Simulations of massive-star explosions
–
“Need for sophisticated microphysics input”

Tobias Fischer

“Astrophysics and Nuclear Structure”

International Workshop XLI on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Kleinwalsertal, Austria, January January 26 - February 1, 2013

GSI theory

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compstar

Physics input in supernova simulations:

neutrino radiation hydrodynamics

(relativistic hydrodynamics coupled to three-flavor Boltzmann neutrino transport)

progenitor models (structure)

(composition/nuclear burning, mixing, mass loss, rotation, magn. fields,...)

nuclear physics

(nuclear EOS, composition, additional nuclear degrees of freedom at high densities, weak processes . . .)

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(thanks to G. Martinez-Pinedo and K. Langanke)

Outline

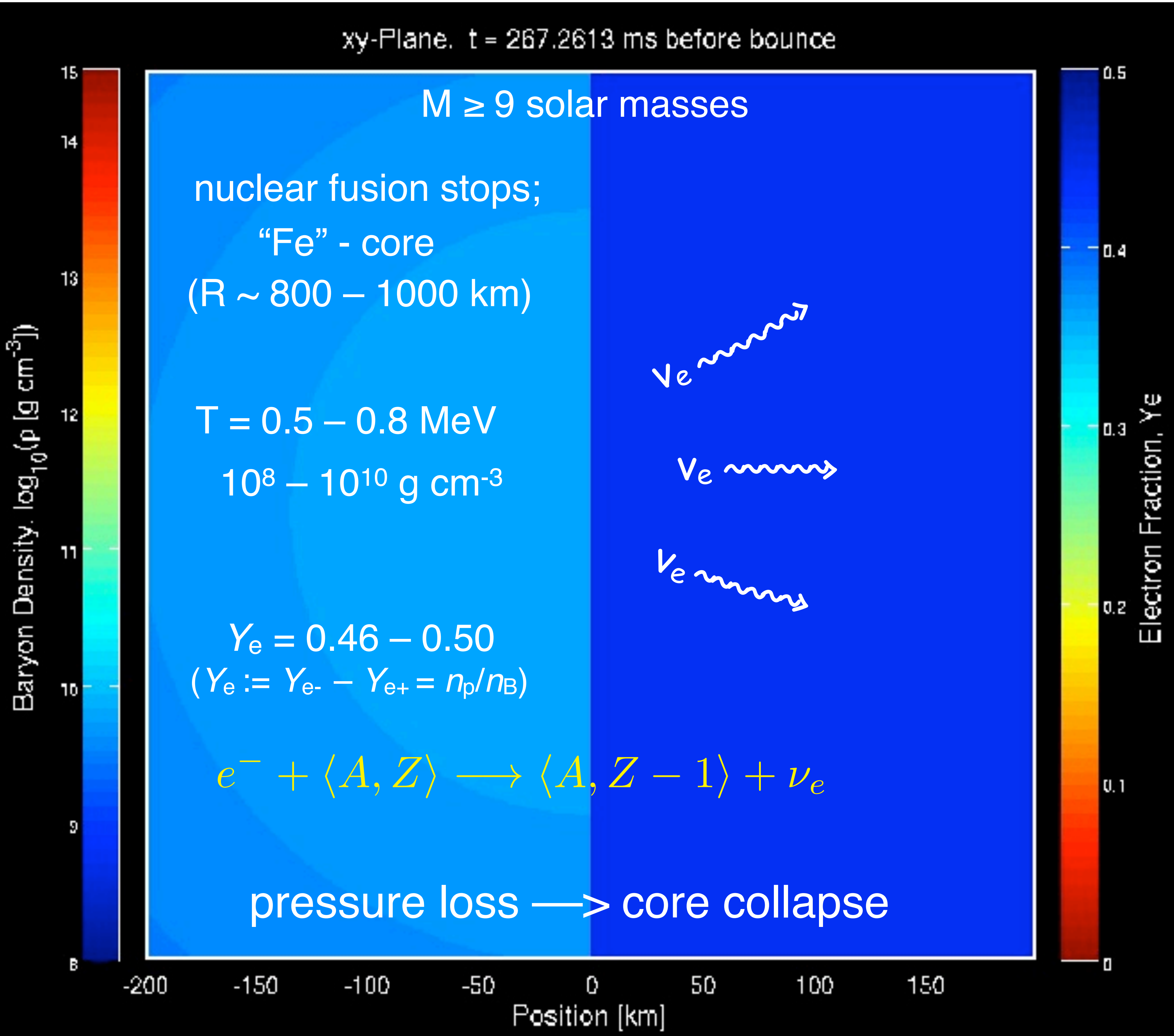
- Introduction – Core-collapse supernova phenomenology

- Long-term evolution – impact on nucleosynthesis (ν-driven wind)

- Summary and outlook

Core-collapse supernova phenomenology

Pre-collapse models



M ≥ 9 solar masses

nuclear fusion stops;
"Fe" - core
(R ~ 800 – 1000 km)

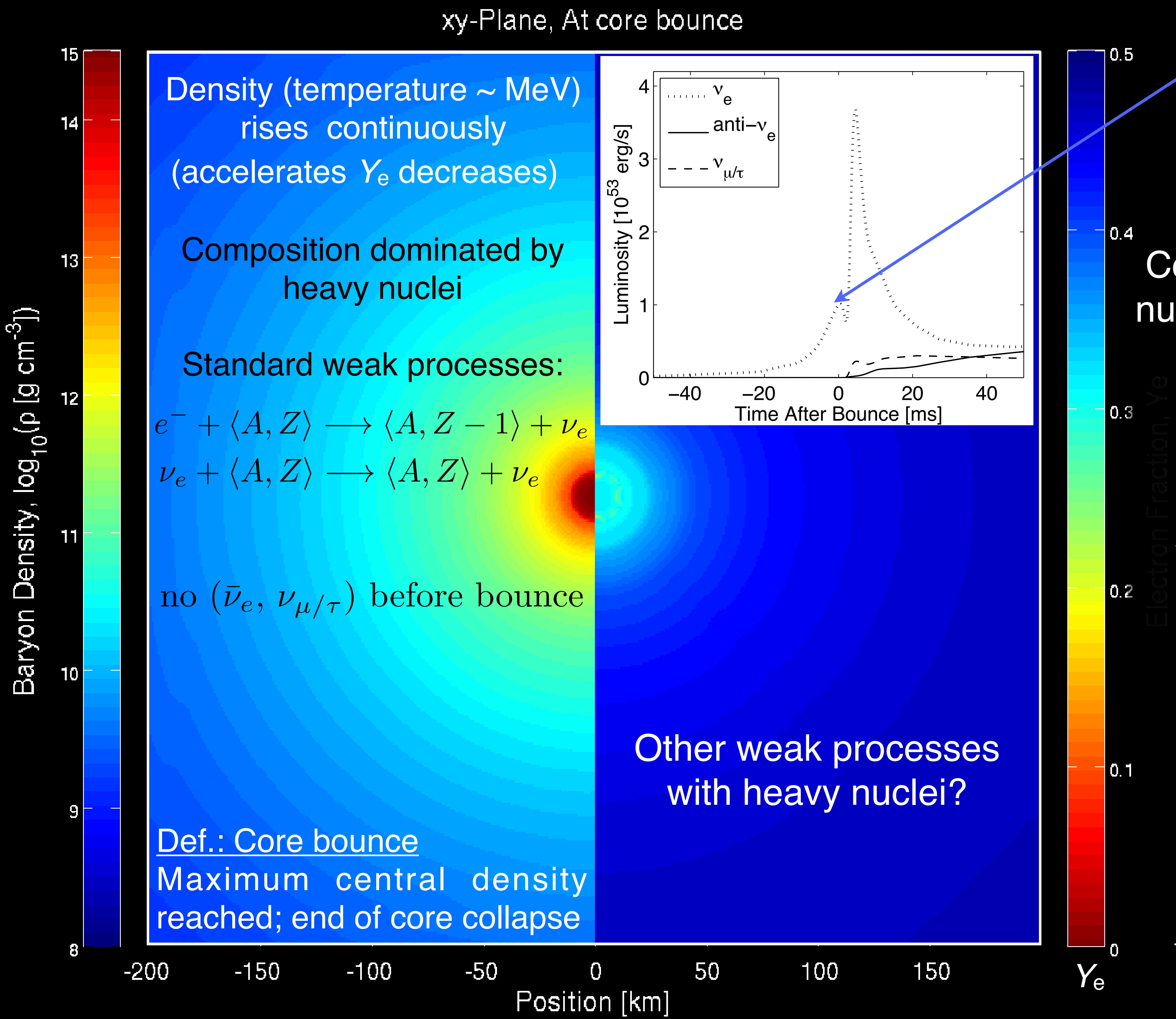
T = 0.5 – 0.8 MeV
$10^8 - 10^{10}$ g cm^{-3}

$Y_e = 0.46 - 0.50$
($Y_e := Y_{e-} - Y_{e+} = n_p/n_B$)

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

pressure loss —> core collapse

Core-collapse and bounce



Density (temperature ~ MeV) rises continuously (accelerates Y_e decreases)

Composition dominated by heavy nuclei

Standard weak processes:

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

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

no $(\bar{\nu}_e,\ \nu_{\mu/\tau})$ before bounce

Def.: Core bounce
Maximum central density reached; end of core collapse

Other weak processes with heavy nuclei?

Neutrino trapping:
$10^{11} – 10^{13}$ g cm^{-3}

Collapse halts above nuclear matter density
2.4×10^{14} g cm^{-3}
(Y_e = 0.28 - 0.32)

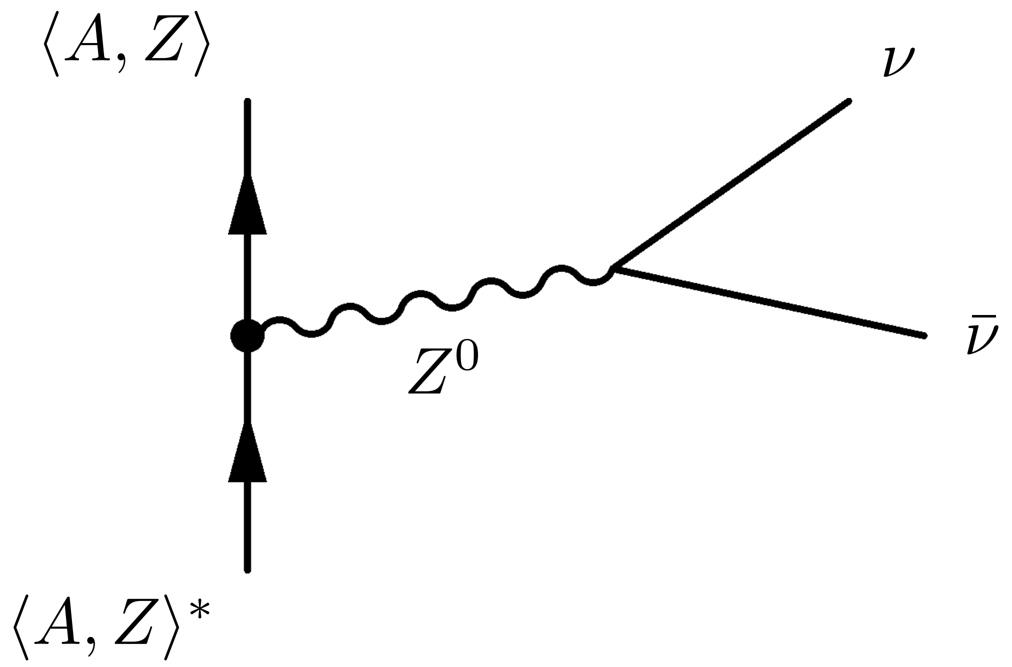
Formation of a shock wave;

