Title: Neutrinos in supernova evolution and nucleosynthesis

Date: Jun 22, 2011 09:30 AM

URL: http://pirsa.org/11060028

Abstract: Massive accretion disks may form from the merger of neutron star (NS)-NS or black hole-NS binaries, or following the accretion-induced collapse (AIC) of a white dwarf. These disks, termed `hyper-accreting' due to their accretion rates up to several solar masses per second, may power the relativistic jets responsible for short duration gamma-ray bursts. Using 1D time-dependent calculations of hyper-accreting disks, I show that a generic consequence of the disk's late-time evolution is the development of a powerful outflow, powered by viscous heating and the recombination of free nuclei into Helium. These outflows - in additional to any material dynamically-ejected during the merger - synthesize heavy radioactive elements as they expand into space. Nuclear heating from the r-process is not yet incorporated in merger simulations, yet has important consequences both for the dynamics of late `fall-back' accretion and in powering a supernova-like transient (`kilonova') 1 day following the merger or AIC.

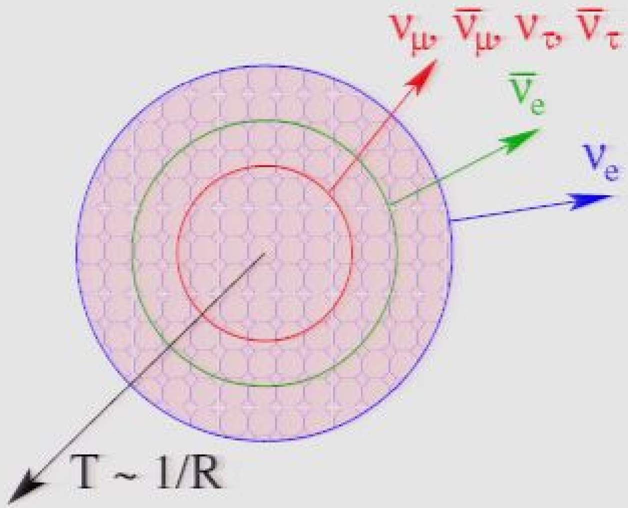
Outline

1. Introduction
2. Neutrino-matter interactions
3. Nucleosynthesis in proton-rich ejecta
   - The νp-process
   - Collective neutrino oscillations
4. Summary

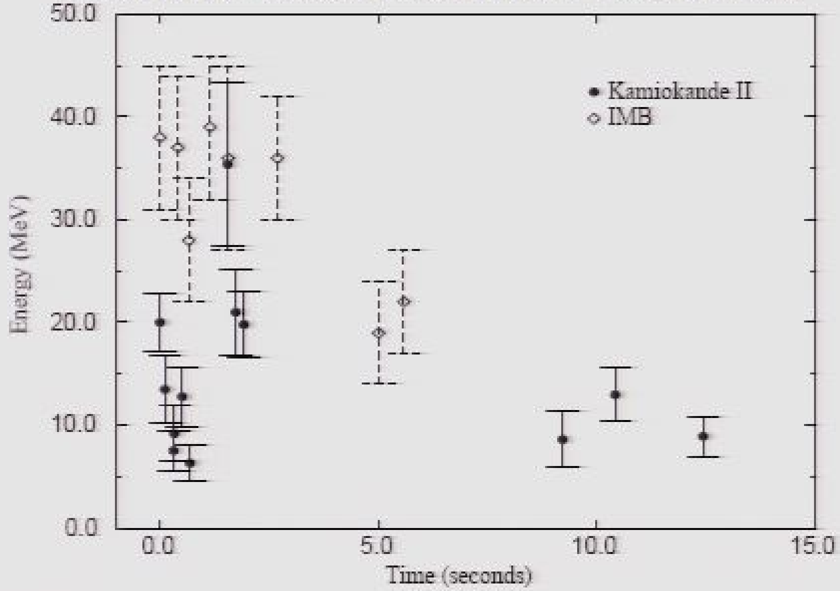
Outline

1. Introduction
2. Neutrino-matter interactions
3. Nucleosynthesis in proton-rich ejecta
   - The νp-process
   - Collective neutrino oscillations
4. Summary

Neutrino emission from the proto-neutron star



Neutrino detection from SN1987A

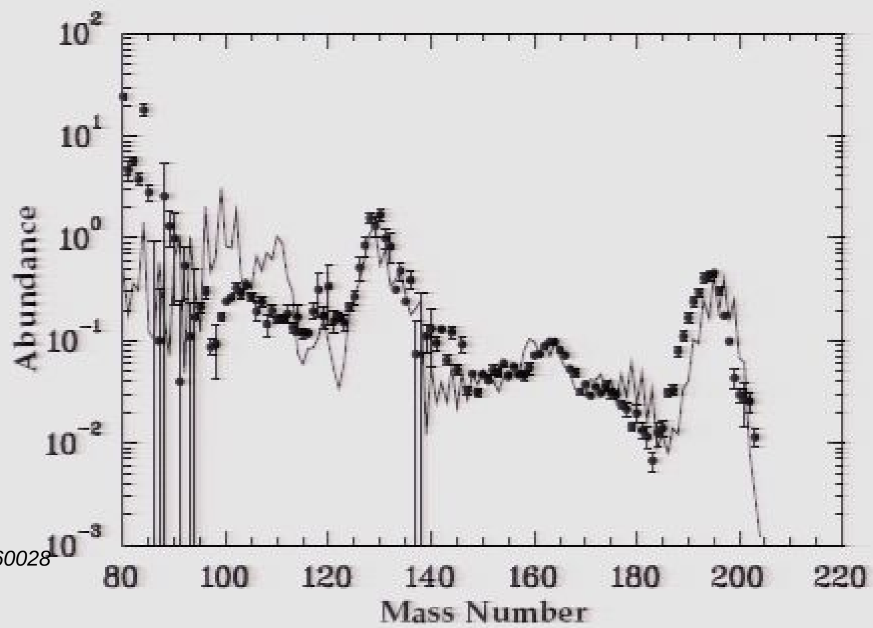


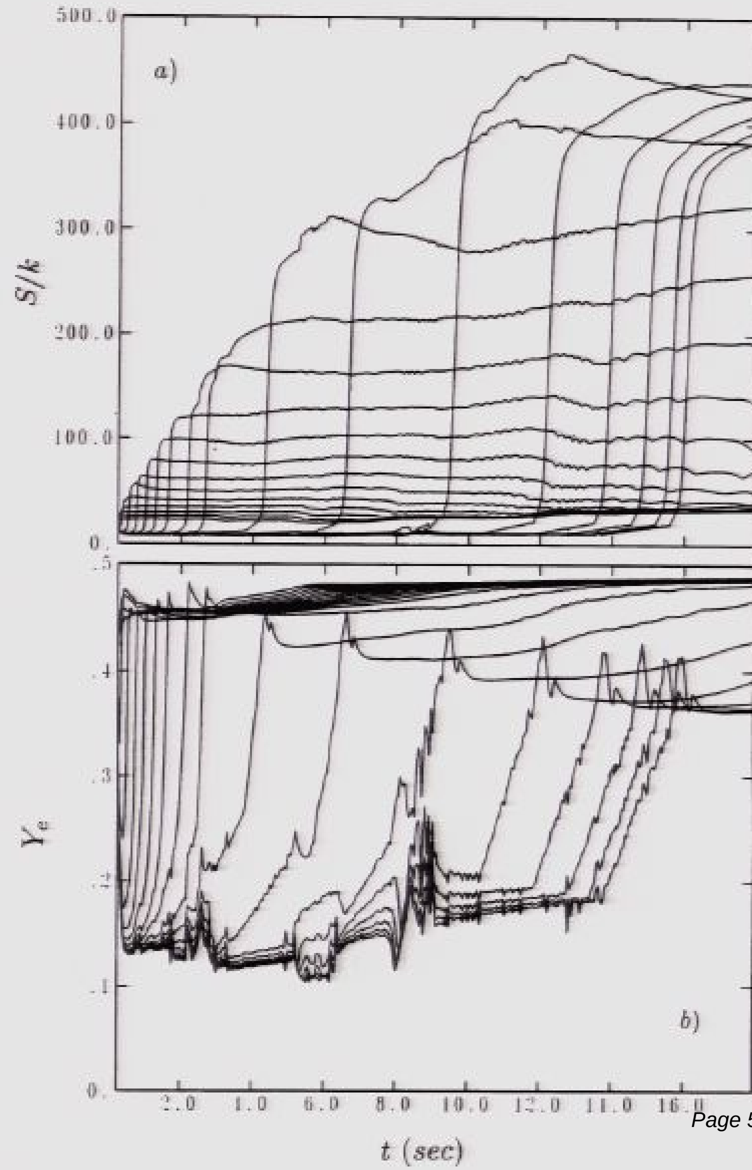
Neutrino spectra and luminosities important for:

- Nucleosynthesis in neutrino driven wind: νp-process and r-process(?).
- Neutrino-nucleosynthesis: production of some key isotopes, ^{11}B, ^{19}F, ^{15}N, ^{138}La and ^{180}Ta, by neutral current spallation reactions and charged-current neutrino absorption in the ONe, C and He layers of the star.
- Possibility of having an r-process in the He layer at low metalicities [Banerjee *et al.*, PRL **106**, 201104 (2011)]
- Neutrino oscillations (collective, MSW, vacuum)
- Neutrino detection on Earth

Neutrino-driven winds and r-process

- Woosley *et al*, ApJ **433**, 229 (1994), suggested neutrino-driven winds as the r-process site.
- High entropy conditions not confirmed by any other group, Takahashi, Witti, Janka, A&A **286**, 857 (1994) …





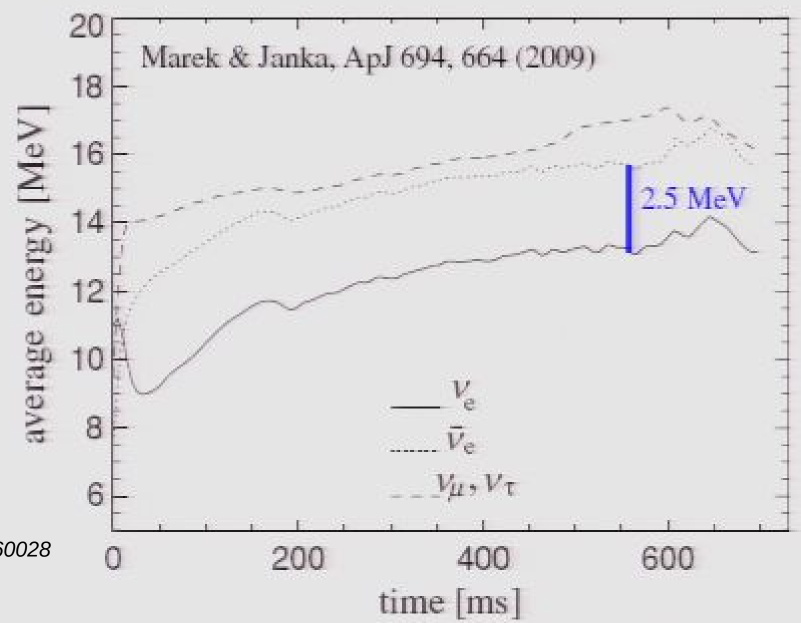
Influence of neutrinos on nucleosynthesis

Main processes:

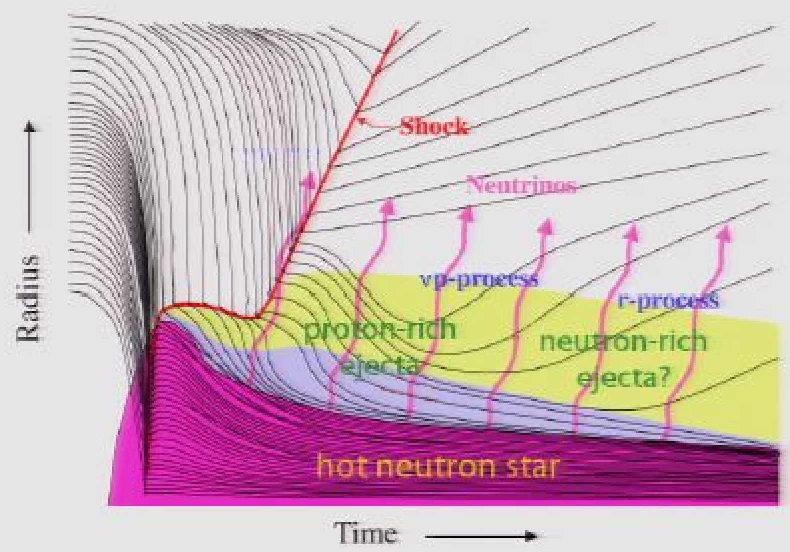
$$\nu_e + n \to p + e^-$$
$$\bar{\nu}_e + p \to n + e^+$$

Neutrino interactions determine the proton to neutron ratio, the ejecta are proton rich if:

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2) \approx 5.2\text{MeV}$$



- Early times (up to 1-2 seconds): proton-rich ejecta (νp-process).
- Later times: neutron-rich ejecta (r-process)??

