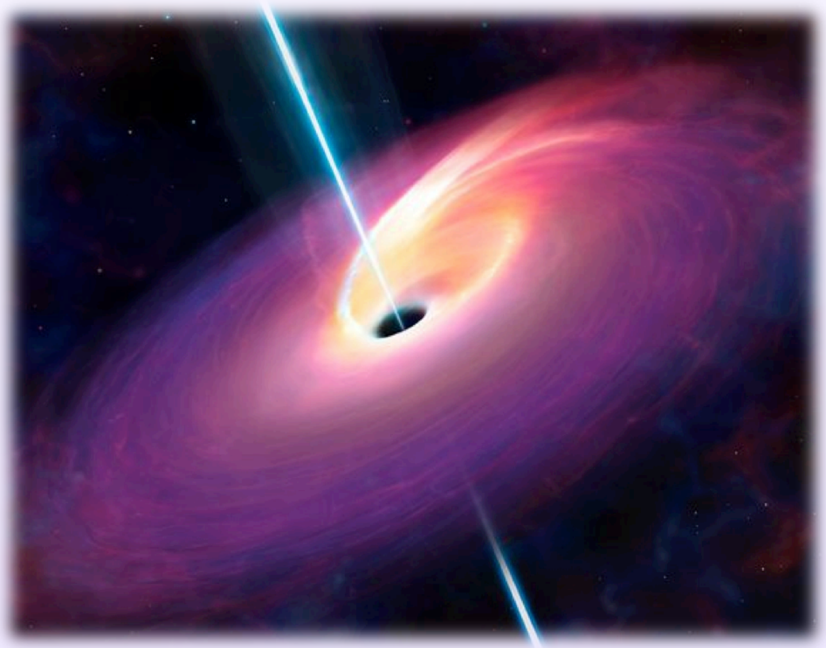
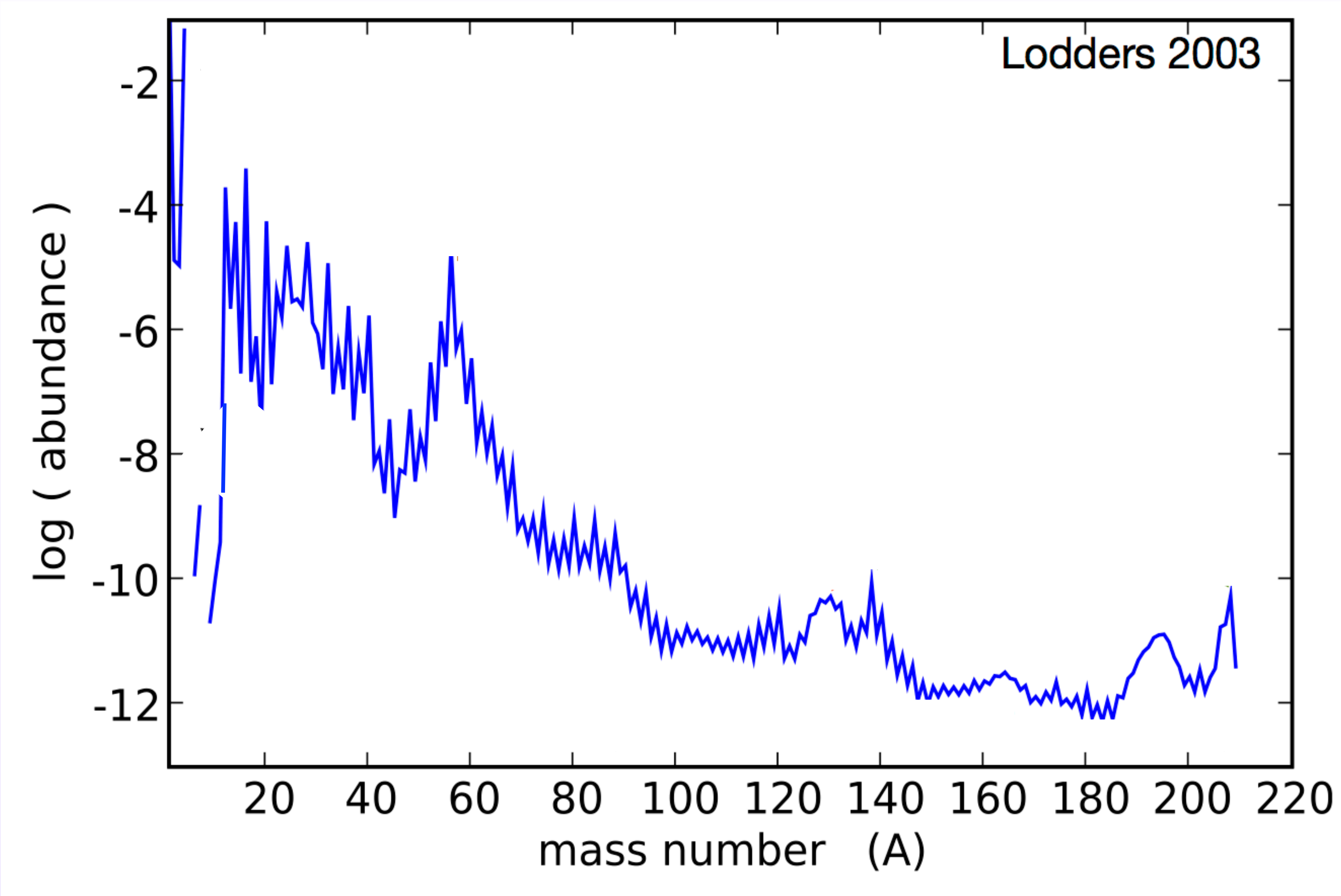
neutrinos and heavy element synthesis



Rebecca Surman
Union College

INFO13
29 August 2013

solar system abundances



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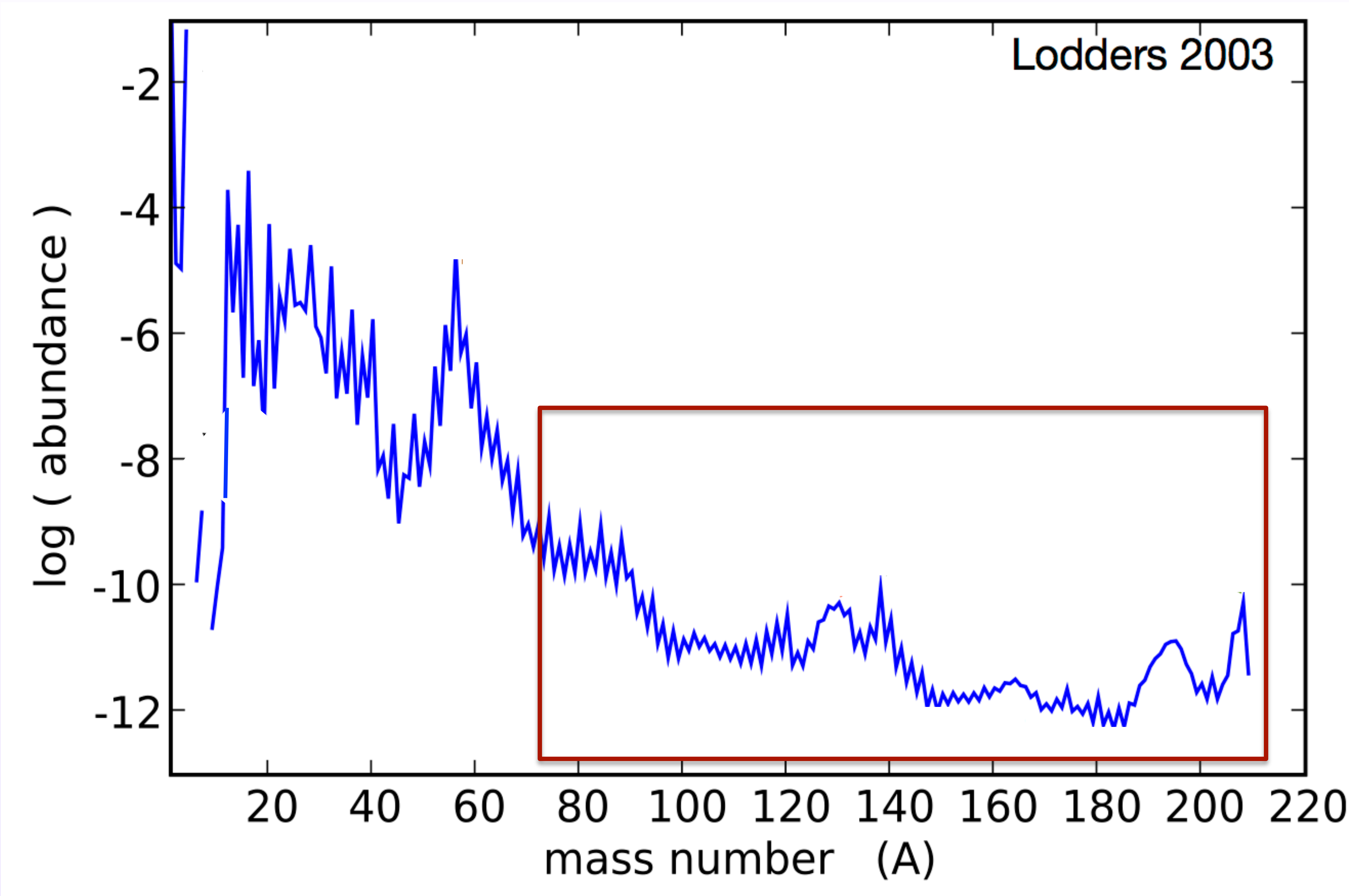
solar system abundances



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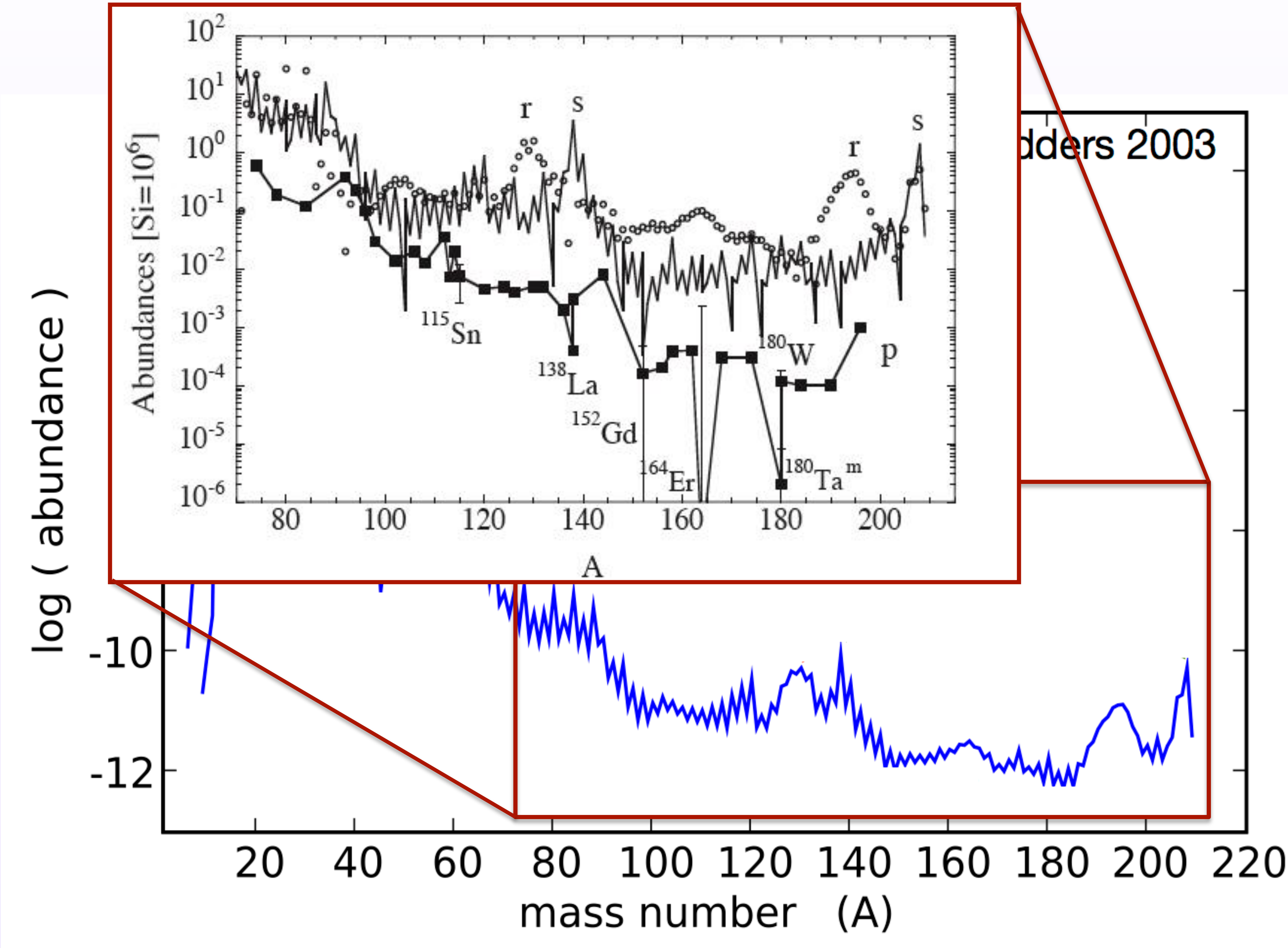
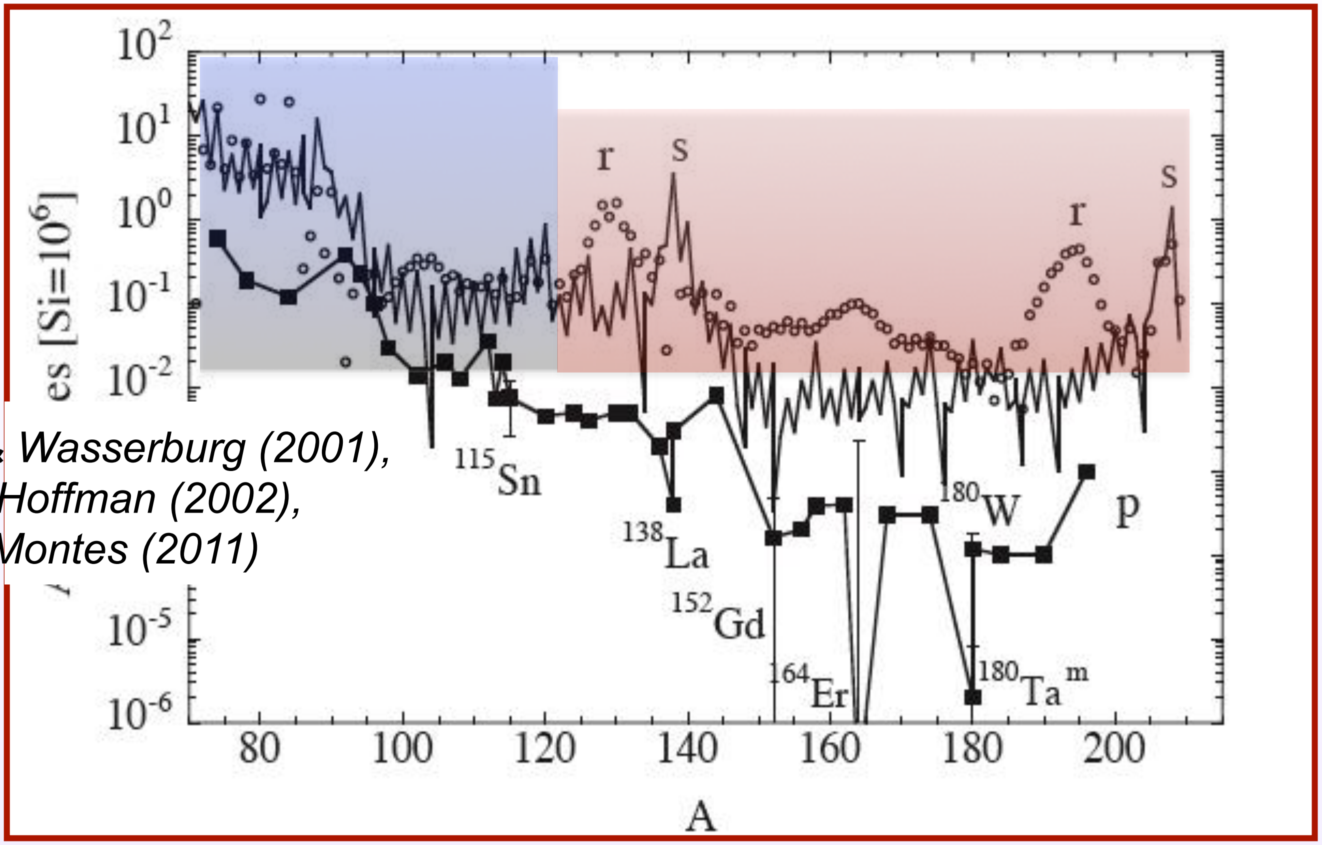
solar system abundances



solar system abundances



weak *r* process?
LEPP?

e.g., Qian & Wasserburg (2001), Woosley & Hoffman (2002), Arcones & Montes (2011)

r process:

