A new quark-hadron hybrid EOS for core-collapse supernovae and neutron star mergers

Matthias Hempel, Basel University

From quarks to gravitational waves, CERN, 6.12.2016

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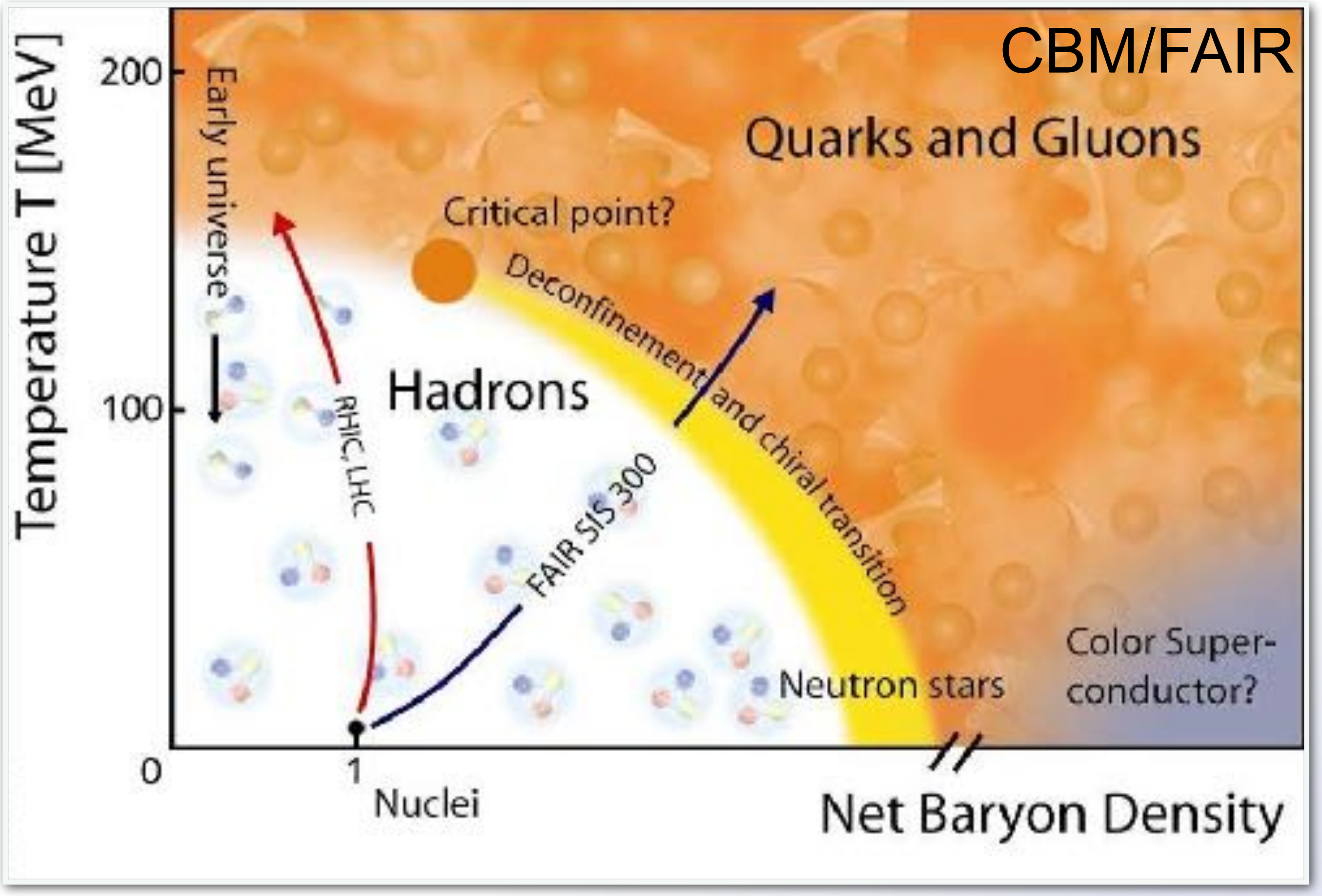
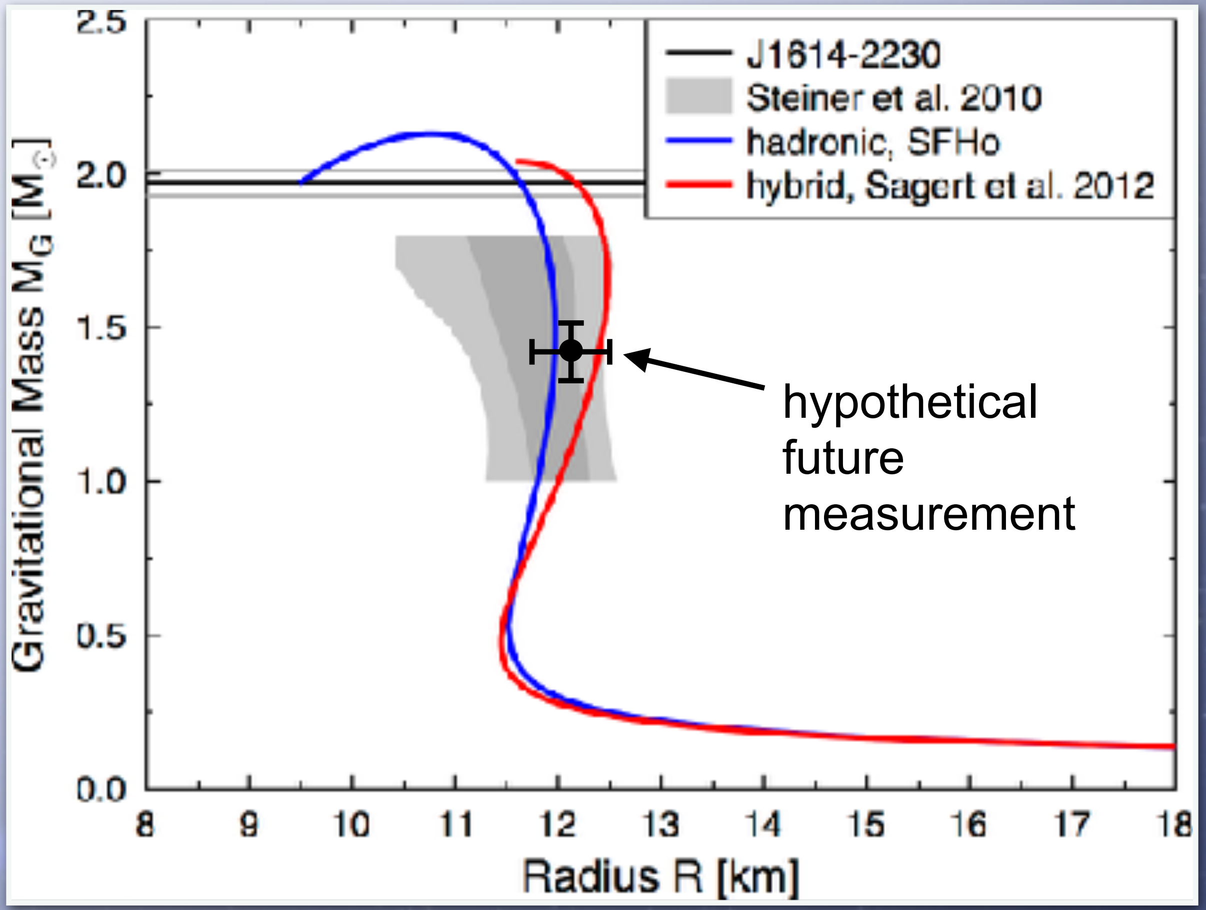
compstar

QCD phase diagram



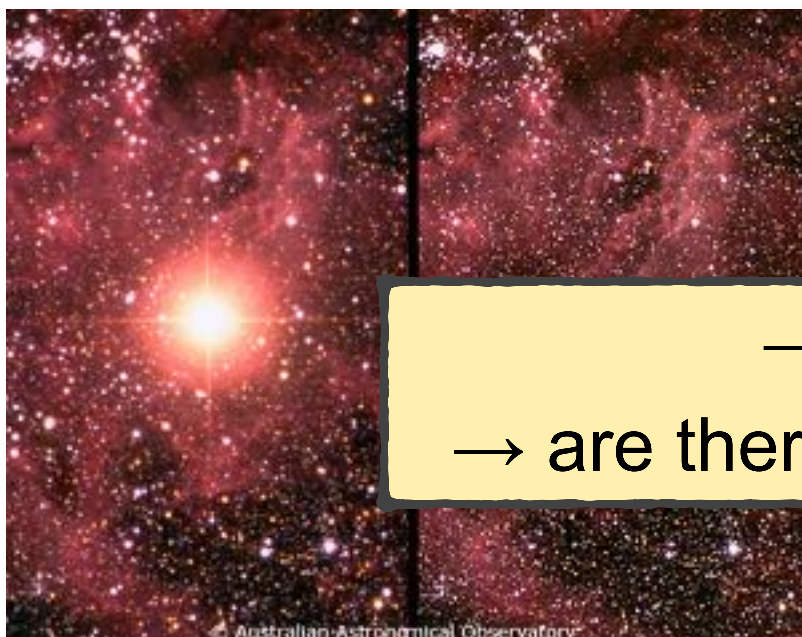
- what is the state of matter at extreme densities?
- is there a first-order phase transition to quark matter?

