Transport in Anisotropic Superfluids: A Holographic Description

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based on 1011.5912 and 1110.0007
in collaboration with J. Erdmenger and P. Kerner

Motivation - Holographics Hydrodynamics

- hydrodynamics: system characterised by a few transport coefficients
- strongly interacting systems: transport properties inaccessible from underlying microscopic theories by standard methods

  examples: Quark-Gluon-Plasma, high T_c superconductors
- Gauge/Gravity duality can help!

$\Rightarrow$ Holographic Hydrodynamics

Motivation - Gauge/Gravity Duality and Anisotropic Systems

- anisotropic systems: more transport coefficients in systems with lower symmetry

- Gauge/Gravity Duality + Anisotropy

$\Rightarrow$ holographic p-wave superfluid

Outline

Gauge/Gravity Duality – brief reminder

- Maldacena in 1997:

$\mathcal{N}=4$ $SU(N_c)$ Super-Yang-Mills theory in D=4	$\Leftrightarrow$	type IIB Superstring theory in $\mathrm{AdS}_5 \times \mathrm{S}^5$

- Generalisation:

Large N gauge theory in D spacetime dimensions	$\Leftrightarrow$	Classical gravitational theory in asymptotically $\mathrm{AdS}_{\mathrm{D}+1}$ spacetime

$$\langle \mathrm{e}^{\int \mathrm{d}^{\mathrm{D}} x \mathcal{O} \phi_{\mathrm{bdy}}} \rangle_{\mathrm{FT}} = \mathcal{Z}_{\mathrm{GRAV}}[\Phi \to \phi_{\mathrm{bdy}}]$$

Gauge/Gravity Duality – extensions

- finite temperature $\Leftrightarrow$ Black Hole solution
- chemical potential ($\Rightarrow$ finite density)
  $\Leftrightarrow$
  Einstein-Maxwell theory with $A_t \neq 0$ at the AdS boundary
- holographic superfluid (arXiv:0810.1563)
  SSB global $U(1)$ + condensate
  $\Leftrightarrow$
  SSB gauged $U(1)$ + condensate hovering over black hole horizon

Hydrodynamics – Overview

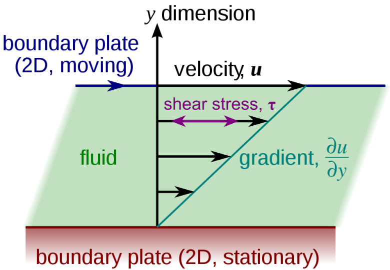
- long wavelength, small frequency fluctuations
- effective theory: macroscopic behaviour of the system
- response of system: transport coefficients
  e.g. shear viscosity, bulk viscosity, diffusion coefficient, conductivity
- constitutive equations

$$T^{\mu\nu} = T^{\mu\nu}_{\text{eq.}} + \Pi^{\mu\nu} \quad \text{and} \quad J^{\mu} = J^{\mu}_{\text{eq.}} + \Upsilon^{\mu}$$

with $\Pi_{ij} \sim \eta \left(\partial_i u_j + \partial_j u_i\right)$

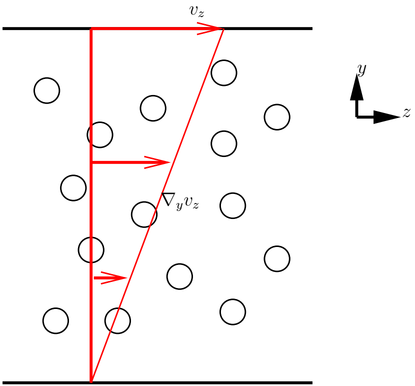
What is the Shear Viscosity?

- momentum diffusion transverse to the momentum
- viscosity tensor $\eta_{\alpha\beta\gamma\delta}$
- anisotropic systems: 21 components
- isotropic systems: 1 shear viscosity
- transversely isotropic systems: 2 shear viscosities

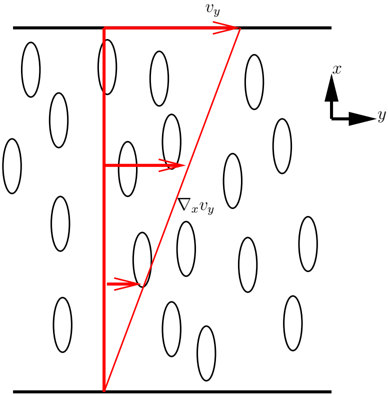


What is the Shear Viscosity?

