Hot QCD matter at the intermediate scale and lattice

1. Intro.

2. An illustrative example: energy-momentum correlator

Yi Yin

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

Institute of Modern Physic, CAS

Lattice QCD China, Oct. 8th, 2023

Weiyao Ke @ LANL -> CCNU

Quark-gluon plasma (QGP)

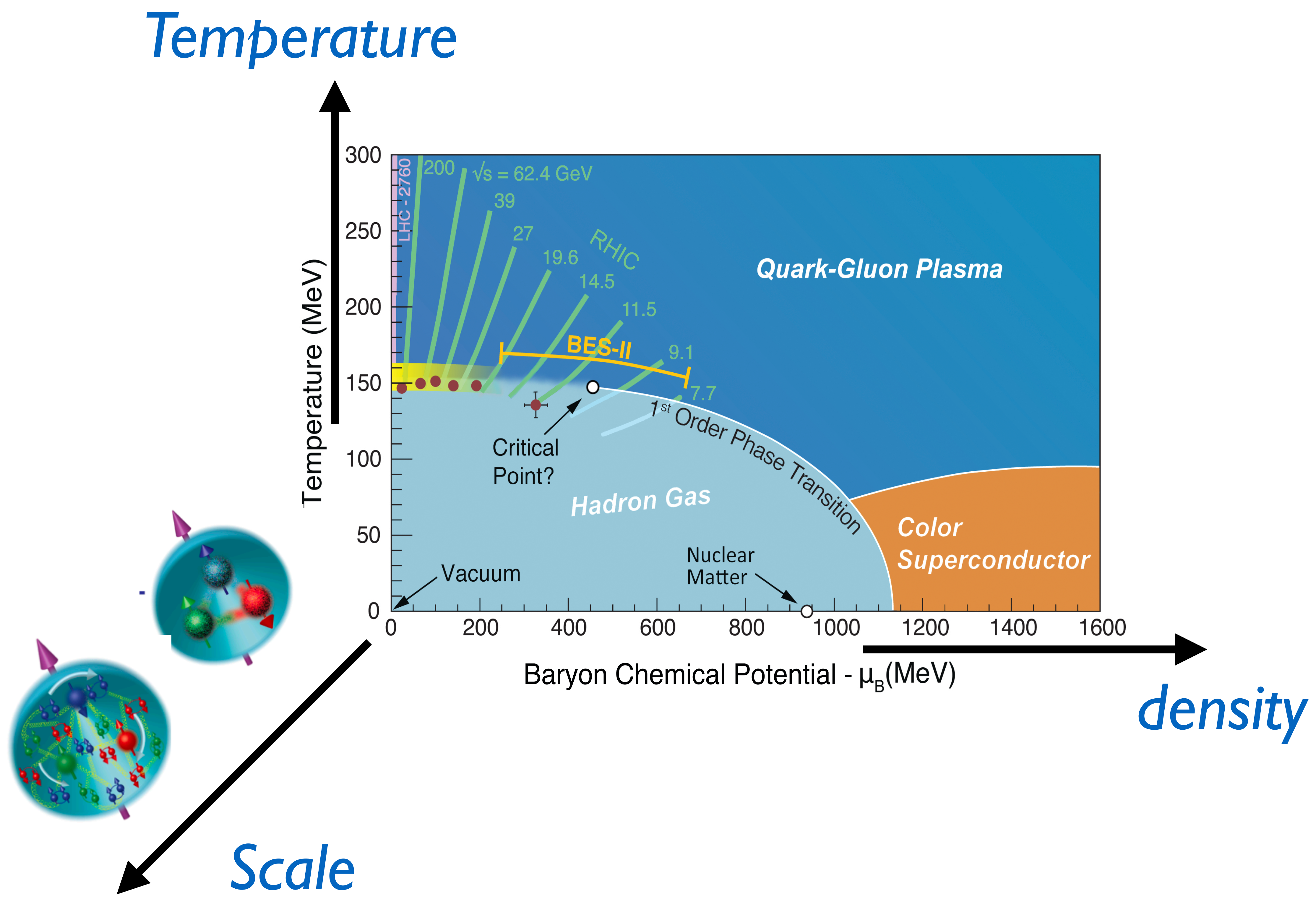
- The de-confined thermal state of QCD; recreated by heavy-ion collisions.
- To date, significant advances in studying QGP.
- Extraordinarily small specific shear viscosity (a measure of dissipation for propagating energy/momentum in a medium):

$$\frac{\eta}{s} \sim \frac{1}{4\pi}$$

  - extracted from data-model comparison, consistent with lattice estimate.
  - this small value is close to that of some gauge theories in strong coupling limit, indicating de-confined partons are not free, but move coherently.

What next?

- Baryon-rich QCD matter and the QCD critical point .
- Quantum and topological aspects of QCD matter (e.g. spin observables).



- Personal view
  - We shall heavily rely on data from “lattice experiment”. (RHIC is shutdown around 25’)
  - It is time to interface with the QCD vacuum study. (Heavy-ion collisions program was originally motivated by understanding the confined state of QCD.)

How does the properties of asymptotic free QGP changes with varying (temporal/spatial) scale? Can medium feature exotic excitations?

Least-explored and crucial regime: QGP at intermediate scale

- By decreasing scale, can we see
  - the transitions from perturbative to non-perturbative regime?
  - the emergence of collective modes from quasi-particles?
  - new features at non-hydro scale?
- Given $k_H \sim \pi T$: thermal lattice correlator is sensitive to real-time dynamics at non-hydro regime $\omega, k \geq 2\pi T$.

