Quark-gluon matter out-of-equilibrium

- Intro.
- Does quark-gluon matter feature an extended hydro. regimes?
- Summary and outlook

Yi Yin

Institute of Modern Physics (IMP), Lanzhou, Chinese academy of sciences

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

XQCD, Dalian, Aug. 3rd, 2023

Weiyao Ke @ LANL

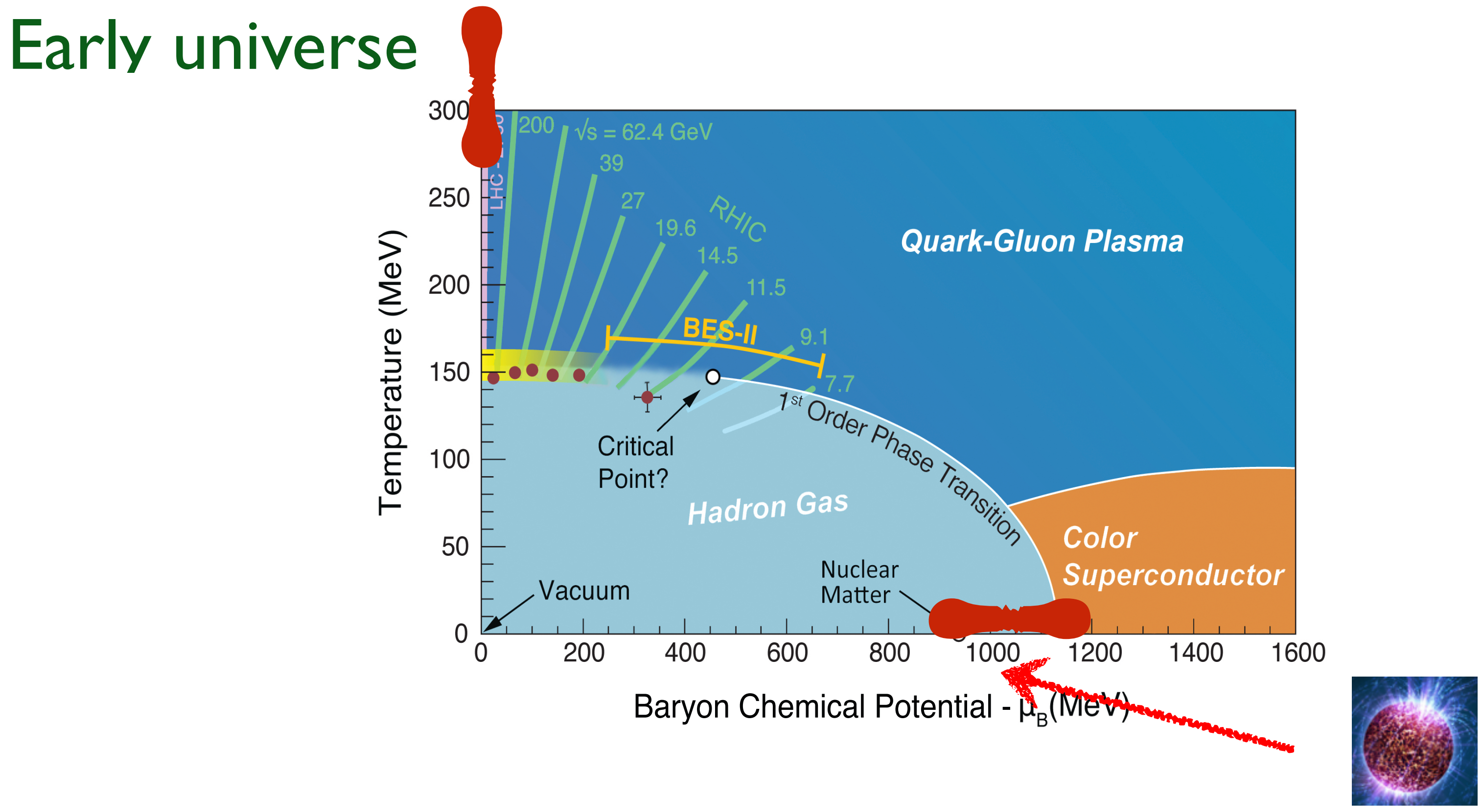
Broad view

- Nuclear structure study: e.g. understand the limits of stability of matter from hadronic many-body interaction.
- Heavy-ion collision: the properties of hot and dense matter from quark-gluon interaction.
- The characterization of many-body systems is complicated (lots of d.o.fs).
- Substantial simplification may emerge (e.g.: Landau Fermi-liquid, Critical points): universality among different systems.
- Cross-fertilizing among different subfields.

Quark-gluon plasma (QGP)

- the de-confined thermal state of QCD.
- recreated by heavy-ion collisions.
- to date, significant advances in studying QGP
  - Extraordinarily small specific shear viscosity $\frac{\eta}{s} \sim \frac{1}{4\pi}$: de-confined partons are not free, but move coherently.
- showing various qualitatively features similar to other strongly coupled theories.

What next?



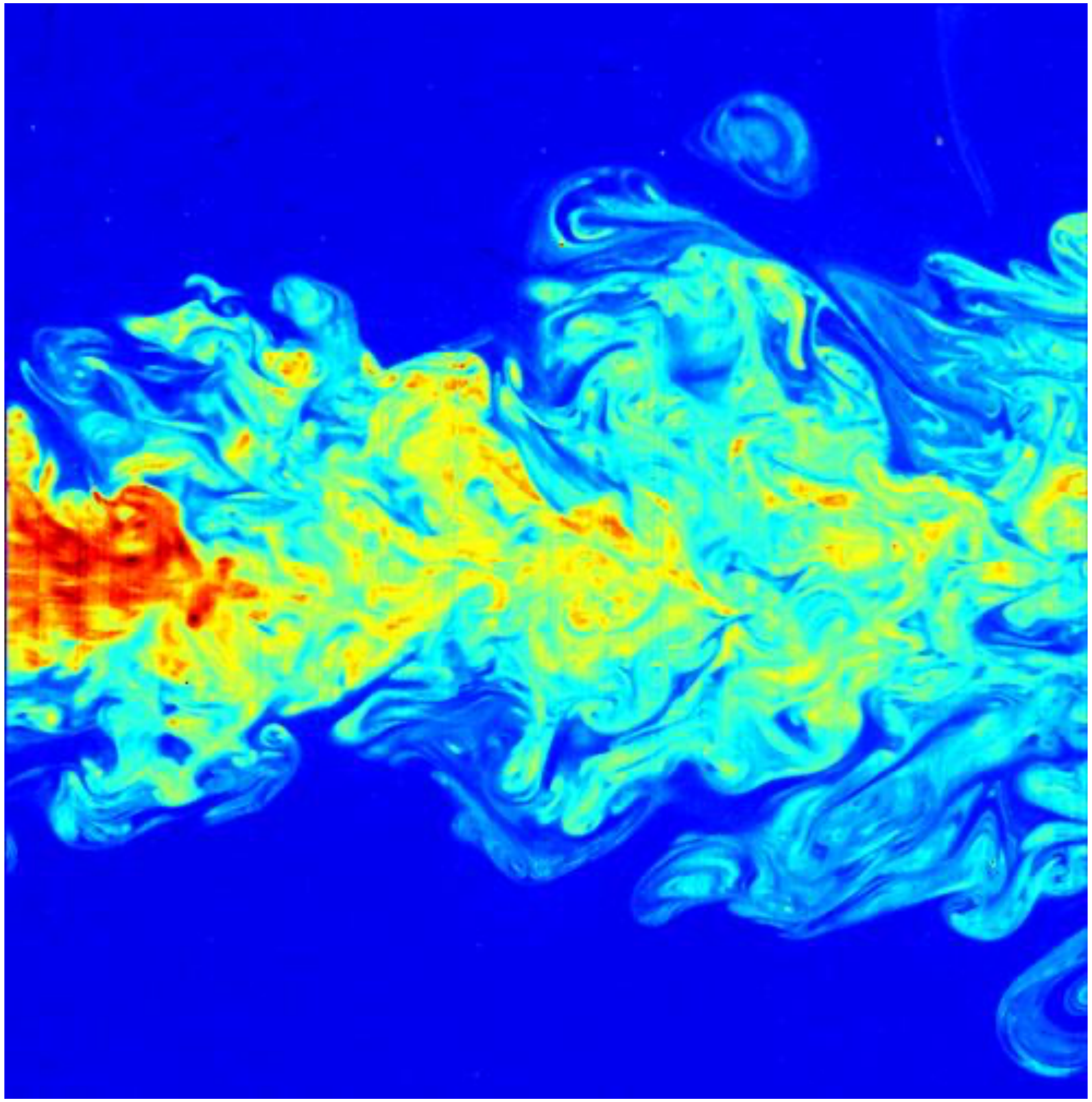
- Exploring baryon-rich QCD matter and search for the QCD critical point .

