Towards a unified equation of state

and the effect of symmetry energy in quark-matter

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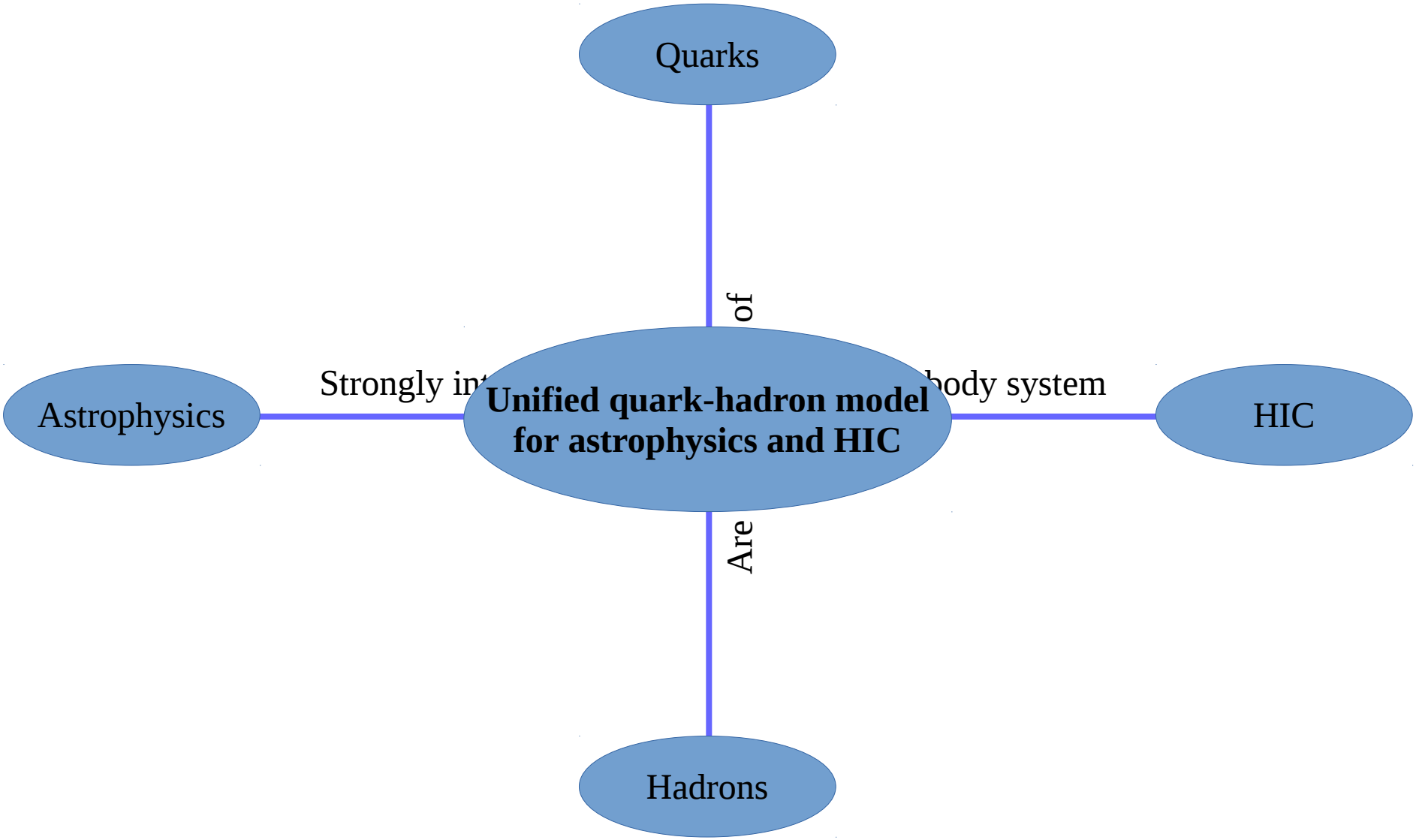
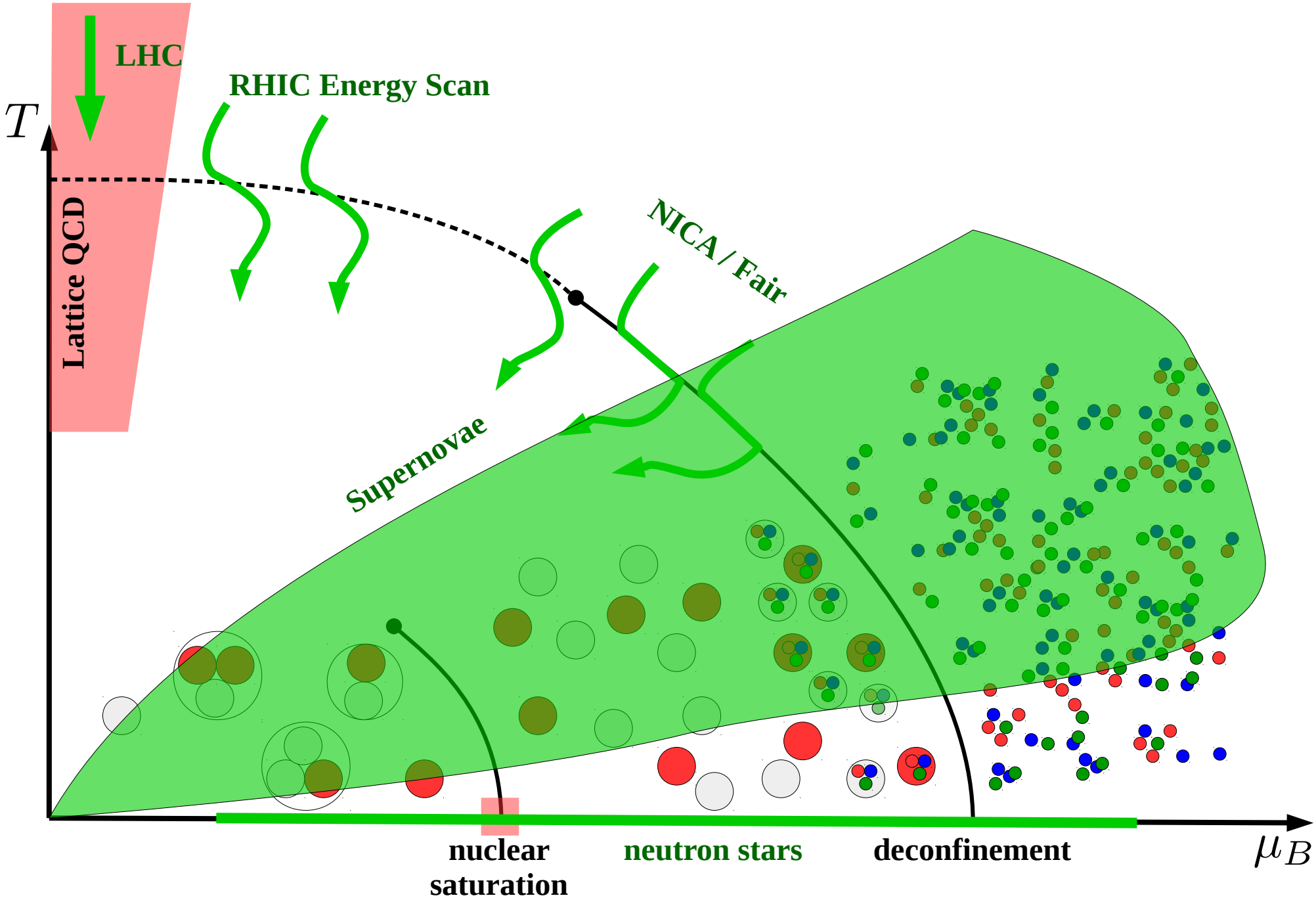
Busan, 13. September 2018

Unified equation of state



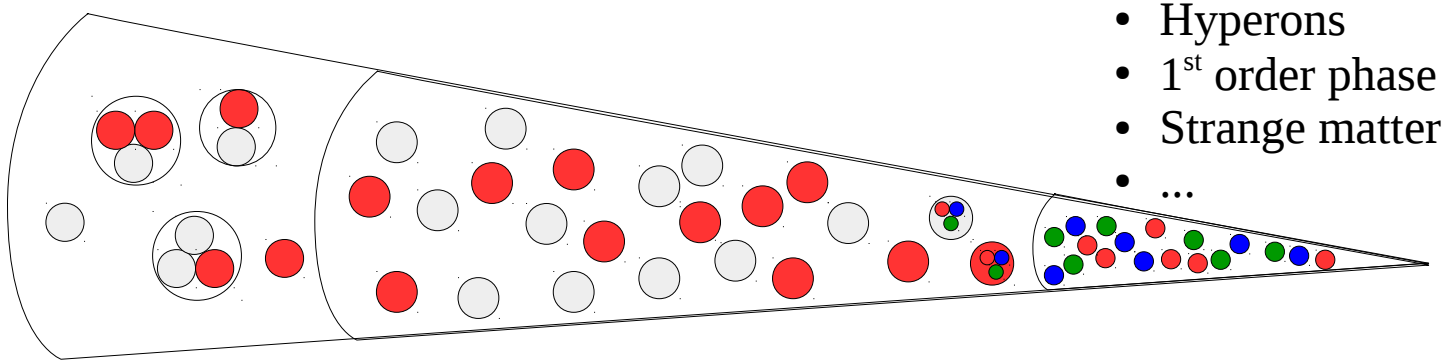
Keywords: nuclear clusters, chiral restoration, deconfinement, HIC, SN, NS, PNS, BNSM, ASSM.

