Does quark-gluon plasma feature an extended hydro. regime?

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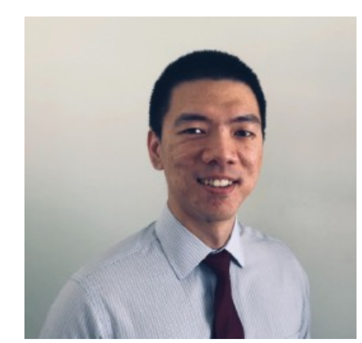
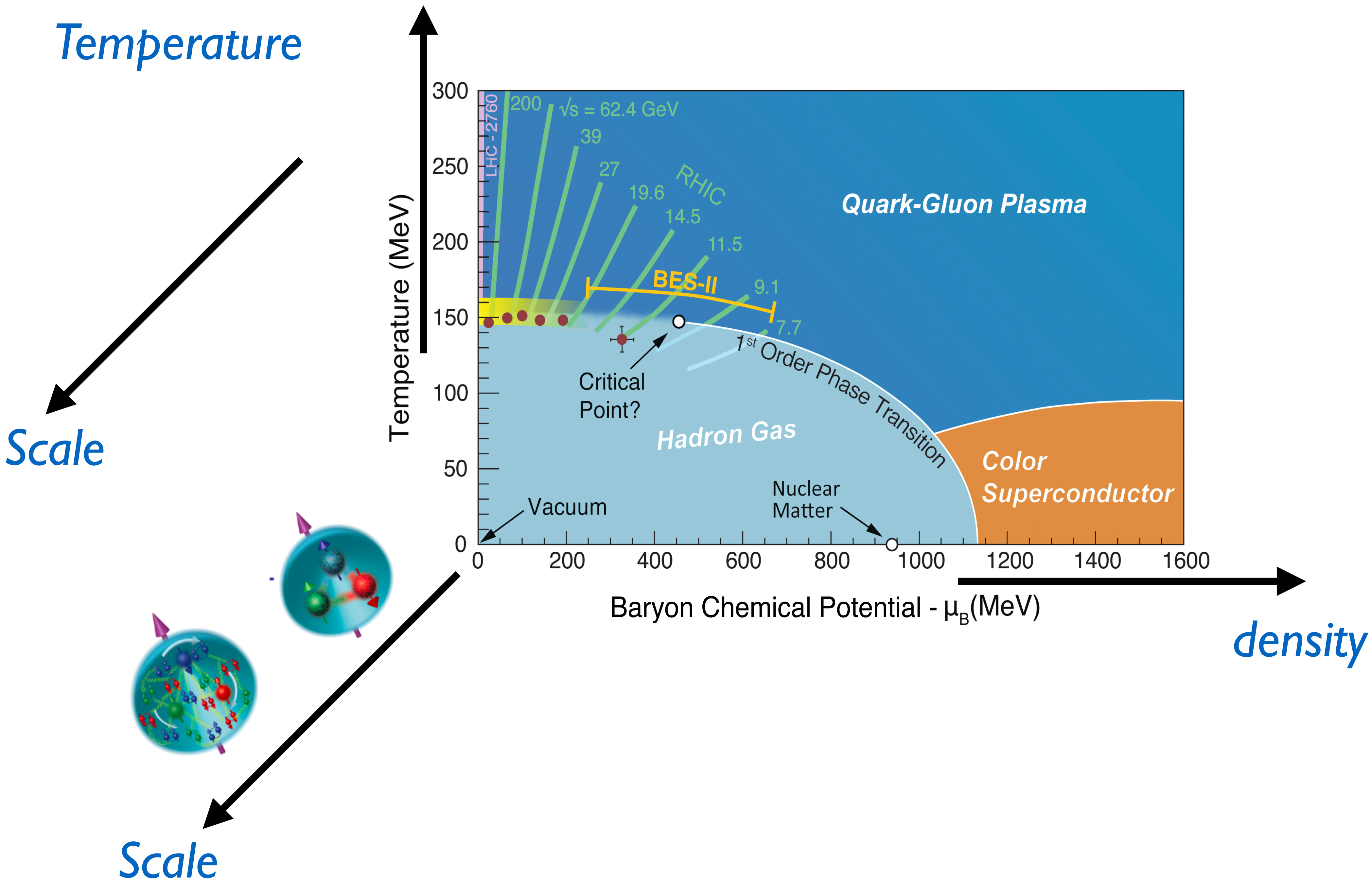
Weiyao Ke and YY, PRL 2023 (2208.01046); and work in preparation

XQCD, Coimbra, July. 28th, 2023



Weiyao Ke @ LANL



Temperature
Scale
Scale
density
Temperature (MeV)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Baryon Chemical Potential - μB(MeV)
LHC - 2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
RHIC
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Vacuum
Nuclear Matter

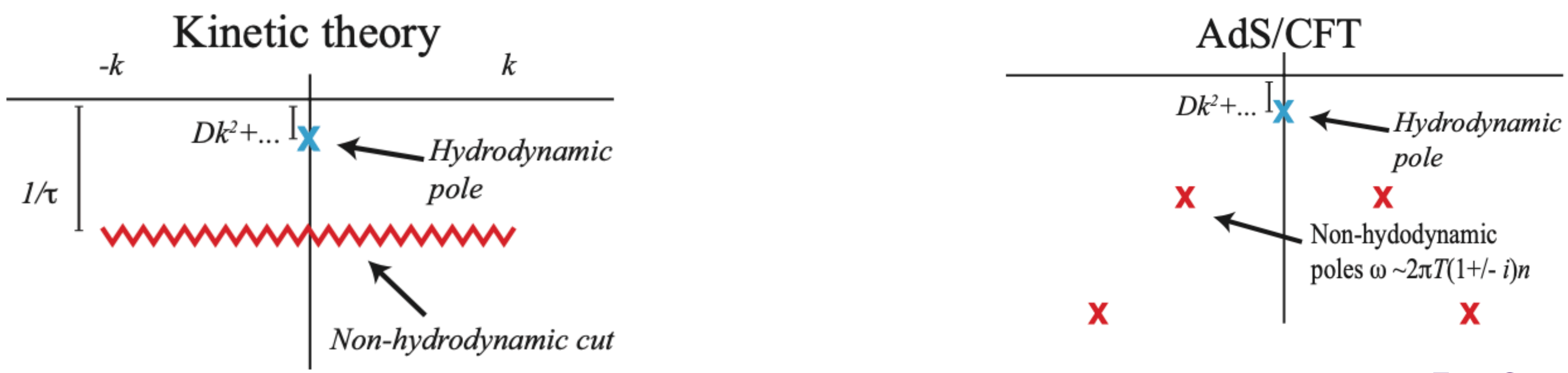
QGP properties vs scale/gradient

- Unexplored regime: QGP at mesoscopic scale where typical gradient k is too large for vHydro. and too short for pQCD.
- Exploring QGP mesoscopy:
  - Large angle scattering between jet and the medium.
  - Collectivity in small systems.
  - This talk: medium response (how response changes with varying gradient).

