Massive Stars within Self-Consistent Approaches

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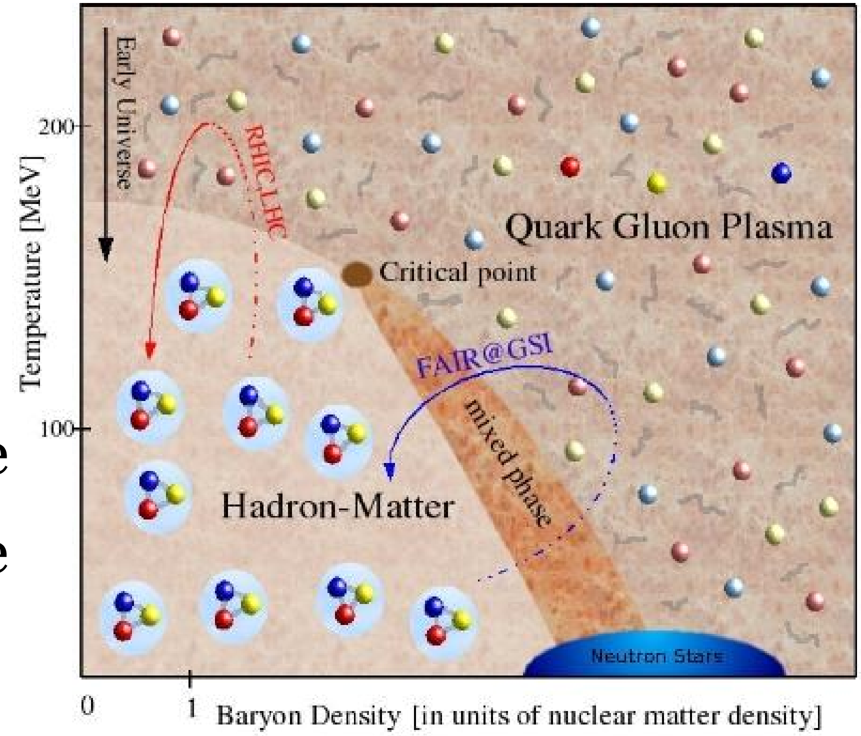
✯ Motivation:

- QCD phase diagram
- chiral symmetry restoration
    - low density / high temperature
    - high density / low temperature
- deconfinement to quark matter
    - low density / high temperature
    - high density / low temperature
- strong magnetic fields up to $10^{18} – 10^{19}$ G
    - low density / high temperature
    - high density / low temperature
- proto-neutron stars with T up to 30 MeV in the center



Ingredients:

- baryon octet: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-
- up, down, strange quark
- chiral partners for baryon octet: N* (1535 MeV), Y* (same splitting)
  - Λ^* (1670 MeV)
  - Σ^* (1750 MeV)
  - no clear data for Ξ

minimum parameters

lighter resonance spin 1/2 negative parity

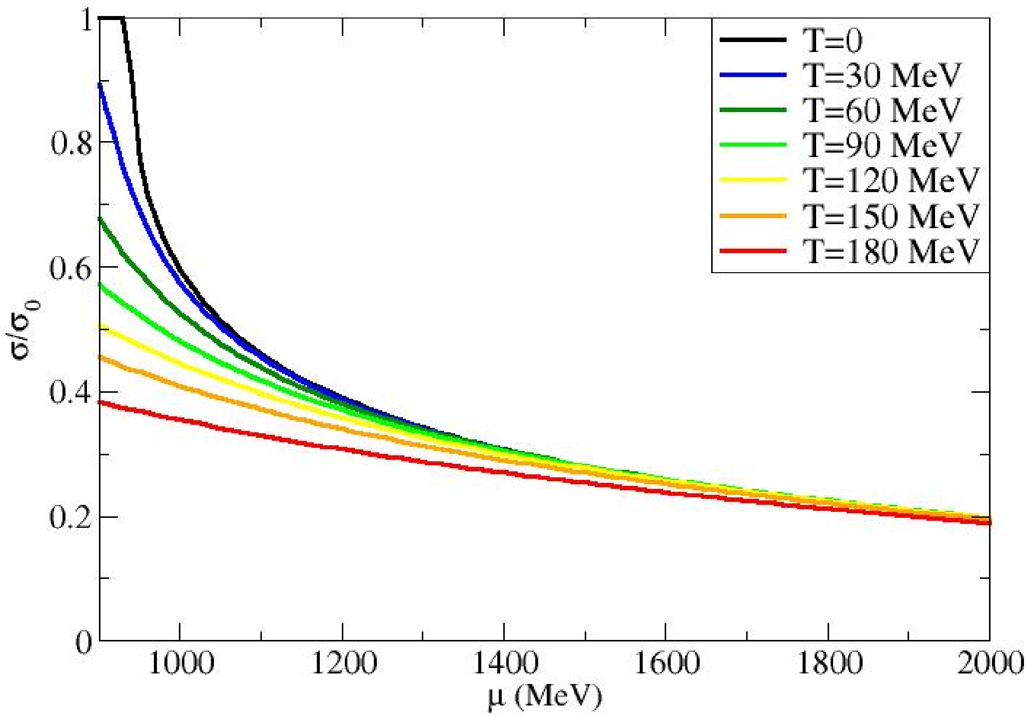
- nuclear physics constraints
  - saturation density
  - binding energy, compressibility at saturation
  - symmetry energy and derivative at saturation
  - hyperon optical potentials at saturation

✶ Non-Linear SU(3) Sigma Model:

