Axial magnetic effect in QCD

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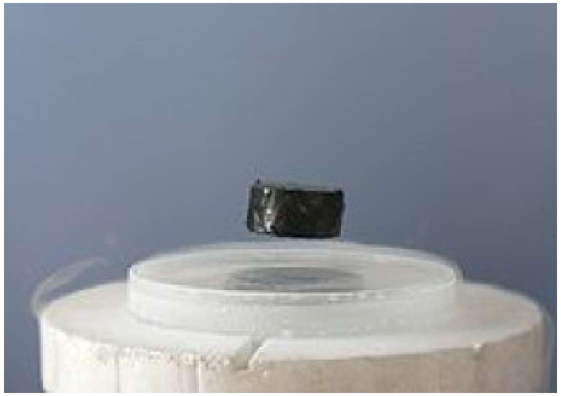
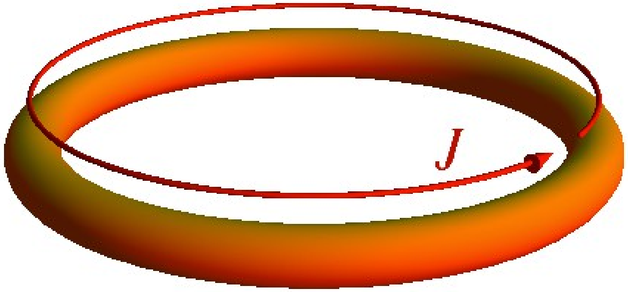
Dissipationless charge transfer: superconductivity



The London equation:

$$\frac{\partial \boldsymbol{J}}{\partial t} = \mu^2 \boldsymbol{E}$$

Ballistic acceleration of the electric current J by applied electric field E.



The electric current in a superconducting wire will flow forever!

Properties:
1) no resistance = no dissipation;
2) superconducting condensate is needed!

Alternative(s) to superconductivity?

- Superconductivity emerges due to the presence of a condensate of electrons pairs (the Cooper pairs).

- The Cooper pairs are quite fragile: thermal fluctuations destroy them quite effectively. That's why the room-temperature superconductivity is not observed (yet).

- May dissipationless charge transfer exist in the absence of any kind of condensation? Do we have alternatives?

Yes, we do. The simplest example is

Chiral Magnetic Effect (CME)

Good review: K. Fukushima, arXiv:1209.5064 (in Lect. Notes. Physics, Springer, 2013)

The Chiral Magnetic Effect (CME)

Electric current is induced by applied magnetic field:

$$\boldsymbol{J} = \tilde{\sigma} \boldsymbol{B}$$

Spatial inversion ($\boldsymbol{x} \to -\boldsymbol{x}$) symmetry (*P*-parity):
- Electric current is a vector (parity-even quantity);
- Magnetic field is a pseudovector (parity-odd quantity).

