Nucleon interaction potentials in core-collapse supernovae and impact on neutrino-driven winds

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Outline:

1.) introduction

2.) potentials

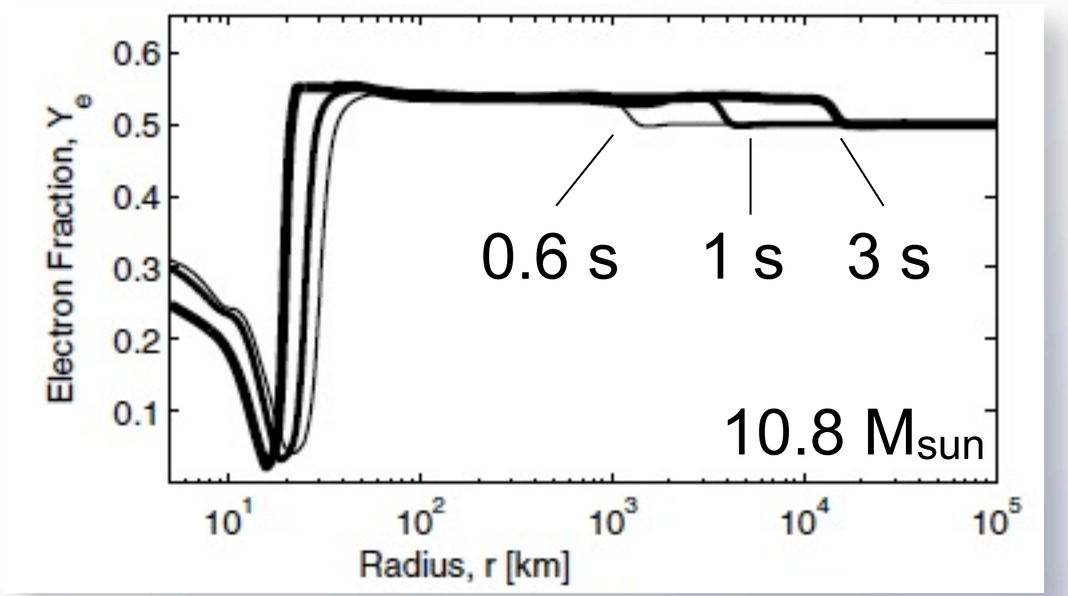
3.) supernova-simulations

Nucleosynthesis conditions in neutrino-driven winds

- neutrino-driven wind: emission of low-density, high-entropy matter from proto-neutron star surface due to energy deposition by neutrinos
- candidate site for r-process nucleosynthesis

- previous long-term core-collapse supernova simulations by Fischer et al (2010), Hüdepohl et al. (2010): the neutrino-driven wind is generally proton rich

[Fischer et al. A&A 517 (2010)]



- allows only νp-process (C. Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006, Arcones et al. 2011, Arcones & Thielemann 2012, ...)

Estimate for Y_e

- Qian & Woosley, ApJ 471 (1996):

$$Y_e \simeq \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle \epsilon_{\bar{\nu}_e} \rangle - 2Q + \frac{1.2\, Q^2}{\langle \epsilon_{\bar{\nu}_e} \rangle}}{\langle \epsilon_{\nu_e} \rangle + 2Q + \frac{1.2\, Q^2}{\langle \epsilon_{\nu_e} \rangle}}\right)^{-1}$$

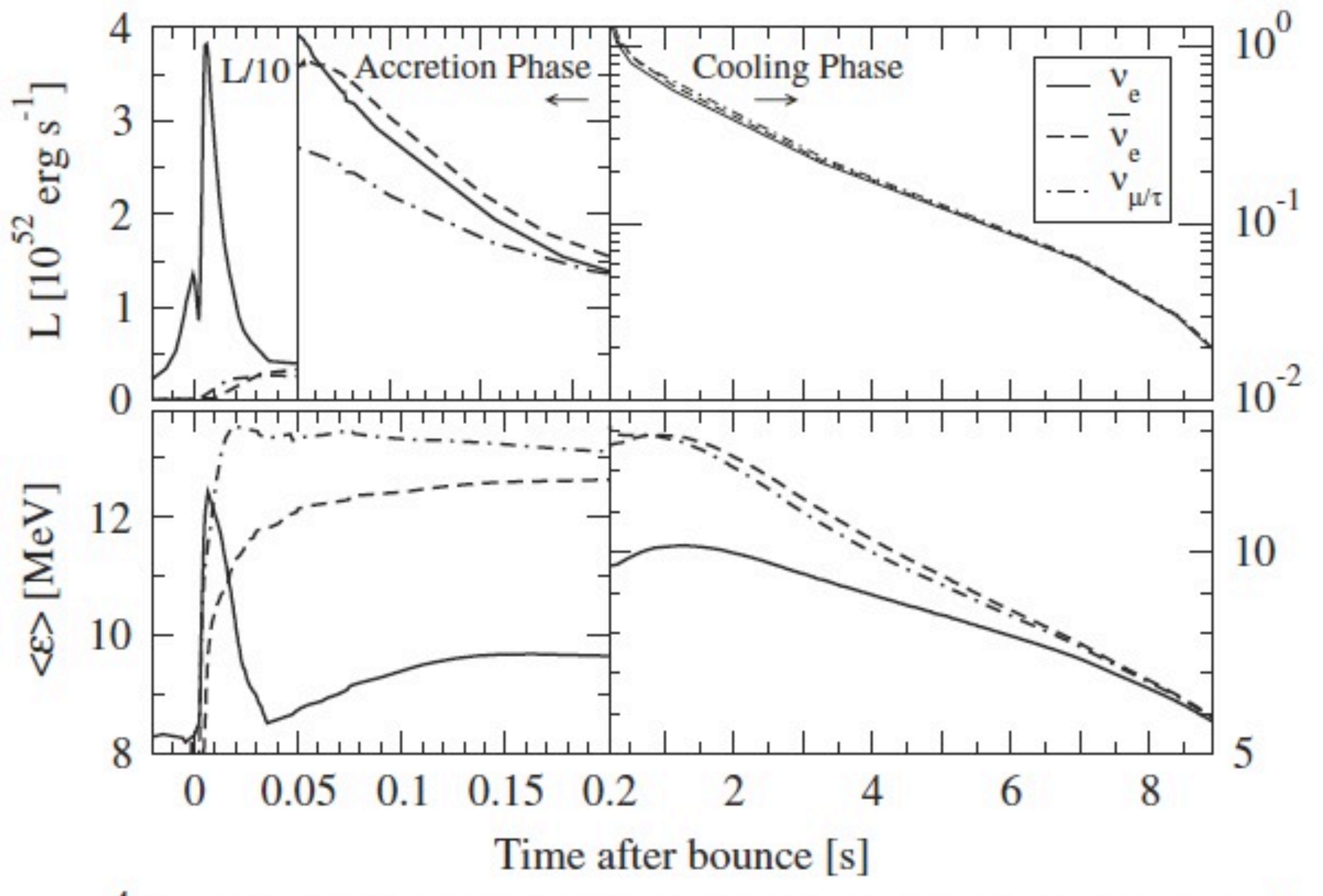
- $Q = m_n - m_p = 1.3$ MeV
- neglects neutrino emission, i.e. electron and positron captures

- for similar luminosities:

$$Y_e < 0.5 \Leftrightarrow E_{\bar{\nu}e} - E_{\nu e} > 4Q$$

Neutrino properties in the “standard“ wind

[Hüdepohl et al. PRL 104 (2010)]



- similar luminosities
- $E_{\nu_{\mu/\tau}} \sim E_{\bar{\nu}_e} > E_{\nu_e}$
- $E_{\bar{\nu}_e} - E_{\nu_e} < 4Q \rightarrow Y_e > 0.5$

