Stiffening of matter in quark-hadron continuity

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Refs) Baym-Hatsuda-TK-Powell-Song-Takatsuka, "QHC", review on neutron stars (2018)

TK, "Stiffening of matter in quark-hadron continuity" PRD (2021)

Fujimoto-TK-McLerran, "IdylliQ matter model" PRL (2024)

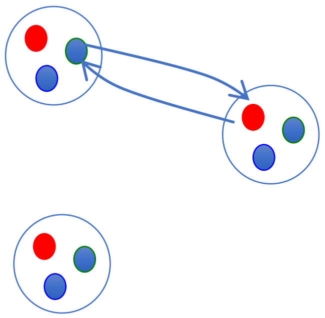
Chiba-TK, PRD(2024); TK-Suenaga-Chiba, "isospin QCD" (2024)

State of matter: overview

(n_0 = 0.16 fm^{-3})

[Masuda+ '12; TK+ '14]

- few meson exchange
- nucleons only

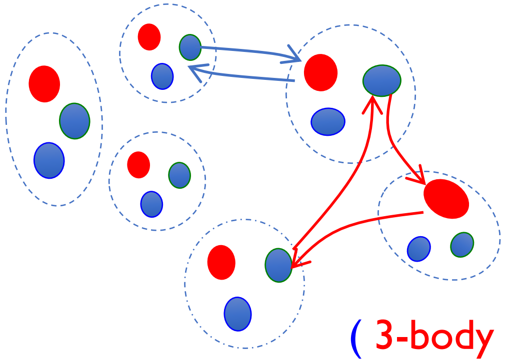


ab-initio nuclear cal.

laboratory experiments

steady progress

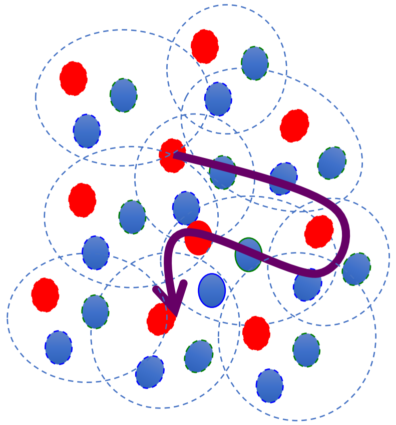
- many-quark exchange
- structural change,...
- hyperons, Δ, ...



most difficult

(d.o.f ??)

- Baryons overlap
- Quark Fermi sea



strongly correlated

(d.o.f : quasi-particles??)

not explored well

pQCD(?)

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

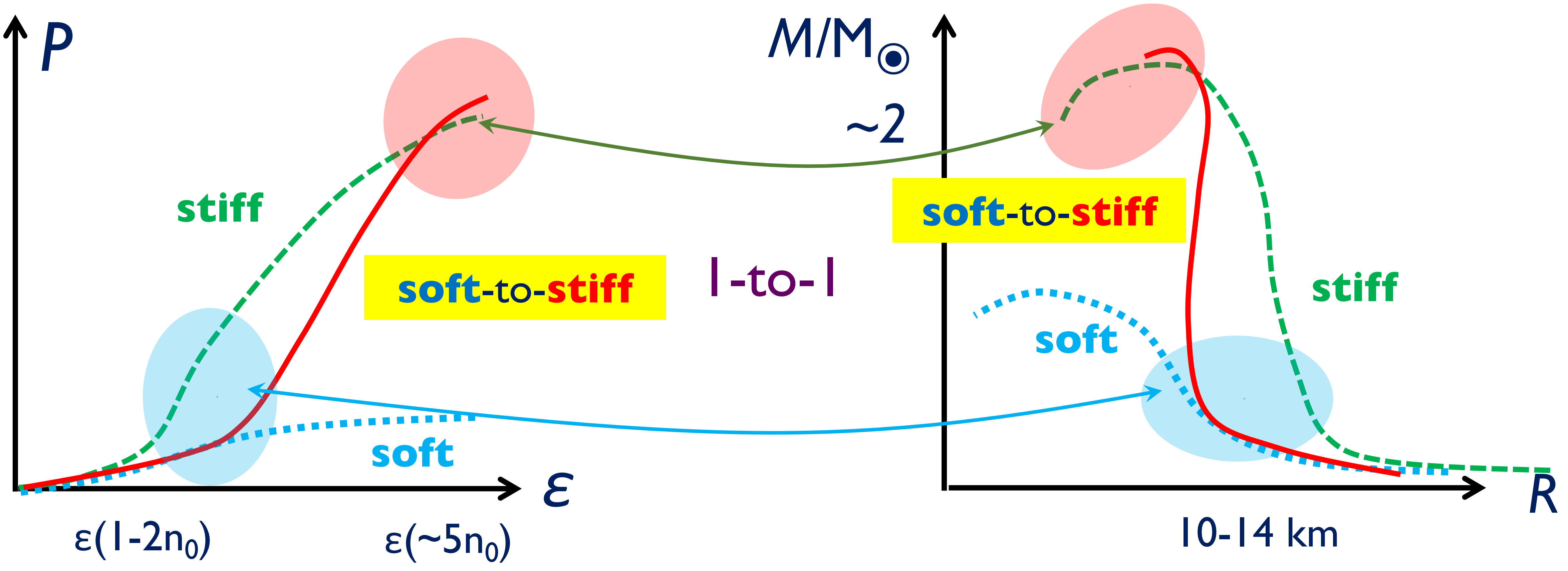
$\sim 1.4\,M_\odot$ $\sim 2\,M_\odot$

n_B

$\sim 2n_0$ **Hints from NS** $\sim 5n_0$ $\sim 40n_0$

EoS & Neutron Star M-R relation

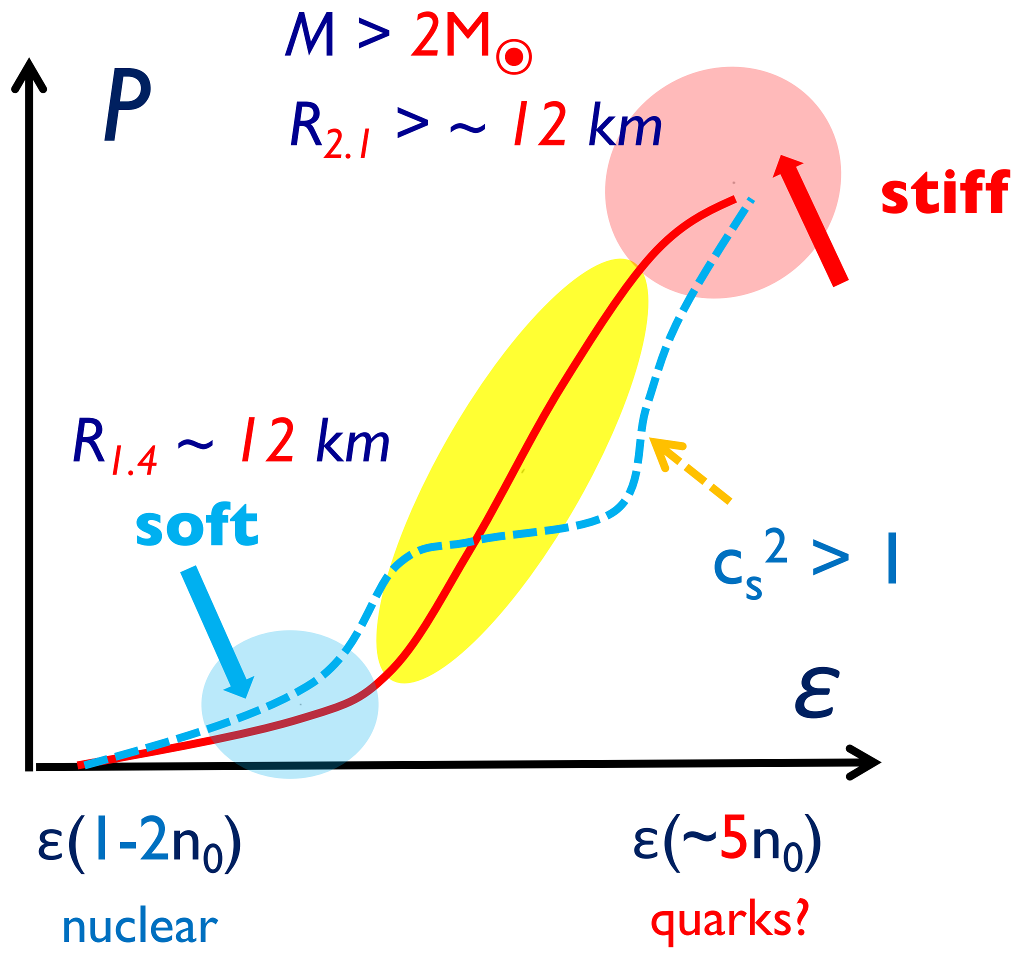
Einstein eq. : $G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ QCD (+EW) EoS

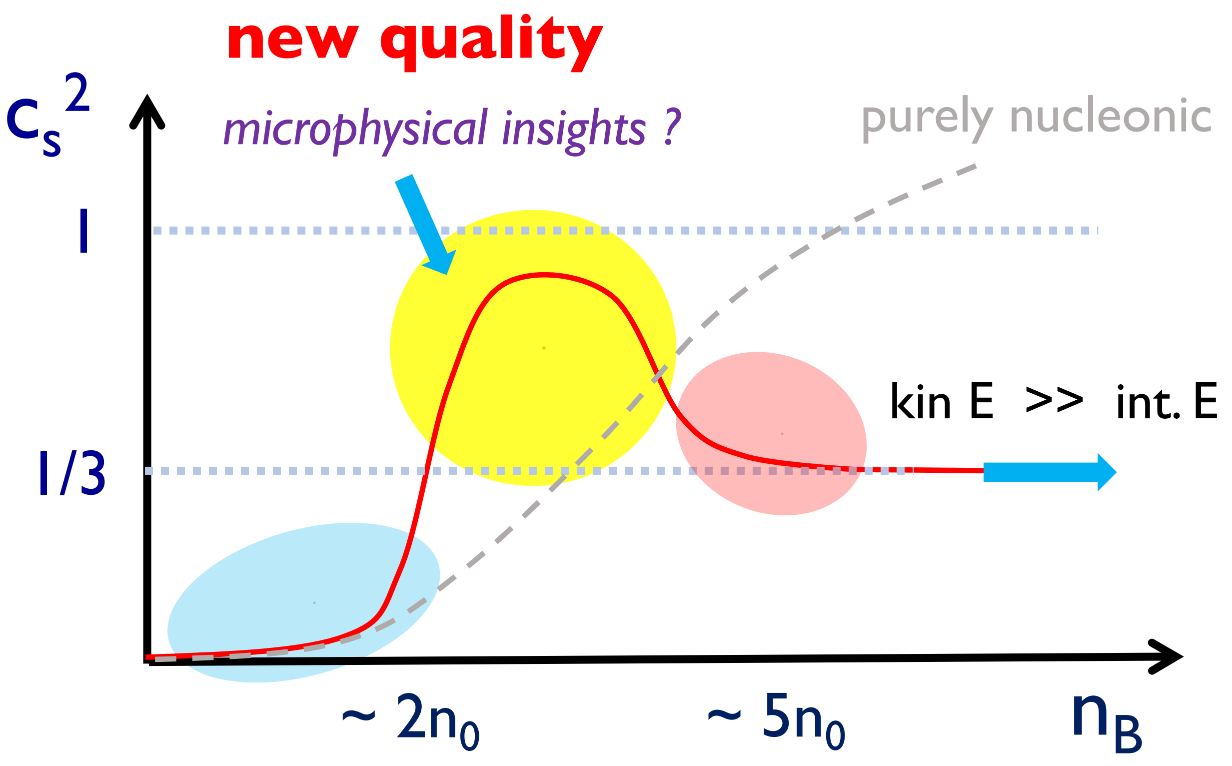


Soft *to* *stiff* *is challenging:*

sound speed: $c_s^2 = dP/d\varepsilon < 1$ (*causality*)

nuclear & *quark* physics constrain each other





baseline: *quark-hadron continuity* **(QHC)**

Contents

Pressure from $\varepsilon(n_B)$

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

e.g.)

gas of heavy particles (massive limit)

$$\varepsilon(n_B) = m_N n_B \;\rightarrow\; \varepsilon/n_B = m_N \;\rightarrow\; P = 0$$ soft

gas of relativistic particles (massless limit)

$$\varepsilon(n_B) = a n_B^{4/3} \;\rightarrow\; \varepsilon/n_B = a n_B^{1/3} \;\rightarrow\; P = \frac{\varepsilon}{3}$$ stiff

Nucleonic models & many-body forces

$$\varepsilon(n_B) = m_N n_B + a\frac{n_B^{5/3}}{m_N} + bn_B^{\alpha} \quad \Rightarrow \quad P = \frac{2}{3}a\frac{n_B^{5/3}}{m_N} + b(\alpha-1)n_B^{\alpha}$$

$m_N n_B$: **large (!)** $a\frac{n_B^{5/3}}{m_N}$: **small (!)** $\frac{2}{3}a\frac{n_B^{5/3}}{m_N}$: **small (!)**

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

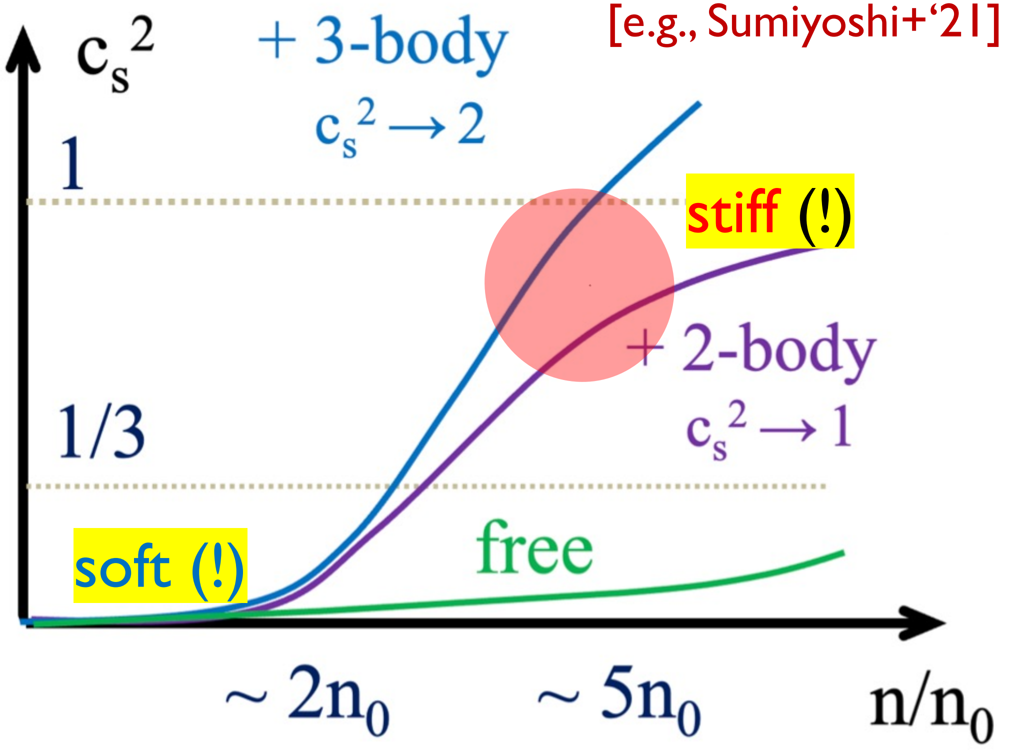
➡ p << ε (at least in dilute regime)

If interactions dominate (at large n_B):

$$P \sim (\alpha-1)\varepsilon \ \rightarrow \ c_s^2 \sim (\alpha-1)$$

2-body int. → α = 2 3-body int. → α = 3

- *causality & convergence ??*
- *stiffening occurs slowly (power growth)*



alternative: quark EOS

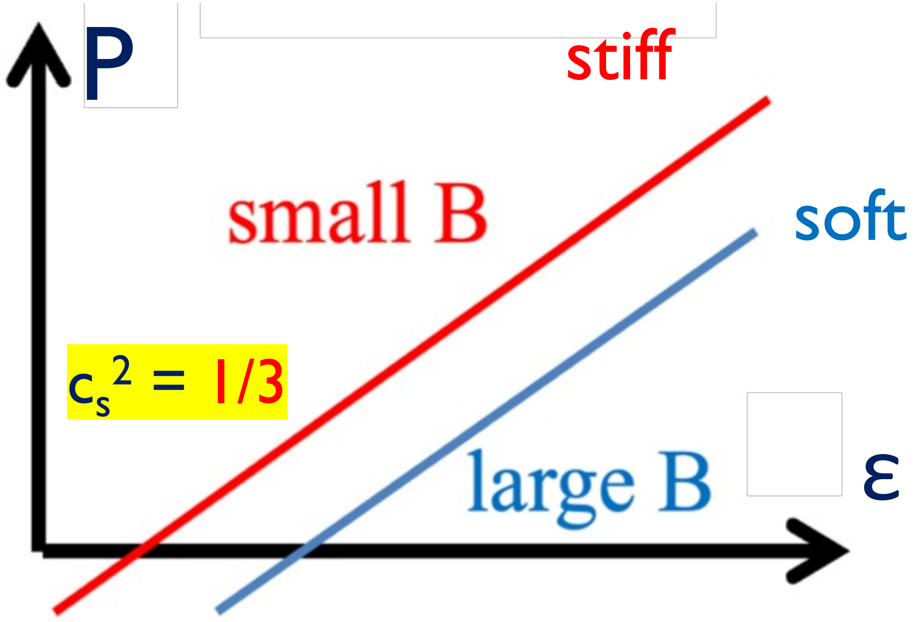
e.g.) free massless quarks

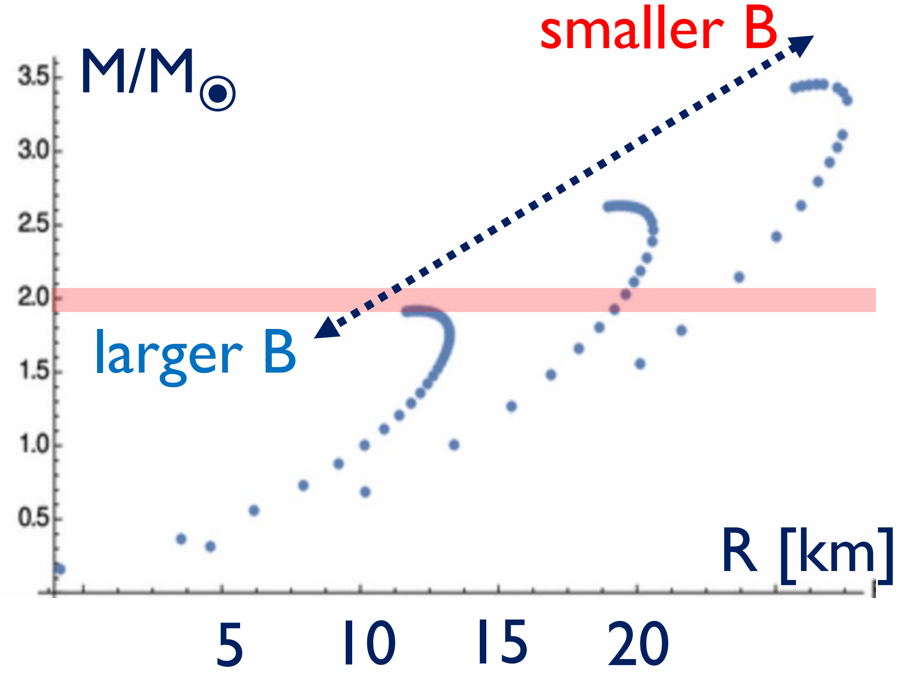
$$P = \frac{\varepsilon}{3} - B'$$

normalization

quark kin. pressure >> baryon kin. pressure

O(N_c) O($1/N_c$)



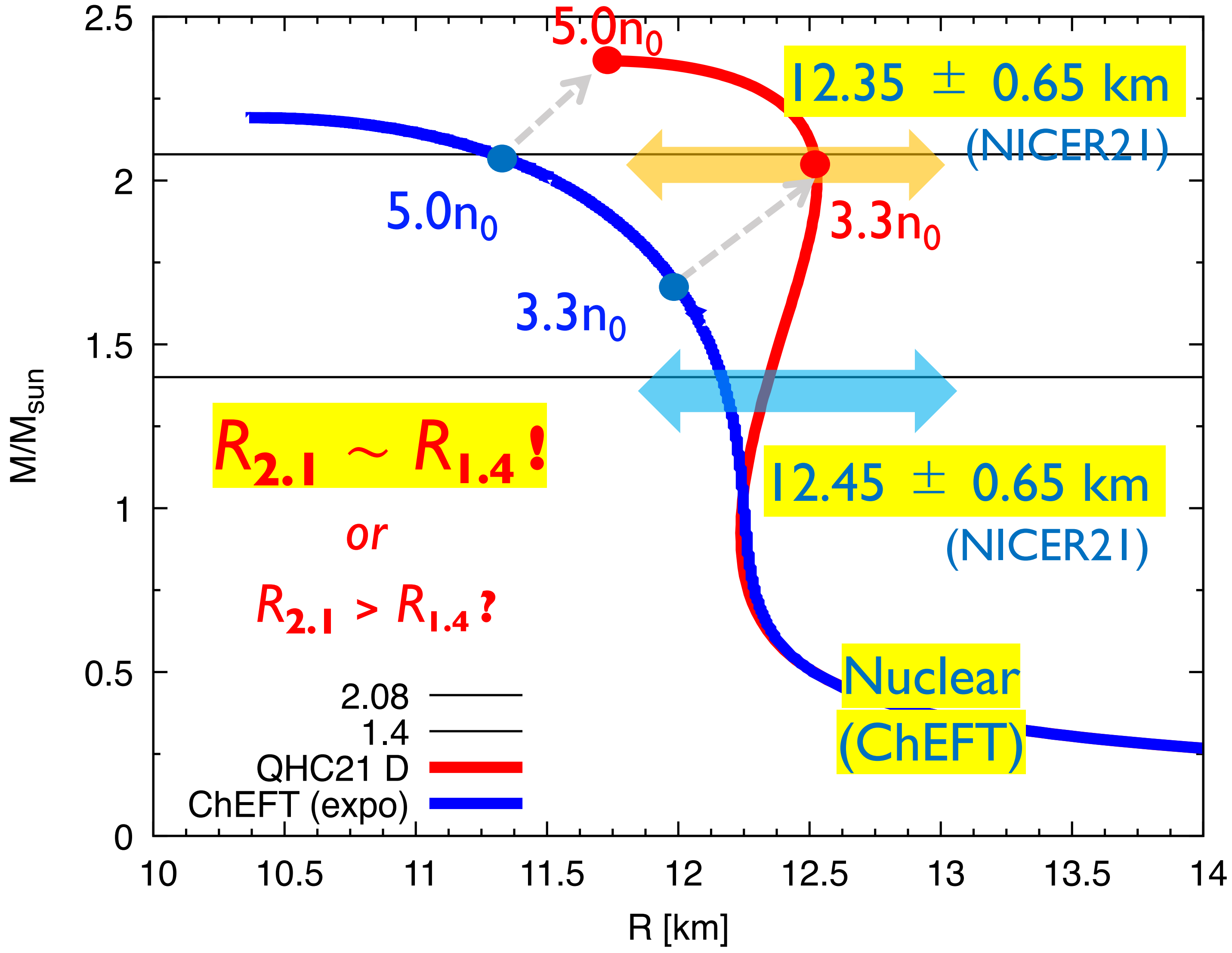


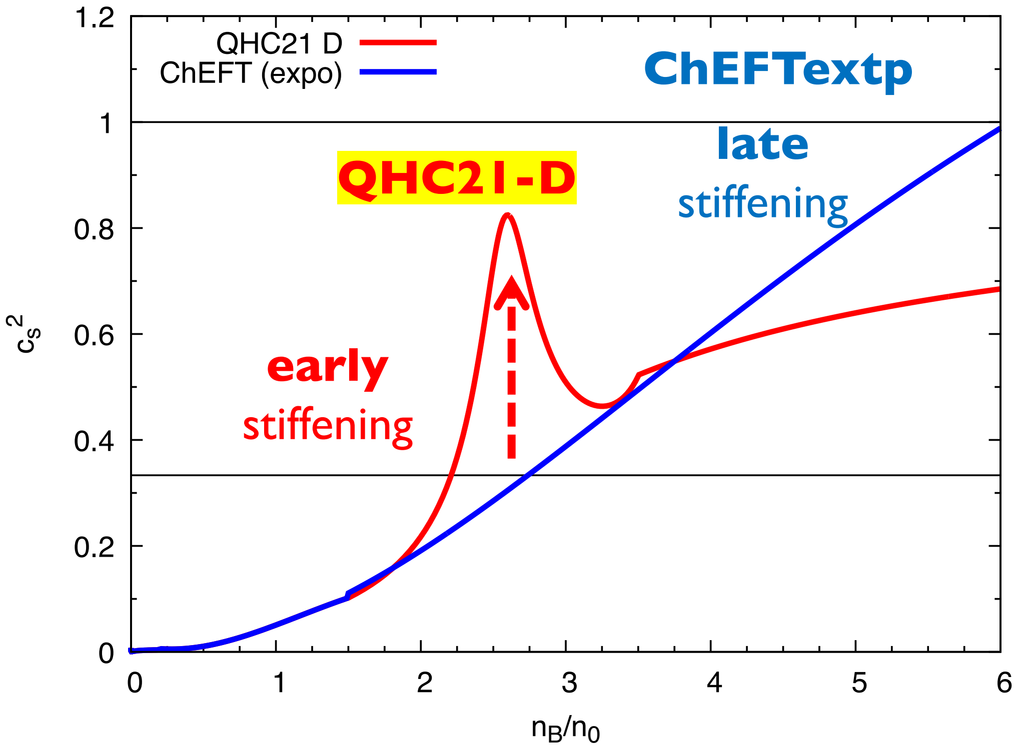
relativistic pressure → stiff EOS ?

depends on ***where*** *to start...*

Early vs late stiffening: QHC vs ChEFTextp

[TK-Hatsuda-Baym '21]





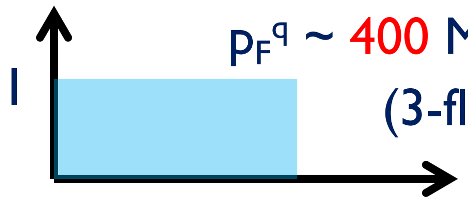
2-$3n_0$: already beyond purely nucleonic regime?

