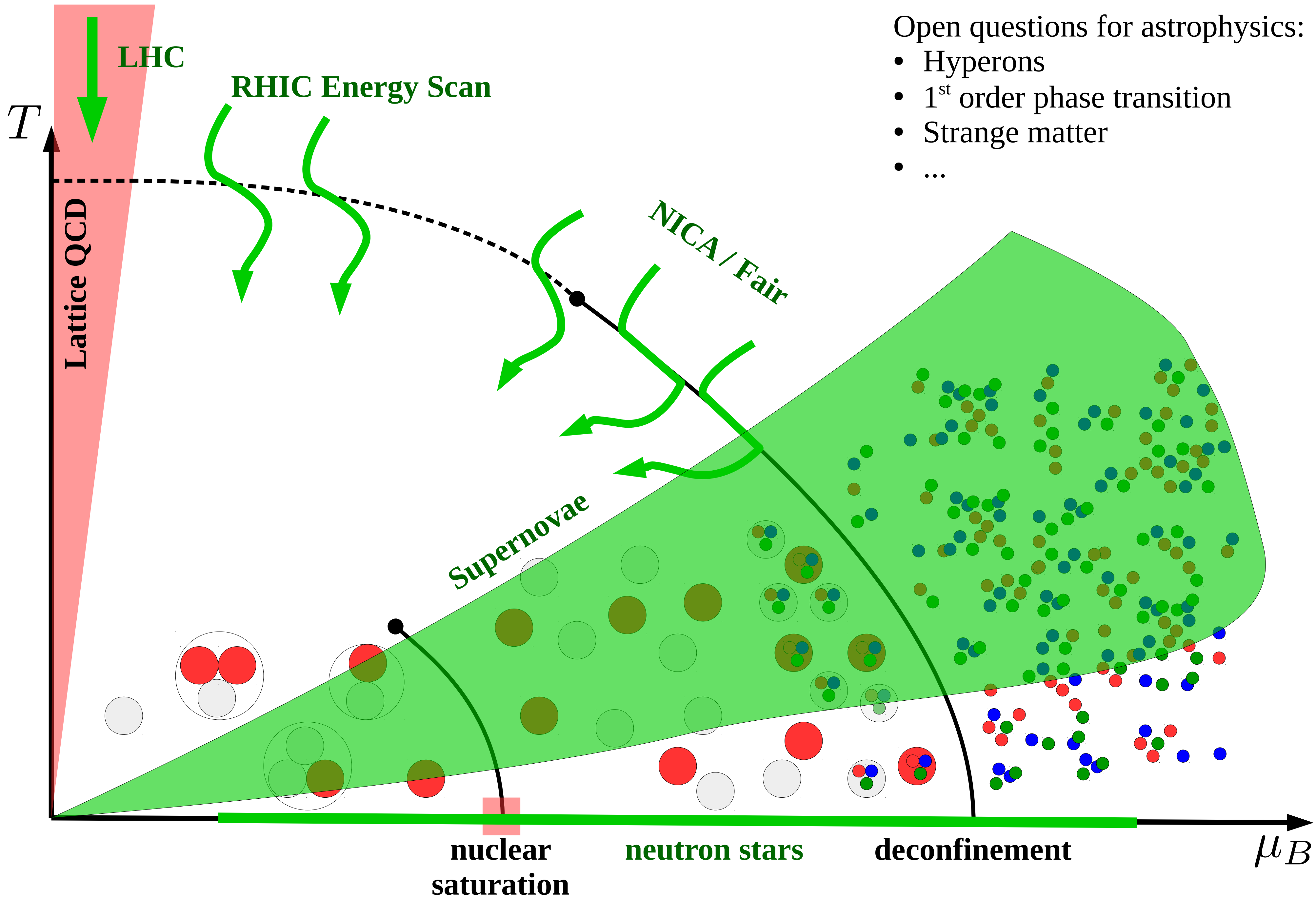
Equation of state of high-density matter

Niels-Uwe Friedrich Bastian
University of Wroclaw, Institute of Theoretical Physics

Bonn, 12. December 2017

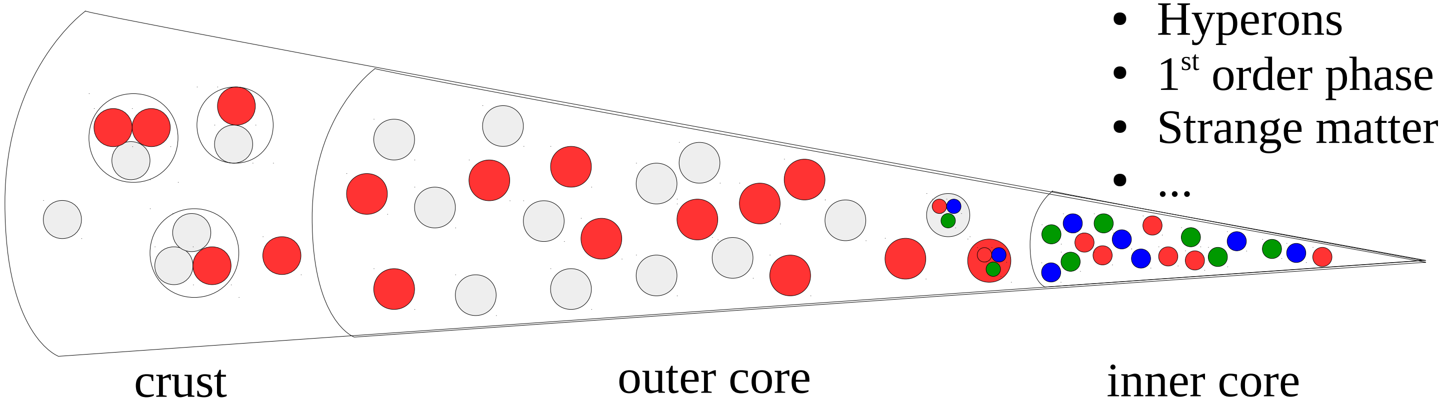
Uniwersytet Wrocławski

Strongly interacting matter



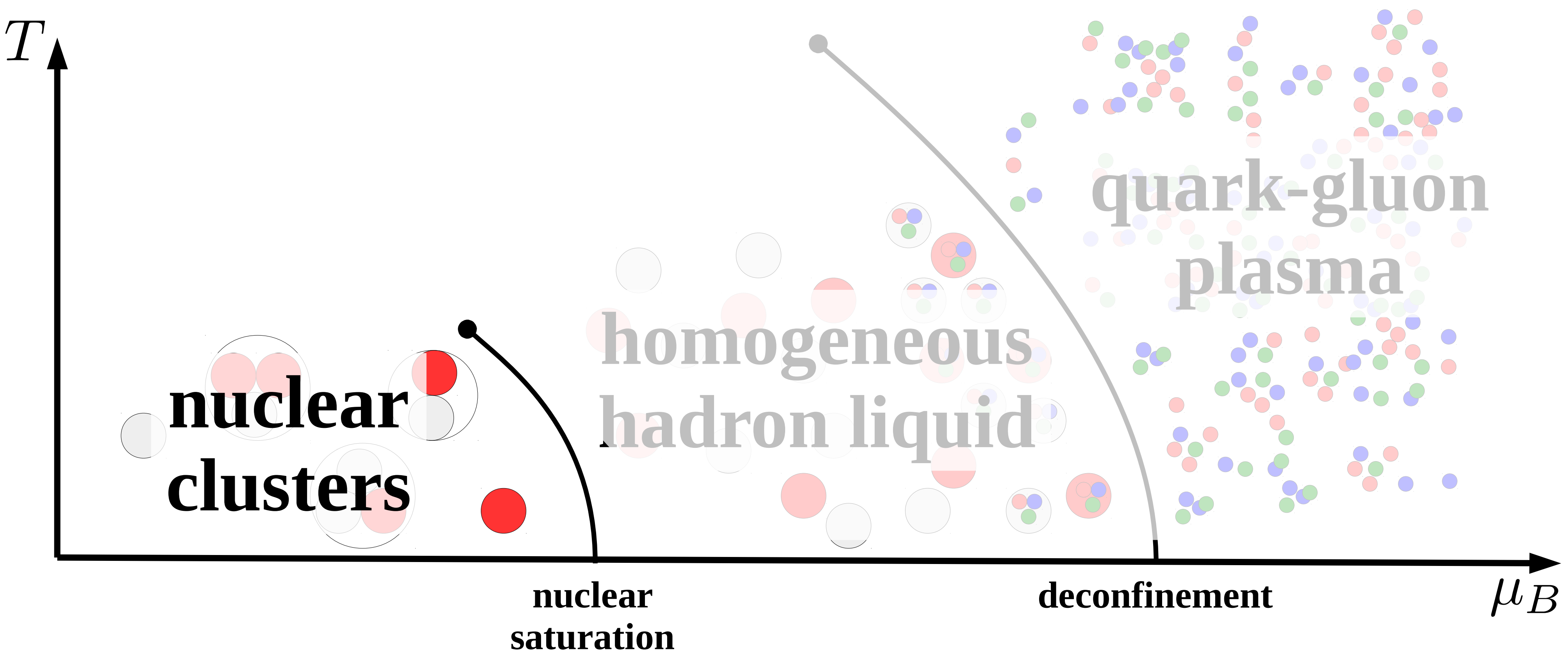
Open questions for astrophysics:

- Hyperons
- 1st order phase transition
- Strange matter
- ...

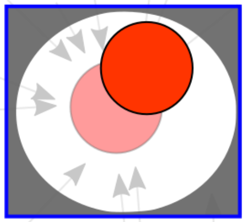


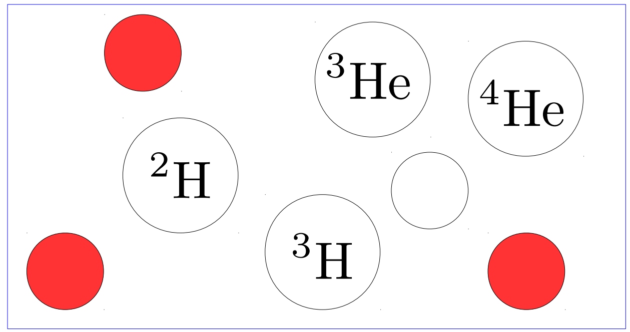
Open questions for astrophysics:

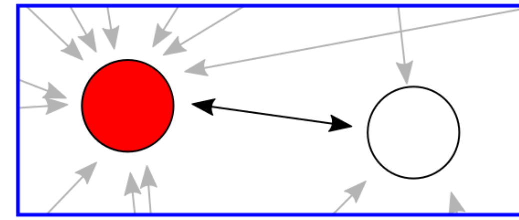
- Hyperons
- 1st order phase transition
- Strange matter
- ...