Mean-field potentials in charged-current rates

- Bruenn `85: charged-current rates based on non-interacting nucleons
- improved charged-current rates (with mean-field effects):
  - Reddy, Prakash & Lattimer, PRD58 (1998)
  - Reddy, Prakash, Lattimer & Pons, PRC59 (1999)
- G. Martínez-Pinedo et al., PRL109 (2012), Roberts & Reddy, PRC86 (2012): crucial for late neutrino spectra

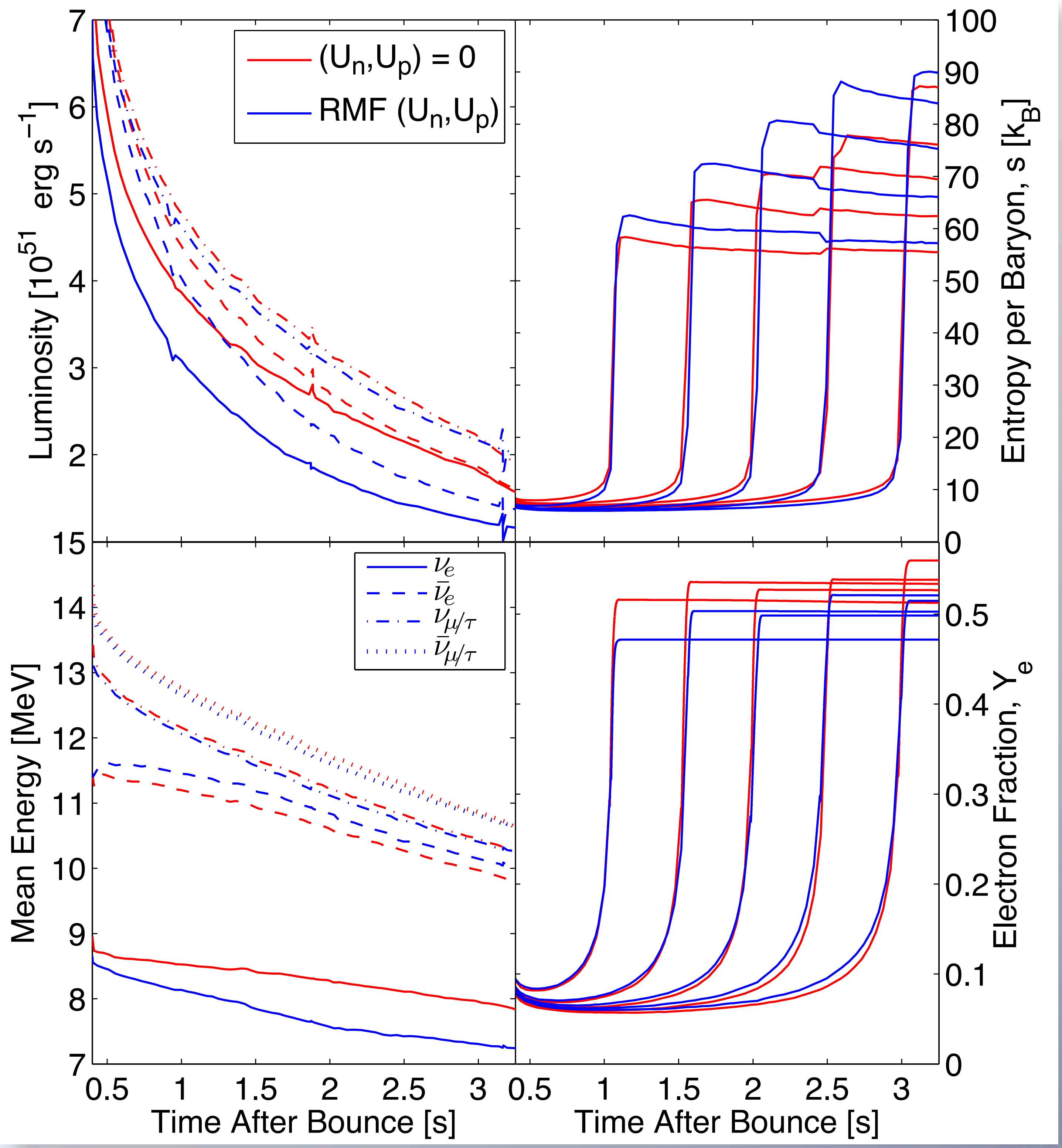
- e.g.: $e + p \rightarrow n + \nu_e$
- energy conservation for a generic mean-field model:

$$\begin{aligned} E_p + E_e &= E_n + E_{\nu_e} \\ \sqrt{p_p^2 + {m_p^*}^2} + U_p + \sqrt{p_e^2 + m_e^2} &= \sqrt{p_n^2 + {m_n^*}^2} + U_n + E_{\nu_e} \end{aligned}$$

- neutron-rich conditions: $\Delta U = U_n - U_p > 0 \rightarrow$ reduces neutrino energies

Effects of mean-field potentials on the neutrino-driven wind

[Martínez-Pinedo et al., PRL109 (2012)]



- $E_{\nu e}$ decrease, $E_{\bar{\nu} e}$ increased, difference increased
- luminosities decreased
- mean-field effects can lead to neutron-richness of the wind
- same conclusions by Roberts et al. 2012

Definition of mean-field potentials

- defined by the application! here: charged-current rates
- general expression for cross section per unit volume of neutrino absorption, e.g. Reddy et al., PRD58 (1998):

$$\frac{\sigma(E_1)}{V} = 2\int \frac{d^3p_2}{(2\pi)^3}\int \frac{d^3p_3}{(2\pi)^3}\int \frac{d^3p_4}{(2\pi)^3} \times (2\pi)^4\delta^4(P_1+P_2-P_3-P_4)\, W_{fi} \times f_2(E_2)(1-f_3(E_3))(1-f_4(E_4))$$

- note: uniform system!
- aim: reconstruct the nucleon distribution functions and single particle energies of the interacting system

→ consistency of the potentials and the used weak interaction rates

Definition of mean-field potentials - uniform nucleon gas

- any momentum-independent relativistic mean-field model can be formulated as

$$P(T,\mu) = P^{\rm kin} + P^{\rm int} = \frac{2}{3}\int \frac{{\rm d}^3k}{(2\pi)^3}\frac{k^2}{(m^{*2}+k^2)^{1/2}} f(k) + P^{\rm int}$$

$$n(T,\mu) = 2\int \frac{{\rm d}^3k}{(2\pi)^3} f(k)$$

$$f = \left[\exp\left(\frac{\sqrt{m^{*2}+k^2}+U-\mu}{T}\right)+1\right]^{-1}$$

$U=\Sigma_V$, vector self-energy Σ_V
$m^*=m+\Sigma_S$, scalar self-energy Σ_S

- thermodynamic consistency relation:

$$n\frac{\partial U}{\partial n} = \frac{\partial P^{\rm int}}{\partial n}$$

→ U(n,T) and m*(n,T) contain all information of the system

- note:

$$\mu - U = \nu = \mu^{\rm free}(T,n,m^*)$$
$$\Rightarrow U = \mu - \mu^{\rm free}(T,n,m^*)$$

Potentials from the virial EOS

[C.J. Horowitz et al., PRC86 (2012)]

