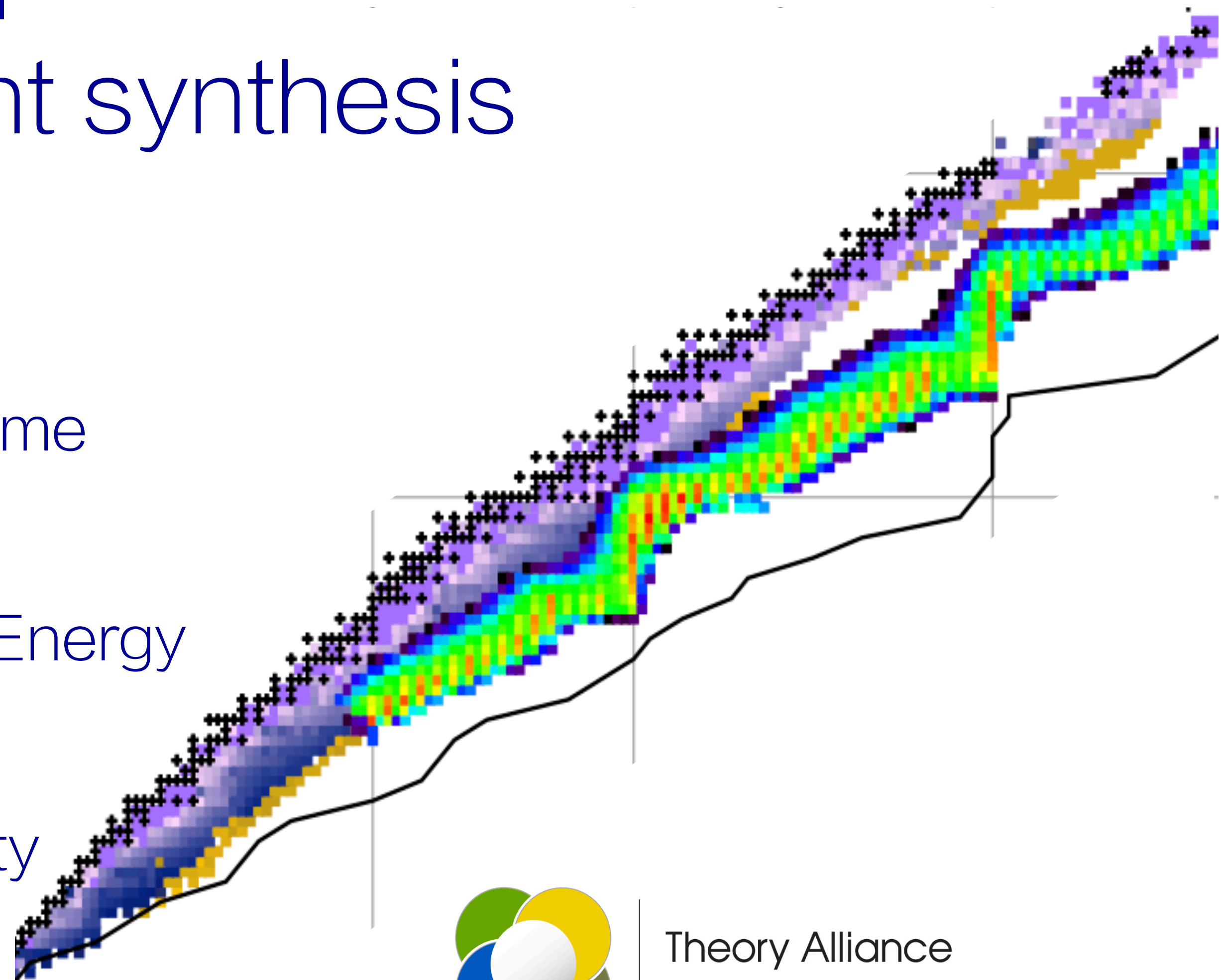
neutrinos and heavy element synthesis

Rebecca Surman
University of Notre Dame

8^{th} Symposium on
Large TPCs for Low-Energy
Rare Event Detection

Paris Diderot University
5-7 Dec 2016



Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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College of Science

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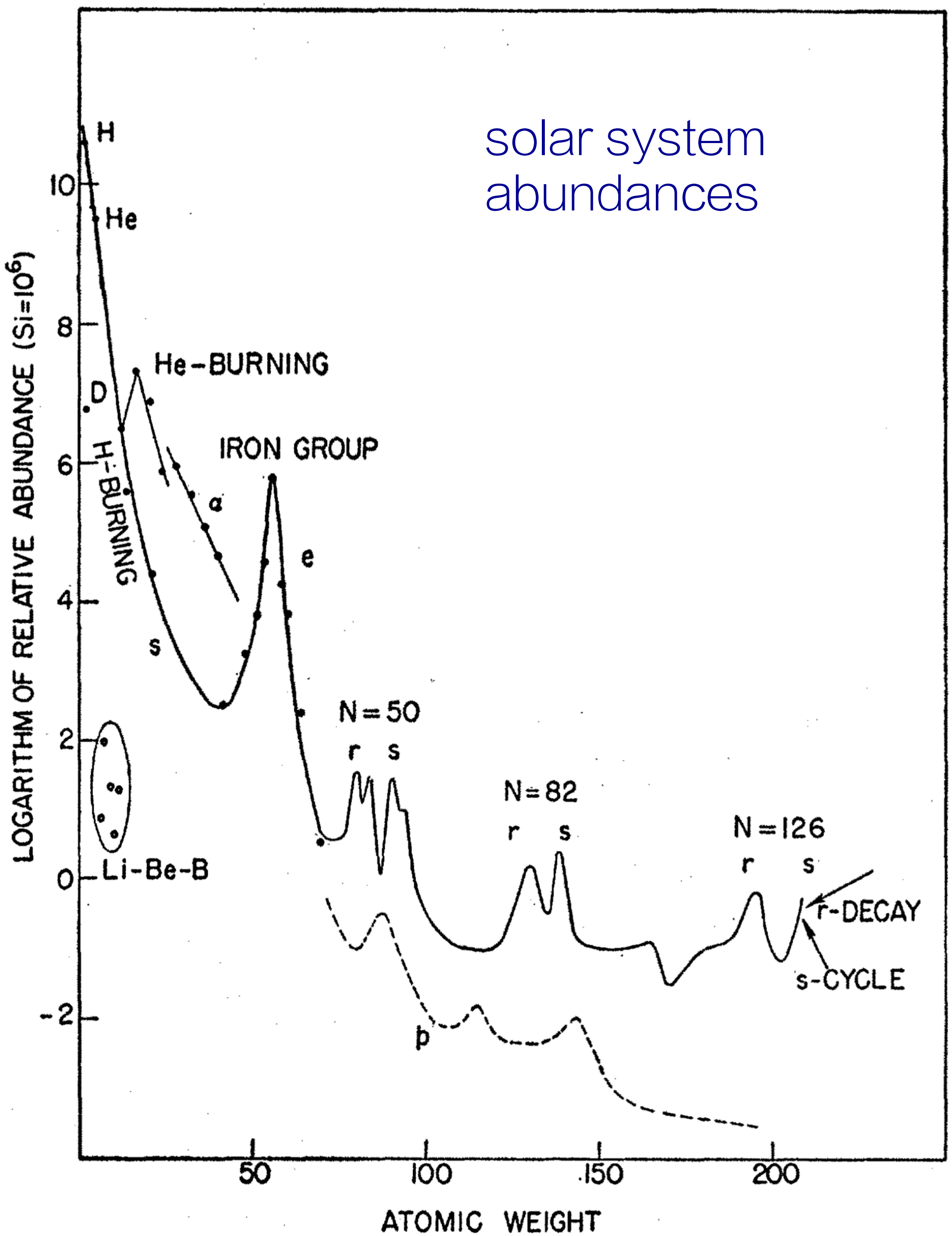
synthesis of the heaviest elements



Burbidge, Burbidge, Fowler, Hoyle 1957

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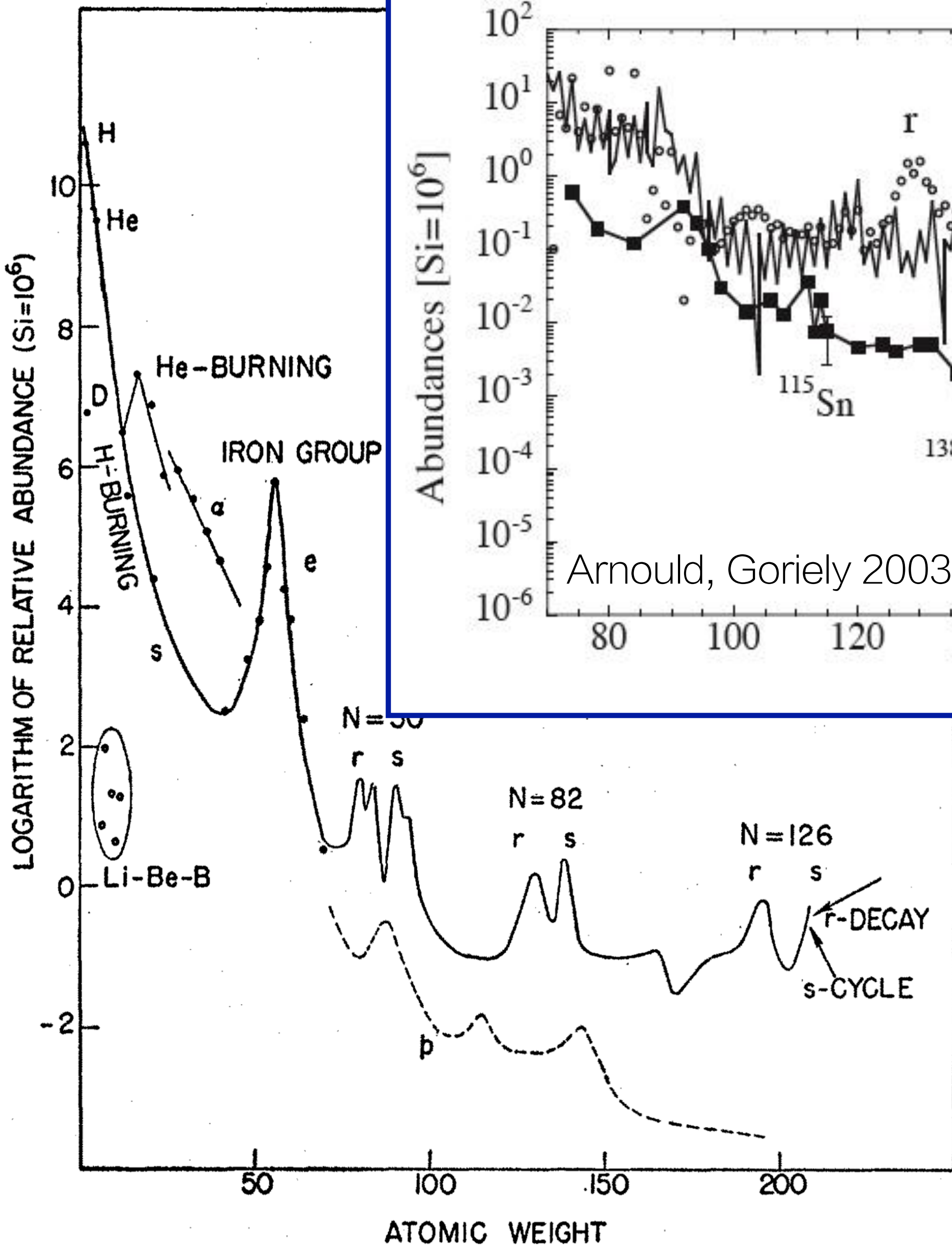
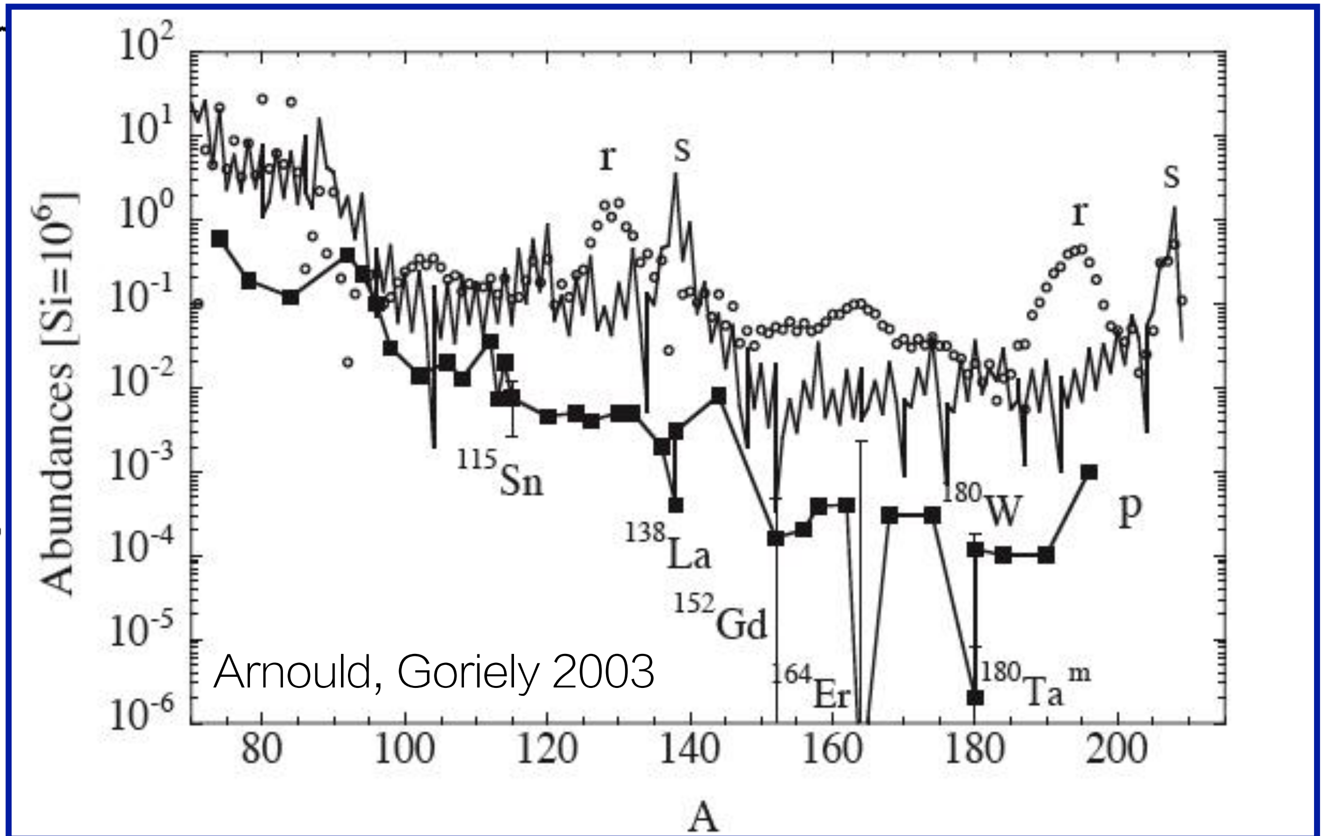
synthesis of the heaviest elements

