Equation of State for Hybrid Compact Stars

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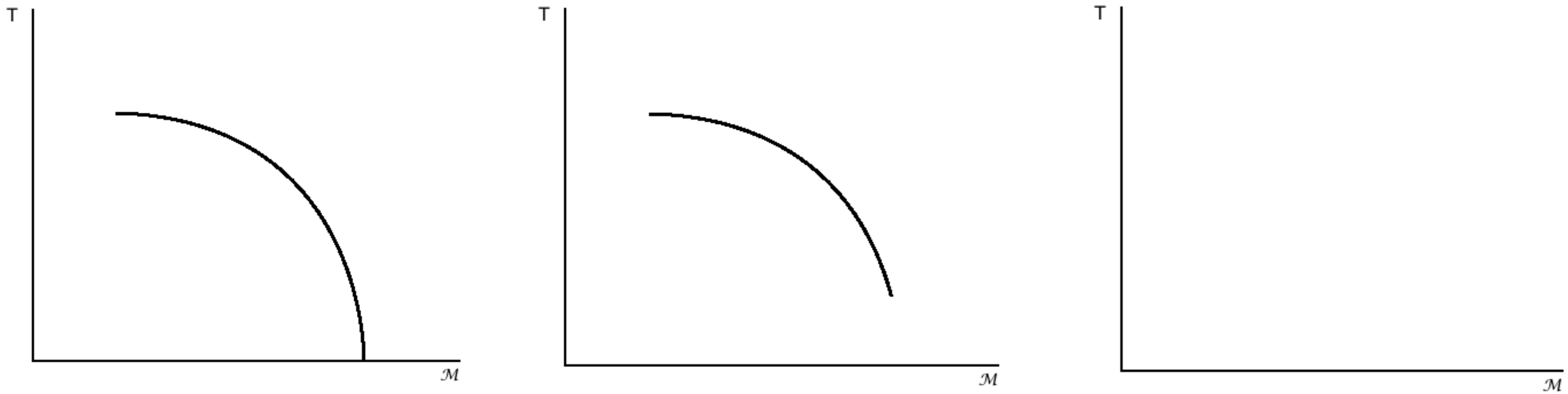
✯ Motivation:

- very little information about the QCD phase diagram at zero or low temperature



- very little information about amount of strangeness in compact stars

hyperons? quarks?

⭑ Ingredients:

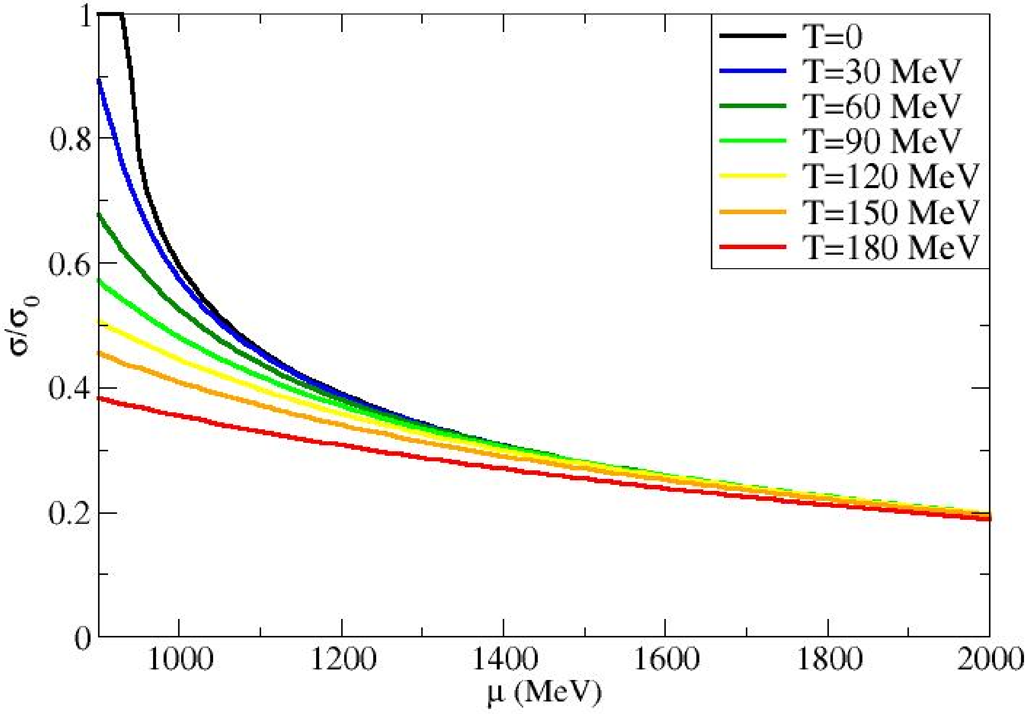
- baryon octet: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-
- up, down, strange quarks
- nuclear physics constraints
  - vacuum masses of baryons and mesons
  - saturation density: 0.15 fm^{-3}
  - binding energy: - 15.65 MeV
    compressibility at saturation: 304.48 MeV
  - symmetry energy at saturation: 32.43 MeV
    and derivative at saturation: 99.90 MeV
  - hyperon optical potentials at saturation
    U_Λ = - 30.44 MeV, U_Σ = 2.47 MeV, U_Ξ = - 26.28 MeV

