New aspects of the QCD phase transition in proto-neutron stars and core-collapse supernovae

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Frankfurt, AstroCoffee, 24.11.2015

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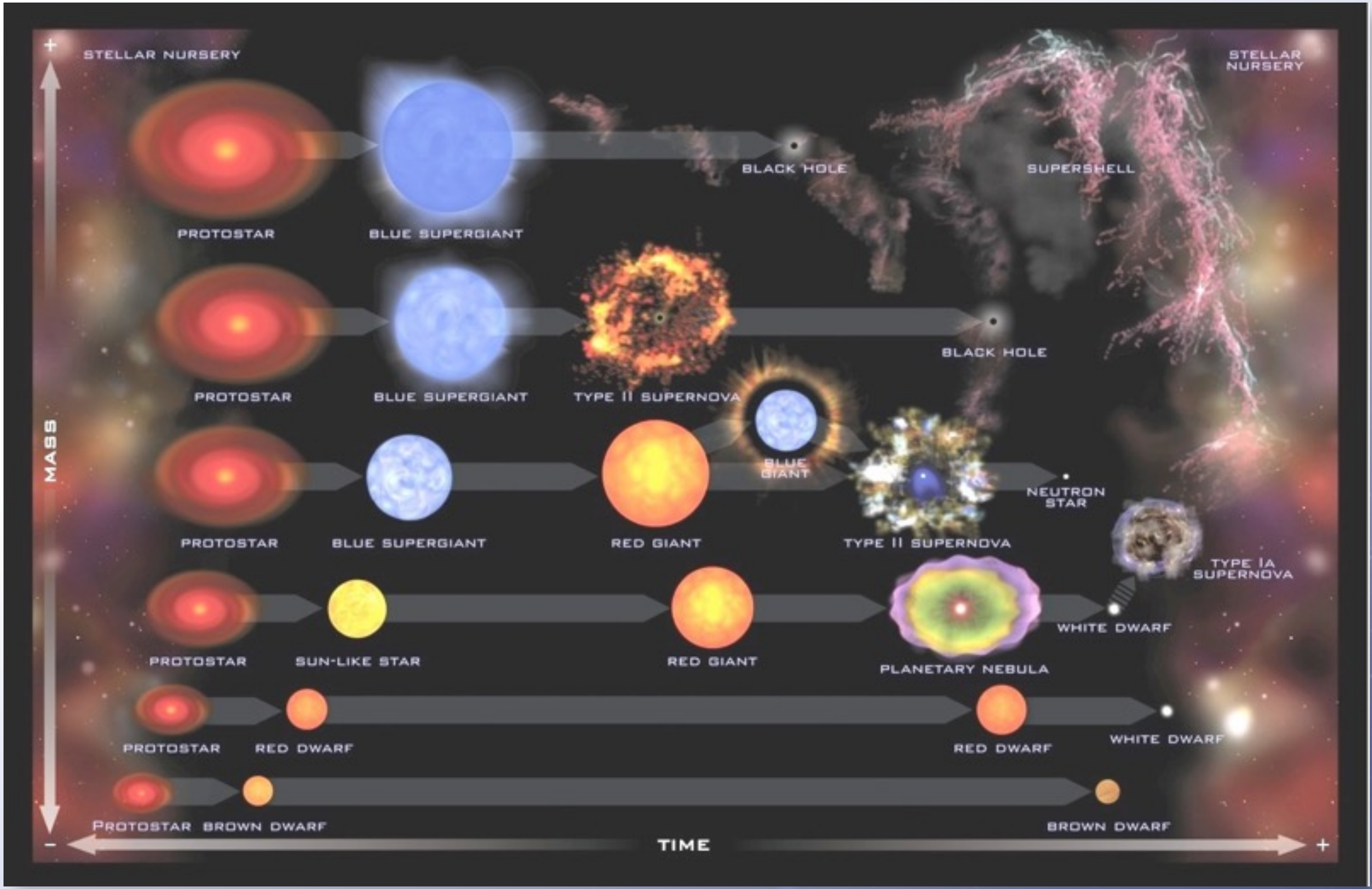
Motivation: core-collapse supernovae

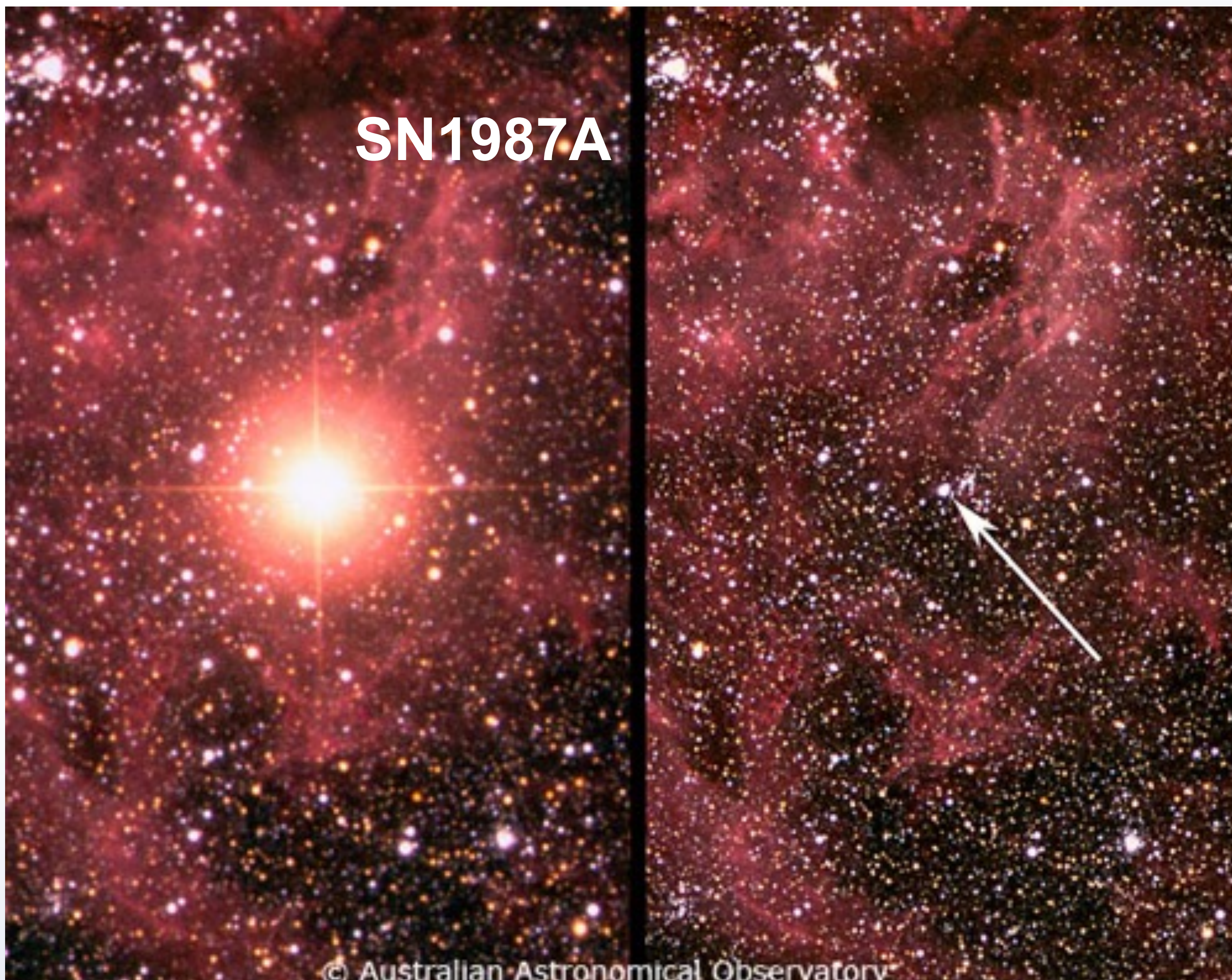
- how do massive stars explode?
- which progenitors end as black holes, which as neutron stars?
- what is their nucleosynthesis contribution, galactical chemical evolution?

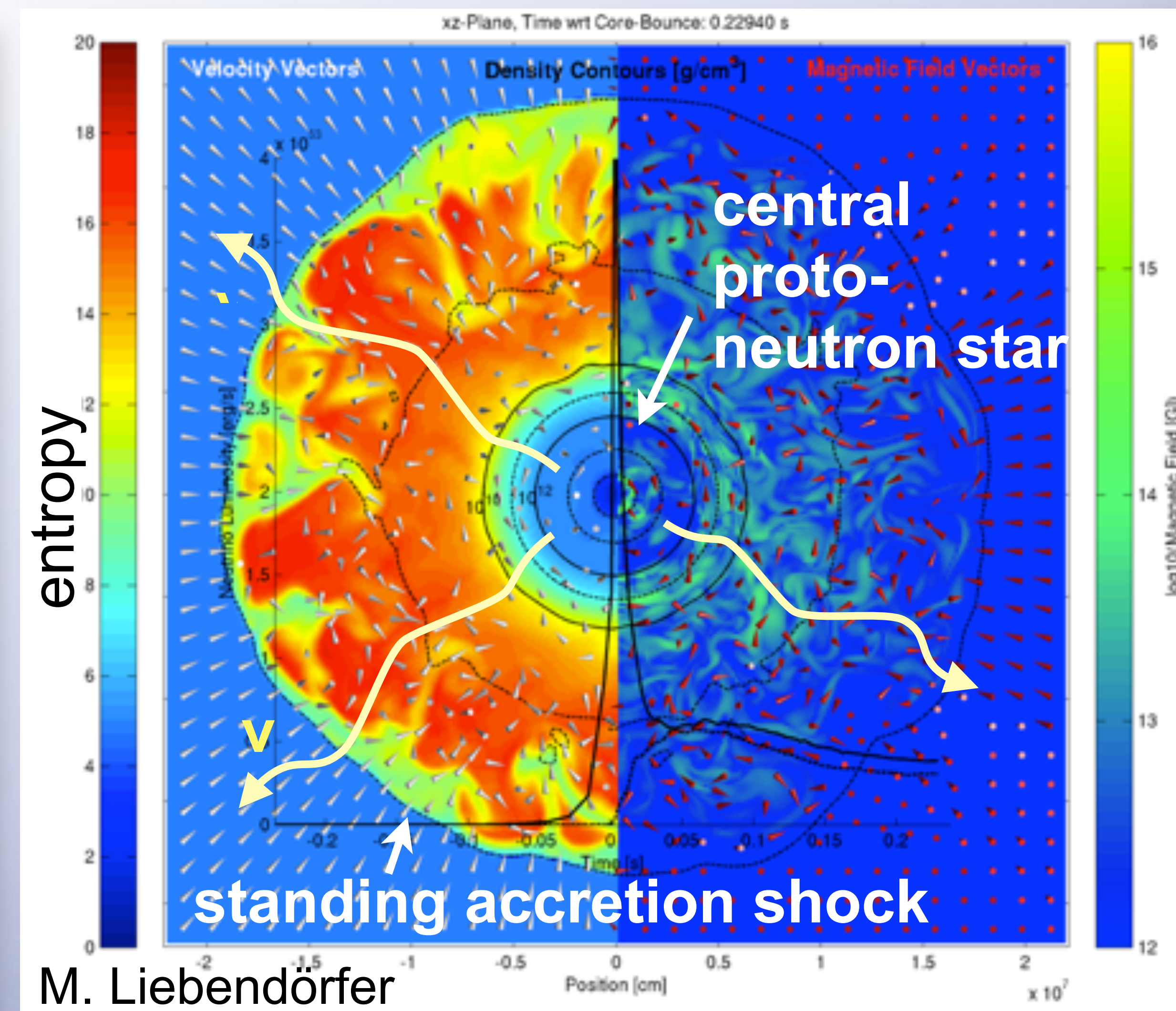


NASA/Chandra

Supernova explosion mechanism

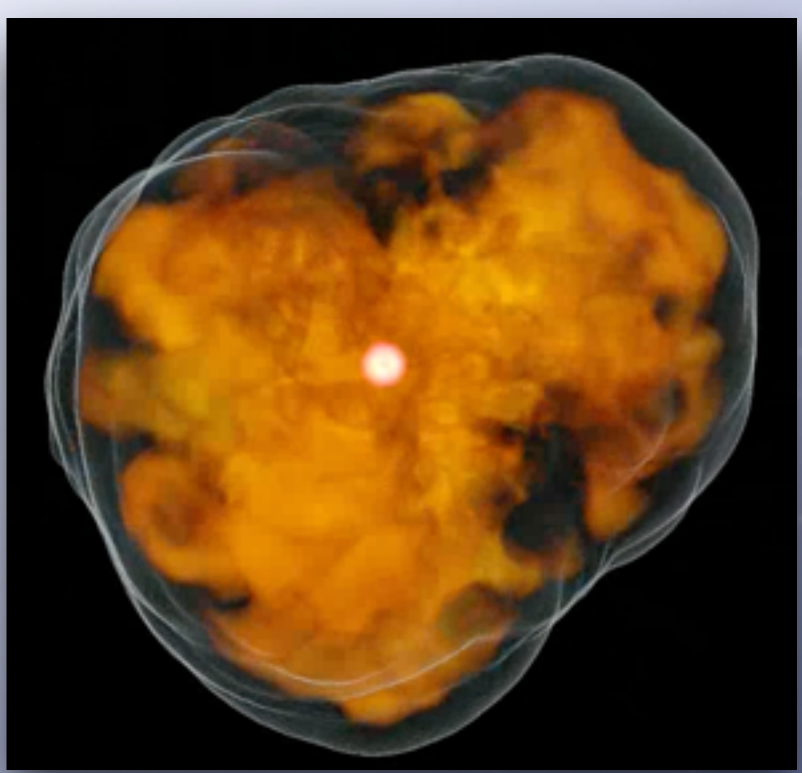
- presently favored: neutrino-driven mechanism (Colgate & White 1966)
- explosion triggered by energy deposition of neutrinos in the infalling matter
- requires multi-dimensional fluid instabilities: convection, turbulence, „standing accretion shock instability“, in general no explosions in 1D simulations
- e.g. increases time of matter in gain region and thereby the neutrino heating





Example of a 3D supernova simulation

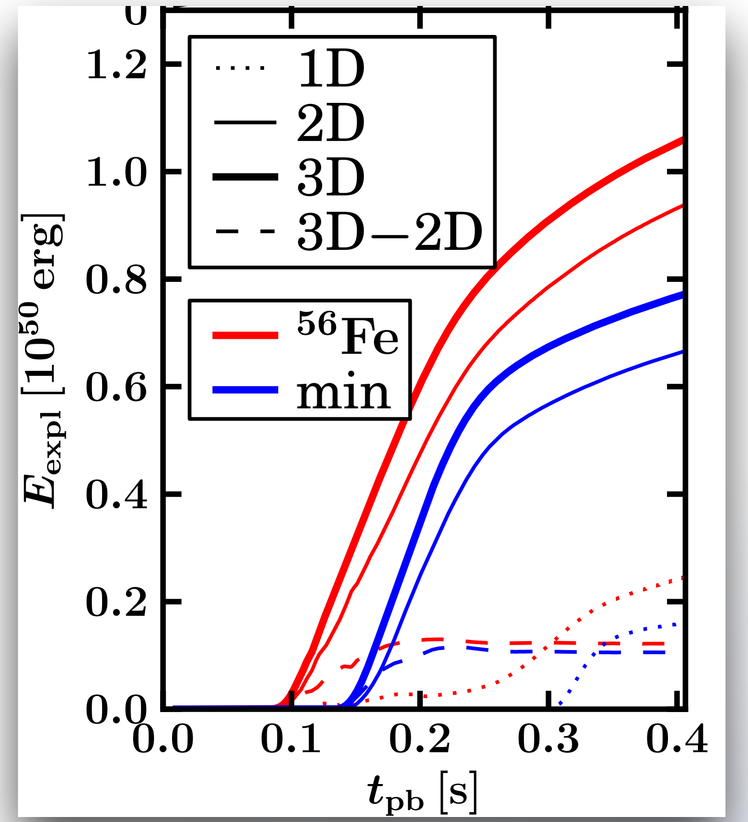
- simulation by Kuo-Chuan Pan, Basel (arXiv:1505.02513)
- 15 M_{sun} progenitor (Woosley et al. 2002)
- HS(DD2) EOS, relativistic-mean field, nucleons, nuclei, electrons (MH and Schaffner-Bielich 2010)
- hydrodynamics: FLASH (Lee 2003)
- neutrino transport: IDSA (Liebendörfer et al. 2009)