(light) Nuclear clusters



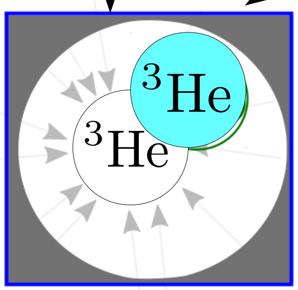


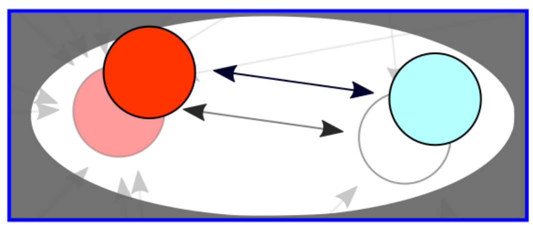


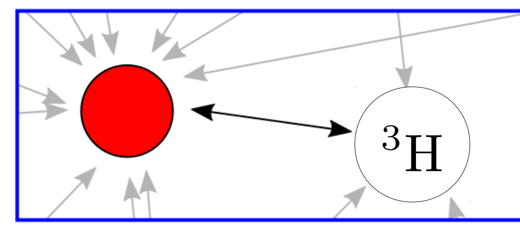
- medium modification of free particles
- selfenergy

- ideal mixture and chemical picture
- NSE

- virial expansion and two-particle correlation
- Beth-Uhlenbeck formula



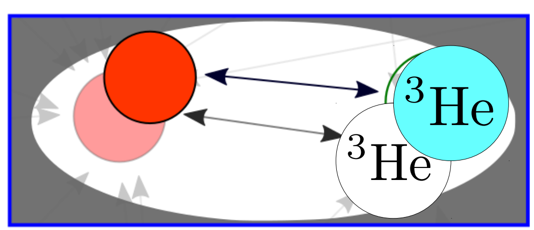




- Cluster-meanfield
- Cluster selfenergy, screening and Pauli blocking

- medium modifications of particles and correlations
- GBU

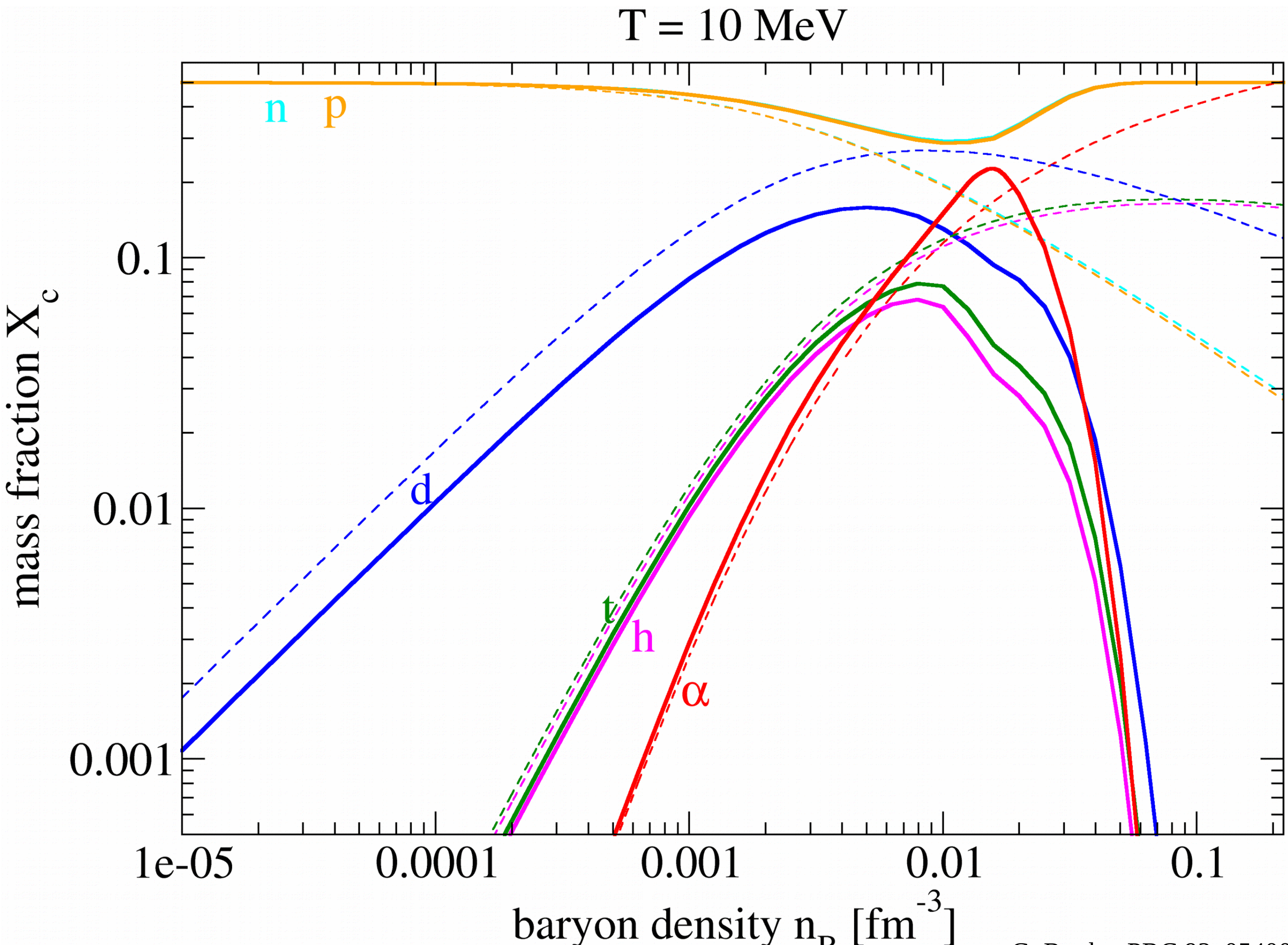
- Cluster-virial expansion



- cluster-virial expansion with medium effects

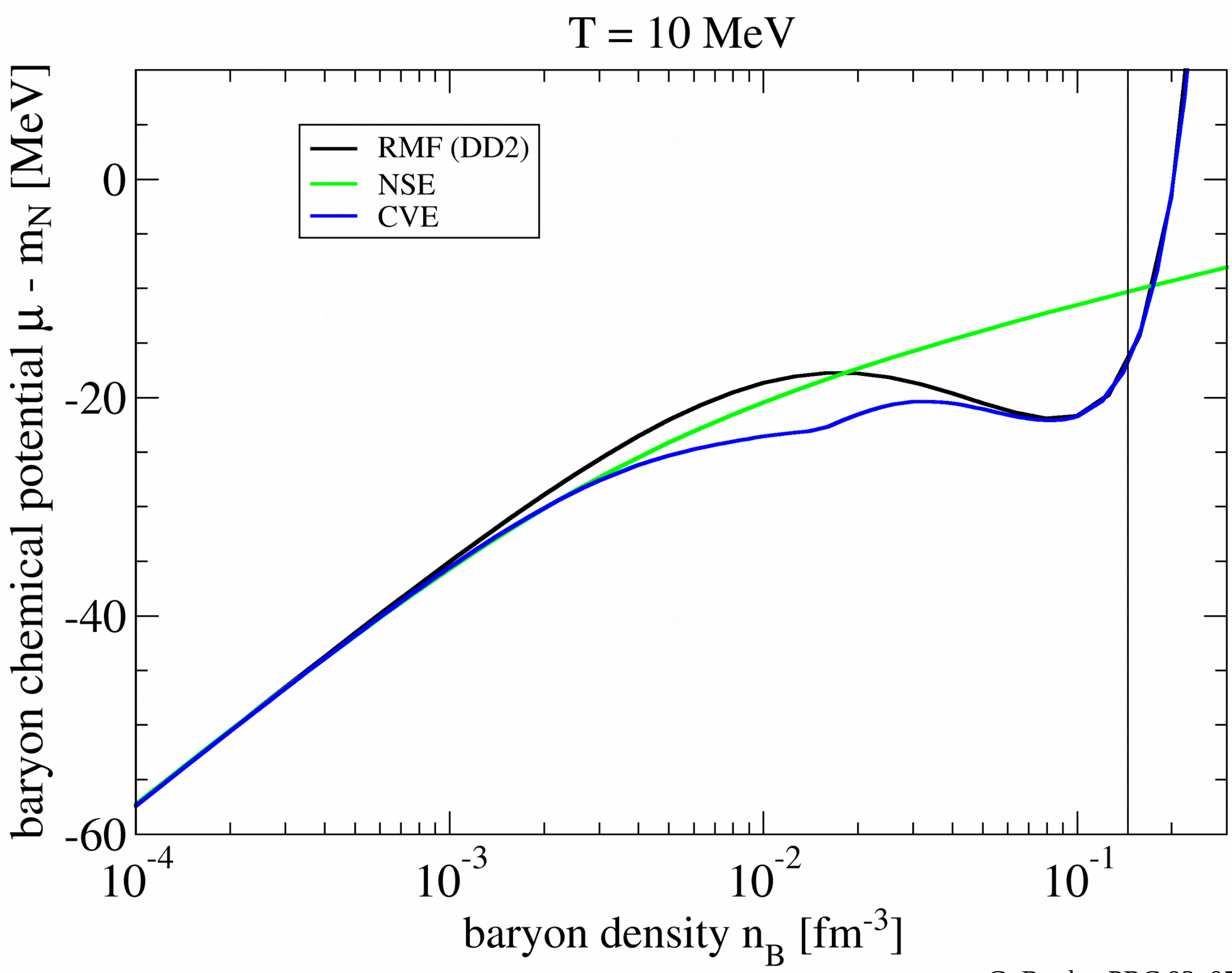
G. Ropke, N.-U. Bastian, D. Blaschke, T. Klahn, S. Typel and H.~H. Wolter, Nucl. Phys. A **897**, 70 (2013)

