Quark-gluon matter out-of-equilibrium

- Introduction
- QCD thermodynamics and hydrodynamics
- Non-equilibrium
- Summary

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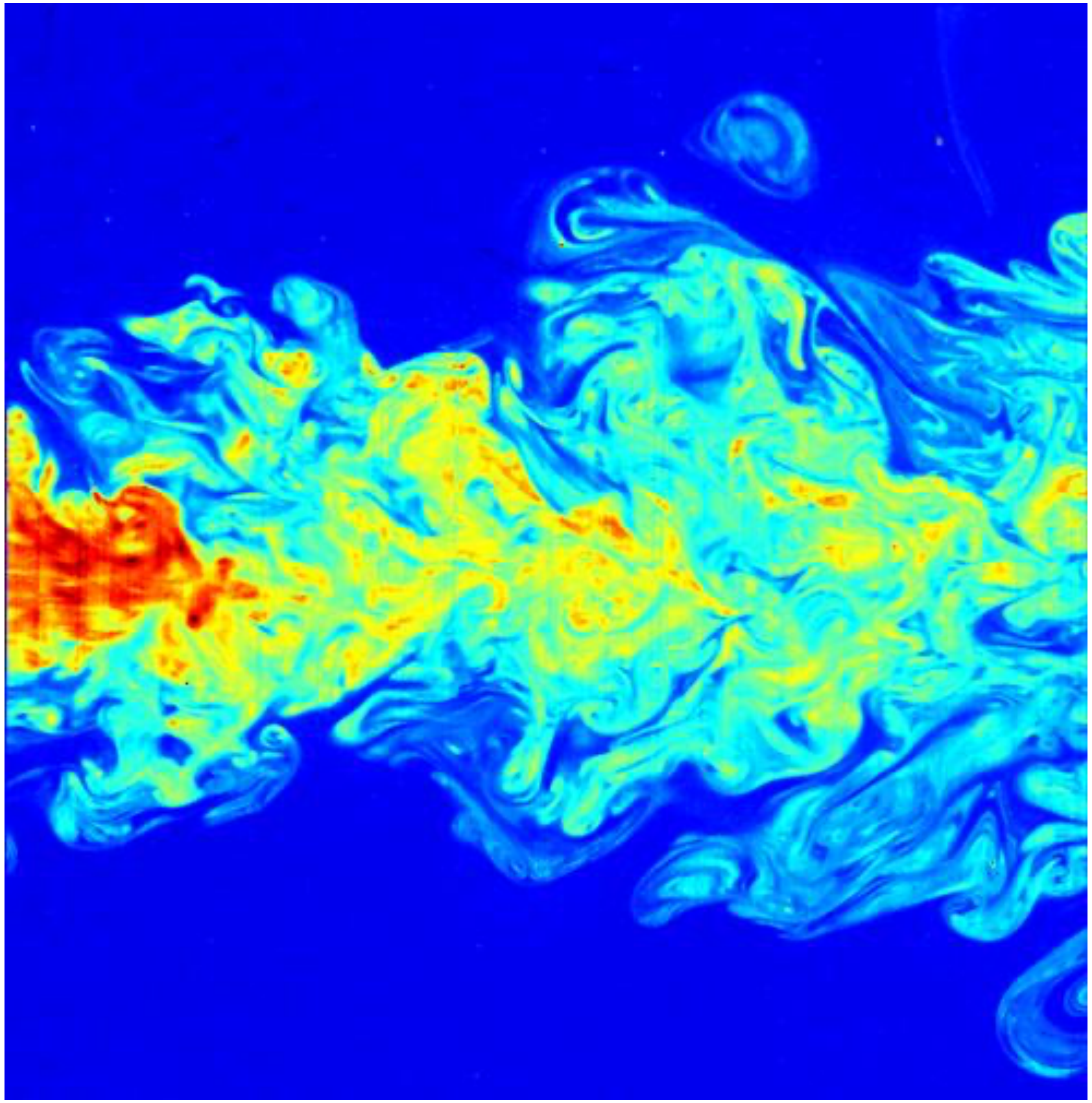
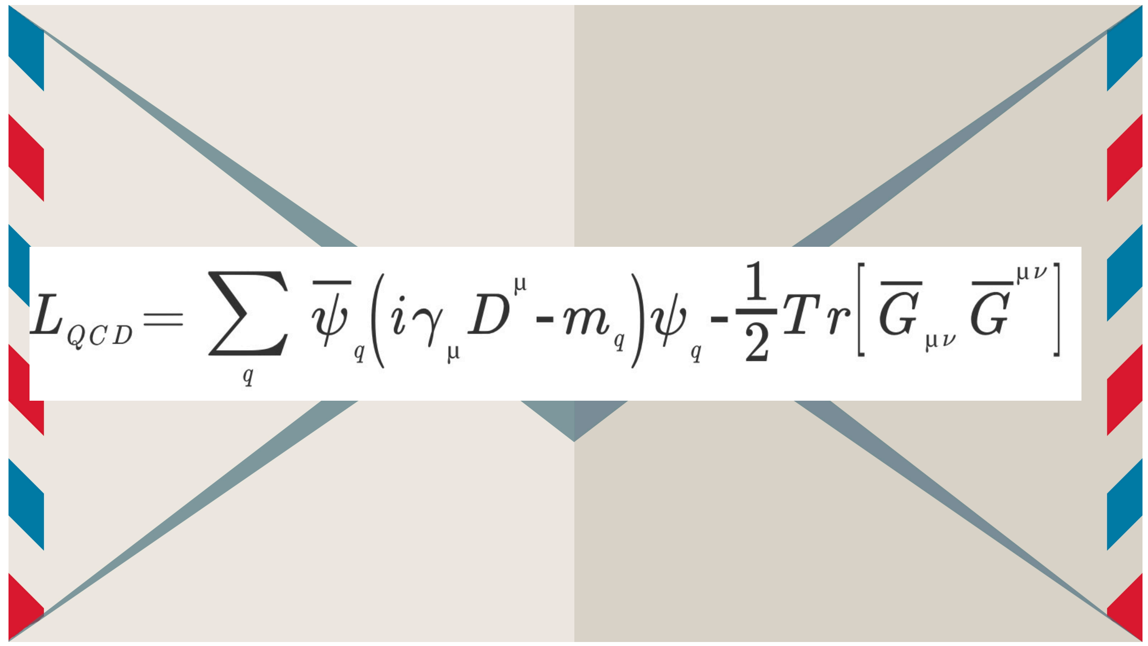
Nuclear summer school at Qingdao, July.22, 2023



Non-equilibrium phenomena is amazing.

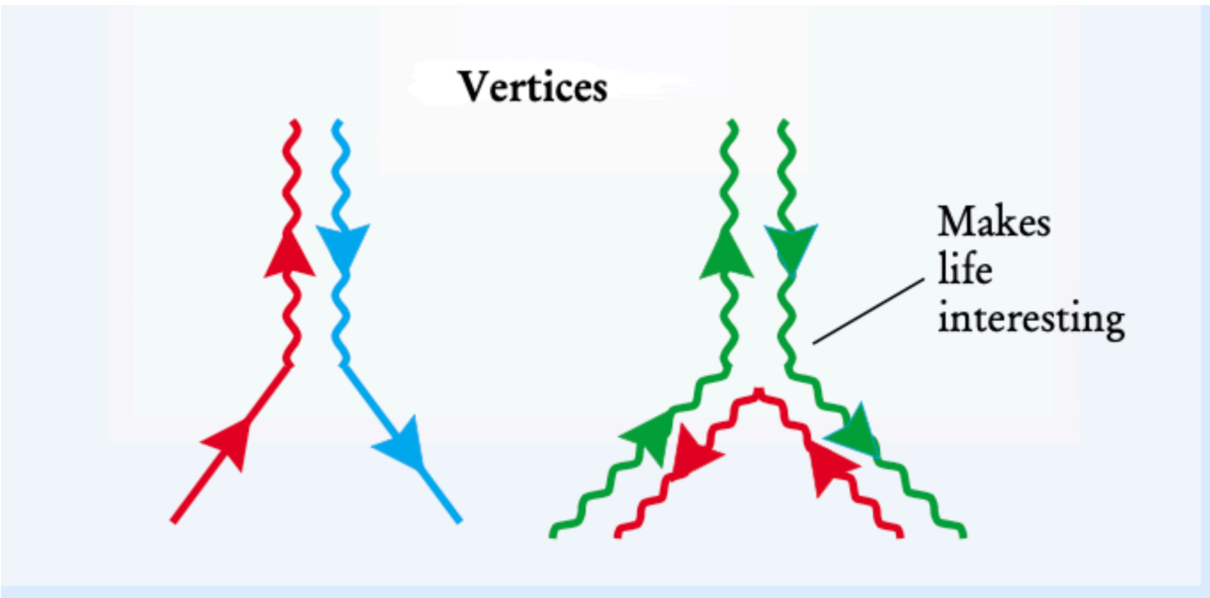
Introduction

The theory of quark, gluon and their interaction: Quantum ChromoDynamics (QCD).

