Colliding poles with colliding nuclei

Alexander Soloviev
with Sukrut Mondkar, Ayan Mukhopadhyay and Anton Rebhan

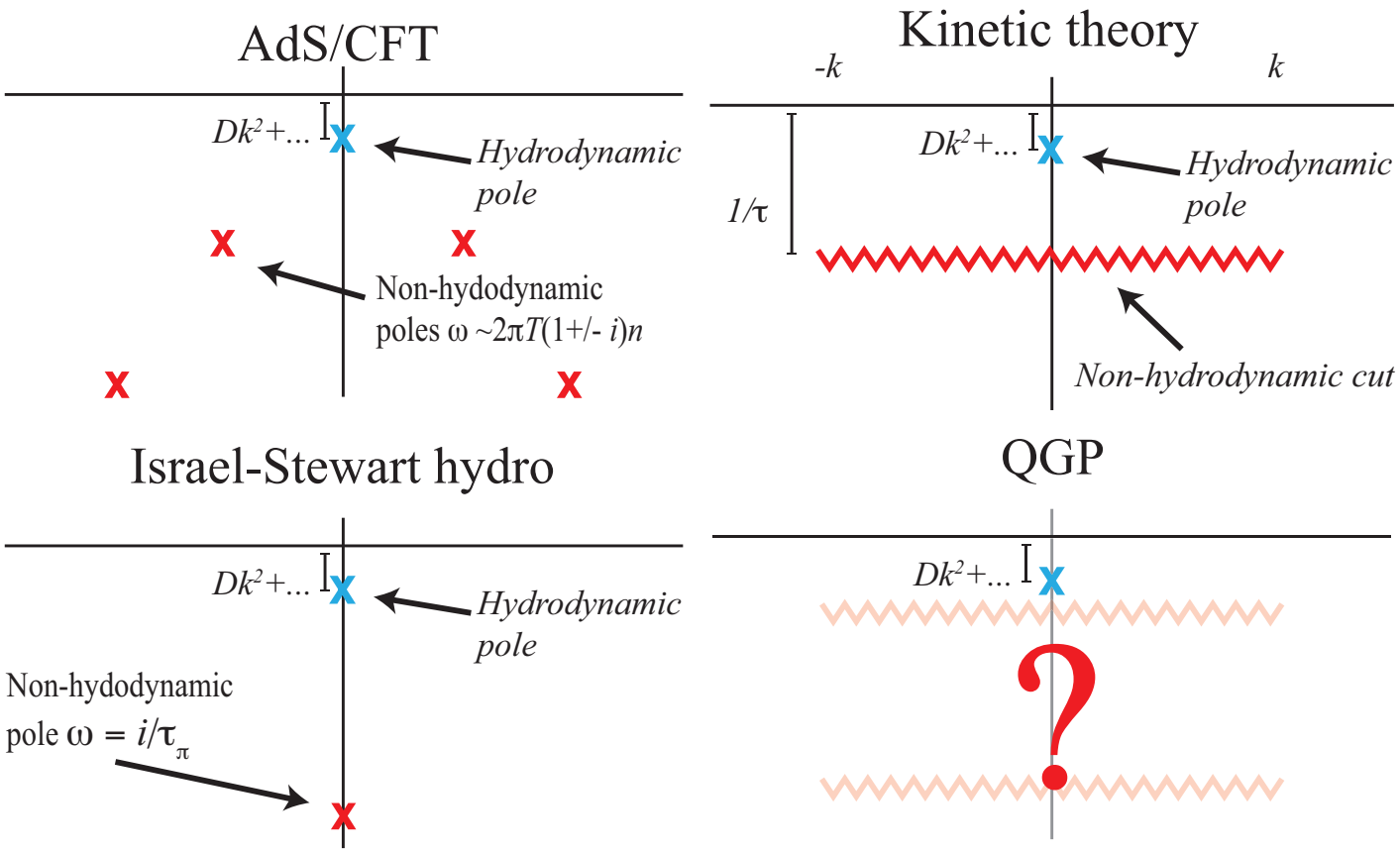
Based on: 2101.10847, 2108.02788, 2111.03640, 2208.XXXXX

Quark Confinement
August 2nd, 2022

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

FWF Der Wissenschaftsfonds.

Complex structure of effective descriptions[1]



Variety of effective theories to describe aspects of QGP, but what is the microscopic structure of QGP?

[1] Kurkela, Wiedemann, Wu 1905.05139

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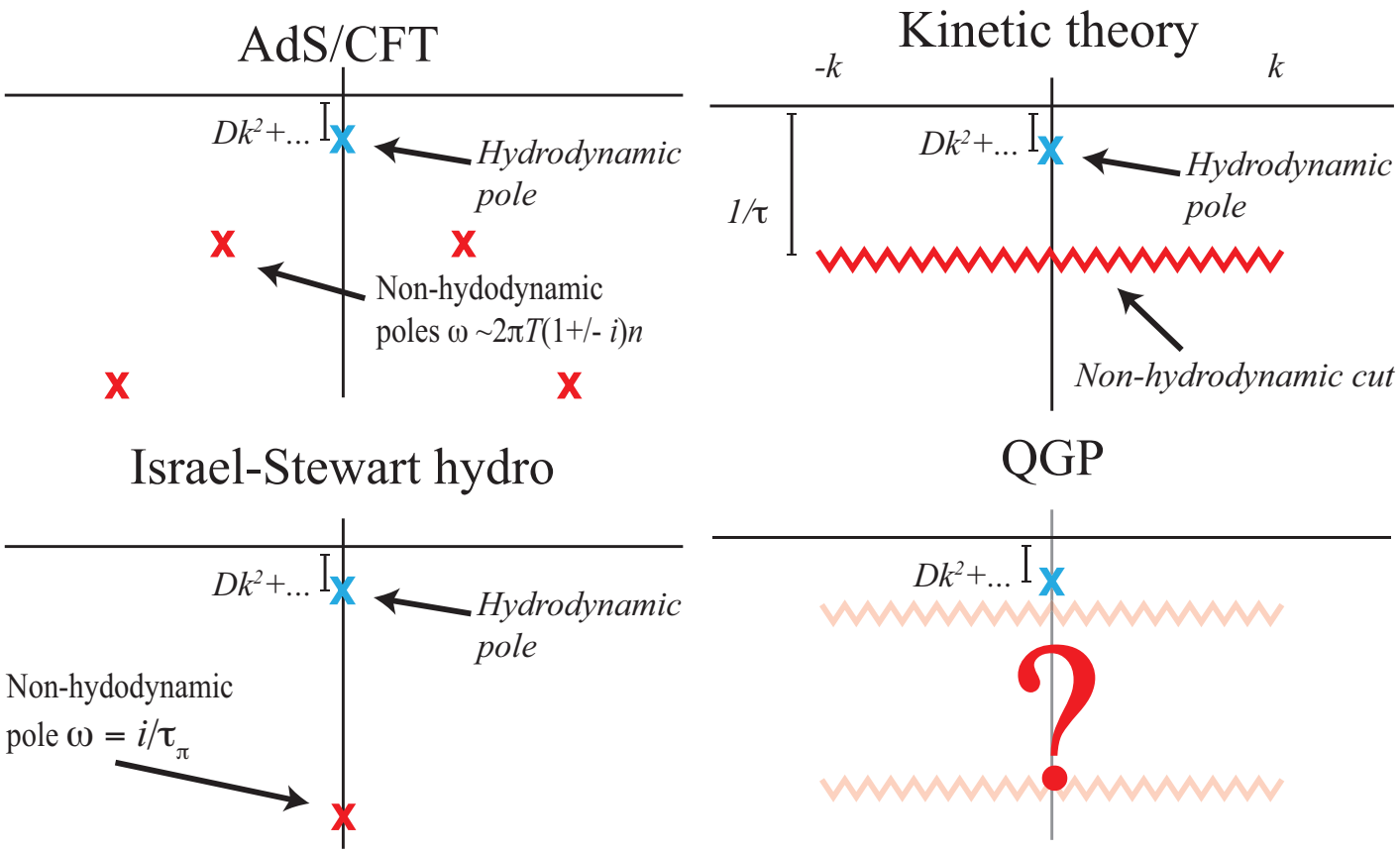

How does analytic structure change near phase transitions?
Poles collide!

[1] Kurkela, Wiedemann, Wu 1905.05139

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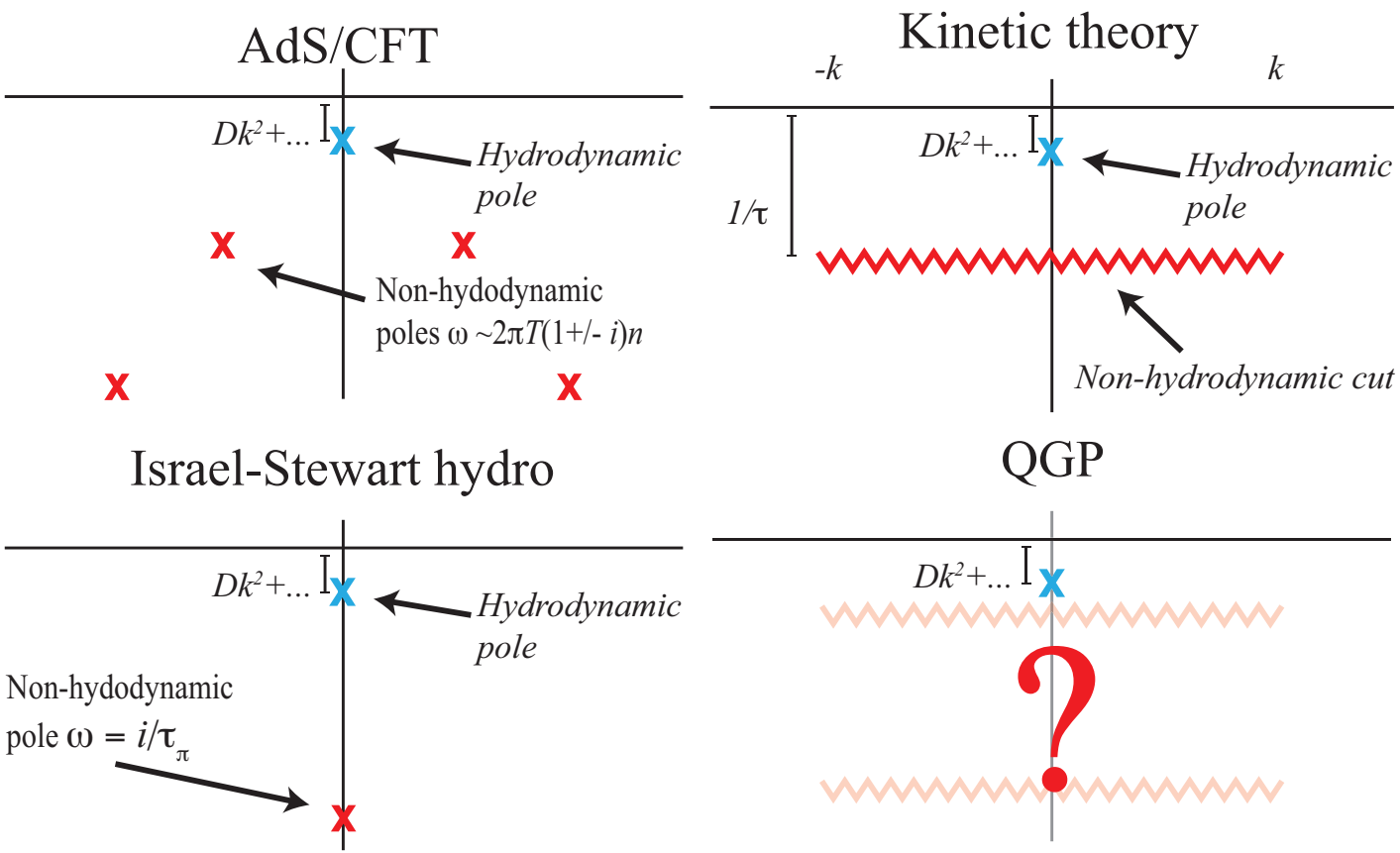

How does one mix effective descriptions?

