



Probing high-density states of QCD matter

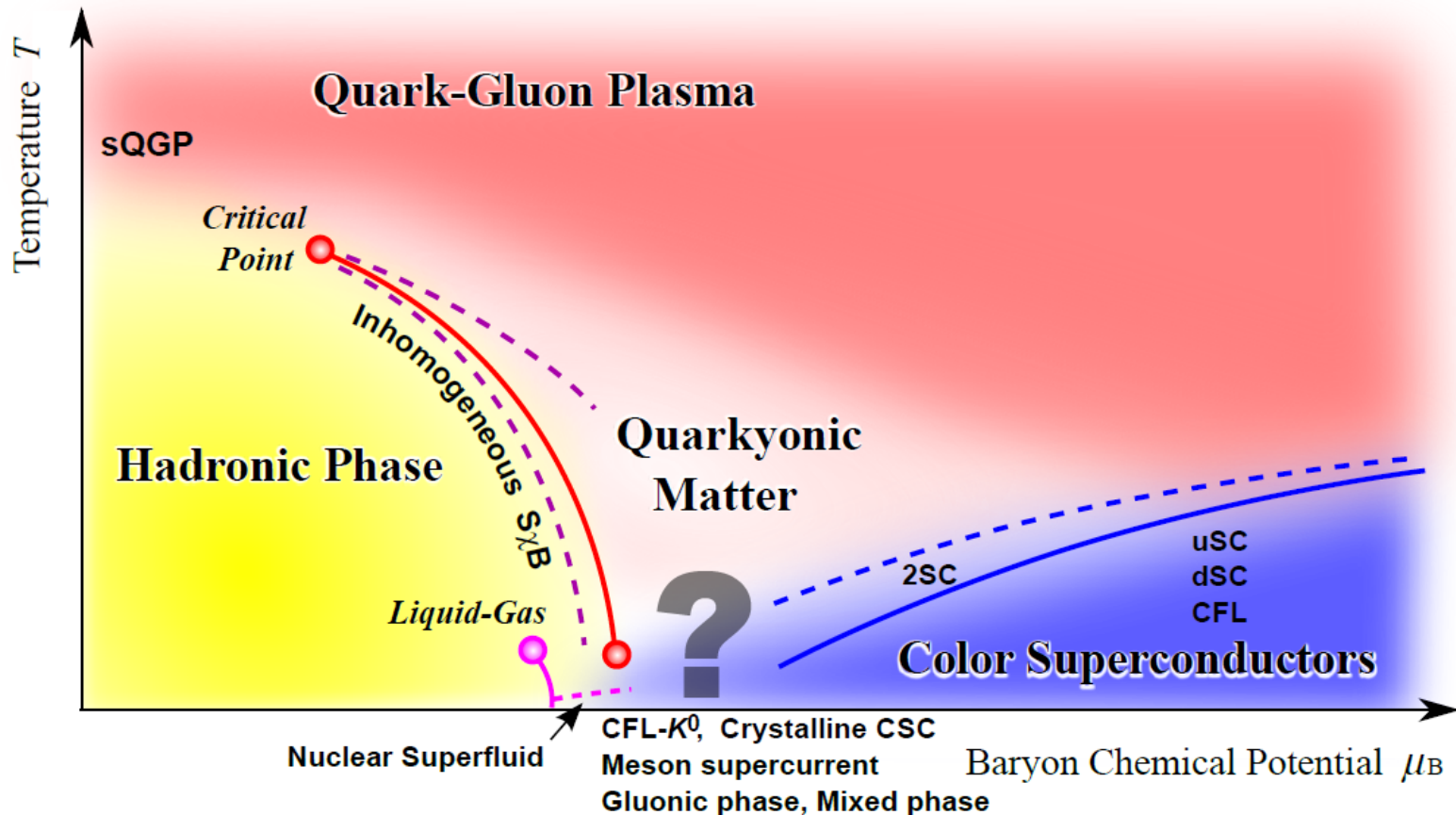


Kenji Fukushima

The University of Tokyo

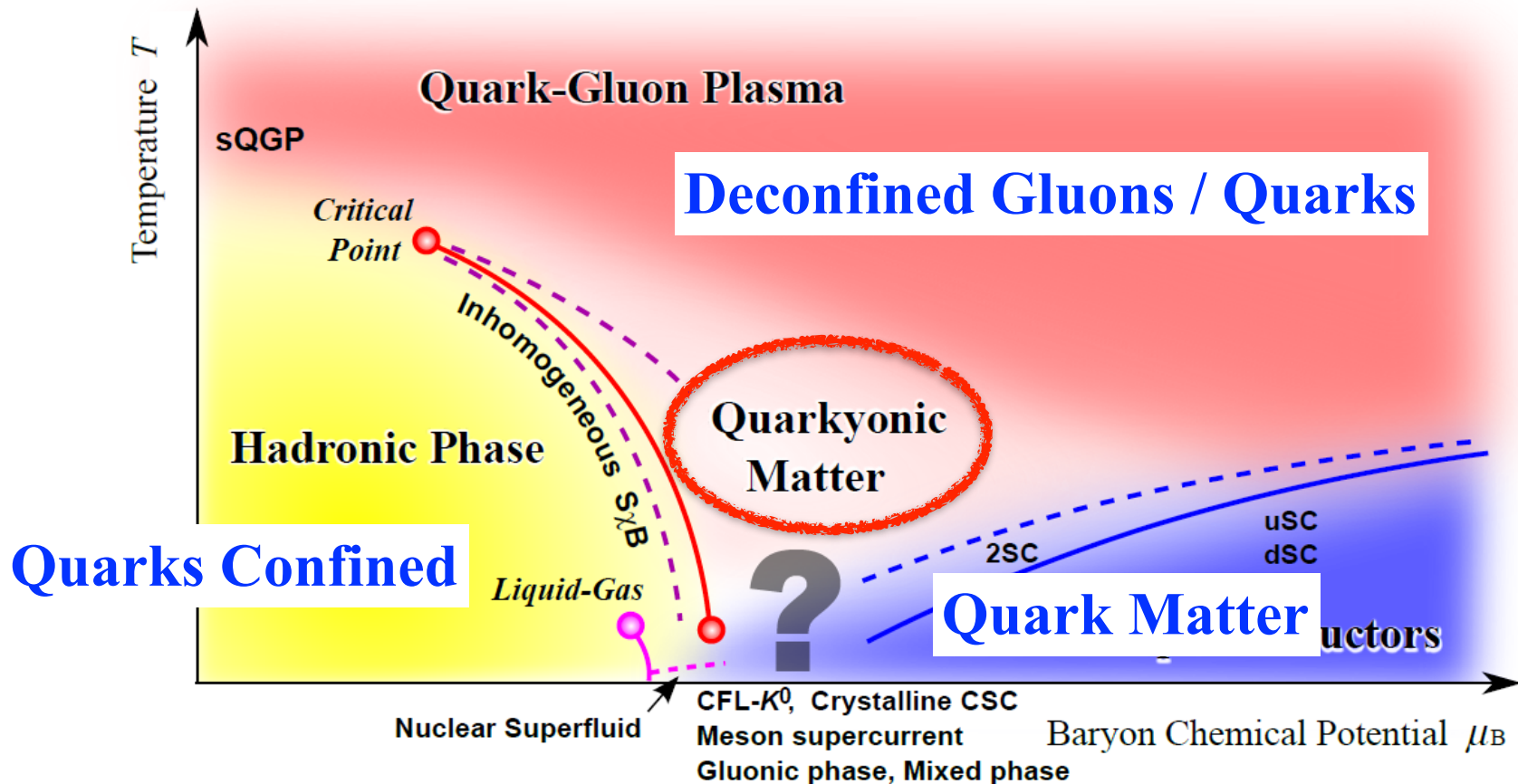
— 2nd Symposium on Intermediate-energy Heavy Ion Collisions (iHIC24) —

