The phase diagram of QCD, third families of proto-compact stars, and the possibility of core-collapse supernova explosions

[MH, O. Heinimann A. Yudin, I. Iosilevskiy, M. Liebendörfer, F.-K. Thielemann, arXiv:1511.06551]

Matthias Hempel, Basel University
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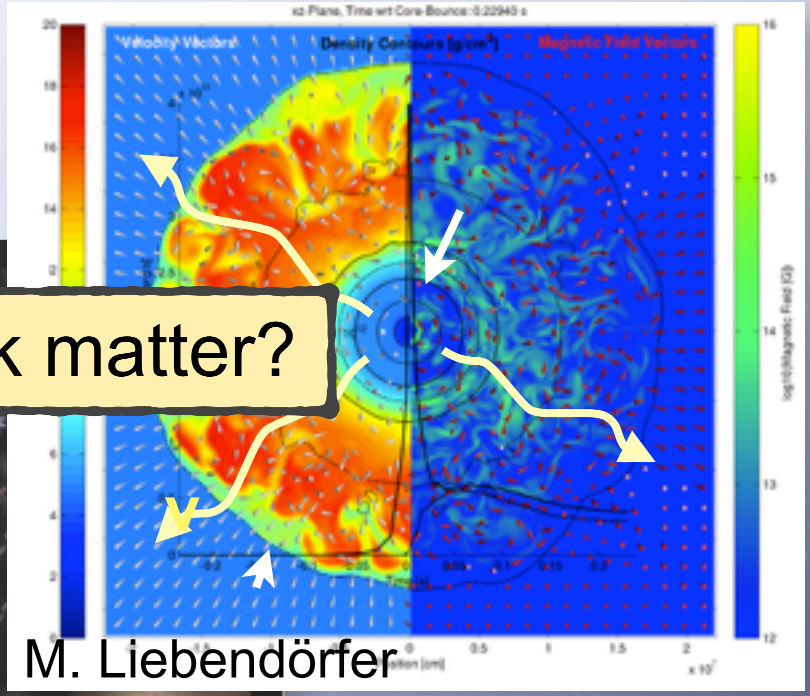
compstar

Motivation: core-collapse supernovae

- how do massive stars explode?
- which progenitors end as black holes, which as neutron stars?
- what is their nucleosynthesis contribution, galactical chemical evolution?
- still many open questions in core-collapse supernova theory



M. Liebendörfer

→ what is/could be the role of quark matter?

NASA/Chandra

Core-collapse supernova explosions triggered by the QCD phase transition

Basel-Frankfurt collaboration in 2009-2011:

I. Sagert, G. Pagliara, J. Schaffner-Bielich, MH,

T. Fischer, M. Liebendörfer, F.-K. Thielemann

Quark-hadron hybrid EOS for supernovae

- hybrid EOSs available as tables for various temperatures and asymmetries, suitable for core-collapse supernova simulations

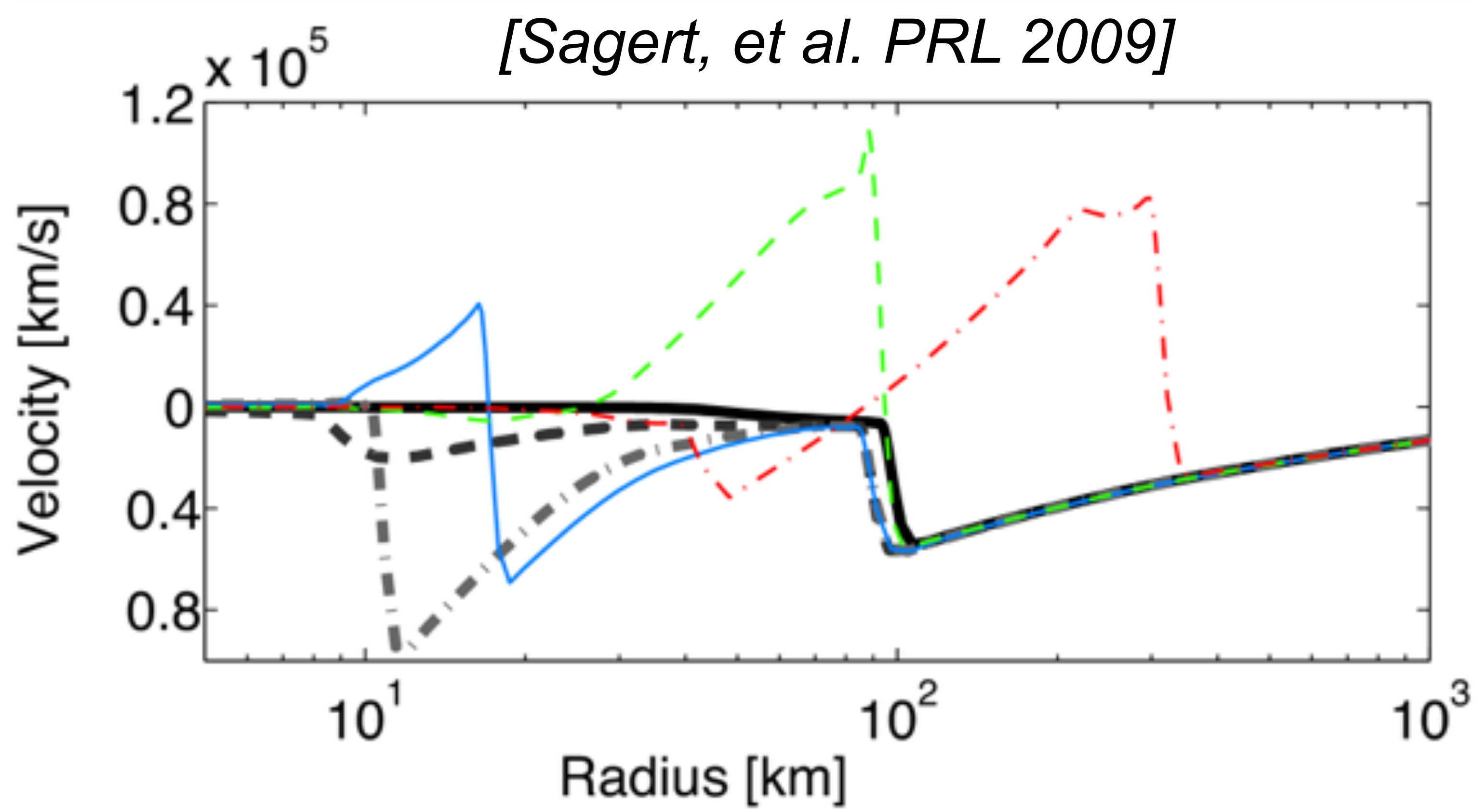
- hadronic phase: „STOS“, Shen, Toki, Oyamatsu and Sumiyoshi 1998, 2011

- quark phase: bag model
  - u,d,s (m_s=100 MeV)
  - first-order corrections for strong interactions, α_S (Farhi and Jaffe 1984)

$$
\boxed{\begin{aligned} p_i(m_i, T, \mu_i, \alpha_s) = \ & p_i(m_i, T, \mu_i, 0) \\ & - \left[\frac{7}{60} T^4 \pi^2 \frac{50\alpha_s}{21\pi} + \frac{2\alpha_s}{\pi} \left(\frac{1}{2} T^2 \mu_i^2 + \frac{\mu_i^4}{4\pi^2} \right) \right] \end{aligned}}
$$

