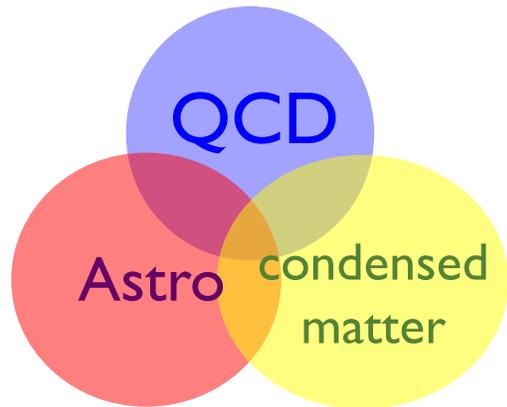
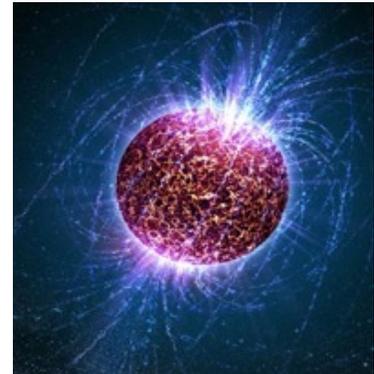


# Phase shifts and baryon momentum distributions in dense matter



Toru Kojo

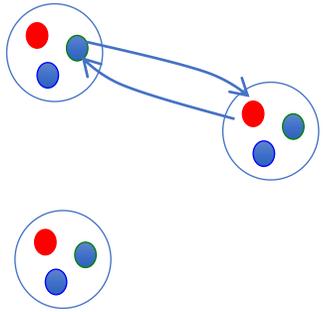
(KEK, Theory Center)



- Refs) Baym-Hatsuda-TK-Powell-Song-Takatsuka, Review on QCD for neutron stars (2018)  
Fujimoto-TK-McLerran, on ideal quarkyonic matter model, PRL (2024)  
Tajima-Iida-TK-Liang, on dense matter of composite baryons, PRL (2025)

# Neutron Star matter $(n_0 = 0.16 \text{ fm}^{-3})$ [Masuda+ '12; TK+ '14]

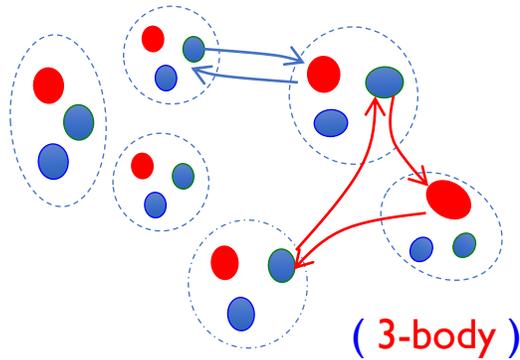
- few meson exchange
- nucleons only



ab-initio nuclear cal.  
laboratory experiments  
steady progress

$\sim 1.4 M_\odot$

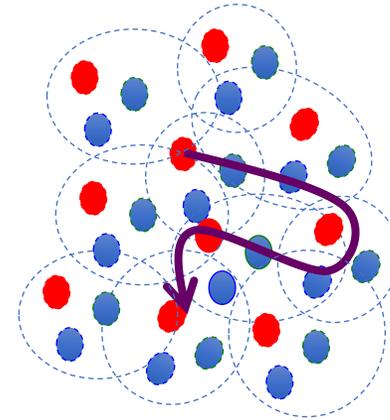
- many-quark exchange
- structural change,...
- hyperons,  $\Delta$ , ...



**most difficult**  
(d.o.f ??)

$\sim 2 M_\odot$

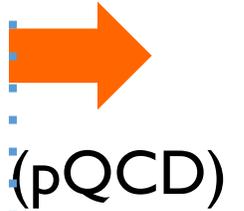
- Baryons overlap
- Quark Fermi sea



**strongly correlated**  
(d.o.f : quasi-particles??)

not explored well

$\sim 40 n_0$



[Freedman-McLerran,  
Kurkela+, Fujimoto+,  
Minato+, ...]

$n_B$

$\sim 2 n_0$  **Hints from NS**

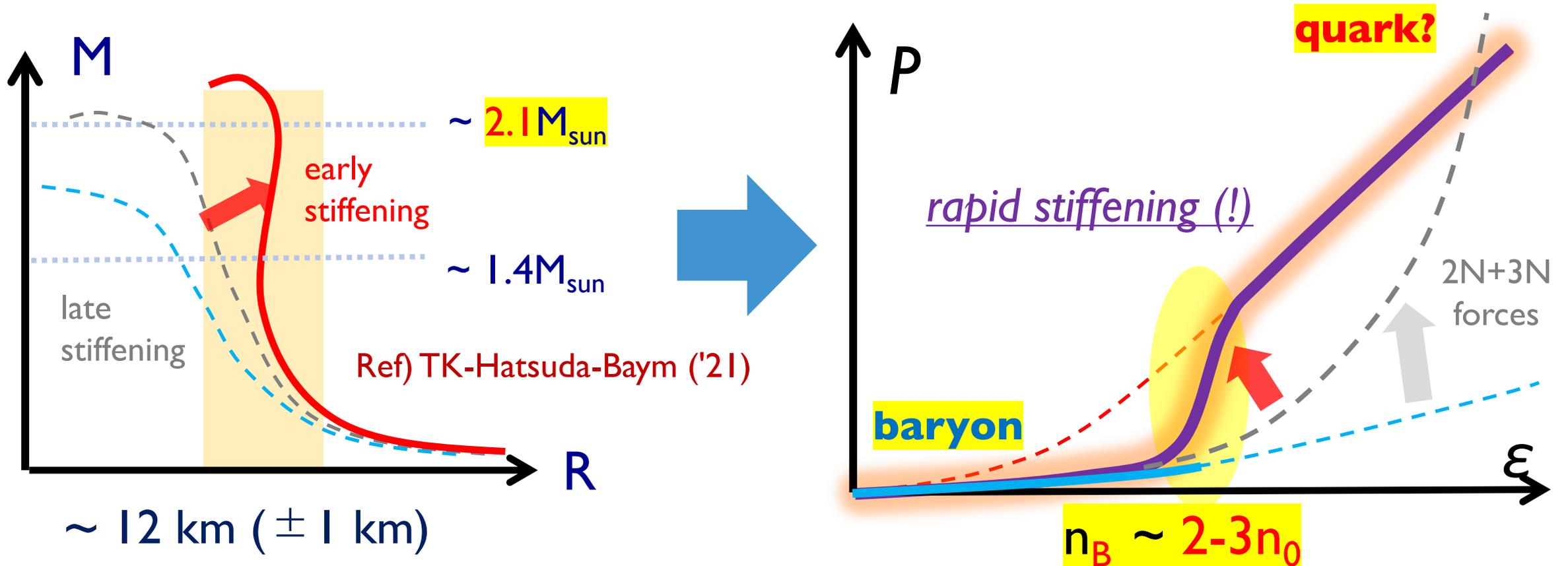
$\sim 5 n_0$



# Implications from NS

NICER for 1.4 & 2.1  $M_{\text{sun}}$  + **GW** + **nuclear** ( $< \sim 1.5n_0$ )

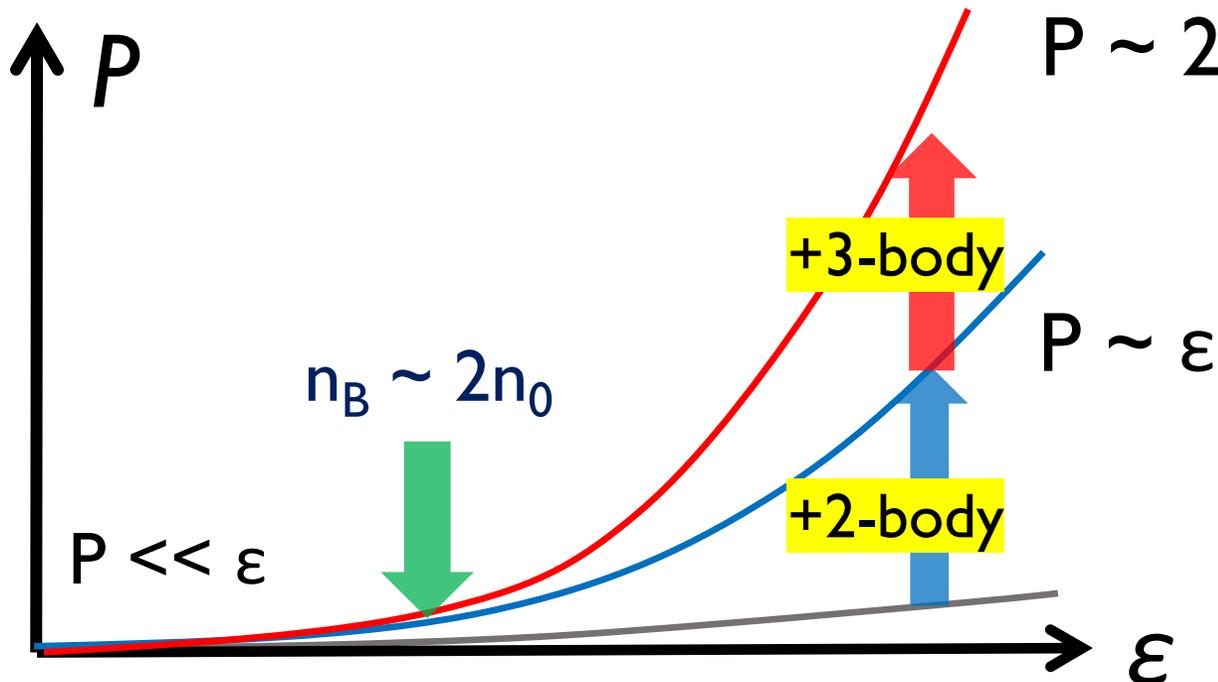
→  $R_{1.4} \sim R_{2.1} (!)$



# Remark I: stiffening of nuclear EOS is slow

$$\varepsilon(n_B) = m_N n_B + a \frac{n_B^{5/3}}{m_N} + \underbrace{b n_B^\alpha}_{\text{soft (!)}} \quad \longrightarrow \quad P = \frac{2}{3} a \frac{n_B^{5/3}}{m_N} + \underbrace{b(\alpha - 1) n_B^\alpha}_{\text{soft (!)}}$$

at large  $n_B$ , many-body forces **must be dominant**



$P \sim 2\varepsilon$   $\leftarrow$  violate causality  $c_s^2 > 1$  at  $\sim 5-6n_0$

stiffening too slow?

convergence of many-body forces?

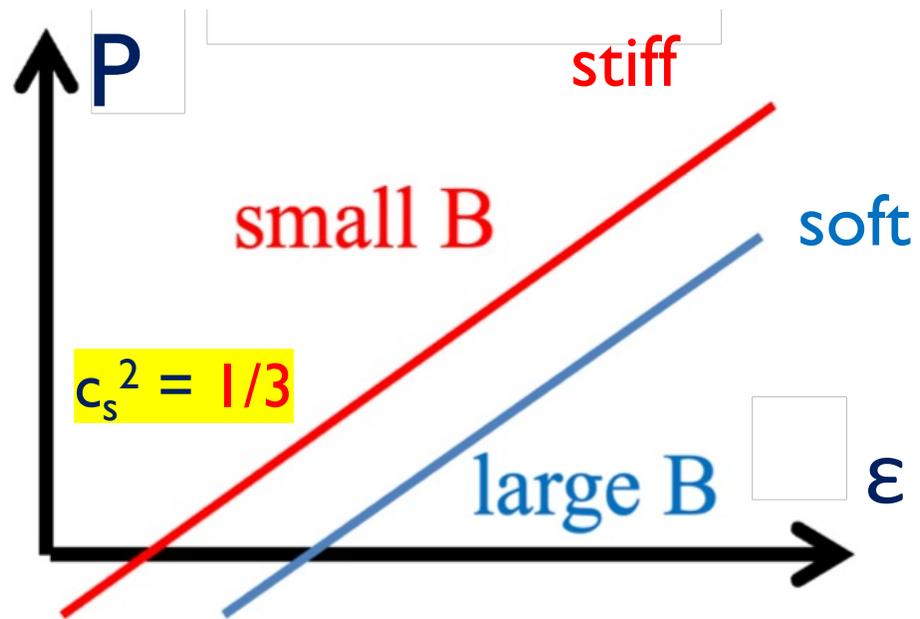
the sign of many-body forces?

# Remark 2: quark EOS can be **stiff**

e.g.) free massless quarks

$$P = \frac{\varepsilon}{3} - B'$$

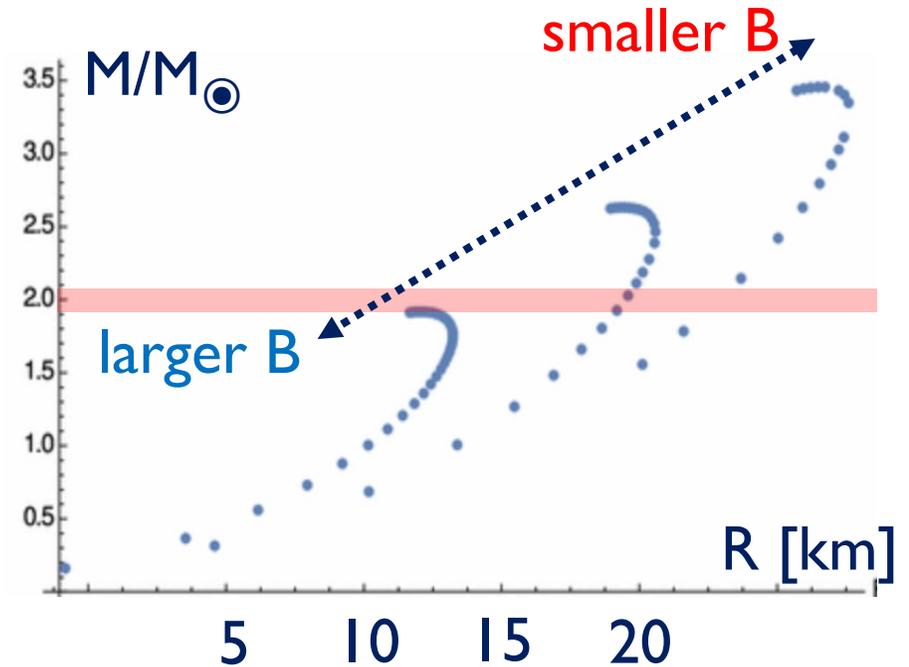
normalization



quark kin. pressure  $\gg$  baryon kin. pressure

$O(N_c)$

$O(1/N_c)$



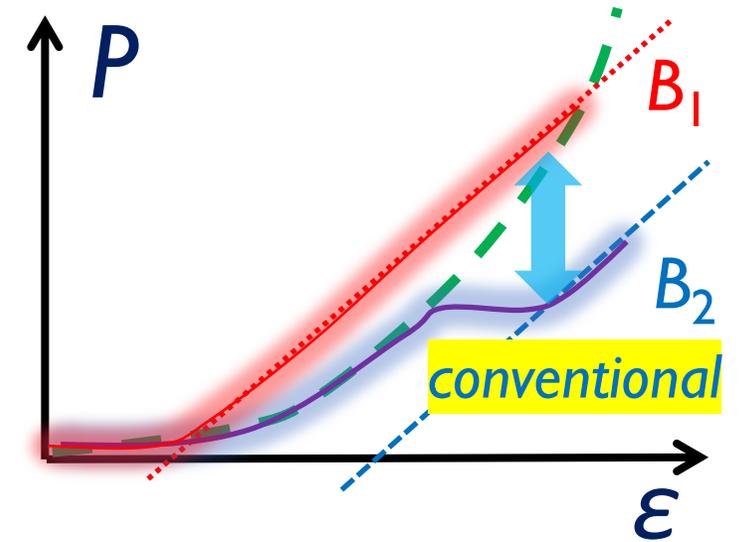
relativistic pressure  $\rightarrow$  stiff EOS ?

