Non-Hydrodynamics And Symmetry

Outline

- Intro.
- Hidden gauge fields and non-hydro. modes
- Discussion

CUHK-SZ

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中高能核物理大会

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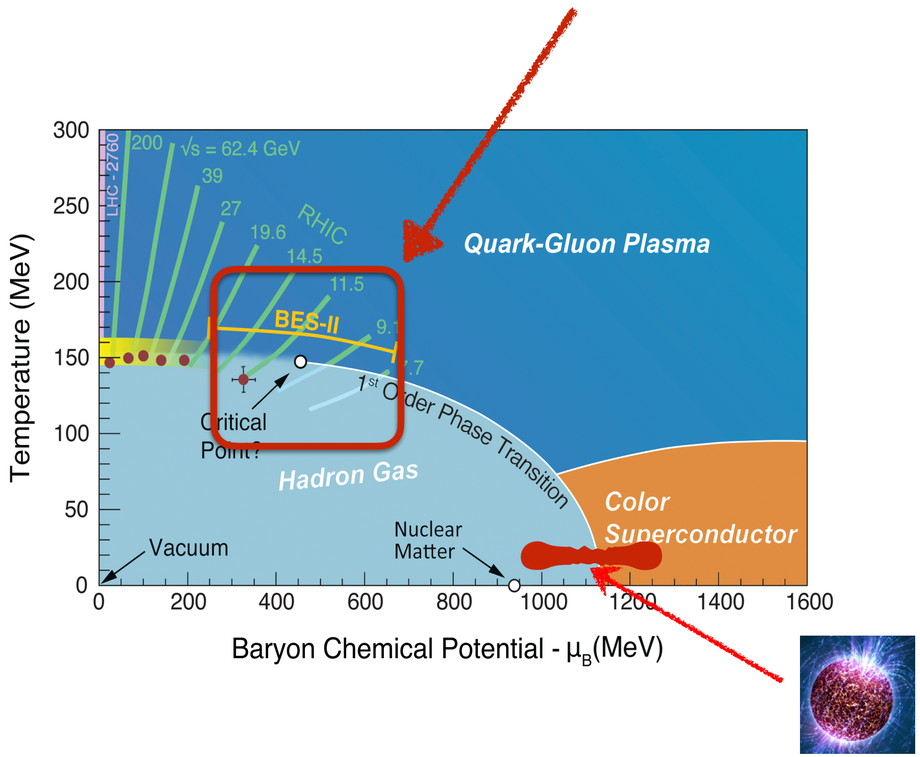
An-Brants-Heller-YY, in preparation

QCD Phase Diagram

- Significant advances on characterizing phases at small density
- Mounting data from RHIC-BESII and future exp. : baryon-rich hot QCD
- Neutron star: cold, ultra-dense regime
  - New: color superconductor with novel topological structure

New info. about EoS



N. Sogabe YY, PRL in press

Besides thermal properties, the dynamics of QCD matter are essential not only for extracting information from data but also significant in their own right

Beyond Hydro.

- Hydro. describes evolution of conserved density and enjoys enormous success

$$\partial_\mu J^\mu = 0 \ \ldots$$

- But diverse phenomena are beyond "vanilla" hydro.
  - Jet-medium interaction, collectivity in small system, spin polarization, hydrodynamization
- Non-hydro: dynamics outside hydro. regime $(k > k_H)$

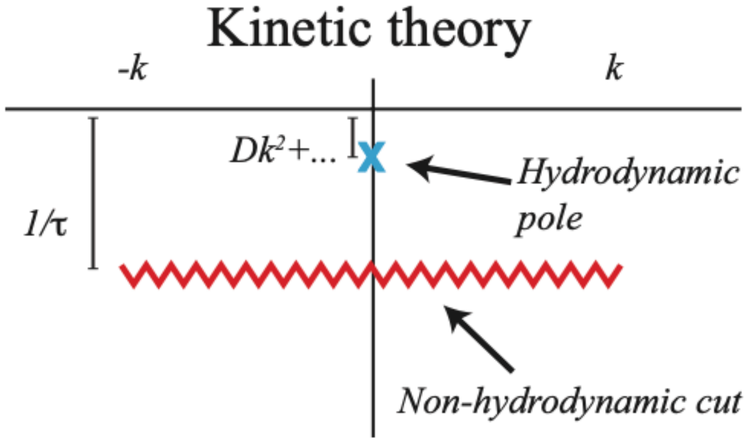
Describing Non-hydro

- Employing microscopic models (kinetic theory, holography) or phenomenological eqns (e.g. Mueller-Isreal-Stewart (MIS))
- A simple guiding principle is absent
- In contrast, (fluctuating) hydro can be derived with symmetry together with EFT philosophy
- New view: a class of non-hydro. behaviors can be described by introducing hidden gauge symmetry

