New equations of state in simulations of core-collapse supernovae

INT Seattle, 6.7.2012

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in collaboration with:

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comp star

New equations of state in simulations of core-collapse supernovae

Outline:

1.) introduction, EOS model, constraints

2.) EOS aspects in simulations at

- a.) sub-saturation densities
- b.) supra-saturation densities and high temperatures

3.) conclusions

Supernova EOS – Introduction

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

- plenty of EOSs for cold neutron stars

- challenge of the supernova EOS:
  - finite temperature: T = 0 – 100 MeV
  - wide density range: $\rho = 10^4 - 10^{15}$ g/cm^3
  - no weak equilibrium: $Y_e = 0 - 0.6$
  - EOS in tabular form, ~1 million grid-points (T, Y_e, ρ)
  - sub-saturation densities: nuclei/non-uniform nuclear matter/crust

- SN EOS: multi-purpose EOS

Supernova EOS – Introduction

- most used SN EOSs:
- Lattimer & Swesty 1991 (LS): non-relativistic liquid drop model
- H. Shen, Toki, Omayatsu and Sumiyoshi 1998 (STOS/Shen): relativistic mean-field (RMF), Thomas-Fermi approximation
- both models:
  - one representative nucleus: “single nucleus approximation”
  - no shell effects
  - only α-particles of light clusters

Available Supernova EOS

Hillebrandt, Wolff, Nomoto (1984)	Skyrme interactions, NSE, Hartree-Fock
Lattimer & Swesty (1991) (LS)	Skyrme interactions, compressible liquid-drop model, three different compressibilities, and tabulated variants
H. Shen et al. (1998) (STOS)	table for TM1, relativistic mean-field (RMF), Thomas-Fermi approximation
MH & Schaffner-Bielich (2010) (HS)	tables for NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx: NSE, RMF, excluded volume
G. Shen, Horowitz, Teige (2010)	tables for NL3 and FSUgold: virial expansion, RMF, Hartree

nucleonic EOS

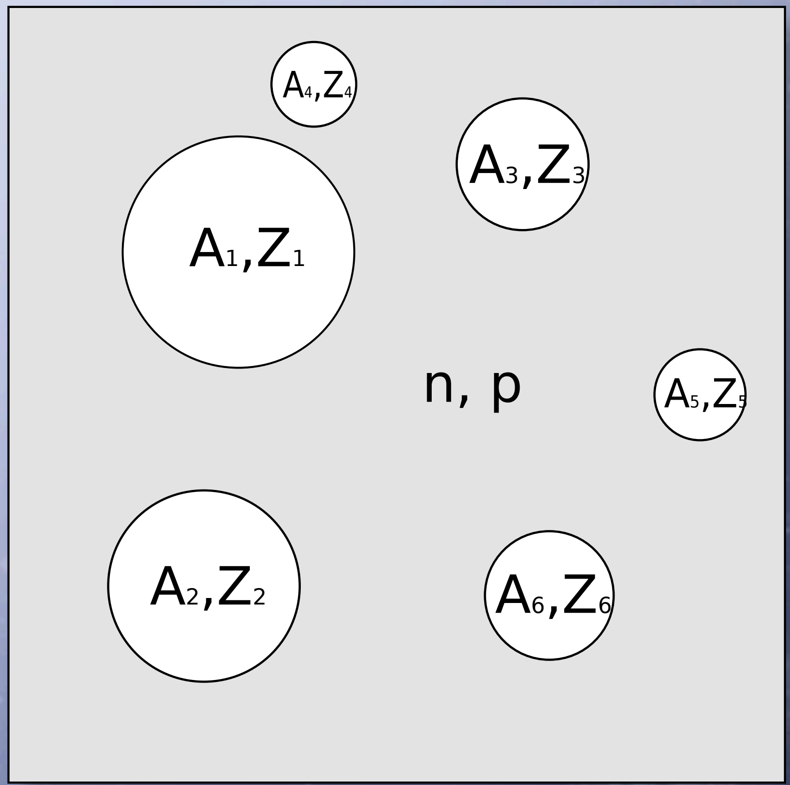
Nakazato et al. 2008	quark matter with large n_c added to STOS
Ishizuka et al. 2008	hyperons added to STOS
Sagert et al. 2009	quark matter with low n_c added to STOS → explosions in 1D
H. Shen et al. 2010	lambdas added to STOS

strange physics at high densities

EOS model: excluded volume NSE with interactions

MH, J. Schaffner-Bieleich; NPA837(2010) (HS)

- chemical mixture of nuclei and interacting nucleons in nuclear statistical equilibrium
- nuclei: theoretical and experimental nuclear mass tables
  - nuclear shell effects
  - ensemble of heavy nuclei and all possible light nuclei
- nucleons: full Fermi-Dirac statistics, various relativistic mean-field (RMF) interactions
- excluded volume effects:
  - interplay nuclei vs. unbound nucleons
  - smooth transition to uniform nuclear matter
- thermodynamic consistent & stable



EOS model: excluded volume NSE with interactions

MH, J. Schaffner-Bieleich; NPA837(2010) (HS)

- seven EOS tables for different RMF interactions:
  NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx
- three additional tables for TM1 with selection of light nuclei:
  {α}, {α,d}, {α,d,t}
- abundances of all nuclei provided by program

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

Nucleons – non-linear RMF (TM1, TMA, FSUgold, NL3)

- relativistic mean-field model (RMF)
- interactions mediated via exchange of mesons and meson (self-) interactions

$$
\begin{aligned}
\mathcal{L} \;=\;& \bar{\psi}(i\gamma^\mu\partial_\mu - M)\psi \\
&+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 - g_\sigma\bar{\psi}\sigma\psi \\
&- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}g_4(\omega_\mu\omega^\mu)^2 - g_\omega\bar{\psi}\gamma^\mu\psi\omega_\mu \\
&- \frac{1}{4}R^a{}_{\mu\nu}R^{a\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu^a\rho^{a\mu} - g_\rho\bar{\psi}\gamma_\mu\tau^a\psi\rho^{\mu a} - \Lambda\omega_\mu\omega^\mu\rho_\nu^a\rho^{a\nu}
\end{aligned}
$$

- alternative: density-dependent coupling constants (DD2)
- coupling constants fitted to experimental data
- well-established description of finite nuclei and nuclear matter