e.g. Eramo, Rajagopal and YY, JHEP 19;

works by Kurkela, Mazeliauskas, Wiedemann, Bin Wu, ….

Medium response and excitations



The analytic structure of retarded Green function

Fig. from Kurkela-Wiedemann-Wu, EPJC 19'

- The (linear) response of a thermal system to an in-homogeneous disturbance is determined by excitations.

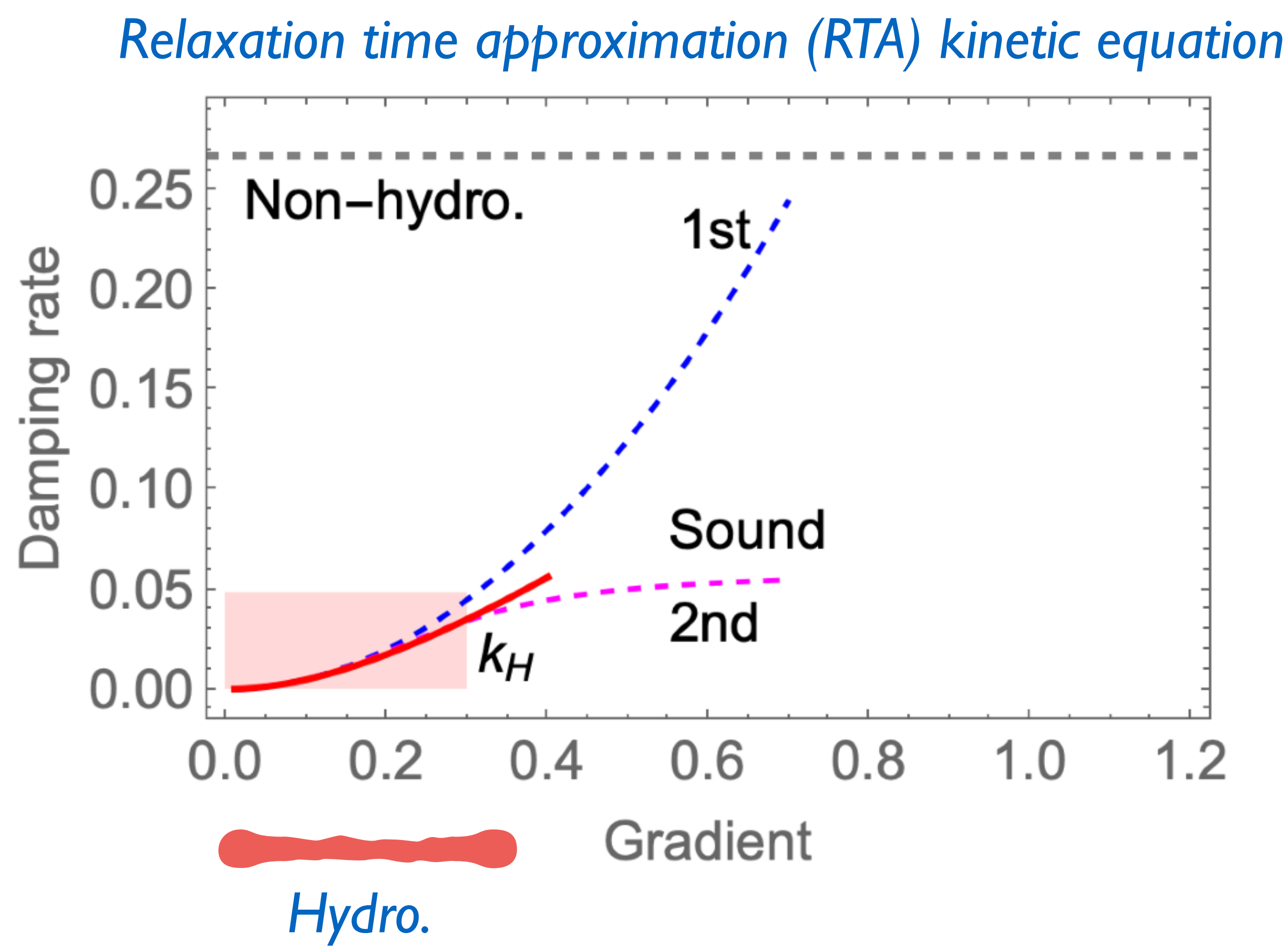
$$O(t,\vec{k}) = A_H e^{-i\Omega_H(k)t}\, e^{-\Gamma_H(k)t} + \text{other excitations}$$

Observables *hydro. modes* *e.g. quasi-normal modes, quasi-particles*

- Describing response is generally complicated as it involves various excitations.

- Simplification?