- second order nucleonic virial expansion

$$P = \frac{2T}{\lambda^3}\{z_n + z_p + (z_n^2 + z_p^2)b_n + 2z_p z_n b_{pn}\}$$

- without explicit deuteron degree of freedom, but contribution of deuteron bound state to the second virial coefficient:

$$b_{pn}(T) \approx -0.9885 + 2.502 \exp\left(\frac{2.099}{T}\right) - 0.0179T$$

- “increased ΔU in virial EOS compared to mean-field models“

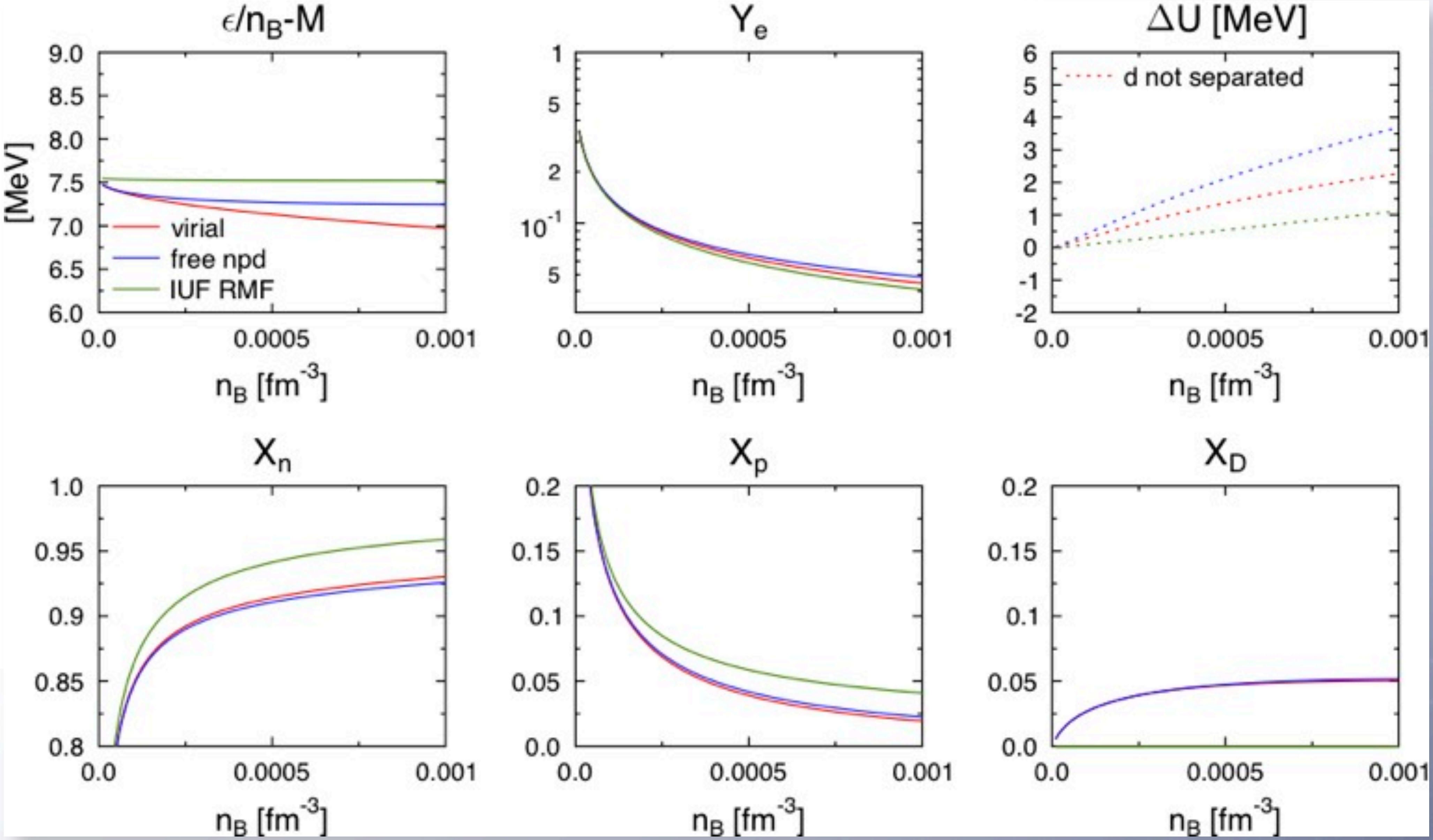
  → used definition of ΔU is not suitable for nucleon charged-current rates

TABLE I. Energy shift ΔU predicted by different approaches at a density $n = 0.001$ fm^{-3} and a temperature $T = 5$ MeV.

Model	ΔU (MeV)
Lowest order virial, Eq. (21)	3.85
Virial $\mu_i - \mu_i^f$, Eq. (31)	2.27
Mean-field model GM3, Eq. (36)	0.23
Mean-field model IUFSU [15]	1.11

Potentials from the virial EOS

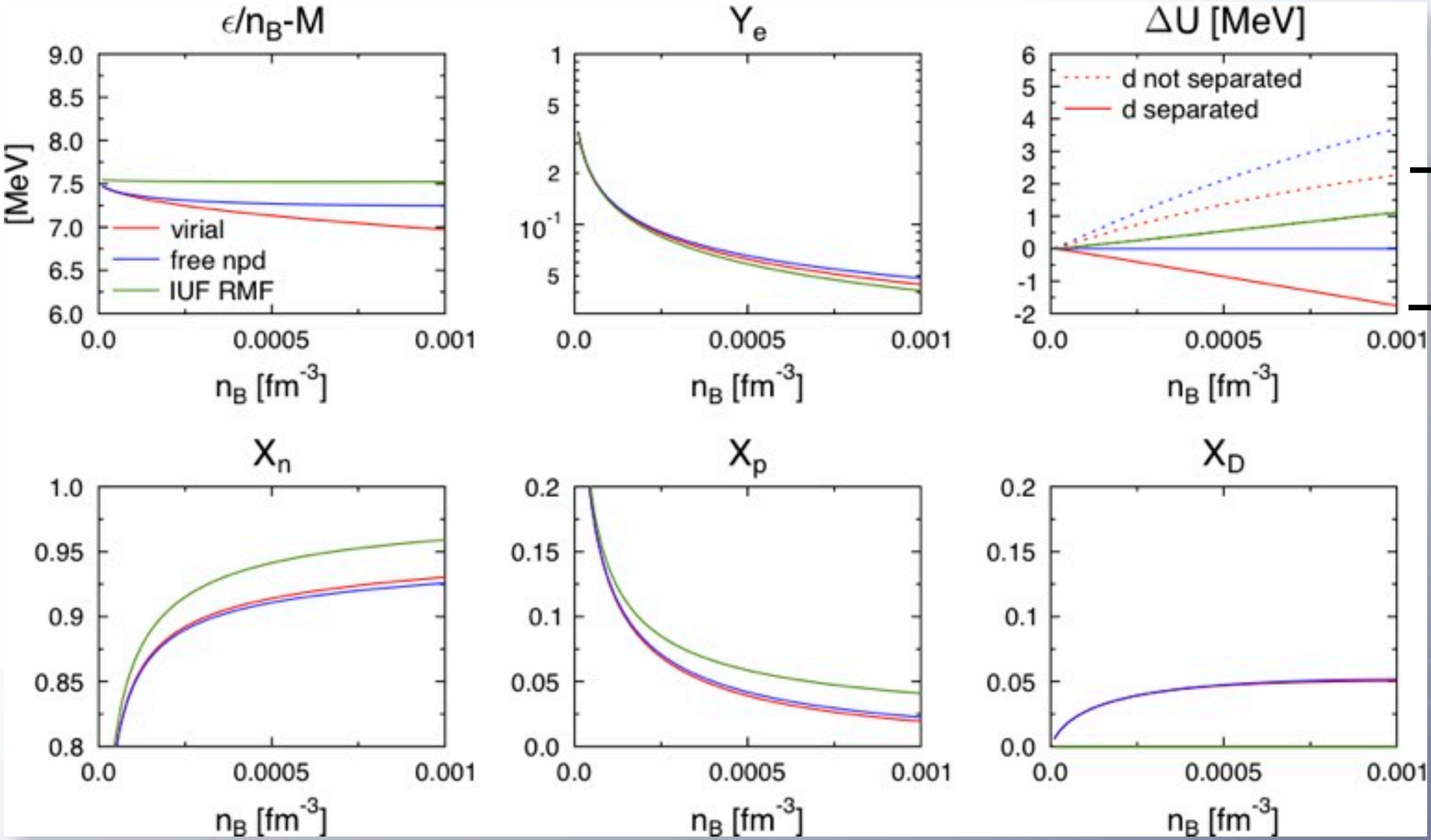
- definition used: $$U_p = \mu_p - \mu^{\mathrm{free}}(T, n_p^{\mathrm{tot}})$$
- beta-equilibrium, T=5 MeV



