Signals of the equation of state from black-hole formation

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in collaboration with:

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comp star

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Outline:

1.) Introduction to the supernova EOS

2.) EOS constraints from experiments and neutron stars

3.) Core-collapse supernova simulations with black-hole formation

4.) 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

	neutron stars	supernovae	heavy ion collisions
timescales	(d - Myrs)	ms	fm/c
equilibrium	full	weak eq. only partly	only strong eq.
temperatures	0	0 - 100 MeV	10 - 200 MeV
charge neutrality	yes	yes	no
asymmetry	high	moderate	low

- matter in SN: no weak equilibrium, finite temperature
  → somewhere between cold neutron stars and heavy-ion collisions
- challenge of the supernova EOS:
  - $T = 0 – 100$ MeV
  - $Y_e = 0 – 0.6$
  - $\rho = 10^4 – 10^{15}$ g/cm^3
  - EOS in tabular form, ~1 million configurations (T, Y_e, ρ)
- SN EOS: multi-purpose EOS

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

Typel et al. (2010)	table for DD2 in preparation: gRMF
Furusawa et al. (2011)	table for TM1 in preparation: liquid drop, NSE, RMF

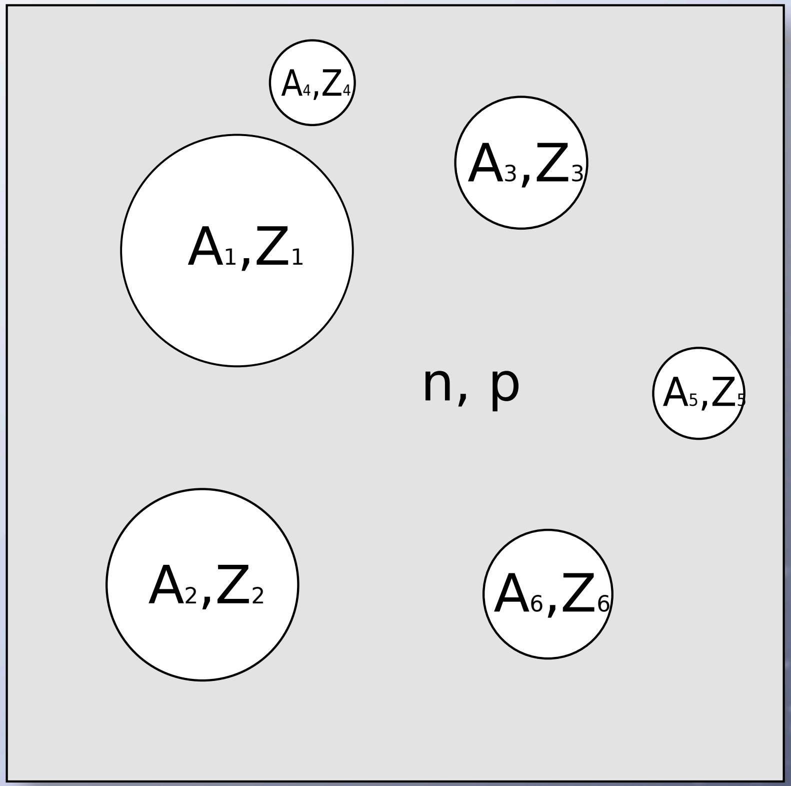
Nakazato et al. 2008	quark matter with large n_c added to STOS
Ishizuka et al. 2008	hyperons added to STOS
Sagert et al. 2009	quark matter with low n_c added to STOS → explosions in 1D
H. Shen et al. 2010	lambdas added to STOS

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
- model characteristics:
  - ensemble of heavy nuclei
  - inclusion of all possible light nuclei
  - nuclear shell effects
  - various nucleon interactions
- input: nuclear mass tables, Coulomb energies, excited states, excluded volume effects, RMF interactions



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

Nucleons – Relativistic Mean-Field

- interaction by meson exchange
- non-linear RMF with meson (self-) interactions (TM1, TMA, FSUgold, NL3)