Use a hybrid description, e.g. **semi-holography**, to see interplay between effective descriptions of QGP.

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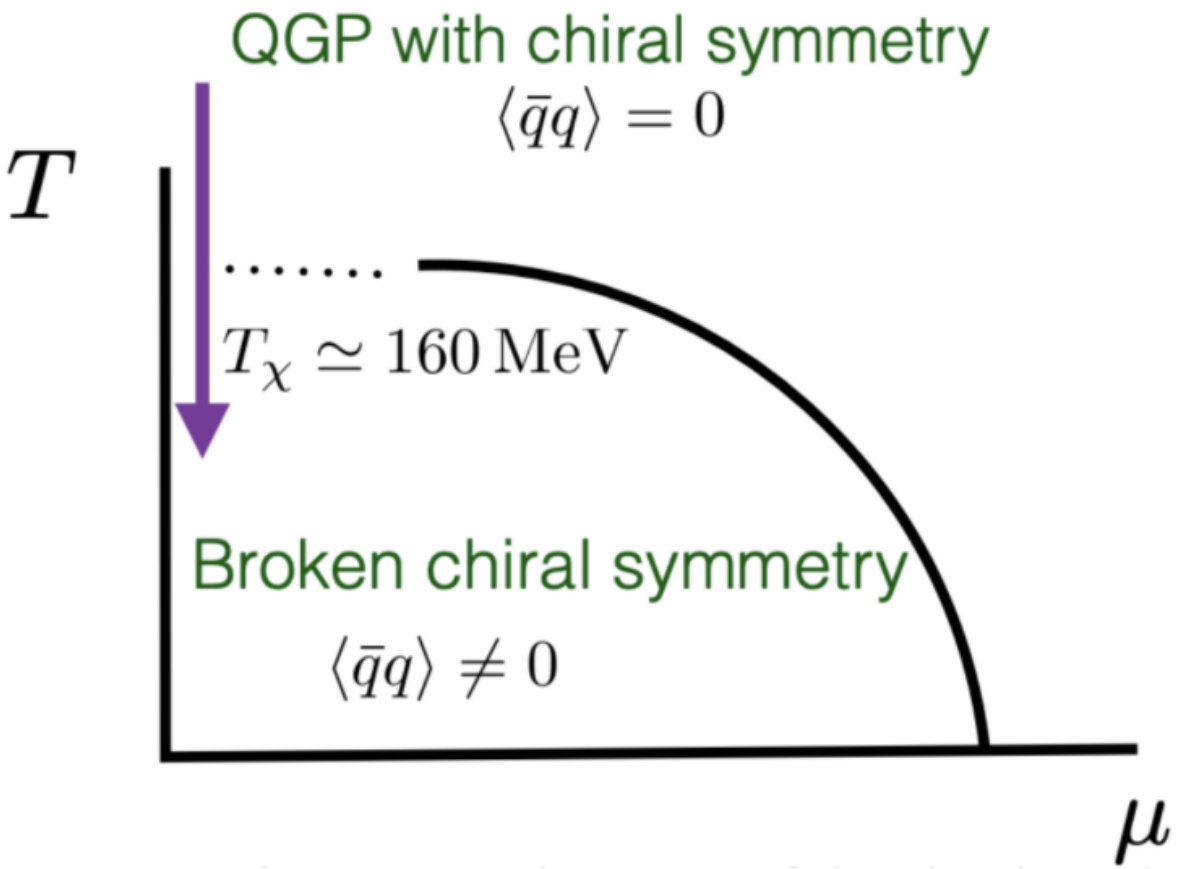
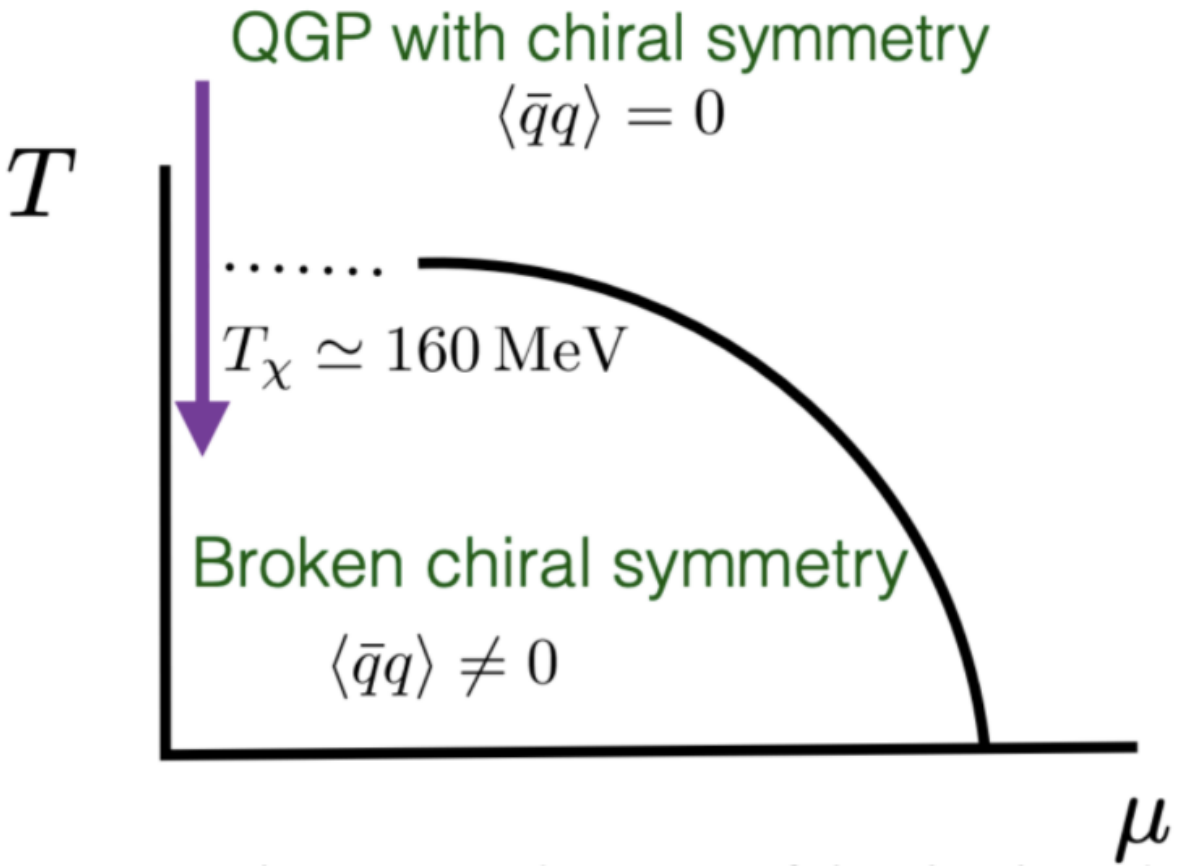
Colliding poles in chiral phase transition

Chiral phase transition



Approximate chiral symmetry $SU(2)_L \times SU(2)_R \sim O(4)$

Chiral phase transition



Approximate chiral symmetry $SU(2)_L \times SU(2)_R \sim O(4)$
Formation of the chiral condensate:

$$\langle \bar{q}q \rangle \to \phi_\alpha = (\underbrace{\sigma}_{\text{order parameter}}, \overbrace{\varphi_i}^{\text{pions}})$$

Model near O(4) critical point[2]

Describe $O(4)$ physics via

$$\mathcal{H} = \int_x p(T) + \frac{\chi_0}{4}\mu_{ab}^2 - \frac{1}{2}\Delta^{\mu\nu} D_\mu \phi_a D_\nu \phi_a + m_0^2 (T - T_c)\phi^2 + \lambda\phi^4 - H\phi$$

- $O(4)$ vector: $\phi_a = (\sigma, \varphi_i)$
- μ_{ab} is the chemical potential

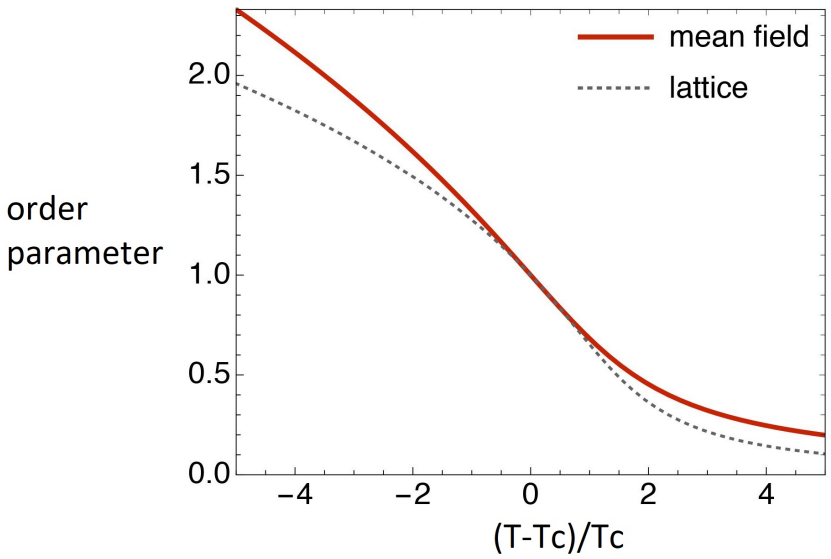
See also talk Friday at 16:10

[2] Rajagopal/Wilczek 9210253,Son/Stephanov 0204226

Example of colliding poles: chiral phase transition[3]

Linearization leads to coupled EOM of pions and chemical potential in mean field with ideal with dissipative corrections:

$$\partial_t \varphi = -\mu_A + \Gamma(\nabla^2 - m^2)\varphi$$
$$\partial_t \mu_A = v^2(-\nabla^2 + m^2)\varphi + D_0 \nabla^2 \mu_A$$



Lattice from: Engels, Vogt 0911.1939, Engels, Karsch 1105.0584

[3] Grossi, AS, Teaney, Yan 2101.10847, Florio, Grossi, AS and Teaney 2111.03640

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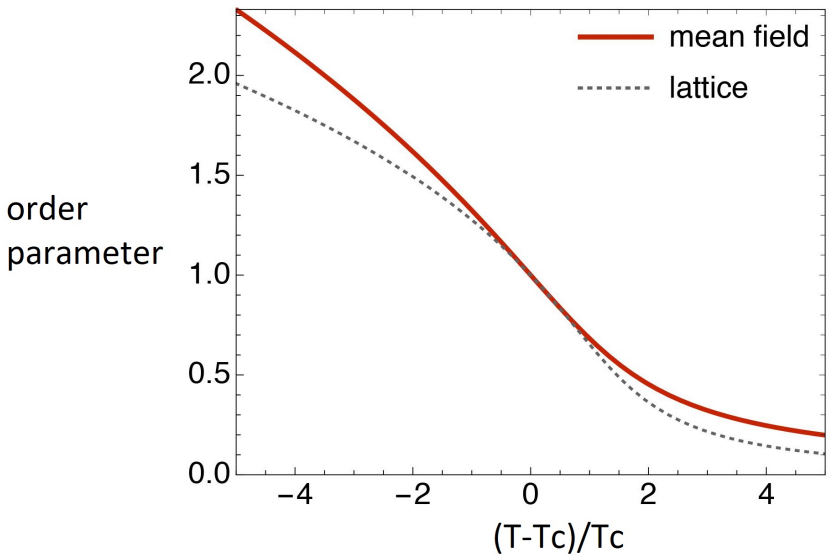

