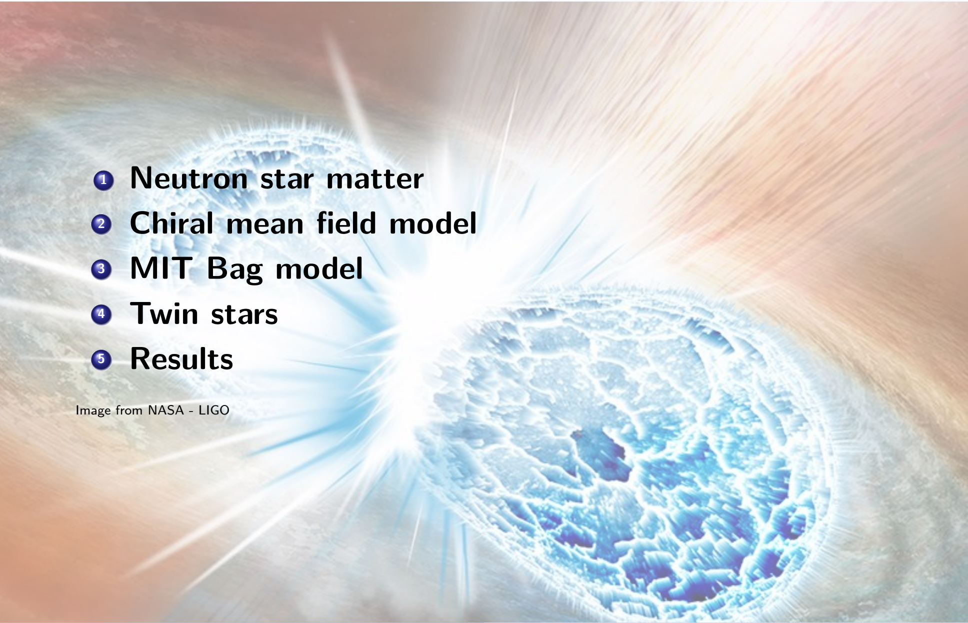
Twin Stars In A Modified Chiral Mean Field Model

Pia Jakobus

Goethe University Frankfurt am Main

October 14, 2019

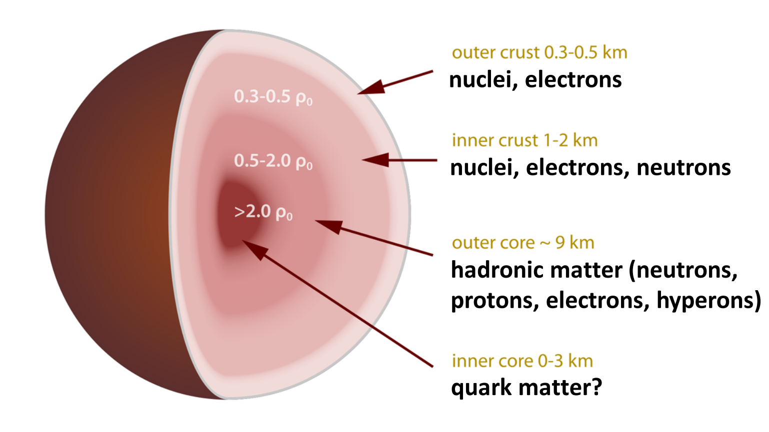
Motivation And Content



1. **Neutron star matter**
2. **Chiral mean field model**
3. **MIT Bag model**
4. **Twin stars**
5. **Results**

