Out of equilibrium Anomalous Transport in Holography

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Índex

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   - Anomalies in QFT
   - Chiral Transport
   - Quark-Gluon plasma

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I. Anomaly Induced Transport

Anomalies in QFT

- In general, a classical symmetry leaves the Lagrangian invariant.
- It may happen that the symmetry is broken by quantum effects. What do we mean by that?
- Path integral formulation:

$$\mathcal{Z} = \int D[\psi]D[\bar{\psi}]D[A^\mu]\dots e^{i\int d^dx\mathcal{L}}$$

- The symmetry is said to be anomalous if the Lagrangian is still invariant but the *measure* is not.

I. Anomaly Induced Transport

Anomalies in QFT

- Chiral transformation:

$$\psi_L \rightarrow e^{i\theta_L}\psi_L$$

$$\psi_R \rightarrow e^{i\theta_R}\psi_R$$

- Invariant Lagrangian ⟹ Classically conserved Noether current.

- For the chiral transformations we find the left and right currents, or equivalently the vector and axial currents:

$$J^\mu = \langle \bar{\Psi}\gamma^\mu\Psi\rangle \ , \ J_5^\mu = \langle \bar{\Psi}\gamma^\mu\gamma^5\Psi\rangle .$$

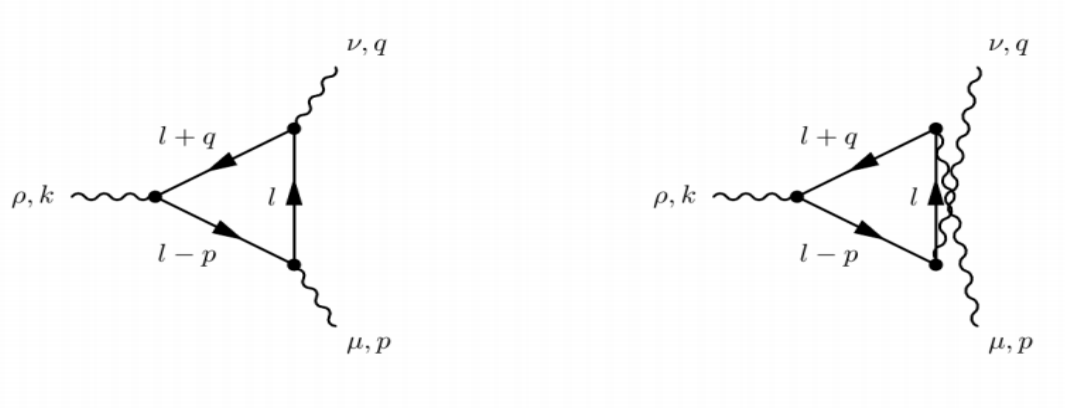
I. Anomaly Induced Transport

Anomalies in QFT

- The chiral symmetry turns out to be anomalous if the coefficient d_{abc} does not vanish.

$$d_{abc} = \sum_l (q_a^l q_b^l q_c^l) - \sum_r (q_a^r q_b^r q_c^r)$$

- The anomaly is manifest in the non-conservation of the Noether currents.

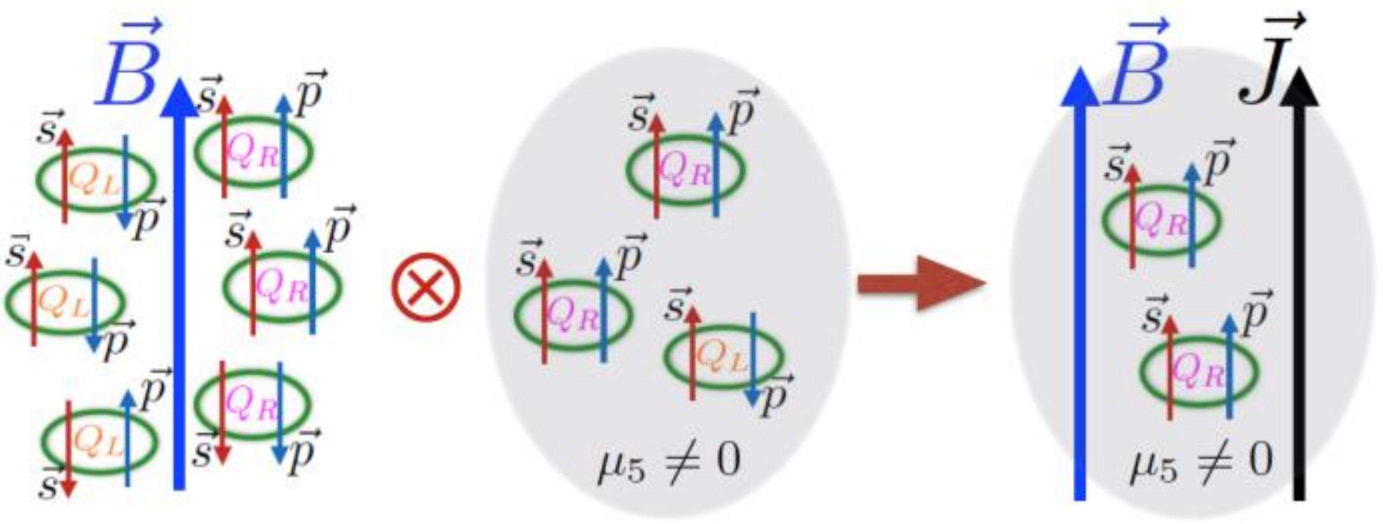


I. Anomaly Induced Transport

Chiral transport

- The chiral anomaly induces macrocopic and novel transport phenomena: CME, CVE, CSE, …

- The CME is induced in a chiral system submitted to a magnetic field B when there is chiral imbalance.