Sugahara & Toki 1994

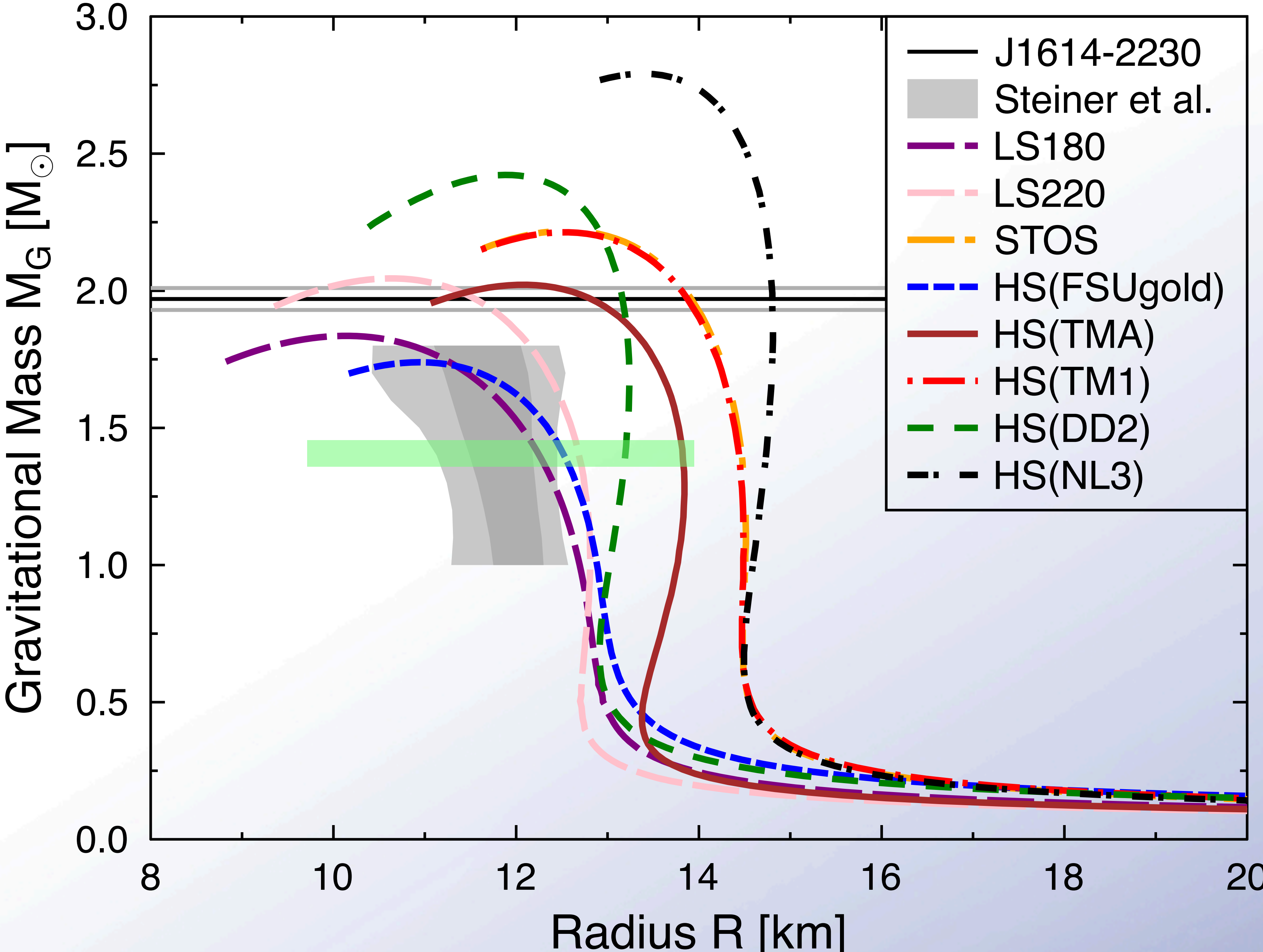
Toki et al. 1995

Todd-Rutel & Piekarewicz 2005

Lalazissis et al. 1997

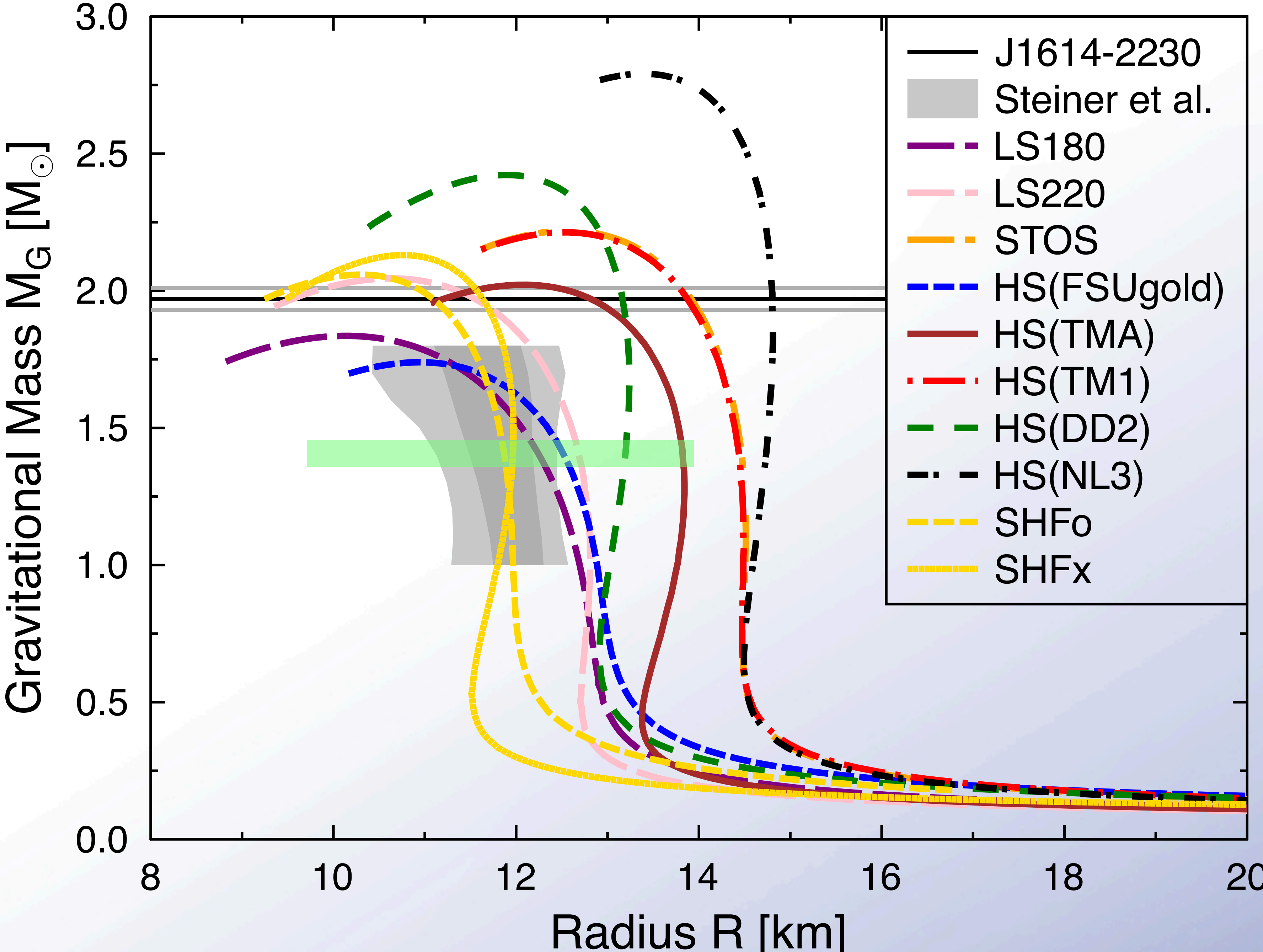
Typel 2005, Typel et al. 2010

EOS constraints – mass and radius measurements



- bayesian analysis of observations of six NS (X-ray burster, low - mass X-ray binaries), Steiner et al. ApJ 2010
- similar results from Chiral EFT (Hebeler et al. 2010)
- new SN EOS fitted to observations: Andrew Steiner (INT), Tobias Fischer (GSI Darmstadt)
- compact PNS → more binding energy release in a SN

EOS constraints – mass and radius measurements



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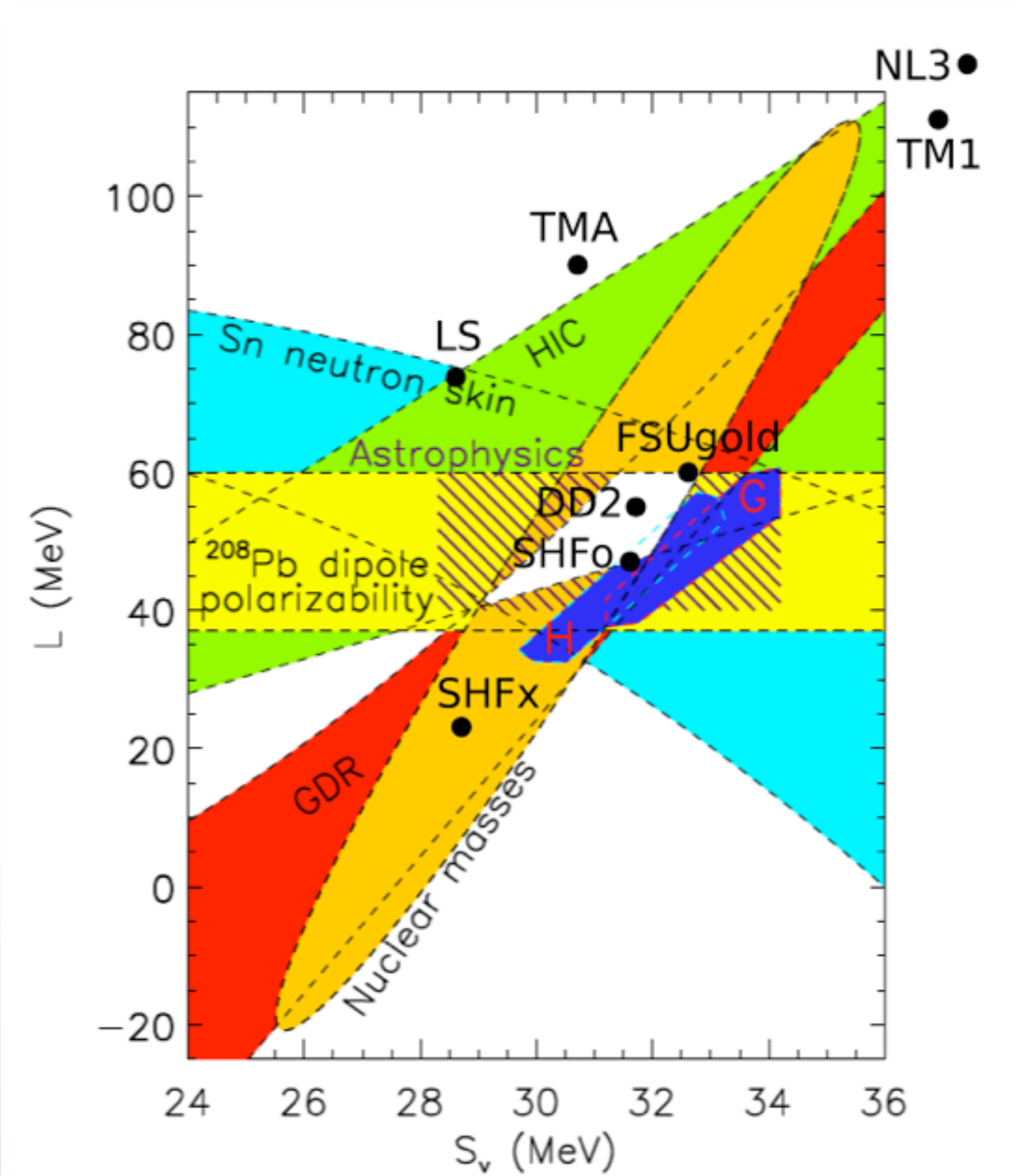
[A. Steiner, MH & T. Fischer, in preparation]

EOS constraints – symmetry energy

[Lattimer & Lim, arXiv:1203.4286]



- convergence of observational, experimental and theoretical constraints
- standard non-linear RMF in disagreement (TM1,NL3,TMA)
- two new RMF models/SN EOS: SHFo (optimal) SHFx (extreme)

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

EOS constraints – saturation properties & maximum mass

	n_B^0 [fm^{-3}]	E_0 [MeV]	K [MeV]	J [MeV]	L [MeV]	$M_{\max}$ [$M_\odot$]
TM1	0.146	-16.31	282	36.95	110.99	2.213
TMA	0.147	-16.03	318	30.66	90.14	2.022
FSUgold	0.148	-16.27	230	32.56	60.44	1.739
NL3	0.148	-16.24	271	37.39	118.50	2.791
DD2	0.149	-16.02	243	31.67	55.04	2.422
SHFo	0.158	-16.19	245	31.57	47.10	2.059
SHFx	0.160	-16.16	239	28.67	23.18	2.130
LS180	0.155	-16.00	180	28.61	73.82	1.828
LS220	0.155	-16.00	220	28.61	73.82	2.031
Exp.	~ 0.15	~ -16	240 ± 10 [1]	30 - 34 [2]	40 - 110 [2]	$> 1.97 \pm 0.04$ [3]

- span a broad range of possible RMF models
- provide a “best fit“ EOS

	references	type of constraint
[1]	Piekarewicz JPG 2010	compilation of measurements of isoscalar giant monopole resonances
[2]	Tsang et al. PRL 2009 Carbone et al. PRC 2010	compilation of experiments: isospin diffusion,pygmy dipole resonance, nuclear masses, GDR, isoscaling, antiprotonic atoms
[3]	Demorest et al. Nature 2010	measurement of Shapiro delay

EOS aspects at subsaturation densities

- heavy nuclei

Supernova simulations

MH, T. Fischer, J. Schaffner-Bielich, M. Liebendörfer, ApJ 748, 70 (2012)

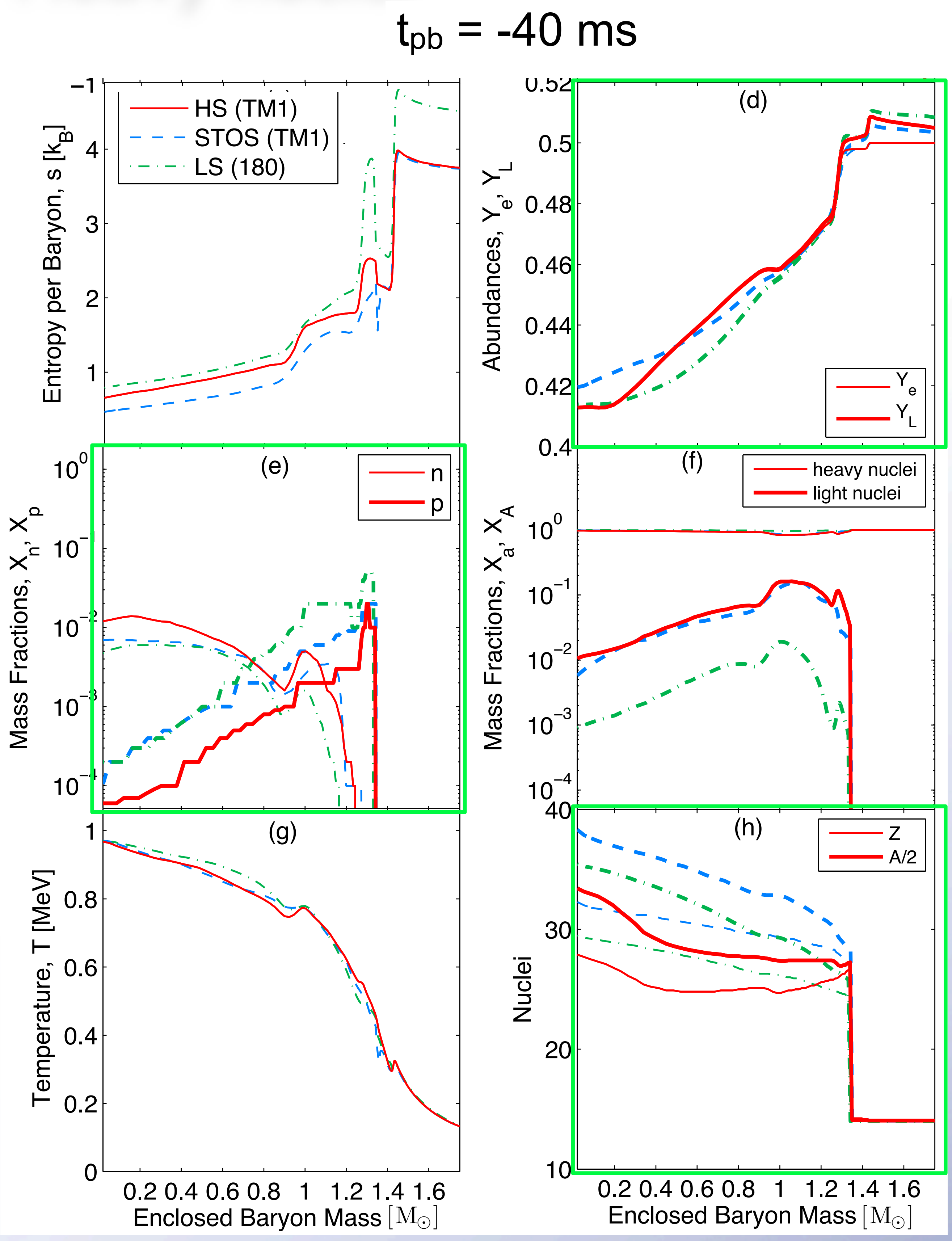
- simulations by Tobias Fischer, GSI Darmstadt
  - general relativistic radiation hydrodynamics in spherical symmetry
  - three flavor Boltzmann neutrino transport
- weak reactions:
  - all light clusters treated as alpha-particles
  - only average heavy nucleus

$$
\begin{aligned}
e^- + <A, Z> &\longleftrightarrow\ <A, Z-1> + \nu_e \\
e^- + p &\longleftrightarrow\ n + \nu_e \\
e^+ + n &\longleftrightarrow\ p + \bar{\nu}_e \\
\nu + e^\pm &\longleftrightarrow\ \nu + e^\pm \\
\nu + N &\longleftrightarrow\ \nu + N \\
N + N &\longleftrightarrow\ N + N + \nu + \bar{\nu} \\
\nu_e + \bar{\nu}_e &\longleftrightarrow\ \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}
\end{aligned}
$$

