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Constraining quark-hadron interface tension in the multi-messenger era

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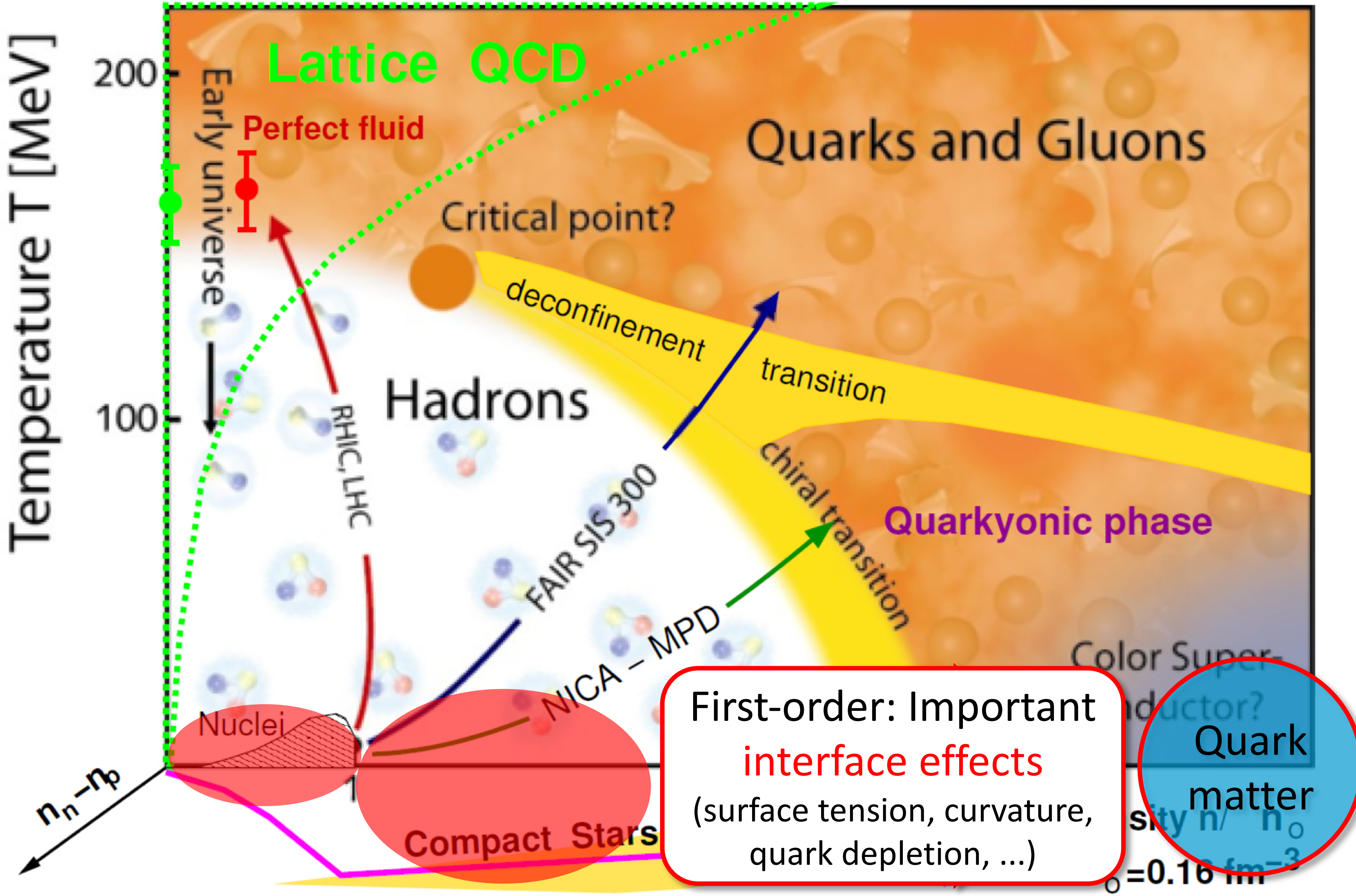
QCD Phase Diagram [McLerran2009_NPB195-275]



Estimations of surface tension

Lattice QCD: Huang, Potvin, Rebbi, Saniele[illegible] de Forcrand, Lucini, Vettorazzo, et al.

For vanishing chemical potentials!

Effective models:

MIT bag model [Oertel_Urban2008_PRD77-074015], Linear sigma model [Palhares_Fraga2010_PRD82-125018, Pinto_Koch_Randrup2012_PRC86-025203, Kroff_Fraga2015_PRD91-025017], NJL model [Garcia_Pinto2013_PRC88-025207, Ke_Liu2014_PRD89-074041], 3f Polyakov-quark-meson model [Mintz_Stiele_Ramos_Schaffner-Bielich2013_PRD87-036004], Dyson-Schwinger equation approach [Gao_Liu2016_PRD94-094030], Equivparticle model [Xia_Peng_Sun_Guo_Lu_Jaikumar2018_PRD98-034031], and Nucleon-meson model [Fraga_Hippert_Schmitt2019_PRD99-014046]

$$\sigma < 30\ \mathrm{MeV/fm^2}$$

Quasiparticle mode [Wen_Li_Liang_Peng2010_PRC82-025809]

$$\sigma = 30\sim70\ \mathrm{MeV/fm^2}$$

NJL model adopting the MRE method [Lugones_Grunfeld_Ajmi2013_PRC88-045803]

$$\sigma = 145\sim165\ \mathrm{MeV/fm^2}$$

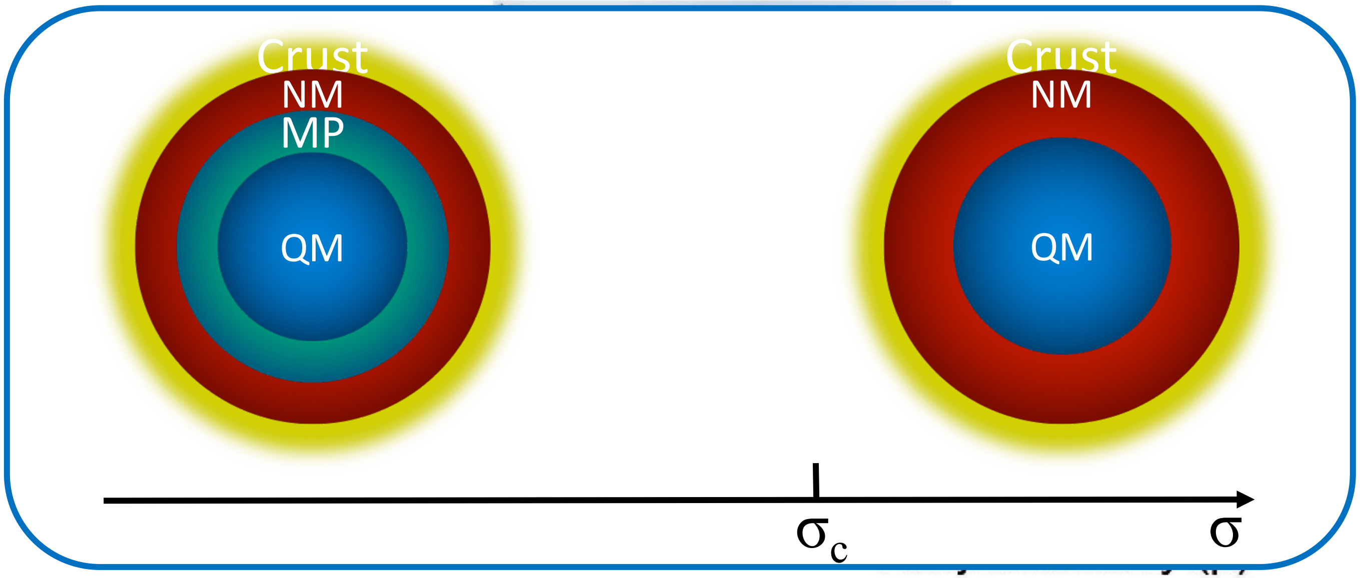
For color-flavor locked SQM, dimensional analysis suggests: [Alford_Rajagopal_Reddy_Wilczek2001_PRD64-074017]

