Emergent conformality in dense QCD matter: lessons from a holographic QCD model

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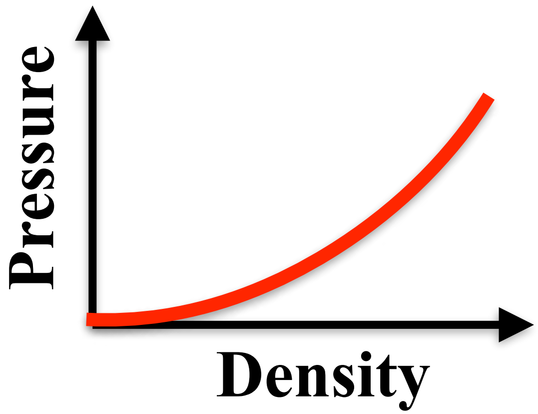
— The QCD Phase Diagram: From Theory to Experimental Signatures —

Experimental signatures
— non-perturbatively conformal

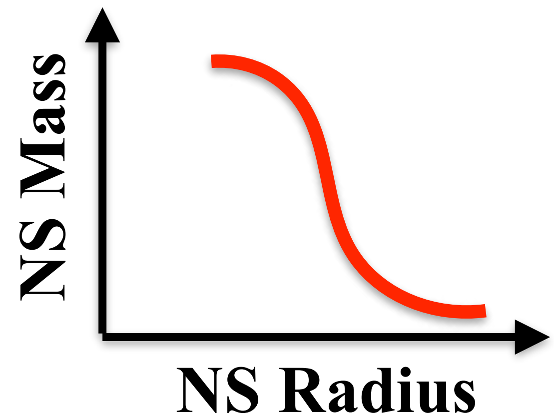
Data Analysis

Equation of State (EoS)

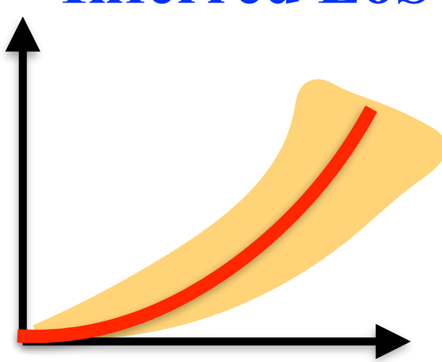


1-to-1

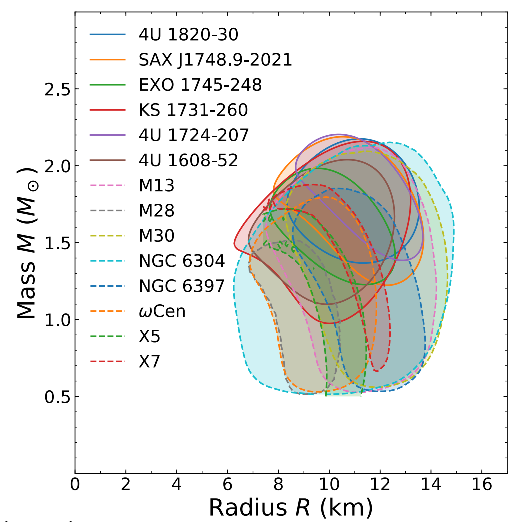
M-R curve of NS



Inferred EoS

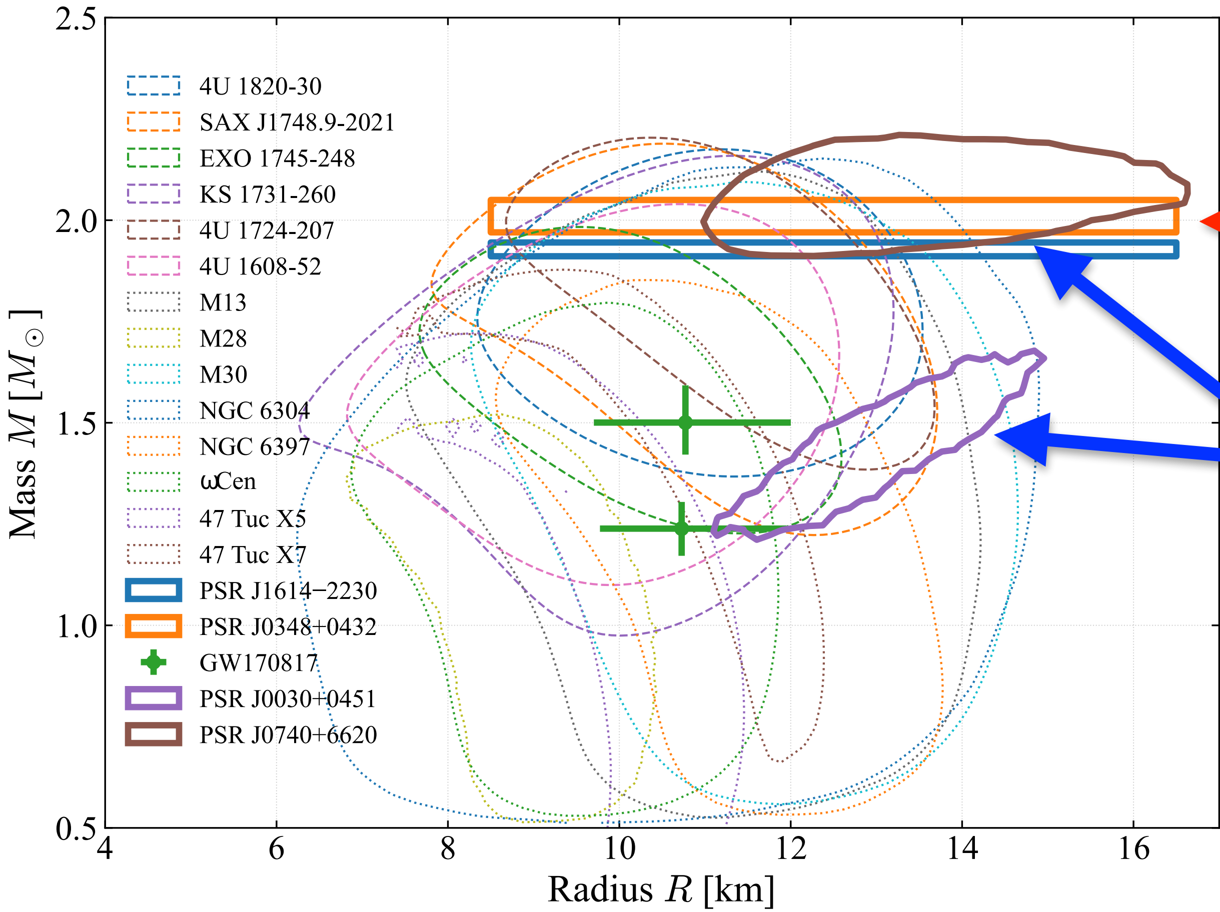


Probabilistic Methods



Real Data

Data Analysis

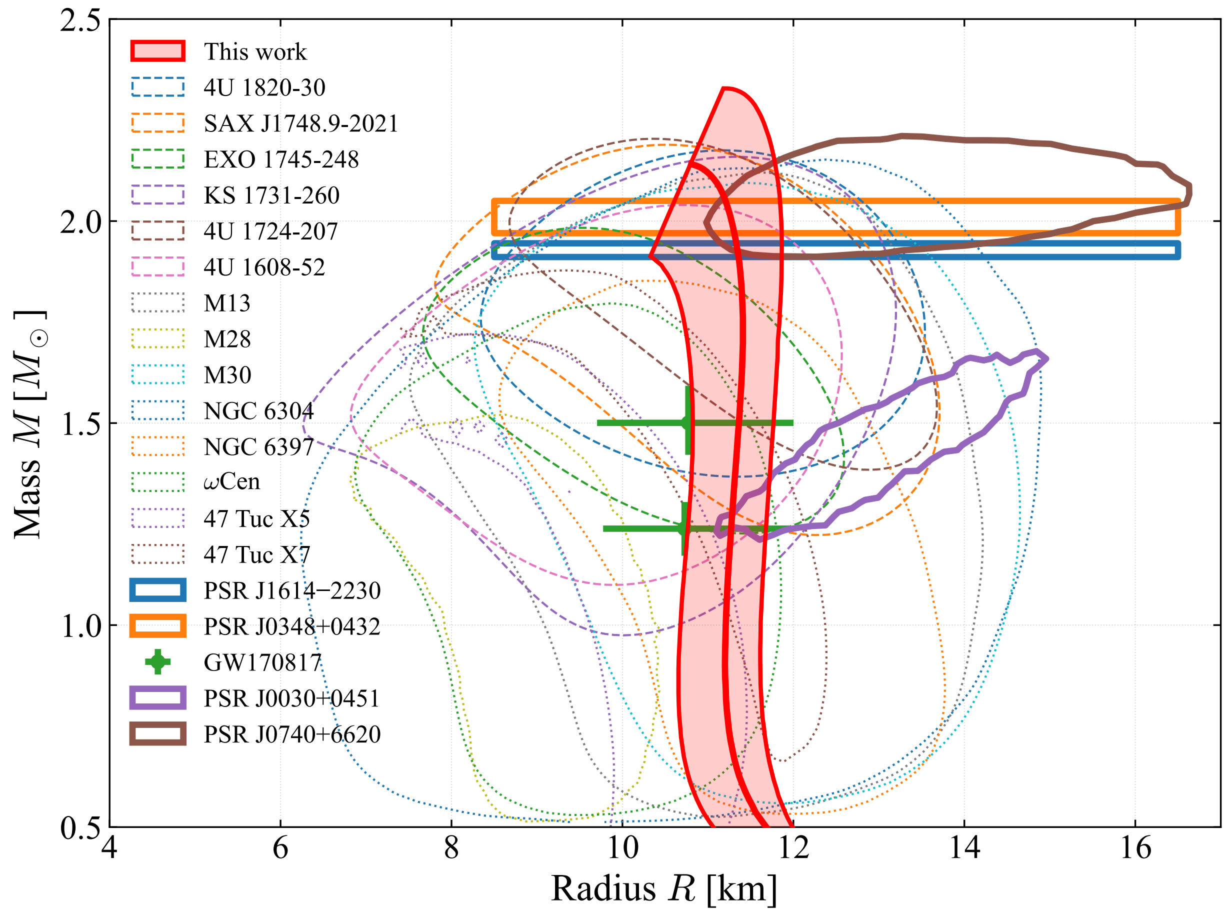


EOS must be "stiff" enough to reach the Shapiro delay observation.