Contents

Claim

- naive estimate for quark matter formation density: ($R_B \sim$ 0.5-0.8 fm)

$$n_B^{overlap} \sim 1/(\, 4\pi R_B^3/3 \,) \sim 4\text{-}7 n_0$$



- we claim the existence of **another scale**, characterizing:
  - breakdown of many-body expansion
  - ***soft-deconfinement*** [not explained today, see Fukushima-TK-Weise '20]
  - ***quark saturation*** [TK '21; Fujimoto-TK-McLerran '24]

$$n_B^{q\text{-}sat} \sim 0.5 \times n_B^{overlap} \sim 2\text{-}3 n_0$$

Sum rules for occupation probabilities

cf) [TK '21, TK-Suenaga '21]

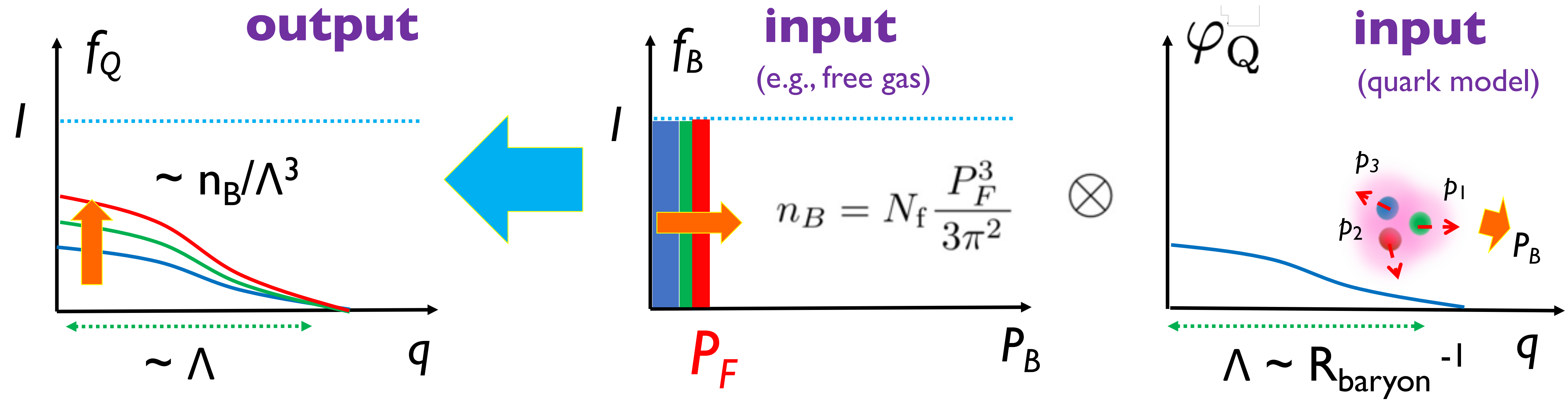
occupation **probability** of **quark** state with p

occupation **probability** of **baryon** state with P_B

quark mom. distribution **in a baryon**

$$f_{\mathrm{Q}}(\mathbf{q}) = \int_{\boldsymbol{P}_B} f_{\mathrm{B}}(\boldsymbol{P}_B)\,\varphi_Q^B(\mathbf{q} - \boldsymbol{P}_B/N_{\mathrm{c}})$$

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: $\varepsilon_{\mathrm{B}}[f_{\mathrm{B}}] = 4 \int_k E_{\mathrm{B}}(k) f_{\mathrm{B}}(k)$ (the factor 4: *isospin, spin*)

2) quark distributions in a baryon remains the same (confinement persists)

3) use a special quark distribution → models become analytically **solvable**

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

nontrivial output

$$f_{\mathrm{Q}}(\mathbf{q}) = \int_{\boldsymbol{P}_B} f_{\mathrm{B}}(\boldsymbol{P}_B) \varphi_Q^B(\mathbf{q} - \boldsymbol{P}_B / N_{\mathrm{c}})$$

natural at ***low*** *density* (f_{B} is the input)

⇄

nontrivial output

$$f_{\mathrm{B}}(N_{\mathrm{c}} \boldsymbol{q}) = \frac{\Lambda^2}{N_{\mathrm{c}}^3} \hat{L}[f_{\mathrm{Q}}(\boldsymbol{q})]$$

natural at ***high*** *density* (f_{Q} is the input)

useful for studies of the *transient regime* (d.o.f are not clear-cut)

Variational problem with sum rule constraints

[Fujimoto-TK-McLerran, PRL'24]

constraint to fix n_B

$$\tilde{\varepsilon} = \varepsilon_B[f_B] - \lambda_B n_B$$

$$E_B(k) = \sqrt{M_B^2 + k^2} \qquad n_B = 4\int_k f_B(k)$$

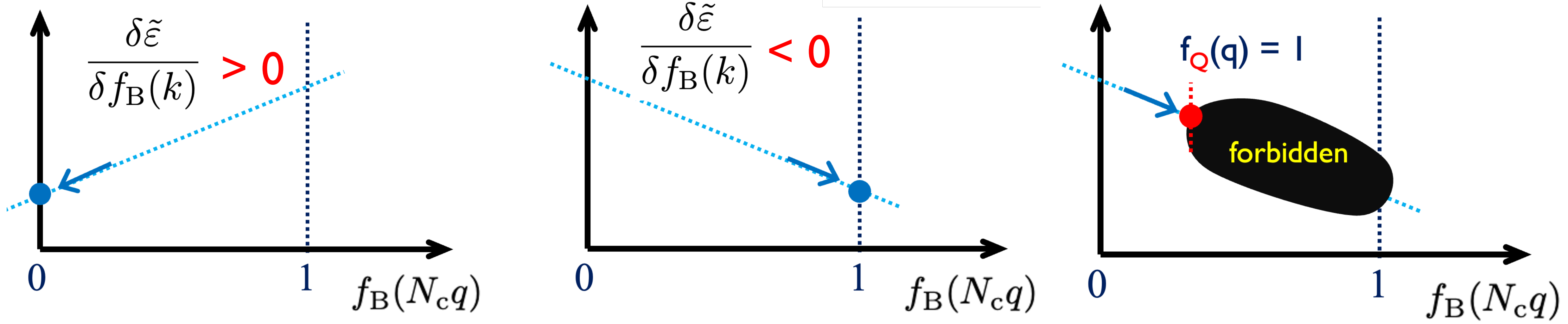
optimization: $$\frac{\delta\tilde{\varepsilon}}{\delta f_B(k)} = E_B(k) - \lambda_B$$ *at a given k*

$E_B(k) > \lambda_B$

$E_B(k) < \lambda_B$

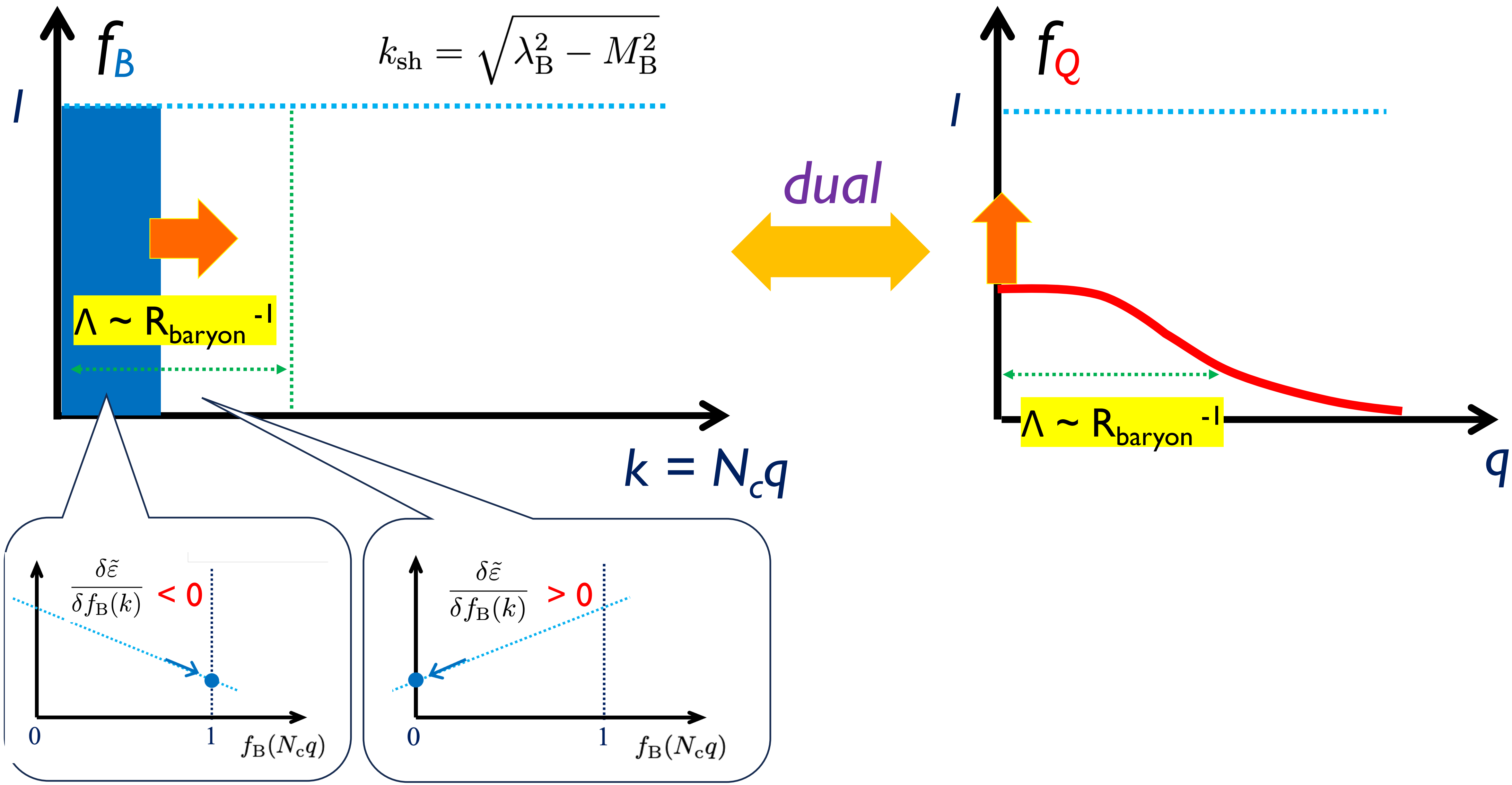
w.o. saturation

with saturation



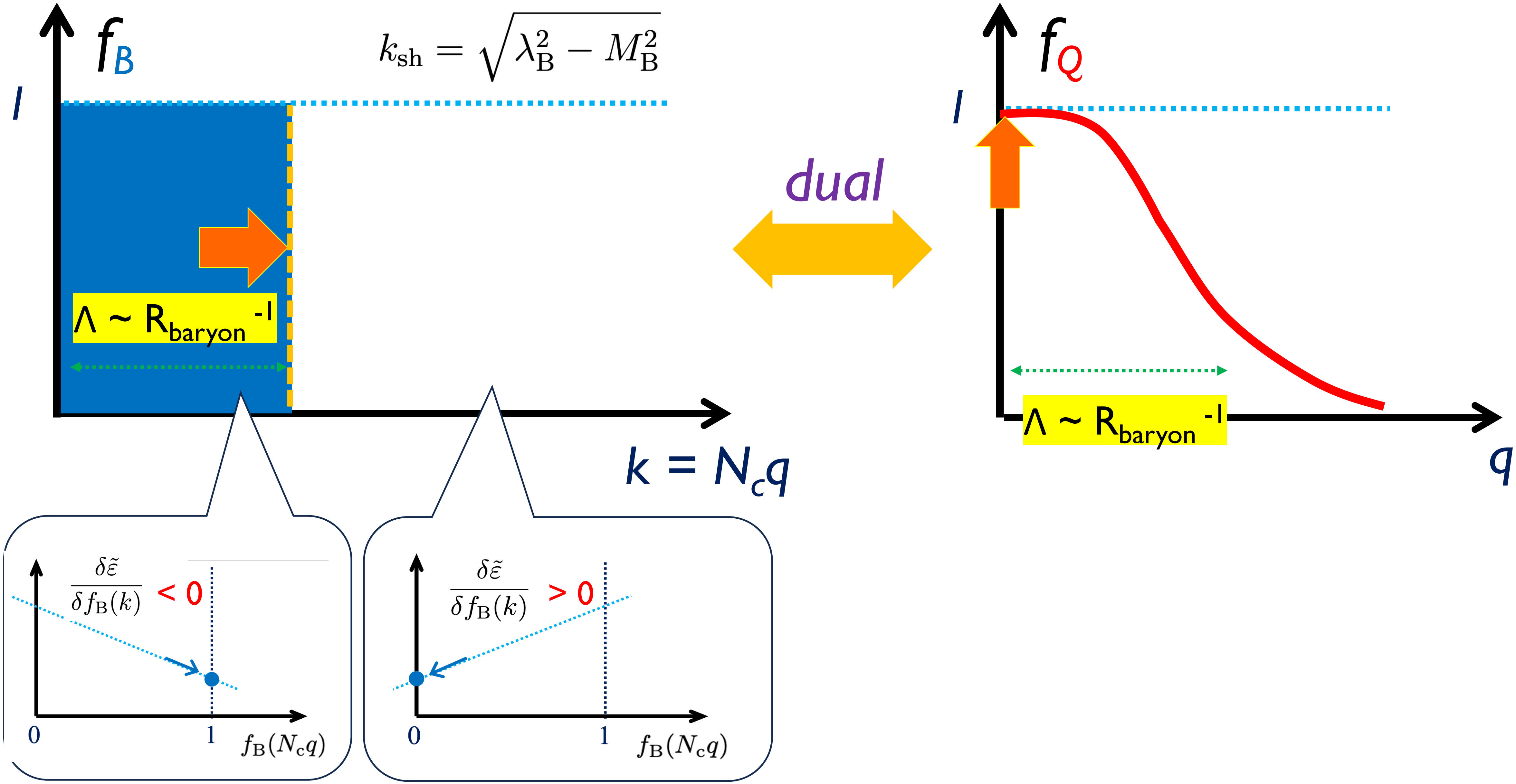
Solution (dilute regime)

[Fujimoto-TK-McLerran, PRL'24]



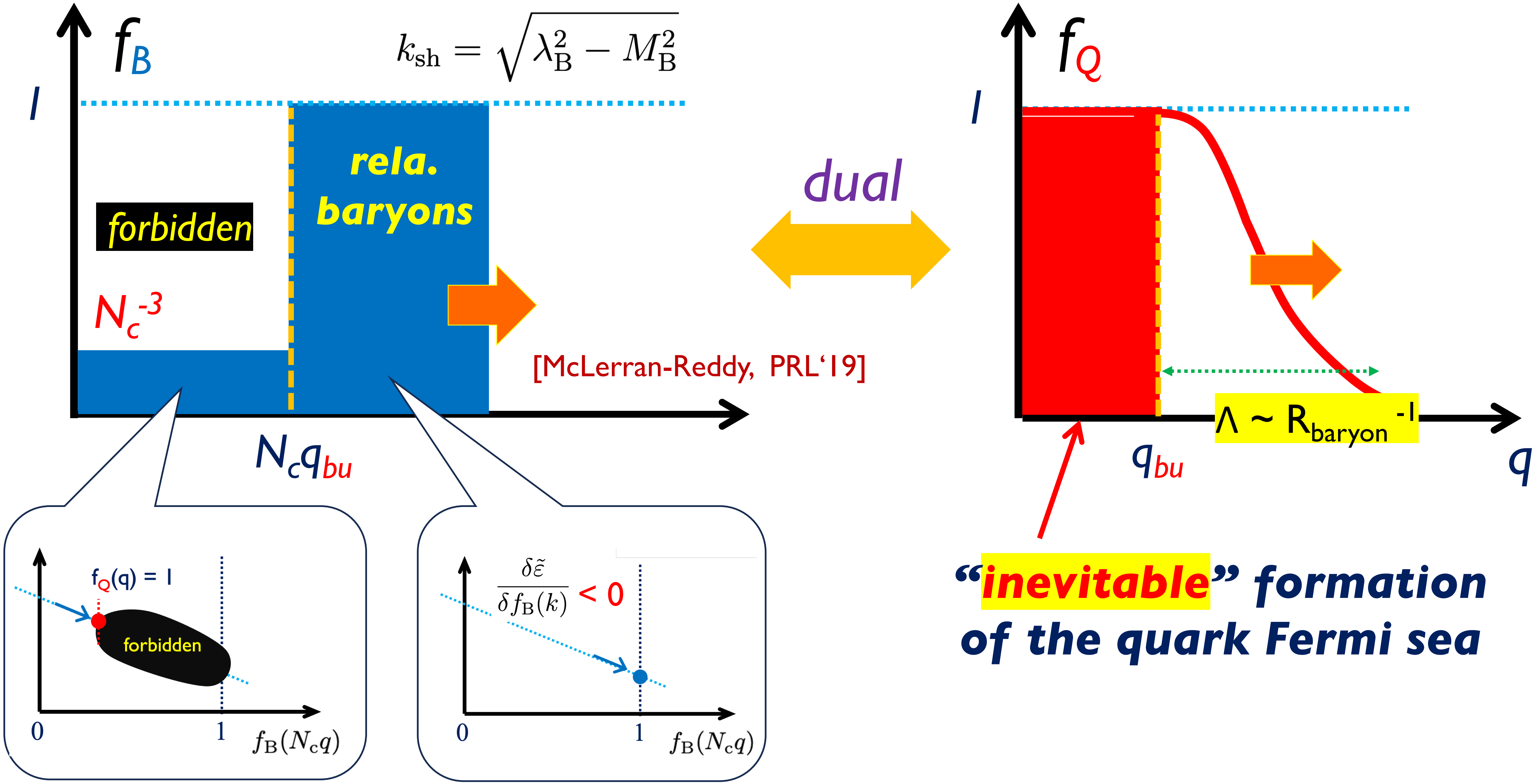
Solution (at saturation)

[Fujimoto-TK-McLerran, PRL'24]



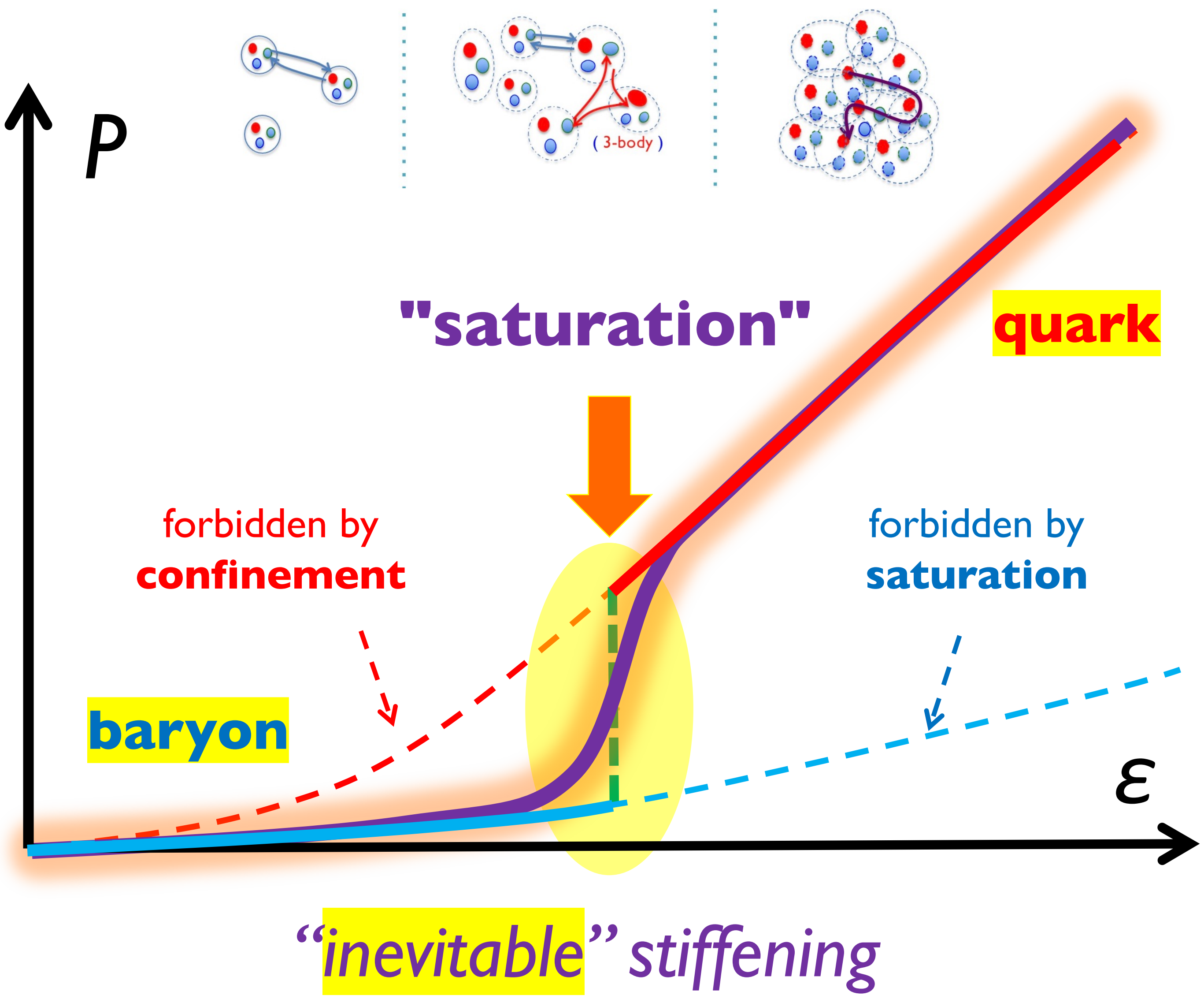
Solution (post saturation)