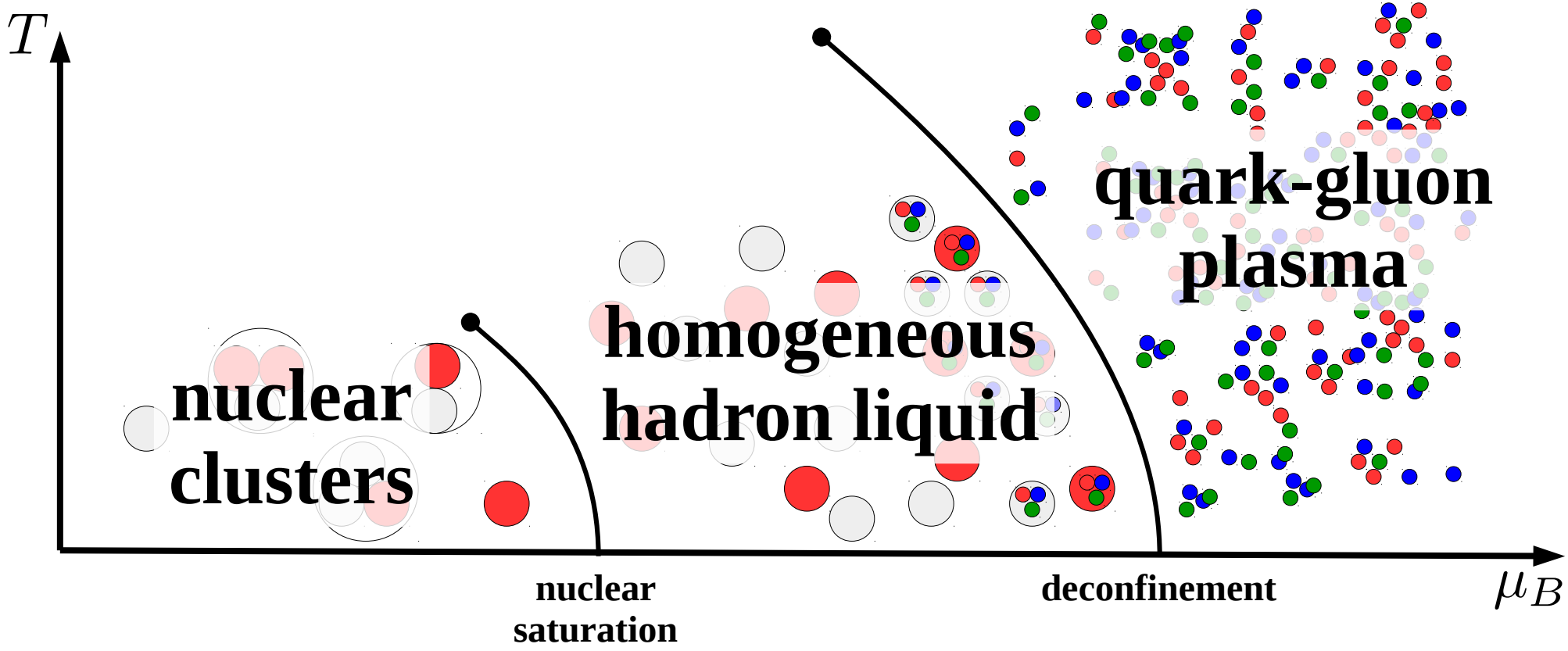
Strongly interacting matter



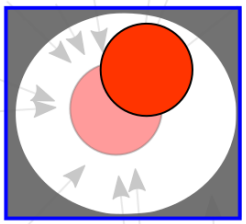
Outline

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

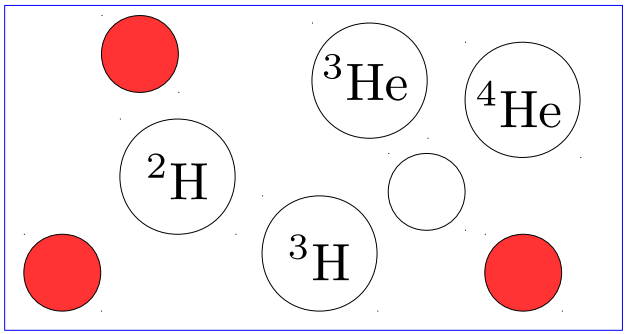




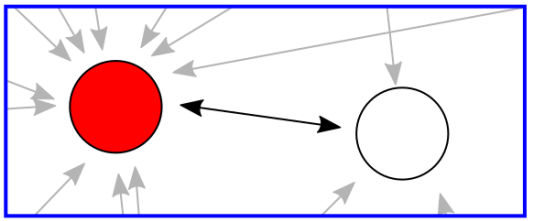
(light) Nuclear clusters



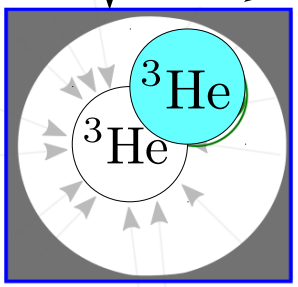
- medium modification of free particles
- selfenergy



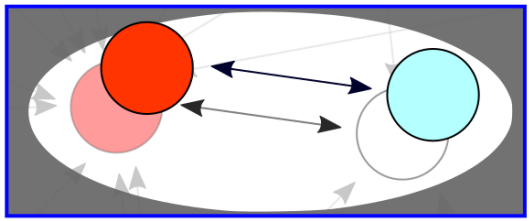
- ideal mixture and chemical picture
- NSE



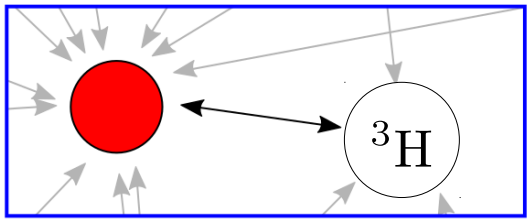
- virial expansion and two-particle correlation
- Beth-Uhlenbeck formula



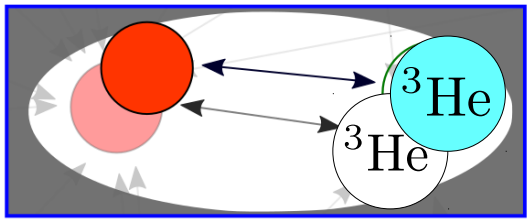
- Cluster-meanfield
- Cluster selfenergy, screening and Pauli blocking