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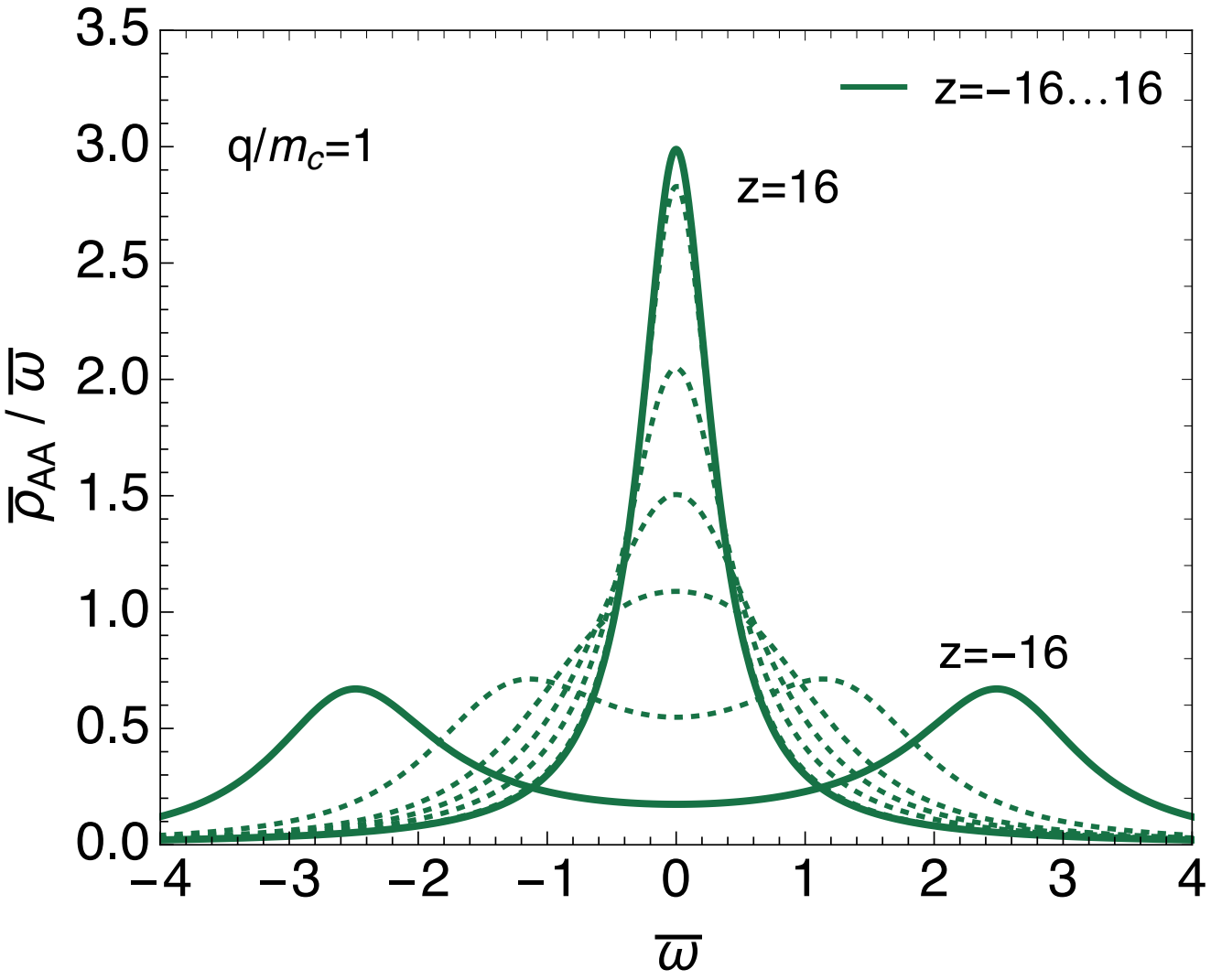
Spectral density for axial charge density-density correlator



$$(\chi_0\omega_k)^{-2}G^{\varphi\varphi}_{sym} = \frac{T}{\omega}\rho_{AA}$$

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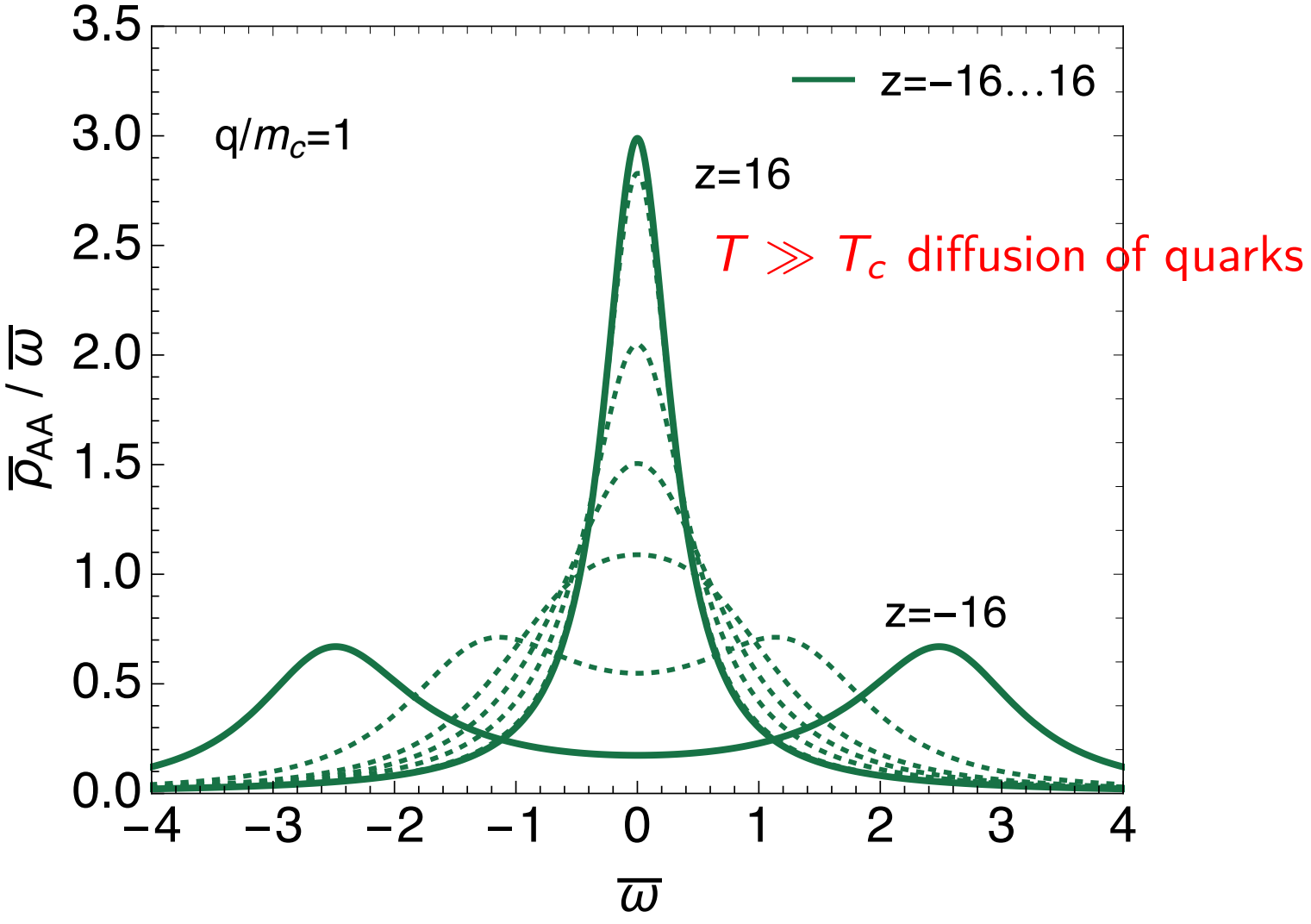
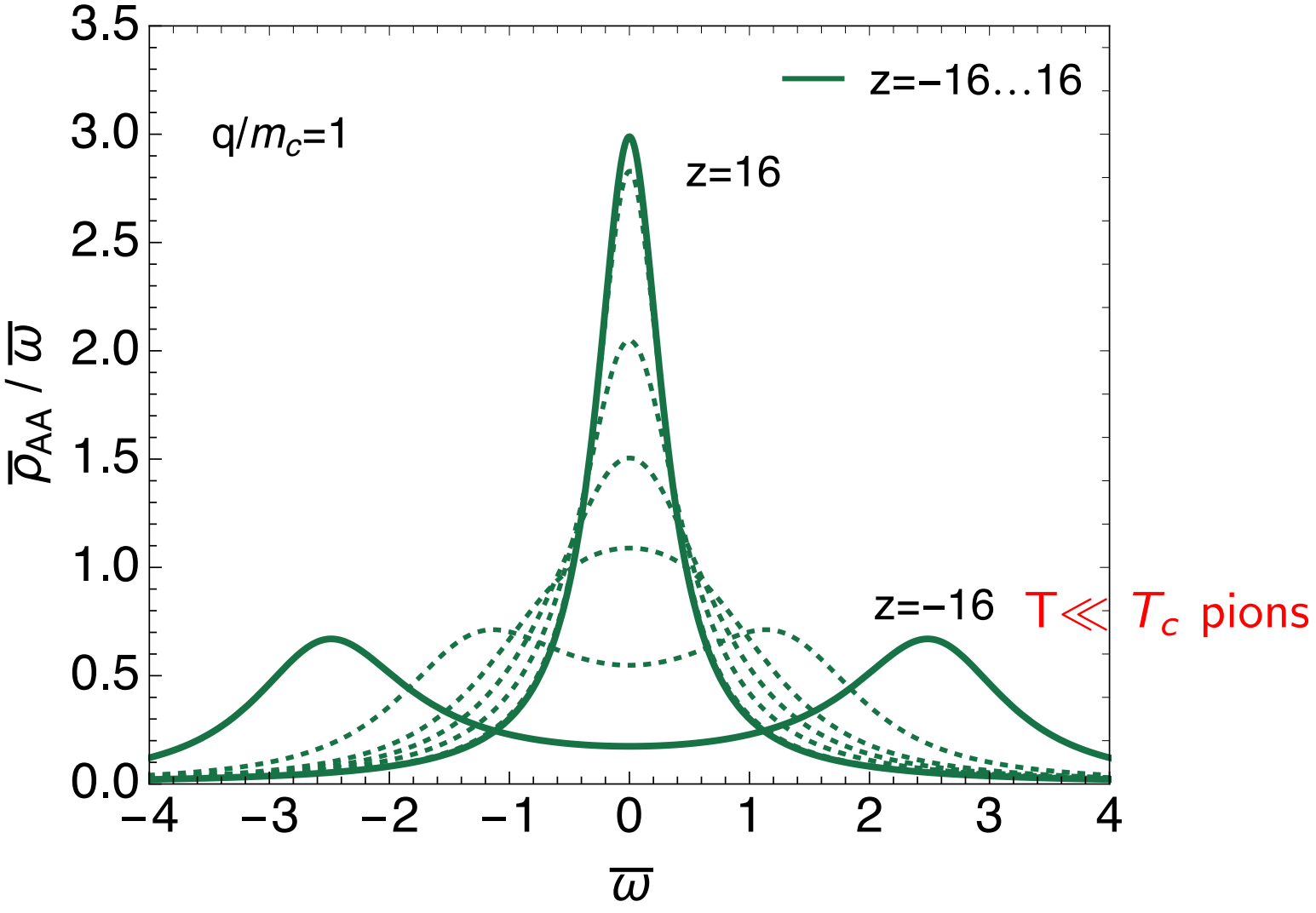