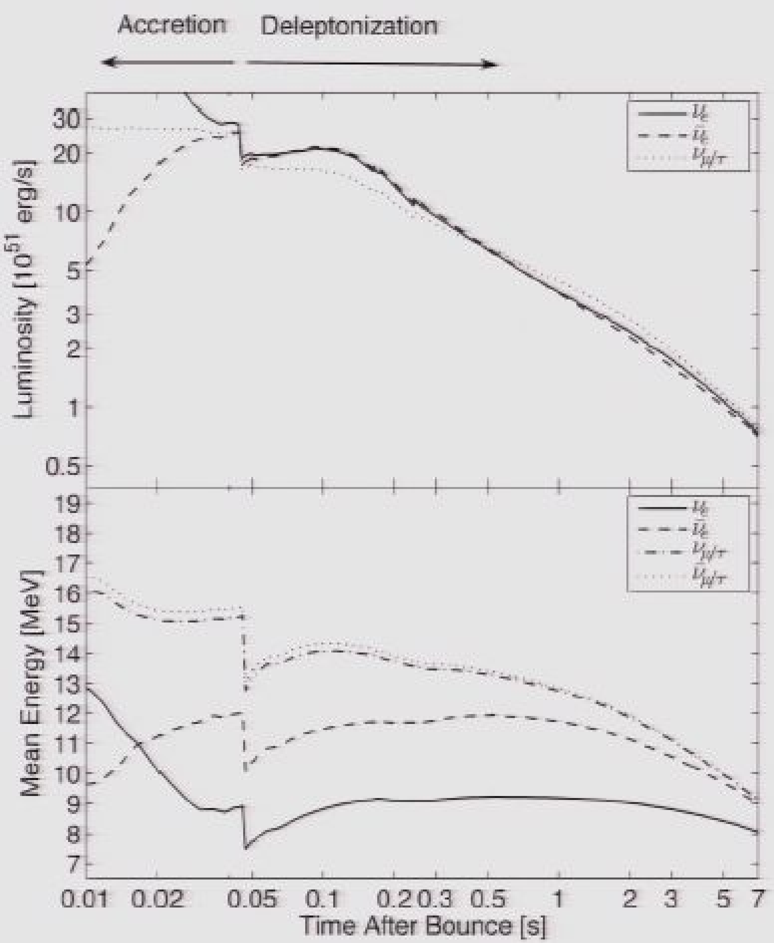


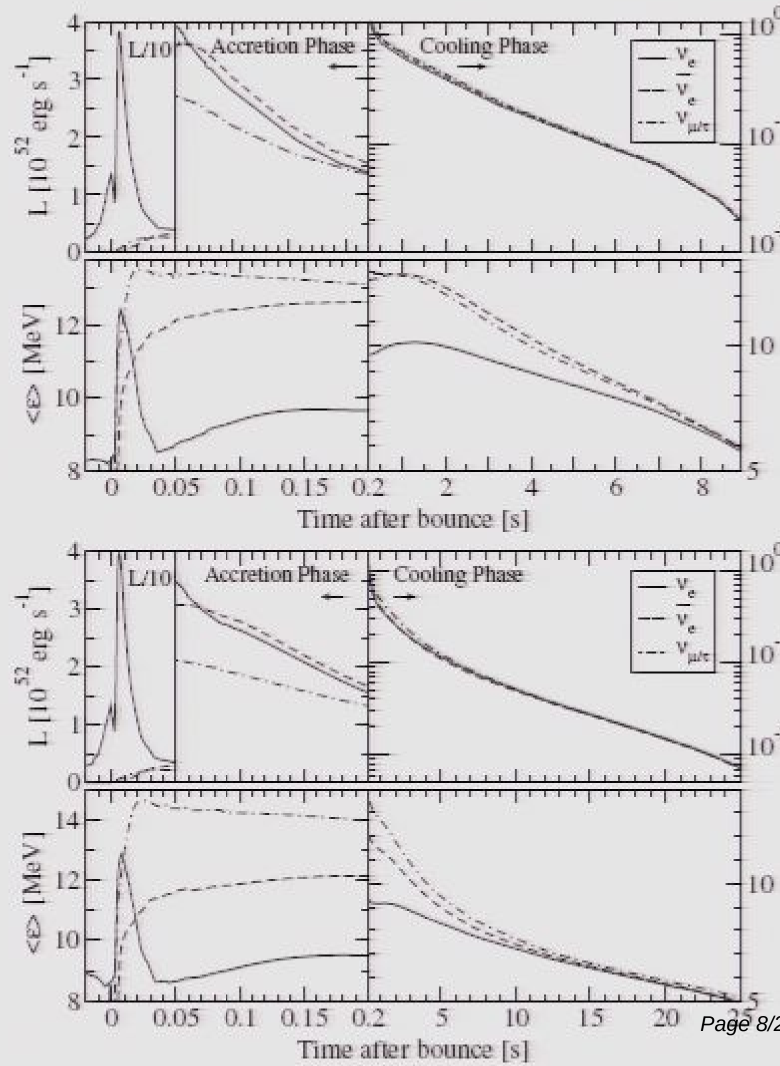
Neutrino-matter interactions

- Charge-current processes:
  $\nu_e + n \rightleftarrows p + e^-$ (Bruenn 1985, Horowitz 2002)
  $\nu_e + A(Z) \rightleftarrows A(Z+1) + e^-$ (Bruenn 1985, Juodagalvis *et al.*, 2010)
  $\bar{\nu}_e + p \rightleftarrows n + e^+$ (Bruenn 1985, Horowitz 2002)
- Elastic scattering processes:
  $\nu + \{n, p\} \rightleftarrows \{n, p\} + \nu$ (Bruenn 1985, Horowitz 2002)
  $\nu + A \rightleftarrows A + \nu$ (Bruenn 1985, Bruenn & Mezzacappa 1997)
- Inelastic Scattering processes:
  $\nu + e^{\pm} \rightleftarrows \nu + e^{\pm}$ (Mezzacappa & Bruenn 1993)
- Pair processes:
  $\nu + \bar{\nu} \rightleftarrows e^+ + e^-$ (Bruenn 1985)
  $\nu + \bar{\nu} + N + N \rightleftarrows N + N$ (Hannestad & Raffelt 1998)
- Additional processes:
  $\nu + \nu \rightleftarrows \nu + \nu$ (Buras *et al* 2003)
  $\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$ (Buras *et al* 2003)
  $\nu + A \rightleftarrows A^* + \nu$ (Langanke *et al* 2008)
  $\nu_e + \{d, t, {}^3\text{He}\} \rightleftarrows \{{}^2\text{He}, {}^3\text{He}, {}^3\text{Li}\} + e^-$ (Nakamura *et al.* 2002)
  $\bar{\nu}_e + \{d, t, {}^3\text{He}\} \rightleftarrows \{{}^2n, {}^3n, t\} + e^+$ (Nakamura *et al.* 2002, Arcones *et al* 2008)
  $\nu + \{d, t, {}^3\text{He}\} \rightleftarrows \{d^*, t^*, {}^3\text{He}^*\} + \nu$ (Nakamura *et al.* 2002, O'Connor *et al* 2007)
  $\nu + N + N \rightleftarrows N + N + \nu$ (Hannestad & Raffelt 1998)
  $\bar{\nu}_e + A(Z) \rightleftarrows A(Z-1) + e^+$

Long term evolution neutrino luminosities and average energie

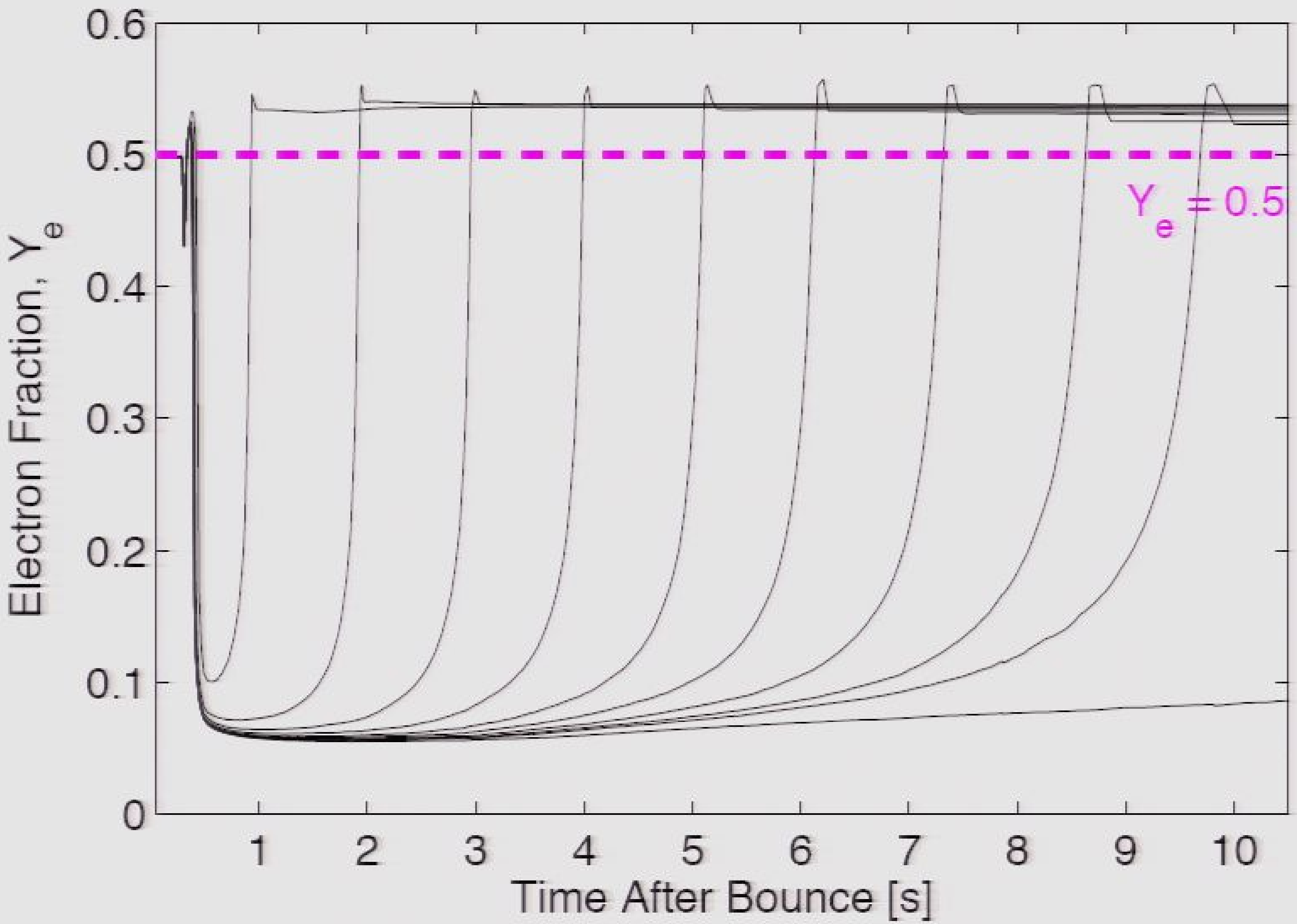
Long-term simulations of the collapse and explosion of an 8.8 $M_\odot$ ONeMg core,





