EoS with quark-hadron phase-transition

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Possible phase-diagrams

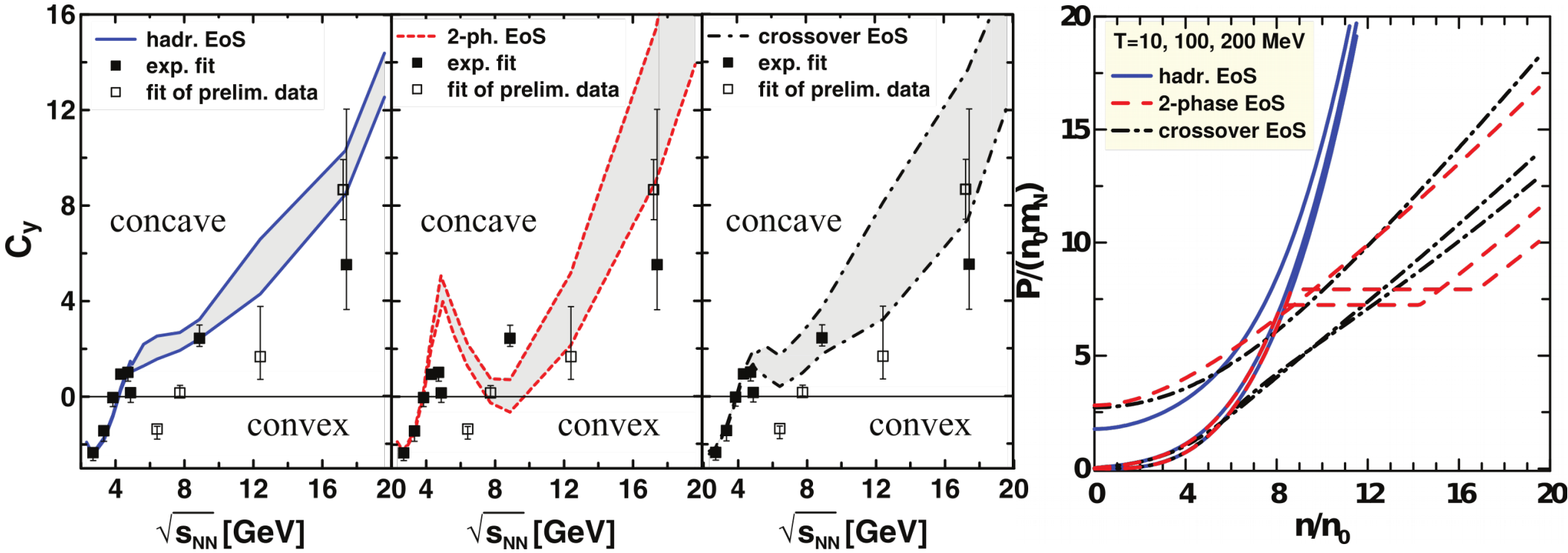
Crossover all over?

Possible phase-diagrams

First order phase-transition at high densities?

Possible indicators in measurable systems?

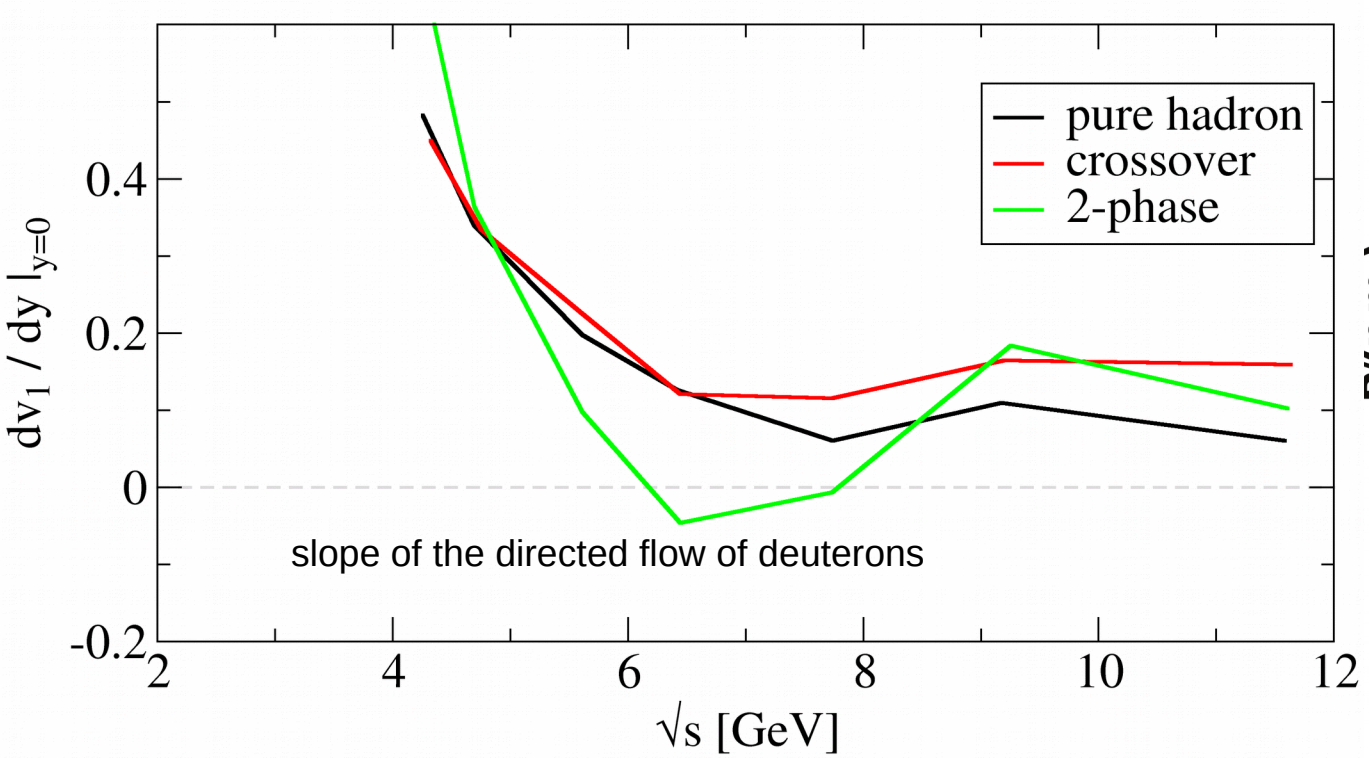
Motivation – Heavy Ion Collisions

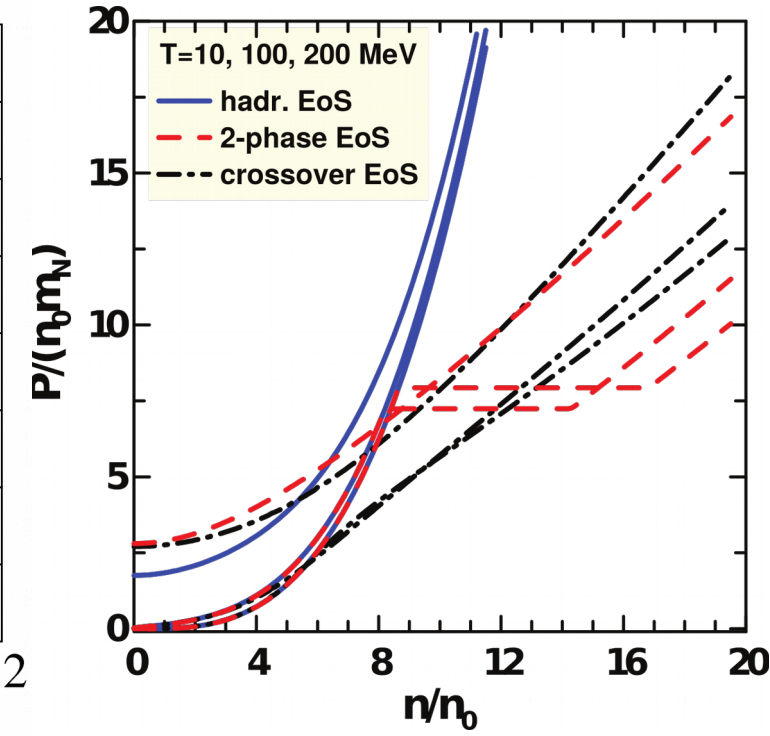


- 1st order phase-transition leads to a strong signal (wiggle) in the baryon stopping signal
- Previous EoS has unreasonable high onset densities and does not fit exp. data

Yu. B. Ivanov, PRC 87, 064904 (2013)
Bastian, Batyuk, Blaschke, et al., Eur.Phys.J. A52 (2016) no.8, 244

