Equation of state of high-density matter

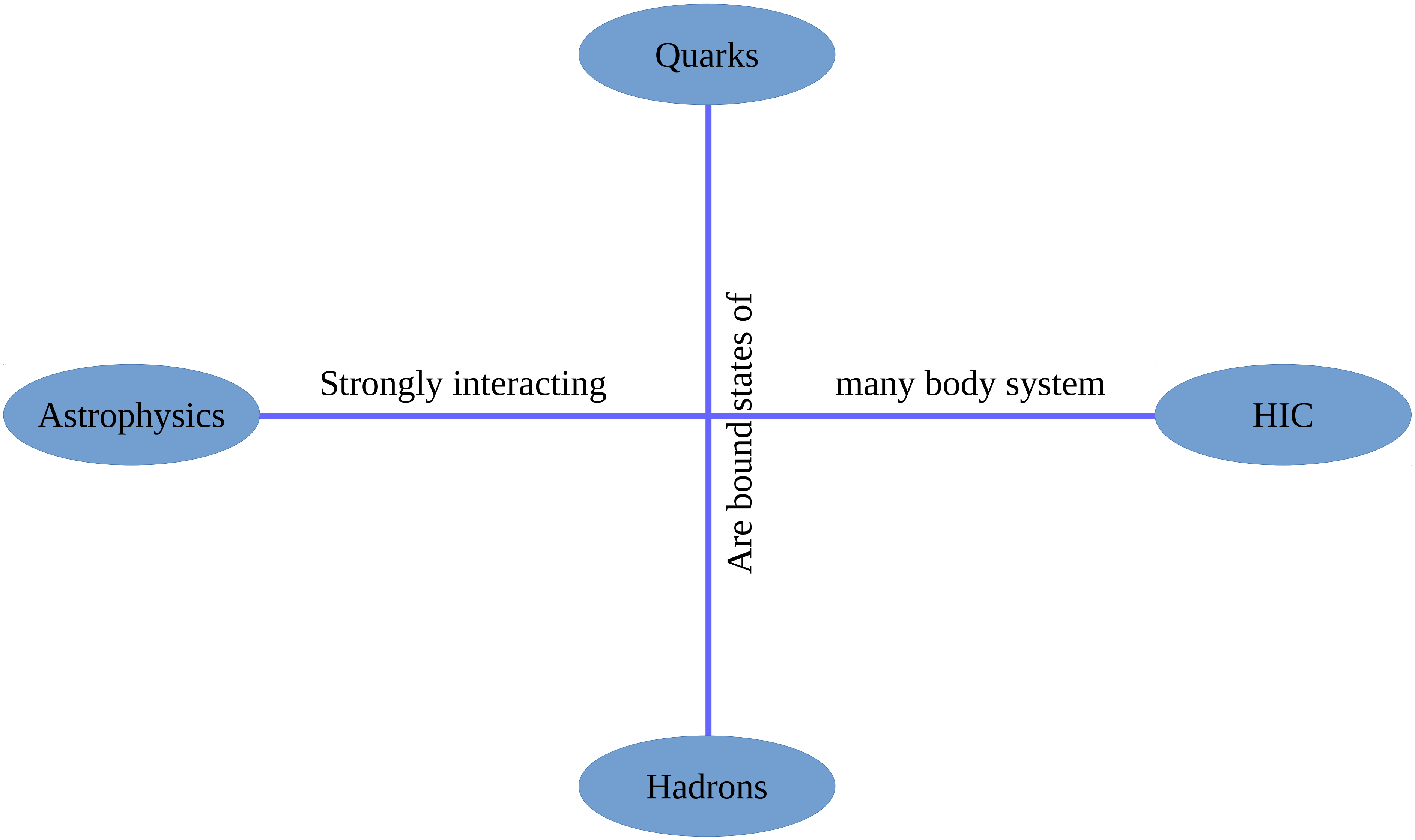
Towards a unified description of the equation of state of strongly interacting matter