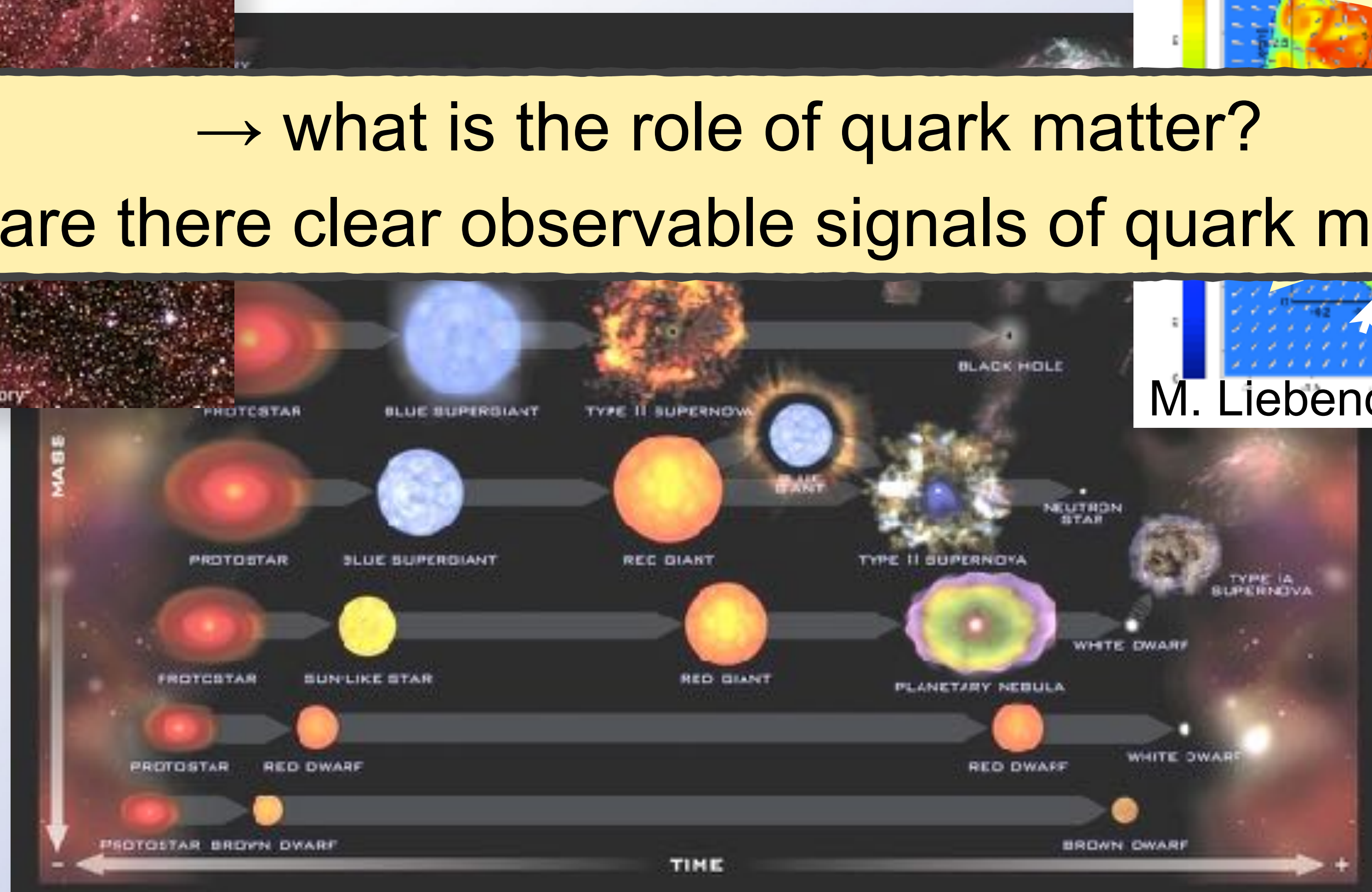
- M-R of neutron stars may not be sufficient to identify quark matter
- „masquerade“, Alford et al. 2005
- → cooling/transport properties, signatures in dynamic scenarios (see, e.g. Buballa et al. arXiv:1402.6911)



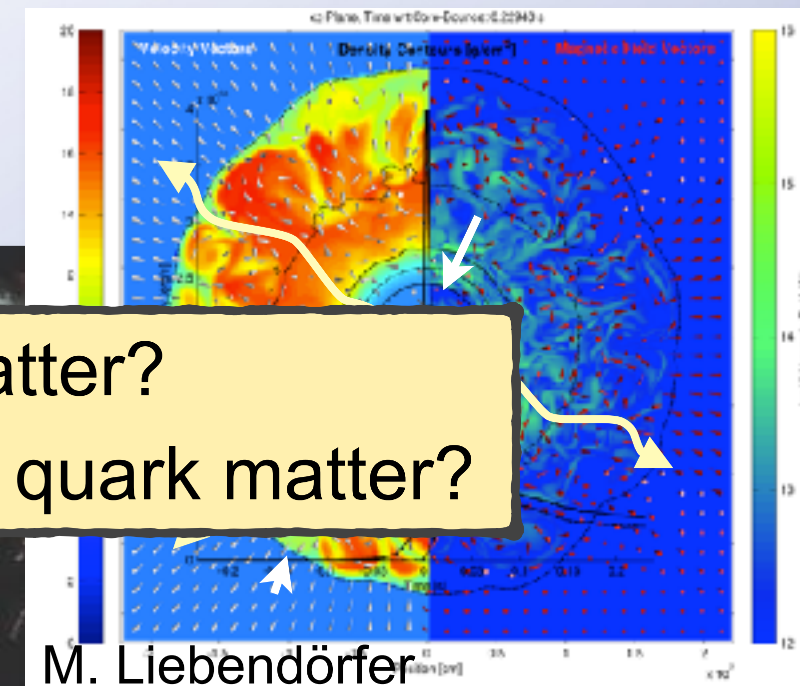
Motivation: core-collapse supernovae

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





NASA/Chandra



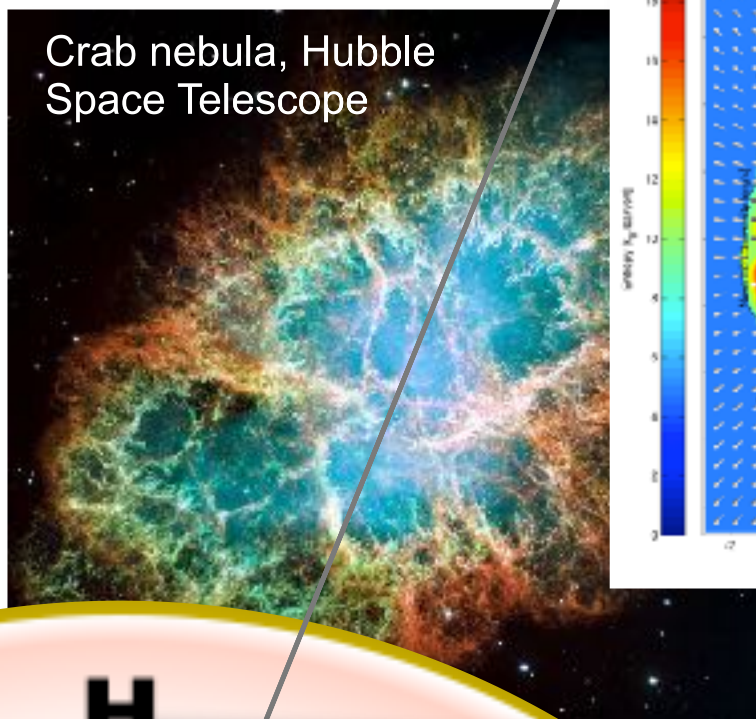
M. Liebendörfer

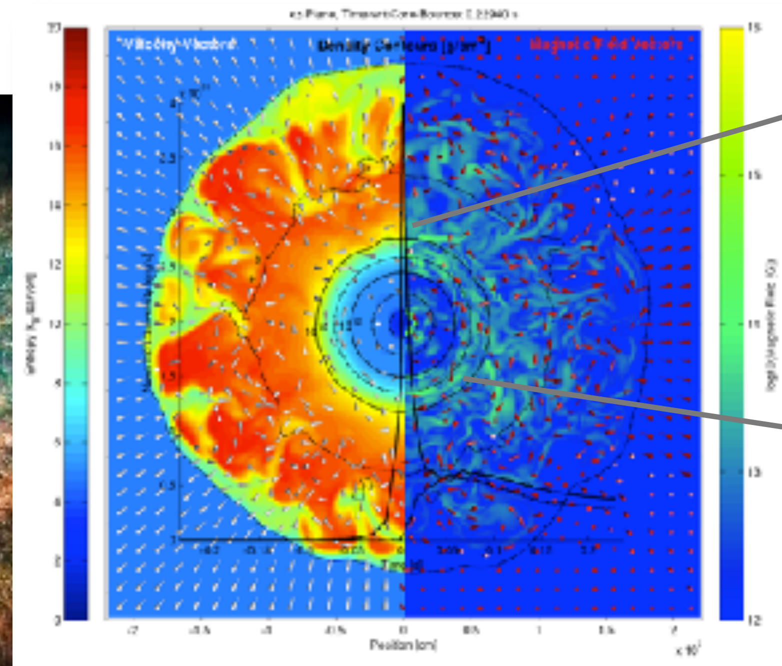
→ what is the role of quark matter?

→ are there clear observable signals of quark matter?

