Neutrinos and Supernova Nucleosynthesis

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Union College

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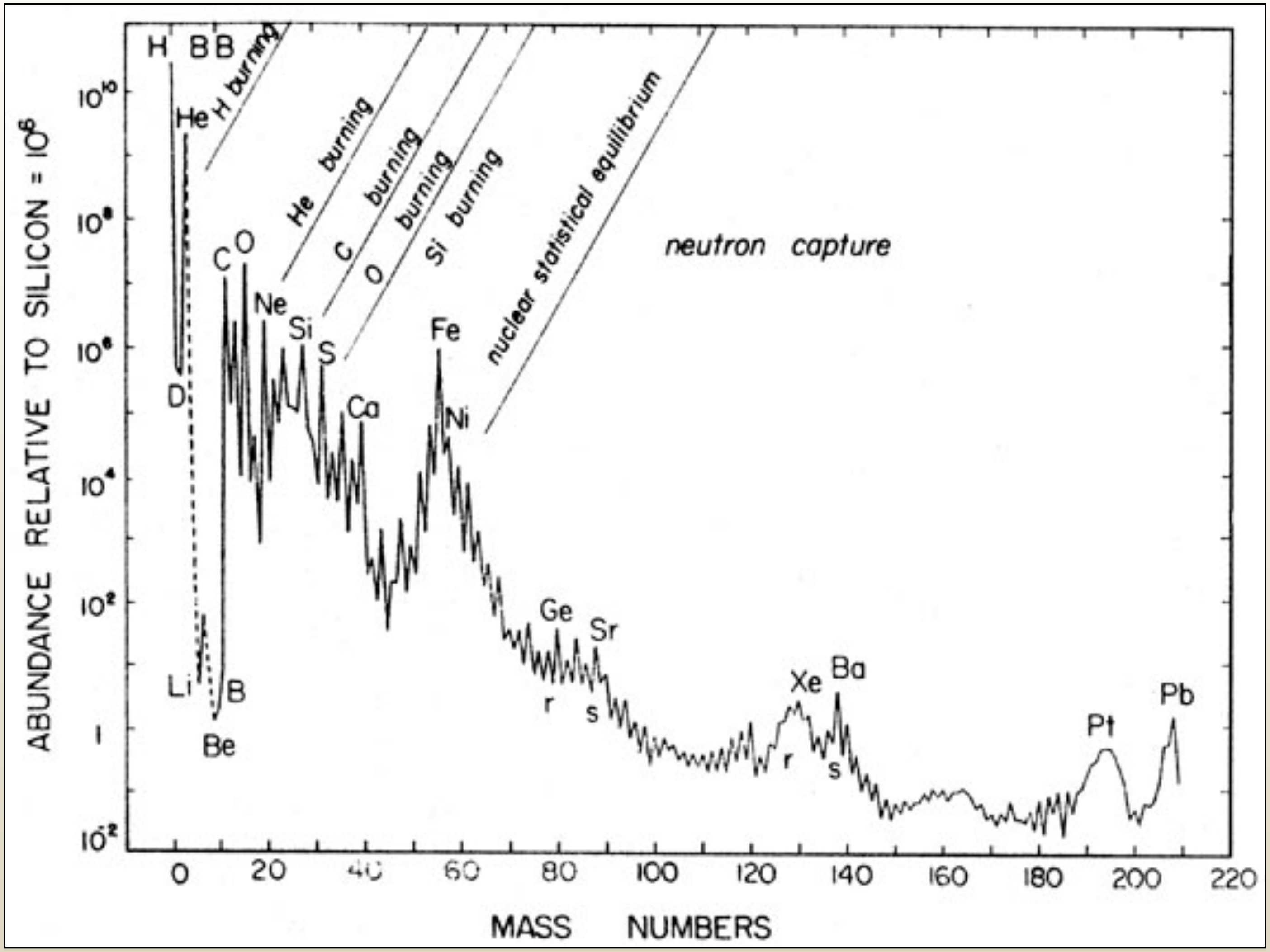
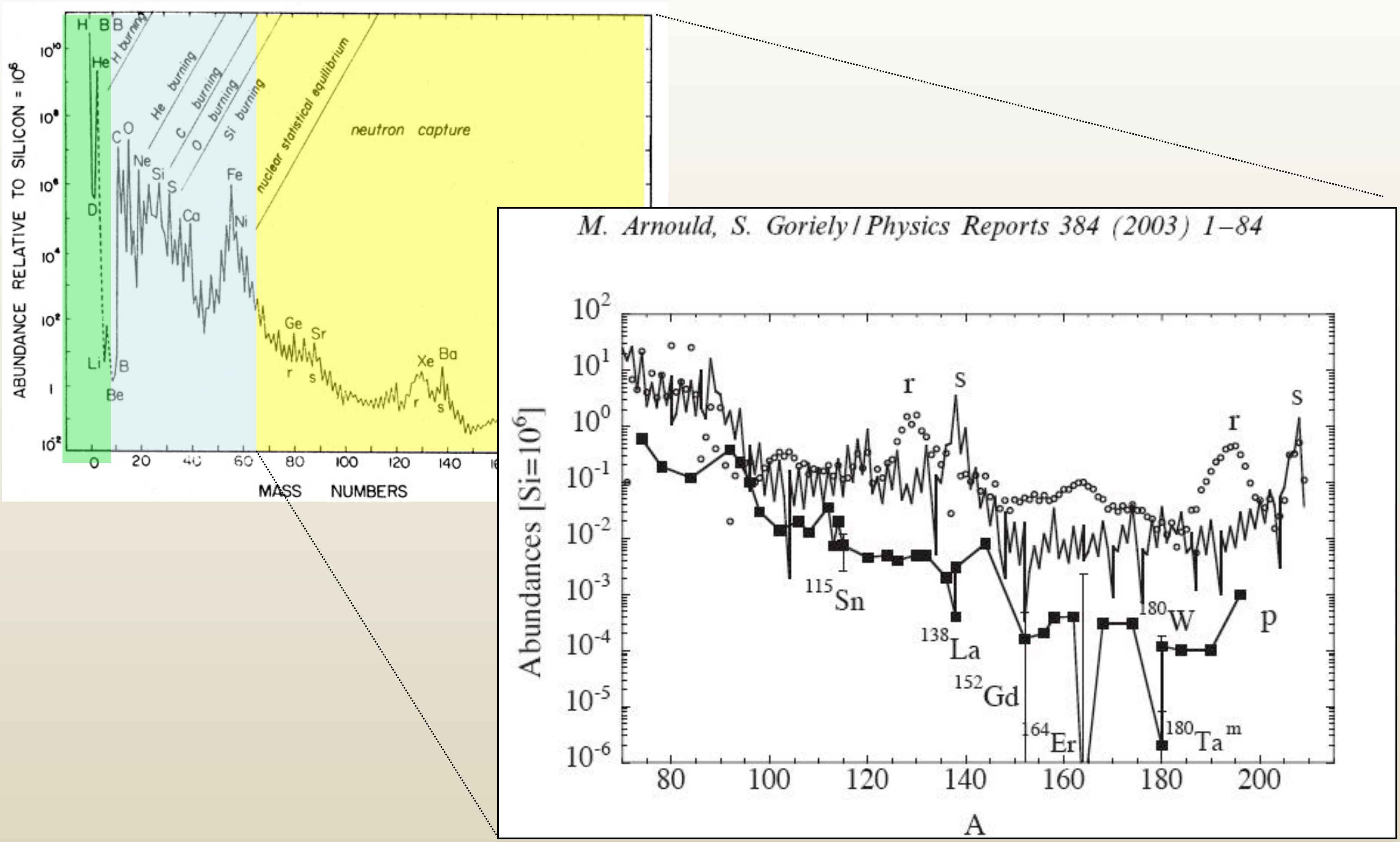
the astrophysical formation of the elements



solar system abundances

heavy element synthesis



heavy element synthesis

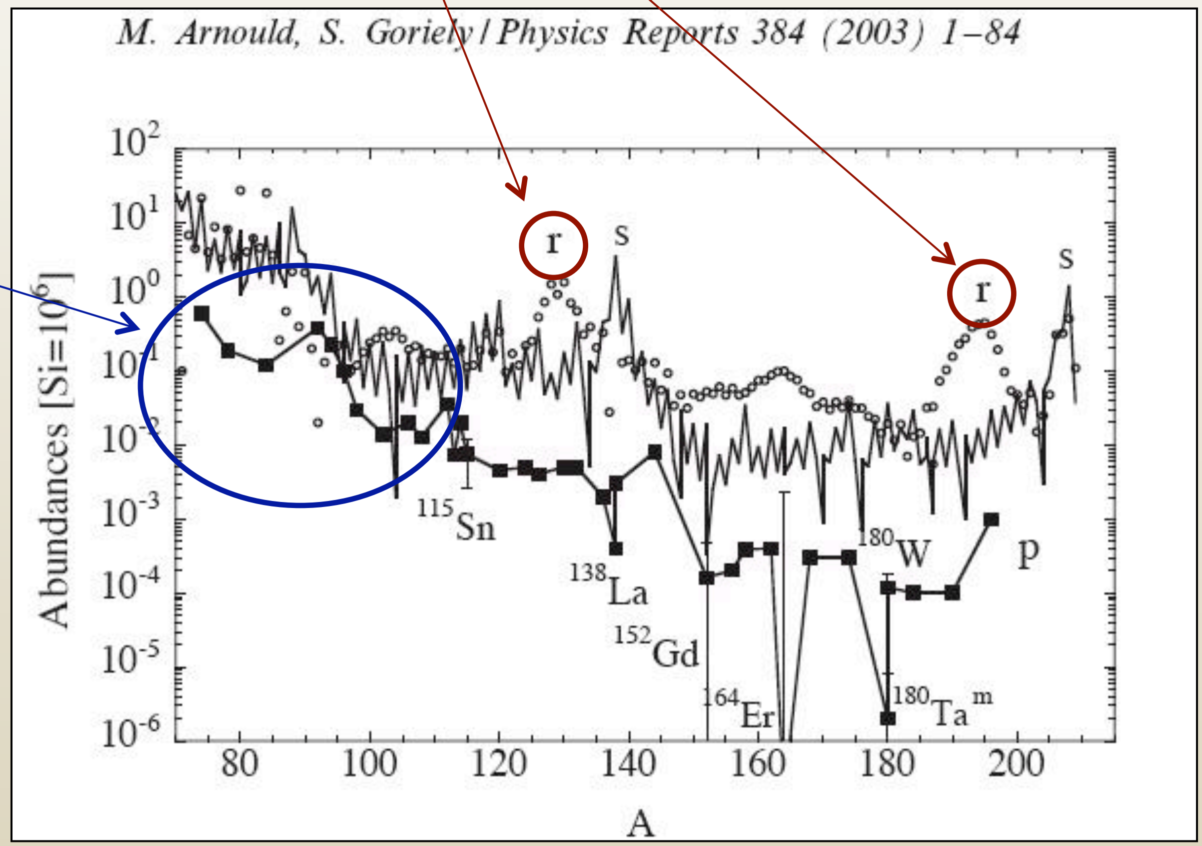
r process: heavy elements built up by rapid neutron captures (n,γ) and beta decays

Burbidge, Burbidge, Fowler, and Hoyle (1957) , Cameron (1957)

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

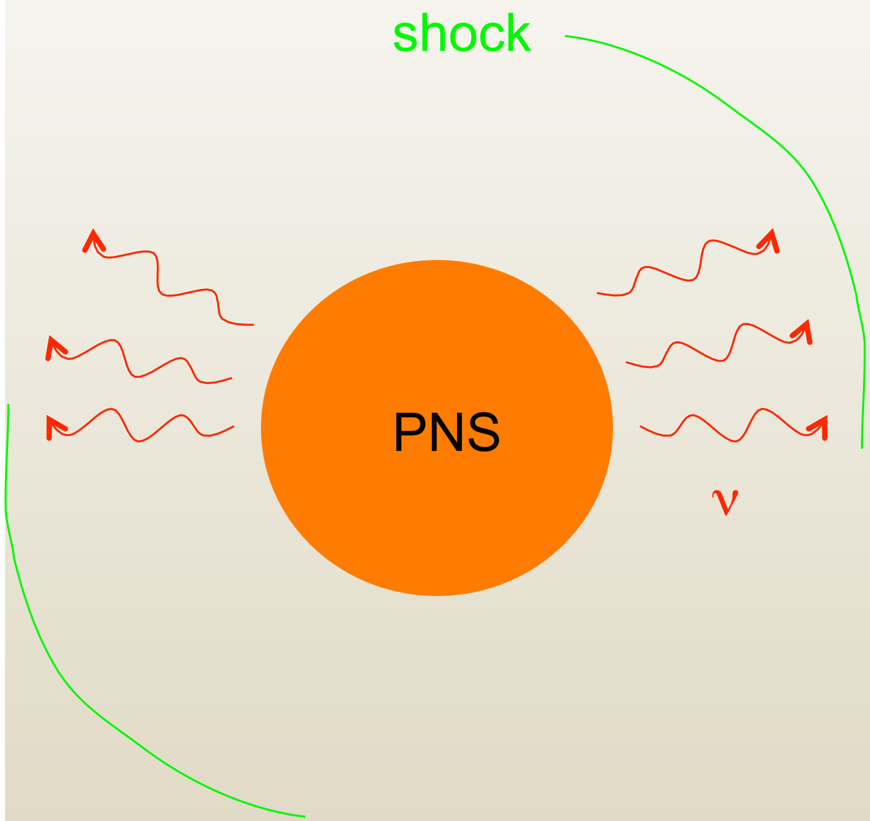
$$p + \bar{\nu}_e \rightarrow n + e^+$$

Frohlich et al (2006) , Pruet et al (2006), Wanajo (2006)

