The 19th International Conference on Strangeness in Quark Matter
May 17-22, 2021, sponsored by Brookhaven National Laboratory, Upton, New York

Repulsive properties of hadrons in lattice QCD data and neutron stars

based on 2009.10848 [hep-ph]

SQM2021

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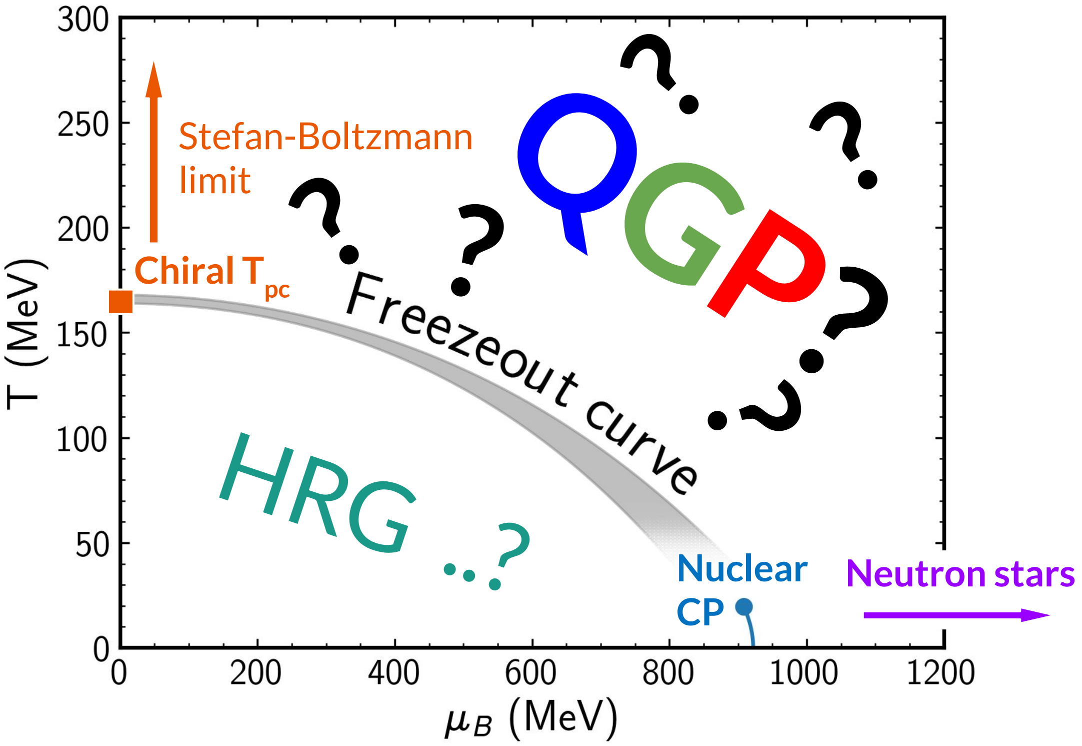
An approach for QCD EOS: CMF model



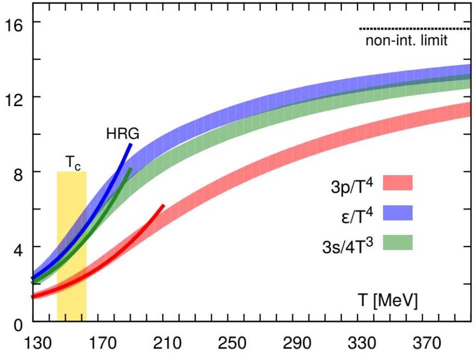
Chiral Mean Field model is a **single framework** for QCD thermodynamics, can be used for

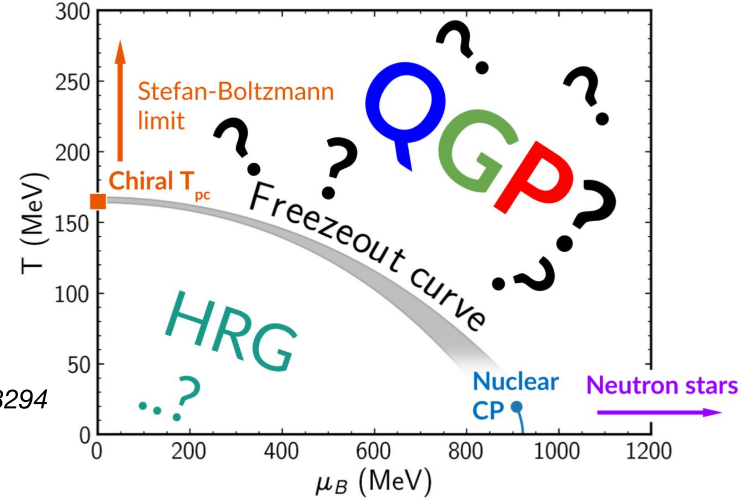
- **analysis of lattice QCD** data
- description of **nuclear matter**
- as well as **neutron star** description

Papazoglou, Schramm, Schaffner-Bielich, Stoecker, Greiner, nucl-th/9706024
Papazoglou, Zschiesche, Schramm, Schaffner-Bielich, Stoecker, Greiner, nucl-th/9806087
Dexheimer, Schramm, 0901.1748
Steinheimer, Schramm, Stoecker 1009.5239
AM, Steinheimer, Vovchenko, Schramm, Stoecker, 1905.00866

QCD phenomenology for the EoS

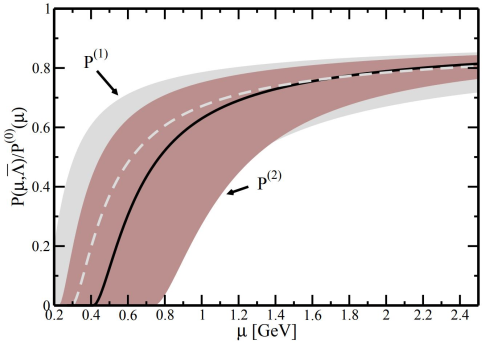
Stefan-Boltzmann limit μ_B=0 *HotQCD, 1407.6387*