I. Anomaly Induced Transport

CHIRAL TRANSPORT

- The CME takes the form:

$$\vec{J}_a = d_{abc} \frac{\mu_b}{4\pi^2} \vec{B}_c$$

- (Not so) Surprisingly, the current is proportional to the anomaly coefficient. Hence the name *anomalous transport*.

- The current is non-dissipative.

- The CME has been first measured in $ZrTe_2$ *

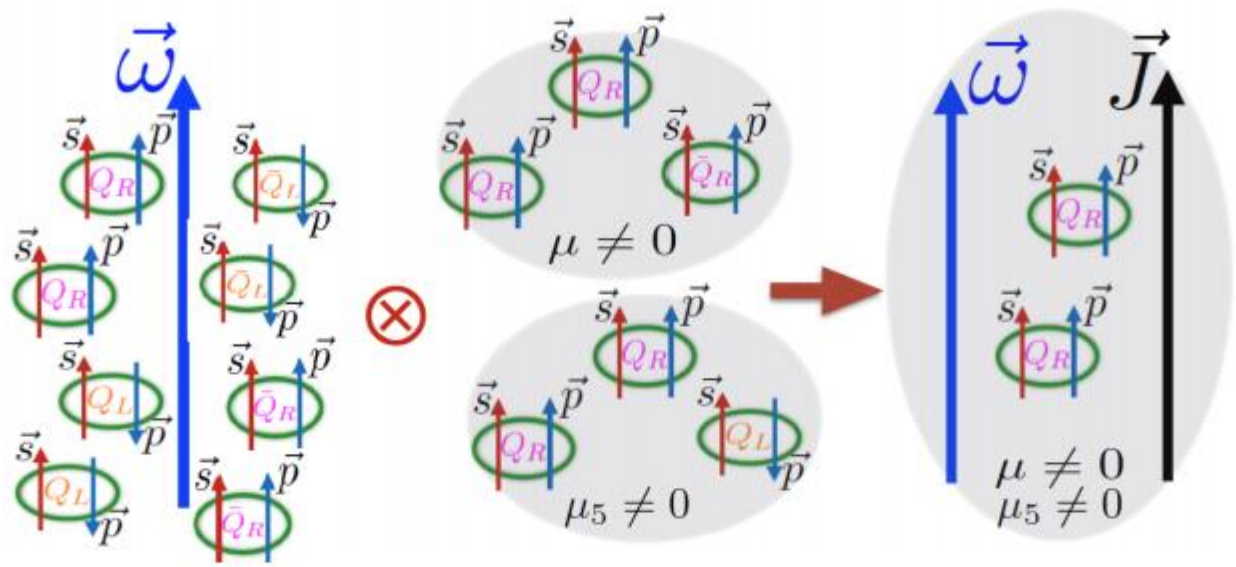
*Q. Li, D. E. Kharzeev, C. Zhang, Y. Huang, I. Pletikosic, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu and T. Valla, arXiv:1412.6543 [cond-mat.str-el].

I. Anomaly Induced Transport

CHIRAL TRANSPORT

- Similarly, the CVE is the generation of a non-dissipative current in a chiral system in the presence of rotation and with chiral imbalance.
- The precise form is now

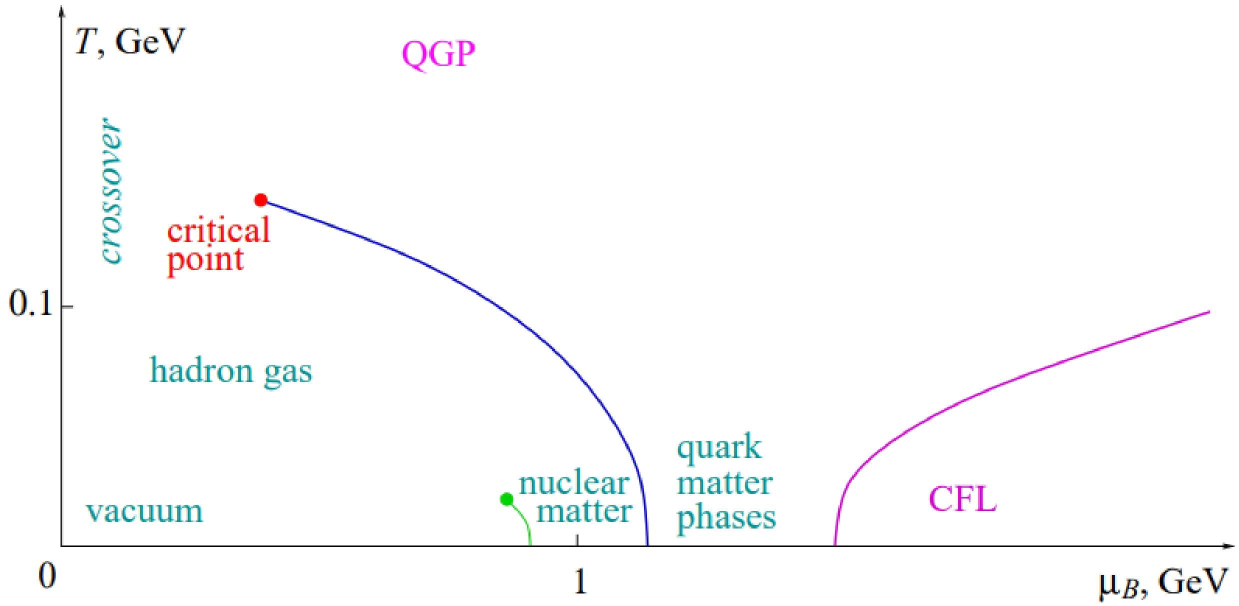
$$\vec{J}_a = \left(d_{abc} \frac{\mu_b \mu_c}{4\pi^2} + b_a \frac{T^2}{12} \right) \vec{\omega}$$



