Constraining the properties of a parity doublet model with a quark-hadron-crossover equation of state and the observations for neutron stars

based on our papers:

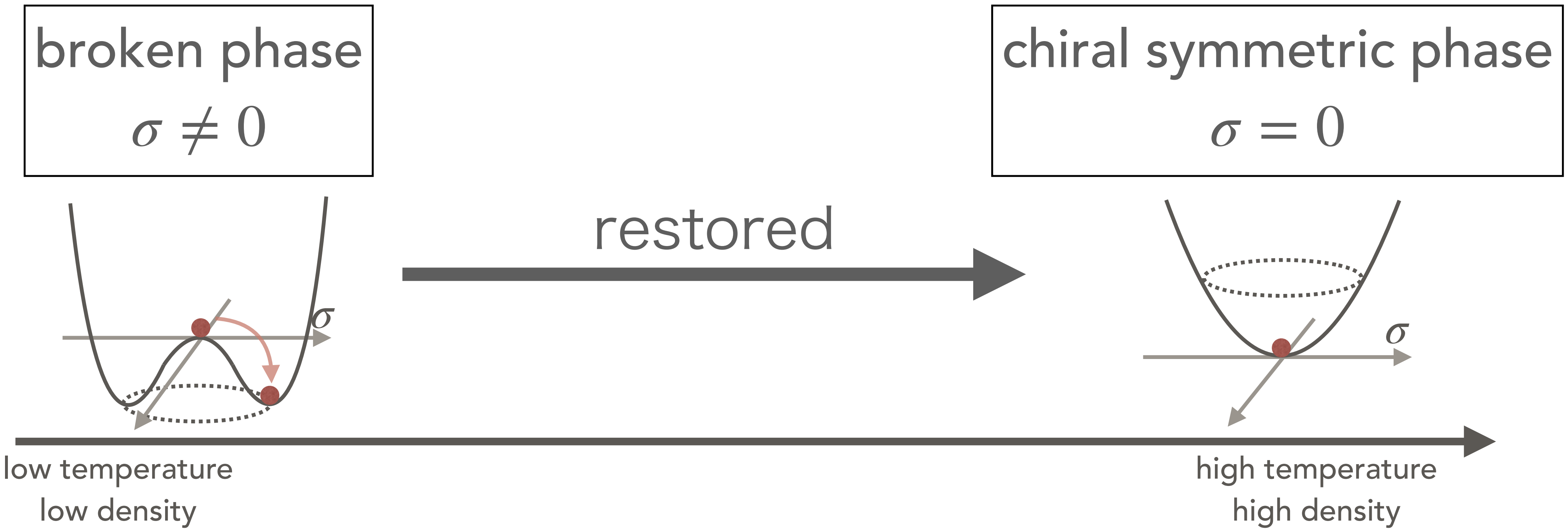
[1] PhysRevC.103.045205 (T.M., M.H., T.K.)

[2] PhysRevC.104.065201 (T.M., M.H., T.K.)

T. Minamikawa (Nagoya Univ.)
collaborators: M. Harada (Nagoya Univ.) and T. Kojo (Tohoku Univ.)

21-23 Feb 2022 Reimei Workshop "Hadrons in dense matter at J-PARC"

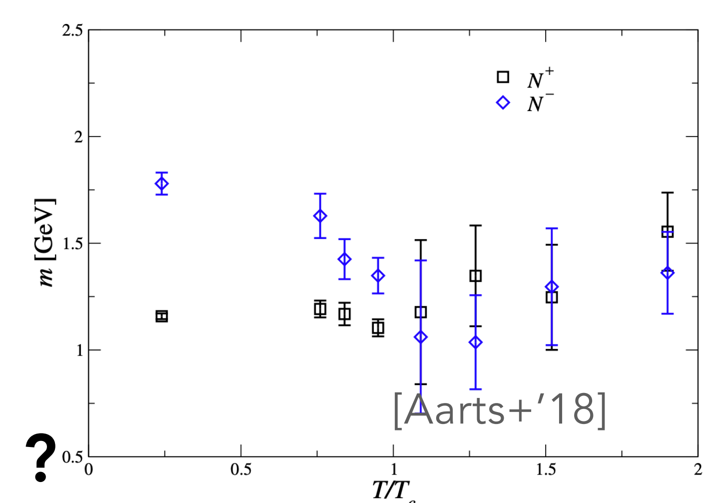
Fate of Nucleon Mass



- In effective models, e.g. the linear-sigma model, $M_N \propto \sigma$

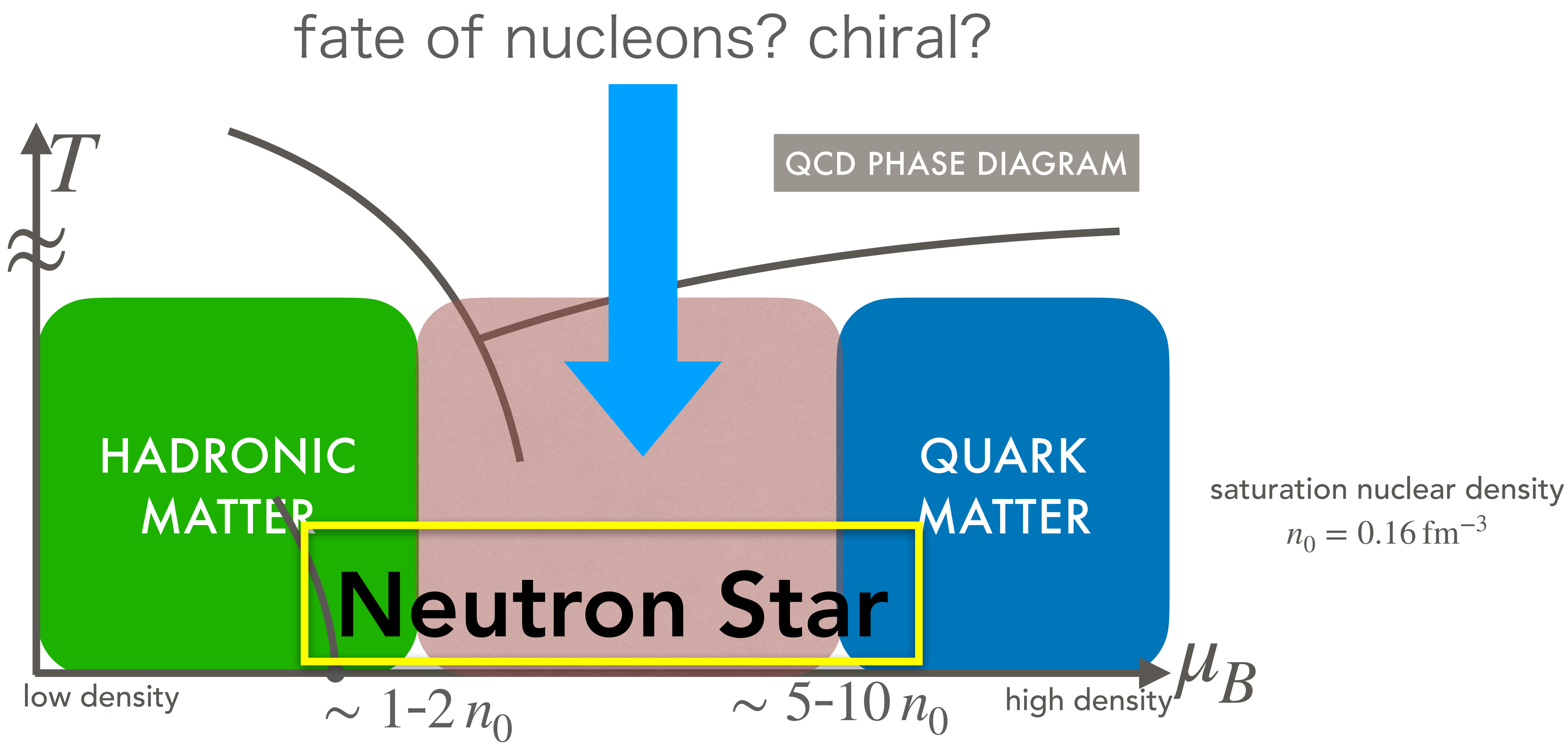
$$M_N \neq 0 \quad \xrightarrow{\sigma \to 0} \quad M_N \to 0\ ?$$

- On the other hand, lattice QCD at finite T (e.g. e.g.Aarts+’15, ’18):
  $\sigma \to 0$ but **M_N remains $\sim 1\,\mathrm{GeV}$**



- **M_N are not very sensitive to the environment ?**
  relevant for the physics of heavy ion collisions and Neutron Stars (NSs)

