Towards a unified quark-hadron equation of state

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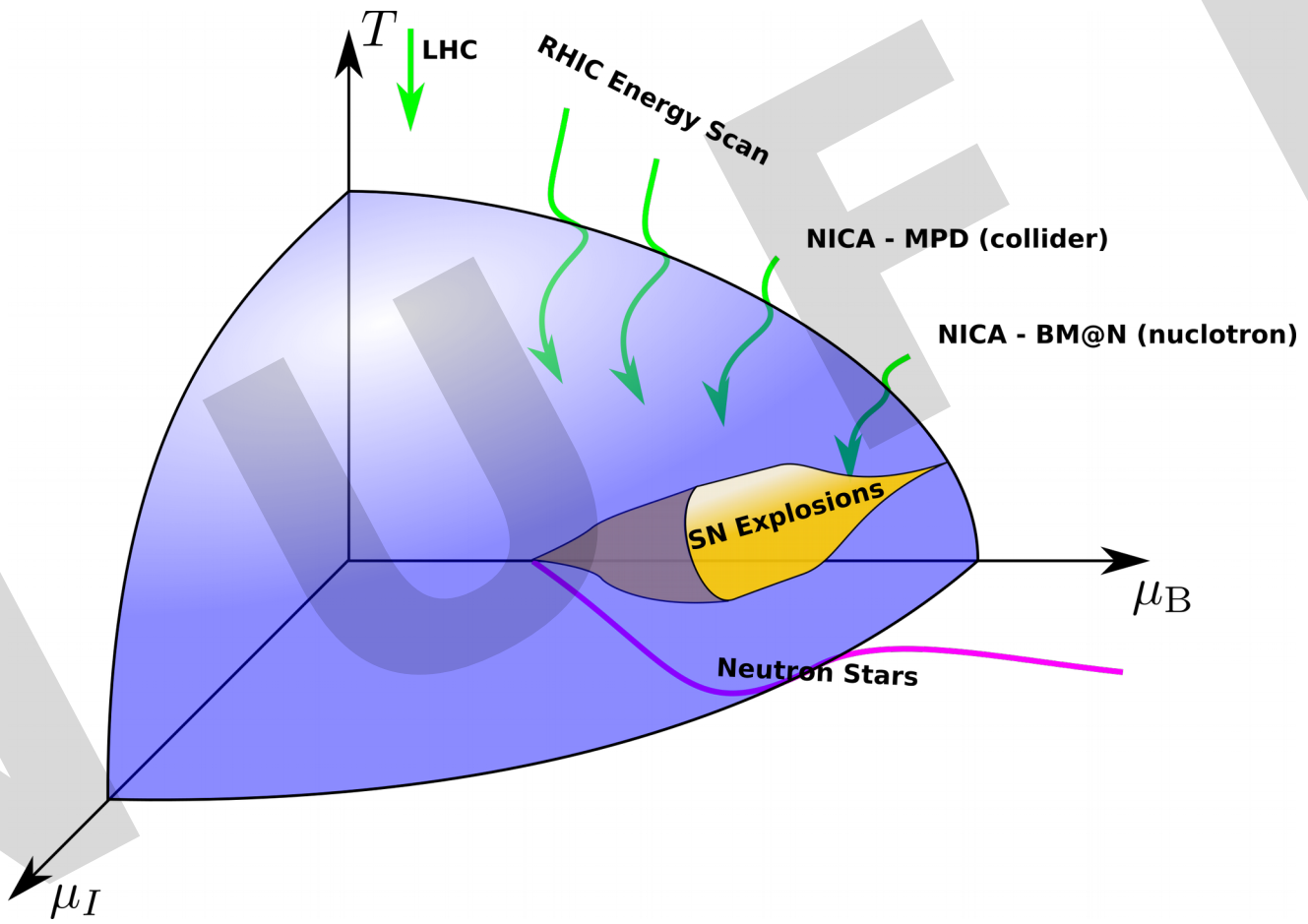
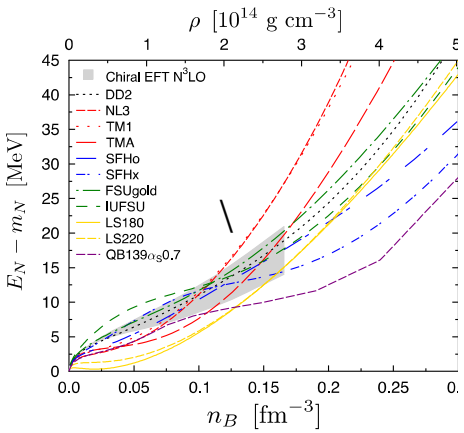
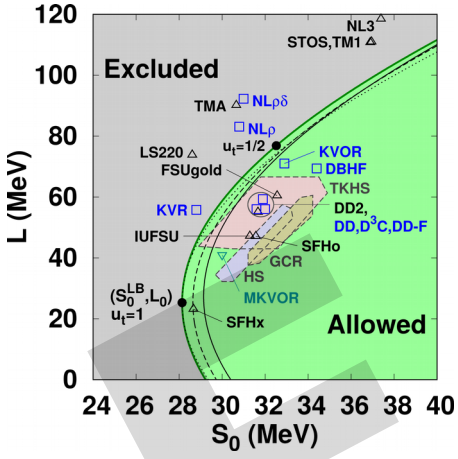
Possible phase-diagrams



Constraints to consider

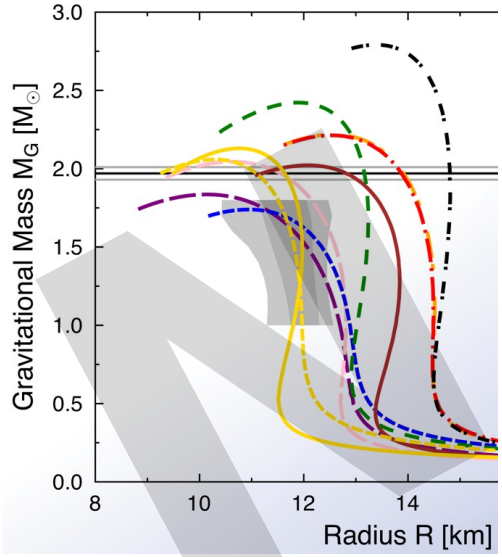


Chiral EFT[1]

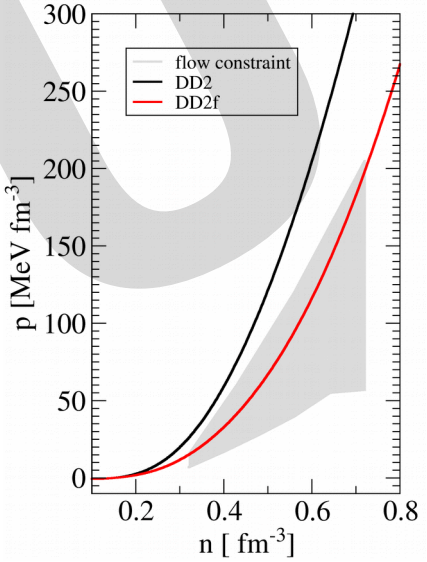


Symmetry energy[2]

Unitary Constraint[3]



