SAŠO GROZDANOV

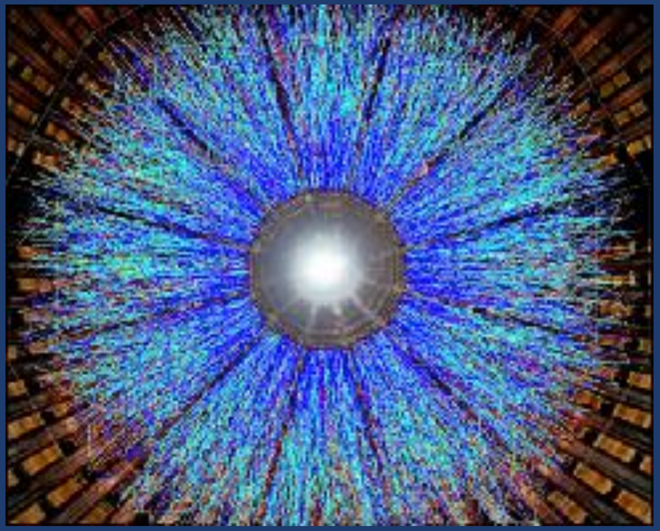
THE UNIVERSITY of EDINBURGH

Univerza v Ljubljani

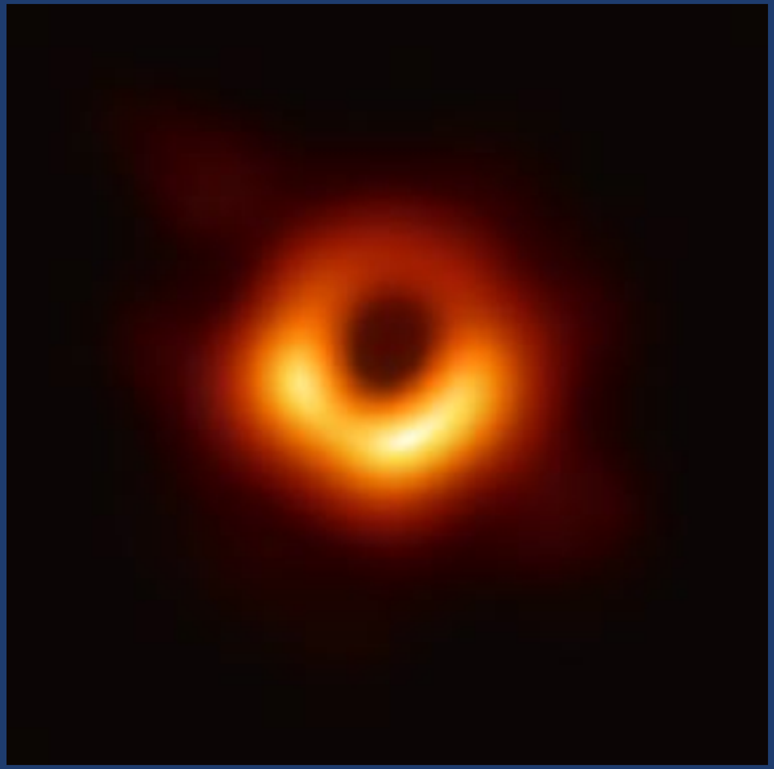
THE SPECTRAL DUALITY RELATION

BEIJING, 15.7.2025

THERMAL FIELD THEORY AND BLACK HOLES

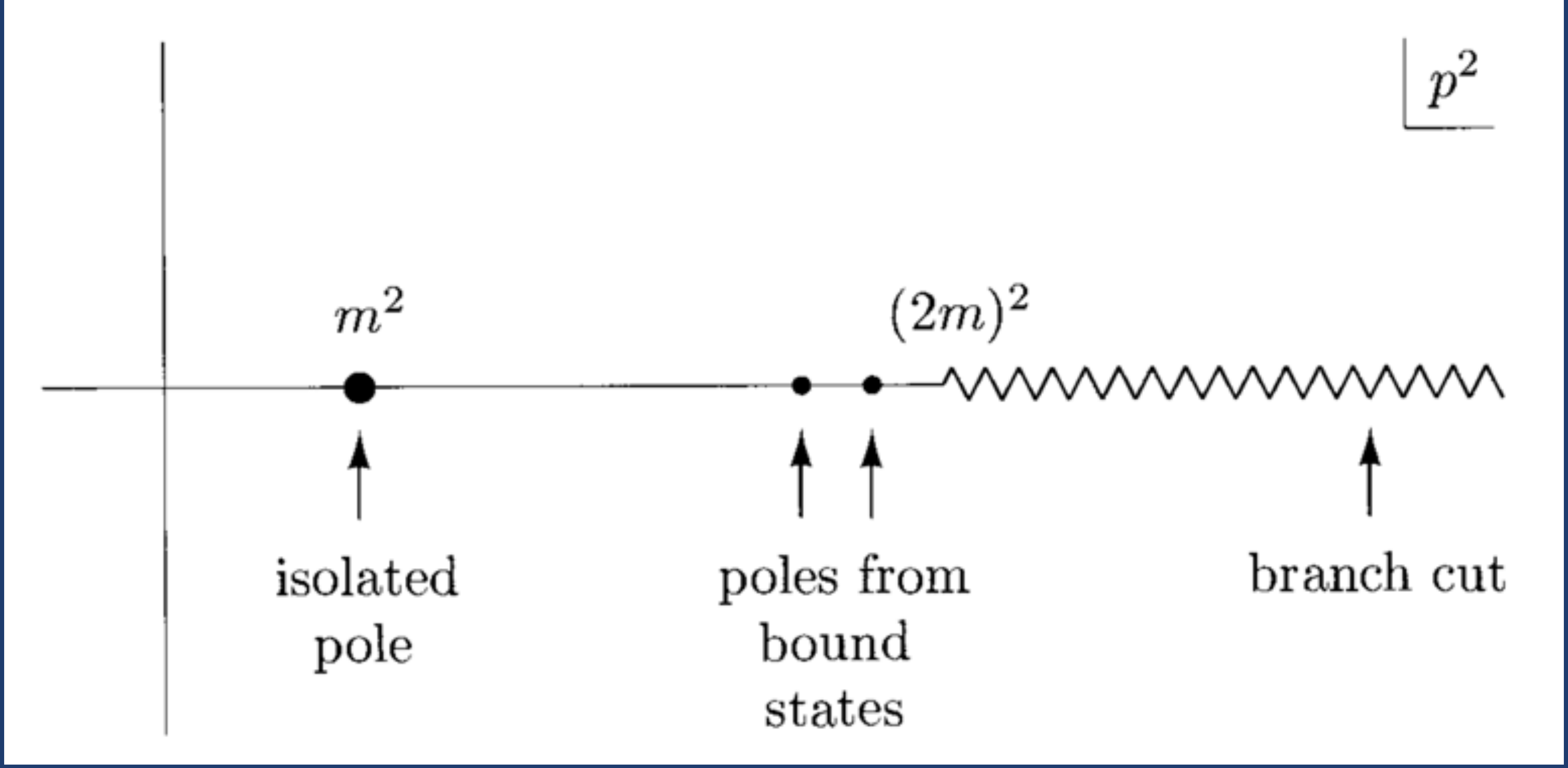


$$Z[\beta = 1/T] = \int \mathcal{D}\Phi \, e^{-\beta H} e^{\frac{i}{\hbar}\int d^d x \, \mathcal{L}(\Phi, \lambda)}$$