Fischer *et al*, A&A **517**, A80 (2010)

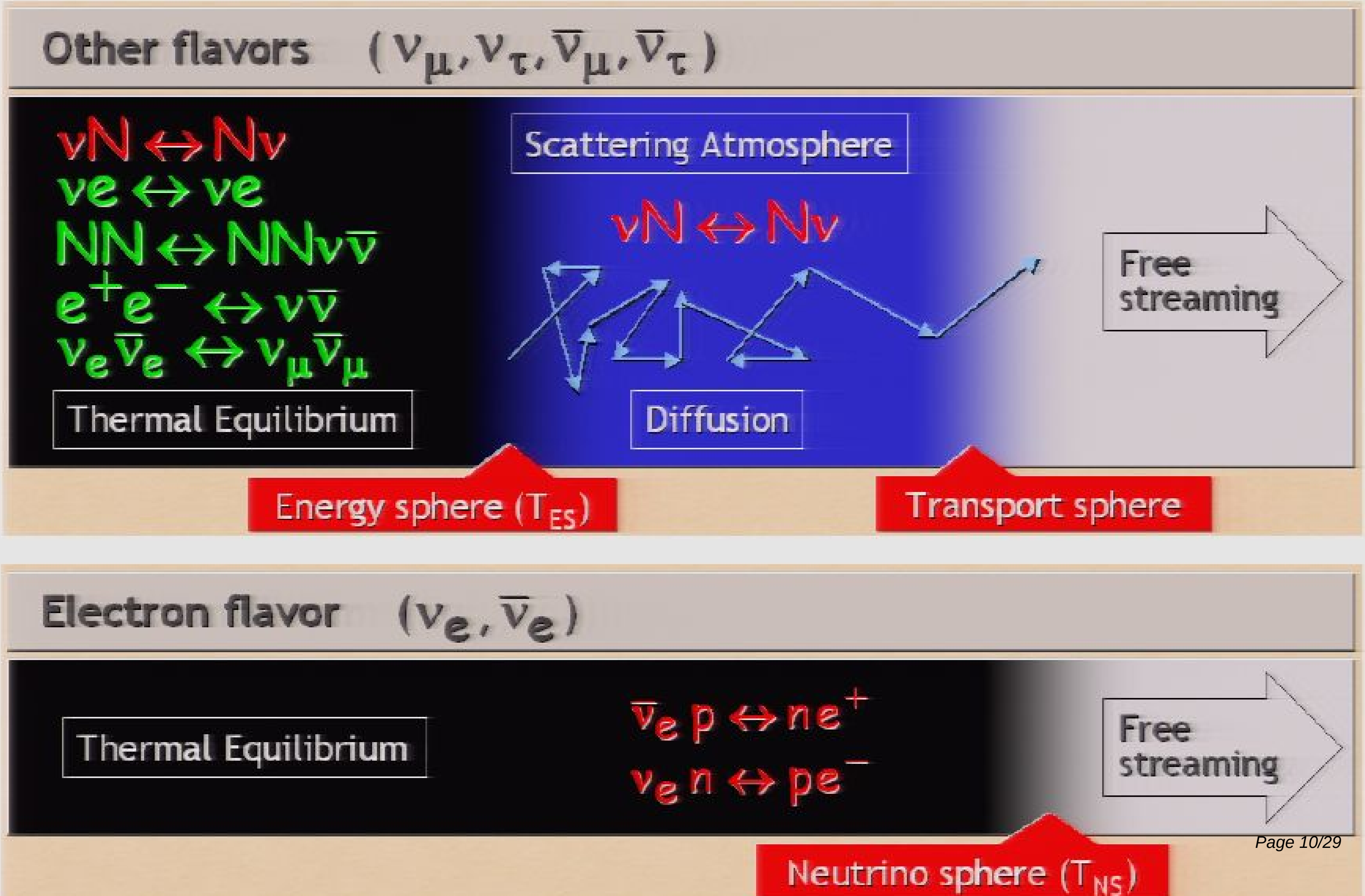
Ejecta are always proton rich



Fischer *et al.* A&A **517**, A80 (2010)

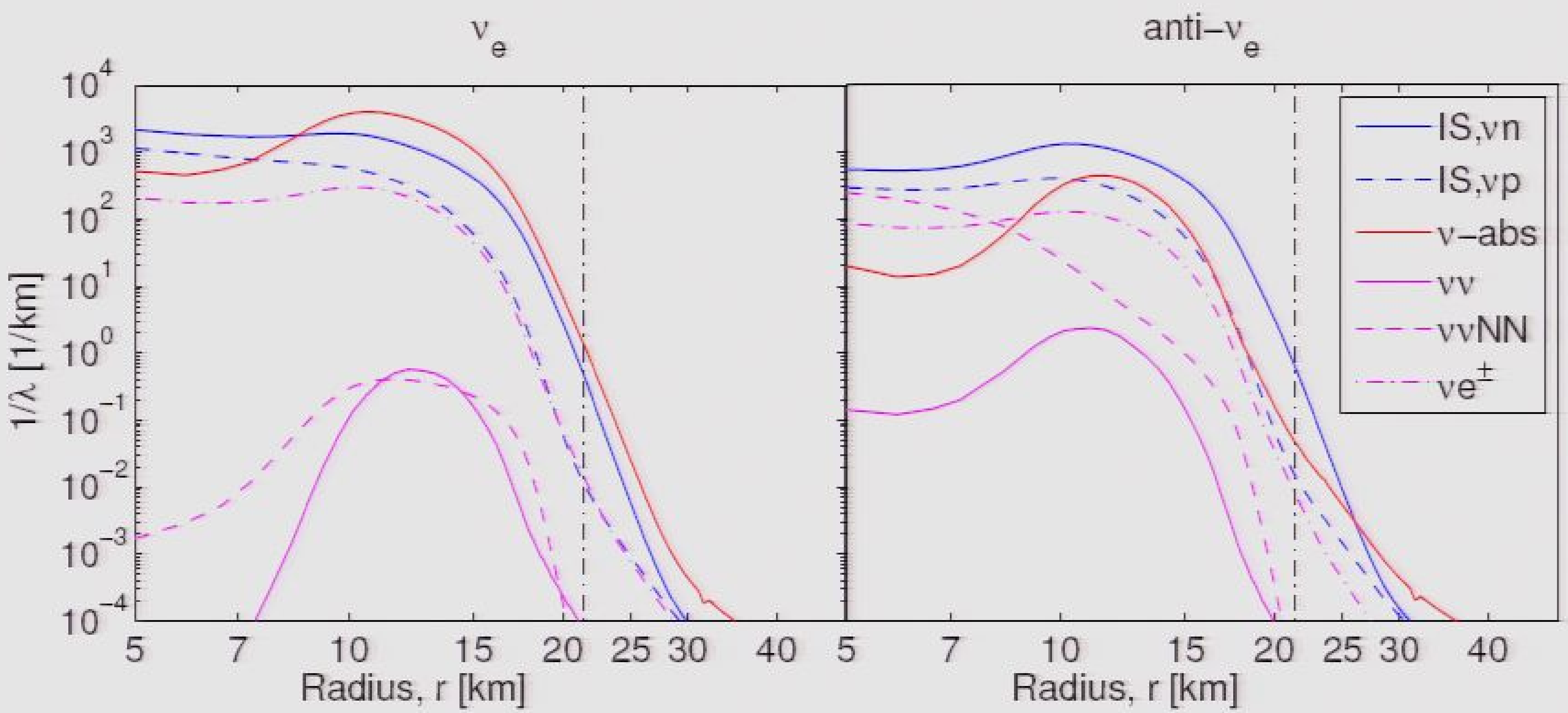
Neutrino spectra formation

(Raffelt 2001; Keil, Raffelt & Janka 2003)



electron neutrino and antineutrino opacities

Based on detailed information from Boltzmann transport long term simulations of ONeMg core.

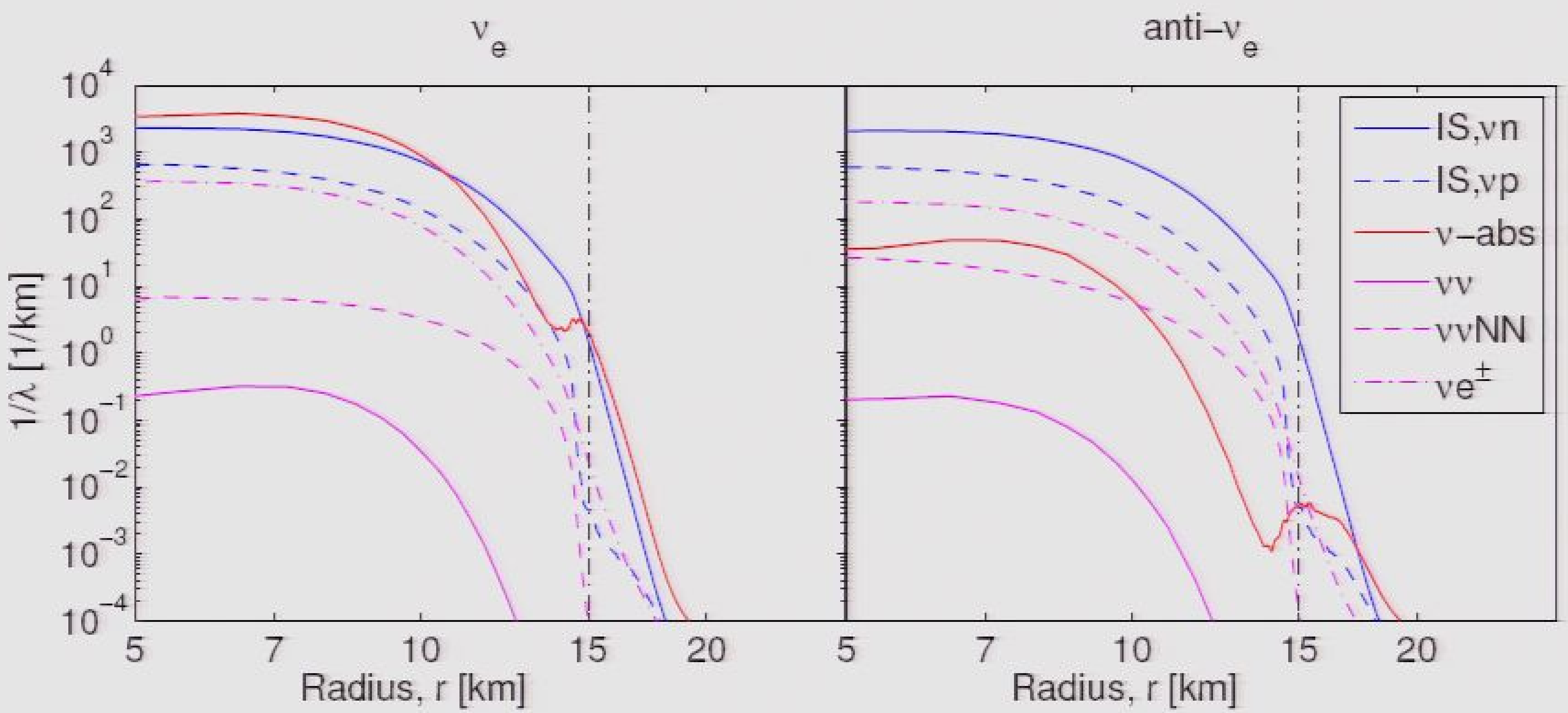


1 s after bounce

Fischer, GMP, Hempel, Liebendörfer, in preparation

electron neutrino and antineutrino opacities

Based on detailed information from Boltzmann transport long term simulations of ONeMg core.