- medium modifications of particles and correlations
- GBU



- Cluster-virial expansion

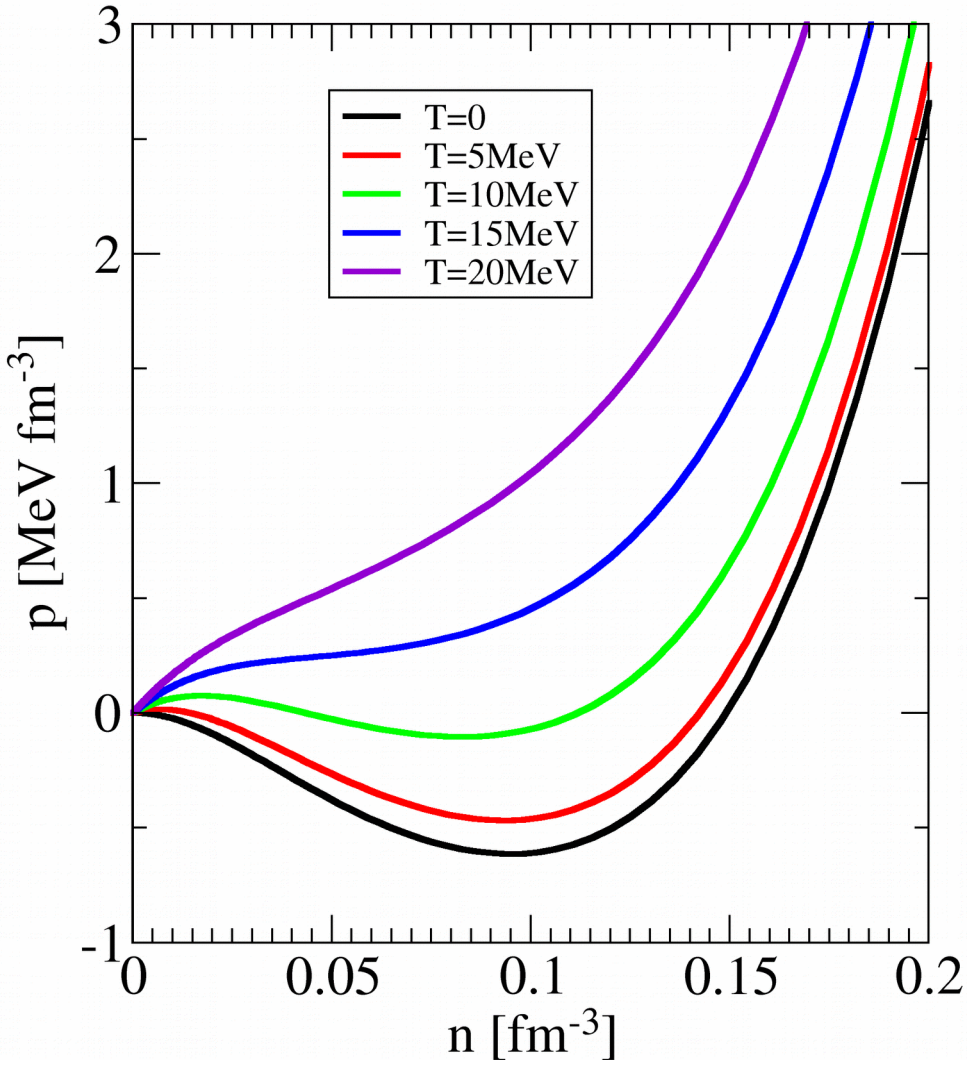


- cluster-virial expansion with medium effects

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

Homogeneous nuclear matter

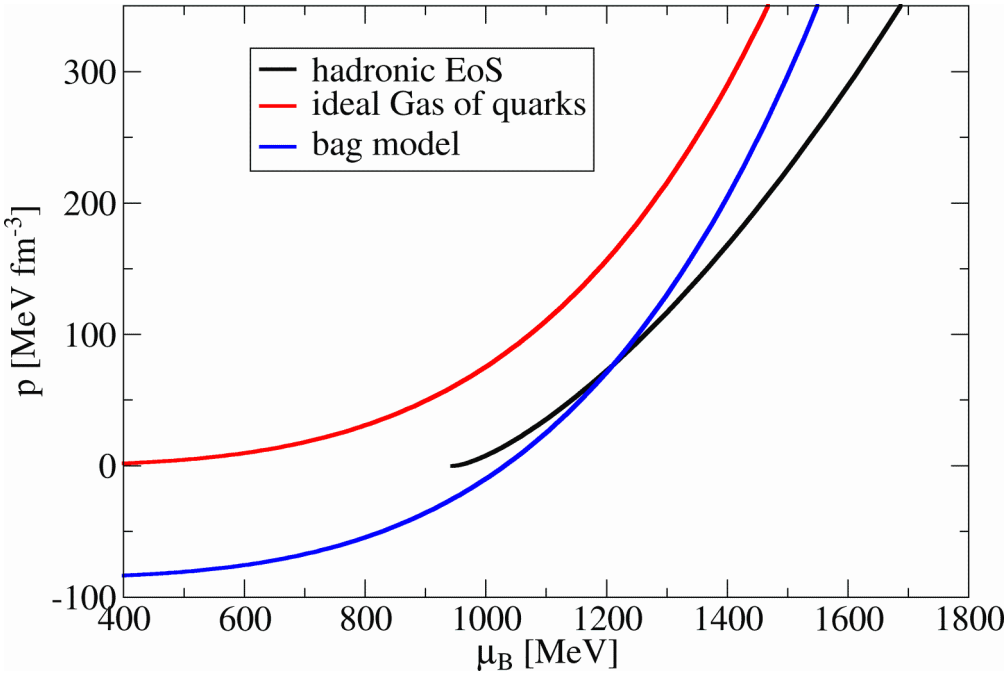
- Density dependent relativistic mean field (RMF) model DD2[1]
- Parameters adjusted to nuclear data
- Fulfills all solid constraints perfectly up to saturation density
- Variations like DD2f[2] and DD2vex[3] alter behavior above saturation