  An-Brants-Heller-YY, in preparation

  - including MIS eqns, holography model, kinetic theory

Puzzle



The analytic structure of retarded Green function

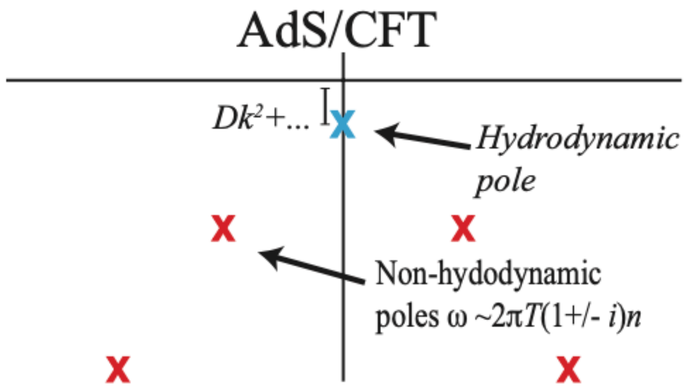


Fig. from Kurkela-Wiedemann-Wu, EPJC 19'

- Gauge symmetry typically implies gapless excitations, whereas non-hydro. modes are gapped (finite relaxation rate). How can these gapped modes be described with additional symmetry ?

MIS-type Equation for Charge Density

- Conversation for conserved density :

$$\partial_t n + \vec{\partial} \cdot \vec{j} = 0$$

- Relaxation for non-hydro. variable $\vec{j}$:

$$\partial_t \vec{j} = -\frac{1}{\tau_J}(\vec{j} - D\vec{\partial} n)$$

- Analogous to MIS equation for stress-energy tensor

Nickel-Son Theory

Nickel-Son, 2010'

Charge $U(1)$ × Hidden $U(1)_H$ $\xrightarrow{\textit{Spontaneous Breaking}}$ $U(1)_{\text{dia}}$

$V_\mu \to V_\mu + \partial_\mu \lambda$ $\qquad$ $A_\mu \to A_\mu + \partial_\mu \lambda_H$ $\qquad$ $\lambda = \lambda_H$

$$\mathscr{L} = f^2 \left(\partial_t \phi - V_t + A_t\right)^2 - g^2 (\vec{\partial}\phi - \vec{V} + \vec{A})^2 + \mathscr{L}_{\text{diss}}[A]$$

- Goldstone ϕ
- Massive gauge field A_μ (Higgs mechanism); $g^2 \sim$ Higgs mass
- Dissipation $\mathscr{L}_{\text{diss}}[\vec{A}] \to \vec{I}_{\text{diss}} = \sigma \partial_t \vec{A}$

NS action → MIS-type Theory

$$f^2\left(\partial_t\phi - V_t\right)^2 - g^2(\vec{\partial}\phi - \overrightarrow{V} + \overrightarrow{A})^2 + \mathscr{L}_{\text{diss}}[A] \qquad (A_t = 0 \text{ gauge})$$

Density: $n = f^2\partial_t\phi$ Current: $\vec{j} = -g^2(\nabla\phi - \overrightarrow{A})$

EoM of $\phi \leftrightarrow \partial_\mu J^\mu = 0$

EoM of $\overrightarrow{A} \leftrightarrow \partial_t\vec{j} = -\frac{g^2}{\sigma}(\vec{j} - \frac{f^2}{\sigma}\vec{\partial}n)$

τ_J^{-1} D

Puzzle Explained

- Hidden gauge symmetry (but spontaneous breaking) can be employed to describe non-hydro.
  - Goldstone ~ hydro. modes (gapless)
  - Massive hidden gauge field ~ non-hydro. (Gapped)
- Symmetry is useful guidance for constructing in a systematical way
  - describing fluctuation outside hydro. regime

Hidden Gauge Symmetry and Vector Mesons

- Massive meson like ρ, a_1 can be treated as the vector boson of spontaneously breaking hidden local $SU(2)$

Bando et al, 1980s

- Generalization to infinite number of HLS (predecessor of AdS/QCD)