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

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

Sugahara & Toki 1994

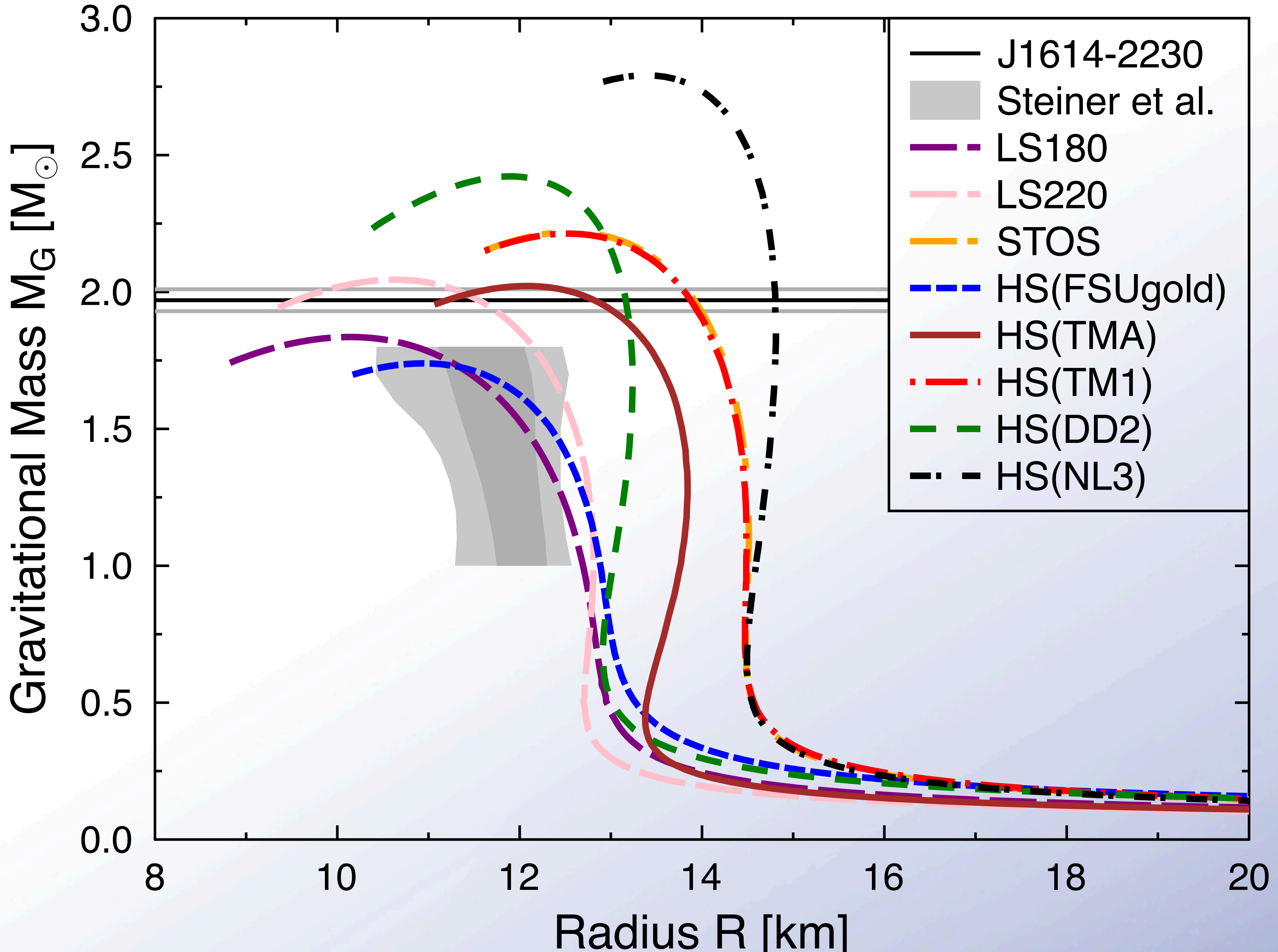
Toki et al. 1995

Todd-Rutel & Piekarewicz 2005

Lalazissis et al. 1997

Typel 2005, Typel et al. 2010

EOS constraints – NS mass and radius measurements



- PSR J1614-2230: Demorest et al. Nature 2010
- bayesian analysis of observations of seven NS, Steiner et al. ApJ 2010, Steiner et al. arXiv 2012

- new EOS fitted to observations: Andrew Steiner(Seattle) Tobias Fischer (GSI)
- compact PNS → more binding energy release in a SN

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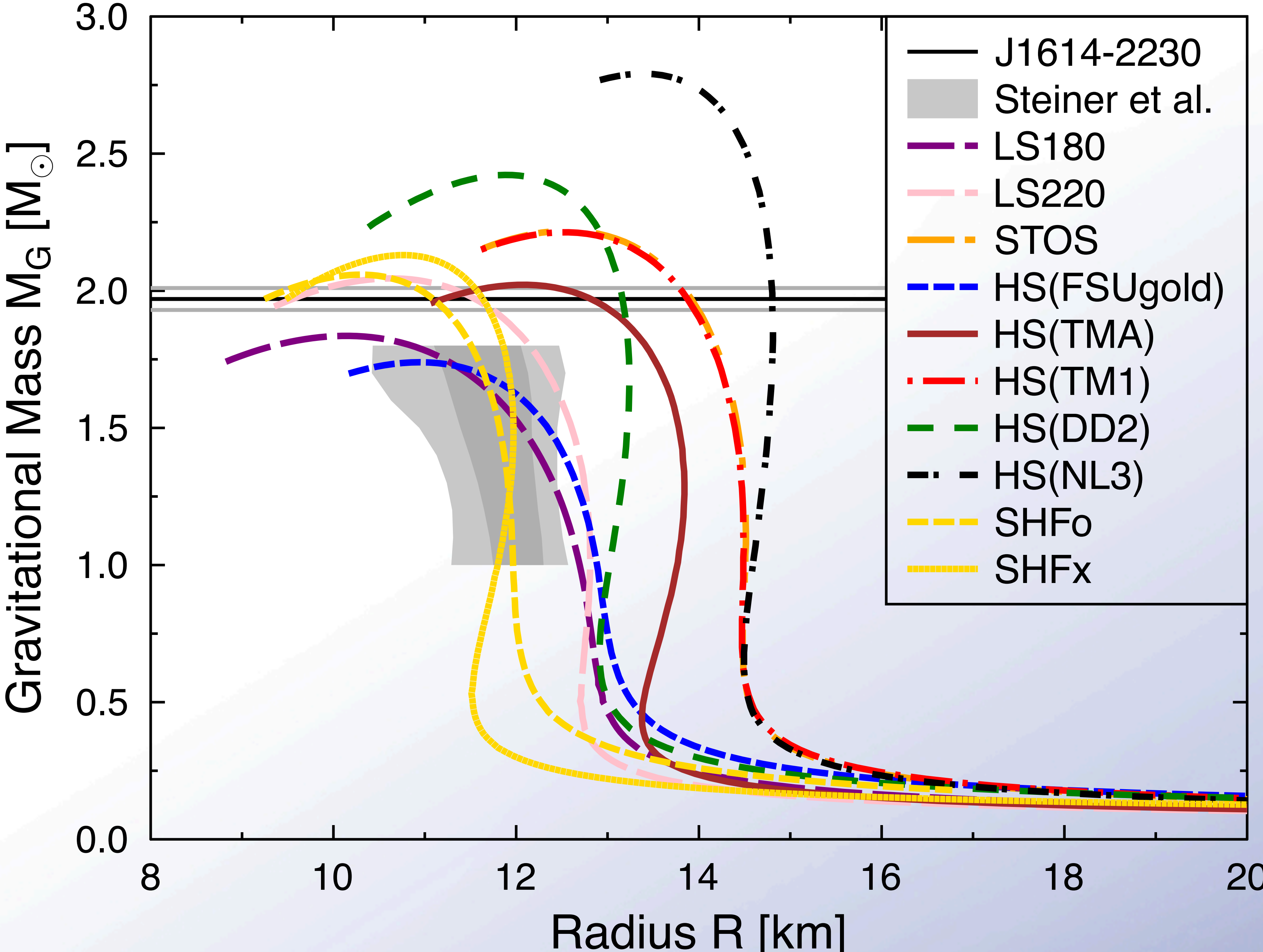