η_{yz}:



$\eta_{x\perp}$:



Shear Viscosity of Weakly Coupled Theories

- shear vicosity $\eta \sim \epsilon l_{\text{mfp}}$
- mean free path $l_{\text{mfp}} \sim \frac{1}{n\sigma}$
- in $\lambda\phi^4$ theory:

$$\eta \sim \frac{T^3}{\lambda^2}\,, \text{ with } \lambda \ll 1$$

- using $s \sim T^3$

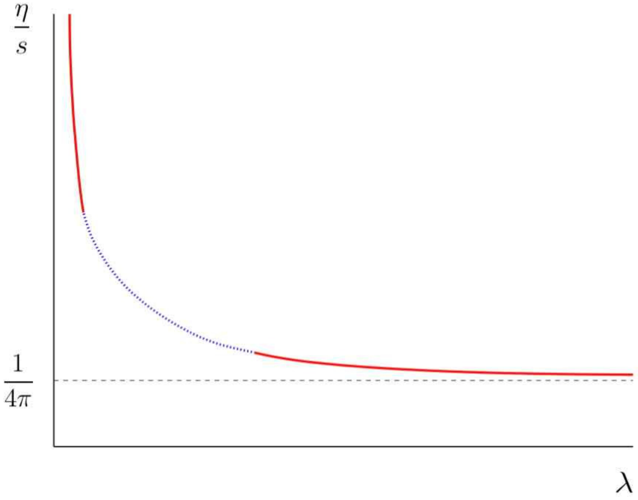
$$\Rightarrow \frac{\eta}{s} \sim \frac{1}{\lambda^2}$$

Shear Viscosity from Gauge/Gravity Duality

- universal property of strongly coupled isotropic field theories with classical, two-derivative gravity dual:

$$\frac{\eta}{s} = \frac{1}{4\pi} \simeq 0.079$$

Shear Viscosity from Gauge/Gravity Duality



arXiv:0709.1523

Shear Viscosity from Gauge/Gravity Duality

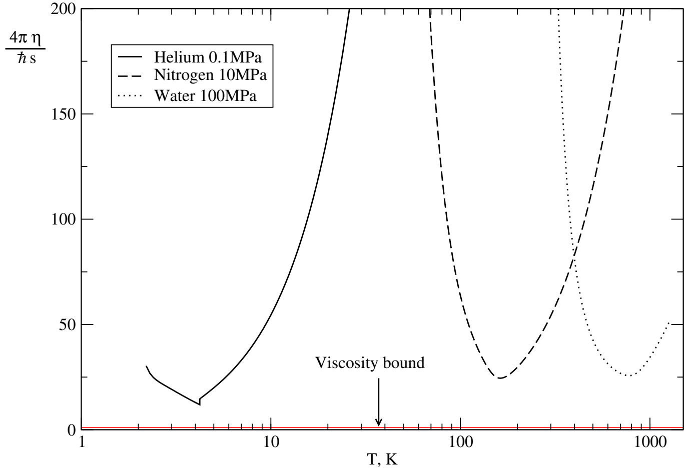
- universal property of strongly coupled isotropic field theories with classical, two-derivative gravity dual:

$$\frac{\eta}{s} = \frac{1}{4\pi} \simeq 0.079$$

- conjecture by Kovtun, Son and Starinets (arXiv:hep-th/0405231):

$$\frac{\eta}{s} \geq \frac{1}{4\pi} \text{ for substances found in Nature}$$

Shear Viscosity from Gauge/Gravity Duality



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- RHIC experiment:

$$\text{Quark-Gluon-Plasma } \frac{\eta}{s} \sim [0 - 0.2]$$

Gravitational Setup for holographic p-wave Superfluid

- $SU(2)$ Einstein-Yang-Mills theory in (4+1)-dimensional asymptotically AdS Space

$$S = \frac{1}{2{\kappa_5}^2} \int \mathrm{d}^5 x \sqrt{-g} \left[R - \Lambda - \frac{\alpha^2}{2} F^a_{MN} F^{aMN} \right] + S_{\mathrm{bdy}}$$

- with

$$\alpha \equiv \frac{\kappa_5}{g_{\mathrm{YM}}}$$

- α measures the backreaction

Hairy Black Hole Ansatz

- metric ansatz

$$\mathrm{d}s^2 = -N(r)\sigma(r)^2\mathrm{d}t^2 + \frac{1}{N(r)}\mathrm{d}r^2 + \frac{r^2}{f(r)^4}\mathrm{d}x^2 + r^2 f(r)^2\left(\mathrm{d}y^2 + \mathrm{d}z^2\right)$$

  with

$$N(r) = -\frac{2m(r)}{r^2} + r^2$$

  AdS boundary $r = r_{\text{bdy}} \to \infty$ & black hole horizon $r = r_h$

- gauge field ansatz

$$A = \phi(r)\tau^3\mathrm{d}t + w(r)\tau^1\mathrm{d}x$$

Motivation for the Ansatz

Field Theory	$\Leftrightarrow$	Gravity
chemical potential μ $SU(2) \to U(1)_3$		$A_t^3 = \phi(r) \neq 0$ $SU(2) \to U(1)_3$
$\langle \mathcal{J}_1^x \rangle \neq 0$ $U(1)_3 \to \mathbb{Z}_2$, $SO(3) \to SO(2)$		$A_x^1 = w(r) \neq 0$ $U(1)_3 \to \mathbb{Z}_2$, $SO(3) \to SO(2)$

- $w(r_{\text{bdy}}) = 0 \Rightarrow$ SSB $U(1)_3 \to \mathbb{Z}_2$ & $SO(3) \to SO(2)$

$\Rightarrow$ holographic p-wave superfluid with backreaction
(Ammon, Erdmenger, Grass, Kerner, O'Bannon: arXiv:0912.3515)

