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

Matthias Hempel, Basel University

L'Aquila, CSQCD V Conference, 26.05.2016

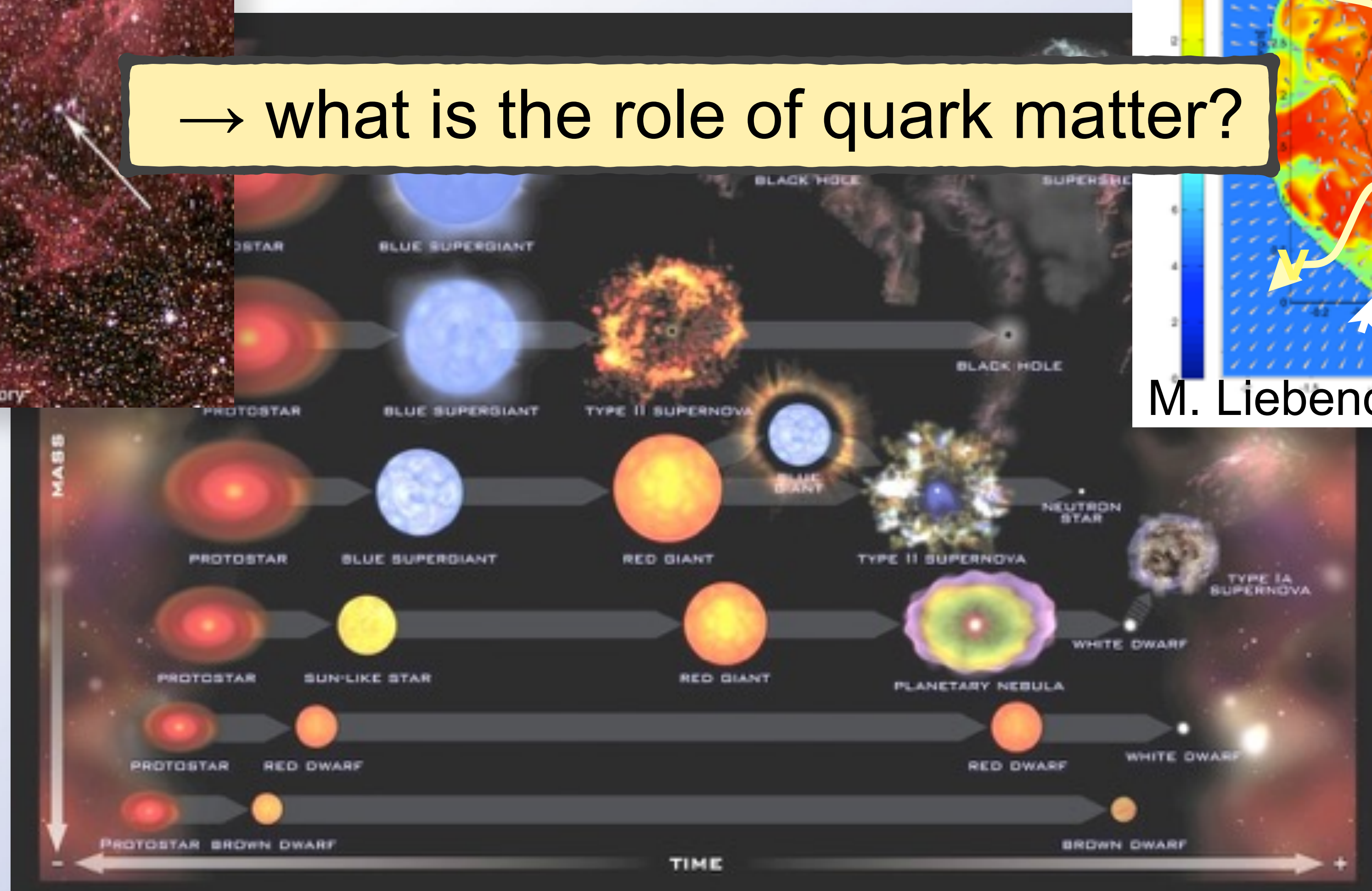
FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

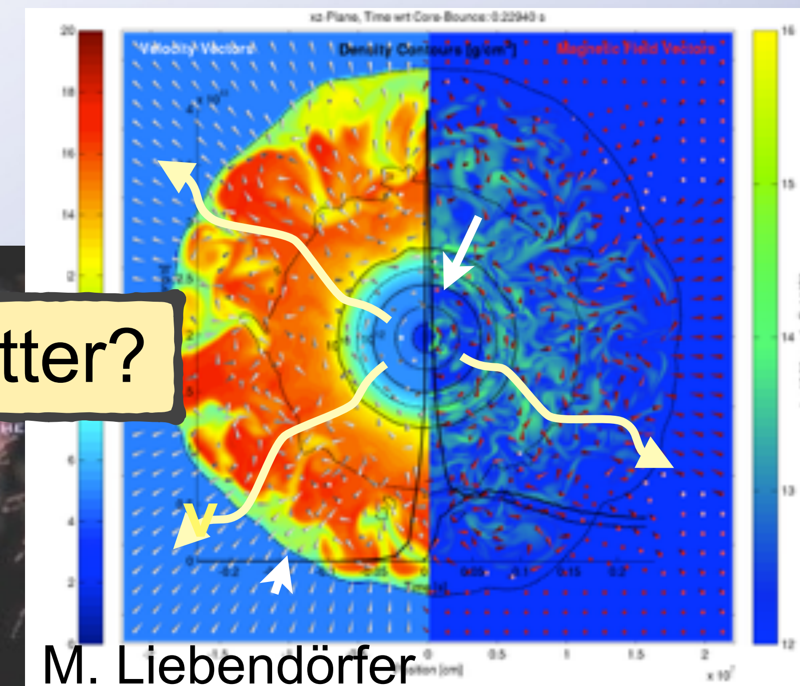
comp star

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

→ what is the role of quark matter?



