Does quark-gluon plasma feature an extended hydrodynamic regime?

Hydro.

Extended Hydro. Regime

(characterized by $\eta, c_s^2,\ldots$)

(characterized by $\eta', \tau'_\pi \ldots$)

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Weiyao Ke and YY, 2208.01046

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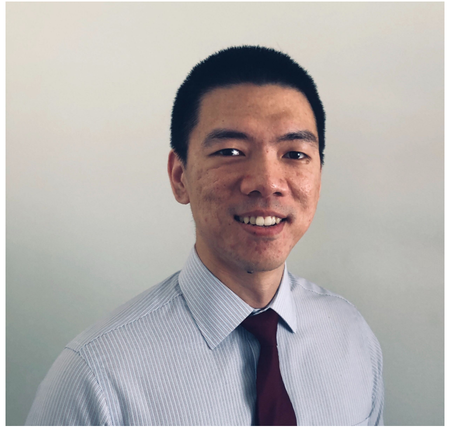


Weiyao Ke @ LANL

QGP properties vs scale/gradient

Fluid

mesoscopy???

parton gas

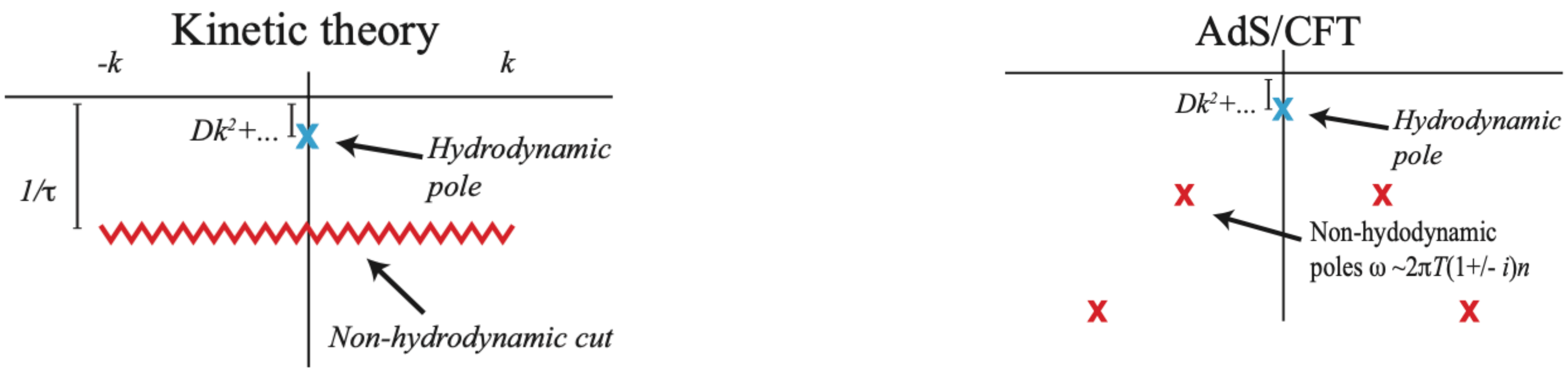
k

- 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.

    e.g. Eramo, Rajagopal and YY, JHEP 19; Hulcher's talk Tues.
  - Collectivity in small systems.

    works by Kurkela, Mazeliauskas, Wiedemann, Bin Wu, ….
  - This talk: medium response (how response changes with varying gradient).

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.

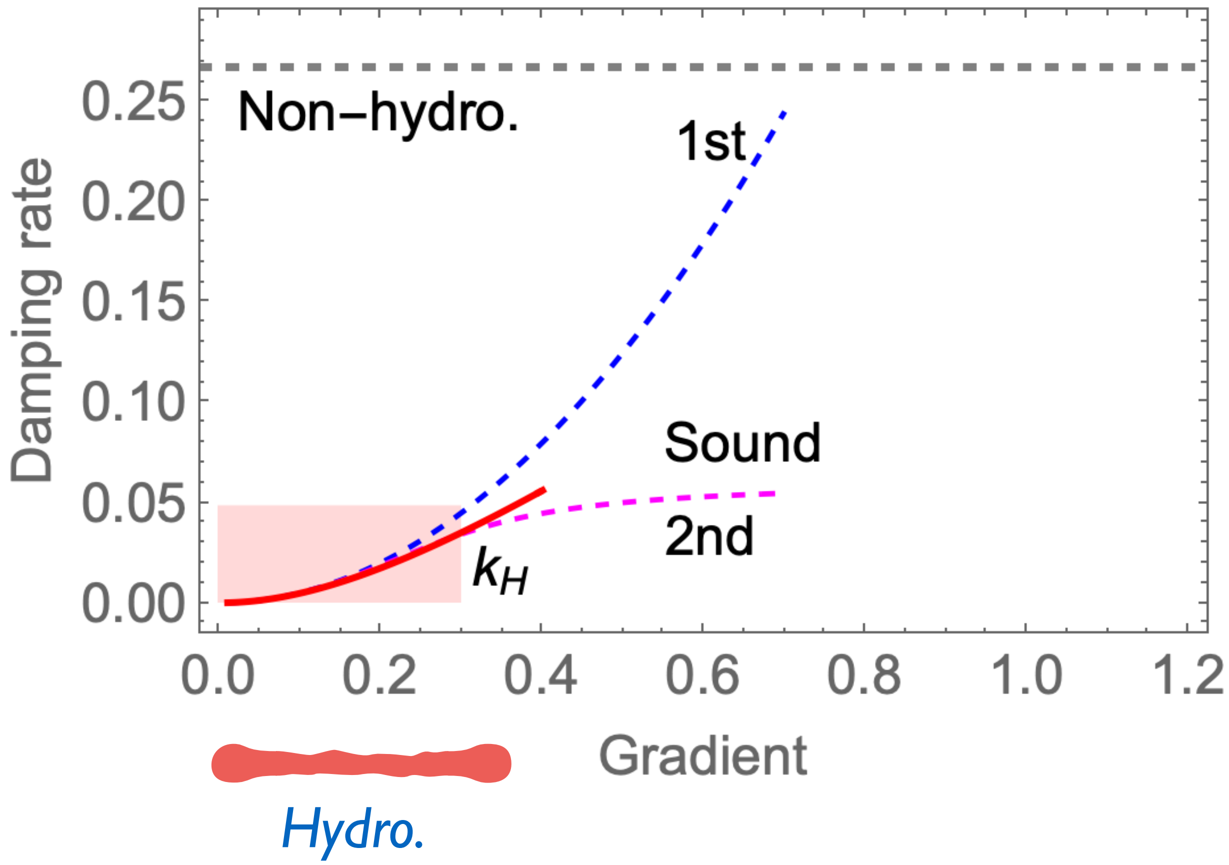
$$O(t, \overrightarrow{k}) = A_H e^{-i\Omega_H(k)t}\, e^{-\Gamma_H(k)t} + \text{other excitations}$$