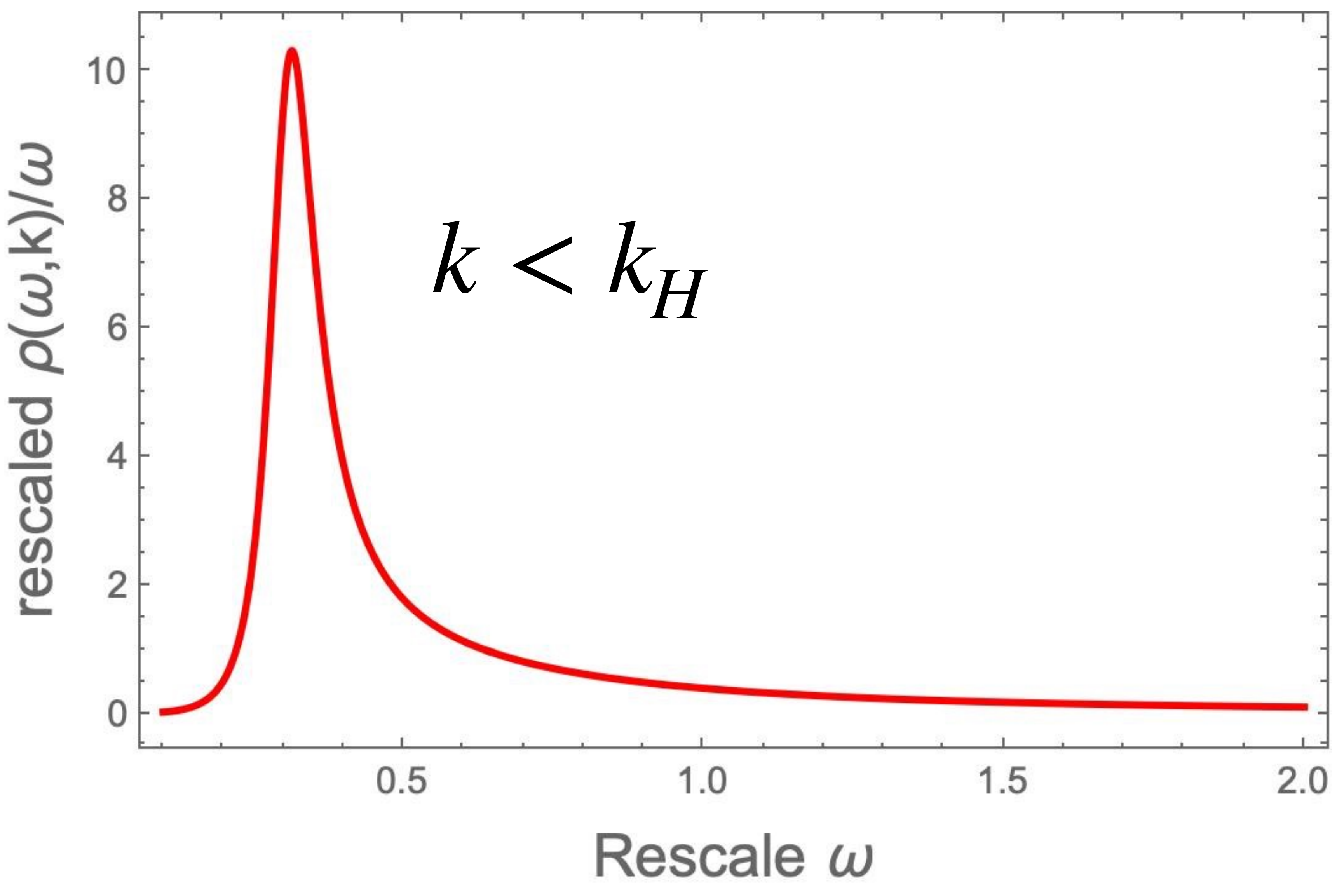
Energy-momentum correlator as an illustrative example

EMT correlators

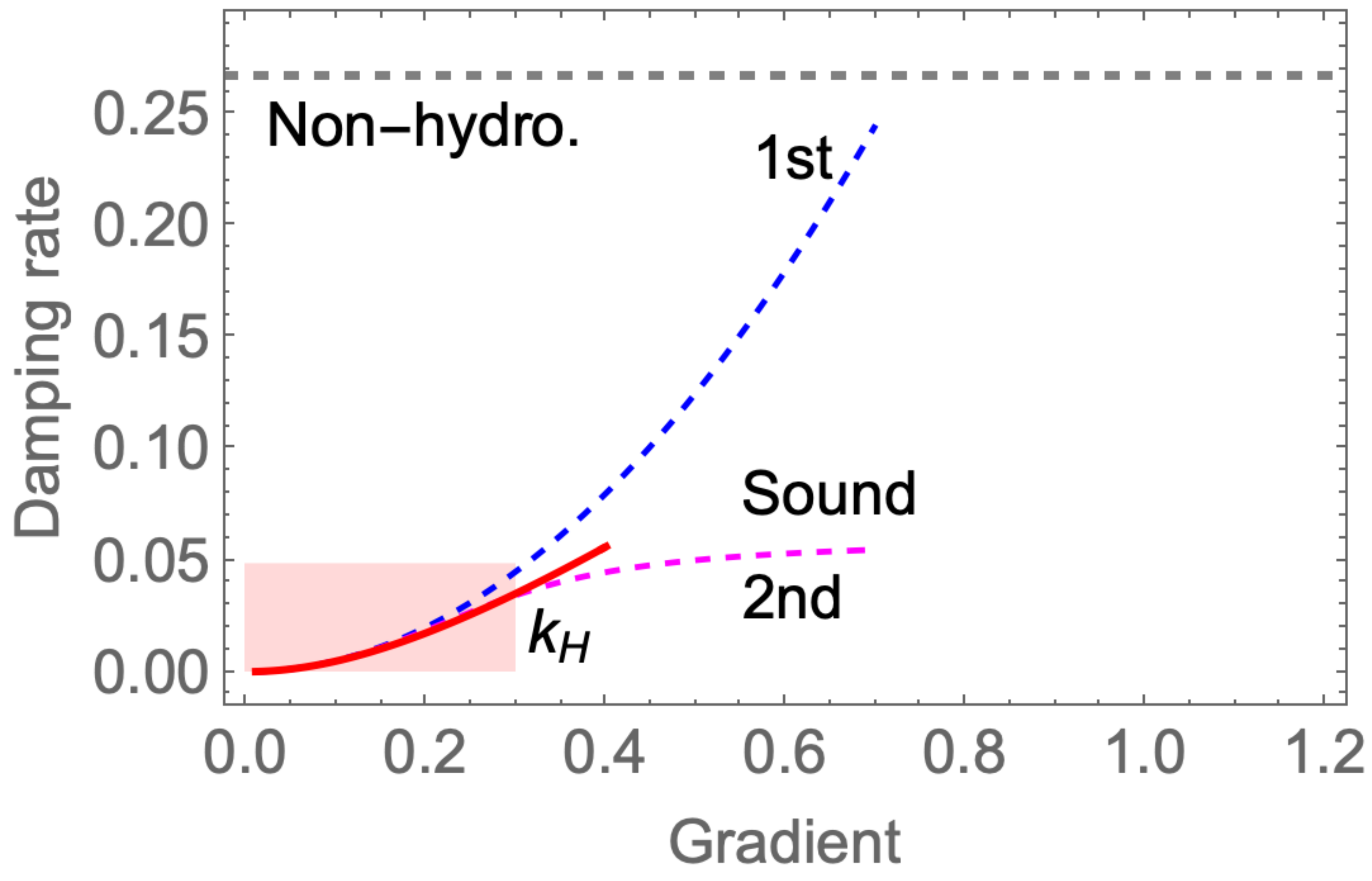
$$G_R^{\mu\nu,\alpha\beta}(\omega,q) \sim \langle T^{\mu\nu}T^{\alpha\beta}\rangle \qquad \rho \propto \mathrm{Im}G$$

- describing the correlation, propagation, dissipation of energy/momemtum density disturbance.
- having non-analytic structure in complex frequency plane: pole (collective modes); branch-cuts (quasi-particle excitations)
- its imaginary part $\rho(\omega,q) \sim \mathrm{Im}G(\omega,q)$, called spectral density, may feature peak associated with collective modes.
- the structure is generally complicated as it involves various excitations. Characterizations?