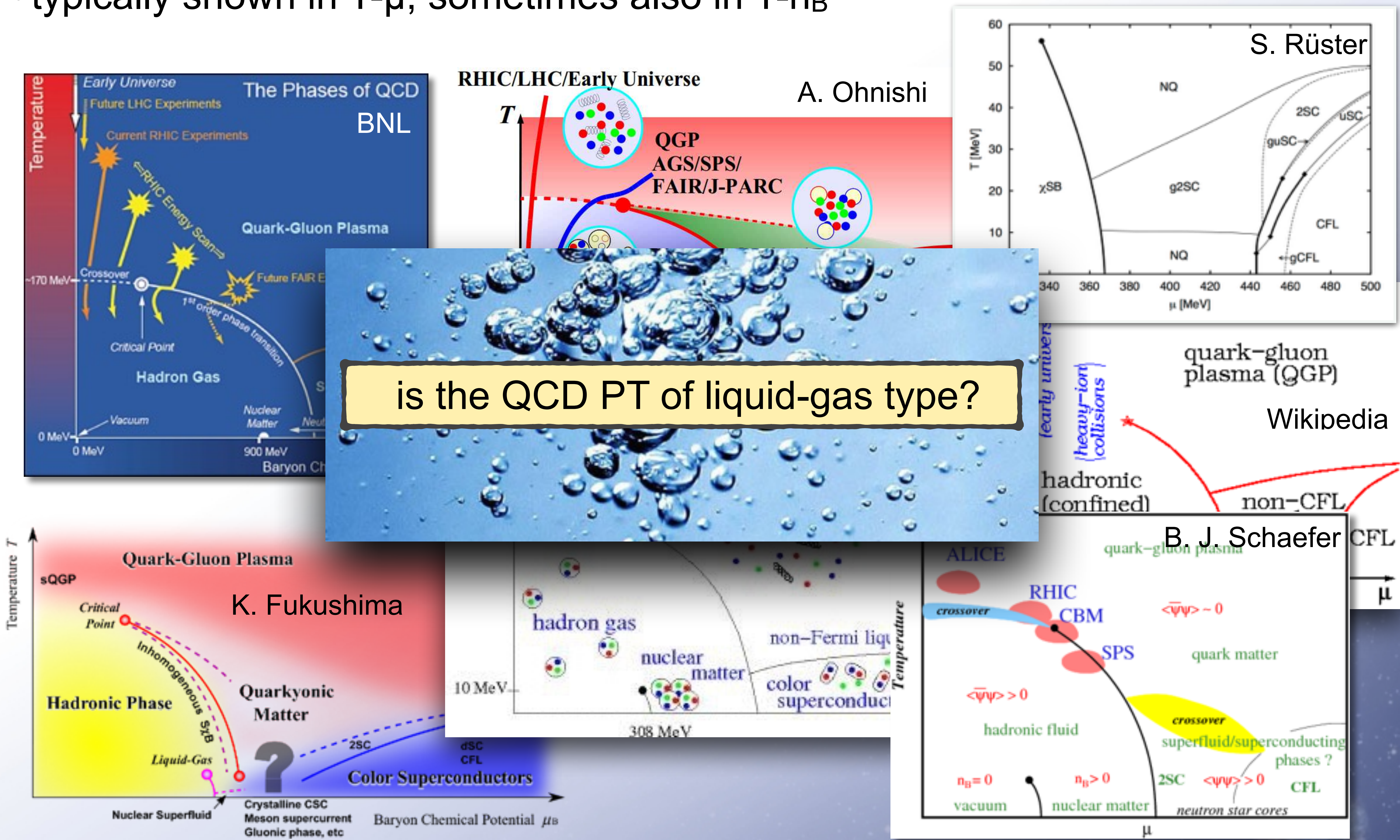


M. Liebendörfer

NASA/Chandra

QCD phase diagrams

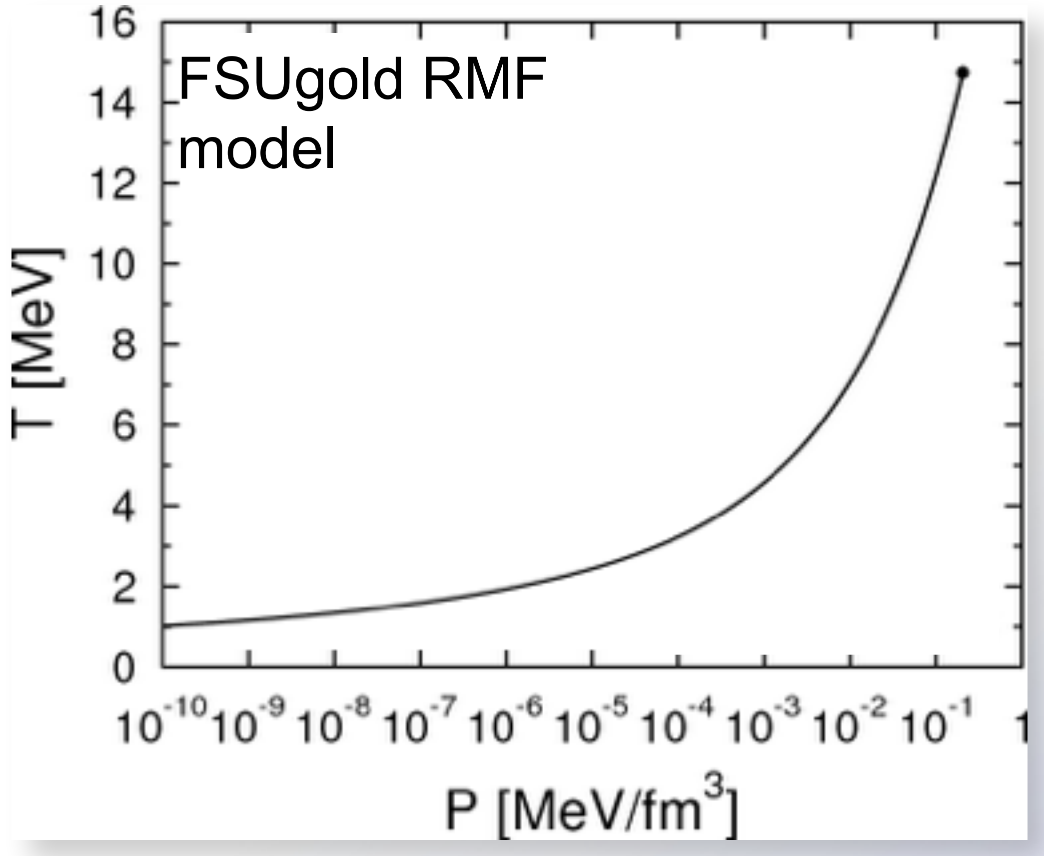
- typically shown in T-μ, sometimes also in T-n_B



Pressure-temperature phase diagrams

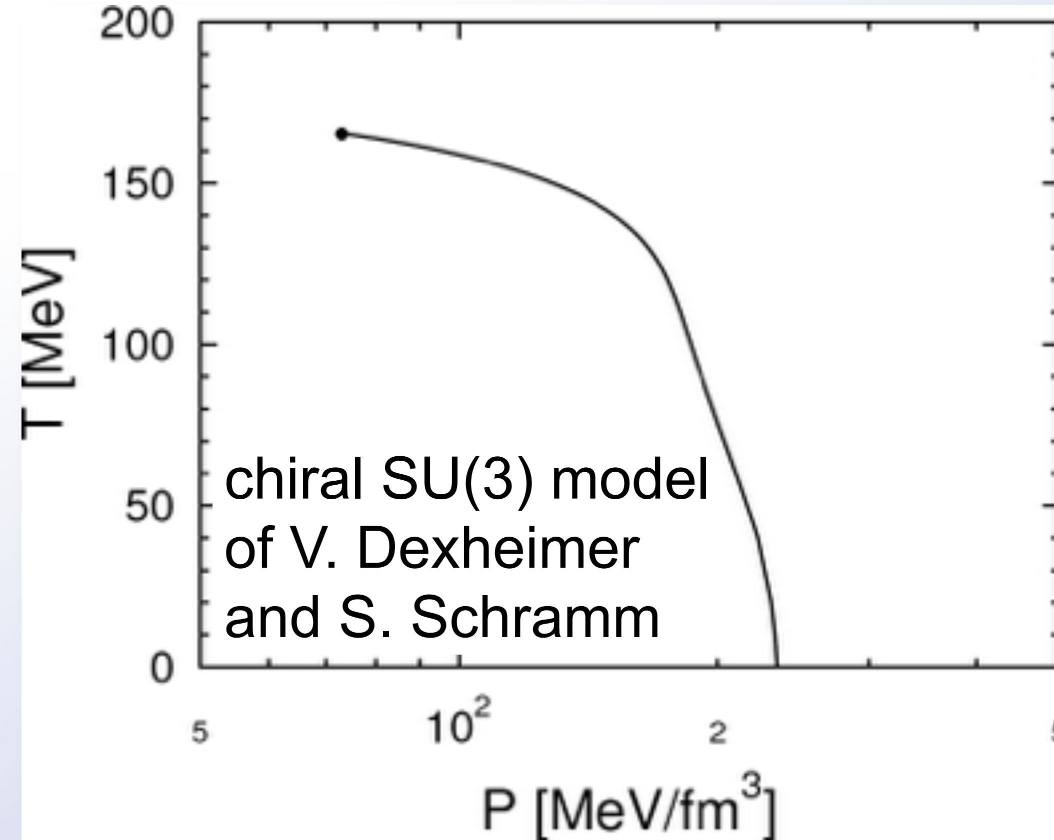
[MH, V. Dexheimer, S. Schramm, I. Iosilevskiy, PRC 88 (2013)]

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)]

[Wambach, Heckmann, Buballla, AIPC1441 (2011)]

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

[Iosilevskiy, arXiv:1403.8053]