The general purpose „supernova“ EOS

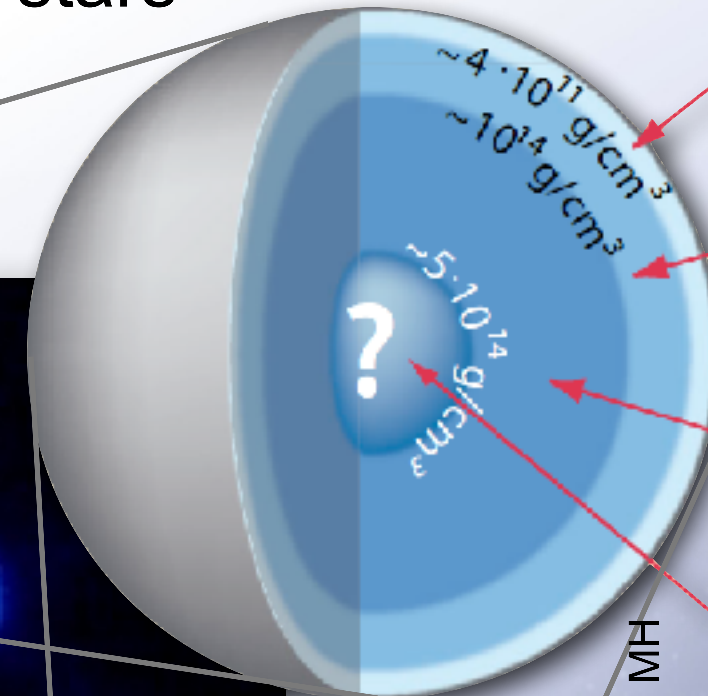
core-collapse supernovae





Liebendörfer

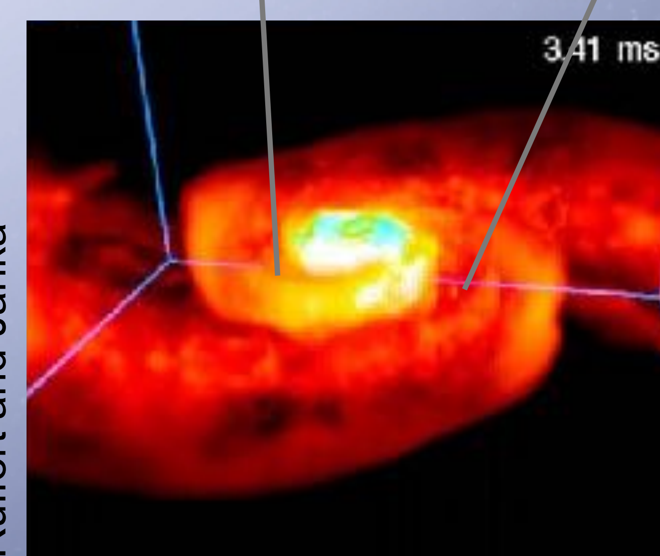
neutron stars



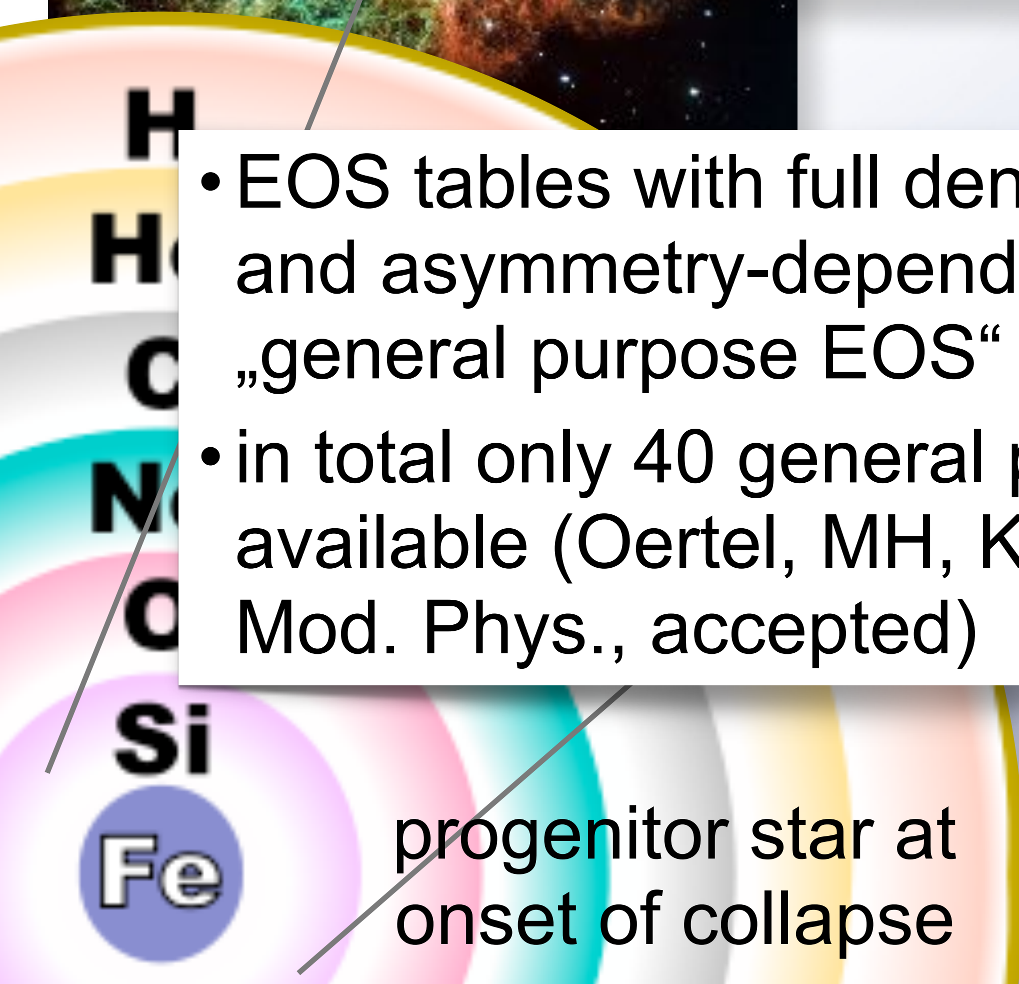
MH

- EOS tables with full density, temperature and asymmetry-dependence needed, „general purpose EOS“
- in total only 40 general purpose EOSs available (Oertel, MH, Klähn, Typel, Rev. Mod. Phys., accepted)

neutron star mergers



Ruffert and Janka



progenitor star at onset of collapse

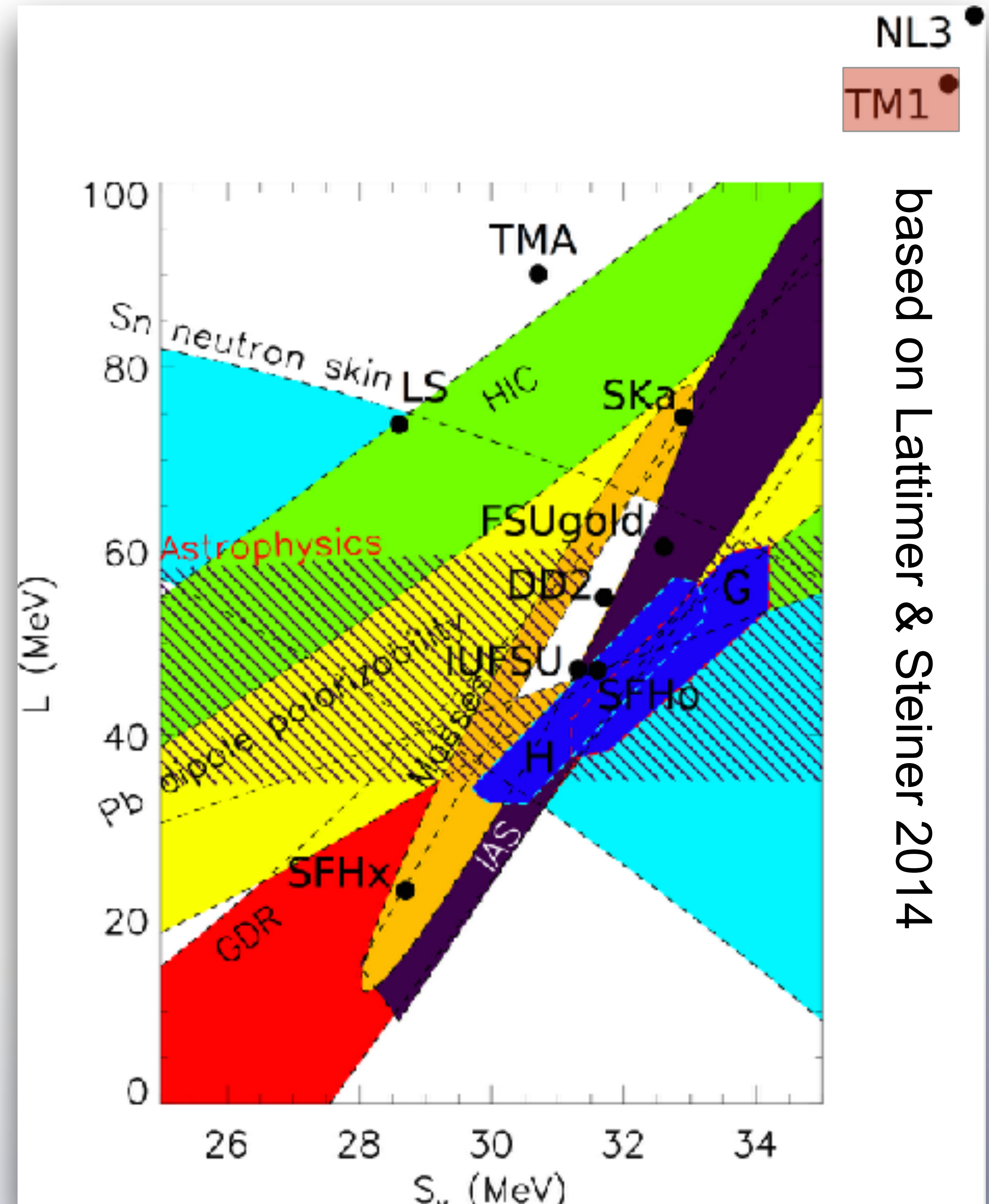
Wikimedia

Quark-hadron hybrid general purpose EOSs

Model	Nuclear Interaction	Degrees of Freedom	$M_{\rm max}$ ($M_\odot$)	$R_{1.4M_\odot}$ (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 hybrid EOSs with sufficiently high M_{max}

Characteristic properties of STOS („Shen“) EOS



- STOS: nucleons, alpha particles, representative heavy nucleus
- non-linear relativistic mean-field interactions (TM1)
- symmetry energy not compatible with various experimental constraints

Quark-hadron hybrid general purpose EOSs

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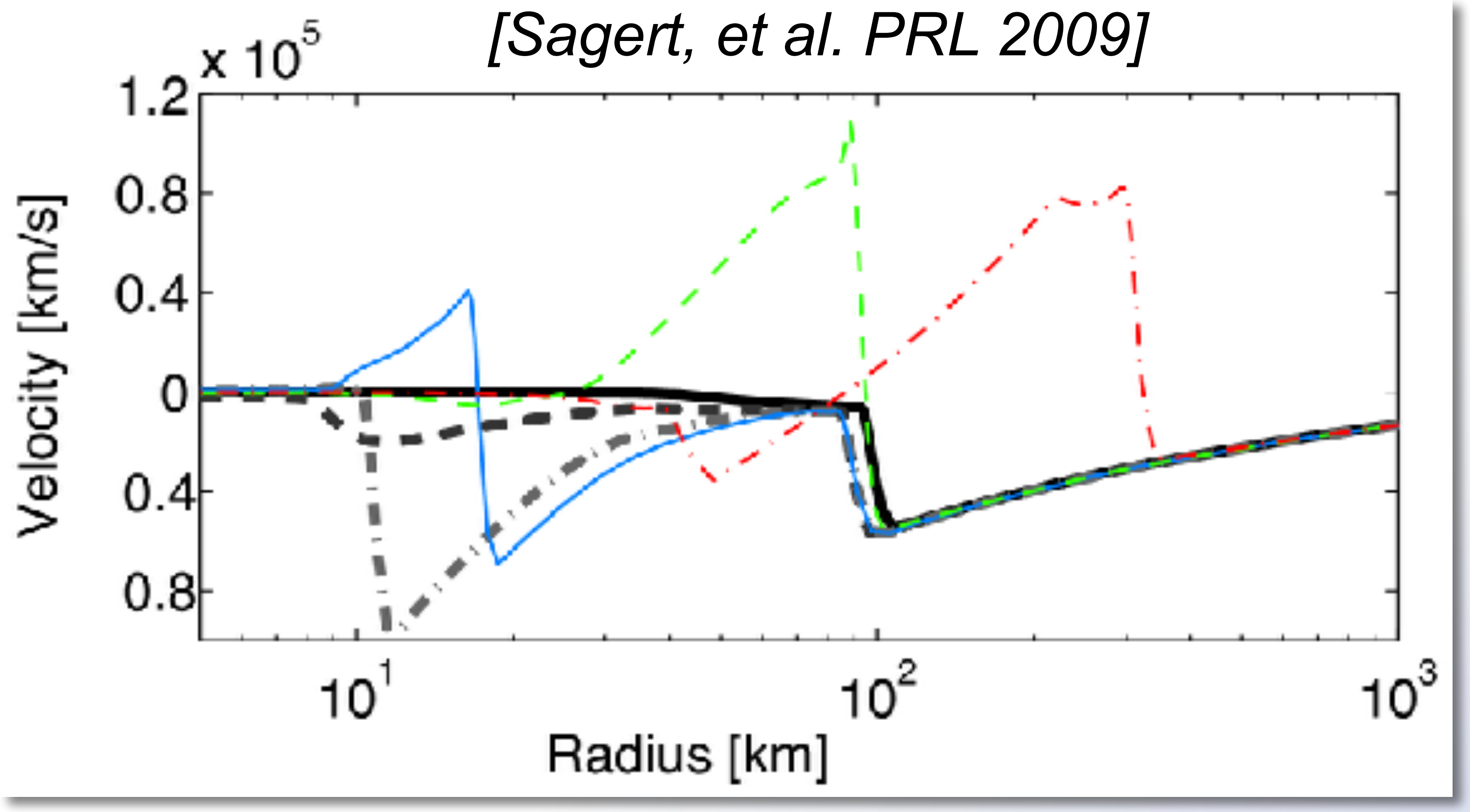
- Gibbs conditions for phase equilibrium
- only two hybrid EOSs with sufficiently high M_{max}
- TM1: unrealistic symmetry energy

→ need for new hybrid EOSs
which quark matter properties could be interesting?

