Equation of state effects in core-collapse supernovae and neutrino-driven winds

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Equation of state effects in core-collapse supernovae and neutrino-driven winds

Outline:

1.) introduction: supernovae, equation of state (EOS)

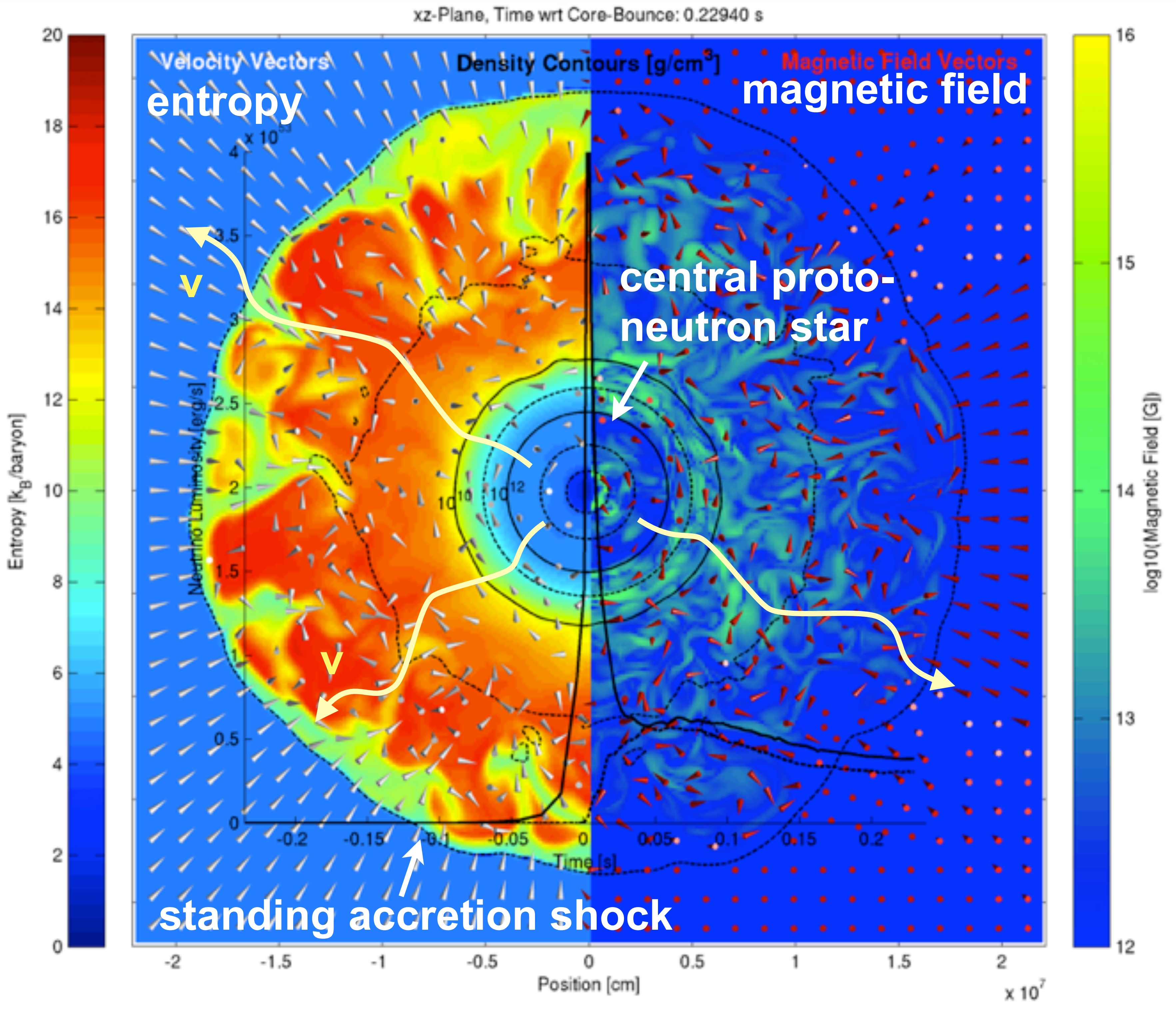
2.) EOS constraints: neutron stars, symmetry energy

3.) supernova simulations

4.) EOS effect on nucleosynthesis conditions in neutrino-driven winds

5.) summary

Neutrino-driven supernova mechanism



- snapshot of 3D-simulation from M. Liebendörfer
- still many open questions for core-collapse supernova explosion mechanism
- role of the EOS?

Supernova EOS – introduction

- EOS provides the nuclear physics input for astrophysical simulations: thermodynamic quantities and nuclear composition

- commonly used EOS:
  - Shen et al. (STOS): Thomas-Fermi, relativistic TM1 interactions
  - Lattimer and Swesty (LS): non-relativistic liquid drop

- plenty of EOSs for cold neutron stars
- challenge of the supernova EOS:
  - finite temperature: $T = 0 – 100$ MeV
  - no weak equilibrium: $Y_e = 0 – 0.6$
  - wide density range: $\rho = 10^4 – 10^{15}$ g/cm^3
  - EOS in tabular form, ~1 million points in (T, Y_e, ρ)
- SN EOS: multi-purpose EOS, e.g., mergers

- effect on SN dynamics and nucleosynthesis?

EOS model: excluded volume NSE with interactions

MH, J. Schaffner-Bielich; NPA 837 (2010) (HS)

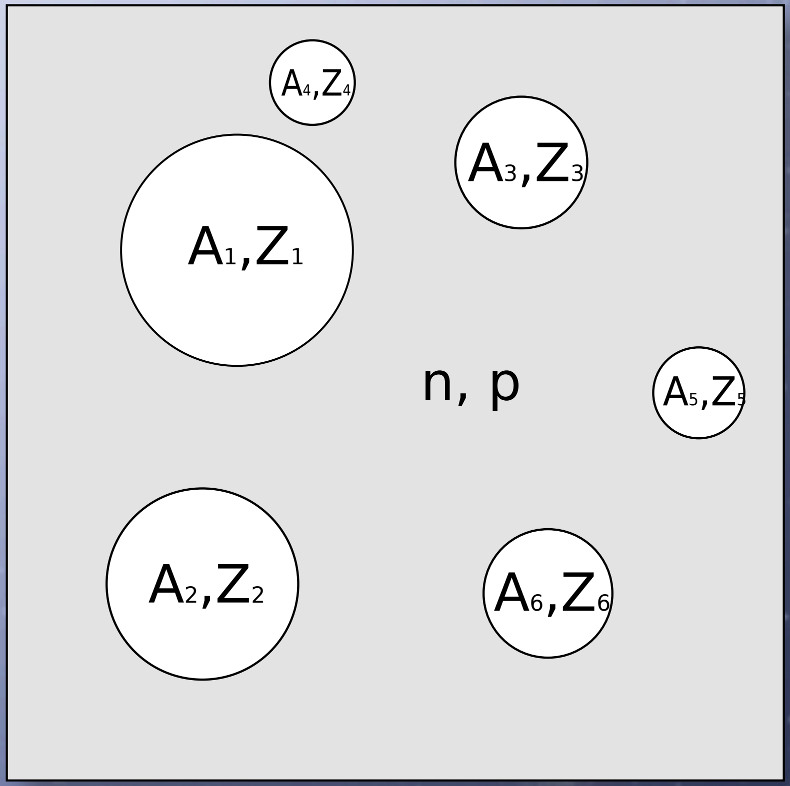
- chemical mixture of nuclei and interacting nucleons in nuclear statistical equilibrium
- subsaturation densities: finite temperature generalization of outer crust EOS
  - nuclear mass tables, medium effects, Coulomb energies, excited states, excluded volume
- supersaturation densities: relativistic mean-field (RMF)
- smooth and continuous change of composition and thermodynamic quantities

- eight EOS tables for different RMF interactions:

  NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx, IUFSU

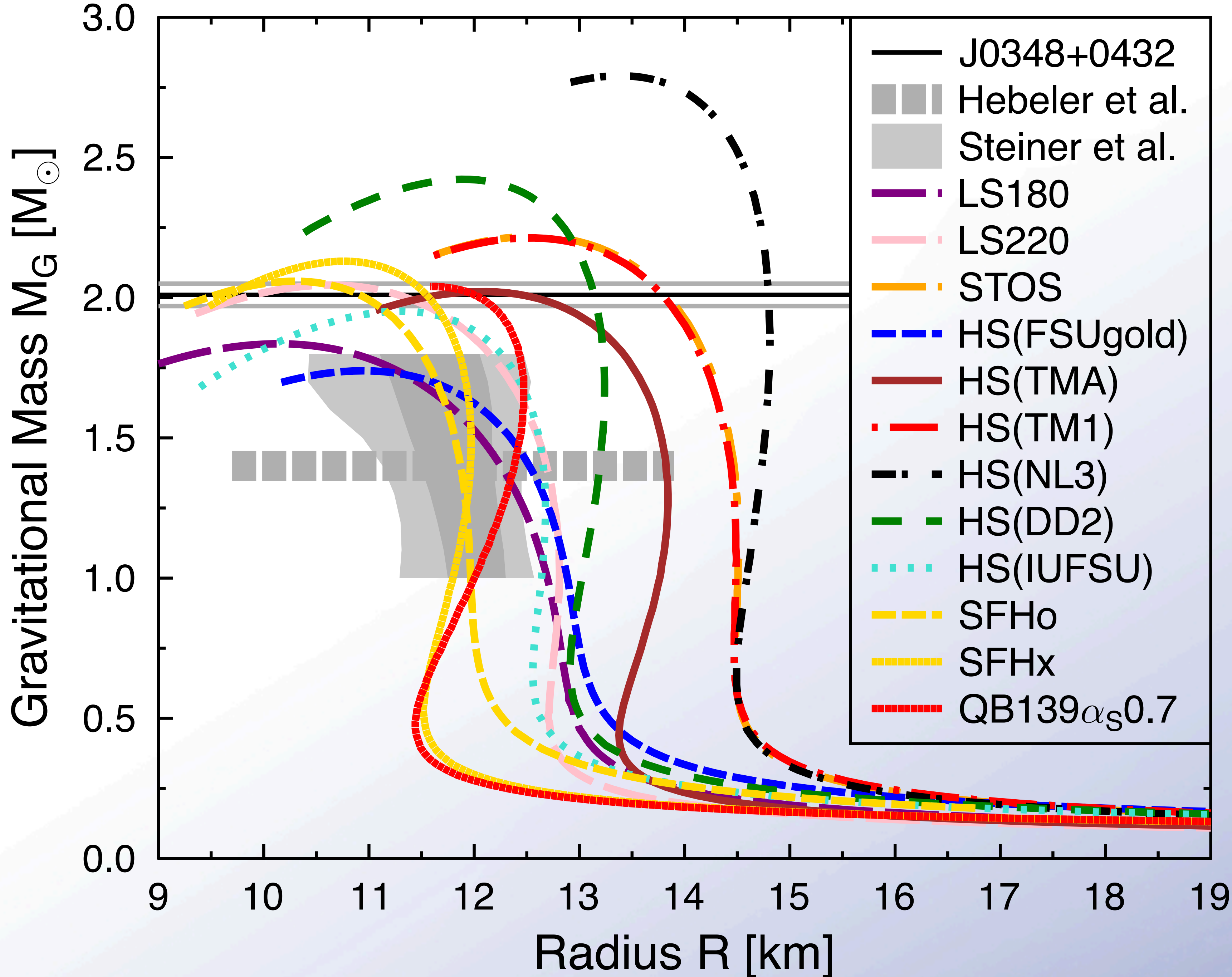
  http://phys-merger.physik.unibas.ch/~hempel/eos.html

  http://compose.obspm.fr/



EOS constraints

EOS constraints – mass-radius relation



- PSR J0348+0432: Antoniadis et al. Science 2013
- Steiner et al. ApJ 2010, Steiner et al. ApJ 2013: bayesian analysis of NS observations
- similar results from Chiral EFT (Hebeler et al. 2010)

T. Fischer, MH, et al. arXiv1307.6190

Symmetry energy

- expansion around the saturation point of nuclear matter

$$E(x,\beta) \simeq E(x,0) + \beta^2 E_{\rm sym}(x),$$
$$\beta = 1 - 2Y_p,\ x = \frac{n_B}{n_0} - 1$$

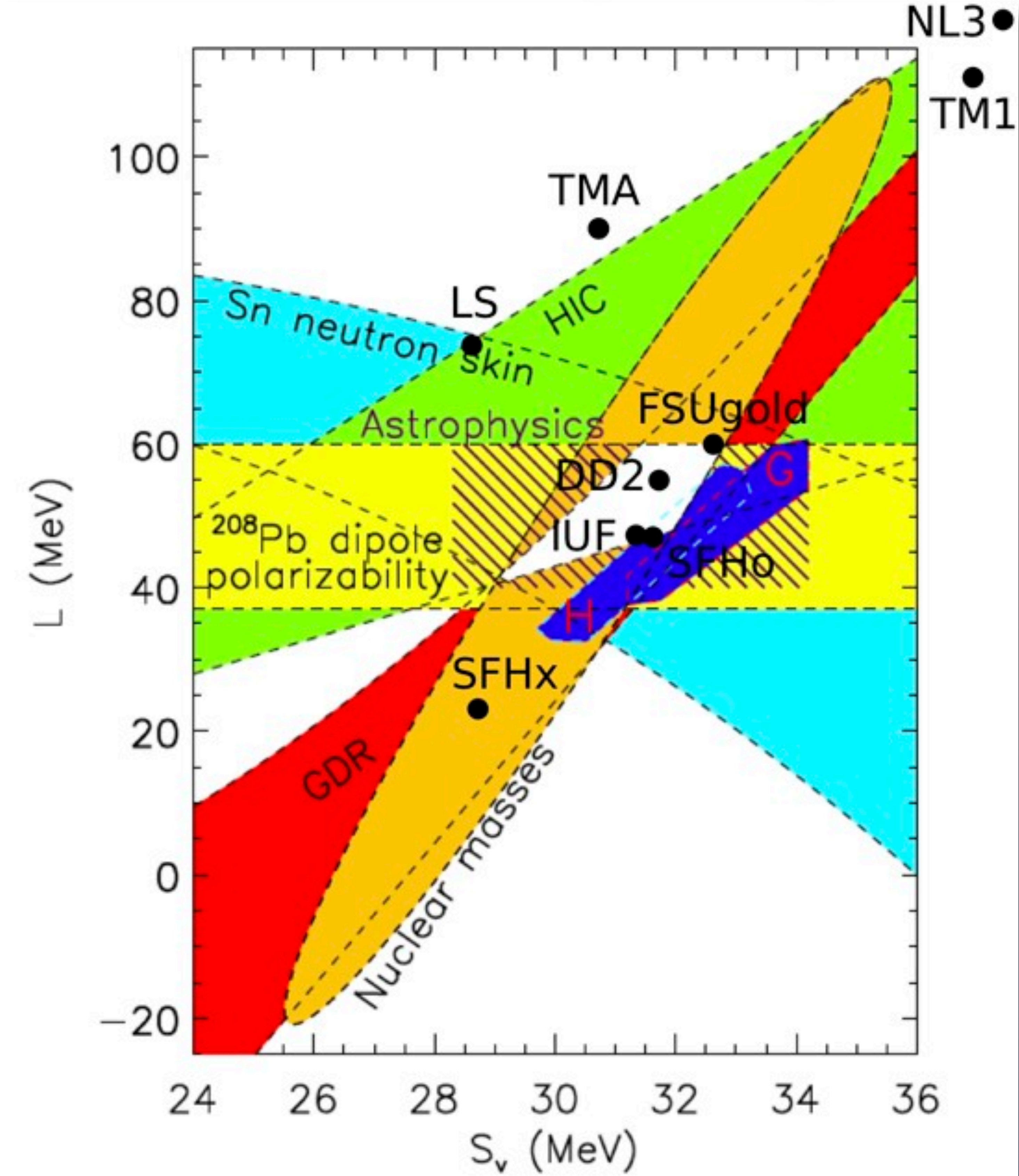
$$E(x,0) \simeq -B_0 + \frac{1}{18}Kx^2 + \frac{1}{162}K'x^3 + \ldots\ ,$$
$$E_{\rm sym}(x) \simeq J + \frac{1}{3}Lx + \frac{1}{18}K_{\rm sym}x^2 + \ldots$$

- binding energy B_0, incompressibility K, skewness K`
- symmetry energy J (S_0), slope parameter L, symmetry incompressibility K_{sym}

- L determines pressure at saturation: $p = \beta^2 n_B L / 3$
- L correlated with neutron skin thickness of heavy nuclei
- L correlated with neutron star radii
- E_{sym} determines Y_e: $\beta = \mu_e / 4E_{sym}$

EOS constraints – symmetry energy

[Lattimer & Lim, ApJ 771, 51 (2013)]

