artistic view of elemental distribution from SN1987A (Feb. 23, 1987) based (Hubble)

Role of neutrinos for the nucleosynthesis of heavy elements from massive-star explosions

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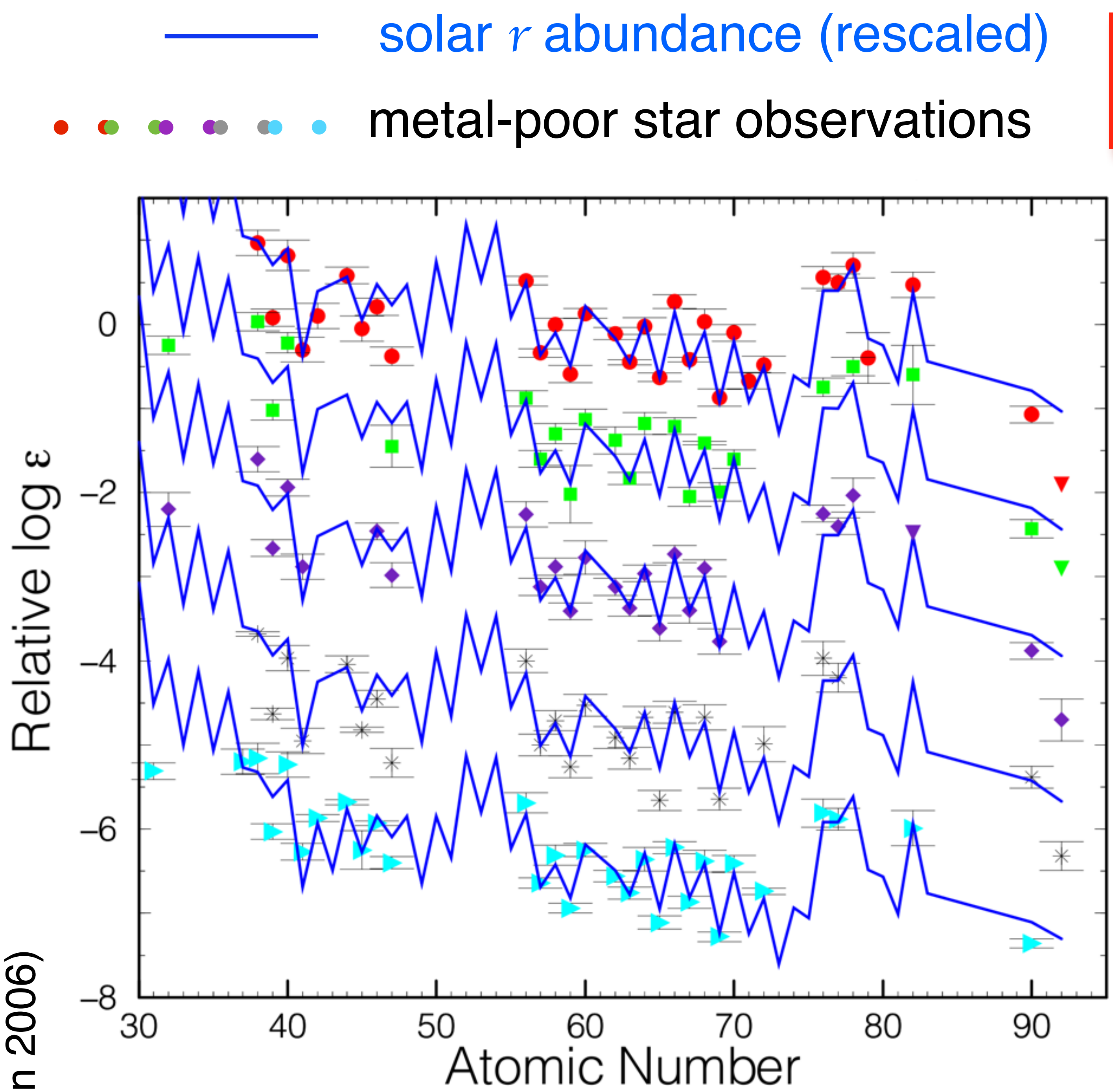
Cosmic fingerprints from heavy-element formation



(Cowan & Sneden 2006)

Main component of the r process

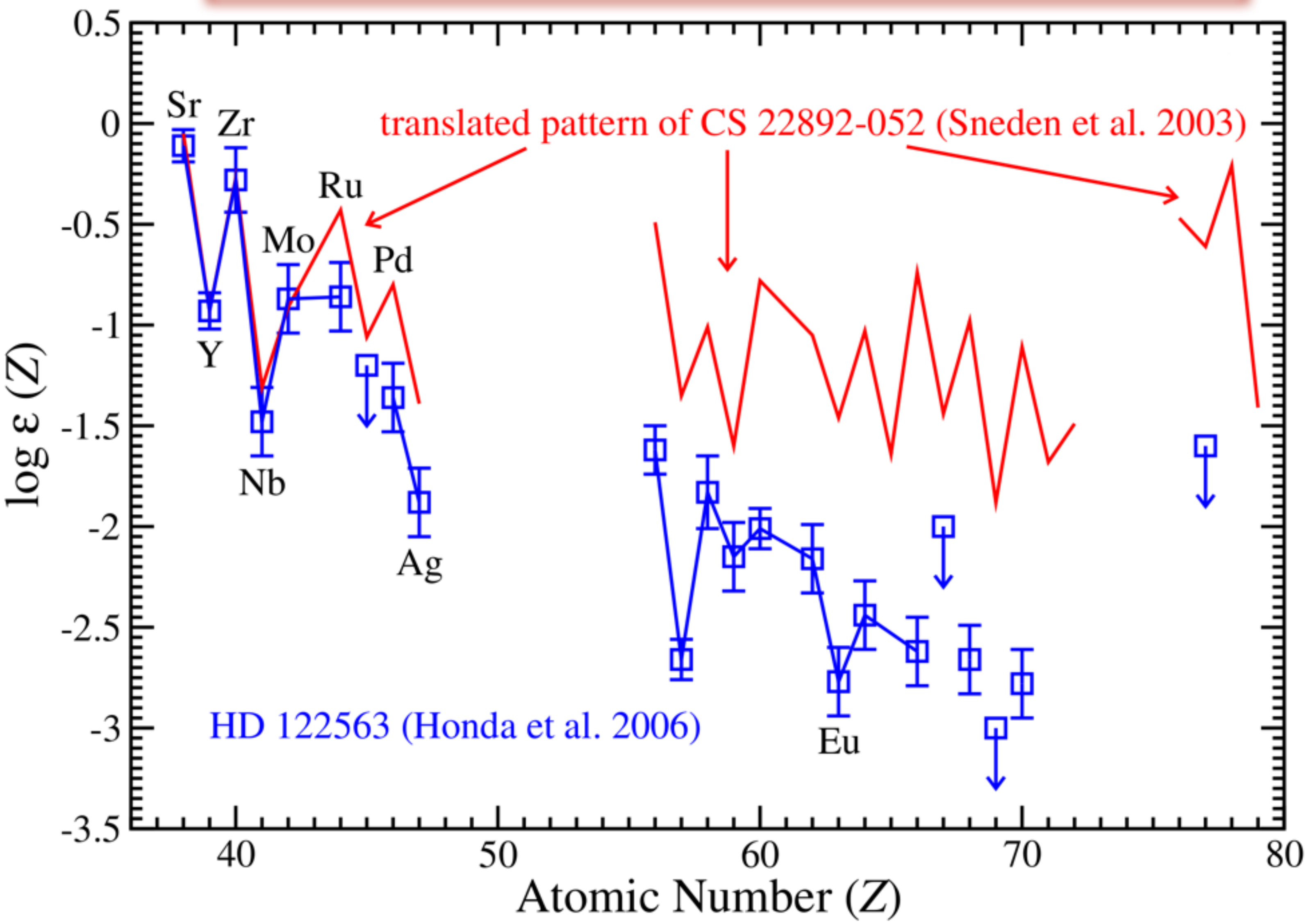
- Robust enrichment of heavy r-process elements ($Z > 52$) and poor in iron (r-II stars, [Eu/Fe] > 1.0)
- Consistent with solar r-process abundance
- **Main astrophysical site still unclear**
  - ★ magnetically-driven massive star explosions
    (models are still highly speculative)
  - ✳ neutron-star mergers
    (start to contribute (too) late to chemical evolution of the Galaxy)

(single heavy elements as r-process “tracers” e.g. Ba or Eu)

Cosmic fingerprints from heavy-element formation

There's another type of metal-poor star observations. . .

Weak component of the r process

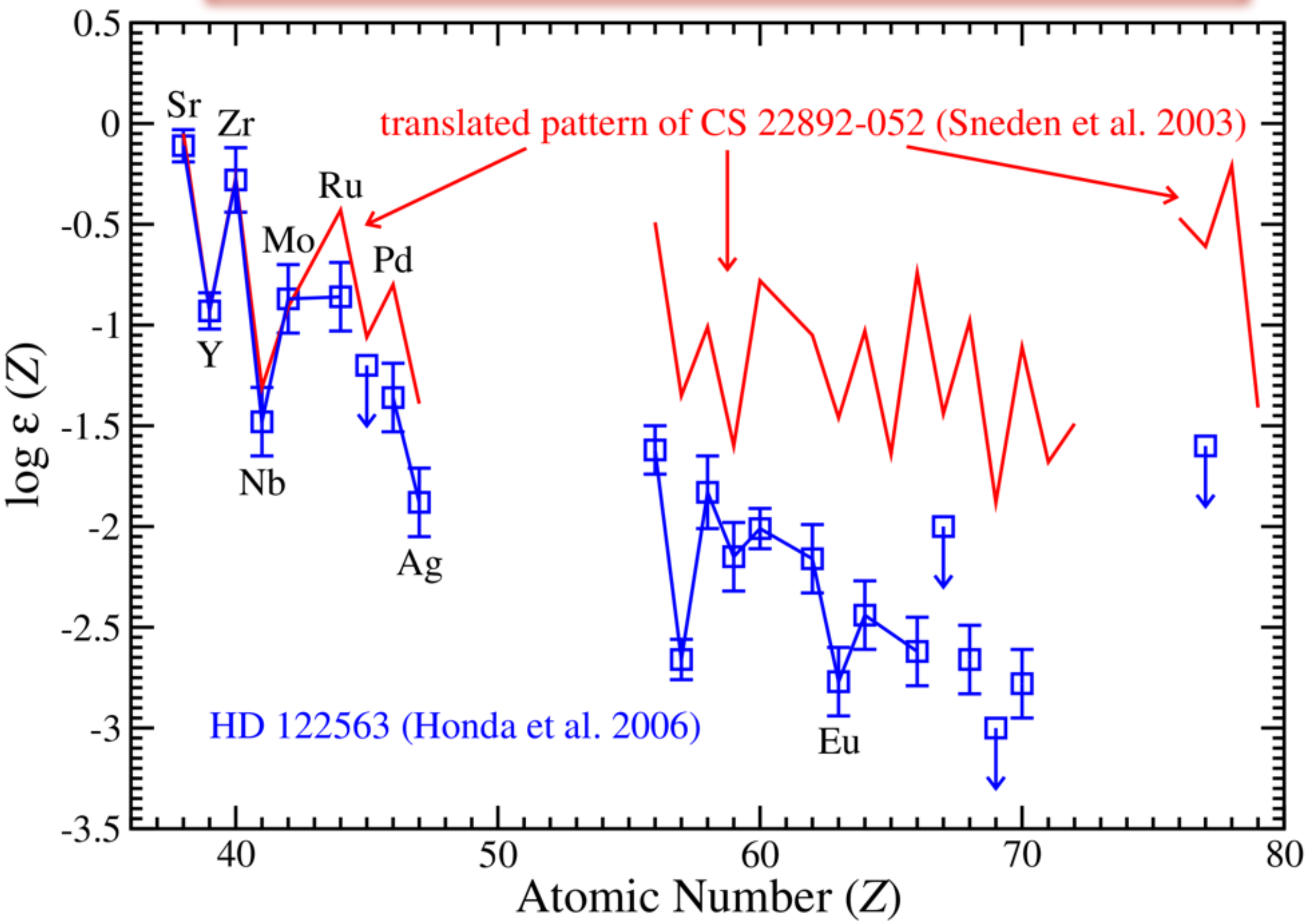


- Poor in heavy neutron-capture elements ($Z > 47$) but large abundances of light neutron-capture elements ($38 < Z < 47$, Sr, Y, Zr, . . .)
- Production of light and heavy neutron-capture elements seem intrinsically decoupled: 2 different sites (?)
- Astrophysical scenario: **neutrino-driven winds from massive-star explosions/ (proto)neutron stars (PNS)**

Cosmic fingerprints from heavy-element formation

There's another type of metal-poor star observations. . .

Weak component of the *r* process



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- Astrophysical scenario: **neutrino-driven winds from massive-star explosions/ (proto)neutron stars (PNS)**

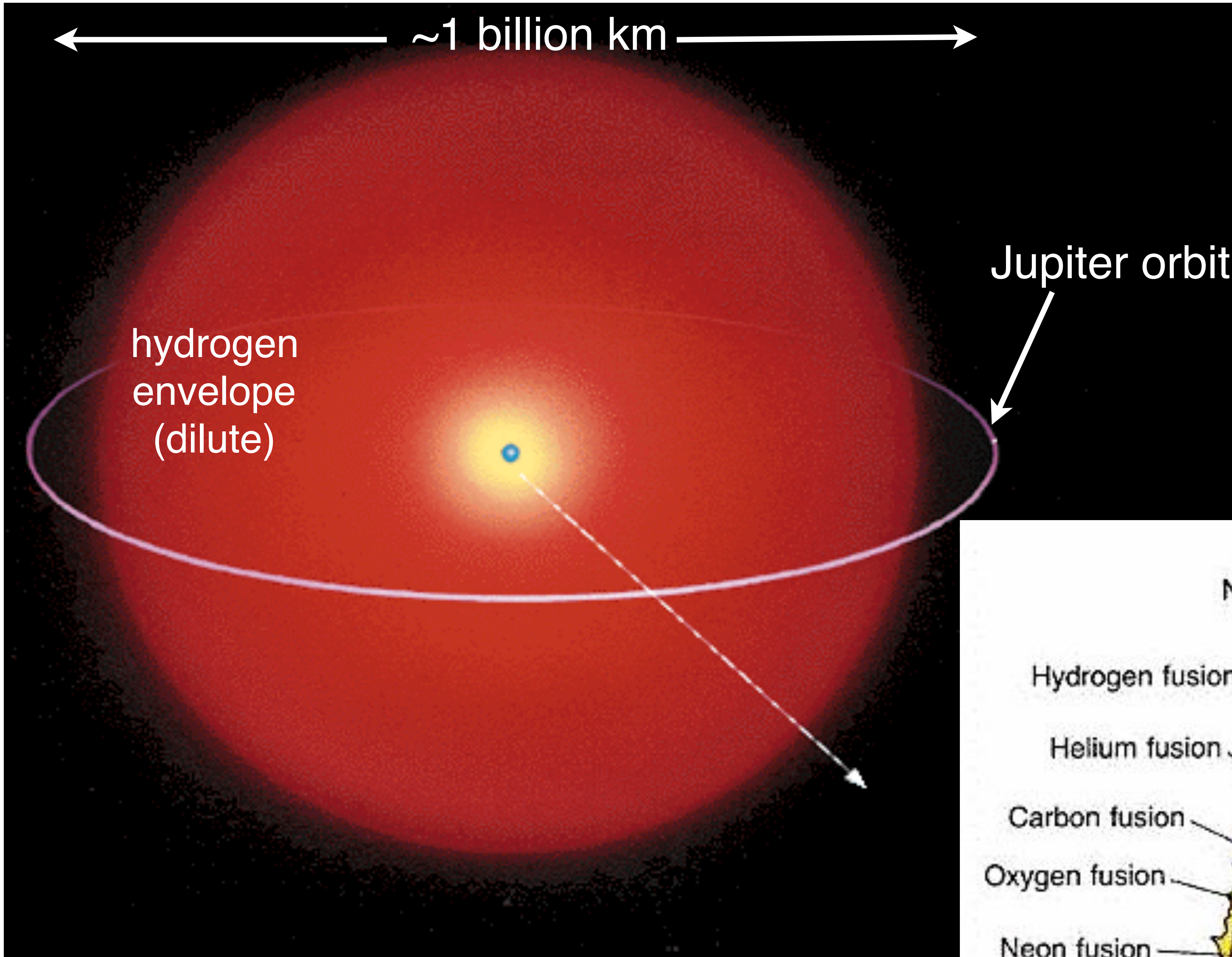
- Which processes determine the nucleosynthesis conditions ?

(Focus of research for the past 3 decades !)