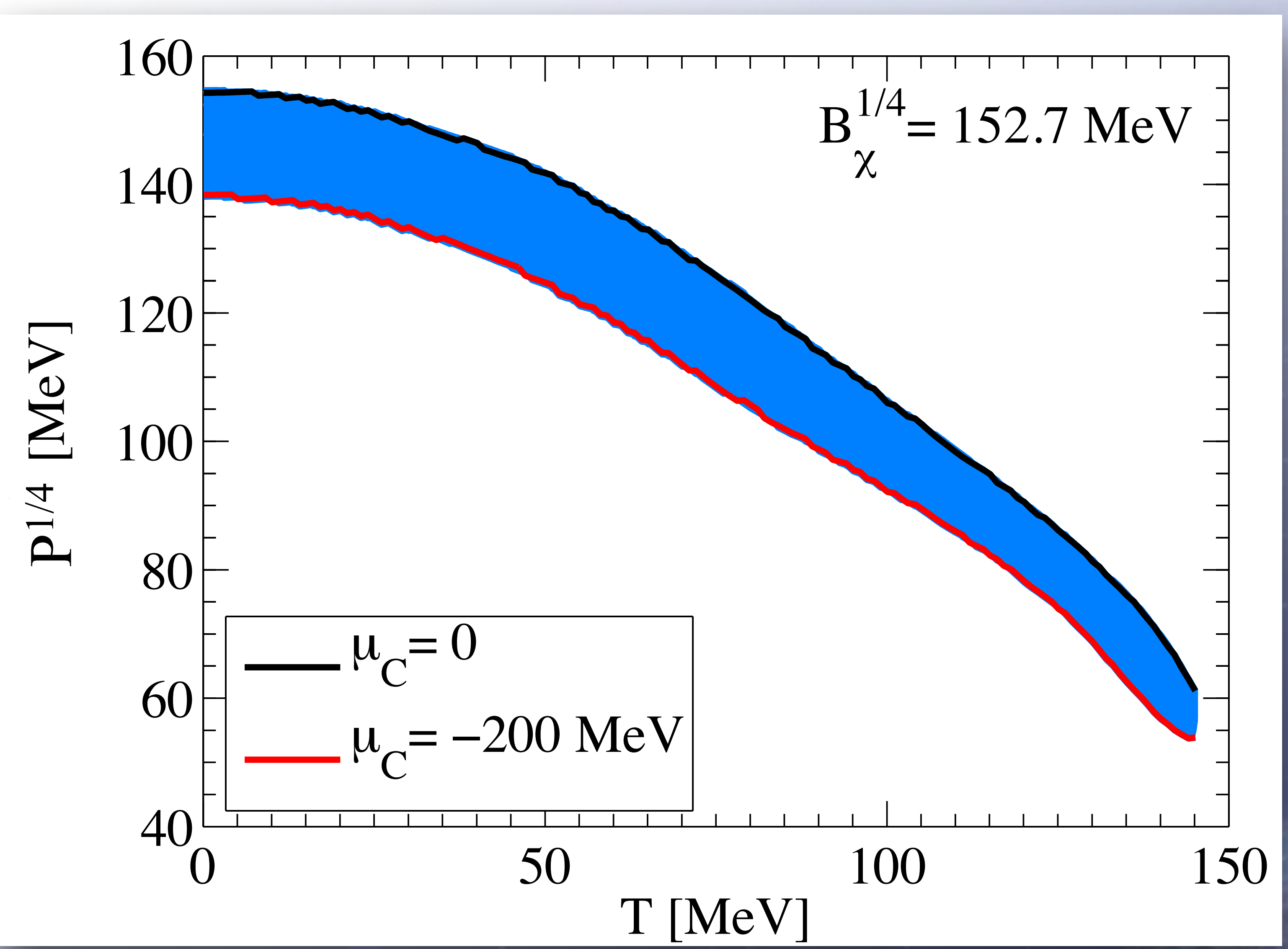
Phase diagram of *vBAG*

[Klähn & Fischer, ApJ 810 (2015)]
[Klähn, Fischer, MH, arXiv:1603.03679]

vBAG:

- vector interactions
- dynamic chiral symmetry breaking
- assumption of simultaneous chiral symmetry restoration and deconfinement
  → $B_{dc}(T,\mu_C)$
- here: only two flavors

also entropic



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

- Clausius-Clapeyron equation

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

- more degrees of freedom (color, strangeness) in the quark phase
  → high specific heat capacity and low temperatures
  → QCD PT always entropic?
- what about color-superconducting or crystalline phases?

Unusual thermal properties of entropic phase transitions

- for Maxwell phase transition

$$\left.\frac{dP}{dT}\right|_{\mathrm{PT}} = \left.\frac{\partial P}{\partial T}\right|_{n_B} \qquad \left.\frac{\partial P}{\partial T}\right|_{n_B} < 0 \Leftrightarrow \left.\frac{\partial T}{\partial n_B}\right|_{S} < 0$$

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

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

- first term small, relativistic correction

entropic PT: unusual thermal properties, softening of the EOS with increasing entropy

Consequences for core-collapse supernovae

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

Quark-hadron hybrid EOSs for CCSNe and NS merger

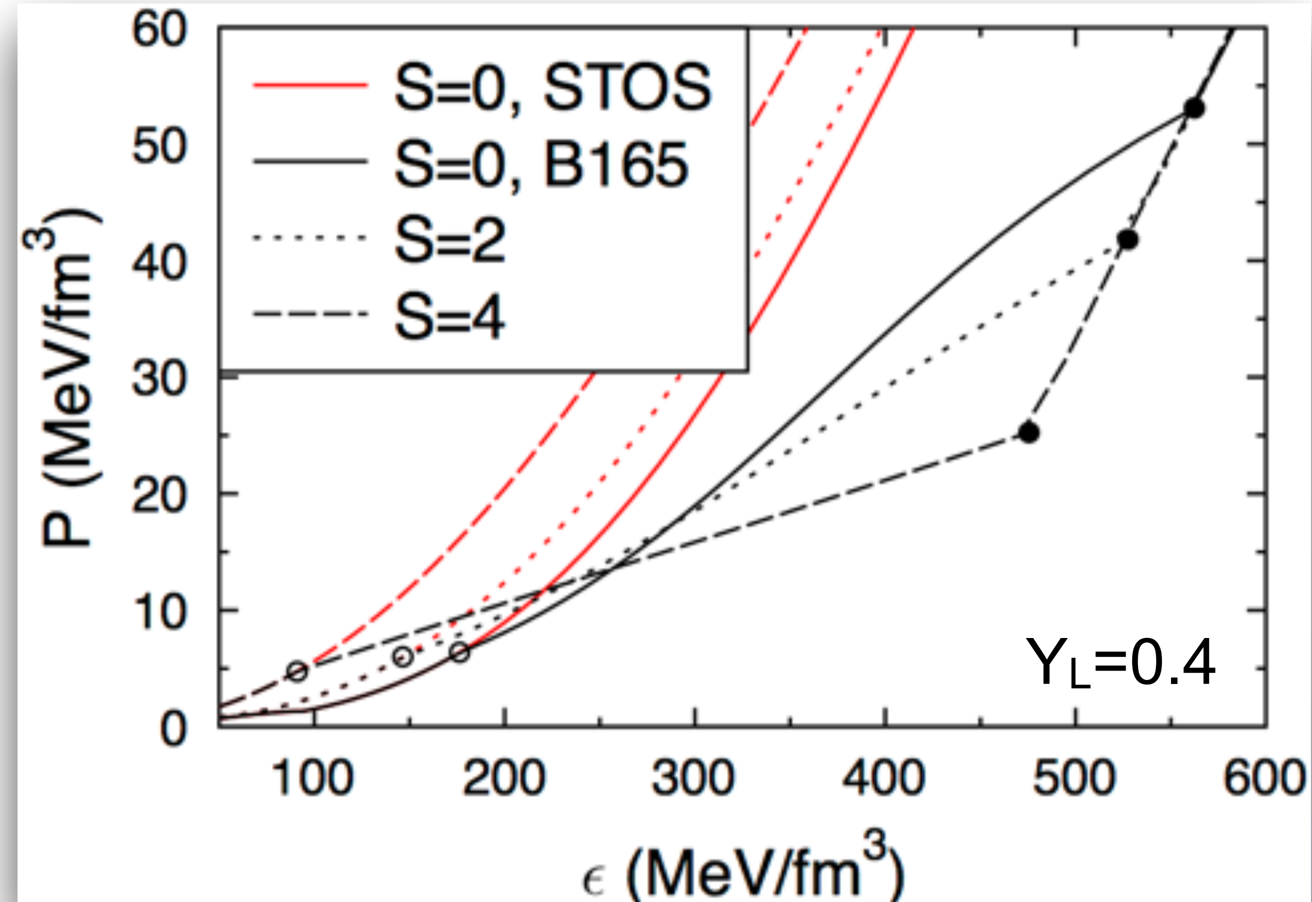
- EOS tables with full density, temperature and asymmetry-dependence needed

Model	Nuclear Interaction	Degrees of Freedom	M_{max} ($\mathrm{M}_\odot$)	$R_{1.4\mathrm{M}_\odot}$ (km)	References
STOSπQ	TM1	$n, p, \alpha, (A, Z), \pi, q$	1.85	13.6	Nakazato *et al.* (2008)
STOSQ	TM1	$n, p, \alpha, (A, Z), q$	1.81	14.4	Nakazato *et al.* (2008)
STOSB139	TM1	$n, p, \alpha, (A, Z), q$	2.08	12.6	Fischer *et al.* (2014)
STOSB145	TM1	$n, p, \alpha, (A, Z), q$	2.01	13.0	Sagert *et al.* (2012)
STOSB155	TM1	$n, p, \alpha, (A, Z), q$	1.70	9.93	Fischer *et al.* (2011)
STOSB162	TM1	$n, p, \alpha, (A, Z), q$	1.57	8.94	Sagert *et al.* (2009)
STOSB165	TM1	$n, p, \alpha, (A, Z), q$	1.51	8.86	Sagert *et al.* (2009)

- hadronic phase: „STOS“, Shen, Toki, Oyamatsu and Sumiyoshi 1998, 2011
- quark phase: bag model (u,d,s), first-order strong interactions, α_S (Farhi and Jaffe 1984)
- Gibbs conditions for phase equilibrium

- only two with M_{max} compatible with Antoniadis et al. 2013
- STOS: symmetry energy in disagreement with experimental constraints