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

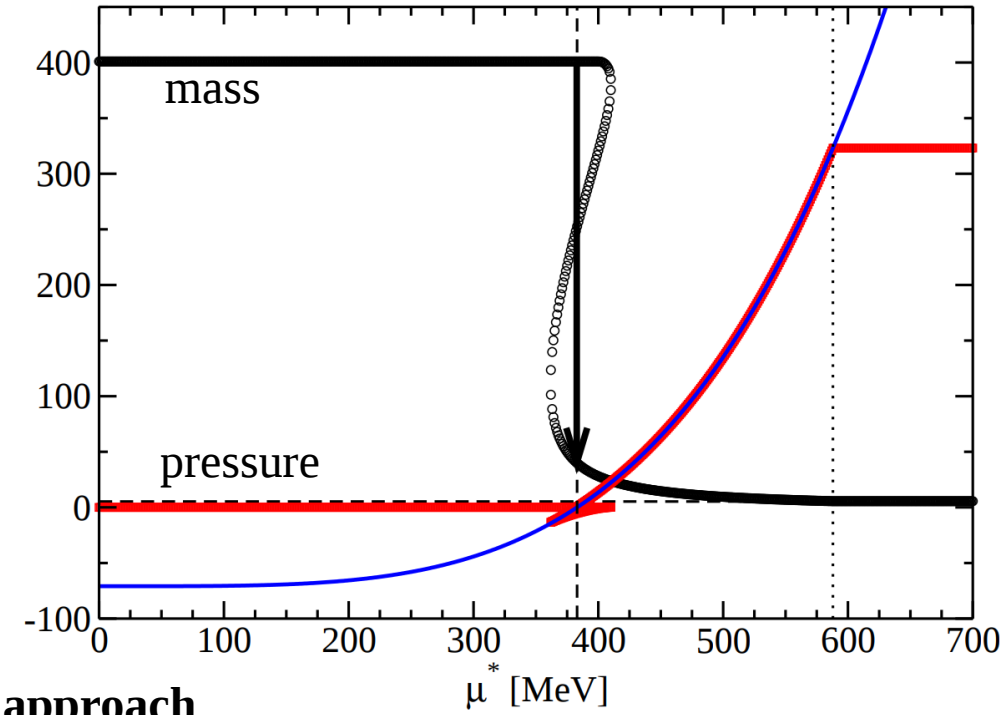
Quarks Models

Bag Model

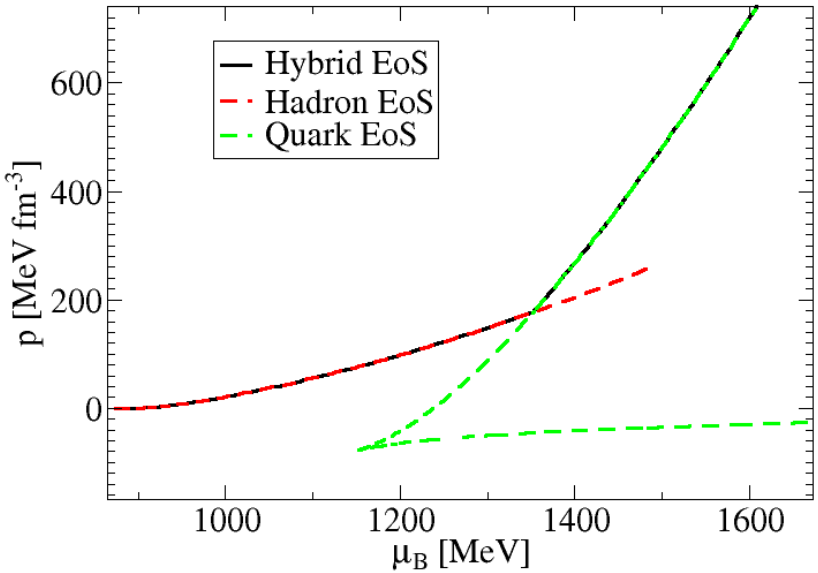


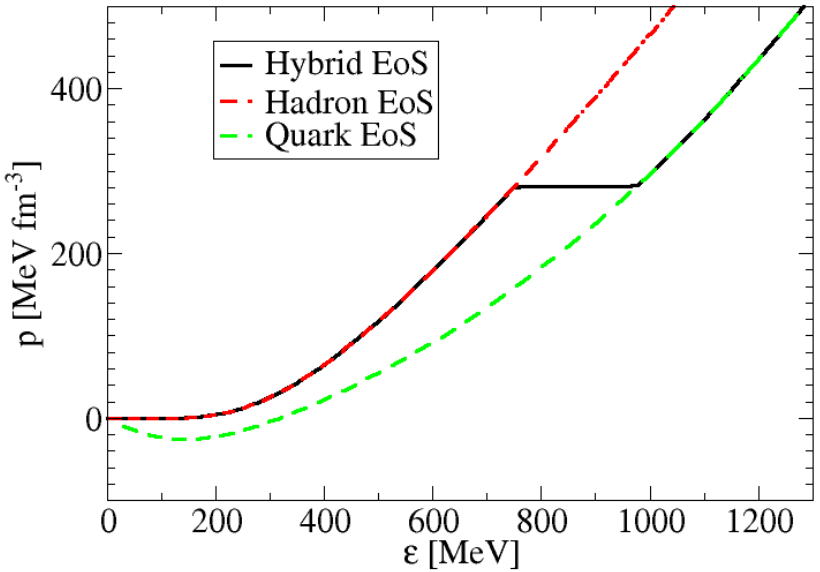
NJL Models

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

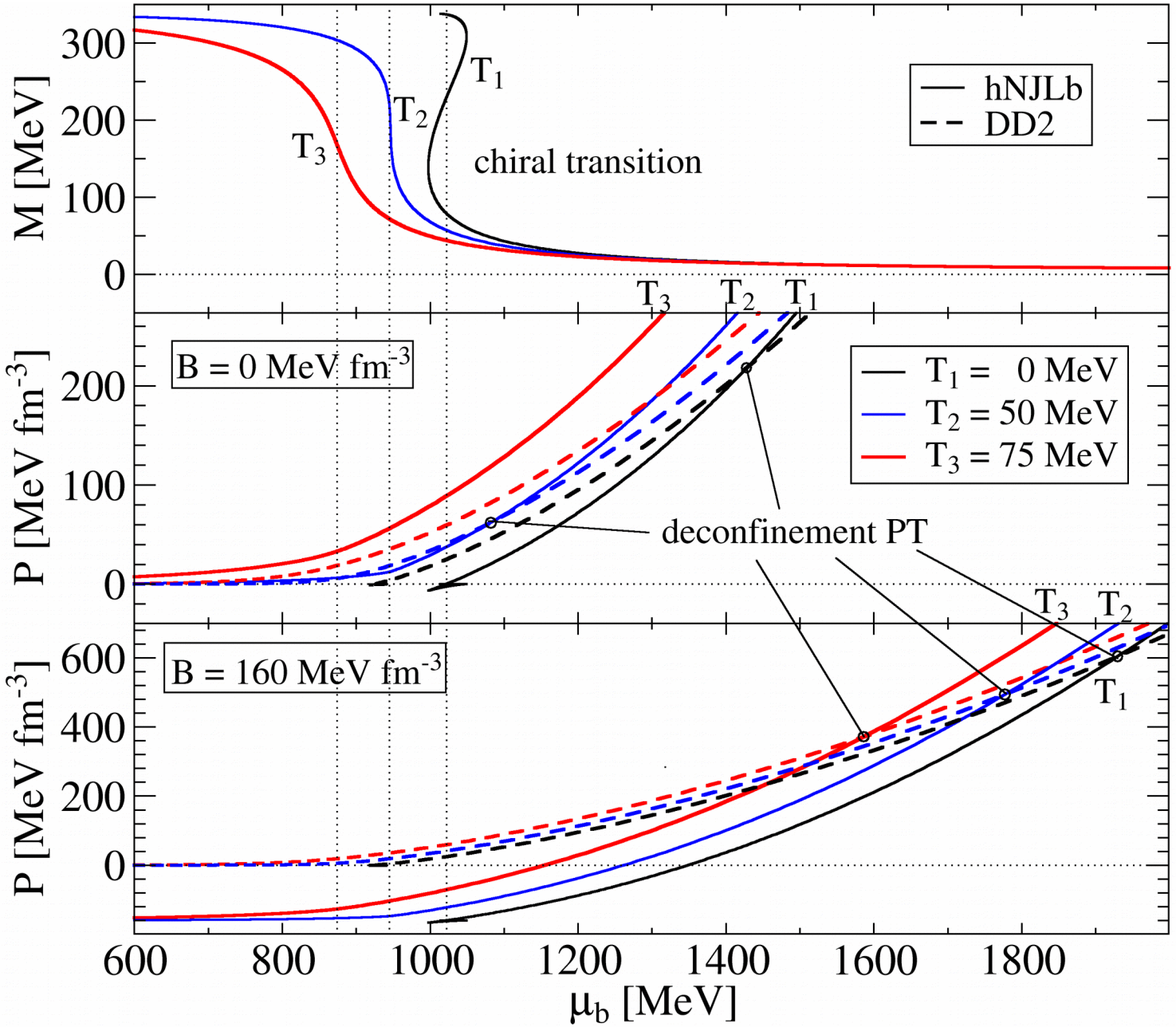


2-phase approach





2-phase construction with NJL



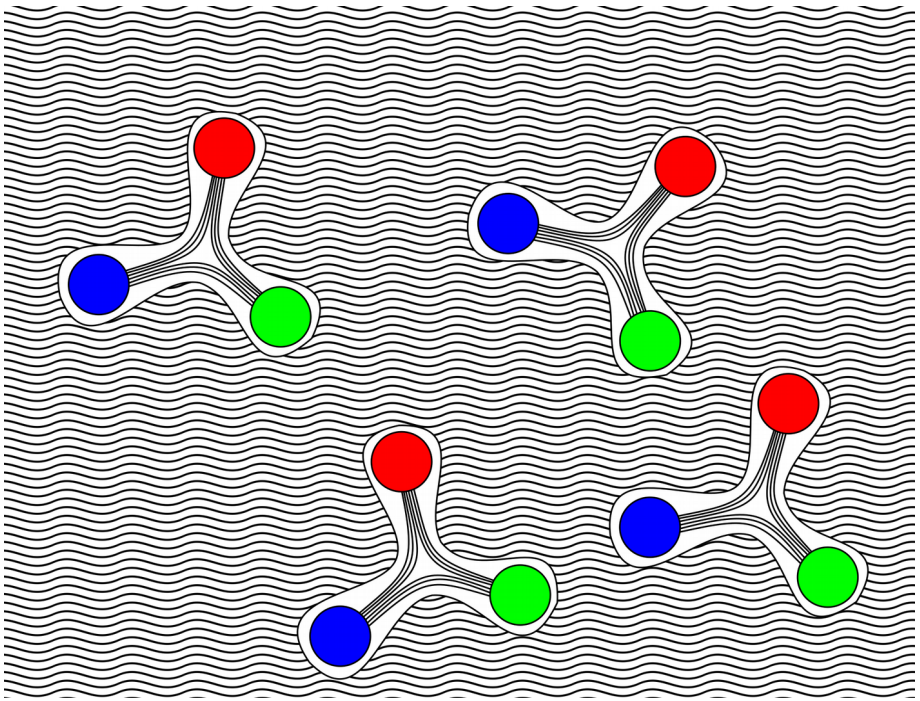
NUFB, D. Blaschke, 2016 J. Phys.: Conf. Ser. 668 012042