$$\sigma \approx 300\ \mathrm{MeV/fm^2}$$

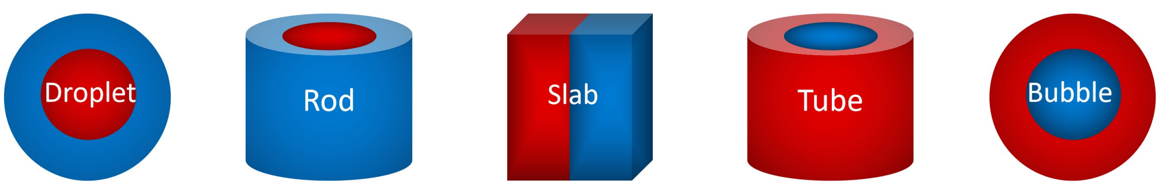
For magnetized SQM, σ has a different value in the parallel and transverse directions with respect to the magnetic field [Lugones_Grunfeld2017_PRC95-015804, Lugones_Grunfeld2019_PRC99-035804]

Hadron-quark mixed phase inside compact stars

First-order phase transition [Masuda_Hatsuda_Takatsuka2016_EPJA52-65]



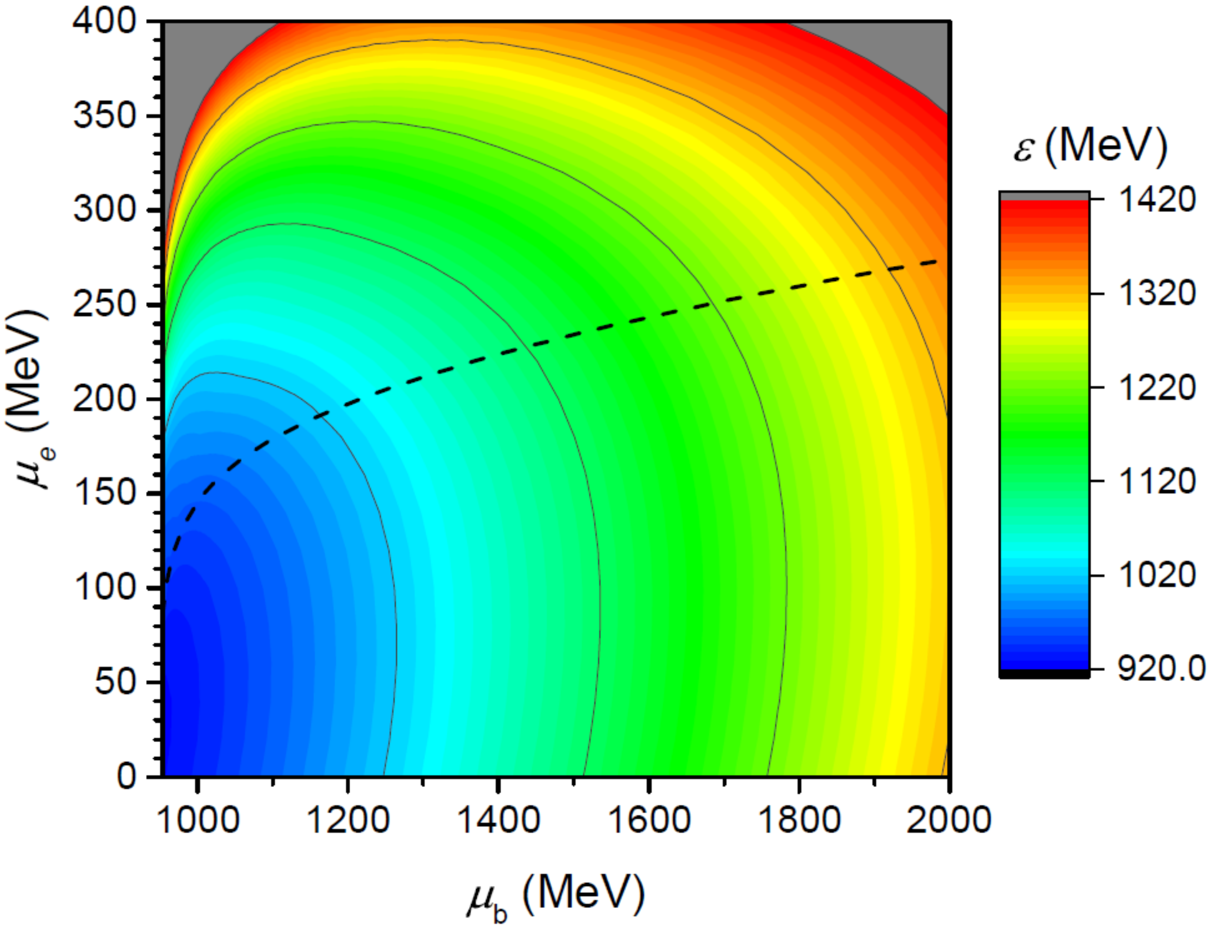
- $\sigma = 0$: point-like hadronic matter (HM) and quark matter (QM), i.e., Gibbs construction.
- Moderate σ : geometrical structures [Chiba, Endo, Heiselberg, Maruyama, Tatsumi, Voskresensky, Yasuhira, Yasutake, ...]



- $\sigma > \sigma_c$: bulk separation of HM and QM, i.e., Maxwell construction.