hydro. modes

- In general, describing response is complicated as it involves various excitations.

- Simplification?

Hydro. regime



Relaxation time approximation (RTA) kinetic equation

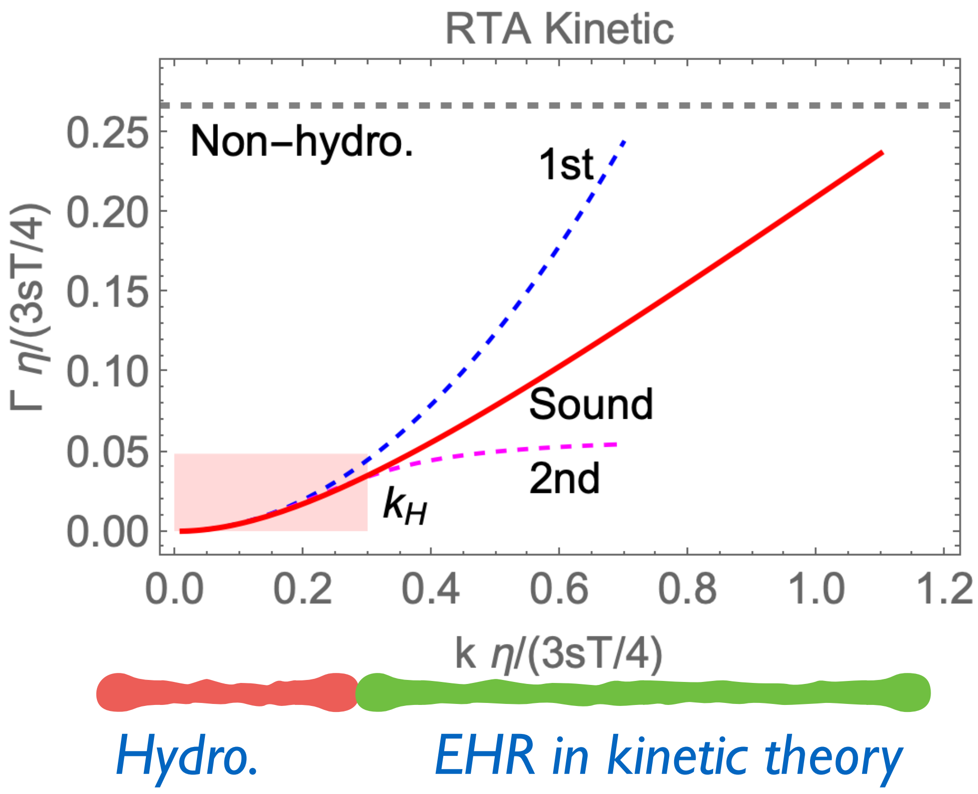
- At small k, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