SPECTRUM OF A SIMPLE $T = 0$ CORRELATOR

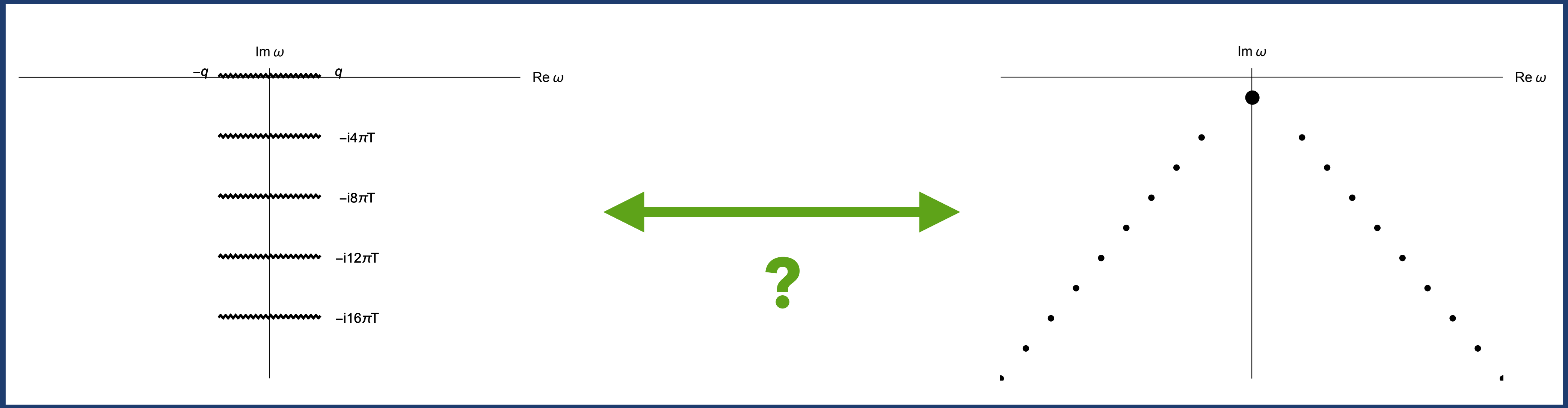
$$\langle \phi(p)\phi(-p) \rangle = \frac{Z(p^2)}{p^2 - m^2 + \Sigma(p^2)}$$



[from Peskin and Schroeder]

ANALYTIC STRUCTURE OF THERMAL CORRELATORS

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)}$$



$\lambda \to 0$

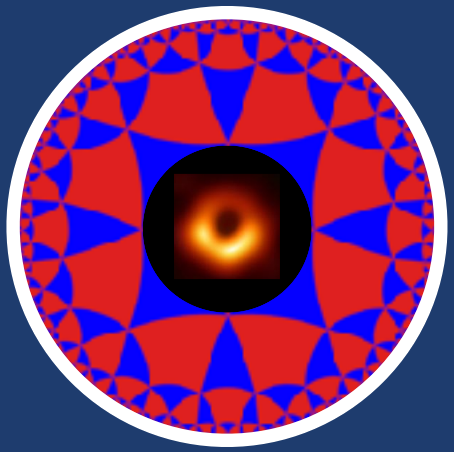
[Hartnoll, Kumar, (2005)]

$\lambda \to \infty$

holography (*N=4 SYM-type theories*)

meromorphic momentum space correlator

quasinormal modes
of black holes



methods:

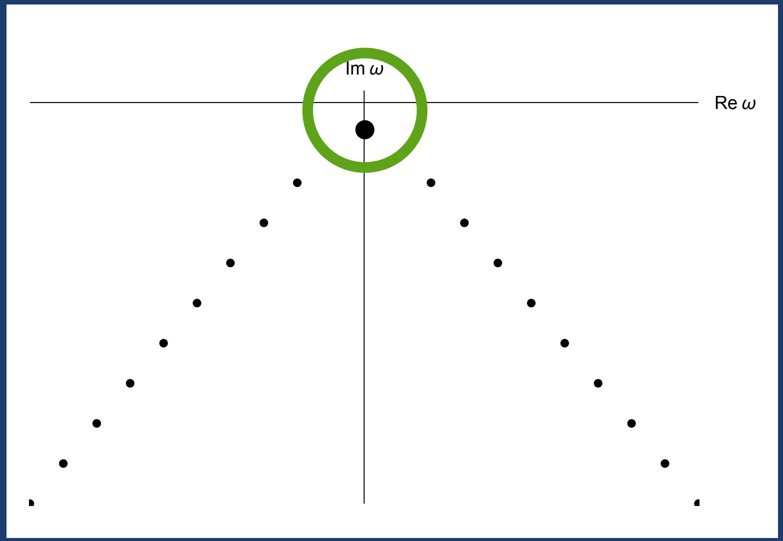
- perturbative QFT: calculation of Feynman diagrams
- holography: solving differential equations in black hole backgrounds

LOW-ENERGY SPECTRUM AND HYDRODYNAMICS

- low-energy limit of (some) thermal QFTs is described hydrodynamics
- conservation laws and global conserved operators

$$\nabla_\mu T^{\mu\nu} = 0$$

- tensor structures (symmetries, gradient expansions) and transport coefficients (QFT)



convergent series

$$T^{\mu\nu} = \sum_{n=0}^{\infty} \left[\sum_i^N \lambda_i^{(n)} \mathcal{T}^{\mu\nu}_{(n)} \right] \xrightarrow[u^\mu \sim T \sim e^{-i\omega t + iqz}]{\nabla_\mu T^{\mu\nu} = 0} \omega(q) = \sum_{n=1}^{\infty} \alpha_n q^n$$

$$\partial u^\mu \sim \partial T \ll 1 \longrightarrow \omega / T \sim q/T \ll 1$$

equilibrium temperature

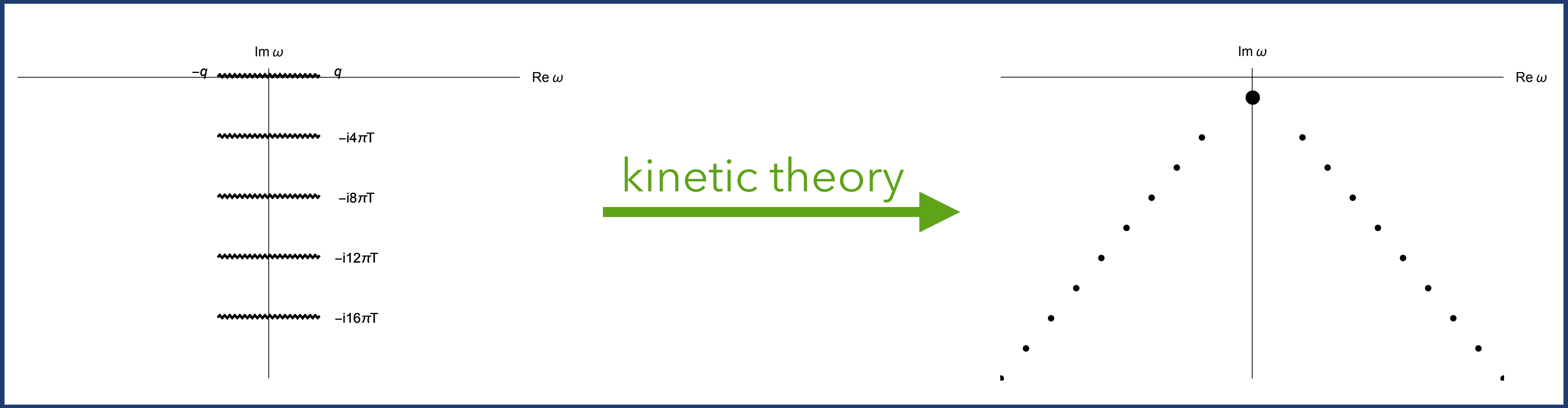
$$q = \sqrt{\mathbf{q}^2}$$

- dispersion relations are poles:

diffusion	sound
$\omega = -iDq^2$	$\omega = \pm v_s q - i\Gamma q^2$

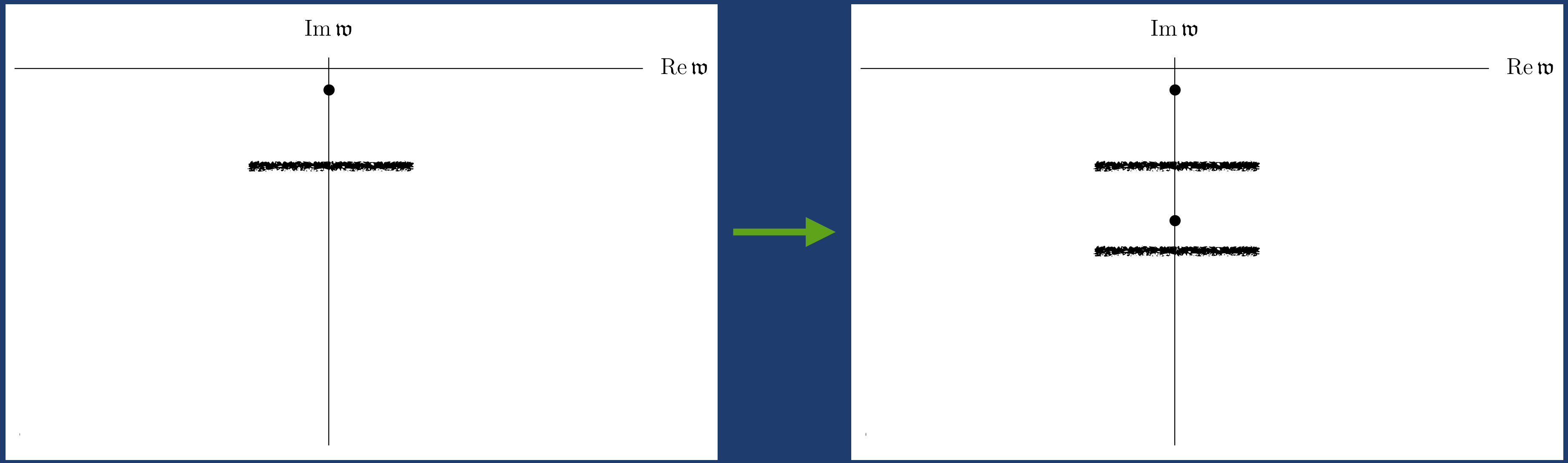
KINETIC THEORY AND THERMAL SPECTRUM

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)}$$



$\lambda \to 0$ $\lambda \to \infty$

poles from a cut?