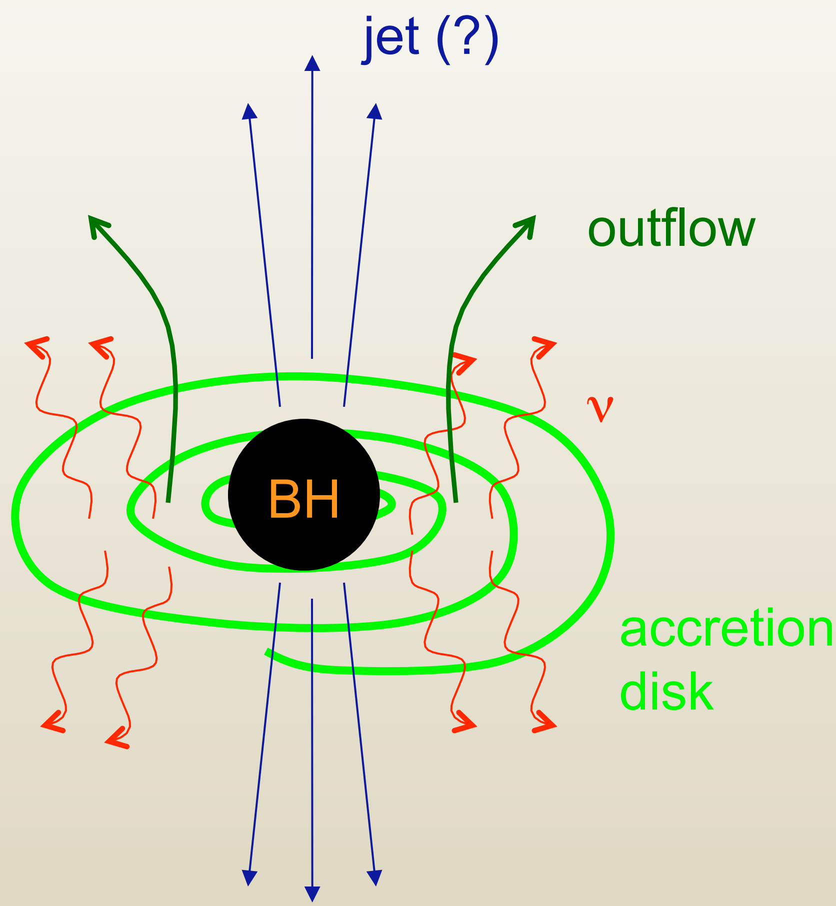


ν-rich environments for heavy element synthesis

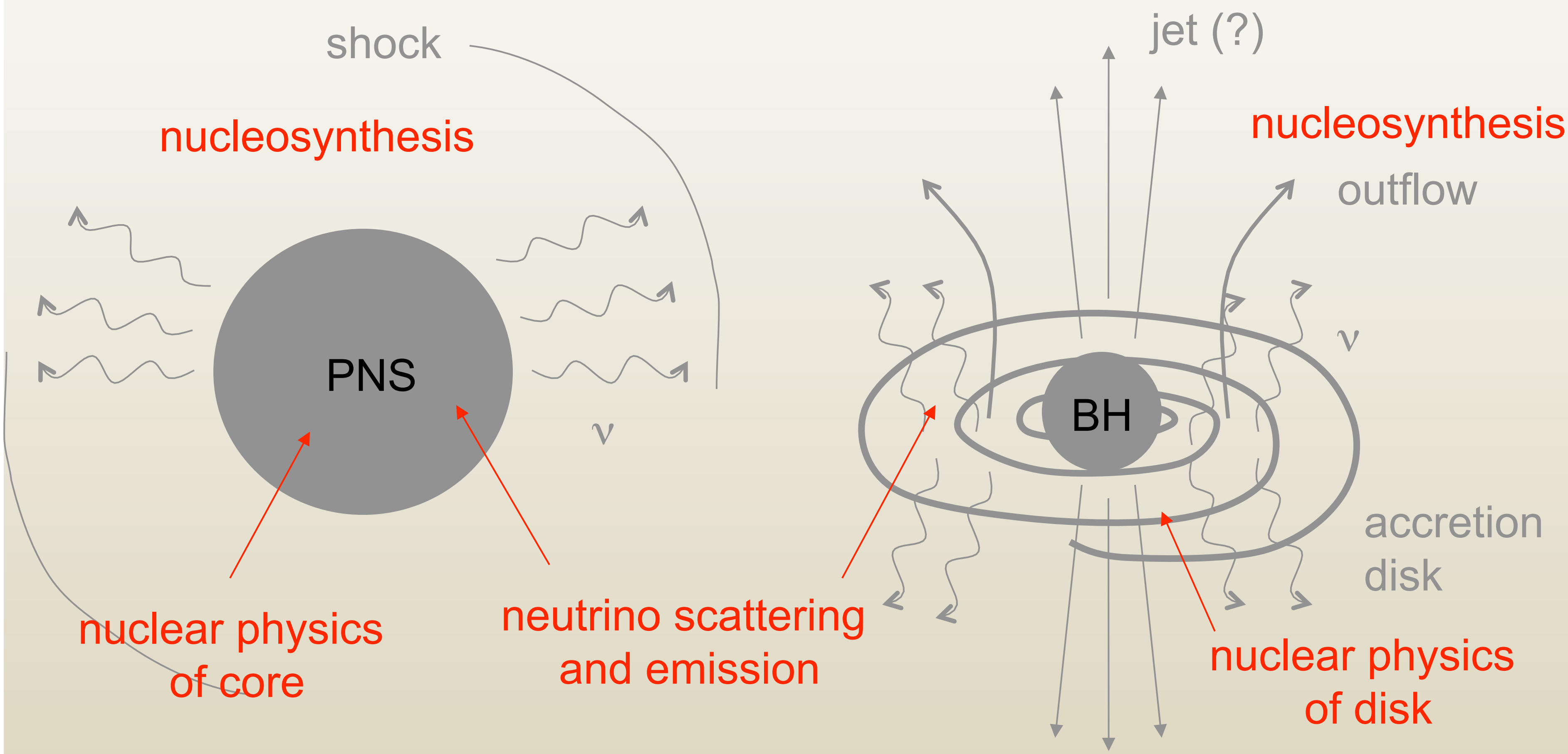
core-collapse supernova



black hole accretion disk



ν-rich environments for heavy element synthesis



stages of heavy element synthesis

(1) free neutrons and protons

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

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

(2) assembly of alpha particles

$$p,\ n \rightarrow \alpha\text{'s} + \text{excess } p \text{ or } n$$

(3) assembly of seed nuclei

$$\alpha\text{'s} + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei } + \text{ remaining } p \text{ or } n$$

(4) free nucleon capture on seeds

$$\text{iron peak nuclei } + \text{ remaining } p \text{ or } n \rightarrow \text{heavy nuclei}$$

stages of heavy element synthesis | impact of ν

(1) free neutrons and protons

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

ν can set the neutron to proton ratio, n/p

n/p determines the subsequent nucleosynthesis

(2) assembly of alpha particles

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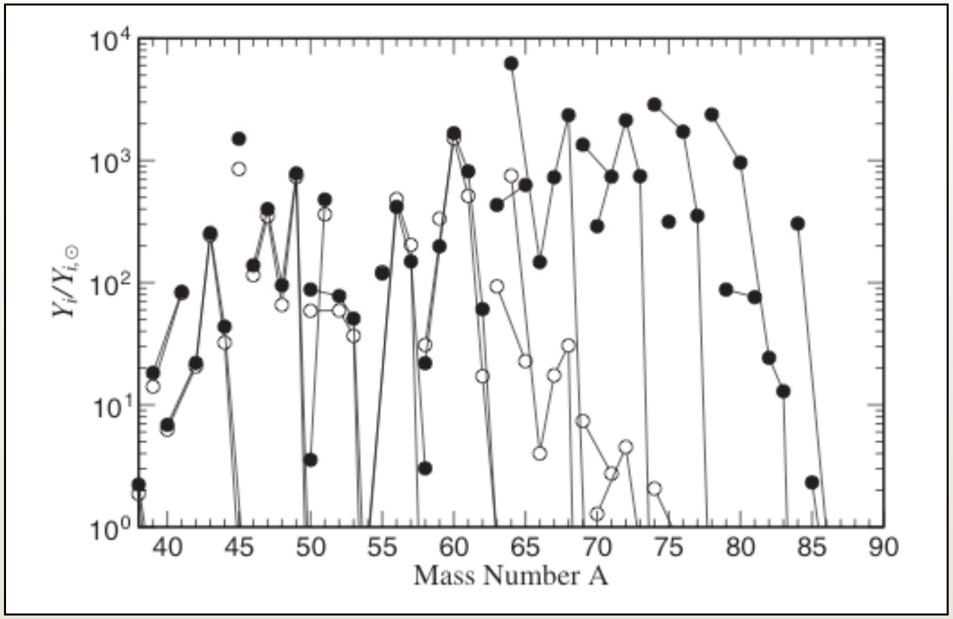
ν can continue to convert the excess *p* or *n*

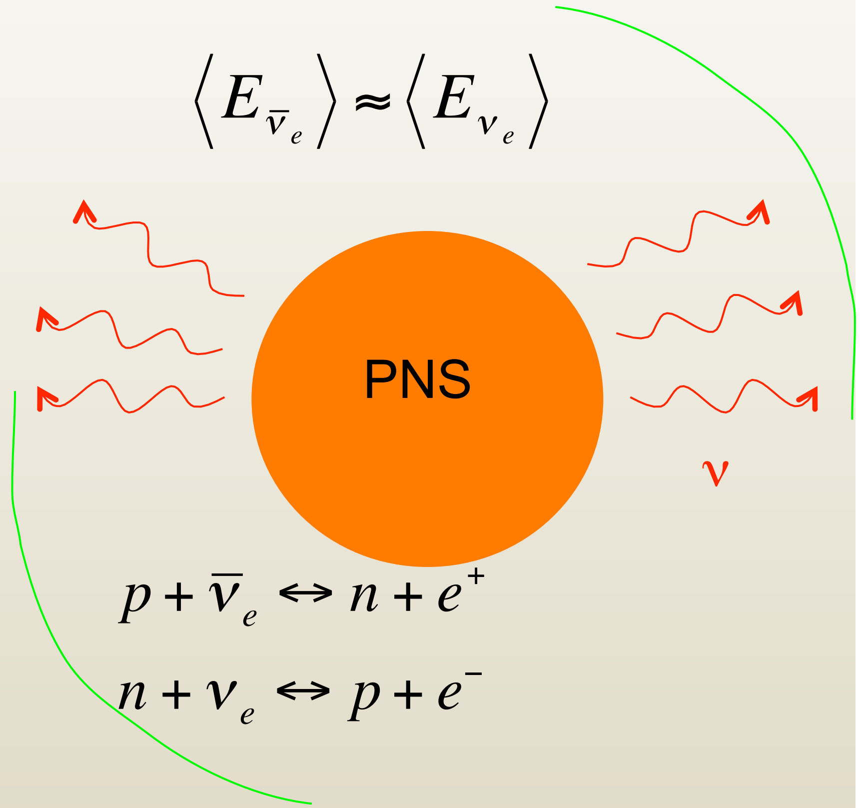
this alters the free nucleons available for capture onto seeds

the early supernova neutrino-driven wind



from Frohlich et al (2006)

