Hydrodynamics and transport of soft pions in heavy ion collisions

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Building on: arXiv:2005.02885

Extreme Nonequilibrium QCD
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FWF Der Wissenschaftsfonds.

Motivation

Chiral symmetry breaking

Chiral phase transition is characterized by:

- formation of the chiral condensate, $\langle \bar{q} q \rangle$
- symmetry breaking pattern
  $SU(2)_L \times SU(2)_R \times U(1) \to SU(2)_V \times U(1)$

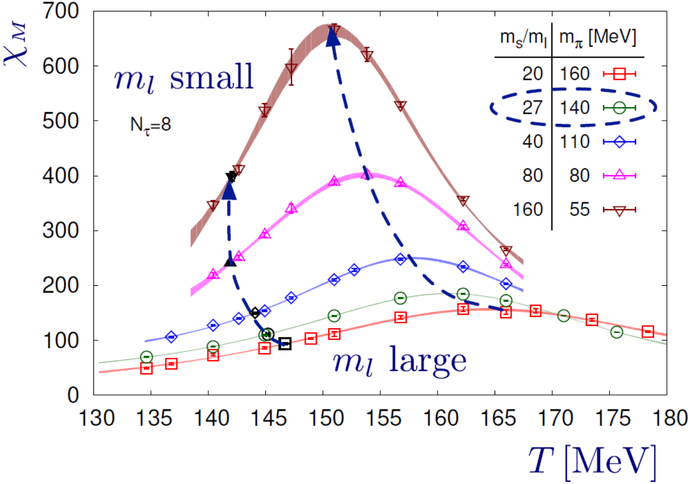
This symmetry is exact in the chiral limit, $m_q \to 0$, with massless Goldstone modes (pions)

Chiral symmetry breaking

In QCD, $m_q \neq 0$, chiral symmetry is not exact ($m_\pi \neq 0$)
Nonetheless, can we see any signatures of this?

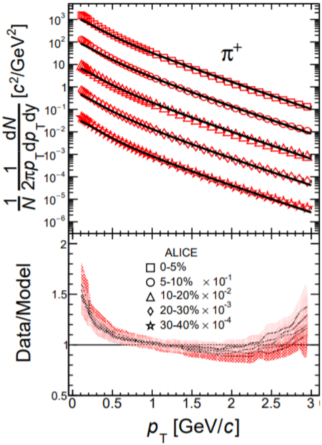
- Lattice points to yes! Evidence points to transition in $O(4)$ universality class
- Future experiments: near T_c, some soft pions can escape $\Rightarrow$ window to chiral dynamics?

$O(4)$ scaling as seen on the lattice



Chiral susceptibility: $\chi_M \propto \frac{\partial\langle\bar{\psi}\psi\rangle}{\partial m_l} \sim m_l^{1/\delta-1} f_\chi(z)$, $z \equiv t m_l^{-1/\beta\delta}$
Plot from HotQCD collaboration: arXiv:1903.04801

Experimental status: What about the soft pions?

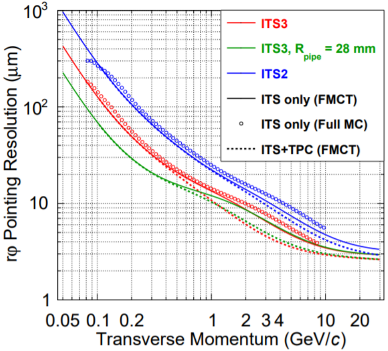


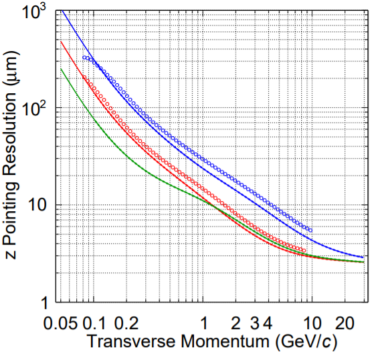
Plot from: D. Devetak *et al*, arXiv:1909.10485

Soft pions are harder to fit to hydrodynamic models.
Adding more primary resonances only improves the situation marginally

Upgrade to ITS detector at ALICE

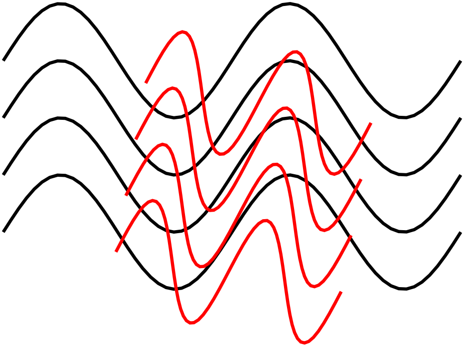
Inner Tracking System allows to see more low p_T particles, especially pions.
Standard observables: multiplicity ratio of charged to neutral pions or correlation functions between charged pions.