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

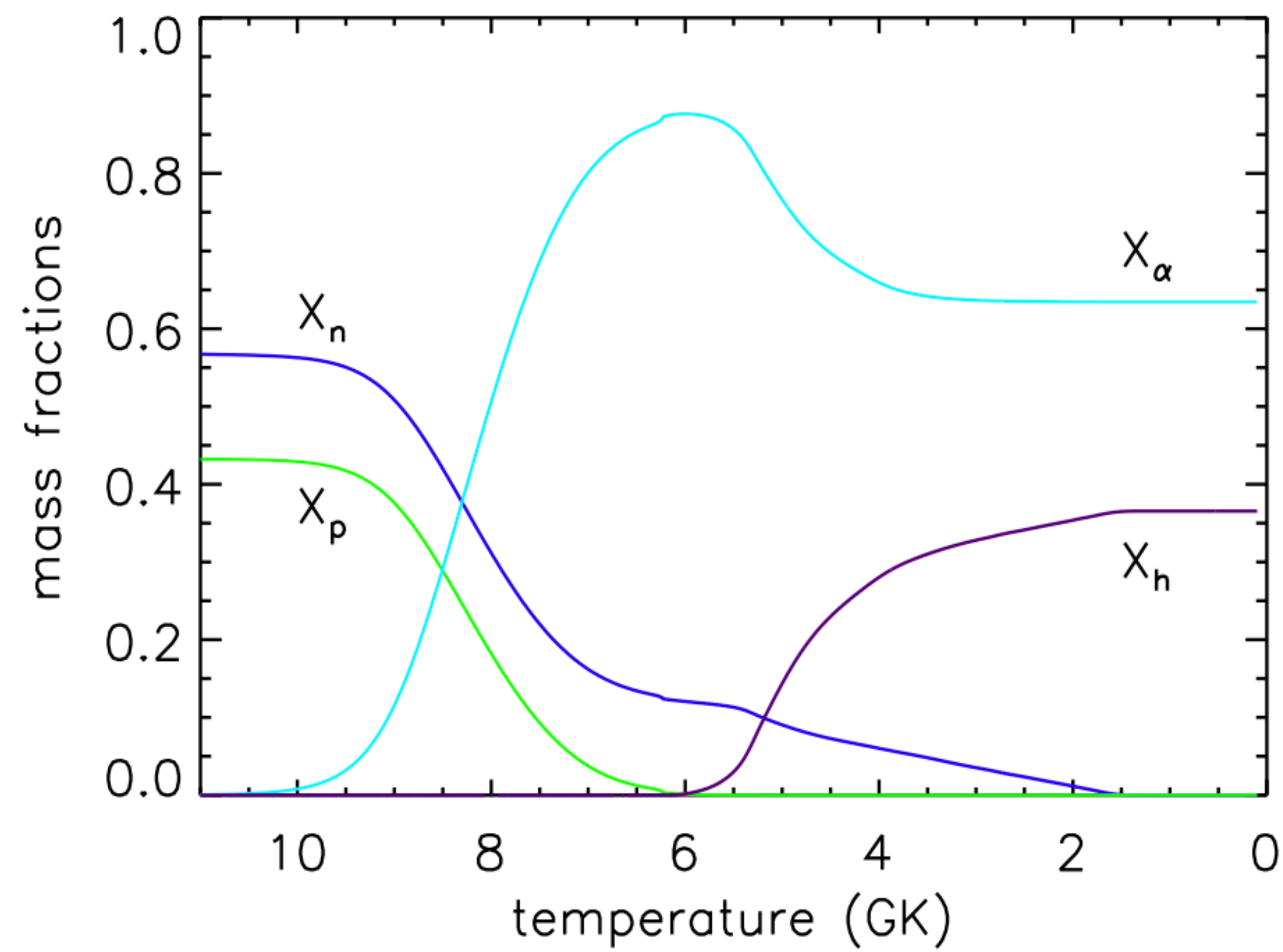
Burbidge, Burbidge, Fowler, Hoyle (1957) , Cameron (1957)

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)

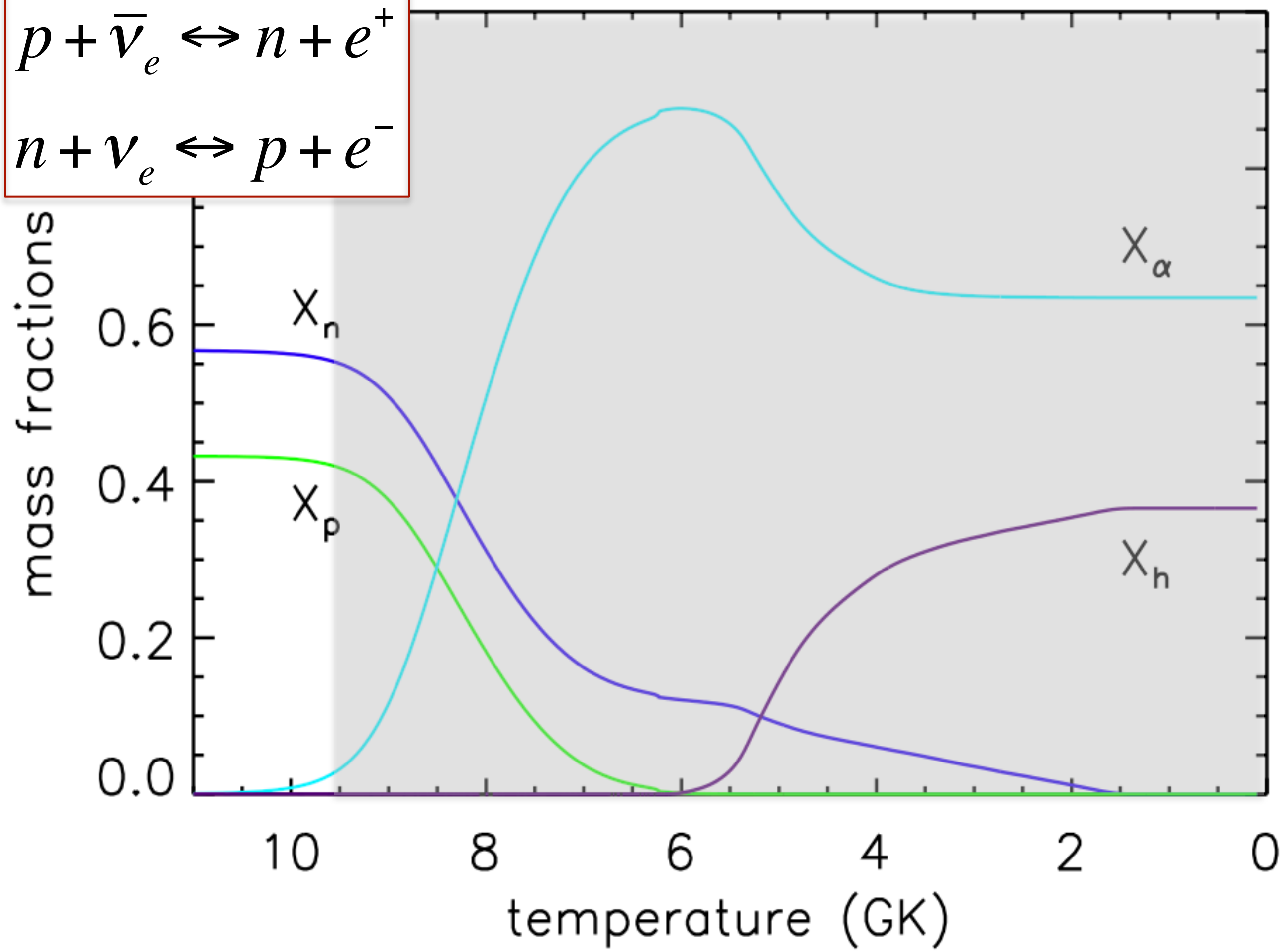
primary heavy element nucleosynthesis



neutrinos and primary nucleosynthesis

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

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



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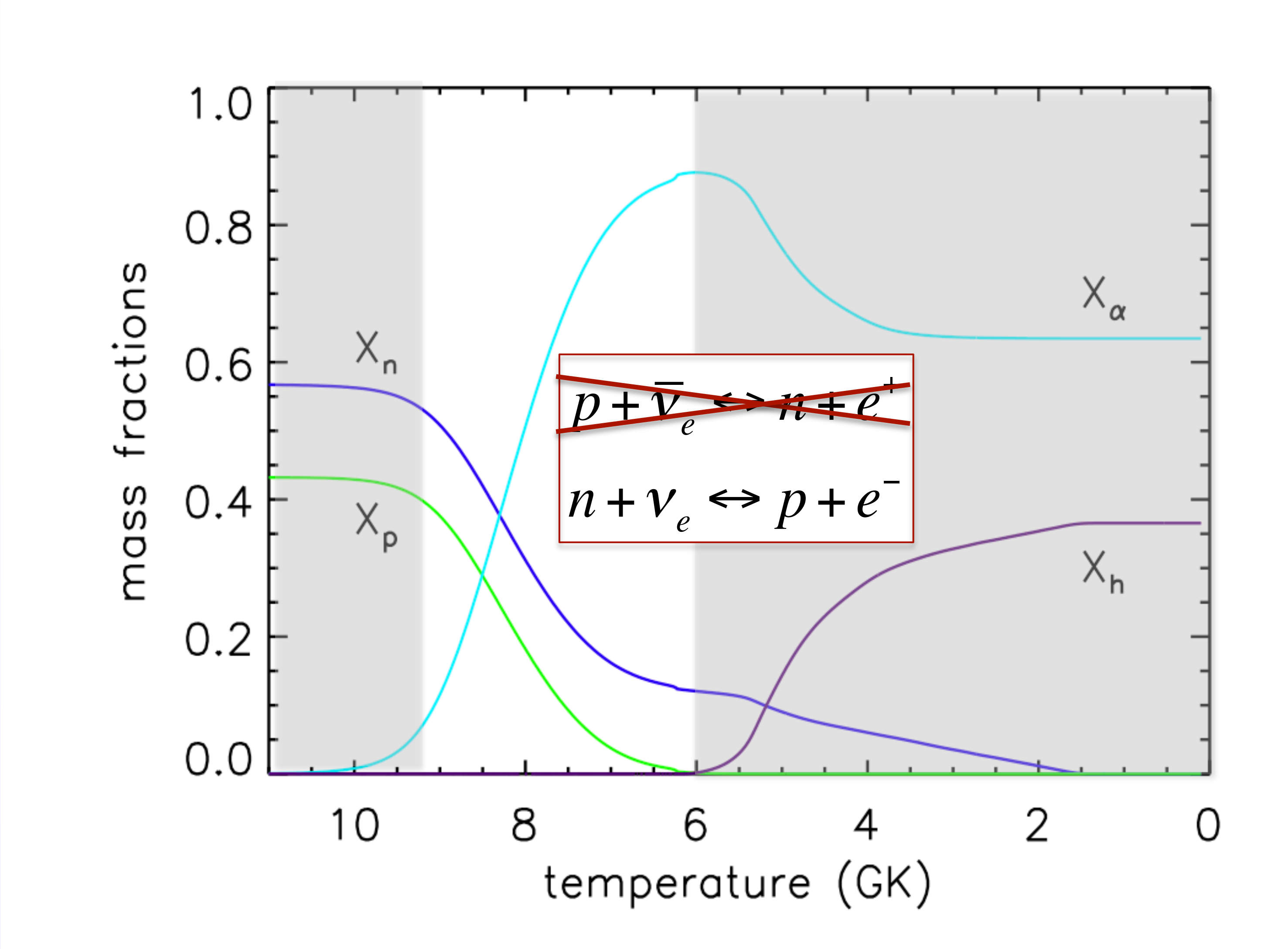
neutrinos and primary nucleosynthesis



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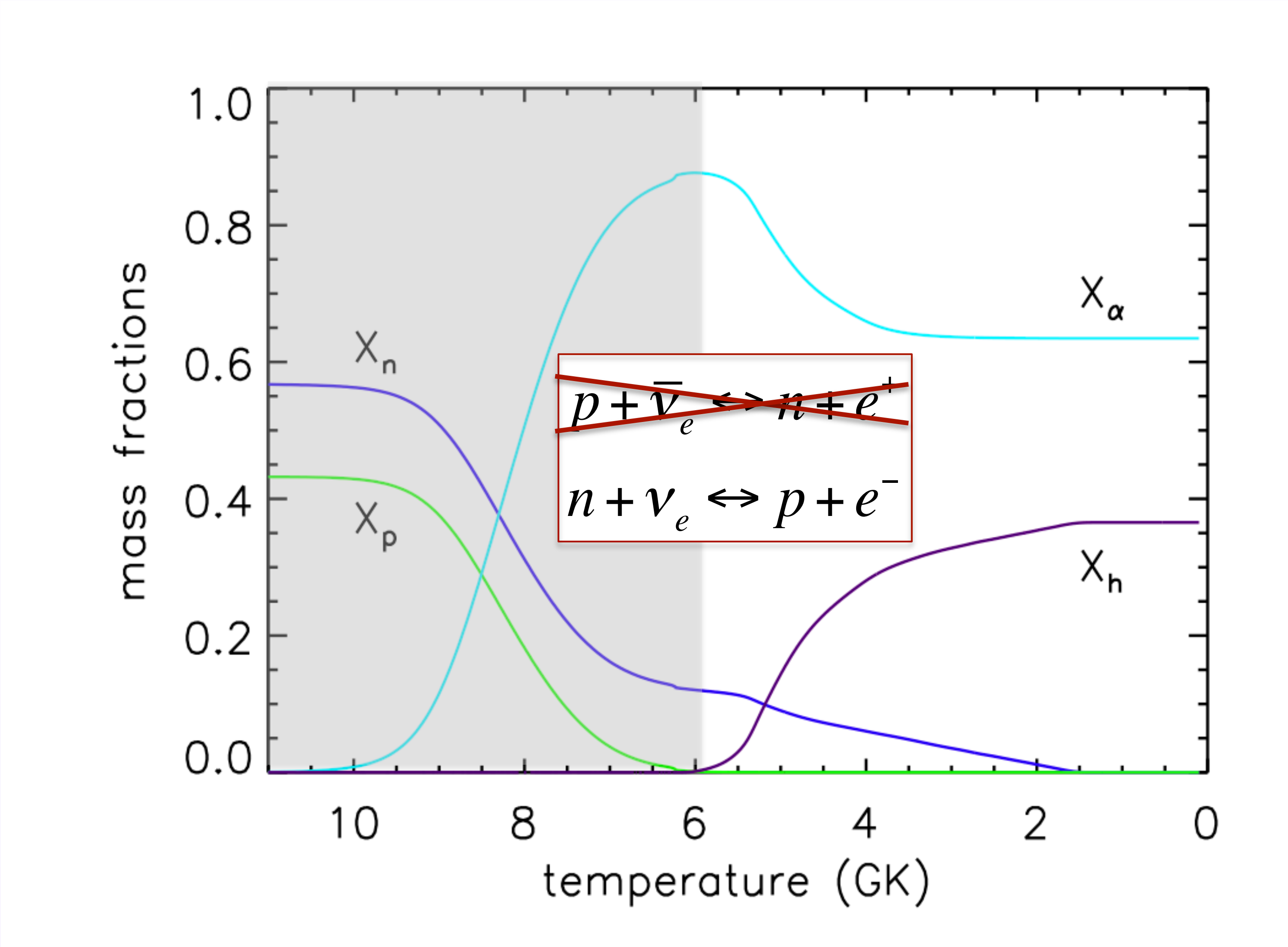
neutrinos and primary nucleosynthesis



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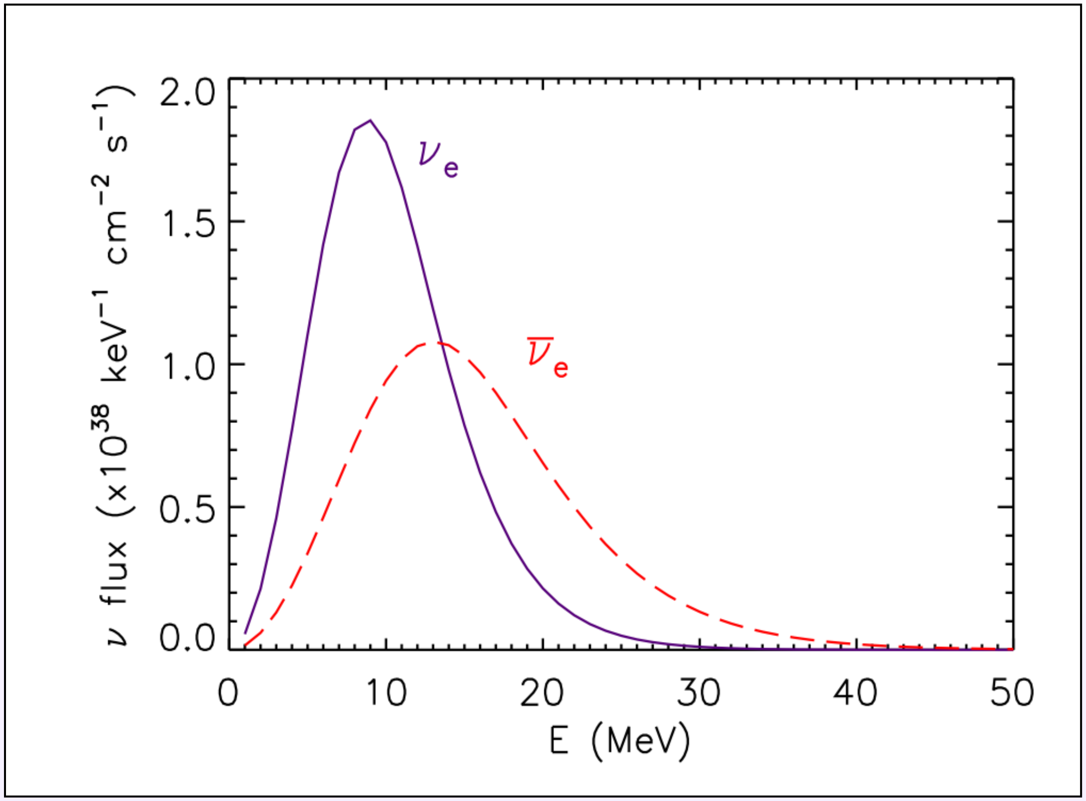
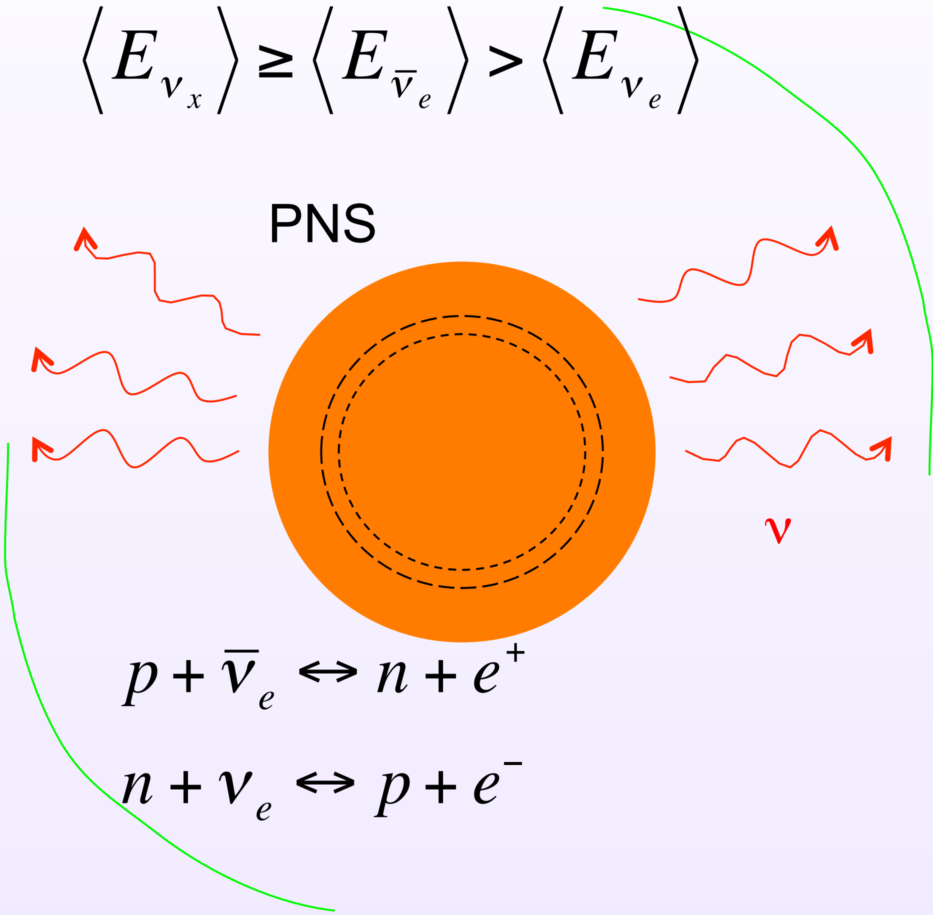
late-time supernova neutrino-driven wind



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

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



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

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

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.