QCD Phase Diagram



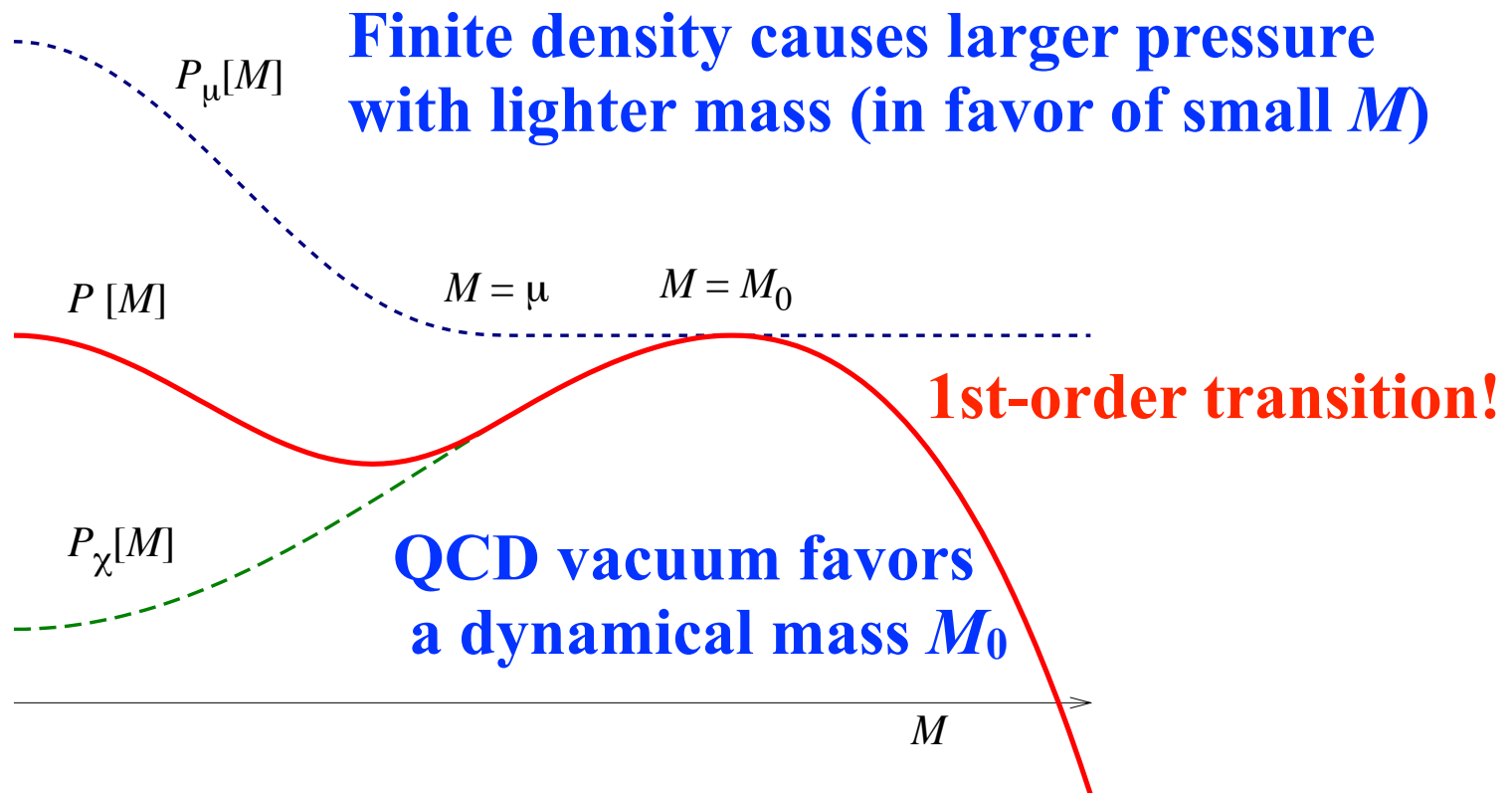
Fukushima-Hatsuda (2010); see also 50 Years of QCD Chap.7 (2023)

QCD Phase Diagram

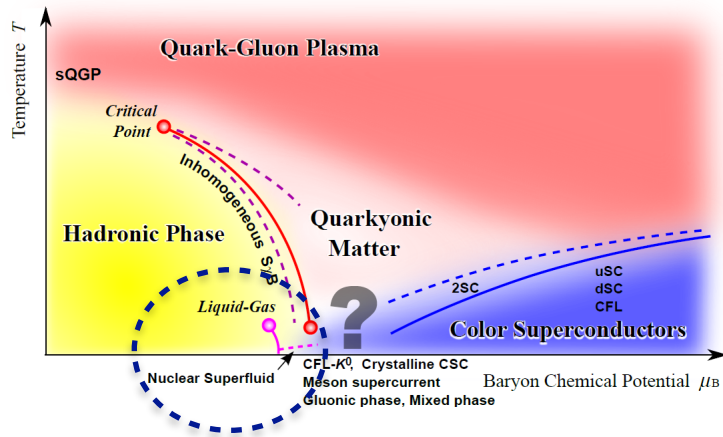


Phase Transition?

Underlying mechanism to favor 1st-order PT



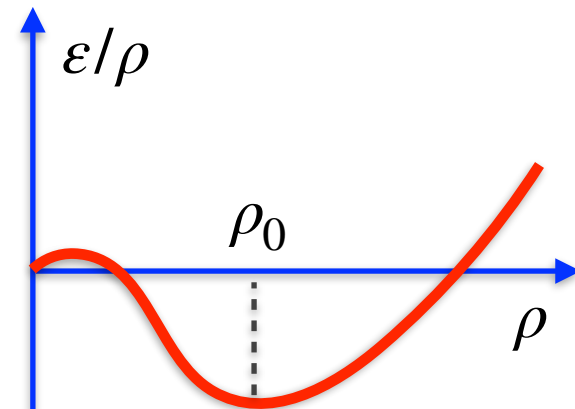
Phase Transition?



Symmetric nuclear matter has a liquid-gas phase transition.

What causes this transition?

Self-bound fermionic systems (with the saturation density) always have a 1st-order phase transition (PT).



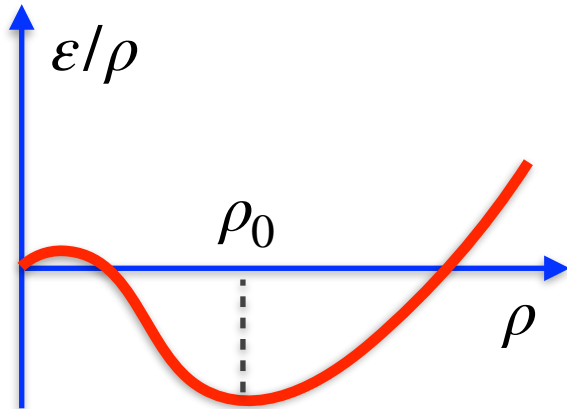
Phase Transition?



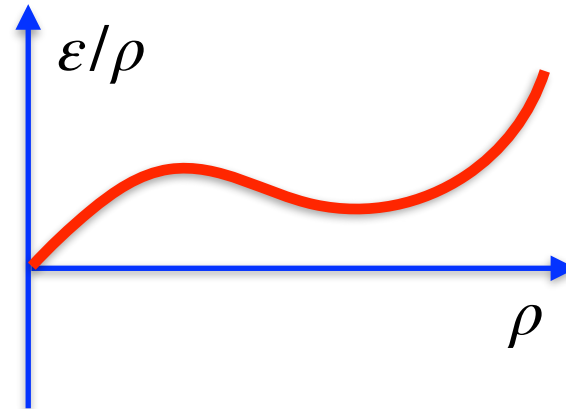
$$\frac{d}{d\rho} \left(\frac{\varepsilon}{\rho} \Big|_{\text{gas}} - \frac{\varepsilon}{\rho} \Big|_{\text{liquid}} \right) = \frac{p_{\text{gas}} - p_{\text{liquid}}}{\rho^2} = 0$$

Metastability

1st-order PT



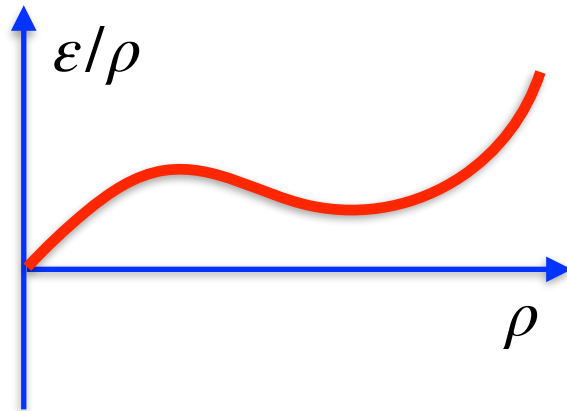
Nuclear Matter



Chiral Quark Models

Phase Transition?

IF this is the case:

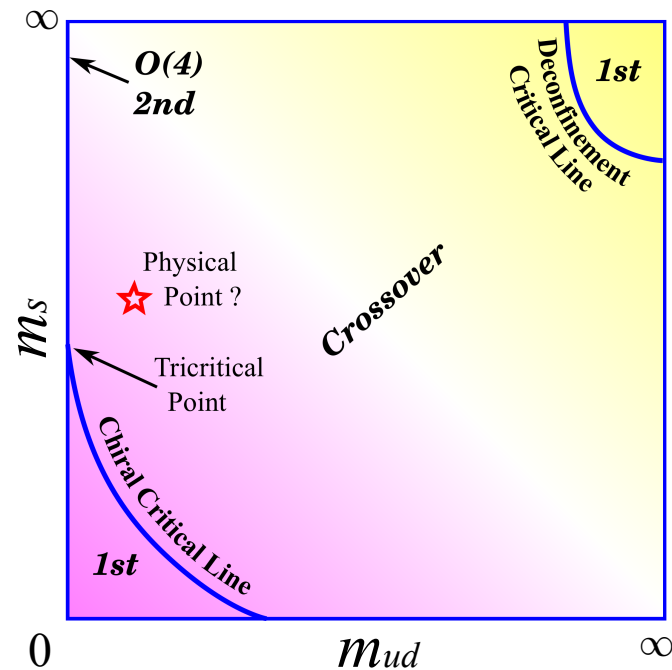


Chance of the first-order PT is quantified by the Columbia plot.