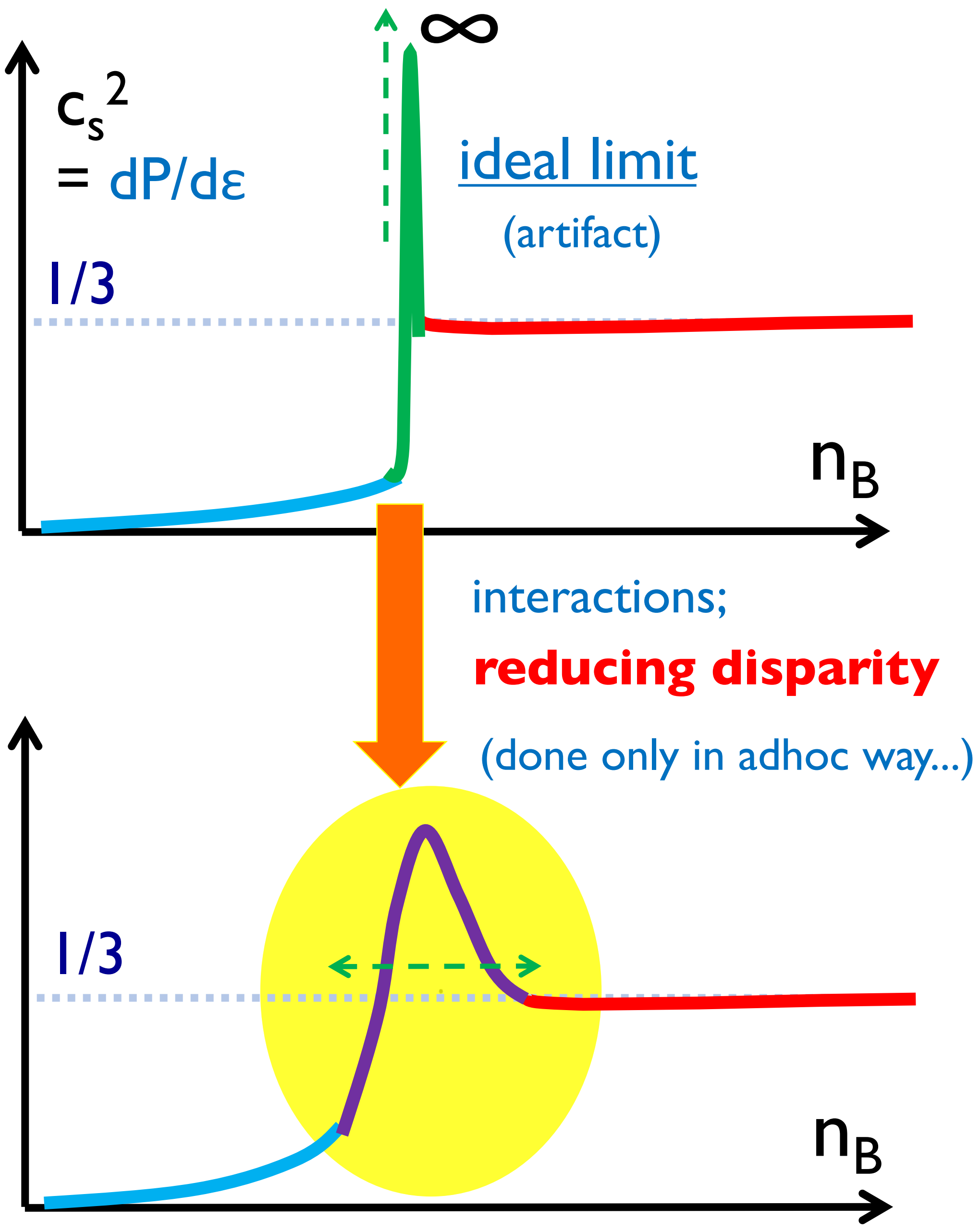
[Fujimoto-TK-McLerran, PRL'24]



"*inevitable*" *formation of the quark Fermi sea*

Peak in sound velocity





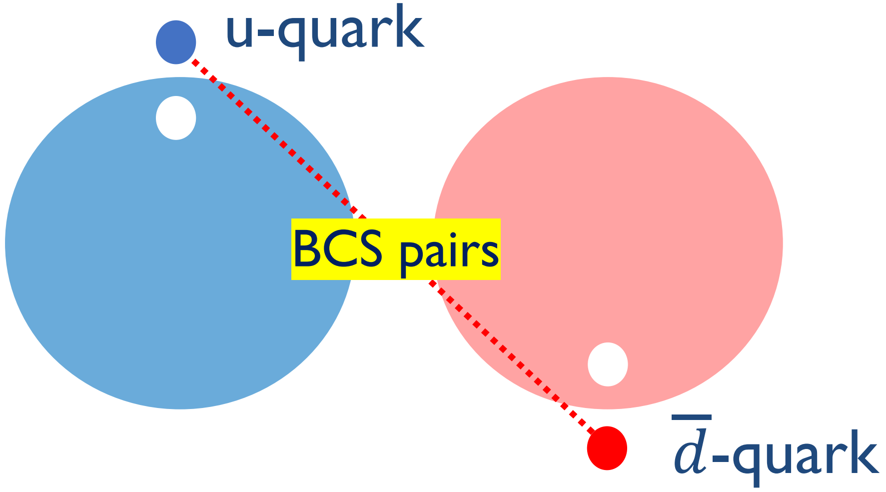
Contents

Isospin QCD

isospin chemical pot. $\mu_I = \mu_u = -\mu_d$ $n_0 = 0.16\ \mathrm{fm}^{-3}$

- onset of finite density → begin with pions (instead of nucleons)

high density

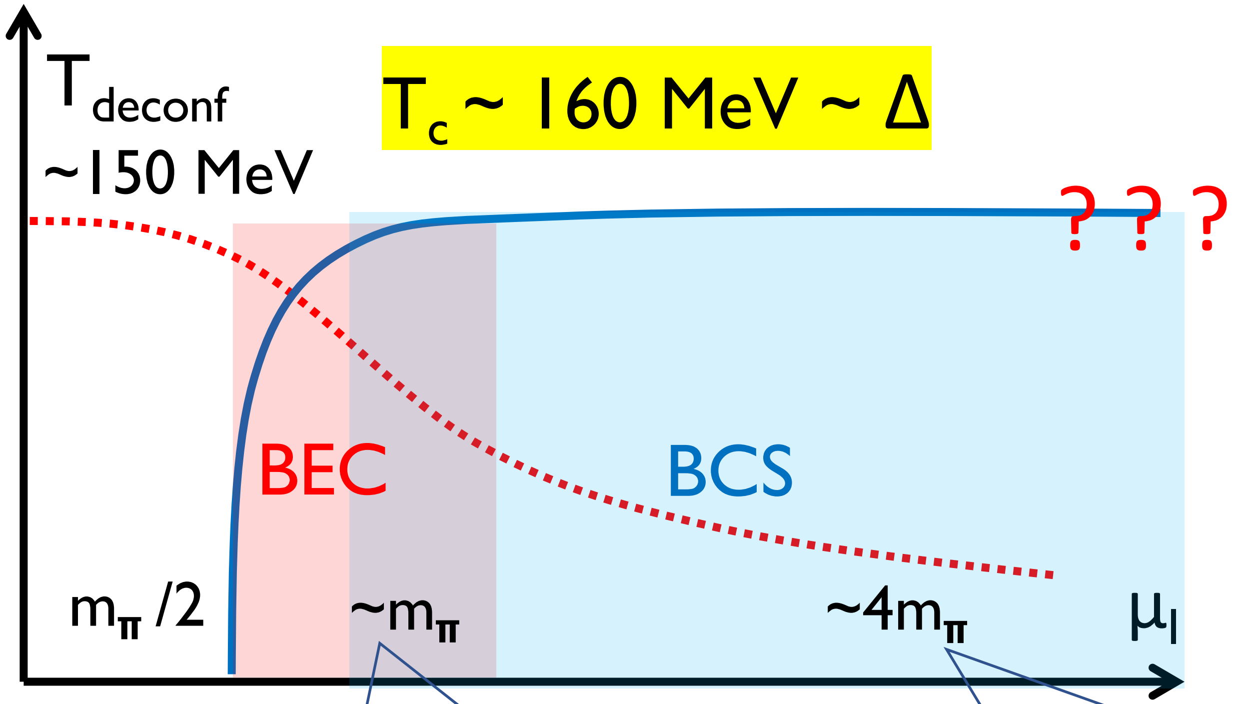


pairing → pion cond. π^+ (p-a) & π^- (h-ah)

→ quark mass gap Δ

$\sim T_c/0.57 \sim$ 280 MeV

[see also Fujimoto '24]



quark substructure important

$n_I \sim 1\text{-}2n_0$

pions ($r_\pi \sim 0.7$ fm) overlap

$n_I \sim 5.2n_0$

Hints for new scale & saturation

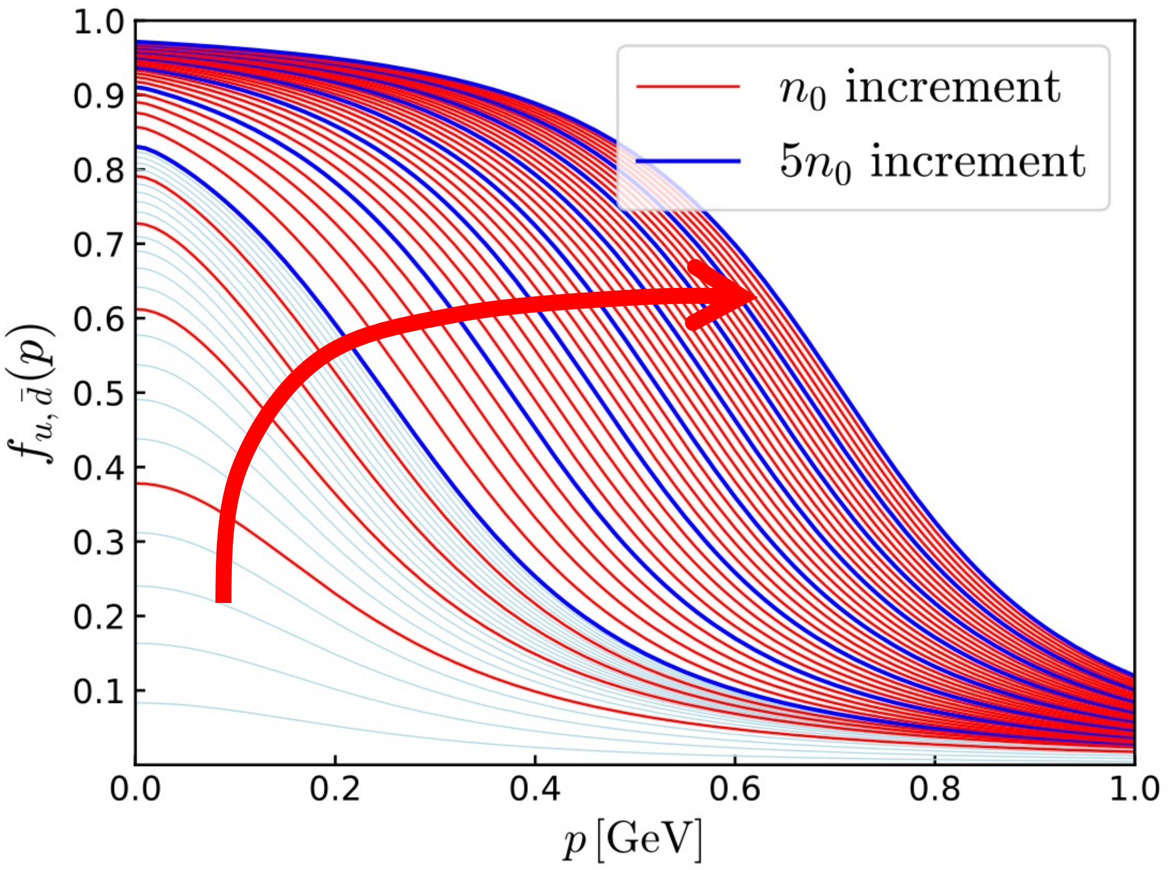
[quark-meson model study, Chiba+ '23; TK+ '24; ...]

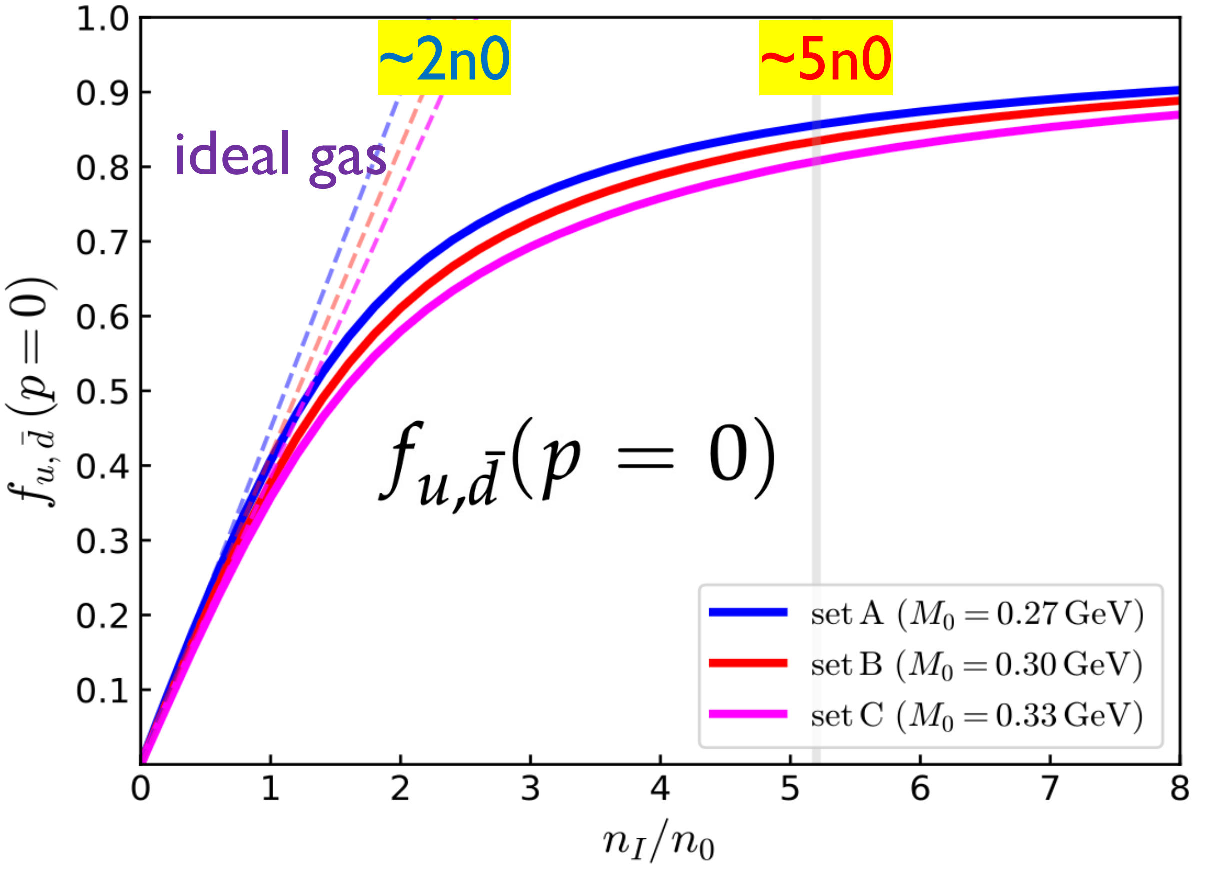
- BCS occ. probability:

$$f_{u,\bar{d}}(p; n_I) = \frac{1}{2}\left(1 - \frac{E_l - \mu_I}{\sqrt{(E_l - \mu_I)^2 + \Delta^2}}\right)$$

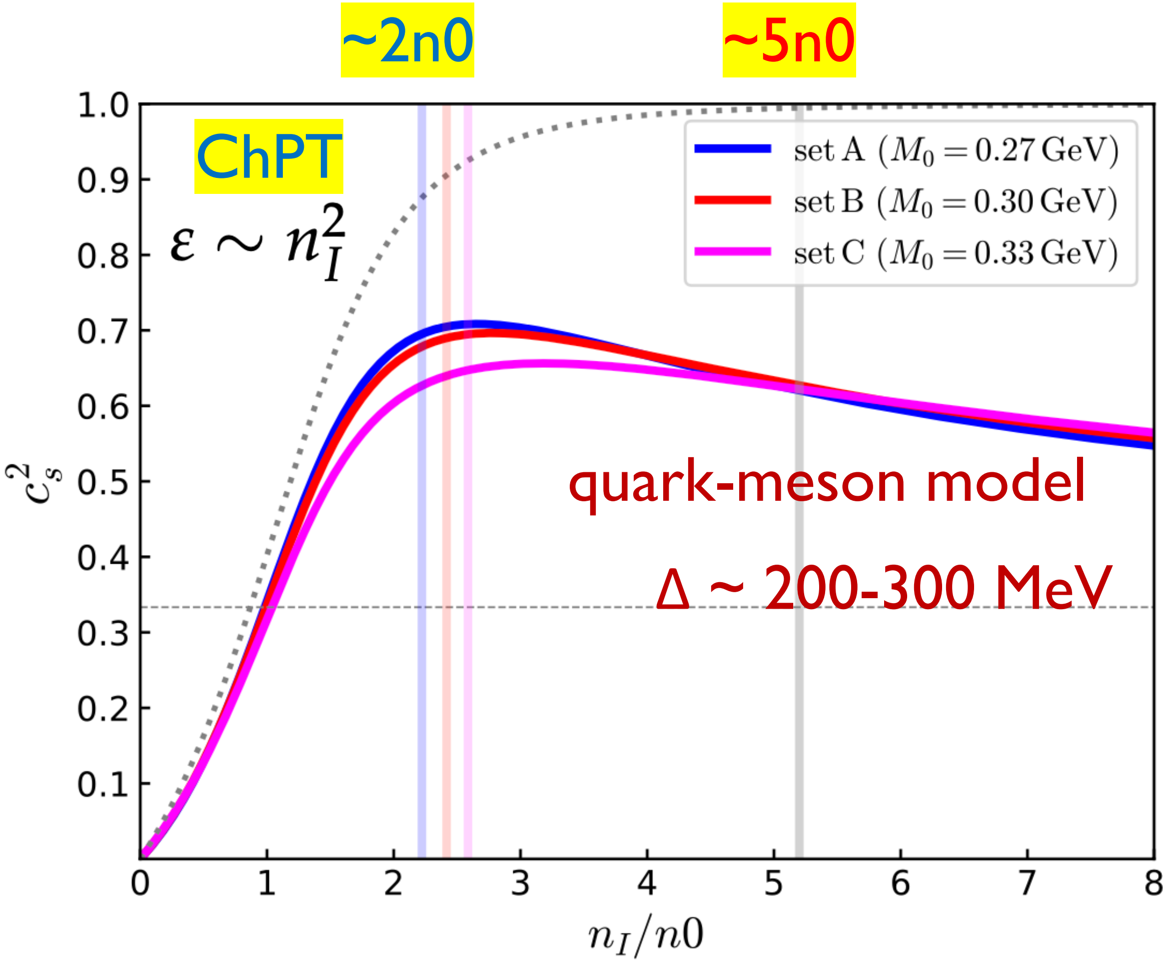
ideal pion gas pic. definitely violated

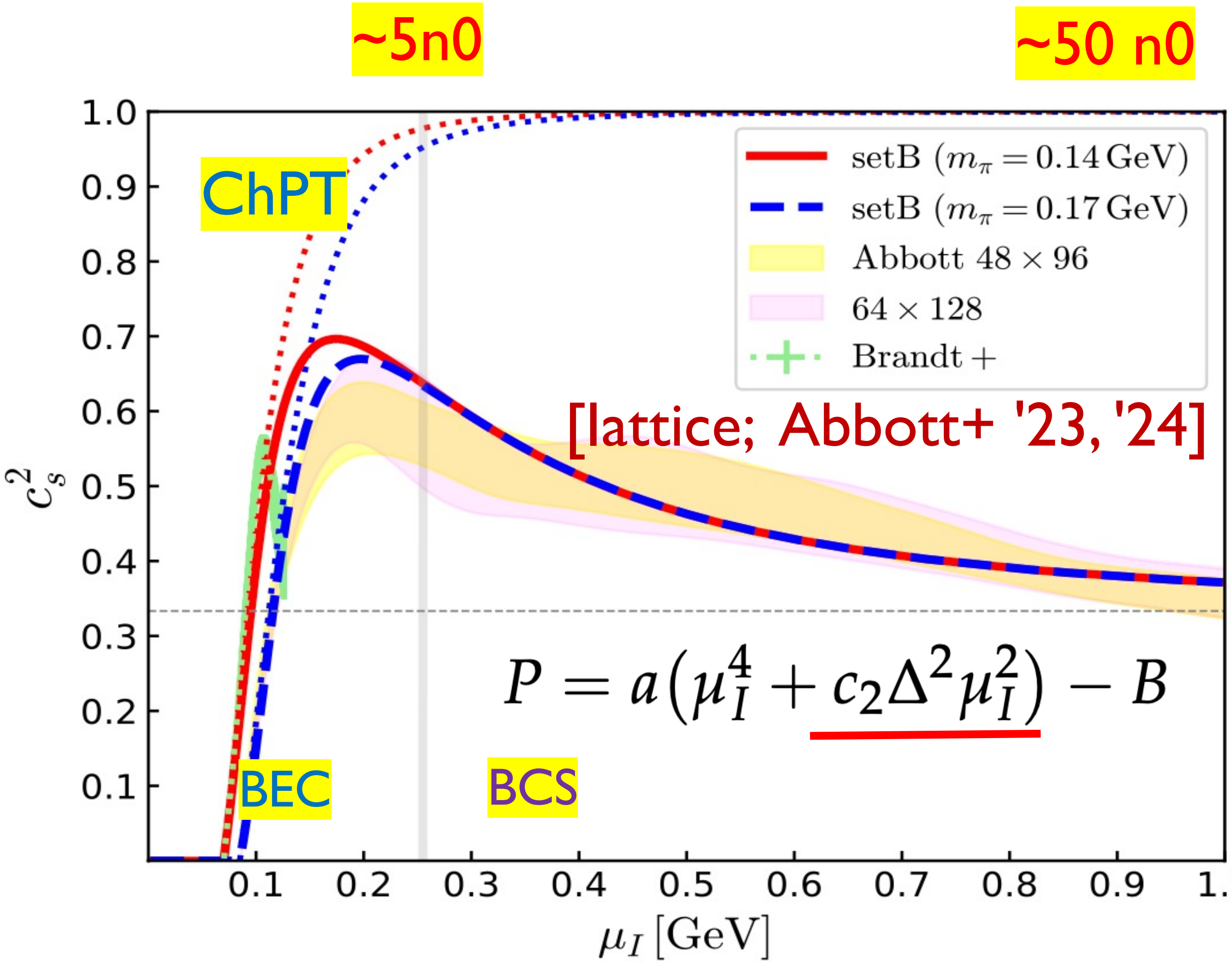
pions with r ~ 0.66 fm overlap





Sound speed: quark-meson model, ChPT, and Lattice





see also two-color QCD, Iida-Itou-Murakami-... ('22, '23, '24)

