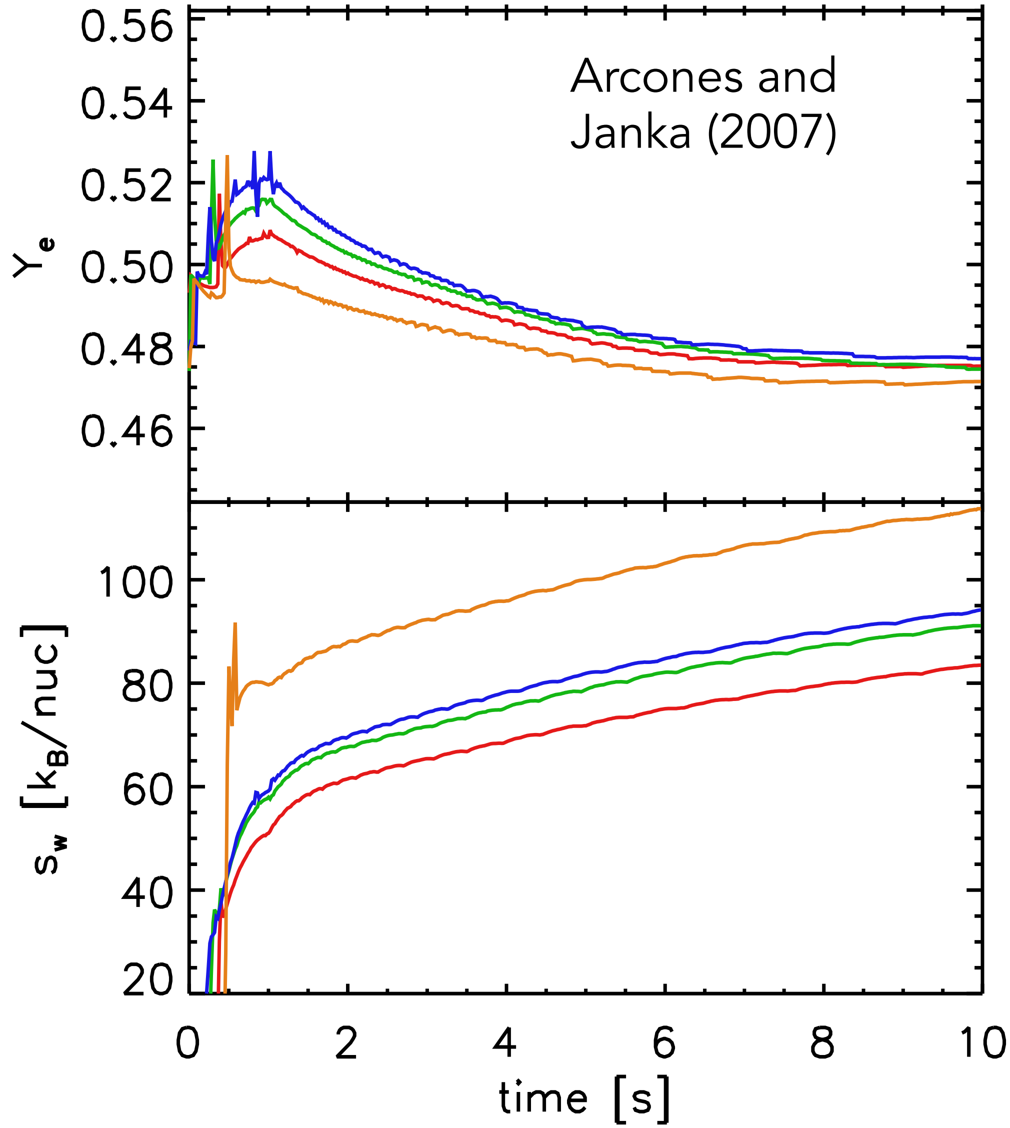
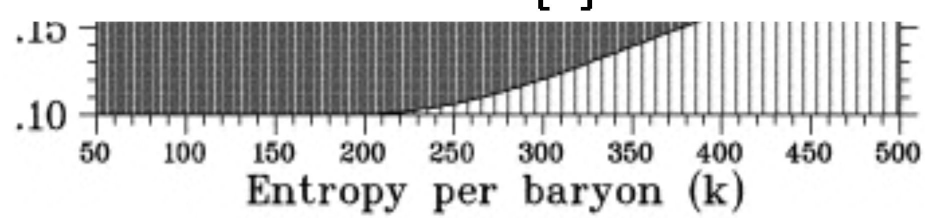
Key quantities:

- electron fraction Y_e
- entropy s/k
- dynamic timescale τ

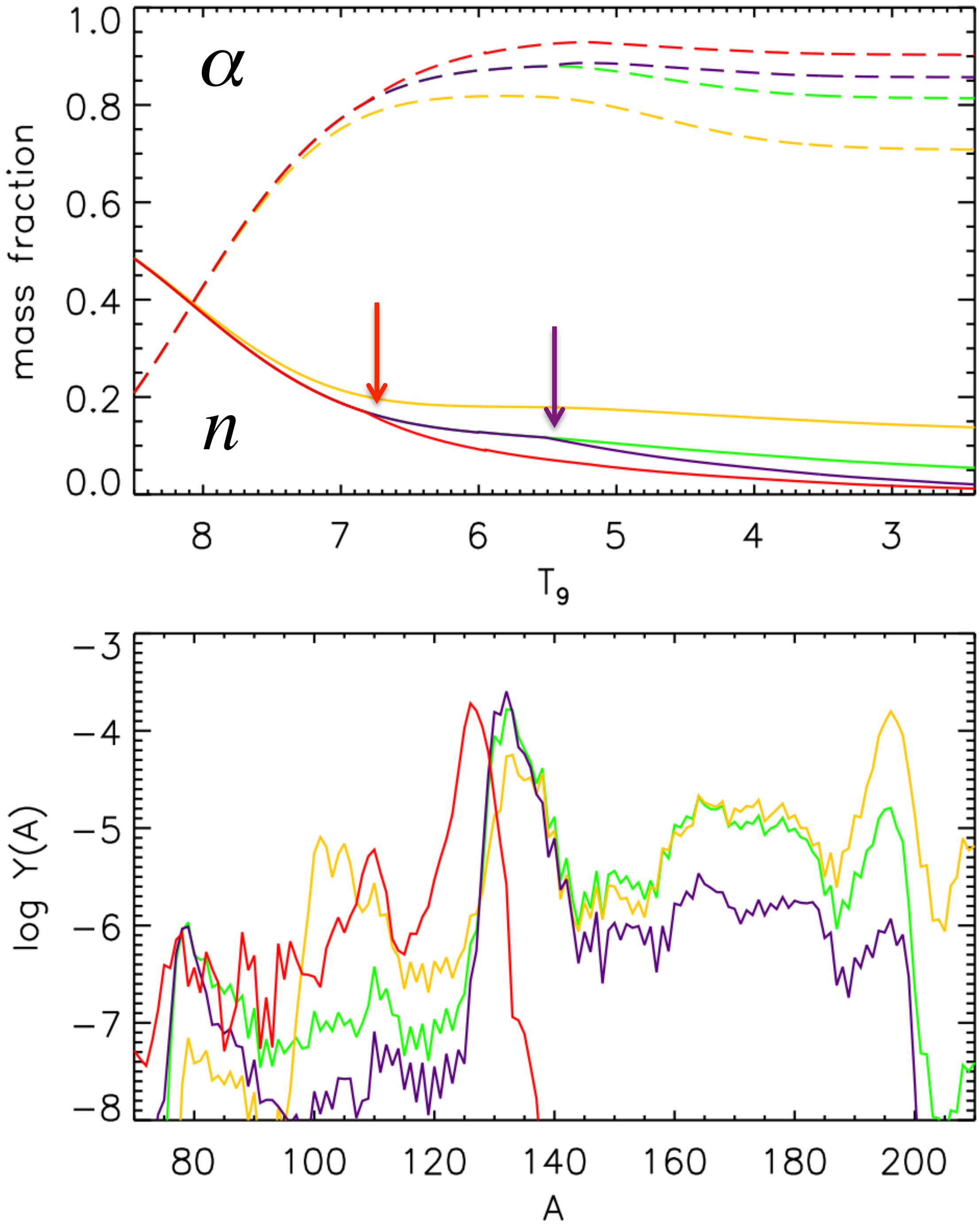


Meyer and Brown (1997)





collective oscillations and a supernova *r* process

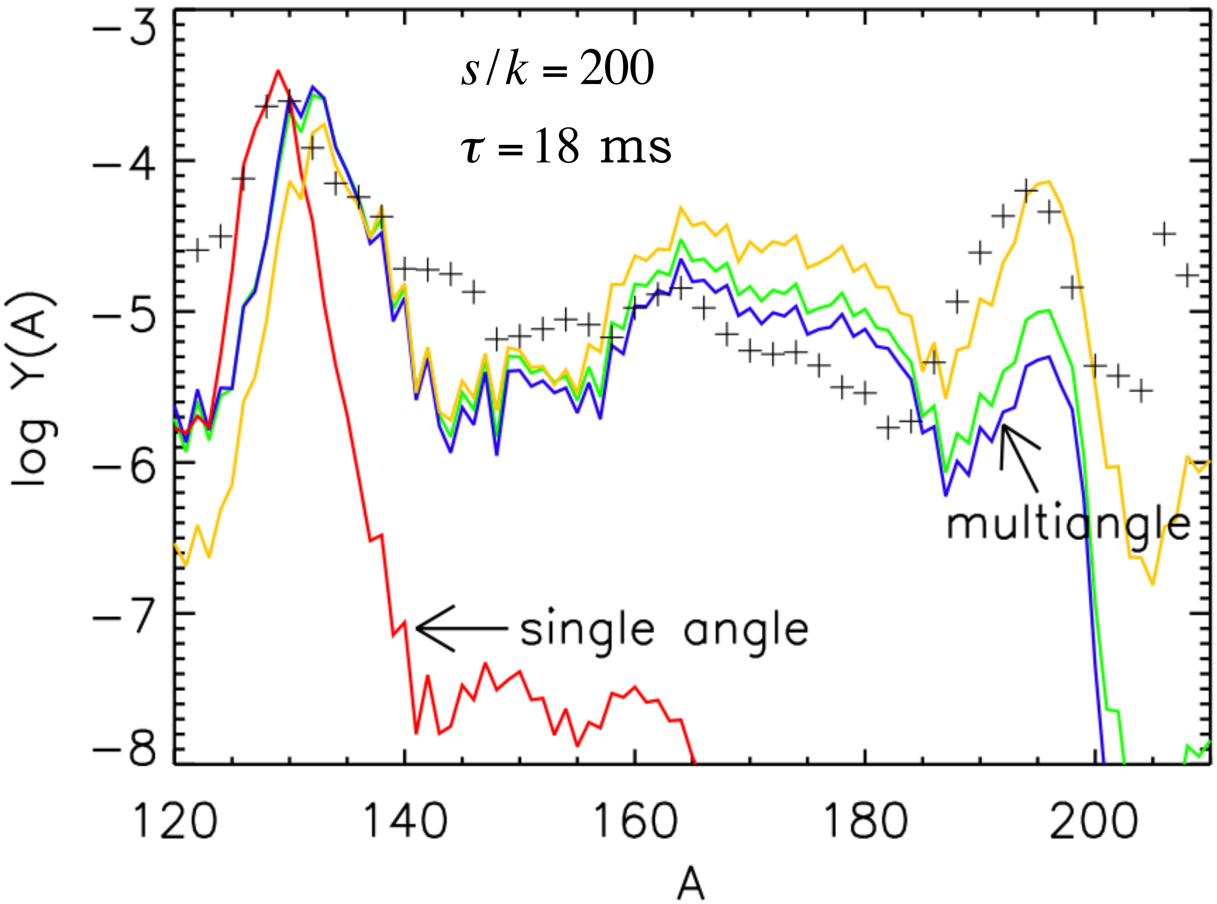


~~$p+\bar{\nu}_e \leftrightarrow n+e^+$~~

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

Duan, Friedland, McLaughlin & Surman (2011)