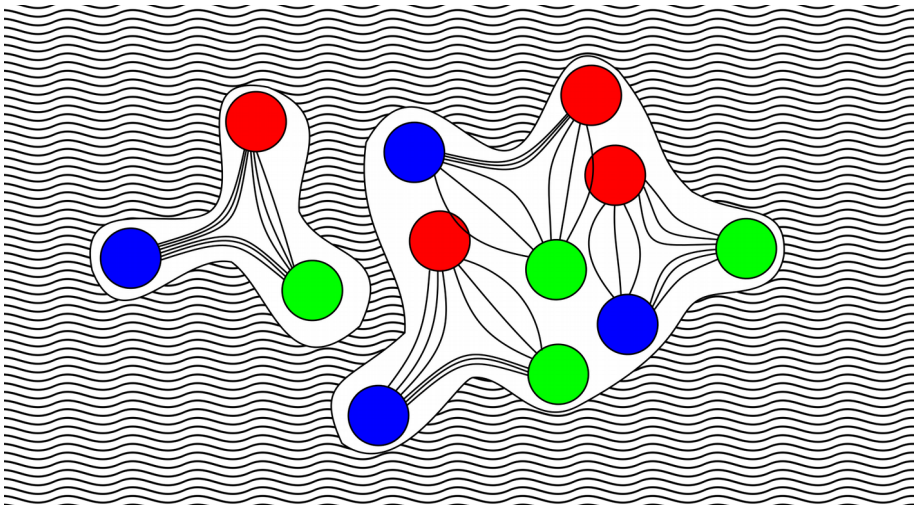
Density functional approach: Stringflip model

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

$$\sigma = \Phi\sigma_0$$

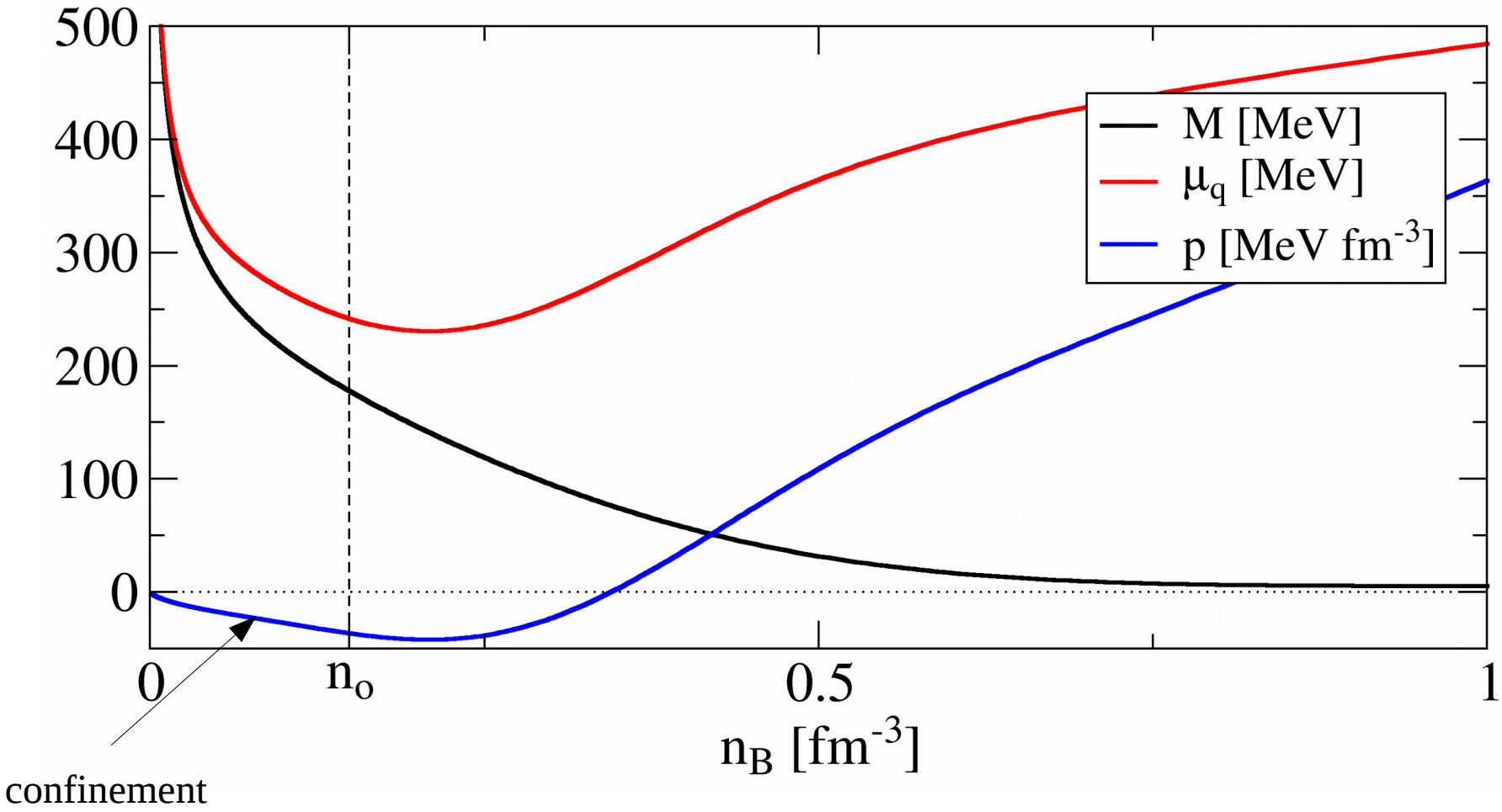
G. Ropke, et. al., Phys.Rev. D34 (1986) 3499-3513
M. Kaltenborn, **NUFB**, D. Blaschke, PRD 96, 056024 (2017)