Upgrade by end of 2021 (???)

Hydrodynamics in the chiral limit



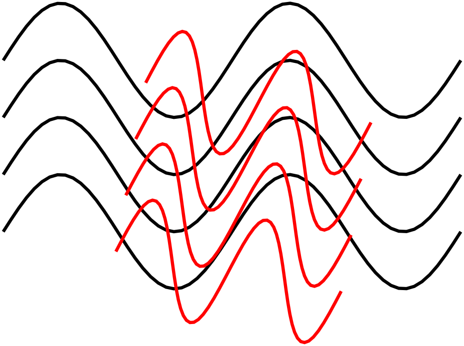
equilibrated hydro modes, $k \ll m_\pi$

superfluid modes, $k \sim m_\pi$

At long distances, effective theory of QCD is hydrodynamics

At finite quark mass, theory should be superfluid-like for $L \sim m_\pi^{-1}$

Hydrodynamics in the chiral limit

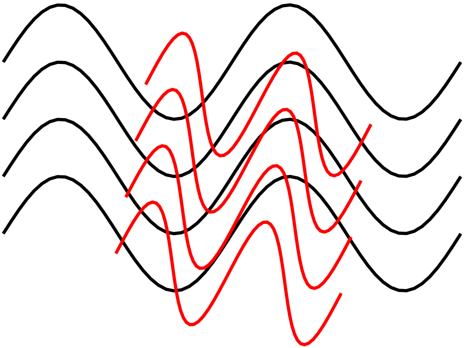


equilibrated hydro modes, $k \ll m_\pi$

superfluid modes, $k \sim m_\pi$

Question: How do these modes contribute to hydrodynamic variables and transport?

Hydrodynamics in the chiral limit



equilibrated hydro modes, $k \ll m_\pi$

superfluid modes, $k \sim m_\pi$

Hydrodynamic variables get correction due to pion mass, e.g.

$$\eta = \eta_{\text{hydro}} + \eta_{\text{superfluid}}$$

Set-up

Superfluid hydrodynamics[1]

Ingredients in the model:

- (Approximately) conserved quantities $T^{\mu\nu}, \hat{J}_a^\mu$
- Chiral condensate $\Sigma = \sigma U = \phi_\alpha \tau_\alpha$
- Temperature, T, velocity, u^μ, chemical potentials, μ_L, μ_R
- Mass for the Goldstone boson

[1] Son arXiv:hep-ph/9912267

$O(4)$ free energy[2]

Free energy near T_c :

$$F = F_{reg}(T) + \underbrace{F_s(t, h)}_{\text{singular part}}$$

Near T_c: Regular part finite, singular part captures critical behavior

[2] Rajagopal, Wilczek arXiv:9210253

$O(4)$ free energy[3]

Free energy near T_c :

$$F = F_{reg}(T) + \underbrace{F_s(t, h)}_{\text{singular part}}$$

$$F_s = \int d^3x \left(\frac{1}{4}\chi_0(\mu_{\alpha\beta})^2 + \nabla\phi_\alpha \cdot \nabla\phi_\alpha + V(\phi_\alpha\phi_\alpha) \right)$$

[3] Rajagopal, Wilczek arXiv:9210253

$O(4)$ free energy[4]

Free energy near T_c :

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where

- $\mu_{\alpha\beta}$ is the $O(4)$ chemical potential (e.g. $\mu_{0i} = \mu_A$)
- $\phi_\alpha = (\sigma, -\pi^a) \in O(4)$, which relates to $\Sigma = \tau_\alpha\phi_\alpha$
- $V(\phi_\alpha\phi_\alpha) = m_0^2(t)\phi^2 + \lambda\phi^4 - H\phi$

where $m_0(t)^2$ depends on reduced temperature: $t = \frac{T-T_c}{T_c}$

[4] Rajagopal, Wilczek arXiv:9210253

Mean field approximation

Work in the mean field by minimizing potential

$$0 = \frac{dV}{d\phi} = m_0^2(t)\,\bar{\sigma} + \frac{\lambda}{3!}\bar{\sigma}^3 - H.$$

