Non-equilibrium Phase Transitions in Gauge-theory Plasma

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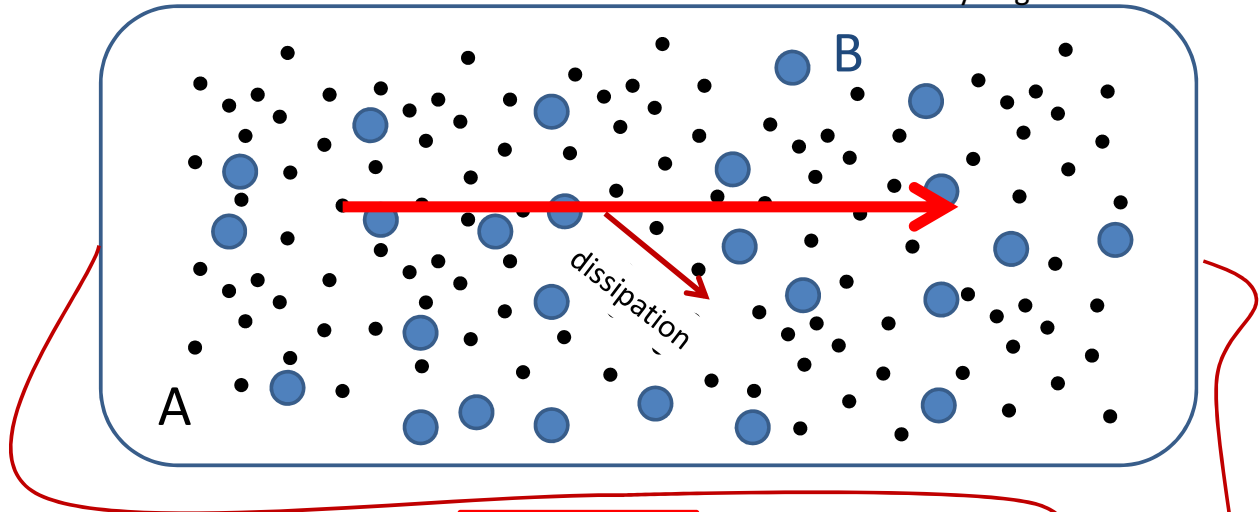# Non-equilibrium Physics

- Success of the linear response theory uncovered the non-equilibrium phenomena at the vicinity of the thermal equilibrium.

- How about the non-linear region, going beyond the linear response theory?

There is a framework coming from superstring theory: AdS/CFT

# Setup: non-equilibrium steady state

Infinitely large volume

B

dissipation

A

- Particles A:
  Equilibrium at temperature T

- Charged particles B:
  Driven by the external force (E),
  not necessarily at thermal equilibrium.

Heat Bath

Degrees of freedom

Much larger
∨
∨
Smaller

Any computable model
in the non-linear regime?

Yes,

if we consider a gauge-theory plasma
mapped to a gravitational theory by
the AdS/CFT correspondence.
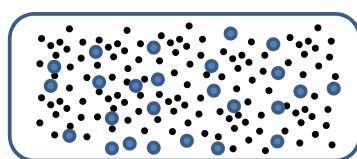
QCD(-like) theory

gluons

quarks
(and anti-quarks)

Gravity theory
(General relativity)

Map: AdS/CFT

J. Maldacena, 1997

● Particle A
● Particle B

AdS/CFT correspondence

J. Maldacena, Adv. Theor. Math. Phys. 2 (1998) 231.

citations: 7850 (2011/Nov.2)

Some categories of strongly-interacting quantum gauge theories are equivalent to higher-dimensional classical gravity theories.

What is the benefit of this correspondence?

- Strongly-interacting theory can be analyzed by using the weakly-interacting gravity.
- Quantum effects can be computed by using the classical gravity.
- Many-body physics is highly simplified in the gravity.

