# Does quark-gluon plasma feature an extended hydro. regime?
# (Collectivity outside hydro. regime)


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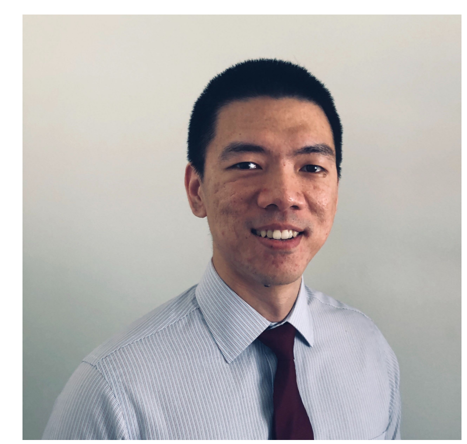
*Weiyao Ke and YY, PRL 2023 (2208.01046); and work in preparation*

**Initial Stages, Copenhagen, June. 21th, 2023**



*Weiyao Ke @ LANL*

# QGP properties vs scale/gradient

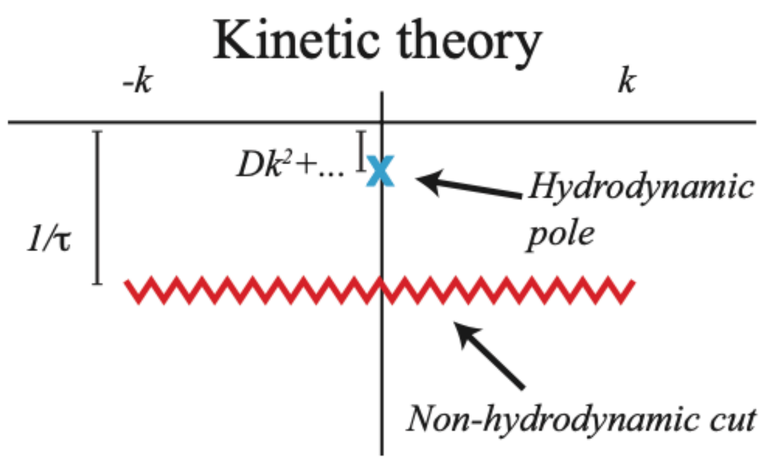

- Unexplored regime: QGP at mesoscopic scale where typical gradient k is too large for vHydro. and too short for pQCD.

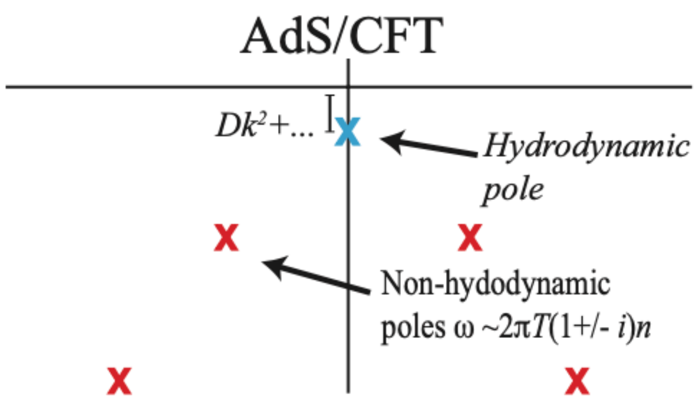
- Exploring QGP mesoscopy:
  - Large angle scattering between jet and the medium.
  - Collectivity in small systems.
  - This talk: medium response (how response changes with varying gradient).

*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.