Son-Stephanov, 2004

Reproducing a host of hadronic phenomena with acceptable precision

Pion ~ hydro. modes

Massive meson ~ non-hydro. modes

Hidden Gauge Symmetry Model for Non-Hydrodynamics

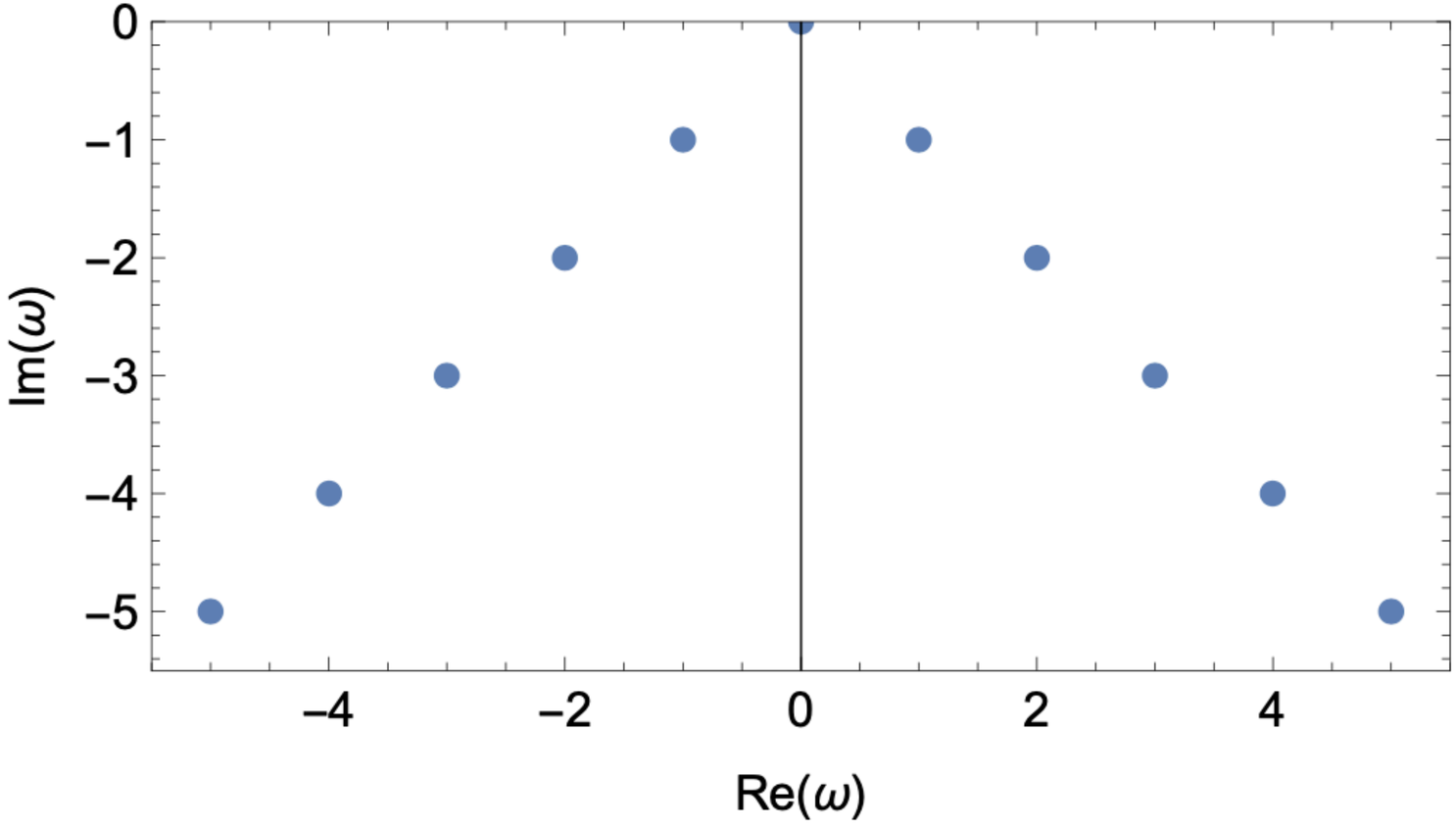
An-Brants-Heller-YY, in preparation

$$V \overset{\phi^K}{\text{-------}} (A)^K \ \ldots \quad (A)^n \overset{\phi^n}{\text{-------}} (A)^{n-1} \ldots \ \text{------} \ (A)^1$$

$$\ldots - g_n^2(\vec{\partial}\phi^n - (\overrightarrow{A})^{n+1} + (\overrightarrow{A})^n)^2 \quad \ldots + \mathscr{L}_{\text{diss}}[A_1]$$