→ mainly sensitive to differences in thermodynamic quantities

- 15 M_{sun} progenitor of Woosley & Weaver ApJS 101 (1995)

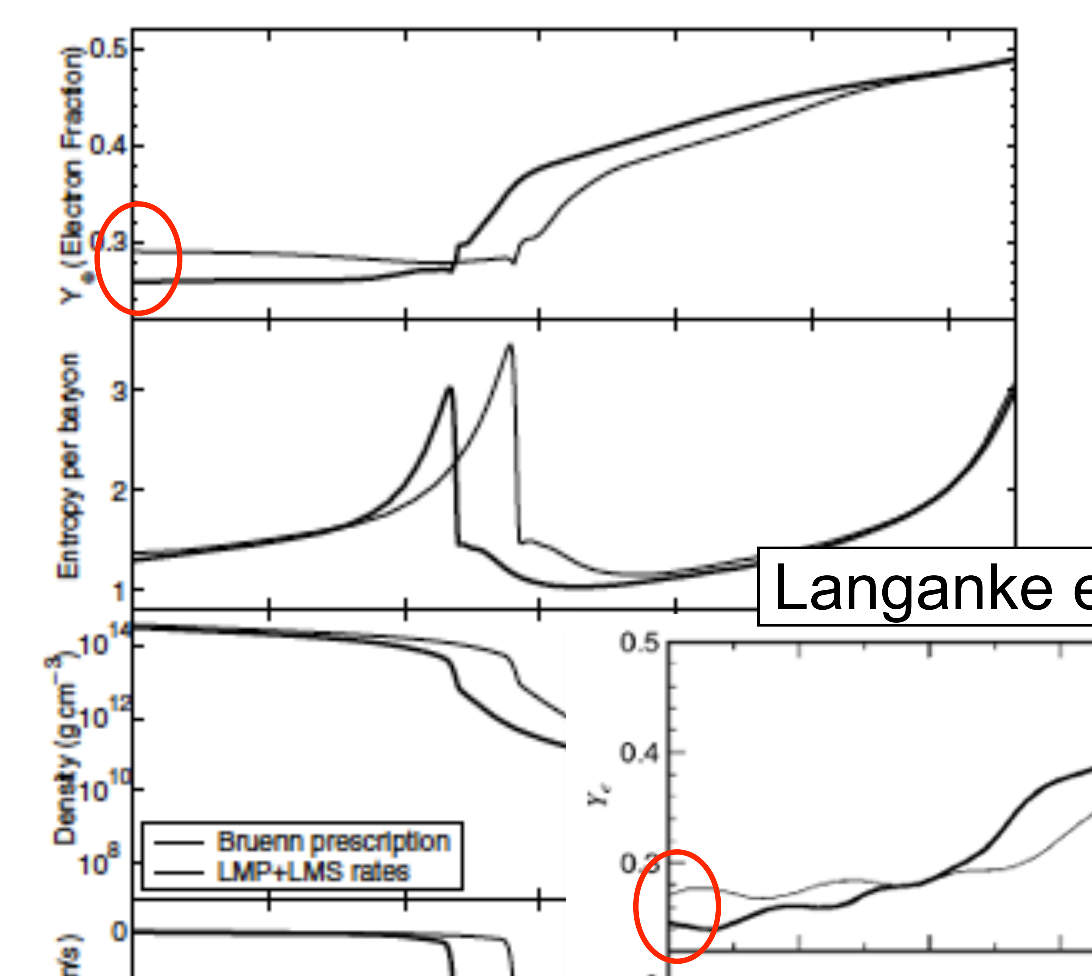
Heavy nuclei



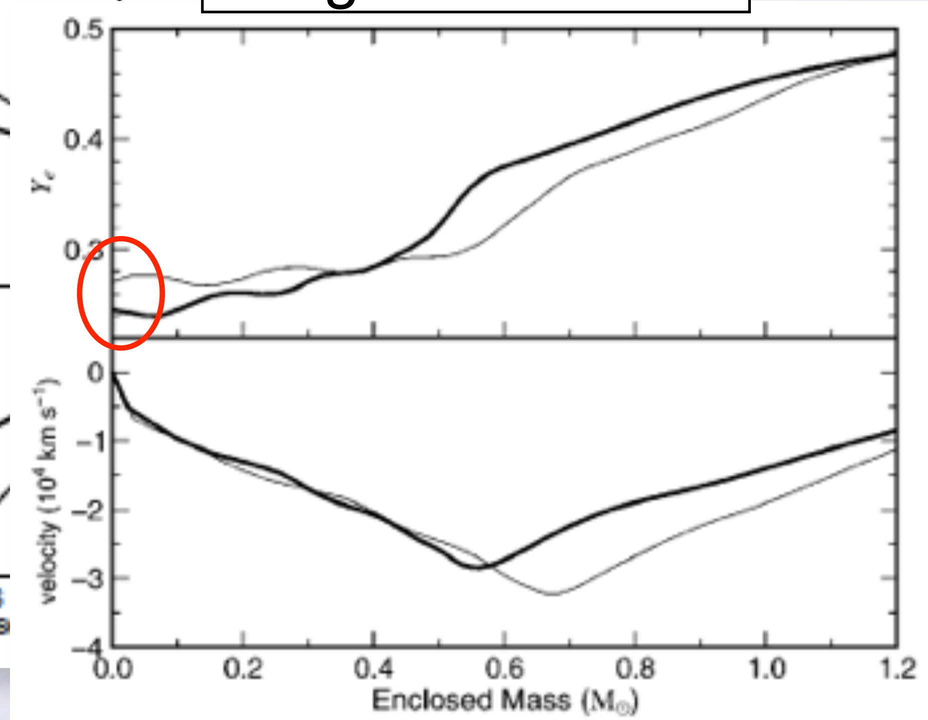
- systematic overprediction of A in STOS → underprediction of e-captures (Bruenn `85 rates)
- indirect effect on X_p → higher Y_e in outer layers
- correct description of nuclei as important as nuclear interactions

