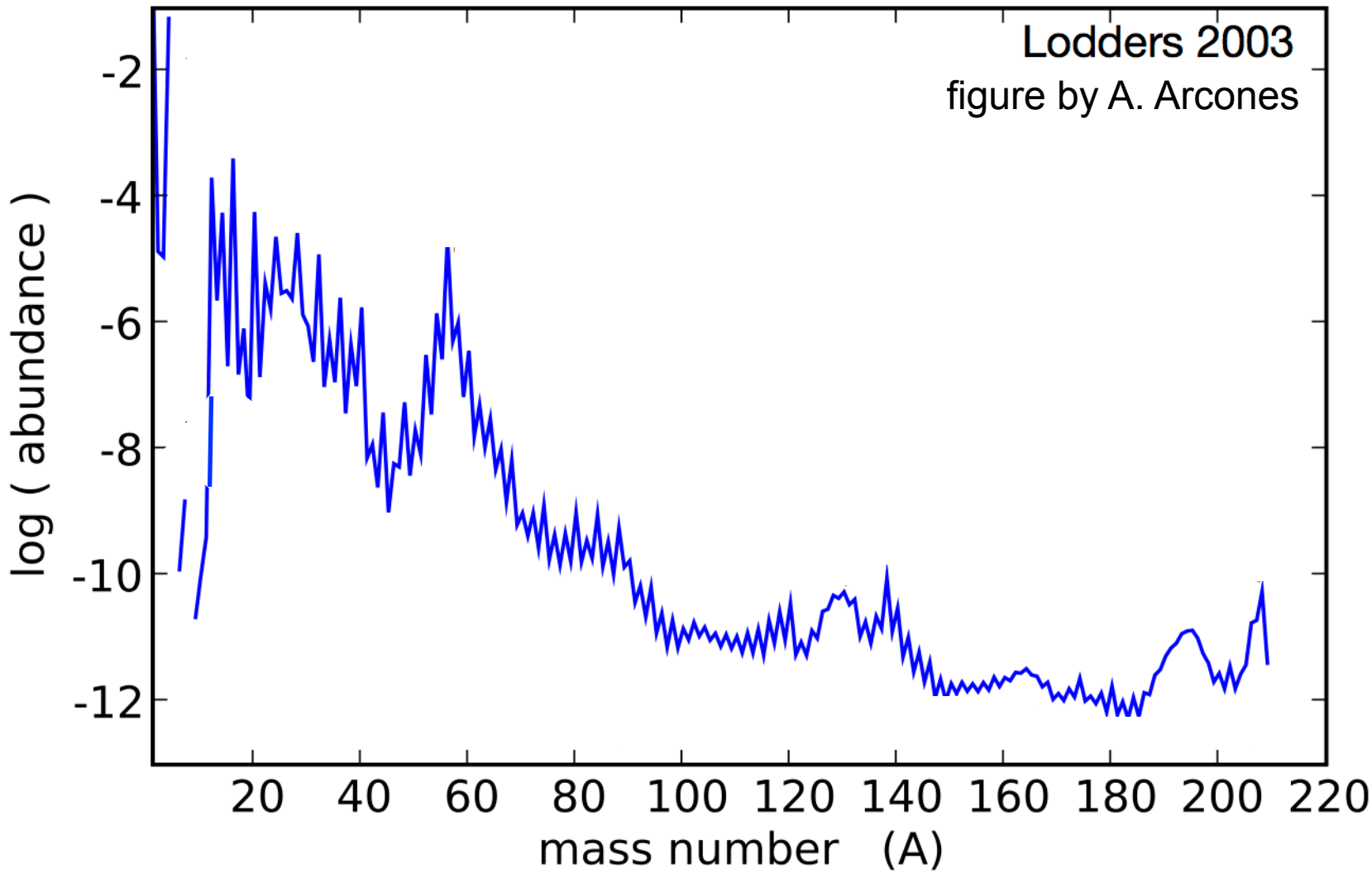
neutrinos and supernova nucleosynthesis

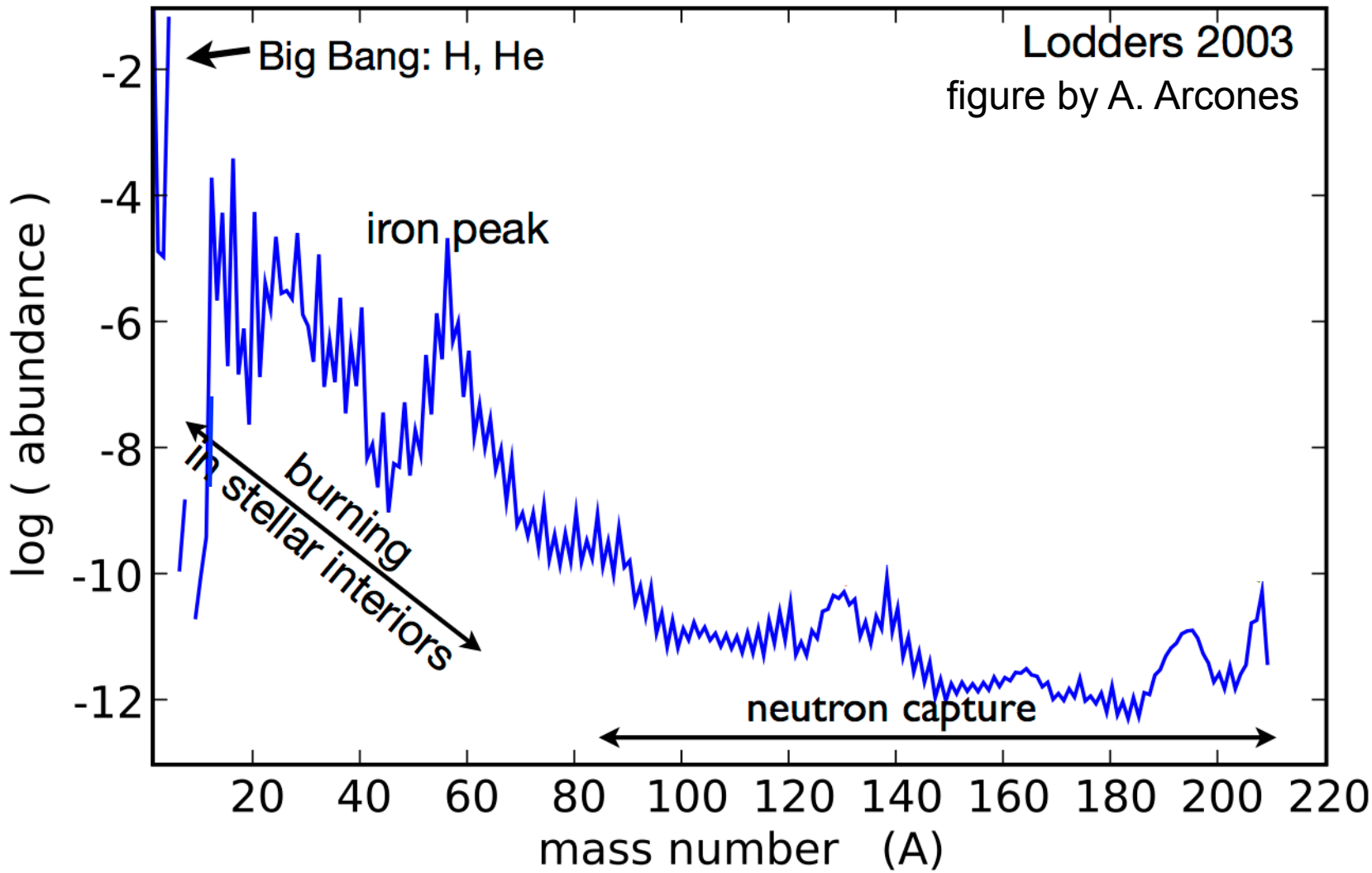
Santa Fe LBNE Workshop
26 April 2014

Rebecca Surman
Union College

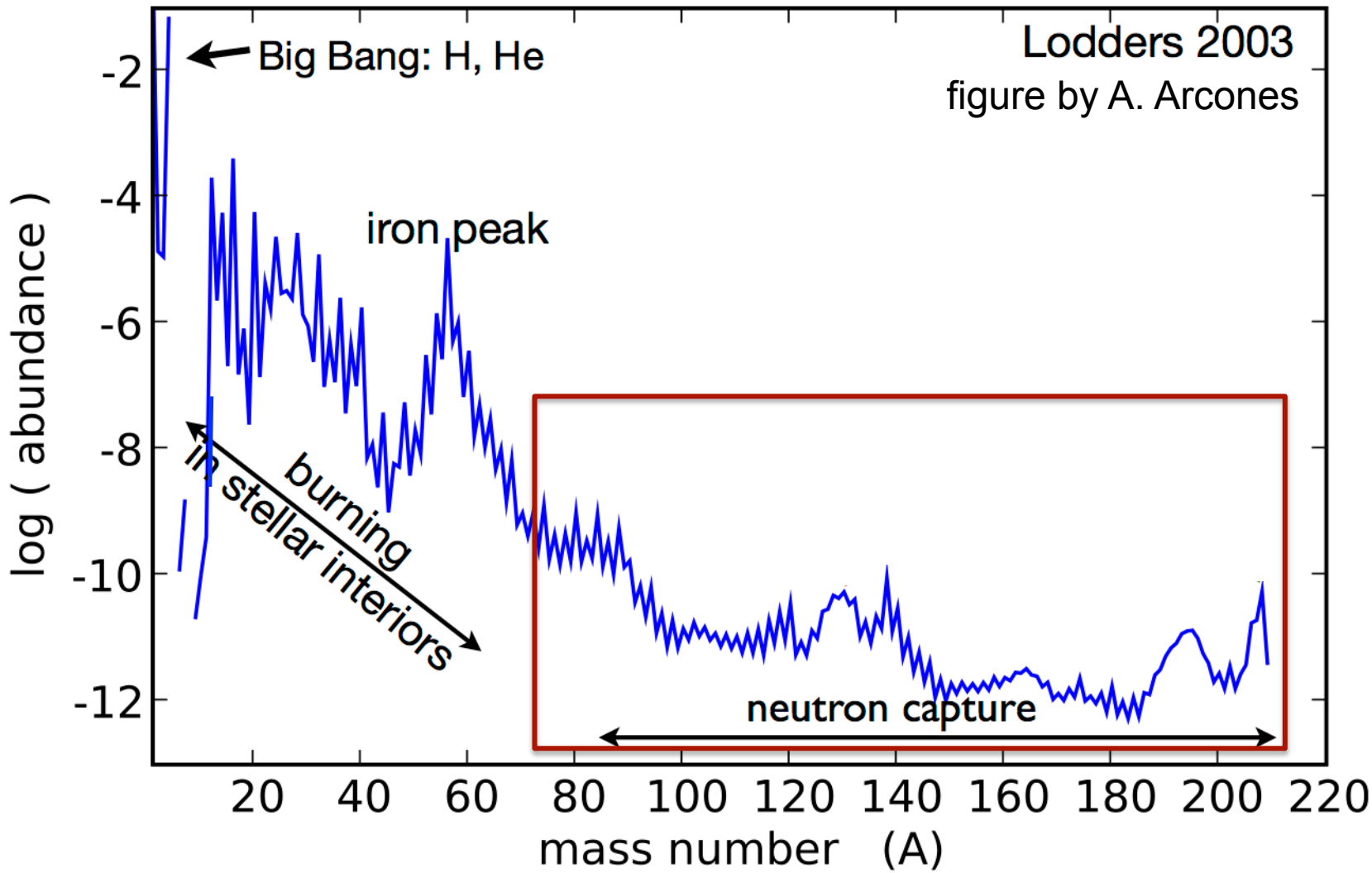
solar system abundances



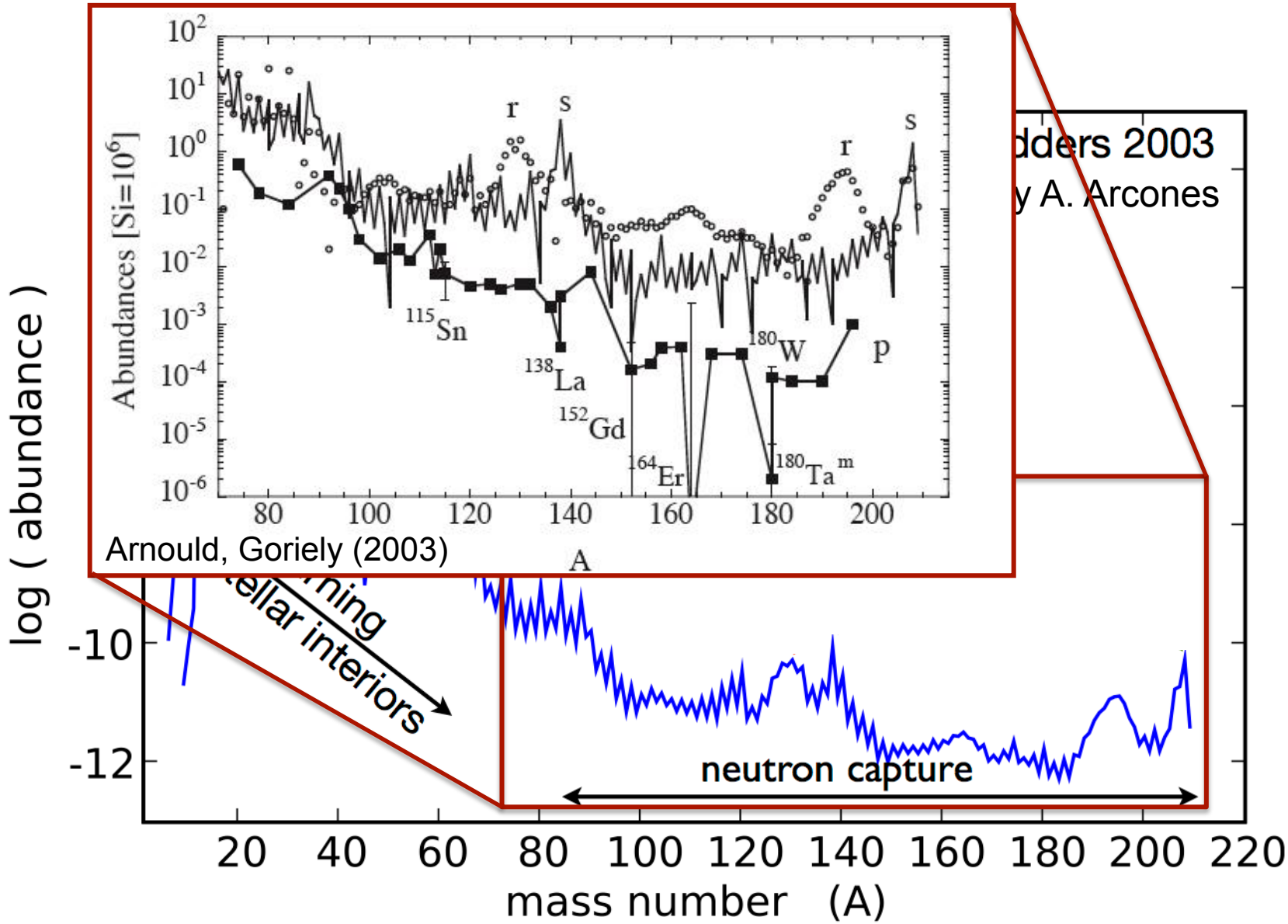
origins of the solar system abundances



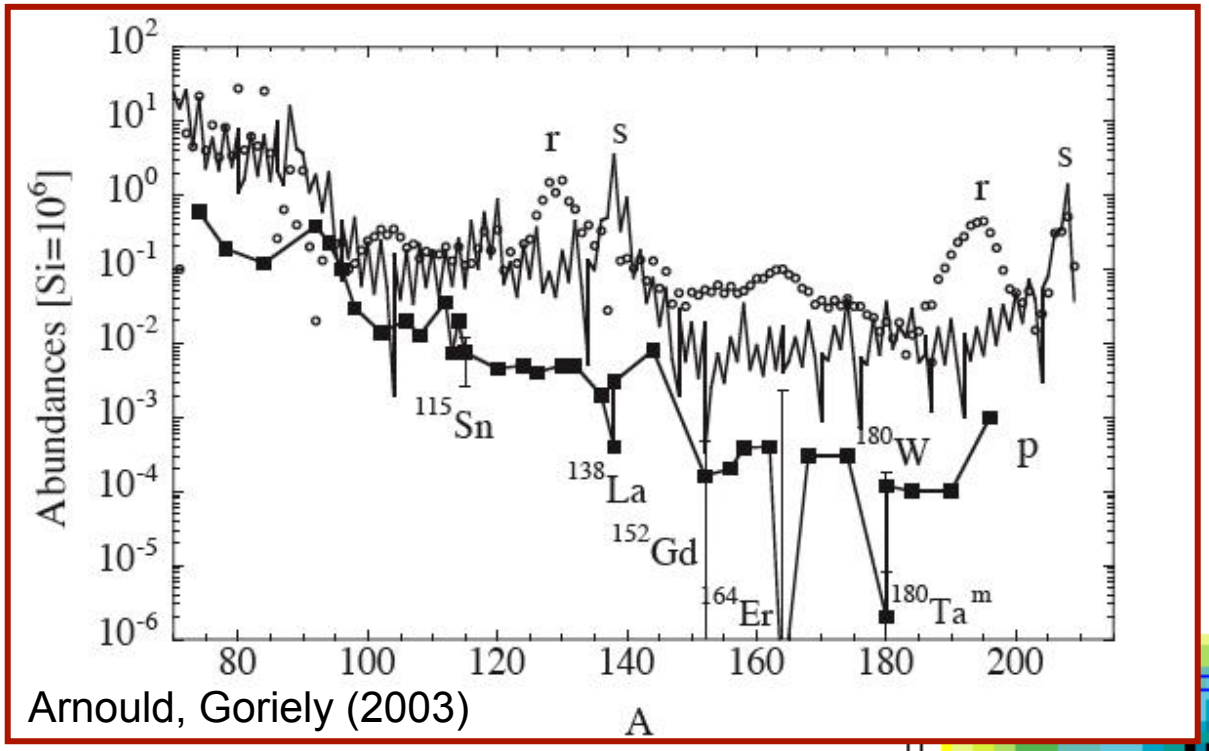
origins of the solar system abundances



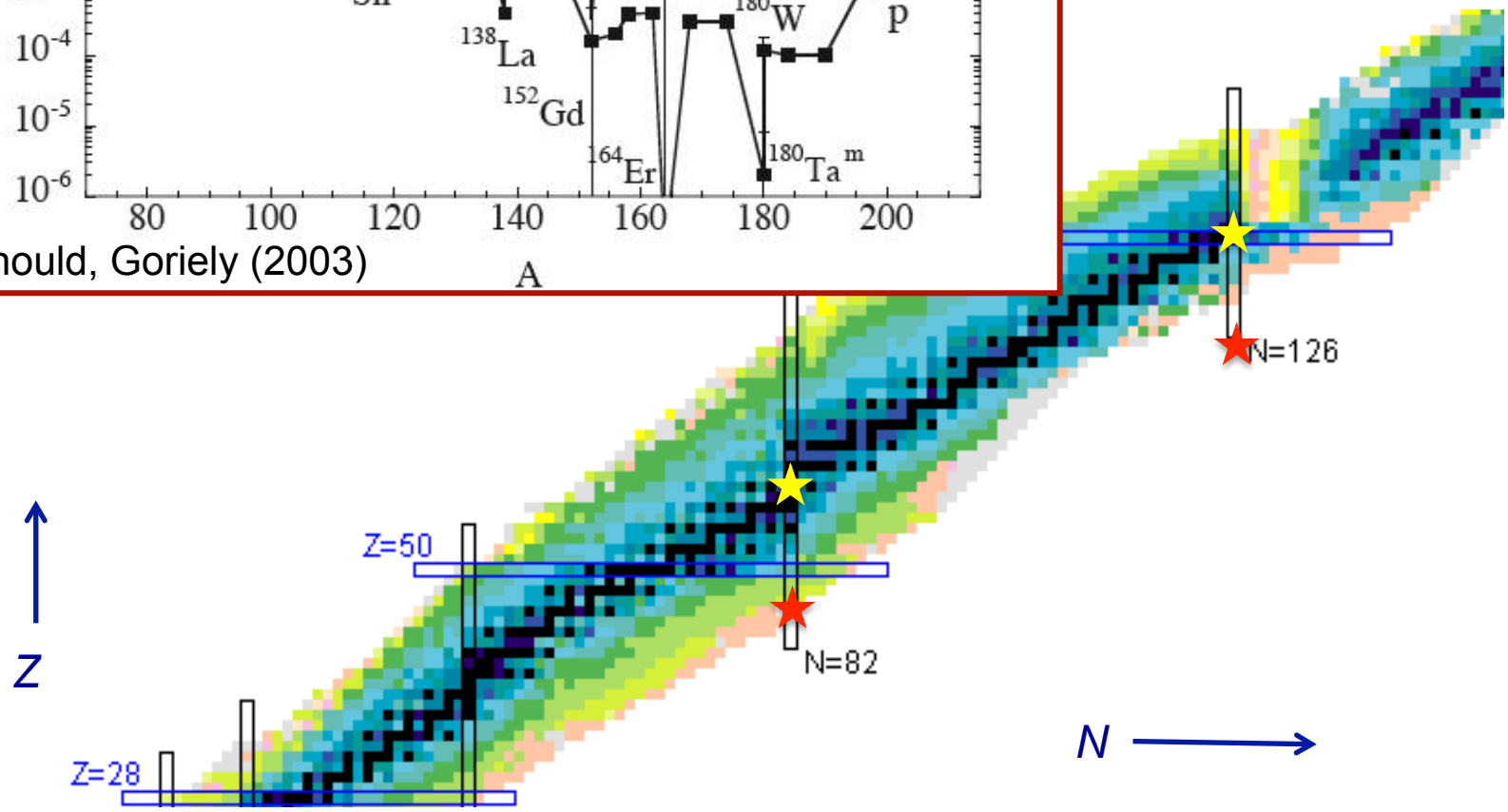
solar system abundances of heavy nuclei



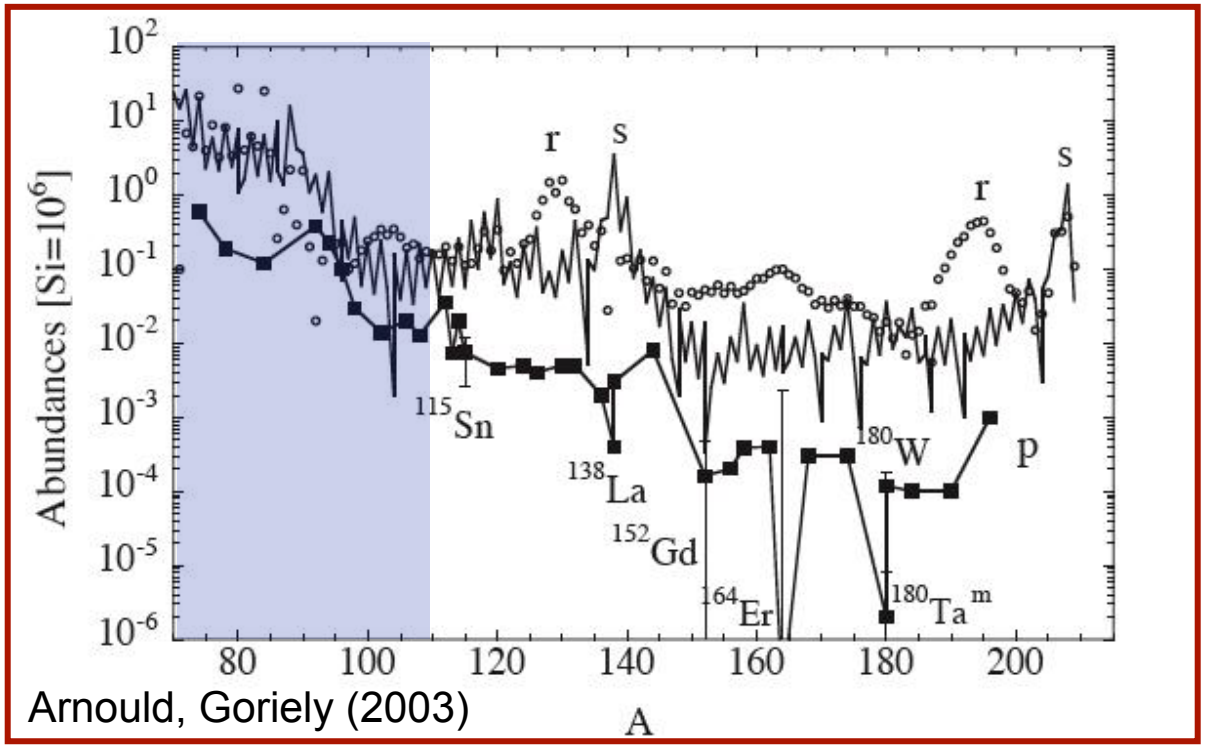
solar system abundances of heavy nuclei



Arnould, Goriely (2003)



solar system abundances of 80<*A*<100 nuclei



Arnould, Goriely (2003)

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