Pressure-energy density relation

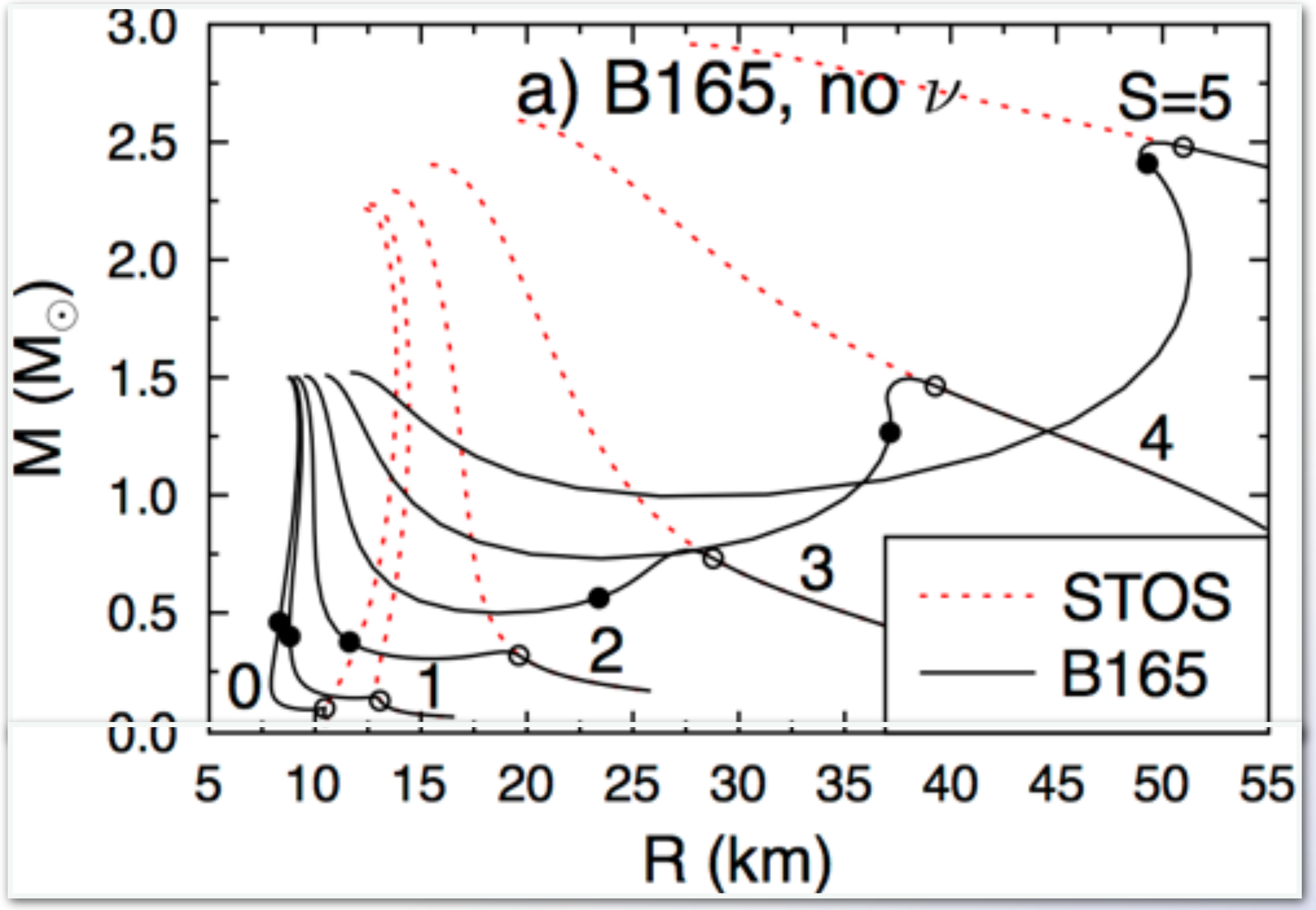


- hadronic and quark matter stiffens when it is heated
- in the phase coexistence region it softens

- however: stability not directly given by $dP/dS|_\varepsilon$, but e.g. by $\Gamma = d(\log P)/d(\log \varepsilon)$, and dependence on the hadronic EOS

→ solution of TOV equations necessary

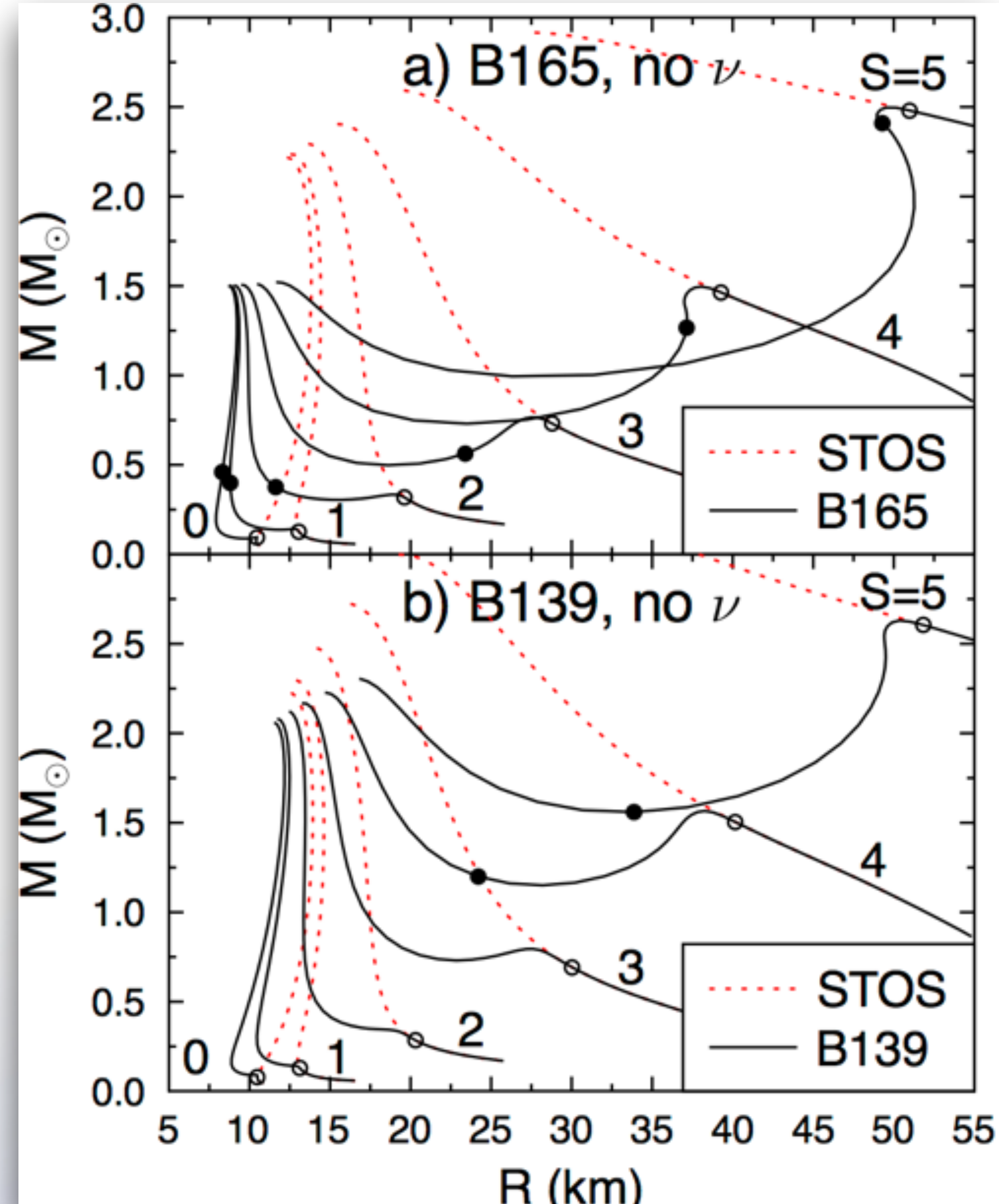
A novel third family of proto-compact stars



- after onset of phase transition: loss of stability, regained for sufficiently large quark matter core
- third family feature („twins“) arises for high entropies
- as expected for the softening due to the entropic property

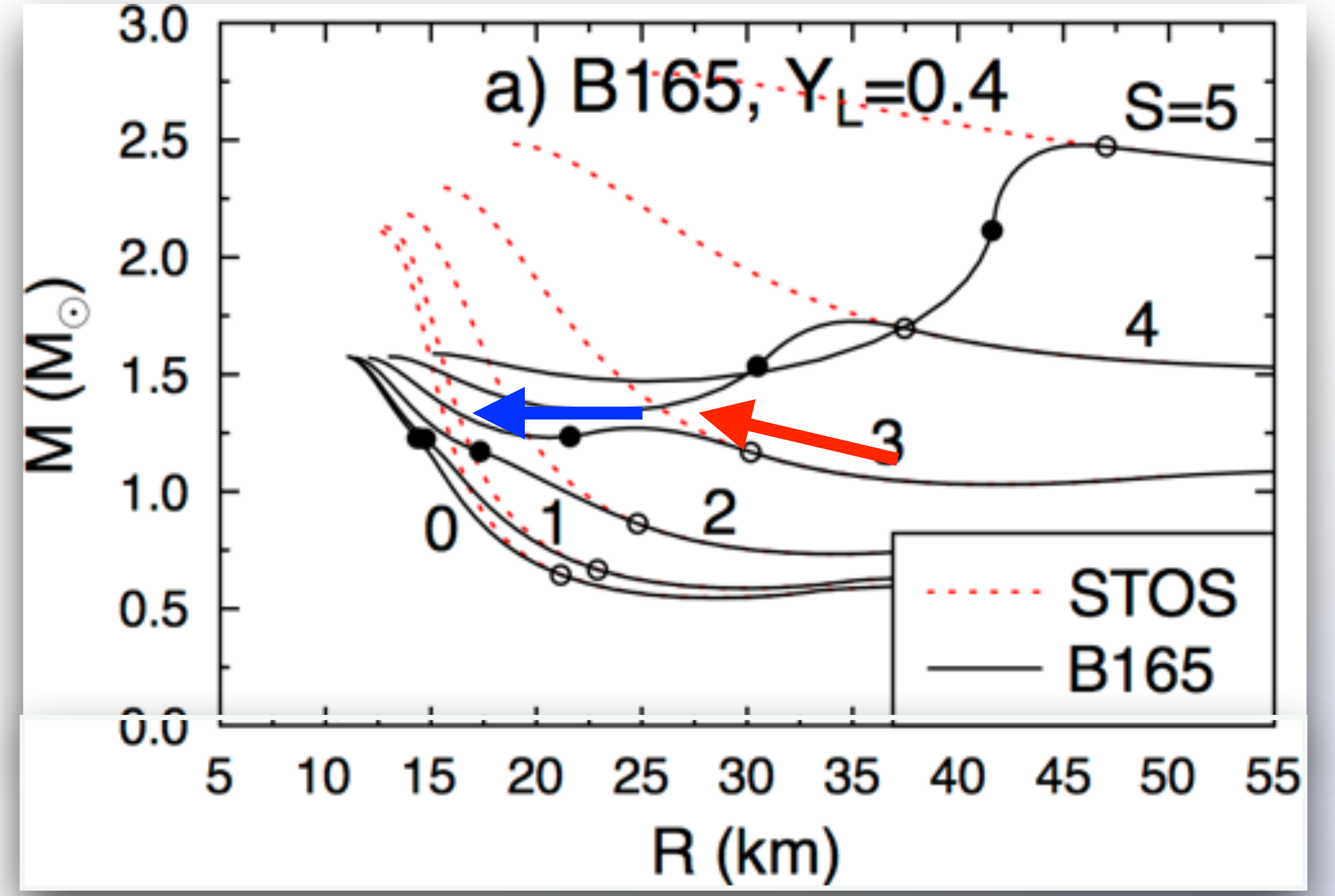
- novel aspect: a third family that exists only in the proto-neutron star stage