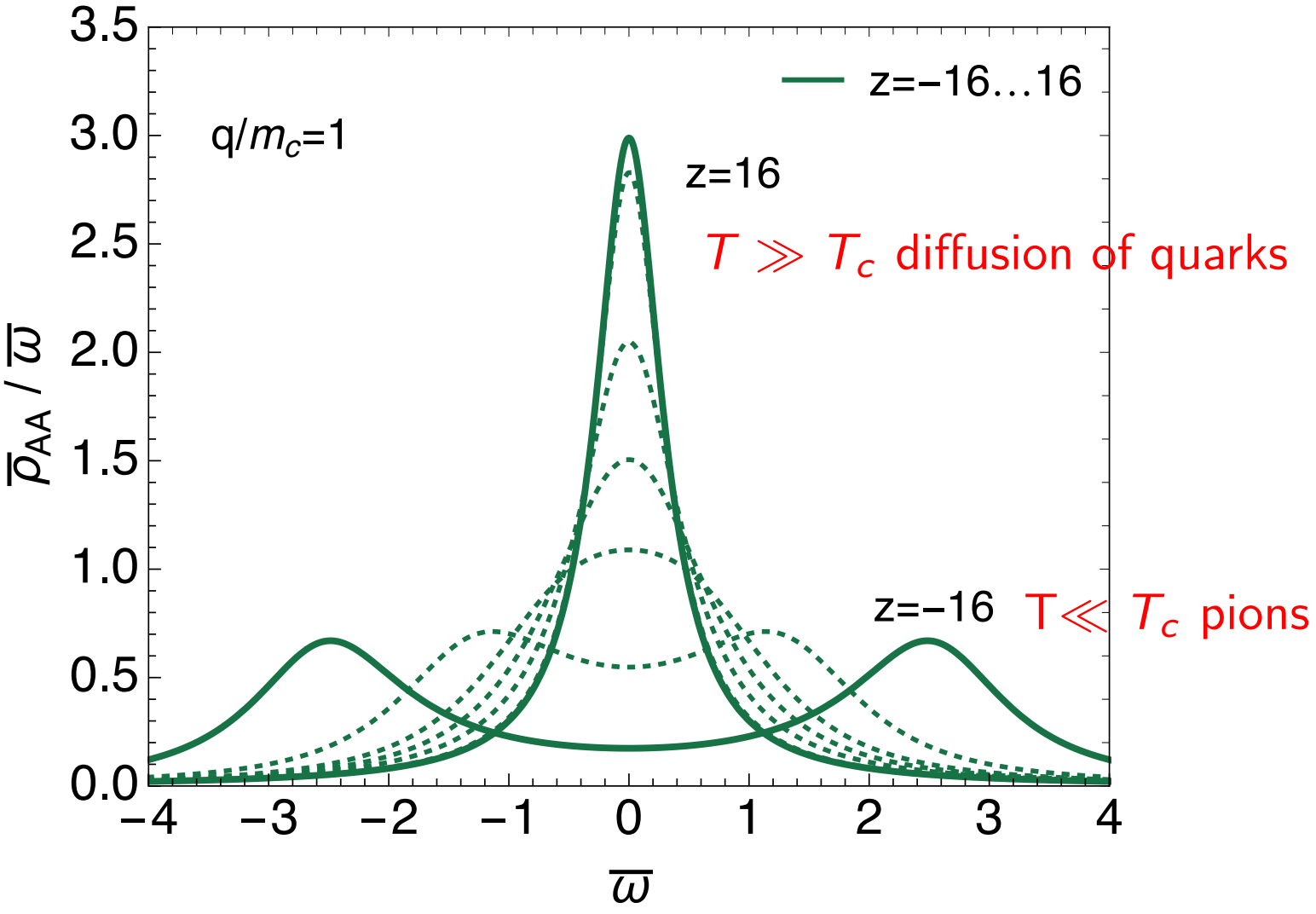
For $z \gg 0$, $\rho_{AA}/\omega \propto Dk^2/(\omega^2 + (Dk^2)^2)$, diffusion of quarks.

Spectral density for axial charge density-density correlator



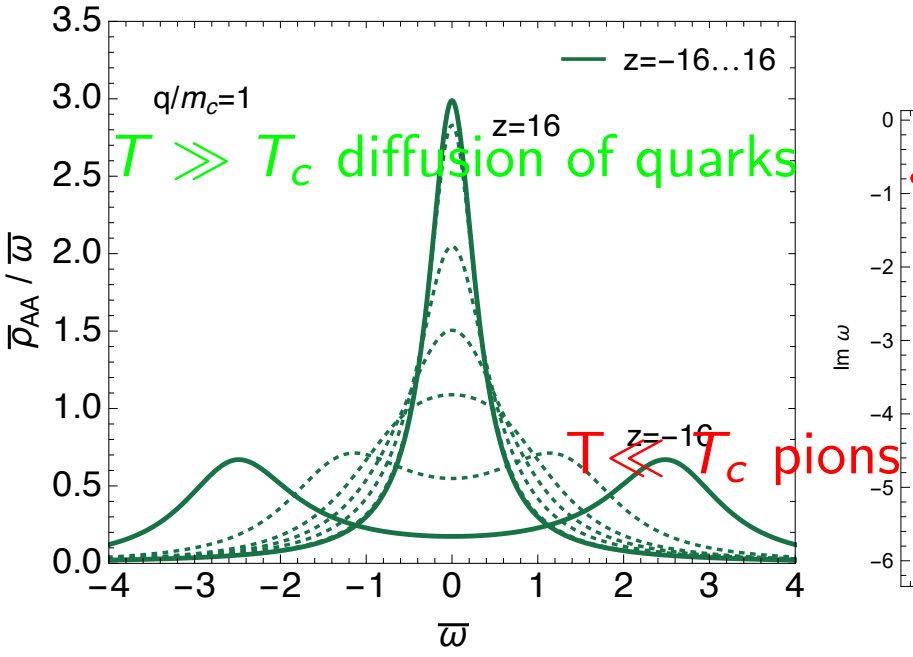
For $z \ll 0$, $\rho_{AA} \propto \Gamma_k/((-\omega+\omega_k)^2+(\Gamma_k/2)^2)$, propagating pions

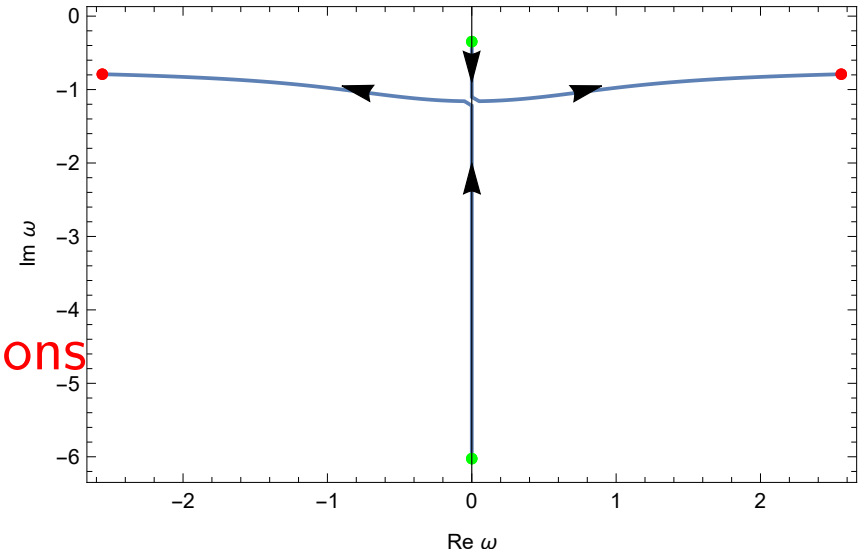
Spectral density for axial charge density-density correlator



Can see hadronization from QGP to soft pions in the propagator!

Collision of poles!





Change of phase seen in collision of poles as temperature drops!

Colliding poles in hybrid description: holography + scalar field

Recap: quasinormal modes in holography

- QNMs describe dissipation of linearized perturbations around equilibrium solutions

$$e^{i\omega t} \sim e^{-t\,\mathrm{Im}\omega} e^{it\,\mathrm{Re}\omega}$$

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- Choose a background, e.g. Eddington-Finkelstein Schwarzschild-AdS$_4$:

$$ds^2 = -\frac{L^2}{r^2}(1 - Mr^3)dt^2 - 2\frac{L^2}{r^2}dtdr + \frac{L^2}{r^2}(dx^2 + dy^2)$$

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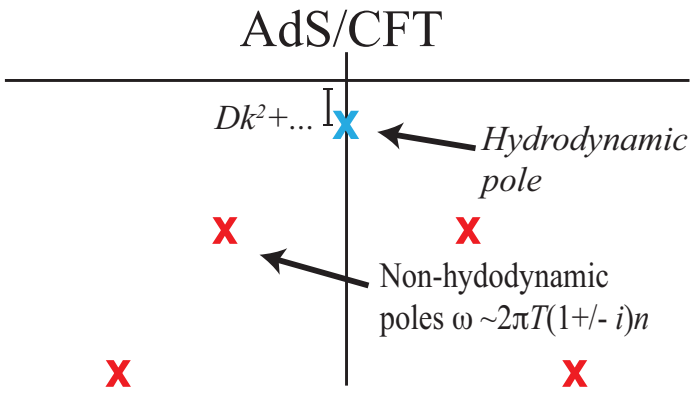
$$\Rightarrow 0 = (Mr^3 - 1)f'' + \frac{Mr^3 + 2 - 2ir\omega}{r} f' + \frac{k^2 r + 2i\omega}{r} f$$



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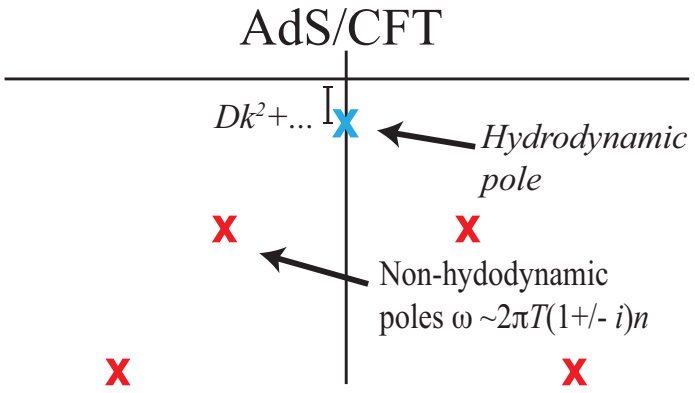
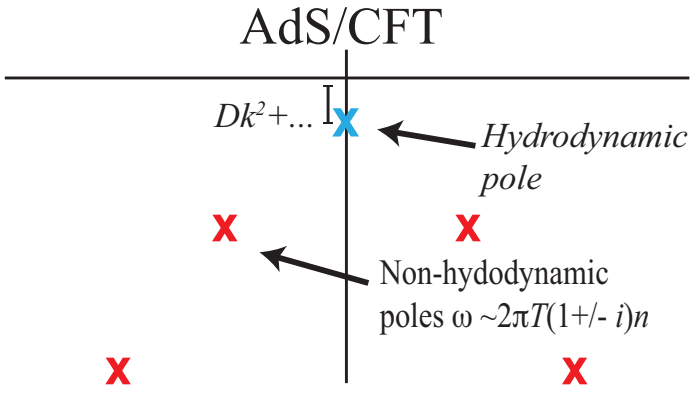


+ scalar field?