⋆ Non-Linear Realization SU(3) Sigma Model:

- effective quantum relativistic model → mean field approximation

- 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



$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B}$$

Dexheimer et al. Astrophys.J. 2008

Lagrangian Density for Hadrons

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

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

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

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

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

gluon condensate

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

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

frozen limit: $\chi=\chi_0$

Self-Consistent EOS:

- quarks included within same model

$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q}$$

- excluded volume for baryons modifies their chemical potentials

$\hat{\mu}_i = \mu_i^* - v_i P$ with $v_B = 0.5\ \mathrm{fm}^{-3}$, $v_q = 0$ and

$$\mu_i^* = Q_{B_i}\mu_B - Q_i\mu_q - g_{i\omega}\omega - g_{\phi}\phi - g_{i\rho}\tau_3\rho$$

- interactions with the medium determine degrees of freedom
- chiral symmetry restoration and deconfinement
- number densities and energy density multiplied by correction factor

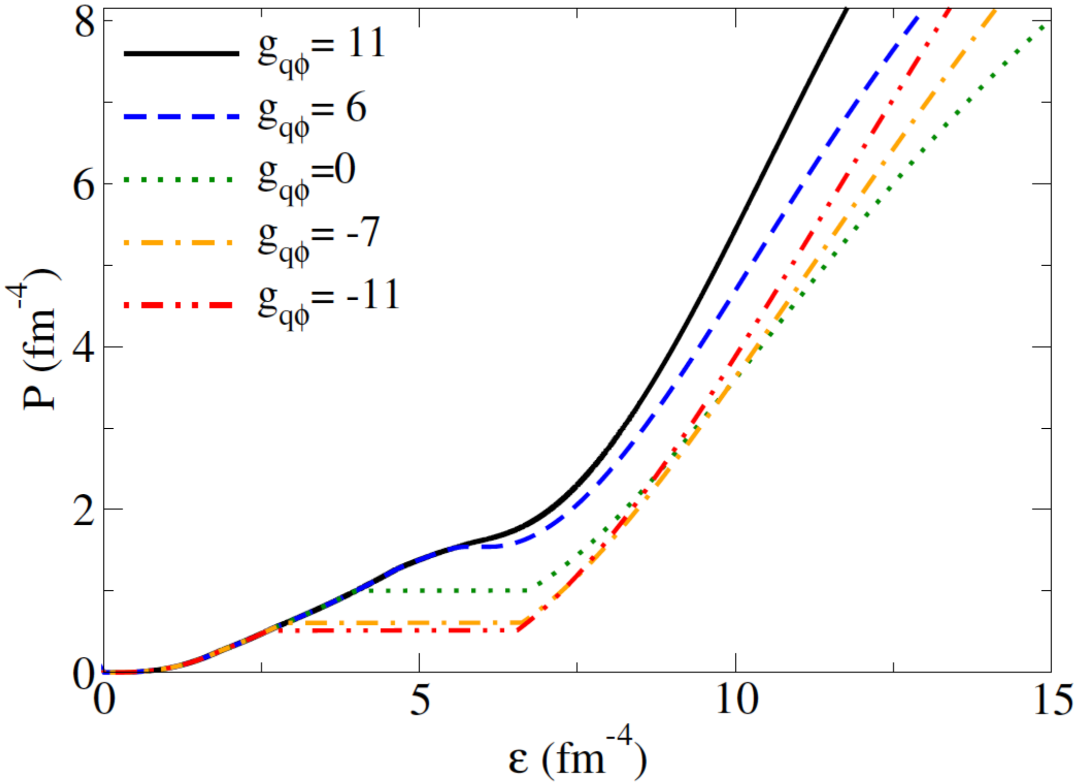
excluded (not occupied) volume

$$f = \frac{V'}{V} = \left(1 + \sum_i v_i\rho_i\right)^{-1}$$ affecting quarks too

✭ Equation of State:

- with charge neutrality and in chemical equilibrium

- different strength of strange quark coupling to strange meson



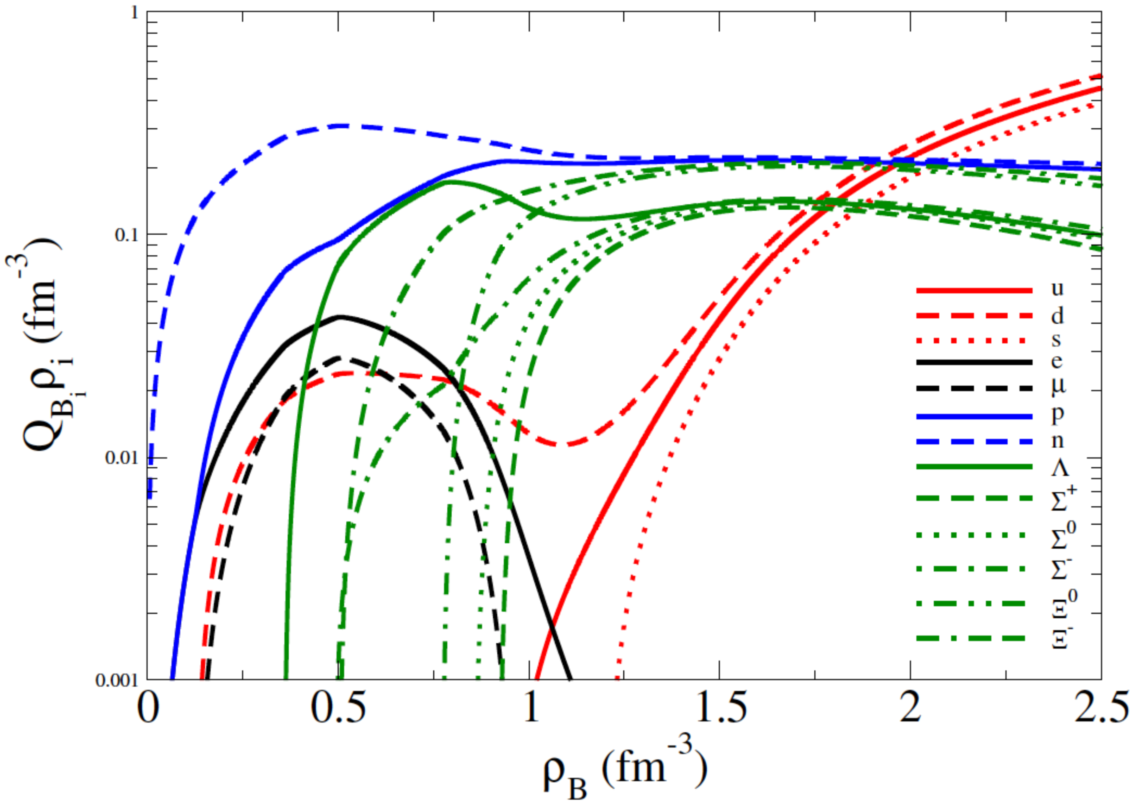
Crossovers at T=0:
Baym et al. J. Phys. G. 2008
Lourenco et al. Phys. Rev. D 2012