Hairy Black Hole Solution

- $w(r) = 0$: AdS Reissner-Nordström black hole solution
- $w(r) \neq 0$: numerical solution (shooting method)

The $w(r) \neq 0$ Solution

- 5 fields: $\{\phi(r), w(r), \sigma(r), f(r), m(r)\}$
- 4 independent parameter at the horizon
- expansion of fields at the boundary:

$$\phi(r \to r_{\rm bdy}) \simeq \mu + \frac{r_h^2}{r^2}\phi_1^b + \ldots$$
$$w(r \to r_{\rm bdy}) \simeq 0 + \frac{r_h^2}{r^2}w_1^b + \ldots$$
$$f(r \to r_{\rm bdy}) \simeq 1 + \frac{r_h^4}{r^4}f_2^b + \ldots$$
$$\sigma(r \to r_{\rm bdy}) \simeq 1 + \mathcal{O}\left(r^{-6}\right)$$
$$m(r \to r_{\rm bdy}) \simeq m_0^b + \mathcal{O}\left(r^{-2}\right)$$

Thermodynamics in the Field Theory

- fix chemical potential $\mu \Rightarrow$ grand canonical ensemble

- Gauge/Gravity dictionary:

$\Rightarrow$ Hawking temperature $\Leftrightarrow$ temperature in field theory

$$T \propto r_h$$

$\Rightarrow$ black hole entropy density $\Leftrightarrow$ entropy density of field theory

$$s \propto {r_h}^3 \propto T^3$$

Thermodynamics in the Field Theory

variation of on-shell action at AdS boundary + GGD dictionary:

- energy-momentum tensor

$$\langle \mathcal{T}_{\mu\mu} \rangle \propto T^4 \cdot \mathrm{Func}(m_0^b, f_2^b), \text{ with: } \langle \mathcal{T}_{yy} \rangle = \langle \mathcal{T}_{zz} \rangle \neq \langle \mathcal{T}_{xx} \rangle$$
$$\langle \mathcal{T}_{\mu\nu} \rangle = 0 \text{ for } \mu \neq \nu$$

- density current

$$\langle \mathcal{J}_3^t \rangle \propto T^3 \phi_1^b$$

- condensate

$$\langle \mathcal{J}_1^x \rangle \propto T^3 w_1^b$$

Thermodynamics in the Field Theory

properties of the energy-momentum tensor:

- traceless ($\Leftarrow$ CFT)

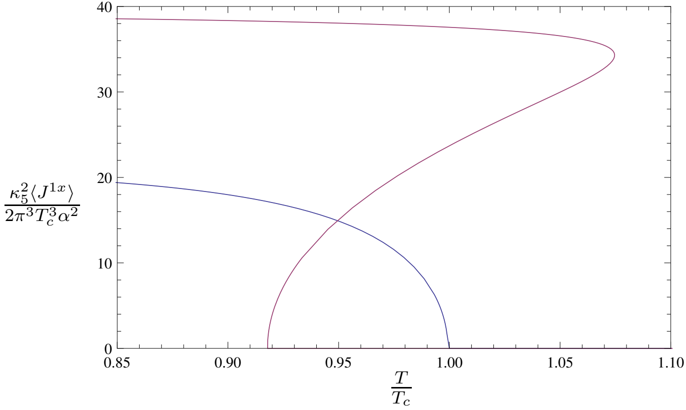
- zero net momentum

$$\langle \mathcal{T}_{tx} \rangle = \langle \mathcal{T}_{ty} \rangle = \langle \mathcal{T}_{tz} \rangle = 0$$

- grand canonical potential

$$\Omega = \lim_{r_{\text{bdy}} \to \infty} T S_{\text{on-shell}} = -V \langle \mathcal{T}_{yy} \rangle$$

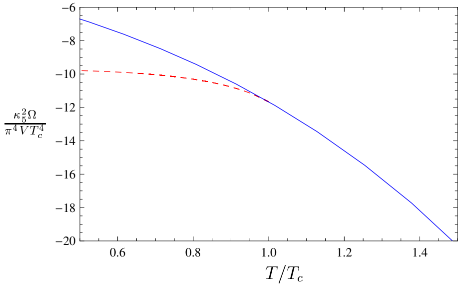
Thermodynamics in the Field Theory

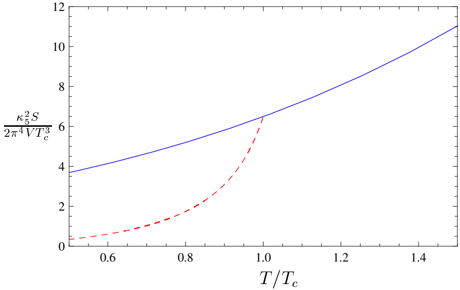


colour coding: $\alpha = 0.316$ and $\alpha = 0.447$
$\langle \mathcal{J}_1^x \rangle \propto (1 - T/T_c)^{1/2}$ for $\alpha = 0.316$

arXiv:0912.3515

Ω and s for $\alpha = 0.316$





colour coding: Reissner-Nordström solution and $w(r) \neq 0$ solution

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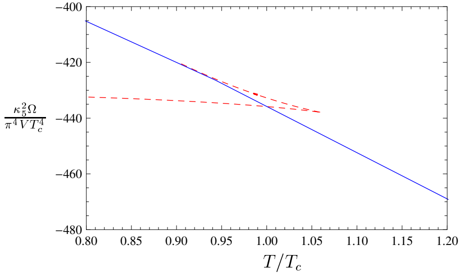