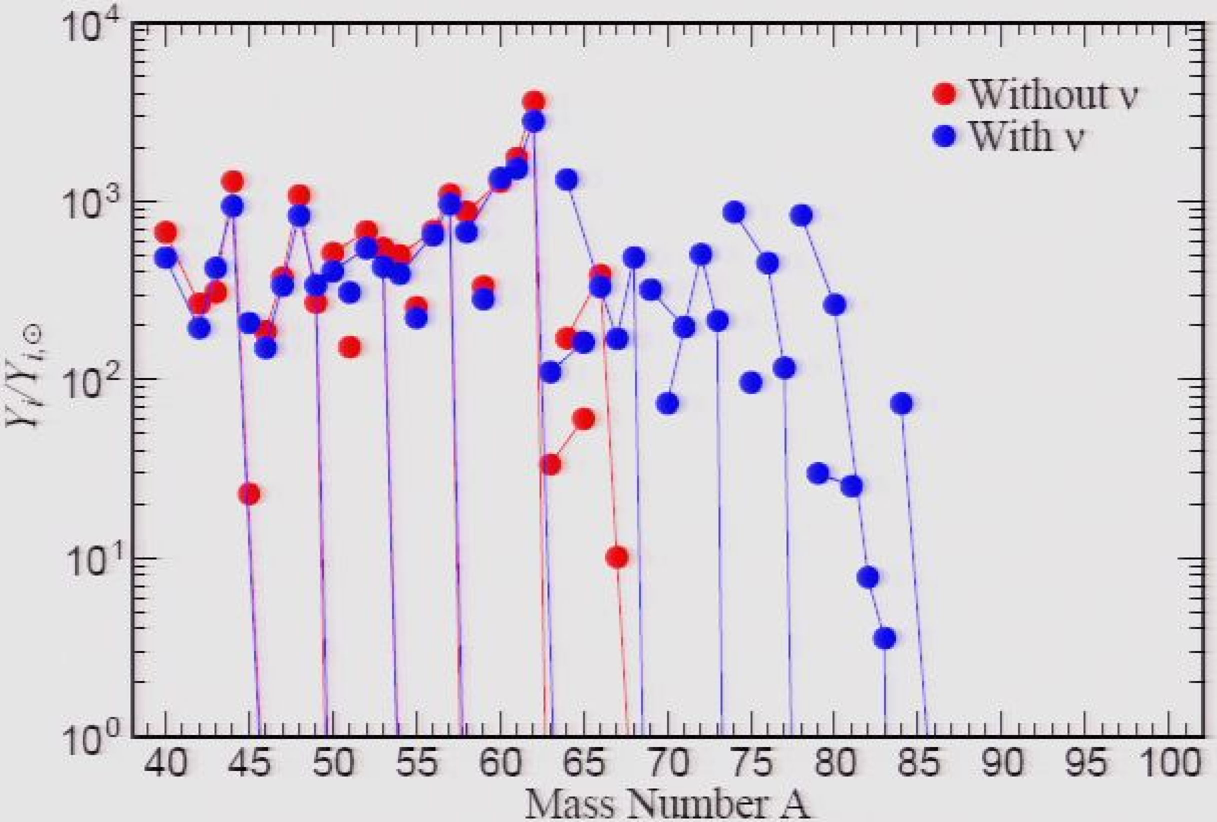


7 s after bounce

Fischer, GMP, Hempel, Liebendörfer, in preparation

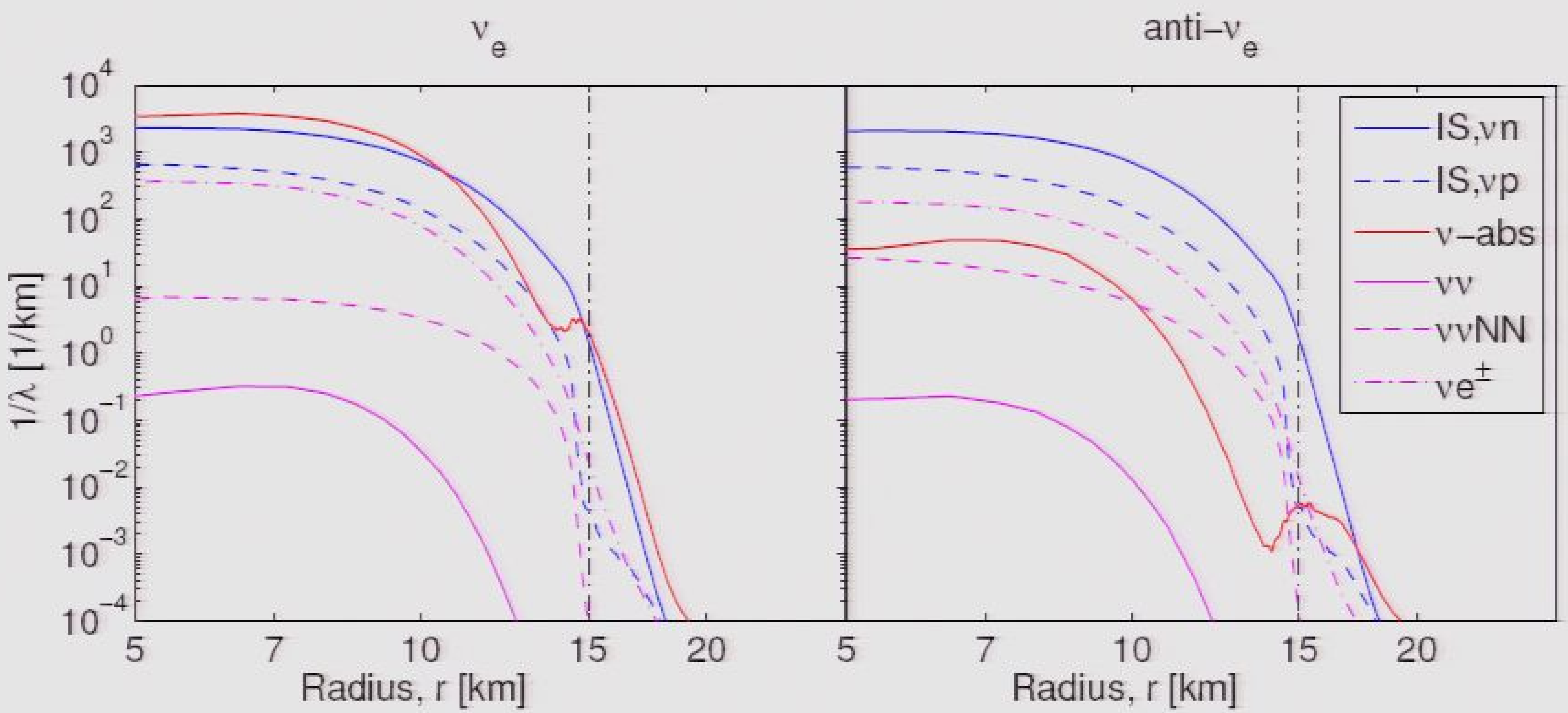
Impact of neutrino interactions on proton-rich ejecta

Once neutrino interactions are consistently included in the nucleosynthesis network, nuclei with $A > 64$ are produced.



electron neutrino and antineutrino opacities

Based on detailed information from Boltzmann transport long term simulations of ONeMg core.