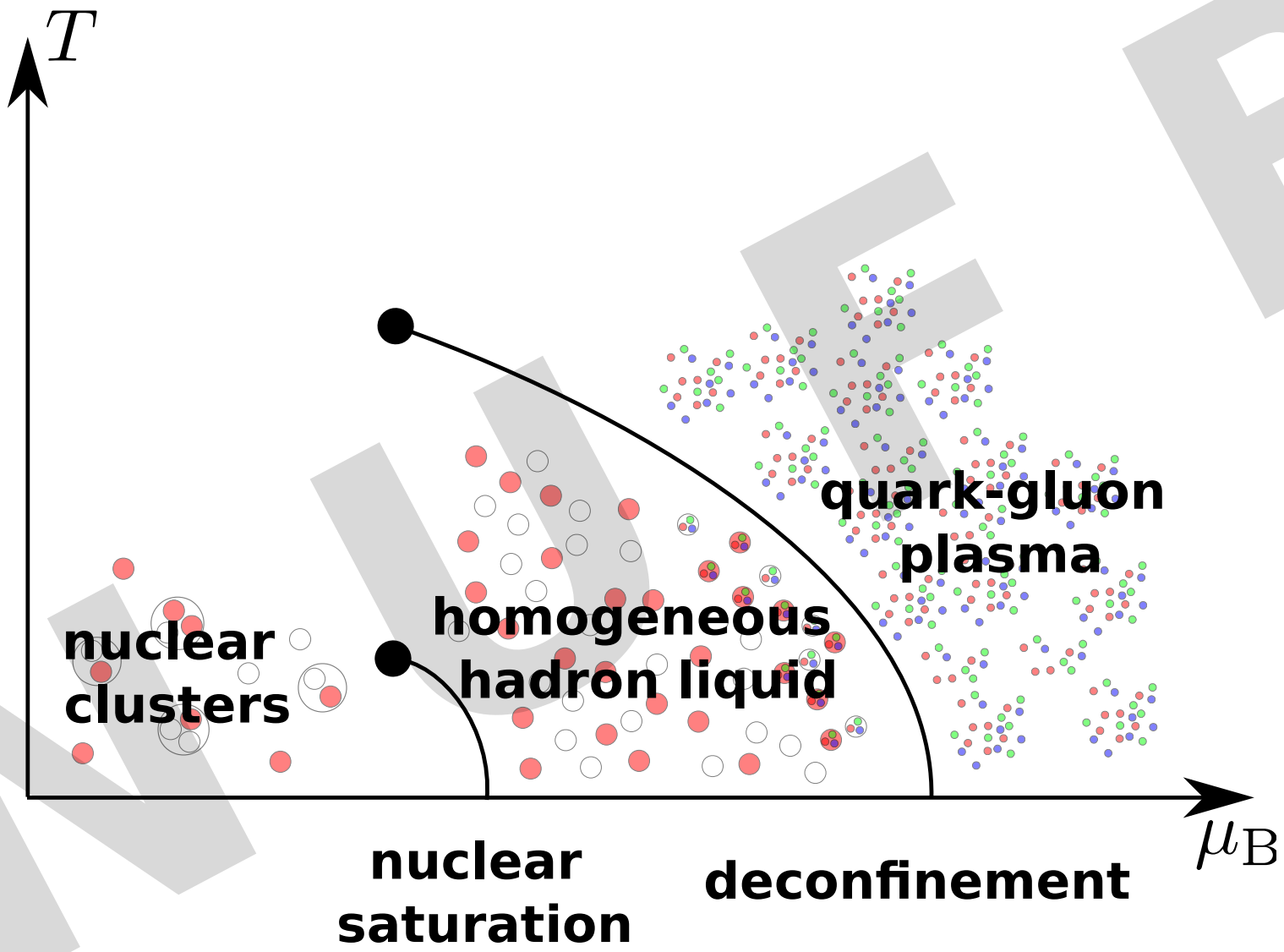
Neutronstar mass



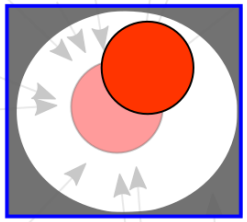
Flow constraint

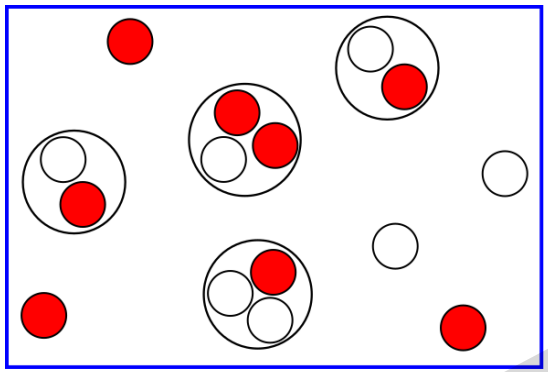
[1] T. Fischer, et. al., (2014) EPJA50, 46
[2] Lattimer & Lim (2013) ApJ 771, 14
[3] Tews, Lattimer, Ohnishi, Kolomeitsev, arXiv:1611.07133
[4] S. Typel, PRC 81 (2010), 015803