Nuclear matter (RMFT)

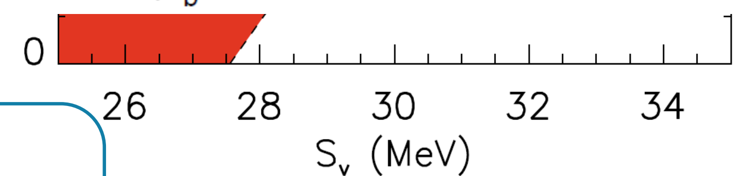
	E_{sym} (MeV)	L (MeV)
NL3	37.35	118.33
TM1	36.84	110.61
PK1	37.64	115.88
PK1r	37.83	116.51
TW99	32.77	55.31
DDME2	32.32	51.30
PKDD	36.80	90.24



Li_Han2013_PLB727-276:

$E_{sym}(\rho_0) = 31.6 \pm 2.66\mathrm{Me}$

$L(\rho_0) = 58.9 \pm 16.0\mathrm{MeV}$



TW99 [Typel_Wolter1999_NPA656-331]

1. the saturation density: ρ_0 (fm^{-3}) **0.153**
2. the energy: E/A (MeV) **-16.25**
3. the incompressibility: k (MeV) **240.2**

Other choices (Δ's):
Sun_Zhang_Zhang_Xia2019
_PRD99-023004

Quark matter [Fraga_Romatschke2005_PRD71-105014]

Perturbation model (pQCD): Expand the thermodynamic potential density up to the order of α_s in the MS scheme:

$$\Omega^{\rm pt} = \sum_i^{N_f} (\omega_i^0 + \omega_i^1 \alpha_s)$$

$$\alpha_s(\bar{\Lambda}) = \frac{1}{\beta_0 L}\left(1 - \frac{\beta_1 \ln L}{\beta_0^2 L}\right),$$

$$m_i(\bar{\Lambda}) = \hat{m}_i \alpha_s^{\frac{\gamma_0}{\beta_0}}\left[1 + \left(\frac{\gamma_1}{\beta_0} - \frac{\beta_1 \gamma_0}{\beta_0^2}\right)\alpha_s\right],$$

where $L = 2\ln\left(\frac{\bar{\Lambda}}{\Lambda_{\overline{\rm MS}}}\right)$ and $\Lambda_{\overline{\rm MS}}$ is the $\overline{\rm MS}$ renormalization point.

The renormalization scale $\bar{\Lambda} = \frac{C}{3}\sum_{i=u,d,s}\mu_i$ with C = 1~4.

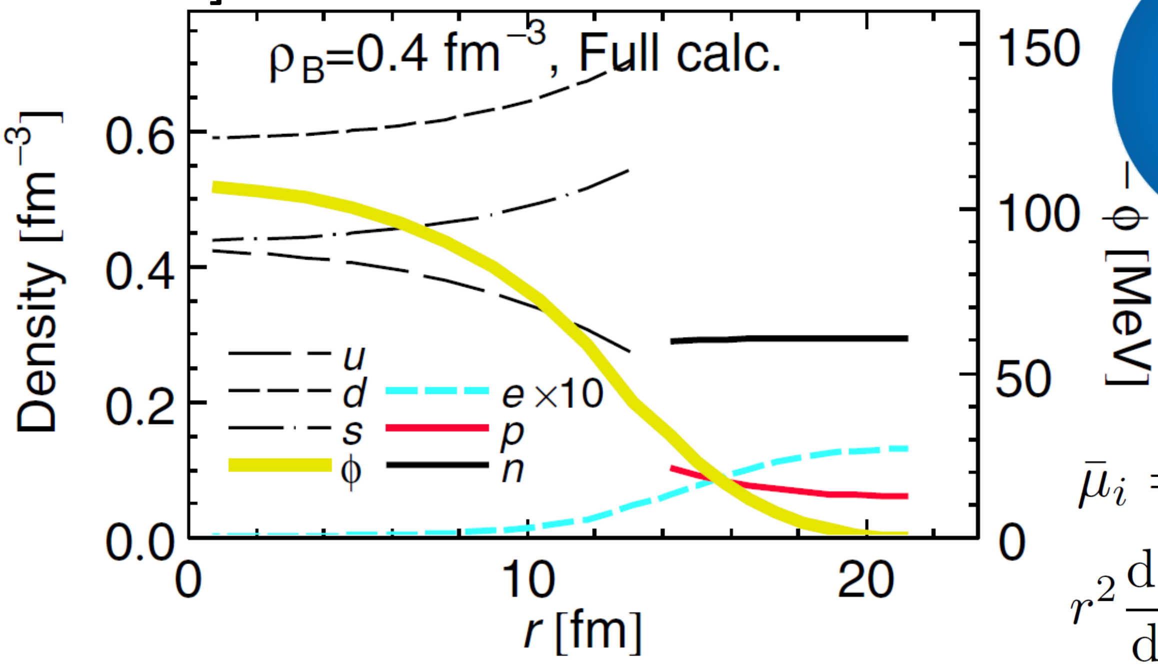
We introduce an extra bag constant B to take into account the energy difference between the physical and perturbative vacua:

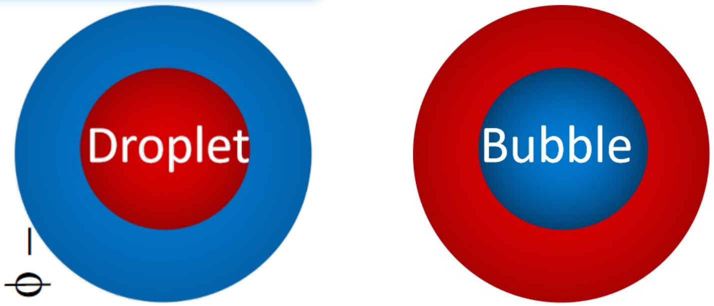
$$\Omega = \Omega^{\rm pt} + B$$

$$B = B_{\rm QCD} + (B_0 - B_{\rm QCD})\exp\left[-\left(\frac{\sum_i \mu_i - 930}{\Delta\mu}\right)^4\right]$$

where $B_0 = 50$ MeV fm^{-3} $\quad$ C, $\Delta\mu$ and $B_{\rm QCD}$ undetermined.

Mixed phase [Maruyama et al.2007_PRD76-123015]





$$\bar{\mu}_i = \mu_i(r) + q_i\varphi(r) = \text{constant}$$

$$r^2\frac{\mathrm{d}^2\varphi}{\mathrm{d}r^2} + 2r\frac{\mathrm{d}\varphi}{\mathrm{d}r} + 4\pi\alpha r^2 n_{\mathrm{ch}}(r) = 0$$

Coulomb potential obtained with linearization

$$\varphi^{\mathrm{I}} = \frac{C^{\mathrm{I}}}{r}\sinh\left(\frac{r}{\lambda_{\mathrm{D}}^{\mathrm{I}}}\right) + \varphi_0^{\mathrm{I}},$$

$$\varphi^{\mathrm{O}} = \frac{C^{\mathrm{O}}}{r\left(R_{\mathrm{W}} + \lambda_{\mathrm{D}}^{\mathrm{O}}\right)}\left[\sinh(\tilde{r})\lambda_{\mathrm{D}}^{\mathrm{O}} + \cosh(\tilde{r})R_{\mathrm{W}}\right] + \varphi_0^{\mathrm{O}}$$