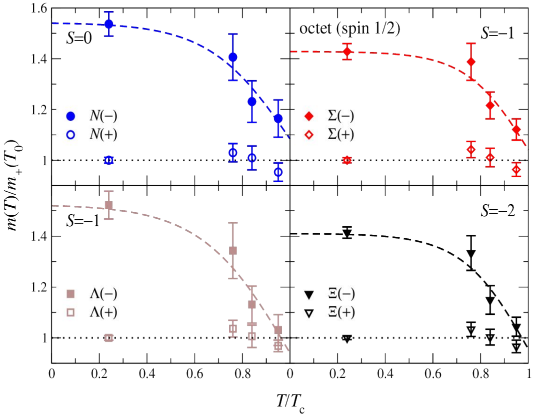


Stefan-Boltzmann limit T=0

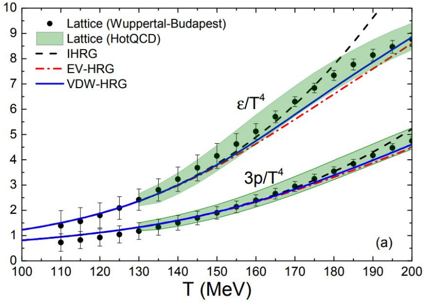
A. Kurkela, P. Romatschke, A. Vuorinen, 0912.1856



Parity doubling *G. Aarts et al., 1710.08294*



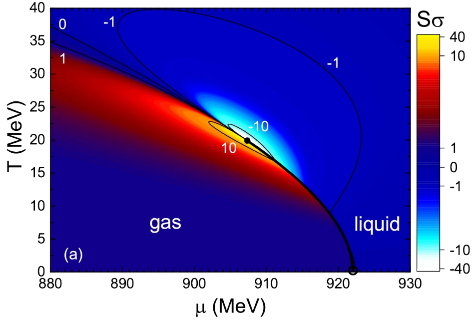
Hadron Resonance Gas



Vovchenko, Gorenstein, Stoecker, 1609.03975

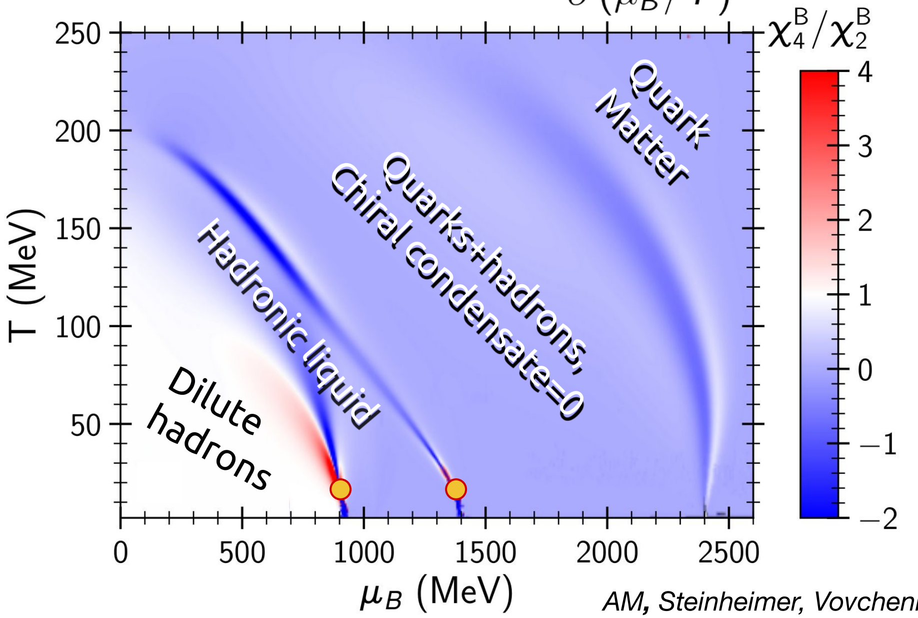
Nuclear matter properties

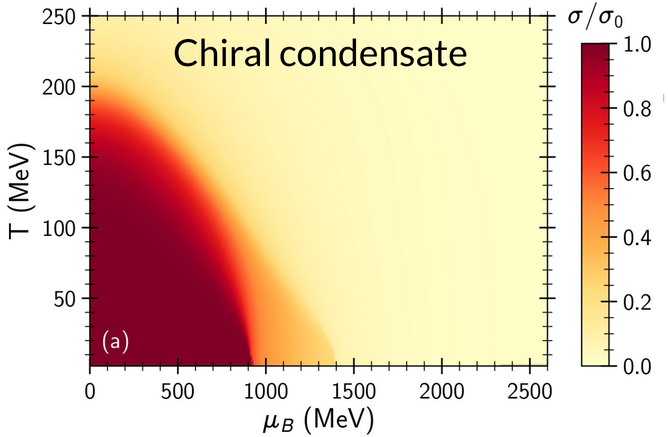
J. Pochodzalla et al., Phys.Rev.Lett. 75 (1995)
V. Vovchenko et al., 1506.05763

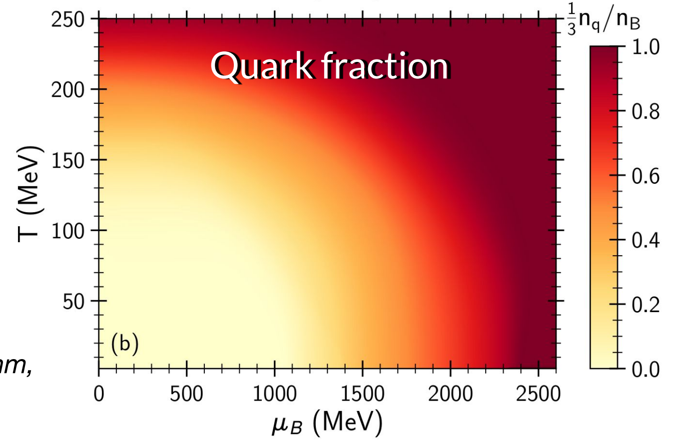


The CMF phase diagram

Kurtosis : $\chi_4^B/\chi_2^B, \quad \chi_n^B = \frac{\partial^n p/T^4}{\partial(\mu_B/T)^n}$