- effective quantum relativistic model → mean field

- describes hadrons interacting via meson exchange (σ, δ, ζ, ω, ρ, ϕ)

- constructed from symmetry relations → allow it to be chirally invariant → masses from interaction with medium



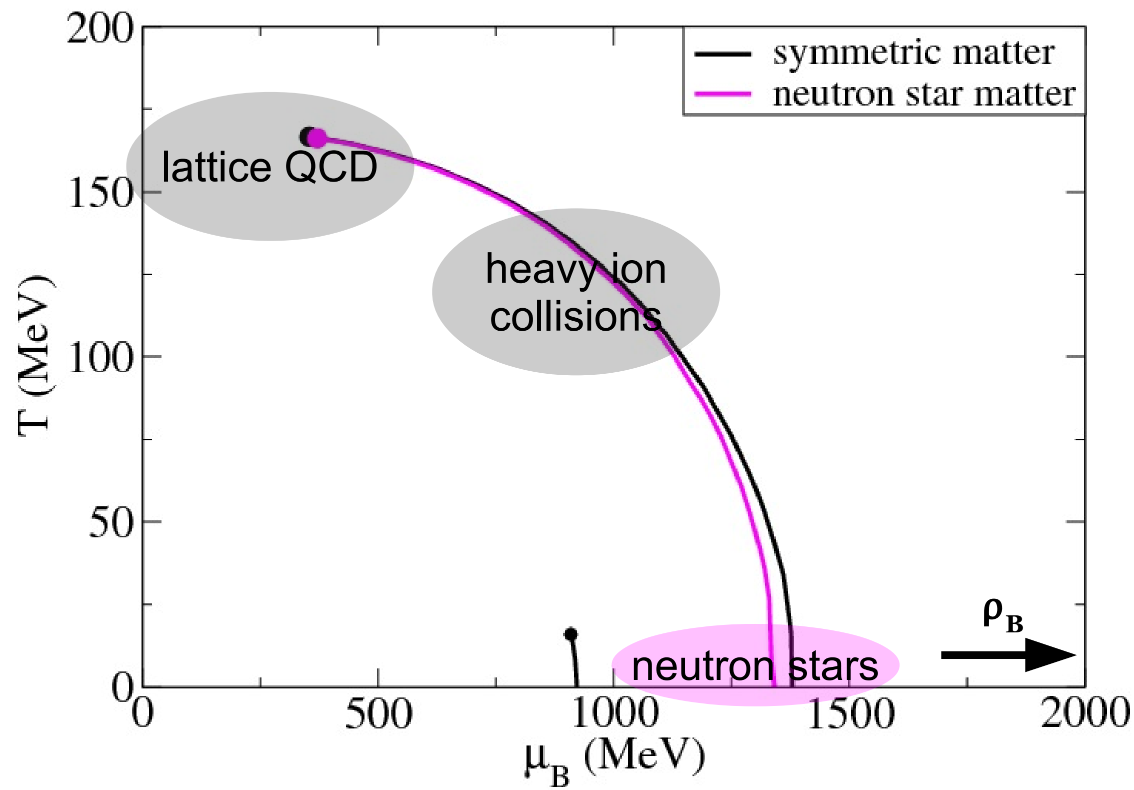
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b$$

$$\delta m_b = 150\, MeV / 376.58\, MeV$$

Dexheimer et al. Astrophys.J. 2008

1. Self-Consistent EOS – Effective Mass:

- hadronic matter + quark matter
- effective masses
- phase transitions or crossovers
- order parameters σ, Φ
- potential for Φ (deconfinement)
- liquid-gas phase transition



Dexheimer et al. Phys. Rev. C 2010

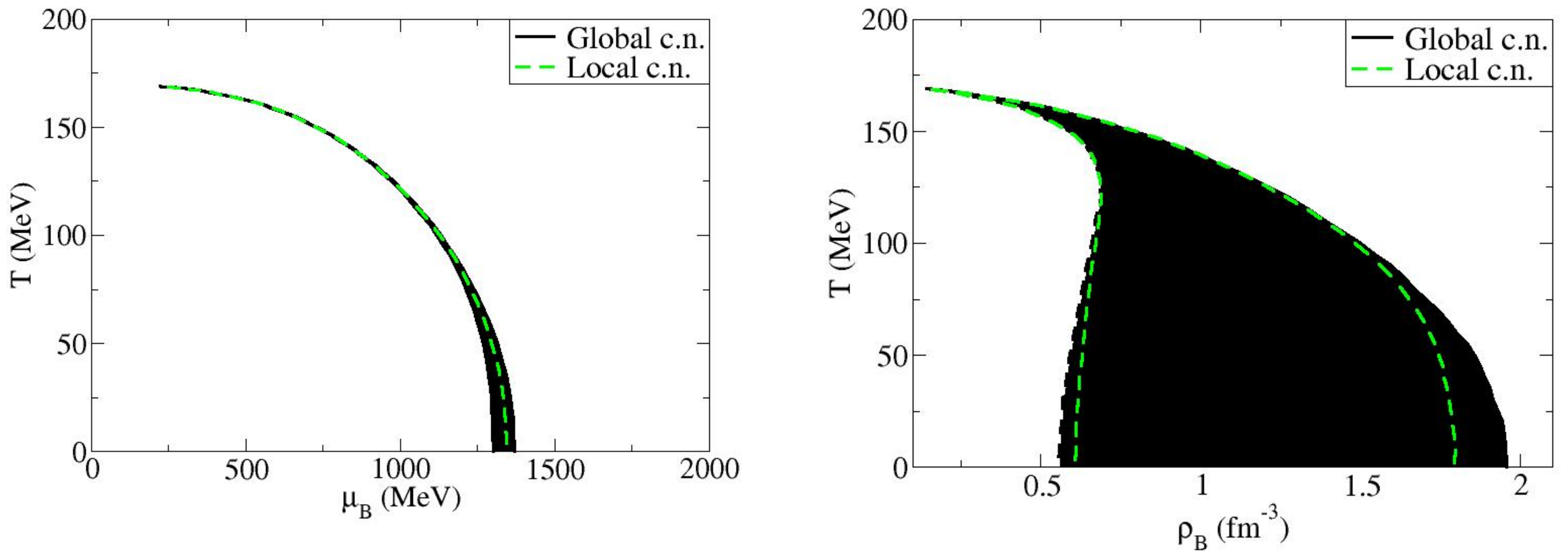
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2$$