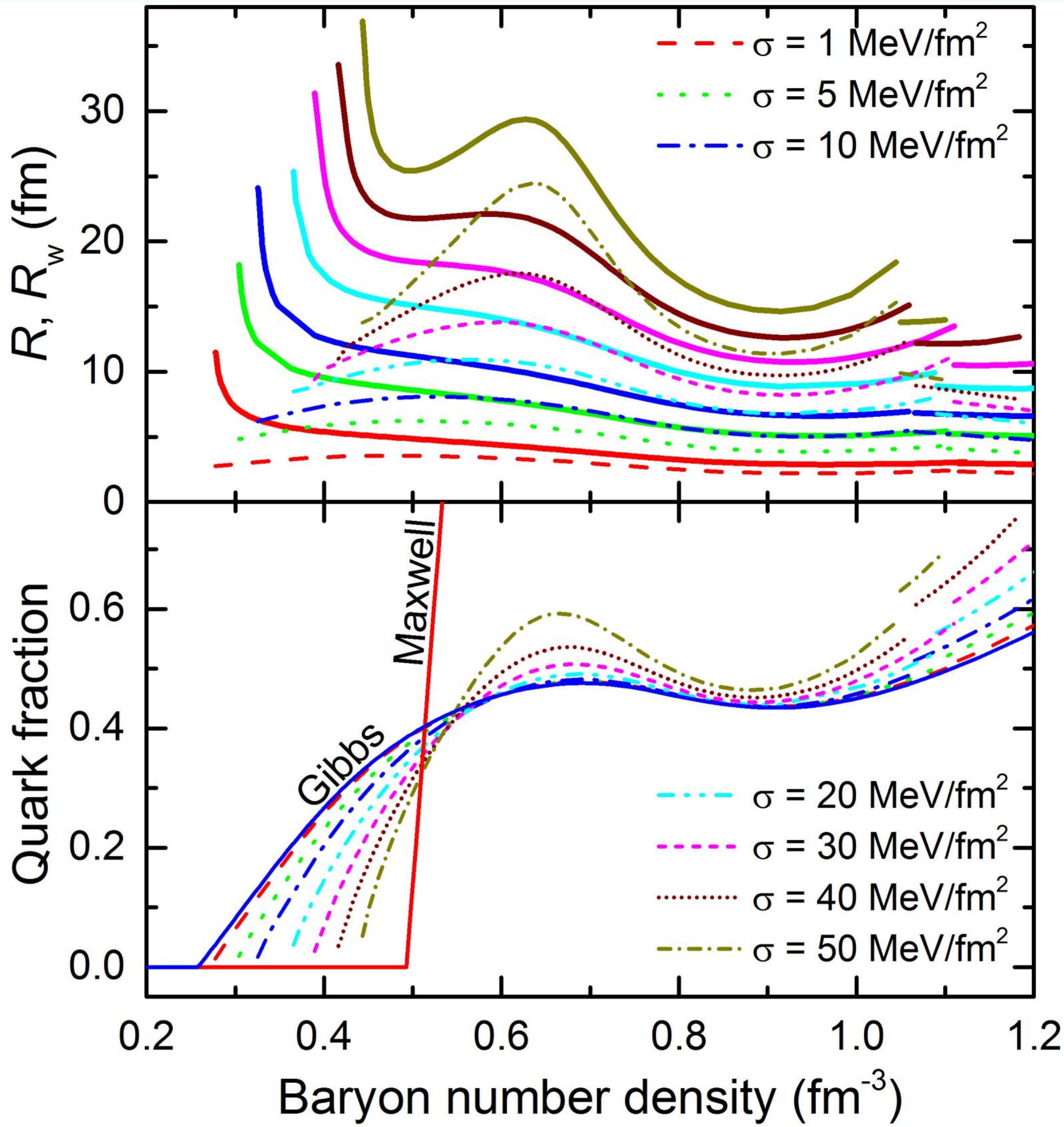
with $\tilde{r} \equiv (r - R_{\mathrm{W}})/\lambda_{\mathrm{D}}^{\mathrm{O}}$.

Dynamic stability of the quark-hadron interface:

$$P^{\mathrm{I}}(R) - 2\frac{\sigma}{R} = P^{\mathrm{O}}(R)$$

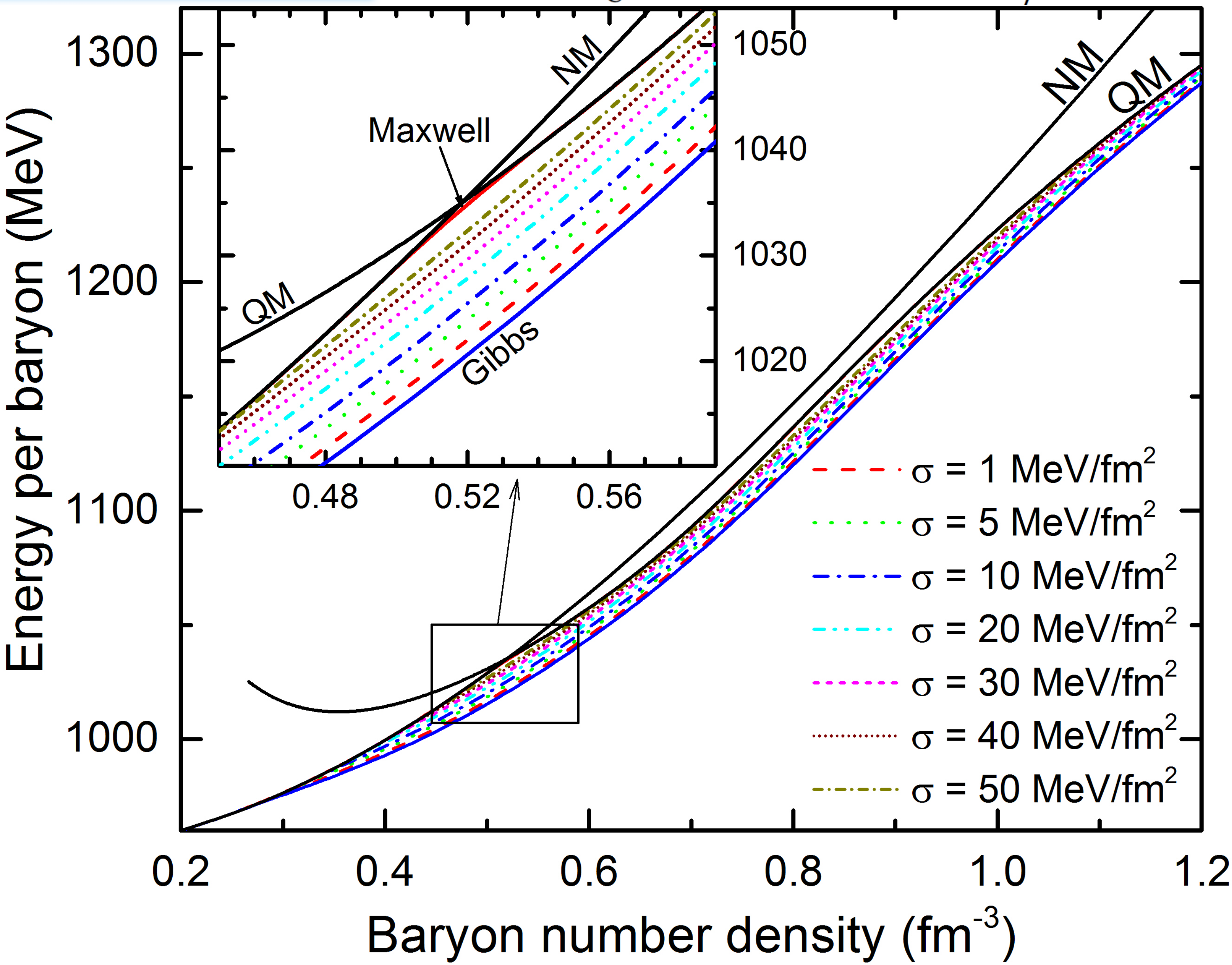
Minimize energy per baryon at fixed density