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

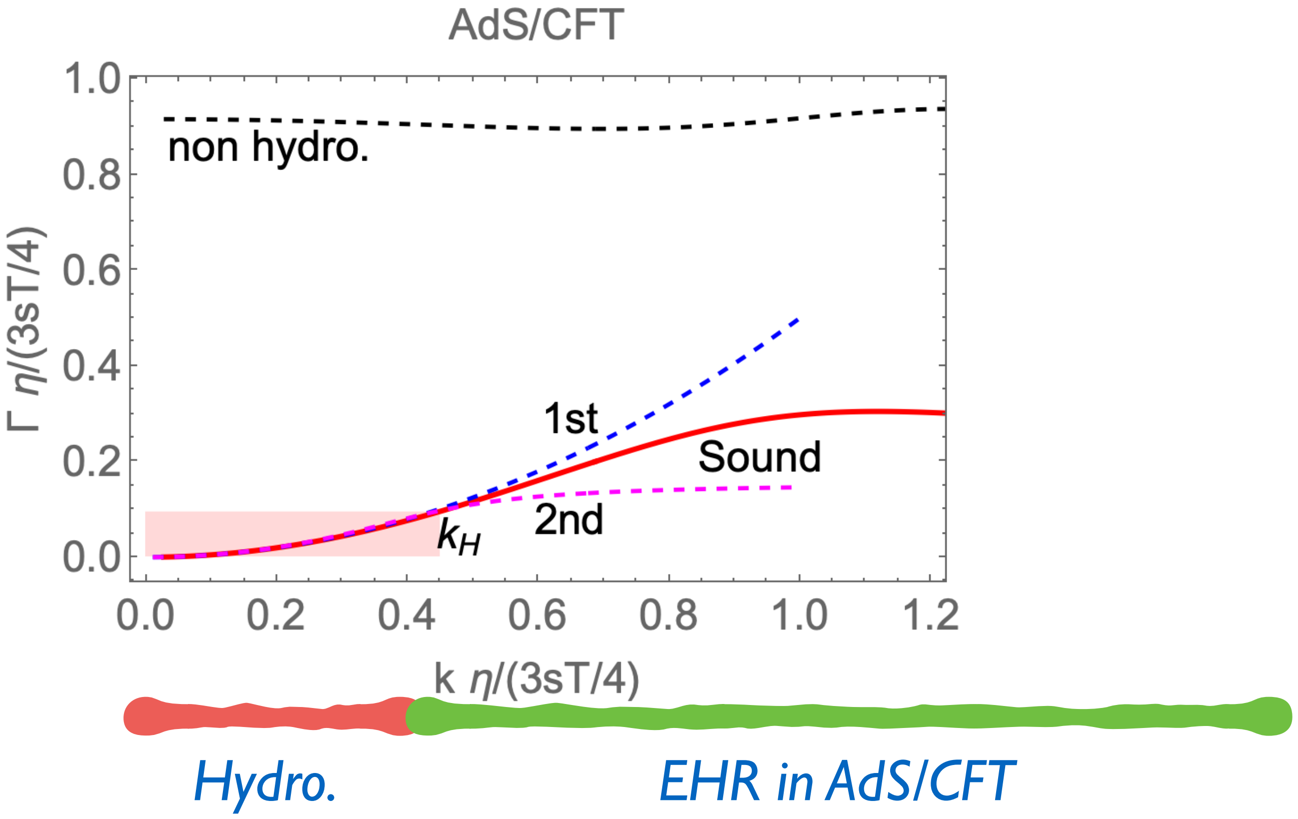
What happens when $k > k_H$?

Extended hydro. regime (EHR) in QGP-like systems

Romatschke, EPJC 16'.



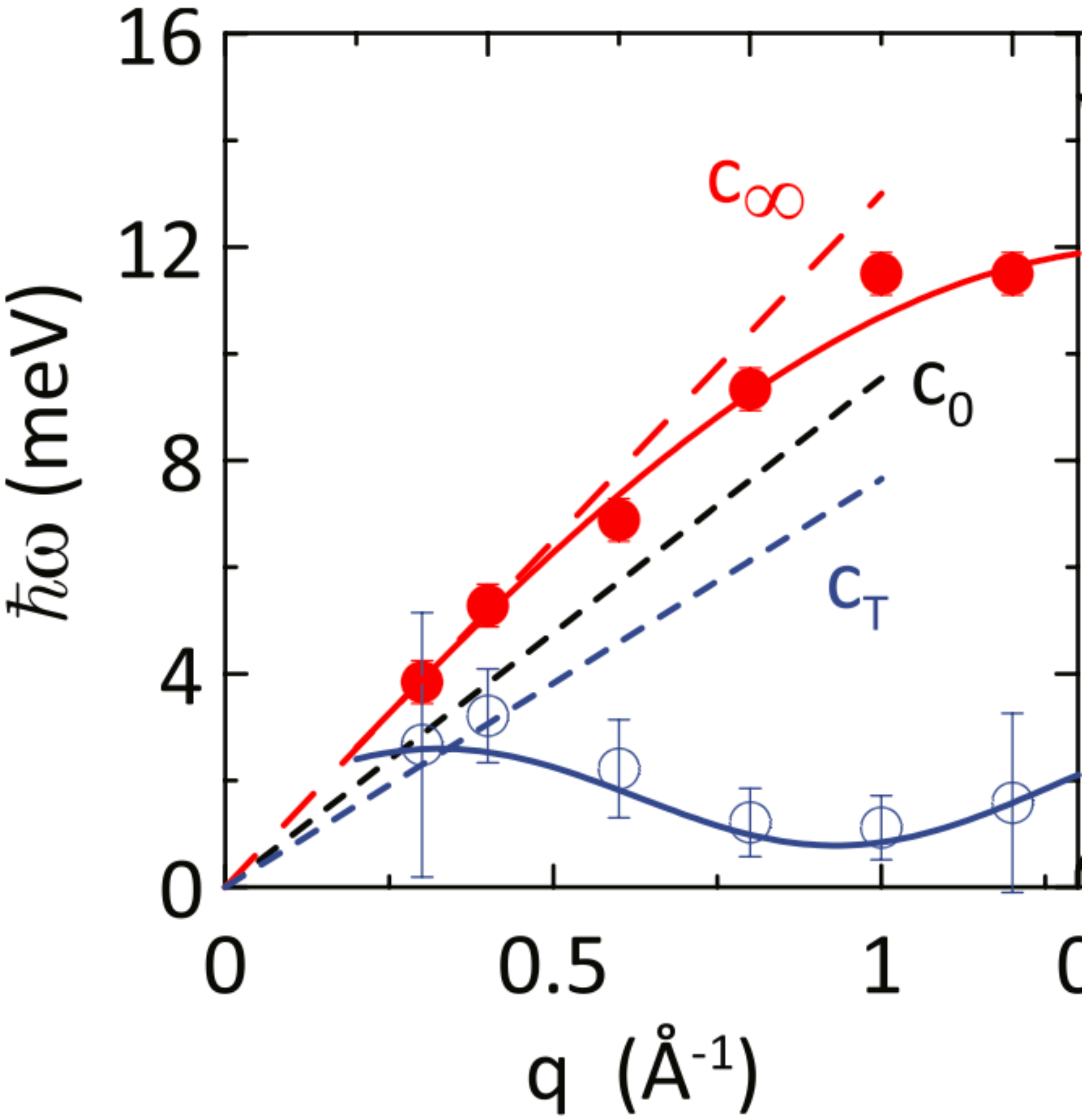
Amado-Hoyos-Landsteiner-Montero, JHEP 08