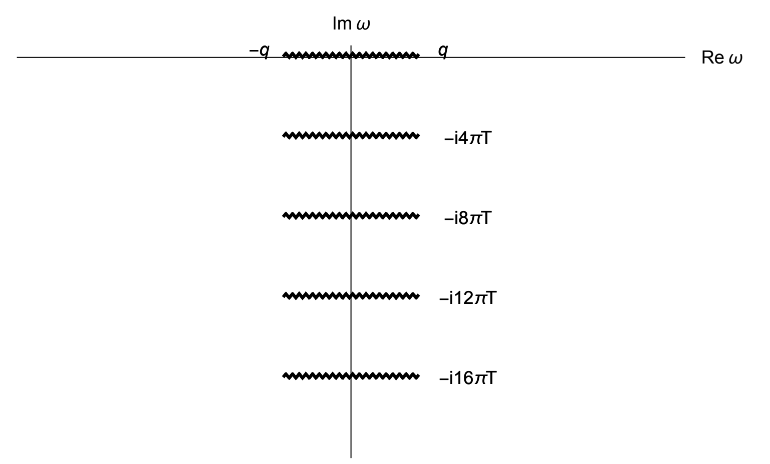


Boltzmann equation – RTA [Romatschke, (2016)]

BBGKY hierarchy – RTA-like truncations [SG, Soloviev (2025)]

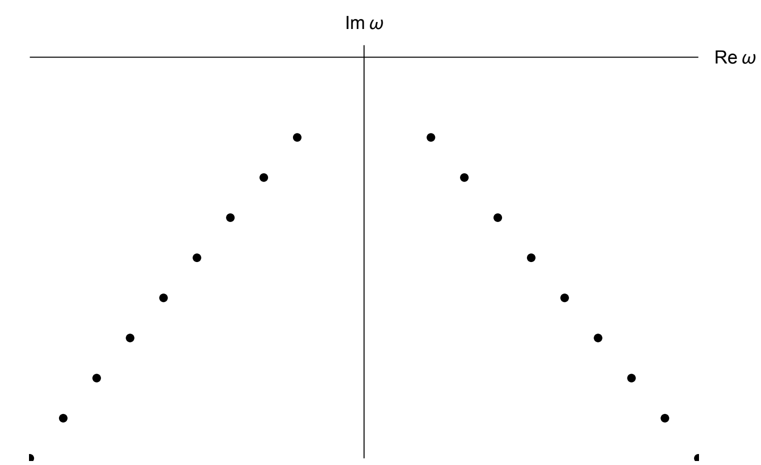
HOLOGRAPHY AND THERMAL SPECTRUM

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)} = \frac{B(\omega,q)}{\prod_{i=0}^{\infty}(\omega-\omega_i(q))}$$