A novel third family of proto-compact stars — EOS dependence



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

Collapse to the third family in a supernova

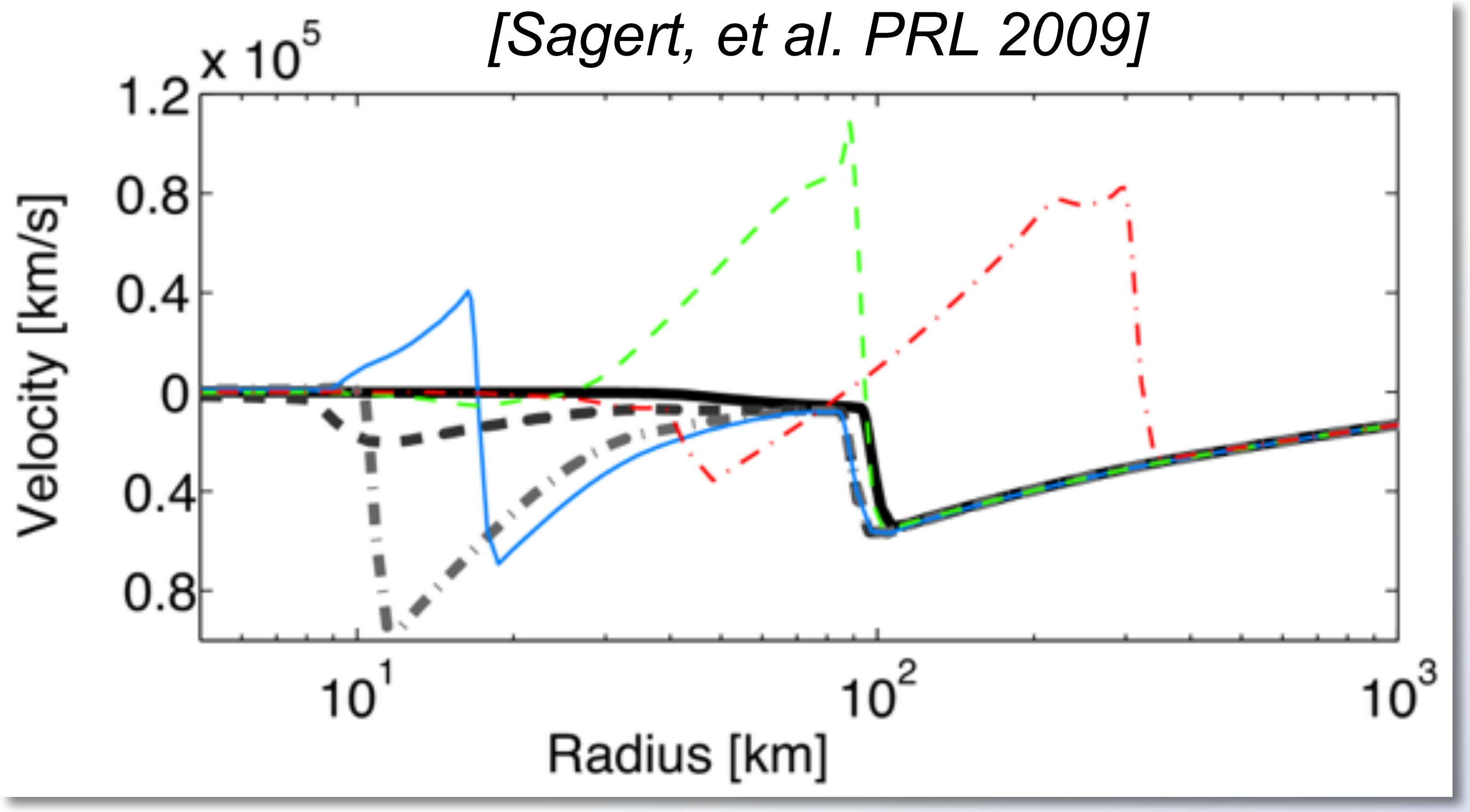


schematically:

- accretion: increase of the proto-neutron star mass from ~1 M_{sun} to ~1.5 M_{sun} in the first 200 ms
- collapse from the second to the third family with gravitational binding energy release

- exactly this was seen in detailed core-collapse supernova simulations by T. Fischer in 2009-2012
- results in an energetic explosion even in spherical symmetry
- new insight: the novel third family induces the collapse

