Many-body Strong Field Physics: From Mott insulators to holographic QCD

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Acknowledge

T. Kitagawa (Harvard → Rakuten), K. Hashimoto (RIKEN → Osaka-U)
A. Sonoda (Osaka-U), K. Murata (Keio-U), S. Kinoshita (Osaka city-U → Chuo-U)

Contents

Strong Field Physics in high energy physics

Target: "the" vacuum

Method:

(1) Free electron laser

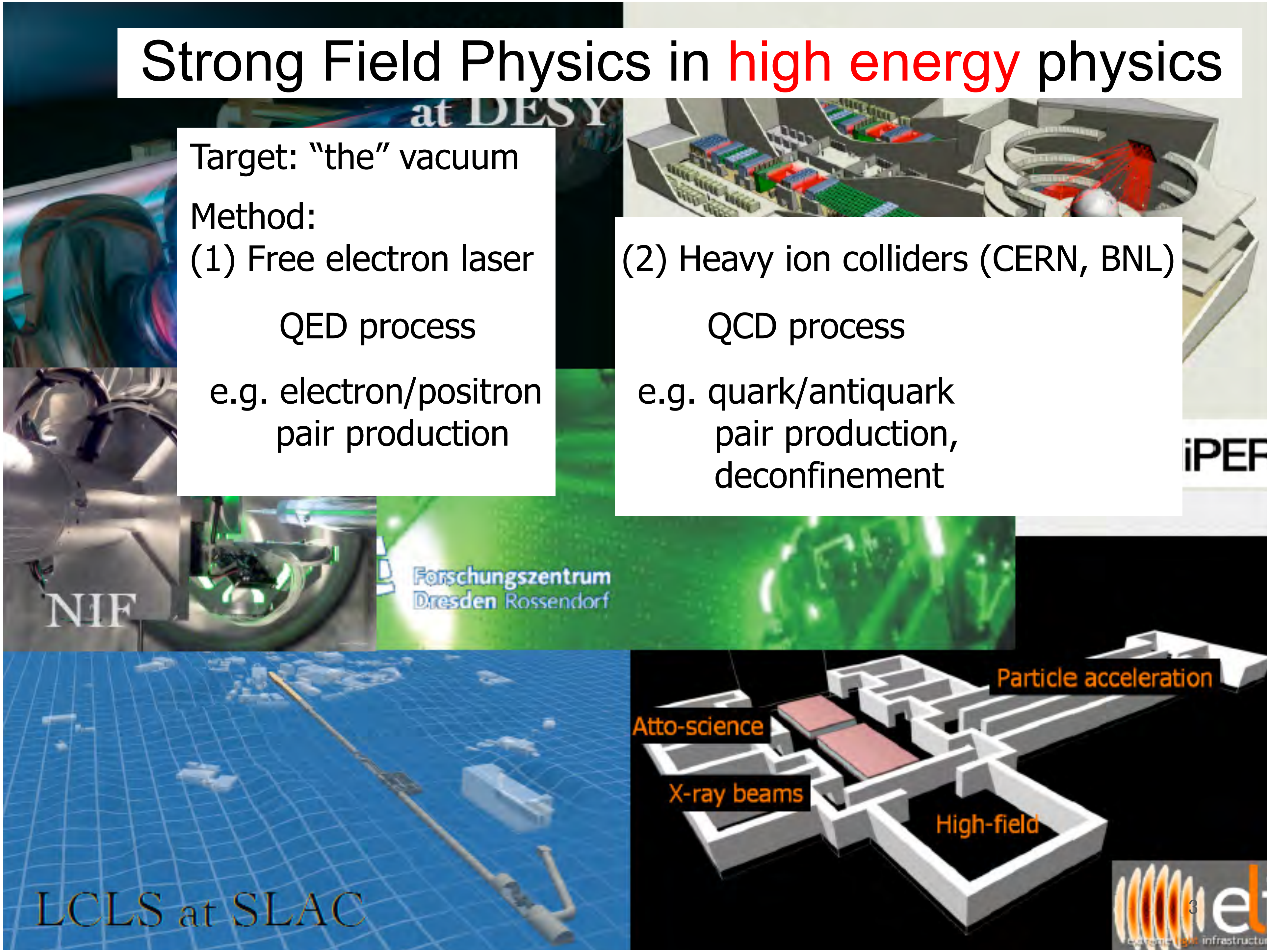
QED process

e.g. electron/positron pair production

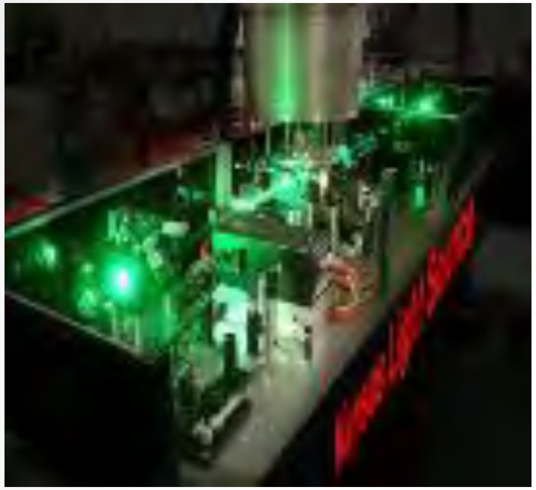
(2) Heavy ion colliders (CERN, BNL)

QCD process

e.g. quark/antiquark pair production, deconfinement



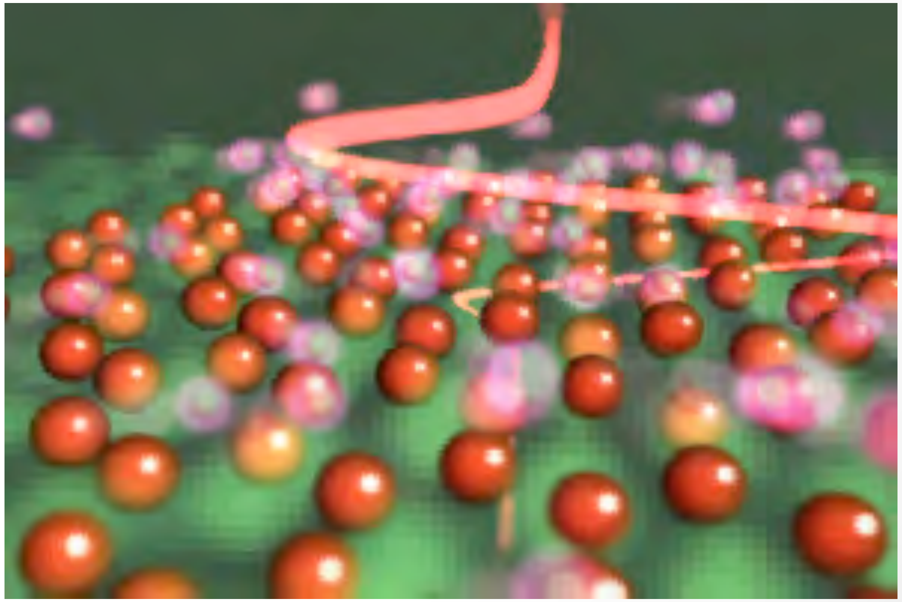
Strong Field Physics in condensed matter physics



Ultrafast pump-probe,
Time resolve ARPES

Target: materials
"Different materials host different universe"

graphene, TMD ~ 2+1D Dirac system
Mott insulator ~ "pseudo-"confinement



animation by K. Tanaka (Kyoto)

