Suppressed flow harmonics: A signature of the QCD critical point ?

Md Hasanujjaman

Darjeeling Government College, India

With Golam Sarwar, Mahfuzur Rahaman, Abhijit Bhattacharyya, and Jan-e Alam

Based on
PRC 102, 034910 (2020), PLB 820 (2021) 136583

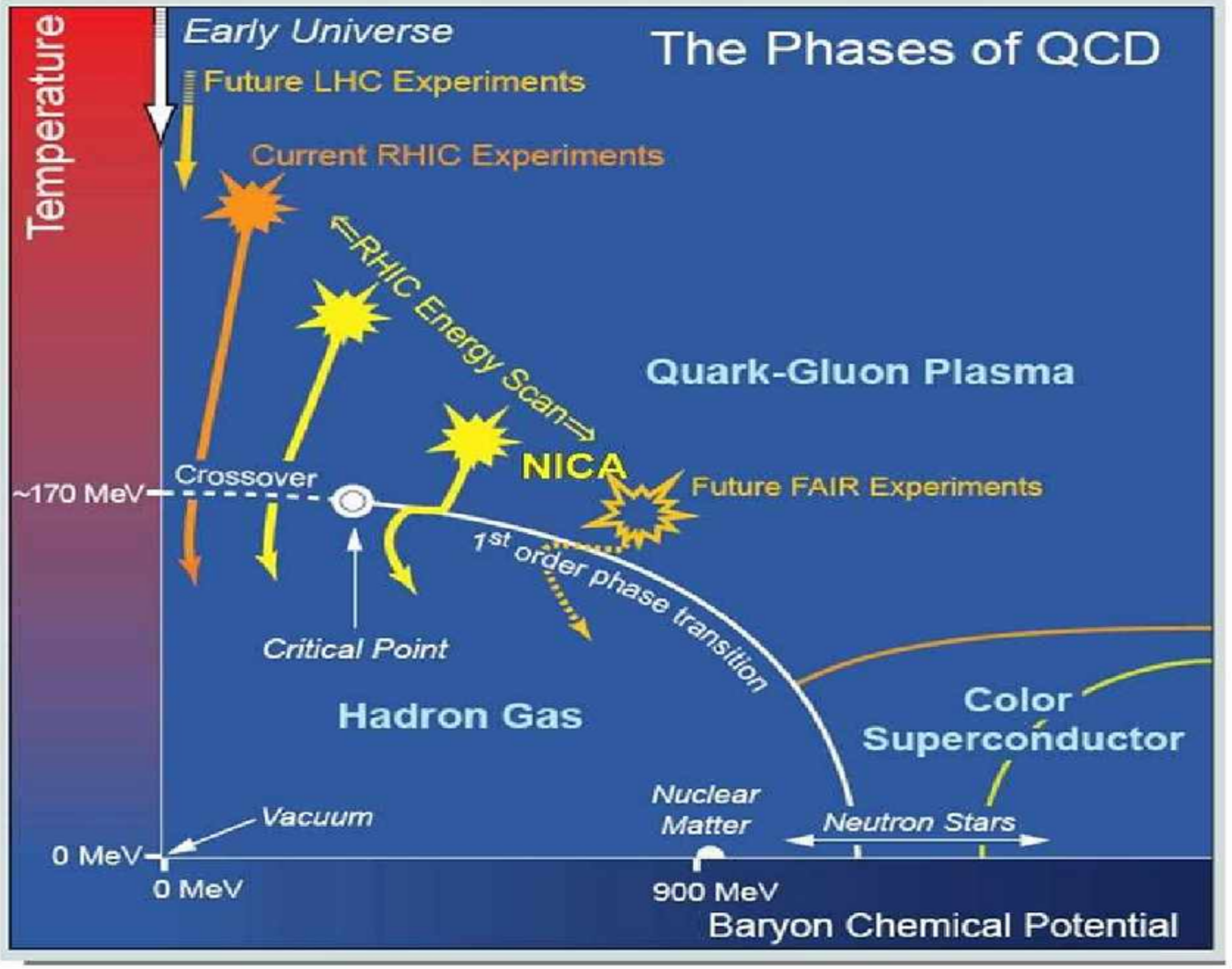
ATHIC2021, 5-9 NOV, 2021

Motivation

- Thermodynamics $\Longrightarrow$ Critical End-Point at the end of the first order phase transition line

- QCD based effective models $\Longrightarrow$ The existence of the CEP based on the parameters of the models used

- Lattice calculations, not valid $\mu_B \neq 0$, $\Longrightarrow$ sign problem exact location of the CEP is still not conclusive.



- **Lack of conclusiveness of the precise location of the CEP demands for more theoretical as well as experimental study**

- Beam Energy Scan (BES) at BNL is particularly dedicated for finding the CEP by tuning the $\sqrt{s}$.

Motivation

- The propagation of the perturbations ⇨ unveil the thermodynamic state of a fluid.

- The hydrodynamic response to the perturbation ⇨ imprinted on the particle spectra.

- Promising observables ⇨ Flow harmonics, is attributed to the hydrodynamic response of the QGP to the initial geometry.

- Consequences of the CEP on the hydrodynamic evolution if an isentropic trajectory passes through the critical region.