Potentials from the virial EOS

- separating deuteron contribution: $U_p = \mu_p - \mu^{\text{free}}(T, n_p)$

  $n_p = n_p^{\text{tot}} - n_D = X_p n_B$
- beta-equilibrium, T=5 MeV



deuteron contribution

→ each bound state has its own effective potential and these have to be separated from nucleons

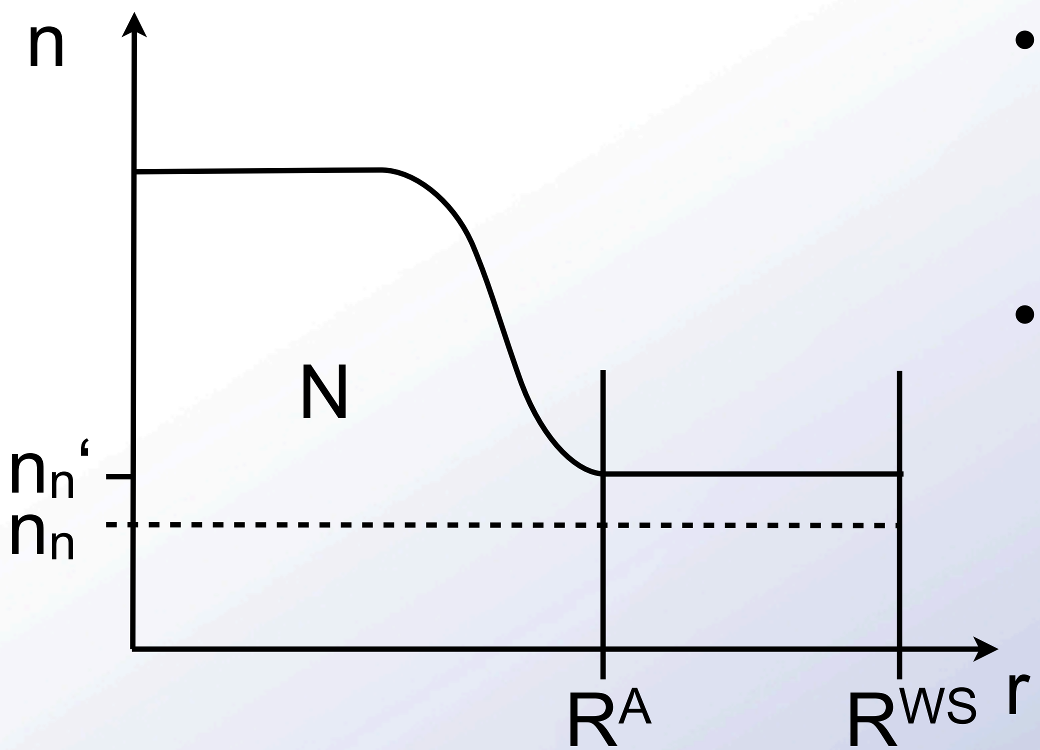
Potentials from SN EOS

- mixture of heavy and light nuclei, unbound nucleons → non-uniform system
- what one should do: calculate the full neutrino response (with mean-field, correlations, nuclear structure, light clusters, etc) of the system as a whole
- done in practice:
  - separate rates for nucleons, light nuclei, heavy nuclei
  - unbound nucleon component treated as uniform

Potentials from (tabulated) SN EOS

- typical tabulated quantities:
  - mass fractions: X_n, X_p, (X_d), (X_h), X_α, $X_{heavies}$, ...
  - thermodynamic quantities: μ_n, μ_p, s, ...
  - possibly some microscopic properties: m*
- naive guess:

$$U_i = \mu_i - \mu_i^{\rm free}(T, n_i, m_i^*),\ n_i = X_i n_B / A_i$$



- but: X_i is an average quantity of the WS cell, the heavy nucleus is defined as a coordinate space cluster (→ F. Gulminelli)
- one should use

$$U_i = \mu_i - \mu_i^{\rm free}(T, n_i', m_i^*),\ n_i' = ?$$

→ available EOS tables allow only an approximated calculation of ΔU

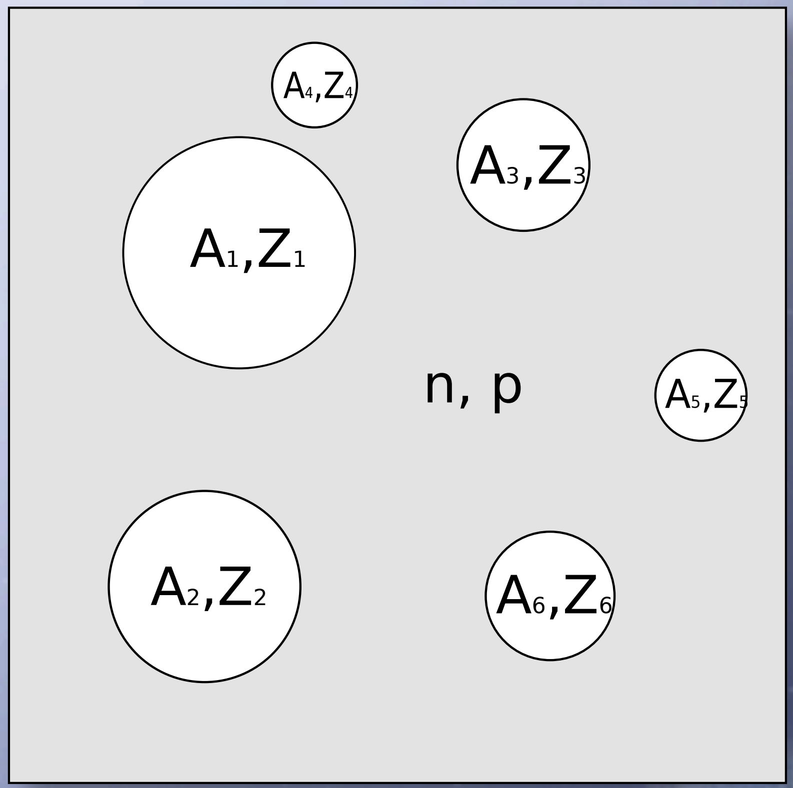
HS EOS: excluded volume NSE with interactions

[MH, J. Schaffner-Bieleich; NPA837(2010)] [A. Steiner, MH, T. Fischer; arXiv1207.2184]

- eight EOS tables for different interactions available:
  NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx, IUFSU
  http://phys-merger.physik.unibas.ch/~hempel/eos.html

- relativistic mean-field interactions and excluded volume effects
- uniform distribution of nucleons outside nuclei

→ allows consistent description of the EOS and neutrino interactions



Potentials from the HS EOS

simple nucleon gas

$$P = \frac{2}{3}\int \frac{\mathrm{d}^3k}{(2\pi)^3}\frac{k^2}{(m^{*2}+k^2)^{1/2}}f(k) + P^{\mathrm{int}}$$

$$f = \left[\exp\left(\frac{\sqrt{m^{*2}+k^2}+U-\mu}{T}\right)+1\right]^{-1}$$

- excluded volume effects can be recast as effective mean-field interactions
- total pressure

$$P = \sum_{i=n,p}\frac{2}{3}\int\frac{d^3k}{(2\pi)^3}\frac{k^2}{(m_i^{*2}+k^2)^{1/2}}f_i + \sum_{A,Z}\frac{g_{A,Z}}{3}\int\frac{d^3k}{(2\pi)^3}\frac{k^2}{m_{A,Z}}f_{A,Z} + P^{\mathrm{fields}} + P^{\mathrm{Coul}}$$