[model study; TK-Suenaga-Chiba '24]

Summary (of claims)

- *nuclear* + $R_{1.4} \sim R_{2.1}$ → *early* stiffening at ~ 0.5 $n^{overlap}$
- *inevitable* quark Fermi sea formation at ~ 0.5 $n^{overlap}$
- *quark saturation* changes the trend of EOS; disparity -> c_s^2 peak
- Quarks can be agents of rapid stiffening:

  can be microscopic origin of many-body repulsion

  nontrivial constraints on the baryon dynamics
- Quarks can be important near nuclear saturation densities, 1-2n0

  → Larry's talk tomorrow

Back Up

Summary (of claims)

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    can be microscopic origin of many-body repulsion

    nontrivial constraints on the baryon dynamics

- Quarks can be important near nuclear saturation densities, 1-2n0

    → see Larry's talk tomorrow

- Quark substructure of hadrons are important

Summary (of claims)

- *nuclear* + $R_{1.4} \sim R_{2.1}$ → *early* stiffening at ~ 0.5 $n^{overlap}$

  (beyond simple nuclear regime)

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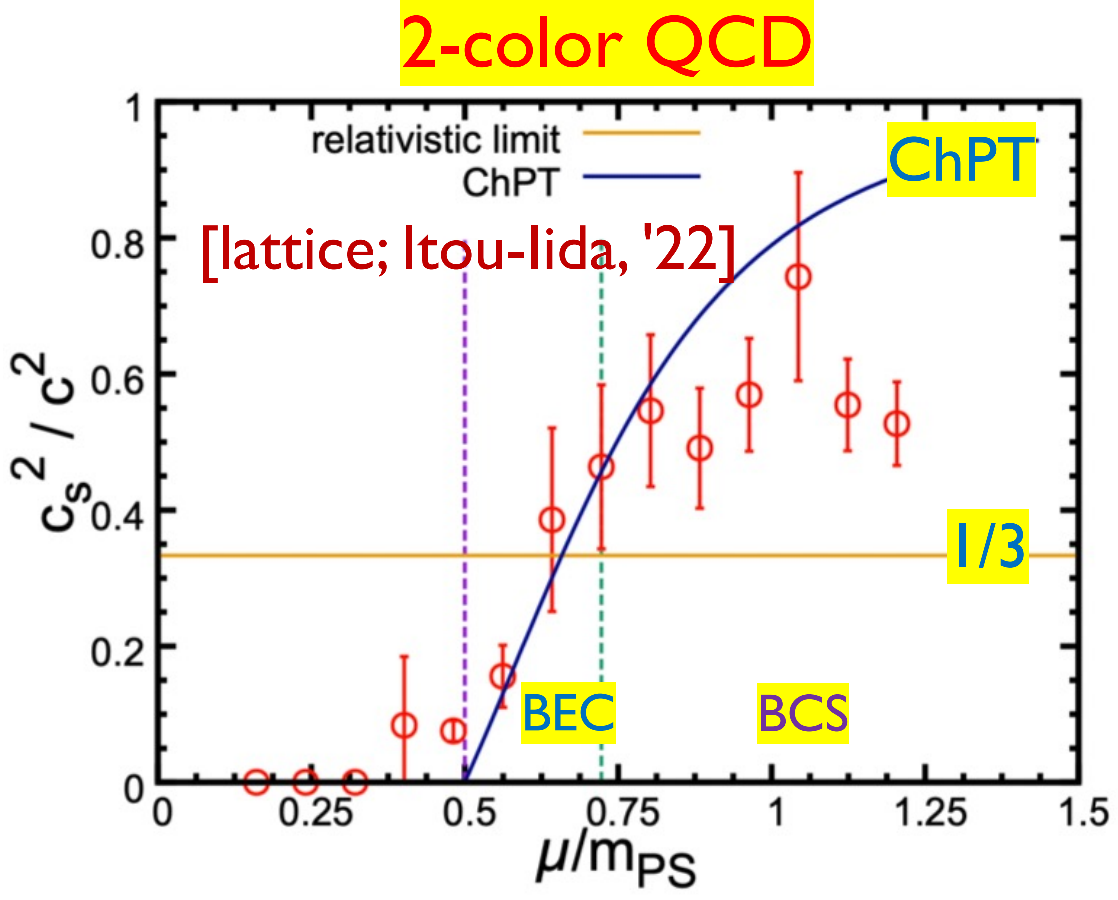
- attractive correlations near the Fermi surface stiffen EOS

- *unreasonable*(?) effectiveness of *quasi-particle* model in isospin QCD

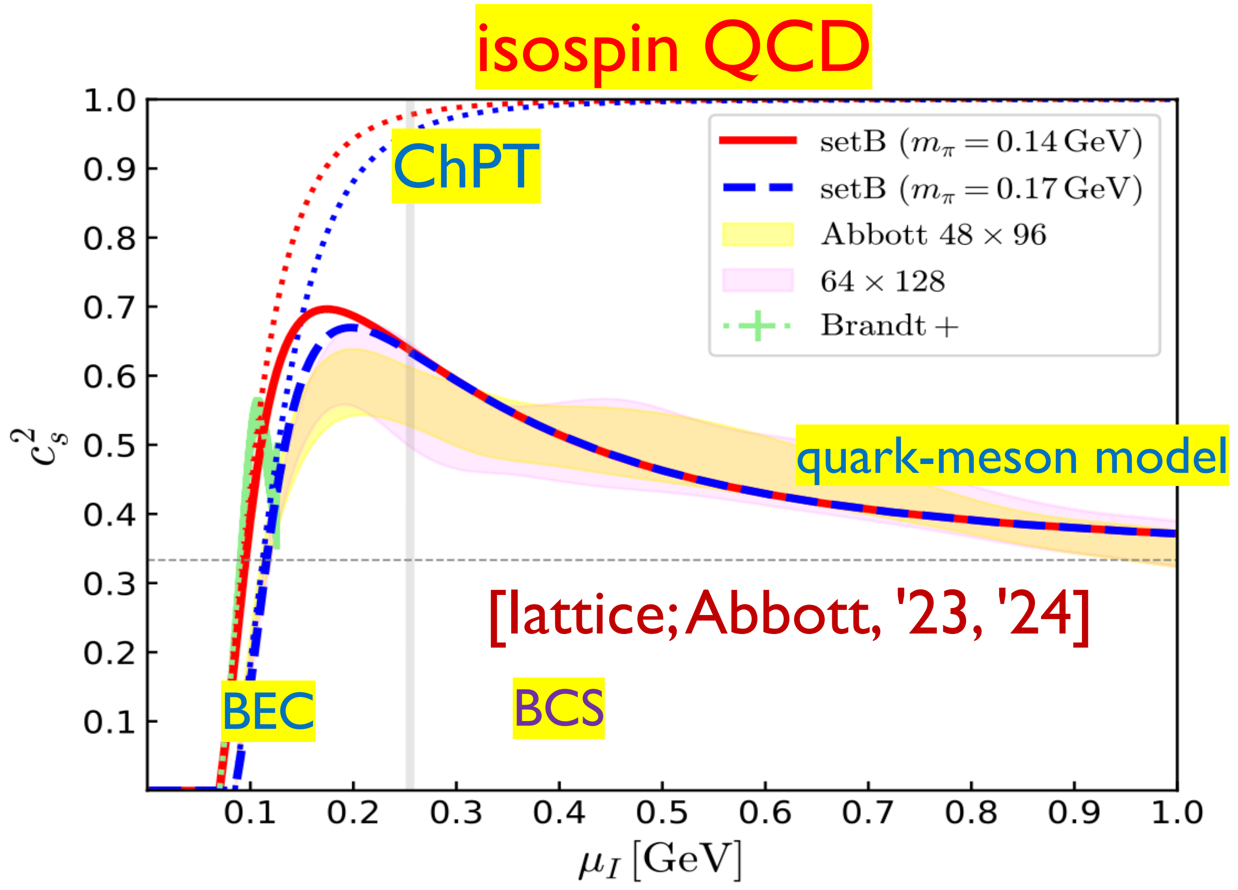
  (as in constituent quark models in hadron spectroscopy)

Examples from QCD-like theories

tests on the lattice



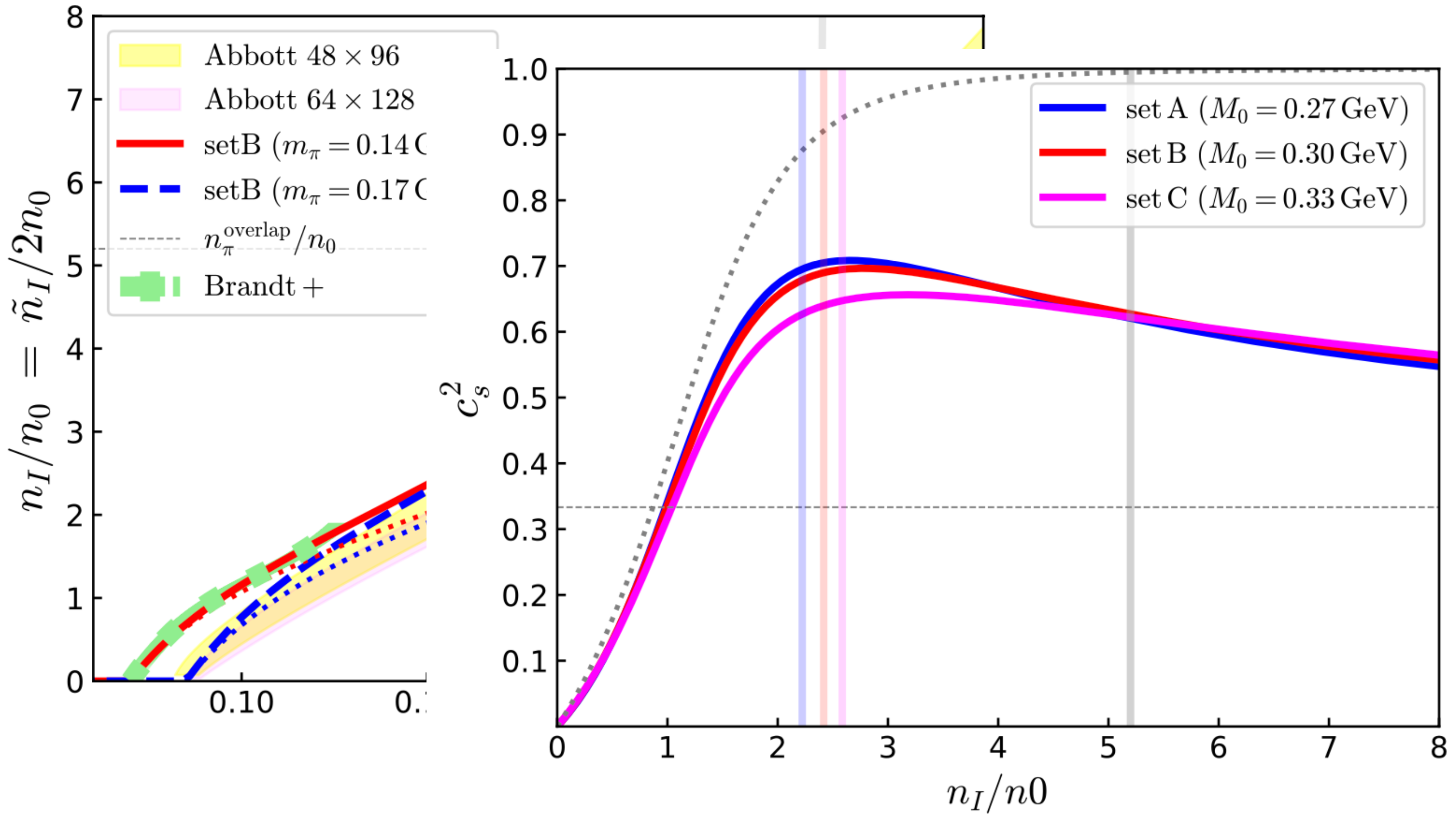
[model study, TK-Suenaga '21]



[model study, Chiba-TK '23; TK-Suenaga-Chiba '24]

Peak in the BEC-BCS type crossover

Hints for new scale & saturation



Back Up

Stiff quark matter

The appearance of c_s^2 peak is characteristic in the QHC scenarios:

good baseline, but NOT necessarily sufficient for ~ 2.1-2.3$M_\odot$ NS.

(just after the crossover, quarks are not fully relativistic.)

Can the chiral restoration stiffens EOS by making quarks relativistic?

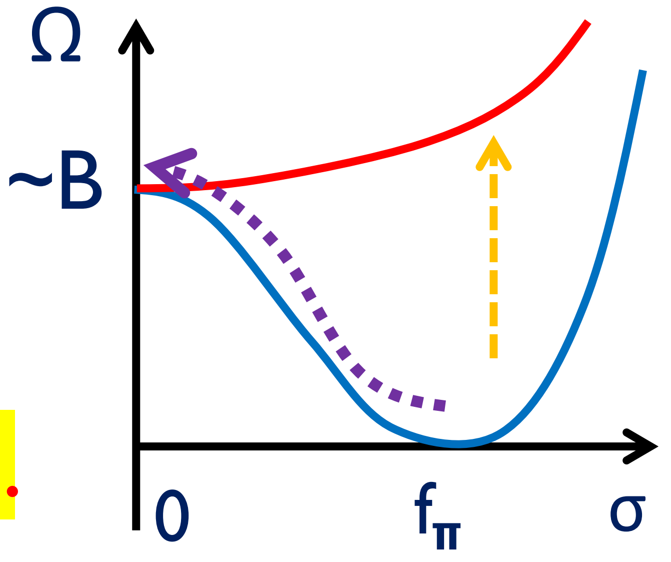
Unlikely: "*the bag constant*" from the Dirac sea

$$\varepsilon \rightarrow \varepsilon + B$$

$$P \rightarrow P - B$$

significant softening!

At this stage, we begin to discuss interactions...



Parametric analyses

[TK-Powell-Song-Baym, '14; QHC18, 19, 21]

rela. kin. energy, interactions

$$\varepsilon(n) = a n^{4/3} + b n^{\alpha}$$

(n: quark density)

→

ideal, interactions

$$P = \frac{\varepsilon}{3} + b\left(\alpha - \frac{4}{3}\right) n^{\alpha}$$

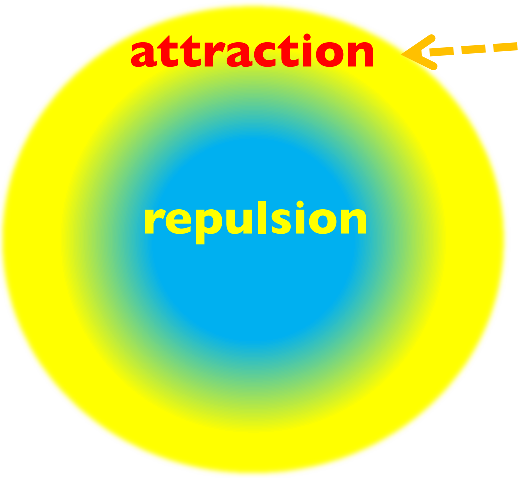
For stiff EOS:

(for large P)

for $\alpha > 4/3$: $b > 0$ (e.g. bulk repulsion, ~ $+ n_B^2/\Lambda^2$)

for $\alpha < 4/3$: $b < 0$ (e.g. surface pairings, ~ $-\Lambda^2 n_B^{2/3}$)

quark Fermi sea



2- or 3-quark correlations

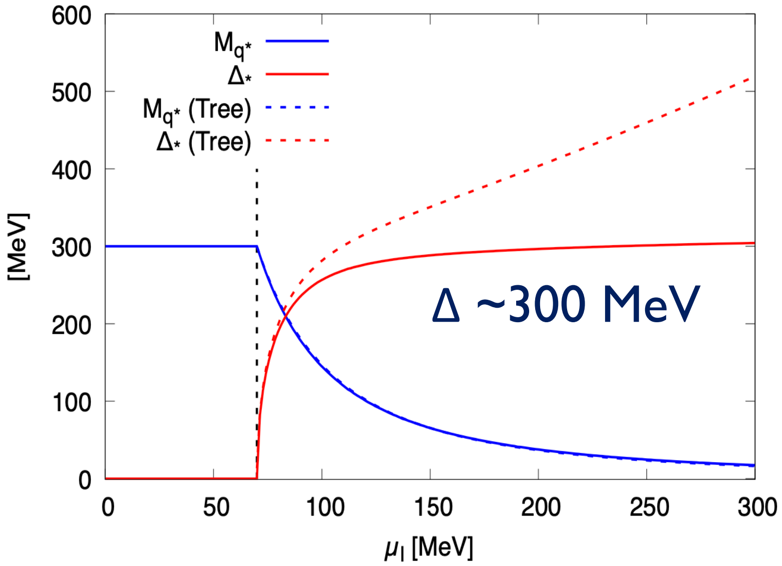
Stiff EOS from attractive forces

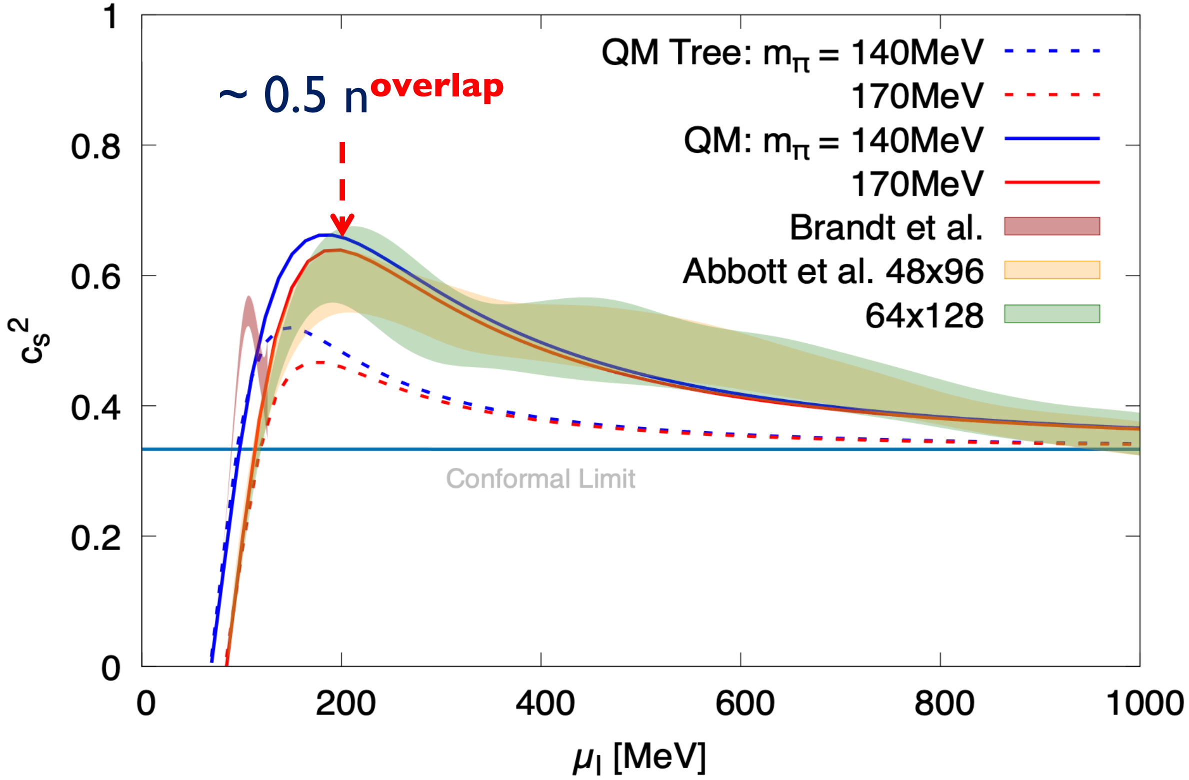
see Gordon-san's slides in the last week

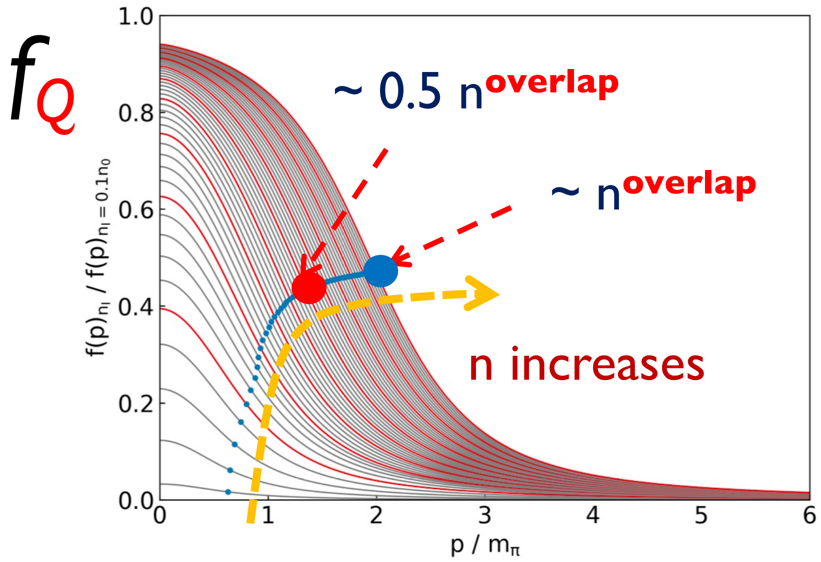
e.g. isospin QCD

quark-meson model vs lattice

[Adhikari+ '17; Chiba-TK '23, ...] [Brandt+ '22; Abbott+ '23, ...]