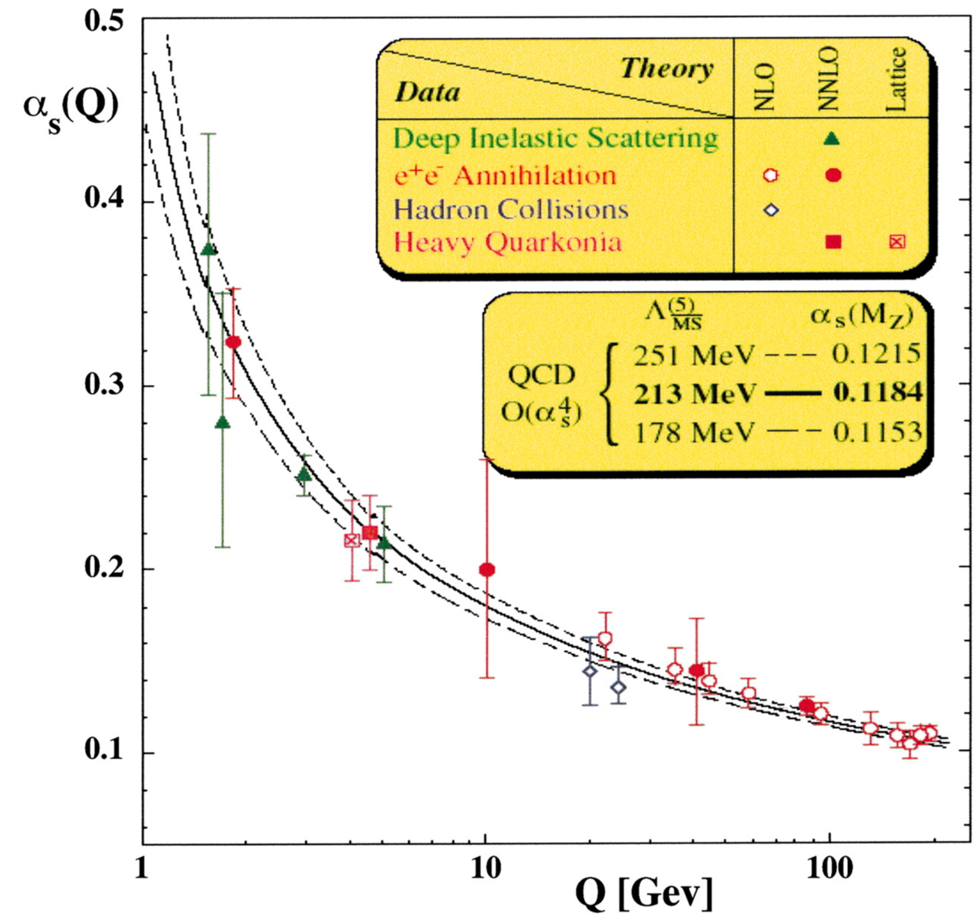


“Often, people in some unjustified fear of physics say you can’t write an equation for life. Well, perhaps we can.” - Feynman

QCD is a theory for life.



α_s



Energy scale

Because of self-interaction among gluons, QCD interaction strength depends on characteristic scales (asymptotic freedom) .

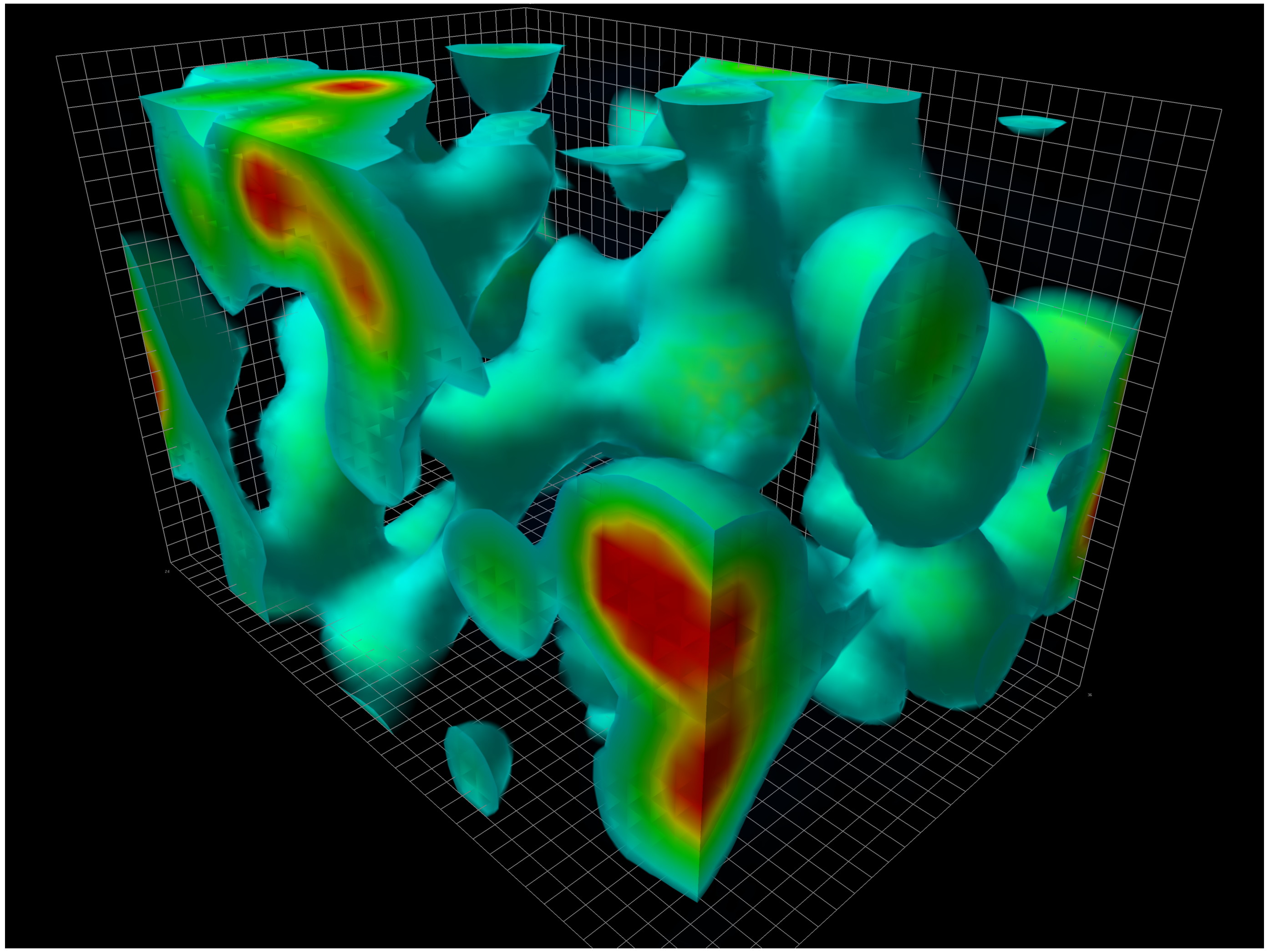


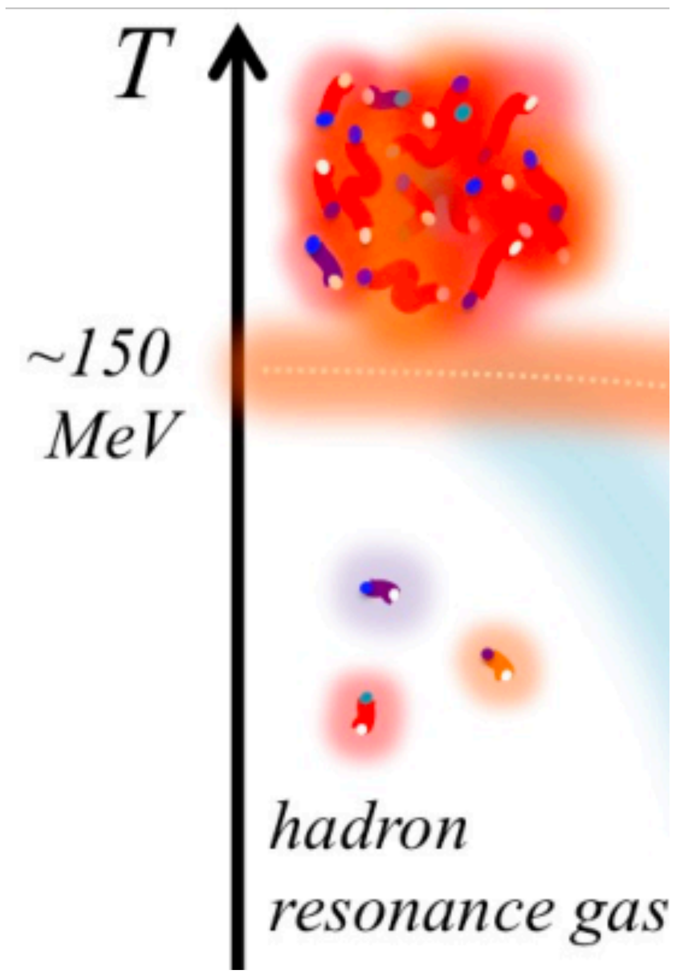
Fig. by Derek Leinweber

QCD vacuum is a prominent example of "interesting vacuum", "a very dense state matter", composed of (virtual) quarks and gluons that interact in a complicated way. *Shuryak, "The QCD vacuum, hadron and Superdense mater "*

How about QCD many-body systems?