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

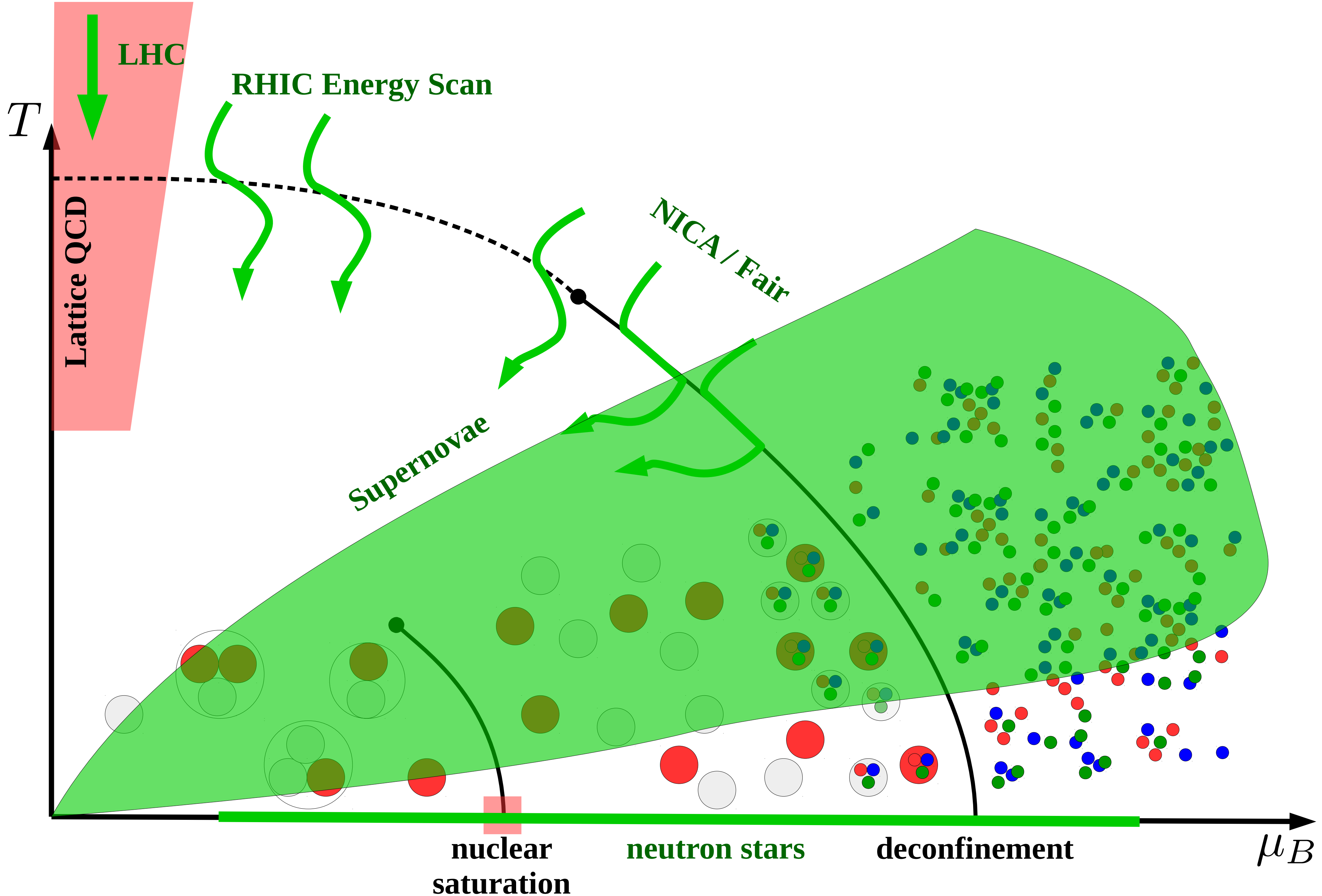
New York, 11. June 2018

Uniwersytet Wrocławski

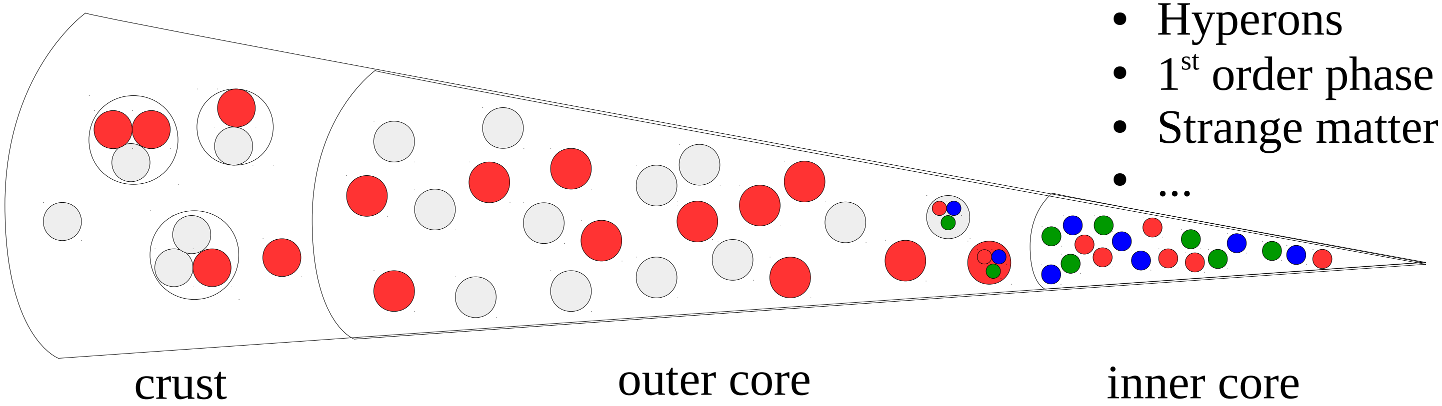
Unified equation of state



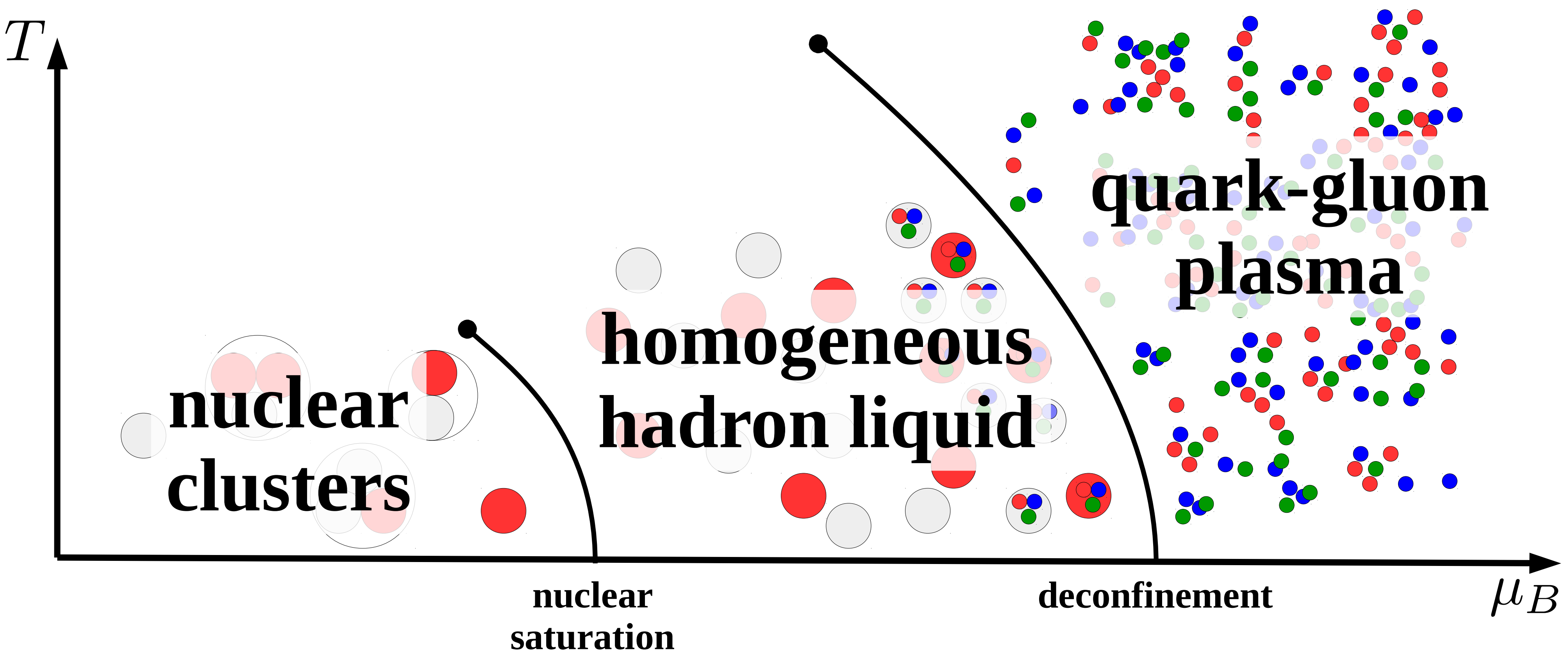
Strongly interacting matter



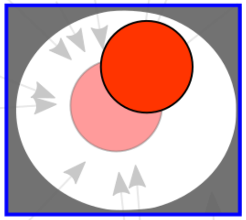
Outline



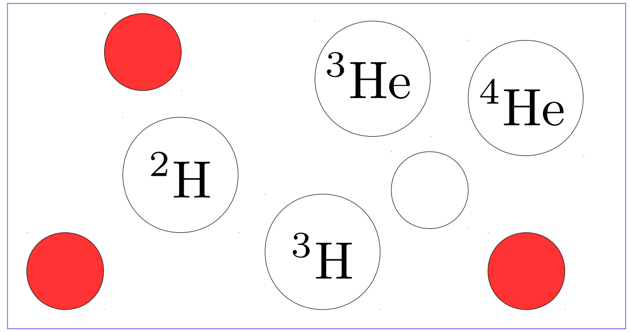
Open questions for astrophysics:
- Hyperons
- 1st order phase transition
- Strange matter
- ...



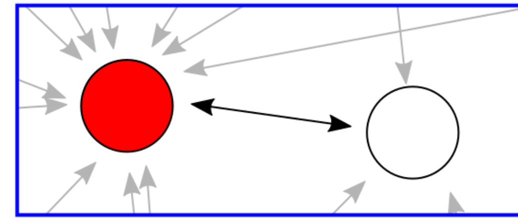
(light) Nuclear clusters



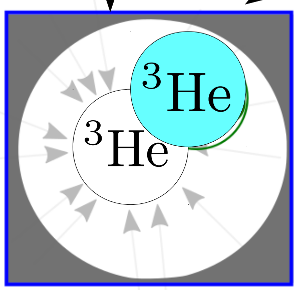
- medium modification of free particles
- selfenergy



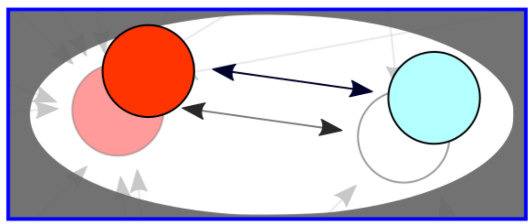
- ideal mixture and chemical picture
- NSE



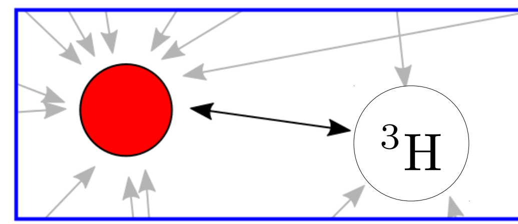
- virial expansion and two-particle correlation
- Beth-Uhlenbeck formula



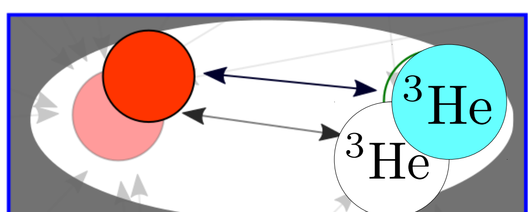
- Cluster-meanfield
- Cluster selfenergy, screening and Pauli blocking