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Union College
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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

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

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Two flavor mixing in matter with a high neutrino flux:

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

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

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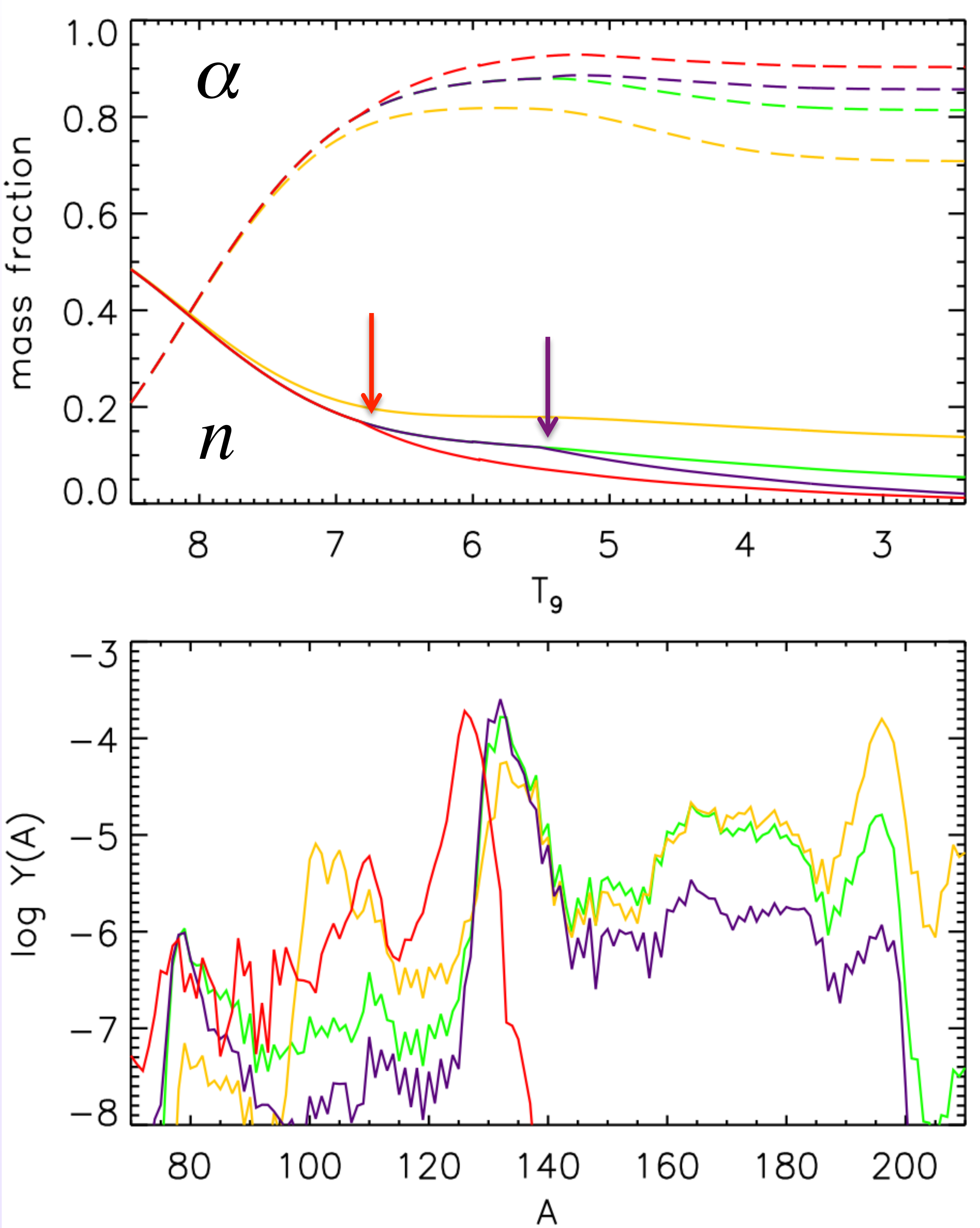
collective oscillations and a supernova r-process: toy model



No ν for $T < 9 \times 10^9$ K

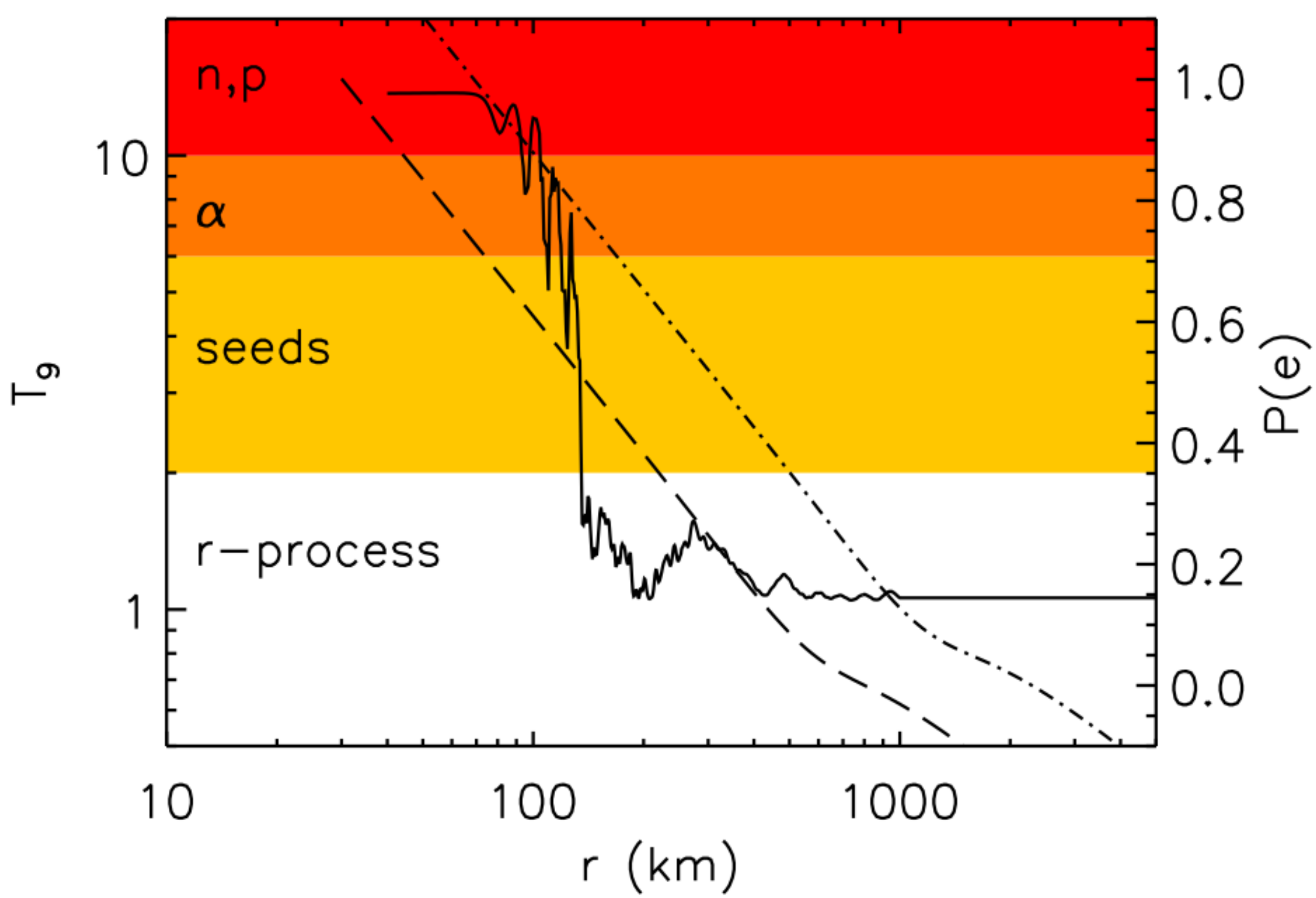
No oscillations

Test swap at seed assembly

Test swap at alpha assembly

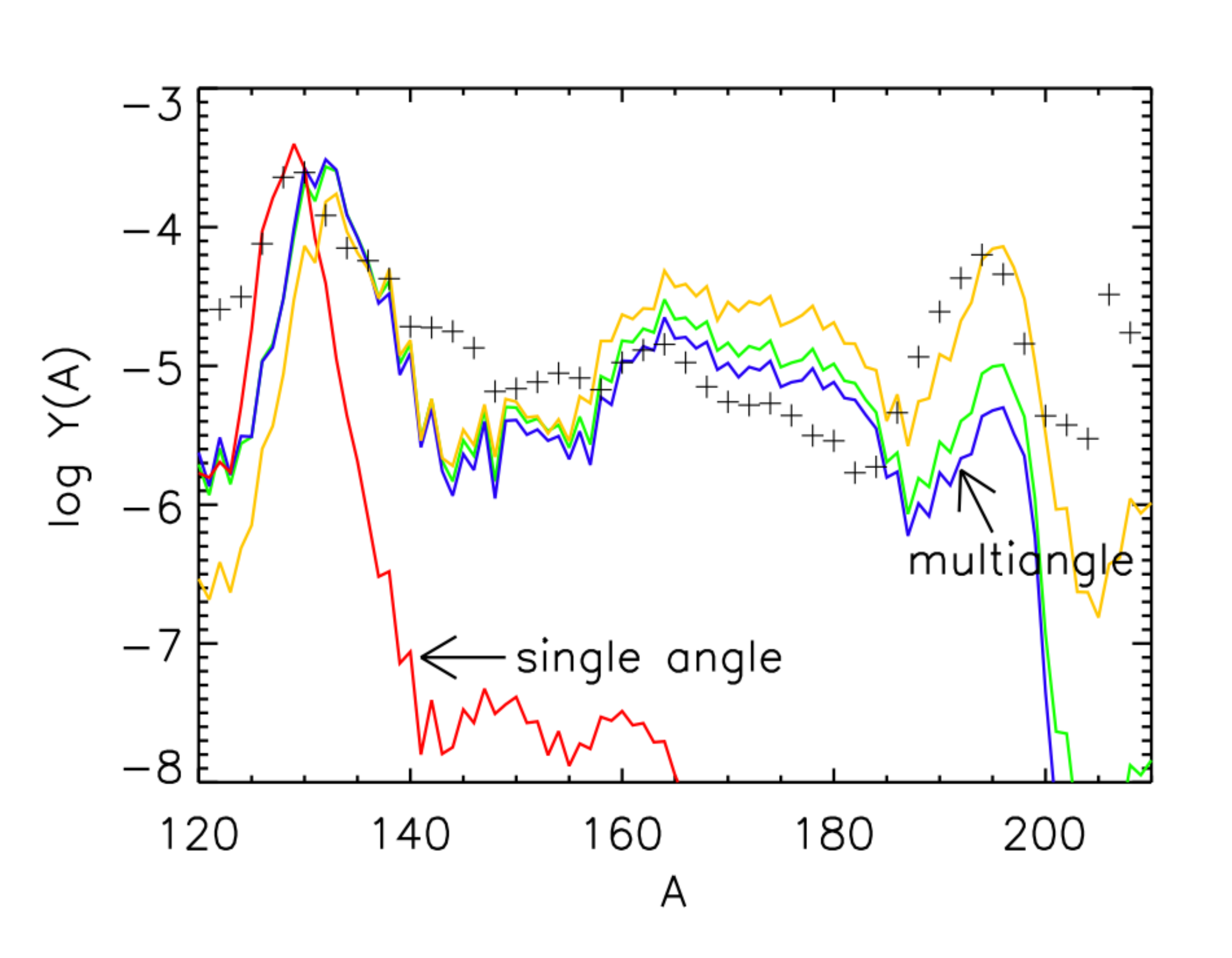
Duan, Friedland, McLaughlin & Surman (2011)

collective oscillations and a supernova r-process



Duan, Friedland, McLaughlin & Surman (2011)

collective oscillations and a supernova r-process



Duan, Friedland, McLaughlin & Surman (2011)

No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

Single angle ν oscillation calculation

$s/k = 200$

$\tau = 18$ ms

no supernova r-process?

All the world's gold came from collisions of dead stars, scientists say

By **Elizabeth Landau**, CNN
updated 3:46 PM EDT, Thu July 18, 2013 | Filed under: **Innovations**

CNN Tech

Colliding neutron stars produce short gamma-ray bursts, as well as gold, platinum and uranium, scientists say.

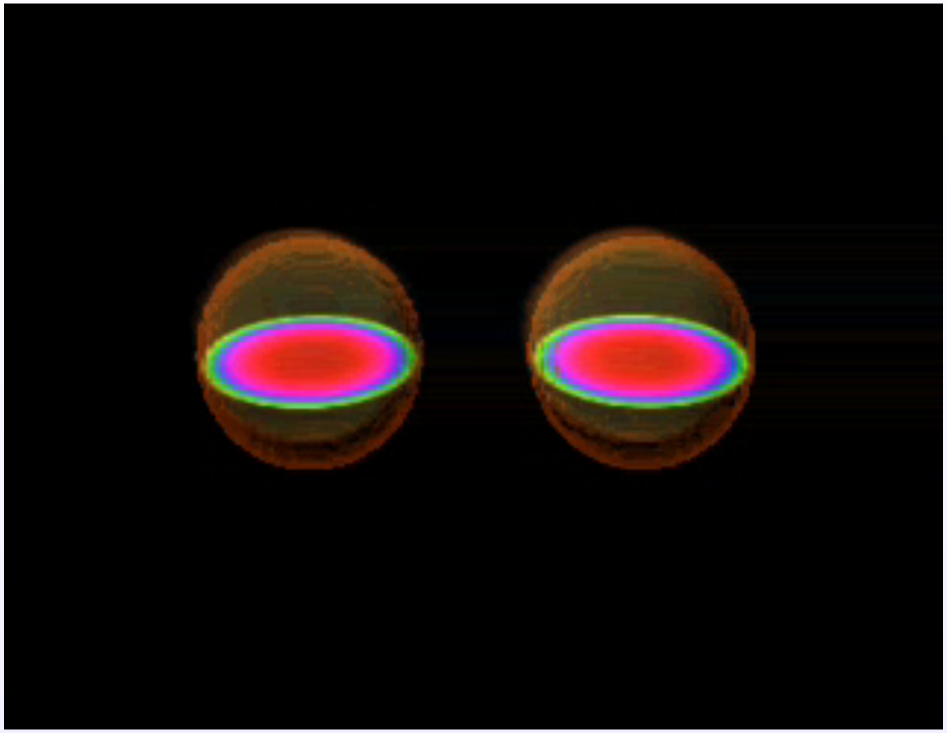
STORY HIGHLIGHTS

- Scientists studied a gamma-ray burst associated with gold
- The burst was 3.9 billion light-years away from Earth
- This burst came from the

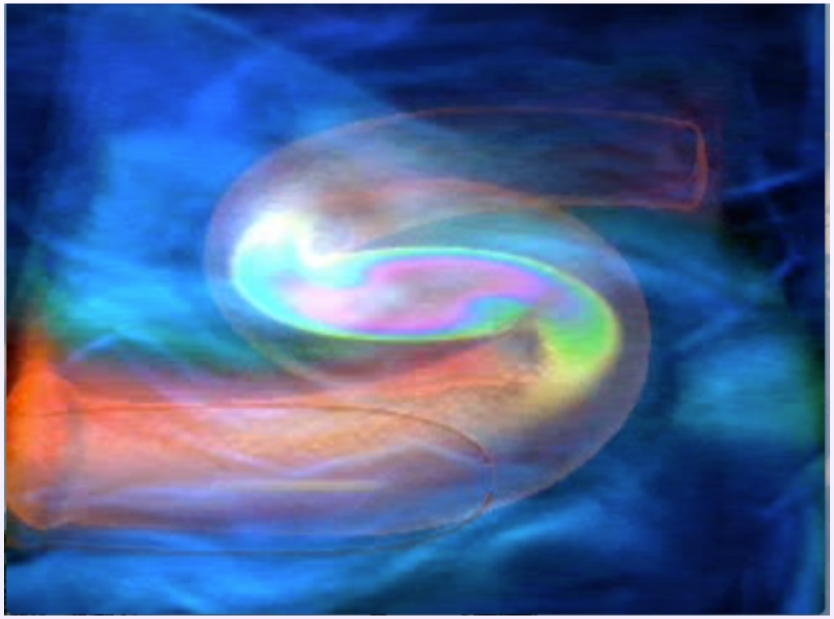
(CNN) -- All that glitters is not gold, they say. But all the gold in the world may come from astronomical events that send a lot of high-energy light out in space.