- Extended hydro. regime (EHR):
    - sound mode is gapped => "sound dominance";

      See our upcoming paper for the discussion of shear channel.
    - dispersion is different from vHydro.
- The presence of EHR seems generic. QGP?

Extended hydro. regime in solid liquids



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

The implication of EHR (if exists)

Fluid

mesoscopy

partons

k

Hydro.

Extended Hydro. Regime

- 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

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.


*EHR in MIS**

Hydro.

EHR in some microscopic theories

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

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

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

- MIS* (for a conformal system):

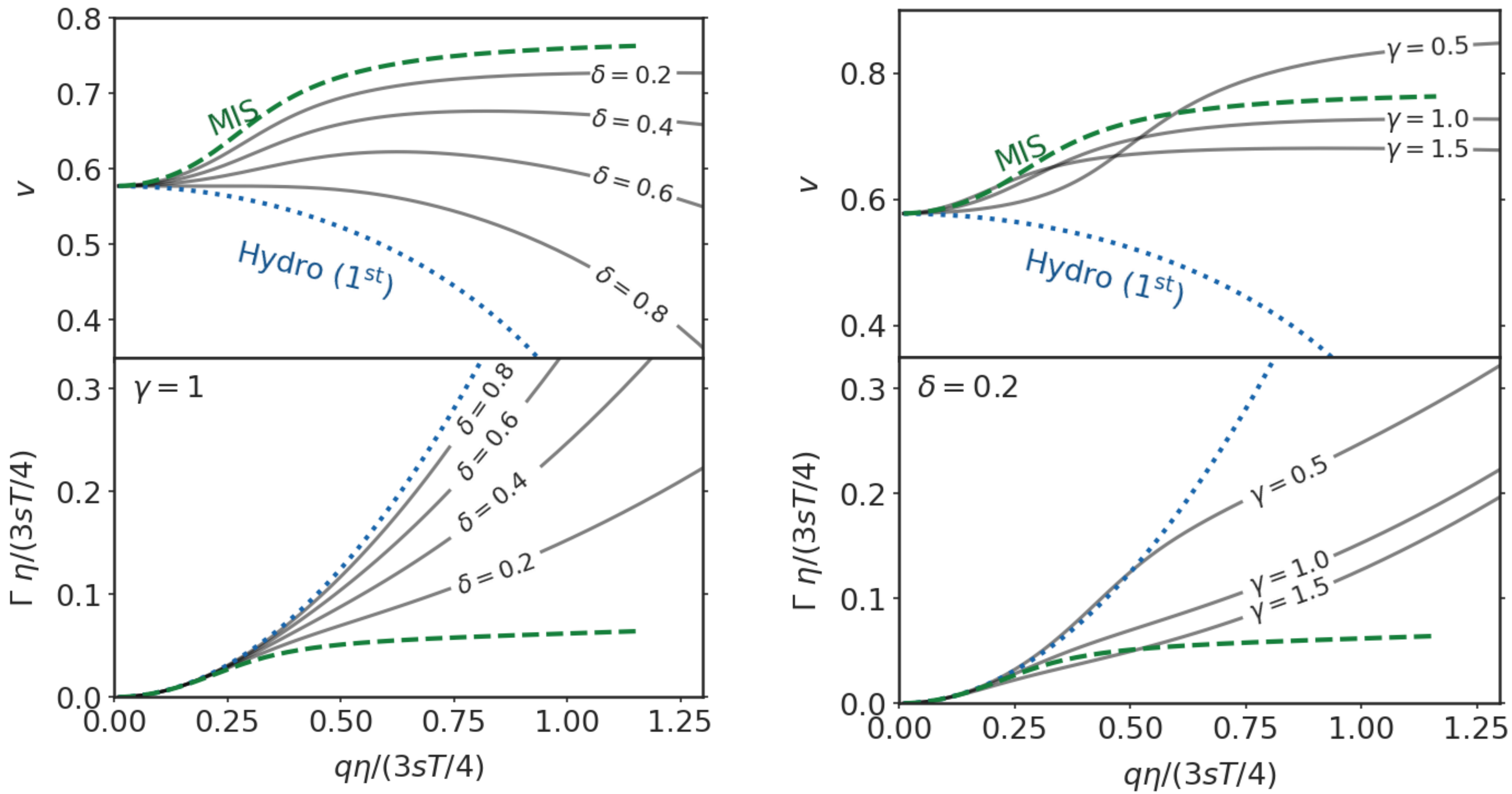
$$\boxed{\begin{aligned} \pi^{\mu\nu} &= -\eta'\partial^{<\mu}u^{\nu>} + \tilde{\pi}^{\mu\nu} \\ D\tilde{\pi}^{\mu\nu} &= -\frac{1}{\tau'_\pi}\left(\tilde{\pi}^{\mu\nu} + (\overset{\text{dynamical}}{\eta - \eta'})\partial^{<\mu}u^{\nu>}\right) - \ldots \end{aligned}}$$