(light) Nuclear clusters

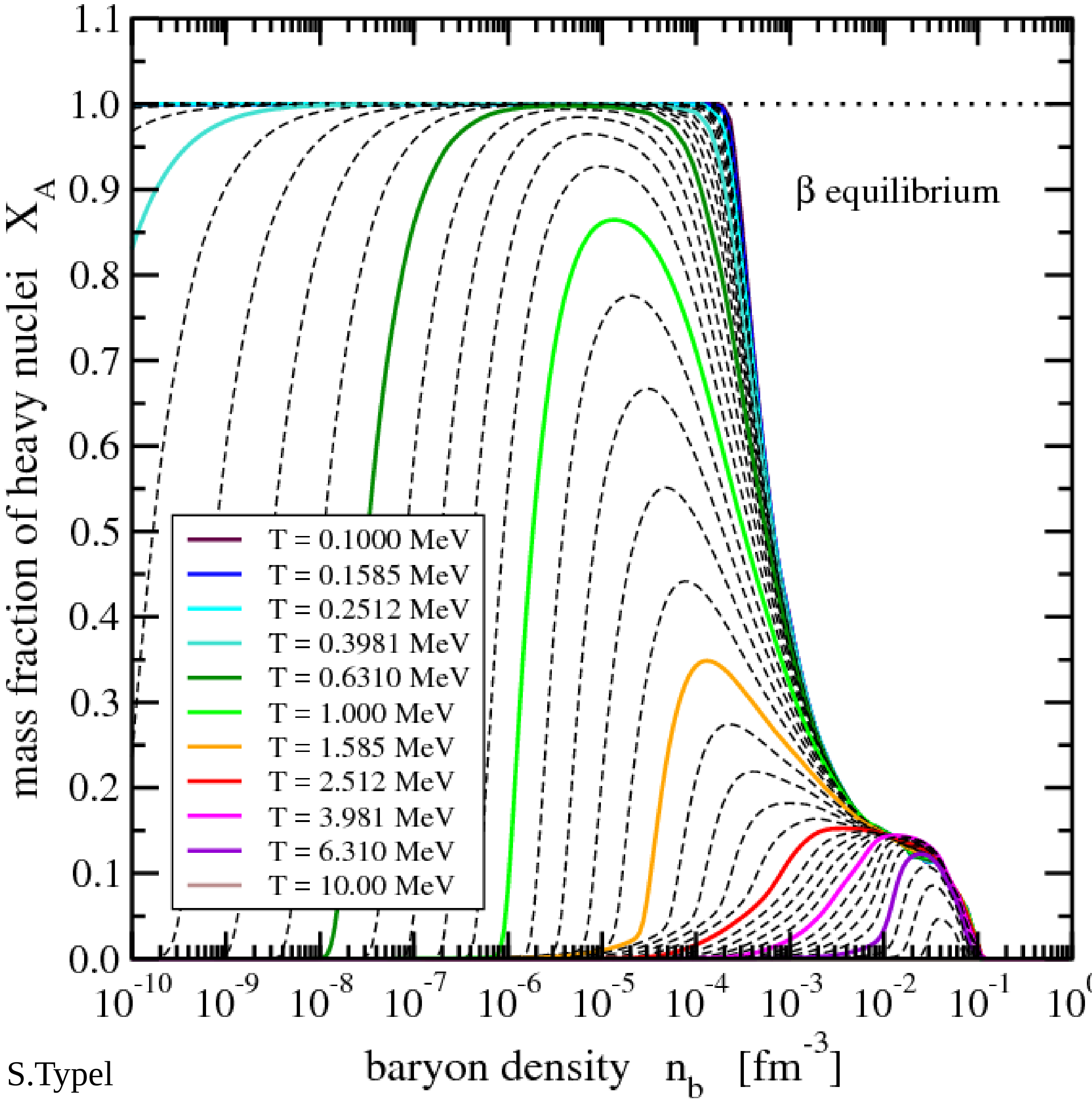


G. Ropke, PRC 92, 054001 (2015)

(light) Nuclear clusters

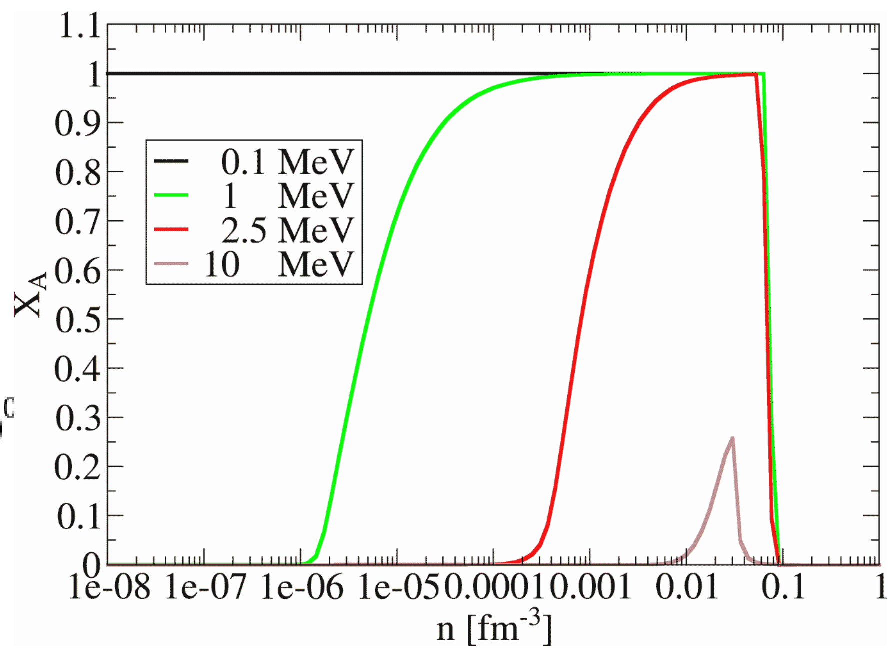


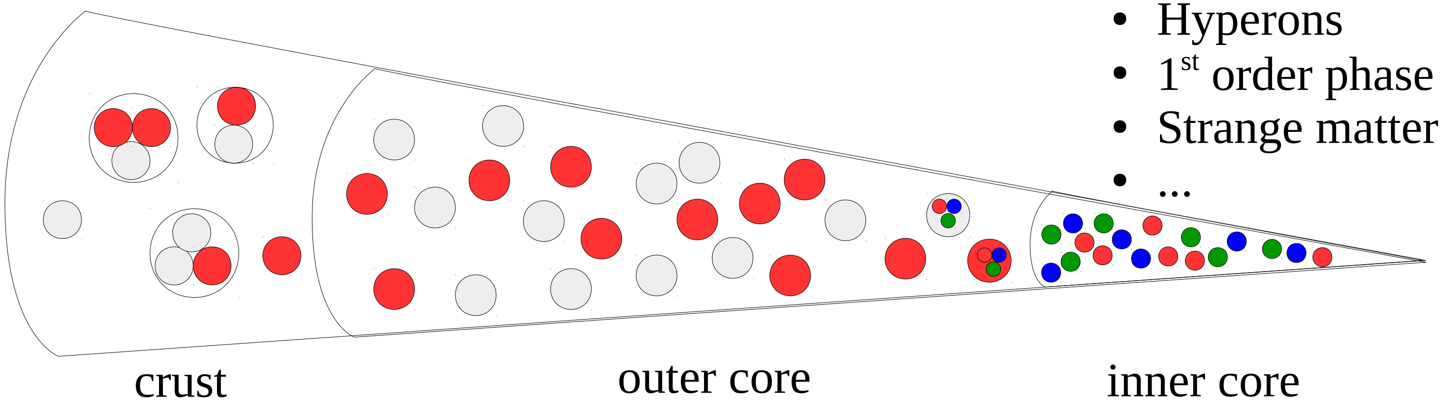
G. Ropke, PRC 92, 054001 (2015)



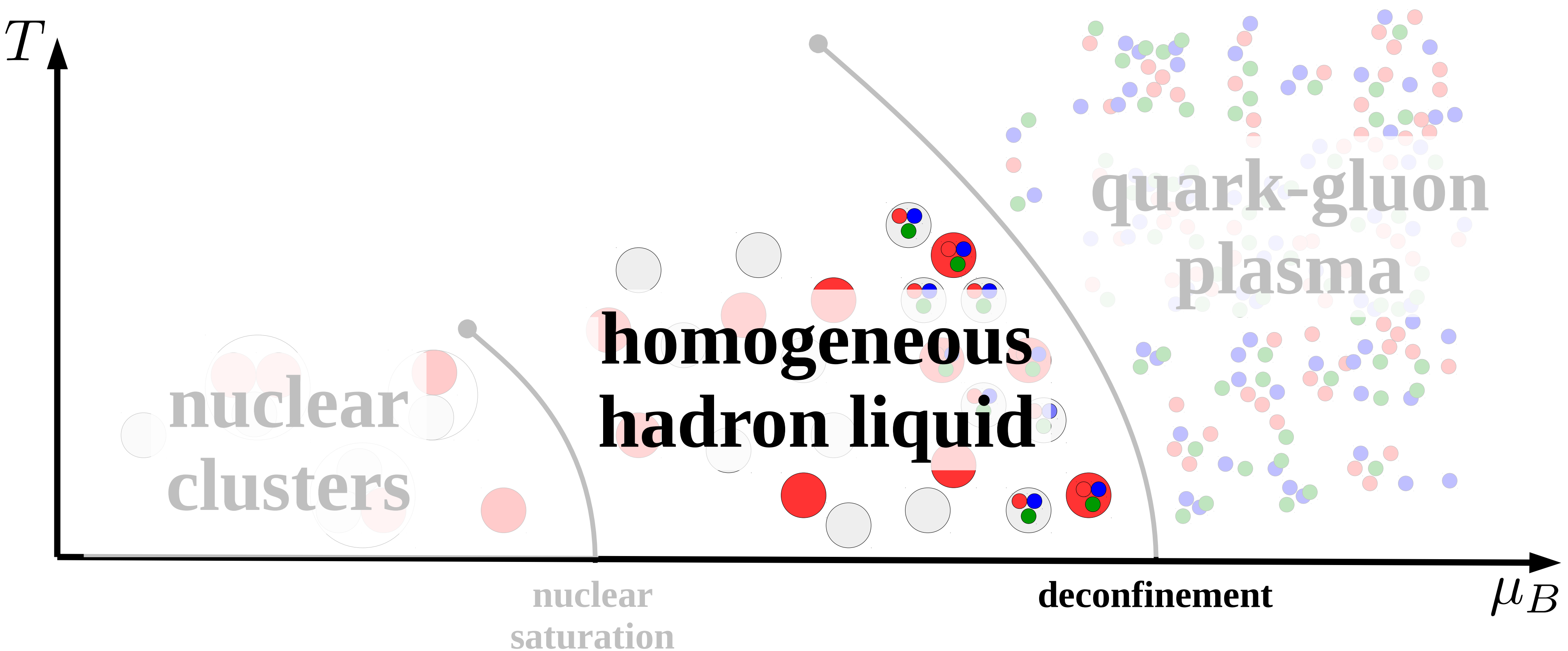
S.Typel

- Simple NSE with excluded volumen highly overestimates heavy clusters



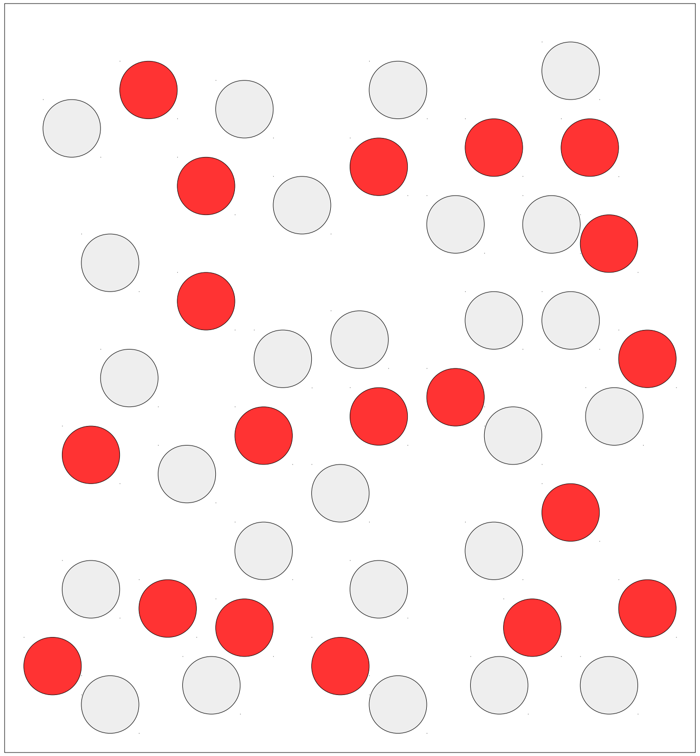


Open questions for astrophysics:
- Hyperons
- 1st order phase transition
- Strange matter
- ...

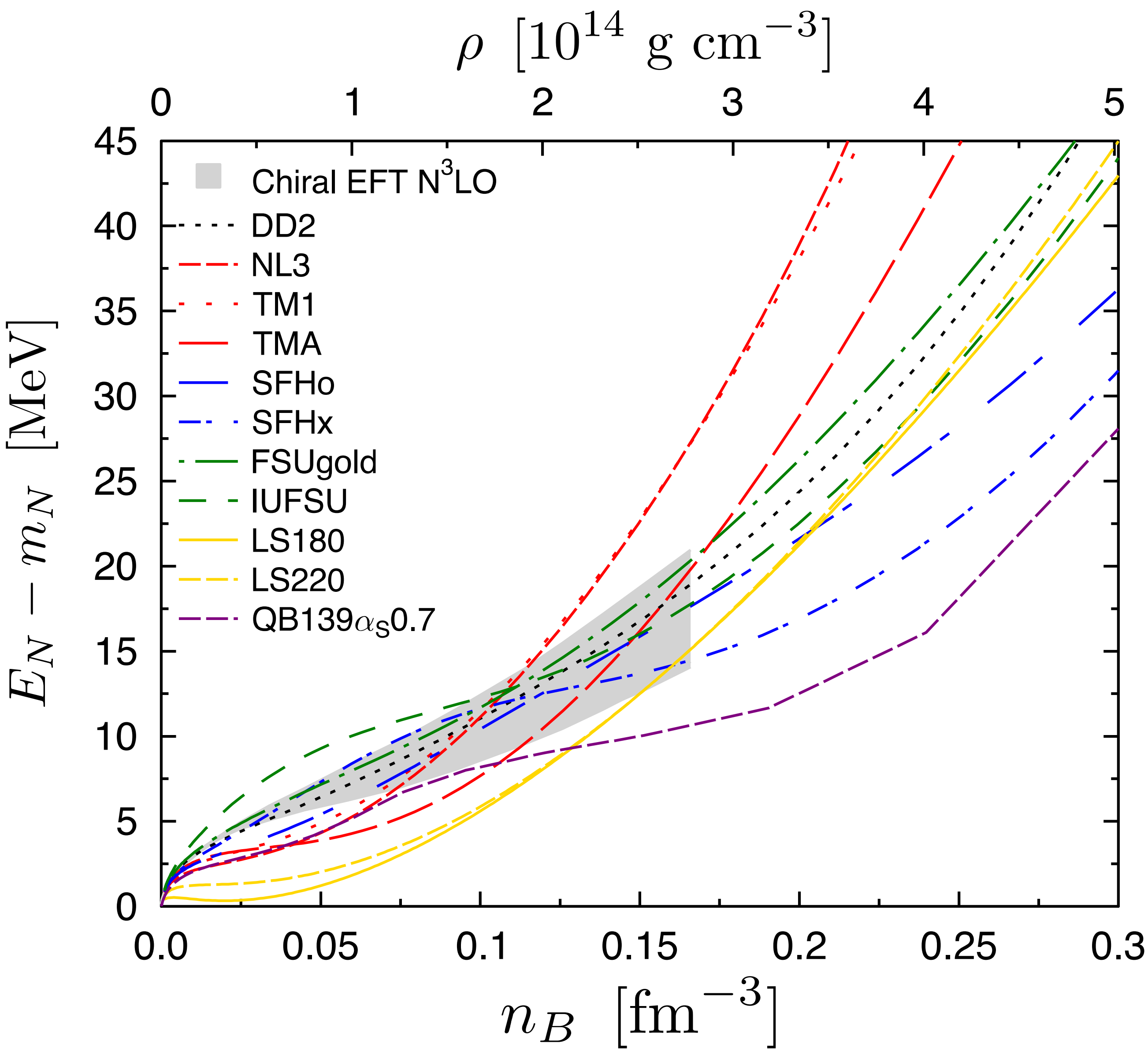


Homogeneous nuclear matter

- No clusters due to Pauli blocking
- Mean-field dominates
- Variety of relativistic and non-relativistic models
- Parameters usually adjusted to nuclear data
- Feature a first-order phase transition for liquid-gas transition with critical endpoint.