Hydro. regime



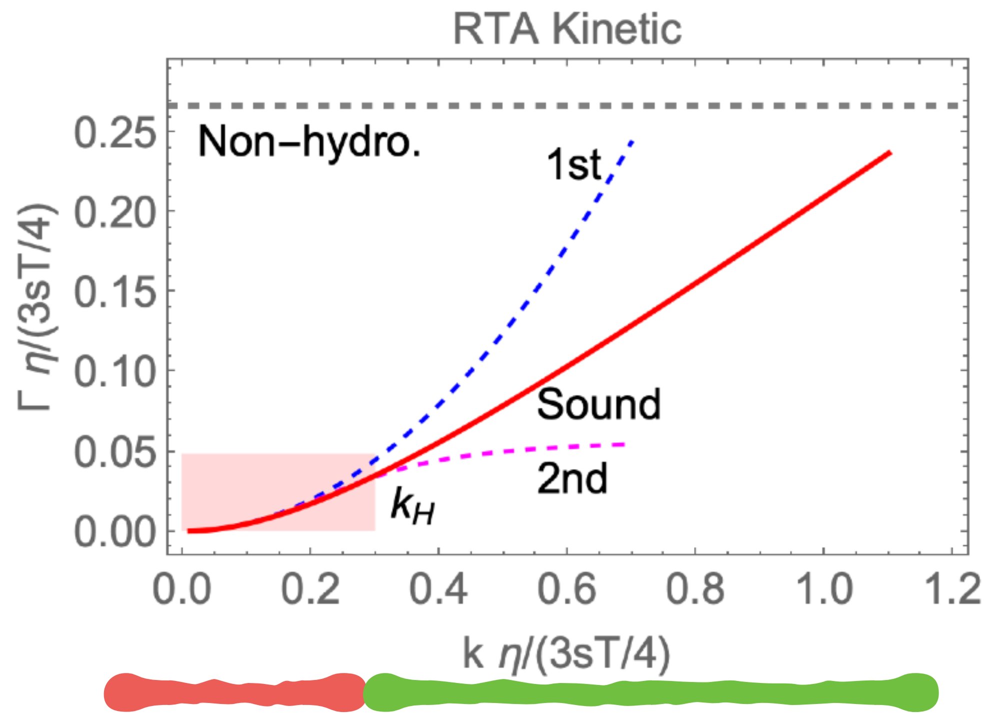
- At small k, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

- Hydro. regime: $k < k_H$ where viscous hydro. works.

What happens when $k > k_H$?

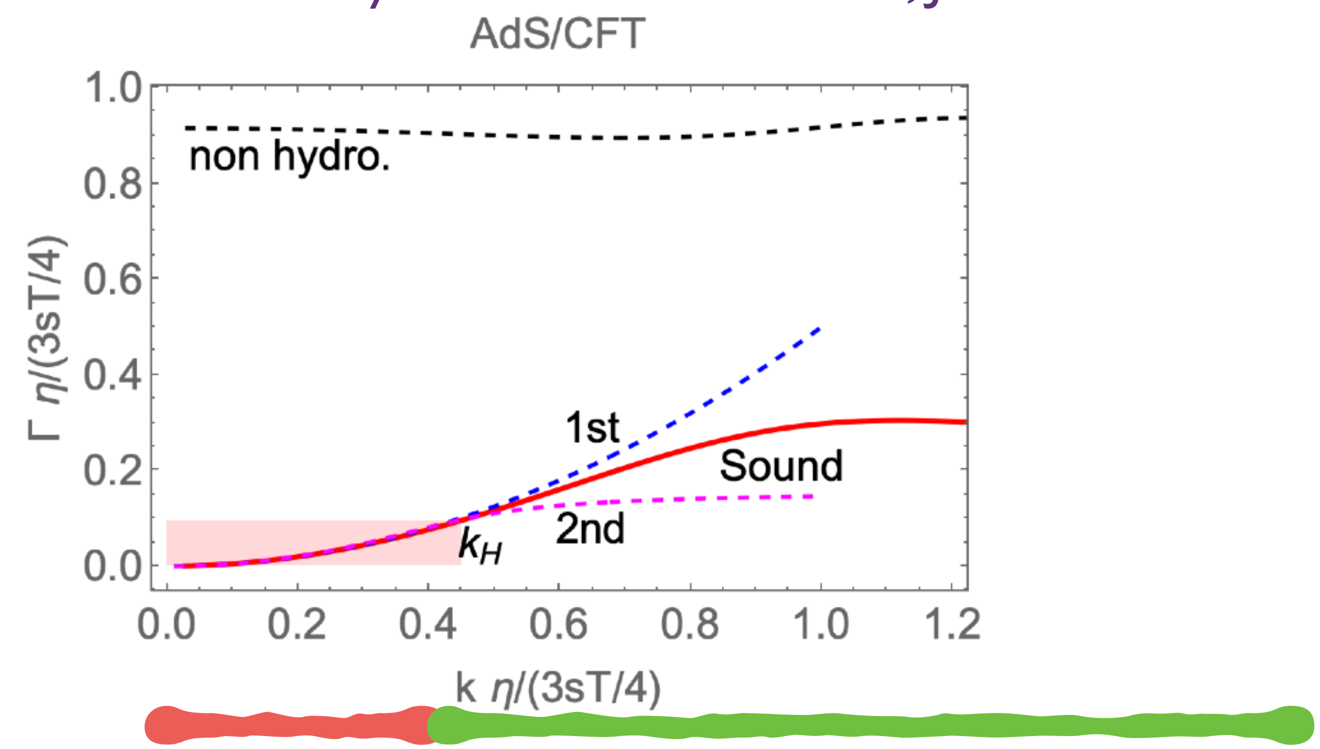
QGP-like systems

Romatschke, EPJC 16'.