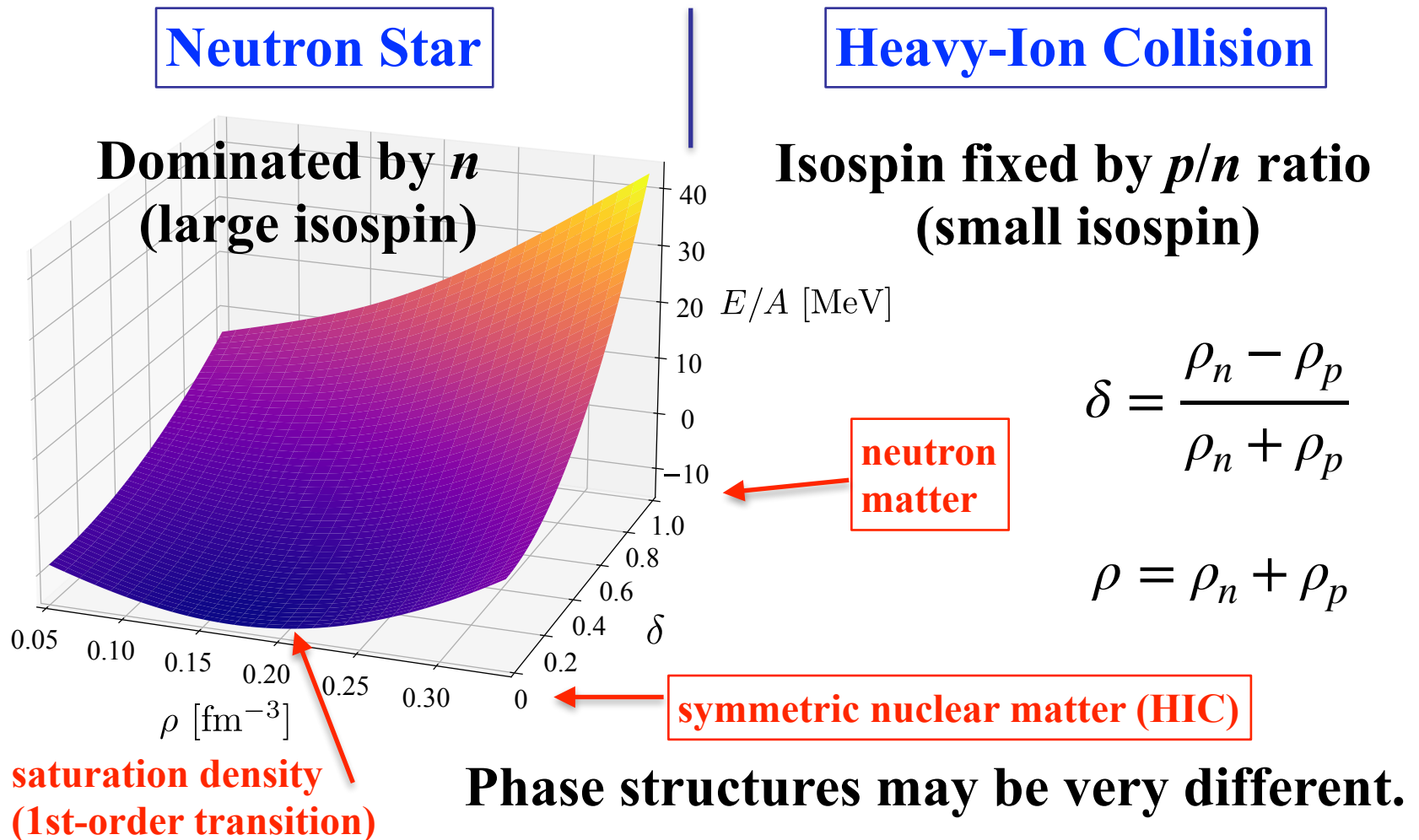
Recent lattice suggests that the first-order region is very small or just gone (Owe Philipsen).

First-order PT

→ **QCD Critical Point**



Lesson from NS Physics



Lesson from NS Physics

Neutron Star

β equilibrium

$$\mu_s = 0$$

High baryon density should involve hyperons (Λ , Σ , etc)

EoS too soft? / Cooling too fast?

Hyperon Puzzle

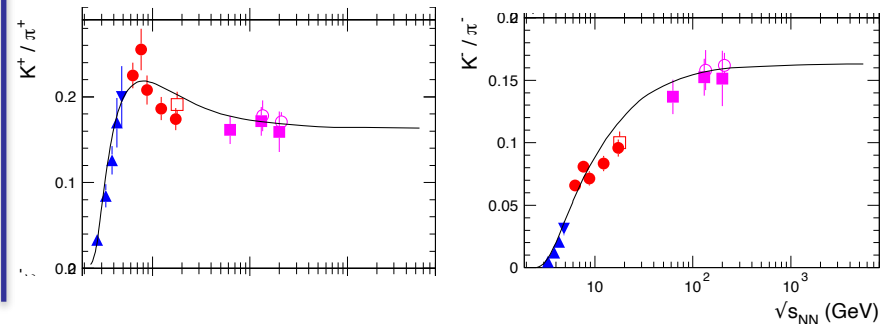
- * Interactions may suppress hyperons (3-body forces YNN)
- * Interactions may make EoS stiff (repulsive forces at high density)

Heavy-Ion Collision

Zero net strangeness

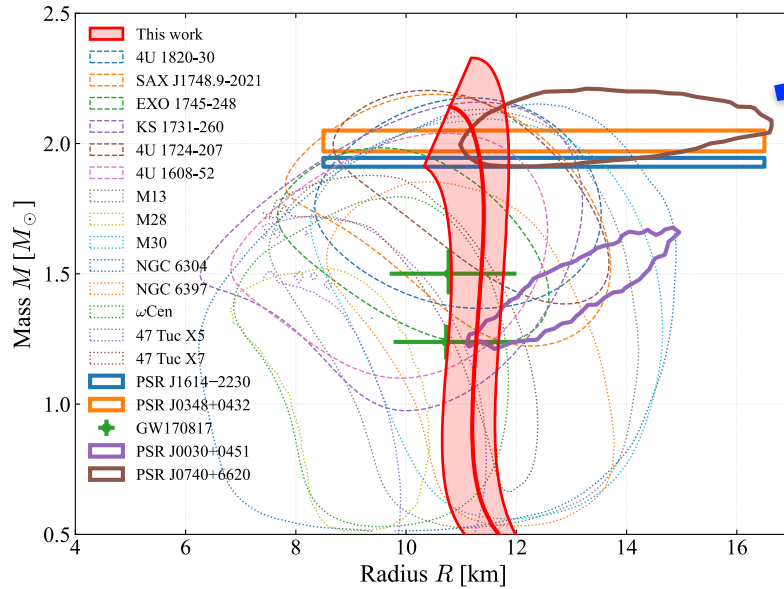
$$n_s = 0 \quad (\mu_s \sim \frac{1}{3} \mu_B)$$

Hyperon strangeness is canceled by strange mesons (\bar{s} in mesons sensitive to μ_B)



Lesson from NS Physics

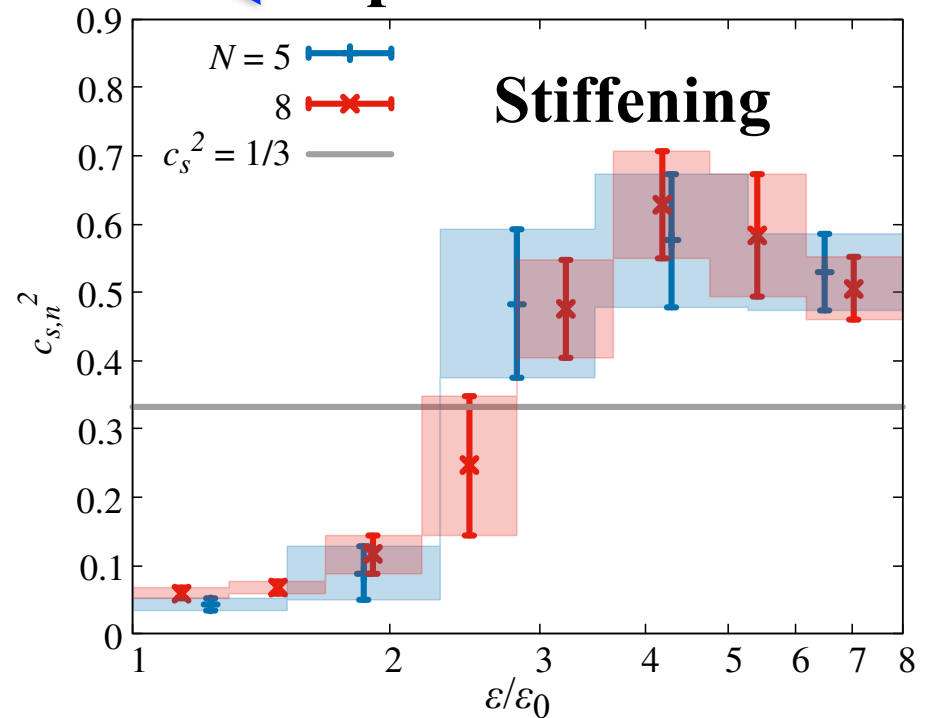
Fujimoto-Fukushima-Murase (2019-2024)