*depends on the normalization...*

## Remark 3: **normalization** of EOS is important

### conventional hybrid EOS

prepare hadronic & quark EOS *as independent*,  
and then choose the energetically favorable one



### Difficulties:

fixing (relative) *normalization* for **two independent** EOSs is difficult

validity domain of *pure* hadronic and quark EOSs are **assumed** to overlap

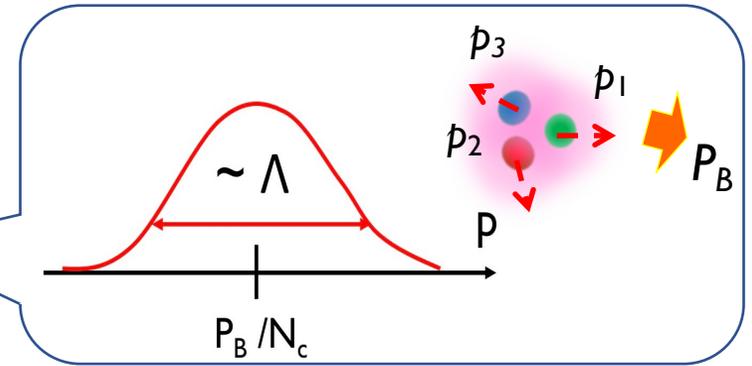
*transformation* of hadronic matter to quark matter is **a priori excluded**

Need: **follow quark states from nuclear to quark matter**

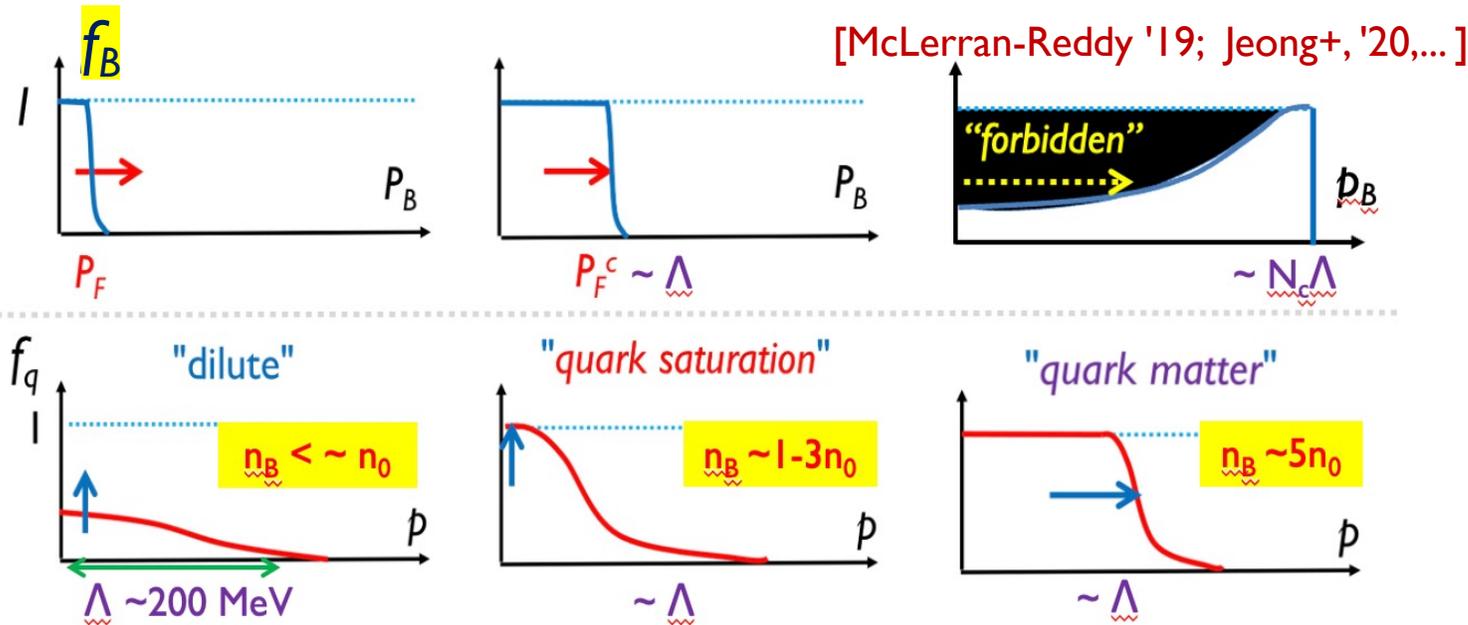
# IdylliQ model

[TK '21, Fujimoto+ '23, Tajima+ '24, ...]

$$f_Q(\mathbf{q}) = \int_{\mathbf{P}_B} f_B(\mathbf{P}_B) \varphi_Q^B(\mathbf{q} - \mathbf{P}_B/N_c)$$

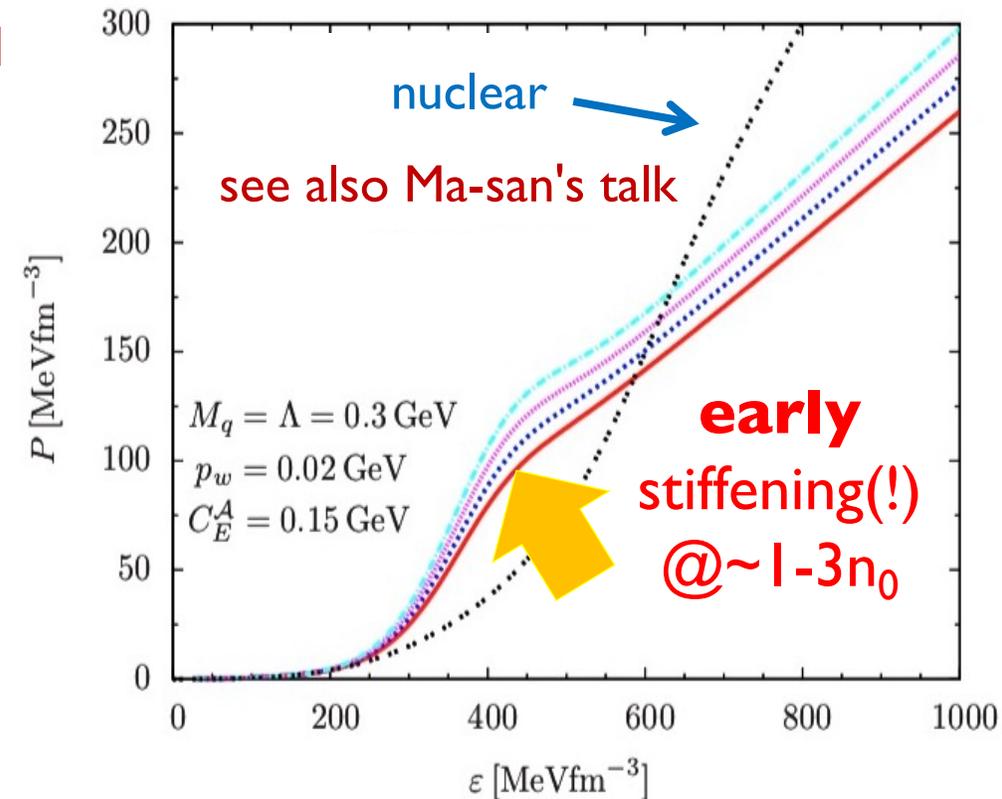


occupation prob. (baryons & quarks)



**"inevitable quark matter formation"**

[see also Hayata-Hidaka-Nishimura '24,  $f_Q$  for I+ID QCD]



# Models for **transient** regime

## 1) **IdylliQ model** (quarkyonic matter model) [not discussed today, see my talk at *Baryons2025*]

assume quarks are confined into baryons, and pack many baryons

→ inevitable formation of quark Fermi sea, quenching of baryons at low  $E$

[TK PRD '21; Fujimoto-Kojo-McLerran PRL '23; ...]

## 2) **phase shift** approach for composite particles

quarks are not necessarily confined into baryons,  
but very similar physics as in IdylliQ model

[Tajima-Iida-TK-Liang, PRL '25]

## 3) **hadron-quark model** (e.g., quark-meson model)

a pragmatic framework, useful for fine-tuning or phenomenological studies

[test in QCD-like theories: TK-Suenaga '21; Chiba-TK PRD '23; ...]

# ***Phase shift*** approach for ***composite*** particles

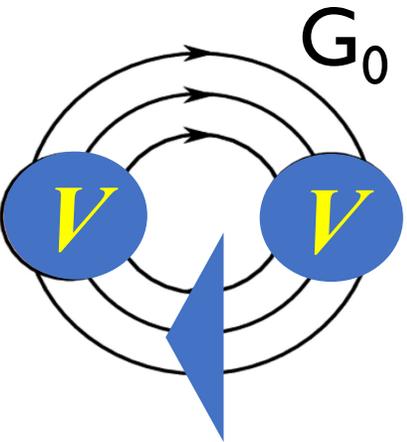
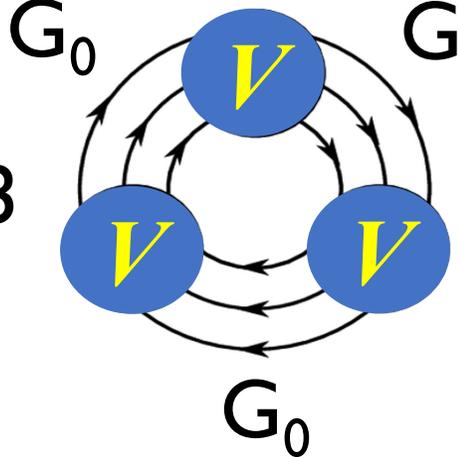
Dashen, Ma, and Bernstein, *Phys. Rev.* 187, 345–370 (1969).

Nozieres and Schmidt-Rink, *J. Low Temp. Phys.* 59, 195 (1985).

Blaschke+, *Ann. Phys. (Amsterdam)* 348, 228 (2014).

Pok Man Lo [arXiv: 1707.04490, review]

# Thermodynamics of **composite particles**

$$\Omega_{3\text{-body}} = 1/2 \text{ (diagram)} + 1/3 \text{ (diagram)} + \dots$$



total frequency & momentum  $(\omega_n, \mathbf{K})$

$$-V = G_{\text{full}}^{-1} - G_0^{-1} \text{ free}$$

$$= -T \sum_{\omega_n, \mathbf{K}} \text{tr}_N \left[ \text{Ln}(1 - G_0 V) + G_0 V \right]$$

$$= T \sum_{\omega_n, \mathbf{K}} \text{tr}_N \left[ \text{Ln}(G/G_0) - G_0 G^{-1} \right] + \text{const.}$$

"trace" over all possible states for given  $(\omega_n, \mathbf{K})$

# Phases of Green's functions

$$G_0 = \frac{1}{\omega - H_0 + i\delta} = |G_0|e^{i\varphi_{G_0}}$$

$$G = \frac{1}{\omega - H + i\delta} = |G|e^{i\varphi_G}$$

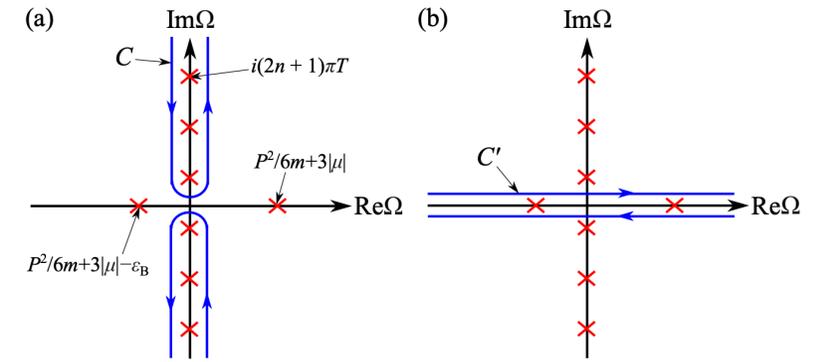
phase "shift"

$$G/G_0 = |G/G_0|e^{i\varphi} \quad \varphi = \varphi_G - \varphi_{G_0}$$

# Thermodynamics of composite particles

$$\Omega_{3\text{-body}} = T \sum_{\omega_n, \mathbf{K}} \text{tr}_N \left[ \text{Ln}(G/G_0) - G_0 G^{-1} \right]$$

contour deformation & integrate by part



$$= -T \sum_{\mathbf{K}} \int \frac{d\omega}{\pi} \ln(1 + e^{-\beta\omega}) \frac{\partial}{\partial \omega} \text{tr}_N \left( \text{Im} [\text{Ln}(G/G_0) - G_0 G^{-1}] \right)$$

use:  $G/G_0 = |G/G_0| e^{i\varphi}$

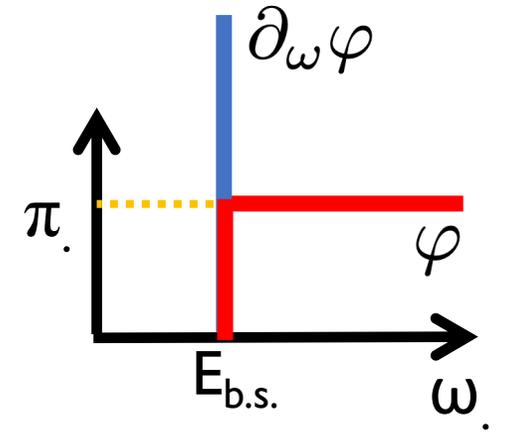
$$= -T \sum_{\mathbf{K}} \int \frac{d\omega}{\pi} \ln(1 + e^{-\beta\omega}) \frac{\partial}{\partial \omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi]$$

**phase shift** representation of **thermodynamic potential**

Ref) xxxx, yyyy

# e.g. Hadron Resonance Gas

e.g.) stable bound particles  $\varphi = \pi \Theta(\omega - E_{\text{b.s.}}(K))$



$$\Omega_{\text{N-body}} = -T \sum_{\mathbf{K}} \int \frac{d\omega}{\pi} \ln(1 + e^{-\beta\omega}) \frac{\partial}{\partial\omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi]$$

$$\boxed{\phantom{x}} = \pi \delta(\omega - E_{\text{b.s.}}) [1 - |G_0/G| \cos \varphi] - \sin \varphi \frac{\partial |G_0/G|}{\partial\omega}$$

$\rightarrow 0$  ( $G \rightarrow \infty$  at pole)  $= 0$

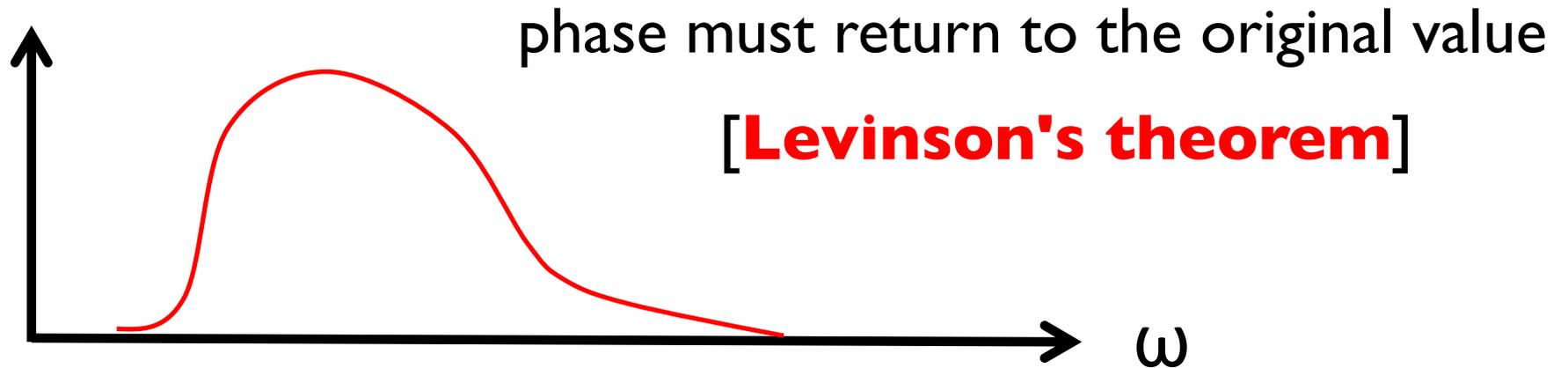
$\rightarrow$  HRG model:  $\Omega_{\text{N-body}} = -T \sum_{\mathbf{K}} \ln(1 + e^{-\beta E_{\text{b.s.}}})$

# Constraints on general theory

num. of states:  $\int_{\omega} \text{Im Tr } G = \int_{\omega} \text{Im Tr } G_0$   $G = \frac{1}{\omega - H + i\delta}$   
 (int. cannot modify)  $G_0 = \frac{1}{\omega - H_0 + i\delta}$

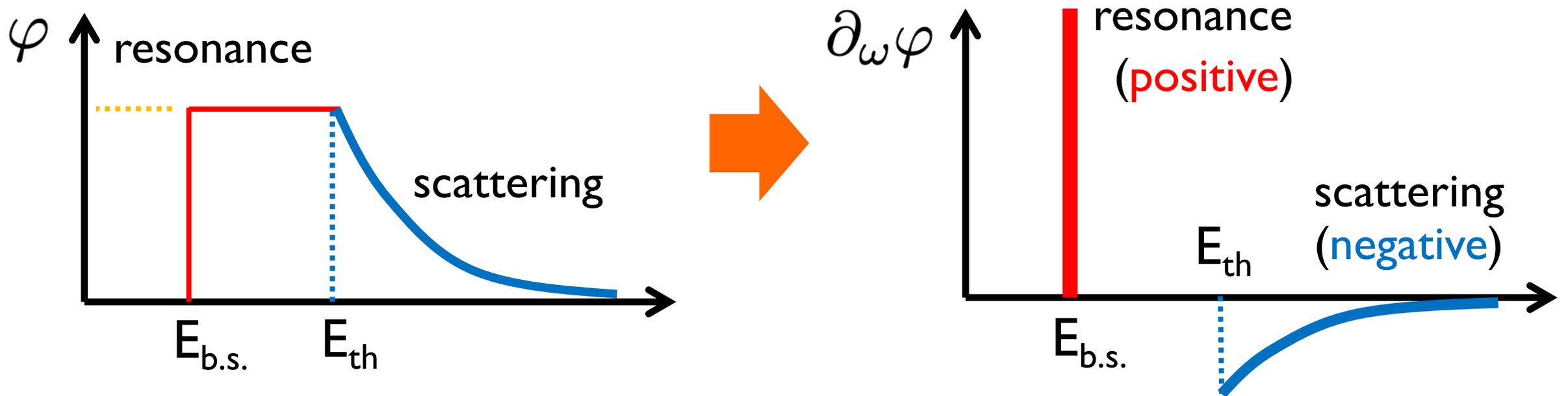
$$G = G \partial_{\omega} G^{-1} = \partial_{\omega} \ln G^{-1}$$

$\rightarrow 0 = - \int_{\omega} \text{Im Tr } \partial_{\omega} \ln (G/G_0) = \int_{\omega} \partial_{\omega} \text{Tr } \varphi = \text{Tr } \varphi(\infty) - \text{Tr } \varphi(-\infty)$