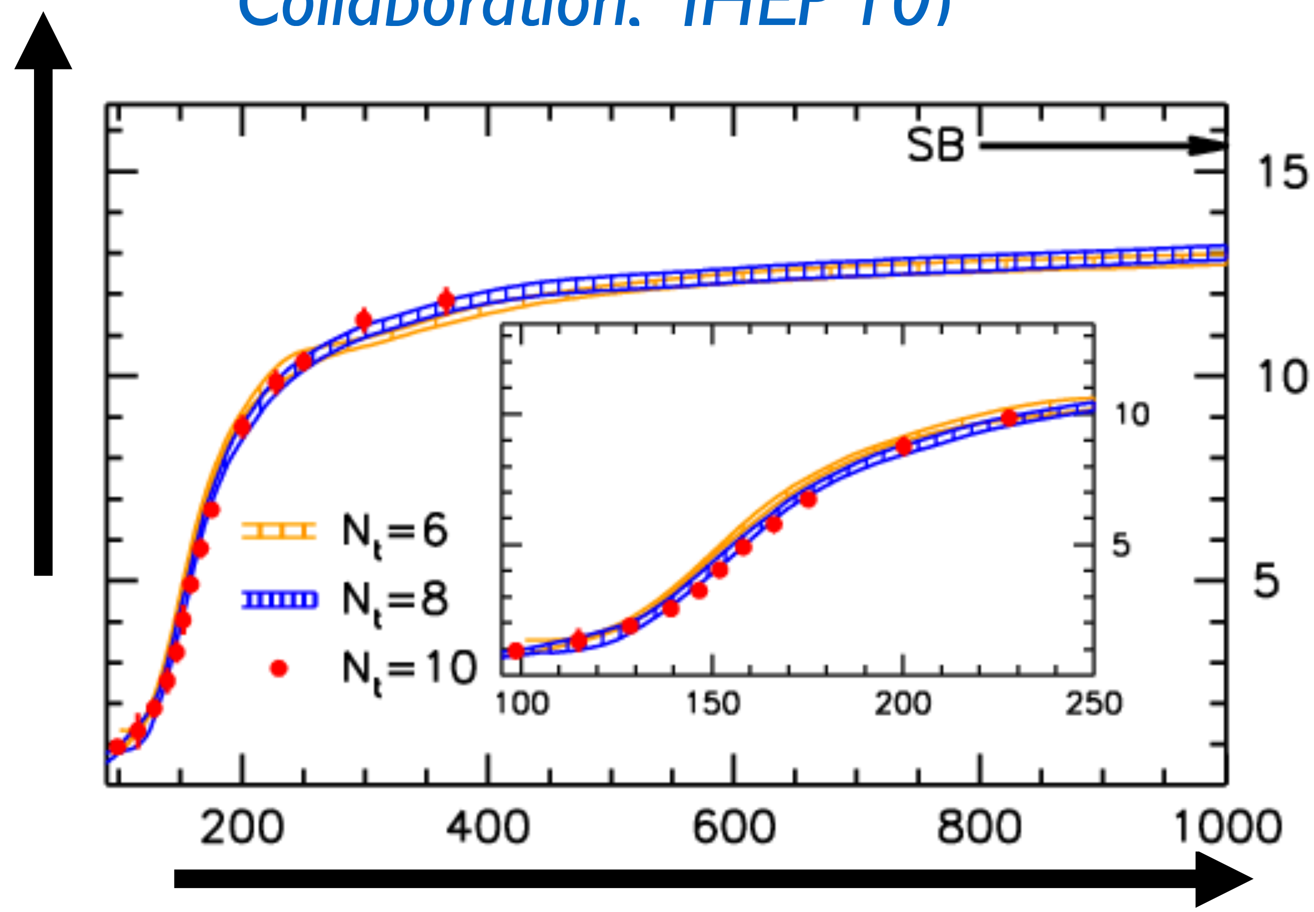
QCD thermodynamics and hydrodynamics

QCD thermodynamics



e/T^4~# of d.o.f

(Budapest-Marseille-Wuppertal Collaboration. IHEP'10)

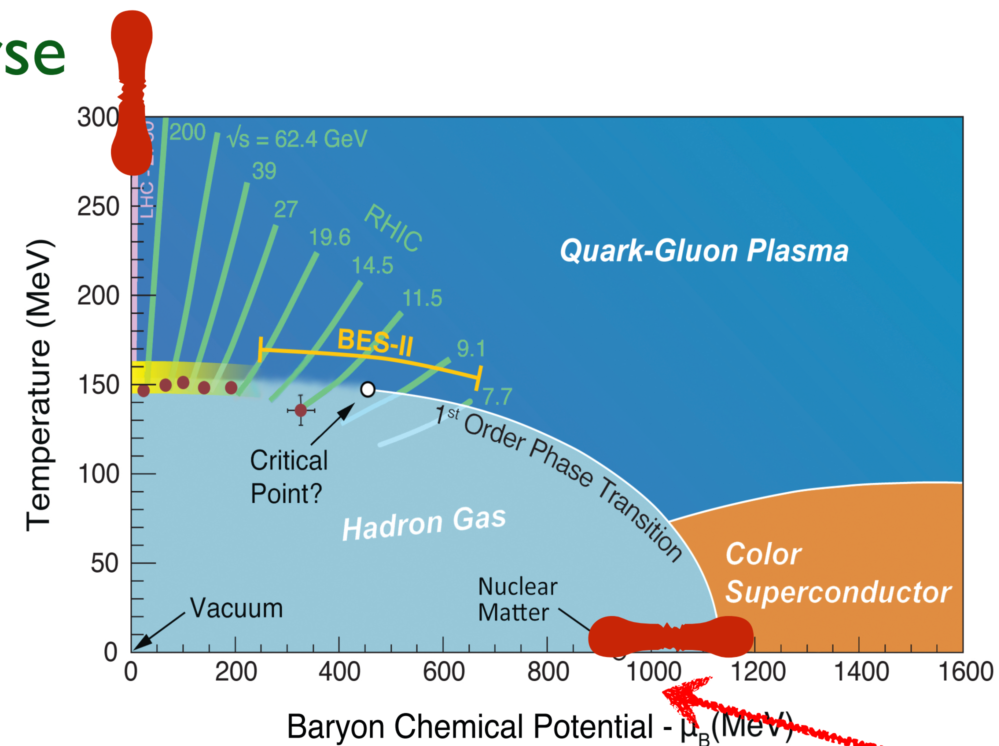


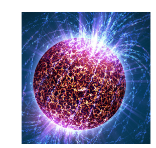
T (MeV)

Significant advances due to first principle lattice calculation.

QCD phase structure is rich

Early universe



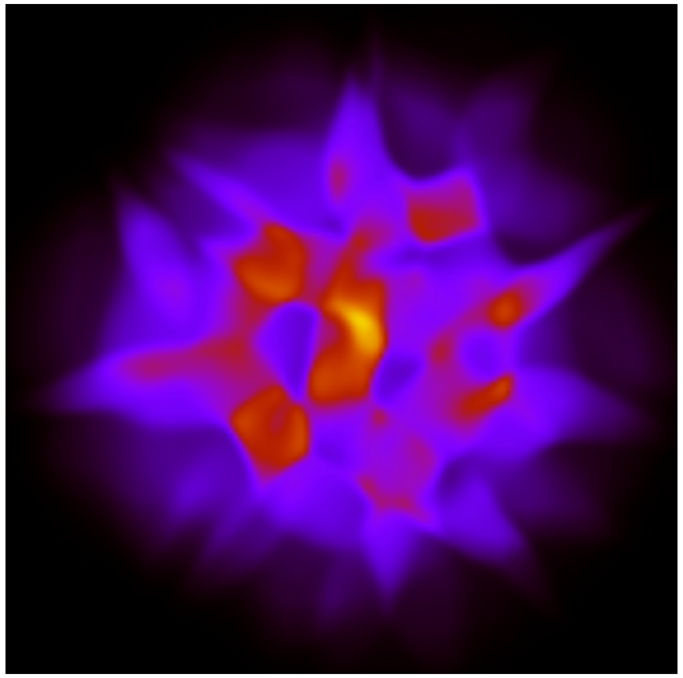


- Exploring baryon-rich QCD matter and search for the QCD critical point .
- Quantum and topological aspects of QCD matter (e.g. spin observables).