Heavy nuclei & e-captures

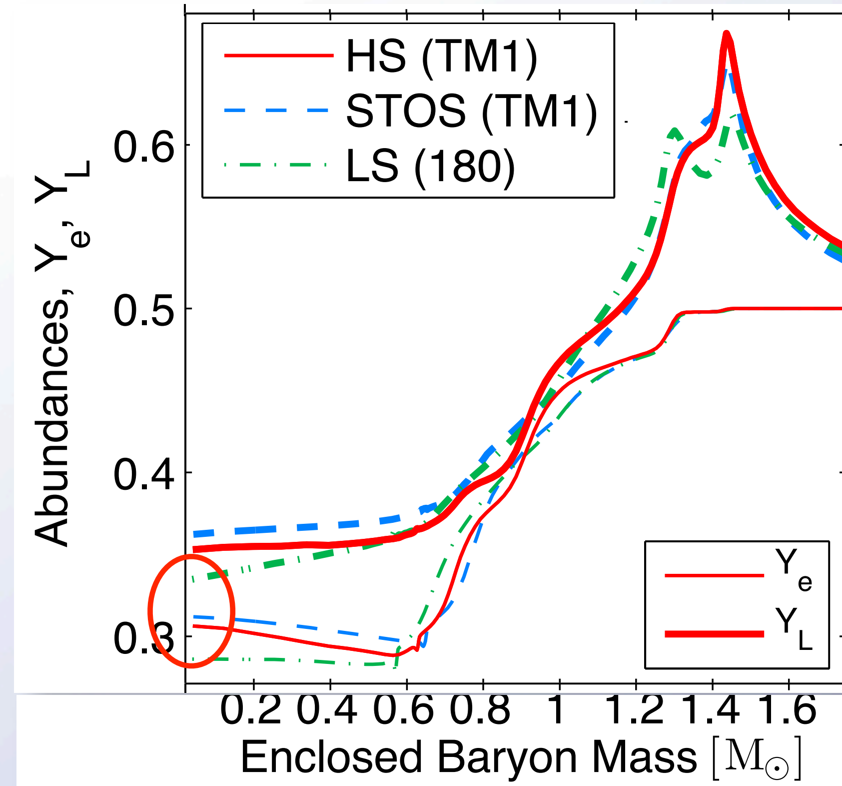
Hix et al. 03



Langanke et al. 03

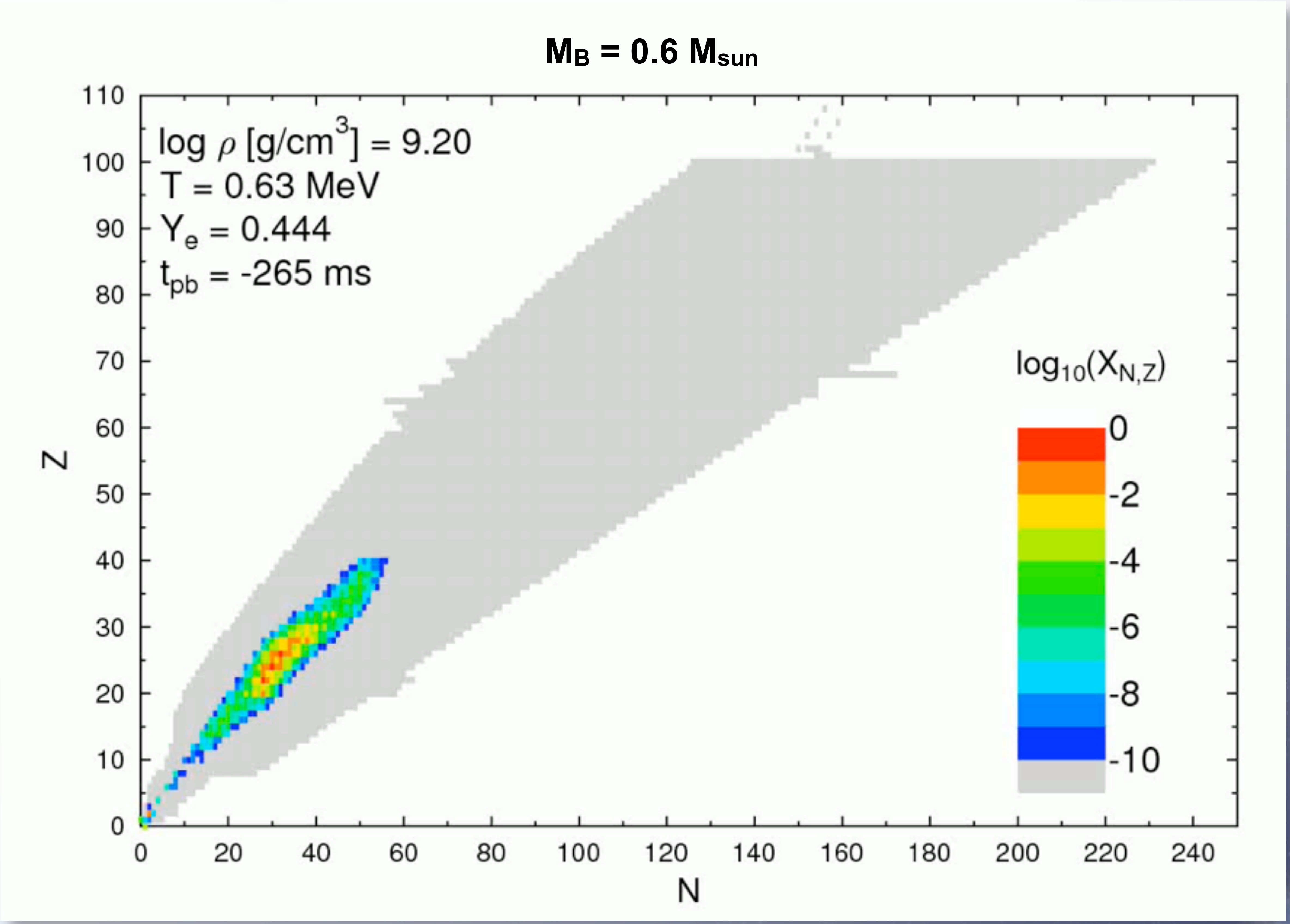


bounce

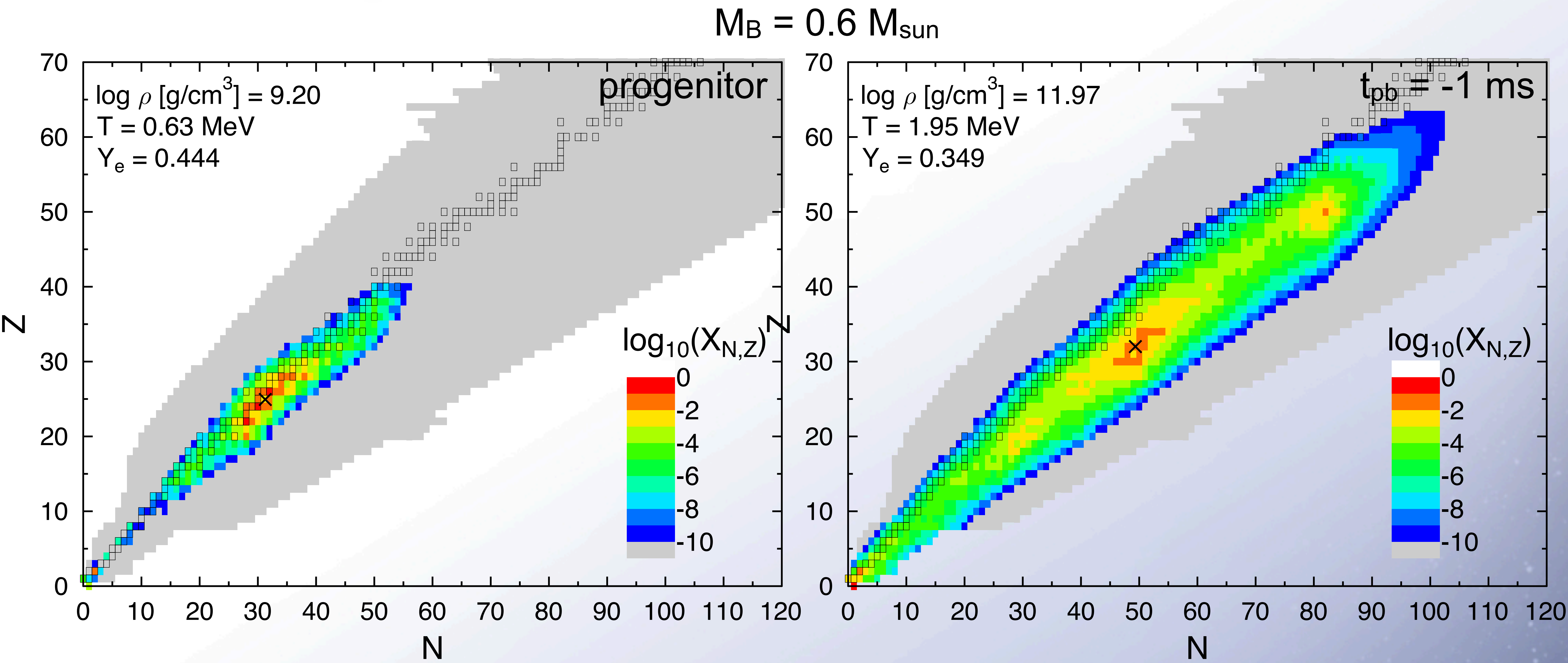


- similar trends as in LMP rates, just due to the EOS
- wiggles in Y_e due to shell effects

Nuclear composition in the SN



Nuclear composition in the SN



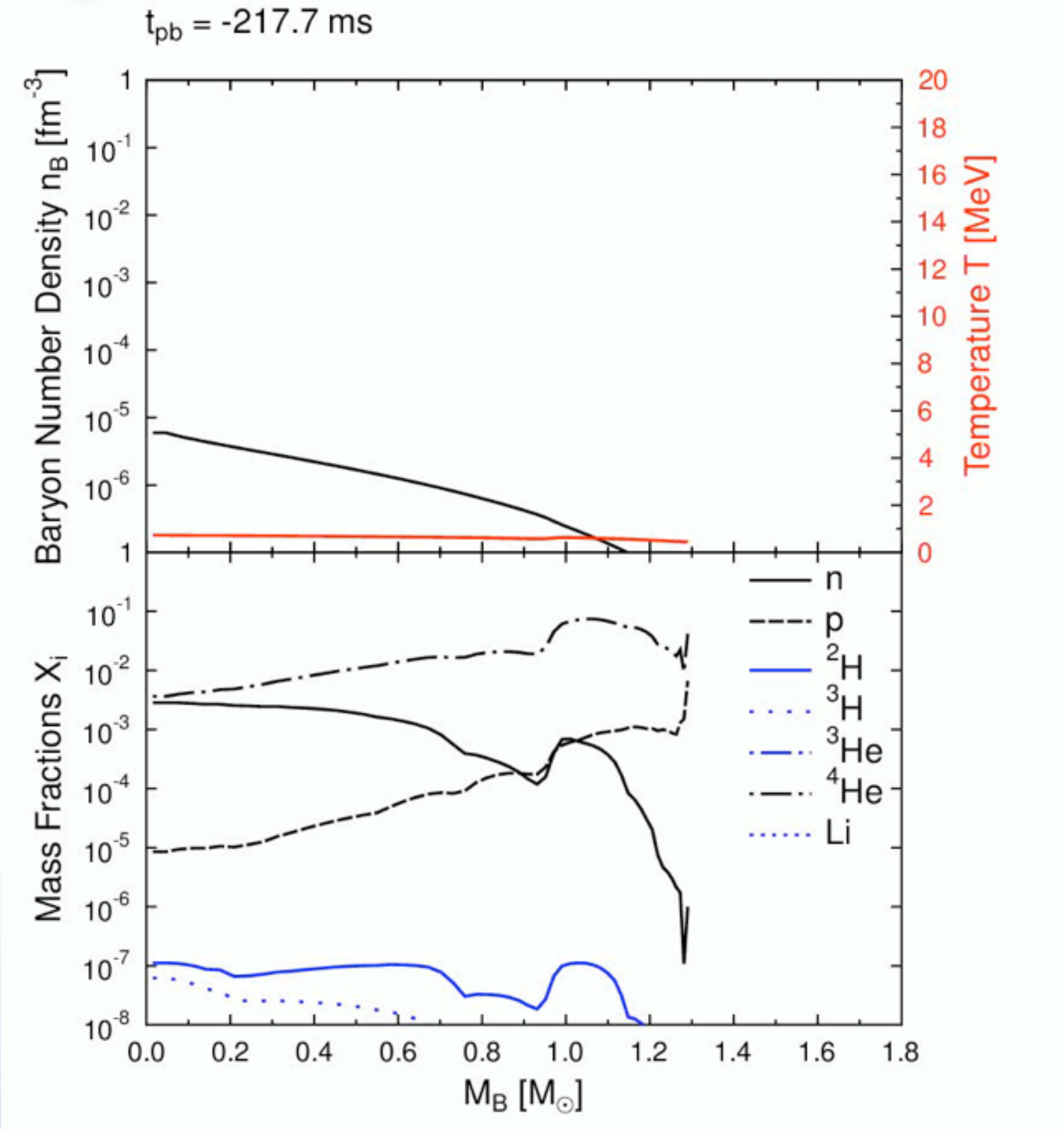
- detailed knowledge of nuclear composition
- based on nuclear structure calculations

→ allows more consistent treatment of e-captures

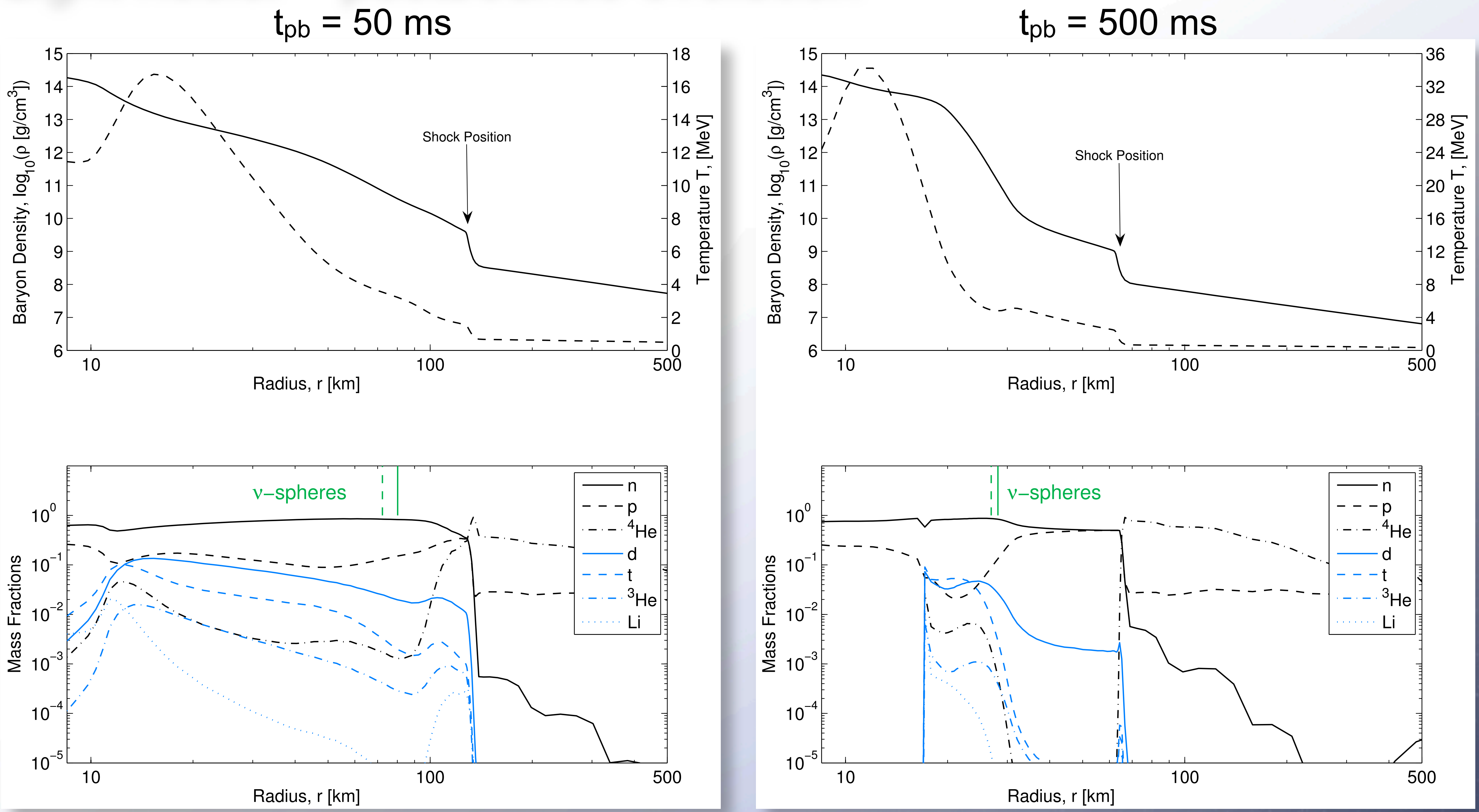
EOS aspects at subsaturation densities

- light nuclei

Light nuclei – animation from simulation



Light nuclei – postbounce evolution



- PNS core: nucleons
- PNS envelope & shock heated matter: light nuclei
- infalling matter: heavies, alphas, nucleons