Scaling solution is

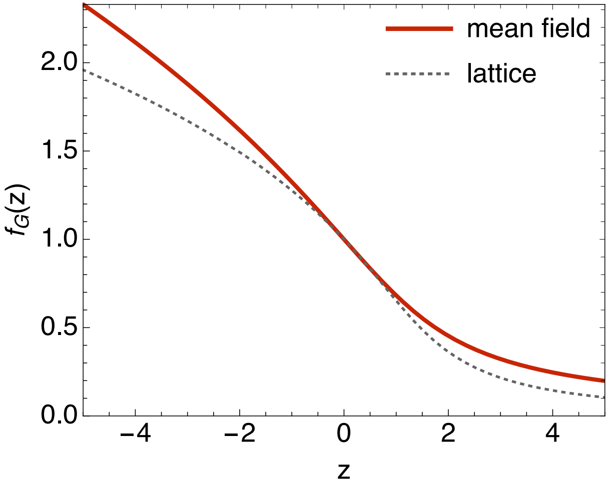
$$\bar{\sigma} = h^{1/3} f_G(z)$$

with

$$z = th^{-1/(\beta\delta)}$$

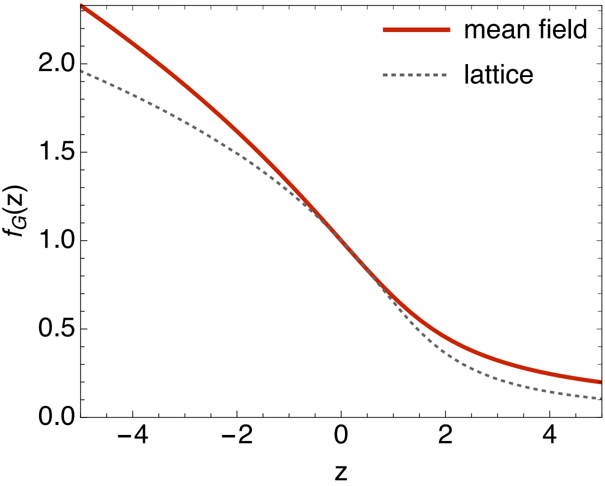
Reduced magnetic field: $h = H/\lambda$
In mean field, $\beta = 1/2$ and $\delta = 3 \Rightarrow z = th^{-2/3}$.

$O(4)$ scaling function



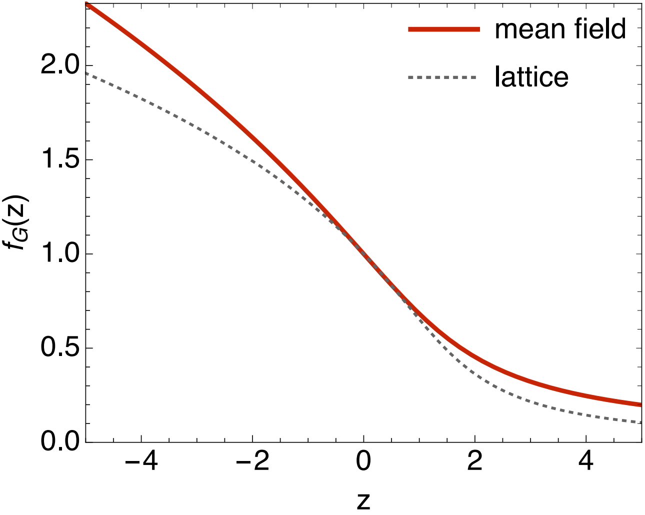
Characterize solutions via $f_G(z) = \bar{\sigma} h^{-1/3}$ where $z = th^{-2/3}$

$O(4)$ scaling function



Interpolates between broken ($T < T_c$ i.e. $z < 0$) and unbroken phase ($T > T_c$ i.e. $z > 0$)

$O(4)$ scaling function



Comparison to lattice from Engels & Vogt arXiv:0911.1939

Engels & Karsch arXiv:1105.0584

Mean field approximation

Now expand fields around mean field

$$\Sigma = \bar{\sigma} + \delta\sigma + i\bar{\sigma}\varphi^a\tau^a$$

τ^a are the Pauli matrices.
Evaluate free energy to quadratic order:

$$\beta F[T,\phi] = \beta F_\sigma(T) + \beta \int d^3x \, \frac{1}{4}\chi_0\mu^2 + \frac{1}{2}\left(\nabla\delta\sigma \cdot \nabla\delta\sigma + m_\sigma^2 \delta\sigma^2\right) + \frac{1}{2}\chi_0 v^2(T)\left(\nabla\varphi^a \cdot \nabla\varphi^a + m^2\varphi^a\varphi^a\right)$$

Mean field approximation

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Note: regular piece gets contribution from mean field

$$F_\sigma(T) = F_{reg}(T) + \mathcal{V}\left(\frac{1}{2}m_0^2(T)\bar{\sigma}^2(T) + \frac{\lambda}{4}\bar{\sigma}(T)^4 - H\bar{\sigma}(T)\right)$$