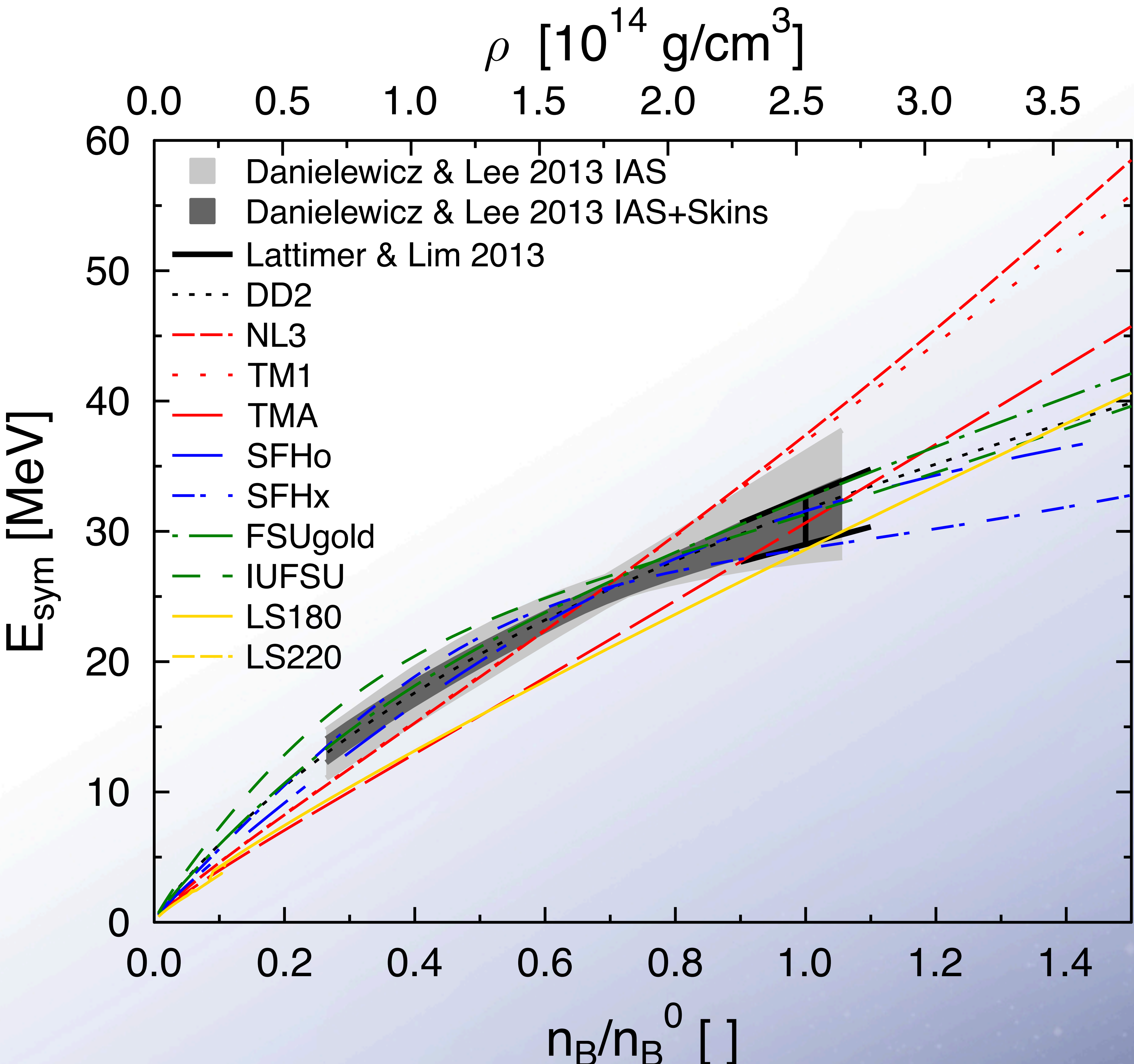


- convergence of observational, experimental and theoretical constraints
- standard non-linear RMF in disagreement (TM1,NL3,TMA)
- SFHo, IUF and DD2 perform well

- G: Gandolfi et al. 2012: quantum Monte-Carlo
- H: Hebeler et al. 2010: Chiral EFT, neutron matter

EOS constraints – symmetry energy

based on:
[Danielewicz & Lee, arXiv:1307.4130]



- derived from binding energies of isobaric analog states
- standard non-linear RMF (NL3, TM1, TMA) in disagreement
- LS EOS extremely low
- DD2: perfect match

$n_0 \sim 0.16\ \mathrm{fm}^{-3}$
$\sim 2\times10^{14}\ \mathrm{g/cm}^3$

Supernova simulations

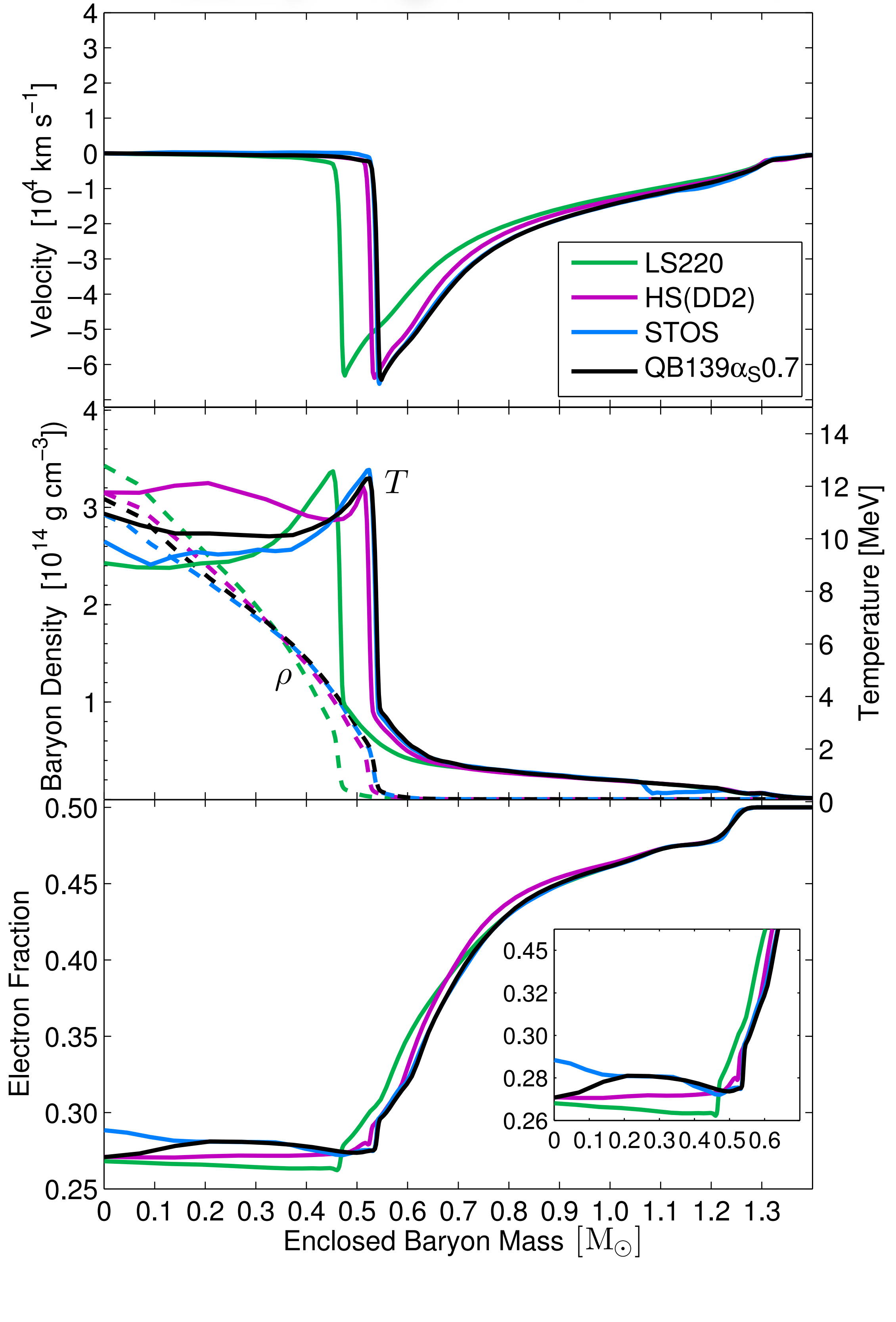
Supernova simulations – setup

MH, T. Fischer, J. Schaffner-Bielich, M. Liebendörfer, ApJ 748, 70 (2012),
A. Steiner, MH, T. Fischer; ApJ 774, 17 (2013),
T. Fischer, MH, et al. arXiv1307.6190

- simulations by Tobias Fischer, University of Wroclaw
  - general relativistic radiation hydrodynamics in spherical symmetry
  - three flavor Boltzmann neutrino transport

- 11.2 M_{sun} progenitor of Woosley et al. RMP 74 (2002)
  - regular core-collapse supernovae
  - comparison of LS220, STOS and HS(DD2)

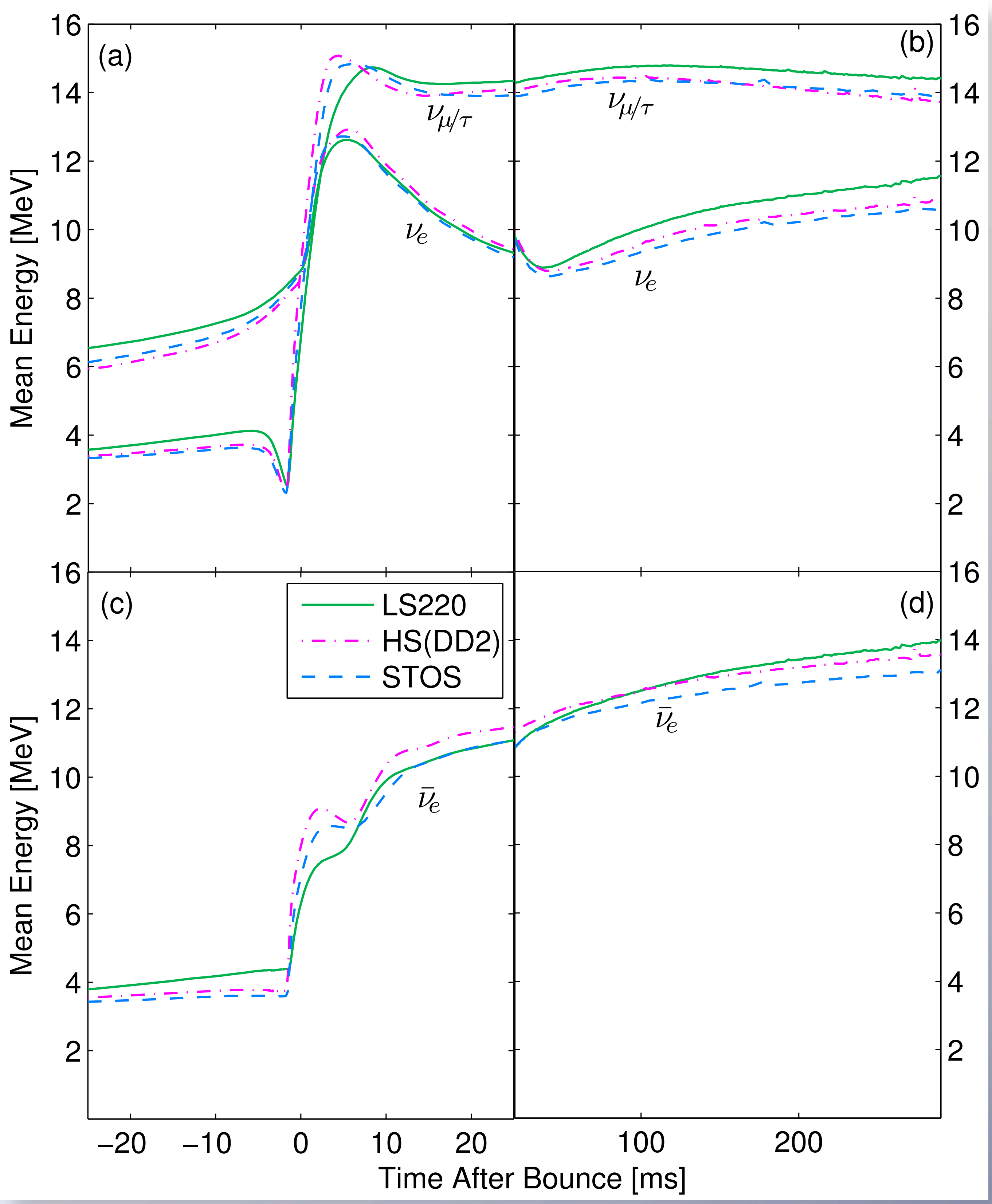
11 M_{sun} progenitor – bounce



- highest densities, lowest bounce mass, lowest Y_e for LS220 ↔ lowest J
- DD2 between LS220 and STOS