Energy loss due to:

- dissociation of heavy nuclei
- ν_e escapes ($Y_e \approx 0.1$) ($L_{\nu_e} \sim 10^{53}$ erg s^{-1})

Shock wave stalls

Heavy-nuclei de-excitations



- Supernova conditions below normal nuclear matter density, where heavy nuclei are abundant:

  T ~ 0.5 – 5 MeV
  Y_e ~ 0.3 – 0.45

- Heavy nuclei become very large and neutron rich, and can exist in <u>excited states</u>

- Neutrino-pair emission from heavy-nuclei de-excitations; reaction rate:

$$\lambda_{\nu\bar{\nu}}(E_i) \propto \int_0^{E_i} dE_f\, S(E_i, E_f) \;\times$$

$$\times \int_0^{\triangle} (\triangle - E_\nu)^2\, E_\nu^2\, dE_\nu\; (1 - f_\nu(E_\nu))\,(1 - f_{\bar{\nu}}(E_{\bar{\nu}}))$$

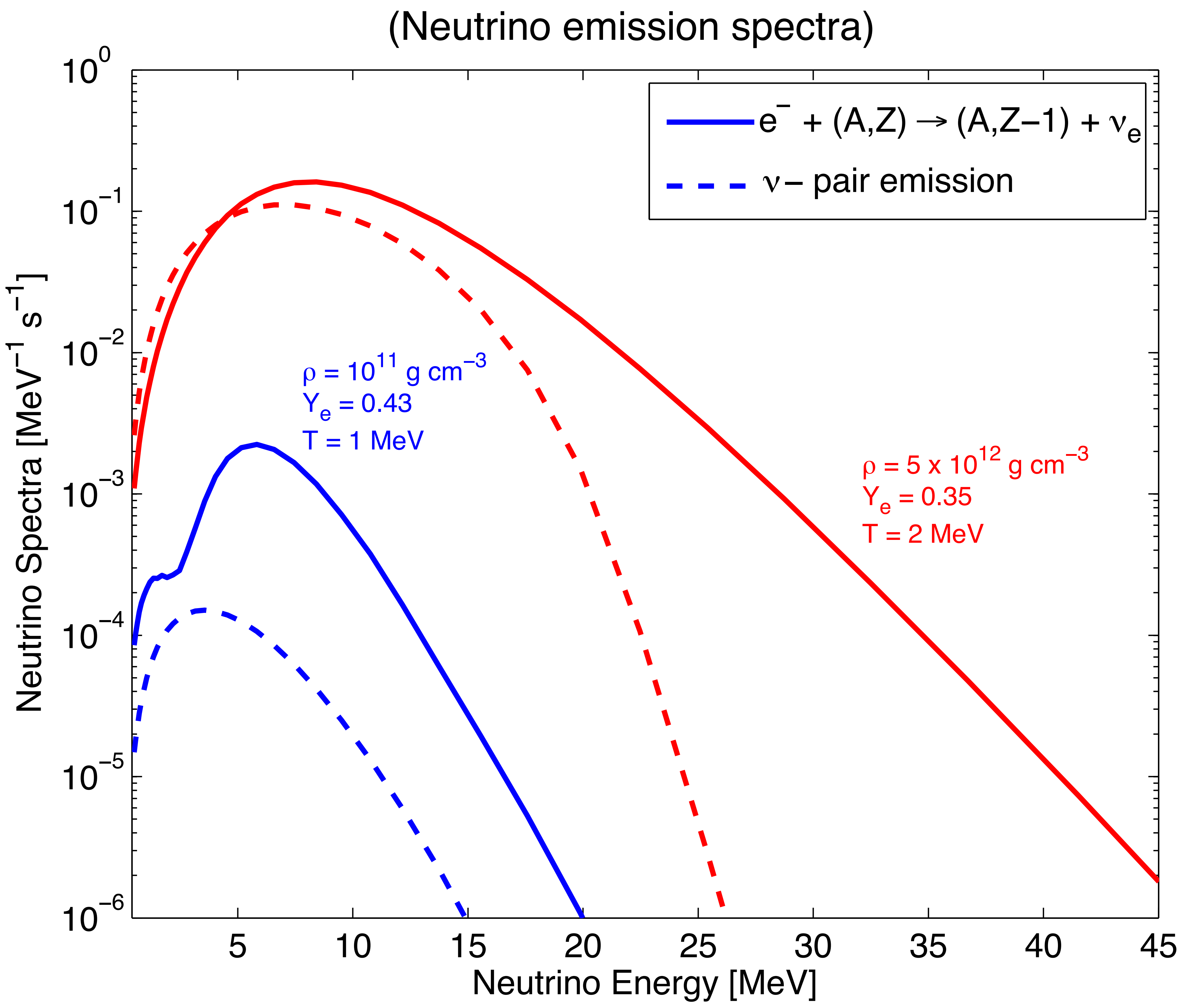
$$(\triangle = E_f - E_i = E_\nu + E_{\bar{\nu}})$$

$$\lambda_{\nu\bar{\nu}}^{\mathrm{total}} = \frac{\int dE_i\, \rho(E_i)\, \lambda_{\nu\bar{\nu}}(E_i)\, e^{-\frac{E_i}{kT}}}{\int dE_i\, \rho(E_i)\, e^{-\frac{E_i}{kT}}},$$

- Approximation based on Fermi-gas fit
  (Fuller & Meyer (1991), ApJ 376, 701)

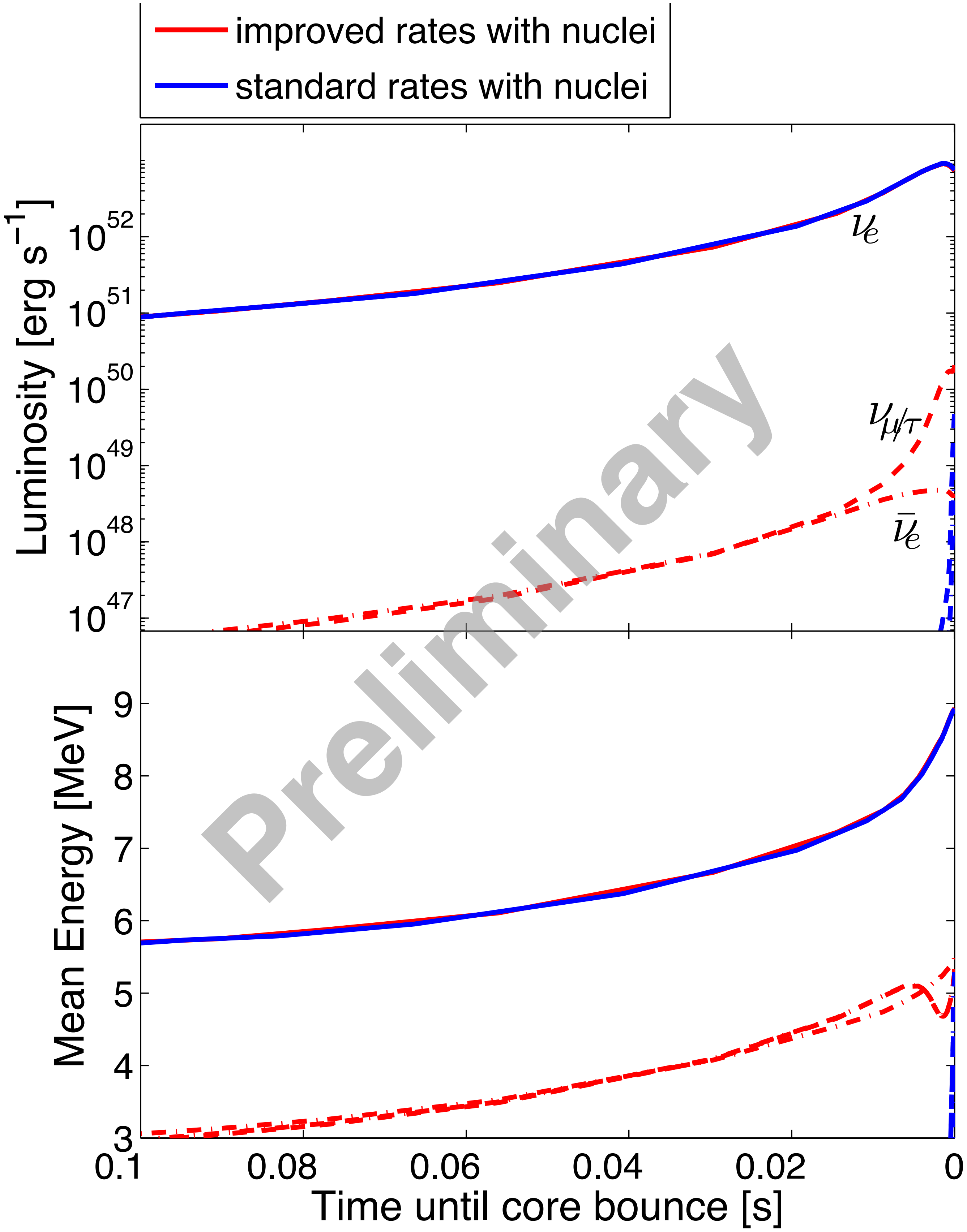
- Comparison with ν_e – emission from e^- – captures on heavy nuclei
  (Juodagalvis et al. (2010), NPA 848, 454)

Pair-production rate for heavy-nuclei de-excitations



(Neutrino emission spectra)