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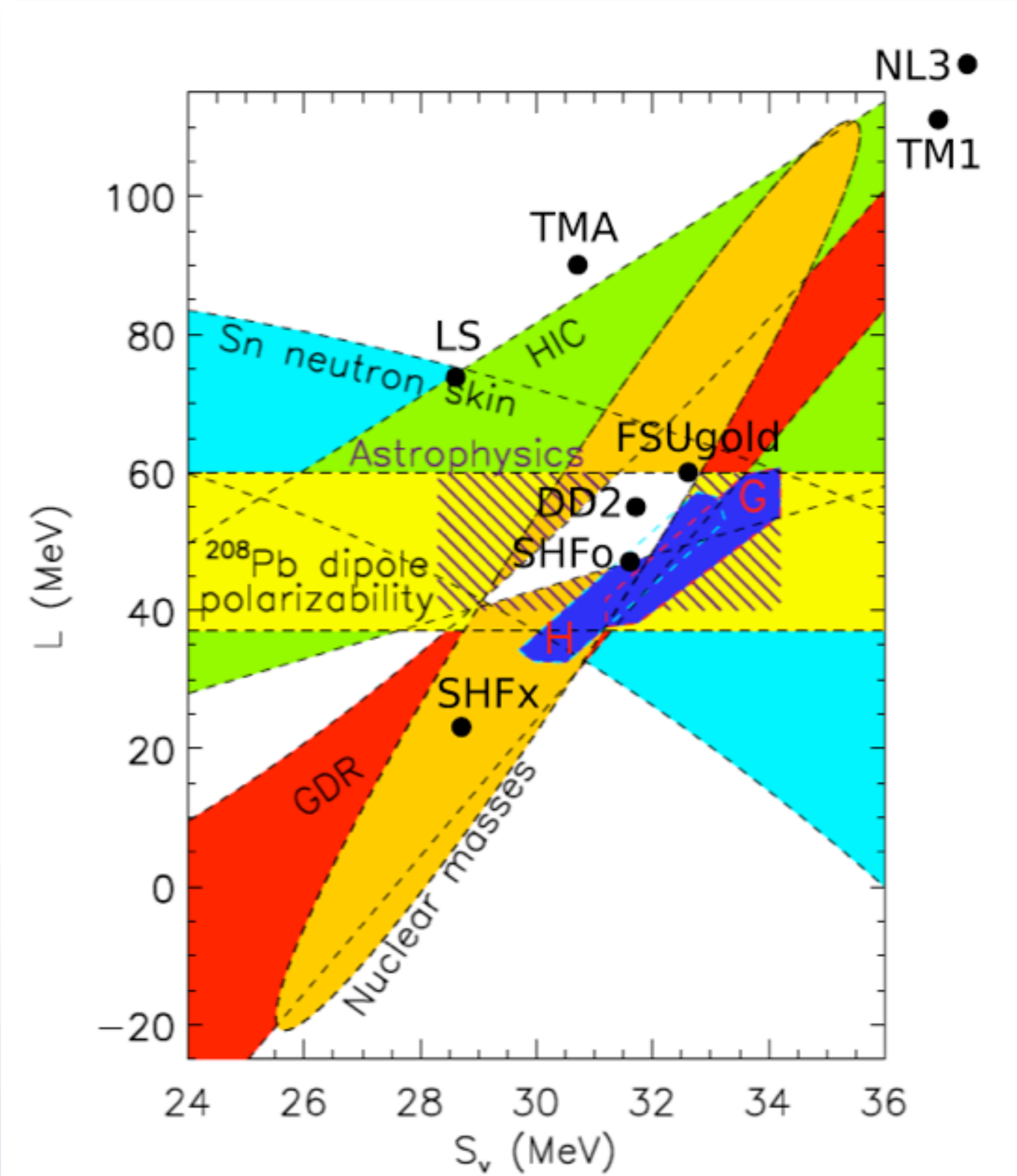
A. Steiner, MH, T. Fischer; arXiv1207.2184

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]

→ additional constraints from heavy-ion experiments at high densities:

FOPI (W. Trautmann/N. Hermann)

KAOS (C. Sturm)

- 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

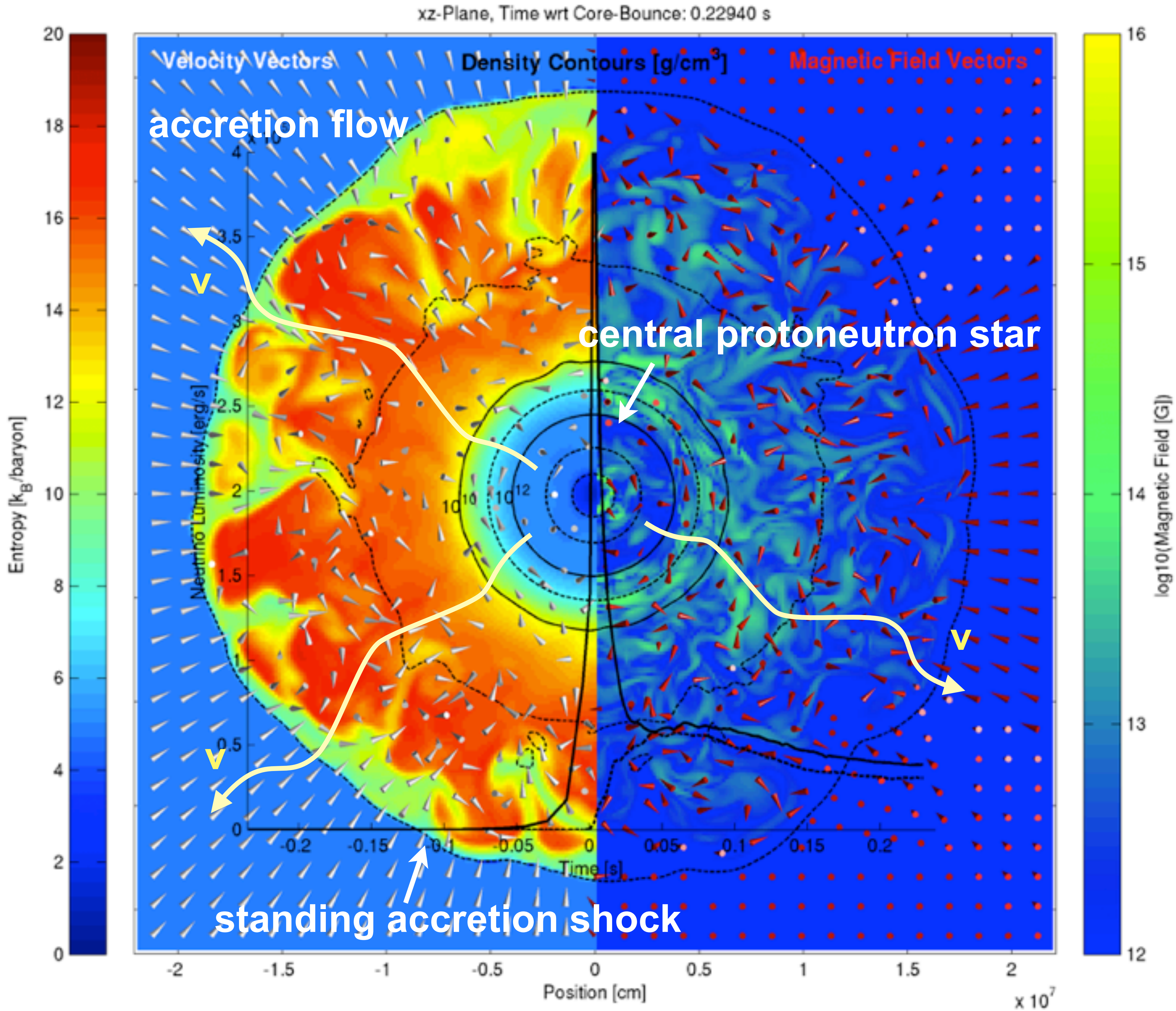
Supernova simulations – EOS signal from black hole formation