- Δ ~ 300 MeV (!) T_c^{QM} ~ 180 MeV vs T_c^{lat} ~ 170 MeV
- Δ > ~100 MeV → c_s^2 > 1/3 at μ_q ~ 1GeV and beyond
- c_s^2 peak found at n ~ 0.5 $n^{overlap}$

Summary

- *nuclear* + $R_{1.4} \sim R_{2.1}$ → *early* stiffening at ~ 0.5 n^{overlap}

  (beyond simple nuclear regime)

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Updated

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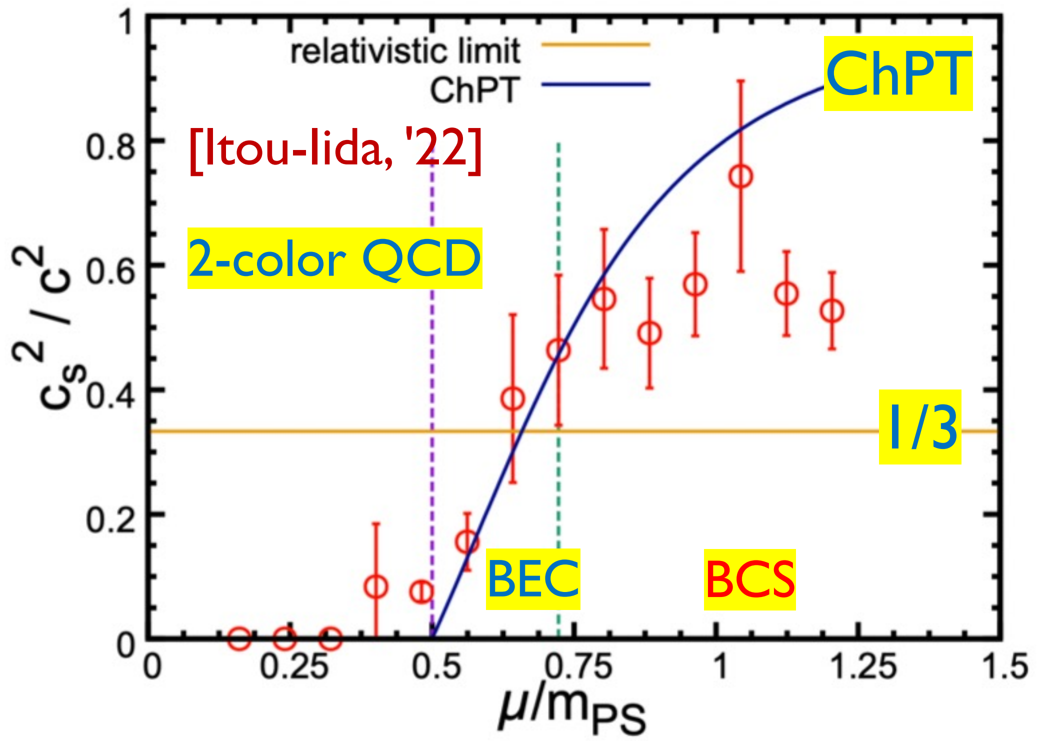
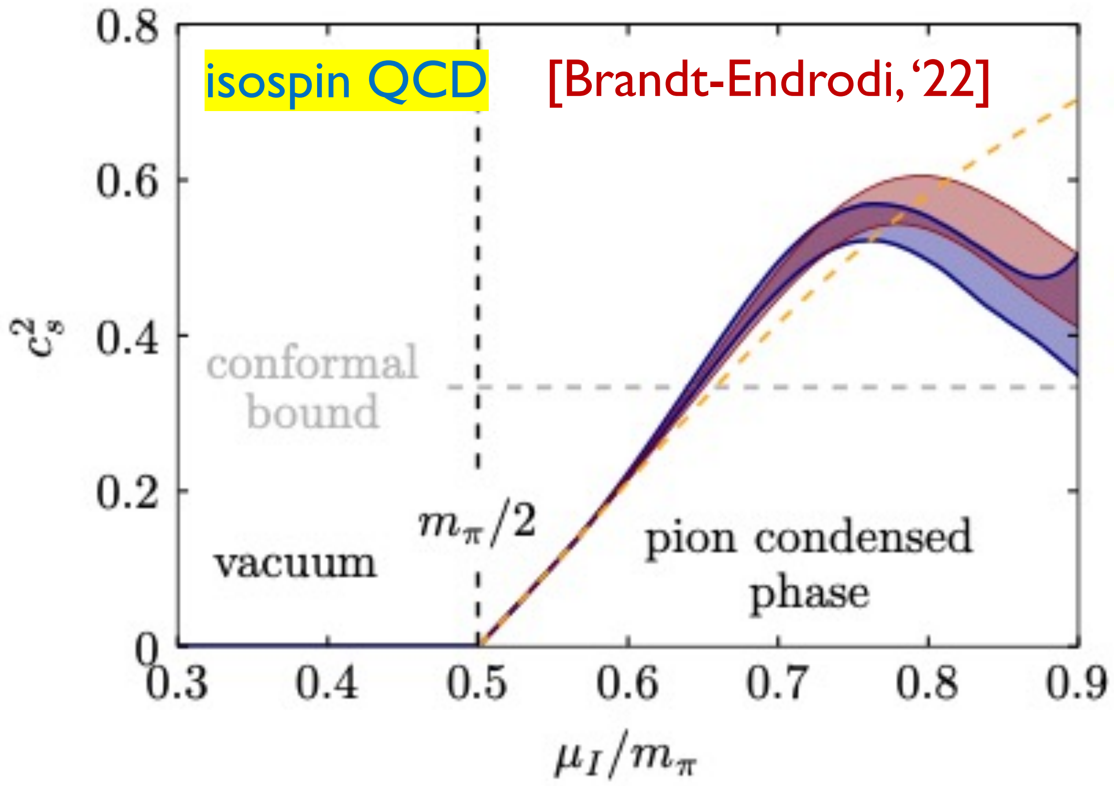


[model study, TK-Suenaga '21]



Peak in the BEC-BCS type crossover

EoS with interactions

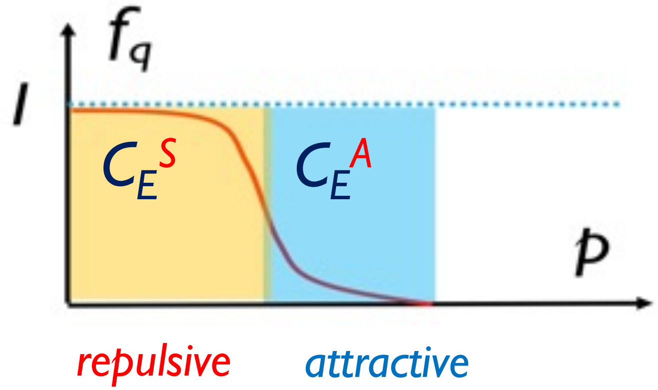
cf) [TK '21, TK-Suenaga '21]

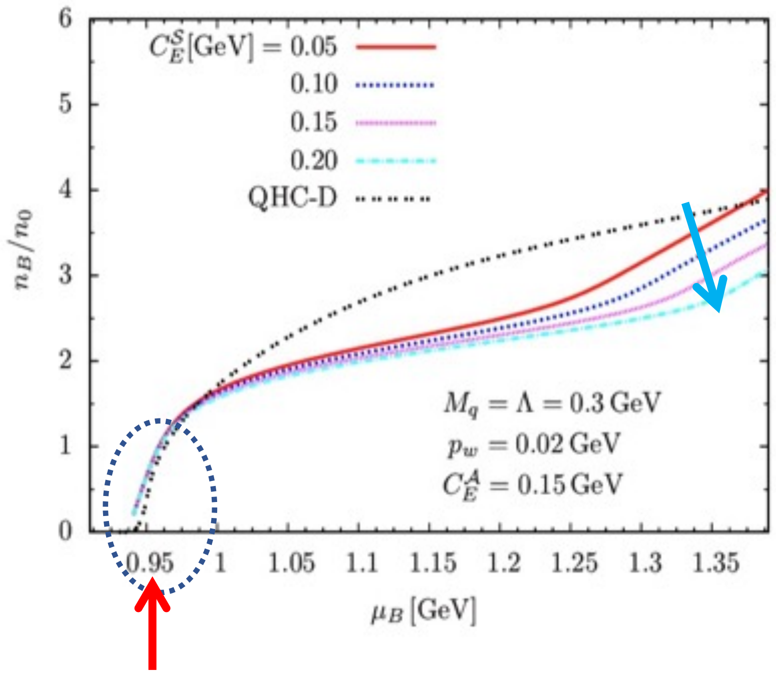
e.g.,

$$\mathcal{V}[f_Q] = -C_E^{\mathcal{A}}\underbrace{\left[1-(f_Q)^n\right]} + C_E^{\mathcal{S}}\underbrace{(f_Q)^n}$$

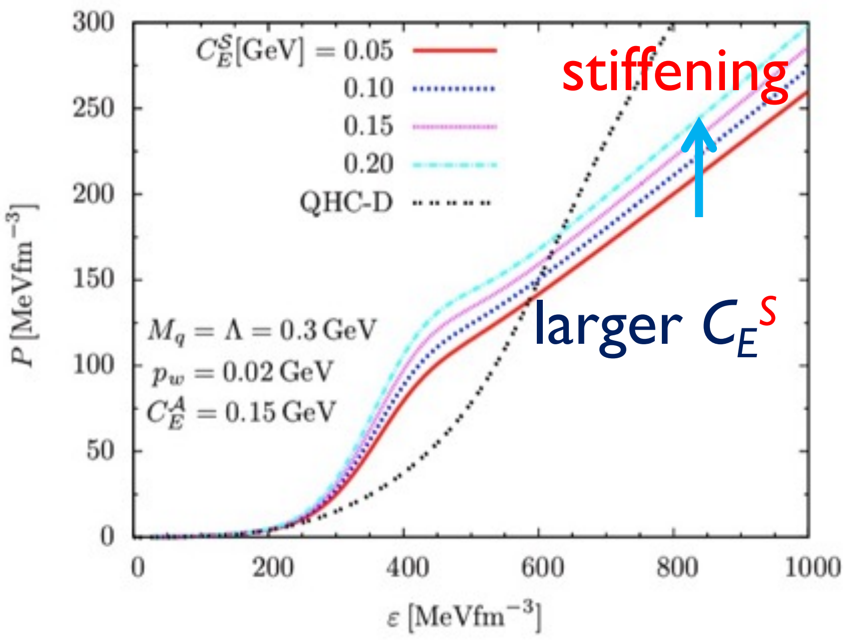
$\rightarrow$ 1 (dilute) $\qquad\qquad$ $\rightarrow$ 0 (dilute)

$\rightarrow$ 0 (dense) $\qquad\qquad$ $\rightarrow$ 1 (dense)

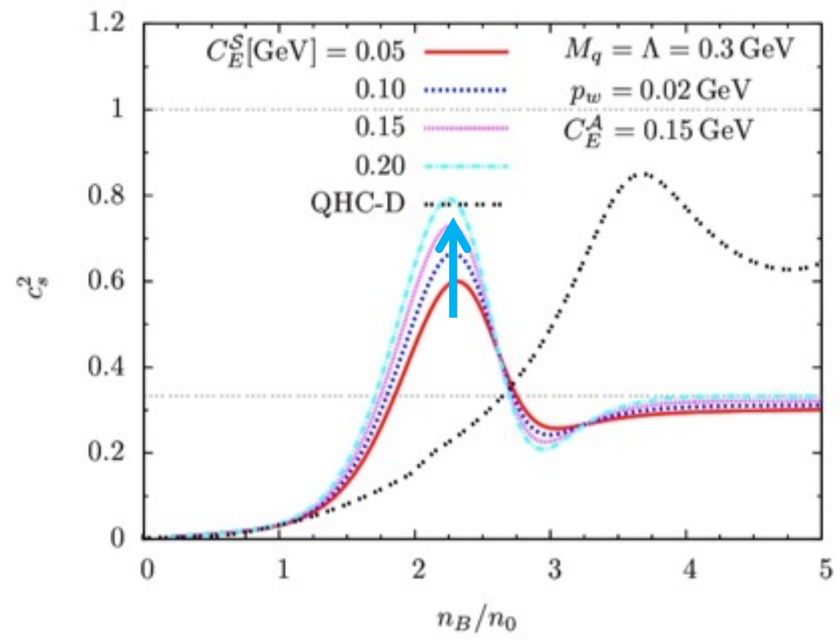




adjust $C_E{}^A$ (fit M_B = 939 MeV)



high density stiffening



stronger peak in c_s

Underlying picture (guess)

- *Gluons remain non-perturbative at 5-10*n_0

  (see, e.g., lattice results for 2-color & isospin QCD)

- *Chiral restoration occurs mildly*

} implicitly included in IdylliQ type models

- *Continuity*: interactions in quark matter should have *natural counterpart* in hadron physics

Short range correlations in a baryon:

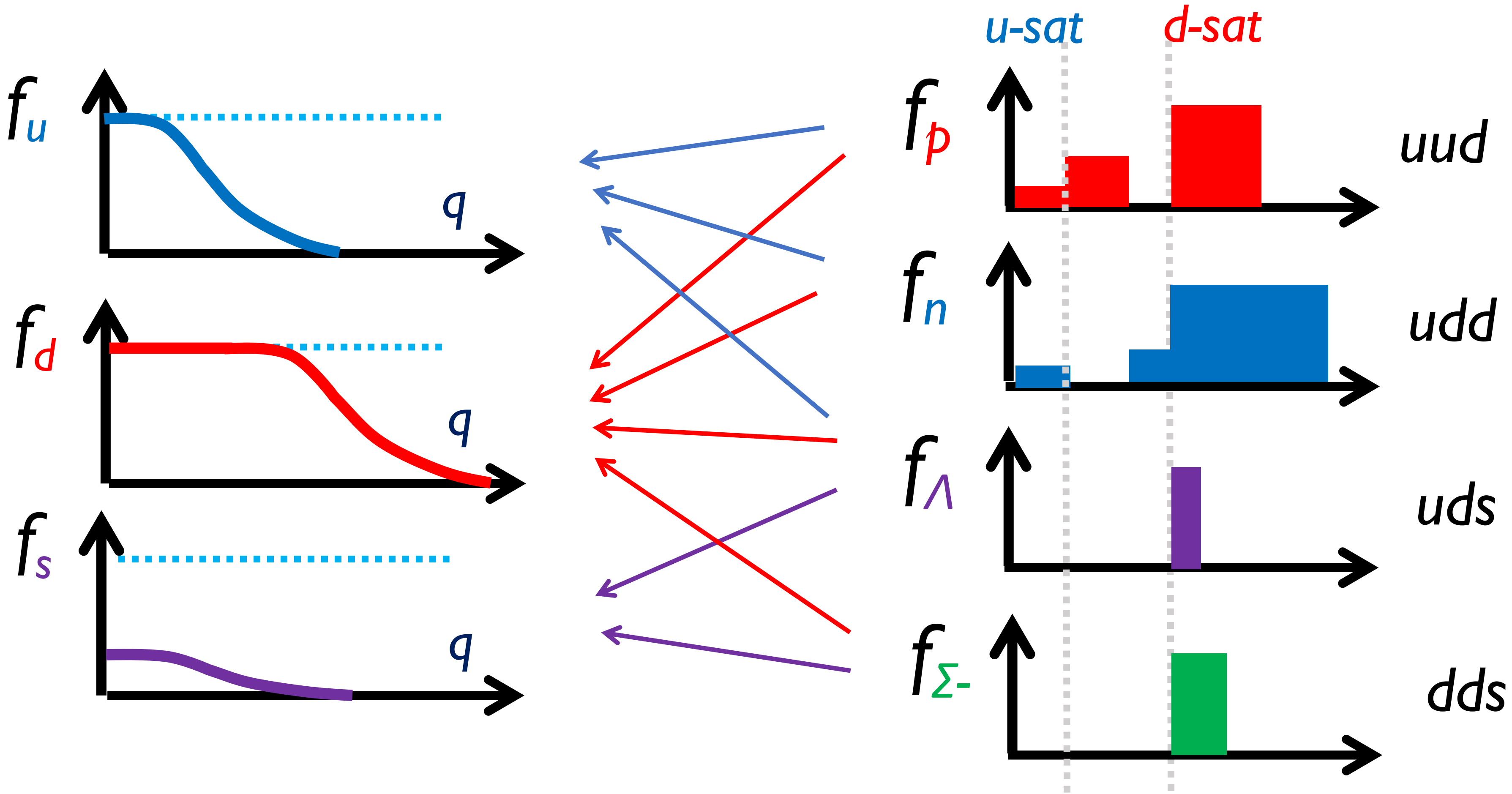
my favorite: *color-electric* & *magnetic interactions*

Multi-hadron extension

[Fujimoto-TK-McLerran, in prep.]

$$f_{\mathrm{Q}}(\boldsymbol{q}) = \sum_{B=p,n,\Sigma,\cdots} N_{\mathrm{Q}}^{\mathrm{B}} \int_{\boldsymbol{k}} f_{\mathrm{B}}(\boldsymbol{k}) \varphi\left(\boldsymbol{q} - \frac{\boldsymbol{k}}{N_{\mathrm{c}}}\right)$$

Q = u, d, s



and so on...

saturation constraints

flavor correlations

Summary

- Soft-to-stiff EOS
- quark-exchange and soft-deconfinement
- quark saturation effects, can be relevant at 2-3n_0 (!)
- not addressed (please ask in Q&A or personally) :

relevant interactions at high density

hyperon puzzle

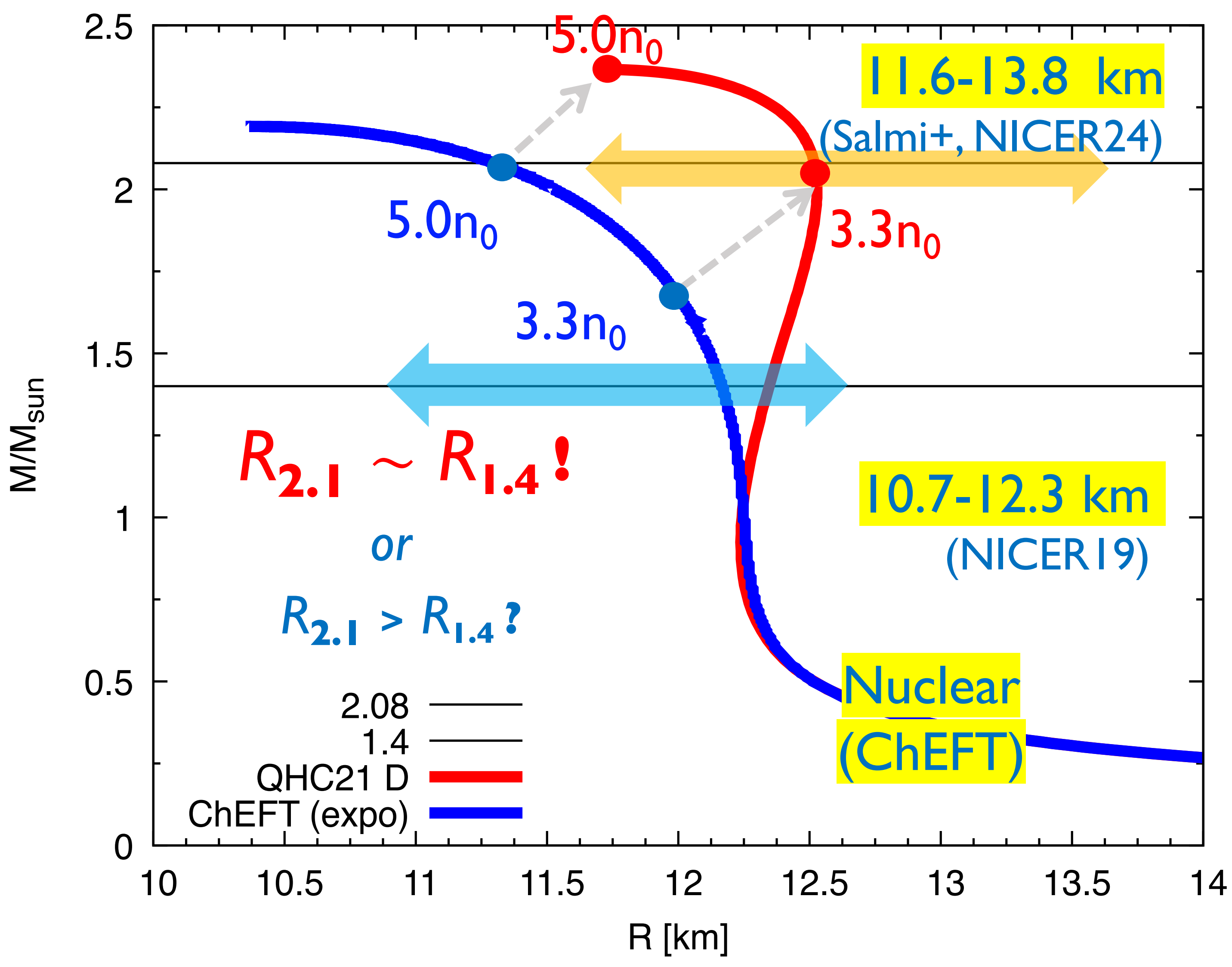
finite temperature effects

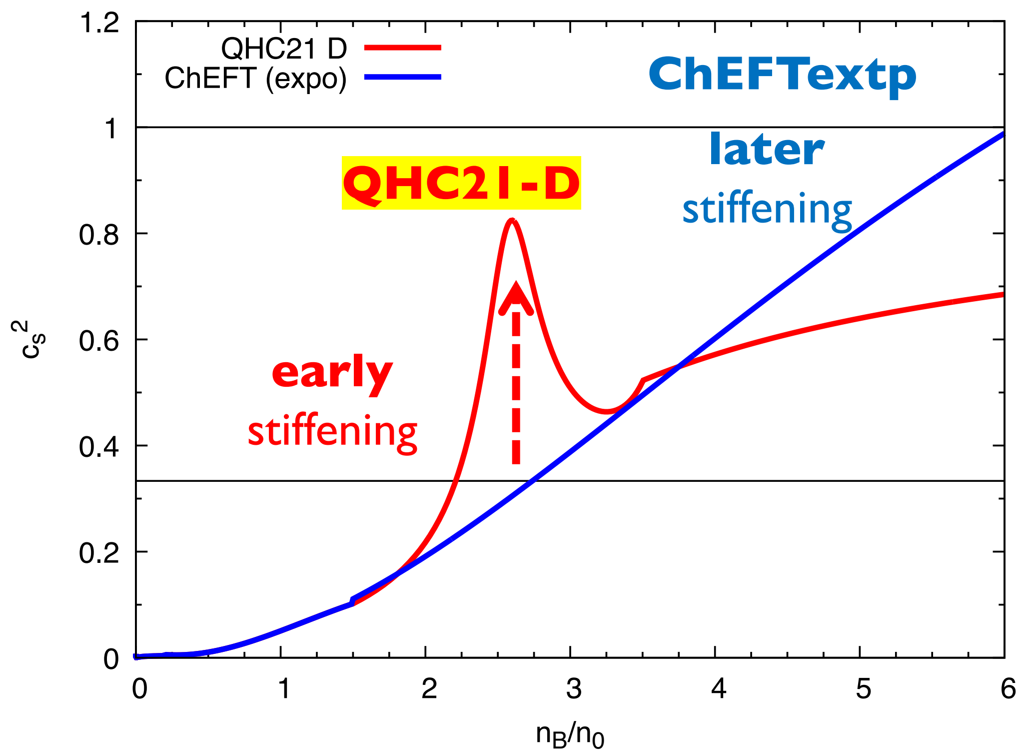
proof of concept: isospin QCD in lattice simulations

....