Semiholography

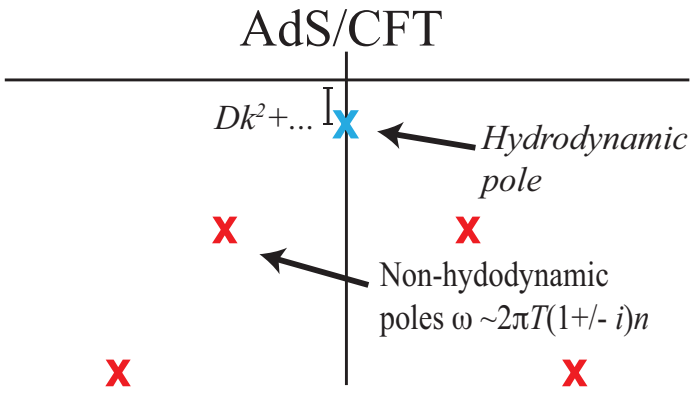


+ scalar field

Use semiholography[4] - framework that mixes holography in the IR with dynamical perturbative degrees of freedom in the UV
Interactions via marginal deformations of couplings

[4] Faulkner, Polchinski 1001.5049; Iancu, Mukhopadhyay 1410.6448; Mukhopadhyay, Preis, Rebhan, Stricker 1512.06445; Banerjee, Gaddam, Mukhopadhyay 1701.01229; Kurkela, Mukhopadhyay, Preis, Rebhan, AS 1805.05213 Ecker, Mukhopadhyay, Preis, Rebhan, AS 1806.01850

Semiholographic model[4]



+ scalar field

$$S = W_{\mathrm{CFT}}[h(x) = -\beta\chi] - \frac{1}{2}\int d^3x \partial_\mu\chi\partial^\mu\chi$$

[4] Mondkar, Mukhopadhyay, Rebhan, AS: 2108.02788

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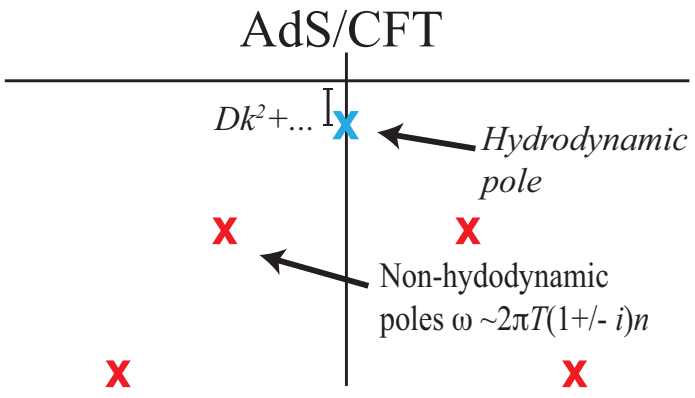

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$$S = W_{\mathrm{CFT}}[h(x) = -\beta\chi] - \frac{1}{2}\int d^3x \partial_\mu\chi\partial^\mu\chi$$

EOMs: $\eta^{\mu\nu}\partial_\mu\partial_\nu\chi = \beta\frac{\delta W_{\mathrm{CFT}}}{\delta h} = \beta \underbrace{\mathcal{H}}_{\text{vev of }\Phi}$

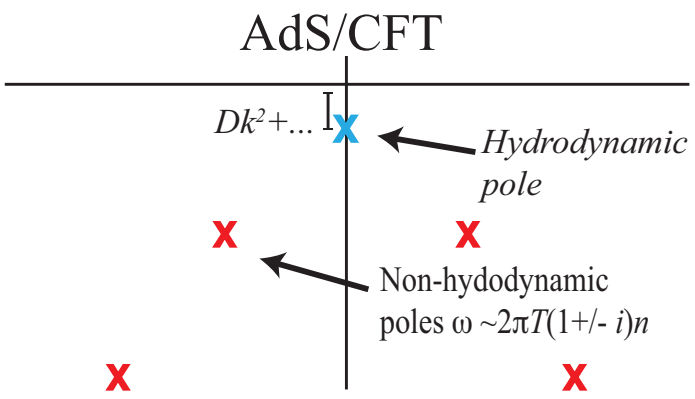
$$R_{MN} - \tfrac{1}{2}RG_{MN} - 3G_{MN} = \kappa(\nabla_M\Phi\nabla_N\Phi - \tfrac{1}{2}G_{MN}(\nabla_P\Phi)^2)$$

$$\nabla_M\nabla^M\Phi = 0.$$

Φ has near boundary expansion: $\Phi = \underbrace{-\beta\chi}_{\text{source}} + \ldots + \frac{3}{\kappa}\mathcal{H}r^3 + \ldots$

[4] Mondkar, Mukhopadhyay, Rebhan, AS: 2108.02788

Semiholographic model[4]



+ scalar field

$$S = W_{\mathrm{CFT}}[h(x) = -\beta\chi] - \frac{1}{2}\int d^3x \partial_\mu\chi\partial^\mu\chi$$

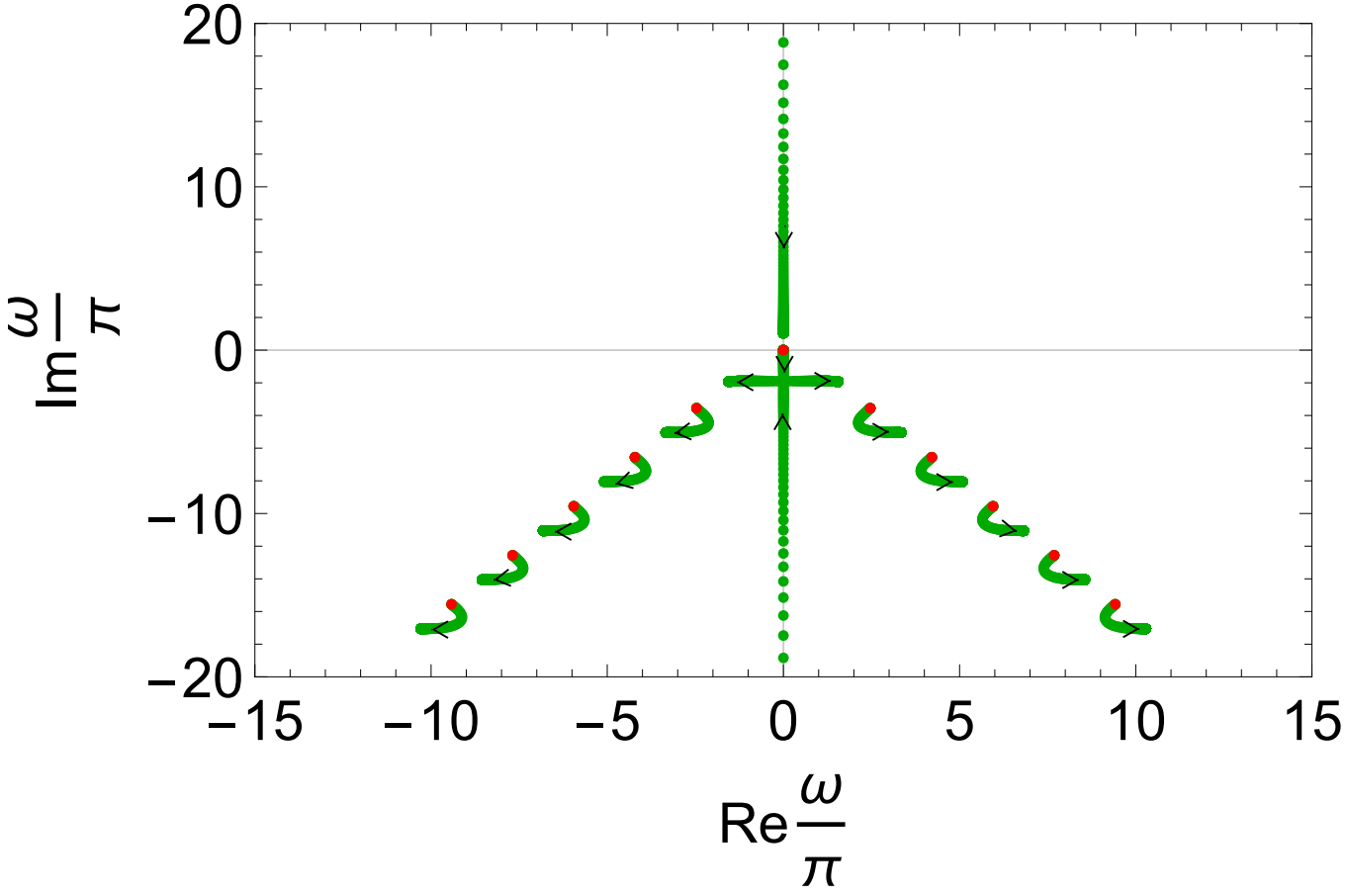
Stress tensor of the full system is conserved, $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = t_\chi^{\mu\nu} + \mathcal{T}^{\mu\nu}$$