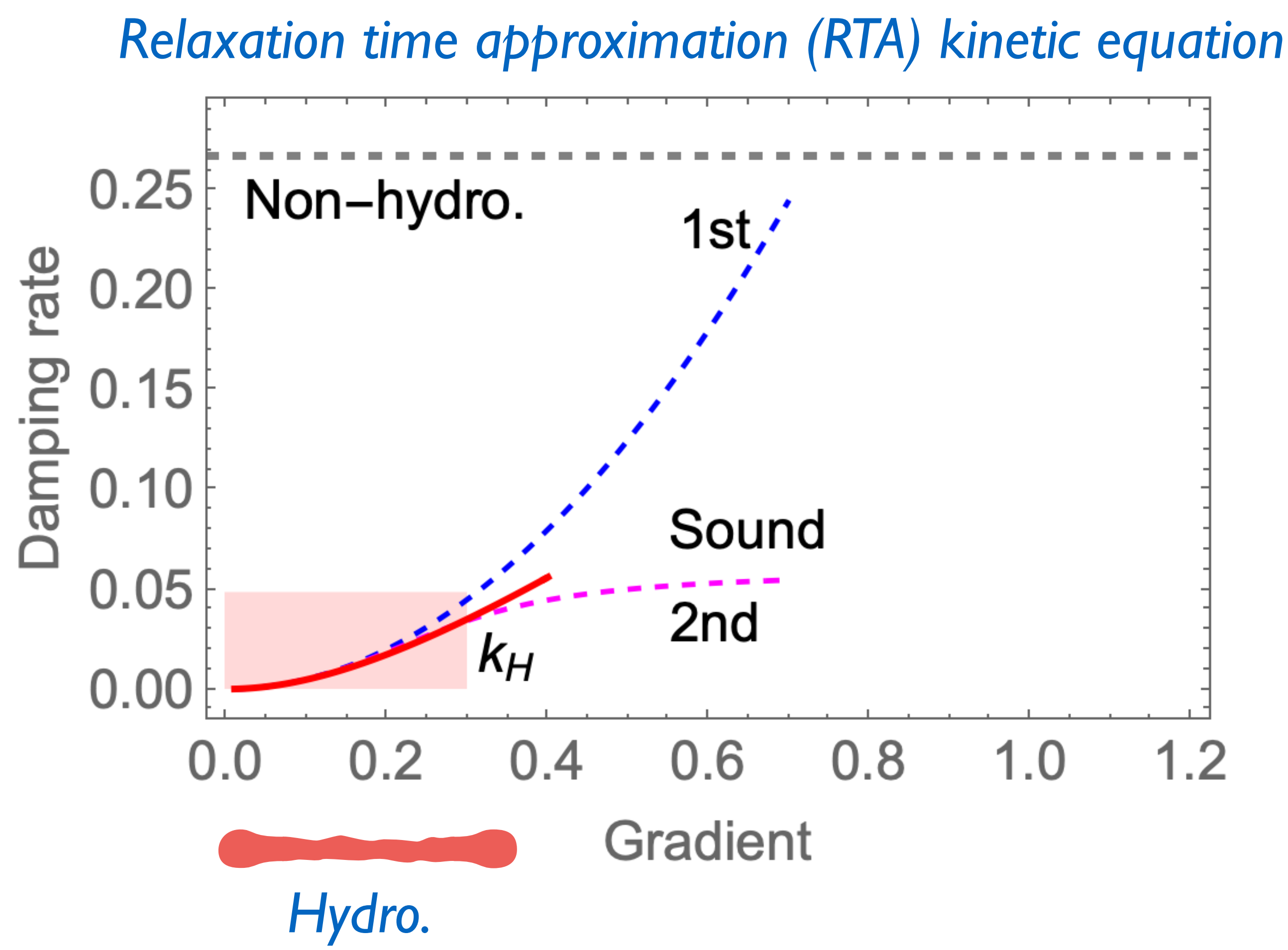
$$O(t,\vec{k}) = A_H e^{-i\Omega_H(k)t}\, e^{-\Gamma_H(k)t} + \text{other excitations}$$

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

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

- Simplification?