14 PREs/qLMXBs
6 HP/NICER/GW

Deep Neural Network

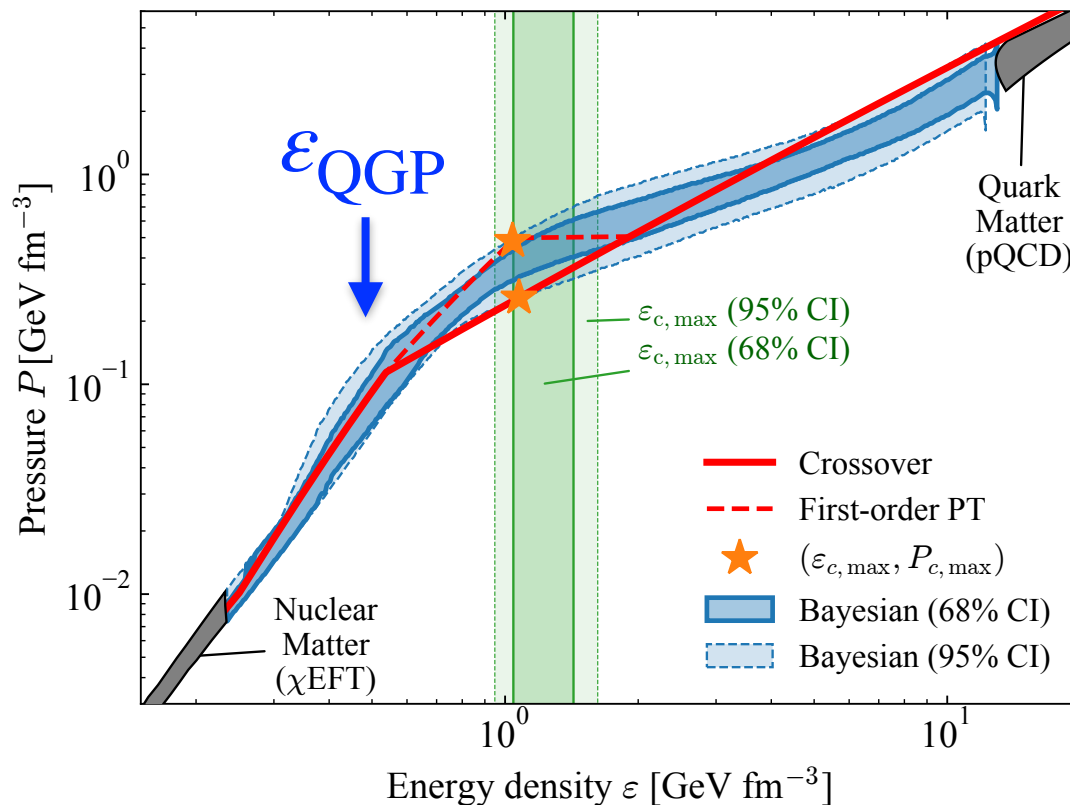
Speed of Sound



Lesson from NS Physics

Fujimoto-Fukushima-Murase (2019-2024)

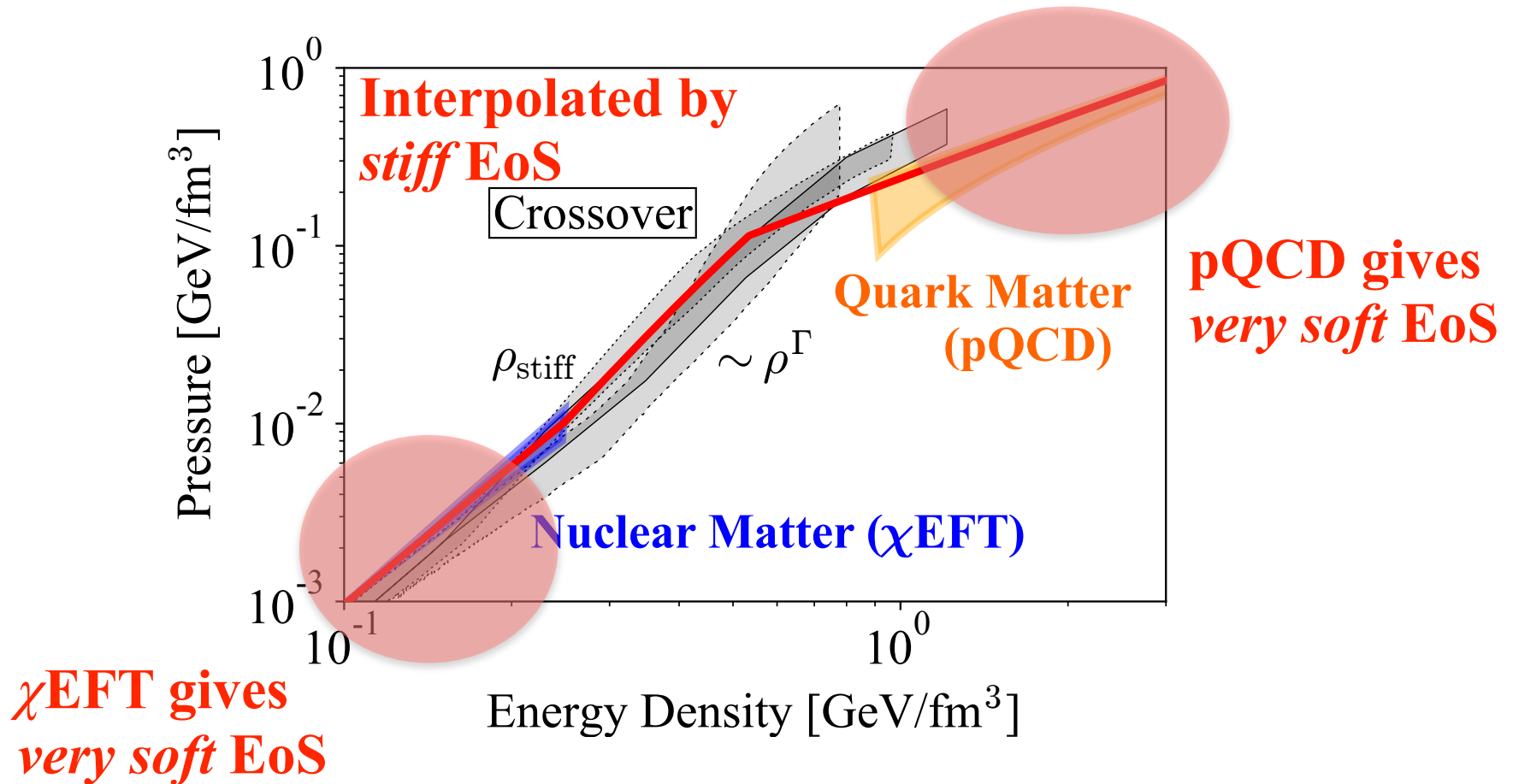
Fujimoto-Fukushima-Kyutoku-Hotokezaka (2022-2024)



**Plot compiled by
Yuki Fujimoto**

Lesson from NS Physics

Fujimoto-Fukushima-Hotokezaka-Kyutoku (2022)



Lesson from NS Physics



(Conventional) Hyperon Puzzle

If hyperons (strangeness d.o.f.) are included,
the EoS is too soft...

How to avoid hyperons or make the EoS stiff?

Real Challenge

EoS must become stiff around **1.5-2** times n_0
(stiffer than the conventional nuclear EoS). **How??**

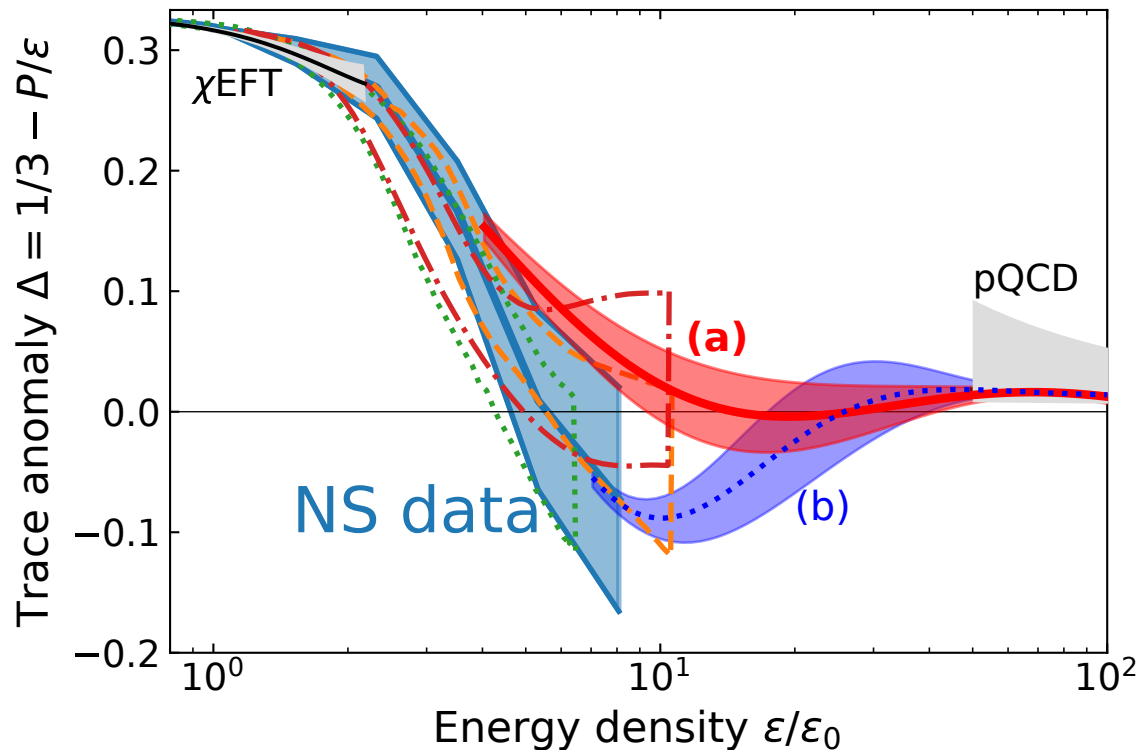
Quarkyonic model?