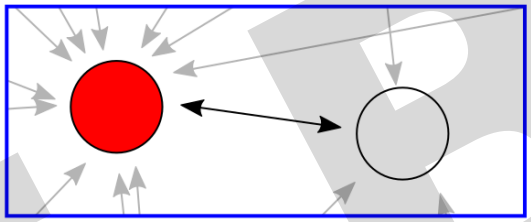
Outline



Nuclear clusters



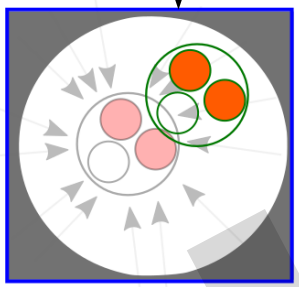


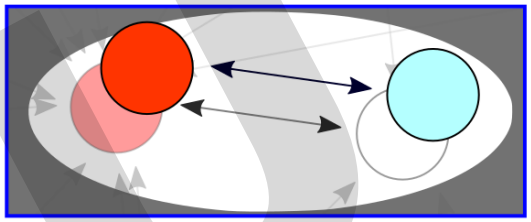


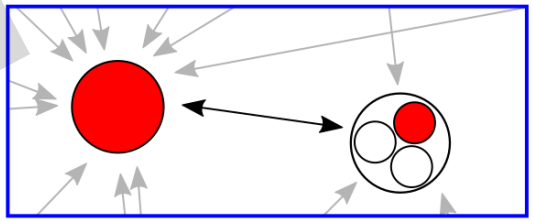
medium modification of free particles

ideal mixture and chemical picture

virial expansion and two-particle correlation



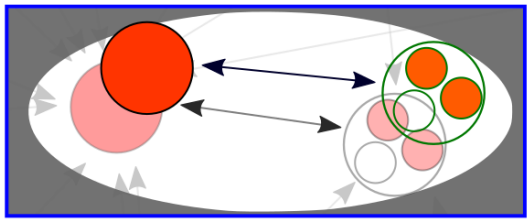




cluster-meanfield

medium modifications of particles and correlations

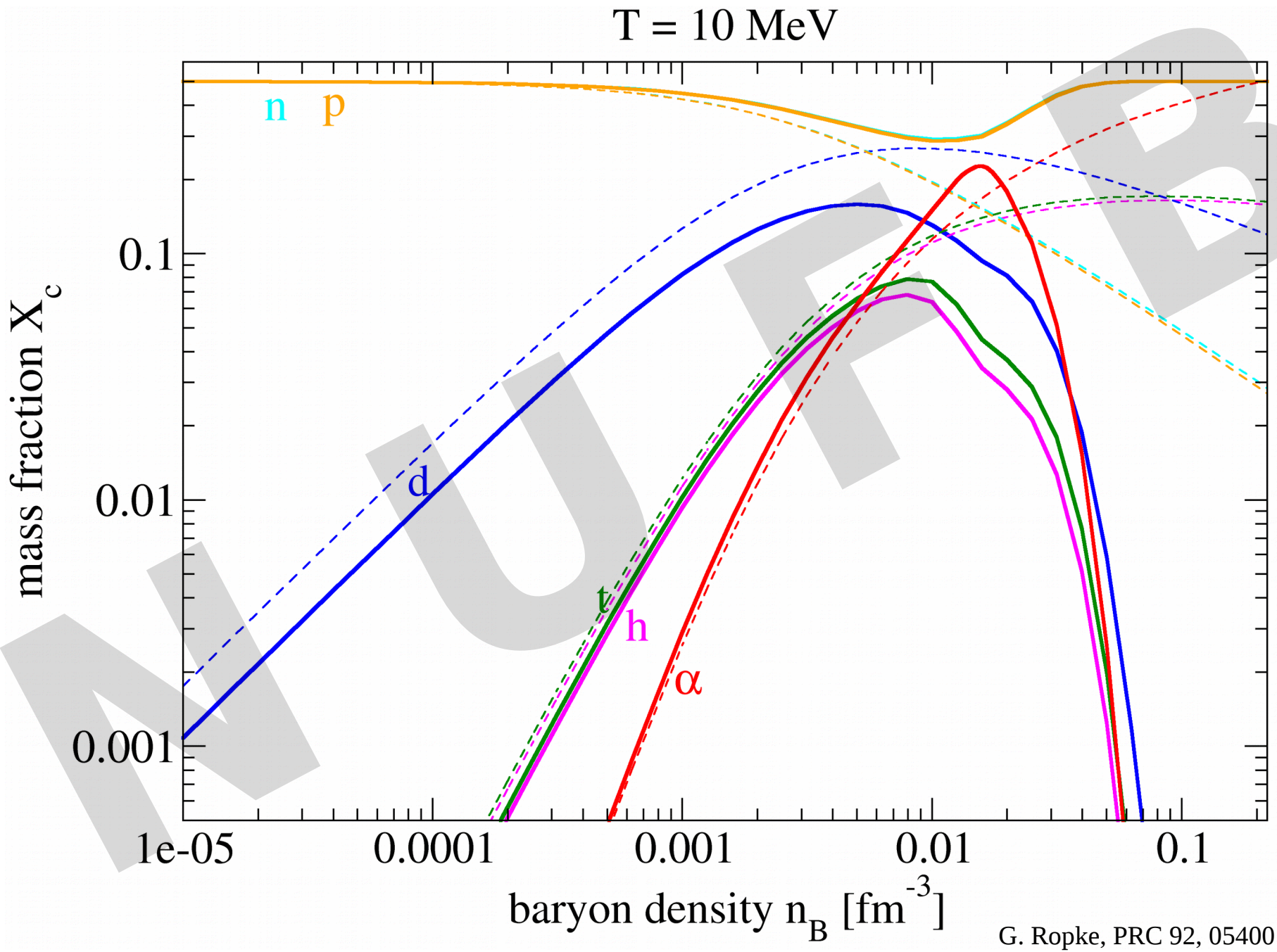
cluster-virial expansion



cluster-virial expansion with medium effects

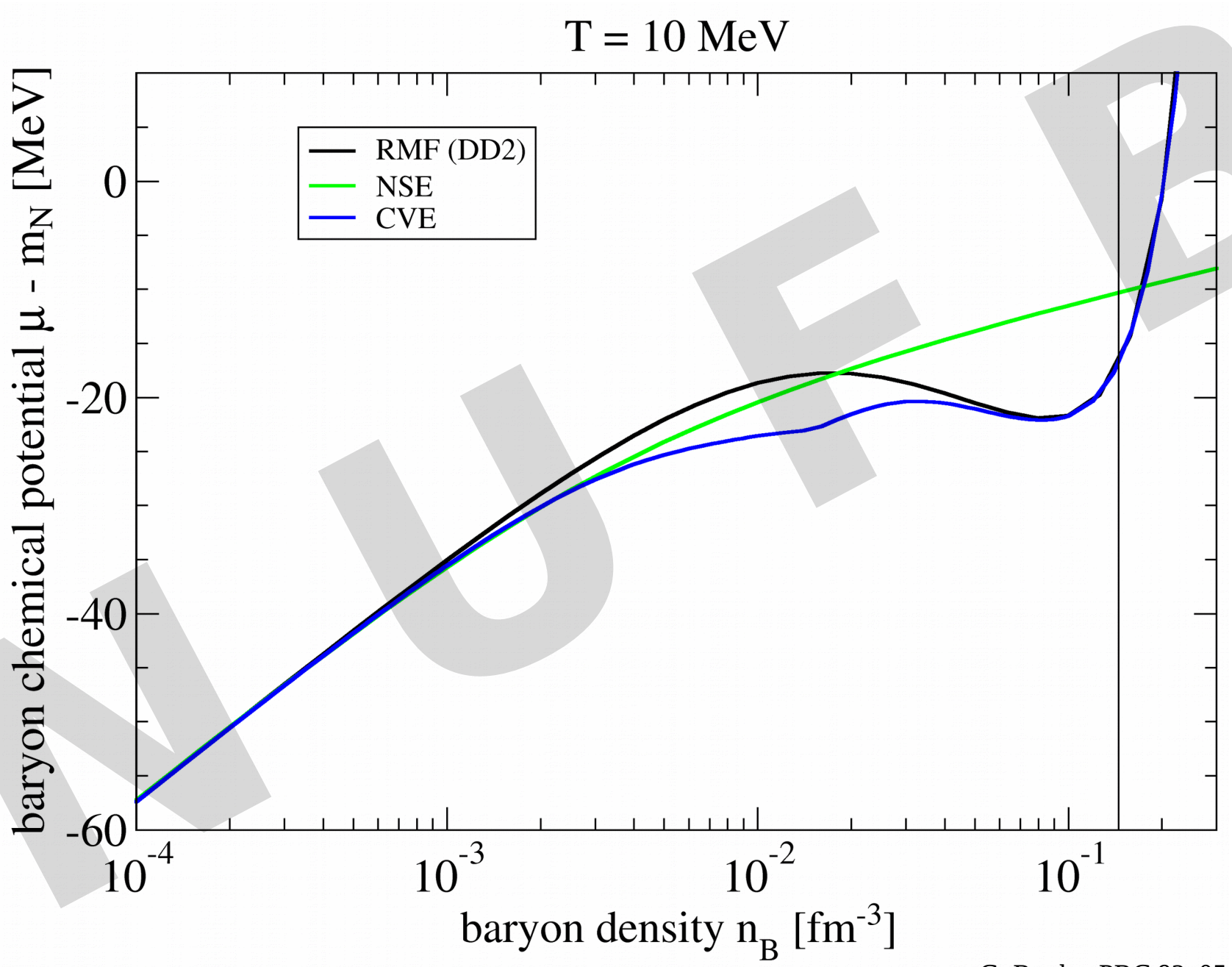
G. Ropke, N.-U. Bastian, D. Blaschke, T. Klahn, S. Typel and H.~H. Wolter, Nucl. Phys. A **897**, 70 (2013)

Nuclear clusters



G. Ropke, PRC 92, 054001 (2015)

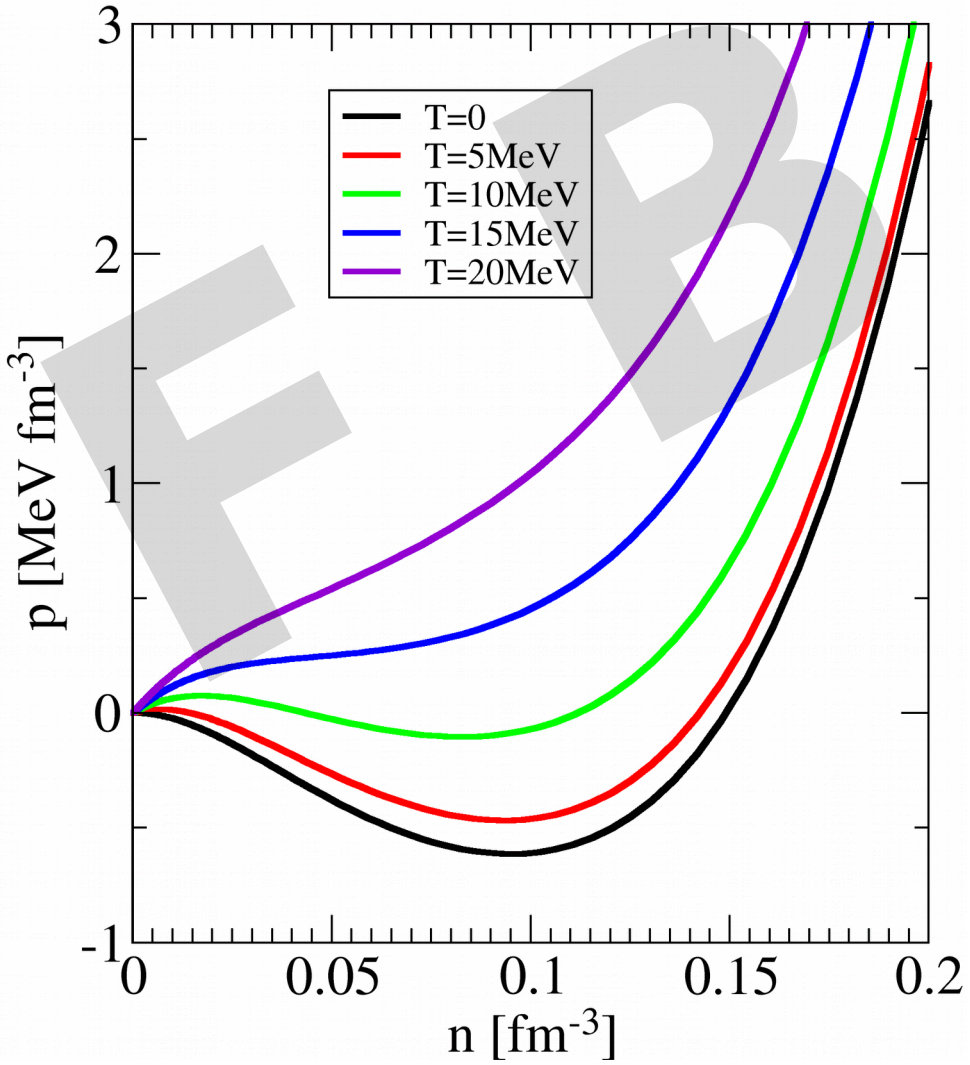
Nuclear clusters



G. Ropke, PRC 92, 054001 (2015)

Homogeneous nuclear matter

- Density dependent relativistic mean field (RMF) model
- Parameters adjusted to nuclear data
- Fulfills all solid constrains perfect
  - Up to saturation density
- Variations like DD2f and DD2vex alter behavior at



Typel, Wolter, NPA **656** (1999) 331
Typel, Röpke, Klähn, Blaschke, Wolter, PRC **81** 015803