$$m_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + \delta m_q + g_{q\Phi}(1-\Phi)$$

$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2 + a_3\, T_0^4\, \ln(1 - 6\phi^2 + 8\phi^3 - 3\phi^4)$$

Local and Global Charge Neutrality:

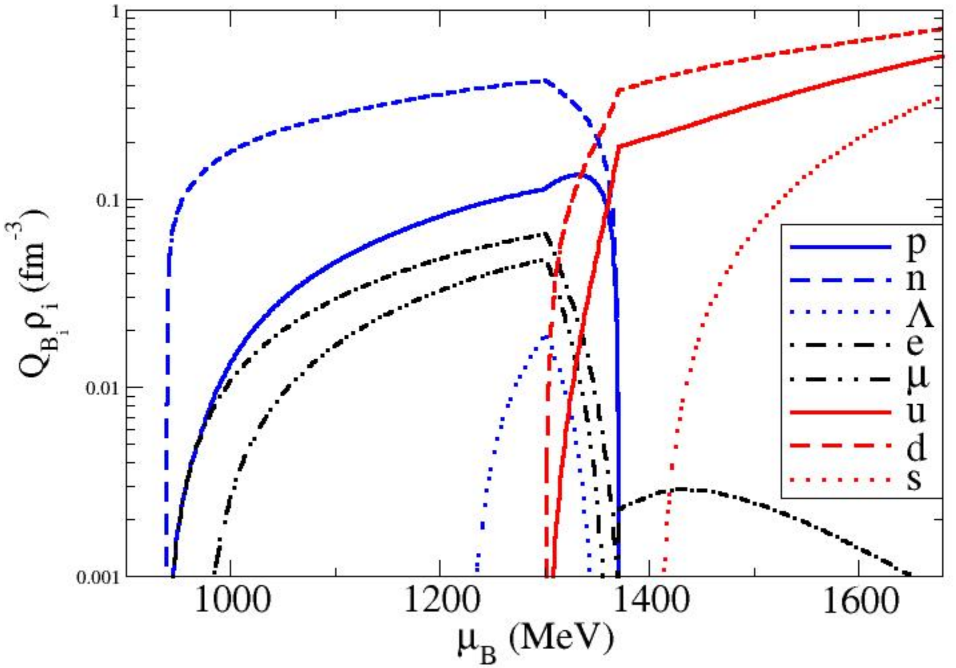
- absence / presence of mixed phase
- "mixed" quantities like $\rho_B = \lambda \rho_B^Q + (1-\lambda)\rho_B^H$