Equation of State

Nonaka and Asakawa, PRC(2005), MH et al, PRC (2020)

- **The effect of the CEP enters into the hydrodynamic evolution through the EoS which contains the critical point.**

- **Constructed on the basis of universality hypothesis ⇨ CEP of the QCD belongs to the same universality class of 3D Ising model.**

- **The critical entropy density S_c is analogous to the magnetization of the Ising model**

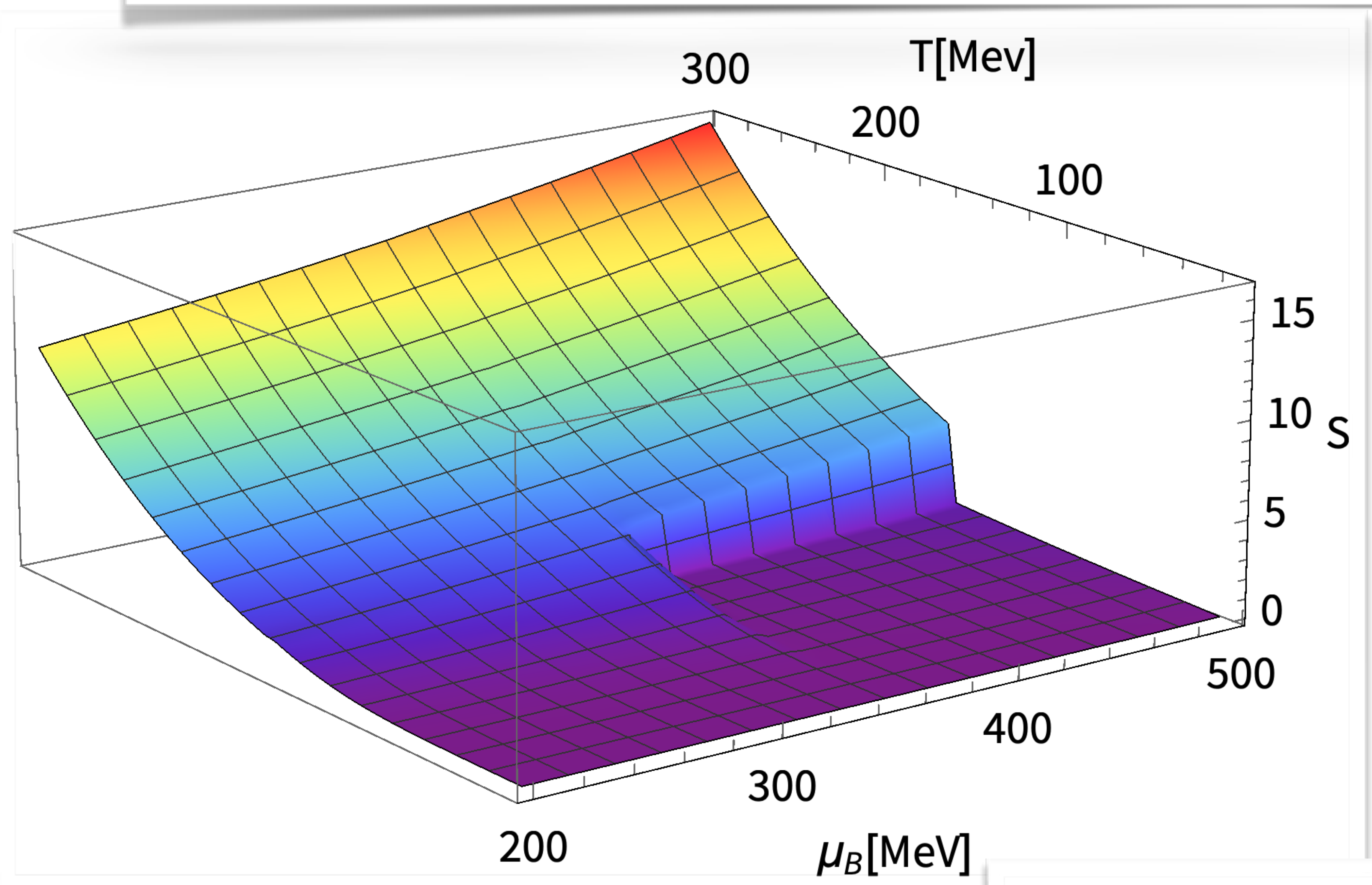
$$S_c = \frac{M(r,h)}{\Delta T_c} = M\left(\frac{\mu - \mu_c}{\Delta \mu_c}, \frac{T - T_c}{\Delta T_c}\right)\frac{1}{\Delta T_c}$$