- different stiffness and strength of phase transition
(1st order for $g_{q\phi} \geq 6$)

✯ Population:

- $g_{q\phi}$= 11 (crossover)

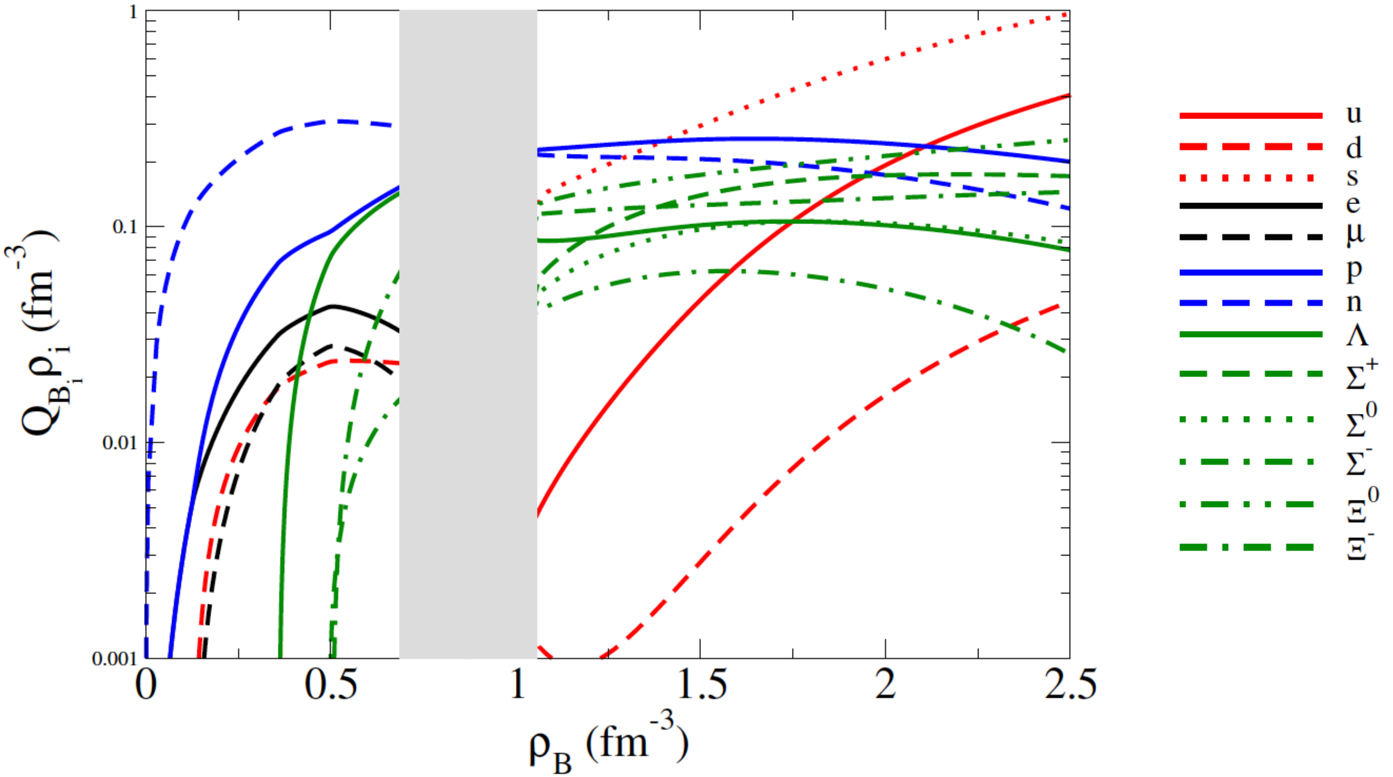
- n, p+e, d, μ, Λ, Σ^-, Ξ^-, Ξ^o, Σ^o, Σ^+, u, s