I. Anomaly Induced Transport

Quark-Gluon Plasma

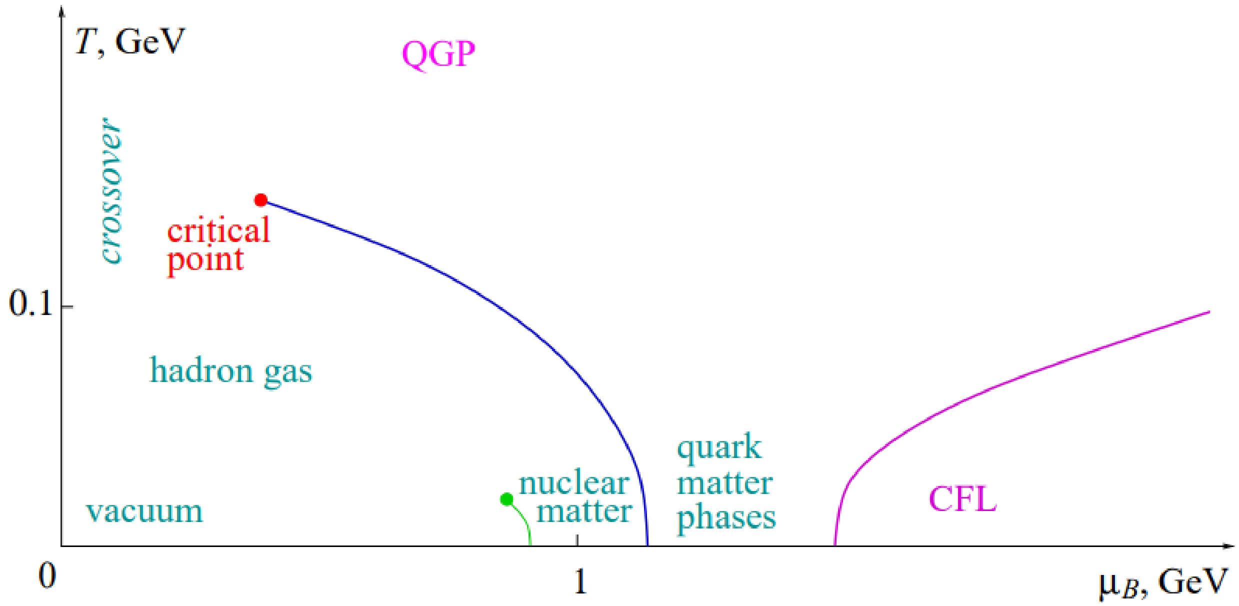
- The CME is also expected to be present in the Quark-Gluon Plasma (QGP).
  - Reproduced at LHC and RHIC.
  - It may also be relevant for the QGP phase in the early universe.
- Under extreme T or μ, QCD enters in a deconfined phase and chiral symmetry is restored.



I. Anomaly Induced Transport

Quark-Gluon Plasma

- The CME requires from magnetic field and chiral imbalance. How are does present in the QGP?
  - *B* is dynamically generated.
  - Chiral topological solutions transfer chirality to quarks through the chiral anomaly.



I. Anomaly Induced Transport

Quark-Gluon Plasma

- The study of the QGP is particularly complicated:
  - Strongly coupled => Perturbative QCD fails.
  - Lattice methods fail.
  - Non-equilibrium QFT formalism complicated.
- Holography seems to be the best alternative.

II. Modelling Chiral Transport in Holography

- We follow a *bottom-up* approach to construct the holograpic dual.

$$S = \frac{1}{2\kappa^2}\int_{\mathcal{M}} d^5x\sqrt{-g}\left[R + \frac{12}{L^2}\right.$$

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$$\left. + \frac{\alpha}{3} \epsilon^{\mu\nu\rho\sigma\tau} A_\mu \left(3 F_{\nu\rho} F_{\sigma\tau} + F^5_{\nu\rho} F^5_{\sigma\tau} \right) \right.$$

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$$X^I = kx^i$$

II. Modelling Chiral Transport in Holography

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$$
\begin{aligned}
S =& \frac{1}{2\kappa^2}\int_{\mathcal{M}} d^5x\sqrt{-g}\left[R+\frac{12}{L^2}-\frac{1}{2}\partial_\mu X^I\partial^\mu X^I-\frac{1}{4}F^2-\frac{1}{4}F_5^2\right.\\
&\left.+\frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}A_\mu\left(3F_{\nu\rho}F_{\sigma\tau}+F^5_{\nu\rho}F^5_{\sigma\tau}\right)+\lambda\epsilon^{\mu\nu\rho\sigma\tau}A_\mu R^\alpha{}_{\beta\nu\rho}R^\beta{}_{\alpha\sigma\tau}\right]\\
&+\frac{1}{\kappa^2}\int_{\partial\mathcal{M}} d^4x\sqrt{-\gamma}K+S_{nf},
\end{aligned}
$$

$$X^I = kx^i$$

II. Modelling Chiral Transport in Holography

- Ansatz for the solution:

1. Metric:

$$ds^2 = -f(v,u)dv^2 - \frac{2}{u^2}dvdu + \frac{1}{u^2}\delta_{ij}dx^i dx^j + \frac{2\epsilon h(v,u)}{u^2}dvdx^3$$

2. Gauge fields:

$$F_{xy} = \epsilon B \qquad F^5_{xy} = \epsilon B_5 \quad F_{uv} = -uq \quad F^5_{uv} = -uq_5$$

$$V_z = \epsilon V, \; A_z = \epsilon A.$$

3. Scalar field

$$X^3 = kz + \epsilon Z$$

II. Modelling Chiral Transport in Holography

- The solution is thermodynamically characterised by Temperature and Chemical potentials.

$$\mu = \frac{q}{2} u_H^2 \quad , \quad \mu_5 = \frac{q_5}{2} u_H^2$$

$$T = \frac{1}{2\pi} \left(-\frac{u^2}{2} \partial_u f(v,u) \right) \Big|_{u=u_H}$$

- Determined by the background solution:

$$f(v,u) = \frac{1}{L^2 u^2} - \frac{1}{4} k^2 - 2m(v) u^2 + \frac{1}{12} [q(v)^2 + q_5(v)^2] u^4$$

- The linear response needs to be solved numerically.

II. Modelling Chiral Transport in Holography

- From the holographic prescription we find

$$J^\alpha = \sqrt{-\gamma} n_\mu \left[F^{\alpha\mu} + 4\alpha \epsilon^{\mu\alpha\beta\gamma\delta} A_\beta F_{\gamma\delta} \right] \Big|_{\partial\mathcal{M}}$$

$$J_5^\alpha = \sqrt{-\gamma} n_\mu \left[F_5^{\alpha\mu} + \frac{4\alpha}{3} \epsilon^{\mu\alpha\beta\gamma\delta} A_\beta F^5_{\gamma\delta} \right] \Big|_{\partial\mathcal{M}}$$

$$T^{\alpha\beta} = 2\sqrt{-\gamma} \left[-K^{\alpha\beta} + \gamma^{\alpha\beta} K \right] \Big|_{\partial\mathcal{M}}$$

- For us:

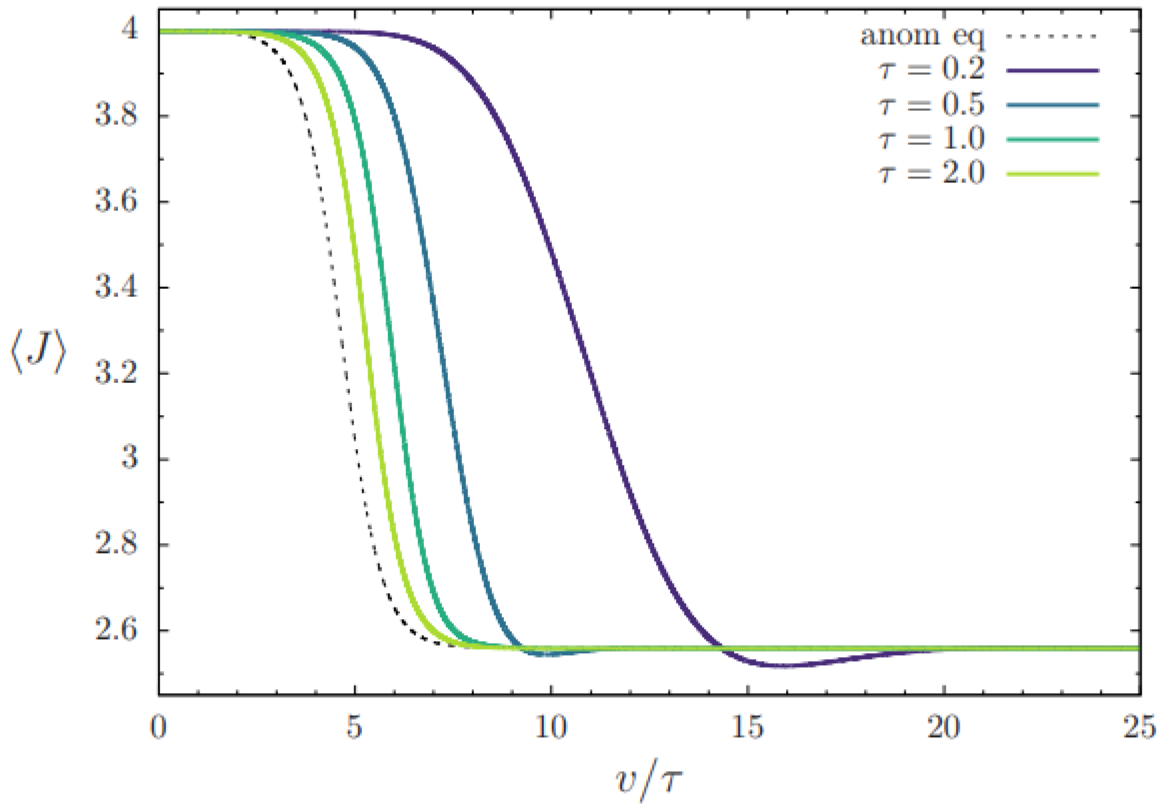
$$\langle J^z \rangle = 2V_2 \epsilon \,,$$