Heavy-nuclei de-excitations during core collapse



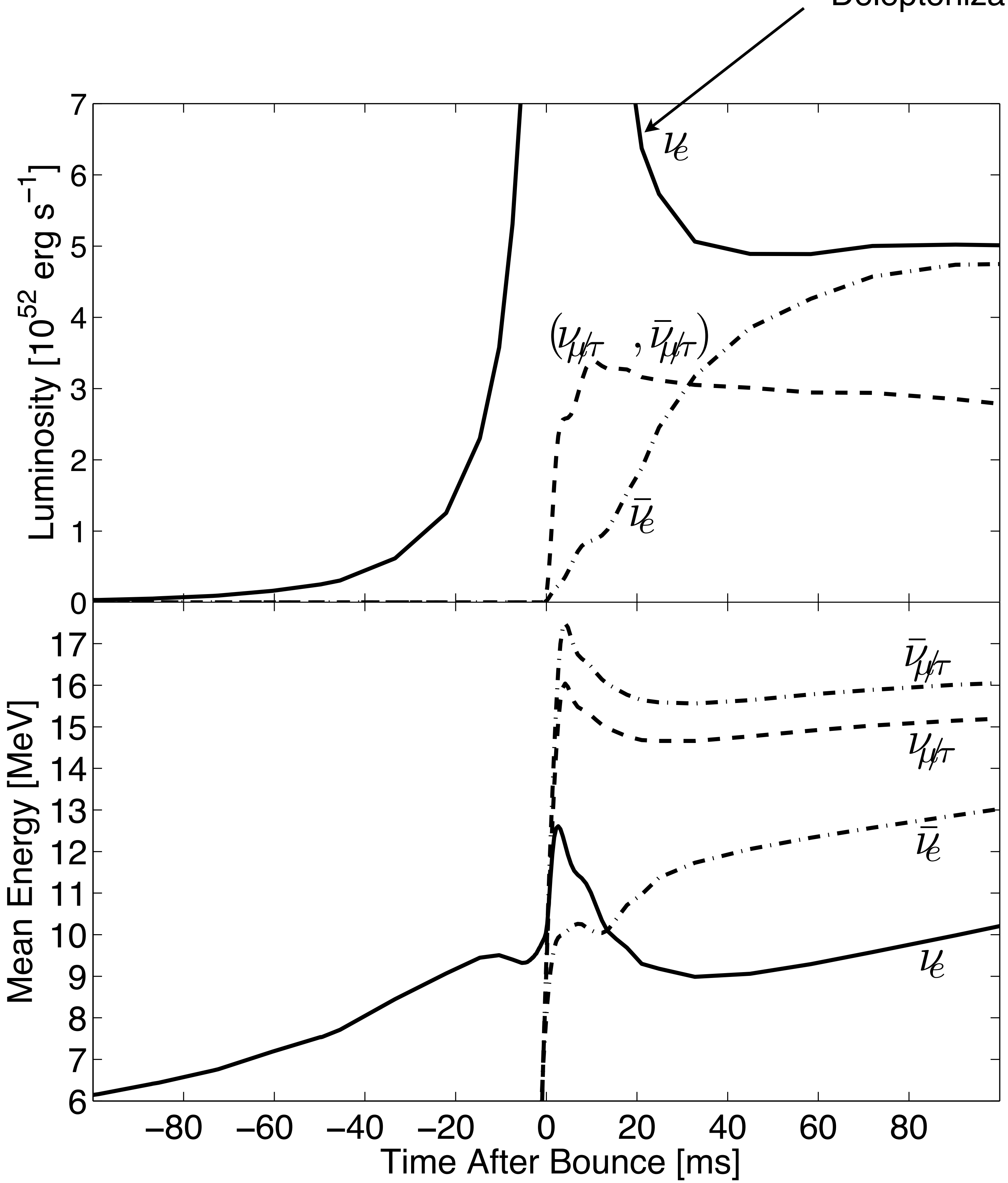
$$
\begin{aligned}
\nu_e + \langle A,Z\rangle &\longrightarrow \langle A,Z\rangle + \nu_e \\
e^- + \langle A,Z\rangle &\longrightarrow \langle A,Z-1\rangle + \nu_e \\
\langle A,Z\rangle^* &\longrightarrow \langle A,Z\rangle + \nu + \bar{\nu}
\end{aligned}
$$

- Only relevant when heavy nuclei are abundant
- ν_e – luminosities/spectra dominated from e⁻ – captures during core collapse
- Significant increase of anti–ν_e and heavy-lepton neutrino luminosities during core collapse (low-energy neutrinos ~ 3–5 MeV)

$$L_{\bar{\nu}_e} \simeq 10^{47} - 10^{48}\ \mathrm{erg\ s^{-1}}$$
$$L_{\nu_{\mu/\tau}} \simeq 10^{47} - 10^{50}\ \mathrm{erg\ s^{-1}}$$
$$\langle E\rangle \simeq 3 - 5\ \mathrm{MeV}$$

- Once ν_e become trapped, no further pair-production

Early post-bounce ν – emission


Deleptonization burst

Charge current reactions

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

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

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

Reddy et al. (1998), PRD 58, 013009
Juodagalvis et al. (2010), NPA 848, 454

Neutral current reactions

$$\text{pair reactions} \left\{ \begin{array}{l} e^- + e^+ \rightleftharpoons \nu + \bar{\nu} \\ N + N \rightleftharpoons N + N + \nu + \bar{\nu} \quad (N = n, p,) \\ \nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau} \end{array} \right.$$

$$\text{scattering} \left\{ \begin{array}{l} \nu + N \rightleftharpoons \nu + N \qquad (N = n, p) \\ (\nu + \langle A, Z \rangle \rightleftharpoons \nu + \langle A, Z \rangle) \\ \nu + e^{\pm} \rightleftharpoons \nu + e^{\pm} \end{array} \right.$$

(thermalization processes)

Bruenn (1985), ApJS 58, 77
Hannestadt & Raffelt, (1998), ApJ 507, 339
Buras et al. (2003), ApJ 587, 320

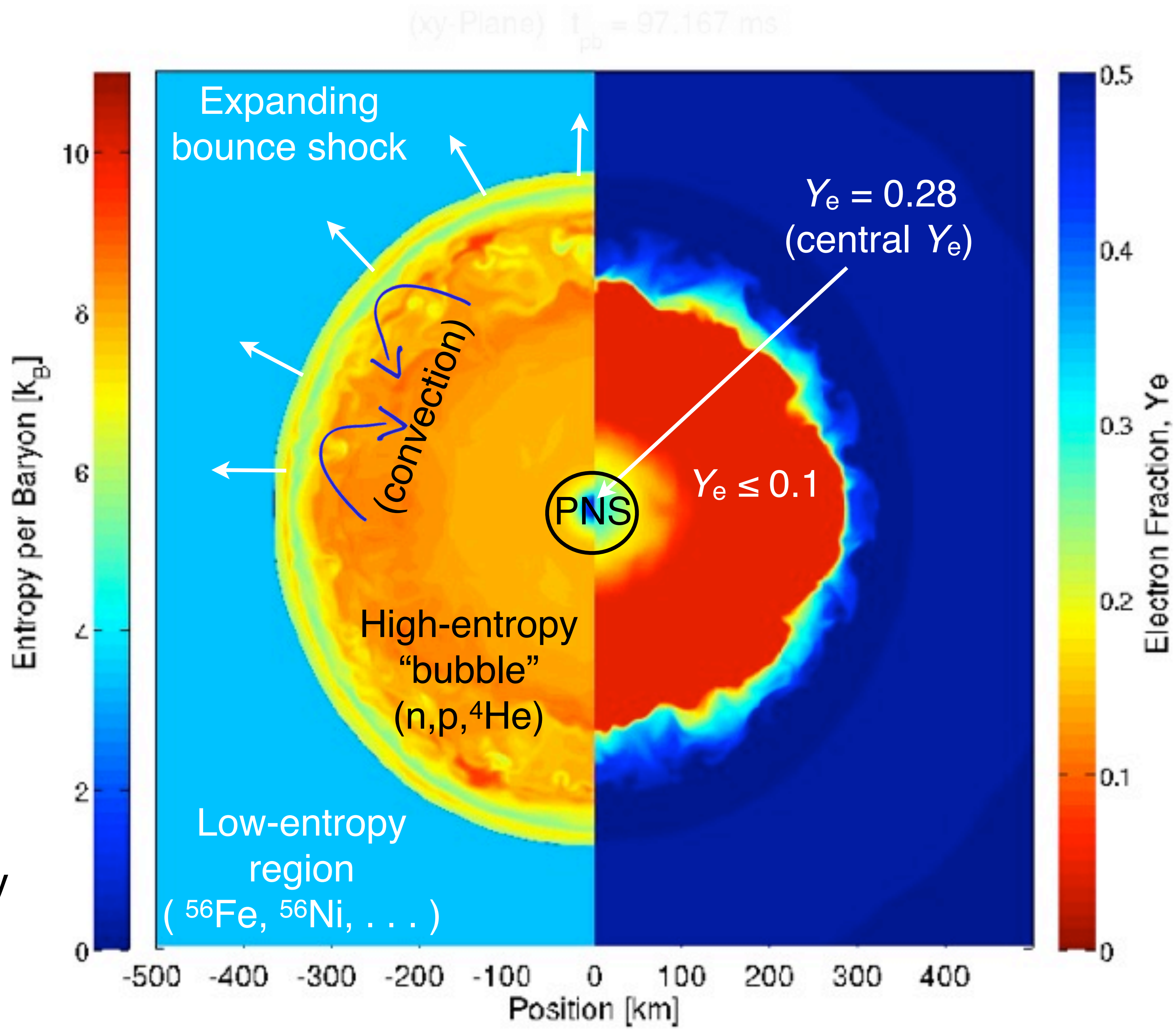
Concept of massive-star explosions ($\gtrsim 9\ \mathrm{M}_\odot$)

Which process drives the supernova explosion ?

Energy transfer from protoneutron star (PNS) to standing shock

- delayed explosions (~100 ms), prompt scenario excluded
- huge energy reservoir available
- explosion is a “surface effect”
- process to liberate energy from proto-neutron star behind the standing shock (?)
- no *ν*-driven explosions in spherically symmetric models

Note: making predictions for nucleosynthesis requires (accurate) neutrino transport



(see talk by Thomas Janka)

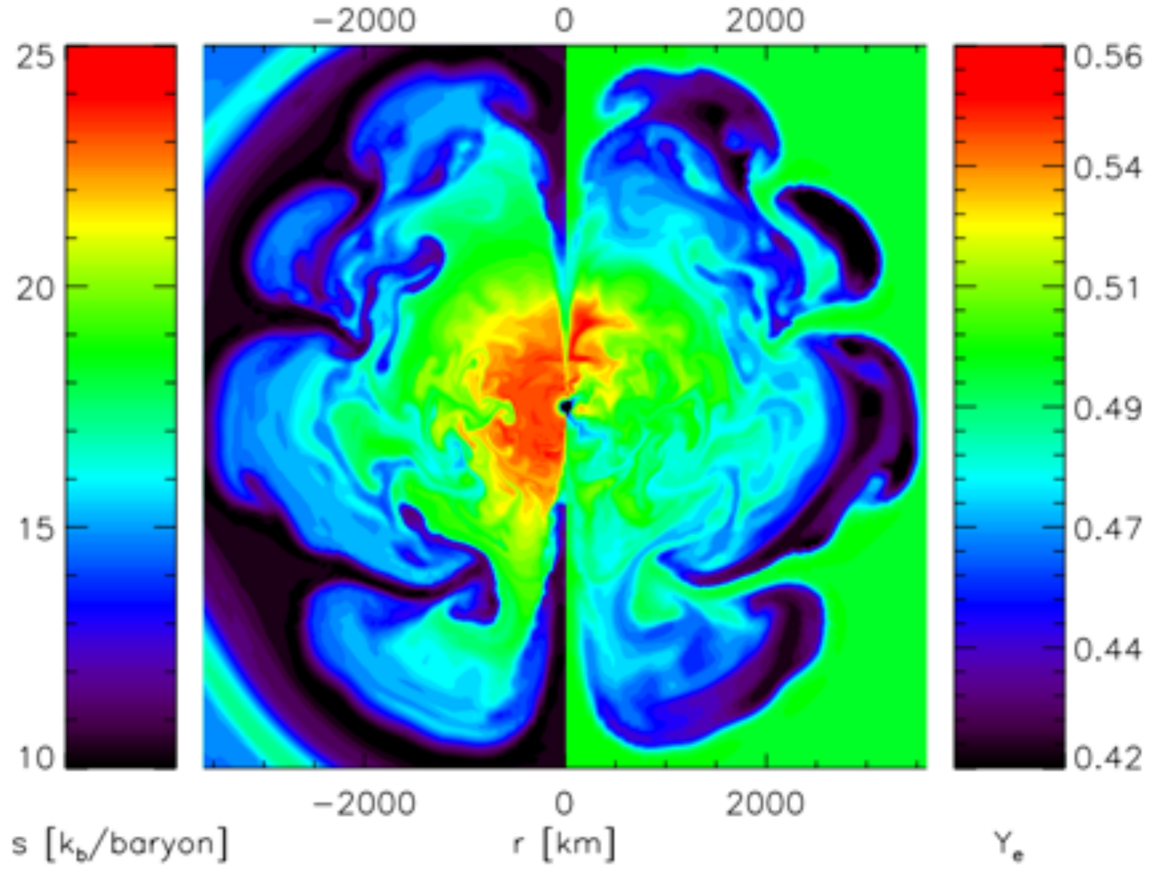
A special case: low-mass massive stars

- ~30% of all massive stars $(\sim 8\text{–}9\ \mathrm{M}_\odot)$
- O-Ne-Mg core (Nomoto 1984/1987)
- explosions <u>even in 1D simulations</u>