- 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).

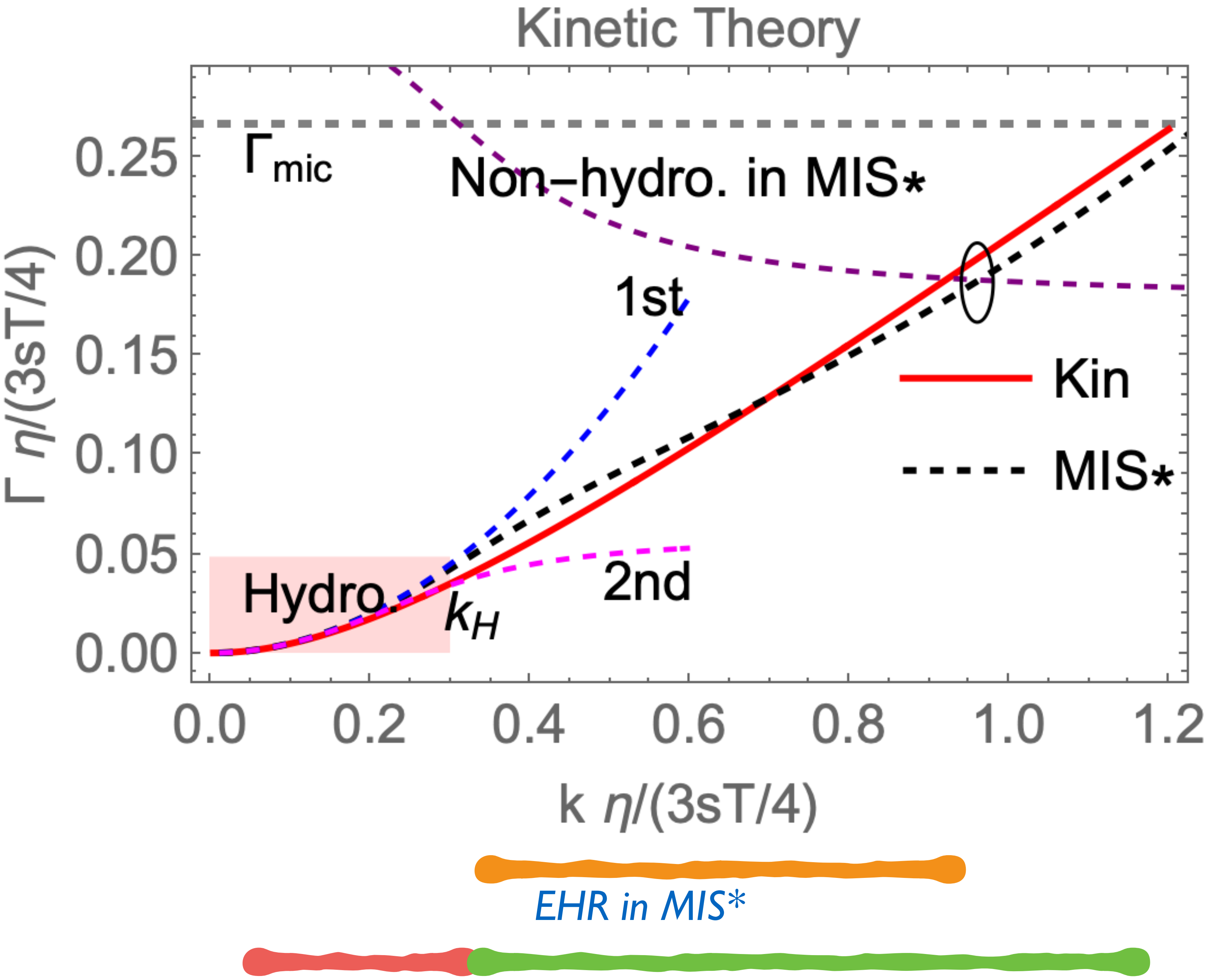
Flexibility/capability of MIS*



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