collective oscillations and a supernova *r* process



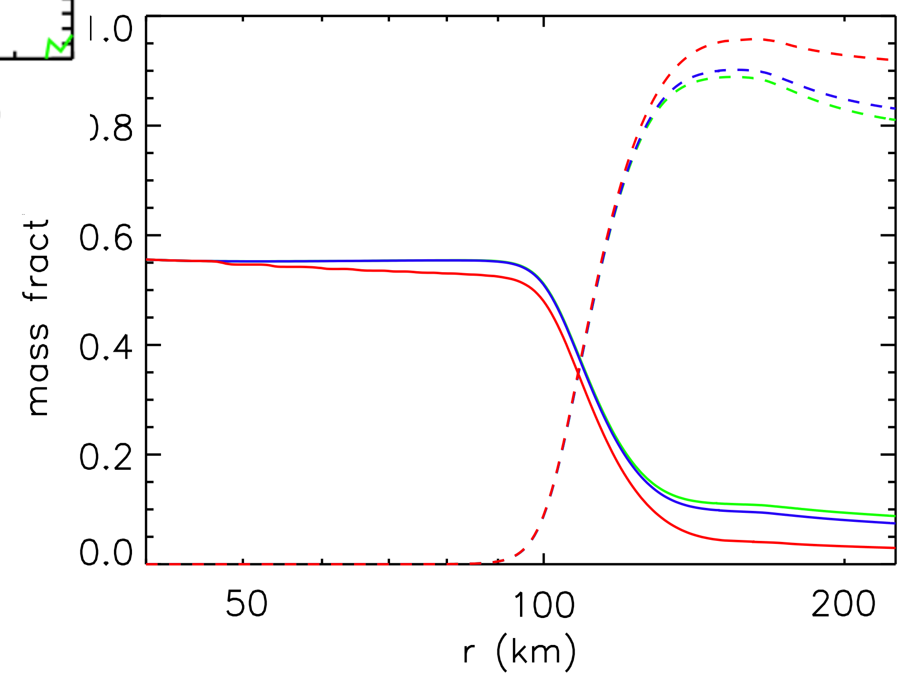
No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

Single angle ν oscillation calculation

Duan, Friedland, McLaughlin & Surman (2011)



collective oscillations and a supernova *r* process

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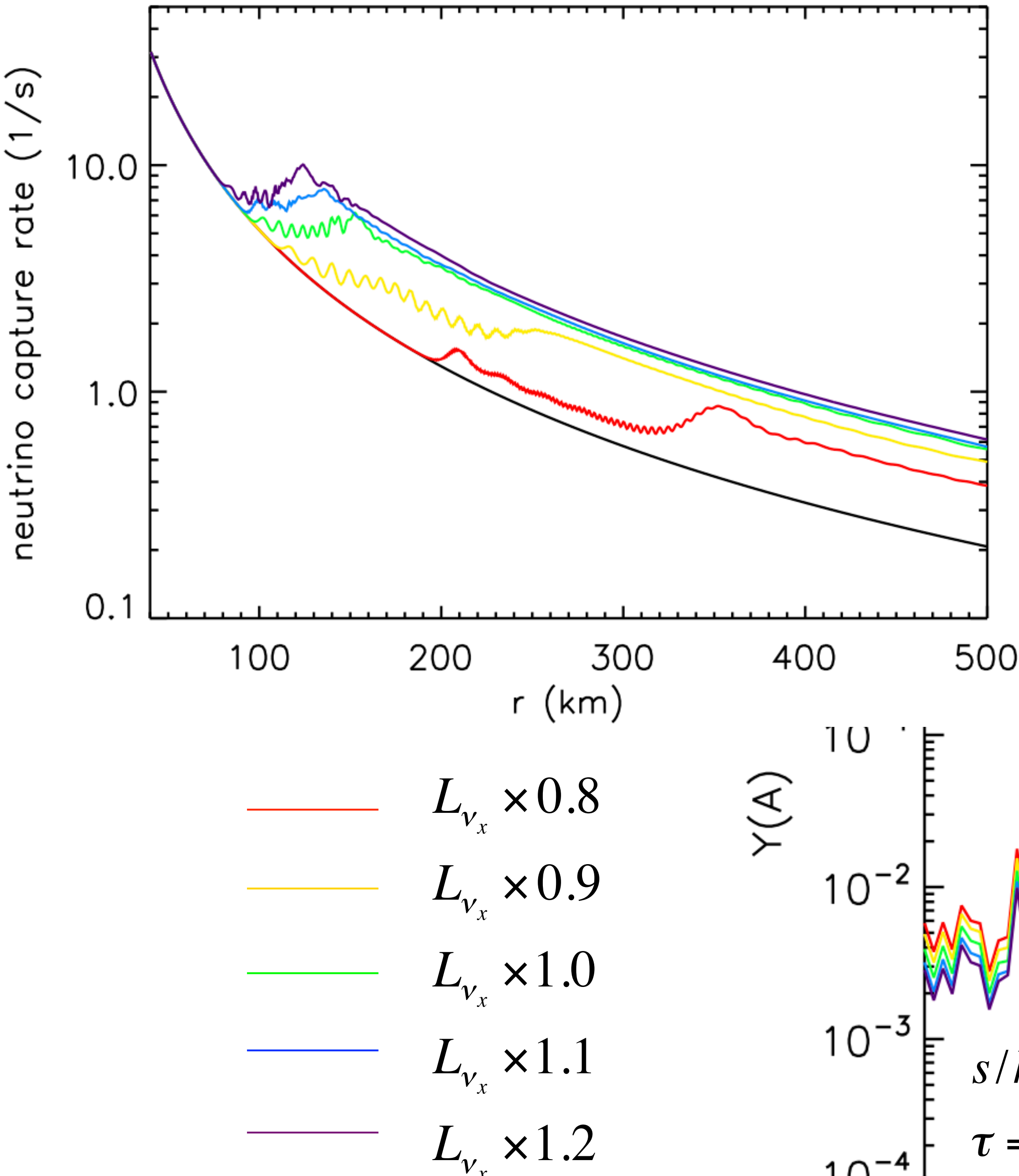
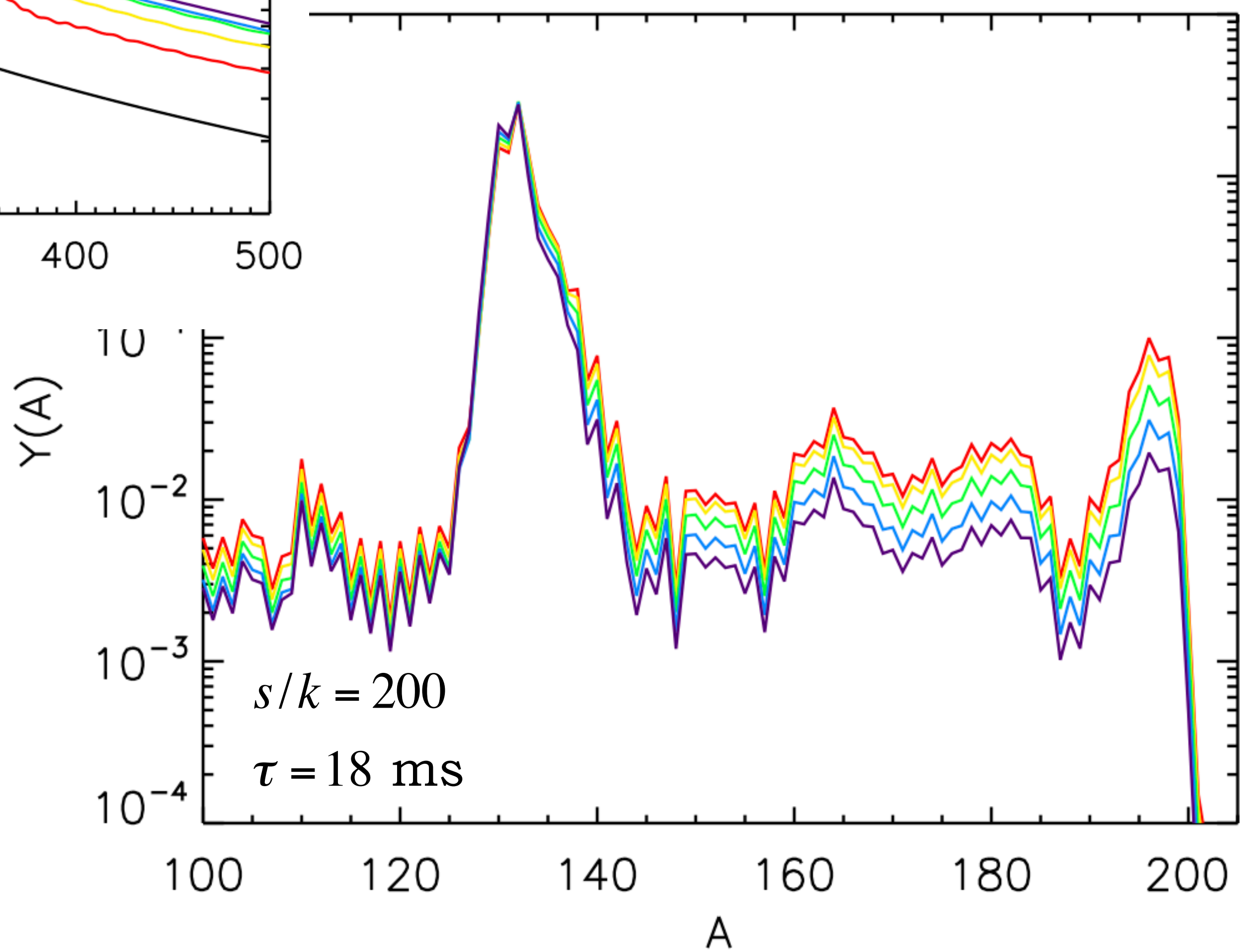