- medium modifications of particles and correlations
- GBU

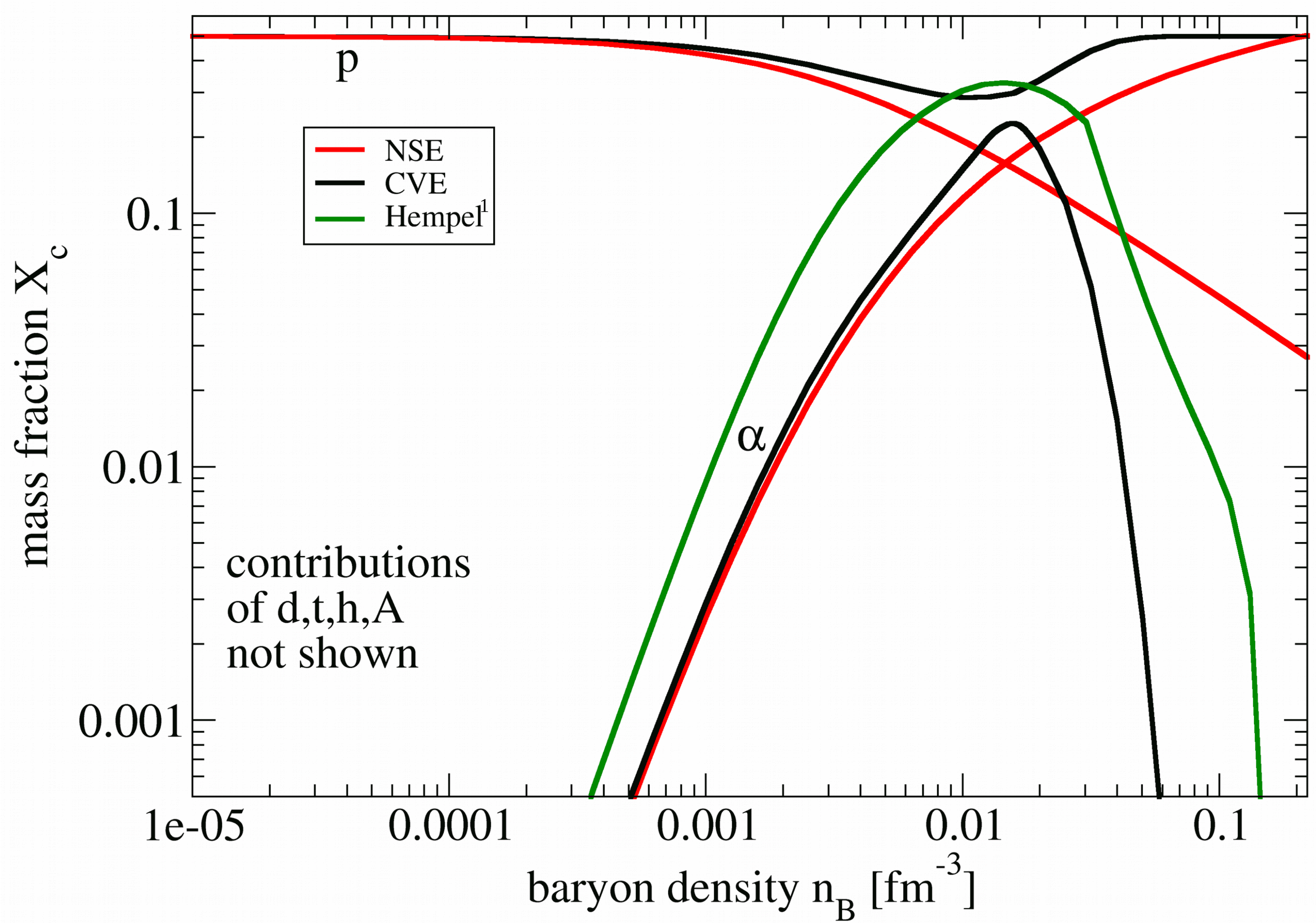


- Cluster-virial expansion



- cluster-virial expansion with medium effects

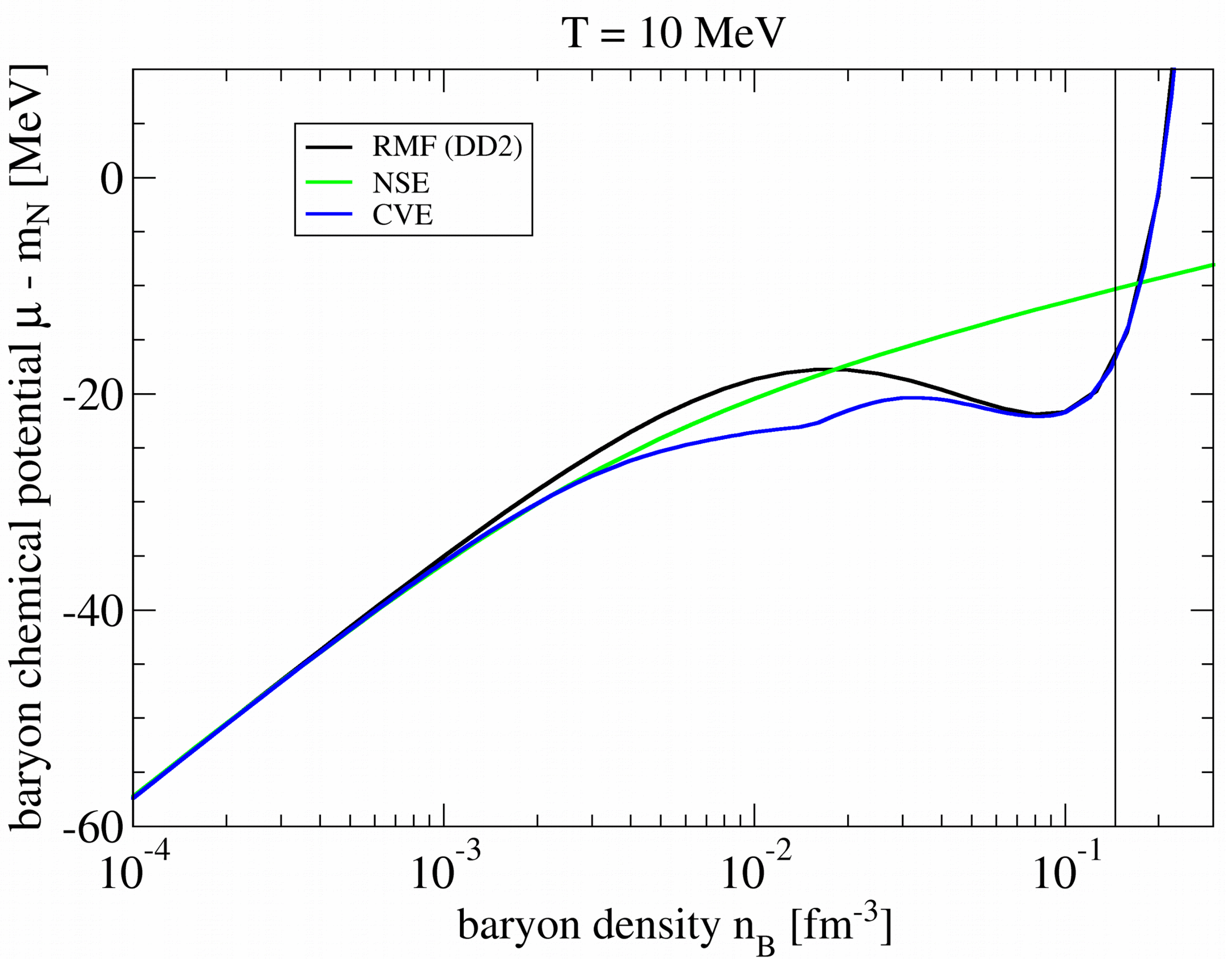
G. Ropke, N.-U. Bastian, D. Blaschke, T. Klahn, S. Typel and H.~H. Wolter, Nucl. Phys. A **897**, 70 (2013)



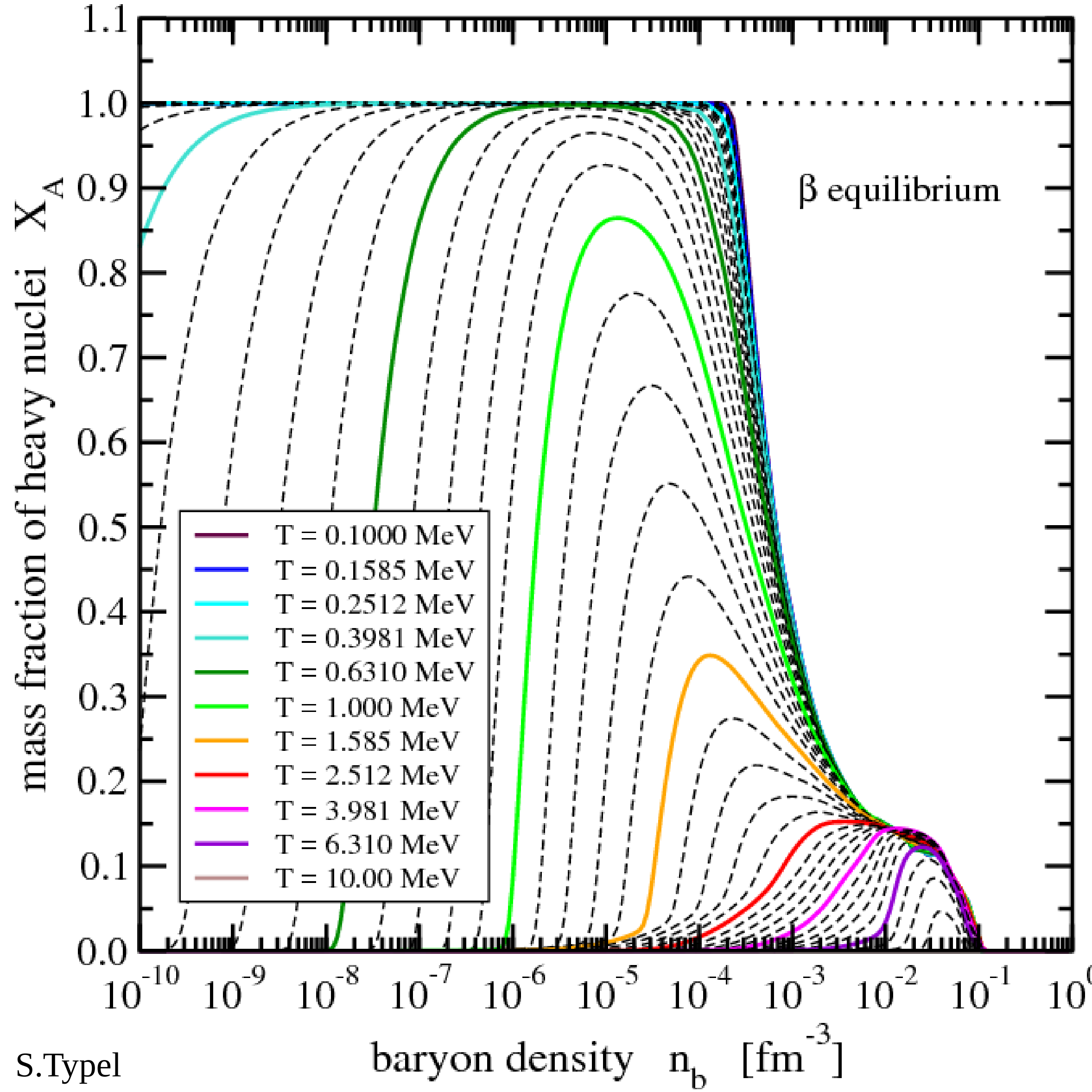
G. Ropke, PRC 92, 054001 (2015)

[1]Hempel, M.; Schaffner-Bielich, J., Nucl. Phys. A 837, 210-254 (2010)