Lensing and timing (NICER) constraining the gravity strength and the radius!

Data Analysis

Fujimoto-Fukushima-Kamata-Murase (2018-2024)



Data Analysis

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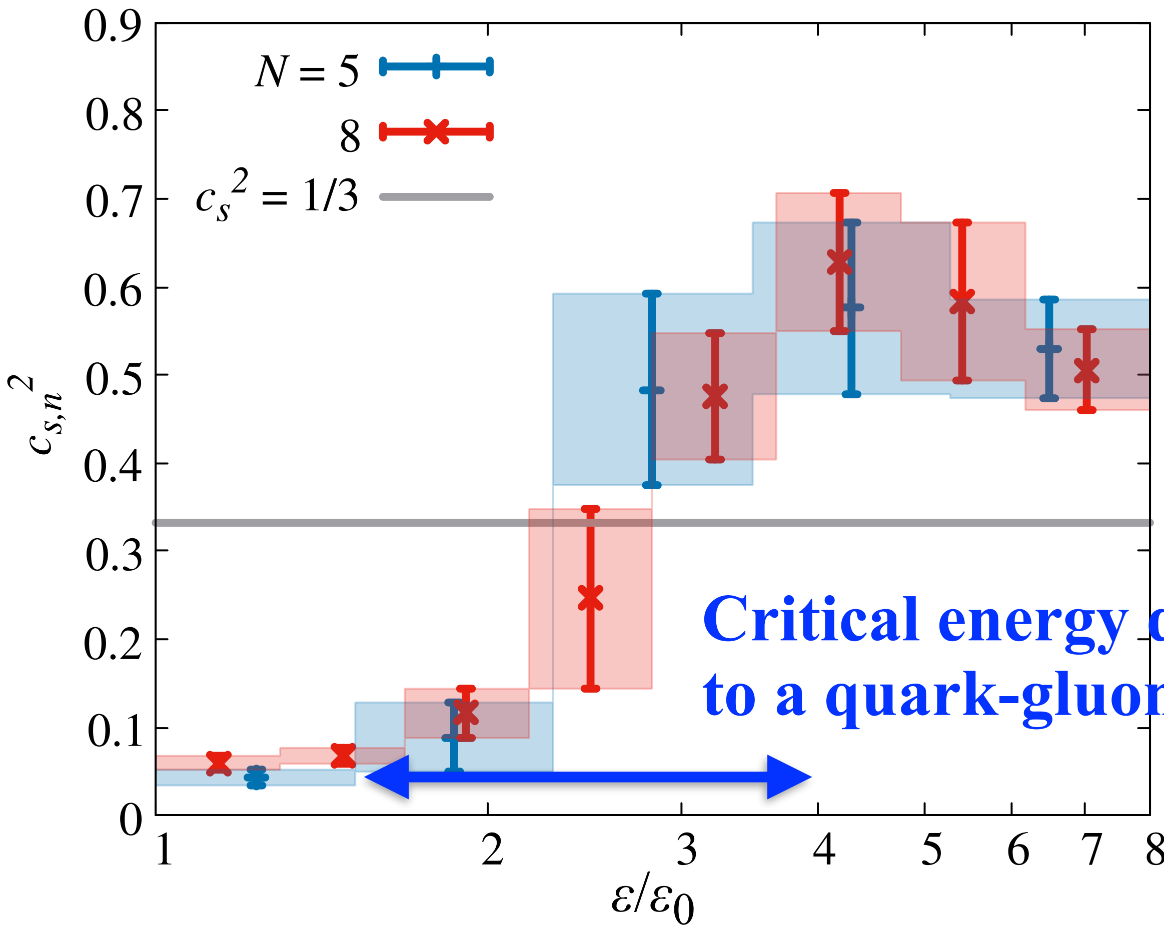


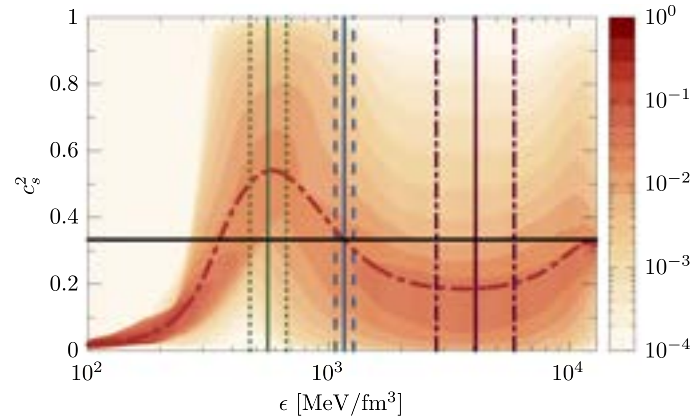
Not minimum, but maximum!?

Critical energy density to a quark-gluon plasma

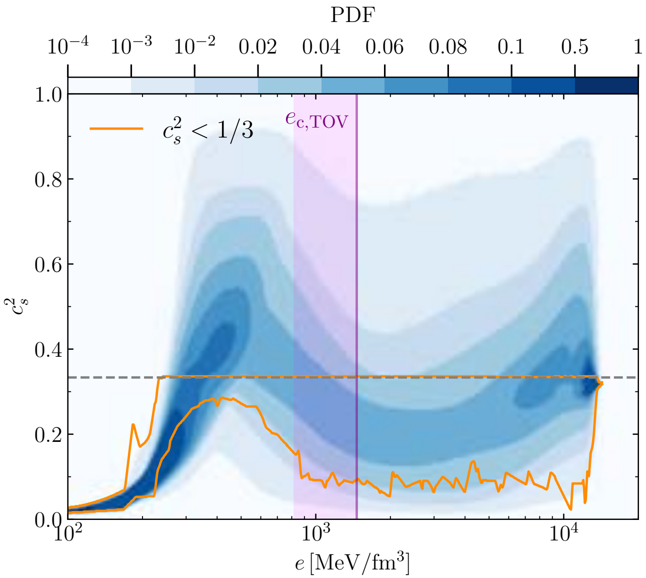
$\varepsilon_0 = 150\,\mathrm{MeV\ fm^{-3}}$

Data Analysis

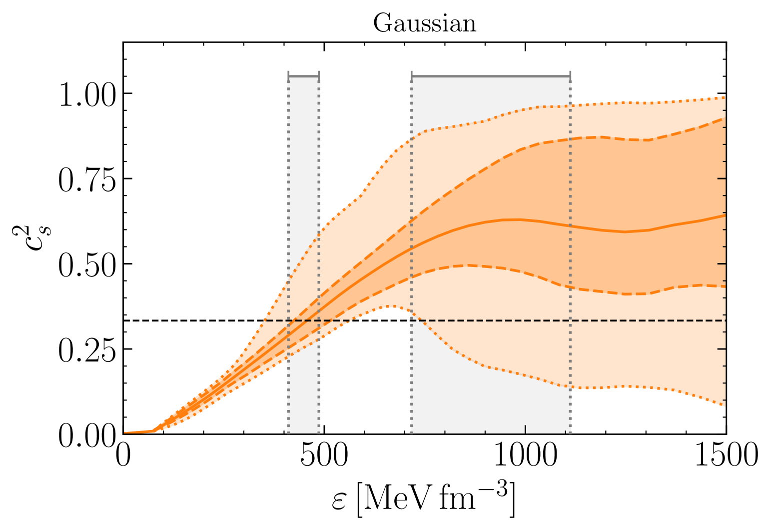
Marczenko-McLerran-Redlich-Sasaki (2022)



Altiparmak-Ecker-Rezzolla (2022)



Brandes-Weise-Kaiser (2022)



Supporting the peak!

Conformality

Fujimoto-Fukushima-McLerran-Praszalowicz (2022)

Measure of conformality: $\boxed{\Delta = \frac{1}{3} - \frac{p}{\varepsilon}}$

Gavai-Gupta-Mukherjee (2004)

$$c_s^2 = \frac{dp}{d\varepsilon} = c_{s,\,\mathrm{deriv}}^2 + c_{s,\,\mathrm{non-deriv}}^2$$

$$c_{s,\,\mathrm{deriv}}^2 = -\,\varepsilon \frac{d\Delta}{d\varepsilon} \qquad c_{s,\,\mathrm{non-deriv}}^2 = \frac{1}{3} - \Delta$$

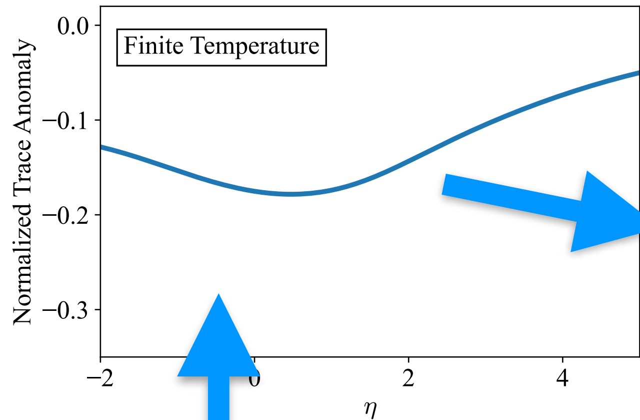
Derivative **Non-Derivative**

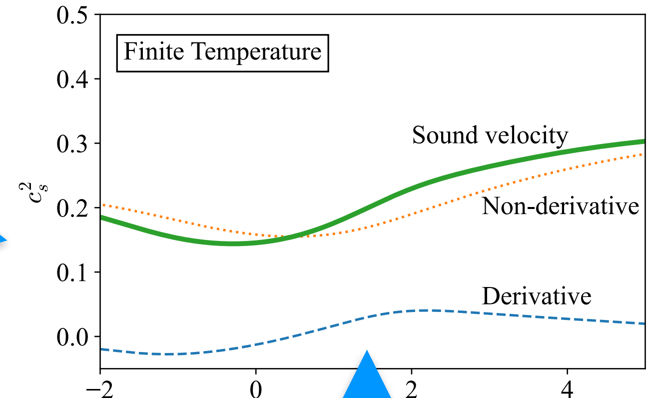
Dominant at high density making a peak!