+Kinetic Term

- Introducing $K \geq 1$ hidden gauge fields
  - $(A)^n$ couples to $(A)^{n\pm1}$ only (nearest neighbor)
  - Dissipative current in terms of $(A)^1 : \vec{I}_{\text{diss}} = \sigma\partial_t(\overrightarrow{A})^1$
- A tower of non-hydro. modes



- Holographic-like modes by tuning model parameter f_n, g_n s

Continuum limit $K \to \infty$

- Large K: discretized 5-d gauge theory in curved spacetime
  - "n" labels lattice site of fifth coordinate ρ $\quad (A_\mu)^n = A_\mu(\rho_n = na)$
  - Goldstone field is related to A_ρ $\quad \phi^n = A_\rho(\rho_n)\, a$
  - $f_n, g_n \to f(\rho), g(\rho)$ specify the metric

$$g_n^2(\vec{\partial}\phi_n - \overrightarrow{A}_{n+1} + \overrightarrow{A}_n)^2 \to g^2(\rho)F_{\rho i}F_{\rho i} \sim h^{\rho\rho}h^{ii}F_{\rho i}F_{\rho i}$$

E.o.M: Maxwell eqn. for $A_M(\rho)$ in curved space with boundary condition

$$A_\mu(\rho \to \infty) = V_\mu \qquad \partial_t A_\mu(\rho \to 0) = \text{dissipative current}$$

Generality of Hidden Gauge Symmetry Model

- K=1: MIS equation
- Continuum limit with specific $f(u), g(u)$: precisely corresponds to holography models for charged fluid
  - $\rho \to \infty$, holography boundary; $\rho \to 0$, blackhole horizon
- Similar philosophy for re-formulating kinetic theory (preliminary)

Nonlinear Bosonization of Fermi Surfaces: The Method of Coadjoint Orbits

Luca V. Delacrétaz,[1,2] Yi-Hsien Du,[1] Umang Mehta,[1,3] and Dam Thanh Son[1,2,4]

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

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Re-discovery of symmetries in collisionless kinetic theory

Canonical Transformation and Hidden Gauge Symmetry

- Symmetry of (collision-less) kinetic eqn.:

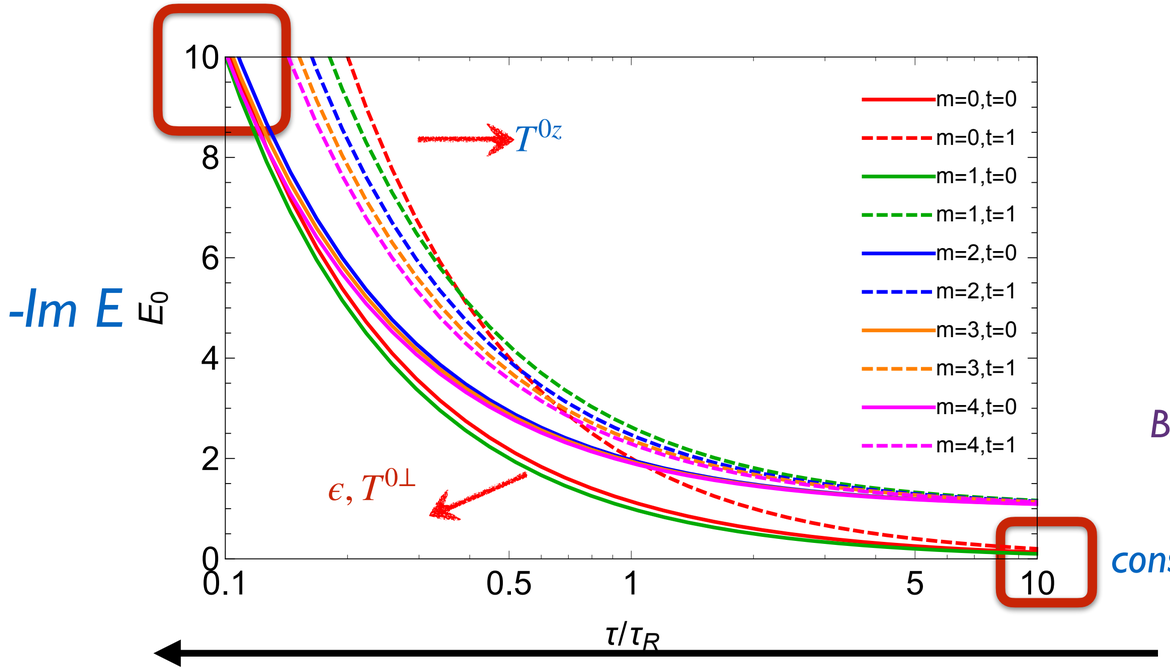
$$\vec{x} \to \vec{x} - \epsilon \nabla_{\vec{p}} G(\vec{x}, \vec{p}) \,, \qquad \vec{p} \to \vec{p} + \epsilon \nabla_{\vec{x}} G(\vec{x}, \vec{p})$$