(light) Nuclear clusters

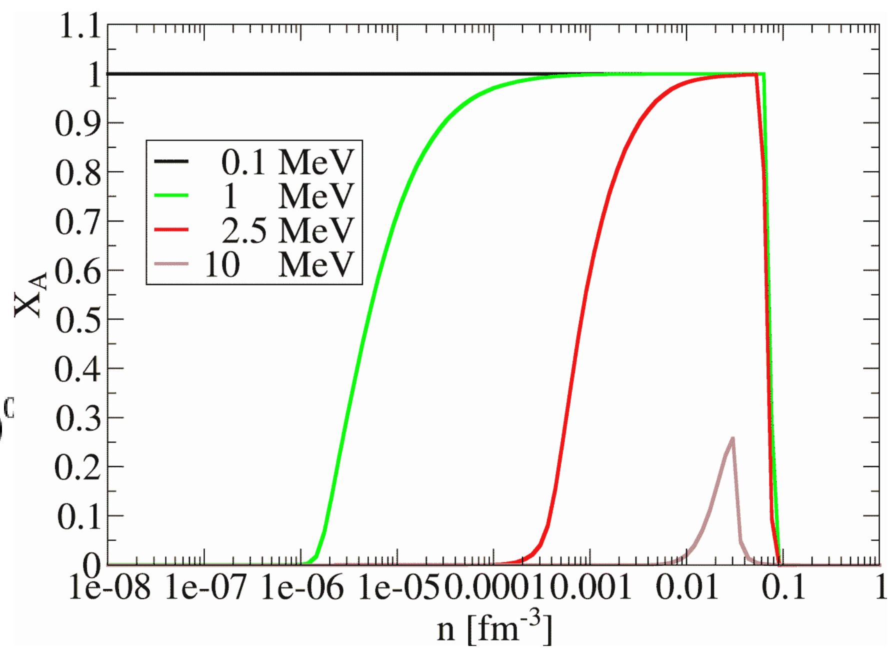


G. Ropke, PRC 92, 054001 (2015)

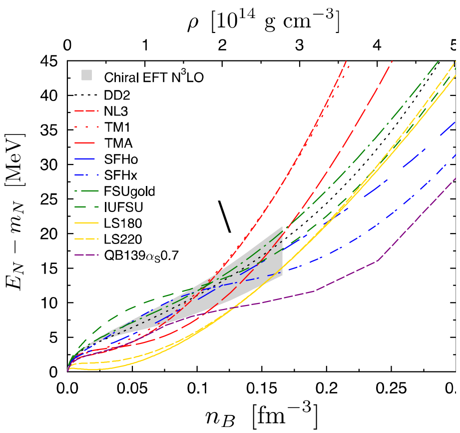


S.Typel

- Simple NSE with excluded volumen highly overestimates heavy clusters

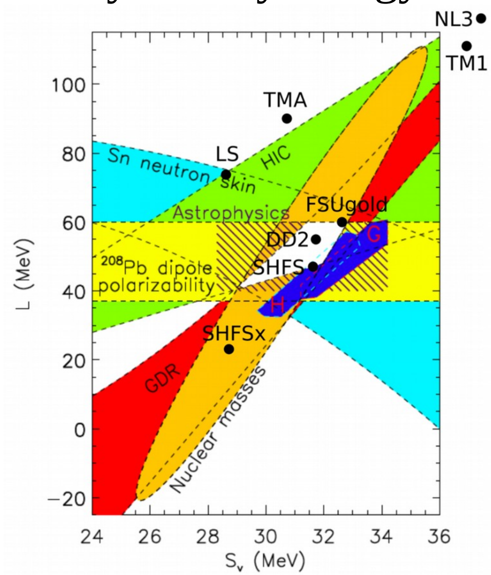


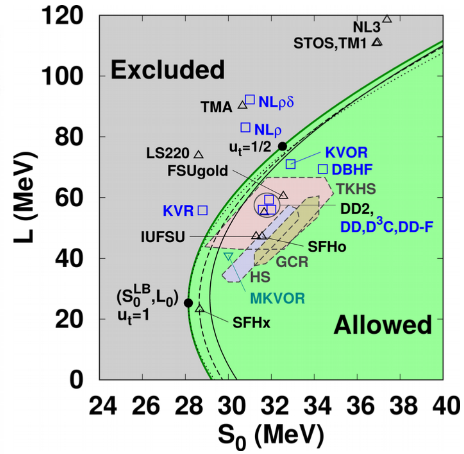
Constraints to consider



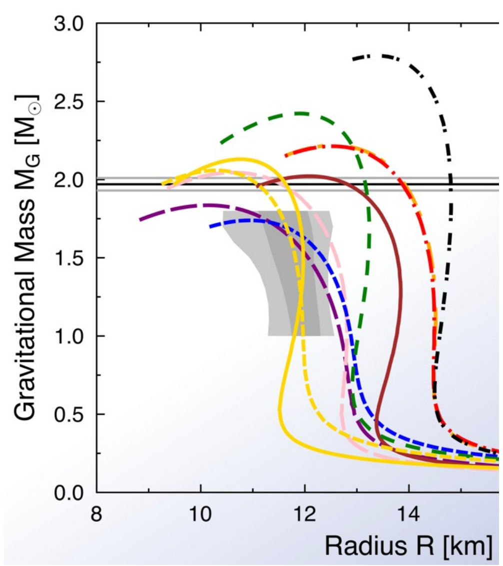
Chiral EFT[1]

Symmetry energy[2]

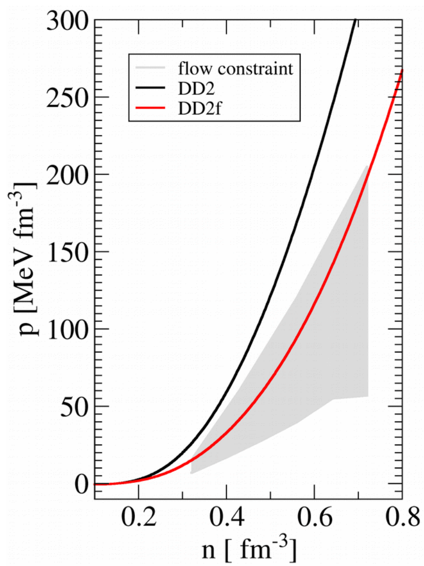




Unitary Constraint[3]



Neutronstar mass[4]

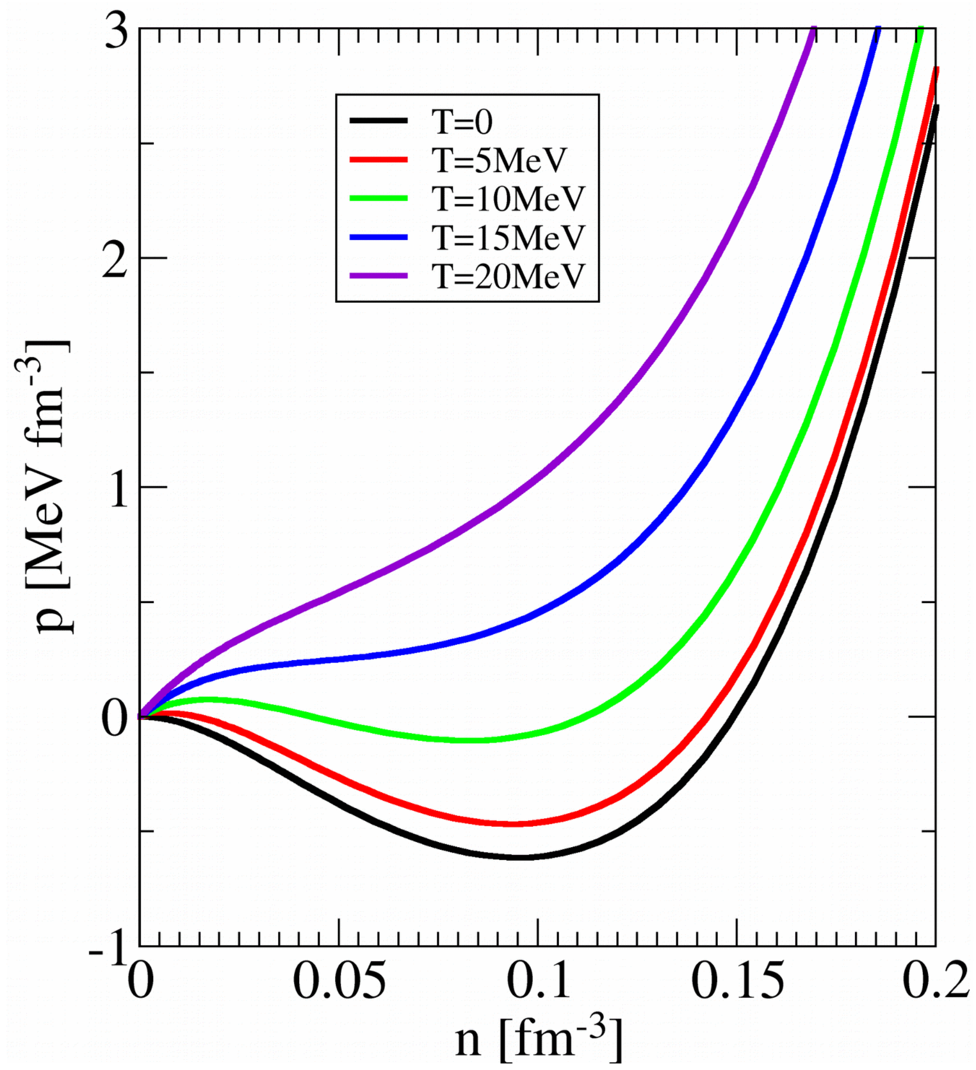


Flow constraint[5]

[1] T. Fischer, et. al., (2014) EPJA50, 46
[2] Lattimer & Lim (2013) ApJ 771, 14
[3] Tews, et.al., (2017) ApJ. 848 no.2, 105
[4] J. Antoniadis, et al., (2013) Science 340 6131
[5] P. Danielewicz, et. al., (2002) Science 298 1592-1596

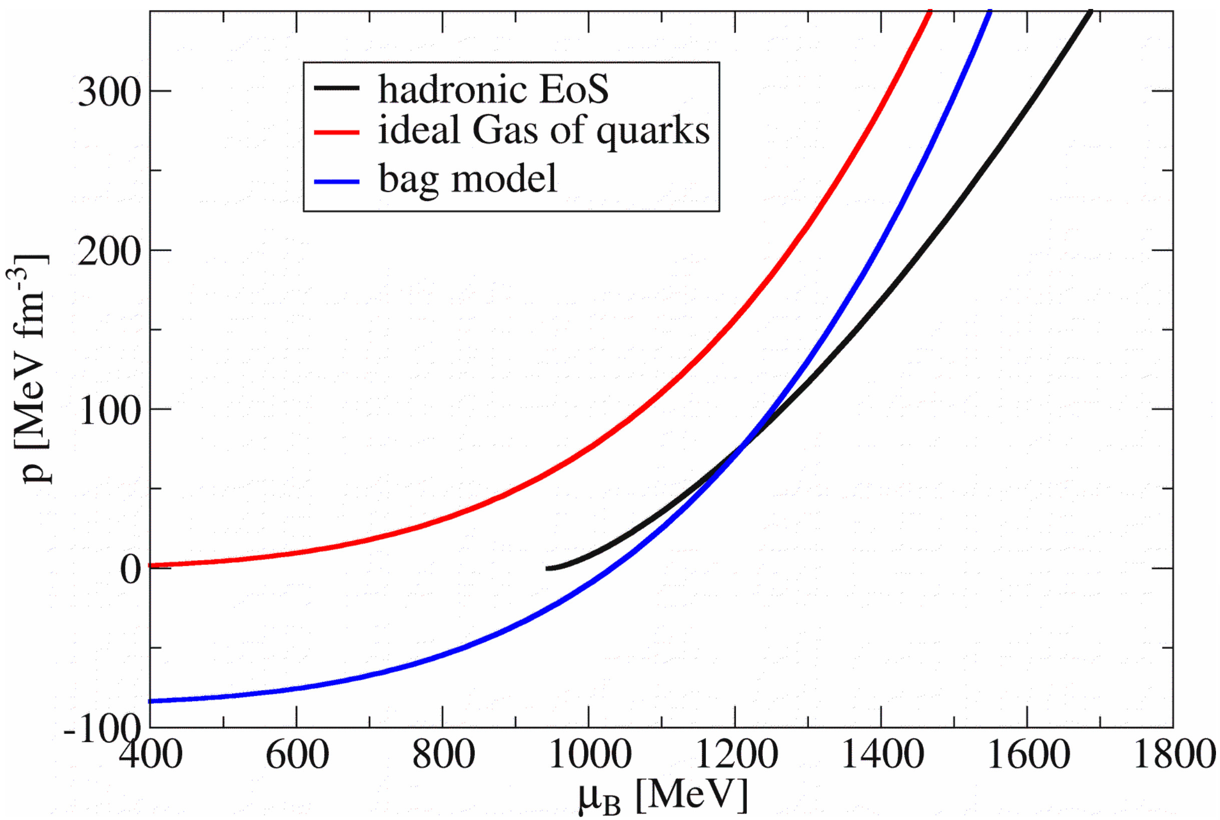
Homogeneous nuclear matter

- Density dependent relativistic mean field (RMF) model DD2[1]
- Parameters adjusted to nuclear data
- Fulfills all solid constraints perfectly up to saturation density
- Variations like DD2f[2] and DD2vex[3] alter behavior above saturation