# e.g.) Hadron Resonance Gas **with the decay**

$$\Omega_{\text{N-body}} = -T \sum_{\mathbf{K}} \int \frac{d\omega}{\pi} \ln(1 + e^{-\beta\omega}) \left[ \frac{\partial}{\partial \omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi] \right]$$



**resonance** and **scattering** contributions **tend to cancel**

# High temperature limit

$$\Omega_{\text{N-body}} = -T \sum_{\mathbf{K}} \int \frac{d\omega}{\pi} \ln(1 + e^{-\beta\omega}) \frac{\partial}{\partial\omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi]$$

Boltzmann factor

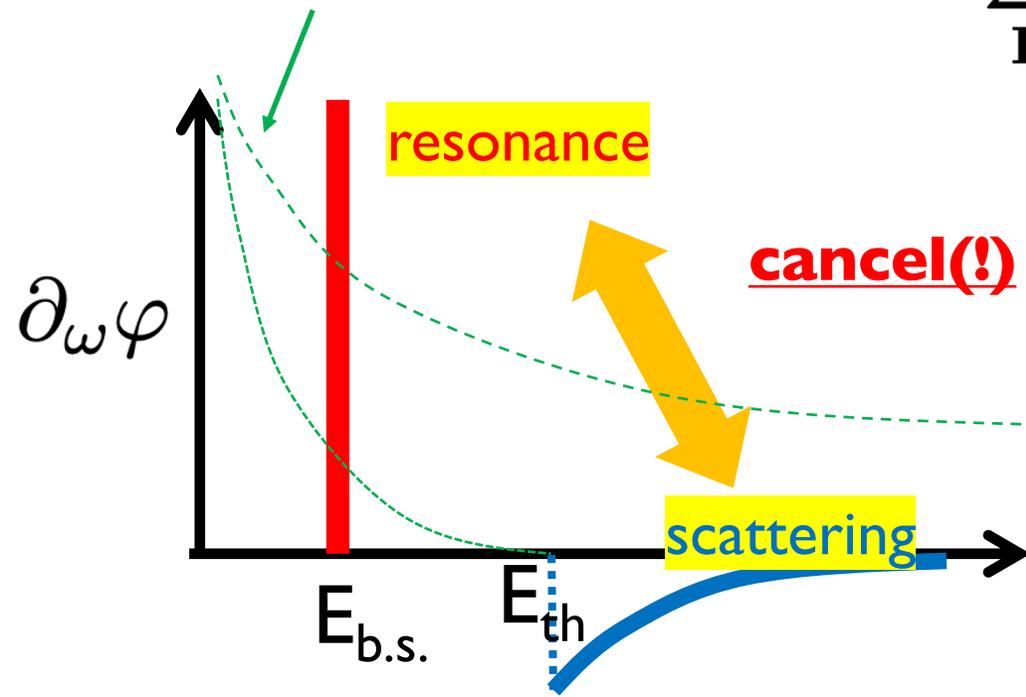
$$\rightarrow -T \sum_{\mathbf{K}} \ln 2 \otimes \int \frac{d\omega}{\pi} \frac{\partial}{\partial\omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi]$$

$$\propto \varphi(\omega = \infty) - \varphi(\omega = 0) \rightarrow 0$$

$$\Omega = \Omega_{q,g} + \Omega_{\text{meson}} + \Omega_{\text{baryon}} + \dots$$

$$\rightarrow \Omega_{q,g} \quad \text{at large } T$$

**saturated by elementary particles**



# At finite density: model study (I+ID)

$$H = \sum_{\mathbf{p}} (E_Q(\mathbf{p}) - \mu_q) c_{\mathbf{p}}^\dagger c_{\mathbf{p}} + V \sum_{\mathbf{K}} B^\dagger(\mathbf{K}) B(\mathbf{K})$$

(B ~ qq̄q operator)

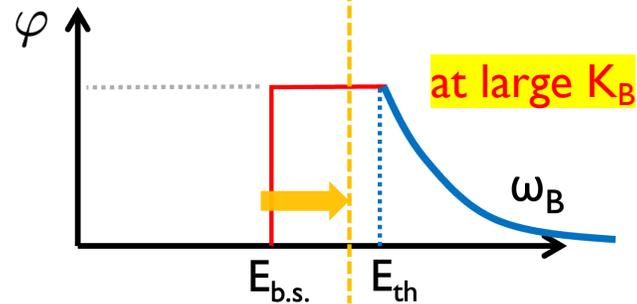
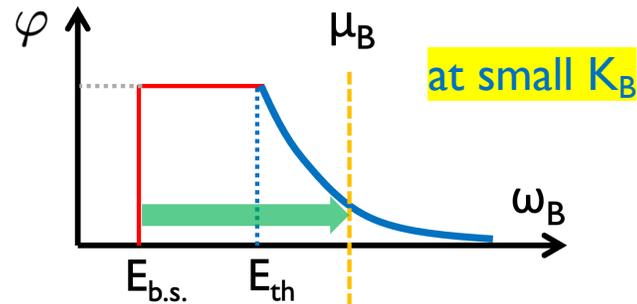
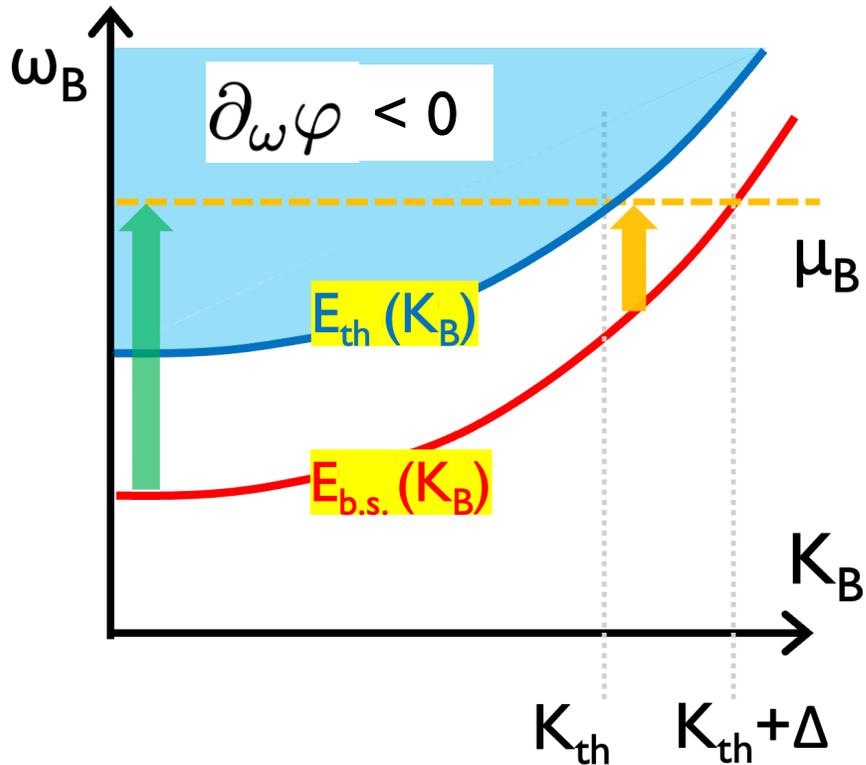
3-to-3 vertex yields a 3-body bound state

$$\begin{array}{ccc} \text{1-body} & \text{3-body} & \\ \Omega = \Omega_Q + \Omega_B & \longrightarrow & \begin{aligned} n_B^Q &\equiv -\frac{\partial \Omega_Q}{\partial \mu_B} \equiv \sum_{\mathbf{p}} f_Q(\mathbf{p}) \\ n_B^B &\equiv -\frac{\partial \Omega_B}{\partial \mu_B} \equiv \sum_{\mathbf{K}} f_B(\mathbf{K}) \end{aligned} \end{array}$$

# Baryonic contributions

$$\Omega_{3\text{-body}} = 1/2 \left[ \text{diagram 1} \right] + 1/3 \left[ \text{diagram 2} \right] + \dots$$

$$n_B^B = \sum_{\mathbf{K}} f_B(\mathbf{K}) = \sum_{\mathbf{K}} \int \frac{d\omega_B}{\pi} \frac{1}{e^{\beta(\omega_B - \mu_B)} + 1} \frac{\partial}{\partial \omega} \text{tr}_N [\varphi - |G_0/G| \sin \varphi]$$

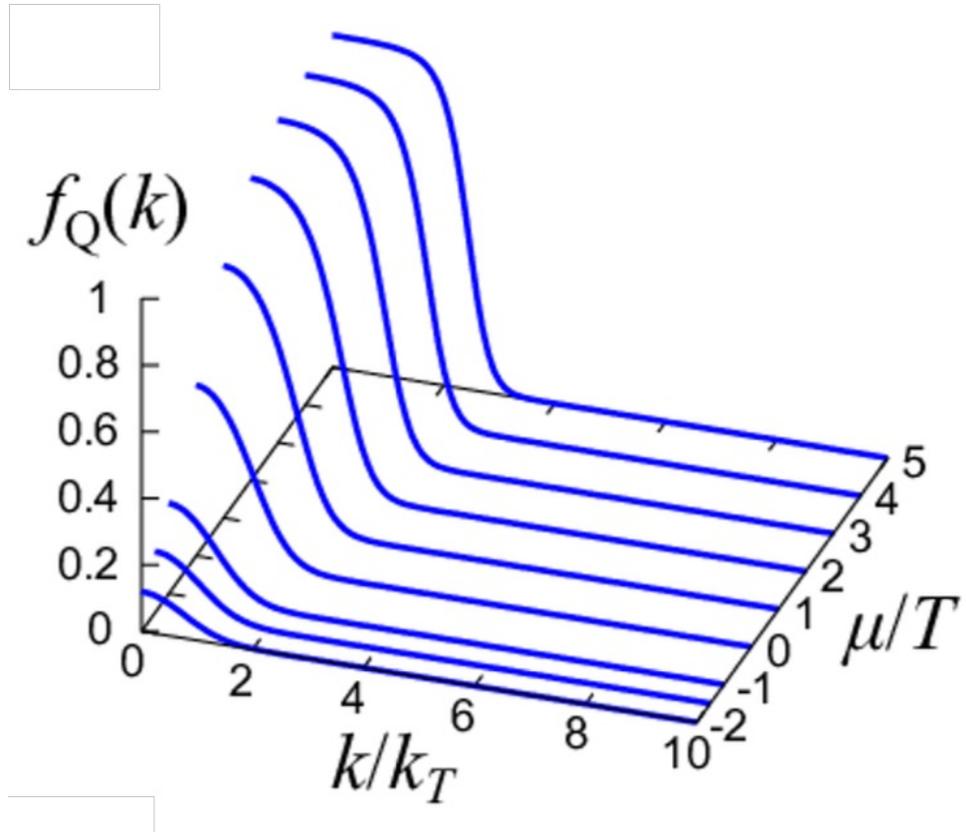


both bound & scattering states are picked up; **they cancel**

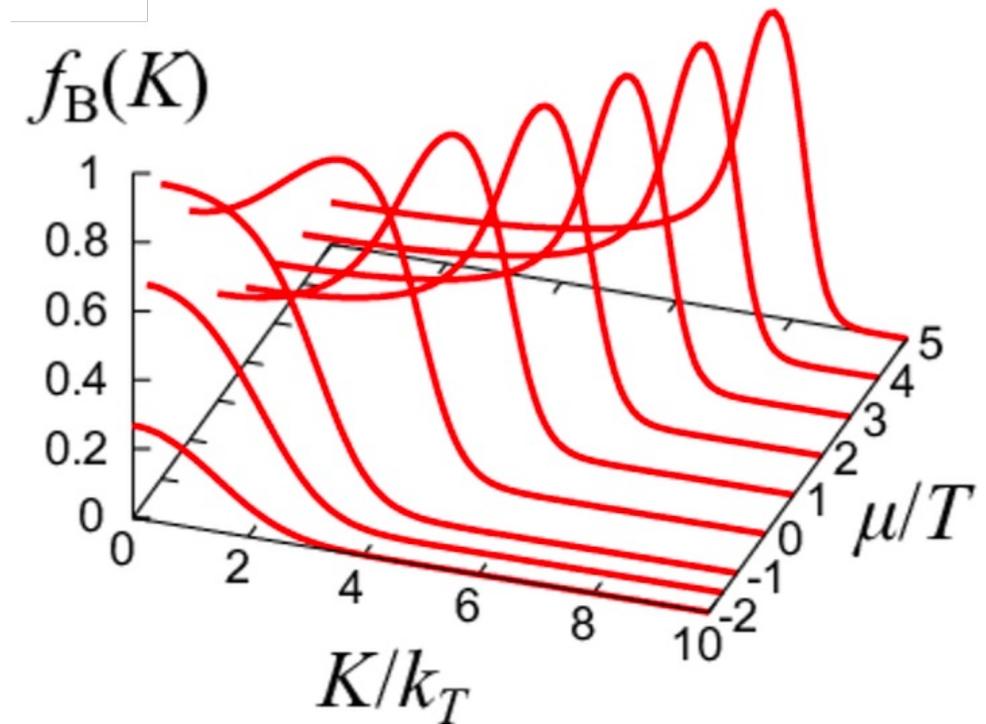
pick up only bound states  
 → **baryons survive**

# quark & baryon distributions

quark Fermi sea



suppression of bulk in  $f_B$



quark Fermi sea + baryonic Fermi surface

# Test of *practical* models in *QCD-like* (lattice simulations doable)

TK-Suenaga '21; Chiba-TK PRD '23; ...

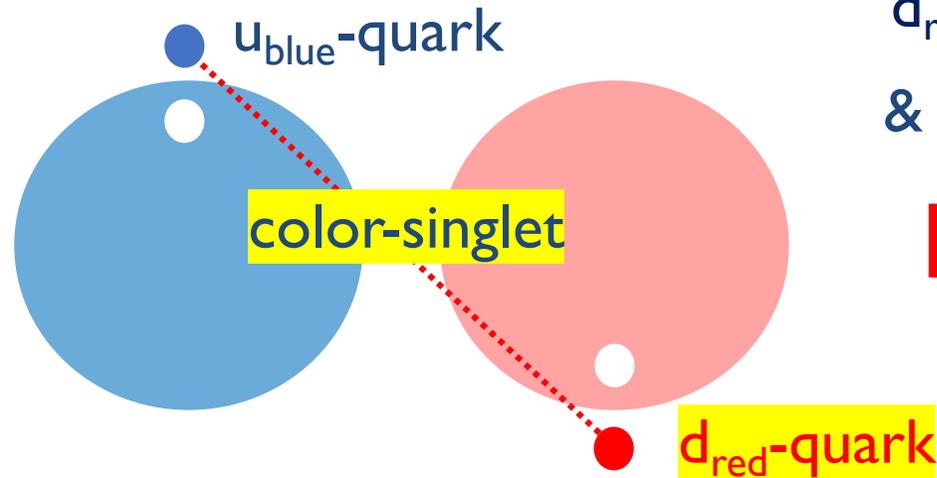
Brandt-Chelnokov-Endrodi-Marko-Smekal, Phys.Rev.D 112 (2025) 5, 054038

Lopes-Duarte-Farias-Ramos, arXiv:2507.14343

# QCD-like theories

Ref) Kogut, Hands, ...; Iida-Itou- ('20, '22, '24),...; Abbott (NPQCD, '23, '25)

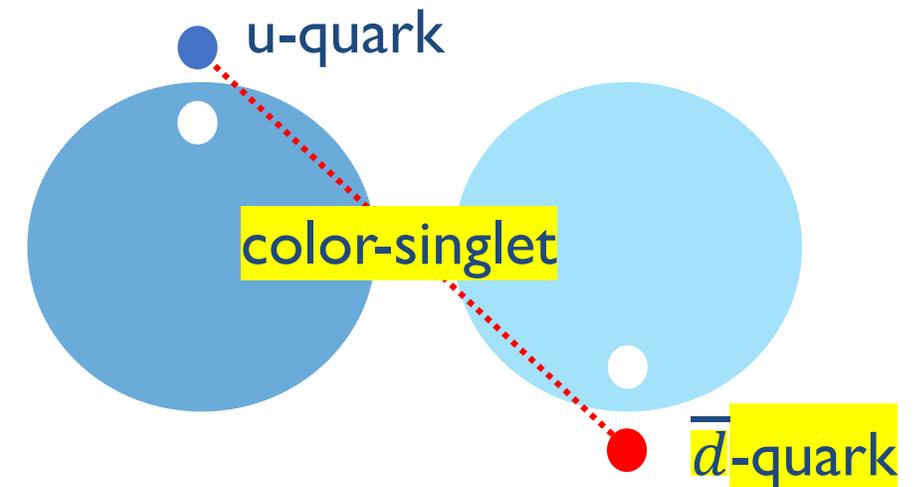
QC<sub>2</sub>D (2-color QCD)



$d_{\text{red}} \rightarrow \bar{d}_{\text{blue}}$   
& sum colors



QCD<sub>I</sub> (isospin QCD)



