

ASPECTS OF SCHWINGER-KELDysh HYDRODYNAMICS

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[2009.01356] AJ, P Kovtun

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THE BIG PICTURE

- Quantum field theory is a robust framework to construct physical models describing high-energy and condensed matter systems.
- The conventional formulation of quantum field theory is only suitable to study fluctuations around the vacuum state. Particularly, it is not suitable to probe a many-body system in a finite temperature state.
- Models describing equilibrium phenomena at finite temperature can be formulated within the framework of euclidean statistical field theory.
- A systematic field theoretic understanding of non-equilibrium phenomena is still unavailable.



HYDRODYNAMICS

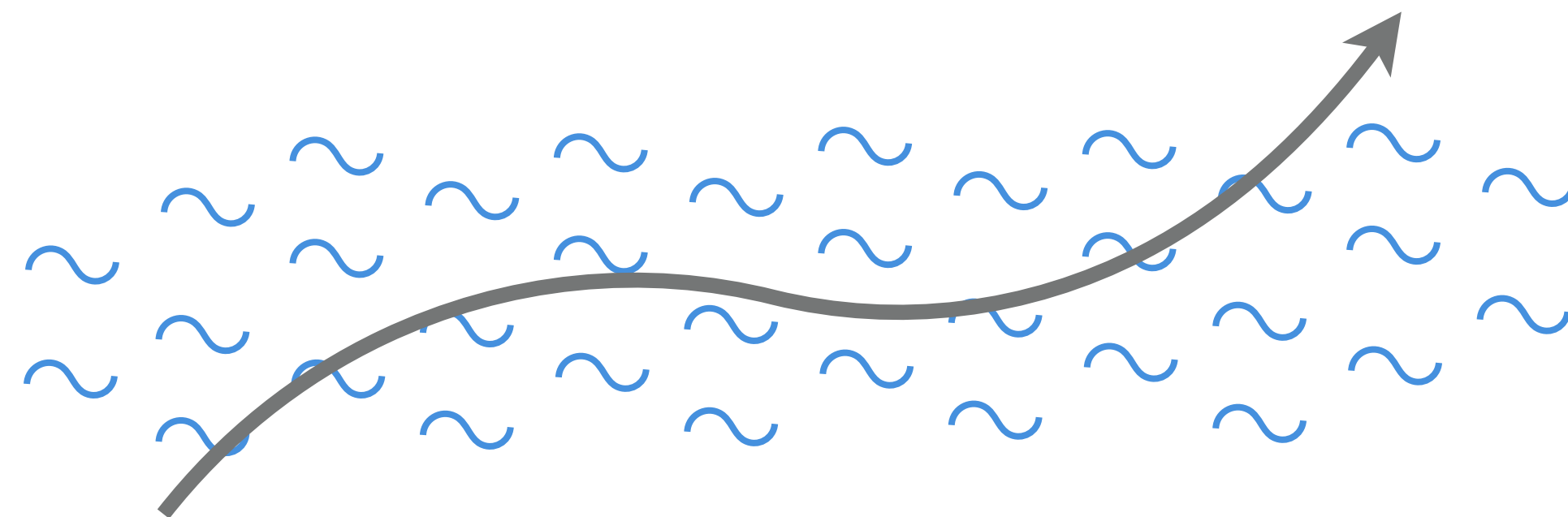


- Hydrodynamics is a **universal** low-energy effective description for many-body systems at finite temperature that allows us to perturbatively depart from equilibrium.
- At macroscopic scales, all the microscopic excitations have effectively dissipated and the dynamics is dominated by the macroscopic conserved charges (e.g. energy, momentum, particle number) that cannot dissipate locally.
- Hydrodynamics is described by **transport coefficients** (e.g. viscosities, conductivity) that characterise how fluxes (e.g. energy current, stress tensor, particle flux) respond to variations in the conserved densities.
- Dynamic evolution of the conserved charges is governed by the respective conservation equations.

$$\partial_t n = - \partial_i J^i[n, \partial n, \partial^2 n, \dots], \quad J^i = - \sigma(n) \partial^i \mu(n) + \dots$$

STOCHASTIC CONTAMINATION

- The **classical** formulation of hydrodynamics based on conservation equations is too simple.
- The non-linear hydrodynamic equations account for mutual interactions between conserved charge modes, but not for possible interactions with the background **thermal noise** arising due to the ignored microscopic excitations.



- These effects lead to physically observable signatures in the low-energy spectrum, known as long-time tails, that cannot be predicted by classical hydrodynamics. [1]

STOCHASTIC HYDRODYNAMICS

- In the **stochastic** formulation of hydrodynamics, one models the microscopic excitations as random Gaussian noise in the hydrodynamic equations. [1]
- The strength of the noise is fixed in terms of the dissipative transport coefficients (e.g. viscosities, conductivity) by the fluctuation-dissipation theorem.
- Physical observables are obtained by performing statistical averages over all **stochastic noise** configurations.
- One can set up a systematic Feynman diagram approach to compute the effects of noisy interactions on the hydrodynamic correlation functions order-by-order in **stochastic loops**.



LONG-TIME TAILS

- Taking stochastic interactions into account, one finds that the low-energy behaviour of hydrodynamic response functions changes qualitatively.
- Ignoring energy-momentum interactions, the retarded Green's function of number density behaves as [1]

$$\frac{\omega}{k^2} \text{Im } G_{nn}^R(\omega, k) = \sigma + a_{cl} \omega^{1/2} k^2 + \dots \quad a_{cl} = \frac{\chi^{7/2} \lambda^2 T}{32\pi \sigma^{3/2}}$$
$$\chi = \frac{\partial n}{\partial \mu} \quad \lambda = \frac{1}{\chi} \frac{\partial(\sigma/\chi)}{\partial \mu}$$

- In the time domain, this implies that the late-time retarded correlation functions fall off polynomially, as opposed to exponentially predicted by classical hydrodynamics.



BEYOND STOCHASTIC HYDRODYNAMICS

- Stochastic hydrodynamics is **not exhaustive**.
- Fluctuation-dissipation theorem uniquely fixes **at most** three-point interactions between noise and hydrodynamic modes. Higher-point interactions are still left ambiguous.
- These ambiguities can be parametrised by new **stochastic transport coefficients** that are invisible in classical hydrodynamics.
- Assuming thermal noise to be Gaussian still leaves room for stochastic transport coefficients.
- Stochastic transport coefficients contaminate hydrodynamic response functions at sub-leading order in frequency/momentum via stochastic loop corrections.