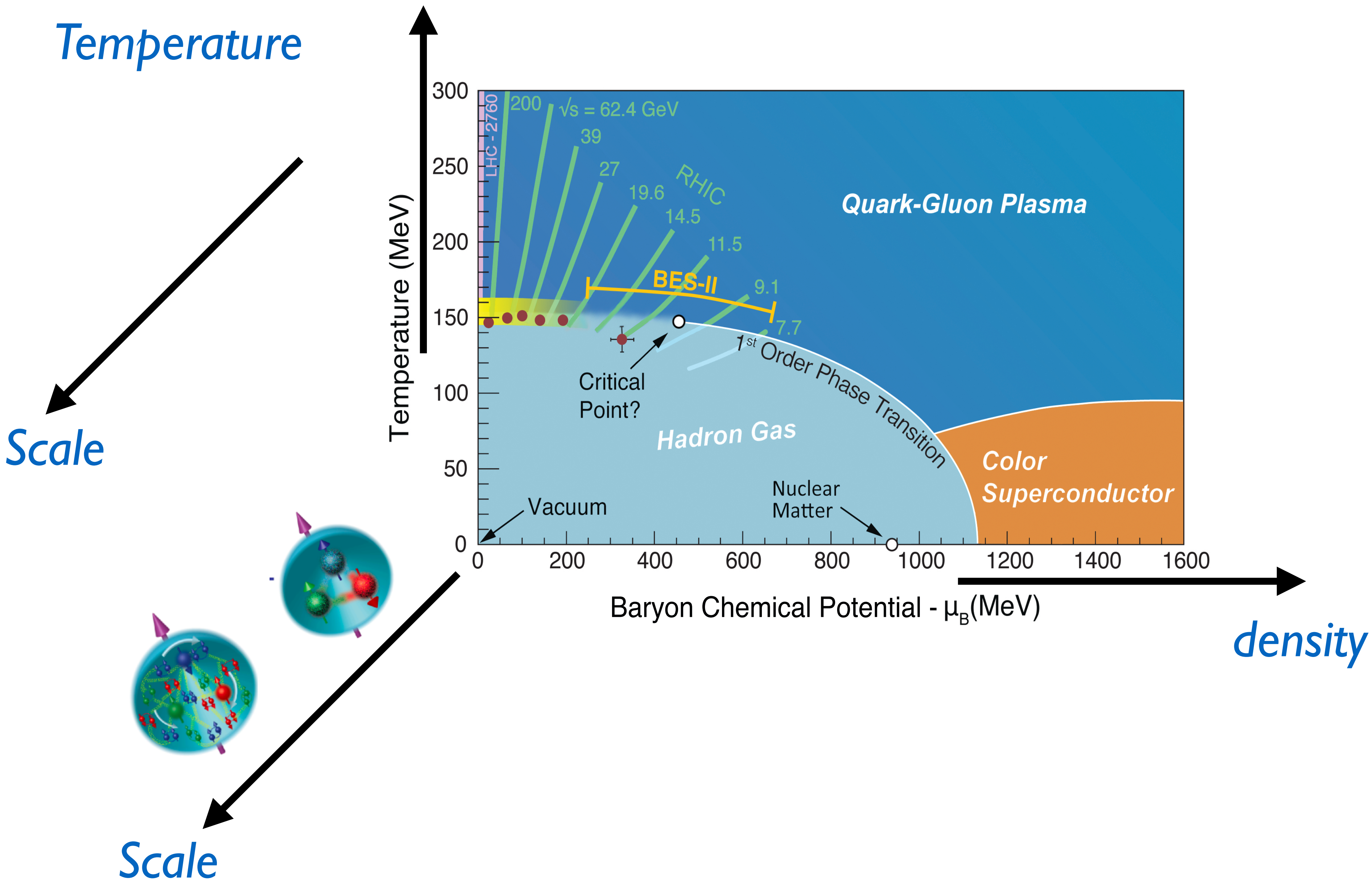
- Quantum and topological aspects of QCD matter (e.g. spin observables/entanglement entropy etc).

- Many more…

- This talk: QGP out-of-equilibrium.

The non-equilibrium phenomenon is amazing





Non-equilibrium properties reveal the behavior of QGP with varying scales.

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 form different perspectives:

  - Large angle scattering between jet and the medium.

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

  - Collectivity in small systems

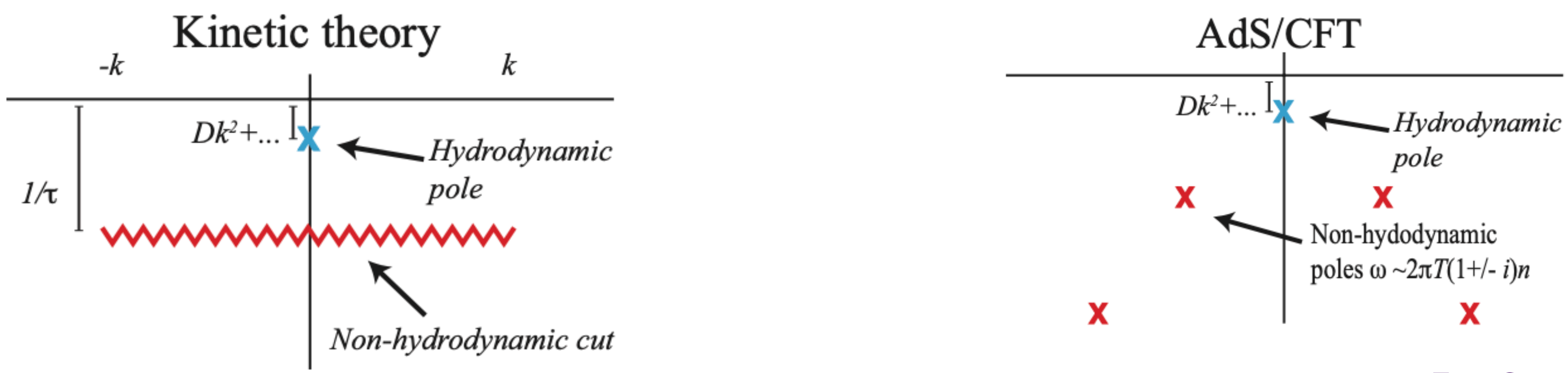
    works by Kurkela, Mazeliauskas, Wiedemann, Bin Wu, ….