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

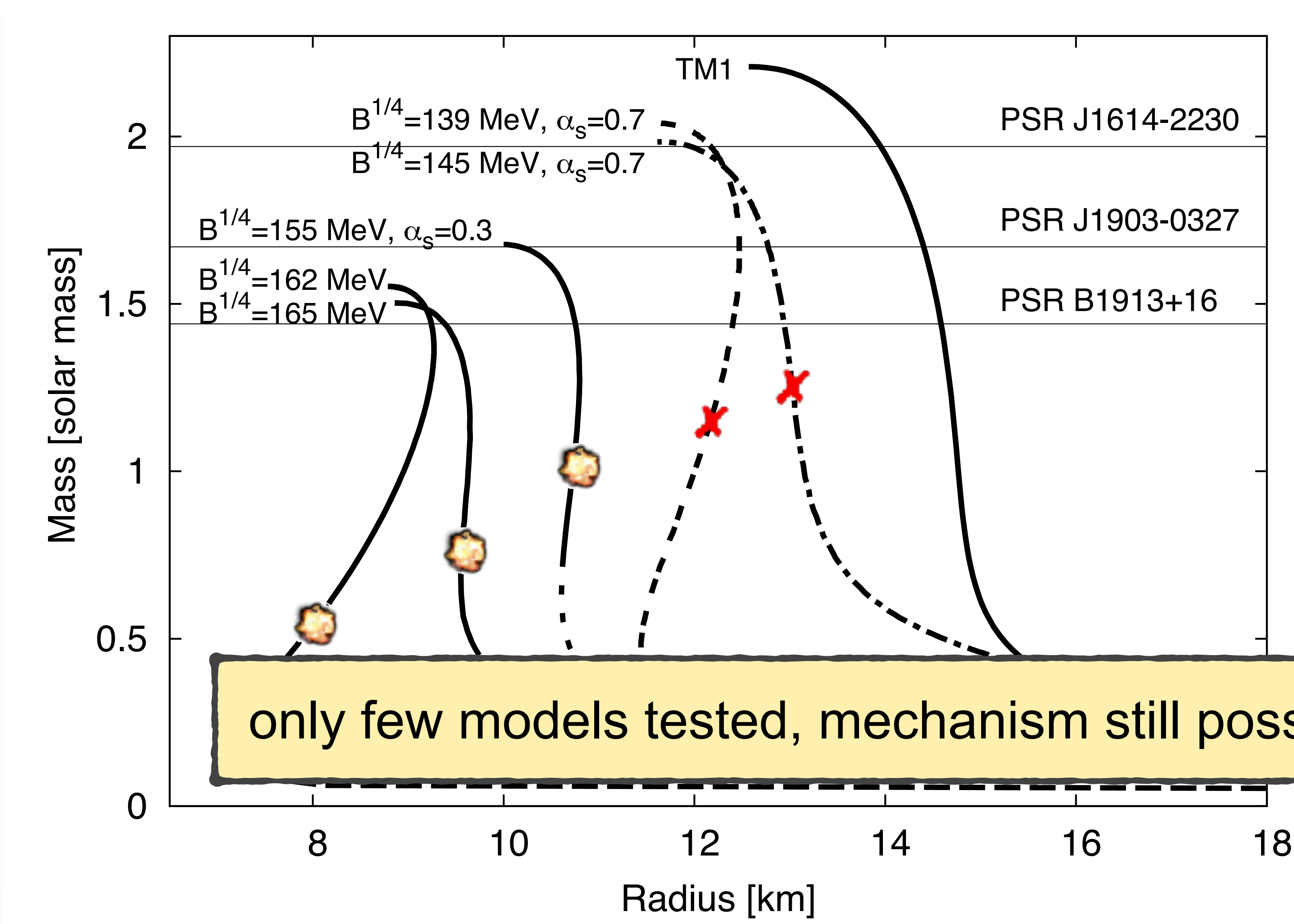
t_{pb}= 256.3 ms

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)

Mass-radius relation of hybrid EOS and SN explosions



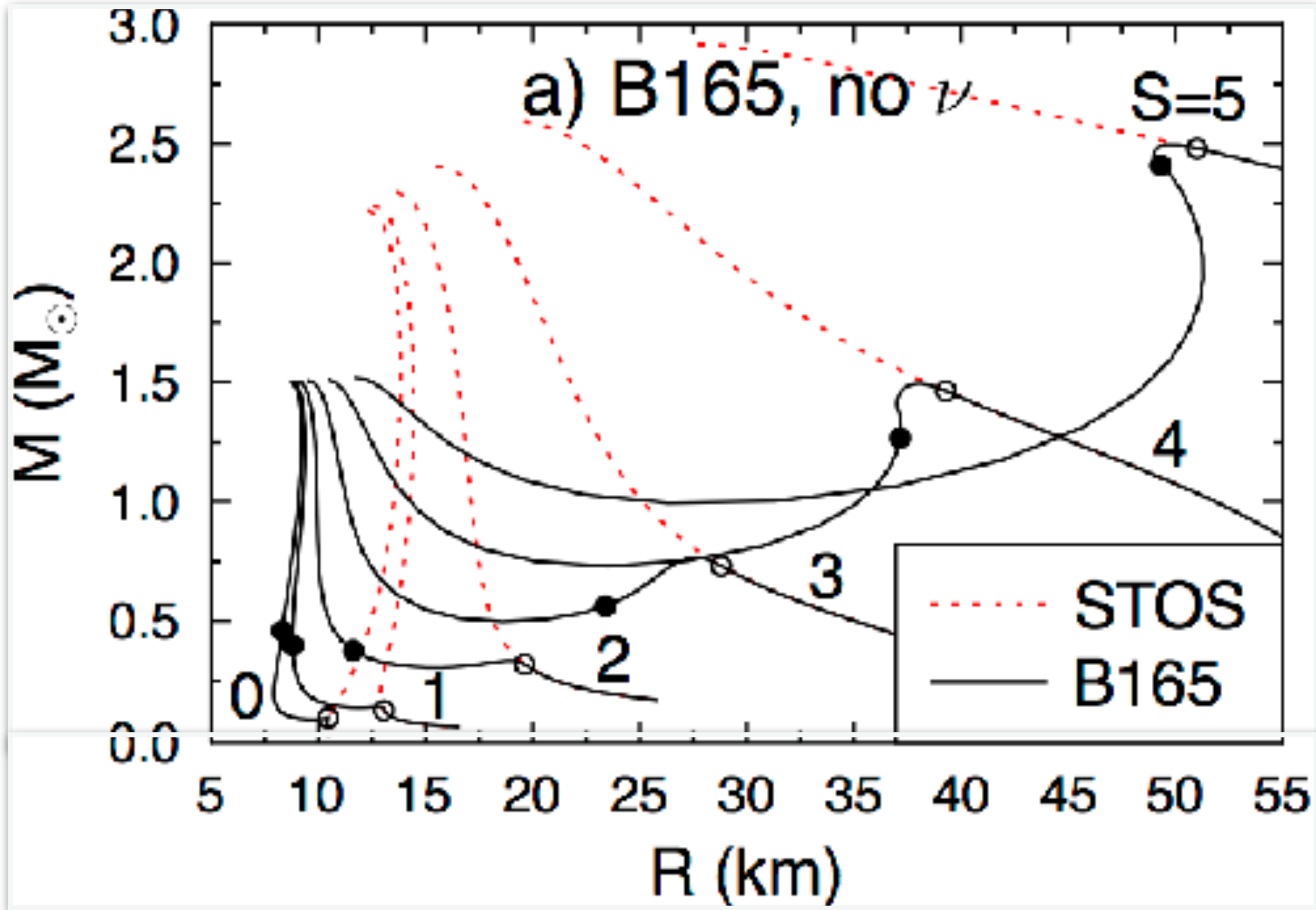
only few models tested, mechanism still possible for others?

- no explosions for sufficiently high maximum mass
- weak phase transition

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

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

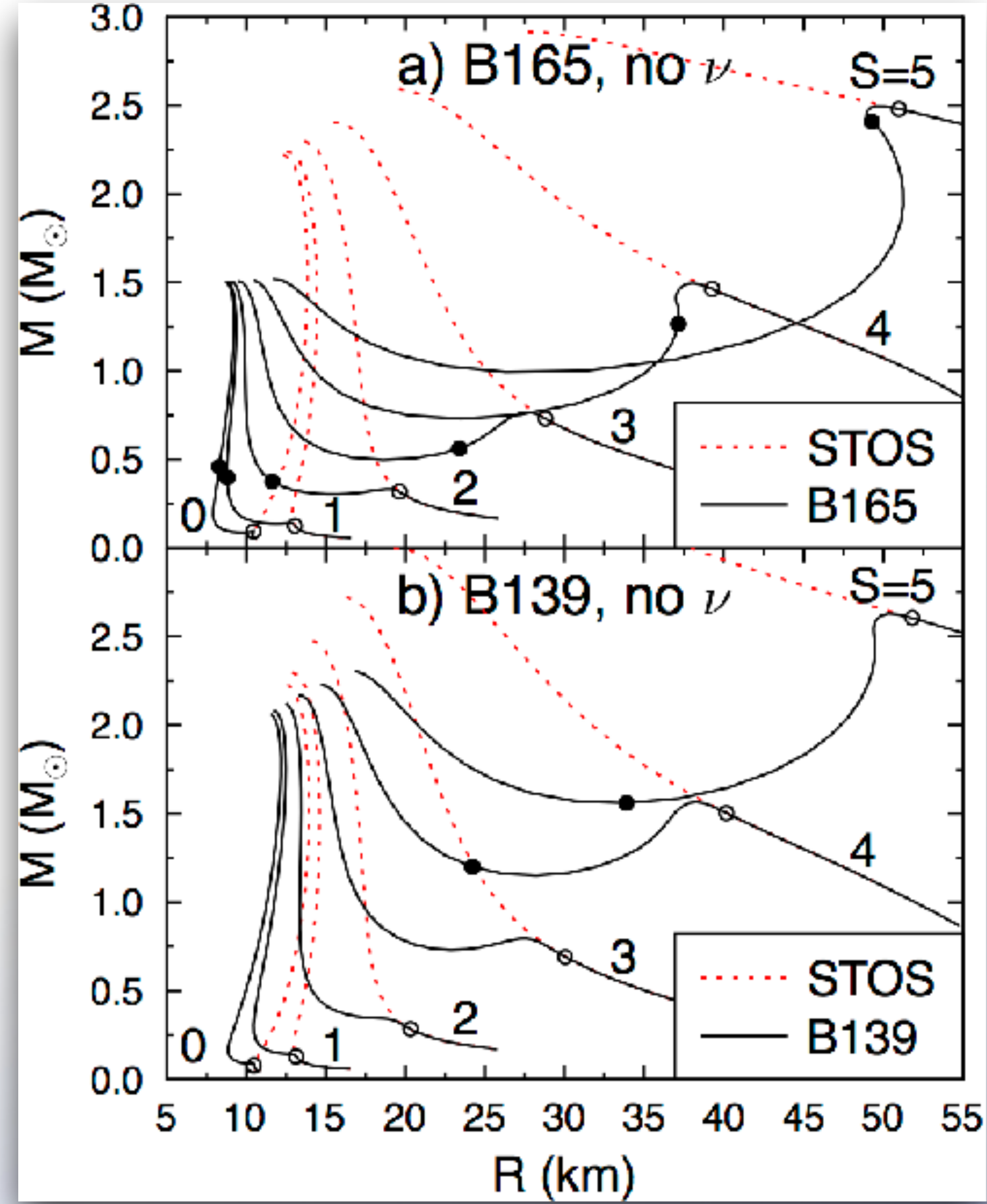
A hot third family of proto-compact stars