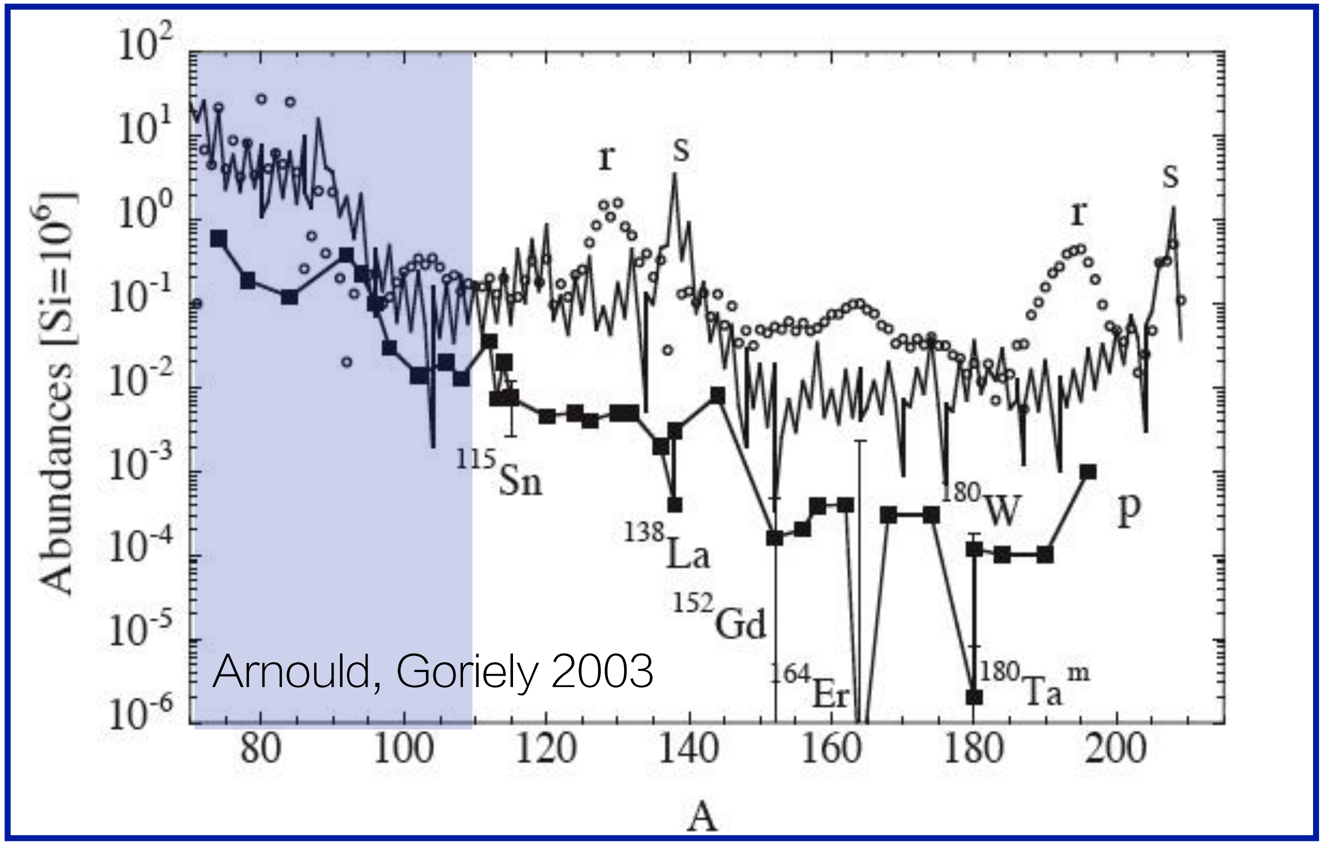




Burbidge, Burbidge, Fowler, Hoyle 1957

synthesis of the heaviest elements

weak *r* process?
weak *s* process?
LEPP?
νp process?



s process:
slow neutron capture
AGB stars

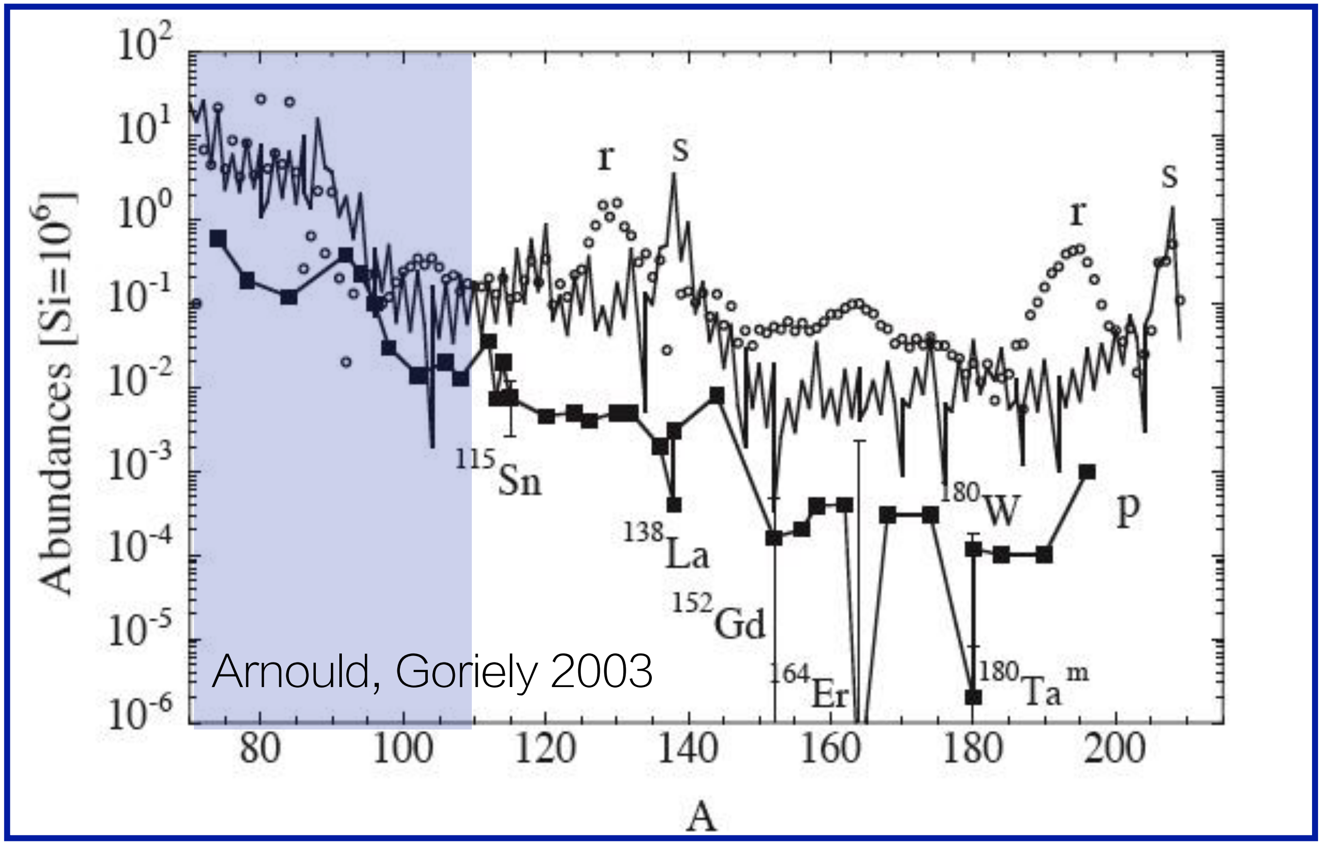
r process:
rapid neutron capture
site unknown

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

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

synthesis of the heaviest elements

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



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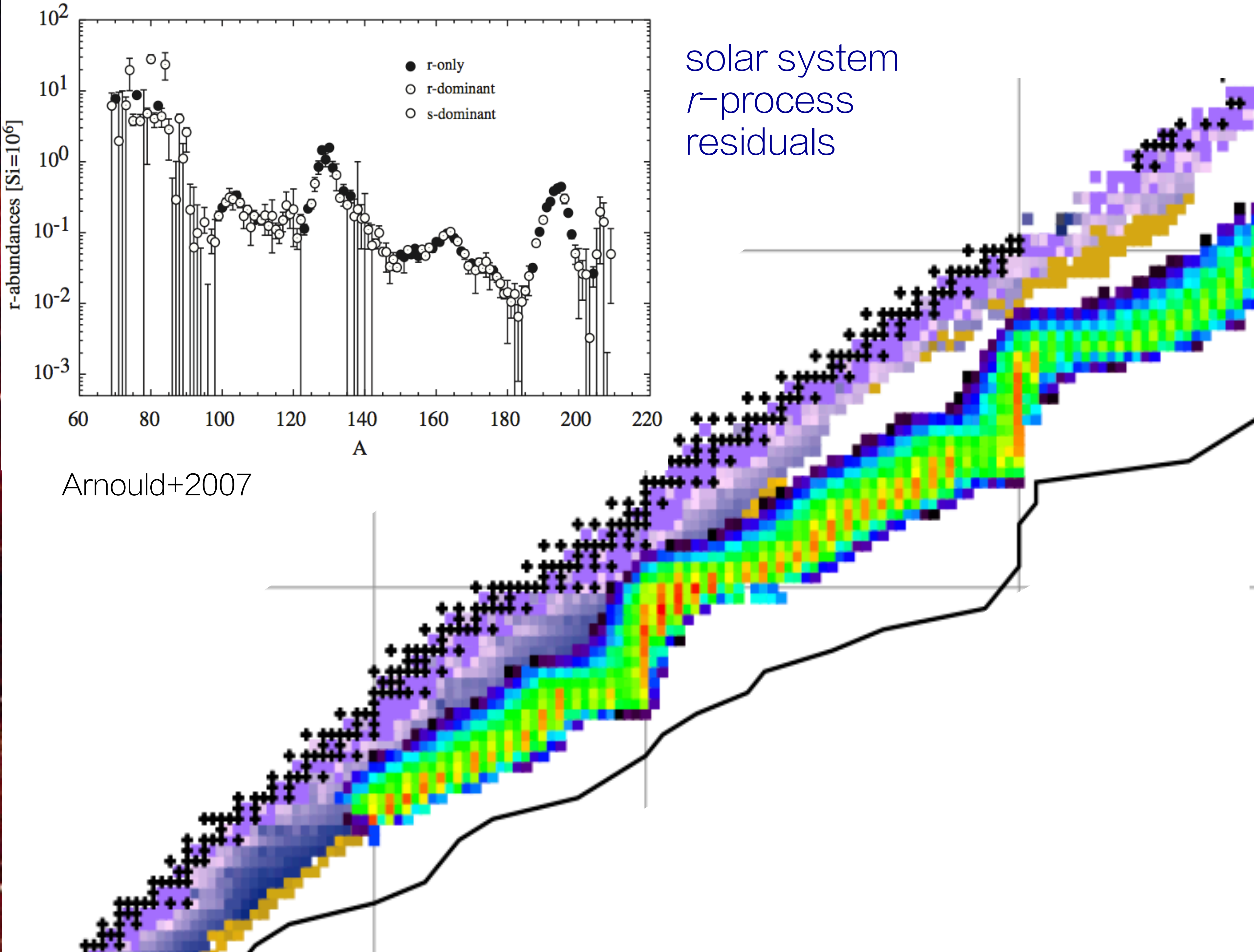
e.g., Mathews+12