Researchers have new evidence that gold comes from the collision of neutron stars.

compact object mergers



Animation credit: NASA/
SkyWorks



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)

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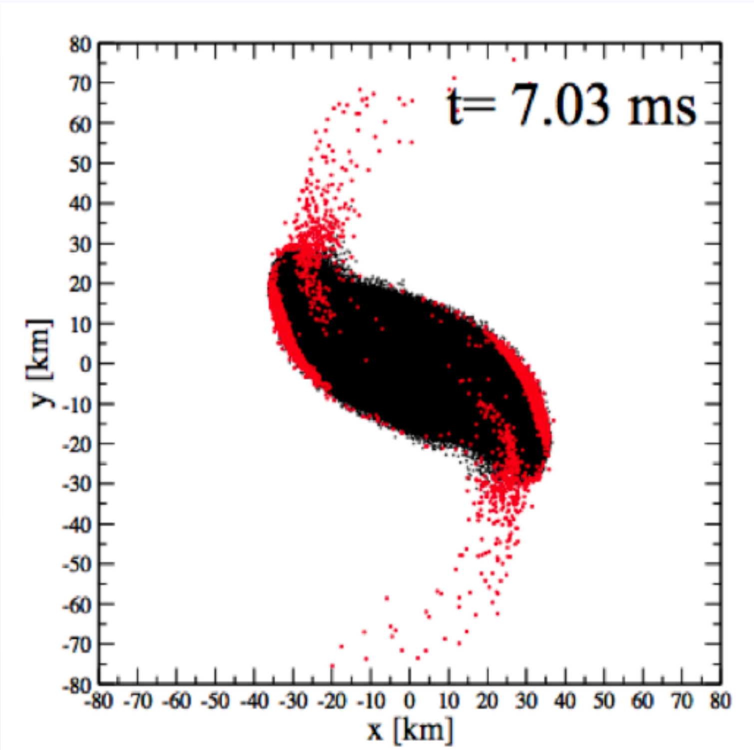
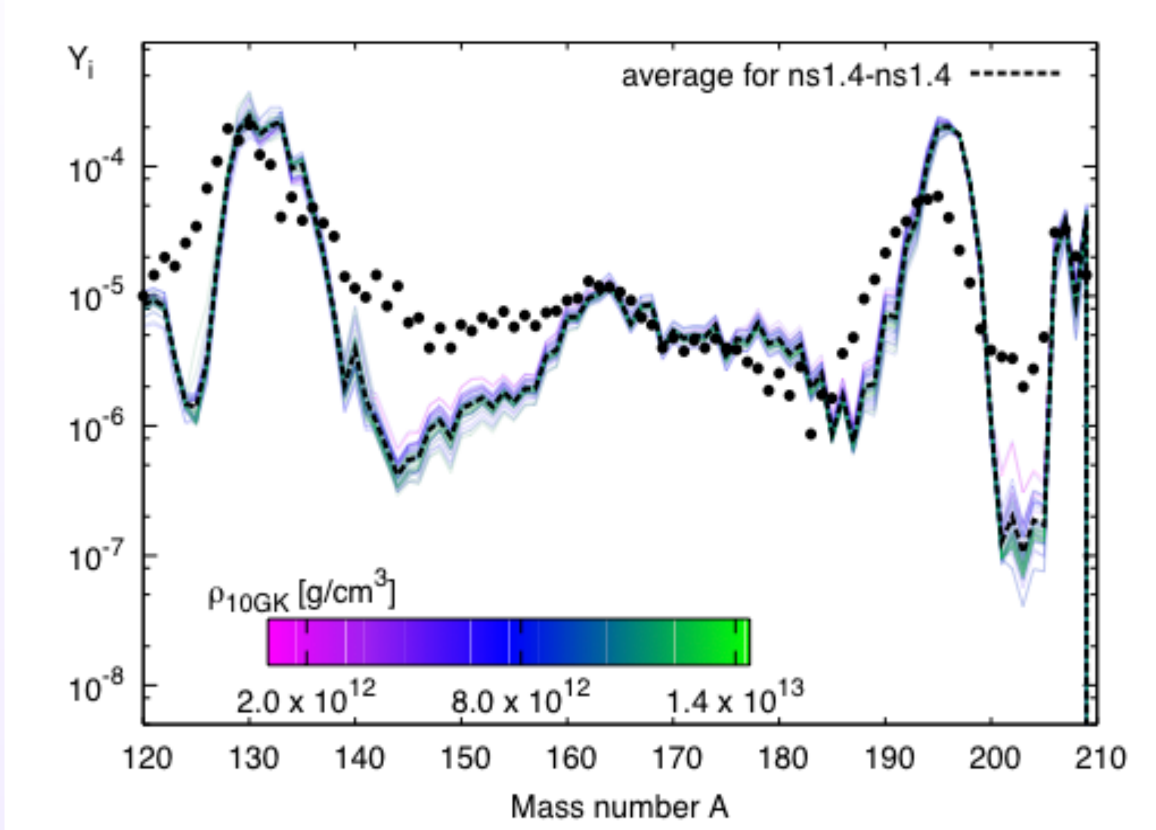
r-process in tidal tails of neutron star mergers

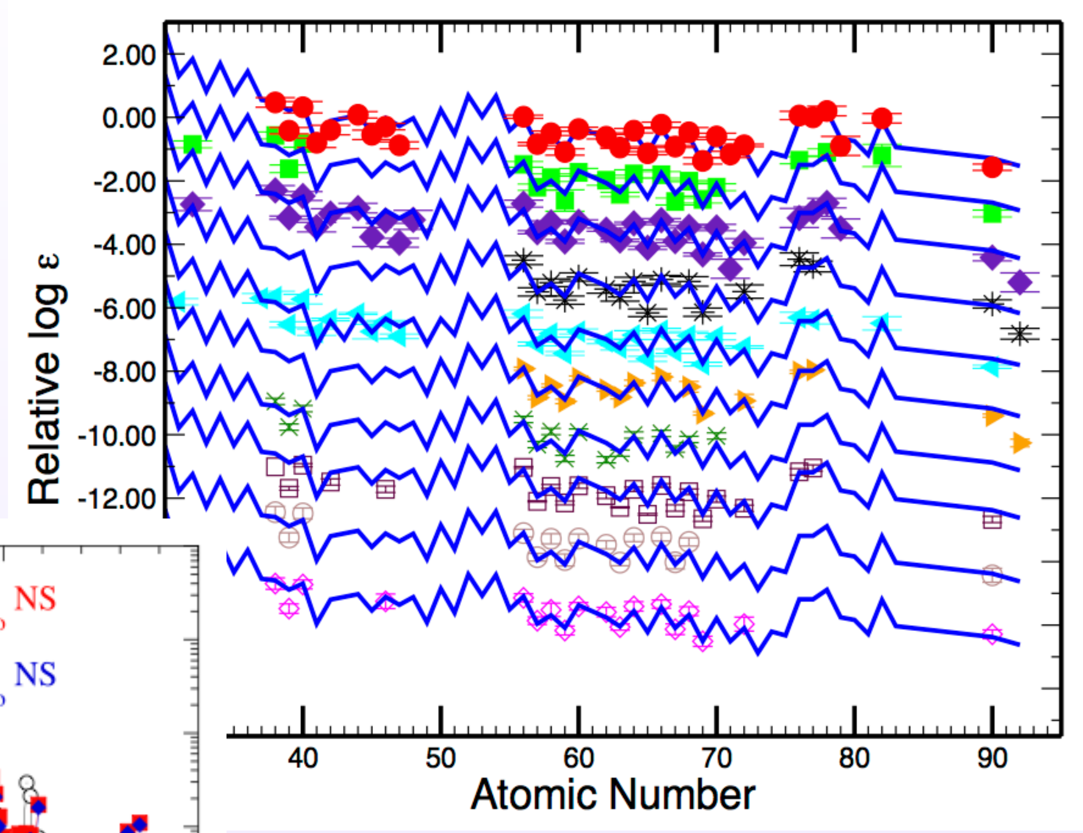




Korobkin et al (2012)

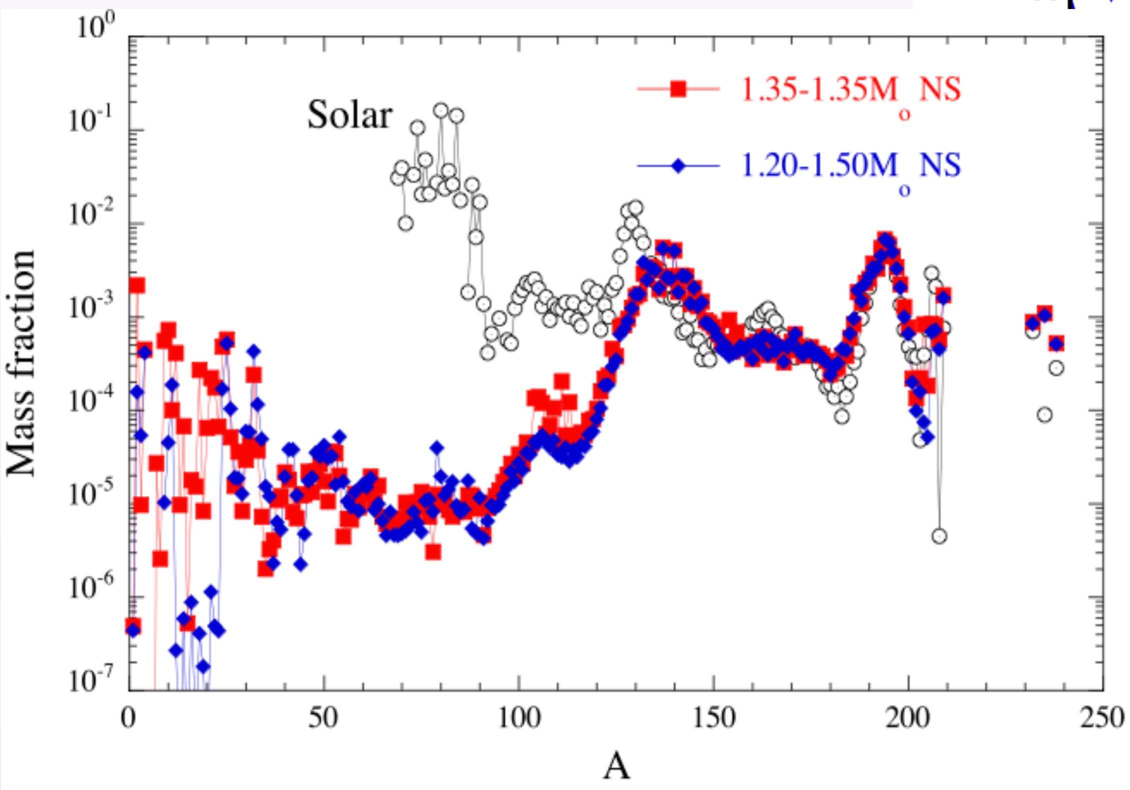
additional open questions

(1) light neutron-capture nuclei?



Cowan et al (2011)

Goriely et al (2012)



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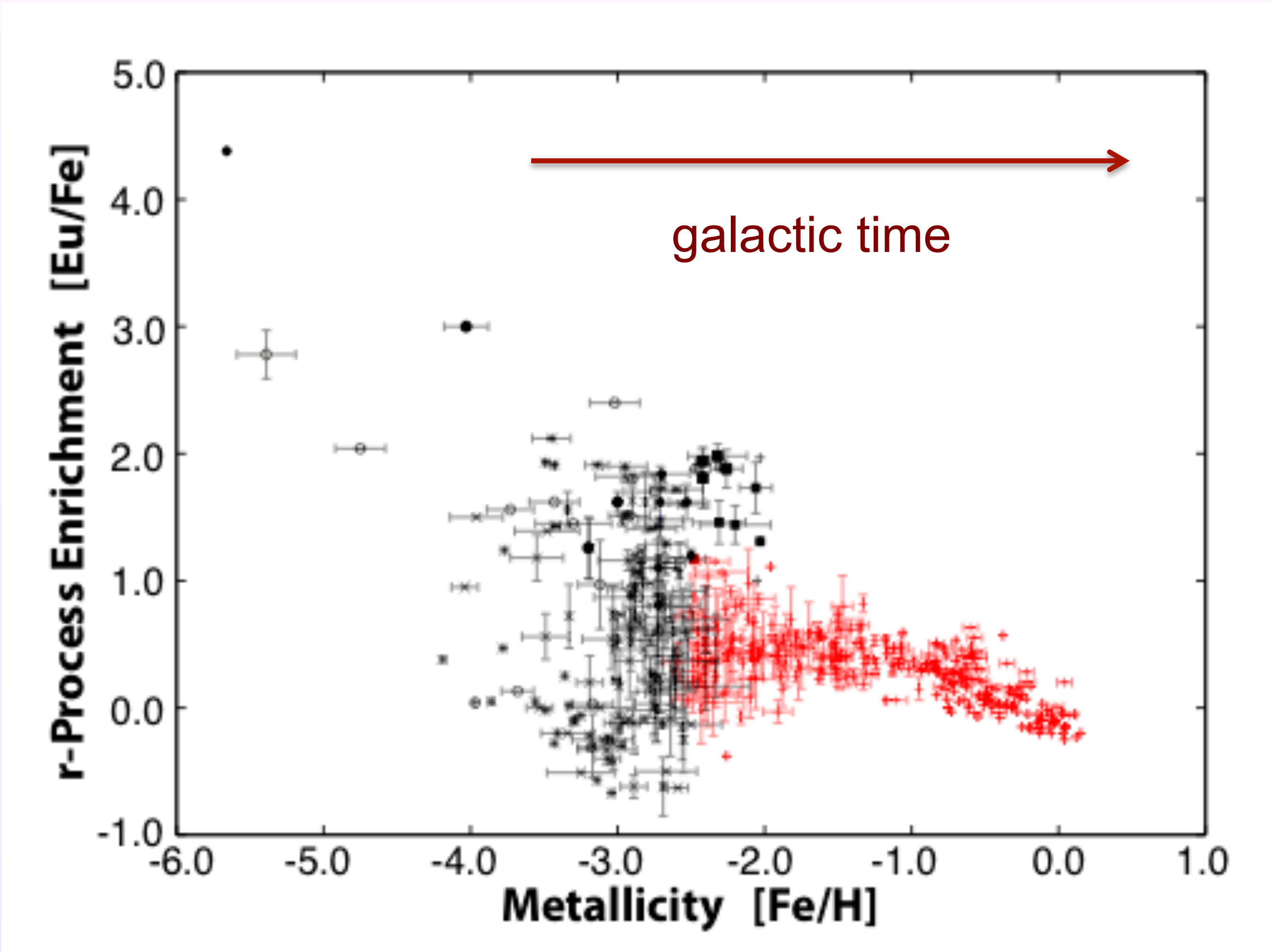
additional open questions

(1) light neutron-capture nuclei?

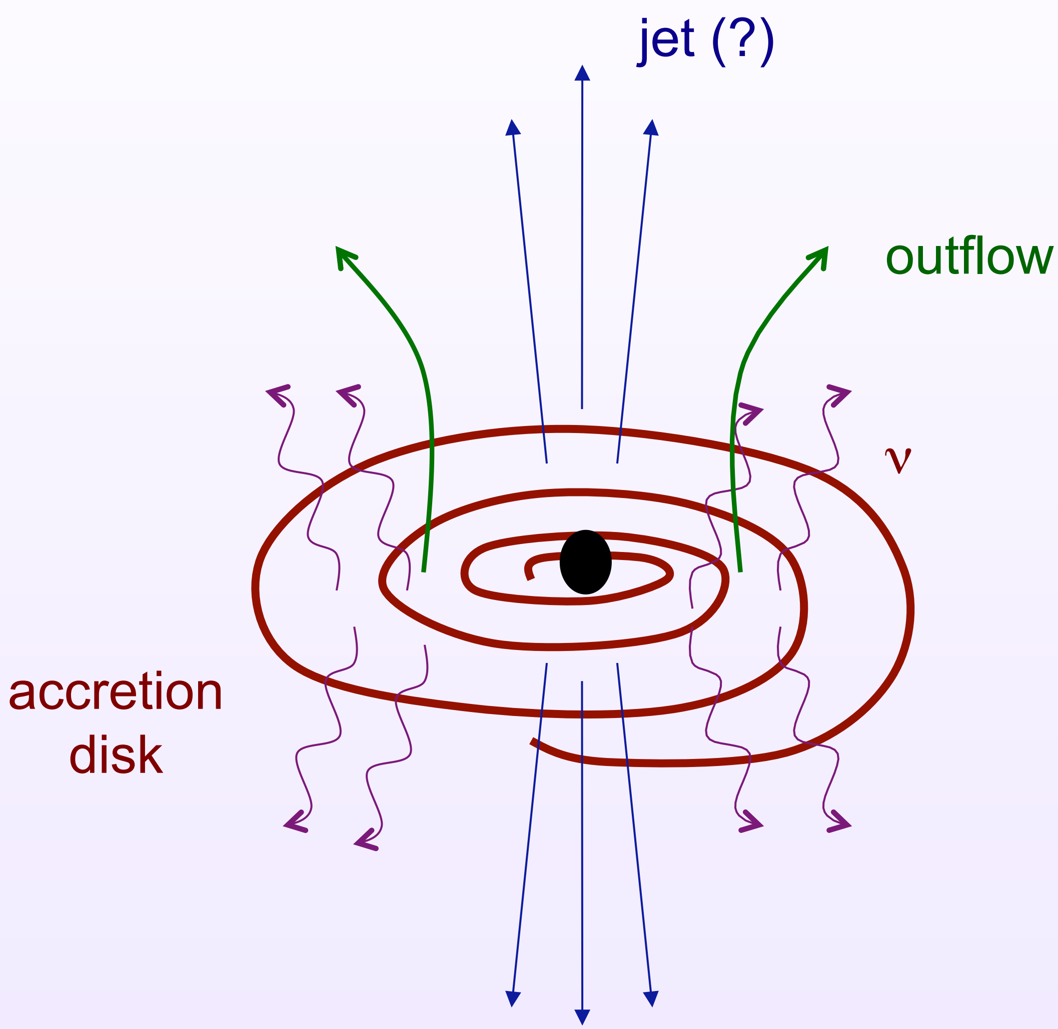
(2) r-process in the oldest stars?