neutrinos and nucleosynthesis

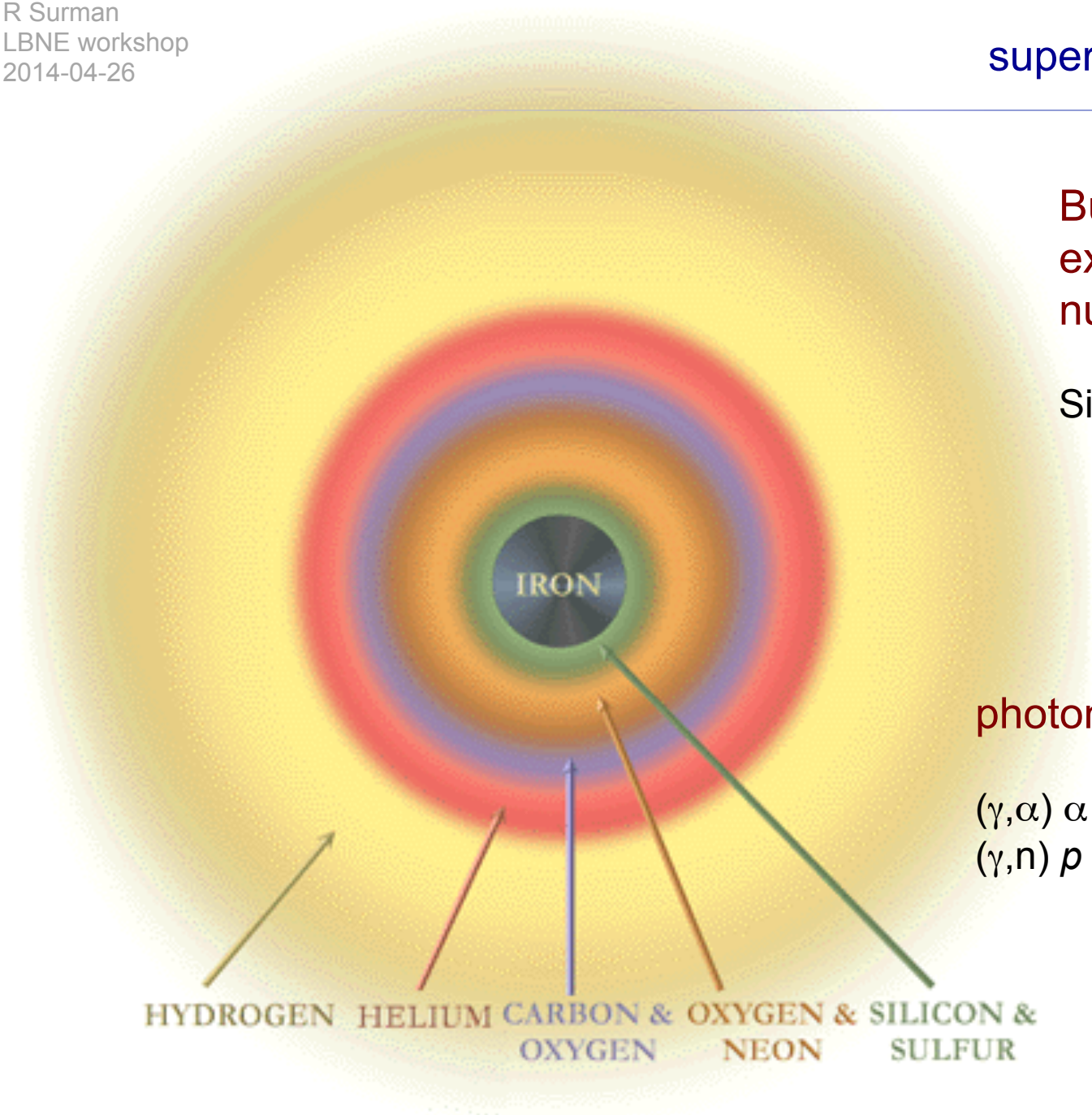
Many rare nuclear species whose origins are not fully understood are formed either directly by neutrino interactions or in neutrino-rich environments

LBNE science goals are linked to some of the key open questions in nuclear astrophysics

Here will focus on:

How do supernovae contribute to the galactic inventory of rare nuclear species?

supernova nucleosynthesis



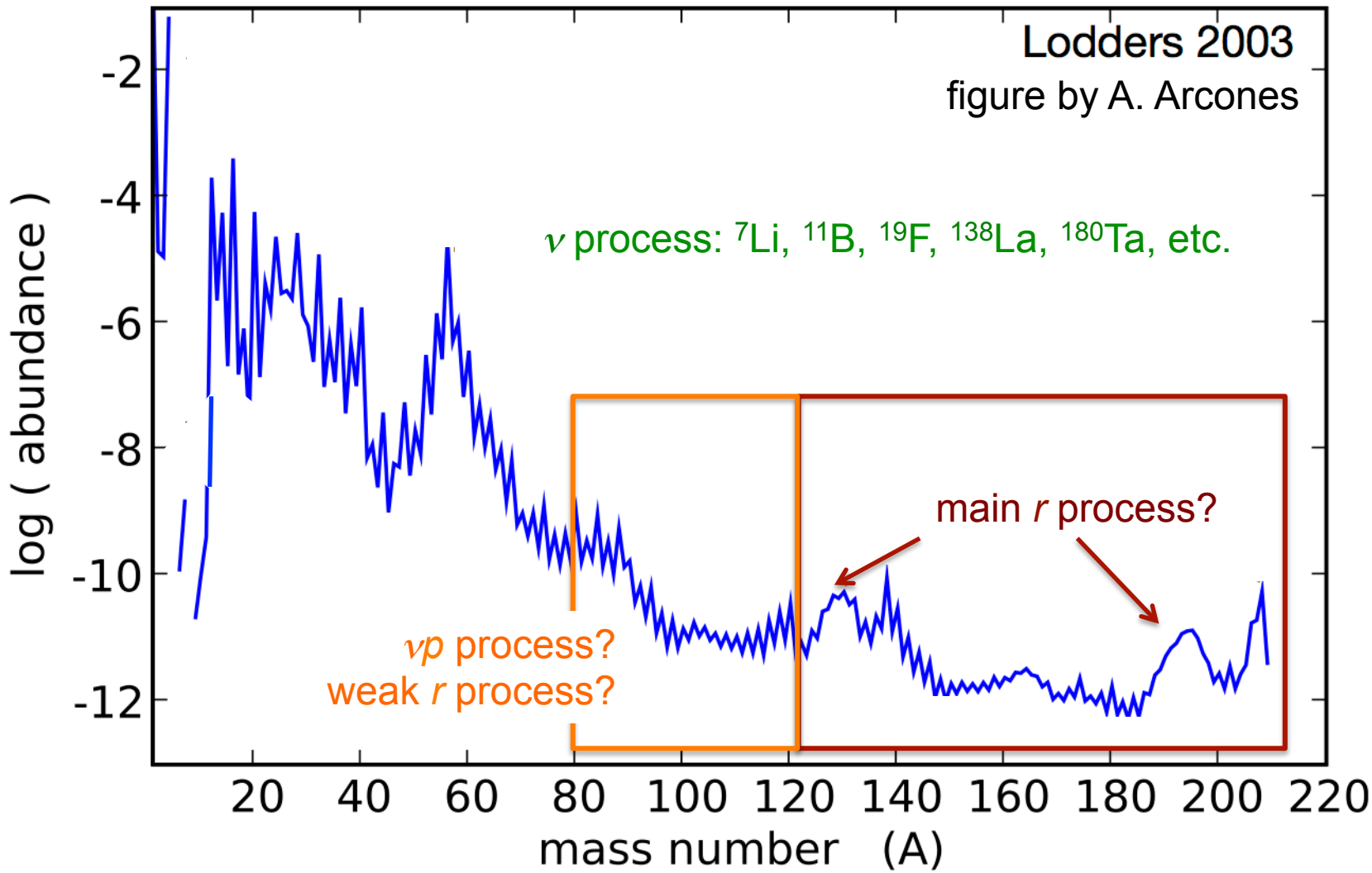
Bulk of output -> explosive nucleosynthesis

Si, S, Ca, Fe peak, etc.

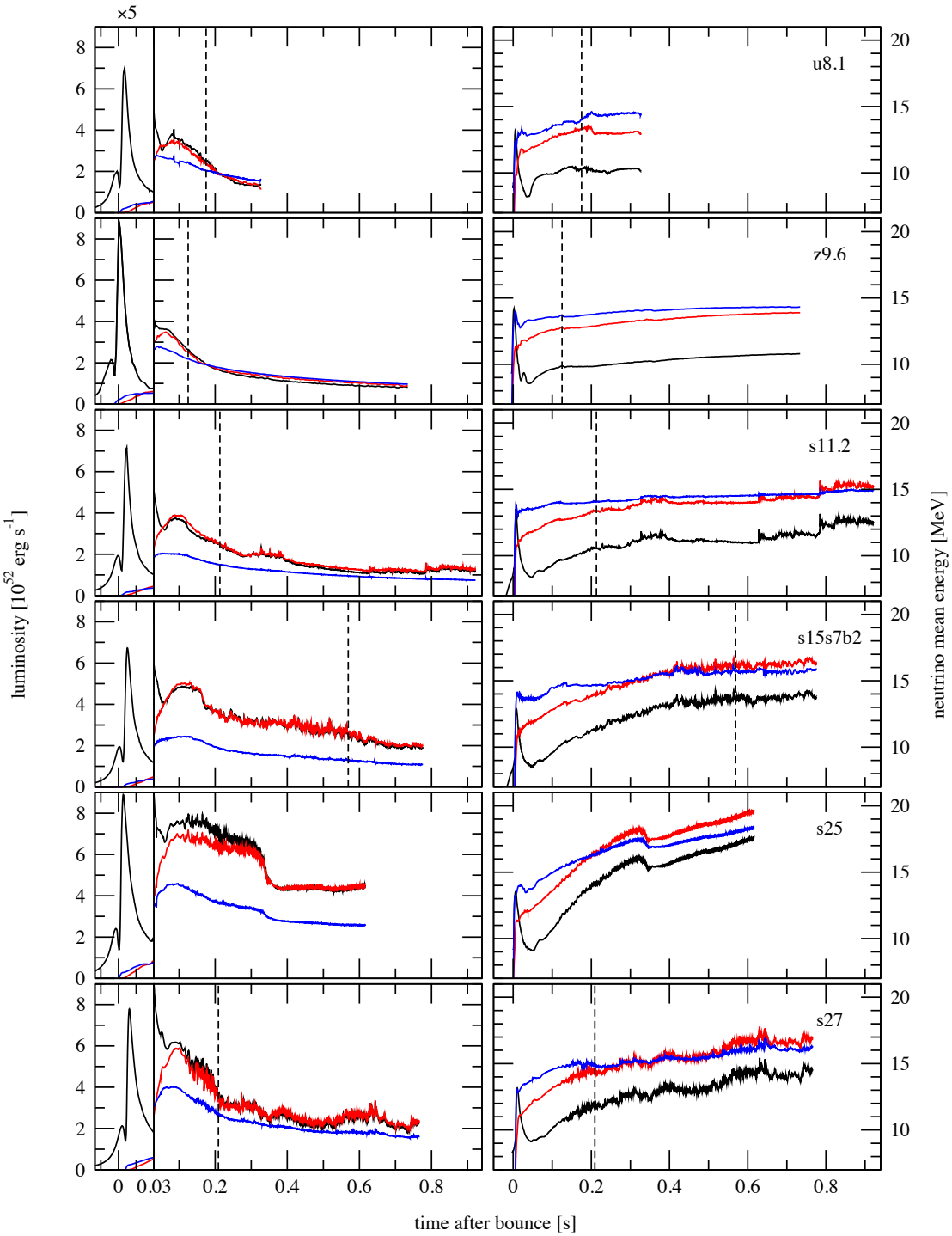
photon-induced spallation

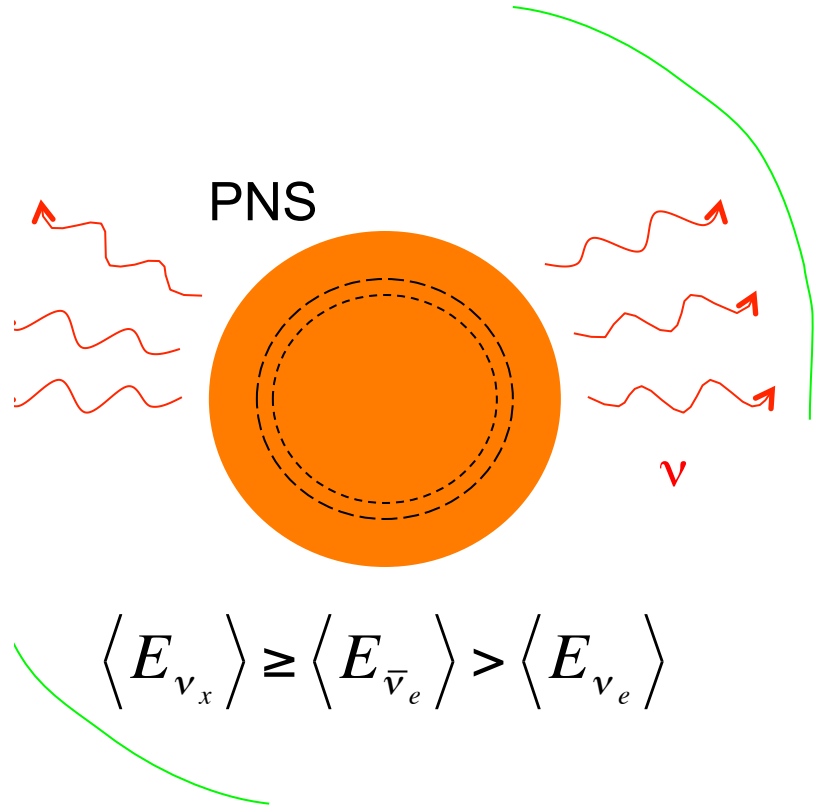
(γ,α) α elements (Ne, Mg, Ca)
(γ,n) *p* process