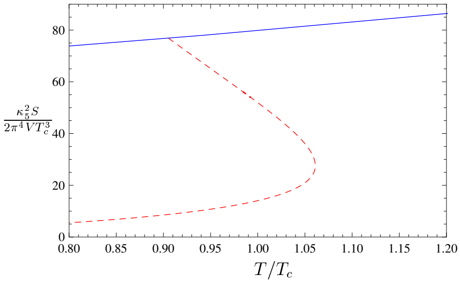

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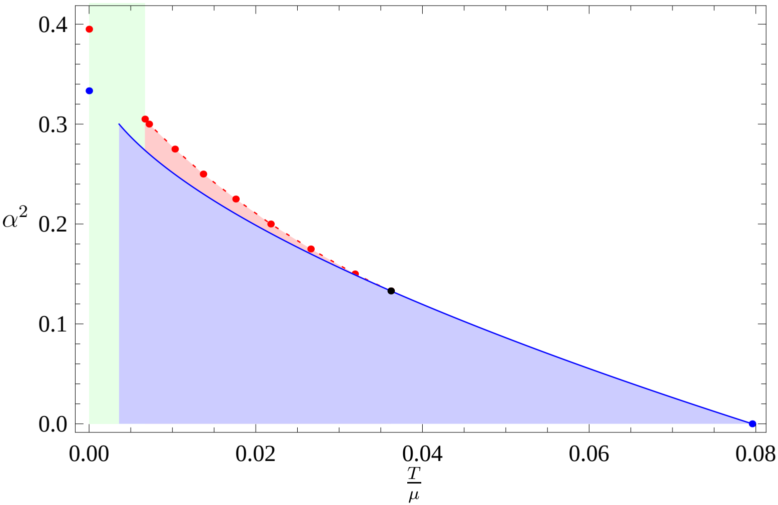
Order of the Phase transition



preferred ground state:

blue: broken phase, $w(r) \neq 0$; white: Reissner-Nordström black hole

Phase Transition

- $\alpha < \alpha_c = 0.365 \pm 0.001$: second order
- $\alpha > \alpha_c$: first order
- $\alpha < \alpha_{\mathrm{max}} = 0.628$

arXiv:0912.3515

Interpretation of α in the Field Theory

$$\langle T_\mu{}^\mu \rangle \propto \frac{1}{\kappa_5^2} \propto \#\text{ of total degrees of freedom}$$

$$\langle J \rangle \propto \frac{1}{g_{\mathsf{YM}}^2} \propto \#\text{ of charged degrees of freedom}$$

$$\Rightarrow \ \alpha^2 = \frac{\kappa_5^2}{g_{\mathrm{YM}}^2} \propto \frac{\#\text{ of charged degrees of freedom}}{\#\text{ of total degrees of freedom}}$$

Perturbations about the Thermodynamical Equillibrium

small perturbations:

- metric $\hat{g}_{MN} = g_{MN}(r) + h_{MN}(x^\mu, r)$
- gauge field $\hat{A}^a_M = A^a_M(r) + a^a_M(x^\mu, r)$
- x^μ-spacetime translational invariance still unbroken

$\Rightarrow$ Fourier decomposition of fluctuations possible:

$$h_{MN}(x^\mu, r) = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \mathrm{e}^{\mathrm{i} k_\mu x^\mu} h_{MN}(k^\mu, r)$$
$$a^a_M(x^\mu, r) = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \mathrm{e}^{\mathrm{i} k_\mu x^\mu} a^a_M(k^\mu, r)$$

- $SO(2)$ symmetry $\Rightarrow$ two distinct momenta needed: $k_\parallel$ and $k_\perp$

Classification of Perturbations

- set $k_\perp = 0$

$\Rightarrow$ classification under $SO(2)$ rotational symmetry around x-axis possible:

	dynamical fields	constraints	# physical modes
helicity 2	$h_{yz}, h_{yy} - h_{zz}$	none	2
helicity 1	$h_{ty}, h_{xy}; a^a_y$	h_{yr}	4
	$h_{tz}, h_{xz}; a^a_z$	h_{zr}	4
helicity 0	$h_{tt}, h_{xx}, h_{yy} + h_{zz}, h_{xt};$ a^a_t, a^a_x	$h_{tr}, h_{xr}, h_{rr}; a^a_r$	4

gauge choice $h_{Mr} = 0$ and $a^a_r = 0 \Rightarrow$ 14 physical modes

How to get transport coefficients:

- find numerical solution to equations of motions and constraints using incoming boundary conditions at horizon
- determine on-shell action at AdS boundary
- determine Green's functions using Son's and Starinets' recipe (arXiv:hep-th/0205051)
- determine transport coefficients using Kubo formula