Core-collapse supernova phenomenology

A massive star at the end of its life... $(\gtrsim 9\ M_\odot)$

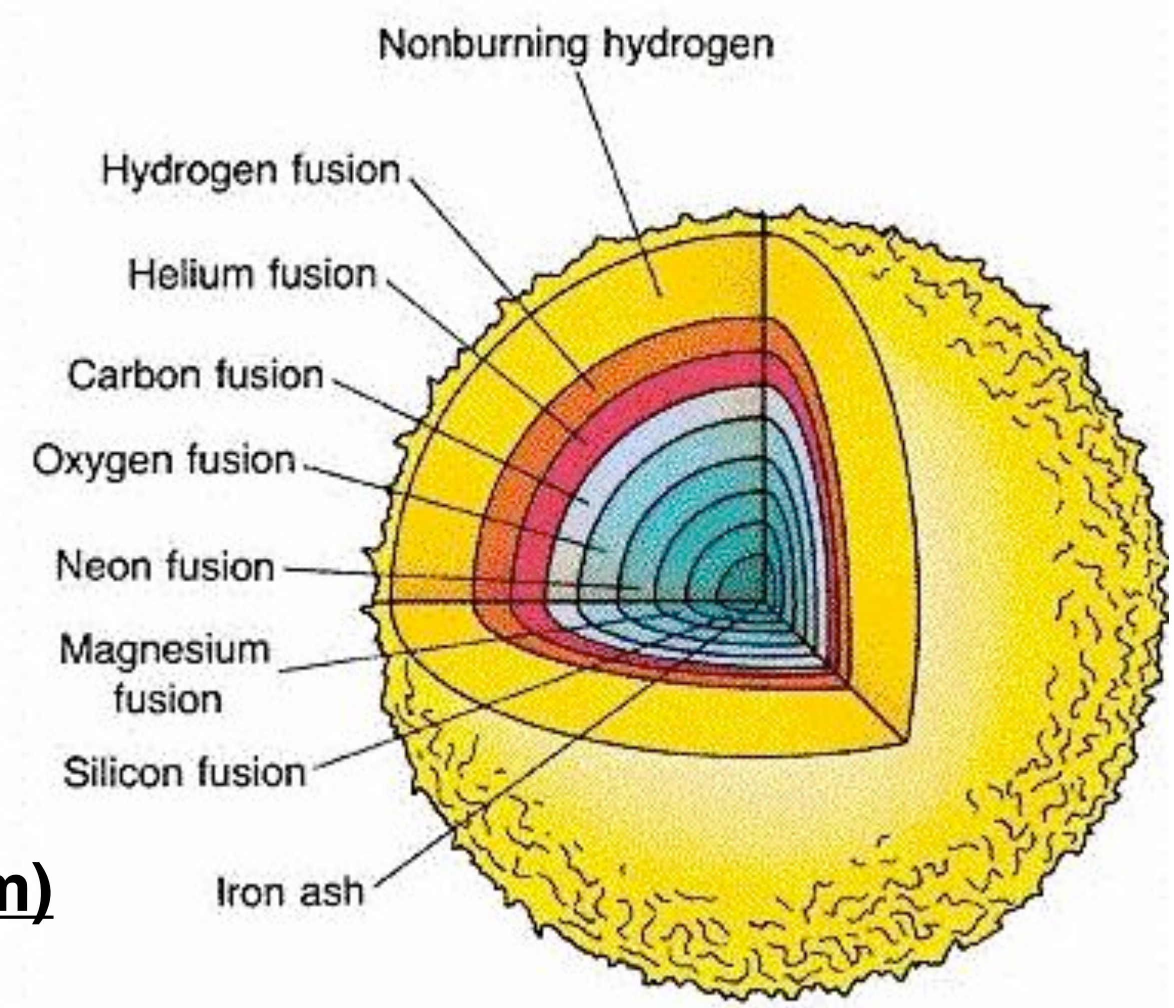
$(1\ M_\odot = 2.98 \times 10^{33}\ \text{g})$



The core of a massive star

–

advanced nuclear burning stages leave onion-like structure:



nuclear fusion stops

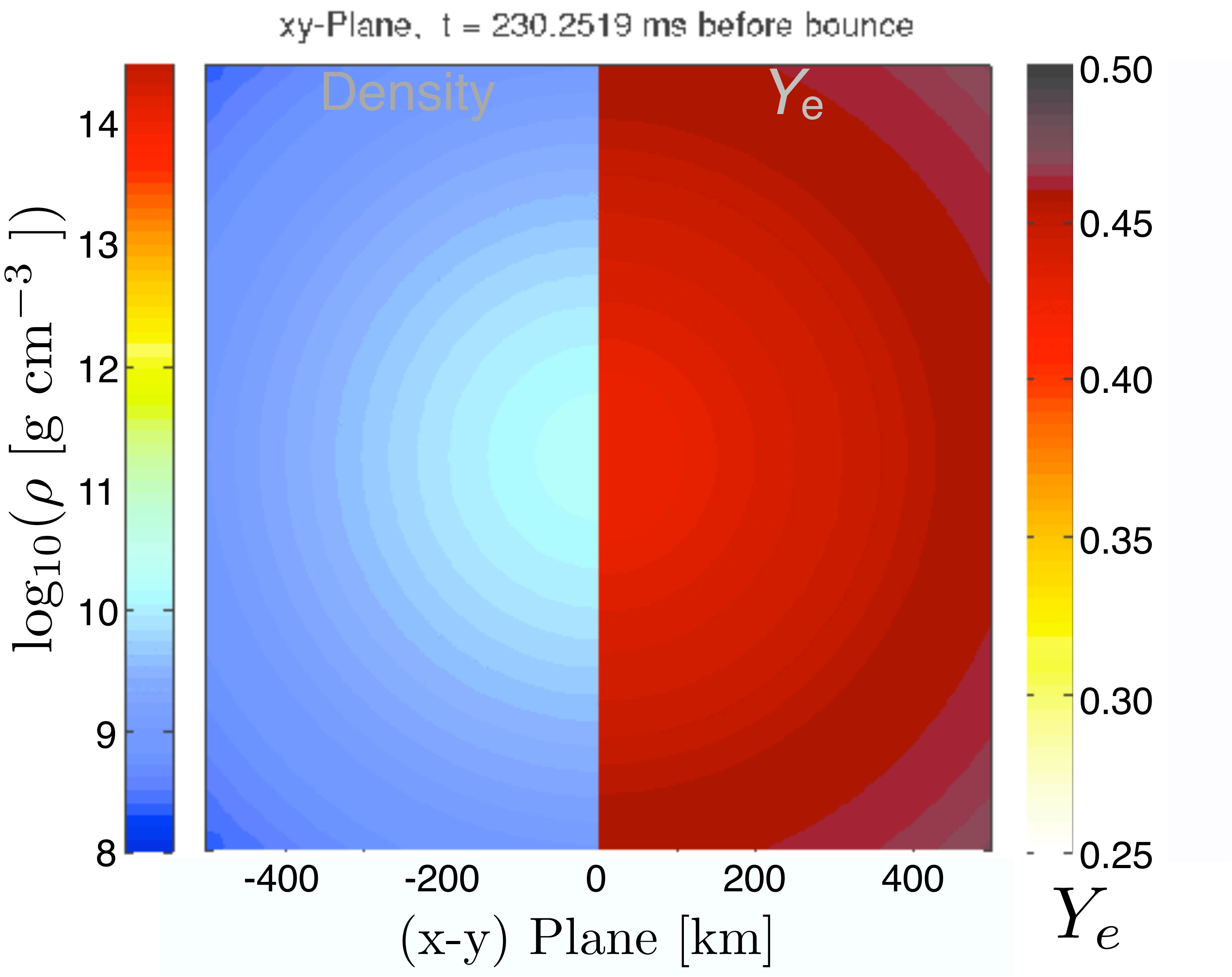
“Fe” – core (^{56}Fe most stable element)

Subject of interest: stellar core (~ 800 – 1000 km)

Explosion starts with stellar implosion

Electron fraction
$(Y_e = n_p/n_B)$
$(Y_e < 0.5 :$ neutron excess $)$
$(Y_e > 0.5 :$ neutron defficient $)$

$(M_{Core} > M_{CH})$



Core collapse is driven by weak processes; e⁻ – captures

$$e^- + {}^{56}\mathrm{Mn} \longrightarrow {}^{56}\mathrm{Fe} + \nu_e$$
$$e^- + {}^{56}\mathrm{Fe} \longrightarrow {}^{56}\mathrm{Co} + \nu_e$$
$$e^- + {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Ni} + \nu_e$$
$$\ldots\ldots$$

Neutrino losses

$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$

Timescale for collapse ~100 ms

Temperature & density rise;

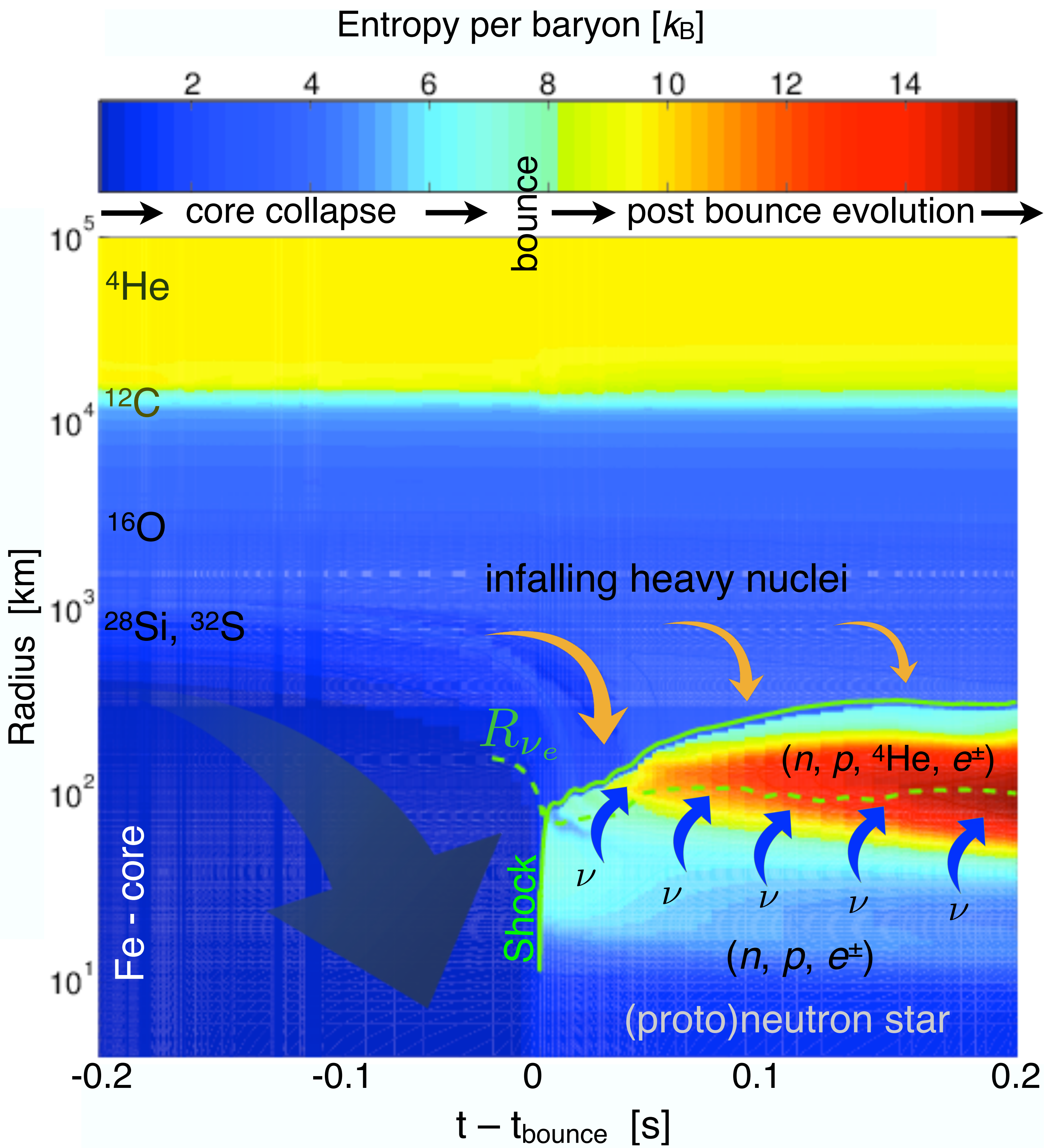
Neutrino trapping $(\rho \simeq 10^{12}\ \mathrm{g\ cm}^{-1})$

$$\nu_e + \langle A, Z\rangle \longrightarrow \nu_e + \langle A, Z\rangle$$

Collapse proceeds adiabatically/ supersonically

Collapse halts at saturation density; **Formation of shock wave**

Supernova evolution – space-time diagram



Shock formation at core bounce (t_{bounce})

Rapid shock acceleration to radii of about 100–200 km

Collapse proceeds continuously at larger radii

Shock stalling due to energy losses – confirmed, no prompt explosions

Later evolution determined from energy-balance due to:

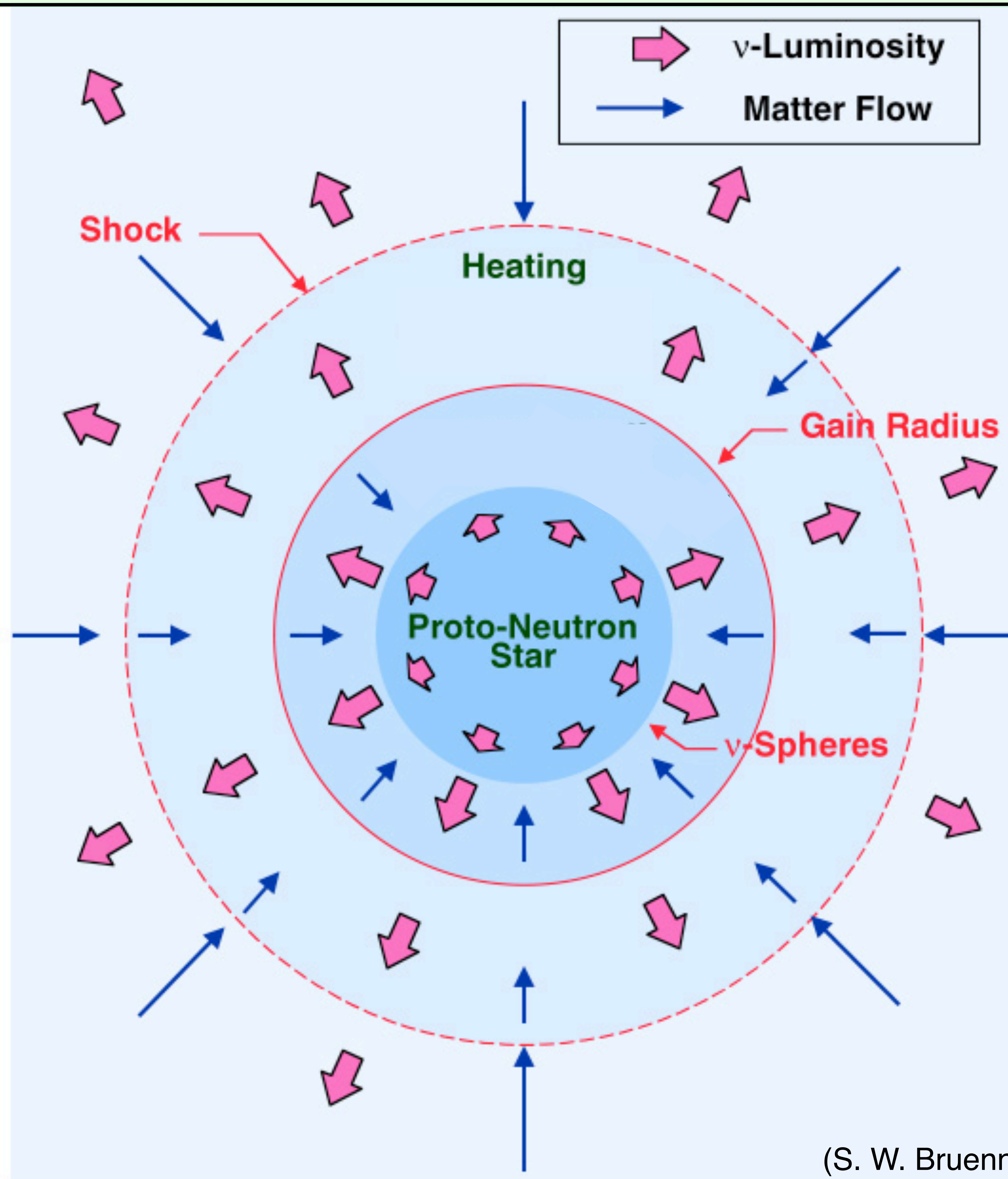
(a) infalling material ahead of shock

(b) energy deposition behind shock

Supernova explosions – concept

General concept: Energy liberation from central (proto)neutron star to standing bounce shock

Continuous energy deposition that drives shock to increasingly larger radii (timescale: ~100 milliseconds)



(S. W. Bruenn)

Supernova explosions – ν heating

General concept: Energy liberation from central (proto)neutron star to standing bounce shock

Continuous energy deposition that drives shock to increasingly larger radii (timescale: ~100 milliseconds)