QGP: Density functionals

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

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

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

$$U(\bar{q}q, \bar{q}\gamma^{\mu}q) = U(n_{\text{S}}, n_{\text{V}}) + \Sigma_{\text{S}}(\bar{q}q - n_{\text{S}}) + \Sigma_{\text{V}}(\bar{q}\gamma^{\mu}q - n_{\text{V}}) + \dots$$

derivatives

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

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

with

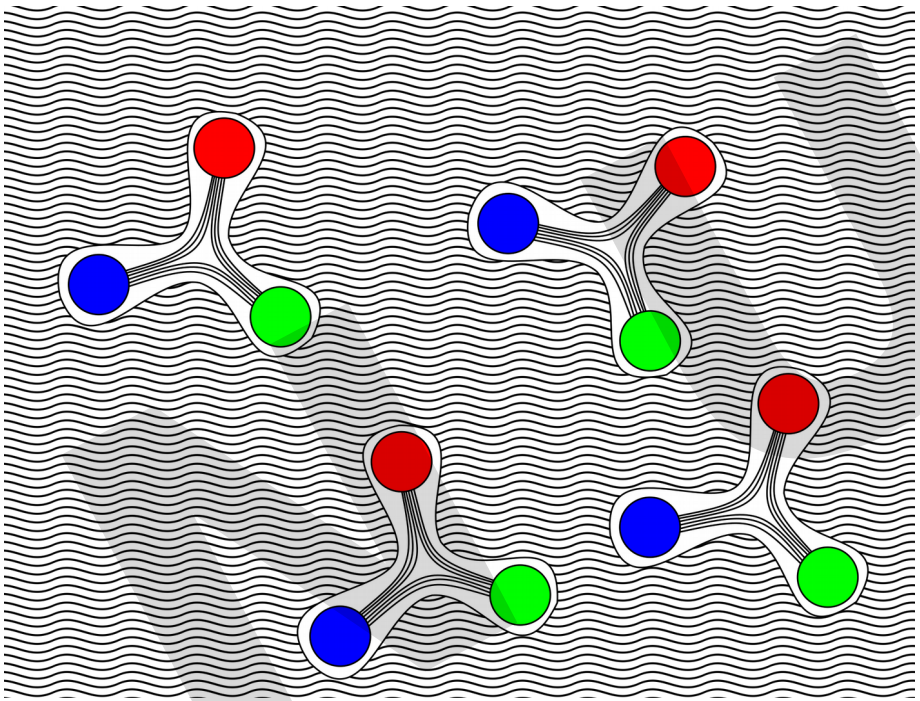
$$n_s = \langle\bar{q}q\rangle \ , \ n_v = \langle\bar{q}\gamma^0 q\rangle \qquad M = m + \Sigma_{\text{S}} \ , \ \tilde{\mu} = \mu - \Sigma_{\text{V}}$$

QGP: Stringflip model

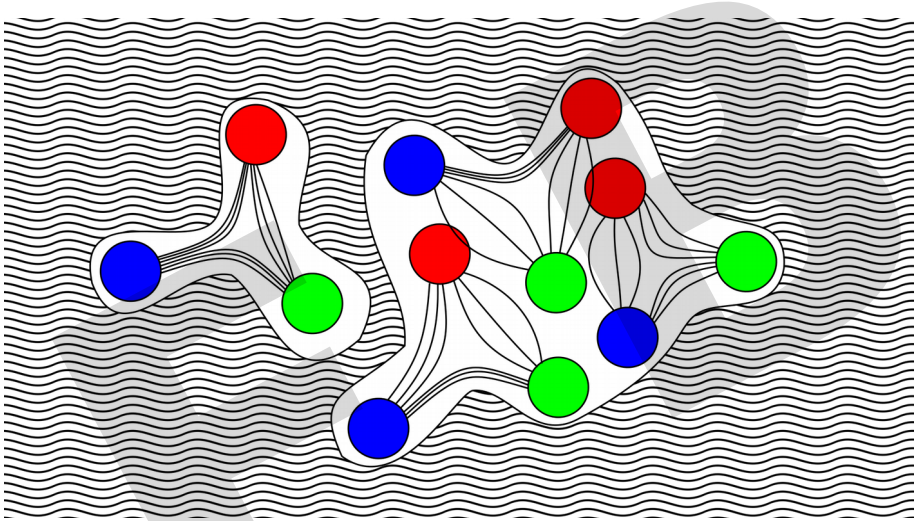
Low density

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

$$\sigma = \sigma_0$$



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



High density

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

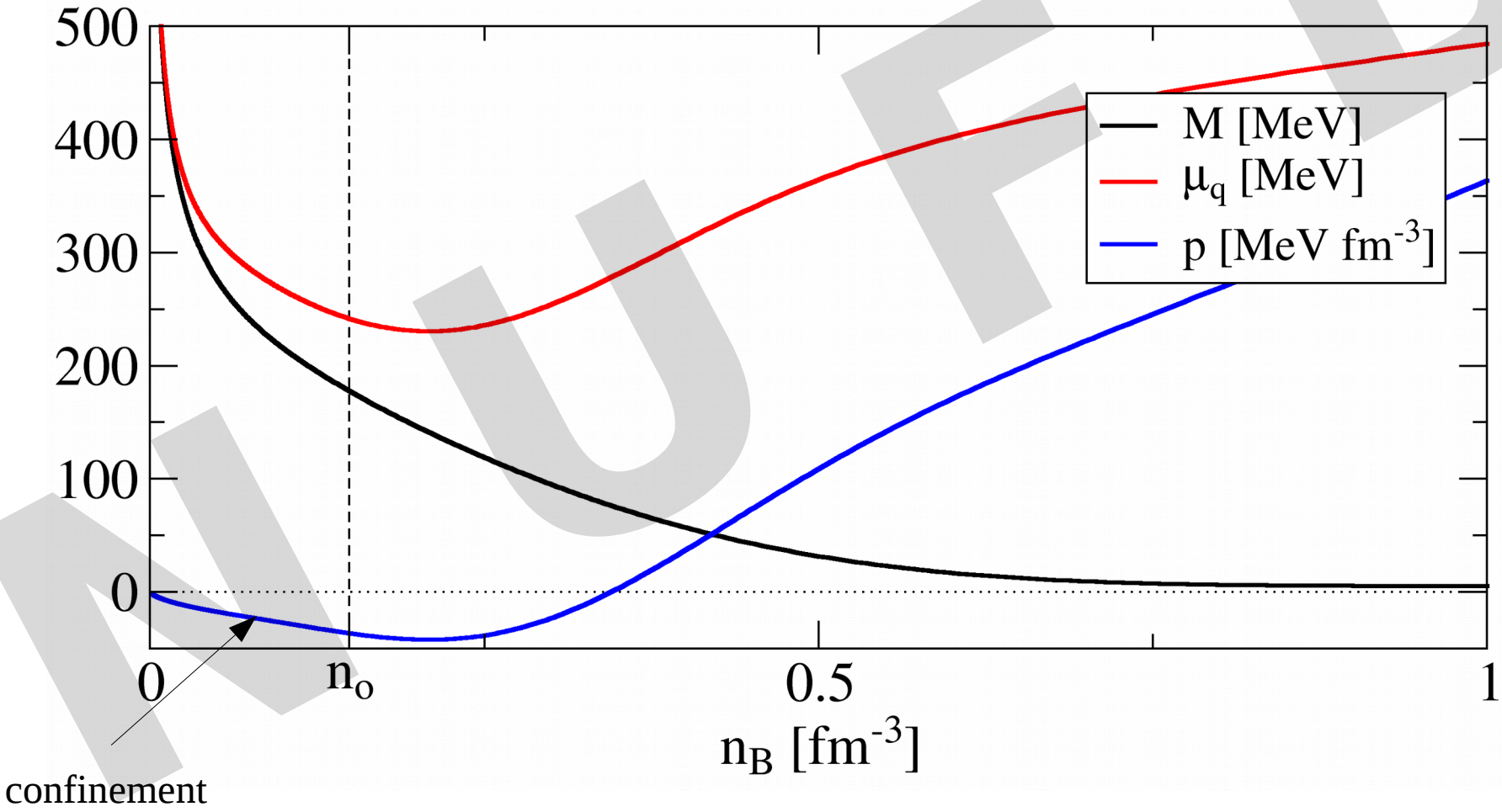
$$\sigma = \Phi\sigma_0$$

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

Stringflip model – effective mass

Mean-field model

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



Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Stringflip model – vector interaction