- down quark appears right after saturation density

- $g_{q\phi} = 0$ (1st order phase transition)

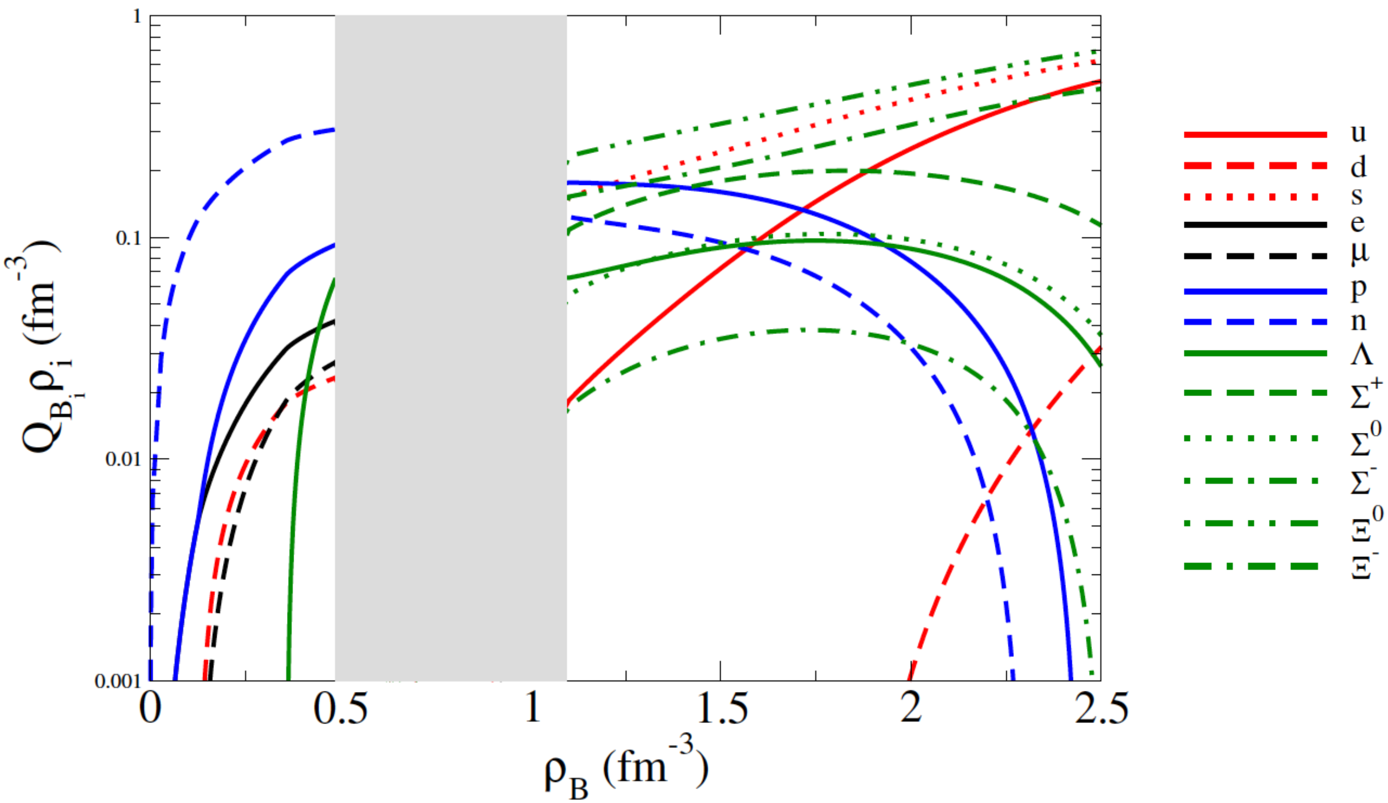
- n, p+e, d, μ, Λ, Σ⁻, Ξ⁻ / s, Ξ⁰, Σ⁺, Σ⁰, u



- density jump of 0.37 fm^{-3} in star

- $g_{q\phi}$= -11 (1st order phase transition)