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

A. Steiner, MH, T. Fischer; arXiv1207.2184

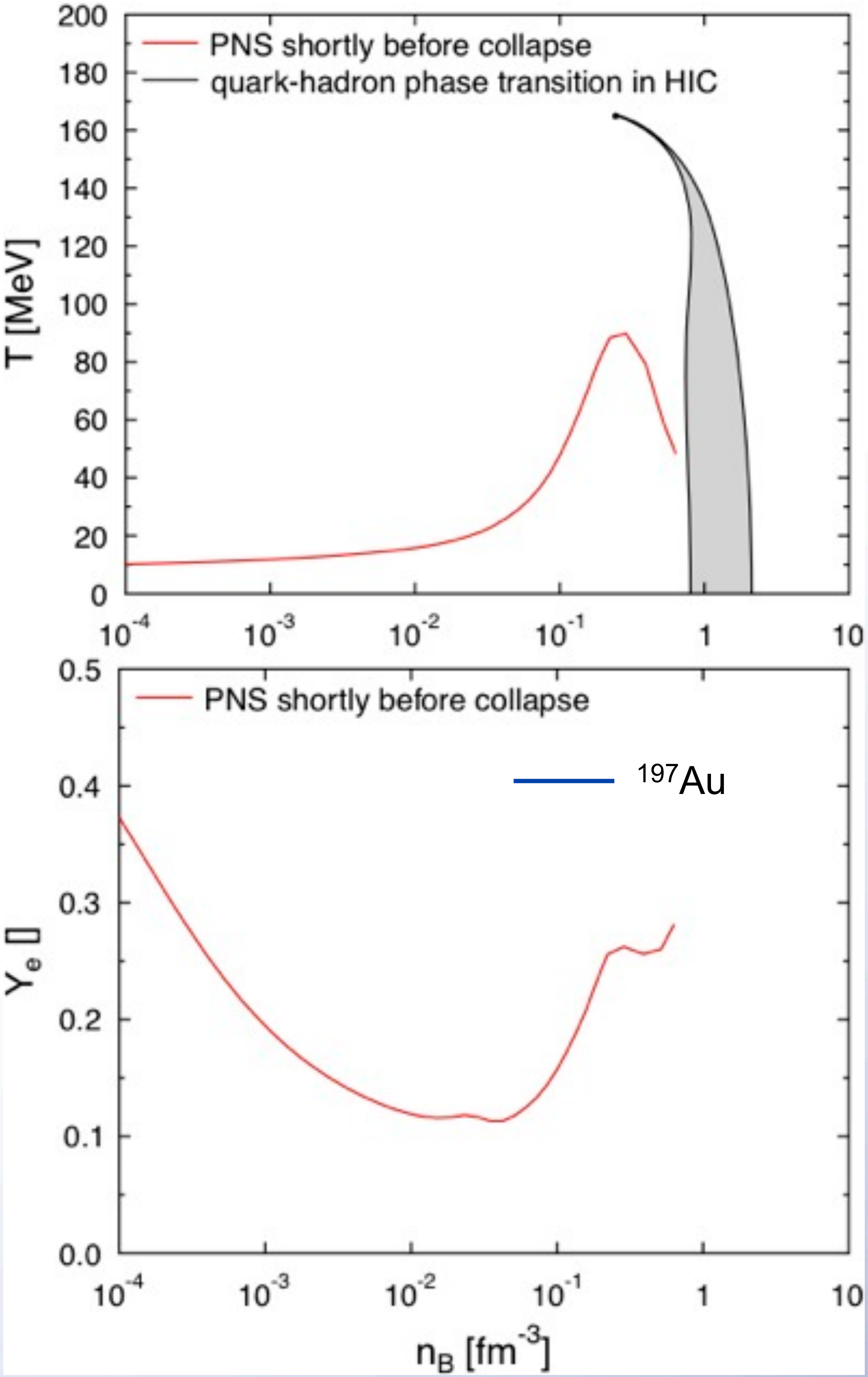
- simulations by Tobias Fischer, GSI/TU Darmstadt
  - general relativistic radiation hydrodynamics in spherical symmetry
  - three flavor Boltzmann neutrino transport

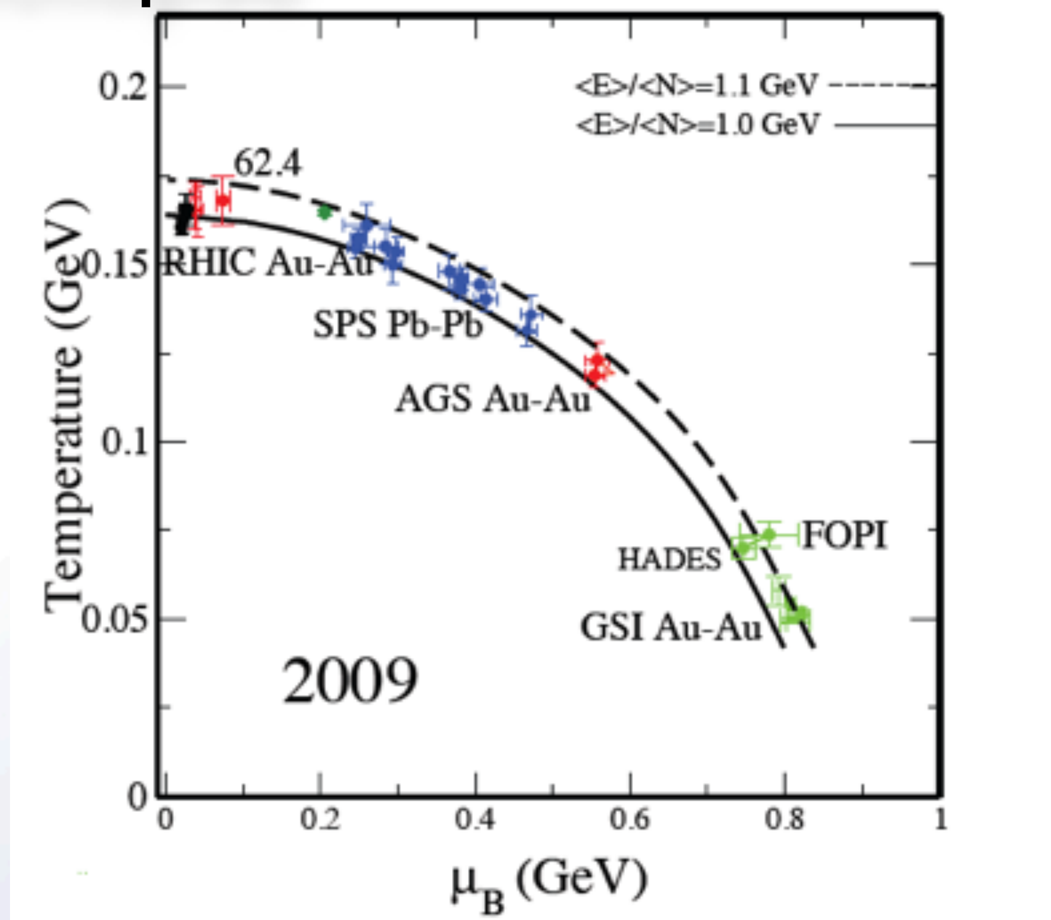
- 40 M_{sun} progenitor of Woosley & Weaver ApJS 101 (1995) (blue supergiant)
- “failed supernova“: core-collapse to stellar black hole



- snapshot from a 3D simulation by M. Liebendörfer (15 M_{sun} progenitor)
- continuous emission of neutrinos, measurable with present neutrino detectors