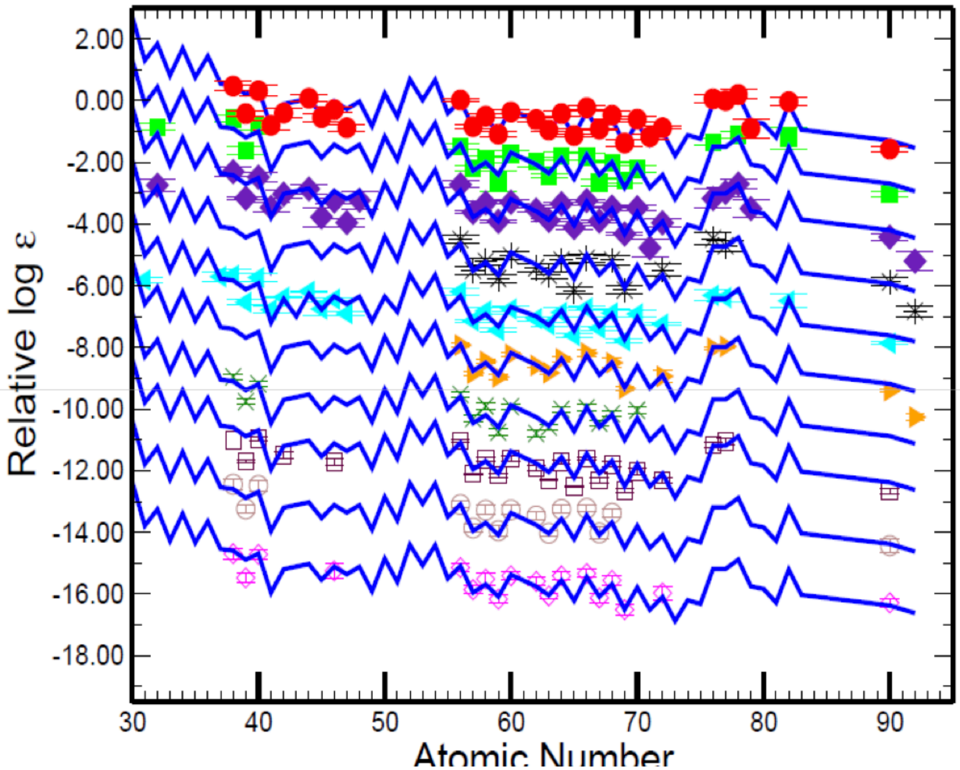
r–process nucleosynthesis



Arnould+2007

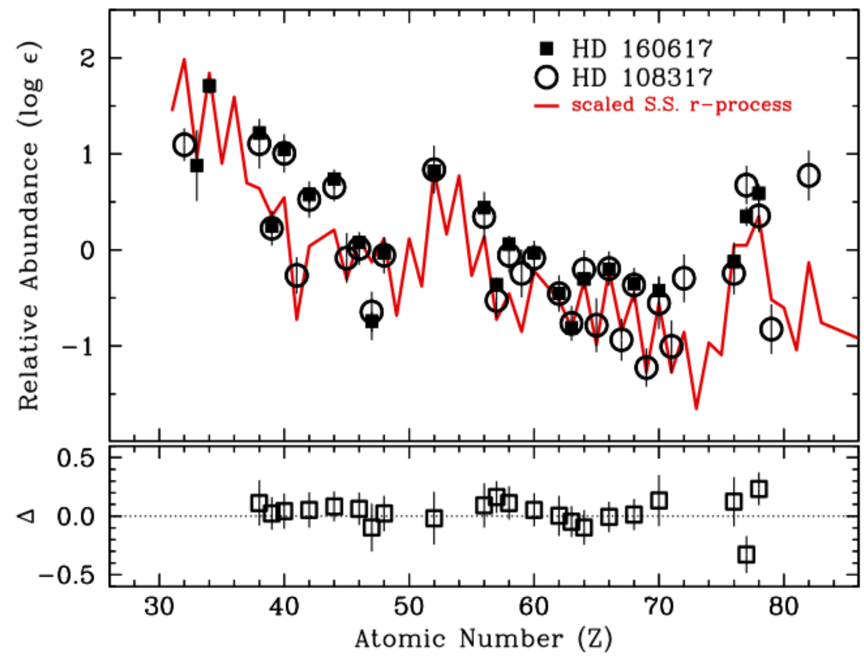
solar system
r–process
residuals

r–process nucleosynthesis



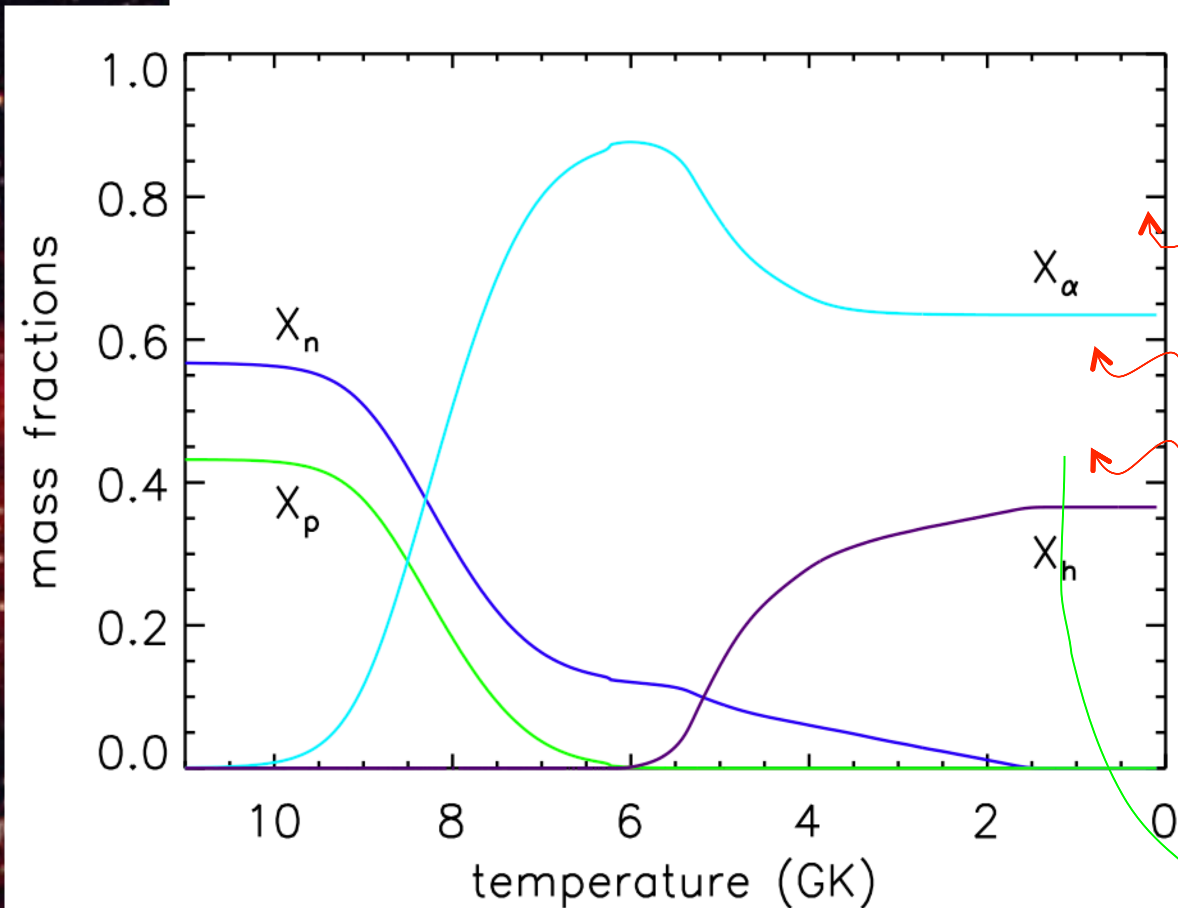
Cowan+2011

elemental abundances from *r*–process–enhanced metal–poor halo stars

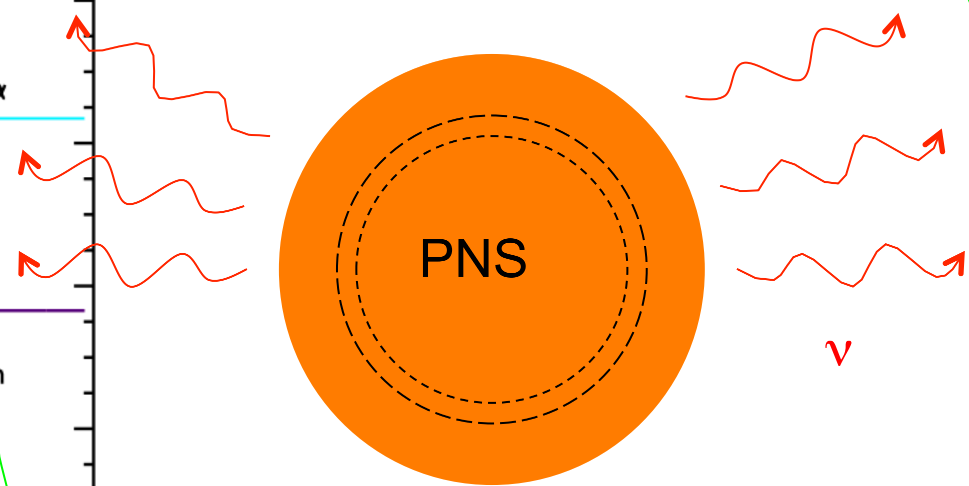


Roederer, Lawler 2012

r–process site: core–collapse supernovae?



$$E_{\nu_x} > E_{\bar{\nu}_e} > E_{\nu_e}$$



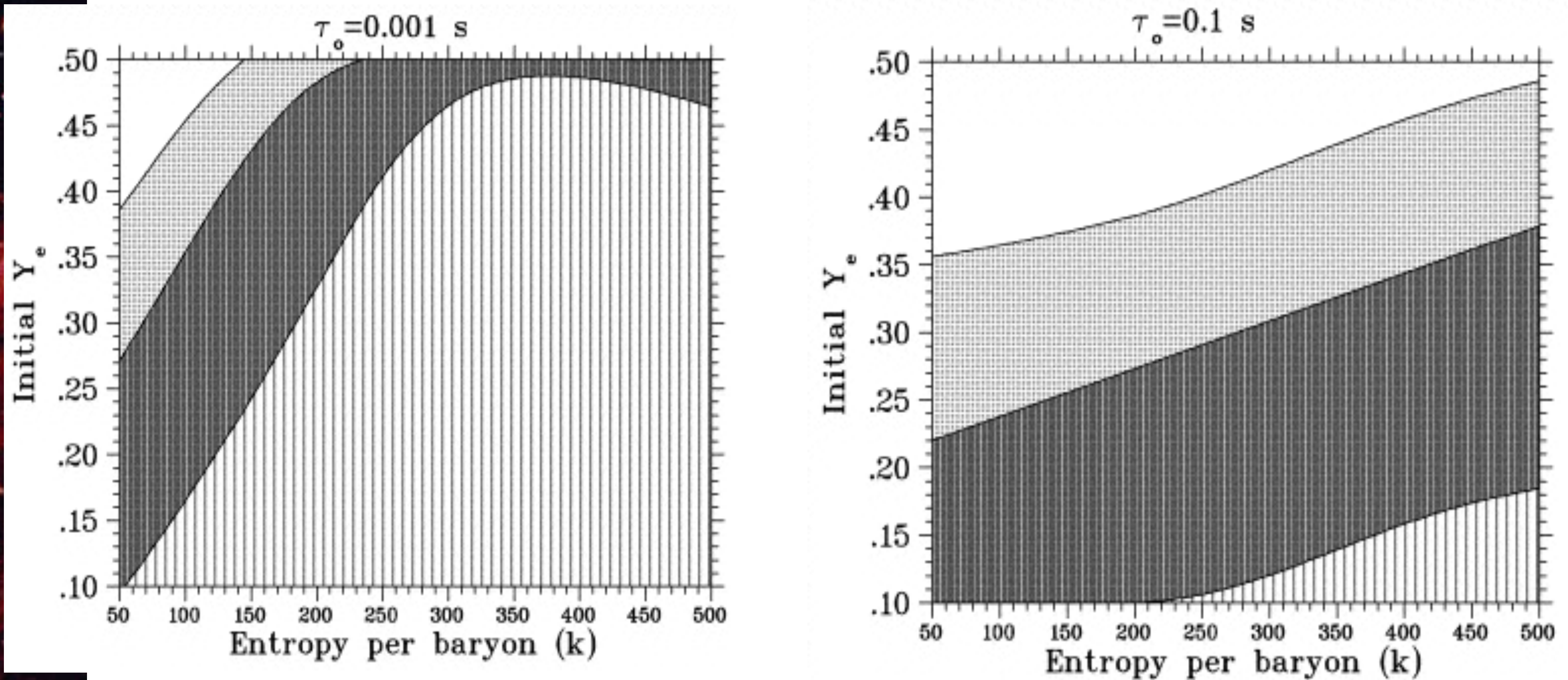
$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

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

neutrino–driven wind

e.g., Meyer+1992, Woosley+1994, Takahashi+1994, Witti+1994, Fuller, Meyer 1995, McLaughlin+1996, Qian & Woosley 1996, Hoffman+1997, Otsuki+2000, Thompson +2001, Terasawa+2002, Liebendorfer+2005, Wanajo 2006, Arcones+2007, Huedepohl+2010, Fischer+2010, Roberts, Reddy 2012, Martinez–Pinedo+2014, Chakraborty+ 2015, Goriely, Janka 2016, etc., etc.

supernova neutrino–driven wind conditions



Meyer, Brown 1997

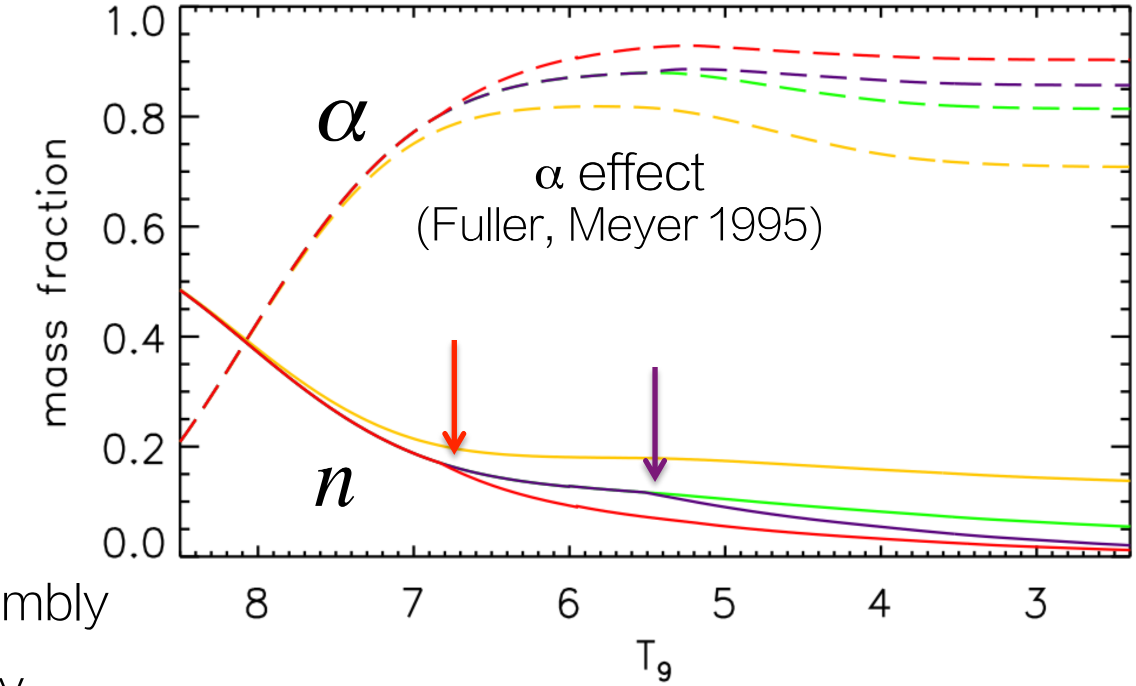
electron fraction Y_e
entropy s/k
dynamic timescale τ

} neutron to seed ratio R

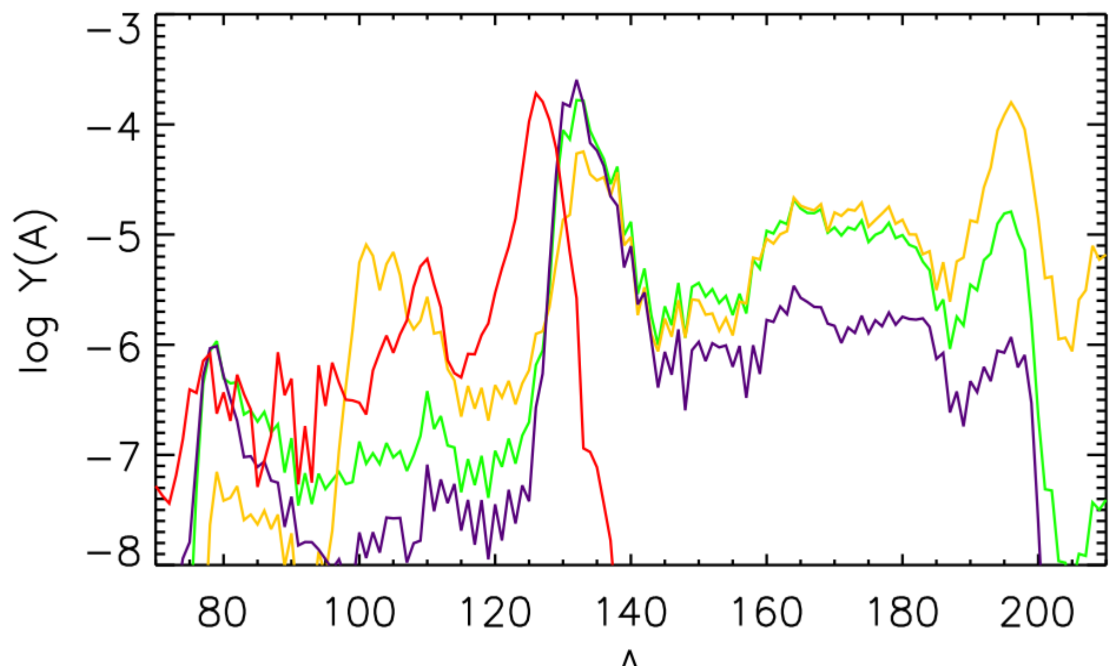
oscillations and a supernova *r* process

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

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



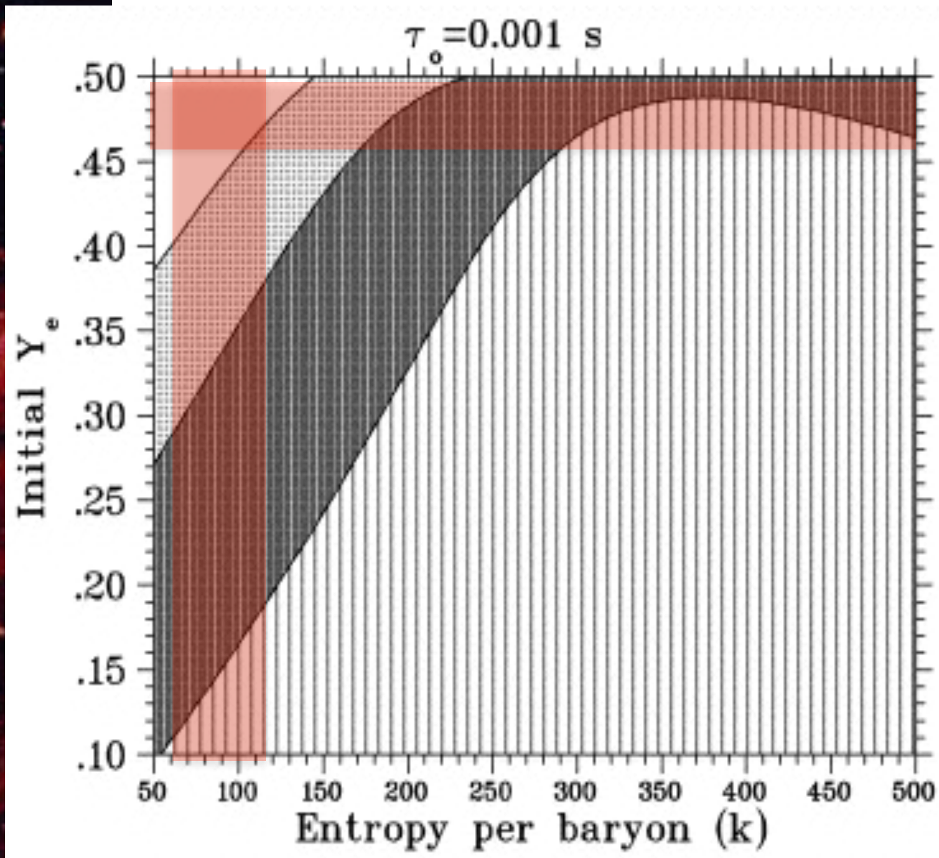
- No ν for $T < 9\times10^9$ K
- No oscillations
- Test swap at seed assembly
- Test swap at α assembly