Basic problems

1. Schwinger effect   Schwinger 1951

    = pair production by quantum tunneling in *E*-fields

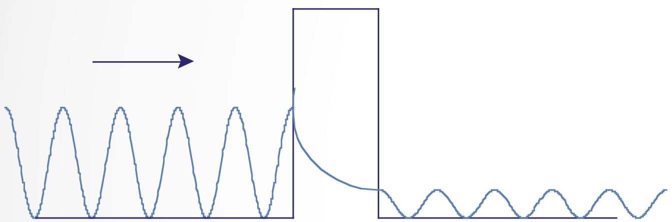
2. Floquet physics

    = stationary noneq. state in periodic driving

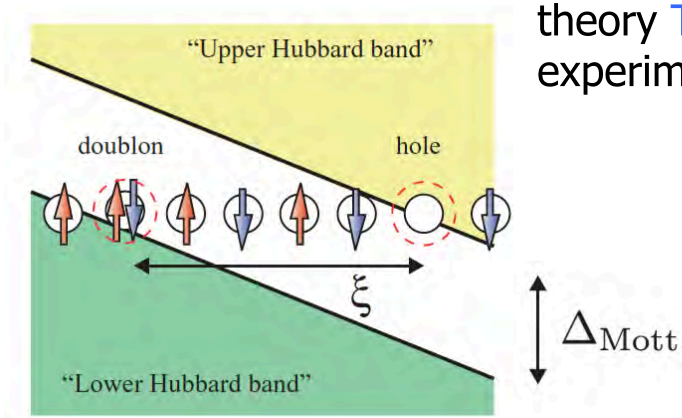
1. Schwinger mechanism
= pair production by quantum tunneling in *E*-fields

Dirac particle: Schwinger 1951
(Heisenberg-Euler 1936, Zener 1932)

Usual tunneling

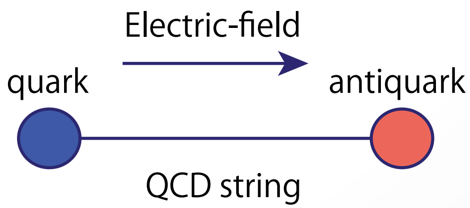


(1.a) Dielectric breakdown in a Mott insulator



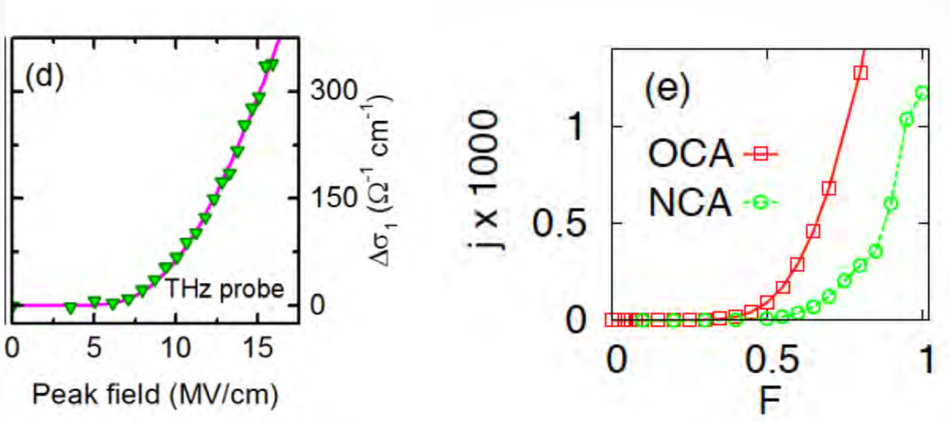
theory TO, Arita, Aoki PRL '03
experiment Mayer *et al.* PRB '15

(1.b) Schwinger mechanism in QCD



Pull apart quark pairs
Leads to deconfinement

Controversy in the *dielectric breakdown* in correlated insulators



$$\propto \exp\left(-\frac{\Delta_{\mathrm{gap}}}{\xi E}\right)$$

E-field

Theory TO, Arita, Aoki PRL '03, Eckstein, TO, Werner PRL '10

VO2 experiment (THz laser) Mayer, TO, Leitenstorfer, Pashkin *et al.* PRB '15

Schwinger limit

something happens down here as well..

filament creation — Rozenberg, Inoue, Sanchez PRL '04

interface Mott transition — TO Nagaosa PRL '05

avalanche — Guiot, Rozenberg, *et al.* Nat. Com. '13

synaptic behavior

exciton Mott transition (weak turbulence) — Hashimoto-Kinoshita-Murata-TO JHEP`14

0 equlibrium Mott insulator

2. Floquet physics

= stationary noneq. state in periodic driving

Classical example: Kapitza's inverted pendulum

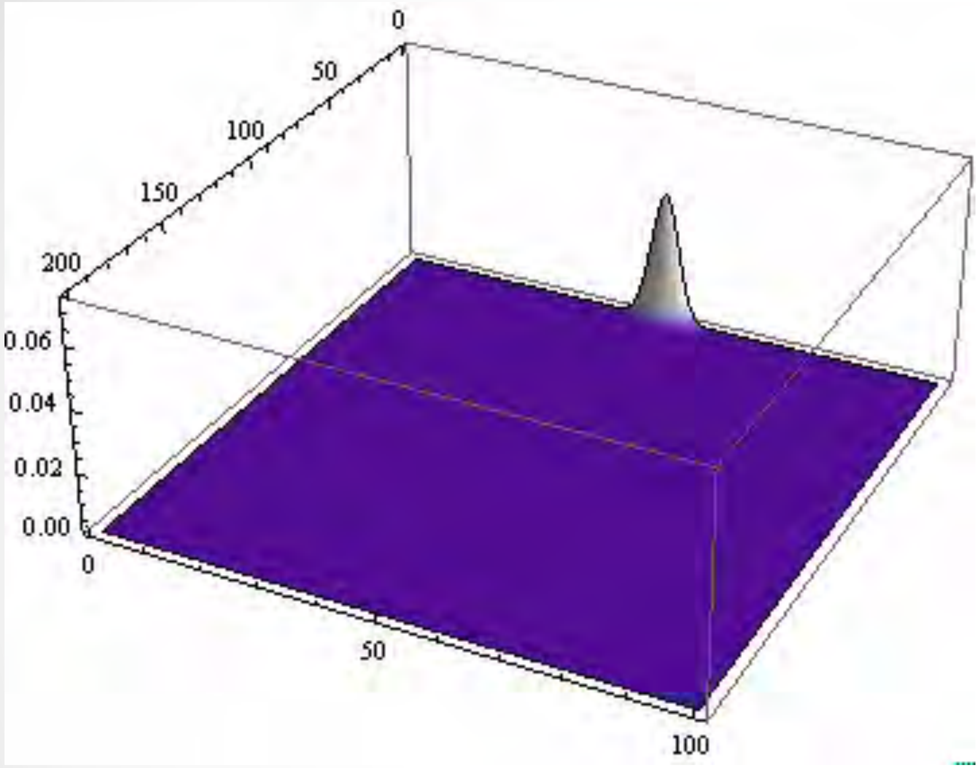
youtube

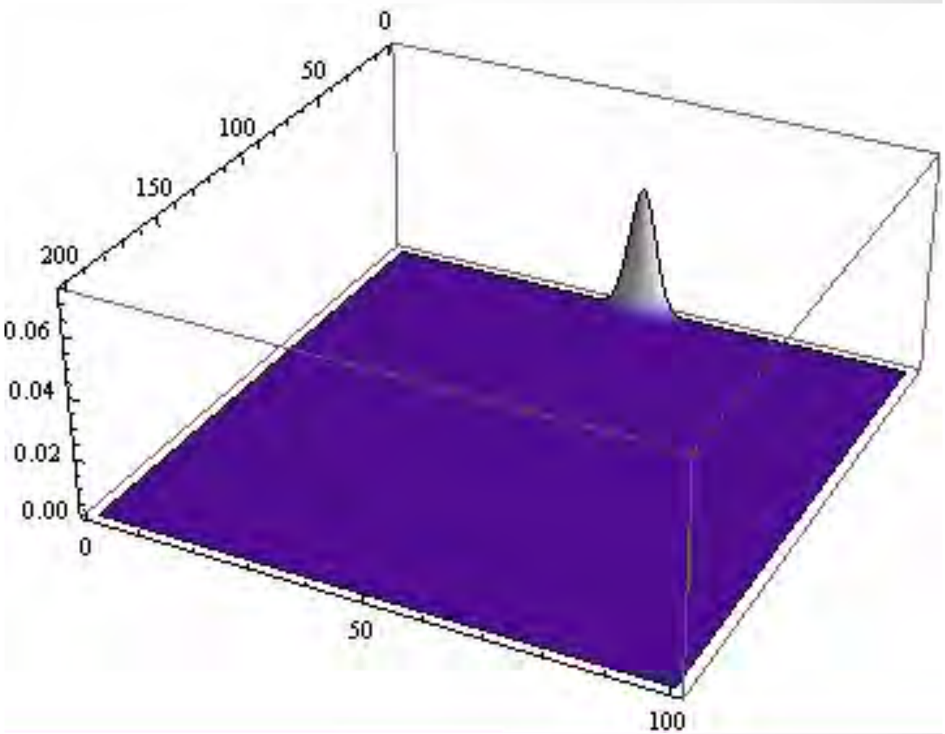
Also possible in quantum many-body systems (sine-Gordon model)