# Hydro. regime



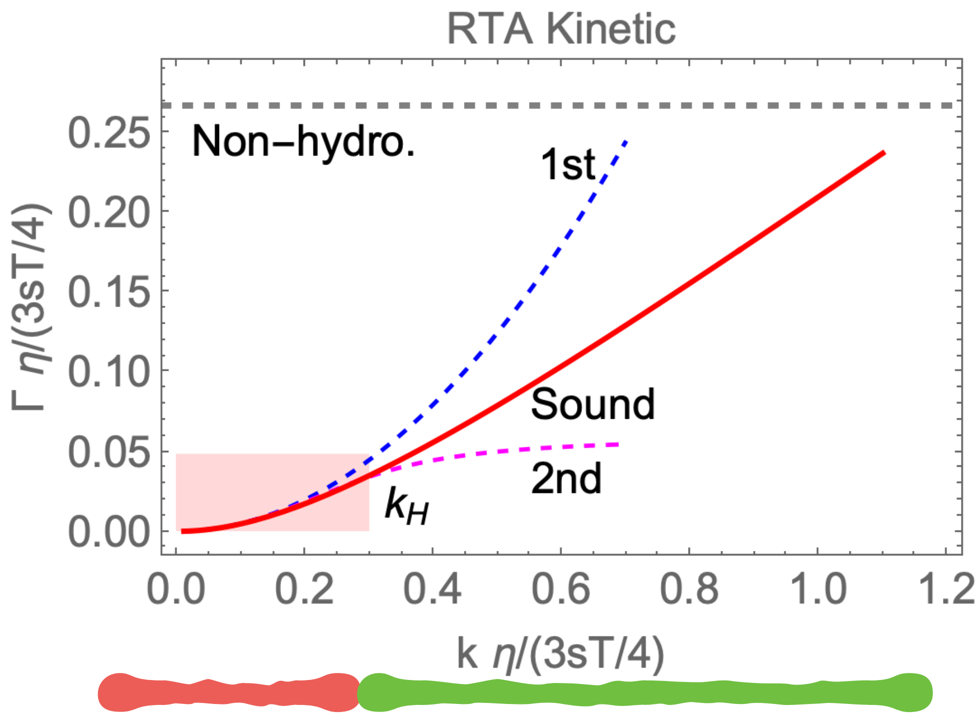

- At small $k$, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

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

*What happens when $k > k_H$ ?*

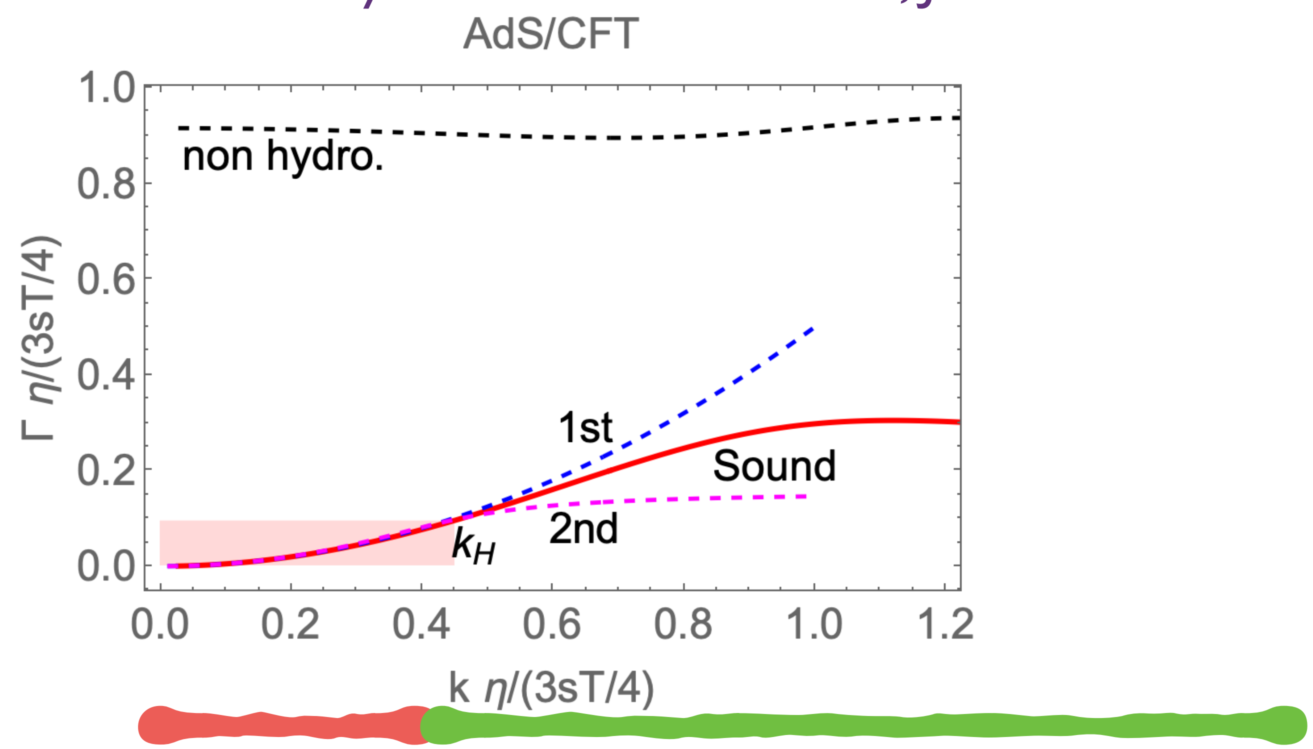
# QGP-like systems

*Romatschke, EPJC 16'.*