State of matter before the collapse





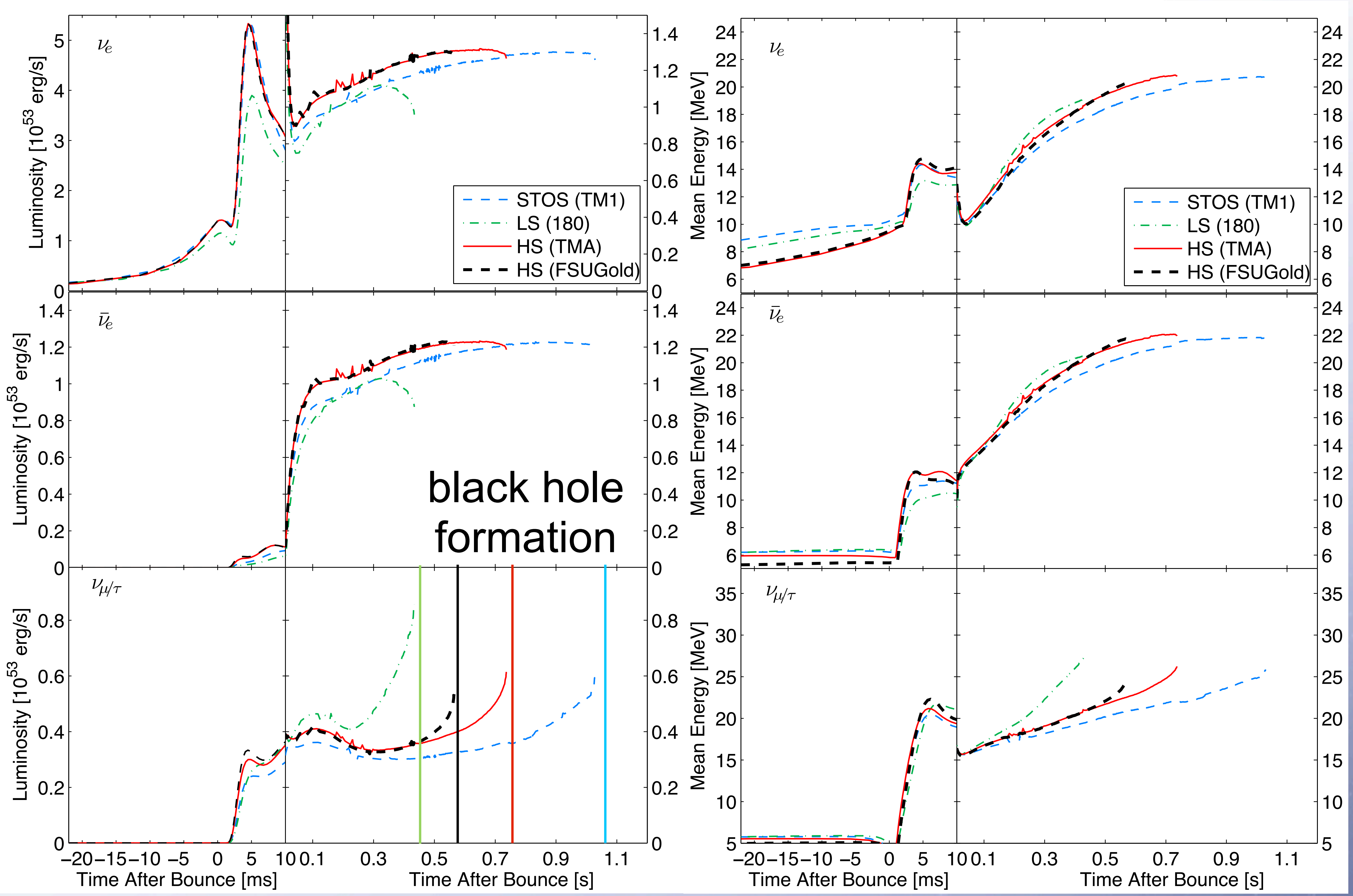
taken from a talk of J. Cleymans

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772, 167, 2006
J. Manninen, F. Becattini, M, Gazdzicki, Phys. Rev. C73 044905, 2006
R. Picha, U of Davis, Ph.D. thesis 2002
J. Takahashi, SQM2008

- phase diagram calculated by V. Dexheimer, Chiral SU(3) model

→ similar conditions as in a heavy-ion collision (but in weak equilibrium)