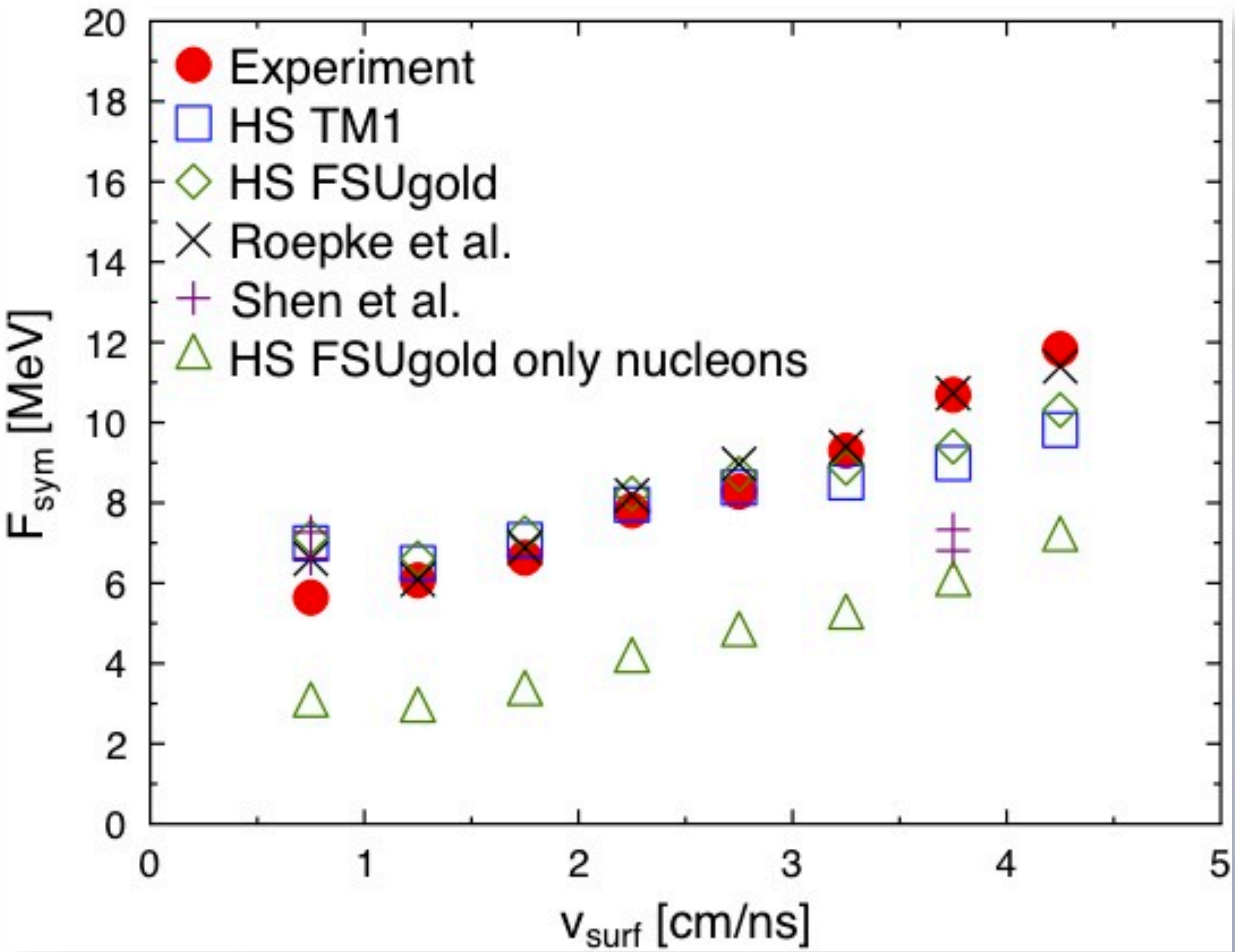
compare also:
Sumiyoshi & Röpke PRC77 2008
Typel et al. PRC81 2010

Effect of light clusters on heating/cooling?

- S. Nakamura's talk
- Arcones et al. 2008: significant change of anti-neutrino energies ~1 MeV
- O'Connor et al. 2007: A=3 breakup important for ν-energy loss
- difficult! more light nuclei ↔ less unbound protons

Light nuclei - measurement of symmetry energy

based on: *[Natowitz et al.; 2010PRL104]*



- free symmetry energy extracted from low-energy heavy ion collisions
- thermodynamic conditions: T = 3 – 7 MeV and n_B= 1/100 – 1/20 n_B^0
- cluster formation leads to increased symmetry energy

→ experimental evidence for appearance of light clusters in SN

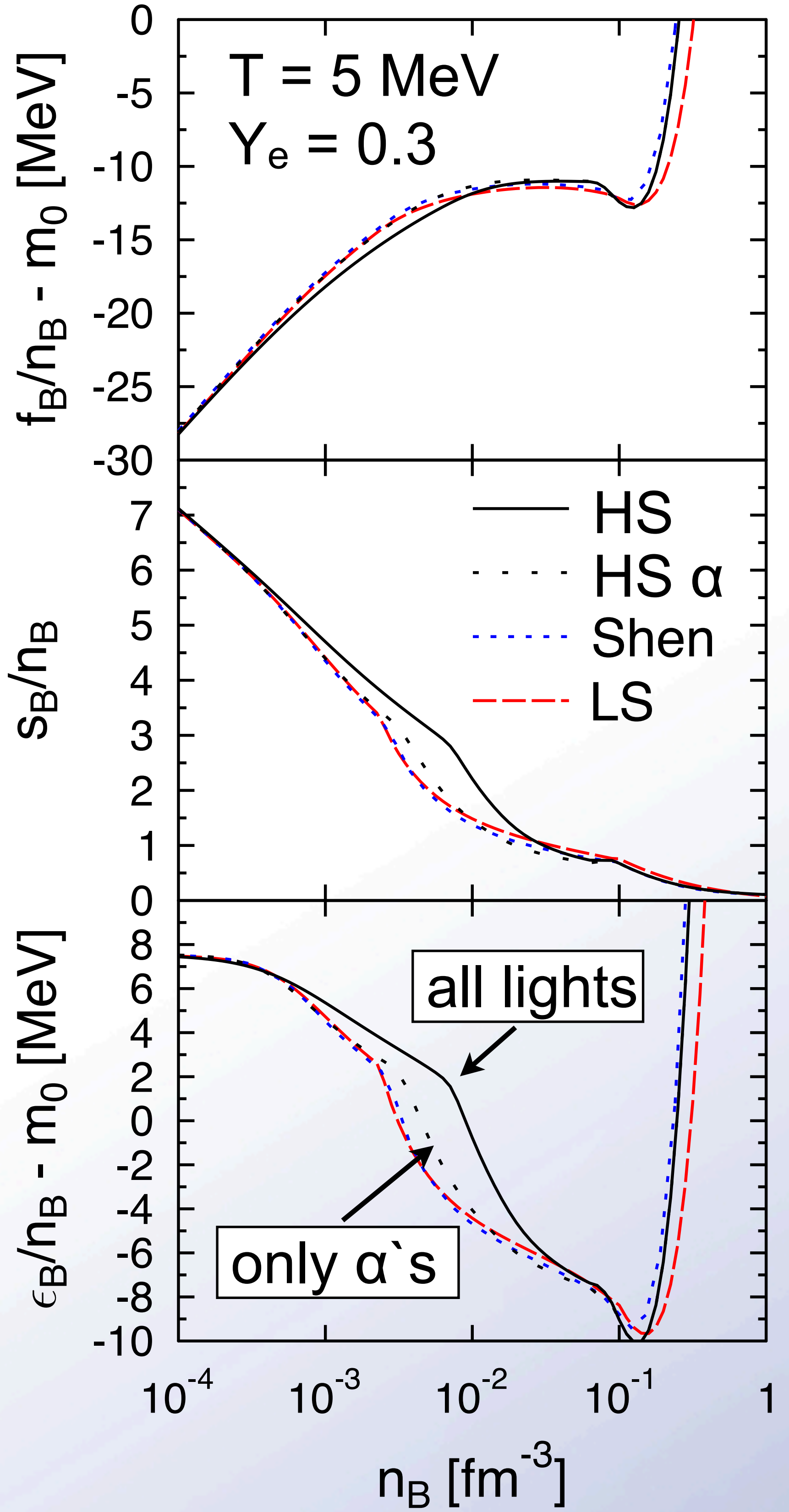
T [MeV]	3.3	3.3	3.6	4.2	4.7	5.3	6.2	7.5
n_B [10^{-3} fm^{-3}]	2.1	1.7	2.3	3.8	4.7	4.9	5.5	6.4

$$E_{sym}(n_B, T) = 1/2\,(E_{sym}(n_B, T, Y_p = 1) + E_{sym}(n_B, T, Y_p = 0)) - E_{sym}(n_B, T, Y_p = 0.5)$$

[Typel et al.; 2010PRC81]

[Kowalski et al.; 2007PRC75]

Effect of light clusters on the EOS



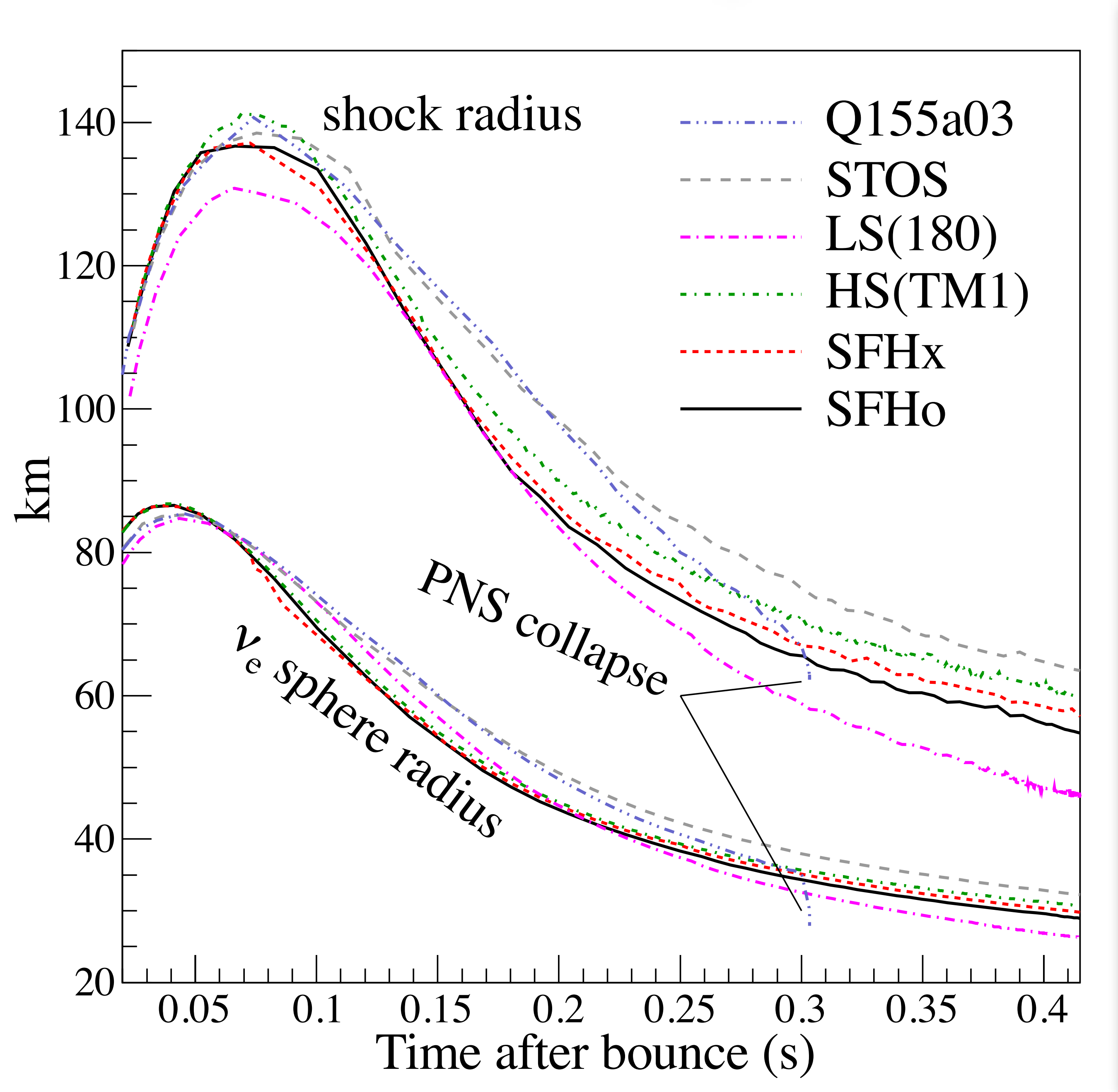
- significant increase of entropy and internal binding energy
- light nuclei contribute to the symmetry energy → increase of Y_e in beta-equilibrium