- Can be viewed as hidden gauge symmetry by generalizing label n to momentum $\vec{p}$

- Implementing collision as spontaneous symmetry breaking of C.T.

Hydrodynamization as Symmetry breaking

Early time slow modes



-Im E E_0

Brewer-Weiyao Ke-Li Yan-YY, PRD Letter 2024

conserved densties

far-from-equilibrium (large $1/\tau$*)* *near-equilibrium (small* $1/\tau$*)*

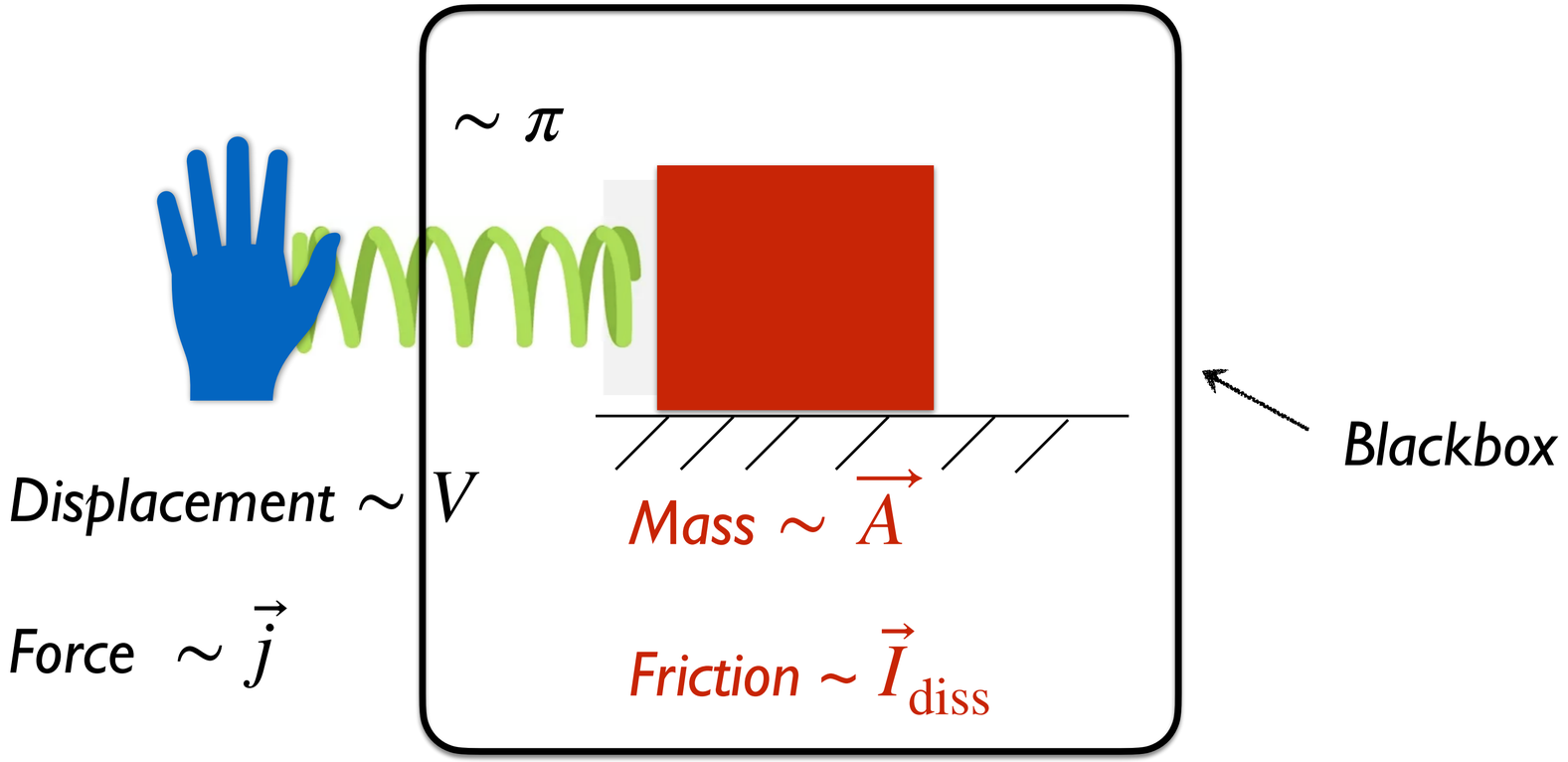
- Far-from-equilibrium: hidden symmetry approximately restored
- Hydro. modes stand out when hidden symmetry is breaking