Then, EoS can be steeply softened (no hyperon puzzle)
around **3-4** times n_0 . **Crossover to Quark Matter**

Lesson from NS Physics

Fujimoto-Fukushima-McLerran-Praszalowicz (2022)

Speed of sound \longleftrightarrow “Trace Anomaly”

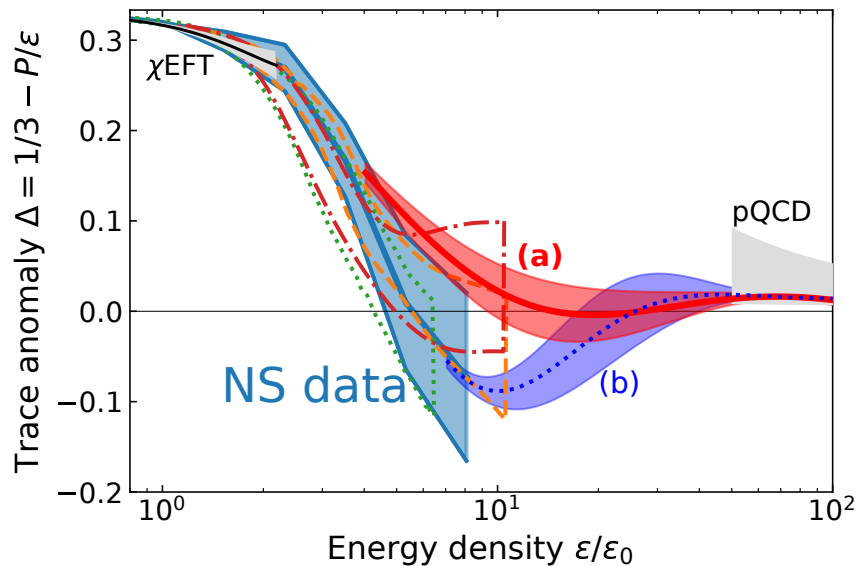


Quick recovery of
conformality ?
Unexpected from QCD

Why? How? Really?

Lesson from NS Physics

Interesting question... $\Delta < 0 \leftarrow$ caused by μ^2



$$\Delta \propto \varepsilon - 3p$$
$$\propto \frac{d}{d\mu} \left(\frac{p}{\mu^4} \right)$$

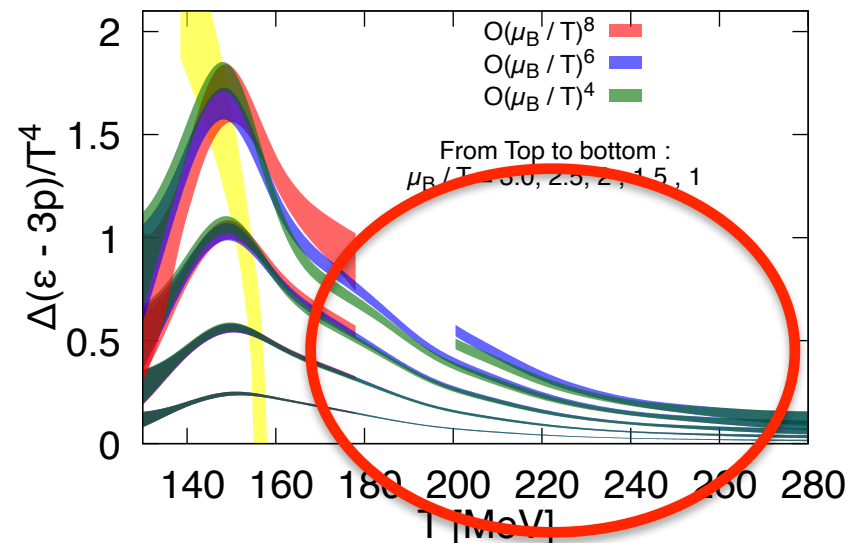
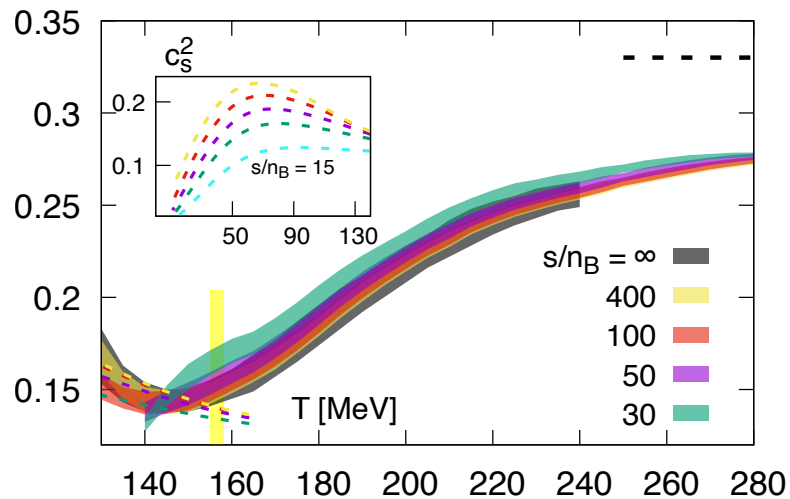
**Thermodynamic
degrees of freedom**

**Negative trace anomaly implies
the presence of “condensates”.**

Lesson from NS Physics

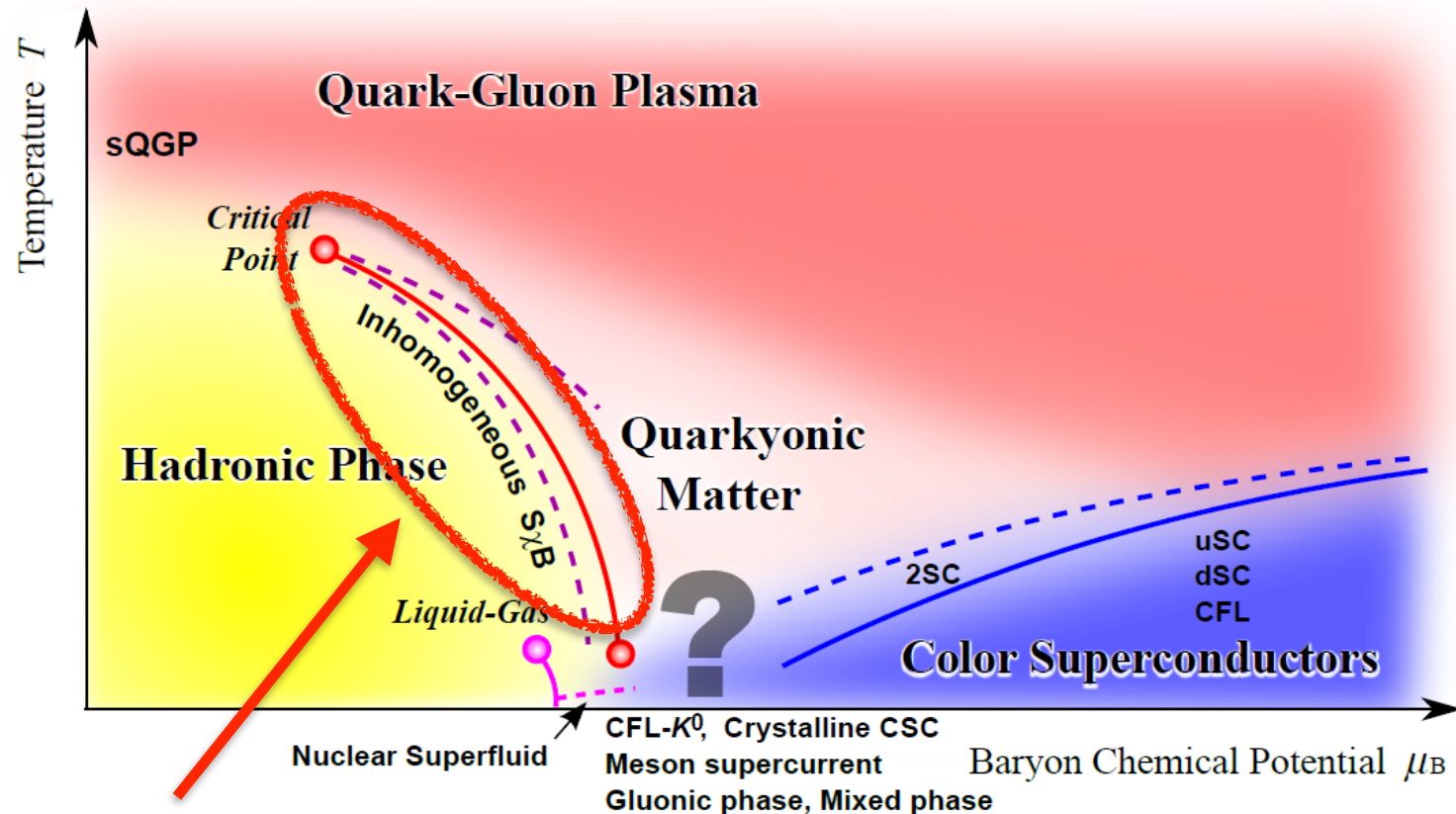
What do we know about **high- T and small- μ** matter?