- first order phase transition in between

CCSN explosions by the QCD phase transition



t_{pb}= 240.5 ms

t_{pb}= 255.2 ms

t_{pb}= 255.4 ms

t_{pb}= 255.5 ms

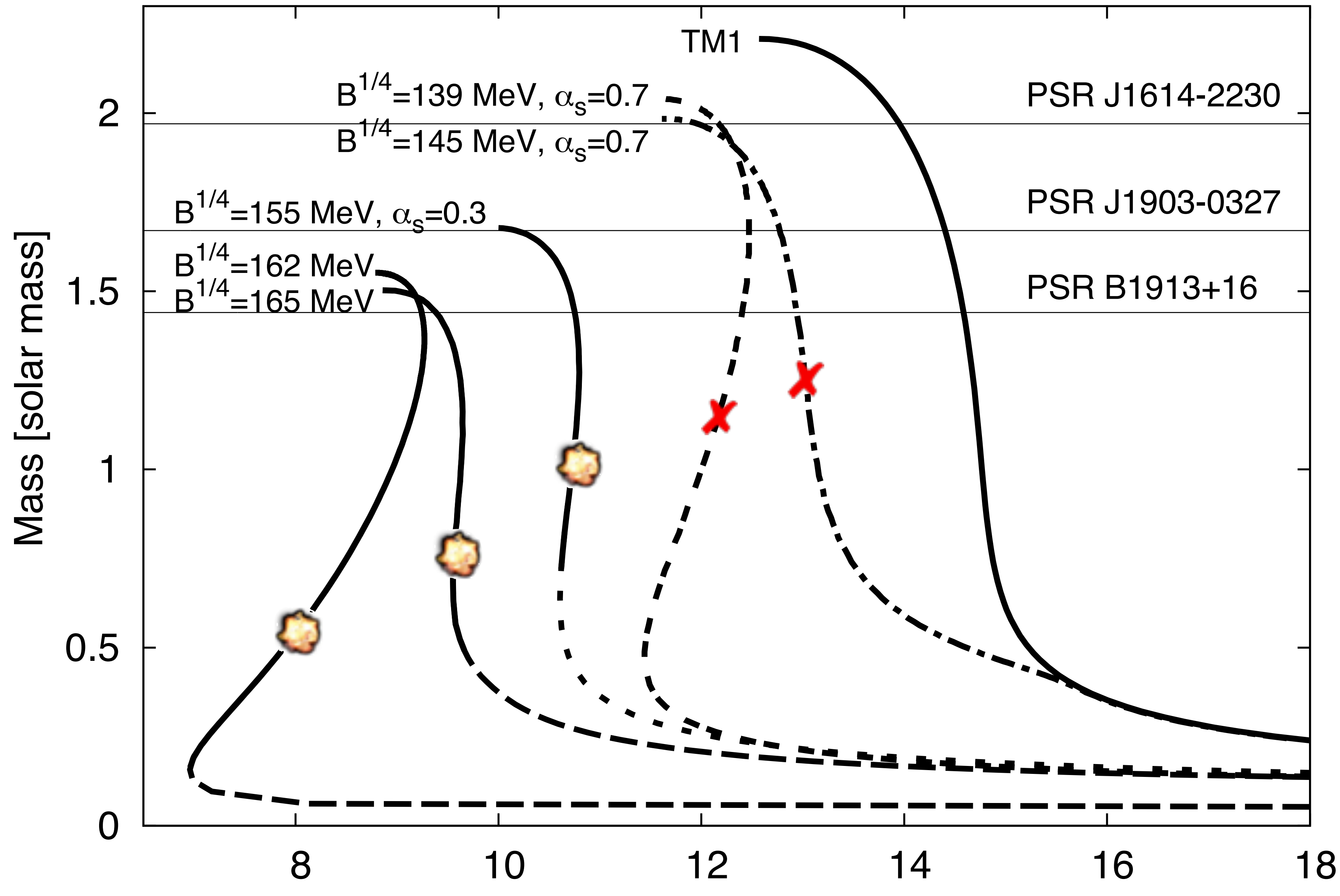
t_{pb}= 256.3 ms

t_{pb}= 261.2 ms

- phase transition induces collapse of the proto-neutron star
- collapse halts when pure quark matter is reached
- formation of a second shock
- shock merges with standing accretion shock, explosion

- observable signal: second neutrino burst (DasGupta et al. 2009)
- weak r-process (Nishimura et al. 2012)