- nucleons:

$$f_i = \frac{1}{1+\exp[(E_i-\mu_i)/T]} \quad E_i = \sqrt{k^2+m_i^{*2}} + U_i$$

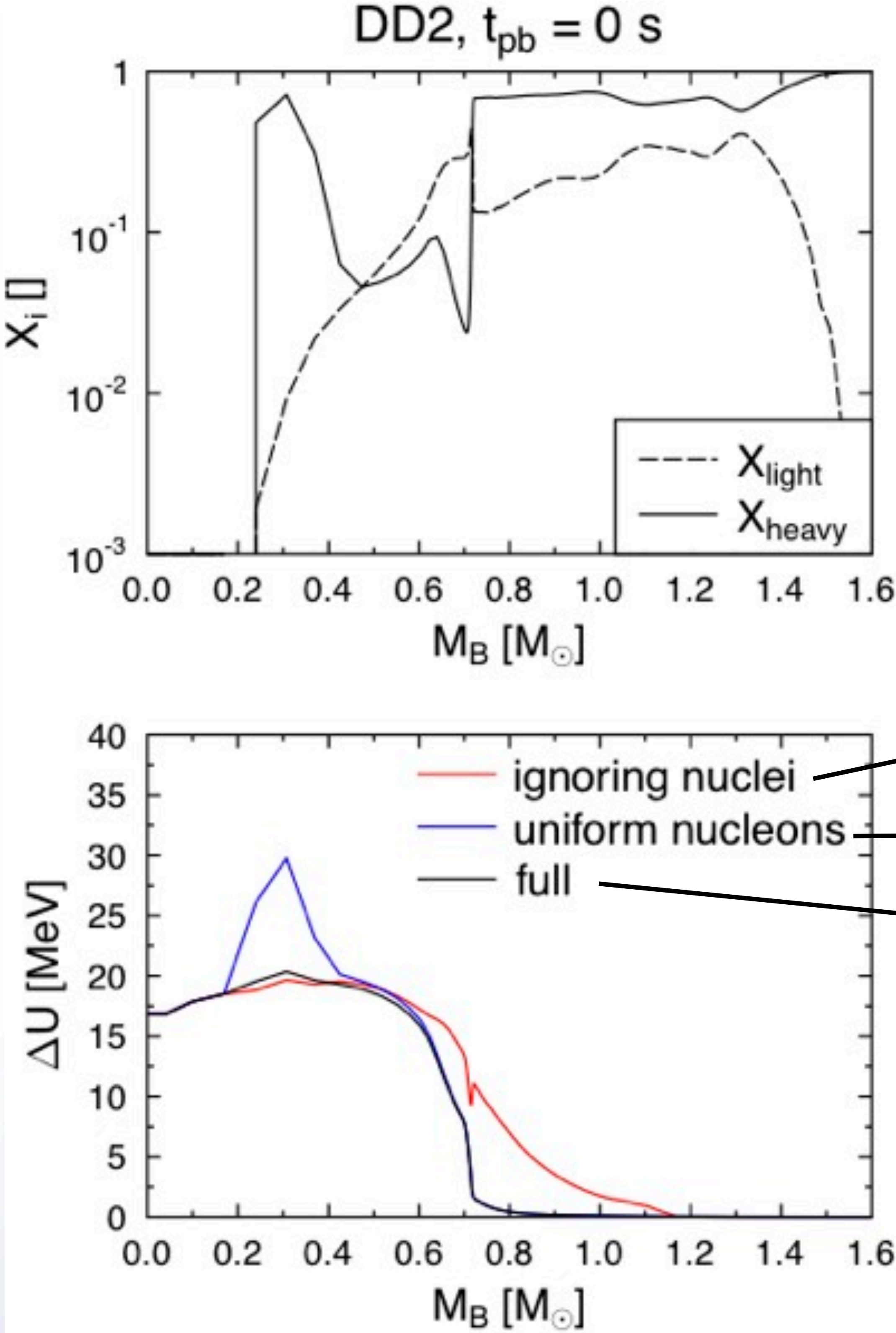
$$U_{n/p} = g_\omega\omega(T,n'_n,n'_p) + (2Z-1)g_\rho\rho(T,n'_n,n'_p) + \frac{1}{\kappa}\sum_{A,Z}p^0_{A,Z}/n^0_B + Zp^{\mathrm{Coul}}/n_e$$

- nuclei:

$$f_{A,Z} = \frac{1}{\exp[(E_{A,Z}-\mu_{A,Z})/T]} \quad E_{A,Z} = M_{A,Z} + \frac{k^2}{2M_{A,Z}} + U_{A,Z}$$

$$U_{A,Z} = \left(p^0_{nuc} + \frac{1}{\kappa}\sum_{A,Z}p^0_{A,Z}\right)A/n^0_B + E^{Coul}_{A,Z} + Zp^{\mathrm{Coul}}/n_e$$

ΔU in a core-collapse supernova



- core-collapse supernova simulation (details later)
- DD2 EOS

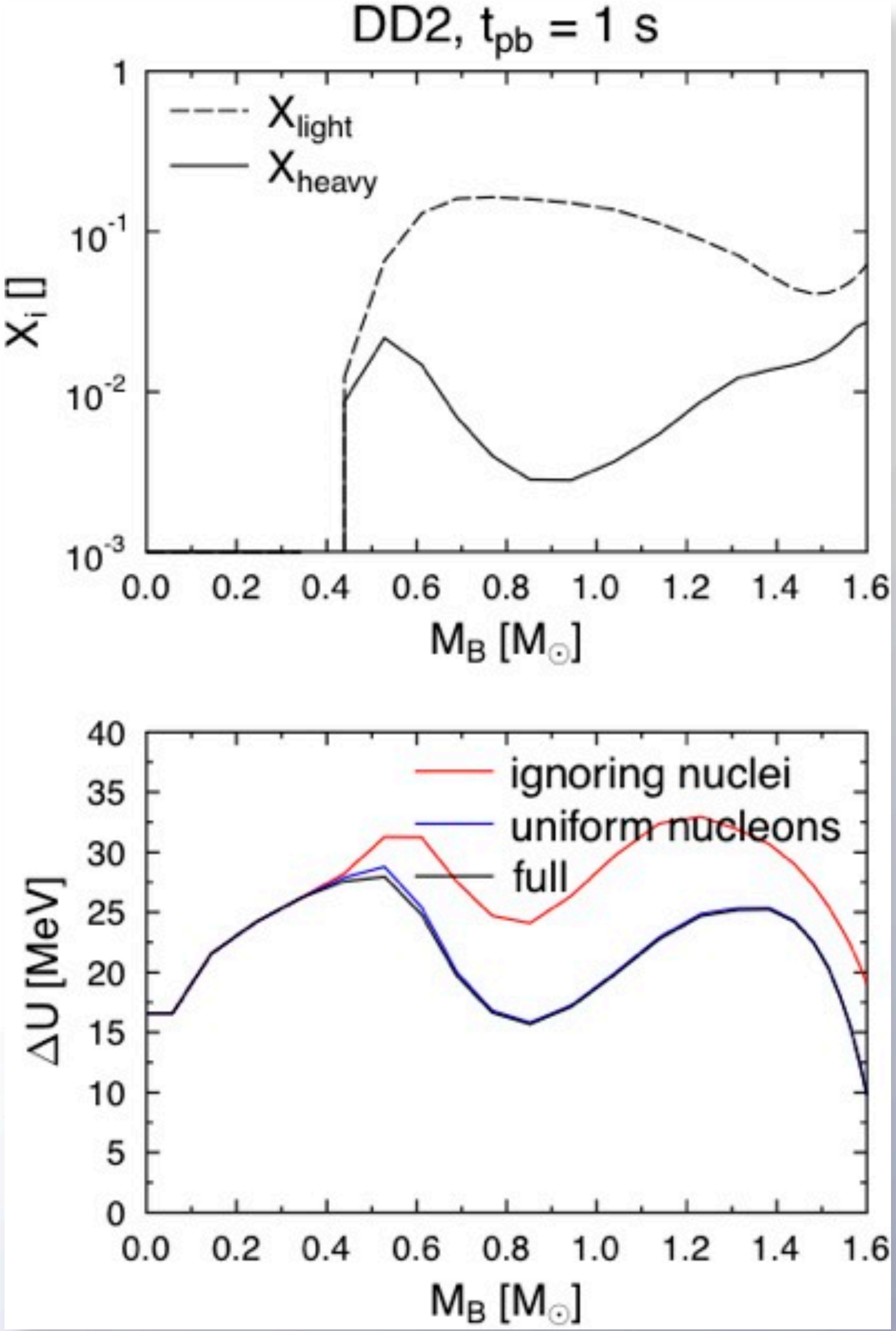
$$U_p = \mu_p - \mu_p^{\rm free}(T, n_p^{\rm tot}, m^*),\ n_p^{\rm tot} = Y_e n_B$$