Constraints up to saturation density

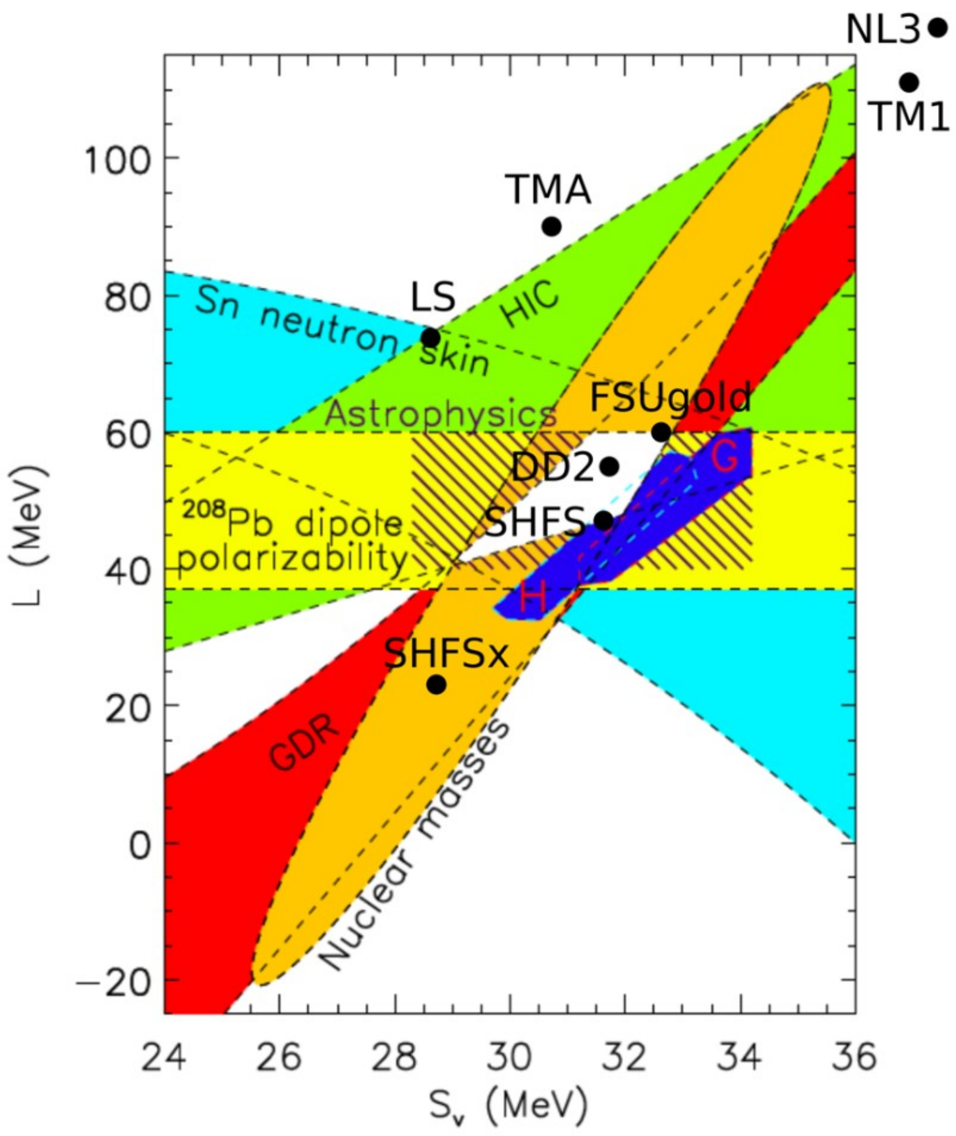


- Chiral effective field theory
- Ab initio calculation for pure neutron matter at $n \lesssim n_0$
-
-

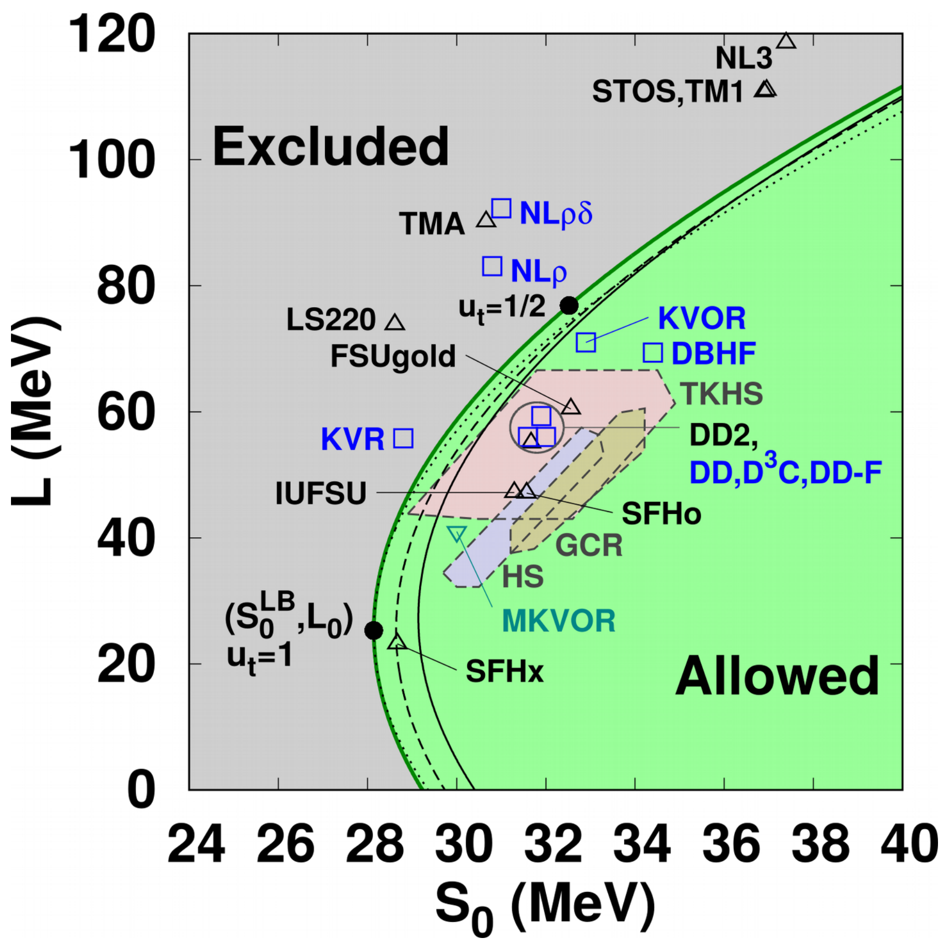
T. Fischer, et. al., (2014) EPJA50, 46

Constraints at saturation density

Symmetry energy

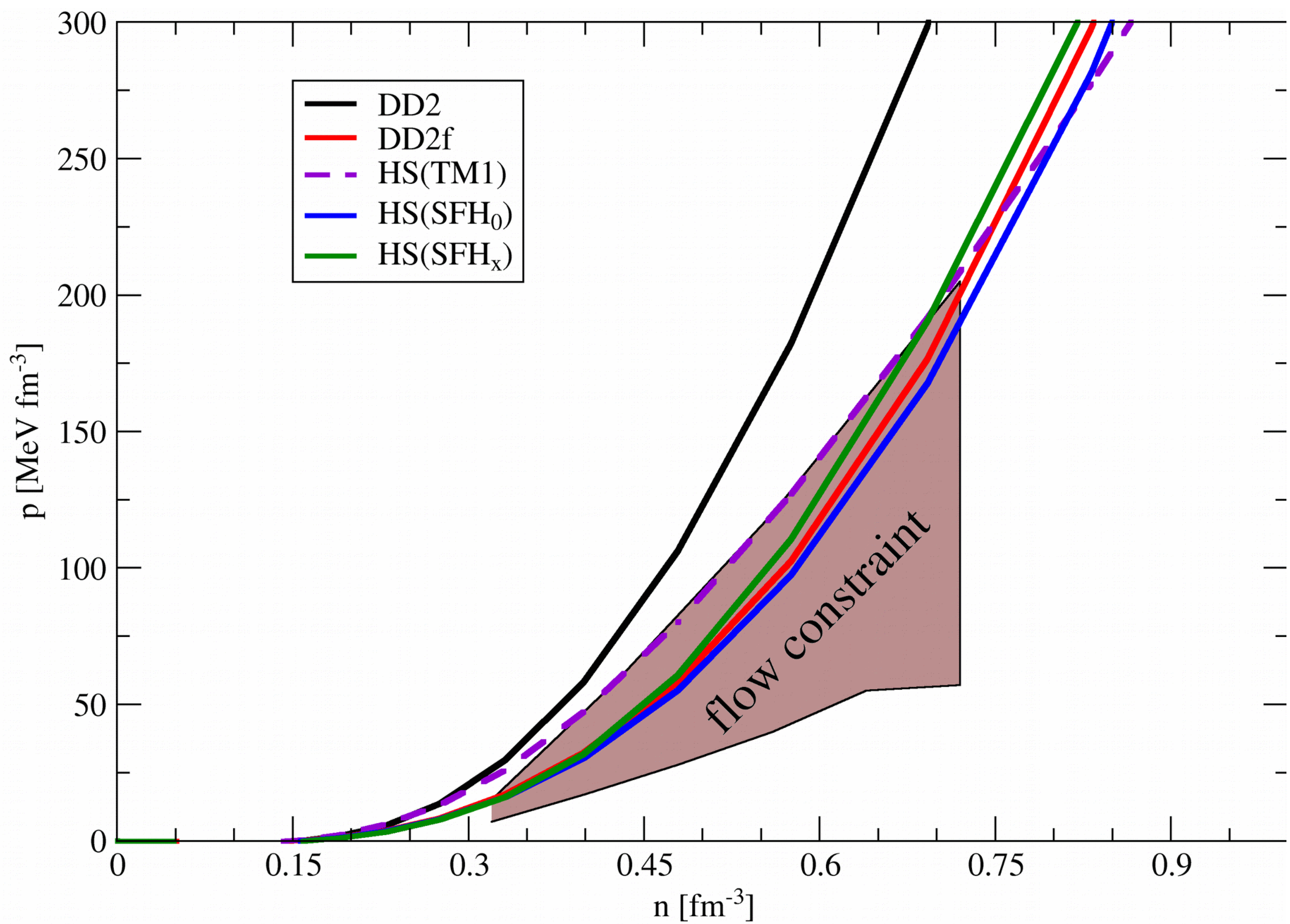


Unitary Constraint



Lattimer & Lim (2013) ApJ 771, 14
Tews, Lattimer, Ohnishi, Kolomeitsev, arXiv:1611.07133