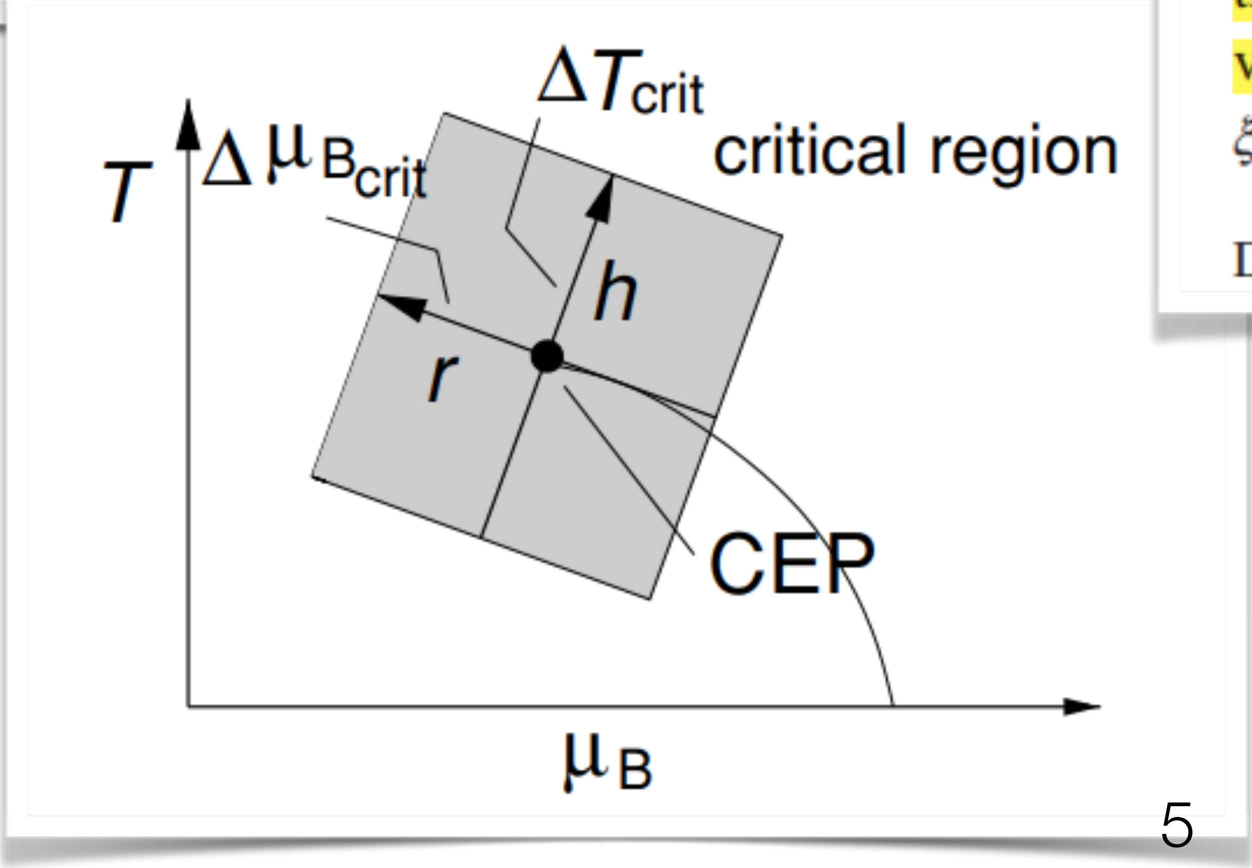
- **In our study, $(T_c, \mu_c) = (154{,}367) MeV$.**

Equation of State

- **The entropy density of s_Q and s_H is connected by using S_c as switching function as:**

$$S(T,\mu) = \frac{1}{2}[1 - \tanh S_c(T,\mu)]s_Q(T,\mu) + \frac{1}{2}[1 + \tanh S_c(T,\mu)]s_H(T,\mu)$$





Critical behavior of the bulk viscosity in QCD

M. Martinez,[1] T. Schäfer,[1] and V. Skokov[1,2]

[1]Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA
[2]RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 16 July 2019; published 15 October 2019)

We study the behavior of the bulk viscosity ζ in QCD near a possible critical end point. We verify the expectation that $(\zeta/s) \sim a(\xi/\xi_0)^{x_\zeta}$, where s is the entropy density, ξ is the correlation length, ξ_0 is the noncritical correlation length, a is a constant, and $x_\zeta \simeq 3$. Using a recently developed equation of state that includes a critical point in the universality class of the Ising model we estimate the constant of proportionality a. We find that a is typically quite small, $a \sim O(10^{-4})$. We observe, however, that this result is sensitive to the commonly made assumption that the Ising temperature axis is approximately aligned with the QCD chemical potential axis. If this is not the case, then the critical ζ/s can approach the noncritical value of η/s, where η is the shear viscosity, even if the enhancement of the correlation length is modest, $\xi/\xi_0 \sim 2$.

DOI: 10.1103/PhysRevD.100.074017

Transport coefficients

- The bulk evolution of a system is controlled by the **EoS and the transport coefficients.**

PHYSICAL REVIEW C **86**, 054911 (2012)

Thermal conductivity and chiral critical point in heavy ion collisions

Joseph I. Kapusta[1] and Juan M. Torres-Rincon[2]

PHYSICAL REVIEW C **95**, 034902 (2017)

