Implication of Quarkyonic duality to the hyperon puzzle

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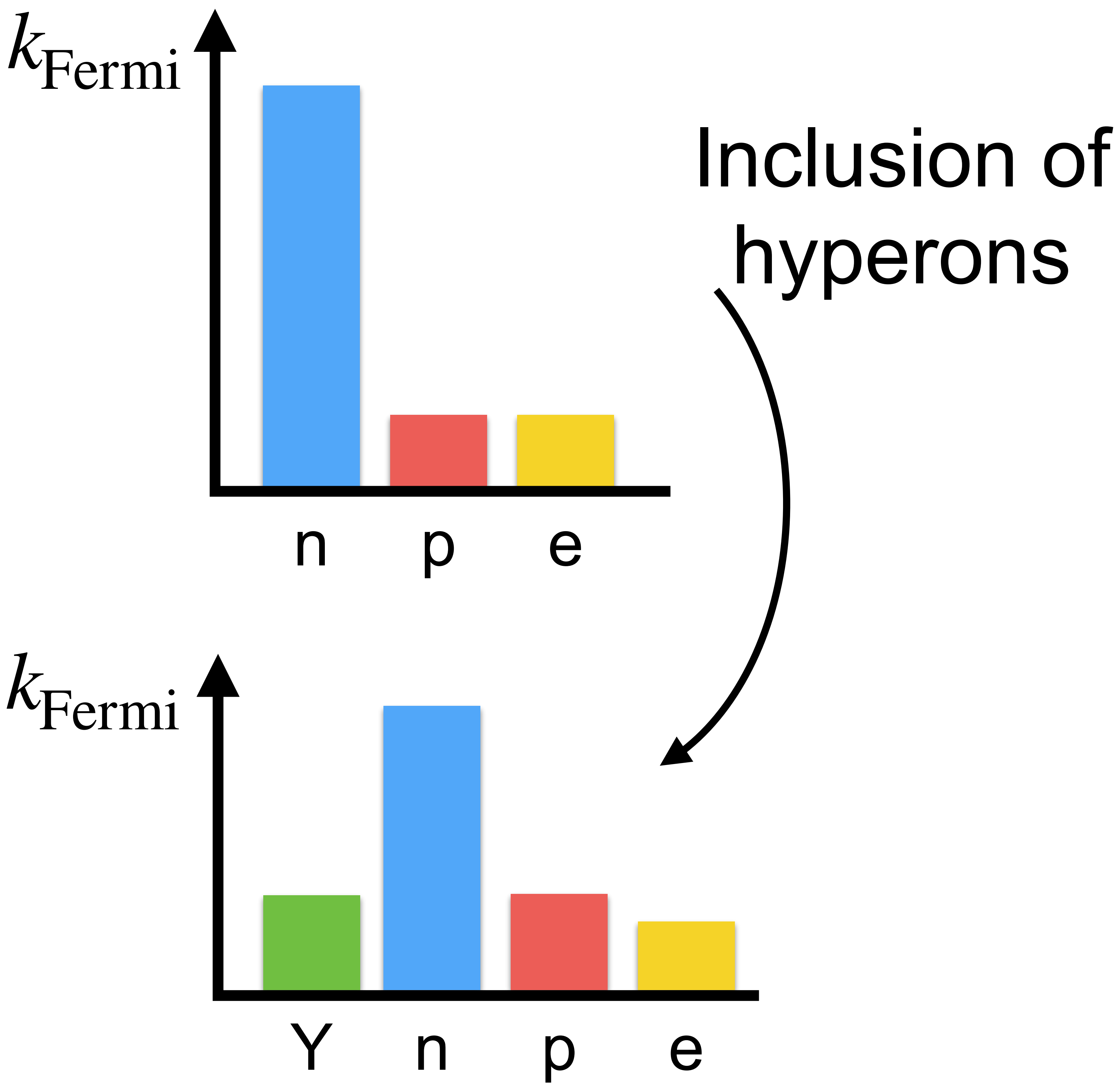
References:
[1] Y. Fujimoto, T. Kojo, L. McLerran, PRL132 (2024) [2306.04304]
[2] Y. Fujimoto, T. Kojo, L. McLerran, in preparation

4 June, 2024 - Strangeness in Quark Matter 2024, Strasbourg

SQM Strasbourg 2024

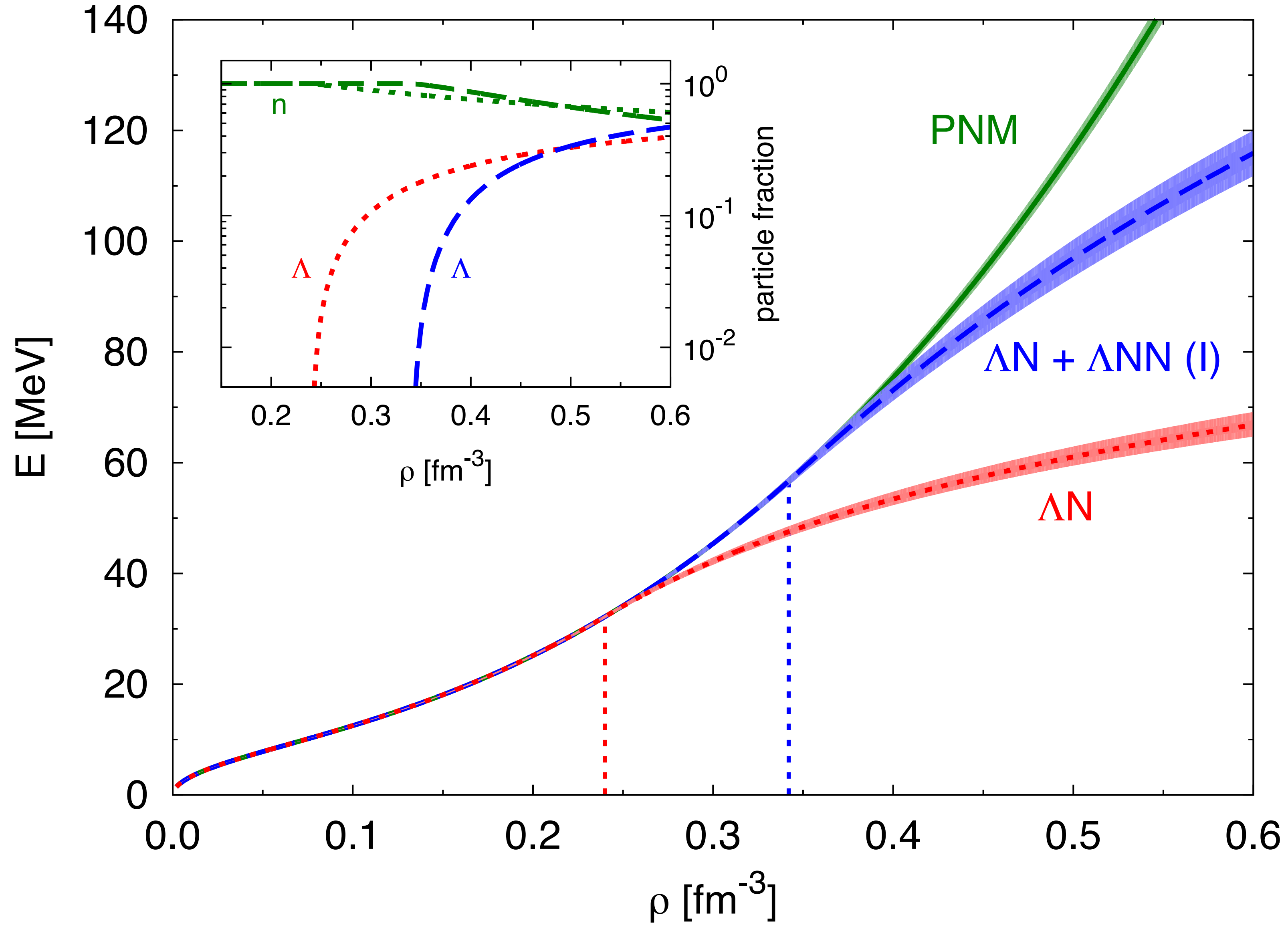
Strangeness in neutron stars

Hyperon puzzle



Hyperons (Y) lower the energy density at a given baryon density

Hyperons soften the EoS drastically …



→ Cannot support heavy neutron stars

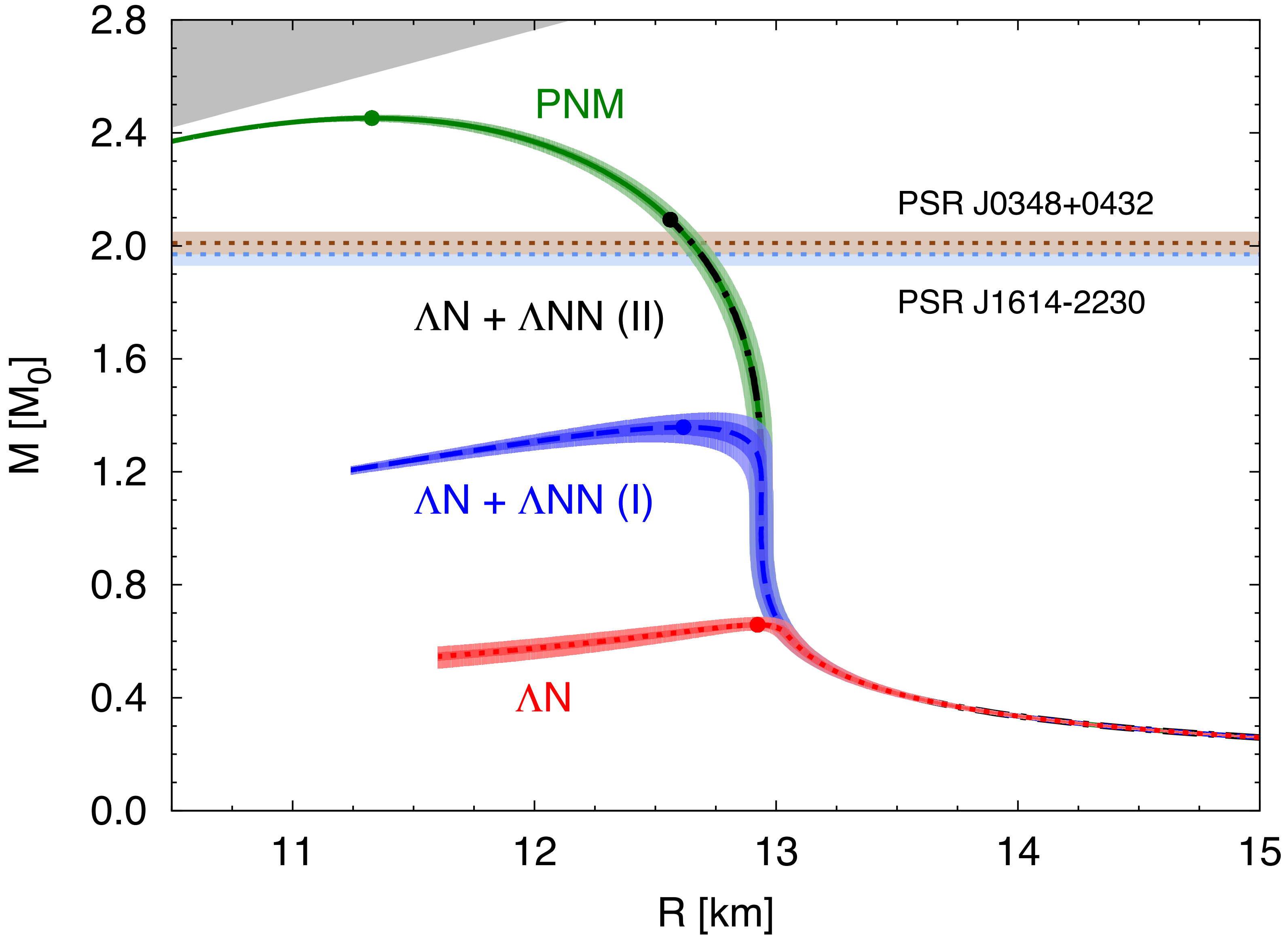
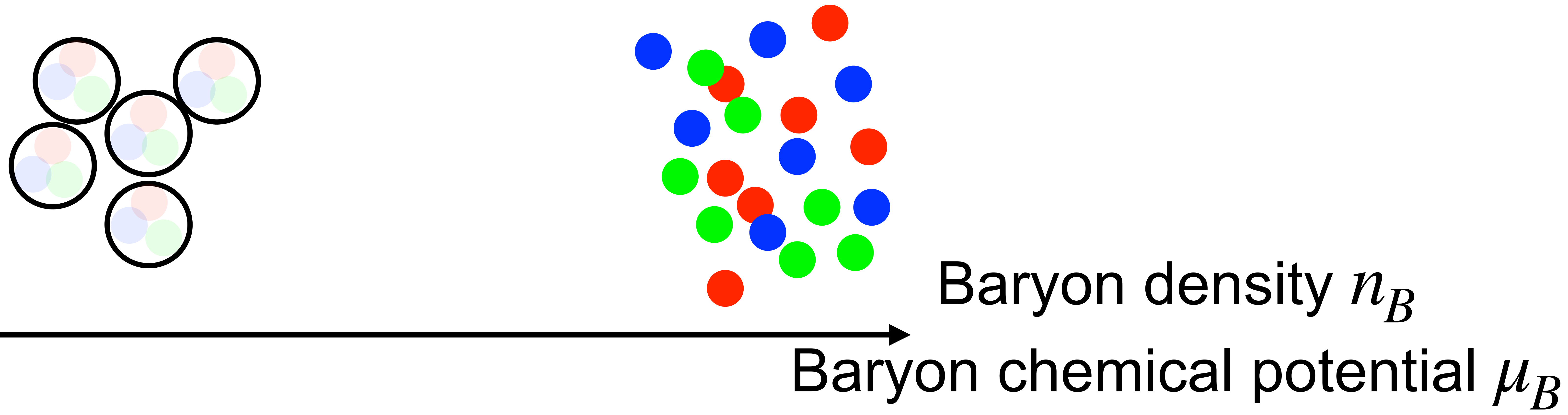