Summary and Outlook

- Introducing hidden gauge symmetry to describe non-hydro.
  - Distinct theories (like holo. and kinetic eqn.) can be unified in a same conceptual framework
  - Insight into emergence of hydro.
  - Collectivity in small system as a manifestation of hidden symmetry
- Model for generative AI?

Back-up

Blackbox Analogy



- A blackbox containing a mass on a rough surface. An observer outside measures the force by stretching the string attached to the mass

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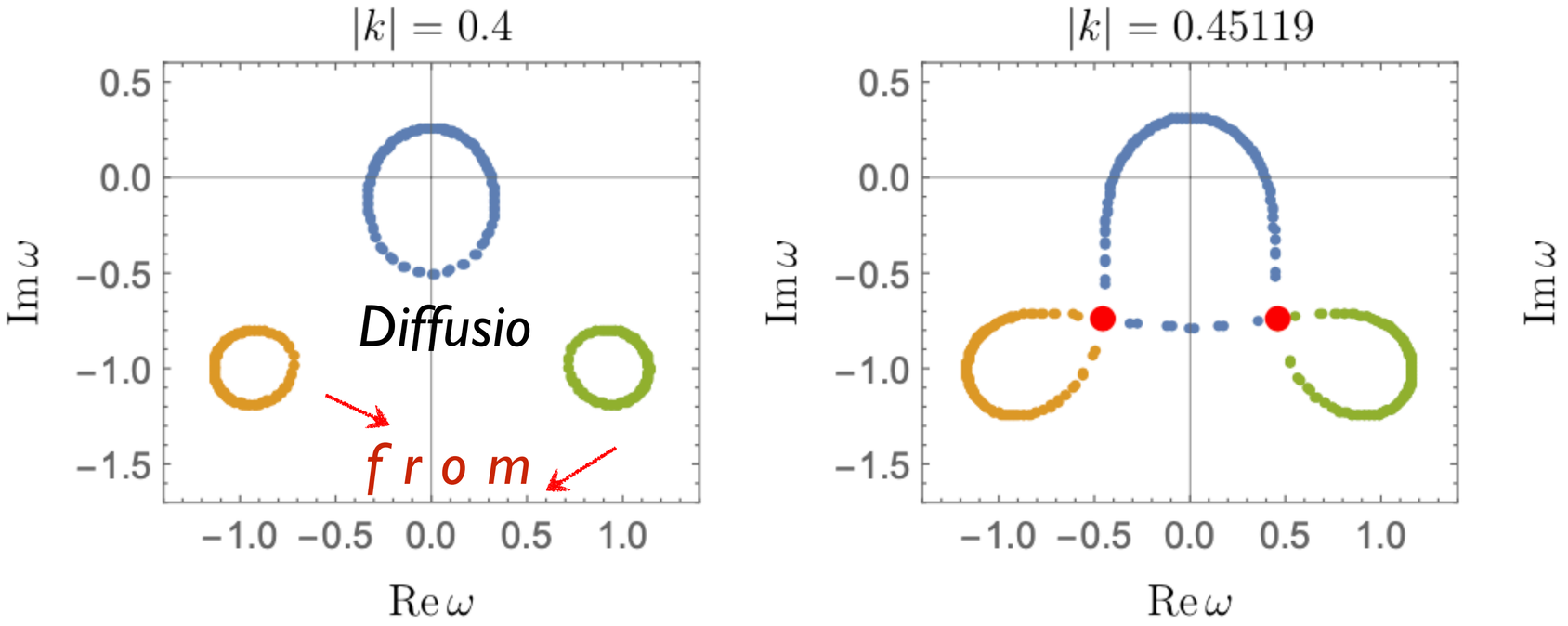
Many recent developments on emergent symmetries in collisionless kinetic theory.

Non-hydro. modes ~ Massive Vector Bosons



The trajectory of the poles of $\langle JJ \rangle$ (longitudinal channel) with varying complex k for K=2