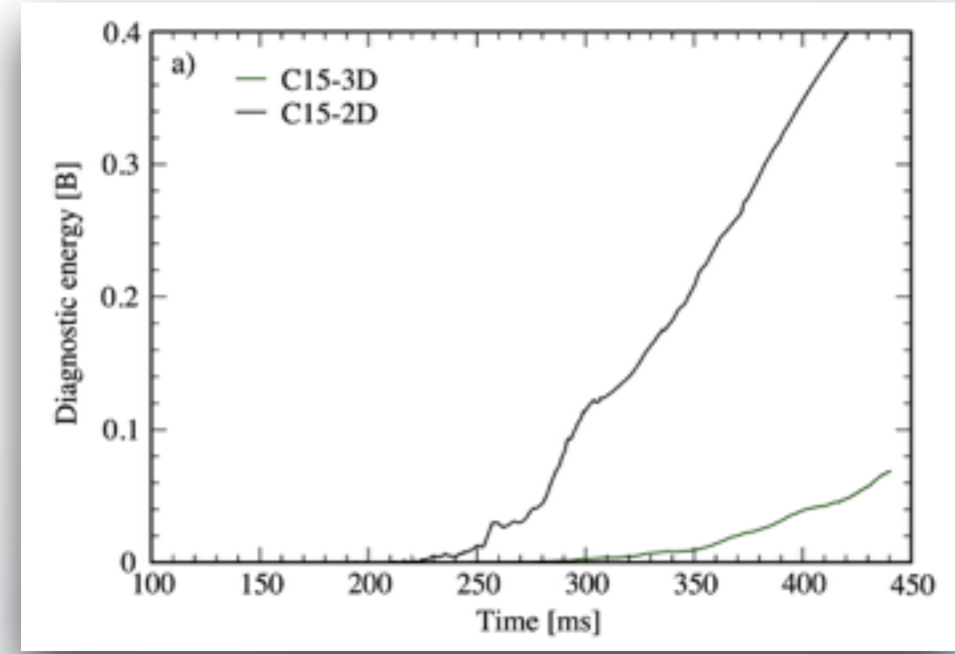

Time = -5.83 ms
7
5
3
1
Entropy (kb/baryon)
2000 km

Open questions in core-collapse supernova theory

- typically low explosion energies, cannot explain all supernovae
- differences between 2D and 3D

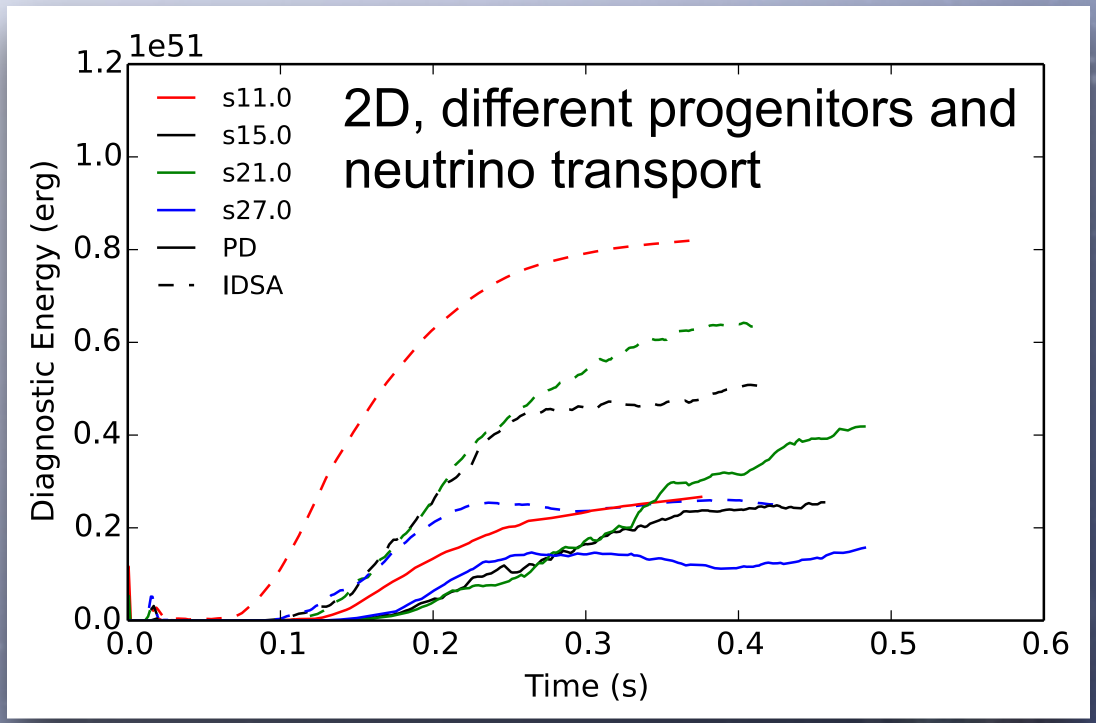


Melson et al. 2015, 9.6 M_{sun}



Lentz et al. 2015, 15 M_{sun}

Pan et al. 2015



- all present 3D simulations still significantly underresolved? (e.g. Radice et al. arXiv:1510.05022)

Role of the EOS in core-collapse supernovae

- different nuclear interactions/hadronic EOSs have only a moderate impact (Janka 2012, MH et al. 2012, Suwa 2013, Kuo-Chuan Pan et al. 2015, …)
- no 2D or 3D simulations with non-nucleonic degrees of freedom yet (!)

→ what is the role of quark matter?

Core-collapse supernova explosions triggered by the QCD phase transition

Quark-hadron hybrid EOS for supernovae

- 2009/2011: Sagert, Pagliara, Schaffner-Bielich, MH
- hybrid EOSs available as tables for various temperatures and asymmetries, suitable for core-collapse supernova simulations

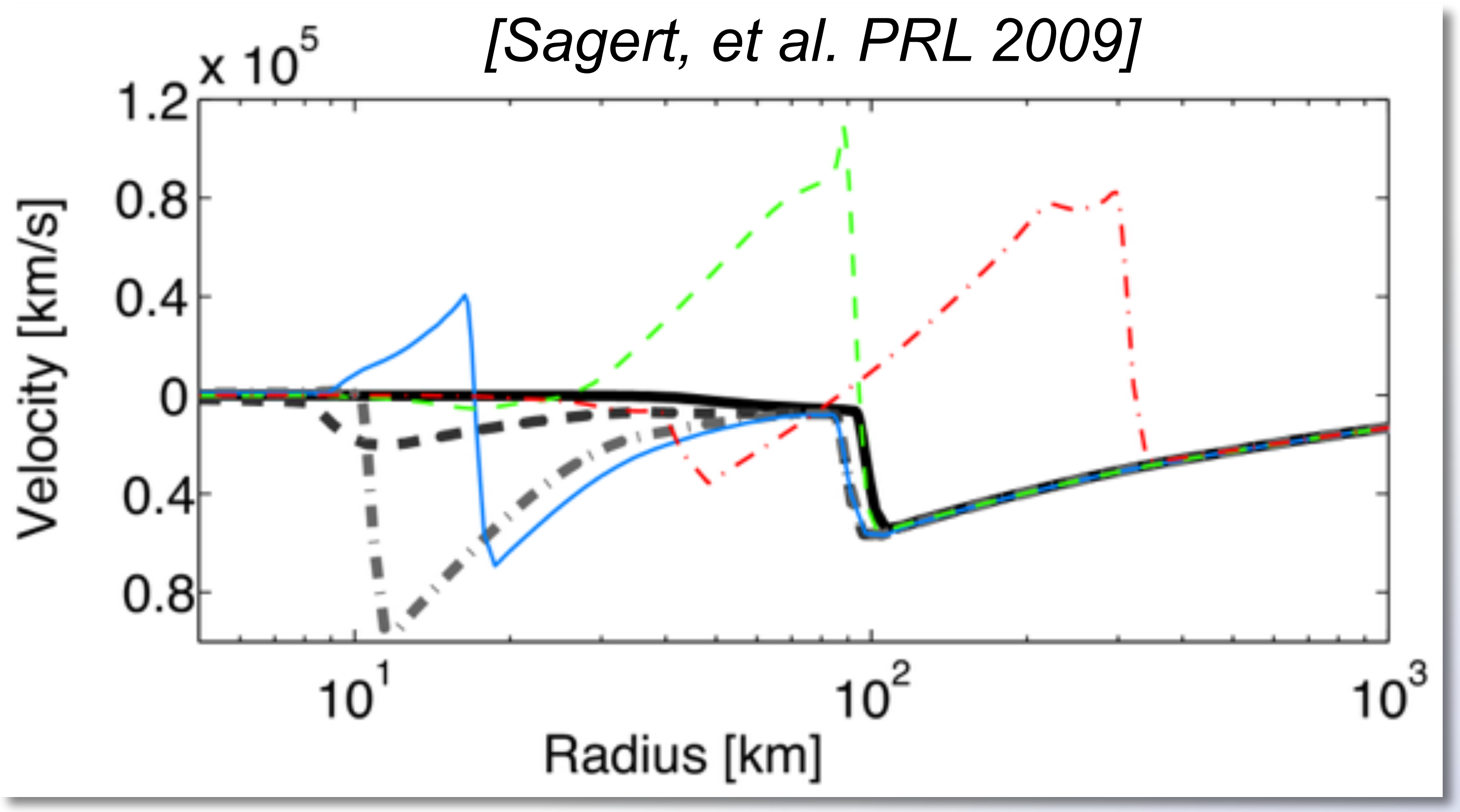
- hadronic phase: „STOS“, Shen, Toki, Oyamatsu and Sumiyoshi 1998, 2011
  - n,p,α,A,e
  - non-linear relativistic mean-field interactions (TM1)
  - Thomas-Fermi approximation for finite nuclei

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

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

- phase transition:
  - global charge neutrality (Gibbs PT/non-congruent PT)

CCSN explosions by the QCD phase transition



t_{pb}= 240.5 ms

t_{pb}= 255.2 ms

t_{pb}= 255.4 ms

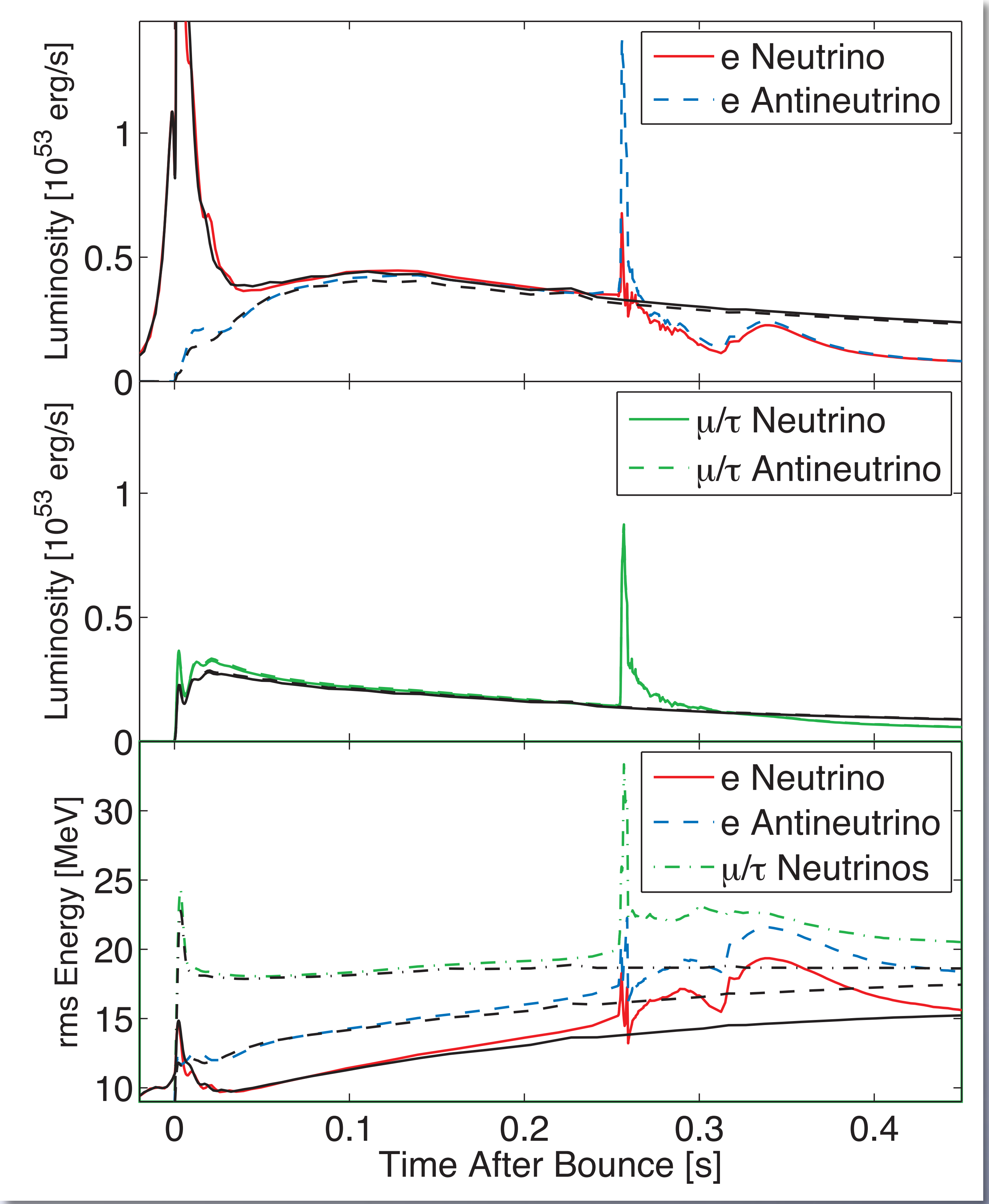
t_{pb}= 255.5 ms

t_{pb}= 256.3 ms

t_{pb}= 261.2 ms

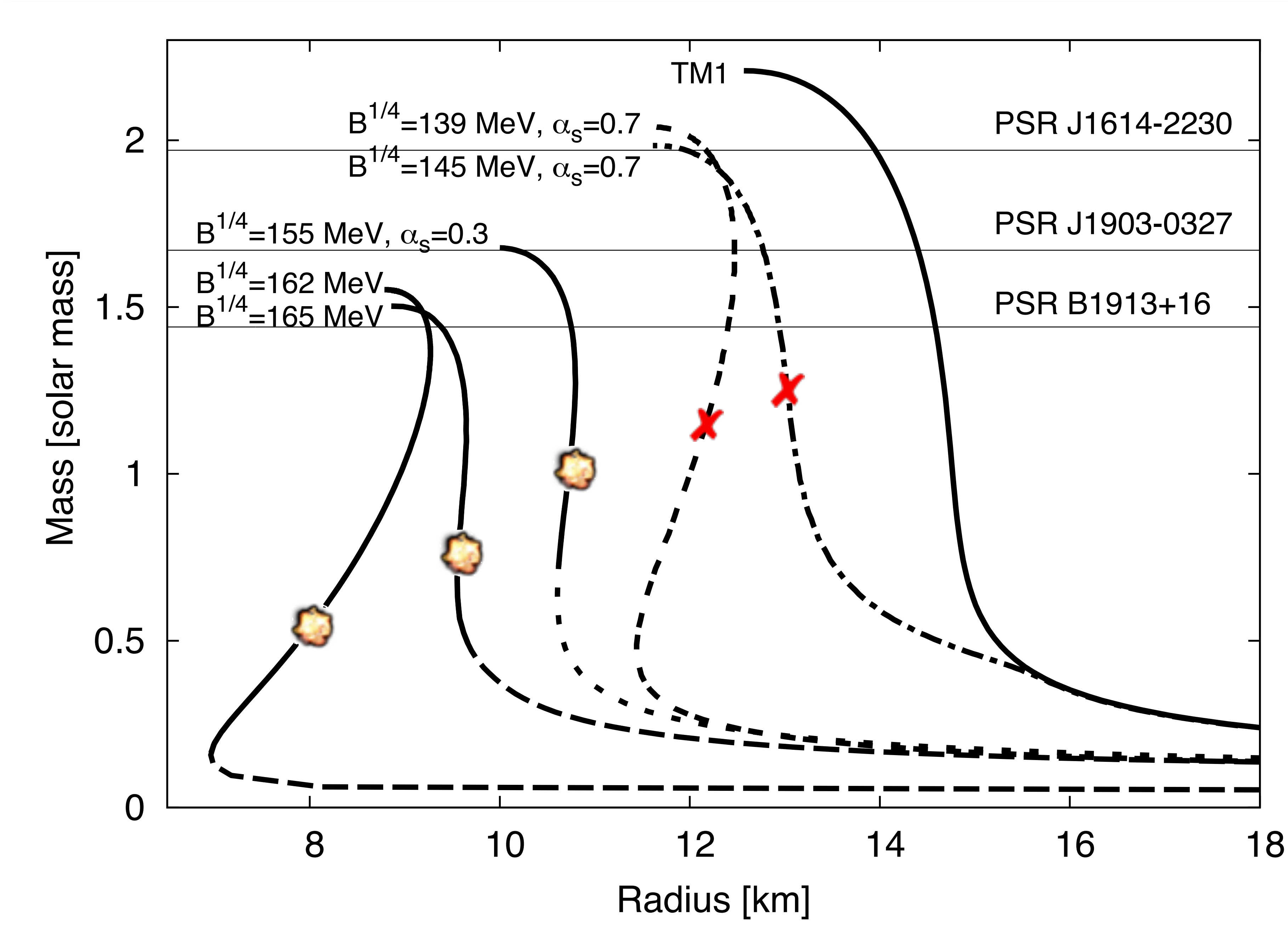
- phase transition induces collapse of the proto-neutron star
- once pure quark matter is reached, collapse halts
- formation of a second shock
- higher temperatures, increased neutrino heating → positive velocities
- shock merges with standing accretion shock
- explosion