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

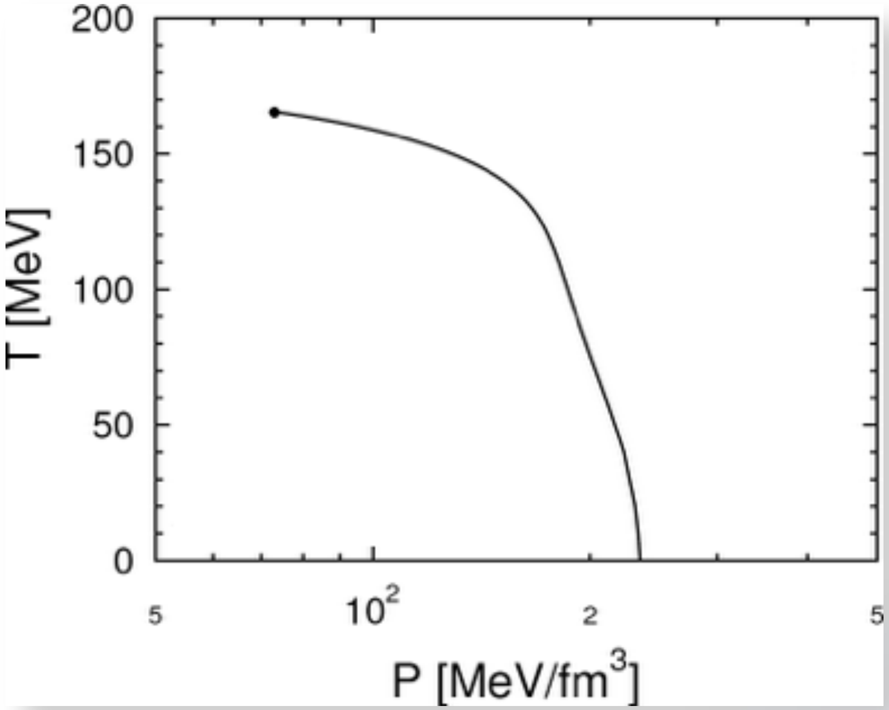
t_{pb}= 256.3 ms

t_{pb}= 261.2 ms

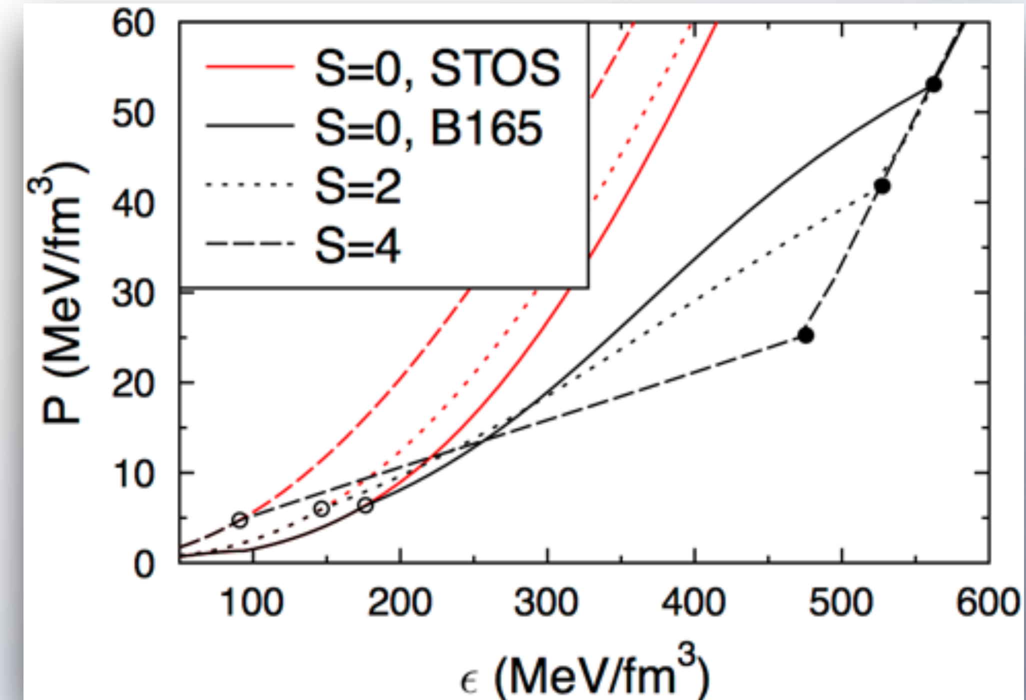
- phase transition induces collapse of the proto-neutron star
- collapse halts when pure quark matter is reached
- formation of a second shock, merges with standing accretion shock and triggers an explosion

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

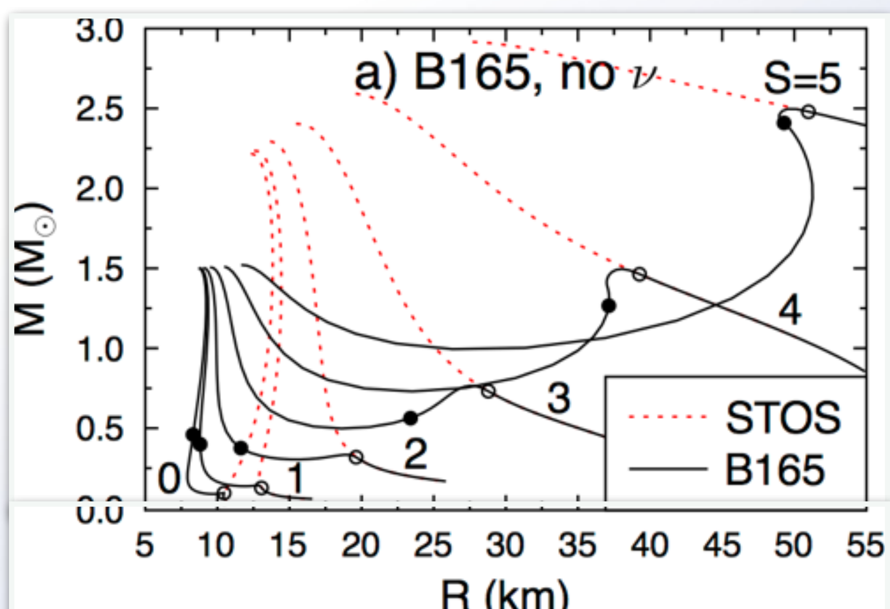
Entropic PT and core-collapse supernova explosion



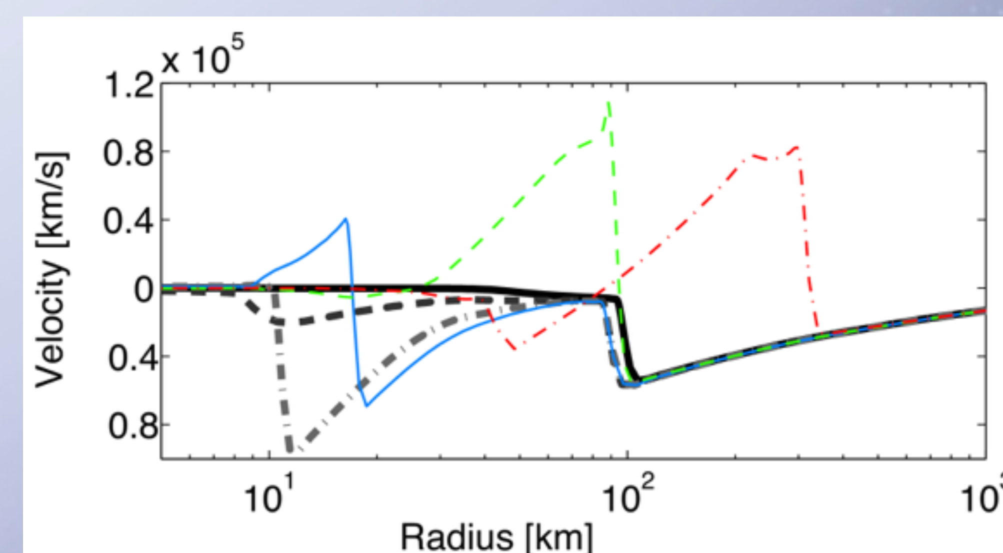
entropic phase transition



unusual thermal properties, softening with heating

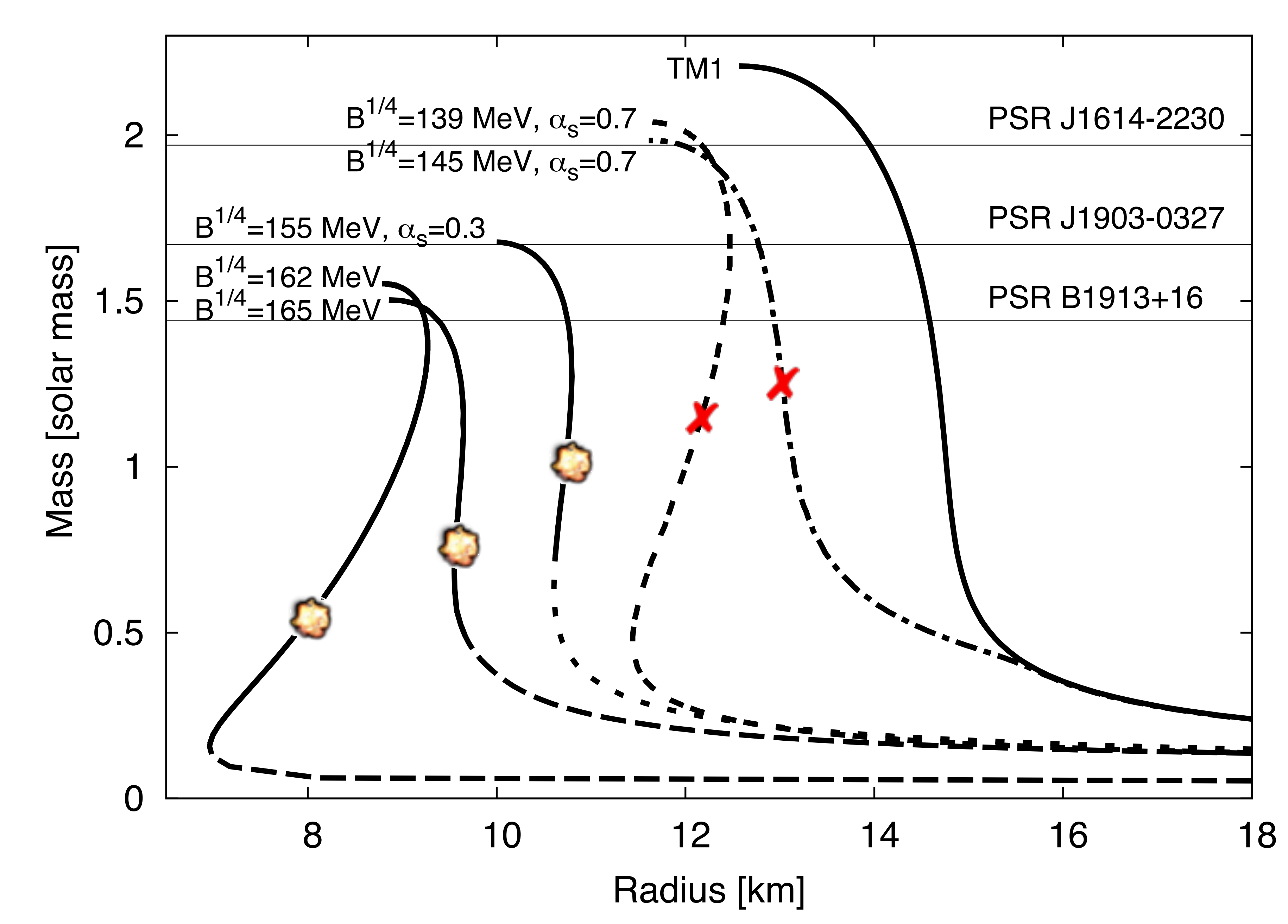


third family of proto-hybrid stars



core-collapse supernova explosion

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“
- agrees with new analysis: B139 has weak third family

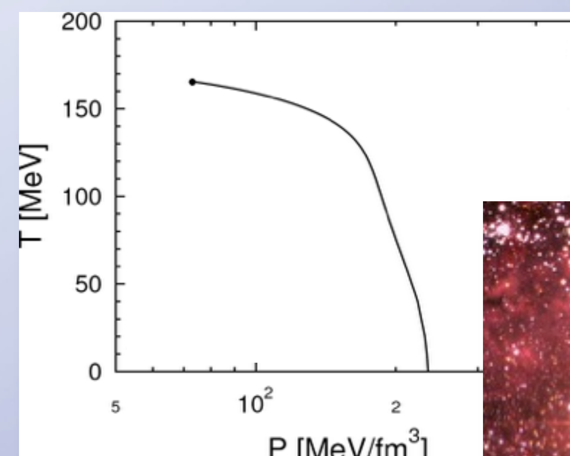
explosions in spherical symmetry (T. Fischer et al. ApJS 2011)

- see also: Fischer, Blaschke, et al. 2012: PNJL hybrid EOS

Is this explosion mechanism still possible?