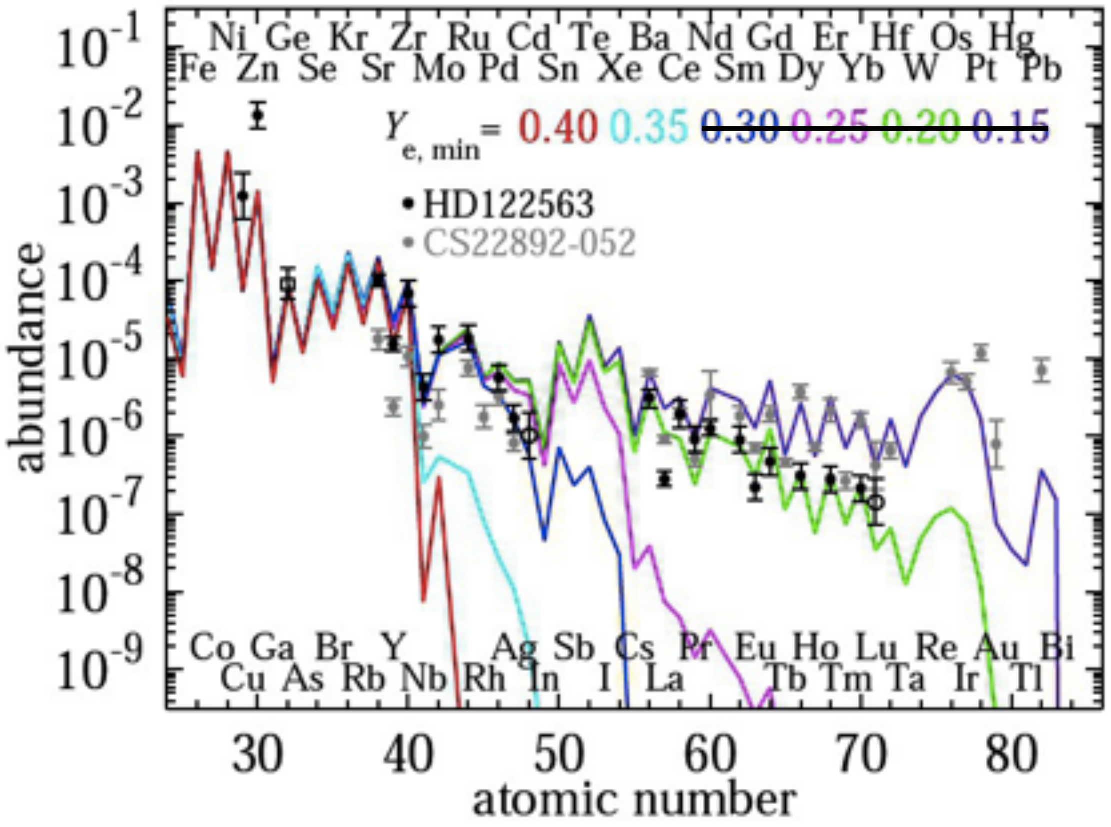
  (Kitaura et al. 2006, 1D, Boltzmann *v*-transport)
- low expl. energies, $M_{\mathrm{Ni}} \sim 10^{-4}$ solar mass, consistent with SN1054
- extremely steep density gradient between core (1.376 solar mass) and envelop
- neutron-rich "pockets" ($Y_{\mathrm{e,min}} \approx 0.40$) allow for weak *r*-process (Z~45)
- improved models are under development

  (Jones & Hirschi, et al., in preparation)

(see talk by Sam Jones)

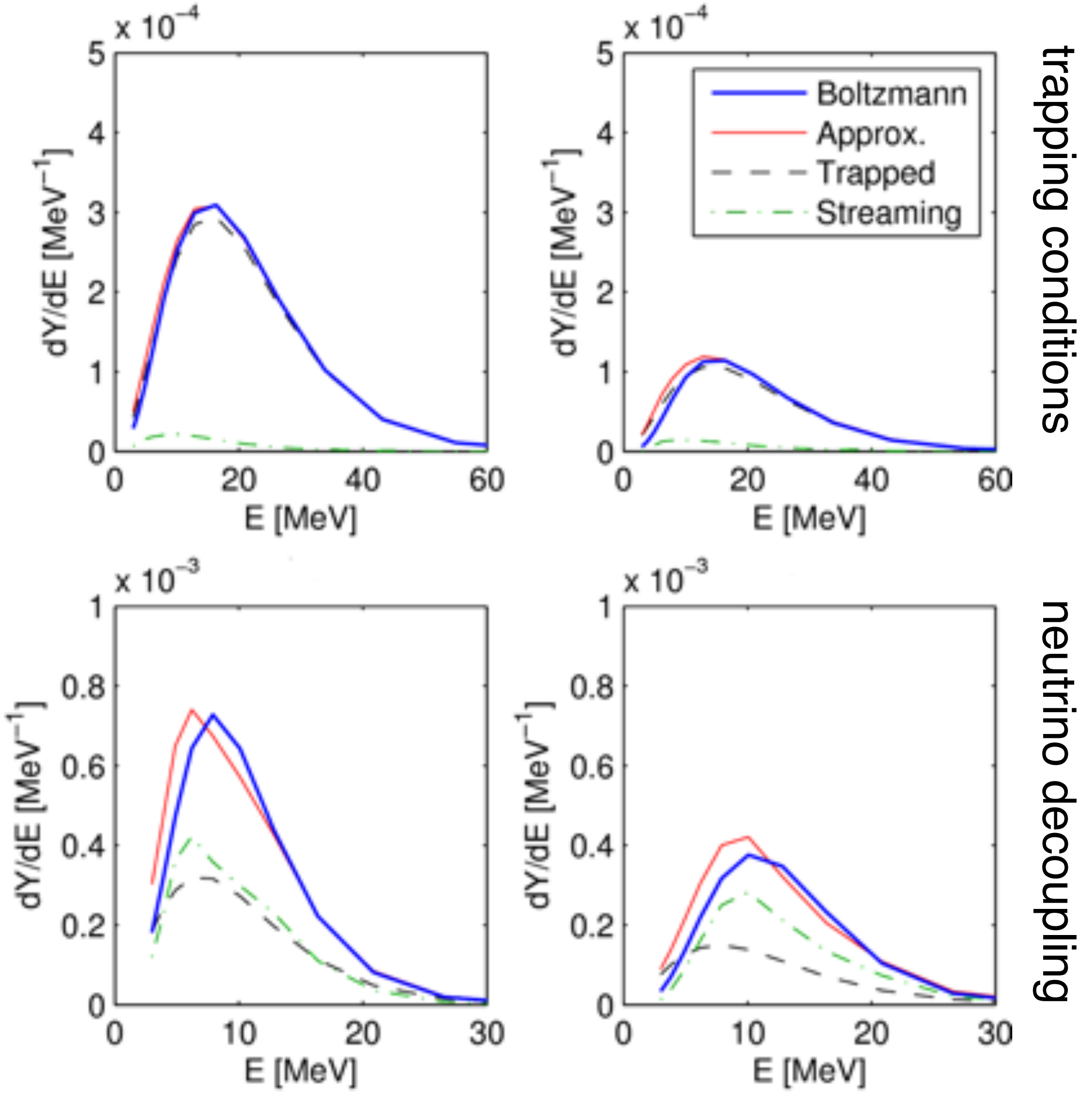


(S. Wanajo, et al. 2011)

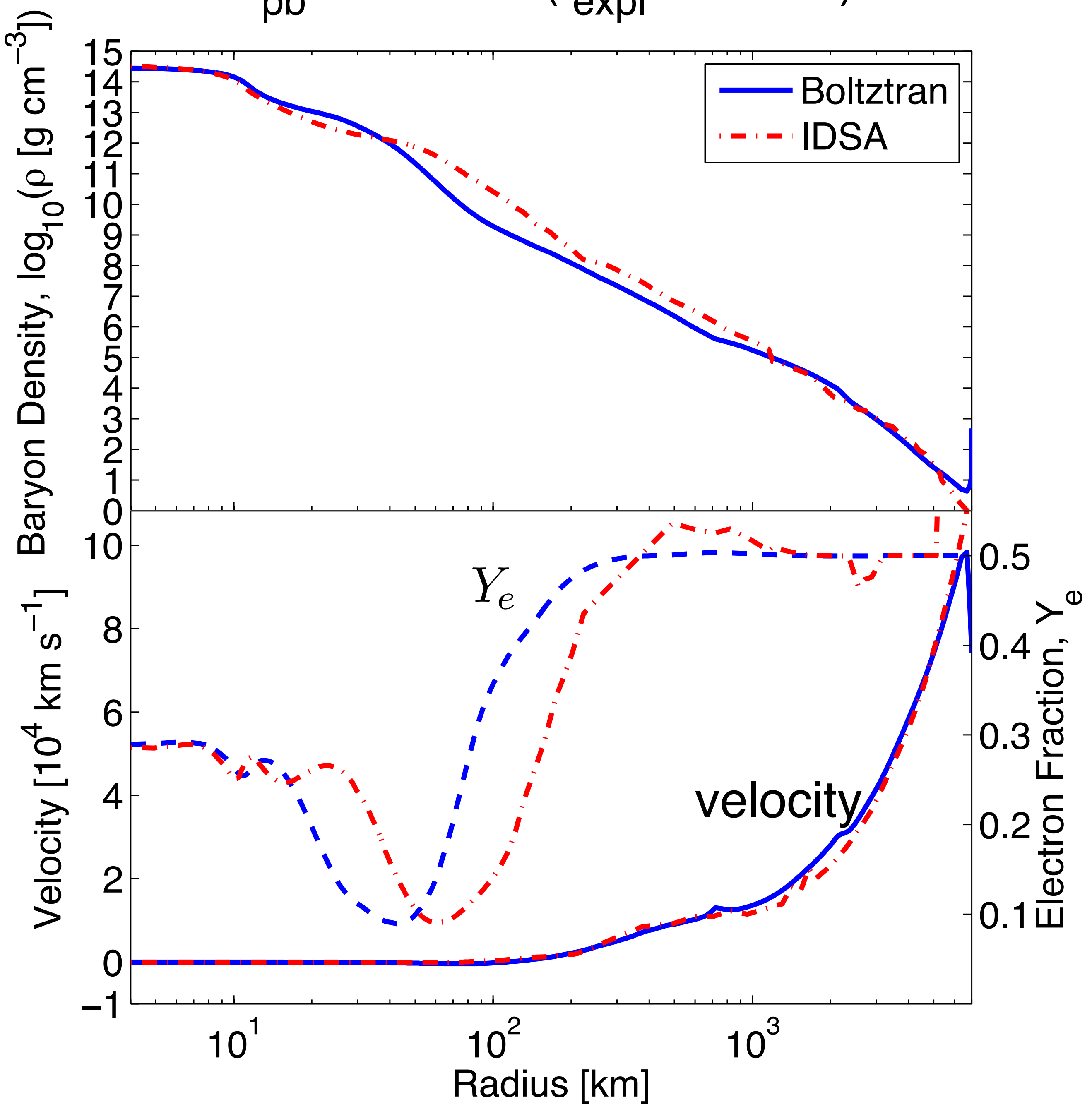


The IDSA in core-collapse supernova explosions

- Isotropic diffusion source approximation (IDSA)
- Separation of trapped and free-streaming neutrinos
- Heavy-lepton neutrinos included (Albino Perego)
- Has been compared with Boltzmann transport during accretion phase, prior to explosion onset



$t_{pb} = 114$ ms ($t_{expl} = 80$ ms)



- After onset of supernova explosion (?)
- Self-consistent explosions in 1D (ONeMg-core) – comparison with Boltzmann transport

(Master project Heiko Möller)

Long-term evolution of massive star explosions: neutrino-driven wind

–

Microphysics relevance for nucleosynthesis?