Neutrino signal



- colored lines with phase transition, black without
- second neutrino burst due to quark matter
- peak and height determine density and strength of the phase transition
- measurable with present day neutrino detectors [DasGupta et al. 2009]

Mass-radius relation of hybrid EOS and SN explosions

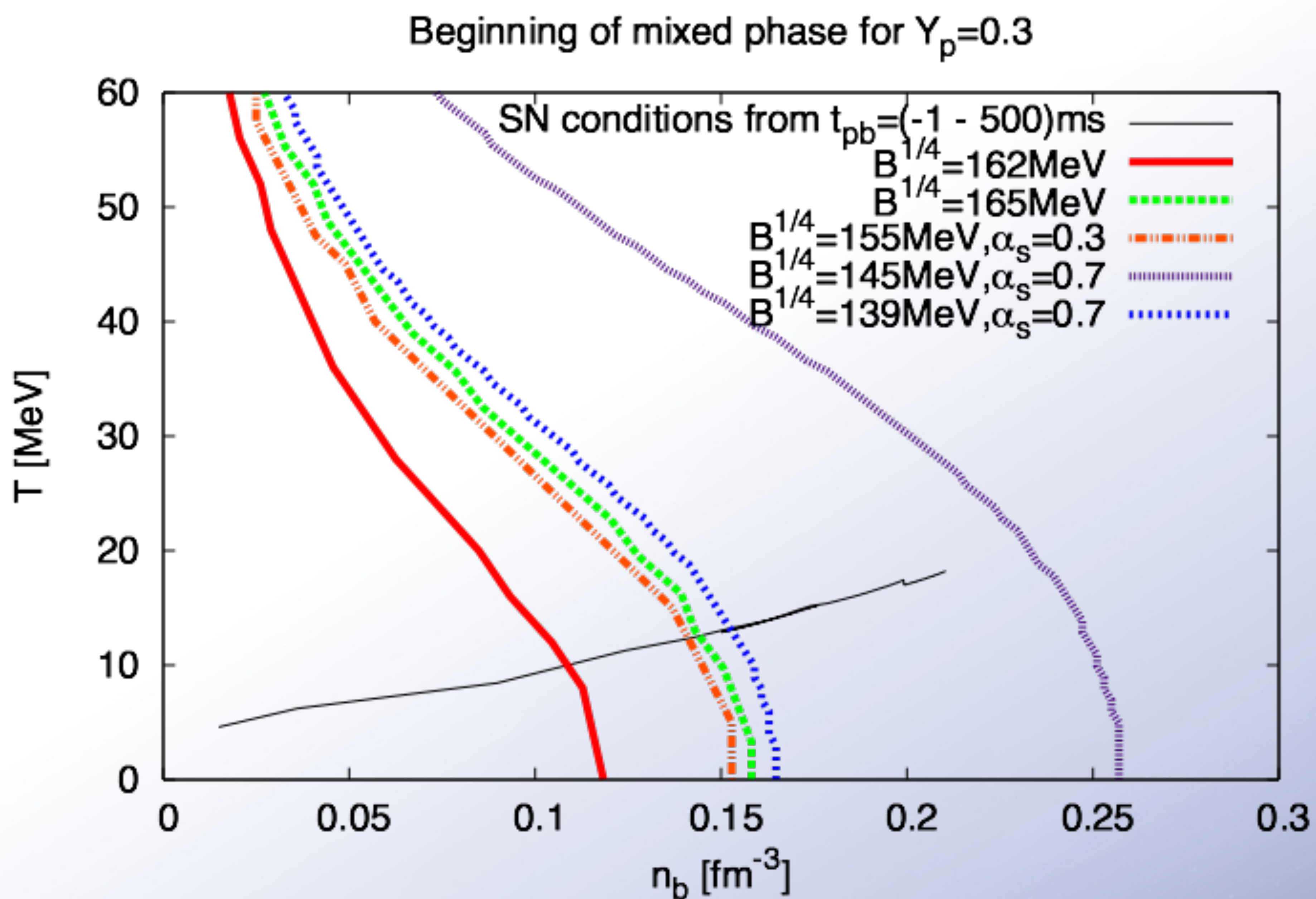


- no explosions for sufficiently high maximum mass
- weak phase transition
- quark matter behaves similarly as hadronic matter „masquerade“
- cf.: Fischer, Blaschke, et al. 2012: PNJL hybrid EOS

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

Densities reached in the supernova

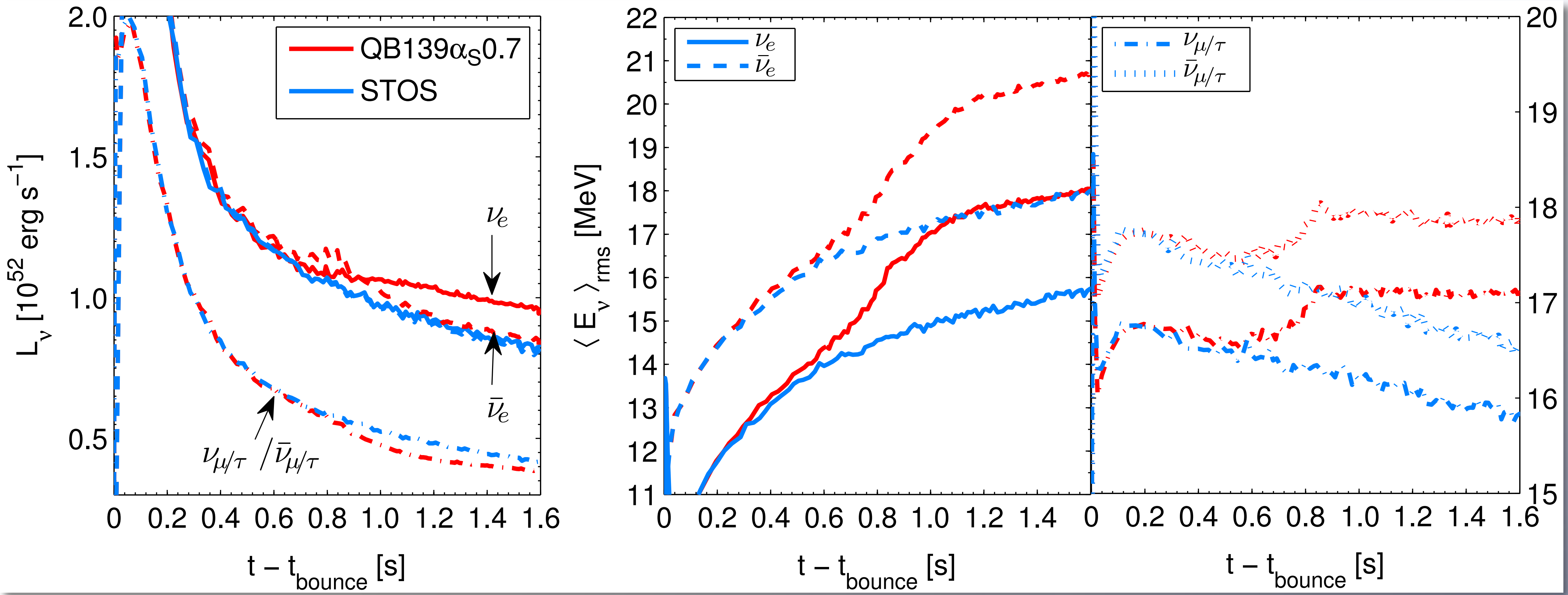
Why does B145 not explode?



→ critical density too high

Neutrino signal for B139 hybrid EOS

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



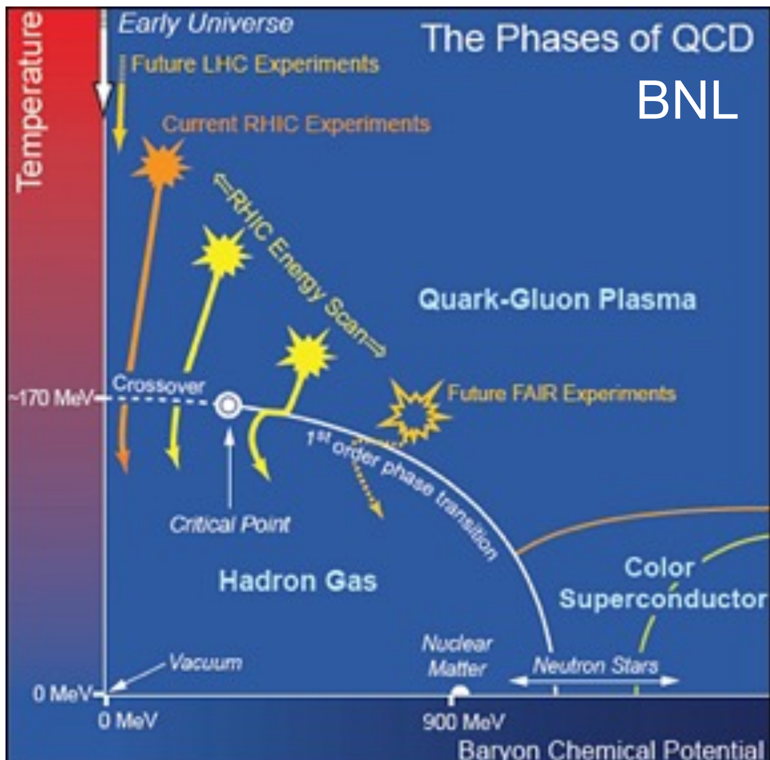
- no second collapse, no explosion, no neutrino burst
- only slight reconfiguration of proto-neutron star
- moderate changes in neutrino signal
- no smoking gun for quark matter in supernovae

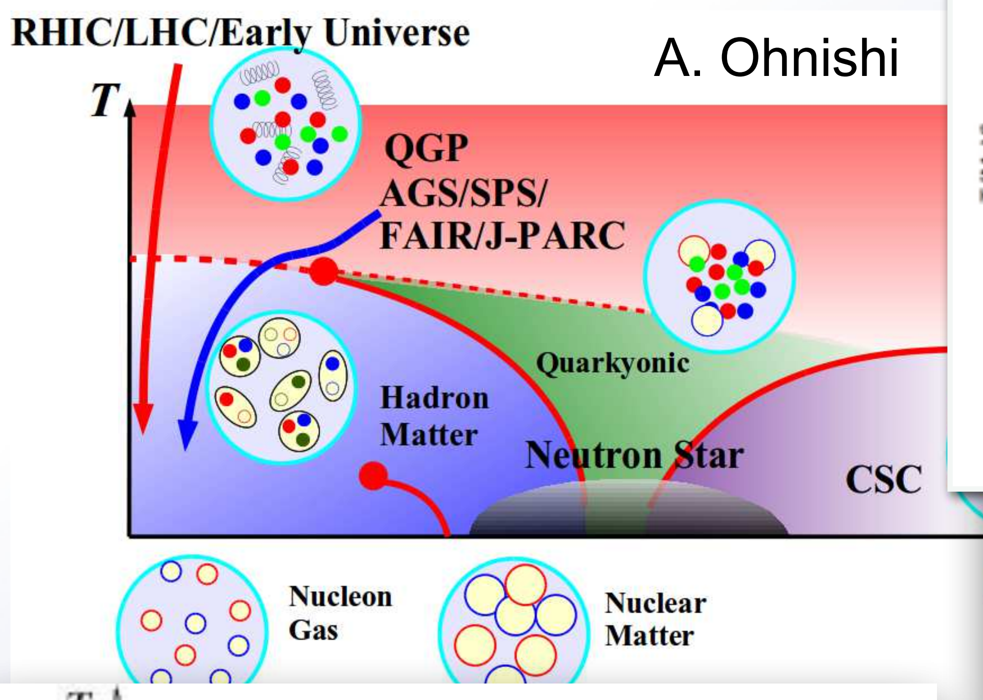
only few models tested, mechanism still possible for others?