BEYOND STOCHASTIC HYDRODYNAMICS

- Ignoring energy-momentum interactions, two- and three-point density retarded Green's functions behave as

$$\frac{\omega}{k^2} \text{Im } G_{nn}^R(\omega, k) = \sigma + a_{cl} \omega^{1/2} k^2 + \dots + a_{st} \omega^2 k^4 + \dots$$

$$\begin{aligned} \frac{\omega^2}{k^4} \text{Re } G_{nnn}^R(\omega, k; -\omega/2, -k/2; -\omega/2, -k/2) \\ = b_{cl} + \dots + b_{st} \omega^{5/2} + \dots \end{aligned}$$

- a_{cl} and b_{cl} are fixed in terms of classical thermodynamic and transport coefficients: $n(\mu)$ and $\sigma(\mu)$.
- a_{st} and b_{st} are **not fixed** in terms of classical coefficients, but get contaminated by stochastic transport coefficients.



GENERAL LESSONS

- Hydrodynamics, classical or stochastic, is **not a universal** description of long-range late-time physics.
- Late-time correlation functions can get contaminated by stochastic transport coefficients pertaining to the microscopic structure of the many-body system.
- Stochastic transport coefficients leave physically measurable low-energy signatures in response functions that can be probed by carefully designed experiments.
- Similar stochastic transport coefficients will arise in any **non-equilibrium finite-temperature** high-energy or condensed matter system including superfluids, viscoelastic fluids, crystals, magnetohydrodynamics etc.



OUTLINE

- Introduction
- Classical and stochastic hydrodynamics
- Effective field theory for hydrodynamics
- Signatures of stochastic transport coefficients
- Outlook



CLASSICAL AND STOCHASTIC HYDRODYNAMICS

review



CLASSICAL HYDRODYNAMICS

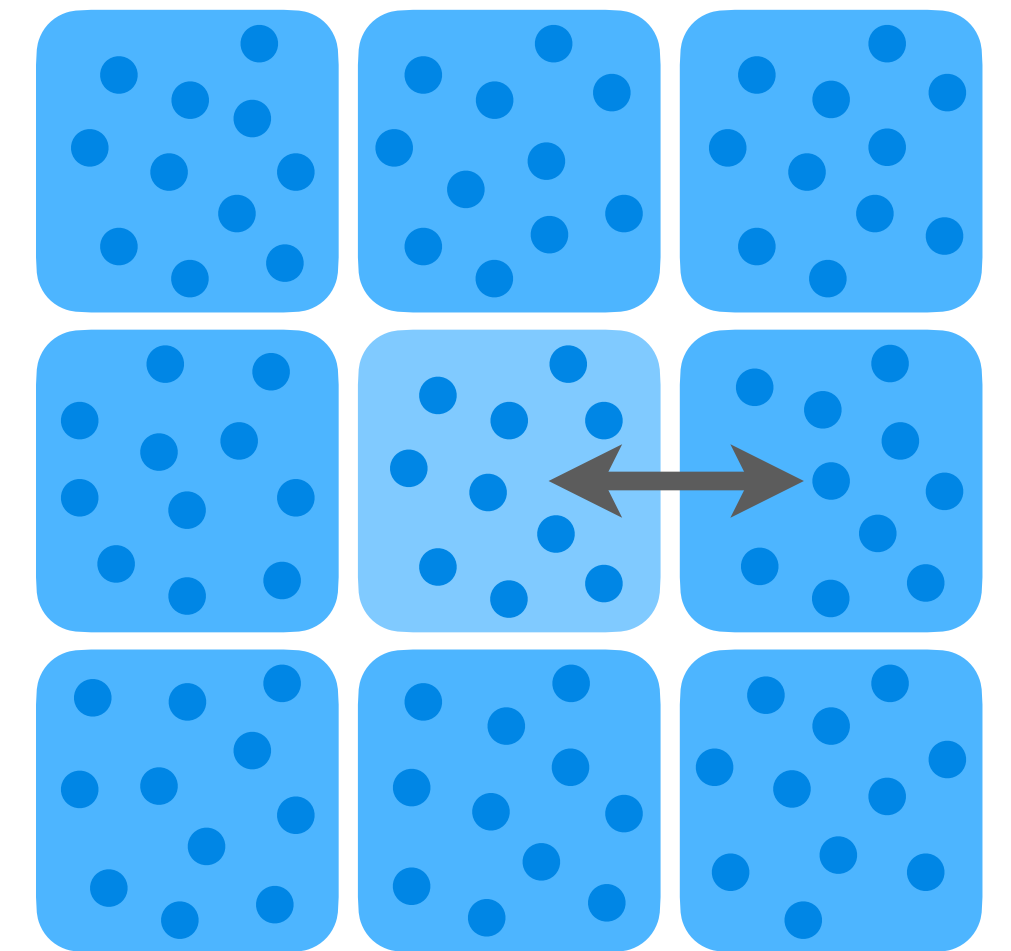
- The dynamical equations of classical hydrodynamics are a set of **conservation equations** associated with the global symmetries that the system enjoys.

$$\text{Energy-momentum: } \partial_\mu T^{\mu\nu} = 0 \quad \text{Charge/particle number: } \partial_\mu J^\mu = 0$$

- The dynamical fields are the thermodynamic conjugates of the conserved densities: fluid velocity u^μ ($u^\mu u_\mu = -1$), temperature T , and chemical potential μ .
- We can introduce background sources: metric $g_{\mu\nu}$ and gauge field A_μ .
- Hydrodynamic systems are characterised by their **constitutive relations**

$$T^{\mu\nu}[u, T, \mu; g, A; \partial], \quad J^\mu[u, T, \mu; g, A; \partial]$$

organised in a derivative expansion and constrained by phenomenological requirements such as symmetries, local second law of thermodynamics, and Onsager reciprocity relations.