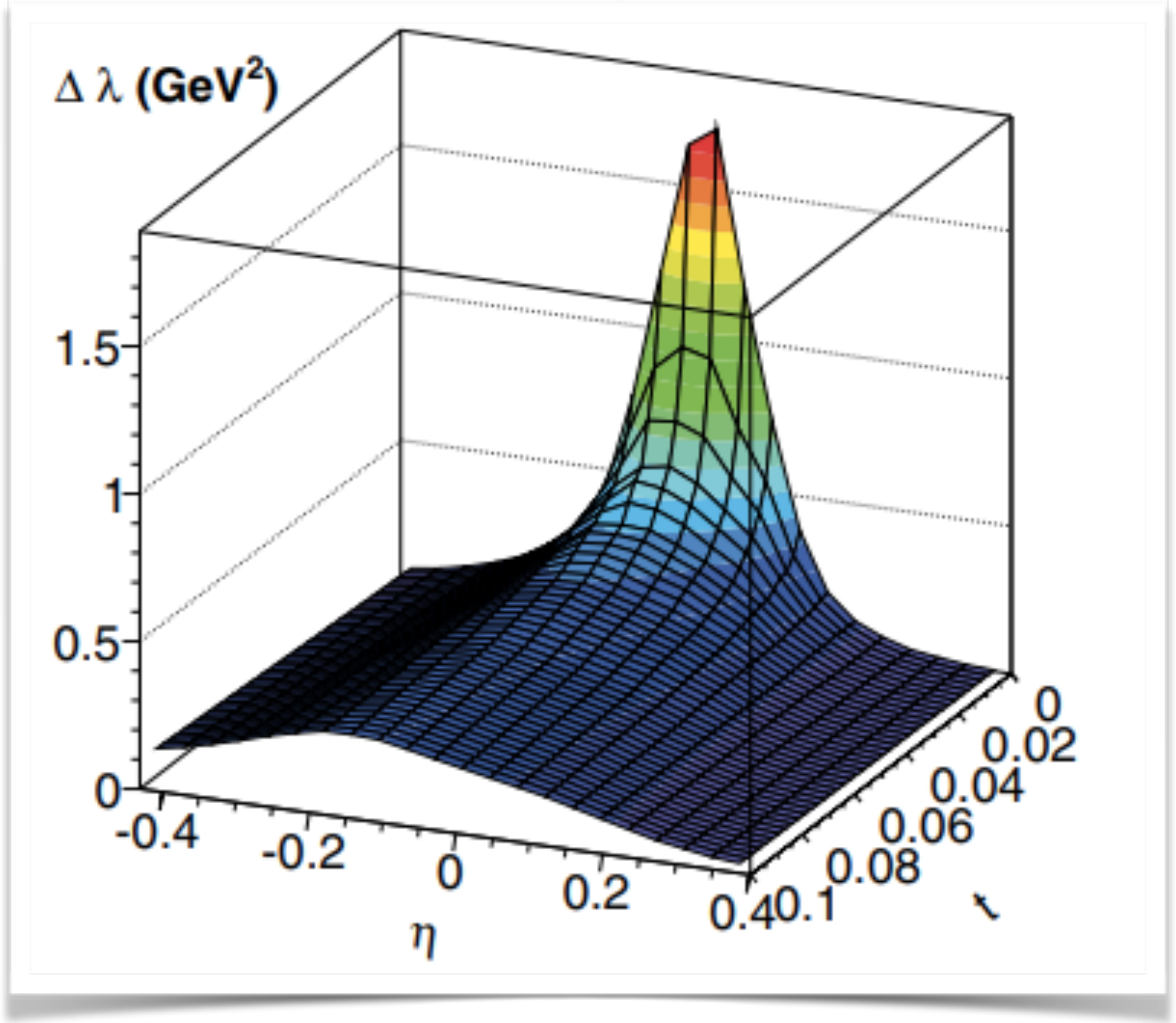
Phenomenological consequences of enhanced bulk viscosity near the QCD critical point

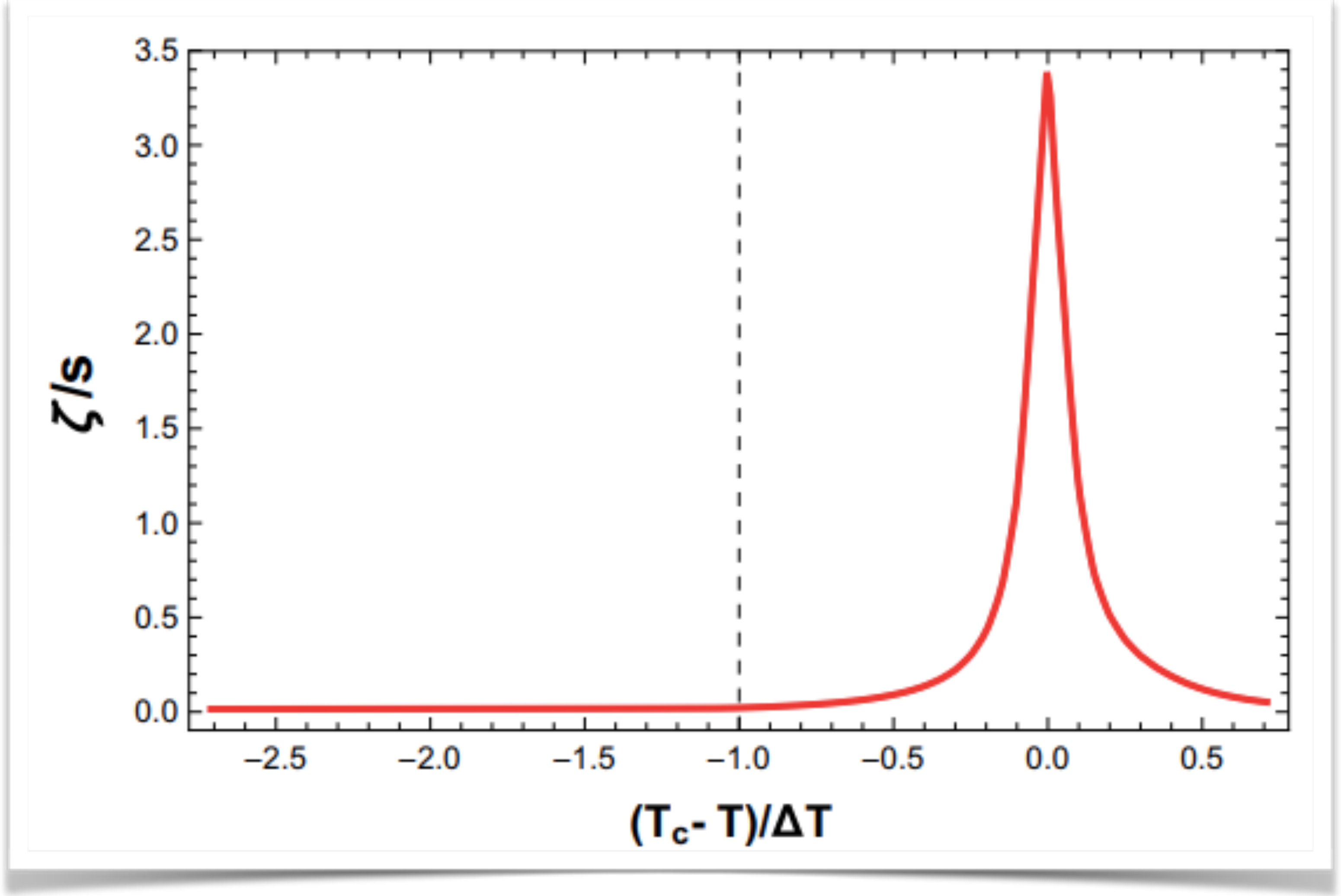
Akihiko Monnai,[1,2] Swagato Mukherjee,[3] and Yi Yin[3,4]