Constraints above saturation density

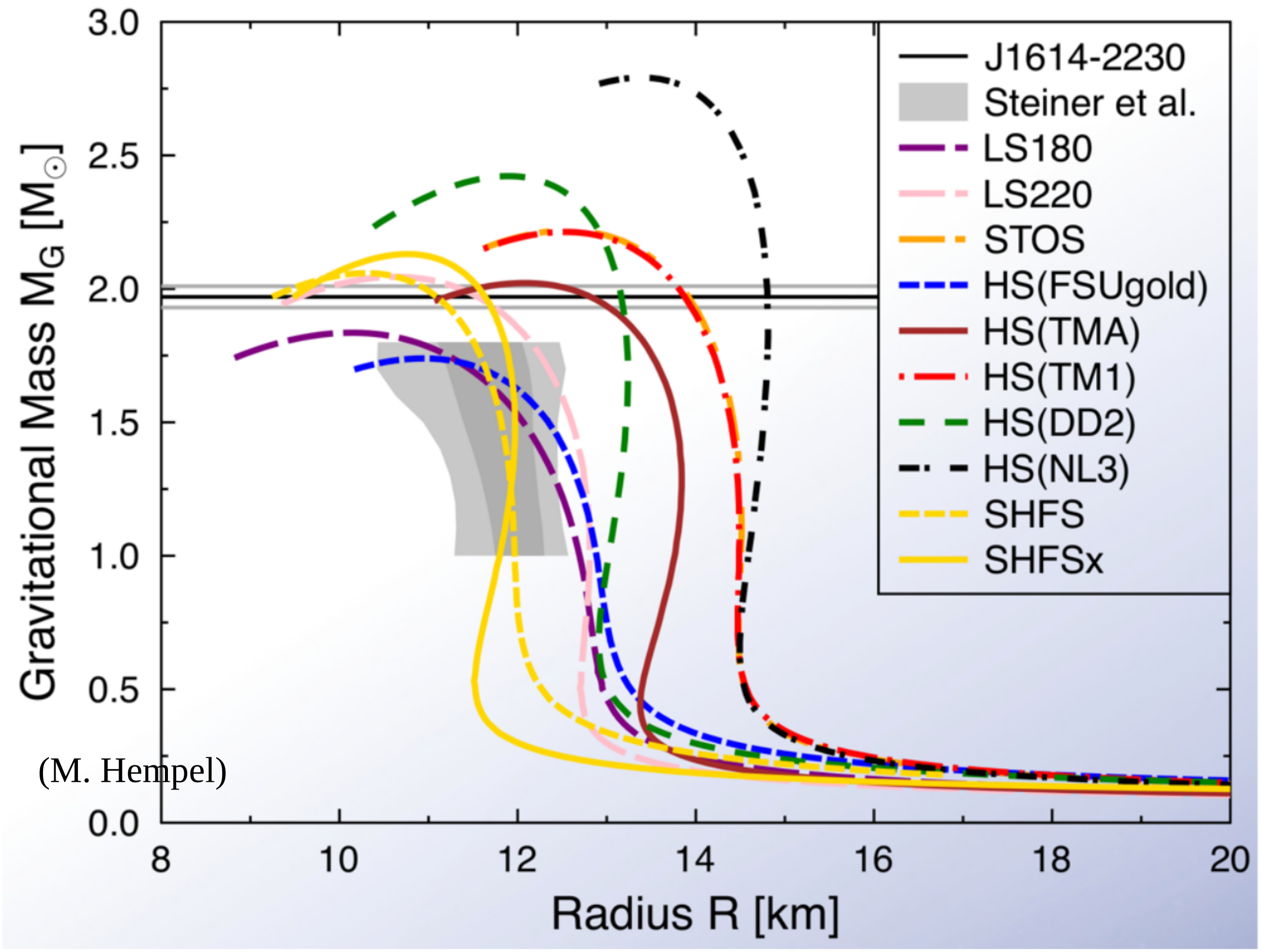


Flow constraint

- Rules out to stiff EoS

P. Danielewicz, et.al., Science **298** (2002) 1592

Constraints above saturation density



(M. Hempel)

Massive precisely measured neutron star

$$M = (2.01 \pm 0.04) M_\odot$$

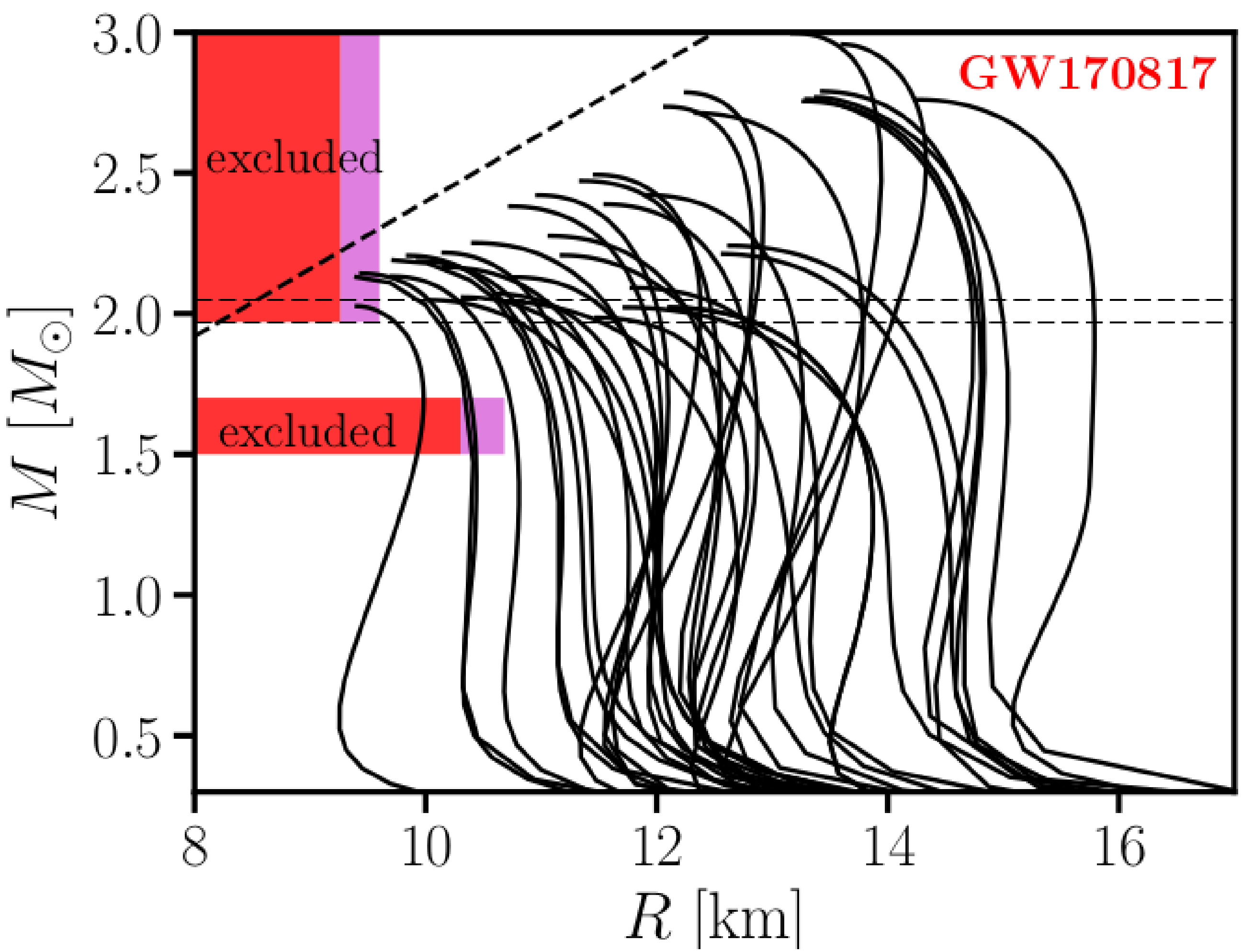
and

$$M = (1.97 \pm 0.04) M_\odot$$

- Any EoS must reproduce them!

J. Antoniadis et al., Science 340, 1233232 (2013)
P. Demorest et al., Nature (London) 467, 1081 (2010)

Constraints above saturation density

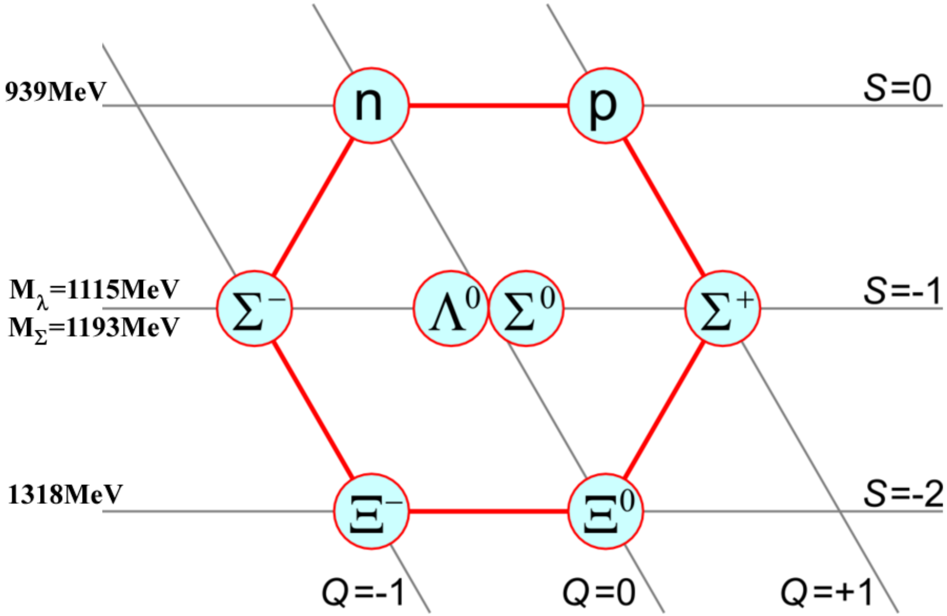


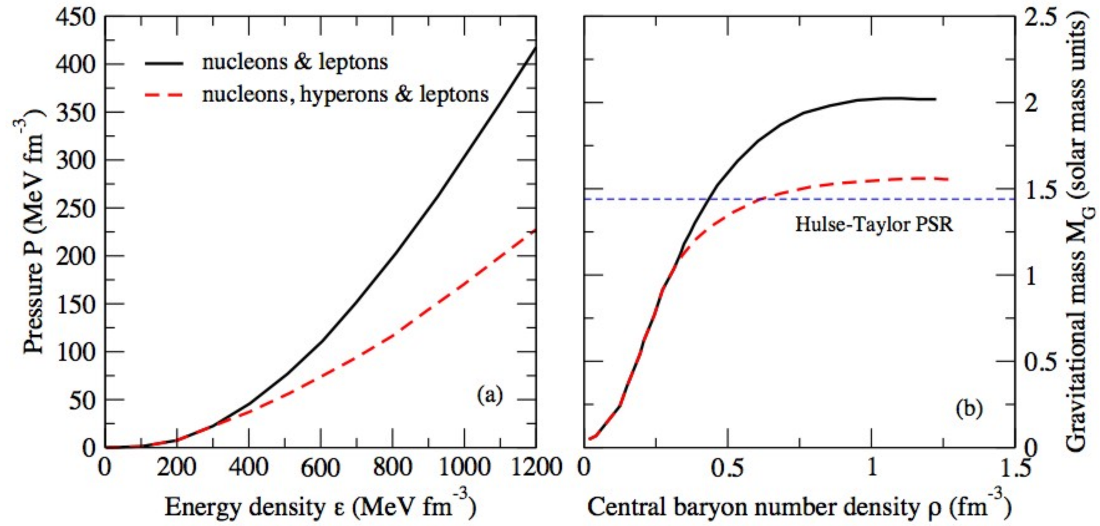
Constraints by GW of neutron star mergers

- Radius of $M = 1.6 M_\odot$ $R \geq 10.30\text{km}$
- Radius of maximal mass $R \geq 9.26\text{km}$