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

4-quark interaction

8-quark interaction

High-density correction to preserve causality

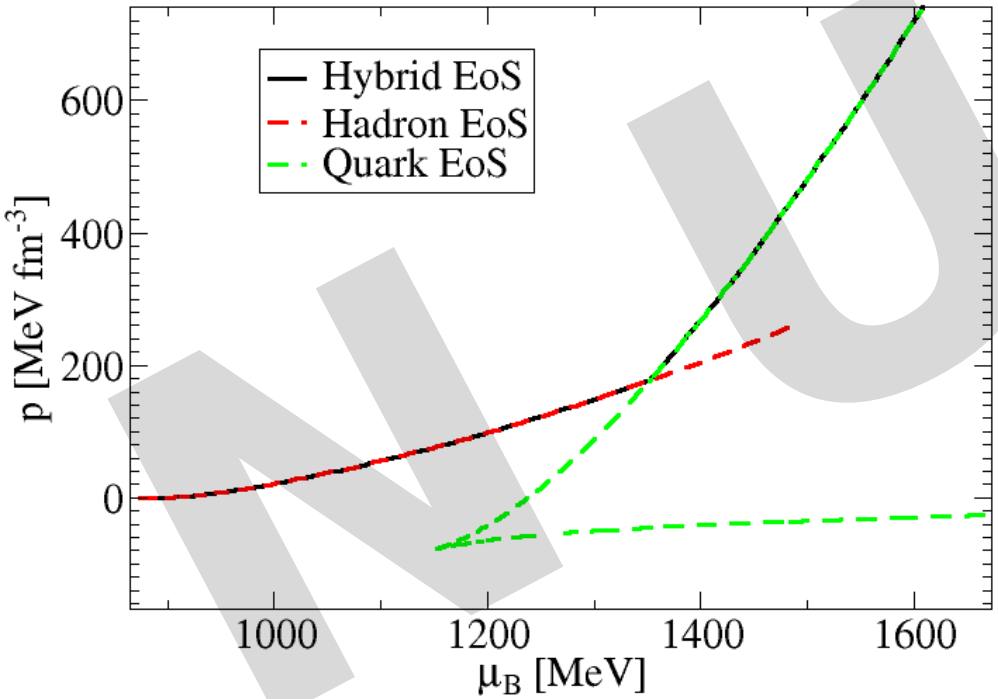
- Effective chemical potential

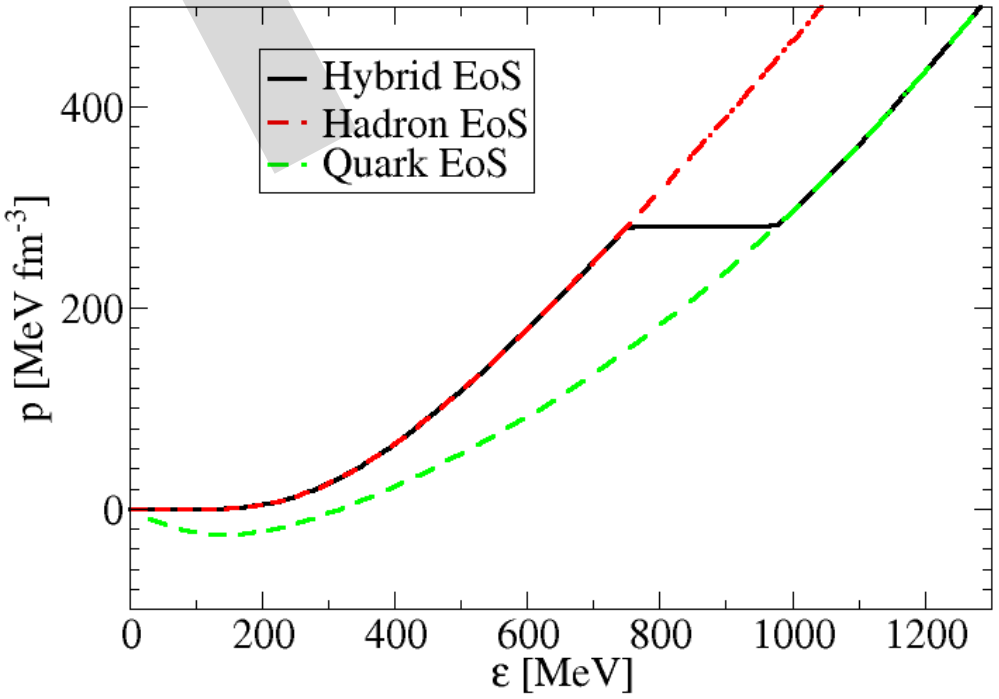
$$\tilde{\mu}_i = \mu_i - \left(a n + b n^3 \frac{1}{1 + c n^2} \right) - E_i^{\mathrm{R}}$$

Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Hybrid EOS - phasetransition

- 2-phase approach: phase transition via Maxwell construction

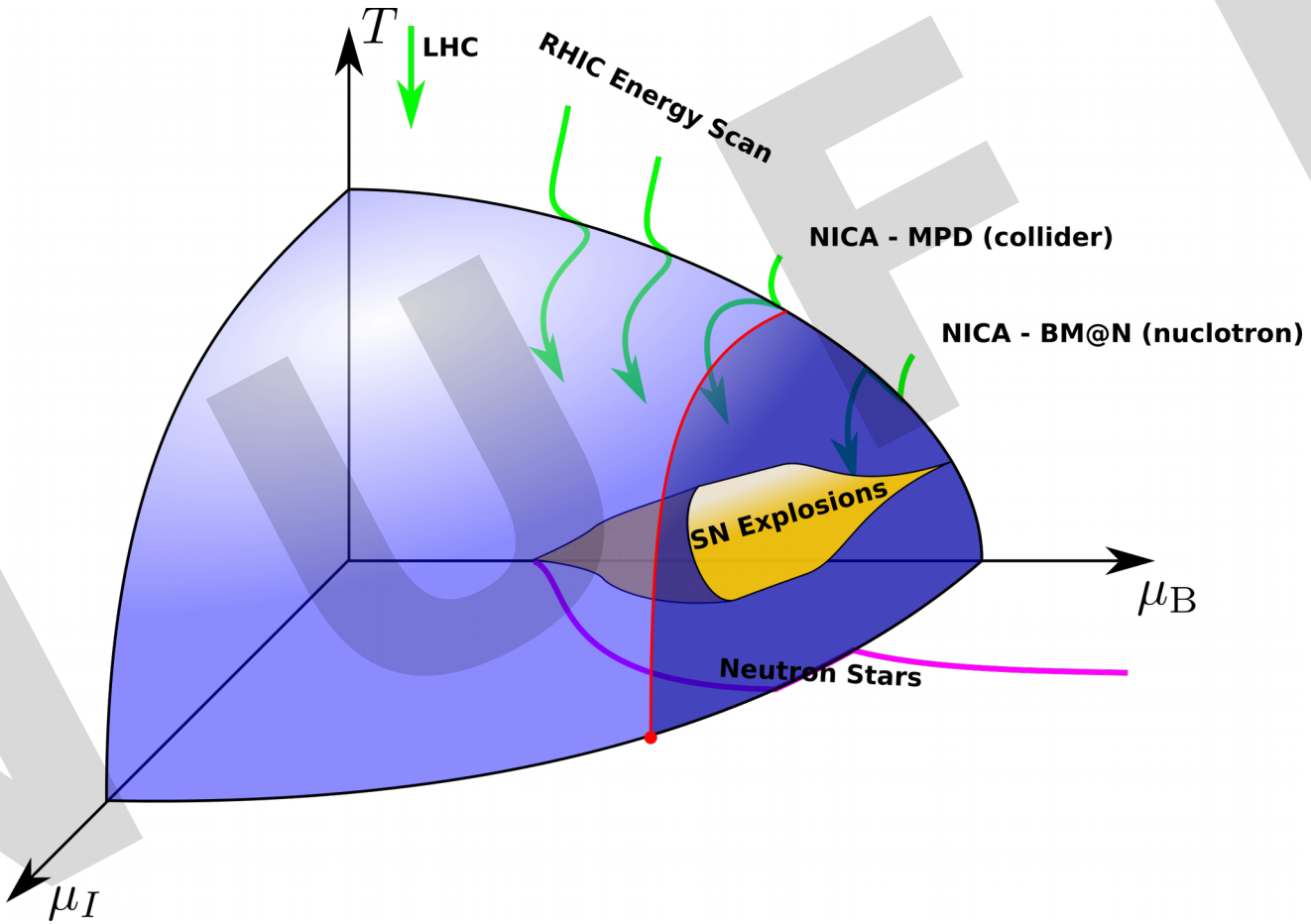




Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Possible phase-diagrams

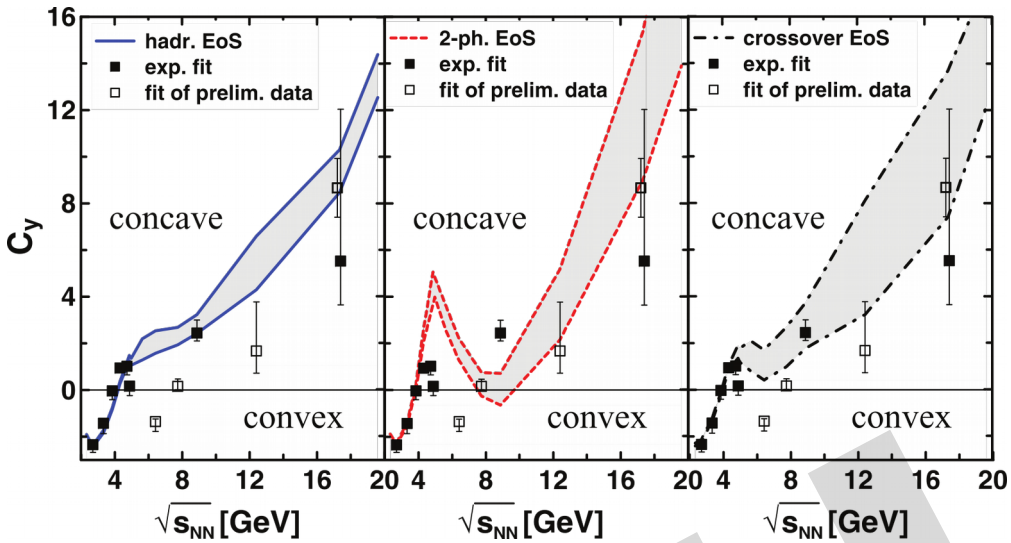
First order phase-transition at high densities?