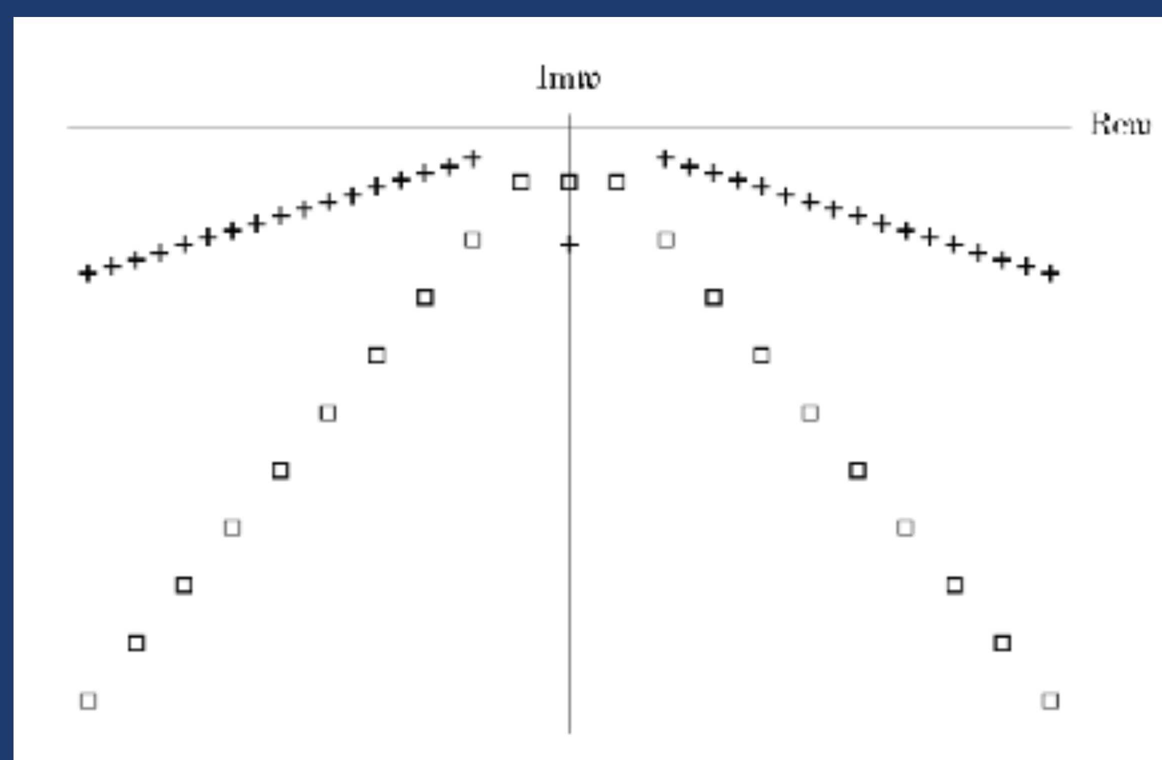


supergravity ←

$$\alpha' \sim 1/\sqrt{\lambda}$$

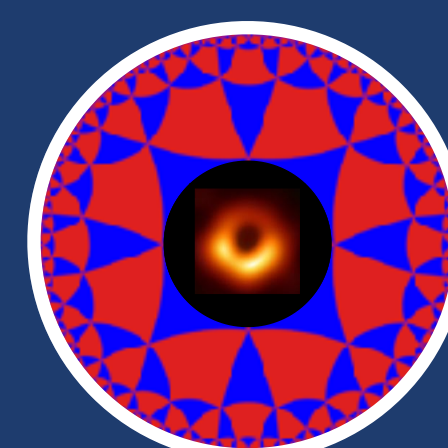


$\lambda \to 0$ cut from poles $\lambda \to \infty$



correlators remain meromorphic

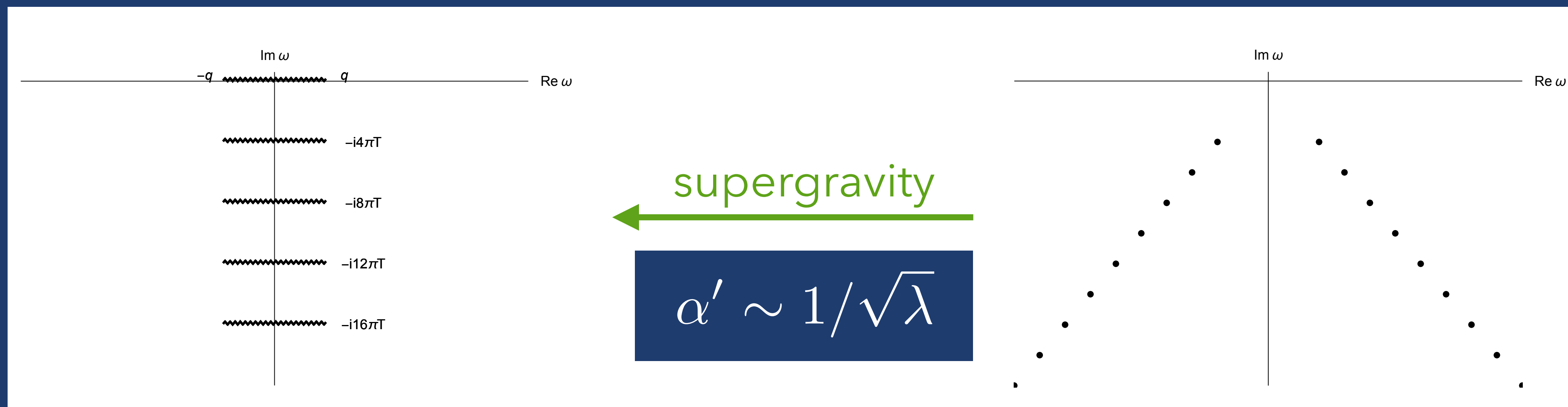
quasinormal modes of black holes



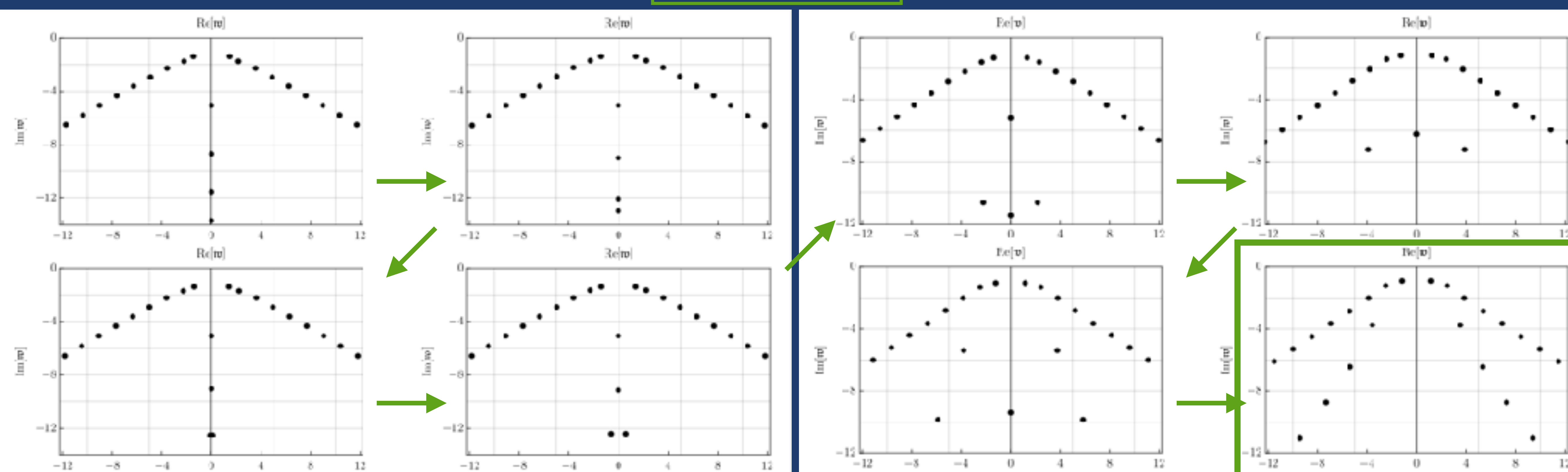
[SG, Starinets …, several papers]

HOLOGRAPHY AND THERMAL SPECTRUM

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)} = \frac{B(\omega,q)}{\prod_{i=0}^{\infty}(\omega-\omega_i(q))}$$



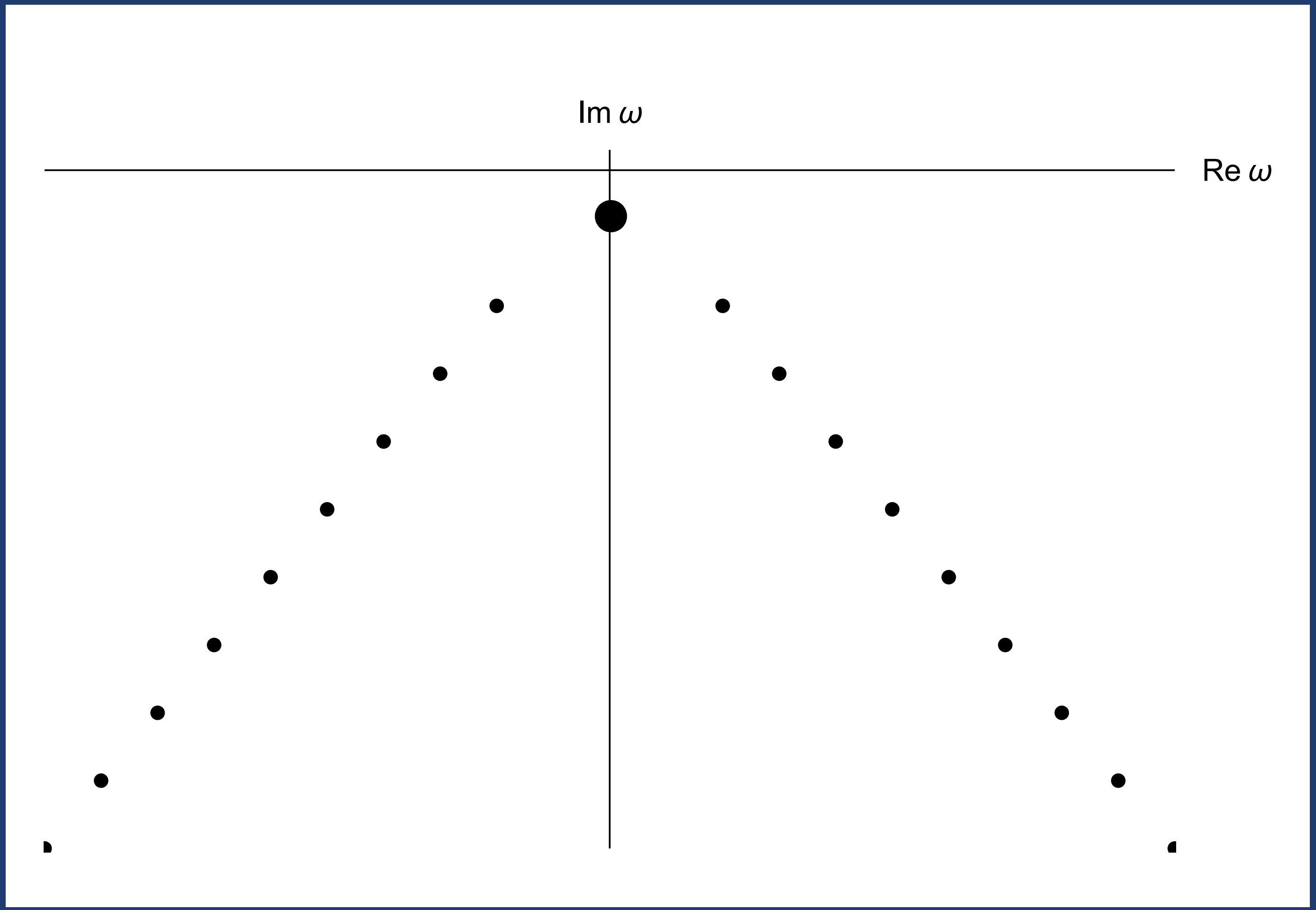
$\lambda \to 0$ | cut from poles | $\lambda \to \infty$



[SG, Starinets …, several papers; see also Dodelson on SYK (2025)]

HOLOGRAPHY AND THERMAL SPECTRUM

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)} = \frac{B(\omega,q)}{\prod_{i=0}^{\infty}(\omega-\omega_i(q))}$$



for the rest of the talk:

correlators are meromorphic in $\omega \in \mathbb{C}$

important recent result:

the thermal product formula [Dodelson, Iosso, Karlsson, Zhiboedov (2023)]