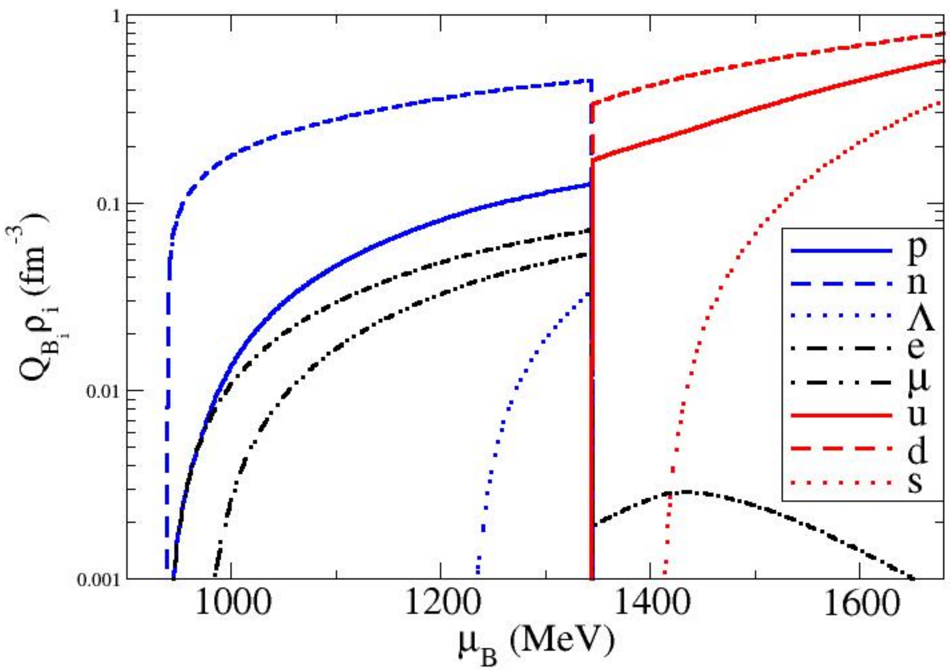


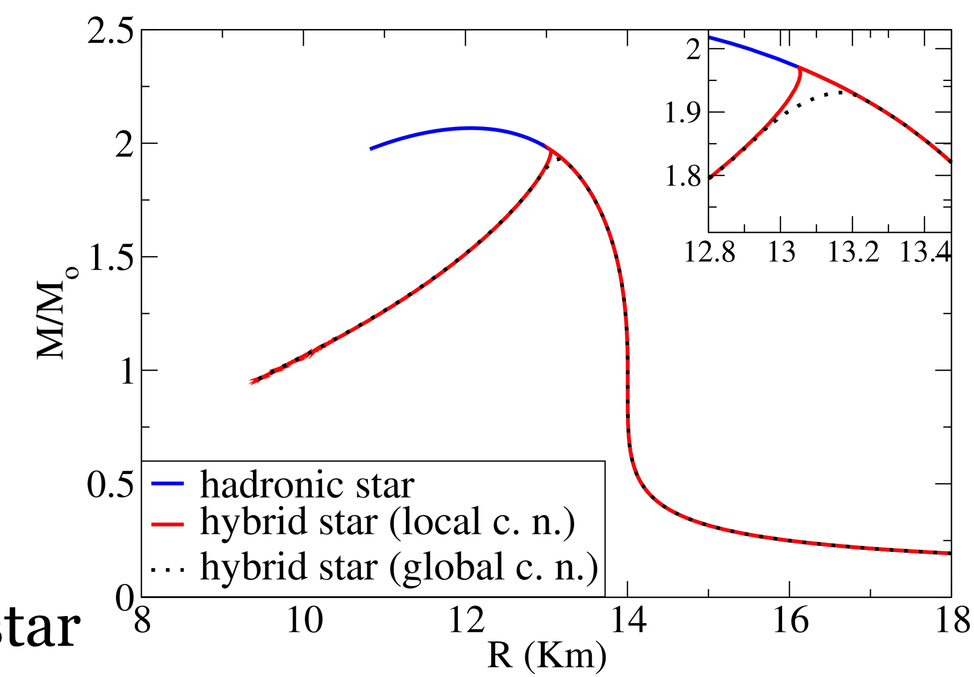
Hempel et al. Phys. Rev. C 2010

- different from liquid-gas
- negative slope in the pressure-temperature plan
- non-congruent features vanishingly small at critical point

- Population and Mass-Radius Diag. with Local/Global Charge Neutrality:

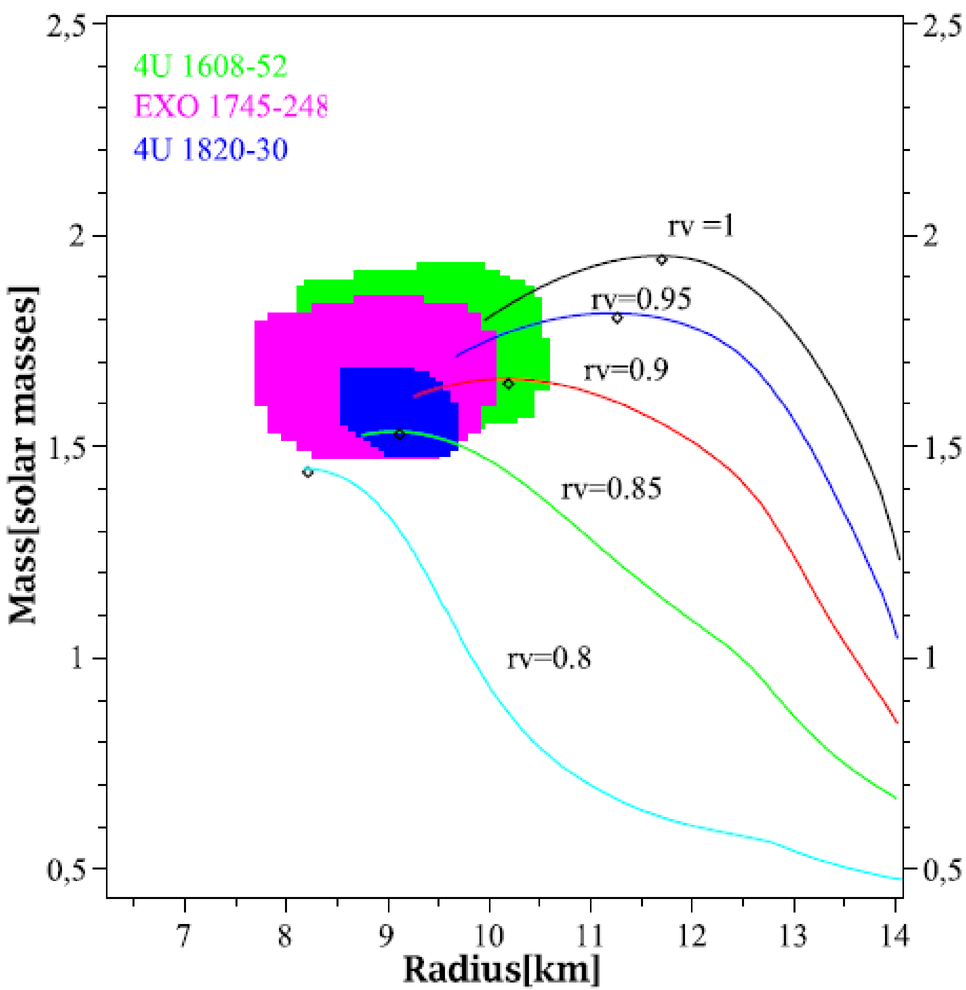






- mixed phase of up to 2 km in star
- massive stars

⭑ Inclusion of Δ Resonances in the Non-linear SU(3) Sigma Model:



– increase of delta coupling decreases radius but decreases maximum mass

$$r_v = \frac{g_{\Delta\omega}}{g_{N\omega}}$$

Schurhoff et al. Astrophys. J. 2010

Steiner et al. Astrophys. J. 2010

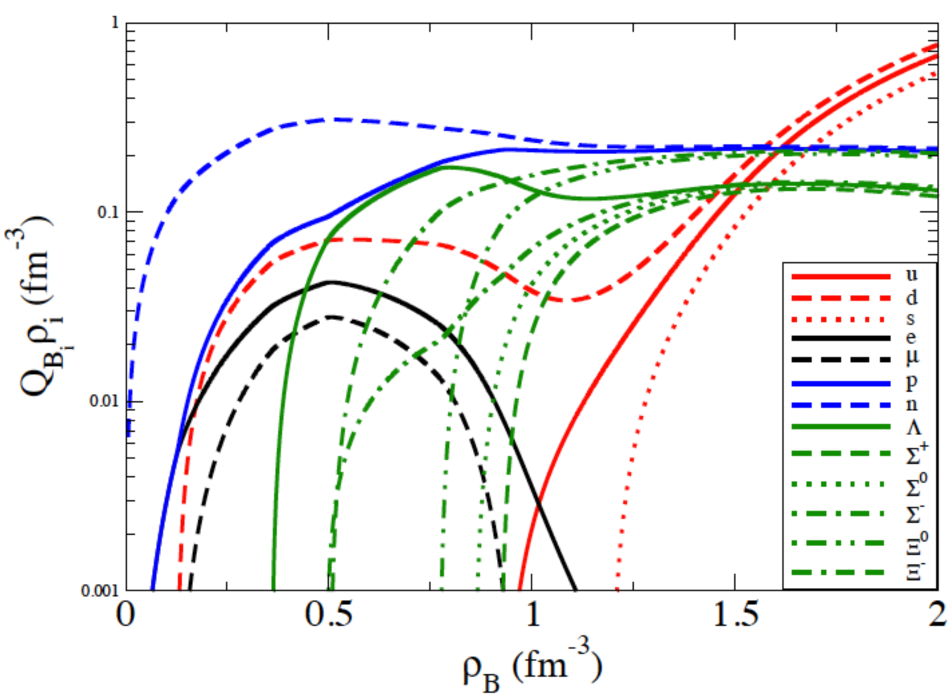
Oezel et al. Phys. Rev. D 2010

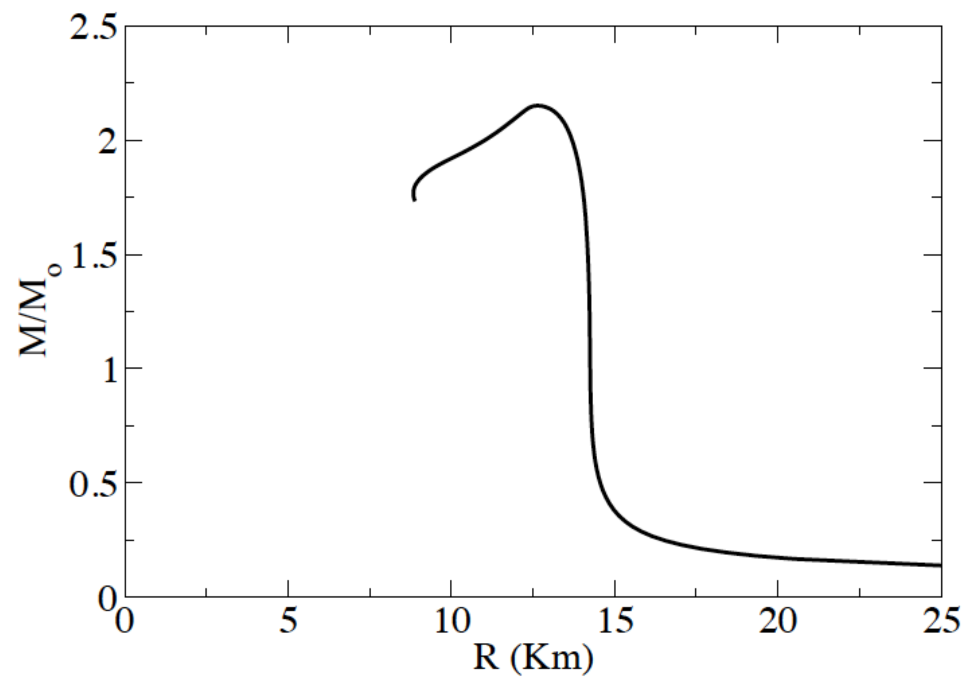
2. Self-Consistent EOS – Excluded Volume