- obvious tension: high maximum mass ↔ strong phase transition
- only few models tested so far (progenitors and EOS)

- new insight: the thermal properties of quark matter are crucial
- third family feature in cold neutron stars helpful, but not required



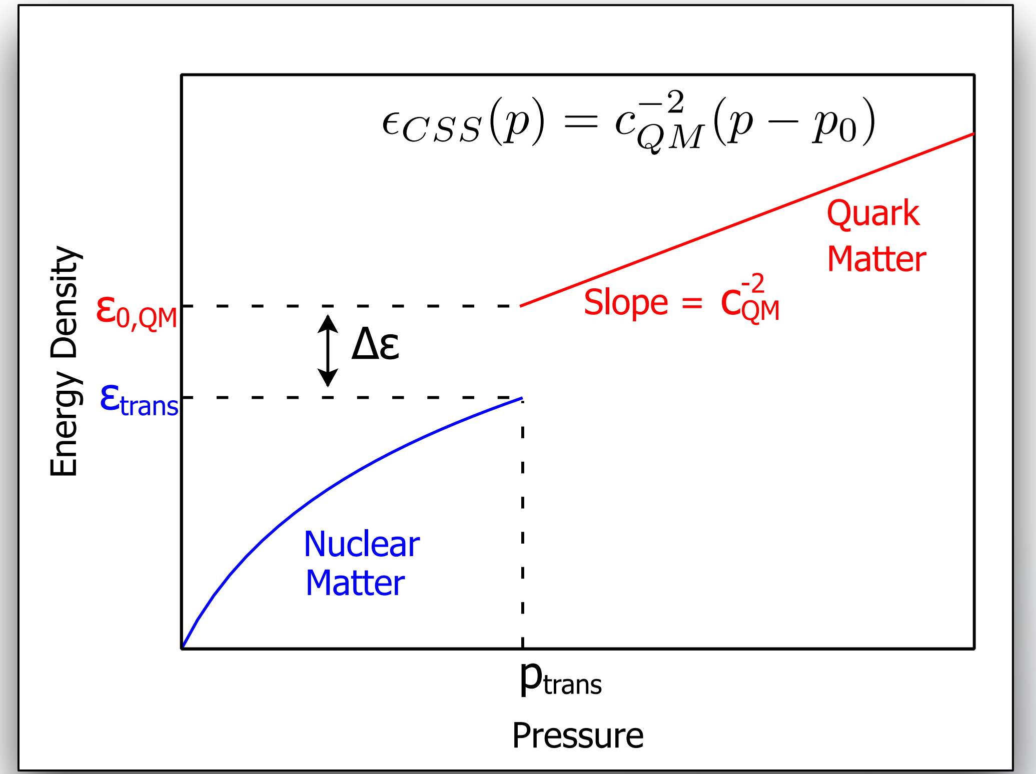
Matthias Hempel
L'Aquila, 26.05.2016

In the search for a new hybrid supernova EOS: A systematic analysis of hybrid stars (and the problem of reconfinement)

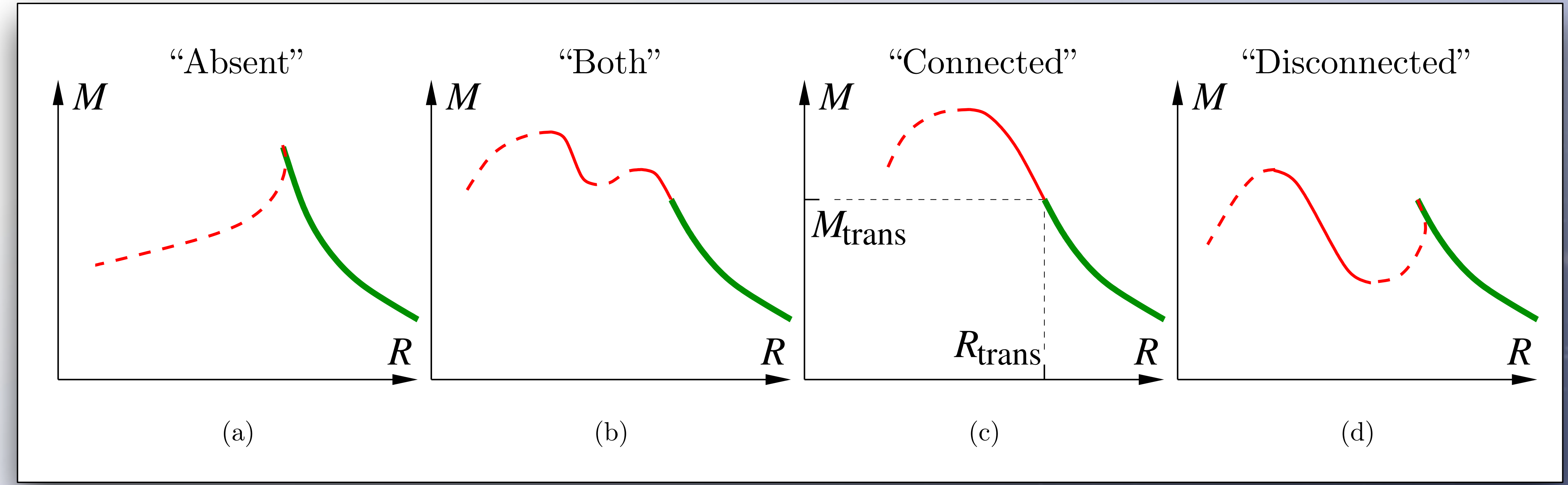
Oliver Heinimann, MH, in preparation

Alford's parameter scan

[Alford, Han, Prakash, PRD88 (2013)]