NSs as Cosmic Laboratories

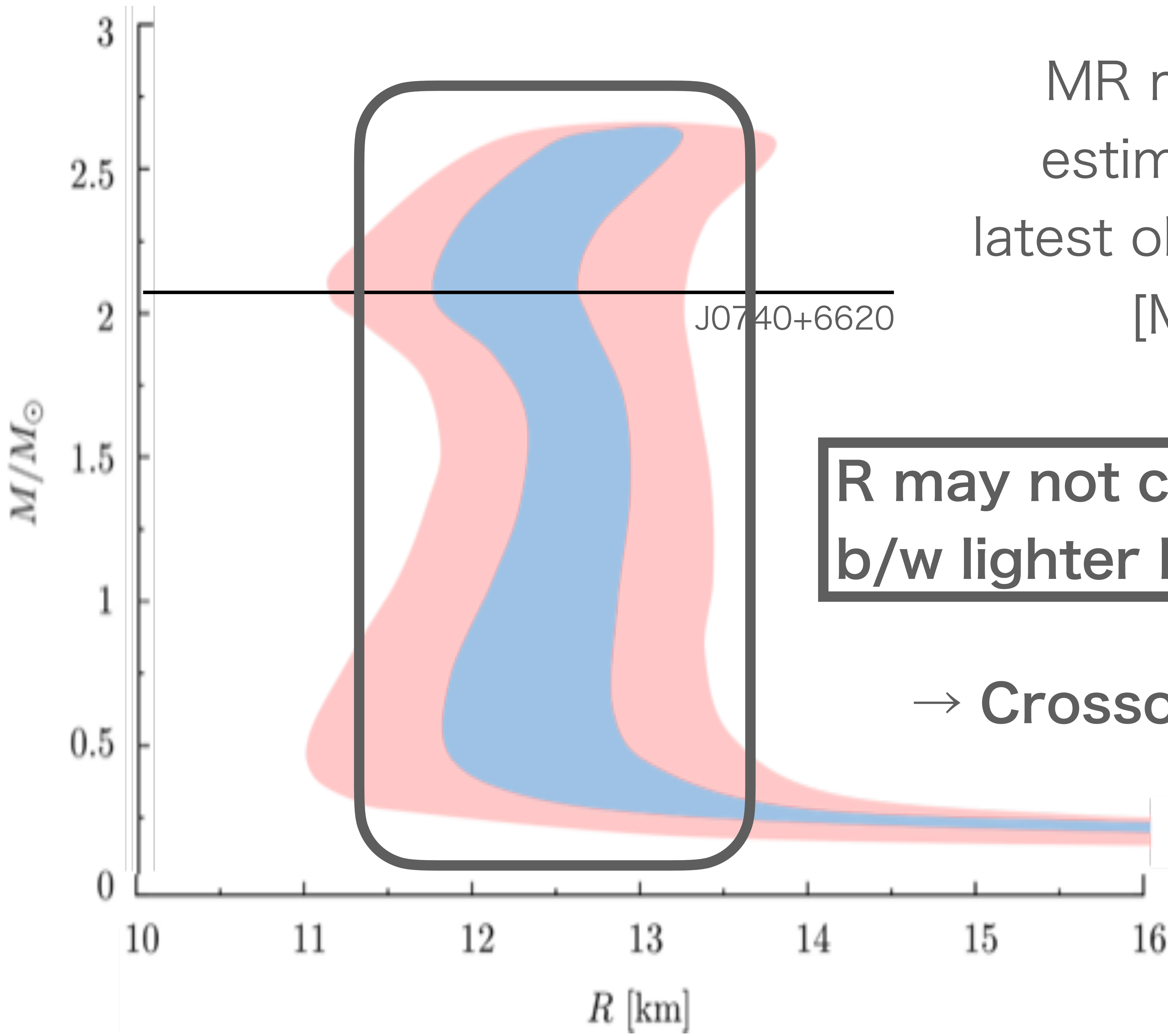


EOS ⇄ (1-to-1) NS M-R

EOS → constraints on the microphysics

Latest Observ. of NSs

[Miller+ (2021)]

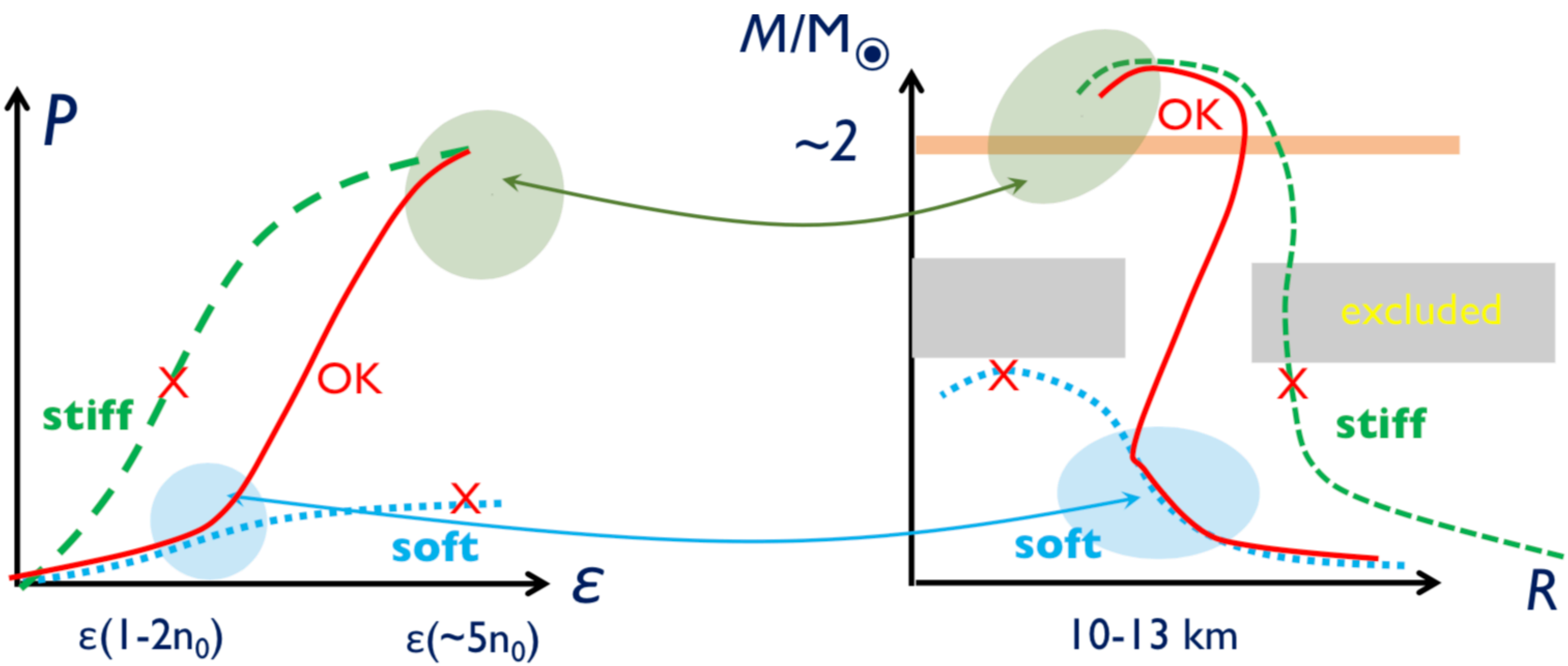


MR relation of NSs estimated from the latest observational data [Miller+, '21]

R may not change radically b/w lighter NSs & heavier NSs

→ **Crossover is preferred**

EOS vs M-R relation

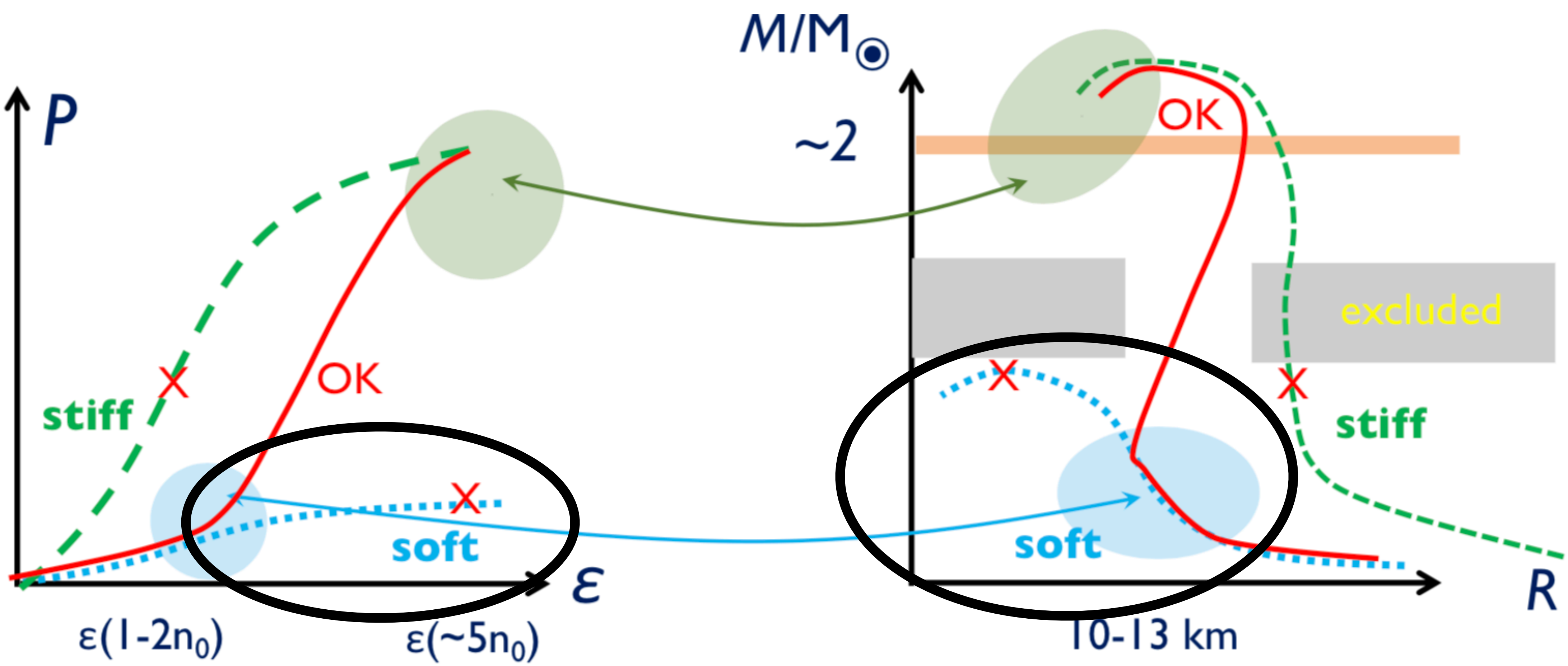


considering NSs data, a recent trend of EOS is: from soft to stiff

→ **crossover phase transition from hadrons to quarks**

(1st transition change a radius of NS radically.)