AM, Steinheimer, Vovchenko, Schramm, Stoecker, 1905.00866

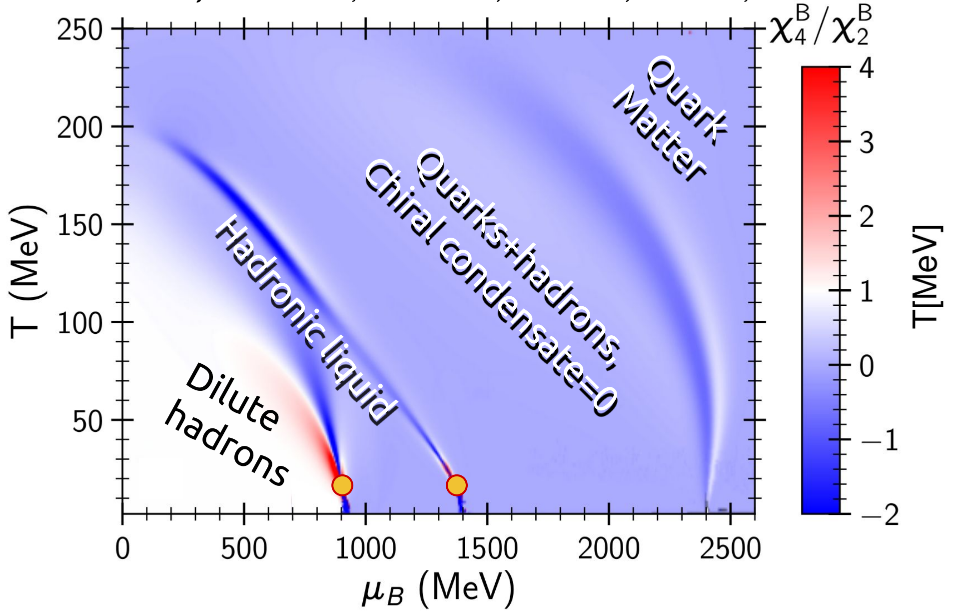
Three transitions:

hadron gas ➜ hadronic liquid ➜ chiral symmetry restoration ➜ quark matter

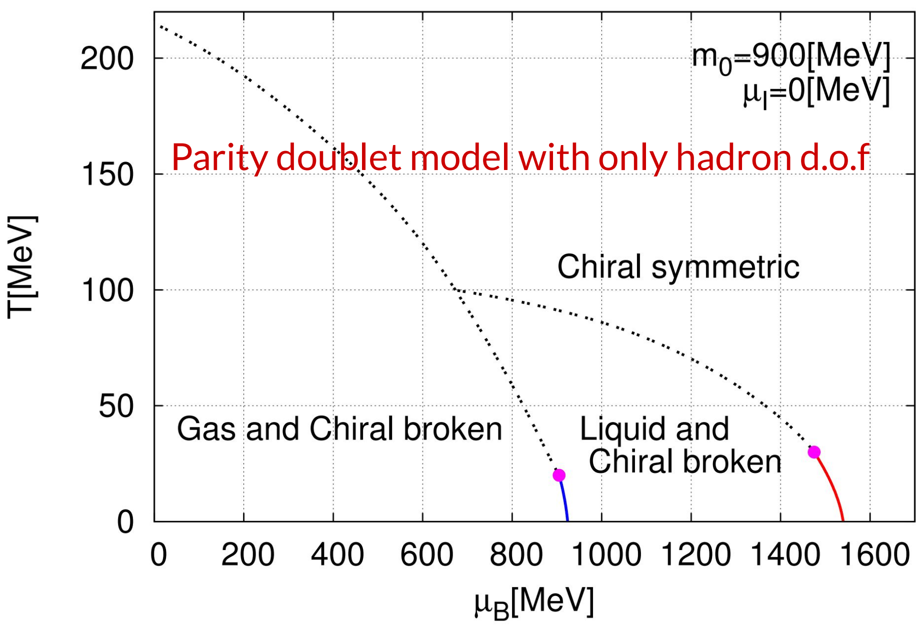
Two critical points: nuclear CP $T_{CP} \approx 17$ MeV, chiral CP $T_{CP} \approx 17$ MeV

The CMF phase diagram

AM, Steinheimer, Vovchenko, Schramm, Stoecker, 1905.00866



Motohiro, Kim, Harada, 1505.00988



The phase transitions are only driven by **hadrons**. **Deconfinement is always smooth.**

CMF: beyond the lattice data

The lattice QCD calculations allow to go beyond the $\mu_B = 0$ by using Taylor expansion which involves conserved charge susceptibilities χ:
(Allton *et al.* hep-lat/0204010)

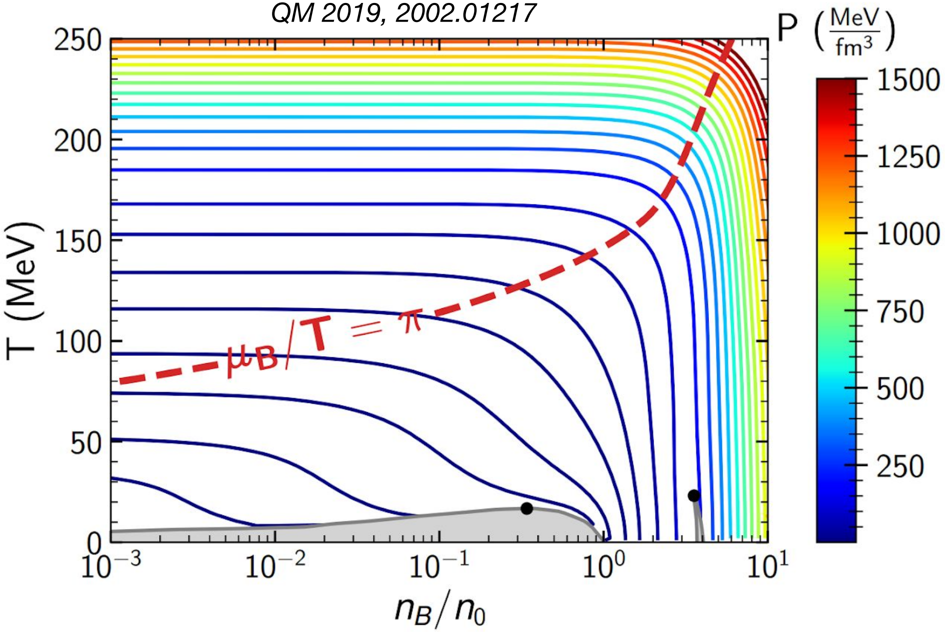
$$P = P_0 + T^4 \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{i,j,k}_{B,Q,S} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

$$\chi^{i,j,k}_{B,Q,S} = \frac{\partial^i \partial^j \partial^k P(T, \mu_B, \mu_Q, \mu_S)/T^4}{\partial (\mu_B/T)^i \, \partial (\mu_Q/T)^j \, \partial (\mu_S/T)^k}$$

Radius of convergence — distance to the closest singularity of ***P/T*** ^{4} in the **complex** μ_B/T **plane**, could be QCD critical point.