Conformality

High-T — Non-Derivative Dominant $c_s^2 \simeq p/\varepsilon$

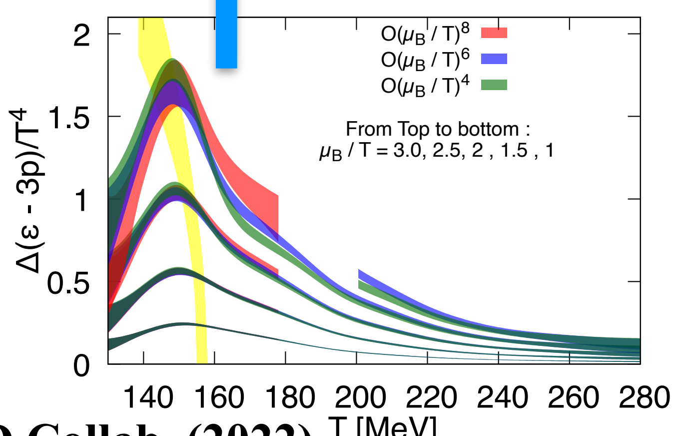
Sign Flipped $-\Delta$

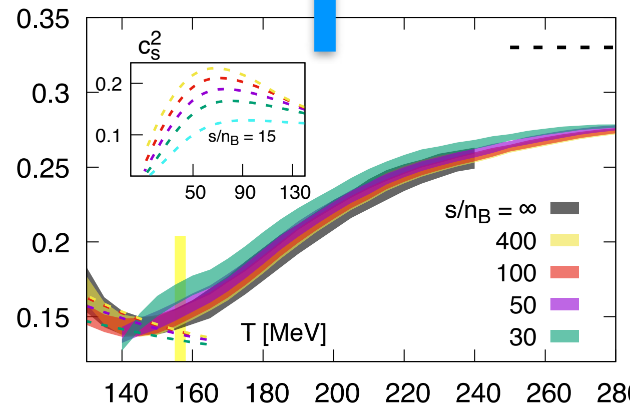




$\eta = \ln(\varepsilon/\varepsilon_0)$

Speed of Sound



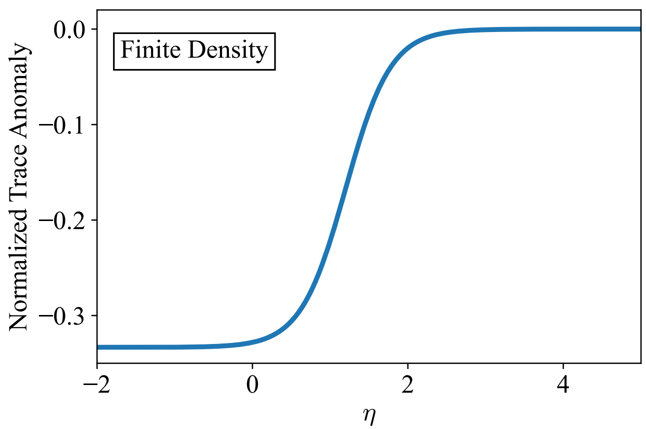


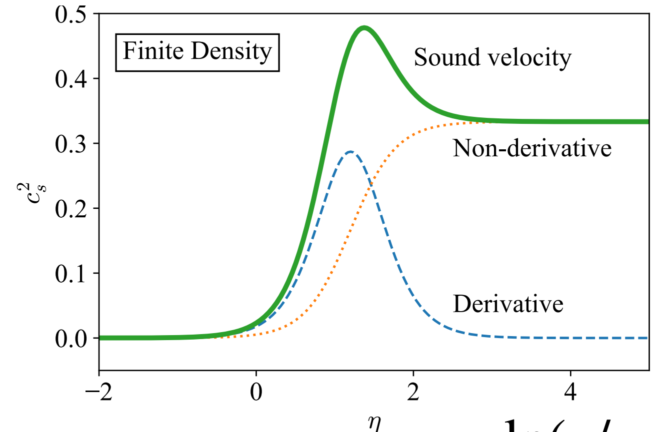
Hot QCD Collab. (2022)

Conformality

High Density — Derivative Peak ← Rapid Conformality

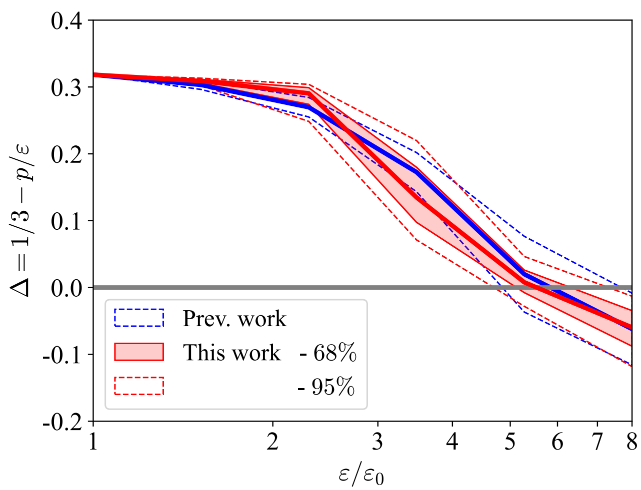
Sign Flipped $-\Delta$

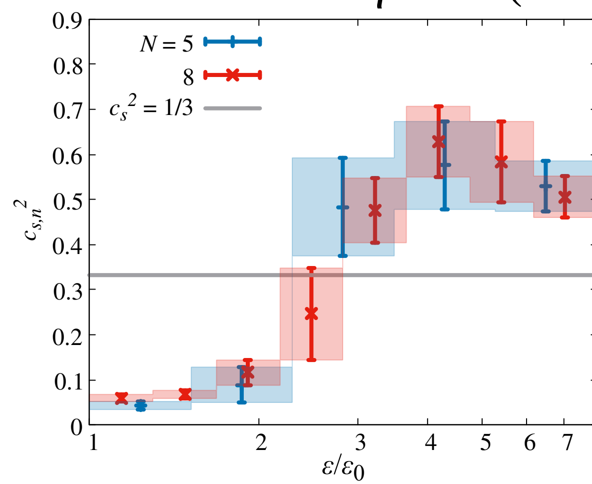




$$\eta = \ln(\varepsilon/\varepsilon_0)$$

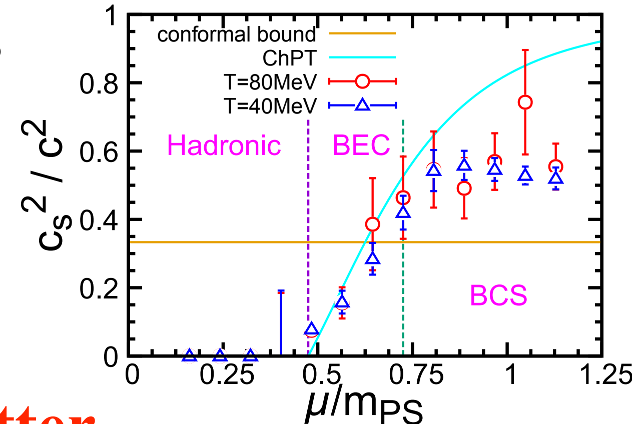
Speed of Sound





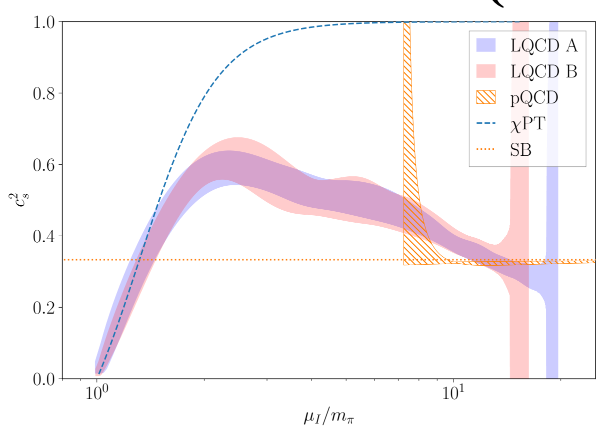
Conformality

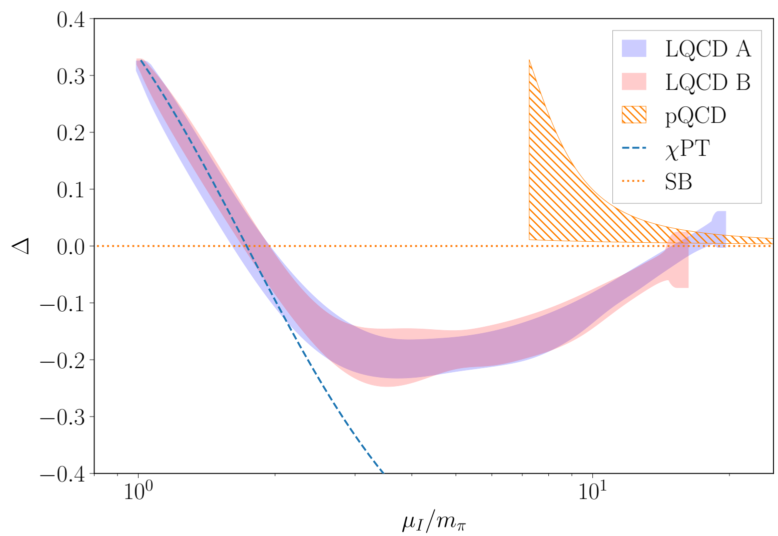
Lattice results for QCD-like theories



* **Diquark superfluid in QC_2D**
To be compared with
Lattice: Itou+ (2023-2024)

* **Pion-condensed high-isospin matter**
To be compared with
Lattice: Abbott+ (2023)