CONSTITUTIVE RELATIONS & CLASSICAL EVOLUTION

- For simplicity, we will ignore energy-momentum conservation and focus only on a single conserved U(1) charge. Generalisation to full hydrodynamics is straight-forward. [1]
- Constitutive relations at first order in derivatives are given as

$$J^t = n(\mu), \quad J^i = -\sigma(\mu)(\partial^i \mu - E^i)$$

$$E_i = \partial_i A_t - \partial_t A_i$$

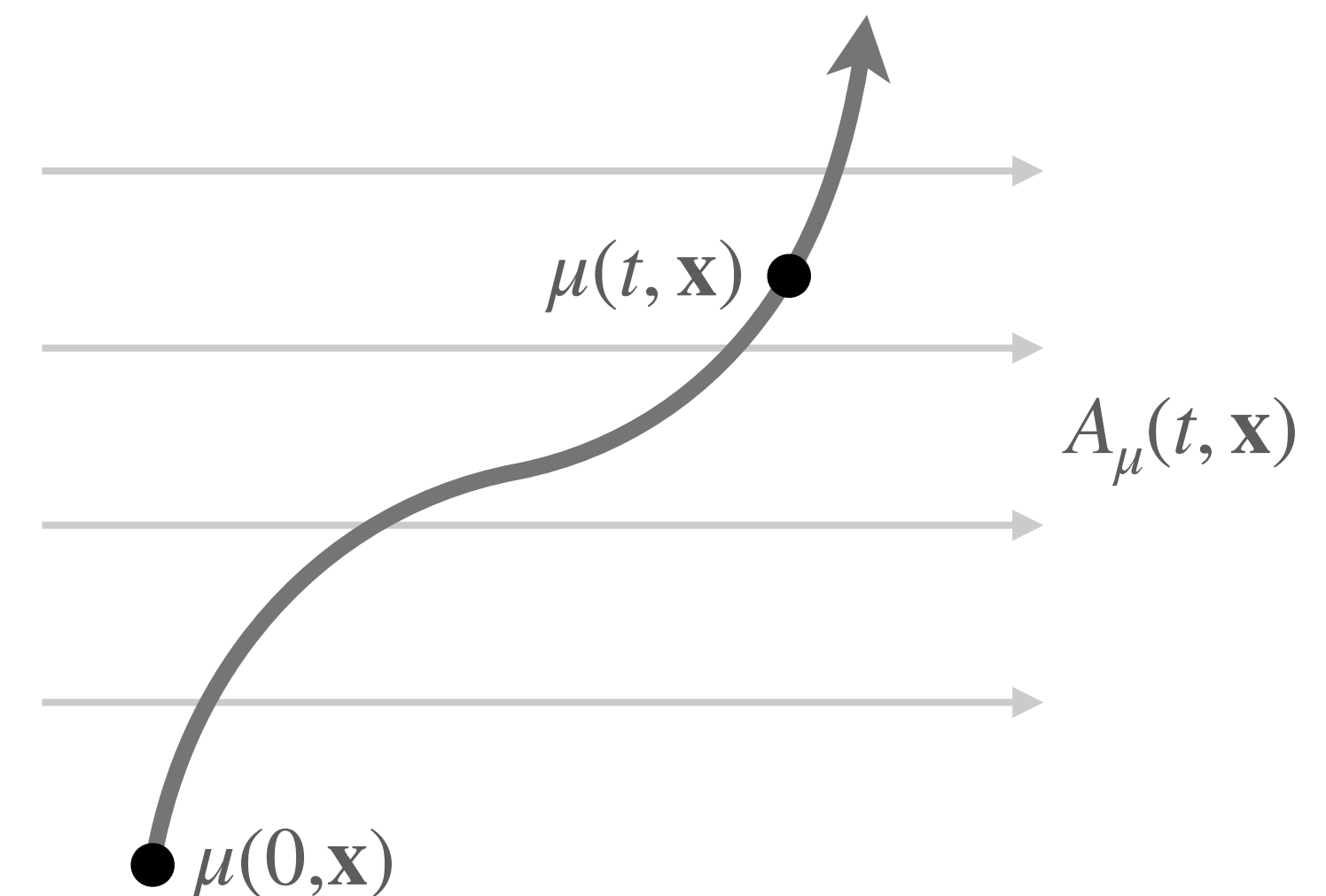
Second law of thermodynamics requires that $\sigma(\mu) \geq 0$.

- Classical trajectory of $n(t, \mathbf{x})$ or $\mu(t, \mathbf{x})$ for a given initial state $n(0, \mathbf{x})$ or $\mu(0, \mathbf{x})$ and background field configuration $A_\mu(t, \mathbf{x})$ is given by the dynamical equation

$$\partial_t n(\mu) = \partial_i (\sigma(\mu)(\partial^i \mu - E^i)) .$$

- We can define the classical expectation values

$$\langle J^\mu(x) \rangle_A^{cl} = J^\mu|_{\mu=\mu_{cl}[A]}$$



RESPONSE FUNCTIONS

- Response functions capture how hydrodynamic observables respond to fluctuations in the background sources. [1]

$$G_{J^\mu J^\nu J^\rho \dots}^{R,cl}(x, y_1, y_2, \dots) = \left(\frac{\delta}{\delta A_\nu(y_1)} \frac{\delta}{\delta A_\rho(y_2)} \dots \right) \langle J^\mu(x) \rangle_A^{cl} \Big|_{A=0}$$

$$\langle J^\mu(x) \rangle_A = \langle J^\mu(x) \rangle_{A=0} + \int d^4 y_1 G_{J^\mu J^\nu}^R(x, y_1) A_\nu(y_1) + \frac{1}{2} \int d^4 y_1 d^4 y_2 G_{J^\mu J^\nu J^\rho}^R(x, y_1, y_2) A_\nu(y_1) A_\rho(y_2) + \dots$$

- For example, two- and three-point classical response functions of density, in momentum space, are given as

$$G_{nn}^{R,cl}(\omega, k) = \frac{ik^2 \sigma}{\omega + iDk^2} + \dots$$

$$\chi = \partial n / \partial \mu$$

$$D = \sigma / \chi$$

$$G_{nnn}^{R,cl}(\omega, k; -\omega/2, -k/2; -\omega/2, -k/2) = \frac{ik^4 \chi^2 D^2 / 4 (\lambda k^2 - \tilde{\lambda} (k^2 - 2i\omega/D))}{(\omega + iDk^2)(\omega + iDk^2/2)^2} + \dots$$

$$\lambda = \chi^{-1} \partial D / \partial \mu$$

$$\tilde{\lambda} = \chi^{-2} \partial \sigma / \partial \mu$$

- Ellipsis denote contributions coming from higher derivative terms the constitutive relations. Note that such corrections will always be **analytic**, i.e. positive integer powers of ω, k^2 .