  - The emergent properties of expanding QGP.

  - This talk: medium response (how response changes with varying gradient).

Medium’s response

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.

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

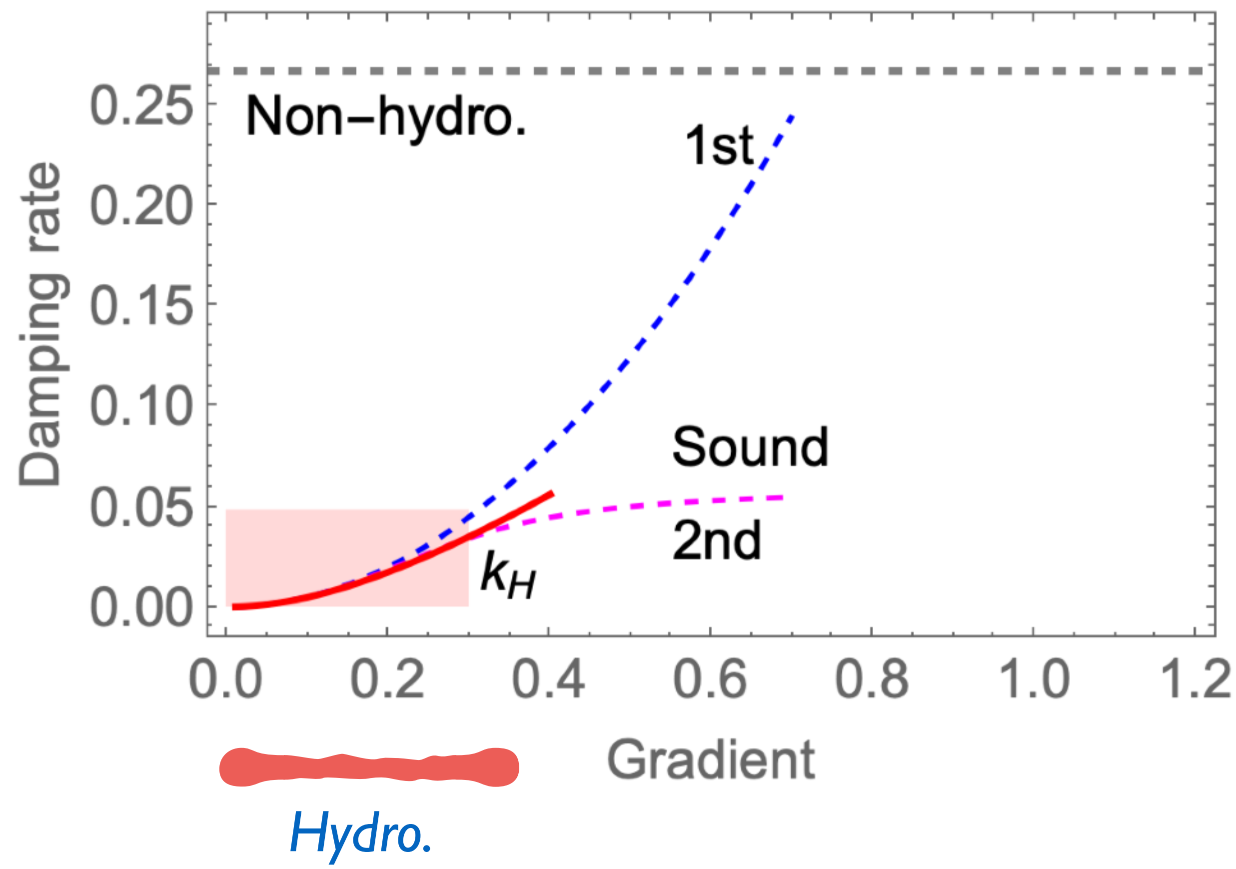
Observables — *hydro. modes* — *e.g. quasi-normal modes, quasi-particles*

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

- Simplification?

Hydro. regime

Relaxation time approximation (RTA) kinetic equation



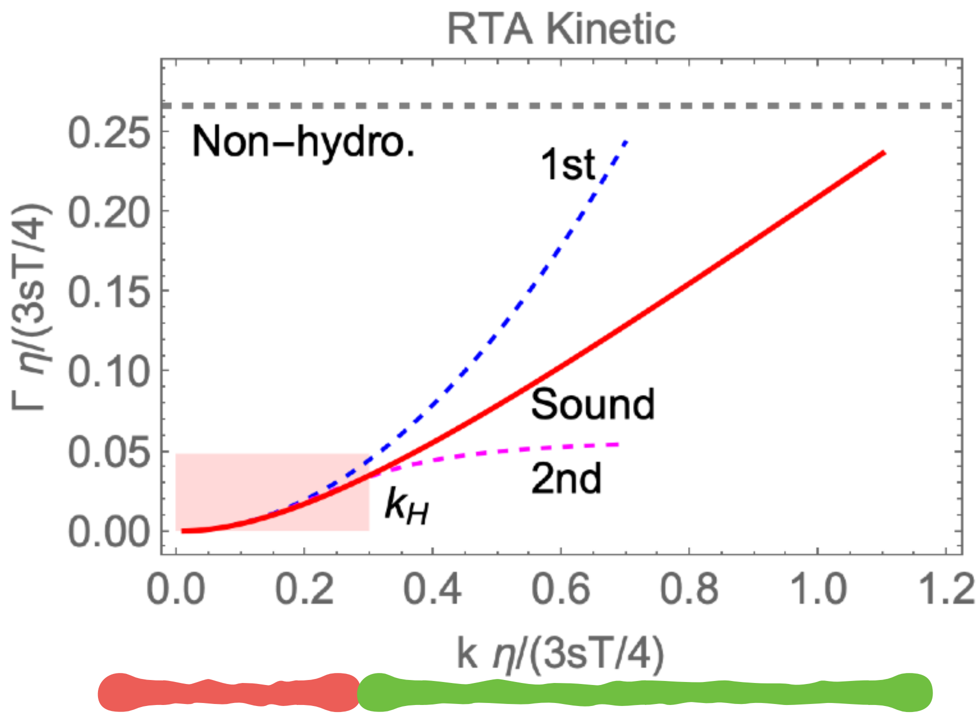
- At small k, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

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

What happens when $k > k_H$?