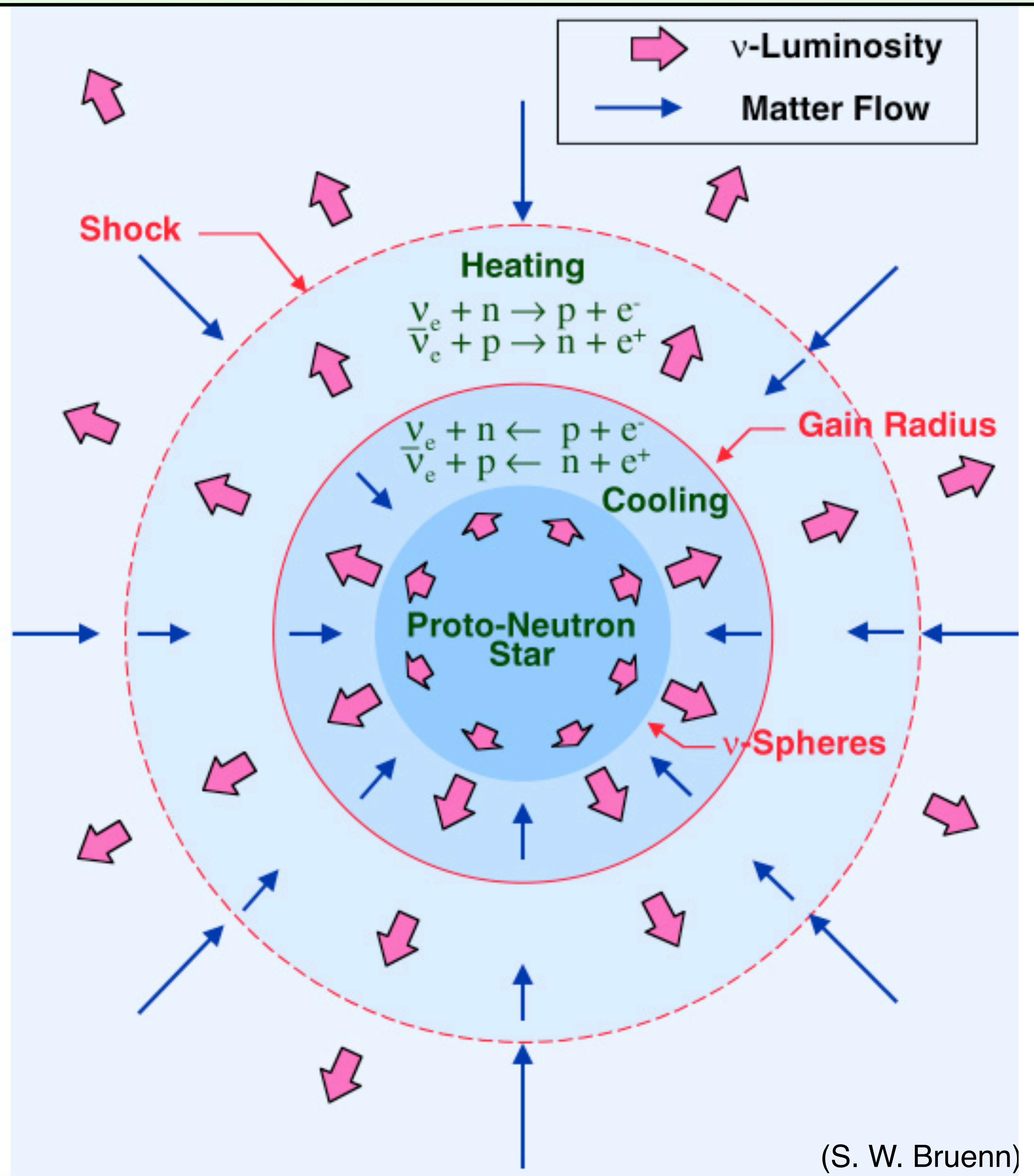
E_ν = 3 – 6 *x* 10^{53} erg (available)

E_{expl} ~ 10^{50} – 10^{51} erg
(kinetic energy of ejecta)

- Neutrino cooling at high density
- Neutrino transport to larger radii
- Neutrino heating at lower density

Bethe & Wilson (1985) ApJ 295, 14

<u>Alternative scenarios:</u>
magnetic fields
(Le Banc & Wilson (1970) ApJ 161, 542)
sound waves
(Burrows et al.,(2006) ApJ 640, 878)
high-density phase transition
(Sagert & TF et al.,(2009) PRL 102, 081101)



(S. W. Bruenn)

Nucleosynthesis: explosive Silicon burning

Ejection of stellar mantle;

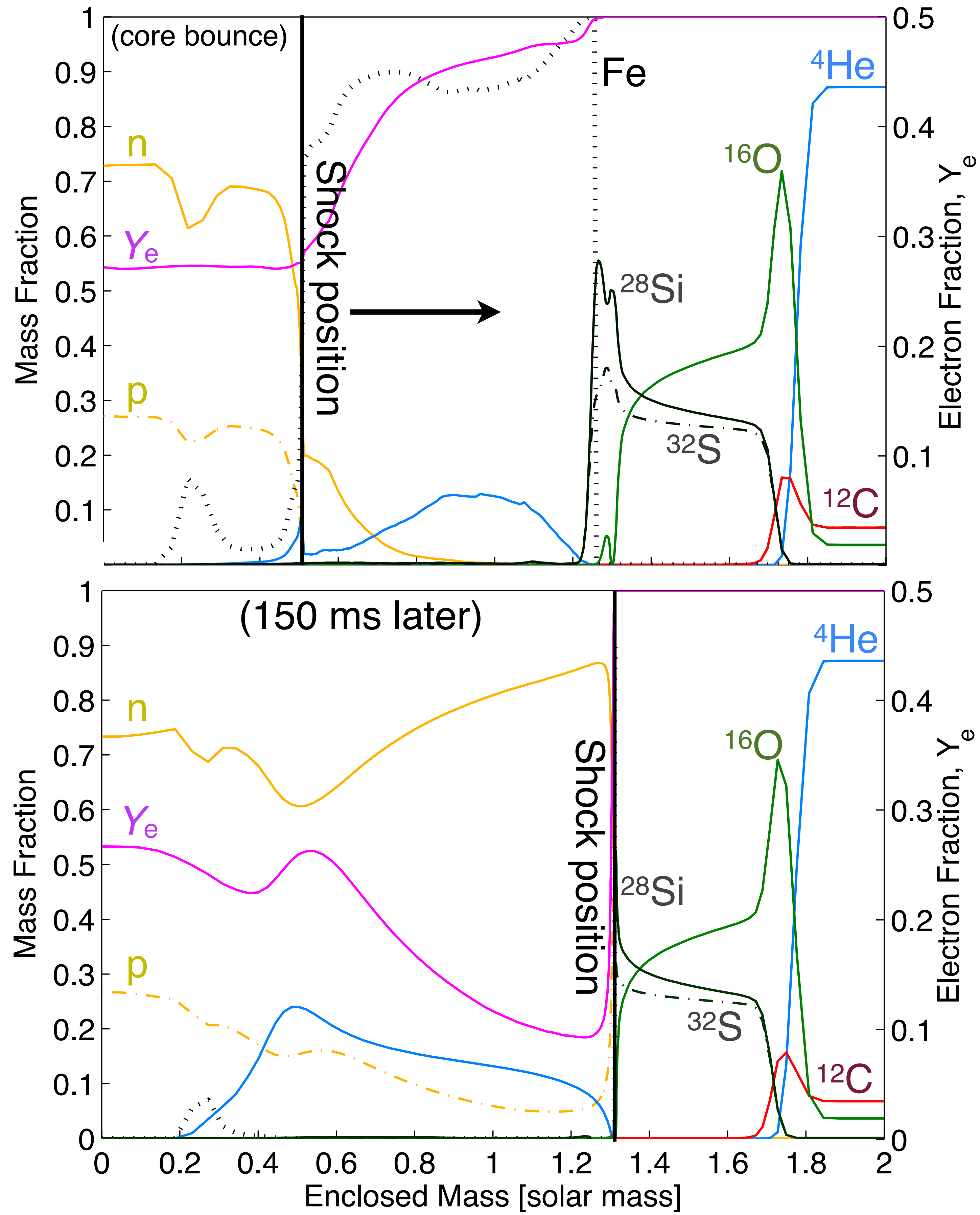
outer layers of progenitor star

^{16}O, ^{12}C, ^{4}He,...

^{28}Si, ^{40}Ca, ^{44}Ti, Fe-group nuclei (?) depends on details of explosion and progenitor composition

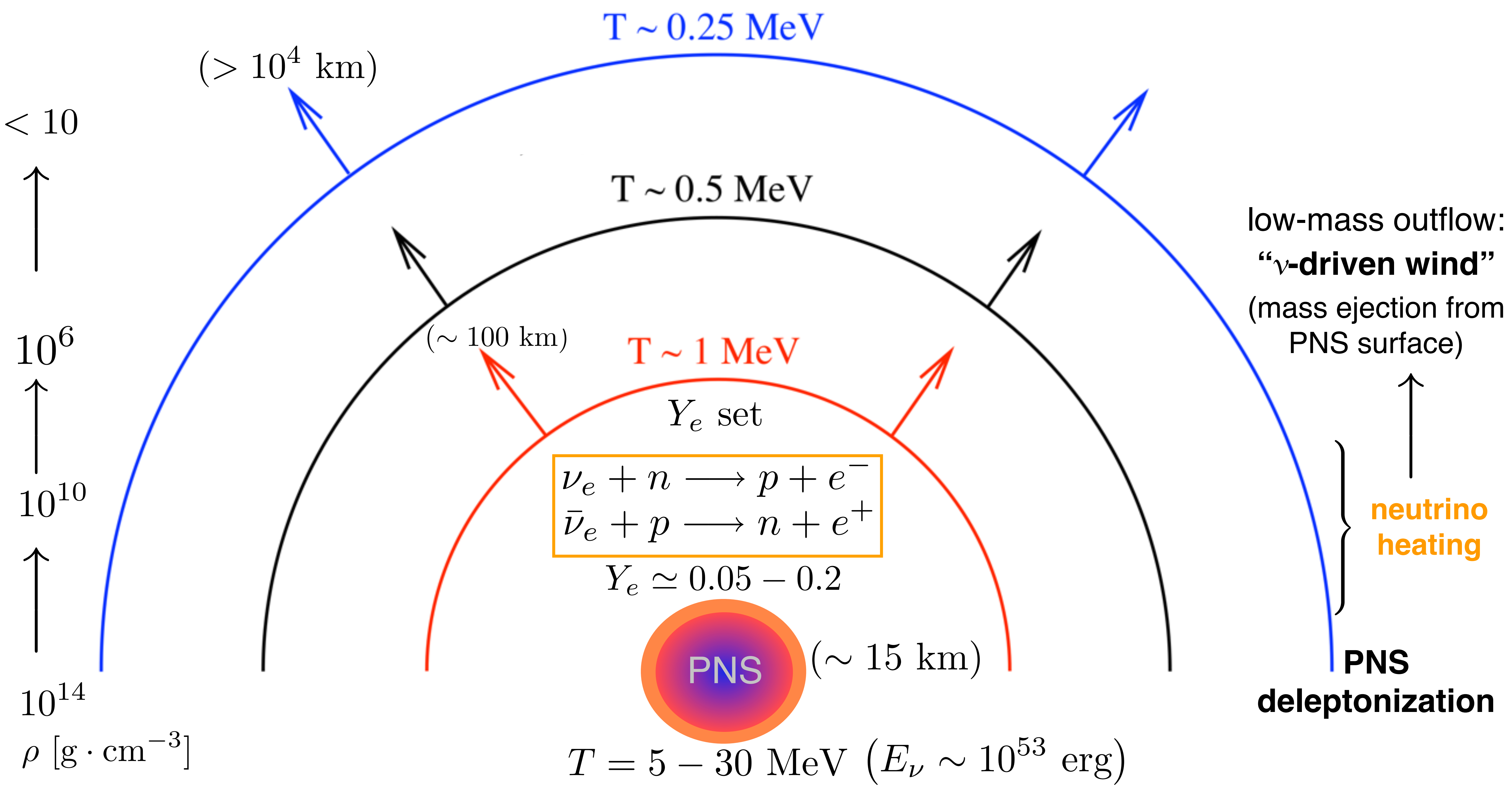
(in particular on peak temperature at shock front, timescale of shock expansion, Y_e, and progenitor composition)

(see talk by Andre Sieverding)



Schematic picture of “late”– time mass ejection

Once the stellar mantle is ejected . . . the supernova story continues.



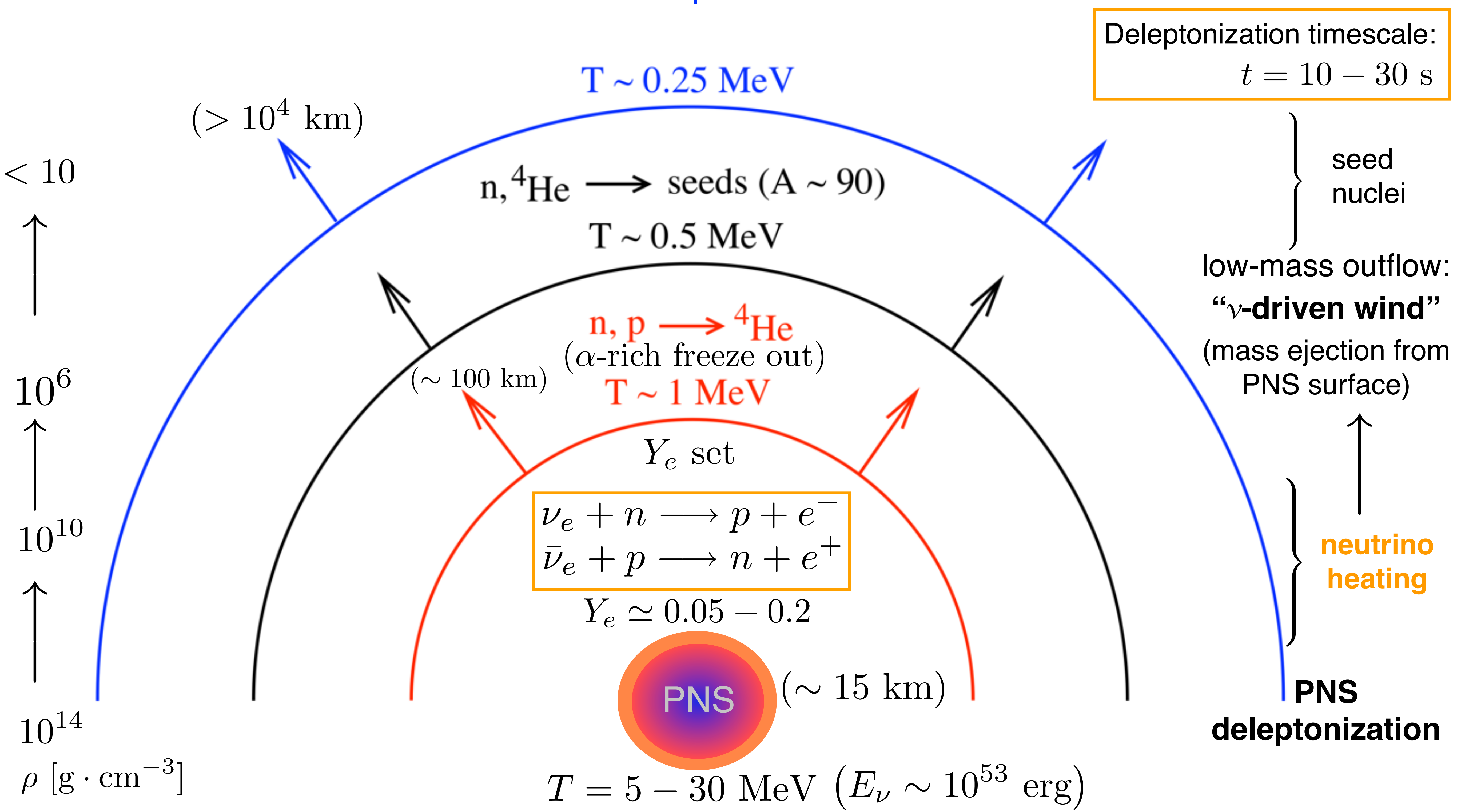
Schematic picture of “late”– time mass ejection

Nucleosynthes is determined at neutrino decoupling

proton rich ($Y_e > 0.5$)
νp process

neutron rich ($Y_e < 0.5$)
neutron-capture process

formation of heavy nuclei (?)

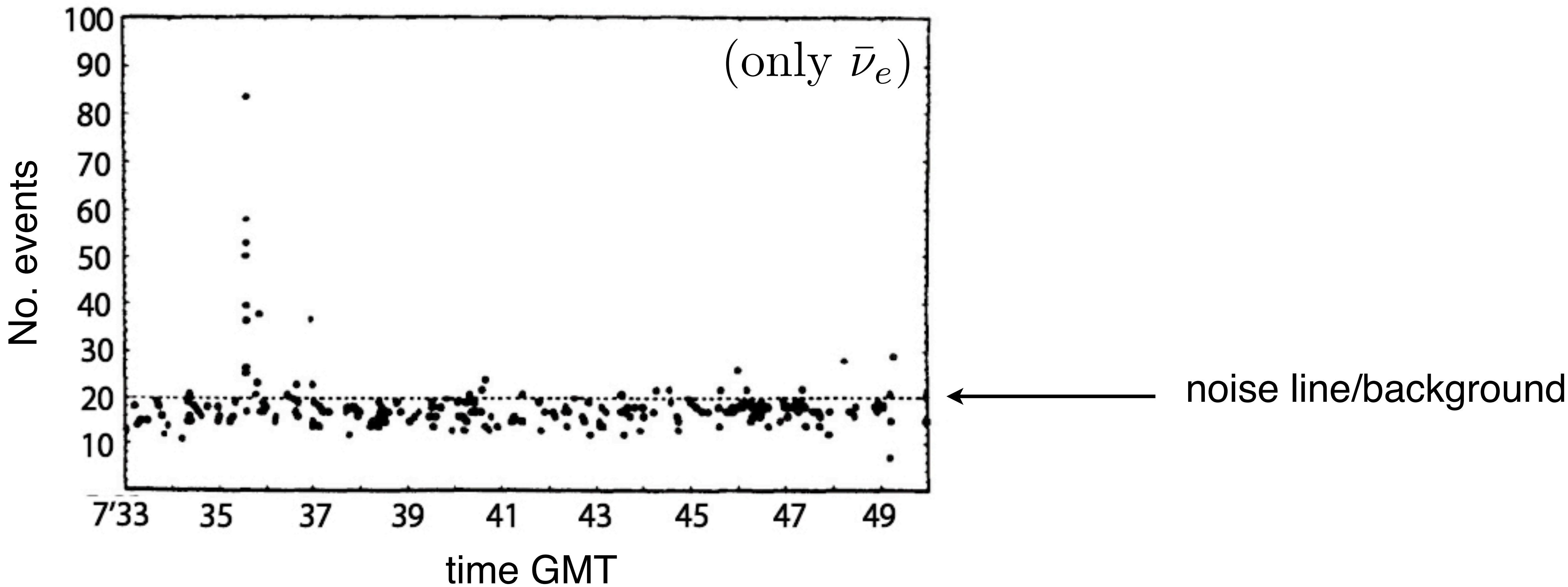


Neutrinos from massive star explosions

Neutrinos from SN1987A

(large Magellanic Cloud)

Feb. 23rd, 1987, 7:35 a.m.