OUTLINE

pole skipping and reconstruction of hydrodynamics

spectral duality relation

summary and future directions

POLE SKIPPING AND RECONSTRUCTION OF HYDRODYNAMICS

POLE SKIPPING

- pole skipping: ubiquitous feature of thermal correlators and black hole perturbations [SG, Schalm, Scopelliti, PRL (2017); Blake, Lee, Liu, JHEP (2018); Blake, Davison, SG, Liu, JHEP (2018); SG, JHEP (2019)]
- originally: all-order hydrodynamic sound mode $$\omega(q) = \sum_{n=1}^{\infty} \alpha_n \left(T, \mu_i, \langle \mathcal{O}_j \rangle, \lambda\right) q^n$$

  passes through a 'chaos point' at where the associated *2*-pt function is '0/0':

$$\boxed{\omega(q = i\lambda_L/v_B) = i\lambda_L = 2\pi T i}$$

$$\boxed{G_R = \frac{0}{0} = N(\delta\omega/\delta q)}$$

- relation to maximal quantum chaos as measured by the out-of-time-ordered correlation functions and entanglement wedge […; Chua, Hartman, Weng (2025)]
- triviality of the Einstein equation at the horizon
- infinite number of such '0/0' points at negative Matsubara frequencies for $q \in \mathbb{C}$ [SG, Kovtun, Starinets, Tadić, JHEP (2019); Blake, Davison, Vegh, JHEP (2019)]

$$\boxed{\omega_n(q_n) = -2\pi T i n} \quad \boxed{n \geq 0}$$

POLE SKIPPING

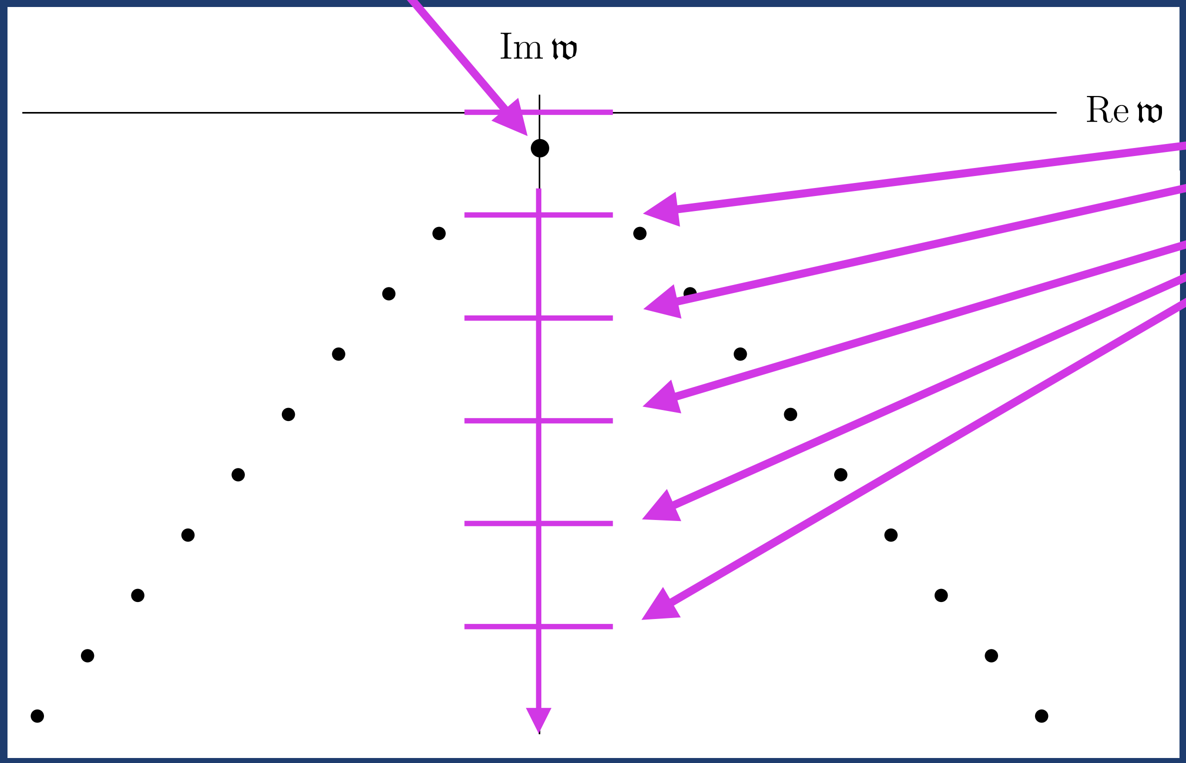
- consider momentum diffusion in a neutral CFT dual to AdS-Schwarzschild black brane

$$\mathfrak{w}_{\text{shear}} = -i \sum_{n=1}^{\infty} c_n \left(\mathfrak{q}^2\right)^n = -i\mathfrak{D}\mathfrak{q}^2 + \ldots$$

convergent series

[SG, Kovtun, Starinets, Tadić, PRL (2019); … ; Withers; JHEP (2018); Heller, et.al. (2020, …)]

for increasing real q



$$\omega_n(q_n) = -2\pi T i n$$

analytic result in AdS4/CFT3

[SG, PRL (2021)]

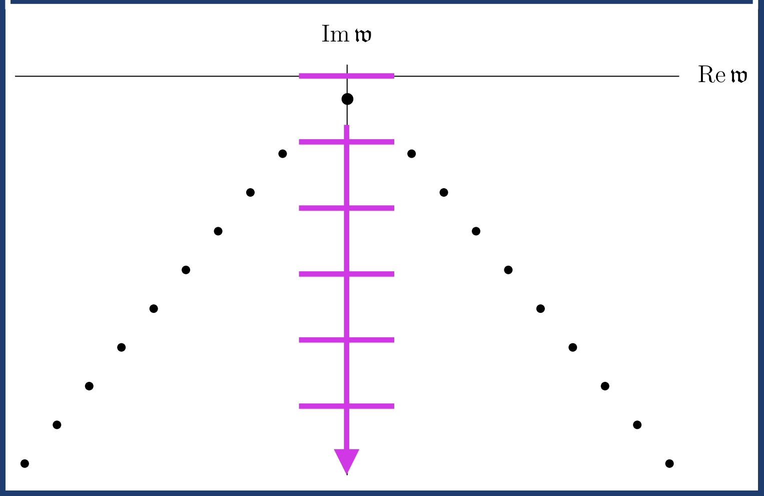
$$q_n = \frac{4\pi T}{\sqrt{3}} n^{1/4}, \quad n = 0, 1, 2, \ldots$$

POLE SKIPPING AND HYDRODYNAMICS

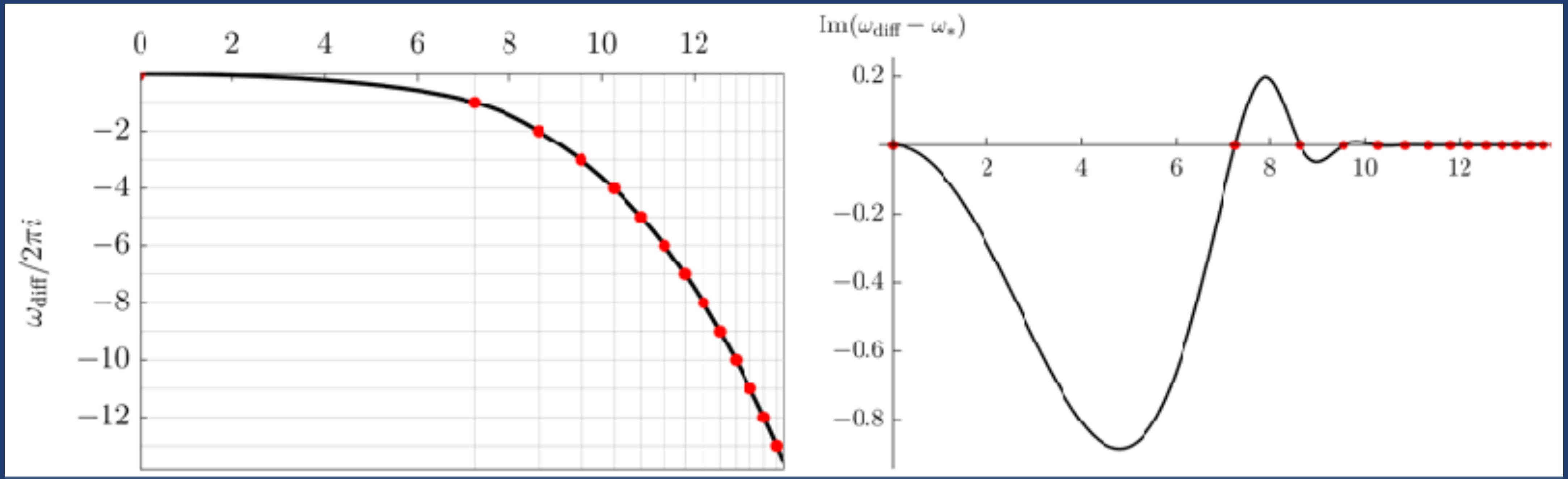
- consider momentum diffusion in a neutral CFT dual to AdS-Schwarzschild black brane

$$\mathfrak{w}_{\text{shear}} = -i \sum_{n=1}^{\infty} c_n \left(\mathfrak{q}^2\right)^n = -i\mathfrak{D}\mathfrak{q}^2 + \ldots$$