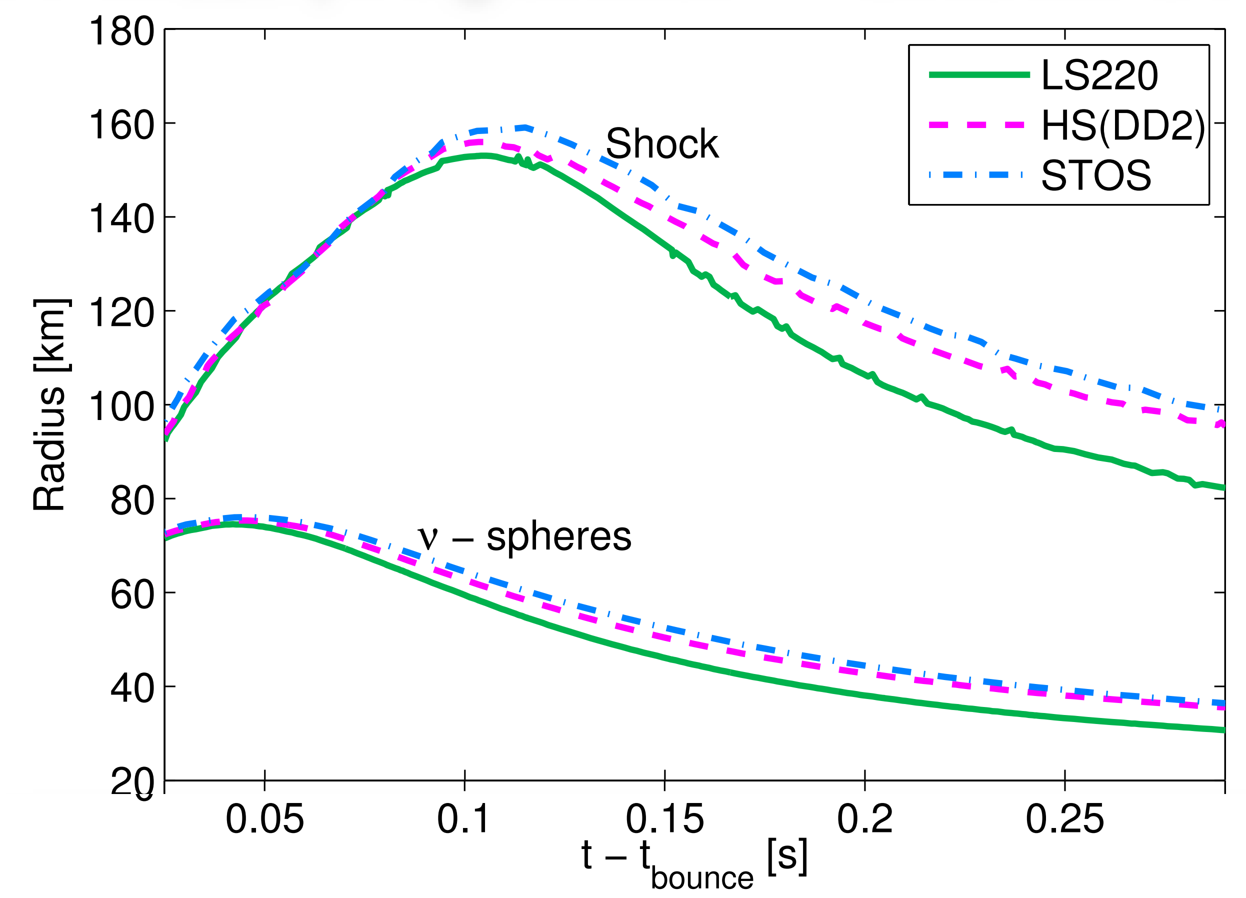
EOS	J [MeV]
LS220	28.6
HS(DD2)	31.7
STOS	36.9

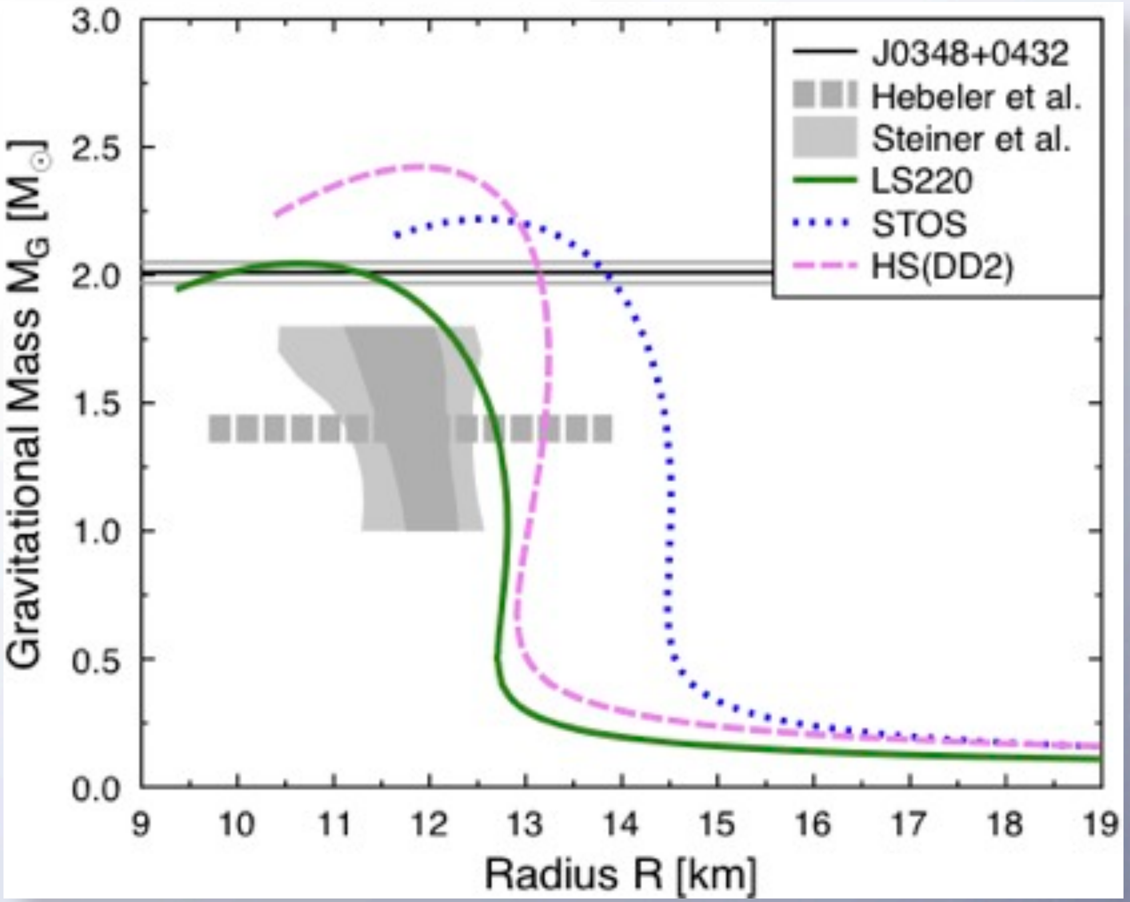
11 M_{sun} progenitor – Neutrinos



- ordering of mean energies: LS220 > HS(DD2) > STOS

11 M_{sun} progenitor – Shock evolution





- higher mean energies of LS220 as a result of faster proto-neutron star contraction
- DD2 between the more extreme cases of STOS and LS
- radius evolution in agreement with TOV solutions
- small differences, but shown to be amplified in Multi-D (Suwa et al. 2013, Marek et al, 2009, Couch 2013)