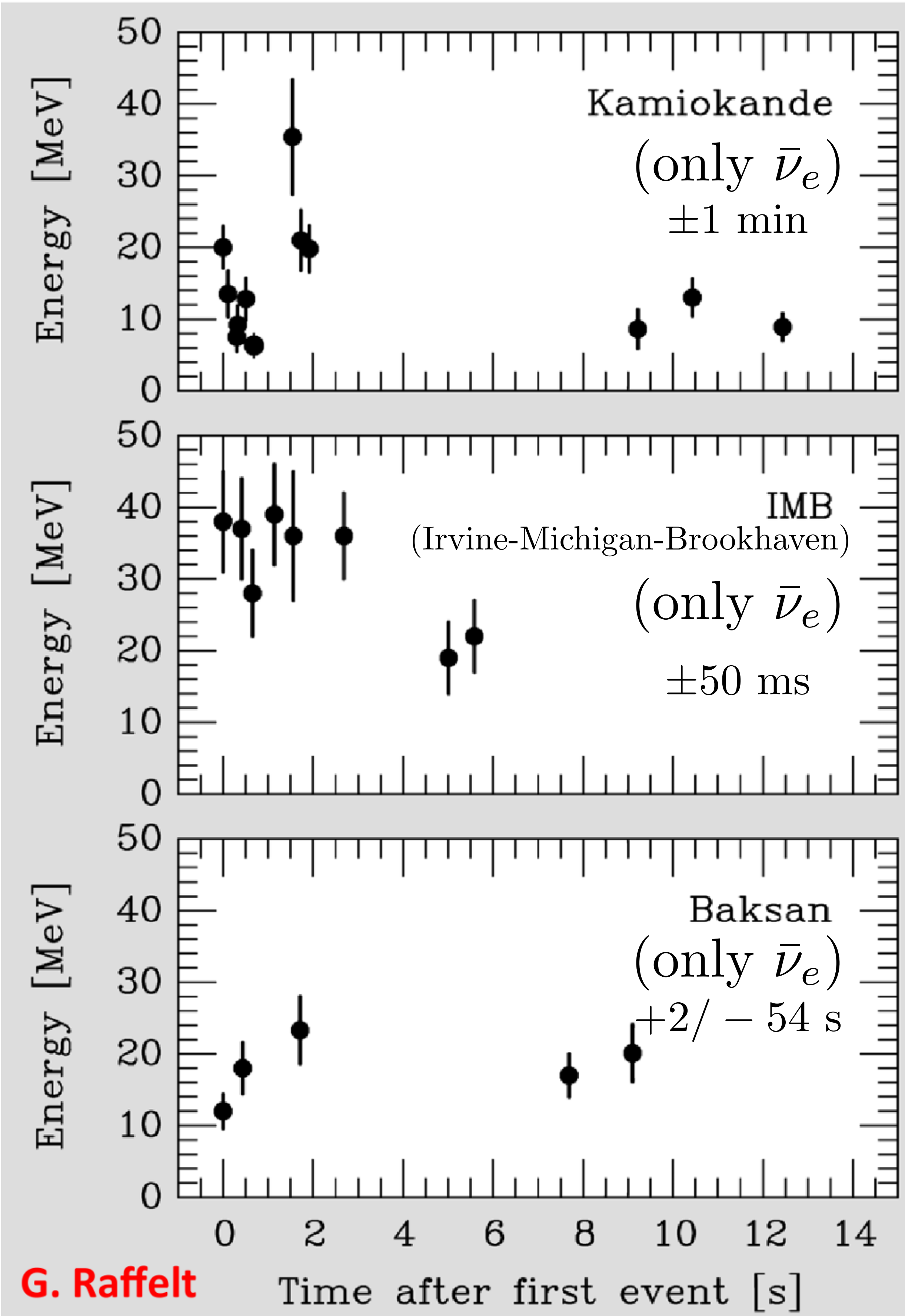
(Observed signal at Kamiokande)

Neutrino events – 10^3 tons water Cherenkov detectors

Total no. of events observed: 11 (12)

Duration of neutrino signal: 13 seconds

Neutrinos from SN1987A



Insights from SN1987A:

- Progenitor star $18\ M_\odot$
- Confirmation of the basic model
- Available energy ~3 x 10^{53} erg (# 10^{58} neutrinos)
- >99% emitted in neutrinos over timescale ~10–30 seconds
- Explosion energetics from lightcurve; $10^{50} – 10^{51}$ erg (kinetic energy of ejecta)

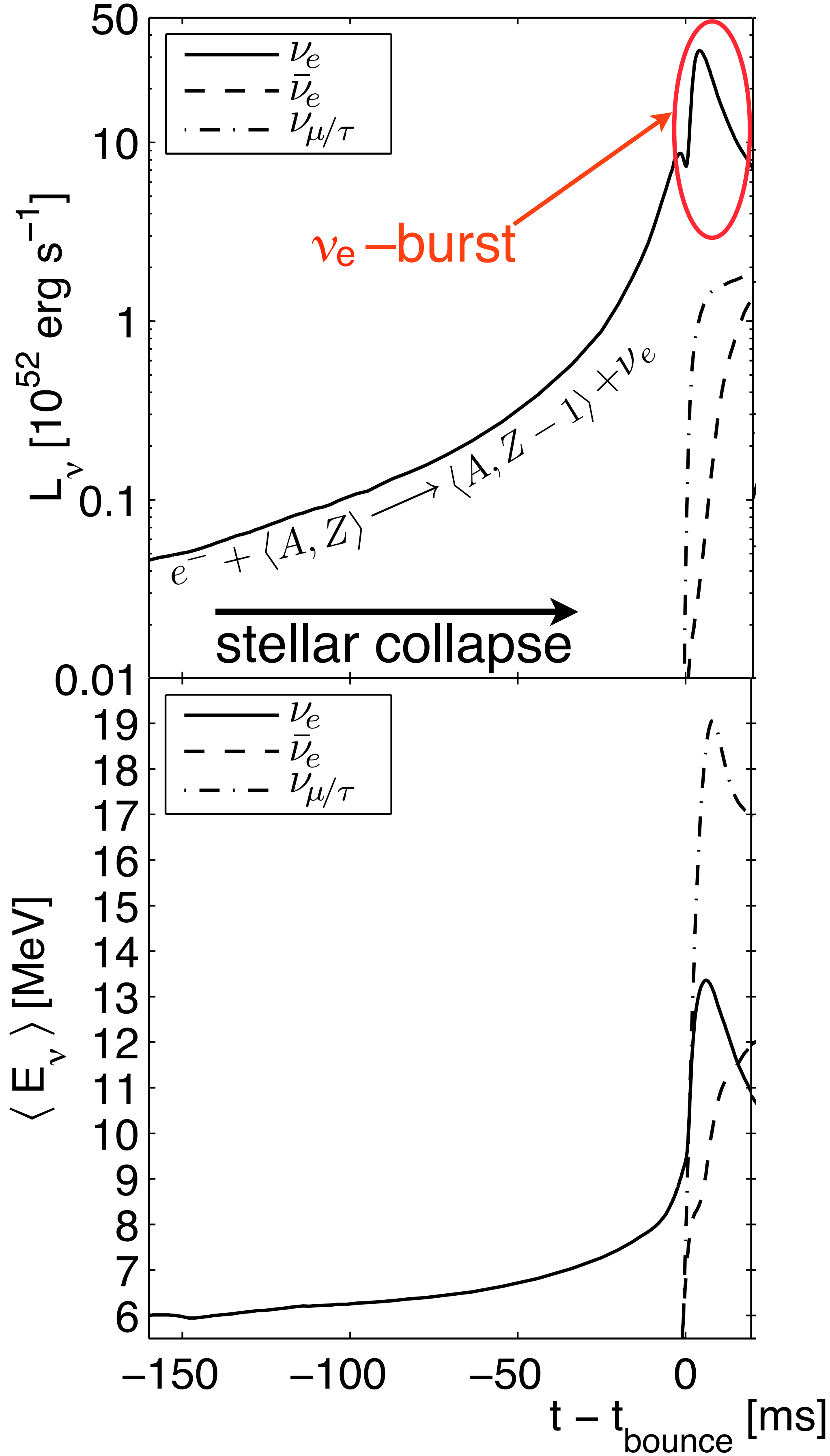
Core-collapse supernova rates:

1SN s^{-1} universe^{-1}

1SN year^{-1} 10^6 pc^{-1}

1SN 100 years^{-1} Milky Way^{-1}

Simulations – Neutrino signal I



nuclear electron captures

$$e^- + \langle A, Z \rangle \longrightarrow \langle A, Z-1 \rangle + \nu_e$$

nuclear de-excitations

$$\langle A, Z \rangle^* \longrightarrow \langle A, Z \rangle + \nu + \bar{\nu}$$

Fuller & Meyer (1991), ApJ 376, 701
TF et al.,(2013) PRC 88, 065804

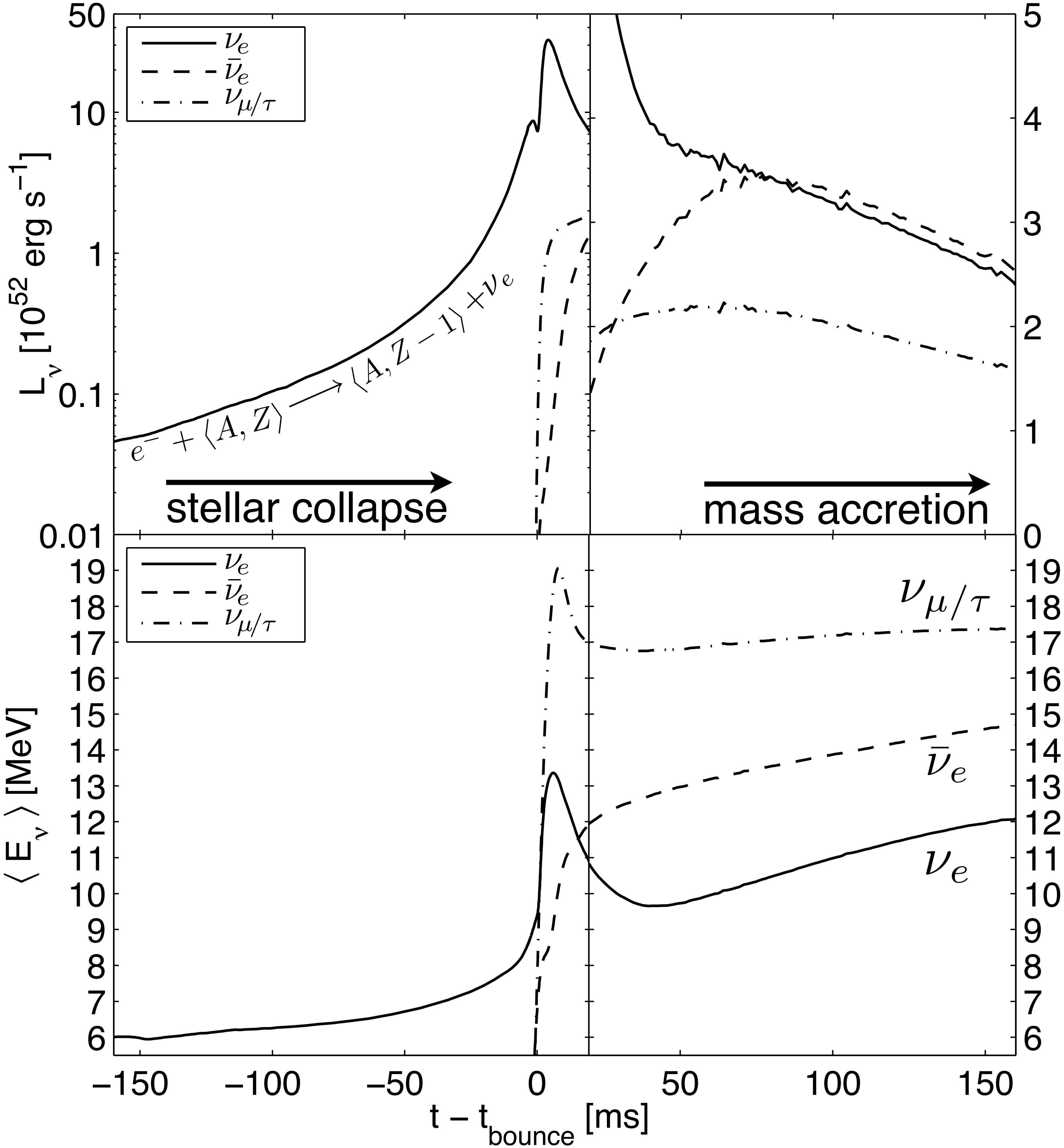
Supernova shock propagation across the sphere of last inelastic scattering (ν-sphere)

ν_e–deleptonization burst is generic feature

charged current reactions

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

Simulations – Neutrino signal II



charged current reactions

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

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

pair processes

$$e^- + e^+ \leftrightarrows \nu + \bar{\nu}$$

$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$

$$\nu_e + \bar{\nu}_e \leftrightarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

elastic scattering

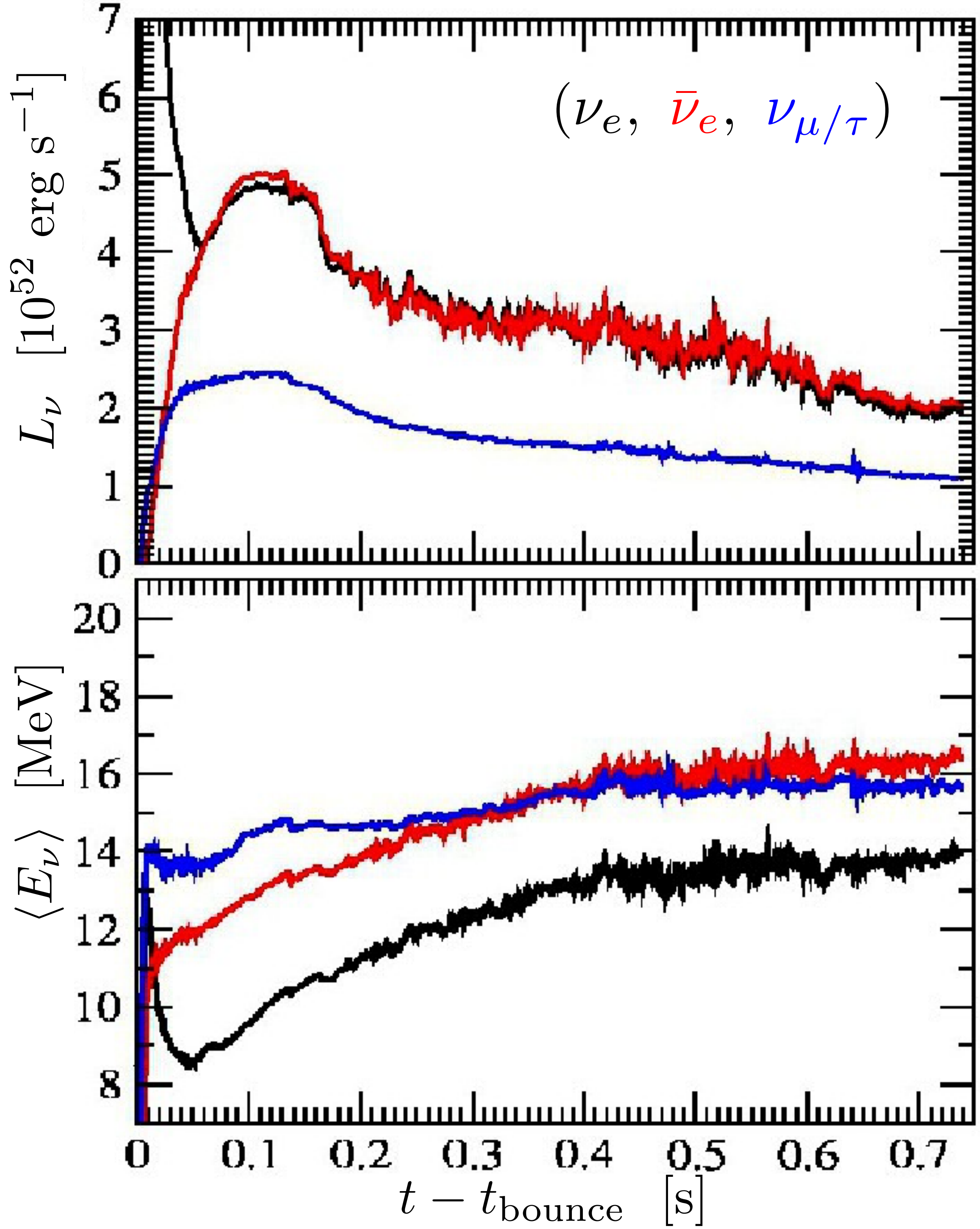
$$\nu + N \leftrightarrows \nu' + N$$

inelastic scattering

$$\nu + e^\pm \leftrightarrows \nu' + e^\pm$$

Neutrino-energy hierarchy reflects strength of coupling to matter

Neutrino signal in multi-dim'l simulations



Müller & Janka (2014) ApJ 788, 82

Presence of millisecond variations of the neutrino signal

Induced from convection and associated shock oscillations

Persist even in detection on Earth

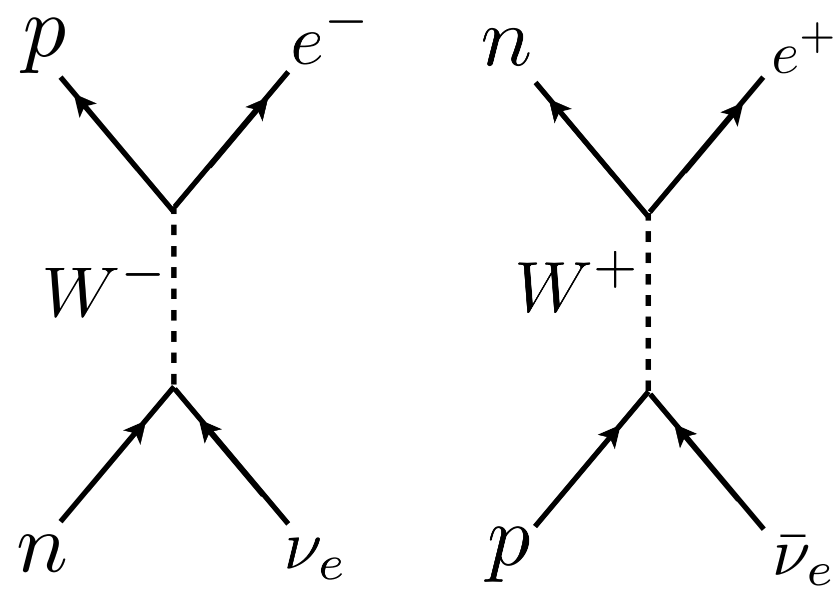
May allow distinction of strong bi-polar explosions