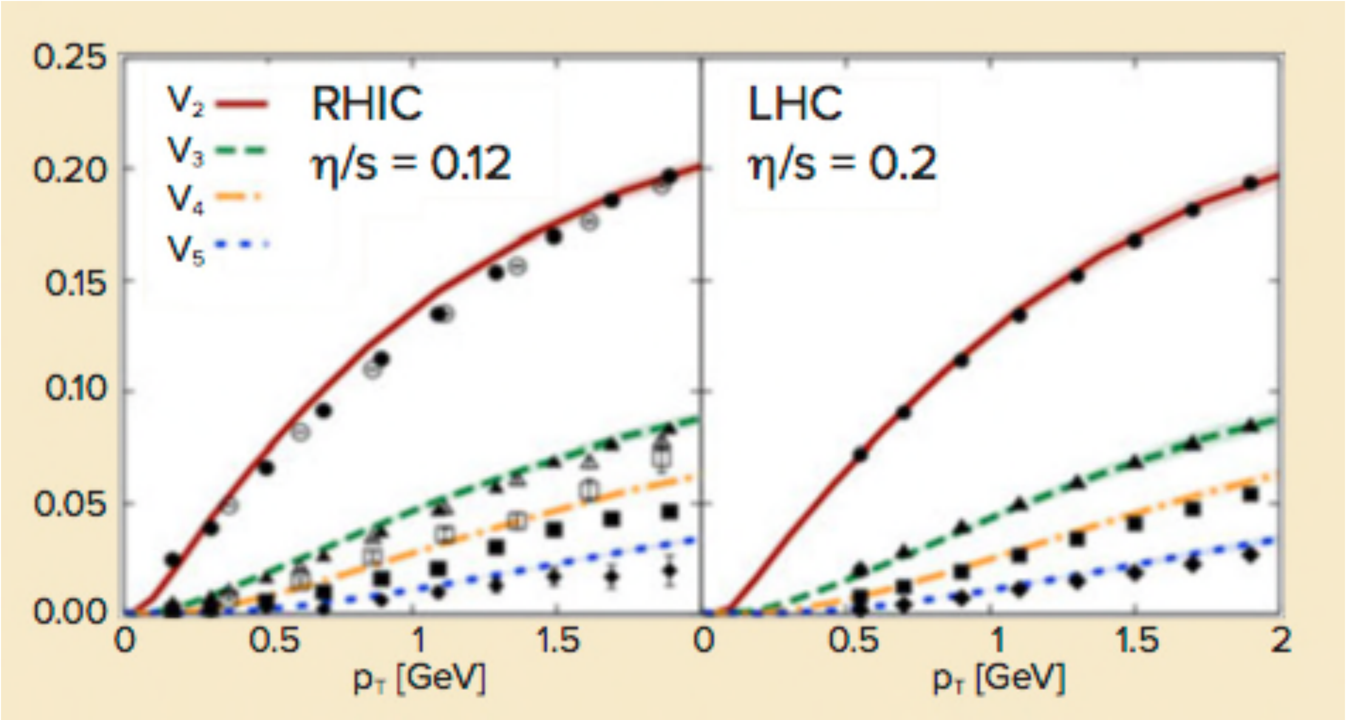
Near-equilibrium (hydro.) limit

- The system is in-homogeneous but the variation in time/space is slow as compared with other intrinsic scale (e.g. temperature, mean-free path).
- In this limit, hydro. works as an effective description.
  - dynamical d.o.f.: conserved densities, e.g, energy and momentum density (related to flow velocity) which evolves slowly.
- E.o.M: conservation law + constitutive relation
- (additional parameters): diffusive constant, shear-viscocity etc characterizing dissipation.

QGP liquid



Hydro. simulation for heavy-ion collisions (by Schenke)



Hadron spectrum vs hydro. simulations by McGill Group

- Extraordinarily small specific shear viscosity $\dfrac{\eta}{s} \sim \dfrac{1}{4\pi}$: de-confined partons are not free, but move coherently.

- So far, we see for QCD matter,
  - Thermodynamics counts density of d.o.f. in different phases
  - Hydro. describes collective and coherent motion of partons.
  - non-equilibrium (beyond hydro.)??

Beyond hydro.

- There are various ways of asking: how to characterize non-equilibrium quark-gluon matter
  - Medium response with varying gradient.
  - QGP at large expansion rate (far-from-equilibrium).
  - …

Method

- Currently, non-equilibrium QCD matter can not be studied from the first principle at general coupling constant:
  - Weak coupling limit: effective QCD kinetic theory.
  - Strong coupling: AdS/CFT models
  - Future: Quantum simulation
  - Current strategy: studying solvable QCD-like theories, then drawing general lessons. (assuming the unity of physics)
- In this context, the goal of model studies is not to describe data, but to extract underlying physics that might be model independent.

That it works does not make it right!

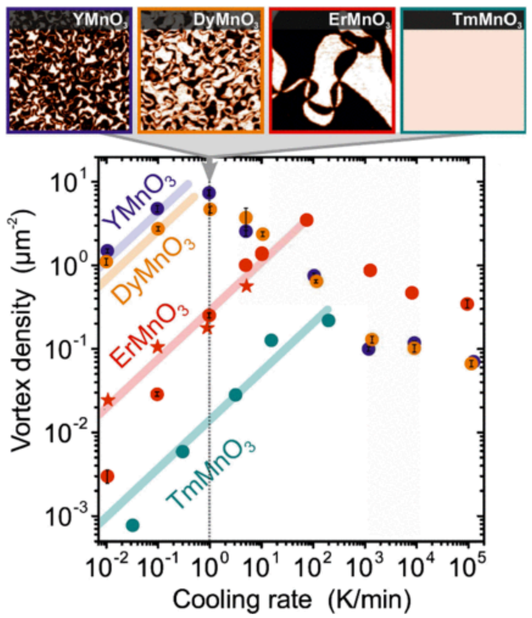
Cancelling the six's

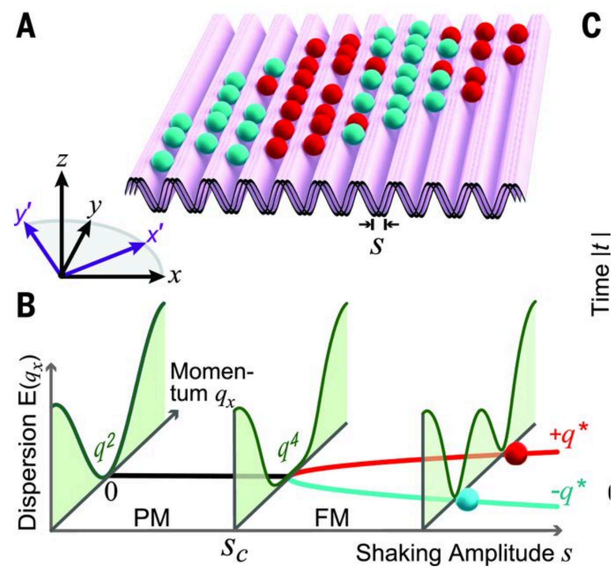
$$\frac{16}{64} = \frac{1\cancel{6}}{\cancel{6}4} = \frac{1}{4}$$

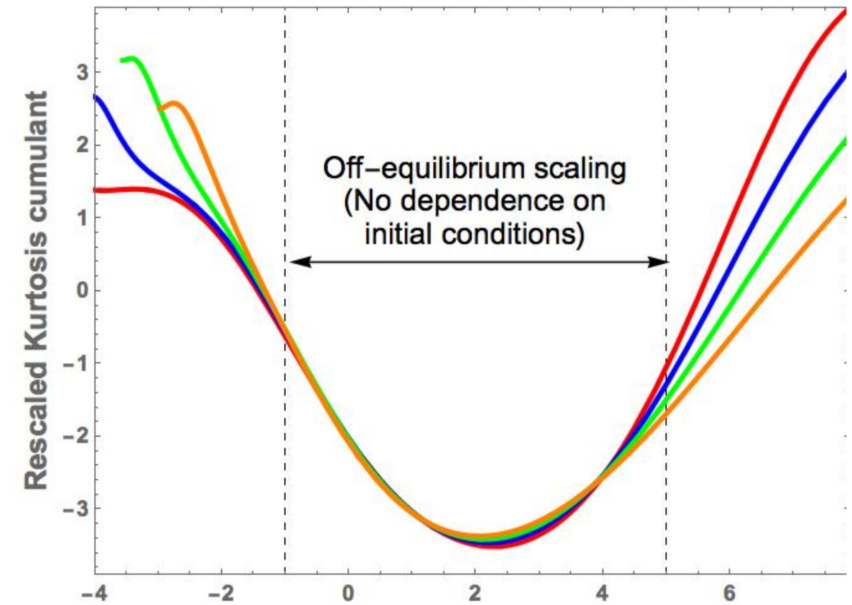
$$\frac{19}{95} = \frac{1\cancel{9}}{\cancel{9}5} = \frac{1}{5} \qquad \frac{18}{85} = \frac{1\cancel{8}}{\cancel{8}5} \simeq \frac{1}{5}$$

From Gordon Baym's slides

Some features of non-equilibrium system can be universal.







Bosons in a shaken optical lattice, W. Clark et al, Science' 16

Hexagonal Manganites, M. Griffin et al, Phys.Rev.X ' 12

Conjecture for critical quark matter, S. Mukherjee, R.Venugopalan and YY, PRL, Editors' suggestion, '16.

For example, the offequlibrium critical scaling (Kibble-Zurek scaling) behavior in HIC is expected to be observed. If so, this would be a nice demonstration of the unity of physics.

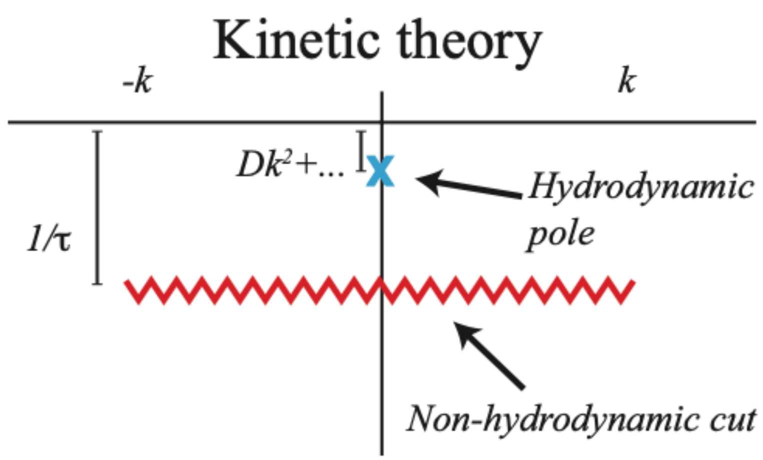
Simplicity from complexity

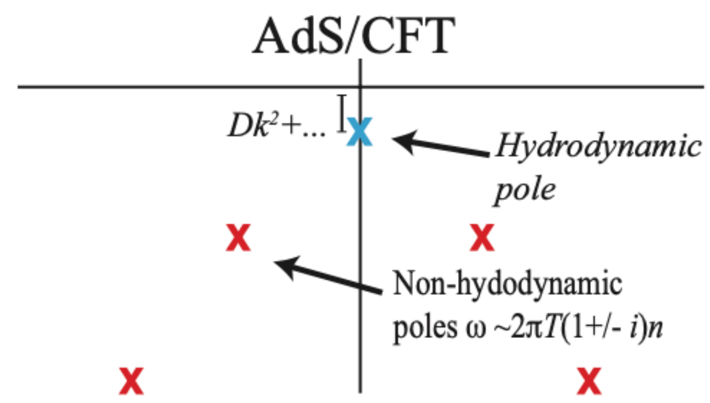
- The characterization of many-body systems is complicated (lots of d.o.fs).
- Substantial simplification would occur when relevant relevant d.o.fs is reduced (e.g.: Landau Fermi-liquid, Critical points).
- Below, I shall showcase two examples on relevant d.o.fs of non-equilibrium QCD-like systems.