Mass-radius relation of hybrid EOS and SN explosions

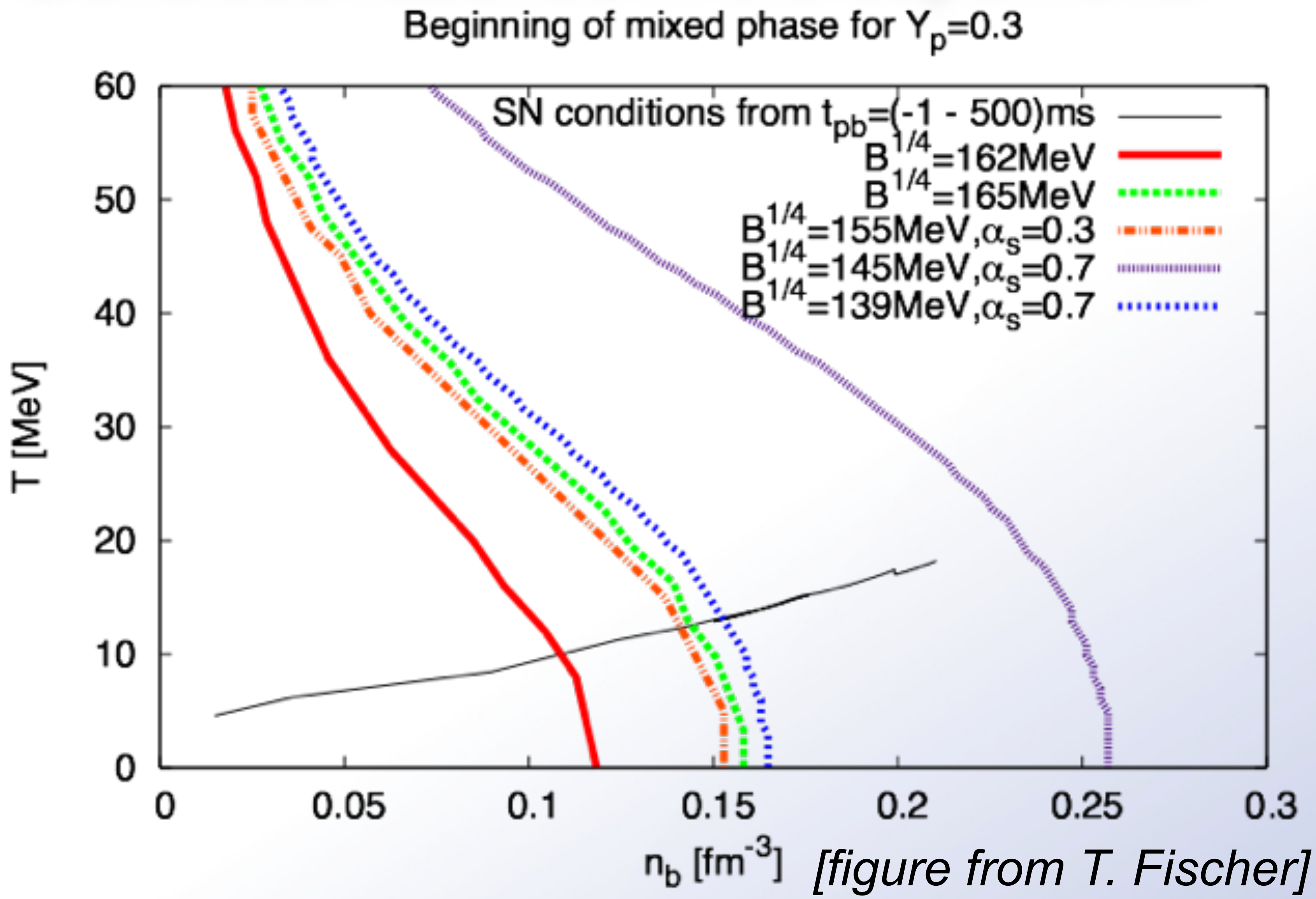


[figure adapted from I. Sagert]

- no explosions for sufficiently high maximum mass
- weak phase transition
- quark matter behaves similarly as hadronic matter „masquerade“
- cf.: Fischer, Blaschke, et al. 2012: PNJL hybrid EOS

 explosions in spherical symmetry (T. Fischer et al. ApJS 2011)

Densities reached in the supernova



[figure from T. Fischer]

- B145 does not explode because there is no quark matter
- B139 does not explode either
- no second collapse, no explosion, no second neutrino burst
- only weak effect of quark matter on the neutrino signal

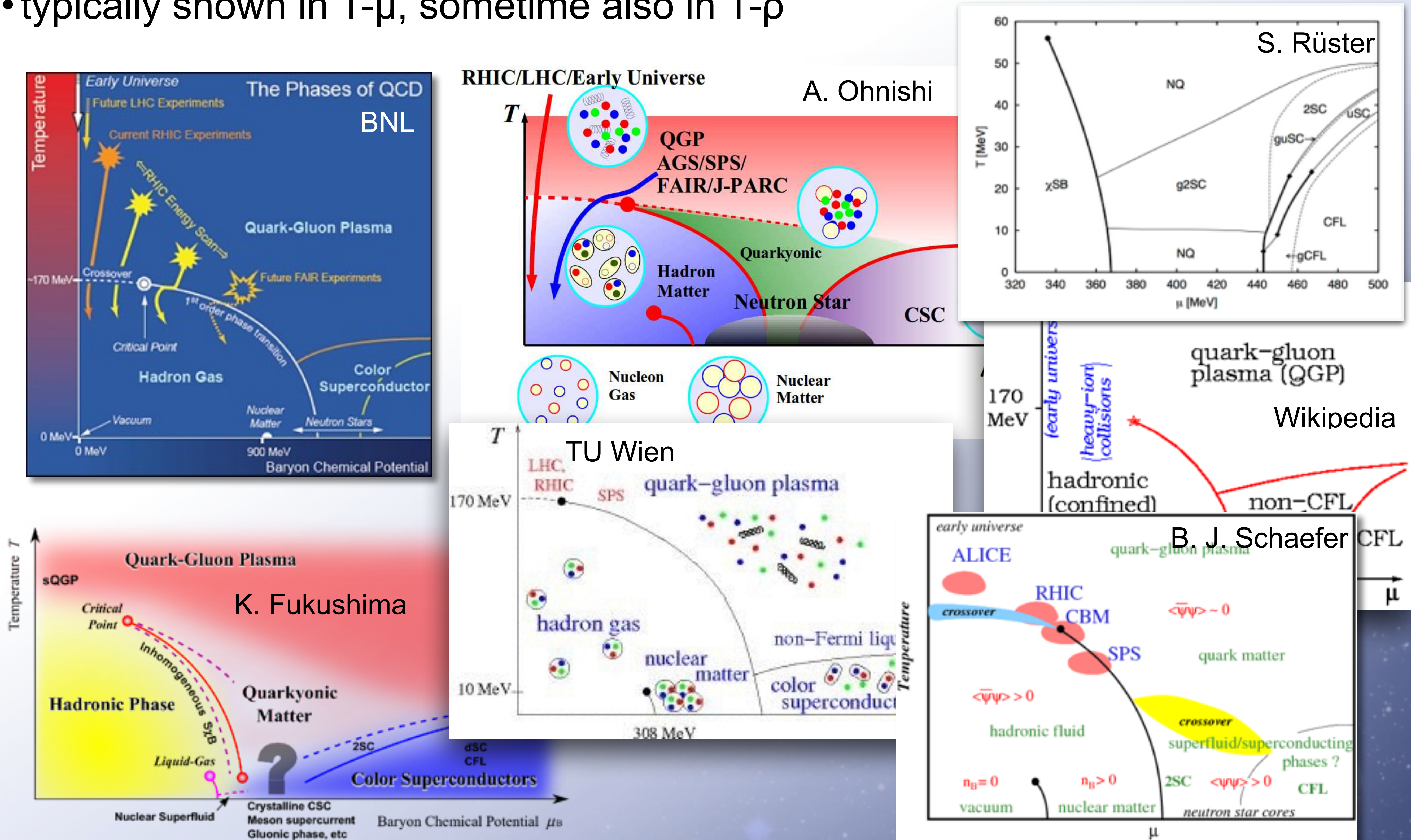
[Fischer, et al. Acta Phys. Polon. Suppl. 7 (2014)]

only few models tested, explosion mechanism still possible for others?

Thermal properties of the hybrid EOS

QCD phase diagrams

- fundamental question: phase diagram of strongly interacting matter
- typically shown in T-μ, sometime also in T-ρ