MIS* vs kinetic theory

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



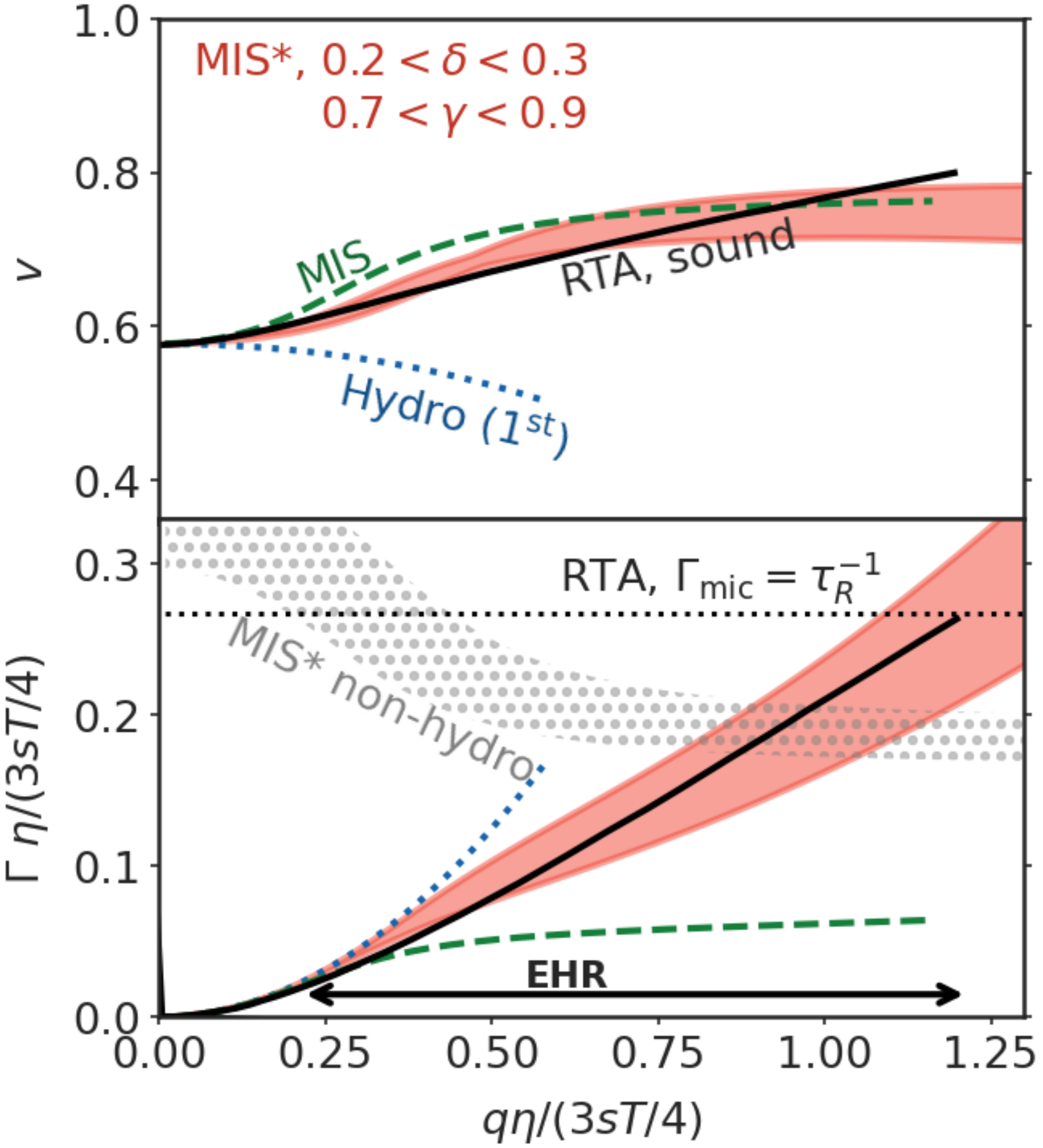
*EHR in MIS**

Hydro.

