The sharpness of the quark hadron transition and the properties of hybrid stars

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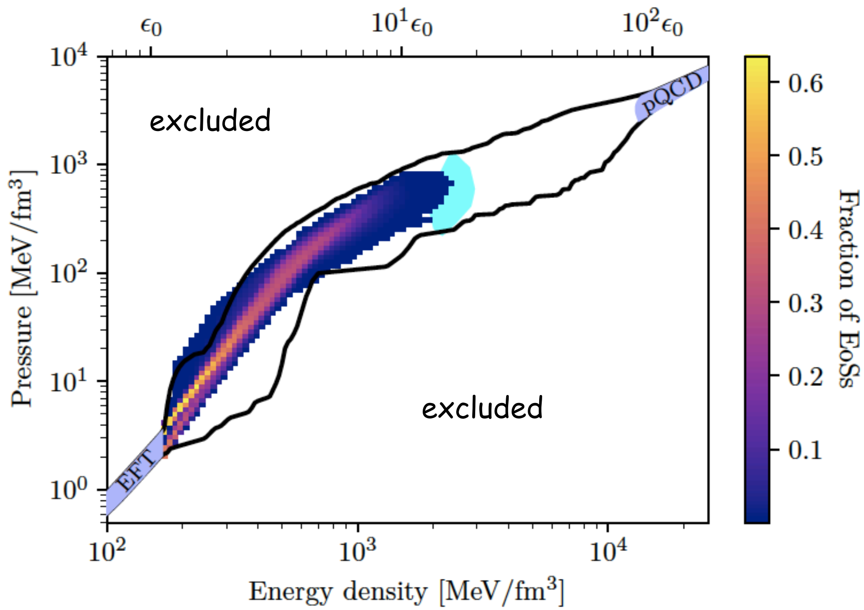
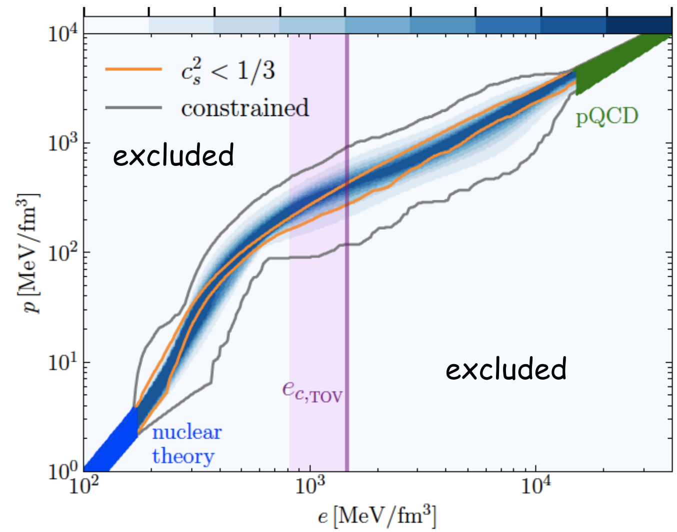
The EOS of compact stars



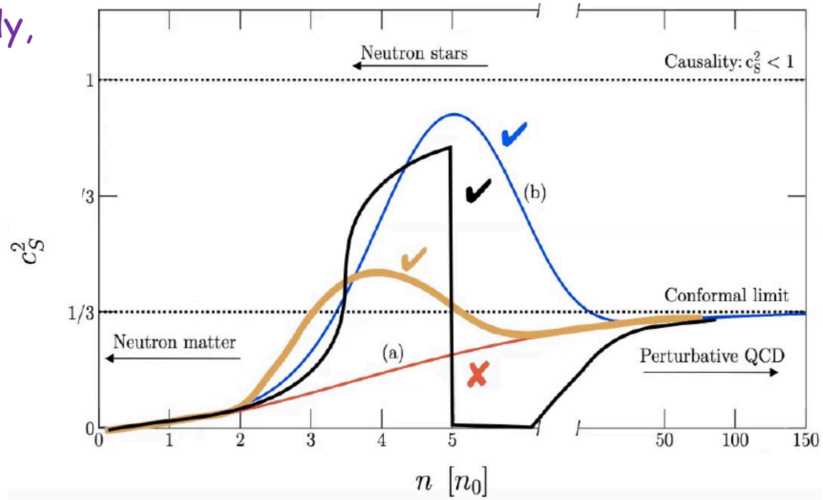
Gorda, Hebeler, Kurkela, Schwenk, Vuorinen,
, arXiv:2212.10576



Altiparmak, Ecker, Rezzolla,
arXiv:2212.10576

The speed of sound

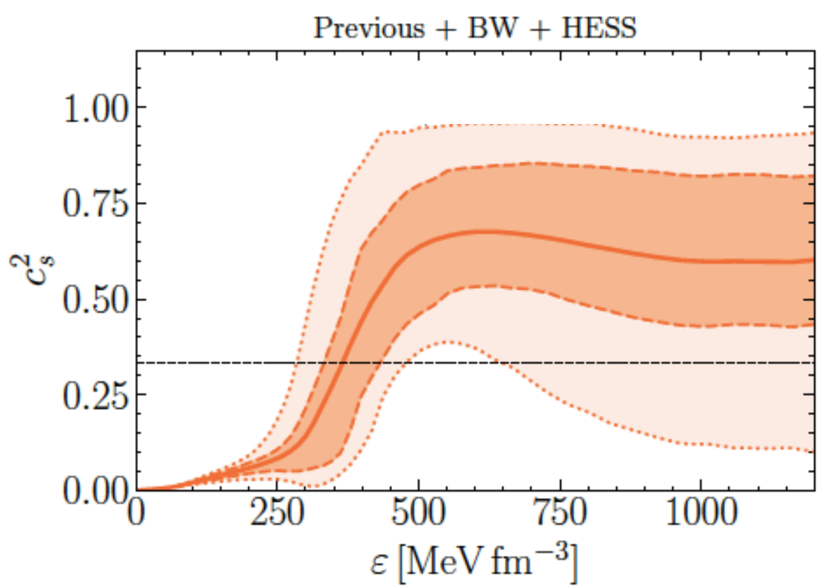
Tews, Carlson, Gandolfi. Reddy, arXiv:1801.01923



$$c_s^2 = \frac{\partial p}{\partial \epsilon}$$

Brandes,Weise,Kaiser arXiv:2306.06218

Evidence against a first-order phase transition in neutron star cores: impact of new data



Can data tell us how sharp is the phase transition in hybrid stars?

Phenomenology of the phase transition

Hadron-Quark Crossover and Massive Hybrid Stars
Masuda, Hatsuda, Takatsuka, arXiv:1212.6803

Two Novel Approaches to the Hadron-Quark Mixed Phase in Compact Stars
Abgaryan, Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, arXiv:1807.08034

On the stability of strange dwarf hybrid stars
Alford, Harris, Sachdeva, arXiv:1705.09880

Tidal deformability with sharp phase transitions in (binary) neutron stars
Han and Steiner, arXiv:1810.10967

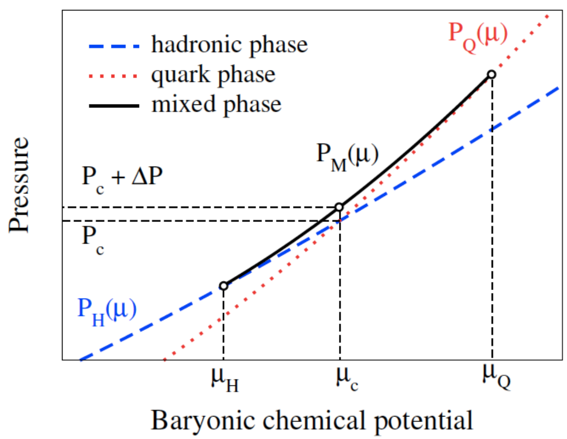
Differentiating between sharp and smoother phase transitions in neutron stars
Pereira, Bejger, Zdunik, Haensel, arXiv:2201.01217