neutrinos and supernova nucleosynthesis



supernova neutrino emission

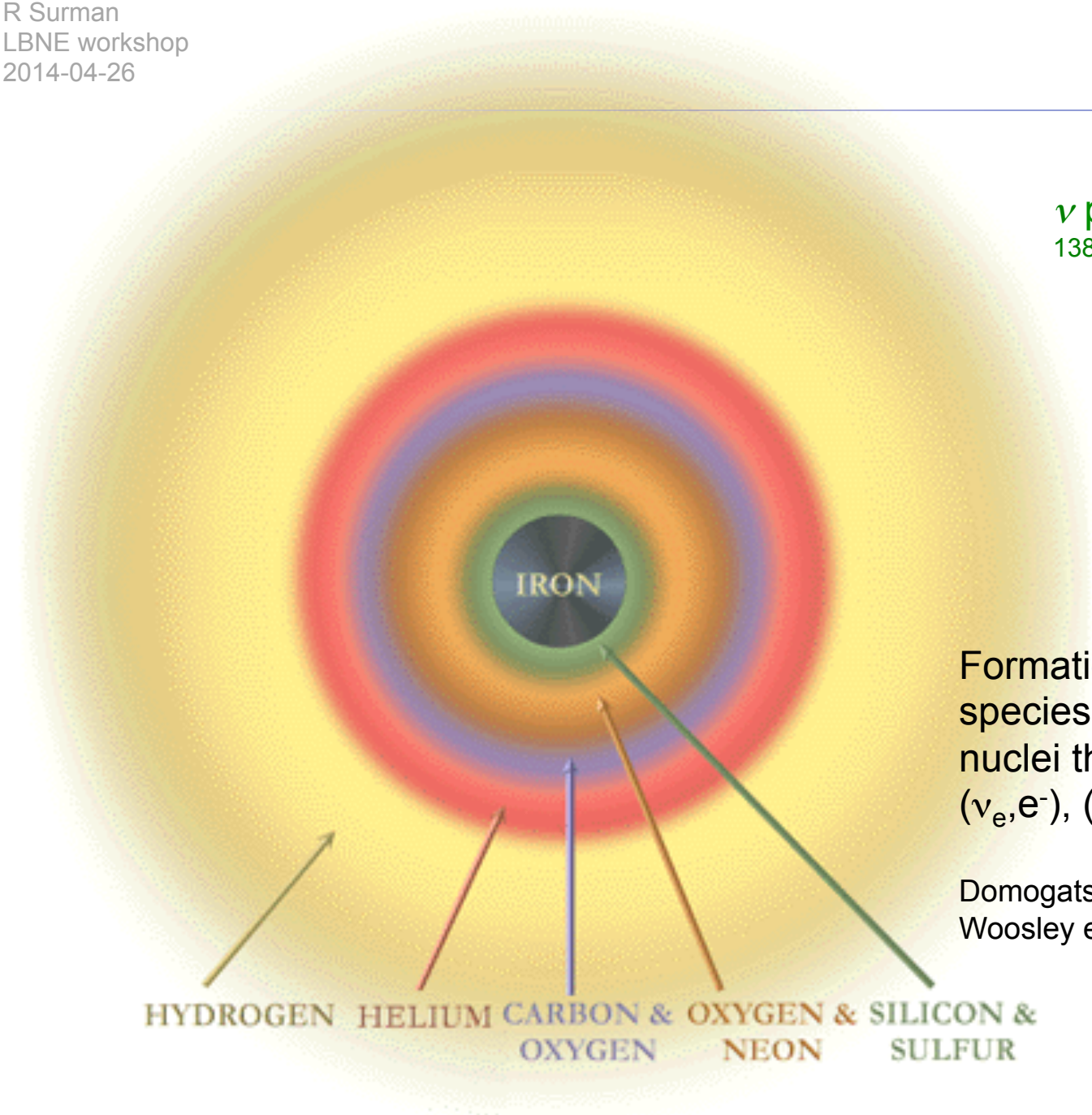




$$\langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

Müller and Janka (2014)

ν process



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

Formation of rare light nuclear species and rare odd-odd nuclei through $(\nu,\nu'n)$, $(\nu,\nu'p)$, (ν_e,e^-), $(\bar{\nu}_e,e^+)$ reactions

Domogatsky et al (1978),
Woosley et al (1990)

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

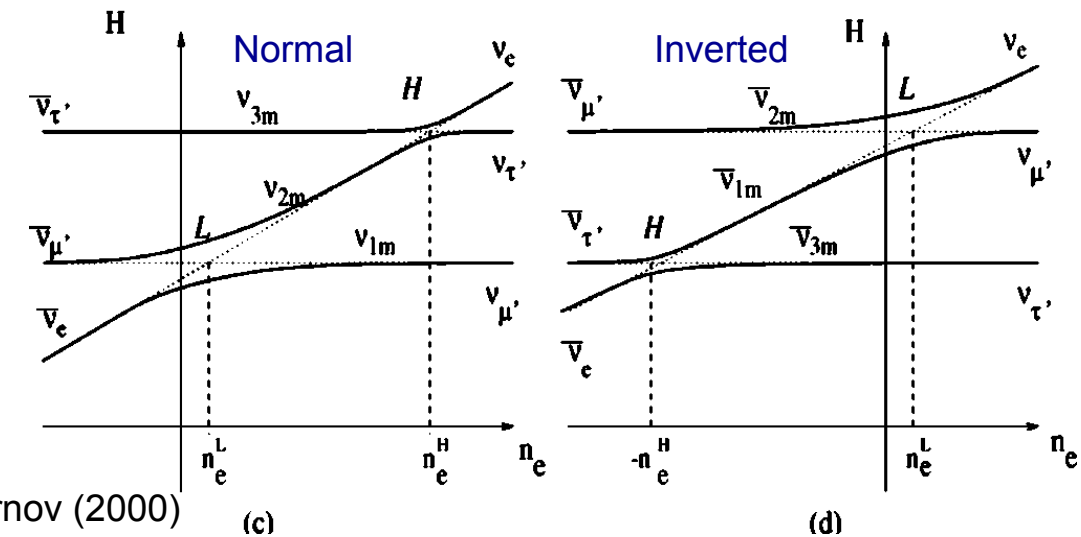
Two flavor mixing in matter with a high neutrino flux:

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

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

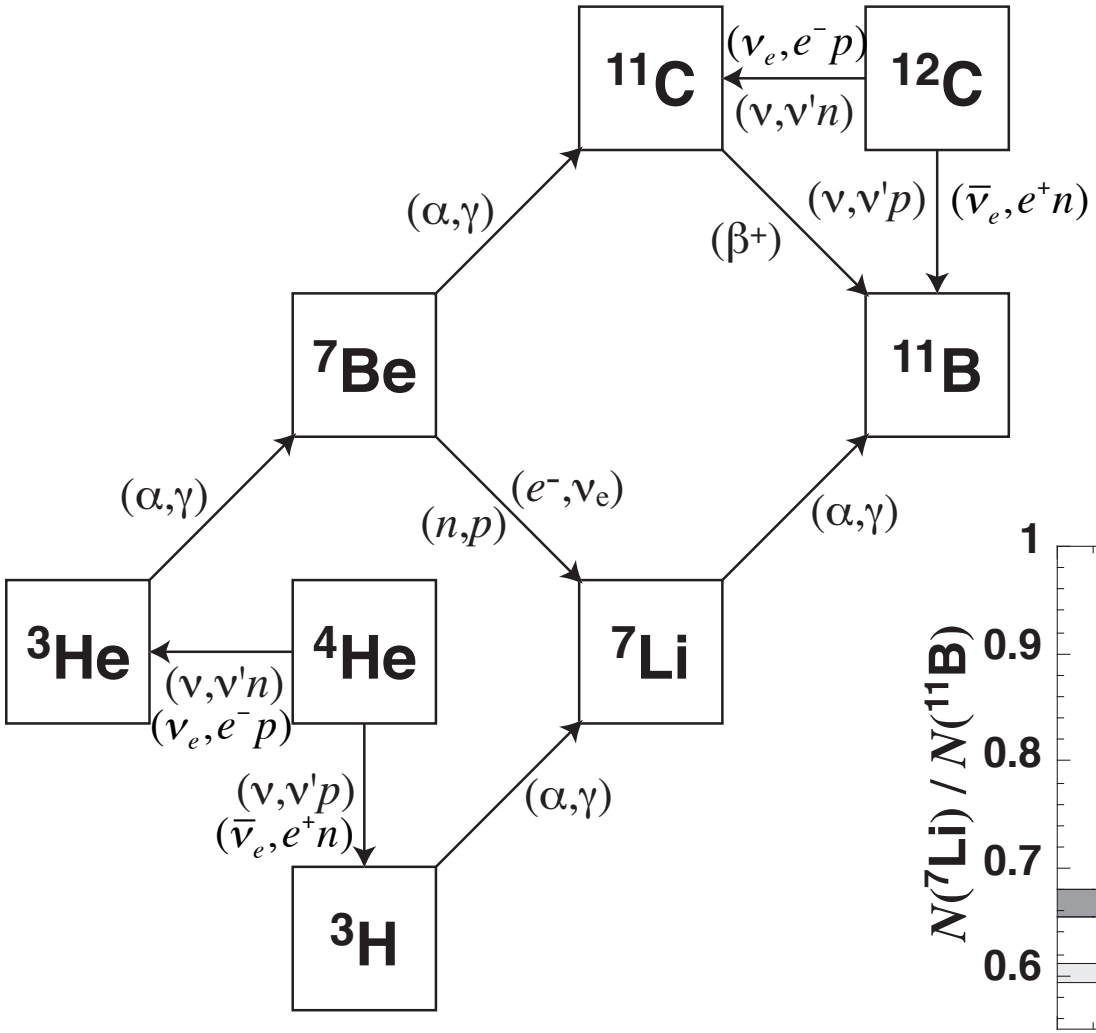
MSW flavor transition:

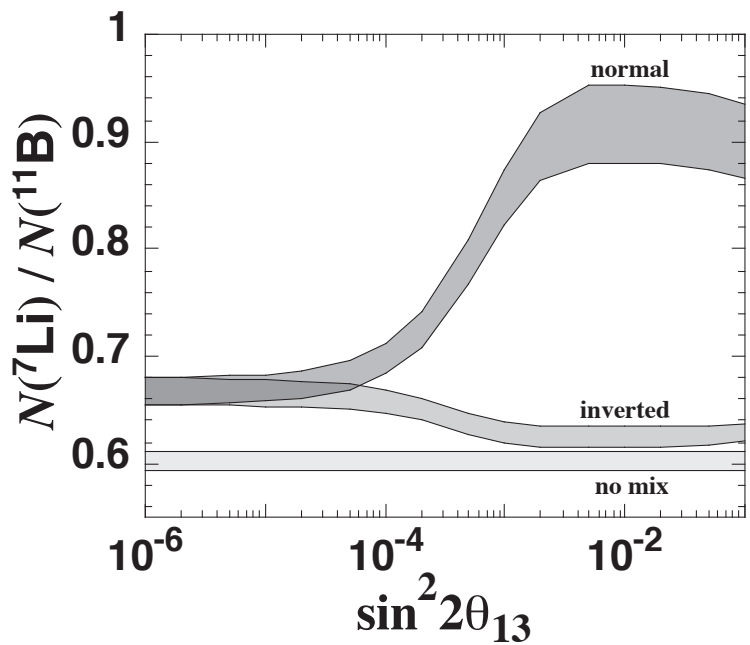
$$V_e \approx \frac{\delta m^2}{4E}\cos(2\theta)$$



Dighe and Smirnov (2000)

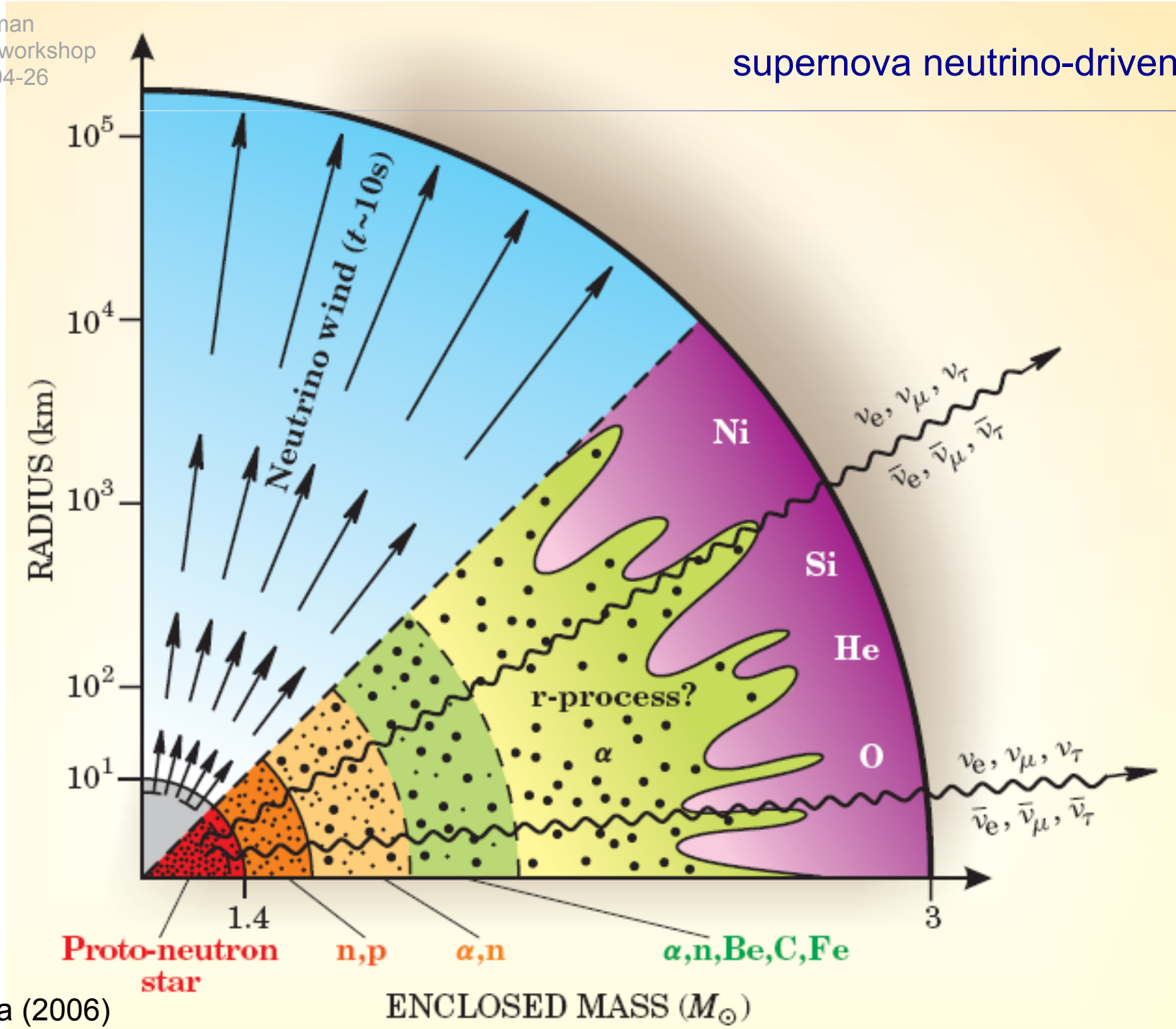
ν process: example of sensitivity to neutrino parameters