figure from Lonardoni et al. (2014)

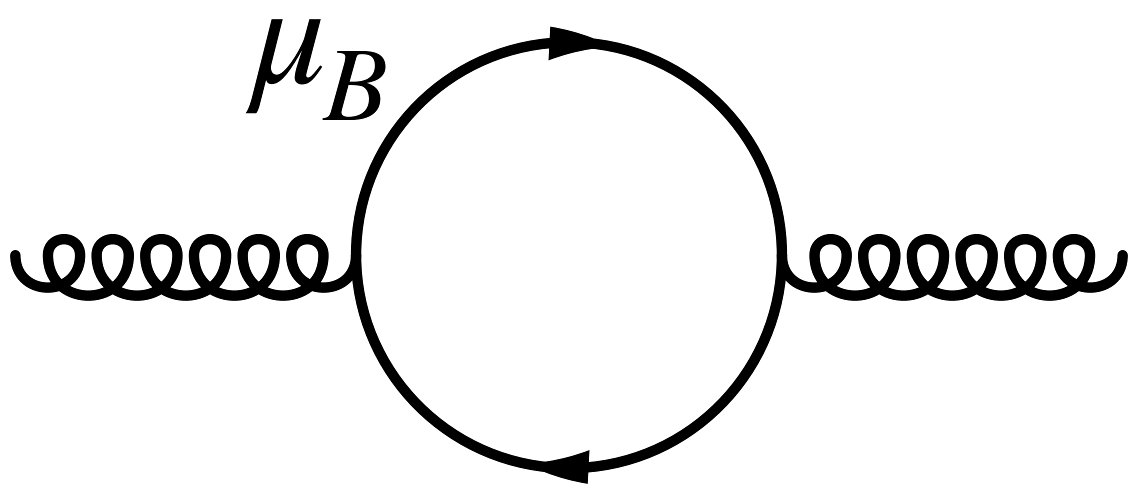
Confinement at high baryon densities

Collins & Perry (1974): **Naive picture of deconfinement at high density**

In weak-coupling regime, quarks liberate



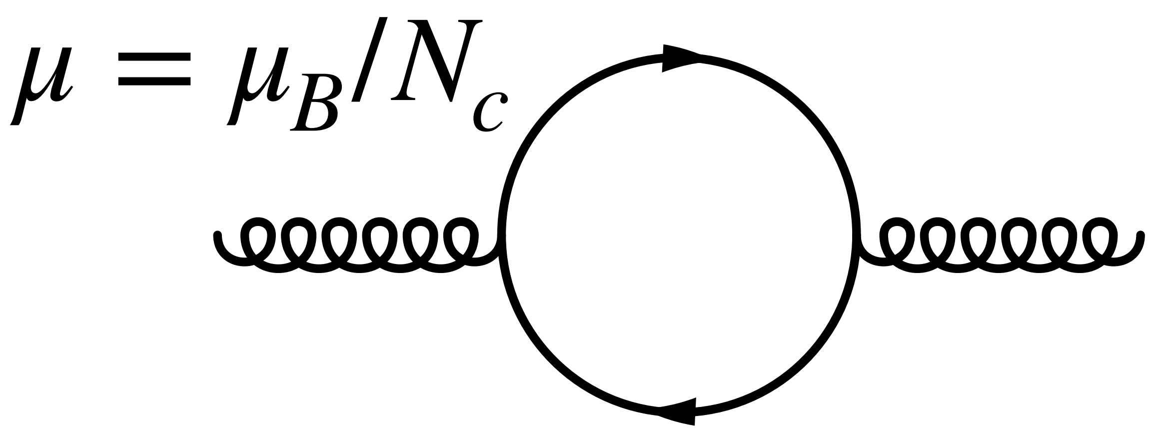
This is led by screening of the confinement potential



Confinement at high baryon densities

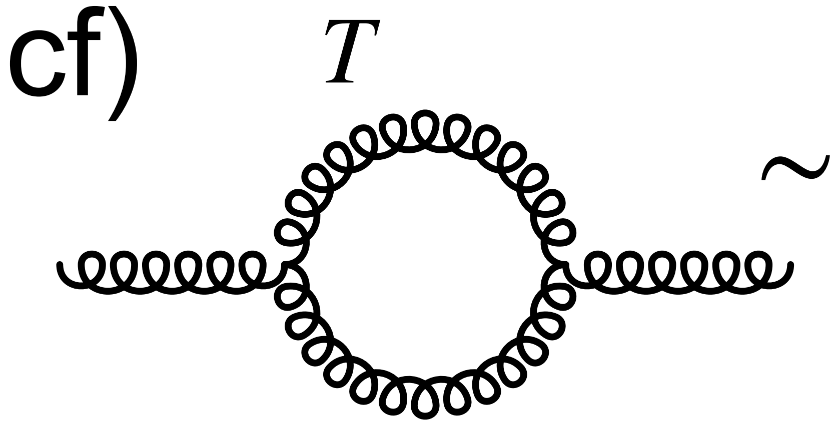
McLerran & Pisarski (2007): **Quarkyonic duality**

Large-N_c QCD implies…



$$\sim g^2 \mu^2 \sim \lambda_{'t\ Hooft} \mu^2 / N_c$$

cf)



$$\sim g^2 N_c T^2$$
$$\sim \lambda_{'t\ Hooft} T^2$$

… confinement is less affected by quarks!

Dense QCD matter can be described either as

- Confined baryons (because confining interaction is less screened)
- (Weakly-coupled) Quarks

→ **implies duality between <u>quark</u> and confined bar<u>yonic</u> matter**

Quark yonic

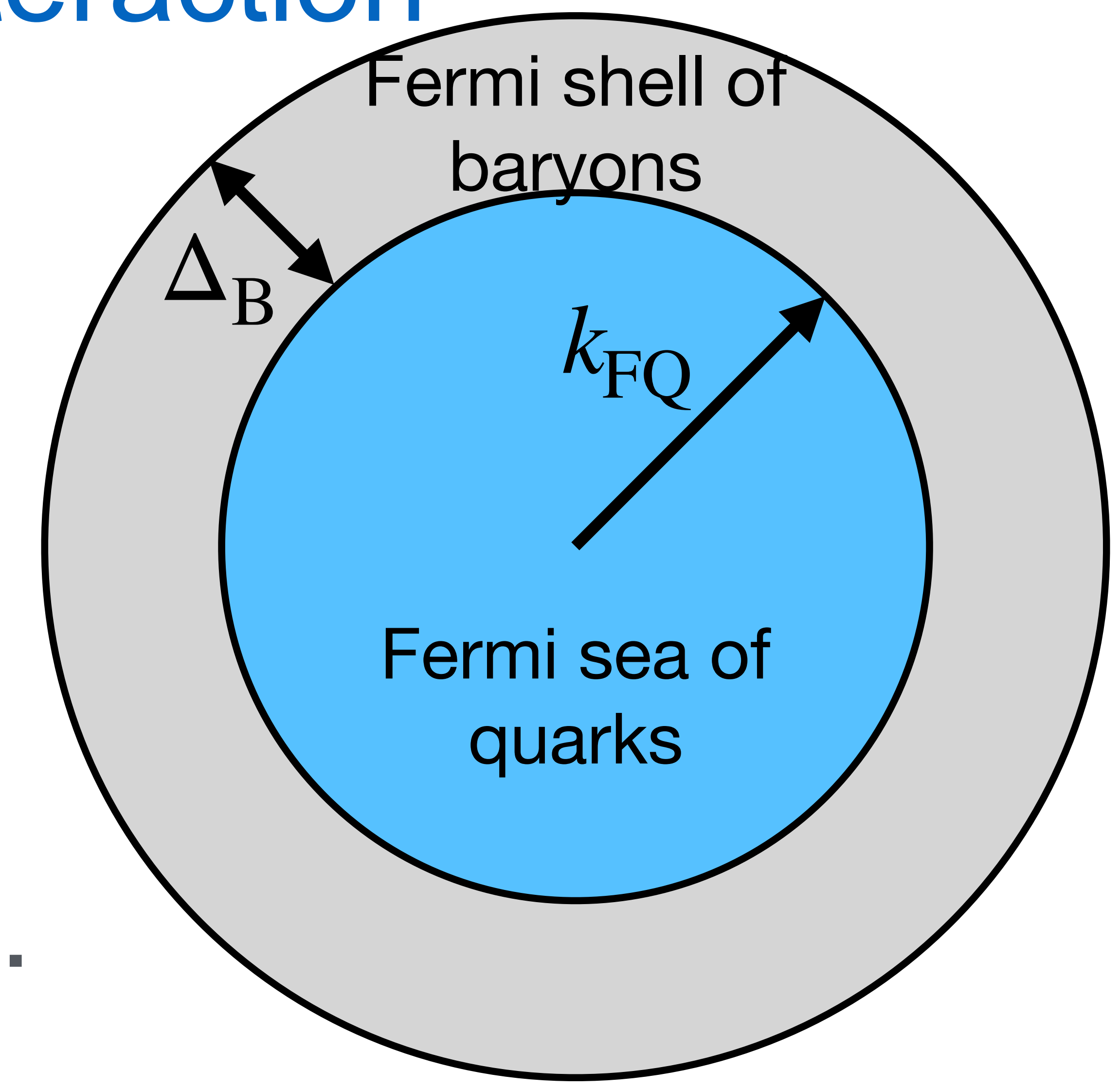
Quarkyonic "shell" model

McLerran & Pisarski (2007):

To resolve the duality "paradox", the following picture of Fermi shell of baryons is proposed:

Fermi sea: dominated by interaction that is less sensitive to IR
→ quarks

Fermi shell: interaction sensitive to IR d.o.f.
→ baryons, mesons, glues…



Quarkyonic model for neutron stars

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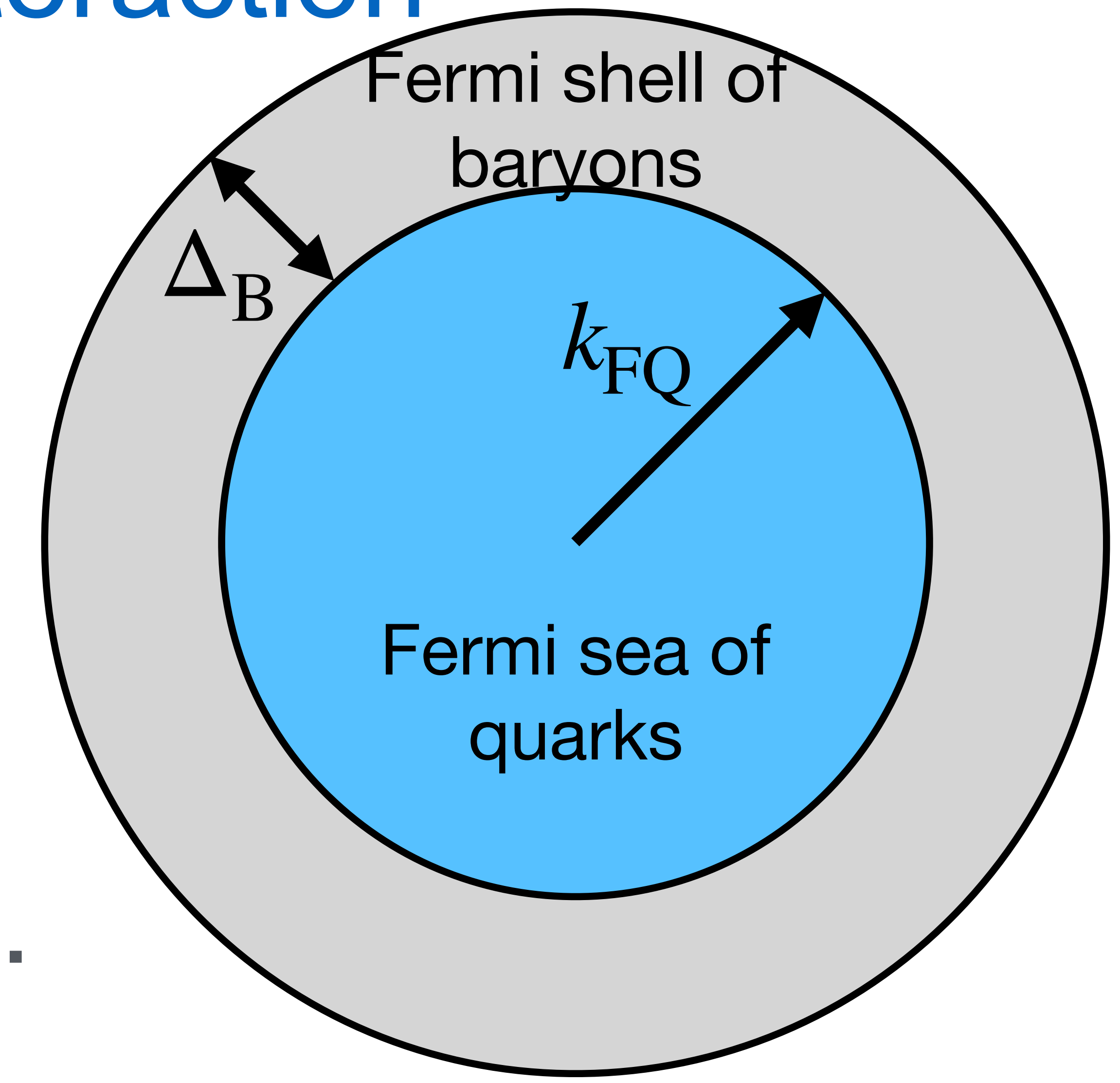
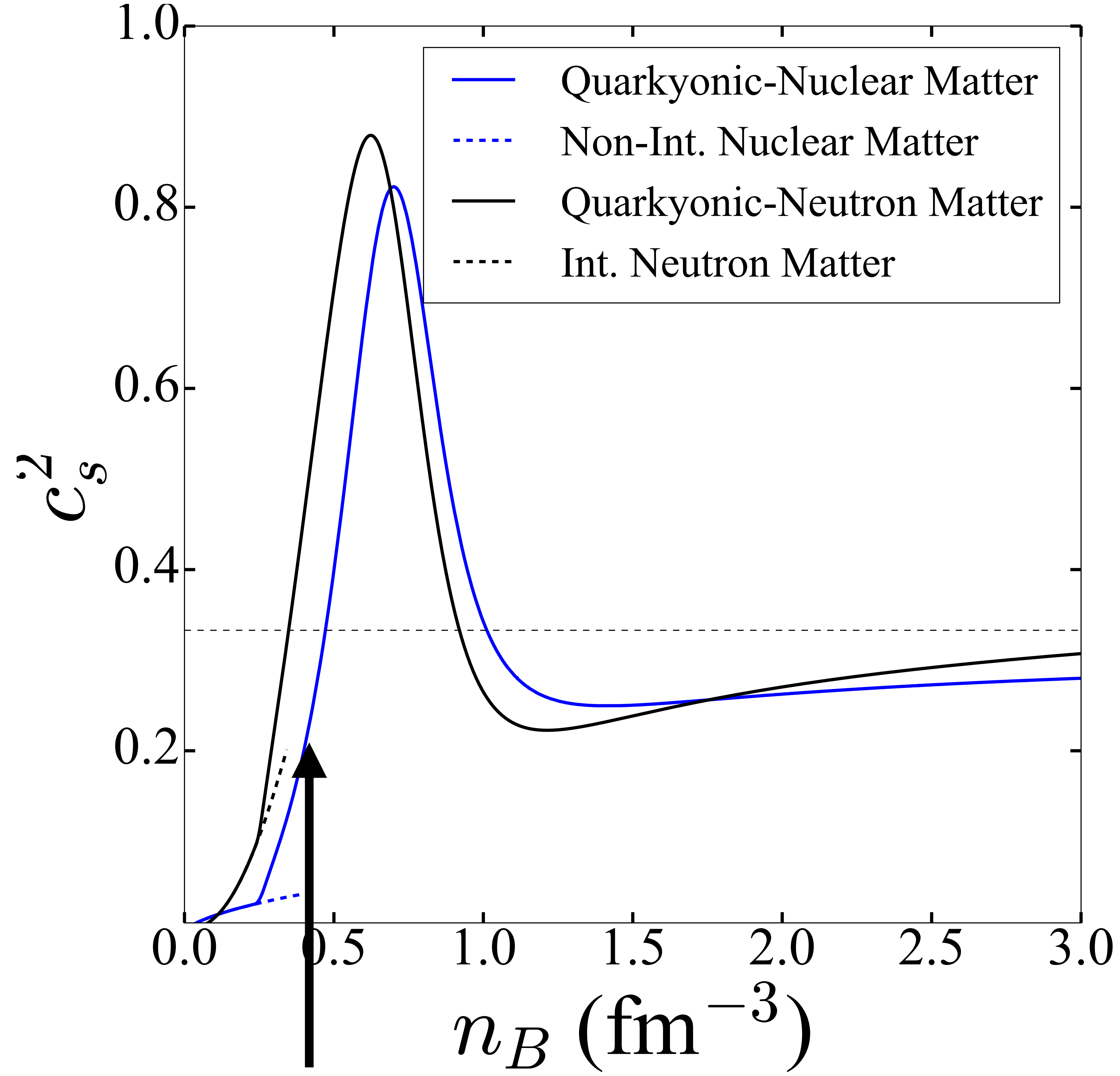


McLerran,Reddy (2018):

Quarkyonic model applied to NS EoS:



can reproduce rapid stiffening in EoS
(the only robust feature confirmed in NS EoS)

Quarkyonic model for neutron stars

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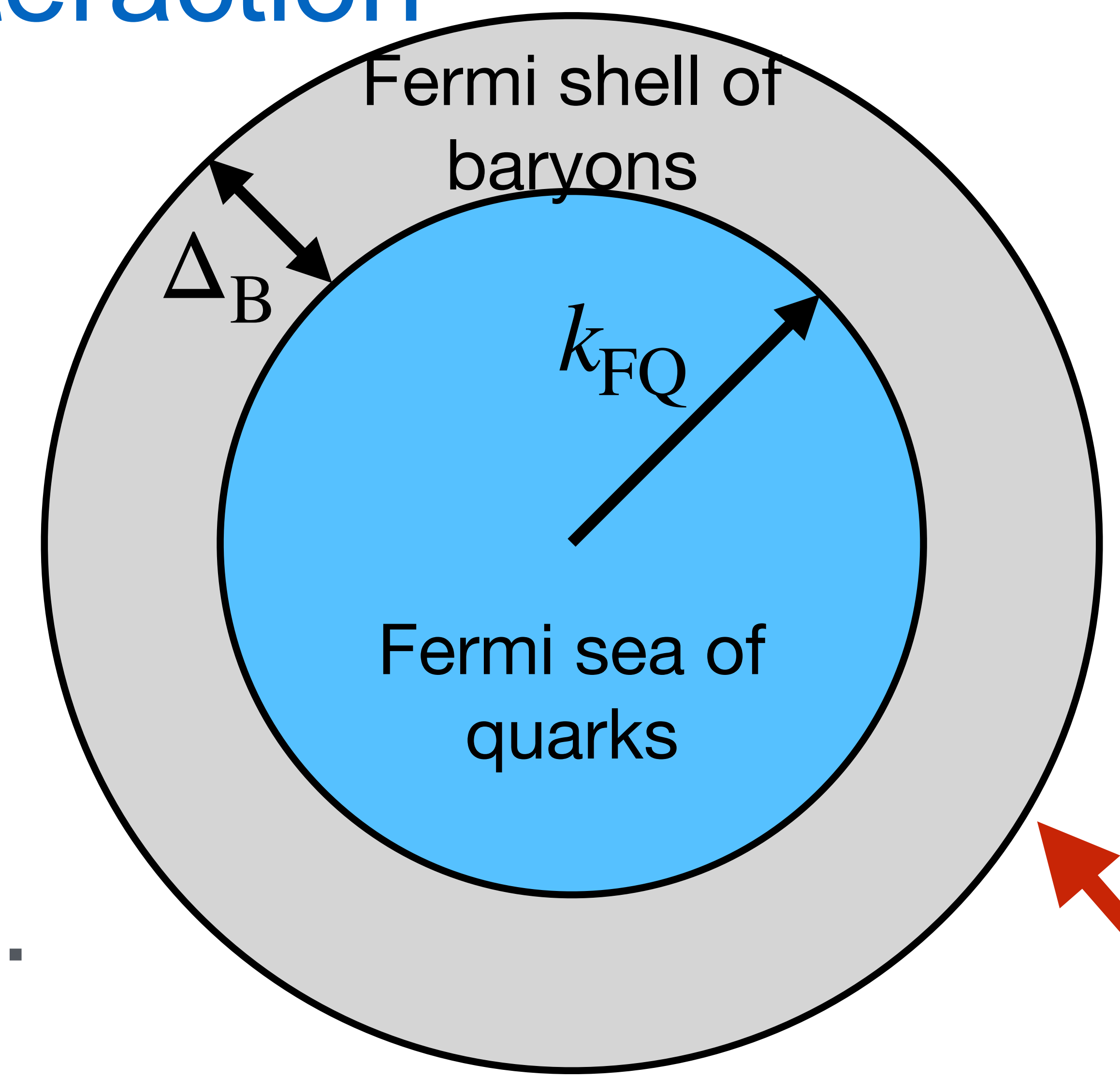