*Hydro.* *EHR in kinetic theory*

*Amado-Hoyos-Landsteiner-Montero, JHEP 08*



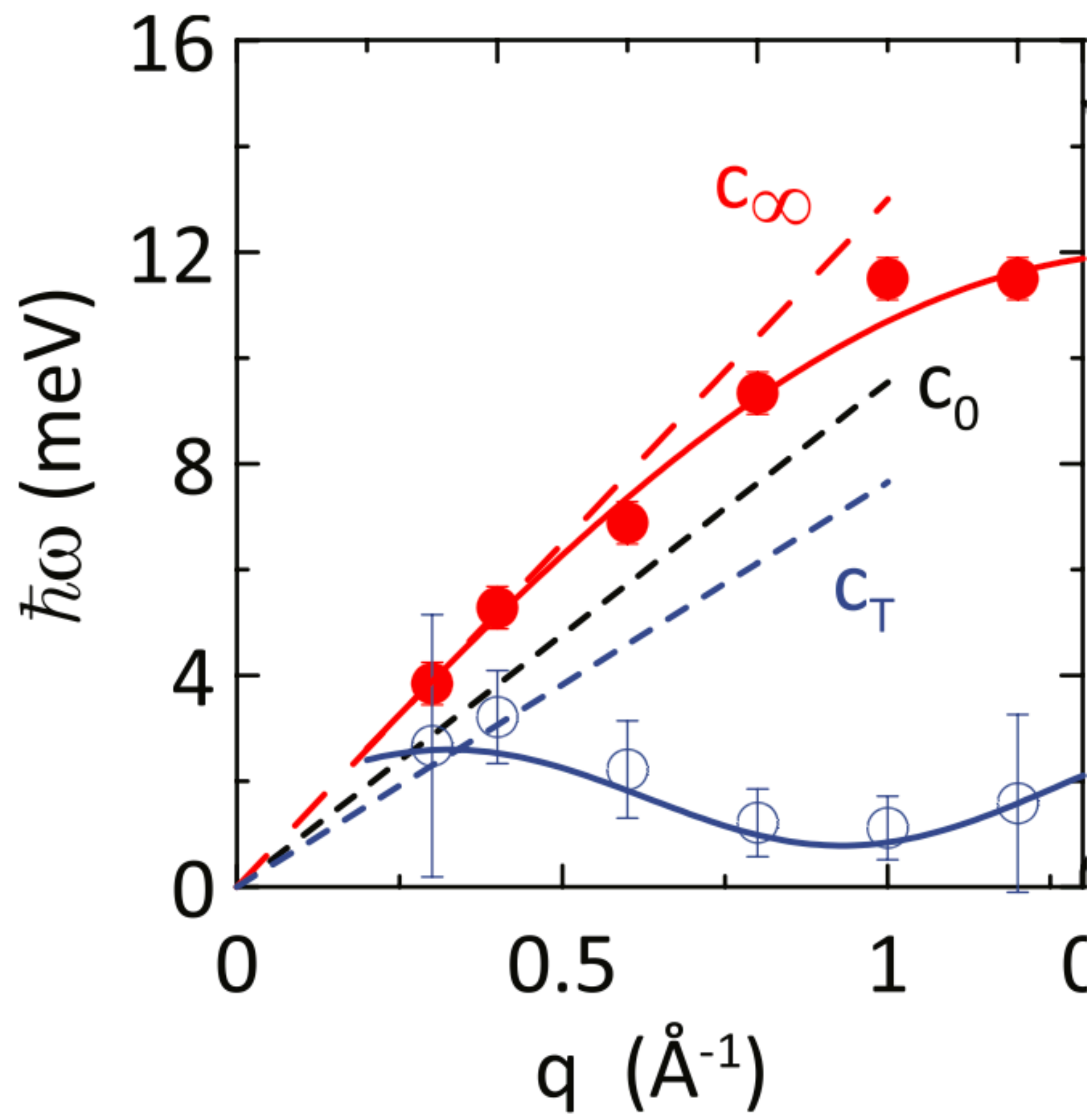

*Hydro.* *EHR in AdS/CFT*

- 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*

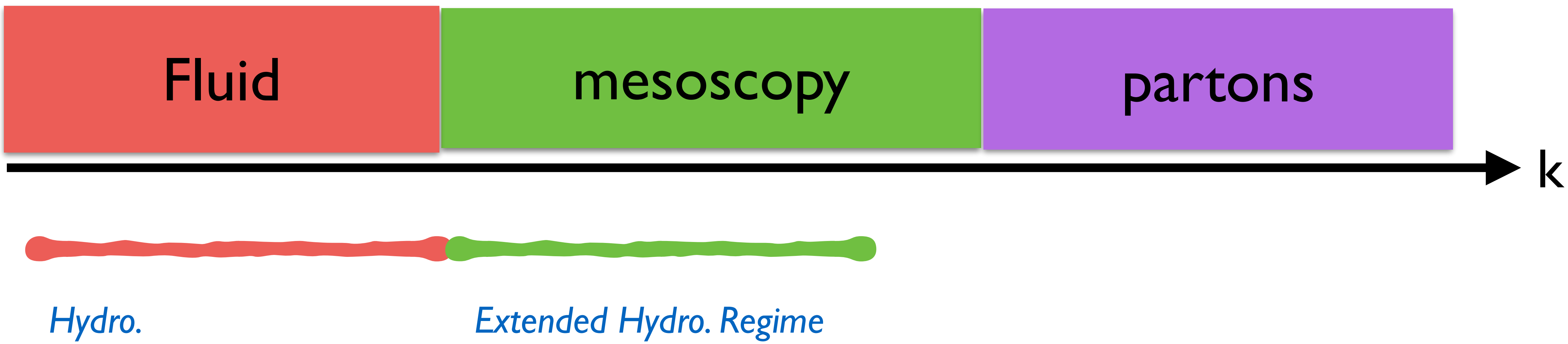
# *Extended hydro. regime in solid liquids*




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