Friedland, Surman, et al



supernova neutrino-driven wind conditions

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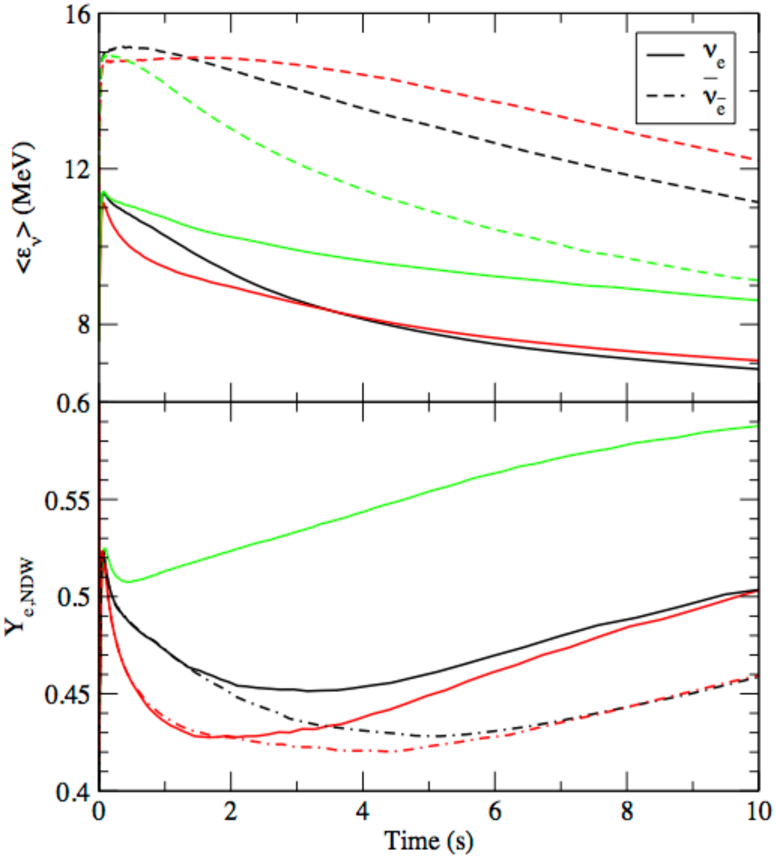
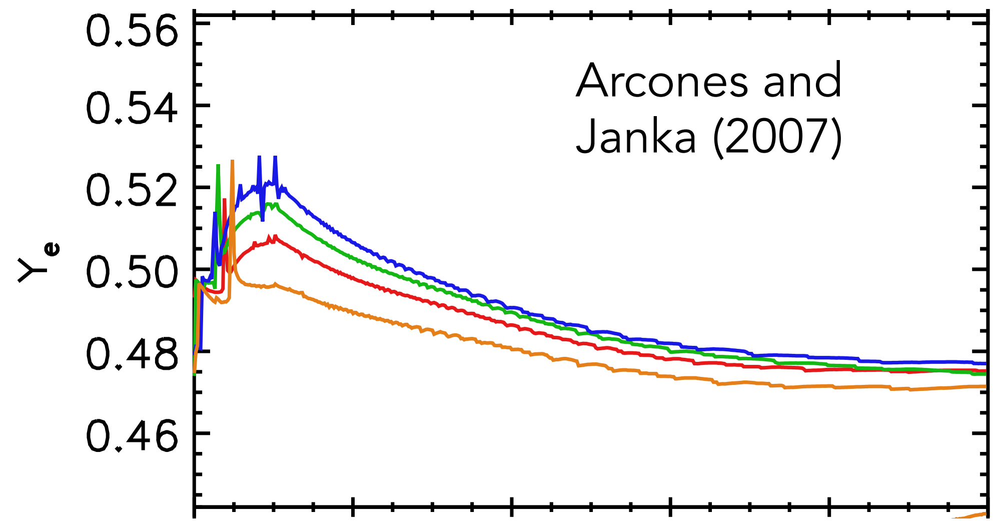
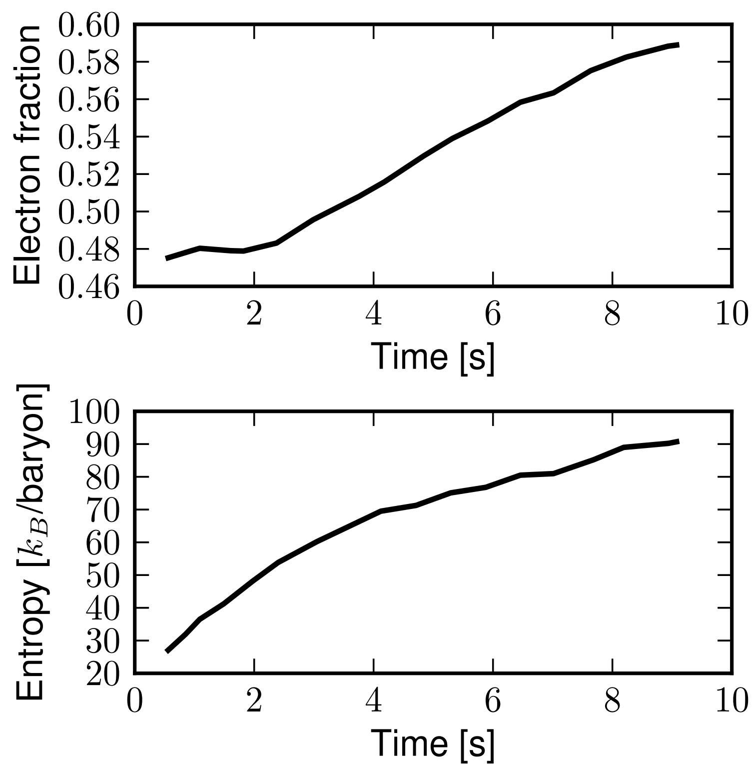
Roberts, Reddy & Shen (2012)





Arcones and Janka (2007)



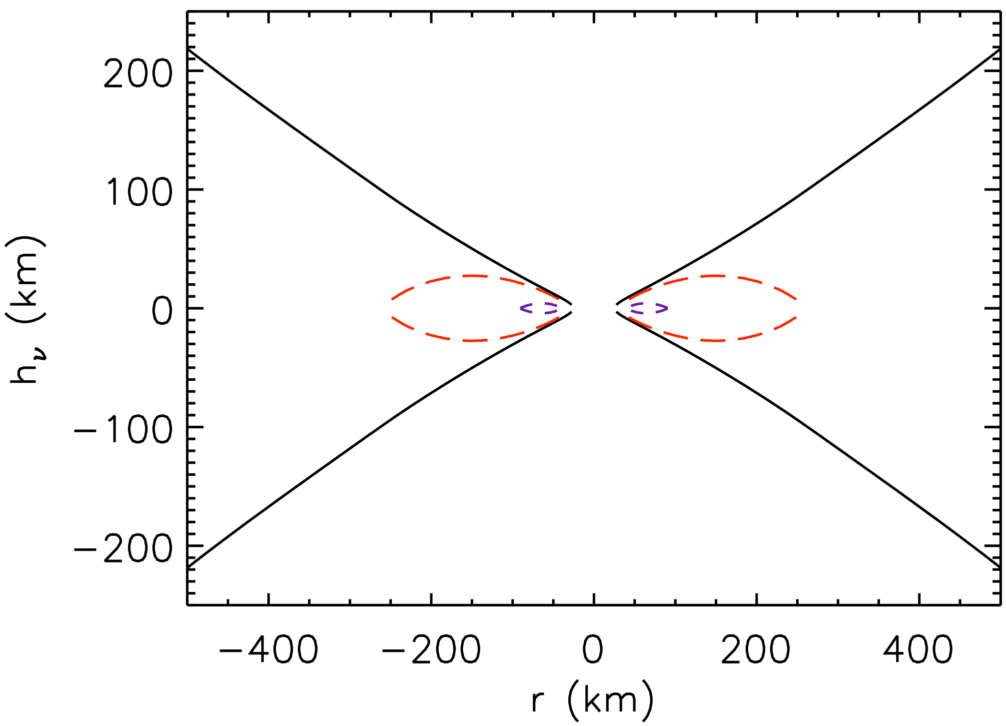
Martínez-Pinedo et al (2014)

collapsar AD-BH neutrino emission

Neutrino emission from black hole accretion disks (AD-BH) is similar to that from a PNS, but there are key differences:

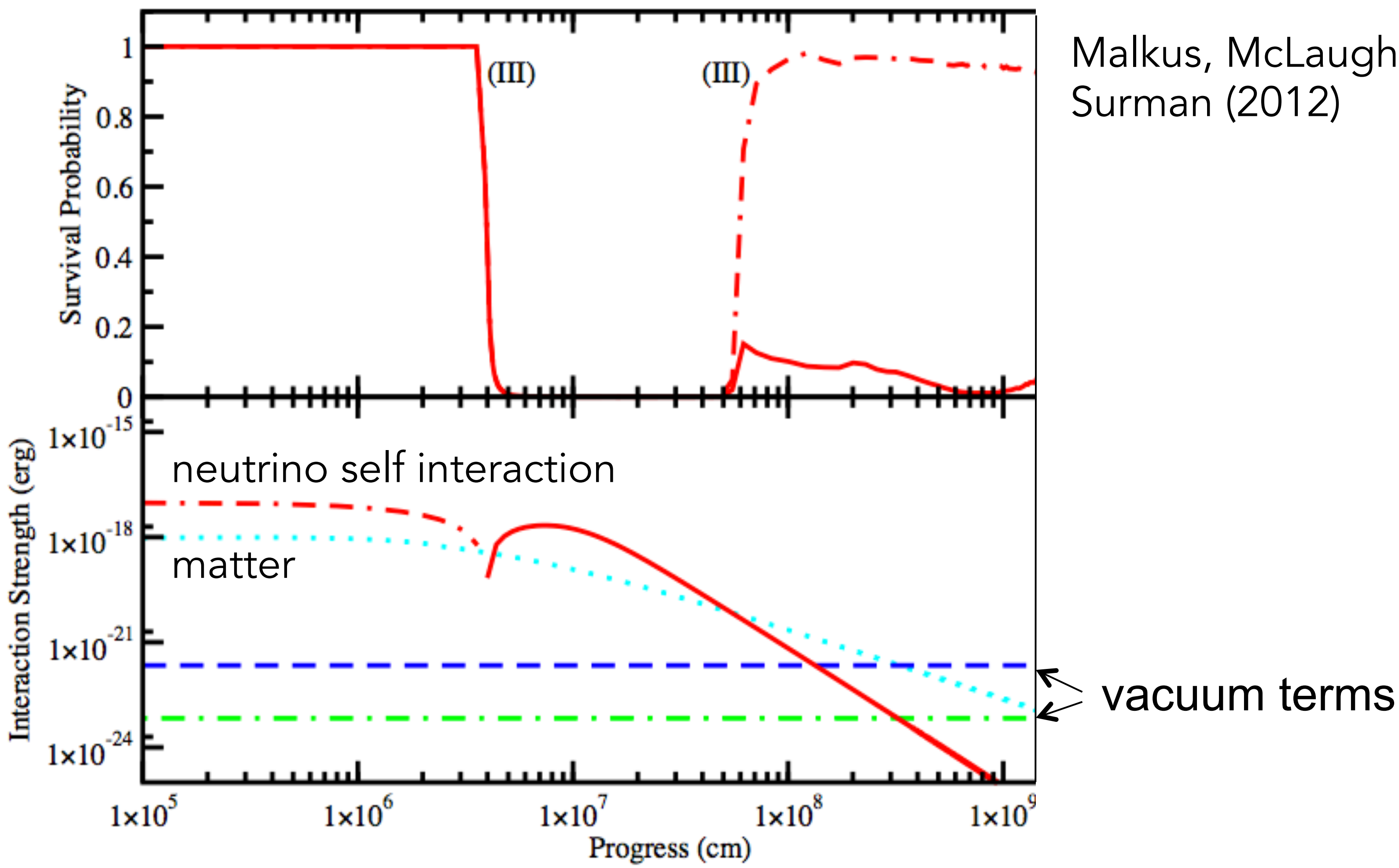
- primarily ν_e and $\bar{\nu}_e$ (vs. all flavors in a PNS)
- emission surfaces not spherical
- ν_e emission surface much larger than that for $\bar{\nu}_e$