Medium response

Weiyao Ke and YY, PRL 23'

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.

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

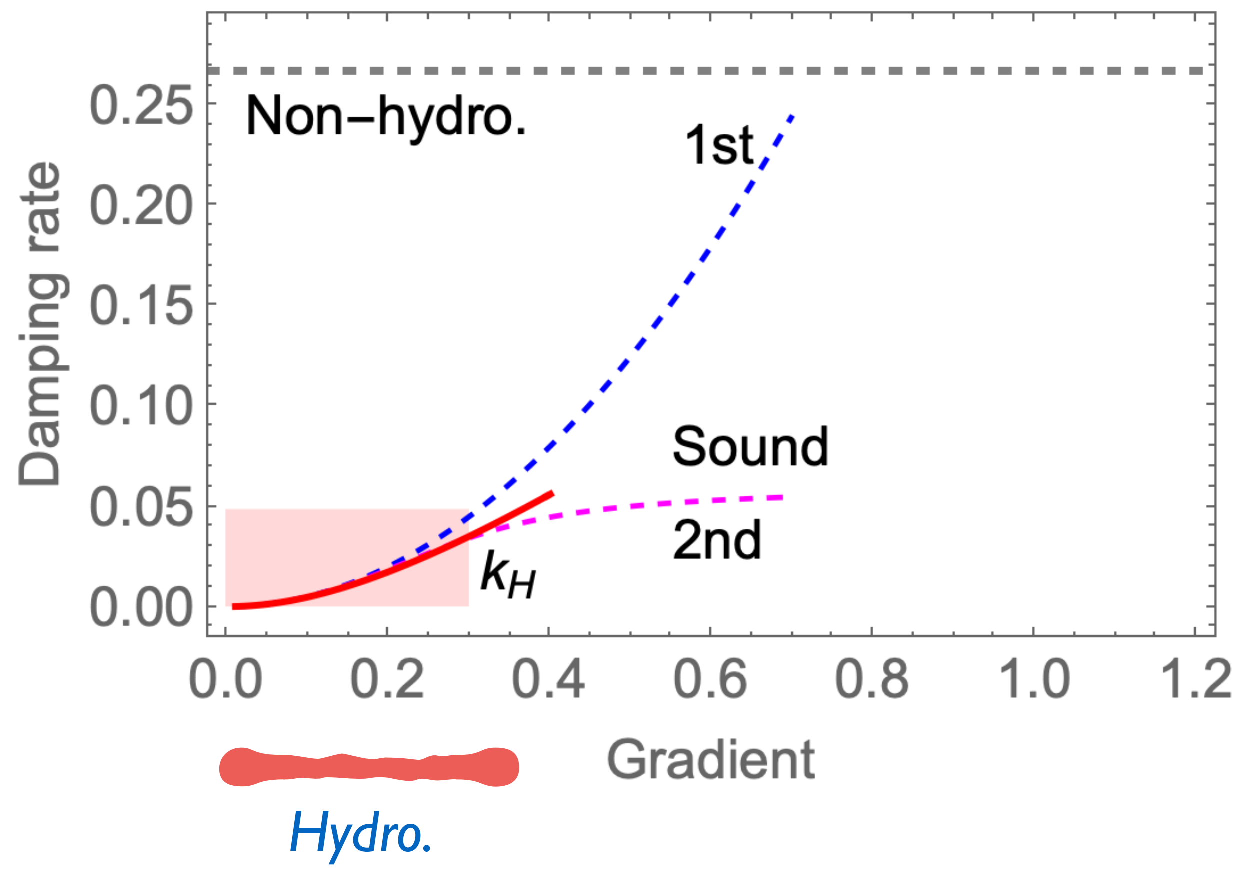
Observables *hydro. modes* *e.g. quasi-normal modes, quasi-particles*

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

- Simplification?

Hydro. regime

Relaxation time approximation (RTA) kinetic equation

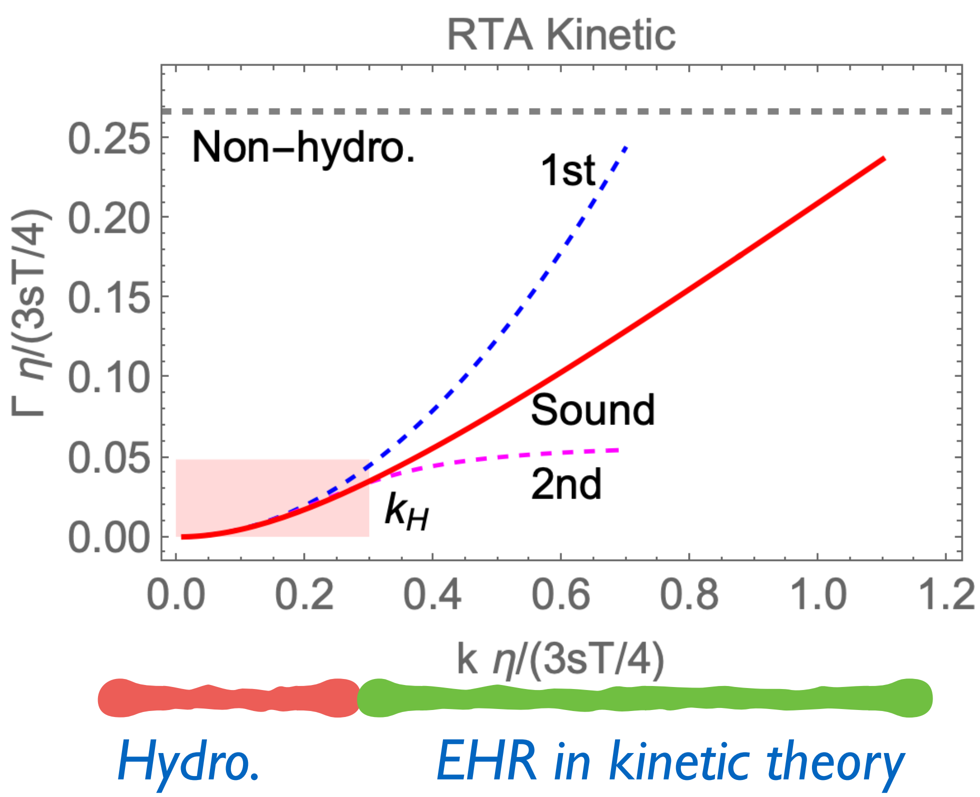


- At small k, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.
  - Hydro. regime: $k < k_H$ where viscous hydro. works.

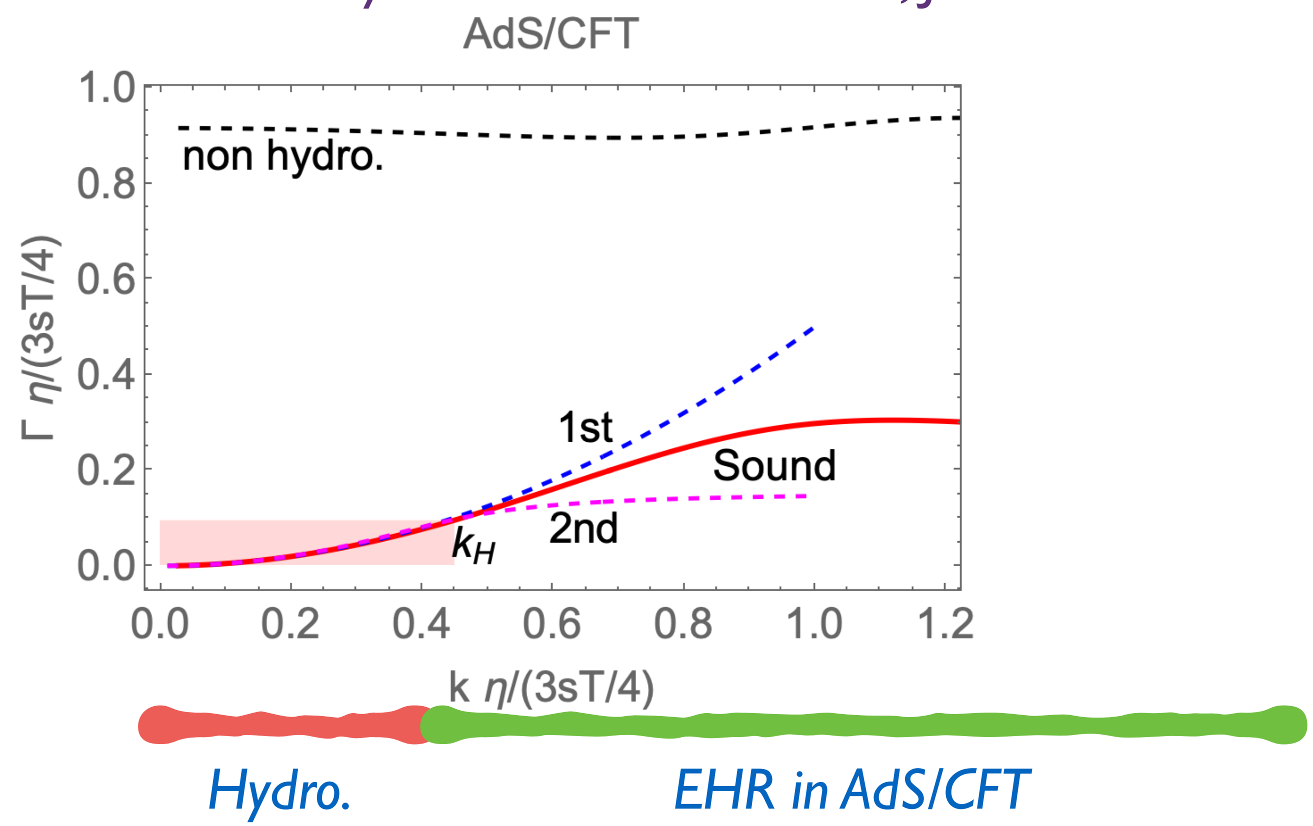
What happens when $k > k_H$?