Motivation – Heavy Ion Collisions

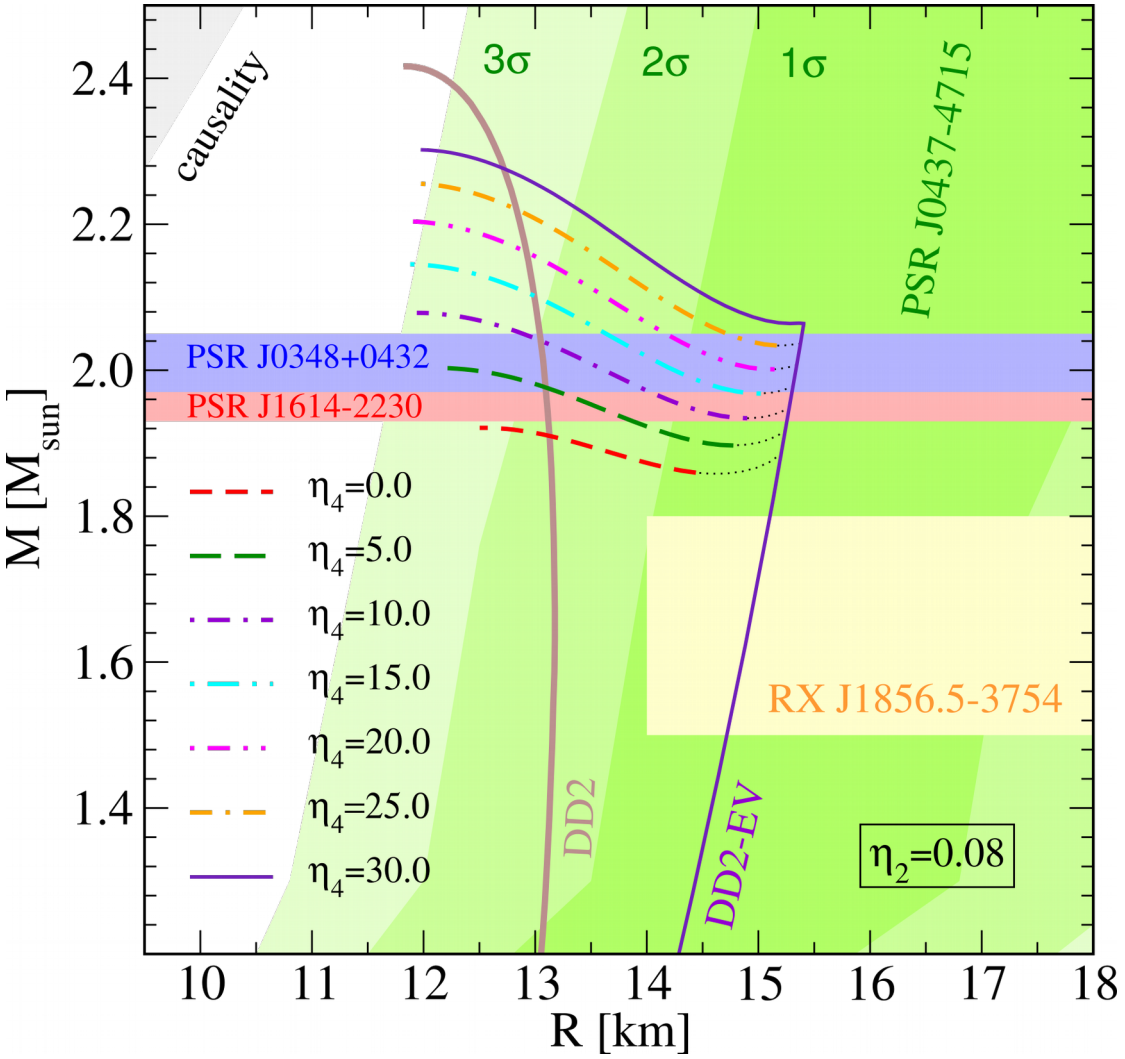




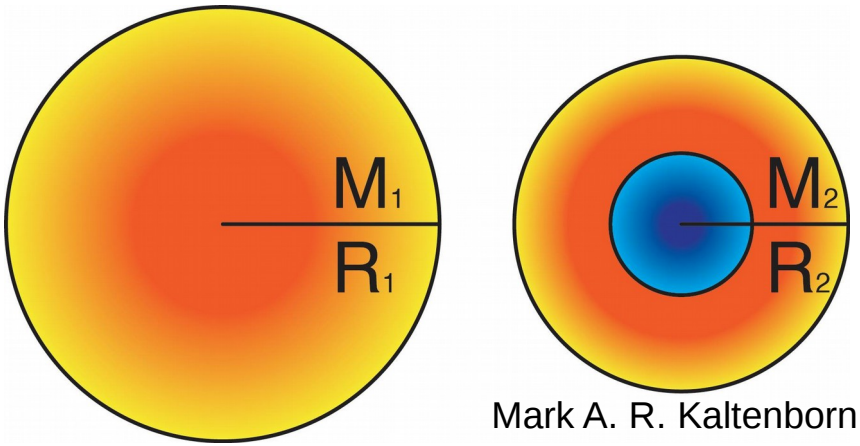
- 1st order phase-transition leads to a strong signal (wiggle) in the baryon stopping signal
- Previous EoS has unreasonable high onset densities and does not fit exp. data
- Anti-flow occurs if assuming 1st order phase-transition
- Position of signals depends on characteristic of phase-transition

Yu. B. Ivanov, PRC 87, 064904 (2013)
Bastian, Batyuk, Blaschke, et al., Eur.Phys.J. A52 (2016) no.8, 244

Motivation – Neutron stars (Twins?)



- Star configurations with same masses, but different radii

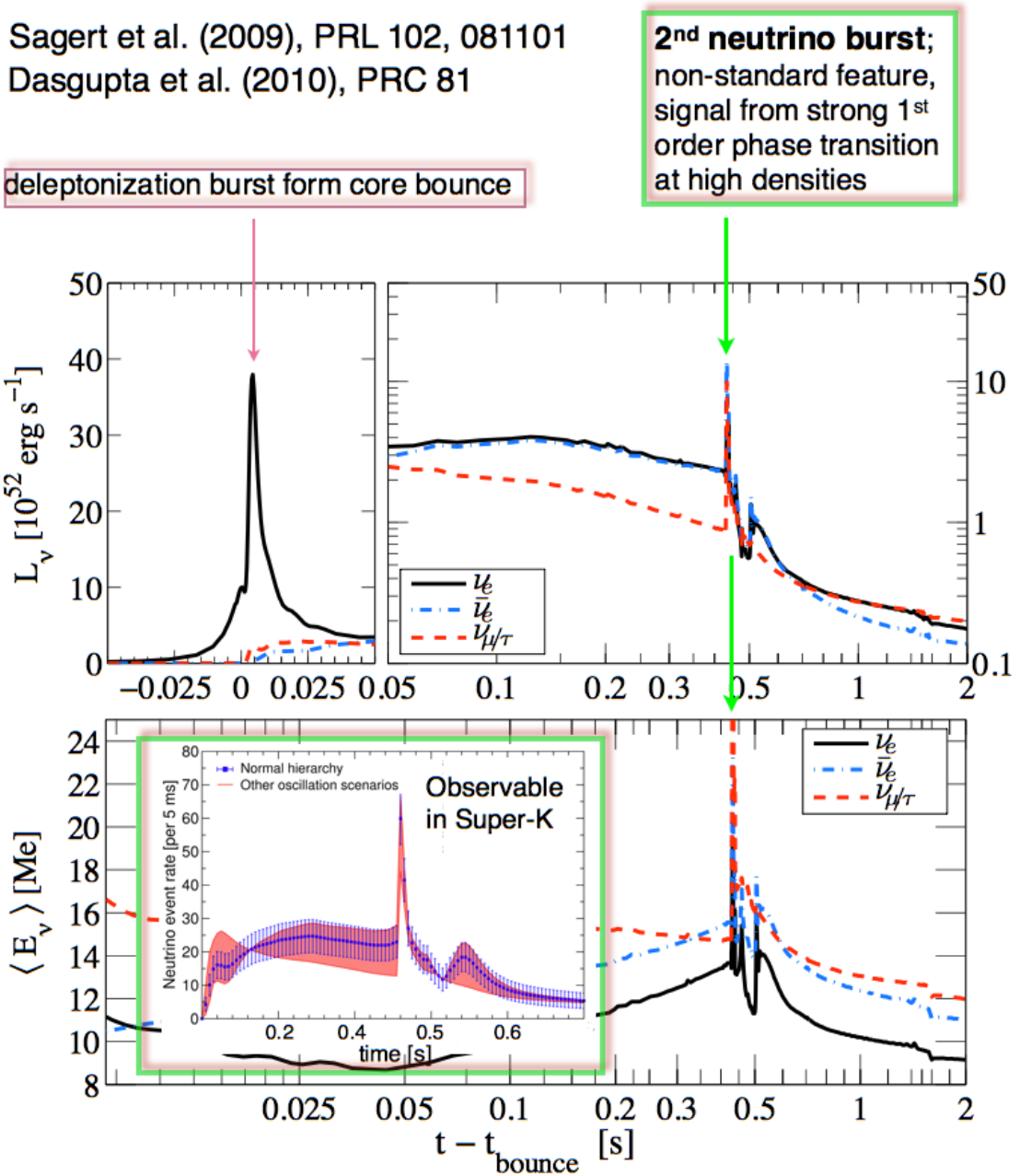


Mark A. R. Kaltenborn

- **New class of EOS, that features high mass twins**
- NASA NICER mission: radii measurements ~ 0.5 km
- Existence of twins implies 1st order phase-transition and hence a critical point

Benic, Blaschke, Alvarez-Castillo, Fischer, Typel, A&A 577, A40 (2015)