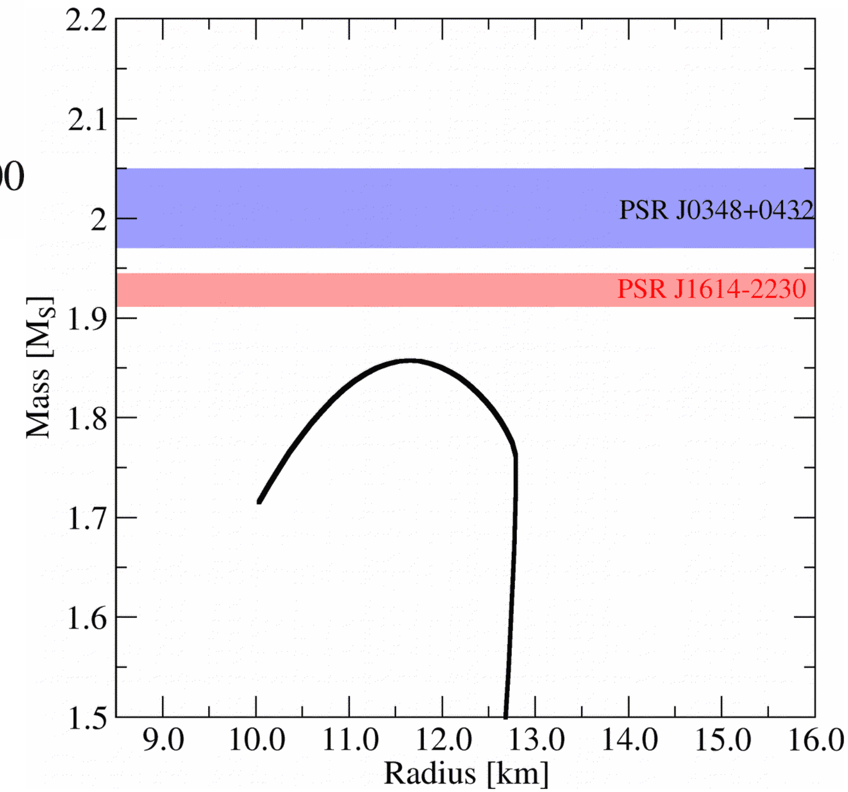


[1]Typel, Wolter, NPA **656** (1999) 331
[2]Typel, Röpke, Klähn, Blaschke, Wolter, PRC **81** (2017) 015803
[3]Typel, EPJA (2016)

Thermodynamic Bag Model

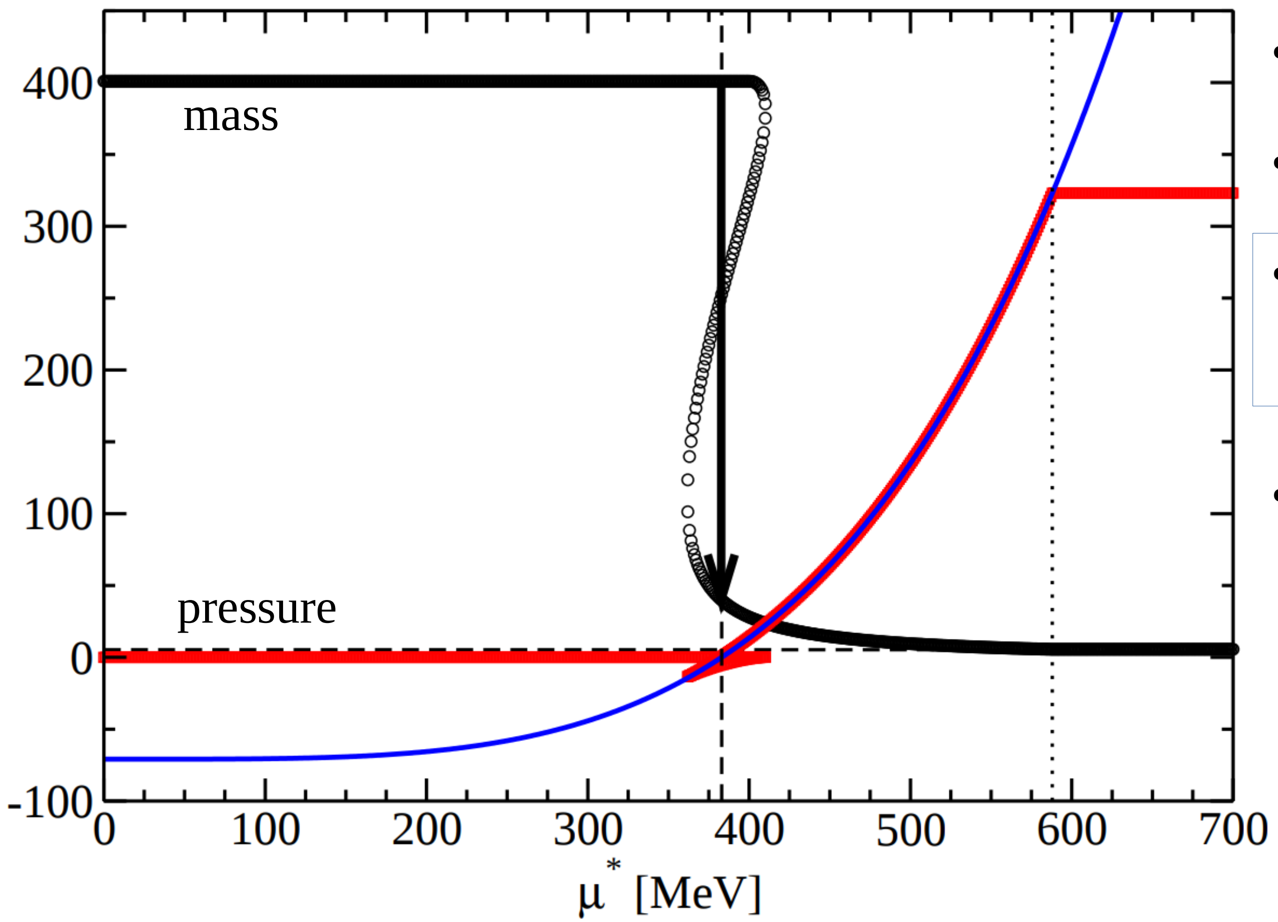


- Ideal gas for quarks
- Added constant "Bag" pressure to mimic confinement



- **Does not satisfy the neutron star mass constraint**

Nambu-Jona-Lasinio Models



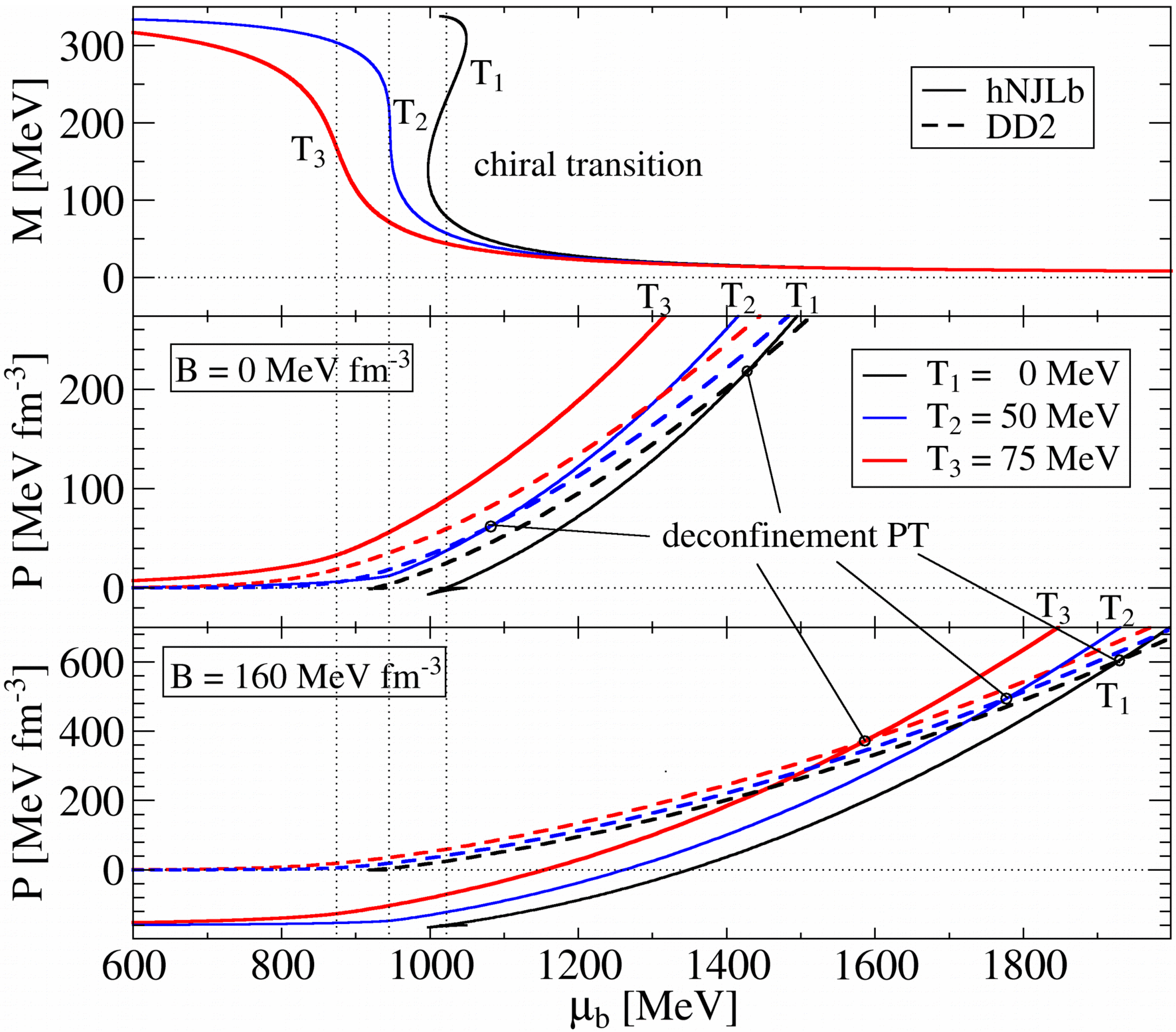
T. Klahn and T. Fischer, APJ **810**, 2, 134 (2015)