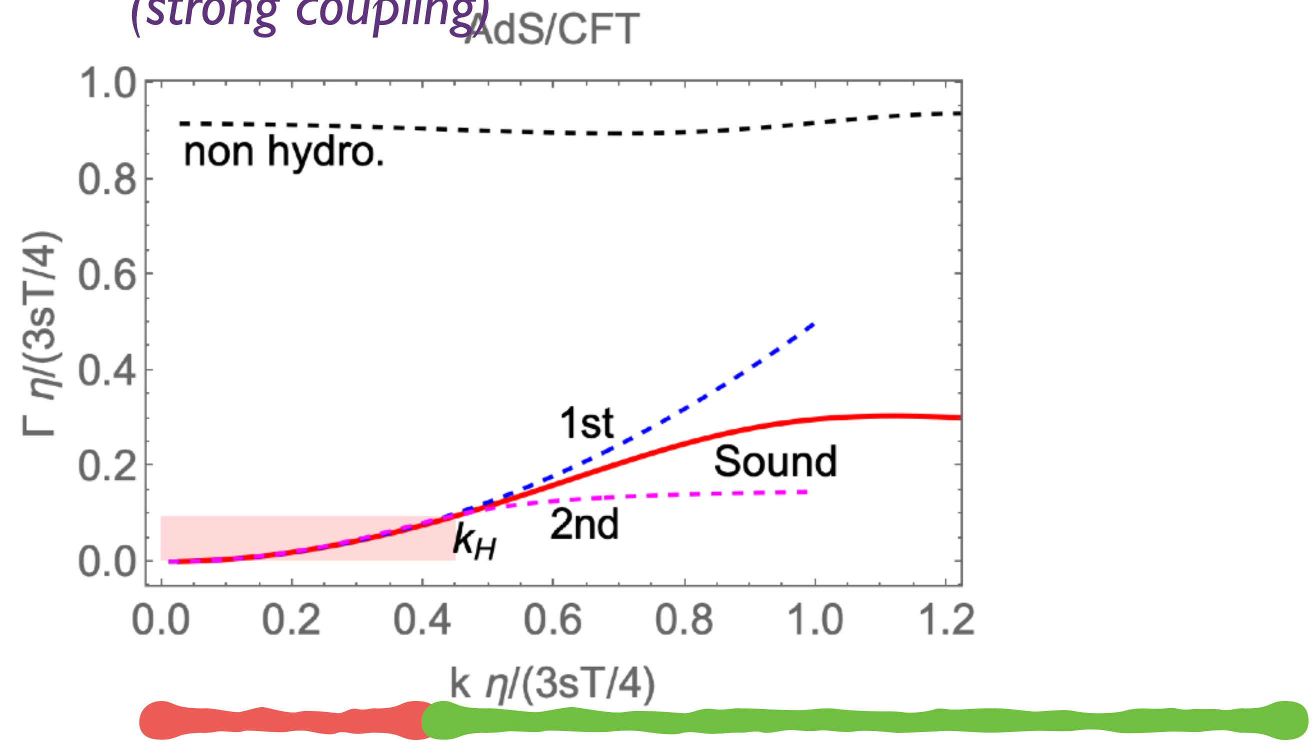
QGP-like systems

Romatschke, EPJC 16'. (weak-coupling)



Hydro. *EHR in kinetic theory*

Amado-Hoyos-Landsteiner-Montero, JHEP 08 (strong coupling)



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.

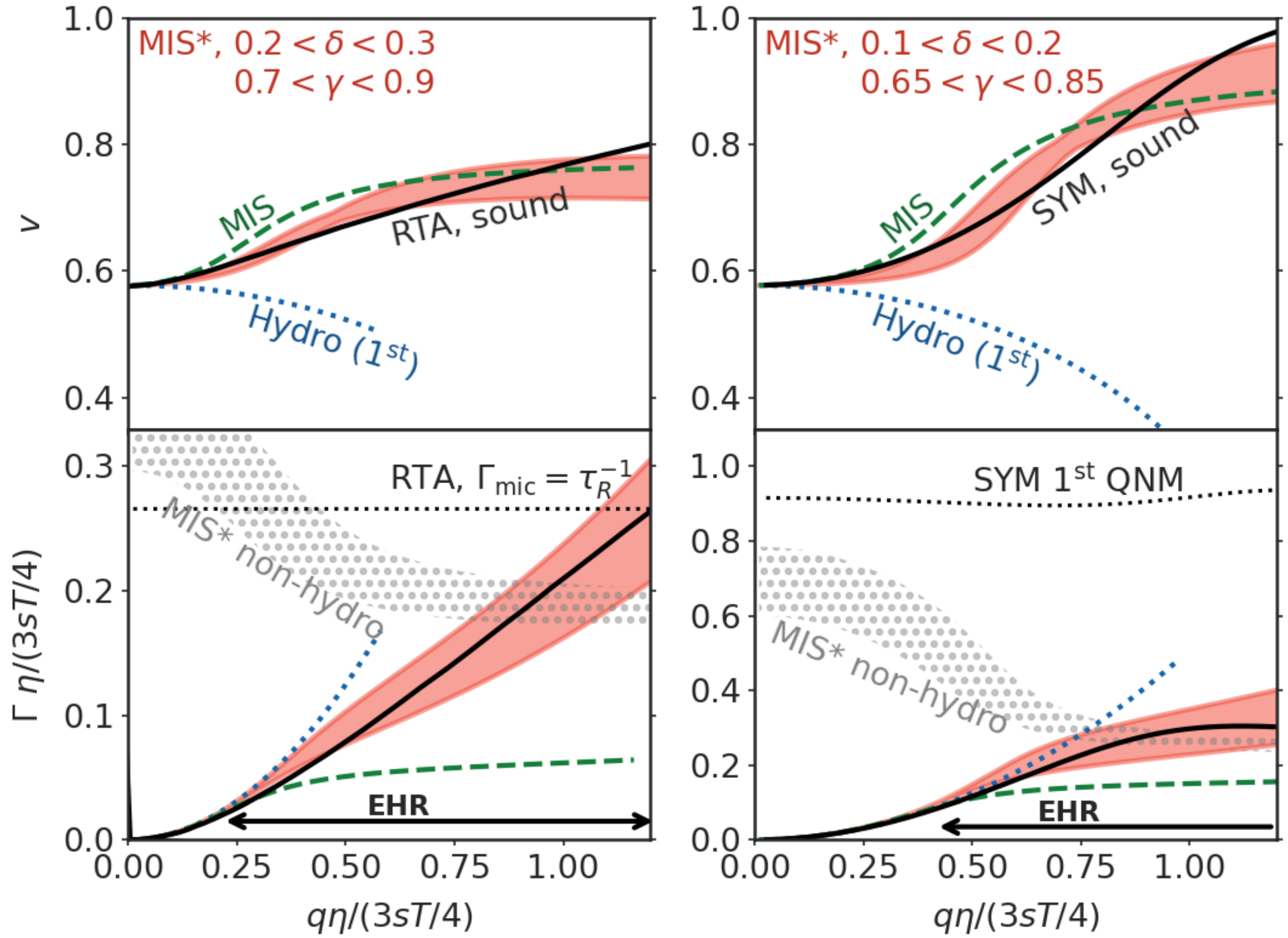
  - the dispersion is different from ordinary sound (called high-frequency sound in condense matter literature).

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

Shared properties of high-frequency sound

Phase velocity

Damping rate



- Supersonic phase velocity.
- Less dissipative effects (compared with first-order hydro.).