$$\langle E_{\bar{\nu}_e} \rangle \approx \langle E_{\nu_e} \rangle$$

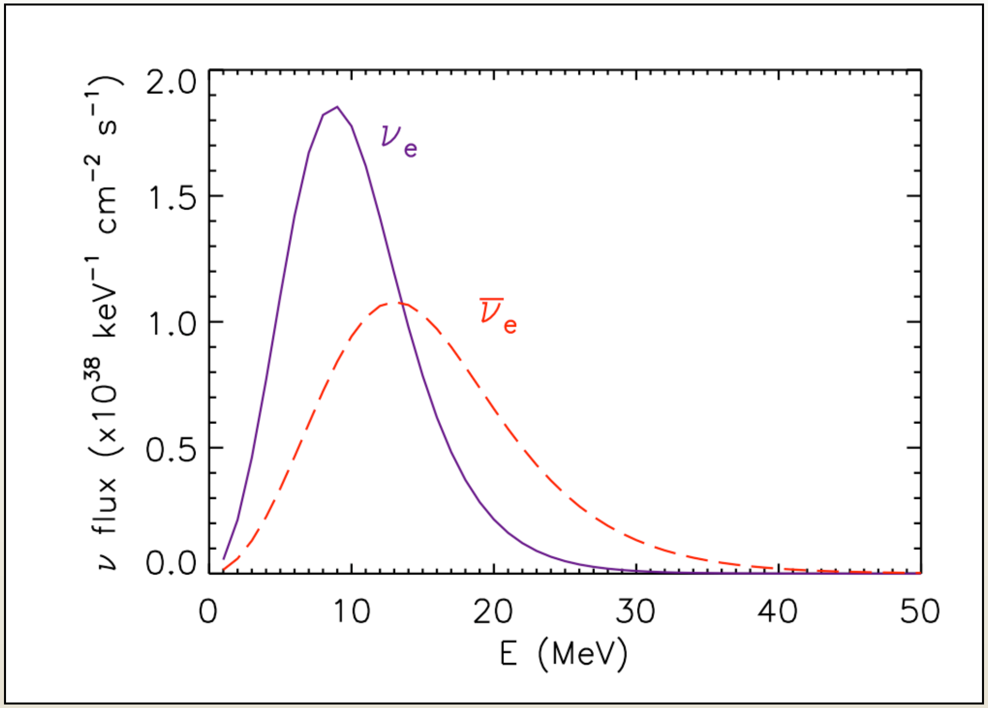


$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

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

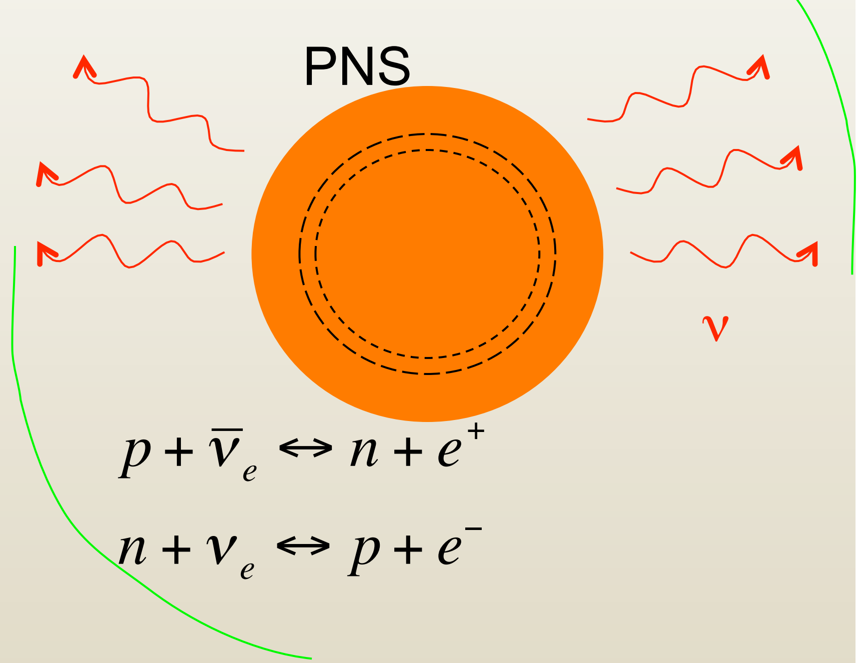
$p, n \rightarrow \alpha, p \rightarrow$ seed nuclei + $p \rightarrow \nu p$ process

the late-time supernova neutrino-driven wind



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

$$\langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$



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

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

p, *n* → α, *n* → seed nuclei + *n* → *r* process

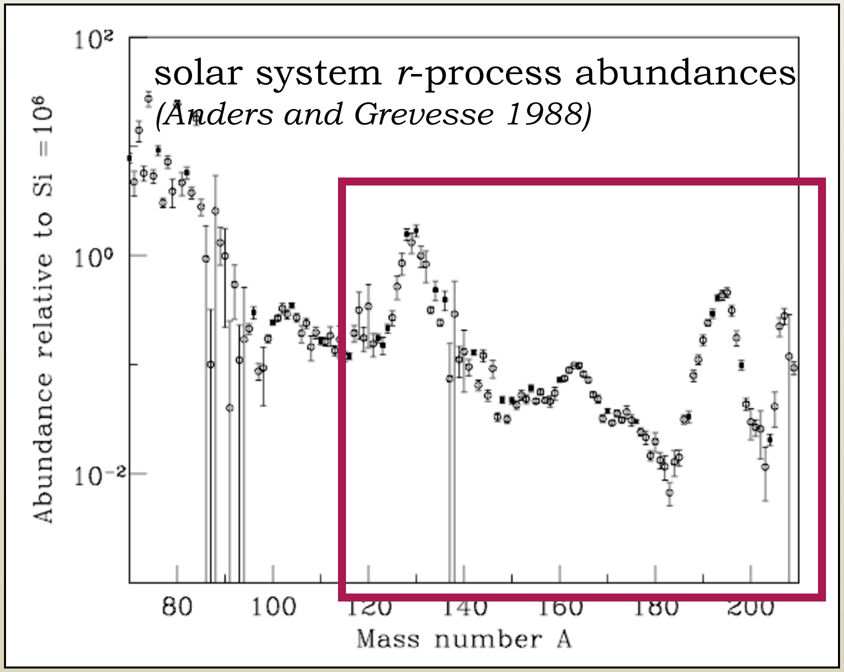
a supernova neutrino-driven wind *r* process?

Initial studies were very promising….

e.g., Meyer et al (1992), Woosley et al (1994)

…but it was found to be more difficult to produce the requisite conditions than first thought

e.g., 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), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), etc., etc.



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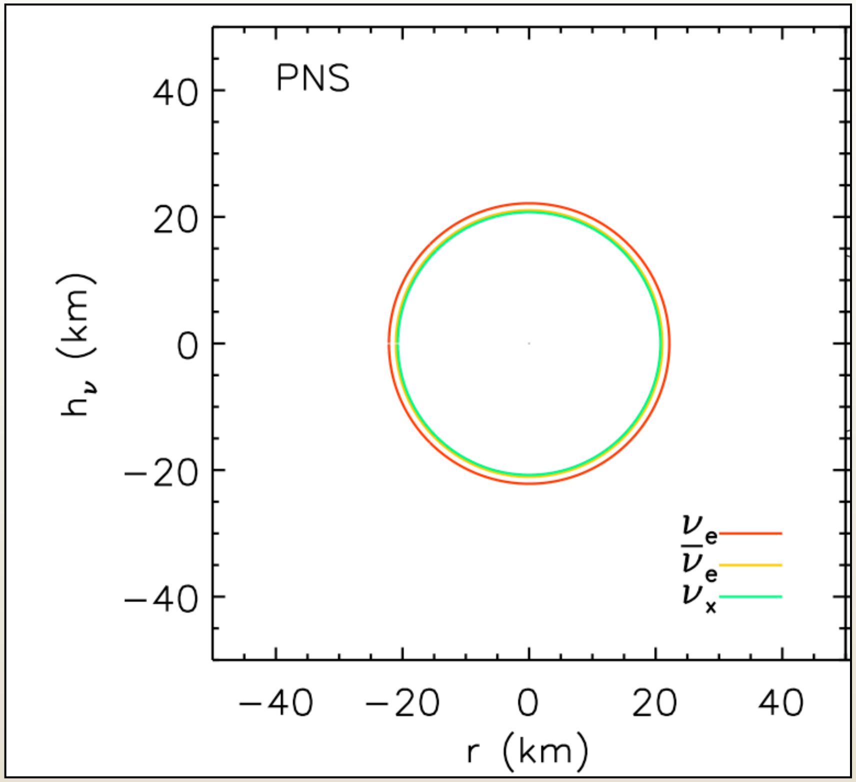
The most recent calculations of proto-neutron star evolution predict no robustly neutron-rich outflows

Huedepohl et al (2010), Fischer et al (2010)

neutrino oscillations and the *r* process



McLaughlin and Surman (2007)

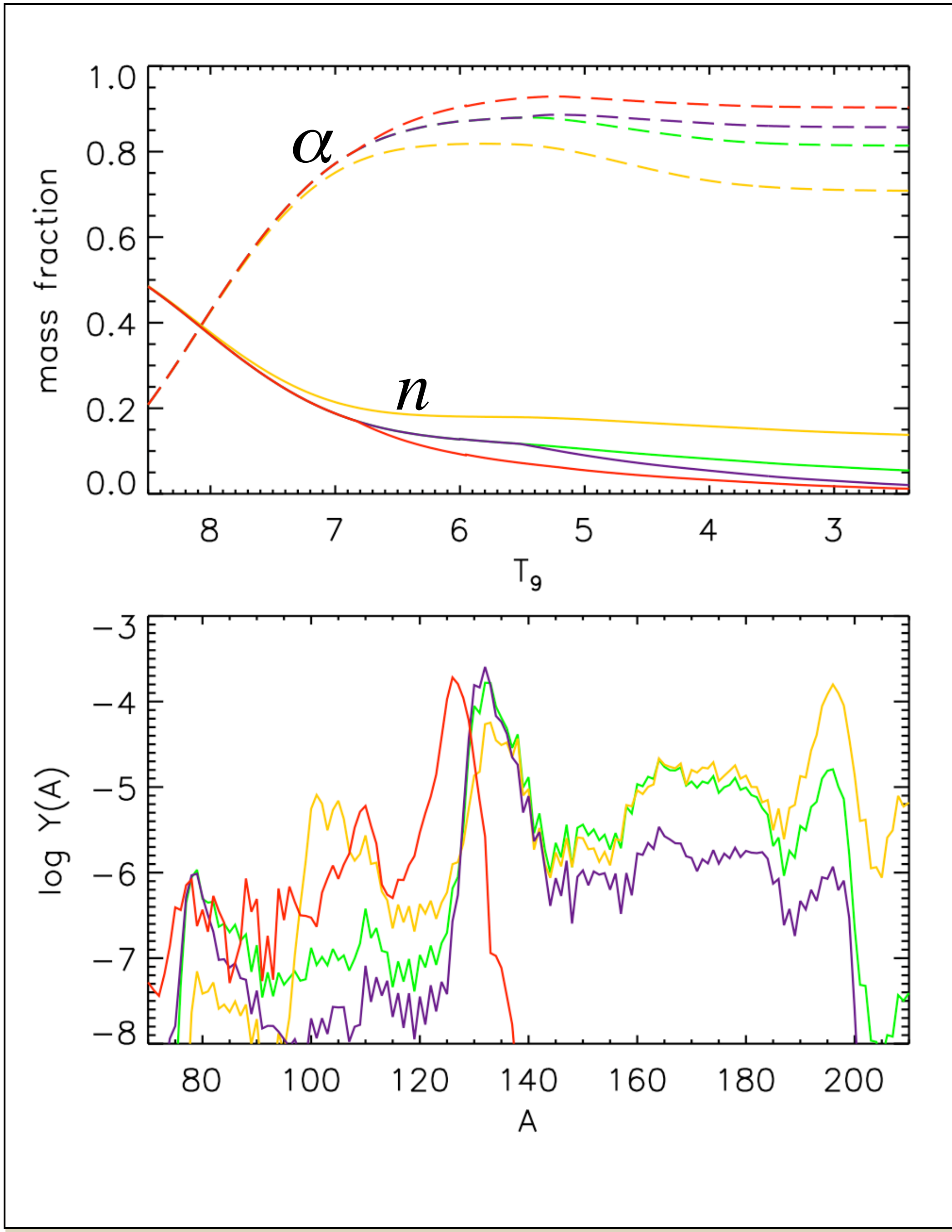
Hydrodynamic conditions required to build the heaviest nuclei are difficult to achieve, in part due to the neutrino-induced alpha effect.

In the standard SNe energy heirarchy, neutrino oscillations only enhance the role of neutrinos.

$$\langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

While standard MSW oscillations occur at densities too low to influence the *r* process, neutrino self interactions can cause neutrinos to flavor transform much closer to the PNS *see, e.g., the work of Pantaleone, Samuel, Qian and Fuller, Balantenkin and Yuksel, Dasgupta, Dighe, Raffelt, Lisi, Mirizzi, Volpe, etc.*

a toy model

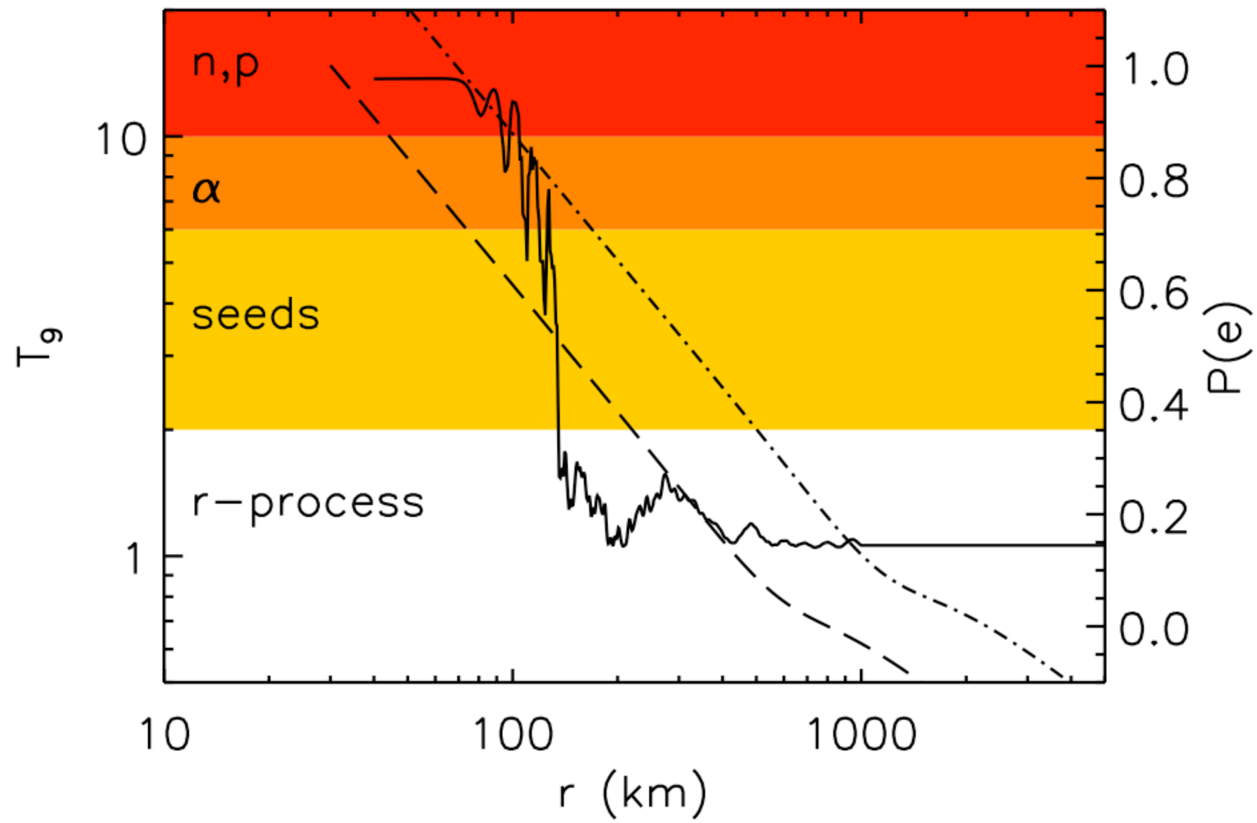


- No ν for $T < 9\times10^9$ K
- No oscillations
- Test swap at seed assembly
- Test swap at alpha assembly