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)}$$



for increasing real q



claim: in holographic theories of the type discussed here (N=4 SYM, M2, M5, …), the hydrodynamic dispersion relation follows from only a discrete set of pole-skipping points

POLE SKIPPING AND HYDRODYNAMICS

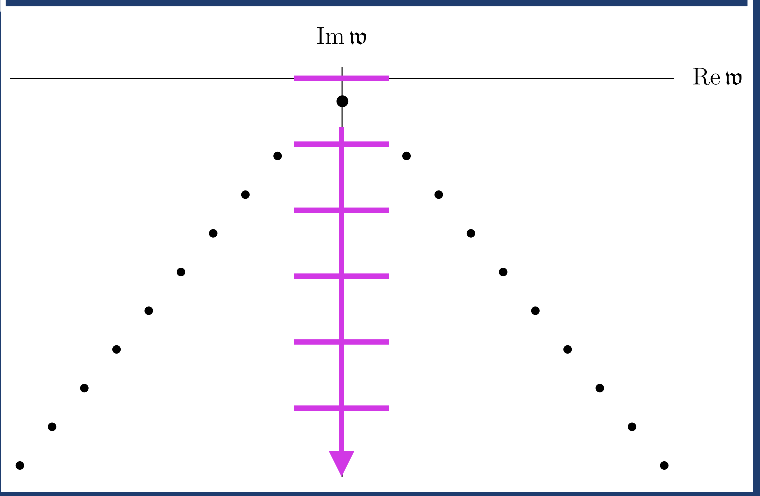
- interpolation problem:

$$\omega_n(q_n) = -2\pi T i n$$

$$\downarrow$$

$$\mathfrak{w}_{\text{shear}} = -i \sum_{n=1}^{\infty} c_n \left(\mathfrak{q}^2\right)^n = -i\mathfrak{D}\mathfrak{q}^2 + \ldots$$

$$\langle T_{\mu\nu}(-\omega,-q), T_{\rho\sigma}(\omega,q)\rangle_R \sim \frac{b(\omega,q)}{a(\omega,q)}$$



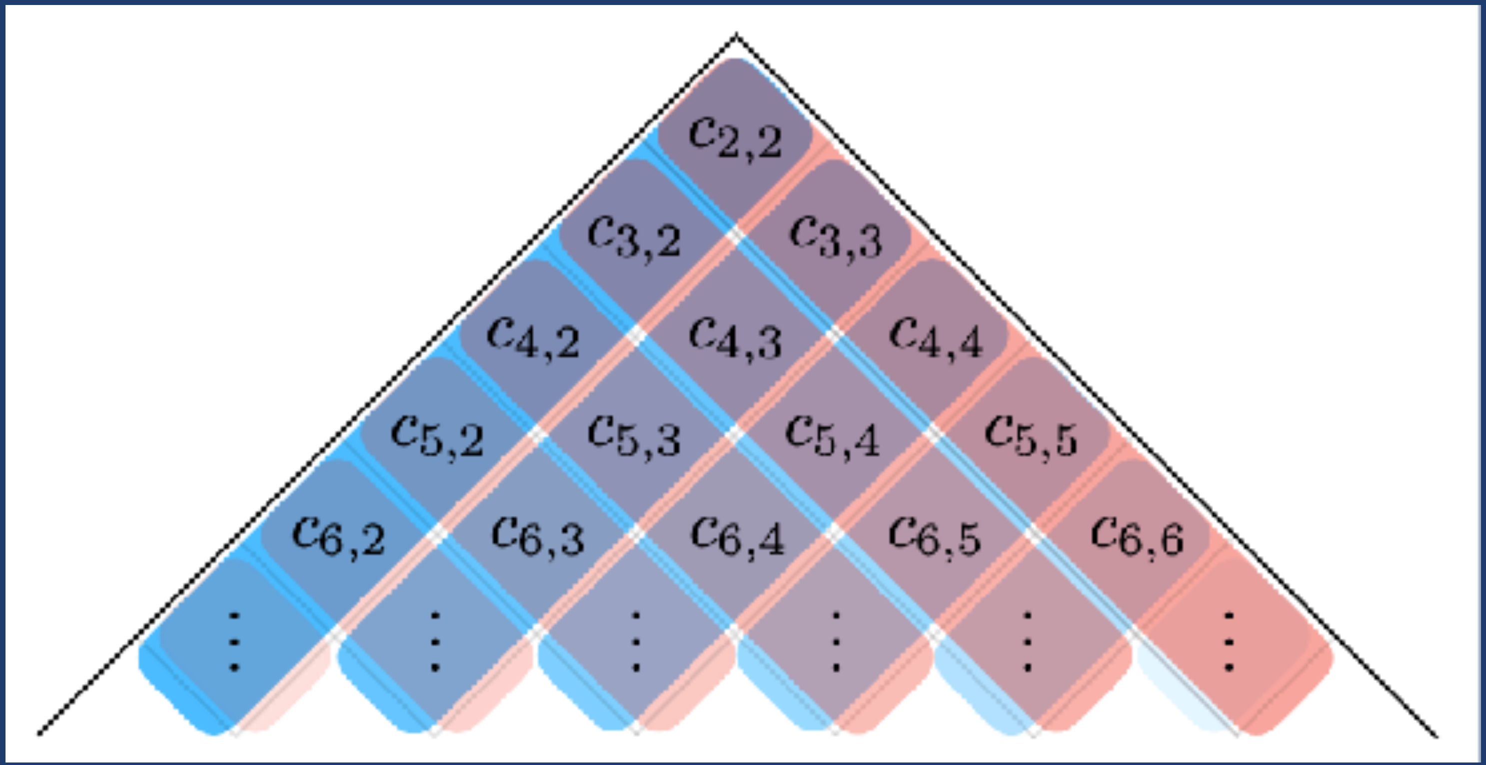
for increasing real q

- unique solutions to interpolation problems are rare (Weierstrass-Hadamard, Nevanlinna-Pick)
- trick: 'analytic continuation' to *d* spacetime dimensions and expansion around infinite *d* [SG, Lemut, Pedraza, PRD (2023)]
- general relativity in large *d* drastically simplifies: $V \sim 1/r^d$
- recall: large-*d* limit of quantum mechanics is useful in atomic physics (e.g., for Helium)

POLE SKIPPING AND HYDRODYNAMICS

- interpolation: $\omega_n(q_n) = -2\pi T i n$ → $\mathfrak{w}_{\text{shear}} = -i \sum_{n=1}^{\infty} c_n \left(\mathfrak{q}^2\right)^n = -i\mathfrak{D}\mathfrak{q}^2 + \ldots$
- 'analytic continuation' to *d* spacetime dimensions and expansion around infinite *d*

$$\omega_0(q = Q\sqrt{d}) = -iQ^2 - \frac{i}{d^2}\left(c_{2,2}Q^4\right) - \frac{i}{d^3}\left(c_{3,2}Q^4 + c_{3,3}Q^6\right) - \frac{i}{d^4}\left(c_{4,2}Q^4 + c_{4,3}Q^6 + c_{4,4}Q^8\right) + \ldots$$



POLE SKIPPING AND HYDRODYNAMICS

- interpolation: $\omega_n(q_n) = -2\pi T i n$ → $\mathfrak{w}_{\text{shear}} = -i\sum_{n=1}^{\infty} c_n \left(\mathfrak{q}^2\right)^n = -i\mathfrak{D}\mathfrak{q}^2 + \dots$

- 'analytic continuation' to *d* spacetime dimensions and expansion around infinite *d*

$$\omega_0(q) = -i\left(\frac{q}{\sqrt{d}}\right)^2 - i\sum_{m=2}^{\infty}\frac{1}{d^m}\sum_{j=2}^{m} c_{m,j}\left(\frac{q}{\sqrt{d}}\right)^{2j}$$

$$\frac{q_n}{\sqrt{d}} = \sqrt{\frac{nd}{2}}\left(1 + \sum_{m=1}^{\infty}\frac{b_{n,m}}{d^m}\right)$$