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



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

collapsar AD-BH neutrino oscillations



Malkus, McLaughlin, Kneller, Surman (2012)

consequences for AD-BH outflow nucleosynthesis

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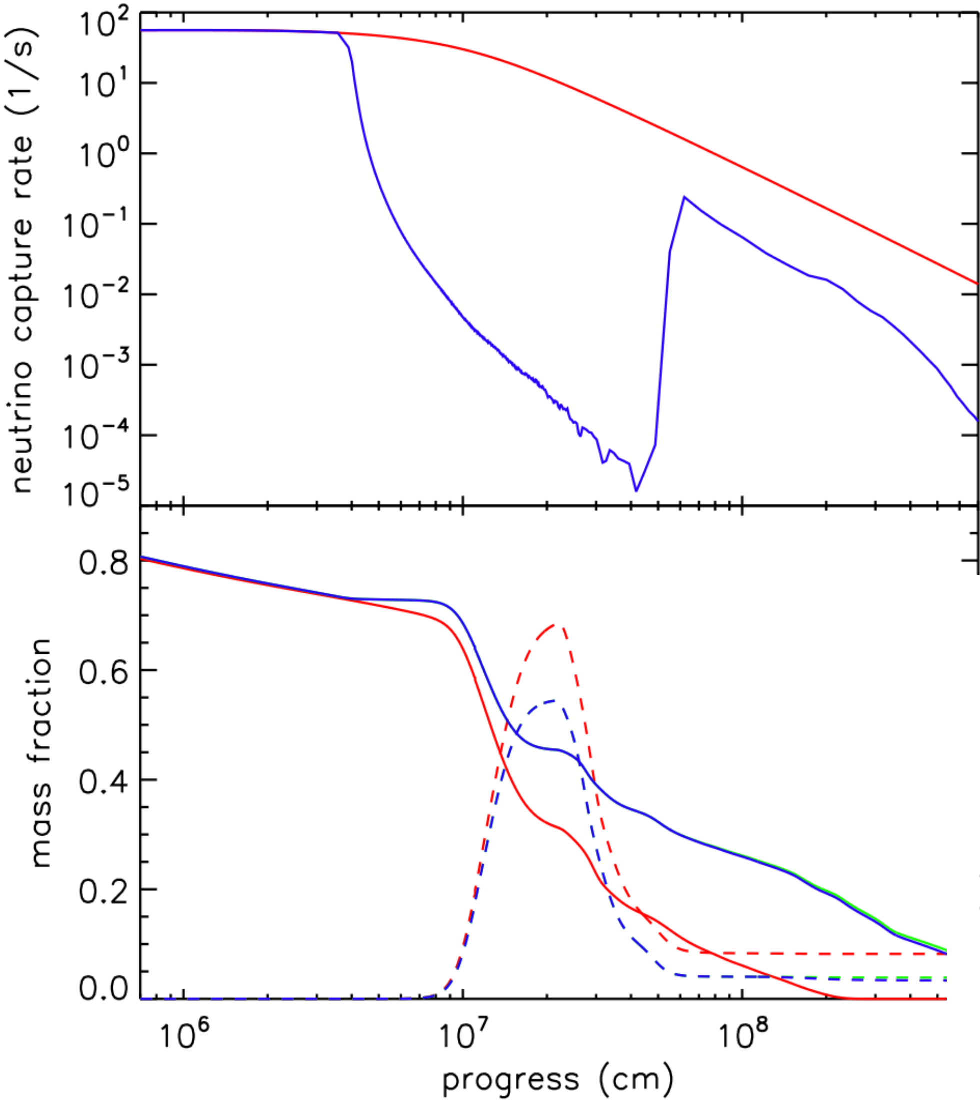
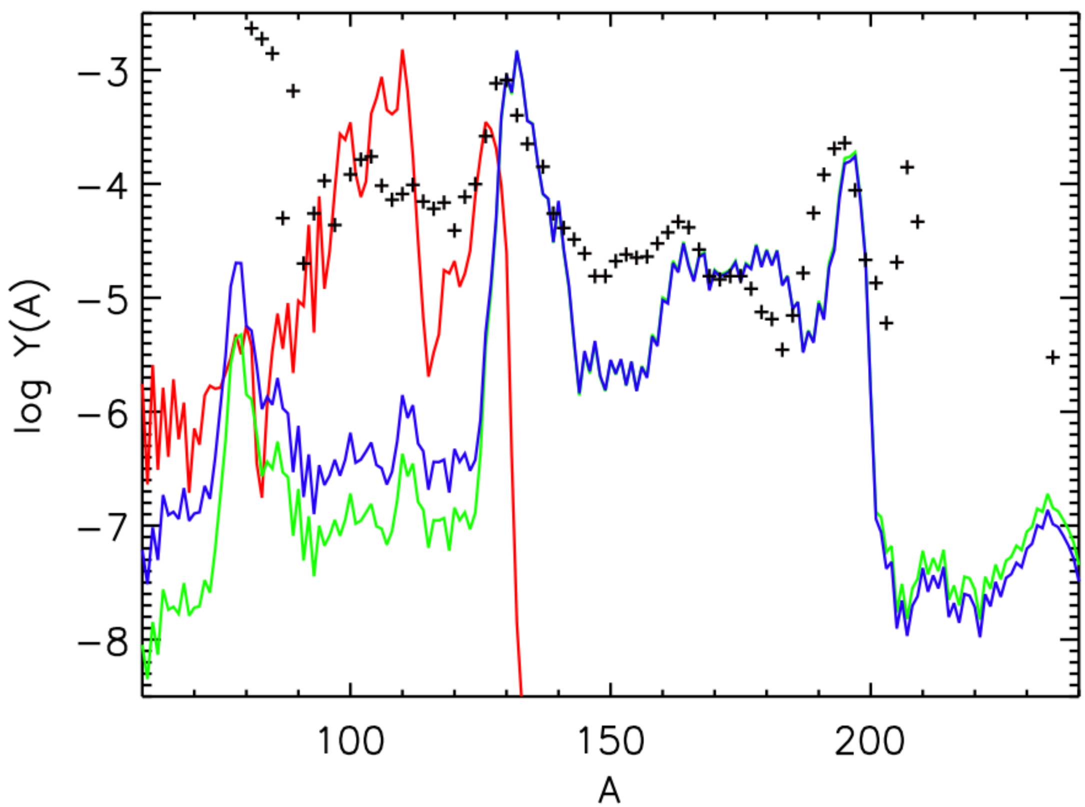


no oscillations

single angle ν oscillation calculation

Malkus, McLaughlin, Kneller, Surman (2012)



nucleosynthesis from a merger AD-BH

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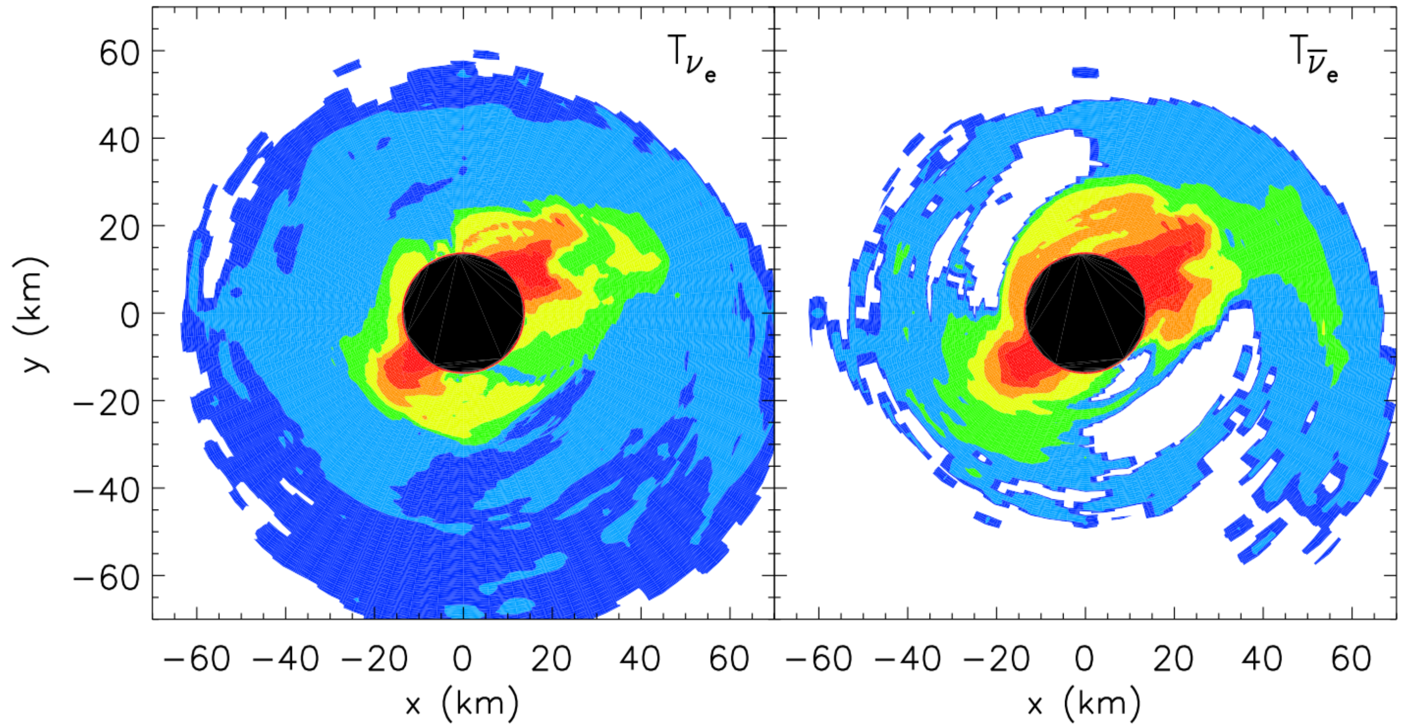
positron captures dominate in merger disks, so