$f_{\nu_e}(E)$ replaced by $f_{\nu_\mu}(E)$

Duan, Friedland, McLaughlin, & Surman, J Phys G, 38, 035201 (2011)

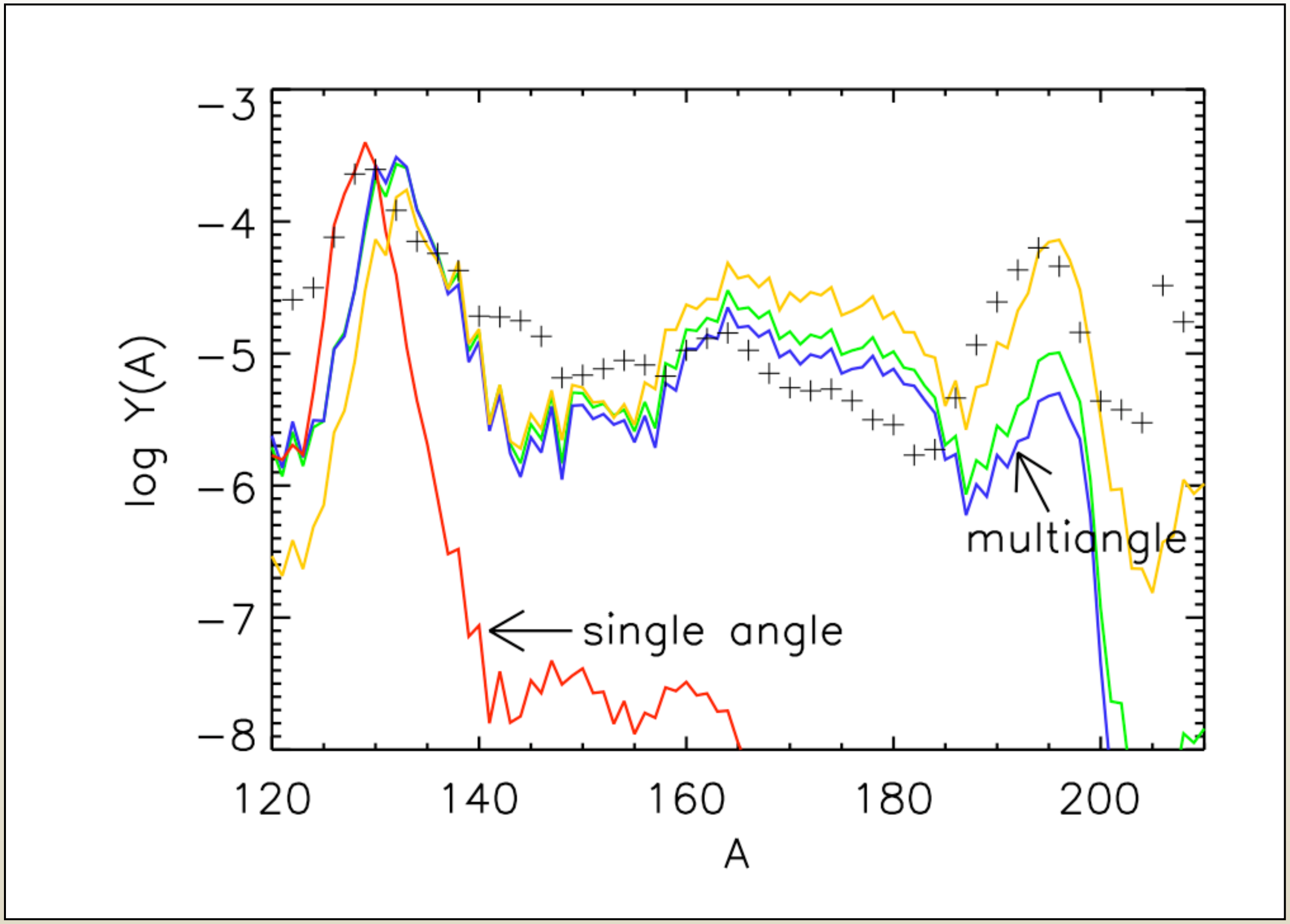
where does each nucleosynthesis stage take place?



Duan, Friedland, McLaughlin, & Surman, J Phys G, 38, 035201 (2011)

ν oscillation calculation by Huaiyu Duan and Alex Friedland
(as in hep-ph/10062359)

a full neutrino oscillation + *r*-process calculation



No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

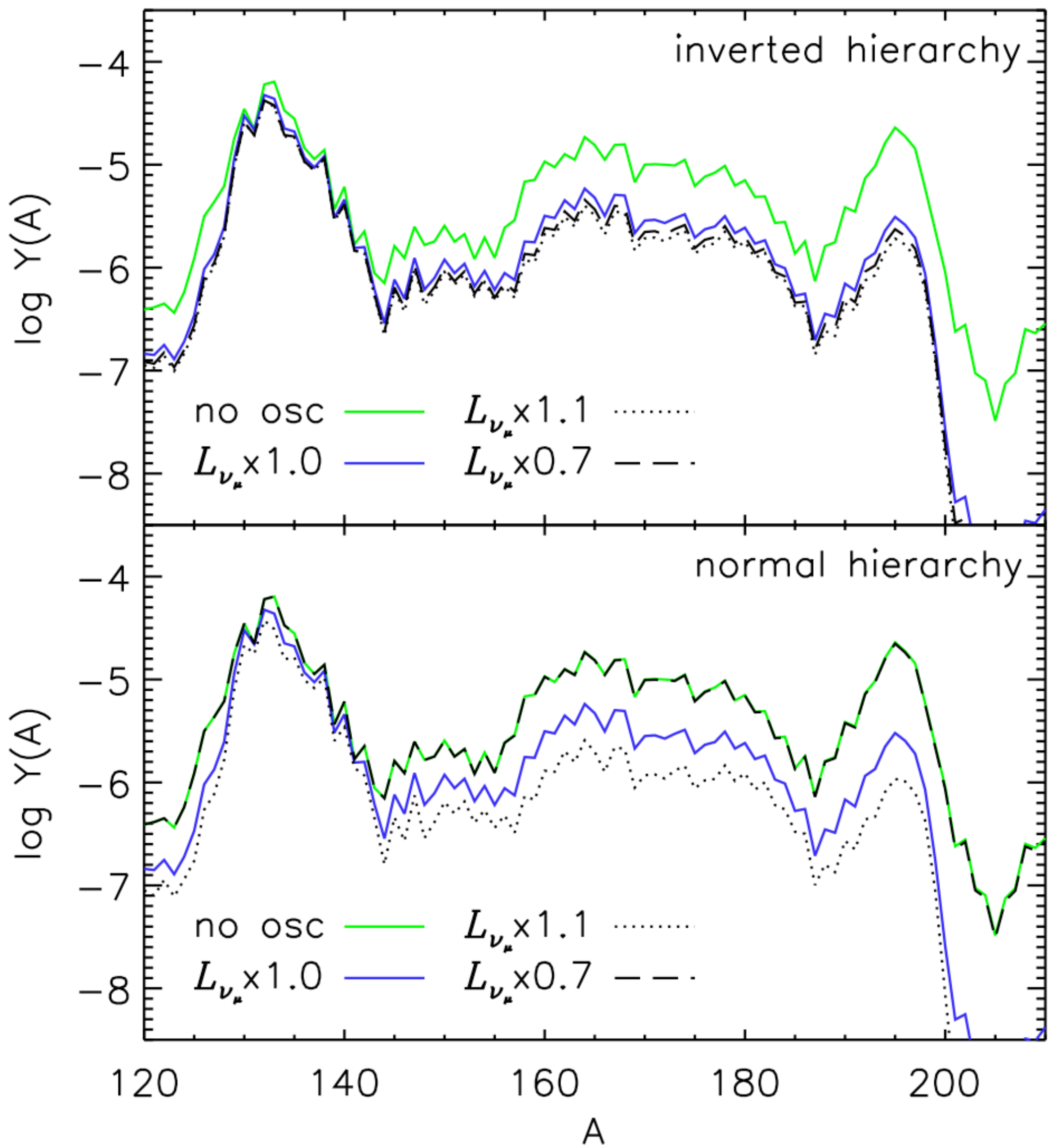
Single angle ν oscillation calculation

$s/k = 200$

$\tau = 18$ ms

Duan, Friedland, McLaughlin, & Surman, J Phys G, 38, 035201 (2011)

mass hierarchy



Duan, Friedland, McLaughlin, & Surman, J Phys G, 38, 035201 (2011)

$s/k = 300$

$\tau = 35$ ms

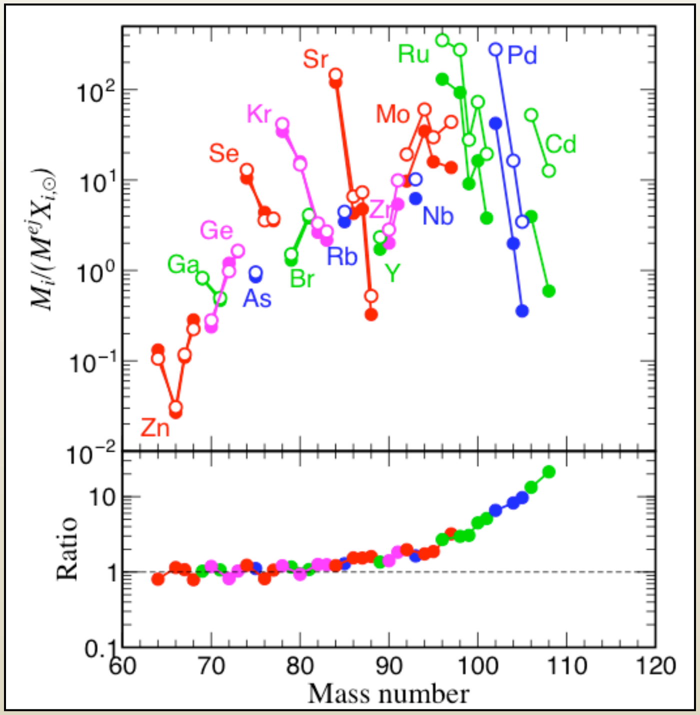
collective oscillations and supernova nucleosynthesis

Supernova nucleosynthesis calculations cannot (safely) ignore neutrino oscillations

⇒ act only increase the importance of neutrino interactions

⇒ important for *νp* process as well as the *r* process

Martinez-Pinedo et al (2011)



Correctly predicting the radius at which the flavor transformations occur is of key importance for the nucleosynthesis - this requires a multiangle ν oscillation calculation

black hole accretion disk (AD-BH) outflows

The AD-BH can be produced by:

- stellar collapse

  Woosley (1993), Paczynski (1993), MacFadyen and Woosley (1999)

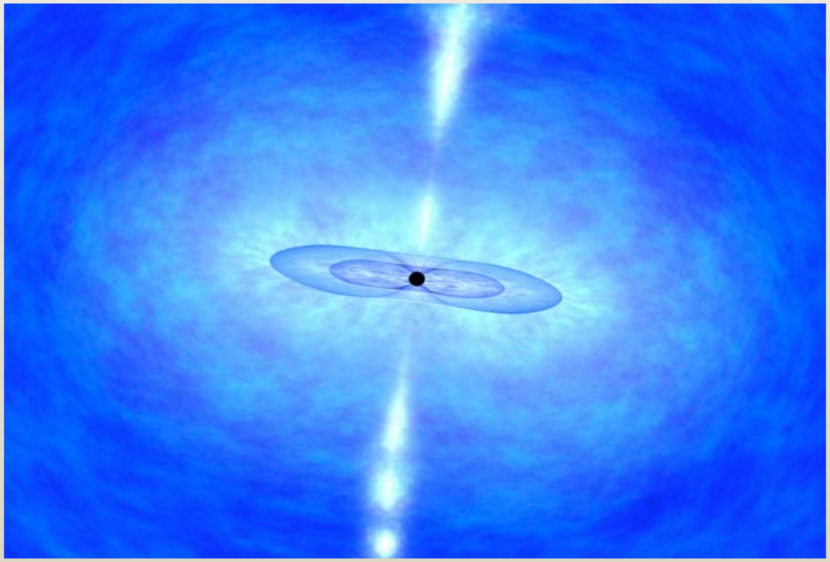
- compact object merger

  Paczynski (1986), Eichler et al (1989), Janka et al (1999), Rosswog & Leibendoerfer (2003)