Image from NASA - LIGO

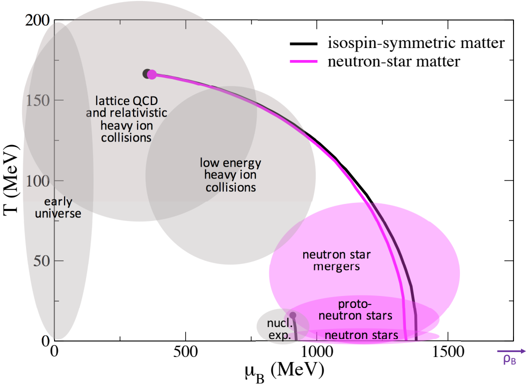
Neutron star matter



from `kent.edu/physics/profile/veronica-dexheimer`

Properties of Neutron star matter

- Charge neutral
  $\sum_i \rho_{B_i} Q_{B_i} = 0$
- Conserved Baryon number
- Beta equilibrium
  $\mu_n = \mu_p + \mu_e$
- isospin asymmetry
- $T_{\mathrm{Thermal}} \ll T_{\mathrm{Fermi}}$



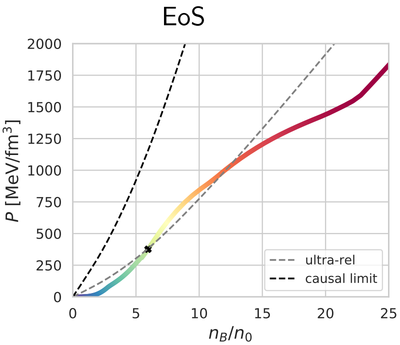
kent.edu/physics/profile/veronica-dexheimer

Equation of state

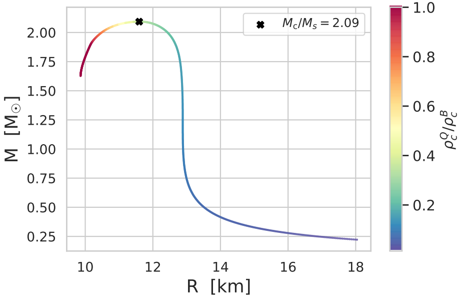
Chiral SU(3)-flavor parity-doublet Polyakov-loop quark hardon mean-field model:
Unified approach to model QCD from low to high temperatures and densities.

- **Baryon octet**
- **Chiral symmetry restoration**
- **Smooth crossover to quarks**
- **Excluded-volume effects**

Anton Motornenko et al: Universe **5** (2019) no.6, 156.



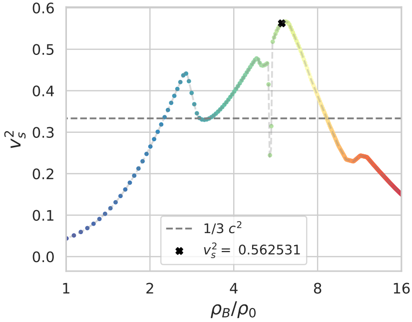
Maximum mass 2.1 $M_\odot$ (quark ratio in core $\approx$ 30%)



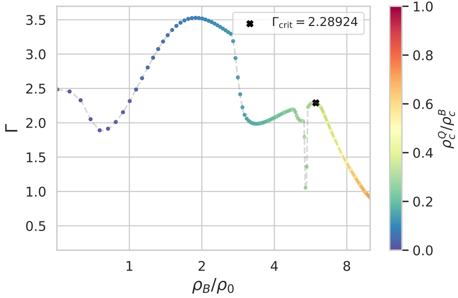
- Baryons only presented by nucleons and their parity partners
- chiral symmetry restoration at $n \approx 4n_B$
- Crossover to quark matter

Chiral mean field model

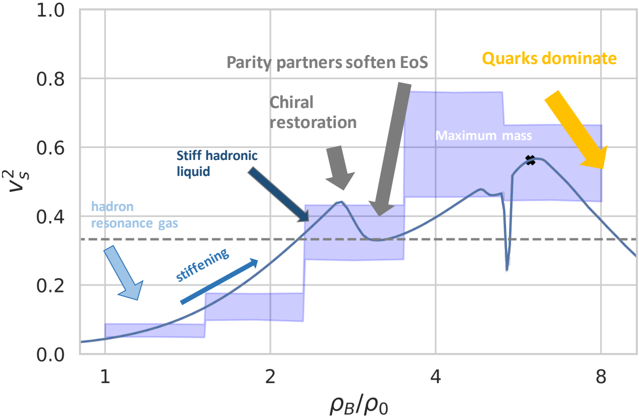
(Speed of sound)^2



Adiabatic index $\Gamma \equiv \frac{P+\epsilon}{P} v_s^2$



Anton Motornenko et al: Universe **5** (2019) no.6, 156.