EOS vs M-R relation

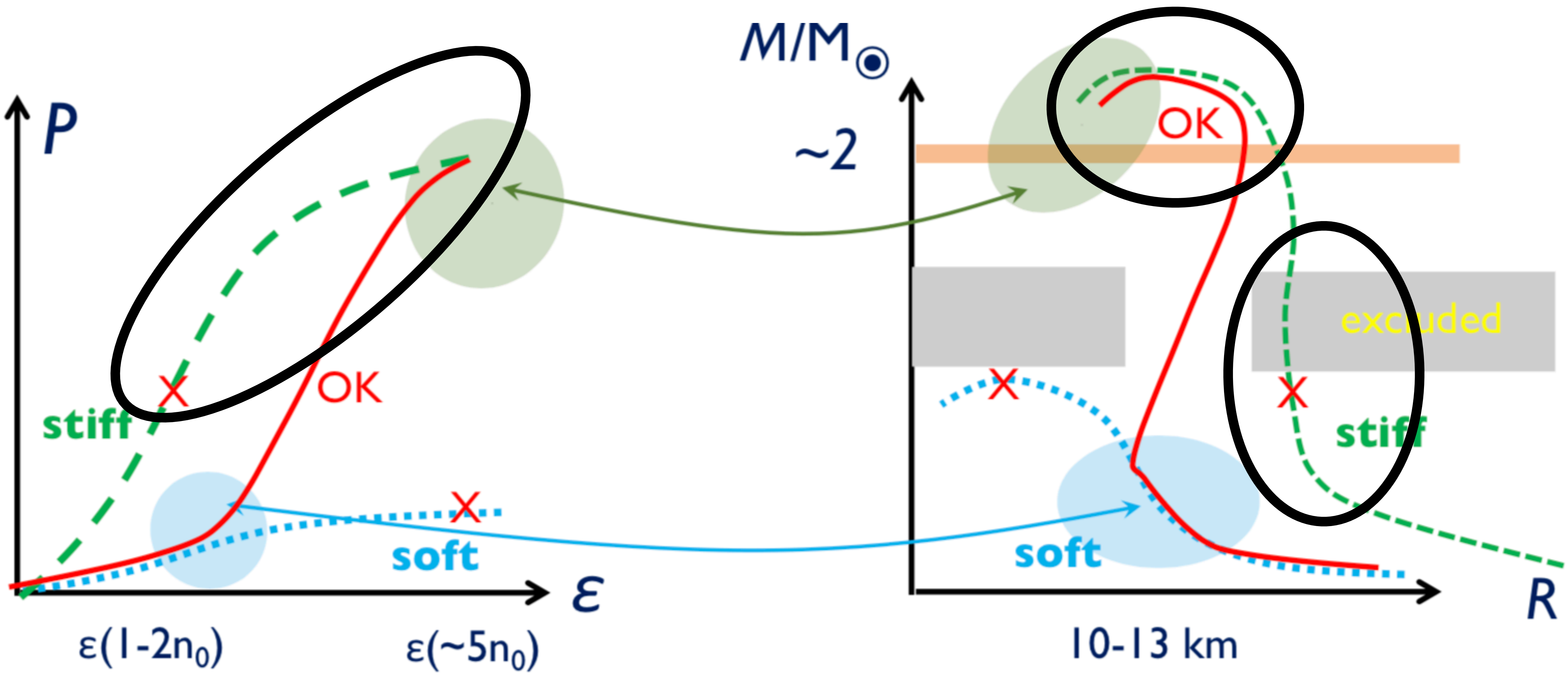


considering NSs data, a recent trend of EOS is: from soft to stiff

→ **crossover phase transition from hadrons to quarks**

(1st transition change a radius of NS radically.)

EOS vs M-R relation

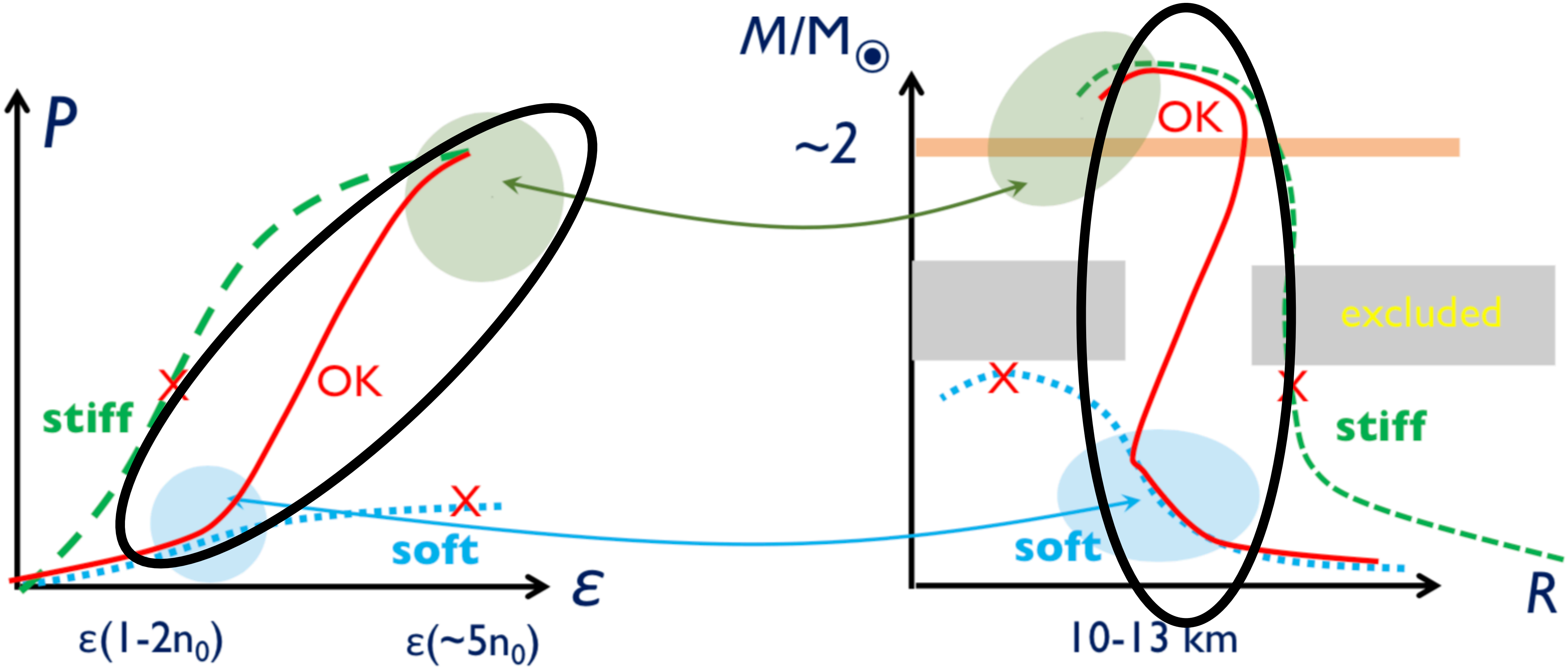


considering NSs data, a recent trend of EOS is: from soft to stiff

→ **crossover phase transition from hadrons to quarks**

(1st transition change a radius of NS radically.)

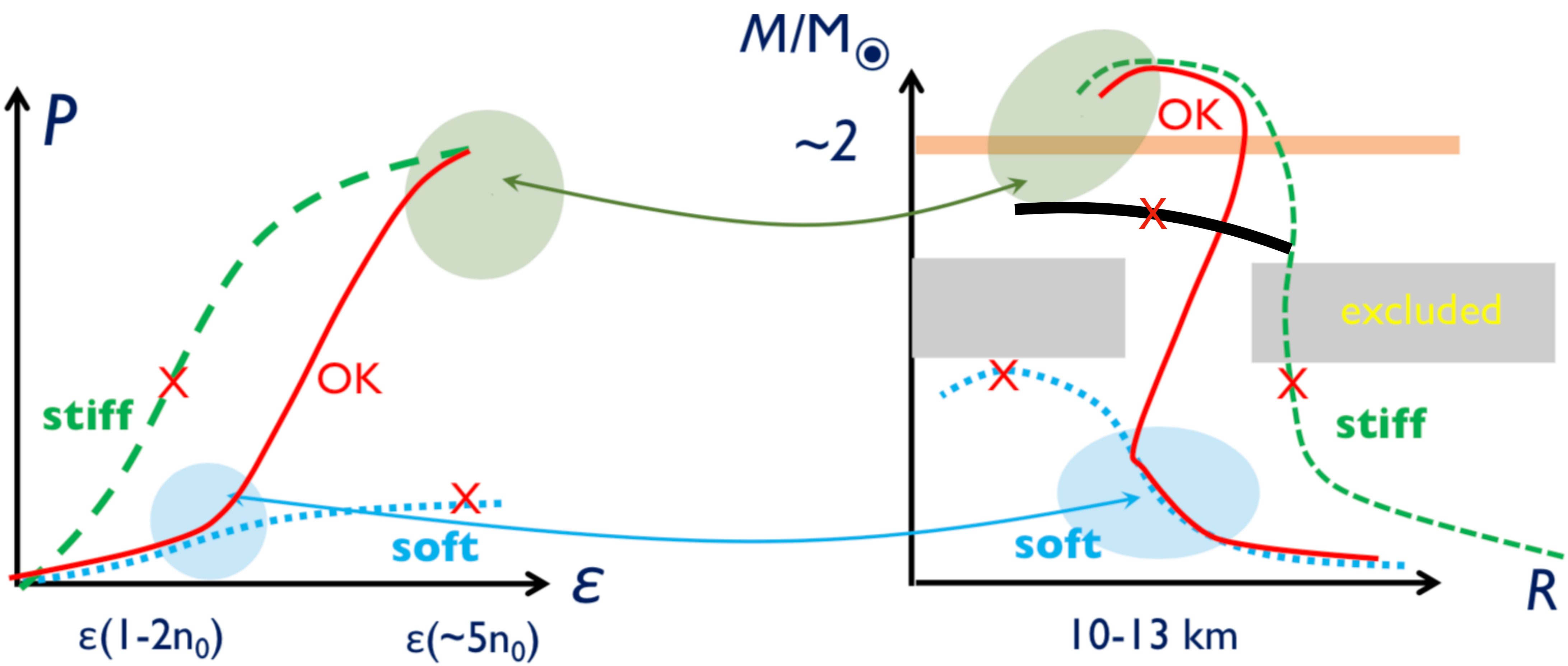
EOS vs M-R relation



considering NSs data, a recent trend of EOS is: from soft to stiff

→ **crossover phase transition from hadrons to quarks**
(1st transition change a radius of NS radically.)