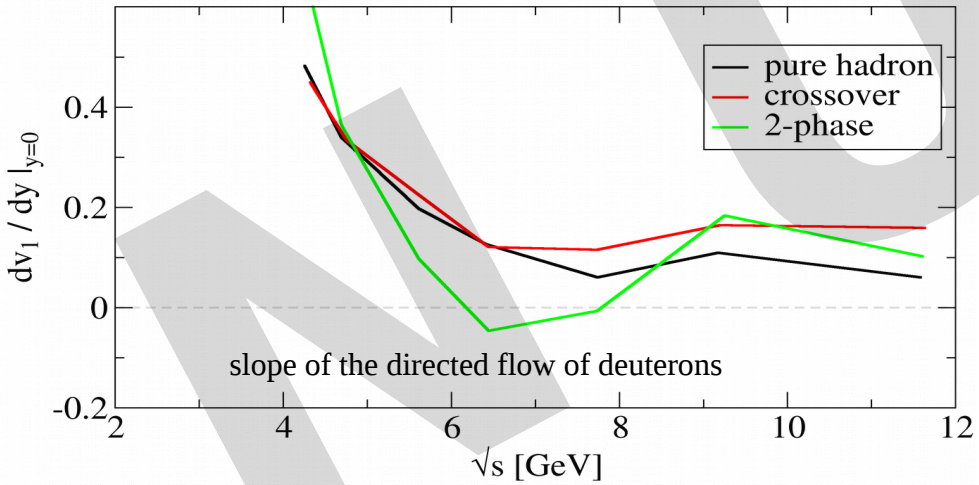
Possible indicators in measurable systems?

Possible signals for 1st order phase transition

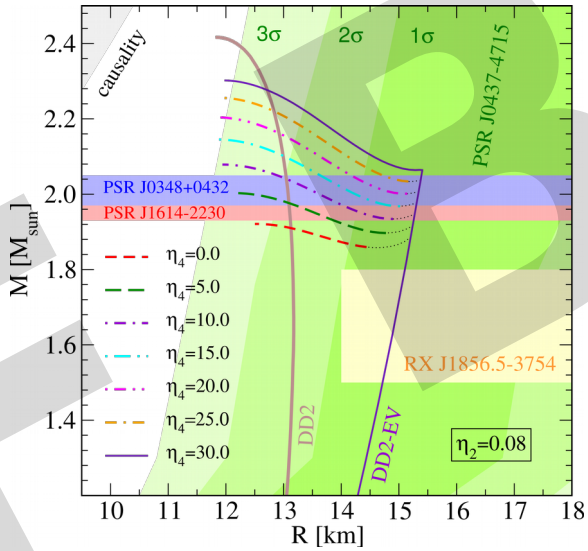
strong signal (wiggle) in the baryon stopping signal [1]



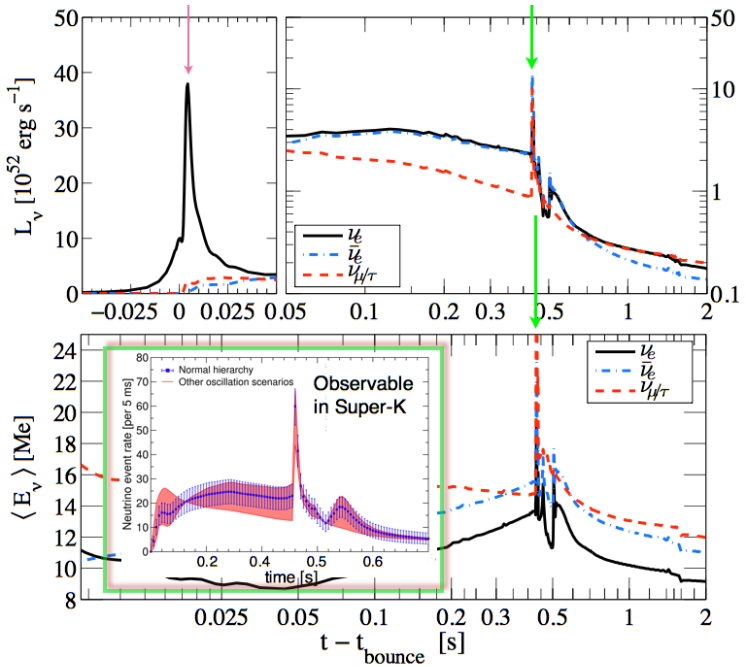
Anti-flow of clusters occur [2]



(twin-) Star configurations [3]



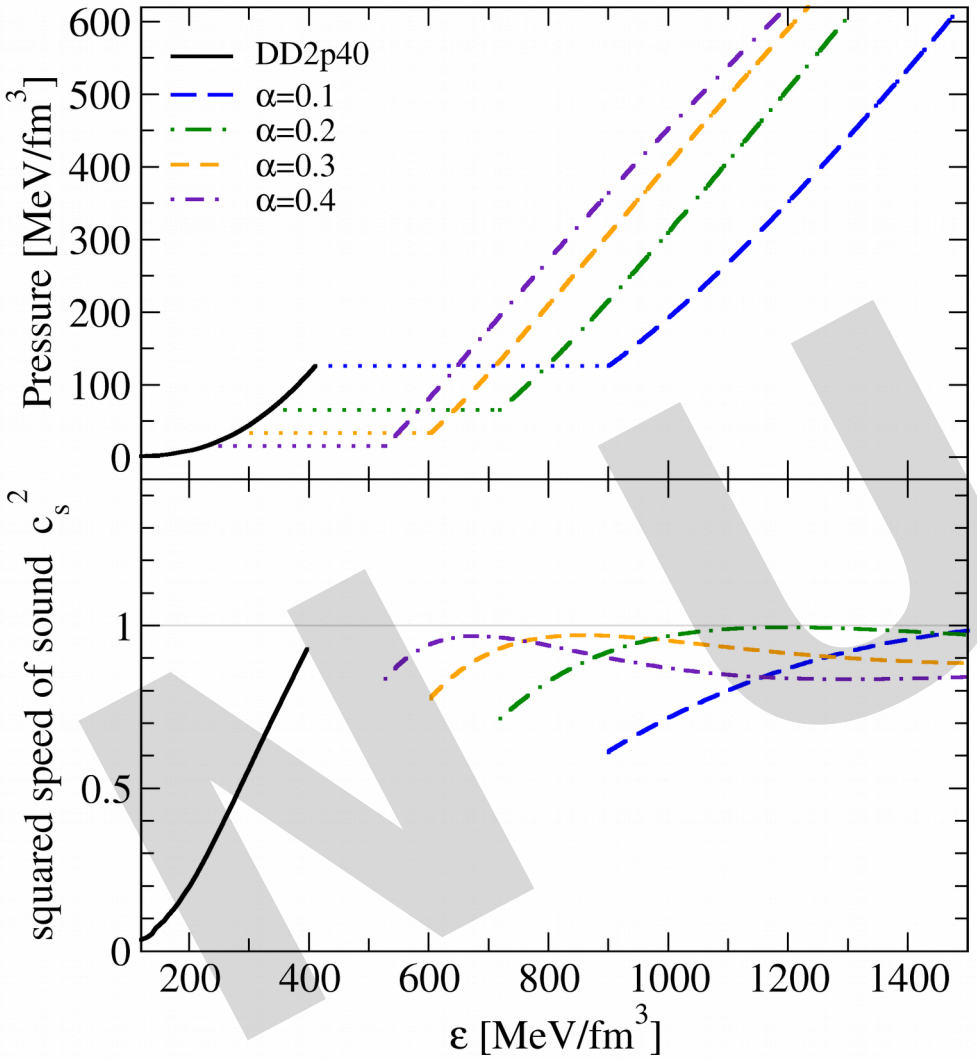
Additional neutrino outburst(s) in all flavors [4,5]