HotQCD Collab. (2212.09043)



Longstanding puzzle of the origin of T^2 term

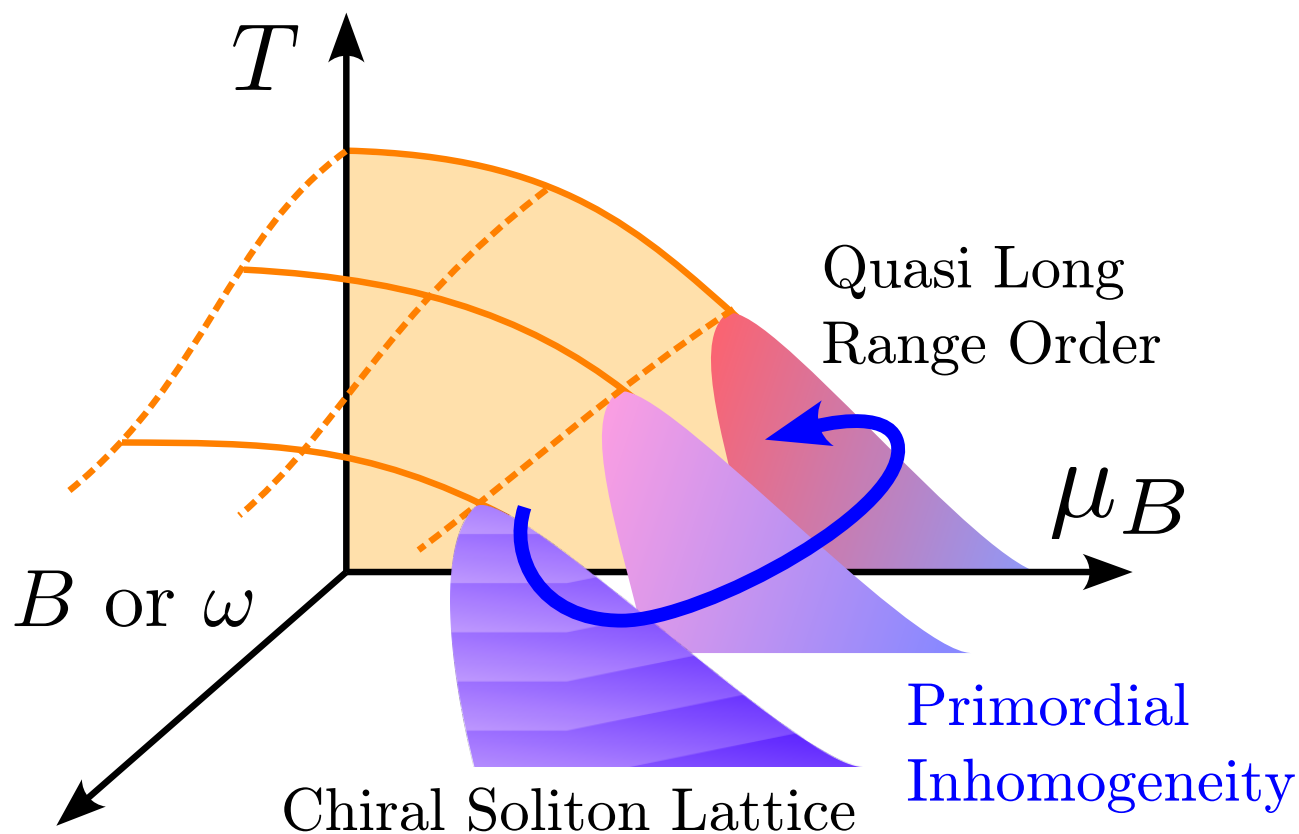
Inhomogeneous Phase



Prediction from many models as robust as Critical Point
Fragile if the system is 3D rotationally symmetric, but...

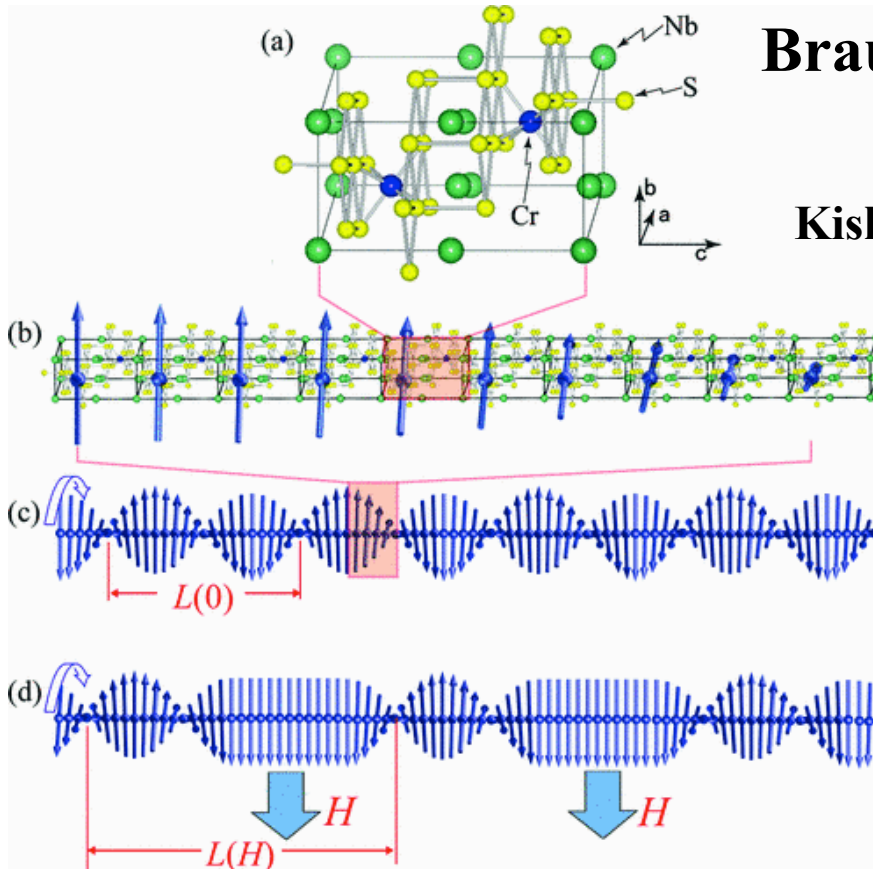
Inhomogeneous Phase

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)



Inhomogeneous Phase

Dense QCD Matter with Strong $B \sim$ Chiral Magnet



Brauner-Yamamoto, JHEP (2016)

Kishine *et al.*, PRL108, 107202 (2012)