Hydro. regime



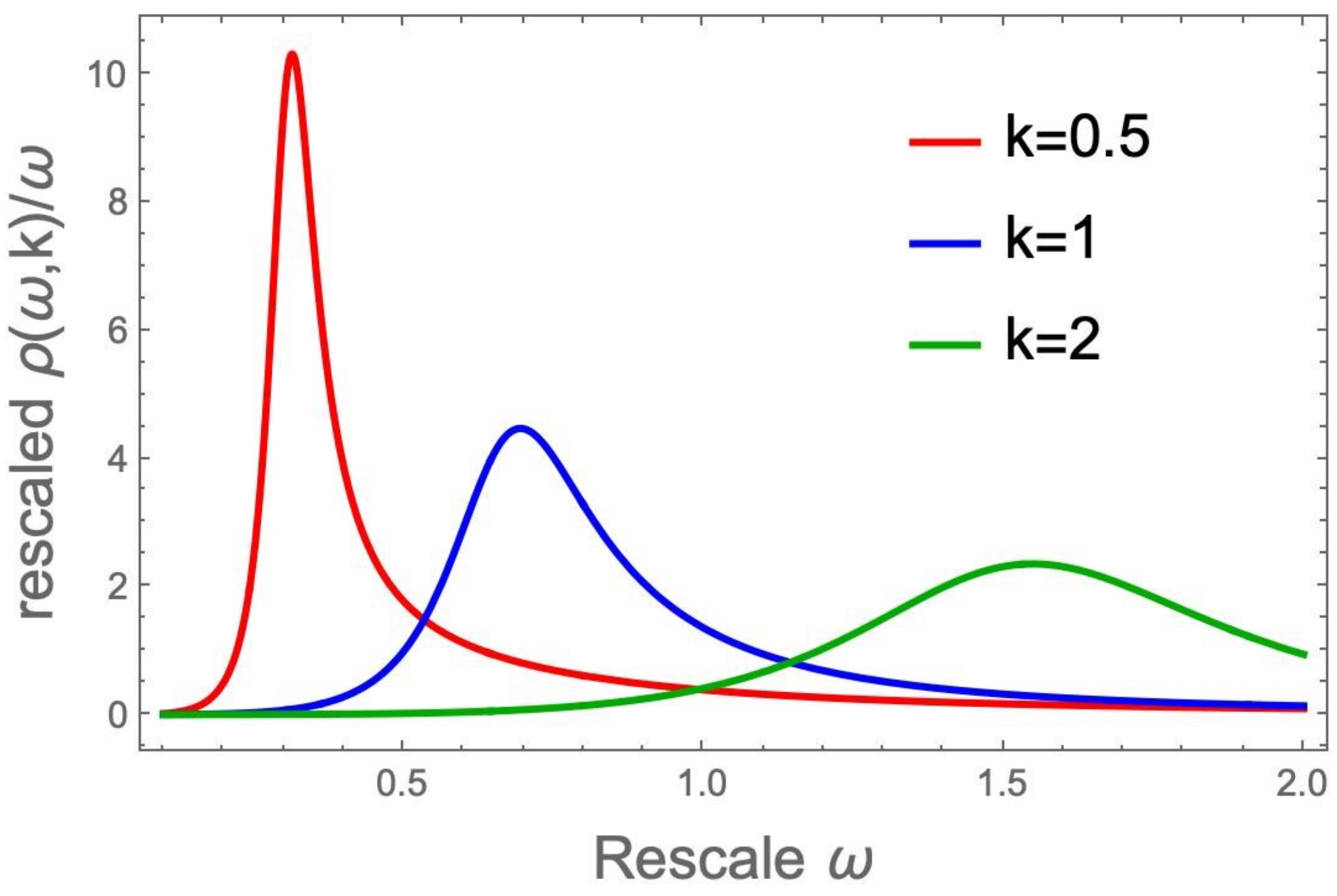
computed from Relaxation time approximation (RTA) kinetic equation (representing weakly-coupled gauge theories)