Study hybrid fluctuations of bulk dilaton Φ and the boundary scalar field χ

[4] Mondkar, Mukhopadhyay, Rebhan, AS: 2108.02788

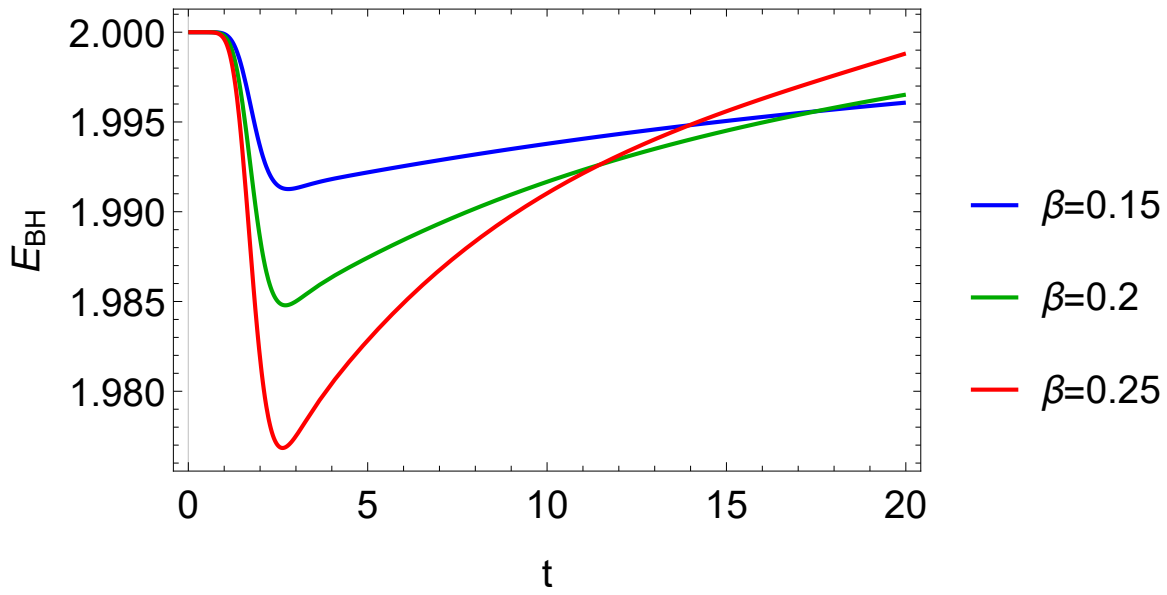
Homogeneous QNM - varying β at $k = 0$

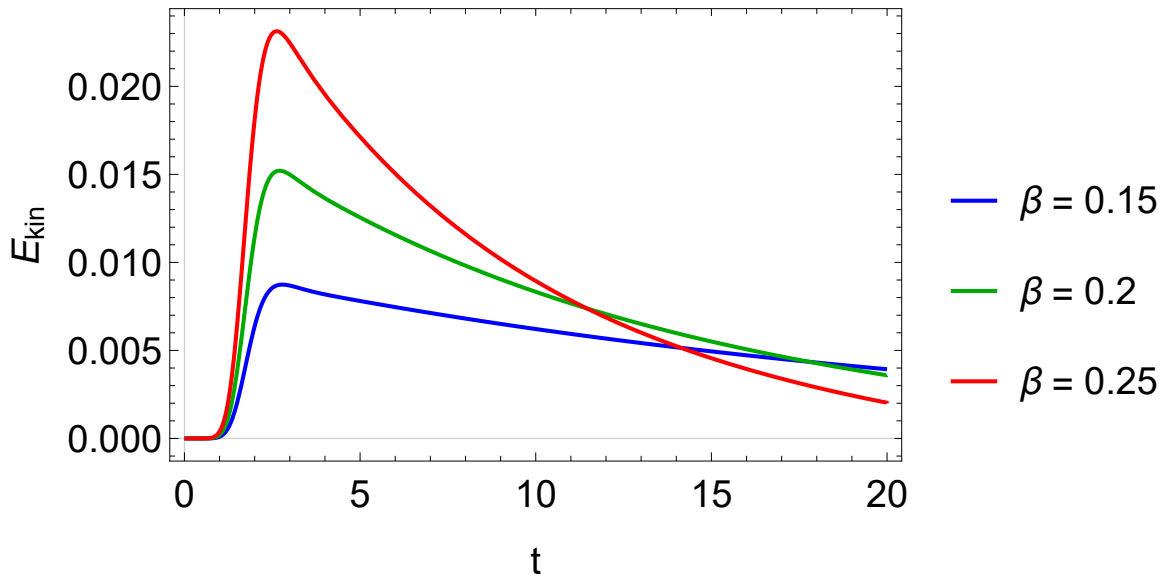


- Saturation for $\beta\sqrt{T} \to \infty$ and emergent conformality
- Unstable mode drives energy from holographic sector to boundary scalar at early time

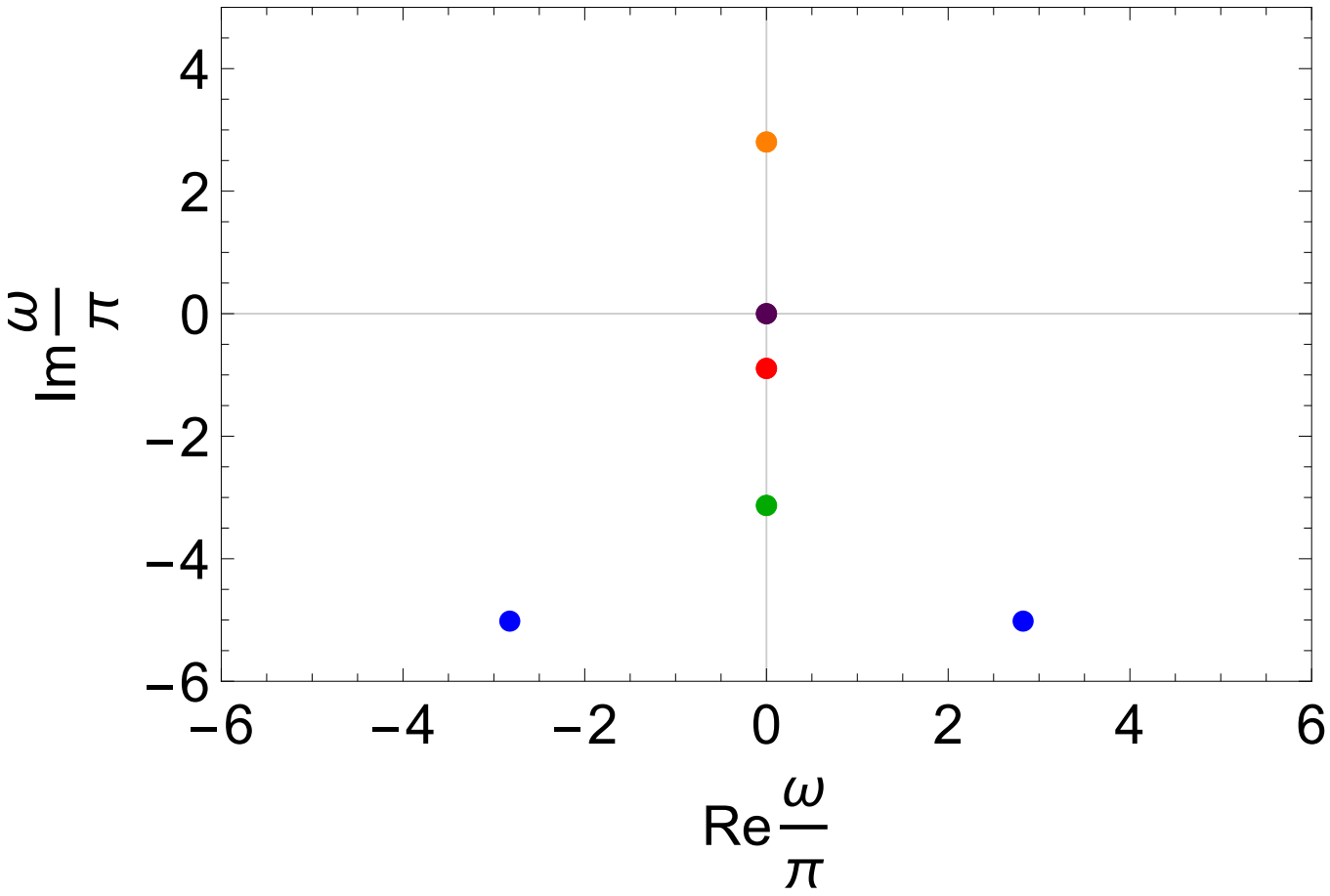
Homogeneous QNM - varying β at $k = 0$

- Unstable mode drives energy from holographic sector to boundary scalar at early time
- Total system has no instability!





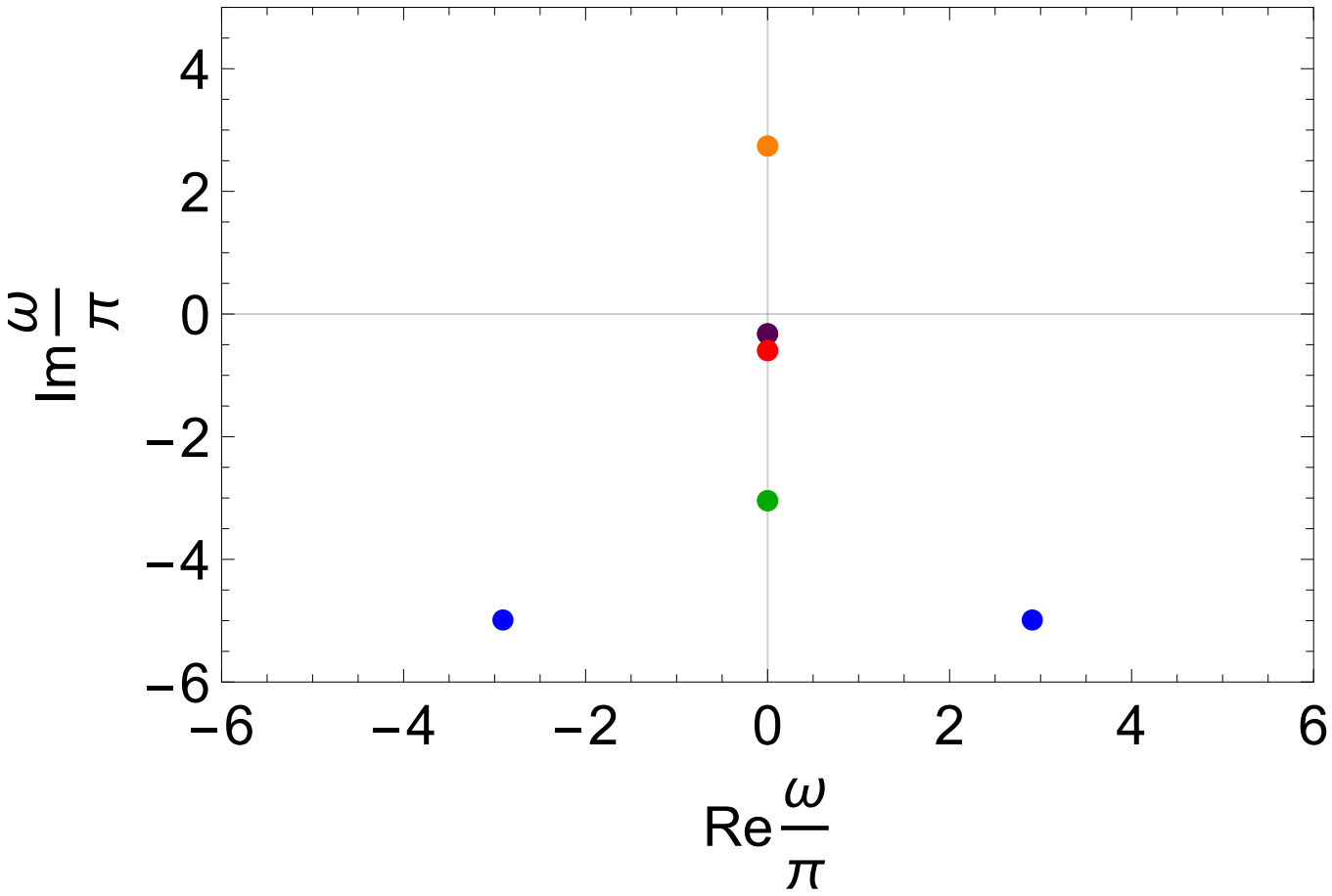
Inhomogeneous QNM - $\beta\sqrt{T} = 0.35$



$k = 0$

diffusion pole, quasi-hydro pole, transient unstable mode, semiholographic pole, holographic QNM

Inhomogeneous QNM - $\beta\sqrt{T} = 0.35$



$k = 0.554\pi$

diffusion pole, quasi-hydro pole, transient unstable mode, semiholographic pole, holographic QNM