One singularity is known at $\mu_B/T = i\pi$
Roberge-Weiss transition
(Roberge, Weiss, *Nucl.Phys.B 275 (1986) 734-745*)
However, estimates suggest $R_{\mu B/T} \approx 2$-3 (Bazavov *et al.* 1701.04325, Vovchenko *et al.* 1711.01261, Giordano *et al.* 1911.00043)

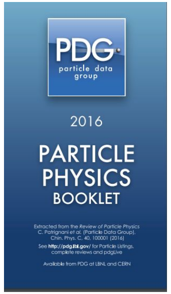
AM, Vovchenko, Steinheimer, Schramm, Stoecker, QM 2019, 2002.01217



In a realistic EOS beyond $\mu_B/T \approx \pi$ the lines of constant pressure depend strongly on density. Interactions and finite baryon density strongly affect the EOS.

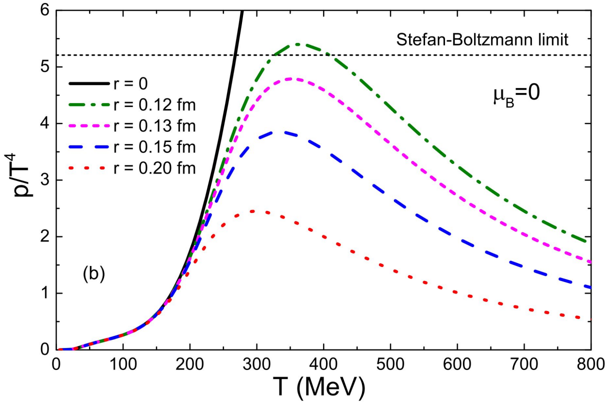
Hadron-quark transition in CMF

Excluded Volume triggers the switch between hadron and quark degrees of freedom.



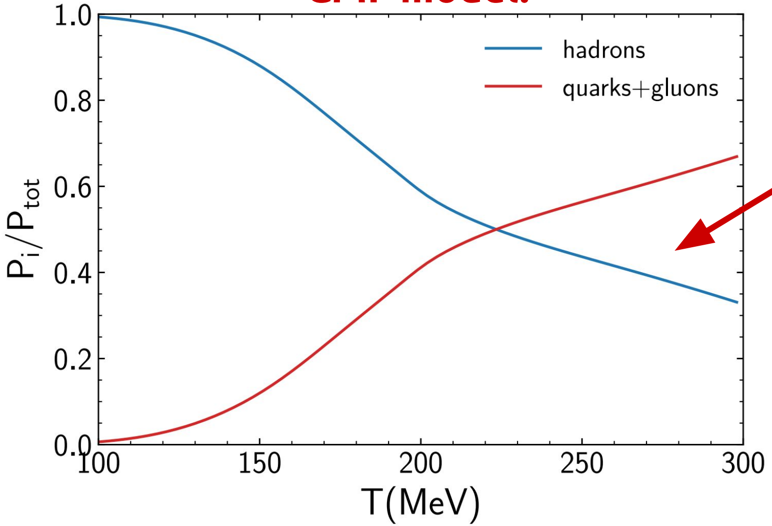
$$\rho_i = \frac{\rho_i^{\mathrm{id}}(T,\mu_i^* - v_i\, p)}{1 + \sum_j v_j \rho_j^{\mathrm{id}}(T,\mu_j^* - v_j\, p)}$$

$$\varepsilon_i = \frac{\varepsilon_i^{\mathrm{id}}(T,\mu_i^* - v_i\, p)}{1 + \sum_j v_j \rho_j^{\mathrm{id}}(T,\mu_j^* - v_j\, p)}$$



Vovchenko, Anchishkin, Gorenstein, 1412.5478

CMF model:



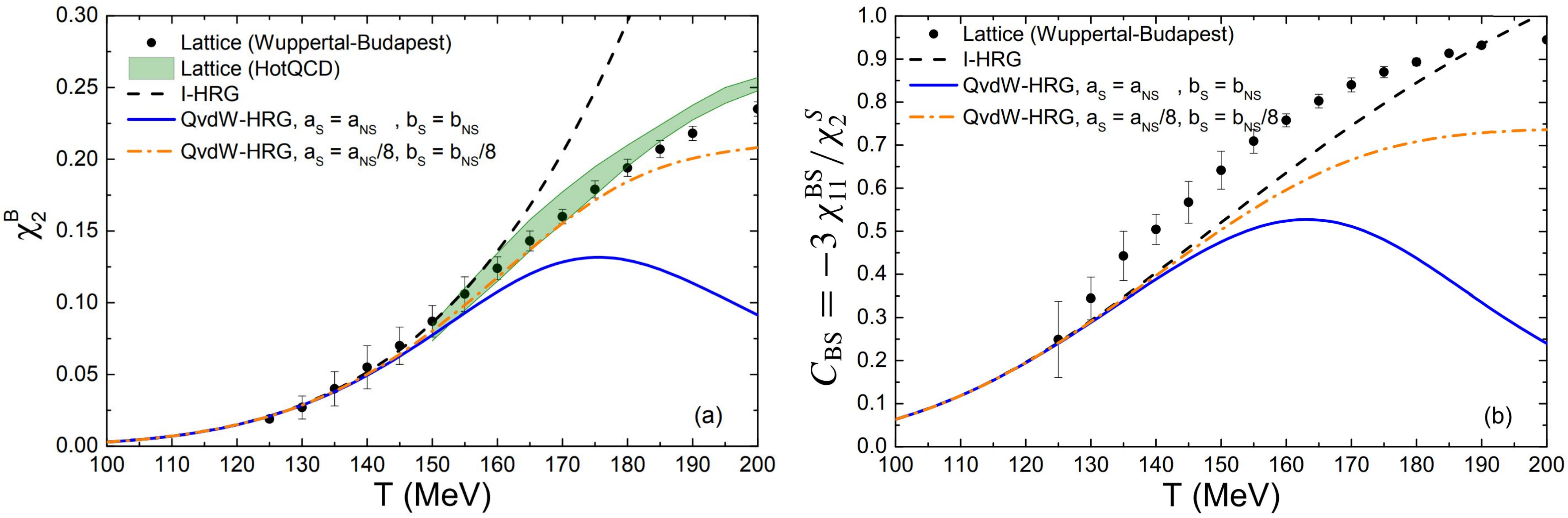
Excluded volume interactions suppress hadrons

How to constrain excluded volume parameters?