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

Stringflip model – effective mass

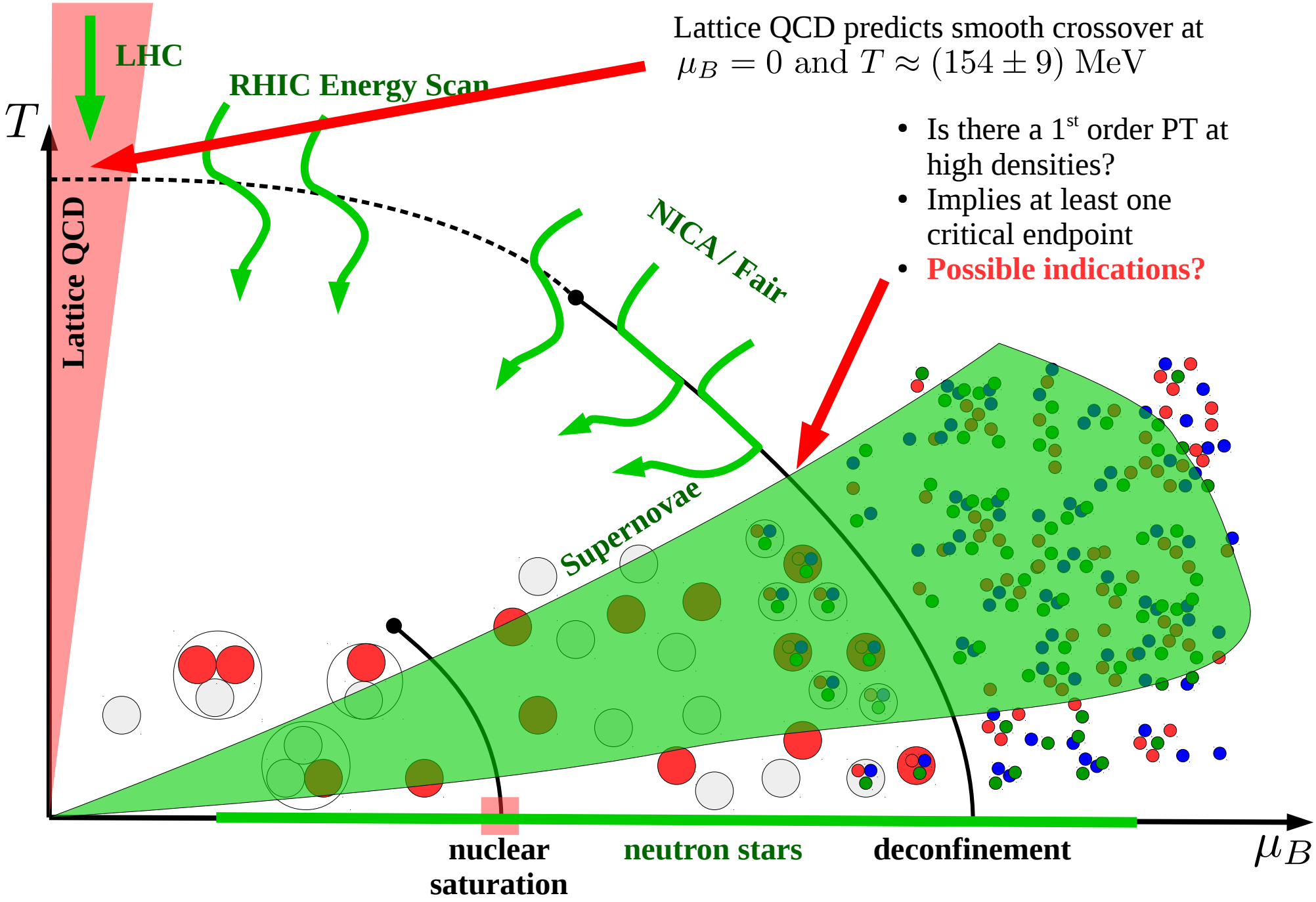
Mean-field model

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



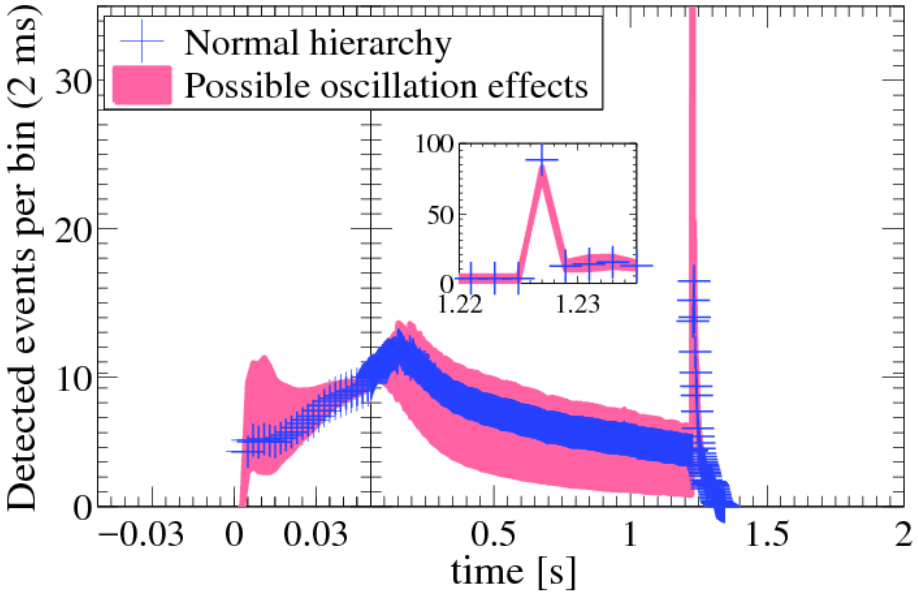
M. Kaltenborn, **NUFB**, D. Blaschke, PRD 96, 056024 (2017)