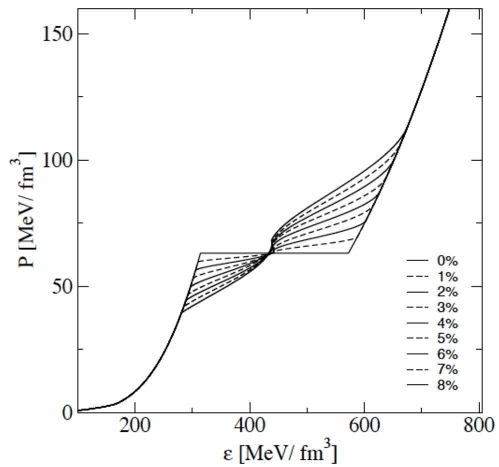
Phase Transition Phenomenology with Nonparametric Representations of Neutron Star EOS
Essick, Legred, Chatziioannu, Han, Landry, arXiv:2305.07411

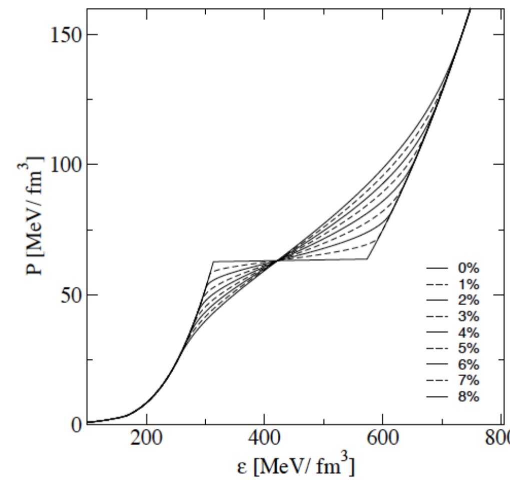
Evidence against a first-order phase transition in neutron star cores: impact of new data
Brandes, Weise, Kaiser arXiv:2306.06218

Controlling the sharpness of the transition

Abgaryan, Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, arXiv:1807.08034

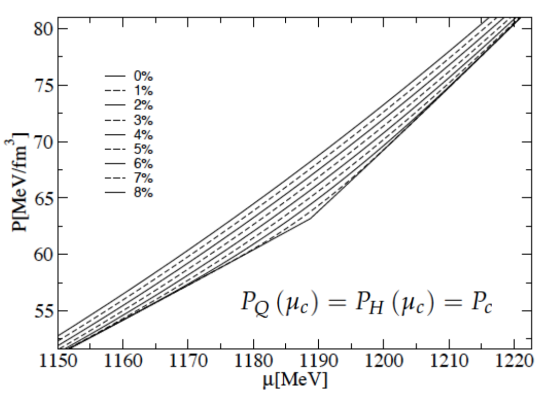


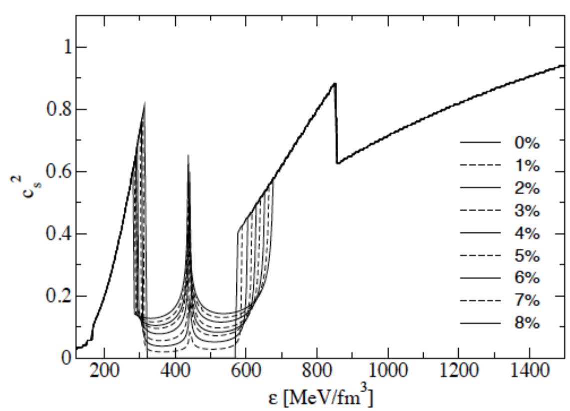


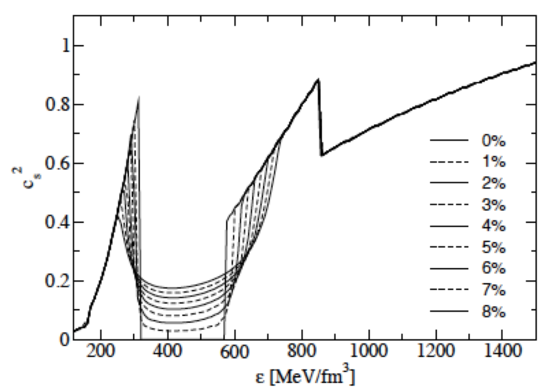


$$P_M(\mu) = \alpha_2 (\mu - \mu_c)^2 + \alpha_1 (\mu - \mu_c) + (1 + \Delta_P) P_c$$

$$P(\mu) = P_H(\mu) f_{\rm off}(\mu) + P_Q(\mu) f_{\rm on}(\mu) + \Delta(\mu) \Delta P$$