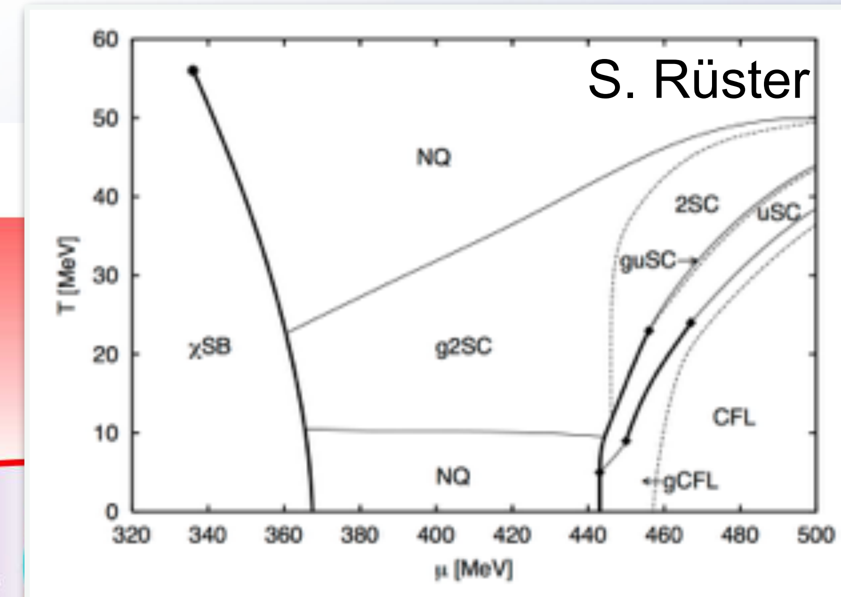
Thermal properties of the hybrid EOS

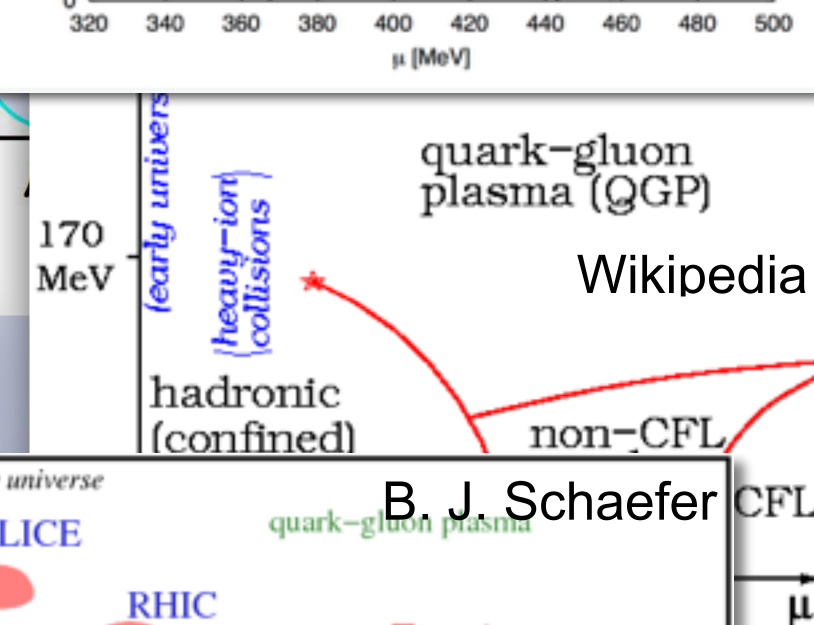
QCD phase diagrams

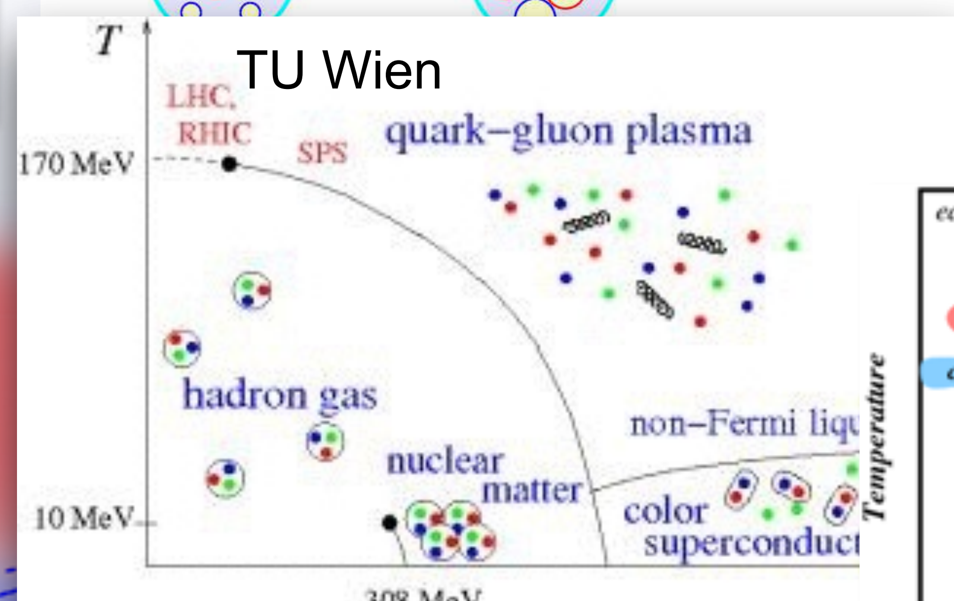
- fundamental question: phase diagram of strongly interacting matter
- typically shown in T-μ, sometime also in T-ρ

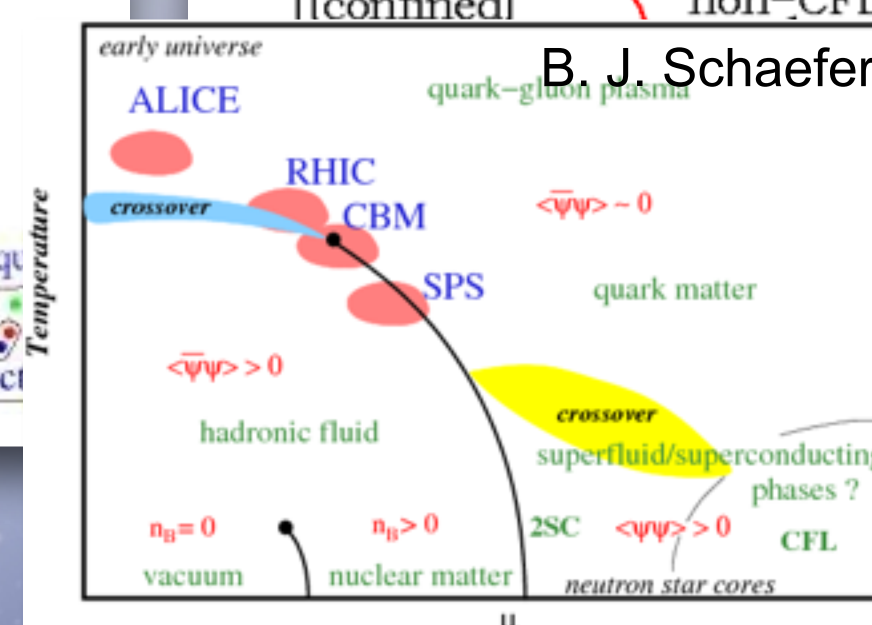


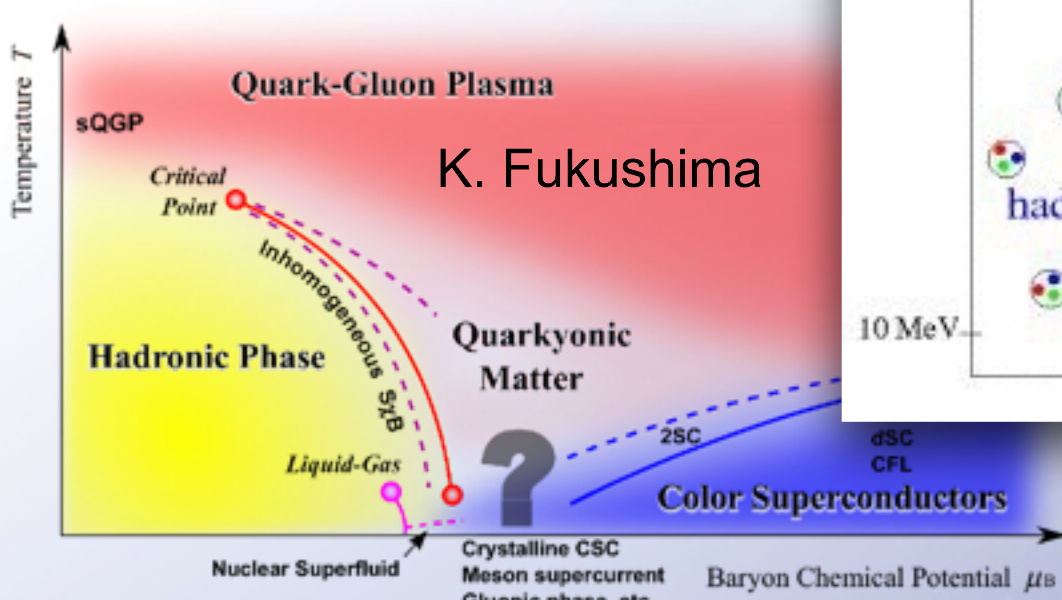










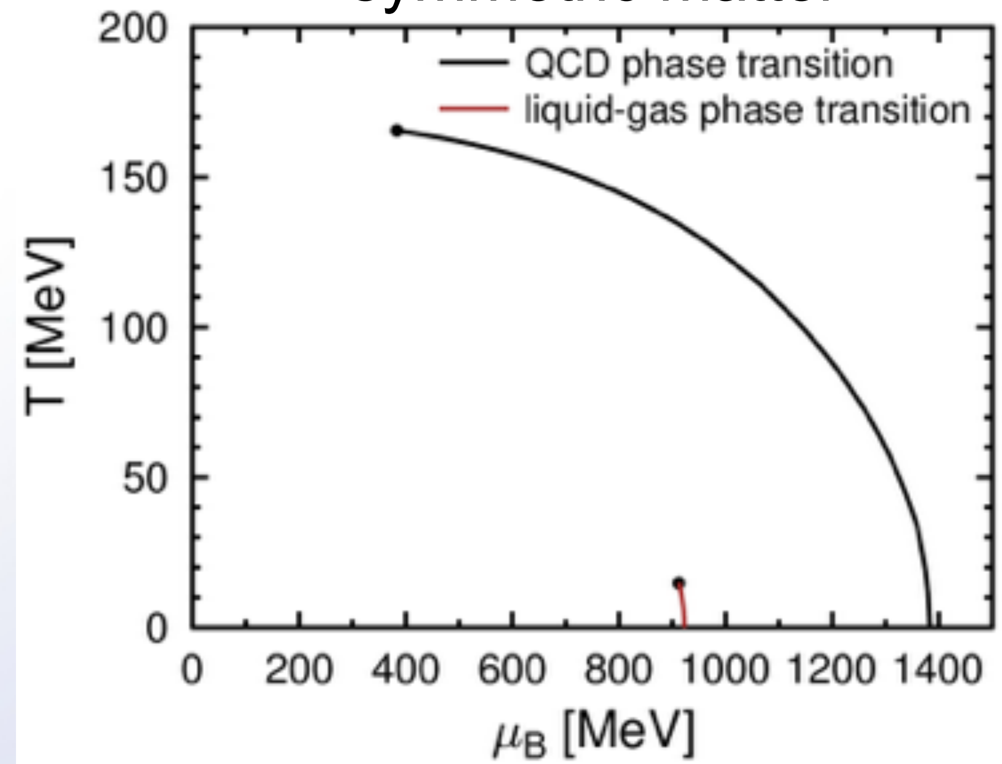


Non-congruence of the nuclear liquid-gas and QCD phase transition

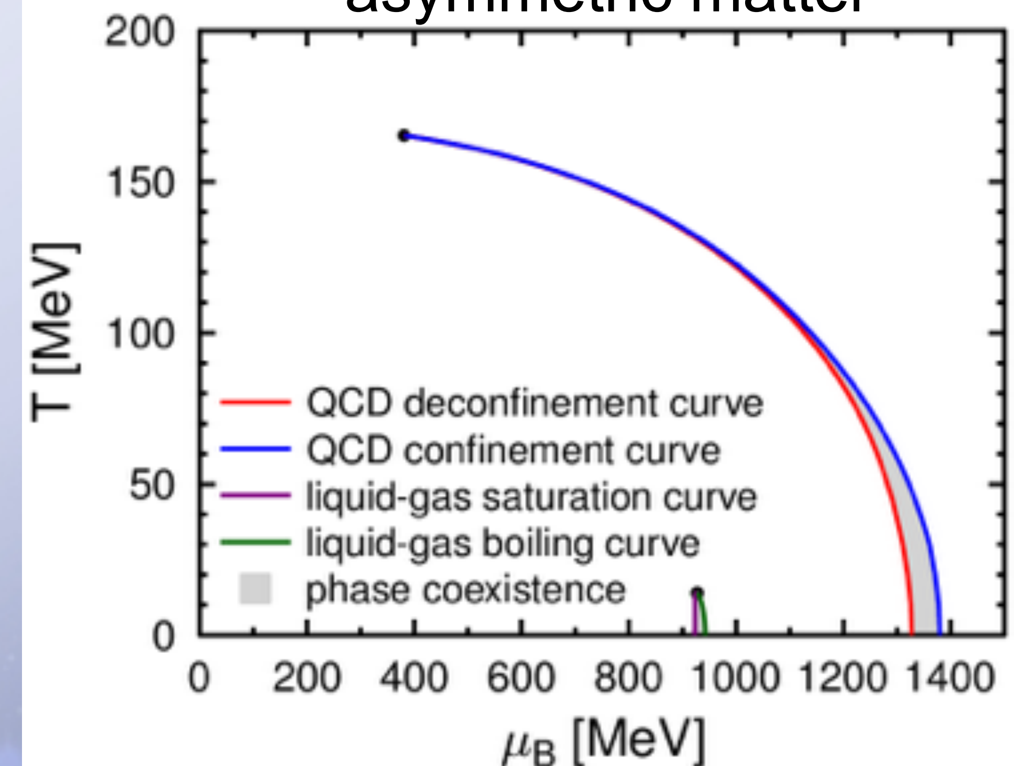
[MH, V. Dexheimer, S. Schramm, I. Iosilevskiy, PRC 88 (2013)]

- main topic: differences of phase transitions with single or multiple conserved charges
- effects of isospin symmetry on phase diagrams
- „congruent“ and „non-congruent“ phase transitions, commonly known as „Maxwell“ and „Gibbs“

symmetric matter



asymmetric matter



Setup

- liquid-gas phase transition of nuclear matter: non-linear relativistic mean-field model FSUgold *[Todd-Rutel and Piekarewicz, PRL (2005)]*

- QCD phase transition: Chiral SU(3) model, includes quarks and hadrons as a chemical mixture of quasi-particle degrees of freedom
[Dexheimer and Schramm, PRC81 (2010)]

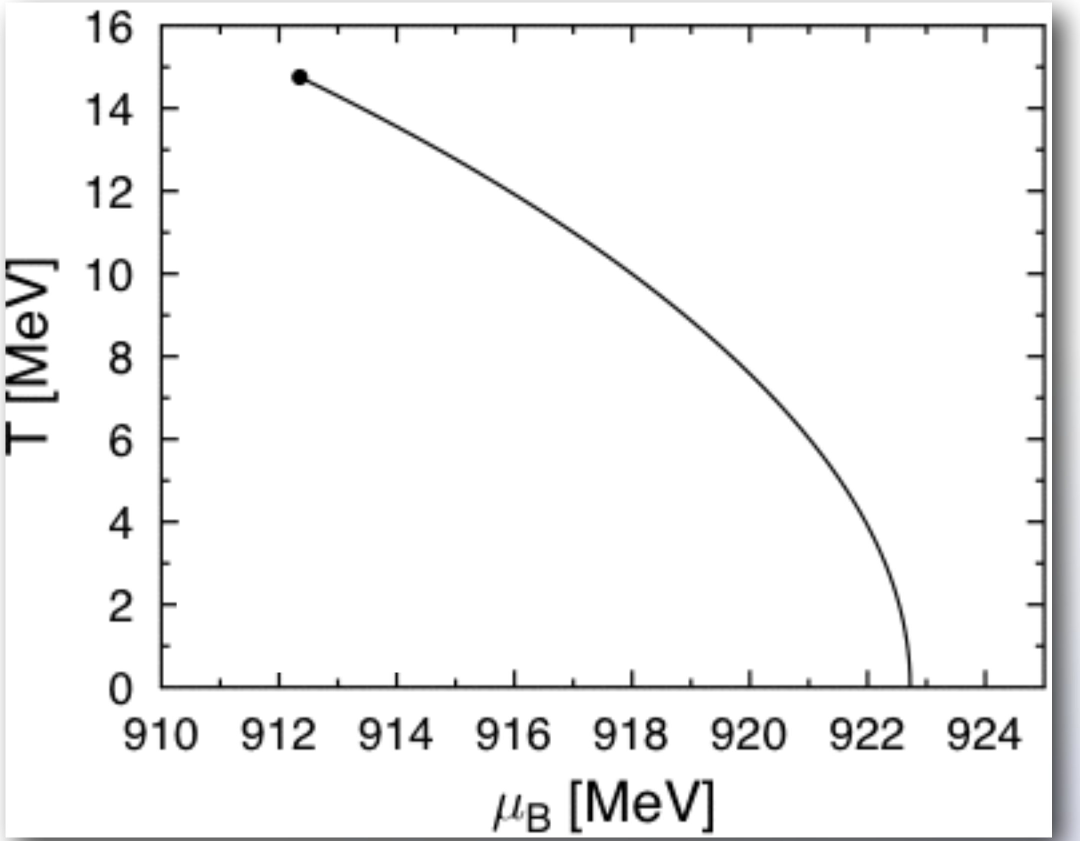
- neglect of all Coulomb interactions, “Coulomb-less“ approximation (cf. works by Gulminelli, Raduta, Typel, …)