Data from SAGA database (2008, 2011), plot by M Mumpower

collapsars and black hole accretion disks (AD-BHs)

e.g., Woosley (1993), Paczynski (1993), MacFadyen and Woosley (1999)



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), Wanajo & Janka (2012)

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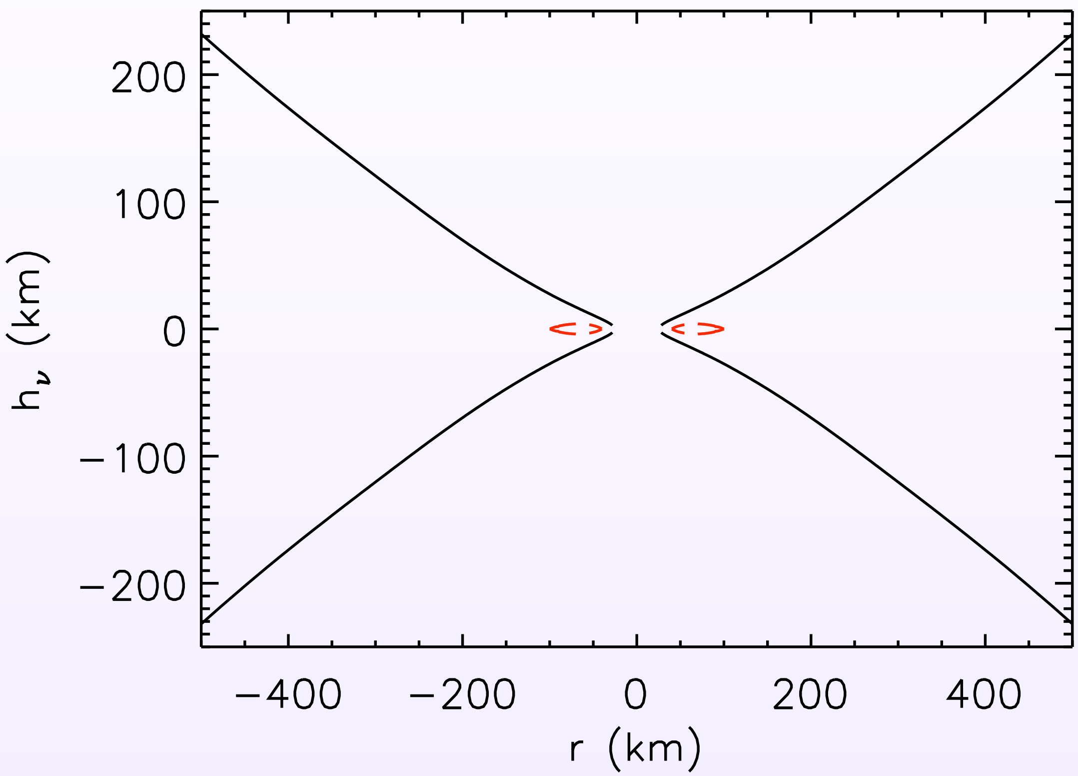
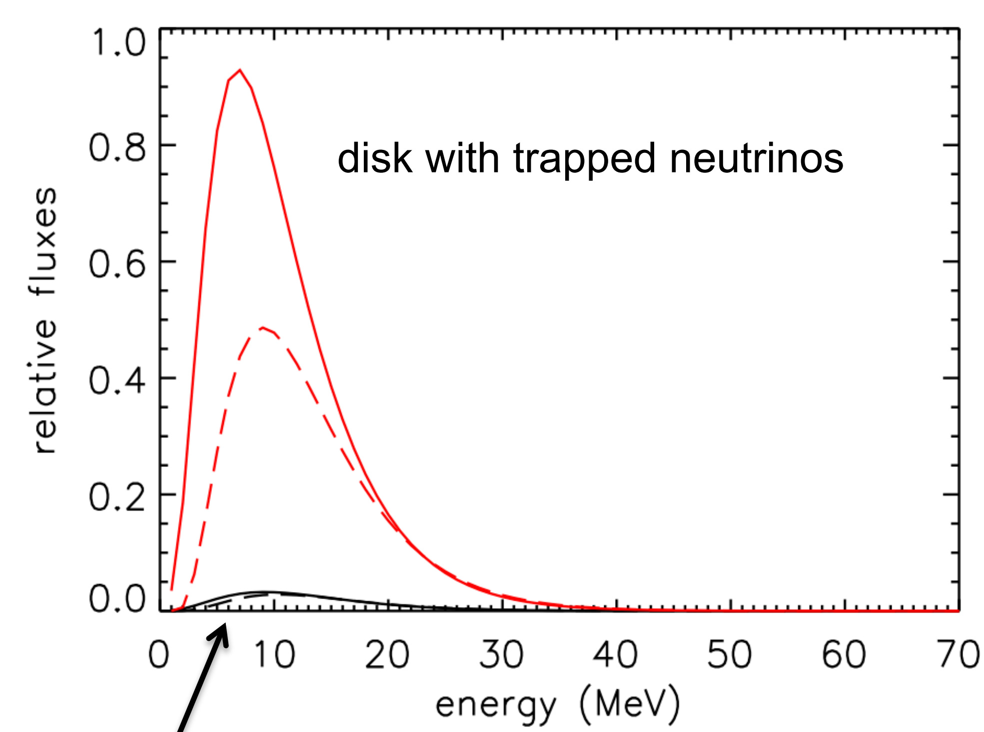
black hole accretion disk neutrino emission



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

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

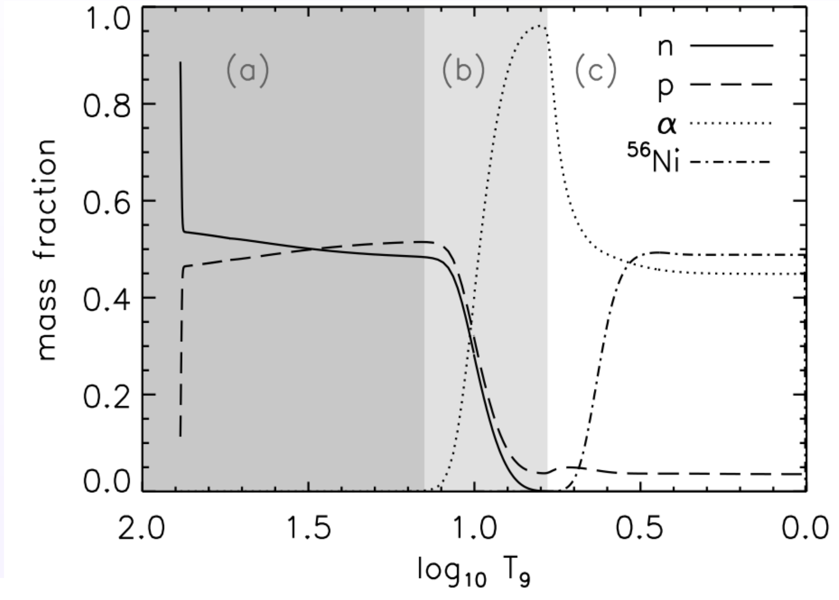


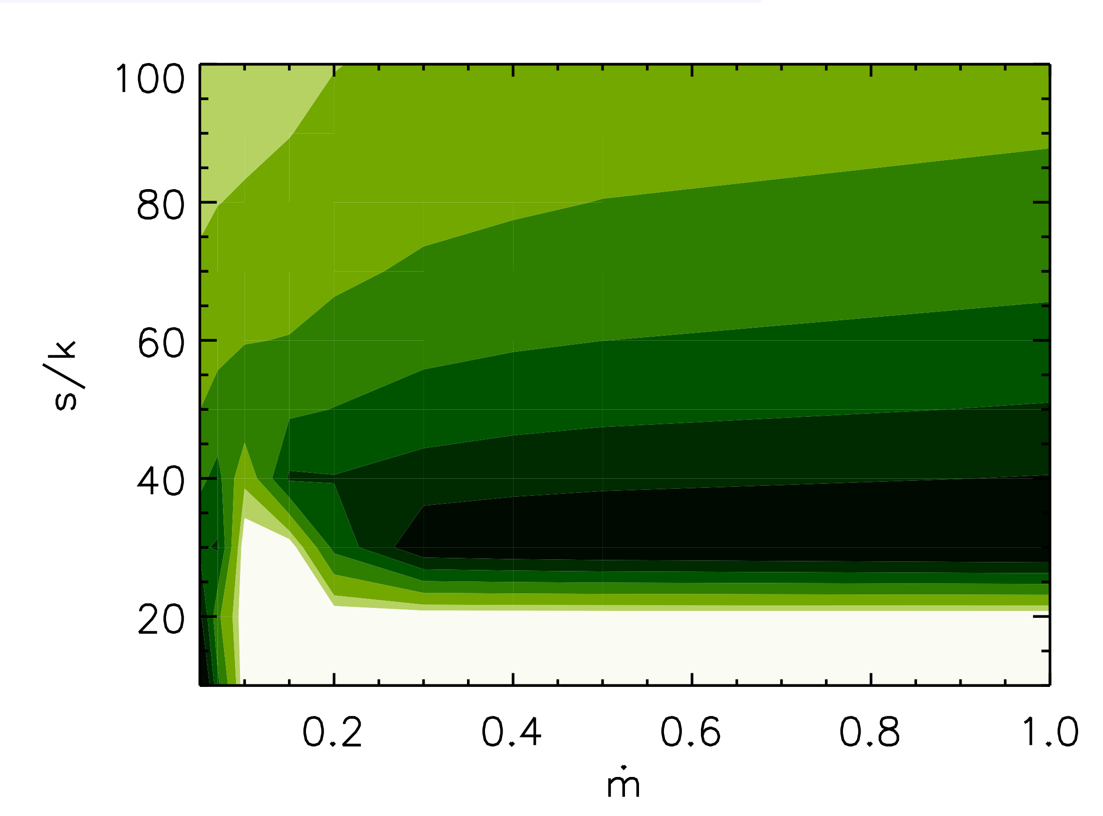
disk with free-streaming neutrino emission

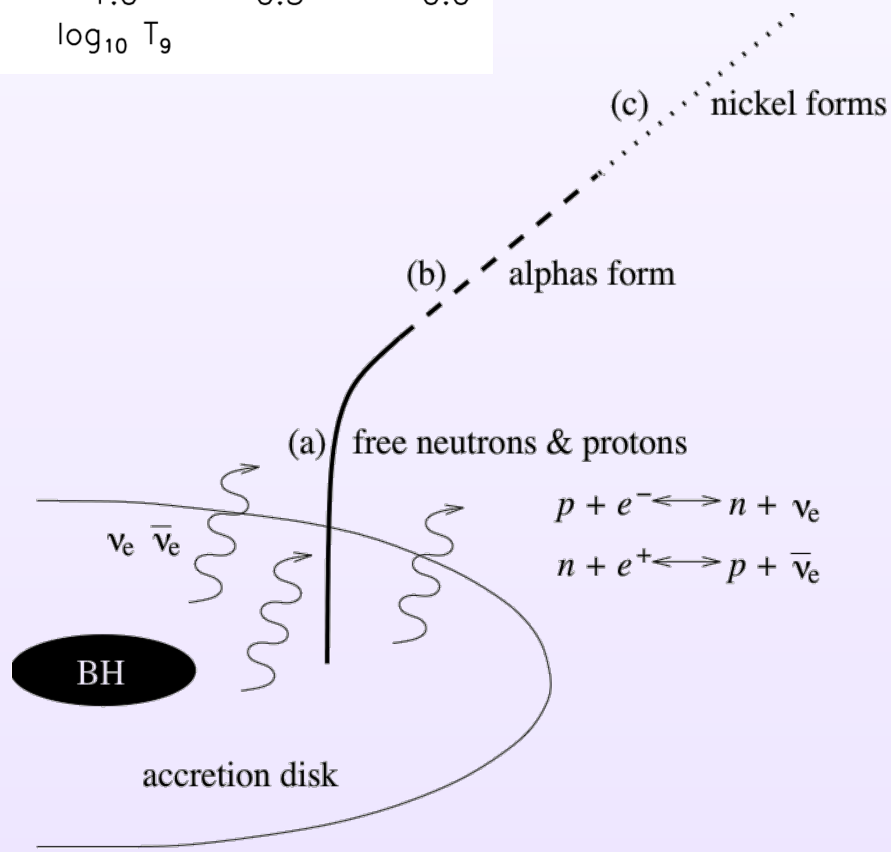
Disk models from Chen and Beloborodov (2008), neutrino calculation from Surman and McLaughlin

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

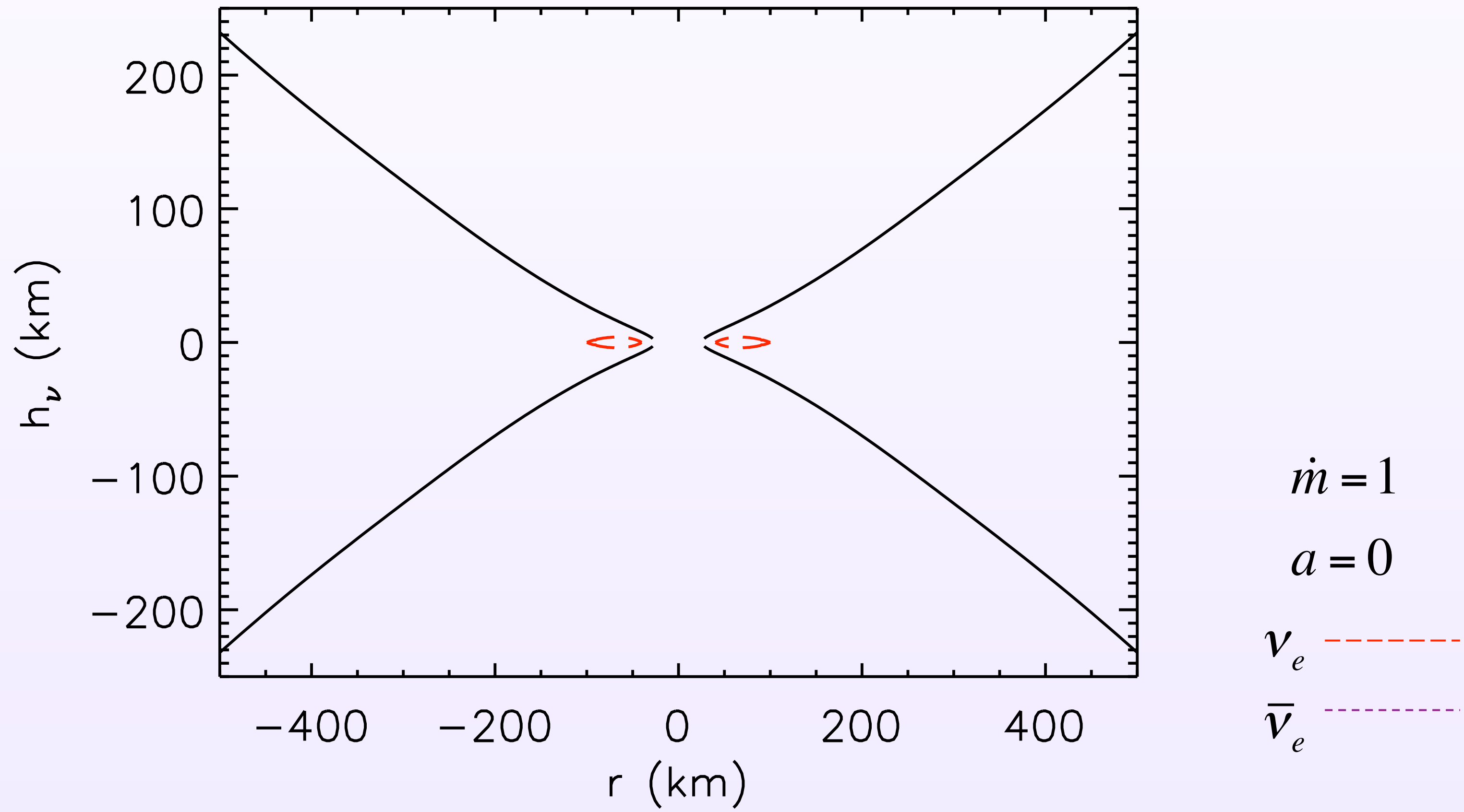
Surman, McLaughlin, Sabbatino (2011)







black hole accretion disk neutrino emission



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

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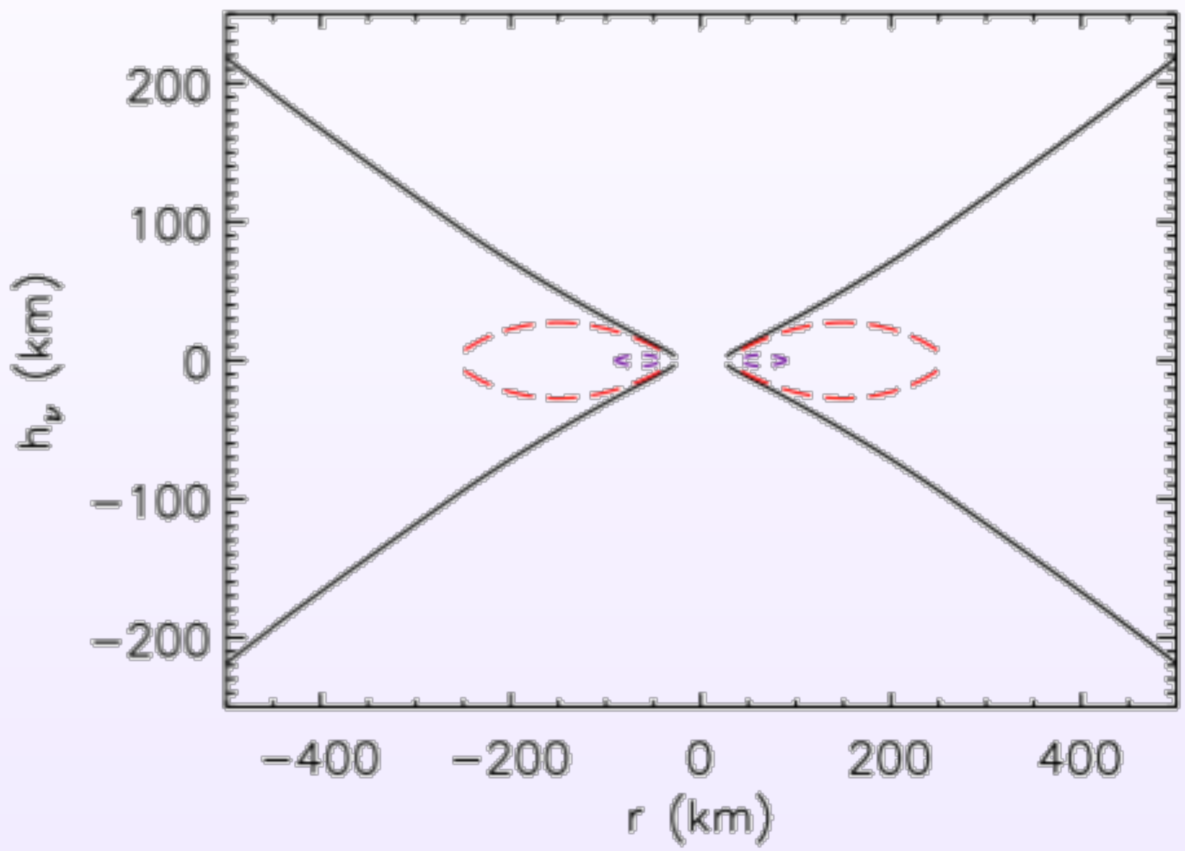
black hole accretion disk neutrino emission