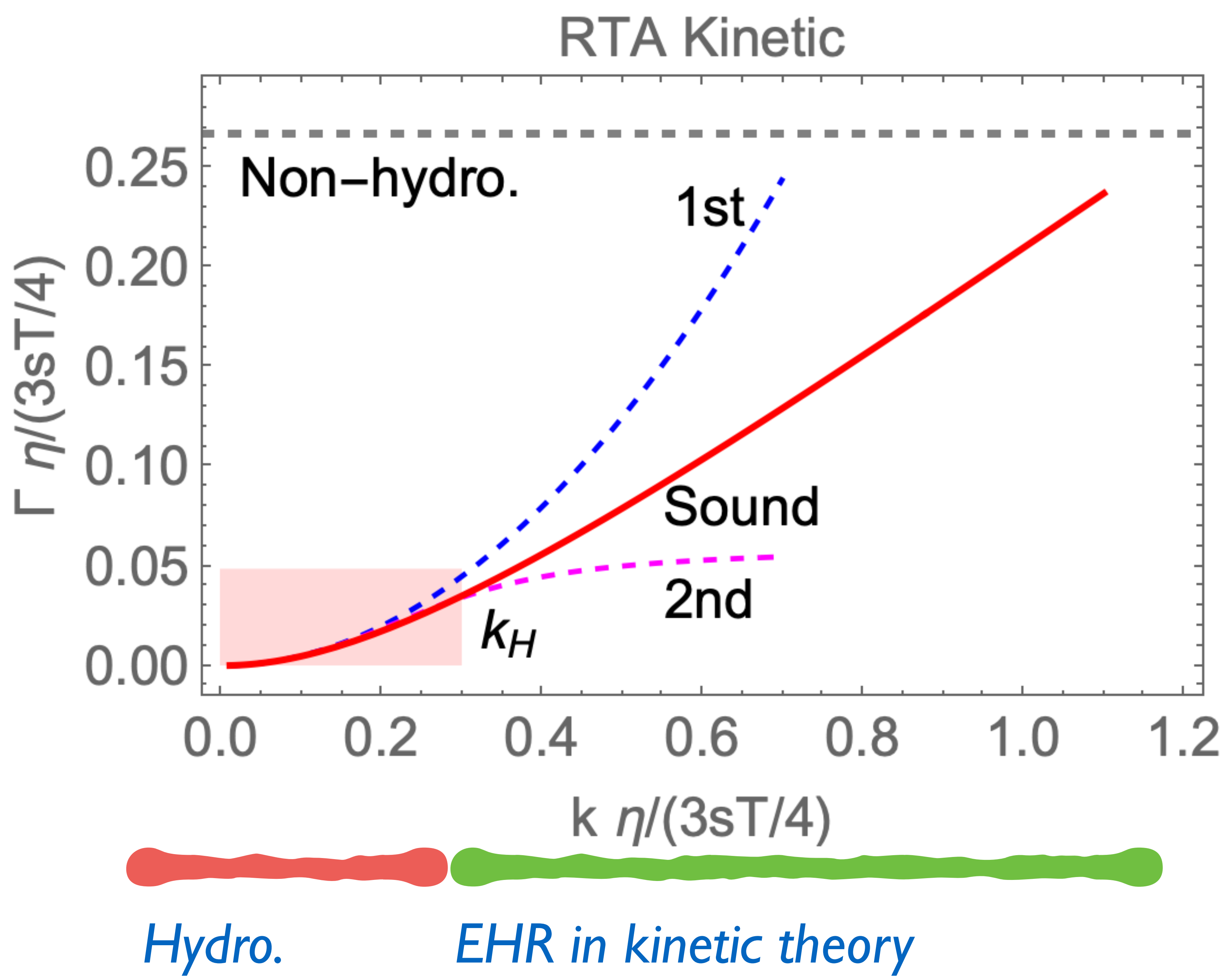


Attenuation rate of sound mode ($\omega = c_s k - i\Gamma k^2$)

- Focus on energy-density channel. $\rho(\omega, k)$ at $k < k_H$ features a sound peak.
  - Peak location ~ sound velocity c_s .
  - Width ~ viscosity .

Beyond hydro. regime





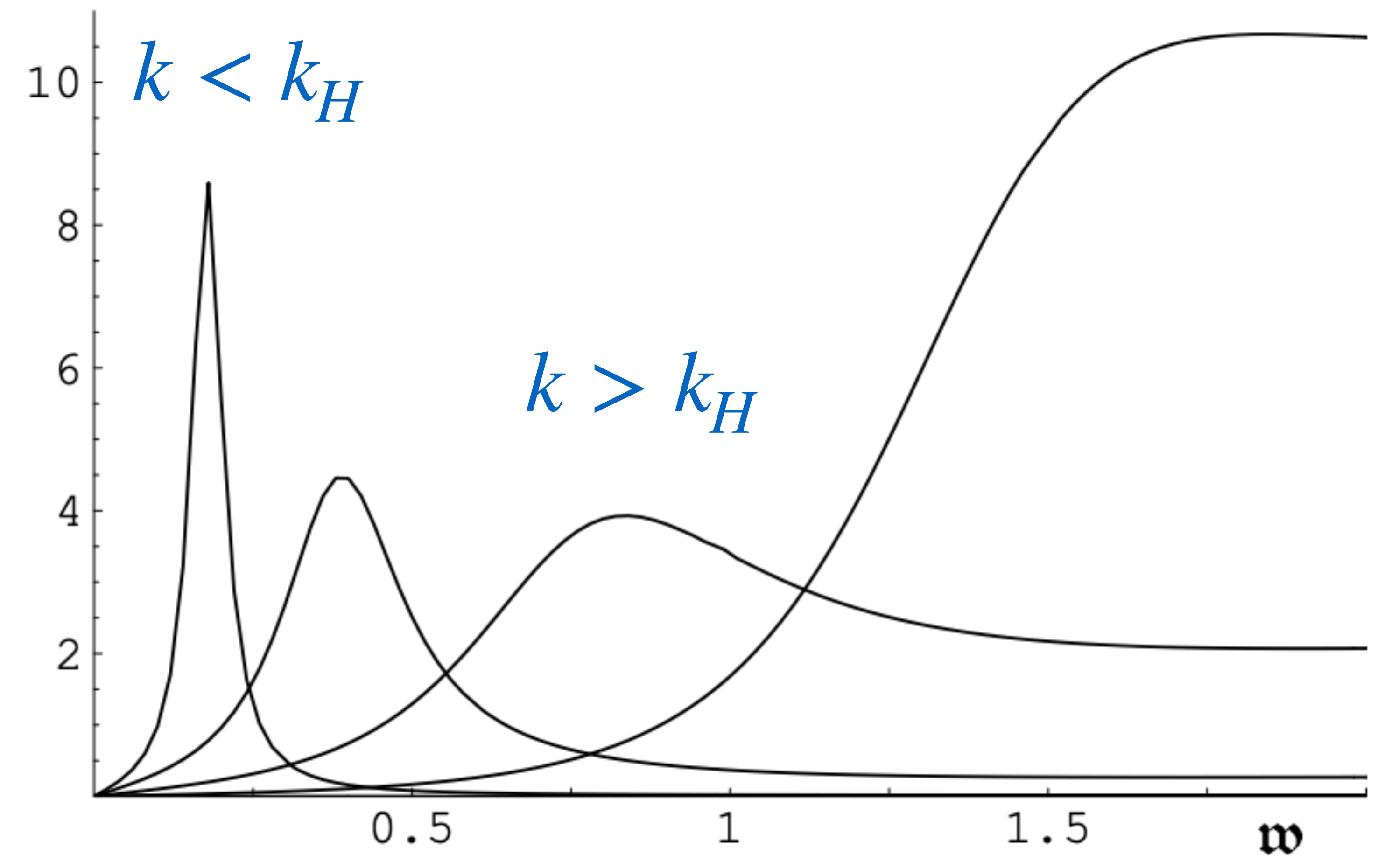
Attenuation rate of sound mode ($\omega = c_s k - i\Gamma k^2$)

Sound peak persists!

This universal feature have been seen in weakly coupled ϕ^4 theory, QCD kinetic theory.