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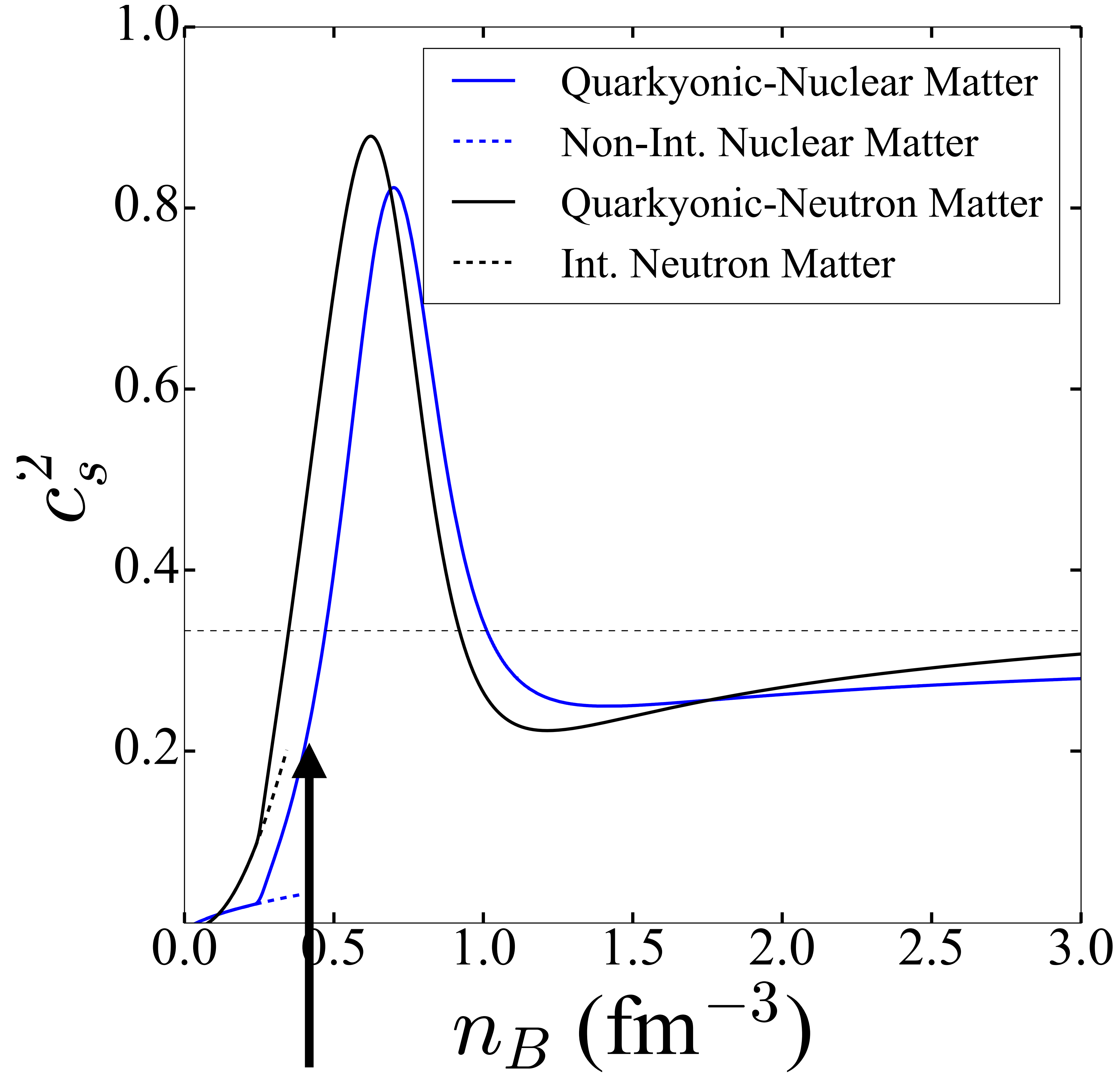


can reproduce rapid stiffening in EoS

This talk: reinterpretation of this baryon shell nfirmed in NS EoS)

Duality in Fermi gas model

Kojo (2021); Fujimoto,Kojo,McLerran (2023)

Implement duality in Fermi gas model
(= simultaneous description in terms of baryons & quarks)

Fermi gas model w/ an explicit duality:

$$\varepsilon = \int_{\boldsymbol{k}} E_{\mathrm{B}}(k) f_{\mathrm{B}}(k) = \int_{\boldsymbol{k}} E_{\mathrm{Q}}(q) f_{\mathrm{Q}}(q)$$

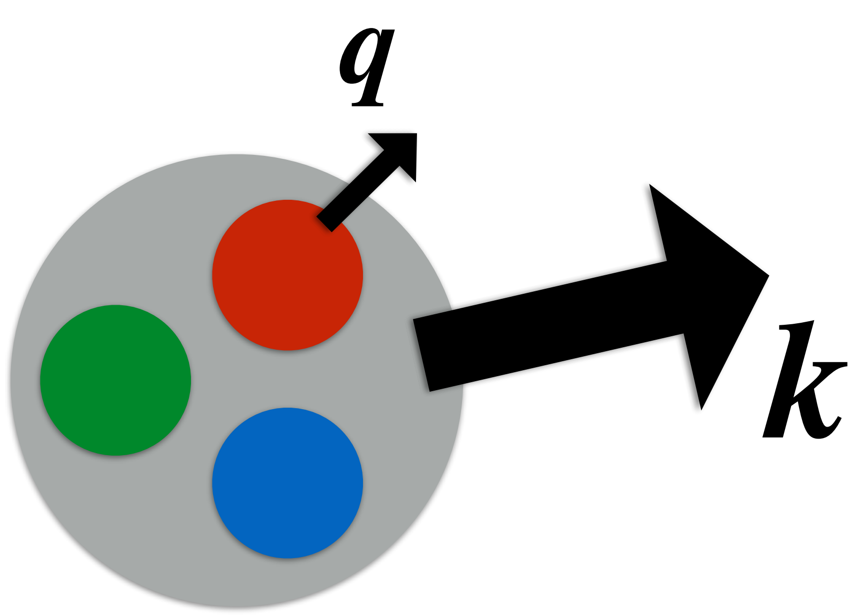
$$n_{\mathrm{B}} = \int_{\boldsymbol{k}} f_{\mathrm{B}}(k) = \int_{\boldsymbol{q}} f_{\mathrm{Q}}(q)$$

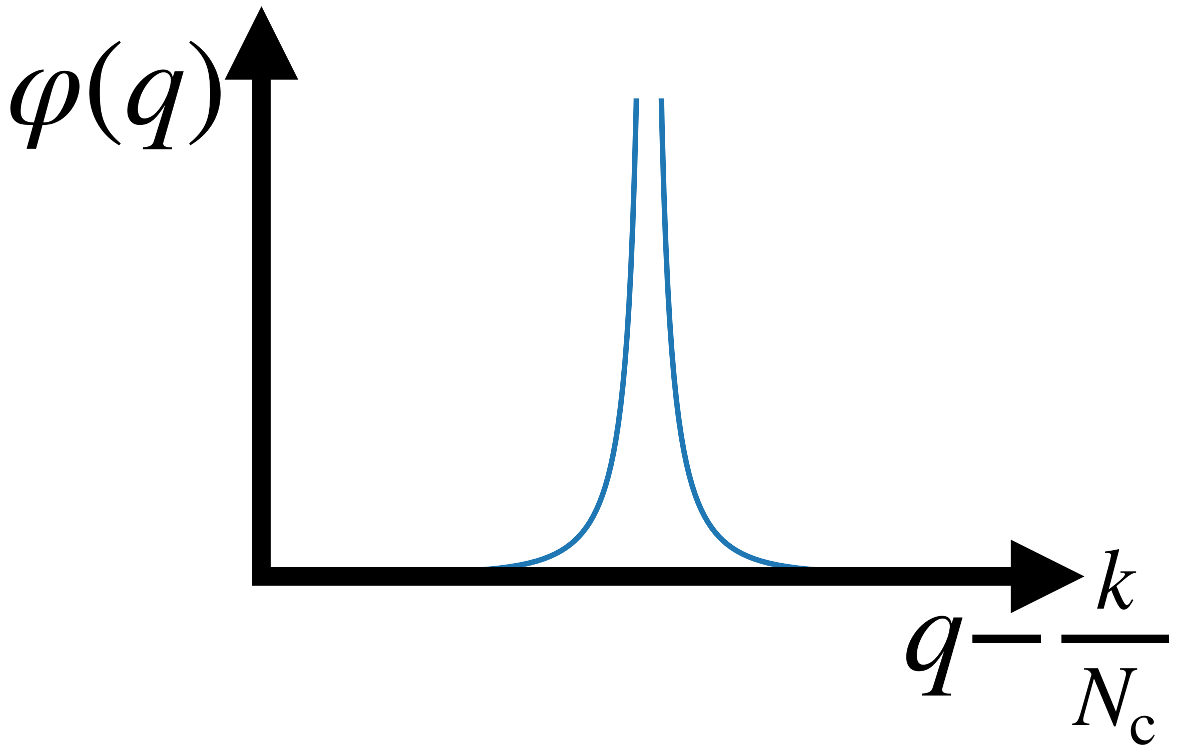
$0 \leq f_{\mathrm{B,Q}} \leq 1$: Pauli exclusion

$E_{\mathrm{B}}(k) = \sqrt{k^2 + M_N^2}$: ideal baryon dispersion relation

Modeling of confinement:

$$f_{\mathrm{Q}}(q) = \int_{\boldsymbol{k}} \varphi\left(\boldsymbol{q} - \frac{\boldsymbol{k}}{N_{\mathrm{c}}}\right) f_{\mathrm{B}}(k)$$





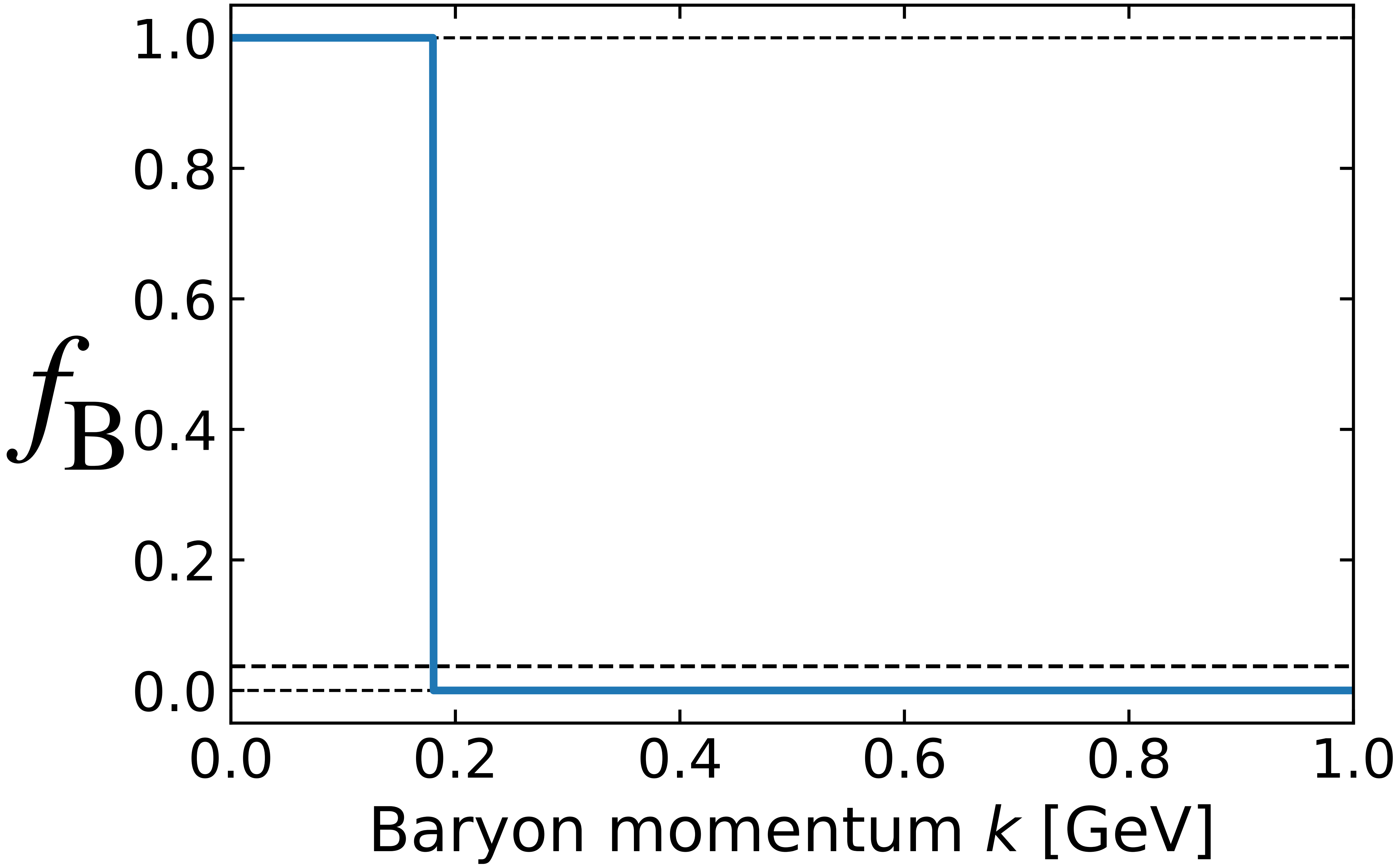
Ideal dual Quarkyonic model (**IdylliQ** model)
→ Find a solution for f_{B} and f_{Q} with minimum ε at a given n_B