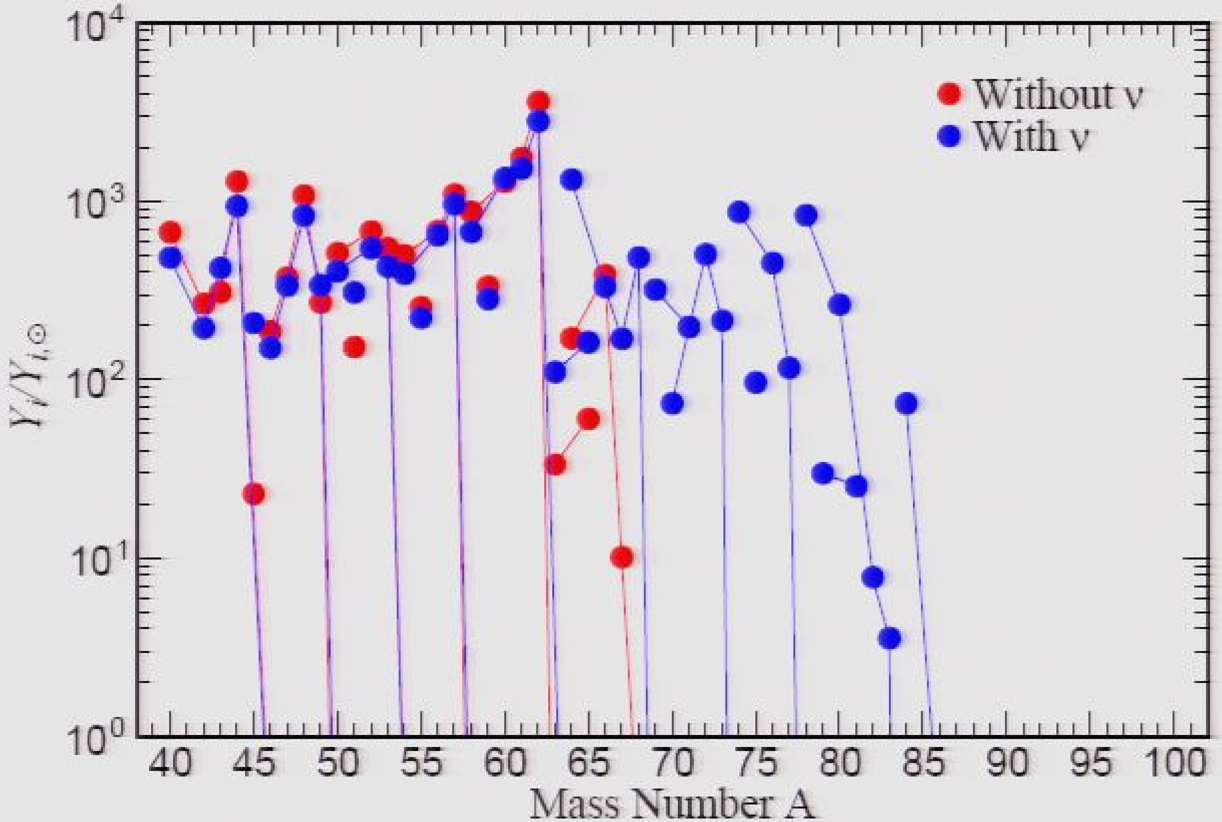


7 s after bounce

Fischer, GMP, Hempel, Liebendörfer, in preparation

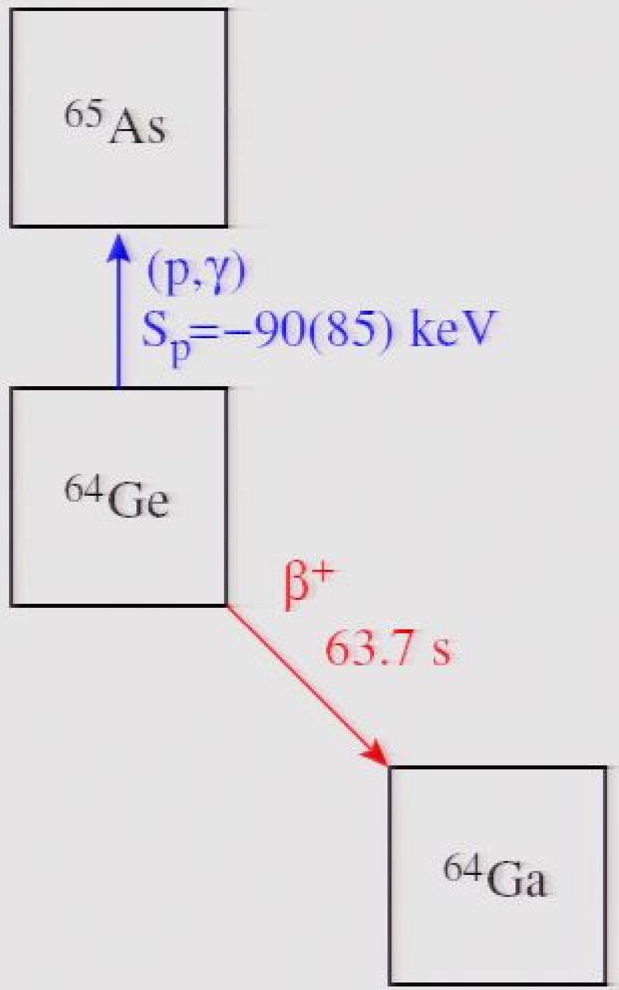
Impact of neutrino interactions on proton-rich ejecta

Once neutrino interactions are consistently included in the nucleosynthesis network, nuclei with $A > 64$ are produced.



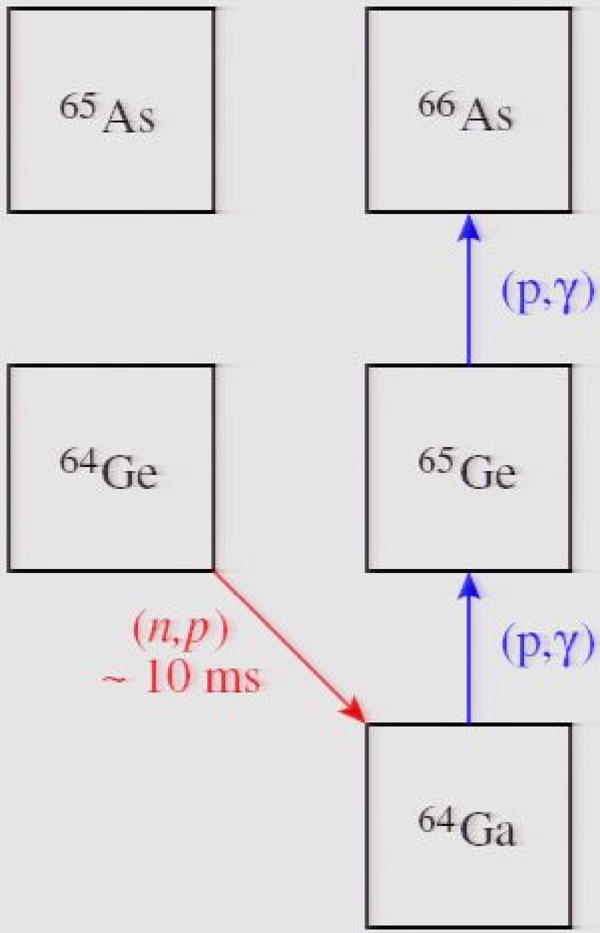
The νp-process

- Without neutrino interactions proton-rich ejecta form $N = Z$ iron-group nuclei with $A < 64$.
- However, nucleosynthesis occurs at the presence of substantial neutrino fluxes.



The νp-process

- Without neutrino interactions proton-rich ejecta form $N = Z$ iron-group nuclei with $A < 64$.
- However, nucleosynthesis occurs at the presence of substantial neutrino fluxes.
- Antineutrino absorption and expansion time scales are similar (~ 1 s)



Neutrinos speed-up the matter flow

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p$$
$${}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge} \quad \ldots$$

These reactions constitute the νp-process

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)

The νp-process

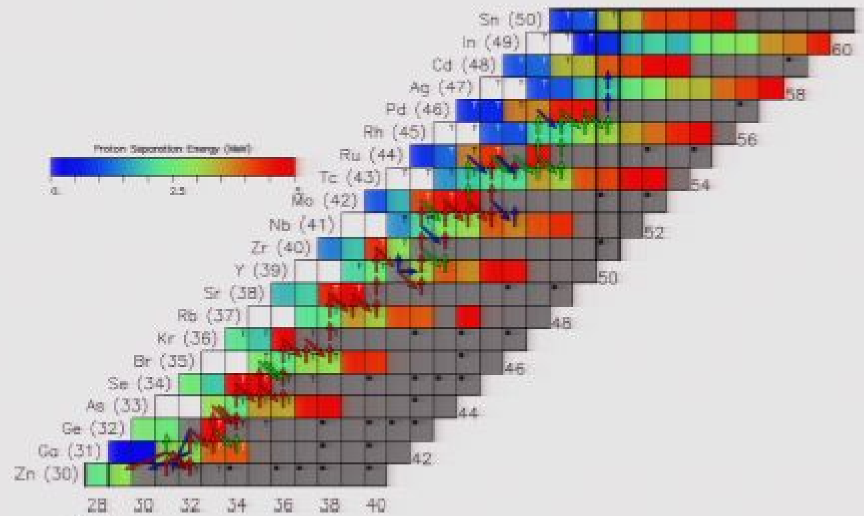
- Without neutrino interactions proton-rich ejecta form $N = Z$ iron-group nuclei with $A < 64$.
- However, nucleosynthesis occurs at the presence of substantial neutrino fluxes.
- Antineutrino absorption and expansion time scales are similar (~ 1 s)

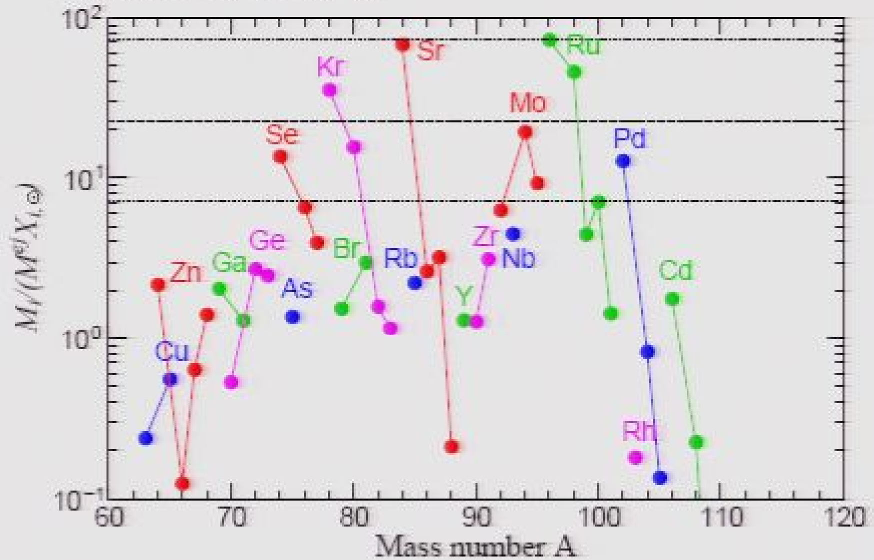
Neutrinos speed-up the matter flow

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p$$
$${}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge} \quad \ldots$$

These reactions constitute the νp-process

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)





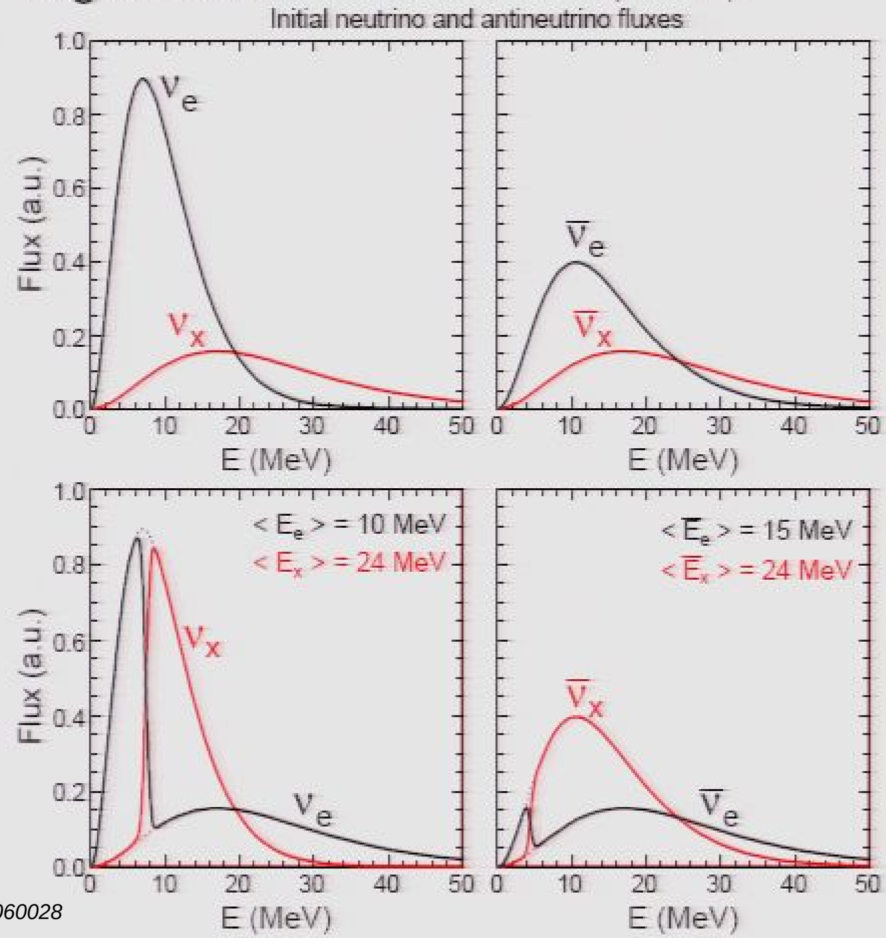
Trajectories from supernova simulation (Janka)

Collective neutrino oscillations

νp-process nucleosynthesis is sensitive to collective neutrino oscillations.