- solve for thermal, mechanical, and chemical equilibrium

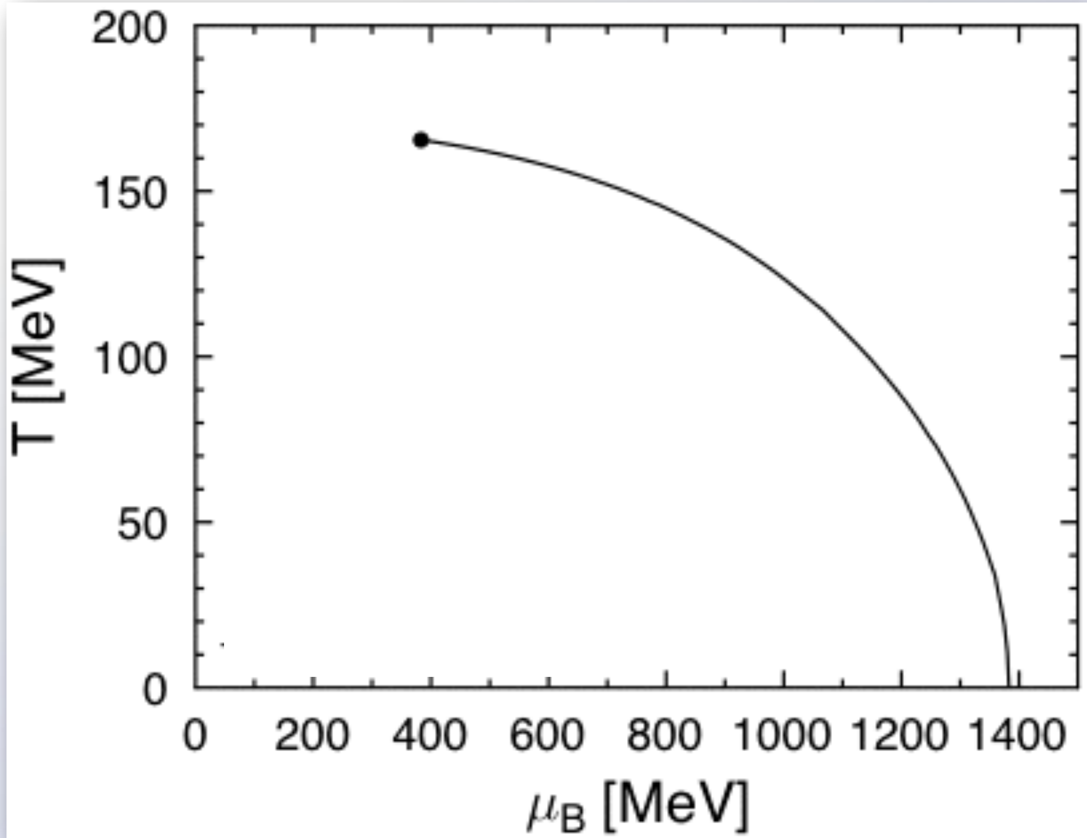
- in the following: symmetric nuclear matter, zero strangeness locally, no leptons

Phase diagram of symmetric baryonic matter — T-μ_B

liquid-gas phase transition



chiral/deconfinement phase transition



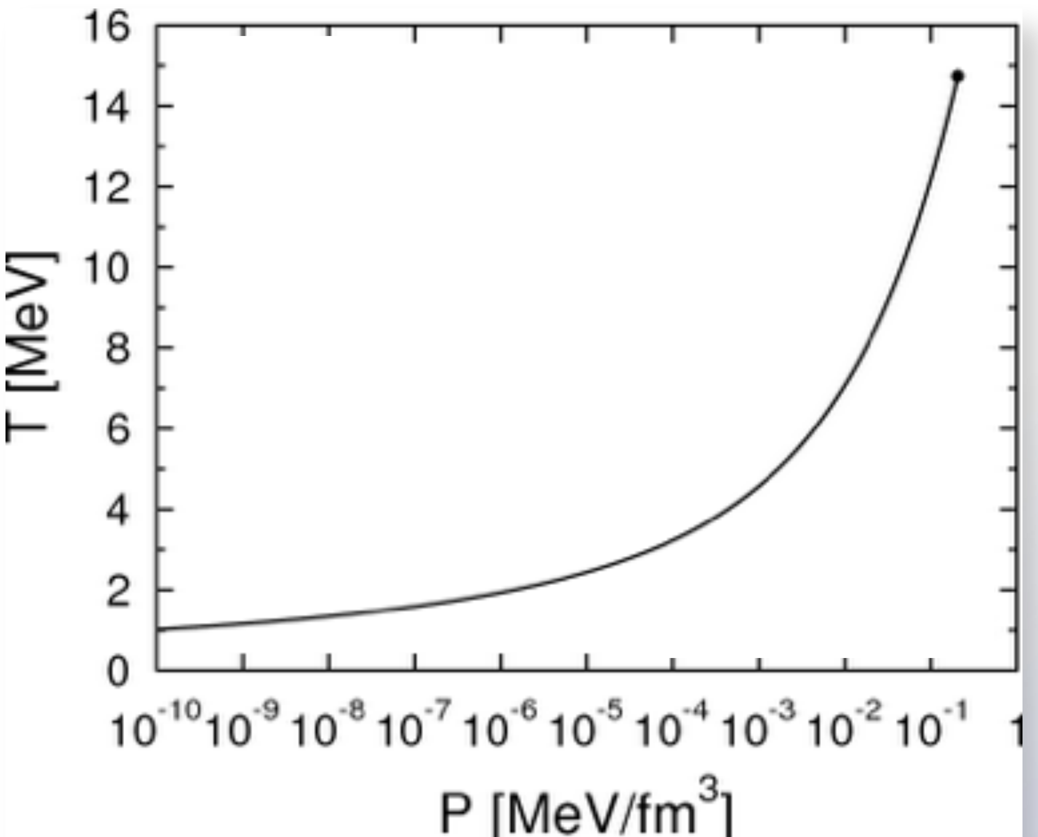
- different scales
- similar shape, both phase transitions terminate in critical point

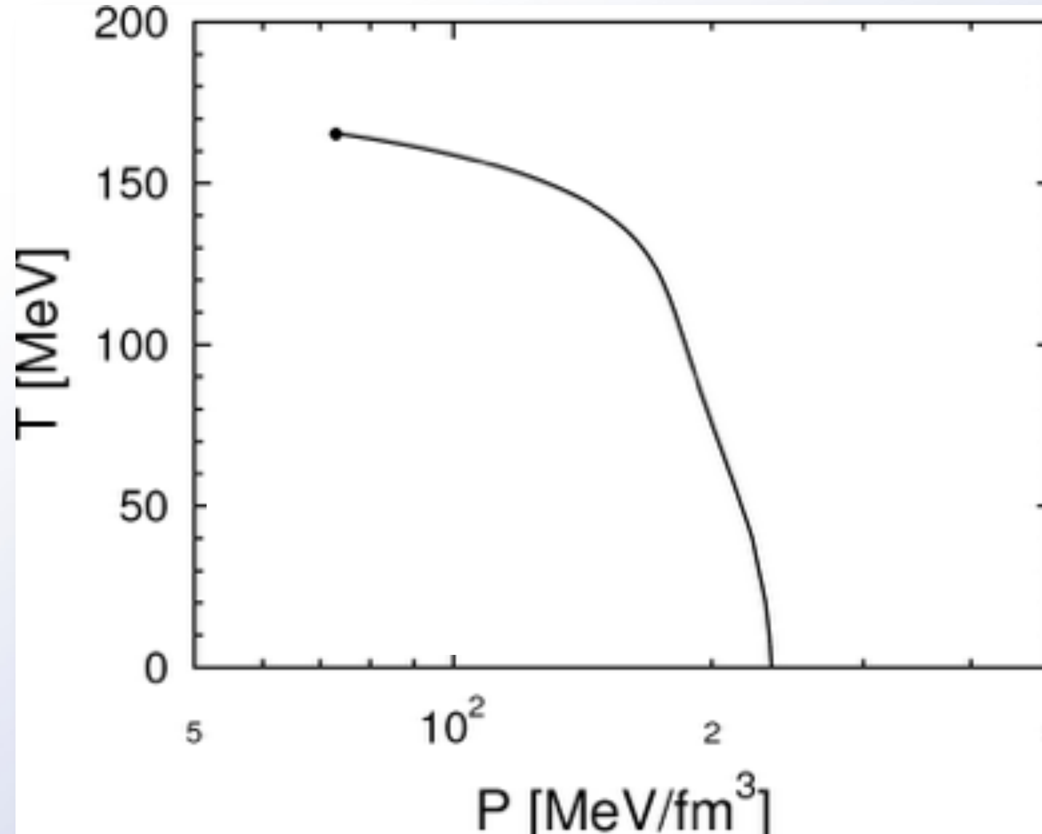
Is the QCD PT of liquid-gas type?

Phase diagram of symmetric baryonic matter — T-P

liquid-gas phase transition

chiral/deconfinement phase transition





enthalpic

entropic

- opposite slope in T-P as fundamental difference

see also:

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

[Bombaci et al., PLB680 (2009)]

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

[Iosilevskiy, arXiv:1403.8053]

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

- Clausius-Clapeyron equation

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

- Steiner et al. 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 ($dP/dT|_{PT}<0$)

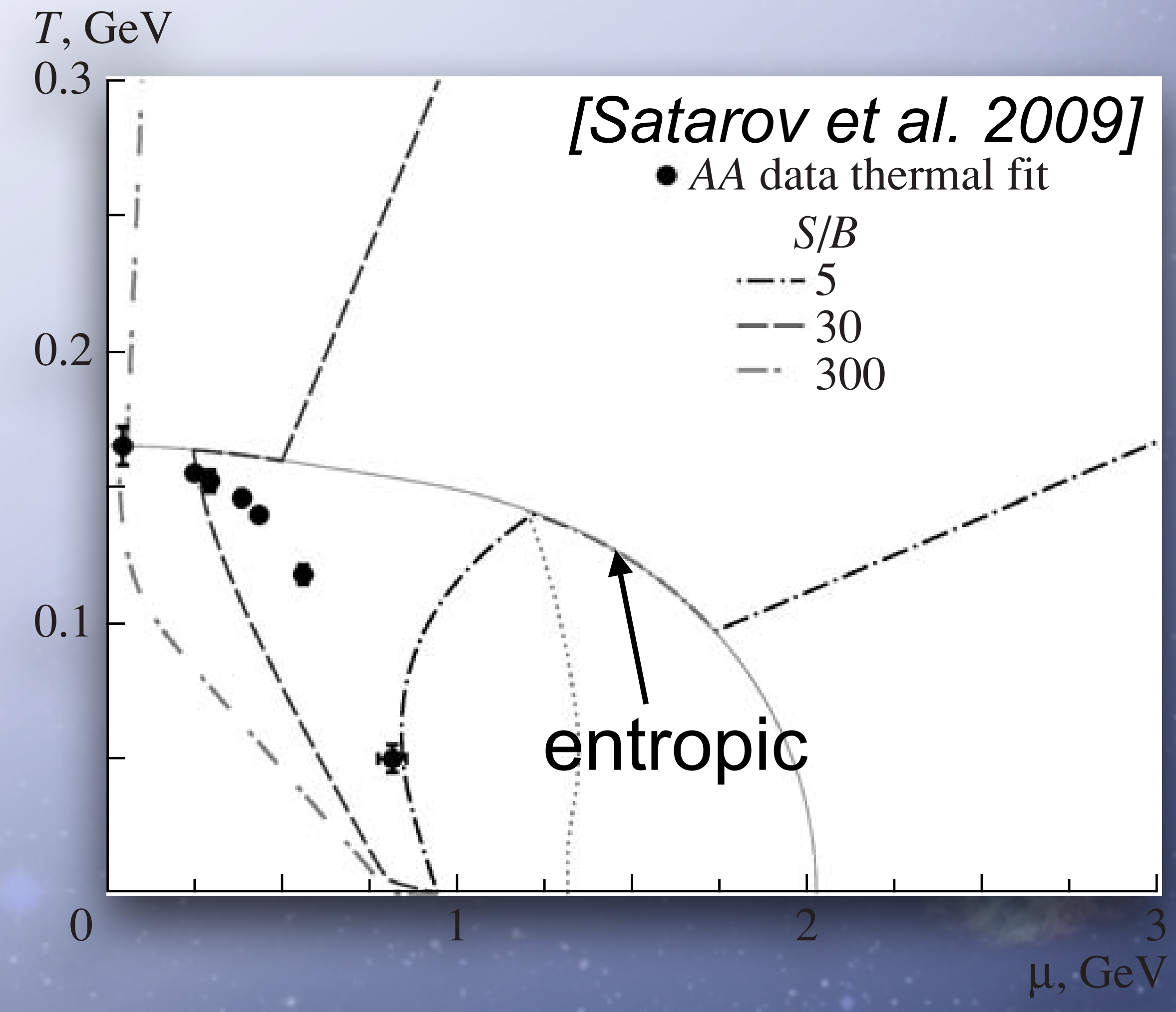
- note: Clausius-Clapeyron equation only valid for a *congruent* (aka Maxwell) PT, i.e. where one has only one conserved charge
- then one also has:

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

- using general thermodynamic relations: unusual sign of 2nd cross derivatives, „abnormal thermodynamics", e.g.: *[Iosilevskiy, arXiv:1403.8053]* *[Iosilevskiy, arXiv:1504.05850]*

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

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



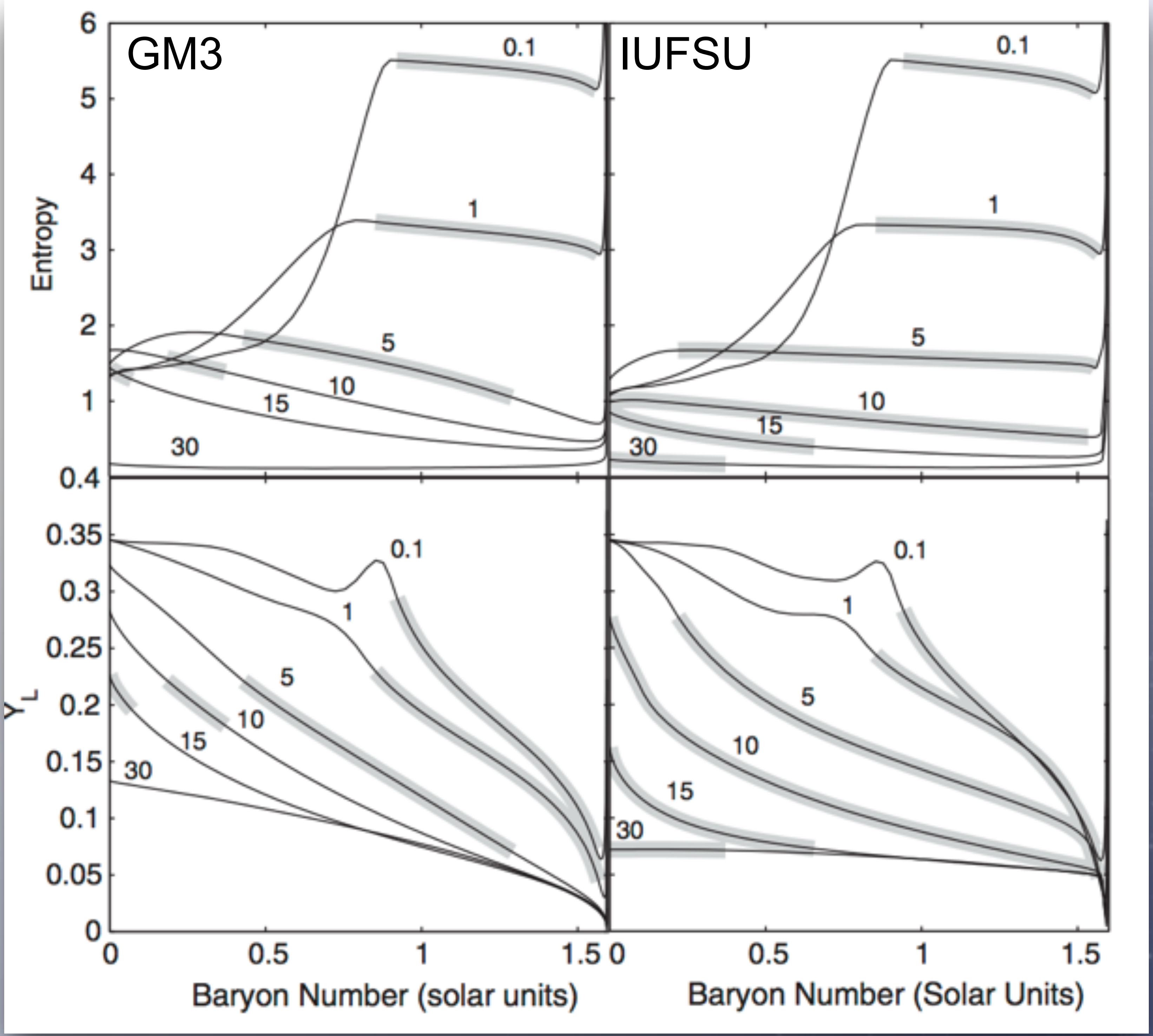
Inverted convection in proto-hybrid stars