No symmetry breaking



Explicit breaking



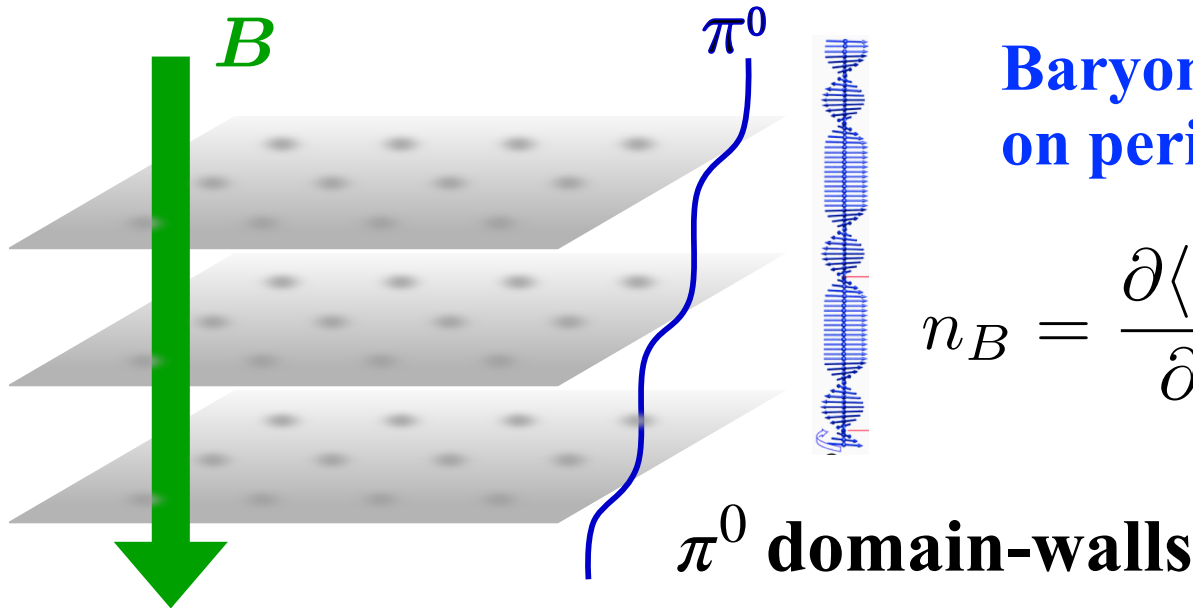
$H \sim m$ (mass) in QCD

Inhomogeneous Phase



Brauner-Yamamoto, JHEP (2016)

**Baryon density localized
on periodic domain walls**



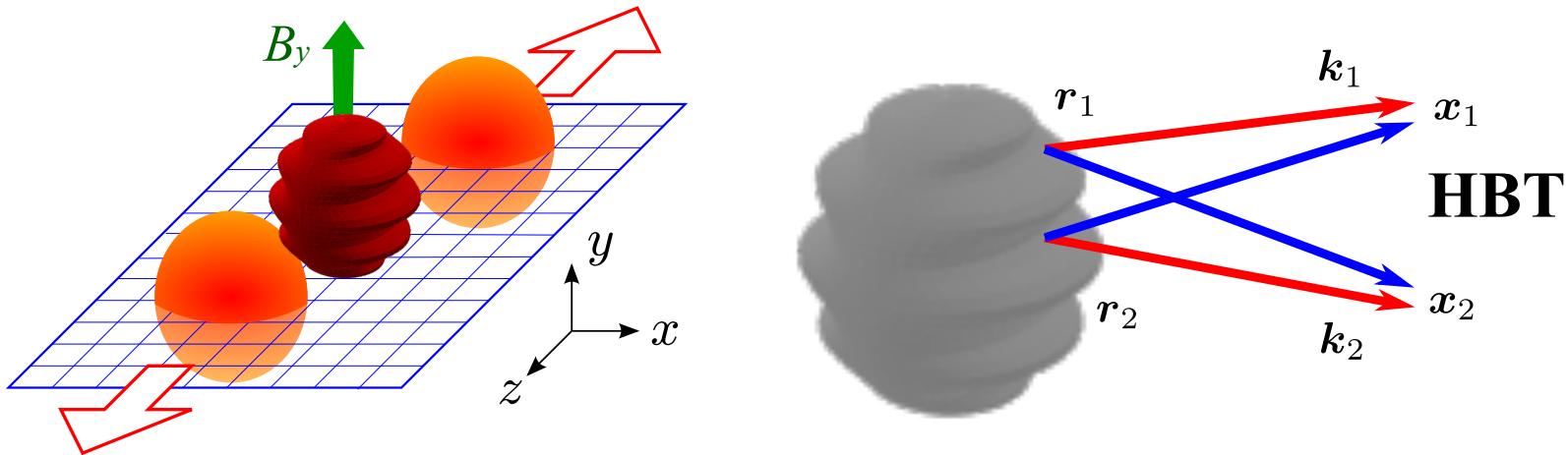
$$n_B = \frac{\partial \langle \mathcal{H} \rangle}{\partial \mu} = \frac{B_z}{4\pi^2 f_\pi} \partial_z \pi^0$$

Usually the domain wall is characterized by Z_N interfaces.

π^0 domain-walls are **1D windings** extending transversely.

Probing Clusters

How to hunt for the inhomogeneity in HIC?



HBT is used to determine the system size but it should be more sensitive to the **cluster size**!?

c.f. Moat regime with HBT by Pisarski-Rennecke-Rischke

Probing Clusters

See reviews by Scott Pratt

HBT = Source + Wavefunctions (plain waves)

$$C_2(\mathbf{q}) = \int d^3r S(\mathbf{r}) |\psi_{\text{rel}}(\mathbf{q}, \mathbf{r})|^2$$

$$|\psi_{\text{rel}}(\mathbf{q}, \mathbf{r})|^2 = 1 + \cos(\mathbf{q} \cdot \mathbf{r})$$

Source = Convolution of source function

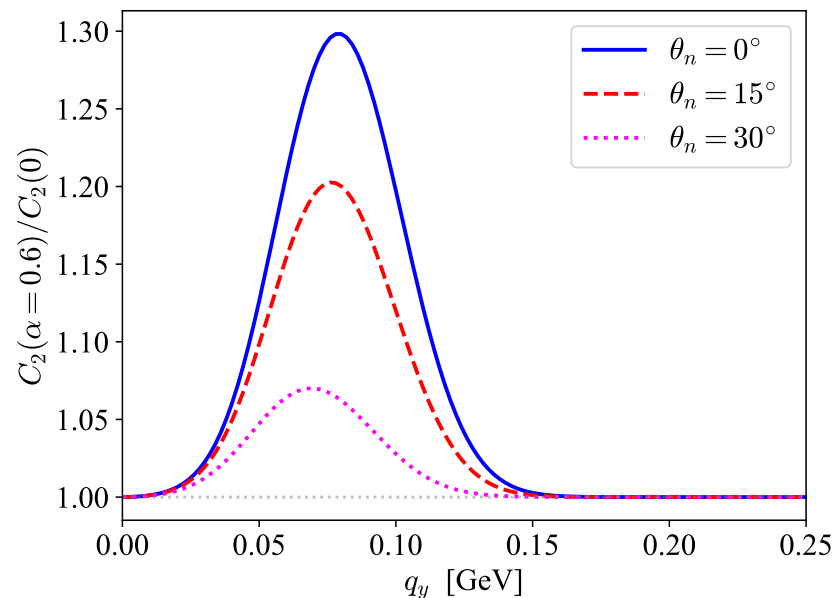
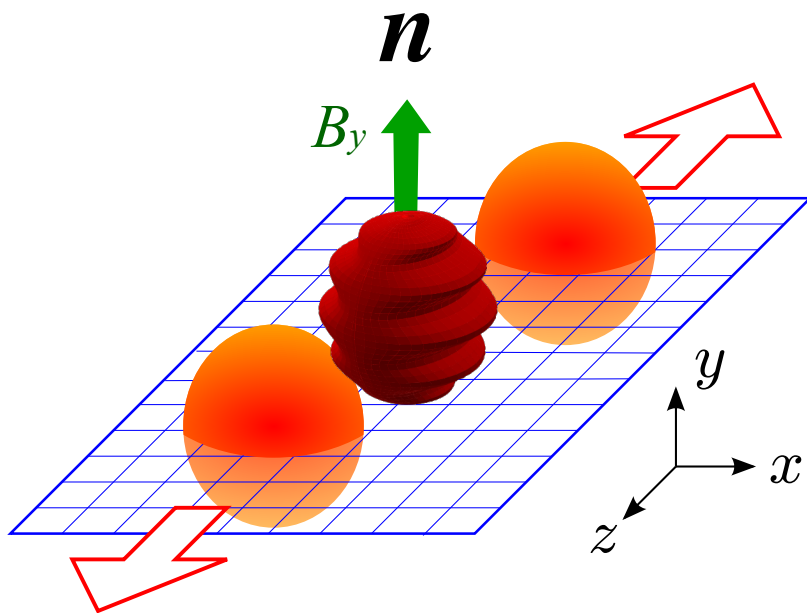
$$S(\mathbf{r}) = \int d^3r_1 d^3r_2 s(\mathbf{r}_1) s(\mathbf{r}_2) \delta(\mathbf{r} - \mathbf{r}_1 - \mathbf{r}_2)$$

Probing Clusters

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)