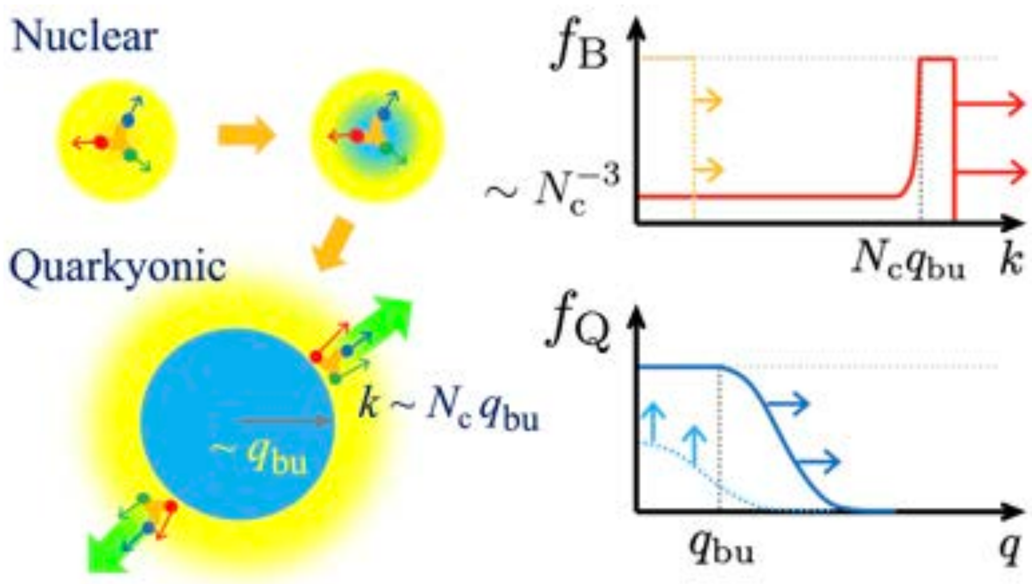




Theoretical understanding
— plausible but not satisfactory

Quarkyonic Scenario

Idyllic **Fujimoto-Kojo-McLerran (2024)**

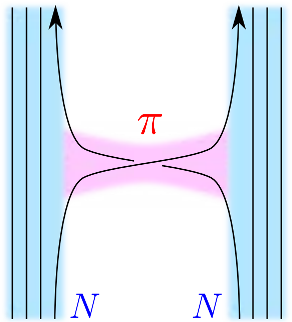


$$n_B \sim \mu_B^3 \sim N_c^3 \mu_q^3$$

$\wr\wr$ **Dual**

$$n_q \sim \mu_q^3$$

Suppression of nucleon distribution should be caused by quark saturation at short range due to quark exchanges.



Quarkyonic Scenario

Important Observation

I realized this more than 15 years ago…

Simple example of flaw in the PNJL model

$$\int d^3k\, e^{-N_c(\sqrt{k^2+M_q^2}-\mu_q)/T} = \frac{1}{N_c^3}\int d^3k'\, e^{-(\sqrt{k'^2+M_N^2}-\mu_B)/T}$$

From Dirac determinant in the PNJL in the confined phase where tr$L$=0

Free baryon contribution

PNJL underestimates the baryon excitations by a factor $1/N_c^3$

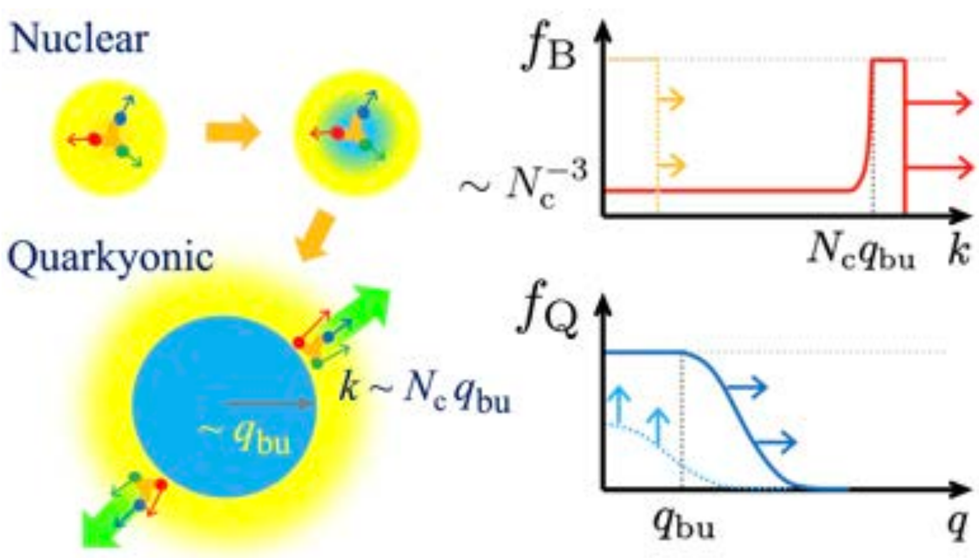
April 6 2010 at DM2010

I thought this was a flaw, but… this is PHYSICS!

Quarkyonic Scenario

Quarkyonic *requires* duality between baryons and quarks

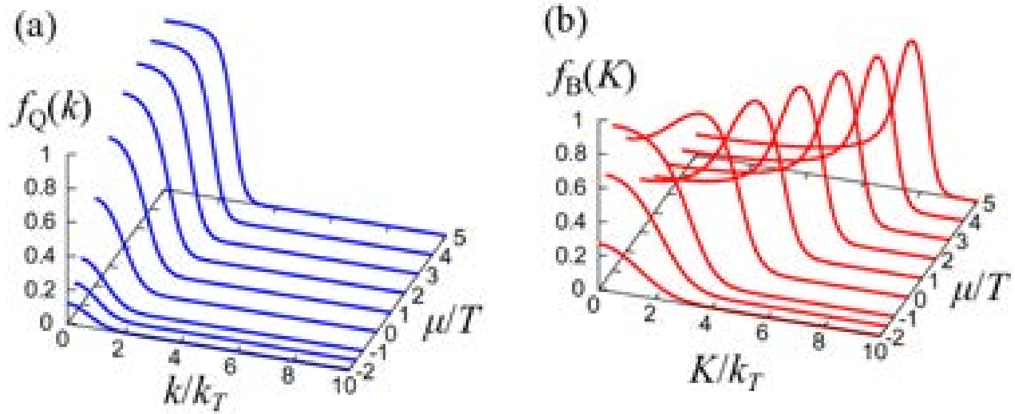
Baryons — Less d.o.f. but more Phase Space
Quarks — More d.o.f. but less Phase Space

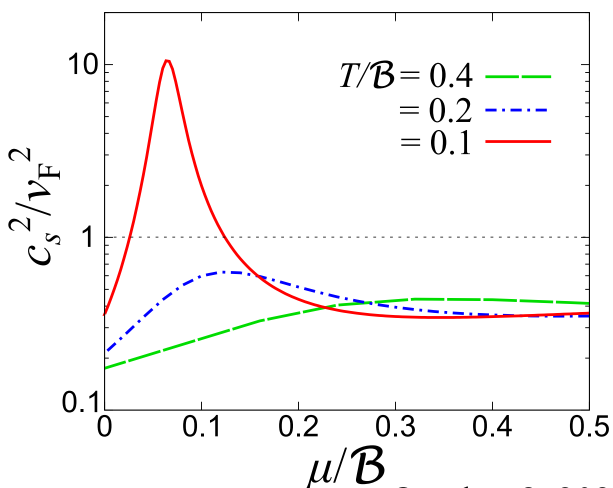


Quark saturation is realized earlier than baryon saturation, suppressing baryon distribution by N_c^{-3}.

Quarkyonic Scenario

Tajima-Iida-Kojo-Liang (2025) **Cond-mat calculations**



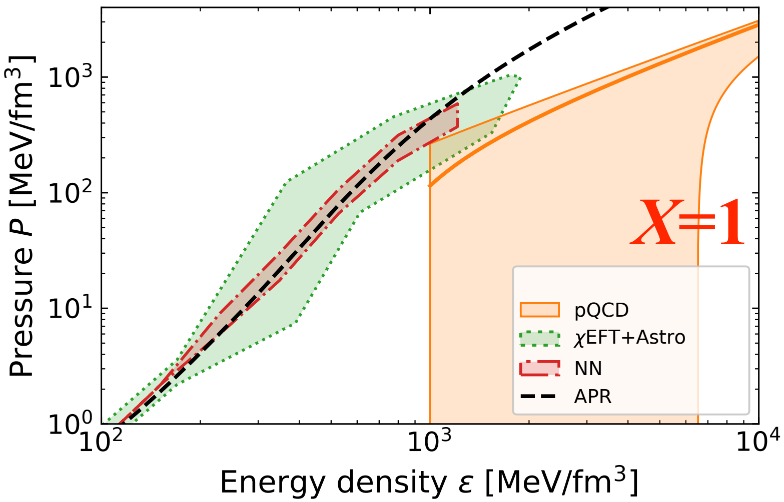


Good to have a peak, BUT this cannot explain why the system gets conformality???

Conformality at High Density

Fujimoto-Fukushima (2020) / F-F-Kyutoku-Hotokezaka (2022-2024)

pQCD uncertainty is often too much emphasized…



Resummation makes the coupling run, but it is an arbitrary choice which (non-log) terms are resummed.
Renormalization Scale Uncertainty

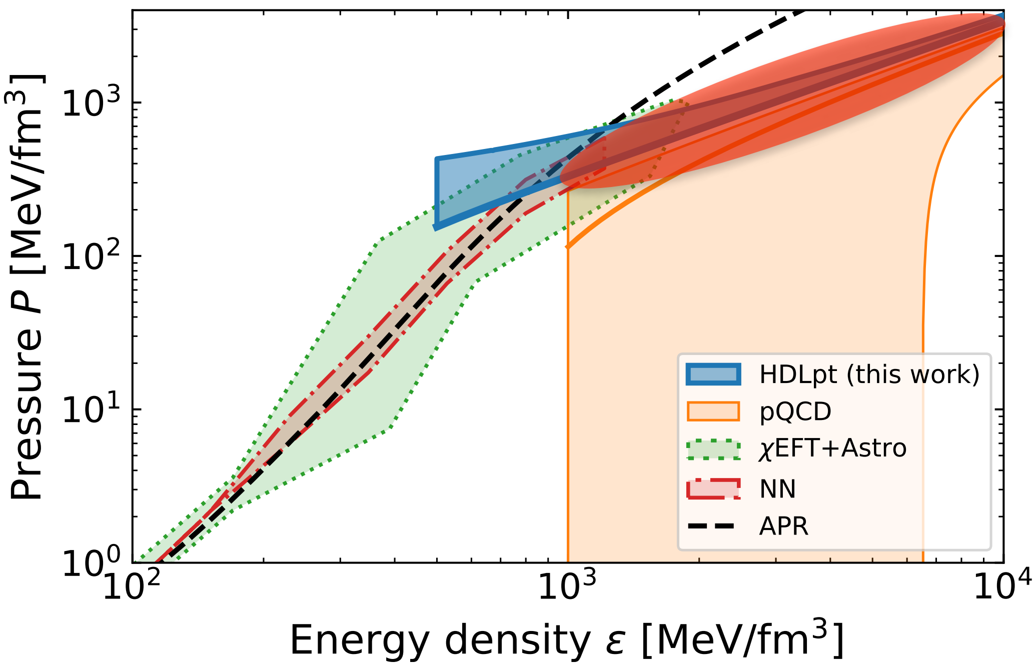
$$\alpha_s \;\to\; \alpha_s(\bar{\Lambda}/\mu_0)$$

If $\bar{\Lambda} = X\mu$ then μ-dependent log is killed, but the question is: X=1? X=2? X=4? (notation by Fraga-Kurkela-Vuorinen 2014)

Only X=1 behaves bad (but naturally so; α_s is large then)…

Conformality at High Density

Fujimoto-Fukushima (2020) / F-F-Kyutoku-Hotokezaka (2022-2024)



For X>2 the EOS hardly moves, and this is because conformality is almost realized.