R. Citro, E. G. Dalla Torre, L. D'Alessio, A. Polkovnikov, M. Babadi, TO, and E. Demler, '*15*

Floquet topological state

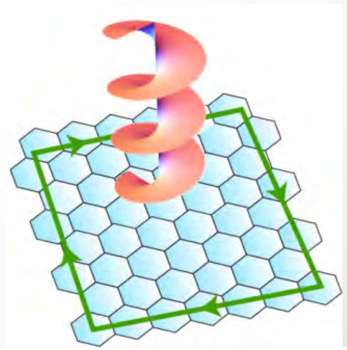
Wave packet dynamics in a honeycomb lattice





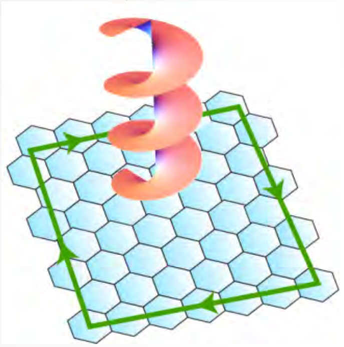
Without field

With circularly polarized laser



Floquet topological state

Topological Hall effect
by circularly polarized laser



TO, Aoki PRB'09
Kitagawa, TO, Fu, Brataas, Demler PRB '11

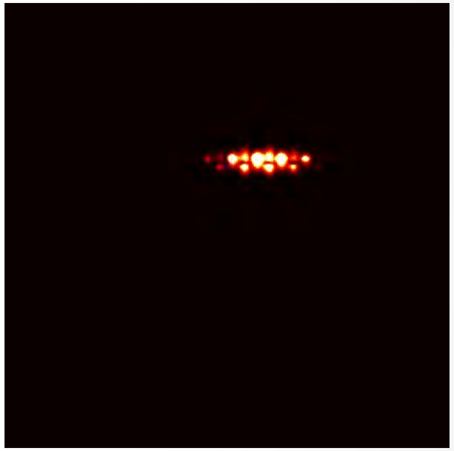
Floquet Chern insulator

Experiment 1 "Laser induced Hall effect in graphene"

Karch *et al*. (Ganichev@Regensburg) PRL '10, '11

Experiment 2 "Photonic Floquet topological insulator"

Rechtsman *et al.* Nature '13



Experiment 3 "Observation of Floquet-Bloch States on the Surface of a Topological Insulator"

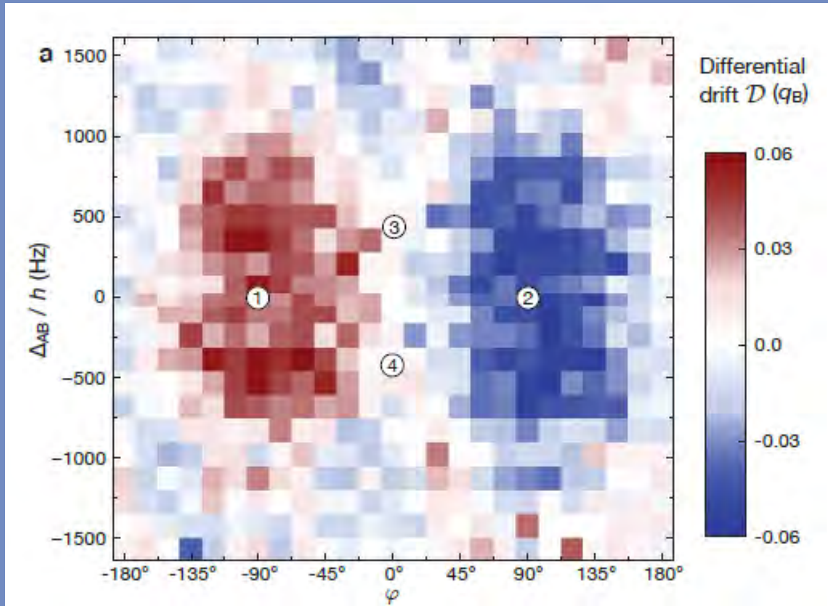
Wang *et al.* (Gedik MIT) Science '13

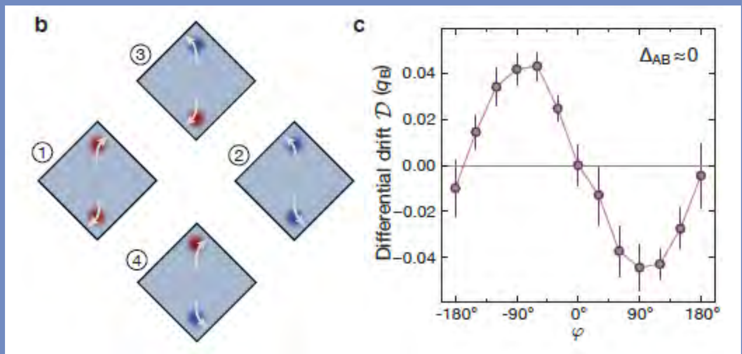
Related theory papers:
Lindner *et al.* Nat. Phys. '11, …

LETTER

doi:10.1038/nature13915

Drift measurement ~ conductivity



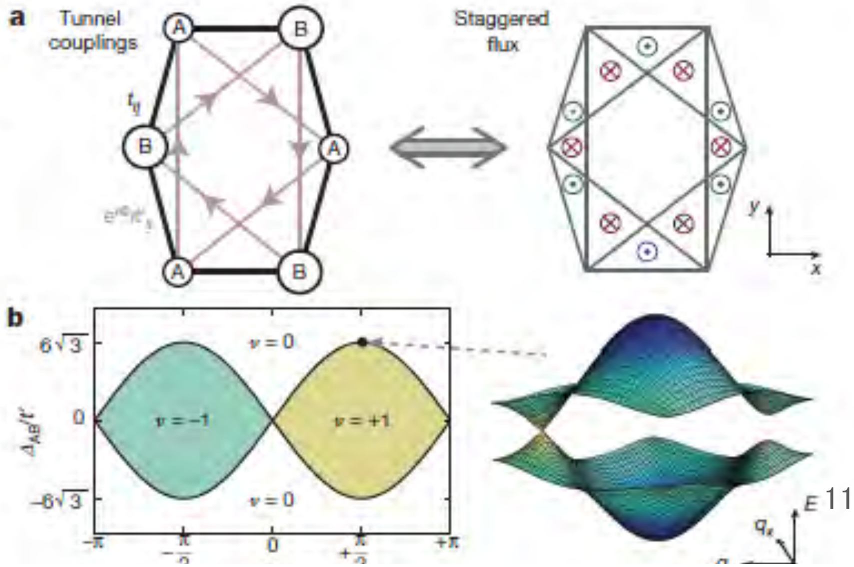


f the topological Haldane ions

[1], Thomas Uehlinger[1], Daniel Greif[1] & Tilman Esslinger[1]