Possibility of 1st order PT at hight densities

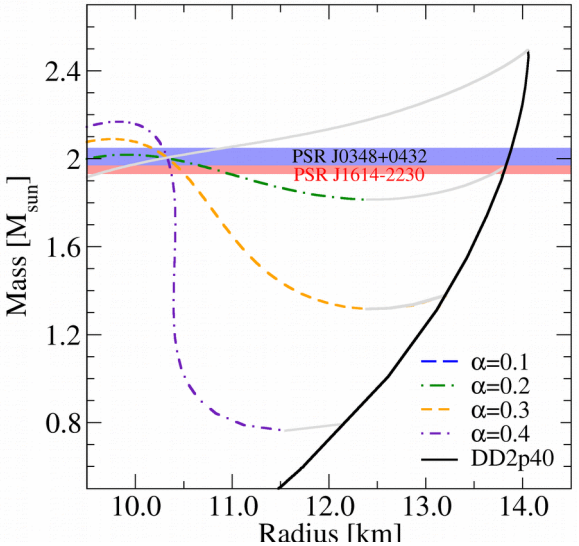


1st order PT – Astrophysics

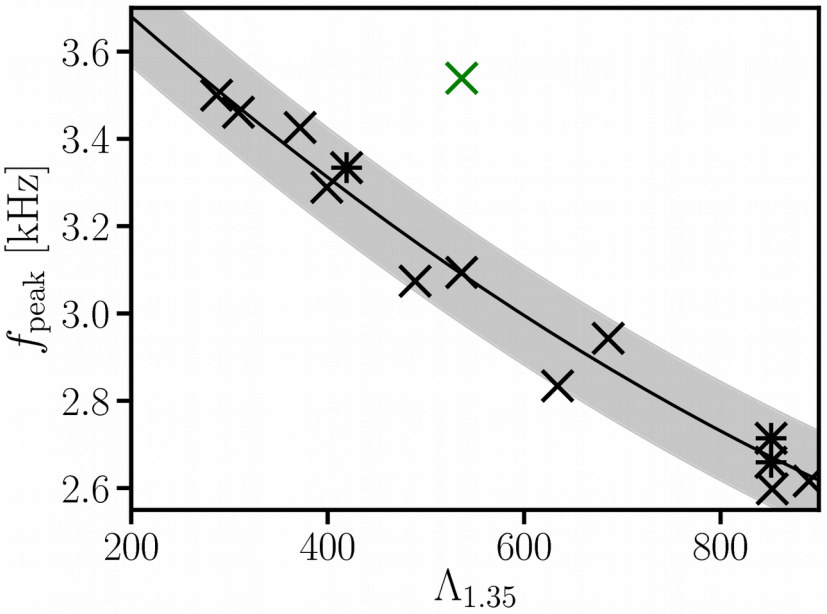
Supernova explosions
of 50Ms stars



Neutron star configurations



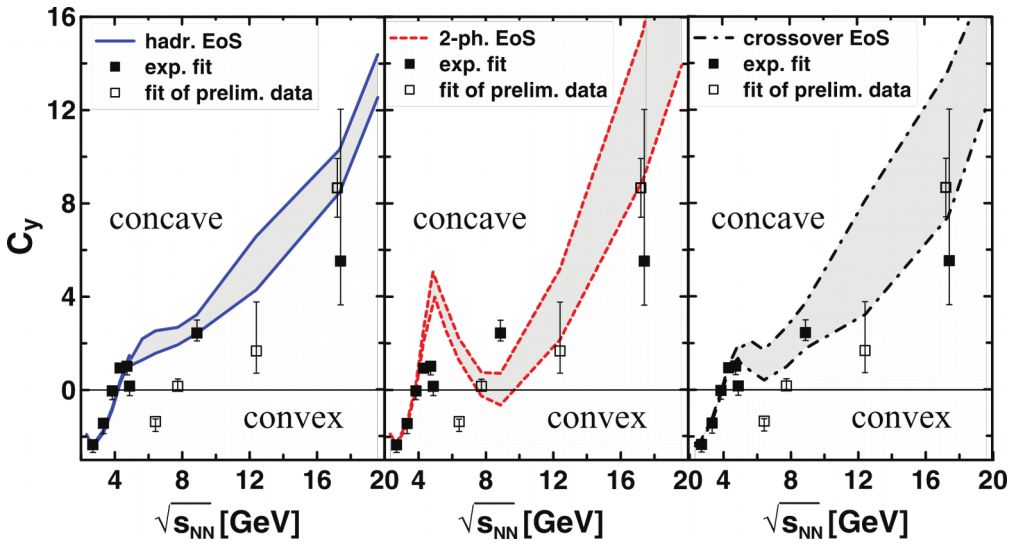
Binary neutron star mergers



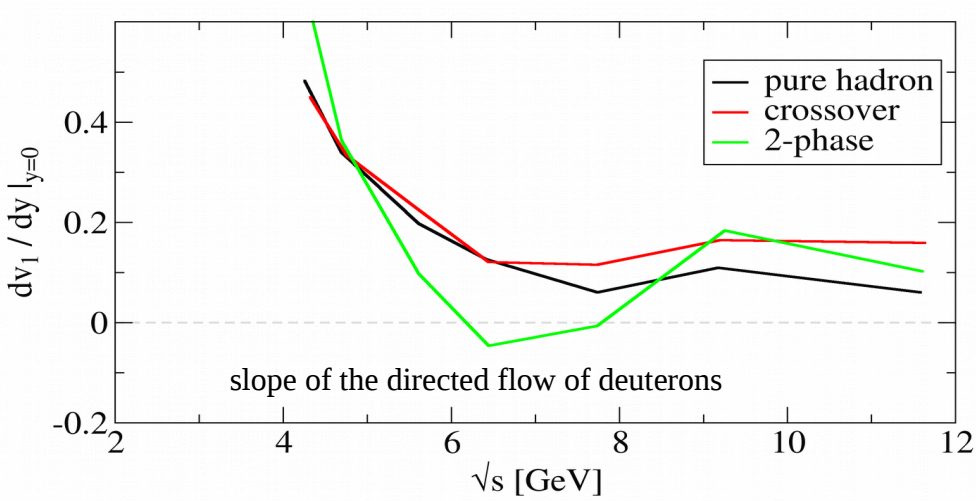
M. Kaltenborn, **NUFB**, D. Blaschke, PRD 96, 056024 (2017)
T. Fischer, **NUFB**, and others. arXiv:1712.08788
A. Bauswein, **NUFB**, and others, arXiv: 1809.01116, PRL (submitted)

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] **NUFB**, P. Batyuk, D. Blaschke, and others, Eur.Phys.J. A52 (2016) no.8, 244

Stringflip model – vector interaction

$$U^{\mathrm{VI}}(n_{\mathrm{S}}, n_{\mathrm{V}}) = a n_{\mathrm{V}}^2 + \frac{b n_{\mathrm{V}}^4}{1 + c n_{\mathrm{V}}^2} + \rho_1 n_{\mathrm{I}}^2$$

4-quark interaction

8-quark interaction

High-density correction to preserve causality

iso-spin interaction

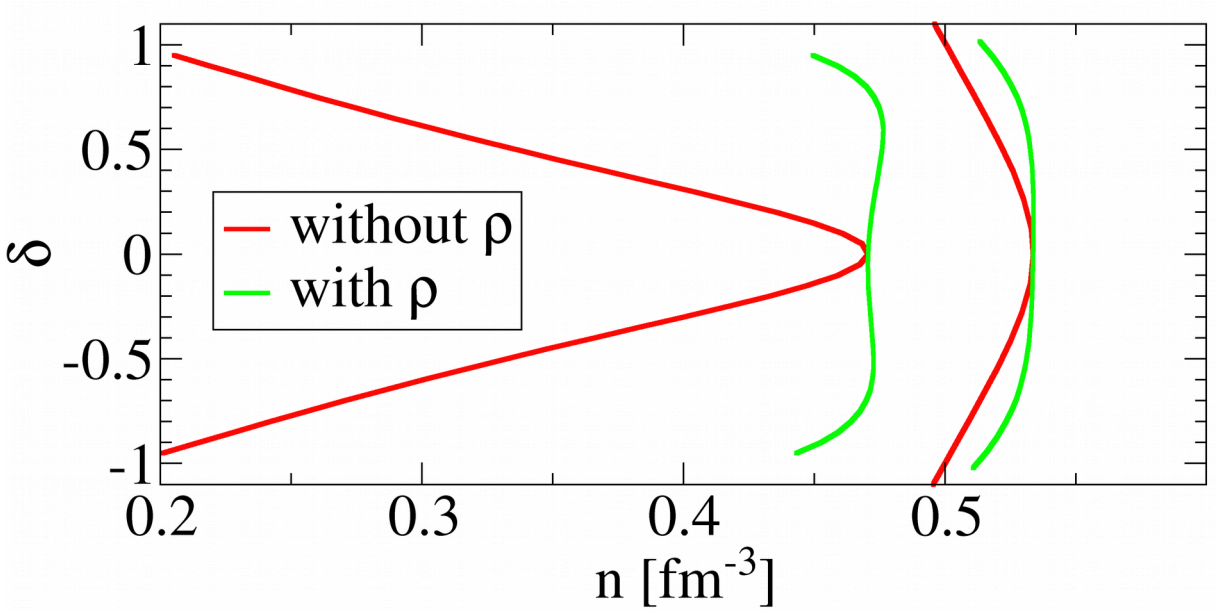
- Effective chemical potential

$$\tilde{\mu}_i = \mu_i - \left(a n + b n^3 \frac{1}{1 + c n^2} + \rho n_{\mathrm{I}} \right) - E_i^{\mathrm{R}}$$

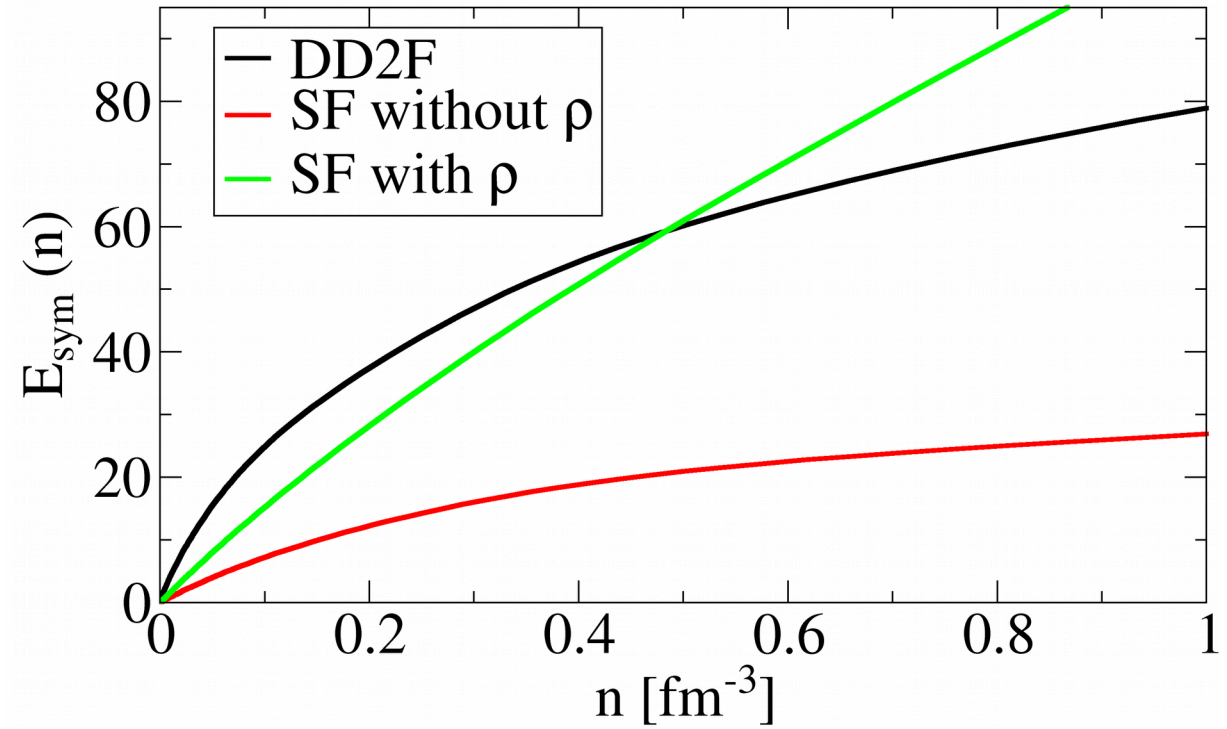
- How to adjust the coupling?