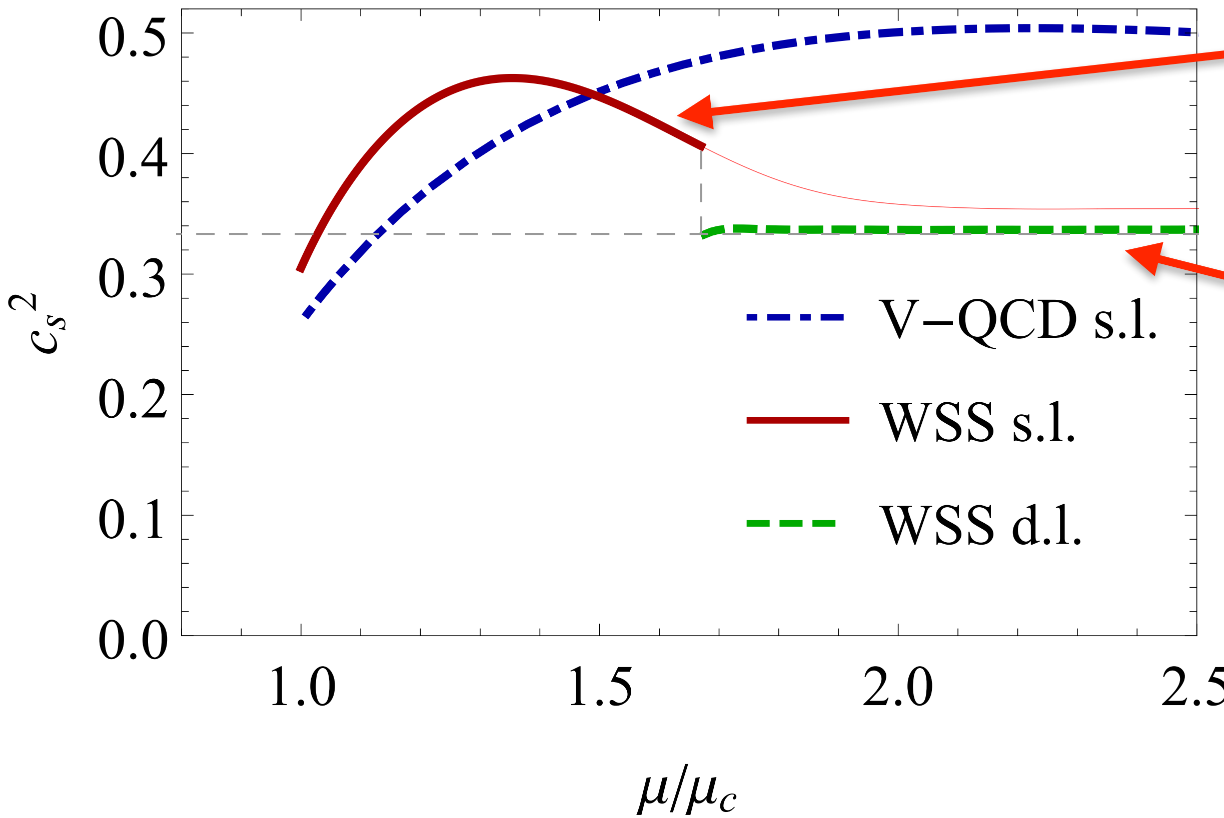
Self-energy resummation cures the problem and even for X=1 the uncertainty is not large at all.

Conformality is suggested by pQCD, but the onset is located even earlier than the pQCD regime…?

Holographic QCD
— not a conformal theory and yet!?

Our Big Surprise

Rojas-Demircik-Jarvinen (2023)



Peak in the sound speed

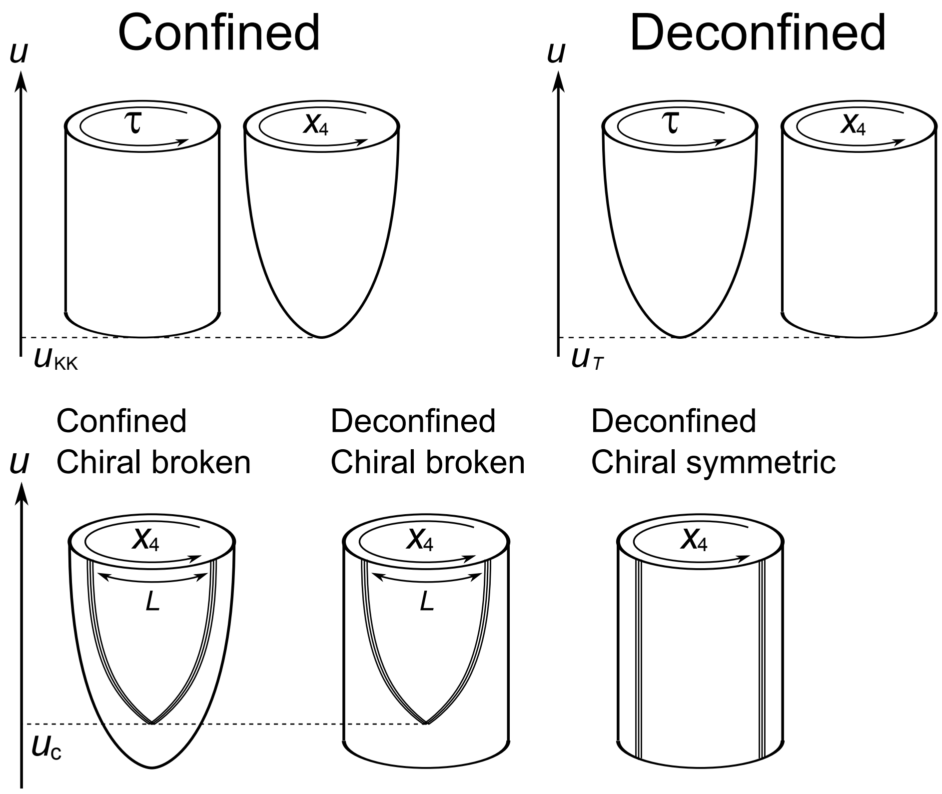
Almost conformal

Too good to be true?

To my knowledge, only QCD-like model showing this!

Holographic QCD ≒ QCD

Sakai-Sugimoto Model



No super-particles, so the same d.o.f. as QCD below M_{KK}.

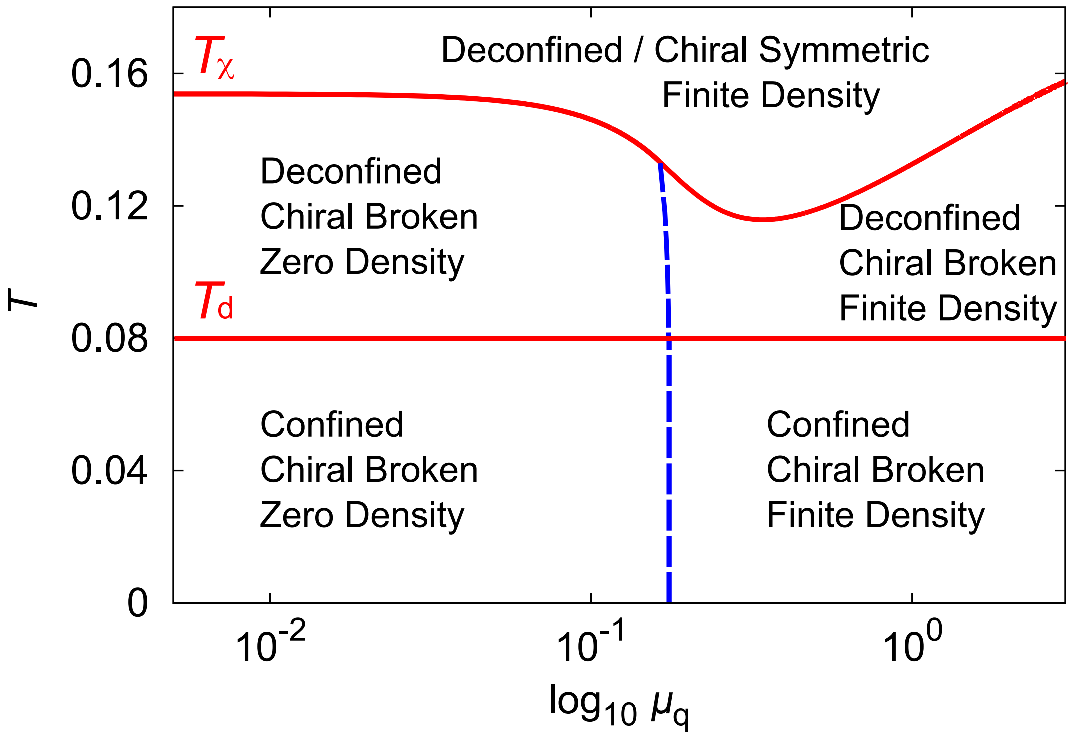
Chiral symmetry is realized in the same way as QCD.

Chiral anomaly is easily seen from the equation of motion.

This is QCD itself in the large N_c limit!