Mean field approximation

Evaluate free energy to quadratic order:

$$\beta F[T,\phi] = \beta F_\sigma(T) + \beta \int d^3x \, \frac{1}{4}\chi_0\mu^2 + \frac{1}{2}\left(\nabla\delta\sigma\cdot\nabla\delta\sigma + m_\sigma^2\delta\sigma^2\right) + \frac{1}{2}\chi_0 v^2(T)\left(\nabla\varphi^a\cdot\nabla\varphi^a + m^2\varphi^a\varphi^a\right)$$

Physical quantities of interest:

- Pion screening mass

$$m^2 = \frac{H}{\bar\sigma(T)} = \frac{m_c^2}{f_G(z)}$$

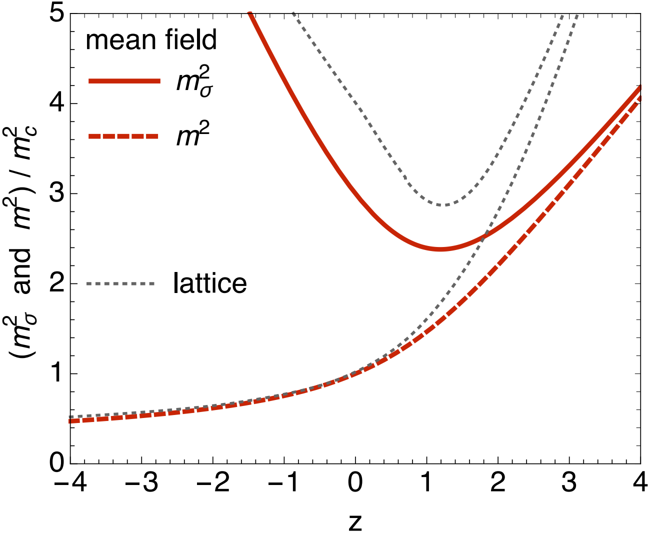
- Sigma screening mass

$$m_\sigma^2 = m_c^2\left(z + 3f_G^2(z)\right)$$

- Pion velocity squared

$$v^2(T) = \frac{\bar\sigma^2(T)}{\chi_0}$$

Comparison to lattice



From Engels & Vogt 0911.1939 and Engels & Karsch 1105.0584

Equations of motion

- Partial current conservation:

$$\partial_\mu \hat{J}^\mu_a = -i\frac{H}{8}(\Sigma - \Sigma^\dagger)$$

- Dissipative Josephson constraint:

$$-iU\partial_t U^\dagger = \mu_A + \mu_A^{diss}$$

- Diffusion equation for condensate:

$$\partial_t \sigma = D_{m_\sigma}\frac{\partial F}{\partial \sigma} + \xi$$

Linearized equations of motion

- Coupled EOM are the ideal PCAC ($\partial_\mu \hat{J}^\mu_a = -i\frac{H}{8}(\Sigma - \Sigma^\dagger)$) and Josephson constraint get dissipative corrections and noise[5]:

$$\hat{J}^i = f\partial^i\varphi - \sigma_A \partial^i \mu_A + \xi^i_J$$
$$-\partial_t \varphi = \mu_A + \zeta^{(2)}(-\partial_\mu(f^2\partial^\mu\varphi) + f^2 m^2 \varphi) + \xi_s$$

  Linearized axial current:

$$\hat{J}^\mu_a = \underbrace{\hat{n}_a u^\mu}_{normal} + \underbrace{f^2 \partial^\mu \varphi_a}_{super}$$

- Diffusion equation for condensate: $\partial_t \sigma = D_{m_\sigma} \frac{\partial F}{\partial \sigma} + \xi$

[5] Son/Stephanov arXiv:0204226

Equations of motion

Linearized equations of motion involving φ and μ are

$$\begin{pmatrix} -i\omega + \Gamma(k^2+m^2) & \omega_k \\ -\omega_k & -i\omega + D_0 k^2 \end{pmatrix} \begin{pmatrix} \omega_k \varphi \\ \mu_A \end{pmatrix} = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix},$$

where the noises have vanishing mean and non-zero variance:

$$\langle \xi_1(k)\xi_1(-k)\rangle = \frac{2T}{\chi}\Gamma(k^2+m^2),$$
$$\langle \xi_2(k)\xi_2(-k)\rangle = \frac{2T}{\chi}D_0 k^2.$$