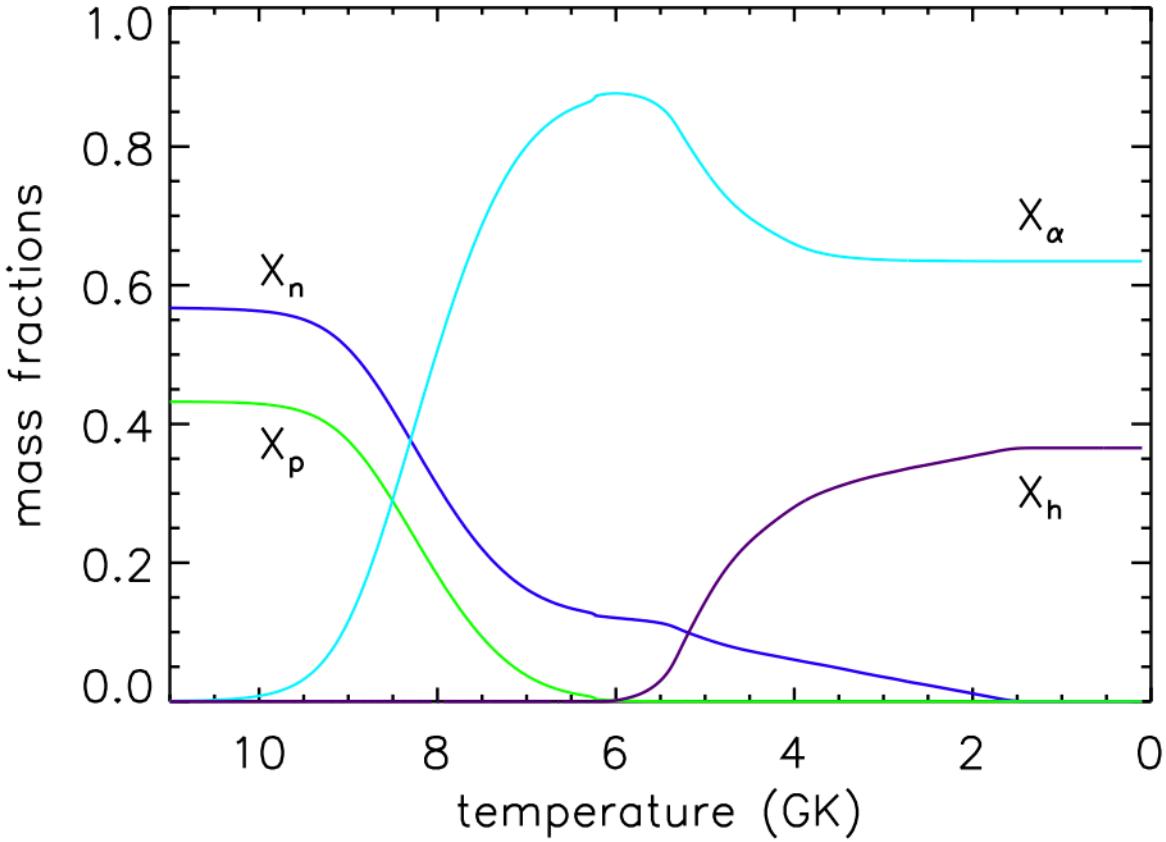
Mathews et al (2012), Kajino (2013)

supernova neutrino-driven wind

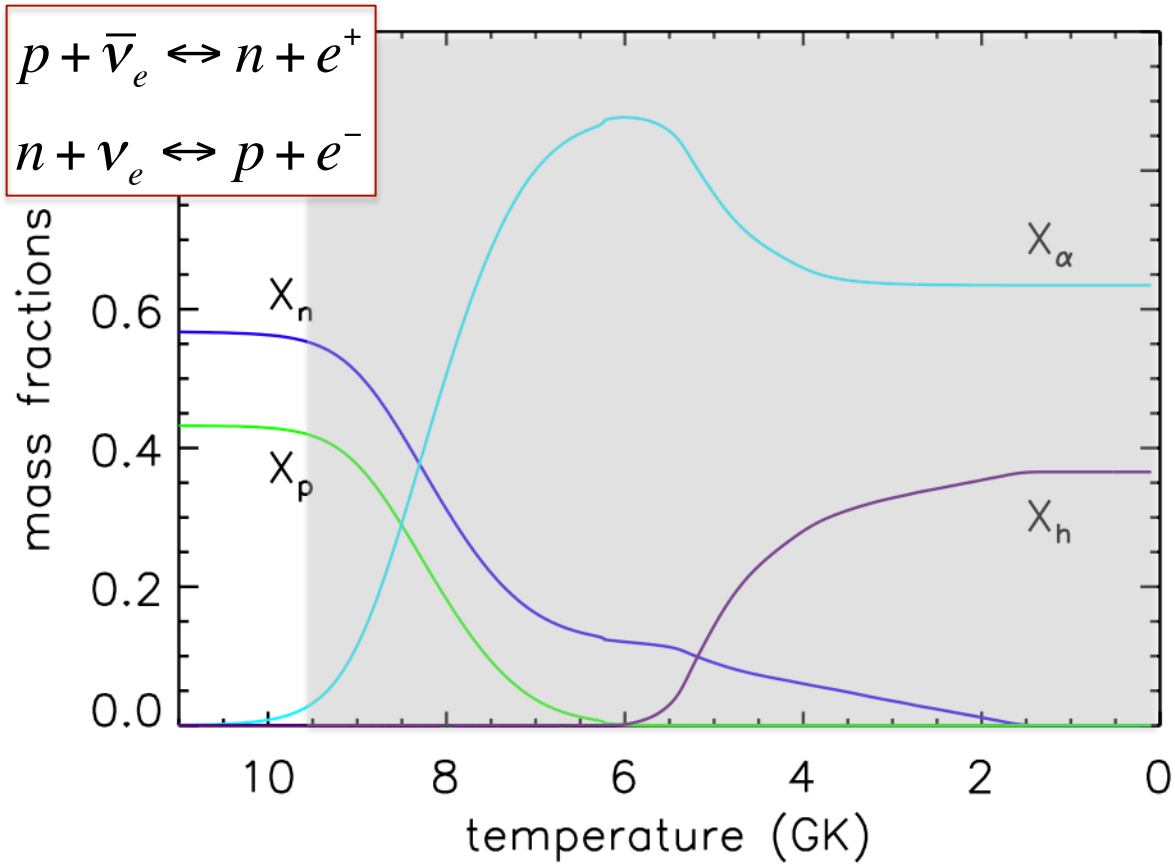


Janka (2006)

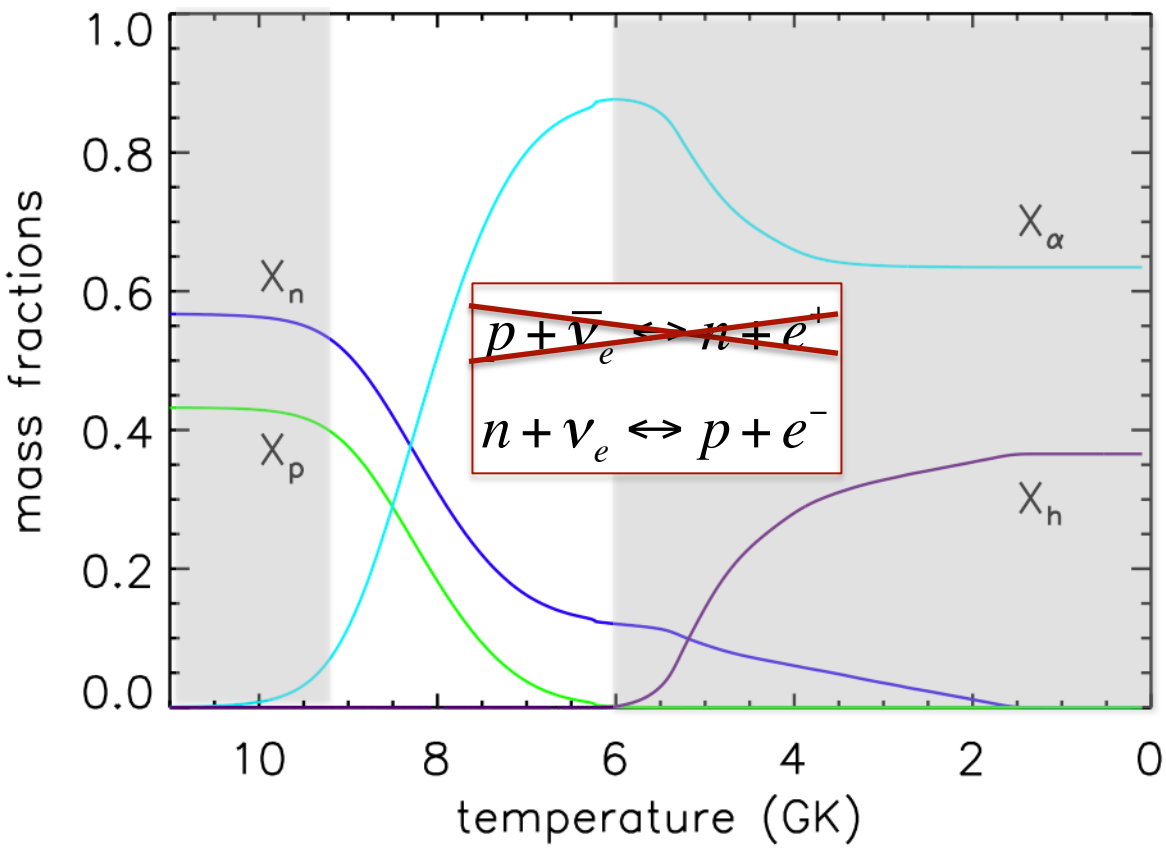
primary heavy element nucleosynthesis



neutrinos and primary nucleosynthesis



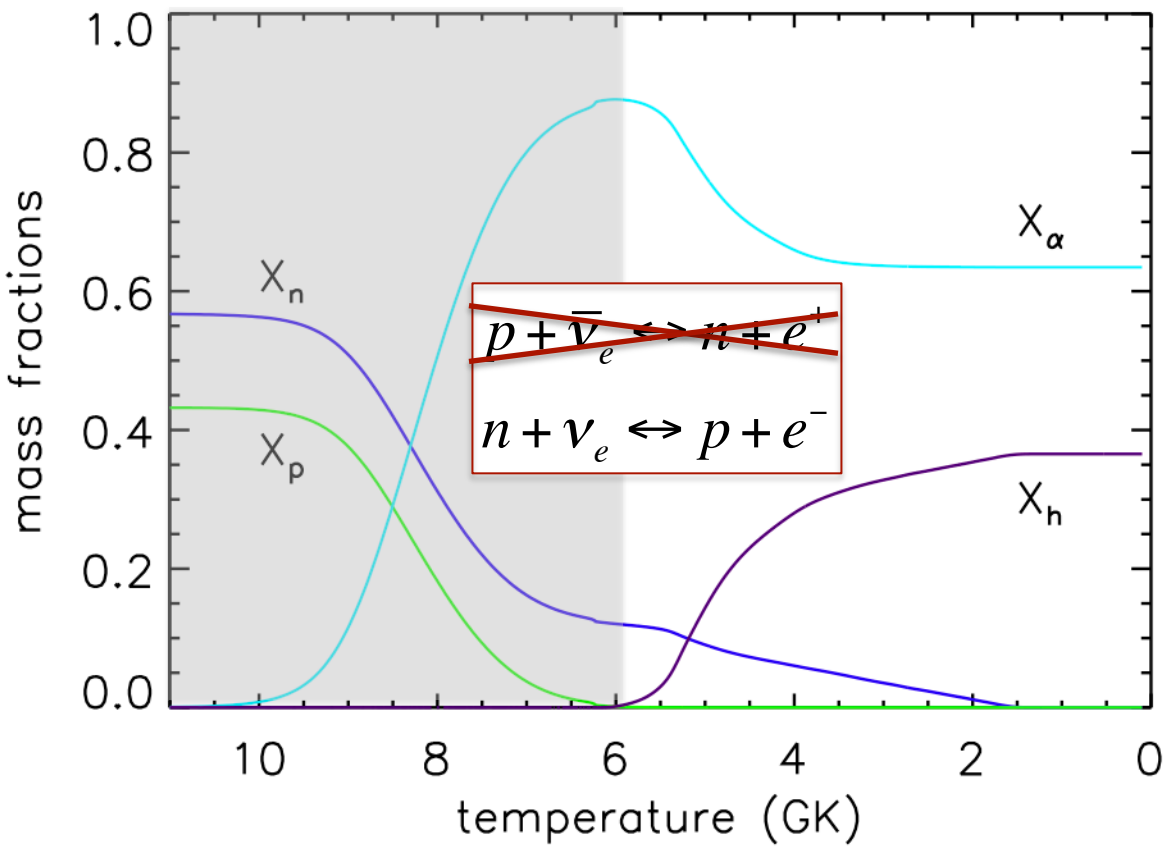
neutrinos and primary nucleosynthesis



'alpha effect'

Fuller and Meyer (1995)

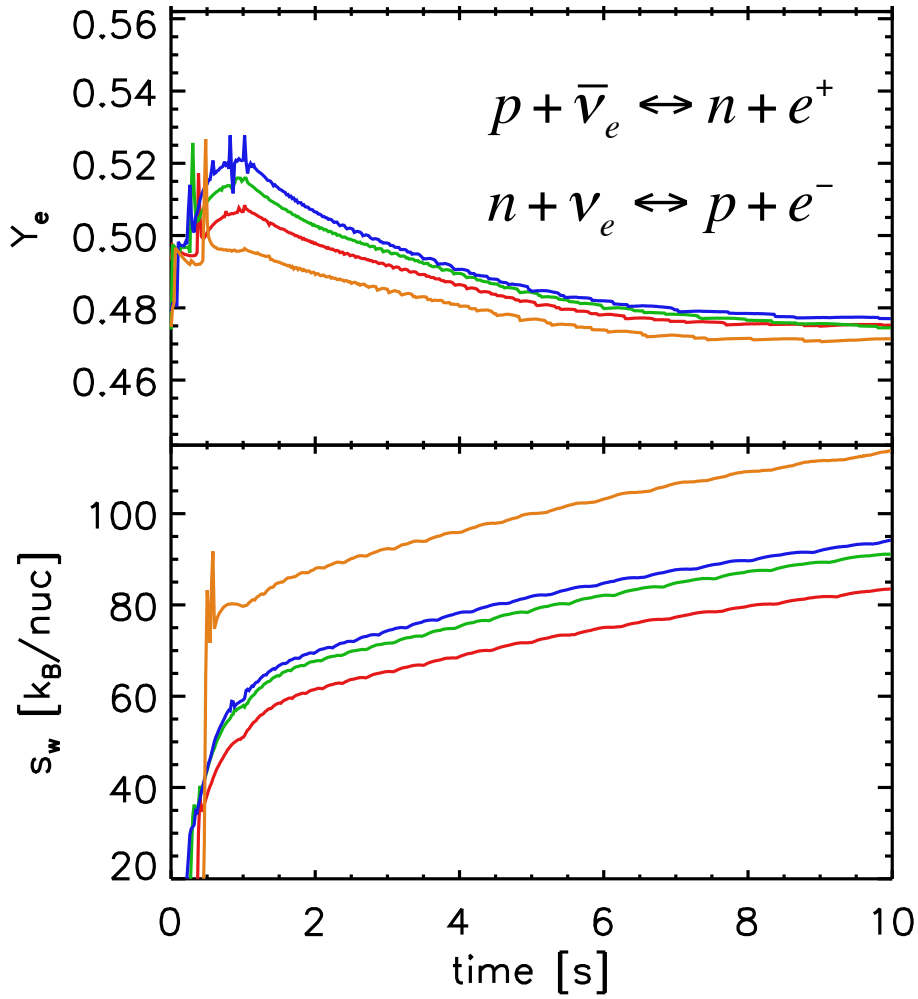
neutrinos and primary nucleosynthesis

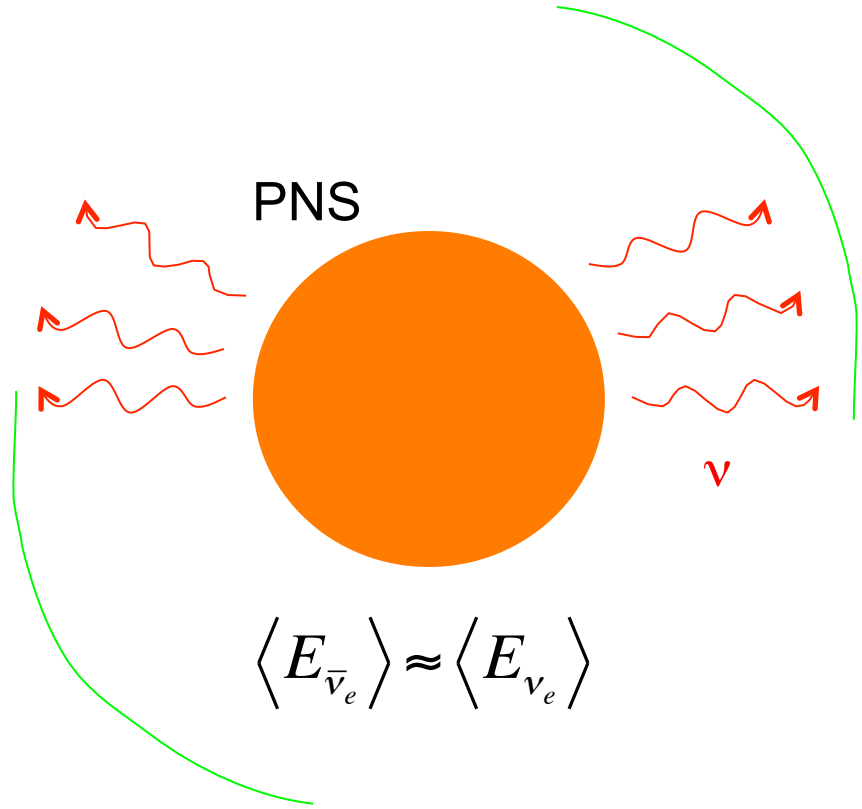


early-time supernova neutrino emission

Conditions proton rich if:

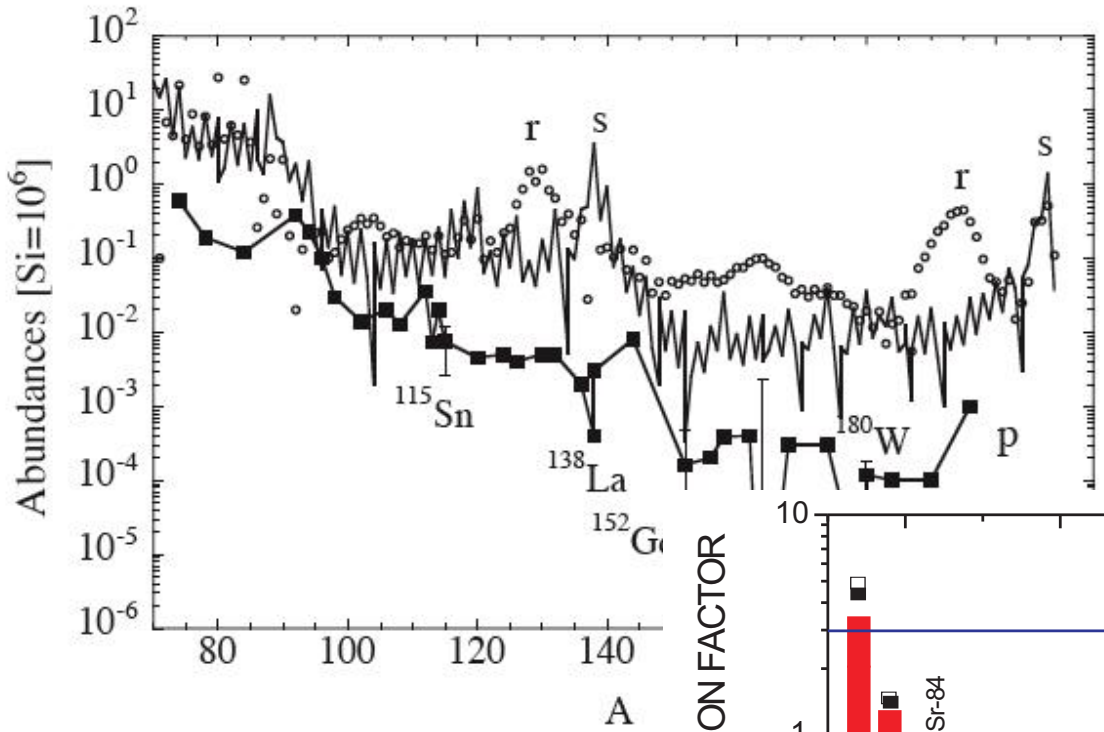
$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2)$$

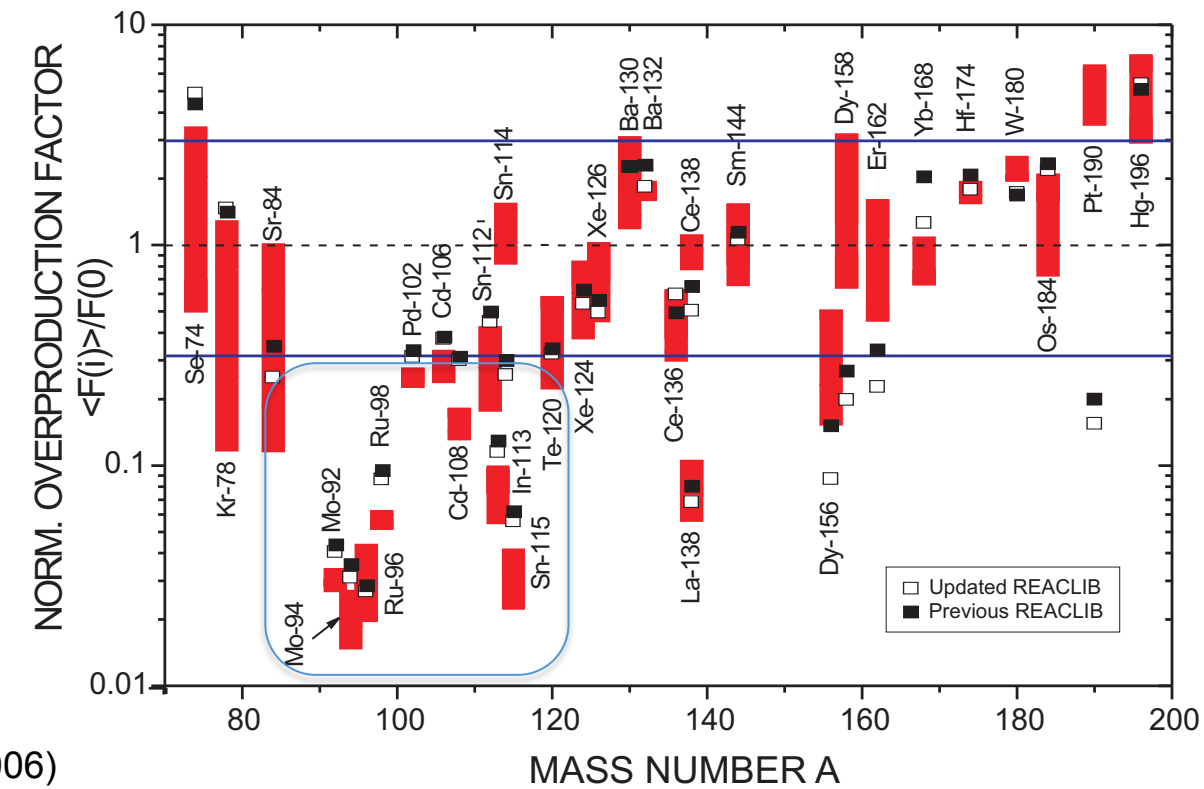




Arcones and Janka (2007)

light *p* process nuclei?