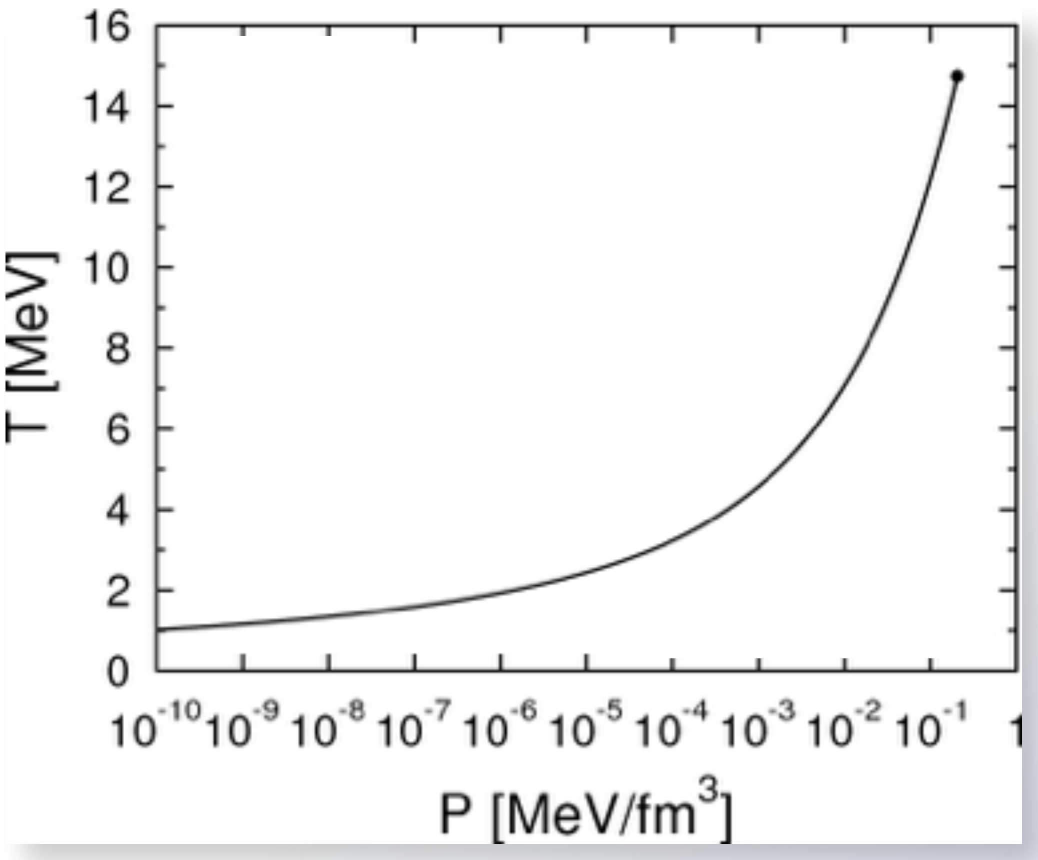


Is the QCD PT of liquid-gas type?

[MH, V. Dexheimer, S. Schramm, I. Iosilevskiy, PRC 88 (2013)]

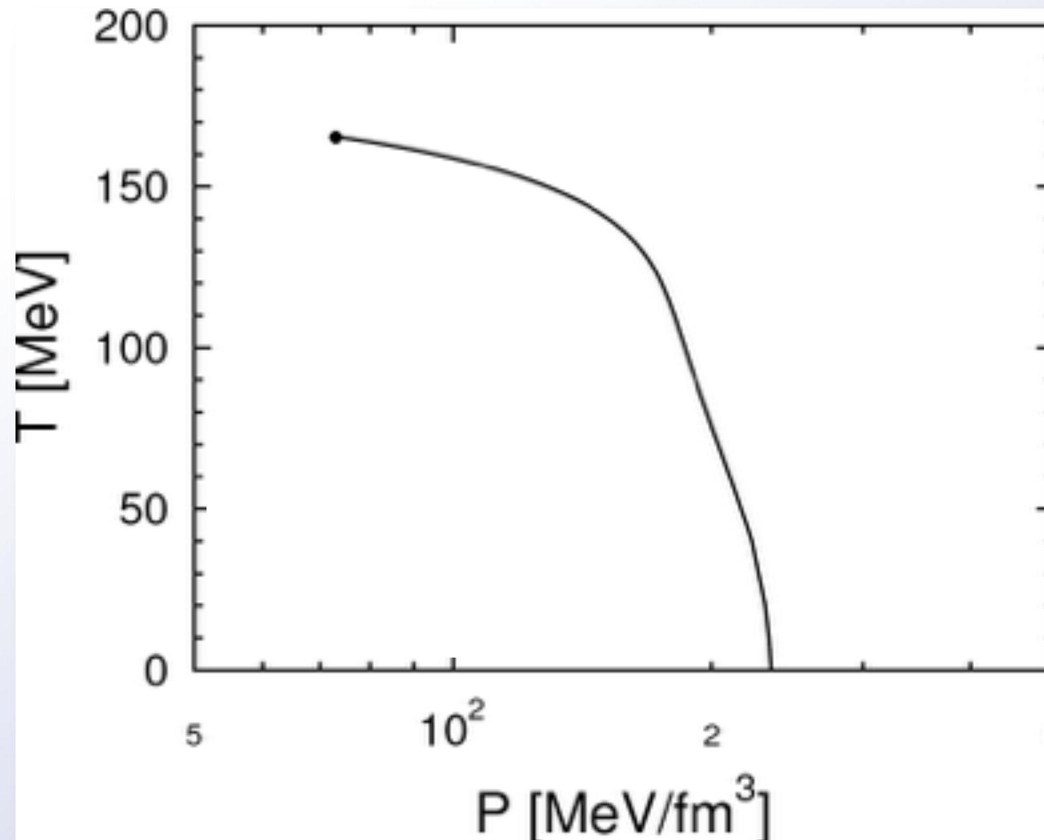
Phase diagrams of symmetric nuclear matter in P-T

liquid-gas phase transition



enthalpic

chiral/deconfinement phase transition



entropic

- opposite slope in P-T as fundamental difference

see also:

[Satarov, Dmitriev, Mishustin, PAN72 (2009)]

[Bombaci et al., PLB680 (2009)]

[Steinheimer, Randrup, Koch, PRC89 (2014)]

[Iosilevskiy, arXiv:1403.8053]

[MH, V. Dexheimer, S. Schramm, I. Iosilevskiy, PRC 88 (2013)]

The *entropic* QCD PT ($dP/dT|_{PT}<0$)

- Clausius-Clapeyron equation

$$\left.\frac{dP}{dT}\right|_{\rm PT} = \frac{S^I - S^{II}}{1/n_B^I - 1/n_B^{II}}$$

- Steiner, Lattimer and Prakash PLB 468 (2000):

$$S = T\pi^2 \frac{\sum_i p_{F_i}\sqrt{p_{F_i}^2 + (m_i^*)^2}}{\sum_i p_{F_i}}$$

- more degrees of freedom (color, strangeness) in the quark phase, and more relativistic
- leads to high specific heat capacity and low temperatures
- → QCD PT always entropic?
- what about color-superconducting phases? (cf. Rüster et al. PRD73 (2006))

General properties of *entropic* PTs ($dP/dT|_{PT}<0$)