Solution of IdylliQ model

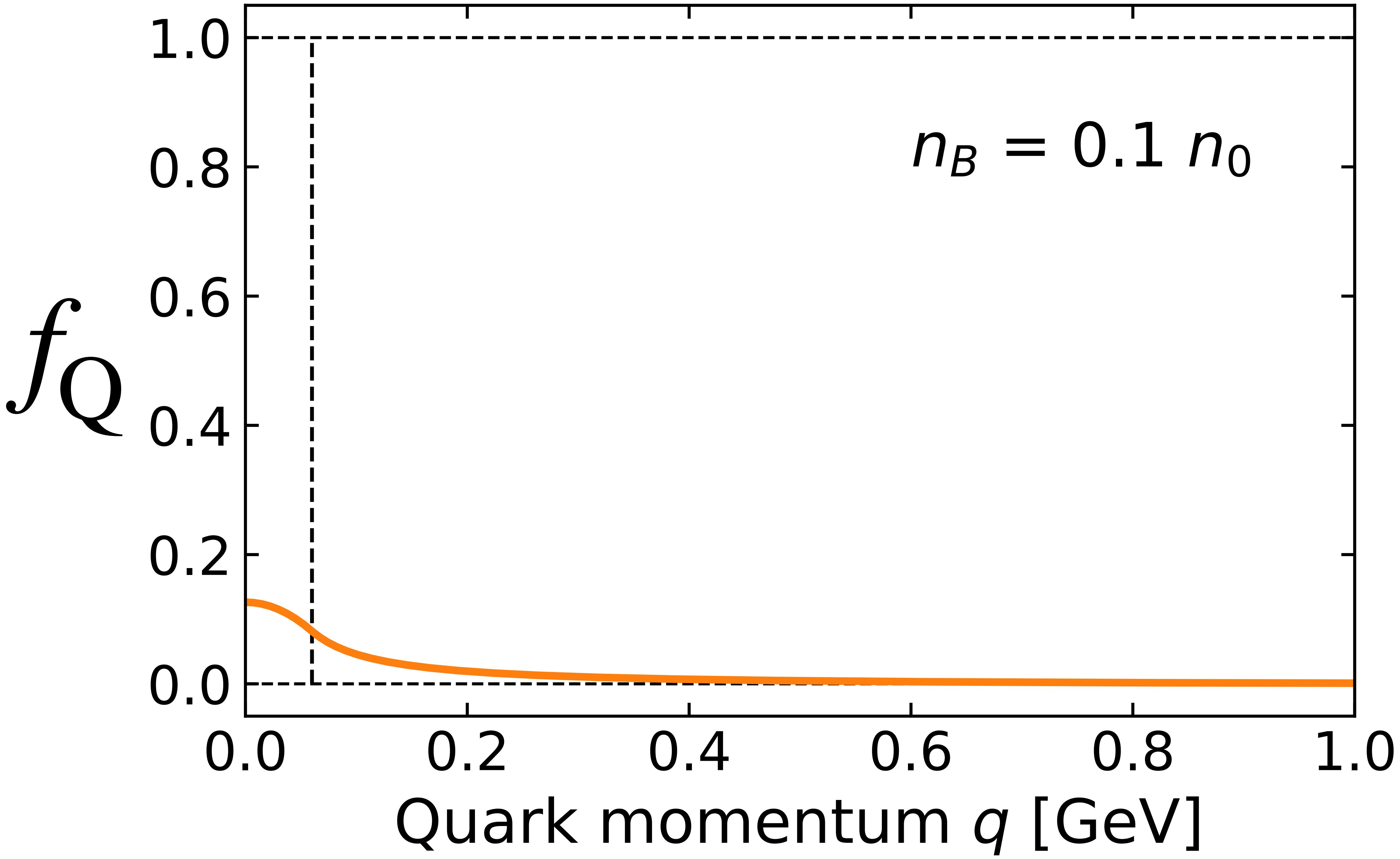
Kojo (2021); Fujimoto,Kojo,McLerran (2023)

At low density…

Fermi-Dirac distribution
for baryons



Quarks do not fill up
the Fermi sea yet

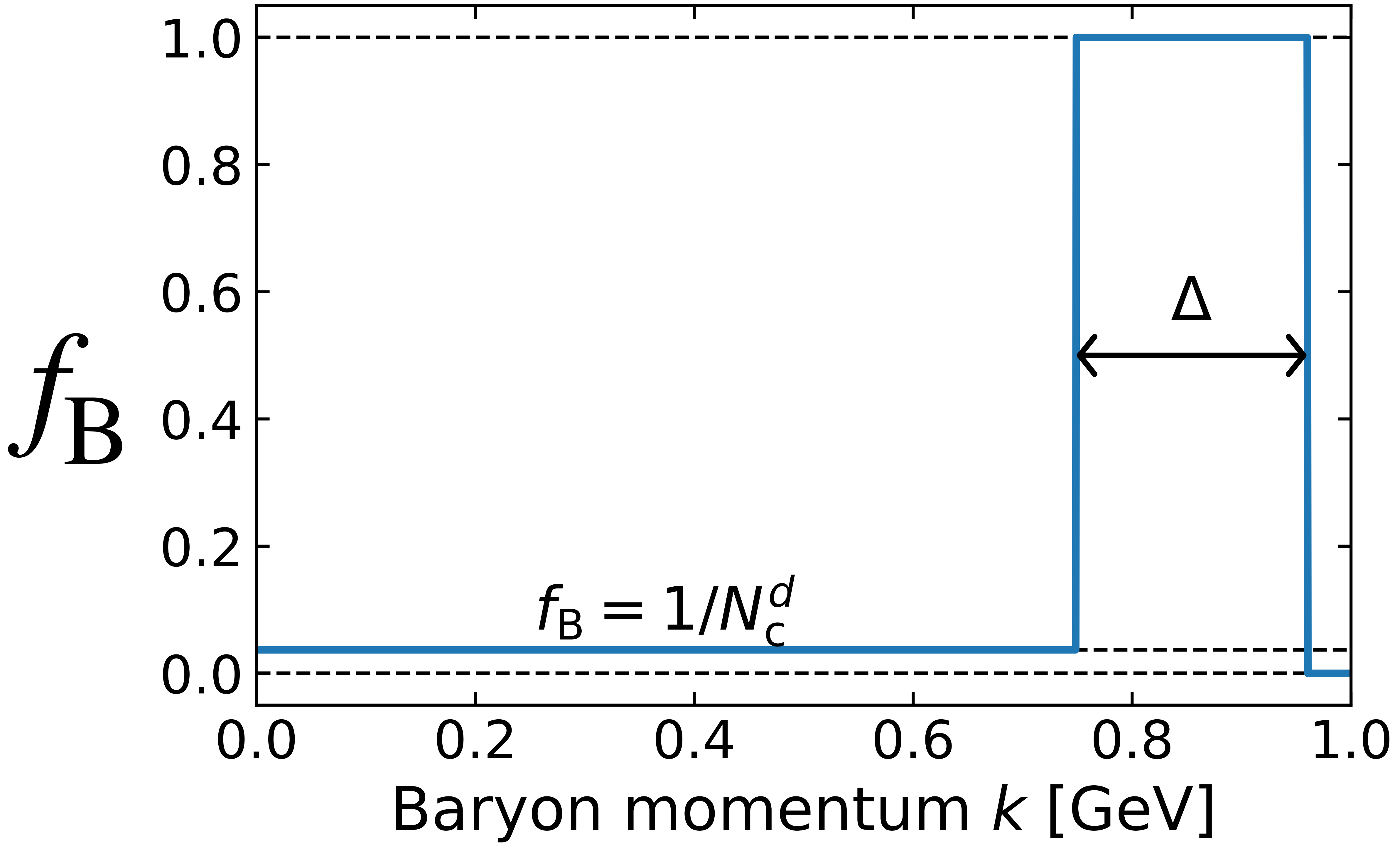


Solution of IdylliQ model

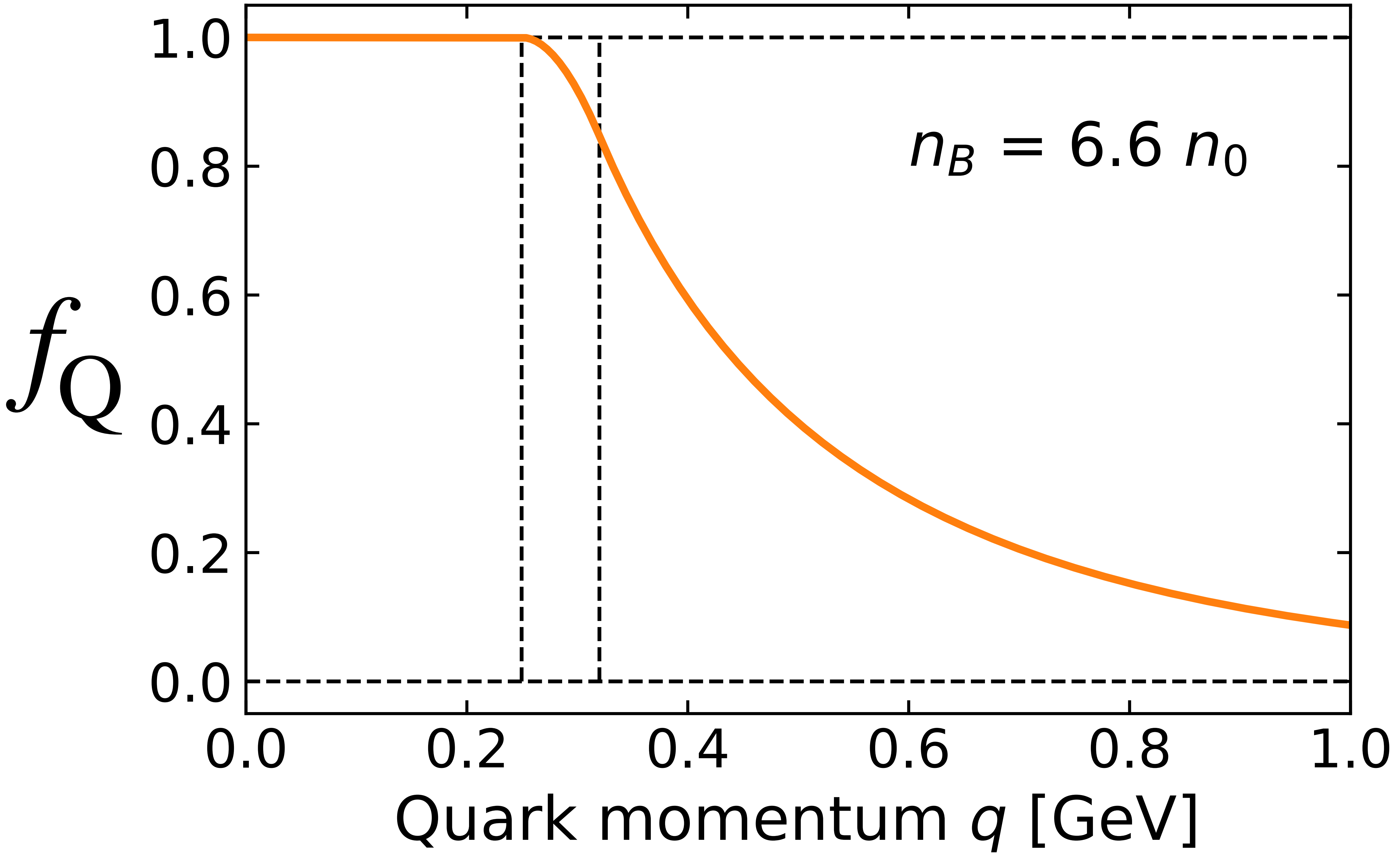
Fujimoto,Kojo,McLerran (2023)

At sufficiently high density…

Fermi-Dirac distribution for baryons is modified



Quark obeys the FD distribution (with a tail from confinement)