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

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

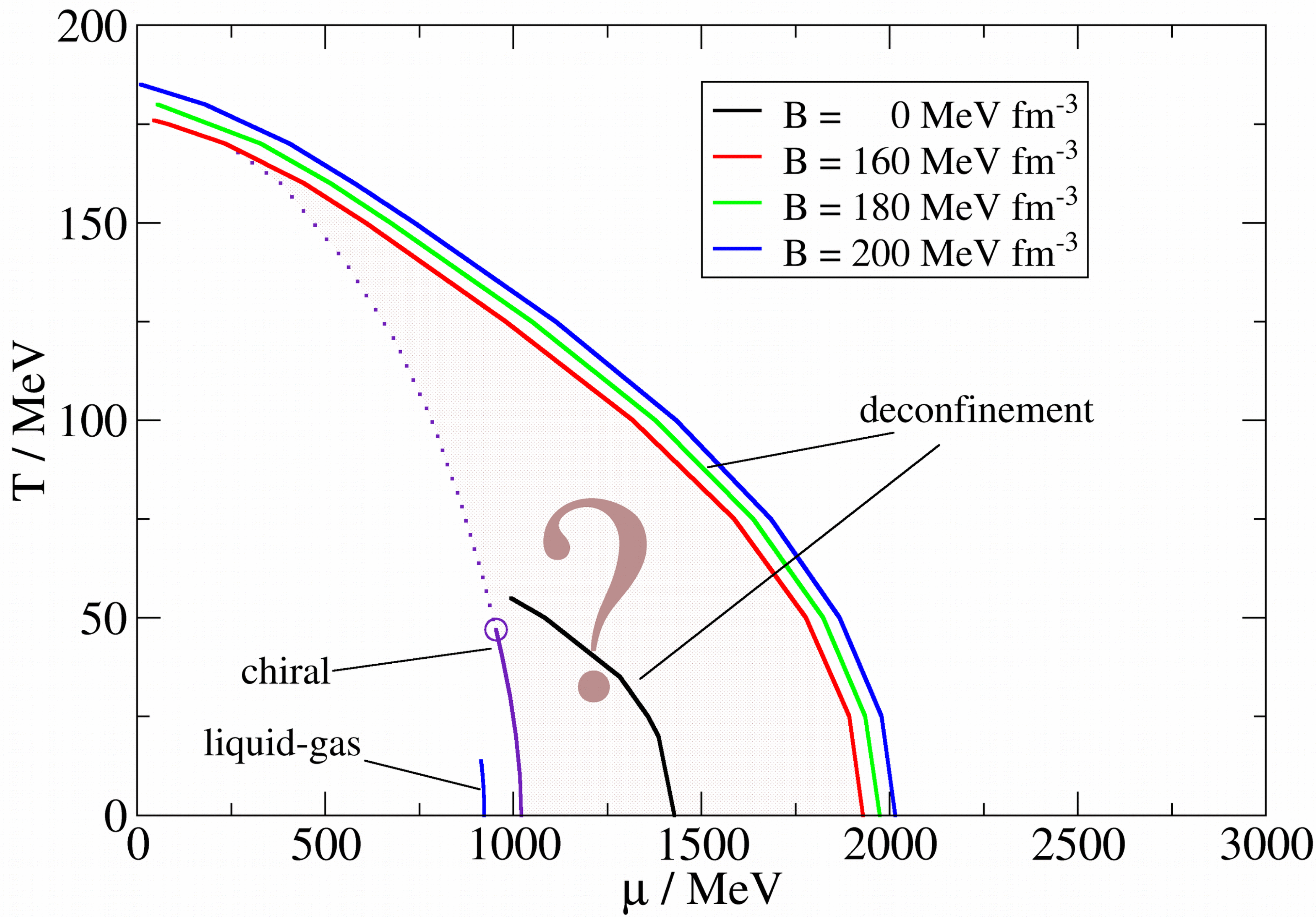
- Additional Bag constant needs to be added

2-phase construction with NJL



NUFB, D. Blaschke, 2016 J. Phys.: Conf. Ser. 668 012042

2-phase construction with NJL



NUFB, D. Blaschke, 2016 J. Phys.: Conf. Ser. 668 012042

QGP: Density functionals

Starting with free fermion Lagrangian plus an interaction term, which depends on quark currents

$$\mathcal{L}_{\mathrm{eff}} = \underbrace{\bar{q}\left(\imath\gamma^{\mu}\partial_{\mu} - m\right) q}_{\mathcal{L}_{\mathrm{free}}} - U\left(\bar{q}q, \bar{q}\gamma^{\mu}q\right)$$

Mean field → linear dependence of U on densities is important! → expansion around expectation values

$$U\left(\bar{q}q, \bar{q}\gamma^{\mu}q\right) = U\left(n_{\mathrm{S}}, n_{\mathrm{V}}\right) + \Sigma_{\mathrm{S}}\left(\bar{q}q - n_{\mathrm{S}}\right) + \Sigma_{\mathrm{V}}\left(\bar{q}\gamma^{\mu}q - n_{\mathrm{V}}\right) + \ldots$$

derivatives

$$\mathcal{L}_{\mathrm{eff}} \approx \underbrace{\bar{q}\left(\gamma^{\mu}\left(\imath\partial_{\mu} - \Sigma_{\mathrm{V}}\right) - \left(m + \Sigma_{\mathrm{S}}\right)\right) q}_{\mathcal{L}_{\mathrm{quasi}}} - \Theta\left(n_{\mathrm{S}}, n_{\mathrm{V}}\right)$$

⬇

$$P = g \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \left[\ln\left(1 + e^{-\beta\left(\sqrt{p^2 - M^2} - \tilde{\mu}\right)}\right) + \mathrm{a.p.}\right] - \Theta$$

with

$$n_s = \langle \bar{q}q \rangle \;,\; n_v = \langle \bar{q}\gamma^0 q \rangle \qquad M = m + \Sigma_{\mathrm{S}} \;,\; \tilde{\mu} = \mu - \Sigma_{\mathrm{V}}$$

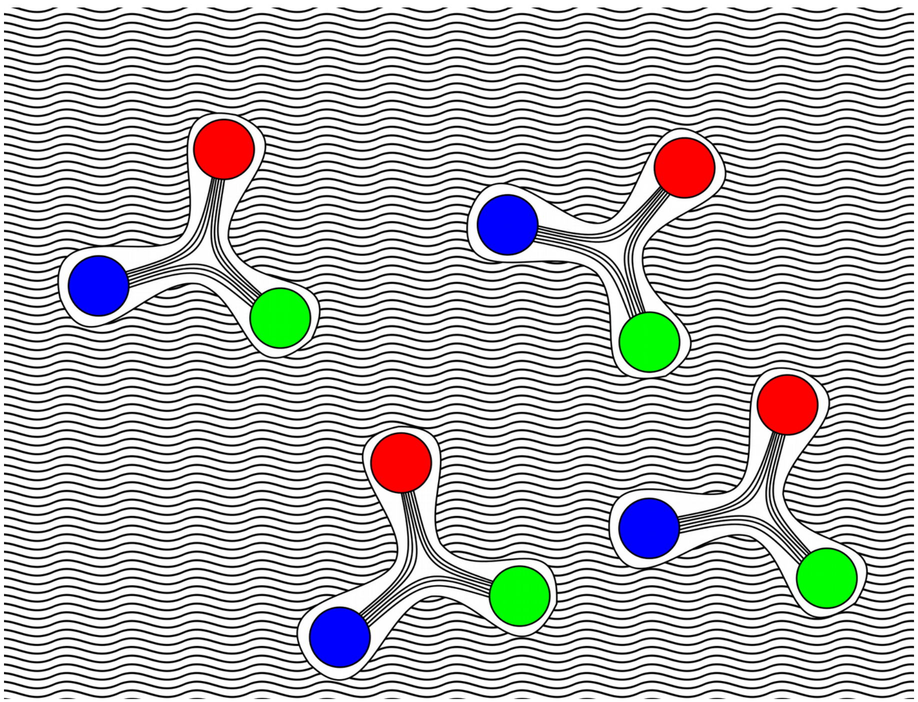
M. Kaltenborn, NUFB, D. Blaschke. Phys. Rev. D 2017, 96, 056024

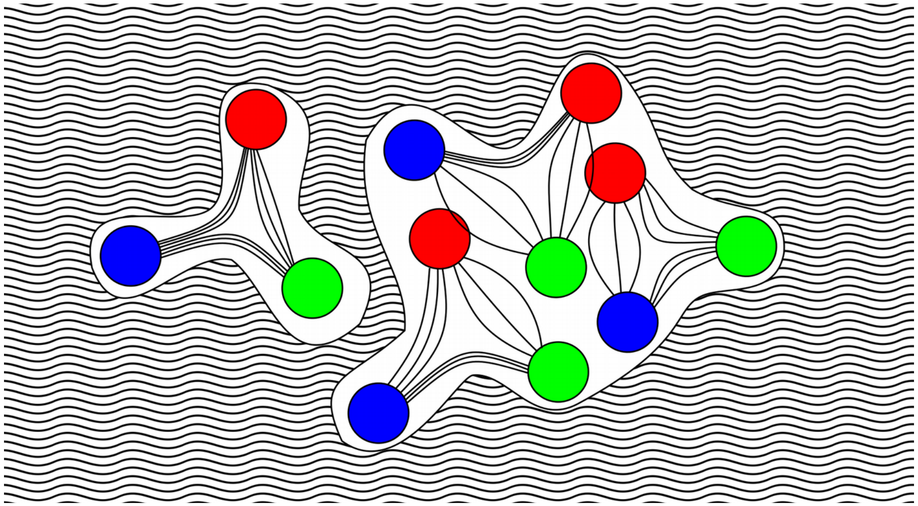
Density functional approach: Stringflip model