ETH group, Nature '14

tunnelling[13]. In higher dimensions this allowed the study of phase transitions[14,15], and topologically trivial staggered fluxes were realized[16,17]. Furthermore, uniform flux configurations were observed using rotation and laser-assisted tunnelling[18,19], although for the latter method, heating seemed to prevent the observation of a flux in some experiments[20]. In a honeycomb lattice, a rotating force, as proposed by T. Oka and H. Aoki, can induce the required complex tunnelling[7]. Using arrays of coupled waveguides, a classical version of this proposal was used to study topologically protected edge modes in the inversion-symmetric regime[21]. We



vanishing gap at a single Dirac point, we map out this transition line experimentally and quantitatively compare it to calculations using Floquet theory without free parameters. We verify that our approach, which allows us to tune the topological properties dynamically, is suit-

Contents

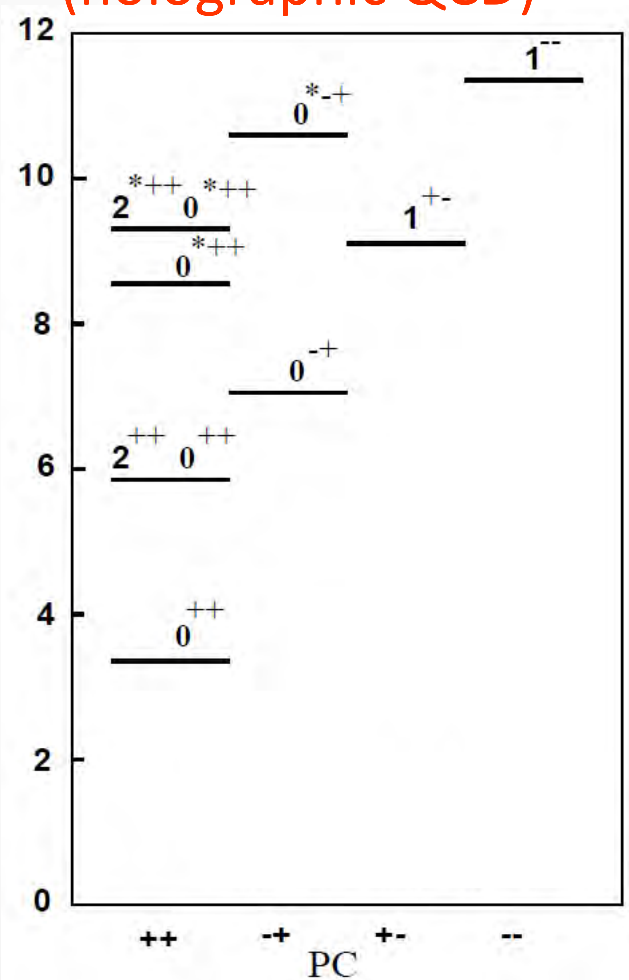
Slide by Koji Hashimoto

3-2 Superstring: better than simulations?

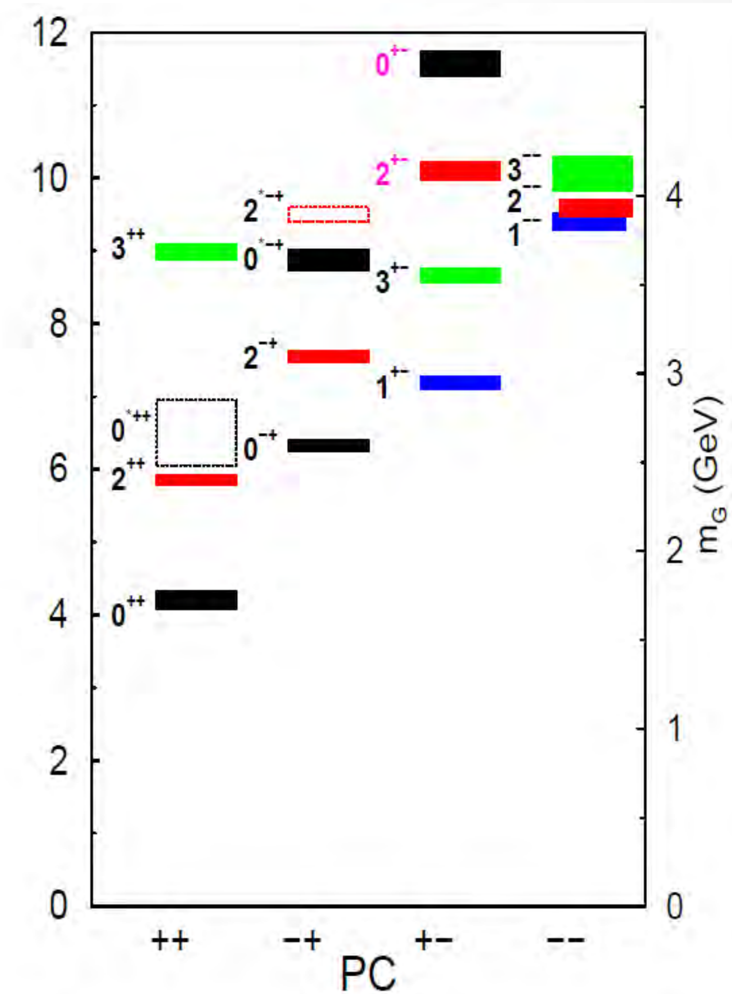
Superstring (holographic QCD)

meson spectrum

Lattice QCD



[Brower,Mathur,Tan (03)]



[Morningstar,Peardon (99)]

Our team and motivation

string theory	general relativity	condensed matter
K. Hashimoto	K. Murata	T. Oka
A. Sonoda	S. Kinoshita	

posters

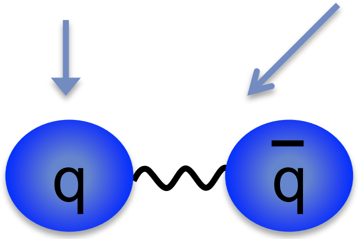
New phenomena in string theory	Dynamics of "extended" Black holes	Effect of correlation in noneq. quantum dynamics

"Holography" is our link

N=2 super symmetric QCD (large N_c limit)

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i i(\gamma^\mu D_\mu)_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a + \text{SUSY partners}$$

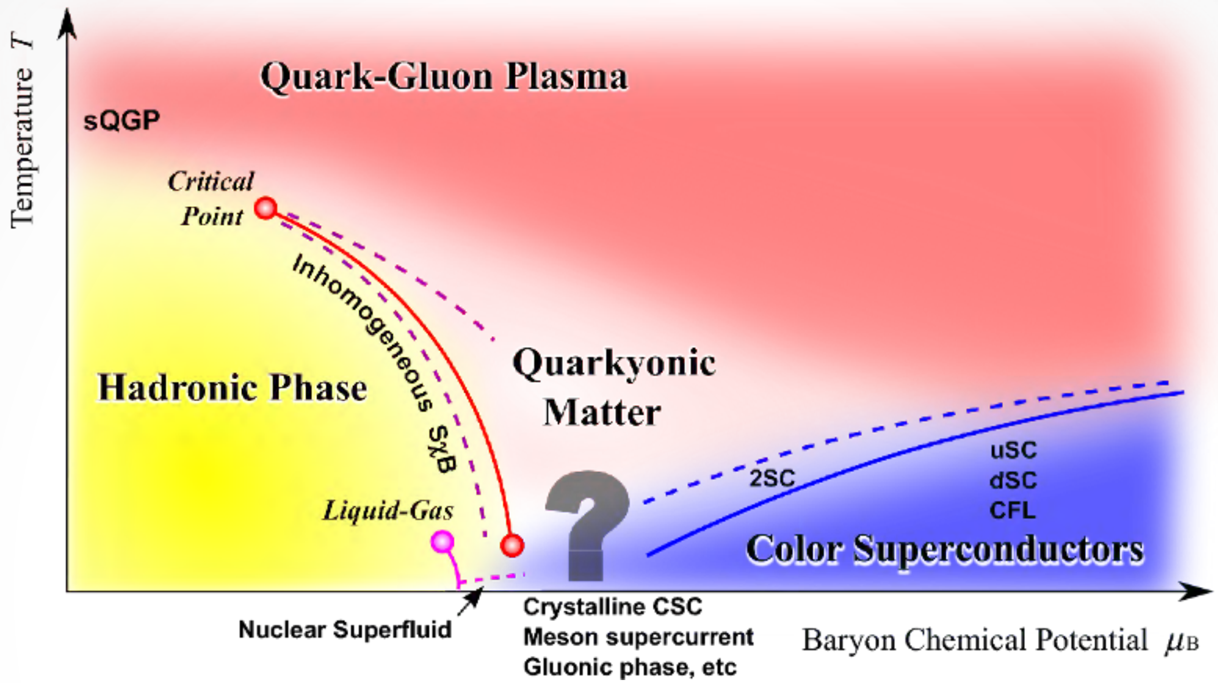
quark gluon



+ interaction mediated by gluons

3+1d Dirac fermion

Proposed phase diagram of QCD (Fukushima, Hatsuda, ..)