A. Bauswein et.al., arXiv:1710.06843v2

Hyperon Puzzle





COMPSTAR

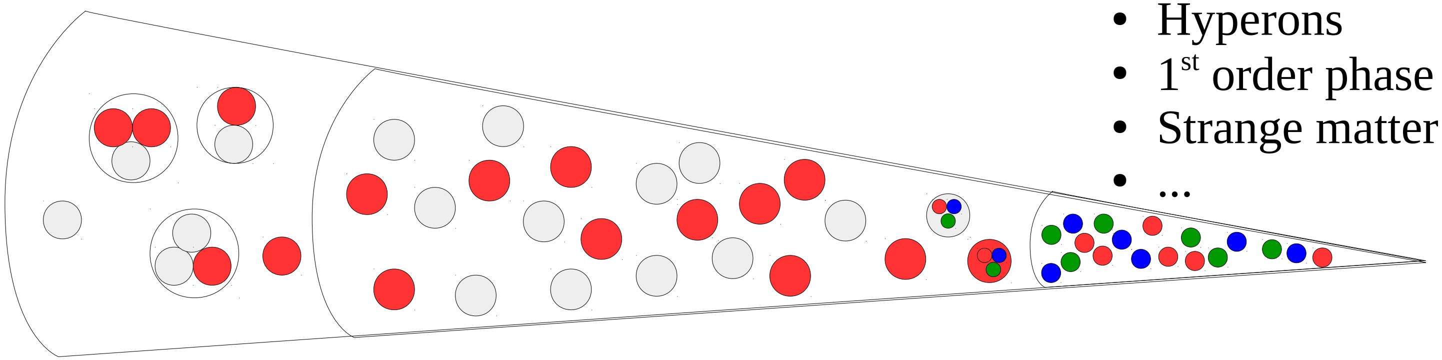
- RMF with ϕ coupling causes repulsion

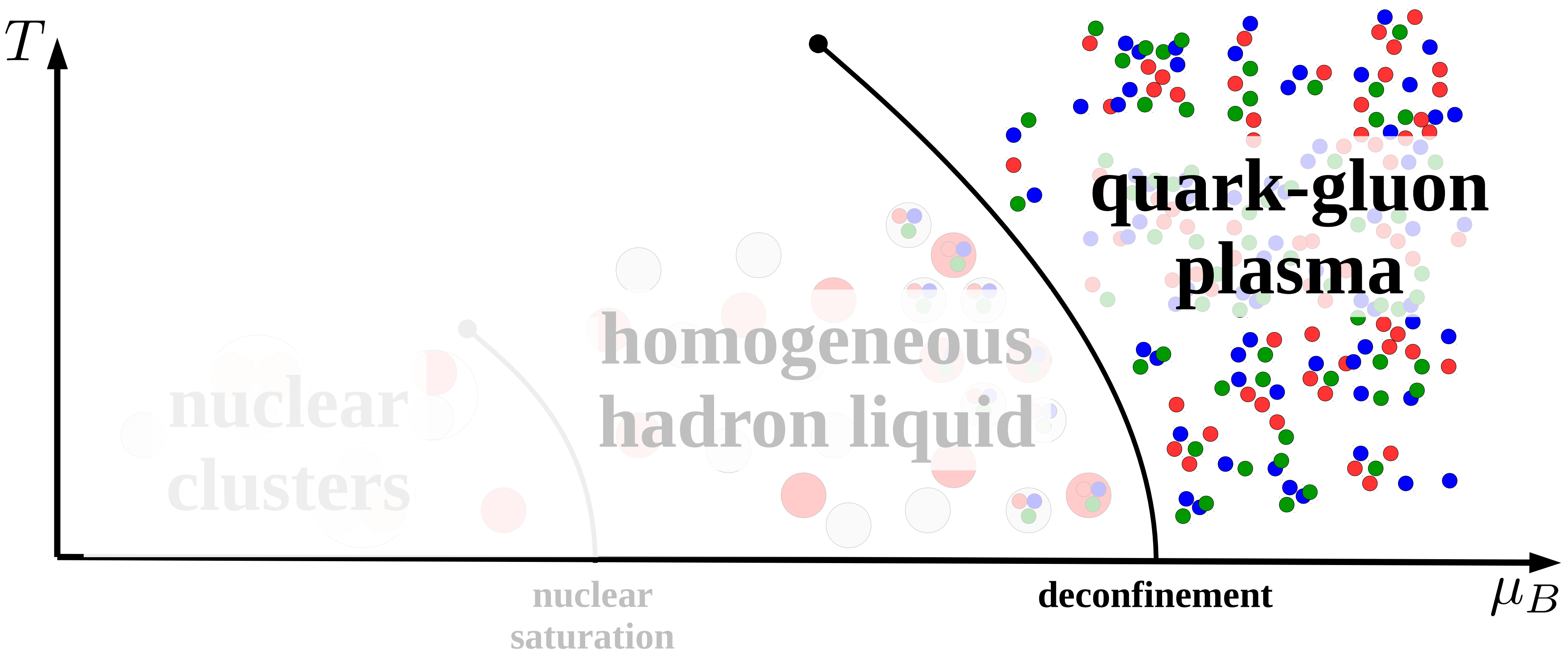
$$\mathcal{L} \sim \bar{\Psi}\Gamma_\Phi \Phi \Psi + \dots$$

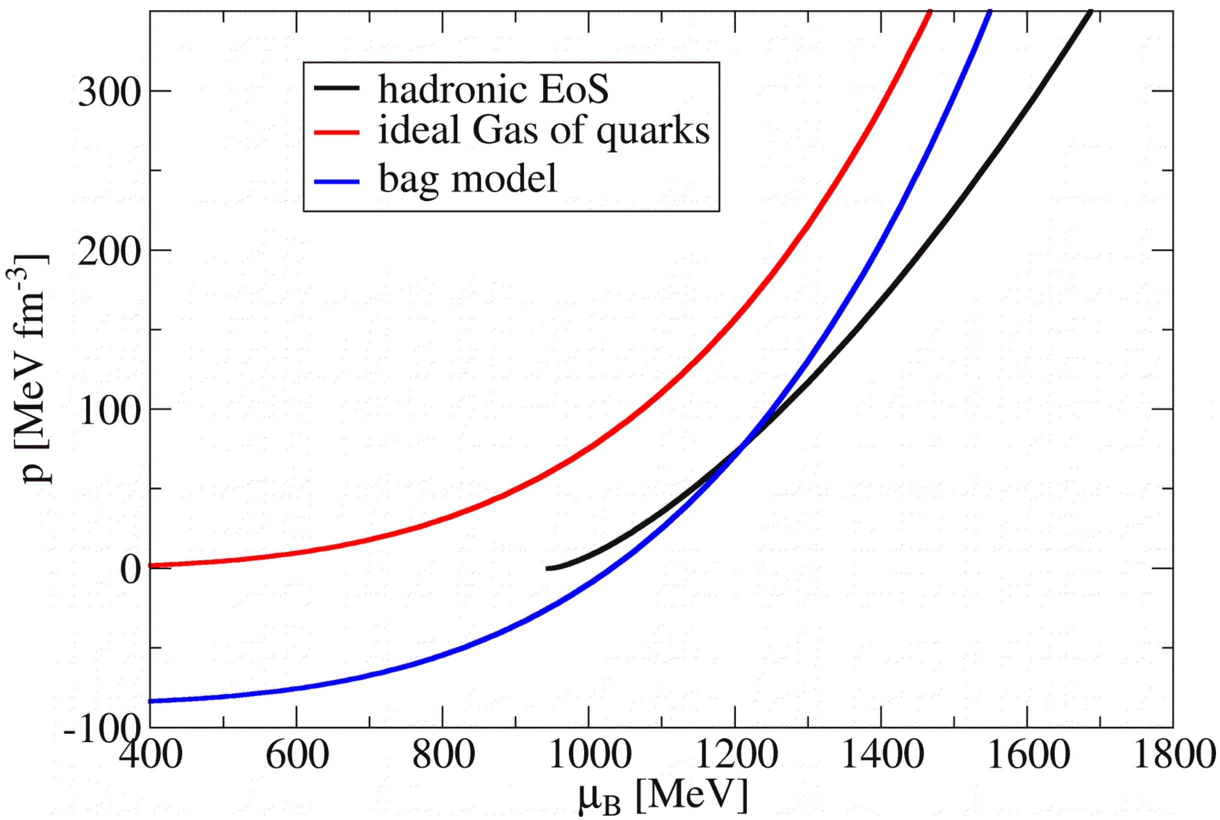
- QCD phase transition with stiff quark EoS

Outline

Open questions for astrophysics:
- Hyperons
- 1st order phase transition
- Strange matter
- ...