$\dot{m} = 3$

$a = 0$

ν_e

$\bar{\nu}_e$

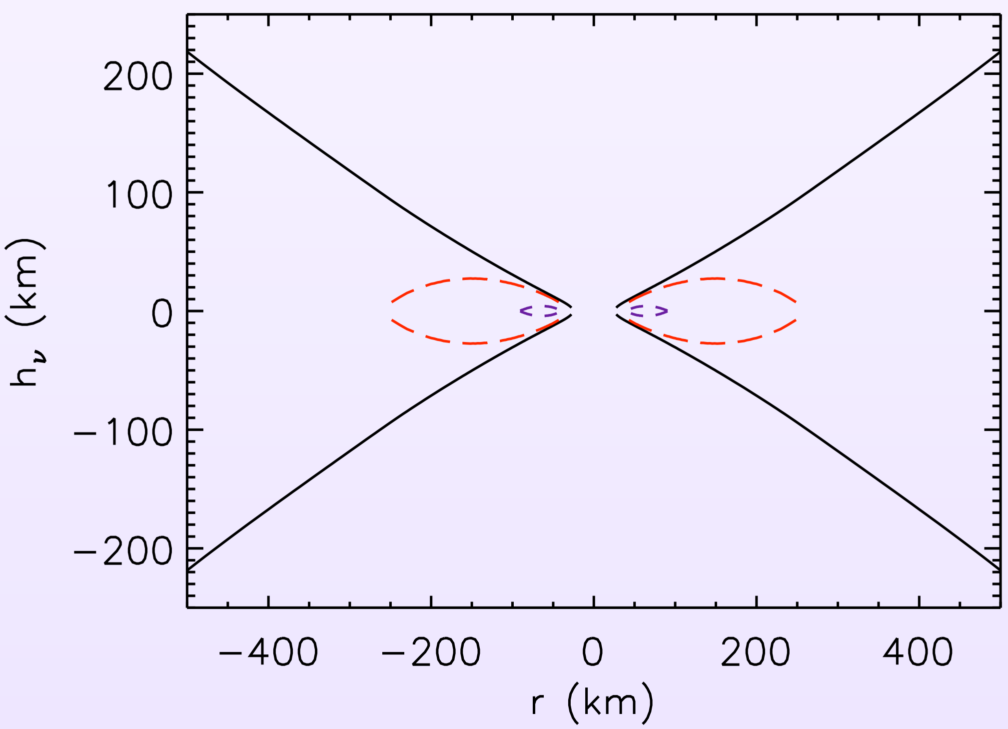
Disk model from Chen and Beloborodov (2008), neutrino decoupling surface calculation by Surman and McLaughlin

black hole accretion disk neutrino oscillations

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



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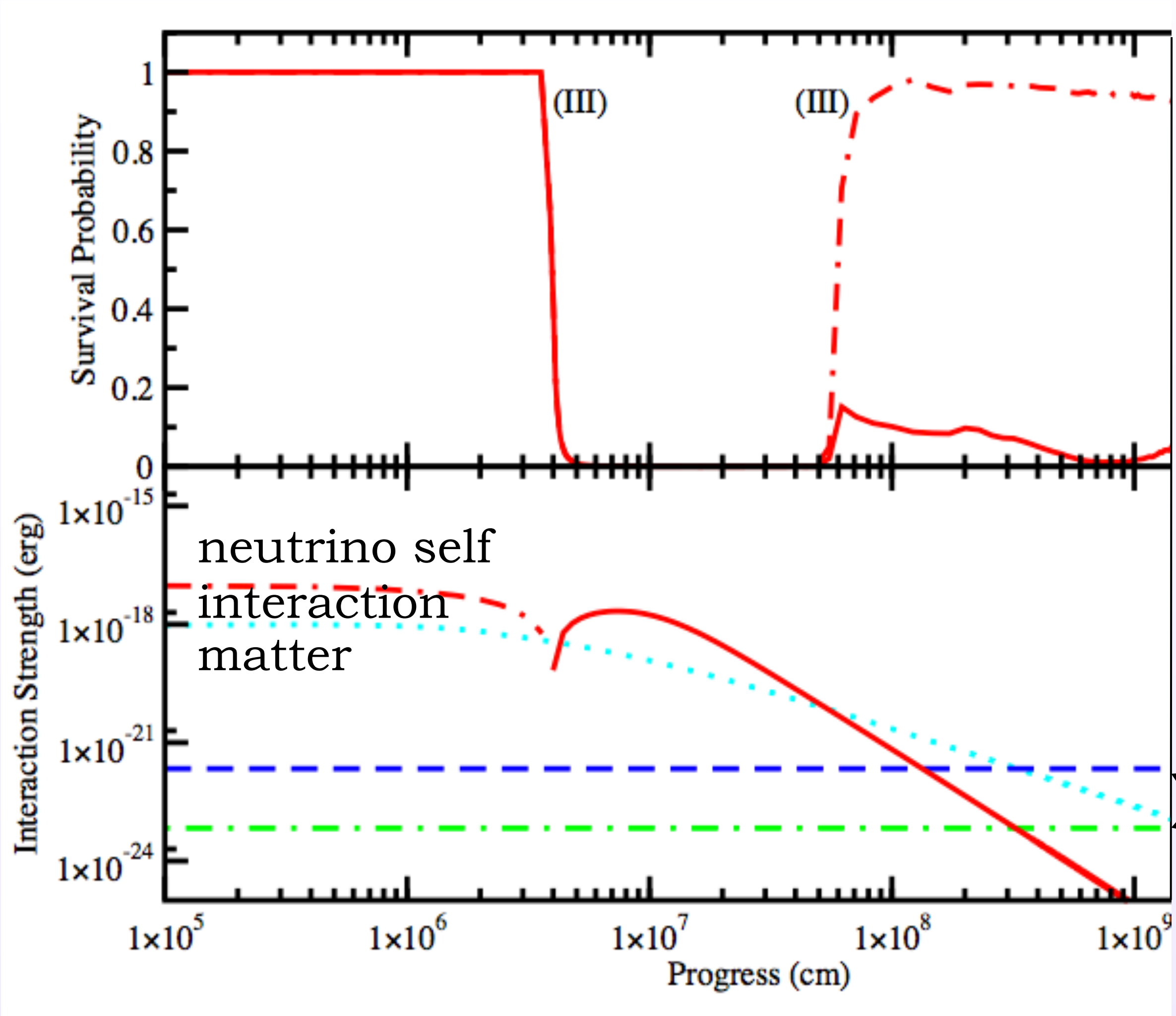
black hole accretion disk neutrino oscillations

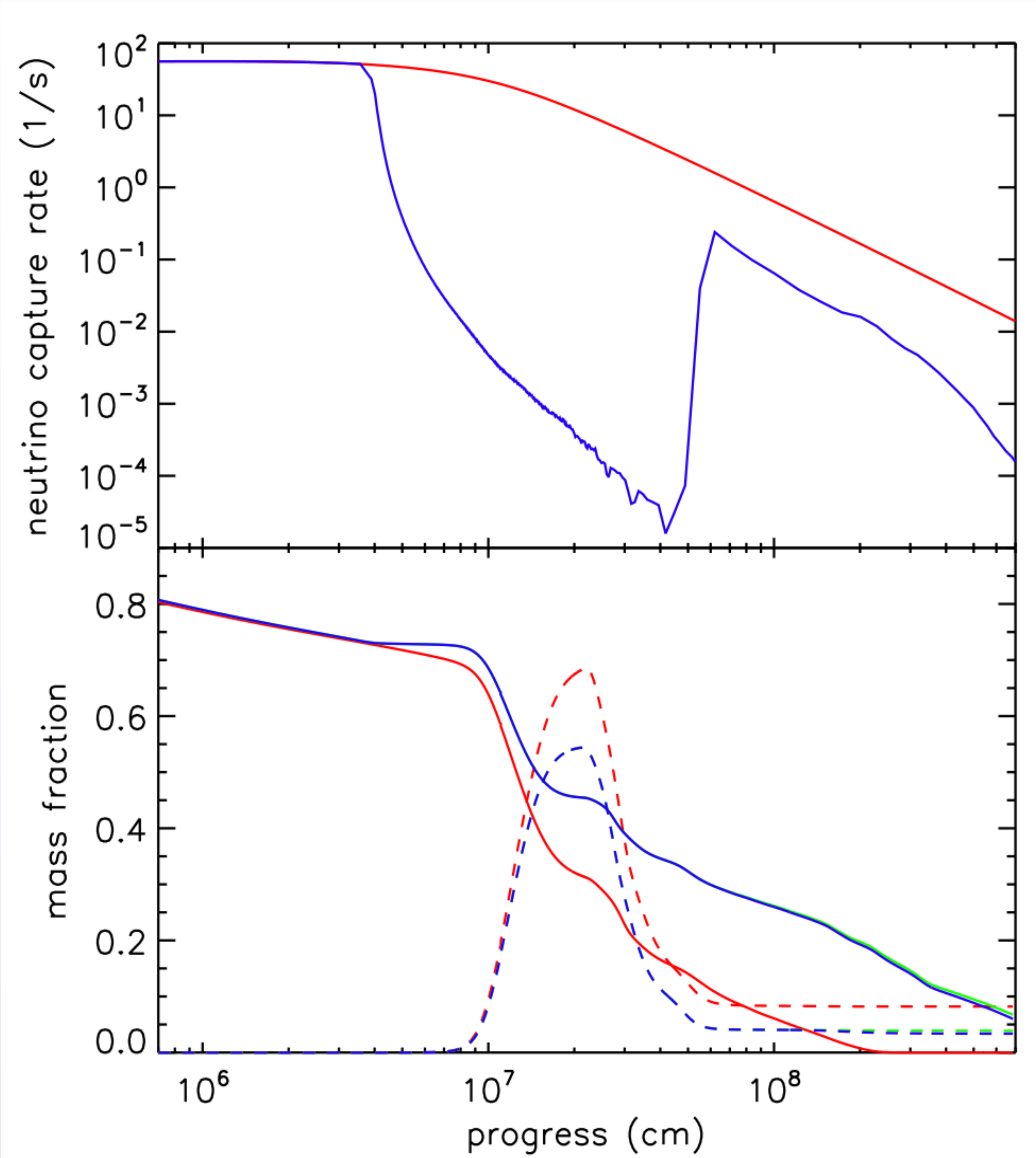


Malkus, McLaughlin, Kneller, Surman (2012)

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)

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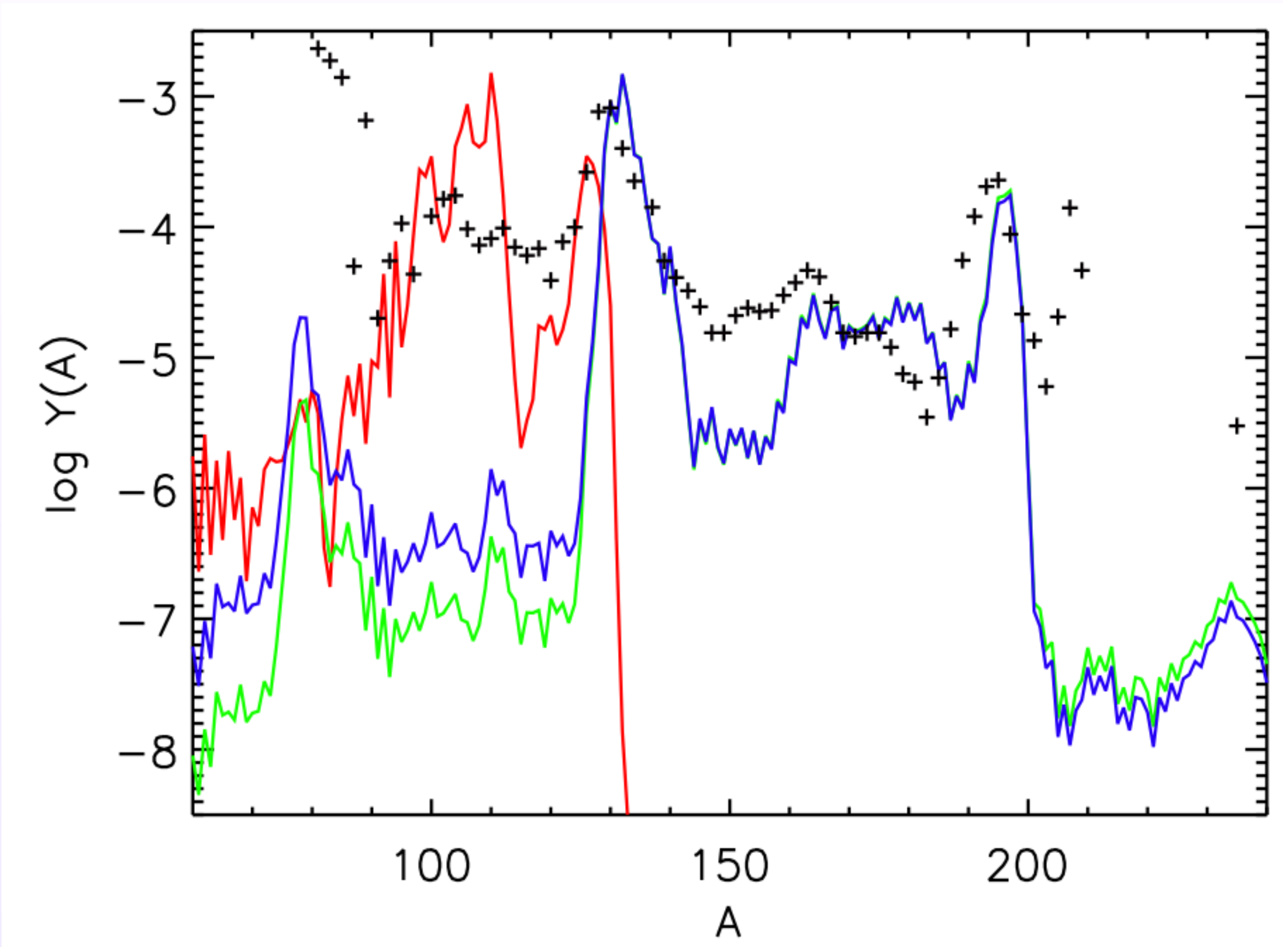
AD-BH neutrino oscillations: consequences for nucleosynthesis