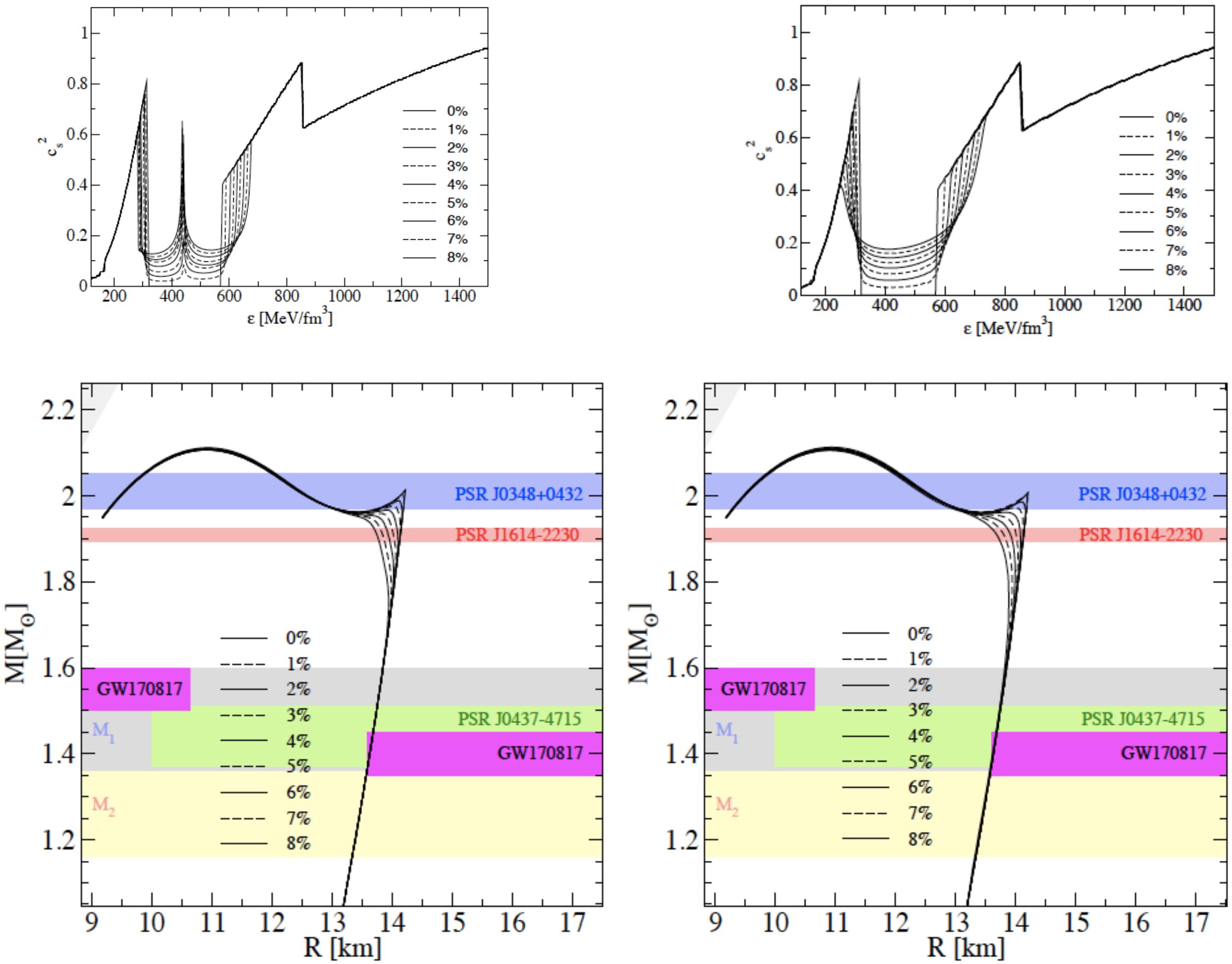






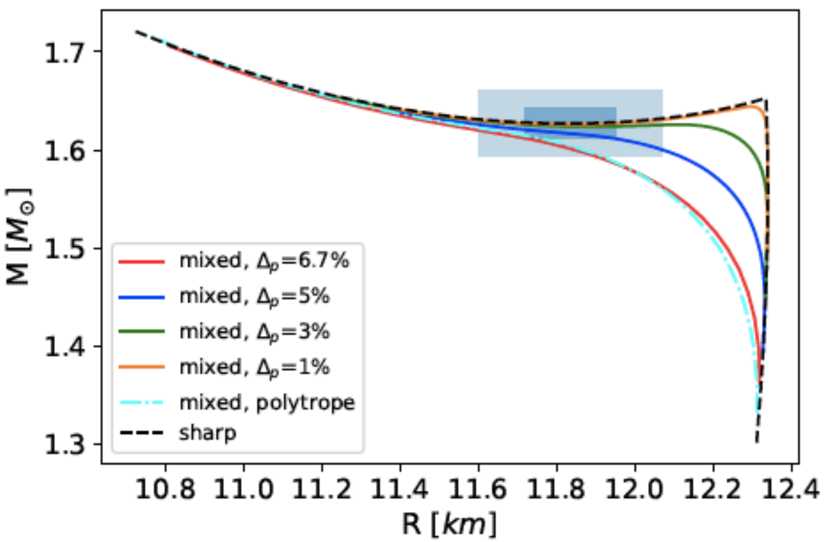
Controlling the sharpness of the transition

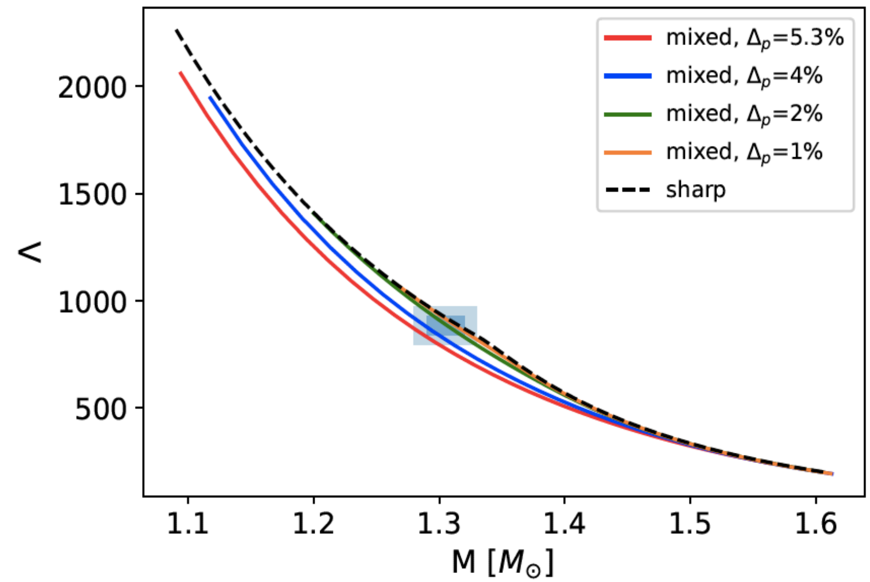
Abgaryan, Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, arXiv:1807.08034



Modest changes in the M-R diagram ...

Pereira, Bejger, Zdunik, Haensel, arXiv:2201.01217





Zhang et al., eXTP, arXiv:1607.08823

Watts et al., eXTP, arXiv:1812.04021

Chatziioannou et al., LIGO, arXiv:2108.12368

Uncertainty less than 5 %

New way of matching the two phases with continuous c_s

$$(P - P_Q)(P - P_H) = \delta^2(\mu_B)$$

$$\delta(\mu_B) = \delta_0 \exp\left[-\frac{(\mu_B - \mu_c)^2}{2\sigma^2}\right]$$

$$\frac{1}{c_S^2} = \frac{\mu}{n}\frac{\partial^2 P}{\partial \mu^2}$$

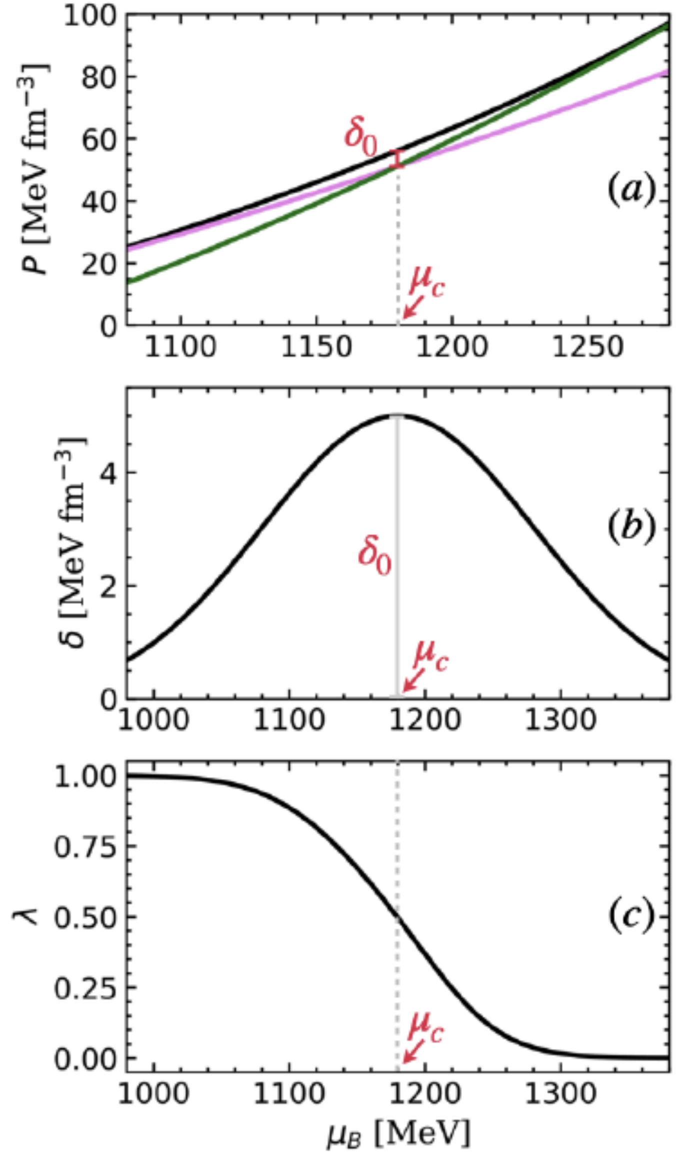
$$P_H(\mu_c) = P_Q(\mu_c)$$

$\sigma =$ width of the transition region

$\delta_0 =$ "overpressure" in the transition

$$P = \lambda P_H + (1-\lambda)P_Q + \frac{2\delta^2}{\sqrt{(P_Q - P_H)^2 + 4\delta^2}}$$

$$\lambda(\mu_B) = \tfrac{1}{2}\left[1 - \frac{P_Q - P_H}{\sqrt{(P_Q - P_H)^2 + 4\delta^2}}\right]$$