$$\langle J_5^z \rangle = 2A_2 \epsilon \,,$$

$$\langle T^{vz} \rangle = -4h_4 \epsilon .$$

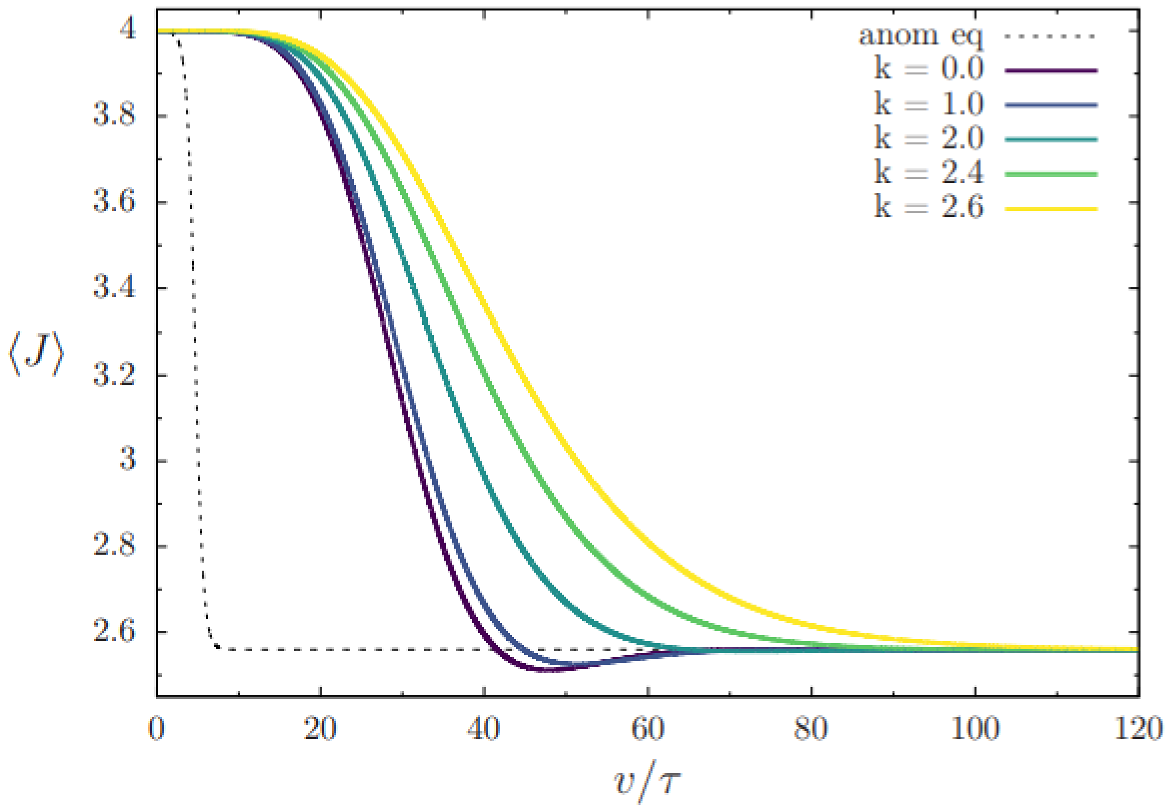
III. Results

- Vector current for various quench times.



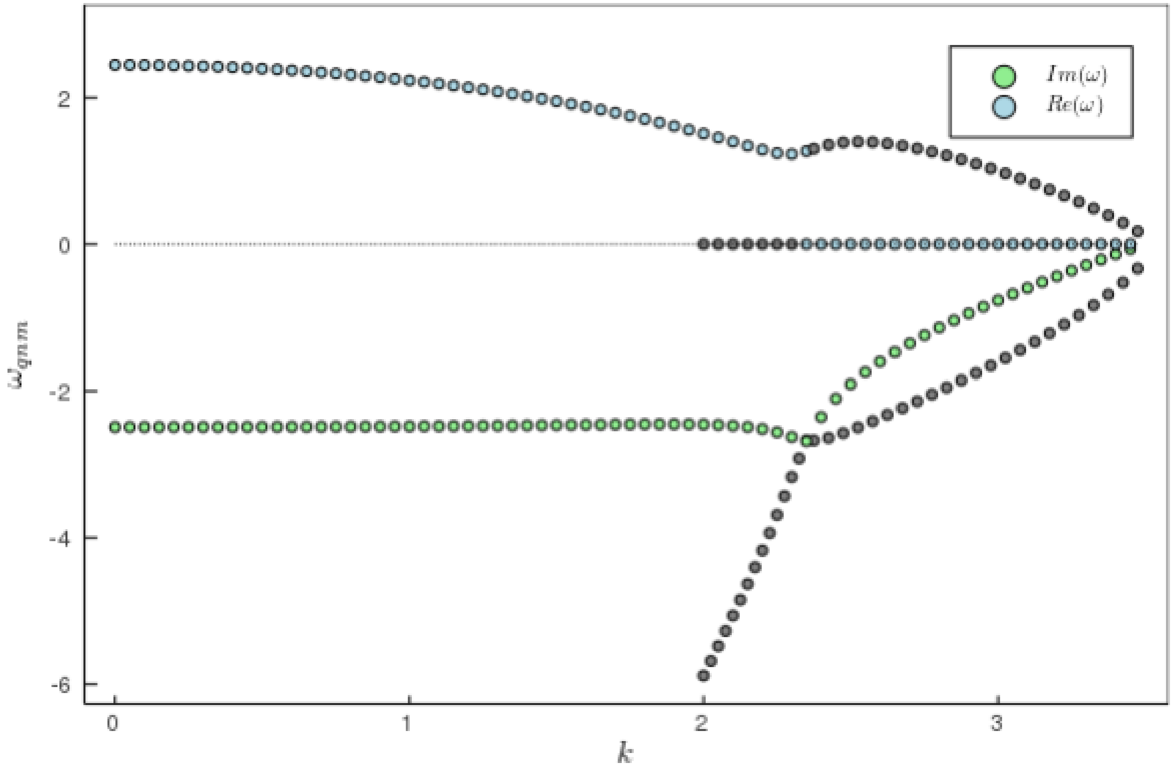
III. Results

- Vector current for various momentum relaxation parameters.