EOS vs M-R relation

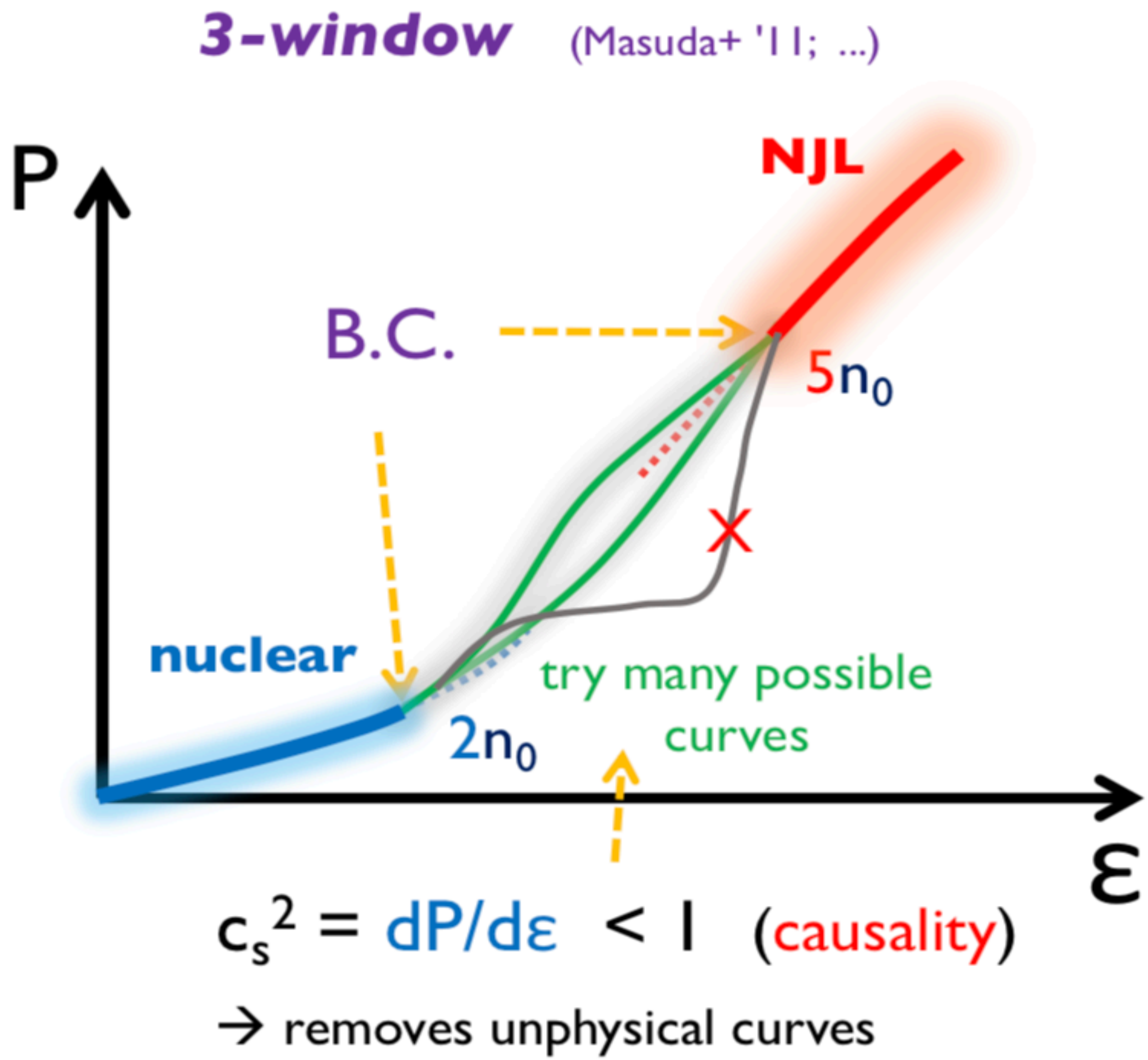


considering NSs data, a recent trend of EOS is: from soft to stiff

→ **crossover phase transition from hadrons to quarks**

(1st transition change a radius of NS radically.)

Crossover Model for Unified EOS



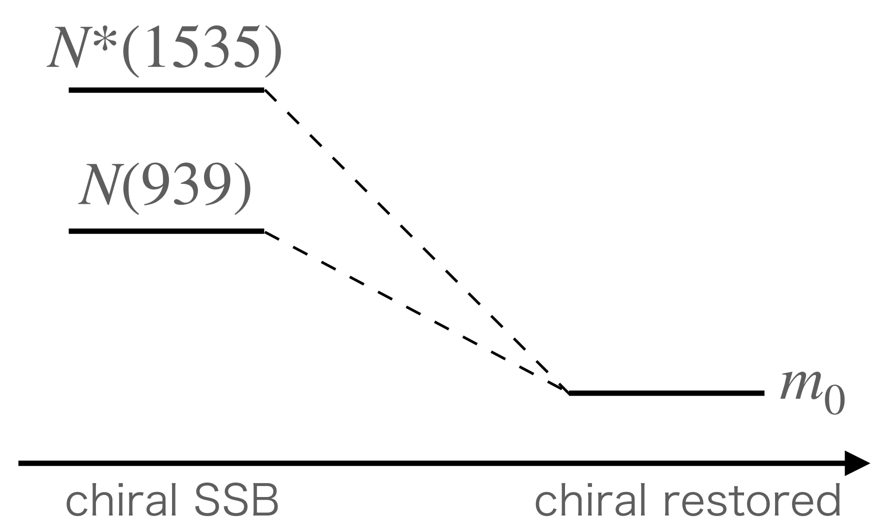
quark & nuclear EOS constrain each other

Parity Doublet Model for Nucleons

$$\mathscr{L}_{\mathrm{PDM}} = \mathscr{L}_{\mathrm{Nucleon}} + \mathscr{L}_{\mathrm{Meson}}(\sigma, \omega, \rho)$$

$$m_0(\bar{\psi}_1\gamma_5\psi_2 - \bar{\psi}_2\gamma_5\psi_1)$$

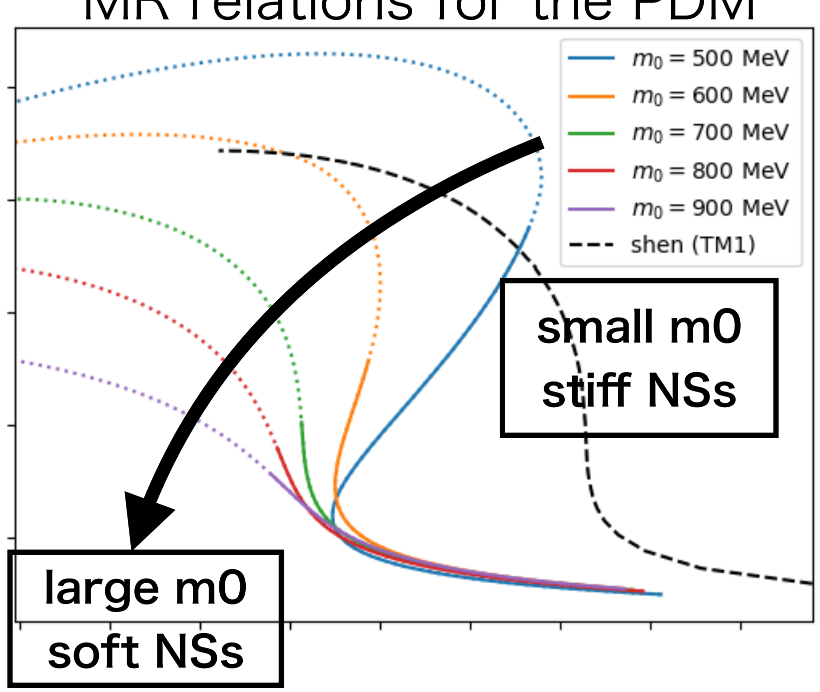
m_0: the chiral invariant mass



nucleons N(939)[N_+] and N*(1535)[N_-] are degenerate

$$M_{N\pm} = \sqrt{m_0^2 + g_+^2\sigma^2} \mp g_-\sigma \xrightarrow{\sigma \to 0} m_0(\gtrsim 500\,\mathrm{MeV})$$

MR relations for the PDM



large m0 ←→ soft EOS

if m0 is large → small coupling b/w σ & nucleons

→ small coupling for omega (balance b/w σ & ω)

→ small interaction, soft EOS, light&small NS

NJL Model for Quarks

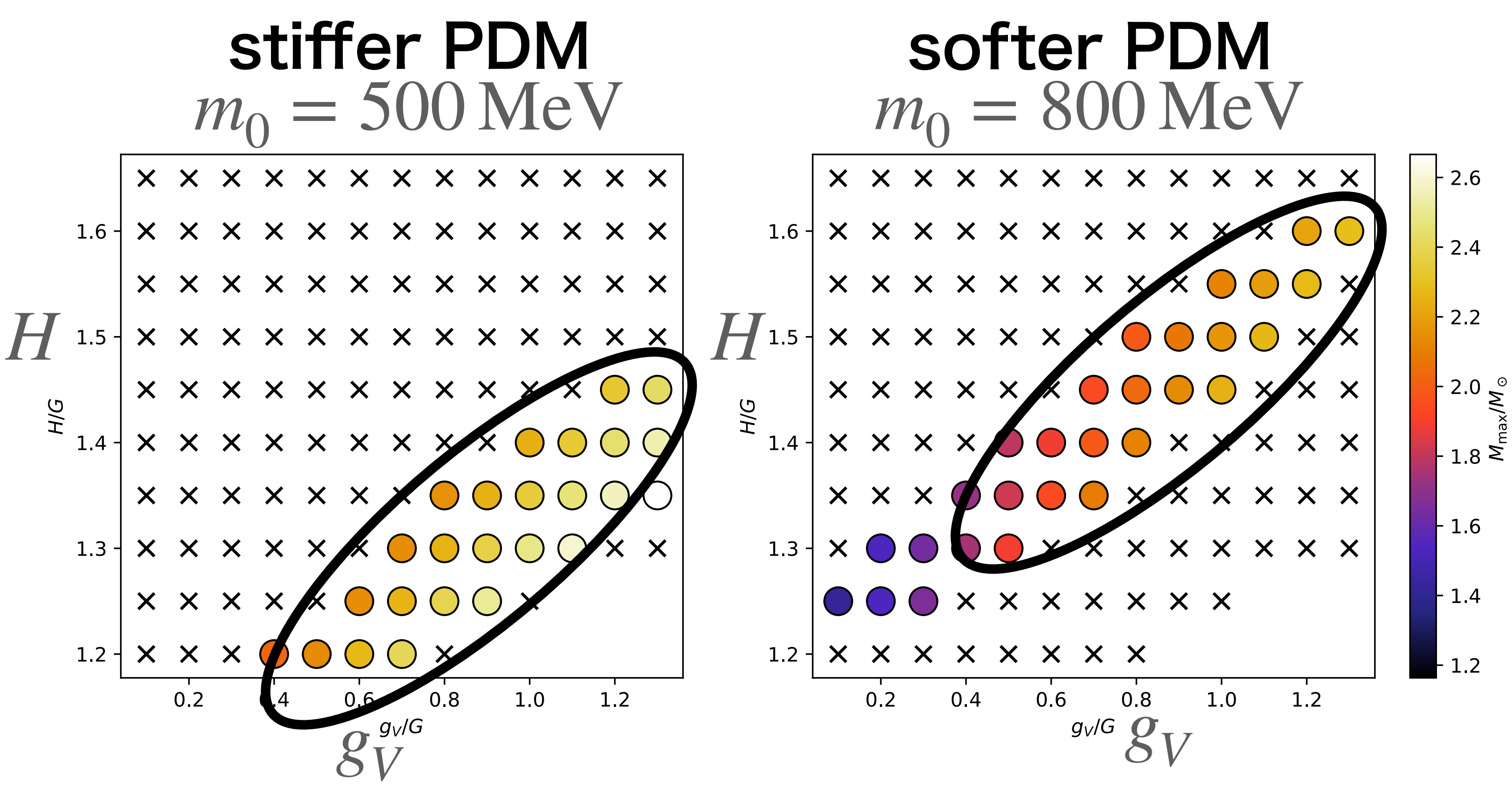
chiral | color-mag. | nB-nB int.