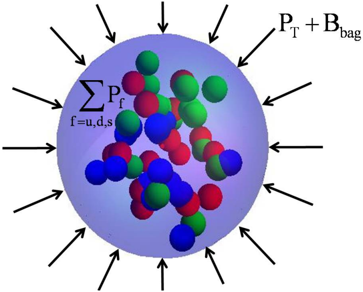
Fukushima 2019: arxiv.org/abs/1903.03400

Bag model

MIT Bag model

- two and three flavor Bag model
- vanishing masses

Rischke et al., arXiv:nucl-th/9504021



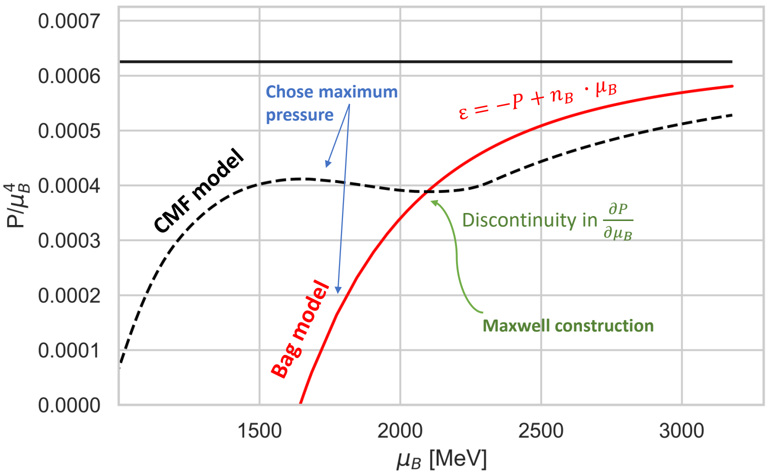
Picture taken from: arXiv:1203.3820

vMIT Bag model

- repulsive quark-meson coupling $g_q^{(\omega)} \gamma^\mu V_\mu^{(\omega)}$
- 3 flavor Bag model
- massive quarks
- leptons included
  $\rightarrow \sum_i q_i n_i = 0$
  $\rightarrow \mu_s = \mu_d = \mu_u + \mu_e$

Gomes et al., arXiv:1806.04763v1

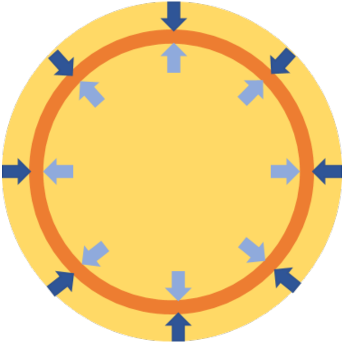
Constructing the combined model



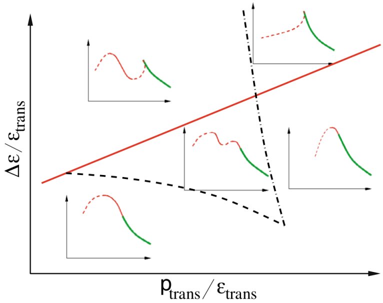
Tolman-Oppenheimer-Volkoff Equation

$$p' \propto \underbrace{-\frac{\epsilon(r)\, m(r)}{r^2}}_{\text{Newton}} \underbrace{\left[1 + \frac{p(r)}{\epsilon(r)}\right] \left[1 + \frac{r^3 p(r)}{m(r)}\right]}_{\text{SR correction}} \underbrace{\left[1 - \frac{r_s}{r}\right]^{-1}}_{\text{GR correction}}; \qquad m' \propto r^2 \epsilon$$