WS cell radius, droplet radius, and quark fraction

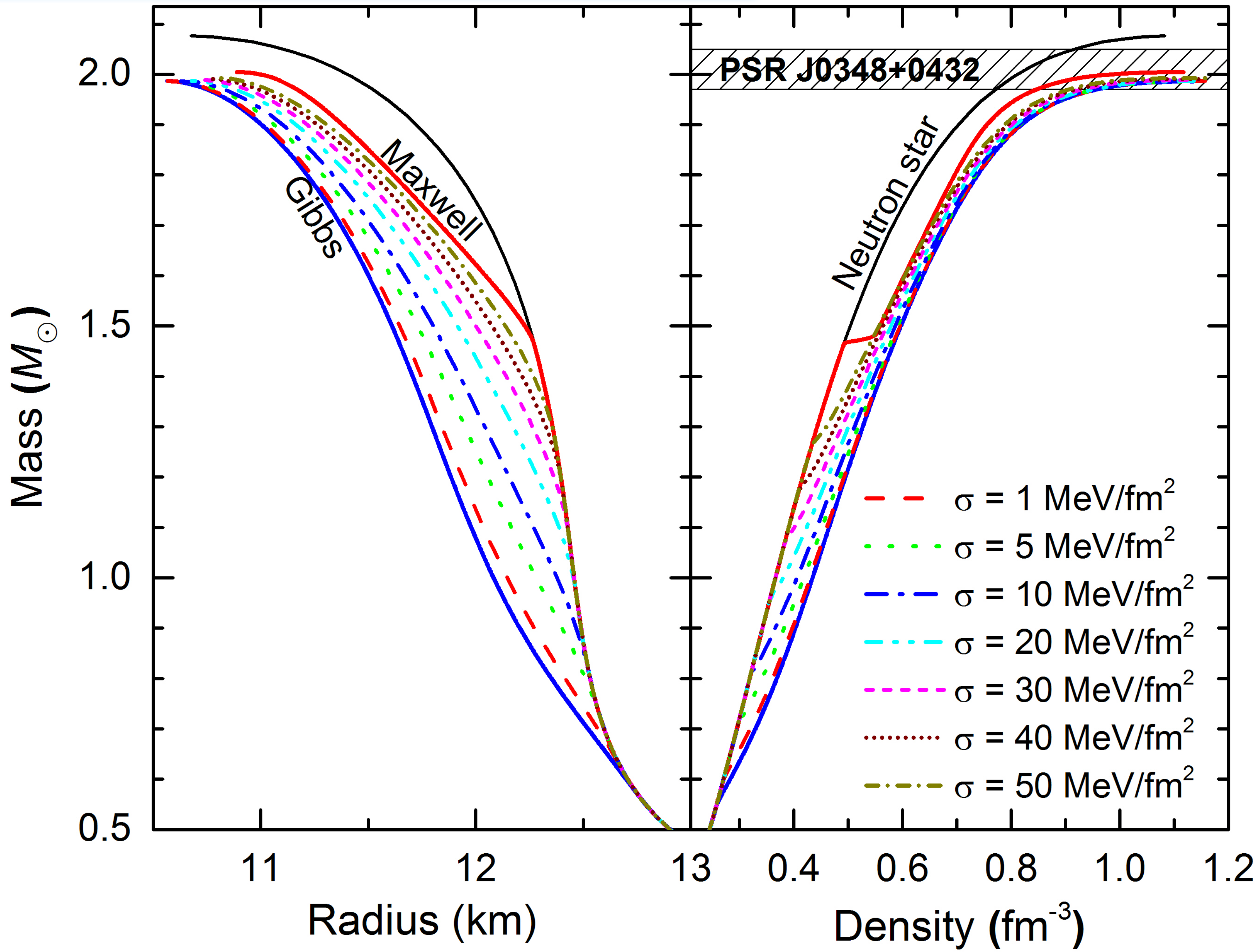


Equation of states

$\sigma_c = 79.12\ \mathrm{MeV/fm^2}$



Mass, radius, and central density

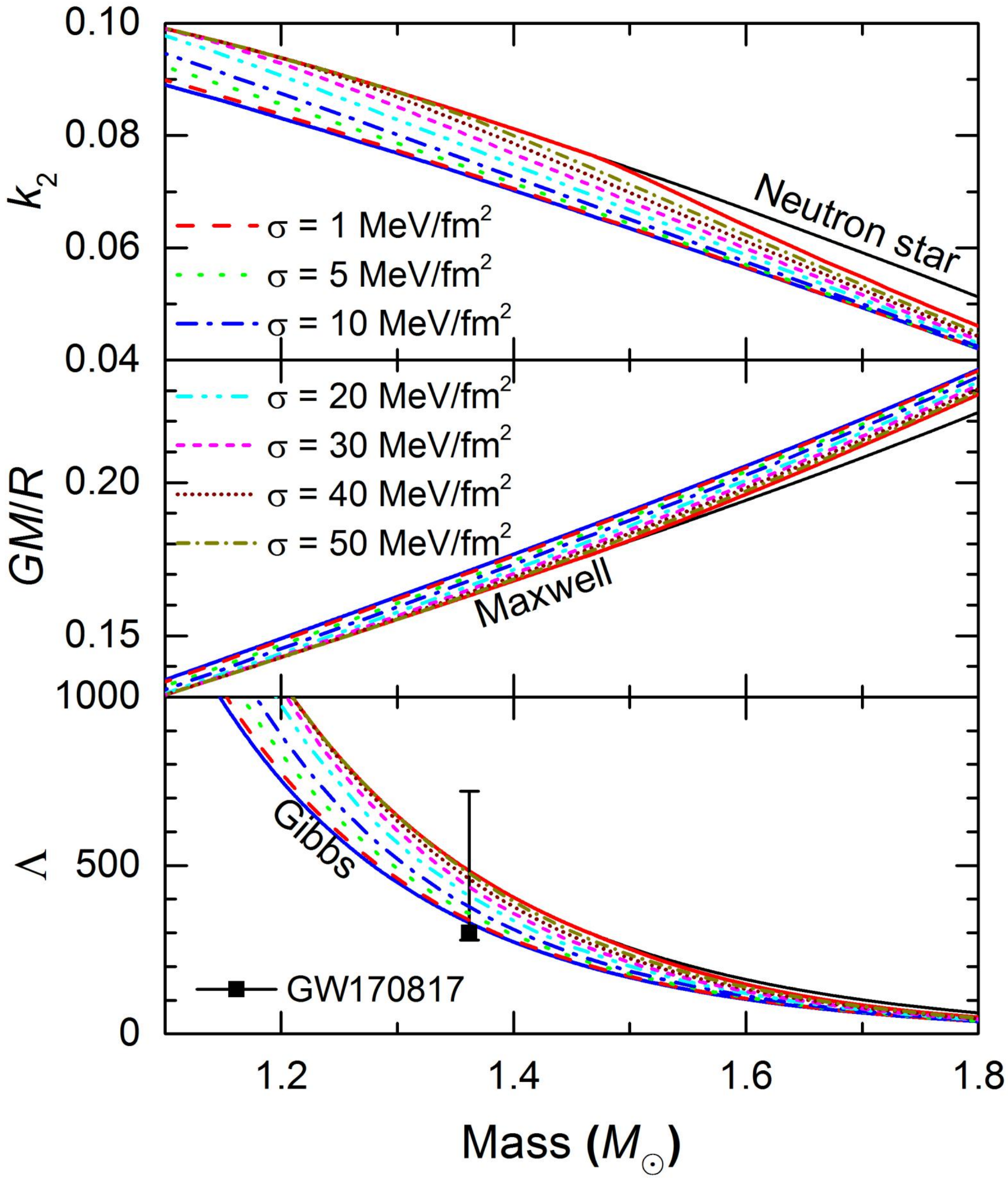


Love number, compactness, and tidal deformability