High frequency sound in liquid metals

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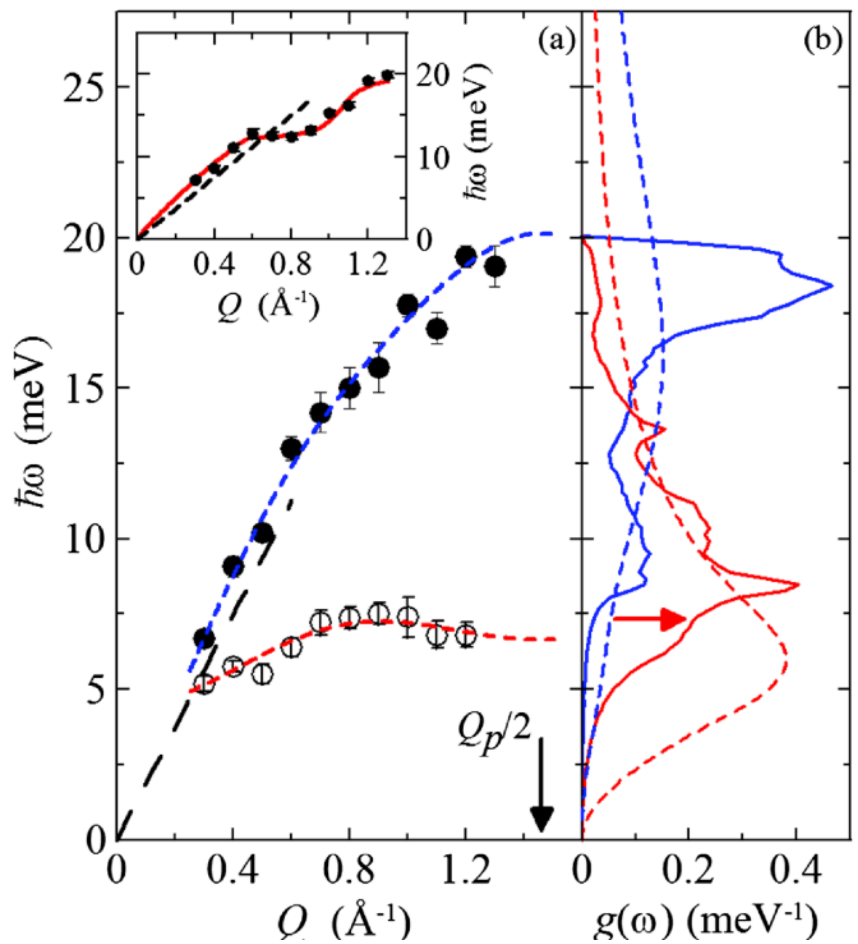


The high-energy mode $\omega_1(Q)$ (black dots) displays a sinusoidal shape with a maximum at $Q_p/2 = 1.46$ Å^{-1} (dashed blue line) and can be identified as a longitudinal acoustic mode. The apparent high-frequency sound velocity is $v_L^\infty = 3380 \pm 60$ m/s, about 20% higher than the hydrodynamic value v_L^0. Although Zn is not the best candidate for an approximation based on the homogeneous electron gas, we can compare the longitudinal mode dispersion relation to that derived by means of the Bohm-Staver approximation [4]. Assuming two electrons per atom, the sound velocity turns out to be $c_{\mathrm{BS}} =$ 4175 m/s. Conversely, if $e - e$ interactions are taken into account by using the compressibility sum rule for the homogeneous electron gas [28], we get $c_{\mathrm{ex}} = 3195$ m/s, which provides a fair agreement with the experimental value of v_L^∞. A similar behavior was also observed in liquid mercury [29], which belongs to the same element group although in both cases the agreement might be accidental [4].

Many studies since the seminal work of Copley and Rowe who in 1974 demonstrated the existence of a long-living collective mode in liquid Rb.

The implication of EHR (if exists)

- We propose the existence of EHR as a conceivable scenario for QGP.
  - c.f. QCD vacuum: pion is not the only effective d.o.f. at scale larger than its decay constant f_π
- If true, one can use the properties of high-frequency sound to characterize the medium at non-hydro. regime.

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: $T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu}$
- MIS Eqns

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

shear strength

- MIS* (for a conformal system):

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

dynamical

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

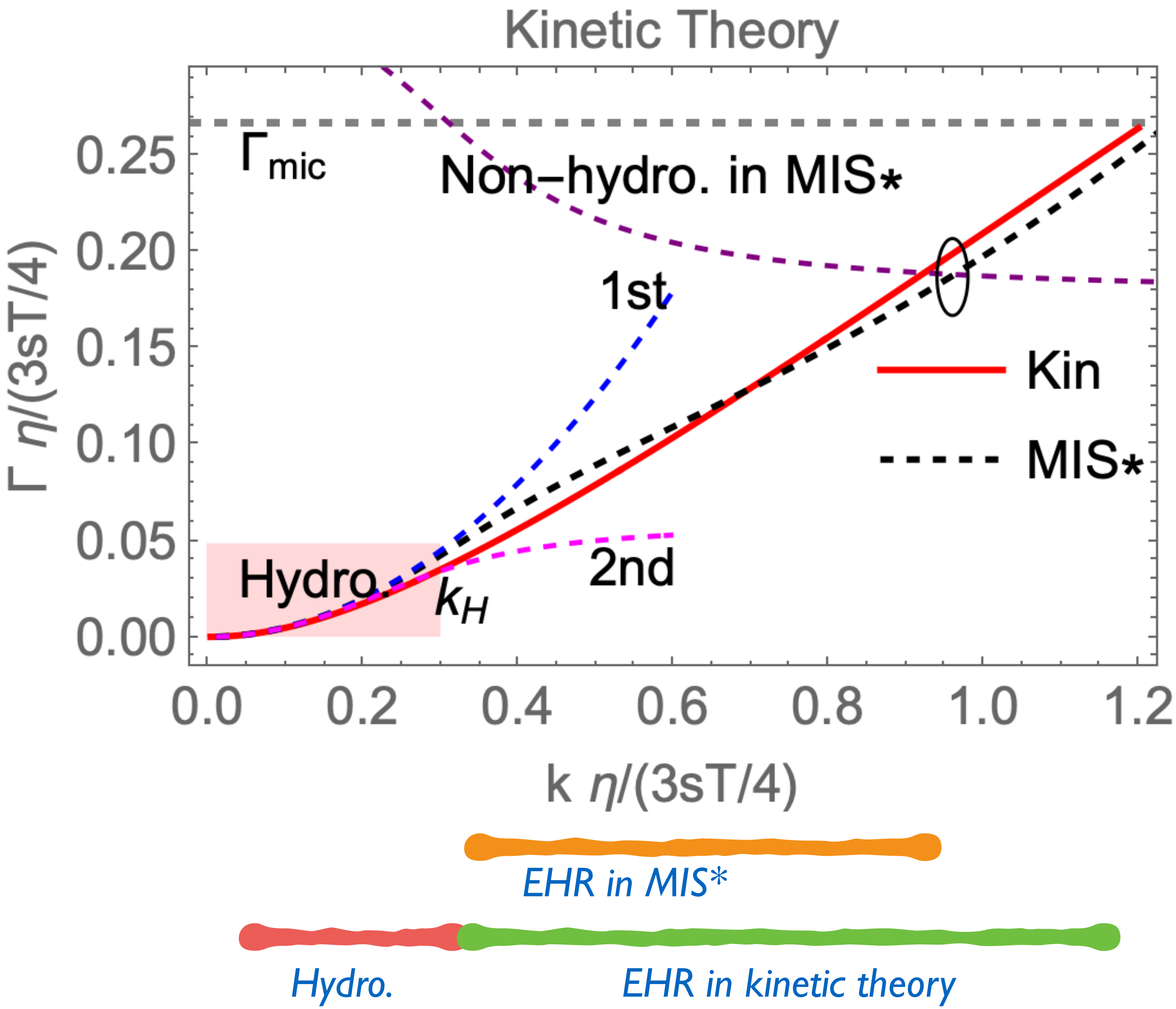
- MIS* parameters: $\eta' \sim$ the effective viscosity in EHR and τ'_π controls the boundary separating hydro. and EHR.