STOCHASTIC HYDRODYNAMICS

- Stochastic effects in hydrodynamics can be modelled by random microscopic noise contributions to the constitutive relations [1]

$$J_r^t = n(\mu), \quad J_r^i = -\sigma(\mu)(\partial^i \mu - E^i) + r^i \quad \langle J^\mu(x) \rangle_{A,r}^{cl} = J^\mu|_{\mu=\mu_{st}[A,r]}$$

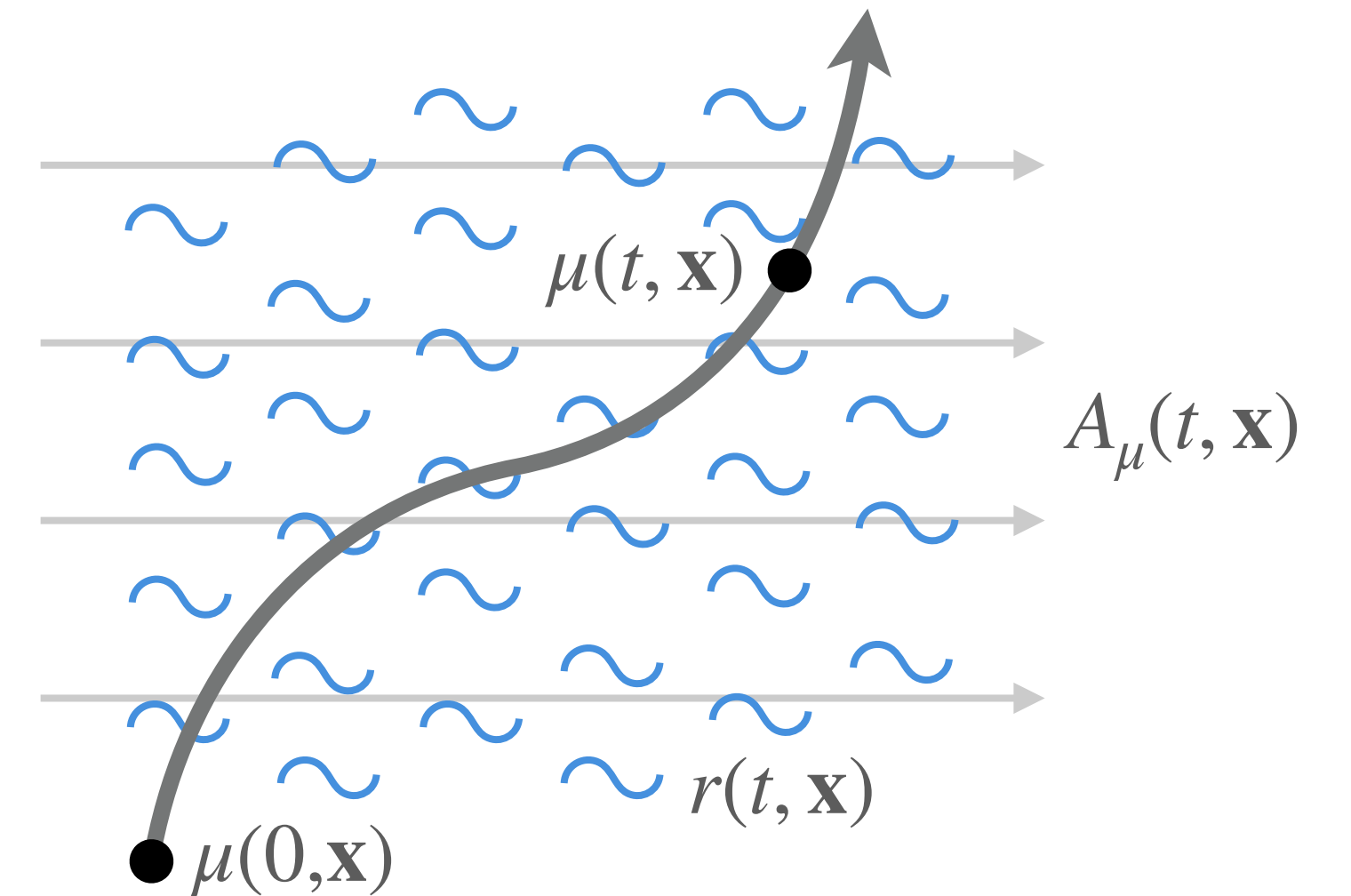
- Expectation values can be computed by averaging over all noise configurations

$$\langle J^\mu(x) \dots \rangle_A^{st} = \frac{1}{Z_0} \int \mathcal{D}r_i \langle J_r^\mu(x) \dots \rangle_{A,r}^{cl} \exp \left(-\frac{1}{4} \int d^4y r^i r^j \lambda_{ij}^{-1}[\mu_{st}[A, r], A] \right)$$

$\lambda^{ij}[\mu, A]$ is an undetermined Gaussian weight factor for stochastic noise correlations.

- This can be used to derive stochastic corrections to classical response functions

$$G_{J^\mu J^\nu J^\rho \dots}^{R,st}(x, y_1, y_2, \dots) = \left(\frac{\delta}{\delta A_\nu(y_1)} \frac{\delta}{\delta A_\rho(y_2)} \dots \right) \langle J^\mu(x) \rangle_A^{st} \Big|_{A=0}$$



FLUCTUATION-DISSIPATION THEOREM

- The Gaussian weight factor can be expanded in derivatives

$$\lambda^{ij}[\mu, A] = C(\mu) \delta^{ij} + \vartheta_1(\mu) \partial^i \mu \partial^j \mu + \dots$$

- Two-point **fluctuation-dissipation theorem** requires the symmetric correlation functions to be fixed in terms of the retarded one

$$\langle J^\mu(\omega, k) J^\nu(-\omega, -k) \rangle = \frac{2T}{\omega} \text{Im} G_{J^\mu J^\nu}^R(\omega, k) \quad \implies \quad C(\mu) = T \sigma(\mu)$$

- Similar fluctuation-dissipation theorem exists for three-point functions. However at four- or higher-points, retarded correlation functions are no longer enough to fix the symmetric correlation function. [1]
- Therefore, $\vartheta_1(\mu)$ is **not fixed** by the fluctuation-dissipation theorem. It is an example of a **stochastic transport coefficient**.