Analysis of nucleon phase shifts suggests v_b=1 fm^3

(Vovchenko, AM, Gorenstein, Stoecker, 1710.00693)

Flavor dependent EV interactions: QvdW

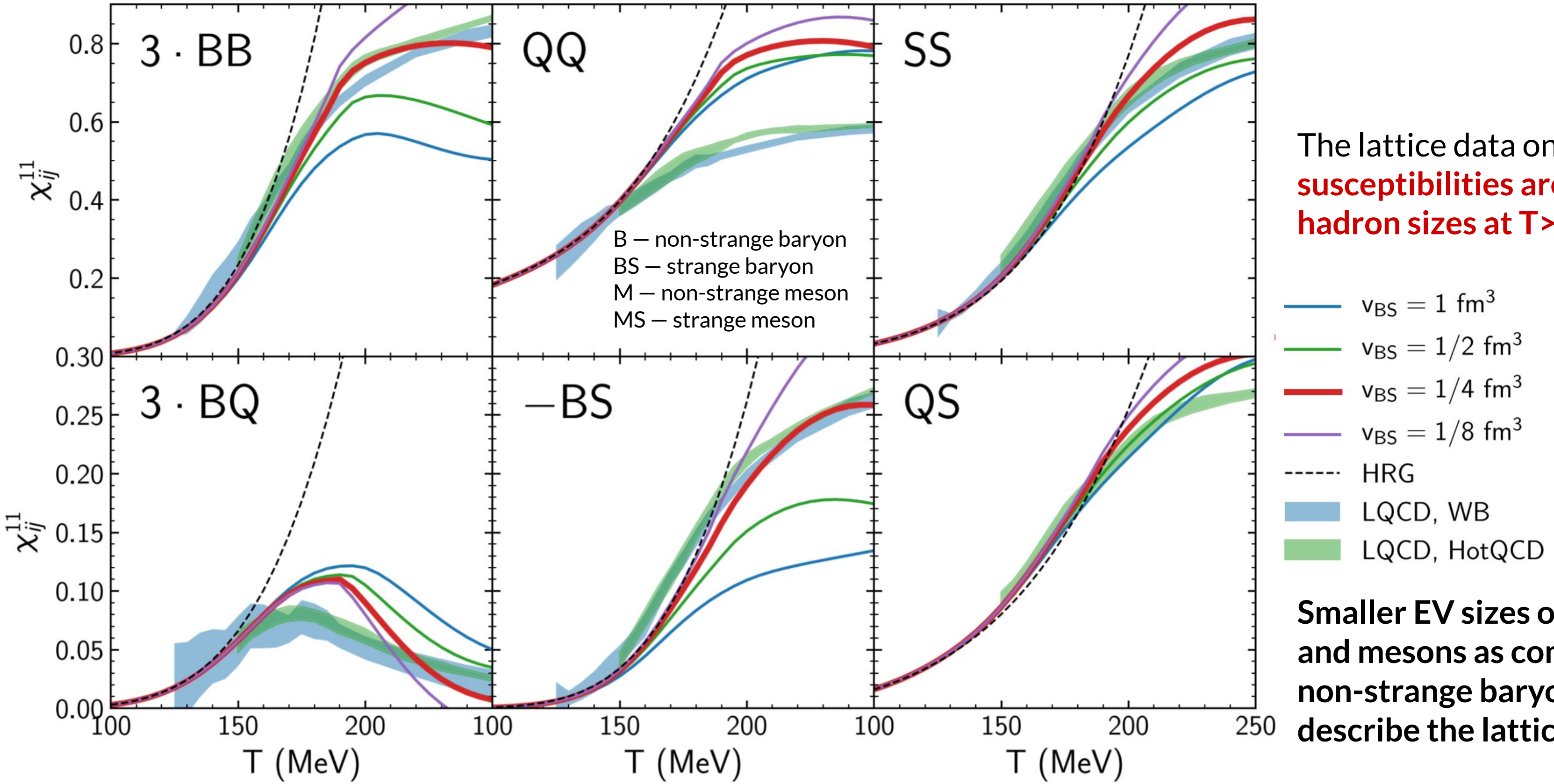


Vovchenko, AM, Alba, Gorenstein, Satarov, Stoecker, 1707.09215

A study within the Quantum van der Waals model hints:
smaller EV size of strange baryons ➡ improvement in baryon and strange susceptibilities

Flavor dependent EV interactions: CMF model

$v_B = 1\ fm^3,\ v_M = 1/8\ fm^3,\ v_{MS} = 1/8\ fm^3$ **Variation of hyperons size**