STOS too pessimistic, LS220 too optimistic for explosion models

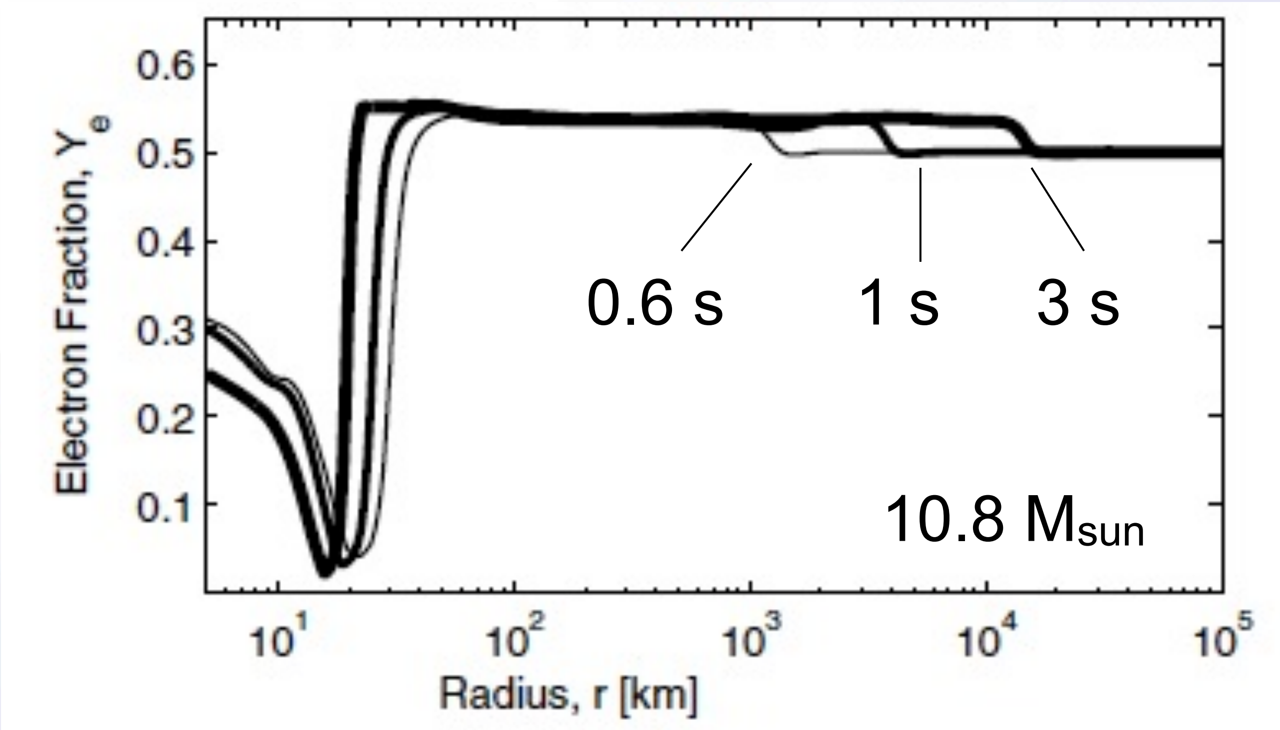
Neutrino-driven winds

Neutrino-driven winds

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

- previous long-term core-collapse supernova simulations by Fischer et al (2010), Hüdepohl et al. (2010):

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



- the neutrino-driven wind is generally proton rich
- allows 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):

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

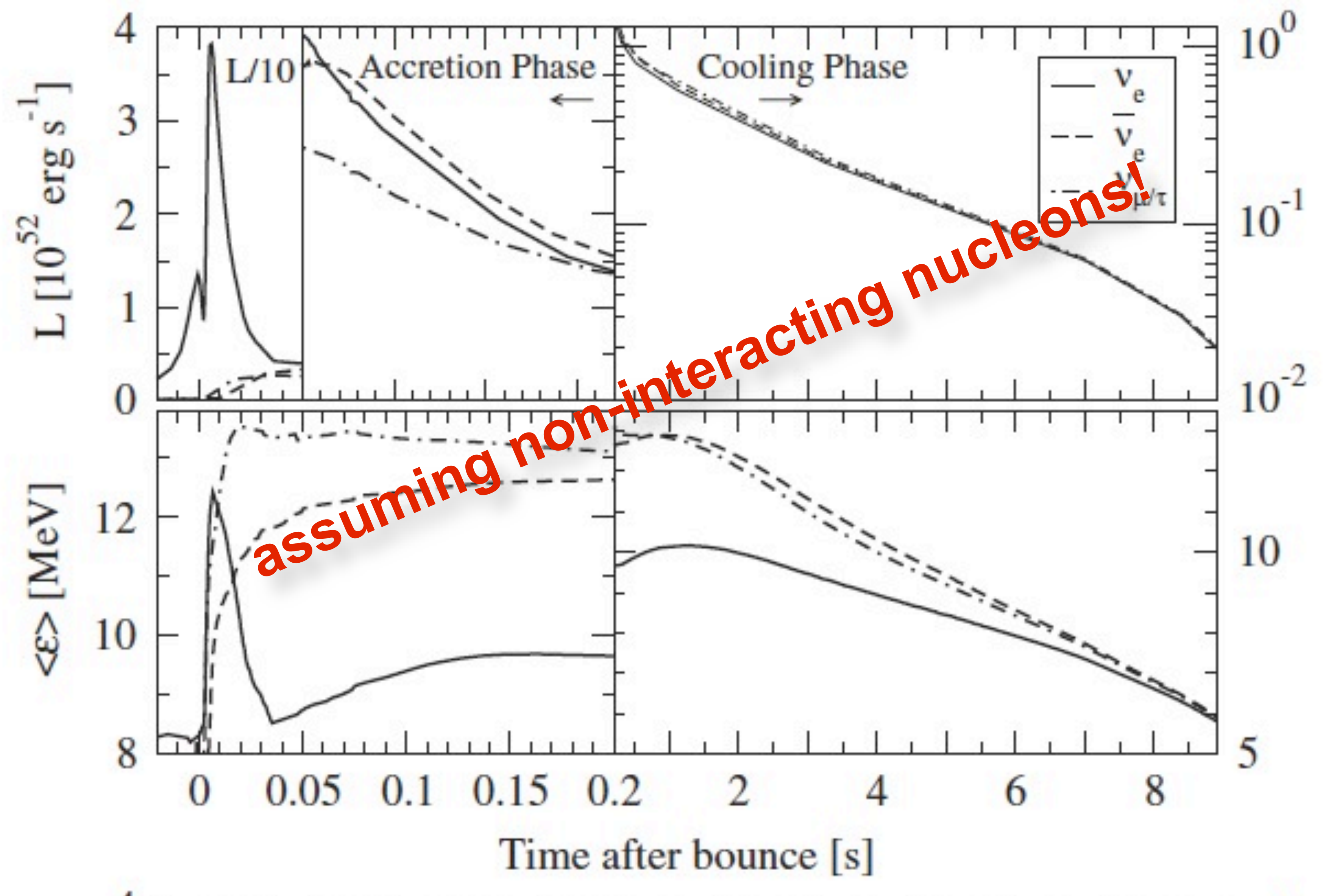
- $Q = m_n - m_p = 1.3$ MeV
- neglects neutrino emission, i.e. electron and positron captures

- for similar luminosities:

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

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

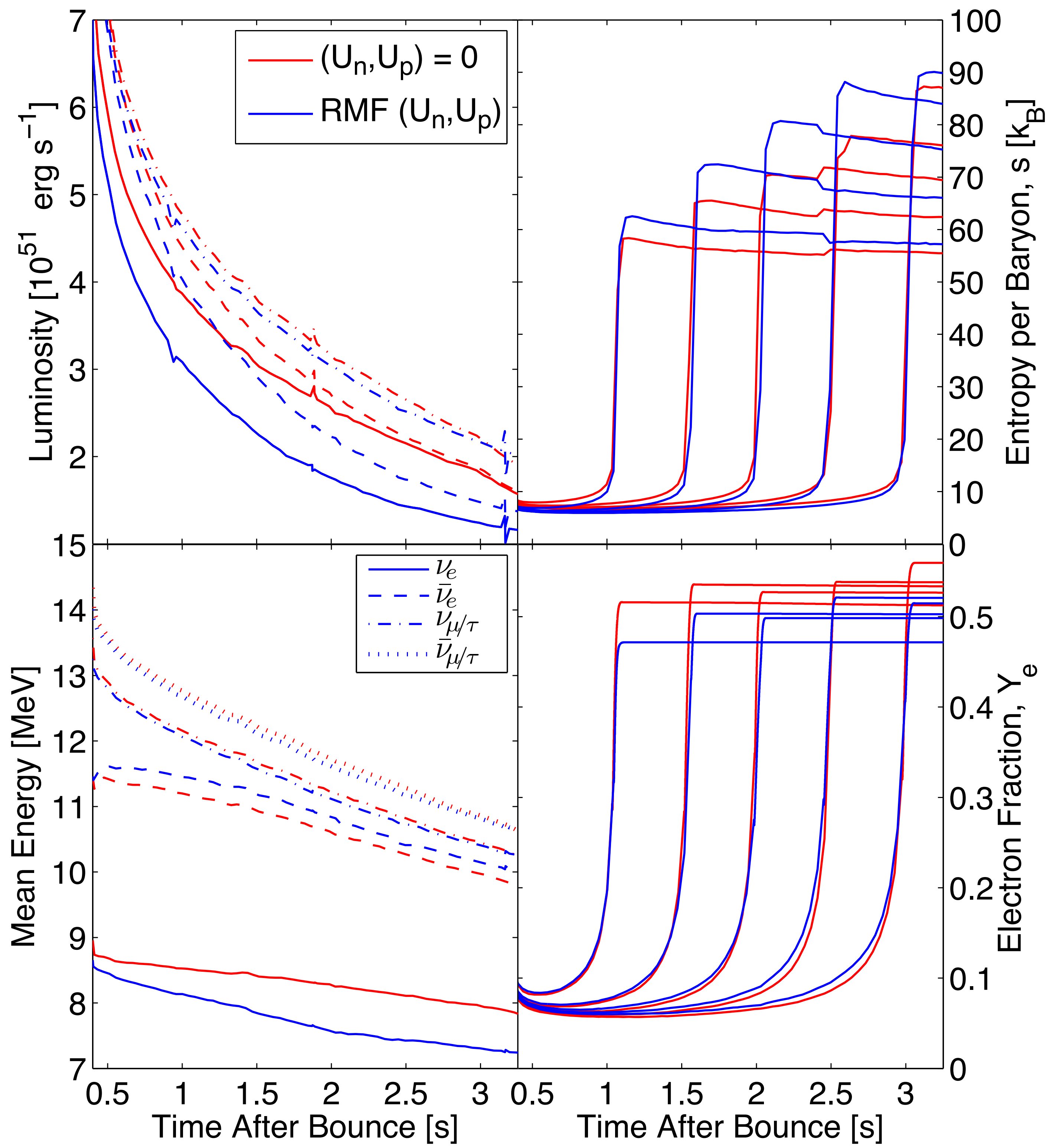
- nucleons in self-generated mean-field potentials U_i
- energy conservation for a generic mean-field model e.g.: $e + p \rightarrow n + \nu_e$

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

- neutron-rich conditions: $\Delta U = U_n - U_p > 0 \rightarrow$ reduces neutrino energies
- only relevant at high densities

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
- mean-field effects lead to slightly neutron-rich wind
- same conclusions by Roberts et al. 2012, different EOS: IUFSU, lowest Y_e of 0.43

EOS: STOS (TM1)

definition of nucleon mean-field potentials

What sets ΔU?