Hydro. *EHR in kinetic theory*

Amado-Hoyos-Landsteiner-Montero, JHEP 08



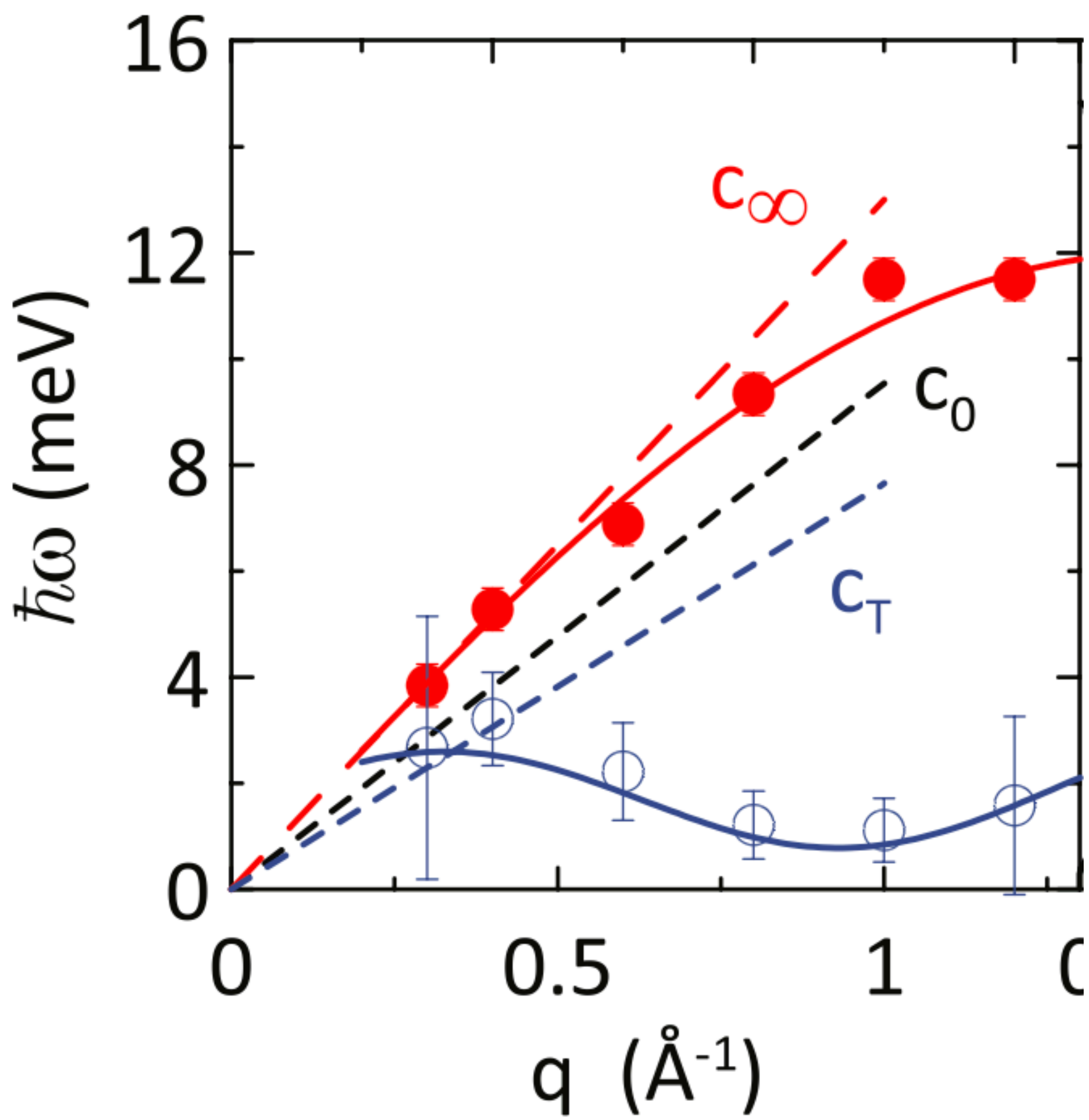
Hydro. *EHR in AdS/CFT*

- Extended hydro. regime (EHR):
  - "sound dominance": sound mode is gapped from other excitations;

    shear channel is discussed in detail in our paper.
  - the dispersion is different from ordinary sound (called high-frequency sound in condense matter literature).

NB: 2306.09094 by Xiaojian Du et. al demonstrate the generality of sound dominance for a class of kinetic theory

Extended hydro. regime in solid liquids



liquid Hg, Petrillo and Sacchetti ,Advances in Physics 21'; many other examples

High frequency sound modes has been observed up to $1/k$ comparable to intro-atom distances.

The implication of EHR (if exists)

- The presence of EHR seems generic. QGP?
  - The collectivity at intermediate gradient.
  - Description of medium's mesoscopy might be simplified.
  - Search for EHR via data-model comparison?

NB: the notion of EHR bears a certain similarity to the far-from-equilibrium hydro. for expanding QGP. The main difference is that EHR describes perturbation around a bulk profile but not the bulk evolution itself.

Towards describing EHR

- How to describe EHR and high-frequency sound through extending hydro.? (Extending hydrodynamics is an active field in condensed matter physics.)
  - describing different systems with EHR from the same framework.
  - needed to test EHR conjecture via data-model comparison in heavy-ion collisions.
- We propose an extension of Müller-Israel-Stewart (MIS) theory, namely MIS*, which serves the purpose.

Weiyao Ke and YY, PRL 23, 2208.01046; partly inspired by Hydro+, Stephanov-YY PRD 18'

MIS*: deforming MIS equation

- Consider the decomposition: $T^{\mu\nu} = T^{\mu\nu}_{\rm ideal} + \pi^{\mu\nu}$
- MIS Eqns

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} + \eta\partial^{<\mu}u^{\nu>}\right) - \ldots$$

shear strength

- MIS* (for a conformal system):

$$\pi^{\mu\nu} = -\eta'\partial^{<\mu}u^{\nu>} + \tilde{\pi}^{\mu\nu}$$

dynamical

$$D\tilde{\pi}^{\mu\nu} = -\frac{1}{\tau'_\pi}\left(\tilde{\pi}^{\mu\nu} + (\eta - \eta')\partial^{<\mu}u^{\nu>}\right) - \ldots$$