$$\mathscr{H} = \mathscr{H}_{\mathrm{NJL}} - \underline{H}(q^T\Gamma_A q)(\bar{q}\Gamma^A\bar{q}^T) + \underline{g_V}(\bar{q}\gamma^0 q)^2$$

NJL: parameters of Hatsuda-Kunihiro

(H,gV): not well-constrained before

→ survey wide range for given nuclear EOS + NS constraints



x: not causal

blue: too light

causality + M_max

↓

m0 ⟷ (H,gV)
constrain each other

can examine microphysics

NJL Model for Quarks

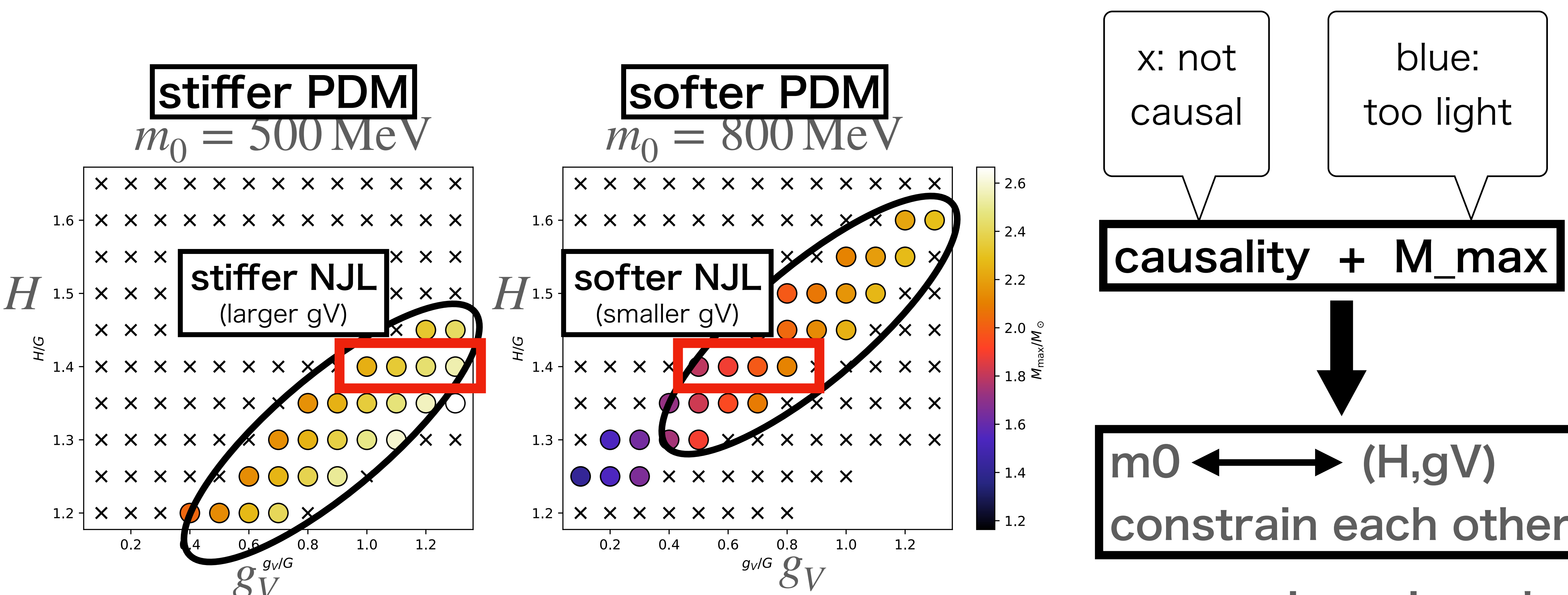
chiral — color-mag. — nB-nB int.

$$\mathscr{H} = \mathscr{H}_{\rm NJL} - \underline{H}(q^T\Gamma_A q)(\bar{q}\Gamma^A\bar{q}^T) + \underline{g_V}(\bar{q}\gamma^0 q)^2$$

NJL: parameters of Hatsuda-Kunihiro

(H,gV): not well-constrained before

→ survey wide range for given nuclear EOS + NS constraints



causality + M_max

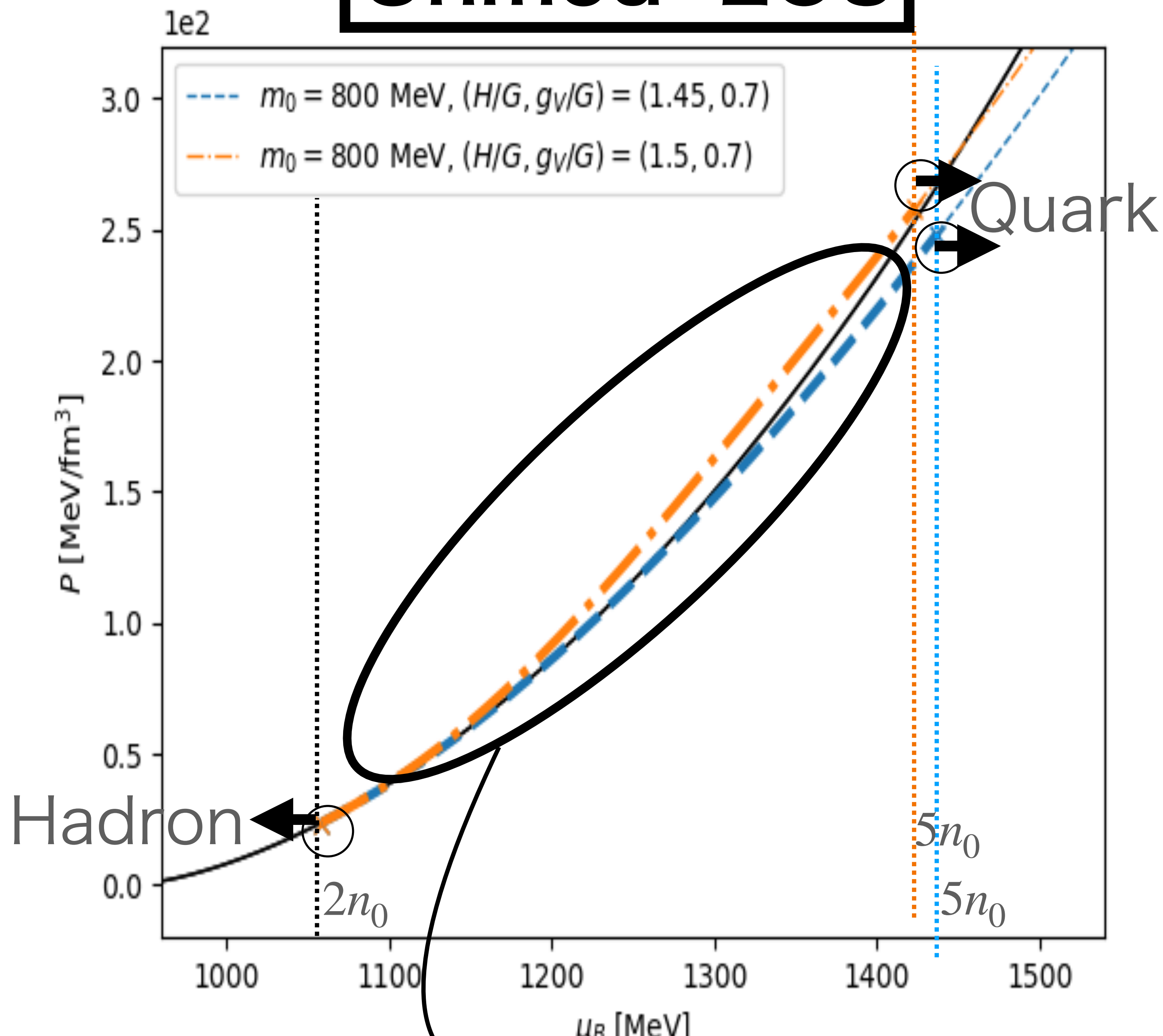
m0 ⟷ (H,gV)
constrain each other

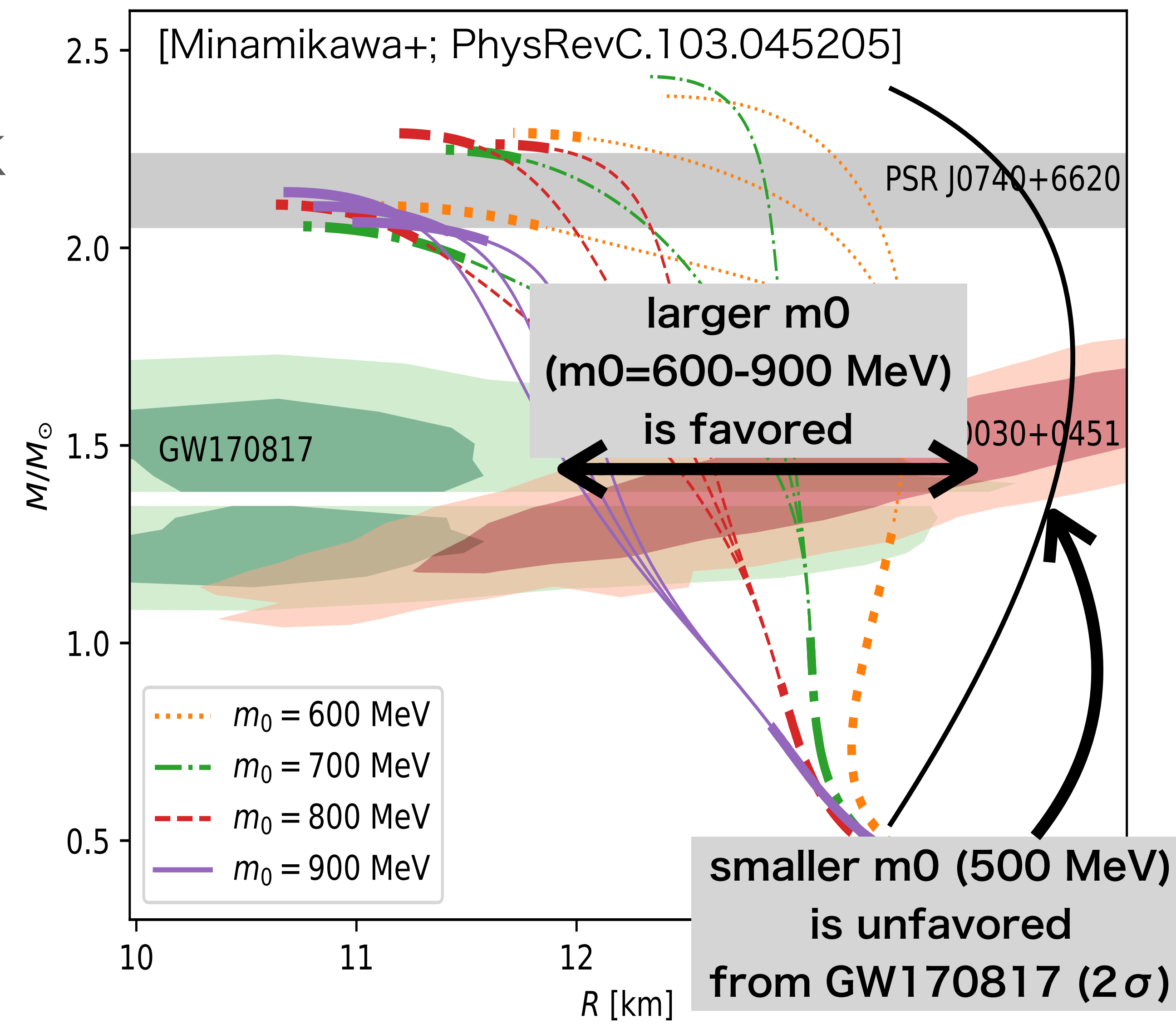
can examine microphysics

Unified EOS and its MR

[1] PhysRevC.103.045205 (T.M.,M.H.,T.K.)