- after onset of phase transition: loss of stability, regained for sufficiently large quark matter core
- third family feature („twins“) arises for high entropies
- novel aspect: a third family that exists only in the proto-neutron star stage

[MH et al., PRD 94 (2016)]

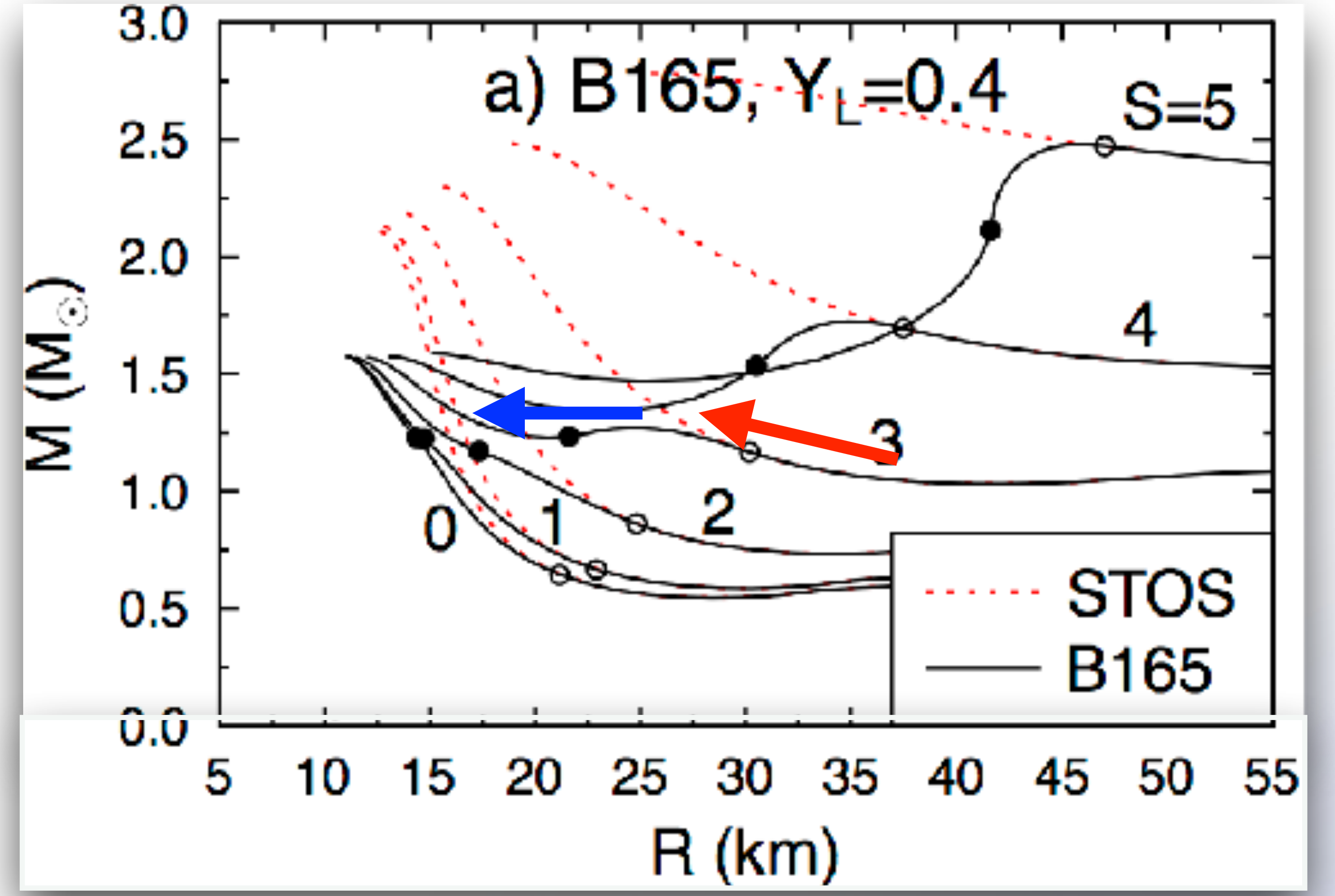
A hot third family of proto-compact stars — EOS dependence



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

[MH et al., PRD 94 (2016)]

Collapse to the third family in a supernova



schematically:

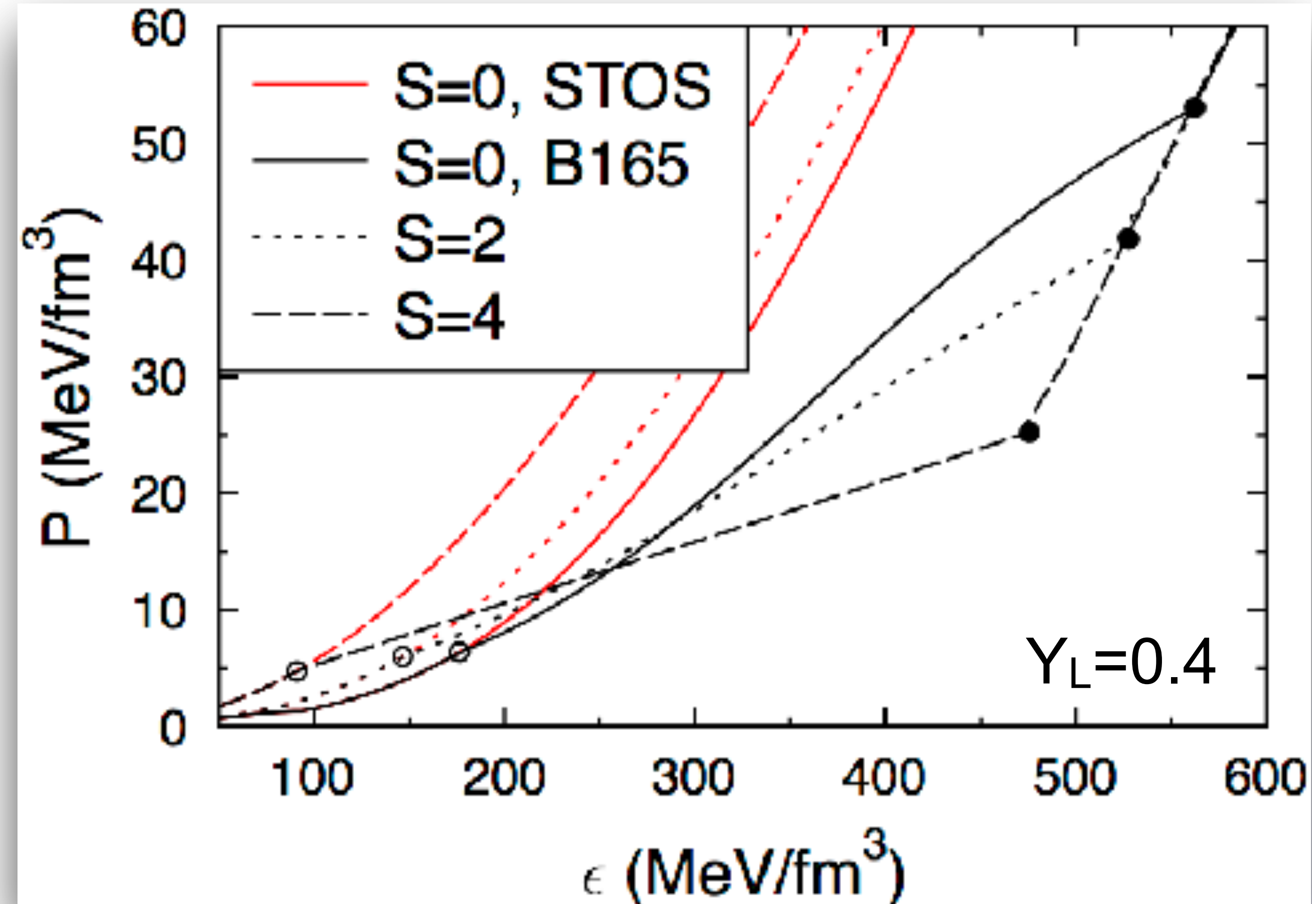
- accretion: increase of the proto-neutron star mass from ~1 M_{sun} to ~1.5 M_{sun} in the first 200 ms
- collapse from the second to the third family with gravitational binding energy release

- exactly this was seen in the core-collapse supernova simulations by T. Fischer in 2009-2012
- results in an energetic explosion even in spherical symmetry

- new insight: the unusual thermal properties and the hot third family stand behind the explosion
- third family feature in cold neutron stars helpful, but not necessary

[MH et al., PRD 94 (2016)]