Classification of the supernova ejecta

- “**direct**” explosion ejecta

  outer layers of progenitor star

  ^{28}Si, ^{16}O, ^{12}C,...

- **neutrino-driven wind:**

  late/long-time (10–30 s) mass ejection due to *ν*-heating

  low-mass outflow (10^{-4} solar masses)

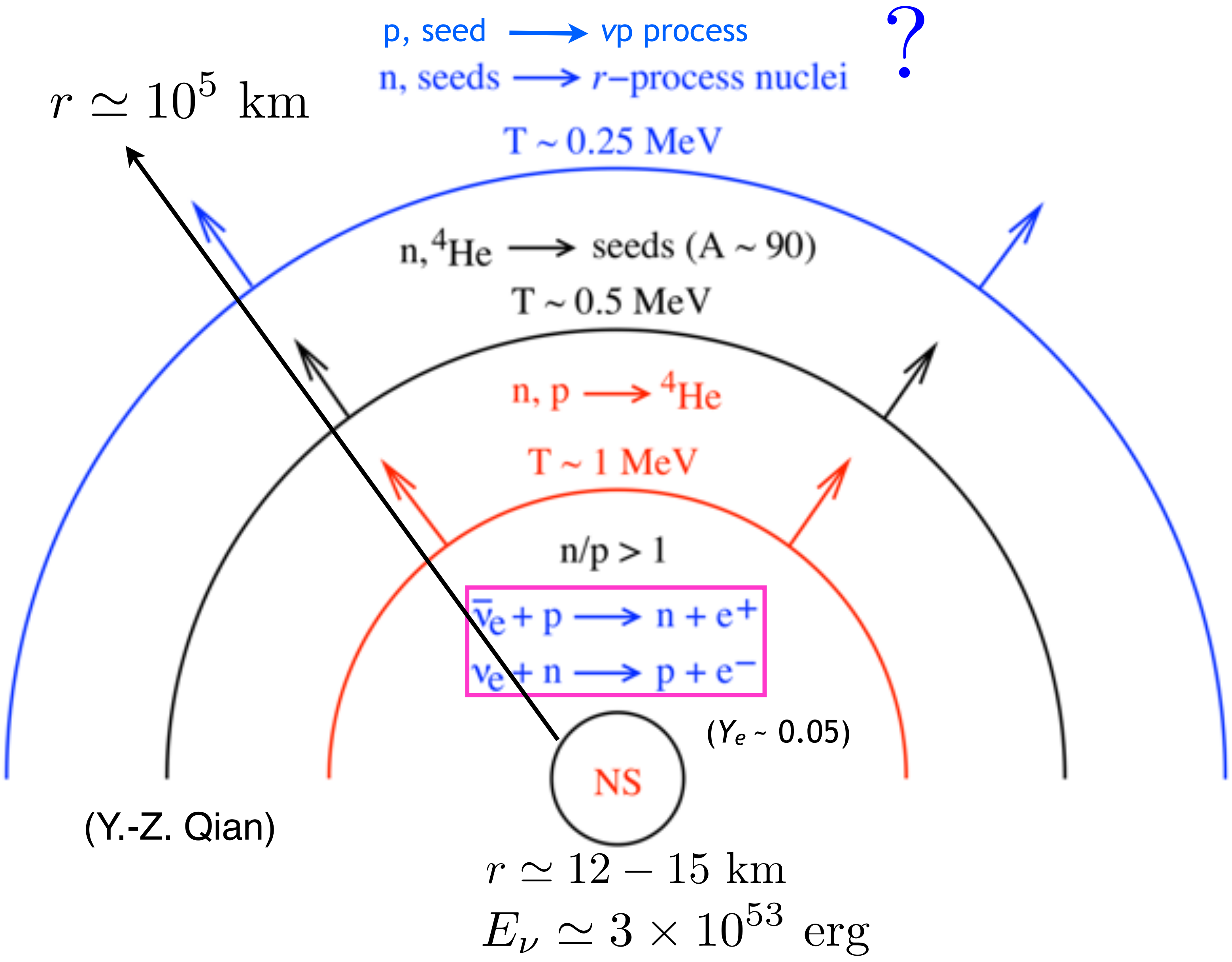
  ν–spectra determined at neutrino decoupling

  PNS deleptonizes

  matter stays neutron rich, if:

  $$\langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle > 4 \times (m_n - m_p)$$

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



<u>Note</u>: n/p depends sensitively on the neutrino spectra !

Neutrino-spectra evolution after explosion onset

Deleptonization phase:

- First simulations with three-flavor Boltzmann neutrino transport for ~10 s

  T. F., et al. (2010), A&A 517, A80

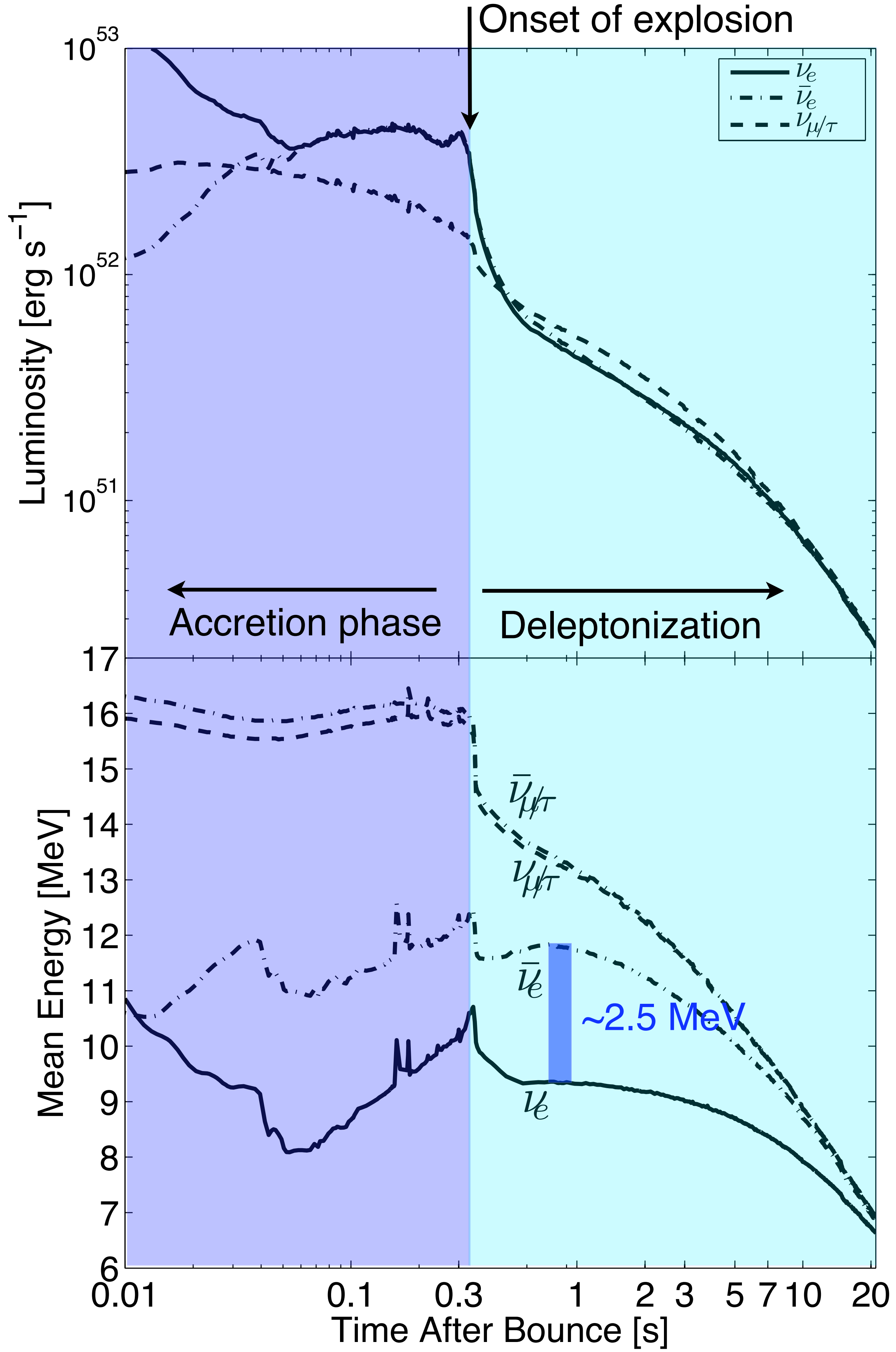
  Hüdepohl, et al. (2010), PRL 104, 251101

- *ν*-driven wind always develops, independent from explosion mechanism
- Continuous decrease of the neutrino fluxes and energies
- Neutrino spectra become similar

$$\langle\epsilon_{\bar{\nu}_e}\rangle - \langle\epsilon_{\nu_e}\rangle > 4 \times (m_n - m_p)$$

$$\longrightarrow Y_e < 0.5$$

- Current models generally proton-rich conditions ($Y_e \sim 0.65$)
- No *r* process in *ν*-driven ejecta (!)



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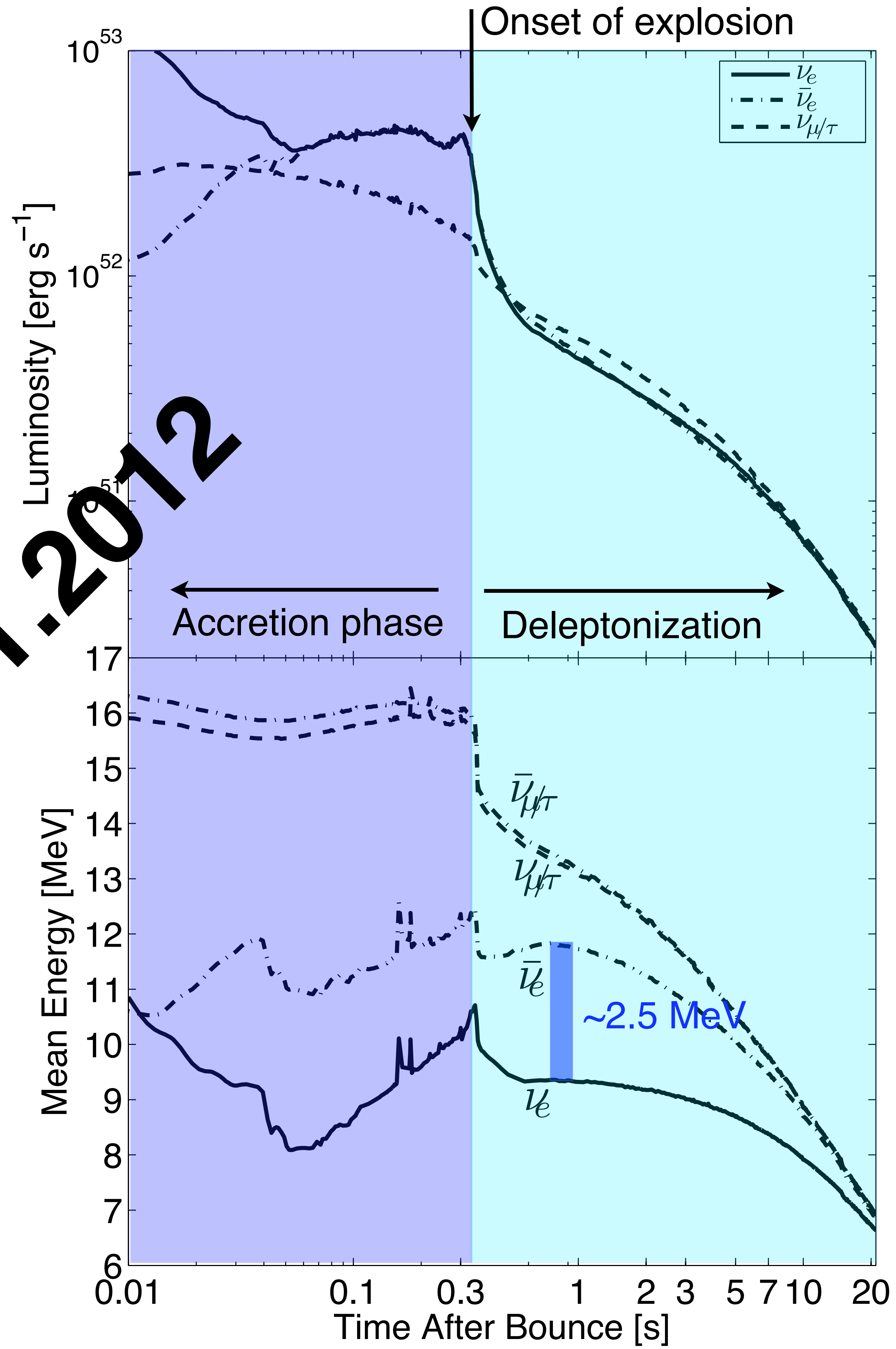