EFFECTIVE FIELD THEORY FOR HYDRODYNAMICS

effective action formalism



SCHWINGER-KELDYSH FRAMEWORK

- Schwinger-Keldysh (SK) framework for hydrodynamics provides a systematic prescription to introduce (non-Gaussian) stochastic noise into the hydrodynamic setup. [1]
- Non-linear fluctuation-dissipation theorem requirements are built into the SK framework.
- The framework proposes a set of effective low-energy degrees of freedom and associated symmetries that can be used to construct an effective action for hydrodynamics from scratch.
- This can be used to systematically classify the possible stochastic transport coefficients and contribute their contribution to hydrodynamic observables.

[1] Crossley, Glorioso, Liu [1511.03646]; Haehl, Loganayagam, Rangamani [1511.07809]; Jensen, Pinzani-Fokeeva, Yarom [1701.07436]



EFFECTIVE ACTION FOR STOCHASTIC HYDRODYNAMICS

- We can manipulate the correlation functions to obtain [1]

$$\begin{aligned}
 \langle J^\mu(x) \dots \rangle_A^{st} &= \frac{1}{Z_0} \int \mathcal{D} r_i \langle J_r^\mu(x) \dots \rangle_{A,r}^{cl} \exp \left(-\frac{1}{4} \int d^4y r^i r^j \lambda_{ij}^{-1} \right) \\
 &= \left(\frac{-i\delta}{\delta A_{a\mu}(x)} \dots \right) \ln \int \mathcal{D} r_i \mathcal{D} \varphi_a \mathcal{D} \mu \exp \left(i \int d^4y \left(-\varphi_a \partial_\mu J_r^\mu + A_{a\mu} J_r^\mu + \frac{i}{4} r^i r^j \lambda_{ij}^{-1} \right) \right) \Big|_{A_a=0} \\
 &= \left(\frac{-i\delta}{\delta A_{a\mu}(x)} \dots \right) \ln \int \mathcal{D} r_i \mathcal{D} \varphi_a \mathcal{D} \mu \exp \left(i \int d^4y \left((\partial_\mu \varphi_a + A_{a\mu}) J^\mu + (\partial_i \varphi_a + A_{ai}) r^i + \frac{i}{4} r^i r^j \lambda_{ij}^{-1} \right) \right) \Big|_{A_a=0} \\
 &= \left(\frac{-i\delta}{\delta A_{a\mu}(x)} \dots \right) \ln \int \mathcal{D} \varphi_a \mathcal{D} \mu \exp \left(i \int d^4y \underbrace{\left((\partial_\mu \varphi_a + A_{a\mu}) J^\mu + i \lambda^{ij} (\partial_i \varphi_a + A_{ai}) (\partial_j \varphi_a + A_{aj}) \right)}_{S[\mu, \varphi_a; A, A_a]} \right) \Big|_{A_a=0}
 \end{aligned}$$

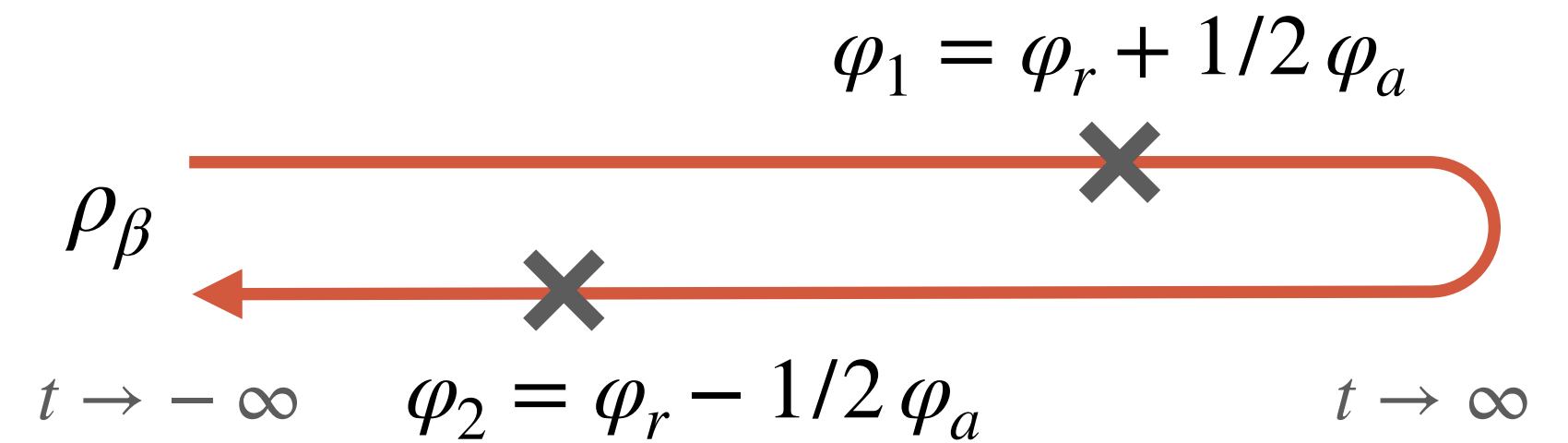
- Retarded response functions can be computed via

$$G_{J^\mu J^\nu J^\rho \dots}^{R,st}(x, y_1, y_2, \dots) = \left(\frac{-i\delta}{\delta A_{a\mu}(x)} \frac{\delta}{\delta A_\nu(y_1)} \frac{\delta}{\delta A_\rho(y_2)} \dots \right) \ln \int \mathcal{D} \varphi_a \mathcal{D} \mu \exp \left(i S[\mu, \varphi_a; A, A_a] \right) \Big|_{A, A_a=0}$$