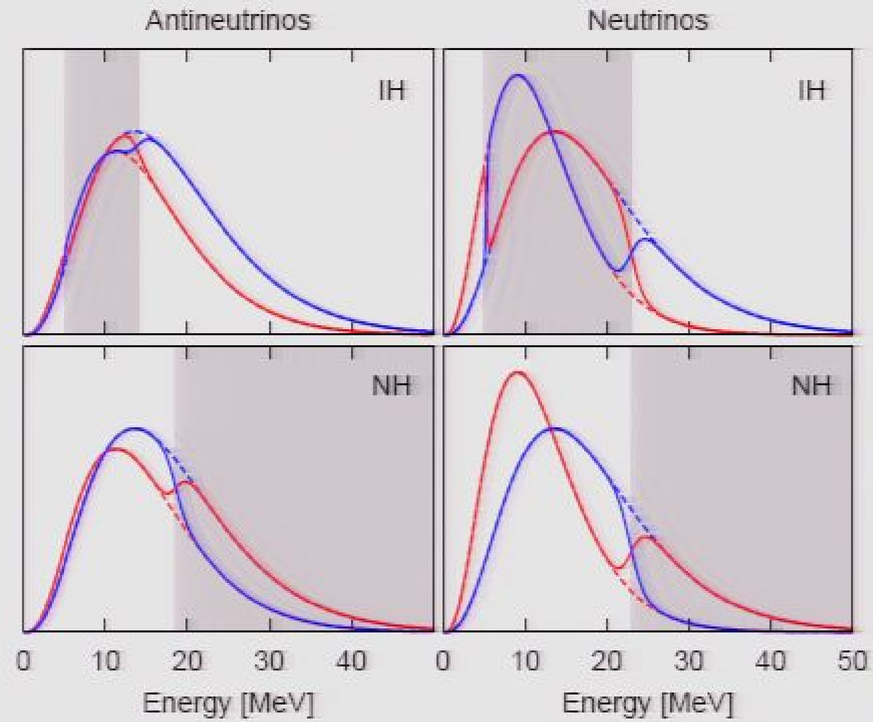
Changes in neutrino spectra depend on neutrino fluxes and hierarchy.

Fogli, *et al*, PRD **78**, 097301 (2008)



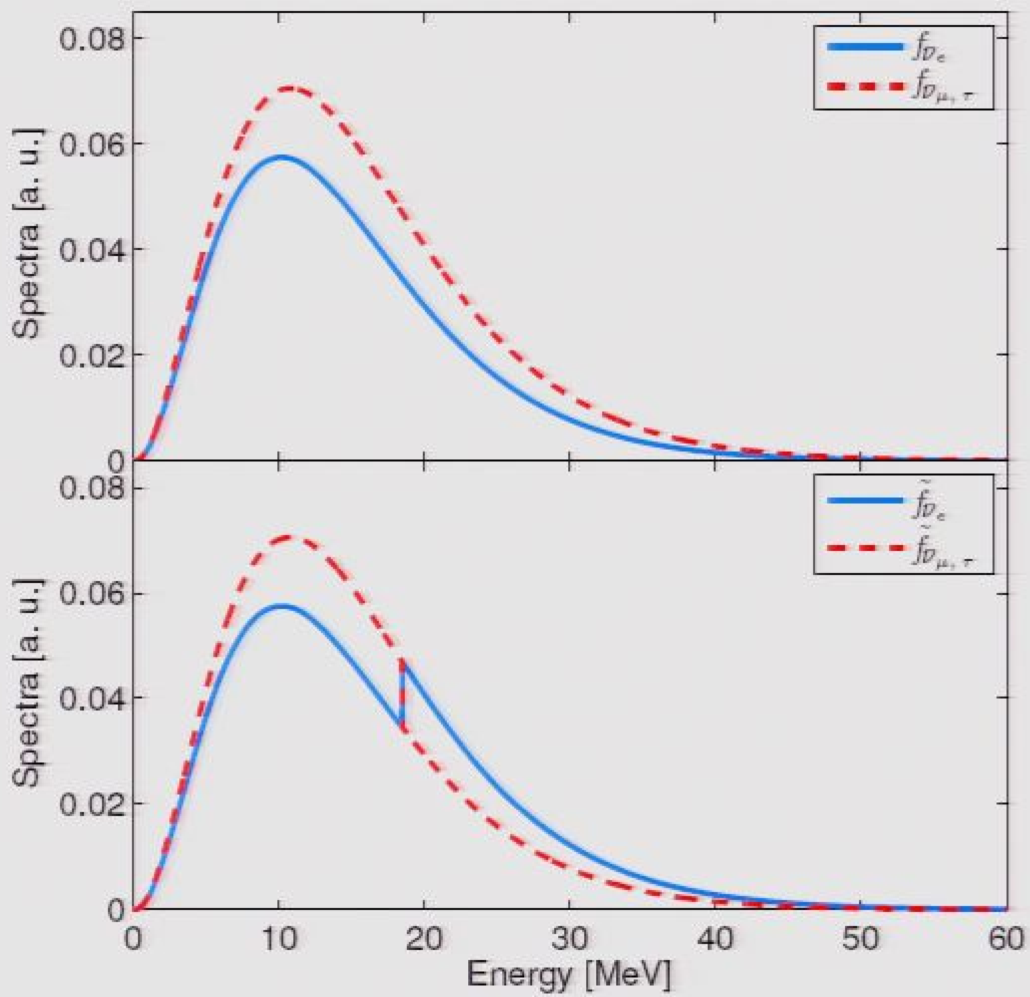
Inverted hierarchy

Dasgupta *et al*, PRL **103**, 051105 (2009)



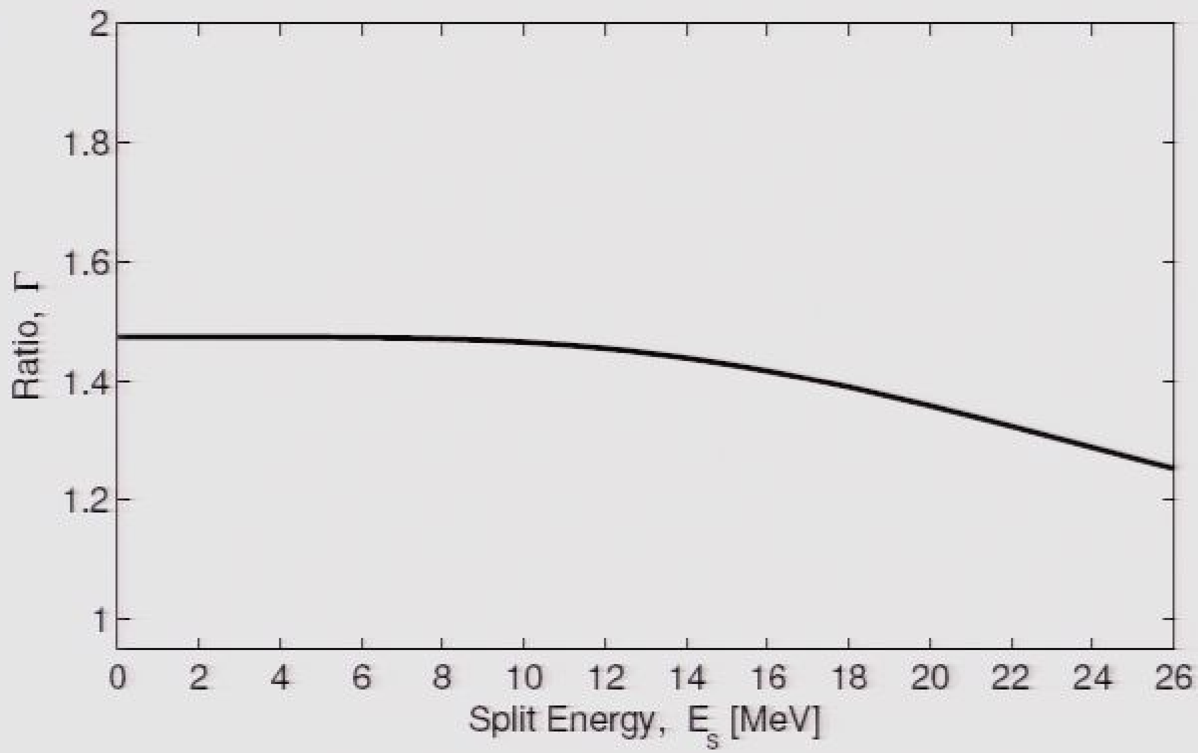
Collective-neutrino oscillations may result in a harder antineutrino spectrum and larger antineutrino absorption rate on protons.

Schematical treatment of spectral split

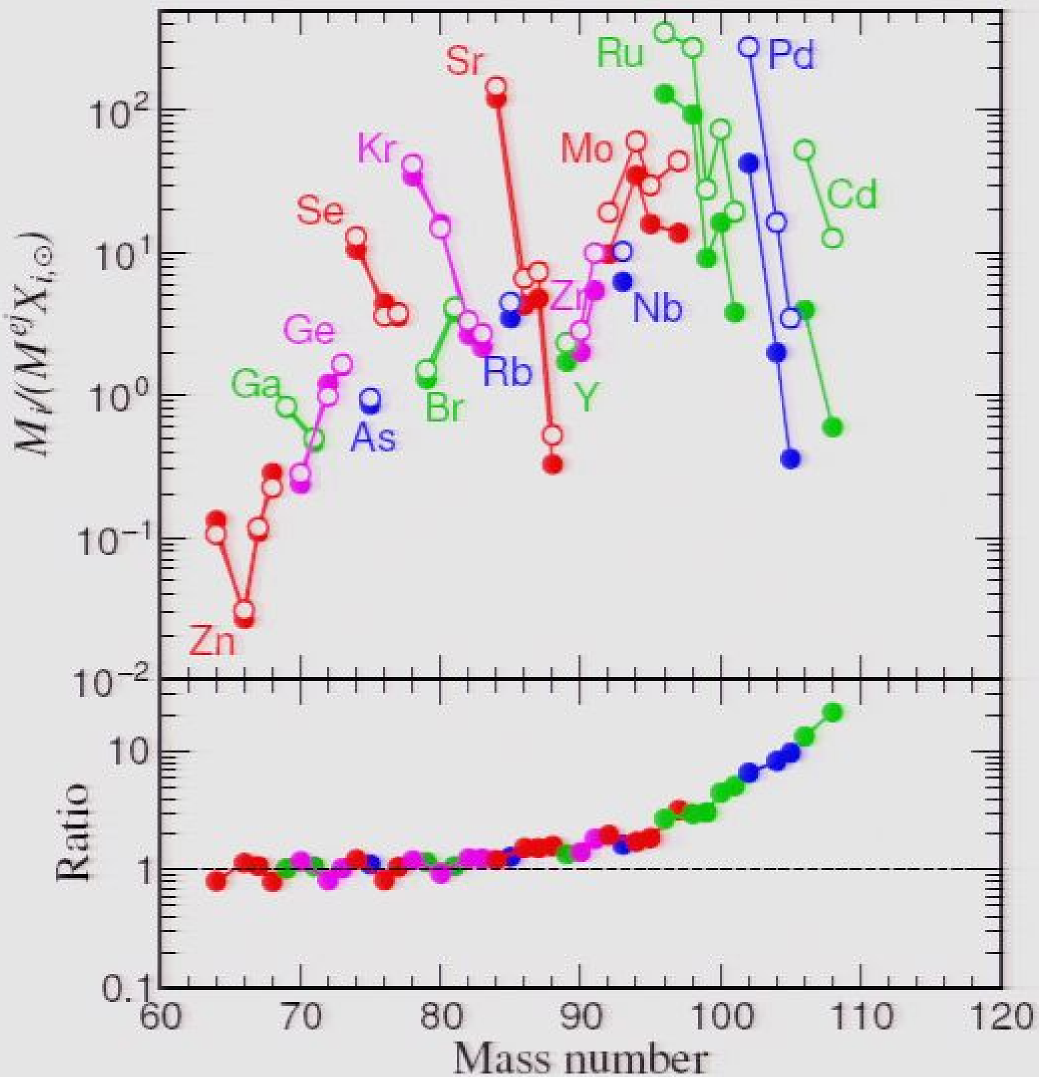


Spectra from Buras *et al.* ApJ **447**, 1049 (2006).