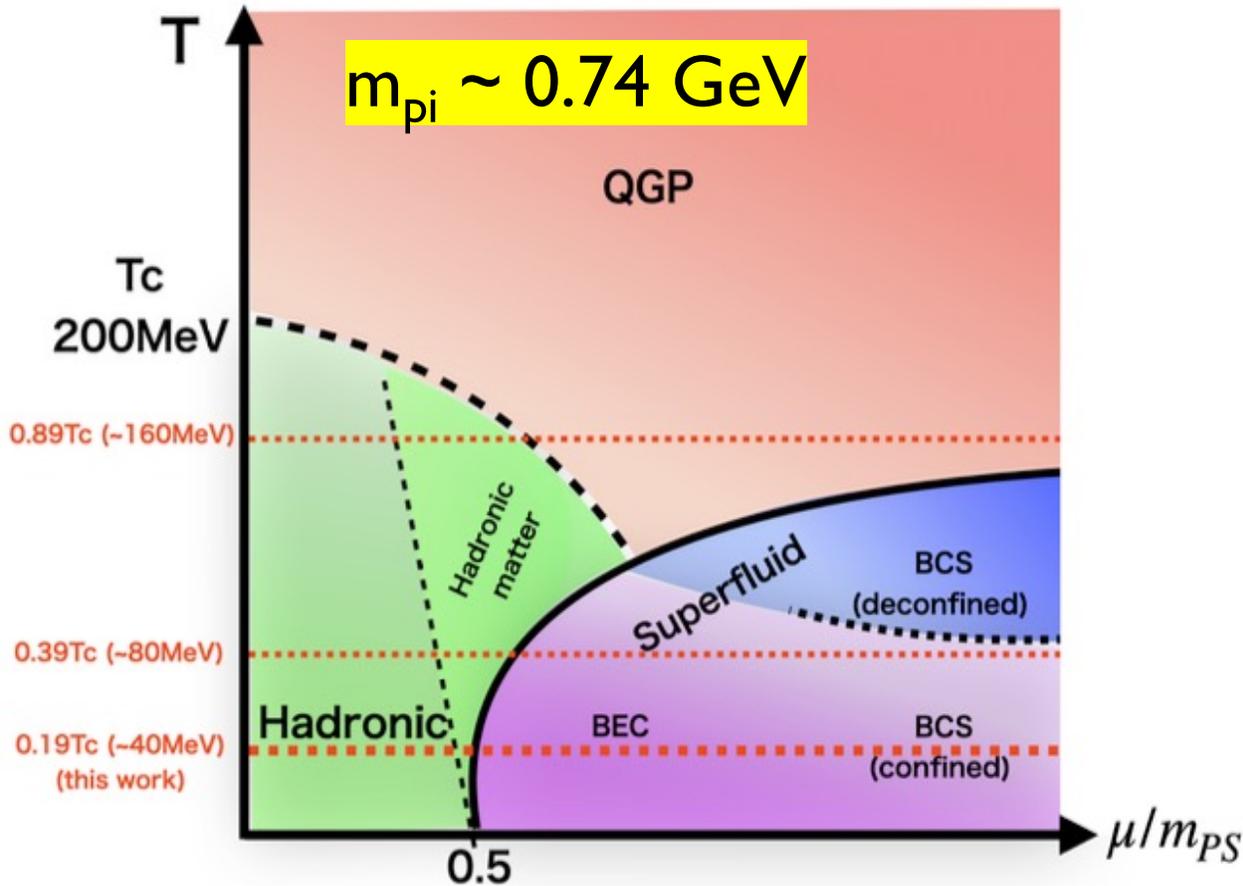
- 😊 simulations lighter
- 😓 need to unify scale setting

- 😓 simulations heavier
- 😊 same scale setting with QCD
- 😊 additional tool (e.g.  $1/N_c$  expansion)

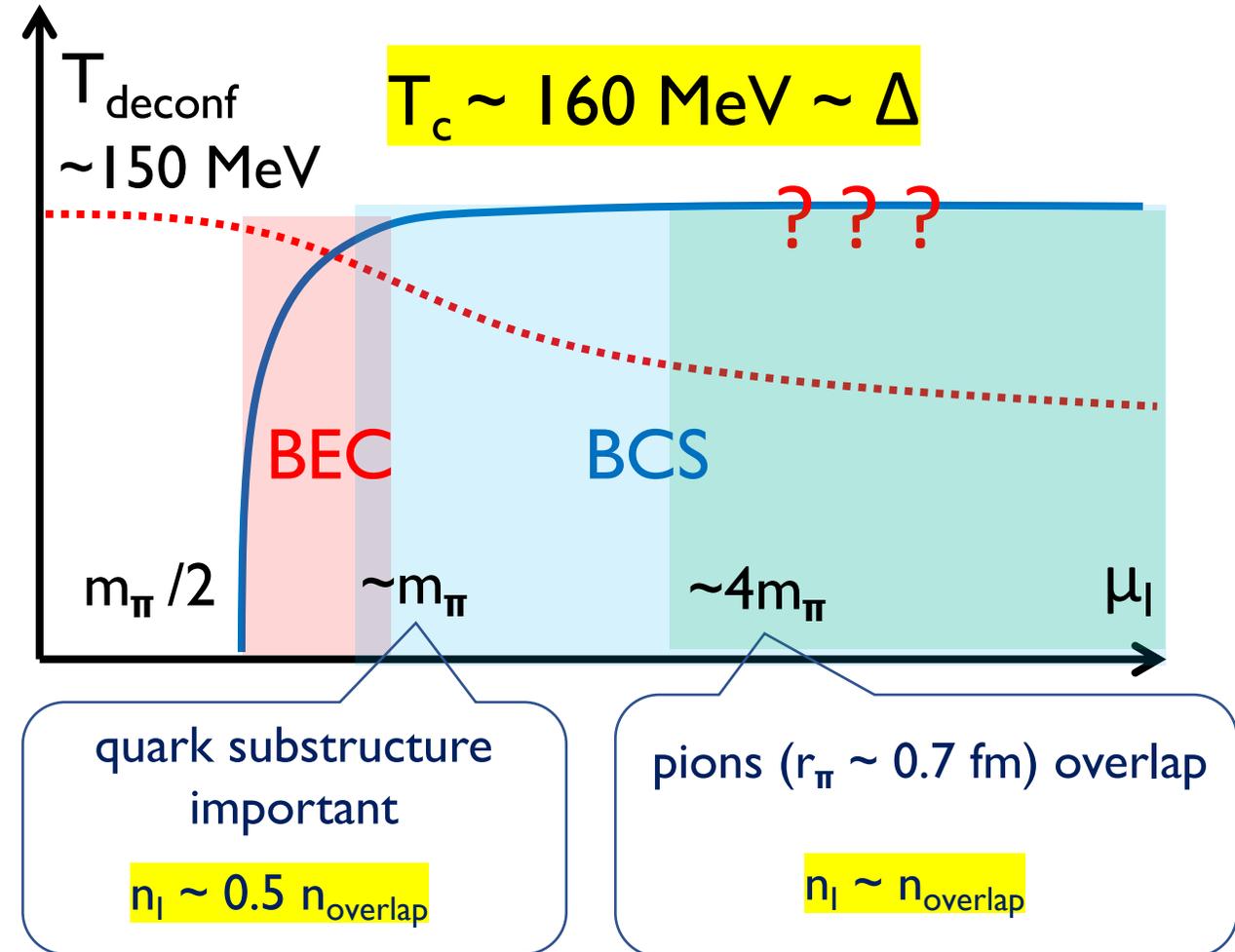
# Phase structure

QC<sub>2</sub>D

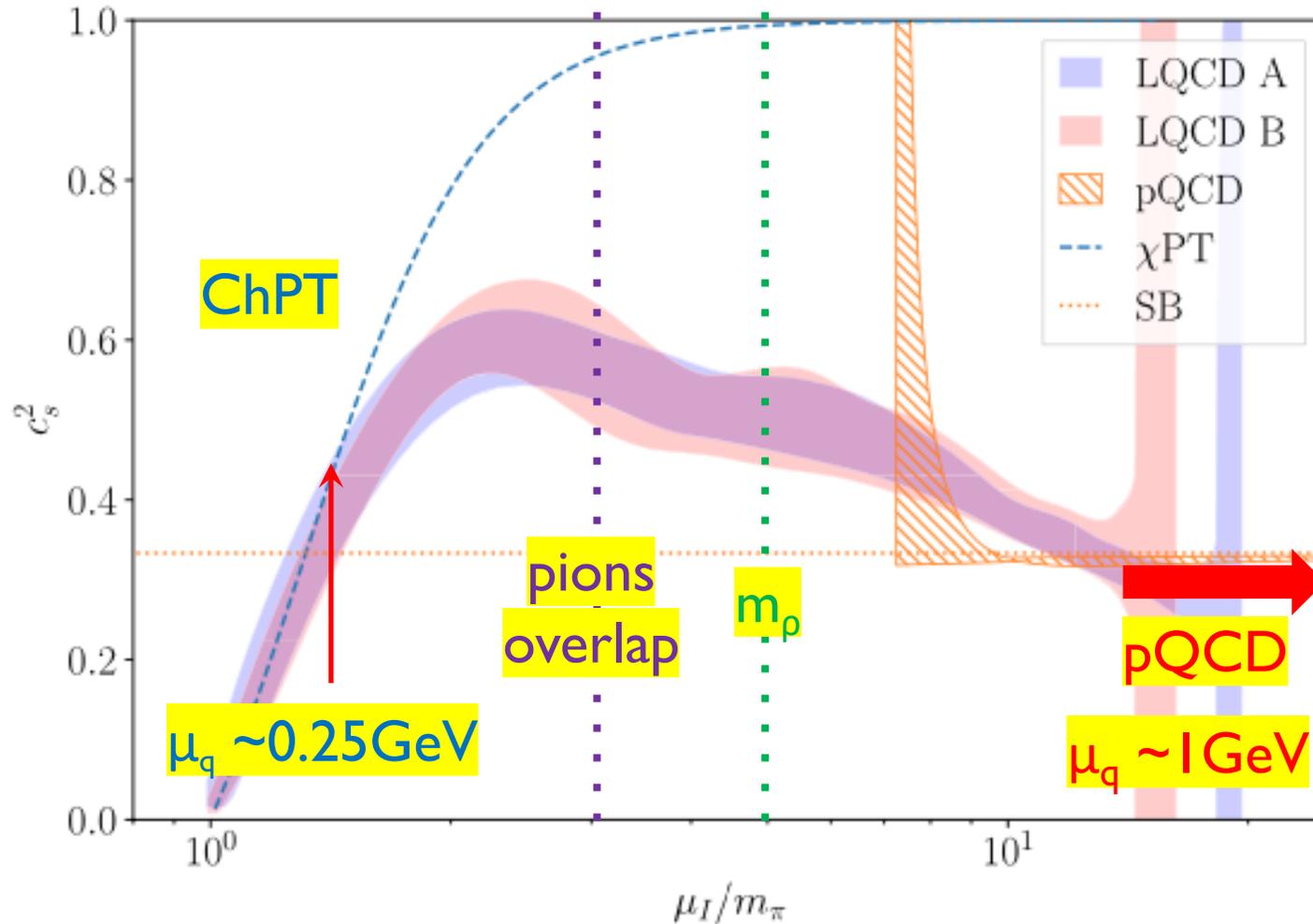
[Iida-Itou-Murakami-Suenaga '24]



QCD<sub>I</sub>



# lattice EOS<sub>I</sub>: sound speed vs $\mu_I$ Abbott (NPQCD, '23, '25)

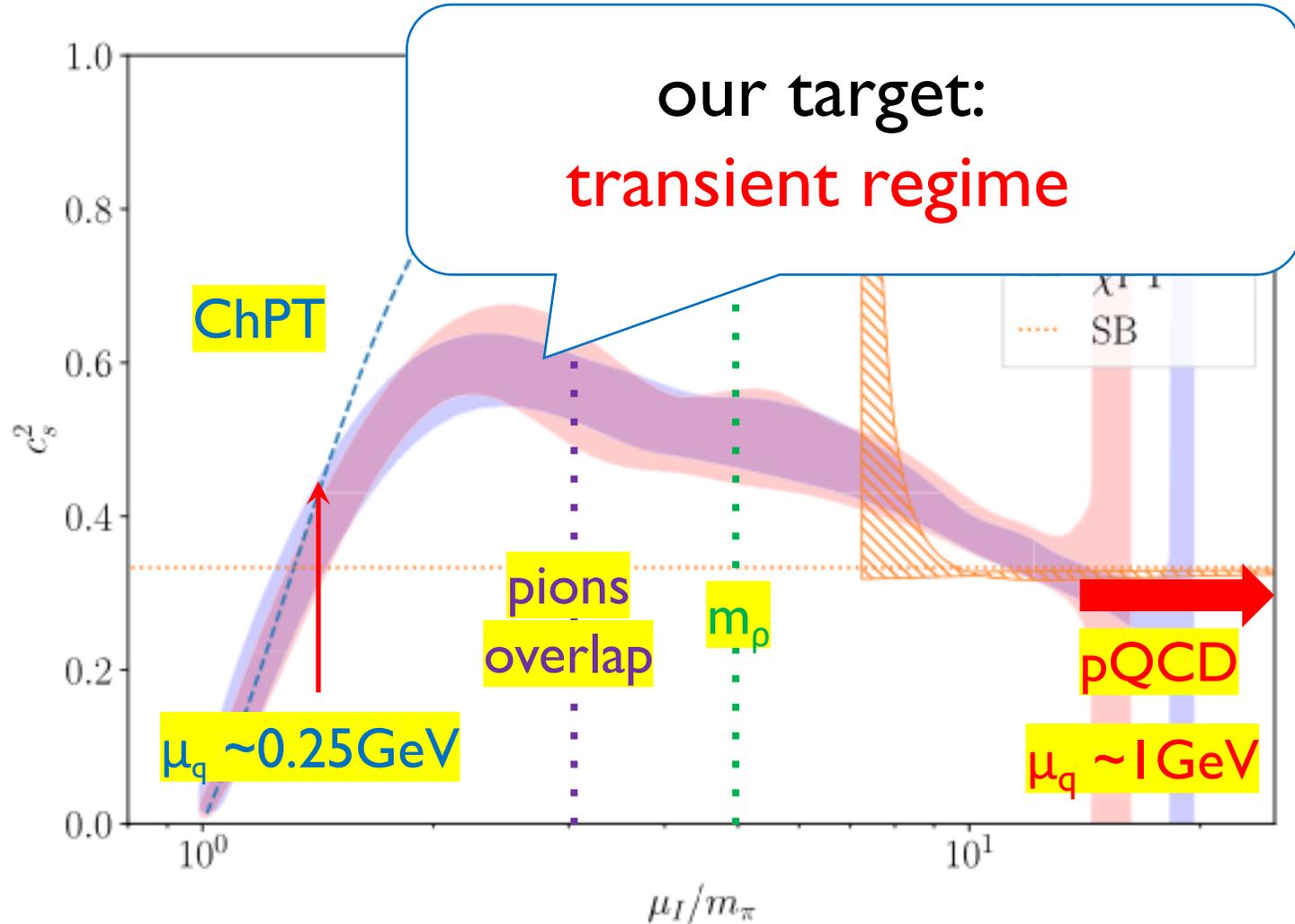


## Remarks:

- at **low  $n_I$** : **agree with ChPT**
- at **intermediate  $n_I$** : **sound speed peak**  
consistent with **Itou+** for 2-color hadronic EOS fails before pions overlap
- at **high  $n_I$** : **agree with pQCD + gaps**

[Chiba-TK '23; Fujimoto '24; Fukushima-Minato '24; ...]

# lattice EOS<sub>I</sub>: sound speed vs $\mu_I$ Abbott (NPQCD, '23, '25)



## Remarks:

- at low  $n_I$ : agree with ChPT
- at intermediate  $n_I$ :  
sound speed peak  
consistent with Iida-Itou+ for 2-color  
hadronic EOS fails before pions overlap
- at high  $n_I$ :  
agree with pQCD + gaps

[Chiba-TK '23; Fujimoto '24;  
Fukushima-Minato '24; ...]