Unified EOS → **MR relation**



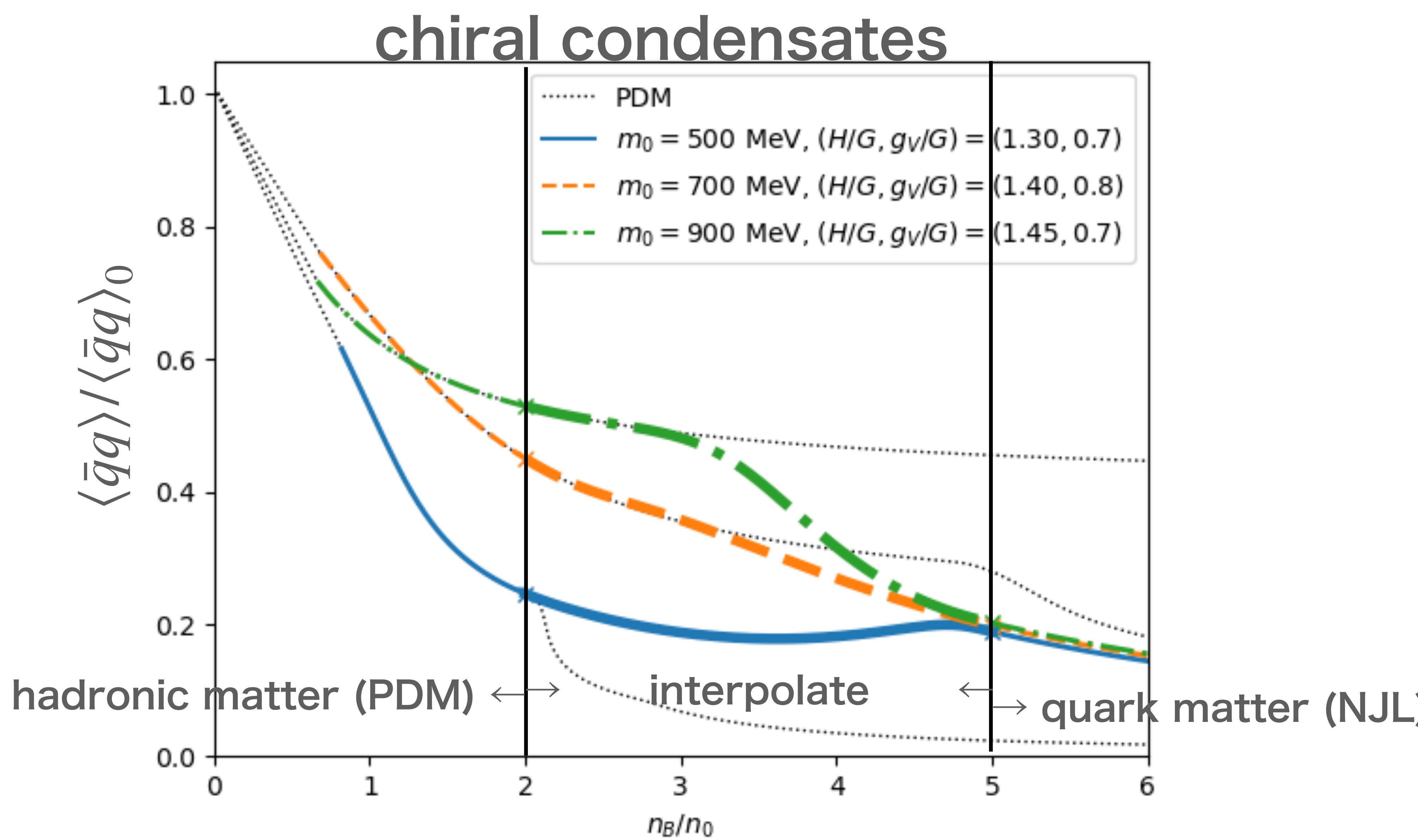


interpolate w/ a polynomial: $P(\mu_B) = \sum_{n=0}^{5} c_n \mu_B^n$

(six) Boundary Conditions → (six) coefficients c_n

Microphys. in Crossover

[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)



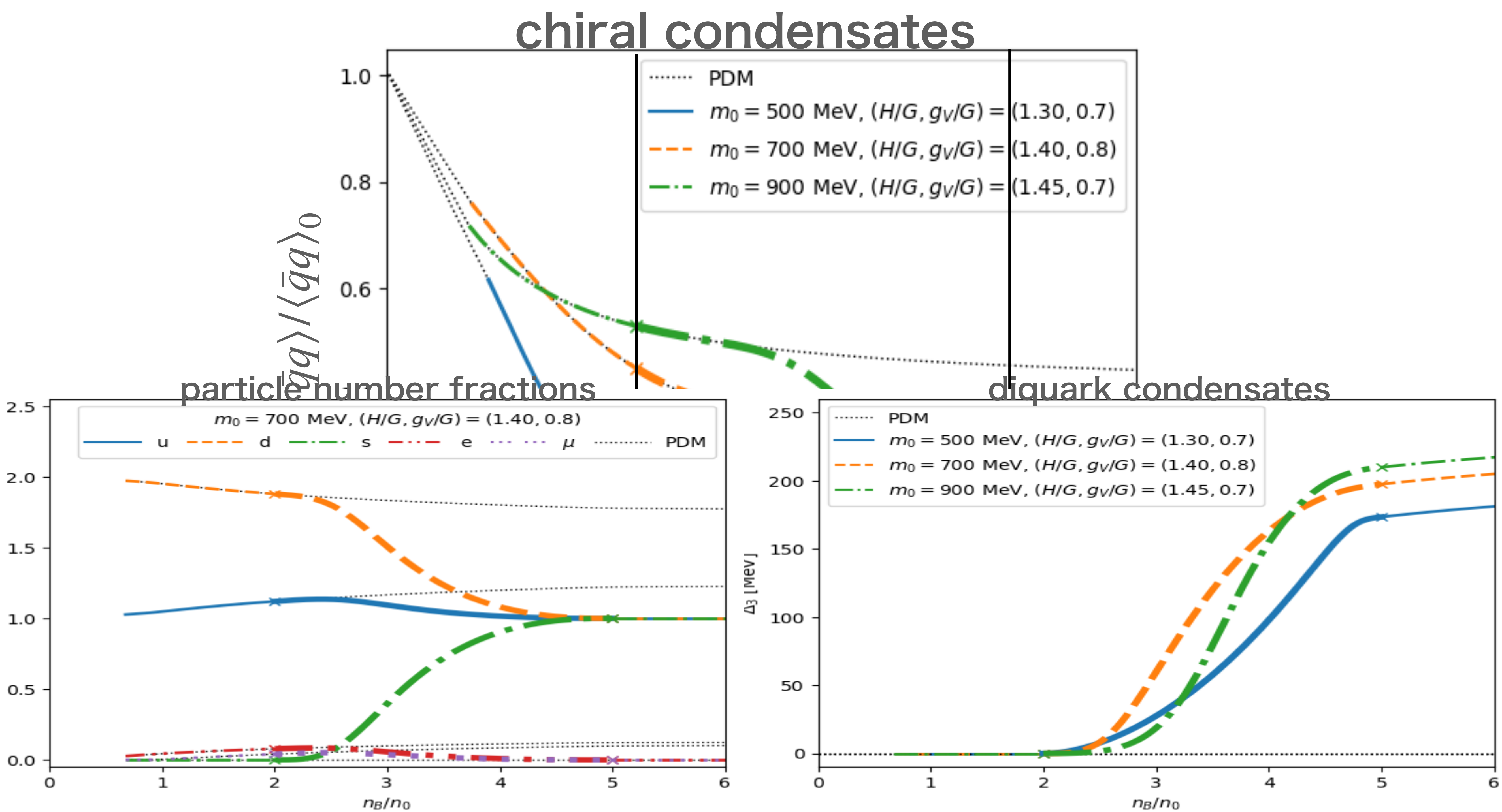
[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)

$\langle \bar{q}q \rangle = \dfrac{\partial \Omega}{\partial m_q}$ (Hellmann-Feynman Thm.)

extend $P(\mu_B) = \sum a_n \mu_B^n \rightarrow P(\mu_B, m_q) = \sum a_n(m_q) \mu_B^n$