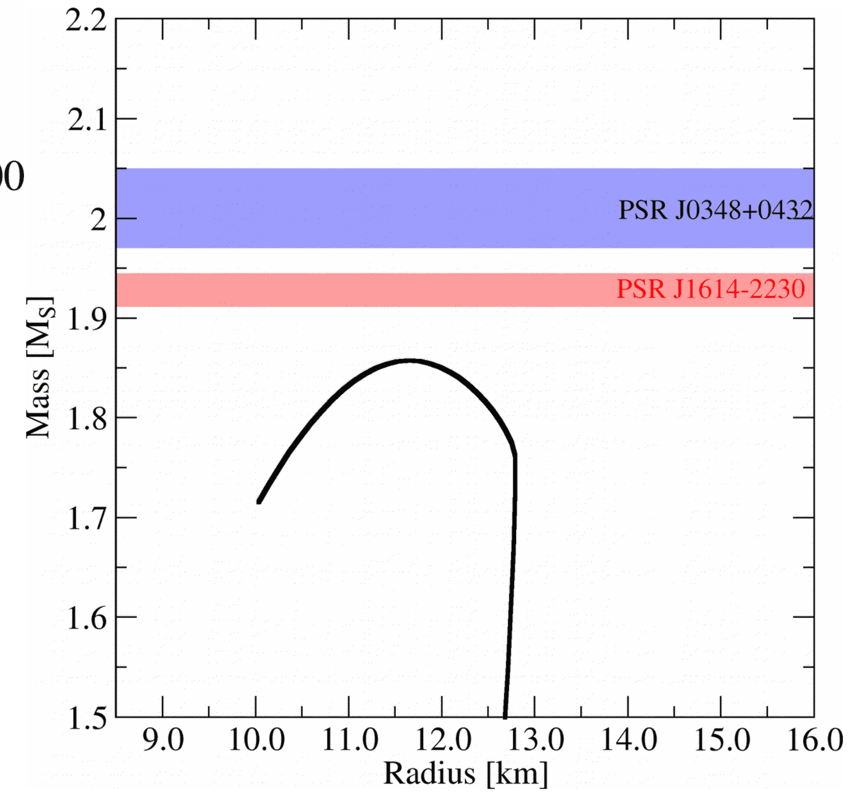




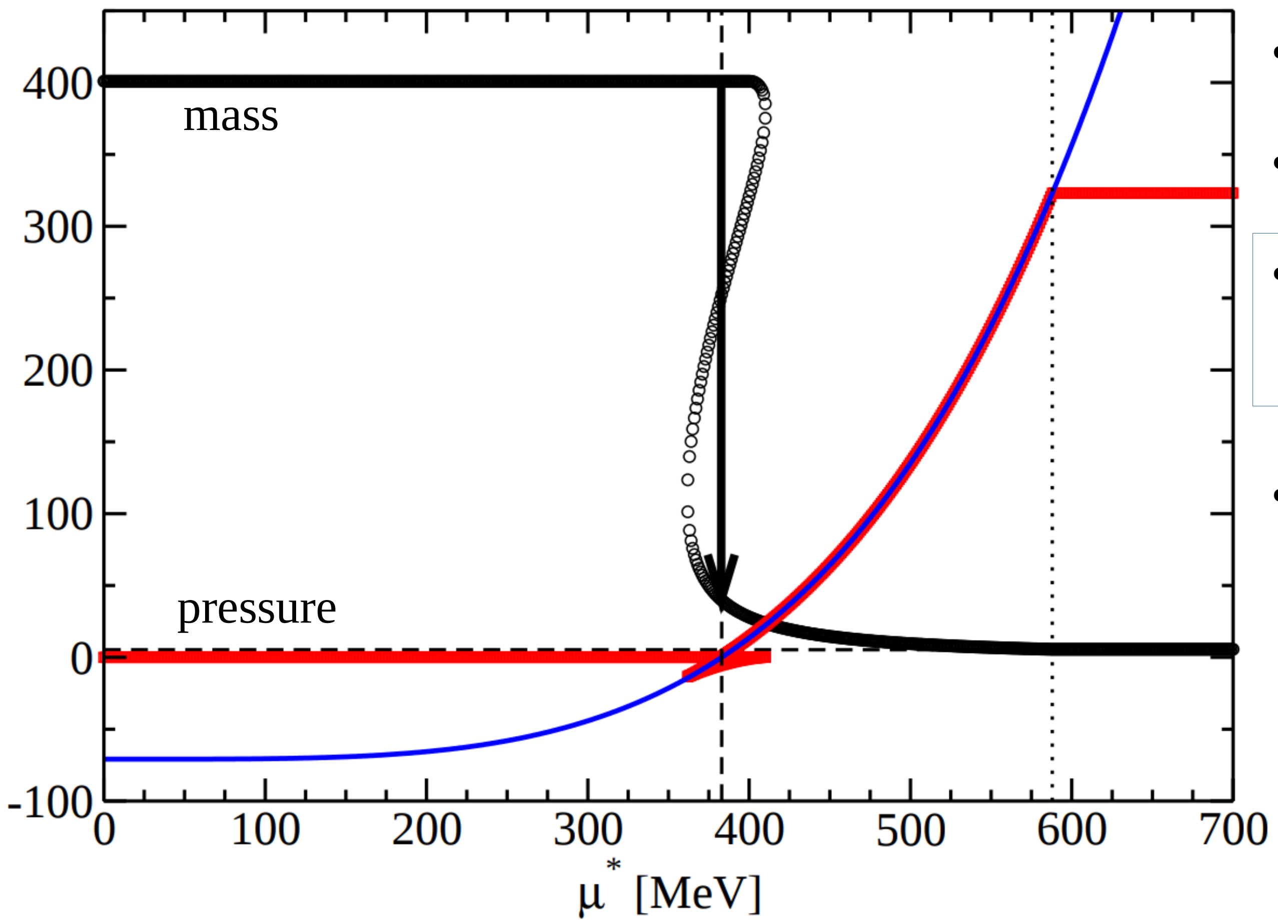


- Ideal gas for quarks
- Added constant "Bag" constant to mimic confinement

- Does not sustain the neutron star mass constrain



Nambu-Jona-Lasinio Models



T. Klahn and T. Fischer, APJ **810**, 2, 134 (2015)

- Effective QCD Lagrangian
- Dynamical chiral symmetry breaking
- Repulsive vector interaction

$$\Rightarrow M_{\max} > 2M_{\odot}$$

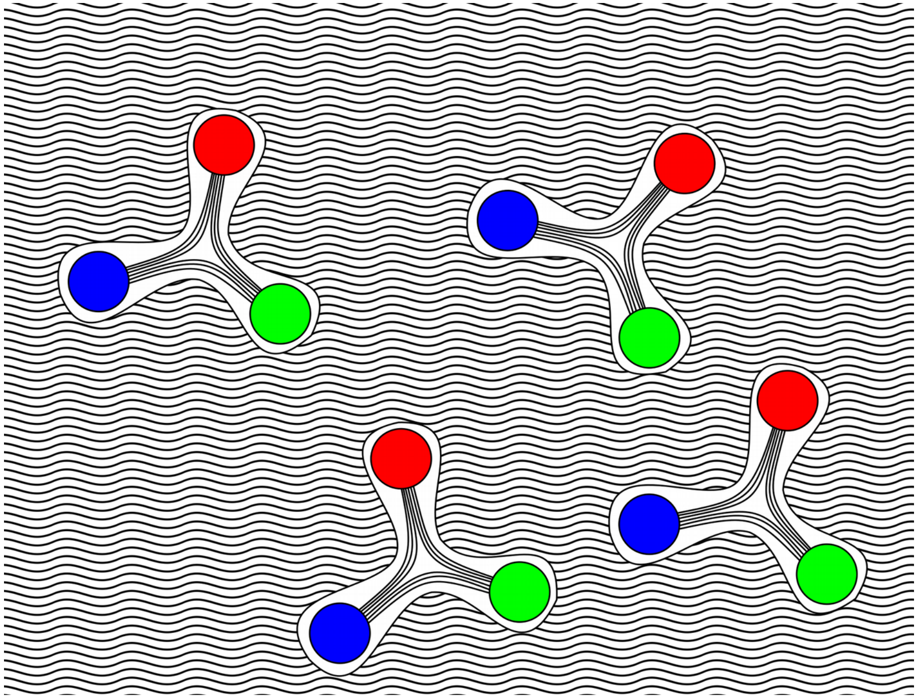
- Additional Bag constant added/
no confinement

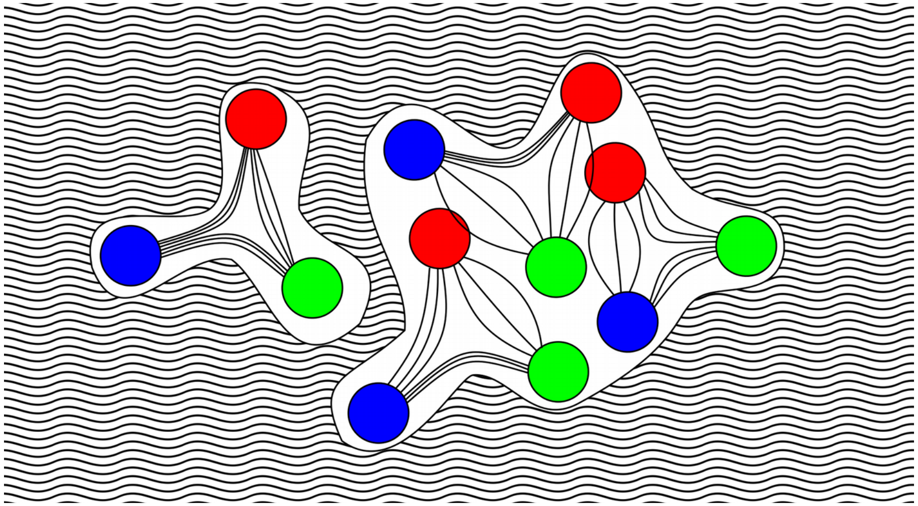
Density functional approach: Stringflip model