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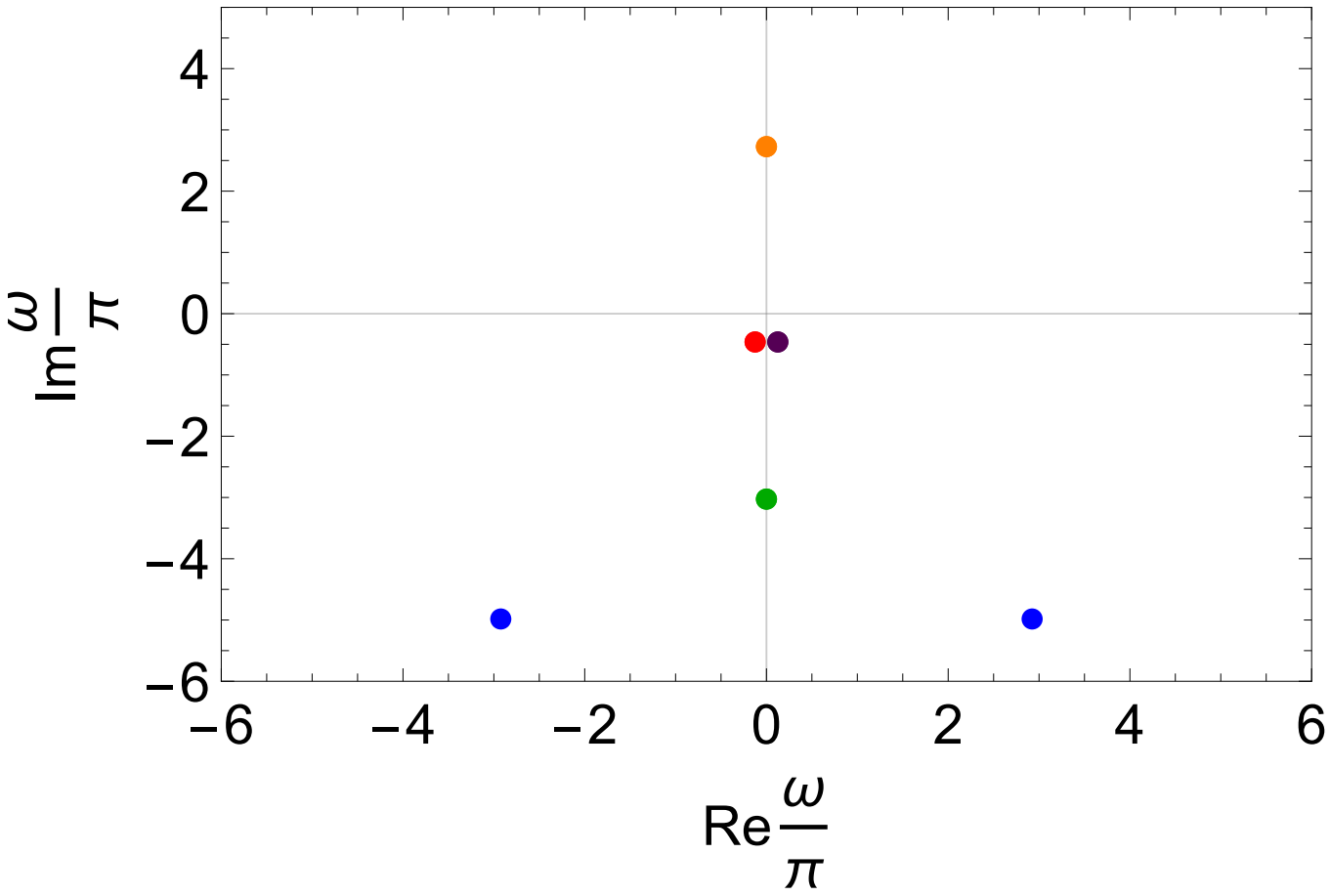

$k = 0.6\pi$

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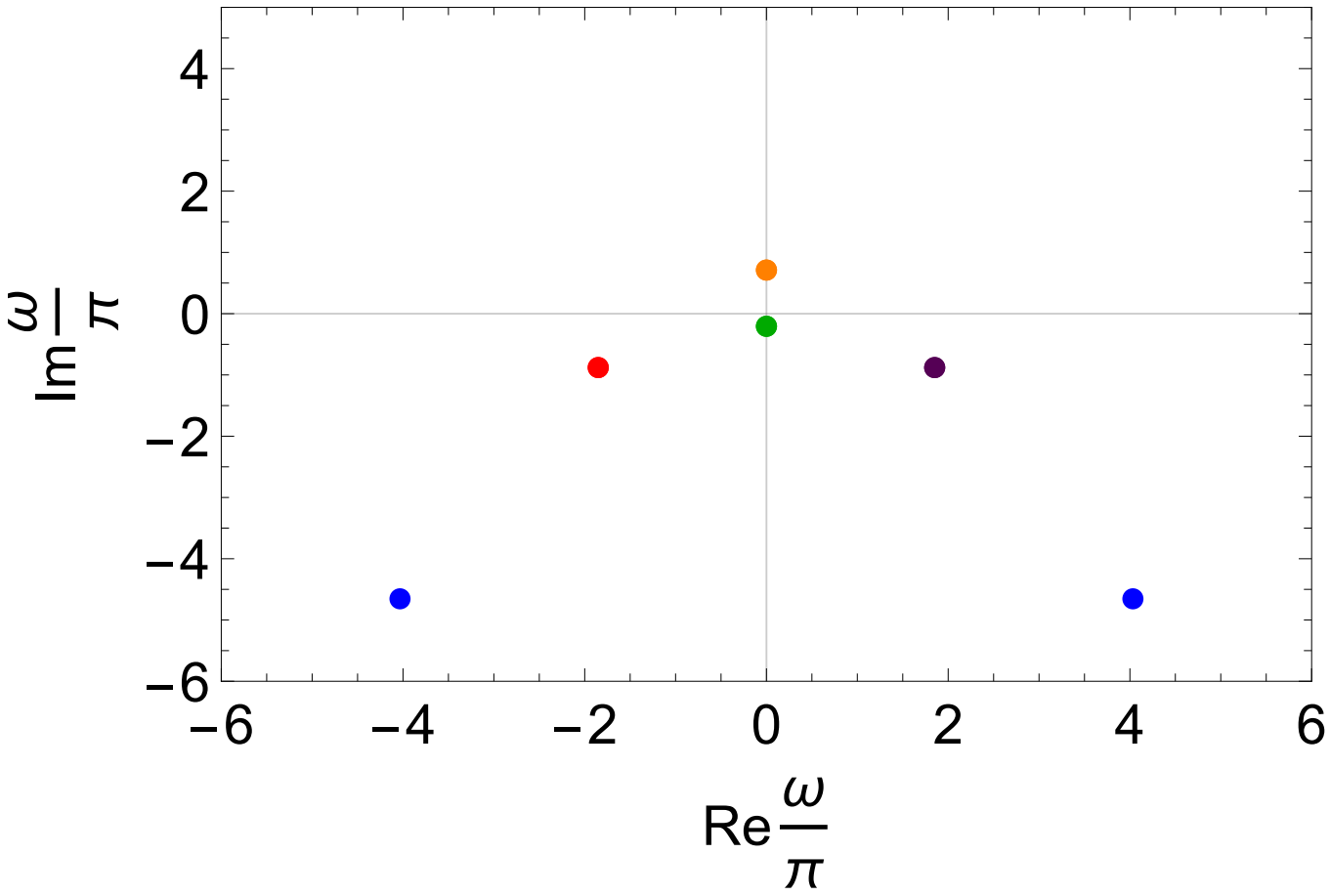

$k = 2.4\pi$

diffusion pole, quasi-hydro pole, transient unstable mode, semiholographic pole, holographic QNM

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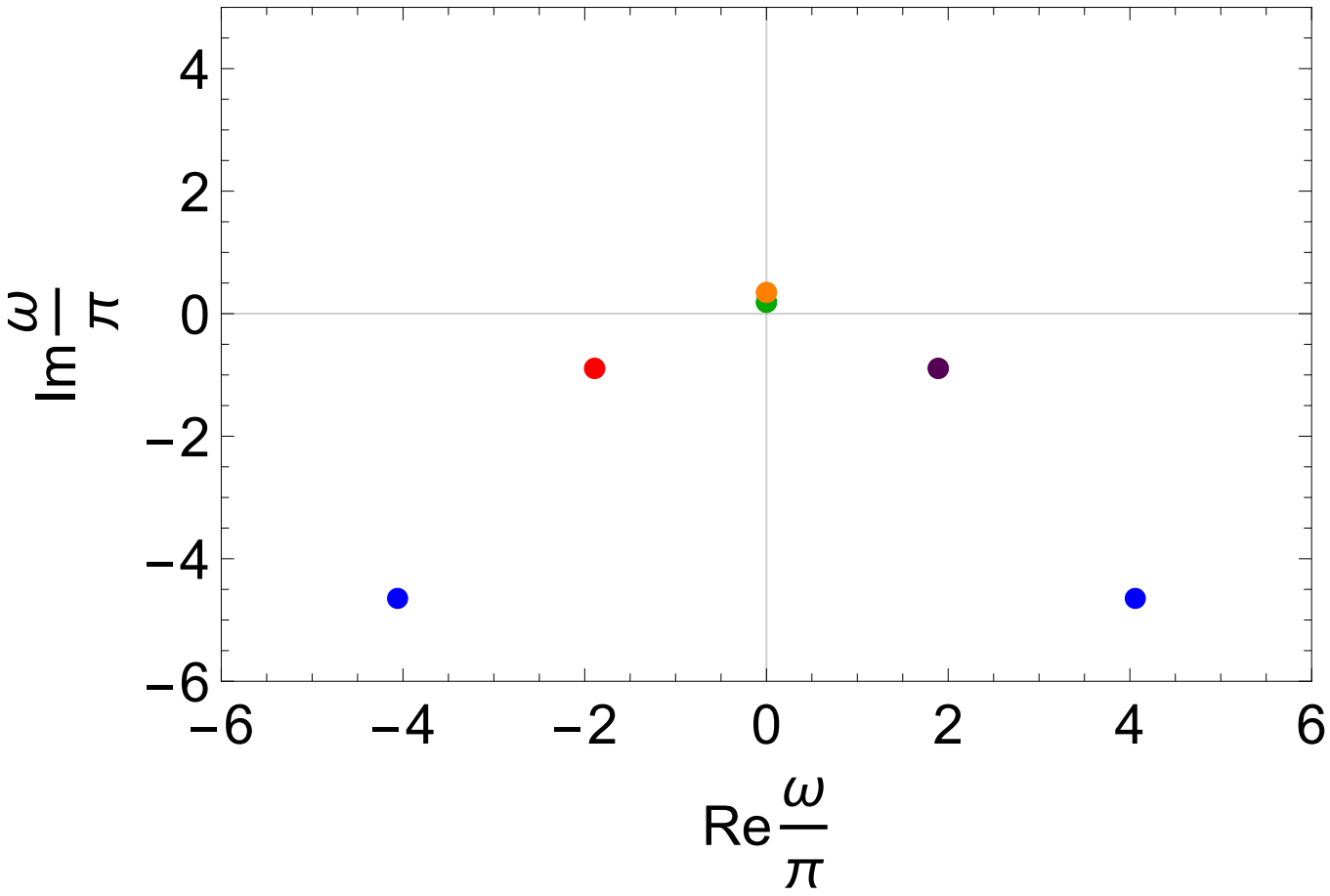
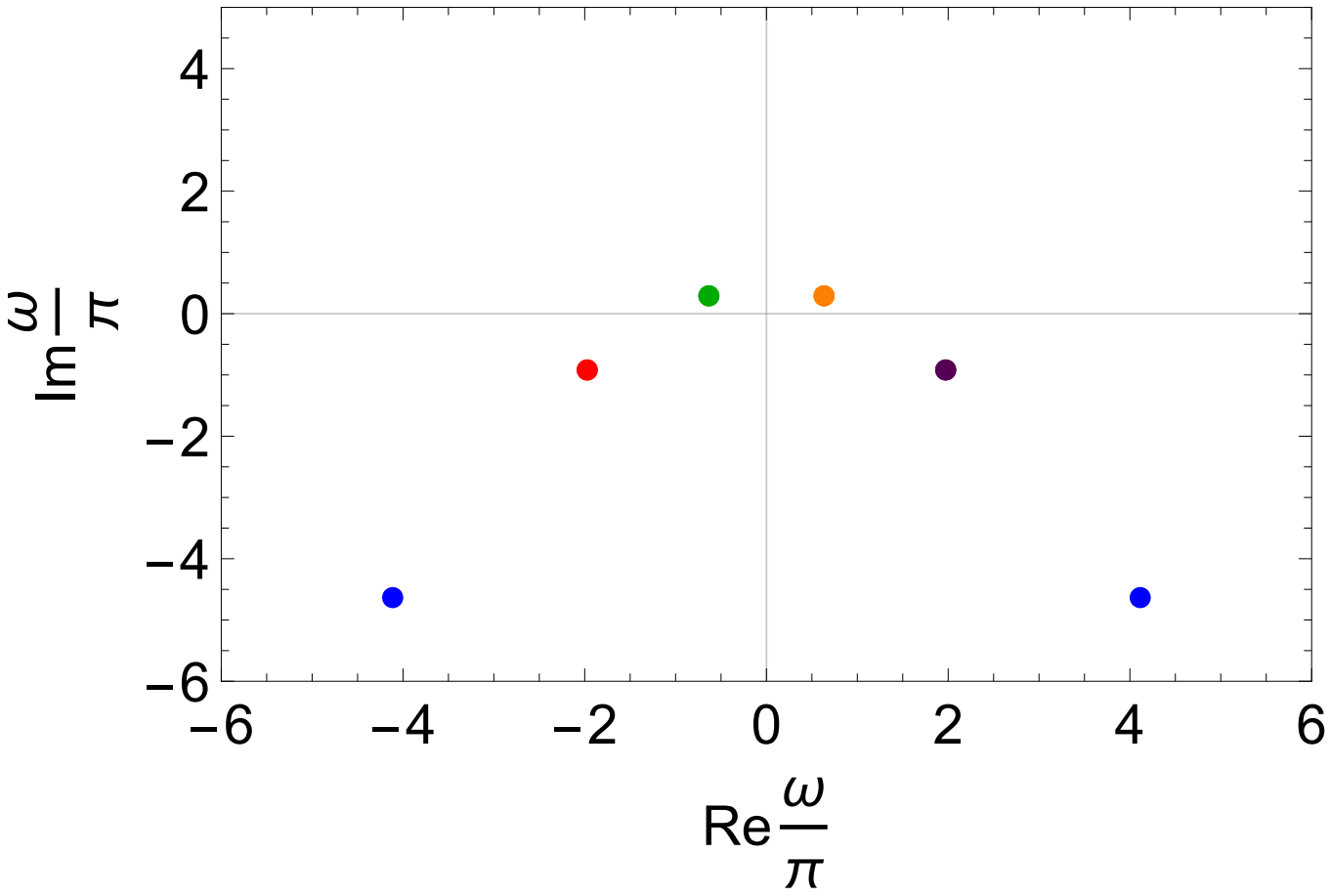