Early vs later stiffening: QHC21 vs ChEFTextp

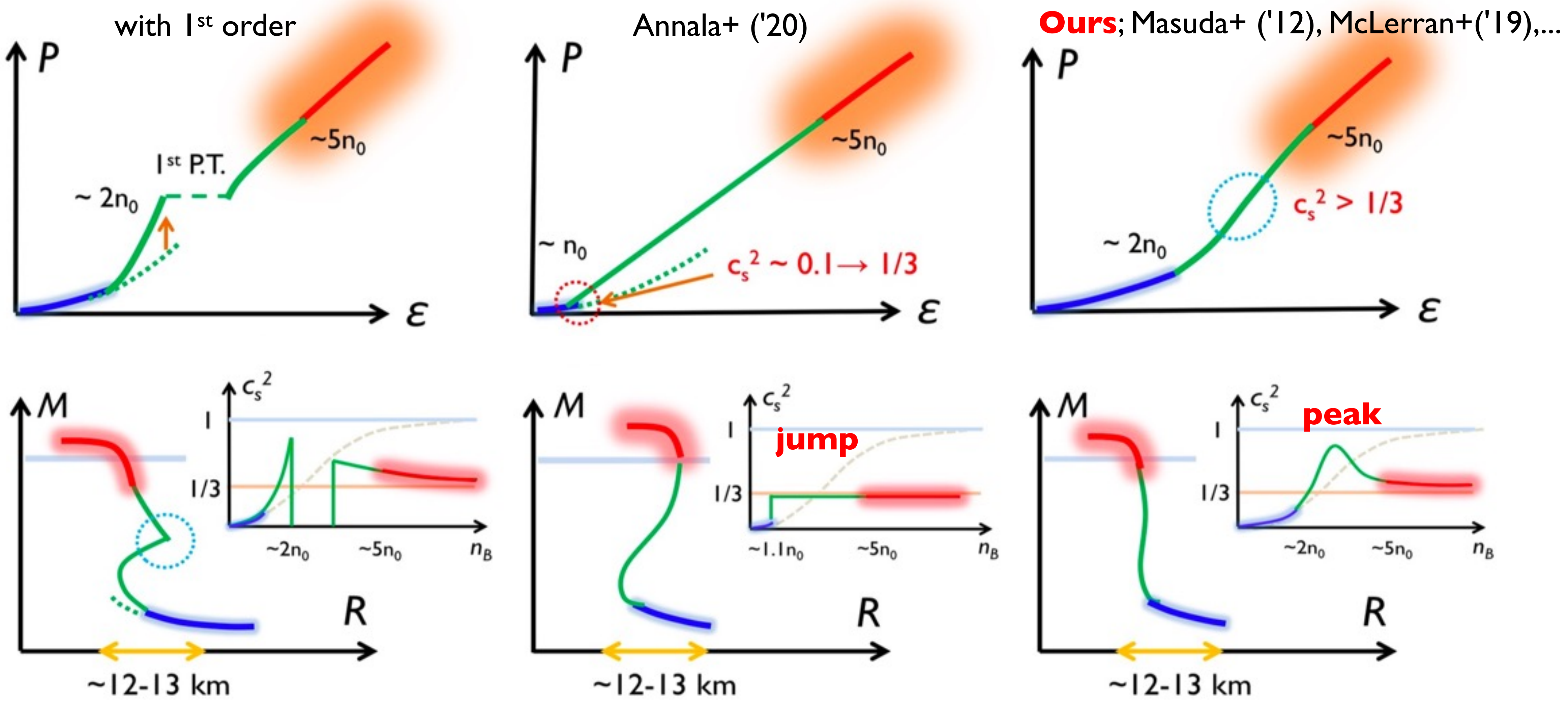
[TK-Hatsuda-Baym '21]





$2\text{-}3n_0$: already beyond purely nucleonic regime?

Three possible scenarios



→ $R_{1.4}$ and $R_{2.1}$?

→ nuclear physics ?

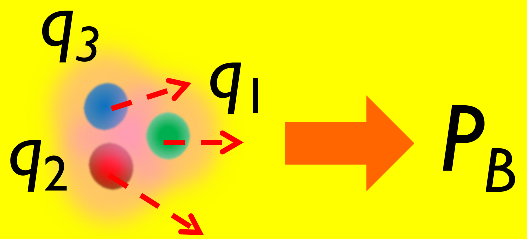
→ my favorite

Quarks in a baryon

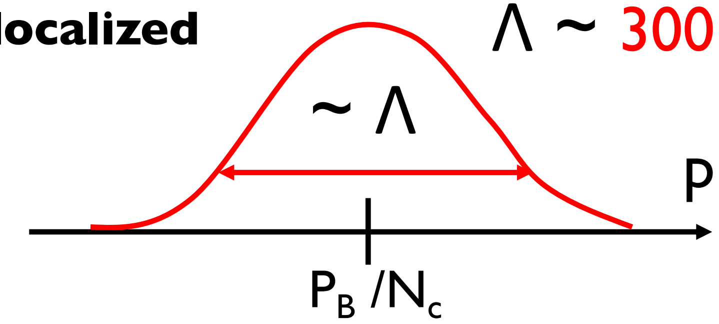
N_c (=3): number of colors

probability density:

$$\varphi(\boldsymbol{q};\boldsymbol{P}_{\rm B}) = \mathcal{N} e^{-\frac{1}{\Lambda^2}\left(\boldsymbol{q}-\frac{\boldsymbol{P}_{\rm B}}{N_{\rm c}}\right)^2}$$



localized



Λ ~ 300 MeV

variance: $\left\langle \left(\boldsymbol{p} - \frac{\boldsymbol{P}_B}{N_c}\right)^2 \right\rangle \sim \Lambda^2$ *energetic !*

→ large *"mechanical"* pressure

$$\langle E_q(\boldsymbol{p})\rangle_{\boldsymbol{P}_B} = \mathcal{N}\int_{\boldsymbol{p}} E_q(\boldsymbol{p}) e^{-\frac{1}{\Lambda^2}\left(\boldsymbol{p}-\frac{\boldsymbol{P}_B}{N_c}\right)^2} \simeq \langle E_q(\boldsymbol{p})\rangle_{\boldsymbol{P}_B=0} + \frac{1}{6}\left\langle \frac{\partial^2 E_q}{\partial p_i \partial p_i}\right\rangle_{\boldsymbol{P}_B=0}\left(\frac{\boldsymbol{P}_B}{N_c}\right)^2 + \cdots$$

average energy (quark)

x N_c x N_c

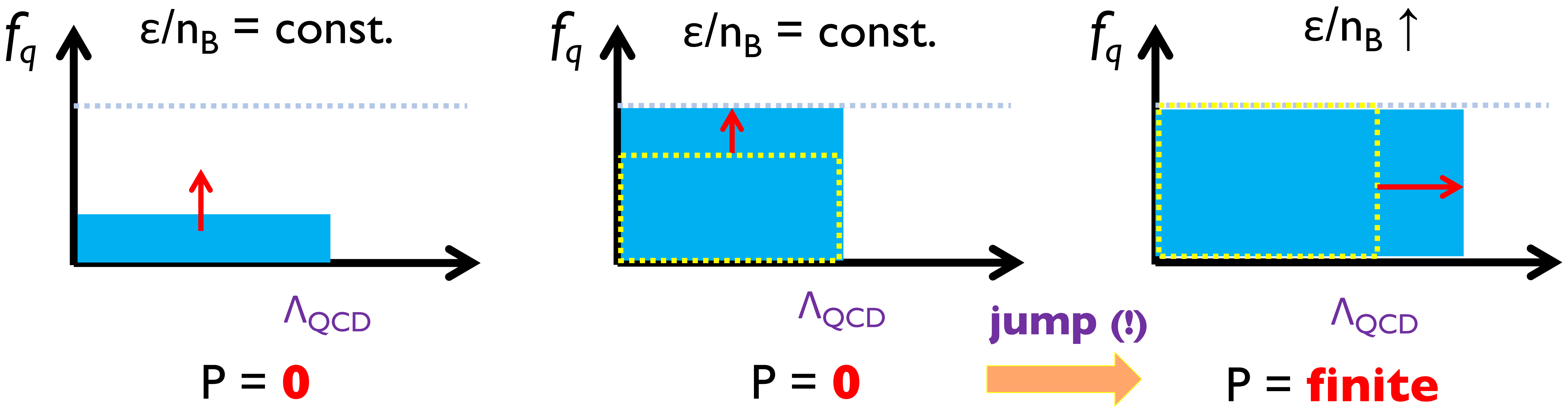
~ N_c (M_q + E_{kin}) ≫ ~ P_B^2 /($N_c E_q$)

baryon mass baryon kin. energy

Jump in pressure : schematic picture

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

energy per particle

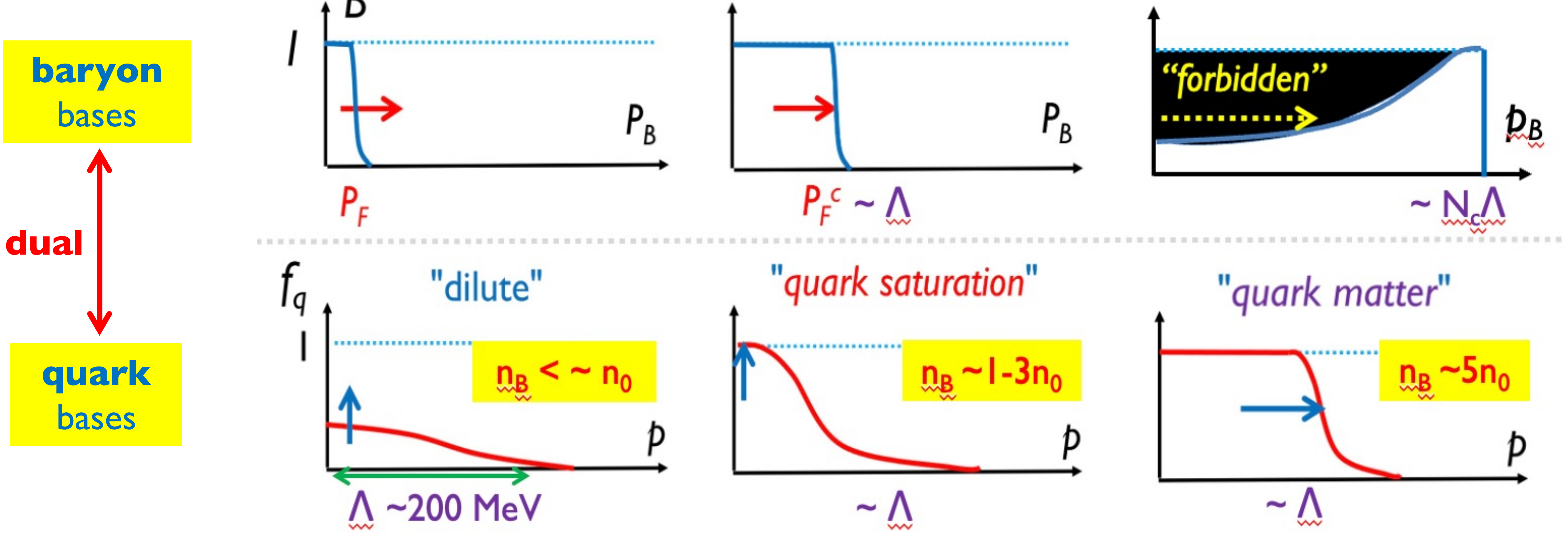


f_q continuous → ε, n_B are continuous

*Quarks do contribute to **ε** even before saturation; but to P only after the saturation!!*

Evolution of occ. probabilities

$$f_Q(\boldsymbol{q}; n_B) = \int_{\boldsymbol{P}_B} f_B(\boldsymbol{P}_B; n_B)\varphi_Q^B(\boldsymbol{q}; \boldsymbol{P}_B)$$



"quark saturation" constraint

→ **relativistic baryons at low density, n_B ~ 1-3n_0 !**

cf) McLerran-Reddy model (2019); microscopic description, TK (2021)

Quantum numbers ?

quark quantum numbers; N_c, N_f, 2-spins (for a given spatial w.f.)

how many **baryon species** are needed to **saturate** quark states?

$\rightarrow$ need only **$2N_f$ = 6** species for $N_f = 3$

(full members of singlet, octet, decuplet are NOT necessary)

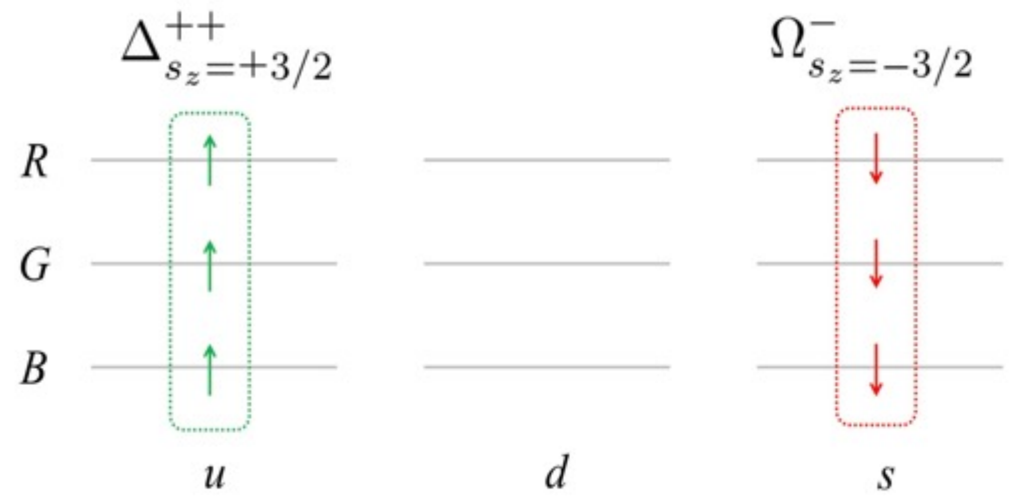
convenient **color-flavor-spin** bases

[neglect N-Δ splitting etc. for simplicity]

$$\Delta^{++}_{s_z=\pm 3/2} = [u_R\uparrow u_G\uparrow u_B\uparrow],\quad [u_R\downarrow u_G\downarrow u_B\downarrow],$$

$$\Delta^{-}_{s_z=\pm 3/2} = [d_R\uparrow d_G\uparrow d_B\uparrow],\quad [d_R\downarrow d_G\downarrow d_B\downarrow],$$

$$\Omega^{-}_{s_z=\pm 3/2} = [s_R\uparrow s_G\uparrow s_B\uparrow],\quad [s_R\downarrow s_G\downarrow s_B\downarrow],$$



Underlying picture (guess)

- *Gluons remain non-perturbative at 5-10*n_0

  (see, e.g., lattice results for 2-color & isospin QCD)

- *Chiral restoration occurs mildly*

} implicitly included in IdylliQ type models

- *Continuity*: interactions in quark matter should have *natural counterpart* in hadron physics

Short range correlations in a baryon:

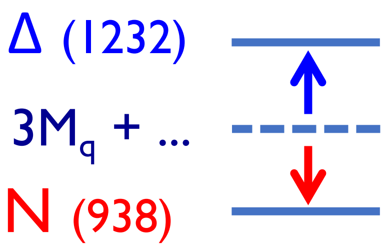
my favorite: *color-electric* & *magnetic interactions*

Color-magnetic interaction play **many** roles

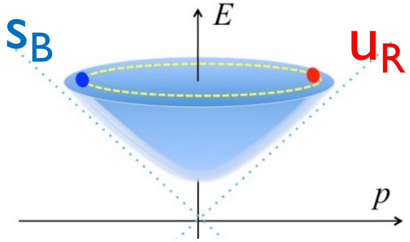
1) **Coupling** $\propto$ **velocity** ~ **p/E**

become important in relativistic regime & high density

cf)



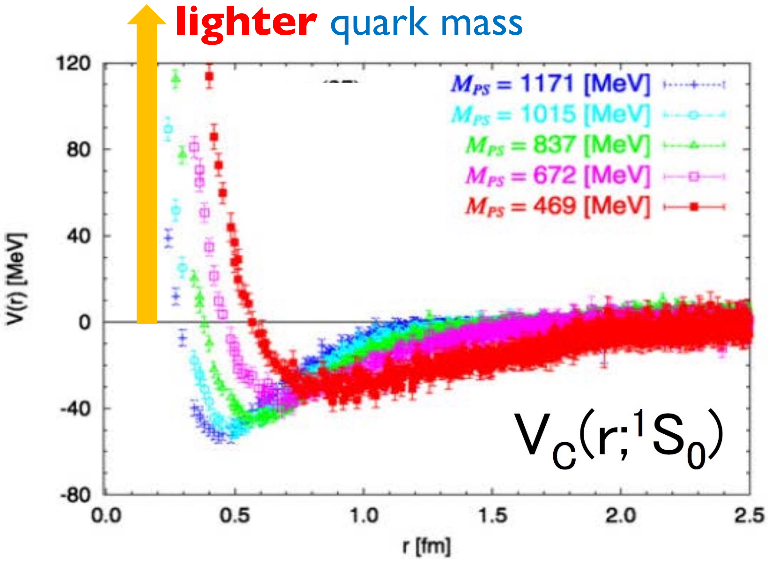
2) **Pairing** : strongly channel dependent



hadron mass ordering: N-Δ, etc. [DeRujula+ (1975), Isgur-Karl (1978), ...]

color-super-conductivity [Alford, Wilczek, Rajagopal, Schafer,... 1998-]

3) **Baryon-Baryon int.** : **short-range** correlation



(**Pauli** + **color-mag.**) [Oka-Yazaki (1980),...]

channel dep. → non-universal hard core (some are attractive!)

mass dep. → stronger hard core in relativistic quarks

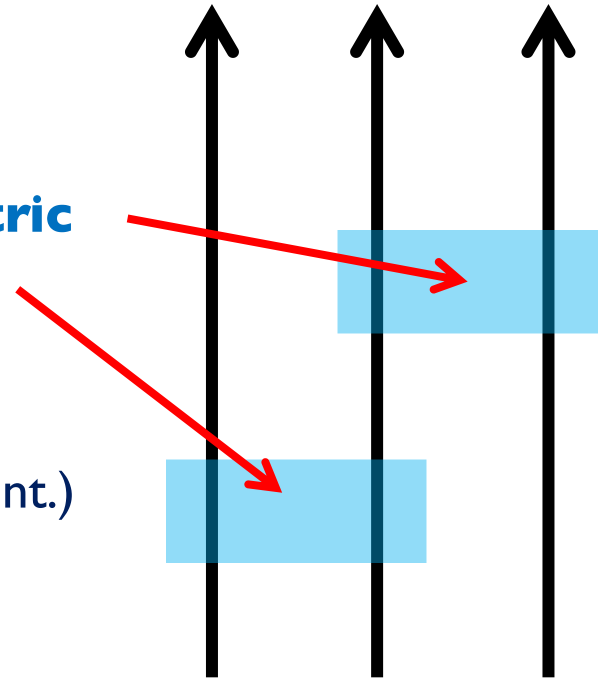
→ **consistent with the lattice QCD** [HAL-collaboration]

a baryon in dilute regime

(color-singlet)

(always) color-**antisymmetric**

(attractive **electric** int.)



e.g., **nucleons**

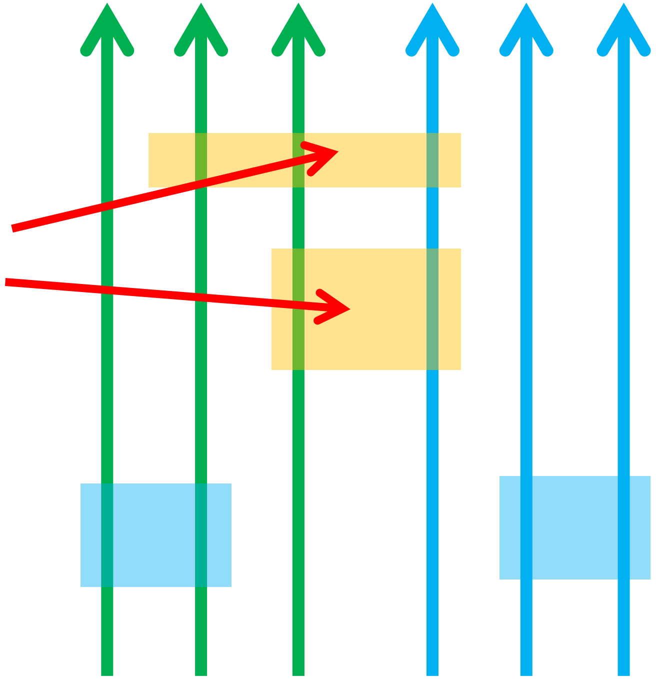
$$M_N \sim 3M_{q.} + \text{kin.} + \text{color-EM}$$

~ 940MeV ~ 1100MeV ~ −150-200MeV

in dense regime

sometimes color-**symmetric**

(repulsive)



more chances to feel repulsion

EoS with interactions

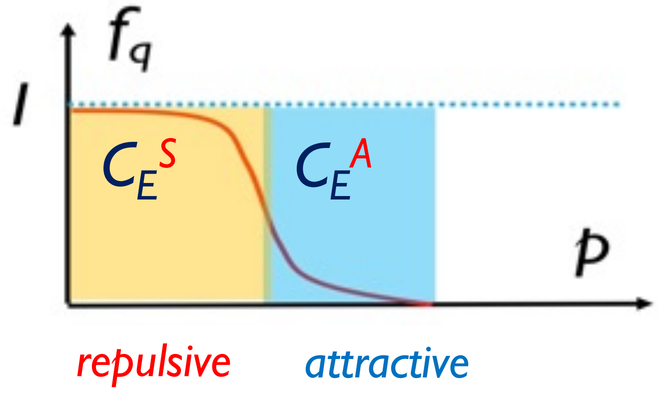
cf) [TK '21, TK-Suenaga '21]

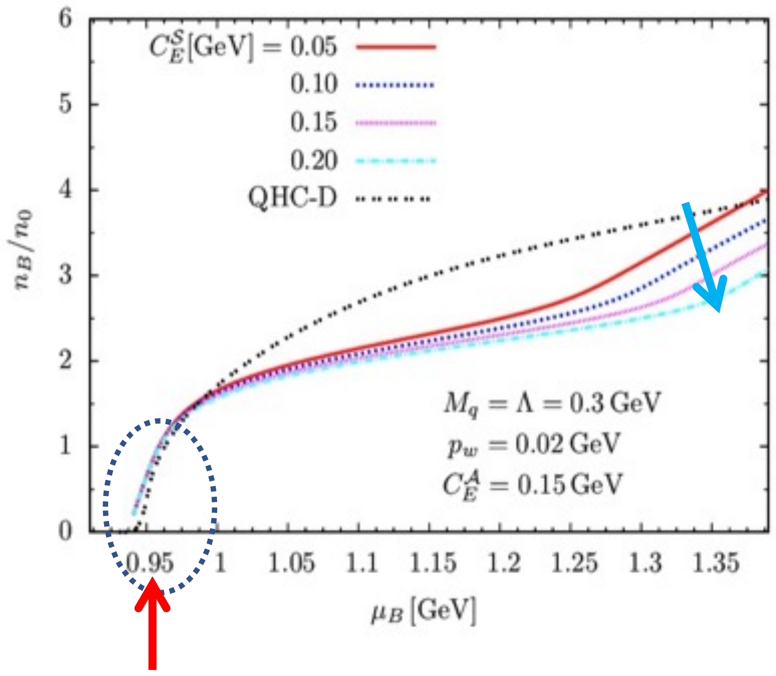
e.g.,

$$\mathcal{V}[f_Q] = -C_E^{\mathcal{A}}\left[1-(f_Q)^n\right] + C_E^{\mathcal{S}}(f_Q)^n$$