2012: Improved weak rates consistent with EOS

- Direct impact of nuclear EOS (symmetry energy) on neutrino-spectra formation

- Charged-current weak processes, based on free Fermi gas

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

$$\begin{aligned} 1/\lambda(E_{\nu_e}) &= \frac{G_F^2}{\pi}(g_V^2 + 3g_A^2) \cdot {E_e}^2[1 - f_e(E_e)] \times \\ &\times \frac{n_n - n_p}{1 - e^{\beta((\mu_p - U_p) - (\mu_n - U_n))}} \end{aligned}$$

(neutrino opacity/reaction rate,
zero-momentum transfer approximation)

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

(energy conservation)

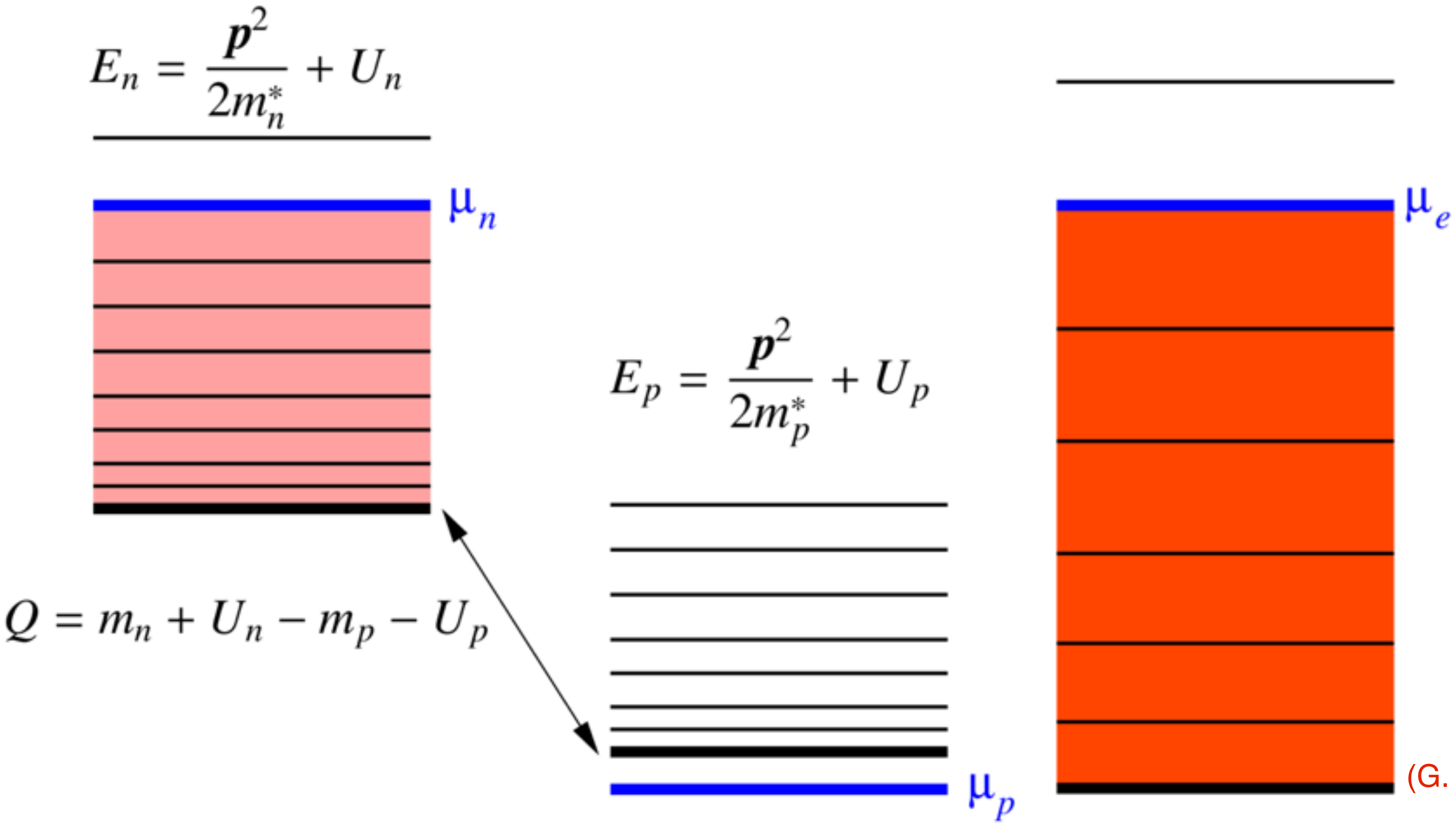
$$E_i(\vec{p}_i) = \frac{\vec{p}_i^{\,2}}{2m_i^*} + m_i + U_i, \quad (i = n, p)$$

Reddy et al., (1998) PRD 58, 013009

Energetics for charged-current reaction rates

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

Supernova EOS(T,n_B, Y_e): nucleons as quasi-free particles that move in a mean-field potential;



$$E_n = \frac{p^2}{2m_n^*} + U_n$$

$$E_p = \frac{p^2}{2m_p^*} + U_p$$

$$Q = m_n + U_n - m_p - U_p$$

(G. Martinez-Pinedo)

$$\boxed{E_{\nu_e} \gtrsim \mu_e - (m_n - m_p) - (U_n - U_p)}$$

$(\mu_e \simeq 50 - 100 \text{ MeV})$

$(U_n - U_p \simeq 10 - 50 \text{ MeV})$

Improved weak rates consistent with EOS

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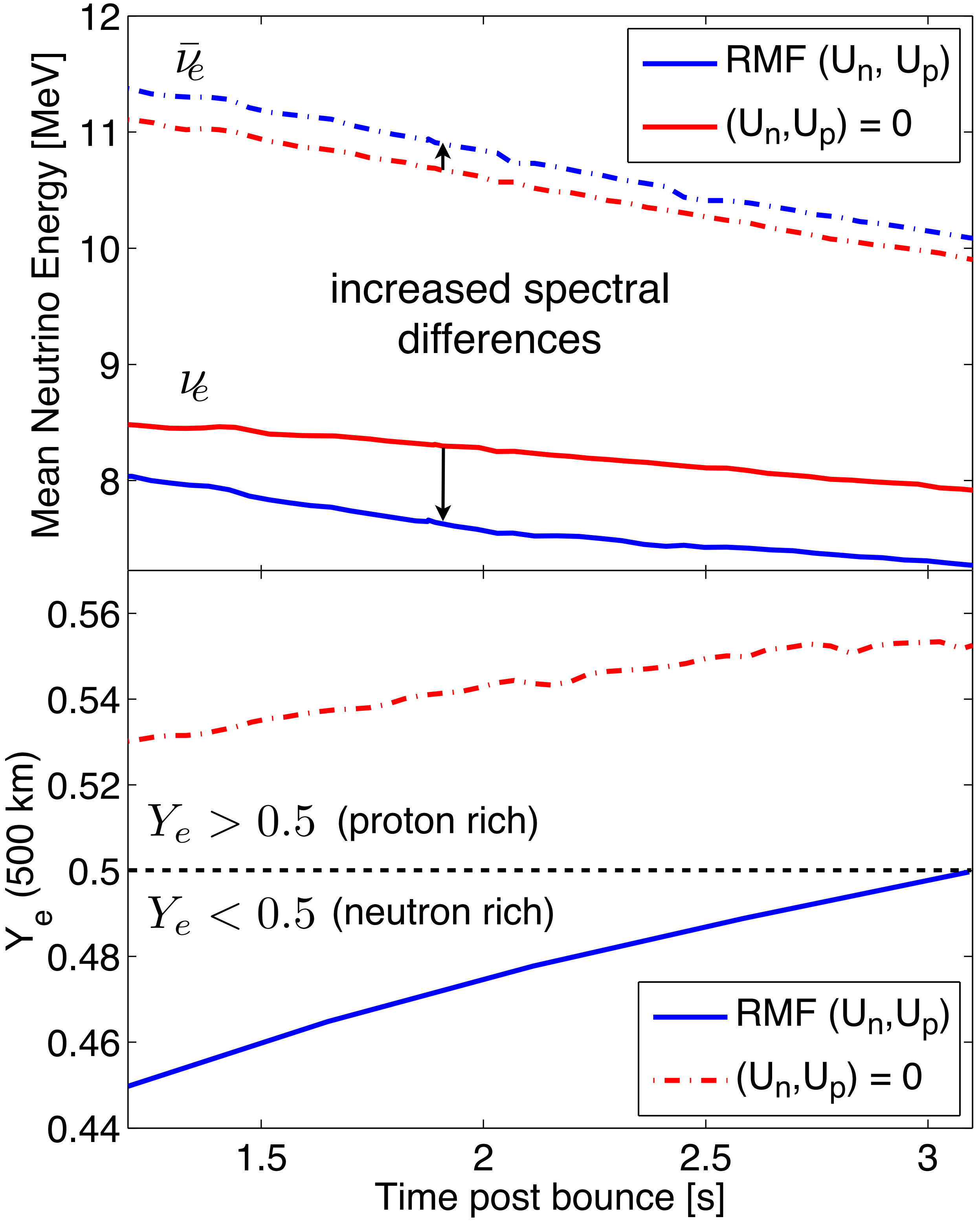
Reddy et al., (1998) PRD 58, 013009

Roberts et al., (2012) PRC 86, 065803

The early *ν*-driven wind phase



- Strong impact on nucleosynthesis of heavy elements, $Y_e = 0.45 - 0.49$ ($Y_e > 0.53 - 0.55$)

Martinez-Pinedo & T.F., et al. 2012, PRL,109, 251104

Improved weak rates consistent with EOS

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(neutrino opacity/reaction rate, zero-momentum transfer approximation)