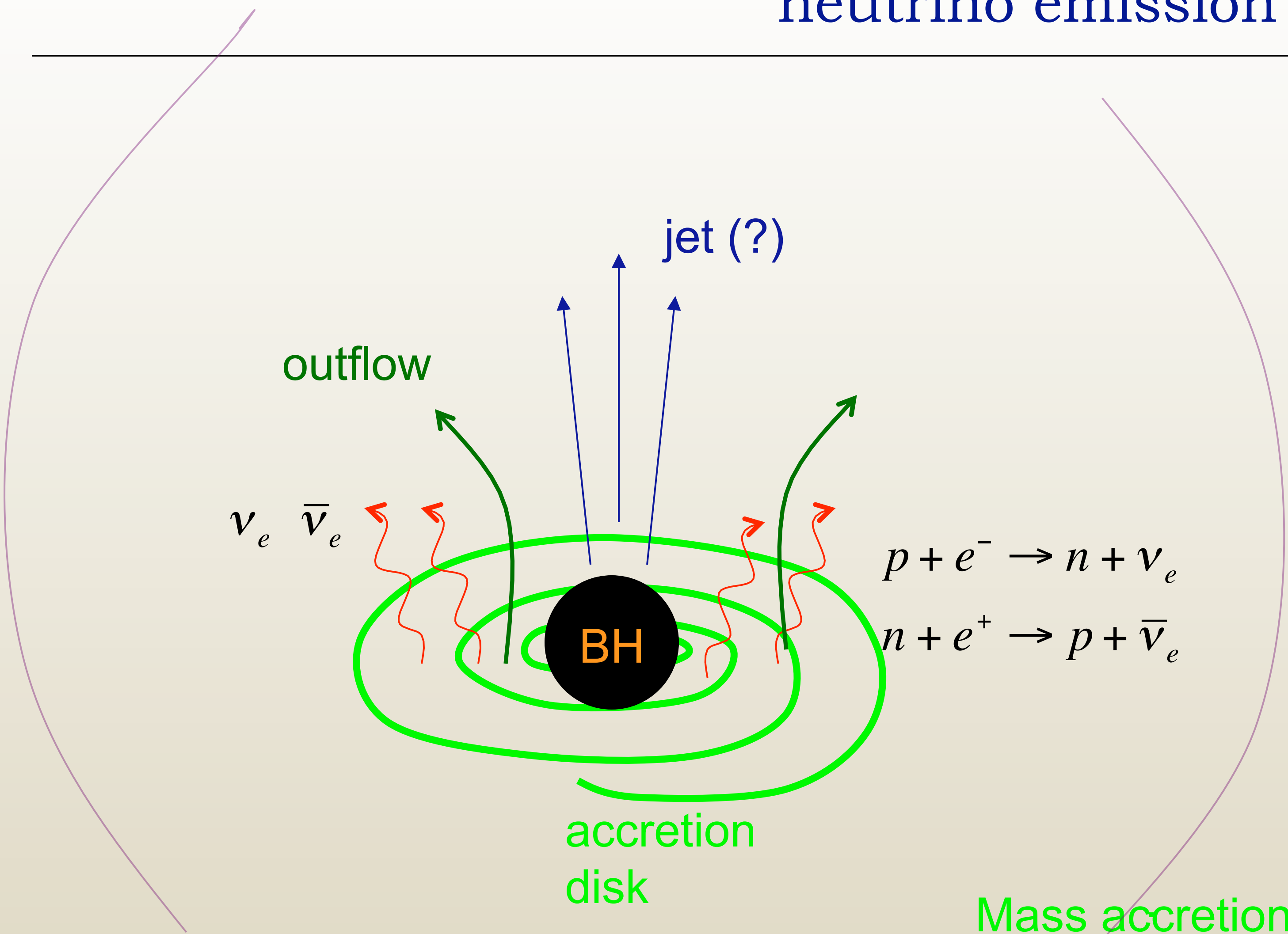
The nucleosynthesis produced in baryon-rich outflows from the AD-BH is in a large part determined by the neutrino emission from the disk

AD-BH disk outflows have been studied in, e.g.,

Pruet, Thompson, & Hoffman (2004), Surman & McLaughlin (2004), Surman, McLaughlin, & Hix (2006), Metzger, Thompson, & Quataert (2008), Nakamura et al (2011)



neutrino emission from AD-BH



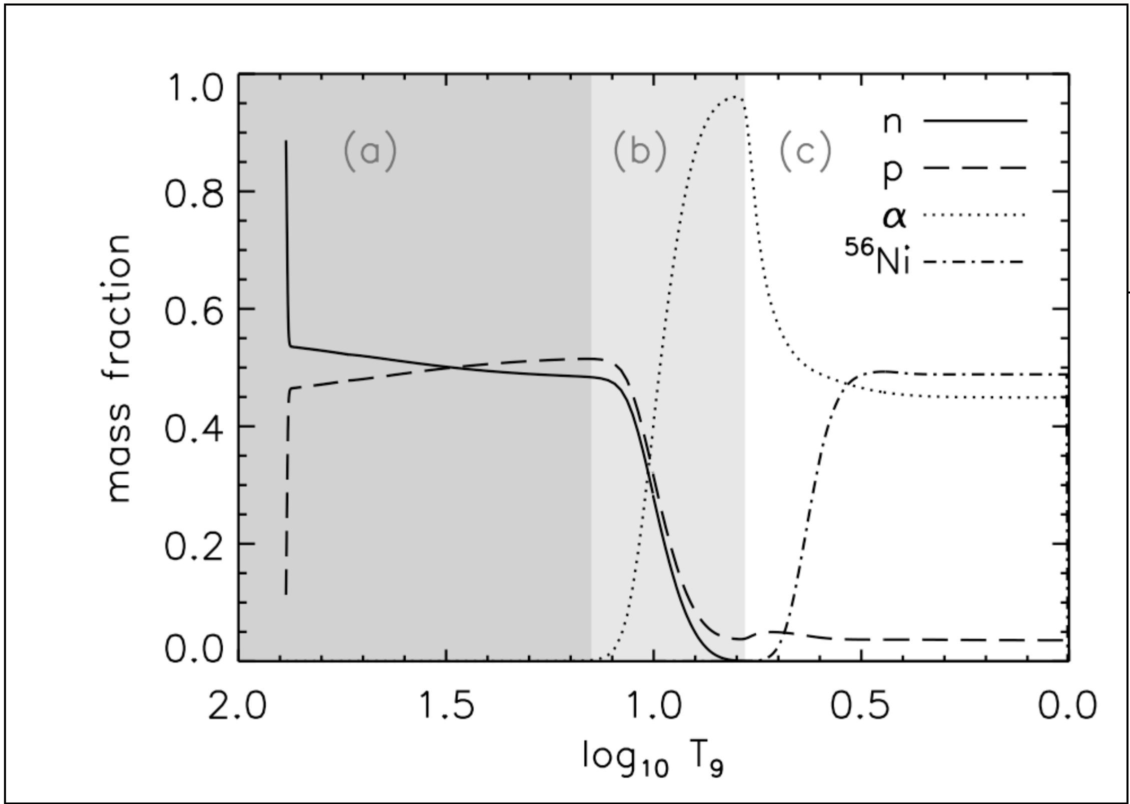
$$p + e^- \rightarrow n + \nu_e$$

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

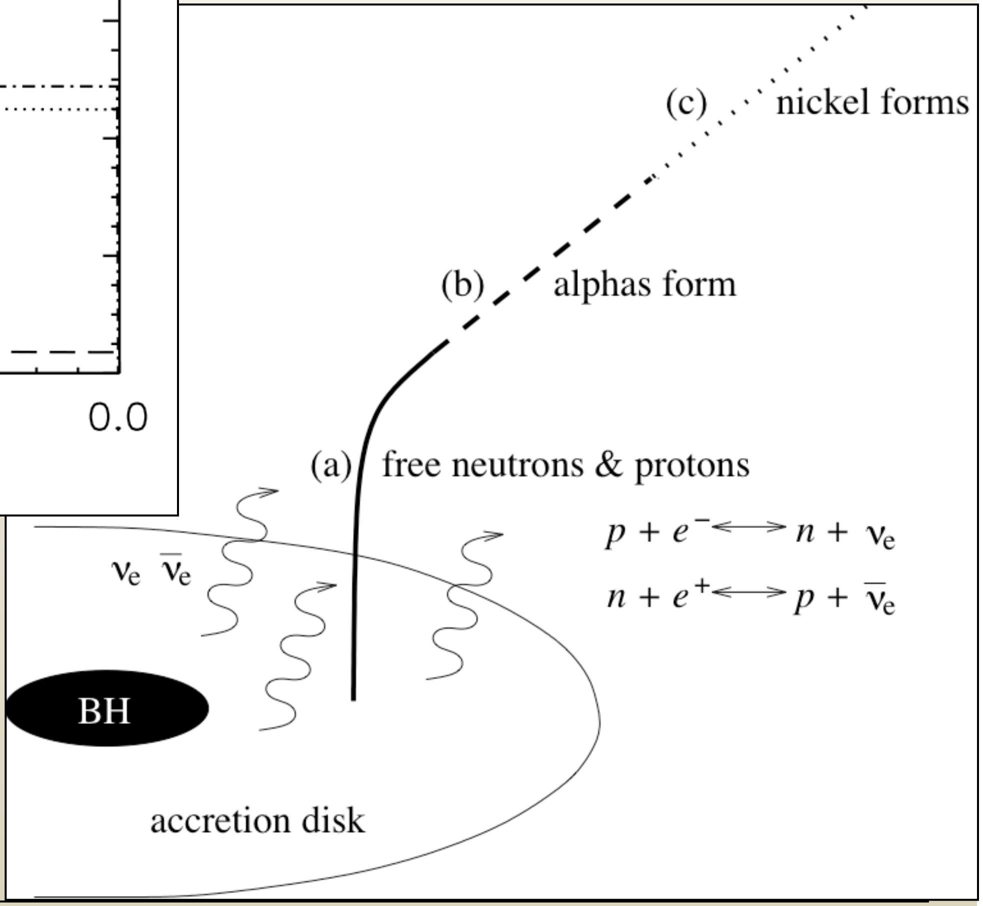
Mass accretion rate

$$\dot{m} \sim 0.001 - 10$$

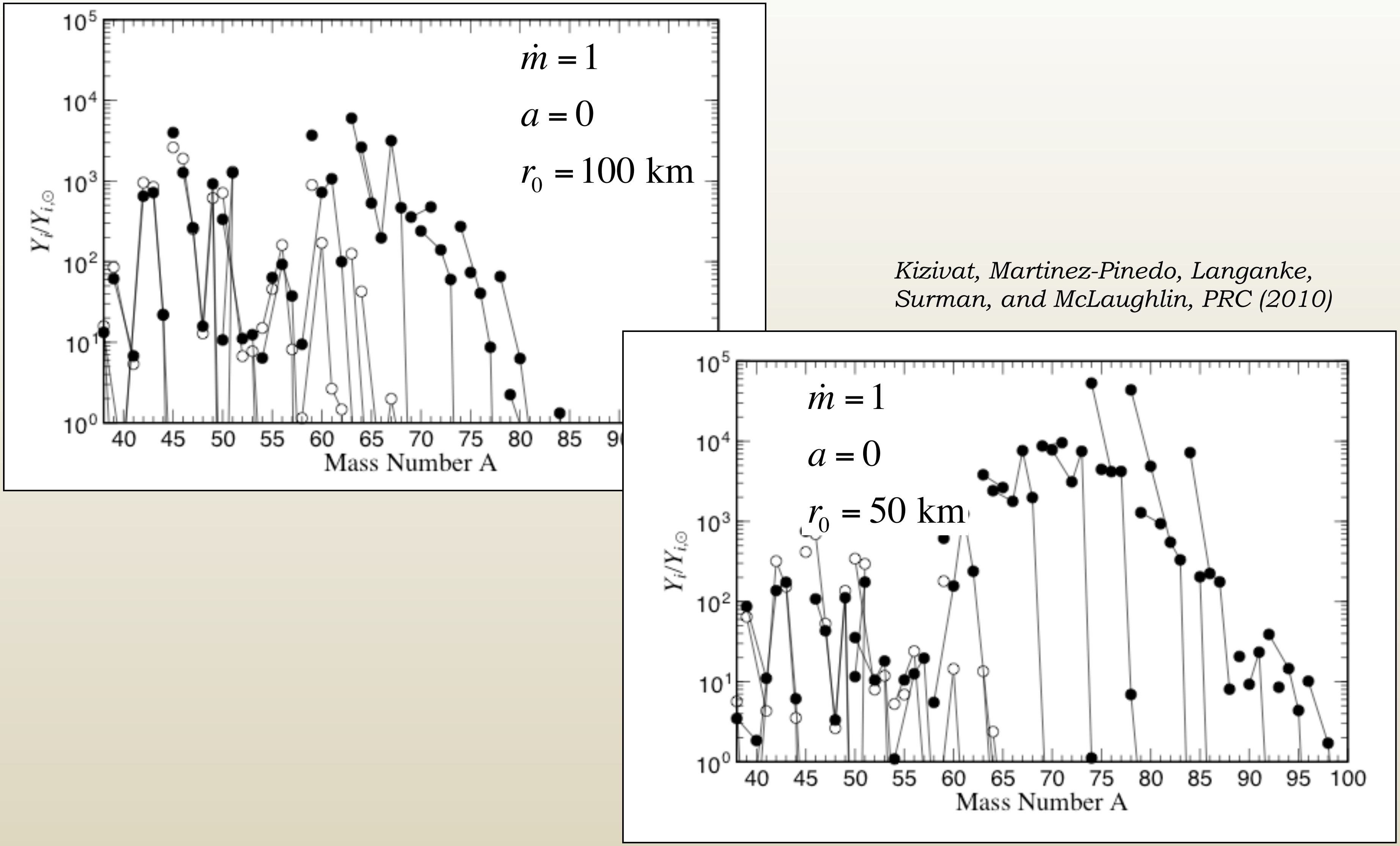
nucleosynthesis from low $\dot{m}$ AD-BHs: ^{56}Ni