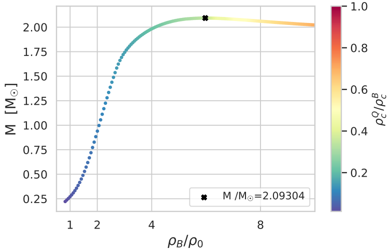
Solution in hydrostatic equilibrium,
as obtained from TOV solver



Twin stars are solutions of the TOV equation for one EoS where both stars have identical masses but different radii



Branch stable if: $\frac{\mathrm{d}M}{\mathrm{d}\rho} \geq 0$

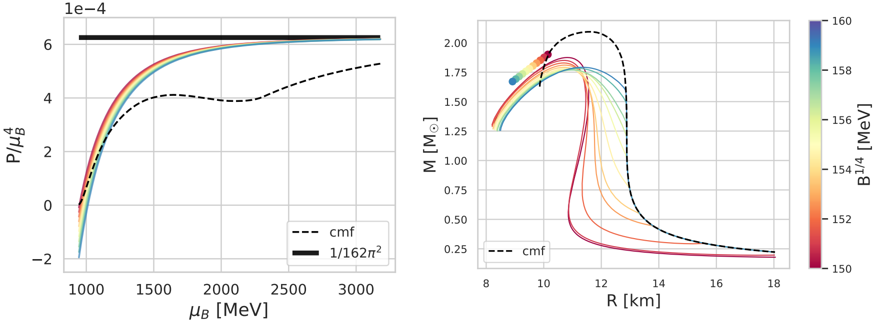


Seidov: $\frac{\Delta\epsilon_{\mathrm{trans}}}{\epsilon_{\mathrm{trans}}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\mathrm{trans}}}{\epsilon_{\mathrm{trans}}}$

Alford et al. arXiv:1508.01261v2

2 flavor MIT Bag model

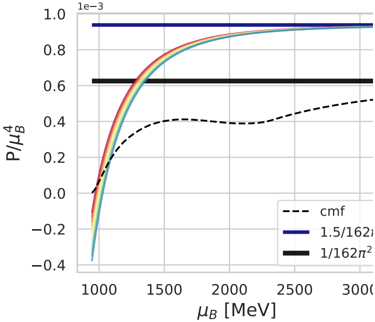
Bag model softens EoS $\rightarrow$ stiff enough for second branch?

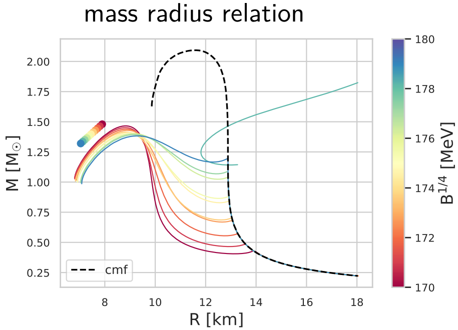


Bag EoS: $P = \frac{1}{3}(\epsilon - 4B)$

3 flavor MIT Bag model

Bag EoS "steeper" $\frac{P}{\mu_B^4} = \tilde{\nu} - \frac{B}{\mu_b^4}$, $\tilde{\nu} = 1.5/162\pi^2$

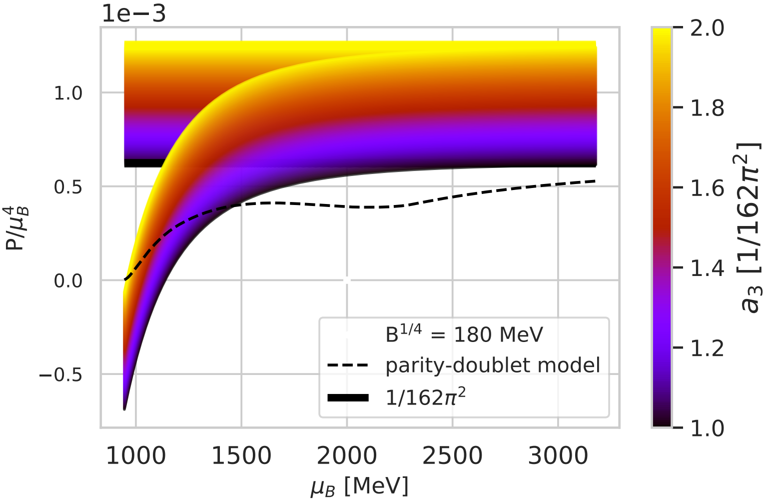




The gap in energy density is bigger for 3 flavors

Change in slope at Maxwell construction:

$$n_B^{(1)} - n_B^{(2)} = \left[\frac{\partial P^{\mathrm{CMF}}}{\partial \mu_B} - \frac{\partial P^{\mathrm{BAG}}}{\partial \mu_B} \right]_{\mu_B = \mu_B^{MC}}$$



Two solar mass constraint

MIT Bag model

Speed of sound for Bag Model fixed to 1/3, high masses not obtained within this framework!

MSR J0740+6620: $2.14^{+0.2}_{-0.18}$ $M_\odot$

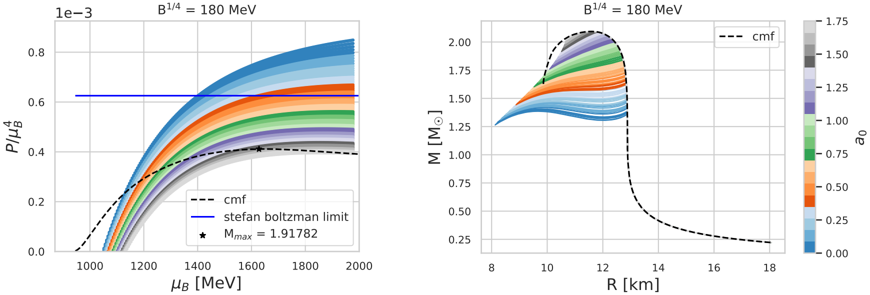
Can a stiffer Quark-EoS support twins stars above 2 $M_\odot$?

- how does vector enhanced Bag model change transition pressure and energy gap?
- how relevant is the ratio of stiffness?

Vector enhanced MIT Bag model

Additional meson-ω-quark coupling. Does one obtain Twin star solutions with higher masses by stiffening the vMIT Bag model EoS?

Colorbar now a_0 instead of B

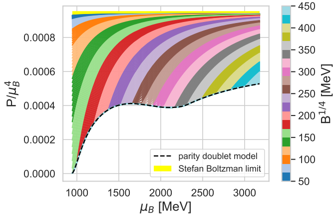


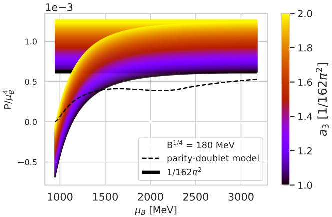
MIT Bag model

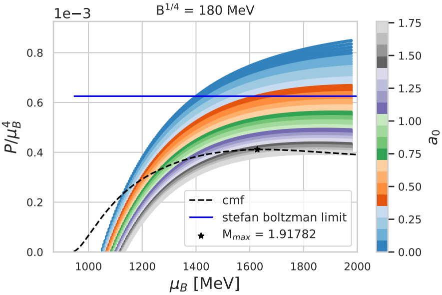
Bag constant B, Stephan Boltzman limit $a_{3,SB}$

vMIT Bag model

Bag constant B, repulsive quark-ω-meson coupling $a_{3,\omega}$



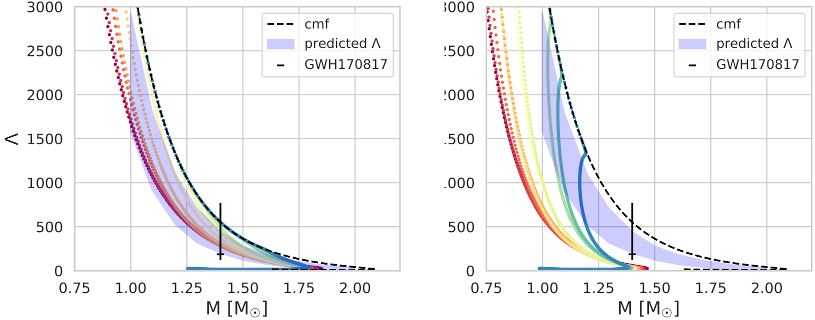




Outlook

GW170817

Experimental comparison with merger event



2 flavor (l), 3 flavor (r)