Weak rates

Neutrino reaction rates: charged-current absorption

Bruenn (1985), ApJS 58, 771
Reddy et al.,(1998), PRD 58, 013009

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



$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^7}(g_V^2 + 3g_A^2) \int \frac{d^3p_e}{(2\pi)^3}(1 - F_e(E_e))\, S(q_0, q)$$

$$q_0 = E_\nu - E_e \;, \qquad q = |\mathbf{p}_\nu - \mathbf{p}_e|$$

$$S(q_0, q) = \frac{m_p^*}{\pi\, q} \int p_n dp_n f_n(E_n)(1 - f_p(E_p))$$

(neutrino response to the nuclear medium)

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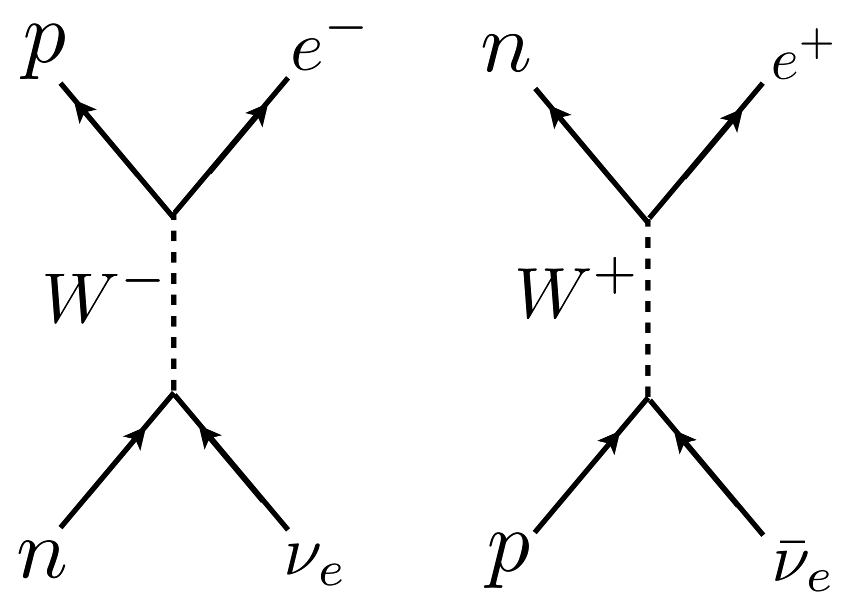

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(neutrino response to the nuclear medium)

Zero-momentum transfer (*elastic*) approximation:

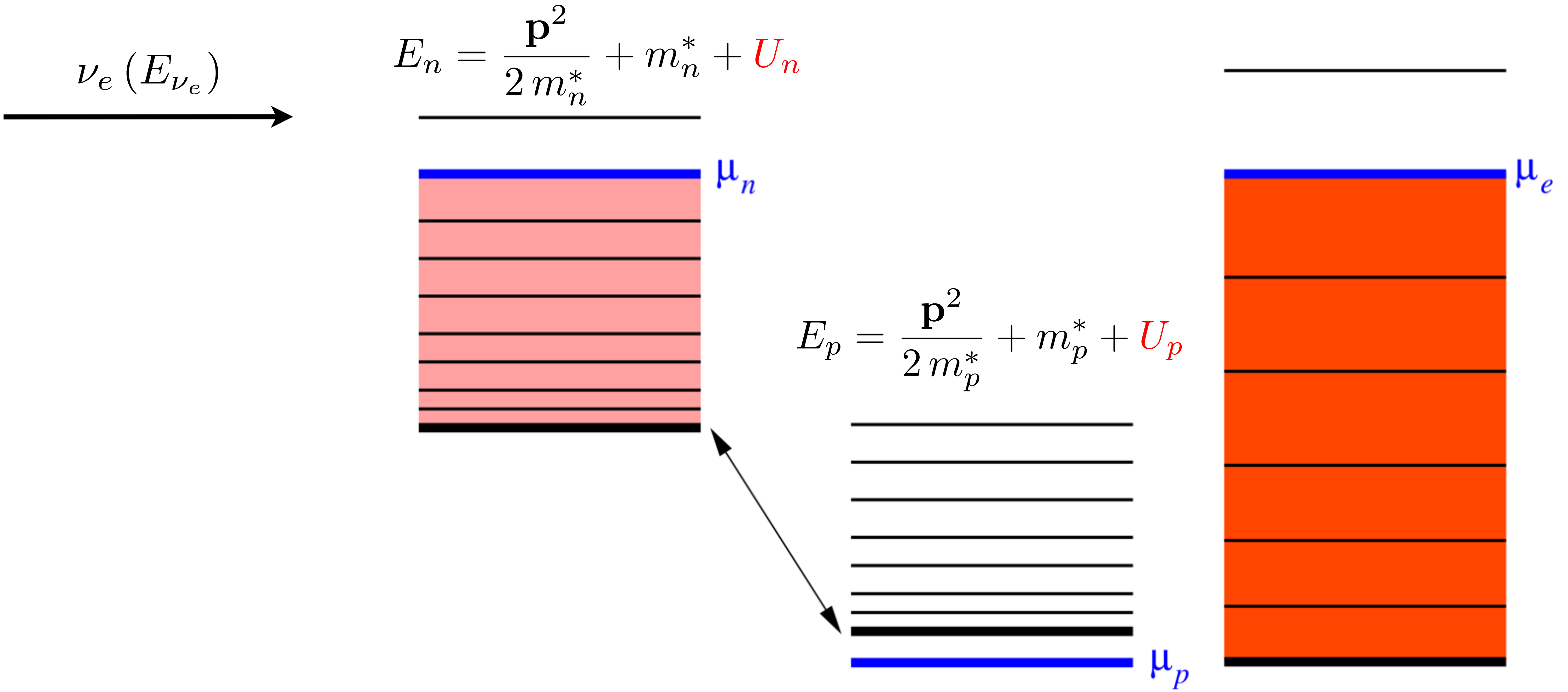
$$1/\lambda_\nu(E_\nu) \simeq \frac{G_F^2 V_{ud}^2}{\pi (\hbar c)^4} (g_V^2 + 3 g_A^2)\, p_e\, E_e (1 - F_e(E_e)) \frac{n_n - n_p}{1 - e^{\beta(\mu_p^0 - \mu_n^0)}}$$

$$E_N = \frac{\mathbf{p}_N^2}{2\, m_N^*} + m_N^* + U_N$$ (assuming non-relativistic nucleons)

Description of weak processes must be consistent with nuclear equation of state

Weak rates consistent with the equation of state

Similar situation as in heavy neutron rich nucleus



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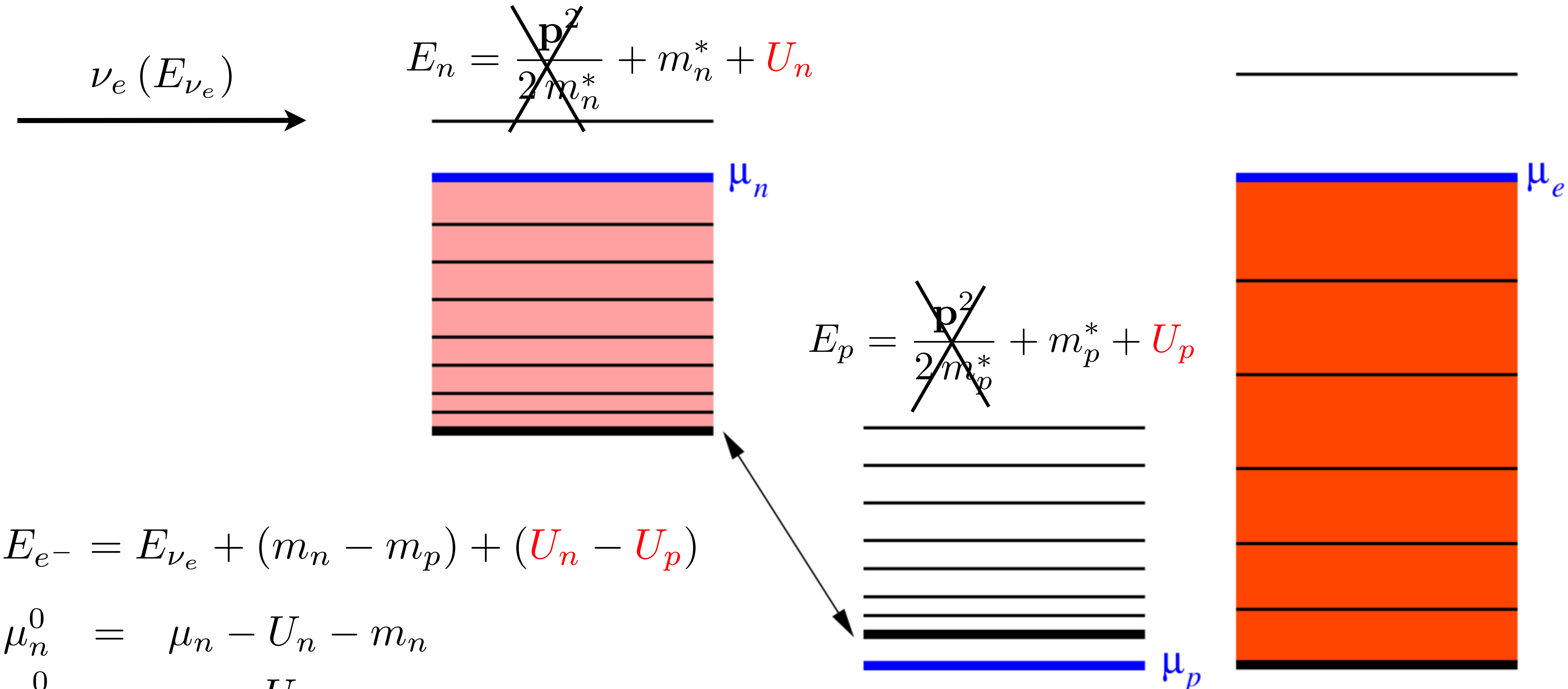


$$E_{e^-} = E_{\nu_e} + (m_n - m_p) + (U_n - U_p)$$

$$\mu_n^0 = \mu_n - U_n - m_n$$
$$\mu_p^0 = \mu_p - U_p - m_p$$

$U_n - U_p$: medium modification of the vacuum $Q-$ value (in elastic approximation)

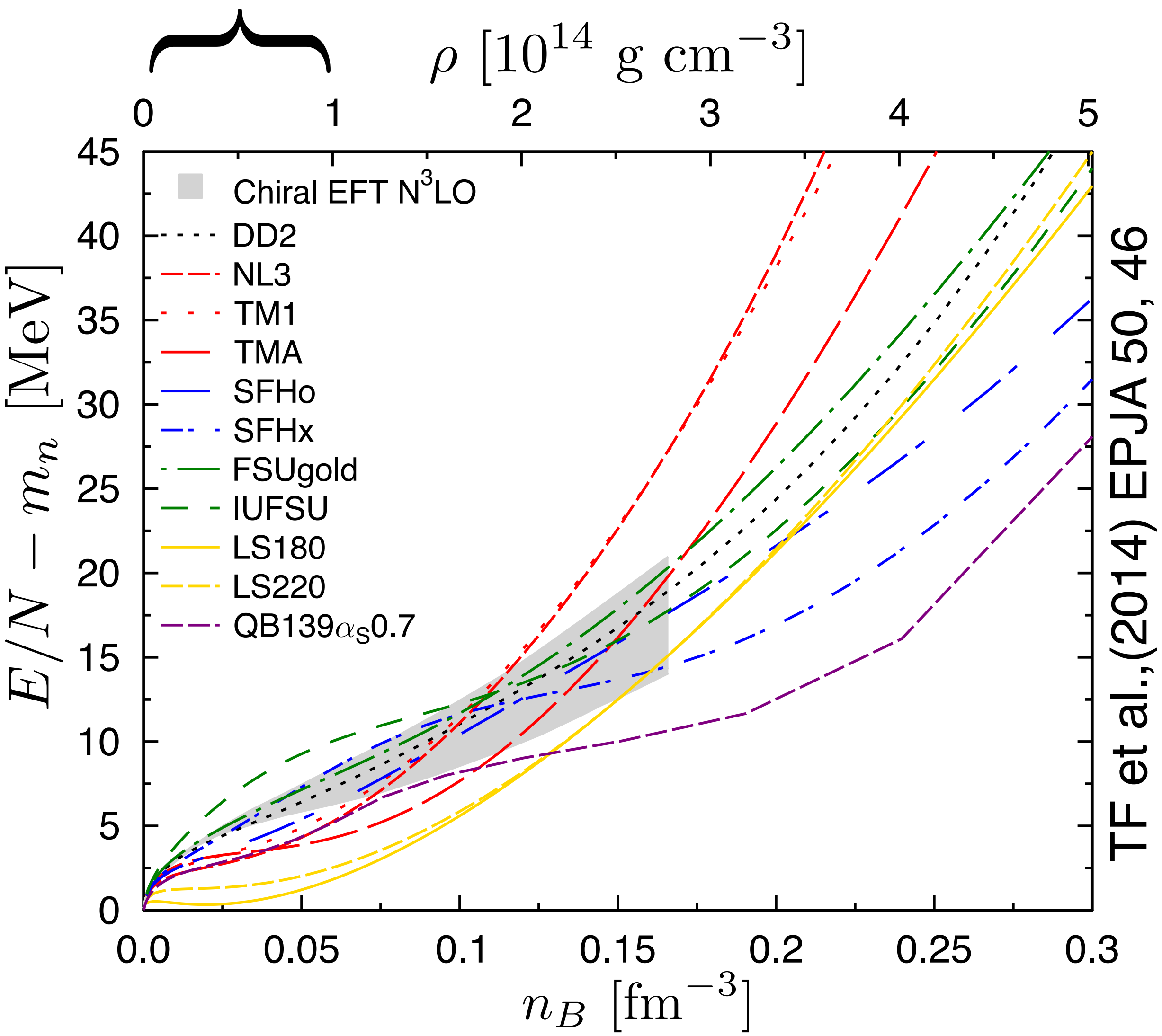
Note: $U_n(\rho, T, Y_e) - U_p(\rho, T, Y_e) \propto 4(1 - 2Y_e)\, S_B^F(\rho, T)$

(nuclear symmetry energy)

Role of the supernova equation of state

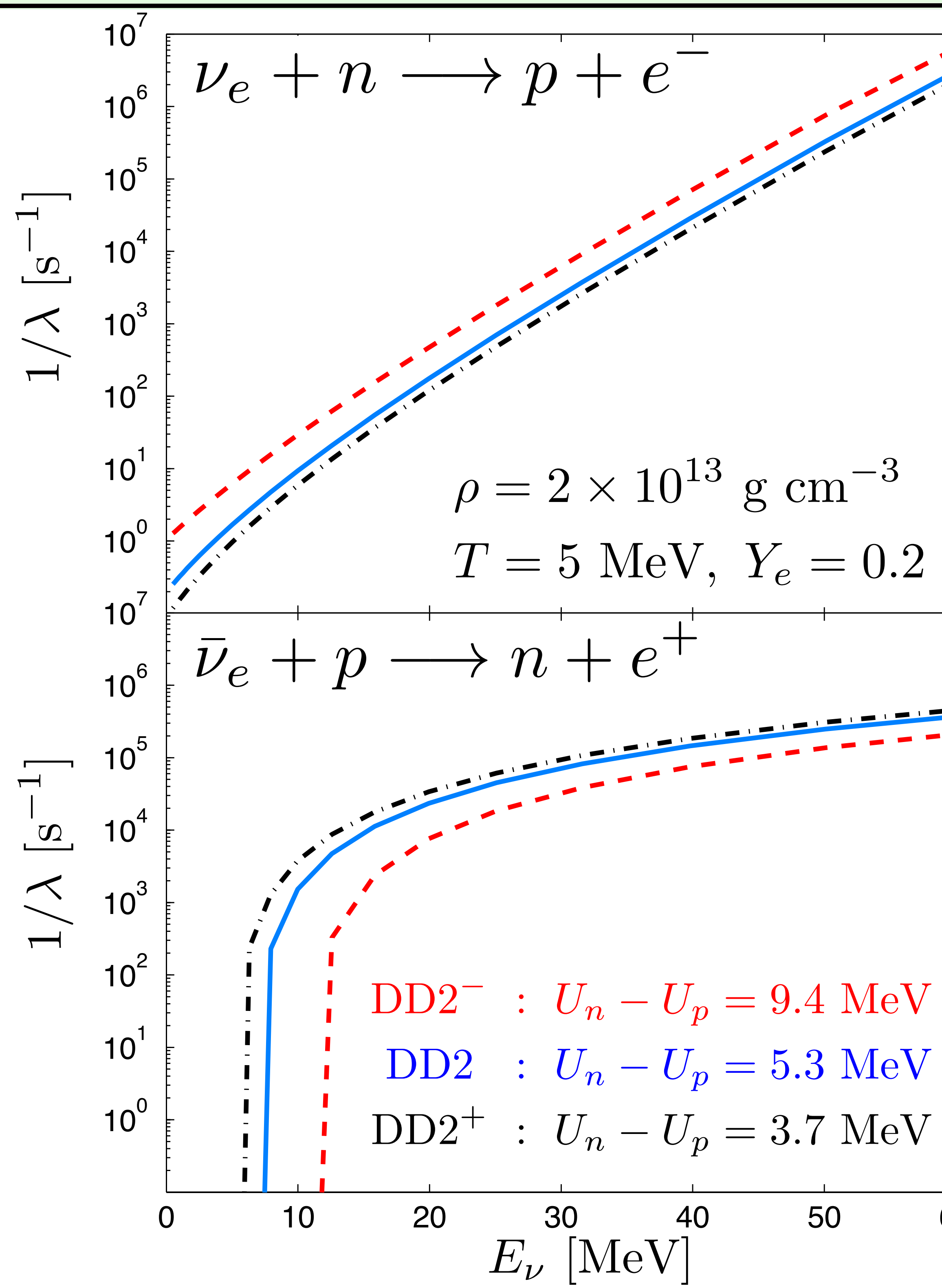
Nuclear EOS determines energetics/coupling to matter for $(\nu_e, \bar{\nu}_e)$ and their spectral differences