Surman, McLaughlin, and Sabbatino, in preparation (2011)

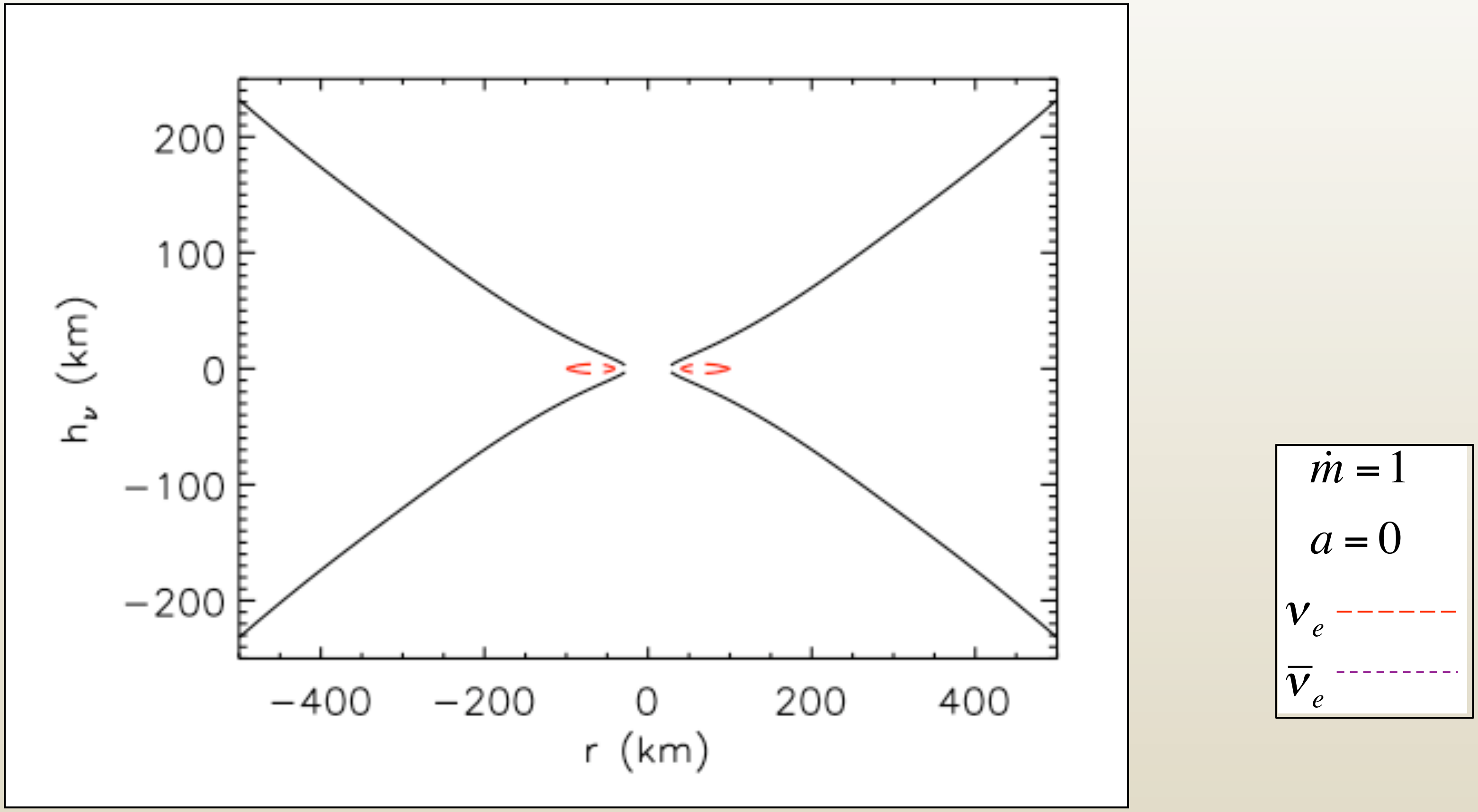


nucleosynthesis from low $\dot{m}$ AD-BHs: νp process



Kizivat, Martinez-Pinedo, Langanke, Surman, and McLaughlin, PRC (2010)

AD-BH neutrino decoupling surfaces



Disk model from Chen and Beloborodov (2008),
neutrino decoupling surface calculation by R Surman

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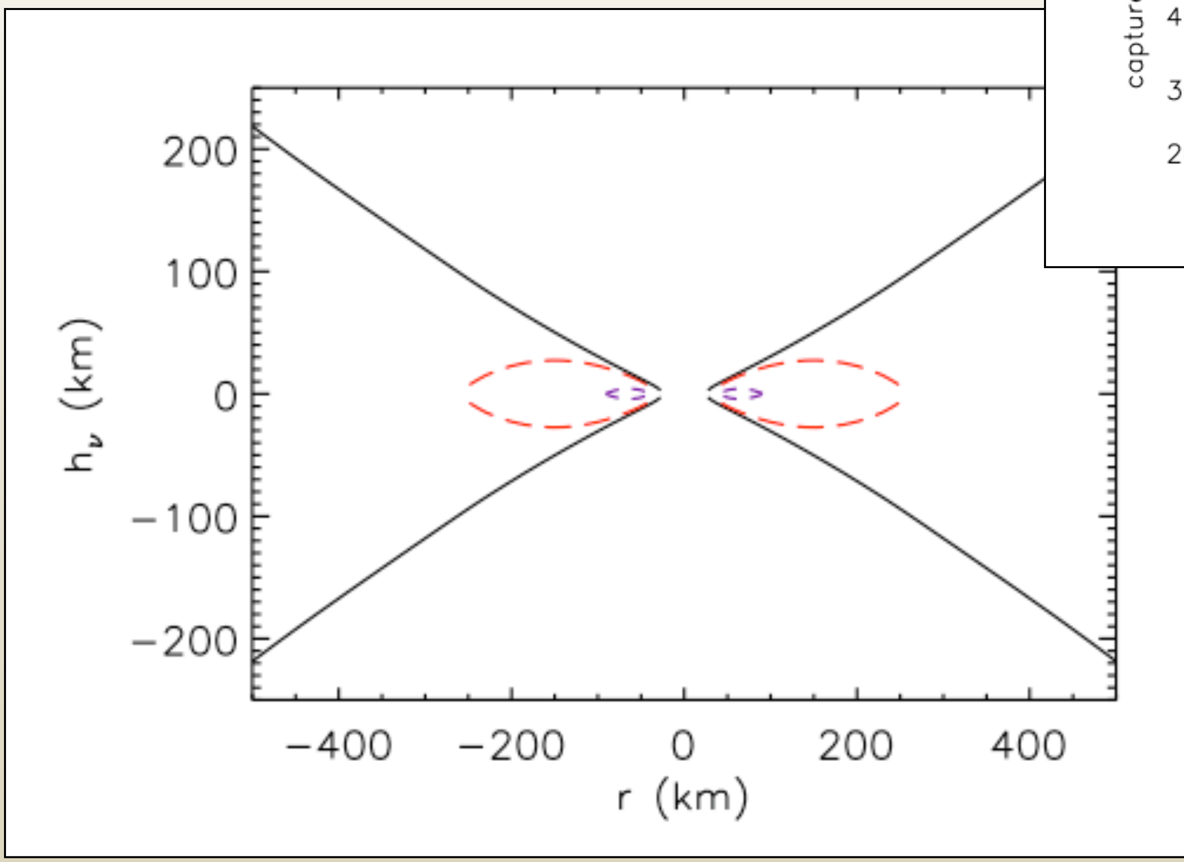
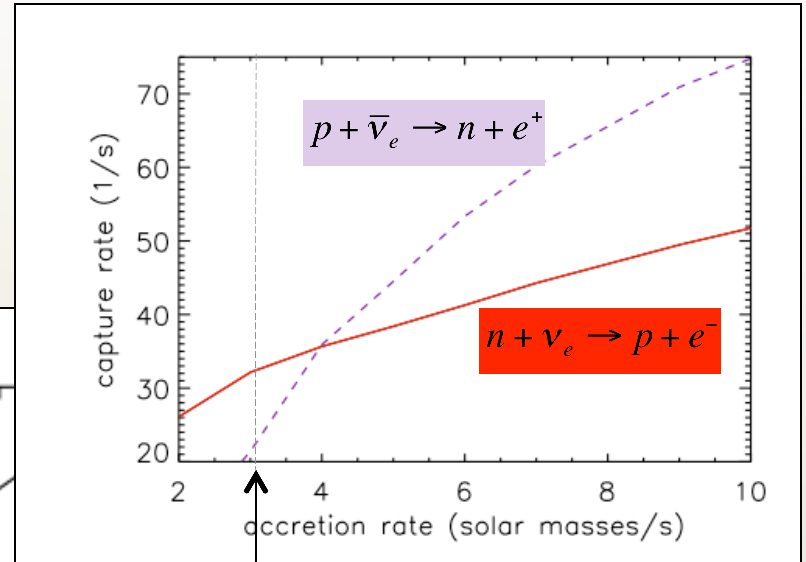
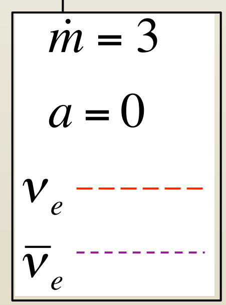
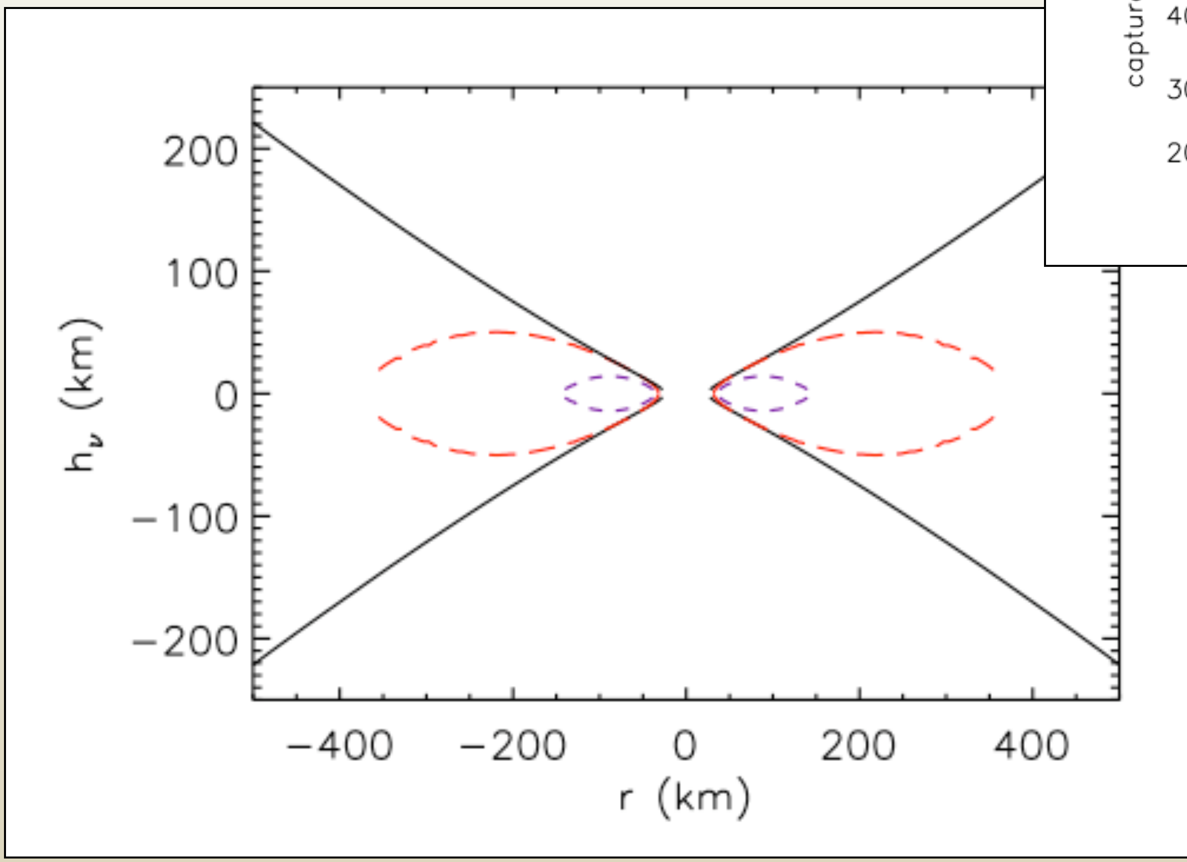