New way of matching the two phases with continuous c_s

$$n_B = \frac{\partial P}{\partial \mu_B}$$

$$n_B = \lambda\, n_{B,H} + (1-\lambda)\, n_{B,Q} - \frac{(\mu_B - \mu_c)}{2\,\sigma^2}\, \frac{\delta^2}{\sqrt{(P_Q - P_H)^2 + 4\,\delta^2}}$$

$$\delta(\mu_B) = \delta_0 \exp\left[-\frac{(\mu_B - \mu_c)^2}{2\sigma^2}\right]$$

$$\epsilon = -P + \mu_B\, n_B$$

$$\frac{1}{c_S^2} = \frac{\mu}{n}\frac{\partial^2 P}{\partial \mu^2}$$

The quark EOS

MIT bag model with vector interactions

Lopes, Biesdorf, Menezes, arXiv:2005.13136 ; arXiv: 2005.13552

$$\mathcal{L} = \sum_q \left\{ \bar{\psi}_q \left[i\gamma^\mu \partial_\mu - m_q \right] \psi_q - B \right\} \Theta \left(\bar{\psi}_q \psi_q \right)$$
$$+ \sum_q g \left\{ \bar{\psi}_q \left[\gamma^\mu V_\mu \right] \psi_q \right\} \Theta \left(\bar{\psi}_q \psi_q \right) + \tfrac{1}{2} m_V^2 V_\mu V^\mu$$
$$+ \bar{\psi}_e \gamma_\mu \left(i\partial^\mu - m_e \right) \psi_e,$$

$$m_V V_0 = G_V^{1/2} (n_u + n_d + n_s)$$

$$\Omega = \sum_q \Omega_q^* + B - \tfrac{1}{2} m_V^2 V_0^2 + \Omega_e$$

$$\mu_q^* = \mu_q - G_V^{1/2} m_V V_0 \qquad G_V = \left(\frac{g}{m_V} \right)^2$$

The hadron EOS

Generalized piecewise polytropic (GPP) with continuous speed of sound

O'Boyle, Markakis, Stergioulas and Read, arXiv:2008.03342

Consistent with chiral effective field theory results

$$p(\rho) = K\rho^{\Gamma} + \Lambda$$

$$\epsilon(\rho) = \frac{K}{\Gamma - 1}\rho^{\Gamma} + (1 + a)\rho - \Lambda$$

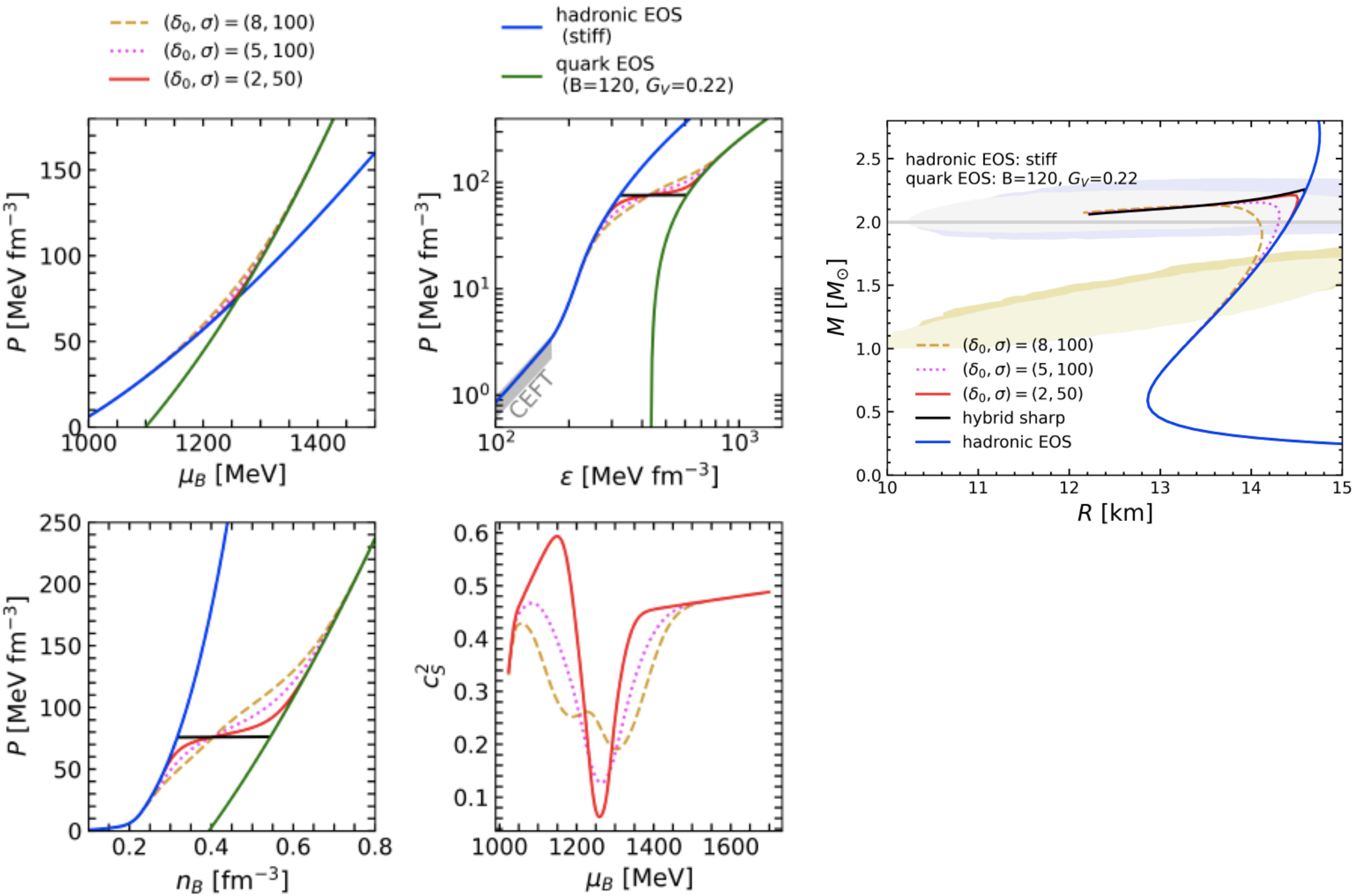
$$c_s = \left[\frac{1}{\Gamma_i - 1} + \frac{1 + a_i}{K_i \Gamma_i \rho^{\Gamma_i - 1}}\right]^{-\frac{1}{2}}$$