Supernova relevant densities



TF et al.,(2014) EPJA 50, 46

(Neutron matter energy per particle)



Typel et al.,(2014), PRC89, 064321

$$E_{e^-} = E_{\nu_e} + (m_n - m_p) + (U_n - U_p)$$
$$E_{e^+} = E_{\bar{\nu}_e} - (m_n - m_p) - (U_n - U_p)$$

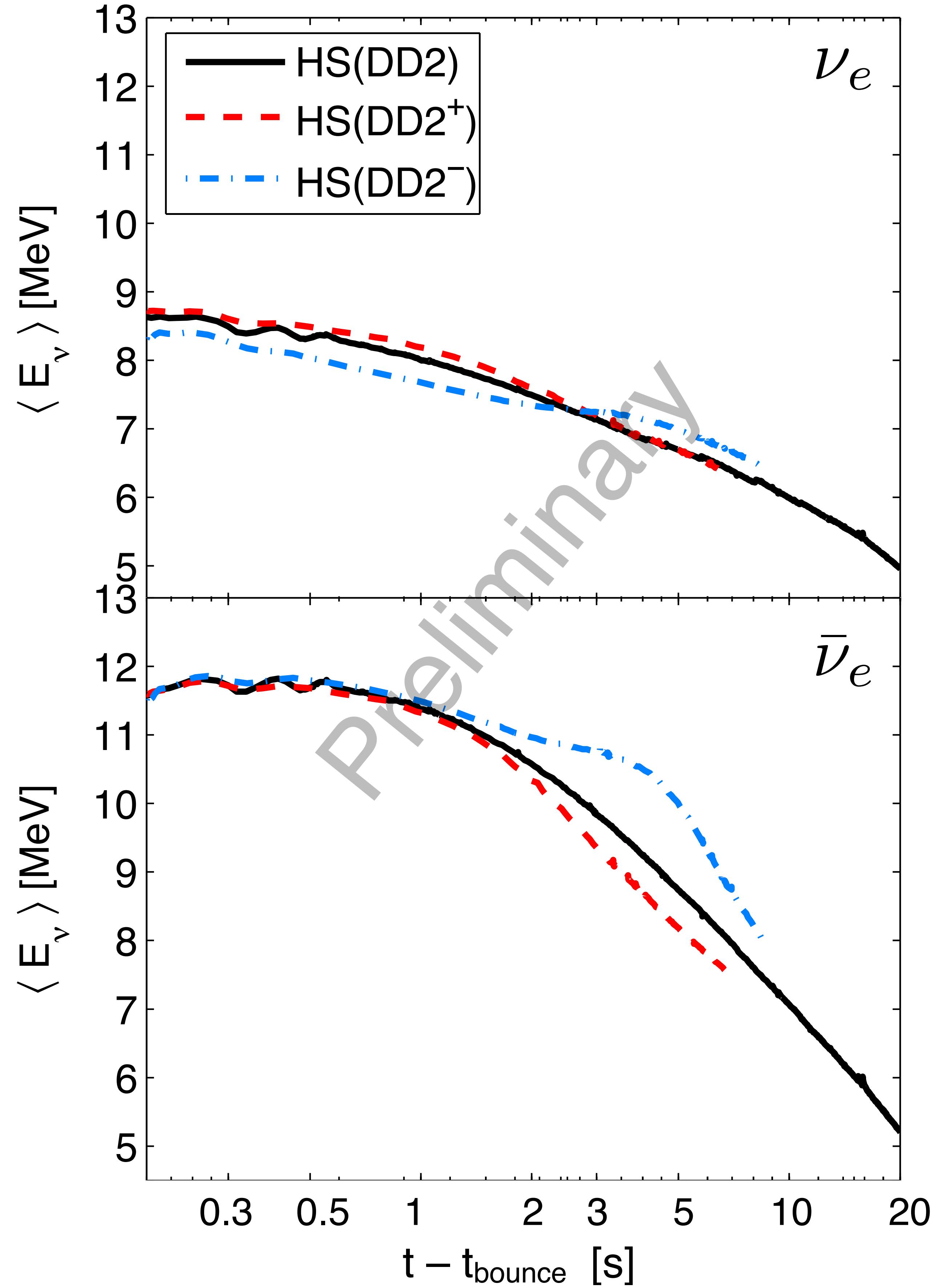
Long-term (10–30 s) neutrino signal

- **Evolution of neutrino signal depends on nuclear EOS**
- Similar neutrino fluxes for all flavors
- Initial neutrino energy hierarchy broken

Large nuclear symmetry energy / large spectral differences

Reference EOS

Low nuclear symmetry energy / small spectral differences



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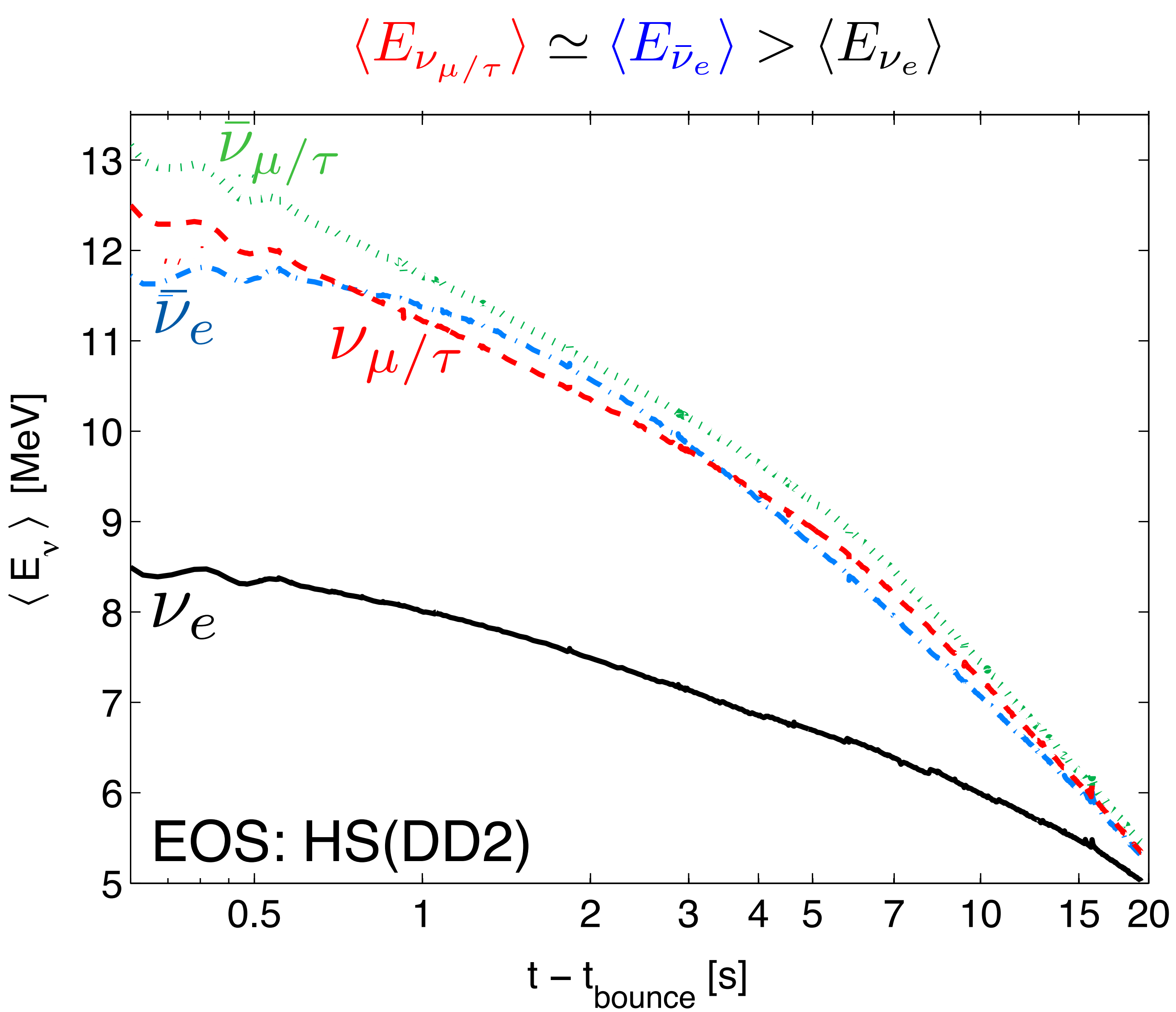

Martinez-Pinedo & TF et al.,(2014) JPhG41, 04408

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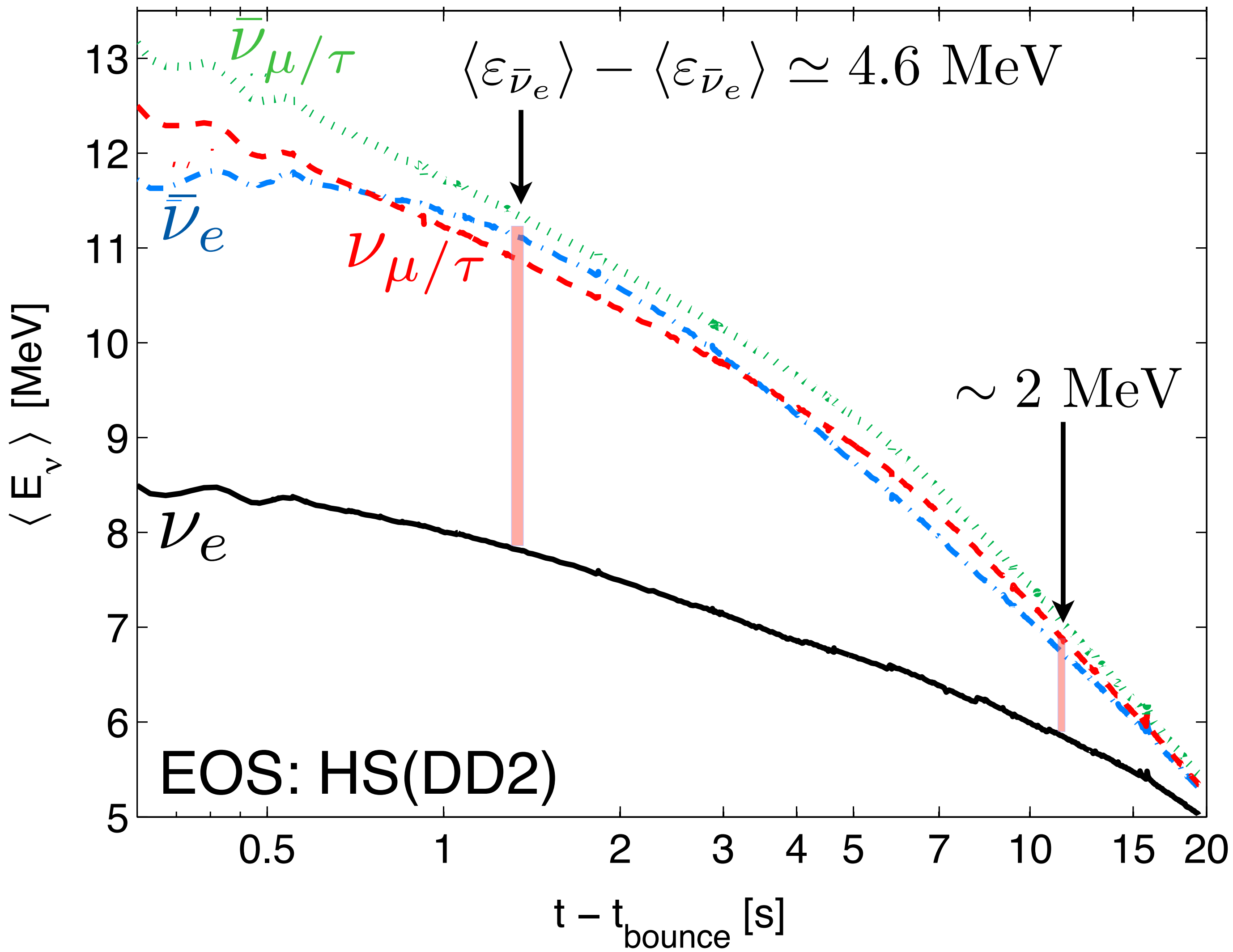


Martinez-Pinedo & TF et al.,(2014) JPhG41, 04408

- Important consequences for nucleosynthesis of heavy elements, i.e. nucleosynthesis relevant conditions:

$$Y_e \simeq \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2Q + 1.2Q^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} - 2Q + 1.2Q^2/\varepsilon_{\nu_e}}\right)^{-1}$$

$$\langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle \begin{cases} \gtrsim 5 \text{ MeV} & (Y_e < 0.5) \\ & \text{neutron rich} \\ < 5 \text{ MeV} & (Y_e > 0.5) \\ & \text{proton rich} \end{cases}$$

$$\left(\langle \varepsilon_\nu \rangle = \langle E_\nu^2 \rangle / \langle E_\nu \rangle \right)$$

Qian et al. (1996), ApJ 471, 331

- Large spectral differences favor neutron rich conditions

$$\bar{\nu}_e + p \longrightarrow n + e^+ \quad \text{(neutron rich)}$$
$$\nu_e + n \longrightarrow p + e^- \quad \text{(proton rich)}$$

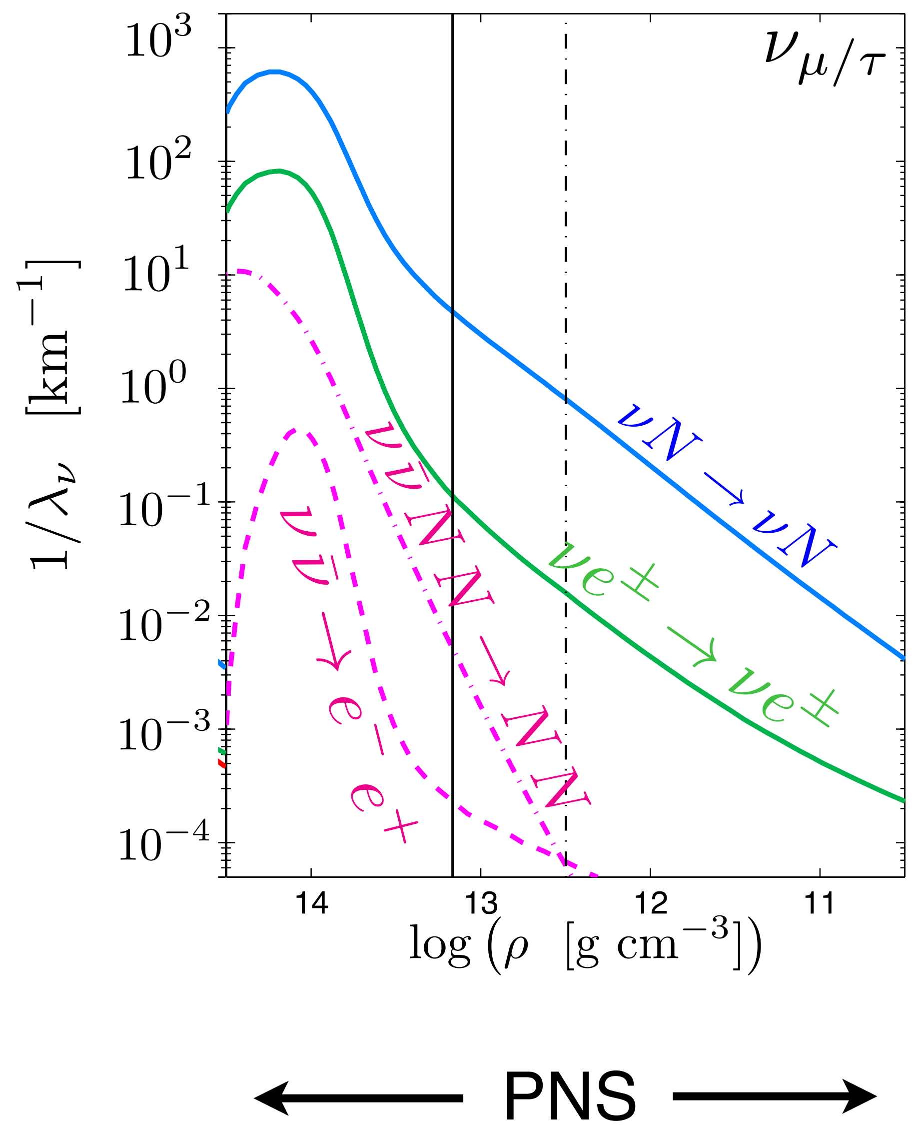
How can we understand this neutrino signal?