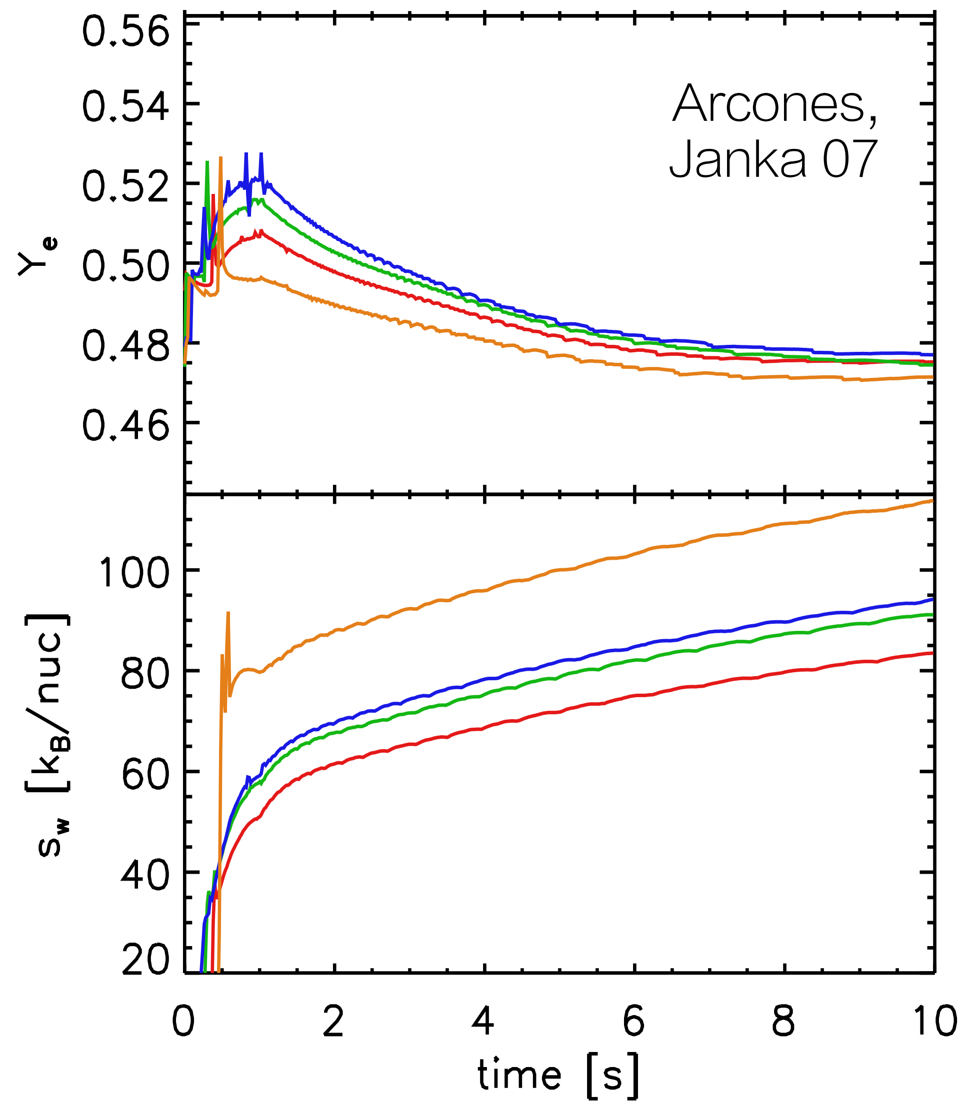
Duan, Friedland, McLaughlin, Surman 2011

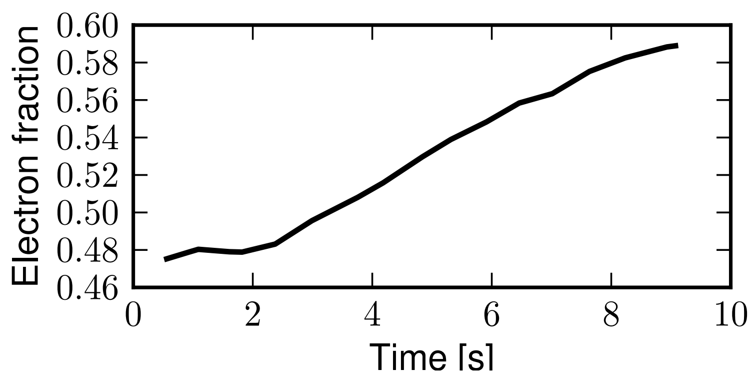
Collective oscillations:
talk of K. Scholberg
and see, e.g., the work of Pantaleone, Samuel, Qian and Fuller, Balantenkin and Yuksel, Dasgupta, Dighe, Raffelt, Lisi, Mirizzi, Volpe, Freidland, Duan, Kneller, Pehlivan, etc., etc.

supernova neutrino-driven wind conditions



Meyer, Brown 1997





Martinez-Pinedo+2014

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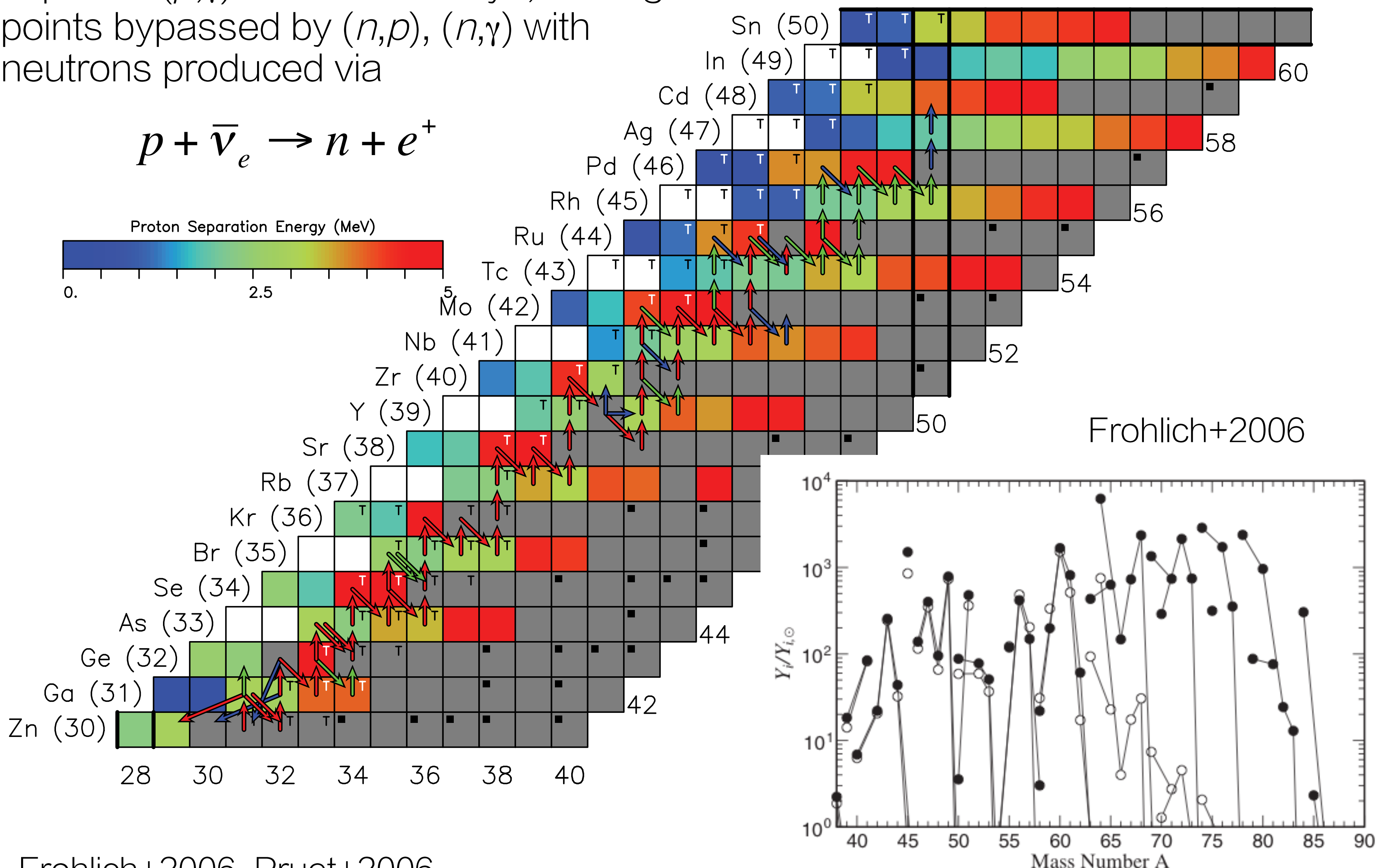
νp process

heavy elements built up by proton captures (p,γ) and beta decays; waiting points bypassed by (n,p), (n,γ) with neutrons produced via

$$p + \overline{\nu}_e \rightarrow n + e^+$$

Pruet+2006



Frohlich+2006, Pruet+2006, Wanajo 2006

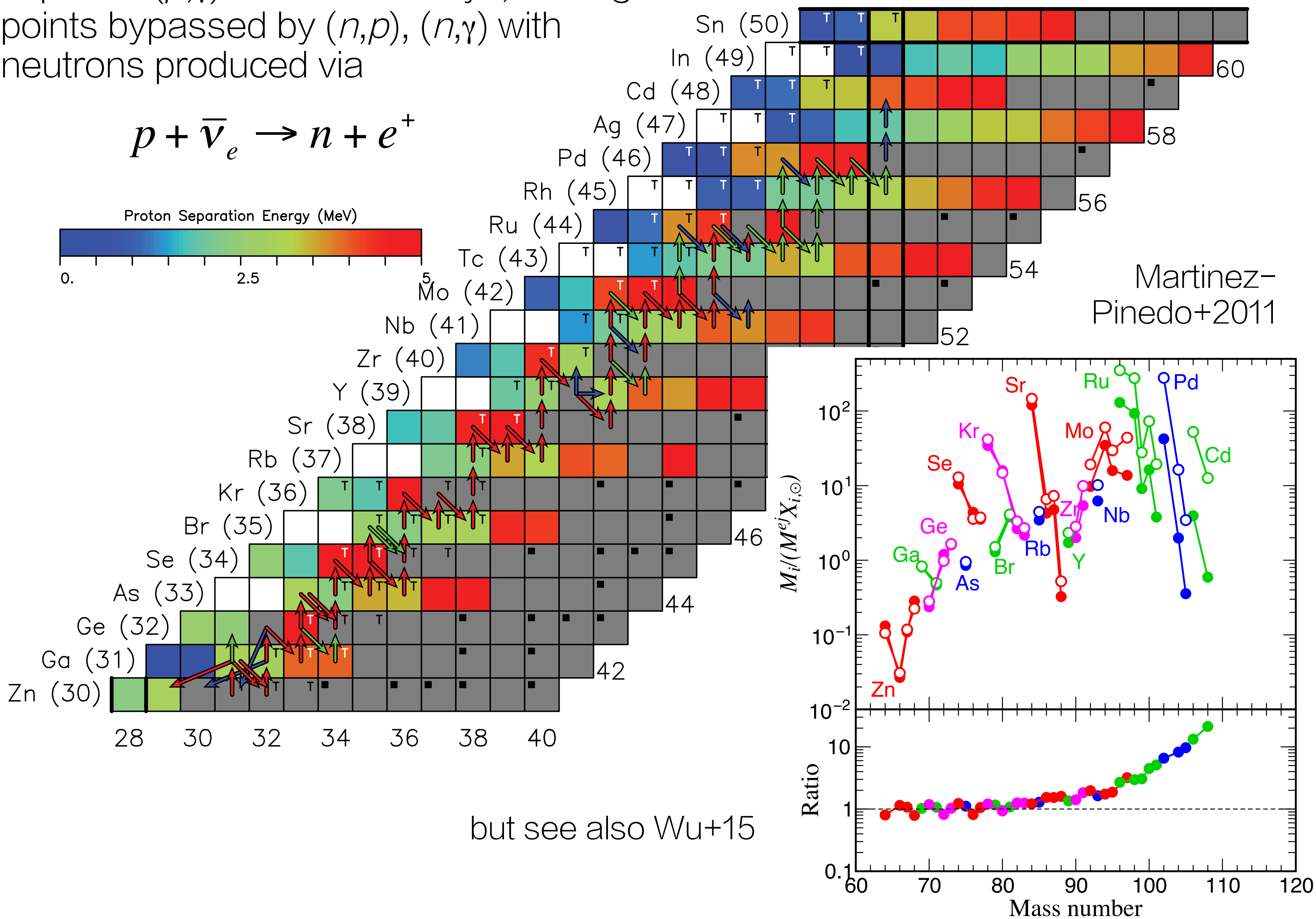
νp process + collective oscillations?

heavy elements built up by proton captures (p,γ) and beta decays; waiting points bypassed by (n,p), (n,γ) with neutrons produced via

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

Pruet+2006

Martinez-Pinedo+2011

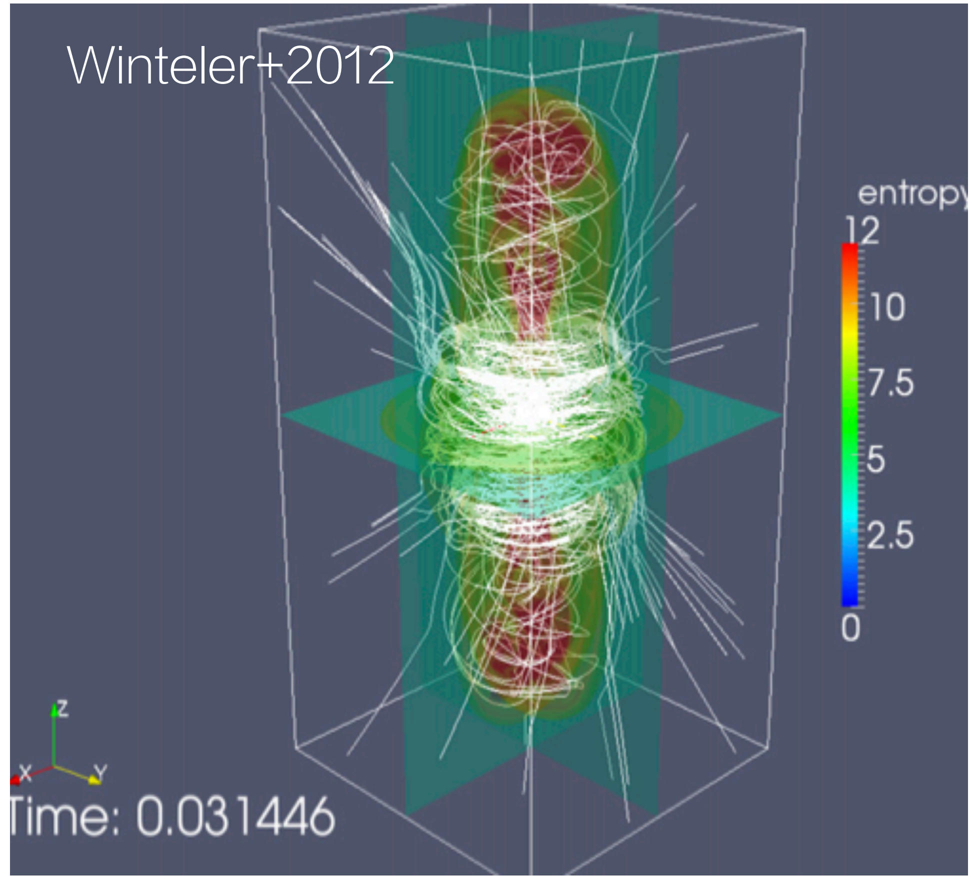


but see also Wu+15

exotic supernovae?

neutron-rich MHD jets

e.g., Cameron+2003, Kotake+2004, Nishimura+2006, Fujimoto+2008, Winteler+2012, Mösta+2014, Shibagaki +2016, etc.