"Many-body physics" in the gravity

Particles A: gluons (heat bath) ➡ single black hole

(Hawking and Bekenstein said that black hole has the notion of temperature and entropy.)
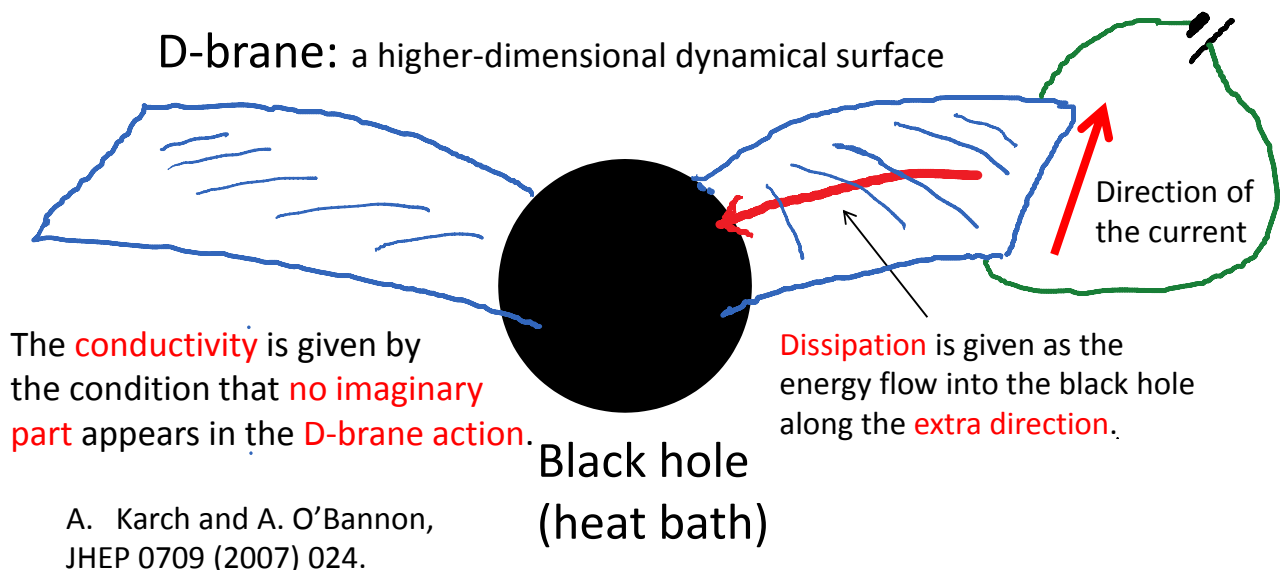
E. Witten, Adv. Theor. Math. Phys. 2 (1998) 505.

Particles B: quark/antiquarks ➡ brane-like object (D-brane)

A. Karch and E. Katz, JHEP 0206 (2002) 043.

The non-linear conductivity can be computed in terms of the dynamics of the D-brane on the curved spacetime.

A cartoon of the gravitational setup

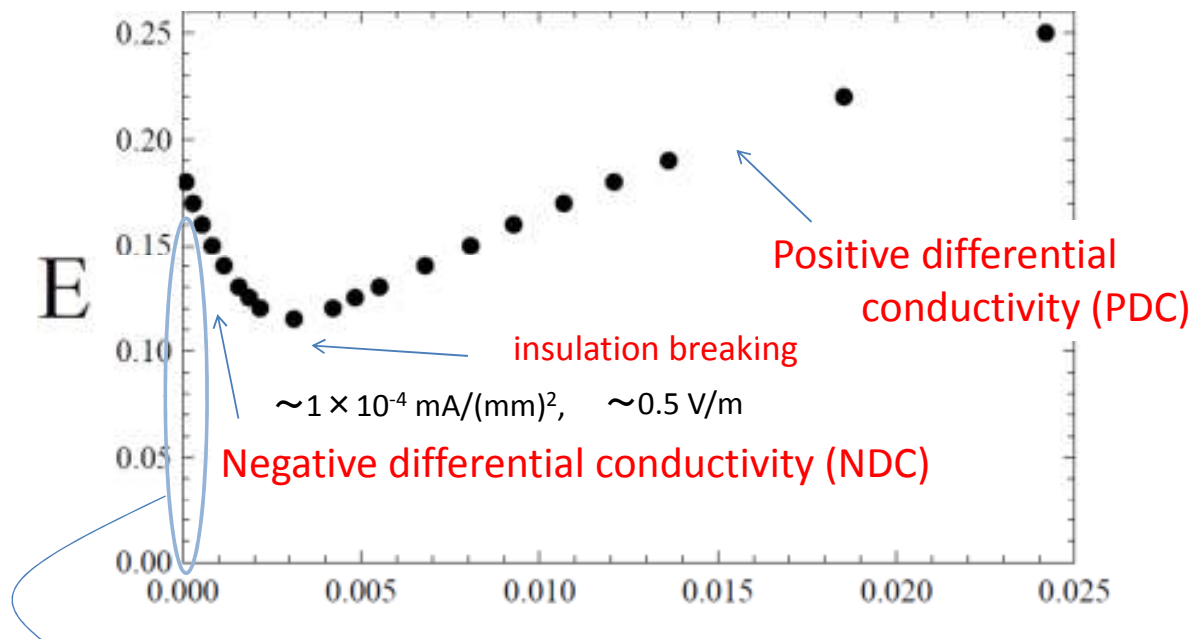D-brane: a higher-dimensional dynamical surface

Direction of the current

The conductivity is given by the condition that no imaginary part appears in the D-brane action.

A. Karch and A. O'Bannon, JHEP 0709 (2007) 024.

Dissipation is given as the energy flow into the black hole along the extra direction.

Black hole (heat bath)

The gravity theory is built on a higher-dimensional spacetime (10 dimensions). The "direction of dissipation" is visualized.

Some more details

- The gauge theory I have employed is:
  N=4 SU(Nc) large-Nc Supersymmetric Yang-Mills theory
    + N=2 flavor hyper-multiplet,
                  at the large 't Hooft coupling limit.