Enhancement of antineutrino absorption rate



Impact on nucleosynthesis



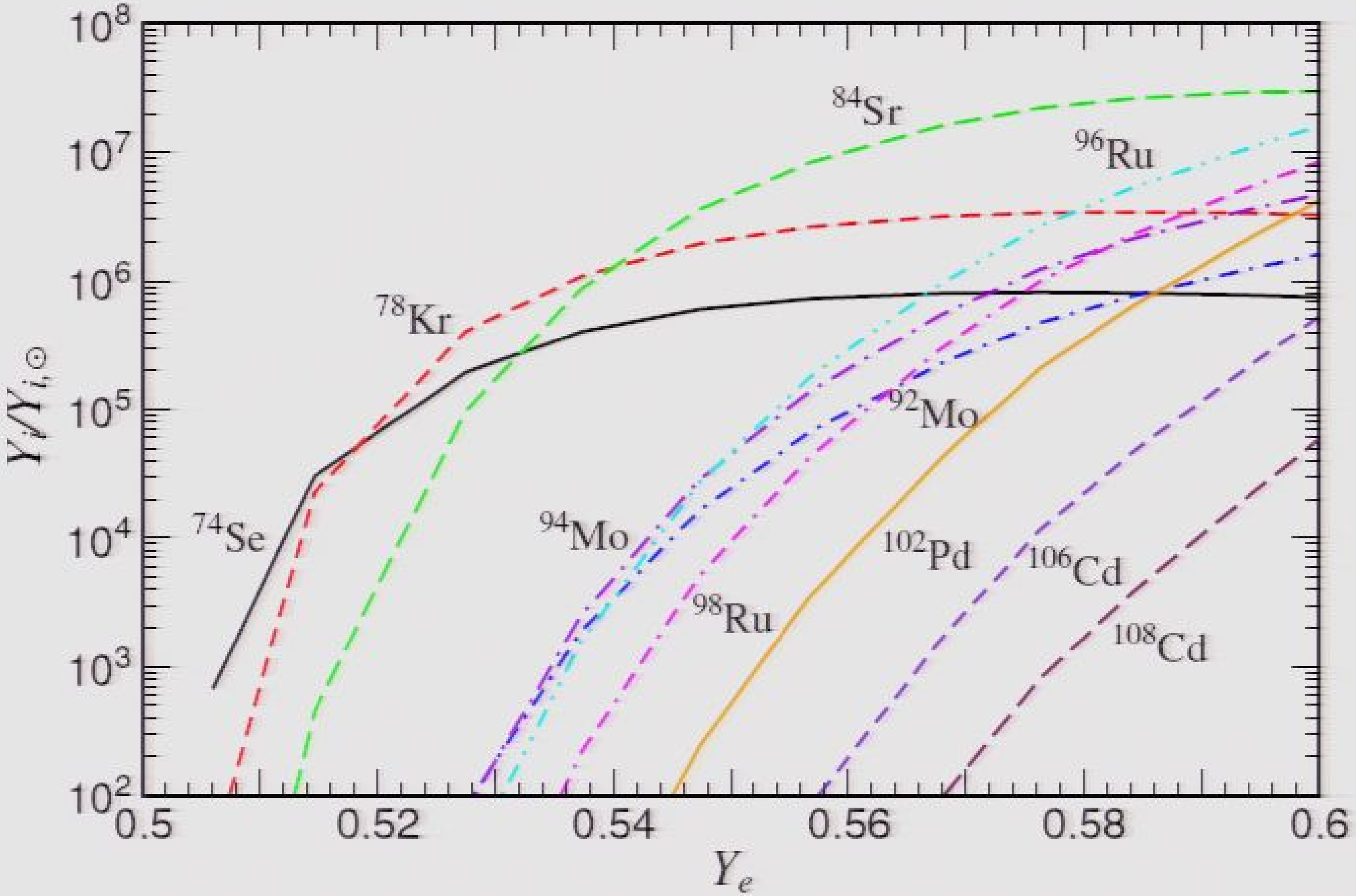
GMP, Zieharth, Fischer, Langanke, arXiv:1105.5304

Summary

- Neutrino-driven winds produce proton-rich ejecta that constitute the site for the νp-process.
- The νp-process can explain the solar abundances of light p nuclei (^{92,94}Mo, ^{96,98}Ru).
- Collective neutrino oscillations can have a strong impact in the nucleosynthesis.
- The dominating opacity channel at late times for all (anti)neutrino species is elastic scattering on nucleons resulting in very similar spectra.
- Neutron rich ejecta are not possible at late times.

Sensitivity to Y_e

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)

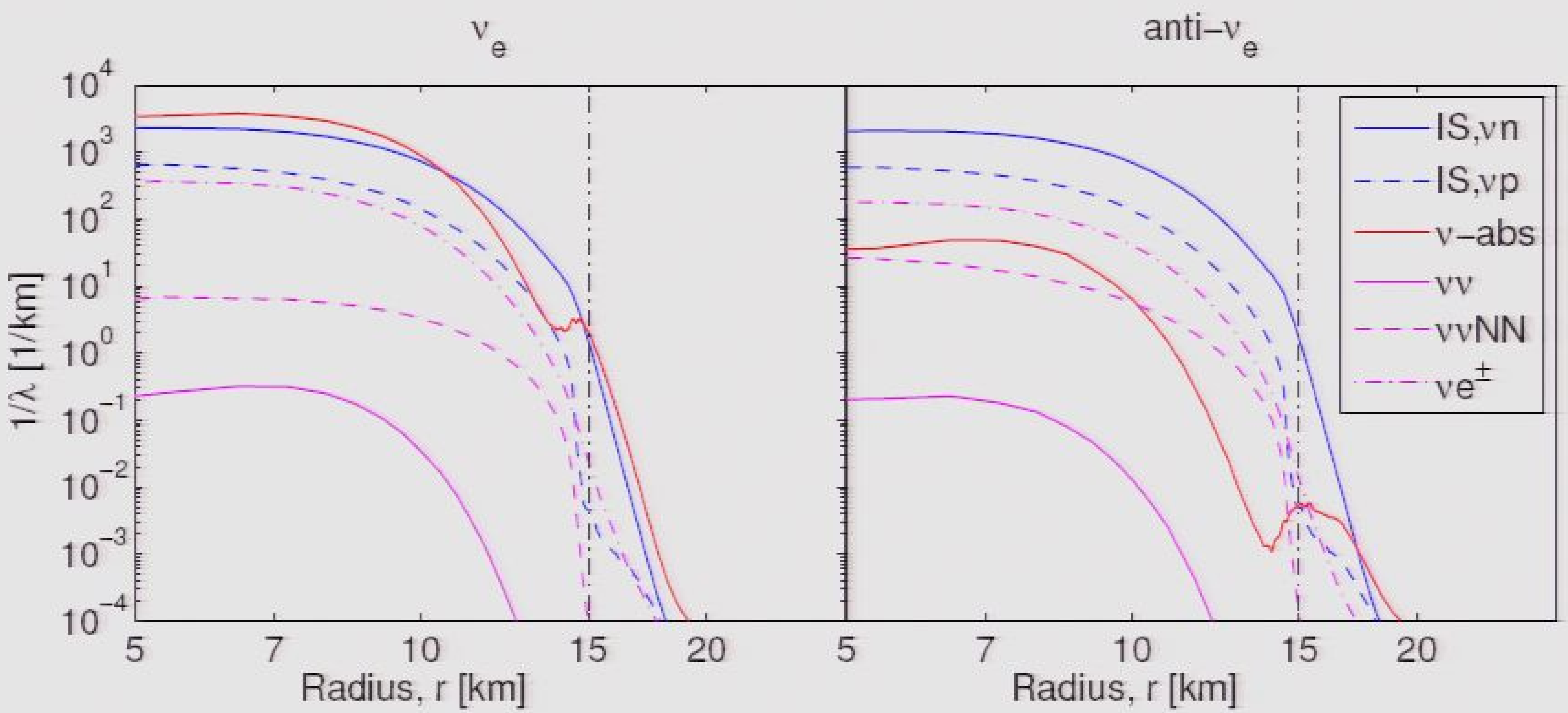


$$Y_p = 2Y_e - 1$$

Sensitivity may be reduced if additional sources for neutrons are included:

electron neutrino and antineutrino opacities

Based on detailed information from Boltzmann transport long term simulations of ONeMg core.