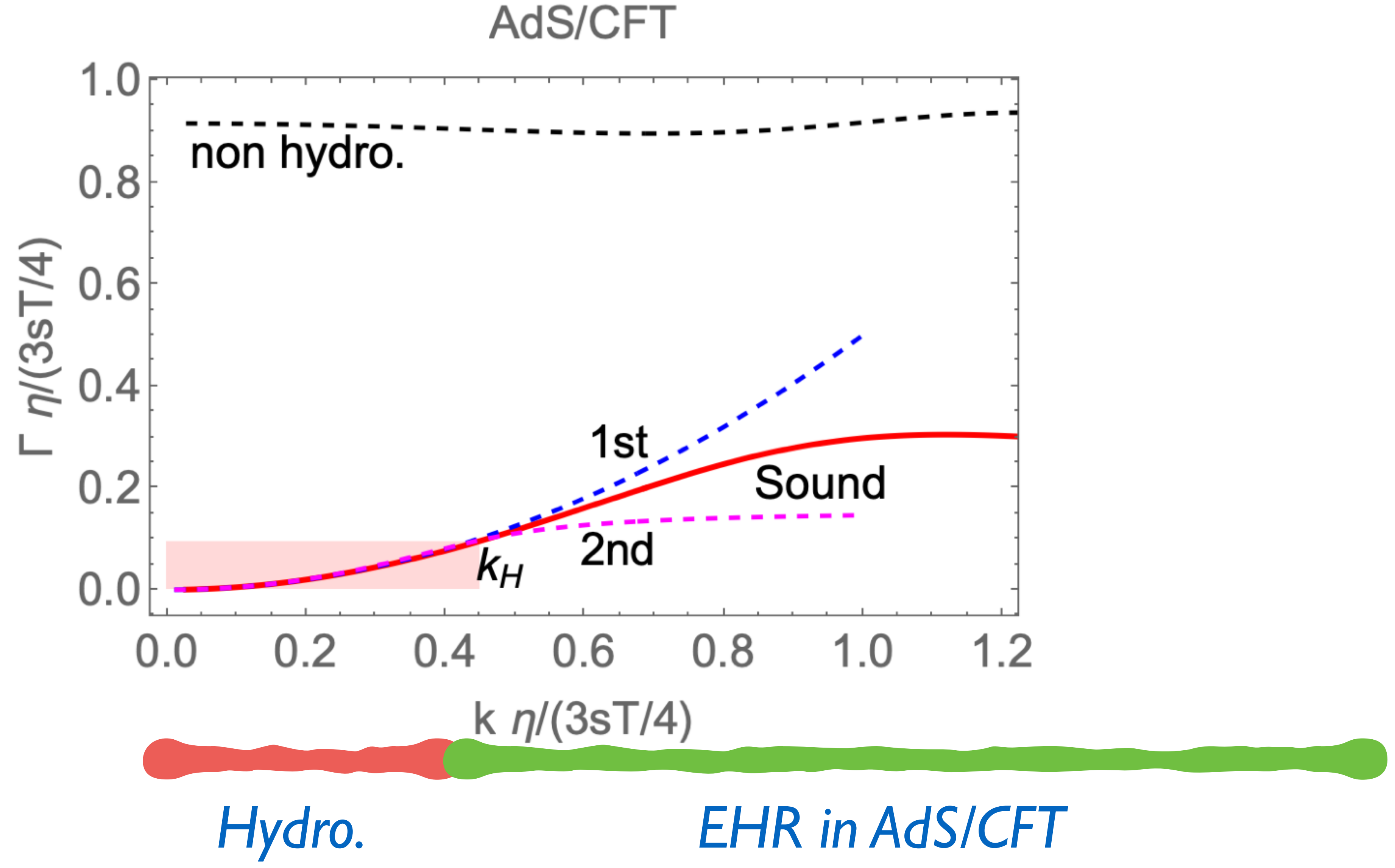
Hong-Teany, PRD10'; Xiaojian Du et. al PLB 23'

Some strongly coupled gauge theory also feature high-frequency sound peak



rescaled spectral density vs rescaled frequency from strongly coupled supersymmetric Yang-Mills theory. Kovtun-Starinets. (PRL 2006)

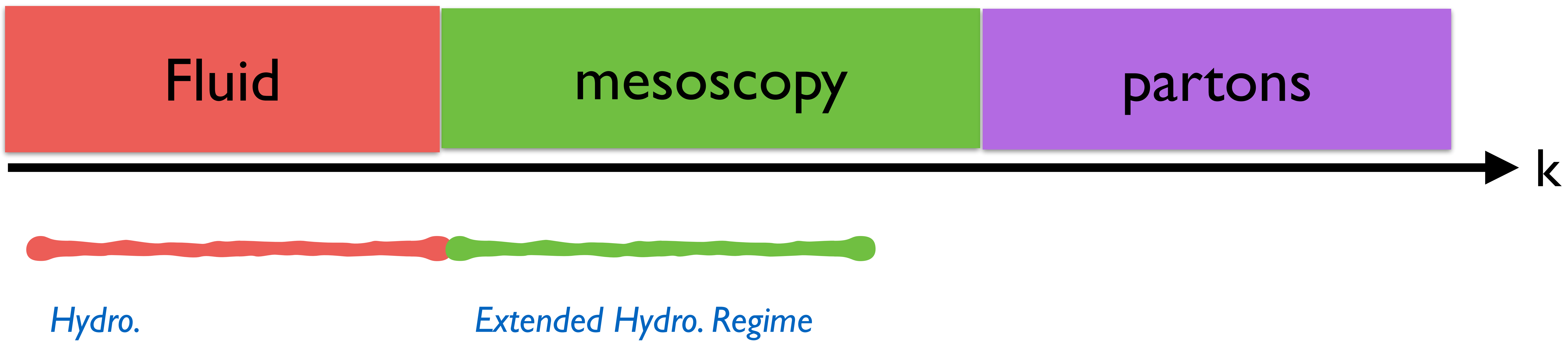
Amado-Hoyos-Landsteiner-Montero, JHEP 08



Attenuation rate of sound mode ($\omega = c_s k - i\Gamma k^2$)