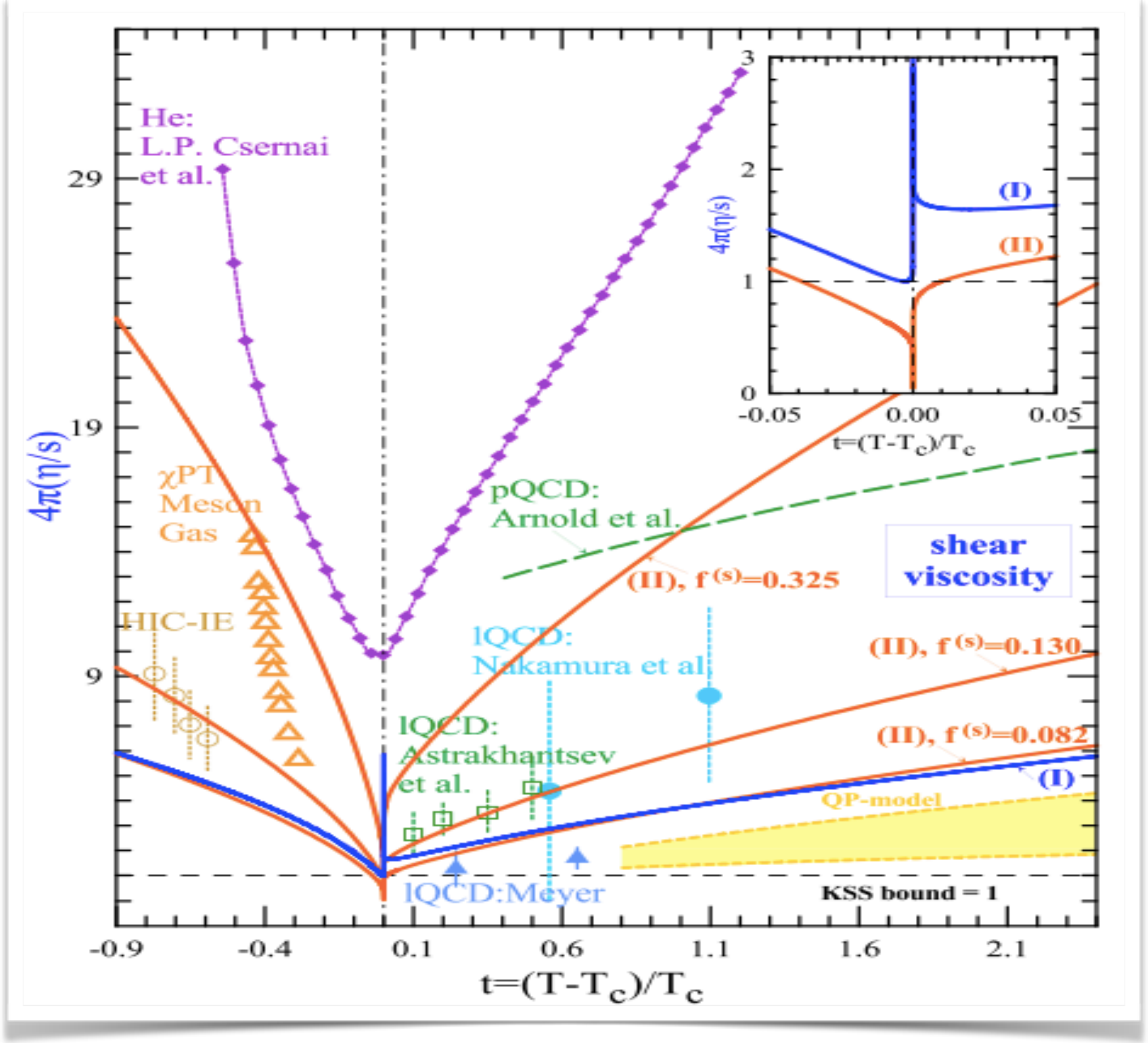
PHYSICAL REVIEW C **96**, 055207 (2017)

Viscosity of a net-baryon fluid near the QCD critical point

N. G. Antoniou,[*] F. K. Diakonos,[†] and A. S. Kapoyannis[‡]







- To observe the effects of EoS only in the evolution, we have kept the **transport coefficients η, ζ, χ to be at the lower bound.**

Framework: Hydrodynamics

- Ideal Hydro is not suitable

Bemfica et al, PRD(2021), arXiv:2009.11388

- First order theory is known to violate causality and gives unstable solution.