Neutrino signal



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

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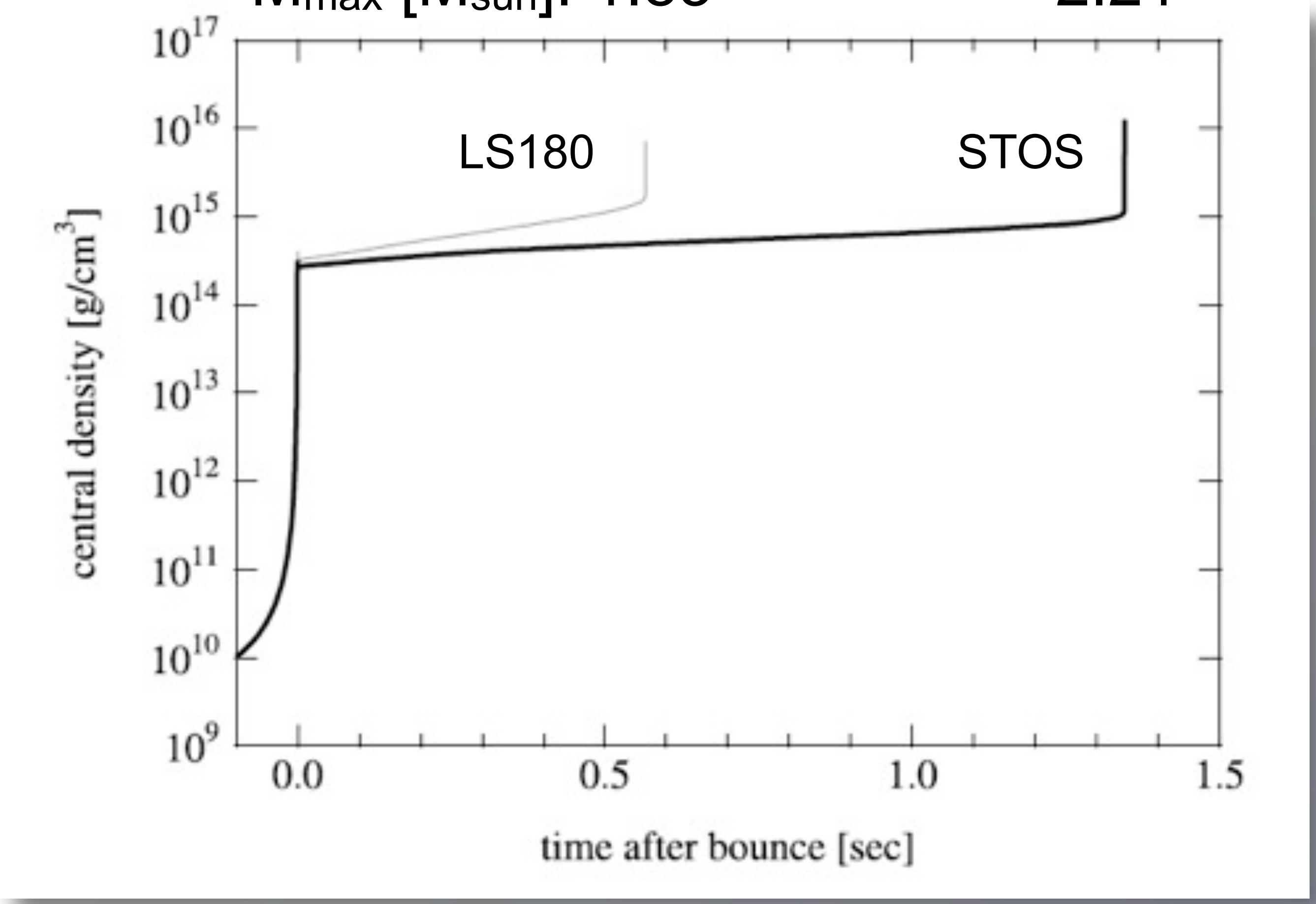
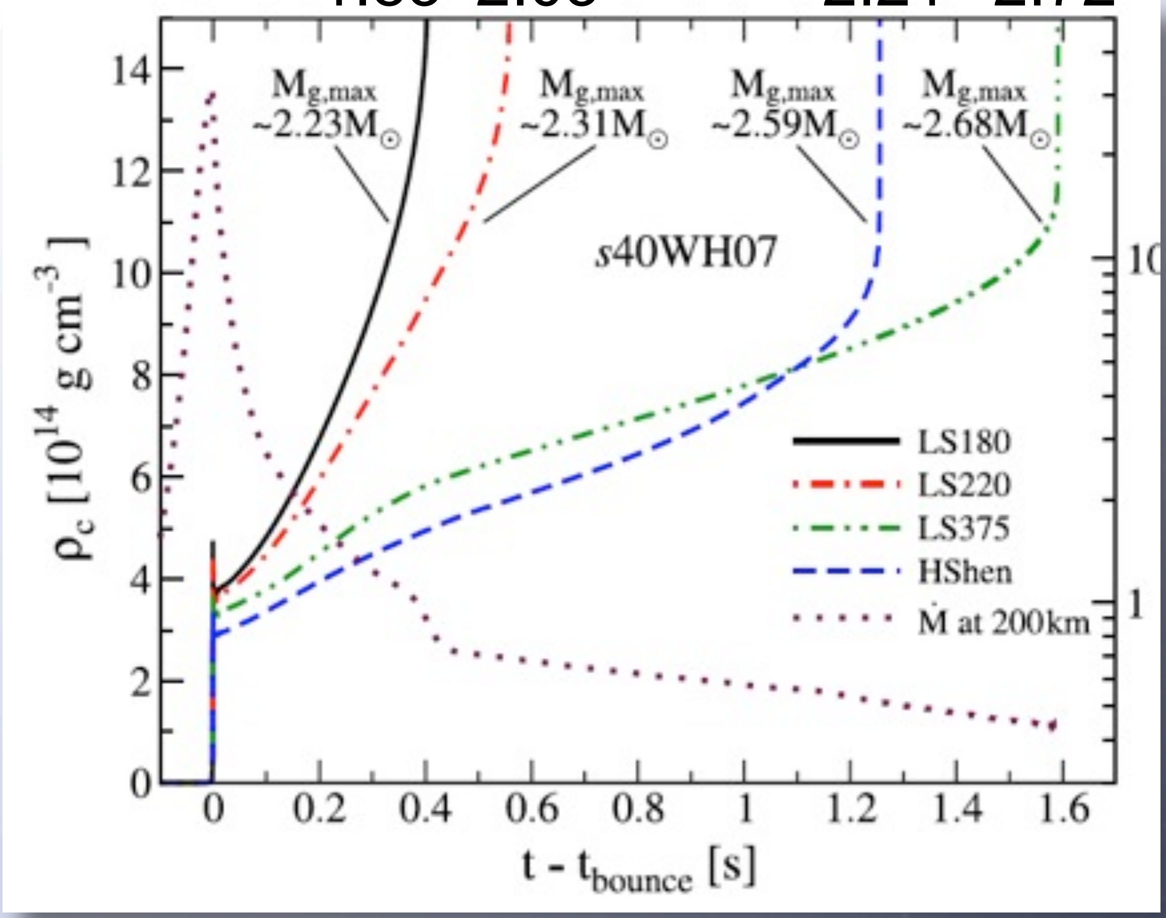
Time until black hole formation

- previous EOS studies for this progenitor

K [MeV]:	180	282	180	220	282	375
M_{max} [M_{sun}]:	1.83	2.21	1.83	2.03	2.21	2.72



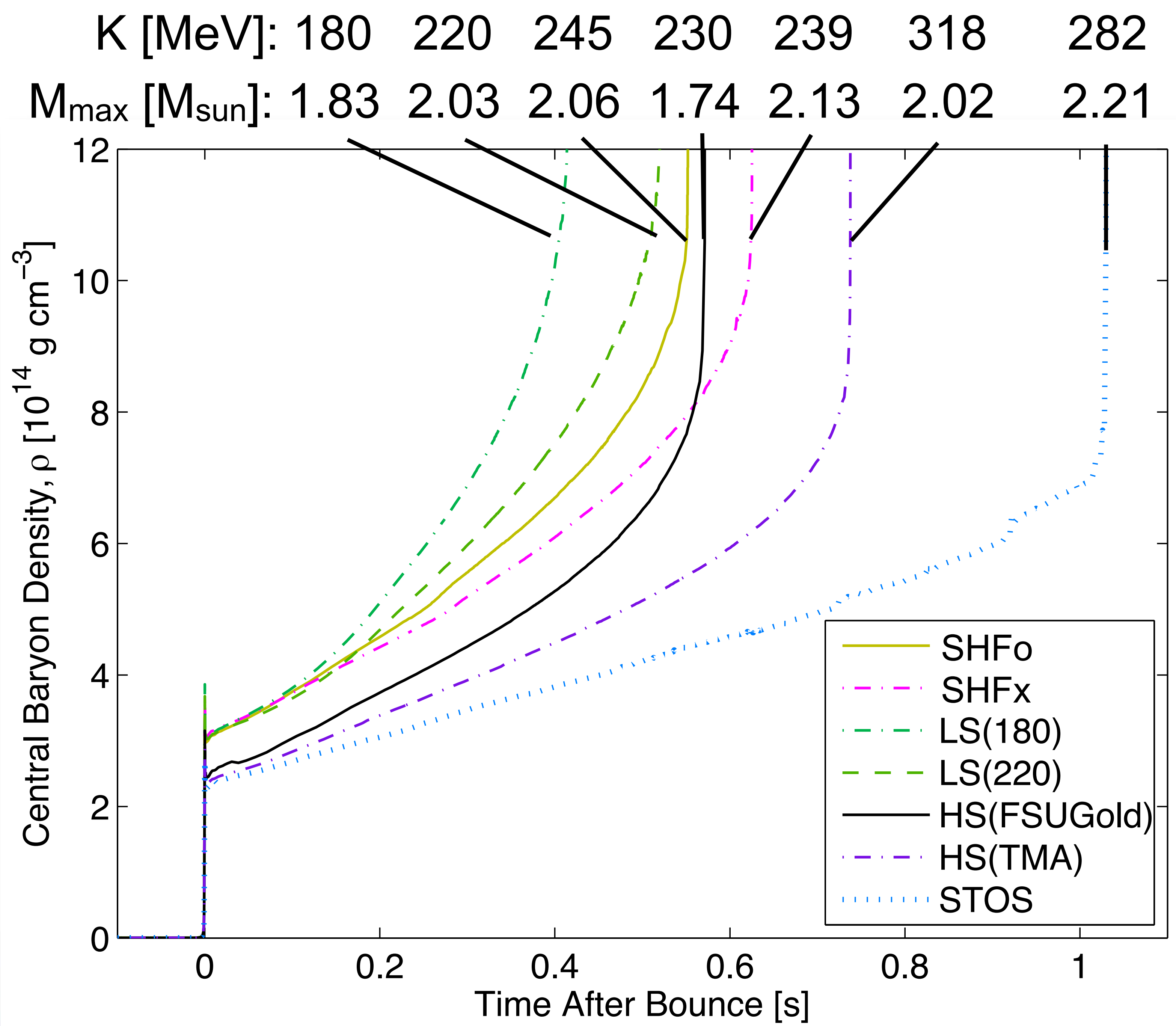
[Sumiyoshi et al.; 2007ApJ667]