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

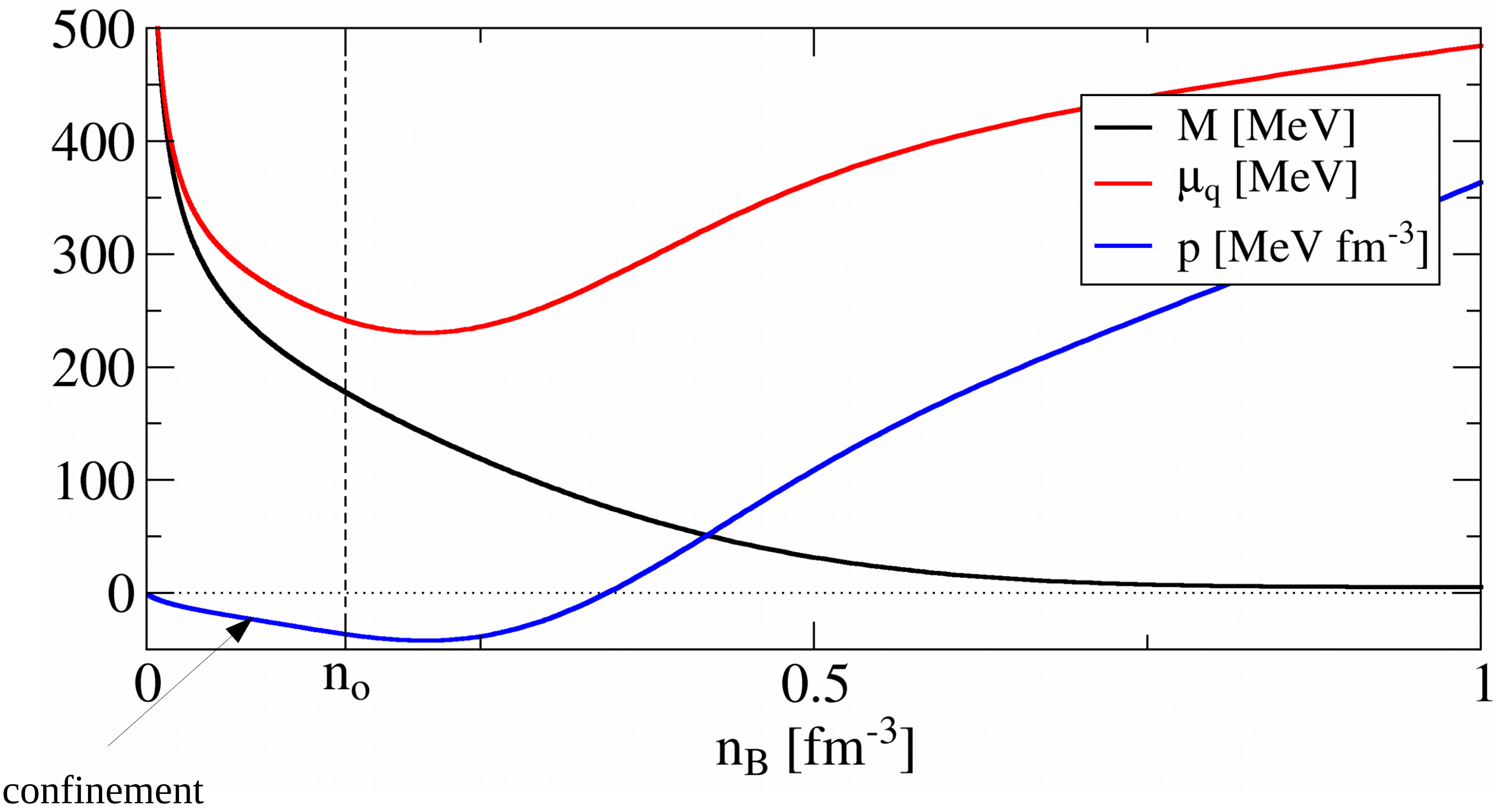
$$\sigma = \Phi\sigma_0$$

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

$$U^{\mathrm{SF}}(n_{\mathrm{S}}, n_{\mathrm{V}}) = D(n_{\mathrm{V}}) n_{\mathrm{S}}^{2/3}$$

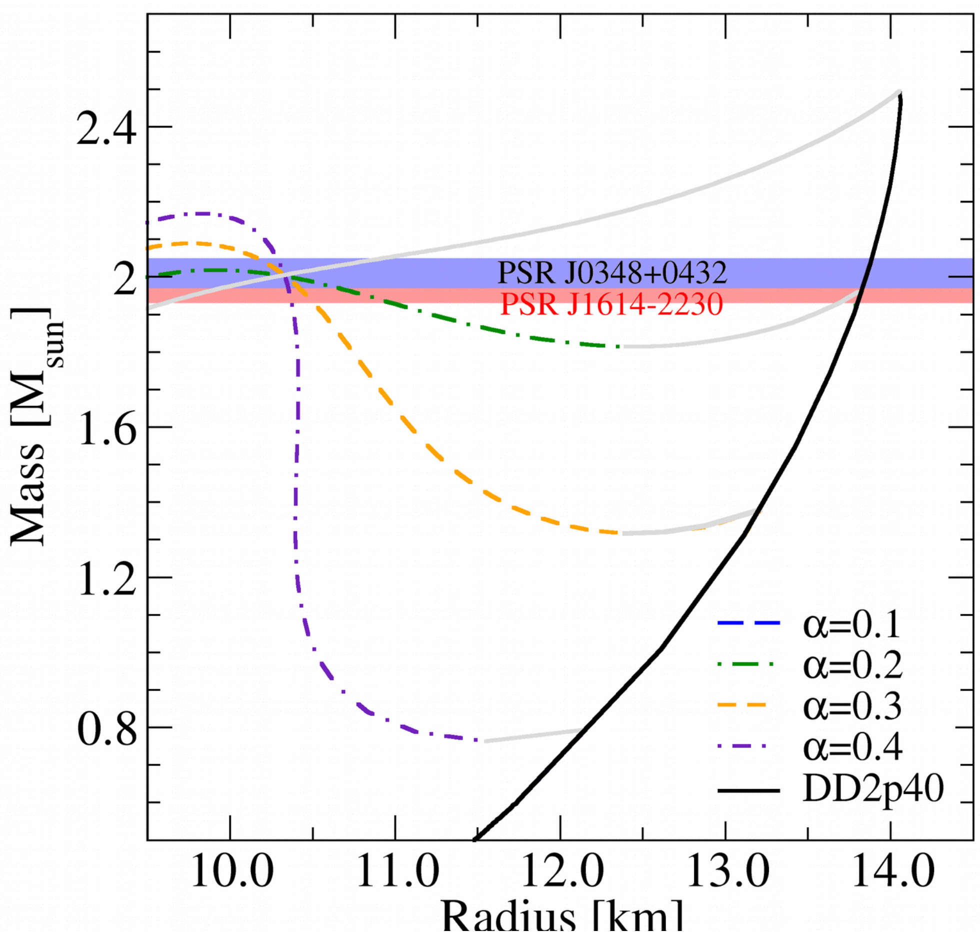
Mean-field model

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



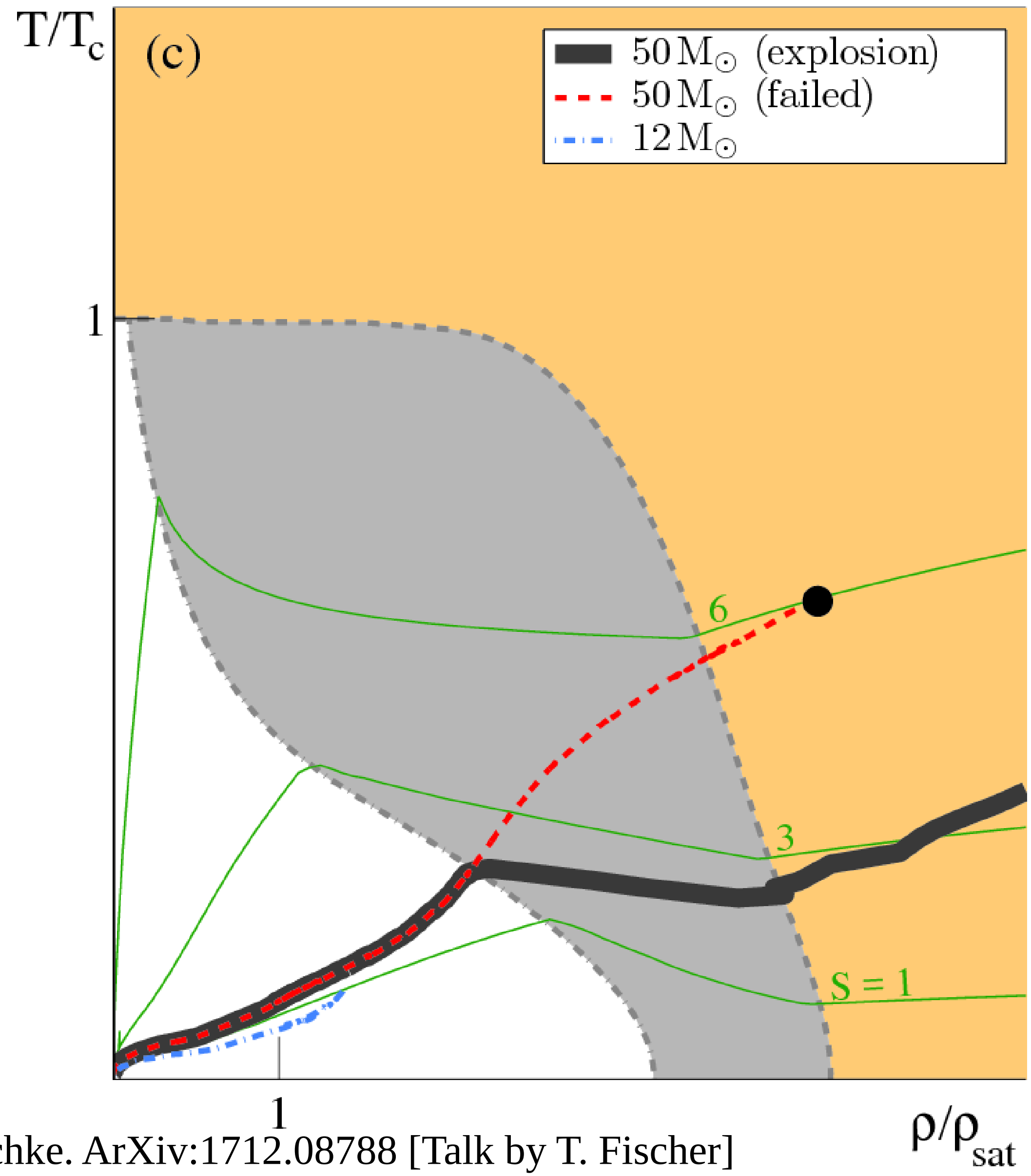
Kaltenborn, Bastian, Blaschke, PRD 96, 056024 (2017)