$$\text{deformability} \propto \frac{\text{induced quadrupole}}{\text{perturbing tidal field}}$$

Fukushima 2019: arxiv.org/abs/1903.03400

c

Summary and Outlook

- **Twin stars** can be obtained but the **masses are too low**
- In order to obtain higher Twin masses: **Soft behaviour of quark matter at hadron-quark transition**, in order to have a sufficient latent heat
- stiffening of quark matter by **density dependend coupling** necessary in order to obtain higher mass

on the other hand ...

- **Exotic** degrees of freedom **soften hadronic EoS** .. at which densities?
- **Repulsive couplings** can **violate lQCD results**[1][2]

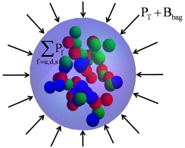
[1] Physics Letters B, 696(3):257–261, 2011
[2] Physics Letters B, 736:241–245, 2014

Thank you for your attention!

Summary

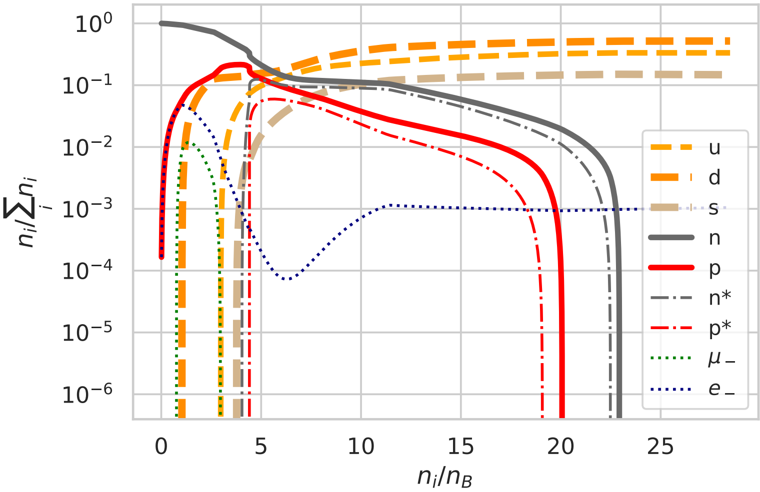
MIT Bag model

- $B \uparrow, \mu_{\mathrm{trans}} \uparrow$
- $a_3 \uparrow \measuredangle(\text{bag,cmf})\uparrow \Delta\epsilon \uparrow$
- $M_{\mathrm{bag}}^{\mathrm{max}} \leq M_{\mathrm{trans}} \wedge$
  $\frac{\Delta\epsilon_{crit}}{\epsilon_{trans}} \geq \frac{1}{2} + \frac{3}{2}\frac{p_{trans}}{\epsilon_{trans}}$
  no twins
- $P = 1/3(\epsilon - 4B)$:
  $dP/d\epsilon = c^2/3^2 \ \forall B, a_3$



vMIT Bag model

- $B \uparrow, \mu_{\mathrm{trans}} \uparrow$
- $a_0 \uparrow \measuredangle(\text{bag,cmf})\downarrow \Delta\epsilon \downarrow$


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$n_i/\sum_i n_i$
0
5
10
15
20
25
n_i/n_B
u
d
s
n
p
n*
p*
μ_-
e_-

ρ_0	0.14 ± 0.02 fm^{-3}
$E_{\rm bind}$/nucleon	16.6 ± 0.8 MeV
Compressibility K_0	269 ± 54 MeV
$E_{\rm asym}$	30 ± 6 MeV