→

$$b_{n,1} = -\sum_{m=2}^{\infty}\frac{n^{m-1}c_{m,m}}{2^m}$$

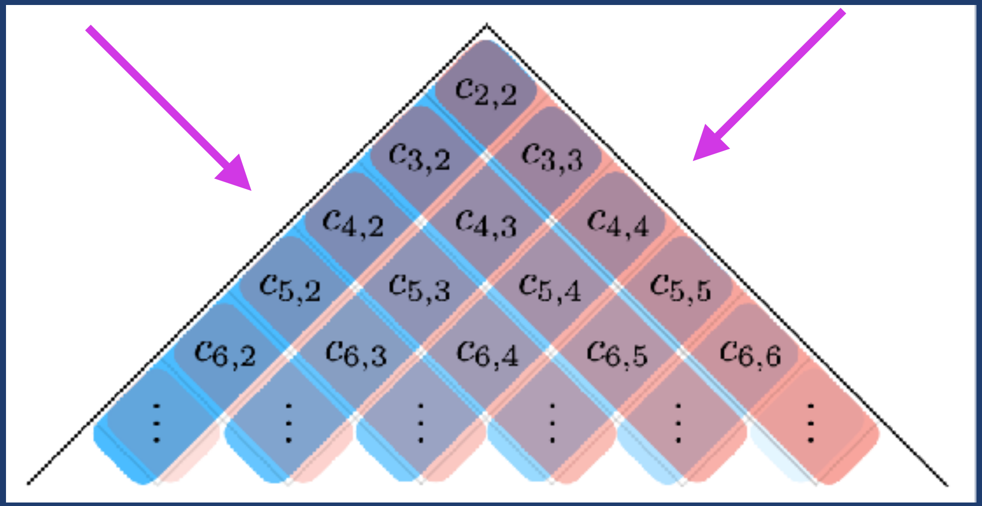
$$b_{n,2} = -\frac{b_{n,1}^2}{2} - \sum_{m=2}^{\infty}\frac{n^{m-1}\left(c_{m+1,m} + 2m b_{n,1} c_{m,m}\right)}{2^m}$$

second analytic continuation

$$n \in \mathbb{Z} \to x \in \mathbb{R}$$

hydrodynamics

pole skipping



symmetry?

$$c_{m,m} = -\frac{2^m}{(m-1)!}\partial_x^{m-1} b_1(0)$$

$$c_{m+1,m} = -\frac{2^m \partial_x^{m-1} b_2(0)}{(m-1)!} + \sum_{j=2}^{m-1}\left(j - \frac{1}{4}\right) c_{j,j}\, c_{m-j+1,m-j+1}$$

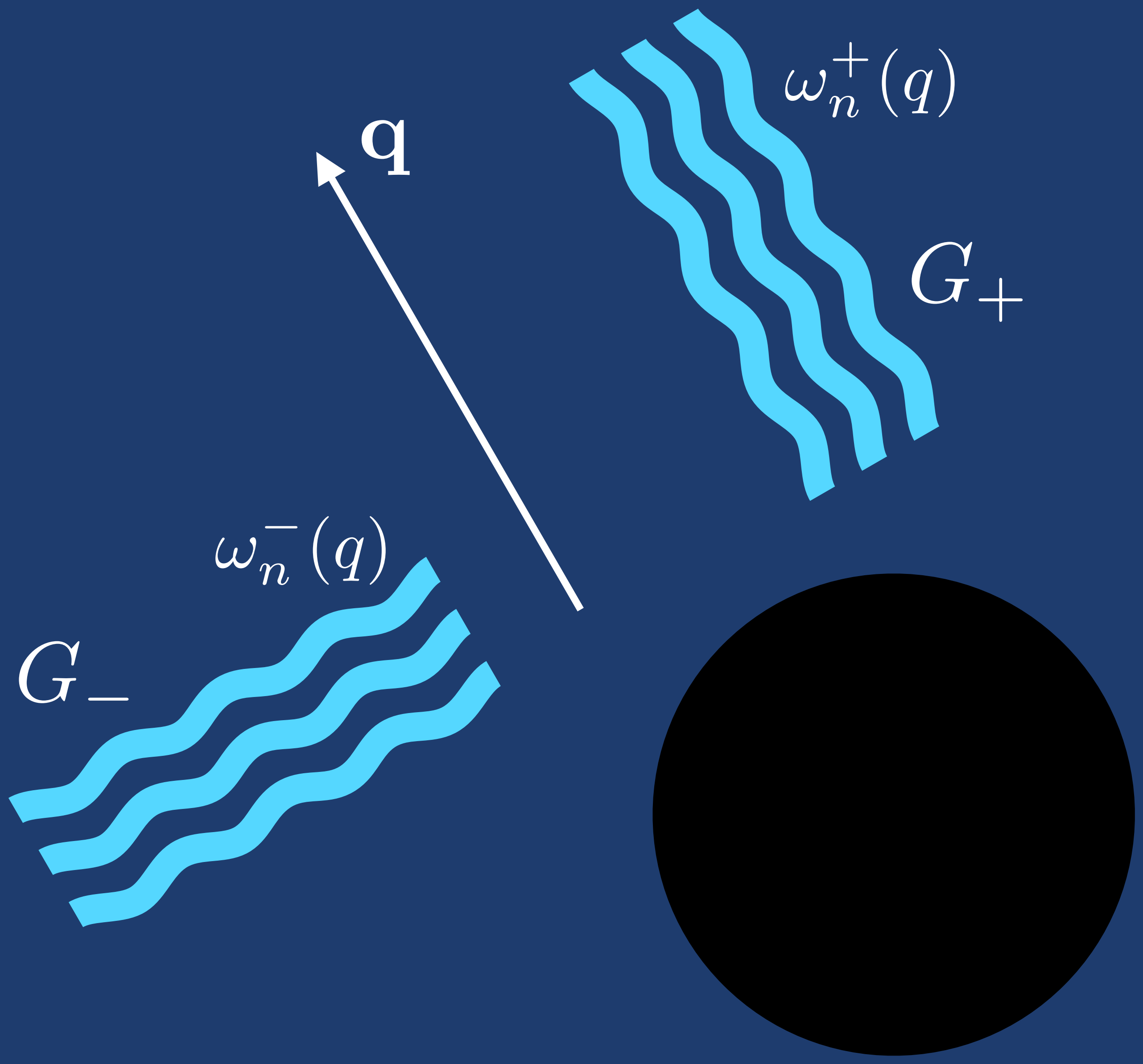
generating functions

SPECTRAL DUALITY RELATION

[SG, Vrbica, PRL (2024), 2505.14229
and another paper *very soon*]

SPECTRAL DUALITY RELATION

- two channels of black hole perturbations in AdS4/CFT3 cases: even (or sound) and odd (or shear)
- in each channel, we have QNMs $\omega_n^{\pm}(q)$ with associated dual correlators $G_{\pm}(\omega, q)$



isospectrality

in asymptotically flat black holes

[Chandrasekhar, Detweiler (1975)]

$$\omega_n^{+}(q) = \omega_n^{-}(q)$$

spectral duality relation

in asymptotically AdS black holes

$$\omega_n^{+}(q) \leftrightarrow \omega_m^{-}(q)$$

SPECTRAL DUALITY RELATION

- two channels of black hole perturbations in AdS4/CFT3 cases: even (or sound) and odd (or shear)
- two meromorphic CFT retarded correlators $G_{\pm}(\omega, q)$ with QNMs $\omega_n^{\pm}(q)$ (e.g. of $T^{\mu\nu}$ or J^{μ})
- CFT3s have S-duality or particle-vortex duality
  gravity in 4*d* has Chandrasekhar duality, Darboux duality, EM duality

duality:

$$G_+(\omega, q)G_-(\omega, q) = \frac{\omega^2}{\omega_*^2(q)} - 1$$

self-duality: $\omega_*(q) \to \infty$

$$G_+(\omega, q)G_-(\omega, q) = -1$$

algebraically special frequencies
relation to pole skipping
[SG, Vrbica, EPJC (2023)]
easy to compute using the
Robinson-Trautman ansatz

SPECTRAL DUALITY RELATION

- define infinite convergent product

$$S(\omega, q) \equiv \left(1 + \frac{\omega}{\omega_*(q)}\right) \prod_n \left[1 - \frac{\omega}{\omega_n^+(q)}\right] \left[1 + \frac{\omega}{\omega_n^-(q)}\right]$$

- duality relations, the thermal product formula and details about QNM and Greens function asymptotics give a ‘universal’ relation:

$$S(\omega, k) - S(-\omega, k) = 2i\lambda(k) \sinh \frac{\beta\omega}{2}$$

$$\lambda(k) = \frac{2}{i\beta} \left[\frac{1}{\omega_*(k)} + \sum_n \left(\frac{1}{\omega_n^-(k)} - \frac{1}{\omega_n^+(k)}\right)\right]$$