- The system is neutral.
  But, the current appears if the electric field is large enough to pair-create the quark and the anti-quark.

An example of J-E characteristics

E

Positive differential conductivity (PDC)

insulation breaking

$\sim 1 \times 10^{-4}$ mA/(mm)^2, ~ 0.5 V/m

Negative differential conductivity (NDC)

J=0 branch exists

J

If we use "meV" (mili-electron volt) as the unit.

Temperature: ~ 5 K
Fine structure constant read form the Coulomb interaction : $\sim O(1)$

$m_q = 1.315$

Negative Differential Conductivity

Negative Differential Conductivity (NDC) has been widely observed in strongly-correlated systems of electrons.
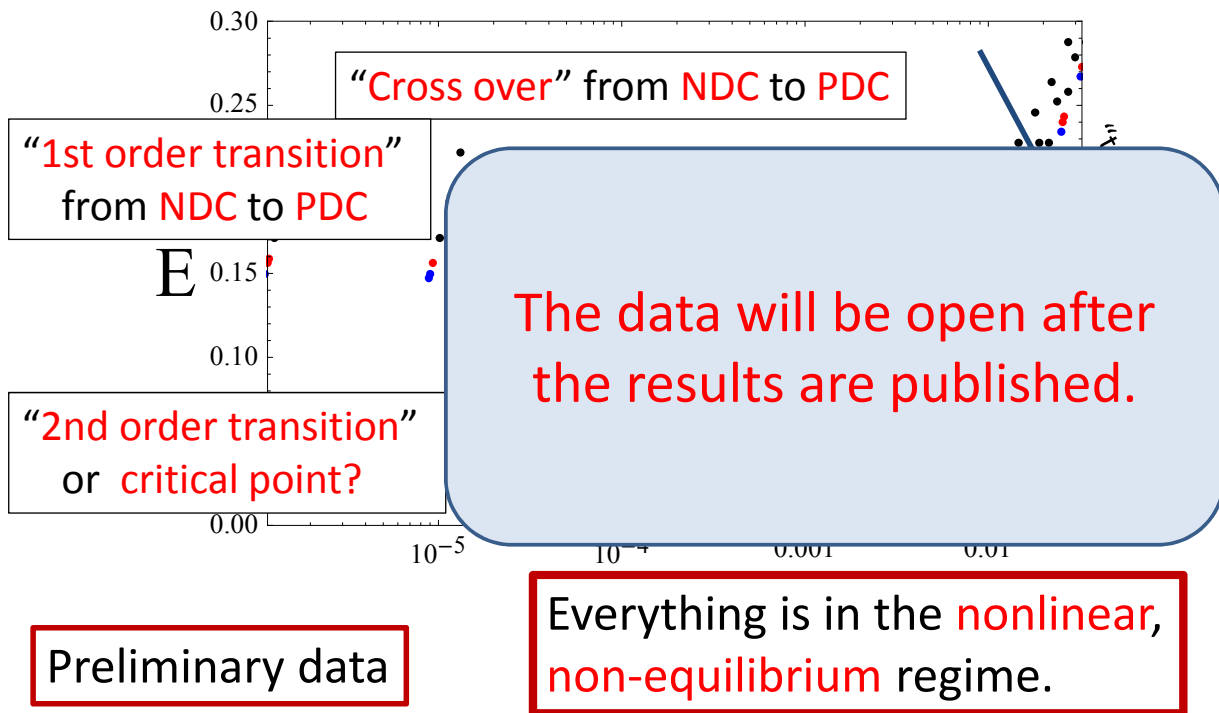
(See, e.g.   [Oka, Aoki, arXiv:0803.0422])

E

NDC

J
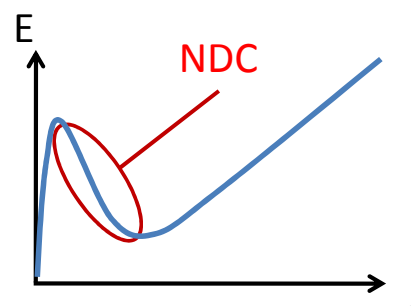
As far as I know, NDC of non-ballistic conduction in 3+1 dimensional systems has been reproduced from a microscopic theory for the first time.

Heat-bath dependence

("Temperature" dependence)

"Cross over" from NDC to PDC

"1st order transition" from NDC to PDC

E

"2nd order transition" or critical point?

The data will be open after the results are published.

Preliminary data

Everything is in the nonlinear, non-equilibrium regime.

Many questions arise

- Any critical phenomena at the "2nd-order" transition? Any massless mode?
- Any universality?
- Any critical exponents, scaling relations?
- Any Landau-like, or Van-der-Waals-like theory for the non-equilibrium transitions?
- Any observation?
- Any notion of the "effective temperature"?
- ....

Message

The AdS/CFT correspondence may open a
new window for non-equilibrium physics.

Einstein came back to the non-equilibrium physics!

 1905: Brownian motion

100 years later → AdS/CFT

general relativity and black hole

Let us talk the physics of next 100 years.