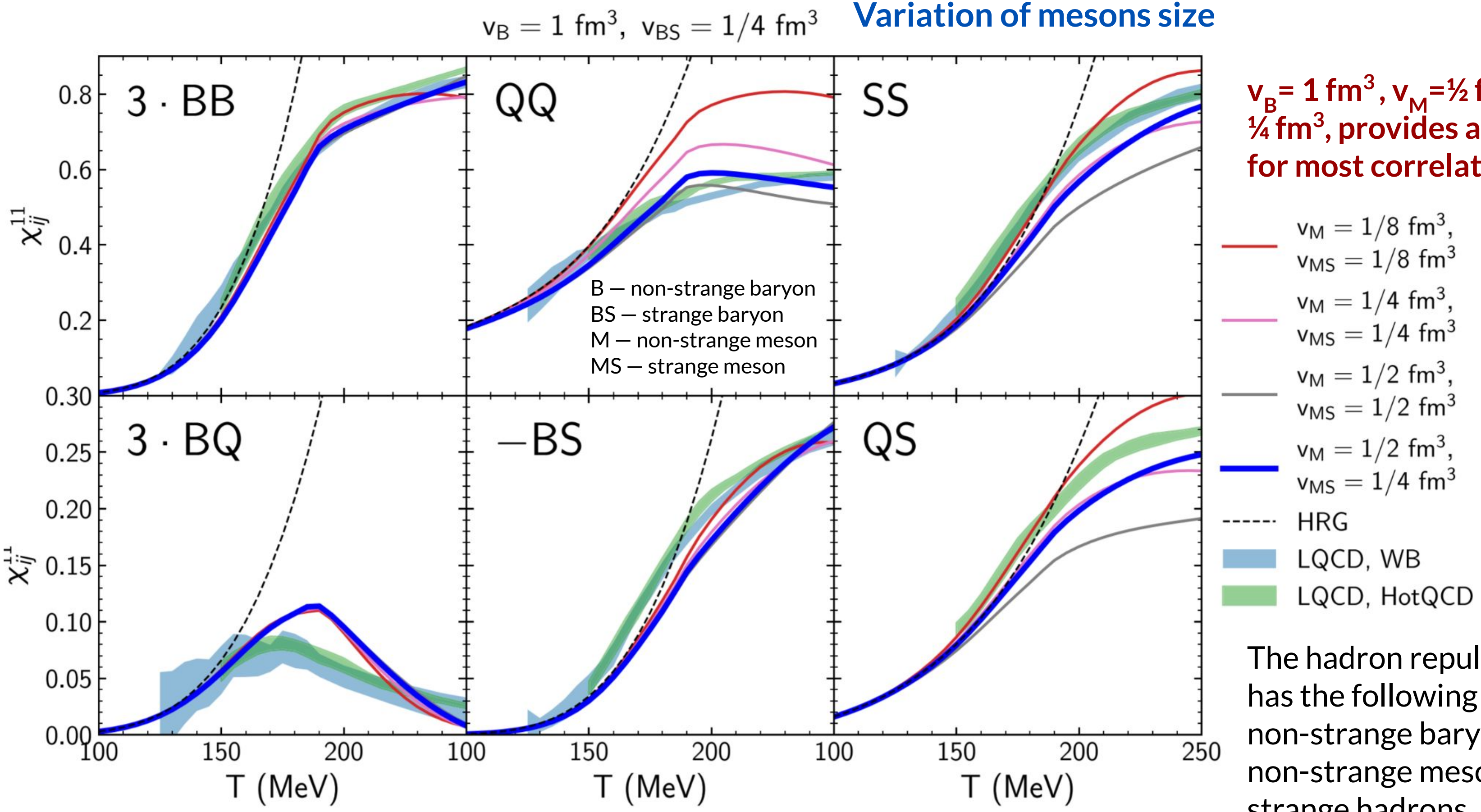


The lattice data on second order **susceptibilities are sensitive to hadron sizes at $T>T_{pc}$**

Smaller EV sizes of hyperons and mesons as compared to non-strange baryons help to describe the lattice data.

Flavor dependent EV interactions: CMF model

Variation of mesons size

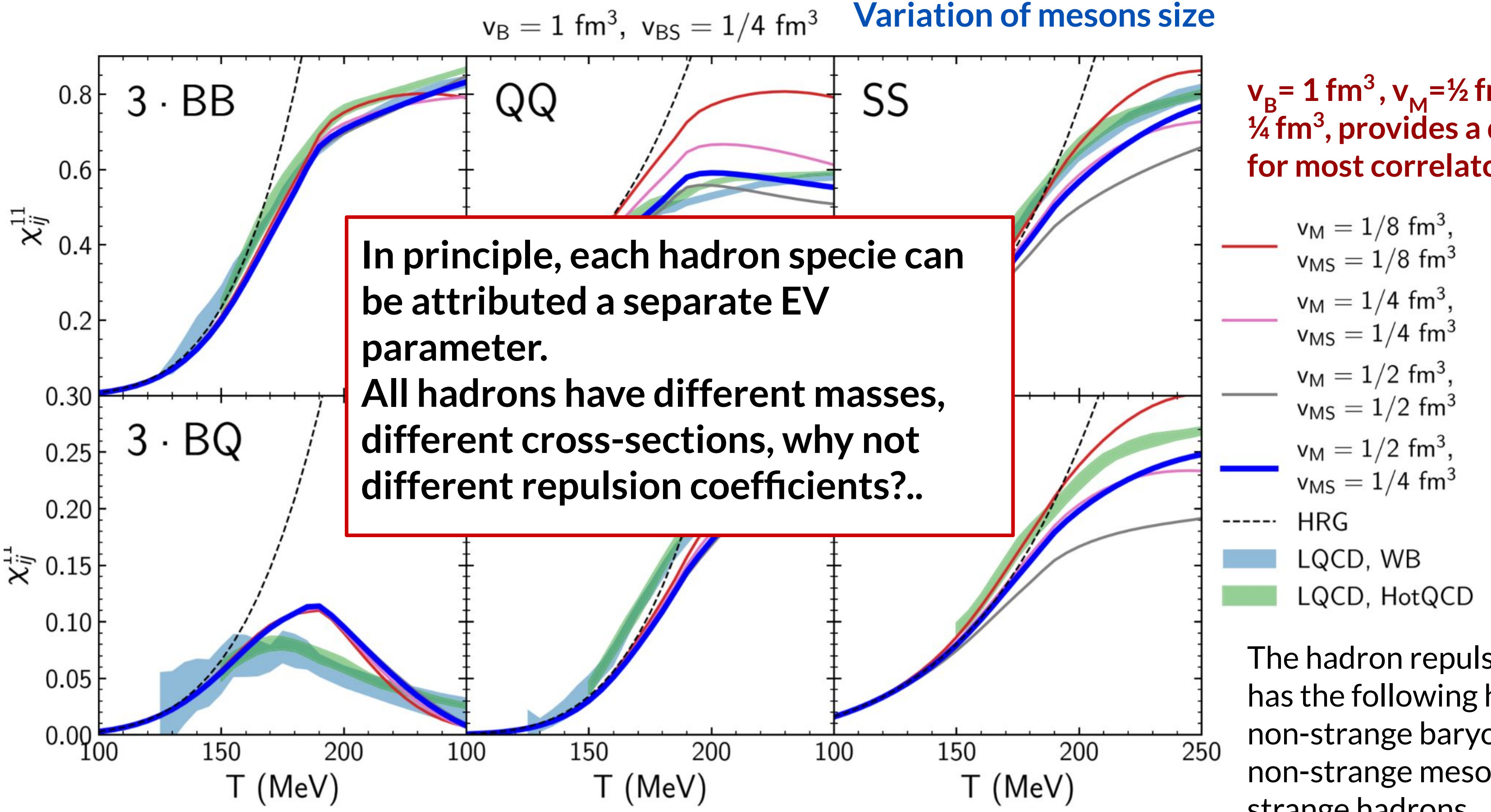


v_B= 1 fm^3, v_M=½ fm^3, v_{BS}=v_{MS}= ¼ fm^3, provides a description for most correlators.