- for the eight relativistic SN EOS available:

$$
\begin{aligned}
E &= E^{\text{kin}} + E^{\text{int}} \\
E^{\text{int}} &= E^{\text{int}}(T, n_B, Y_p, \Sigma_S, \Sigma_V^i)
\end{aligned}
$$

- Σ_S: scalar self energy
- Σ_V: vector self energy

$$\Delta U \simeq 4(1-2Y_e)E^{\text{int}}_{\text{sym}}$$

$$E^{\text{int}}_{\text{sym}}(n_B) = \frac{1}{8n_B}\frac{d}{dY_p}\bigg|_{n_B,T=0}\frac{\partial E^{\text{int}}}{\partial Y_p}$$

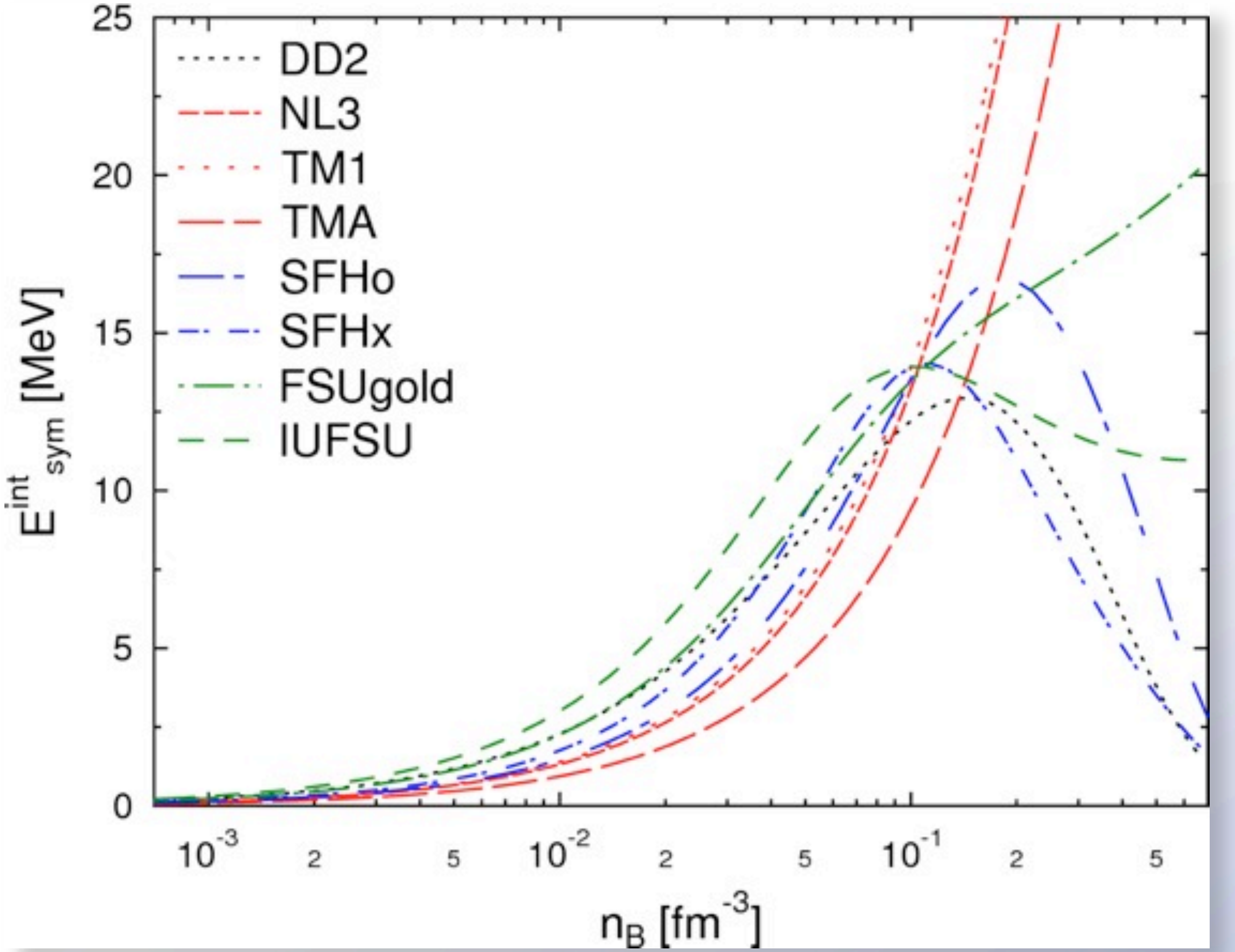
- interaction part of the symmetry energy