Examples of Results

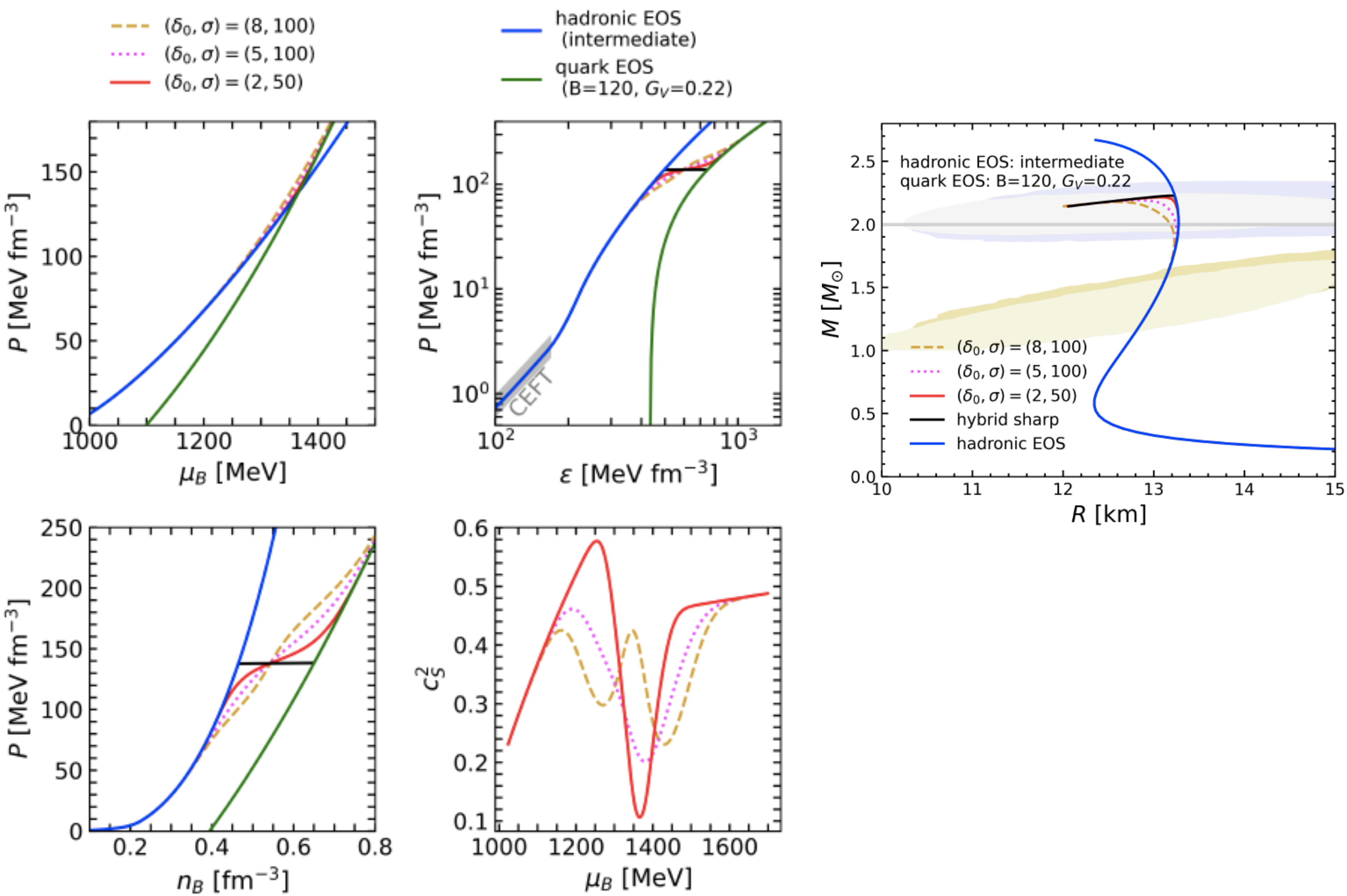
Three hadronic EOS (OMSR soft, intermediate, stiff)

Two quark EOS (B, G_V : softer or stiffer)