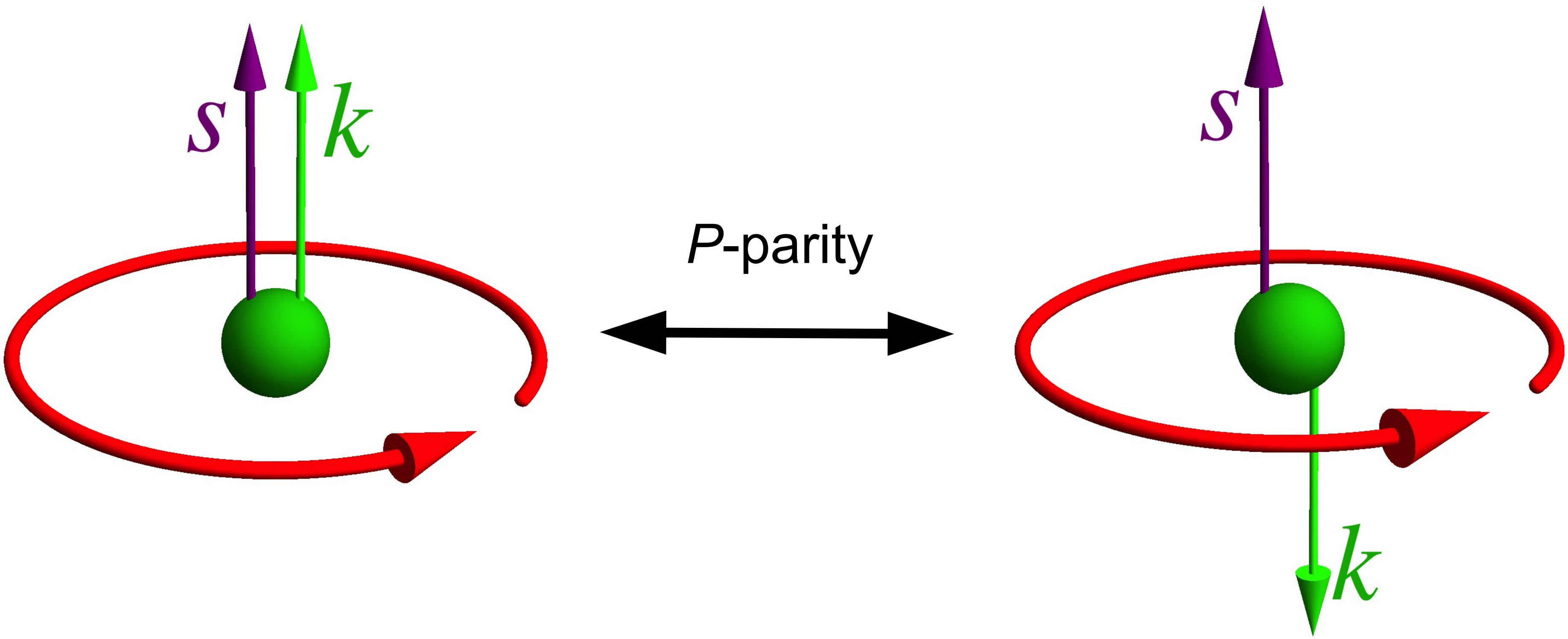
Thus, the CME medium should be parity-odd!
In other words, the spectrum of the medium which supports the CME should not be invariant under the spatial inversion transformation.

[A. Vilenkin, '80; M. A. Metlitski, A. R. Zhitnitsky, '05; K. Fukushima, D. E. Kharzeev, H. J. Warringa, '08; D. E. Kharzeev, L. D. McLerran and H. J. Warringa, '08, + ...]

Good review: V. Zakharov, arXiv:1210.2186 (in Lect. Notes. Physics, Springer, 2013)

An example of a parity-odd system?

Consider a massless fermion:

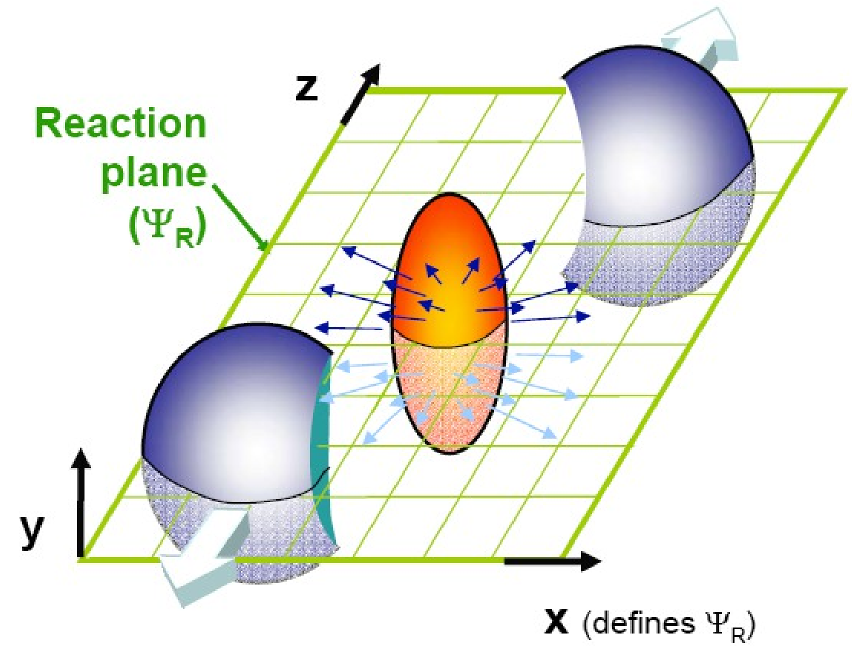


Right handed **Left handed**

The chirality (left/right) is a conserved number.