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



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

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

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

nucleosynthesis from a merger AD-BH

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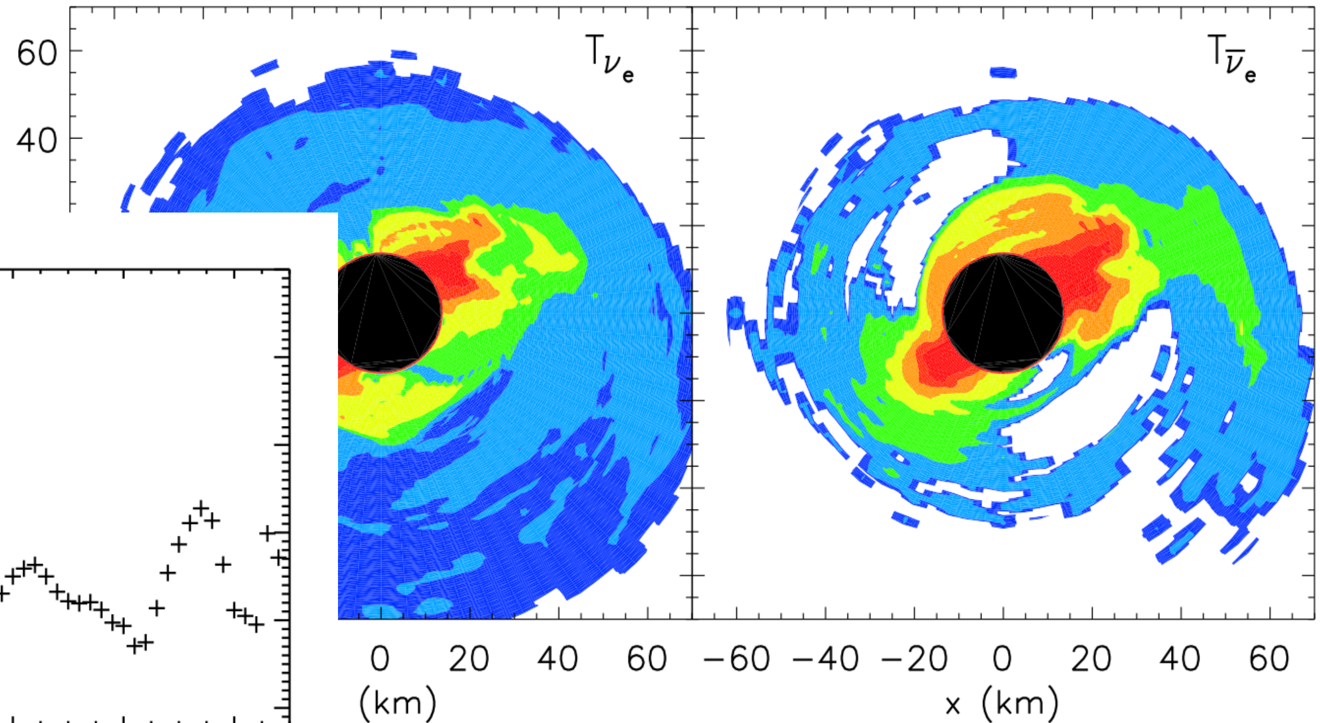

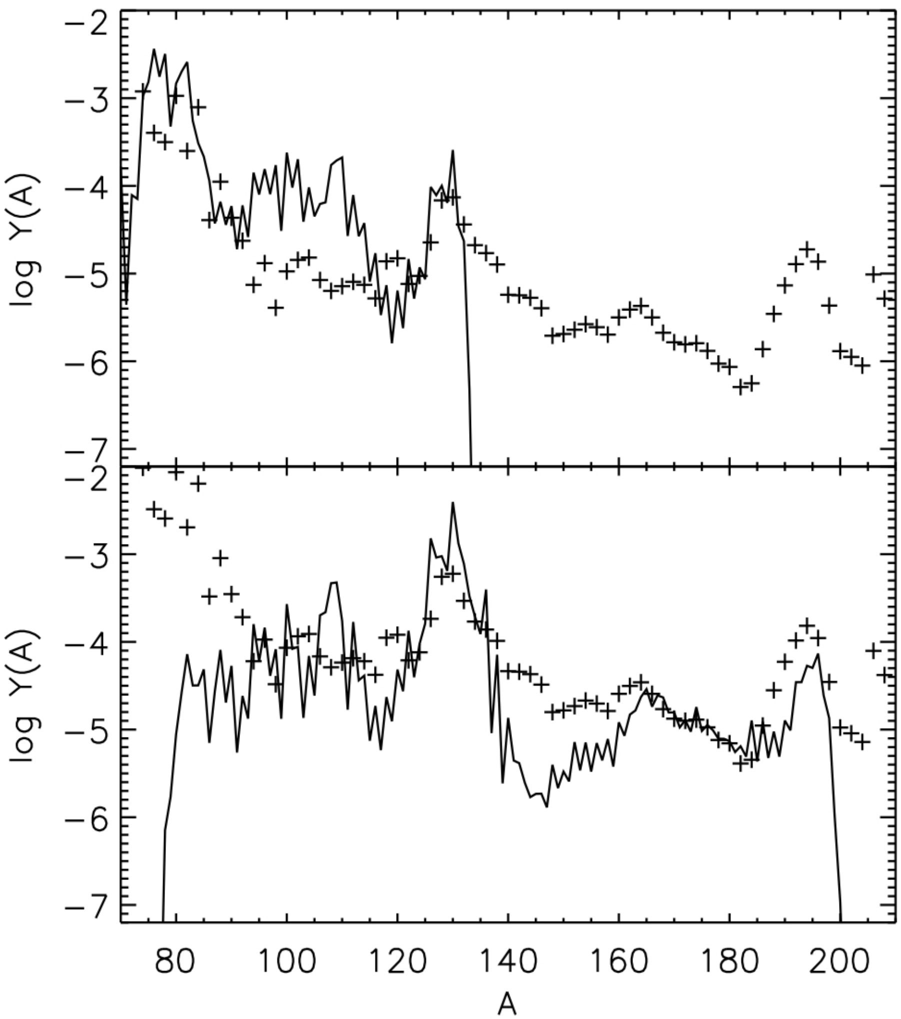

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

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

nucleosynthesis from a merger AD-BH

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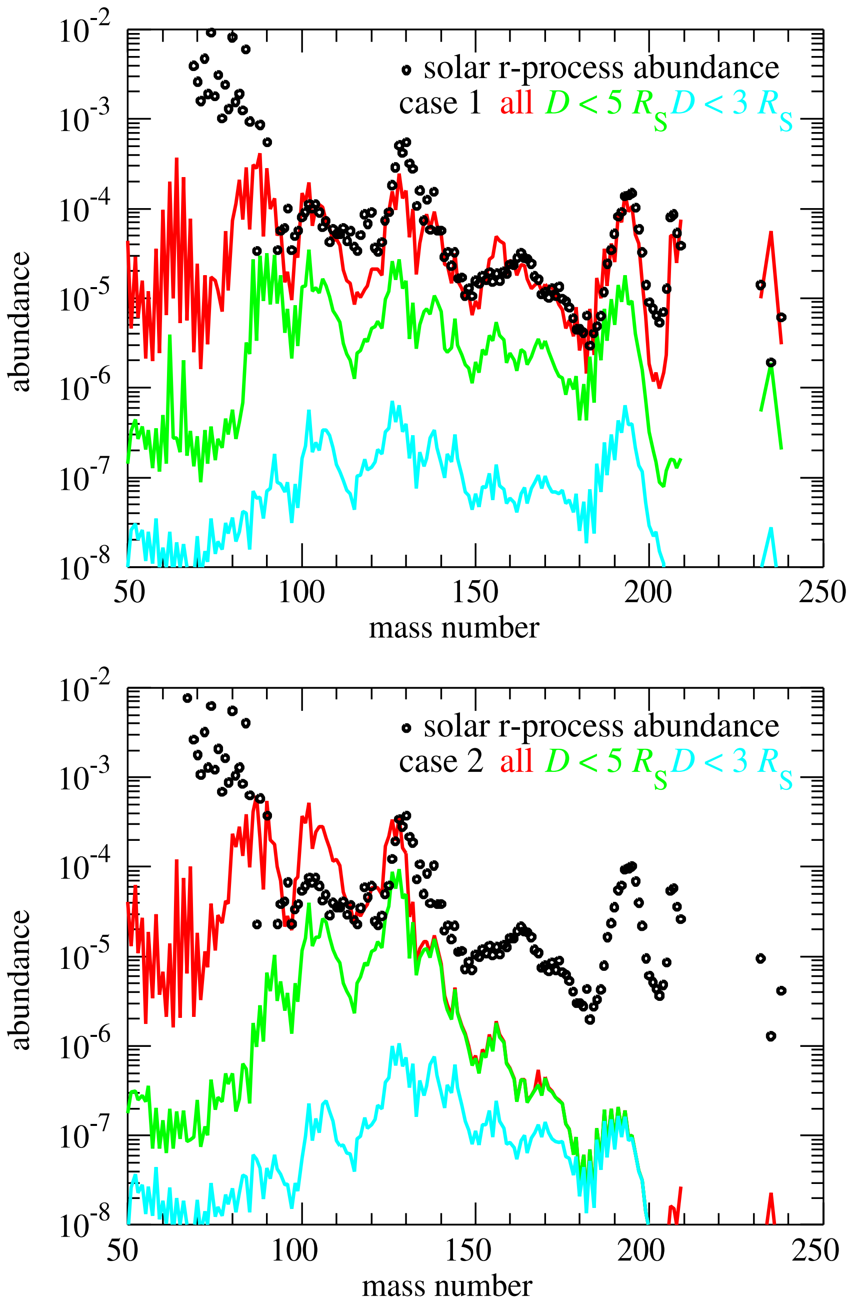
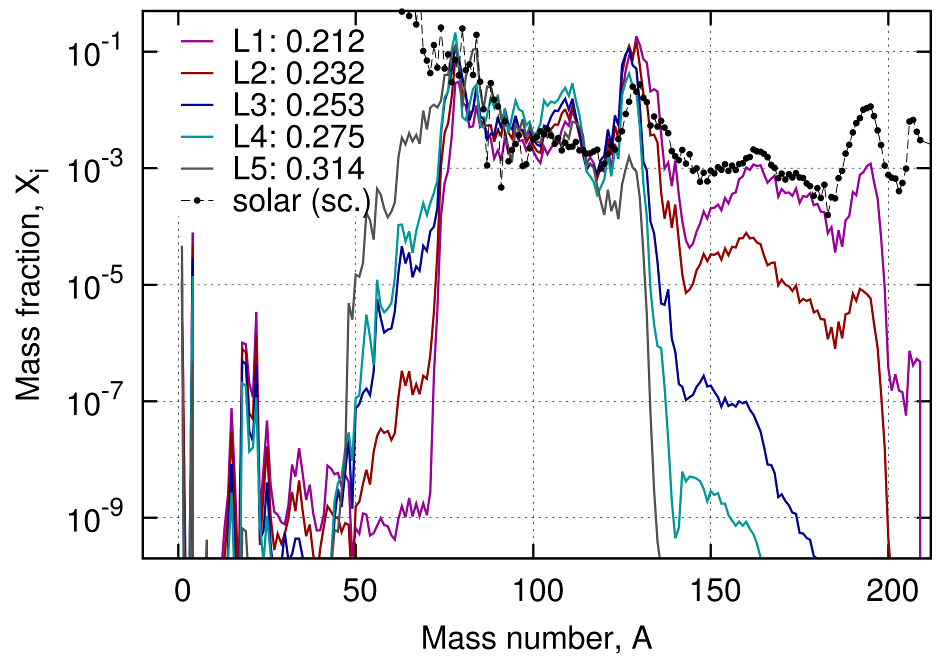
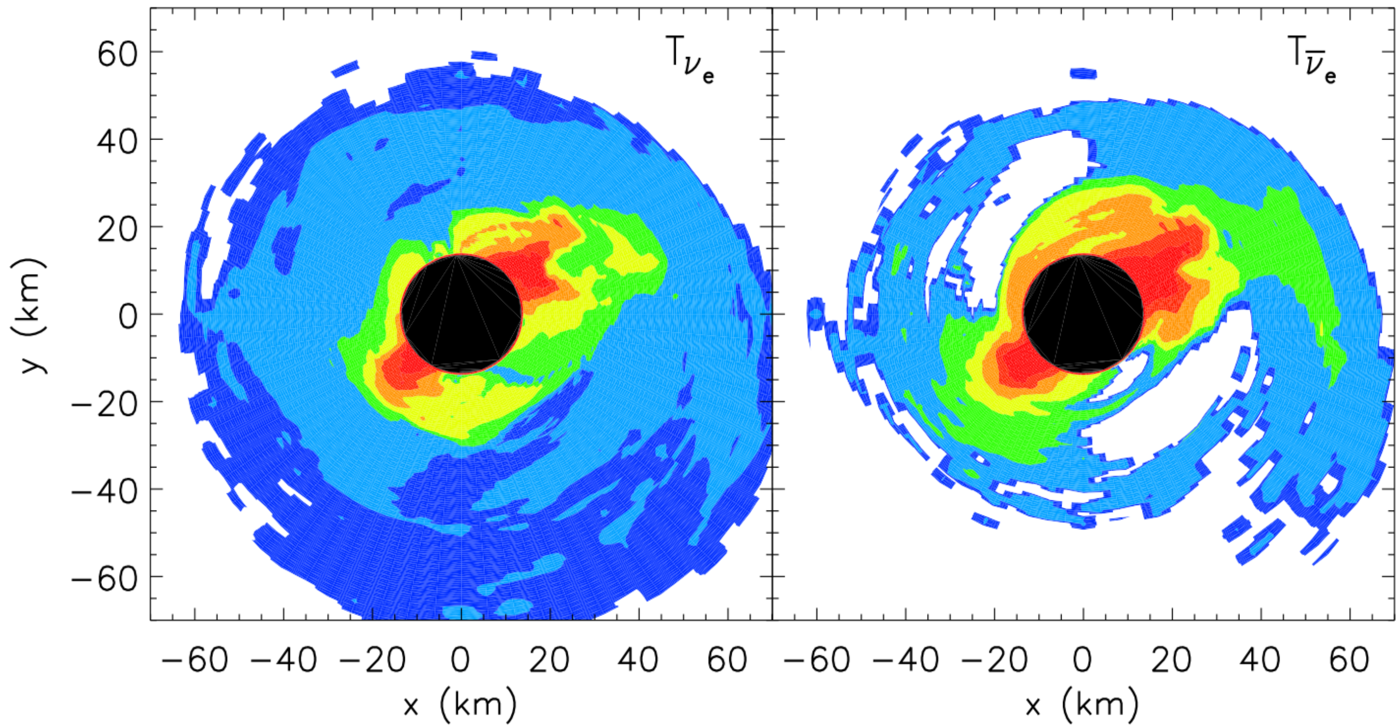