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

- MIS* (for a conformal system):

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

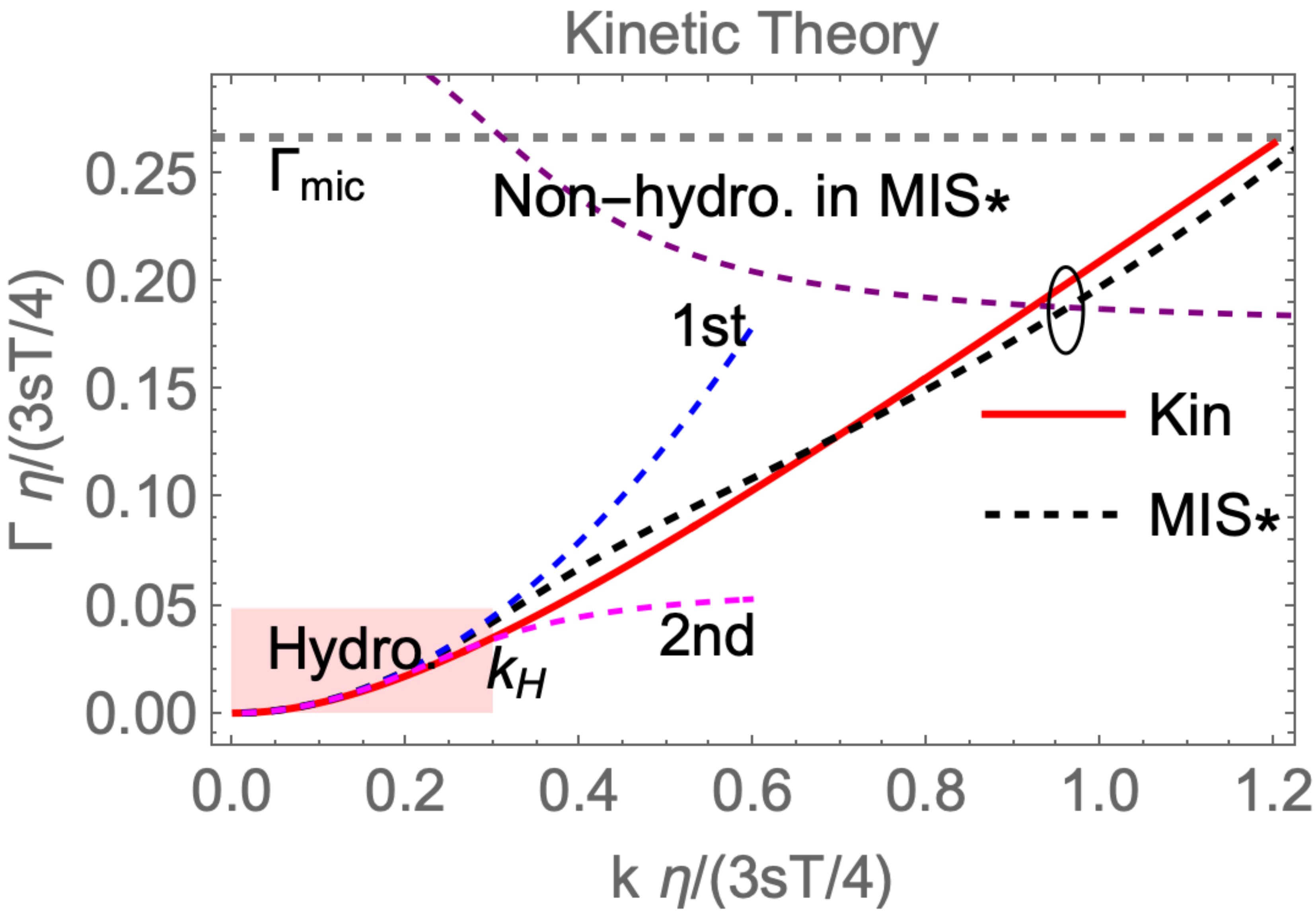
- MIS* parameters: $\eta' \sim$ the effective viscosity in EHR and $\tau'_\pi$ controls the boundary separating hydro. and EHR.