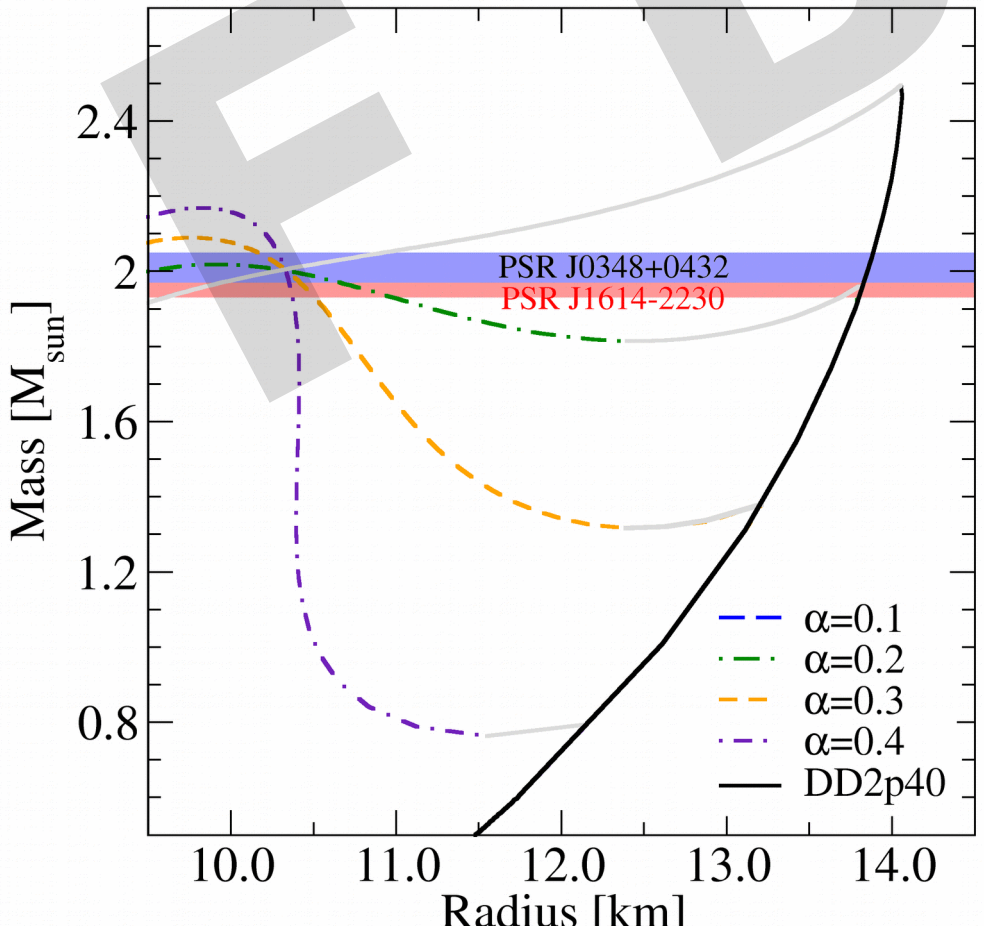


[1] Yu. B. Ivanov, PRC 87, 064904 (2013)
[2] Bastian, Batyuk, Blaschke, et al., Eur.Phys.J. A52 (2016) no.8, 244
[3] Benic, Blaschke, Alvarez-Castillo, Fischer, Typel, A&A 577, A40 (2015)
[4] Sagert et al. (2009), PRL 102, 081101
[5] Dasgupta et at. (2010), PRC 81

Hybrid EOS - parameters

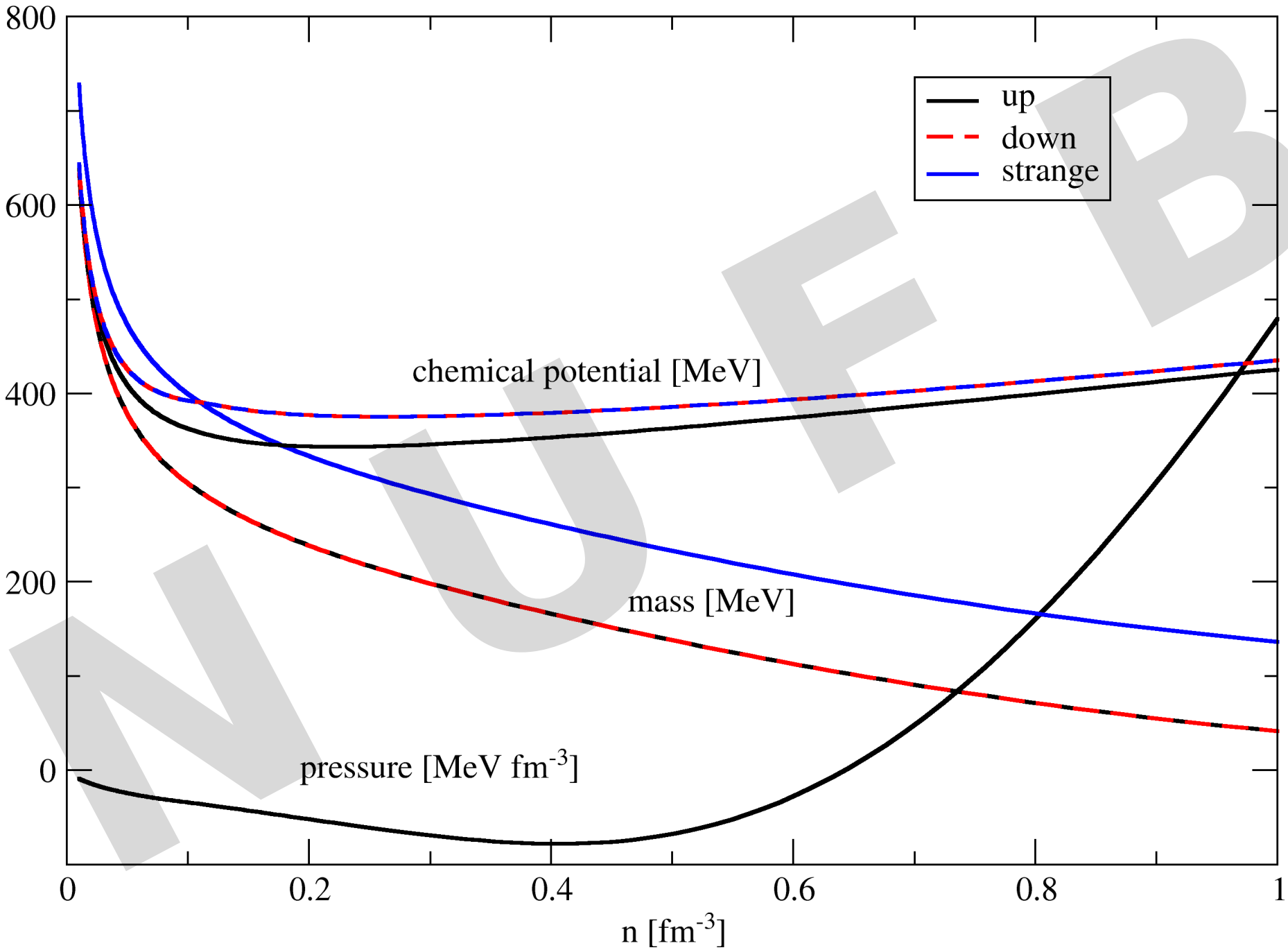
$\underline{\alpha}, a, b$





Kaltenborn, Bastian, Blaschke, arXiv:1701.04400

Exploratory calculation with strangeness



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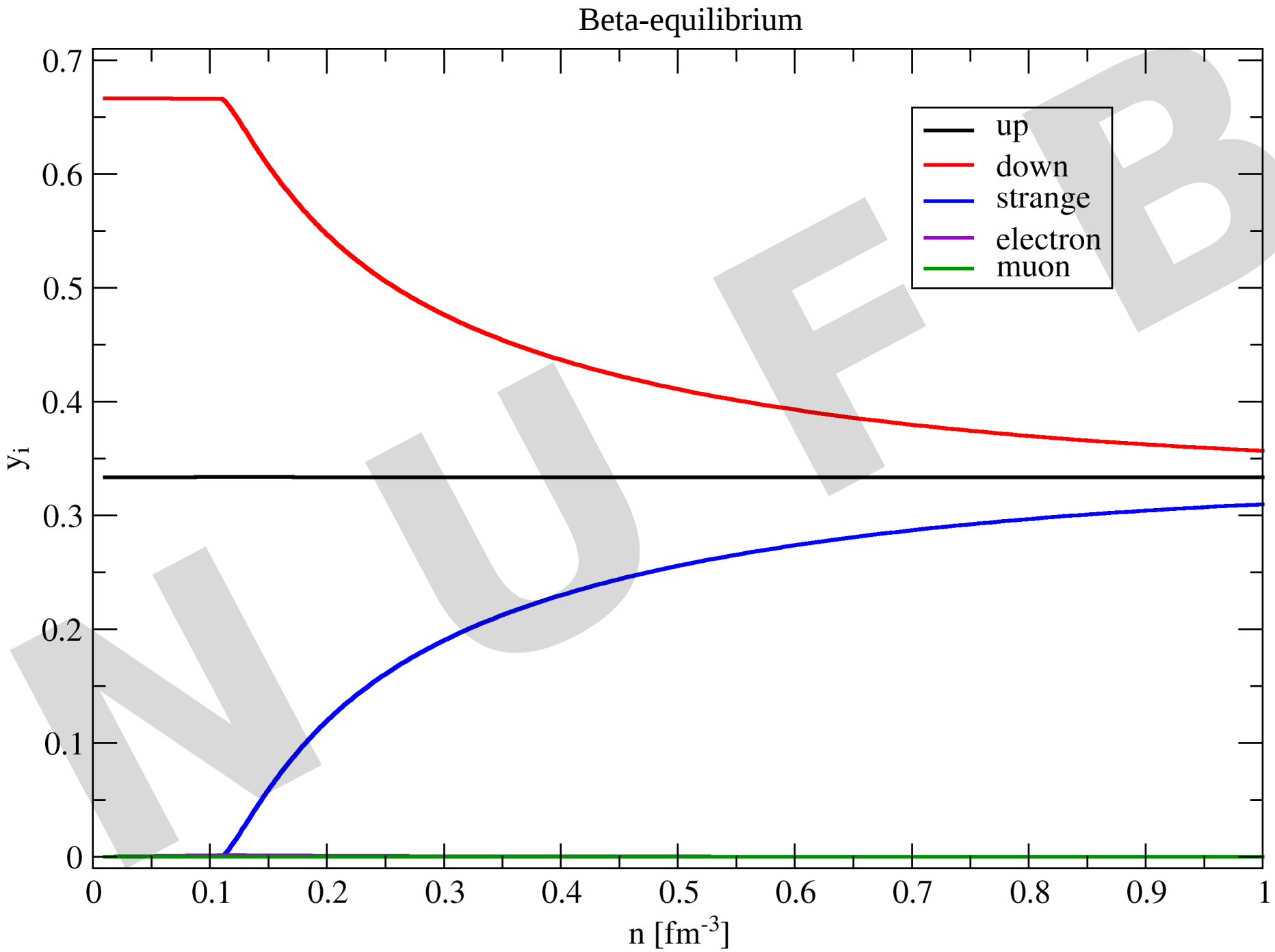