Equations of motion

Linearized equations of motion involving φ and μ are

$$\begin{pmatrix} -i\omega + g_1 & \omega_k \\ -\omega_k & -i\omega + g_2 \end{pmatrix} \begin{pmatrix} \omega_k \varphi \\ \mu_A \end{pmatrix} = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix},$$

where the noises have vanishing mean and non-zero variance:

$$\langle \xi_1(k) \xi_1(-k) \rangle = \frac{2T}{\chi} g_1,$$
$$\langle \xi_2(k) \xi_2(-k) \rangle = \frac{2T}{\chi} g_2.$$

Computing correlator

We find

$$G_{\mathrm{sym}} = \frac{2T}{\chi} \frac{1}{(-\omega^2 + \omega_q^2 + g_1 g_2)^2 + (\omega \Gamma_q)^2} \times \begin{pmatrix} g_1(\omega^2 + g_2^2) + g_2 \omega_q^2 & -i\omega_q \omega \Gamma_q \\ i\omega_q \omega \Gamma_q & g_2(\omega^2 + g_1^2) + g_1 \omega_q^2 \end{pmatrix}$$

Useful shorthands (to keep structure apparent):

$$\begin{aligned} \omega_q^2 &= v^2(q^2 + m^2) \\ g_1 &= \Gamma(q^2 + m^2) \\ g_2 &= D_0 q^2, \\ \Gamma_q &= \Gamma(q^2 + m^2) + D_0 q^2 \end{aligned}$$

The correlators

In other words,

$$G_{\mathrm{sym}} = \begin{pmatrix} G^{\varphi\varphi} & G^{\varphi\mu} \\ G^{\mu\varphi} & G^{\mu\mu} \end{pmatrix}$$

and

$$G^{\sigma\sigma}_{sym}(\omega, k) = \frac{2T\Gamma}{\omega^2 + \Gamma^2(k^2 + m_\sigma^2)^2}$$

In depth

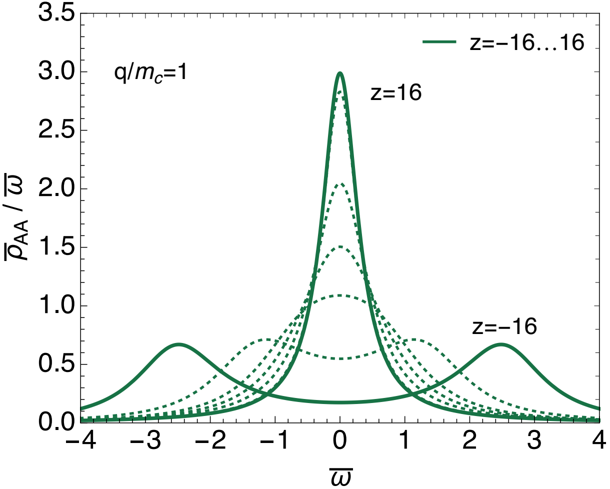
Let's plot one of the propagators

$$G^{\mu\mu}_{\mathrm{sym}} = \frac{2T}{\chi} \frac{g_2(\omega^2 + g_1^2) + g_1 \omega_q^2}{(-\omega^2 + \omega_q^2 + g_1 g_2)^2 + (\omega \Gamma_q)^2}$$

where

$$\begin{aligned}
\omega_q^2 &= v^2(q^2 + m^2) \\
g_1 &= \Gamma(q^2 + m^2) \\
g_2 &= D_0 q^2, \\
\Gamma_q &= \Gamma(q^2 + m^2) + D_0 q^2
\end{aligned}$$

Spectral density for axial charge density-density correlator



For $z \gg 0$, $\rho_{AA}/\omega \propto Dk^2/(\omega^2 + (Dk^2)^2)$, diffusion of quarks.
For $z \ll 0$, pair of peaks interpret as propagating pions
$\Rightarrow$ Transition from QGP to pion propagation from EOM!

Hydrodynamic loops

Computing transport coefficients

Find transport coefficients via Kubo formula:

- The shear viscosity is

$$2T\eta = \int d^4x \left\langle \tfrac{1}{2}\{T^{xy}(t,\boldsymbol{x}), T^{xy}(0,\boldsymbol{0})\}\right\rangle$$

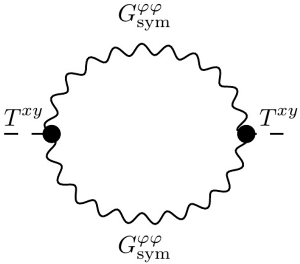
- The isovector conductivity is

$$2T\sigma_I = \int d^4x \frac{1}{d_A} \left\langle \tfrac{1}{2}\{J^x_{V,a}(t,\boldsymbol{x}), J^x_{V,a}(0,\boldsymbol{0})\}\right\rangle ,$$