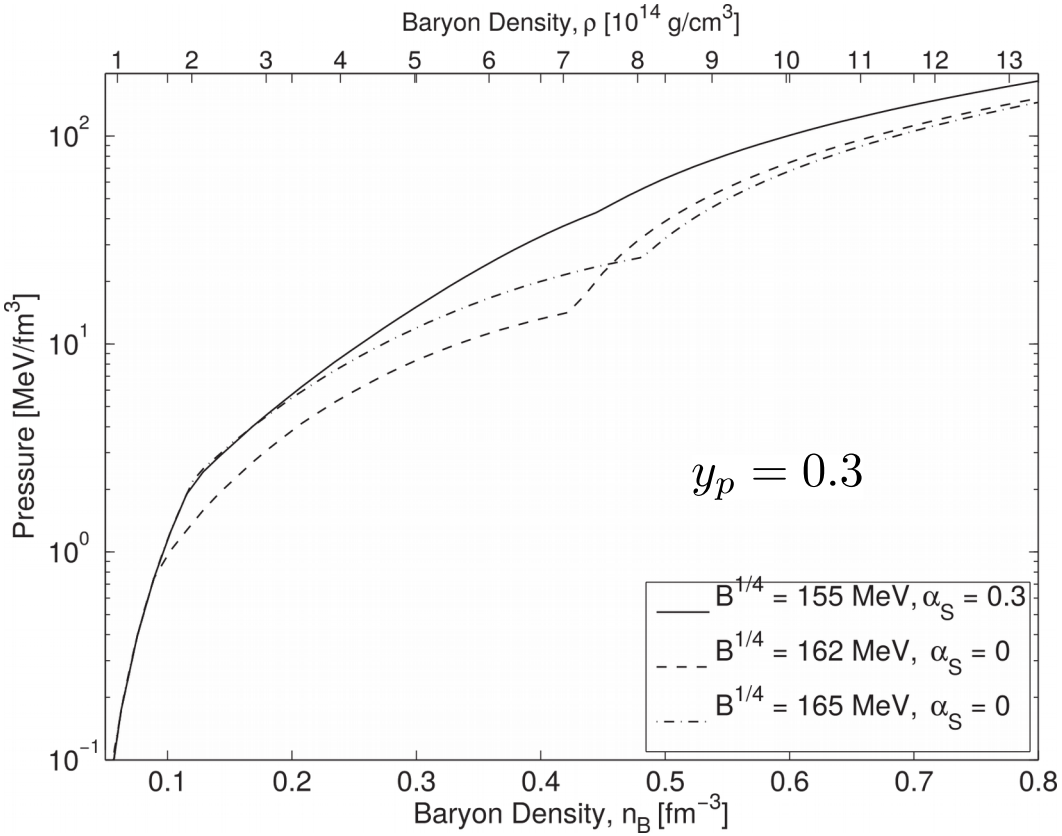
Motivation – Supernovae



- Core-collapse supernovae as laboratories to probe the state of matter?
- Evidence for exotic states of matter: non-standard behavior of neutrino fluxes/energies (?)
- Additional neutrino outburst(s) due to high-density phase transition
- All flavors, unlike deleptonization burst
- Associated millisecond features observable with current neutrino detectors
- Structure of neutrino signal contains information about details of phase transition

Previously used EOS (for SN)

- Hadronic equation of state is TM1[1]
- Simple bag model for quark EOS
- Phase transition via Gibbs-construction
- Does not coincide with modern constraints and needs to be updated

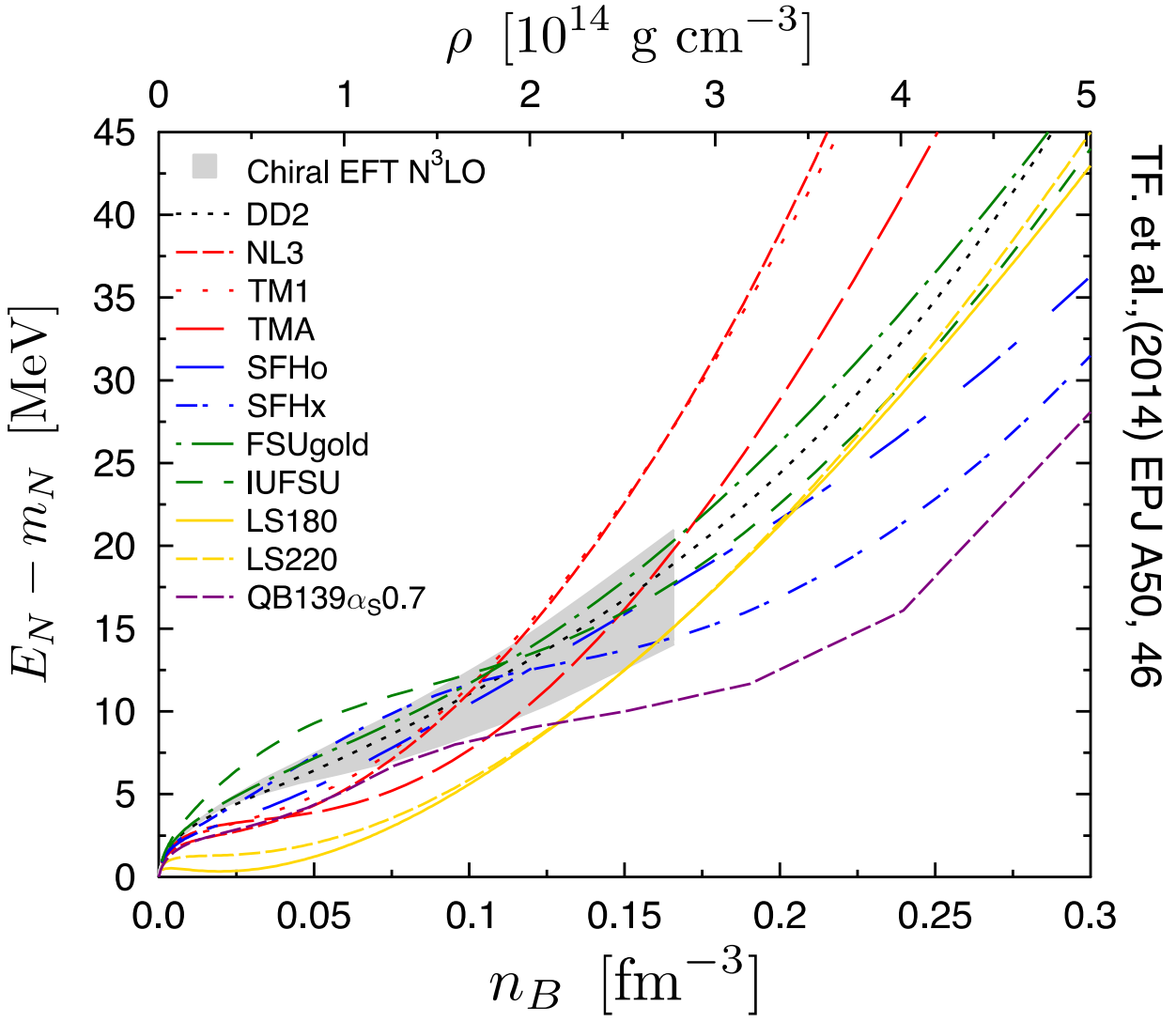


Sagert & Fischer et al.(2009) PRL 102, 081101
Fischer et al.(2011) ApJS 194, 39

[1]Shen, H., Toki, H., Oyamatsu, K., & Sumiyoshi, K. 1998, Nucl. Phys. A, 637, 435

What do we know about the EOS?

Actual constraint: chiral EFT for neutron matter at $n \lesssim n_0$

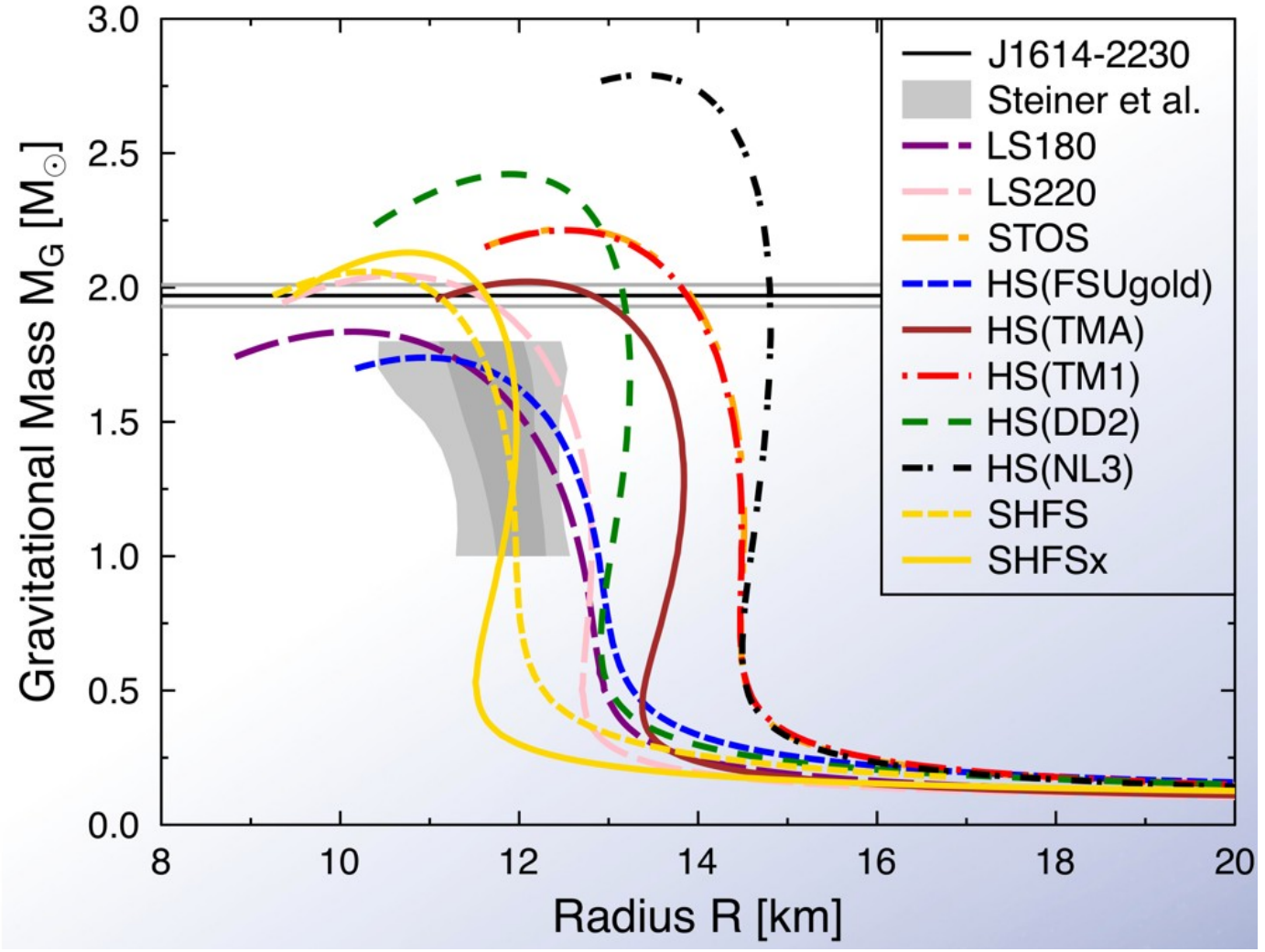


- Chiral EFT is a solid constraint
- DD2[1] fits this constraint
- Many others are ruled out (e.g. QB139)