The CME in quark-gluon plasma

1) The quark-gluon plasma is created in heavy-ion collisions (RHIC and LHC).



2) Typical energies of *u* and *d* quarks are so high, that these quarks may be considered as massless fermions.

3) The imbalance in chirality is produced due to rapid topological transitions mediated by QCD sphalerons: a left quark may turn into a right quark (and vice versa) due the axial QCD <u>anomaly</u> (→ the CME is “anomalous”)

4) Noncentral collisions create huge magnetic field (QCD scale).

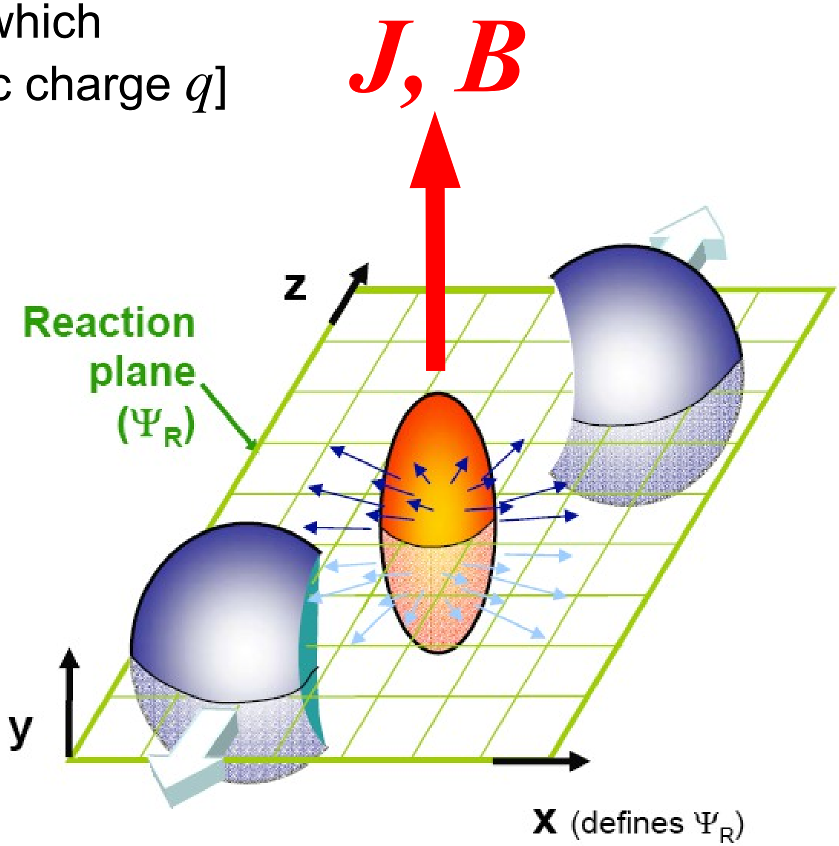
Good review: Bzdak, Koch, Liao, arXiv:1207.7327 (in Lect. Notes. Physics, Springer, 2013)

The CME in heavy-ion collisions

The induced electric current in the quark-gluon plasma is proportional to the chiral chemical potential which controls imbalance between left-handed and right-handed quarks.

$$\vec{J} = \frac{\mu_5}{2\pi^2} q \vec{B}$$

[this formula is written for one quark flavor which carries the electric charge q]



The CME predicts that there should be an asymmetric flow of charged particles along the normal to the reaction plane. And such asymmetry was indeed observed both at RHIC and at LHC.

A list of anomalous non-dissipative effects (I)

1) **Chiral Magnetic Effect –** the electric current is induced in the direction of the magnetic field due to the chiral imbalance:

$$\vec{J} = \frac{\mu_5}{2\pi^2} q \vec{B}$$

[all formulae are written for one flavor of fermions]

2) **Chiral Vortical Effect** – the axial current is induced in the rotating quark-gluon plasma along the axis of rotation:

$$\vec{J}_5 = \frac{T^2}{12} \vec{\omega}$$

The axial current = the difference in currents of right-and left-handed quarks.