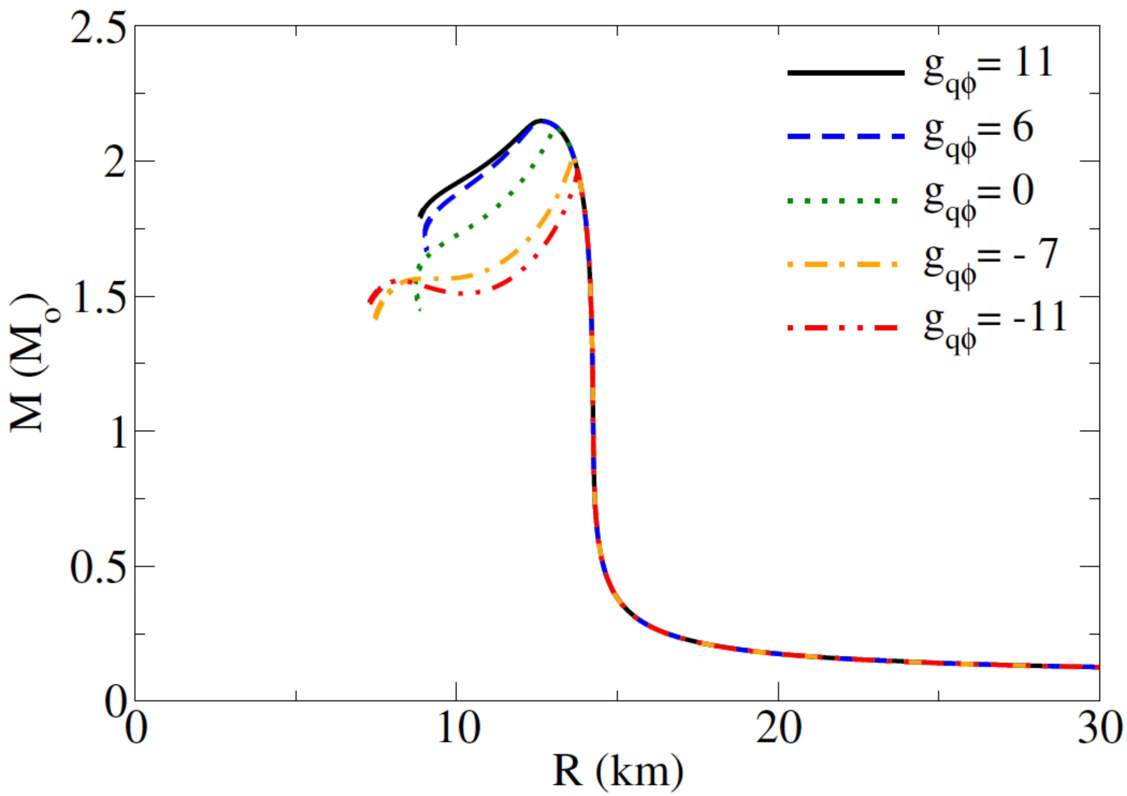
- n, p+e, d, μ, Λ / Ξº, Ξ⁻, s, Σ⁺, Σº, u, Σ⁻



- density jump of 0.61 fm^{-3} in star

Mass-Radius Diagram:

- solving the TOV equations



- for $g_{q\phi} = 11$
  $f_S(R=14.15\text{ km})=0.13$
  $f_S(R=8.22\text{ km})=1.34$

$$f_s = \sum_i \rho(i) Q_{S_i} / \rho_B$$

- different maximum masses ($M = 2.15\ M_\odot$ for $g_{q\phi} = 11$)
- twin star solutions for $g_{q\phi} \leq -7$ ($\Delta\rho_B = 0.57\text{ fm}^{-3}$, $\Delta\varepsilon = 738.09\text{ MeV/fm}^3$)

Summary:

- hybrid stars with self-consistent EOS
  nucleons + hyperons +quarks

- reproduces nuclear constraints

- strange coupling: crossover / 1st order phase transitions

- reproduces massive stars

- strange coupling: twin star solutions

Outlook:

- calculate cooling curves (including pairing)

- include finite temperature effects and neutrino trapping to calculate supernova EOS