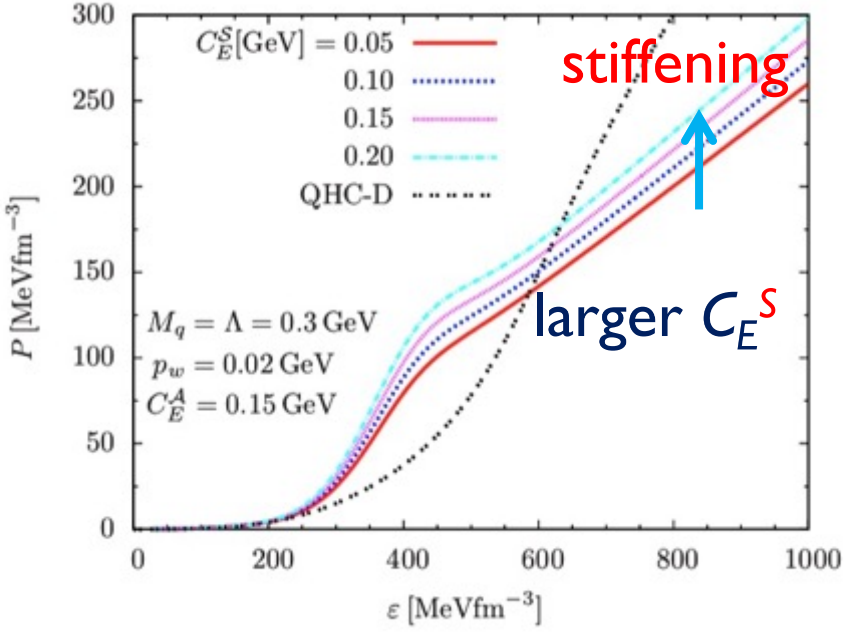
$\left[1-(f_Q)^n\right]$ → 1 (dilute), → 0 (dense)

$(f_Q)^n$ → 0 (dilute), → 1 (dense)

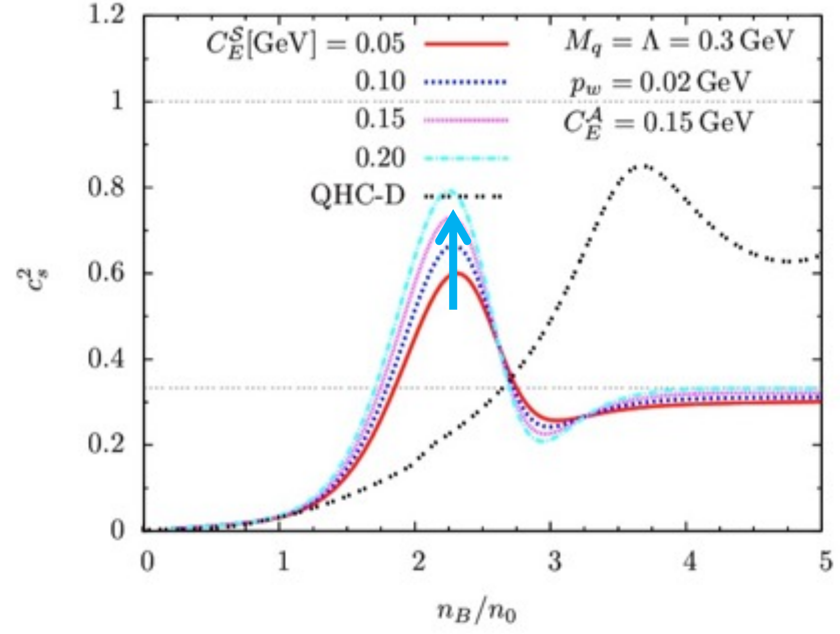




adjust C_E^A (fit M_B = 939 MeV)



high density stiffening



stronger peak in c_s

Important relations

sum rule — single baryon contain single R- or G- or B- quark

$$n_q^{R,G,B} = \int_{\mathbf{p}} f_q(p) = \int_{\mathbf{p}} \left(\int_{\mathbf{P_B}} \mathcal{B}(P_B) Q_{\rm in}(\mathbf{p}; \mathbf{P_B}) \right) = \int_{\mathbf{P_B}} \mathcal{B}(P_B) = n_B$$

energy density

$$E_B(P_B) \equiv N_c \int_{\mathbf{p}} E_q(\mathbf{p}) Q_{\rm in}(\mathbf{p}; \mathbf{P_B})$$

$$\varepsilon = \int_{\mathbf{P_B}} E_B(P_B) \mathcal{B}(P_B) = N_c \int_{\mathbf{P_B}} \left(\int_{\mathbf{p}} E_q(\mathbf{p}) Q_{\rm in}(\mathbf{p}; \mathbf{P_B}) \right) \mathcal{B}(P_B) = N_c \int_{\mathbf{p}} E_q(\mathbf{p}) f_q(p)$$

Dual expression: one can freely switch descriptions

No double counting

Finite-T model

Hadron Resonance Gas model for quark distribution

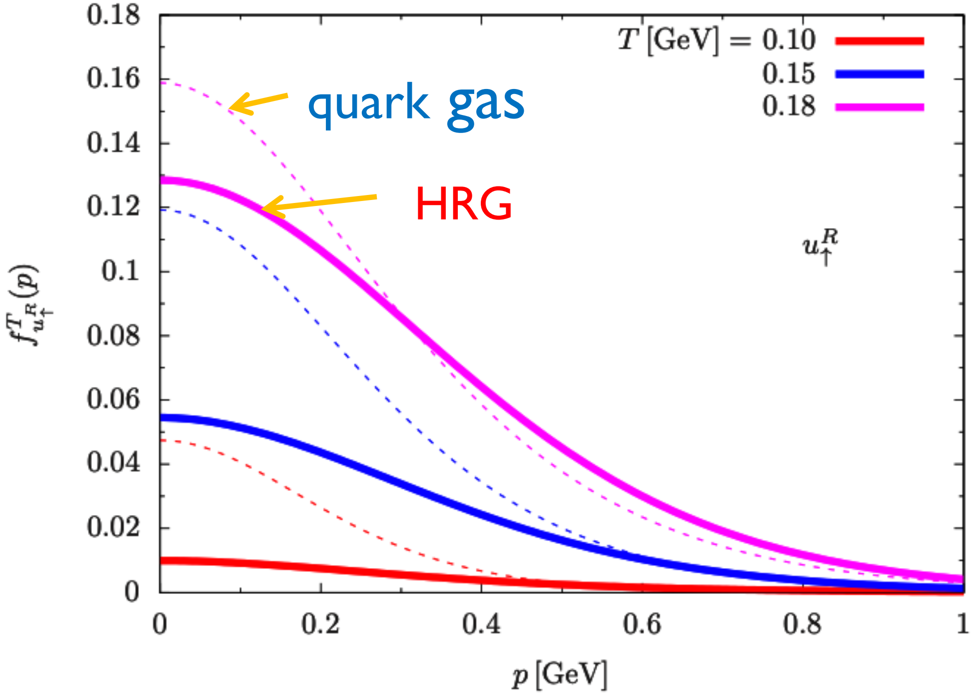
see [TK-Suenaga, '22]

$$f^T_{\mathbf{q}}(\boldsymbol{p}) = \sum_h \int_{\boldsymbol{P}_h} n^T_h(\boldsymbol{P}_h) Q^{h\mathbf{q}}_{\rm in}(\boldsymbol{p};\boldsymbol{P}_h)$$

$$n^T_h(\boldsymbol{P}_h) = [e^{E_h(\boldsymbol{P}_h)/T} - 1]^{-1}$$

- calculate quark w.f. for mesons up to L = 3, n_r = 4; E < ~ 2.5 GeV

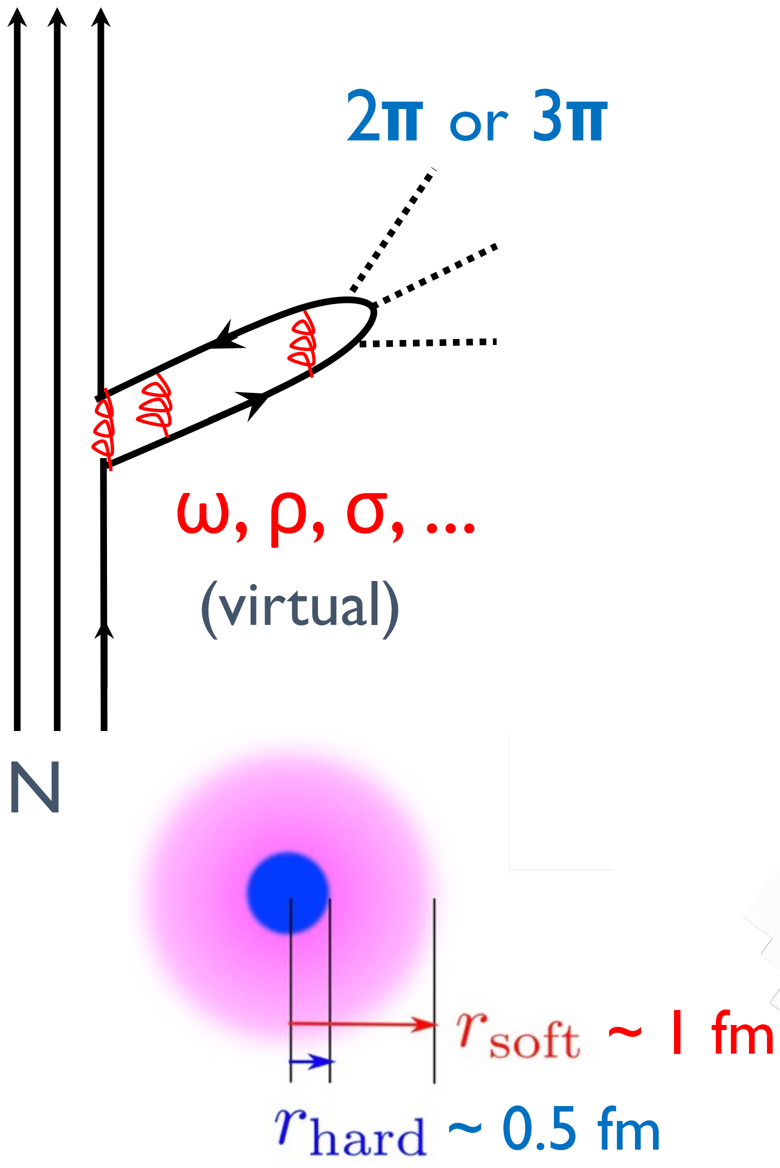
	$n_r\,^{2S+1}L_J$	$M_{\rm exp}$	$M_{\rm cal}$	$\bar{\boldsymbol{P}}^2$	$\sqrt{\langle \boldsymbol{r}^2\rangle}$	f_S	α_s
π	1^1S_0	0.14	0.16	0.47	0.50	0.70	0.80
	2^1S_0	1.30	1.28	0.43	0.98		
	3^1S_0	1.81	1.82	0.55	1.38		
	4^1S_0	2.07**	2.22	0.67	1.66		
ρ	1^3S_1	0.78	0.76	0.21	0.66	0.74	0.80
	2^3S_1	1.47	1.44	0.35	1.17		
	3^3S_1	1.91*	1.87	0.48	1.55		
	4^1S_1	2.27**	2.22	0.61	1.83		
K	1^1S_0	0.49	0.49	0.42	0.49	0.72	0.77
	2^1S_0	1.46*	1.46	0.45	0.98		
K^*	1^3S_1	0.89	0.91	0.24	0.63	0.75	0.77
	2^3S_1	1.41	1.54	0.39	1.10		

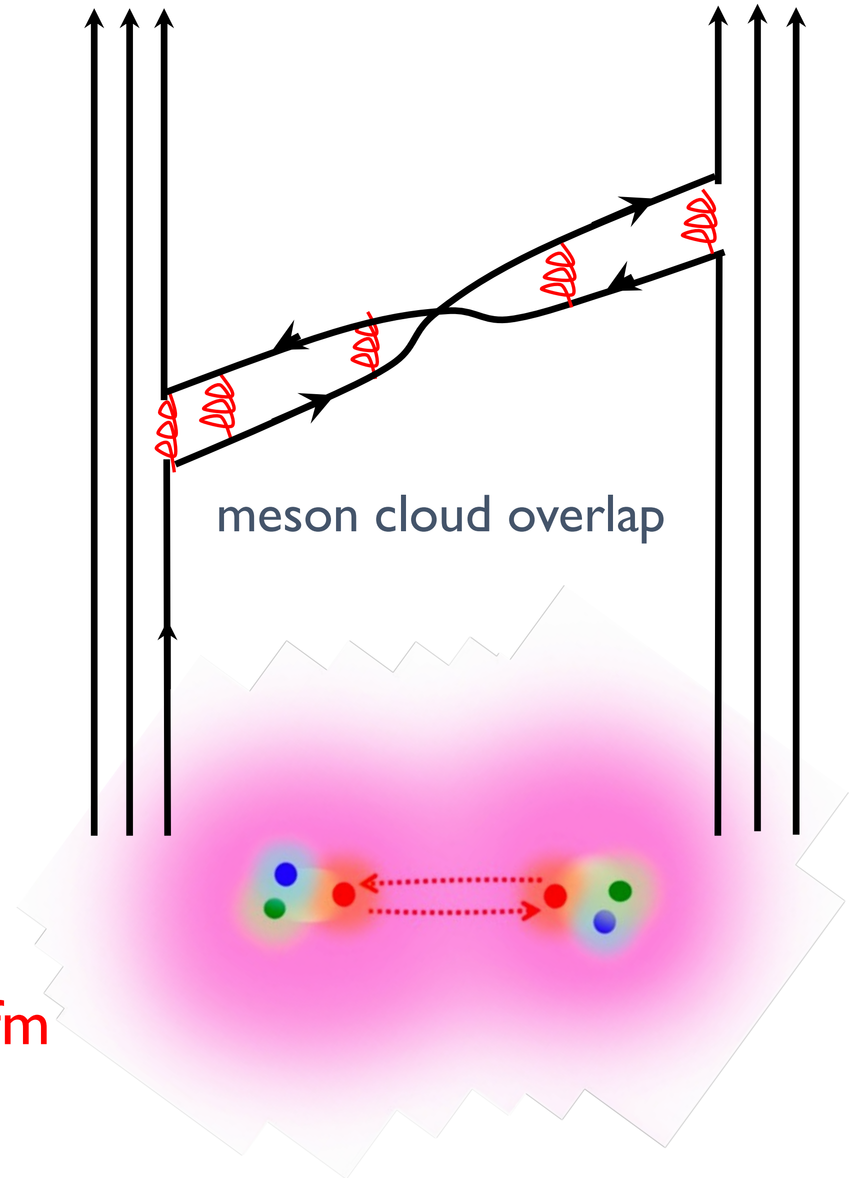


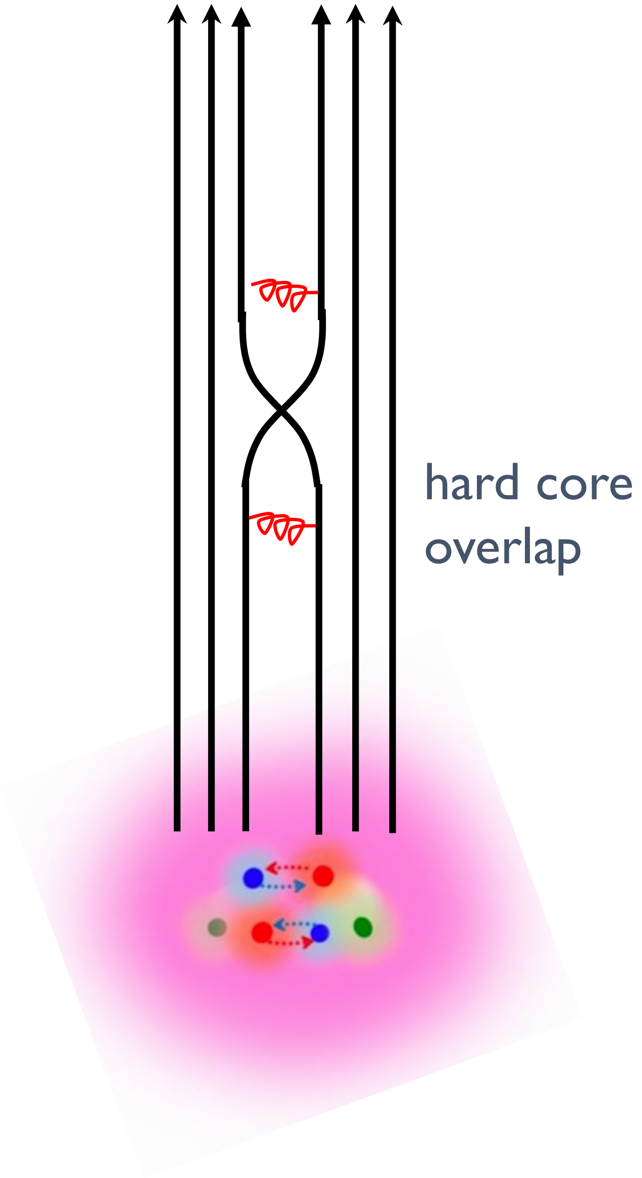
quark gas ~ HRG

at ~ 0.15-0.18 GeV

"Soft" & "Hard" scales in a nucleon

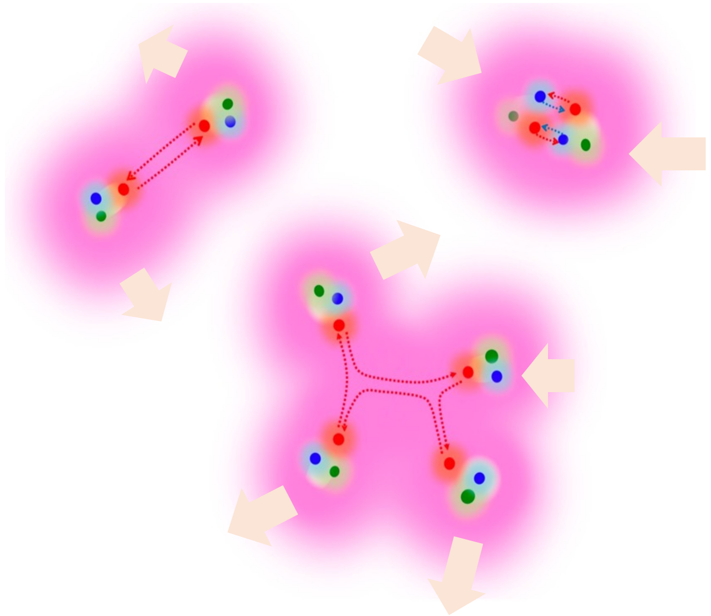


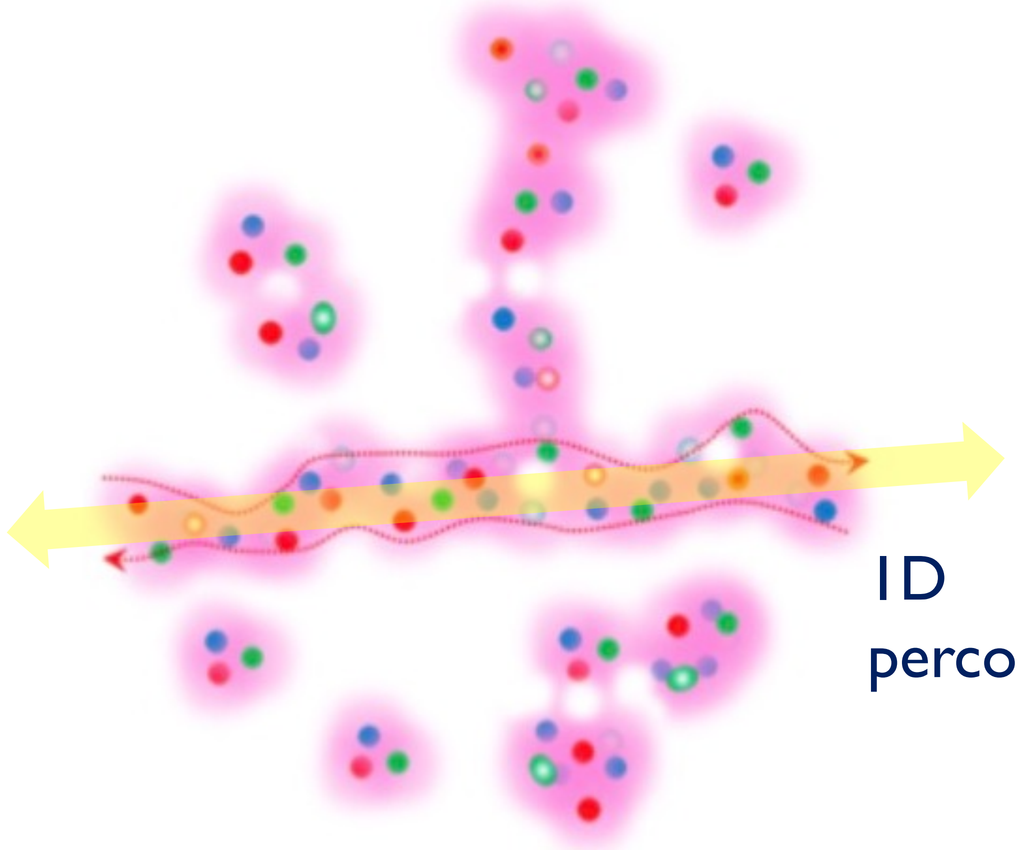




Soft Deconfinement

relating "*multi-quark exchanges*" to "*delocalization of quark w.f.*"





how can this transition be described?