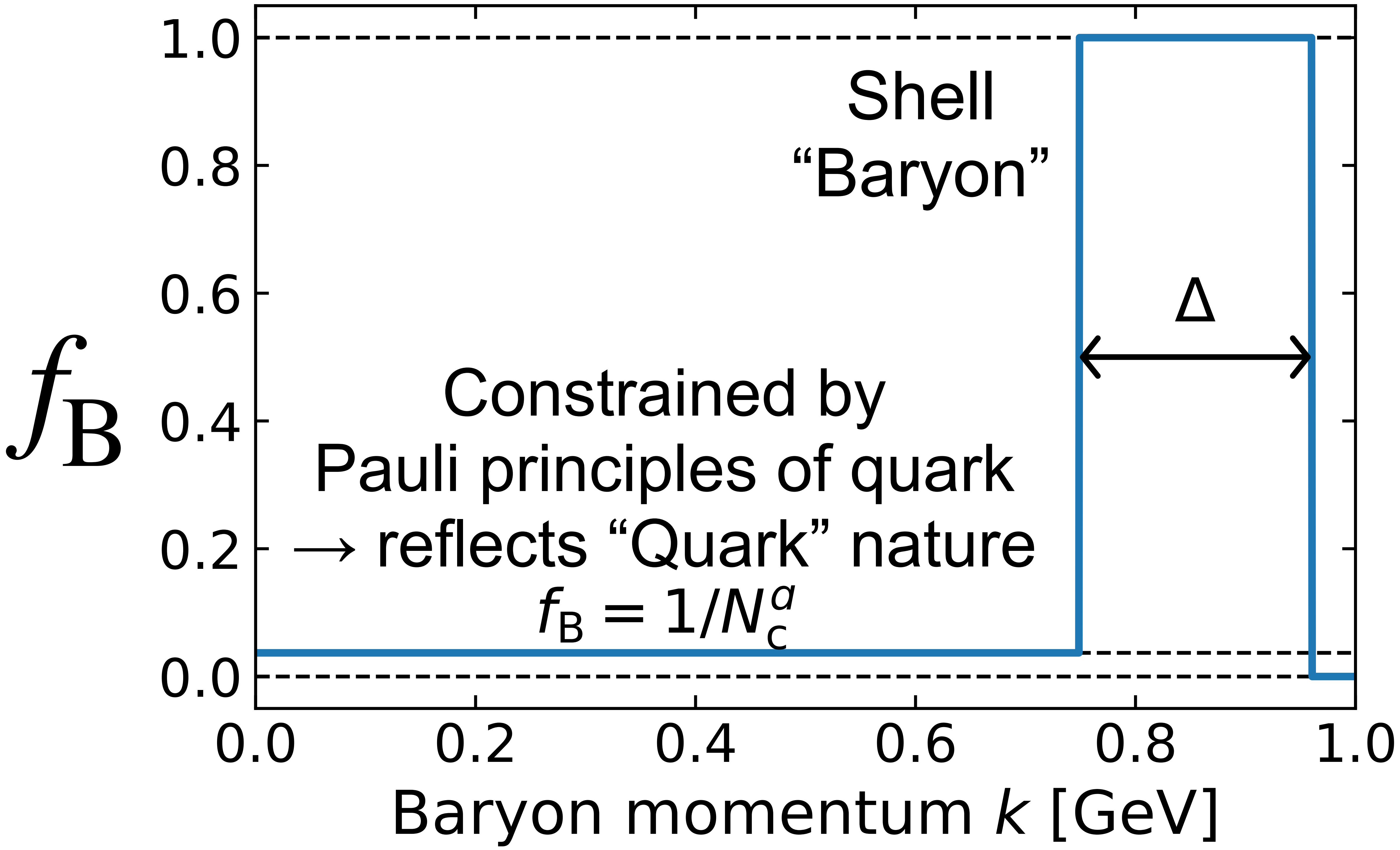


Equivalence to Quarkyonic model

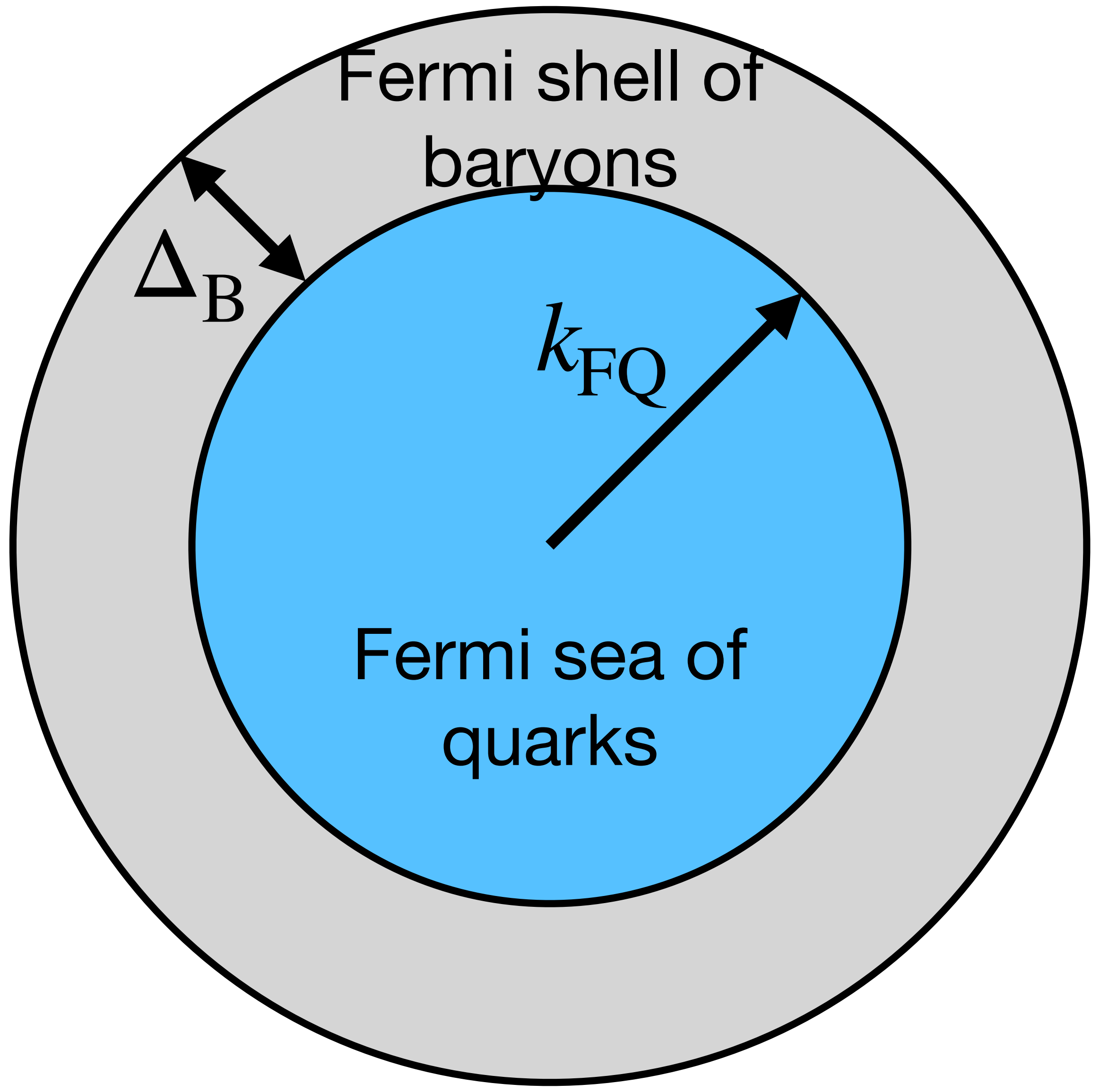
Fujimoto,Kojo,McLerran (2023)

At sufficiently high density…

Fermi-Dirac distribution for baryons is modified



McLerran,Pisarski (2007)
McLerran,Reddy (2018)



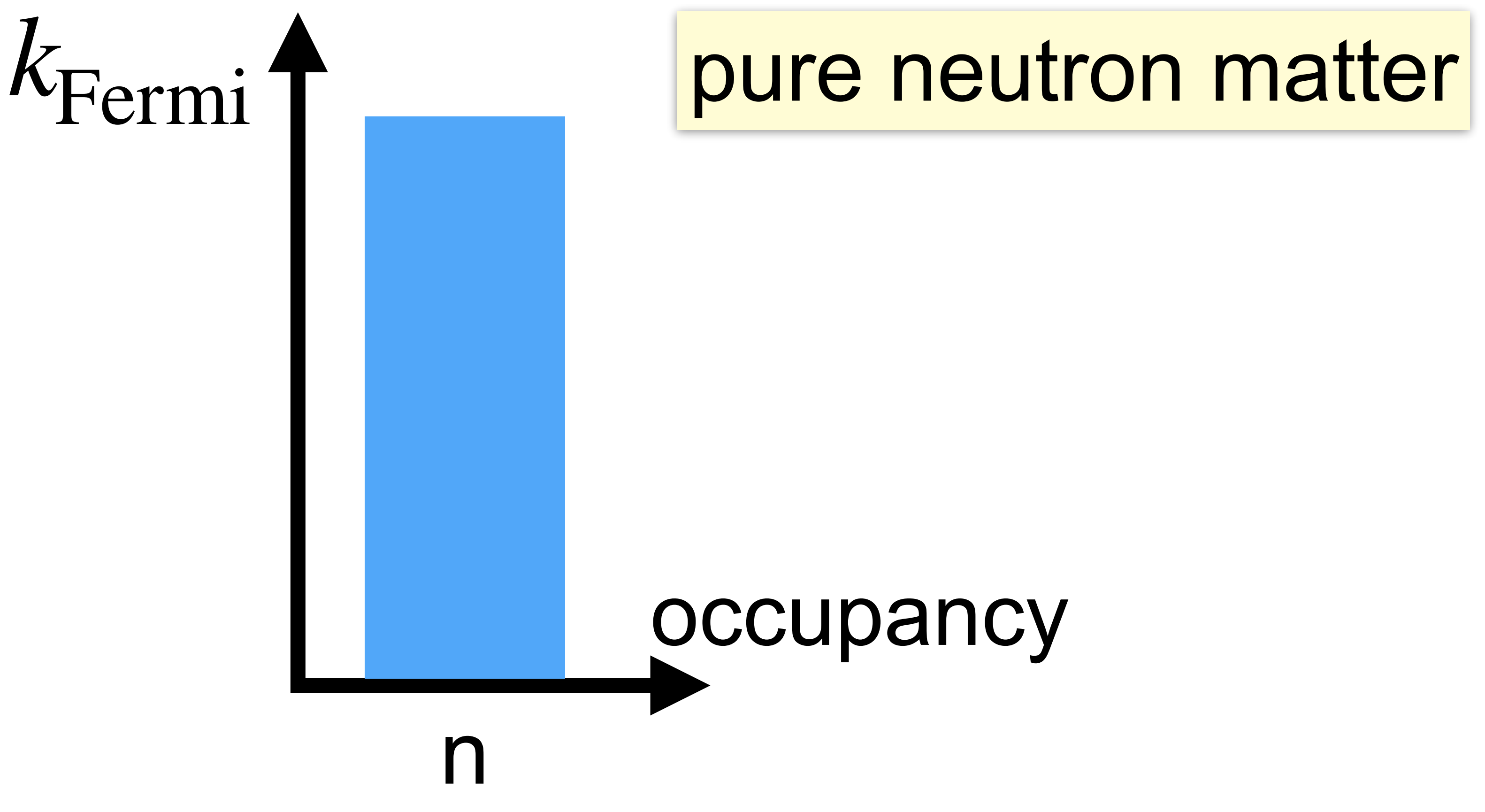
Fermi shell structure arises in f_B
(Note: this is **purely baryonic description**)