M. Kaltenborn, **NUFB**, D. Blaschke, PRD 96, 056024 (2017)
T. Fischer, **NUFB**, and others. ArXiv:1712.08788

Iso-Spin Mean Field



$\rho = 80\,\mathrm{MeVfm}^3$



Cluster expansion

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

$$\Omega = -\mathrm{Tr}\ \ln(-G_1) - \mathrm{Tr}\Sigma_1 G_1 + \Phi \qquad \text{With} \qquad \Sigma_1(1,1') = \frac{\delta\Phi}{\delta G_1(1,1')}.$$

Can be generalized for a consistent cluster expansion[3]

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

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

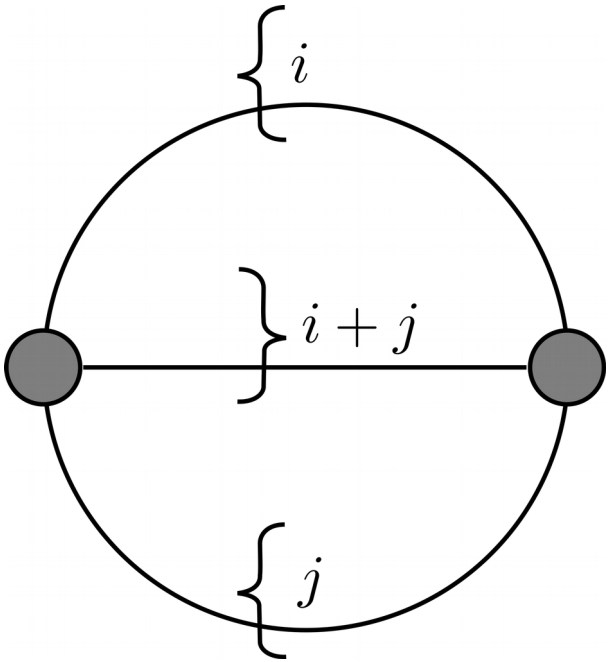
$$G_A = G_A^0 - \Sigma_A \qquad \frac{\partial\Omega}{\partial G_A} = 0$$

Reduction on generalized sunset diagrams is recommended

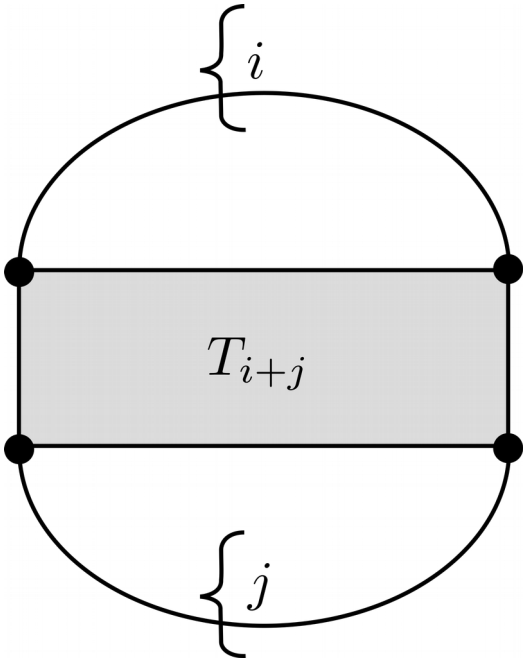
[1]Baym, G.; Kadanoff, L.P. Phys. Rev. 1961, 124, 287–299.
[2]Baym, G. Phys. Rev. 1962, 127, 1391–1401.
[3]**NUFB**, and others, Universe 2018, 4(6), 67

Cluster expansion

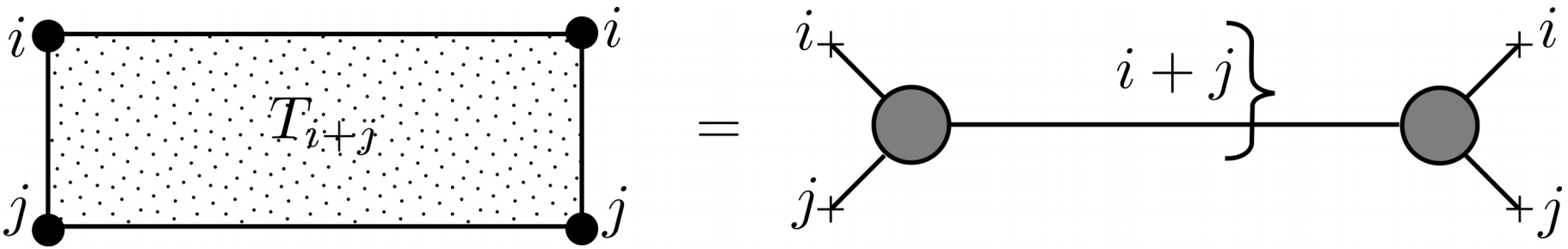
$\Phi[G_i, G_j, G_{i+j}]$



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

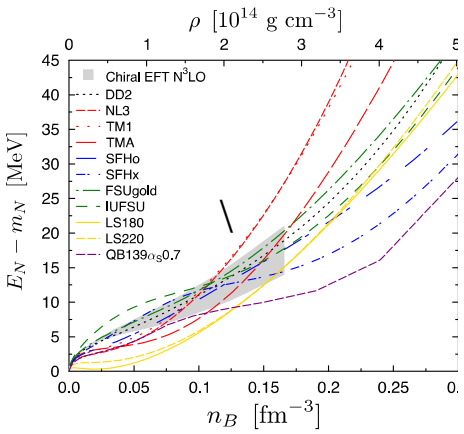


Defining the vertex



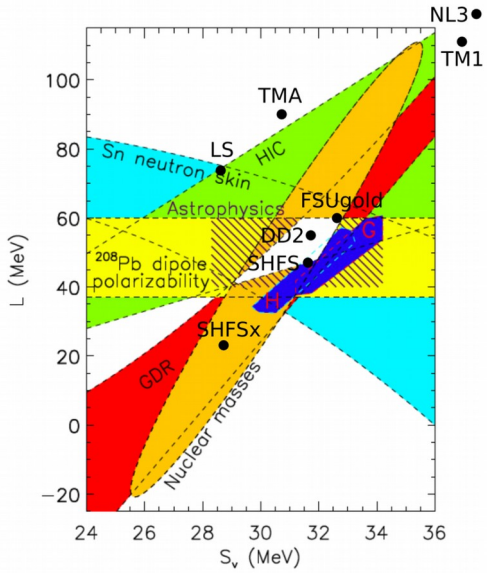
NUFB, and others, Universe 2018, 4(6), 67

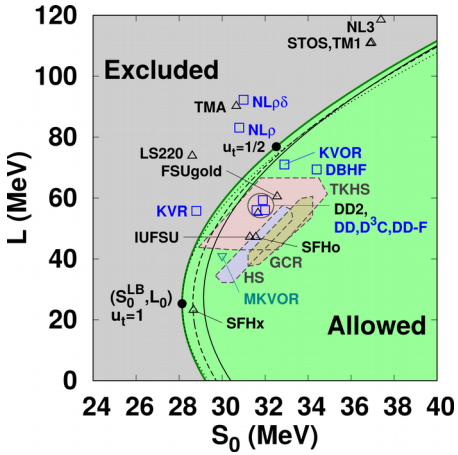
Constraints to consider



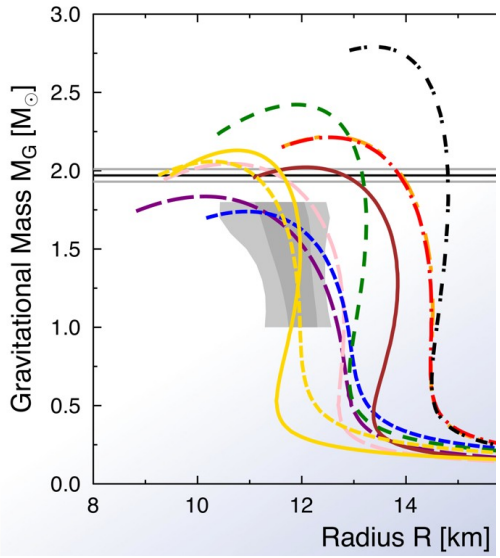
Chiral EFT[1]

Symmetry energy[2]

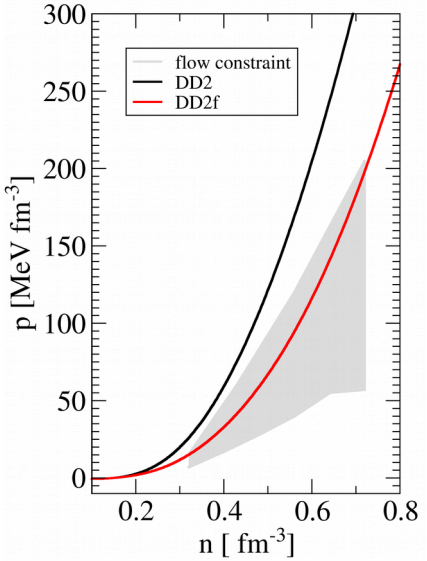




Unitary Constraint[3]



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

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!