The hadron repulsion strength has the following hierarchy non-strange baryons → non-strange mesons → strange hadrons

Flavor dependent EV interactions: CMF model

Variation of mesons size

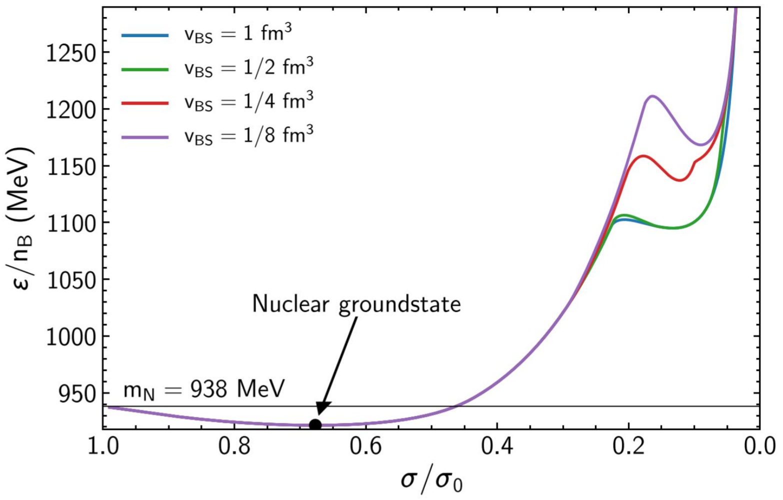


In principle, each hadron specie can be attributed a separate EV parameter.
All hadrons have different masses, different cross-sections, why not different repulsion coefficients?..

v_B= 1 fm^3, v_M=½ fm^3, v_{BS}=v_{MS}= ¼ fm^3, provides a description for most correlators.

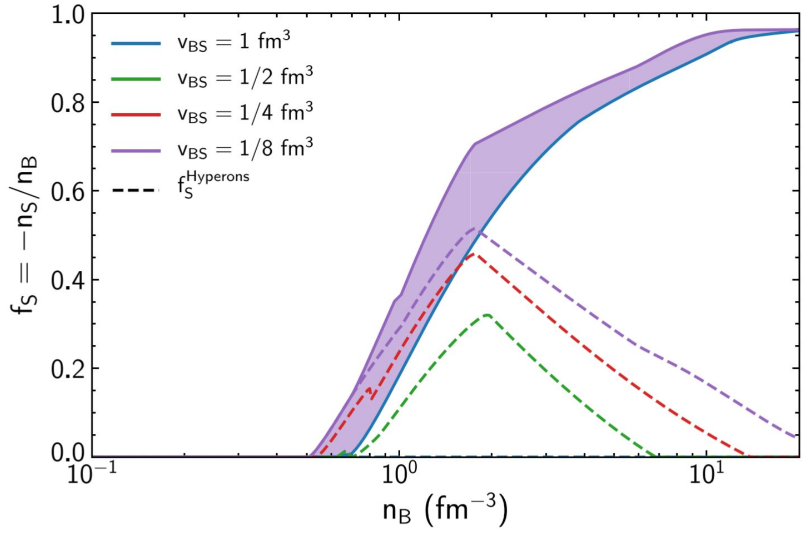
The hadron repulsion strength has the following hierarchy
non-strange baryons →
non-strange mesons →
strange hadrons

Phase structure



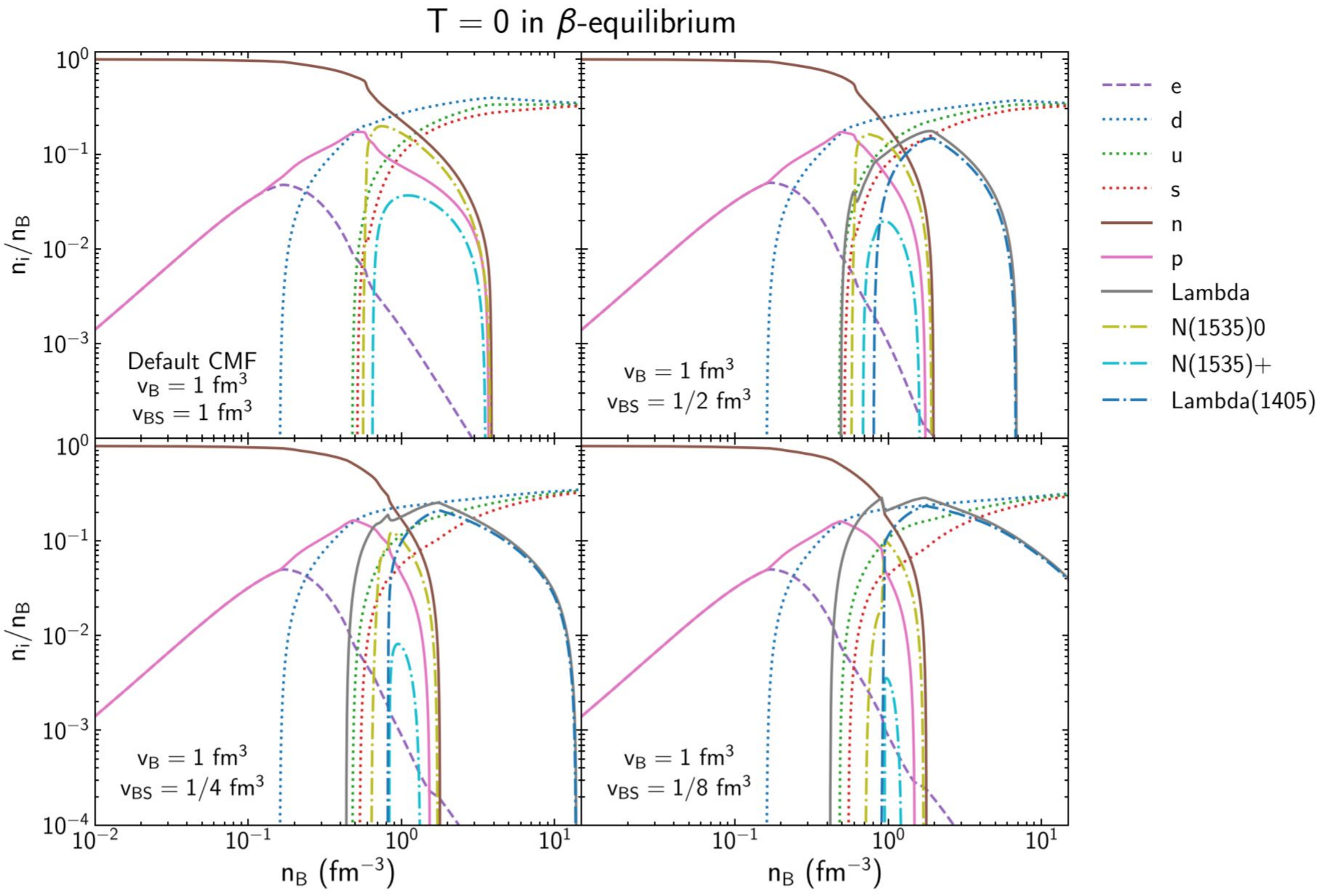
An important benchmark for the CMF model:
the model phase structure is robust to different interaction schemes.