- for a Maxwell phase transition one has

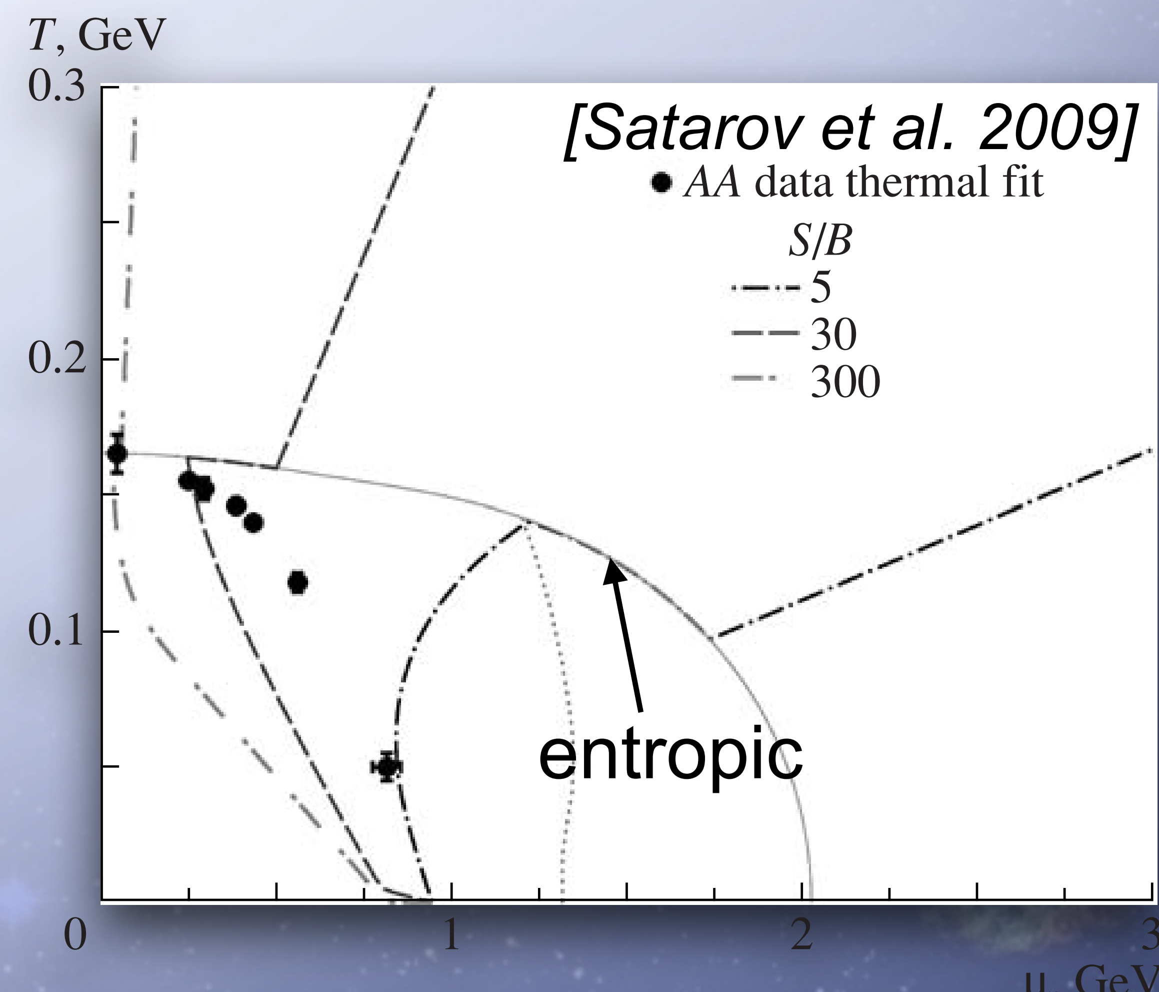
$$\left.\frac{dP}{dT}\right|_{\mathrm{PT}} = \left.\frac{\partial P}{\partial T}\right|_{n_B}$$

- using general thermodynamic relations: unusual sign of 2nd cross derivatives, „abnormal thermodynamics“, e.g.:

$$\left.\frac{\partial P}{\partial T}\right|_{n_B} < 0 \Leftrightarrow \left.\frac{\partial T}{\partial n_B}\right|_{S} < 0$$

[Iosilevskiy, arXiv:1403.8053]
[Iosilevskiy, arXiv:1504.05850]

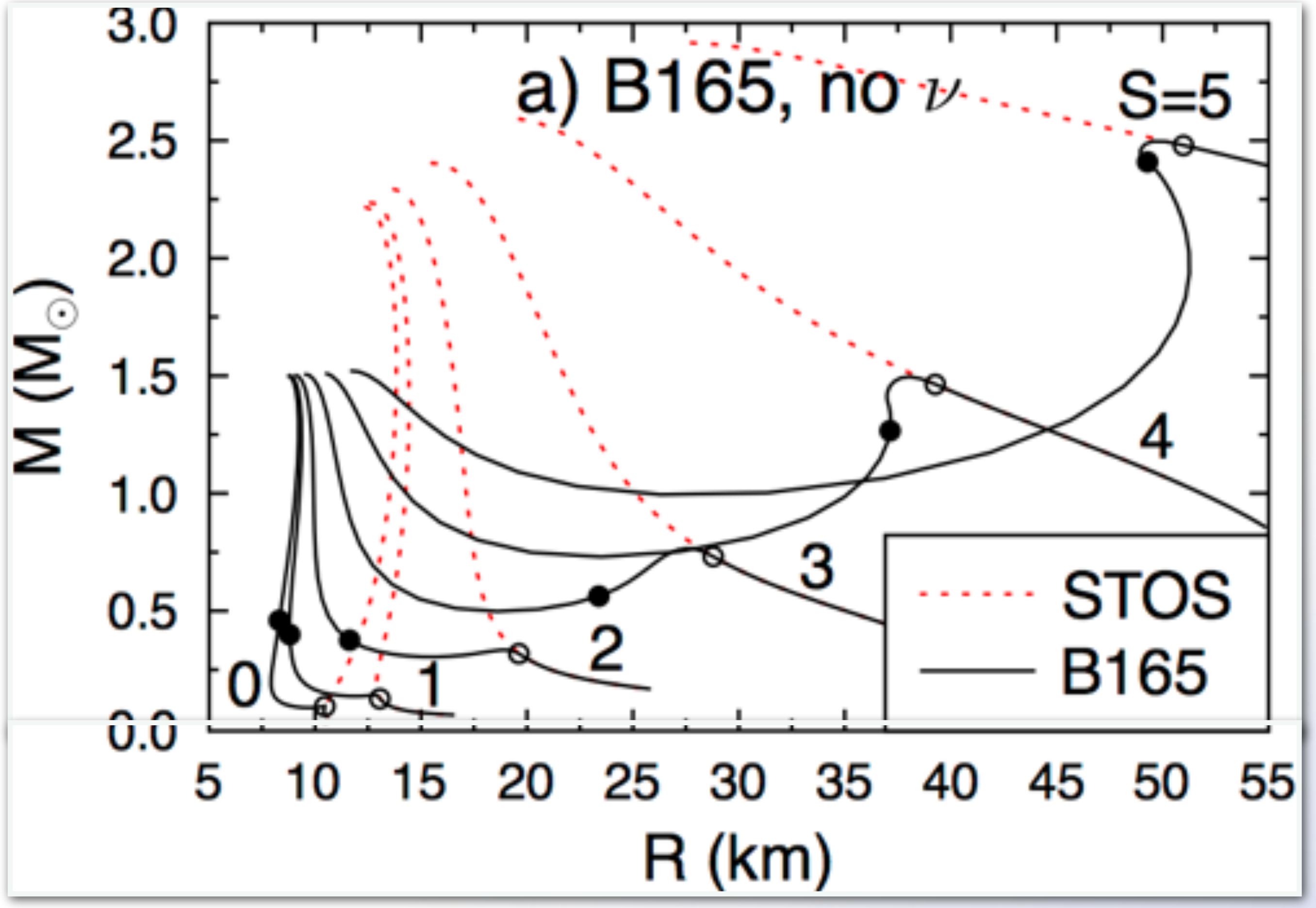
- $dT/dn_B|_S<0$ observed by many authors, also well-known in heavy-ion collisions
  - Steiner et al. PLB 2000
  - Nakazato et al. APJ 2010
  - Fischer et al. APJS 2011
  - Yudin et al. Astron. L 2013
  - …