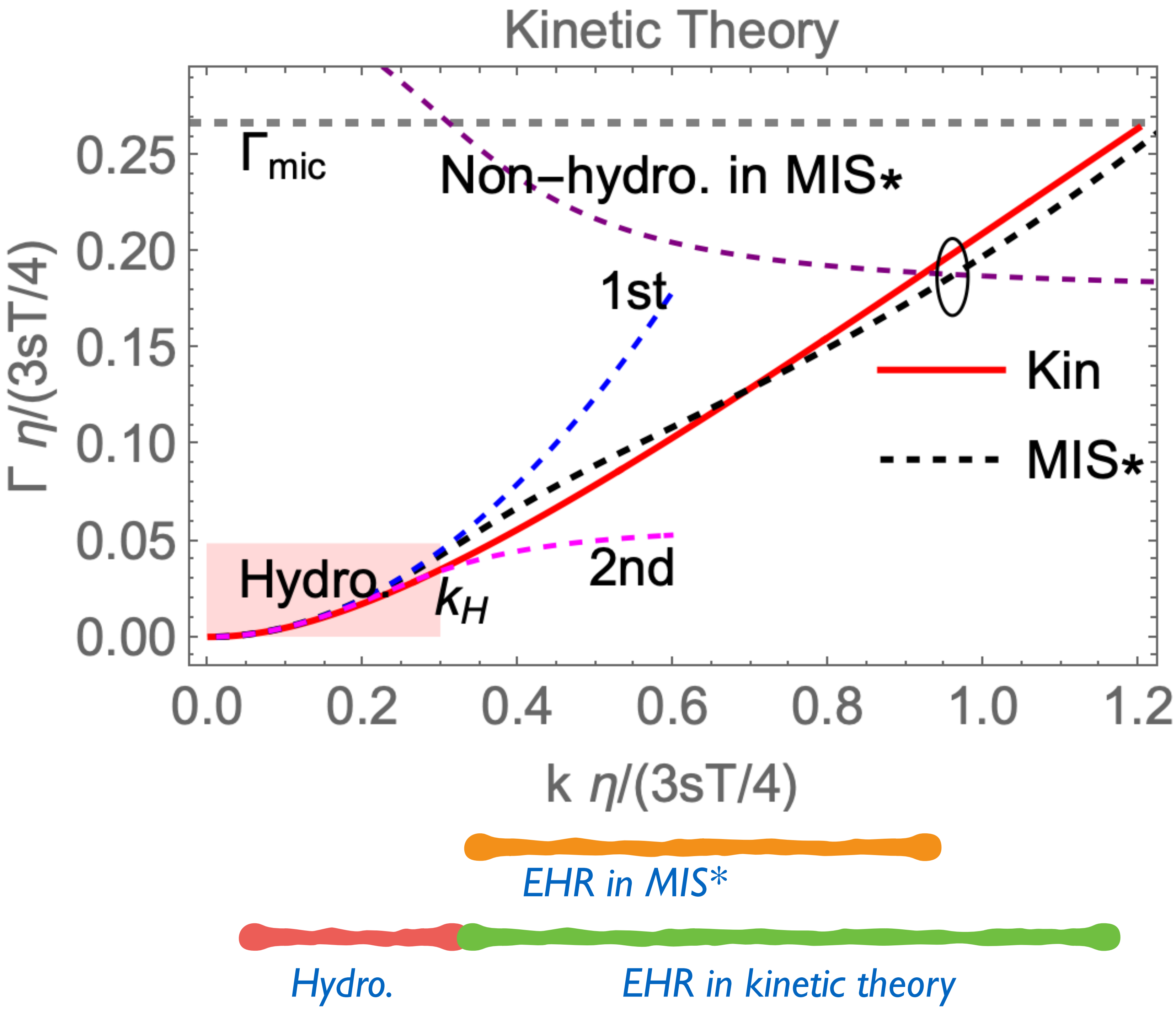
- MIS* parameters: $\eta' \sim$ the effective viscosity in EHR and τ'_π controls the boundary separating hydro. and EHR.

$$\delta = \frac{\eta'}{\eta} \qquad \gamma = \frac{\tau'_\pi}{\tau_\pi}$$

When $\delta = 0$,
$\gamma = 0$ (1st order hydro.);
$\gamma = 1$ (2nd order hydro).