QGP-like systems

Romatschke, EPJC 16'.



Amado-Hoyos-Landsteiner-Montero, JHEP 08



- 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

High frequency sound in liquid metals

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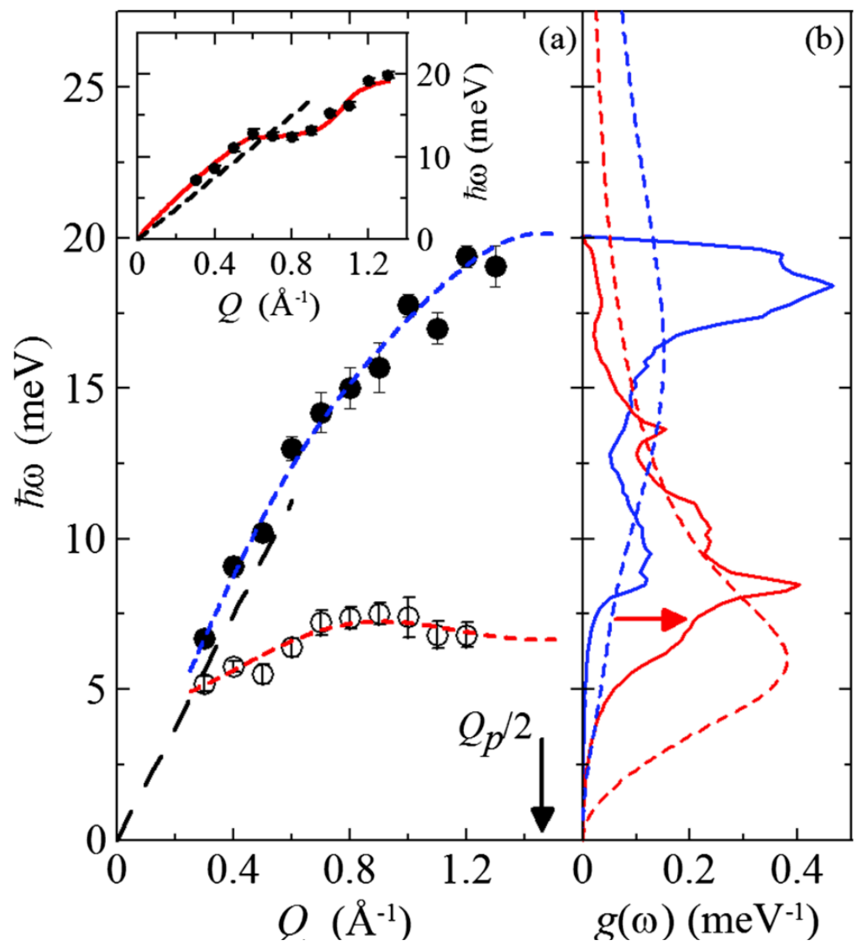
PRL **114**, 187801 (2015) PHYSICAL REVIEW LETTERS week ending 8 MAY 2015

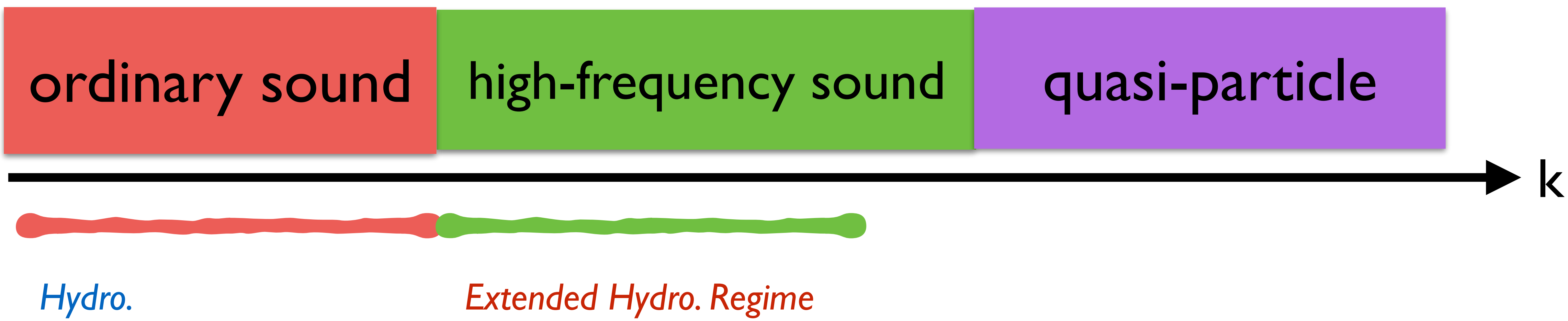


The high-energy mode $\omega_1(Q)$ (black dots) displays a sinusoidal shape with a maximum at $Q_p/2 = 1.46$ Å^{-1} (dashed blue line) and can be identified as a longitudinal acoustic mode. The apparent high-frequency sound velocity is $v_L^\infty = 3380 \pm 60$ m/s, about 20% higher than the hydrodynamic 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 $c_{BS} = 4175$ 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 $c_{ex} = 3195$ 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.

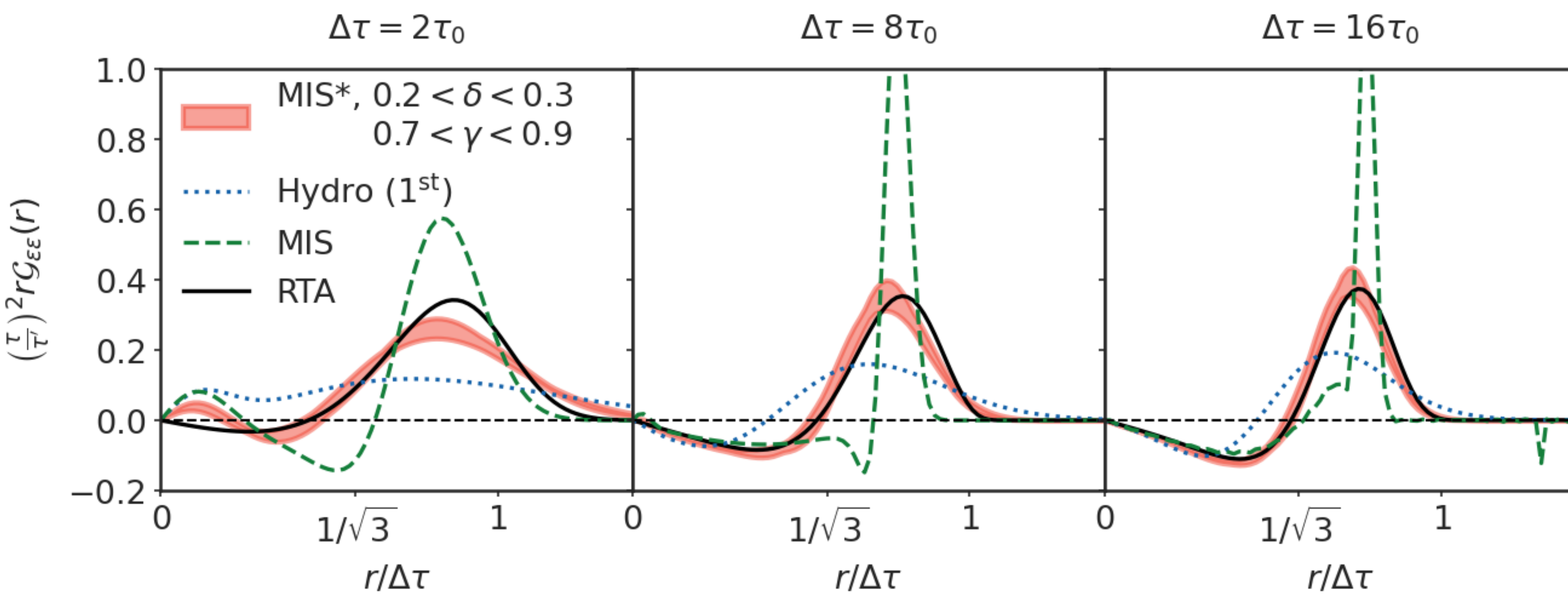
EHR conjecture for QGP

Weiyao Ke and YY, PRL 23'



- 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.
- We construct the extended hydro. theory to describe EHR.