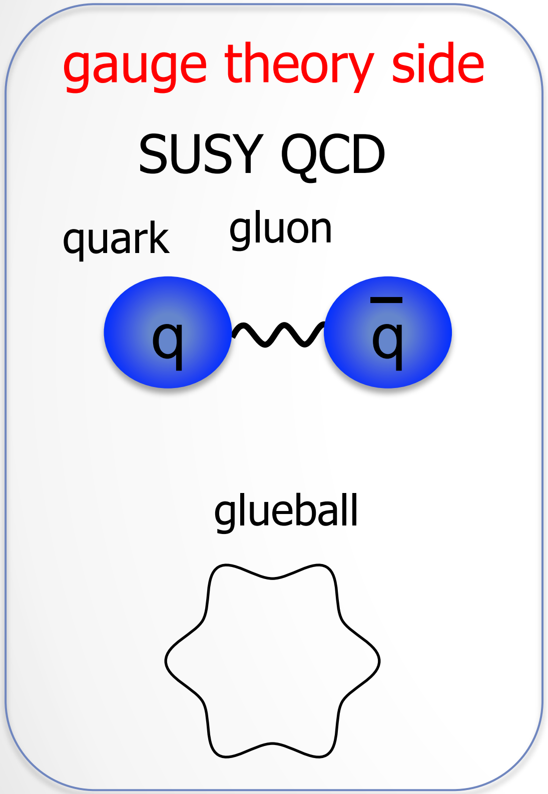
Are you
bad enough?

Probably yes

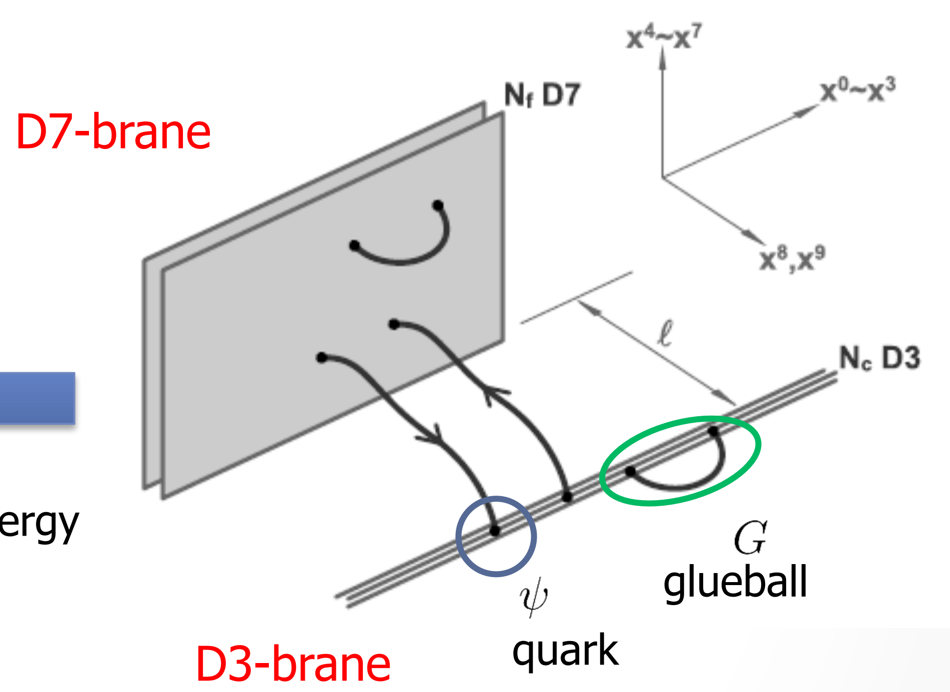
e.g. S-shape IV in the Hadron phase S. Nakamura PTP '10, PRL'12

SUSY Yang Mills: Maldecena ’99
SUSY QCD: Karch Katz ’02
Sakai Sugimoto ‘04

D3/D7 configuration (string theory)



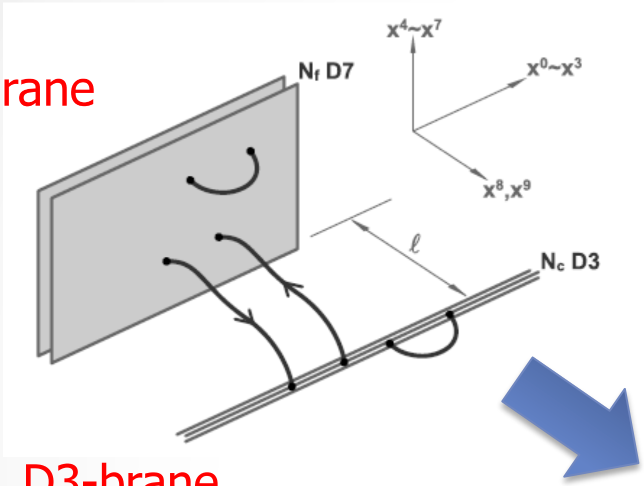
low energy



review: Erdmenger *et al.* 0711.4467
Kim *et al.* 1205.4852

SUSY Yang Mills: Maldecena ’99
SUSY QCD: Karch Katz ’02
Sakai Sugimoto ‘04

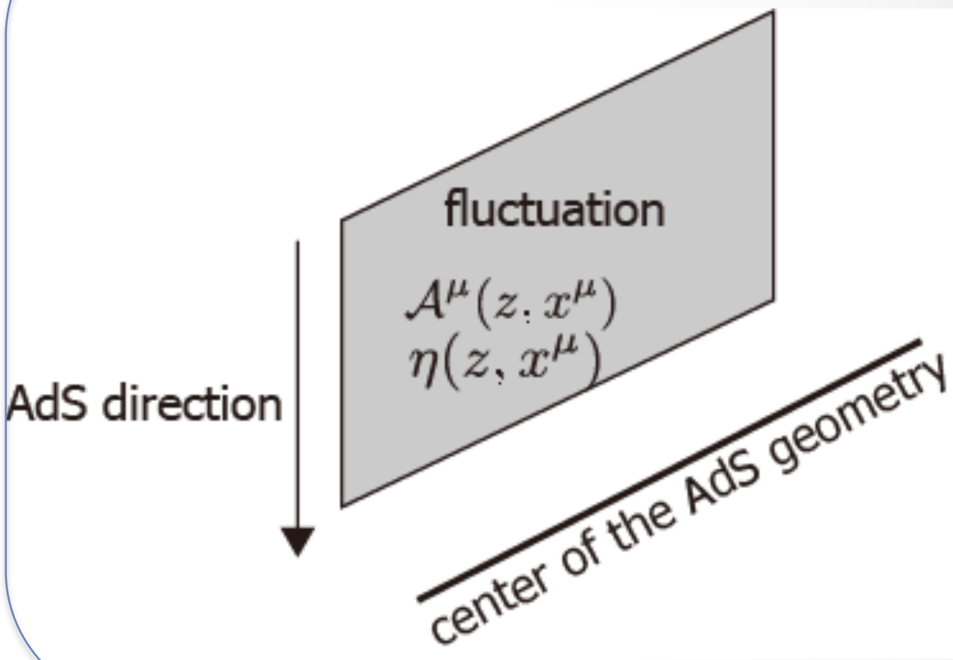
D7-brane



D3-brane

$N_c \to \infty$ limit

gravity theory side



Dirac-Born-Infeld (DBI) action governs the classical fluctuation

$$S_{\rm DBI} = -T_p \int d\sigma e^{-\Phi} \sqrt{-\det(g_{mn} + 2\pi\alpha' \mathcal{F}_{mn})}$$

$$\mathcal{F}_{mn} = \partial_m \mathcal{A}_n - \partial_n \mathcal{A}_m$$

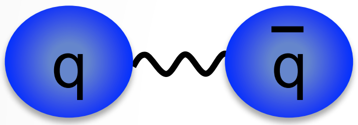
review: Erdmenger *et al.* 0711.4467
Kim *et al.* 1205.4852