Microphys. in Crossover

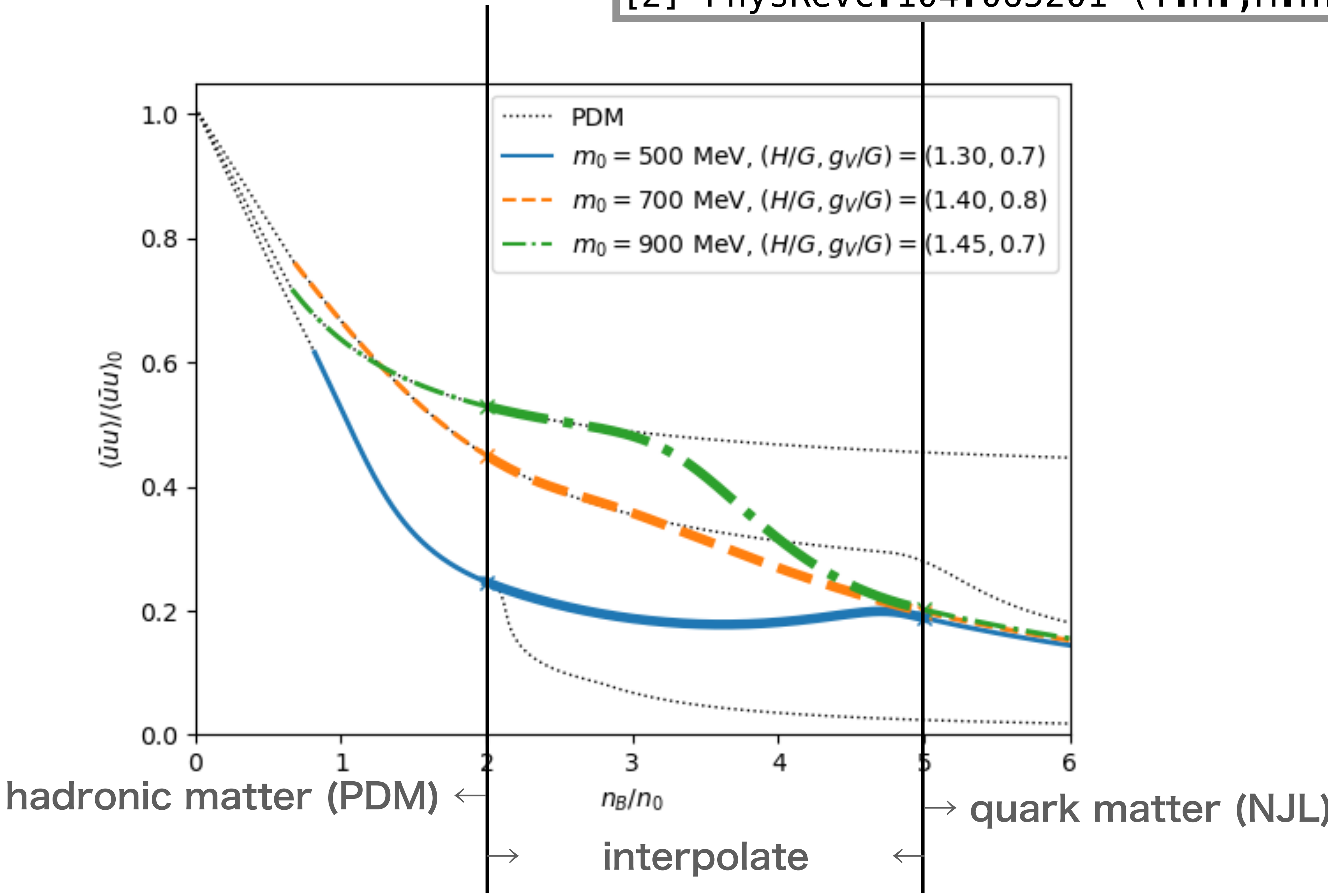
[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)



qualitative guideline
to extend models in the future

Unified $\langle \bar{q} q \rangle$

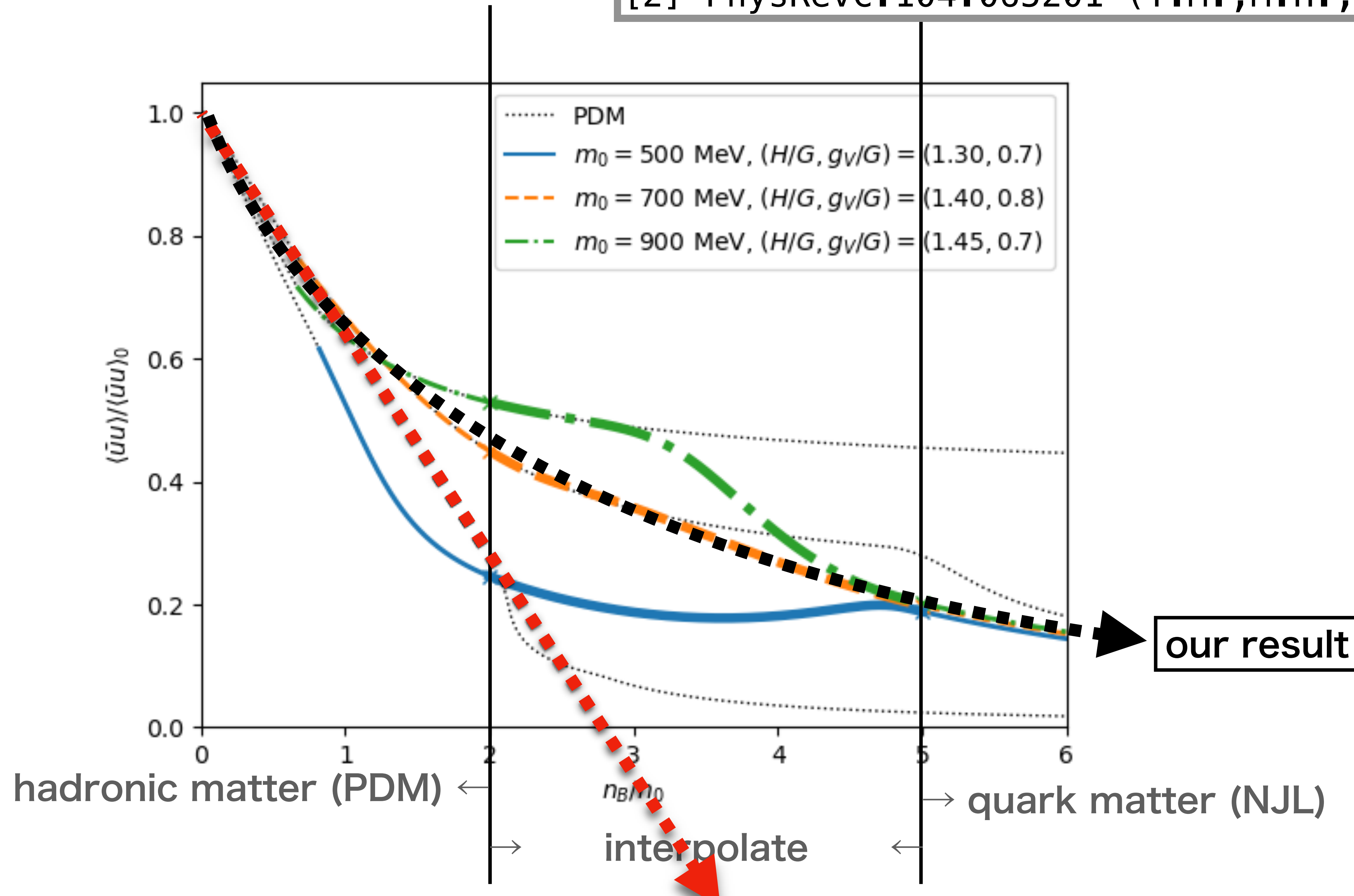
[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)



causality→ match w/ both Hadronic & Quark matter

Unified $\langle \bar{q}q \rangle$

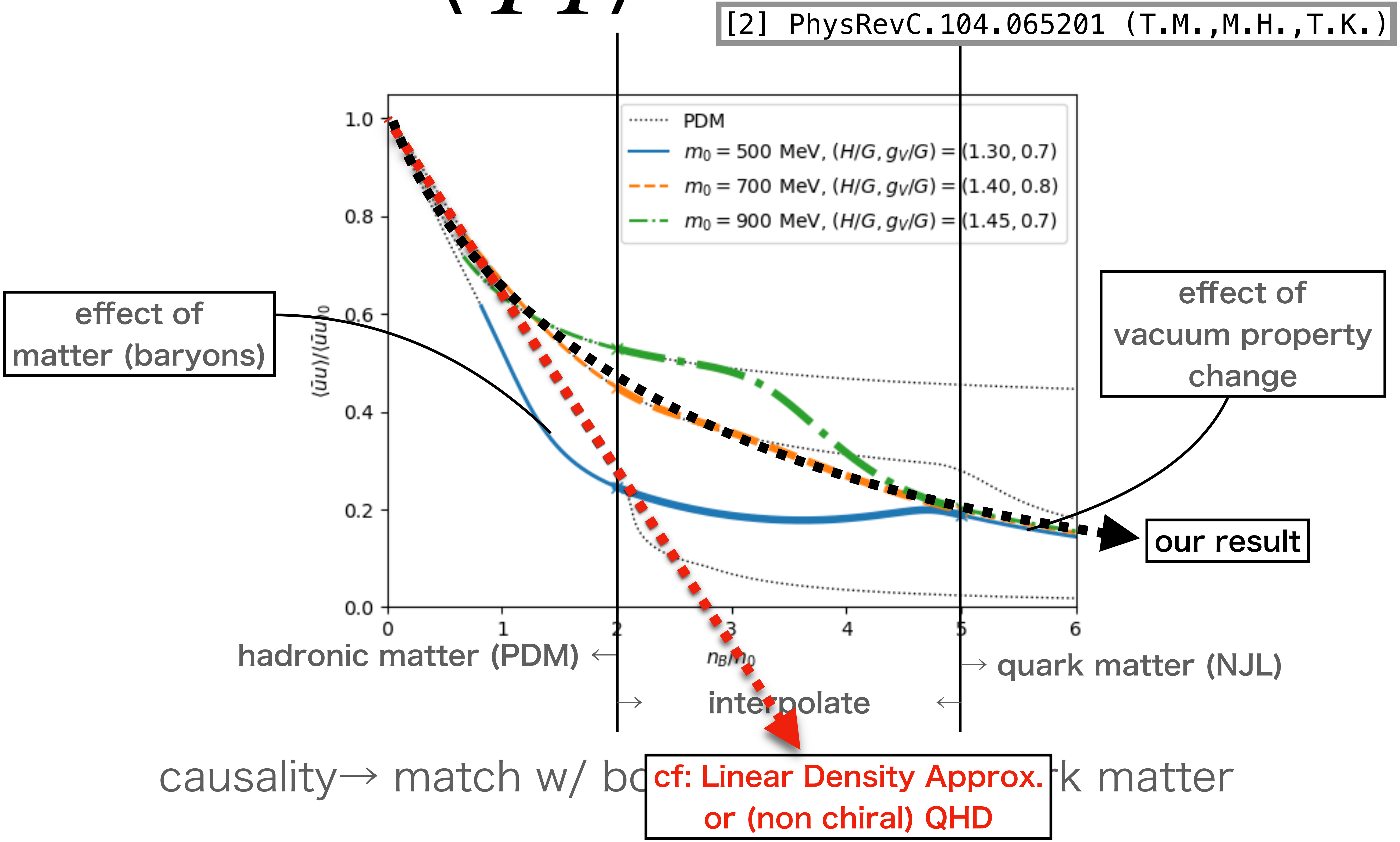
[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)