Does QGP feature an extended hydro. regime

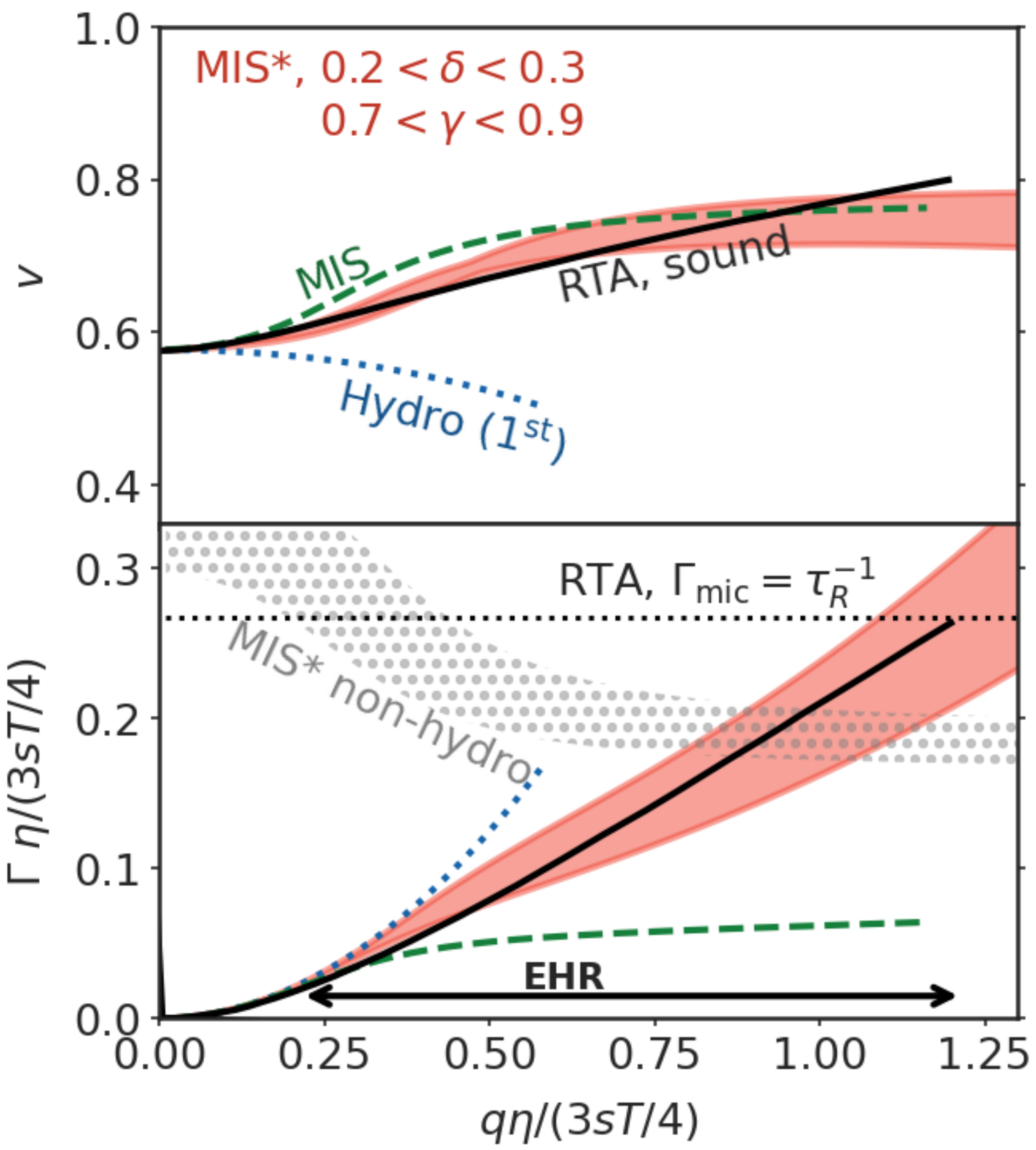
Weiyao Ke and YY, PRL 2023 (2208.01046)



- We propose extended hydro. regime (EHR) as a conceivable scenario for QGP.:
  - "sound dominance": sound mode is gapped from other excitations, meaning a visible sound peak in spectral density.
  - the dispersion is different from ordinary sound (called high-frequency sound in condense matter literature).
  - If true, it implies that QGP at non-hydro. scale can be characterized by effective shear viscosity and sound velocity in EHR.

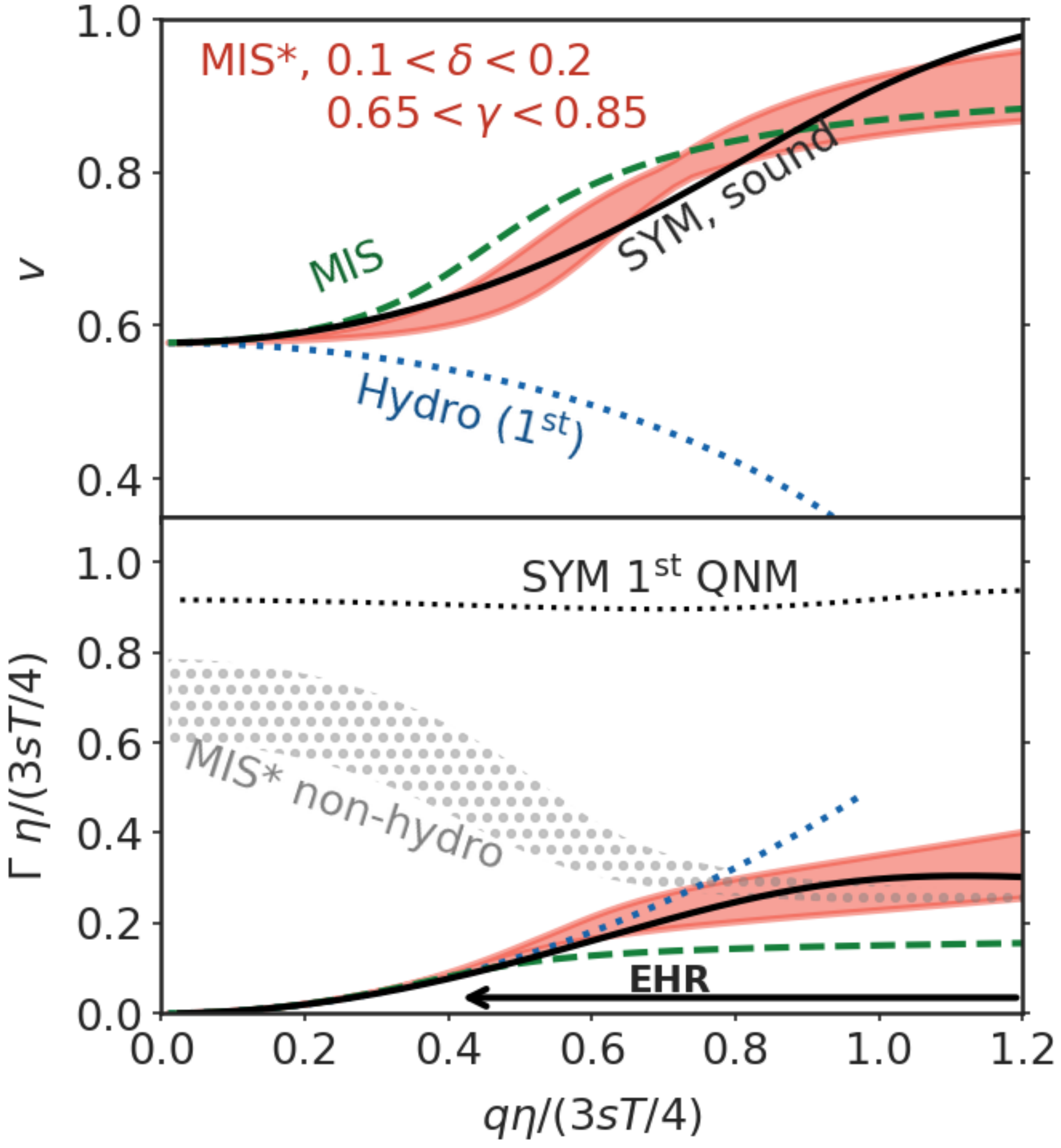
Ansartz for EHR

RTA Kinetic theory



Hydro. EHR in MIS*

AdS/CFT



Hydro. EHR in MIS*

EHR dispersion relation and spectral density are well-described by a simple ansartz with two additional parameters, EHR shear viscosity $\eta'_{\rm eff}$ and sound velocity c' .