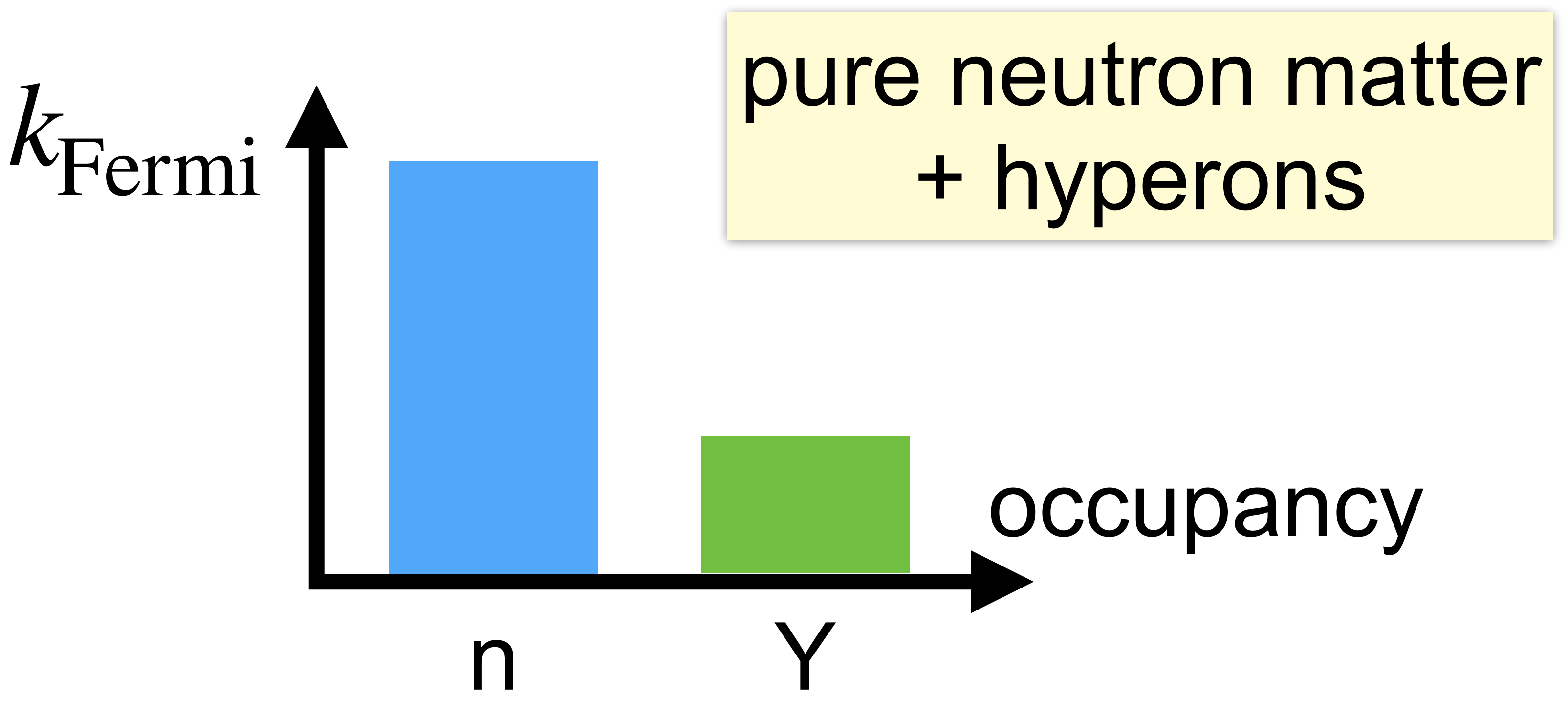
This picture is equivalent to McLerran-Reddy model of the NS based on the McLerran-Pisarski picture

Including hyperons in IdylliQ model

Fujimoto,Kojo,McLerran, in preparation (2024)

Conventional picture:



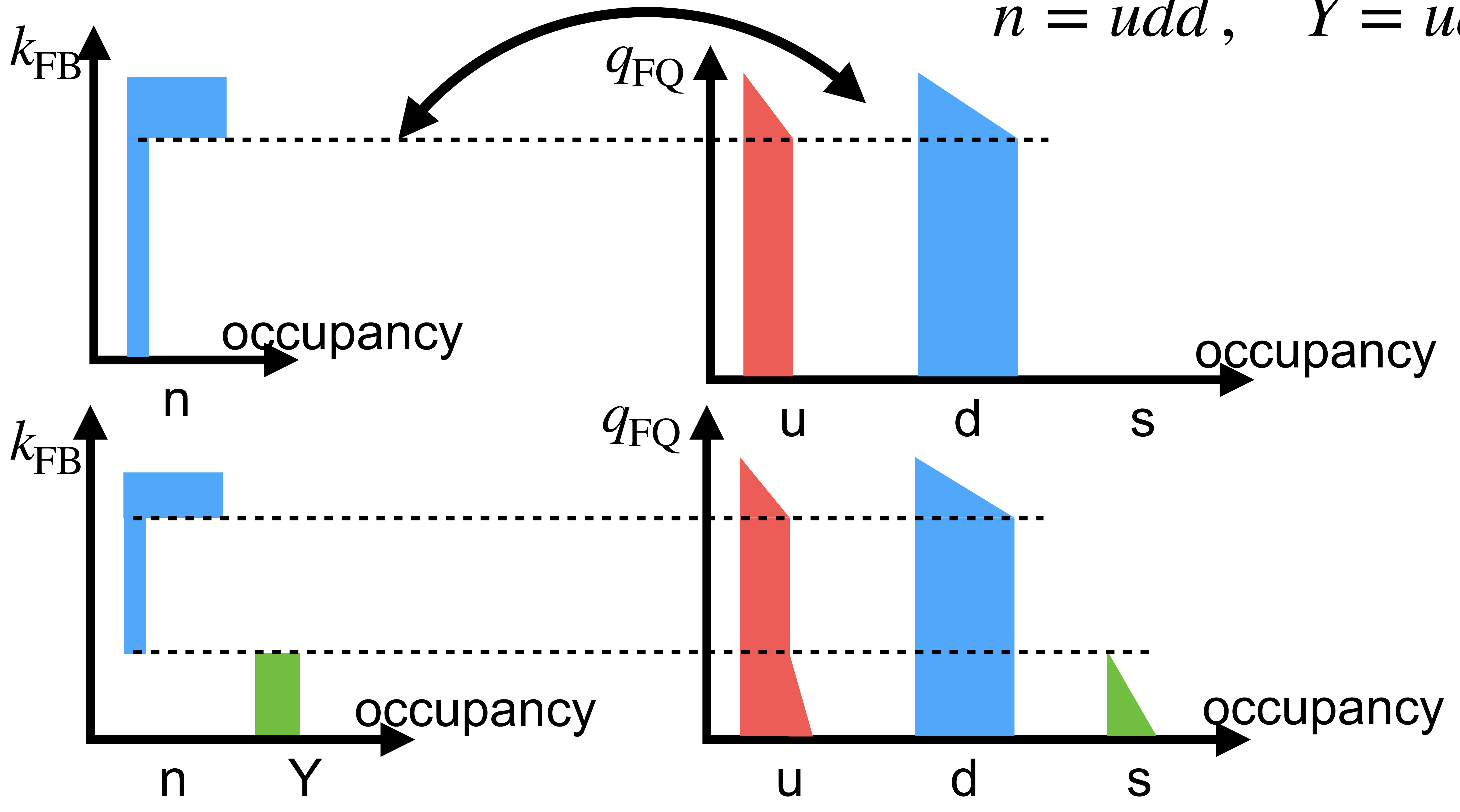


Hyperons (Y) lower the energy density at a given baryon density

Threshold: $\mu_B = M_Y$

Quarkyonic picture: **dual to each other**

$n = udd\,, \quad Y = uds$



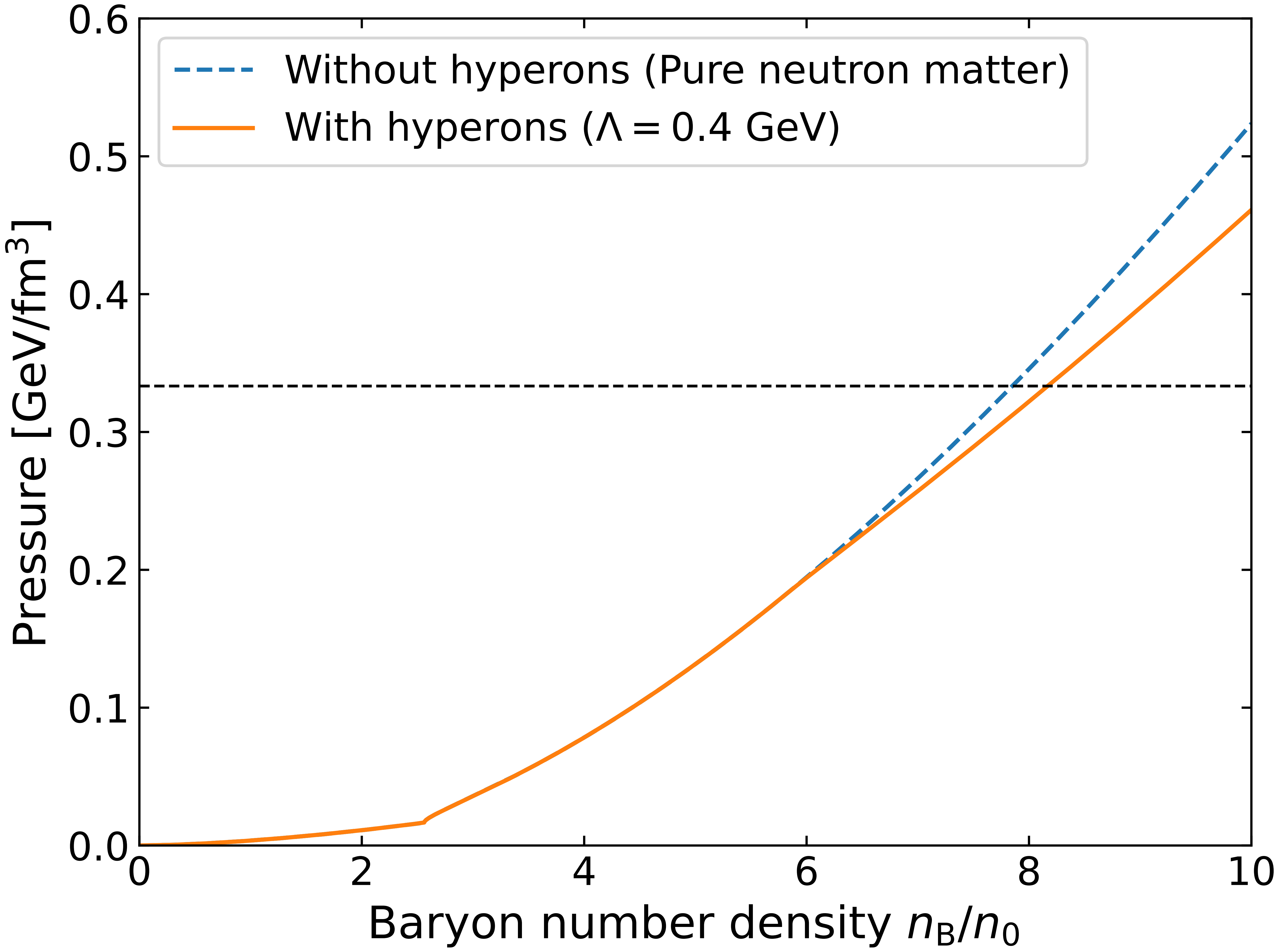
Y has to appear so that d-quark states are kept saturated:

n = u**dd** → Y+Y = uu**dd**ss

Threshold shifted to: $\mu_B = 2M_Y - M_n$

Including hyperons in IdylliQ model

Fujimoto, Kojo, McLerran, in preparation (2024)



Due to the saturation of d-quark states, softening in the EoS is mild

Summary

- **Quarkyonic:** reinterpretation as a duality between confined baryons and weakly-coupled quarks

- **Saturation of quark momentum distribution**
  → under-occupied states in baryonic momentum distribution
  (modification from Fermi-Dirac distribution)

- **Implication to hyperon puzzle:**
  Because of the saturation in d-quark states,
  1) The threshold of hyperons shifted to a higher μ_B
  2) The softening in the EoS is milder

Supplemental materials

Underoccupied f_{B} and occupied f_{Q}

Baryon number in the bulk "quark" region in the quark language:

$$n_{\mathrm{B}} = \int_0^{k_{\mathrm{FQ}}} \frac{d^3q}{(2\pi)^3} f_{\mathrm{Q}}(q) \sim k_{\mathrm{FQ}}^3 f_{\mathrm{Q}}$$

In the baryon language:

$$n_{\mathrm{B}} = \int_0^{k_{\mathrm{FB}}} \frac{d^3k}{(2\pi)^3} f_{\mathrm{B}}(k) \sim k_{\mathrm{FB}}^3 f_{\mathrm{B}} \sim N_{\mathrm{c}}^3 k_{\mathrm{FQ}}^3 f_{\mathrm{B}}$$

where the Fermi momenta are related as $k_{\mathrm{FB}} \sim N_{\mathrm{c}} k_{\mathrm{FQ}}$.