Thielemann et al (2006)

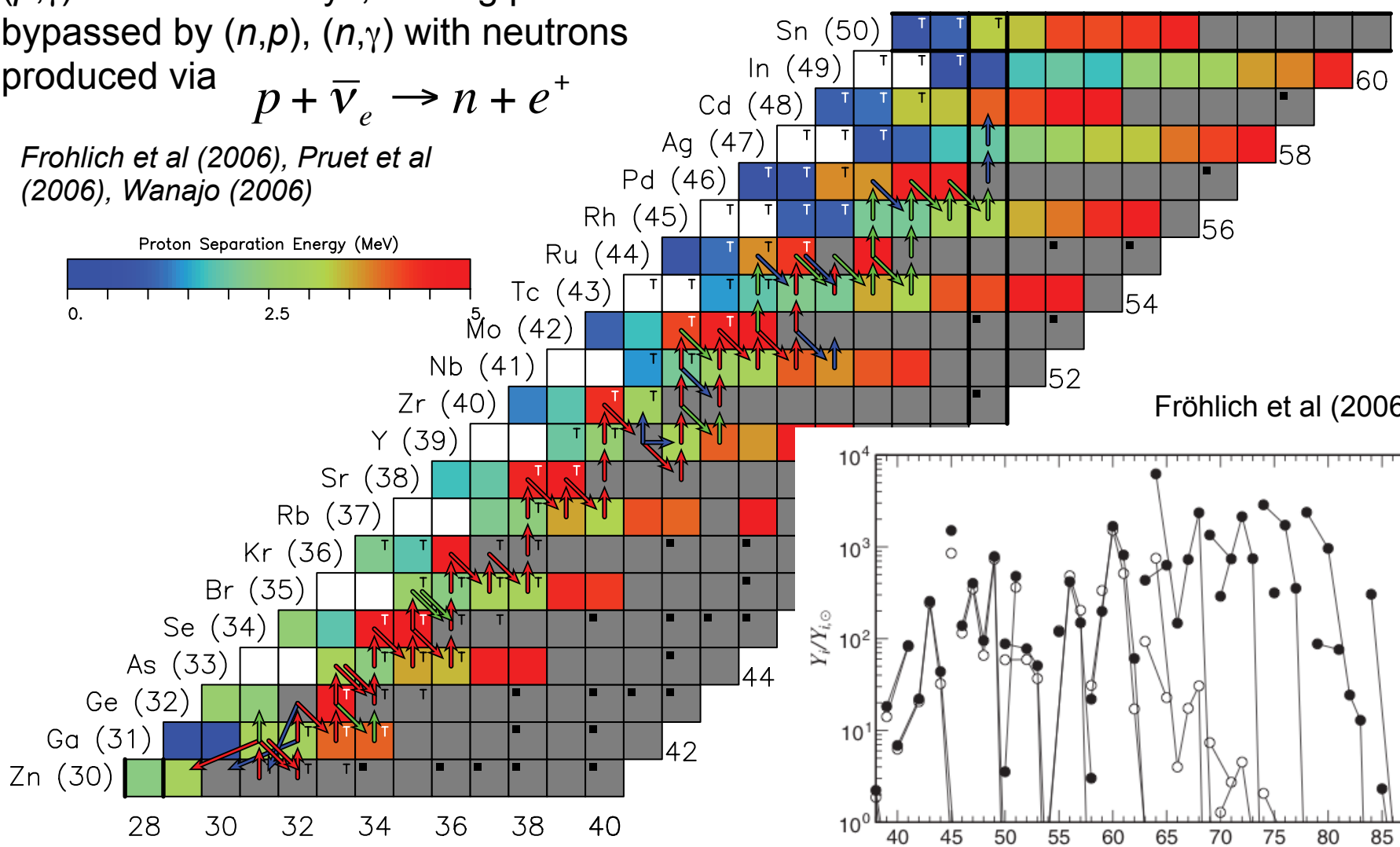
νp process

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

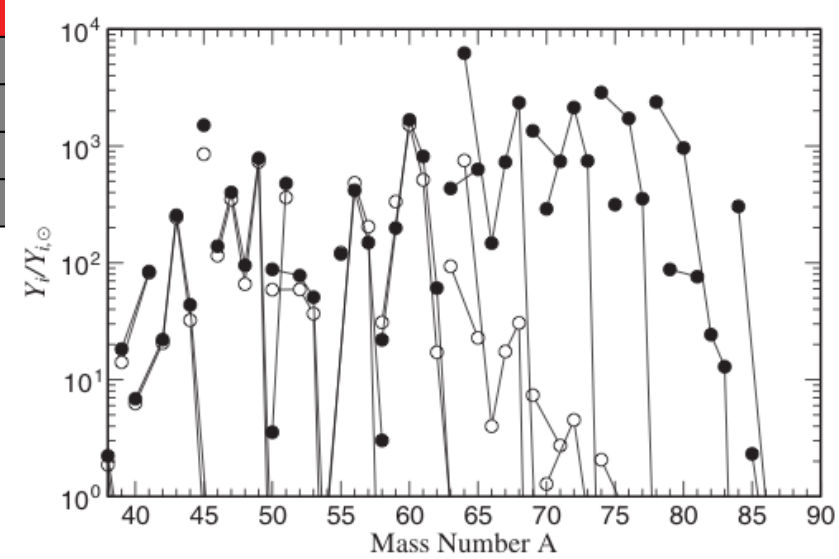
$$p + \bar{\nu}_e \rightarrow n + e^+$$

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

Pruet et al (2006)



Fröhlich et al (2006)



neutrino oscillations

Two flavor mixing in matter with a high neutrino flux:

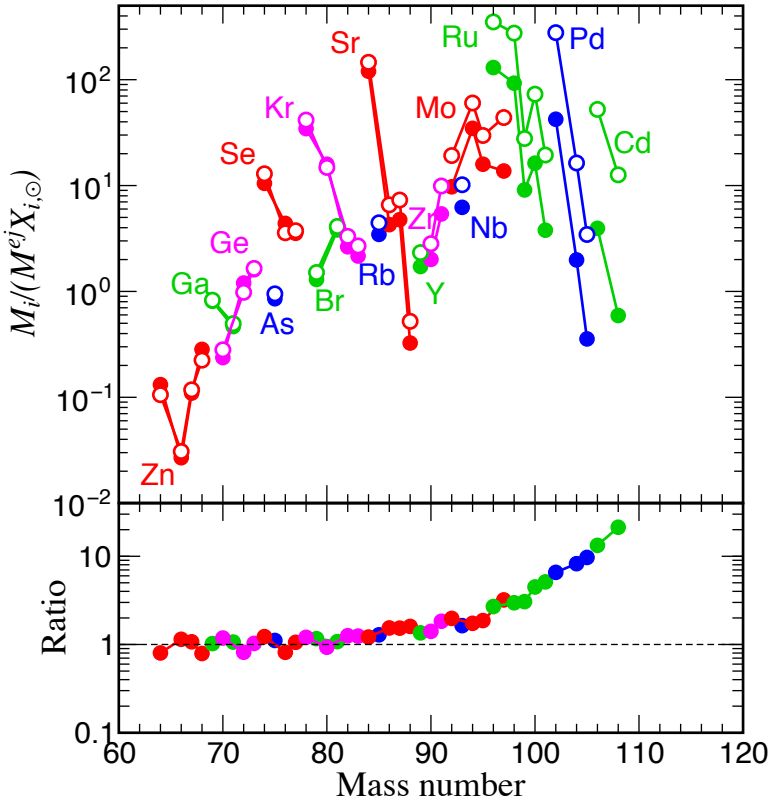
$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} \cancel{V_e} + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -\cancel{V_e} - V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

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

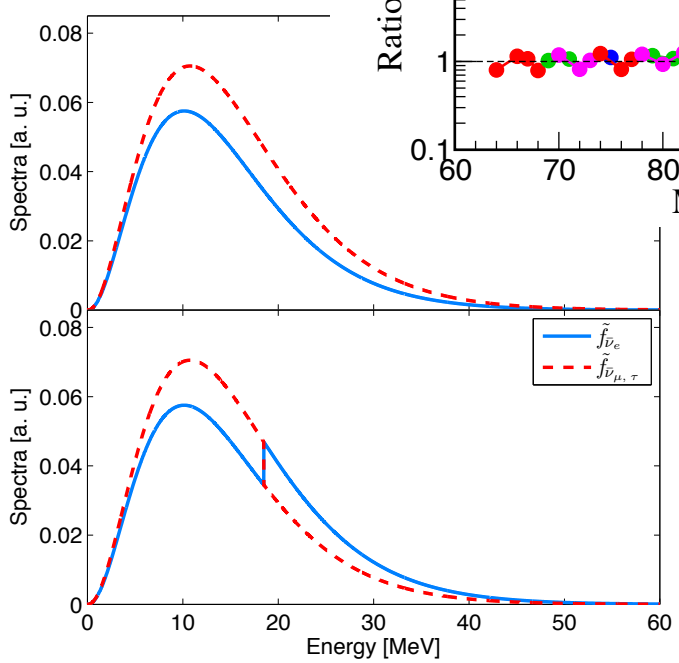
Collective flavor transformation: $V_\nu \approx \frac{\delta m^2}{4E}\cos(2\theta)$

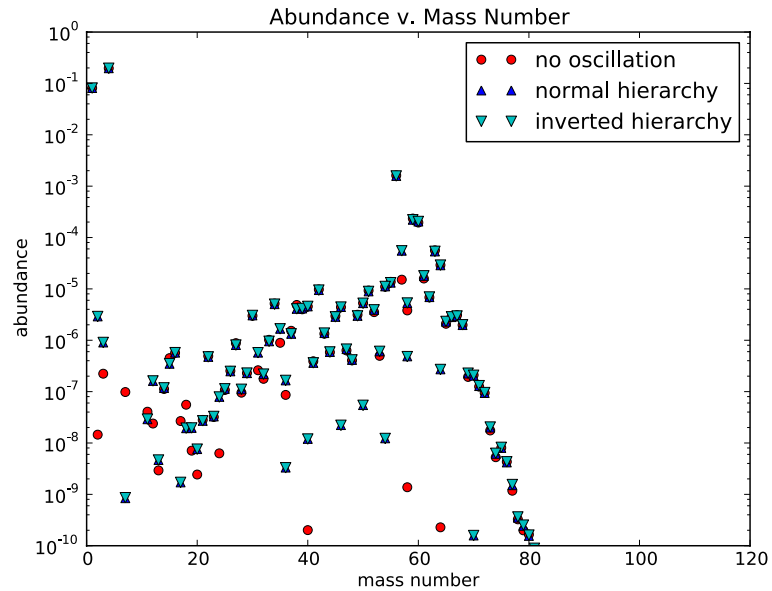
e.g. talks by B. Balantekin and G. Fuller and references therein

collective flavor transformations and the νp process



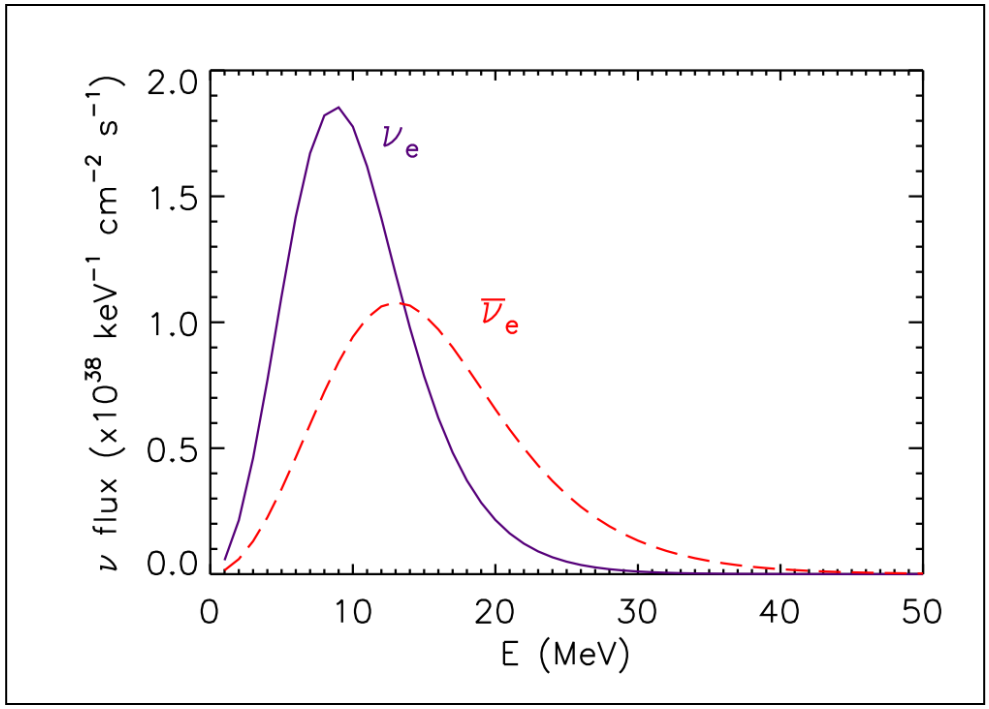
Martínez-Pinedo et al (2011)





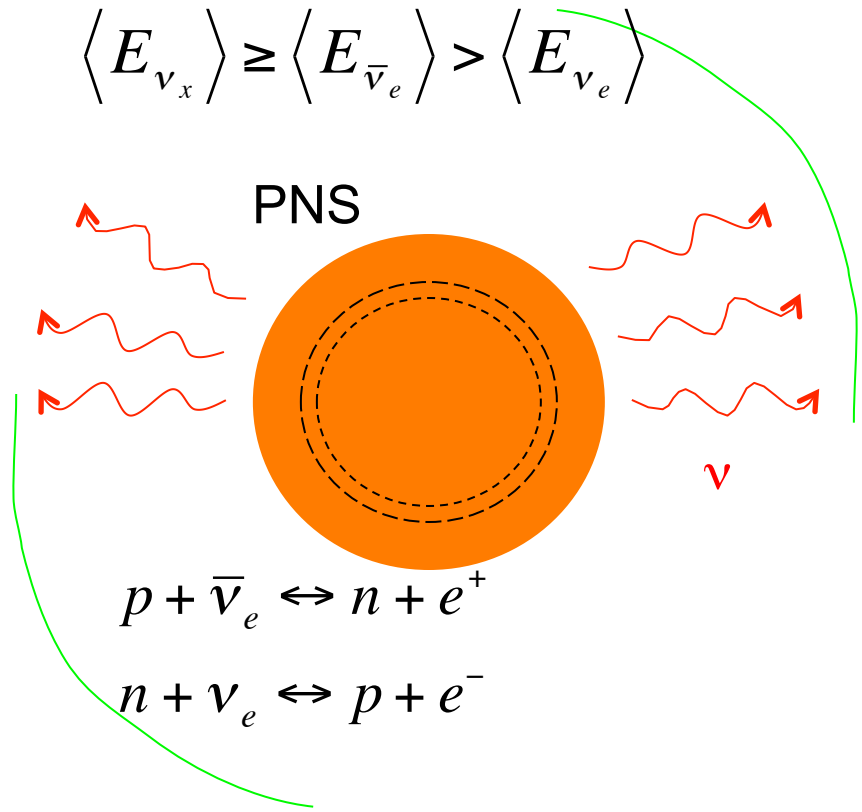
Fröhlich et al (2014)