Wanajo, Janka (2012)



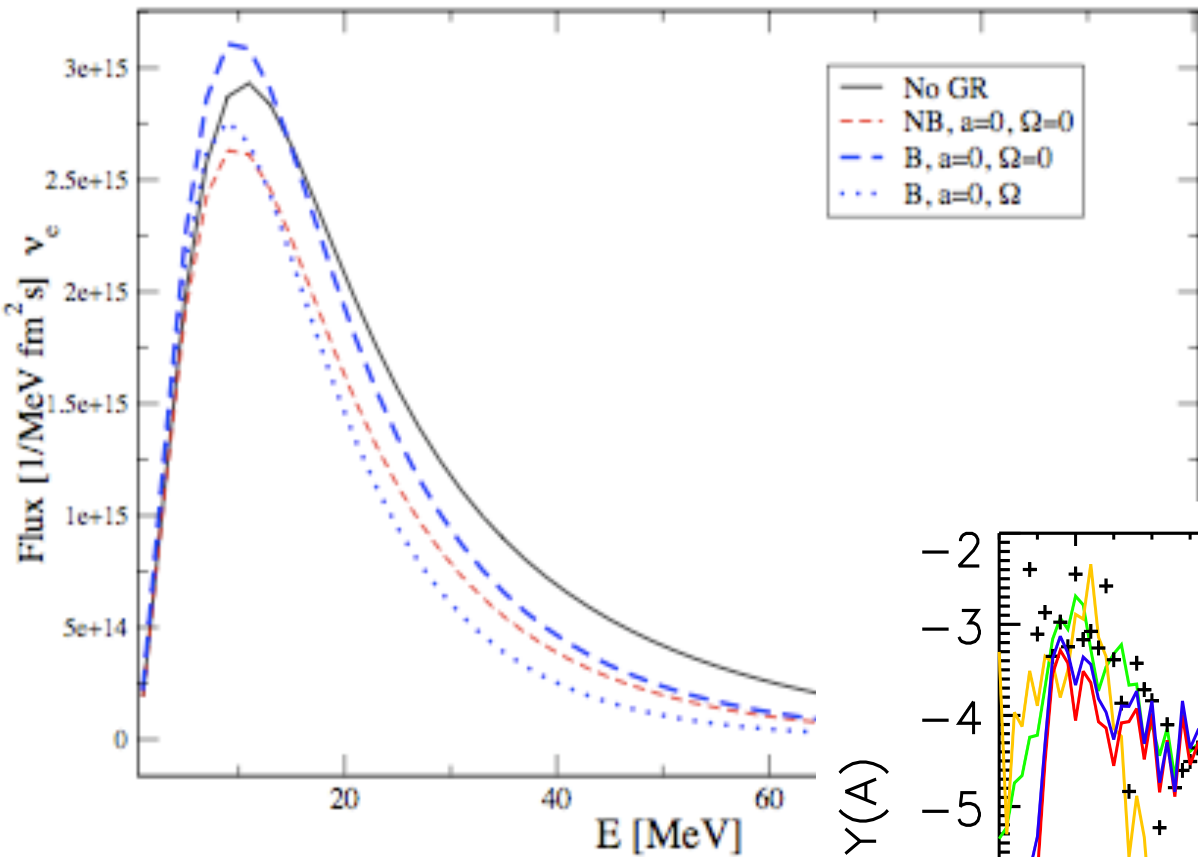
Perego et al (2014)

nucleosynthesis from a merger AD-BH

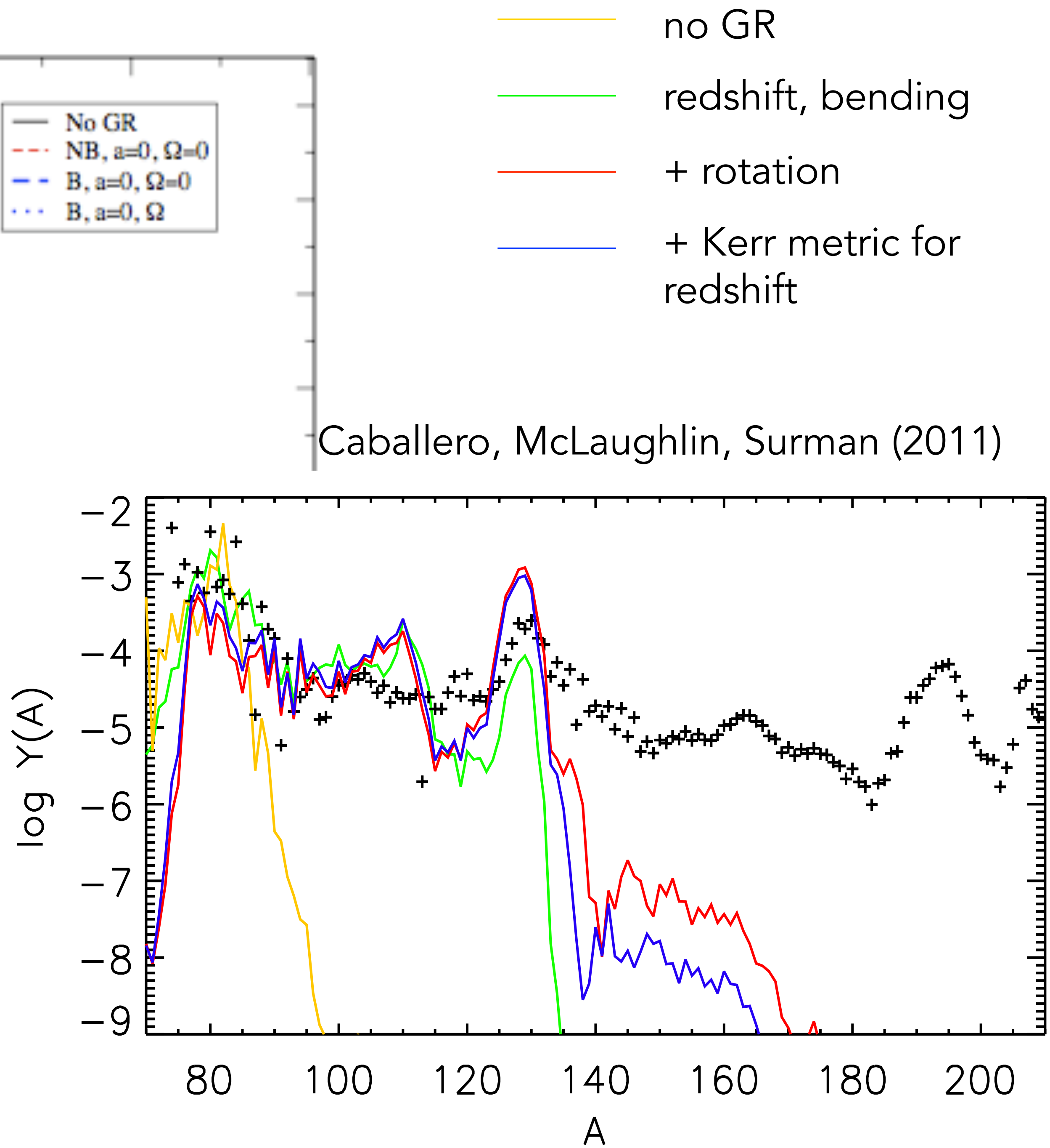


Surman, McLaughlin, Ruffert, Janka, Hix (2008)

general relativistic effects on the neutrino spectra



low *s/k*,
rapid acceleration



Caballero, McLaughlin, Surman (2011)

general relativistic effects on the neutrino spectra

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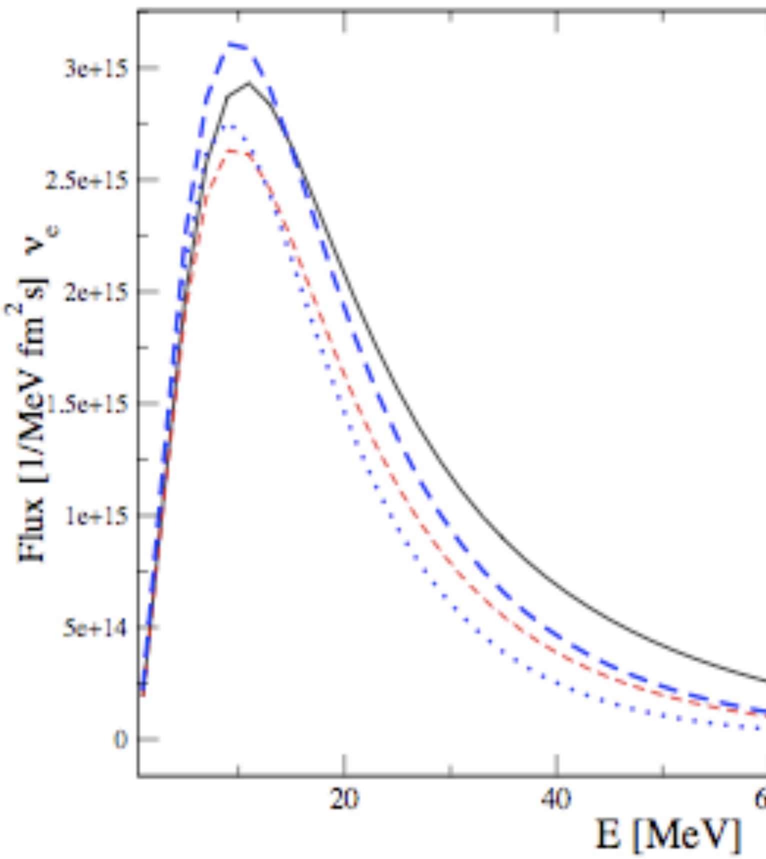