First-order theories can be causal and stable.

- We use Second-order hydrodynamics to study the propagation of the perturbation.

- Causality is restored by introducing a time delay in the response of the dissipative currents from gradients of the fluid dynamical variables.

Landau-Lifshitz frame:

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$N^\mu = nu^\mu + \nu^\mu = nu^\mu - \frac{nq^\mu}{\epsilon + p}$$

$$\Pi = -\frac{1}{3}\zeta(\partial_\mu u^\mu + \beta_0 D\Pi - \alpha_0 \partial_\mu q^\mu)$$

$$\pi^{\lambda\mu} = -2\eta\Delta^{\mu\nu\alpha\beta}\left[\partial_\alpha u_\beta + \beta_2 D\pi_{\alpha\beta} - \alpha_1 \partial_\alpha q_\beta\right]$$

$$q^\mu = \kappa T\Delta^{\mu\nu}[\frac{nT}{\epsilon + P}(\partial_\nu \alpha) - \beta_1 D q_\nu + \alpha_0 \partial_\nu \Pi + \alpha_1 \partial_\lambda \pi^\lambda_\nu]$$

Strategy

- A space-time dependent perturbation, $e^{-i(\omega t-kx)}$ is placed into the fluid via P, ϵ, n, T, μ, and u^{μ}.

S. Weinberg, Astrophys. J. 168, 175 (1971)

- The EOM for different components of perturbation is obtained by the conservation equations:

$$\partial_{\mu}T^{\mu\nu} = 0; \partial_{\mu}N^{\mu} = 0$$

- Real and imaginary part dictates the propagation and dissipation of the perturbation into the fluid.

- A threshold wavelength$(\lambda_{th} = 2\pi/k_{th})$ is evaluated by the condition $\left|\frac{\omega_{\Re e}}{\omega_{\Im m}}\right| = 1.$

Liao and Koch, PRC (2010)

Strategy

- A wave with wavelength $\lambda \geq \lambda_{th}$, can only propagate and rest will dissipate in the medium.

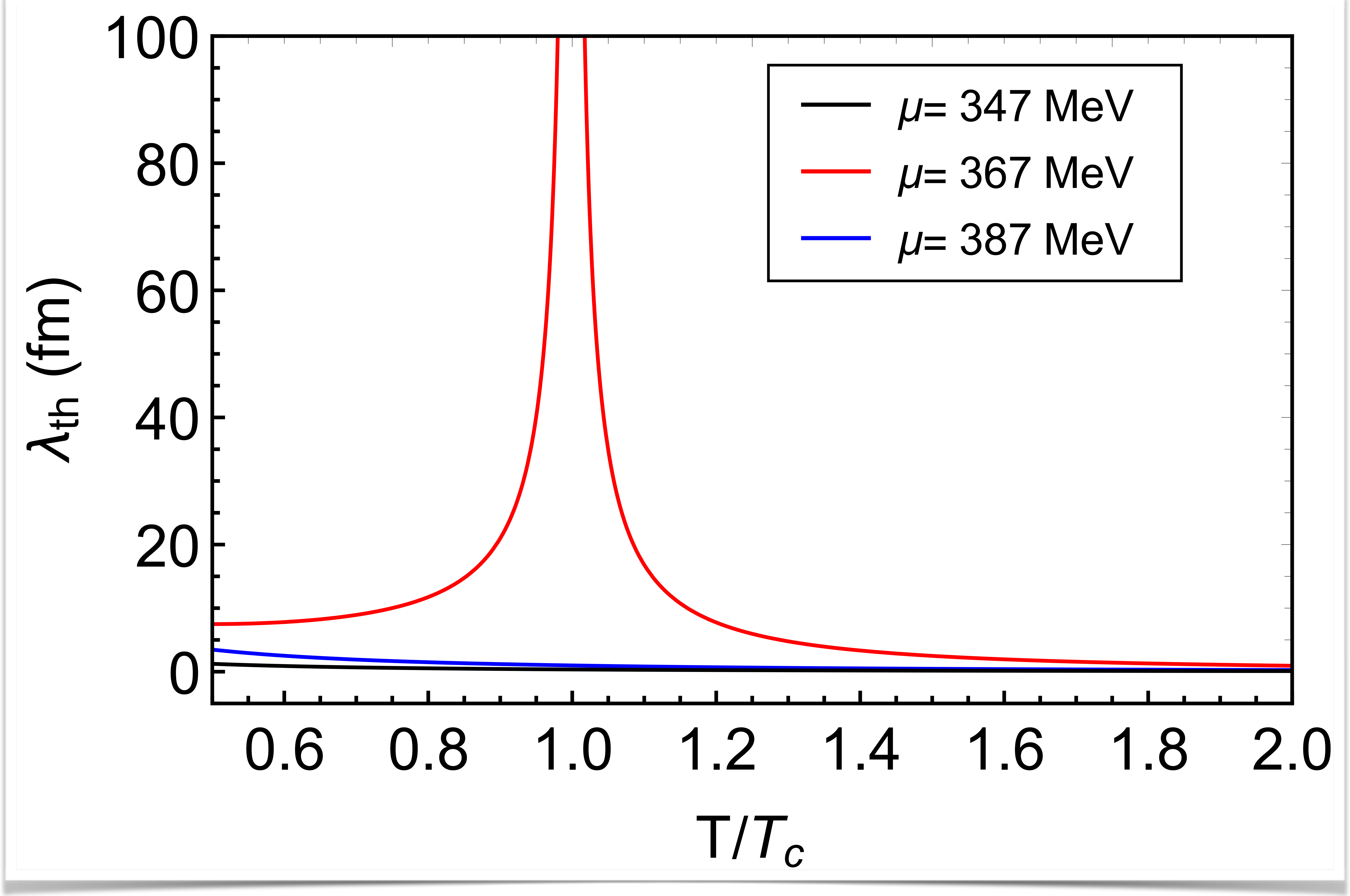
- Viscous horizon is a length scale $(R_v) \sim \lambda_{th}$: separates the wavelengths of the sound which are and are not dissipated by the viscosity effects.