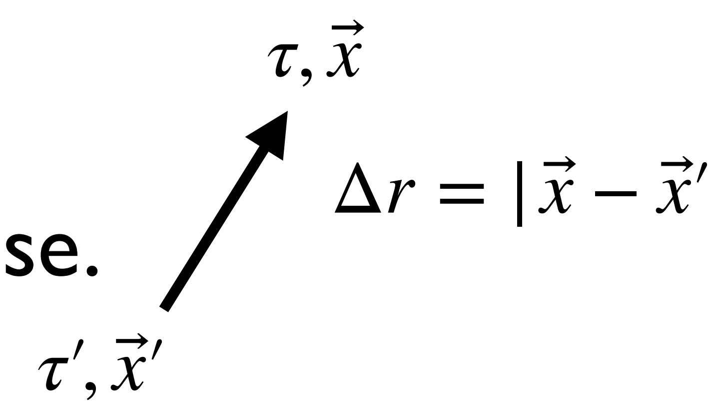
Results from RTA kinetic theory.

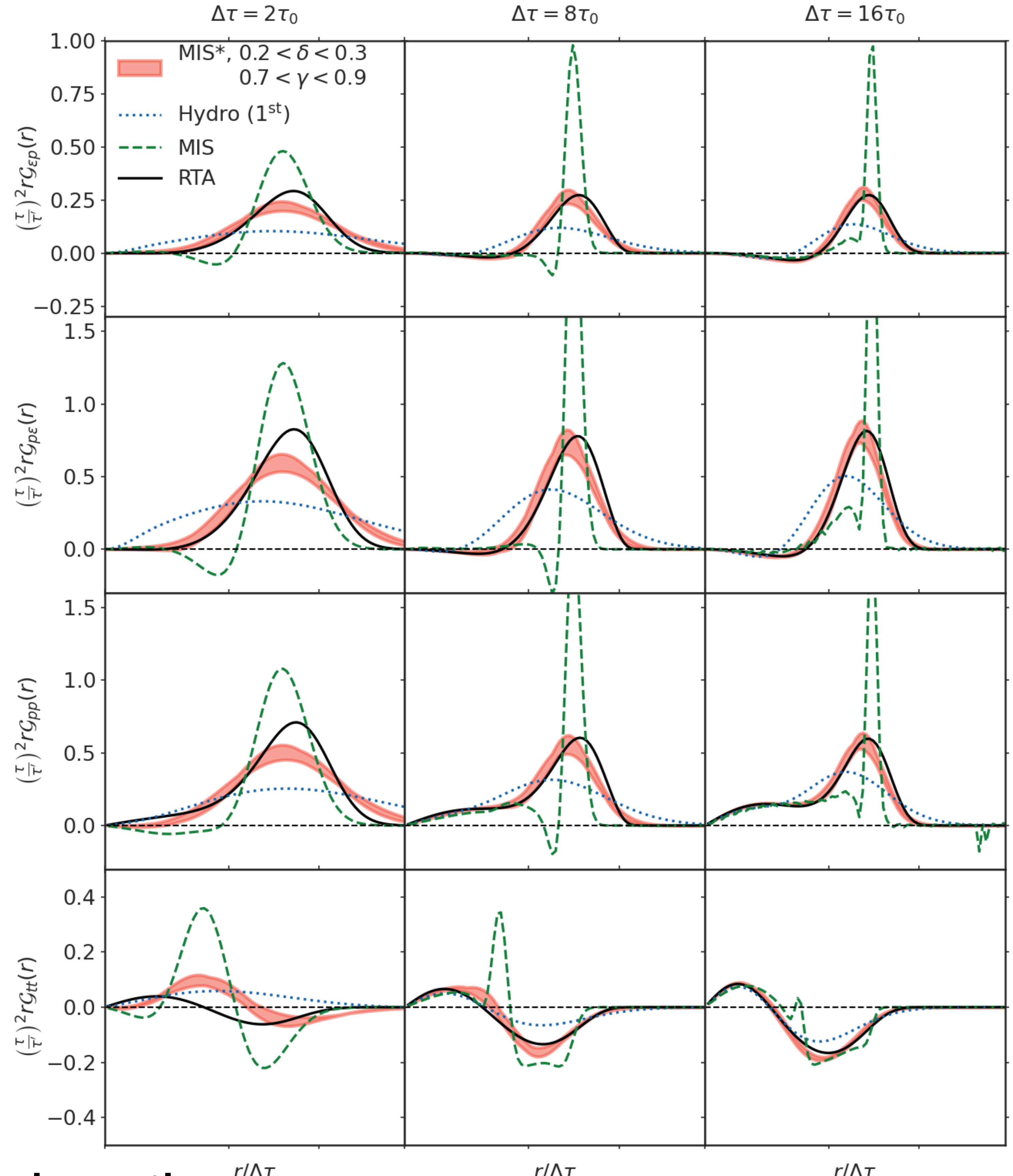


larger characteristic k

smaller characteristic k

- MIS* describes extended hydro. response.





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

Far-from-equilibrium QGP

Far-from-equilibrium QGP

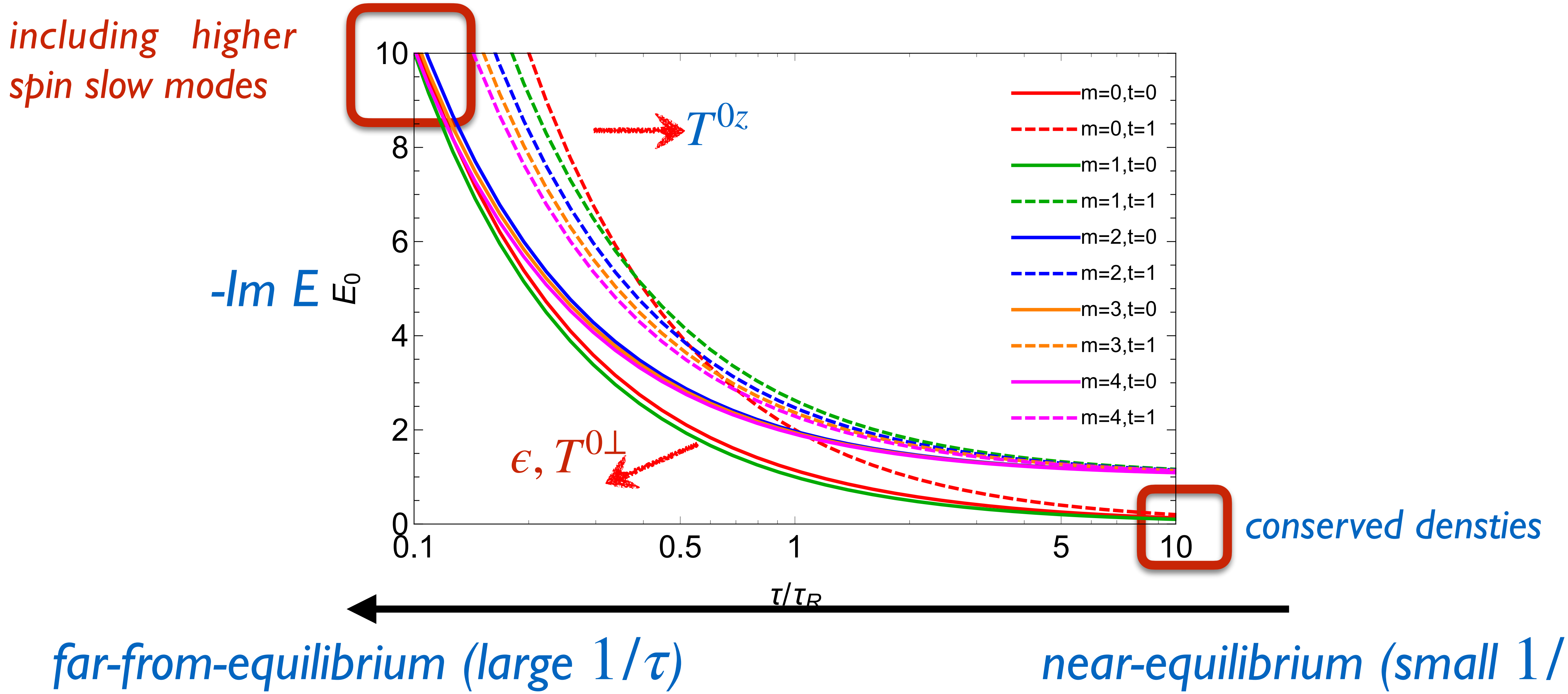
- In a heavy-ion collision, QGP is born out of equilibrium: unique opportunity for studying off-equilibrium property.
- Experiment: intriguing data in small colliding systems.
- Theory: significant progress (attractor, far-from-equilibrium hydro., non-thermal fixed point, KOMPOST etc).

Works by many; Review: Burgers et al, Rev.Mod.Phys. 2020

- Question
  - Do slow modes exist?
  - If so, what are they (are they related to conserved densities)?