Neutron star configurations



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

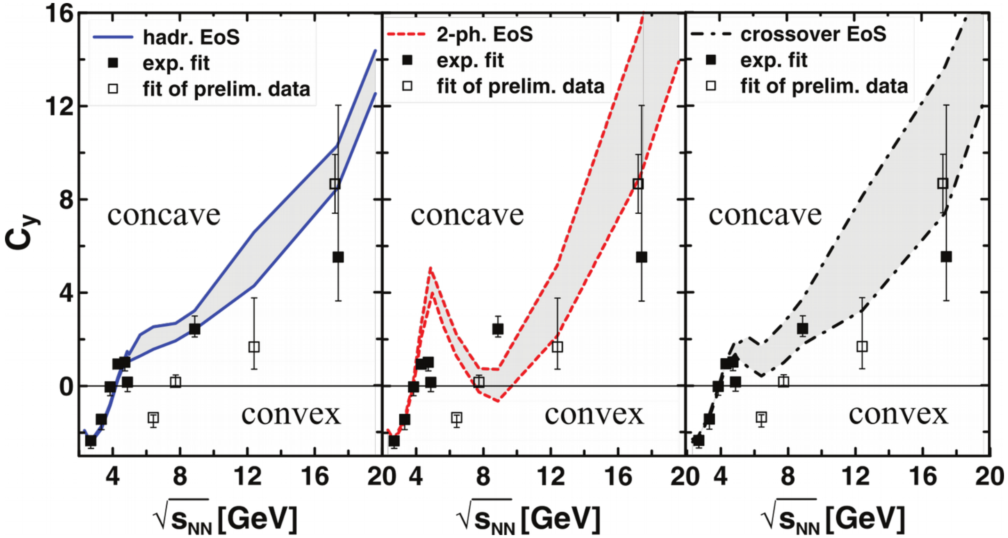
Supernova explosions



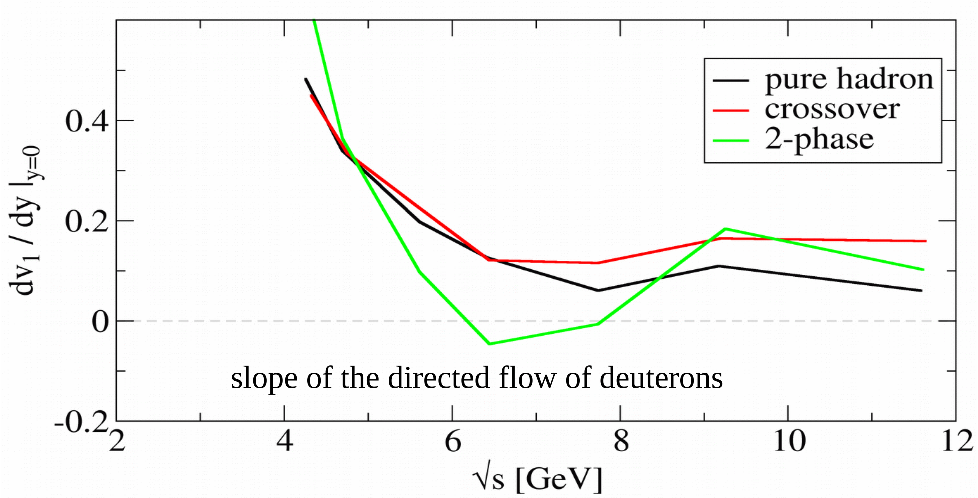
T. Fischer, NUFB, M.-R. Wu, S. Typel, T. Klähn, D. Blaschke. ArXiv:1712.08788 [Talk by T. Fischer]

1st order PT – Heavy Ion Collisions

strong signal (wiggle) in the baryon stopping signal [1]



Anti-flow of clusters occur [2]



- Application of the SFM to HIC is ongoing work

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

Cluster expansion

Generating functional formalism by Baym and Kadanoff [1,2]

$$\Omega = -\mathrm{Tr}\ \ln(-G_1) - \mathrm{Tr}\Sigma_1 G_1 + \Phi$$

With

$$\Sigma_1(1,1') = \frac{\delta\Phi}{\delta G_1(1,1')}.$$

Can be generalized for a consistent cluster expansion

$$\Omega = \sum_{l=1}^{A} \Omega_l = \sum_{l=1}^{A} \left\{ c_l \left[\mathrm{Tr}\ln\left(-G_l^{-1}\right) + \mathrm{Tr}\left(\Sigma_l\ G_l\right)\right] + \sum_{\substack{i,j \\ i+j=l}} \Phi[G_i, G_j, G_{i+j}] \right\}$$

with

$$\Sigma_A(1\ldots A, 1'\ldots A', z_A) = \frac{\delta\Phi}{\delta G_A(1\ldots A, 1'\ldots A', z_A)}$$

Always sustains full Dyson equation and thermodynamic stability

$$G_A = G_A^0 - \Sigma_A$$

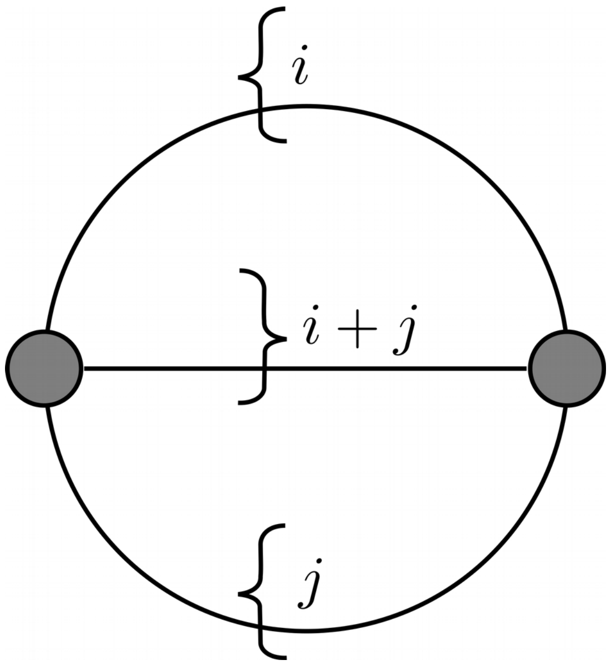
$$\frac{\partial\Omega}{\partial G_A} = 0$$

Reduction on generalized sunset diagrams is recommended

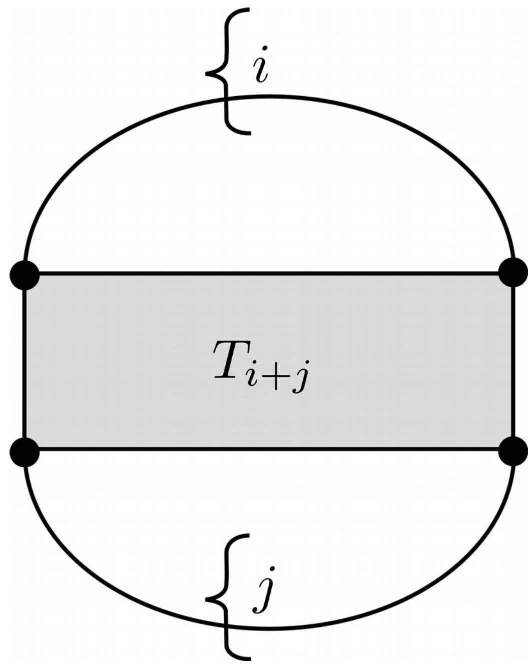
[1] Baym, G.; Kadanoff, L.P. Phys. Rev. 1961, 124, 287–299.
[2] Baym, G. Phys. Rev. 1962, 127, 1391–1401.

Cluster expansion

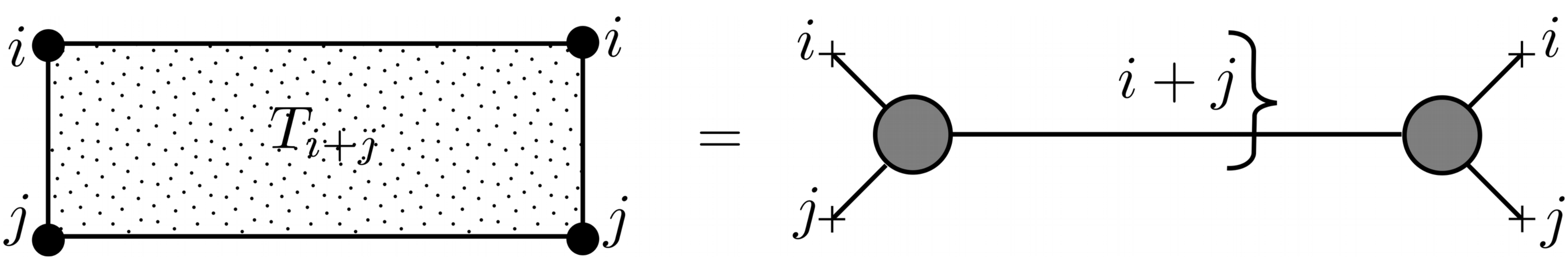
$$\Phi[G_i, G_j, G_{i+j}]$$



$$\Phi[G_i, G_j, T_{i+j}]$$



Defining the vertex



Analogy to density functional approach

Phi-derivable approach

$$\Omega = -\mathrm{Tr}\ \ln(-G_1) - \mathrm{Tr}\Sigma_1 G_1 + \Phi[G_1]$$

Density functional approach

$$\Omega = -T \ln \mathcal{Z} = \Omega^{\mathrm{quasi}} - n_{\mathrm{s}}\Sigma_{\mathrm{s}} - n_{\mathrm{v}}\Sigma_{\mathrm{v}} + U(n_{\mathrm{s}}, n_{\mathrm{v}})$$

First step: cluster expansion on basis of densities instead of Green functions
Zeroth step: density functional to describe chiral restoration

Last Slide

Conclusions

- Astrophysical objects and HIC collisions are based on the same physics of strongly interacting many-particle systems
- A sophisticated equation of state should be able to describe both
- Hadrons are bound states of quarks and should be treated as such
- This would cure problems with inconsistent inclusion of confinement and chiral physics
- Leads to consistent inclusion of substructure effects of Baryons

  (e g. Pauli blocking)

Outlook

- Density functional with chiral physics
- Cluster expansion on basis of density functionals
- Ongoing and future experiments (NICER, NICA, FAIR, GW) will provide further insight and might exclude models

Collaboration

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

Thank you!