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

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

# MIS* vs kinetic theory

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




*EHR in MIS**

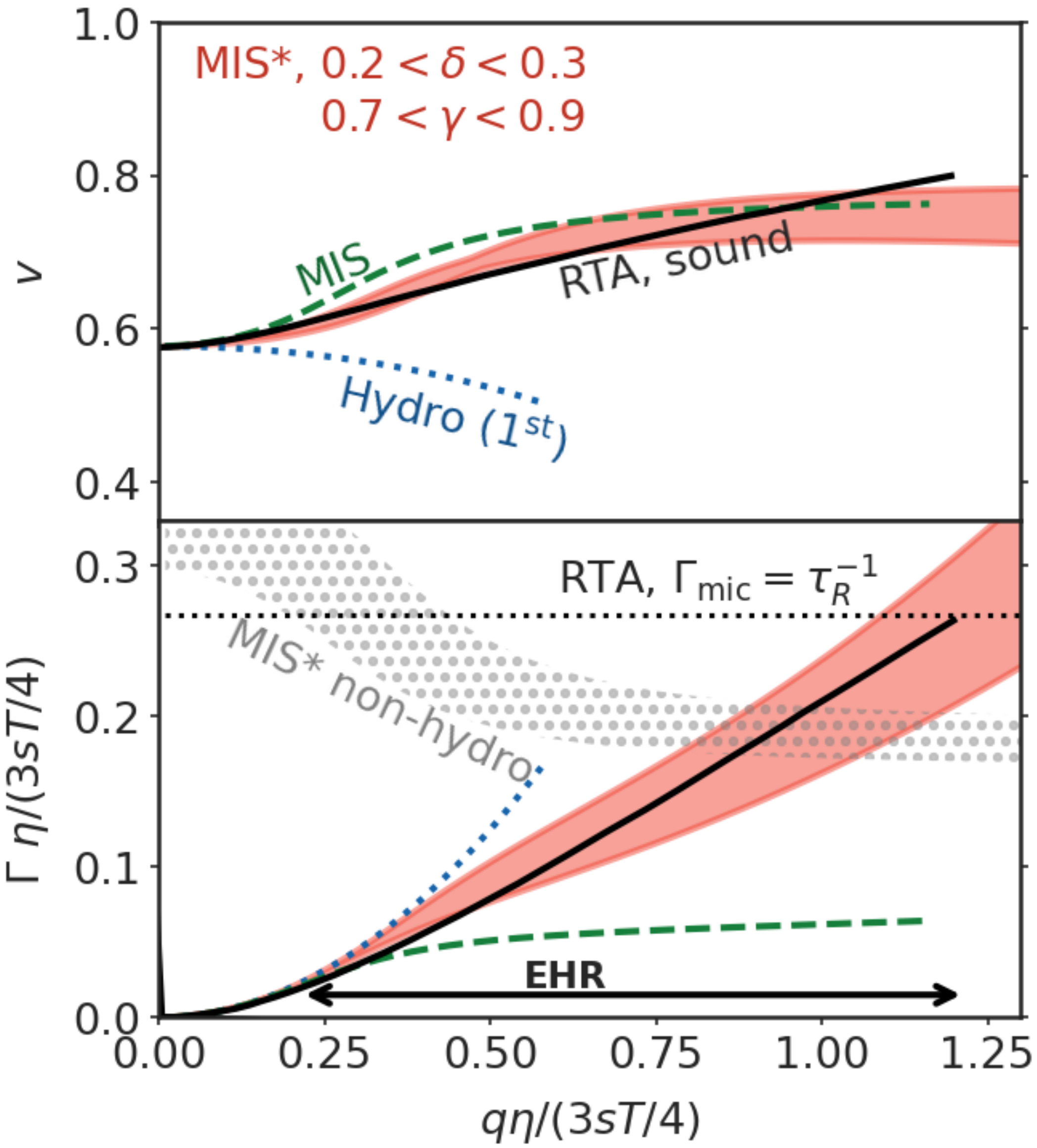
*Hydro.*

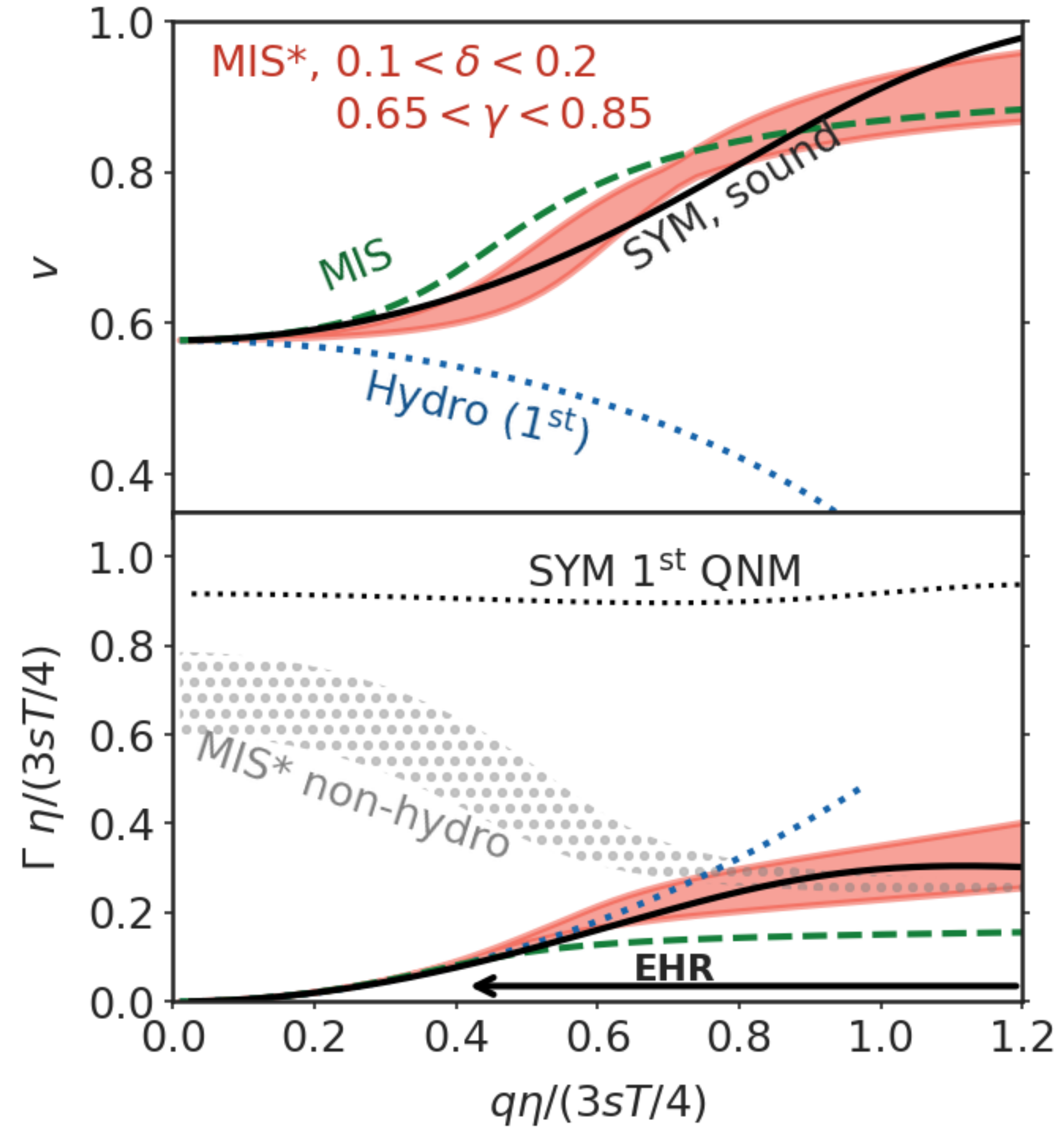
*EHR in kinetic theory*

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

RTA Kinetic.