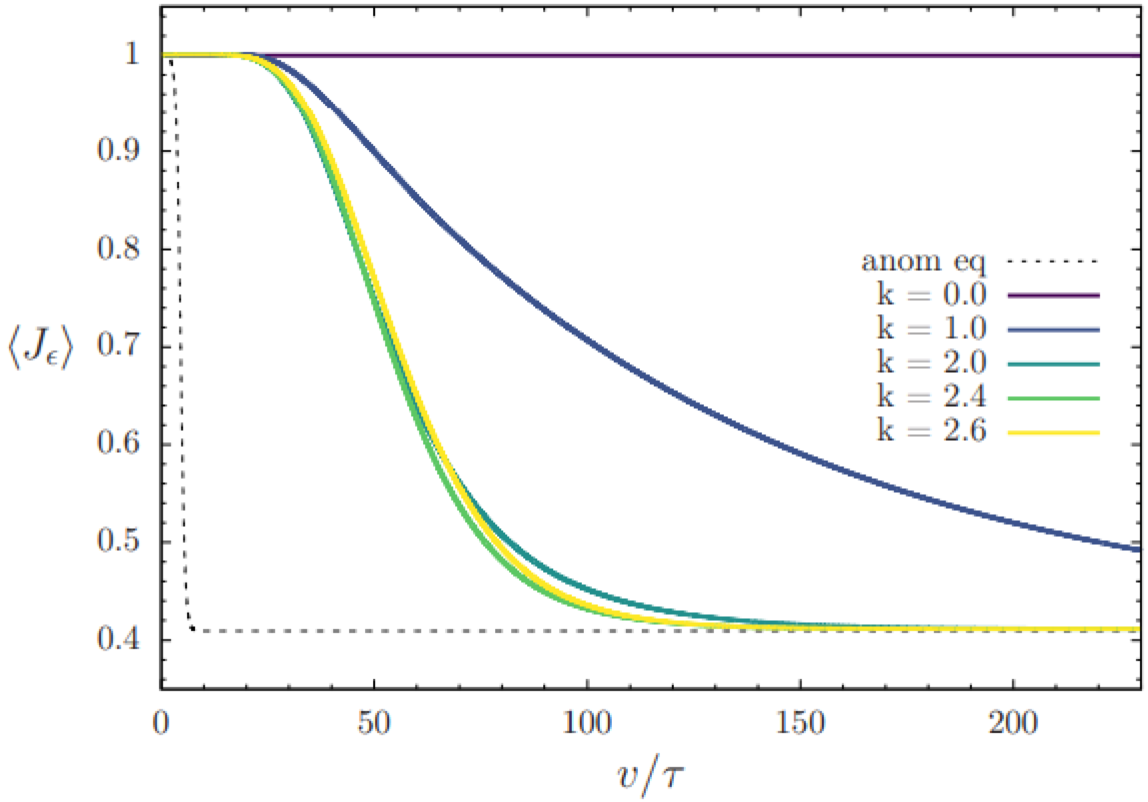
III. Results

- Quasinormal mode description.