Gaussian model - analytically calculable

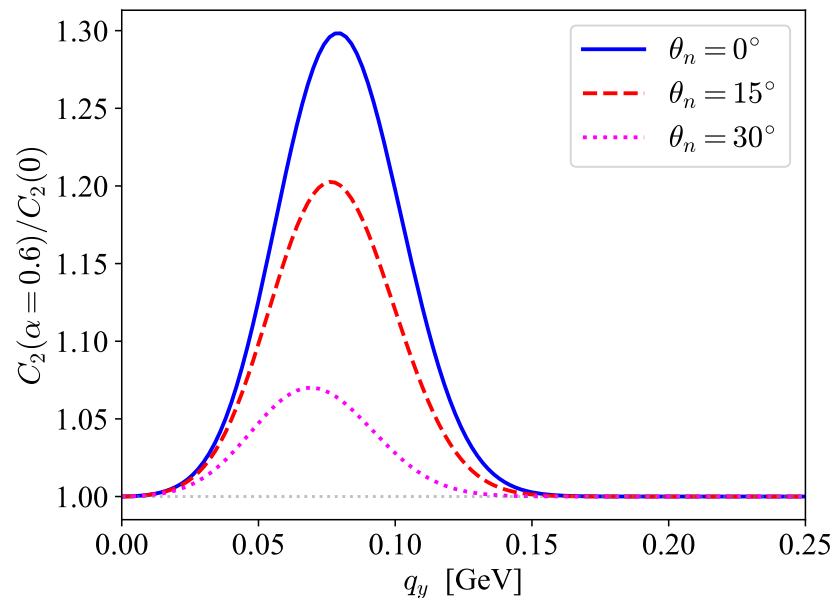
$$s(\mathbf{r}) \propto e^{r^2/(2r_0^2)} [1 + \alpha \cos(2k\mathbf{n} \cdot \mathbf{r})]$$



Probing Clusters

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)

**HBT ratio with and without
the inhomogeneity**



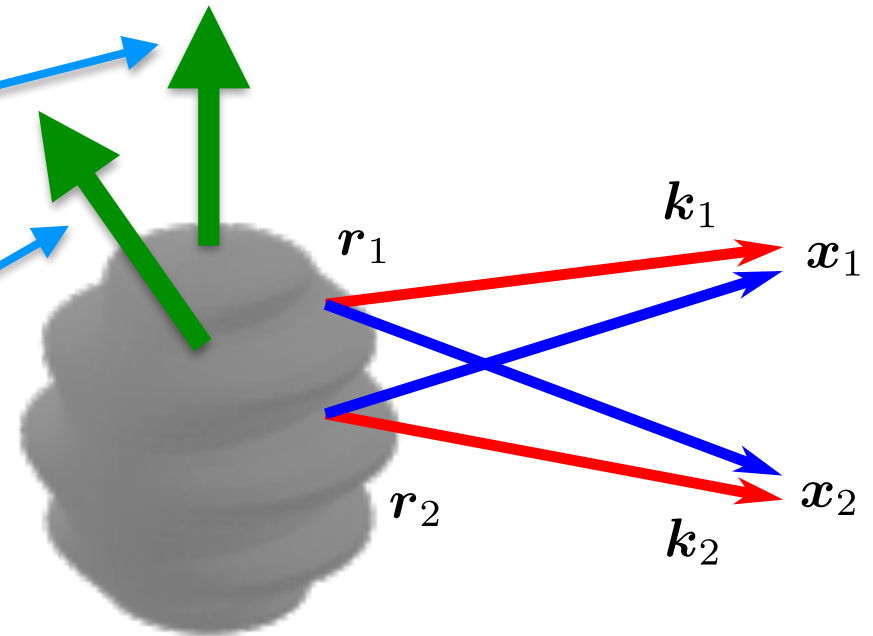
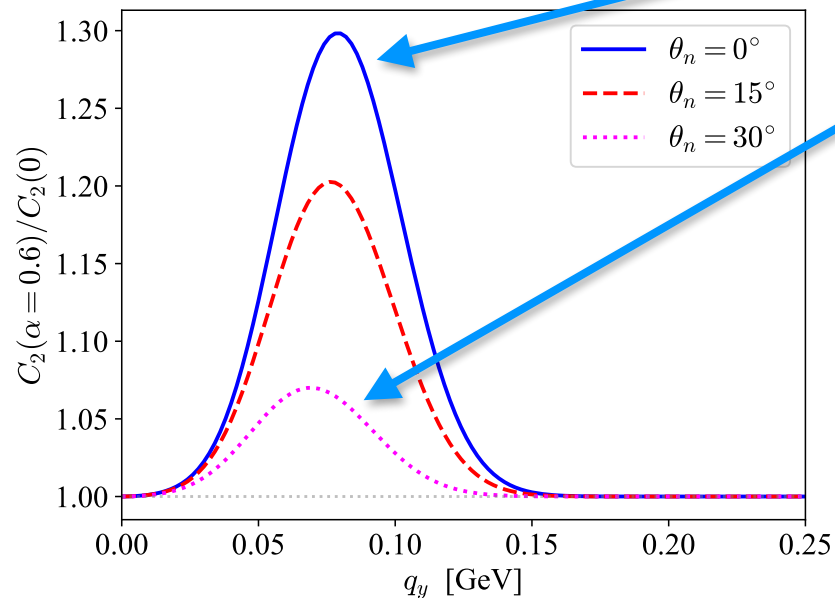
**Clear peak is seen at the
momentum of wave-number.**

**Peak is suppressed by tilted
axis identification...!**

Probing Clusters

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)

Signal is washed out
by interference...



Probing Clusters

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)

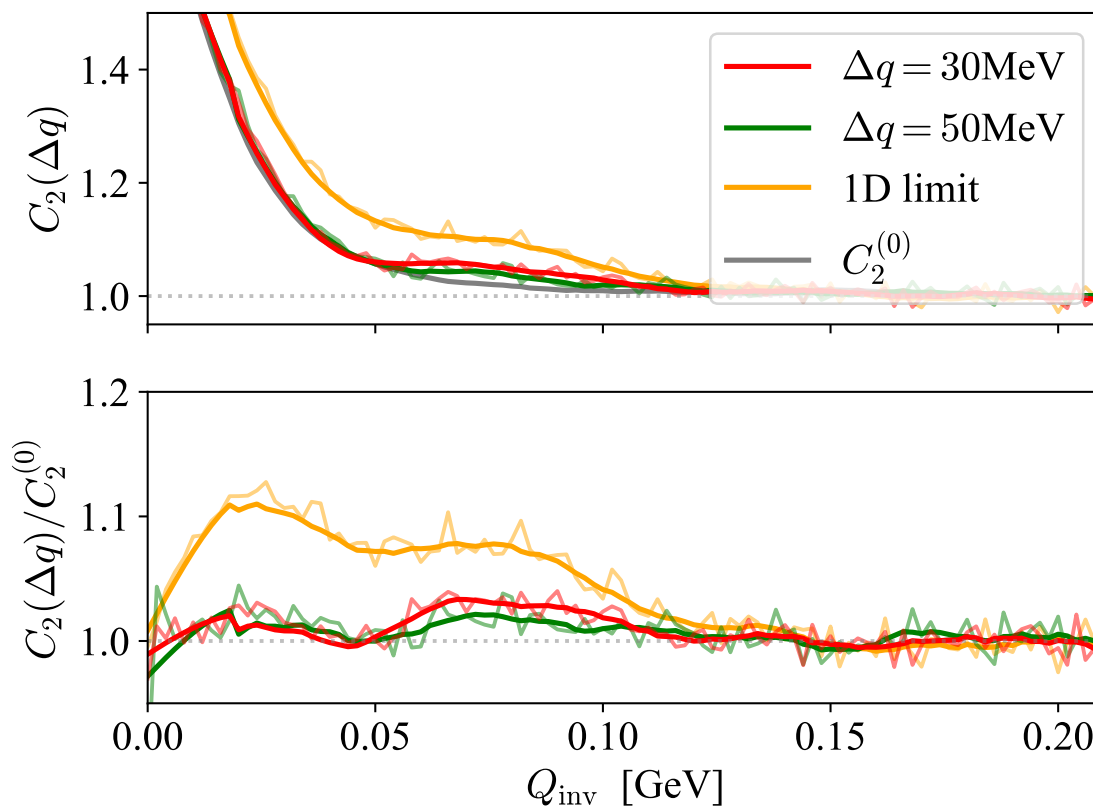
AMPT

@ $\sqrt{s_{NN}} = 39 \text{ GeV}$

$3 \text{ fm} < b < 4 \text{ fm}$

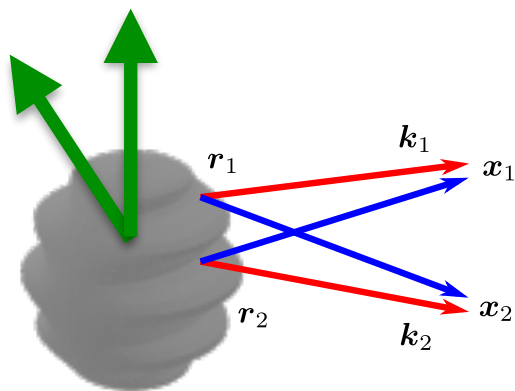
Cosine modulation
set by hand
(feasibility test)

$\theta_n = 20^\circ$



Probing Clusters

Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)



In principle, the signal is nonzero.


However...

Huge statistics dropped by momentum filter along the y -axis (modulation axis); see Δq dep...

A small tilt suppresses the signal...

We are looking for a better observable... any idea? ML?

Summary

- 
- **NS analysis of EoS poses various new questions which may be studied by HIC.**
 - **Stiffening or increasing sound speed before $2n_0$ awaits explanations (new state of matter?).**
 - **Inhomogeneous phases could favor clustered substructures along the magnetic axis.**
 - **HBT can in principle detect it, but any better way?**