WSS Phase Diagram

Bergman-Lifschytz-Lippert (2007)



Hawking-Page Transition

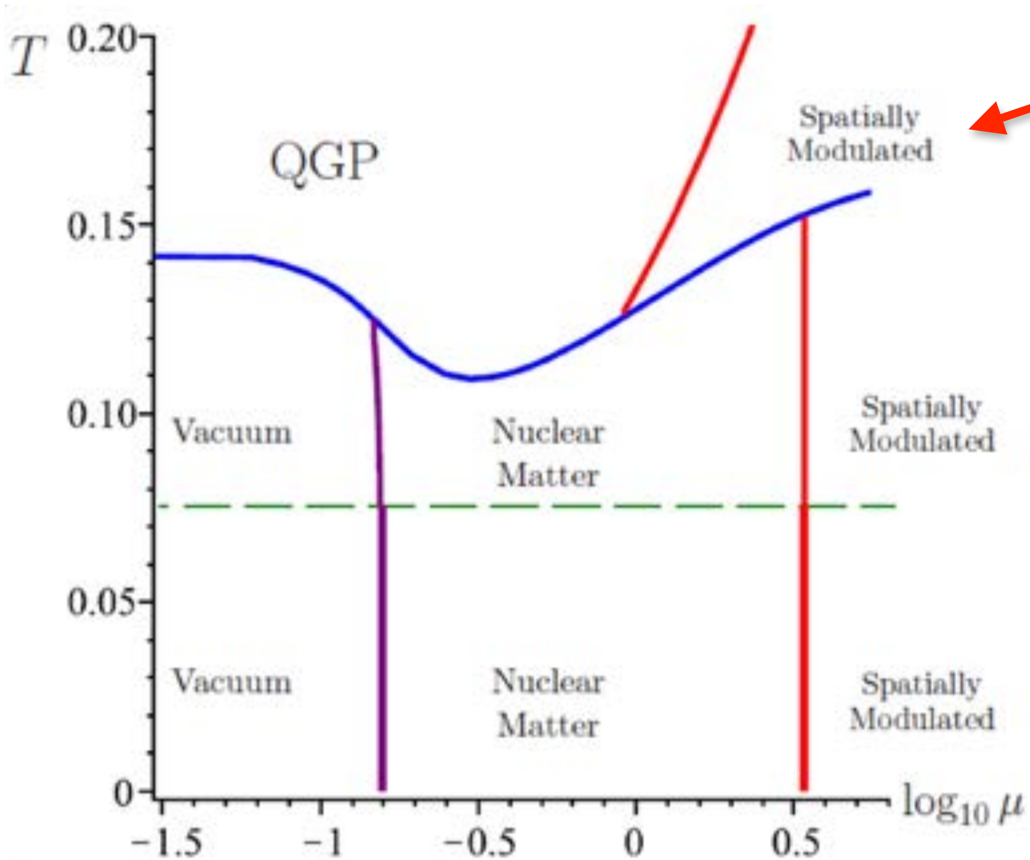
$$T_c = M_{\mathrm{KK}}/(2\pi)$$

$$M_{KK} = 0.95\,\mathrm{GeV}$$

$$\lambda = 16.63$$

Inhomogeneity

Chuang-Dai-Kawamoto-Lin-Yeh (2010)

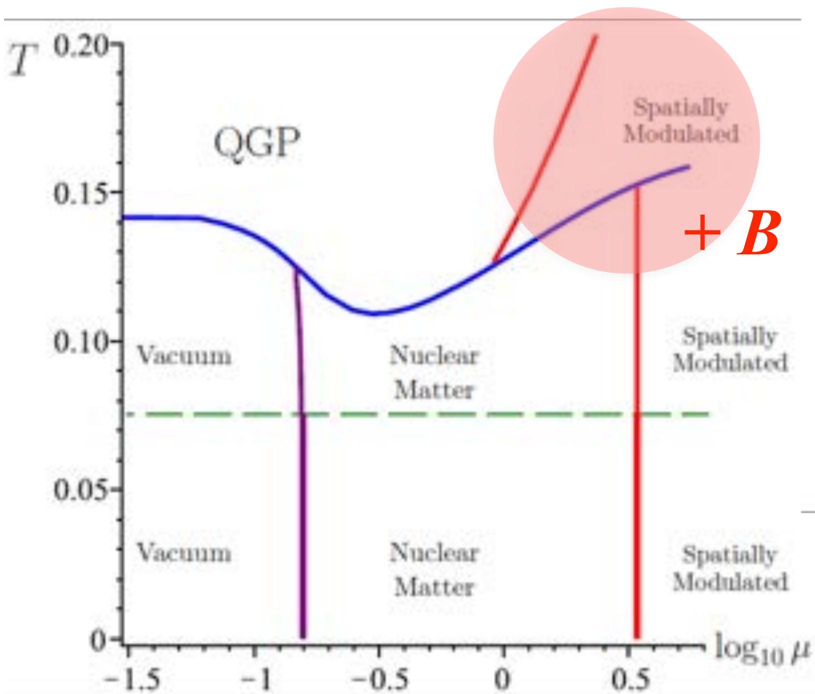


Inhomogeneity possible thanks to large N_c.

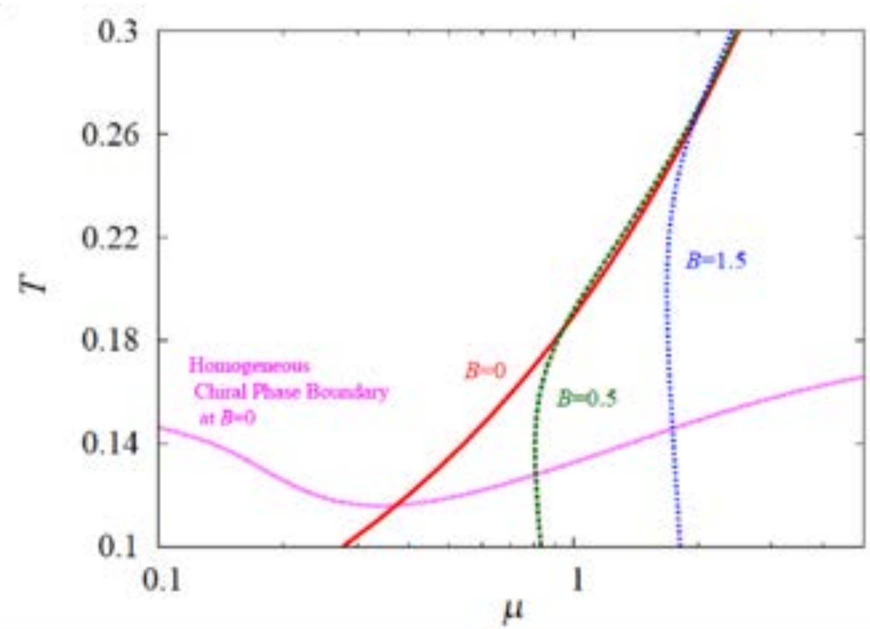
Can become a moat regime for finite N_c.

Inhomogeneity

Enhanced spin-isopin interaction could reduce inhomogeneity…?



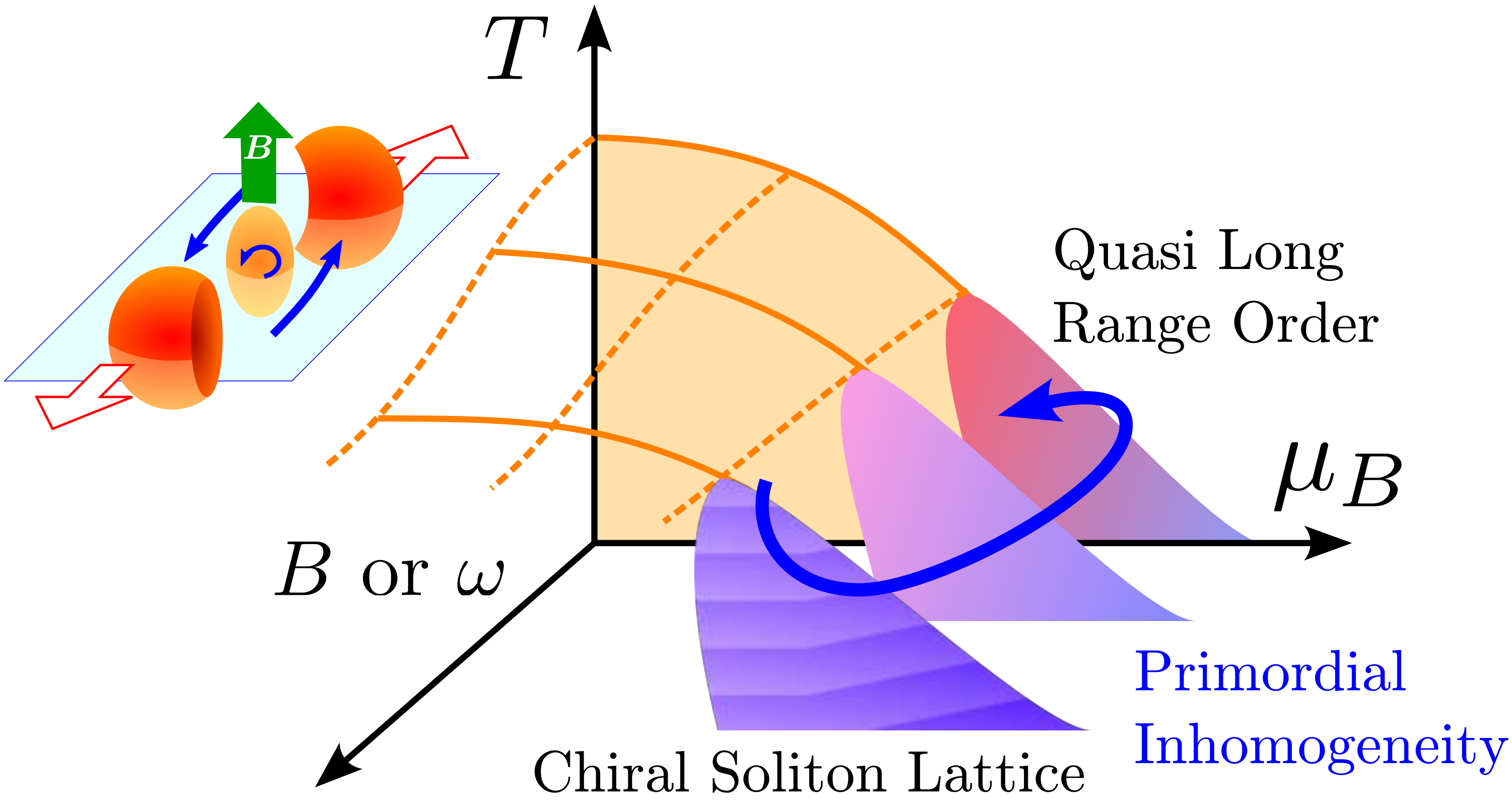
Fukushima-Morales (2013)



WSS model results including axial (CSE) current.