# Hadron-quark coupling model

$$\vec{\phi} = (\sigma, \vec{\pi})$$

$$\begin{aligned} \mathcal{L} = & \frac{1}{2} [(\partial_\mu \sigma)^2 + (\partial_\mu \pi_3)^2] + [\partial_\mu + \underline{2i\mu_I \delta_\mu^0}] \pi_+ [\partial^\mu - \underline{2i\mu_I \delta_0^\mu}] \pi_- - \frac{m_0^2}{2} \phi^2 - \frac{\lambda}{4} (\phi^2)^2 + h\sigma \\ & + \bar{q} [\underline{i\not{\partial} - \mu_I \gamma_0 \tau_3 - g(\sigma + i\gamma_5 \vec{\pi} \cdot \vec{\tau})}] q \end{aligned}$$

## outline of calculations:

- **define** the model by **renormalizing it in vacuum** [ignore  $1/N_c \rightarrow$  **omit meson-loop**]
- construct **one-loop** effective potential:  $\Omega(M_q, \Delta; \mu_I)$  [**mean-field**]
- **minimization**  $\rightarrow$  solutions:  $M_q^*$  &  $\Delta^*$   $M_q = g\langle\sigma\rangle$   $\Delta = g\langle\pi_1\rangle$
- substitute solutions for  $M_q^*$  &  $\Delta^*$   $\rightarrow$   $\underline{\Omega_{\text{EOS}}(\mu_I)} = \Omega(M_q^*, \Delta^*; \mu_I)$

# Renormalized potential

$$V = V_0 + \underbrace{V_{1\text{-loop}} + V_{\text{counter}}^{\overline{\text{MS}}}}_{V_{1\text{-loop}}^R} + \underbrace{V_{\text{counter}}^{\text{finite}}}_{\substack{\text{(polynomials in } M_q \text{ \& } \Delta) \\ \sim \mu_I^2 \Lambda_{\text{QCD}}^2 \text{ at high density}}}$$

$\sim \mu_I^4$  at high density

threshold  $\rightarrow \mu_I = m_\pi / 2$

$$V_0^{\text{tree}} = \frac{m_0^2}{2g^2} M_q^2 + \frac{m_\pi^2 - 4\mu_I^2}{2g^2} \Delta^2 + \frac{\lambda}{24g^4} (M_q^4 + \Delta^4) - \frac{h}{g} M_q \quad m_\pi^2 = m_0^2 + \frac{\lambda}{6} \langle \sigma \rangle^2$$

$$V_{1\text{-loop}}^R = -N_c \int_{\mathbf{p}} (E_u + E_d + E_{\bar{u}} + E_{\bar{d}}) \quad \underline{\text{+ UV counter terms}}$$

$$E(\mu_I) = \sqrt{(E_D - \mu_I)^2 + \Delta^2} \quad E_u = E_{\bar{d}} = E(\mu_I), \quad E_d = E_{\bar{u}} = E(-\mu_I)$$

# large $\mu$ , Impact of quarks: **tree** vs **1-loop**

tree:  $\Omega_{\text{tree}} \rightarrow -\frac{2\mu_I^2}{g^2} \Delta^2 + \frac{\lambda}{24g^4} \Delta^4 \rightarrow \Delta_* \sim \mu_I \times \frac{g}{\sqrt{\lambda}} \propto \mu_I$

**balanced**

$$\Omega_{\text{tree}}(\Delta_*) \sim -\frac{24}{\lambda} \mu_I^4$$

controlled by  
2-body hadronic repulsion

1-loop:  $\Omega \rightarrow \Omega_l^R + \frac{2\mu_I^2 \Delta^2}{(4\pi)^2} \left[ -\frac{1}{g^2} + \frac{4N_c}{(4\pi)^2} \ln \frac{\Delta^2}{M_0^2} \right] + \frac{\lambda}{24g^4} \Delta^4$

**balanced**

insensitive to  $\mu_I$

$$\rightarrow \Delta_* \sim M_{\text{vac}} e^{-1 + \frac{8\pi^2}{N_c g^2}}$$

$$\Omega(\Delta_*) \sim \Omega_Q^{\text{ideal}} - \frac{N_c}{2\pi^2} \mu_I^2 \Delta_*^2$$

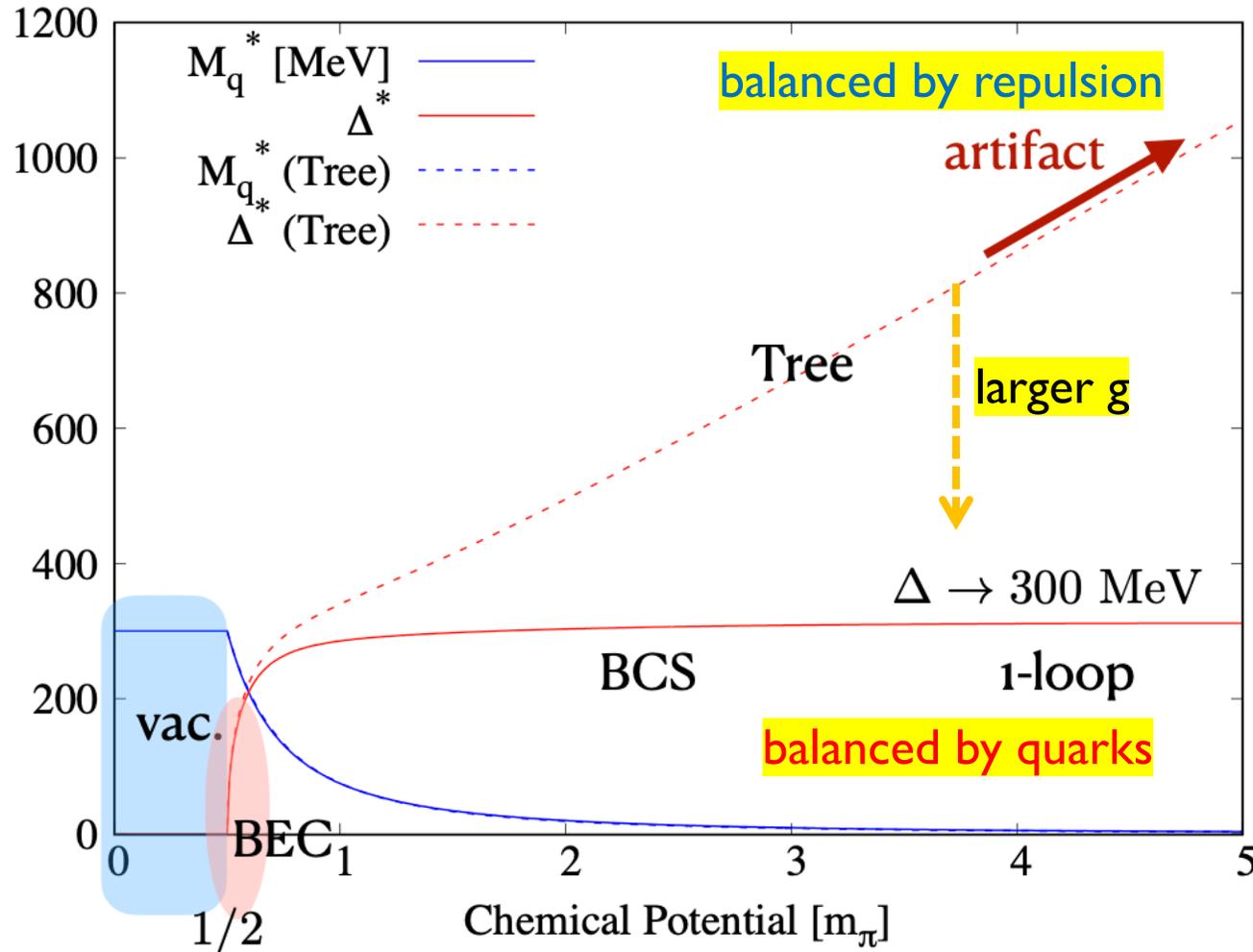
**hadronic para. dep. is all absorbed into  $\Delta$  (!)**

# Gaps: chiral & pion condensates

parameters

$$m_\pi = 140\text{MeV}, \quad m_\sigma = 600\text{MeV},$$

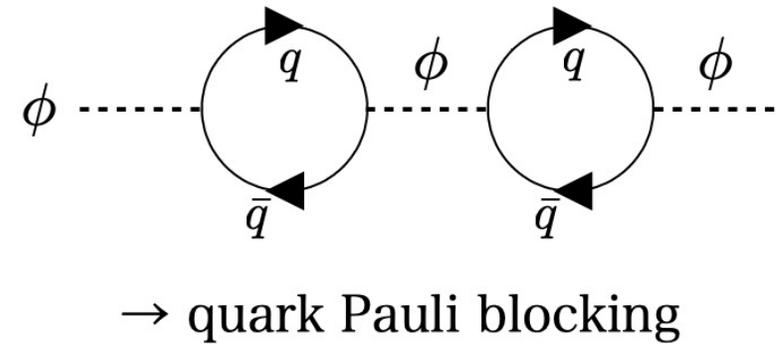
$$f_\pi = 90\text{MeV}, \quad M_q = 300\text{MeV}$$



Tree: mesons as elementary particles

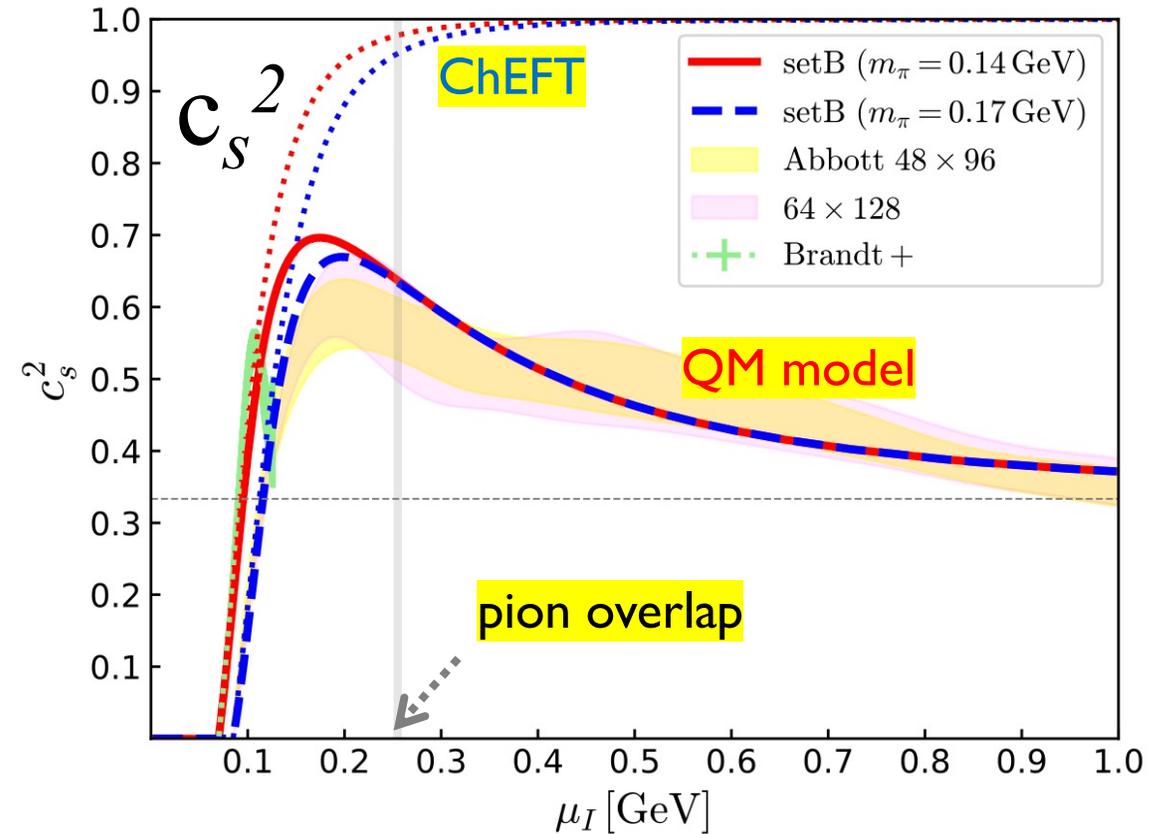
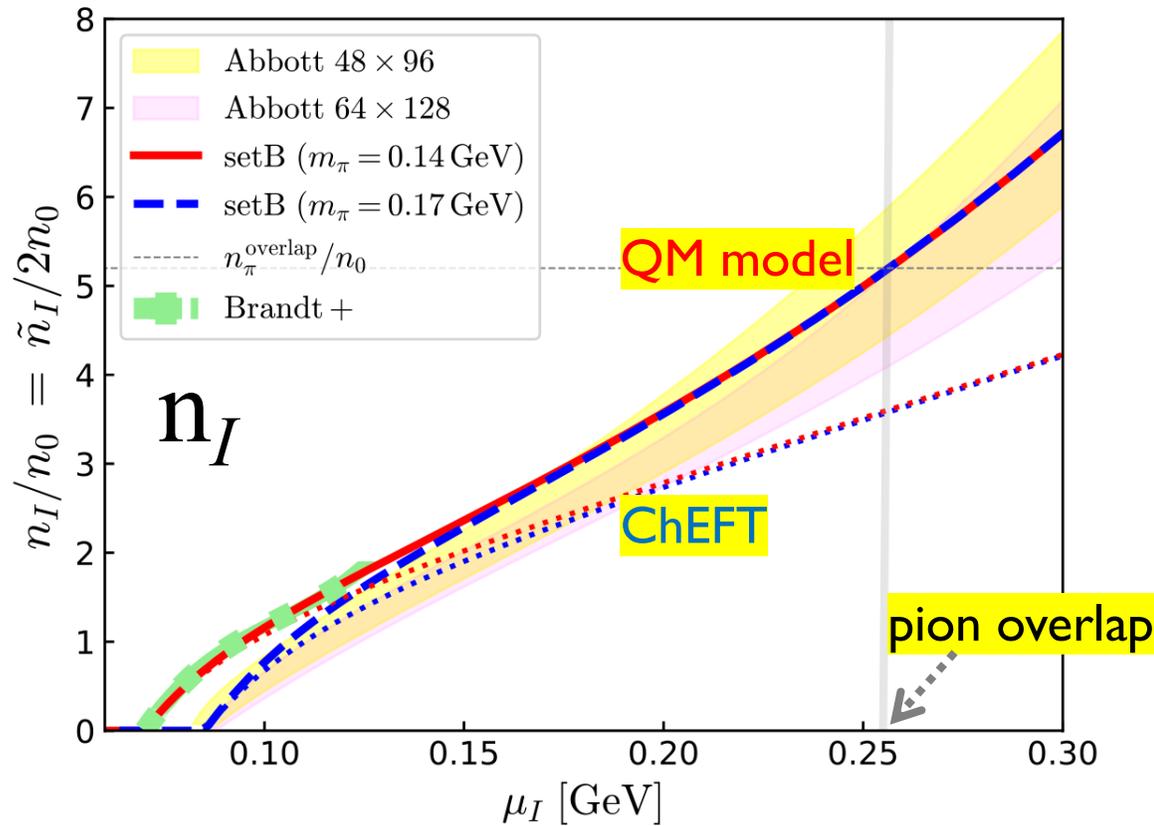


1-loop: mesons as composite particles



quarks temper the growth of the amplitude of the BEC

# Equations of state



- semi-quantitative agreement with lattice data
- the trend changes before pions ( $r_\pi \sim 0.7$  fm) overlap

# Summary & Outlook

- **revolutionary** NS observations in the last decade, more will come
- interplay btw nuclear & quark physics; more important **than ever**
- quark substructures of hadrons directly impact NS physics

## many questions related to hadron physics

*at which density does the quark saturation set in?*

*how does quark w.f. for baryons change in medium?*

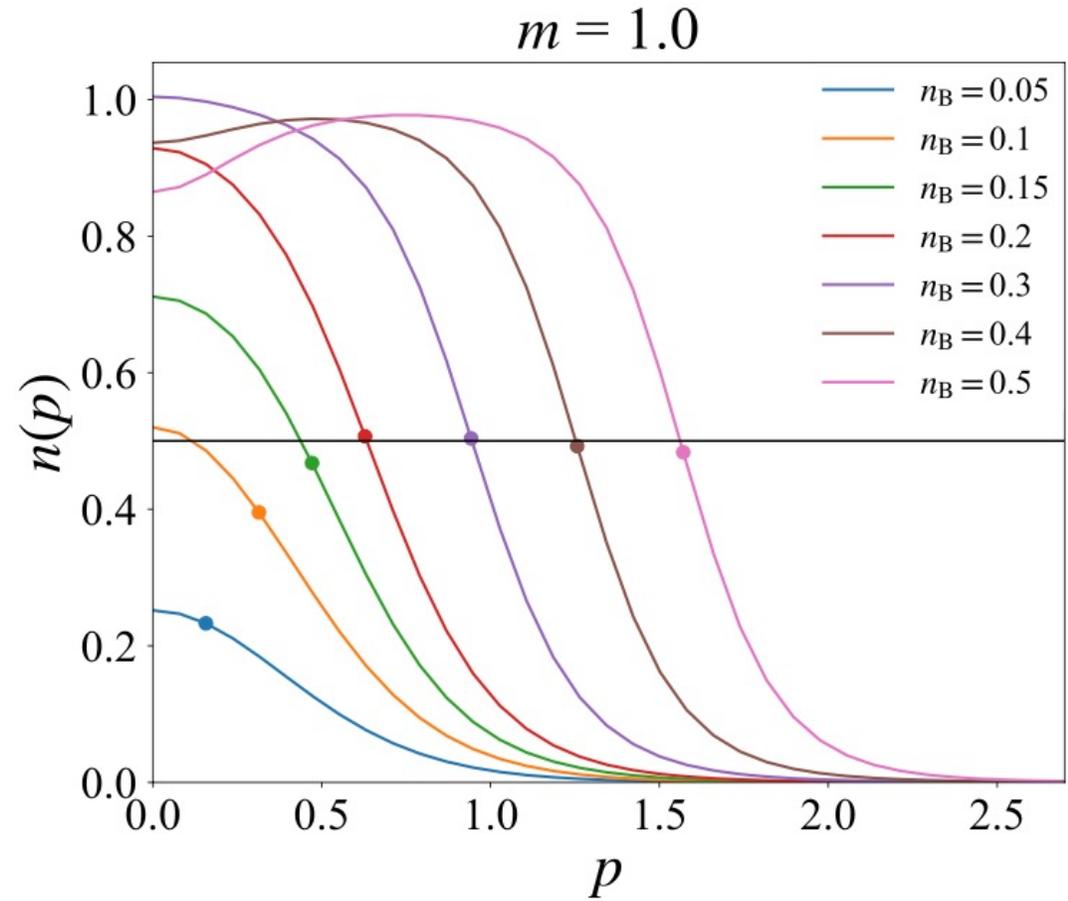
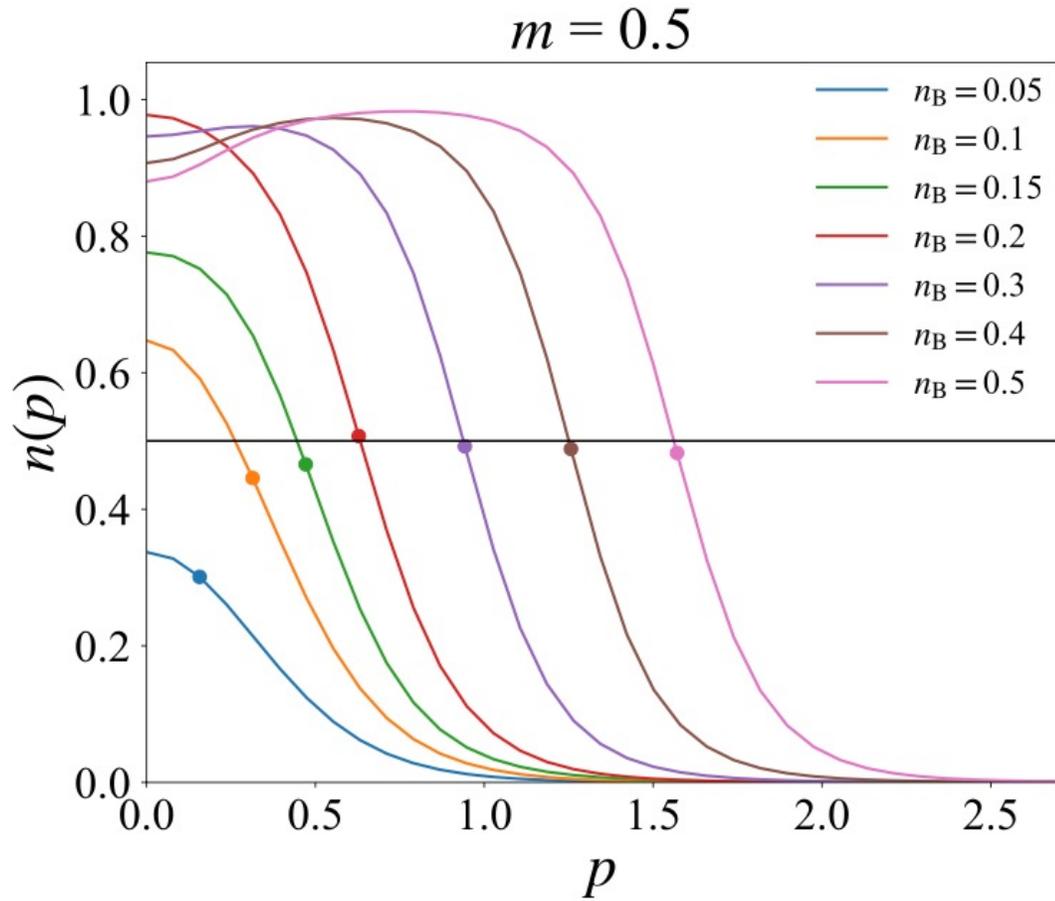
*the relation btw baryonic many-body forces & statistical repulsion?*