$$E_{\text{sym}} = E^{\text{int}}_{\text{sym}} + E^{\text{kin}}_{\text{sym}}$$

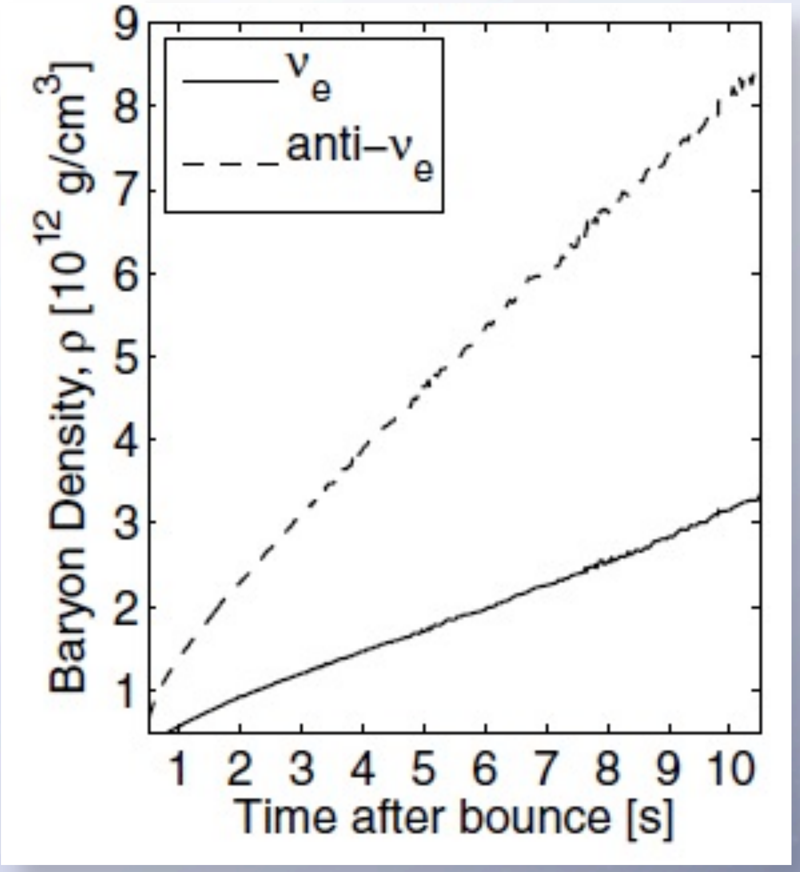
MH, in preparation

Interaction part of the symmetry energy

$n_0 \sim 0.16$ fm^{-3}
$\sim 2\text{x}10^{14}$ g/cm^3



neutrinosphere



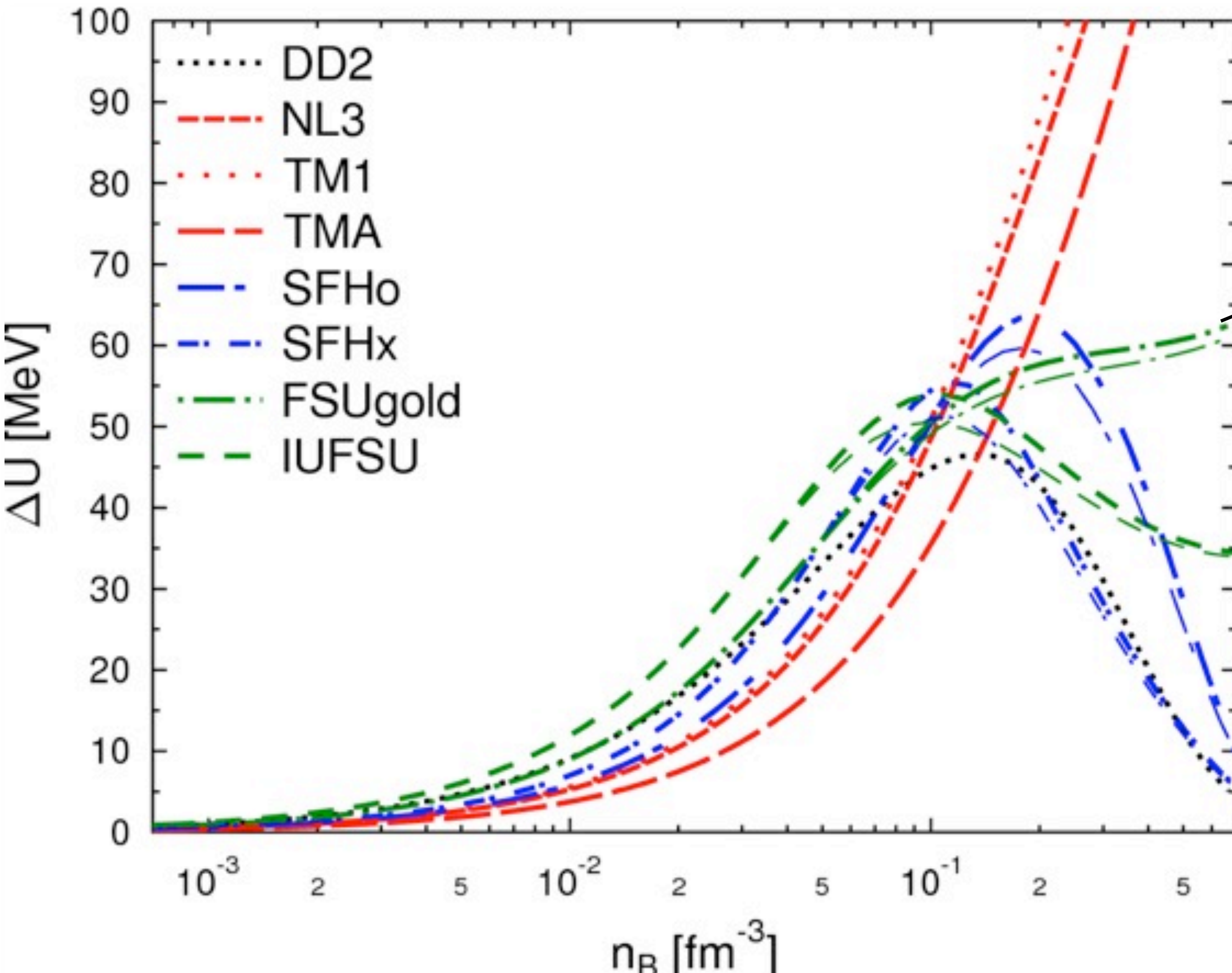
[Fischer et al. A&A 517 (2010)]

- even at low densities substantial differences
- diverging for $n_B > 0.1$ fm^{-3}

$$\Delta U \simeq 4(1-2Y_e)E_{\rm sym}^{\rm int}$$

- compensation effect: higher E_{sym} → higher Y_e

ΔU in beta-equilibrium



- beta-eq: upper limit for ΔU
- compensation by Y_e less important than differences due to E_{sym}^{int}