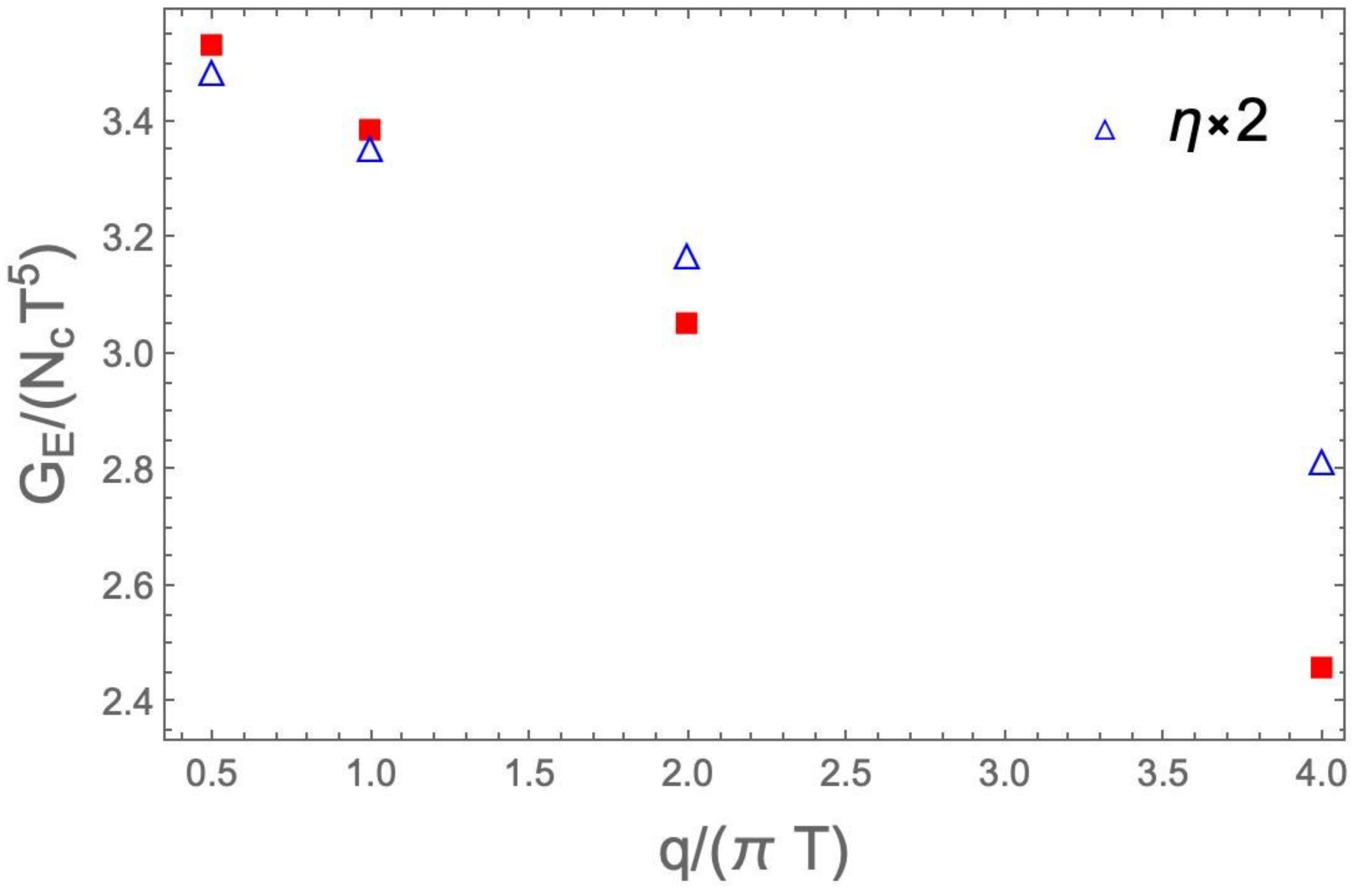
Lattice perspective

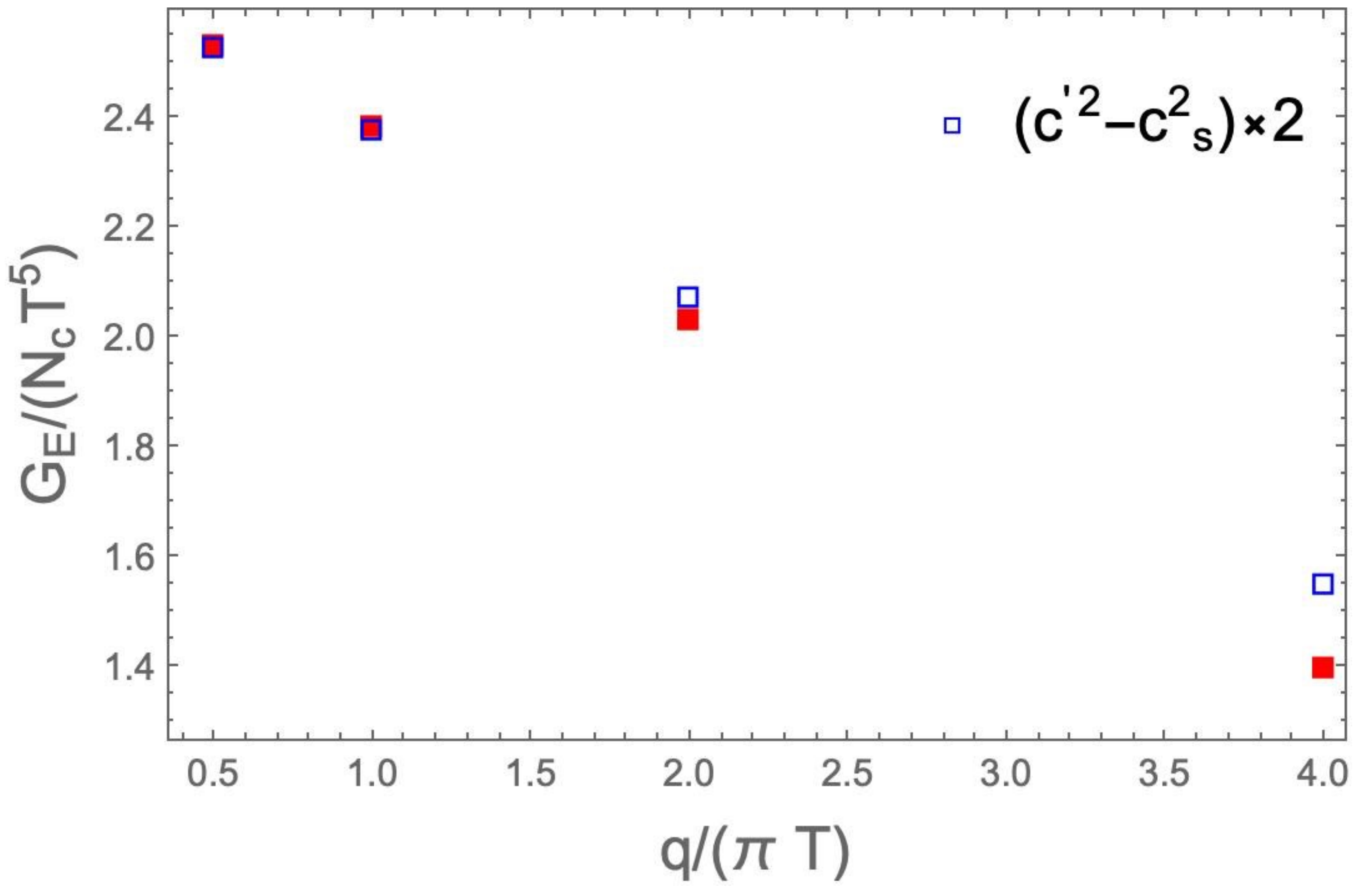
Extracting shear viscosity from lattice is very chanllenging