SUSY Yang Mills: Maldecena ’99
SUSY QCD: Karch Katz ’02
Sakai Sugimoto ‘04

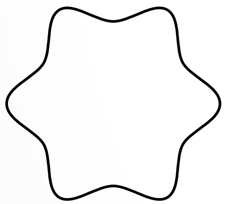
gauge theory side

strong coupling limit of SUSY QCD

quark gluon



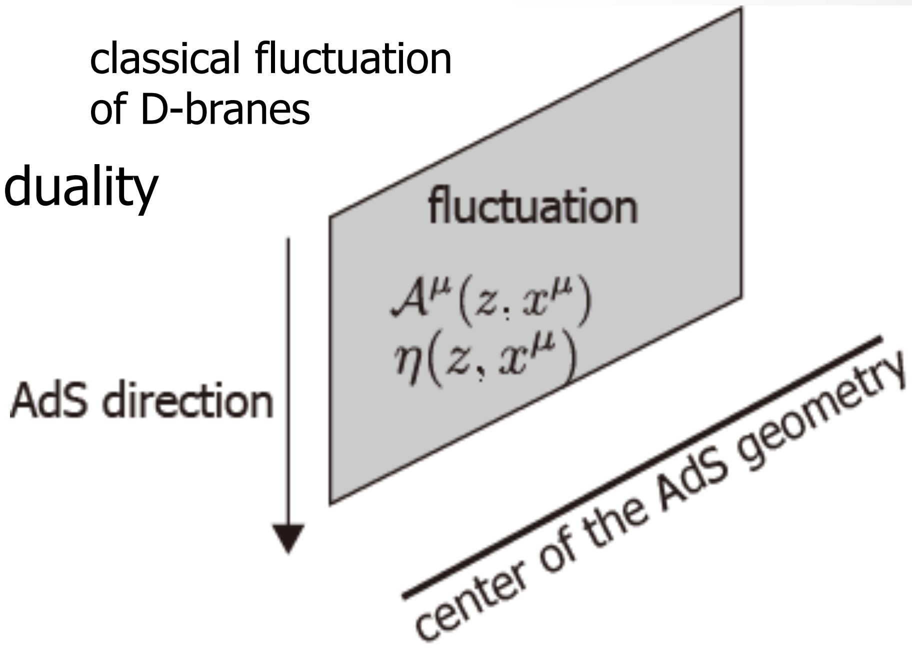
glueball



Gauge/Gravity duality

gravity theory side

classical fluctuation of D-branes



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$$\mathcal{F}_{mn} = \partial_m \mathcal{A}_n - \partial_n \mathcal{A}_m$$

review: Erdmenger *et al.* 0711.4467
Kim *et al.* 1205.4852

Equation of motion

$$S_{\rm DBI} = -T_p \int d\sigma e^{-\Phi}\sqrt{-\det(g_{mn} + 2\pi\alpha'\mathcal{F}_{mn})}$$

cf Maxwell equation

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\partial_\mu F^{\mu\nu} = 0$$

$$-\partial_z\left(\frac{\sqrt{1+\frac{z^6}{R^4}d^2\partial_z A_1}}{z\sqrt{1-\frac{z^4}{R^4}\{(\partial_0 A_1)^2-(\partial_z A_1)^2\}}}\right)+\partial_0\left(\frac{\sqrt{1+\frac{z^6}{R^4}d^2\partial_0 A_1}}{z\sqrt{1-\frac{z^4}{R^4}\{(\partial_0 A_1)^2-(\partial_z A_1)^2\}}}\right)=0$$

"nonlinear Maxwell equation + AdS metric"

* The actual equations are much more complicated

$$K_1 V_{,uv} = \frac{3}{2}Z(Z\Psi)_{,u}(Z\Psi)_{,v} + \frac{3}{2}\tan(Z\Psi)\{(Z\Psi)_{,u}V_{,v} + (Z\Psi)_{,v}V_{,u}\}$$

$$K_1 Z_{,uv} = -\frac{3}{2}ZF(Z\Psi \ldots$$

$$-\frac{1}{2}K_3(FV_{,u}V_{,v} + V_{,u}Z_{,v} + V_{\ldots}$$

$$\ldots + \frac{\tan(Z\Psi)}{Z}\Big)(Z\Psi)_{,u}(Z\Psi)_{,v}$$

$$\ldots\{K_2 - 3Z\Psi\tan(Z\Psi)\}\{(Z\Psi)_{,u}Z_{,v} + (Z\Psi)_{,v}Z_{,u}\}$$

$$\ldots\frac{\Psi}{2Z}\left(K_3 + \frac{3\tan(Z\Psi)}{Z^2\Psi}\right)(FV_{,u}V_{,v} + V_{,u}Z_{,v} + V_{,v}Z_{,u})$$

$$-\frac{3\Psi}{Z^2}Z_{,u}Z_{,v} + \frac{FZ^2\Psi}{2}\left(K_2 - \frac{3\tan(Z\Psi)}{FZ\Psi}\right)a_{x,u}a_{x,v}\,, \qquad \text{(B.7)}$$

$$K_1 a_{x,uv} = \frac{3}{2}\tan(Z\Psi)\{(Z\Psi)_{,u}a_{x,v} + (Z\Psi)_{,v}a_{x,u}\} + \frac{1}{2Z}K_2(Z_{,u}a_{x,v} + Z_{,v}a_{x,u})\,. \qquad \text{(B.8)}$$

where functions K_1, K_2 and K_3 are defined as

$$K_1 = 1 + d^2\frac{Z^6}{\cos^6(Z\Psi)}\,, \quad K_2 = 1 - 2d^2\frac{Z^6}{\cos^6(Z\Psi)}\,,$$
$$K_3 = F_Z - 5\frac{F}{Z} + d^2\frac{Z^6}{\cos^6(Z\Psi)}\left(F_Z - 2\frac{F}{Z}\right)\,. \qquad \text{(B.9)}$$