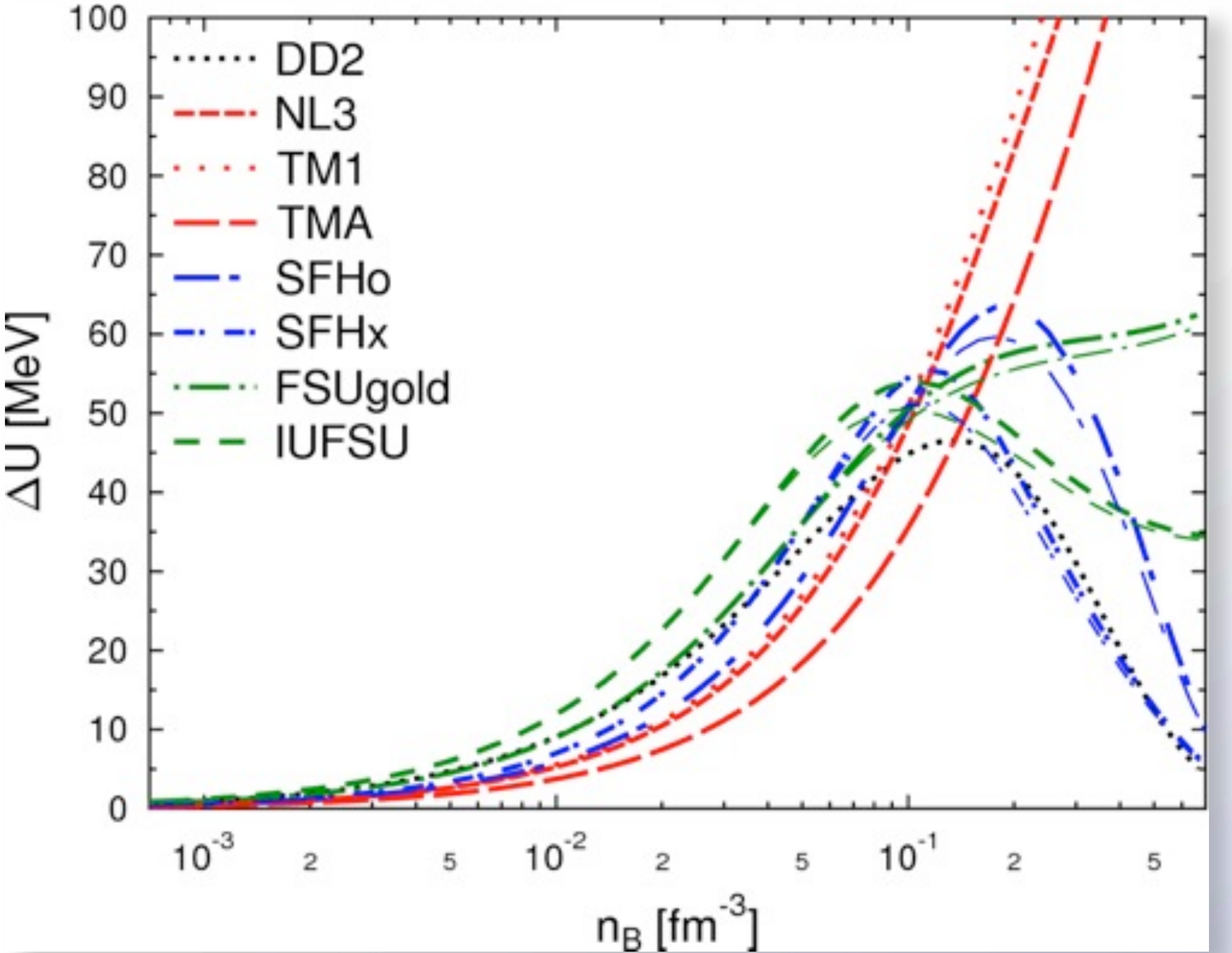
exact

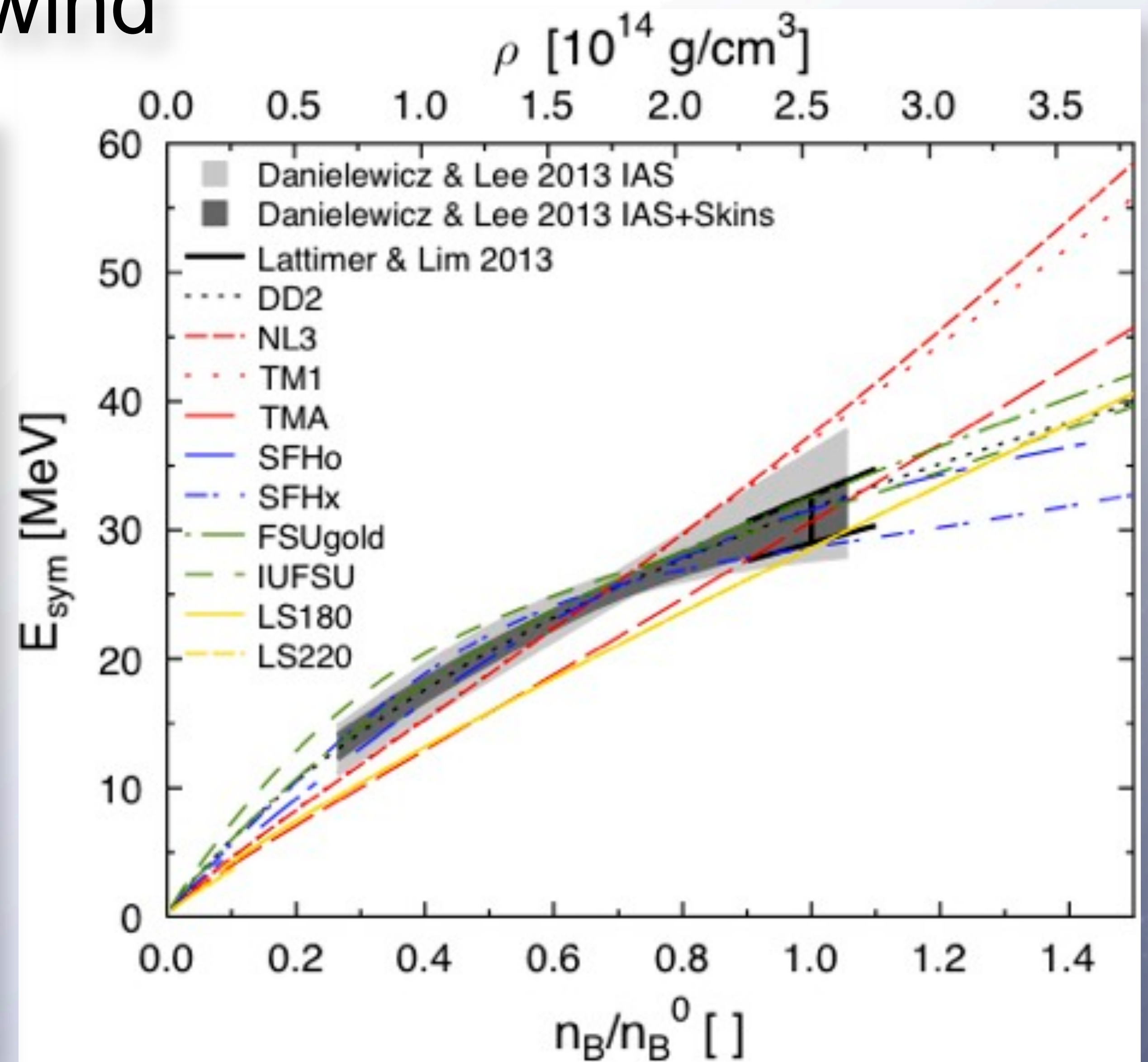
approx. by E_{sym}^{int}

$$\Delta U \simeq 4(1-2Y_e)E_{\mathrm{sym}}^{\mathrm{int}}$$

- approximation accurate up to 10%

Expectations for neutrino-driven wind



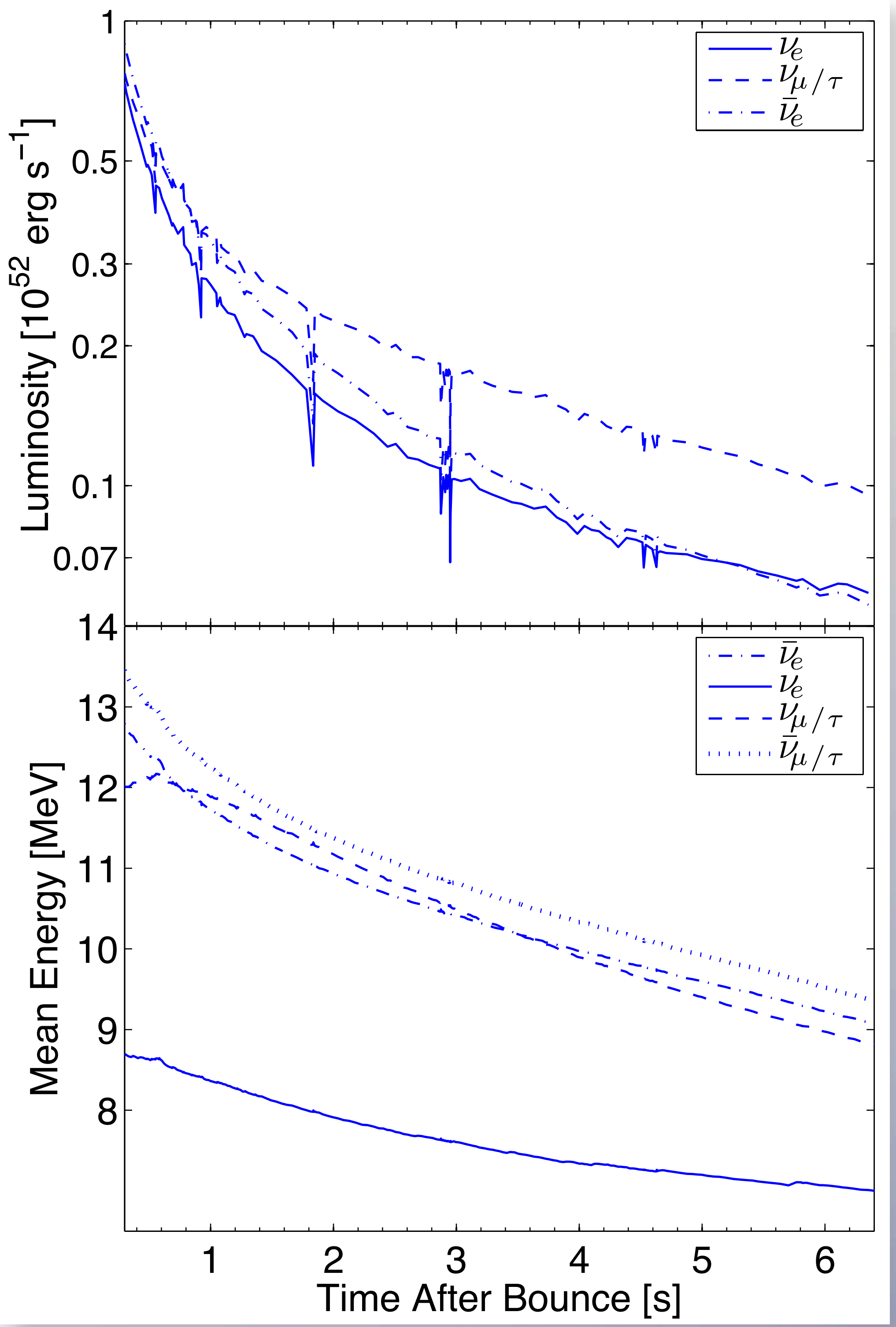


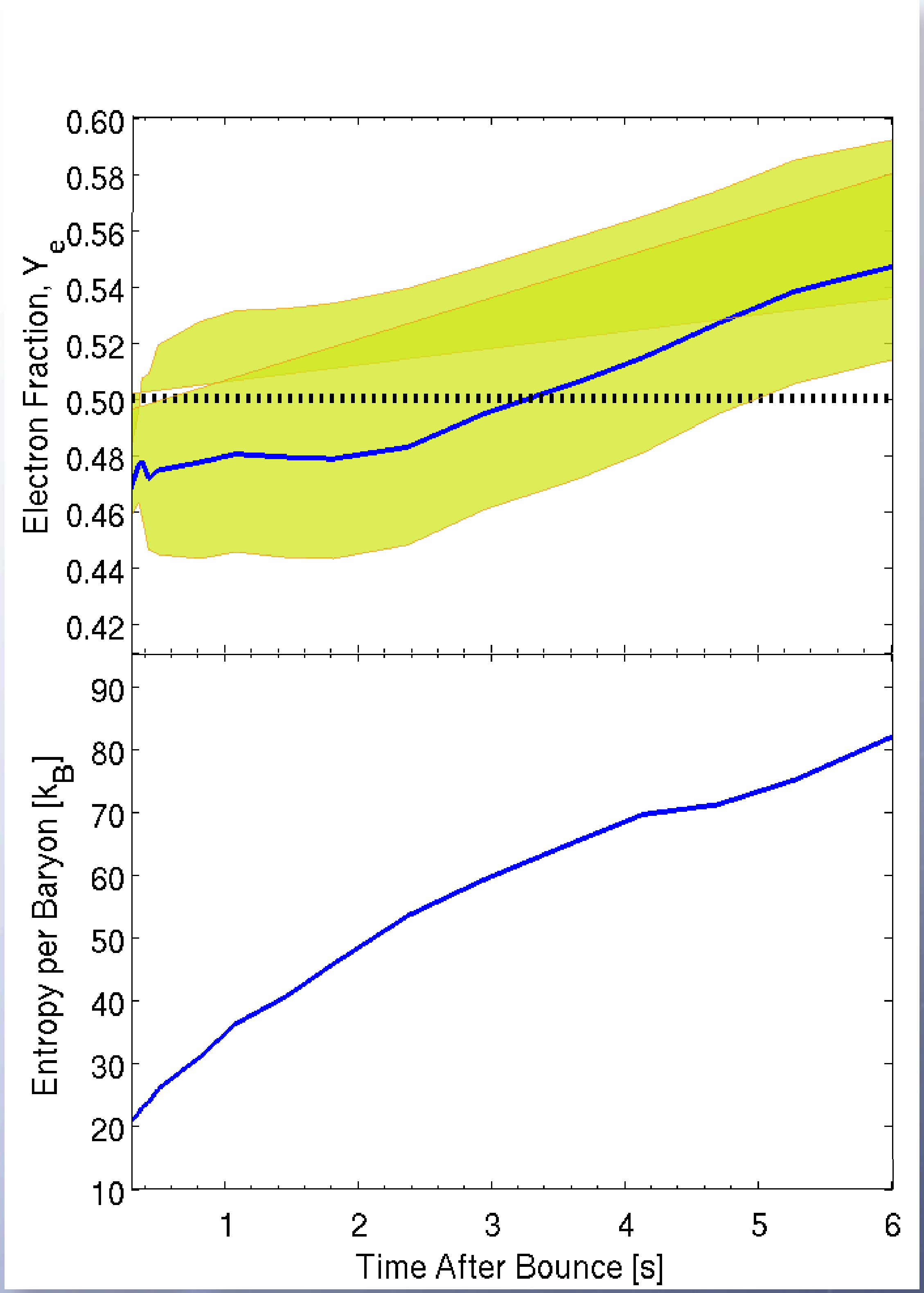
- tested so far: TM1 → lowest Y_e of 0.47 at ~ 1 s pb
- most realistic EOS: DD2 with higher ΔU at low densities → lower Y_e ?

- scattering vs. charge current rates?
- uncertainties in rates (e.g. Bremsstrahlung)?
- effects of correlations, light nuclei?
- momentum-dependent interactions?

Wind simulations for DD2 EOS

- (preliminary) results for DD2 EOS with artificial explosion by T. Fischer, L. Huther and G. Martinez-Pinedo





Conclusions

- EOS tables and routines for composition available for NL3, TM1, TMA, FSUgold, IUFSU DD2, SFHo, SFHx:

  http://phys-merger.physik.unibas.ch/~hempel/eos.html

  http://compose.obspm.fr/ CompOSE CompStar Online Supernovæ Equations of State

- symmetry energy and neutron matter EOS at and below n_0 well constrained

- puts constraints on the dynamics of supernovae
- classical SN EOS (LS and STOS) disfavored, new EOS models indicate an intermediate behavior in SN → multi-D studies

- interaction symmetry energy influences neutrino spectra evolution
- the asymmetry at high densities determines the asymmetry of the wind ejecta
- uncertainties, implications on nucleosynthesis?