Strategy (in dilute regime)

Separate **fast** quark dynamics from **slow** baryon dynamics

=> *Born-Oppenheimer* descriptions

1, The velocity : $k_B/E_B \sim 1/Nc \ll k_q/E_q \sim 1$ $(k_B \sim k_q \sim n_B^{1/3})$

$n_B = n_q^R = n_q^G = n_q^B$

2, Find quark eigenstates for **a given** baryon configuration

3, Take the "**time** average" $\rightarrow$ "**ensemble** average" of baryons

A model of **quantum** percolation

[Kirkpatrick-Eggarter '72,...]

tight-binding Hamiltonian

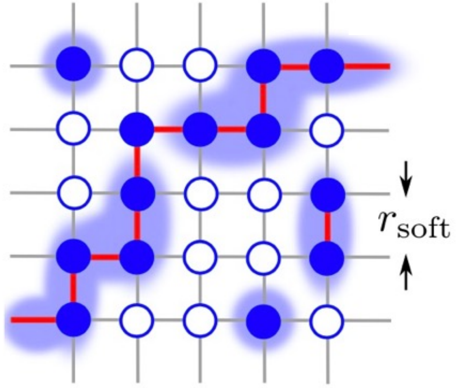
on-site energy, hopping

$$H = \sum_n |n\rangle \varepsilon_n \langle n| + \sum_{n \neq m} |n\rangle V_{nm} \langle m|$$

$|n>$: a quark state exists at a site *n*

$$V_{nm} = -V \ (V > 0)$$

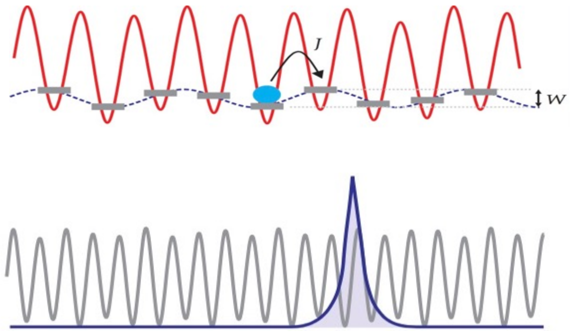
nearest-neighbor hopping



- ε,V depends on a given baryon distribution
- ε → ∞ when quarks are out of baryons
- quarks hop only within connected clusters (setup)

  → geometrical (classic) percolation must occur first

"dirty" potentials



- interference may kill amplitudes (*Anderson localization*)

  connected path does not necessarily lead to delocalization

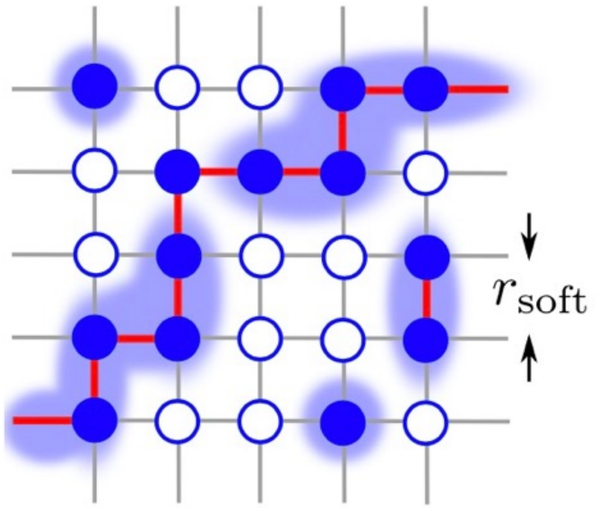
→ ***mode-by-mode*** *percolation*

(some modes delocalize earlier, the others later)

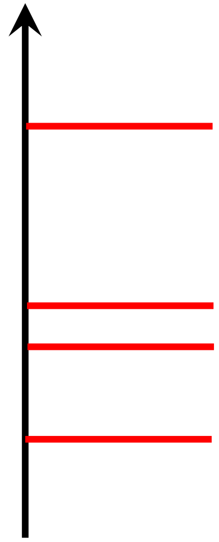
Delineating quark wavefunctions

procedures (e.g. 3D lattice model)

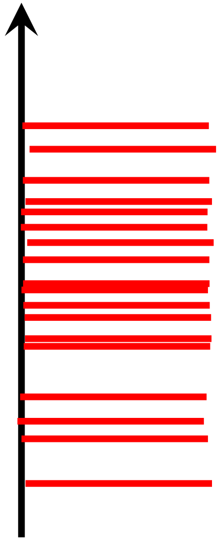
solve a **single** particle problem
for **a given geometry**



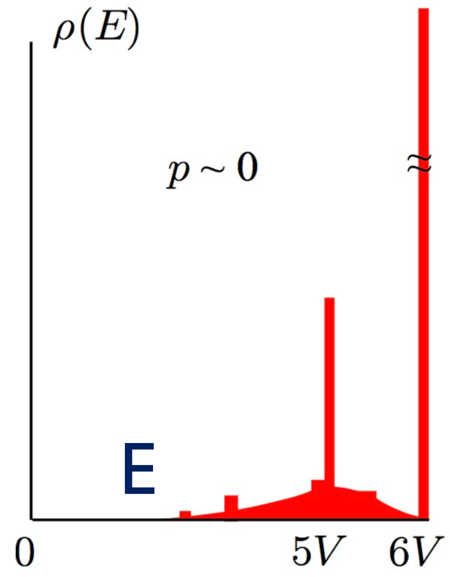
prepare single
particle levels



sum geometries
(& normalize)



make histogram
(take inf. vol. limit)

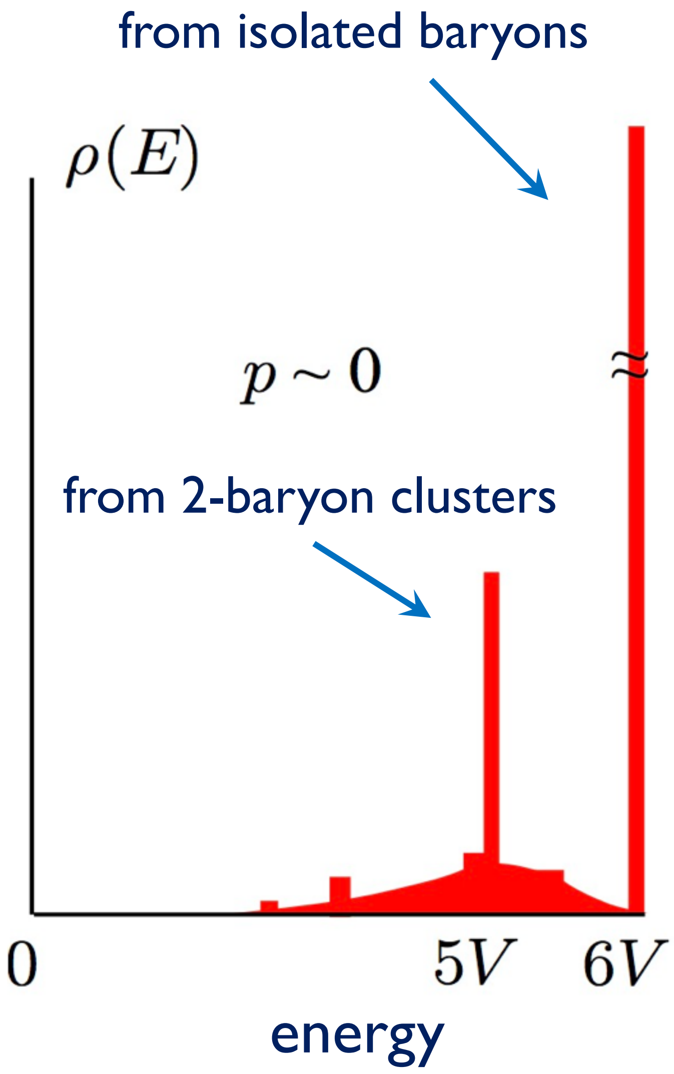


=> we diagnose the **quark contents** of given baryon configurations

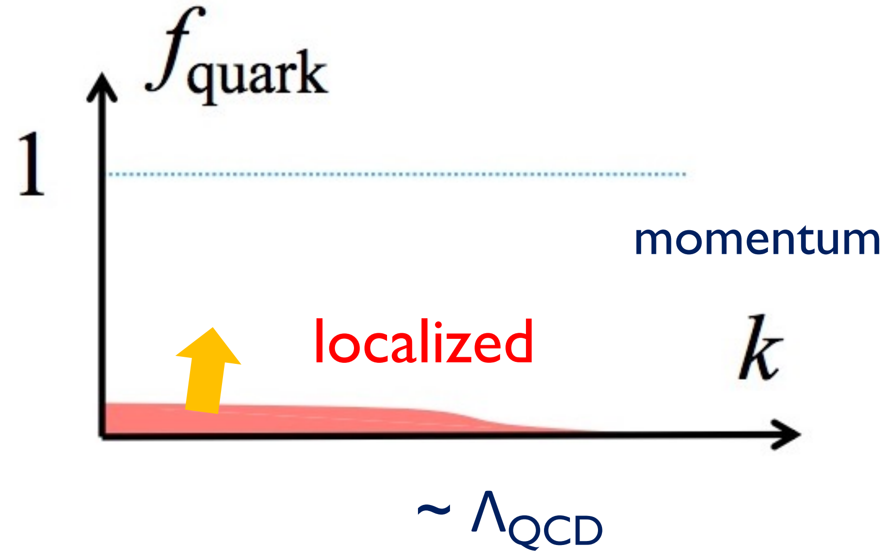
quark Fermi sea & mode-by-mode percolation

$$\int dE\rho(E) = 1$$

localized quark
→ energy ~ R_B^{-1}



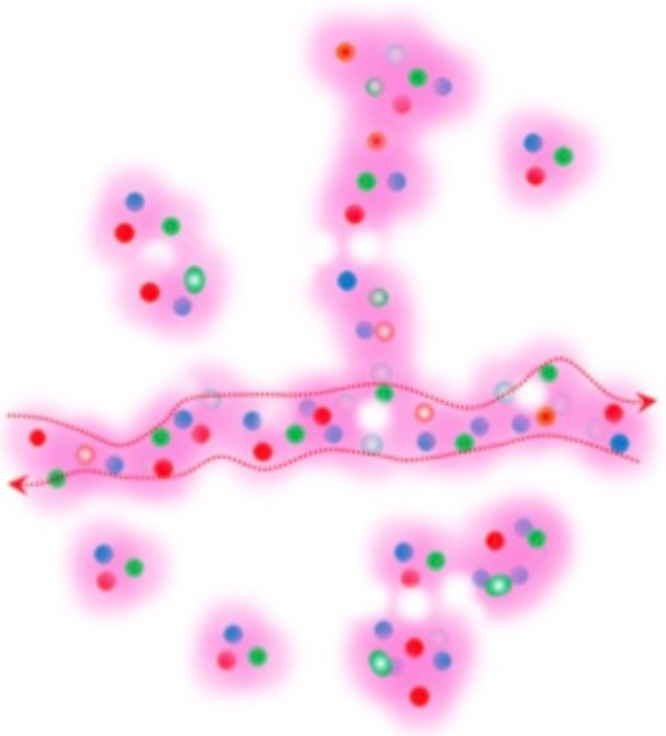
occupation probability

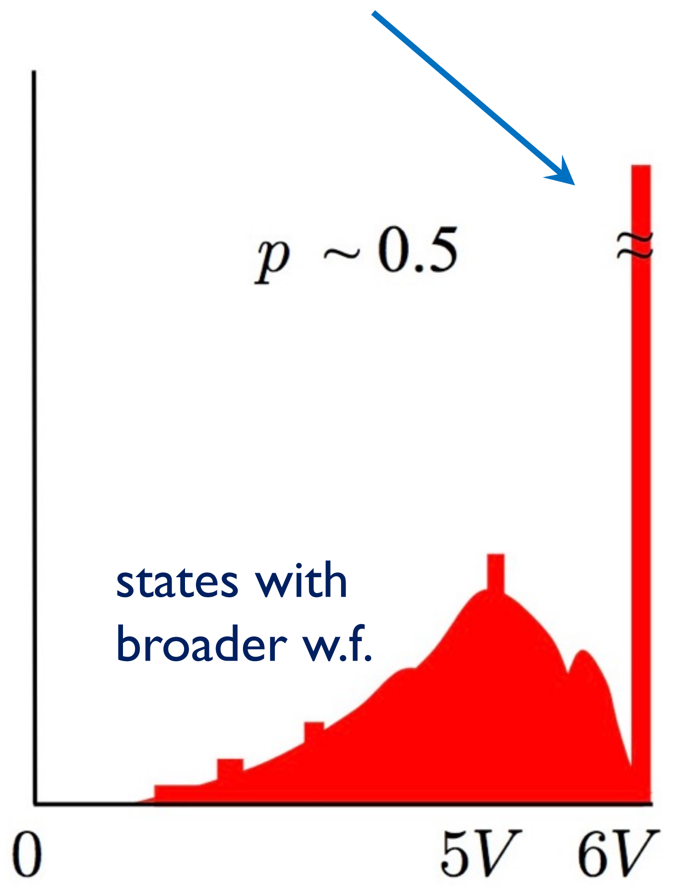


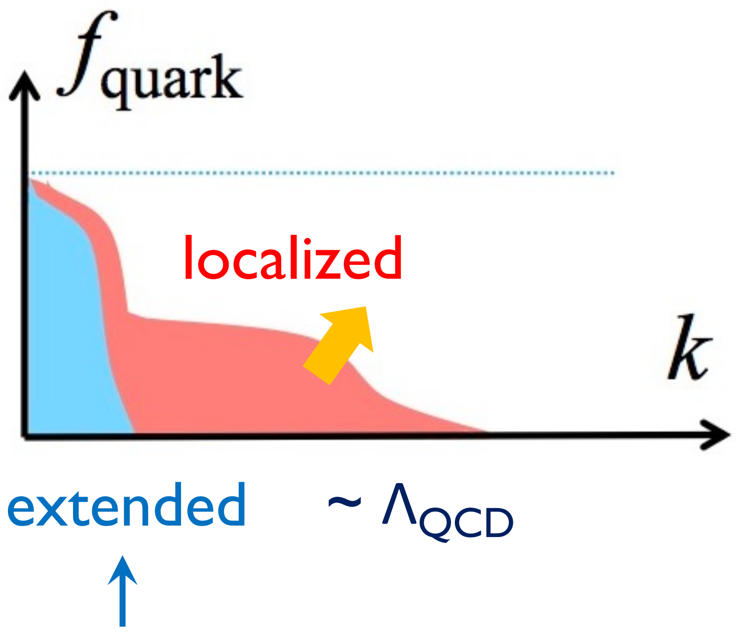
"nuclear"

quark Fermi sea & mode-by-mode percolation

$$\int dE \rho(E) = 1$$



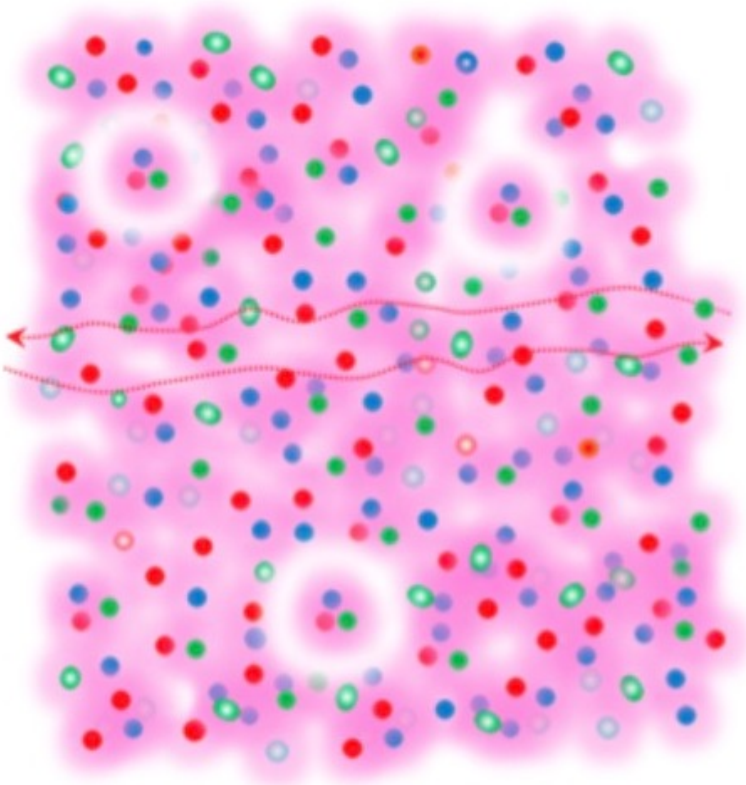


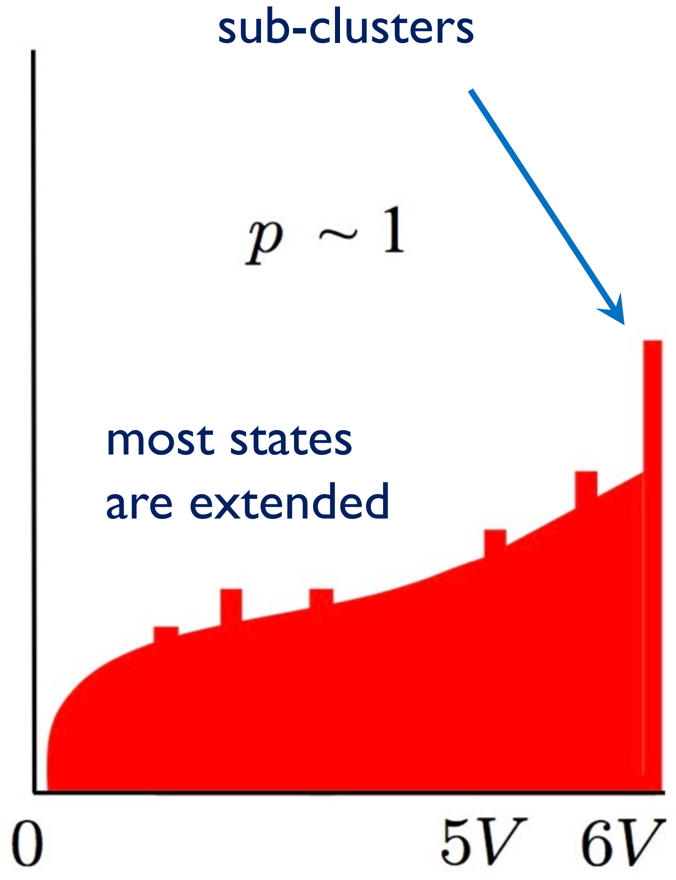


"quark-hadron continuity"

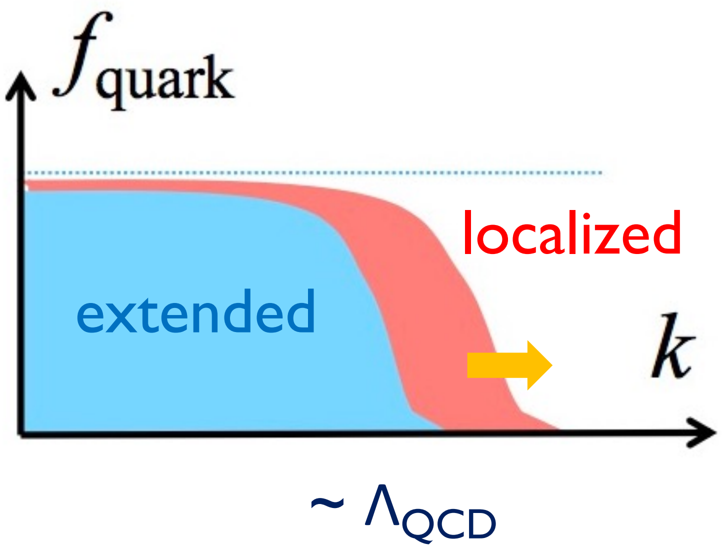
quark Fermi sea & mode-by-mode percolation

$$\int dE \rho(E) = 1$$





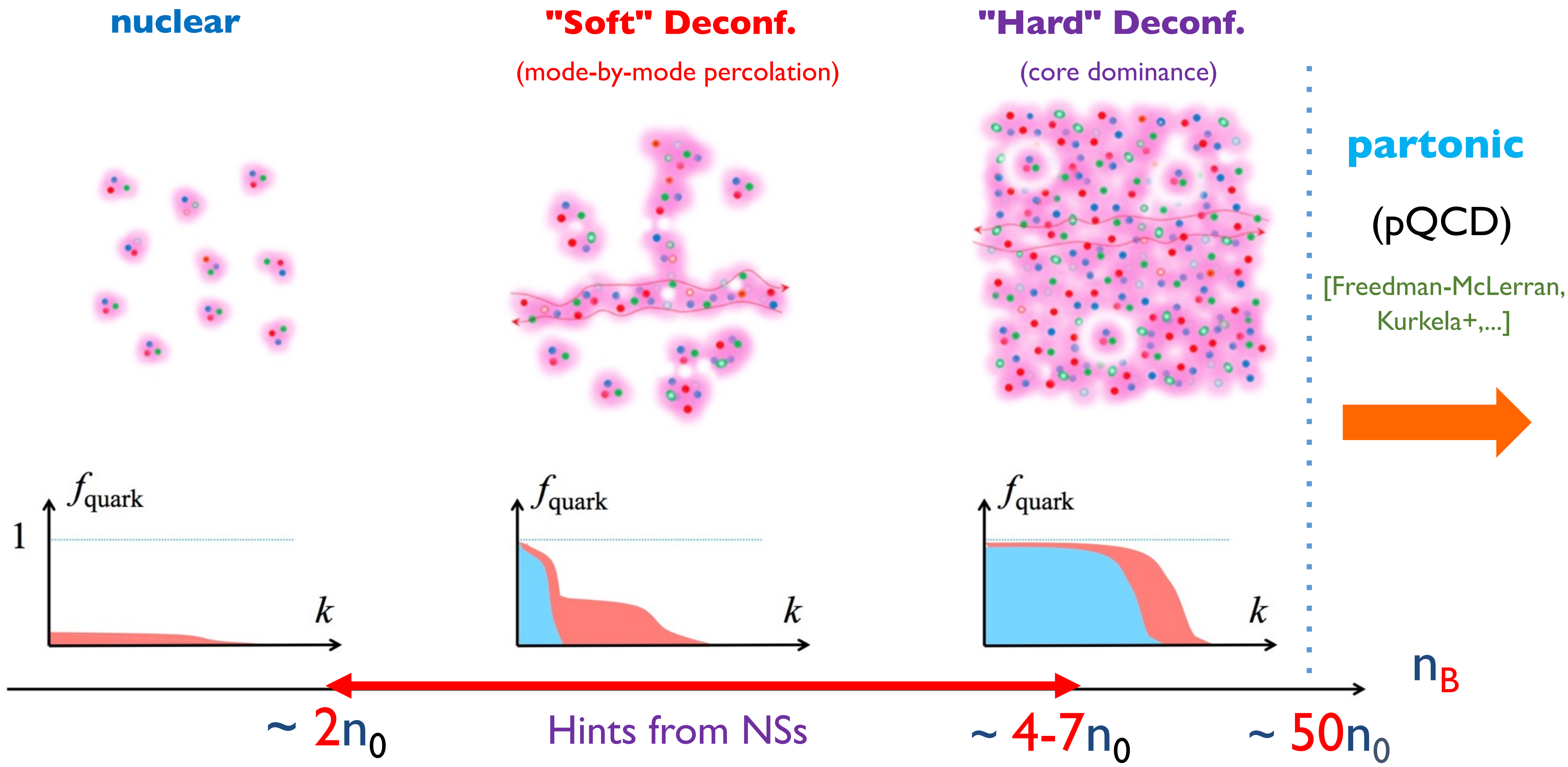
occupation probability



"quarkyonic"

[McLerran-Pisarski '06,...]

a cartoon


nuclear
"Soft" Deconf.
(mode-by-mode percolation)
"Hard" Deconf.
(core dominance)
partonic
(pQCD)
[Freedman-McLerran, Kurkela+,...]
f_{quark}
1
k
f_{quark}
k
f_{quark}
k
n_B
~ $2n_0$
Hints from NSs
~ $4\text{-}7n_0$
~ $50n_0$