Side Remark: Inhomogeneity

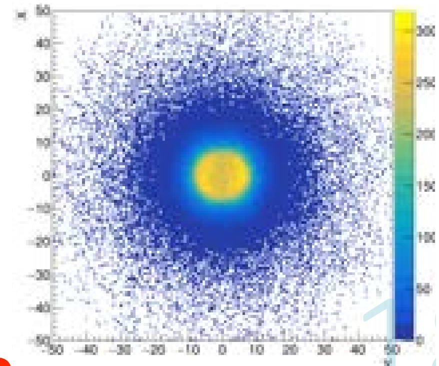
Fukushima-Hidaka-Inoue-Shigaki-Yamaguchi (2023)

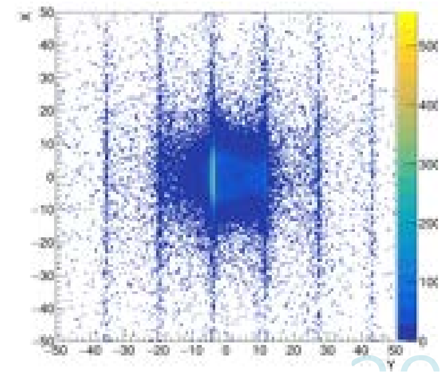


Side Remark: Inhomogeneity

Recent analysis by Yamauchi (Hiroshima U.)

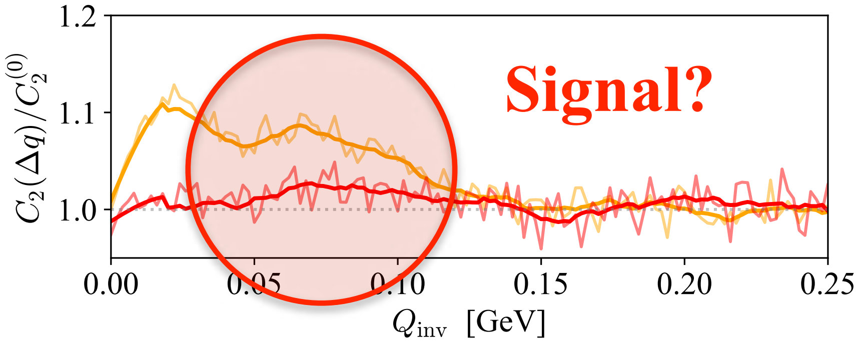
Source distribution: generated by AMPT modulated by hand



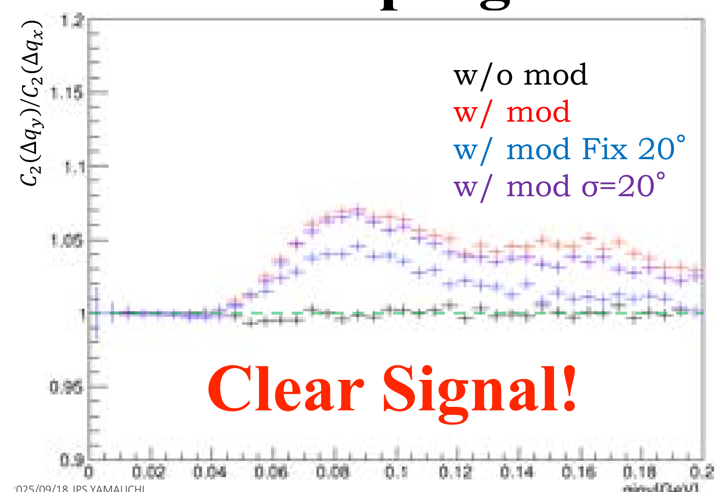


HBT detects clusters?

Previous (2023)

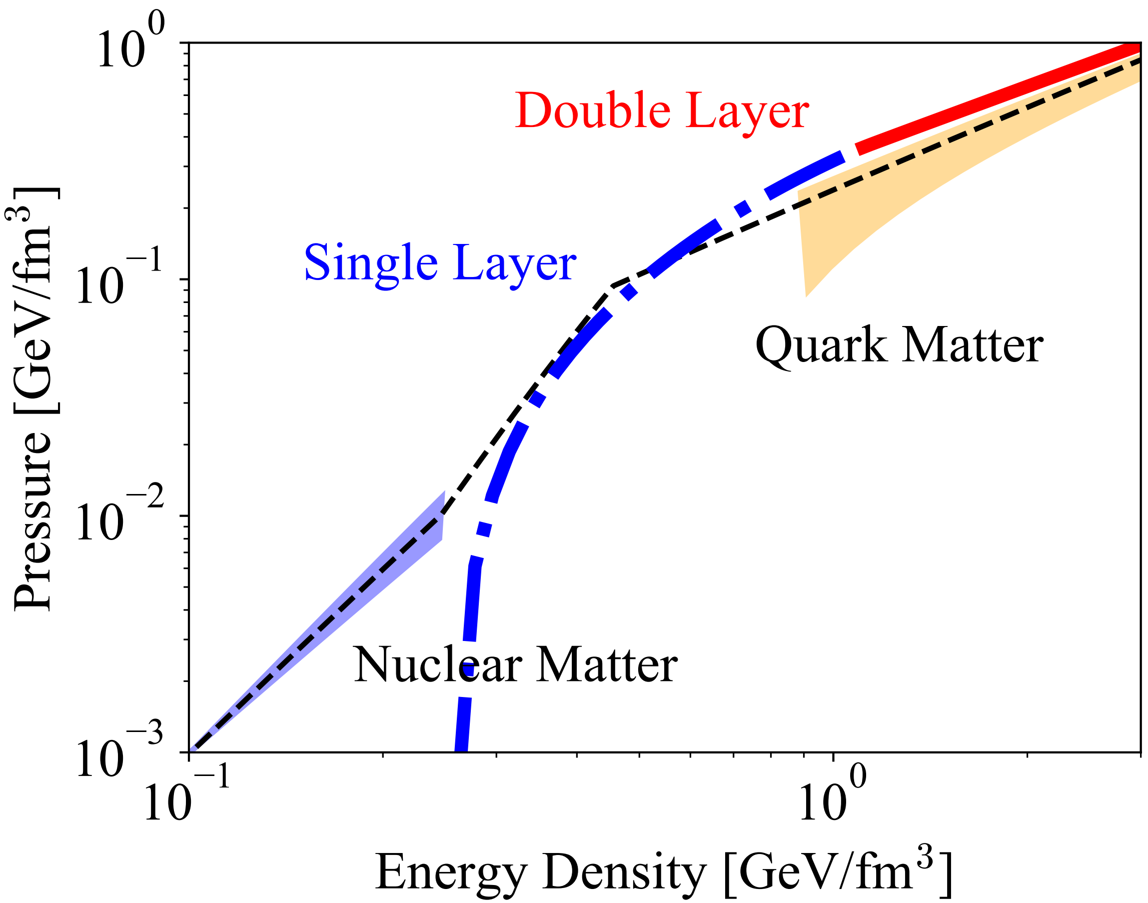


Now in progress



Witten-Sakai-Sugimoto

Fukushima-Jarvinen-Okutsu-Watanabe (in progress)

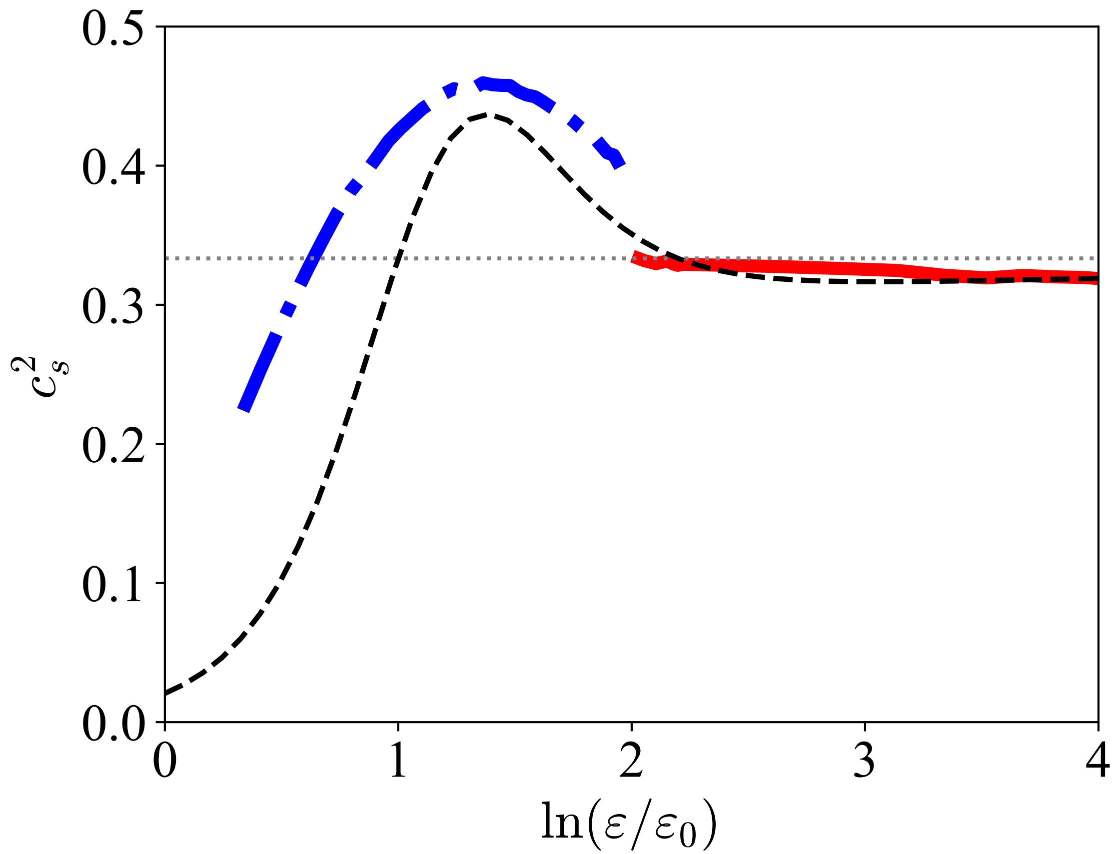


Nuclear matter cannot be well described, but high-density states are fairly good enough.