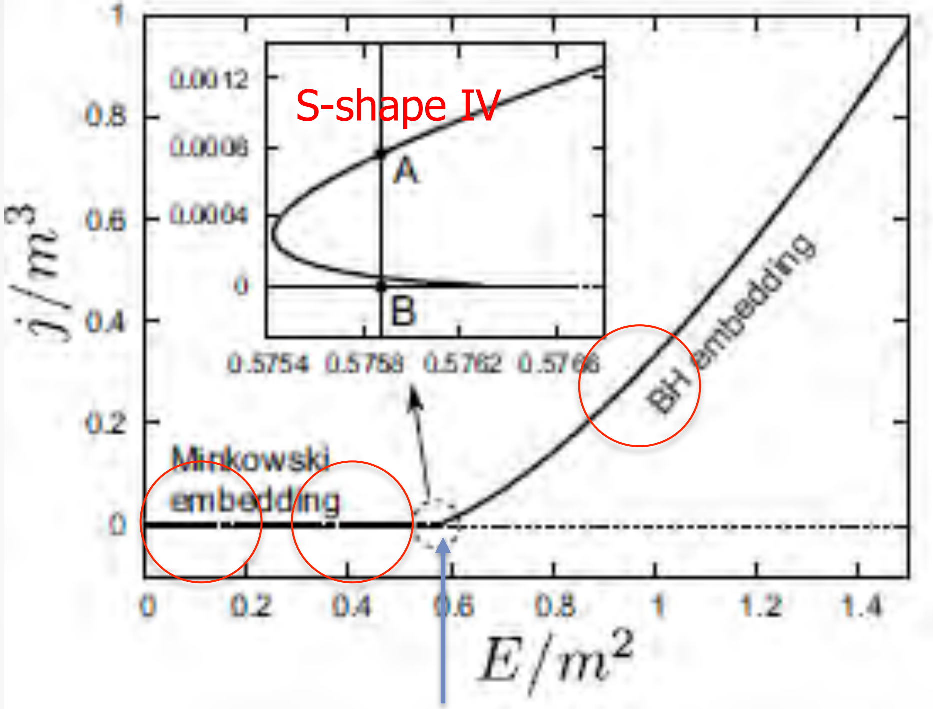
general relativity

K. Murata
S. Kinoshita

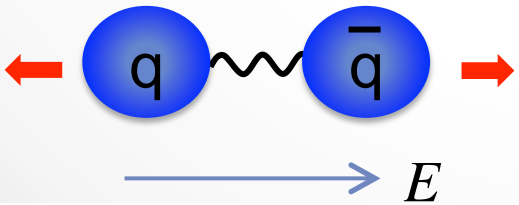
Static IV-characteristics in holographic QCD

Hashimoto-Kinoshita-Murata-TO JHEP`14

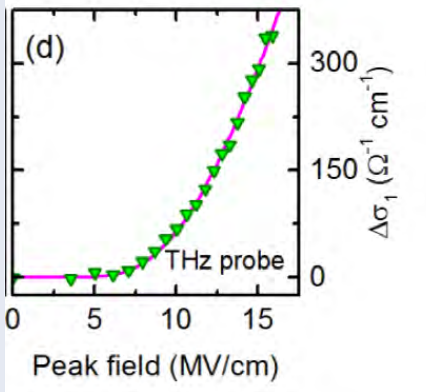
S-shape IV in the Hadron phase
first obtained by S. Nakamura PTP '10, PRL'12



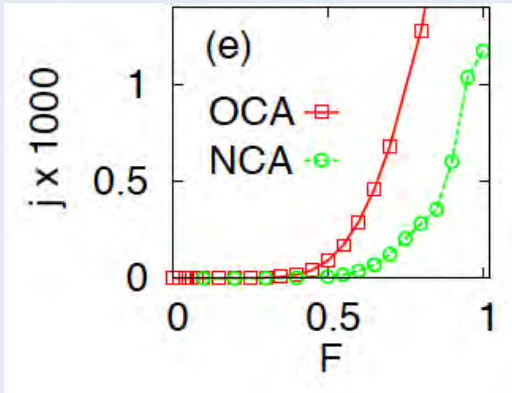
E_{cr}
QCD Schwinger limit
= confining force



VO2 experiment (THz laser)
Mayer, TO, Leitenstorfer, Pashkin *et al.* PRB '15



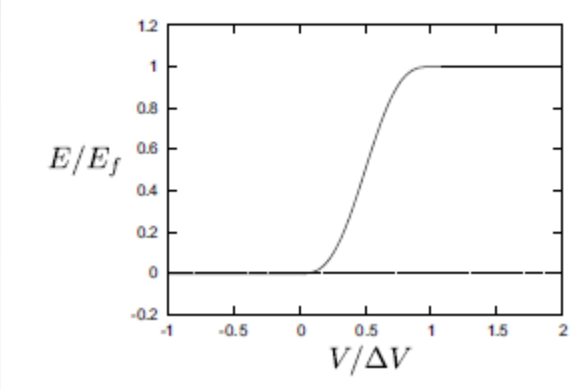
Hubbard model (noneq.DMFT)
Eckstein, TO, Werner PRL '10



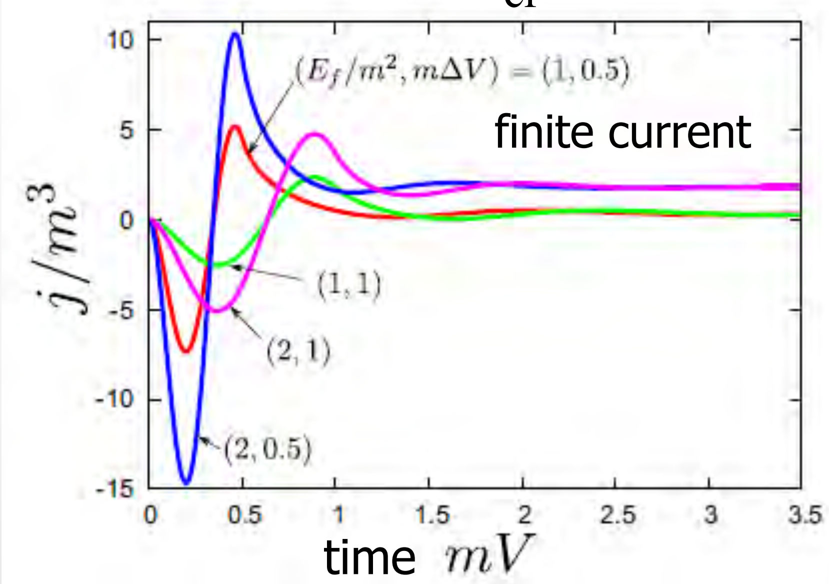
E-field quench above the Schwinger limit

Hashimoto-Kinoshita-Murata-TO JHEP`14

E-field

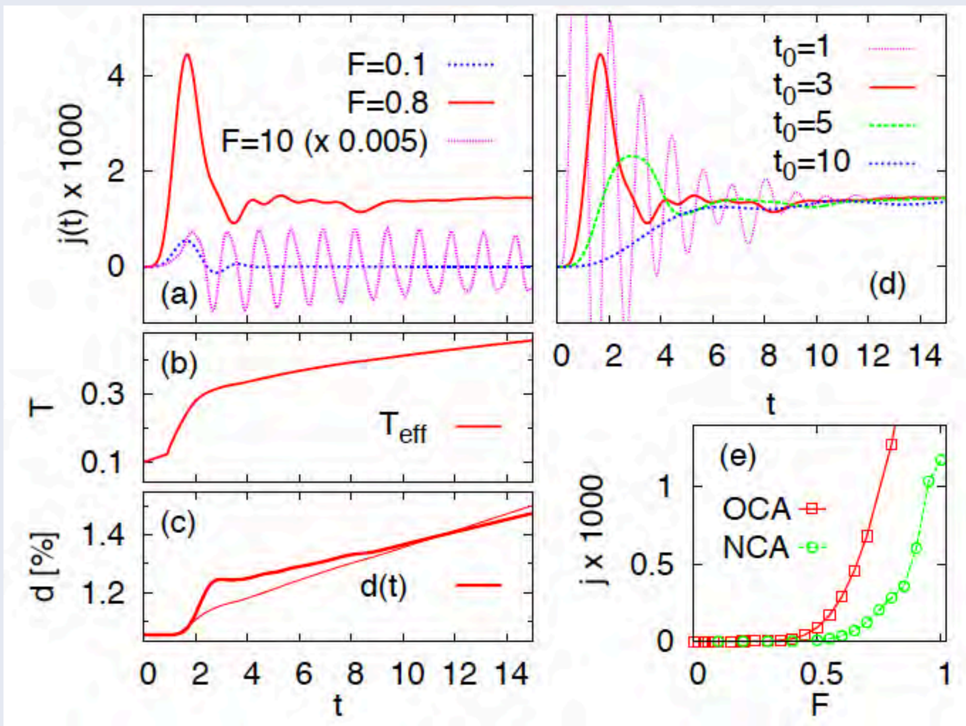


$E > E_{\rm cr}$



Hubbard model (noneq.DMFT)