[O'Connor & Ott.; 2011ApJ730]

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

Time until black hole formation



- unexpected: maximum mass of cold neutron stars and K are not directly correlated with t_{BH}
- not found before, because only STOS and LS were available

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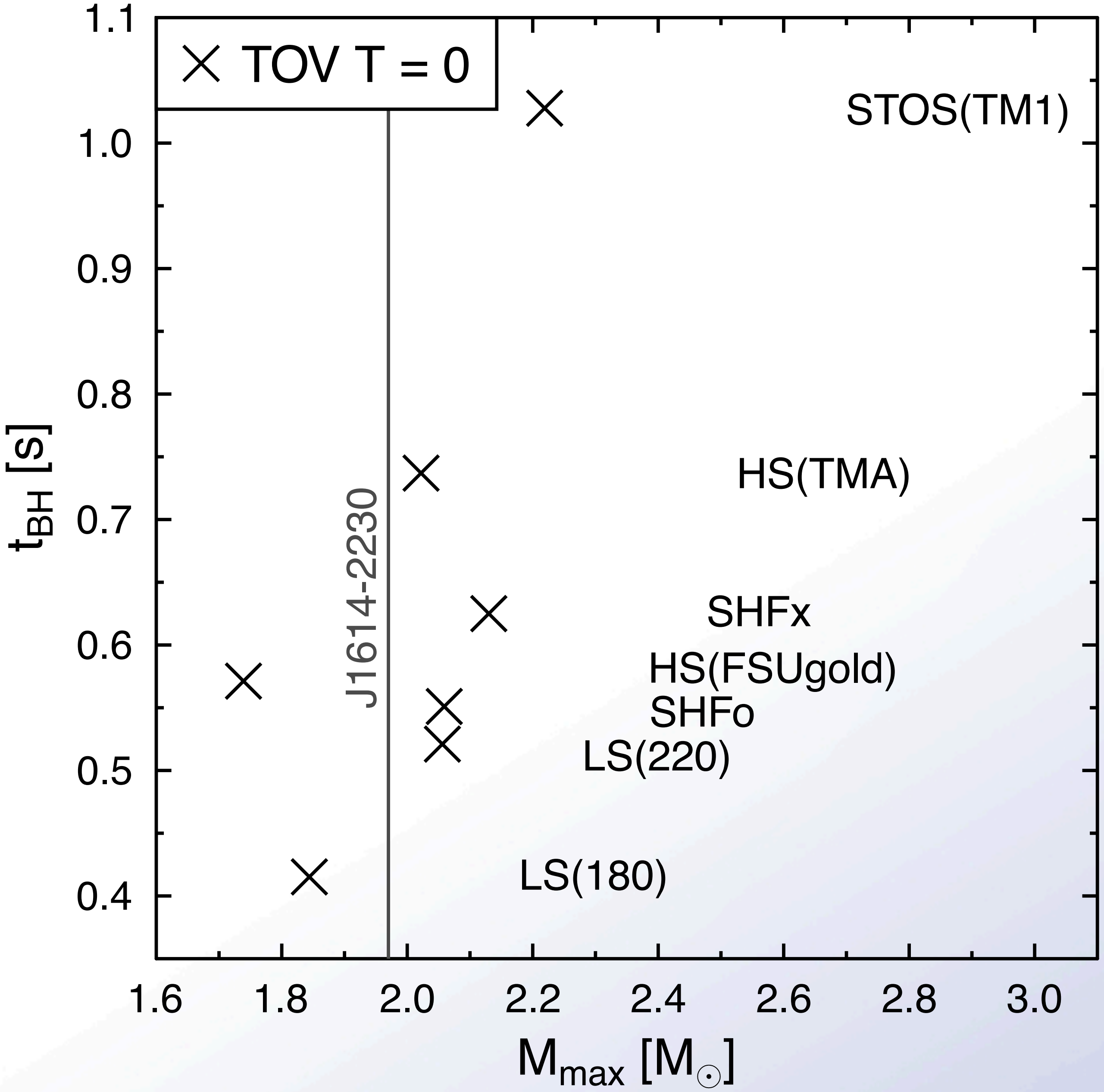
Correlation of t_{BH} with maximum mass