Because $f_{\mathrm{Q}} \leq 1, \quad f_{\mathrm{B}} \sim 1/N_{\mathrm{c}}^3$ … composite baryon states are underoccupied

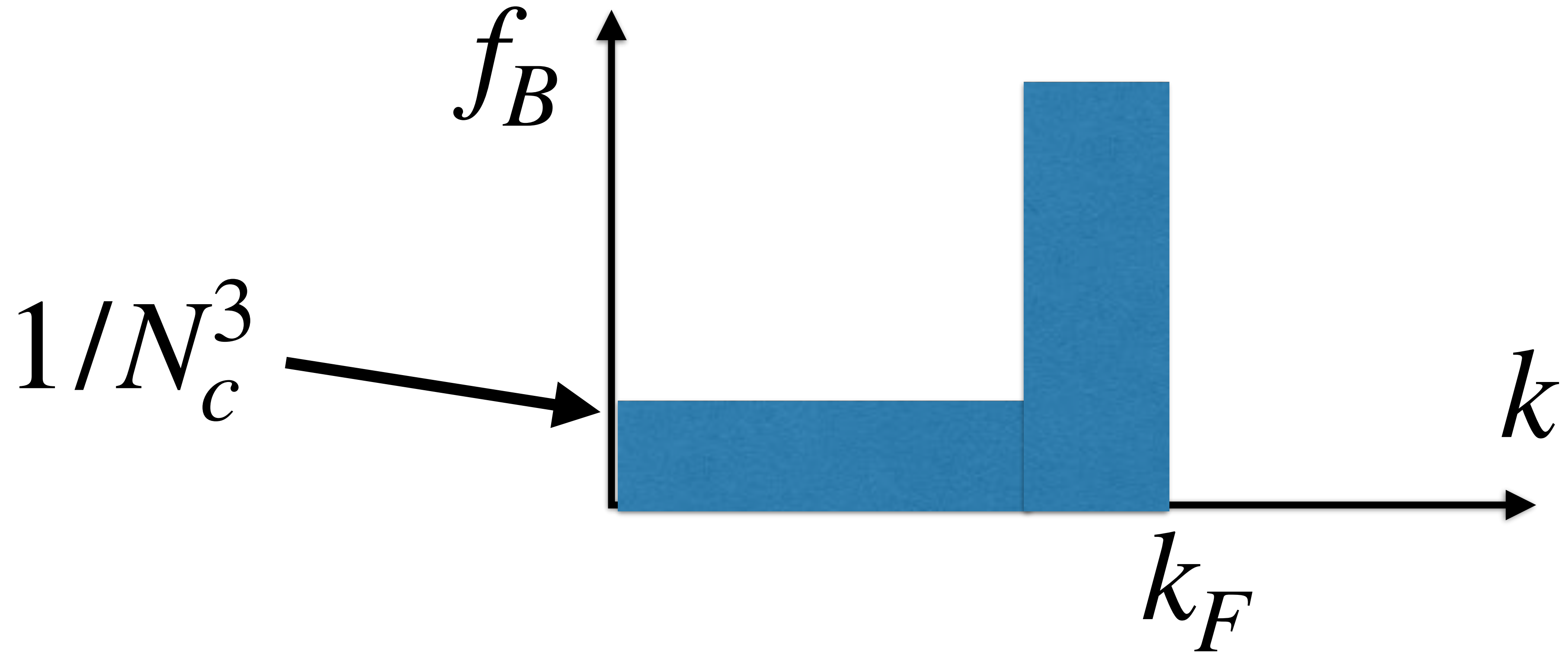
Rapid stiffening in the EoS

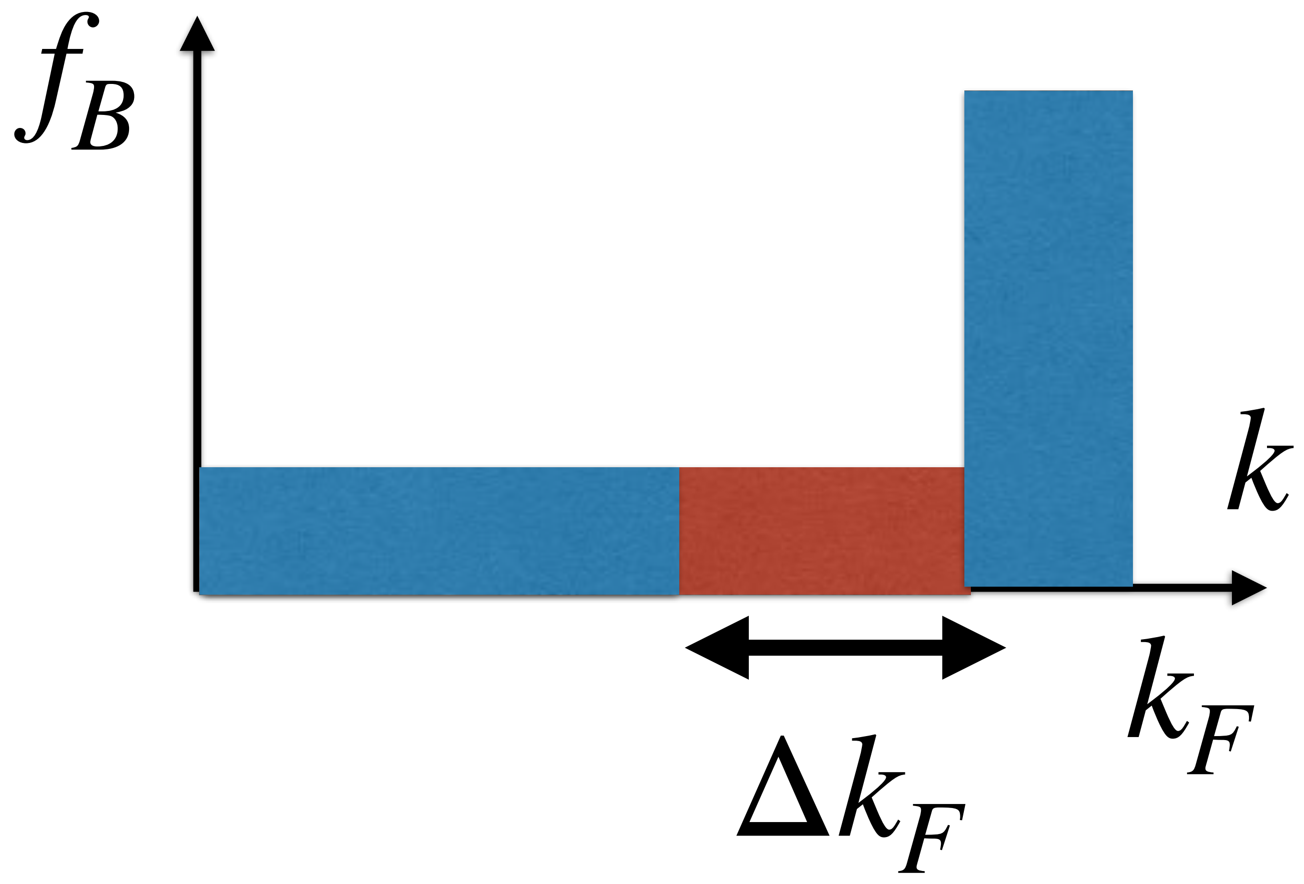
Fujimoto,Kojo,McLerran (2023)

A partial occupation of available baryon phase space leads to **large sound speed:**

$$v_s^2 = \frac{n_\mathrm{B}}{\mu_\mathrm{B} dn_\mathrm{B}/d\mu_\mathrm{B}} \rightarrow \frac{\delta\mu_\mathrm{B}}{\mu_\mathrm{B}} \sim v_s^2 \frac{\delta n_\mathrm{B}}{n_\mathrm{B}}$$

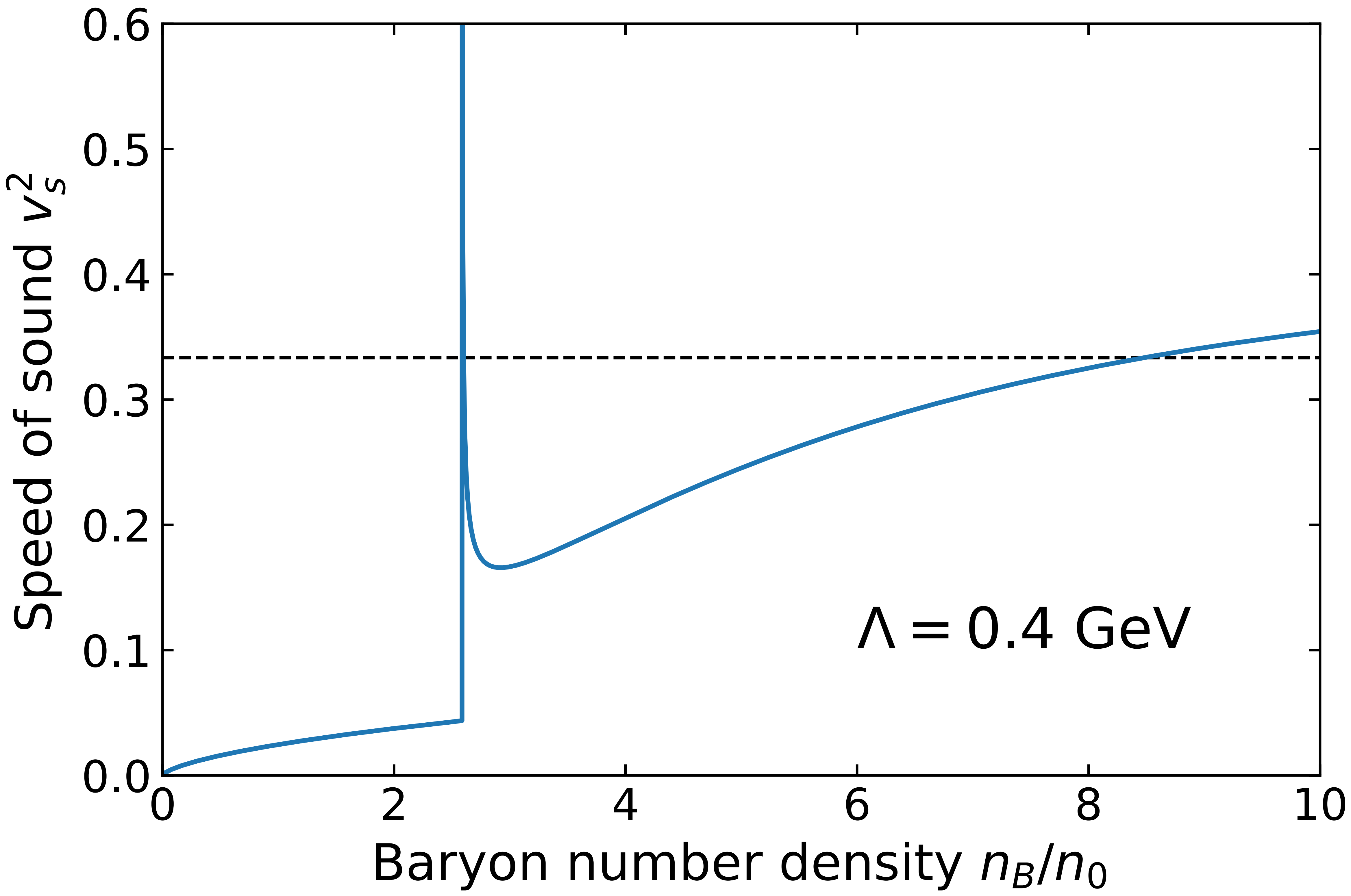
If baryons have underoccupied state, the change in density is small while the change in Fermi energy ($\sim k_F$) is large





$\rightarrow$ Favor the crossover from nucleons to quarks

Speed of sound



Singularity arises due to the sharpness of the Fermi surface.
Our theory is completely ideal. Interaction needs to be included.

cf. Short range correlation → smearing the Fermi surface