$$G_E(\tau, k) = \int_0^\infty d\omega\, \rho(\omega, k) \frac{\cosh[\omega(\frac{1}{2T} - \tau)]}{\sinh[\frac{\omega}{2T}]}$$

- Reconstructing spectral density from Euclidean correlator is an ill-conditioned inverse problem.
- Euclidean correlator is not sensitive to the behavior of $\rho(\omega)$ at $\omega < \pi T$.
- Consider $k > \pi T$

Euclidean correlator (at $\tau = 1/(2T)$)





- EHR ansarts for spectral density, examine the resulting Euclidean correlator.

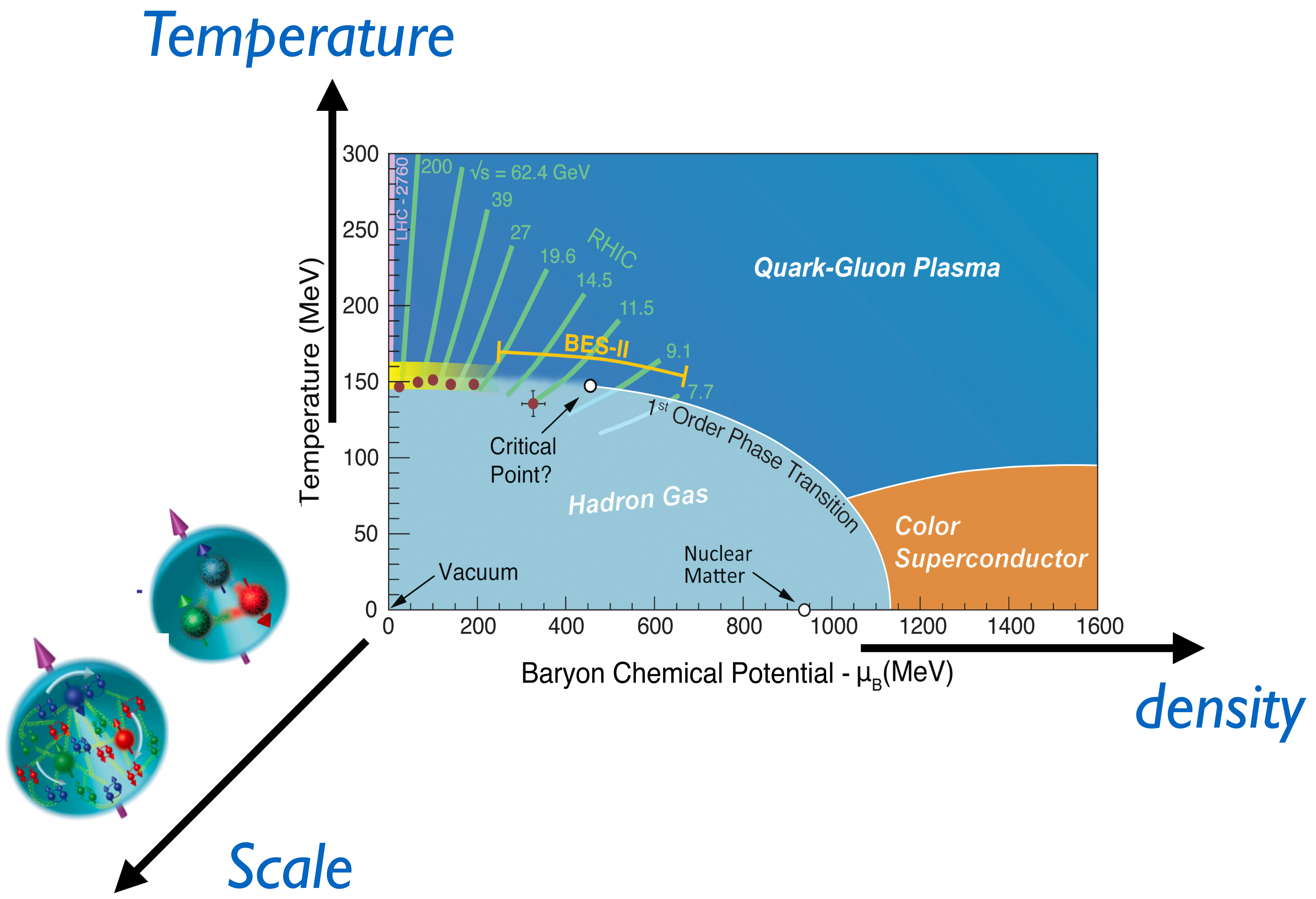
$$\rho(\omega, k) = \rho_{\mathrm{EHR}}(\omega, k; c_s, \eta, \eta', c_s')\theta(\omega - k) + \rho_{\mathrm{free}}(\omega, k)\theta(k - \omega)$$

- The Euclidean correlator show sensitivity to shear viscosity and effective shear viscosity when $k > k_H$.

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.
  - The description at mesoscopic scale simplifies under EHR scenario.
- Our study showcases the possible rich structure of QCD medium.
- Lattice is suitable for exploring QCD matter at intermediate scale.



"*Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.*" -- Feynman

Ultimately, understanding the QCD evolution at both confined and de-confined sates.

Back-up