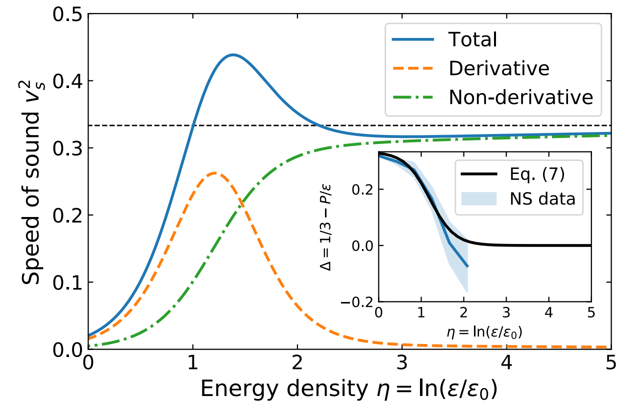
Overall scale was treated as a fitting parameter.

Witten-Sakai-Sugimoto

Fukushima-Jarvinen-Okutsu-Watanabe (in progress)

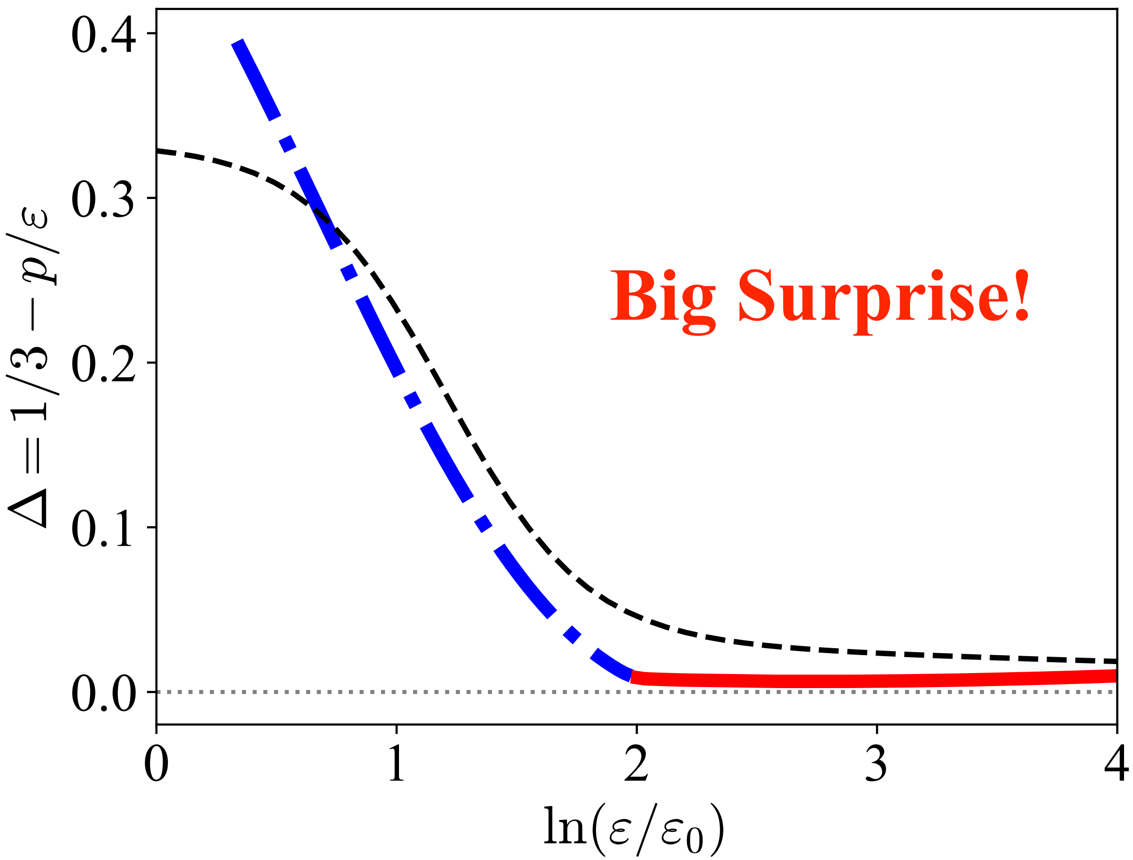


Overall scale was chosen to fit the peak position in the speed of sound.



Witten-Sakai-Sugimoto

Fukushima-Jarvinen-Okutsu-Watanabe (in progress)



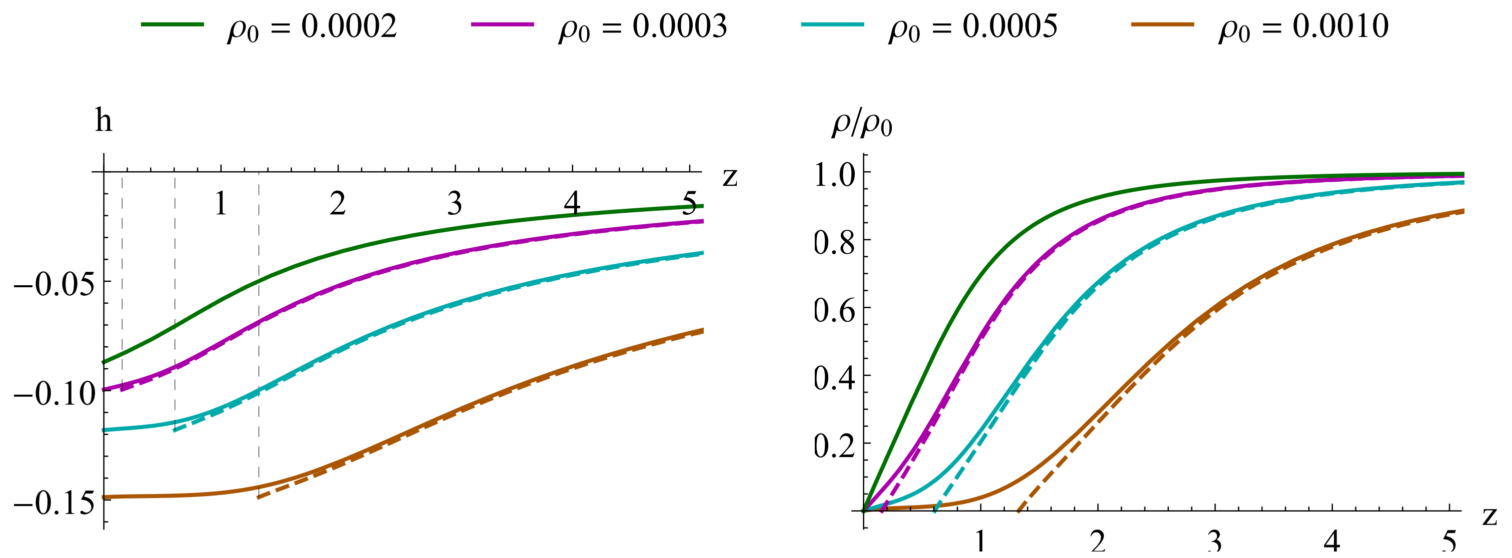
This model has a scale $M_{KK} \sim 1$ GeV so not conformal at all…

Strongly correlated conformal window of quark matter!?

Witten-Sakai-Sugimoto

Fukushima-Jarvinen-Okutsu-Watanabe (in progress)

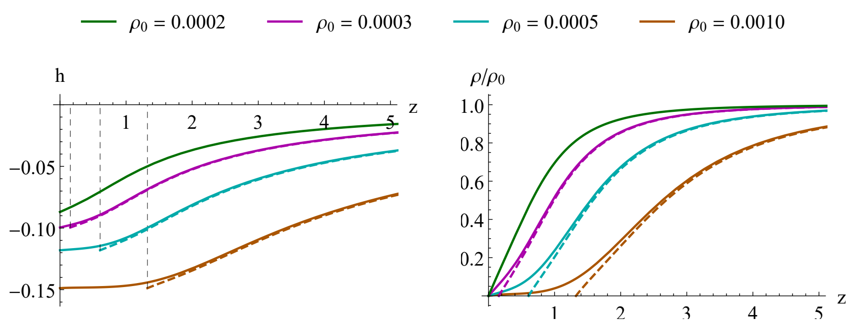
Why this is so conformal???
5d configuration of baryonic instanton $A^i \sim \sigma^i h(z)$ —



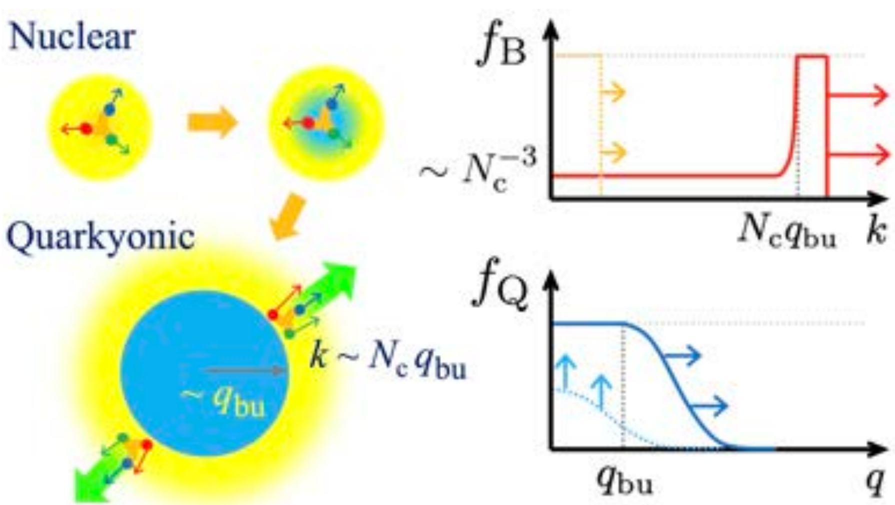
Plateau or density gap appears in IR… a sort of saturation?

Witten-Sakai-Sugimoto

Fukushima-Jarvinen-Okutsu-Watanabe (in progress)



5d coordinate z corresponds to the renormalization scale, and the gap should be related to the saturaion in the quarkyonic scenario.



We can confirm this speculation by calculating the Dirac spectra on top of the 5d backgrounds.

Summary

Experimental Signatures

- □ Speed of sound at high density exceeds the conformal value making a peak.
- □ Conformal symmetry is rapidly restored already at intermediate densities (3-5 times normal nuclear).

Theory

- □ Baryons have larger phase space, and quarks feel Pauli blocking earlier, suppressing the baryon distribution.
- □ Witten-Sakai-Sugimoto model is QCD at low energy, demonstrating emergent conformality!