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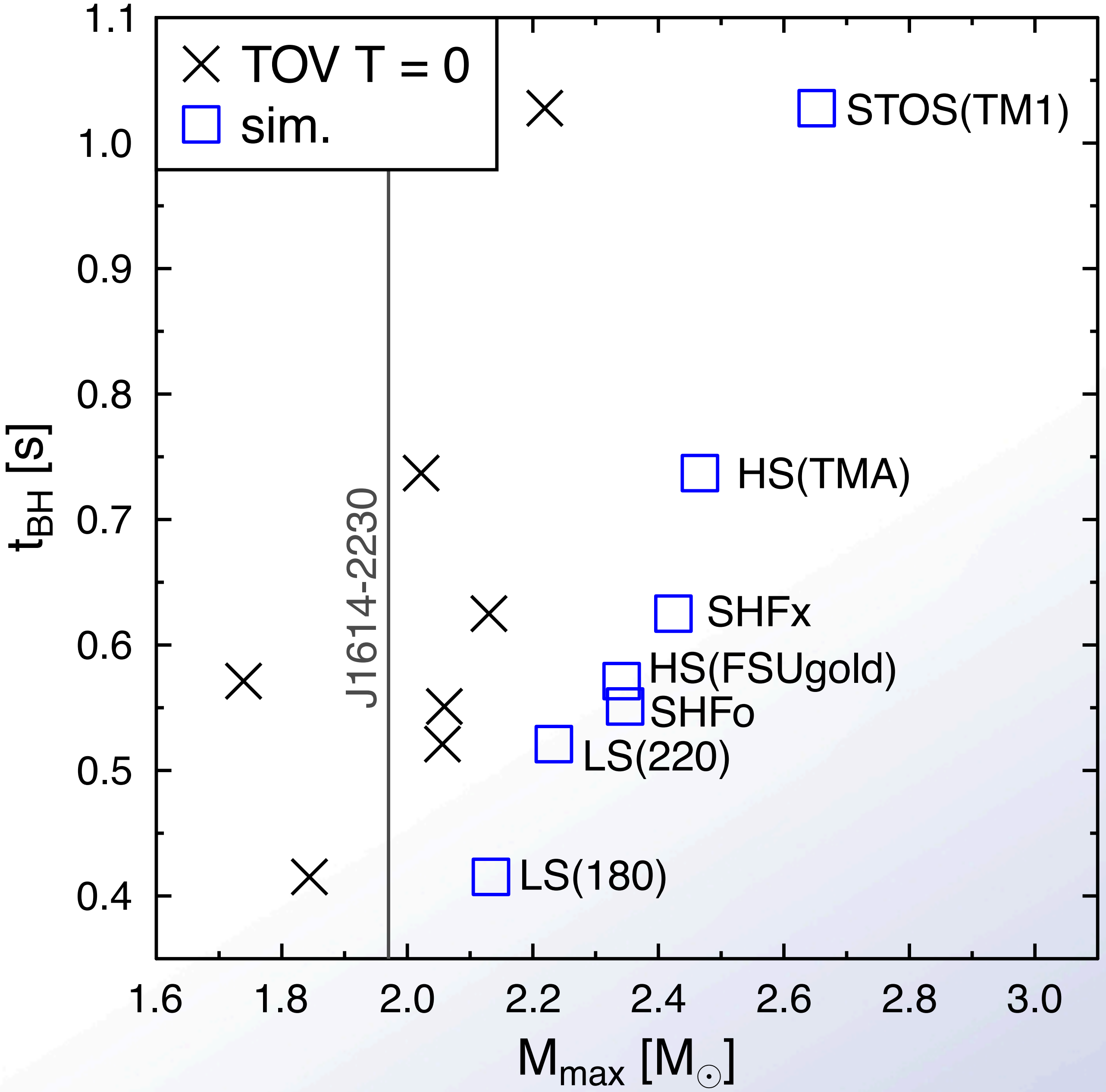
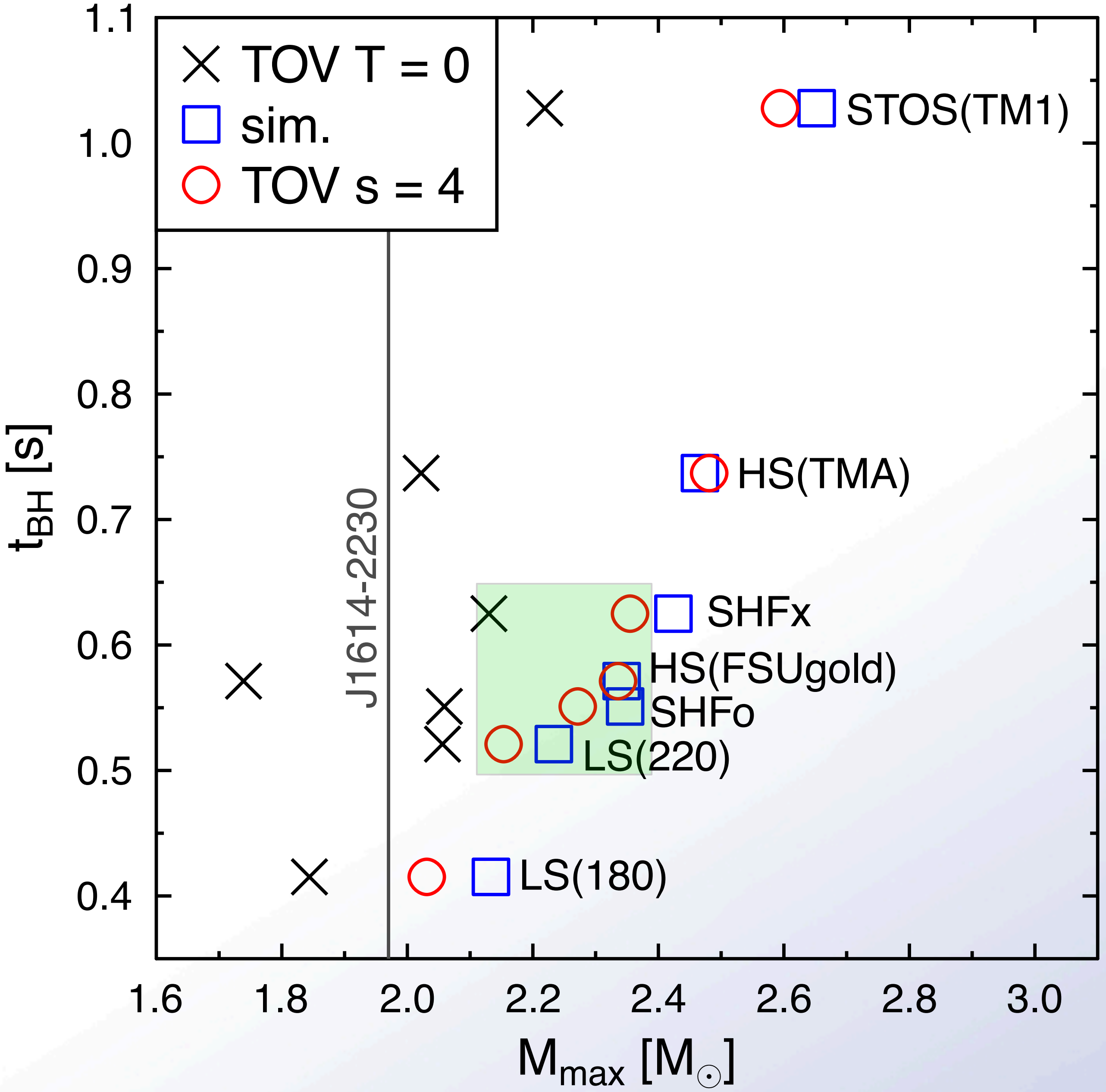


- maximum masses in the simulations are significantly increased (up to 0.6 M_{sun}) compared to T = 0

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

- complex temperature effects
- due to: effective mass, symmetry energy, non-relativistic vs. relativistic
- new correlation: t_{BH} gives information about the finite entropy EOS

- EOS constraints important

Conclusions

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

- conditions in supernovae are somewhere between heavy-ion collisions and neutron stars

- theory, nuclear experiments and neutron stars constrain supernova dynamics

- black hole formation gives information about the finite temperature EOS

- temperature effects are EOS model dependent
  → extract information about nucleon effective mass or symmetry energy