Opacity during deleptonization

Neutrino energy integration:

$$\frac{1}{\lambda_\nu} \propto \frac{1}{n_\nu} \int E^2 dE \frac{1}{\lambda_\nu}(E) f_\nu(E)$$

Neutrino reaction rate

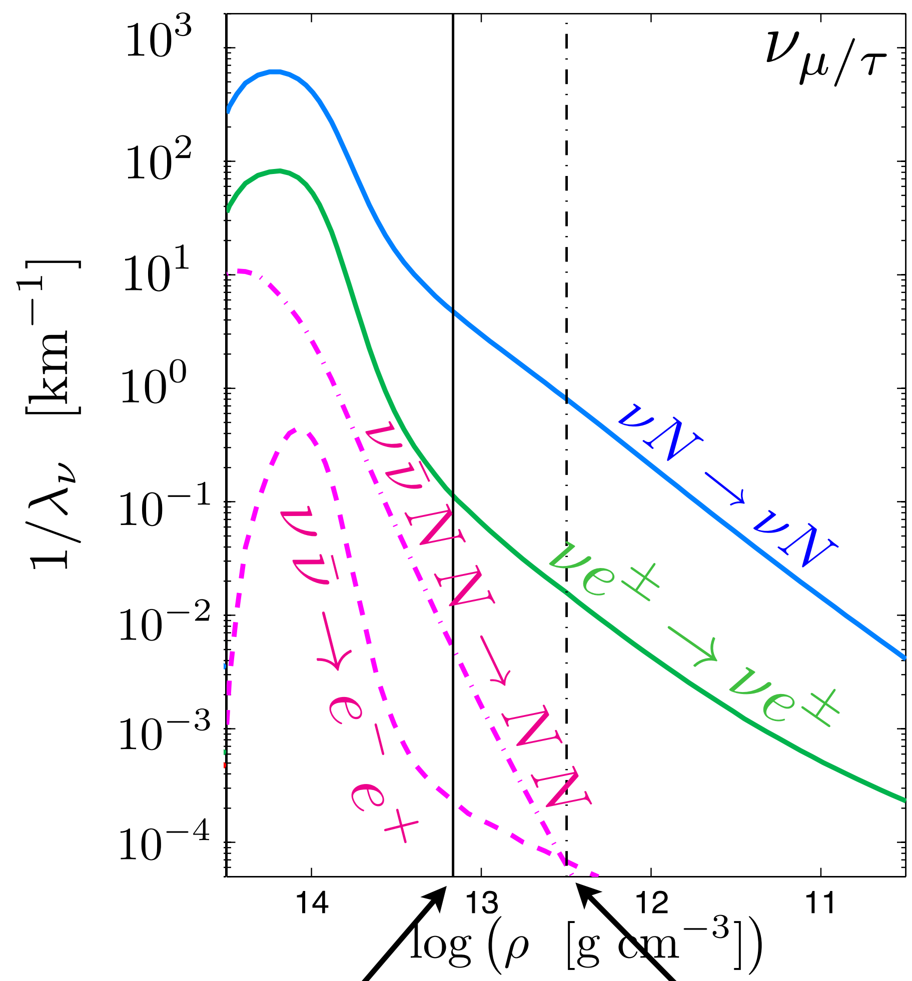


1 second after explosion onset

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization

(Note: no charged-current processes for μ-neutrinos)



1 second after explosion onset

Neutrinospheres: last energy exchange   last elastic scattering

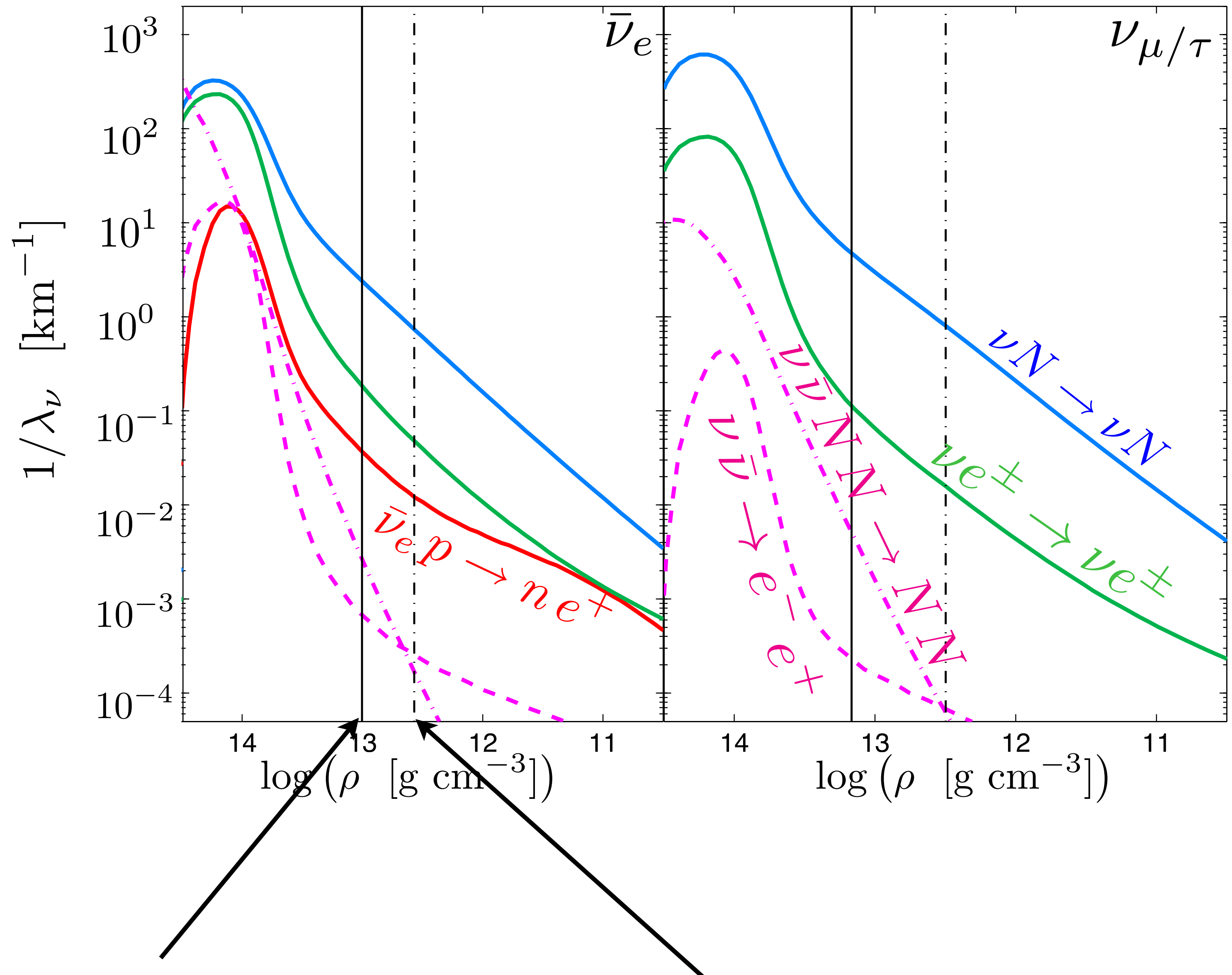
Raffelt (2001), ApJ 561, 890

Largest opacity: scattering on nucleons (elastic process)

Largest energy exchange: scattering on $e^\pm$

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization



1 second after explosion onset

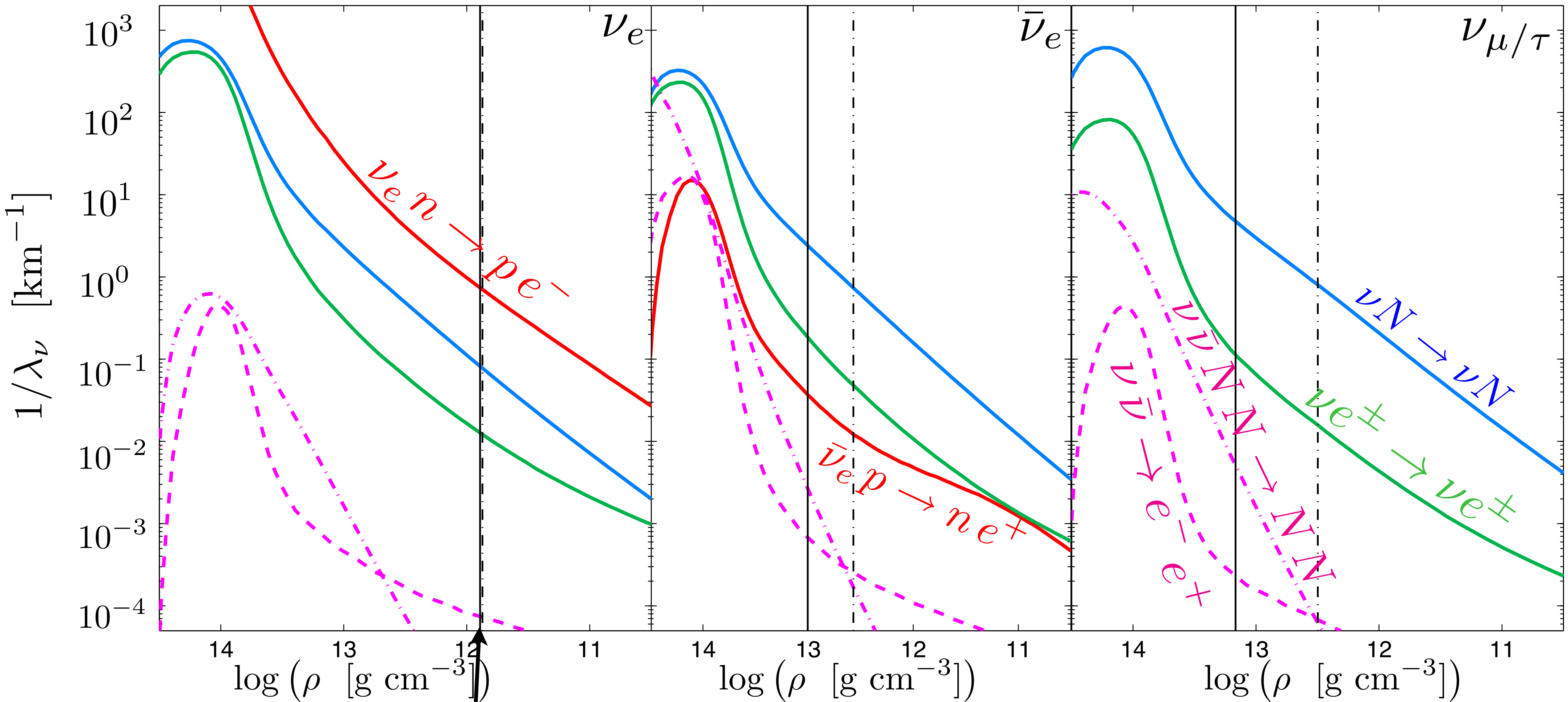
Raffelt (2001), ApJ 561, 890

Largest opacity: scattering on nucleons (elastic process)

Largest energy exchange: scattering on $e^\pm$ ~ absorption on protons

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization



1 second after explosion onset

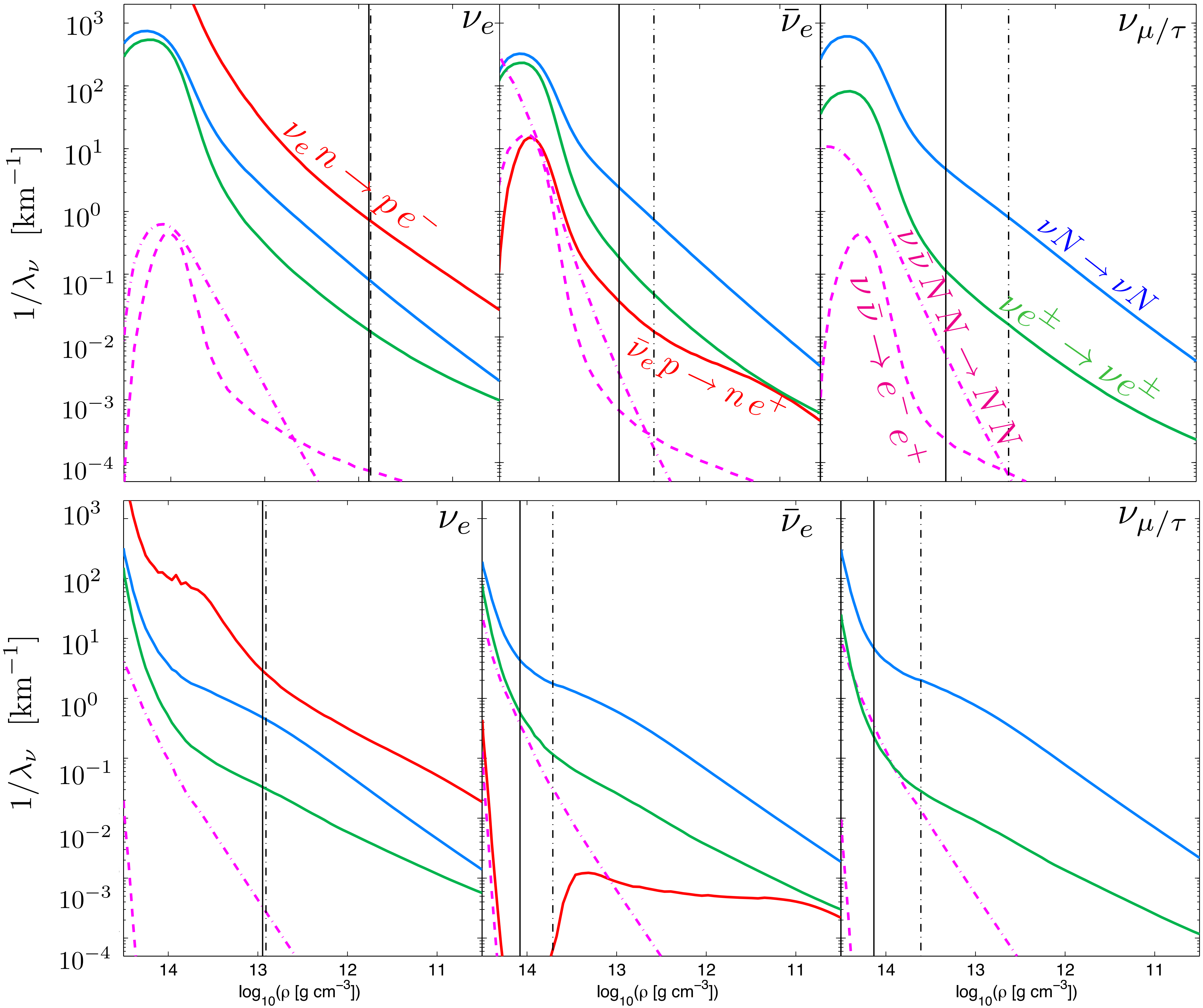
Raffelt (2001), ApJ 561, 890

last energy exchange ~ last elastic scattering

Largest opacity: absorption on neutrons (inelastic process)