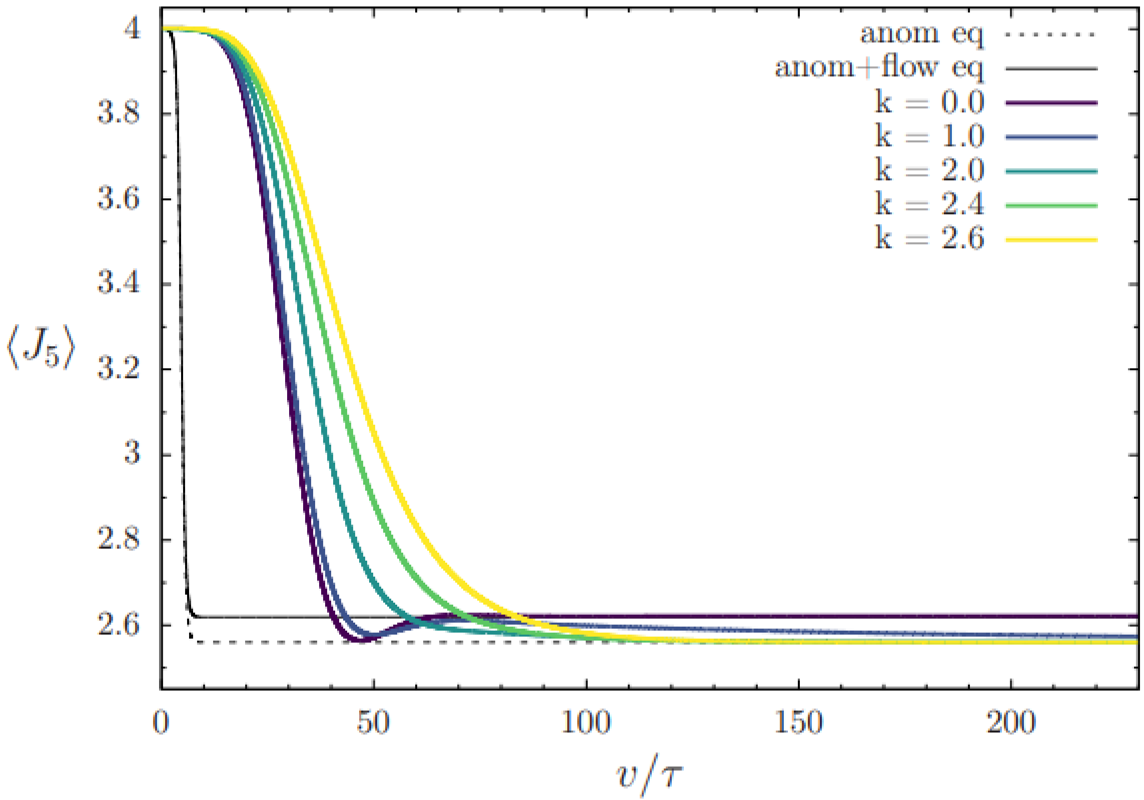
III. Results

- Energy current for various momentum relaxation parameters.



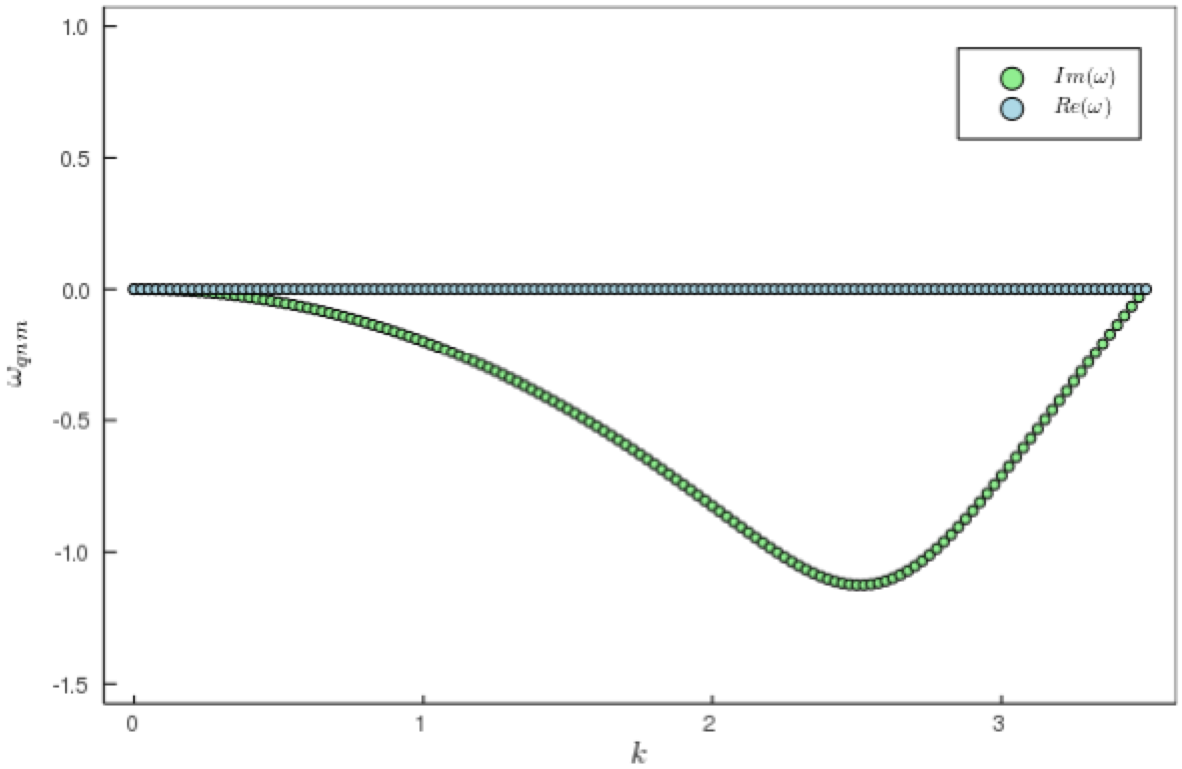
III. RESULTS

- Axial current for various momentum relaxation parameters.