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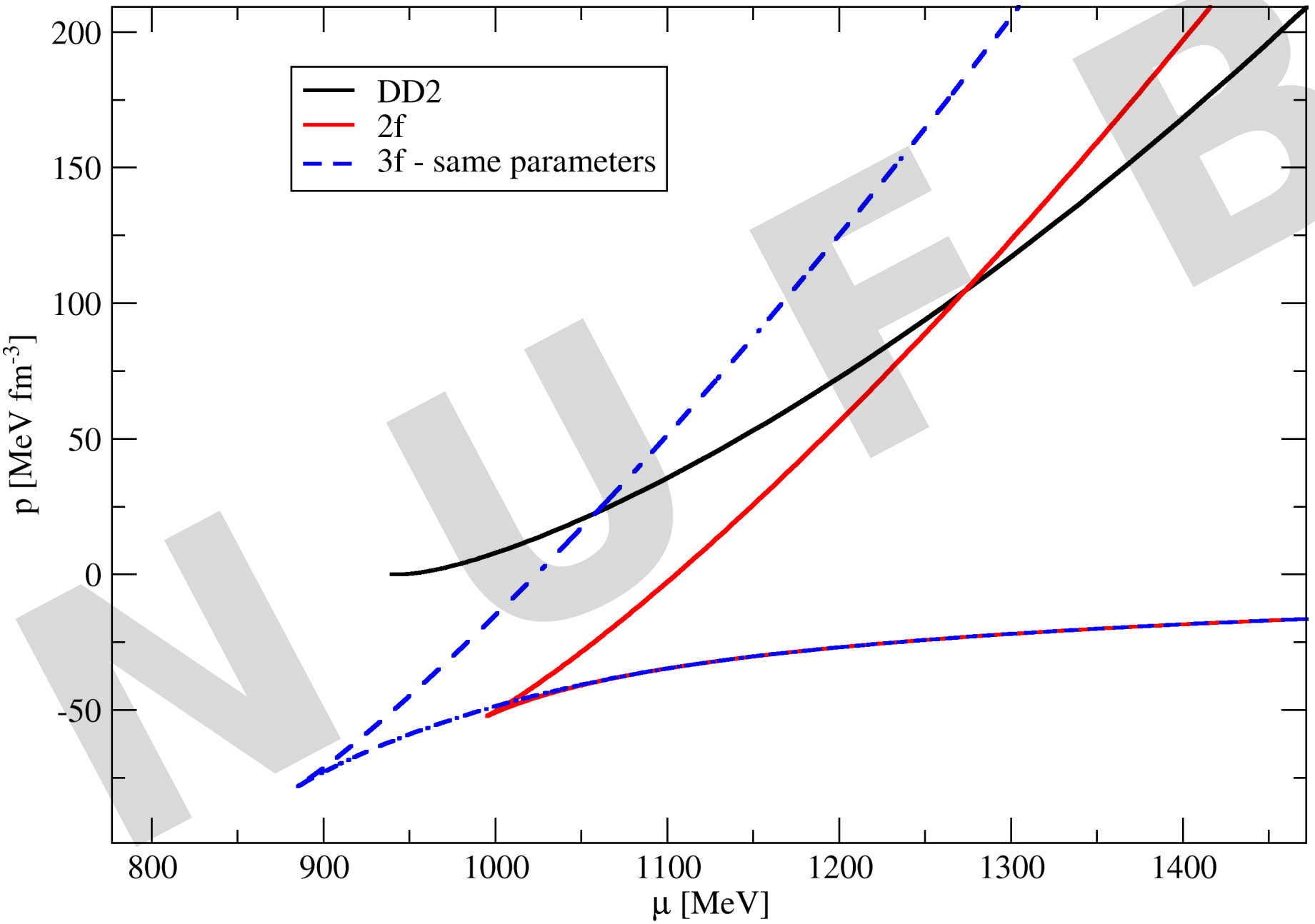
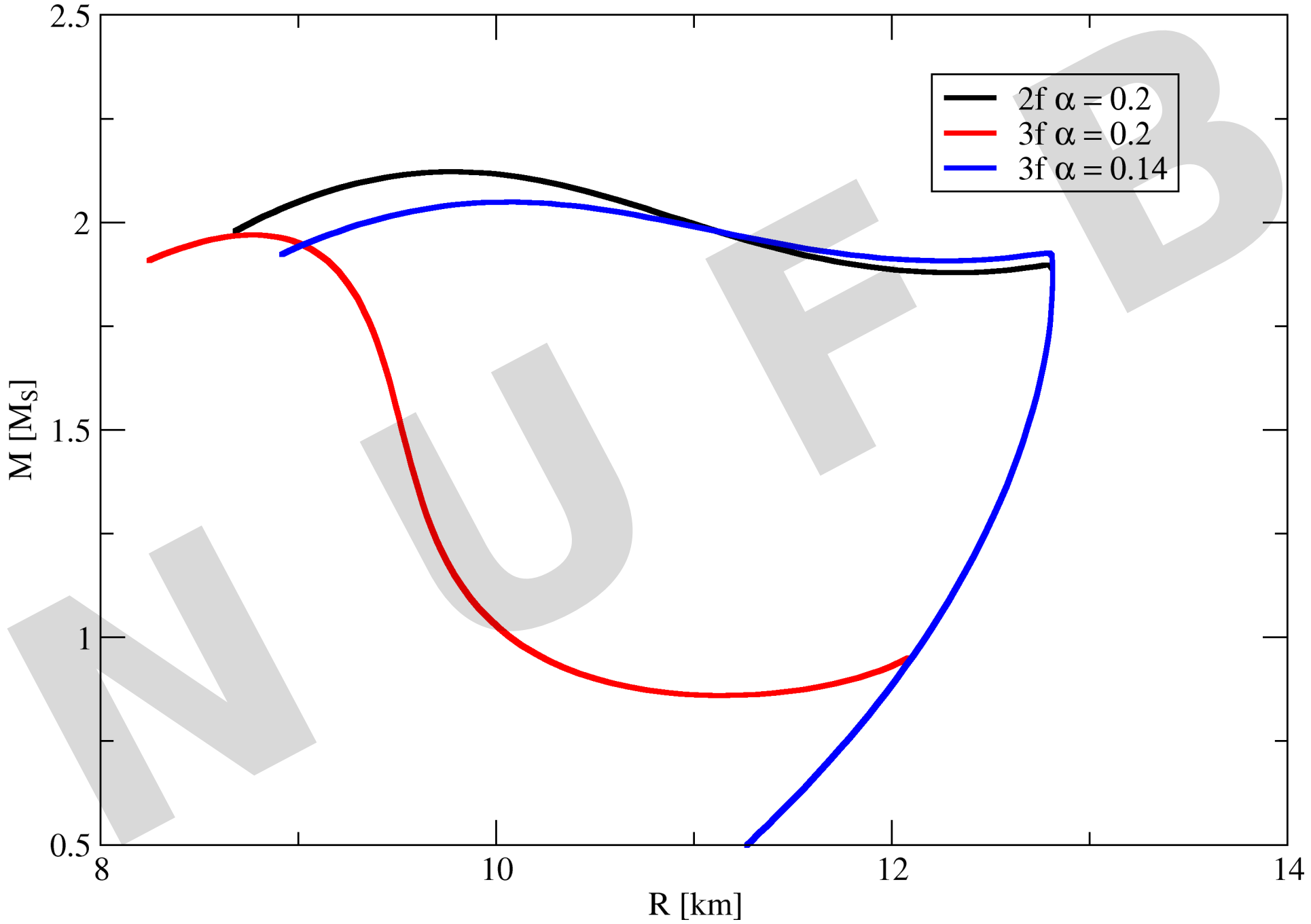


Exploratory calculation with strangeness



Checklist: constraints

Necessity

- Chiral EFT
- Symmetry energy[1]
- Unitary gas constraint[2]

} Fulfilled by our choice of hadronic EoS: DD2[3]

- Flow constraint[4]
- 2 solar mass NS

→ High-density corrections (e.g. DD2f, excluded volume)

→ Vector repulsion for quark matter

Sufficiency

- Phase transition with reasonable early onset density
  - Occurs in considered phenomena

[1] Lattimer & Lim (2013) ApJ 771, 14
[2] E. E. Kolomeitsev, J. M. Lattimer, A. Ohnishi,I. Tews, arXiv:1611.07133v1
[3] S. Typel, PRC 81 (2010), 015803
[4] P. Danielewicz, et. al., Science 298 (2002) 1592-1596

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
- Within the stringflip model the quark core of neutron stars contains strange quarks as soon as it appears

Outlook

- Fixing parameters and tabulation of data for supernova simulations, NS-NS merger and heavy-ion collisions is in progress
- Investigate different scenarios
- Adding direct current terms in the Lagrangian

Collaboration

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

Thank you!