SCHWINGER-KELDysh HYDRODYNAMICS

- Fundamental fields in SK hydrodynamics are the phase field φ_r and the associated noise φ_a .
- We can also introduce two copies of background gauge fields $A_{a\mu}$, $A_{r\mu}$ coupled to the physical current J_r^μ and the associated noise J_a^μ respectively. [1]

$$J_r^\mu = \frac{\delta S}{\delta A_{a\mu}}, \quad J_a^\mu = \frac{\delta S}{\delta A_{r\mu}}$$



- Chemical potential is defined as $\mu = \mu_0 + \partial_t \varphi_r + A_{rt}$. The classical constitutive relations are obtained via $J^\mu = J_r^\mu |_{\varphi_a, A_a \rightarrow 0, A_r \rightarrow A}$.
- The effective action $S[\varphi_r, \varphi_a; A_r, A_a]$ must satisfy various global and local symmetries/constraints. In particular, the discrete **KMS symmetry** implements fluctuation-dissipation theorem [2]

$$\begin{aligned} \varphi_r(x) &\rightarrow -\varphi_r(-x), & \varphi_a(x) &\rightarrow -\varphi_a(-x) + i/T \partial_t \varphi_{r\mu}(-x) \\ A_{r\mu}(x) &\rightarrow A_{r\mu}(-x), & A_{a\mu}(x) &\rightarrow A_{a\mu}(-x) - i/T \partial_t A_{r\mu}(-x) \end{aligned}$$

EFFECTIVE ACTION

- Classical hydrodynamics (diffusion) is completely characterised by the Lagrangian [1]

$$\mathcal{L}_1 = n(\mu) B_{at} + iT\sigma(\mu) B_{ai} \left(B_a^i + \frac{i}{T} \partial_t B_r^i \right)$$

$$B_{a\mu} = \partial_\mu \varphi_a + A_{a\mu}$$

$$B_{r\mu} = \partial_\mu \varphi_r + A_{r\mu}$$

This is the same Lagrangian derived using stochastic hydrodynamics.

$$\mu = B_{rt} = \partial_t \varphi_r + A_{rt}$$

$$\partial_t B_{ri} = \partial_i \mu + \partial_t A_{ri} - \partial_i A_{rt}$$

- This Lagrangian is KMS-invariant up to a total derivative

$$\mu(x) \rightarrow \mu(-x), \quad B_{r\mu}(x) \rightarrow B_{r\mu}(-x), \quad B_{a\mu}(x) \rightarrow B_{a\mu}(-x) - \frac{i}{T} \partial_t B_{r\mu}(-x).$$

- The SK symmetries allow extra terms in the Lagrangian that do not contribute to the classical constitutive relations [2]

$$\mathcal{L}_2 = i\vartheta_1(\mu) B_{ai} B_{aj} \left(\partial_t B_r^i \partial_t B_r^j - \delta^{ij} \partial_t B_r^k \partial_t B_{rk} \right) + iT^2 \vartheta_2(\mu) B_a^i B_{ai} \left(B_a^j + \frac{1}{T} \partial_t B_r^j \right) \left(B_{aj} + \frac{i}{T} \partial_t B_{rj} \right)$$

$\vartheta_1(\mu)$, $\vartheta_2(\mu)$ are stochastic transport coefficients. $\vartheta_2(\mu)$ is non-Gaussian in noise.

SIGNATURES OF STOCHASTIC TRANSPORT COEFFICIENTS

non-universality of hydrodynamics



PERTURBATIVE THEORY OF STOCHASTIC FLUCTUATIONS

- We can perturbatively expand the effective action in fluctuations around an equilibrium state

$$n = n_0 + \delta n, \quad \varphi_a, \quad A_{r\mu} = 0, \quad A_{a\mu} = 0$$

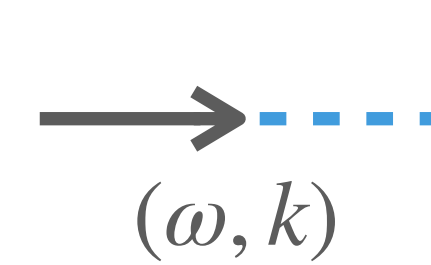
- The **classical** part of the effective action expanded to quadratic order in fields leads to the free theory

$$\mathcal{L}_1^{\text{free}} = -\varphi_a (\partial_t \delta n - D \partial^2 \delta n) + iT \sigma \partial^i \varphi_a \partial_i \varphi_a$$

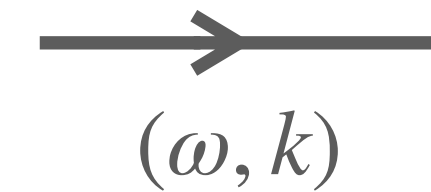
- Expanding to further orders in fields, we lead to the interaction vertices [1]

$$\mathcal{L}_1^{3pt} = \frac{1}{2} \lambda \delta n^2 \partial^2 \varphi_a + i\chi T \tilde{\lambda} \delta n \partial^i \varphi_a \partial_i \varphi_a$$

$$\mathcal{L}_1^{4pt} = \frac{1}{3} \lambda_4 \delta n^3 \partial^2 \varphi_a + i\chi T \tilde{\lambda}_4 \delta n^2 \partial^i \varphi_a \partial_i \varphi_a$$



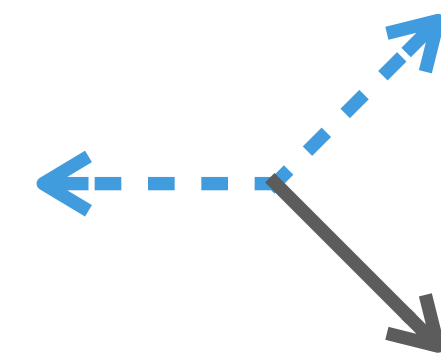
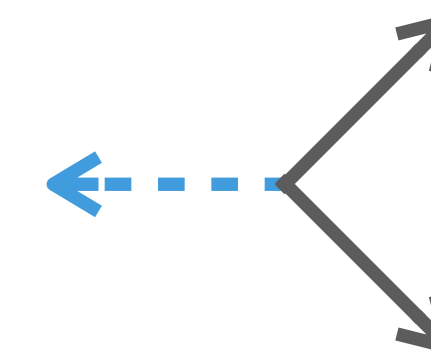
$$\frac{1}{\omega + iDk^2}$$