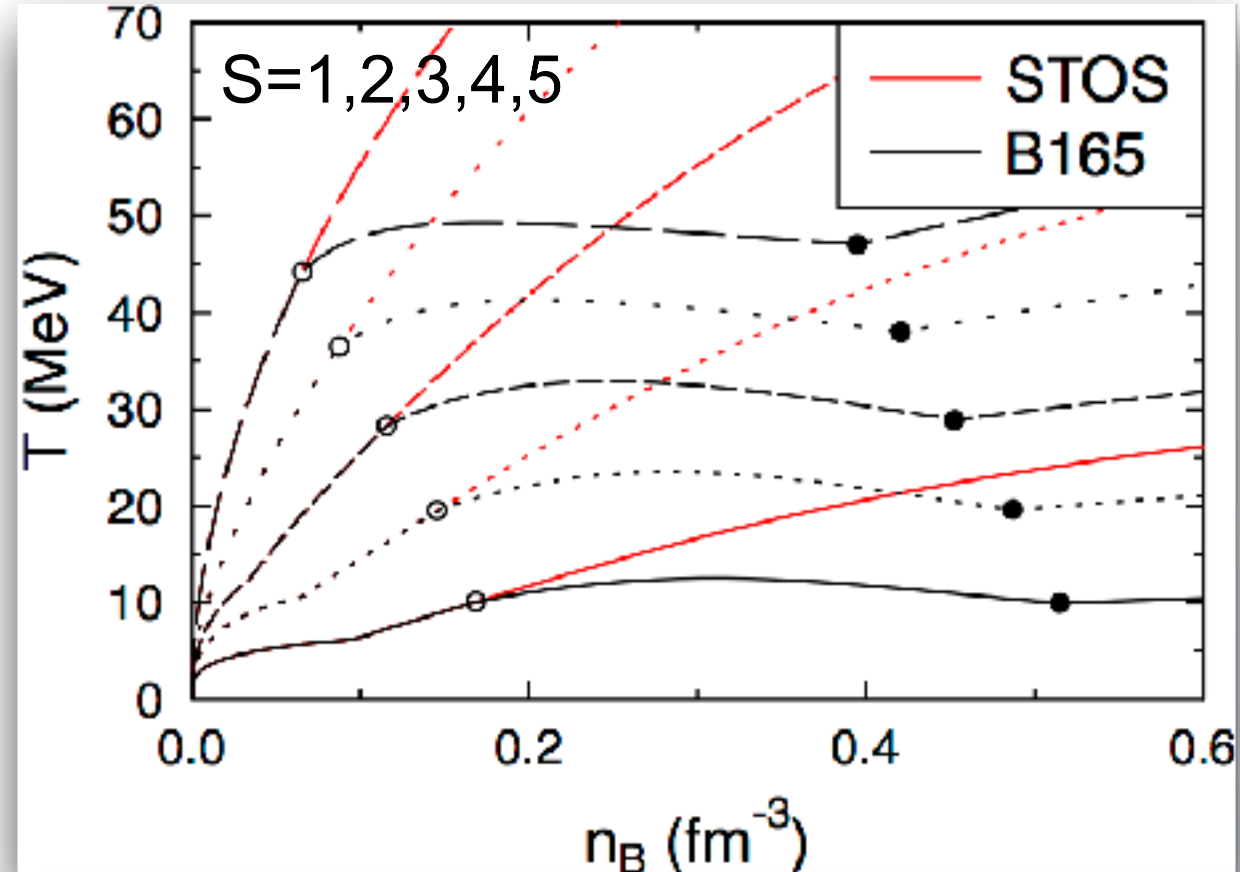
Pressure-energy density relation



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

[MH et al., PRD 94 (2016)]

Temperature for isentropes with B165 hybrid EOS



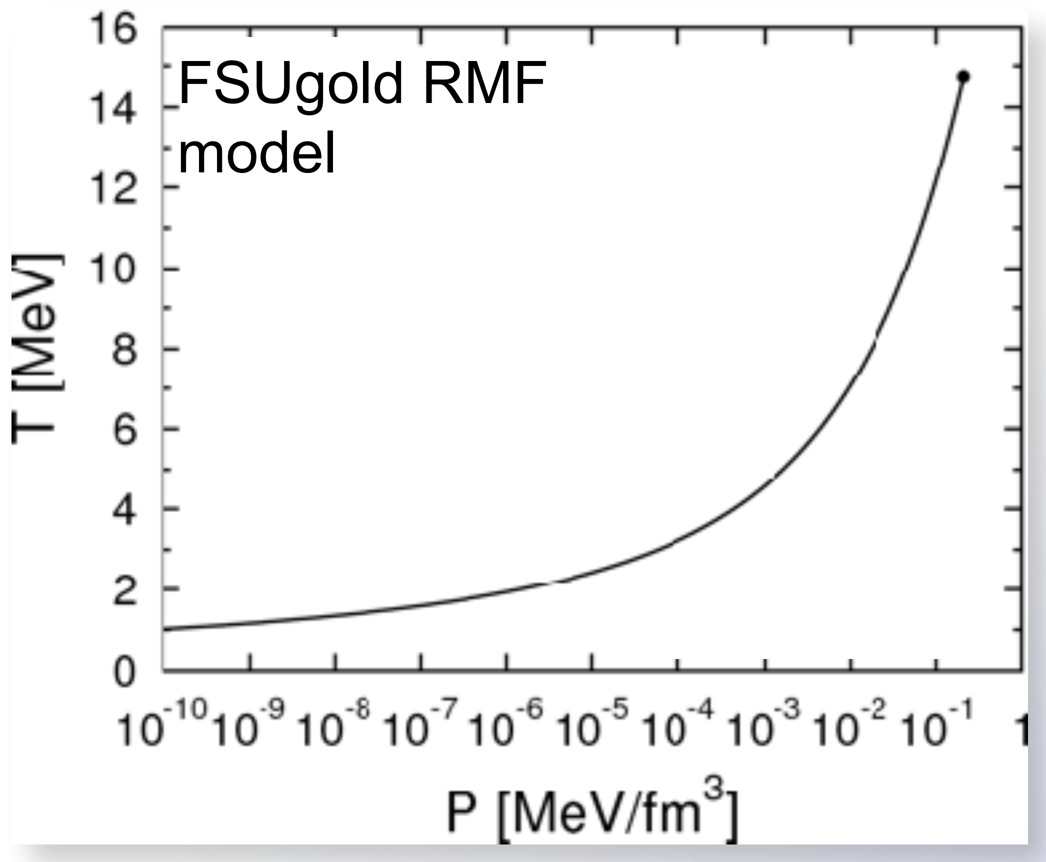
- $dT/dn_B<0$ in parts of the phase coexistence region

[MH et al., PRD 94 (2016)]

Pressure-temperature phase diagrams

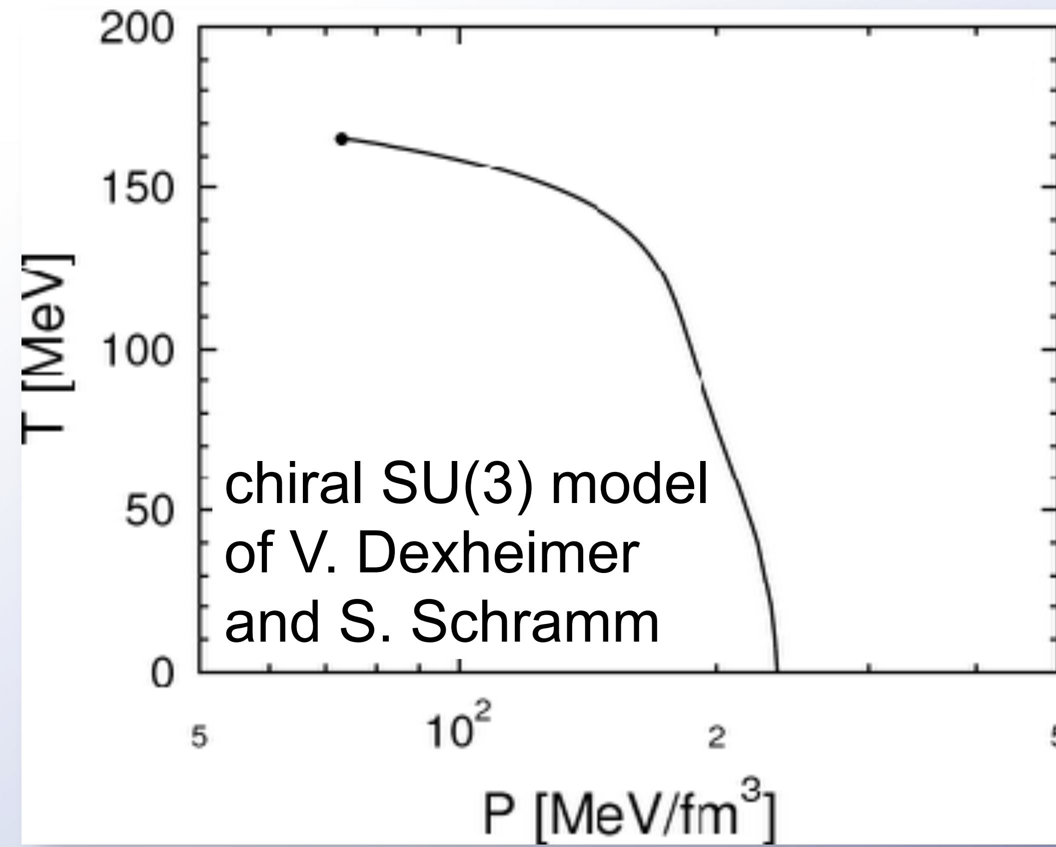
[MH, V. Dexheimer, S. Schramm, I. Iosilevskiy, PRC 88 (2013)]

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]

Unusual thermal properties of entropic phase transitions

- Clausius-Clapeyron equation

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

- for Maxwell phase transition

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

- mass-radius relation given by 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

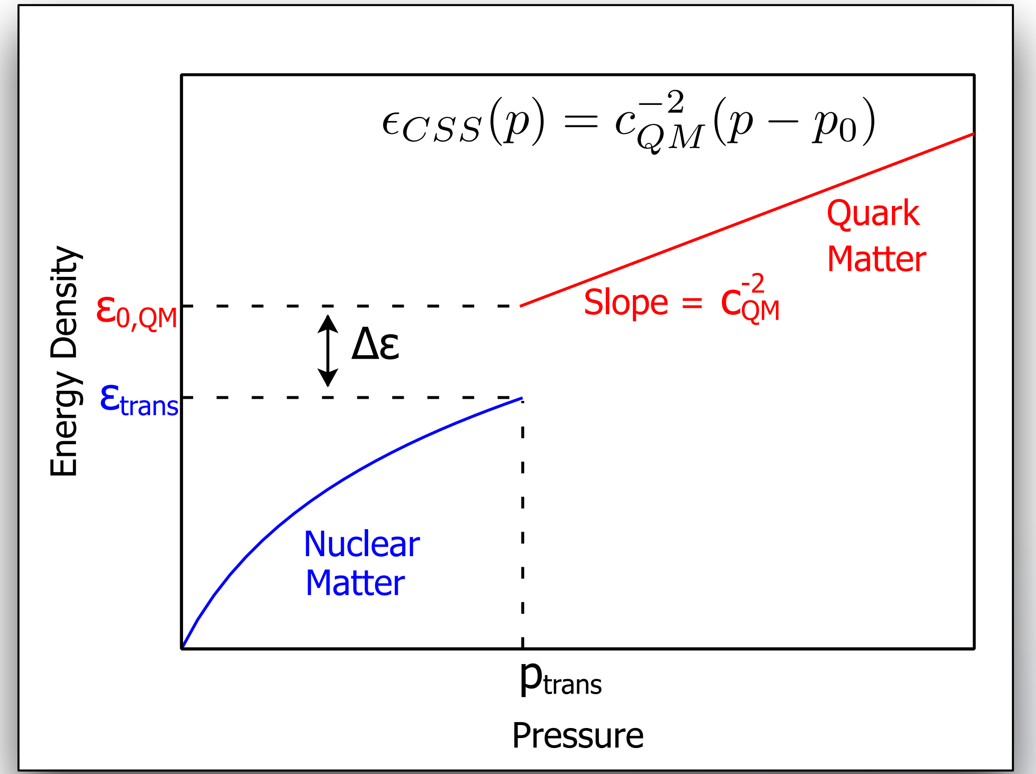
entropic PT: unusual thermal properties, softening of the EOS with increasing entropy