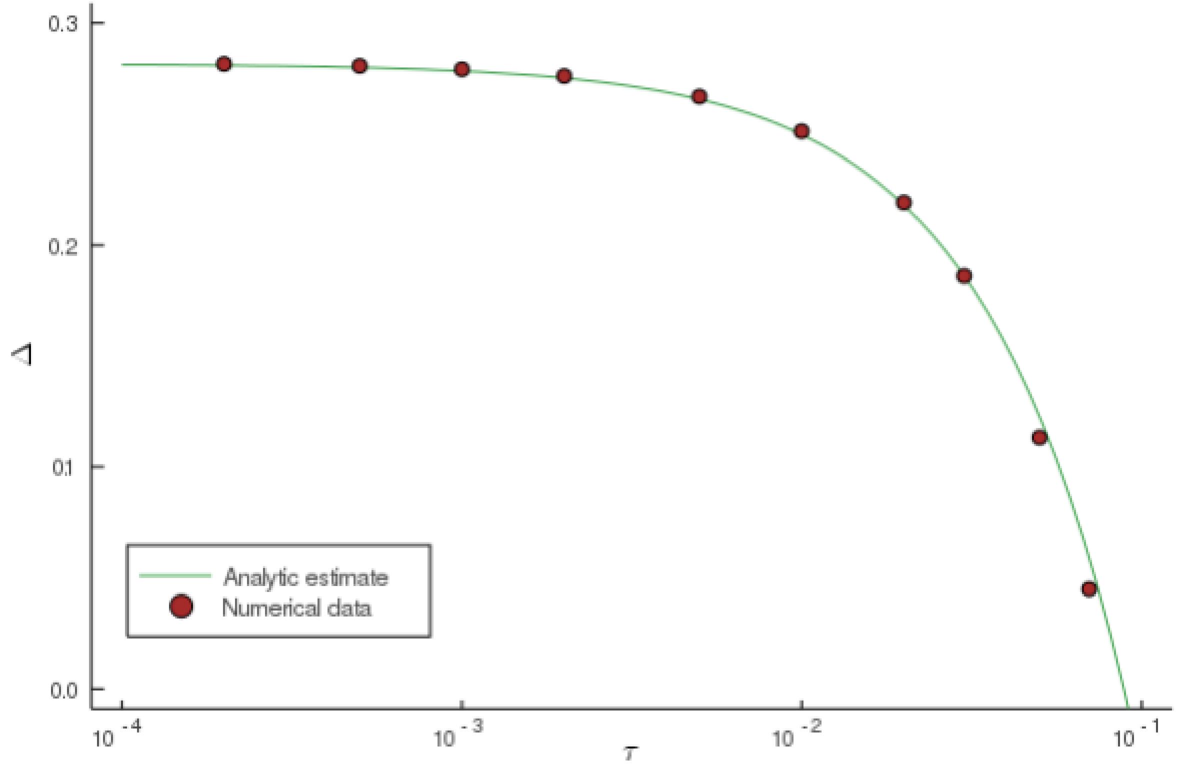
III. Results

- Description in terms of Quasinormal modes.



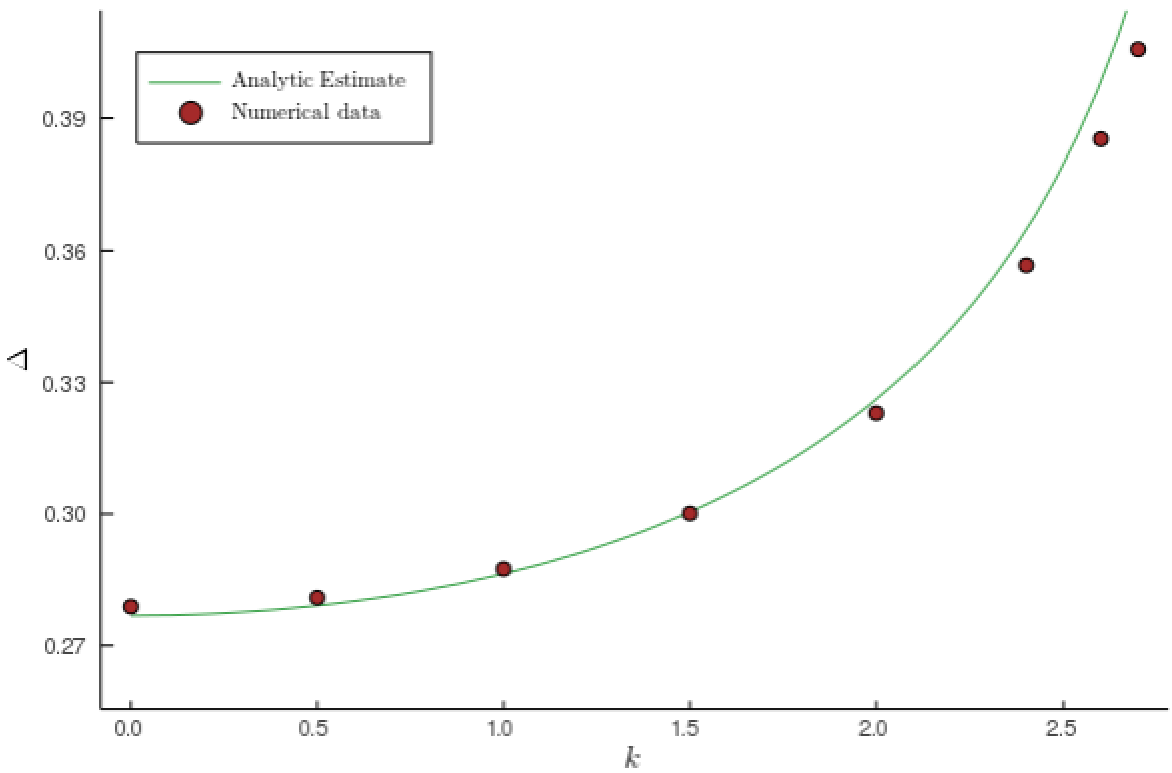
III. RESULTS

- Quench dependence of the time delay.



III. Results

- Symmetry breaking dependence of the time delay.



IV. Conclusions and Outlook

- The Chiral Anomaly induces novel and non-dissipative transport phenomena.
- The CME is at current search in LHC and RHIC. The results are not conclusive yet.
- Holograpy seems to be a suitable tool to study the non-equilibrium QGP.
- The delay observed in simulations might justify the disagreement between both experiments.
- Some generalisations are in order:
  1. Time-dependent charge.
  2. Arbitrarily intense magnetic field.
  3. Time-dependent magnetic field.
  4. …

References

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