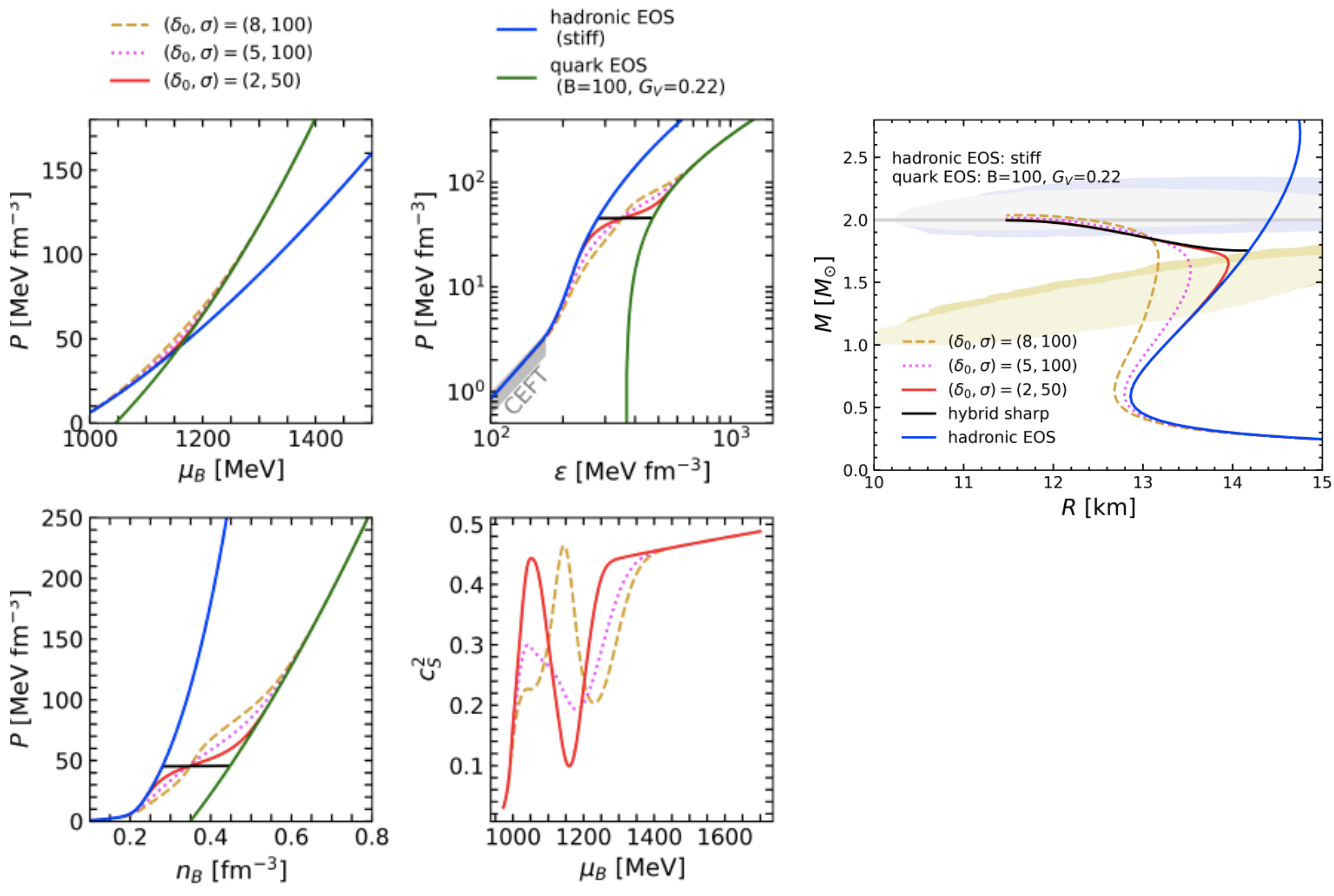
Stiff hadron EOS + soft quark EOS



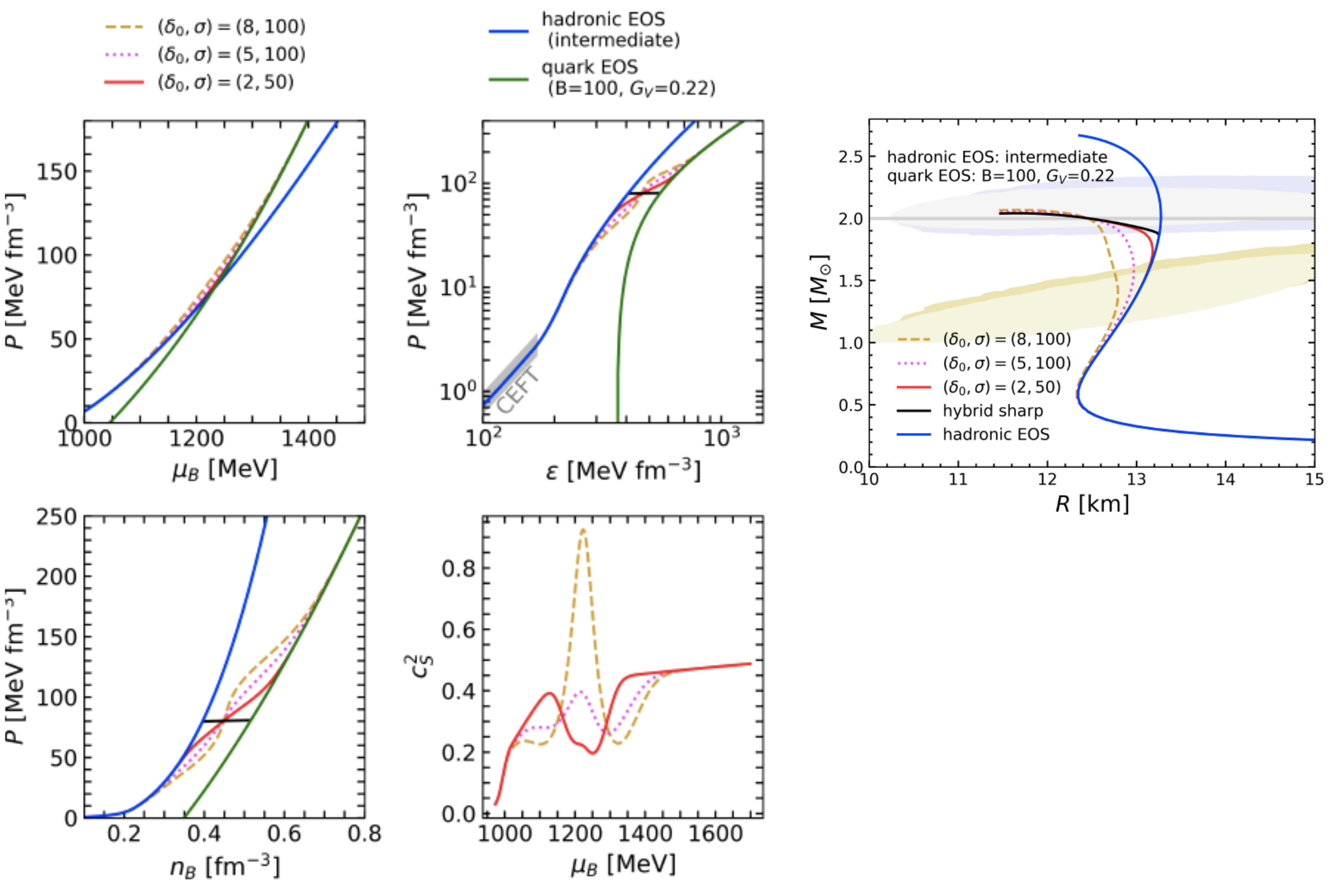
Intermediate hadron EOS + soft quark EOS