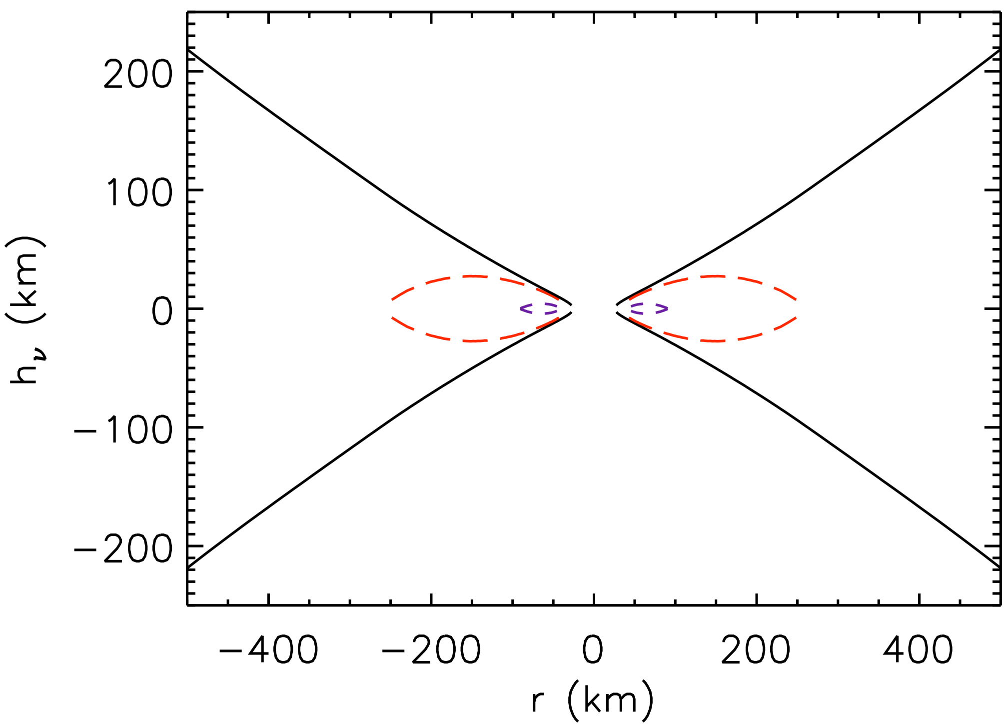
collapsars/lGRBs

e.g., Beloborodov 2003, Nagataki+2003, Surman, McLaughlin 2005, Nagataki +2006, Fryer+2006, Fujimoto+2007, Fujimoto+2008, Tominaga 2009, Maeda,Tominaga 2009, Nomoto+2010, Horiuchi +2012, Shibata, Tominaga 2012, Malkus+2012, Nakamura+2013, etc.

collapsar AD−BH neutrino emission

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

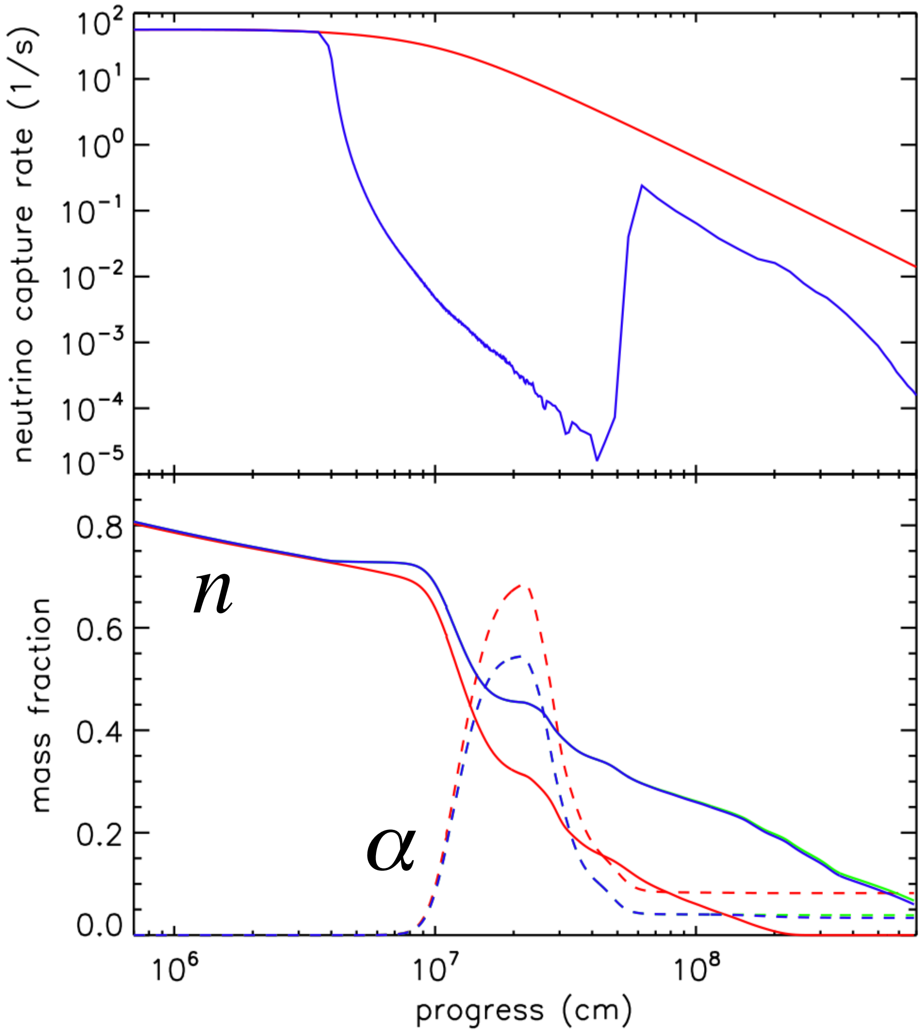
- primarily ν_e and $\bar{\nu}_e$ (vs. all flavors in a PNS)
- emission surfaces not spherical
- ν_e emission surface much larger than that for $\bar{\nu}_e$



new type of oscillation possible: a *matter−neutrino resonance (MNR)*

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

collapsar AD–BH outflow nucleosynthesis

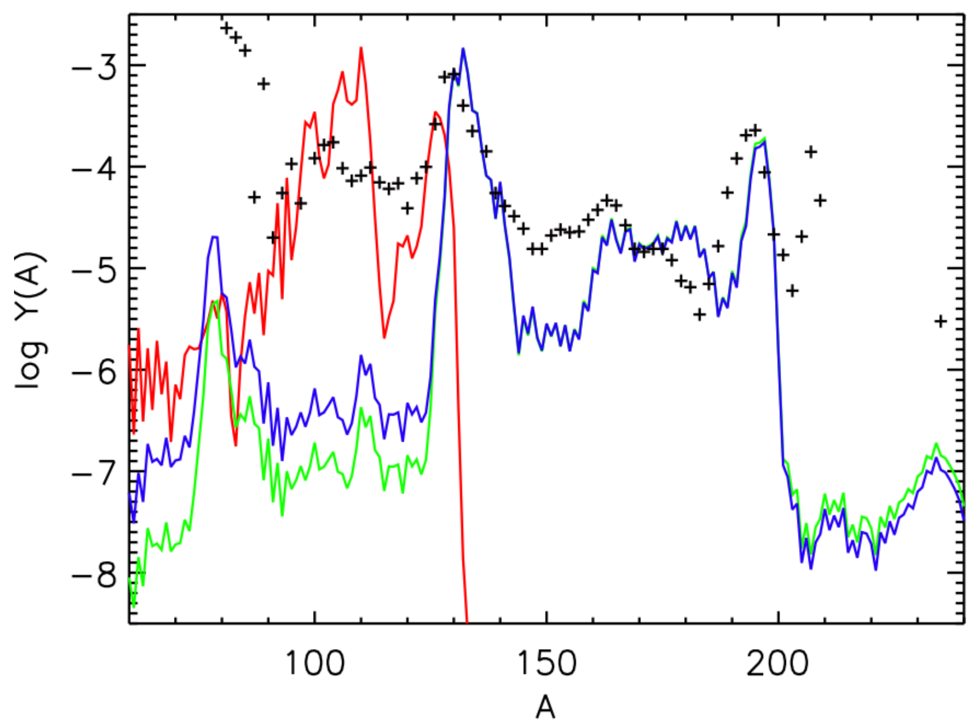


no oscillations

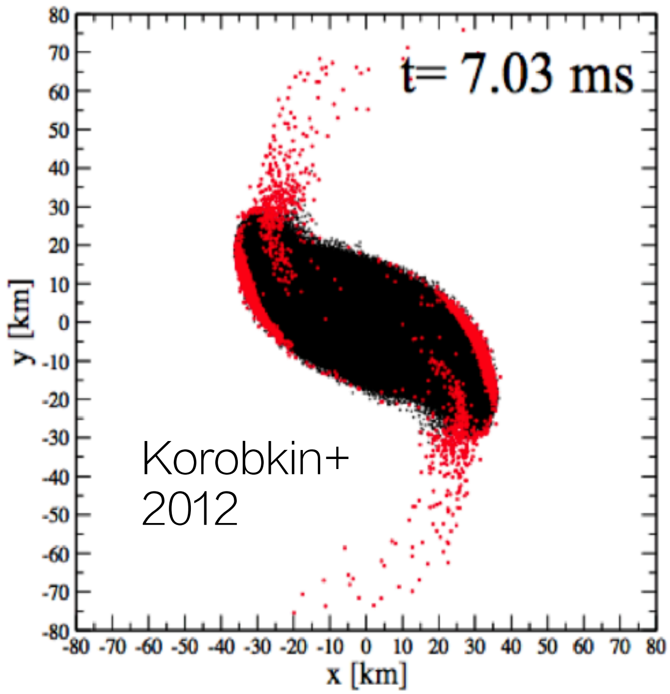
single angle ν oscillation calculation

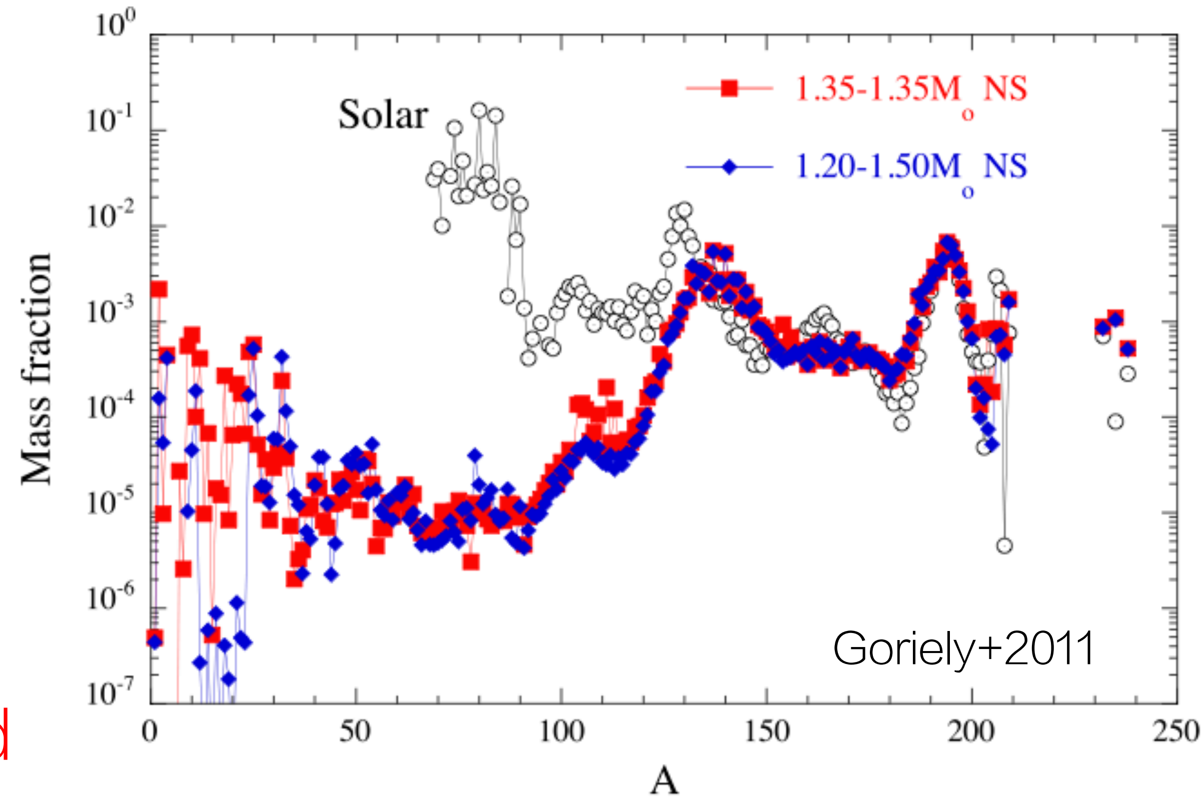
no ν for $r > 5 \times 10^{7}$ cm

Malkus, McLaughlin, Kneller, Surman 2012



r–process site: compact object mergers?