late-time supernova neutrino-driven wind



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

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

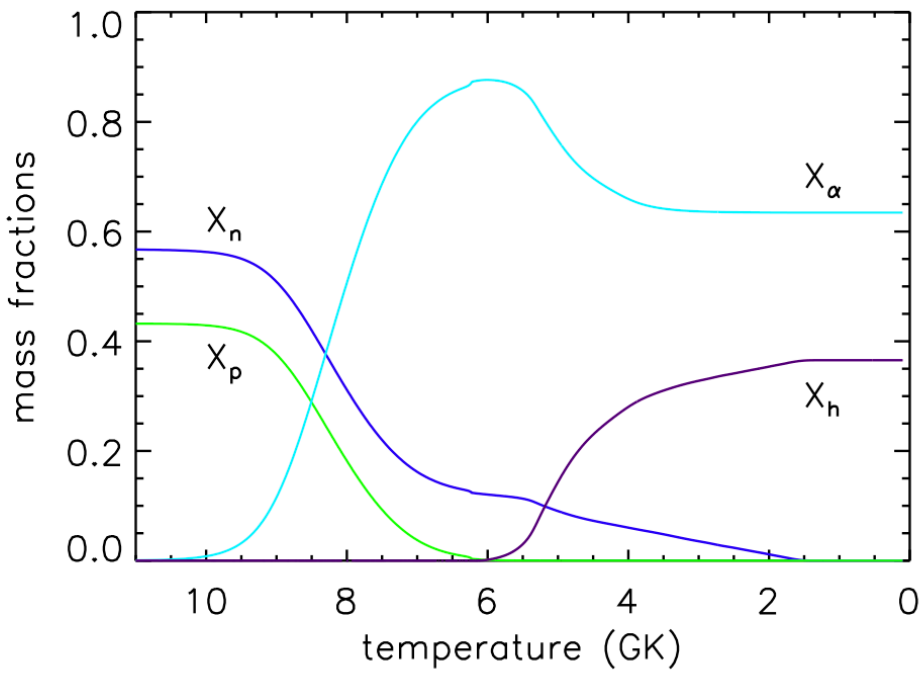


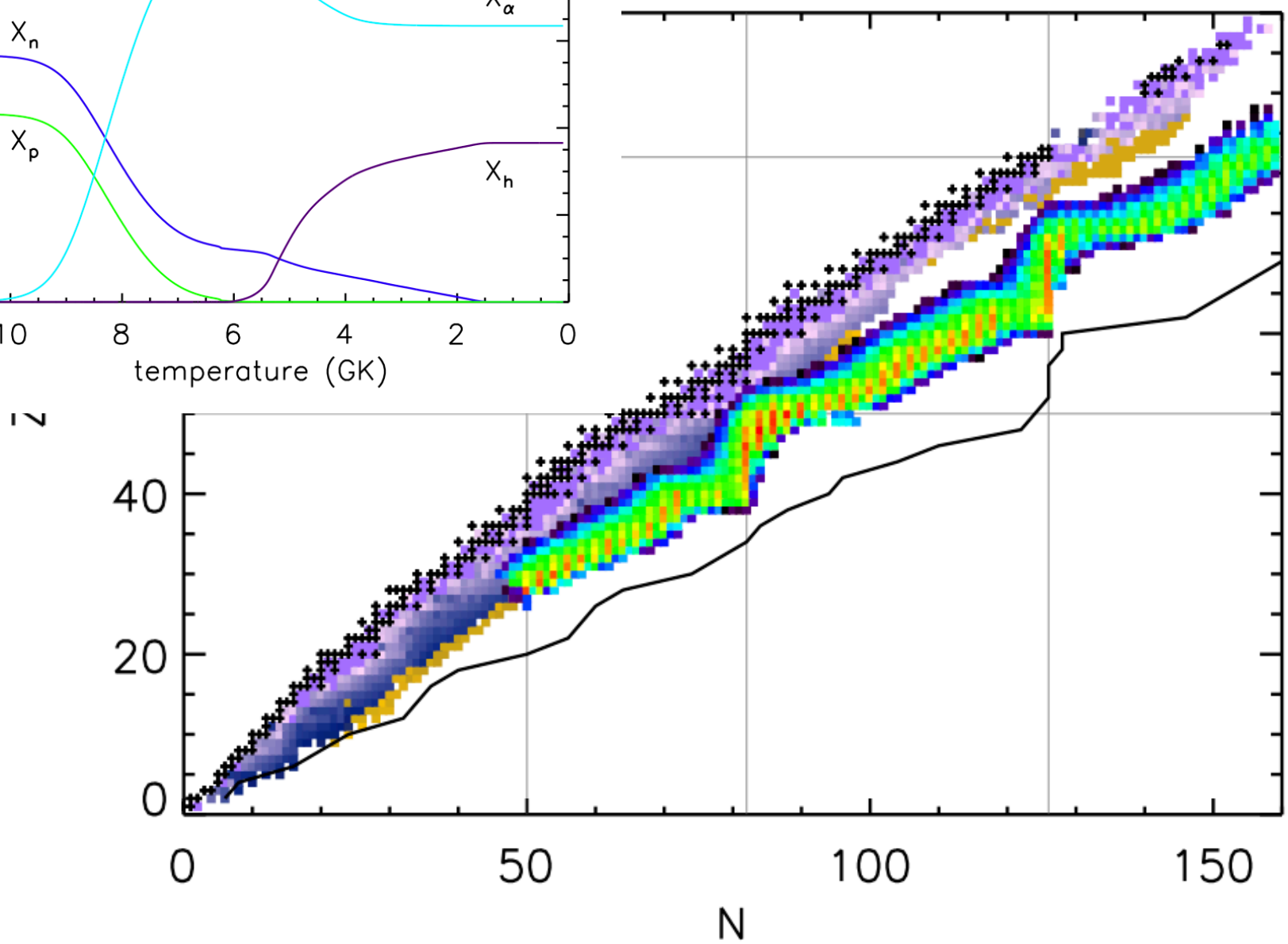
$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

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

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.

r-process nucleosynthesis



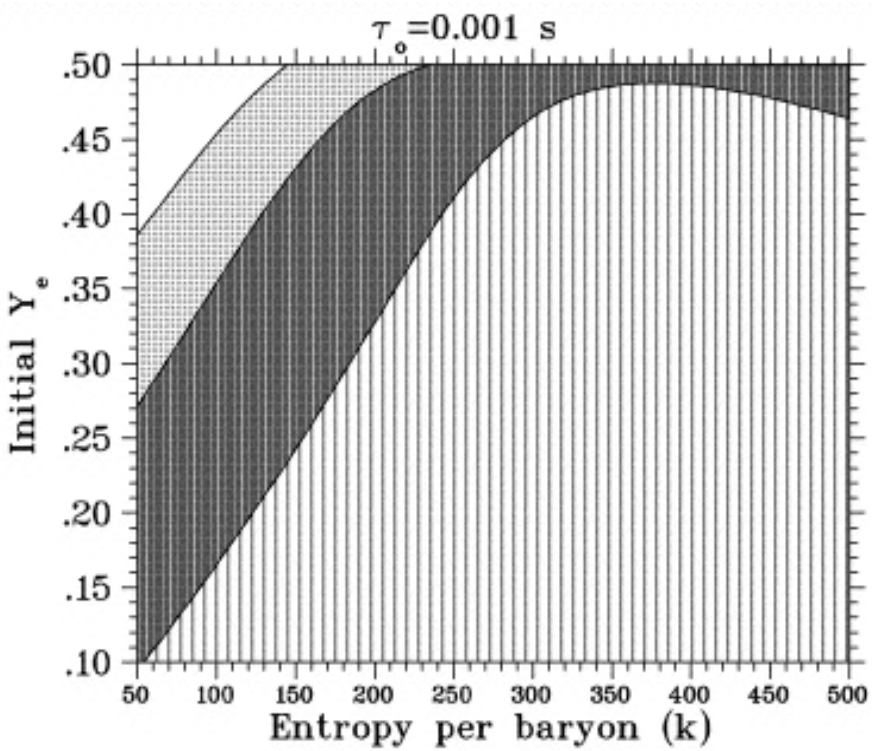


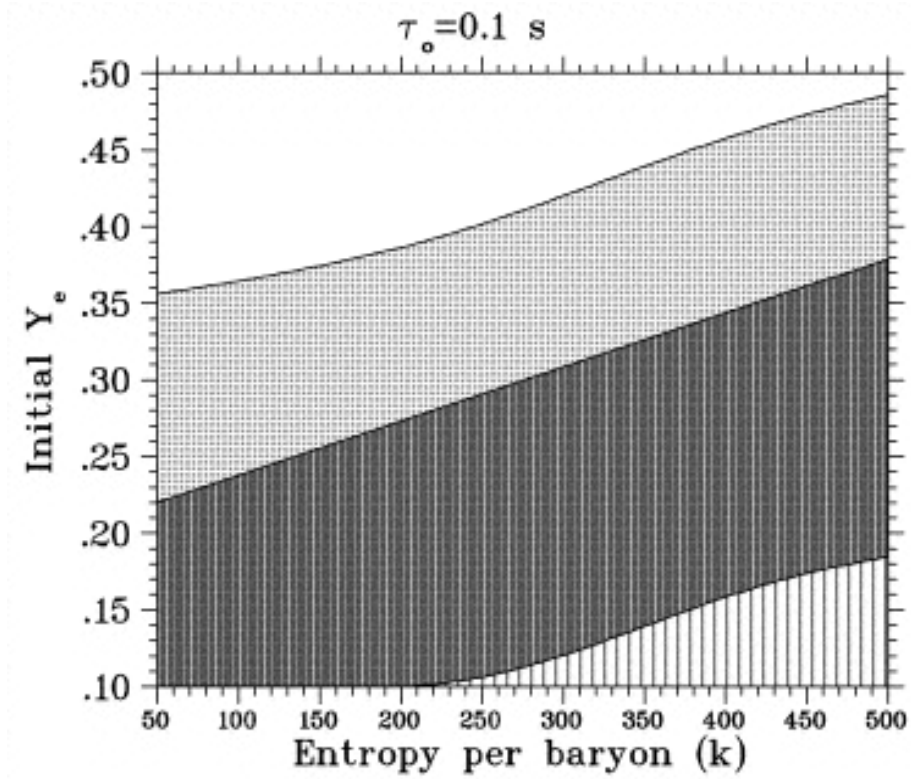
supernova *r*-process conditions

Key quantities:

electron fraction Y_e
entropy s/k
dynamic timescale t

} neutron to seed ratio R



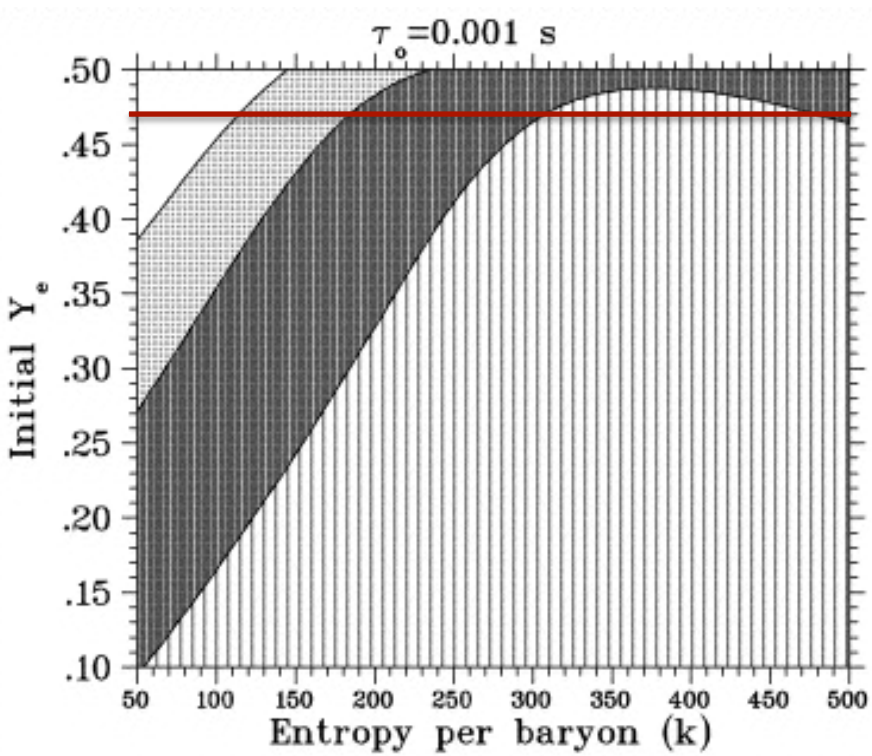


Meyer and Brown (1997)

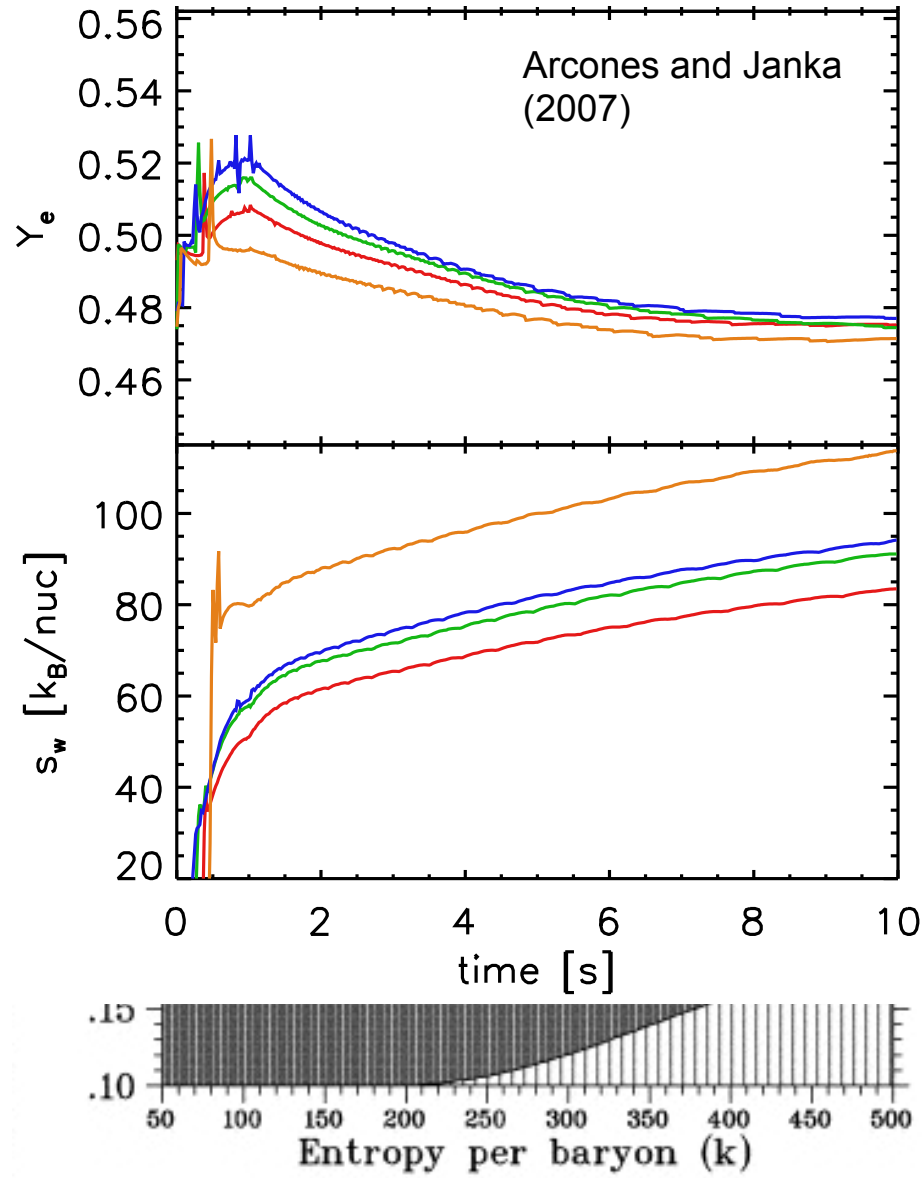
supernova *r*-process conditions

Key quantities:

electron fraction Y_e
entropy *s/k*
dynamic timescale *t*

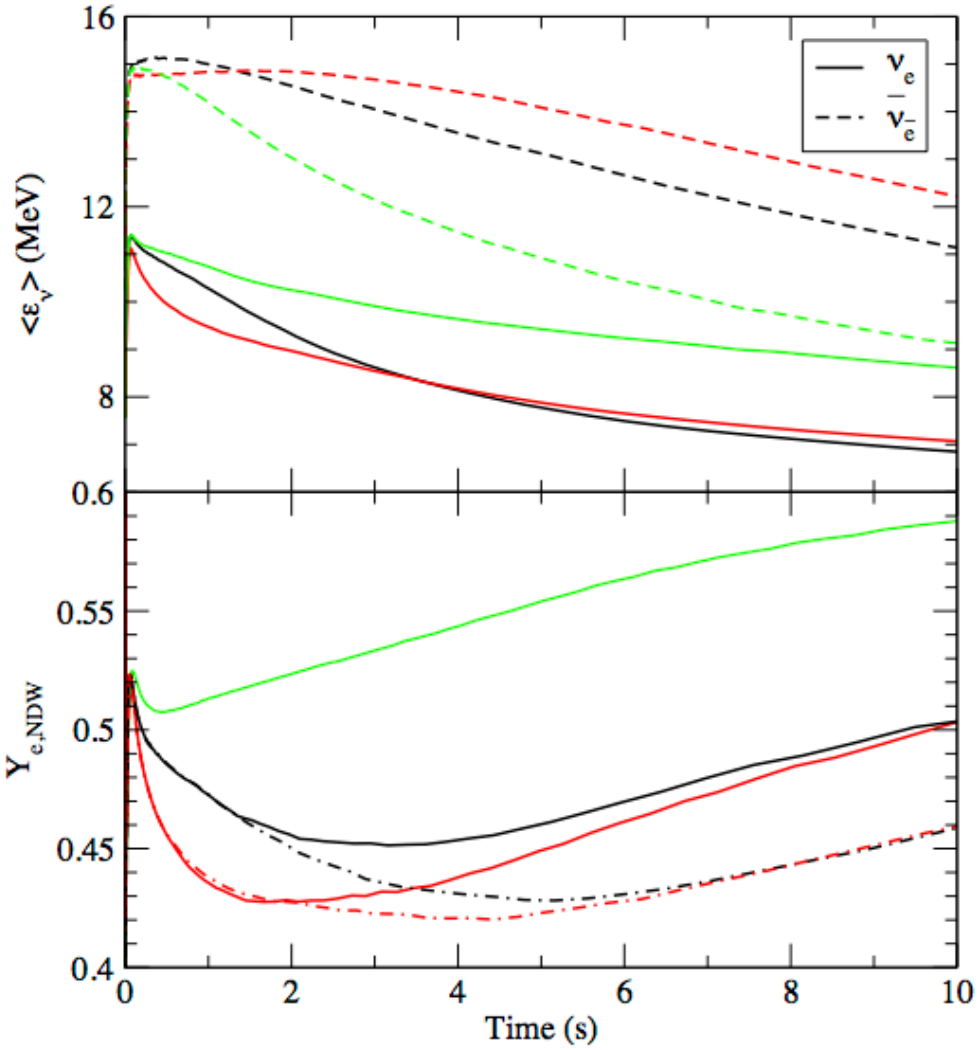


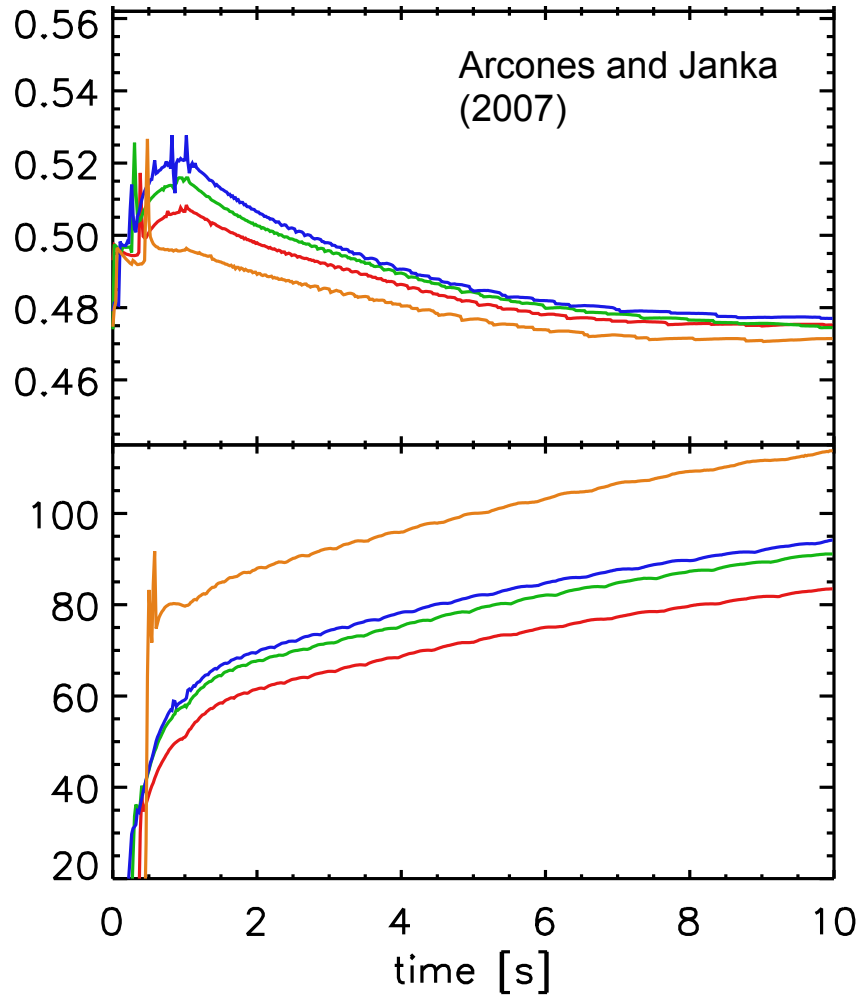
Meyer and Brown (1997)