MIS* vs kinetic theory

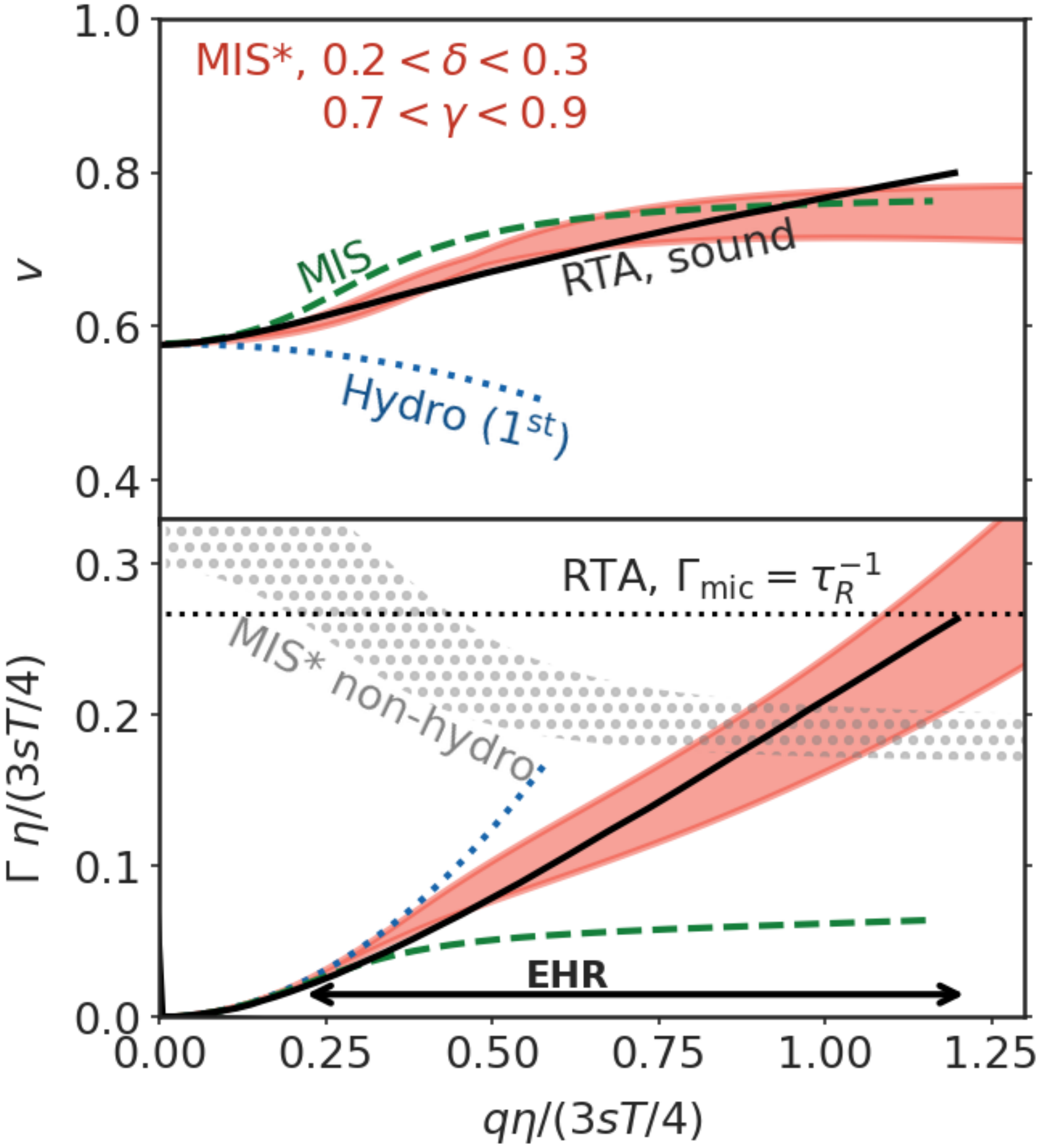
$(\delta, \gamma) = (0.25, 0.8)$

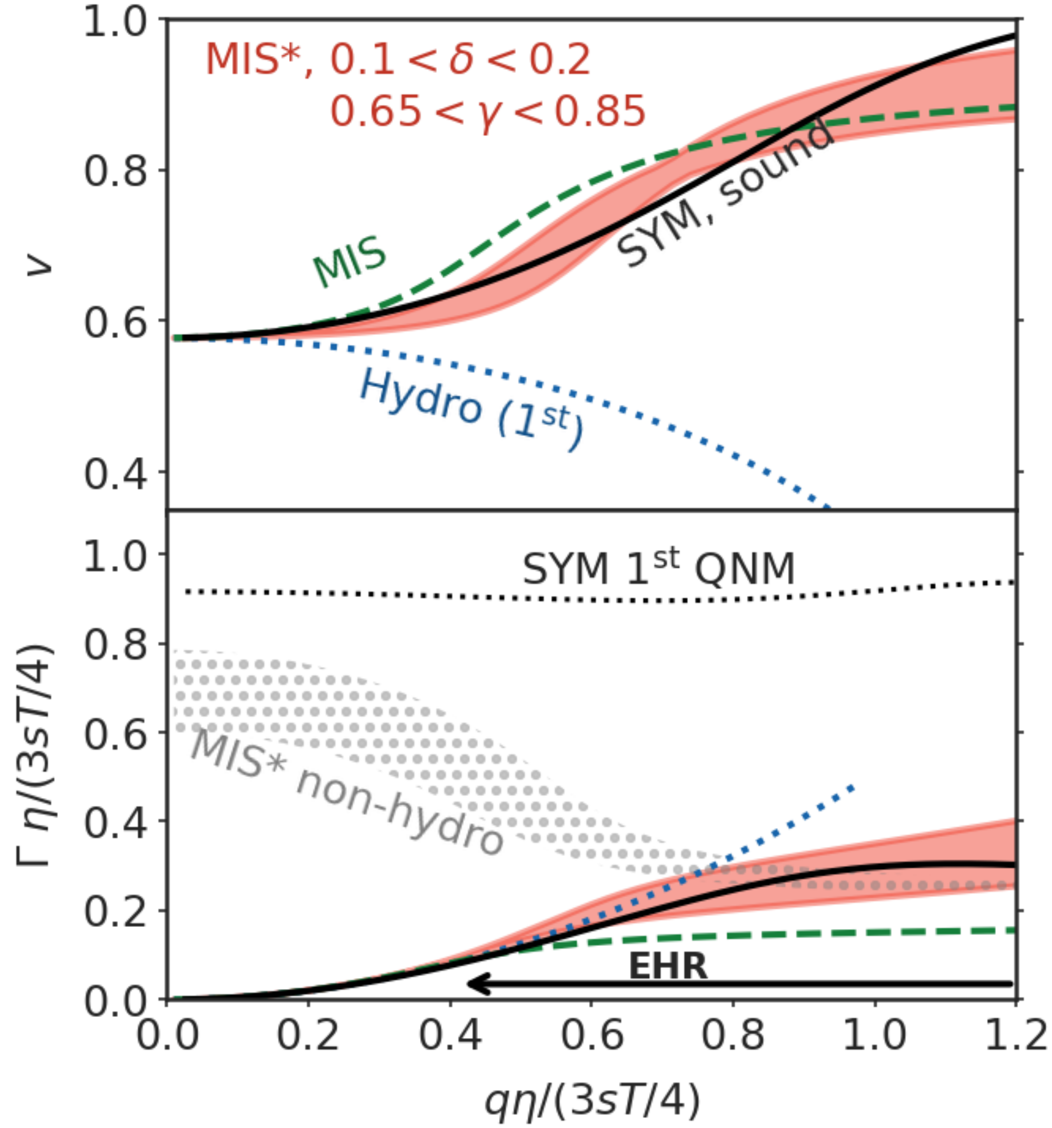


MIS* describes both kinetic and AdS/CFT theory in EHR

RTA Kinetic.