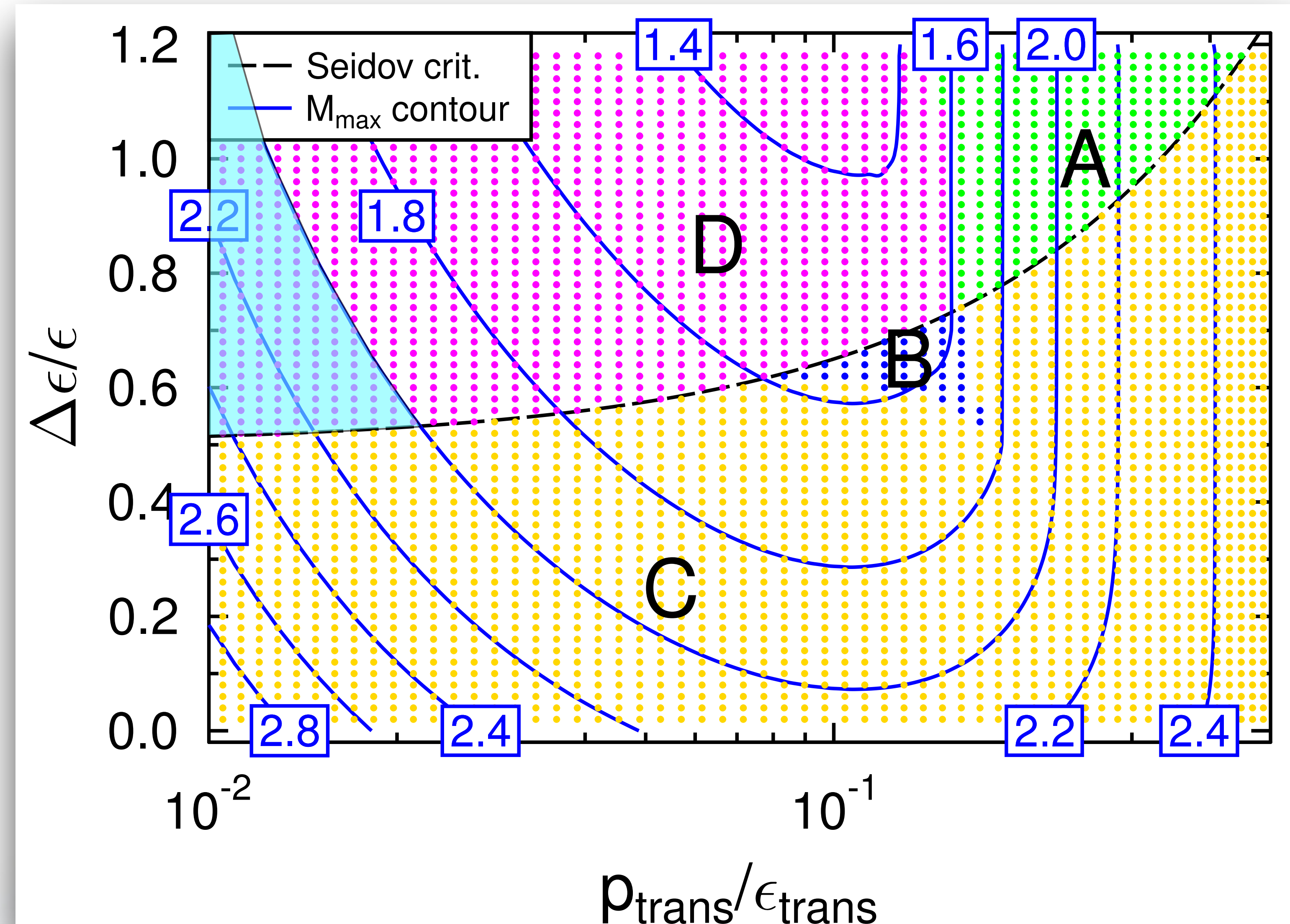


- quark matter: constant speed of sound
- systematic variation of transition pressure and energy density discontinuity
- maximum mass and classification of hybrid stars



New parameter scan for HS(DD2) hadronic EOS

- HS(DD2): general purpose (supernova) EOS, good nuclear matter properties, $M_{max} = 2.42\ M_{sun}$



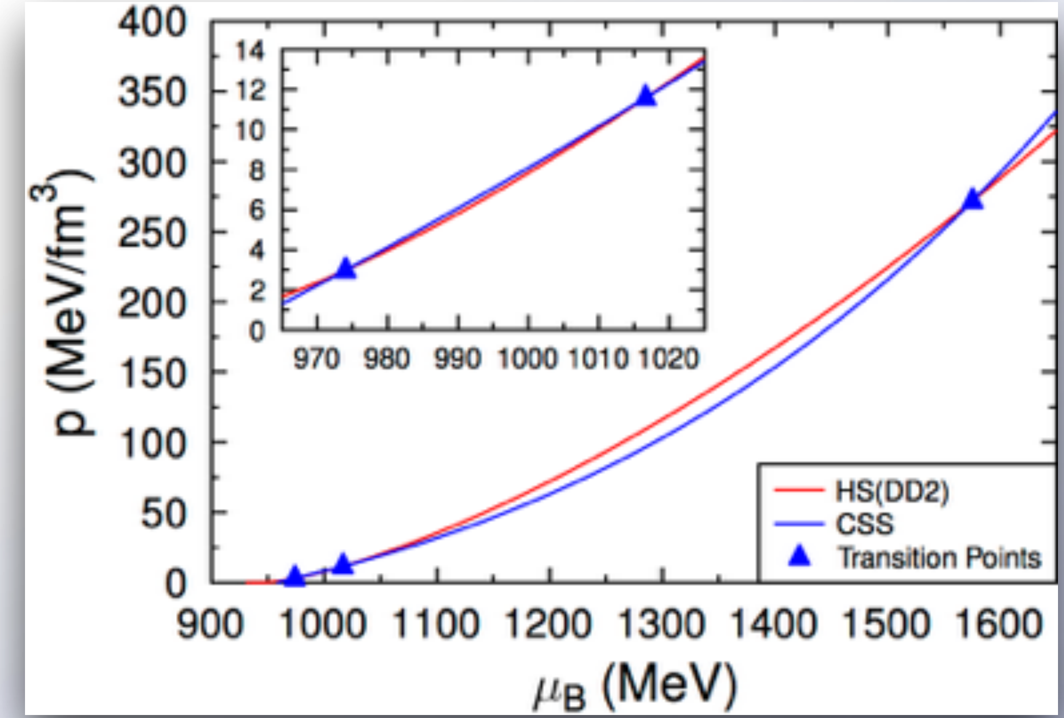
- $M_{max} > M_{max}$(HSDD2) possible
- limited parameter region with $M_{max} > 2\ M_{sun}$ and third family
- favorable region extended for $c_s^2 > 1/3$

Thermodynamic consistency

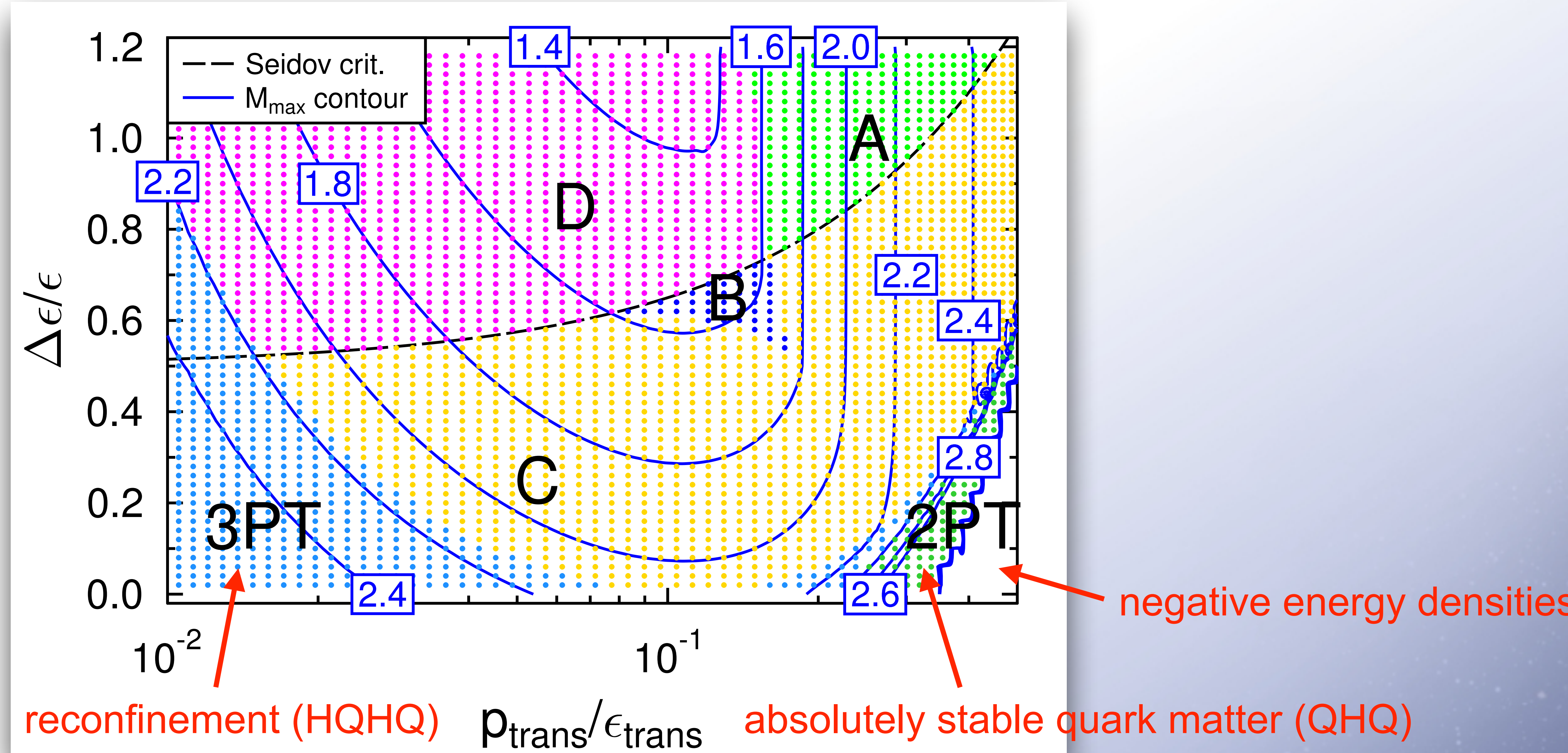
- previous parameter scans: only pressure and temperature equilibrium (T=0)
- p(μ) relation can be derived from p(ε)

$$p^{\mathrm{CSS}}(\mu) = \frac{c_{QM}^2}{1+c_{QM}^2} p_0 \left[\left(\frac{\mu}{\mu_0} \right)^{\frac{1+c_{QM}^2}{c_{QM}^2}} + \frac{1}{c_{QM}^2} \right]$$

- imposing chemical equilibrium fixes μ_0
- several phase transitions and/or reconfinement can occur, ignored previously



Thermodynamic consistent parameter scan



- reconfinement for low transition pressures and weak phase transitions
- (almost pure) quark stars appear
- $M_{max} > M_{max}$(HSDD2) only possible for quark stars

Summary and conclusions

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

- entropic PTs lead to unusual thermal properties of the EOS
- possible consequences in astrophysics:
  - inverted convection in proto-neutron stars (Yudin et al. MNRAS 2016)
  - novel third family of proto-compact stars
  - core-collapse supernova explosions

- new hybrid EOSs are needed (work in progress)
- spherically symmetric and multi-D CCSN simulations