Green's function

$$G^{\mu\nu,\rho\sigma}(\omega,\vec{k}) = \int \mathrm{d}^4x \; \mathrm{e}^{-ik_\mu x^\mu}\theta(t) \; \langle [T^{\mu\nu}(t,\vec{x}), \, T^{\rho\sigma}(0)]\rangle$$

$$G^{\mu\nu,\rho}{}_{a}(\omega,\vec{k}) = \int \mathrm{d}^4x \; \mathrm{e}^{-ik_\mu x^\mu}\theta(t) \; \langle [T^{\mu\nu}(t,\vec{x}), J^\rho_a(0)]\rangle$$

$$G^{\rho,\mu\nu}_a(\omega,\vec{k}) = \int \mathrm{d}^4x \; \mathrm{e}^{-ik_\mu x^\mu}\theta(t) \; \langle [J^\rho_a(t,\vec{x}), \, T^{\mu\nu}(0)]\rangle$$

$$G^{\mu,\nu}_{a,b}(\omega,\vec{k}) = \int \mathrm{d}^4x \; \mathrm{e}^{-ik_\mu x^\mu}\theta(t) \; \langle [J^\mu_a(t,\vec{x}), J^\nu_b(0)]\rangle$$

in the following set $\vec{k} = 0$

Helicity 2 Mode

- only 1 non-trivial helicity 2 mode
- minimal coupled scalar $\Xi = g^{yy} h_{yz}$
- $G^{yz,yz}(\omega, \vec{k} = 0) = \frac{2r_h^4}{\kappa_5^2} \frac{\Xi_2^b(\omega)}{\Xi_0^b(\omega)} - \langle \mathcal{T}_{yy} \rangle + \mathcal{O}(\omega^4)$

Hydrodynamics from the Helicity 2 Mode

- from isotropic case: $\langle T^{yz}\rangle = -(P + \mathrm{i}\omega\eta_{yz})h_{yz}$, with $P = \langle \mathcal{T}_{yy}\rangle$

- Kubo formula:

$$\eta_{yz} = -\lim_{\omega\to 0}\frac{1}{\omega}\mathrm{Im}(G^{yz,yz}) = -\lim\frac{1}{\omega}\frac{2r_h^4}{\kappa_5^2}\frac{\Xi_2^b(\omega)}{\Xi_0^b(\omega)}$$

- from numerics:

$$\frac{\eta_{yz}}{s} = \frac{1}{4\pi}\pm 0.5\%$$

Hydrodynamics from the Helicity 2 Mode

- Ξ minimally coupled scalar
- with $\partial_r \Pi = 0 + \mathcal{O}(\omega)$ and $\partial_r(\omega\Xi) = 0 + \mathcal{O}(\omega)$

$\Rightarrow$ Iqbal *et. al.* (arXiv:0809.3808):

$$\frac{\eta_{yz}}{s} = \frac{1}{4\pi}$$

- using:

$$\eta_{yz} = \lim_{\omega\to 0} \frac{\Pi}{\mathrm{i}\omega\Xi}\bigg|_{r=r_h}$$

Helicity 1 Modes

- in $\vec{k} \to 0$ limit additional symmetry:
  $\mathbb{Z}_2$: $x \to -x$, $w \to -w$

$\Rightarrow$ helicity 1 modes decouple in 2 blocks:

even parity: $\{\Psi_t = g^{yy} h_{t\perp}, a^3_\perp, h_{r\perp}\}$

odd parity: $\{\Psi_x = g^{yy} h_{x\perp}, a^1_\perp, a^2_\perp\}$

Helicity 1 Modes with odd Parity Block

3 equations of motion + 0 constraint

$\Rightarrow$ 3 independent fields: $\Psi_x, a_\perp^1, a_\perp^2$

$\Rightarrow$ Green's function: 3×3 matrix

Hydrodynamics from the Helicity 1 Modes with odd Parity

- choose basis: $a_\perp^\pm = a_\perp^1 \pm \mathrm{i} a_\perp^2$

$\Rightarrow$ transform in fundamental repr. of unbroken $U(1)_3$

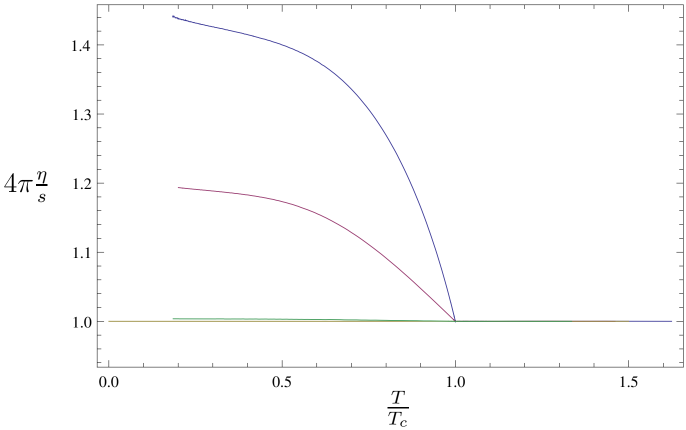
- field theory:

$$\begin{pmatrix} \langle J_+^\perp \rangle \\ \langle J_-^\perp \rangle \\ \langle T^{x\perp} \rangle \end{pmatrix} = \begin{pmatrix} G_{+,+}^{\perp,\perp} & G_{+,-}^{\perp,\perp} & G_+^{\perp\, x\perp} \\ G_{-,+}^{\perp,\perp} & G_{-,-}^{\perp,\perp} & G_-^{\perp\, x\perp} \\ G^{x\perp\, \perp}{}_{+} & G^{x\perp\, \perp}{}_{-} & -\langle T_{xx} \rangle - \mathrm{i}\omega\eta_{x\perp} \end{pmatrix} \begin{pmatrix} a_\perp^+ \\ a_\perp^- \\ h_{x\perp} \end{pmatrix}$$

- with

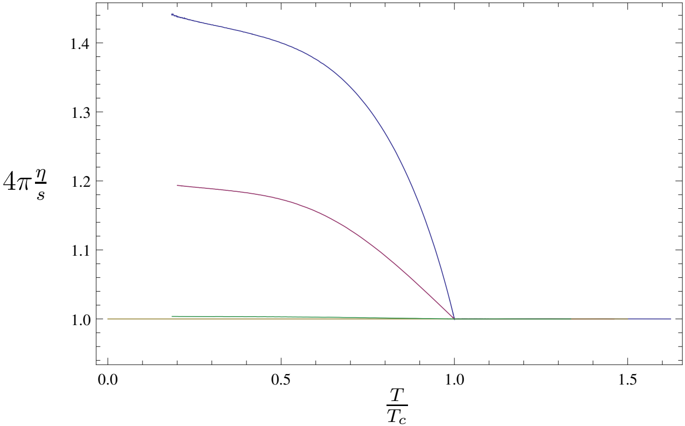
$$\eta_{x\perp} = -\lim_{\omega\to 0} \frac{1}{\omega} \mathrm{Im}\left(G^{x\perp,x\perp} \right)$$

Non-universal $\frac{\eta_{x\perp}}{s}$ for $\alpha < \alpha_c$



colour coding: $\frac{\eta_{yz}}{s} = \frac{1}{4\pi}$ and $\frac{\eta_{x\perp}}{s}$: $\alpha_c > \alpha_1 > \alpha_2 > \alpha_3$

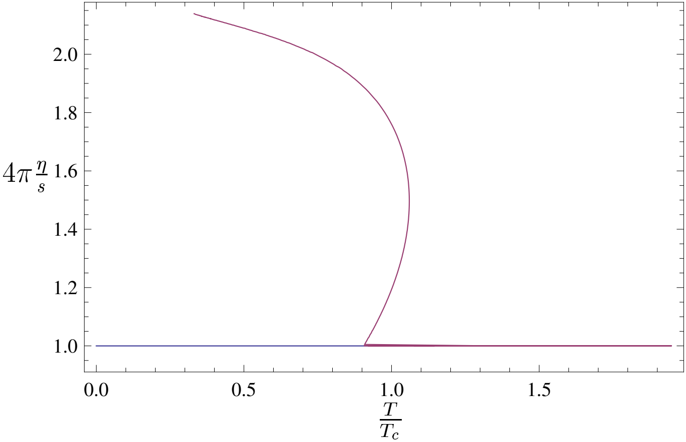
Non-universal $\frac{\eta_{x\perp}}{s}$ for $\alpha < \alpha_c$



$$1 - 4\pi\frac{\eta_{x\perp}}{s} \propto \left(1 - \frac{T}{T_c}\right)^{\beta} \quad \text{with} \quad \beta = 1.00 \pm 3\%$$

confirmed analytically by Basu, Oh (arXiv:1109.4592)

Non-universal $\frac{\eta_{x\perp}}{s}$ for $\alpha > \alpha_c$

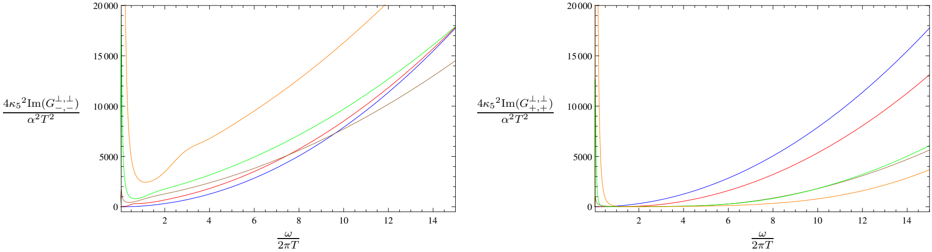


expectation: maximal deviation from $1/(4\pi)$ for α_{max}

$\mathrm{Im}(G^{\perp,\perp}_{\mp,\mp})$ for $\alpha = 0.316$

$$\begin{pmatrix} G^{\perp,\perp}_{+,+} & G^{\perp,\perp}_{+,-} & G_{+}^{\perp}{}^{x\perp} \\ G^{\perp,\perp}_{-,+} & G^{\perp,\perp}_{-,-} & G_{-}^{\perp}{}^{x\perp} \\ G^{x\perp}{}^{\perp}_{+} & G^{x\perp}{}^{\perp}_{-} & -\langle T_{xx}\rangle - \mathrm{i}\omega\eta_{x\perp} \end{pmatrix}$$