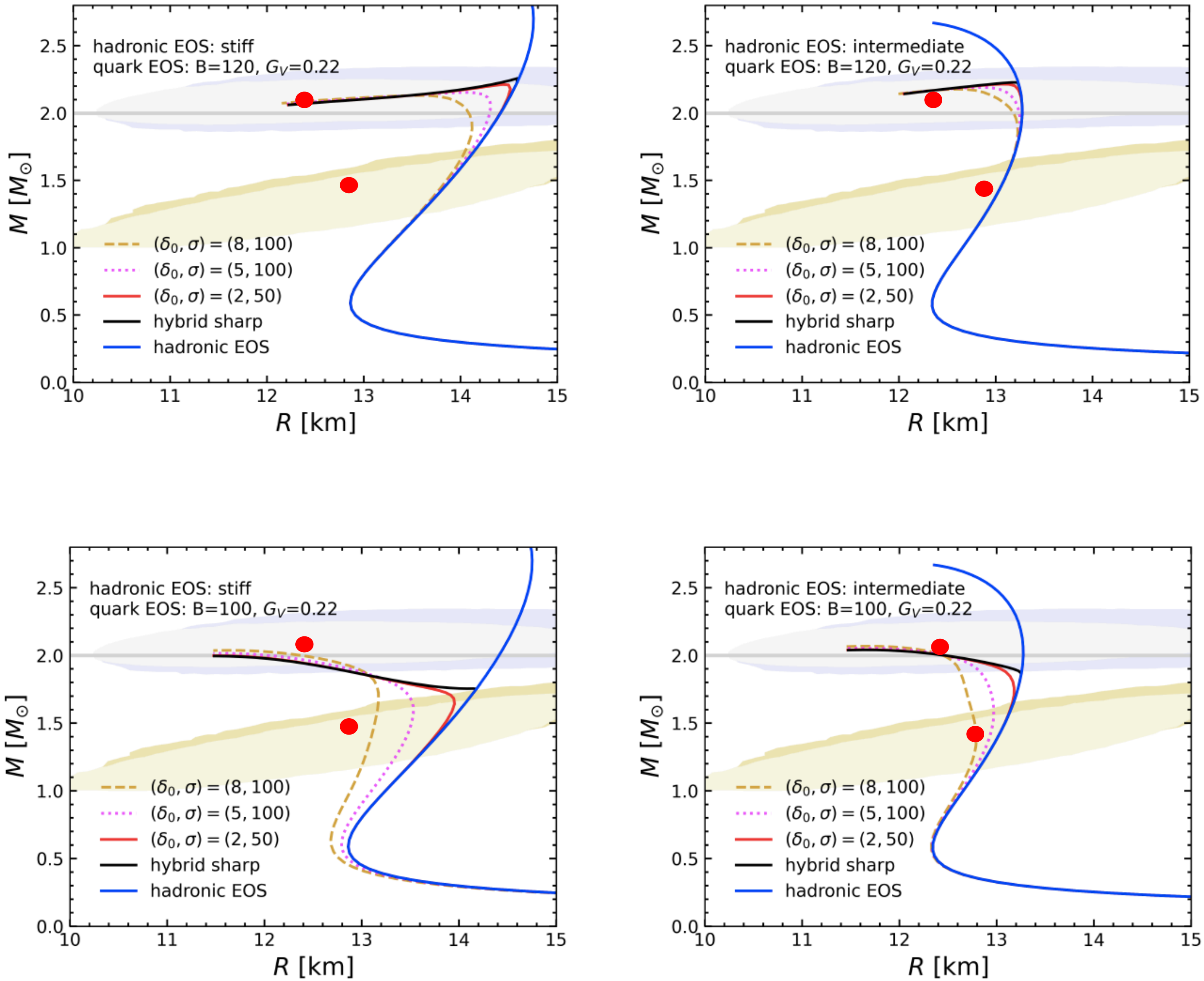


Stiff hadron EOS + stiff quark EOS



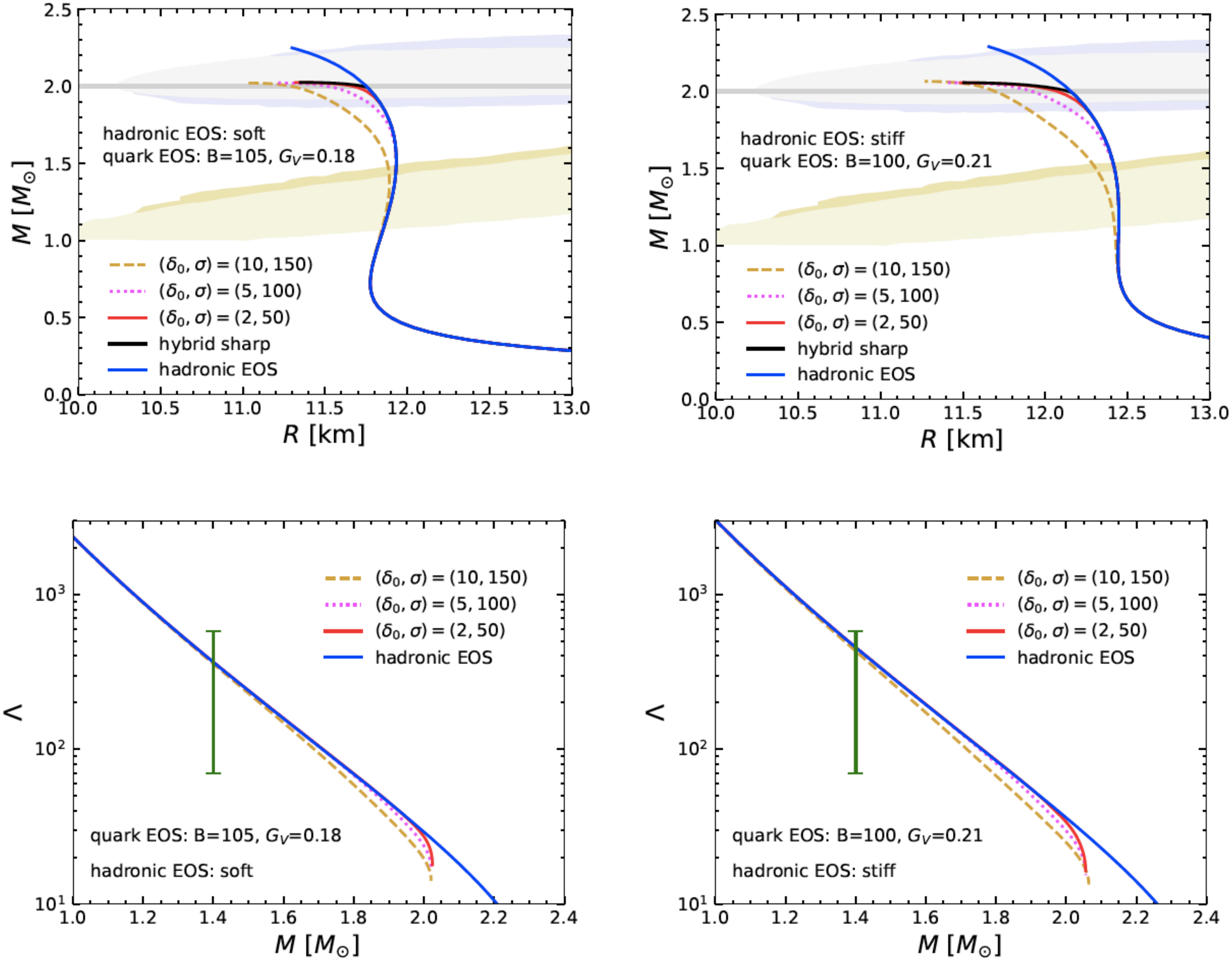
Intermediate hadron EOS + stiff quark EOS





hadronic EOS: stiff
quark EOS: B=120, G_V=0.22
hadronic EOS: intermediate
quark EOS: B=120, G_V=0.22
hadronic EOS: stiff
quark EOS: B=100, G_V=0.22
hadronic EOS: intermediate
quark EOS: B=100, G_V=0.22
$(\delta_0, \sigma) = (8, 100)$
$(\delta_0, \sigma) = (5, 100)$
$(\delta_0, \sigma) = (2, 50)$
hybrid sharp
hadronic EOS
$M\ [M_\odot]$
R [km]
0.0
0.5
1.0
1.5
2.0
2.5
10
11
12
13
14
15

Tidal deformability



Summary

We have updated the studies of sensitivty of NS global observables to the sharpness of the phase transition in hybrid stars

We have introduced a new matching procedure

Results are consistent with previous works

Strong dependence on the choice of hadronic and quark matter EOS

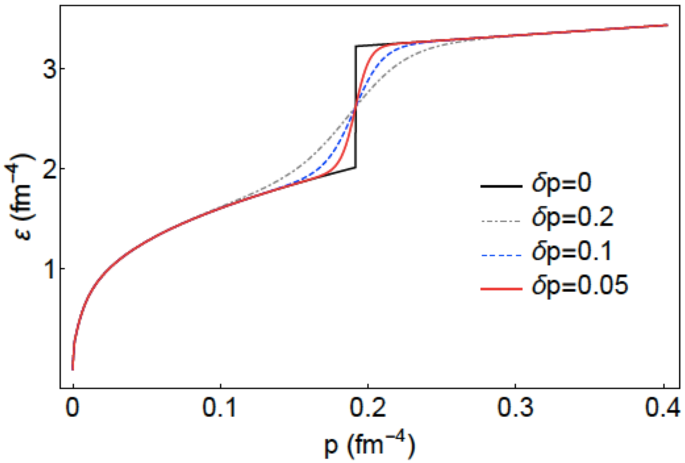
Weak dependence on the matching scheme

Increasing the precision, sharpness may be visible in the M-R diagram

Thank you for
your attention !

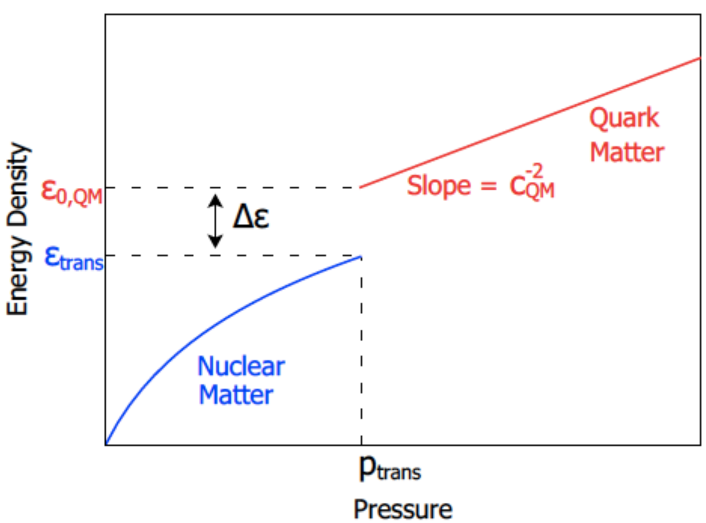
Controlling the sharpness of the transition

Han and Steiner, arXiv:1810.10967



$$\varepsilon(p) = \frac{1}{2}\left[1 - \tanh\left(\frac{p - p_{\rm trans}}{\delta p}\right)\right]\varepsilon_{\rm NM}(p) + \frac{1}{2}\left[1 + \tanh\left(\frac{p - p_{\rm trans}}{\delta p}\right)\right]\varepsilon_{\rm QM}(p),$$

"round the gap"