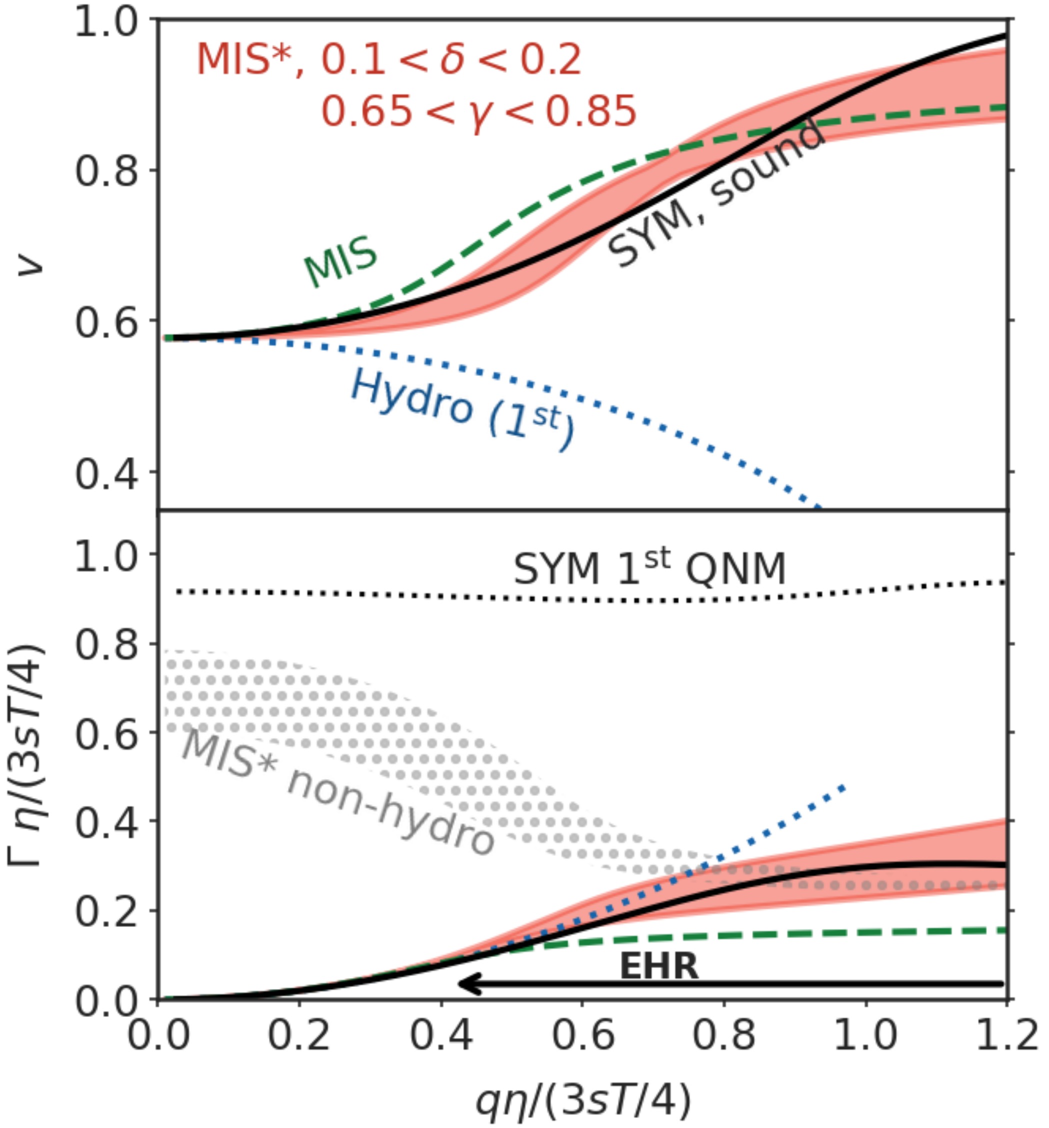
EHR in kinetic theory

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

RTA Kinetic.:



AdS/CFT



Hydro. *EHR in MIS**

Hydro. *EHR in MIS**

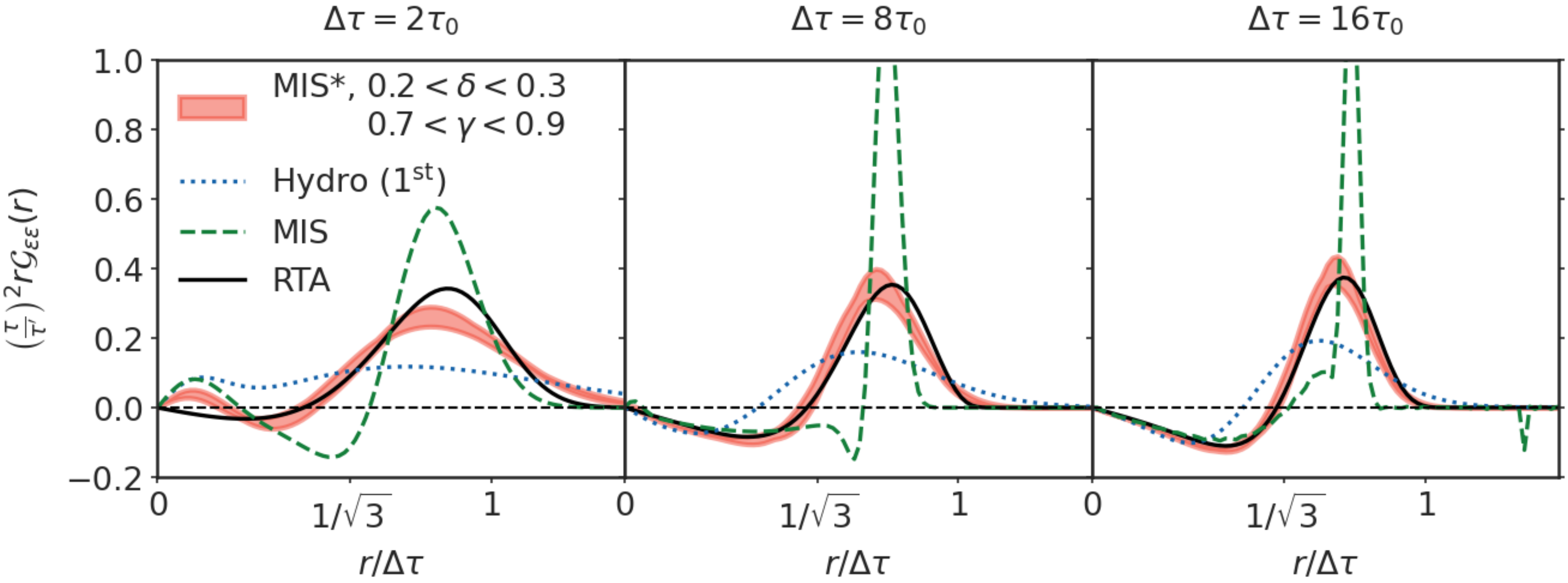
Extended hydro. response for Bjorken expanding plasma