CCSN explosions and the QCD PT

[MH, O. Heinimann A. Yudin, I. Iosilevskiy, M. Liebendörfer, F.-K. Thielemann, arXiv:1511.06551]

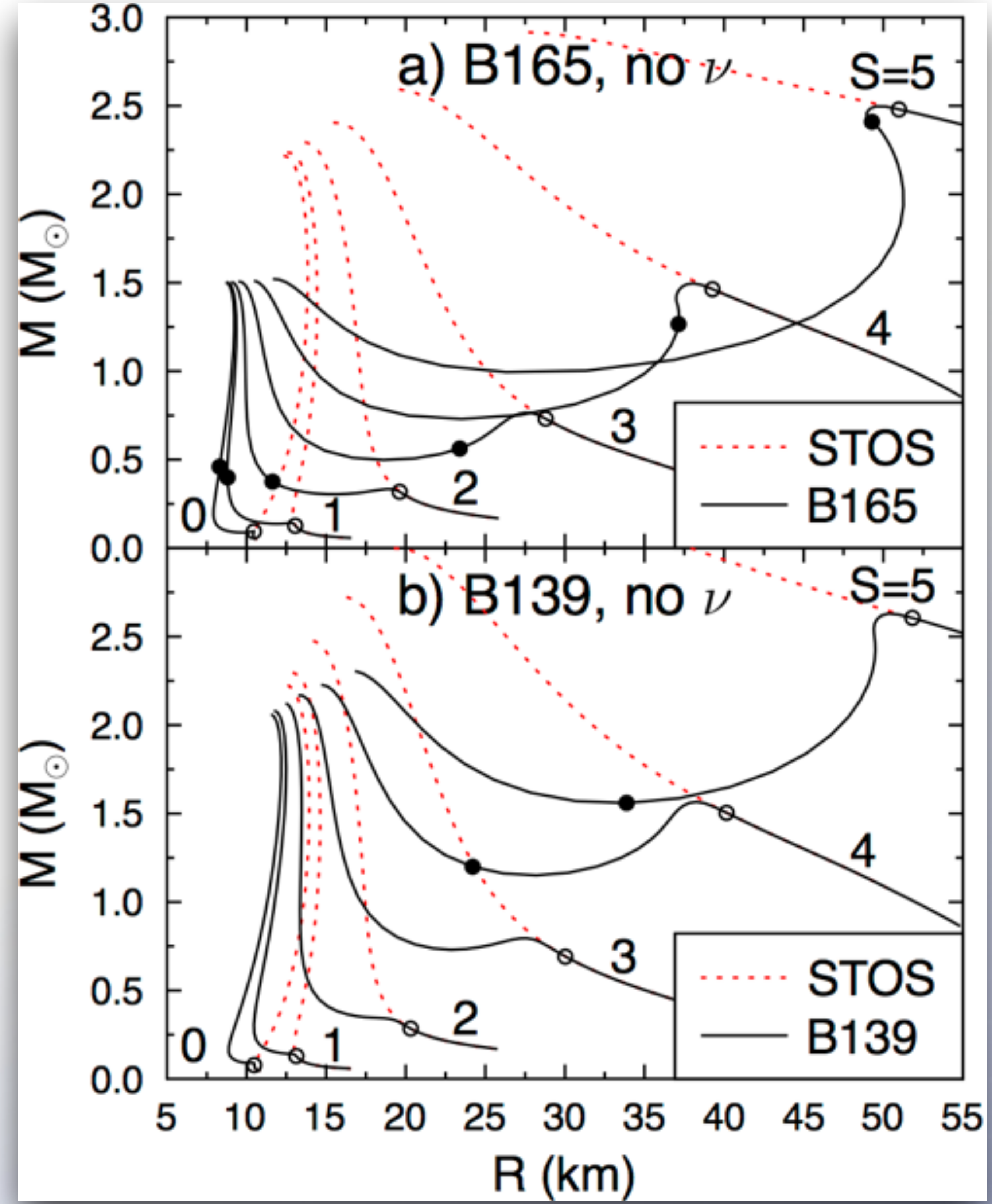
A third family of proto-compact stars



- third family feature („twins“) arises for high entropies
- result of the thermal properties of the EOS
- transition from second to third family releases gravitational energy of 10^{50} to 10^{53} erg

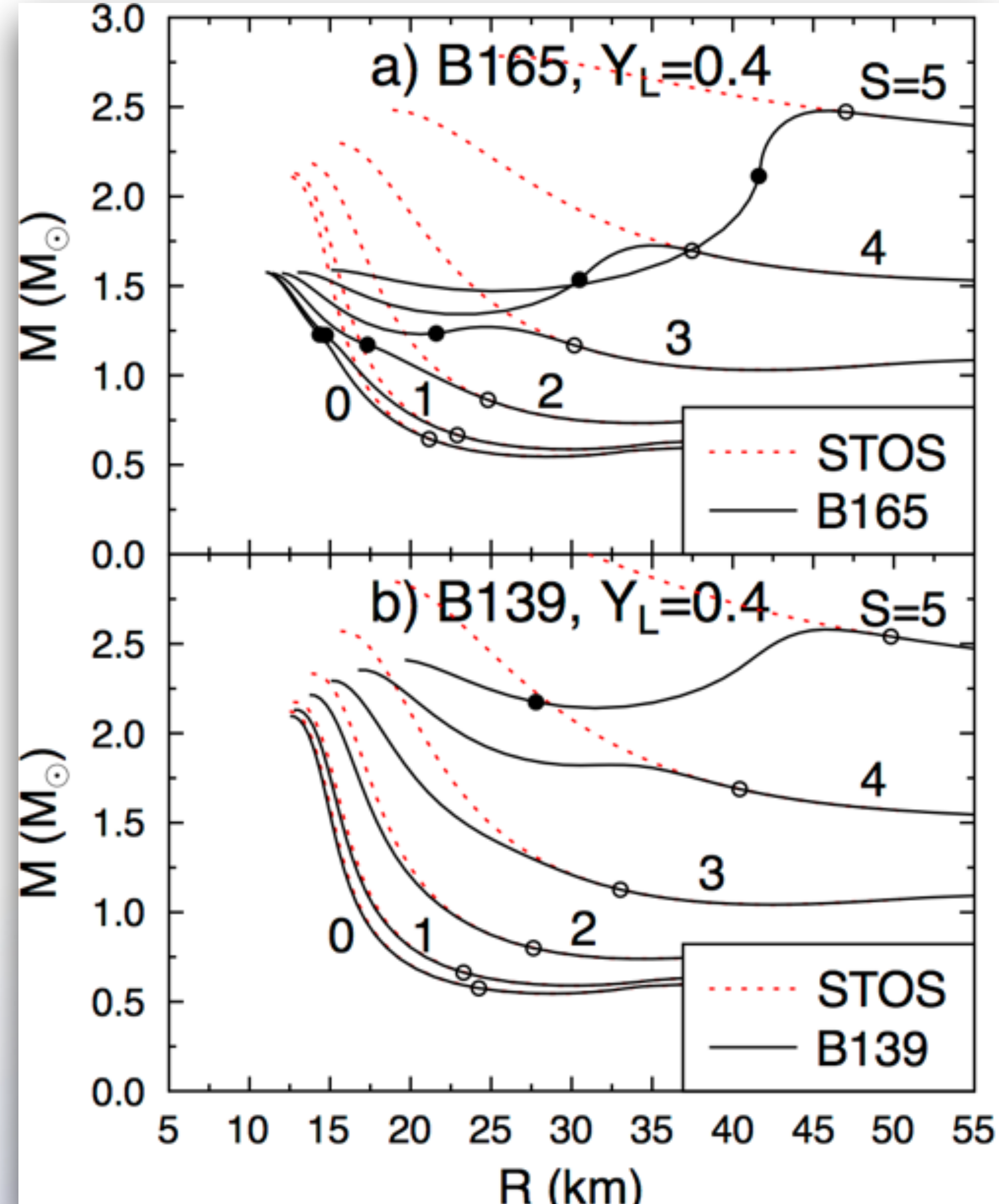
- explains the supernova explosions of Sagert and Fischer et al:
- proto-neutron star first on the second branch
- accretion until maximum reached
- collapse to third family, energy release, formation of 2nd shock, explosion