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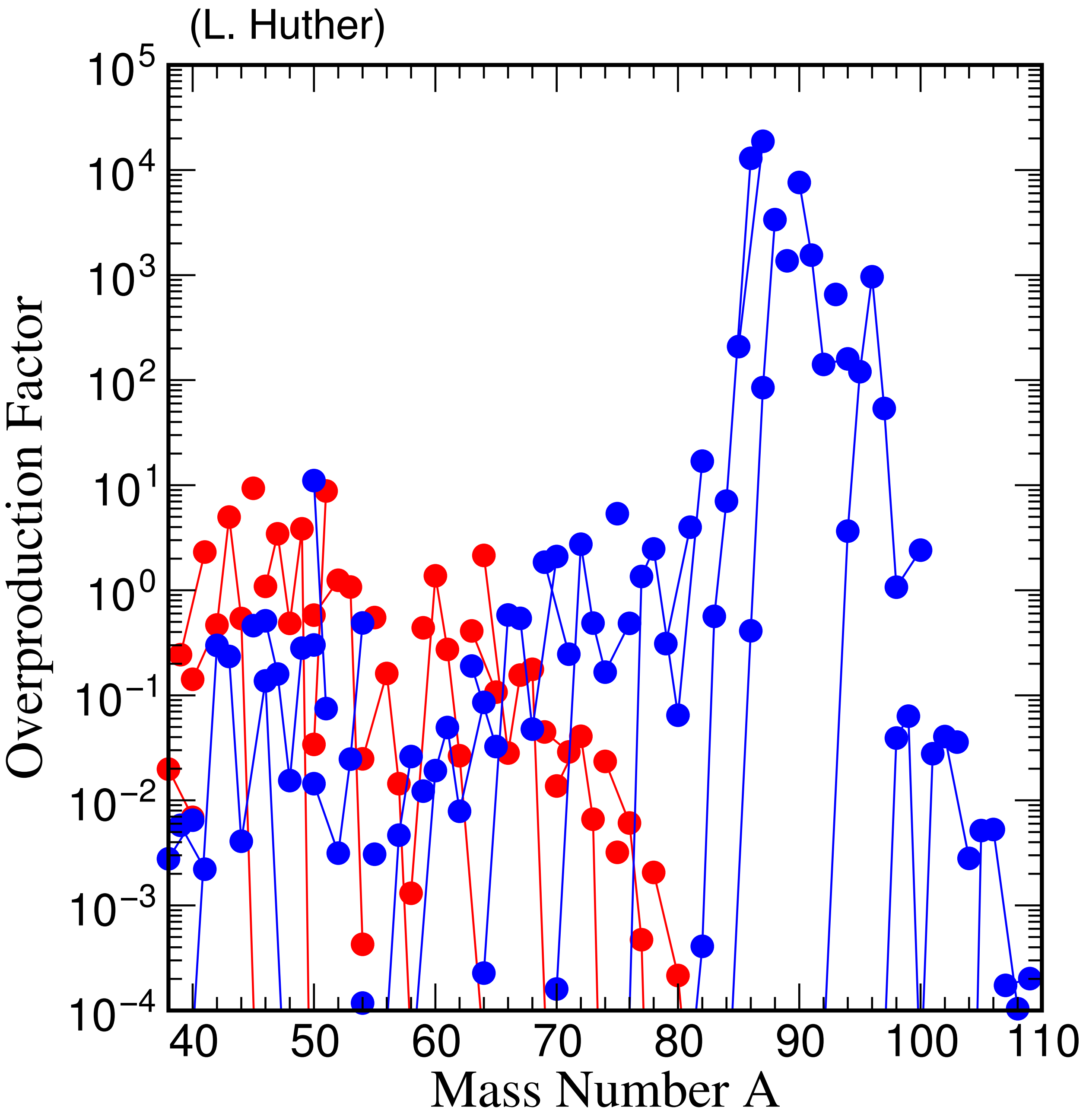

(L. Huther)

- **Weak *r*-process ?**

- Results depend on nuclear symmetry energy

- Strong impact on nucleosynthesis of heavy elements, $Y_e = 0.45 - 0.49$ ($Y_e > 0.53 - 0.55$)

Summary and Outlook

- largest uncertainties in supernova studies:

  progenitor models (rotation, magn. fields,...)

  nuclear physics (weak rates, composition, high-density EOS,...)

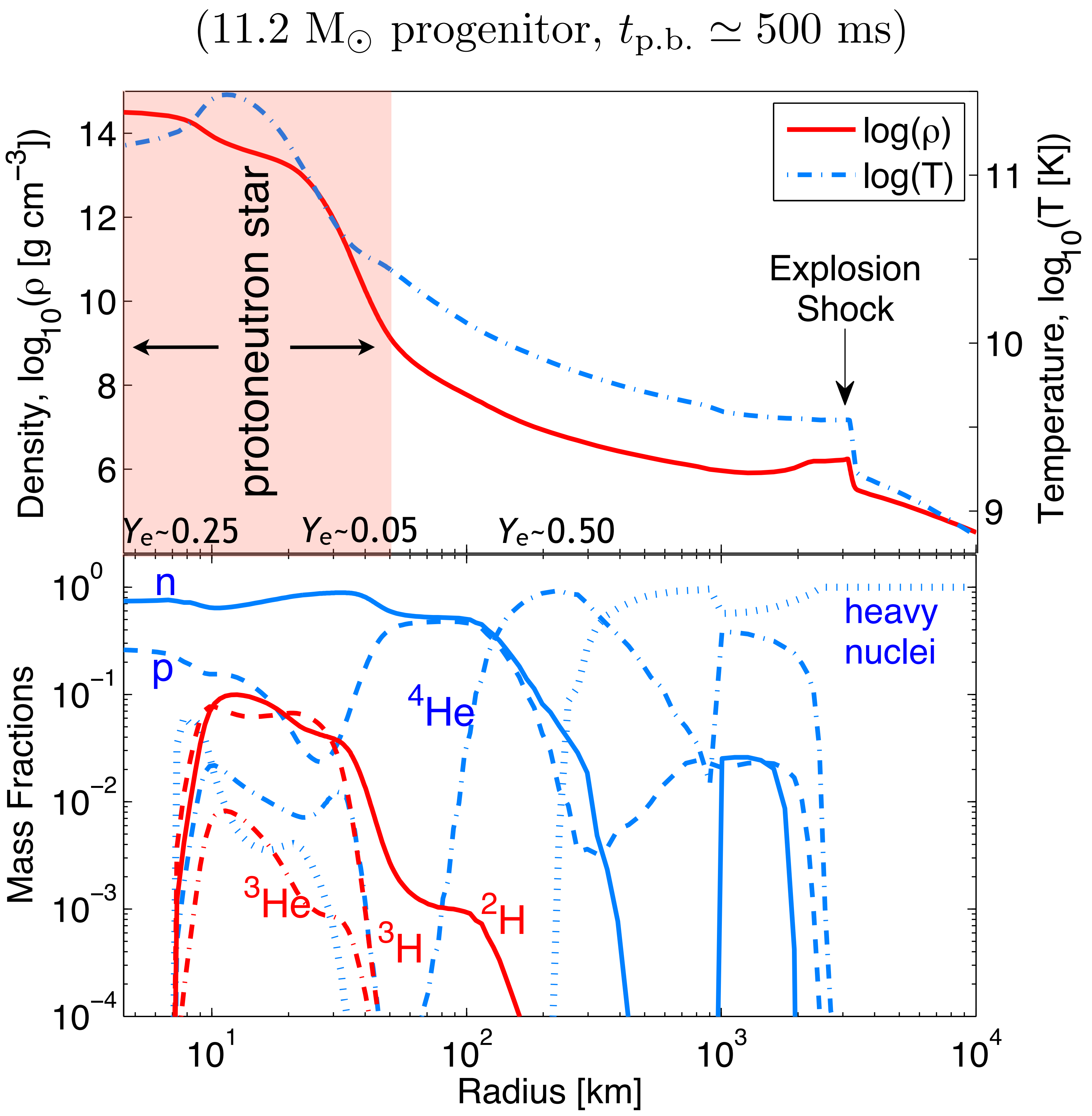
- systematic understanding of nuclear matter properties and their impact in core-collapse supernova simulations
- neutrino luminosities and spectra; relation to observables
- nucleosynthesis...recover the *r*-process (?)
- nuclear clustering and correlations beyond mean field

Light clusters (^2H, ^3H, ^3He) in supernova explosions

Sumiyoshi & Röpke, (2008), PRC 77

Arcones, et al. (2008), PRC 78

Hempel & TF, et al. (2012), ApJ 748, 70



- Light nuclei appear around 0.01 x n_0
- Corresponds to PNS surface
- Modified NSE applied (Hempel & Schaffner-Bielich 2010, NPA837, 210)
- ^2H and ^3H become as abundant as protons
- Relevance for *ν*-cooling?
- Requires weak processes with light nuclei !

Weak processes with light clusters (^2H)

Construct inverse mean-free path/opacity (# of ν_e – absorptions per second)

$$1/\lambda(E_{\nu_e}) = \frac{g}{h^3}\int_0^\infty p_d^2 dp_d \int_{-1}^{+1} d(\cos\theta_{de}) \int_0^{2\pi} d\varphi\, f_d(E(p_d)) \int_0^{E_{\nu_e}} dE_e \int_{-1}^{+1} d(\cos\theta_{\nu_e e}) \frac{d\sigma_{\nu_e d}}{dE_e\, d(\cos\theta_{\nu_e e})}$$

$$\times \int d(\cos\theta_{\nu_e p_1}) d(\cos\theta_{\nu_e p_2})(1-f_e(E_e))(1-f_{p_1}(E_{p_1}))(1-f_{p_2}(E_{p_2}))$$

Nakamura et al., (2001) PRC 61, 034617

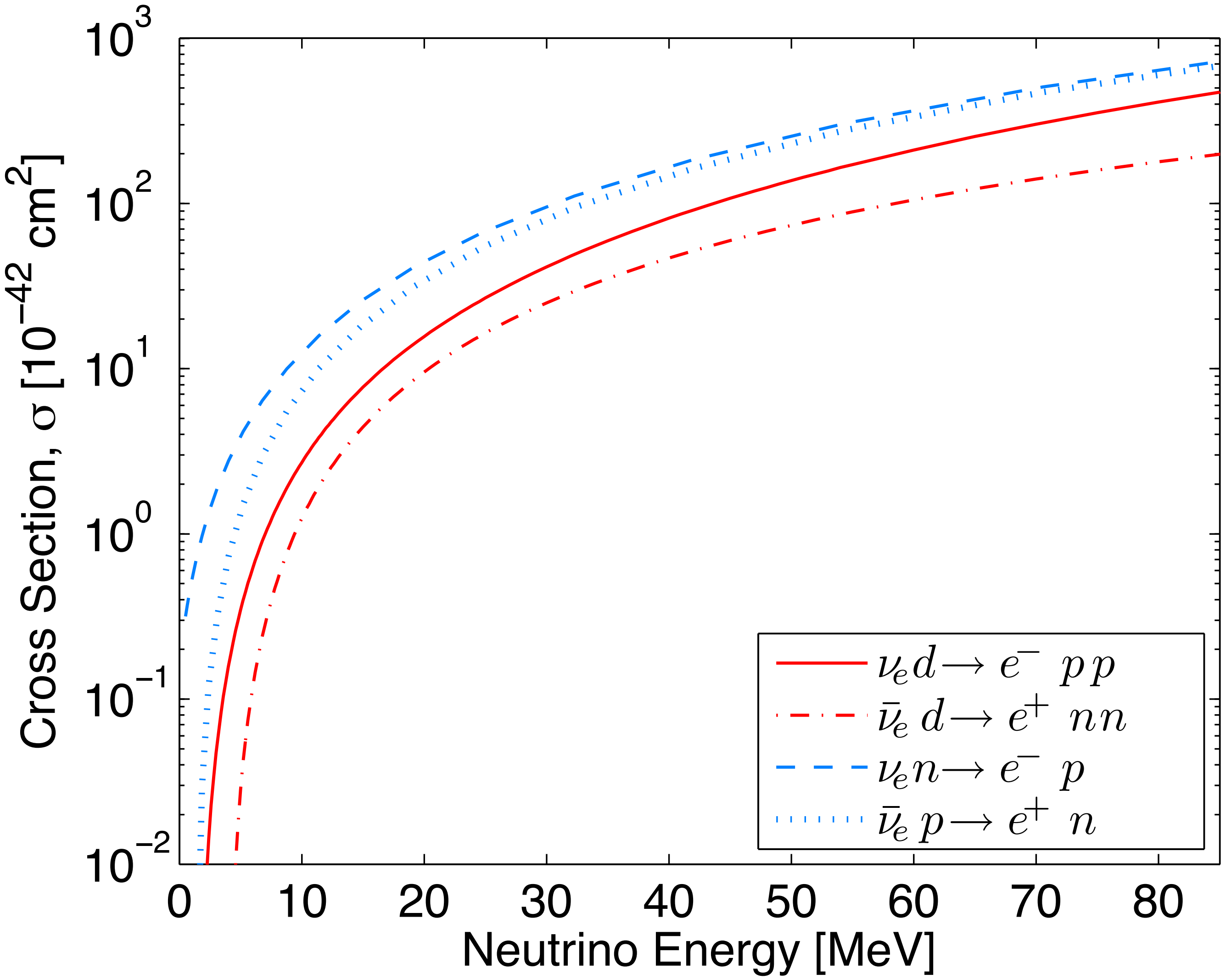
$$\cos\theta_{de} = \cos\theta_{d\nu_e}\cos\theta_{\nu_e e} + \sqrt{(1-\cos^2\theta_{d\nu_e})(1-\cos^2\theta_{\nu_e e})}\cos\varphi$$