- Nuclear ground state is not affected.
- Chiral phase transition is only slightly changed.



The chemical composition is interesting.
Small hyperon repulsion allows for
hyperon-rich phase at n_B>1 fm^3.
These densities to be probed in neutron stars.

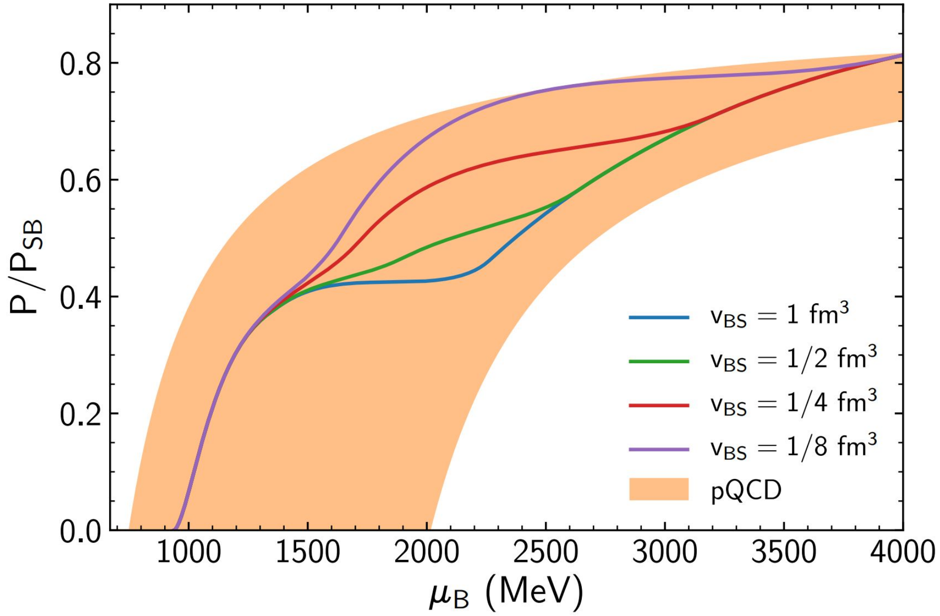
Chemical composition for neutron star matter



The same CMF model, the same parametrizations, electrons are present to maintain □-equilibrium.

Hyperons have smaller EV-size — they are suppressed at larger densities.
A new scenario:
All non-strange baryons are melted into quarks,
but hyperons still survive.

Comparison with pQCD for cold matter



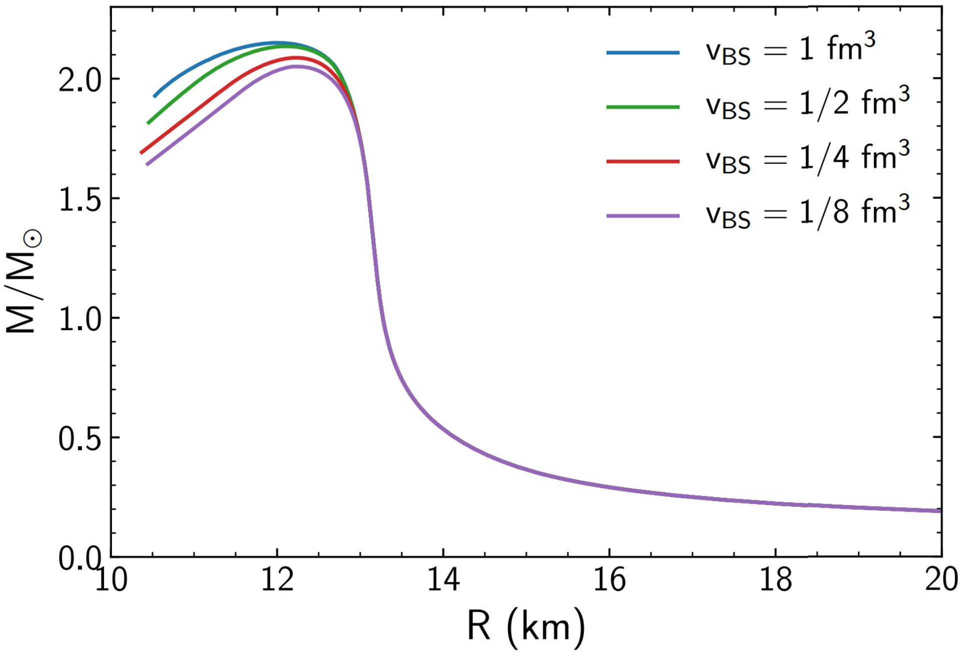
PQCD data from:
Kurkela, Romatschke, Vuorinen, 0912.1856

CMF gives a reasonable description for hyperon EV parameter v_{BS}=¼ fm^3, the favorable value from LQCD data analysis.

The pQCD errorbars are too wide, any scenario fits.

At high mu_B hadrons are suppressed, all parameterizations merge,
SB limit is slowly approached.

Neutron stars



The same EOS is used to model neutron stars by solving TOV equation.

Changes in chemical composition affect NS properties only slightly.

As soon as hyperons emerge — NS family is already approaching unstable branch.

Summary

- Susceptibilities are sensitive to hadronic interactions at at $T>T_{pc}$.
- Lattice QCD data suggests hierarchy in hadron EV repulsion (size). Non-strange baryon excluded volume: v_B=1 fm^3, mesons: v_M=1/2 fm^3, strange hadrons: v_{BS}=v_{MS}=1/4 fm^3.
- Room for improvement:
  Each hadron may be attributed individual EV parameter.
- The CMF phase structure is robust against change in flavor-dependent interaction schemes.
- Interesting scenarios are possible: hyperons melt into quarks at larger densities than non-strange hadrons.
- Hyperons appearance only slightly modifies neutron star properties.

Thanks for your attention!