AdS/CFT




*Hydro.* *EHR in MIS**

*Hydro.* *EHR in MIS**

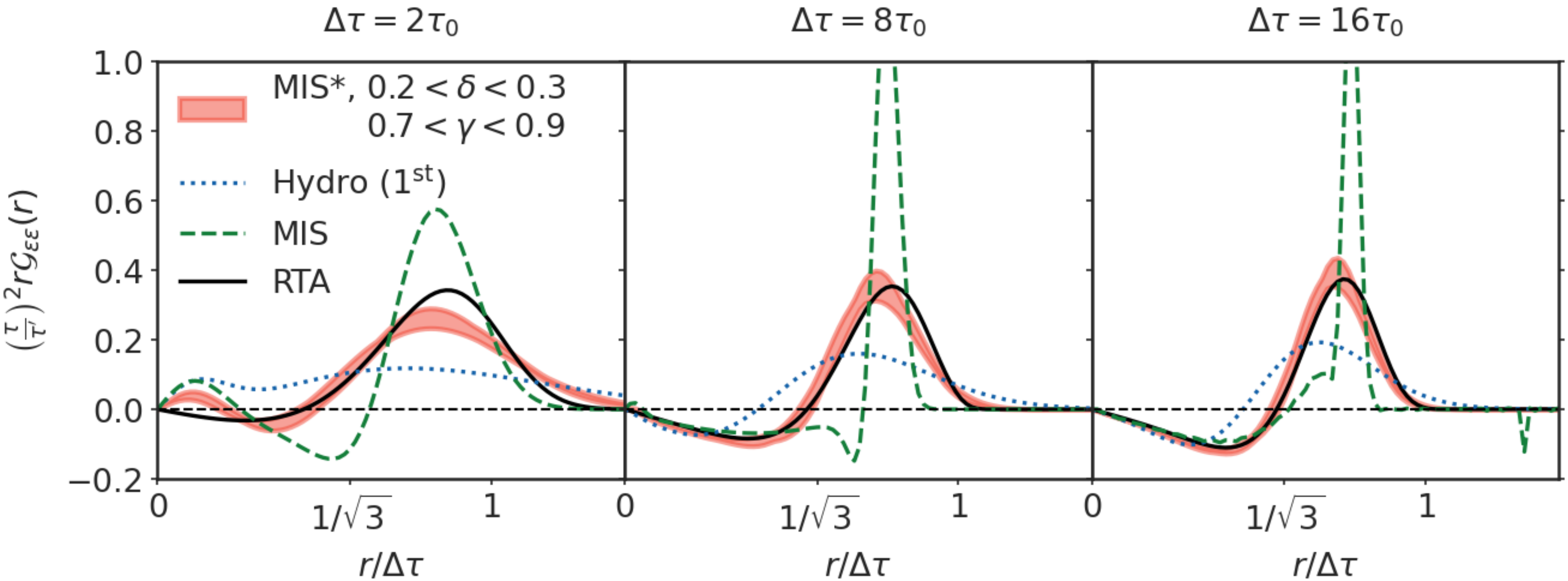
## Extended hydro. response for Bjorken expanding plasma

- 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.