$$\varphi = \varphi_{d\nu_e} - \varphi_{\nu_e e}$$

$$\nu_e + d \rightleftarrows e^- + p + p$$

$$\bar\nu_e + d \rightleftarrows e^+ + n + n$$

$$\nu + d \rightleftarrows \nu' + d + n$$



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

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

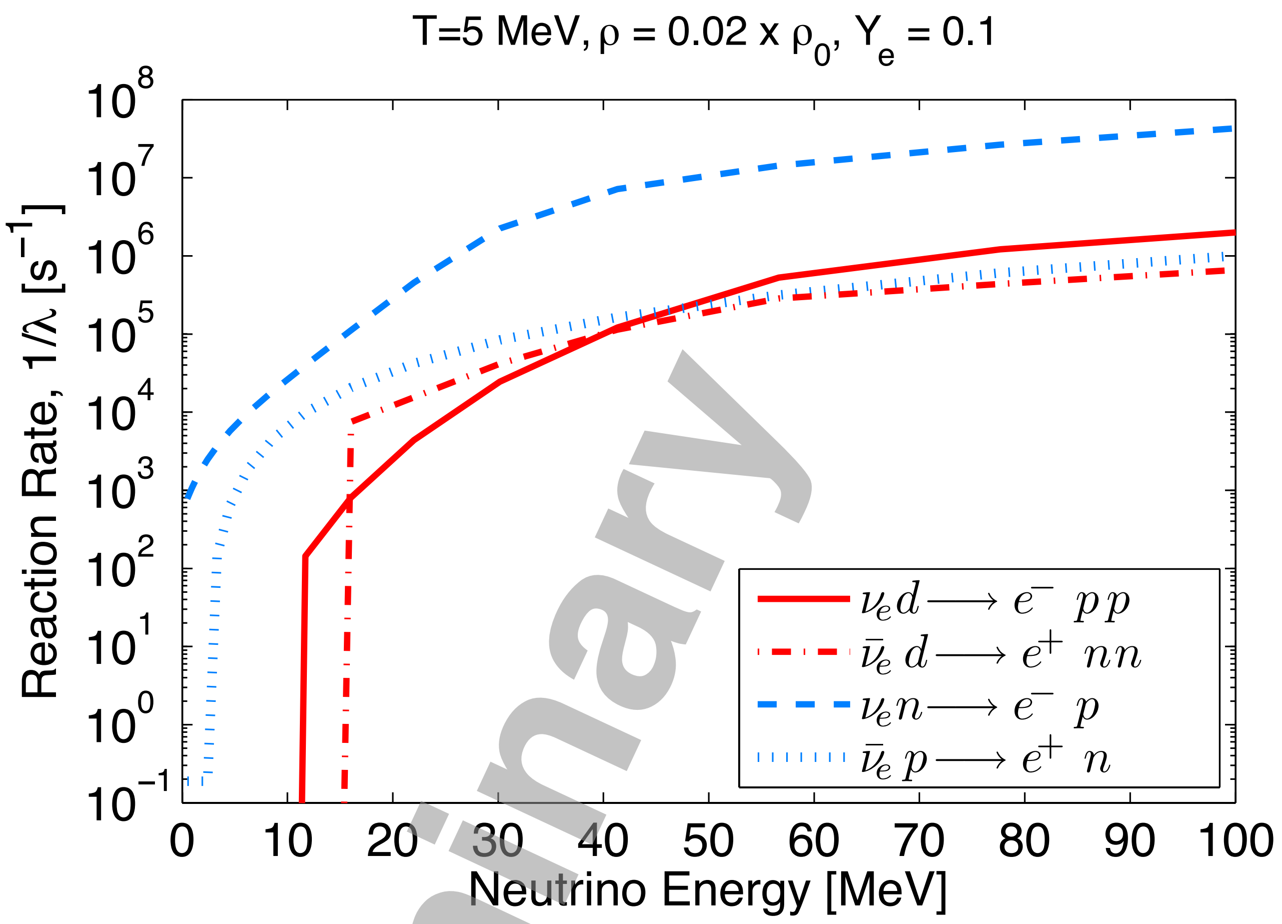
$$\bar\nu_e + p \rightleftarrows e^+ + n$$

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2}{\pi}(g_V^2 + 3g_A^2)\int \frac{d^3p_e}{(2\pi)^3}(1-f_e(E_e))$$

$$\int \frac{d^3p_n}{(2\pi)^3}\frac{d^3p_p}{(2\pi)^3} f_n(E_n)(1-f_p(E_p))$$

$$1/\lambda(E_{\nu_e}) = \sigma_{\nu_e n}\,\eta_{np}(1-f_e(E_e))$$

$$\sigma_{\nu_e n} = \frac{G_F^2}{\pi}\left(g_V^2 + 3\,g_A^2\right)\,E_e^2$$


T=5 MeV, $\rho = 0.02 \times \rho_0$, $Y_e = 0.1$

Composition:

$$x_n = 0.790, \quad x_p = 0.022, \quad x_d = 0.052, \quad x_t = 0.089$$

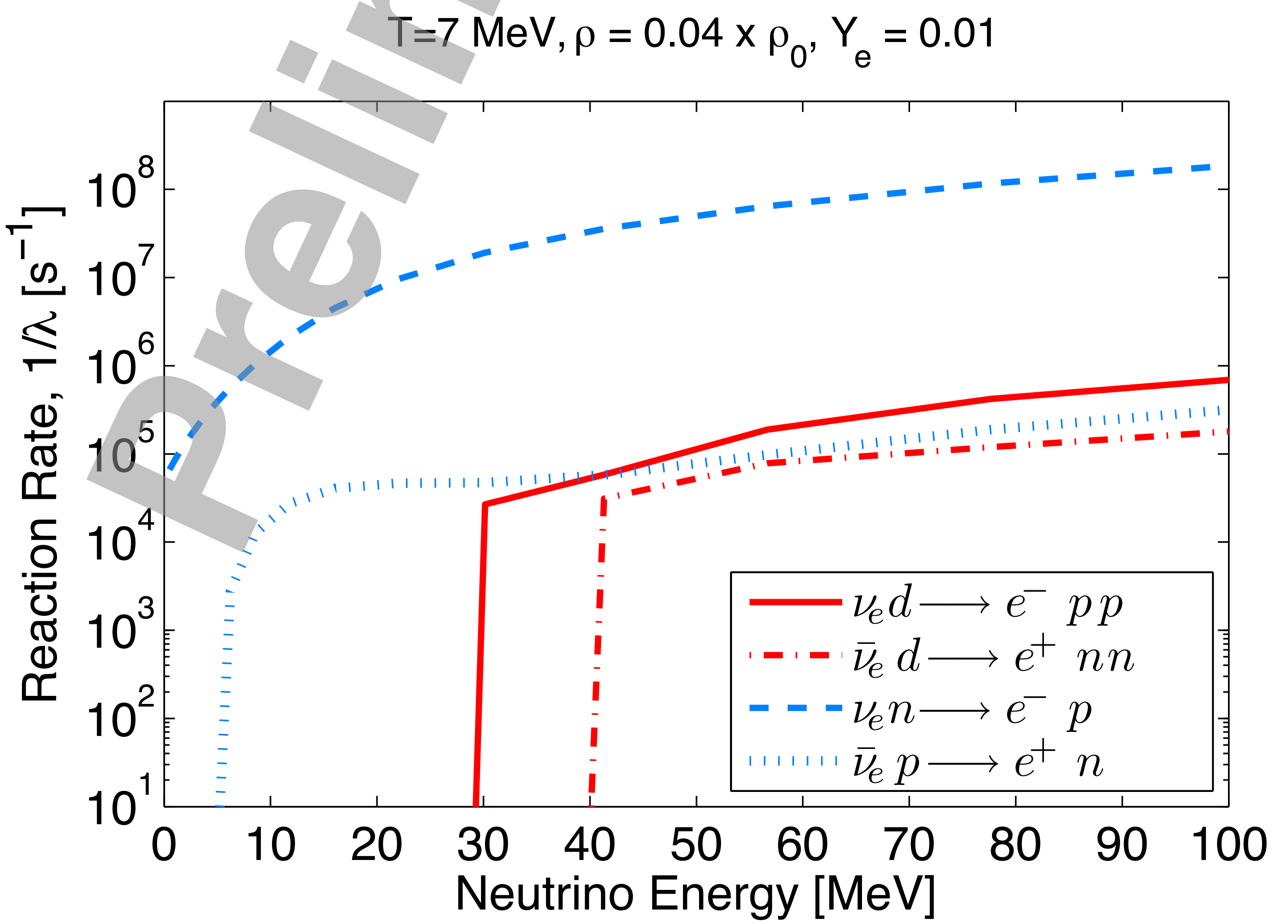
$$U_n = 3.33 \text{ MeV}$$

$$U_n = 2.52 \text{ MeV}$$

$$U_d = -3.42 \text{ MeV}$$

Note: modifications to the vacuum Q-value

$$\boxed{\begin{array}{lcl} \nu_e & : & Q_{\nu_e d} + (2\,U_p - U_d) \\ \bar{\nu}_e & : & Q_{\bar{\nu}_e d} + (2\,U_n - U_d) \end{array}}$$


T=7 MeV, $\rho = 0.04 \times \rho_0$, $Y_e = 0.01$

$$x_n = 0.978, \quad x_p = 0.025, \quad x_d = 0.054, \quad x_t = 0.136$$

$$U_n = 13.46 \text{ MeV}$$

$$U_n = 10.16 \text{ MeV}$$

$$U_d = -2.85 \text{ MeV}$$

Apply these rates with ^2H in supernova simulations . . .

Thanks for your attention