- The bulk viscosity is

$$2T\zeta = \int d^4x \left\langle \tfrac{1}{2}\left\{\mathcal{O}_{\mathrm{bulk}}(t,\boldsymbol{x}), \mathcal{O}_{\mathrm{bulk}}(0,\boldsymbol{0})\right\}\right\rangle .$$

Modification of shear viscosity



$$2T\eta = \int d^4x \left\langle \tfrac{1}{2}\{T^{xy}(t,\boldsymbol{x}), T^{xy}(0,\mathbf{0})\}, \right\rangle$$

Modification of shear viscosity

The stress tensor is

$$
\begin{aligned}
T^{\mu\nu} &= u^\mu u^\nu (e_\Sigma + p_\Sigma) + g^{\mu\nu} p_\Sigma \\
&+ \frac{1}{4}(D^\mu \Sigma D^\nu \Sigma^\dagger + D^\nu \Sigma D^\mu \Sigma^\dagger) - u^\mu u^\nu \frac{1}{2} \hat{u} (u \cdot D\Sigma u \cdot D\Sigma^\dagger),
\end{aligned}
$$

In linearized regime, relevant components for shear viscosity:

$$
T^{xy} = \underbrace{\partial^x \delta\sigma \partial^y \delta\sigma}_{\text{condensate contribution}} + \underbrace{\bar{\sigma}^2 \partial^x \varphi_a \partial^y \varphi_a}_{\text{pion contribution}}
$$

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Break up computation into two pieces:

$$\Delta\eta \equiv I^{xy}_{\sigma\sigma} + I^{xy}_{\varphi\varphi}$$

Modification of shear viscosity

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$$\Delta\eta \equiv I^{xy}_{\sigma\sigma} + I^{xy}_{\varphi\varphi}$$

Sigma correlator:

$$G^{\sigma\sigma}_{sym}(\omega, k) = 2\frac{T}{\omega}\mathrm{Im}\, G^{\sigma\sigma}_{R}(\omega, k) = \frac{2T\Gamma}{\omega^2 + \Gamma^2(k^2 + m_\sigma^2)^2}$$

which leads to

$$I^{xy}_{\sigma\sigma} = 2\int \frac{d^3k}{(2\pi)^3}\frac{d\omega}{(2\pi)}(k^x k^y G^{\sigma\sigma}_{sym})^2$$

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which leads to

$$I^{xy}_{\sigma\sigma} = \frac{2T^2}{(30\pi^2\Gamma)}\int_0^\Lambda \frac{k^6 dk}{(k^2 + m_\sigma^2)^3}$$

Modification of shear viscosity

Break up computation into two pieces:

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which leads to

$$\begin{aligned} I^{xy}_{\sigma\sigma} &= \frac{2T^2}{(30\pi^2\Gamma)} \int_0^\Lambda \frac{k^6 dk}{(k^2 + m_\sigma^2)^3} \\ &= \underbrace{\frac{2T^2}{30\pi^2\Gamma}\Lambda}_{\text{divergent}} - \underbrace{\frac{2T^2 m_\sigma}{32\pi\Gamma}}_{\text{finite piece}} + \dots \end{aligned}$$

Modification of shear viscosity - pion contribution

Break up computation into two pieces:

$$\Delta\eta \equiv I^{xy}_{\sigma\sigma} + I^{xy}_{\varphi\varphi}$$

φ correlator:

$$G^{\varphi\varphi}_{\rm sym} = \frac{2T}{\chi_0}\frac{g_1(\omega^2+g_2^2)+g_2\omega_q^2}{(-\omega^2+\omega_q^2+g_1g_2)^2+(\omega\Gamma_q)^2}$$

with short-hand notation:

$$\begin{aligned}
g_1 &\equiv \Gamma(q^2+m^2)\\
g_2 &\equiv D_0 q^2\\
\Gamma_q &\equiv \Gamma(q^2+m^2)+D_0q^2.
\end{aligned}$$

Integral to evaluate

$$I^{xy}_{\varphi\varphi} = 2\int\frac{d^3k}{(2\pi)^3}\frac{d\omega}{(2\pi)}(k^xk^yG^{\varphi\varphi}_{sym})^2$$