$$U_p = \mu_p - \mu_p^{\rm free}(T, n_p, m^*),\ n_p = X_p n_B$$

$$U_p = \mu_p - \mu_p^{\rm free}(T, n_p', m^*),\ n_p' \text{ local density}$$

- nuclei lead to differences
- “full“ gives smoother ΔU

ΔU in a core-collapse supernova



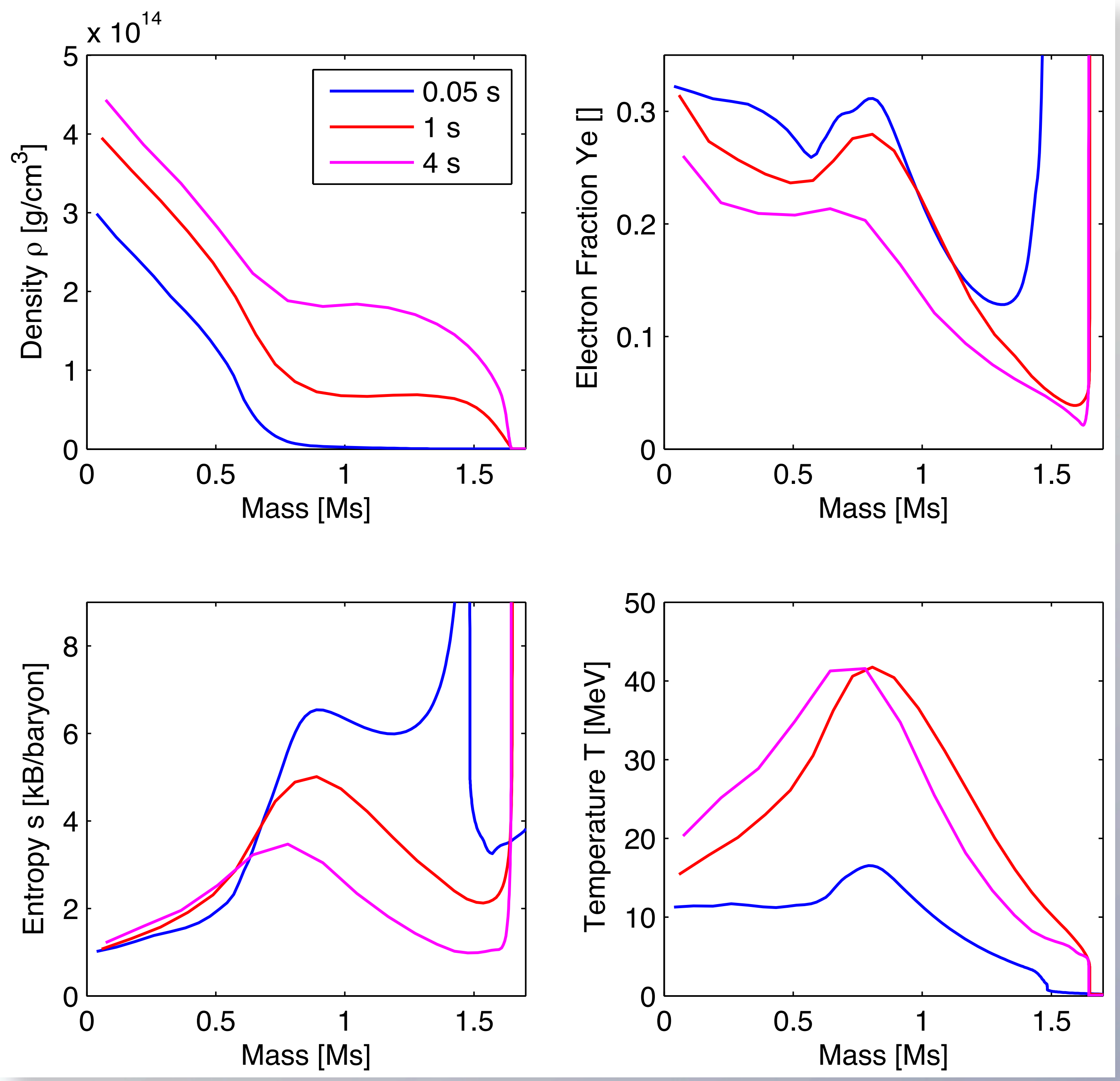
- light nuclei remain abundant in the PNS envelope
- they should be treated separately from unbound nucleons

Simulation setup

- hydrodynamics: AGILE
- e-flavor neutrinos: IDSA (M. Liebendörfer)
- μ/τ neutrinos: Advanced Spectral Leakage (ASL) (A. Perego)
- new PUSH to trigger explosions (A. Perego)
  - total energy emitted in μ/τ neutrinos ~ 5×10^{52} erg, only little reabsorption
  - PUSH: artificially induced explosion via enhanced μ/τ absorption
  - energy deposition parameterized by $k_{push}=1.3$
- simplified alpha-network (K. Ebinger, MH)
  - 25 symmetric and asymmetric nuclei
  - nuclear reactions estimated by burning timescales (Fowler et al. (1975))
  - advection based on Plewa & Müller (1999)
- detailed non-NSE EOS (MH)

- 15 M_{sun} solar metallicity progenitor, Woosley, Heger & Weaver (2002)
- HS(TM1) EOS (similar to Shen)