Staig and Shuryak, PRC(2011)

- $R_v \Rightarrow$ highest order of surviving flow harmonics $(n_v) \sim 1/R_v$

Roy A. Lacey et al, arXiv:1105.3782

Results



MH, M. Rahaman, A. Bhattacharyya, J-e Alam, PRC(2020)

- At the CEP, we found λ_{th} to be very large, implies survival of no wave.
- As consequences, Mach cone formation is prevented.

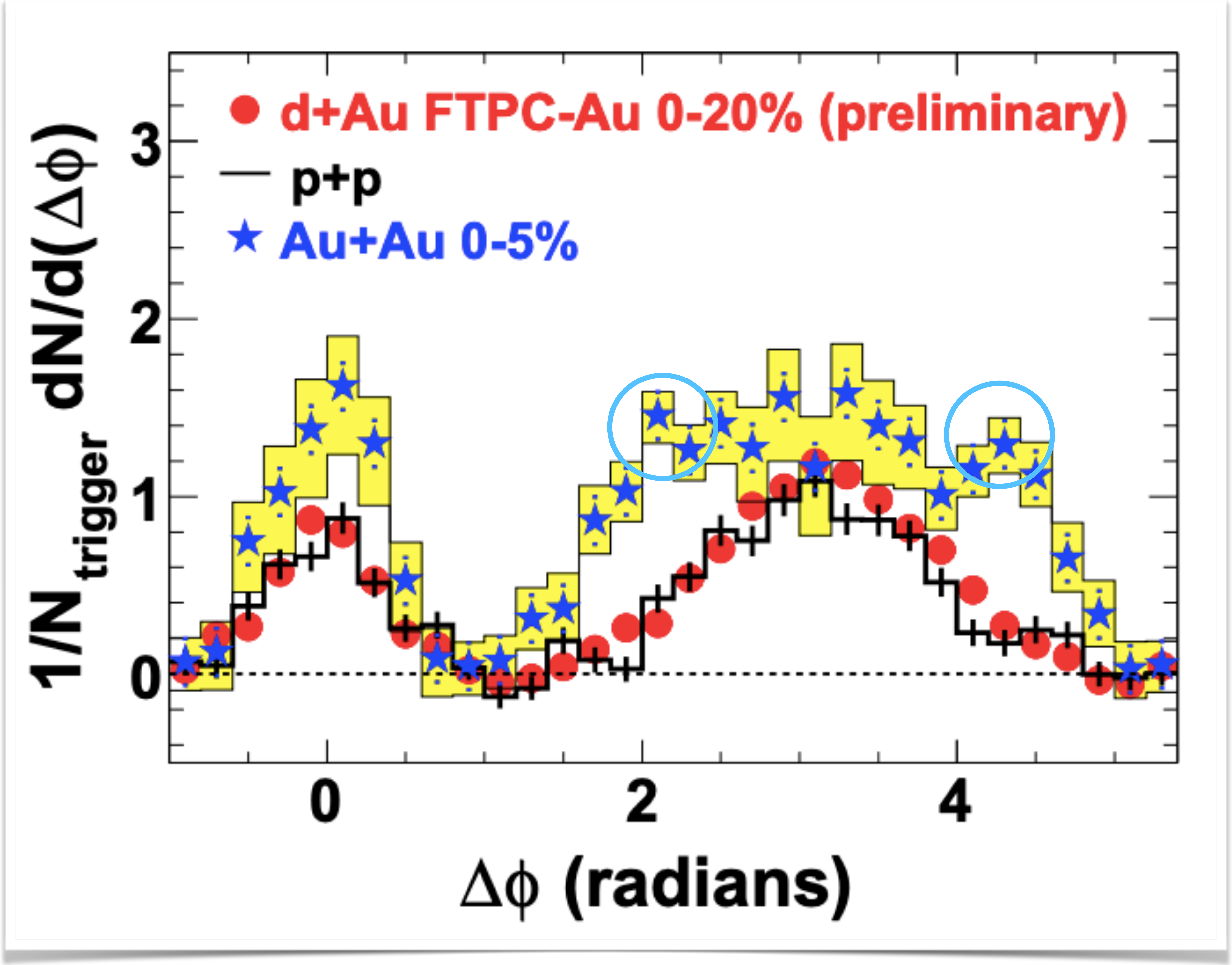
Results

Formation of Mach cone

STAR collaboration, PRL (2005)