- infinite towers of constraints

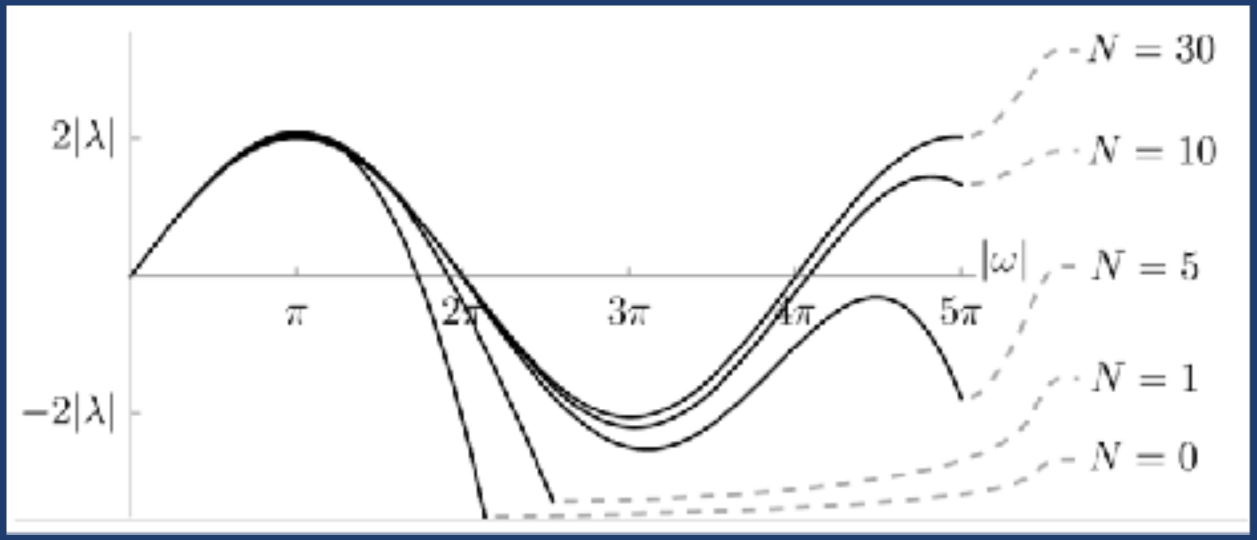
$$e_{2j+1}(\mathcal{W}) = \frac{i\lambda}{(2j+1)!} \left(\frac{\beta}{2}\right)^{2j+1}$$

elementary symmetric polynomials with $j \in \{0,1,\ldots,n\}$

$$\mathcal{W} = \{1/\omega_*, 1/\omega_1^-, \ldots, 1/\omega_n^-, -1/\omega_1^+, \ldots, -1/\omega_n^+\}$$

SPECTRAL DUALITY RELATION

- AdS4-Schwarzschild black brane
  - $\langle J, J \rangle_R$ is self-dual
    poles must converge to Matsubara frequencies $\frac{iD_c\beta}{2} \lim_{q\to 0} k^2 S(\omega) = \sinh \frac{\beta\omega}{2}$
  - $\langle T, T \rangle_R$ has $\omega_* = i\frac{\gamma q^4}{6\bar{\epsilon}}$
    various hydro constraints follow, e.g.: $D/\Gamma = 2$



- AdS4-Reissner-Nordström black brane
  - channels are coupled with $\omega_* = i\frac{\gamma q^4}{6\bar{\epsilon}}\left(\frac{1}{2} \pm \sqrt{\frac{1}{4} + \left(\frac{2Q\gamma}{3\bar{\epsilon}}\right)^2 q^2}\right)^{-1}$

SPECTRAL DUALITY RELATION

- duality relation for any pair of meromorphic correlators:

$$G_+(\omega)G_-(\omega) = -1$$

$$S(\omega) = \prod_n \left(1 - \frac{\omega}{\omega_n^+}\right)\left(1 + \frac{\omega}{\omega_n^-}\right)$$

$$S(\omega) - S(-\omega) = 2i\lambda \sinh\frac{\beta\omega}{2}$$

- knowing one spectrum is sufficient for determining the other spectrum!

- spectral duality relation connects poles and zeros of a single correlator:

$$-G(\omega)G^{-1}(\omega) = -1$$

$$S(\omega) = \prod_n \left(1 - \frac{\omega}{\omega_n}\right)\left(1 + \frac{\omega}{z_n}\right)$$

thermal product formula →

$$r_n = \lambda G(0)\frac{\omega_n \sinh\frac{\beta\omega_n}{2}}{2\prod\limits_{\substack{m \\ m\neq n}}\left(1 - \frac{\omega_n^2}{\omega_m^2}\right)}$$

SPECTRAL DUALITY RELATION

- large-N field theory and double-trace deformed RG flow

$$Z_f[J] = e^{\Gamma[J,f]} = \left\langle e^{\int \mathcal{O}J - \frac{f}{2}\int \mathcal{O}^2} \right\rangle \qquad G(f) = \frac{G_0}{1 + fG_0}$$

$$\left[G(f_1)(f_2 - f_1) + 1\right]\left[G(f_2)(f_2 - f_1) - 1\right] = -1$$

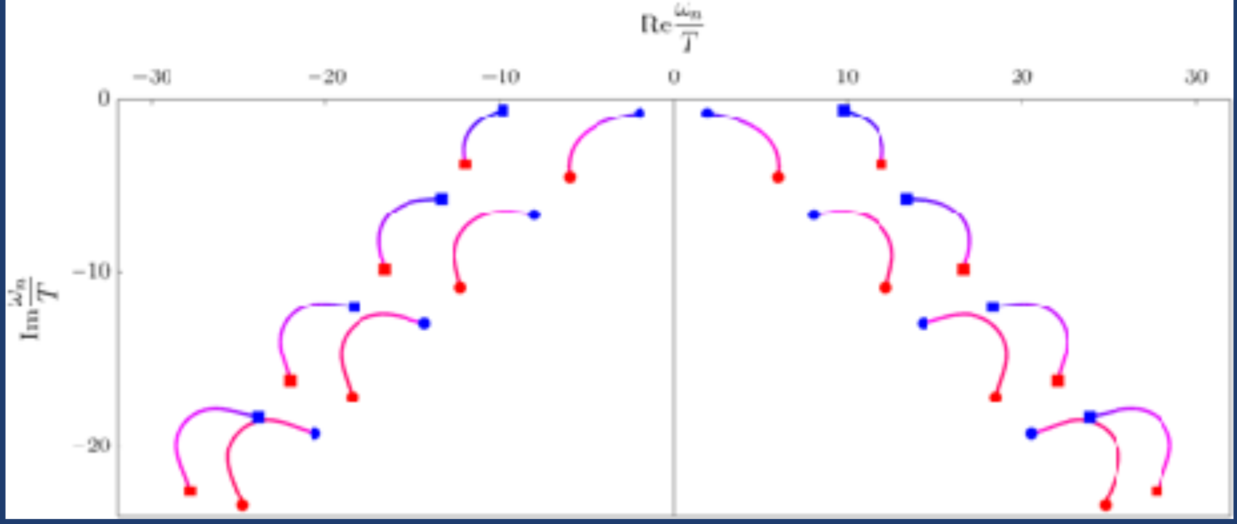
- using duality relations between UV and IR CFTs

$$Z_{f_-}[J_-] = e^{\Gamma_-[J_-,f_-]} = \left\langle e^{\int \mathcal{O}_- J_- - \frac{f_-}{2}\int \mathcal{O}_-^2} \right\rangle_-$$
$$Z_{f_+}[J_+] = e^{\Gamma_+[J_+,f_+]} = \left\langle e^{\int \mathcal{O}_+ J_+ - \frac{f_+}{2}\int \mathcal{O}_+^2} \right\rangle_+$$

$$\Delta_+ + \Delta_- = d$$
$$f_+ f_- = -1$$
$$G_-(f_-) = f_+\left[f_+ G_+(f_+) - 1\right]$$

$$G_0^- G_0^+ = -1$$

- same statement applies to correlators in any pair of theories related by Legendre transform



SUMMARY AND FUTURE DIRECTIONS

SUMMARY AND FUTURE DIRECTIONS

- QFTs and gravity exhibit extremely interesting and powerful (mathematical) structures
- large classes of large-N QFTs and black hole spectra exhibit stringent constraints, in particular, the 'universal' spectral duality relation
- results apply directly to gravity in AdS and the spectra of quasinormal modes
- keep exploring…
… ideally in realistic QFTs beyond the large-N

THANK YOU!