*effective quark mass & chiral restoration? pairing gaps?*

**maybe some of answers can be found in this workshop!**

**Back Up**

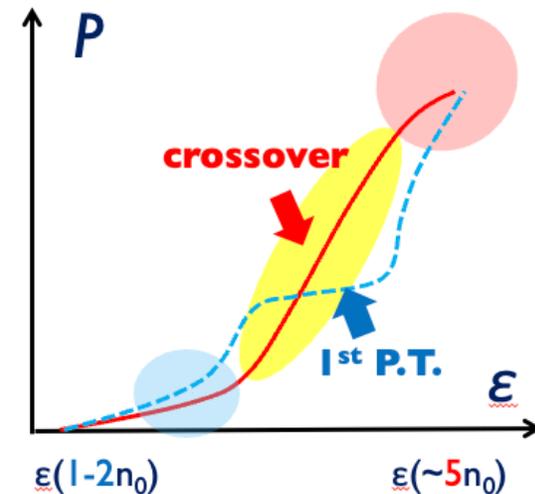
# Hayata-Hidaka-Nishimura '24, $f_Q$ for I+ID QCD



# What to be suggested in this talk

1) how quarks contribute to the *thermodynamic* pressure, *without invoking baryon-to-quark phase transitions*

**crossover descriptions**

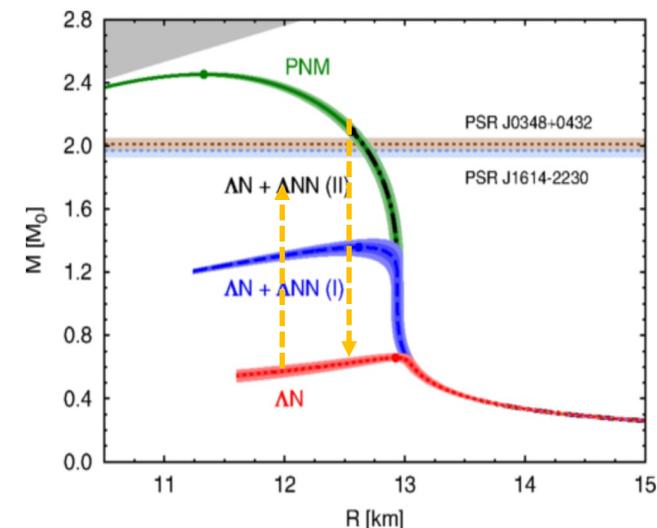


2) what causes rapid stiffening at  $2-3n_0$ ?

**quark saturation**

3) how quarks mitigate *hyperon softening problem*

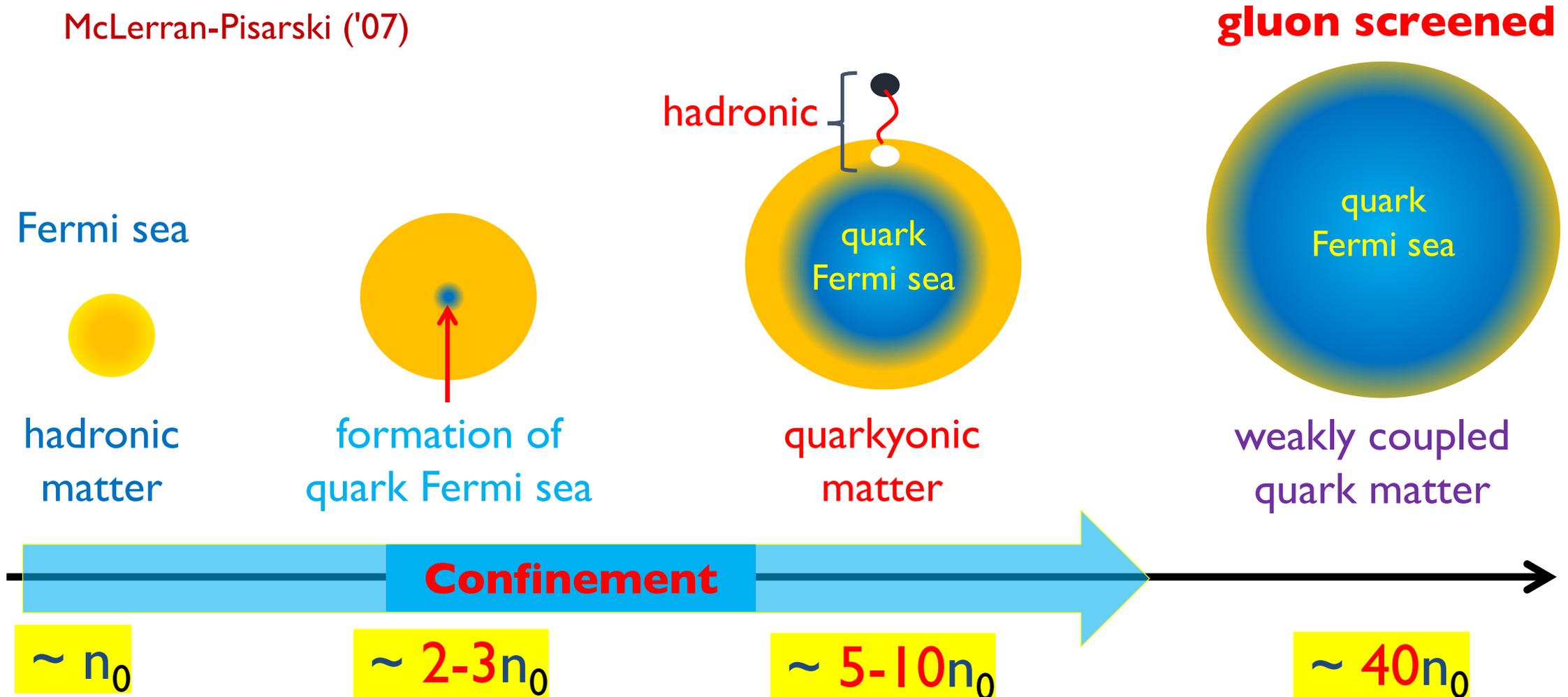
**statistical repulsion**



# A model of crossover

Quarkyonic matter := quark matter with confining gluons

McLerran-Pisarski ('07)





# IdylliQ model

= **I**deal **d**ual **Q**uarkyonic model

Describe **single** physics in **two** languages (baryon/quark)

Powerful in transient regimes ( $2-5n_0$ )

# Sum rules for occupation probabilities

cf) [TK '21]

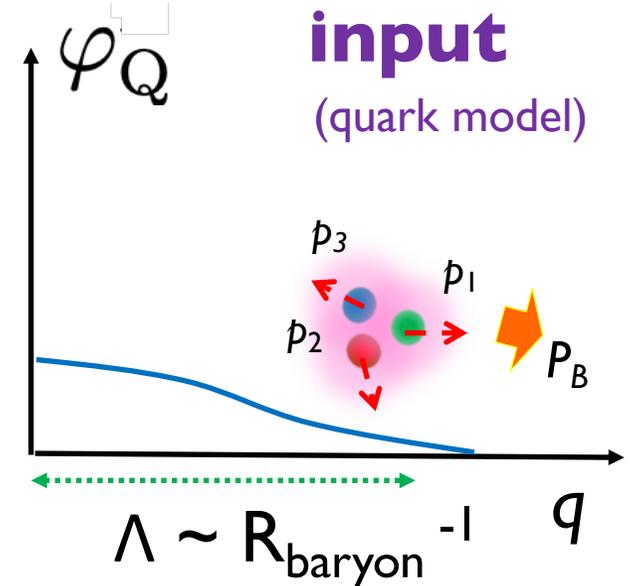
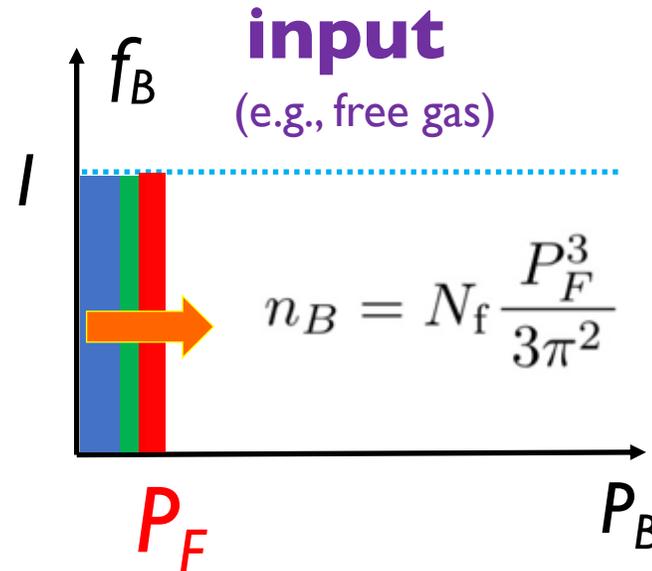
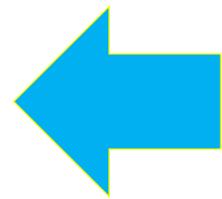
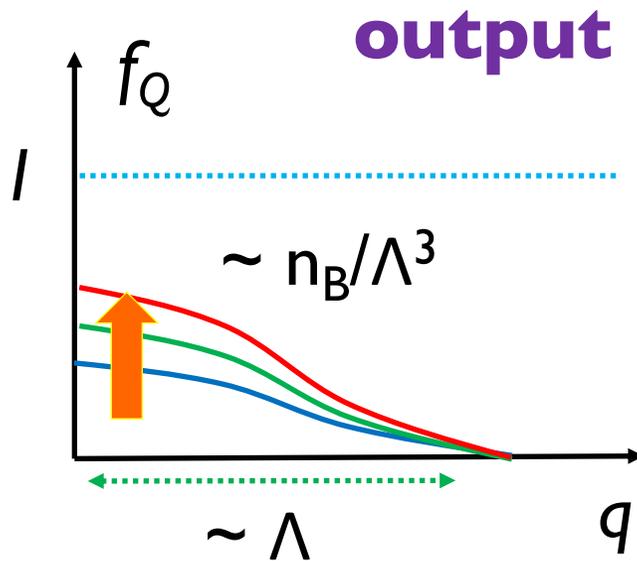
occupation **probability**  
of **quark** state with  $\mathbf{p}$

occupation **probability**  
of **baryon** state with  $\mathbf{P}_B$

**quark** mom. distribution  
**in a baryon**

$$\underline{f_Q(\mathbf{q})} = \int_{\mathbf{P}_B} \underline{f_B(\mathbf{P}_B)} \underline{\varphi_Q^B(\mathbf{q} - \mathbf{P}_B/N_c)}$$

e.g.) in **ideal** baryonic matter



# An ideal model

[Fujimoto-TK-McLerran, PRL'24]

1) neglect interactions *except* confining forces

e.g.) 2-flavor hamiltonian: 
$$\varepsilon_B[f_B] = 4 \int_k E_B(k) f_B(k)$$

2) keep using the same  $\varphi_Q$  (quarkyonic)

3) use a special quark distribution  $\rightarrow$  sum rules analytically **invertible**

$$\varphi_{3d}(\mathbf{q}) = \frac{2\pi^2}{\Lambda^3} \frac{e^{-q/\Lambda}}{q/\Lambda} \quad \hat{L} = -\nabla^2 + \frac{1}{\Lambda^2} \quad \hat{L}[\varphi(\mathbf{p} - \mathbf{q})] = \frac{(2\pi)^3}{\Lambda^2} \delta(\mathbf{p} - \mathbf{q})$$

**nontrivial output**

$$f_Q(\mathbf{q}) = \int_{\mathbf{P}_B} f_B(\mathbf{P}_B) \varphi_Q^B(\mathbf{q} - \mathbf{P}_B/N_c)$$

natural at **low** density

**nontrivial output**

$$f_B(N_c \mathbf{q}) = \frac{\Lambda^2}{N_c^3} \hat{L}[f_Q(\mathbf{q})]$$

natural at **high** density

# An **ideal** model

[Fujimoto-TK-McLerran, PRL'24]

1) neglect interactions *except* confining forces

e.g.) 2-flavor hamiltonian: 
$$\epsilon_B[f_B] = 4 \int_k E_B(k) f_B(k)$$

2) keep using the *(quarkyonic)*

3) To Do: solve variational problem of  $f_B(k)$   
with *quark substructure constraints* !

**nontrivial output**

$$f_Q(\mathbf{q}) = \int_{\mathbf{P}_B} f_B(\mathbf{P}_B) \varphi_Q^B(\mathbf{q} - \mathbf{P}_B/N_c)$$

↑  
natural at **low** density

**nontrivial output**

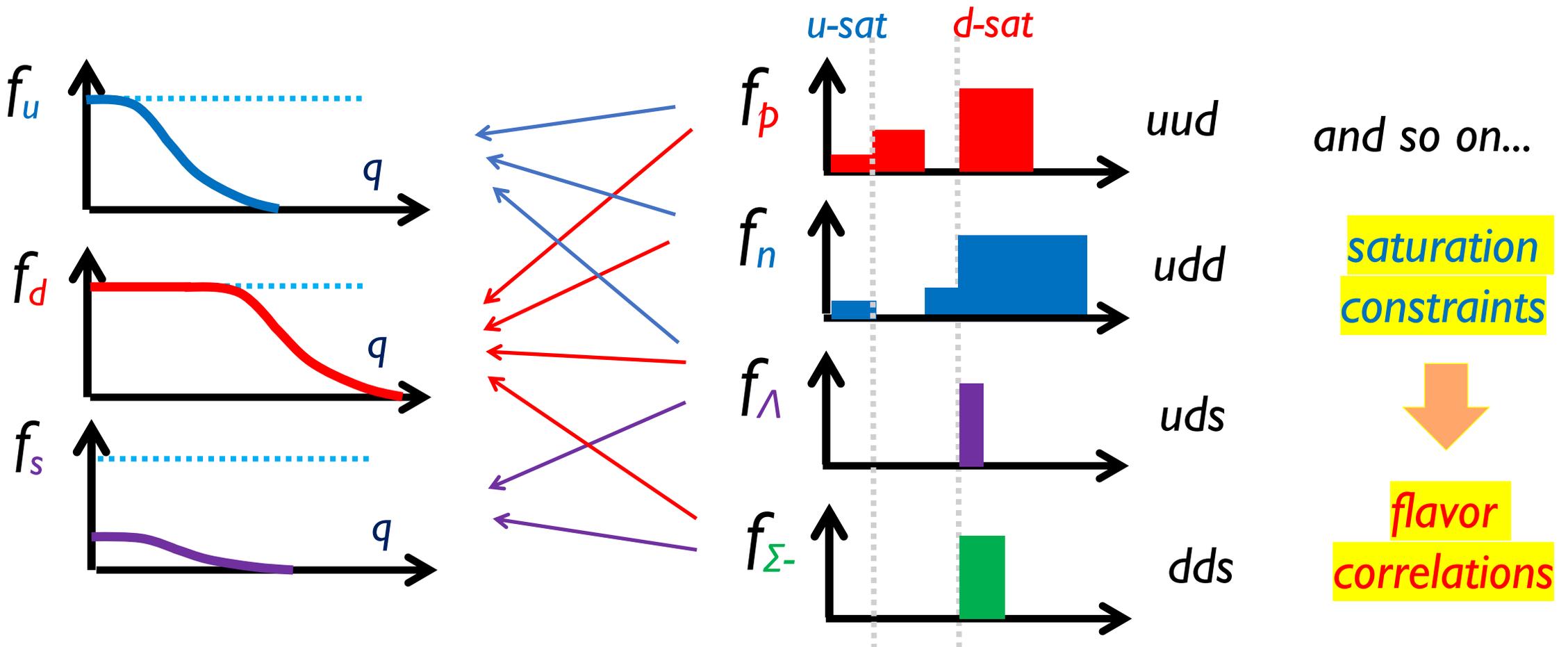
$$f_B(N_c \mathbf{q}) = \frac{\Lambda^2}{N_c^3} \hat{L} [f_Q(\mathbf{q})]$$