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

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

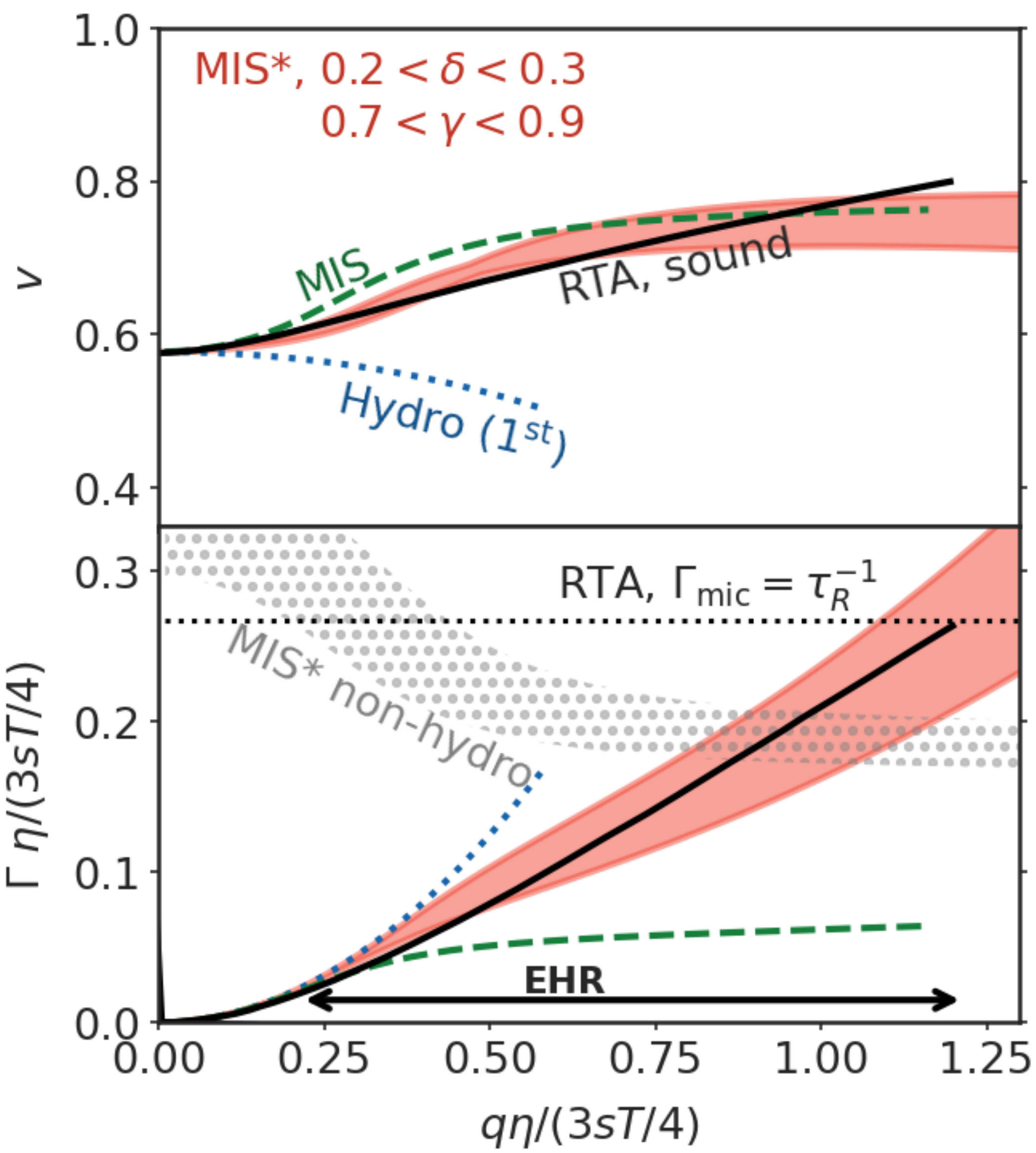
MIS* vs kinetic theory

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



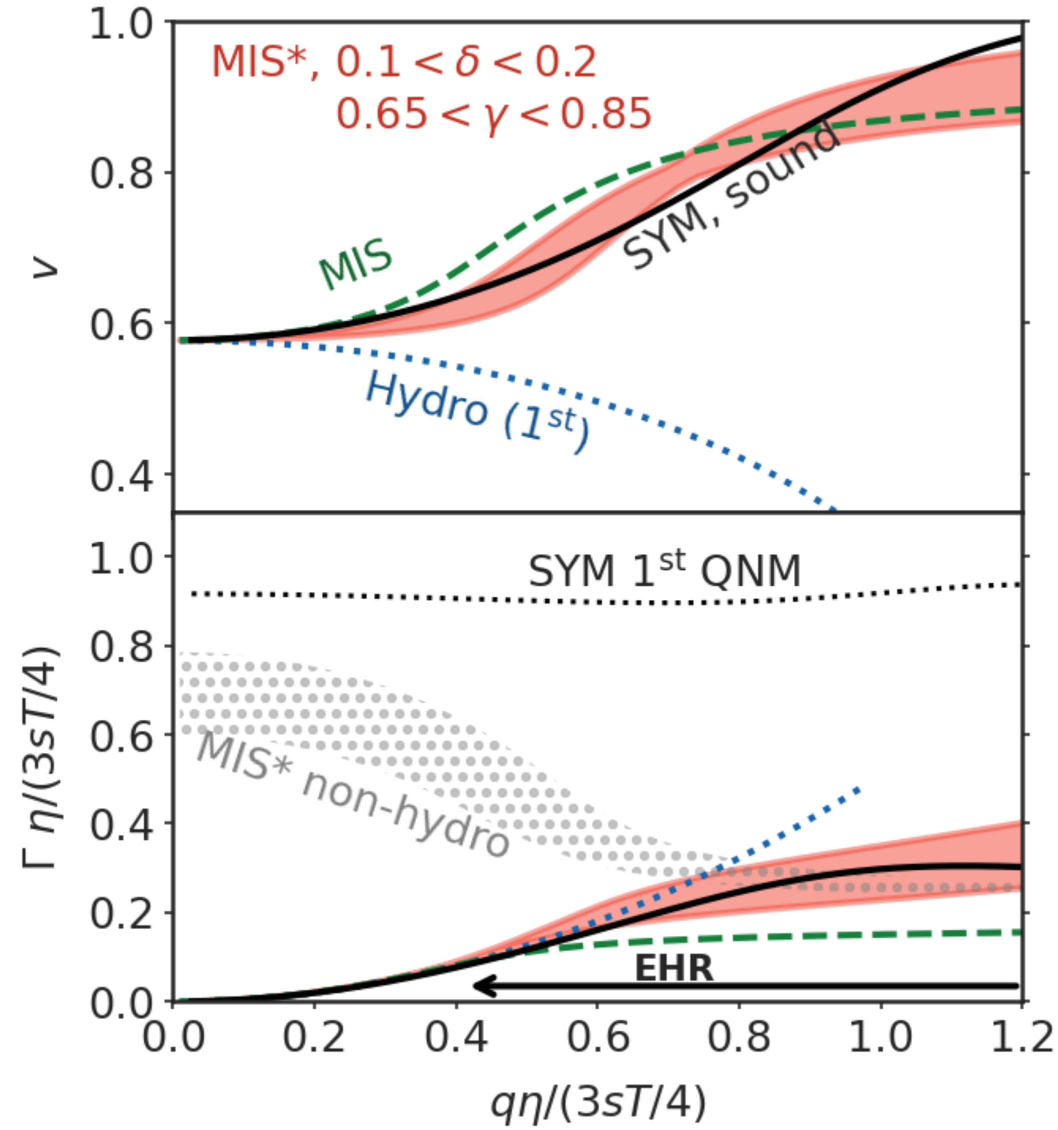
MIS* describes both kinetic and AdS/CFT theory in EHR