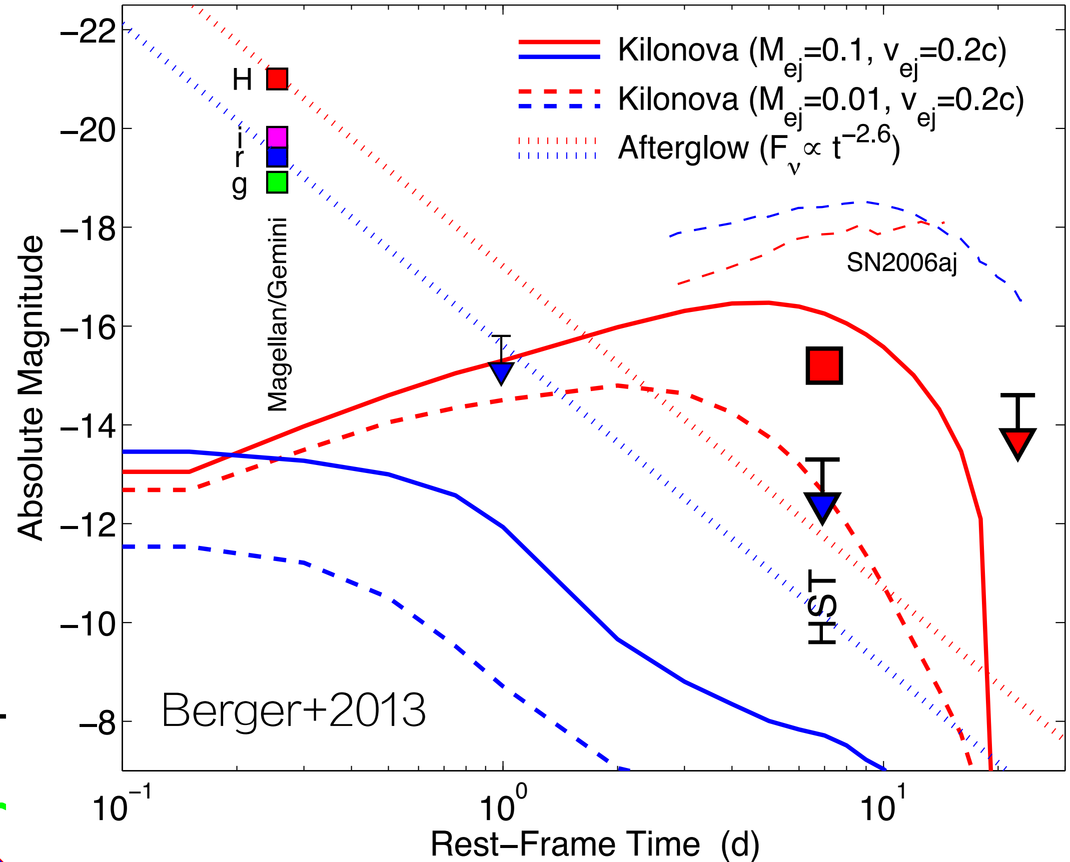


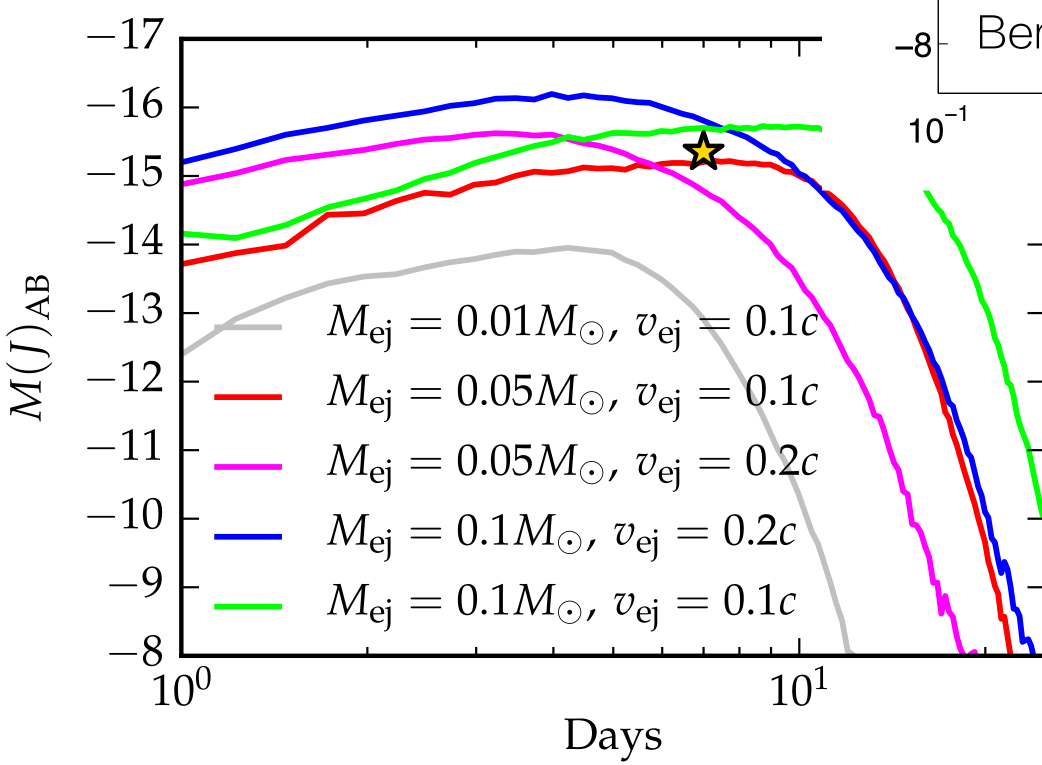
cold/mildly heated prompt ejecta

e.g., Lattimer, Schramm 1974, 1976, Meyer 1989, Frieburghaus+1999, Goriely+2005, Wanajo, Ishimaru 2006, Oechslin+2007, Nakamura+2011, Goriely+2011, Korobkin +2012, Wanajo+2014, Just+2015, Mendoza–Temis+2015, Eichler+2015, etc., etc.

electromagnetic signatures of merger events

Tanvir+2013, Berger 2013: observations of a kilonova candidate sGRB 130603B





Barnes+2016

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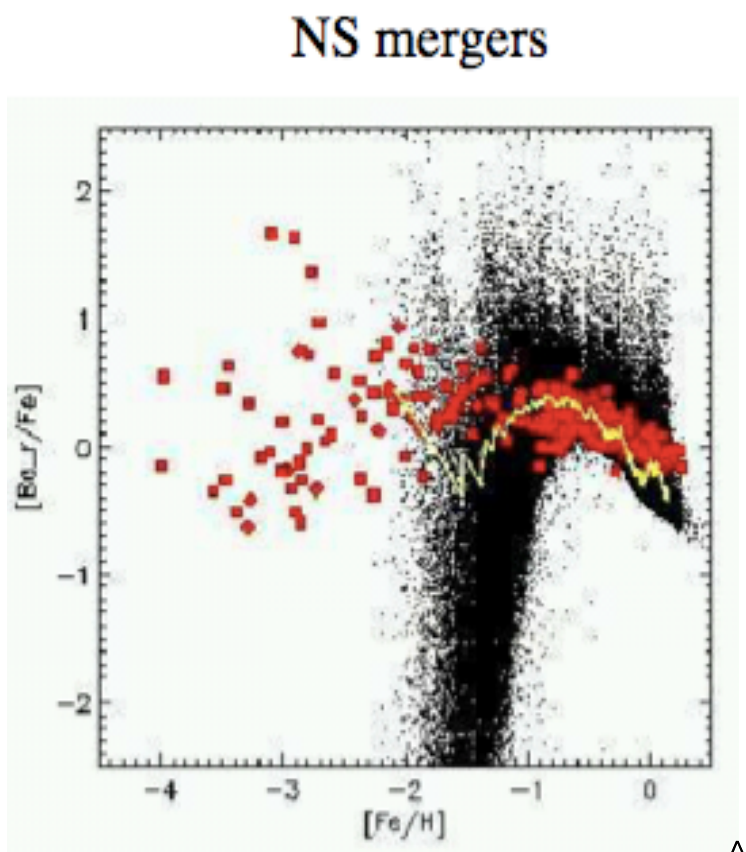
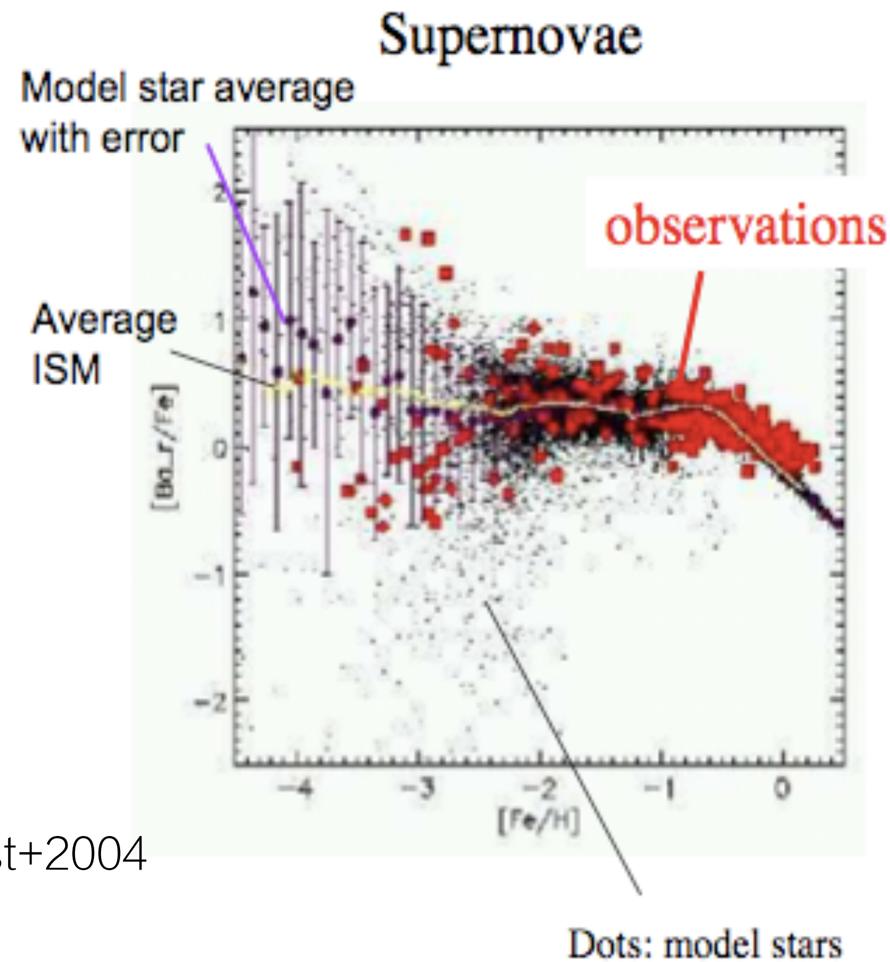
can mergers account for all *r*−process data?





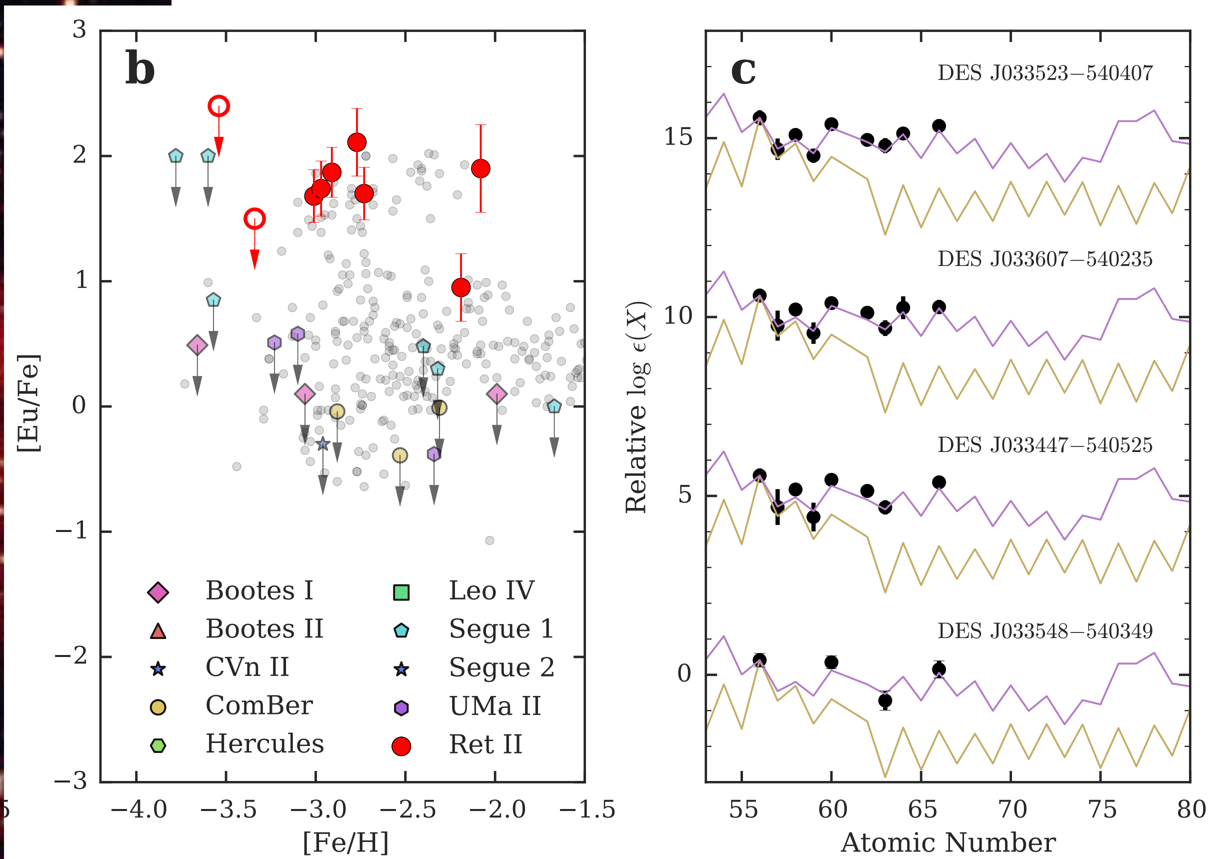
Argast+2004

Mathews, Cowan 1990; Argast+2004: merger timescale too slow

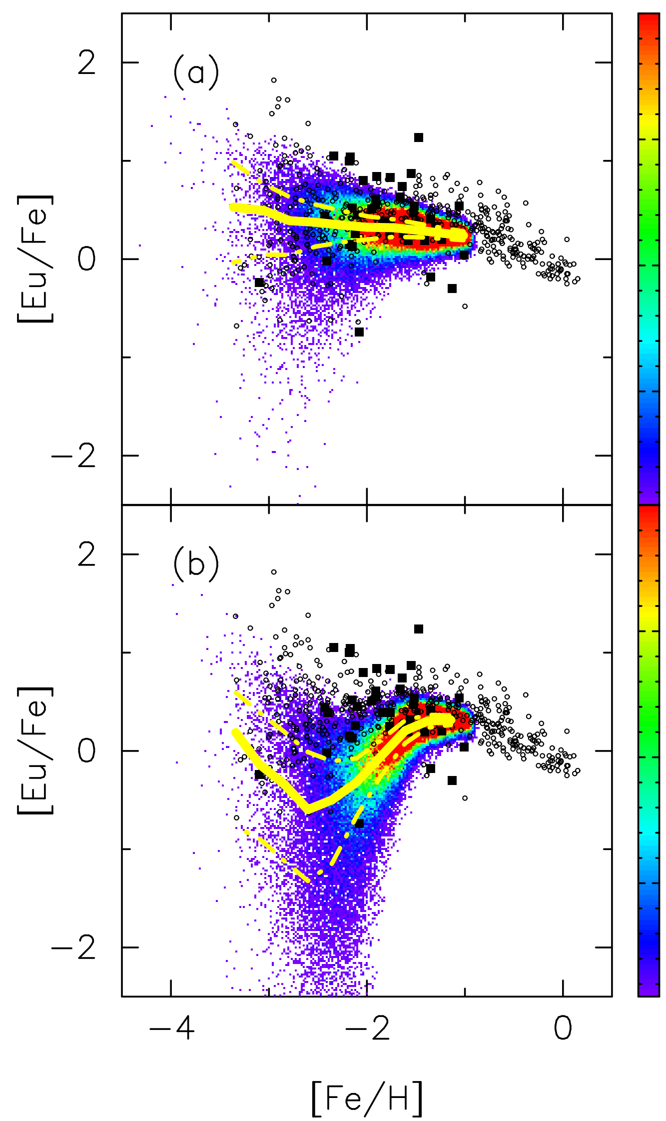
Matteucci+2014, Ishimaru+2015: if coalescence time is ~ 1 Myr

Wanderman, Piran 2014: delay times for sGRB ~3 Gyr

can mergers account for all *r*-process data?