$\mathrm{Im}(G^{\perp,\perp}_{\mp,\mp})$ for $\alpha = 0.316$



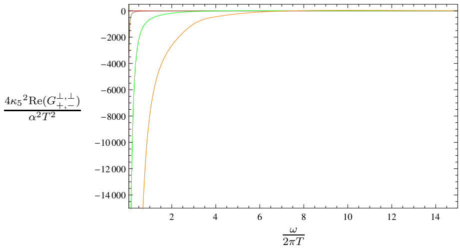
colour coding:

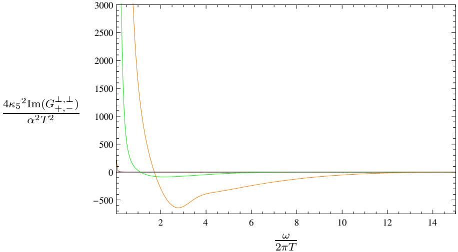
$T = \infty > T = 3.02\,T_c > T = 1.00\,T_c > T = 0.88\,T_c > T = 0.50\,T_c$

$G^{\perp,\perp}_{+,-}$ for $\alpha = 0.316$

$$\begin{pmatrix} G^{\perp,\perp}_{+,+} & G^{\perp,\perp}_{+,-} & G^{\perp\,x\perp}_{+} \\ G^{\perp,\perp}_{-,+} & G^{\perp,\perp}_{-,-} & G^{\perp\,x\perp}_{-} \\ G^{x\perp\,\perp}_{\;\;+} & G^{x\perp\,\perp}_{\;\;-} & -\langle T_{xx}\rangle - \mathrm{i}\omega\eta_{x\perp} \end{pmatrix}$$

$G_{+,-}^{\perp,\perp}$ for $\alpha = 0.316$





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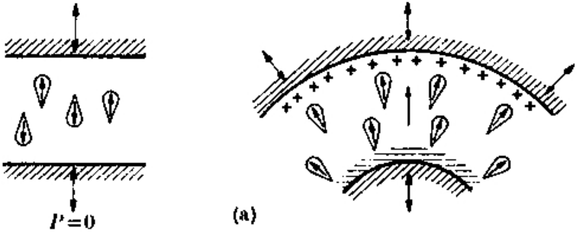
Flexoelectric effect

- strain leads to effective polarization
- electric field leads to stress



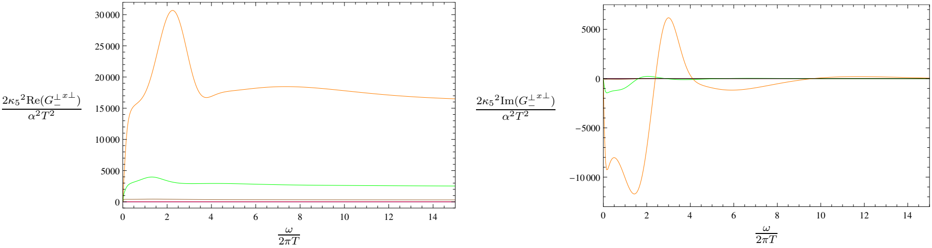
de Gennes

- our system: coupling between flavour fields and strain

$G_{-}^{\perp\, x\perp}$ for $\alpha = 0.316$

$$\begin{pmatrix} G_{+,+}^{\perp,\perp} & G_{+,-}^{\perp,\perp} & G_{+}^{\perp\, x\perp} \\ G_{-,+}^{\perp,\perp} & G_{-,-}^{\perp,\perp} & G_{-}^{\perp\, x\perp} \\ G^{x\perp\, \perp}_{\, +} & G^{x\perp\, \perp}_{\, -} & -\langle T_{xx}\rangle - \mathrm{i}\omega\eta_{x\perp} \end{pmatrix}$$

$G_{-}^{\perp x \perp}$ for $\alpha = 0.316$



colour coding:

$T = \infty > T = 3.02\,T_c > T = 1.00\,T_c > T = 0.88\,T_c > T = 0.50\,T_c$

Helicity 1 Modes - even Parity Block

2 equations of motion + 1 constraint

$\Rightarrow$ 1 independent field: $a_\perp^3$

$\Rightarrow$ Green's function: 2×2 matrix with 1 independent component

Hydrodynamics from the Helicity 1 Modes with even Parity

- Hartnoll (arXiv:0903.3246):
  $E_\perp = \mathrm{i}\omega\left((a^3_\perp)^b_0 + \mu(\Psi_t)^b_0\right)$ and $-\frac{\nabla_\perp T}{T} = \mathrm{i}\omega(\Psi_t)^b_0$