low acceleration

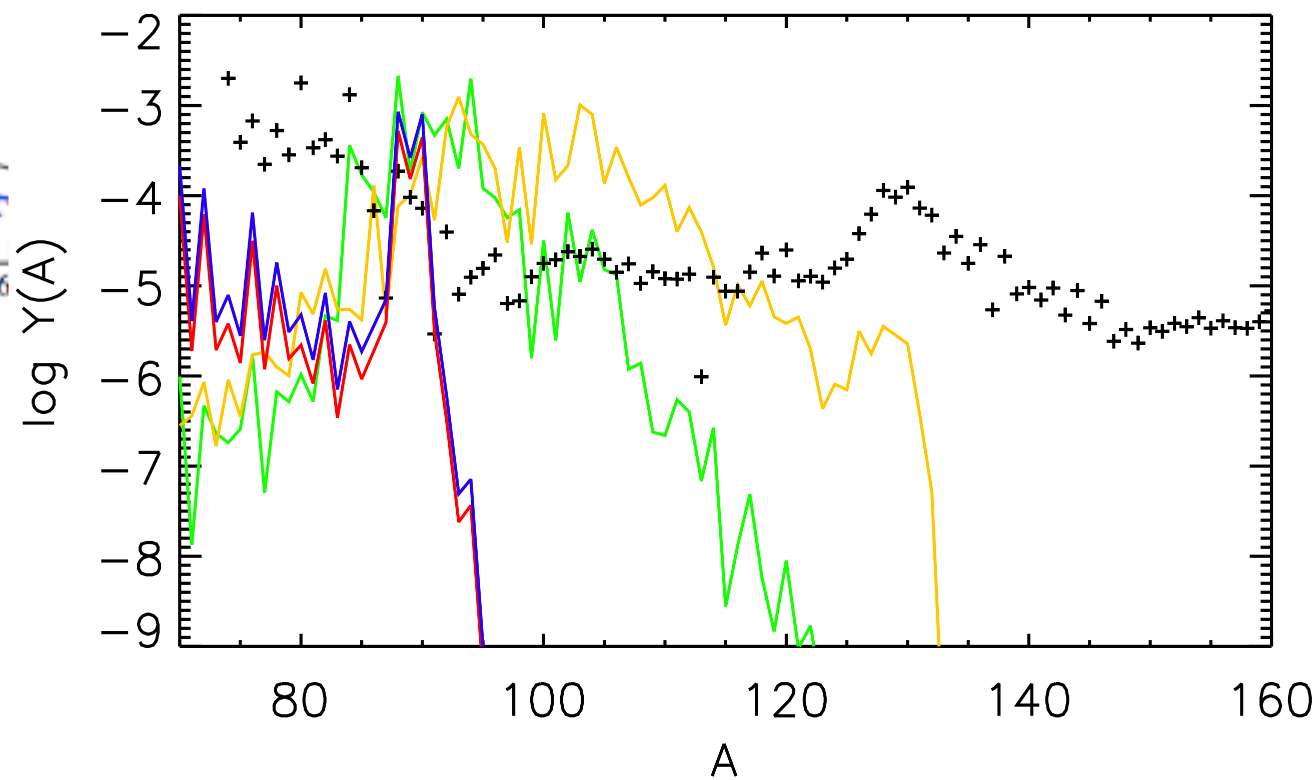
no GR

redshift, bending

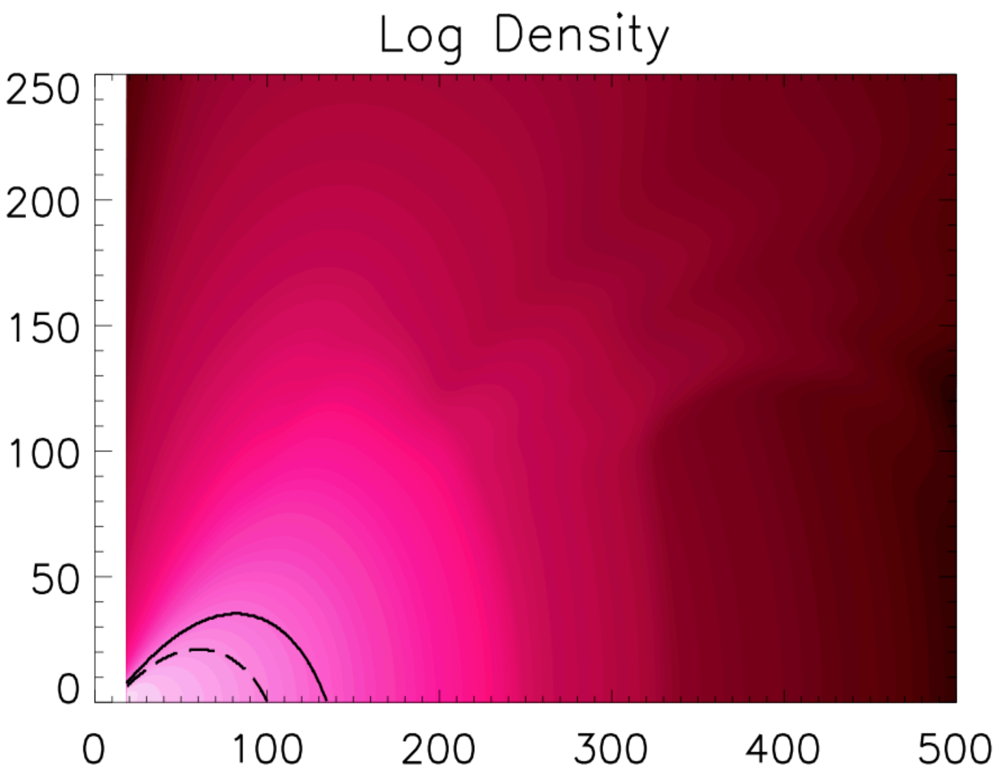
+ rotation

+ Kerr metric for redshift

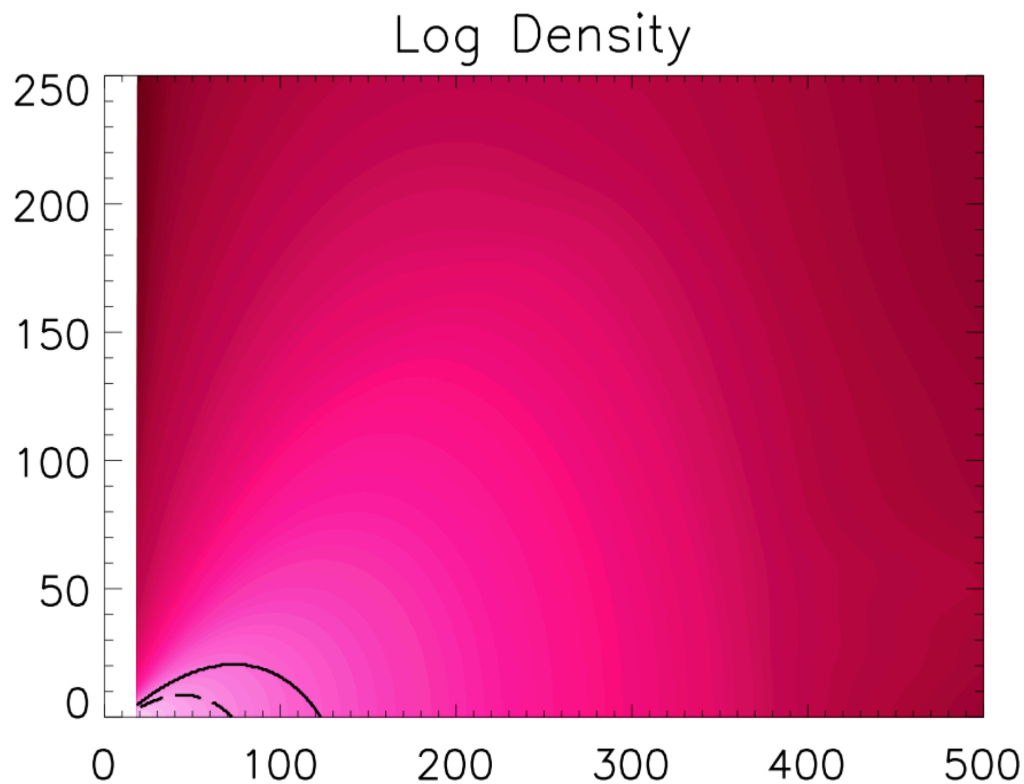
Caballero, McLaughlin, Surman (2011)



nucleosynthesis from a time-dependent merger disk



t = 20 ms



Disk model from Just et al (2014)