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

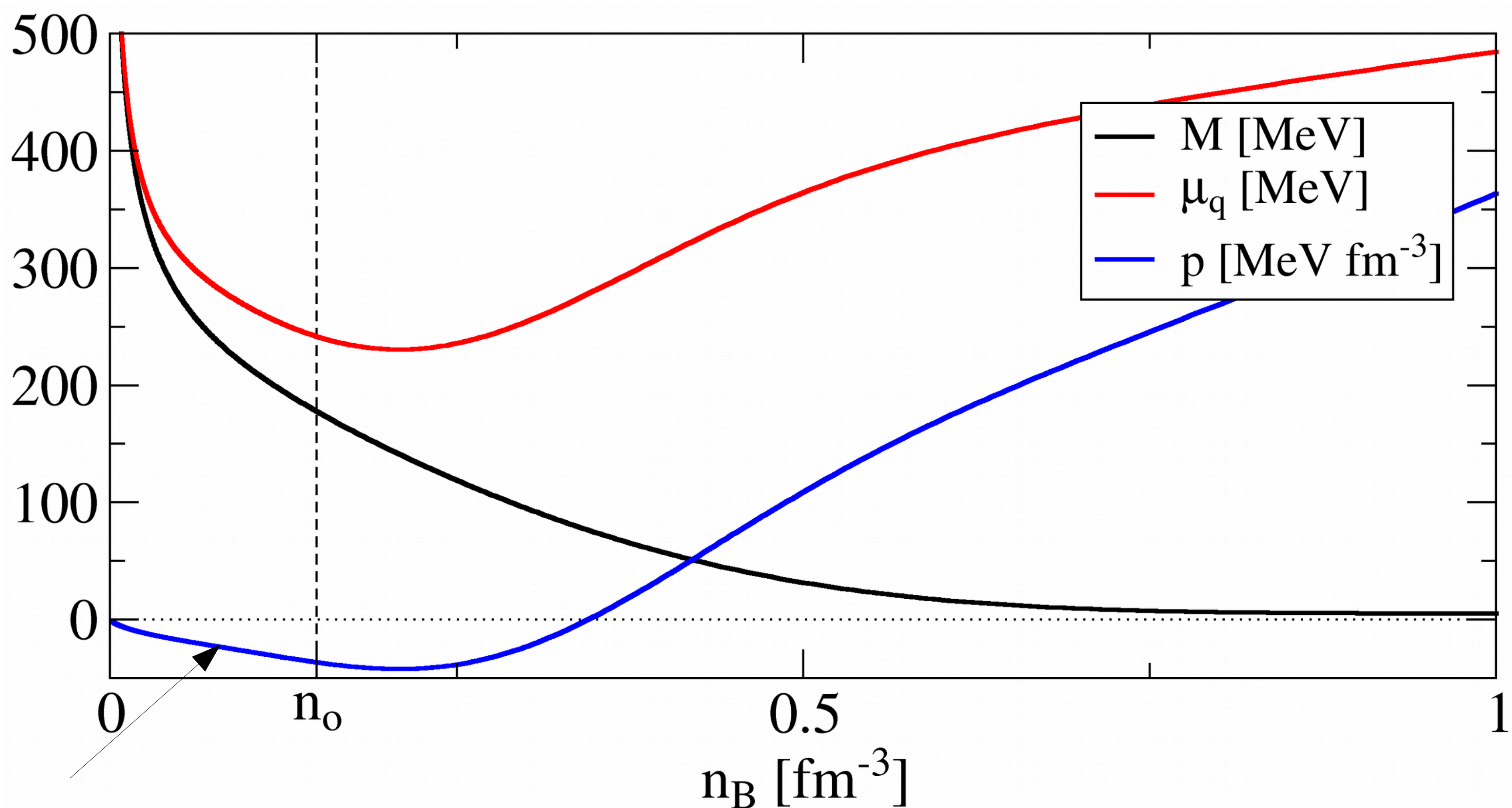
$$\sigma = \Phi\sigma_0$$

G. Ropke, et. al., Phys.Rev. D34 (1986) 3499-3513
Kaltenborn, Bastian, Blaschke, PRD 96, 056024 (2017)

Stringflip model – effective mass

Mean-field model

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

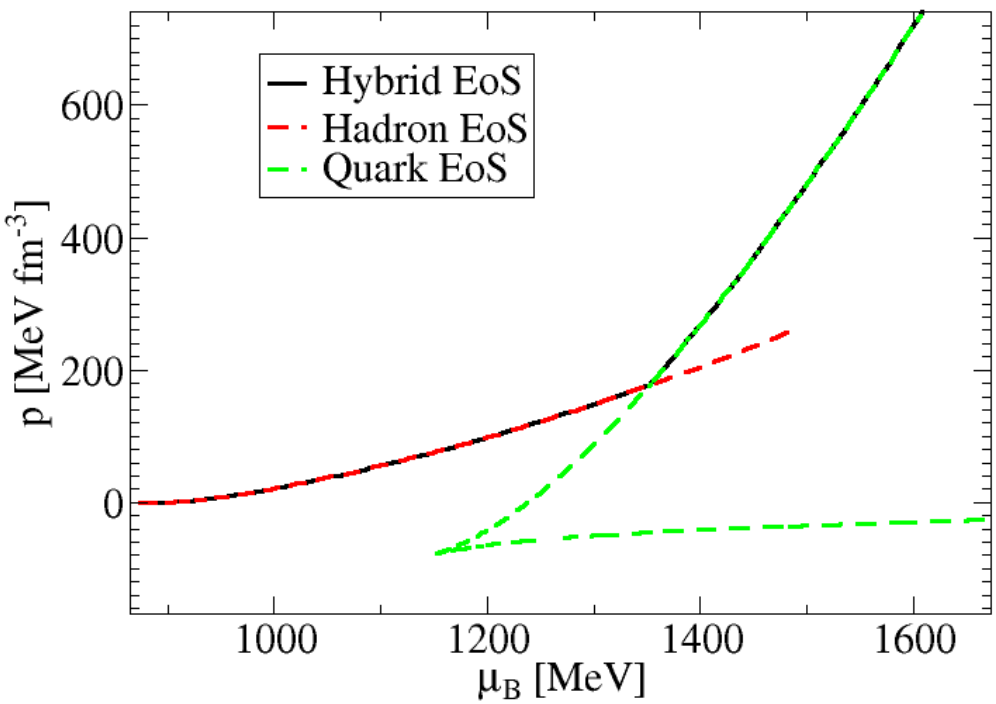


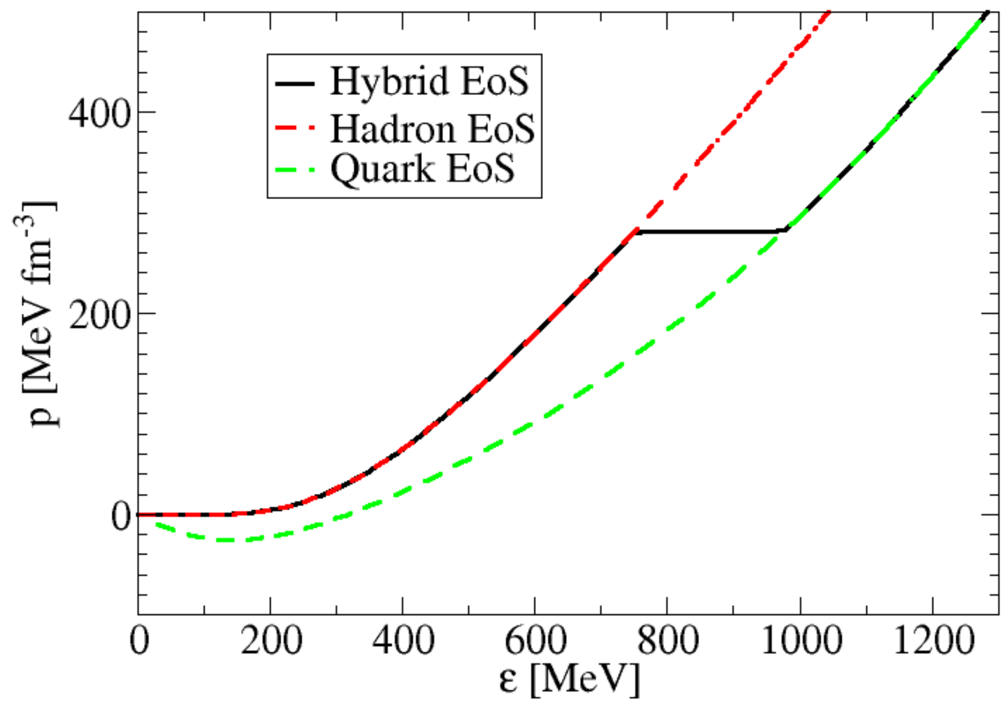
confinement

Kaltenborn, Bastian, Blaschke, PRD 96, 056024 (2017)

Hybrid EOS - phasetransition

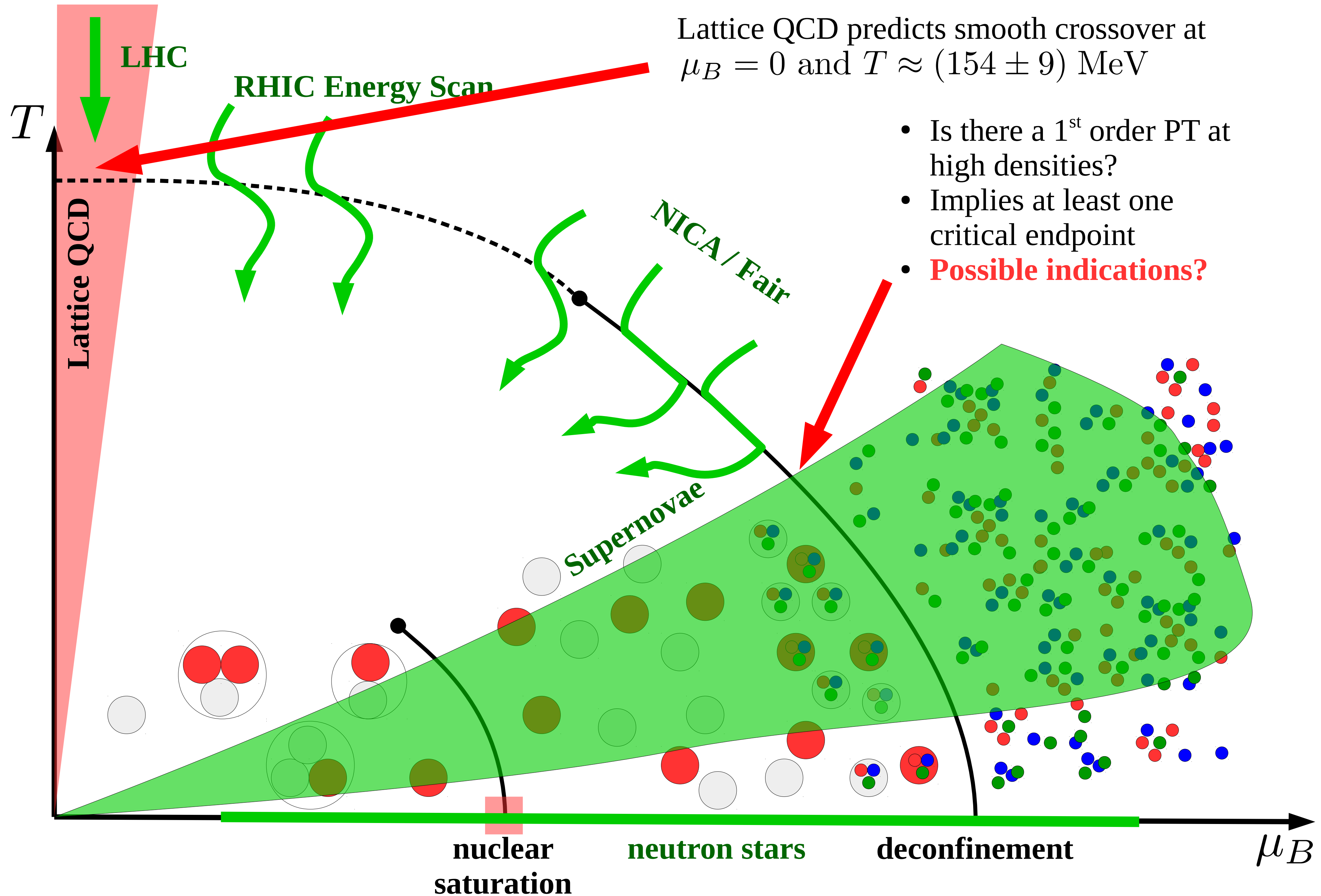
- 2-phase approach: phase transition via Maxwell construction





Kaltenborn, Bastian, Blaschke, PRD 96, 056024 (2017)

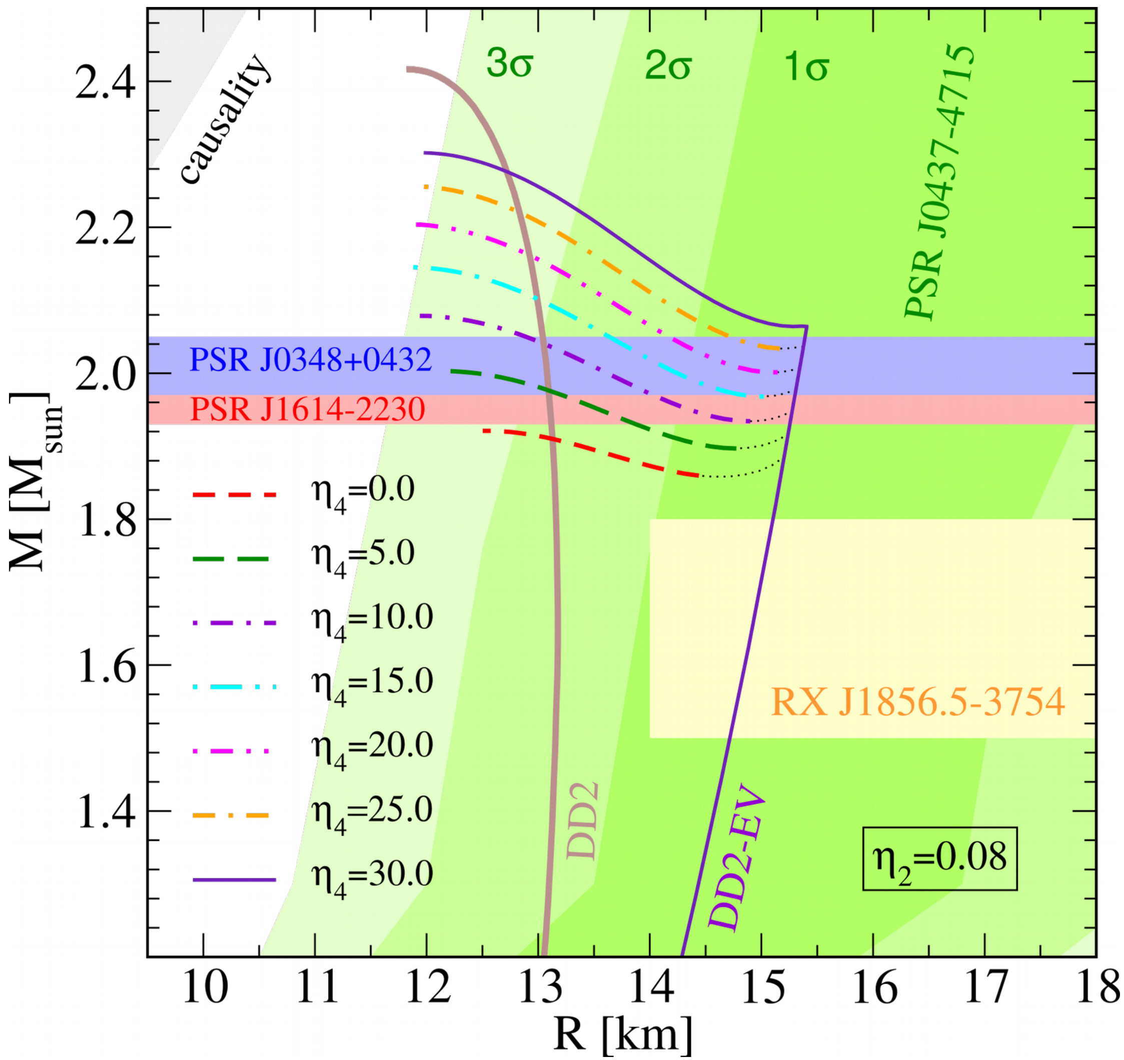
Possibility of 1st order PT at hight densities



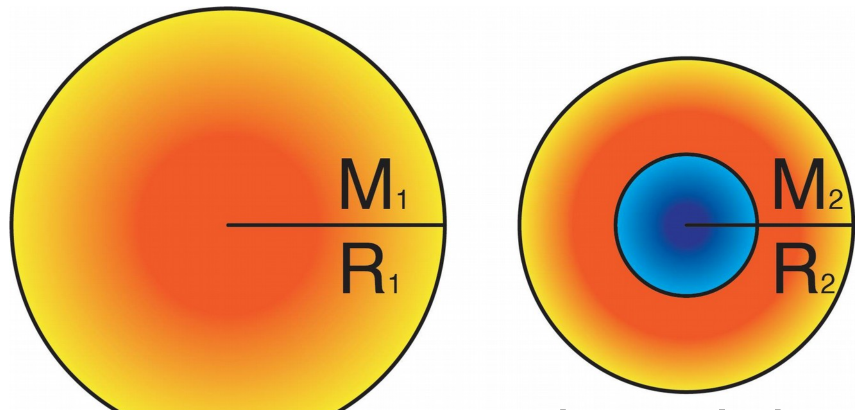
Lattice QCD predicts smooth crossover at $\mu_B = 0$ and $T \approx (154 \pm 9)$ MeV

- Is there a 1st order PT at high densities?
- Implies at least one critical endpoint
- **Possible indications?**

1st order PT - 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)

Last Slide

Conclusions

- Sub-saturated EoS is well constraint; many commonly used EoS are ruled out
- Quantum statistical description of light and heavy clusters necessary
- A first order phase-transition with a big latent heat would result in measurable signals
  - It carries the supernova of super massive stars and creates two solar mass neutron stars at birth
- Appearance of strange quark matter mostly speculative

Outlook

- Ongoing and future experiments (NICER, NICA, FAIR, GW) will provide further insights

Collaboration

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

Thank you!