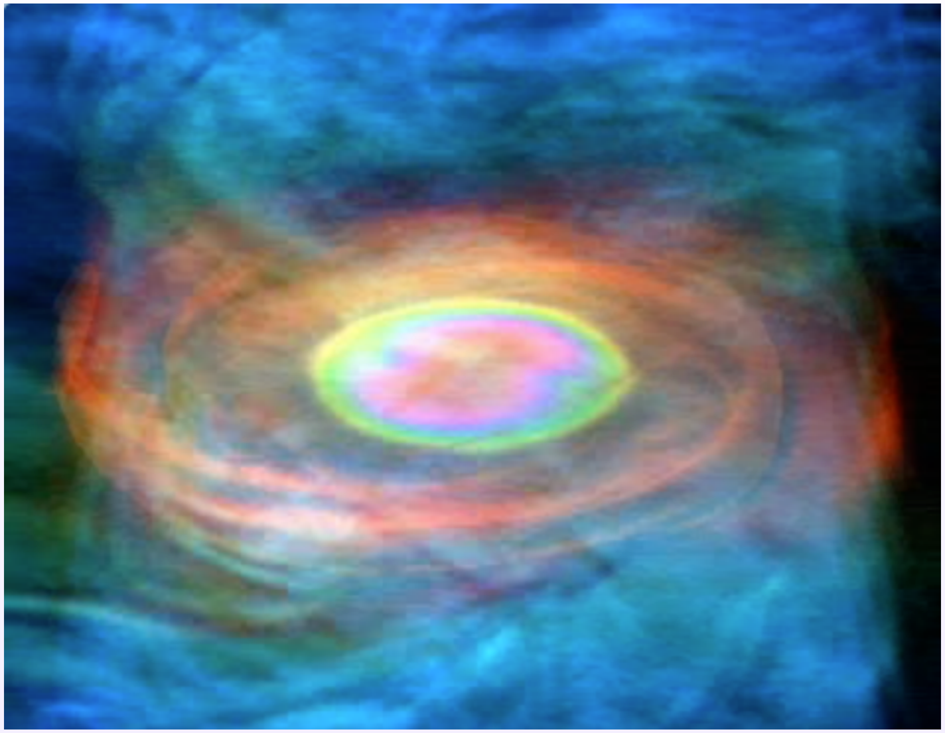


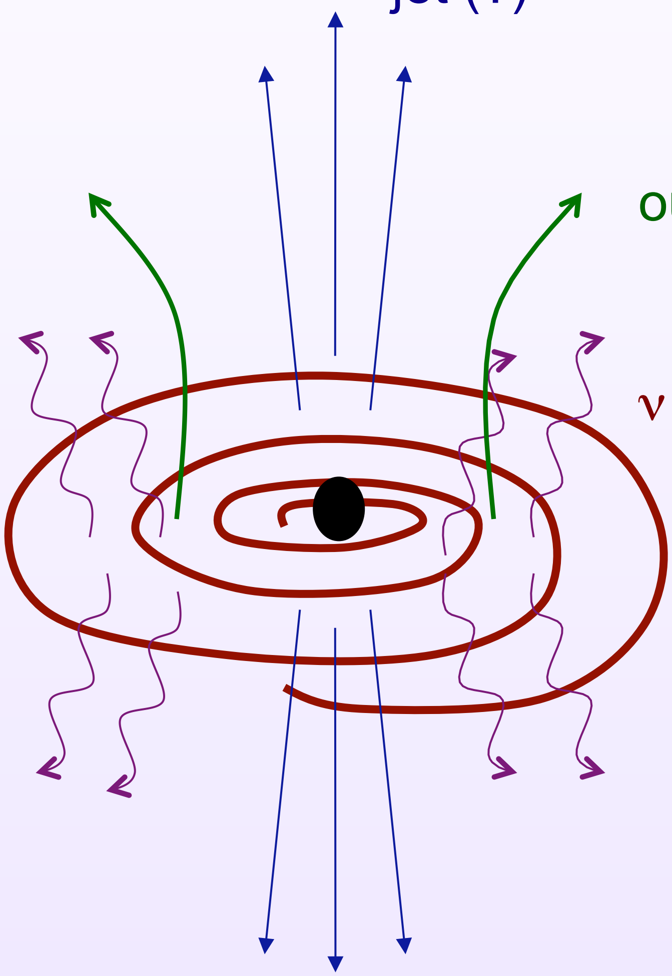
no oscillations

single angle ν oscillation calculation

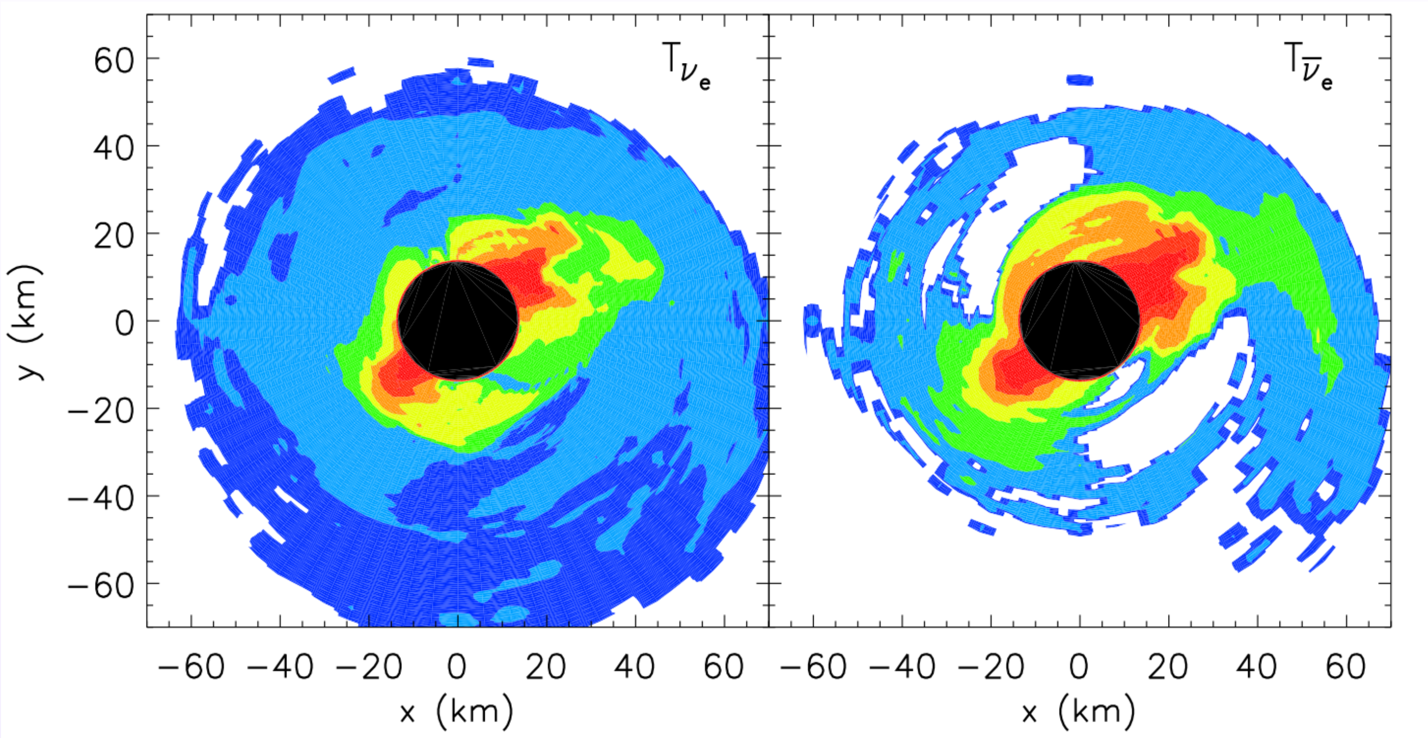
Malkus, McLaughlin, Kneller, Surman (2012)

nucleosynthesis from a merger black hole accretion disk





nucleosynthesis from a merger black hole accretion disk



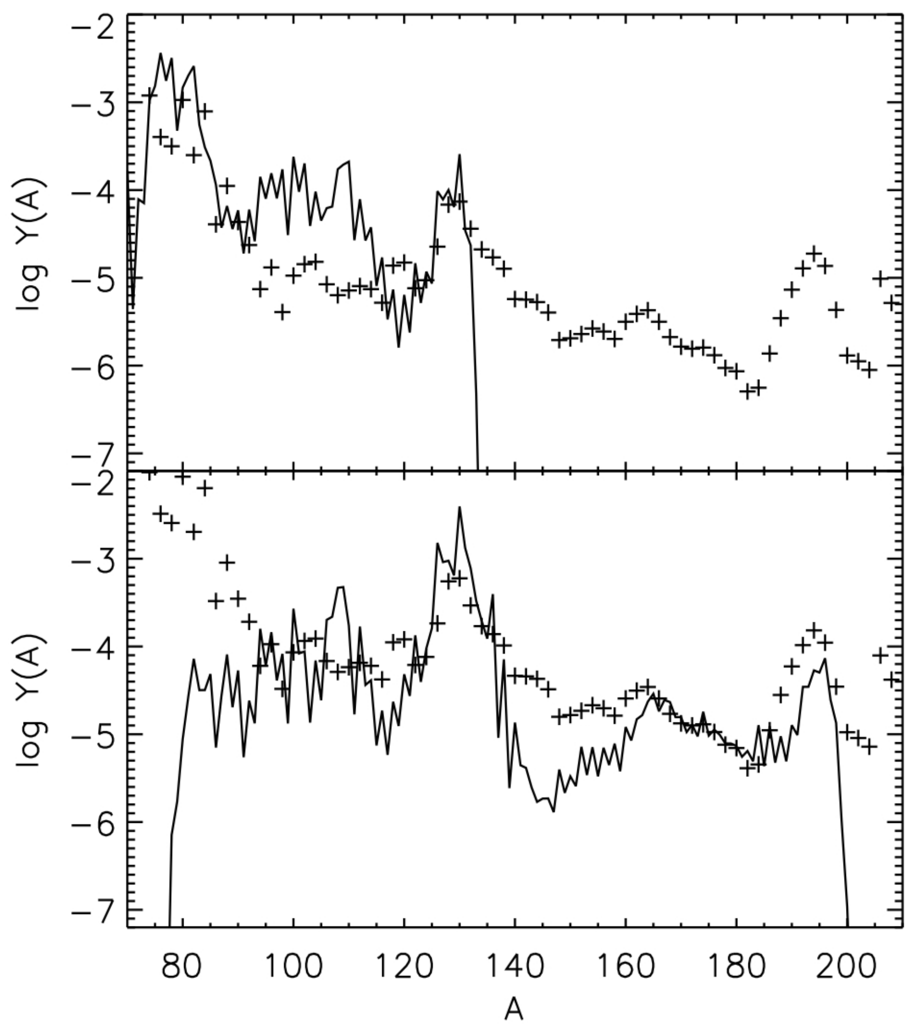
Surman, McLaughlin,
Ruffert, Janka, Hix (2008)

nucleosynthesis from a merger black hole accretion disk

Assume an adiabatic wind with

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

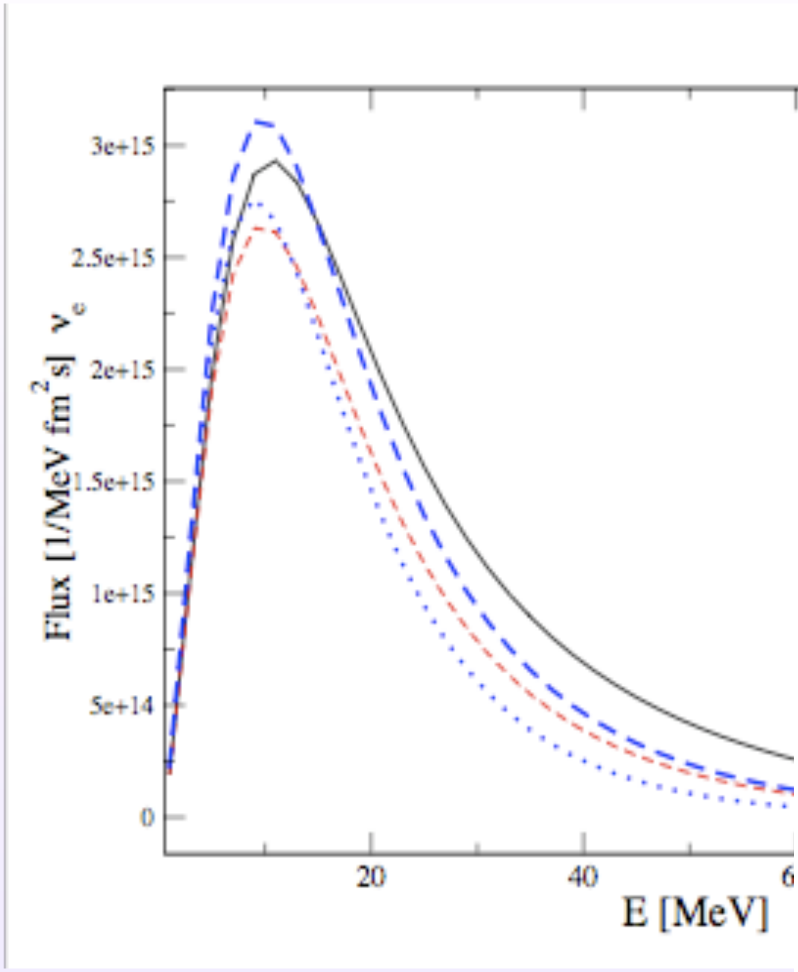
Surman, McLaughlin, Ruffert, Janka, Hix (2008)



low *s/k*,
fast acceleration

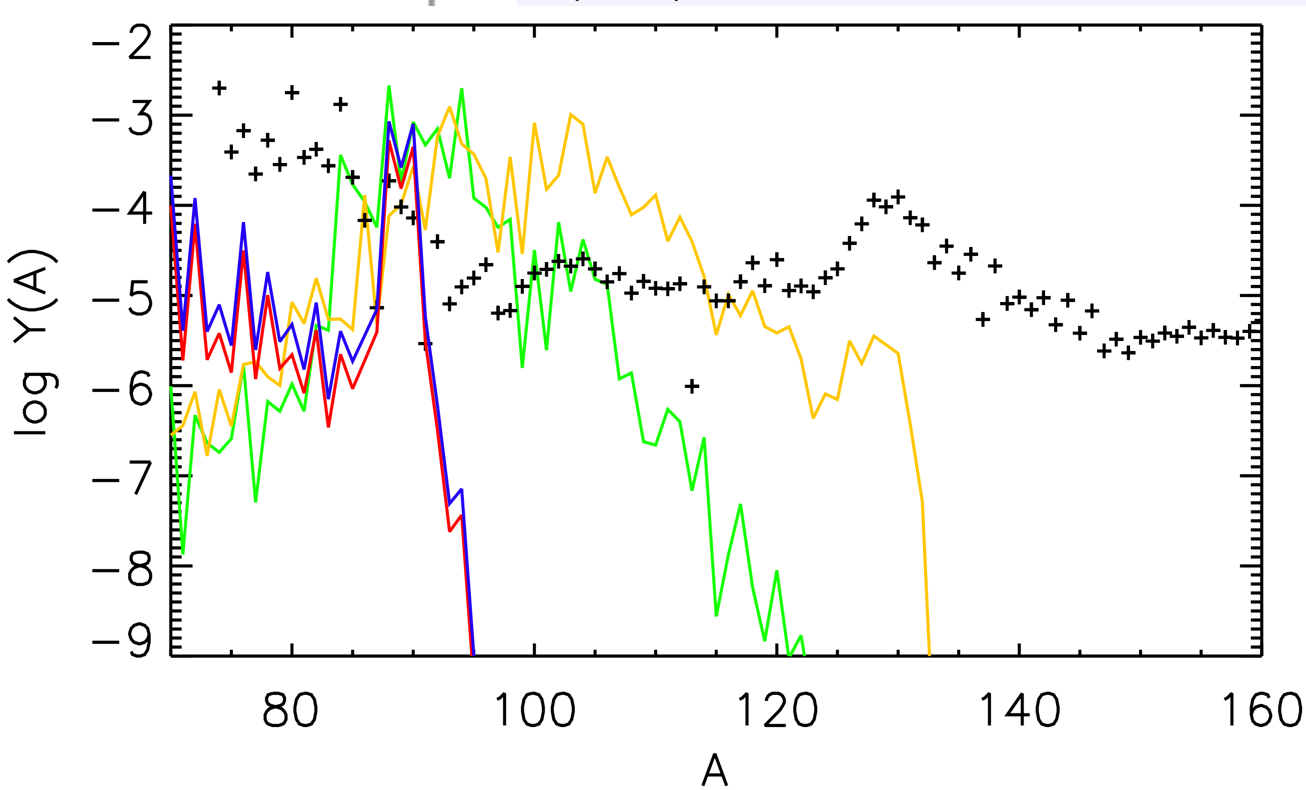
high *s/k*,
slower acceleration

general relativistic effects on the neutrino spectra



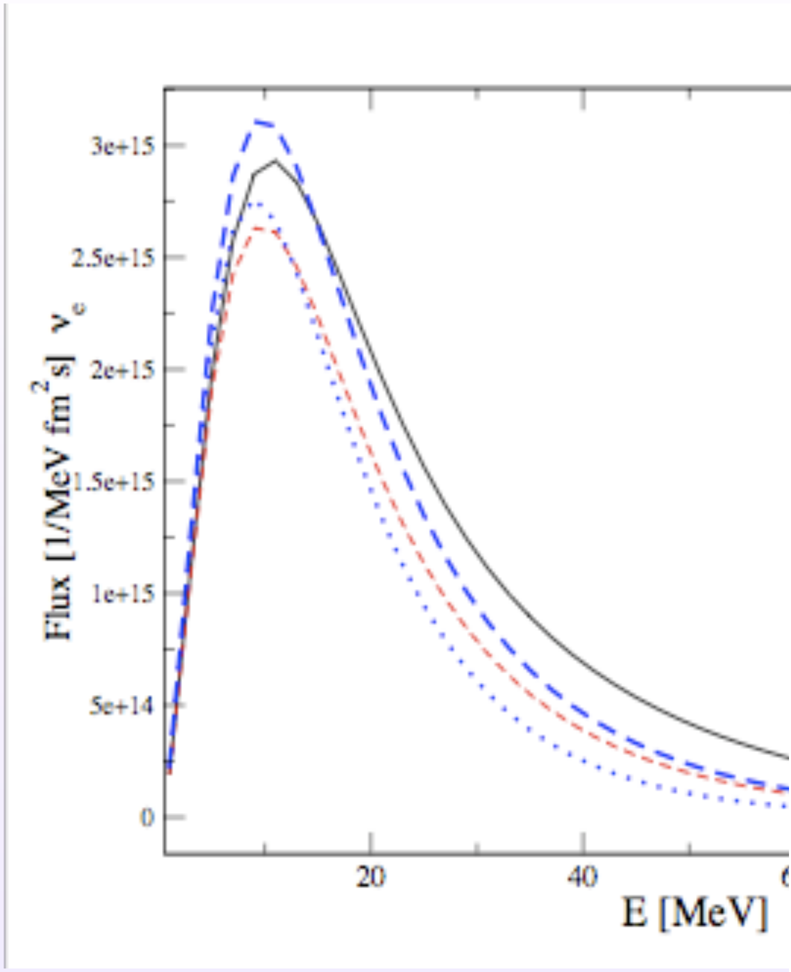
no GR
redshift, bending
+ rotation
+ Kerr metric for redshift