AdS/CFT





Hydro. *EHR in MIS**

Hydro. *EHR in MIS**

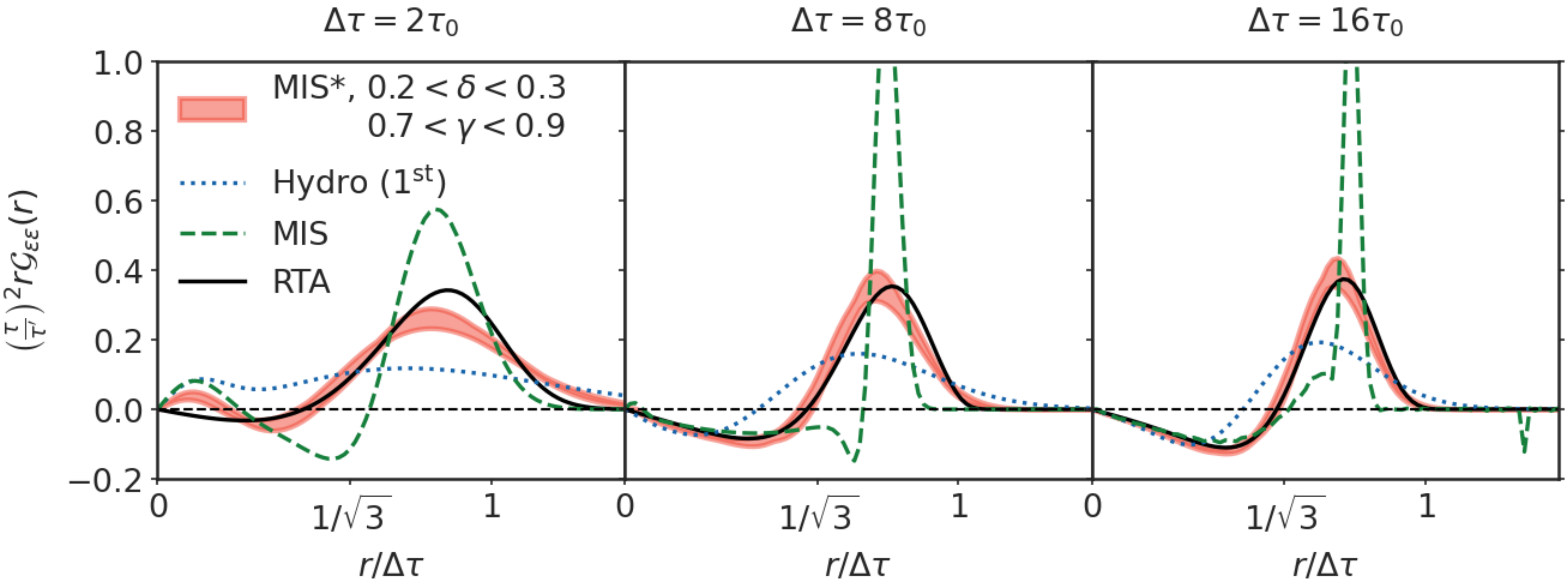
Extended hydro. response for Bjorken expanding plasma

- Motivation:
  - complementing the study of a static medium;
  - exploring the prospects of detecting EHR through jet-medium interaction.
- Consider e.g. energy-energy response function.

c.f. KOMPOST et al

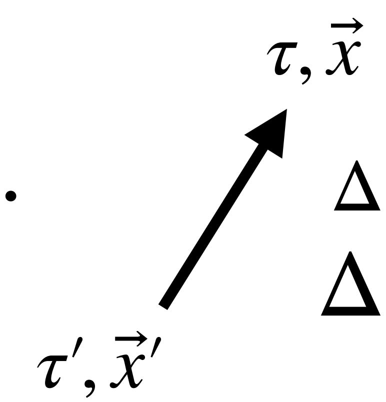
$$\delta\epsilon(\tau, x) = \int_{\tau_I}^{\tau} d\tau' \int_{x'} \underbrace{G_{\epsilon\epsilon}(\tau, \tau'; x - x')}_{\text{response function}} \, \underbrace{S_\epsilon(\tau', x')}_{\text{Source}} + \ldots$$

*RTA kinetic vs MIS**



Energy-energy response function. The disturbance is sourced at $\tau_0 = 2\tau_R$ (equilibrated plasma).

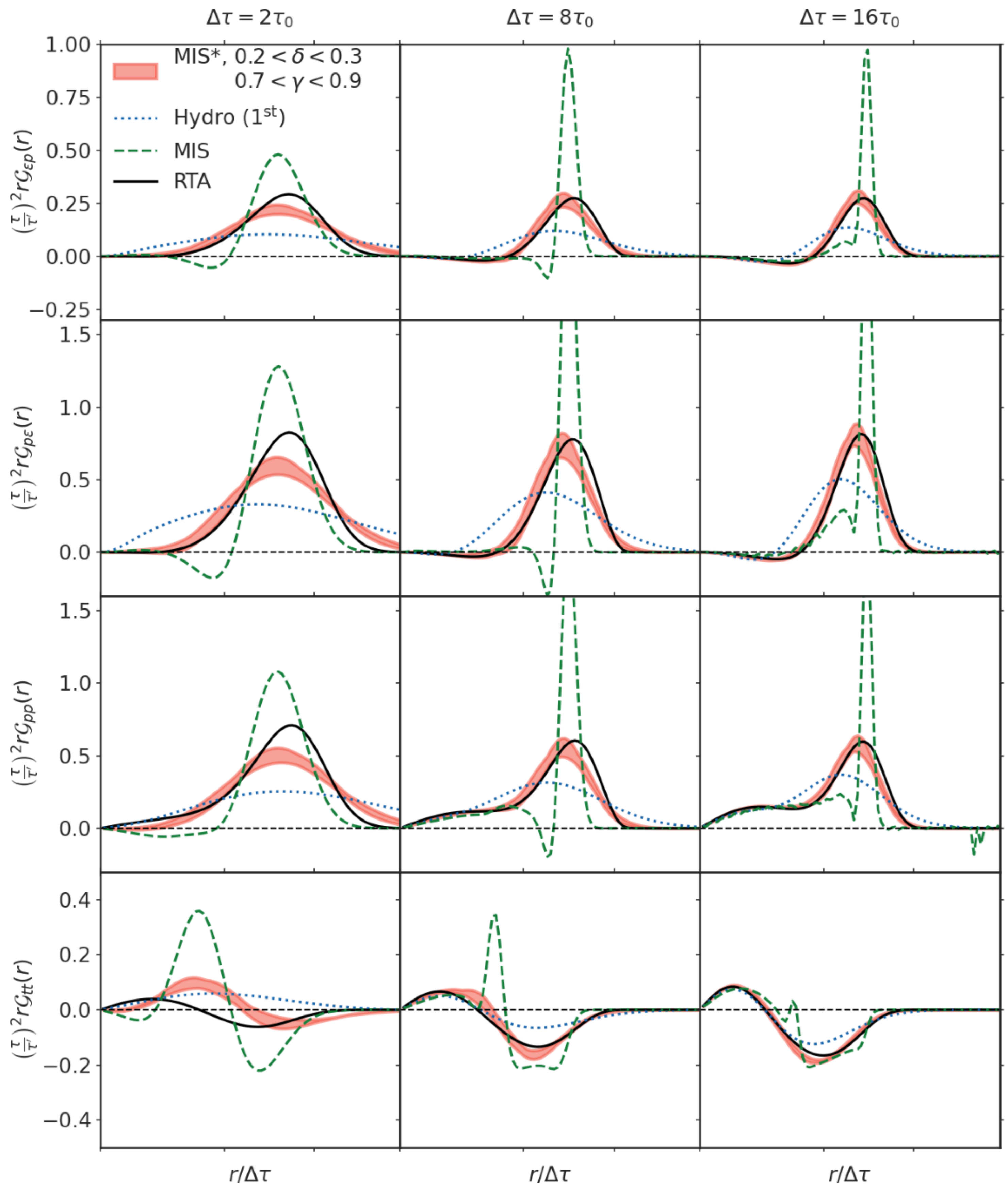
- MIS* describes extended hydro. response.