↑  
natural at **high** density

# Multi-flavor extension

$$f_Q(\mathbf{q}) = \sum_{B=p,n,\Sigma,\dots} N_Q^B \int_{\mathbf{k}} f_B(\mathbf{k}) \varphi\left(\mathbf{q} - \frac{\mathbf{k}}{N_c}\right)$$

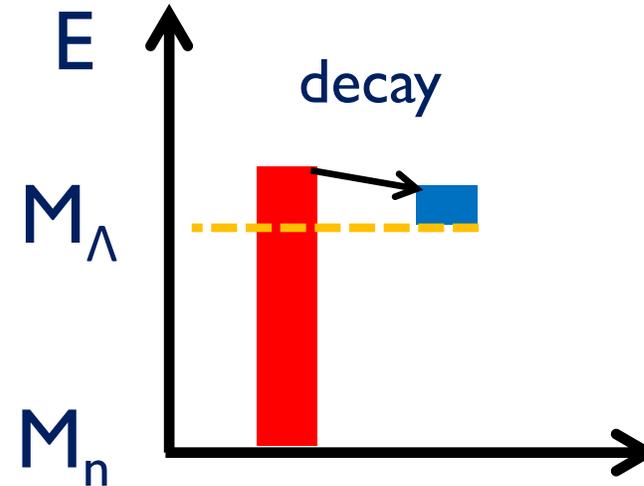
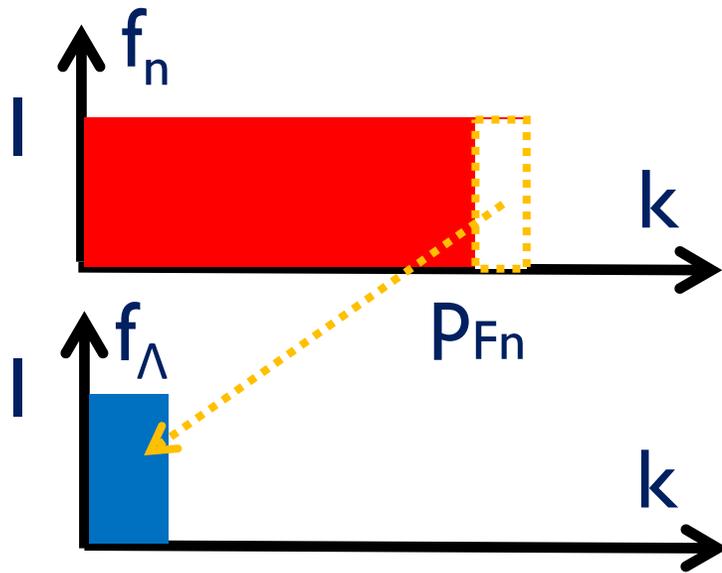
$Q = u, d, s$



# $n$ - $\Lambda_0$ matter

[Fujimoto-TK-McLerran, '24]

## • conventional



at  $n_B \sim 2-3n_0$

neutrons *at high momenta*  $\rightarrow$  *non-relativistic*  $\Lambda$

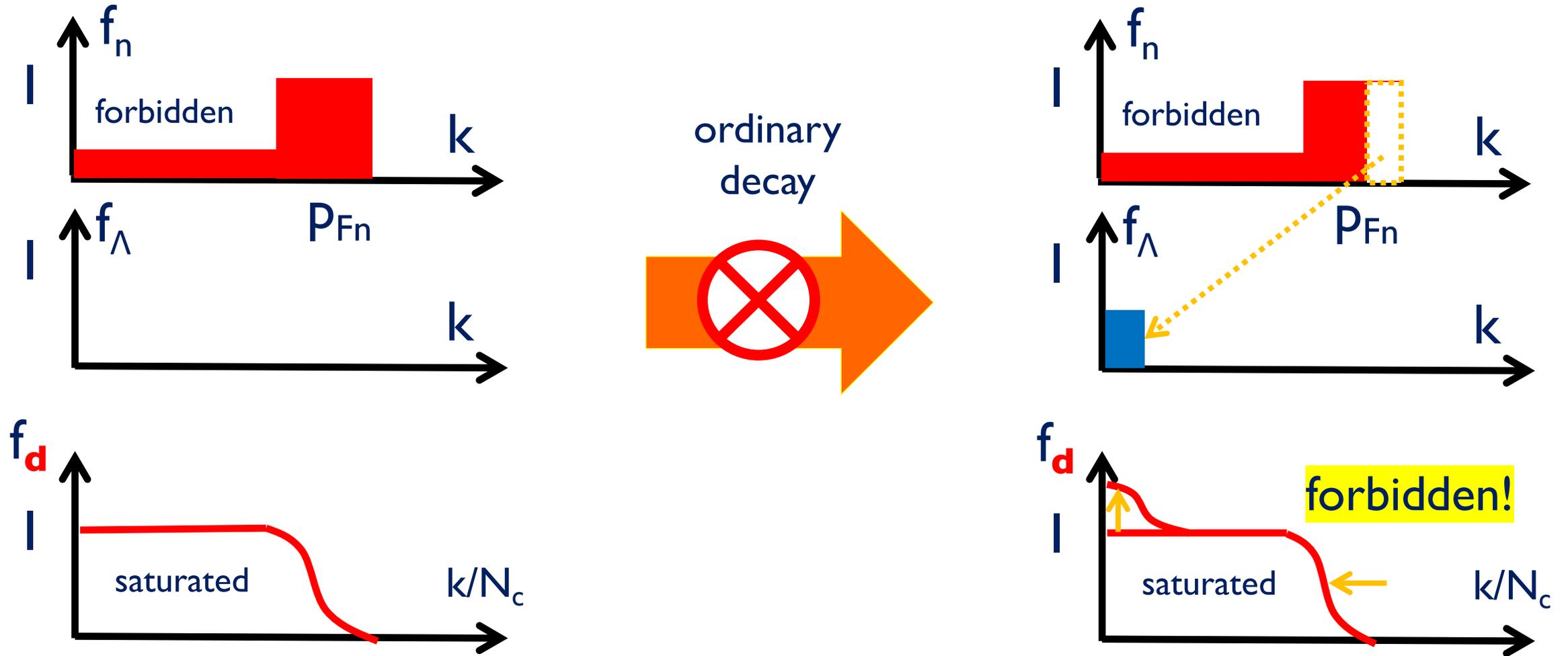


$\epsilon$  increases much but pressure does not (**softening**)

# $n-\Lambda_0$ matter

[Fujimoto-TK-McLerran, '24]

## with d-quark saturation

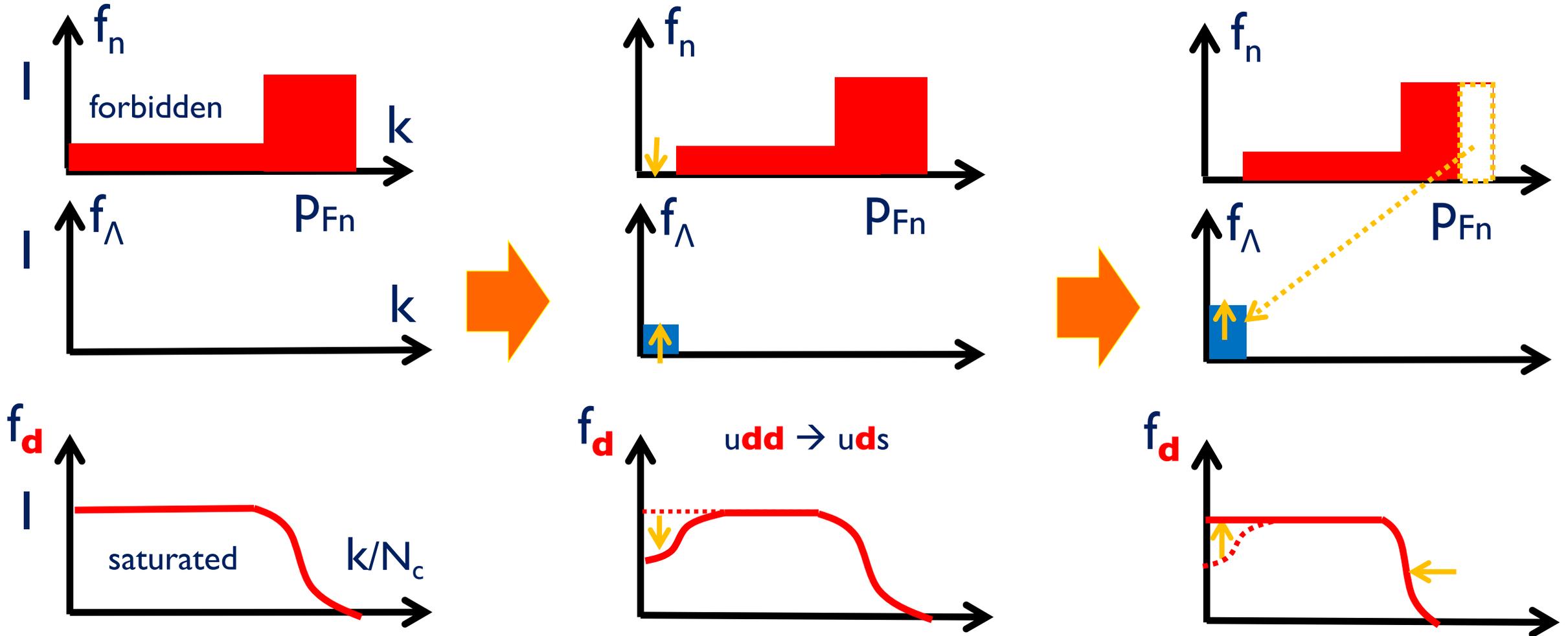


# $n$ - $\Lambda_0$ matter

[Fujimoto-TK-McLerran, '24]

step 1) open phase space

step 2) decay

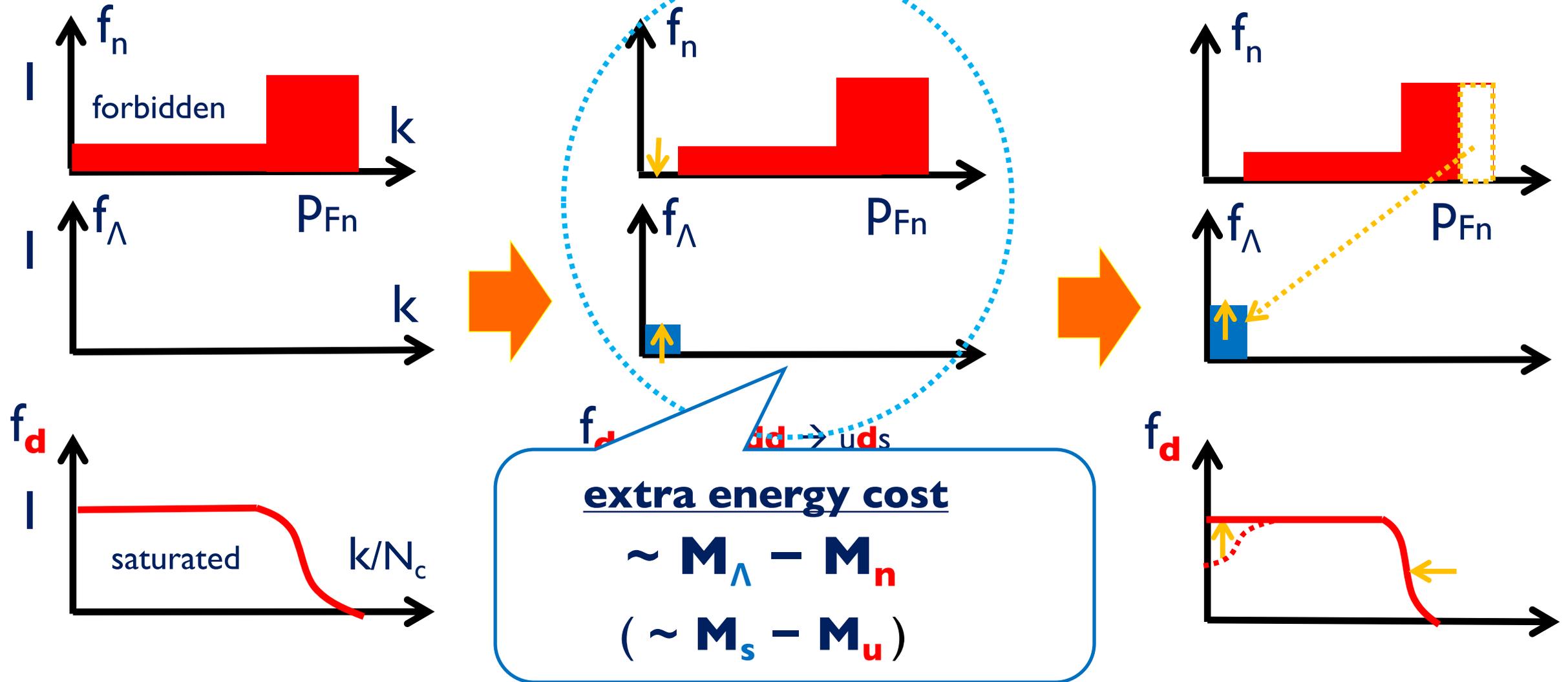


# $n-\Lambda_0$ matter

[Fujimoto-TK-McLerran, '24]

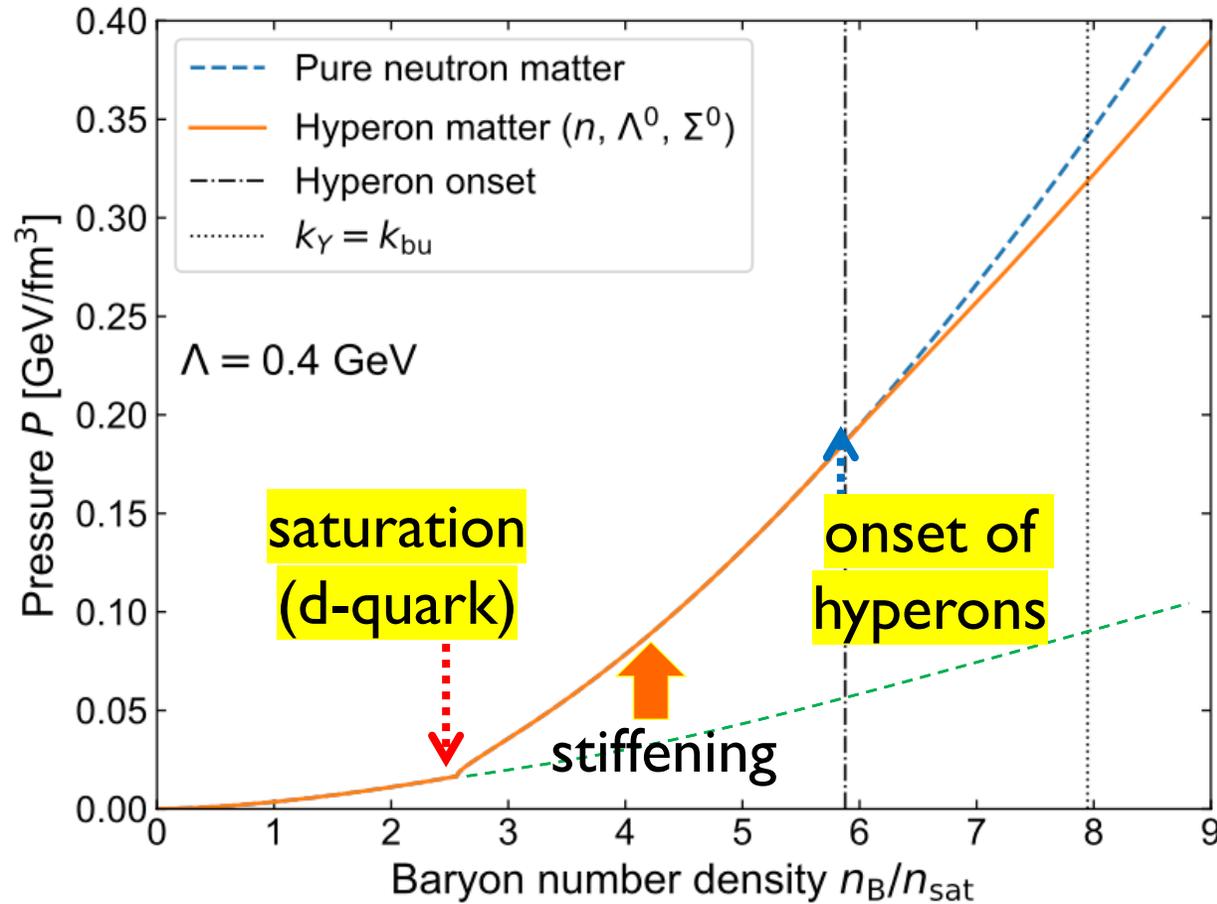
step 1) open phase space

step 2) decay



# EOS: **n- $\Lambda$** matter

[Fujimoto-TK-McLerran, '24]