[1]S. Typel, PRC 81 (2010), 015803

What do we know about the EOS?

Actual constraint: Maximal mass of neutron stars



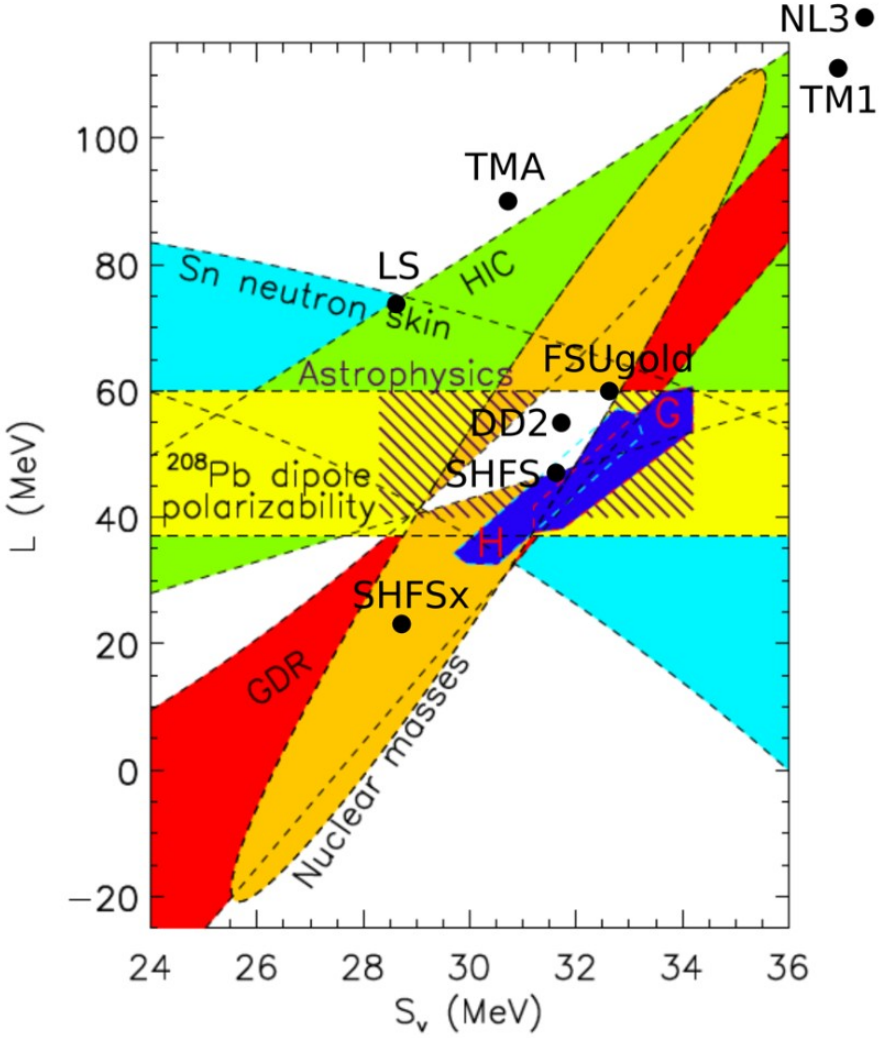
- Existence of $2\,M_\odot$ stars is strong constraint for EOS at high densities

M. Hempel

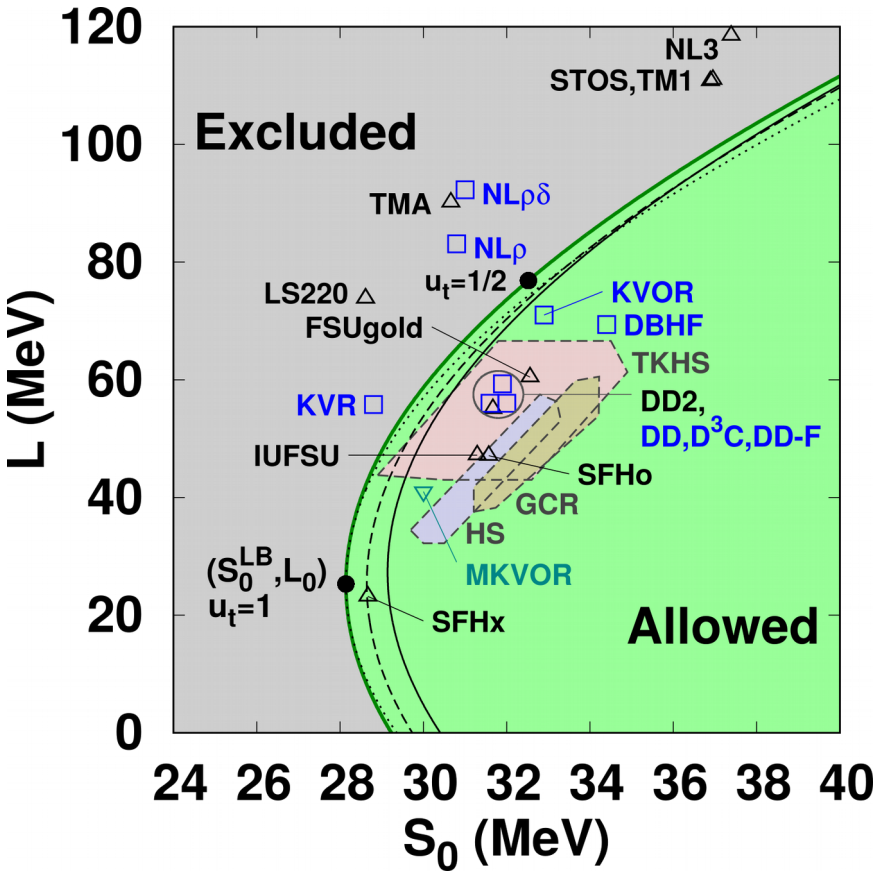
What do we know about the EOS?

Actual constraint: Symmetry energy and its slope at $n = n_0$

Lattimer & Lim (2013) ApJ 771, 14



- Symmetry energy is important EOS property for astrophysics



E. E. Kolomeitsev, J. M. Lattimer, A. Ohnishi, I. Tews, arXiv:1611.07133

Weaknesses in previous used EOS

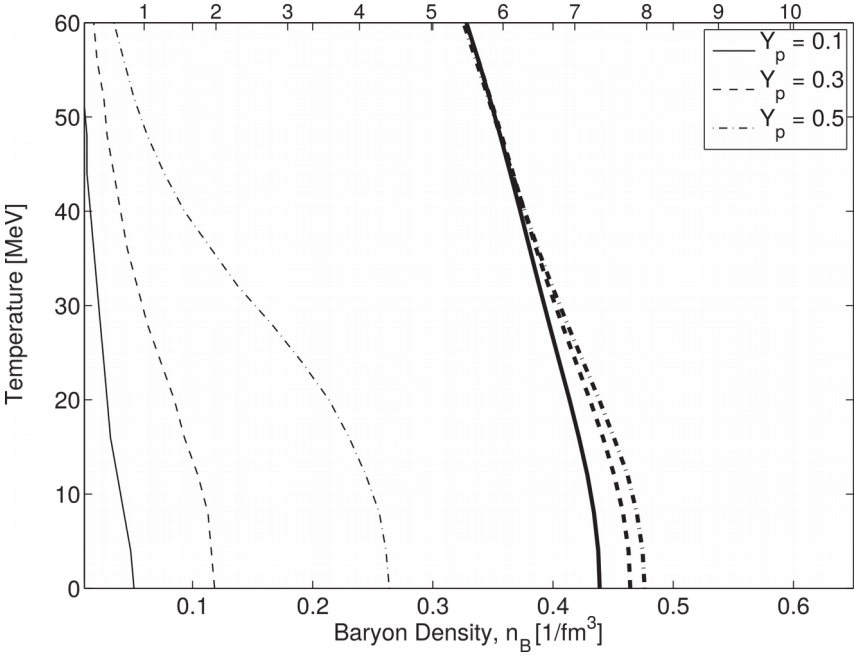
- Very low onset density
- Does not fulfill $2M_{\odot}$ constraint (1.67)
- Does not correspond to chiral EFT data