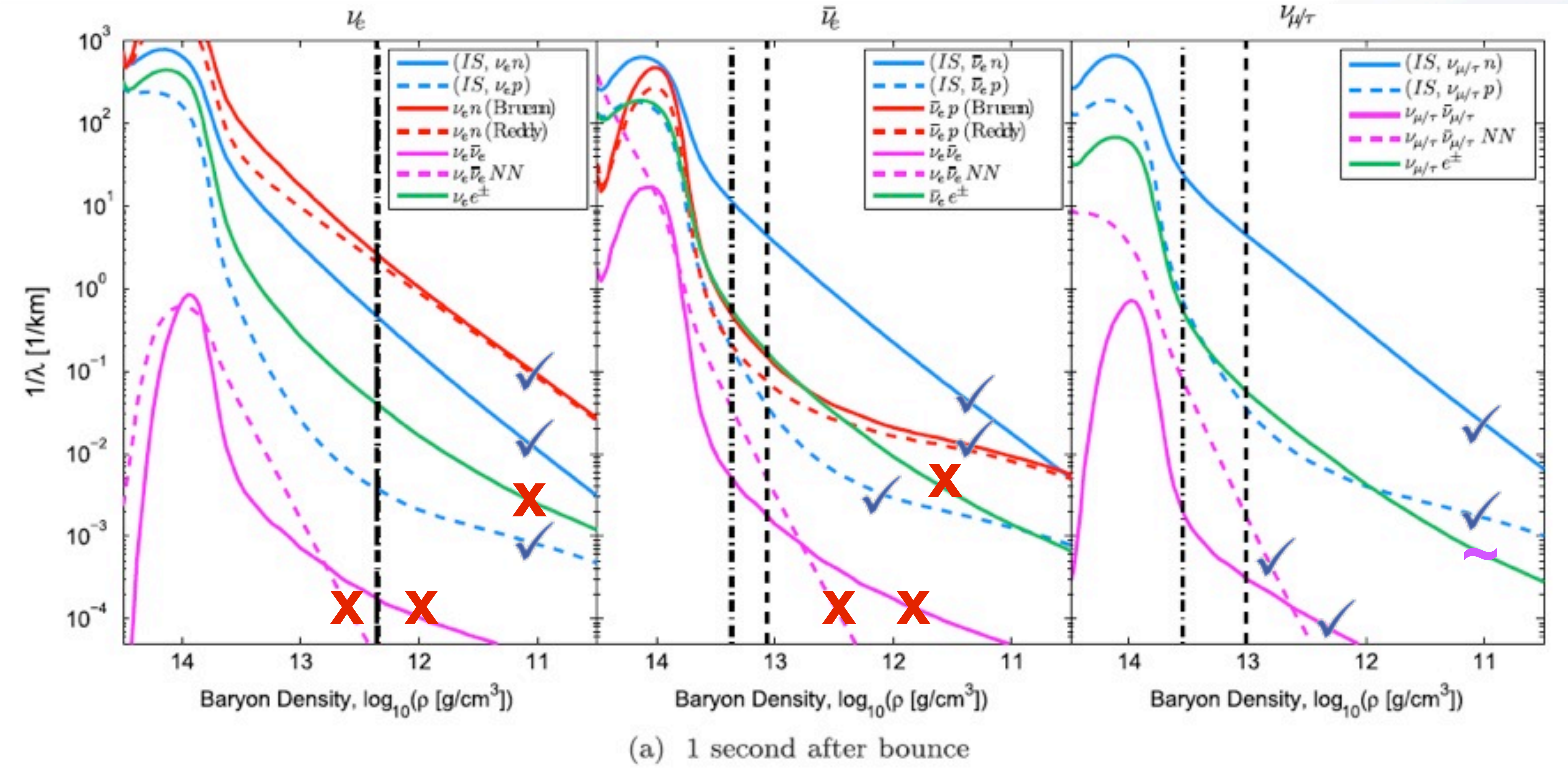
PNS cooling



- results without ΔU
- M_B = 1.642 M_{sun}
- M_G(T=0) = 1.495 M_{sun}
- very satisfactory overall cooling behavior

Contribution of individual rates

[Fischer et al. PRD85 (2012)]



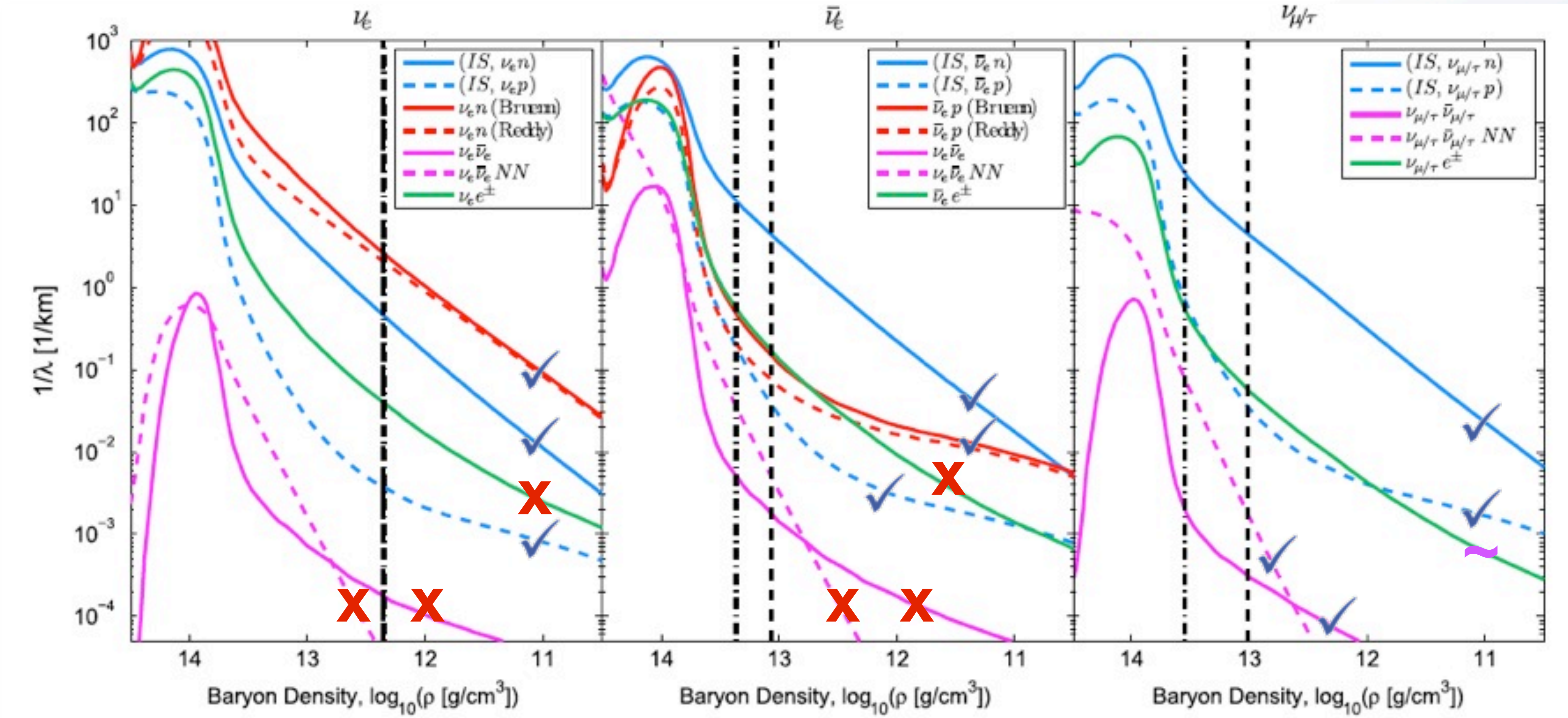
(a) 1 second after bounce

- (IS, vN): iso-energetic neutrino-nucleon scattering
- (vn), (vp): charged-current reactions
- (v $\bar{\text{v}}$): pair production
- (v $\bar{\text{v}}$ NN): Bremsstrahlung
- (ve): neutrino electron scattering (NES)

x not included here

Contribution of individual rates

[Fischer et al. PRD85 (2012)]