- field theory (Thermoelectric effect):

$$\begin{pmatrix}\langle J^\perp\rangle\\ \langle Q^\perp\rangle\end{pmatrix} = \begin{pmatrix}\sigma^{\perp\perp} & T\alpha^{\perp\perp}\\ T\alpha^{\perp\perp} & T\bar{\kappa}^{\perp\perp}\end{pmatrix}\begin{pmatrix}E_\perp\\ -(\nabla_\perp T)/T\end{pmatrix}$$

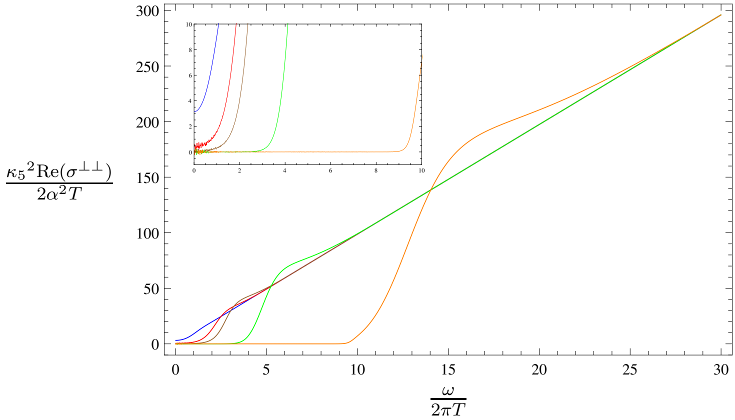
  with $\langle Q^\perp\rangle = \langle T^{t\perp}\rangle - \mu\langle J^\perp\rangle$

- identification with gravity side in our system:

$$\sigma^{\perp\perp} = -\frac{\mathrm{i}G^{\perp,\perp}_{3,3}}{\omega} = -\frac{\alpha^2 r_h}{\kappa_5^2}\frac{\mathrm{i}}{\tilde{\omega}}\left(\frac{2\left(\tilde{a}^3_\perp\right)^b_1}{\left(\tilde{a}^3_\perp\right)^b_0} - \frac{\tilde{\omega}^2}{2}\right)$$

$$T\alpha^{\perp\perp} = \frac{\mathrm{i}}{\omega}\langle\mathcal{J}^t_3\rangle - \mu\sigma^{\perp\perp} \quad , \quad T\bar{\kappa}^{\perp\perp} = \frac{\mathrm{i}}{\omega}\langle\mathcal{T}_{tt}\rangle + \mu^2\sigma^{\perp\perp}$$

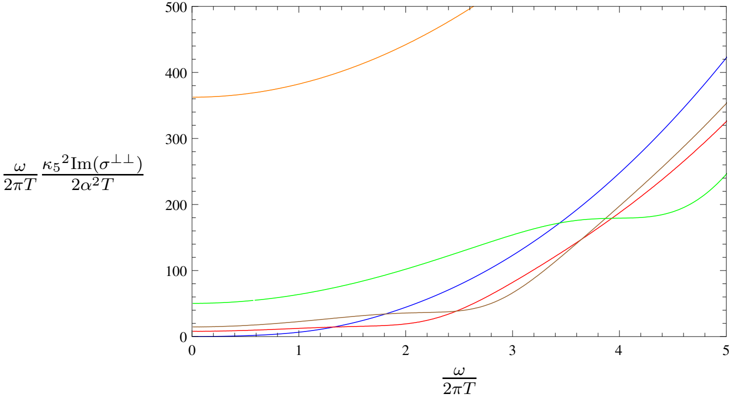
Electrical conductivity at $\alpha < \alpha_c$



colour coding:

$T = \infty > T = 1.00\, T_c > \; T = 0.88\, T_c > T = 0.50\, T_c > T = 0.19\, T_c$

$\omega \mathrm{Im}(\sigma^{\perp\perp})$ at $\alpha < \alpha_c$



colour coding:

$T = \infty > T = 1.00\,T_c > T = 0.88\,T_c > T = 0.50\,T_c > T = 0.19\,T_c$

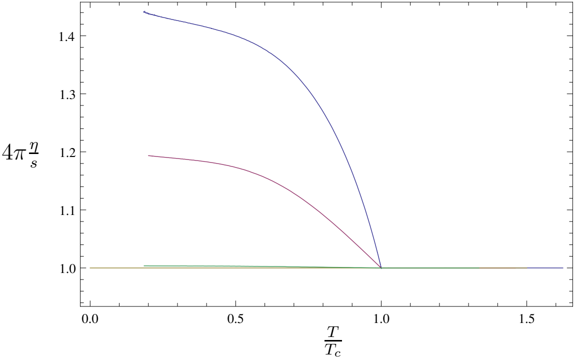
Conclusion

- holographic hydrodynamics: useful tool to compute transport coefficients

- p-wave superfluid with backreaction $\Rightarrow$ two shear modes:

$$\frac{\eta_{yz}}{s} = \frac{1}{4\pi}$$

$$\frac{\eta_{x\perp}}{s}(T) \geq \frac{1}{4\pi}$$



- flexoelectric effect, thermoelectric effect

Open questions...

- What are the bumps in the odd parity helicity 1 block?
- What effects can we see in the helicity 0 modes?
- What happens if we turn on momentum?

Thank you!