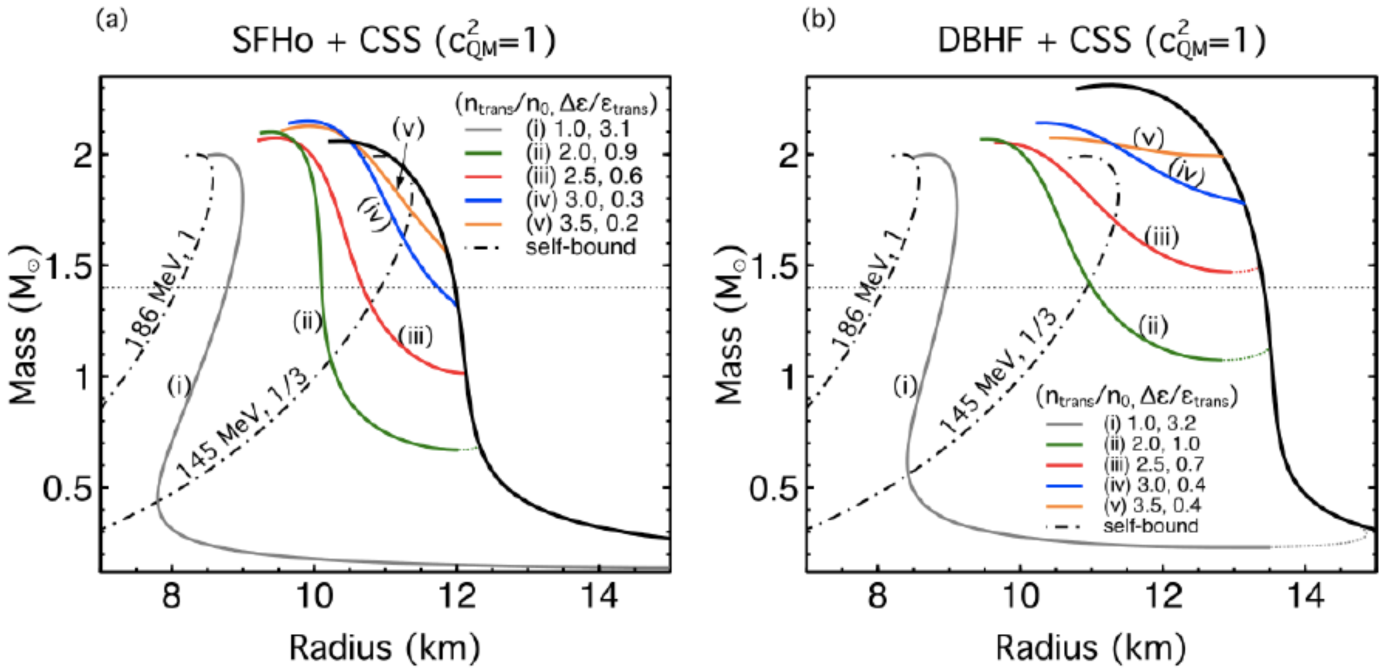


$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm NM}(p) & p < p_{\rm trans} \\ \varepsilon_{\rm NM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}) & p > p_{\rm trans} \end{cases} \tag{1}$$

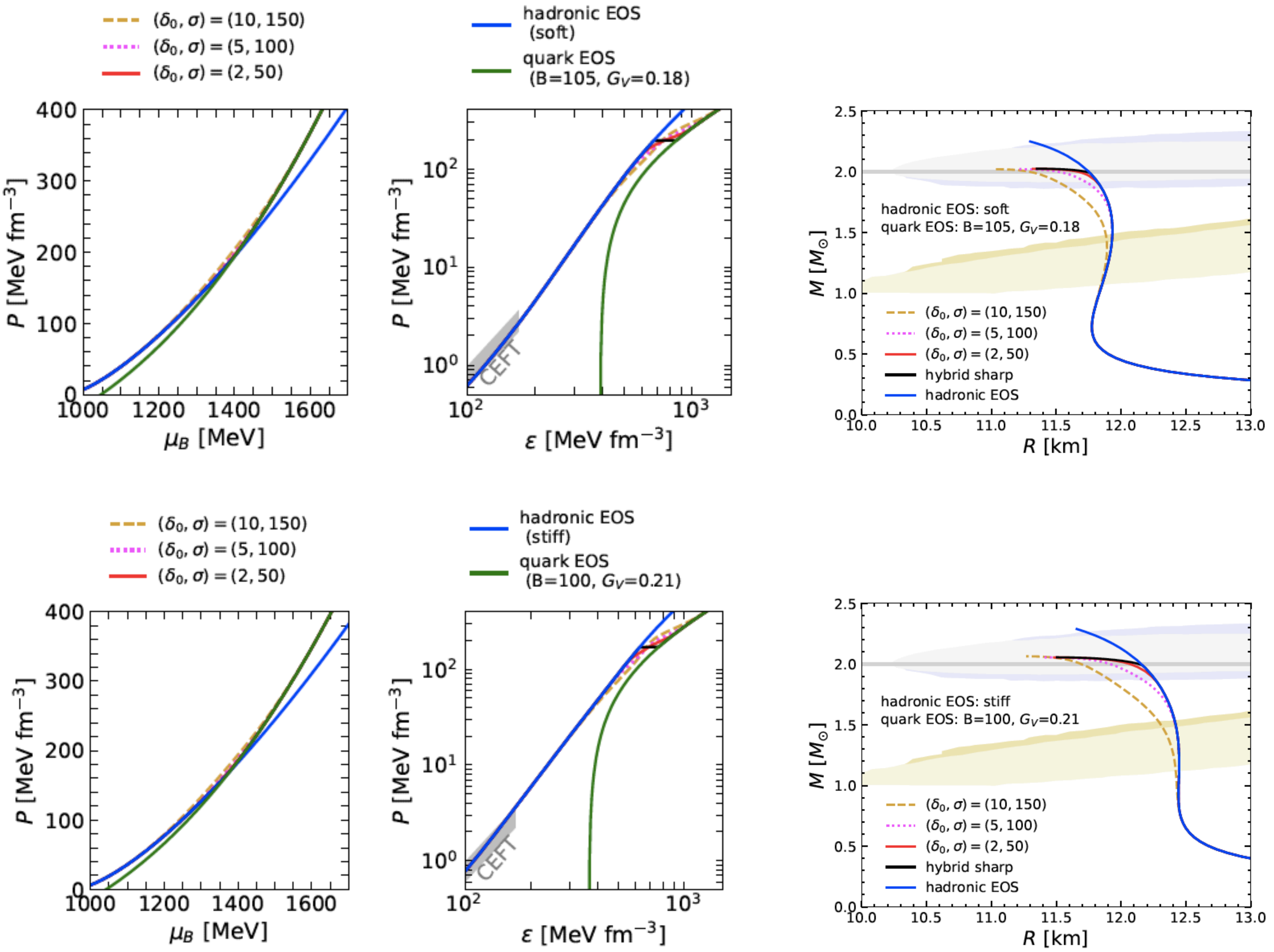
"schrink the gap"

Han and Steiner, arXiv:1810.10967

$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm NM}(p) & p < p_{\rm trans} \\ \varepsilon_{\rm NM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}) & p > p_{\rm trans} \end{cases} \tag{1}$$



Significant changes in the M-R diagram ...



(δ0, σ) = (10, 150)
(δ0, σ) = (5, 100)
(δ0, σ) = (2, 50)
hadronic EOS (soft)
quark EOS (B=105, GV=0.18)
P [MeV fm−3]
μB [MeV]
ε [MeV fm−3]
CEFT
hadronic EOS: soft
quark EOS: B=105, GV=0.18
hybrid sharp
hadronic EOS
M [M⊙]
R [km]
(δ0, σ) = (10, 150)
(δ0, σ) = (5, 100)
(δ0, σ) = (2, 50)
hadronic EOS (stiff)
quark EOS (B=100, GV=0.21)
P [MeV fm−3]
μB [MeV]
ε [MeV fm−3]
CEFT
hadronic EOS: stiff
quark EOS: B=100, GV=0.21
hybrid sharp
hadronic EOS
M [M⊙]
R [km]