$$\frac{2T\chi Dk^2}{\omega^2 + D^2k^4}$$

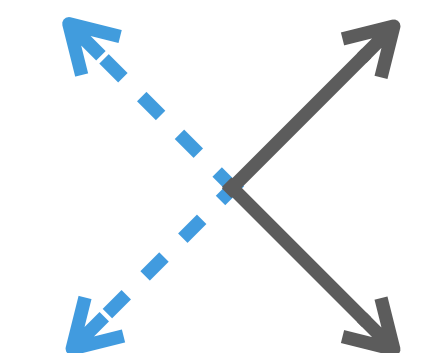
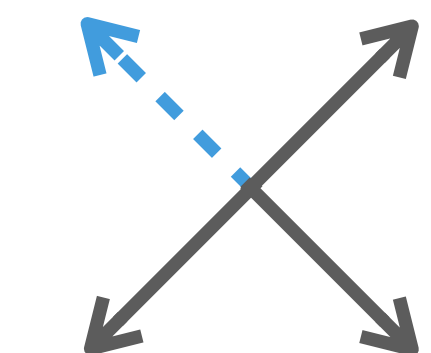
$$D = \sigma/\chi$$

$$\chi = \partial n / \partial \mu$$



$$\lambda = \chi^{-1} \partial D / \partial \mu$$

$$\tilde{\lambda} = \chi^{-2} \partial \sigma / \partial \mu$$



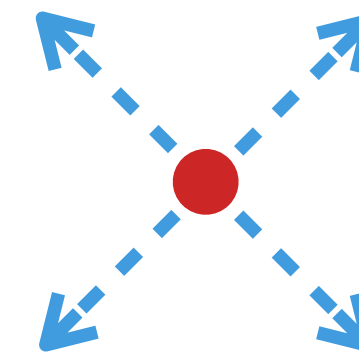
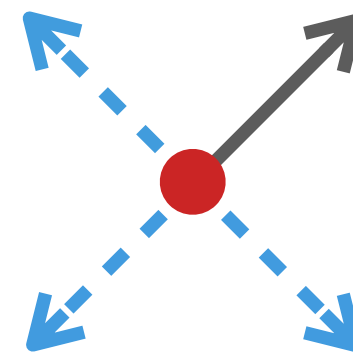
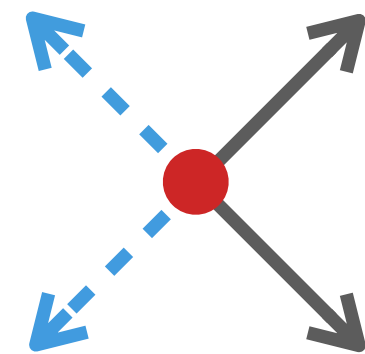
$$\lambda_4 = 1/2 \chi^{-1} \partial \lambda / \partial \mu$$

$$\tilde{\lambda}_4 = 1/2 \chi^{-2} \partial (\chi \tilde{\lambda}) / \partial \mu$$

STOCHASTIC INTERACTIONS

- Stochastic transport coefficients in the effective action lead to the quartic couplings

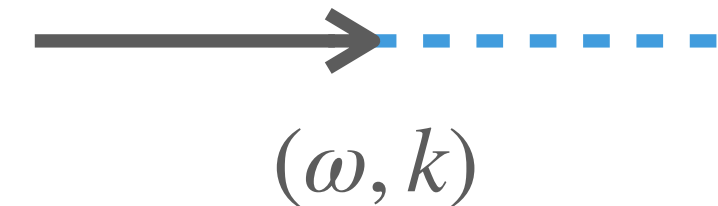
$$\begin{aligned}\mathcal{L}_2^{4pt} = & i\frac{\vartheta_1}{\chi^2}(\partial^i n \partial_i \varphi_a)(\partial^j n \partial_j \varphi_a) - i\frac{\vartheta_1 + \vartheta_2}{\chi^2}(\partial^i n \partial_i n)(\partial^j \varphi_a \partial_j \varphi_a) \\ & - \frac{2T\vartheta_2}{\chi}(\partial^i n \partial_i \varphi_a)(\partial^j \varphi_a \partial_j \varphi_a) + iT^2\vartheta_2(\partial^i \varphi_a \partial_i \varphi_a)(\partial^j \varphi_a \partial_j \varphi_a)\end{aligned}$$



- These couplings do not contribute to tree-level retarded correlation functions.

LONG-TIME TAILS

- ▶ Tree-level retarded two-point Green's function can be recovered using the mixed propagator



$$G_{nn}^R(\omega, k) = \frac{ik^2 \sigma}{\omega + iDk^2} + \dots$$

- ▶ One loop correction to this comes from the diagrams



$$G_{nn}^R(\omega, k) = \frac{ik^2}{\omega + iDk^2} \left(\sigma + \frac{\omega k^2}{\omega + iDk^2} \frac{\lambda^2 \chi^2 T}{32\pi D} \sqrt{k^2 - \frac{2i\omega}{D}} + \dots \right)$$

STOCHASTIC SIGNATURES IN TWO-POINT FUNCTIONS

- The first contribution from stochastic transport coefficients to the retarded two-point Green's functions comes from the two-loop diagrams