supernova *r*-process conditions

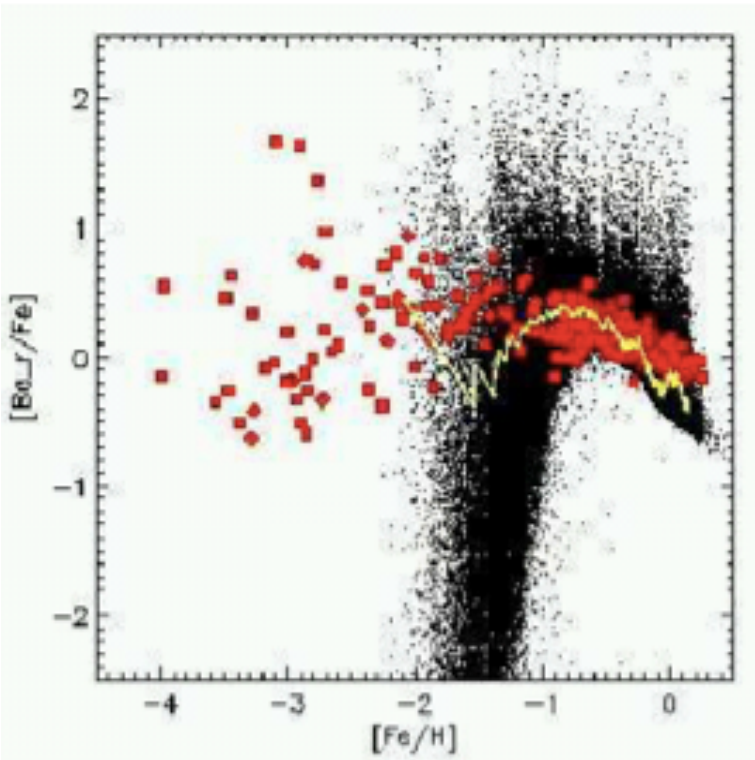
Roberts, Reddy & Shen (2012)





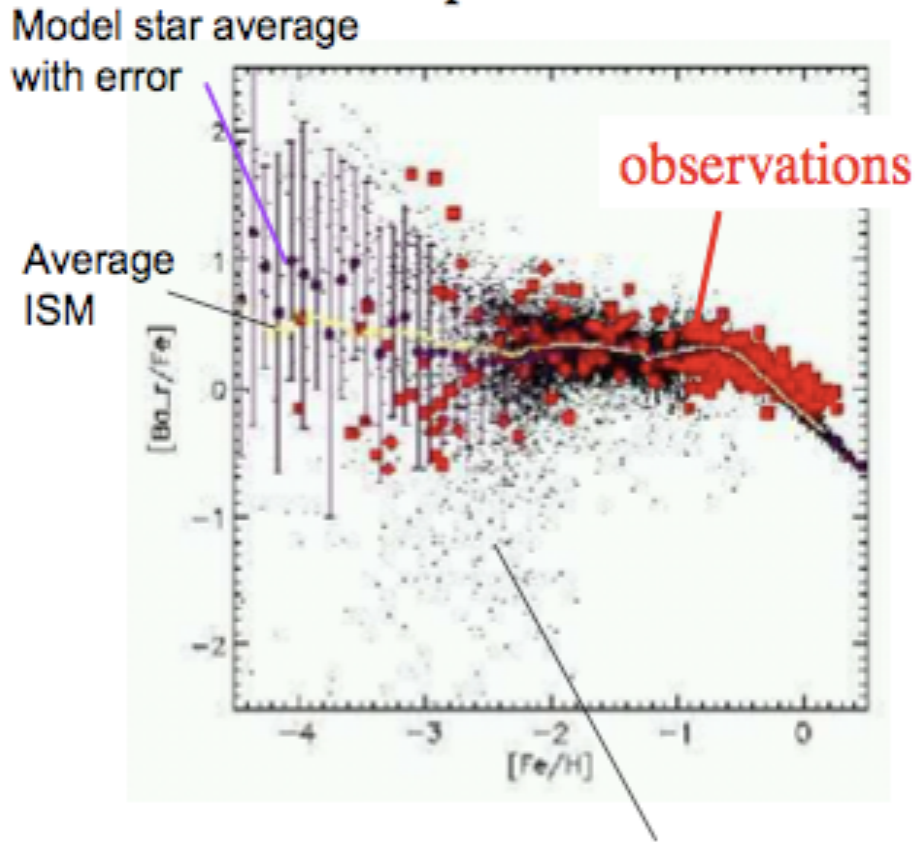
supernovae vs mergers

NS mergers



Argast et al (2004)

Supernovae



Dots: model stars

supernovae vs mergers

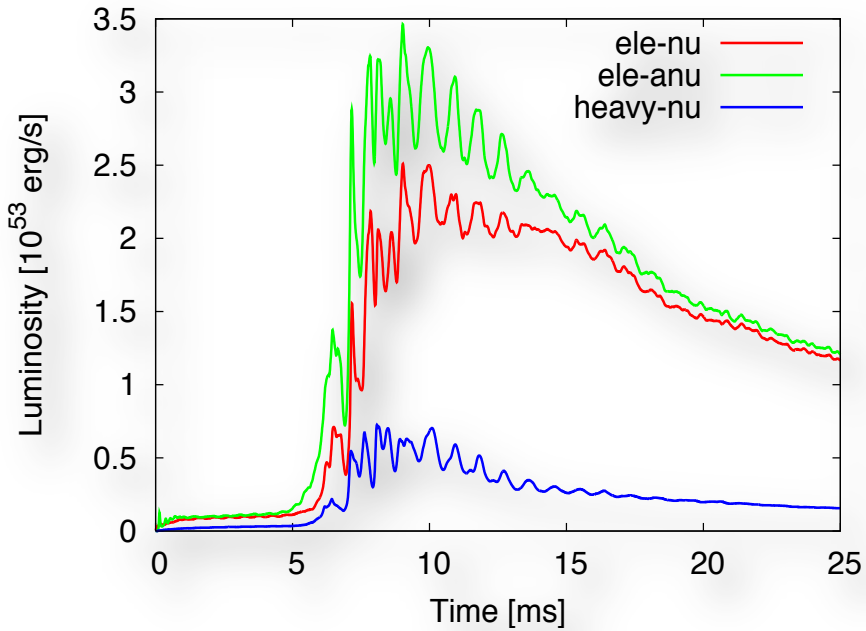
Compact object mergers have plenty of neutrons, but do not evolve on short enough timescales to explain the halo star data

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

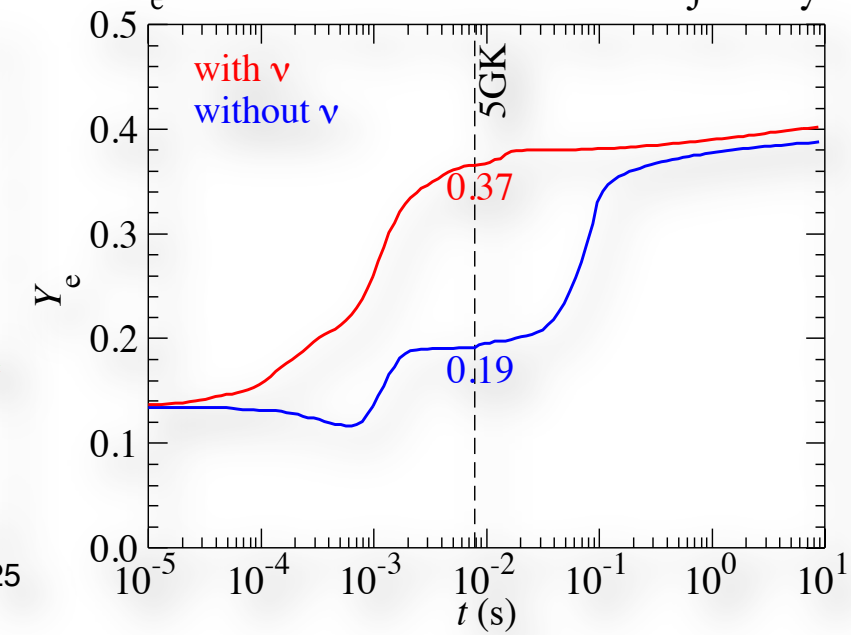
supernovae vs mergers

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

angle-averaged neutrino luminosities



Y_e evolution for a selected trajectory



- neutrino fluxes several times greater than those of SNe
- neutrinos substantially increase Y_e

From talk by S Wanajo, Kyoto GRB workshop, Nov 2013

supernovae vs mergers

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

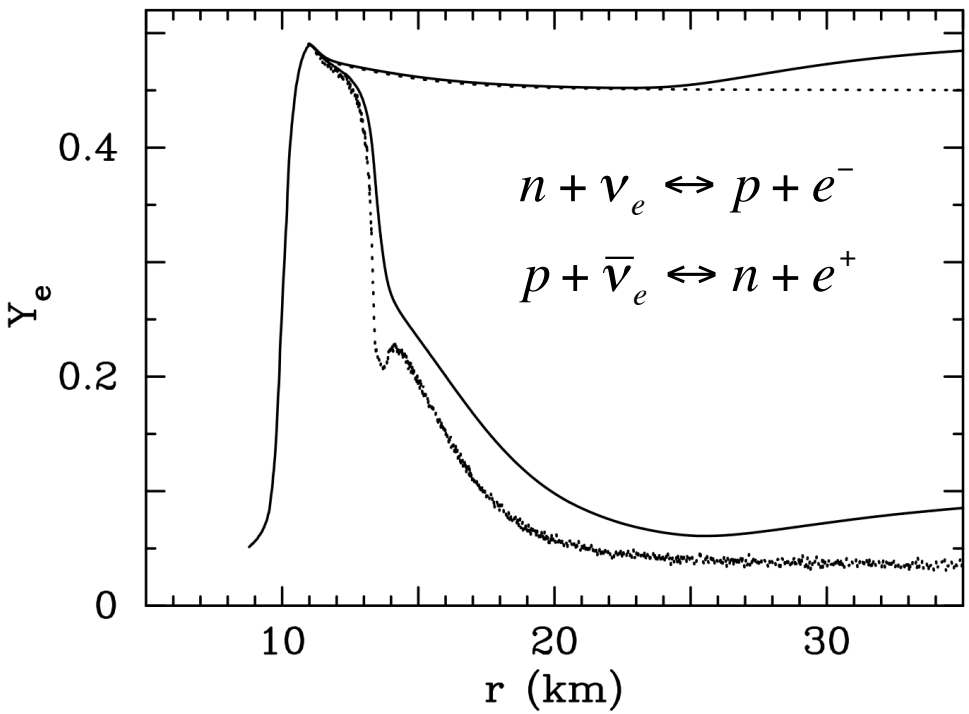
Core-collapse supernovae evolve on the correct timescale to explain the halo star data, but *may* not produce enough neutrons

→ this depends sensitively on the neutrino physics

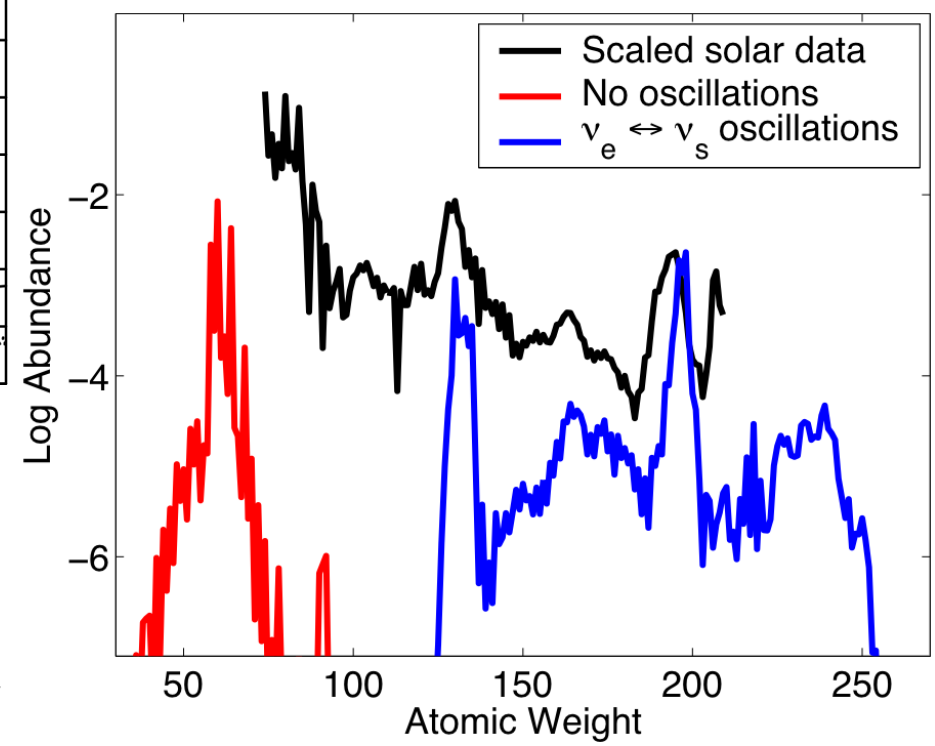
active-sterile mixing and a supernova *r* process

$$\nu_e \leftrightarrow \nu_s \ , \ \ \bar{\nu}_e \leftrightarrow \bar{\nu}_s$$

Peltoniemi (1992), Nunokawa et al (1997),
McLaughlin, Fetter, Balantekin, and Fuller (1999)



McLaughlin, Fetter, Balantekin, and Fuller (1999)

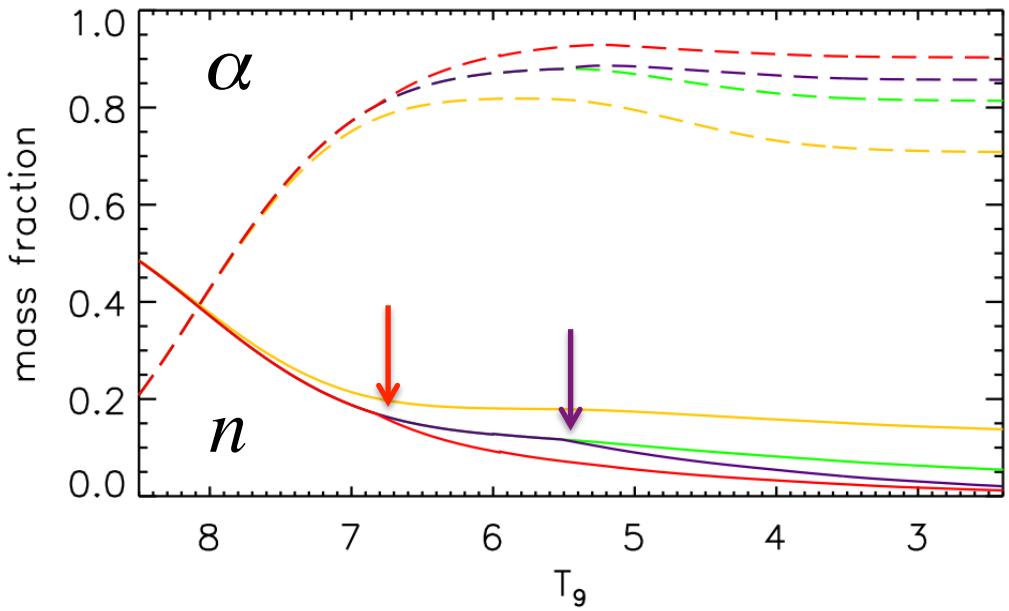


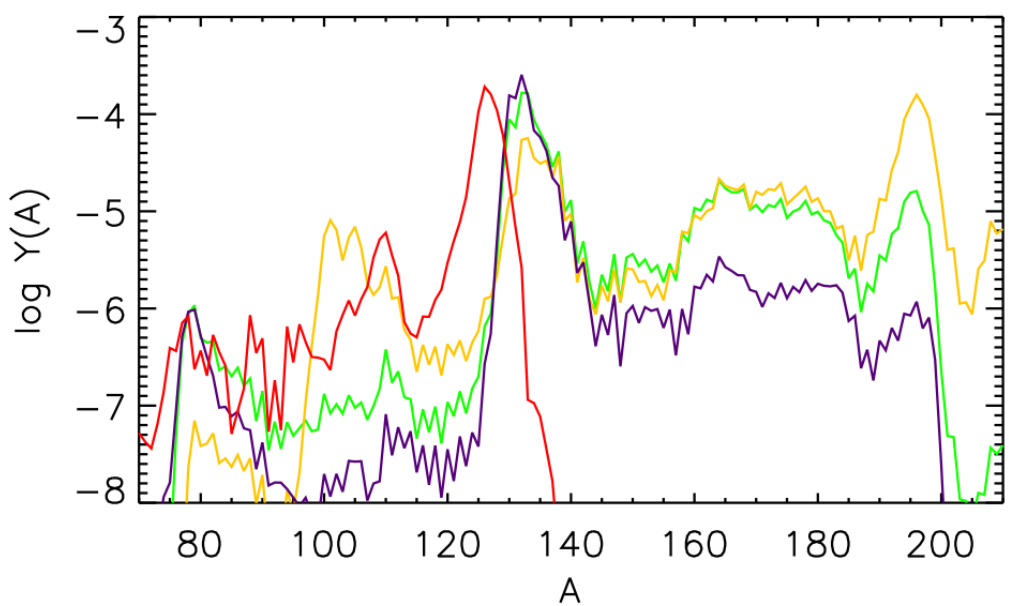
$$\delta m^2 = 2 \text{ eV}^2$$

$$\sin^2 2\theta_\nu = 0.07$$

Beun, McLaughlin, Surman, and Hix (2006)