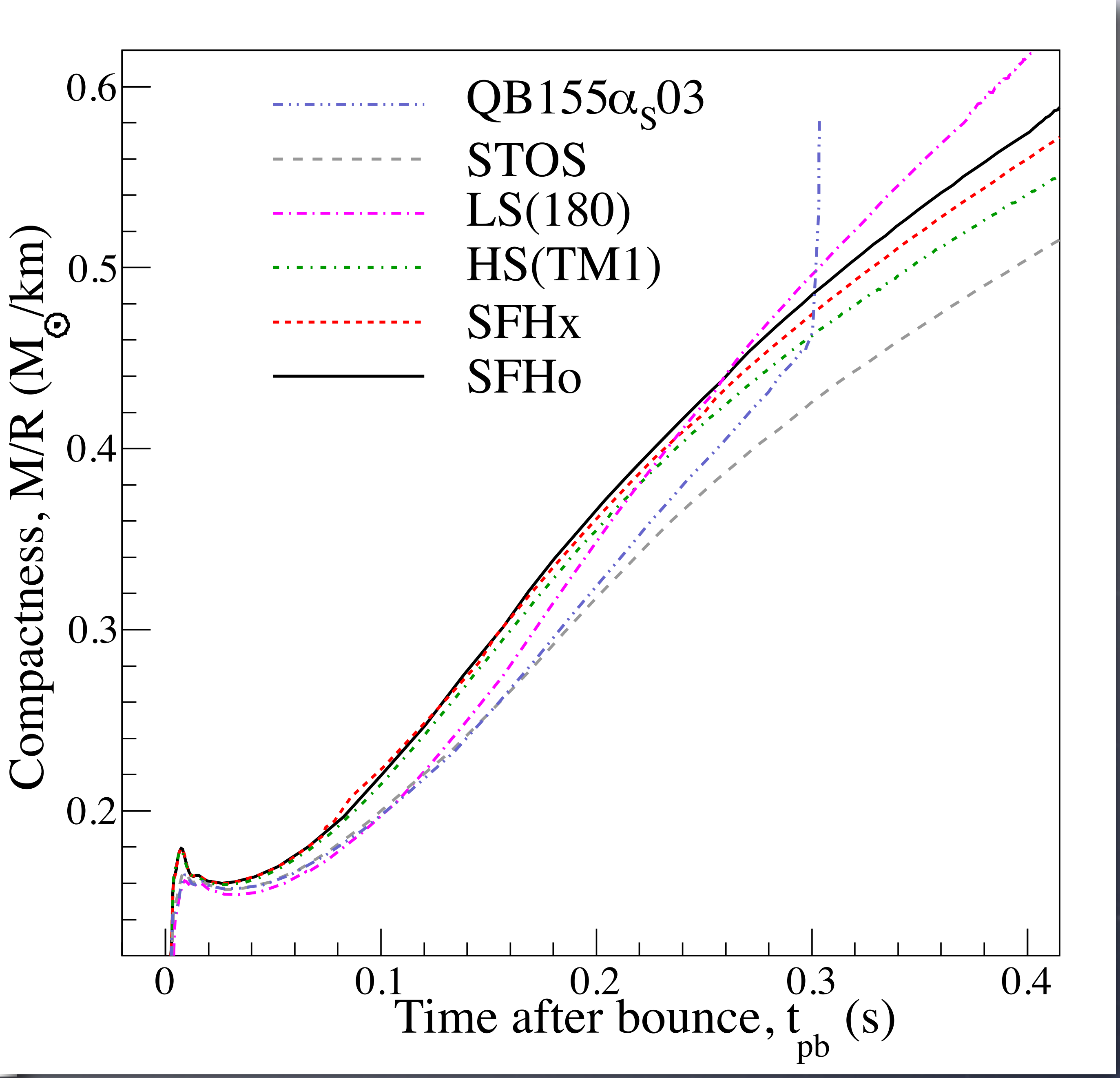
→ non-trivial effect of LC on the EOS

→ change of the structure of the proto-neutron star envelope

EOS effect on SN dynamics

[A. Steiner, MH & T. Fischer, in preparation]





- new EOS give most compact PNS up to 300 ms post-bounce
- complicated role of J, K, L
- low density EOS as important as nuclear interactions

EOS aspects at supersaturation densities

- time until black hole formation for a 40 M_{sun} progenitor

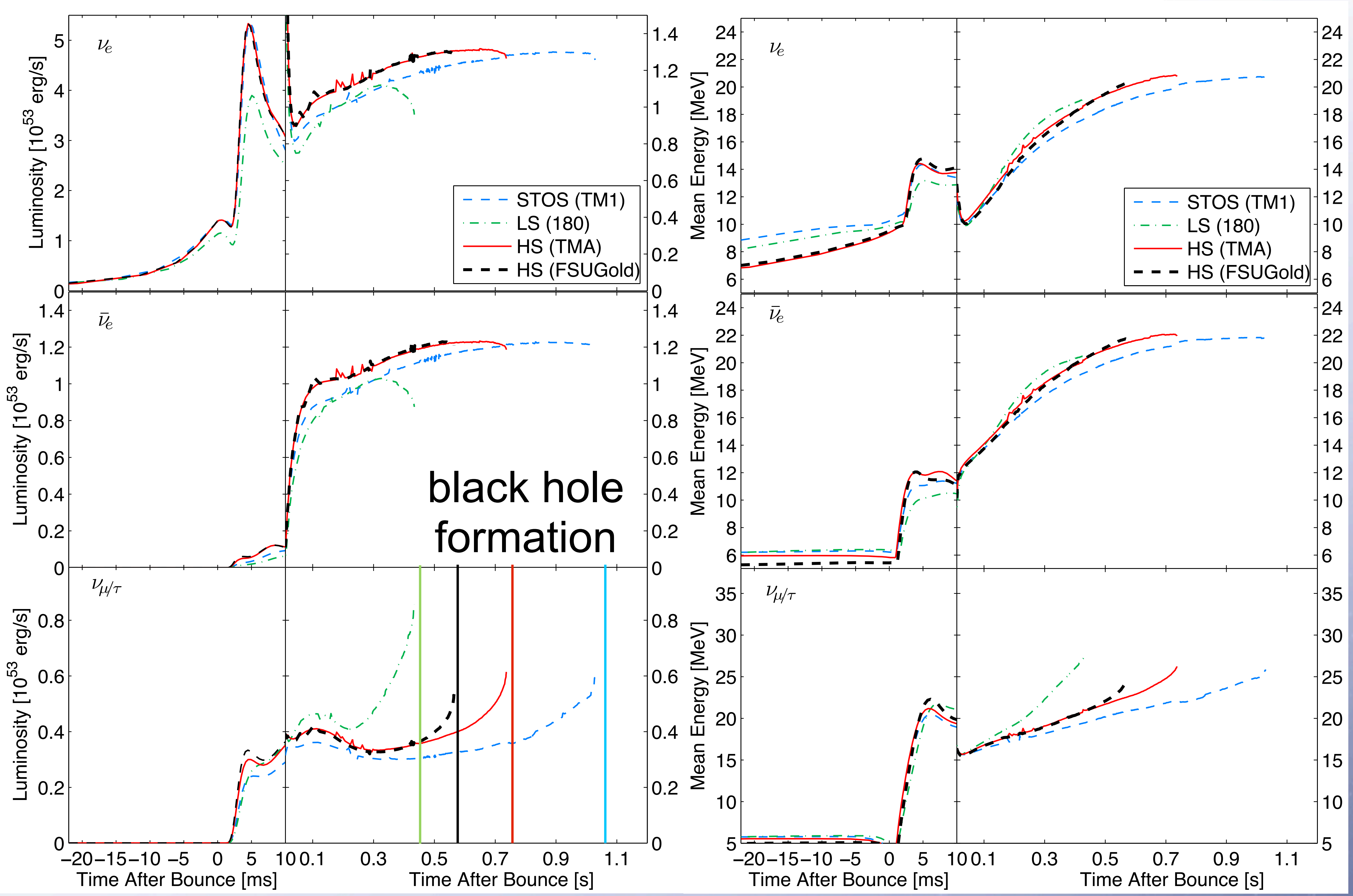
Supernova simulations – EOS signal from black hole formation

MH, T. Fischer, J. Schaffner-Bielich, M. Liebendörfer, ApJ 748, 70 (2012)

- simulations by Tobias Fischer, GSI Darmstadt
- 40 M_{sun} progenitor of Woosley & Weaver ApJS 101 (1995)
- setup as for the 15 M_{sun} progenitor