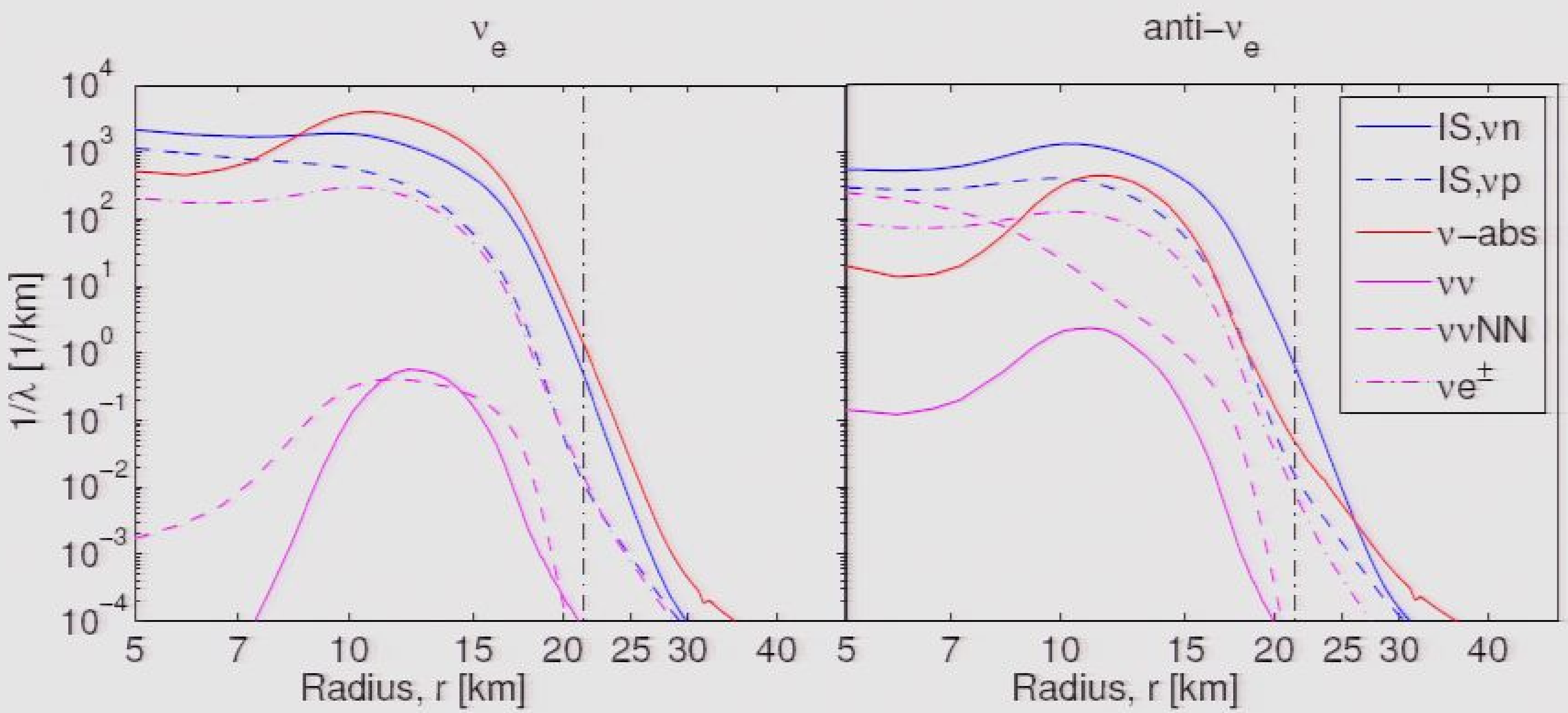


7 s after bounce

Fischer, GMP, Hempel, Liebendörfer, in preparation

electron neutrino and antineutrino opacities

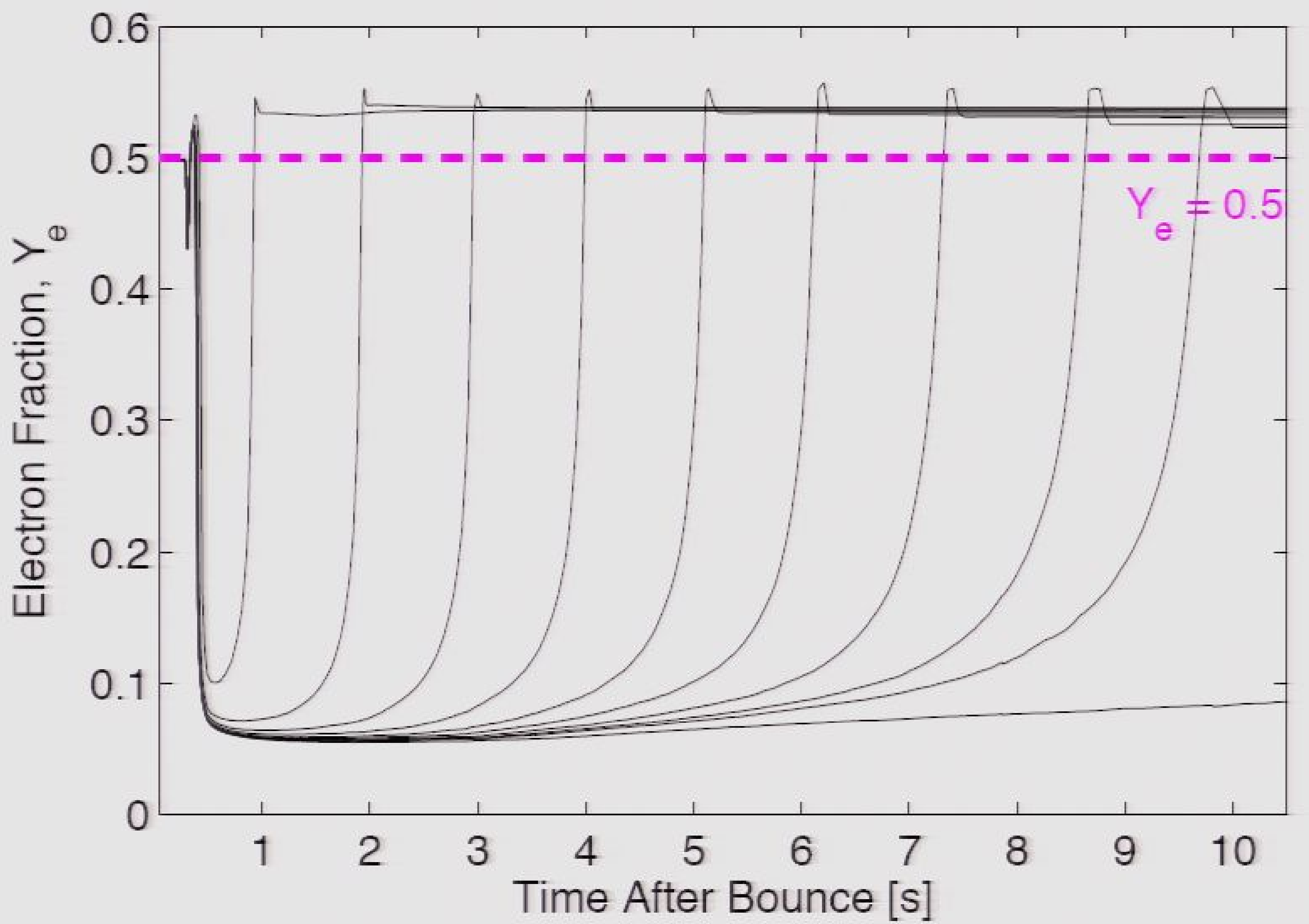
Based on detailed information from Boltzmann transport long term simulations of ONeMg core.



1 s after bounce

Fischer, GMP, Hempel, Liebendörfer, in preparation

Ejecta are always proton rich



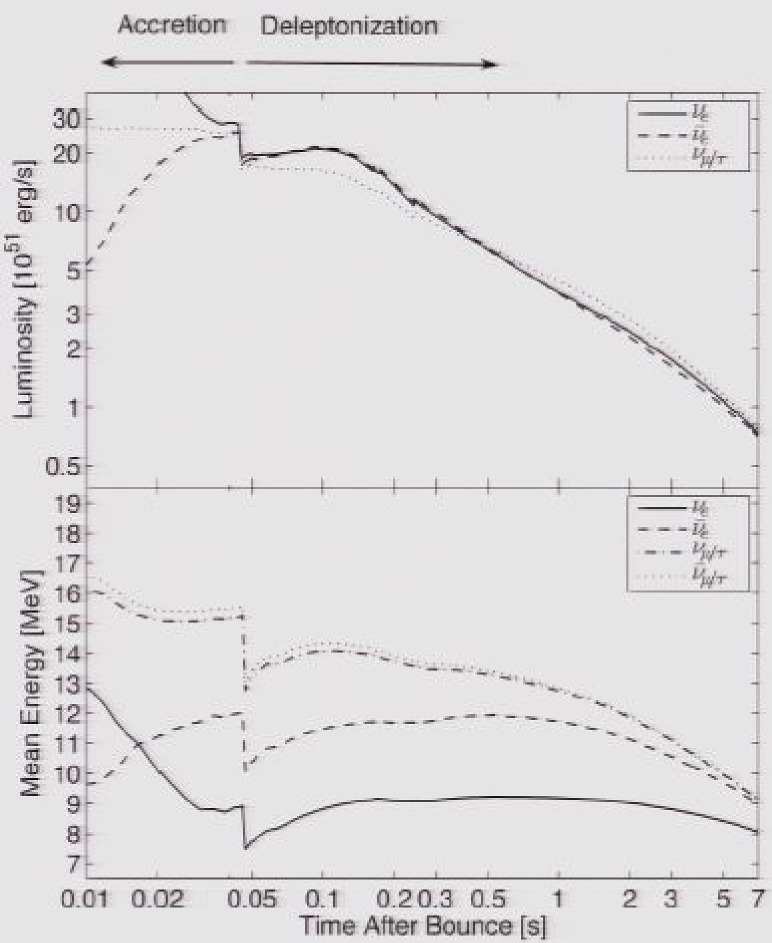
Fischer *et al.* A&A **517**, A80 (2010)

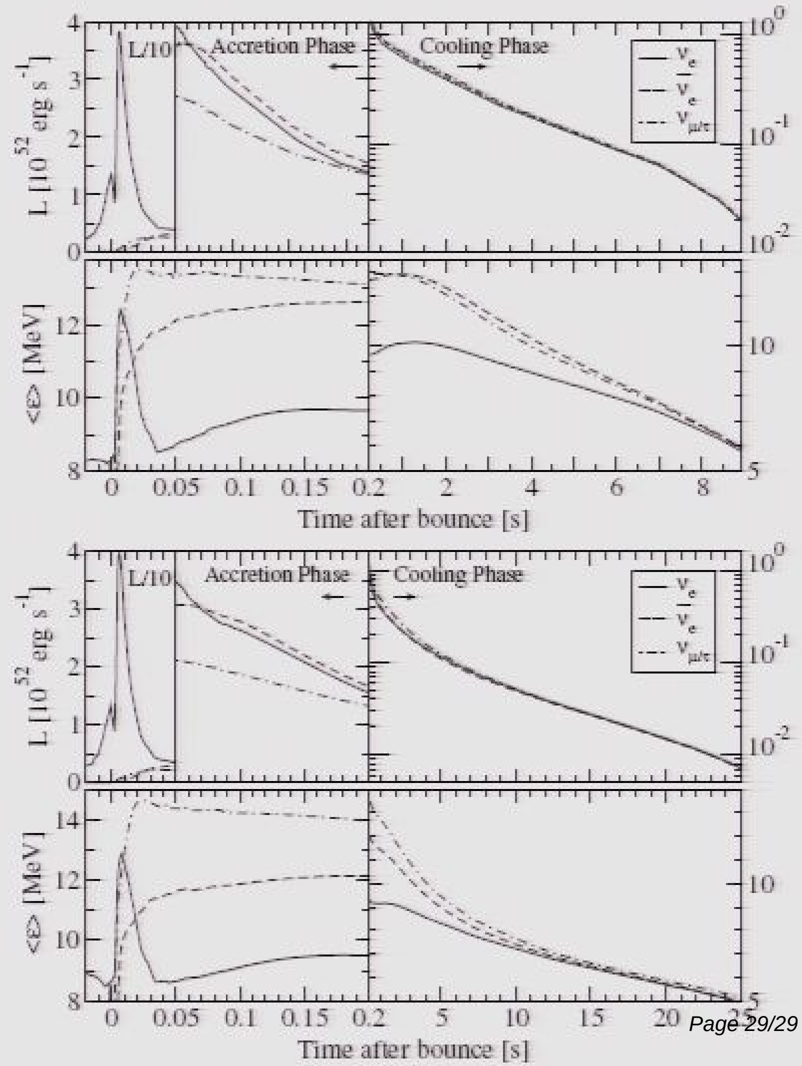
Neutrino-matter interactions

- Charge-current processes:
  $\nu_e + n \rightleftarrows p + e^-$ (Bruenn 1985, Horowitz 2002)
  $\nu_e + A(Z) \rightleftarrows A(Z+1) + e^-$ (Bruenn 1985, Juodagalvis *et al.*, 2010)
  $\bar{\nu}_e + p \rightleftarrows n + e^+$ (Bruenn 1985, Horowitz 2002)
- Elastic scattering processes:
  $\nu + \{n, p\} \rightleftarrows \{n, p\} + \nu$ (Bruenn 1985, Horowitz 2002)
  $\nu + A \rightleftarrows A + \nu$ (Bruenn 1985, Bruenn & Mezzacappa 1997)
- Inelastic Scattering processes:
  $\nu + e^\pm \rightleftarrows \nu + e^\pm$ (Mezzacappa & Bruenn 1993)
- Pair processes:
  $\nu + \bar{\nu} \rightleftarrows e^+ + e^-$ (Bruenn 1985)
  $\nu + \bar{\nu} + N + N \rightleftarrows N + N$ (Hannestad & Raffelt 1998)
- Additional processes:
  $\nu + \nu \rightleftarrows \nu + \nu$ (Buras *et al* 2003)
  $\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$ (Buras *et al* 2003)
  $\nu + A \rightleftarrows A^* + \nu$ (Langanke *et al* 2008)
  $\nu_e + \{d, t, {}^3\mathrm{He}\} \rightleftarrows \{{}^2\mathrm{He}, {}^3\mathrm{He}, {}^3\mathrm{Li}\} + e^-$ (Nakamura *et al.* 2002)
  $\bar{\nu}_e + \{d, t, {}^3\mathrm{He}\} \rightleftarrows \{{}^2n, {}^3n, t\} + e^+$ (Nakamura *et al.* 2002, Arcones *et al* 2008)
  $\nu + \{d, t, {}^3\mathrm{He}\} \rightleftarrows \{d^*, t^*, {}^3\mathrm{He}^*\} + \nu$ (Nakamura *et al.* 2002, O'Connor *et al* 2007)
  $\nu + N + N \rightleftarrows N + N + \nu$ (Hannestad & Raffelt 1998)
  $\bar{\nu}_e + A(Z) \rightleftarrows A(Z-1) + e^+$

Long term evolution neutrino luminosities and average energie

Long-term simulations of the collapse and explosion of an 8.8 $M_\odot$ ONeMg core,





Fischer *et al*, A&A **517**, A80 (2010)