Caballero, McLaughlin, Surman (2011)



high *s/k*,
slower acceleration

general relativistic effects on the neutrino spectra



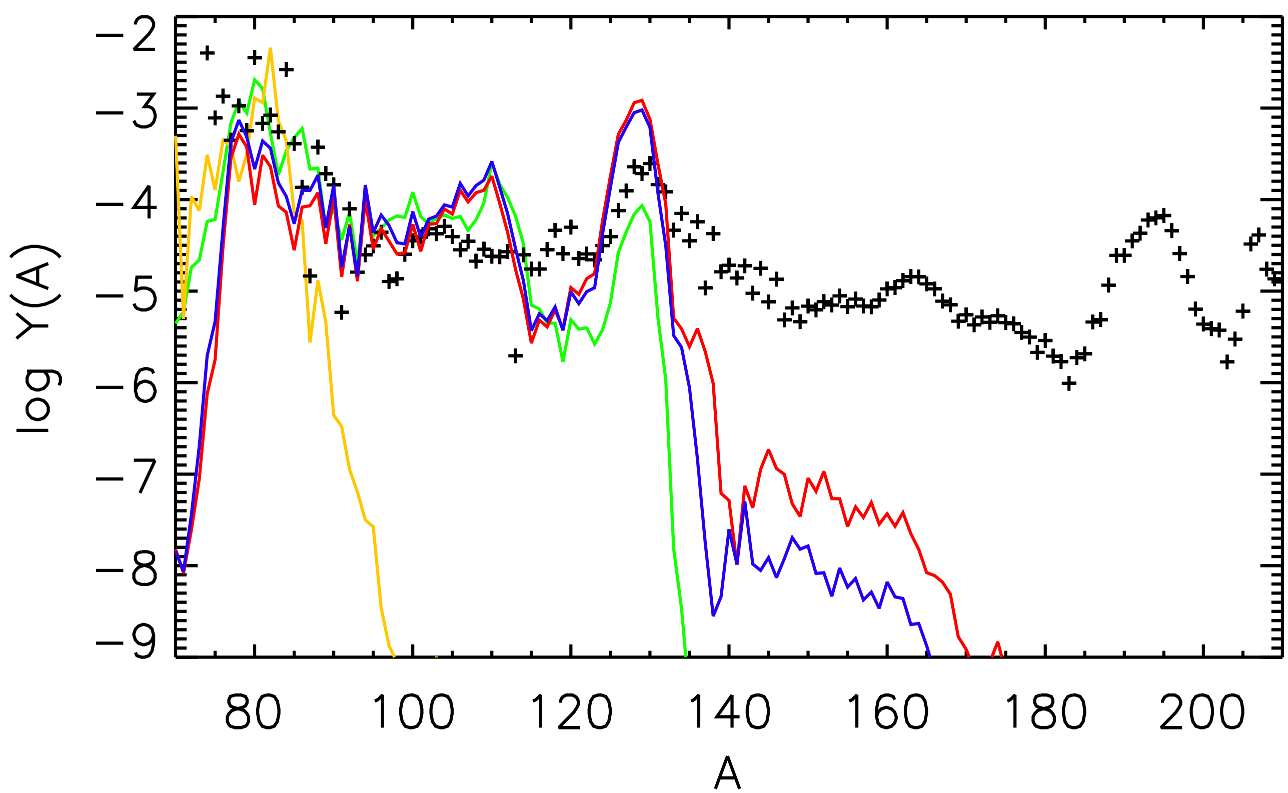
no GR

redshift, bending

+ rotation

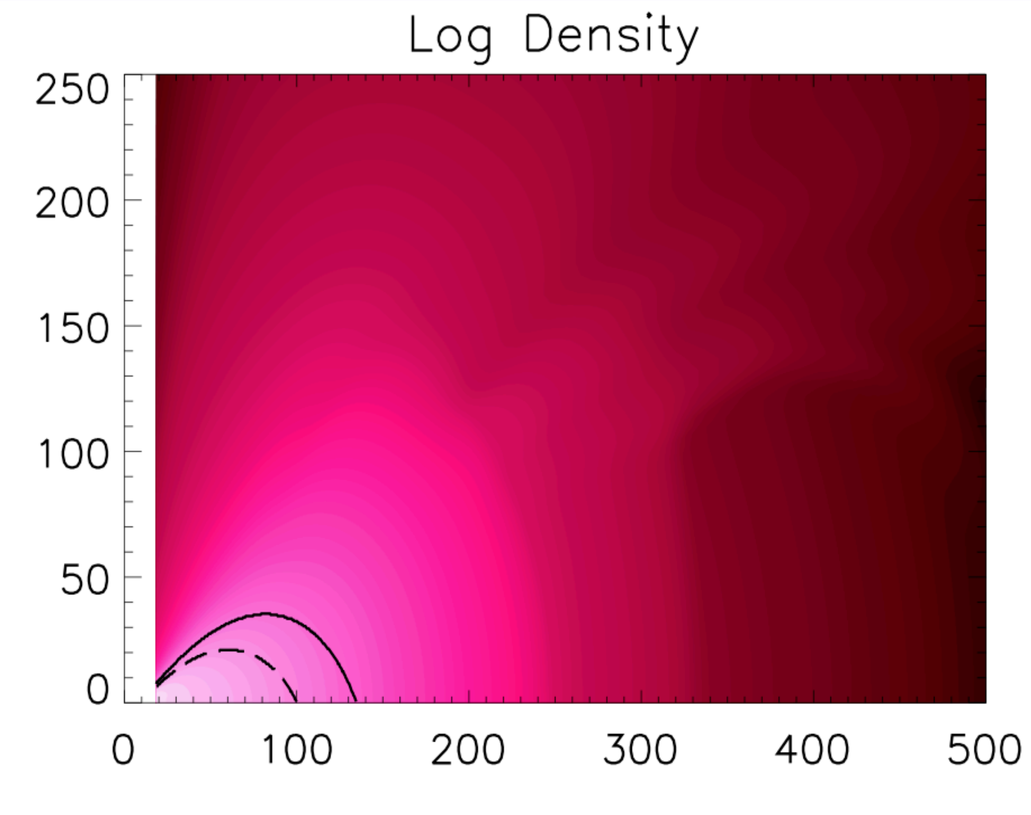
+ Kerr metric for redshift

Caballero, McLaughlin, Surman (2011)

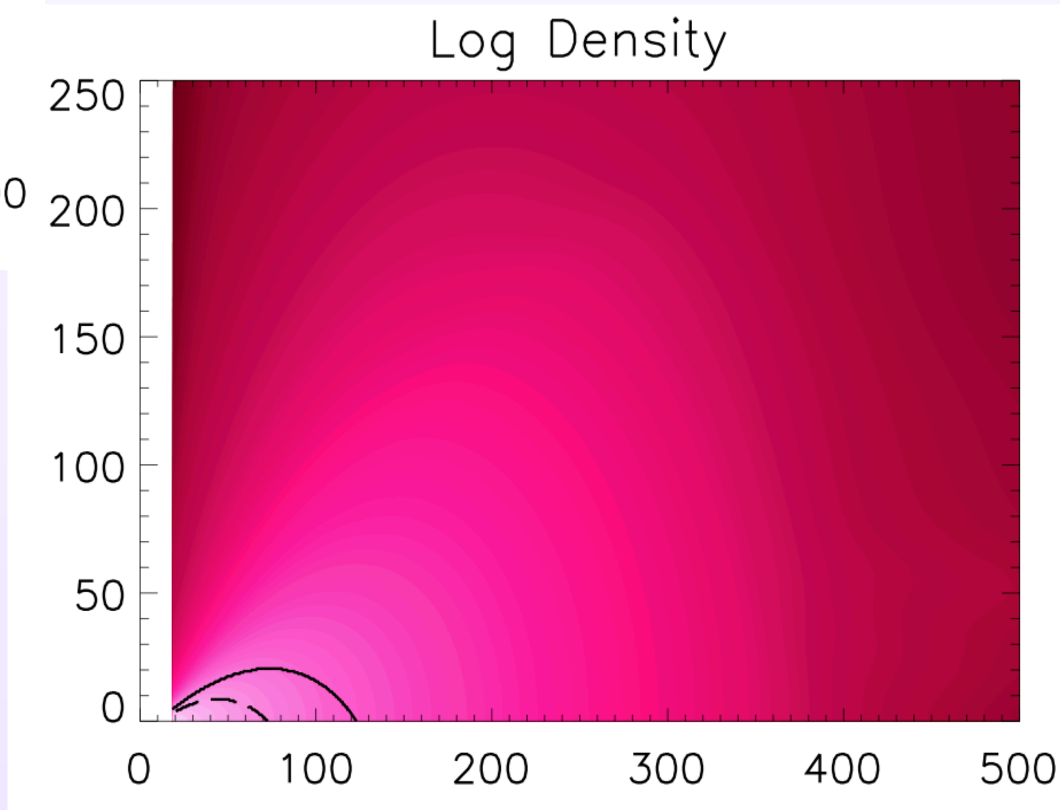


low *s/k*,
fast acceleration

nucleosynthesis from a time-dependent merger disk



t = 20 ms



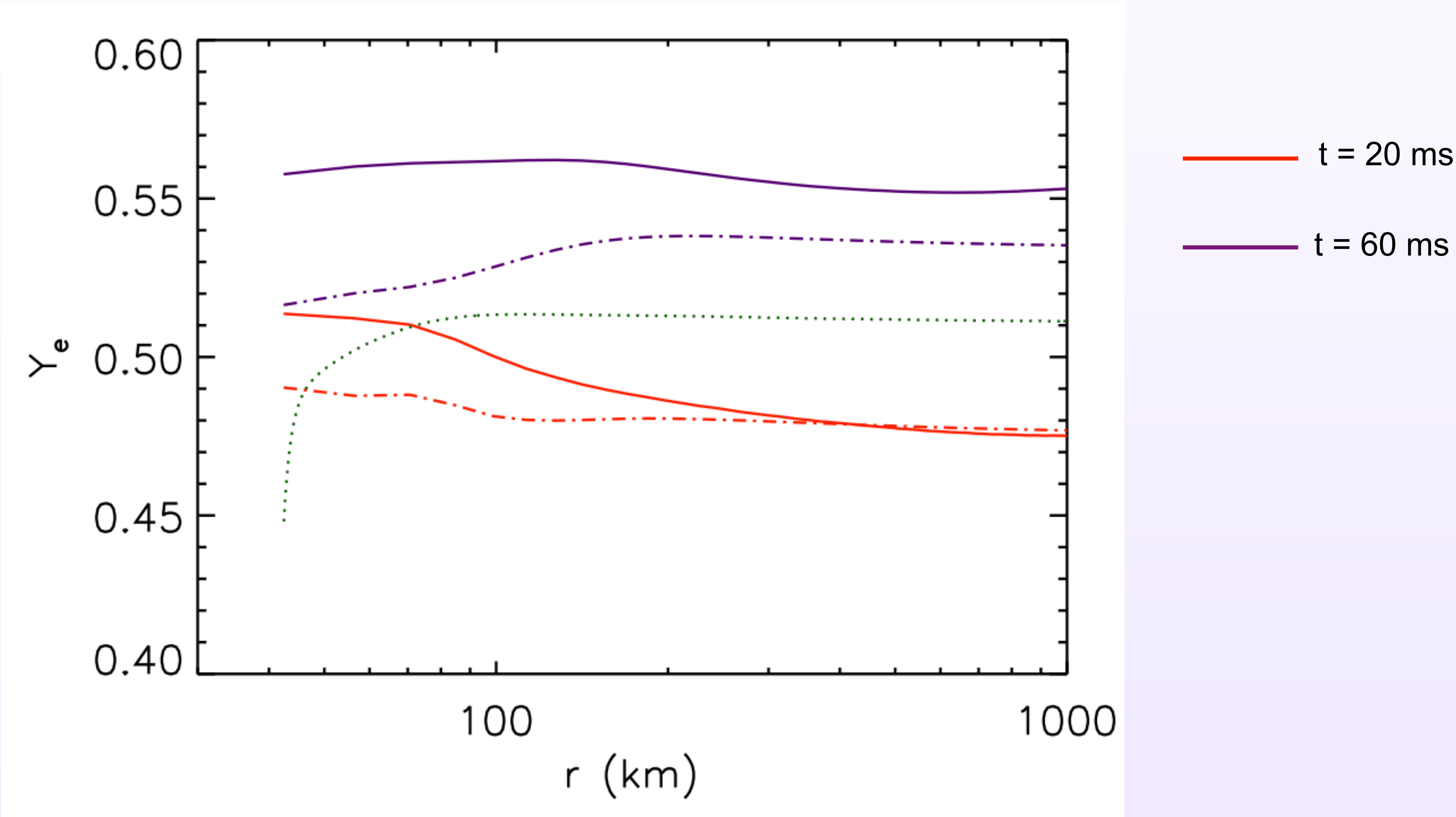
Disk model from H.-Th. Janka

Neutrino decoupling surface calculation by L. Caballero

t = 60 ms

nucleosynthesis from a time-dependent merger disk

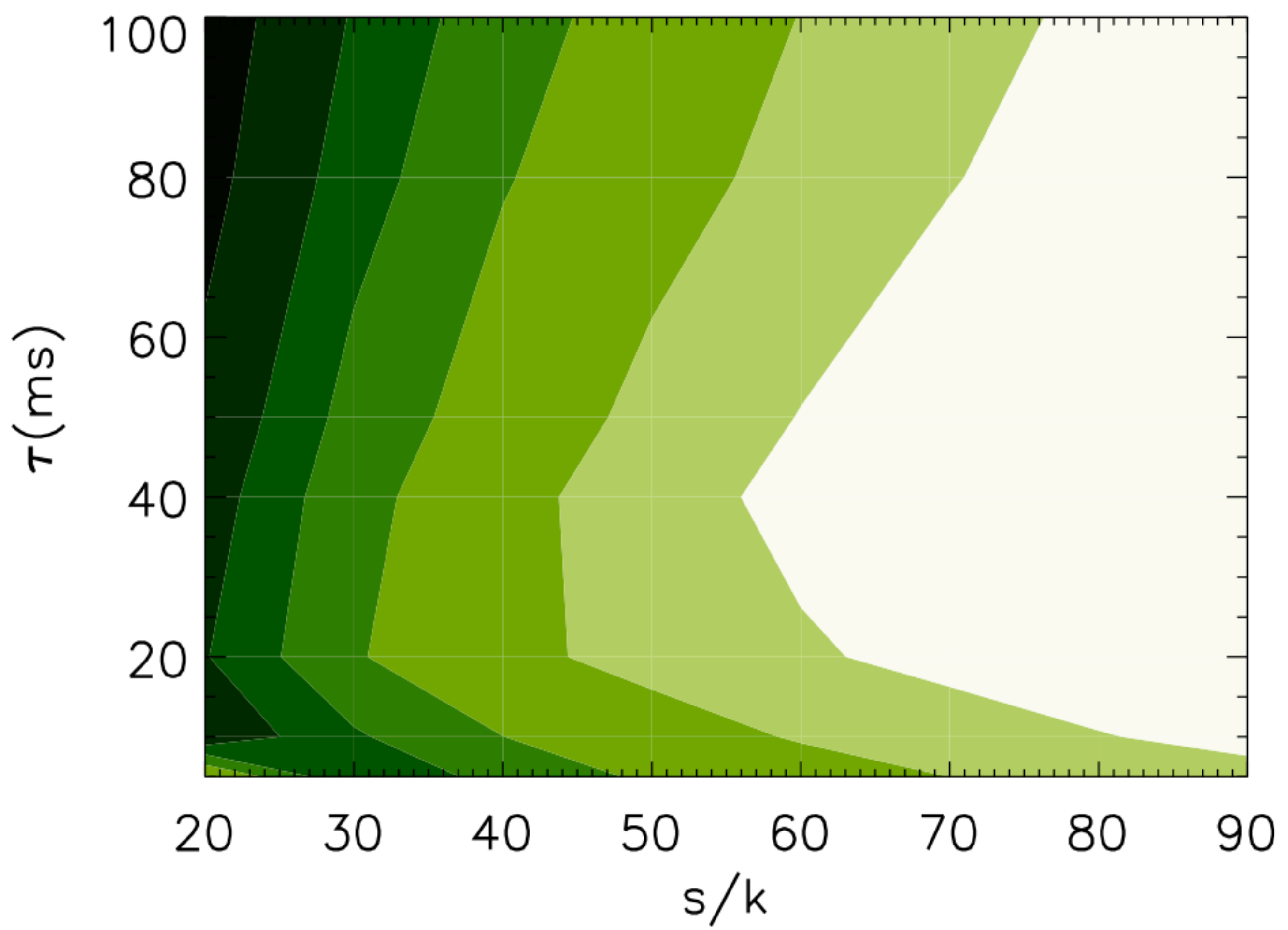
neutrino-only equilibrium electron fractions



Caballero, McLaughlin, Surman, in preparation

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

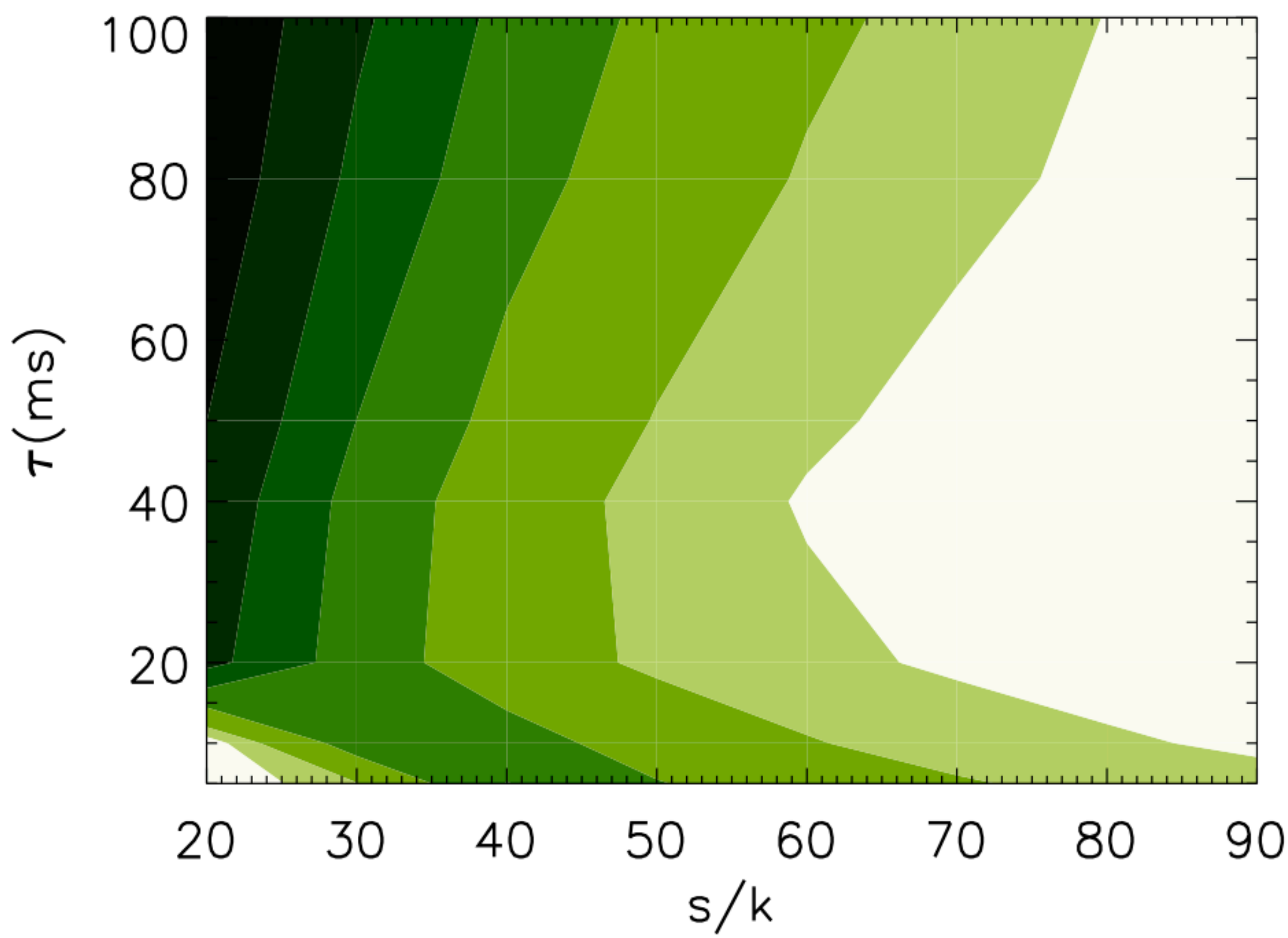
with GR



Caballero, McLaughlin, Surman, in preparation

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

no GR



Caballero, McLaughlin, Surman, in preparation

summary

Neutrinos play a key role in heavy element synthesis in supernovae and 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