- “failed supernova“: collapse to black hole
- high densities and temperatures

Neutrino signal



• μ/τ-neutrinos most sensitive to EOS because emitted from deeper layers

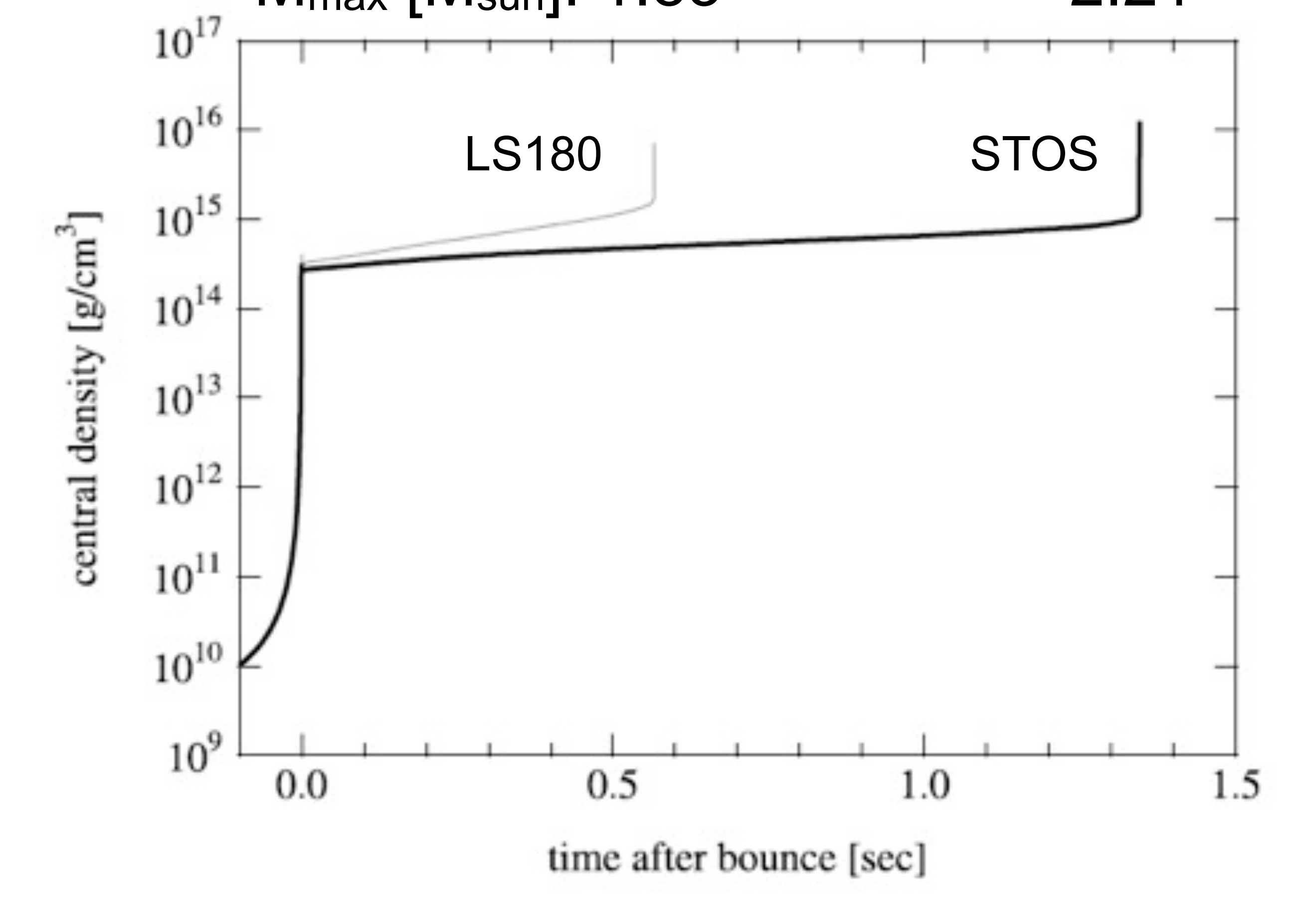
Matthias Hempel
IINT Seattle, 6.7.2012

Time until black hole formation

- previous EOS studies for this progenitor

K [MeV]: 180 282

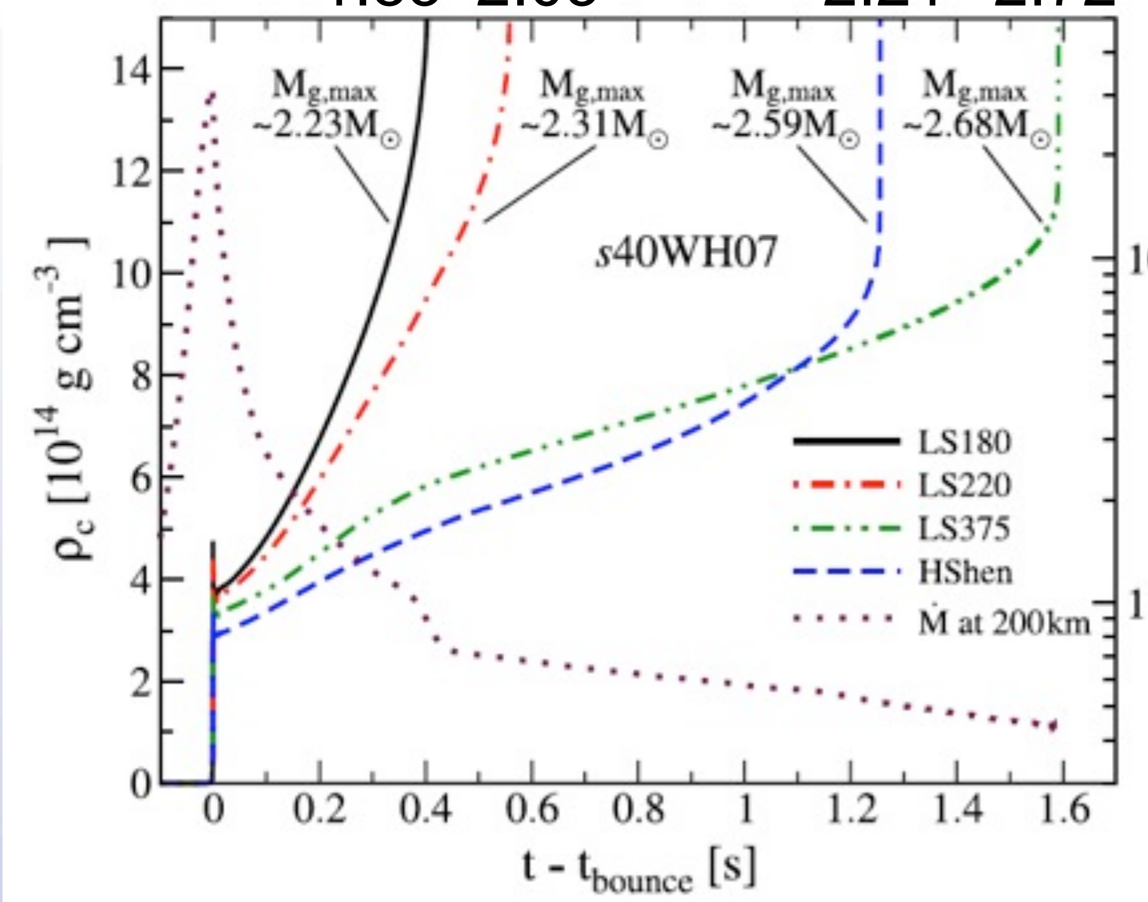
M_{max} [M_{sun}]: 1.83 2.21



[Sumiyoshi et al.; 2007ApJ667]

180 220 282 375

1.83 2.03 2.21 2.72

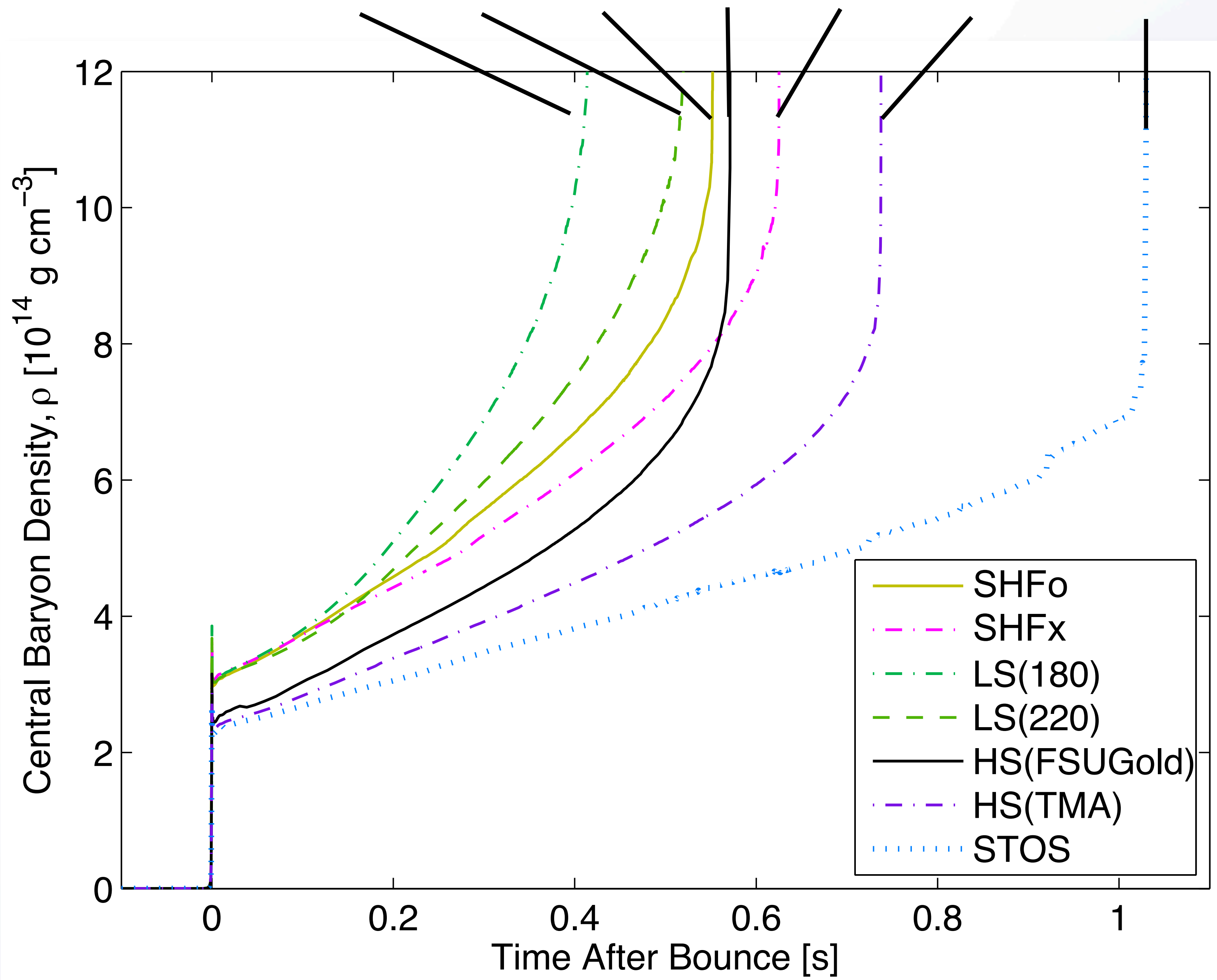


[O'Connor & Ott.; 2011ApJ730]

- possible conclusion: the compressibility K / the maximum mass M_{max} dictates „soft" or „stiff" behavior

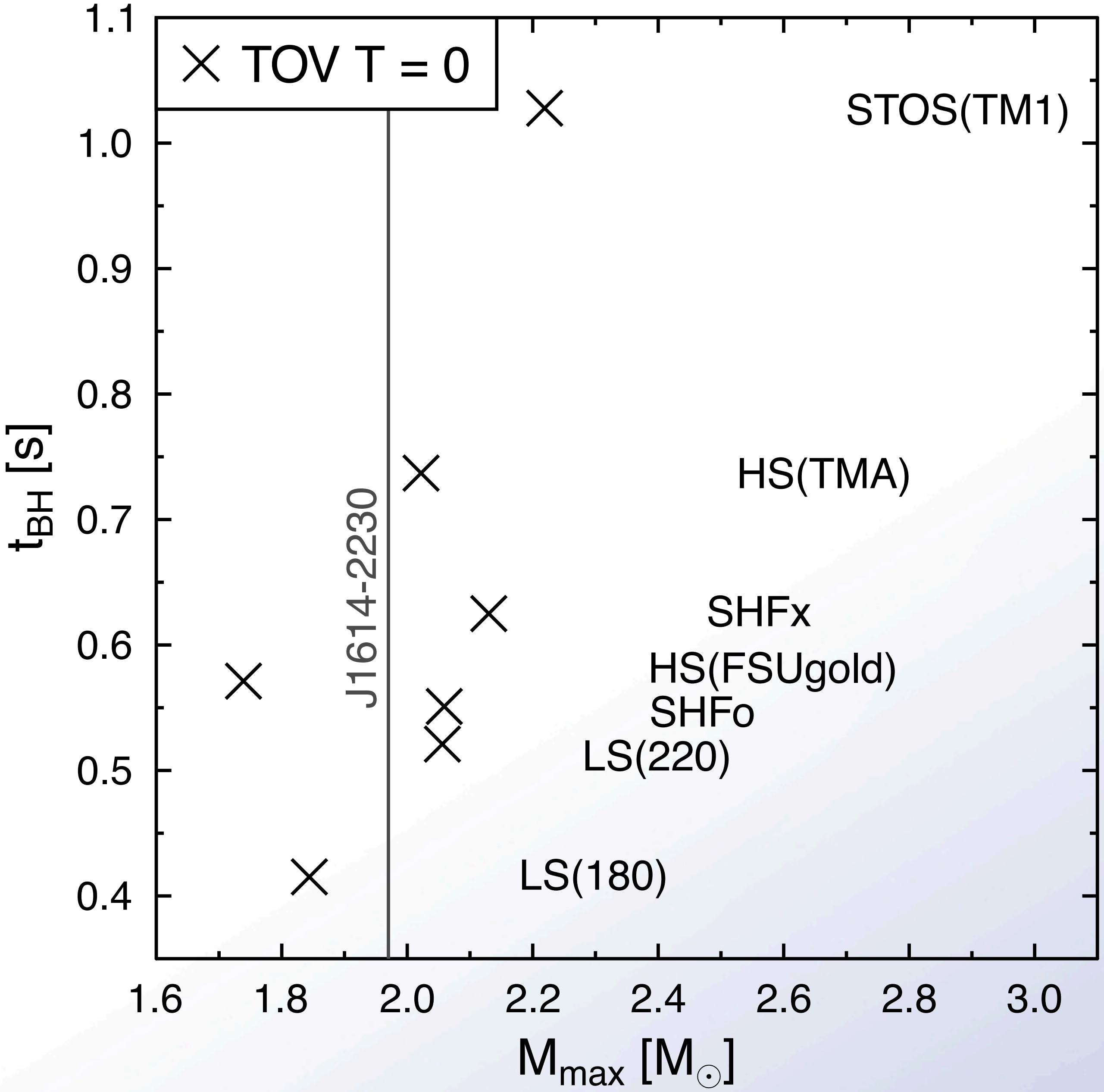
Time until black hole formation

K [MeV]:	180	220	245	230	239	318	282
M_{max} [M_{sun}]:	1.83	2.03	2.06	1.74	2.13	2.02	2.21
J [MeV]:	28.6	28.6	31.6	32.6	28.7	30.7	37.0
L [MeV]:	73.8	73.8	47.1	60.4	23.2	90.1	111.0