- Double hump structure at away side jet in particle correlation

- Disappearance of local maxima's in data for hydro evolution through the CEP



STAR Collaboration, NPA(2006)

Results

PROCEEDINGS OF SCIENCE

Collapse of Flow: Probing the Order of the Phase Transition

Horst Stöcker*

H. Stoecker, arXiv:0710.5089

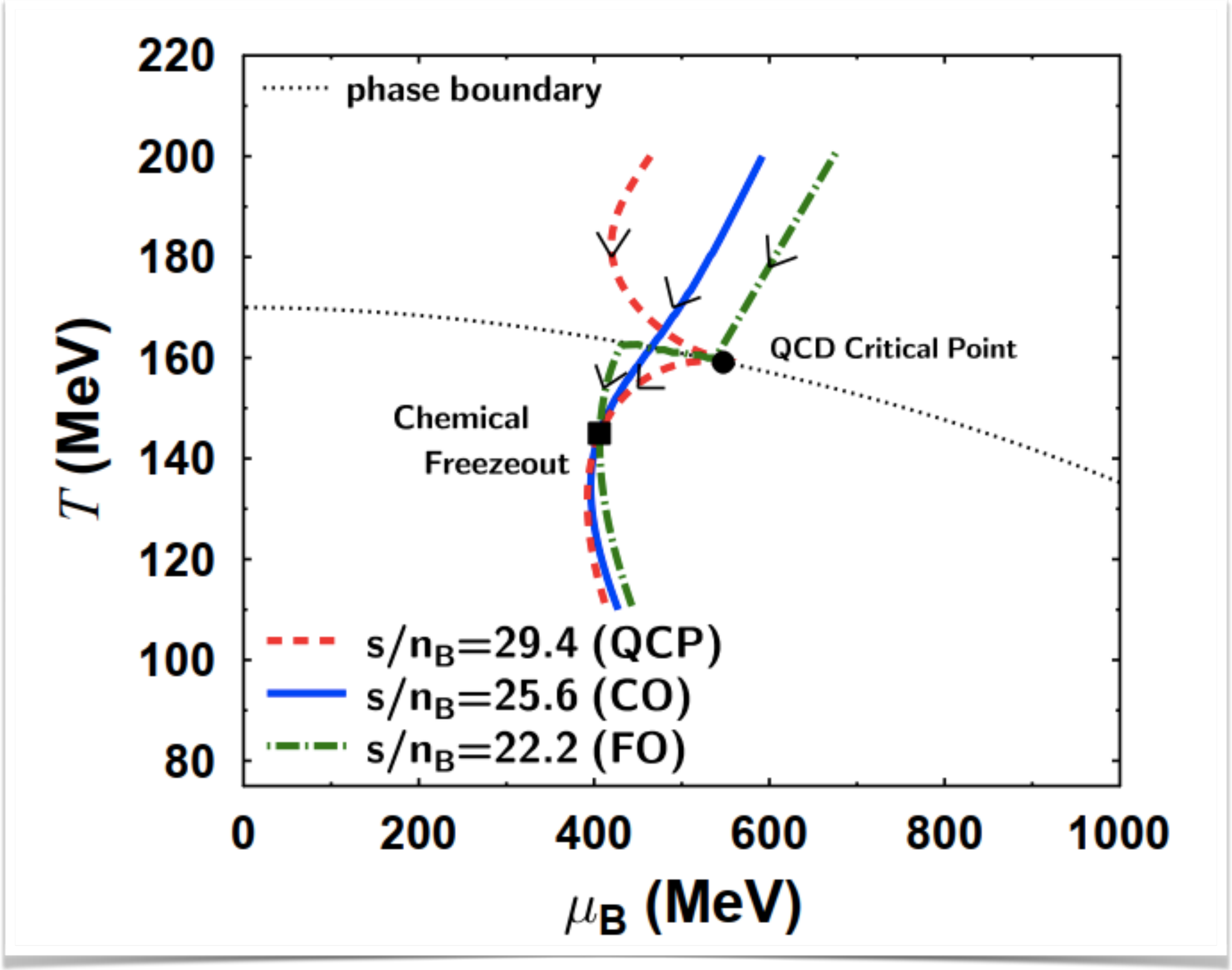
- λ_{th} is divergent at the CEP, the viscous horizon scale is also divergent, means no wave can survive from viscous damping.

- All the possible flow harmonics, collapse at the CEP.

- Ideally fully collapsed harmonics may be the signature of the CEP, but in experiments from the formation of the QGP to hadron is superposition of all the T, μ states, one expects suppression.

Results

Nonaka et al, NPA (2009)



- **Focussing effect around the CEP.**

Stephanov et al, PRL (1998)

- **In event-by-event analysis, isentropic trajectories form a few events may go through the CEP and the others away from the CEP, cause large event-by-event fluctuation of flow harmonics.**

Summary

- Second-order hydro + EoS with the critical point to study the propagation of a perturbation.

- λ_{th} diverges at the CEP, implying that all the modes of the perturbation are dissipated at this point.

- Formation of Mach cone is prevented, the double hump structure at away side jet in particle correlation, disappear.

- All the possible flow harmonics will be suppressed.

- The vanishing Mach cone effects, enhancement of fluctuation of flow harmonics in event-by-event analysis may be considered as the possible signature of detecting the CEP.

Thank You for your kind attention