$k = 2.4334\pi$

diffusion pole, quasi-hydro pole, transient unstable mode, semiholographic pole, holographic QNM

Inhomogeneous QNM - $\beta\sqrt{T} = 0.35$

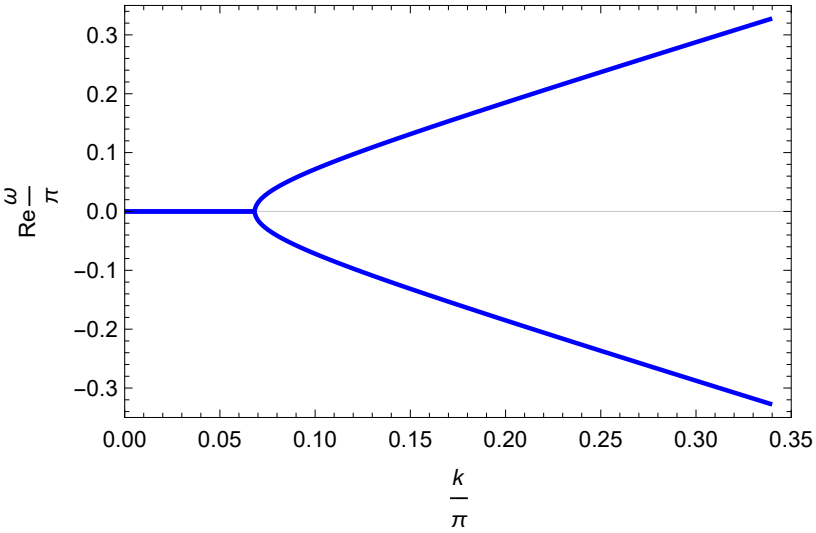


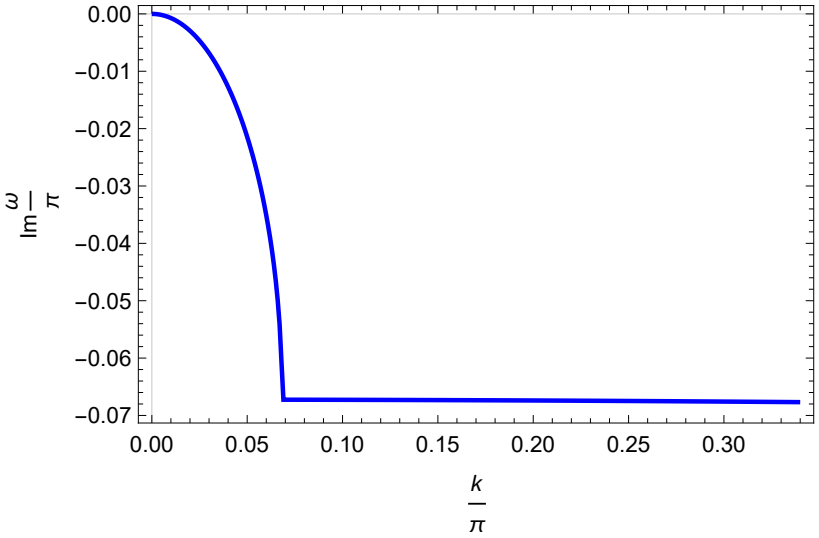
$k = 2.54\pi$

diffusion pole, quasi-hydro pole, transient unstable mode, semiholographic pole, holographic QNM

Emergence of k-gap

For $\beta\sqrt{T} = 0.15$



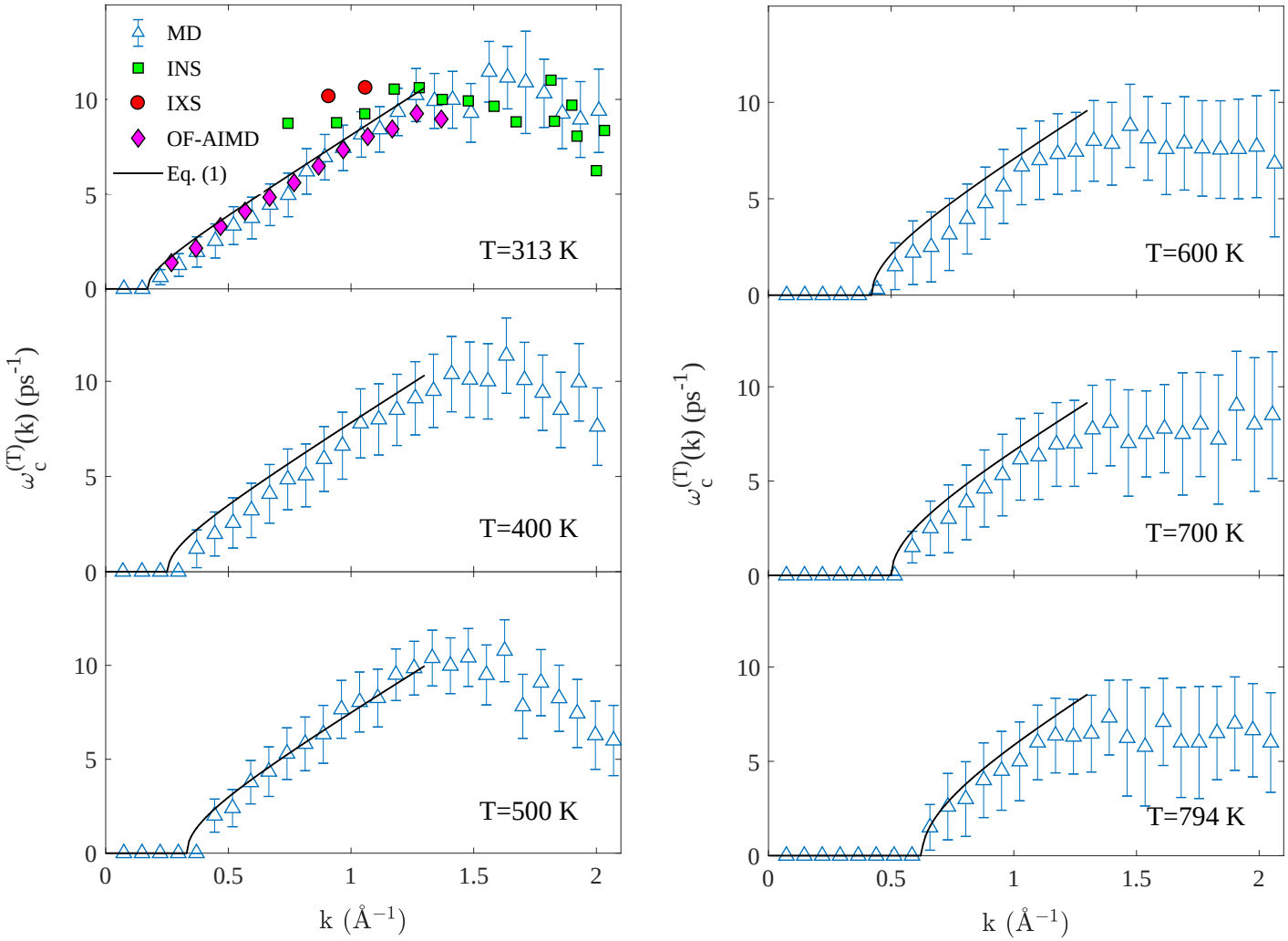


- k-gap is characteristic of systems with a diffusive to propagating mode crossover
- Quasi-hydrodynamic framework[5] relates this to a softly broken global symmetry $\omega = -\frac{i}{2\tau}(1 \pm \sqrt{1 - 4D\tau k^2})$
- Here, global shift symmetry of the theory is

$$\chi \to \chi + \chi_0, \quad \Phi \to \Phi - \beta\chi_0$$

[5] Grozdanov, Lucas, Poovuttikul, 1810.10016

Experimental observation of k-gap[6]



Dispersion of transverse sound-like excitations of gallium

[6] arXiv:2005.00470

Summary and outlook

- Complex structure of the QGP is rich! Need more work to understand theoretical structure better
- How does the quasinormal mode spectrum of a holographic theory interplay with:
  - Israel-Stewart hydrodynamics see arXiv:2208.XXXXX
  - kinetic theory?
- How do branch cuts seen in kinetic theory interact with other complex structure?