RTA Kinetic.



Hydro. EHR in MIS*

AdS/CFT



Hydro. EHR in MIS*

Extended hydro. response for Bjorken expanding plasma

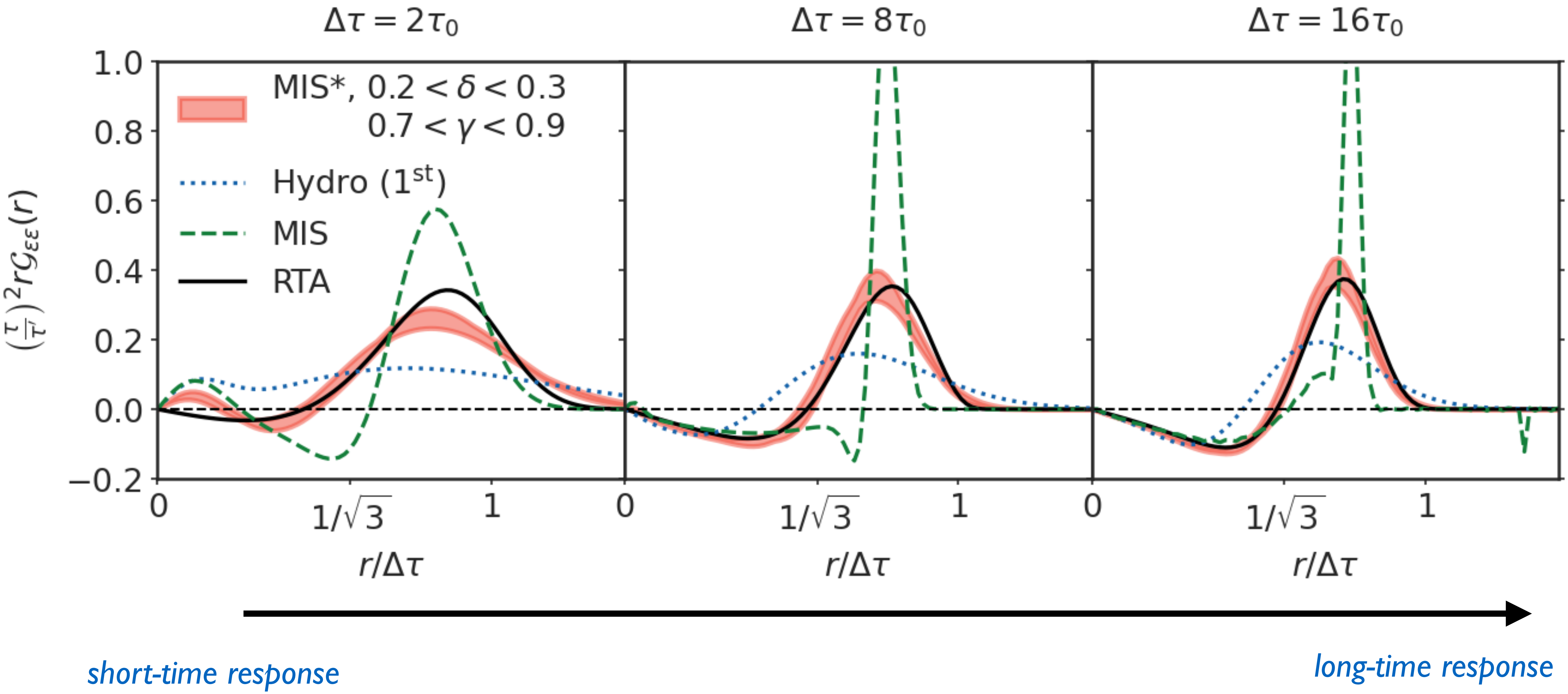
- Motivation:
  - complementing the study of a static medium;
  - exploring the prospects of detecting EHR through jet-medium interaction.
- Consider e.g. energy-energy response function.

c.f. KOMPOST et al

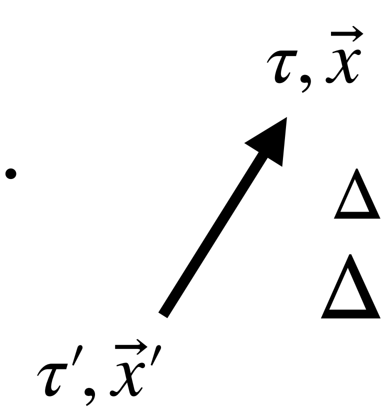
$$\delta\epsilon(\tau, x) = \int_{\tau_I}^{\tau} d\tau' \int_{x'} \underbrace{G_{\epsilon\epsilon}(\tau, \tau'; x - x')}_{\text{response function}} \underbrace{S_\epsilon(\tau', x')}_{\text{Source}} + \ldots$$