- 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

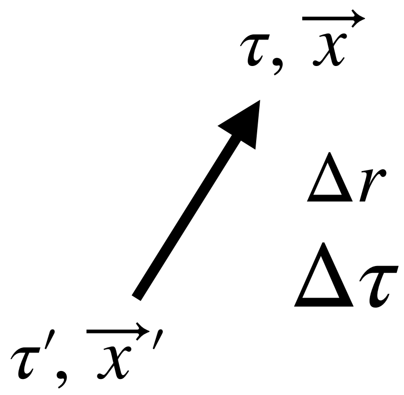
$$\delta\epsilon(\tau,x) = \int_{\tau_I}^{\tau} d\tau' \int_{x'} \underbrace{G_{\epsilon\epsilon}(\tau,\tau';x-x')}_{\text{response function}}\, \underbrace{S_{\epsilon}(\tau',x')}_{\text{Source}} + \ldots$$

RTA kinetic vs MIS*



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

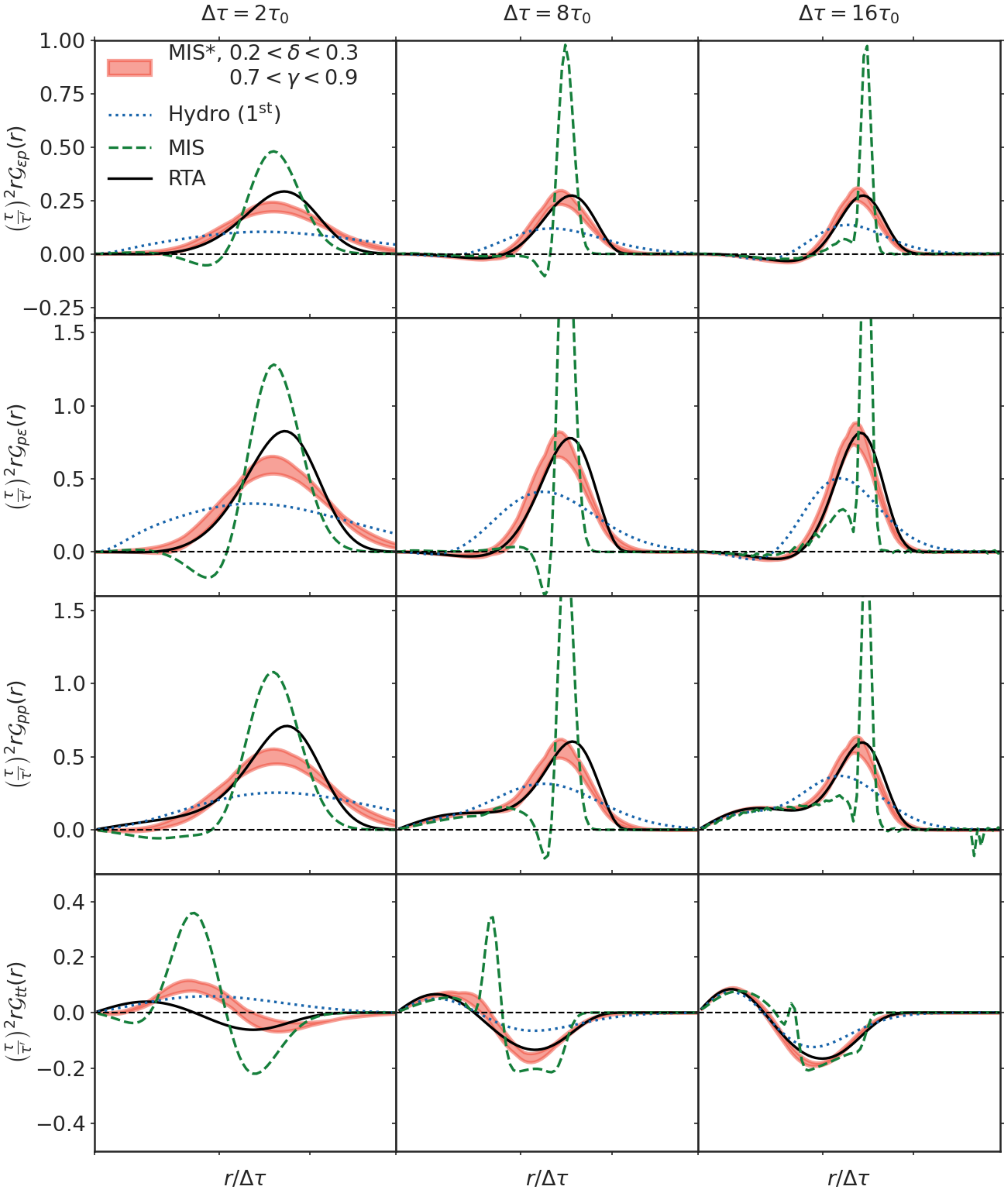
- MIS* describes extended hydro. response.



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

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

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



Discussion

Hydro.

(characterized by $\eta, c_s^2, \ldots$)

Extended Hydro. Regime

(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.

Summary and outlook


Fluid

mesoscopy

parton gas

k

hydro.

extended hydro. regime

- 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?

Back-up

Shear channel

The domain of EHR is relatively narrow in shear channel for both kinetic theory/holography.