- hadron chemical potentials decreased by quarks $\tilde{\mu}_i = \mu_i - v_i P$

excluded volume

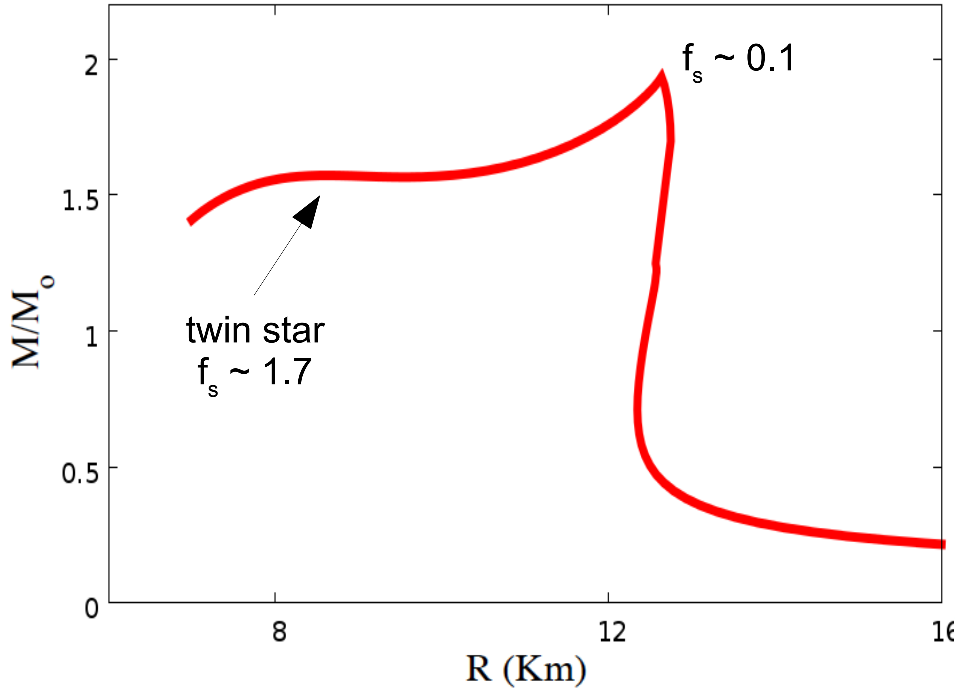
- reproduces nuclear matter constraints
- crossovers — Baym et al. J. Phys. G. 2008
- massive stars — Lourenco et al. Phys. Rev. D 2012





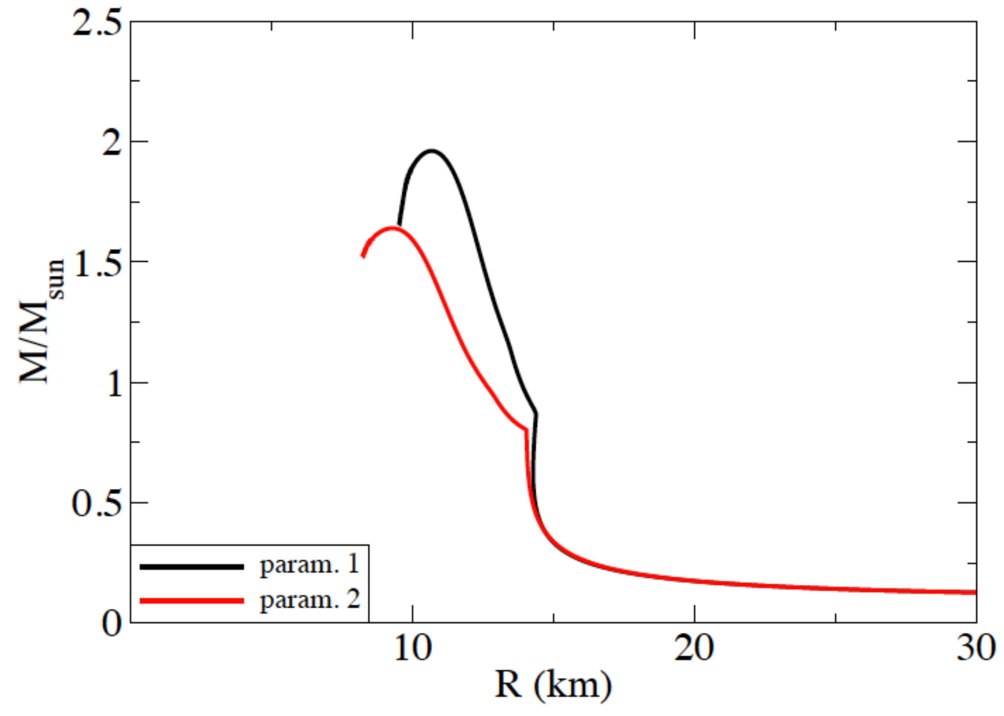
- different quark vector couplings
- reproduces nuclear matter constraints
- first order phase transition star matter
- massive stars + twin stars

HyperoNS 2012 Warsaw, Poland



3. Self-Consistent EOS – Excluded Volume with Chiral Partners

- hadron chemical potentials decreased by quarks
- reproduces nuclear matter constraints
- reproduces heavy ion and lattice QCD results
- massive stars