[A.V. Yudin, MH, D.K. Nadyozhiny, T.L. Razinkova, arXiv:1507.04598, accepted by MNRAS]

Matter and convection in proto-neutron stars

- entropy per baryon of 0-5
- trapped neutrinos in the early stage of the supernova, characterized by lepton fraction Y_L~0.4
- after one minute: neutrino-free, Y_ν=0, beta-equilibrium

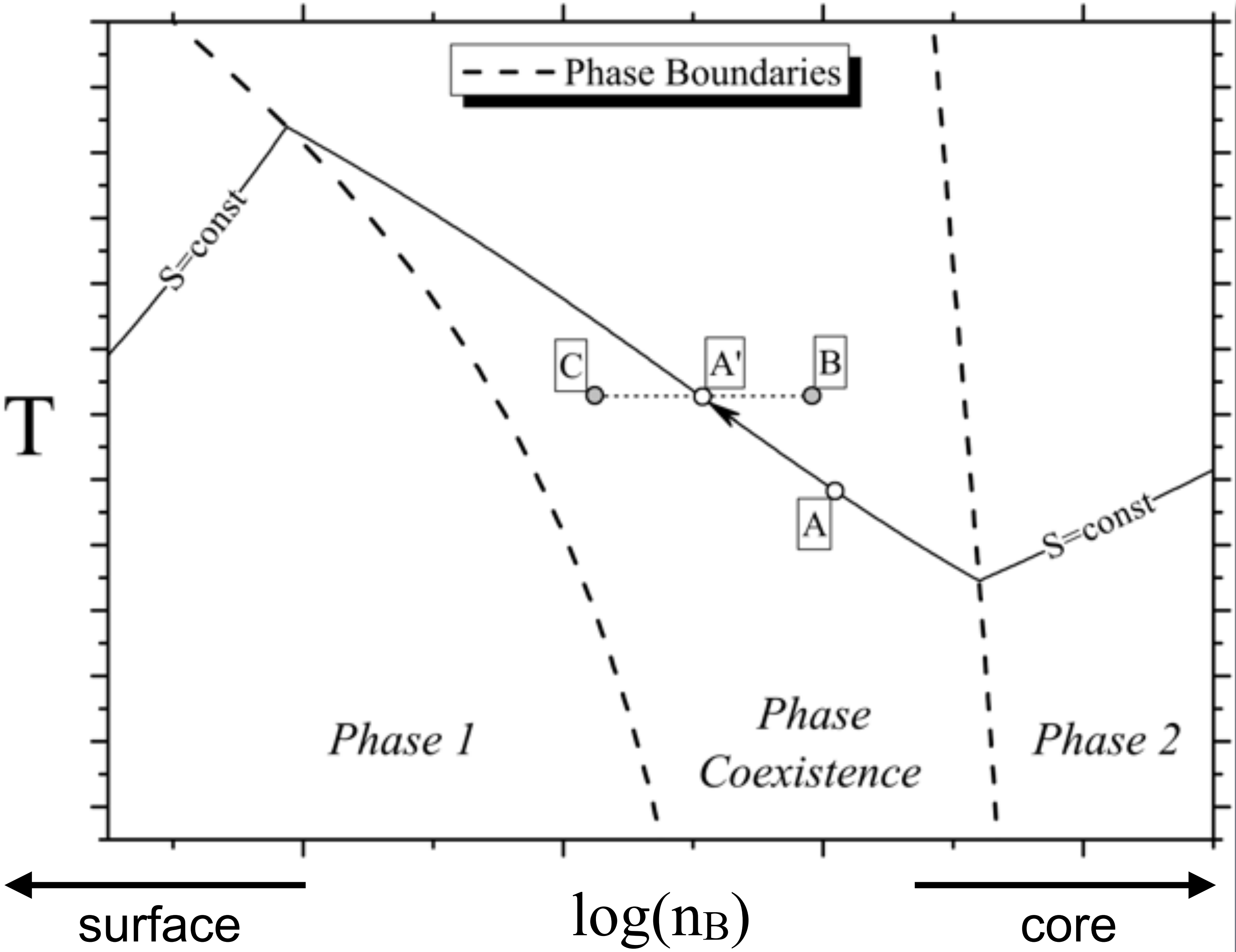
- negative entropy gradients leading to convection in the supernova and proto-neutron star
- effect of convection: outward transport of hot matter, enhanced neutrino luminosities



grayed regions: convectively unstable

[Roberts et al. PRL108 (2012)]

Convection in proto-hybrid stars



- unusual thermal properties (abnormal thermodynamics) due to entropic PT:
  positive entropy gradients are convectively unstable (!)

[Yudin, MH, et al. arXiv:1507.04598]

Convection criteria

- relativistic Ledoux criterion for convection:

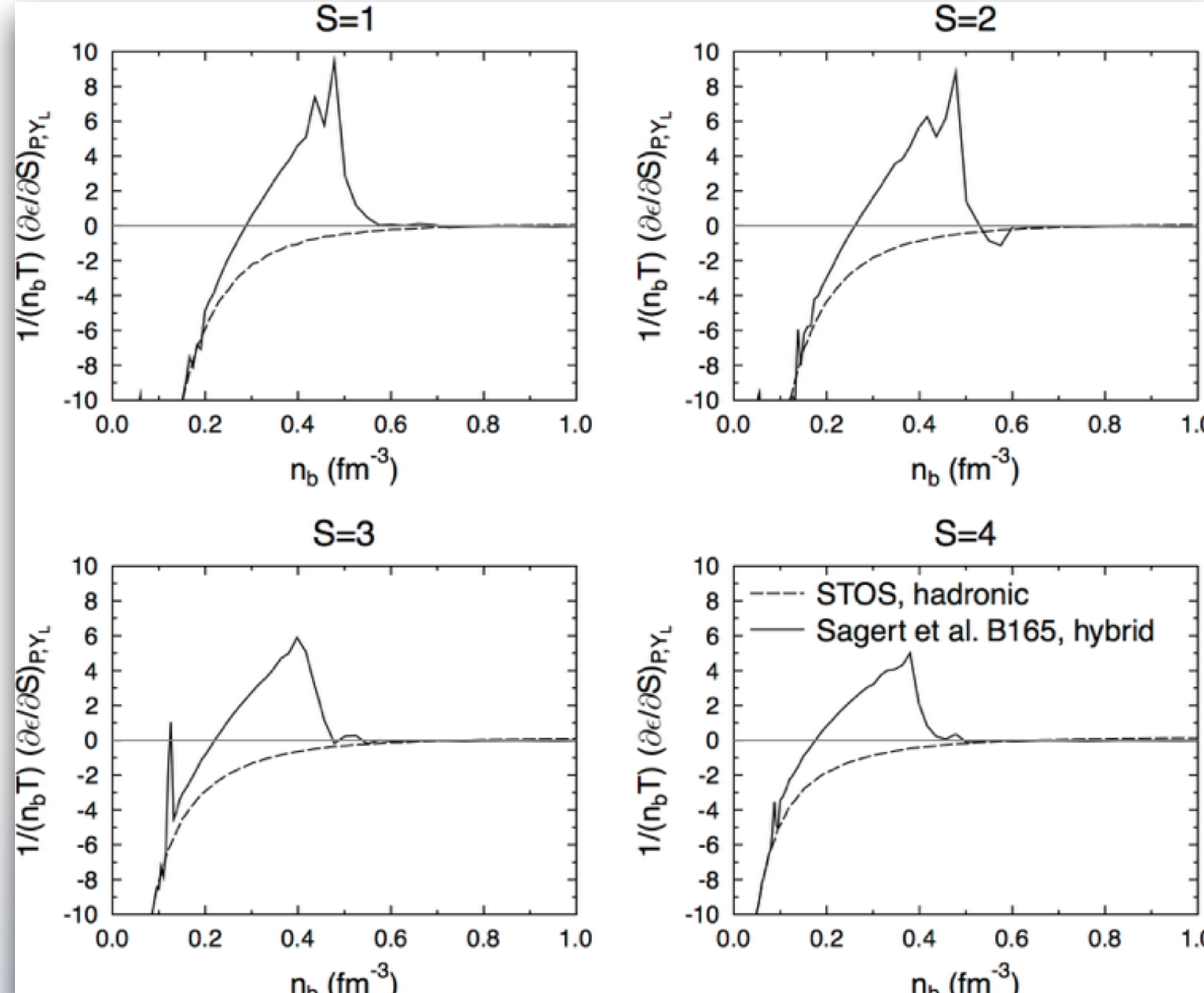
$$\left.\frac{\partial \epsilon}{\partial S}\right|_{P,Y_L} \frac{dS}{dr} + \left.\frac{\partial \epsilon}{\partial Y_L}\right|_{P,S} \frac{dY_L}{dr} > 0$$

- let's ignore composition changes, keep Y_L=0.4=const. → dε/dS determines convection
- dε/dS usually negative → negative entropy gradients are convectively unstable

$$\left.\frac{\partial \epsilon}{\partial S}\right|_{P,Y_L} = n_B T \left\{ 1 - \frac{\epsilon + P}{T \left.\frac{\partial P}{\partial T}\right|_{S,Y_L}} \right\}$$

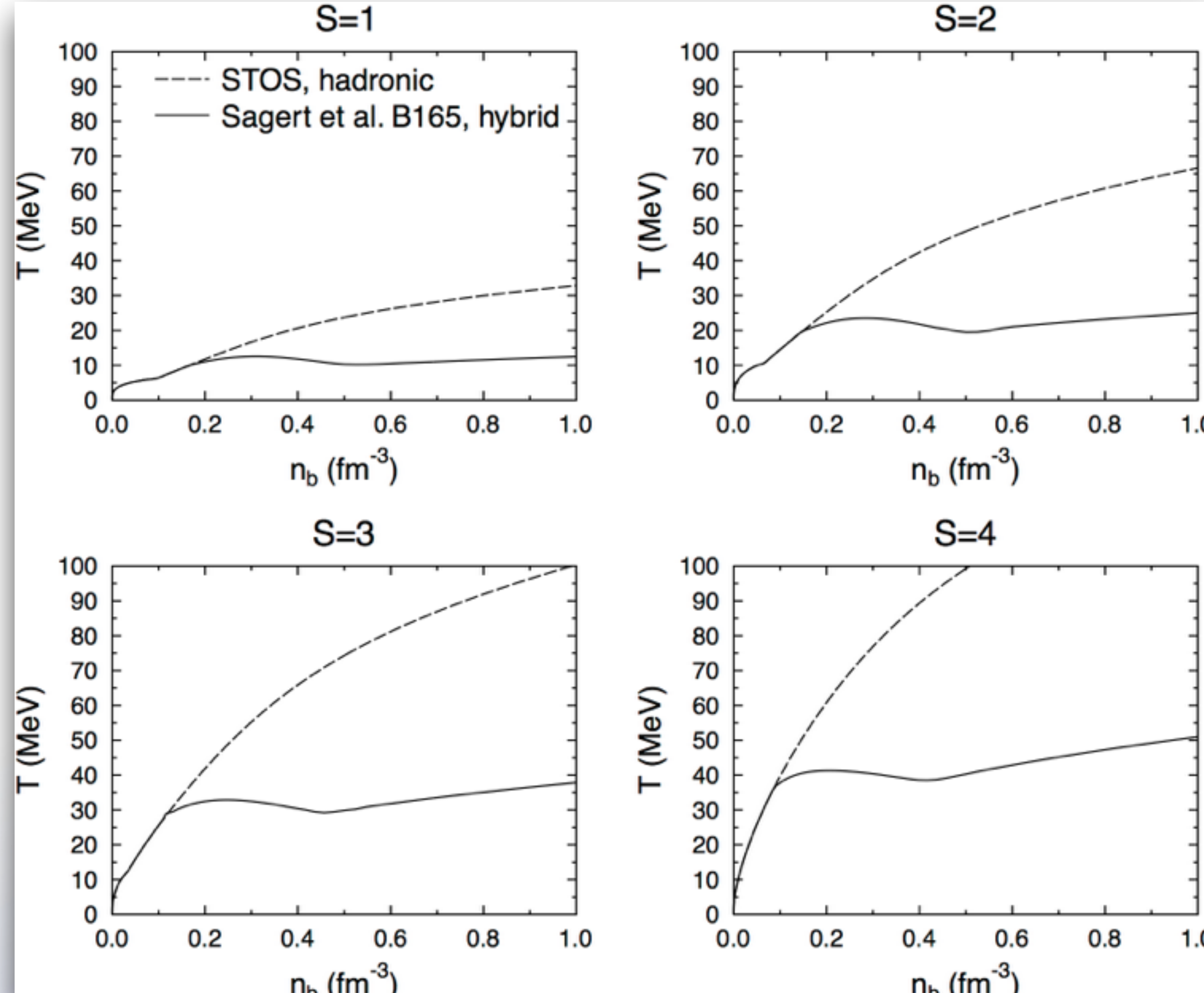
- first term: small, relativistic correction
- → $dP/dT|_S>0 \Leftrightarrow d\varepsilon/dS|_P<0$

Convection criteria for B165



- positive values: convectively unstable for positive entropy gradients

Temperature for isentropes of B165

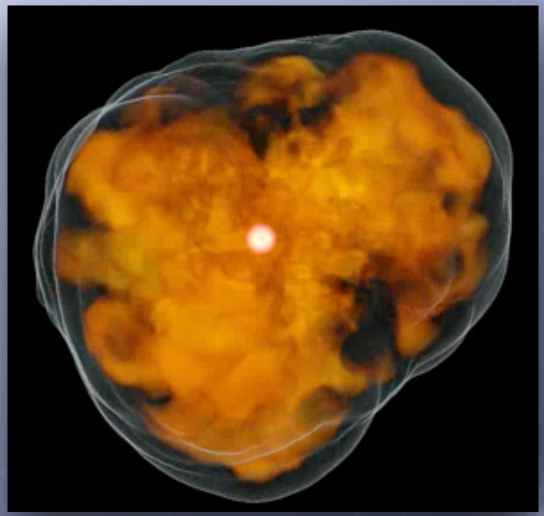


Realizability and possible consequences

- realizability depends on
  - EOS model of hadronic and quark phase
  - description of the phase transition (surface tension)
  - structure of the proto-hybrid star

- possible consequences:
  - starting from quark core with low temperature
  - low entropy bubbles moving outwards, high entropy inwards
  - inward heat flux, increasing temperature of quark core, decreasing temperature of hadronic mantle, until negative entropy gradient is achieved