$$\Delta r = |\vec{x} - \vec{x}'|$$

$$\Delta\tau = \tau - \tau'$$

MIS* describes energy-momentum response (5 different response funs)



Summary

- We introduce extended hydro. regime (EHR) scenario for QGP-like system at intermediate scale and illustrate its generality.
  - Collective excitations dominate even at intermediate gradient.
  - The description at mesoscopic scale simplifies under EHR scenario.
- Observables: jet-medium interaction? small systems?
- Extension of hydro. based on “sound mode dominance”.

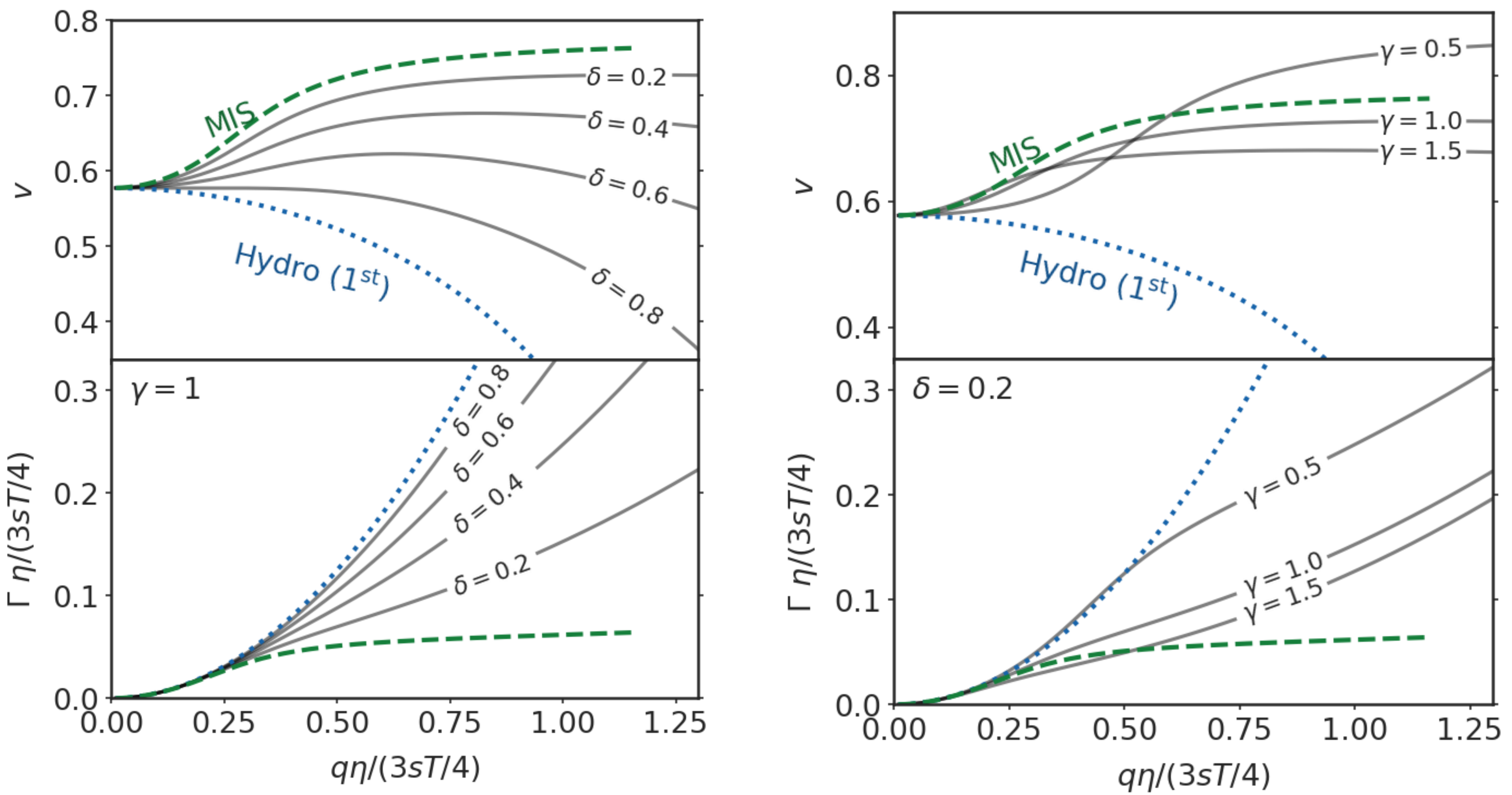
EHR and Lattice

- Helping extracting transport coefficients from lattice with ansartz motivated by EHR;
- Test EHR via lattice? Euclidean correlation should be more sensitive to EHR than to hydro. regime.

exciting things ahead!

Back-up

Flexibility/capability of MIS*



- Increasing δ=η'/η increases damping rate.
- (γ, δ) in combination controls sound propagation in EHR.

Discussion

Hydro. | *Extended Hydro. Regime*

(characterized by $\eta, c_s^2, \ldots$) | *(characterized by $\eta', \tau'_\pi \ldots$)*

- The success of MIS* confirms that in extended hydro. regime (EHR), the characterization of QGP mesoscopy can be simplified.
  - Responses in different microscopic theories can be described by the same effective models such as MIS*.
  - Medium properties are characterized by a few parameters.

Towards describing EHR

Grozdanov-Kovtun-Starients-Tadic, PRL 19', JHEP 19;

Heller-Serantes-Spalinski-Svensson-Withers, PRD 21'.

- Adding higher gradient terms (proliferation of inputs).
- An alternative: constructing a simple model with a few parameters such that
  - it reduces to hydro. in small k;
  - describes sound mode in (at least part of) EHR.

MIS* (a simple yet non-trivial extension of Mueller-Israel-Stewart (MIS) eqns) serves the purpose.

partly inspired by Hydro+, Stephanov-YY PRD 18'