A third family of proto-compact stars — neutrino free



- for B139: third family arises only for very high entropies, much less pronounced

A third family of proto-compact stars — trapped neutrinos



- neutrinos tend to suppress the third family feature
- less gravitational binding energy release, if at all

Unusual thermal properties and stability of compact stars

- for stability: $P(\varepsilon,S)$
- to characterize thermal effects: $dP/dS|_\varepsilon$
- $dP/dS|_\varepsilon>0$: stiffening, $dP/dS|_\varepsilon<0$: softening for increasing entropy

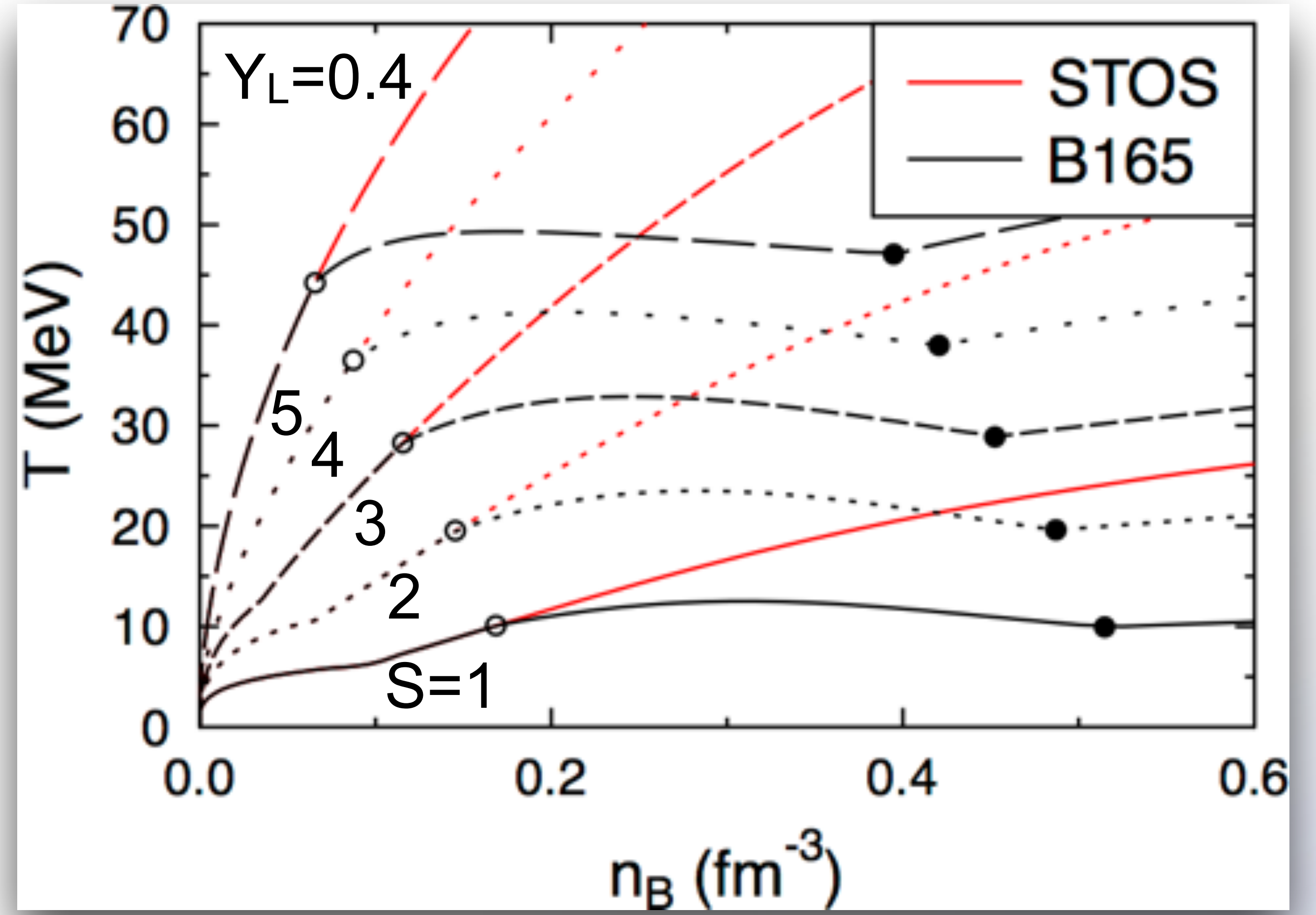
- using general thermodynamic relationships:

$$\left.\frac{\partial P}{\partial S}\right|_{\epsilon} = -T n_B \left(\frac{c_s}{c}\right)^2 + \frac{T}{C_V}\left.\frac{\partial P}{\partial T}\right|_{n_B}$$

- first term small, relativistic correction
- → abnormal thermodynamics/entropic PT induces a softening of the EOS with increasing temperature/entropy (!)