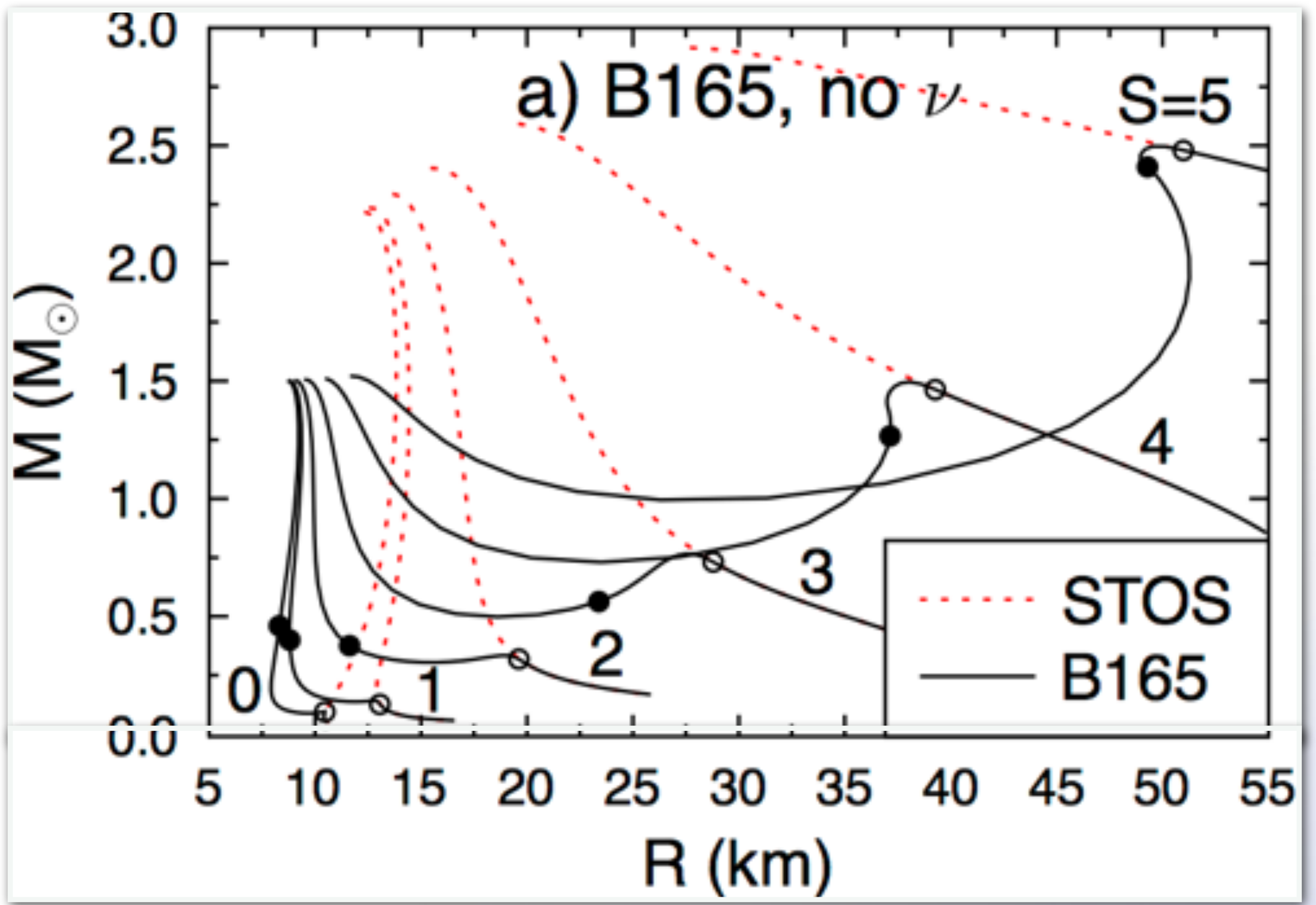
  - impact on supernova dynamics ???
  - imprint of quark matter on neutrino signal ???



CCSN explosions and the QCD PT

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

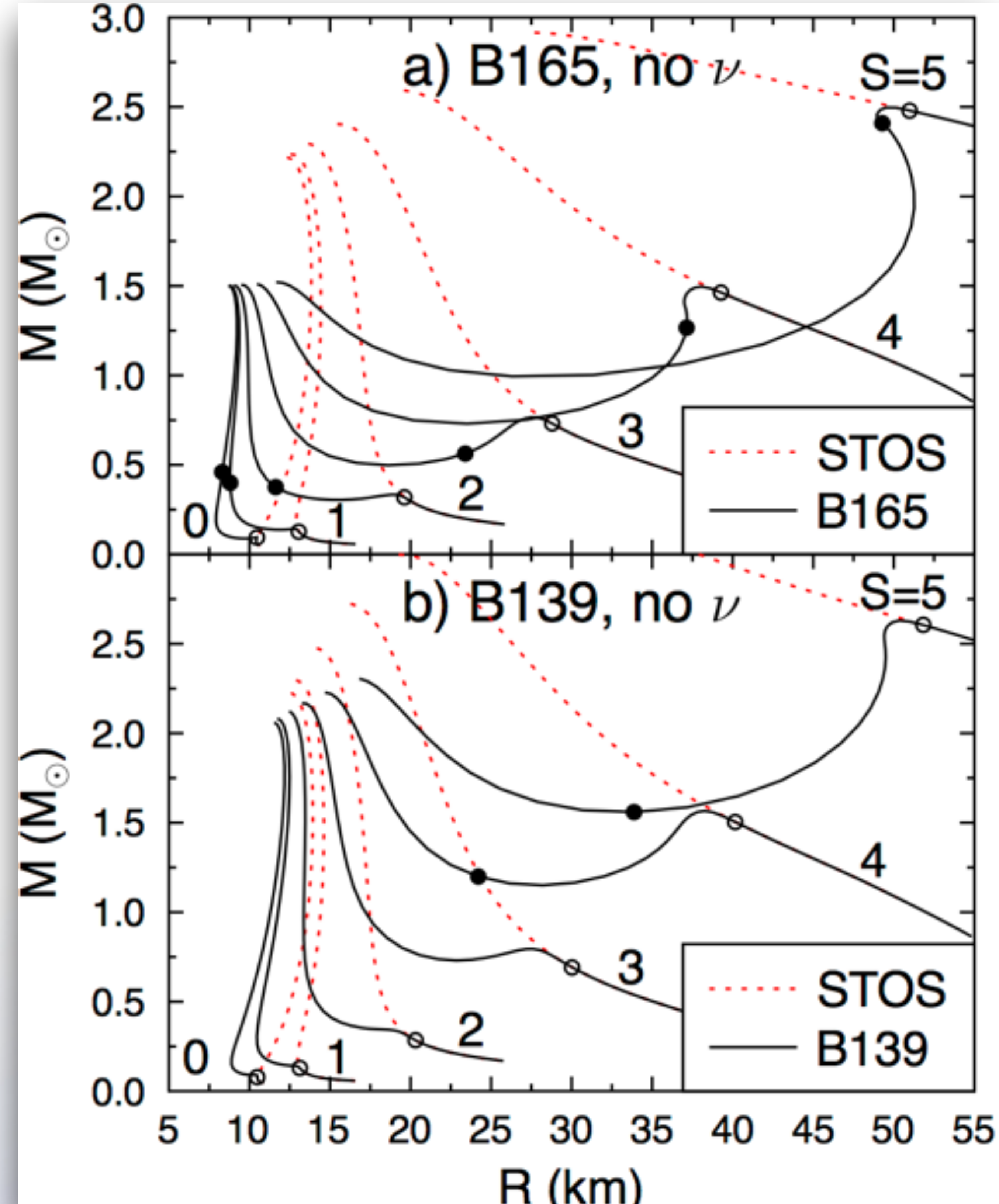
A third family of proto-compact stars



- 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

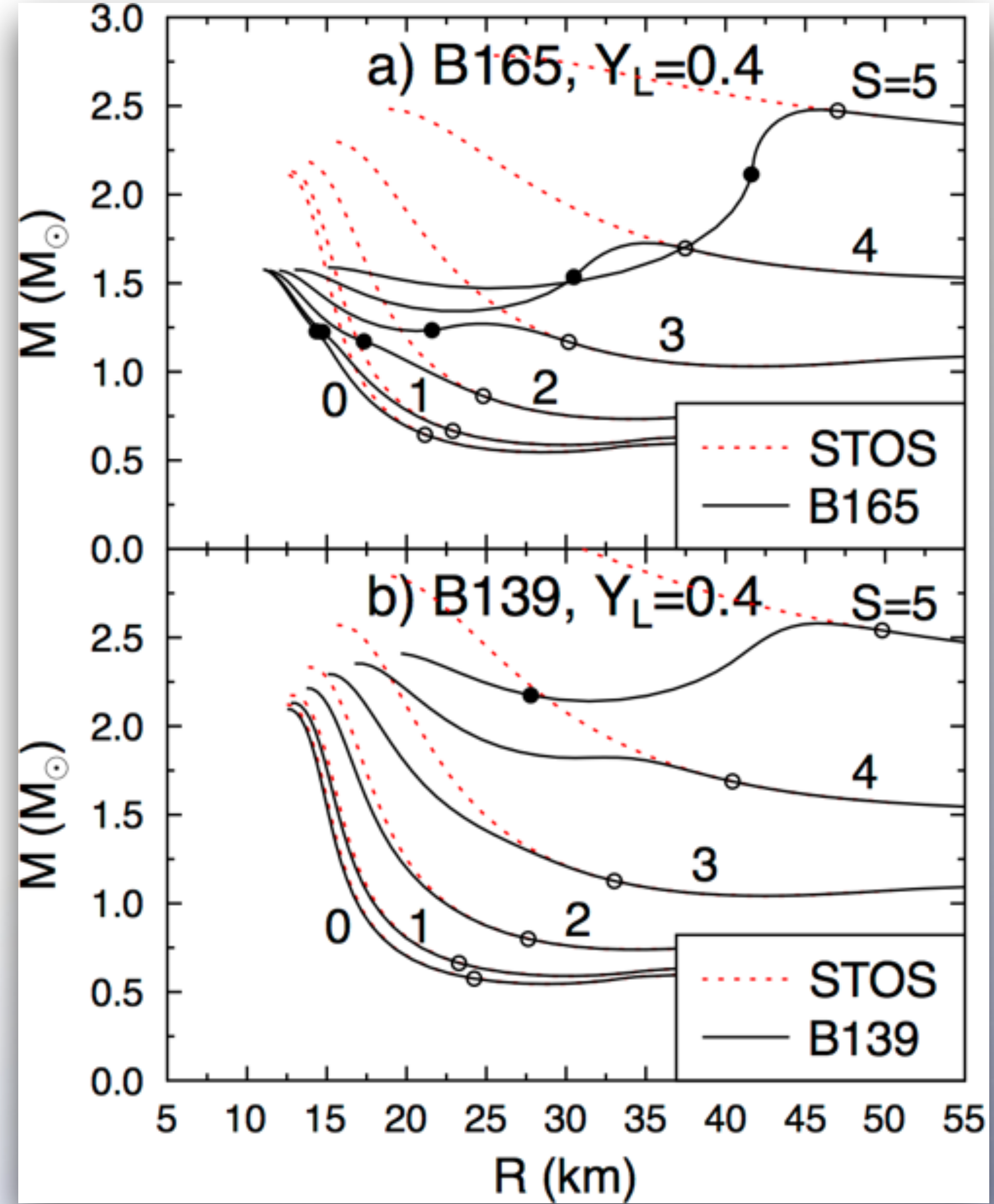
- explains the supernova explosions of Sagert and Fischer et al:
- proto-neutron star first on the second branch
- accretion until maximum reached
- collapse to third family, energy release, formation of 2nd shock, explosion

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 convection: $d\varepsilon/dP|_S$
- for stability: $P(\varepsilon,S)$

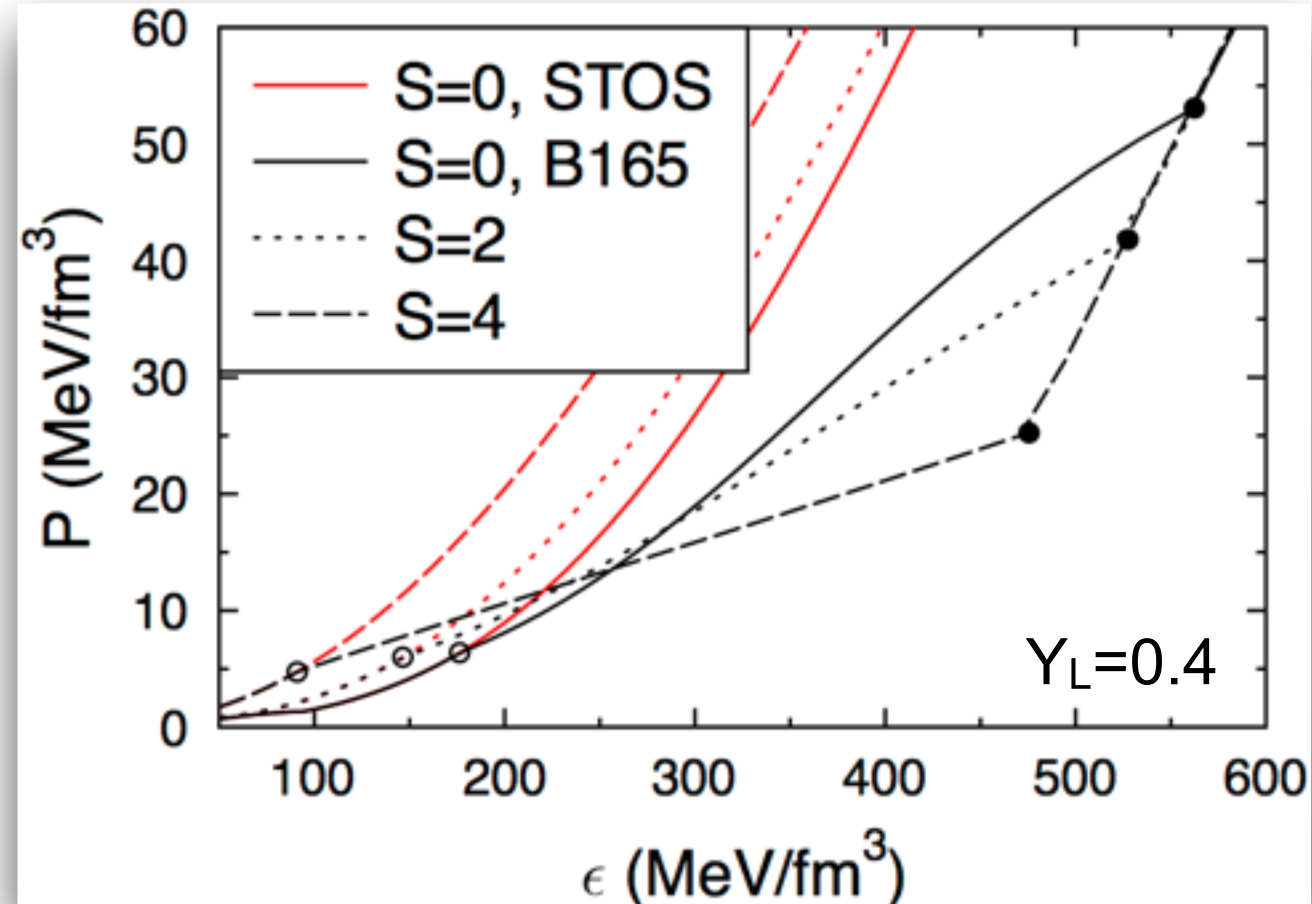
- to characterize thermal effects: $dP/dS|_\varepsilon$
- $dP/dS|_\varepsilon>0$: stiffening, $dP/dS|_\varepsilon<0$: softening for increasing entropy

- using general thermodynamic relationships:

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

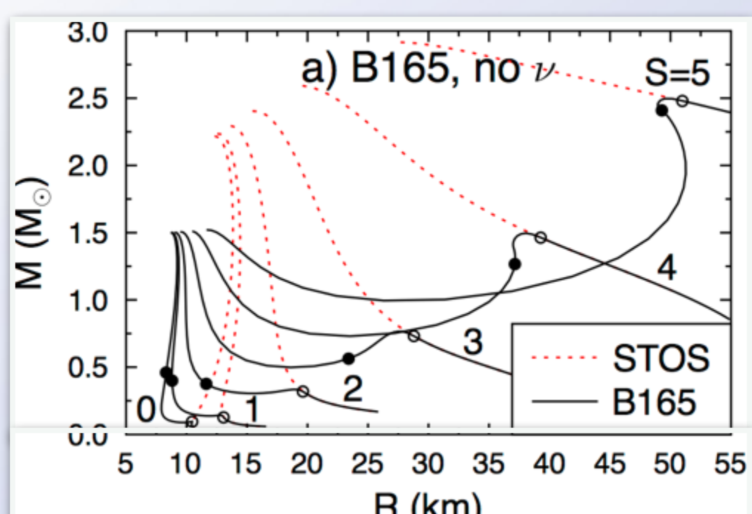
- first term small, relativistic correction
- → abnormal thermodynamics/entropic PT induces a softening of the EOS with increasing temperature/entropy (!)