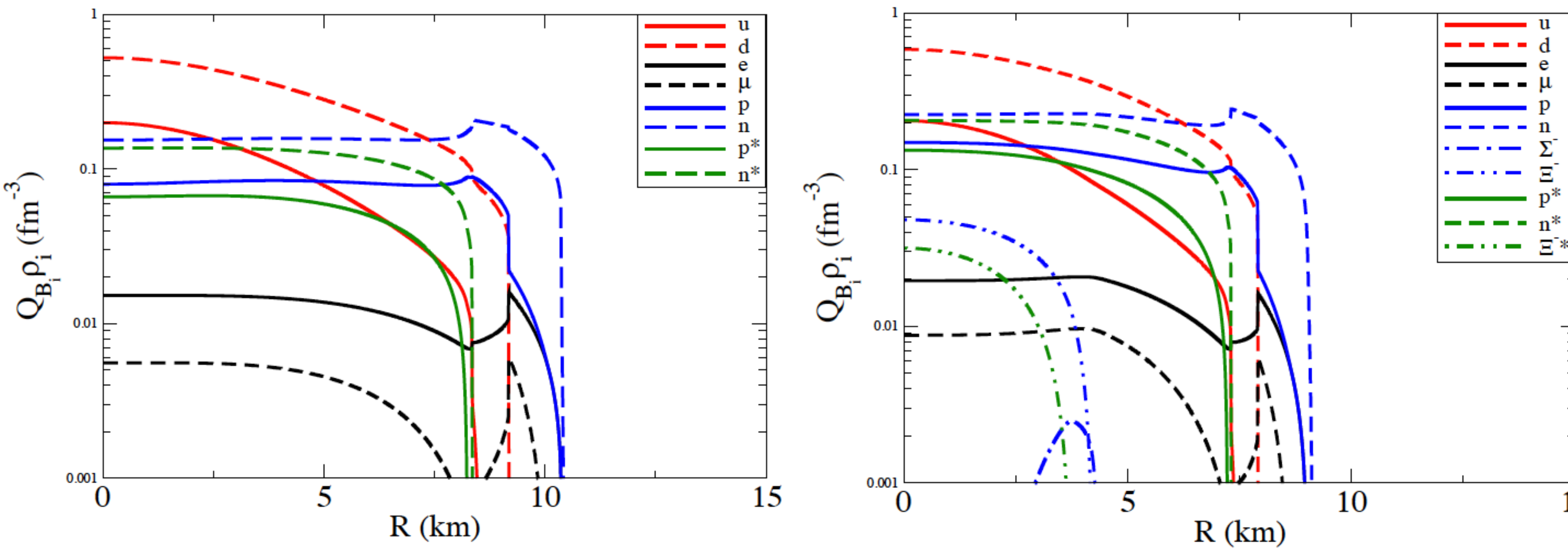


Steinheimer et al. Phys. Rev. C 2011

Dexheimer et al. Phys. Rev. C 2013

Population

- interplay between chiral partners and quarks
- 1st order phase transitions



- much more strange particles at T = 30 MeV

Dexheimer et al. Phys. Rev. C 2013

✯ Summary:

- hybrid stars with self-consistent EOS

  hadron +quark + chiral partners

- 1^{st} order phase transitions / crossovers
- finite temperature
- in agreement with heavy ion collisions and lattice QCD
- reproduces observed cooling curves with pairing

Dexheimer et al. Phys. Rev. C 2013

- massive stars

  + rotation

  + magnetic field effects

Cardall et al. Astrophys J. 2001

Bocquet et al. Astron. Astrophys. 1995

Dexheimer et al. Eur. Phys. J. 2012

Mallick et al. ArXiv 2013

Interaction term between baryons and mesons

$$\mathcal{L}_{int} = -\sqrt{2} g_8^W \left\{ \alpha_W [\bar{B}\mathcal{O}BW]_{AS} + (1-\alpha_W)[\bar{B}\mathcal{O}BW]_S \right\} - g_1^W \frac{1}{\sqrt{3}} \mathrm{Tr}(\bar{B}\mathcal{O}B)\mathrm{Tr}(W)$$

where the antisymmetric coupling is $[\bar{B}\mathcal{O}BW]_{AS} = \mathrm{Tr}(\bar{B}\mathcal{O}WB - \bar{B}\mathcal{O}BW)$ and the symmetric one is $[\bar{B}\mathcal{O}BW]_S = \mathrm{Tr}(\bar{B}\mathcal{O}WB + \bar{B}\mathcal{O}BW) - \frac{2}{3}\mathrm{Tr}(\bar{B}\mathcal{O}B)\mathrm{Tr}(W)$. The matrices $\mathcal{O}$ and W depend on the interaction considered. $\mathcal{O} = 1$ and $W = X$ stand for the interaction between the baryons and the scalar mesons, $\mathcal{O} = \gamma_\mu\gamma_5$ and $W = u_\mu$ for the interaction between the baryons and the pseudoscalar mesons, $\mathcal{O} = \gamma_\mu$ and $W = \tilde{V}_\mu$ for the vector part of the interaction between the baryons and the vector mesons, $\mathcal{O} = \sigma^{\mu\nu}$ and $W = \tilde{V}_{\mu\nu}$ for the tensor part of the interaction between the baryons and the vector mesons and $\mathcal{O} = \gamma_\mu\gamma_5$ and $W = \tilde{A}_\mu$ for the interaction between the baryons and the axial-vector mesons.

$$M_N^* = g_1^X \frac{1}{\sqrt{3}}(\sqrt{2}\sigma + \zeta) - g_8^X \frac{1}{3}(4\alpha_X - 1)(\sqrt{2}\zeta - \sigma),$$

When heavier degrees of freedom are included in the model, e.g. spin 3/2 resonances

$$\mathcal{L}_{int} = \mathcal{L}_{int} - \sqrt{2} g_{D8}^W [\bar{D}^\mu \mathcal{O} D_\mu W] - g_{D1}^W [\bar{D}^\mu \mathcal{O} D_\mu] \mathrm{Tr}(W)$$