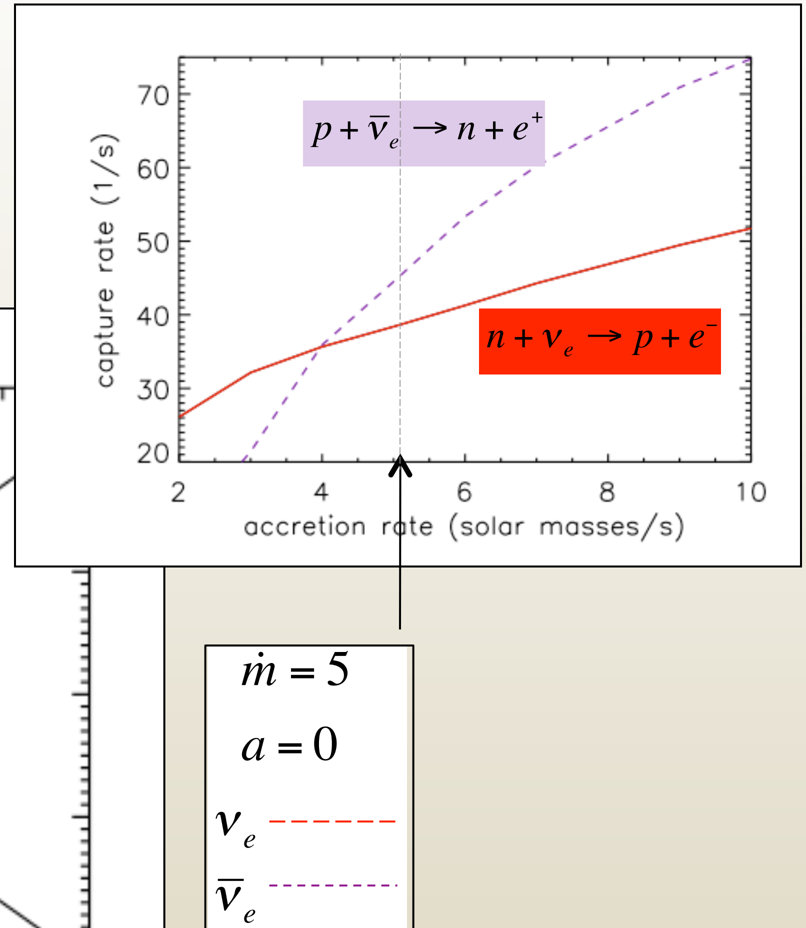




AD-BH neutrino decoupling surfaces

Disk model from Chen and Beloborodov (2008), neutrino decoupling surface calculation by R Surman





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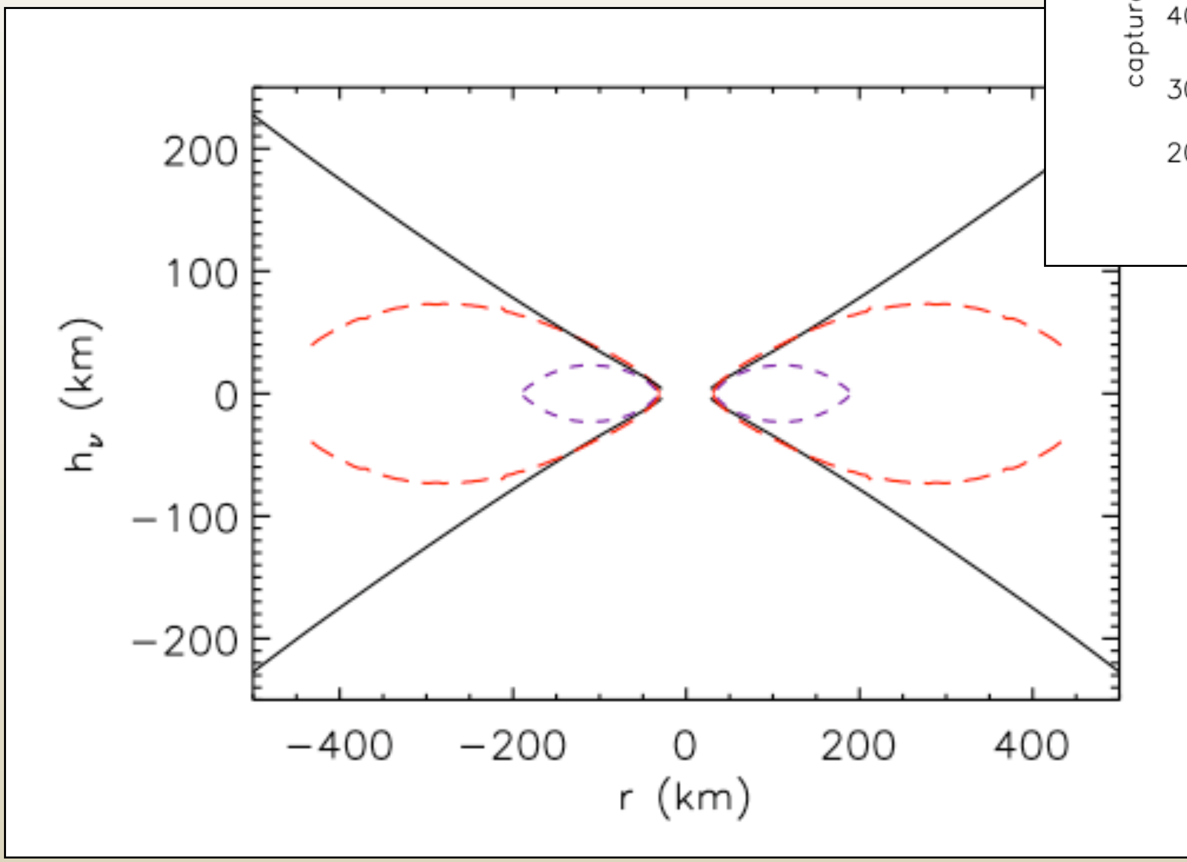
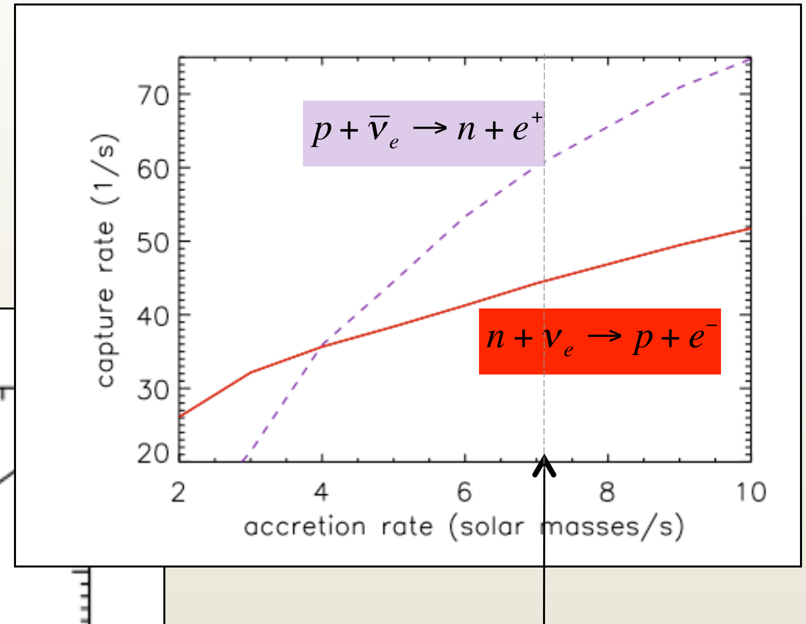
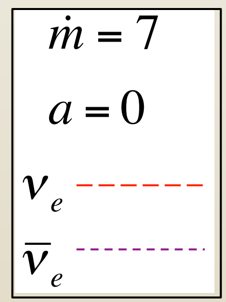
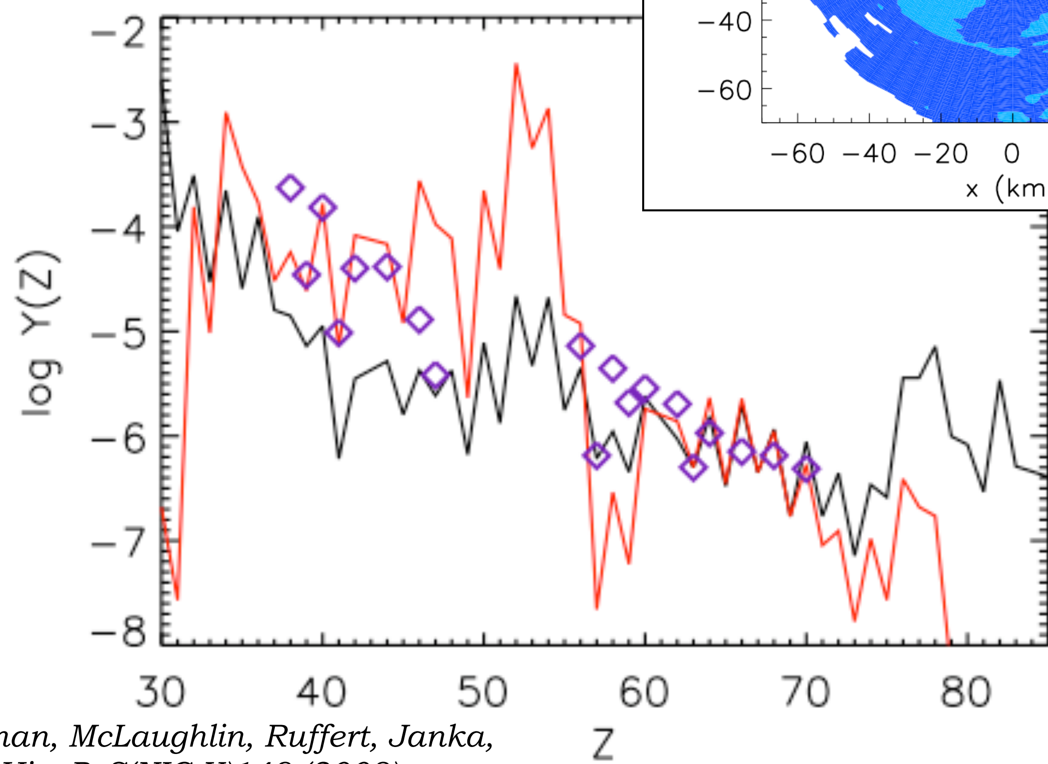


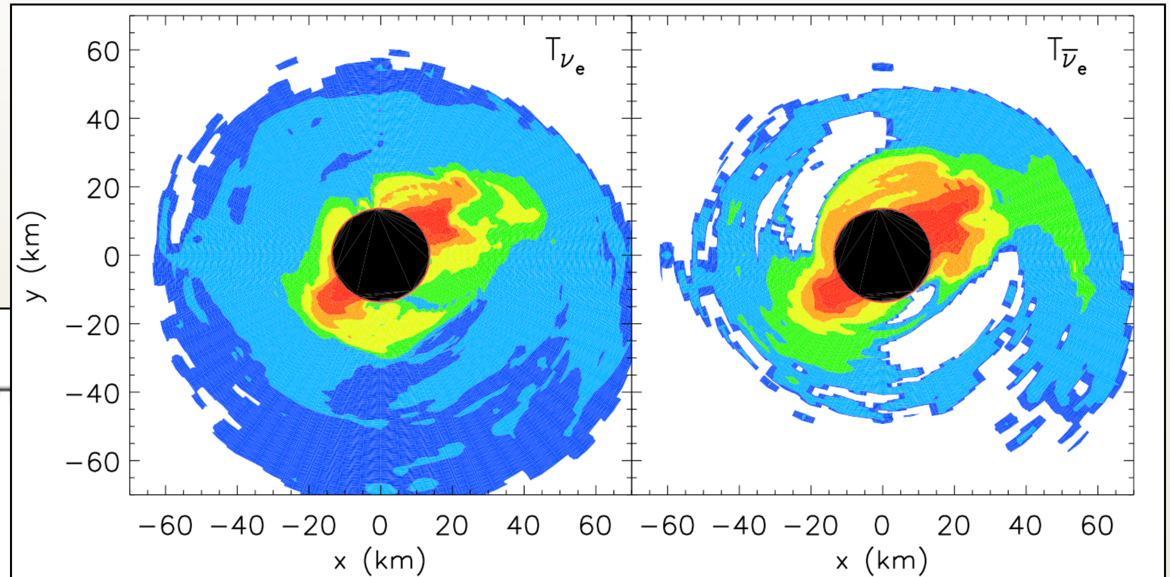




nucleosynthesis from high $\dot{m}$ AD-BHs: *r* process



Surman, McLaughlin, Ruffert, Janka, and Hix, PoS(NIC X)149 (2008)