RTA kinetic vs MIS*

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

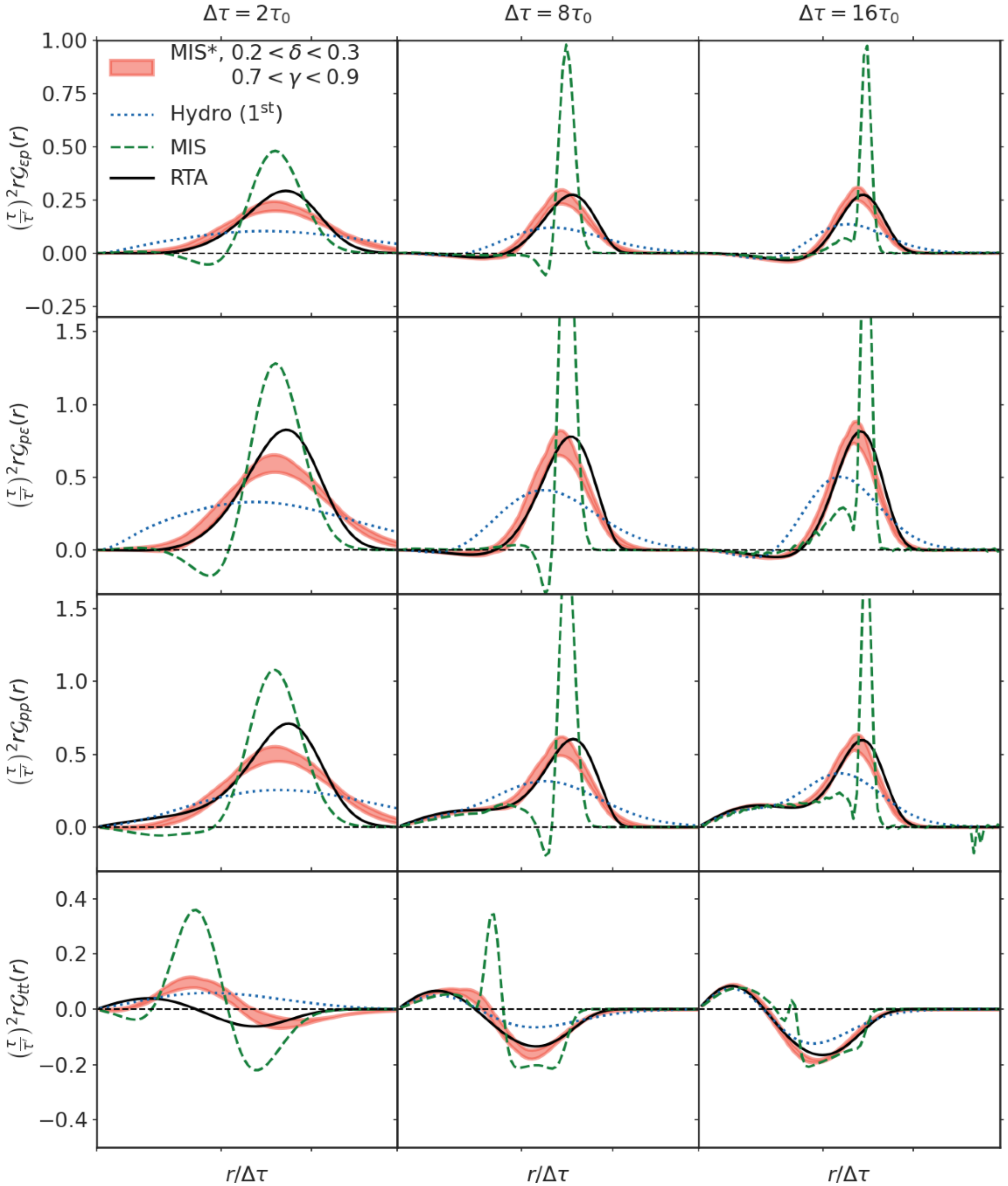


- MIS* describes extended hydro. response.



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

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



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!

Summary and outlook

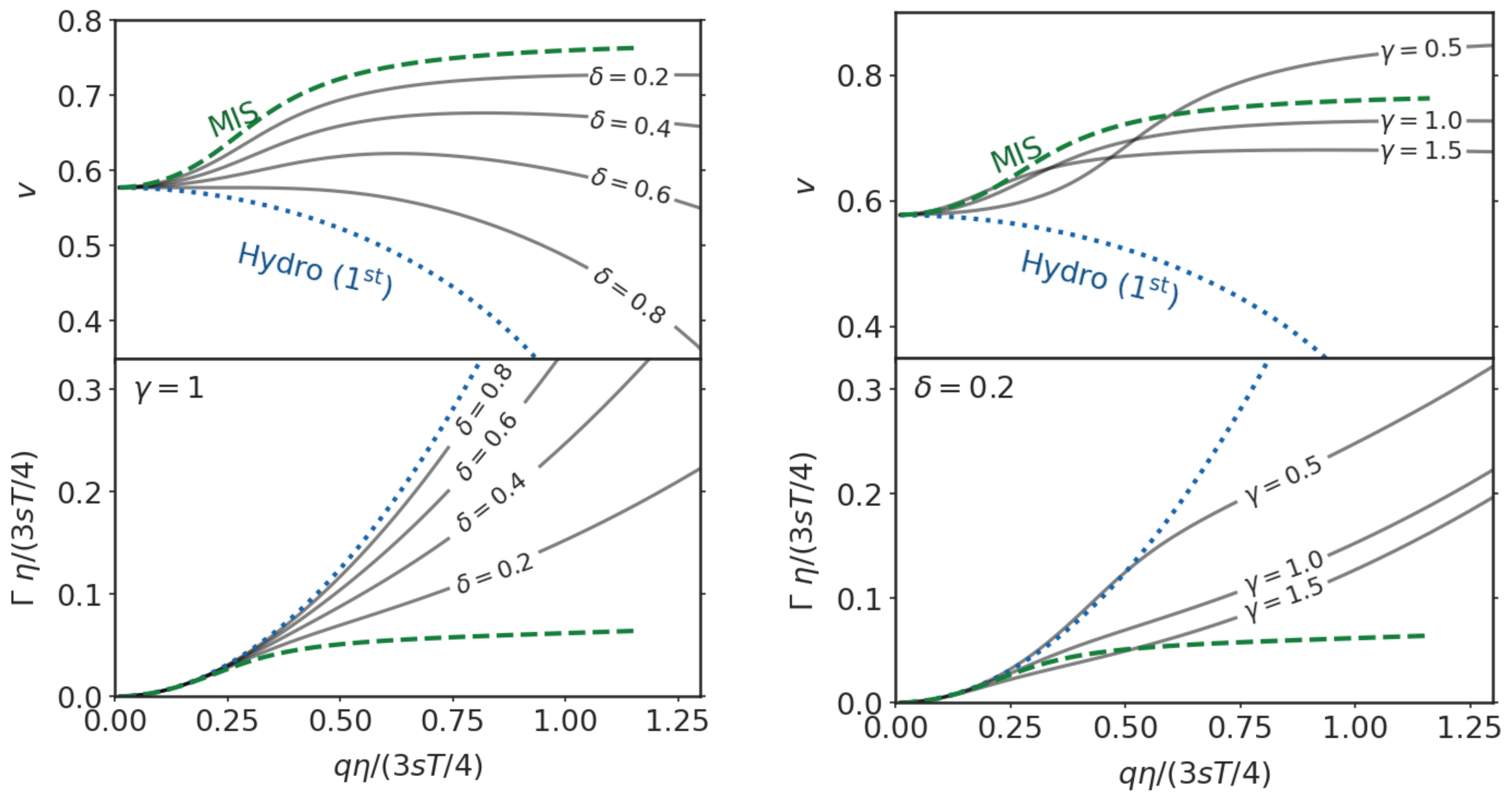
Summary

- 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.
- Observables: jet-medium interaction? small systems?
- Non-equilibrium physics of QGP is rich and is connected to the fundamental question of QCD evolution.
  - Another example: emergent properties of far-from-equilibirum QGP.

J. Brewer (CERN), Weiyao Ke, Li Yan (Fudan), YY, 2212.00820

Back-up

Flexibility/capability of MIS*



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

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'