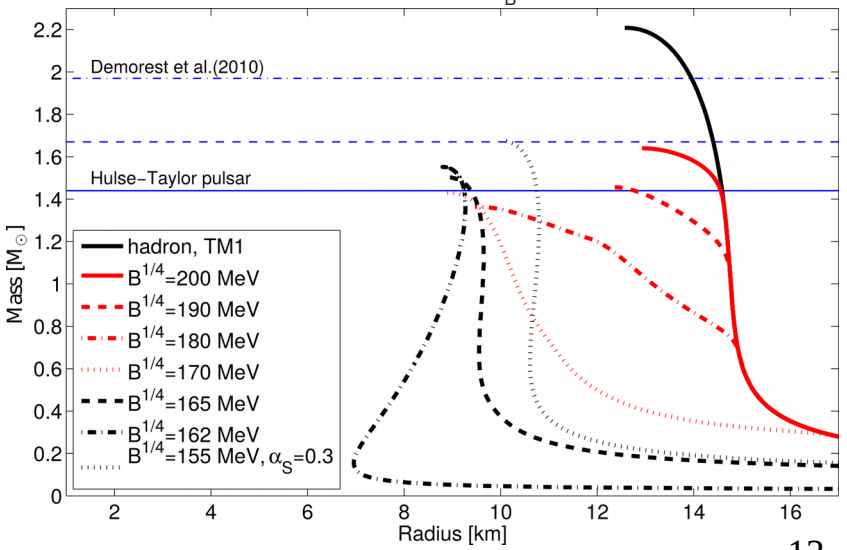
To be fixed by:

- Better hadronic EOS (DD2, DD2f), which fulfills given constraints
- Flexible quark EOS with vector repulsion

Needed for $2M_{\odot}$ constraint

Fix the parameters to optimize properties of phase-transition





Sagert & Fischer et al.(2009) PRL 102, 081101
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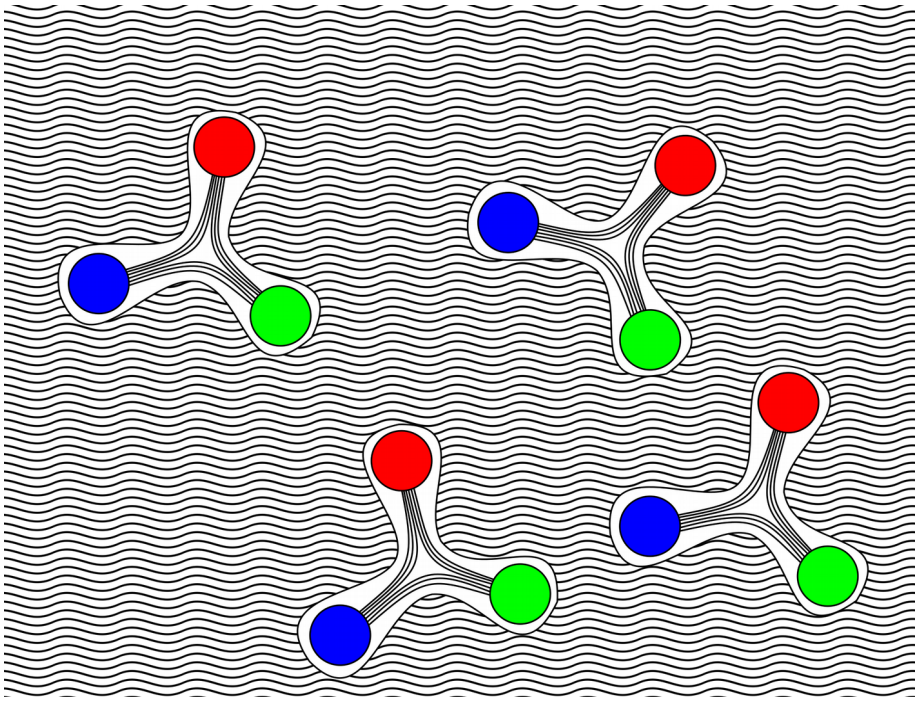
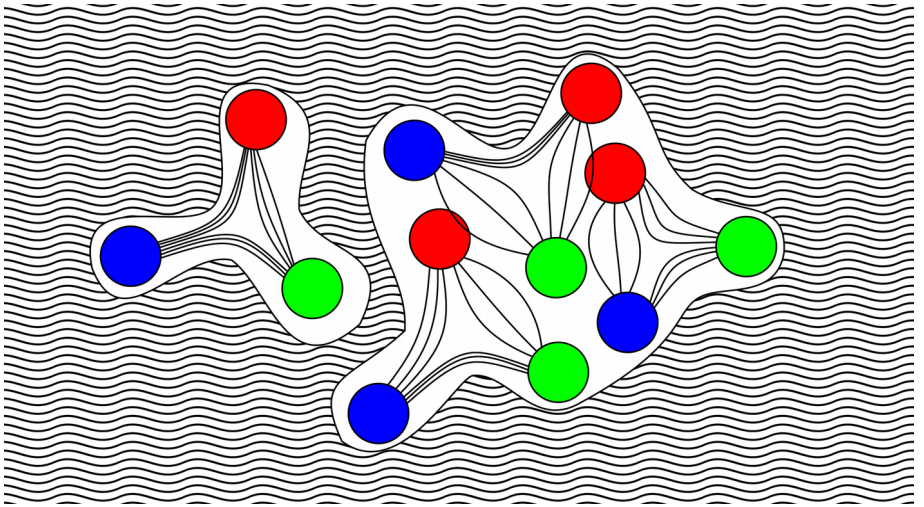
Stringflip model

Low density

- Color field lines compressed by dual meissner effect
- String-tension high

$$\sigma = \sigma_0$$





High density

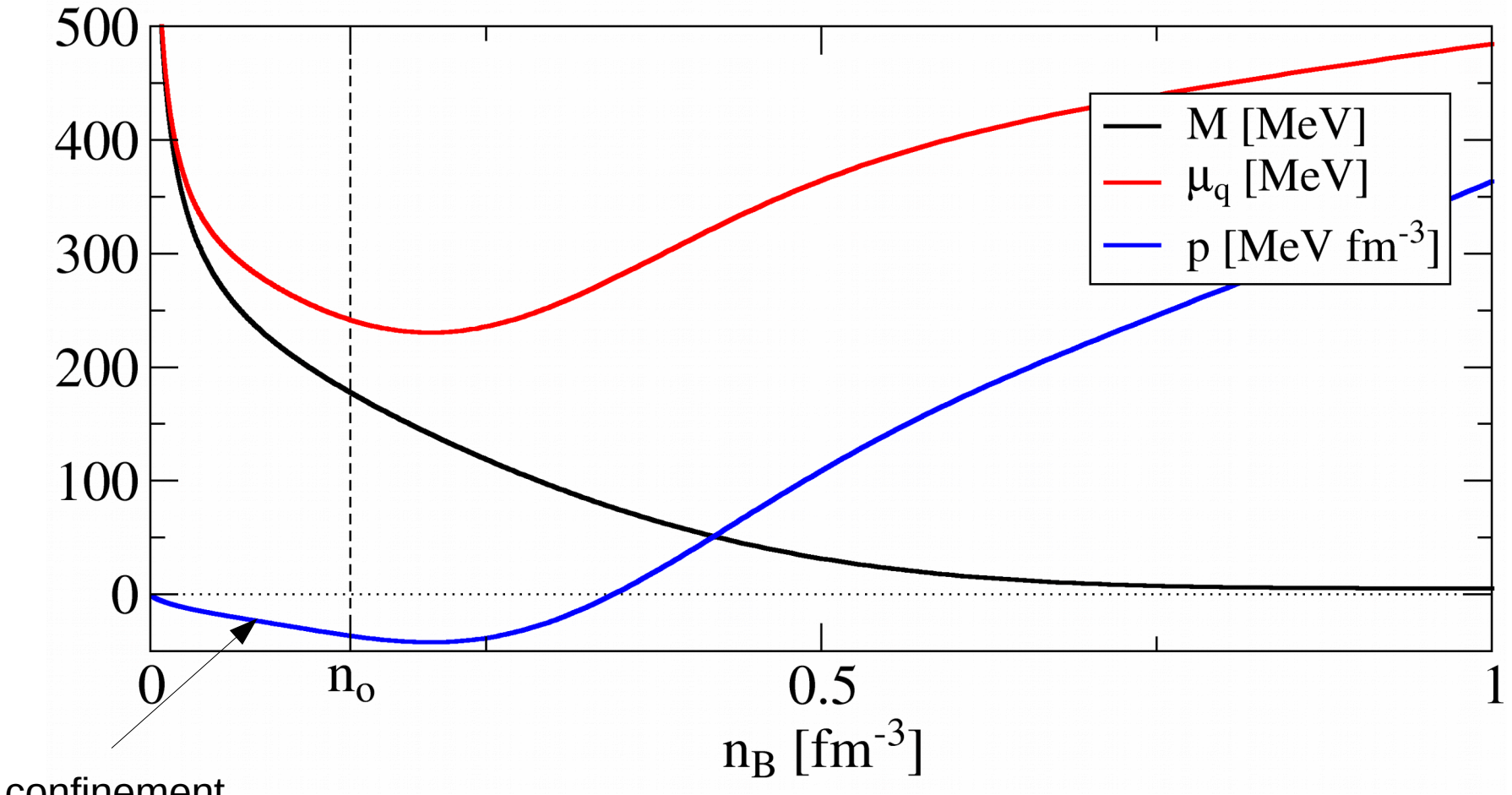
- Dual superconducting vacuum occupied by hadrons
- Pressure on field lines reduced
- Effective string-tension reduced

$$\sigma = \Phi\sigma_0$$

G. Ropke, et. al., Phys.Rev. D34 (1986) 3499-3513
Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Stringflip model – effective mass

$$M_i = m_i + D \cdot (n^{\mathrm{s}})^{-1/3} - m_i^{\mathrm{R}} \qquad D = D_0 \mathrm{e}^{-\alpha(n-n_0)^2}$$



Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Stringflip model – vector interaction

- Effective chemical potential

$$\tilde{\mu}_i = \mu_i - \left(an + bn^3 \frac{1}{1+cn^2} \right) - E_i^{\mathrm{R}}$$

4-quark interaction

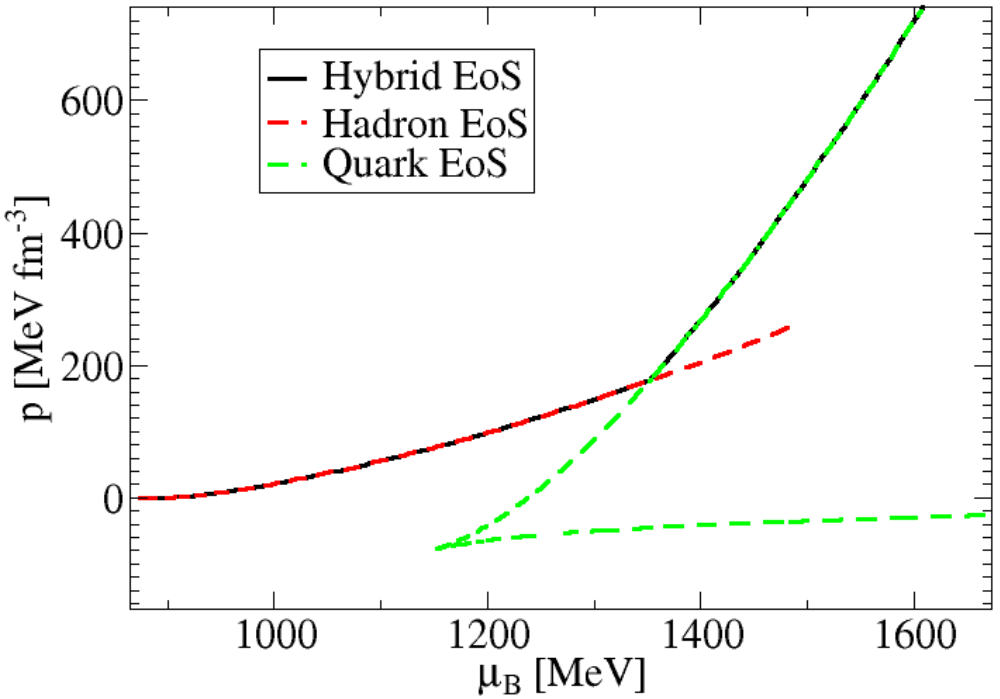
8-quark interaction

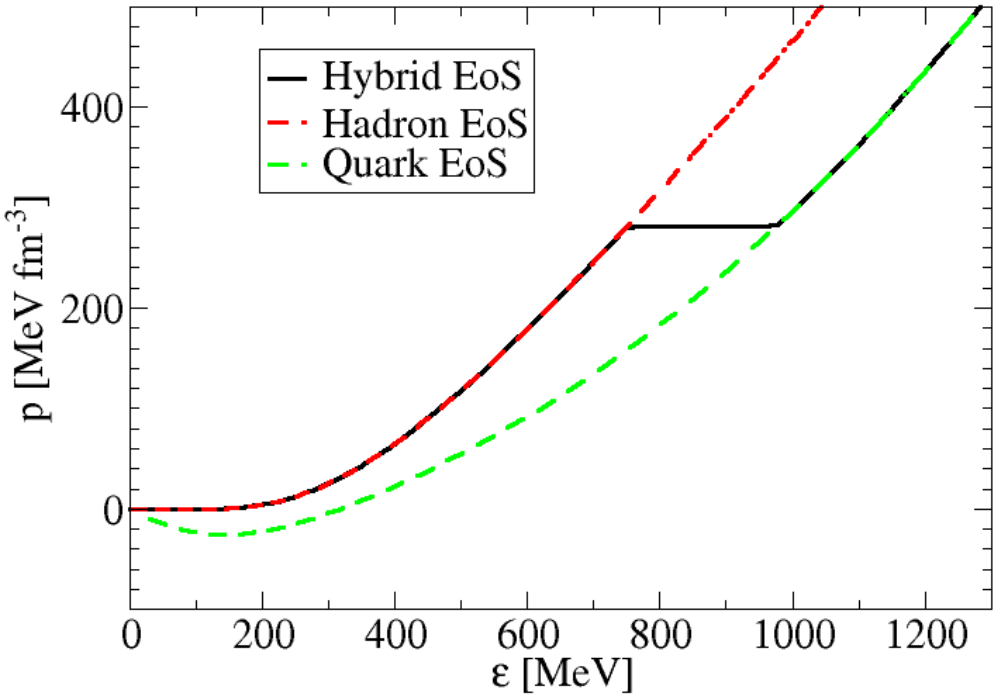
High-density correction
to preserve causality

Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Hybrid EOS - phasetransition