Ji+2016



Hirai+2015

Hirai+2015, Ji+2016: UFD galaxies account for low-metallicity enrichment

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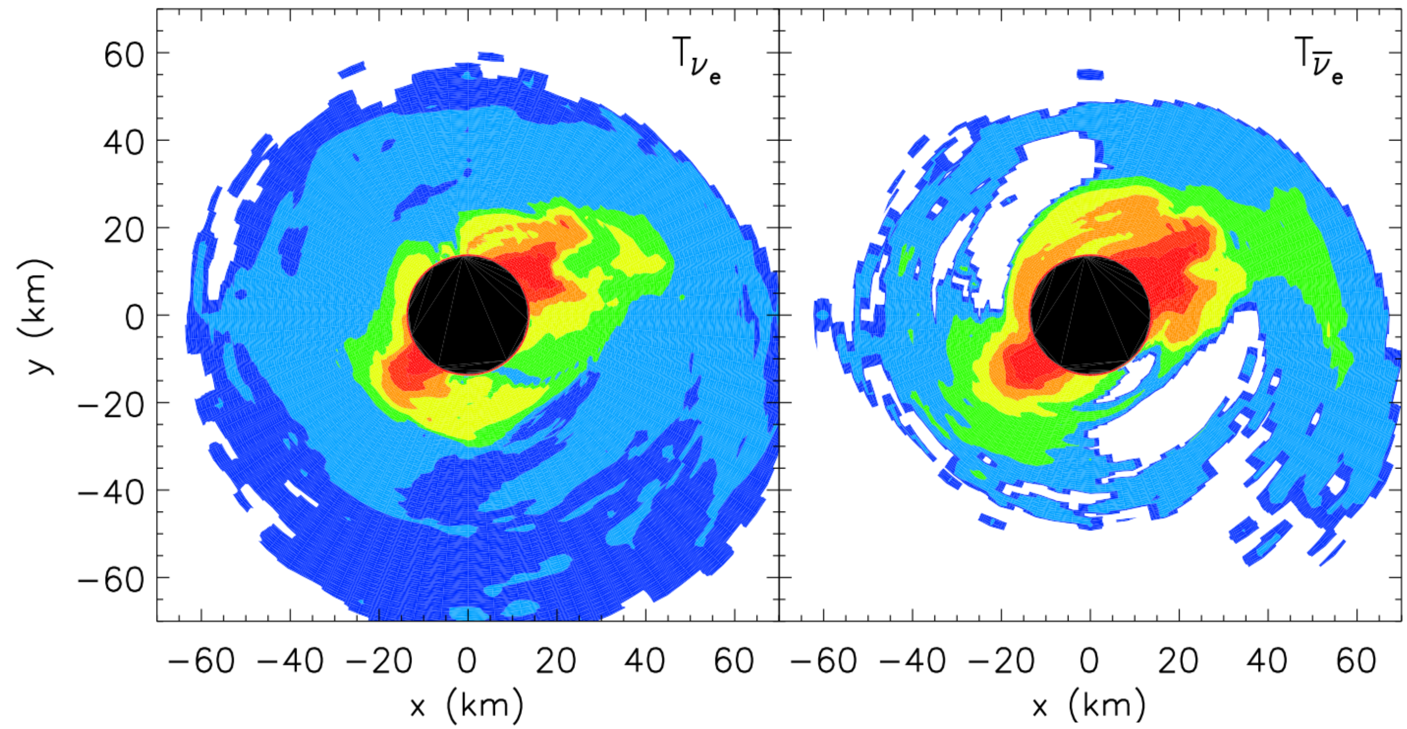
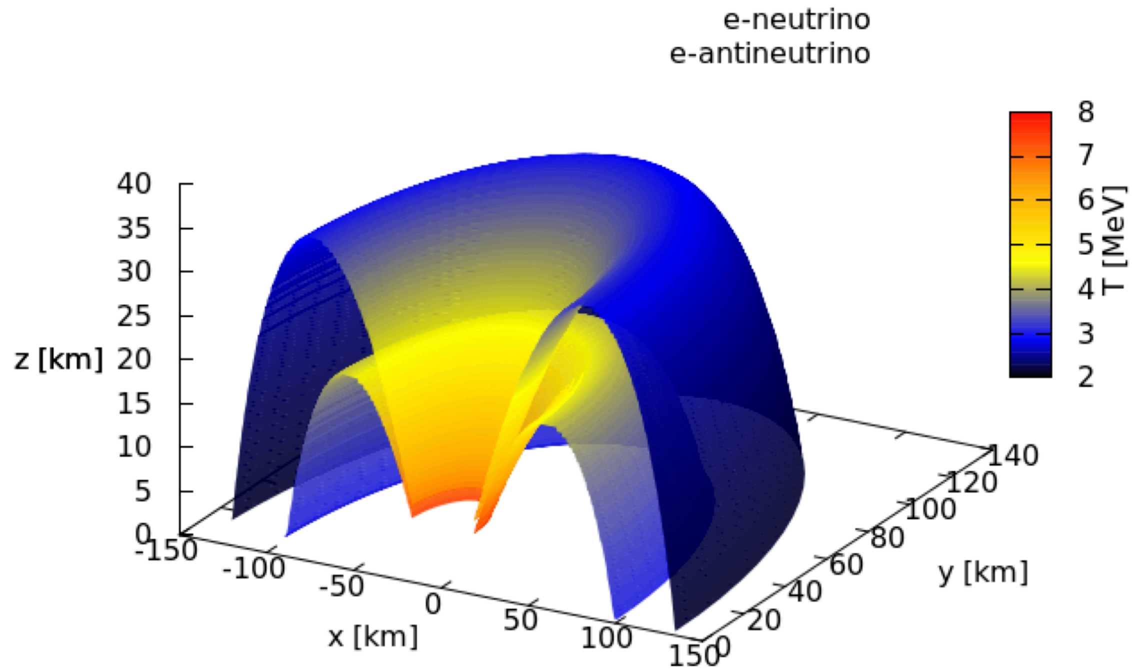
neutrinos from mergers

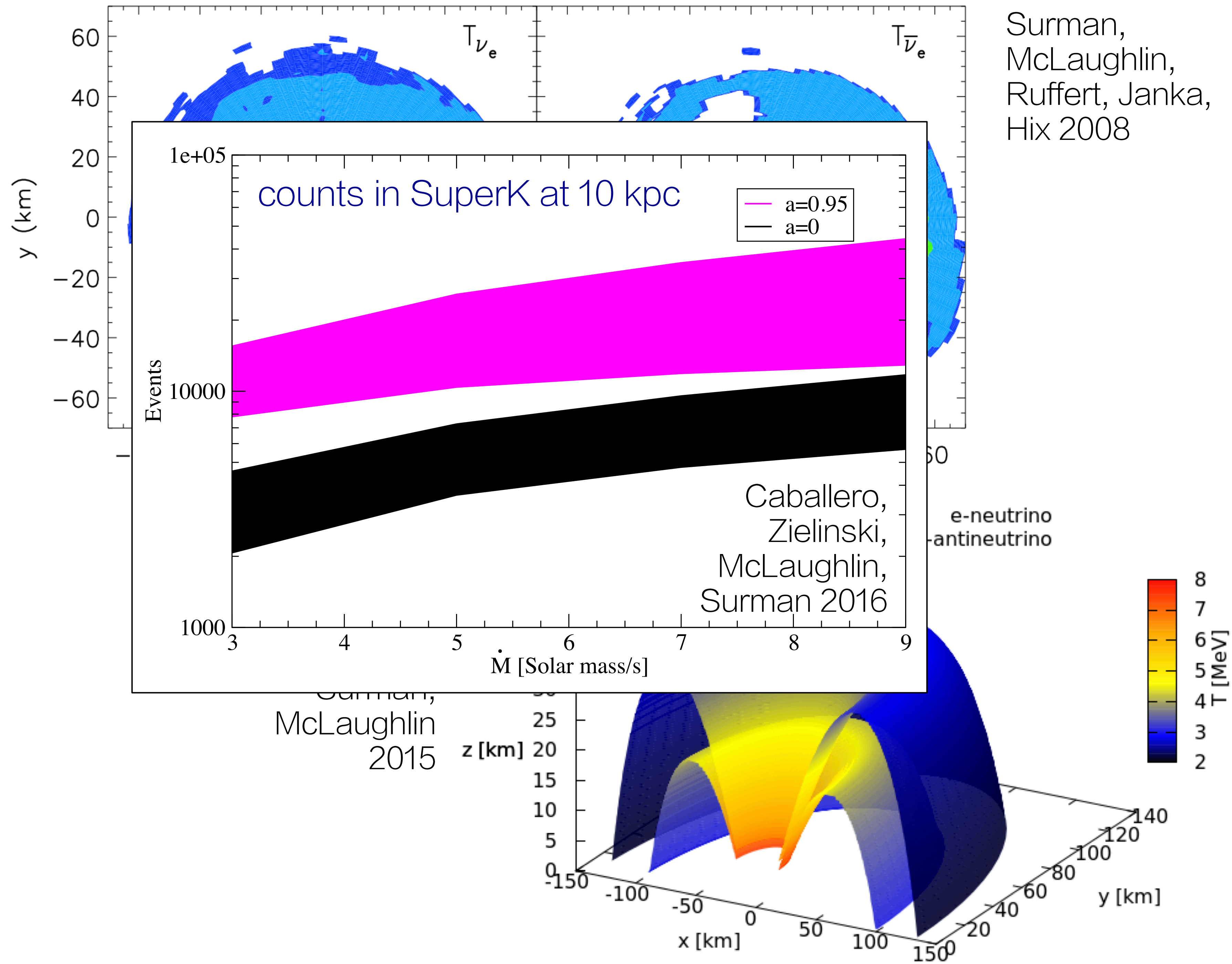


Surman, McLaughlin, Ruffert, Janka, Hix 2008



Caballero, Surman, McLaughlin 2015

neutrinos from mergers



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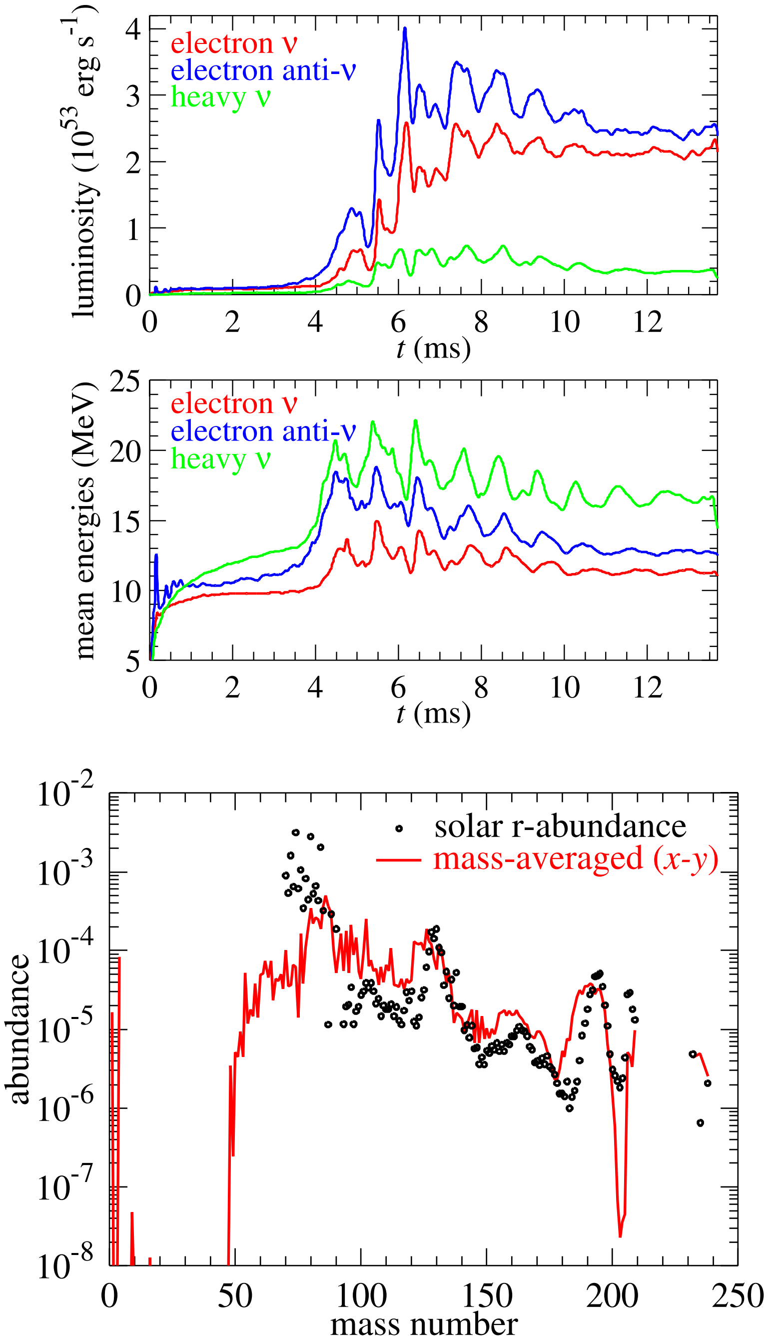
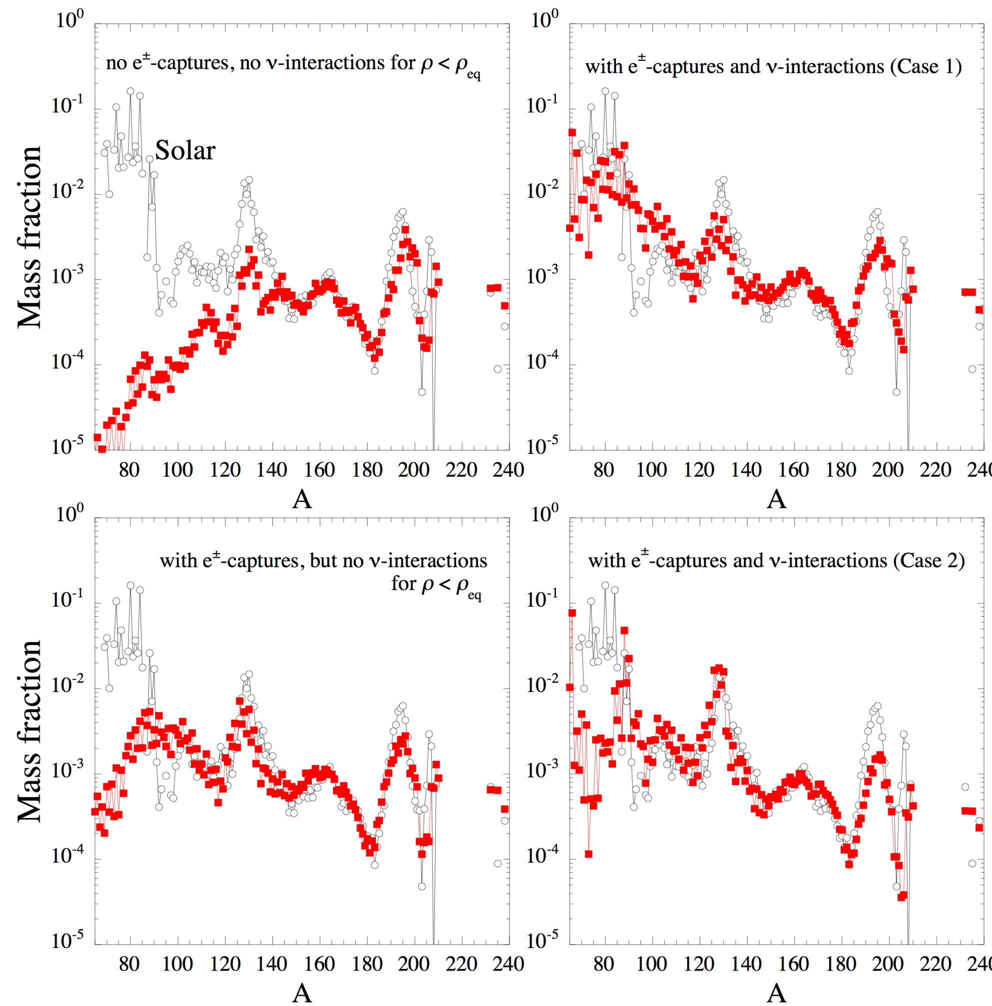
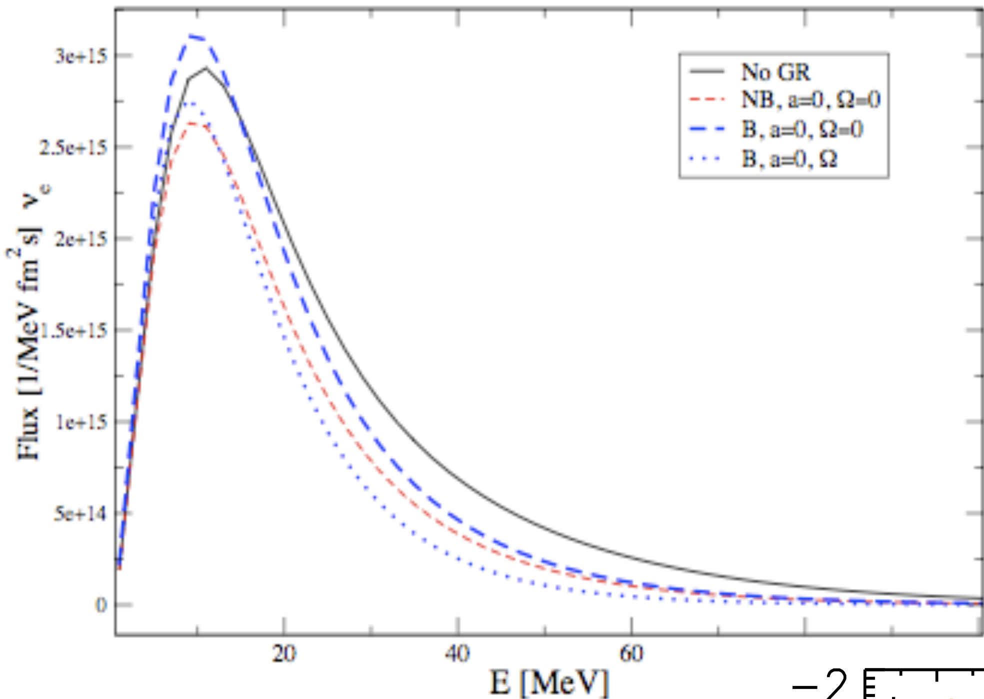