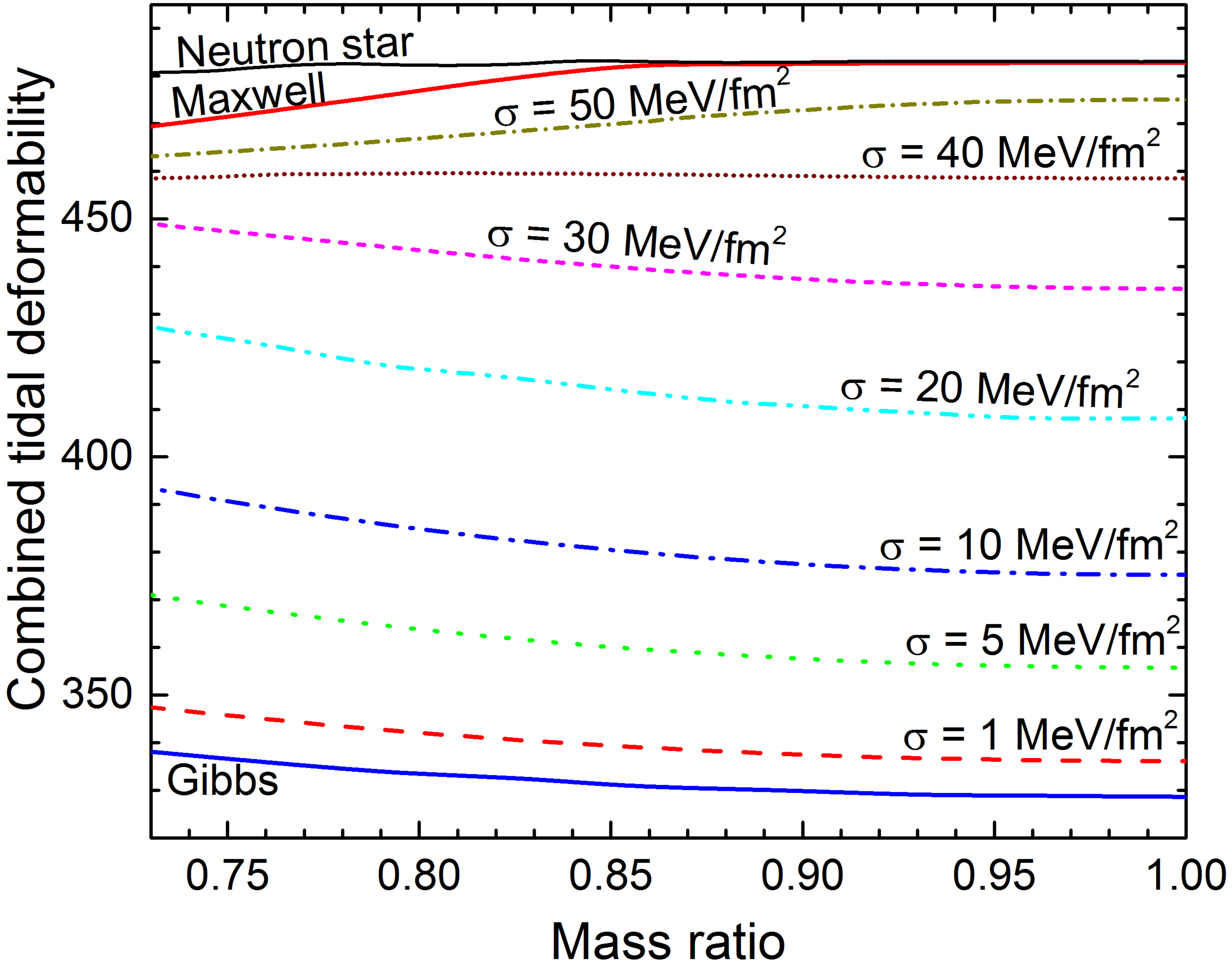
Tidal deformability:

$$\Lambda = \frac{2k_2}{3}\left(\frac{R}{GM}\right)^5$$

k_2: the second Love number [Damour_Nagar2009_PRD80-084035, Hinderer_Lackey_Lang_Read2010_PRD81-123016, Postnikov_Prakash_Lattimer2010_PRD82-024016]



Combined tidal deformability (GW170817)