Saturation properties

Model description. In detail here: Motornenko 2019, arXiv:1905.00866

- Mean field approximation
- Baryon octet interacts via scalar σ, ζ and vector ω, ρ, ϕ mesons

$$\mathcal{L}_B = \sum_i \overline{\psi}_i \left(i\gamma_\mu \partial^\mu + m_i^* \right) \psi_i \tag{1}$$

$$+ \sum_i \overline{\psi}_i \left[\gamma_\mu \left(g_{i\omega} \omega^\mu + g_{i\rho} \rho^\mu + g_{i\phi} \phi^\mu \right) + m_i^* \right] \psi_i \tag{2}$$

- symmetry among parity partners at finite μ_B: $m_{i\pm}^* = \sqrt{(g_{i\sigma}^{(1)} \sigma + g_{i\zeta}^{(1)} \zeta)^2 + (m_0 + n_s m_s)^2} \pm g_{i\sigma}^{(2)} \sigma + g_{i\zeta}^{(2)} \zeta$
- Chiral symmetry breaking term:

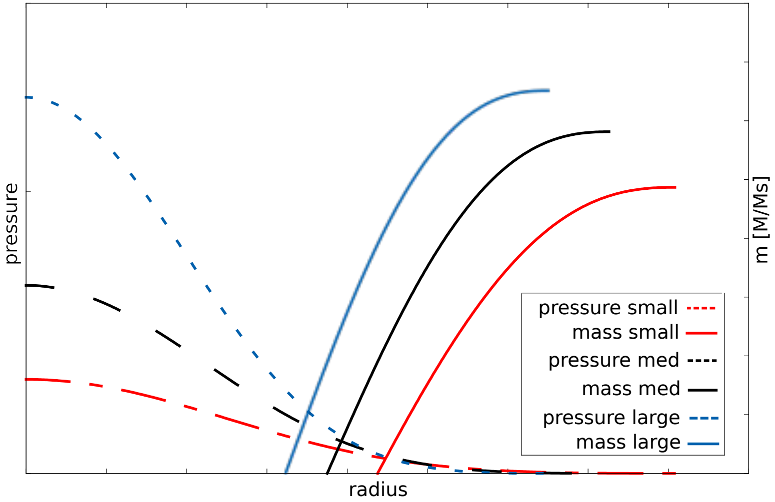
$$V = V_0 + \frac{1}{2} k_0 (\sigma^2 + \zeta^2) - k_1 (\sigma^2 + \zeta^2)^2 + k_2 (\sigma^4/2 + \zeta^4) + k_6 + 4\zeta^6)$$

- Polyakov loop enters grand canonical potential for quarks
- dynanmic quark masses:

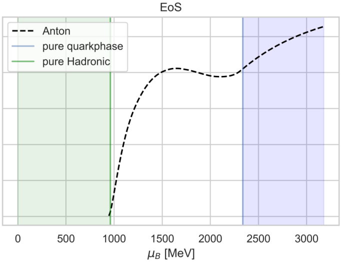
$$m_q^* = g_{q\sigma} \sigma + \delta m_q + m_{0q} \tag{3}$$

$$m_s^* = g_{s\zeta} \zeta + \delta m_s + m_{0s} \tag{4}$$

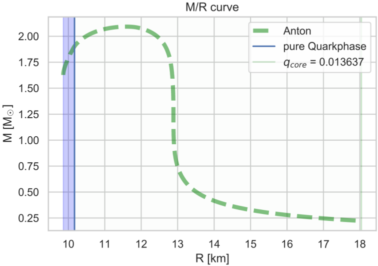
Mass Radius Profiles



CMF model



EoS
Anton
pure quarkphase
pure Hadronic
0
500
1000
1500
2000
2500
3000
μ_B [MeV]



M/R curve
Anton
pure Quarkphase
q_{core} = 0.013637
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
M [$M_\odot$]
10
11
12
13
14
15
16
17
18
R [km]