✯ Non-linear SU(3) Sigma Model Lagrangian Density for Hadrons

$$L_{MFT} = L_{Kin} + L_{Bscal} + L_{Bvec} + L_{scal} + L_{vec} + L_{SB}$$

$$L_{Bscal} + L_{Bvec} = -\sum_i \bar{\psi}_i [g_{i\omega}\gamma_0\omega + g_{i\phi}\gamma_0\phi + g_{i\rho}\gamma_0\tau_3\rho + m_i^*]\psi_i$$

$$L_{vec} = -\frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2)\frac{\chi^2}{\chi_o^2} - g_4\left(\omega^4 + \frac{\phi^4}{4} + 3\omega^2\phi^2 + \frac{4\omega^3\phi}{\sqrt{2}} + \frac{2\omega\phi^3}{\sqrt{2}}\right)$$

$$L_{scal} = \frac{1}{2}k_0\chi^2(\sigma^2 + \zeta^2 + \delta^2) - k_1(\sigma^2 + \zeta^2 + \delta^2)^2 - k_2\left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2\delta^2 + \zeta^4\right)$$

$$-k_3\chi(\sigma^2 - \delta^2)\zeta + k_4\chi^4 + \frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} - \epsilon\ \ \chi^4 \ln\frac{(\sigma^2 - \delta^2)\zeta}{\sigma_0^2\zeta_0}$$

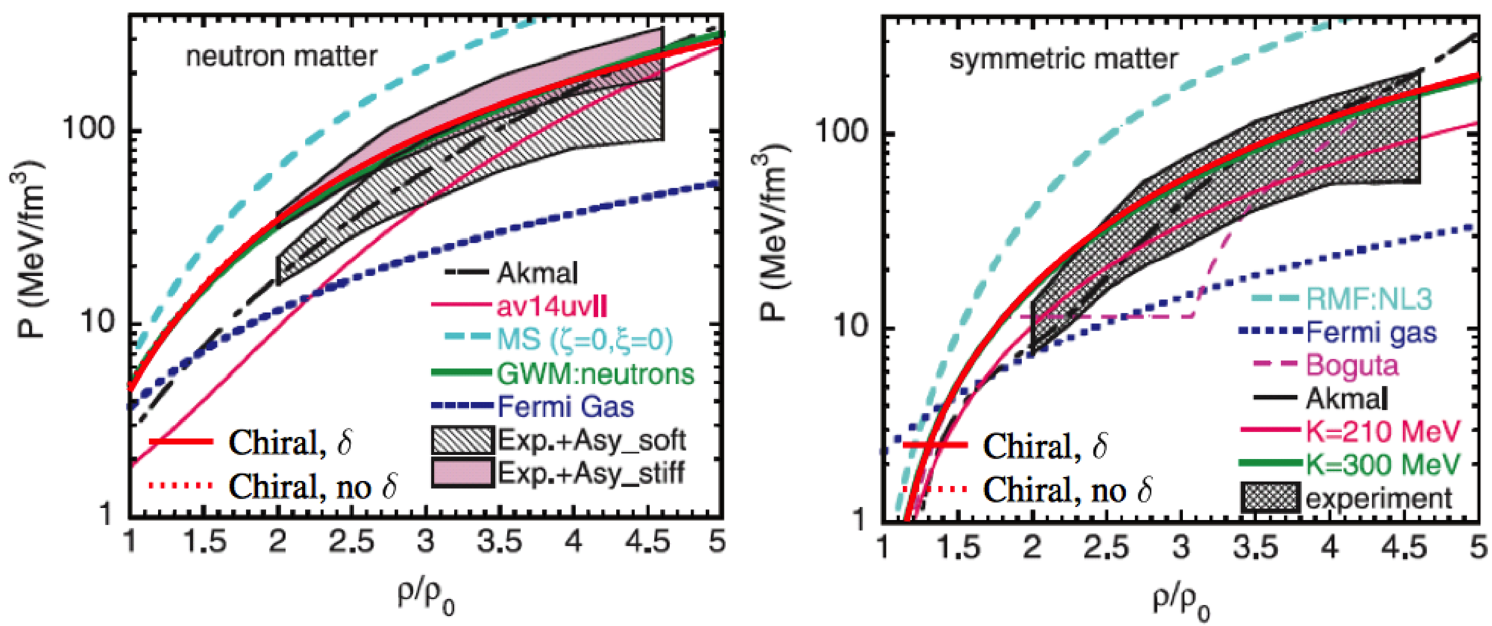
$$L_{SB} = \left(\frac{\chi}{\chi_0}\right)^2 \left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right]$$

$$m^* = g_{i\sigma}\sigma + g_{i\delta}\tau_3\delta + g_{i\zeta}\zeta + \delta m$$

frozen limit: $\chi = \chi_0$

Non-linear SU(3) Sigma Model Parameter Fitting for Hadronic Phase:

- coupling constants reproduce: standard nuclear constraints, baryon vacuum masses, hyperon potentials



Danielewicz et al. Science 2002

- nuclear matter saturation properties
(ϱ_0=0.15 fm^{-3}, B=-16.00 MeV, K_0=298 MeV
$E_{sym\ 0}$=29.56 MeV, L_0=88.18 MeV, p_0=4.52 MeV/fm^3)

- inclusion of the delta meson (scalar-isovector)
($E_{sym\ 0}$=32.47 MeV, L_0=93.85 MeV, p_0=4.82 MeV/fm^3)

⭑ Inclusion of Quarks in the Model

mesons

$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2.$$

$$m_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + \delta m_q + g_{q\Phi}(1 - \Phi).$$

order parameter for deconfinement
in analogy with the Polyakov loop