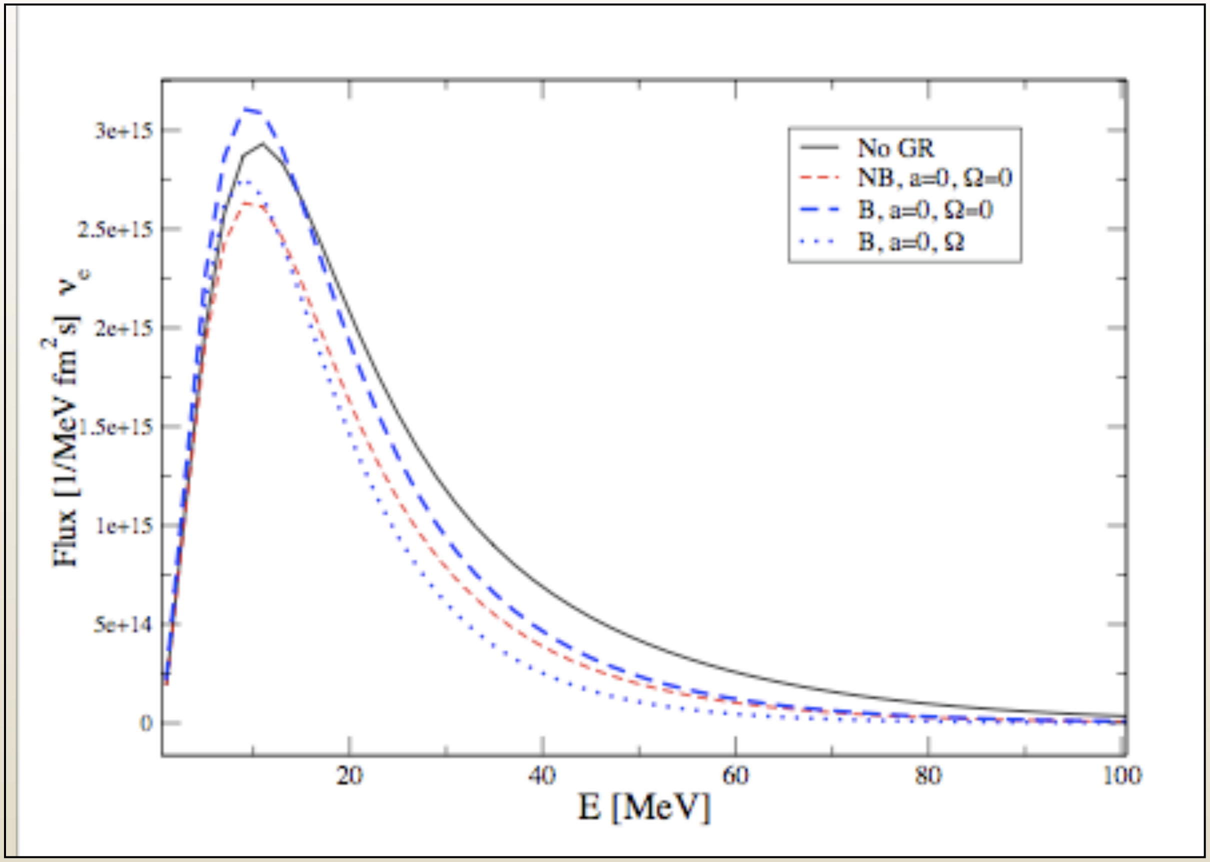
Surman, McLaughlin, Ruffert, Janka, and Hix, ApJ, 679, L117 (2008)

solar

calculation

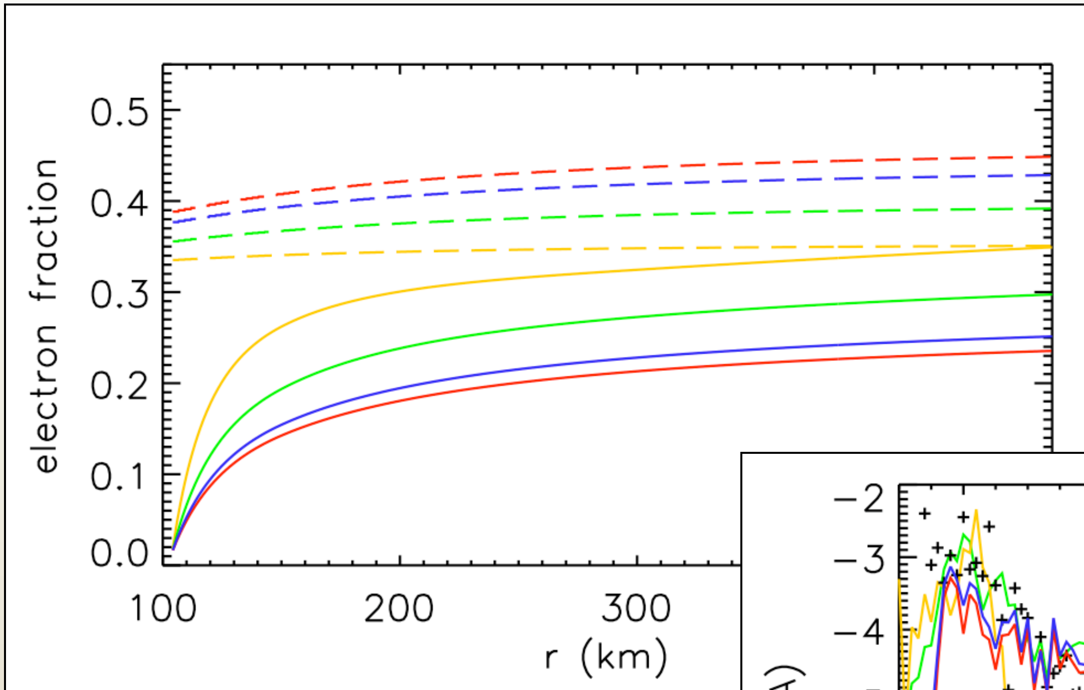
HD122563 (Honda et al 2006)

general relativistic effects in the neutrino spectra



Caballero, McLaughlin, and Surman,
arXiv:1105.6371 (2011)

general relativistic effects in the neutrino spectra



no GR

redshift, bending

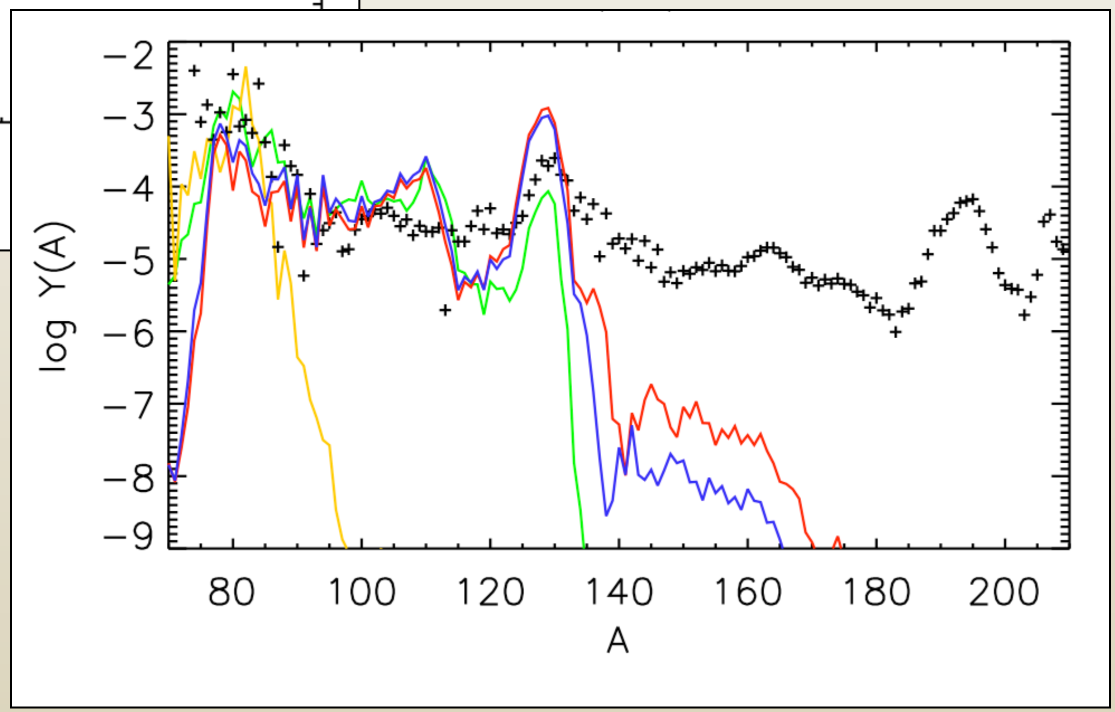
+ rotation

+ Kerr metric for redshift

$s/k = 20$

$\tau = 5$ ms

Caballero, McLaughlin, and Surman, arXiv:1105.6371 (2011)



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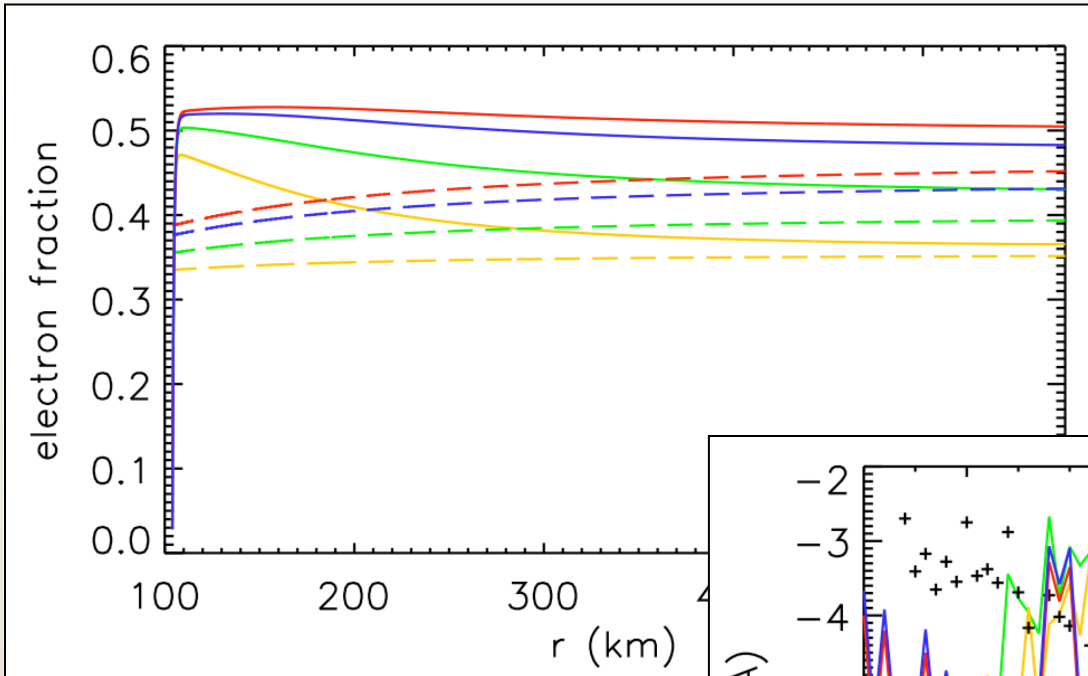


no GR

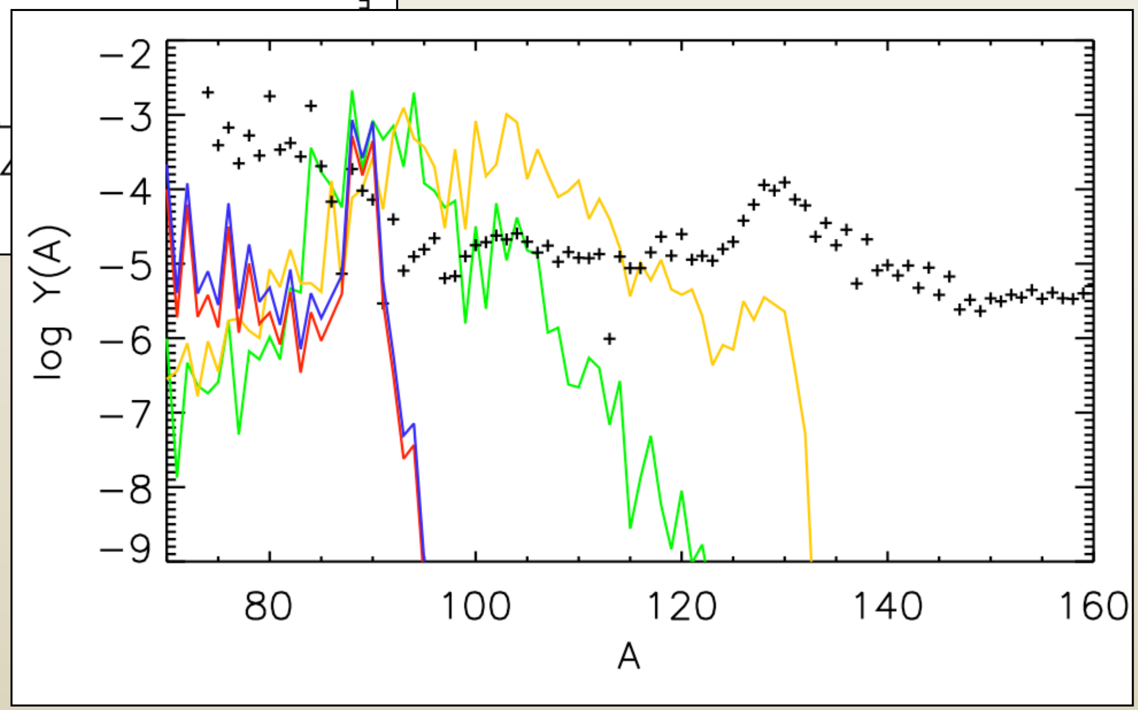
redshift, bending

+ rotation

+ Kerr metric for redshift

$s/k = 75$

$\tau = 50$ ms



Caballero, McLaughlin, and Surman, arXiv:1105.6371 (2011)

neutrinos and supernova nucleosynthesis

Neutrino reactions on nucleons play a key role in the primary synthesis of heavy elements in extreme astrophysical environments

They:

⇒ influence the initial neutron-to-proton ratio

⇒ determine the composition of free nucleons available for capture on seeds

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