All these effects become more complicated (richer) in a rotating, chirally-imbalanced dense plasma subjected to both the usual and axial magnetic fields.

A list of anomalous non-dissipative effects (II)

3) **Chiral Separation Effect –** the axial current is induced in the direction of the magnetic field:

$$\vec{J}_5 = \frac{\mu}{2\pi^2} q\vec{B}$$

Notes:

A) This effect is realized even if the plasma is chirally-trivial.

B) μ is the quark chemical potential (the plasma is dense).

4) **Axial Magnetic Effect** – the energy flow is induced in the direction of the axial (=chiral) magnetic field:

$$\vec{J}_\epsilon = \frac{T^2}{12} q\vec{B}_5$$

Note: the axial magnetic field acts on left-handed and right-handed fermions with opposite signs.

The Axial Magnetic Effect vs. the Chiral Vortical Effect

For a many-flavor system:

The Axial Magnetic Effect: $\vec{J}_\epsilon = \sigma \vec{B}_5$

The Chiral Vortical Effect: $\vec{J}_5 = \sigma \vec{\omega}$

Their anomalous conductivities are the same:

$$\sigma = \left(\sum_l q_l - \sum_r q_r \right) \frac{T^2}{24}$$

They have the same origin! (It is, BTW, quite impressive: the generation of the axial current in a rotating system is related to the induction of the energy flow in a static system).

The Axial Magnetic Effect

For one quark's flavor:

$$\vec{J}_\epsilon = \frac{T^2}{12} q \vec{B}_5$$

The energy flow is given by the off-diagonal component of the energy-momentum tensor

$$J^i_\epsilon = \langle T^{0i} \rangle$$

The axial magnetic field $\vec{B}_5$ is the magnetic field which acts on left-handed and right-handed quarks in the opposite way. It can be described by the axial field $A_{5,\mu}$ in the Lagrangian:

$$\mathcal{L}_5 = \bar{\psi}(\partial_\mu - igA^a_\mu t^a - i\gamma^5 e A_{5,\mu})\gamma^\mu \psi$$

The Axial Magnetic Effect on the lattice (I)

Task: simulate lattice QCD in the background of the axial magnetic field and study the energy flow of fermions

$$J^i_\epsilon = \langle\, T^{0i} \,\rangle \equiv \frac{i}{2} \langle\, \bar{\psi}(\gamma^0 \mathcal{D}^i_5 + \gamma^i \mathcal{D}^0_5)\psi \,\rangle$$

both in the direction of the field $(J^{||}_\epsilon)$
and in transverse direction $(J^{\perp}_\epsilon)$.

[QCD was studied in the quenched limit (= "backreaction of fermions on gluon files was neglected") because the vacuum fermion loops are not important for the AME]

Results [Braguta et al., **arXiv:1303.6266**, **arXiv:1401.8095**]:

a) the effect was not observed in low-temperature phase, where the plasma is absent. This is explained by the quark confinement as the individual quarks do not exist in this phase.
b) the effect is negligible at the deconfinement phase transition.

The Axial Magnetic Effect on the lattice (II)

c) clearly seen in the high-temperature (deconfinement) phase:

V. Braguta,
K. Landsteiner,
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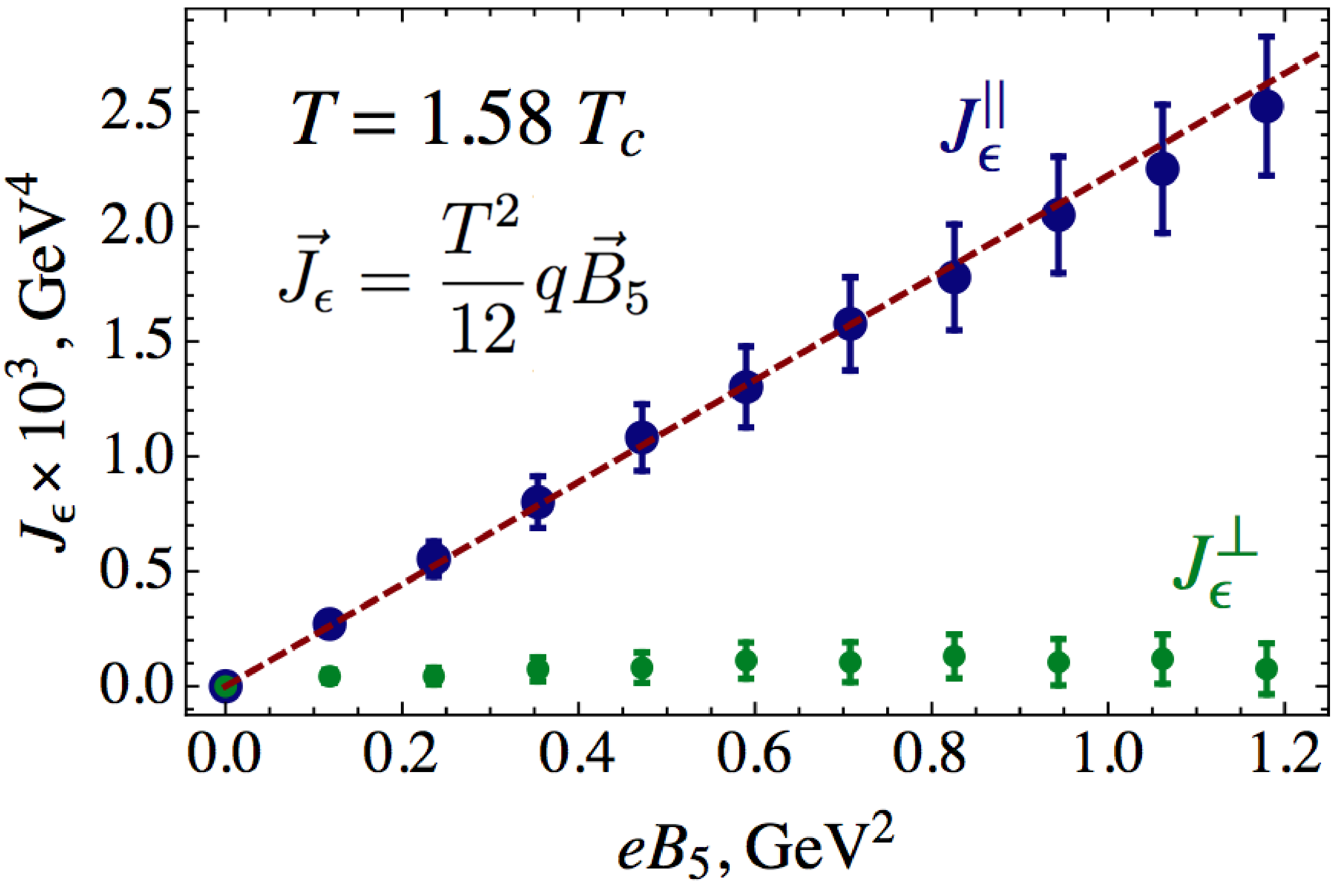
M.V. Ulybyshev,
M. Ch.
arXiv:1303.6266



Important fact: non-dissipative flow is seen at astonishingly high temperature!

Transport law:

$$\vec{J}_\epsilon = \sigma \vec{B}_5$$

Theory:

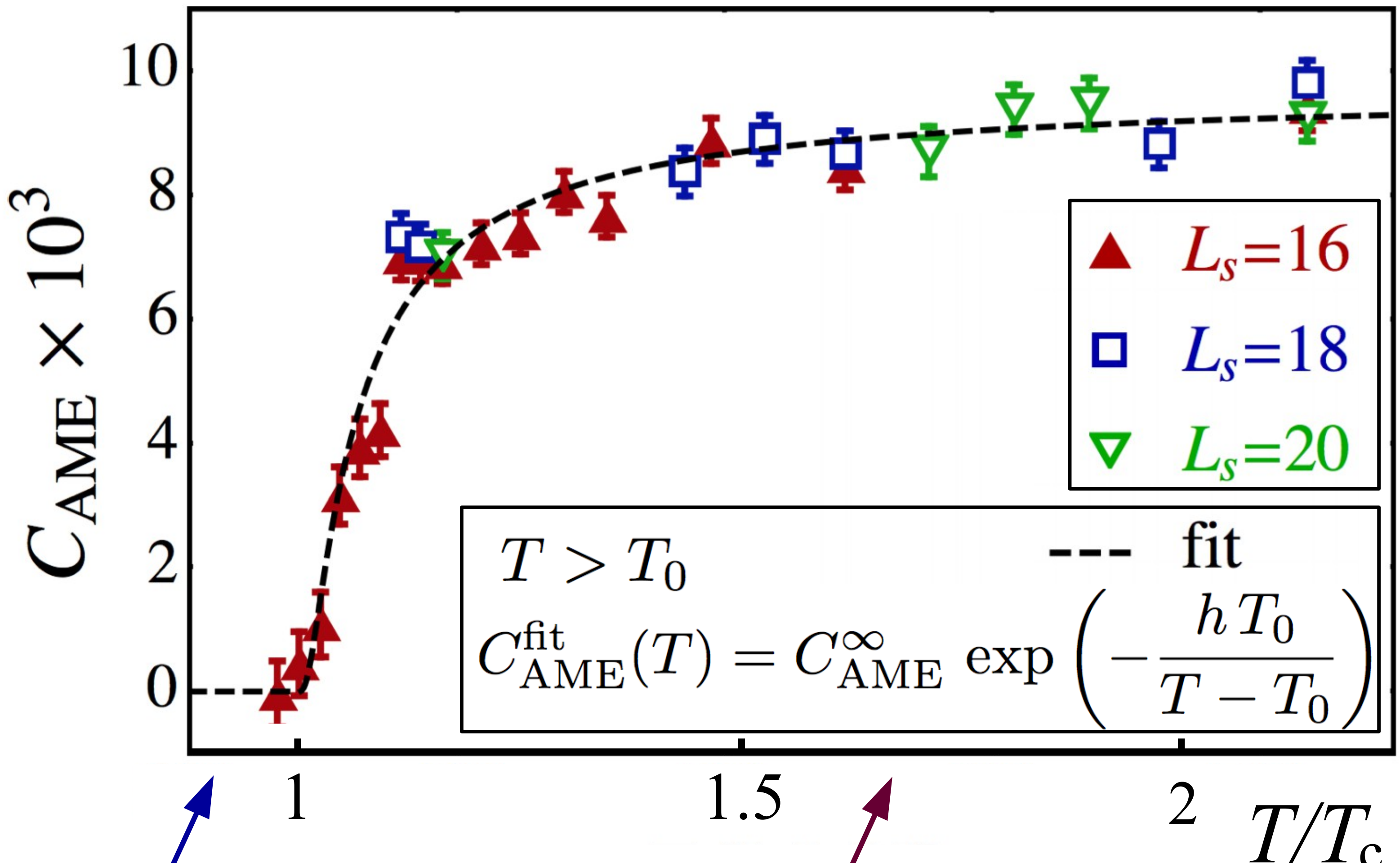
$$\sigma_{\mathrm{theor}} \approx 0.0382\,\mathrm{GeV}^2$$

Lattice:

$$\sigma(T)\Big|_{T=1.58\,T_c} = 2.22(3) \times 10^{-3}\,\mathrm{GeV}^2$$

The anomalous conductivity of the AME

The strength of the dissipationless flow of energy



$C^{\infty}_{\mathrm{AME}} = 0.0097(2)$

Theoretically:

$$C^{\mathrm{th}}_{\mathrm{AME}} = 1/6 \approx 0.166$$

Almost 20-fold difference!

Confinement
(hadron phase)

Deconfinement
(plasma phase)

Best fit parameters:

$h = 0.055(7)$

$T_0 \simeq T_c$

Summary

We have observed – in numerical simulations of (quenched) lattice QCD – the existence of the dissipationless energy transfer induced by the chiral magnetic field in the high-temperature (plasma) phase.

The energy flow increases with temperature T, the asymptotic T^2 behavior is observed in a qualitative agreement with analytical predictions.

The strength of the effect is, however, almost 20 times weaker compared to the analytical estimates (Loss of universality? Radiative corrections? Quenching effects?).