Dependence on σ

•σ = 0: Gibbs construction

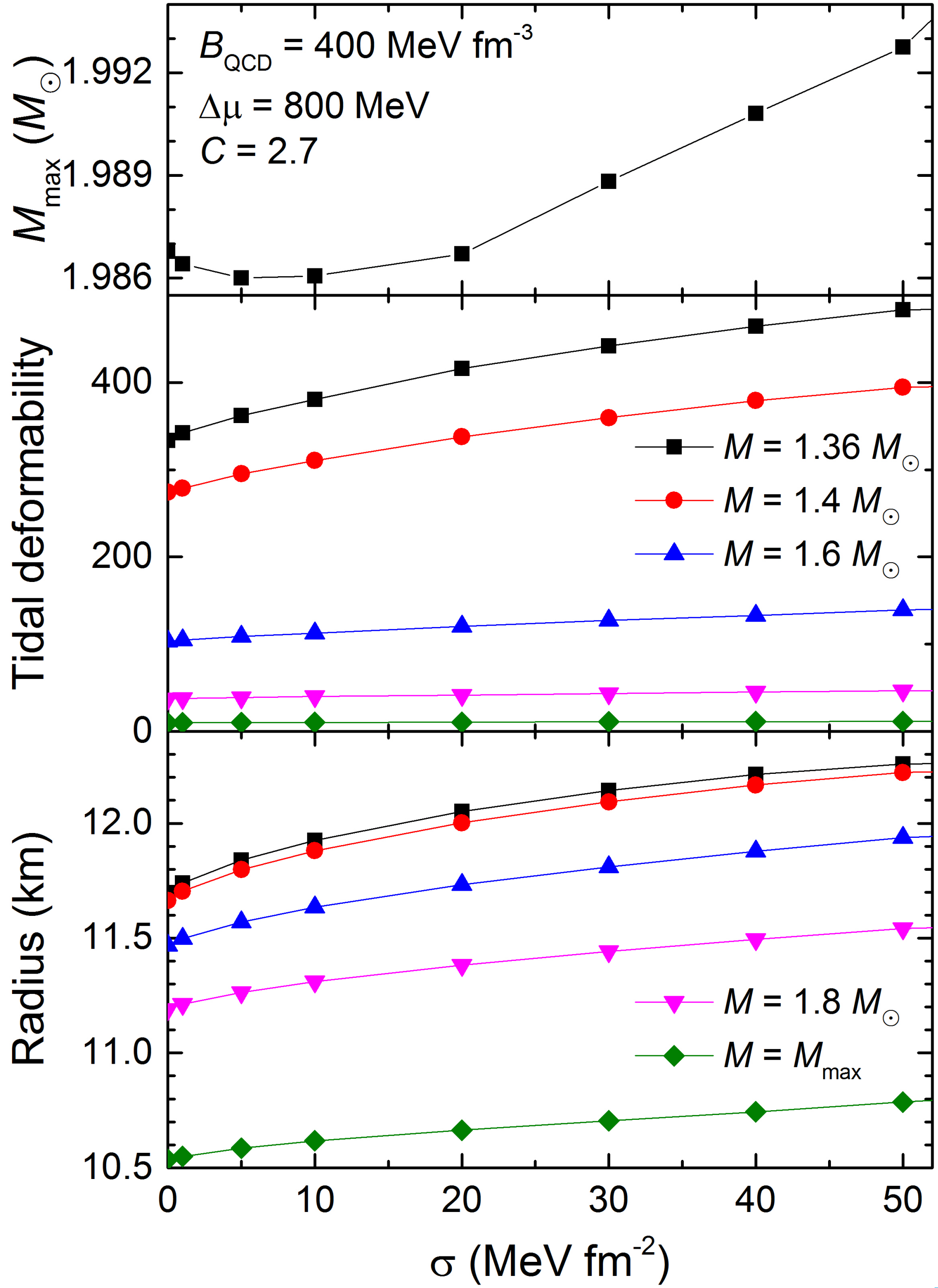
•σ>σ_c: Maxwell construction

$$\sigma_c = 79.12\ \mathrm{MeV/fm^2}$$

Moderate σ: interpolate between two types of values

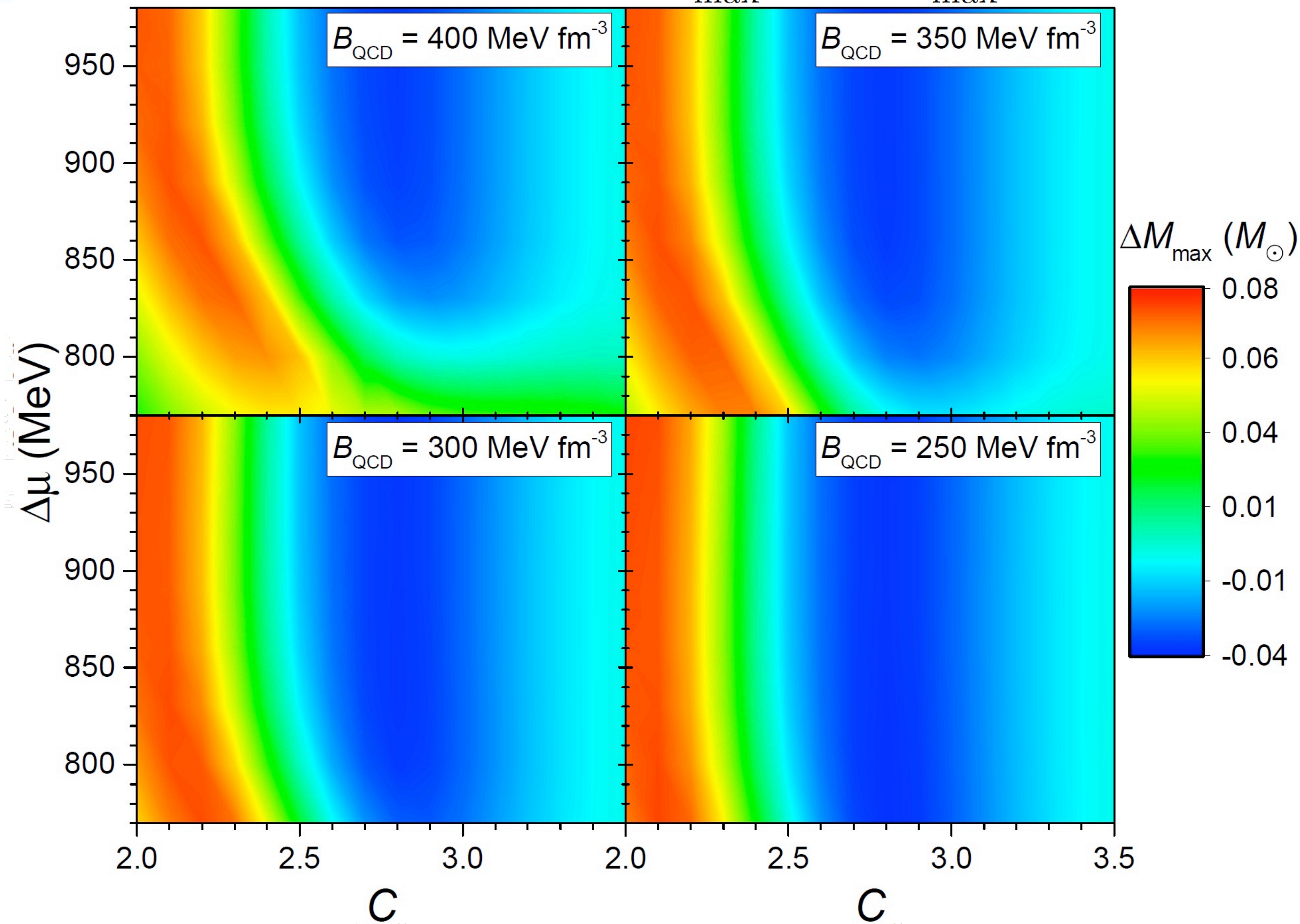
Our goal:

1. A universal function with respect to σ;
2. Constrain σ with pulsar observations.

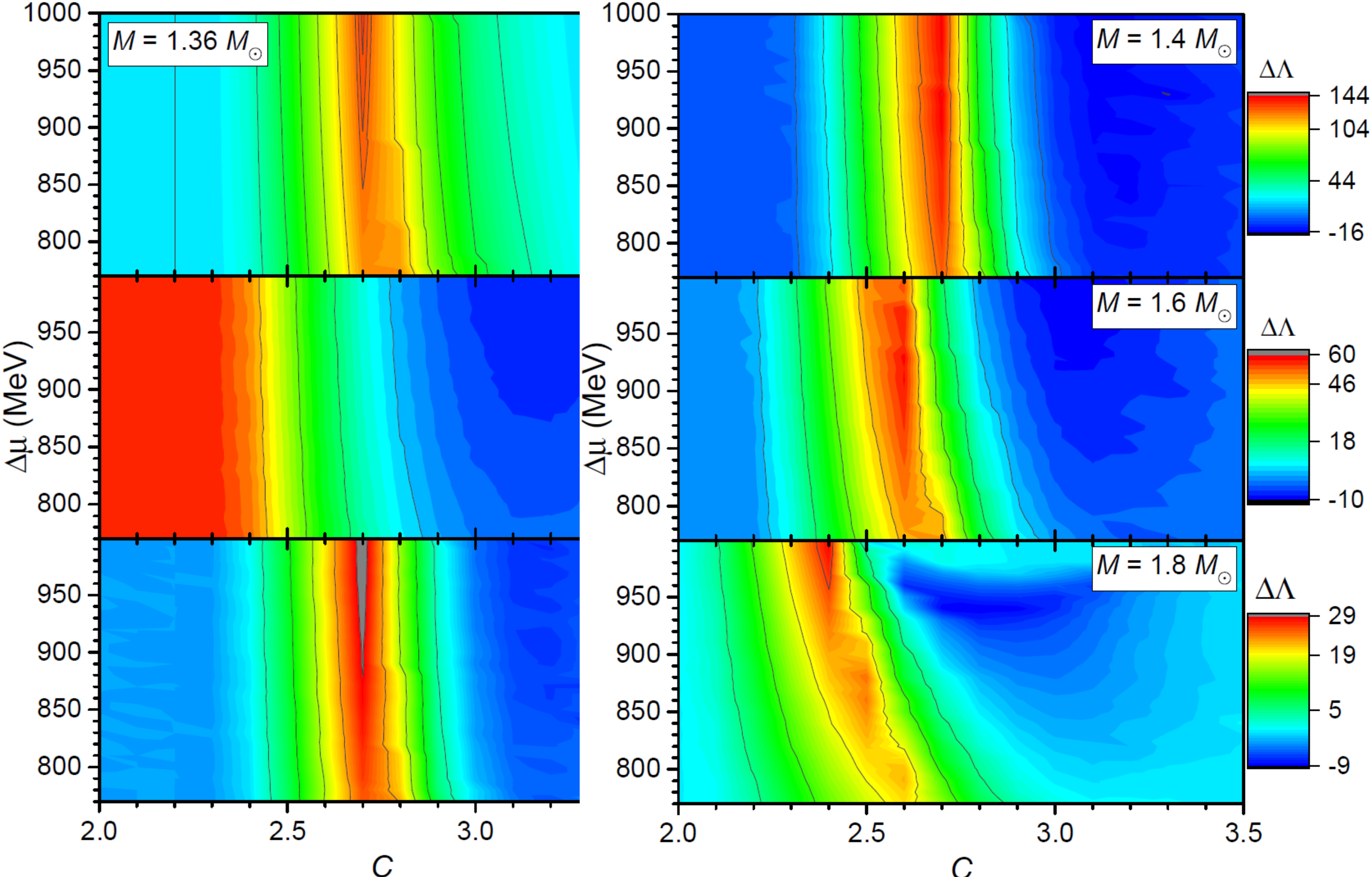


Maximum mass

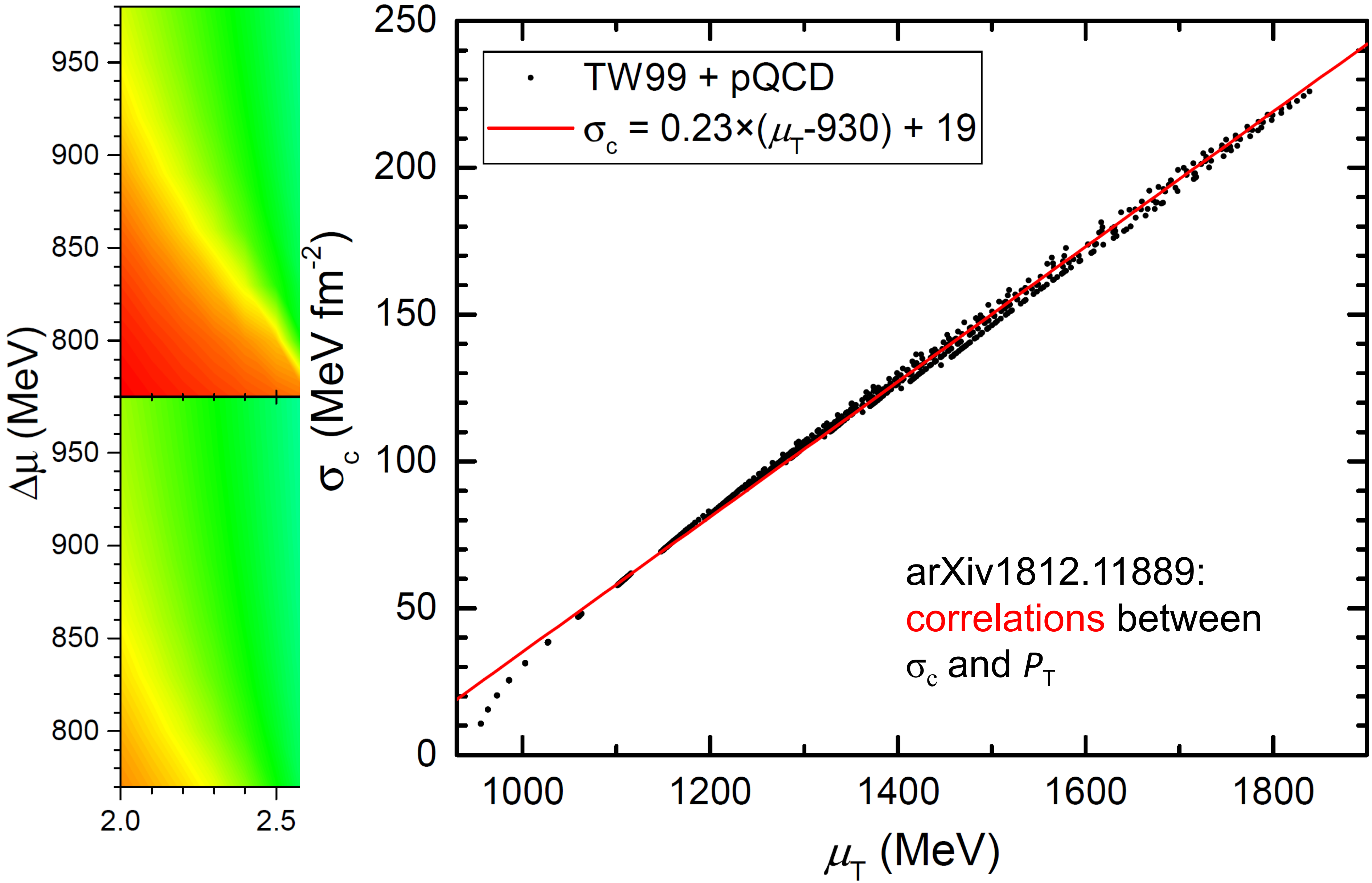
$$\Delta M_{\max} = M_{\max}^{\text{Maxwell}} - M_{\max}^{\text{Gibbs}}$$



Variations on radius and tidal deformability



Critical surface tension



Summary

The interface effects of quark-hadron mixed phase in compact stars were investigated. It was found that:

① The quark-hadron interface has sizable effects on the radii ($\Delta R \approx 600$ m) and tidal deformabilities ($\Delta\Lambda/\Lambda \approx 50\%$) of (1.36 solar mass) hybrid stars for certain choices of parameters;

② The maximum mass, tidal deformability, and radius increase with σ, where the maximum mass varies little;

③ A linear dependence of the critical surface tension σ_c on the chemical potential μ_T was obtained.

Possibilities in constraining the quark-hadron interface tension with GW observations and NICER mission.

Thank you!!!