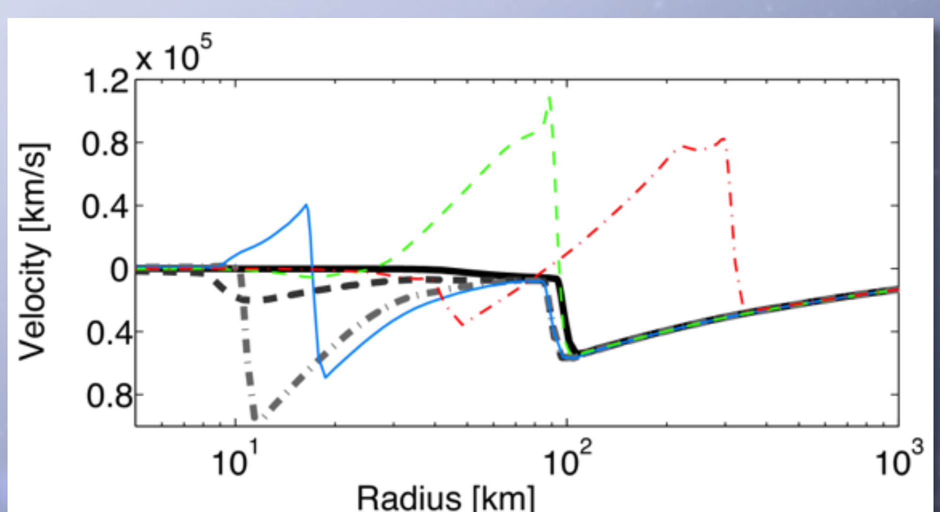
Pressure-energy density relation



- hadronic and quark matter stiffens when it is heated
- in the phase coexistence region it softens (!)
- note: effect occurs only in parts of the phase coexistence (non-congruent PT)

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





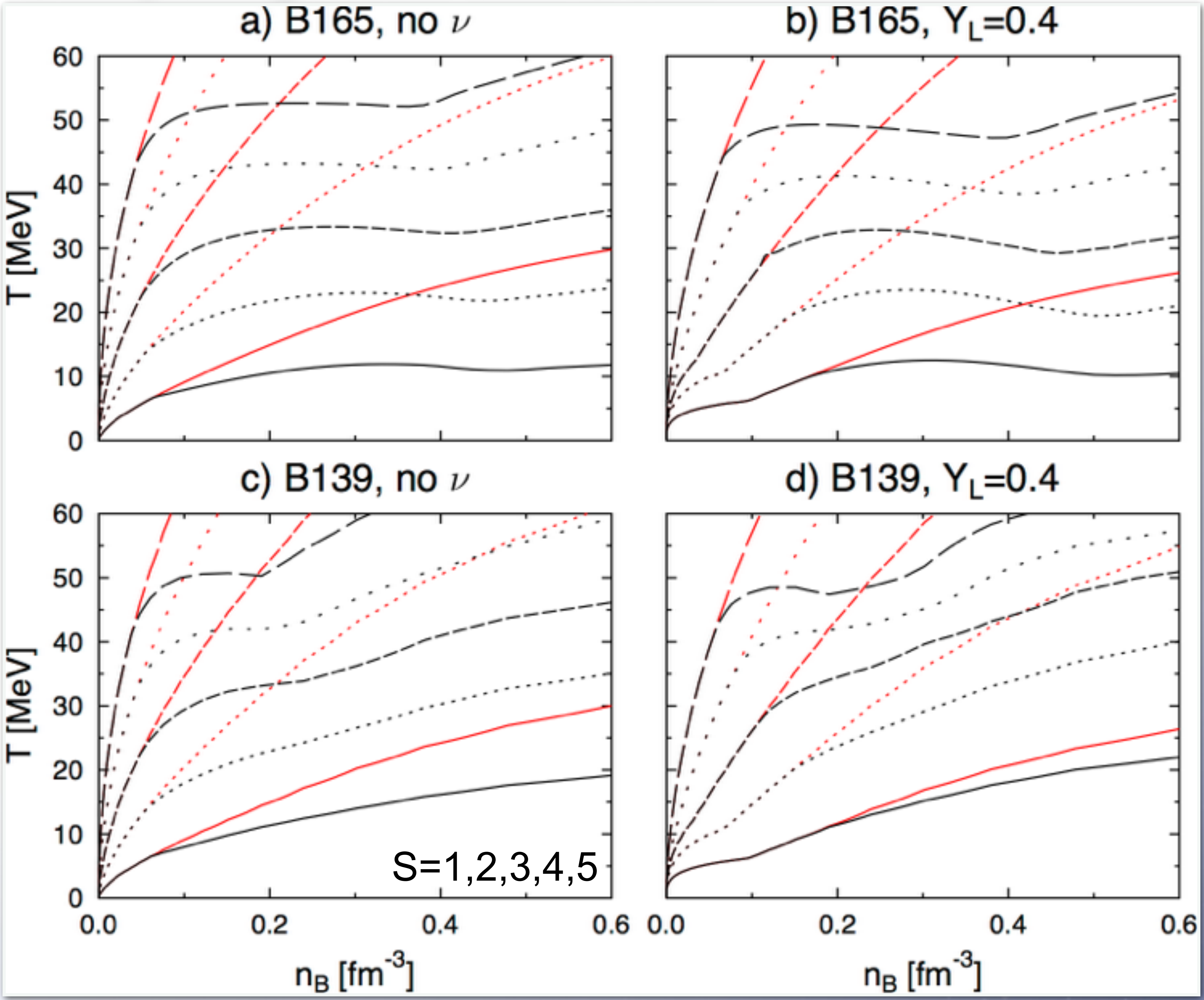
Summary and conclusions

- 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

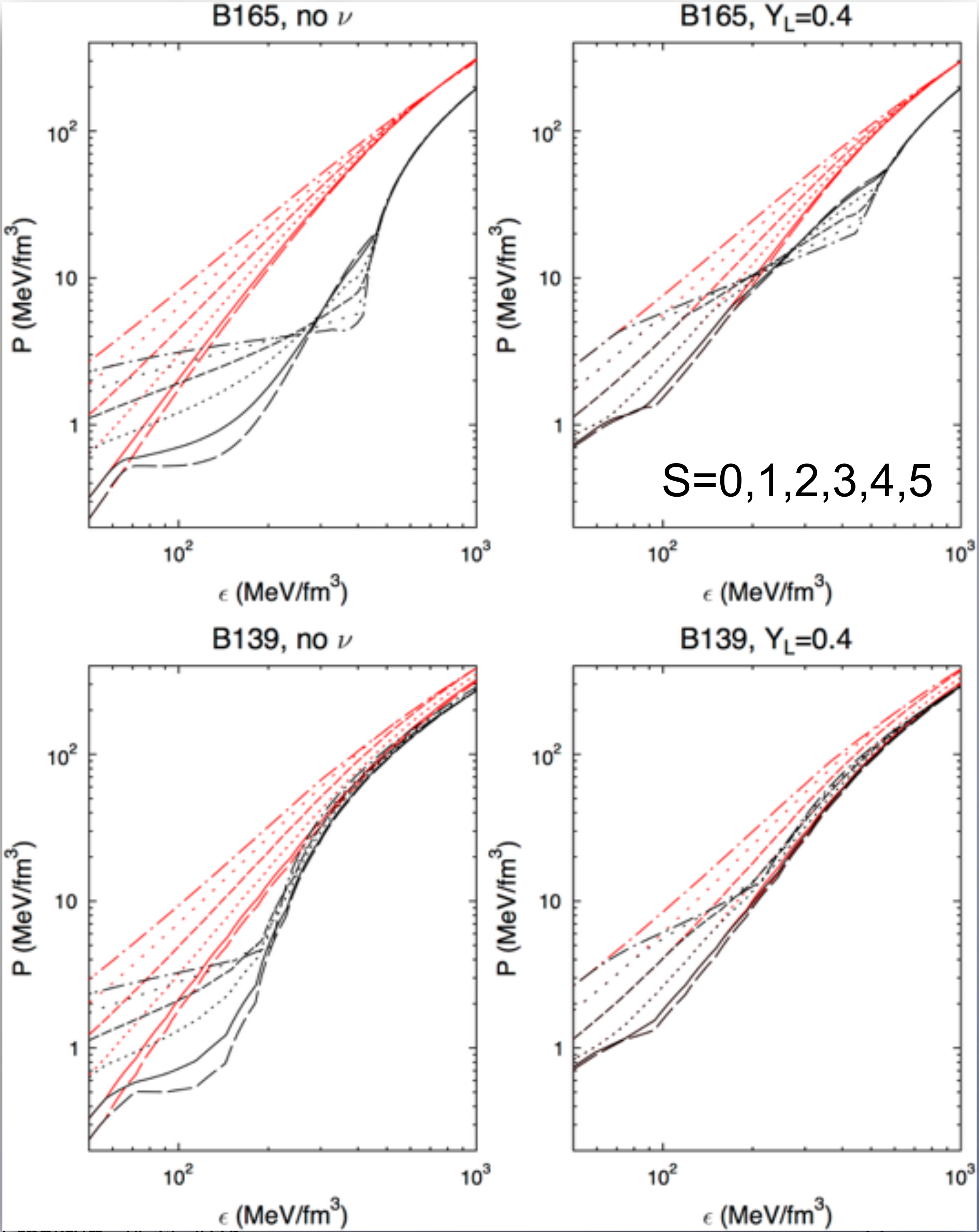
- is it possible to achieve explosions by the QCD PT and have a maximum mass above 2 M_{sun}?
  - difficult to answer, requires new EOSs and new simulations
  - but: the maximum mass is determined at T=0, for the supernova the thermal properties are crucial

Comparing B139 and B165



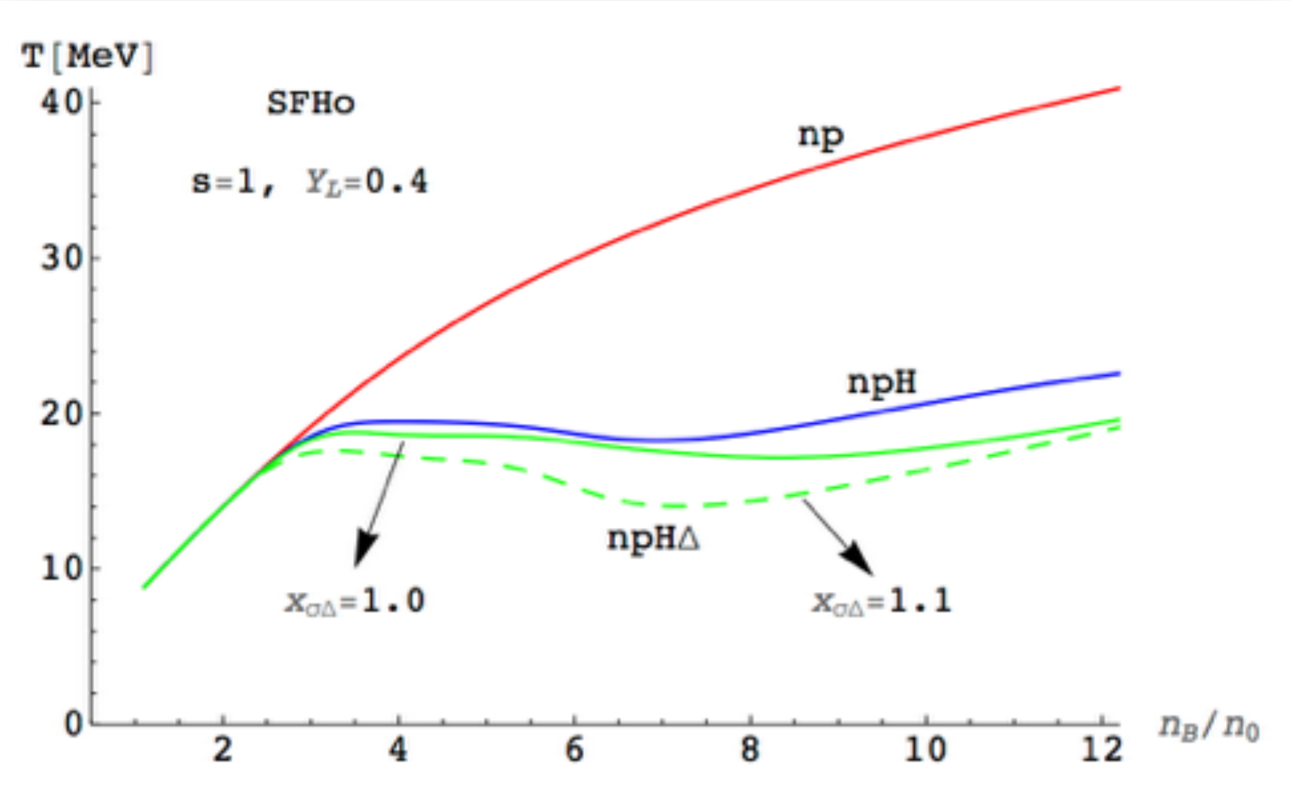
- almost no temperature decrease for B139
- extremely extended phase coexistence
- „masquerade“

Comparing B139 and B165



- interactions stiffen the quark phase
- softening with entropy very weak, if at all

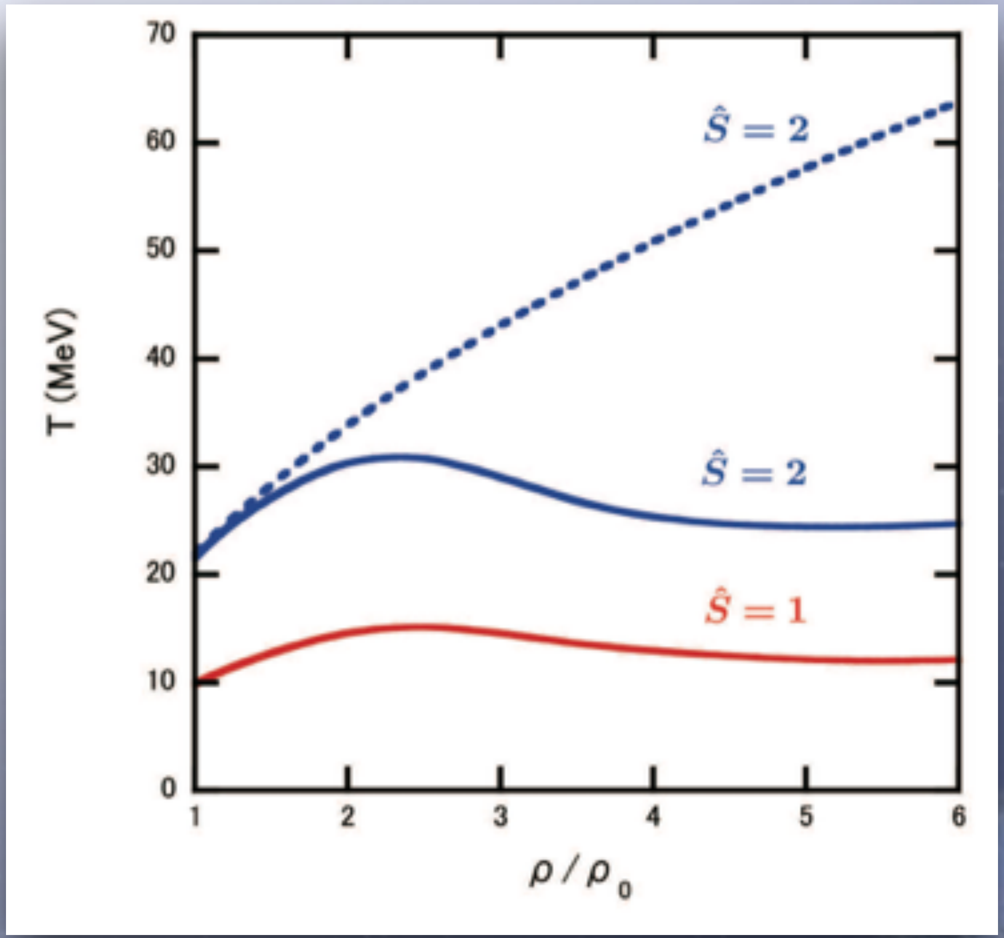
Unusual thermal properties in other EOS



[Drago et al. arXiv:1509.02131]

- relativistic mean-field EOS including hyperons and deltas

[Masuda et al. arXiv:1506.00984]



- cross-over transition to NJL EOS