Towards generating a new hybrid supernova EOS: A systematic analysis of cold hybrid stars

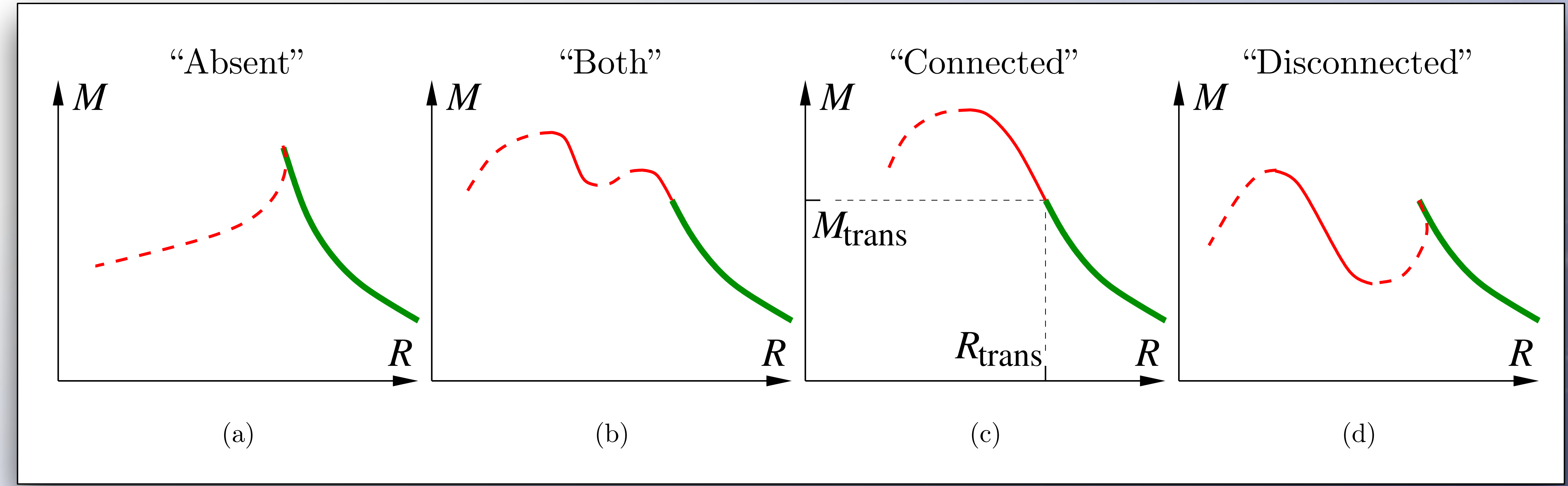
[Oliver Heinimann, MH, Friedrich-Karl Thielemann, PRD 94 (2016)]

Alford's parameter scan

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

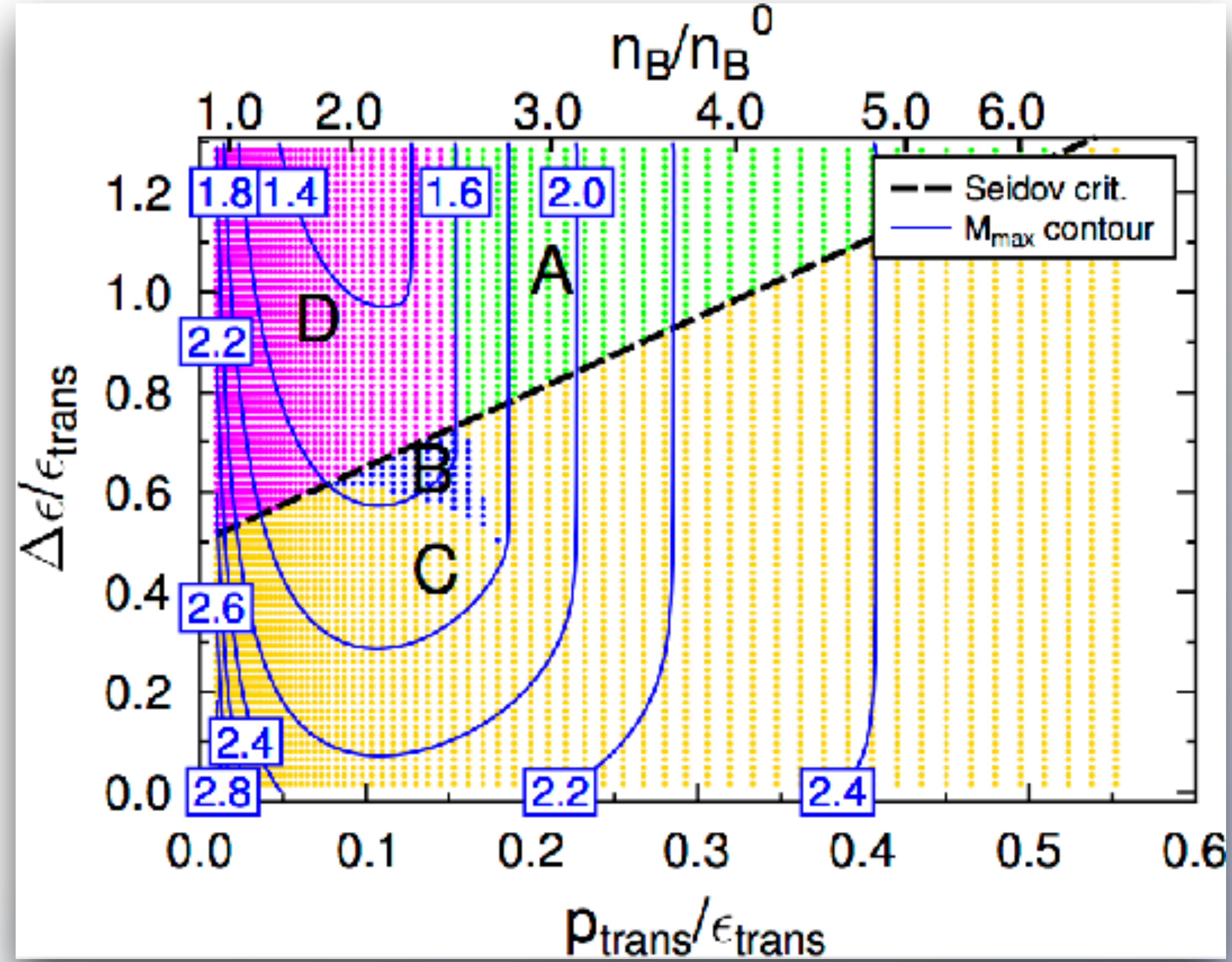


- quark matter: constant speed of sound
- systematic variation of transition pressure and energy density discontinuity
- maximum mass and classification of hybrid stars



New parameter scan for HS(DD2) hadronic EOS

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

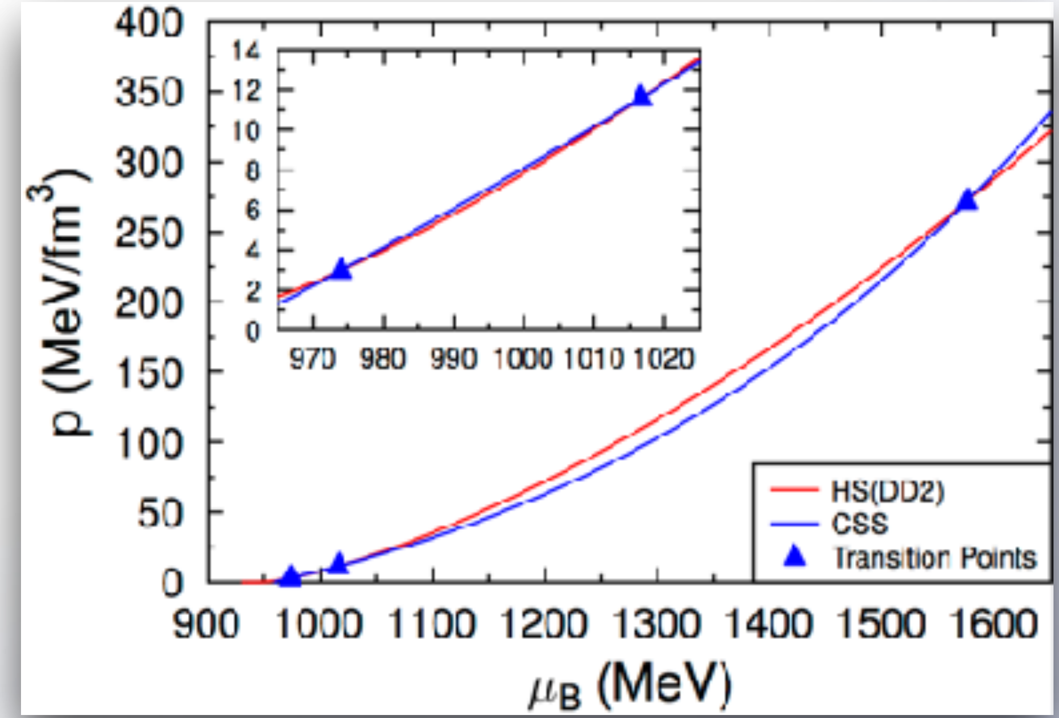


- $M_{max} > M_{max}$(HSDD2) possible
- limited parameter region with $M_{max} > 2\ M_{sun}$ and third family
- favorable region extended for $c_s^2 > 1/3$