Modification of shear viscosity - pion contribution

$$I_{\varphi\varphi}^{xy} = \underbrace{\frac{2T^2 d_A}{30\pi^2\Gamma}\Lambda}_{divergent} - \underbrace{\frac{2T^2 m d_A}{32\pi\Gamma}\left(1 + u^2(1 - r^2)f(r,u)\right)}_{finite}$$

where $r^2 = \frac{\Gamma}{\Gamma + D_0}$ and $u^2 = \frac{v^2}{\Gamma m^2 D_0}$
and

$$\begin{aligned} f(r,u) &= \frac{32\pi}{30\pi^2}\int_0^\infty \frac{dk}{m}\frac{k^6}{(k^2+m^2)^3}\frac{m^2k^2}{(k^2+r^2m^2)(k^2+u^2m^2)}, \\ &= \frac{8u^4 + 24u^3 + 48u^2 + 45u + 15}{15(u+1)^3\left(u^2 - r^2\right)} + (r \leftrightarrow u). \end{aligned}$$

Modification of shear

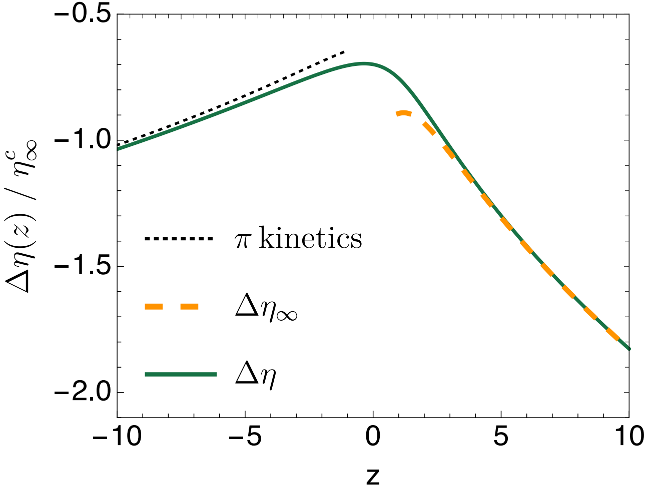
Combining the previous ingredients, we find

$$\eta = \eta_{\Sigma}^{\mathrm{phys}} - \frac{T}{32\pi\Gamma}(md_A + m_\sigma + md_A u^2(1-r^2)f(r,u)),$$

where the physical part captures the cut-off dependent piece

$$\eta_{\Sigma}^{\mathrm{phys}} = \eta_{\Sigma}(\Lambda) + \delta_{\alpha\alpha}\frac{T\Lambda}{30\pi^2\Gamma}.$$

Change in shear viscosity



Remember: $z = \frac{T-T_c}{T_c} h^{2/3}$

Change in conductivity

Similar procedure for conductivity. Need to evaluate:

$$2T\sigma_I = \int d^4x \frac{1}{d_A} \left\langle \tfrac{1}{2}\{J^x_{V,a}(t,\boldsymbol{x}), J^x_{V,a}(0,\mathbf{0})\} \right\rangle ,$$

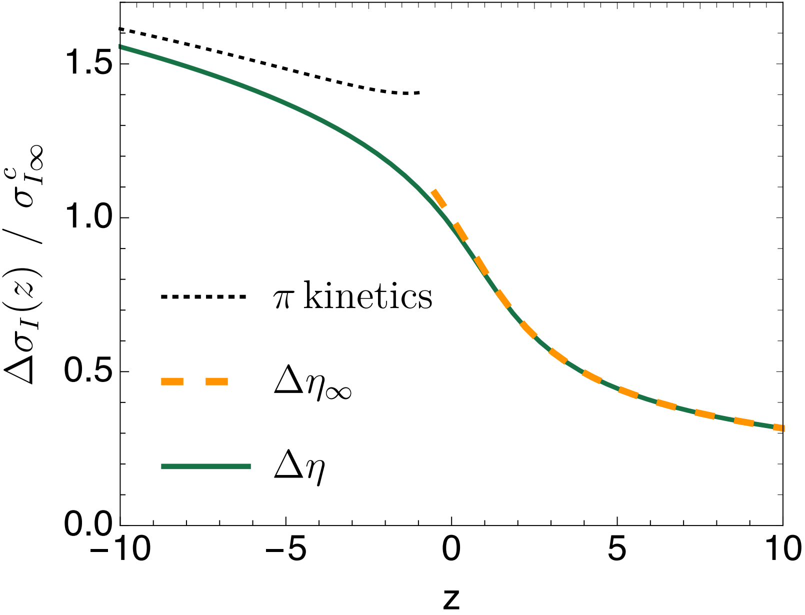
Operator of interest is current

$$J^x_{V,a} = \sigma_0^2 f_{abc}\varphi_b \partial^x \varphi_c$$

We compute

$$\sigma_I = \sigma_I^{phys} + \underbrace{T_A \int \frac{d^3k}{(2\pi)^3}\frac{d\omega}{2\pi}\frac{1}{\omega_k^4}(k^x G^{\varphi\varphi}_{\mathrm{sym}})^2}_{\Delta\sigma_I}$$