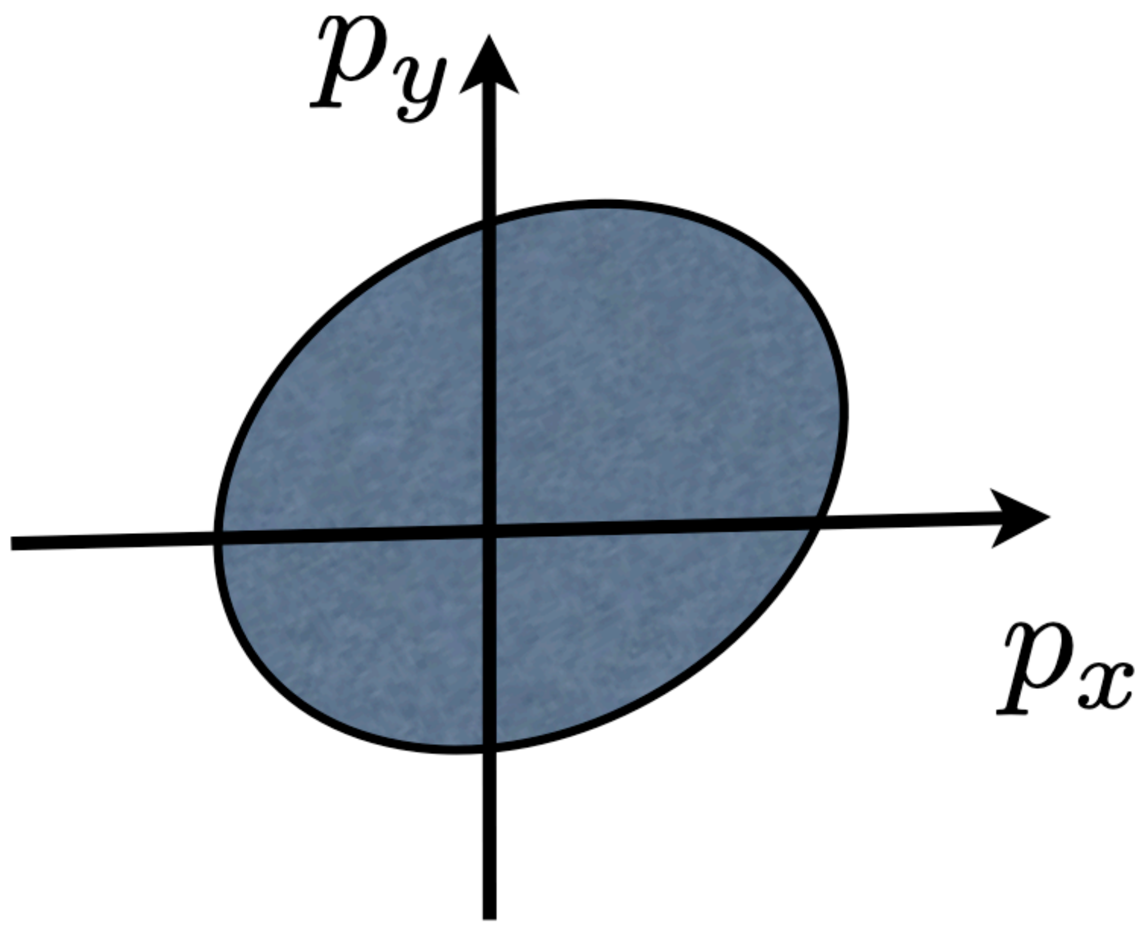
Slow modes in and out of equilibrium

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



- We find effective d.of.s in far-from-equilibrium QGP is qualitative different from those in equilibrium.

Shapes in phase space as slow modes



- The phase space volume is preserved (Liouville theorem) in collisionless limit. (c.f. 2203.05004).

  - For Bjorken expansion at early time, the shape of transverse distribution evolves slowly.

Nonlinear Bosonization of Fermi Surfaces: The Method of Coadjoint Orbits

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Collisionless dynamics of general non-Fermi liquids from hydrodynamics of emergent conserved quantities

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Many recent developments on emergent symmetries (slow modes), dynamics of shape in collisionless kinetic theory.

Some open questions

In a heavy-ion collision, how does the ion quantum state evolve into a thermal system?

Does non-Abelian gauge theories obey eigen-value thermalization hypothesis?

Would other strongly-coupled systems (e.g. cold-atom) help us to understand non-equilibrium QGP?

Summary

Summary

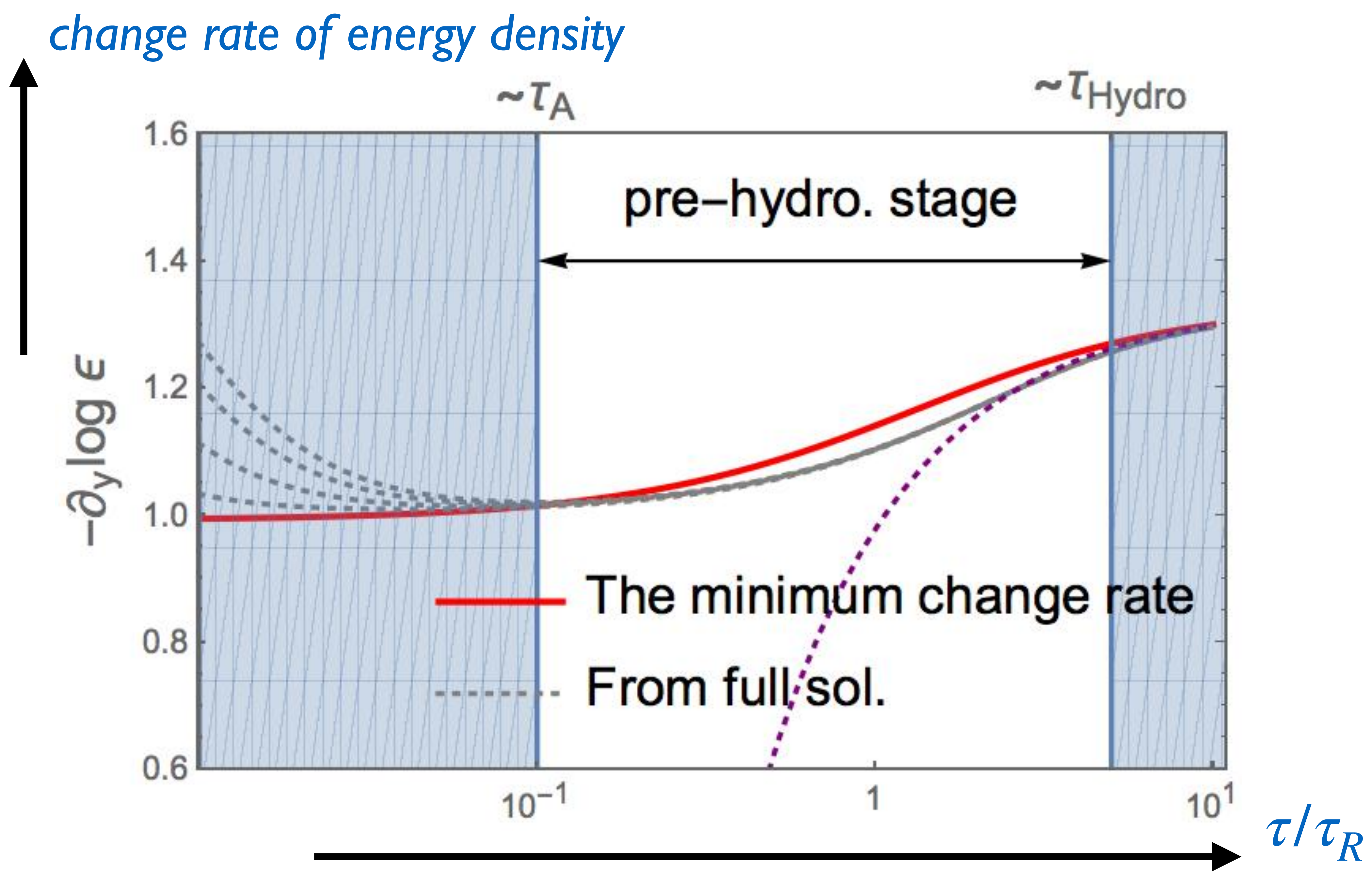
- QGP properties at non-hydro. and non-perturbative regime is yet to be understood (similar for other strongly-coupled systems).
- Medium response: emergence of extended hydro. regime (EHR) where the high-frequency sound dominates.
- Far-from-equilibrium: the shape of distribution as slow modes.
- Non-equilibrium quark-gluon physics is rich, of broad interests and exicting; inviting for young talents to join the adventure.

Back-up

Introduction

- The characterization of many-body systems is complicated (lots of d.o.fs).
- Substantial simplification would occur when relevant relevant d.o.fs is reduced (e.g.: Landau Fermi-liquid, Critical points).
- Hydrodynamics: an EFT in long wavelength and long time (near-equilibrium) limit describing slow evolution of conserved densities, e.g, energy and momentum density.
- But identification of possible slow d.o.fs beyond hydro. regime is challenging.

Energy density sector



Generalized hydrodynamics

In the earlier section, we have discussed modifying (generalizing) hydrodynamic equations by including solid-like elastic effects as one way to describe both elastic and hydrodynamic response of the liquid. 'Generalized hydrodynamics' as a distinct term refers to a number of proposals seeking to achieve essentially the same result by using a number of different phenomenological approaches [5, 7, 8]. One starts with hydrodynamic equations initially applicable to low ω and k, and introduces a way to extend them to include the range of large ω and k.

Trachenko-Branzhkin,Reports on Progress in Physics, 2016

Extending hydrodynamics is an active field in condensed matter physics