collective oscillations and a supernova *r* process: toy model





No ν for $T < 9\times10^9$ K

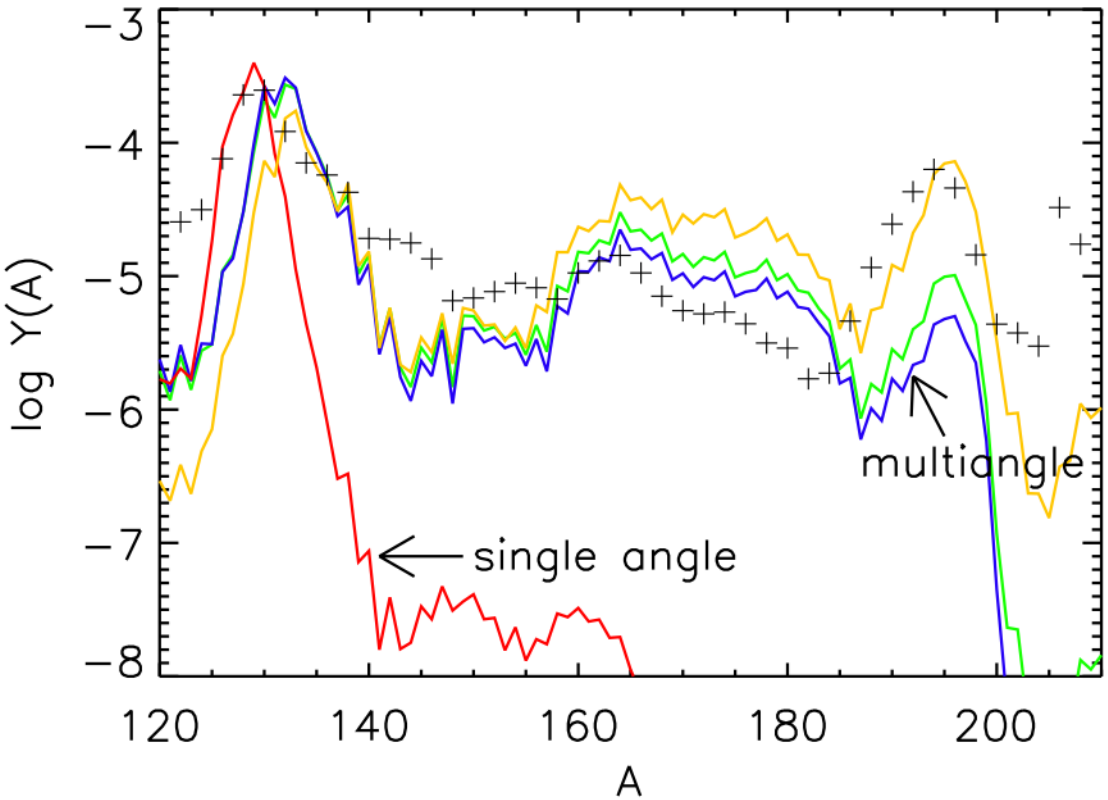
No oscillations

Test swap at seed assembly

Test swap at alpha assembly

Duan, Friedland, McLaughlin & Surman (2011)

collective oscillations and a supernova *r* process

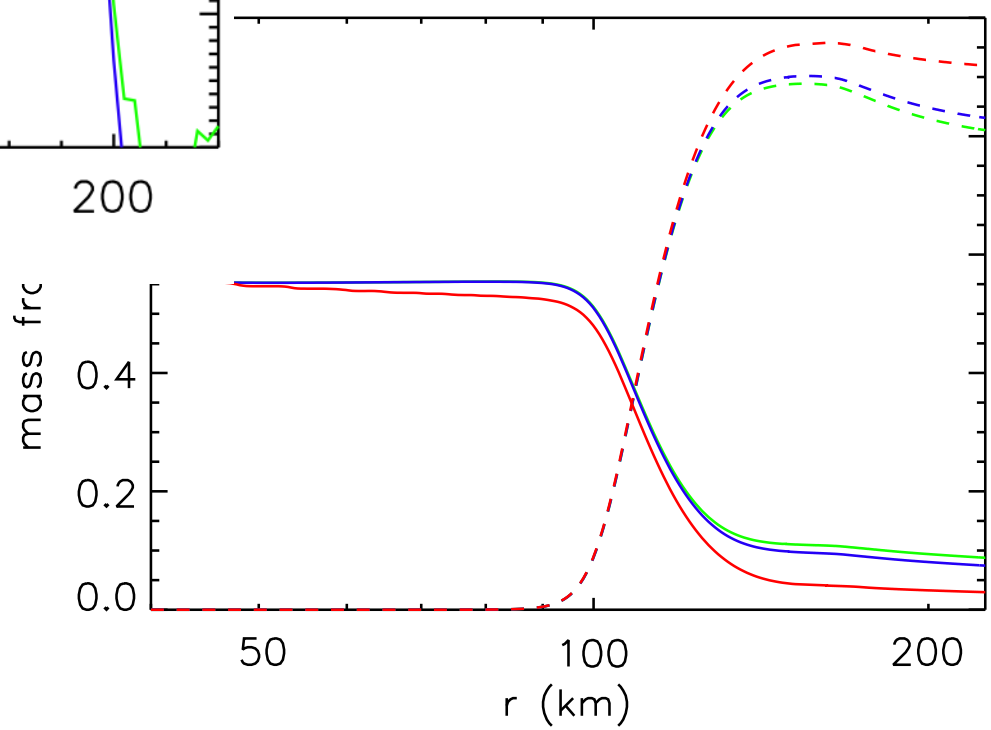


No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

Single angle ν oscillation calculation



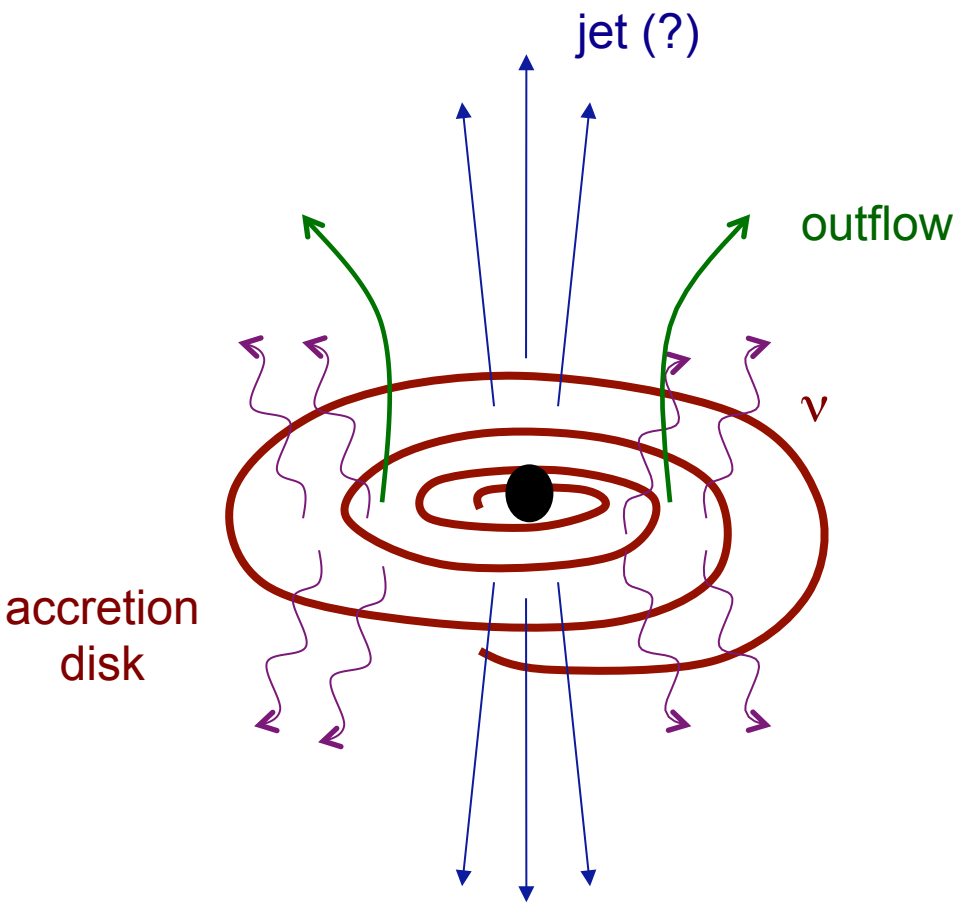
$s/k = 200$

$\tau = 18$ ms

Duan, Friedland, McLaughlin & Surman (2011)

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:

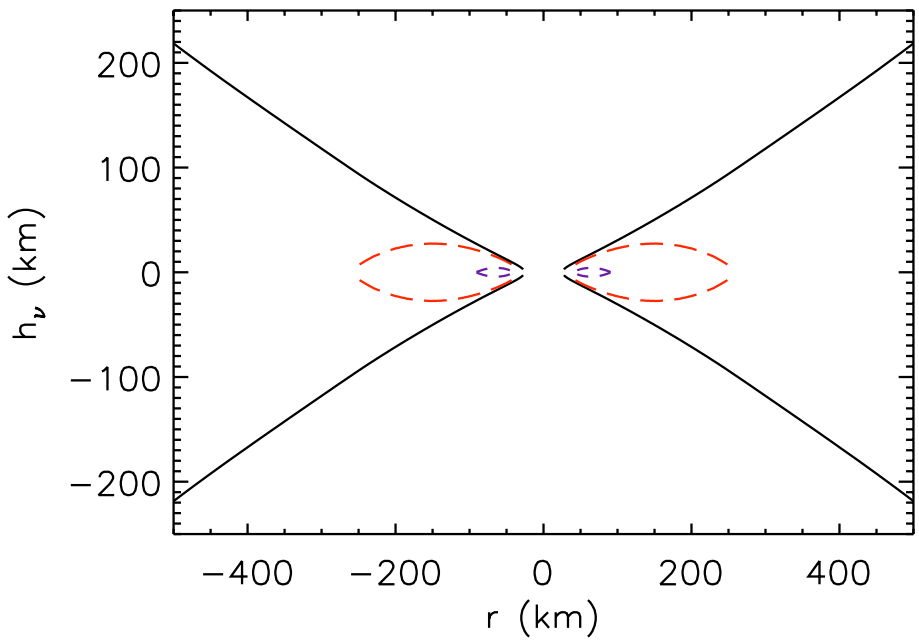
e.g., Pruet, Thompson, & Hoffman (2004), Surman & McLaughlin (2004), Surman, McLaughlin, & Hix (2006), Metzger, Thompson, & Quataert (2008), Nakamura et al (2011), Wanajo & Janka (2012)

black hole accretion disk 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

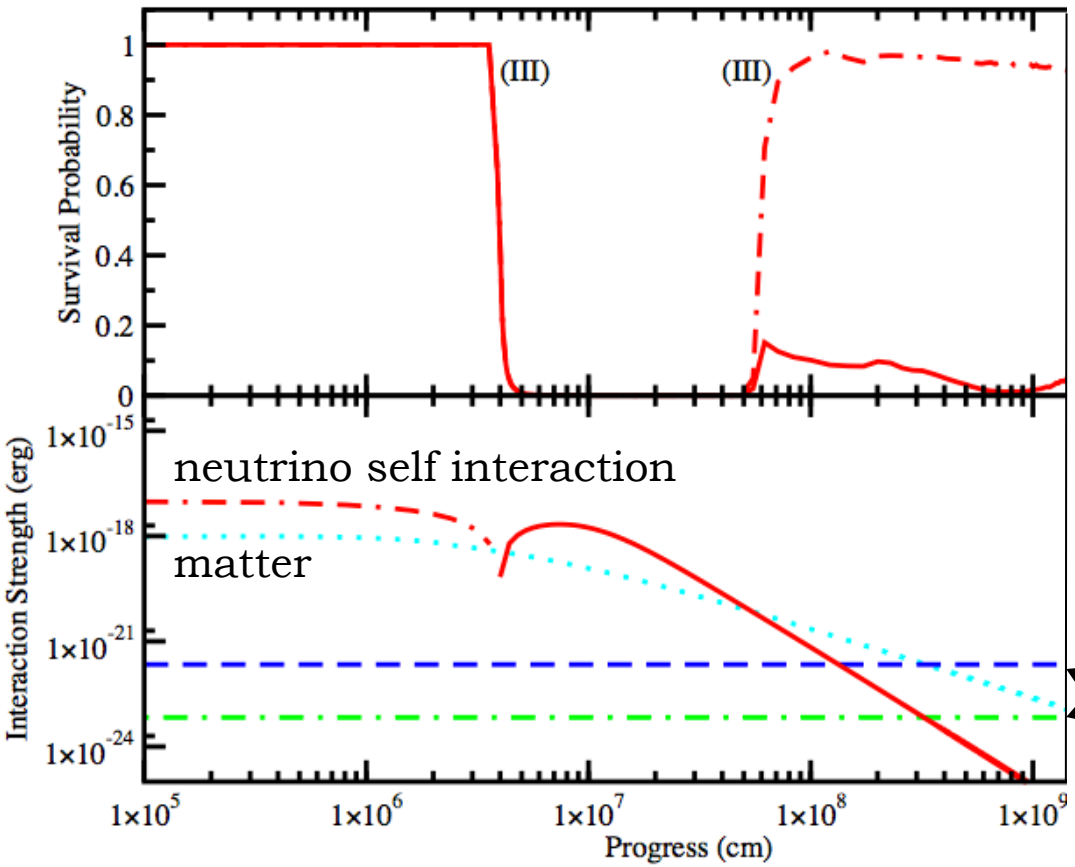
neutrino oscillations

Two flavor mixing in matter with a high neutrino flux:

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

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

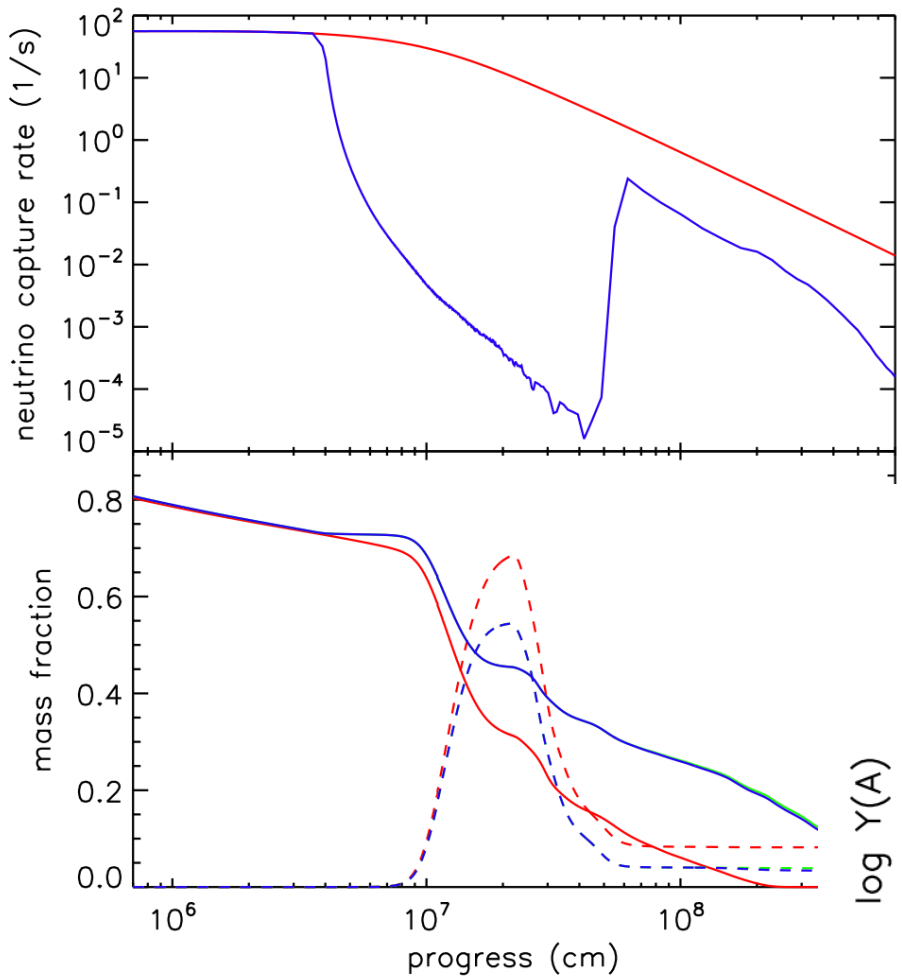
black hole accretion disk neutrino oscillations



Malkus, McLaughlin, Kneller, Surman (2012)

vacuum terms

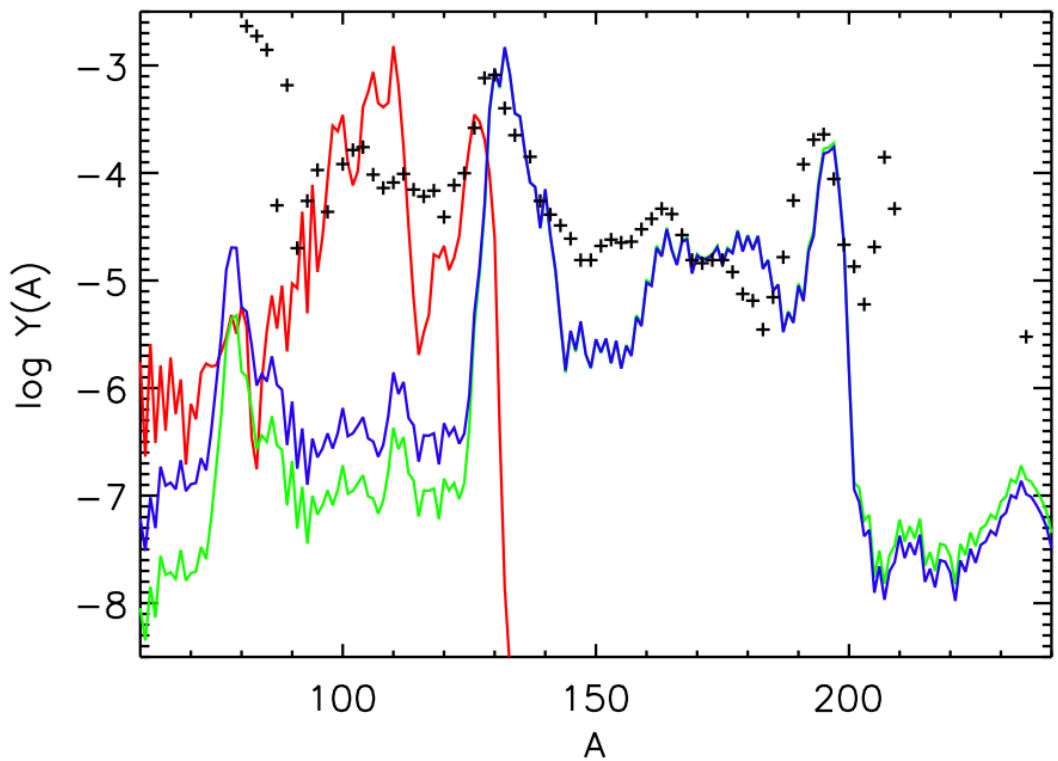
AD-BH neutrino oscillations: consequences for nucleosynthesis



no oscillations

single angle ν oscillation calculation

Malkus, McLaughlin, Kneller, Surman (2012)



summary

Many rare nuclear species whose origins are not fully understood are formed either directly by neutrino interactions or in neutrino-rich environments

LBNE science goals are linked to some of the key open questions in nuclear astrophysics

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

- Neutrino mixing parameters and mass hierarchy
- As much spectral information as possible from the next galactic supernova