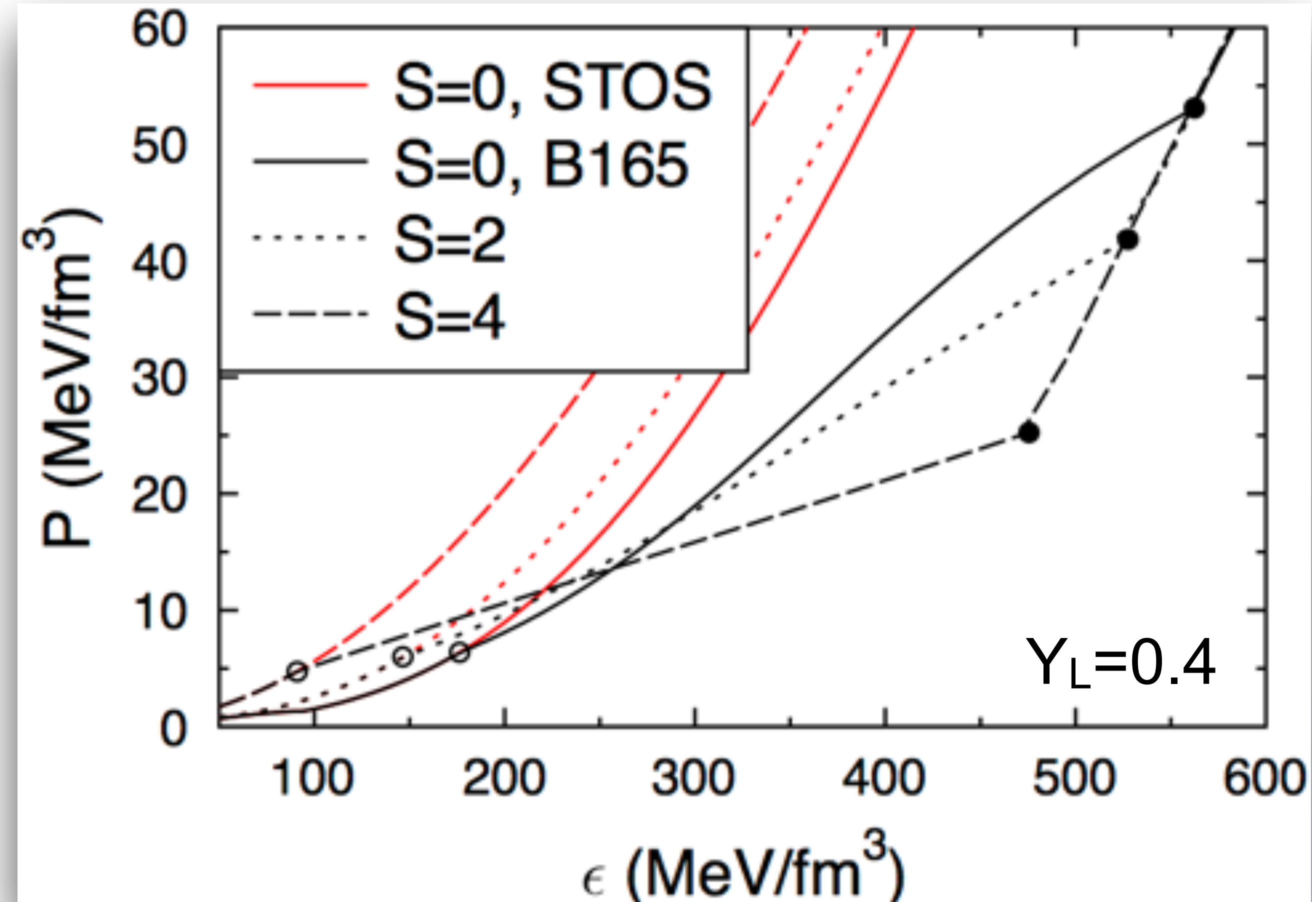
- „inverted convection“ possible, where positive entropy gradients are convectively unstable *[A.V. Yudin, MH, D.K. Nadyozhiny, T.L. Razinkova, MNRAS 45, 4325 (2015)]*

Temperature for isentropes of proto-neutron star matter



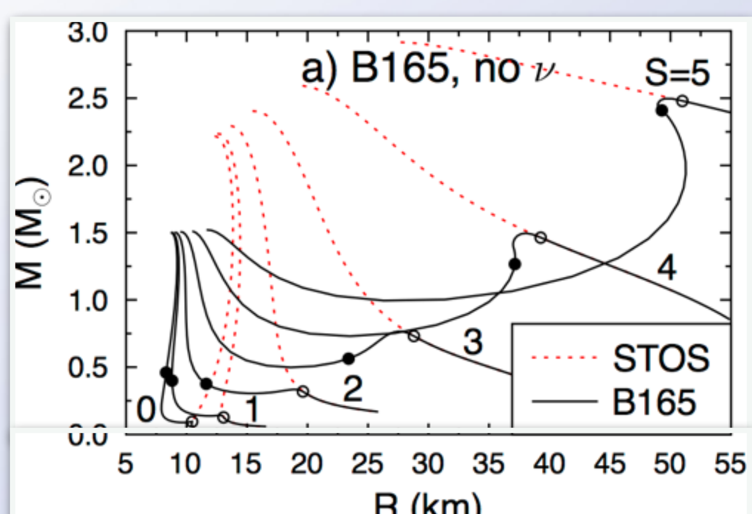
- $dT/dn_B<0$ in parts of the phase coexistence region, >0 elsewhere
- phase transition leads to *abnormal thermodynamics*

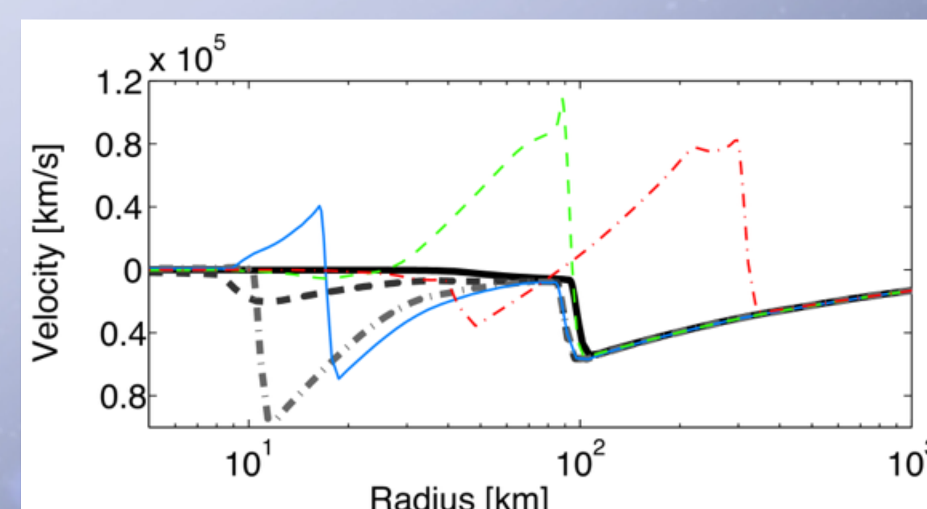
Pressure-energy density relation



- hadronic and quark matter stiffens when it is heated
- in the phase coexistence region it softens (!)

→ the unusual thermal properties of the entropic PT are responsible for the supernova explosions





Summary and conclusions

- phase diagram in P-T can provide interesting information
- is the QCD PT *entropic* ($dP/dT|_{PT}<0$)?

- entropic PTs lead to unusual thermal properties of the EOS, „abnormal thermodyamics“
- possible consequences in astrophysics:
  - inverted convection in proto-neutron stars
  - third family of proto-compact stars which exists only at finite entropy
  - core-collapse supernova explosions

- is it possible to achieve explosions by the QCD PT and have a maximum mass above 2 M_{sun}?
  - requires new EOSs and new simulations → Ph.D. project of O.Heinimann (Basel)
  - note: no multi-D simulations with QCD PT yet
  - the maximum mass is determined at T=0, for the supernova the thermal properties are crucial (!)