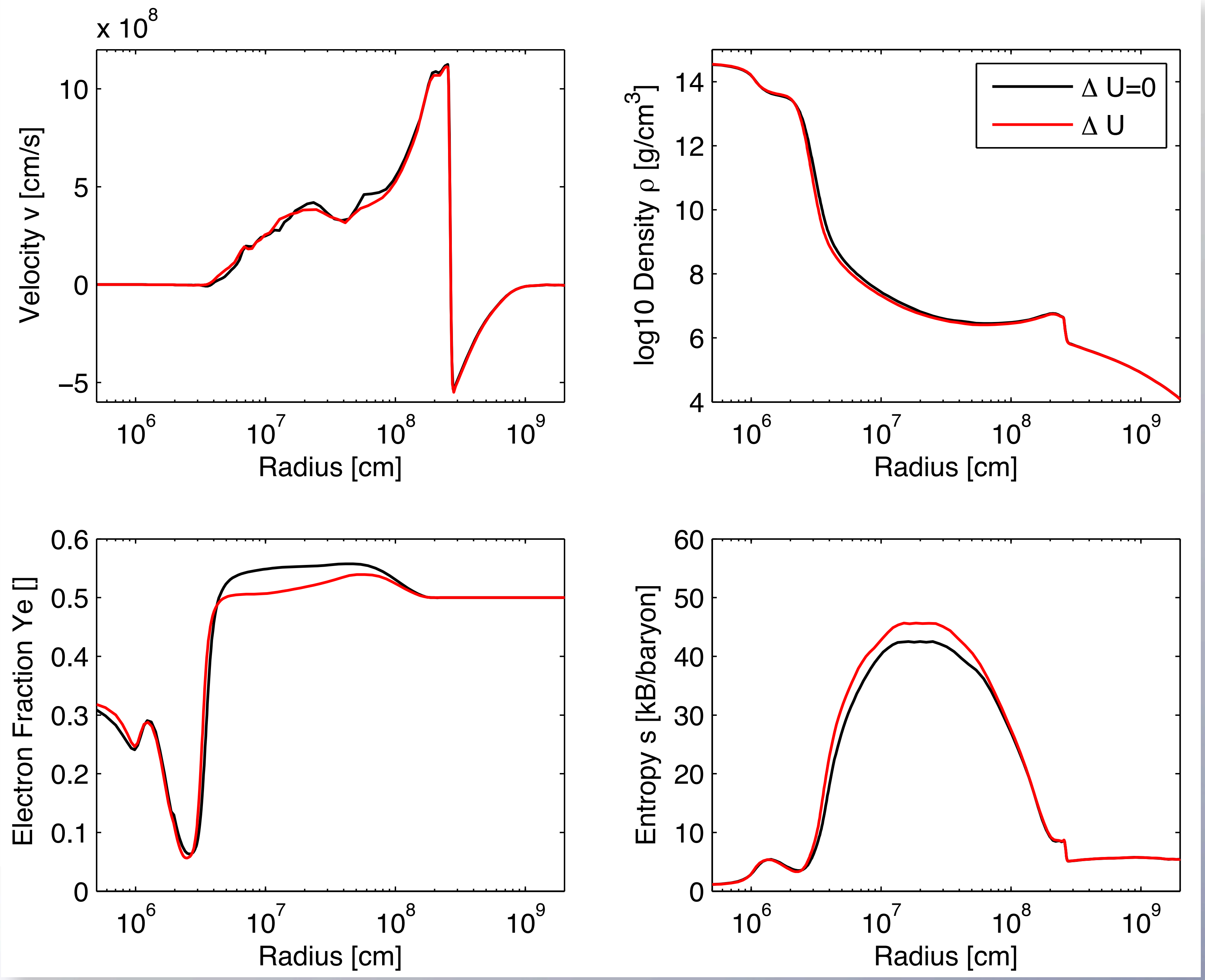


(a) 1 second after bounce

- 1s pb: NES gives an important contribution to inelastic processes of $\bar{\nu}_e$, i.e. thermalization
- significance increases in the later evolution

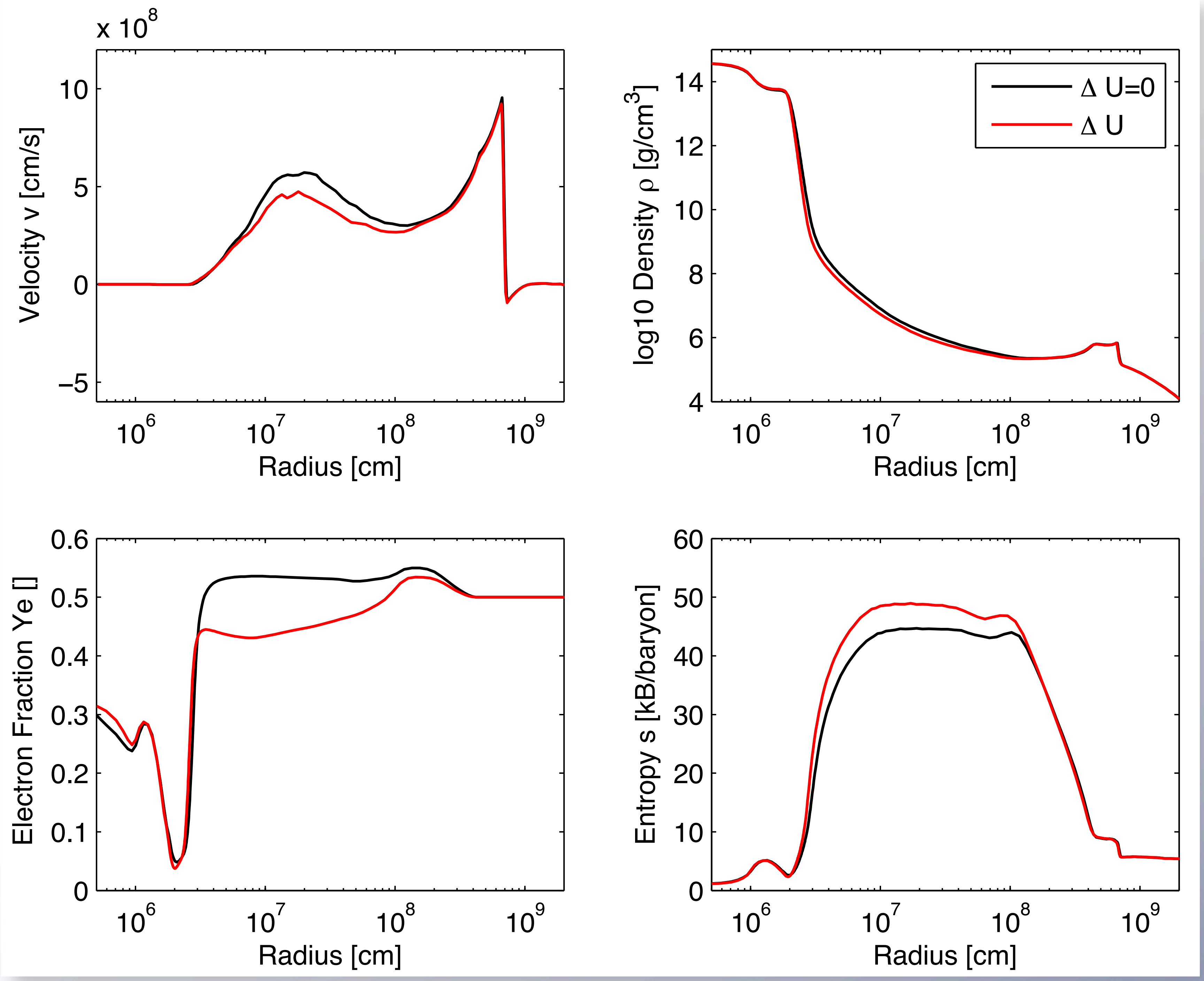
x not included here

Wind formation and effect of ΔU at 0.2 s after explosion



- t^{expl} ~ 300 ms pb
- E^{expl} ~ 6×10^{50} erg
- ΔU delays explosion by 27 ms

Wind formation and effect of ΔU at 0.5 s after explosion



- t^{expl} ~ 300 ms pb
- E^{expl} ~ 6×10^{50} erg
- ΔU delays explosion by 27 ms
- wind formation
- decrease of Y_e due to ΔU

strong effects of ΔU: missing neutrino-reactions, μτ cooling, calculation of ΔU (?)
→ Boltzmann neutrino-transport

Conclusions & Outlook

- nucleosynthesis conditions in neutrino driven winds are influenced by the details of the nuclear interactions - the nucleon interaction potentials

- interesting probe of the symmetry energy

- definition of these potentials depends on the charged-current rates used

- general aim: reproduce the (local) nucleon distribution

- bound-states have to be treated explicitly

- work in progress: online publication of U_i for eight different supernova EOS tables

- identify origin of differences in first exploratory supernova simulations, compare with Boltzmann neutrino transport