Wanajo+14



Goriely+15

merger AD-BH nucleosynthesis: GR effects



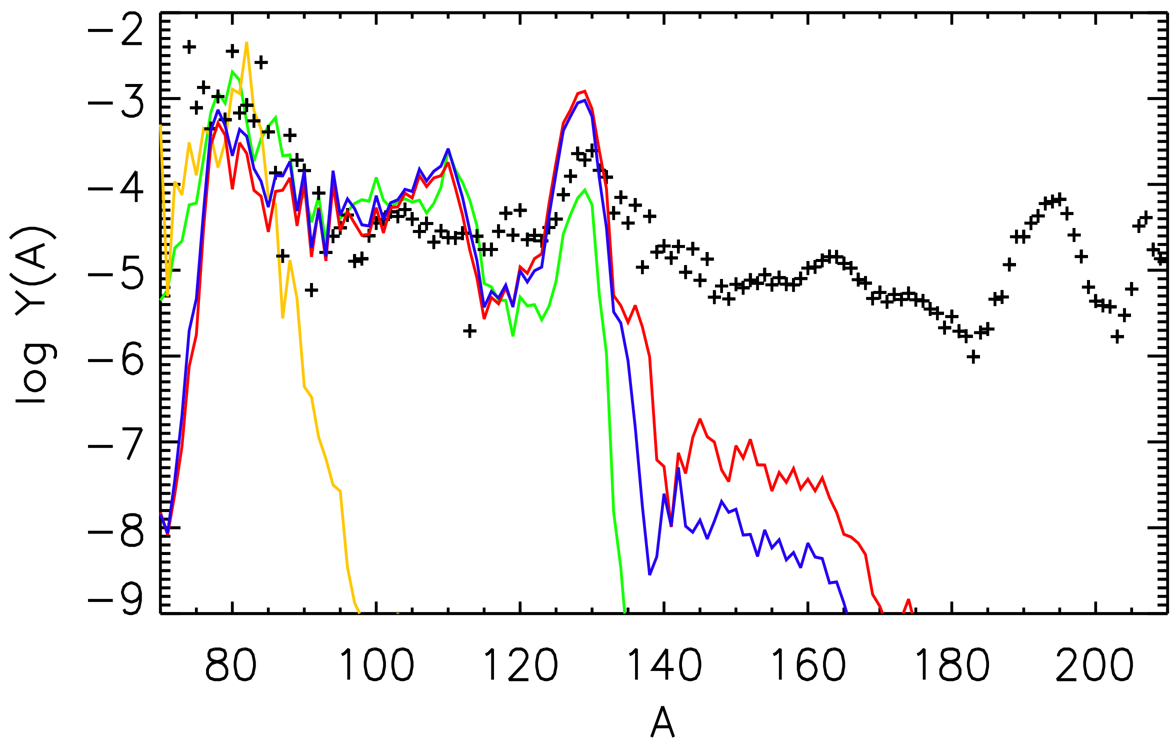
Caballero,
McLaughlin,
Surman 2011

no GR

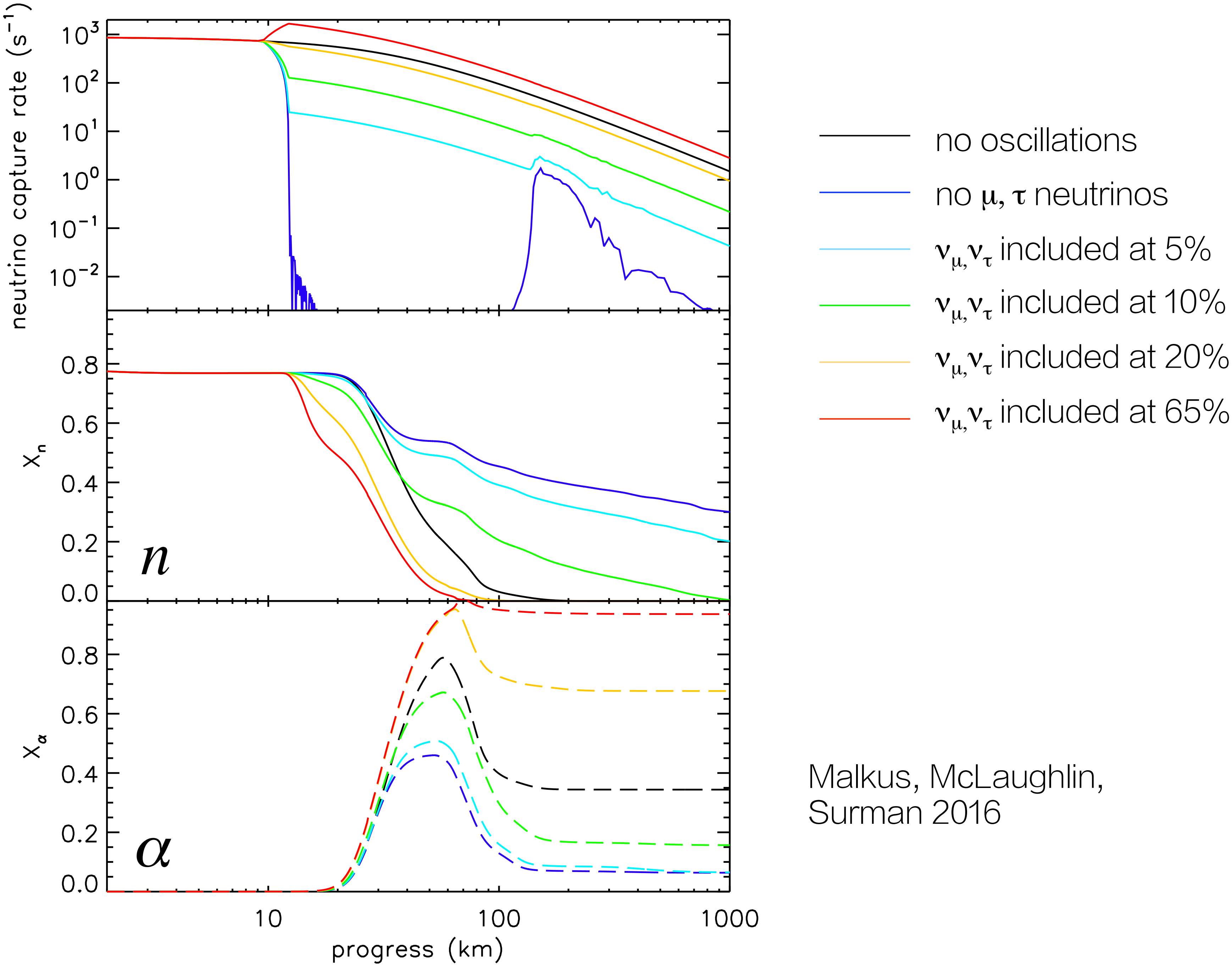
redshift, bending

+ rotation

+ Kerr metric for redshift



merger AD-BH nucleosynthesis: oscillations



Malkus, McLaughlin, Surman 2016

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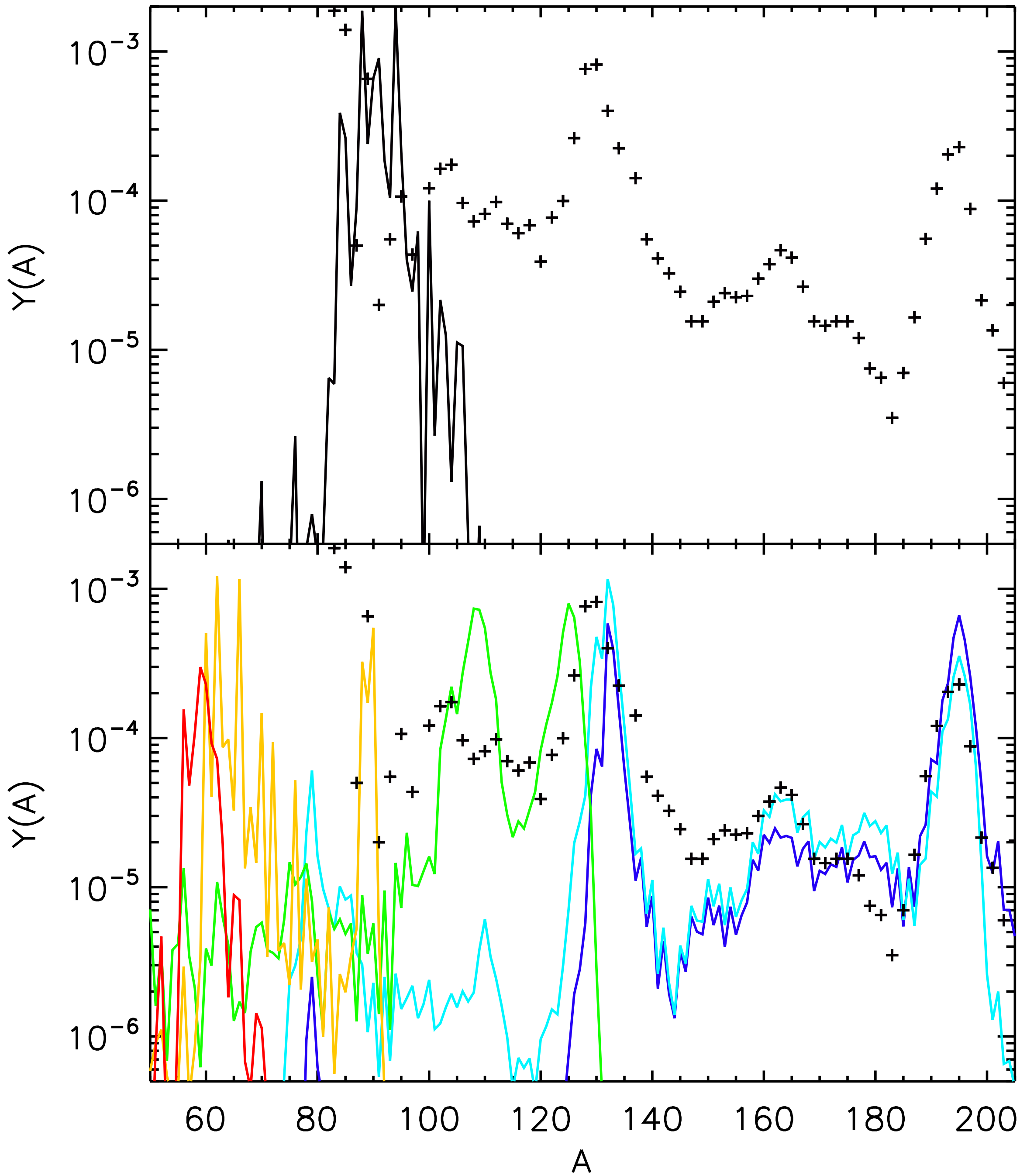
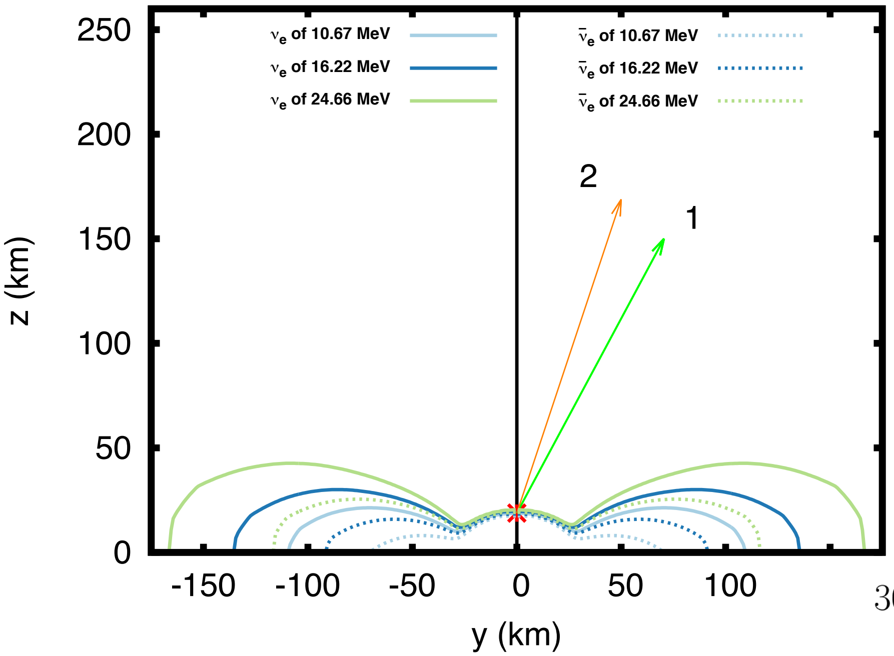
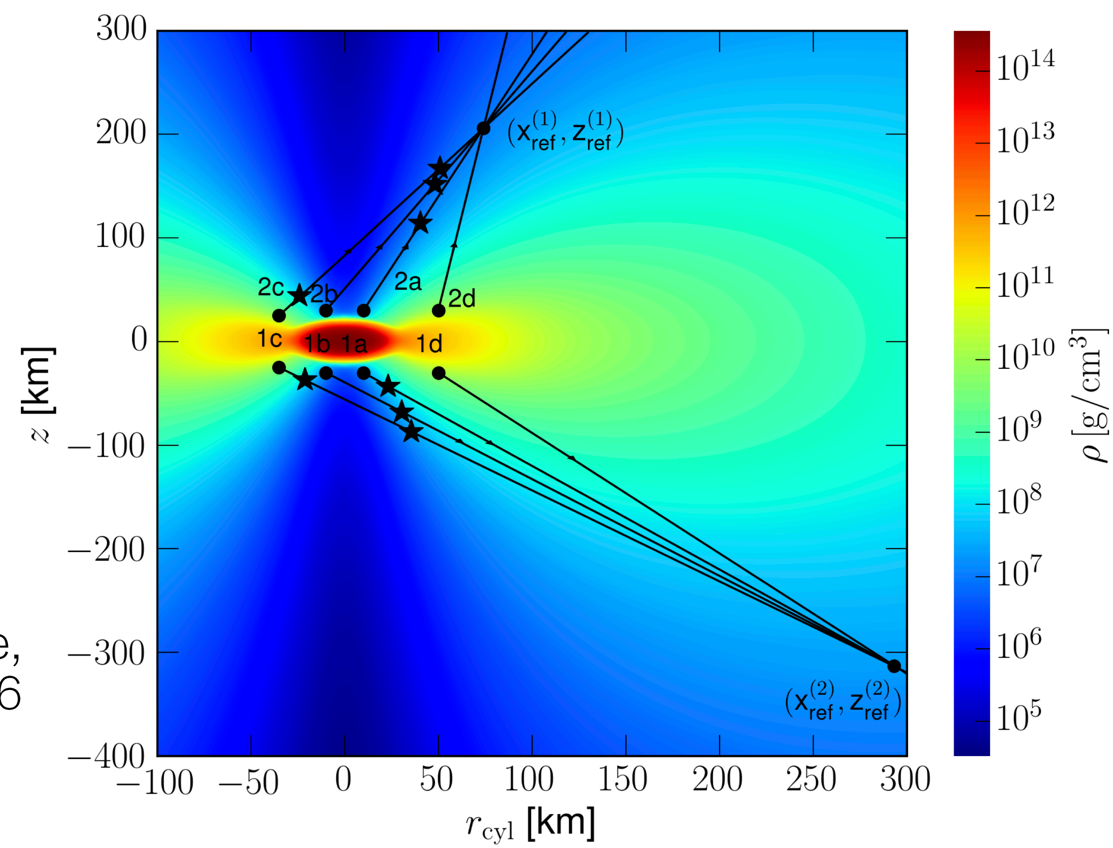


Malkus, McLaughlin, Surman 2016

the MNR above realistic disks



Zhu, Perego, McLaughlin 2016



Frensel, Wu, Volpe, Perego 2016

summary

Neutrinos play a key role in heavy element synthesis in supernovae, and in collapsar and merger accretion disk outflows. Neutrinos can:

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

In order to build a full picture of the origin of heavy elements we need:

- precise neutrino mixing parameters and mass ordering
- as much spectral information as possible from the next galactic supernova/merger