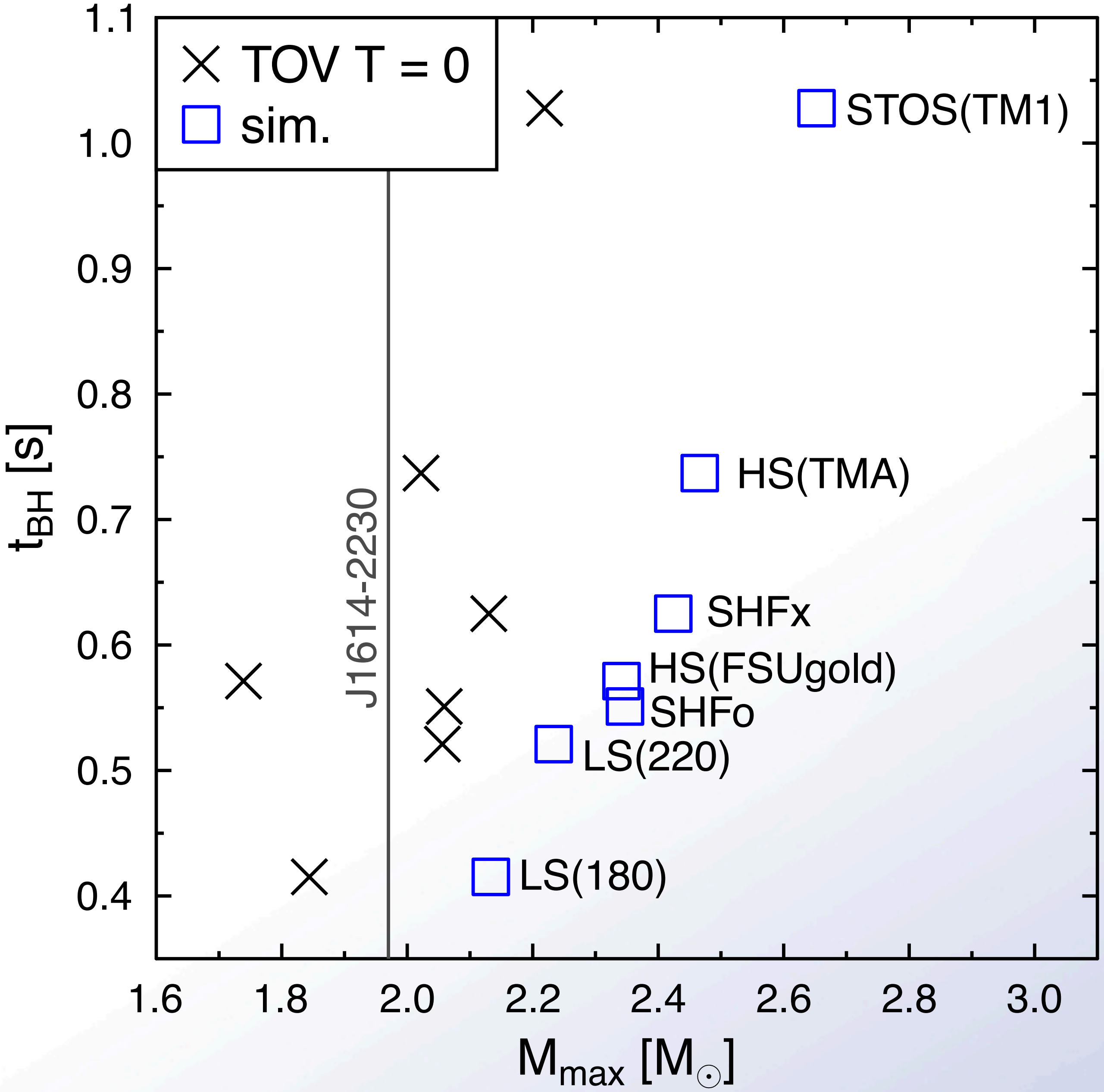


- unexpected: maximum mass of cold neutron stars and K are not directly correlated with t_{BH}
- neither correlated with J or L
- not found before, because only STOS and LS were available

Correlation of t_{BH} with maximum mass

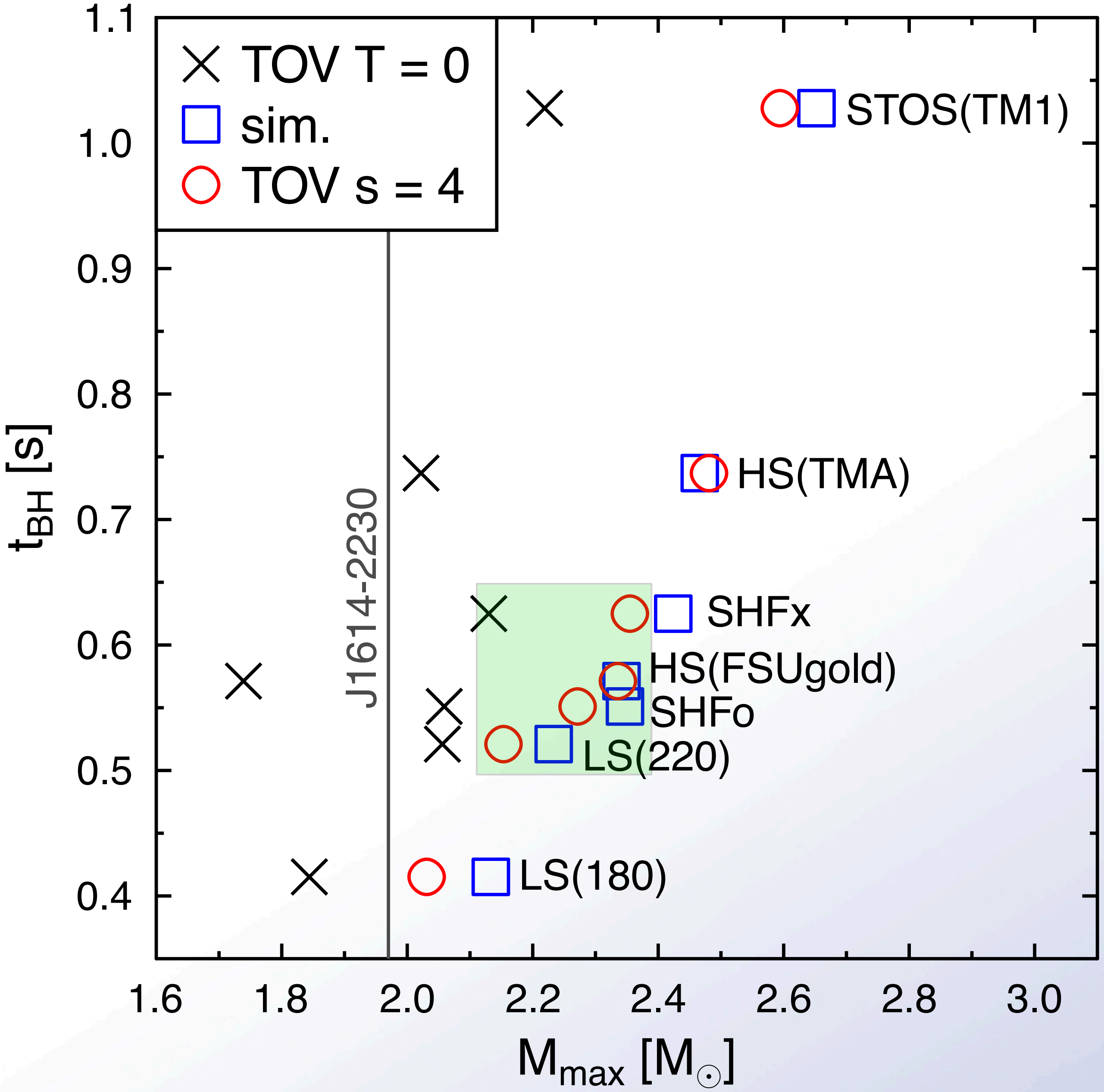


Correlation of t_{BH} with maximum mass



- maximum masses in the simulations are significantly increased (up to 0.6 M_{sun}) compared to T = 0

Correlation of t_{BH} with maximum mass



- maximum masses in the simulations are significantly increased (up to 0.6 M_{sun}) compared to T = 0
- static s = 4 configurations reproduce the simulations
- new correlation: t_{BH} gives information about the finite entropy EOS
- degeneracy with progenitor star

  [O'Connor & Ott.; 2011ApJ730]
- experimental/observational EOS constraints important

- extreme temperature effects

→ is there a simple explanation?

Specific heat

- specific heat in the degenerate limit as a guide-line:

$$c_V = T\alpha_V = s$$

$$\epsilon(T, n_B, Y_e) = \epsilon(T=0, n_B, Y_e) + \frac{1}{2}T^2 n_B \alpha_V$$

$$\alpha_V = \left(\frac{\pi}{3}\right)^{2/3} n_B^{-2/3} m^* \left[Y_e^{1/3} + (1-Y_e)^{1/3}\right]$$ “level-density parameter“

[Lattimer & Prakash, Phys. Rep. 2000]

- change of pressure:

$$p(T, n_B, Y_e) = p(T=0, n_B, Y_e) + \Delta\epsilon \left(\frac{2}{3} - \frac{n_B}{m^*}\frac{\partial m^*}{\partial n_B} - \frac{2}{9}\frac{n_B}{Y_e^{2/3}}\frac{\partial Y_e}{\partial n_B}\right)_{T=0}$$

$$\Delta\epsilon = \frac{1}{2}T^2 n_B \alpha_V$$

Finite entropy effect in neutron stars

- beta-equilibrium, (here: without neutrinos):

$$Y_e = Y_e(n_B)$$

$$Y_e \sim \frac{4^3 E_{\mathrm{sym}}^3}{3\pi^2 n_B}$$

- TOV eqs: only p(ε) relevant, not p(n)
- change of the pressure due to entropy at given energy density:

at n_0: J, L — K, J, L

$$\begin{aligned}\Delta p_\epsilon &= p(s,\epsilon) - p(T=0,\epsilon) \\ &= \frac{1}{2} s^2 n_B \frac{1}{\alpha_V}\left(\frac{2}{3} - \frac{n_B}{m^*}\frac{\partial m^*}{\partial n_B} - \frac{2}{9}\frac{n_B}{Y_e^{2/3}}\frac{\partial Y_e}{\partial n_B} - \frac{n_B}{\mu_B}\frac{\partial \mu_B}{\partial n_B}\right)\end{aligned}$$

<0 — >0 — >0

$$\alpha_V = \left(\frac{\pi}{3}\right)^{2/3} n_B^{-2/3} m^* \left[Y_e^{1/3} + (1-Y_e)^{1/3}\right]$$

J

Finite entropy effect in neutron stars – effective mass?

	m^*/m at n_0	$M_{max}(T=0)$	$\Delta M_{max}(s=4)$
LS(220)	1	2.03	0.09
NL3	0.595	2.79	0.10
DD2	0.563	2.42	0.15
LS(180)	1	1.83	0.19
SHFo	0.761	2.06	0.21
SHFx	0.718	2.13	0.24
TM1	0.634	2.21	0.37
TMA	0.635	2.02	0.46
FSUgold	0.611	1.74	0.62

- despite the same specific heat LS(180) and LS(220) differ
- larger K in agreement with smaller ΔM for LS(220)
- note: ΔM < 0 possible, i.e. softening, e.g. for LS(375) (O`Connor & Ott 2011)
- temperature effects tend to decrease with high $M_{max}(T=0)$

→ it‘s not only m^{*0} or α_V^0

$$\Delta p_\epsilon = \frac{1}{2} s^2 n_B \frac{1}{\alpha_V} \left(\frac{2}{3} - \frac{n_B}{m^*}\frac{\partial m^*}{\partial n_B} - \frac{2}{9}\frac{n_B}{Y_e^{2/3}}\frac{\partial Y_e}{\partial n_B} - \frac{n_B}{\mu_B}\frac{\partial \mu_B}{\partial n_B} \right)$$

$$\alpha_V = \left(\frac{\pi}{3}\right)^{2/3} n_B^{-2/3} m^* \left[Y_e^{1/3} + (1-Y_e)^{1/3} \right]$$

- around saturation density: $\left.\frac{\partial \mu_B}{\partial n_B}\right|_{n_B^0} = \frac{1}{n_B^0}\left(\frac{1}{9}(K + K_{\rm sym}) + \frac{2}{3}L\right)$

Conclusions

- new SHFo and SHFx EOS: fit to NS observations
- EOS tables and nuclear composition available for NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx:
  http://phys-merger.physik.unibas.ch/~hempel/eos.html

- the model for nuclei can be as important as the nuclear interactions

- could light nuclei influence the PNS cooling and/or the ν-driven wind?

- black hole formation gives information about the finite entropy EOS
- temperature effects depend significantly on the EOS model

- complex role of the EOS, not “soft or stiff“
- individual nuclear matter properties are not sufficient to characterize the EOS

- EOS effect on explosions: → 3D simulations

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