Thermodynamic stability

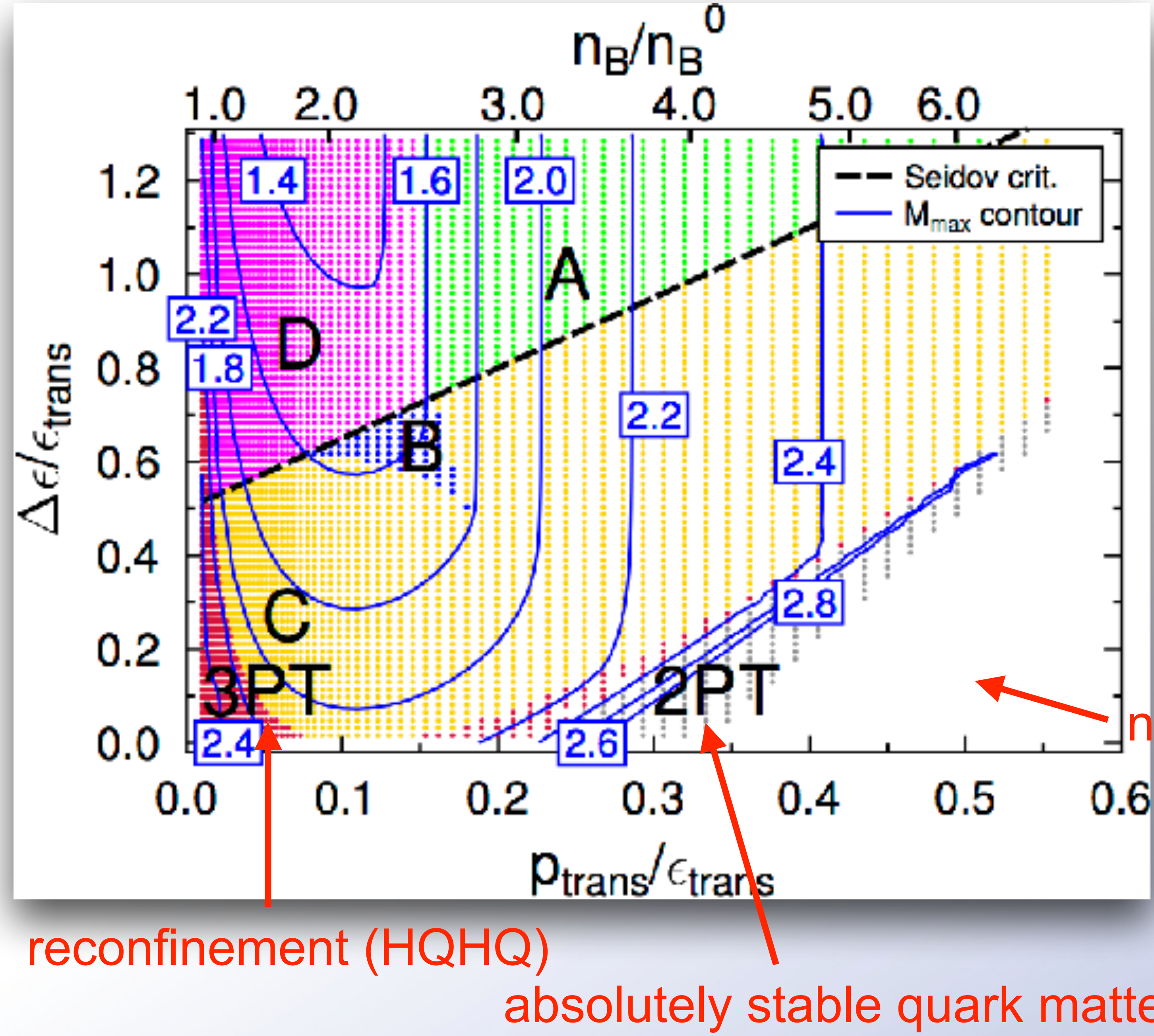
- previous parameter scans: only pressure and temperature equilibrium (T=0)
- p(μ) relation can be derived from p(ε)

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



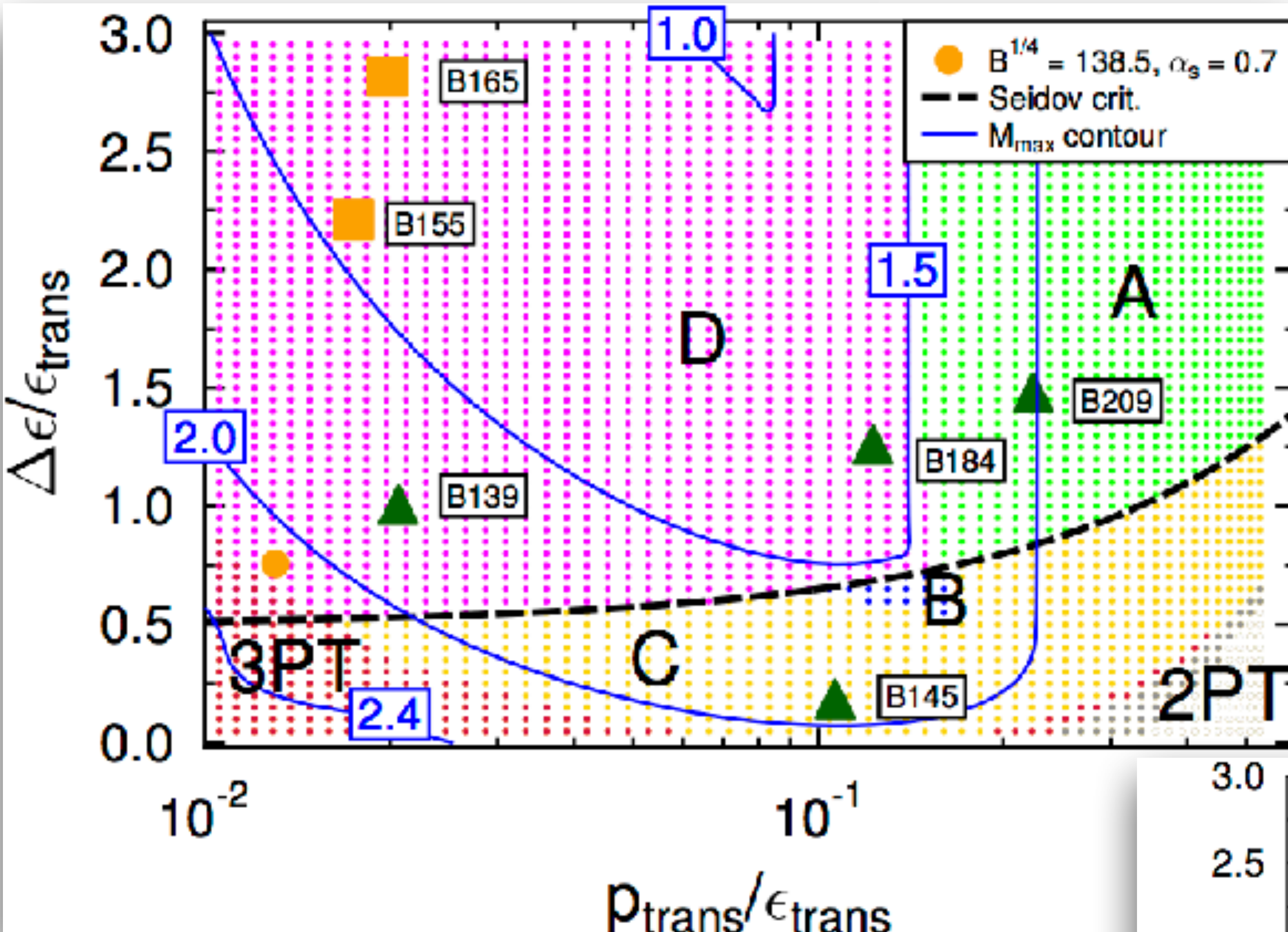
- imposing chemical equilibrium fixes μ_0
- spurious multiple phase transitions and/or reconfinement can occur

Effect of thermodynamic stability

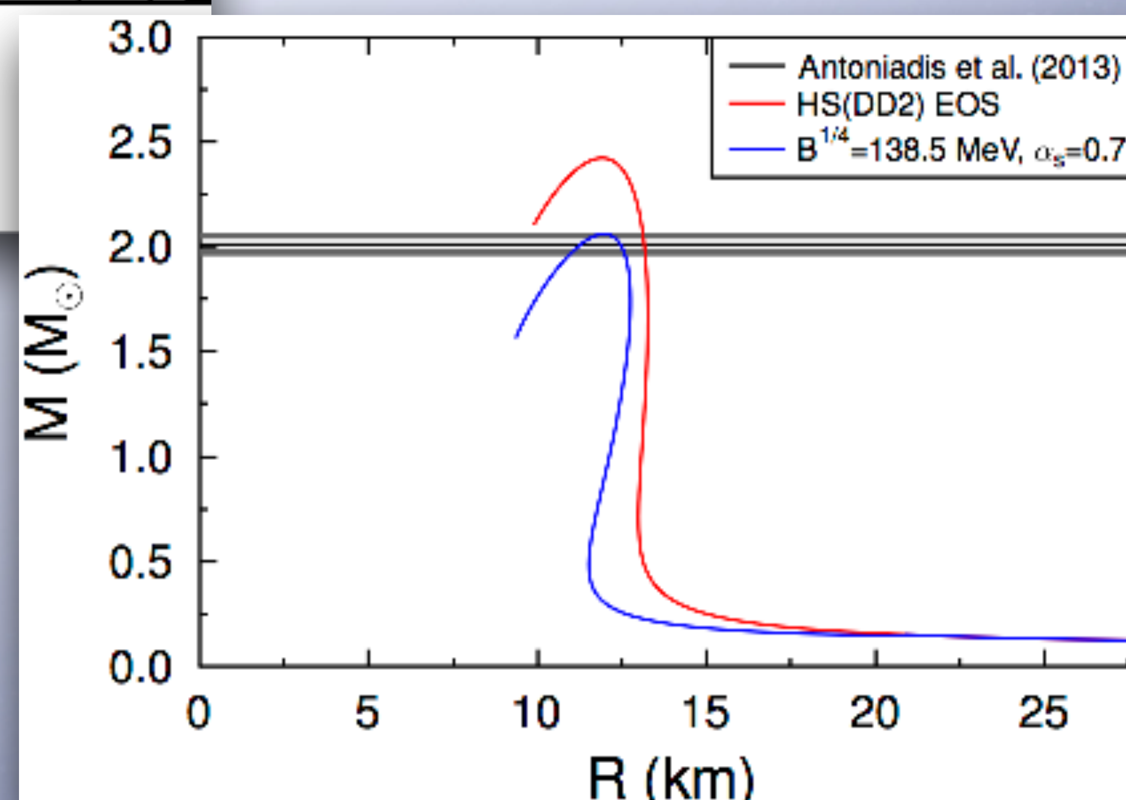


- reconfinement for low transition pressures and weak phase transitions
- (almost pure) quark stars appear
- M_{max} > M_{max}(HSDD2) only possible for quark stars

Comparison with existing hybrid EOSs



- constant-speed of sound EOS can be transferred to bag model
- expectations confirmed, third family favorable for explosions
- new quark-hadron hybrid general purpose EOS just finished



Summary and conclusions

- the QCD phase transition is *entropic* ($dP/dT|_{PT}<0$) and leads to unusual thermal properties

- possible consequences:
  - inverted convection in proto-neutron stars (Yudin et al. MNRAS 2016)
  - hot third family of compact stars
  - core-collapse supernova explosions (?)

- systematic analysis of quark matter properties, reconfinement problem
- new hybrid EOS with interesting properties just finished

- work in progress: spherically symmetric and multi-D CCSN simulations
- compare prediction for neutron star and black hole birth mass distribution with observations

- effects of quark matter in NS mergers?