TF et al.,(2012)
PRD 85, 083003

Opacity during deleptonization

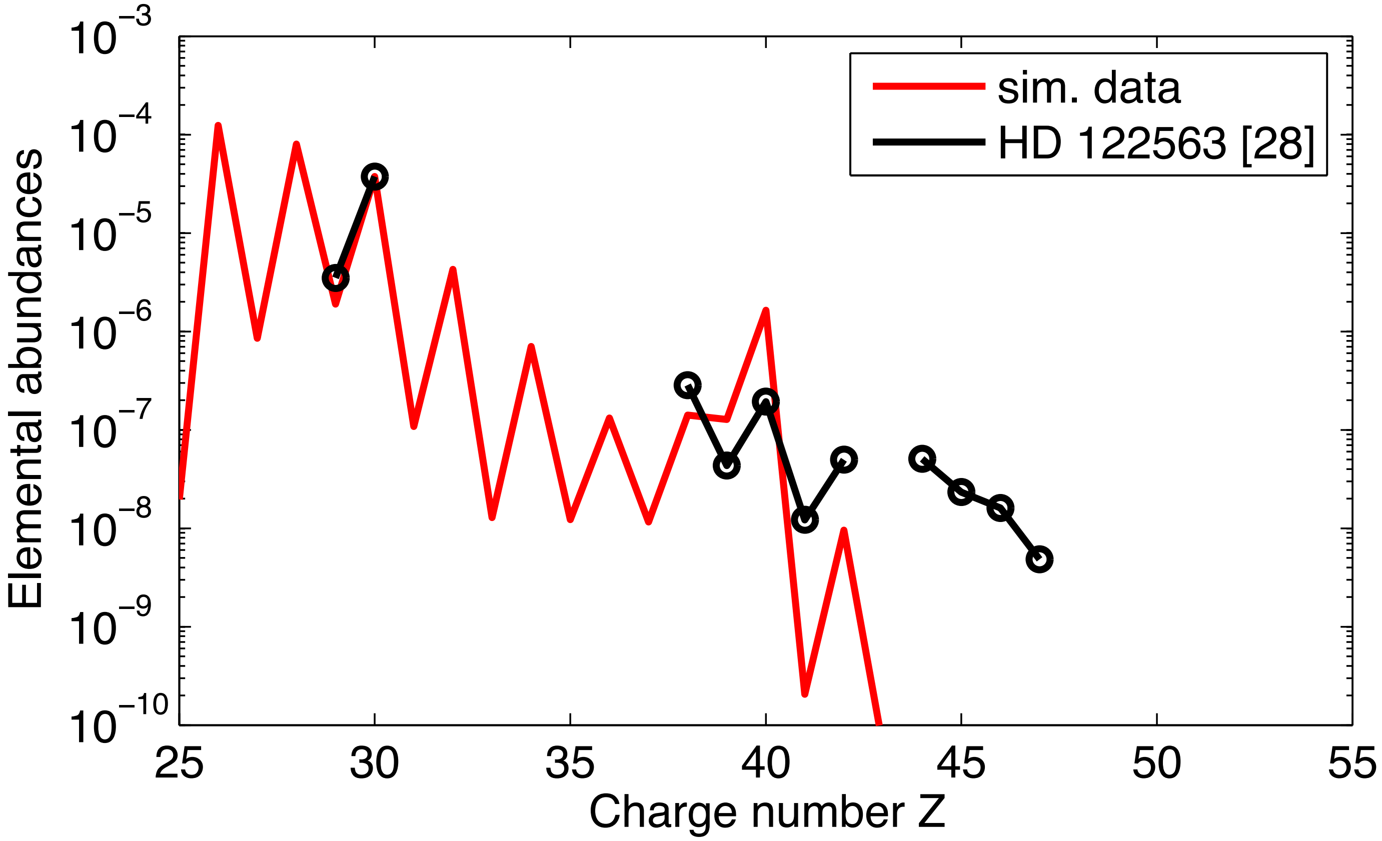


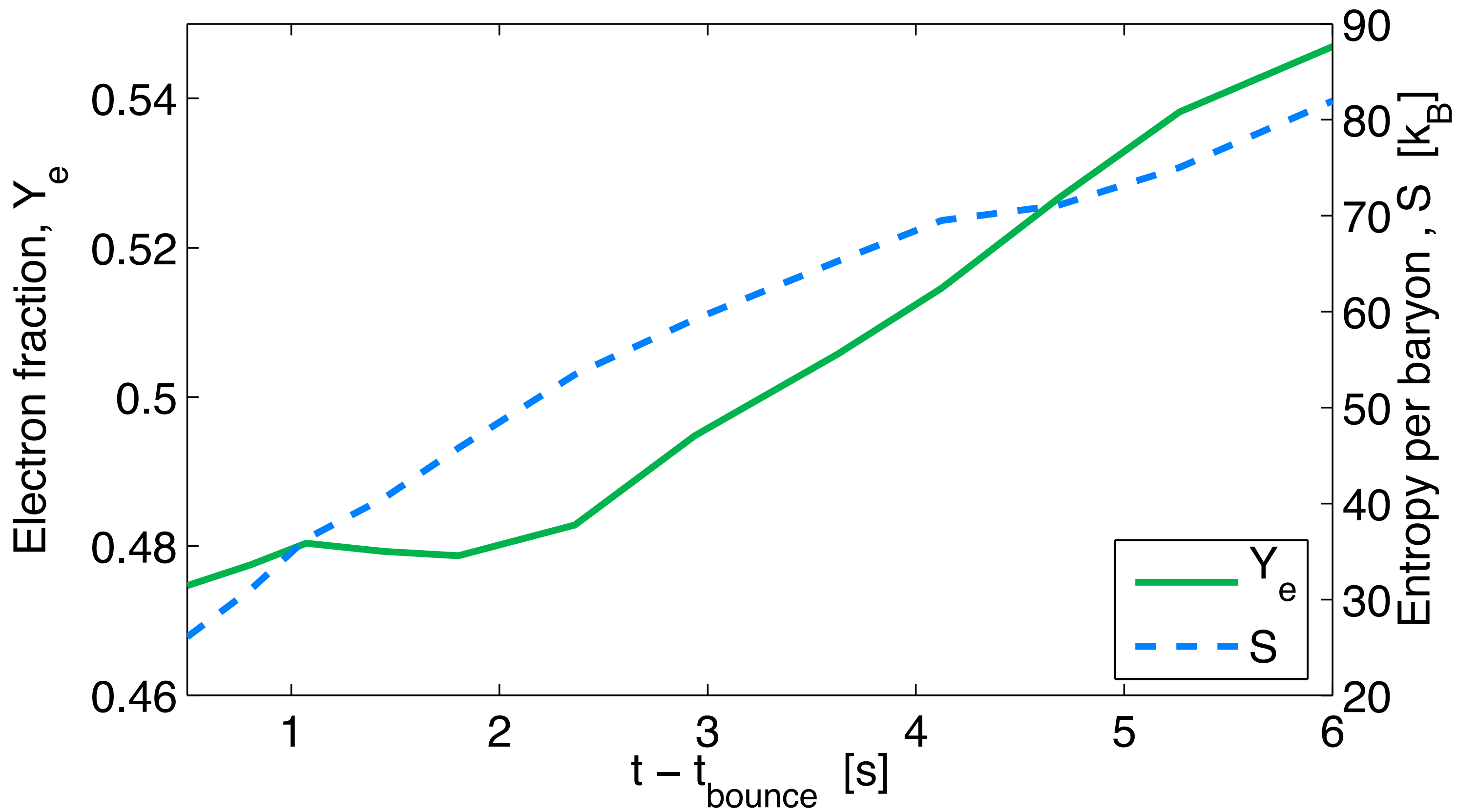
1 second after explosion onset

10 second after explosion onset

TF et al.,(2012) PRD 85, 083003

Results: Integrated Nucleosynthesis





Largest spectral differences found at early times (t ~1–2 s)

Nucleosynthesis relevant conditions:

$Y_e = 0.47– 0.55$

$S = 30 – 100\ k_B$/Baryon

Most mass is ejected at early times (t ~1–2 s)

No νp process nucleosynthesis; requires $Y_e > 0.5$ & high ν-fluxes

Production of light neutron capture elements ($38<\mathcal{Z}<45$)

Lack of heavy neutron capture elements ($\mathcal{A}$~195)

Consistent with metal-poor star observations

Summary/Outlook

- Supernova simulations as laboratories for fundamental physics;
  (strong gravity, strong & electroweak interactions, electromagnetism)

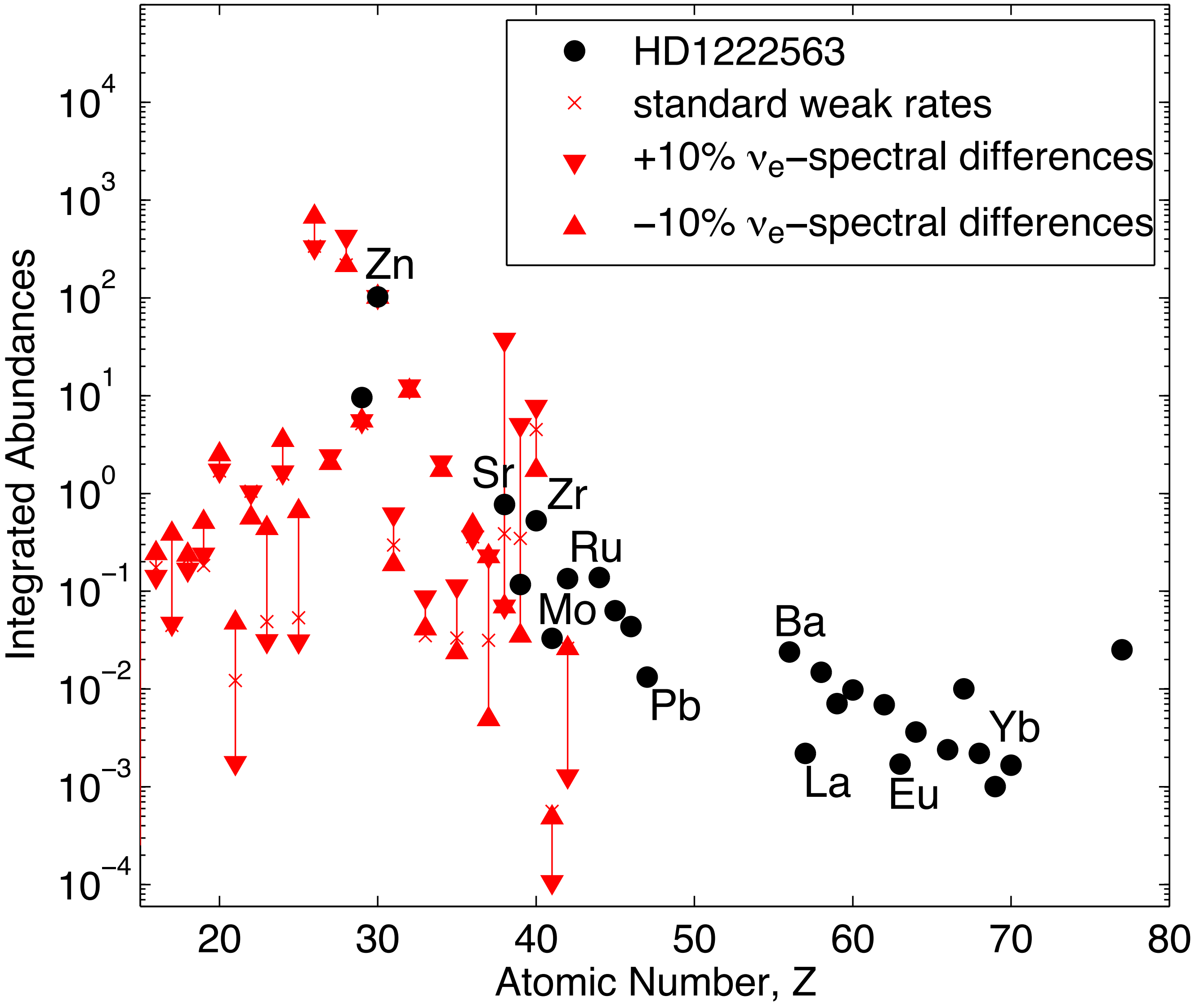
  Probe the state of matter at it's extreme
  (conditions inaccessible in current nuclear/heavy-ion facilities)

- "Universal" observables
  (neutrinos, gravitational waves, nucleosynthesis of heavy element)

Robust site for production of light neutron-capture elements ($38<Z<45$, Sr, Y, Zr,...):

ν–driven wind from (proto)neutron stars
(in agreement with observations)

<u>Lack of systematic understanding</u>
(eos impact, inelastic contributions, weak magnetism corrections,...)



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  Robust site for production of light neutron-capture elements (38<$\mathcal{Z}$<45, Sr, Y, Zr,...):
  ν–driven wind from (proto)neutron stars
  (in agreement with observations)

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- What's possibly missing?

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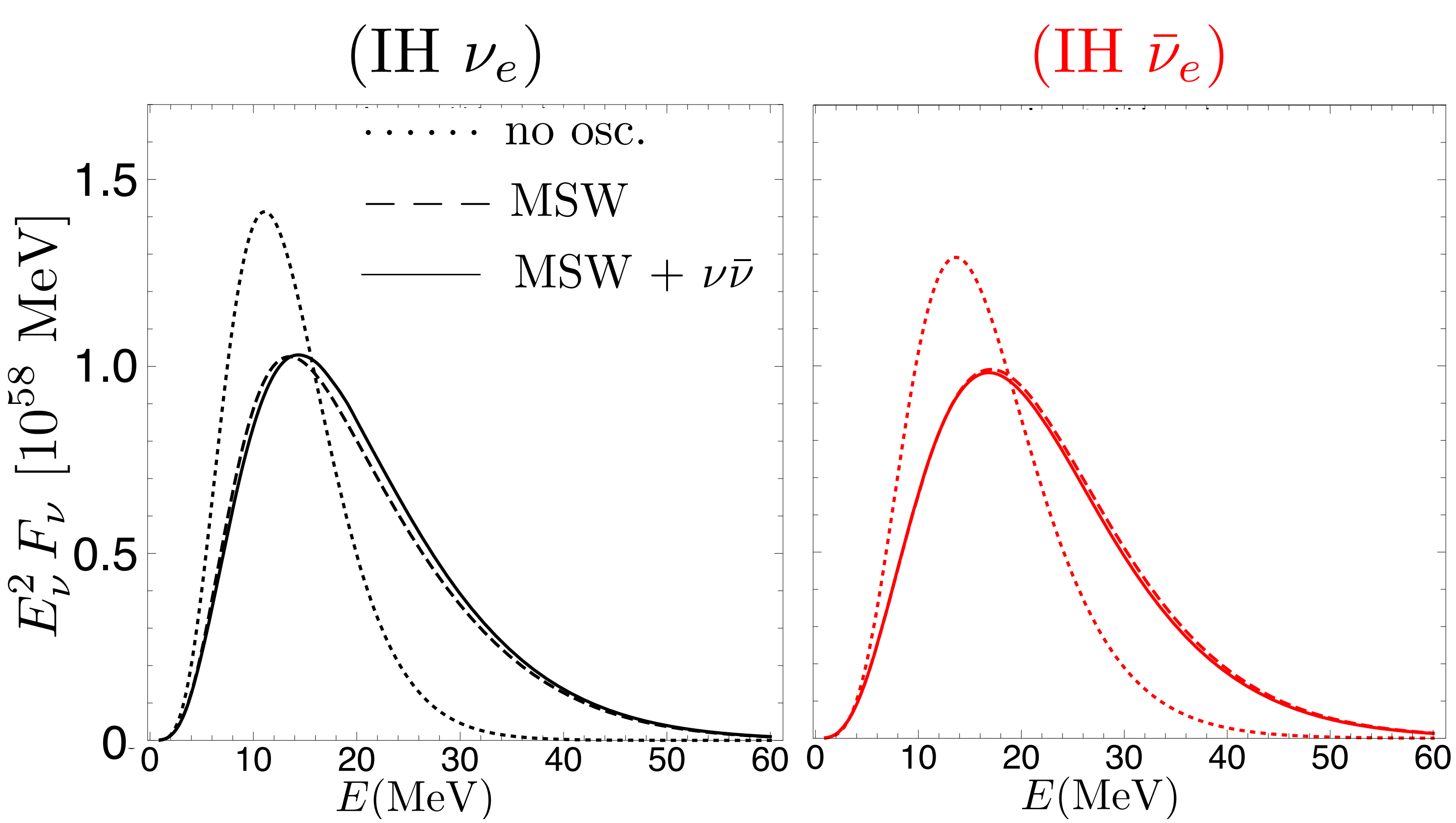
  (see talk by Meng-Ru Wu)



Lunardini & Tambora (2012) JCAP 7, 12

- Supernova simulations as laboratories for fundamental physics;
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$\bar{\nu}_e\,{}^2\mathrm{H} \rightleftarrows n\,n\,e^+$
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$\bar{\nu}_e\,p\,p \rightleftarrows {}^2\mathrm{H}\,e^+$
$\nu_e\,{}^3\mathrm{H} \rightleftarrows n\,p\,p\,e^-$
$\bar{\nu}_e\,{}^3\mathrm{H} \rightleftarrows n\,n\,n\,e^+$
$\nu_e\,{}^3\mathrm{H} \rightleftarrows {}^3\mathrm{He}\,e^-$
$\bar{\nu}_e\,{}^3\mathrm{He} \rightleftarrows {}^3\mathrm{H}\,e^+$
$\nu\,{}^2\mathrm{H} \rightleftarrows p\,n\,\nu$
$\nu\,{}^2\mathrm{H} \rightleftarrows {}^2\mathrm{H}\,\nu$
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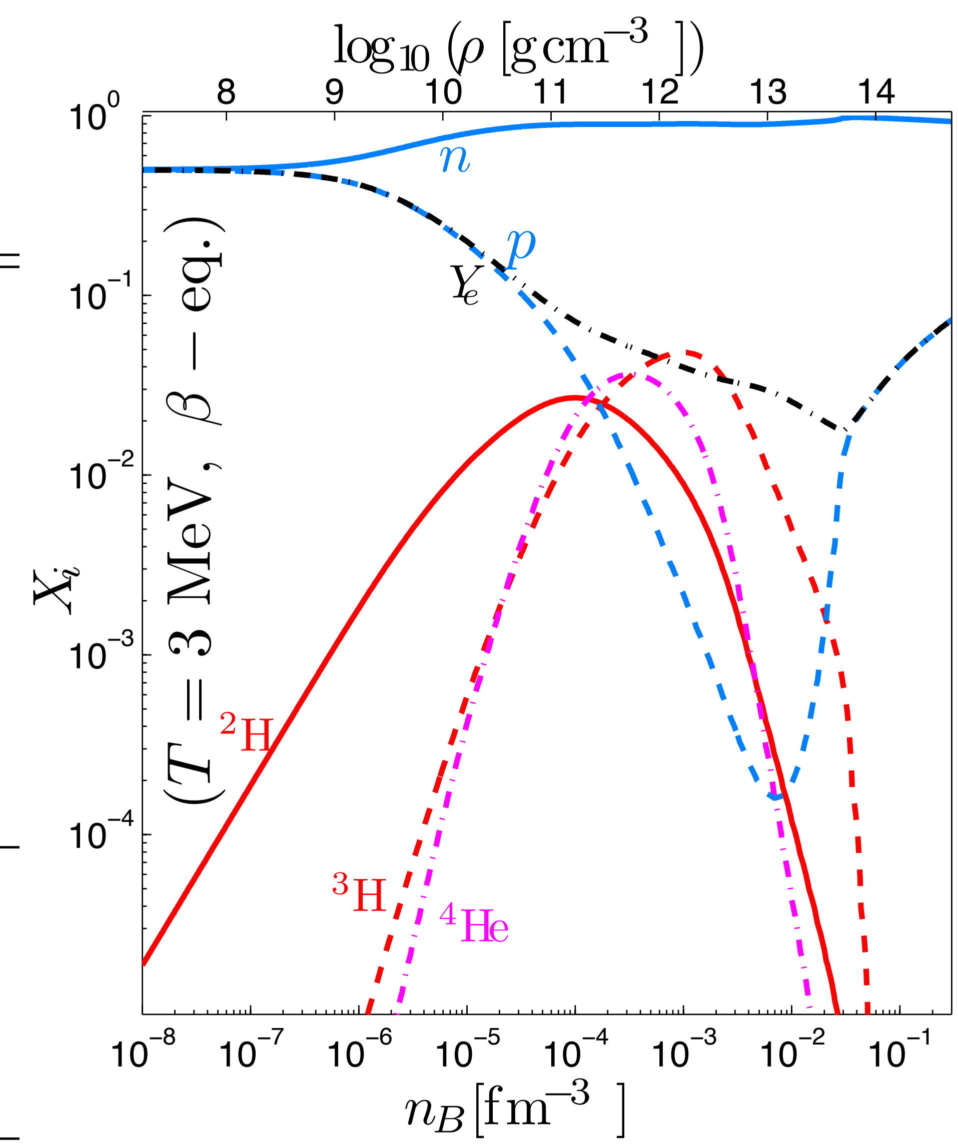
$\nu\,{}^3\mathrm{He} \rightleftarrows {}^3\mathrm{He}\,\nu$



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Thanks for your attention

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$\bar{\nu}_e\, {}^3\mathrm{H} \rightleftarrows n\, n\, n\, e^+$
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