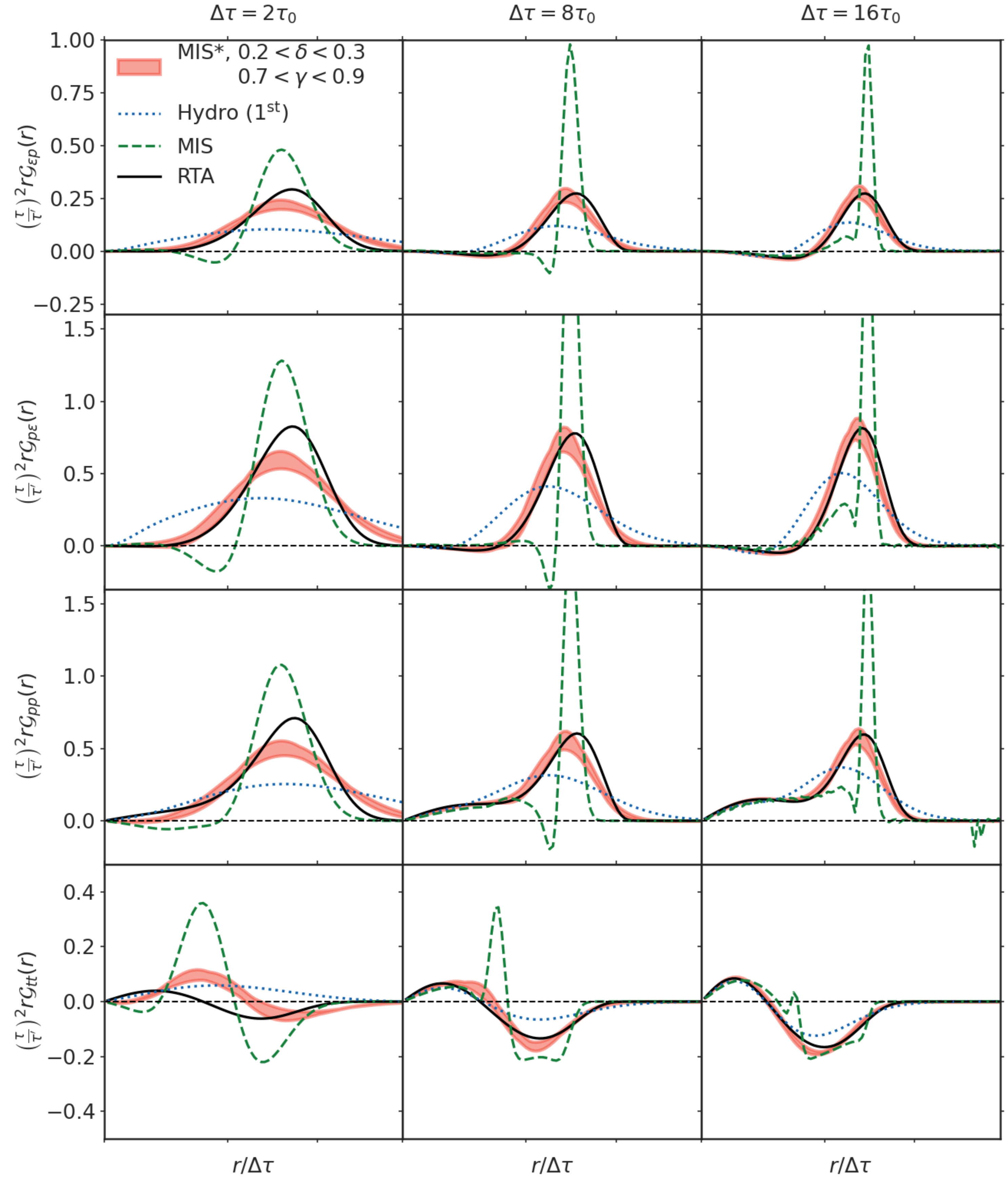
$\tau, \vec{x}$

$\tau', \vec{x}'$

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

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

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

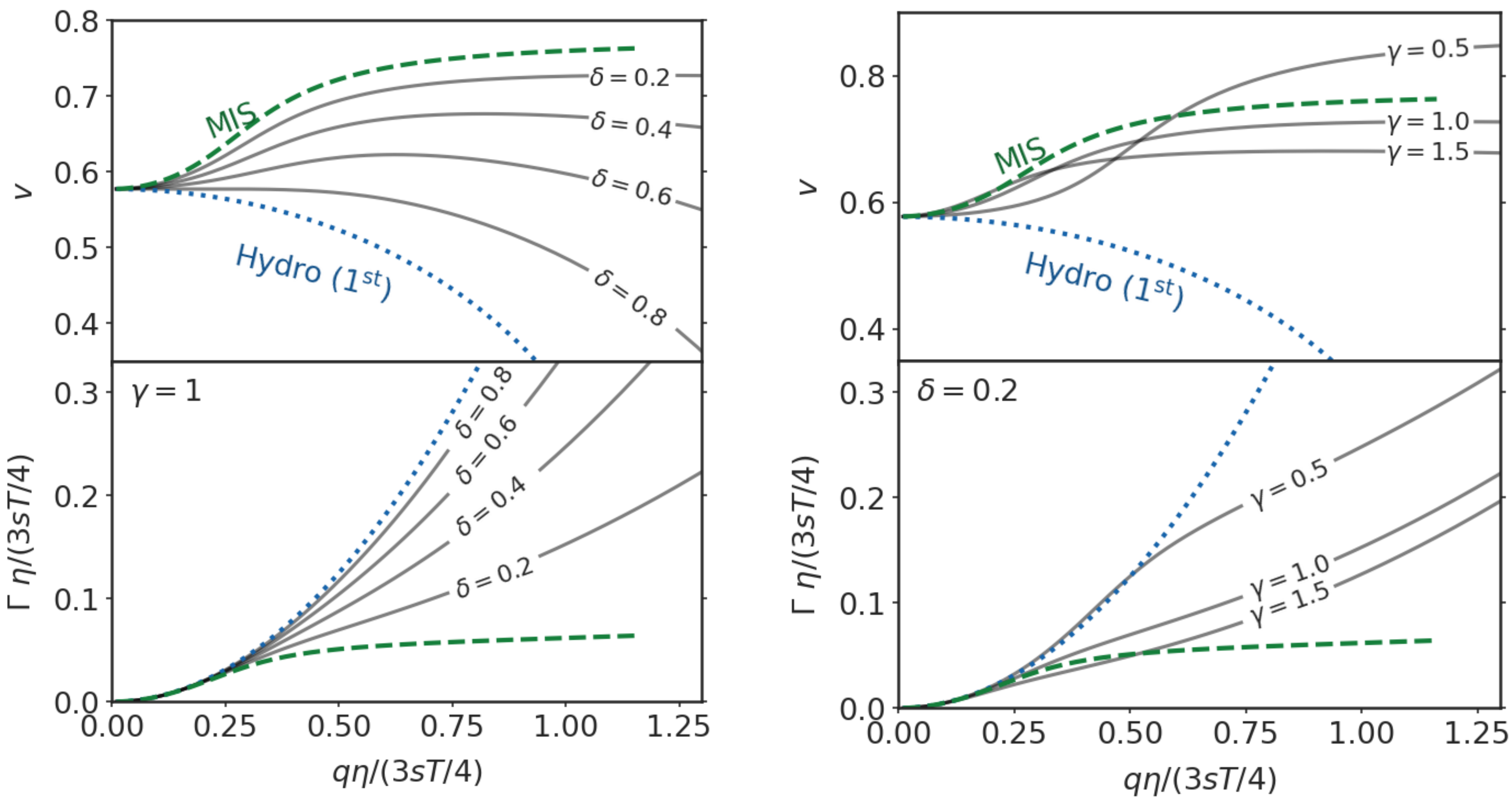


## Summary and outlook


- 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?
- The signature of EHR in Euclidean lattice correlator?
- Extension of hydro. based on “sound mode dominance”.

# Back-up

## *Flexibility/capability of MIS**




- Increasing δ=$\eta'/\eta$ increases damping rate.
- $(\gamma, \delta\ )$ 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'*