Eckstein, TO, Werner PRL '10

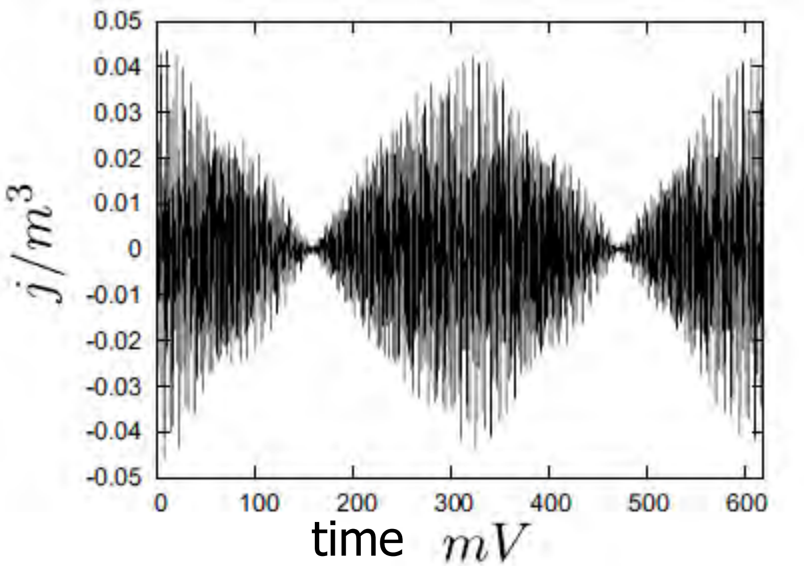


E-field quench in subcritical fields

Hashimoto-Kinoshita-Murata-TO JHEP`14

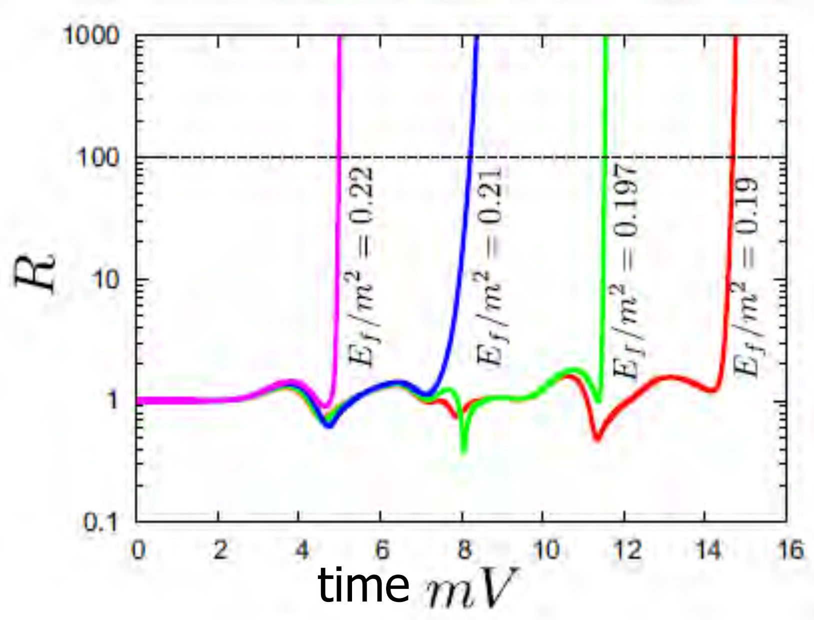
$E < E_{cr}$

very weak field



coherent oscillation
of mesons (excitons)

moderate field



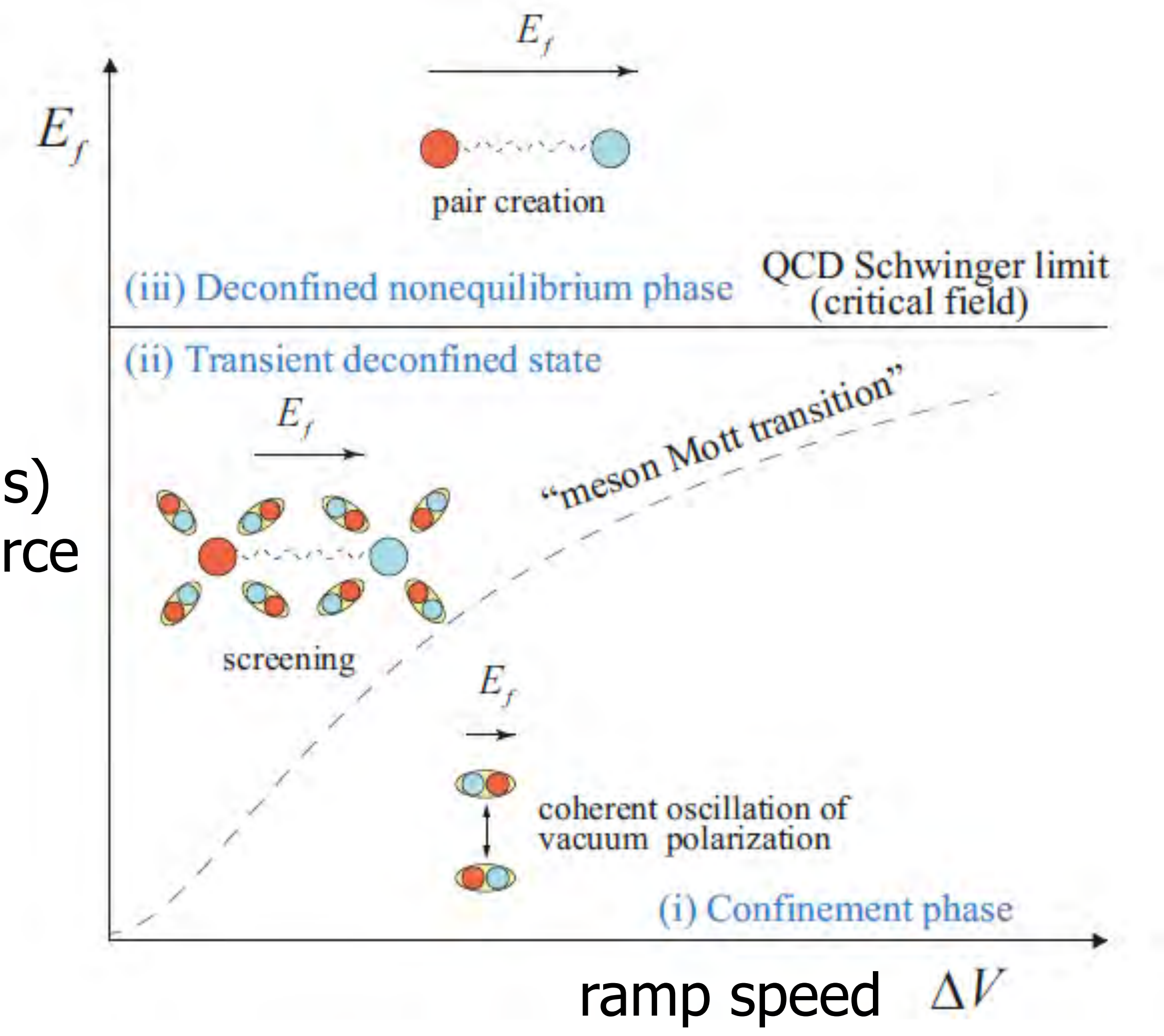
(b) redshift factor

indication of deconfinement

E-field phase diagram of N=2 SQCD

Hashimoto-Kinoshita-Murata-TO JHEP`14

Excited excitons (mesons) screens the attractive force



Summary

Holography is a powerful tool in nonequilibrium physics

1. Dielectric breakdown in QCD and Mott insulator
2. Floquet state (Holographic Floquet Weyl semimetal)

It is also important to develop reliable condensed matter theories and compare, e.g. noneq. DMFT.

Aoki, Tsuji, Eckstein, Kollar, TO, Werner, RMP ’14