causality→ match w/ bo … k matter

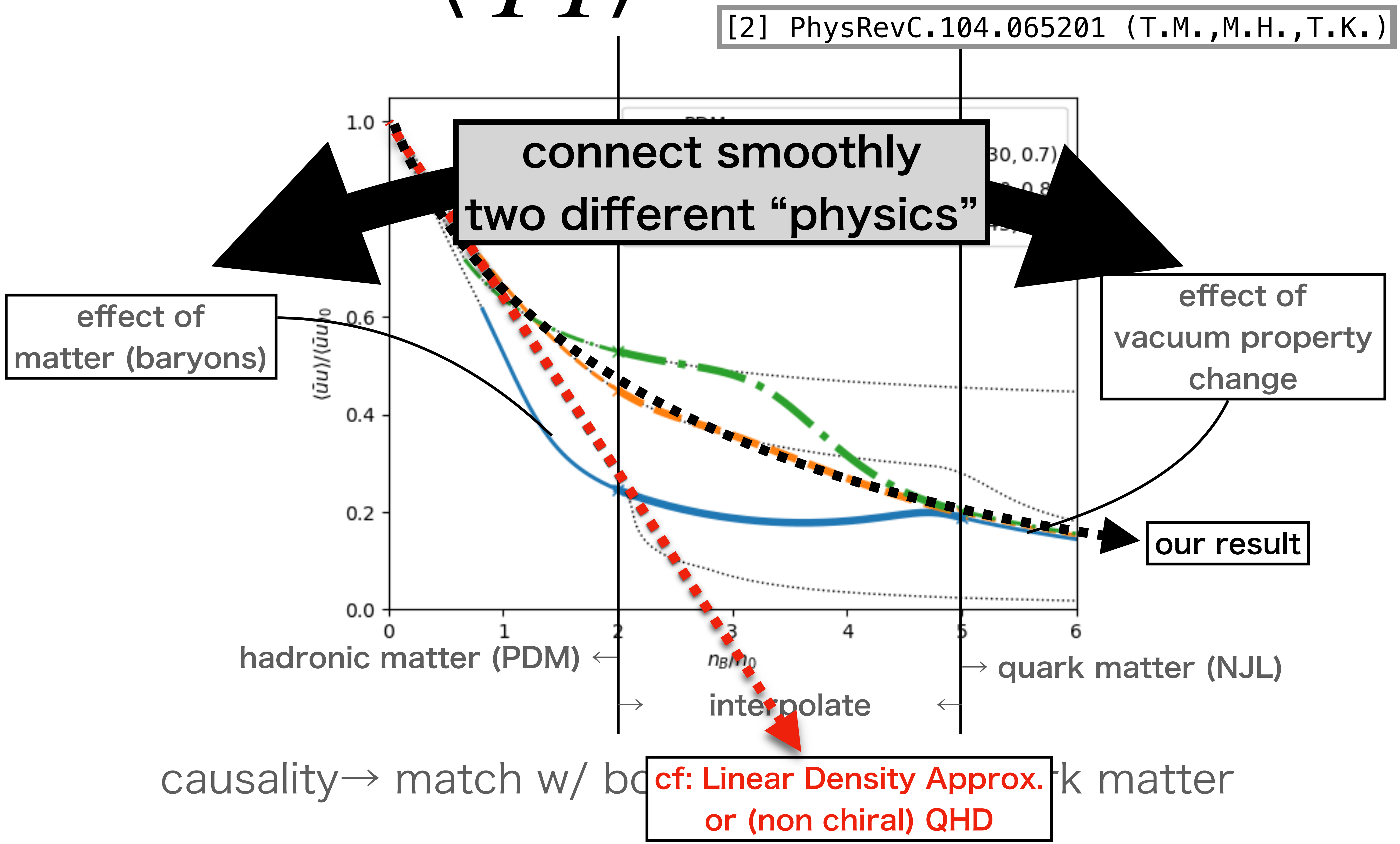
cf: Linear Density Approx.
or (non chiral) QHD

Unified $\langle \bar{q}q \rangle$



causality→ match w/ bo… k matter

Unified $\langle \bar{q}q \rangle$



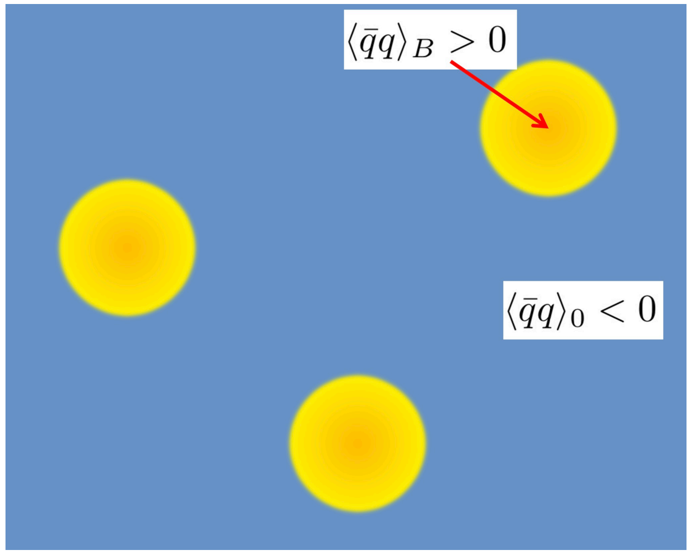
Inhomogeneous $\langle \bar{q}q \rangle$

[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)

Linear Density Approx. inside a nucleon

$$\langle \bar{q}q \rangle \approx -(0.25\,\mathrm{GeV})^3 + \underbrace{N_{\mathrm{scalar}} \frac{N_{\mathrm{baryon}}}{V_{\mathrm{baryon}}}}_{\approx (0.3\,\mathrm{GeV})^3} \quad > \quad 0$$

opposite signs
& similar magnitudes



Inhomogeneous $\langle \bar{q}q \rangle$

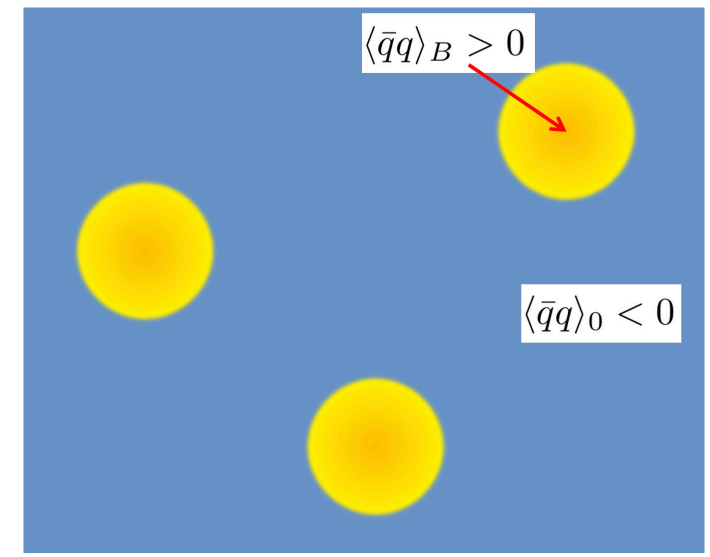
[2] PhysRevC.104.065201 (T.M.,M.H.,T.K.)

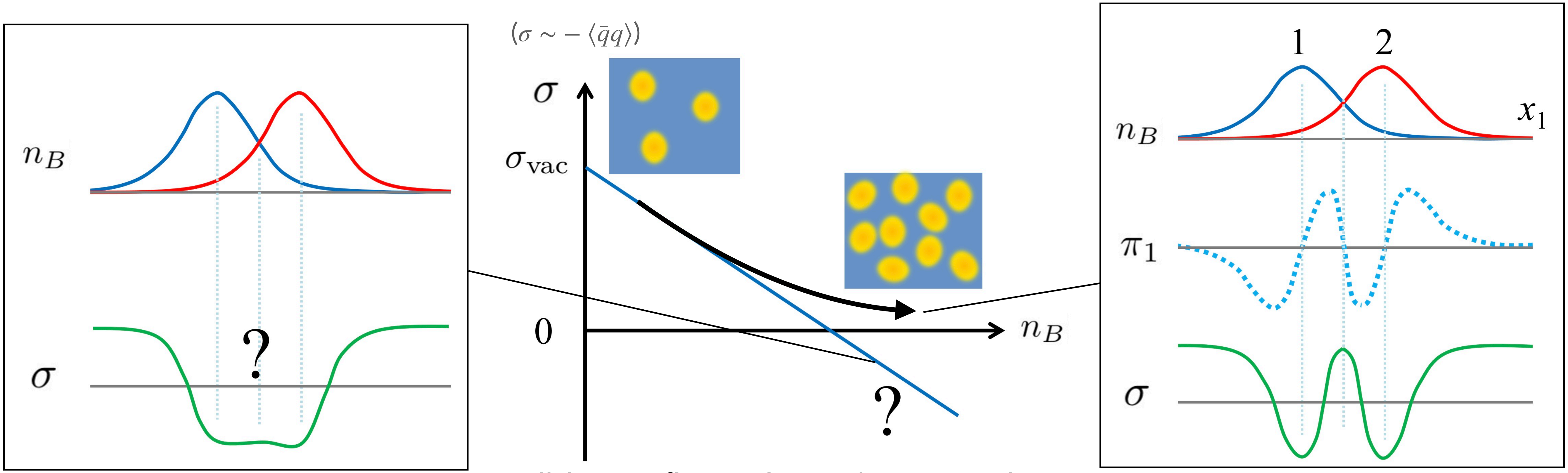
Linear Density Approx. inside a nucleon

$$\langle \bar{q}q \rangle \approx -(0.25\,\mathrm{GeV})^3 + N_{\mathrm{scalar}} \frac{N_{\mathrm{baryon}}}{V_{\mathrm{baryon}}} \quad > \quad 0$$

$\approx (0.3\,\mathrm{GeV})^3$

opposite signs
& similar magnitudes





possible configuration w/ our results:
σ and pions make forms like a wave in nucleons

Summary and Outlook

- unified EOSs for NS constructed by using PDM for nucleons and NJL for quarks
- PDM-EOS & NJL-EOS are constraining each other; the understanding of one EOS improves the other
- observational constraints → $600\,\mathrm{MeV} \lesssim m_0 \lesssim 900\,\mathrm{MeV}$
- we calculated the chiral quark condensate $\langle \bar{q}q \rangle$.
  the interpolation of $\langle \bar{q}q \rangle_{\mathrm{PDM}}$ and $\langle \bar{q}q \rangle_{\mathrm{NJL}}$ is shallow(smooth).

outlook (work in progress):

- extend the PDM to SU(3) (include hyperons)
- effects of the U(1)A anomaly