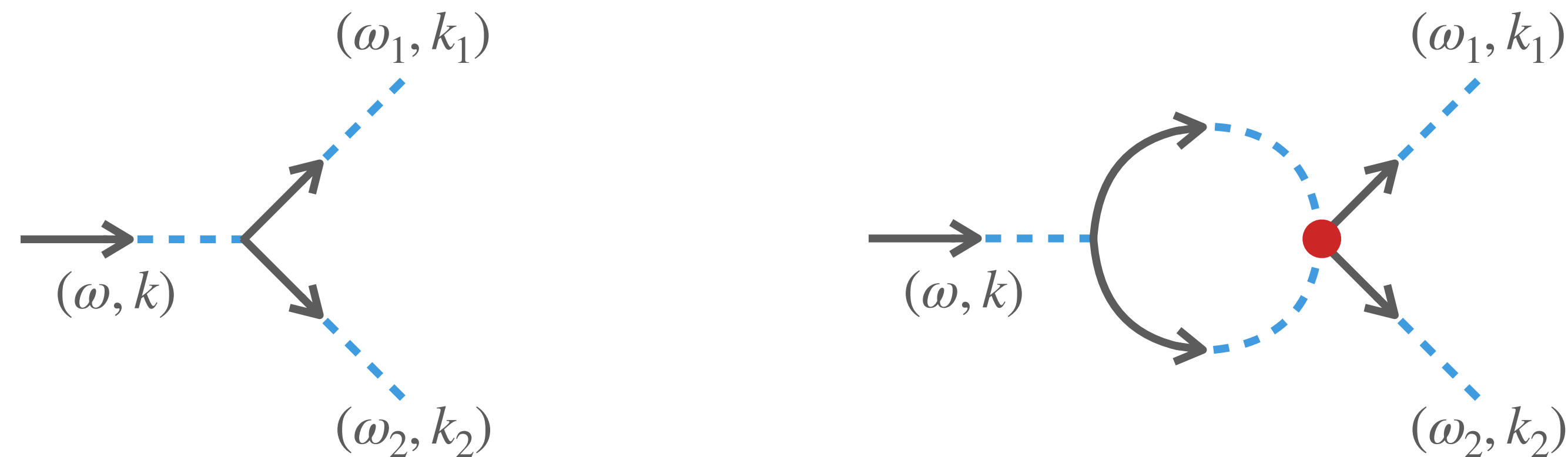


$$G_{nn}^R(\omega, k) = \frac{ik^2}{\omega + iDk^2} \left[\sigma + \frac{\omega k^2}{\omega + iDk^2} \frac{\lambda^2 \chi^2 T}{32\pi D} \sqrt{k^2 - 2i\omega/D} + \dots \right. \\ \left. - \frac{\omega k^2 T \lambda^2}{1024\pi^2 D^2} (k^2 - 2i\omega/D) \left(\frac{1/6 \vartheta_1 k^4}{\omega + iDk^2} + \frac{2/3 \vartheta_1 + \vartheta_2}{D^2} (\omega + iDk^2) \right) + \dots \right]$$

- We see that stochastic transport coefficients contaminate conductivity at the order $\omega^2 k^4$.

STOCHASTIC SIGNATURES IN THREE-POINT FUNCTIONS

- Retarded three-point function gets a contribution from stochastic transport coefficients due to



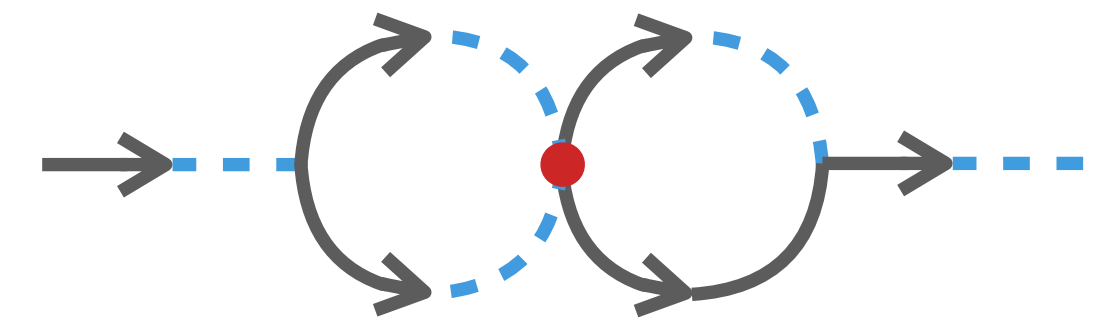
- For $(\omega_1, k_1) = (\omega_2, k_2) = (\omega/2, k/2)$, this evaluates to

$$G_{nnn}^R(\omega, k; -\omega/2, -k/2; -\omega/2, -k/2)$$

$$= \frac{ik^4 \chi^2 D^2}{16F(p)F(p/2)^2} \left[\lambda k^2 - \tilde{\lambda} (k^2 - 2i\omega/D) + \dots \right. \\ \left. - \frac{\lambda \omega^2}{16\pi D^3 \chi^2} \left(\vartheta_2(k^2 - i\omega/D) + \frac{1}{3} \vartheta_1(k^2 - 2i\omega/D) \right) \sqrt{k^2 - 2i\omega/D} + \dots \right]$$

ENHANCING STOCHASTIC SIGNATURES

- Stochastic signatures in hydrodynamic response functions are suppressed in loop and derivative expansion.
- Loop suppression can be mitigated by working in lower spatial dimensions.
- Derivative suppression is relaxed in the presence of momentum interactions due to the convective term.



$\sigma(\omega, k)$	U(1) Model	Incompressible Hydrodynamics
$d = 3$	$\omega^2 k^4$	$\omega^2 k^2$
$d = 2$	$\omega k^4 \log(\omega)^2$	$\omega k^2 \log(\omega)^2$
$d = 1$	k^4	k^2



OUTLOOK



OUTLOOK

- Hydrodynamics, classical or stochastic, is **not a universal** description of long-range late-time physics.
- Late-time correlation functions can get contaminated by stochastic transport coefficients, characteristic of the microscopic structure of the many-body system.
- Stochastic transport coefficients leave physically measurable low-energy signatures in response functions that can be probed by carefully designed experiments.
- Similar stochastic transport coefficients will arise in any **non-equilibrium finite-temperature** high-energy or condensed matter system including superfluids, viscoelastic fluids, crystals, magnetohydrodynamics etc.



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High Energy Physics – Theory

[Submitted on 2 Sep 2020]

Non–universality of hydrodynamics

Akash Jain, Pavel Kovtun

mySpires.

Diffusion

Effective Action

Schwinger-Keldysh

Stochastic Hydrodynamics

We investigate the effects of stochastic interactions on hydrodynamic correlation functions using the Schwinger–Keldysh effective field theory. We identify new "stochastic transport coefficients" that are invisible in the classical constitutive relations, but nonetheless affect the late–time behaviour of hydrodynamic correlation functions through loop corrections. These results indicate that classical transport coefficients do not provide a universal characterisation of long–distance, late–time correlations even within the framework of fluctuating hydrodynamics.

Comments: 5 pages + Supplementary Material

Subjects: **High Energy Physics – Theory (hep-th)**; Statistical Mechanics (cond-mat.stat-mech); High Energy Physics – Phenomenology (hep-ph); Mathematical Physics (math-ph); Fluid Dynamics (physics.flu-dyn)

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