Neutrino decoupling surface calculation by L. Caballero

t = 60 ms

nucleosynthesis from a time-dependent merger disk

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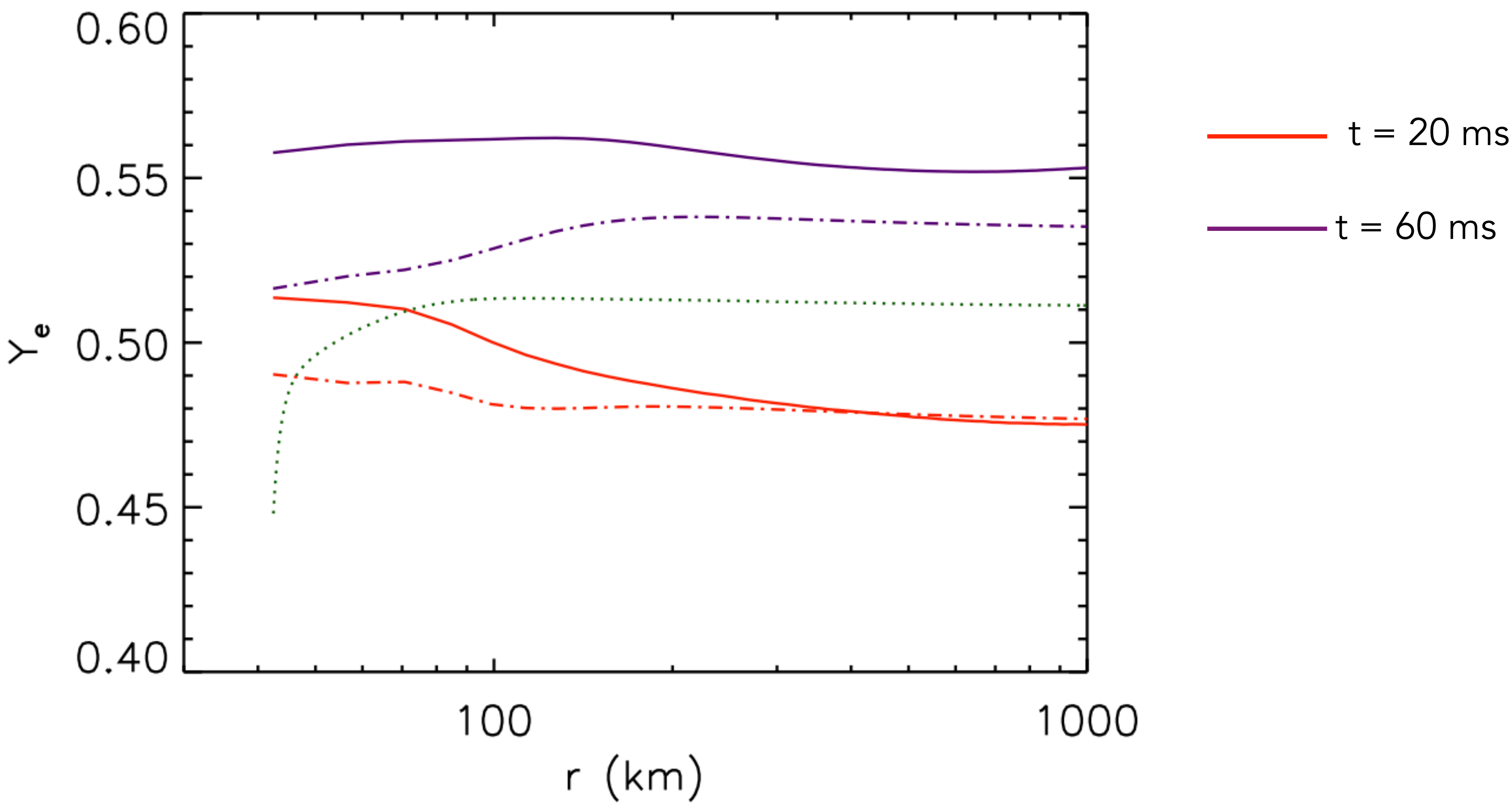
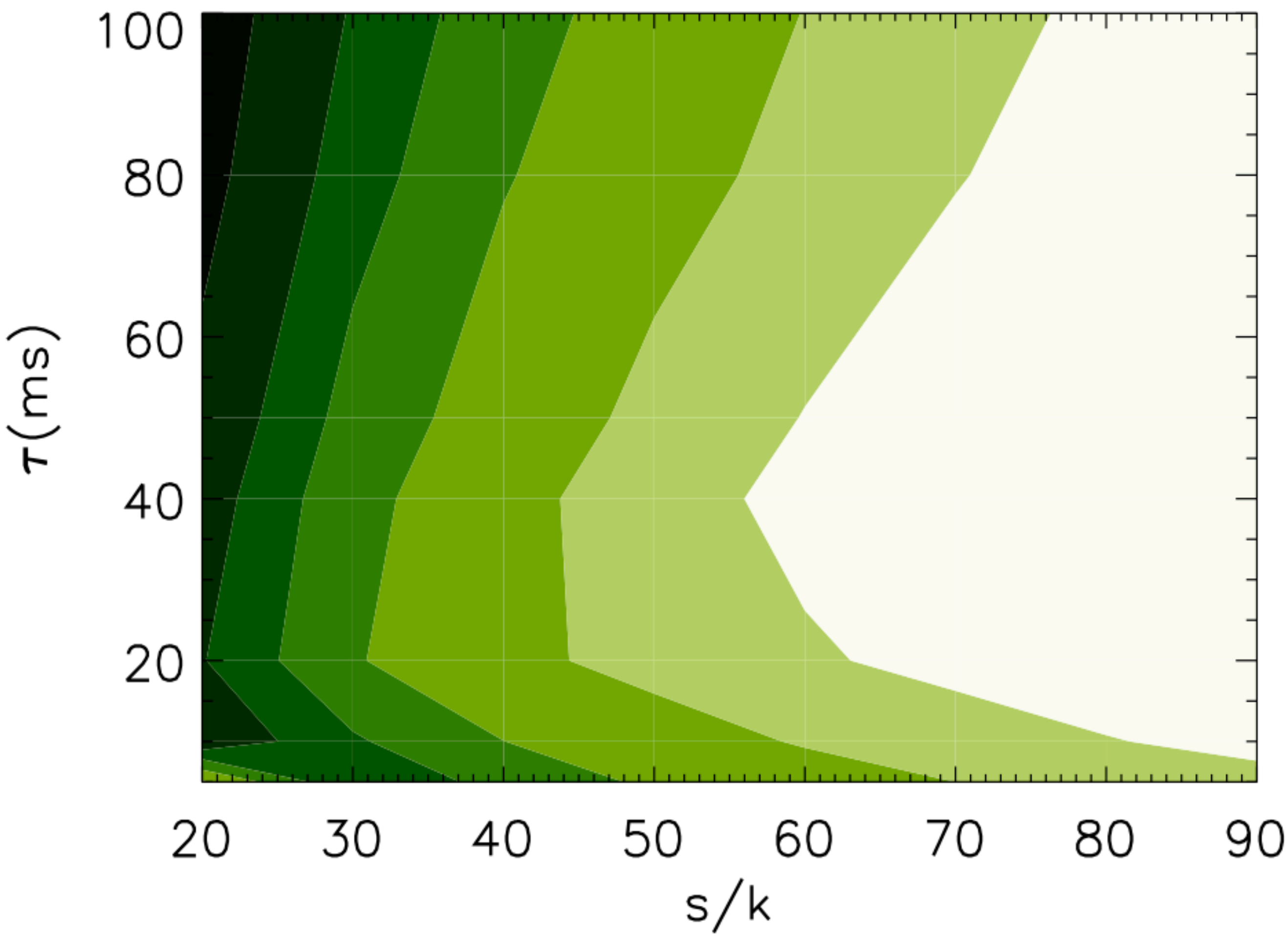
Notre Dame

neutrino-only equilibrium electron fractions



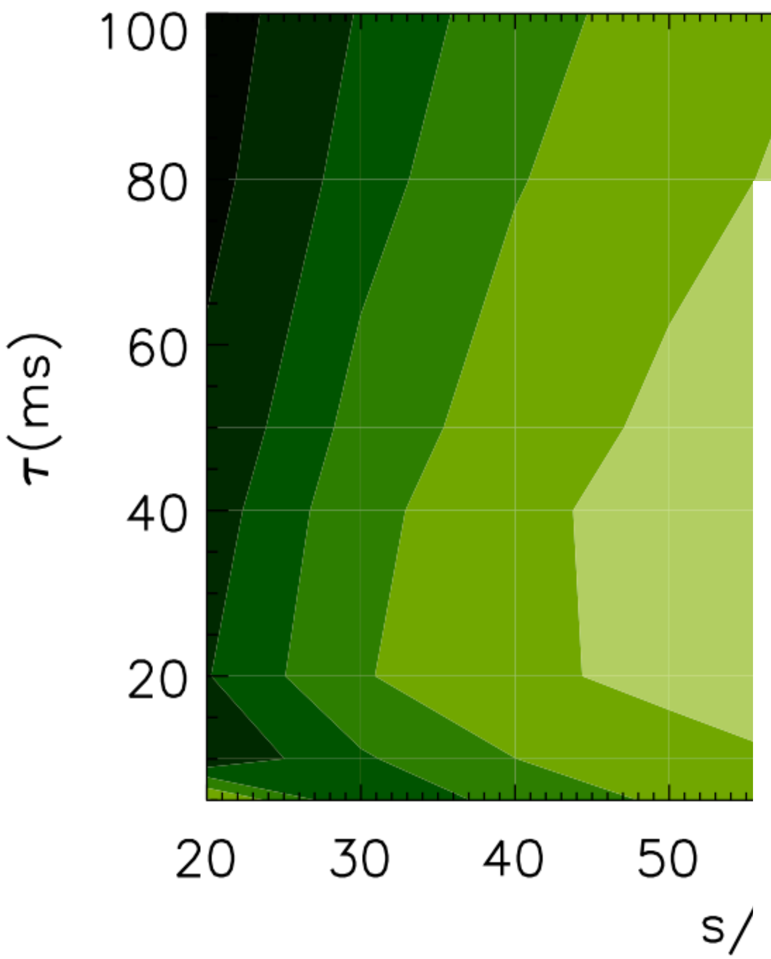
Surman, Caballero, McLaughlin, Just, Janka (2014)

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

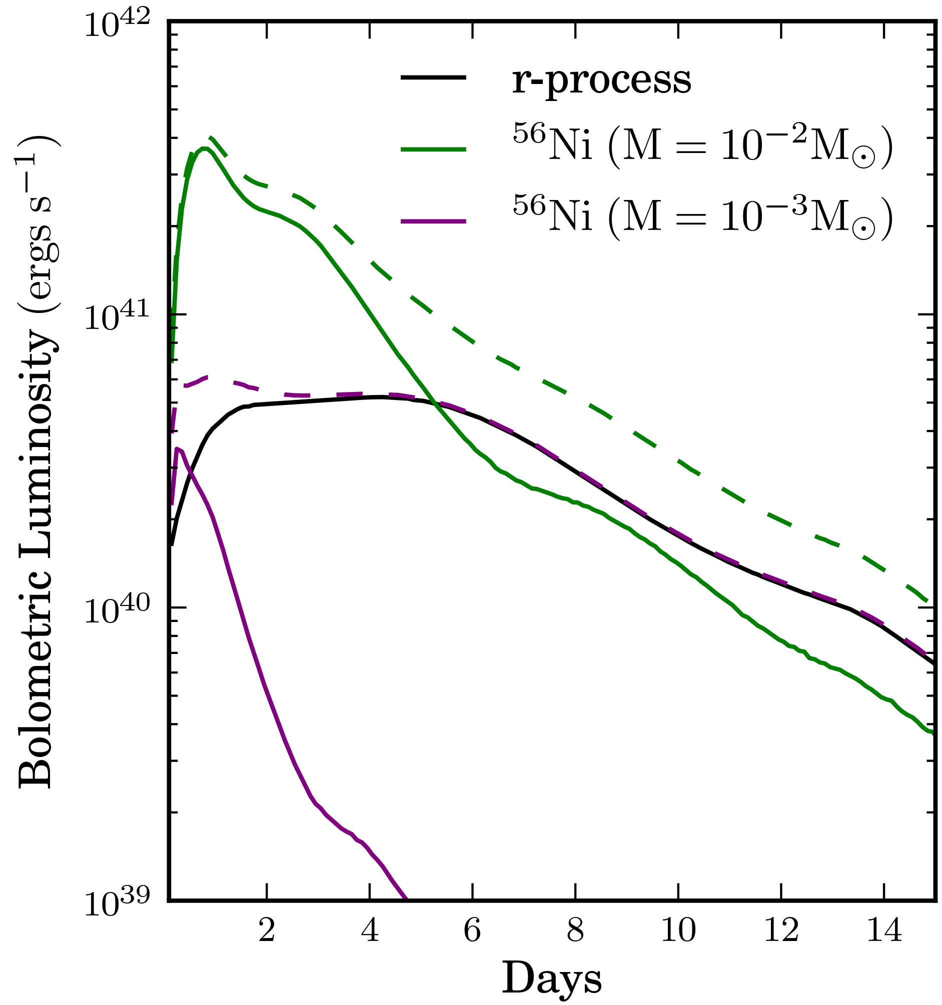


Surman, Caballero, McLaughlin, Just, Janka (2014)

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



Surman, Caballero, McLaughlin, Just, Jar



Barnes & Kasen (2013)

summary

R Surman
Notre Dame
INT 15-2a

Neutrinos play a key role in heavy element synthesis in supernovae and collapsar and merger 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 these environments