Change in conductivity



Change in bulk viscosity

Bulk viscosity is similar, but more complicated.
The bulk viscosity is

$$2T\zeta = \int d^4x \left\langle \tfrac{1}{2} \left\{ \mathcal{O}_{\rm bulk}(t, \boldsymbol{x}), \mathcal{O}_{\rm bulk}(0, \boldsymbol{0}) \right\} \right\rangle .$$

The relevant operator is

$$\mathcal{O}_{\rm bulk} = c_s^2\, T^0{}_0 + \frac{1}{3} T^i{}_i .$$

The full stress tensor is

$$\begin{aligned} T^{\mu\nu} &= u^\mu u^\nu (e_\Sigma + p_\Sigma) + g^{\mu\nu} p_\Sigma \\ &\quad + \frac{1}{4}(D^\mu \Sigma D^\nu \Sigma^\dagger + D^\nu \Sigma D^\mu \Sigma^\dagger) - u^\mu u^\nu \frac{1}{2} \hat{u}(u \cdot D\Sigma u \cdot D\Sigma^\dagger), \end{aligned}$$

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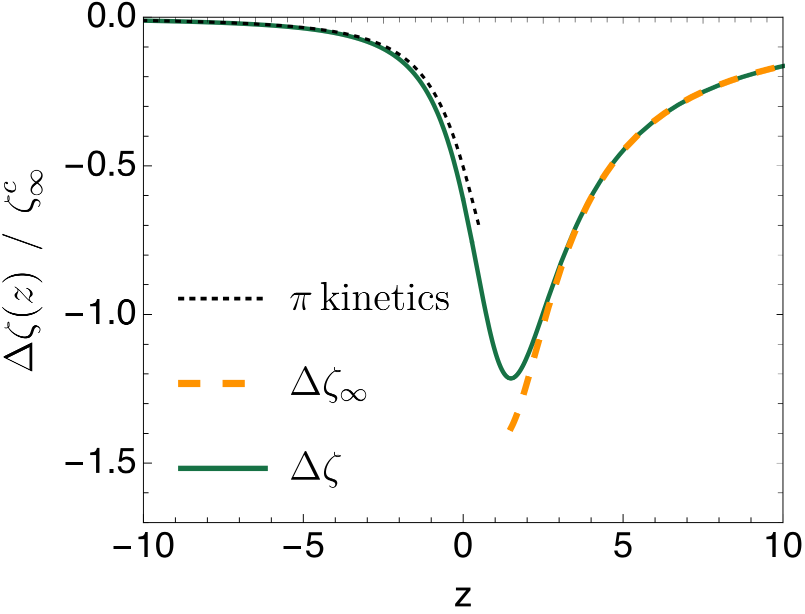
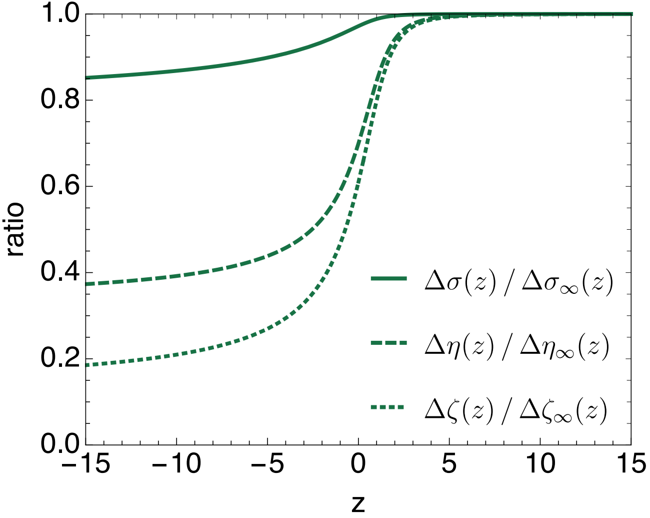
The relevant operator is

$$\begin{aligned}
\mathcal{O}_{\rm bulk} &= c_s^2 \, T^0{}_0 + \frac{1}{3} T^i{}_i \\
&= p_\Sigma + \frac{1}{3\cdot 4}(\partial^i \Sigma \partial_i \Sigma^\dagger + \partial^i \Sigma^\dagger \partial_i \Sigma) - c_s^2 \left(\chi_A \mu_A^2 - \frac{\partial(\beta p_\Sigma)}{\partial \beta} \right),
\end{aligned}$$

Change in bulk viscosity



Summary of change in scaling



Greatest effect on bulk viscosity!

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