- 2-phase approach: phase transition via Maxwell construction

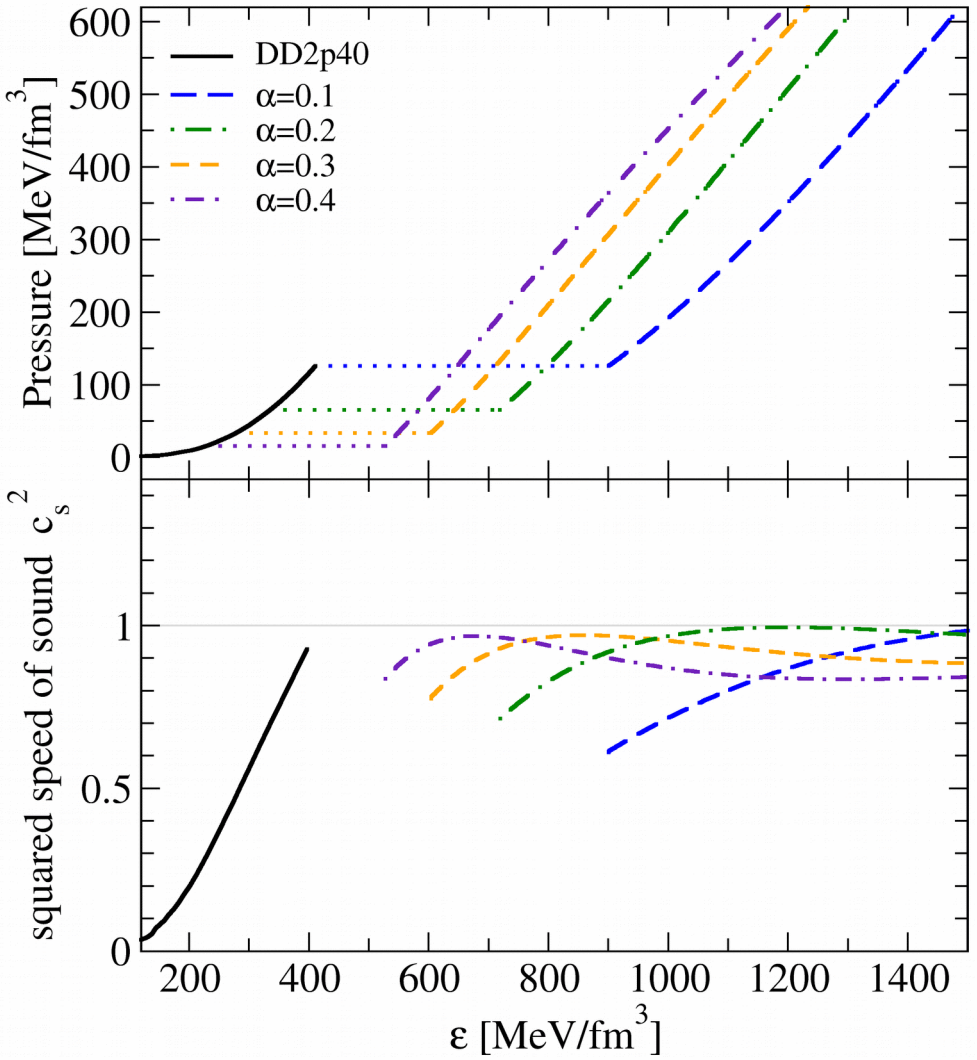


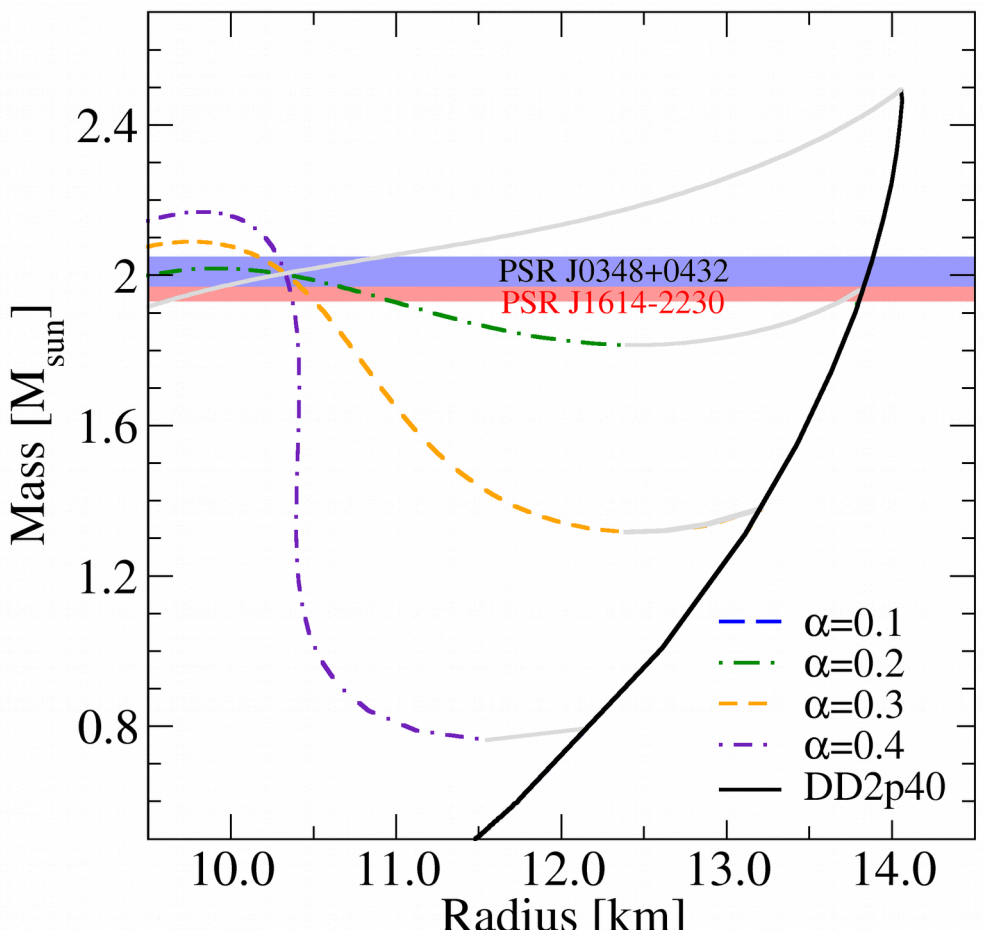


Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Hybrid EOS - parameters

$$\underline{\alpha}, a, b$$

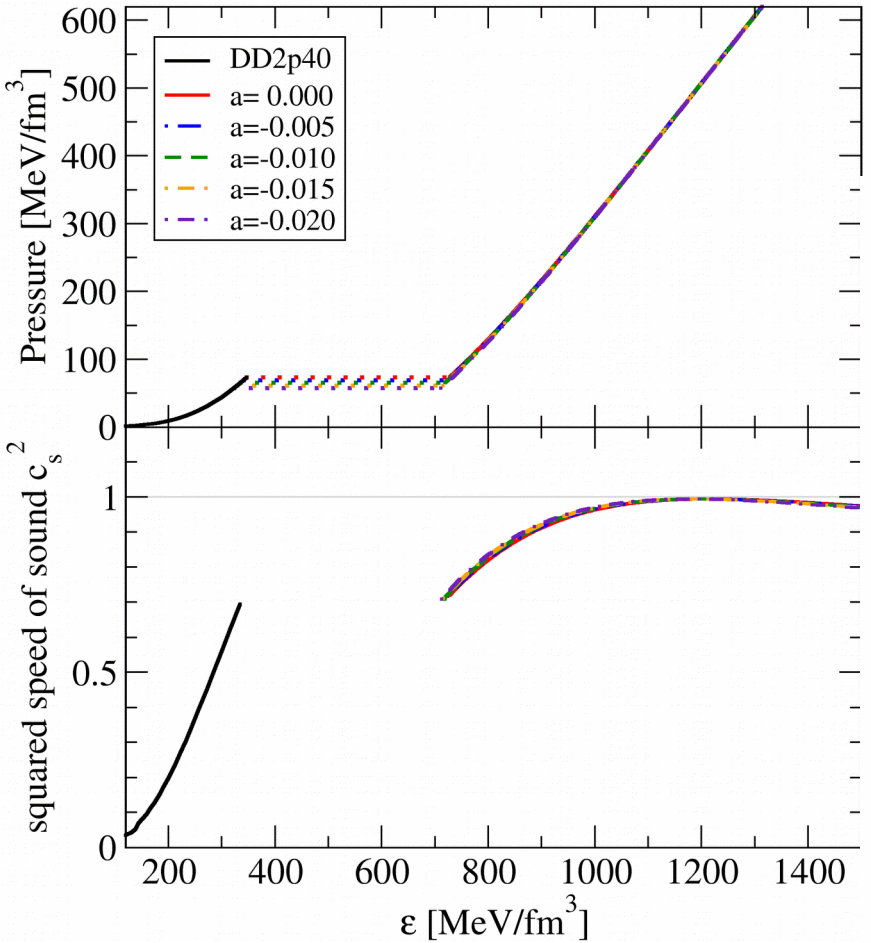


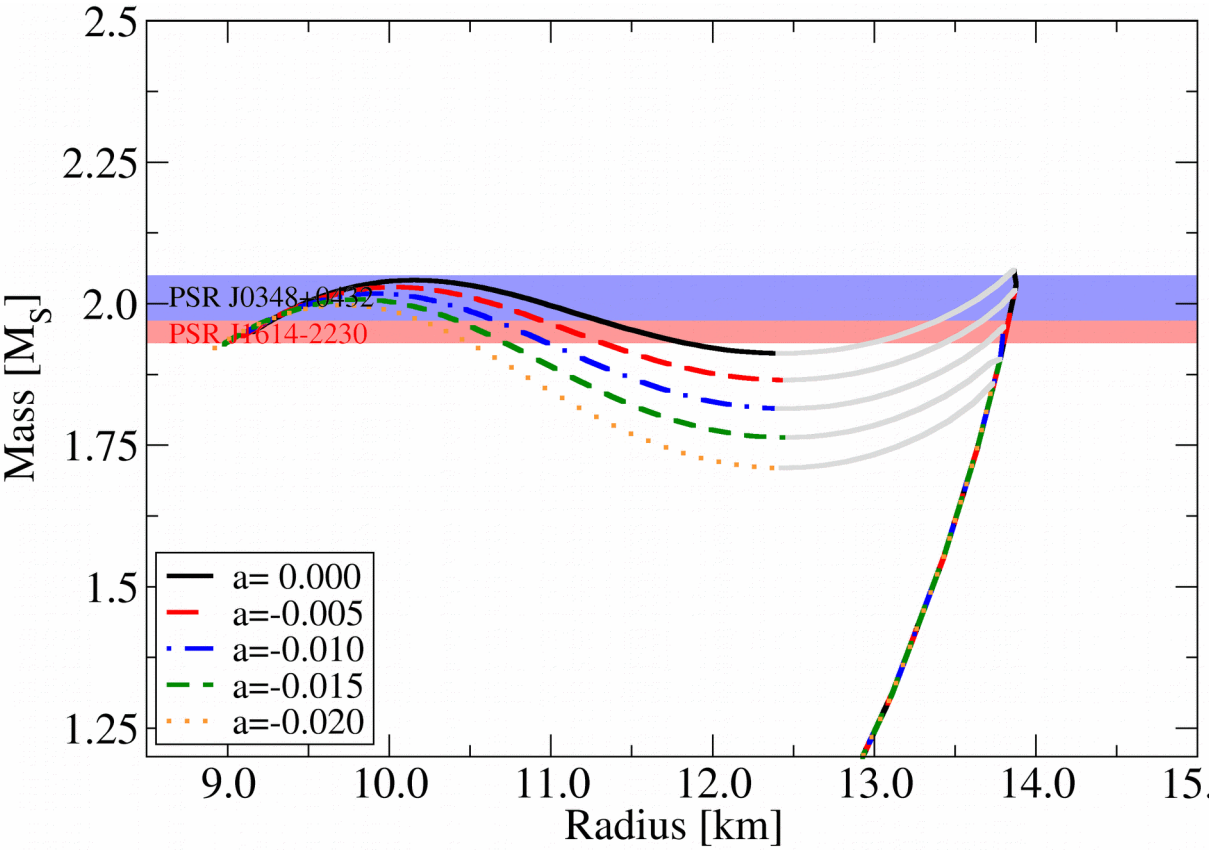


Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Hybrid EOS - parameters

$$\alpha, \underline{a}, b$$

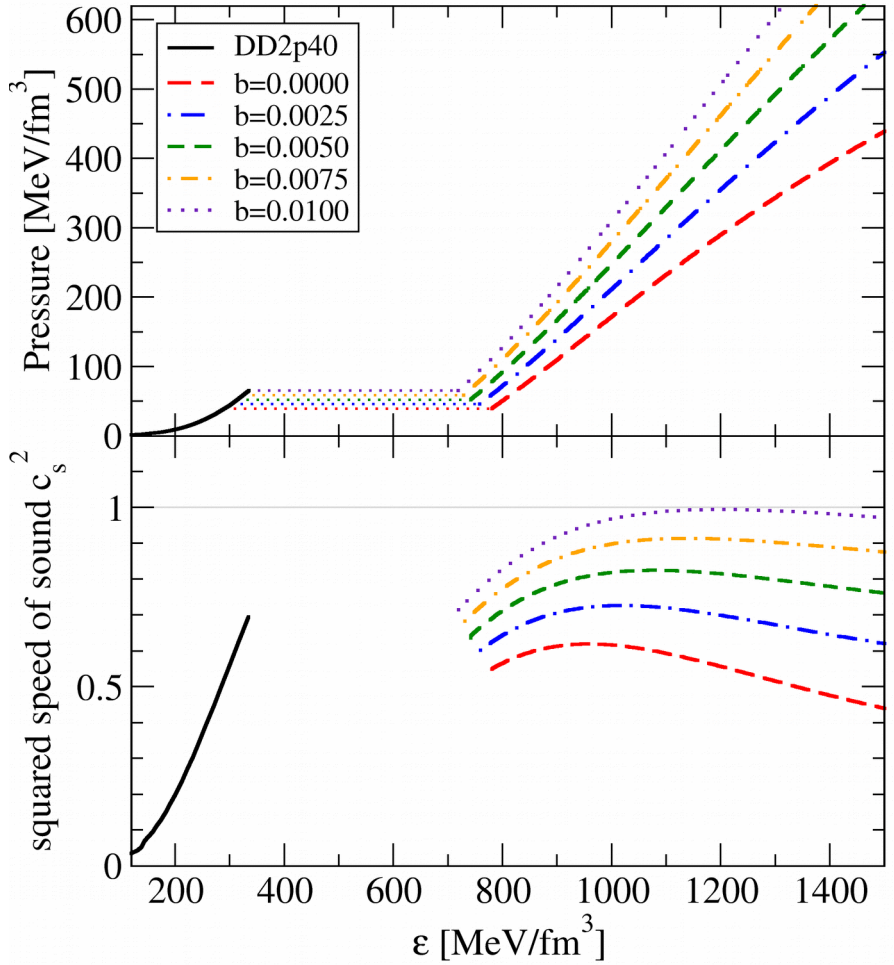


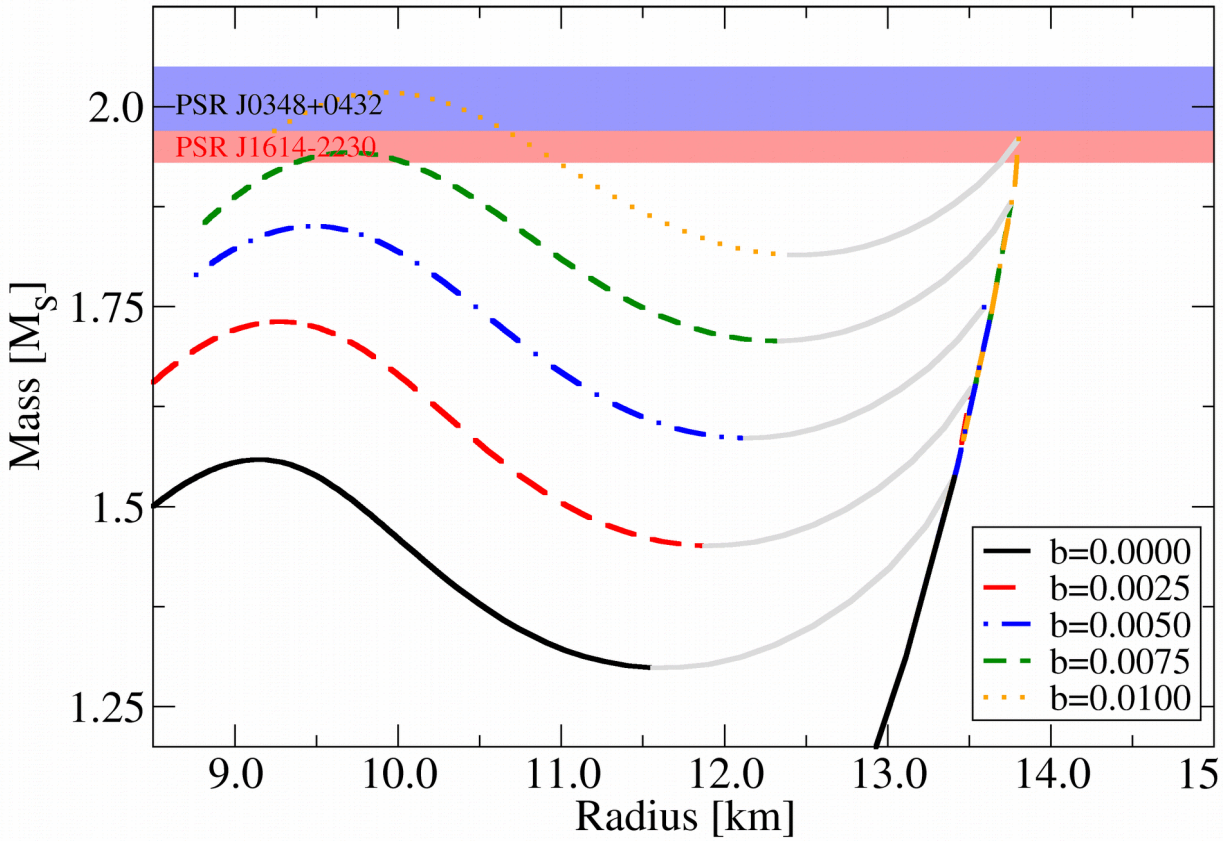


Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Hybrid EOS - parameters

$$\alpha, a, \underline{b}$$





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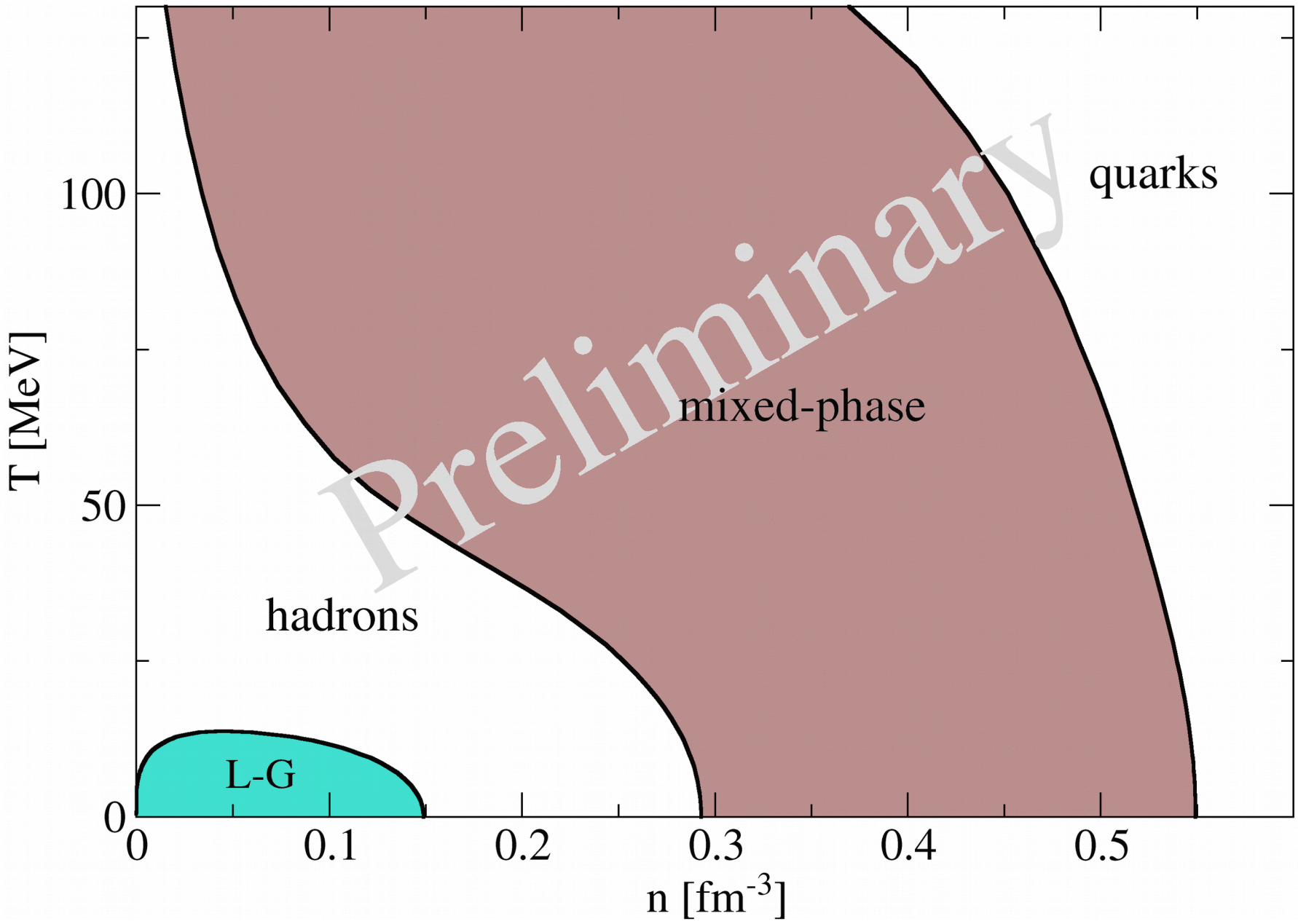
Results


quarks
mixed-phase
hadrons
L-G
Preliminary
T [MeV]
100
50
0
0
0.1
0.2
0.3
0.4
0.5
n [fm^{-3}]

Last Slide

Conclusions

- A first order phase-transition with a big latent heat would result in measurable signals
- Further investigations needed to predict possible scenarios
- Future experiments will provide necessary data.

Outlook

- Fixing parameters and tabulation of data for supernova simulations is in progress
- Adding confined gluons to fit the temperature behavior
- Tabulation of data for HIC simulation and NS-NS merger

Collaboration

- David Blaschke, Tobias Fischer, Stefan Typel, Gerd Röpke, Mark Kaltenborn, Yuri Ivanov

Thank you!