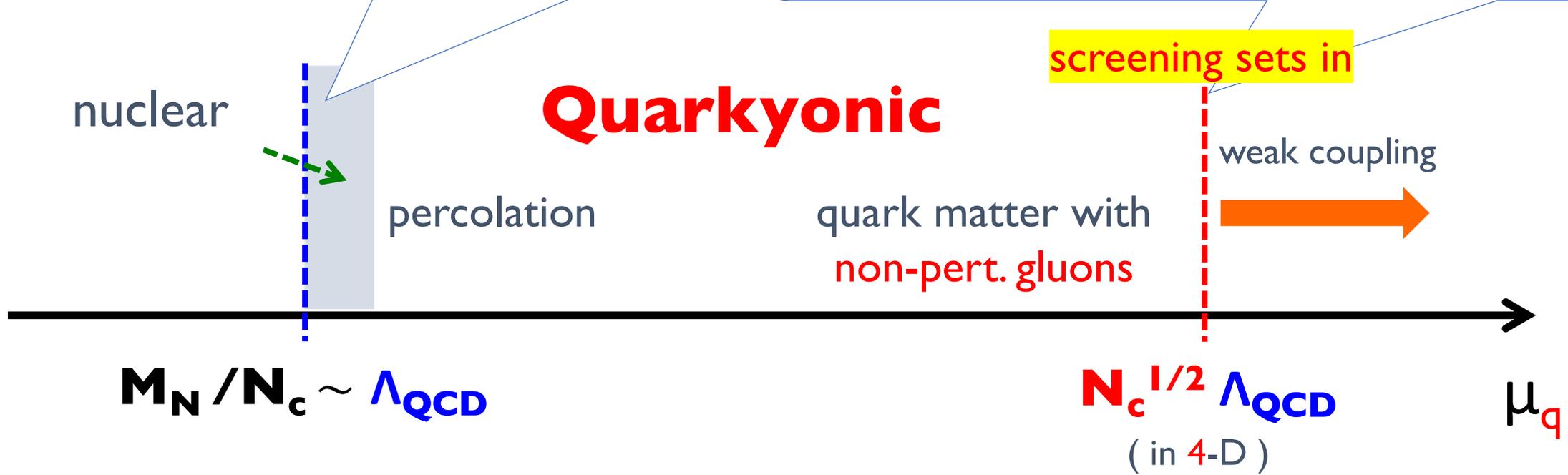
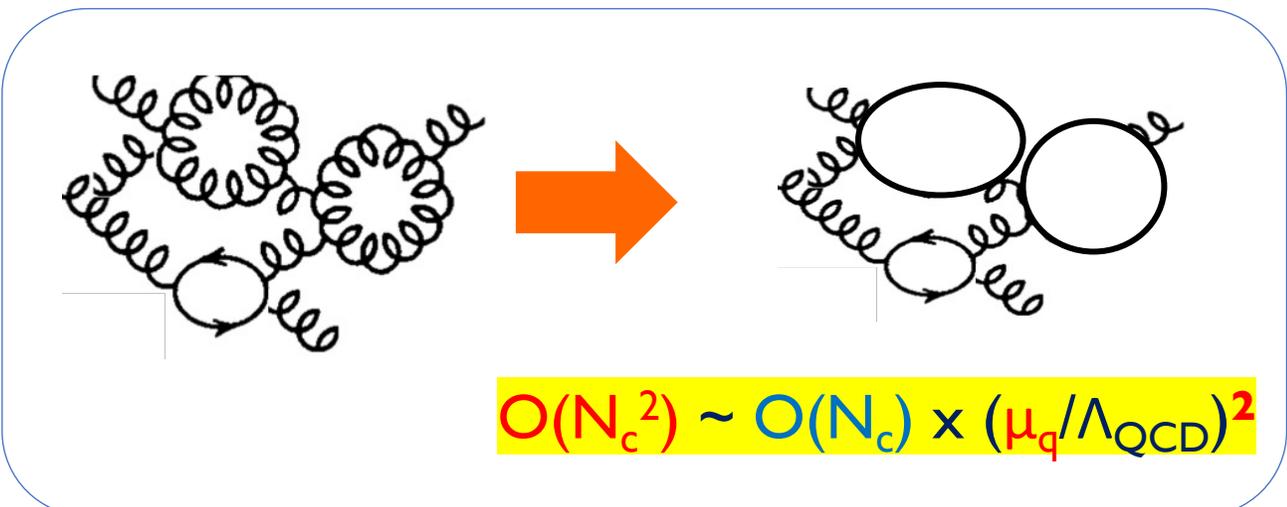
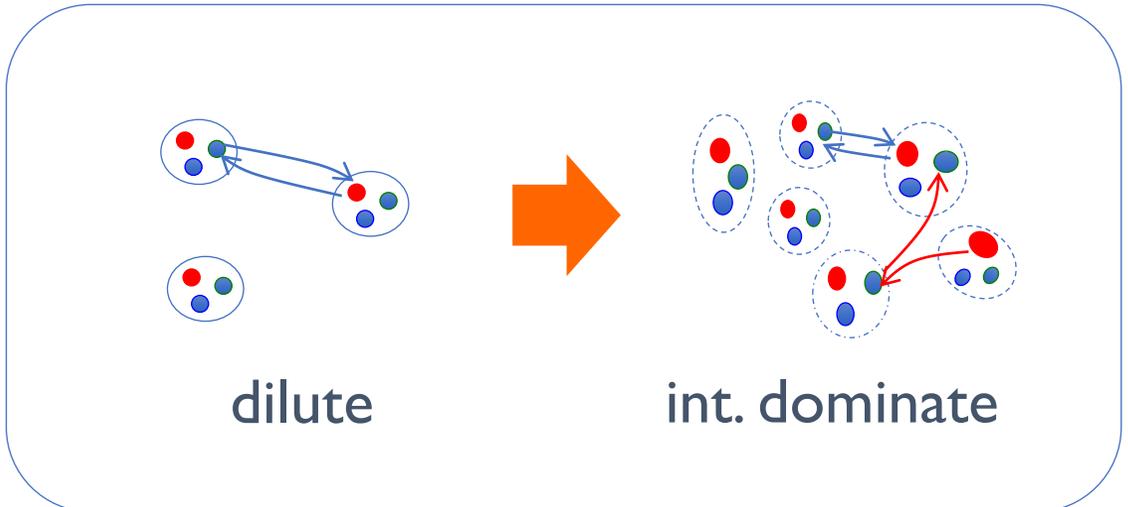


$$n_B^{\Lambda\text{-onset}} \sim 2n_0 \rightarrow 5-6n_0$$

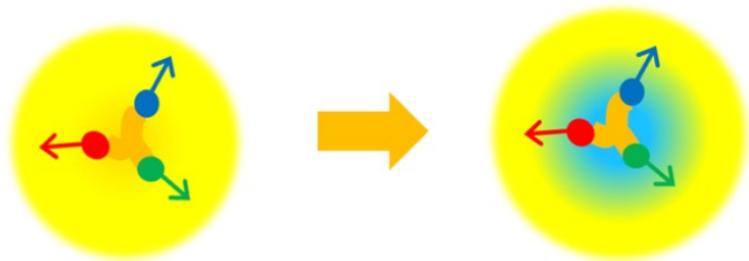
conventional

with saturation

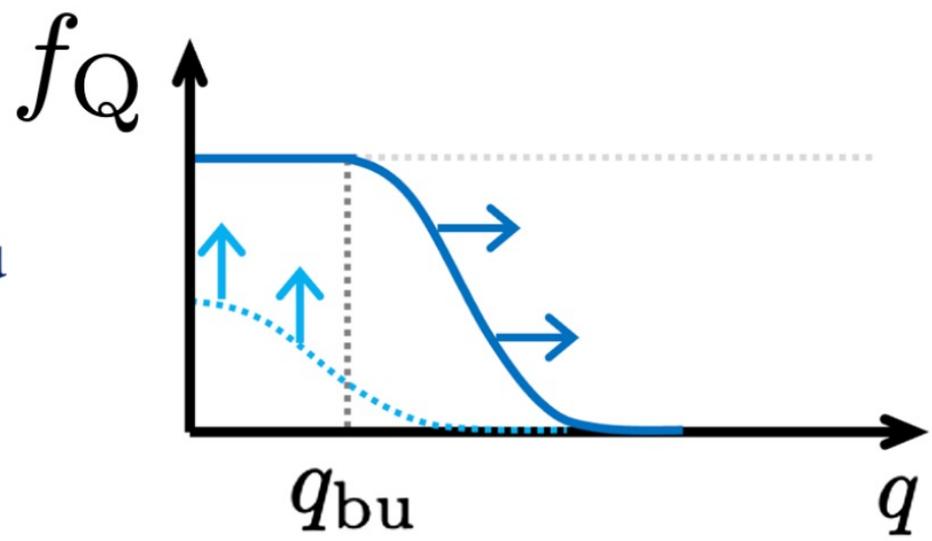
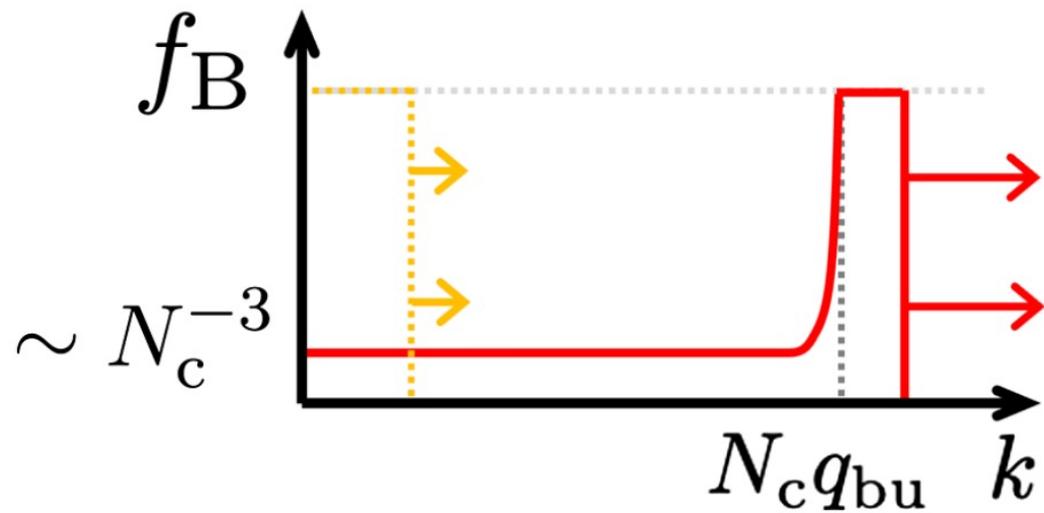
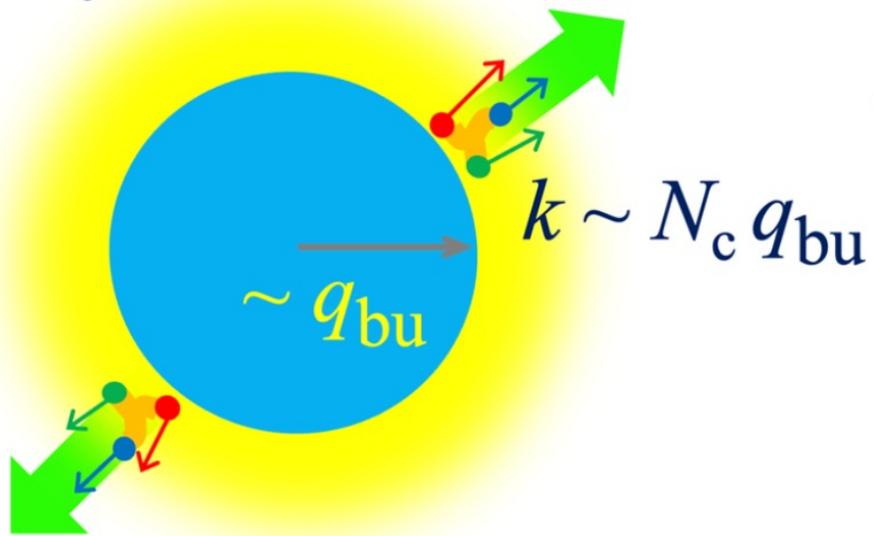
# McLerran-Pisarski's "two-scale picture" [ McLerran-Pisarski '07 ]



Nuclear



Quarkyonic

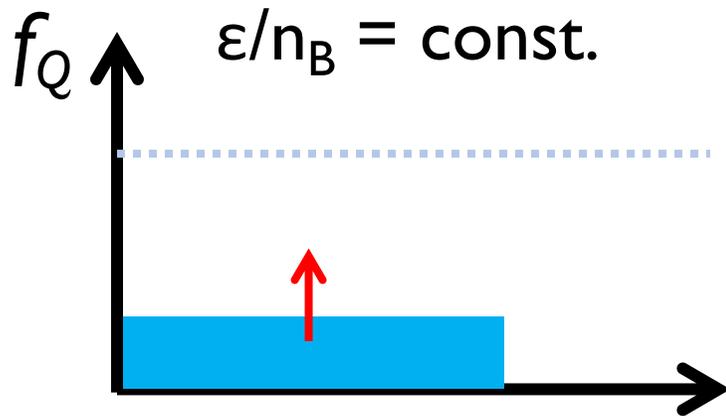
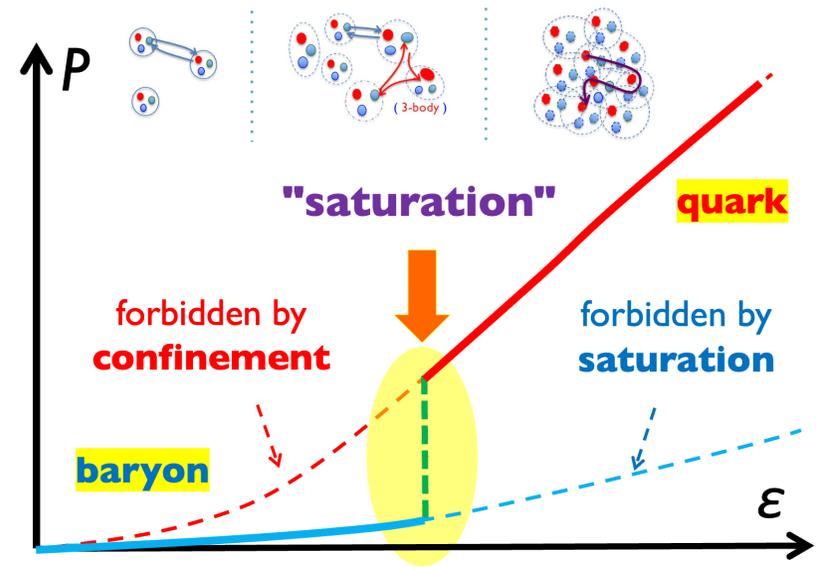


# Stiffening in quark picture

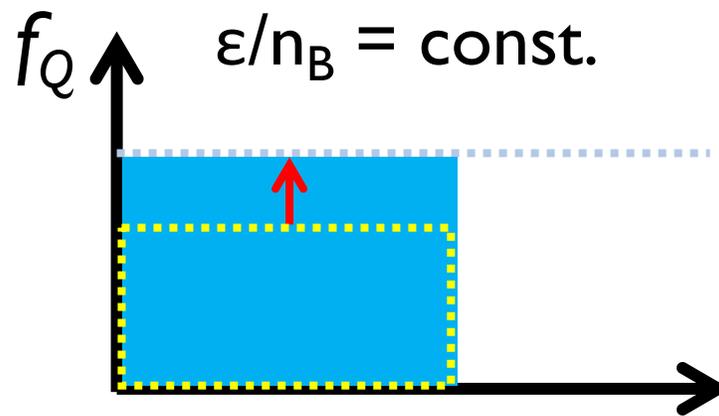
(very schematic)

$$\mathcal{P} = n_B^2 \frac{\partial}{\partial n_B} \left( \frac{\varepsilon}{n_B} \right)$$

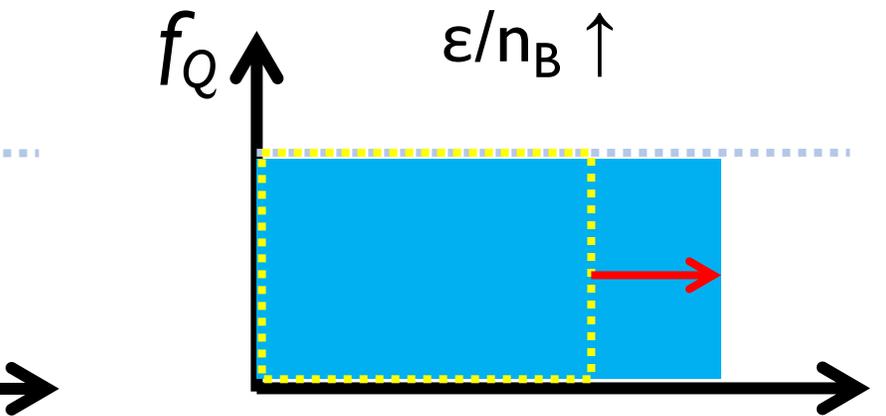
energy per particle



$P = 0$



$P = 0$



jump (!)



$P = \text{finite}$