Strong field QFT in condensed matter – photo-induced topological phase transition and many-body Schwinger mechanism

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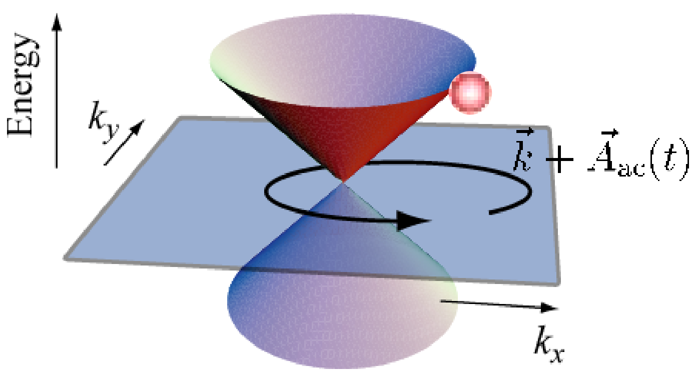
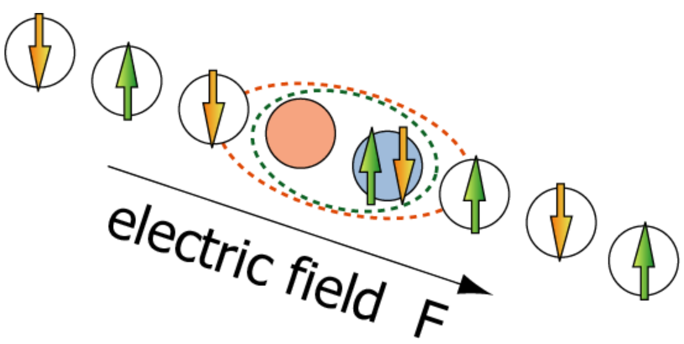




Talk plan

1. Introduction and motivation

2. Photo-induced quantum Hall effect

   Control of parity anomaly by laser
   = Floquet topological insulator

   theory: Volkov state = Floquet picture

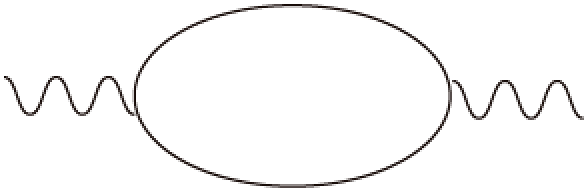
3. Many-body Schwinger mechanism in a Mott insulator

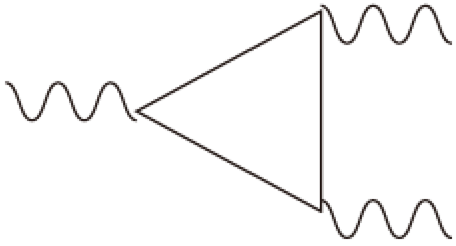
   Laser induced charge deconfinement
   = photo-induced phase transition with THz laser

   theory: Bethe ansatz + Landau-Dykhne method

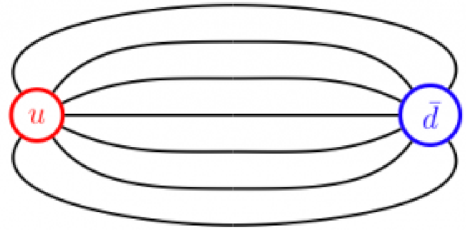
QFT is interesting

quantum anomaly





charge confinement



QFT is universal

HEP

quantum anomaly charge confinement

electron system

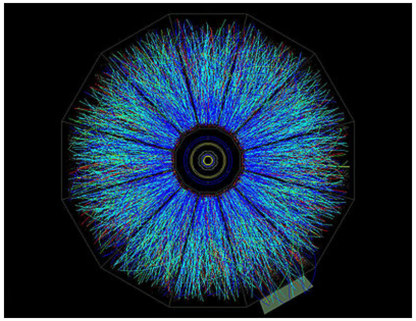
topological insulator metal-insulator transition

Helium, cold atom

topological state solid/liquid/gas transition

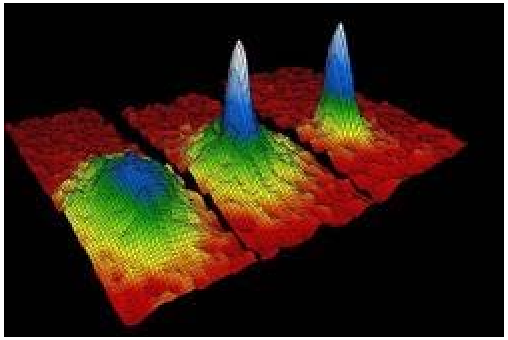
⋮

QFT still has frontiers!!



Strong field QFT: non-equilibrium induced by strong external fields

1. Formation of QGP in RHIC
2. Dynamics in cold atoms
3. Non-equilibrium phase transition in solids

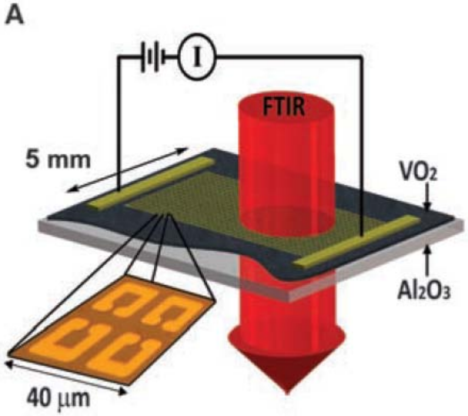


I chose 3. as a field of research because...

almost no competition

experiment : theory ~ 20:1

and,



STRONG motivations!

1. Eco(nomy) friendly

QED vacuum

$$$$ Schwinger mechanism (Heisenberg-Euler)

$$E_{th} = m^2/e = 1.3 \times 10^{16} V/cm$$

Insulator

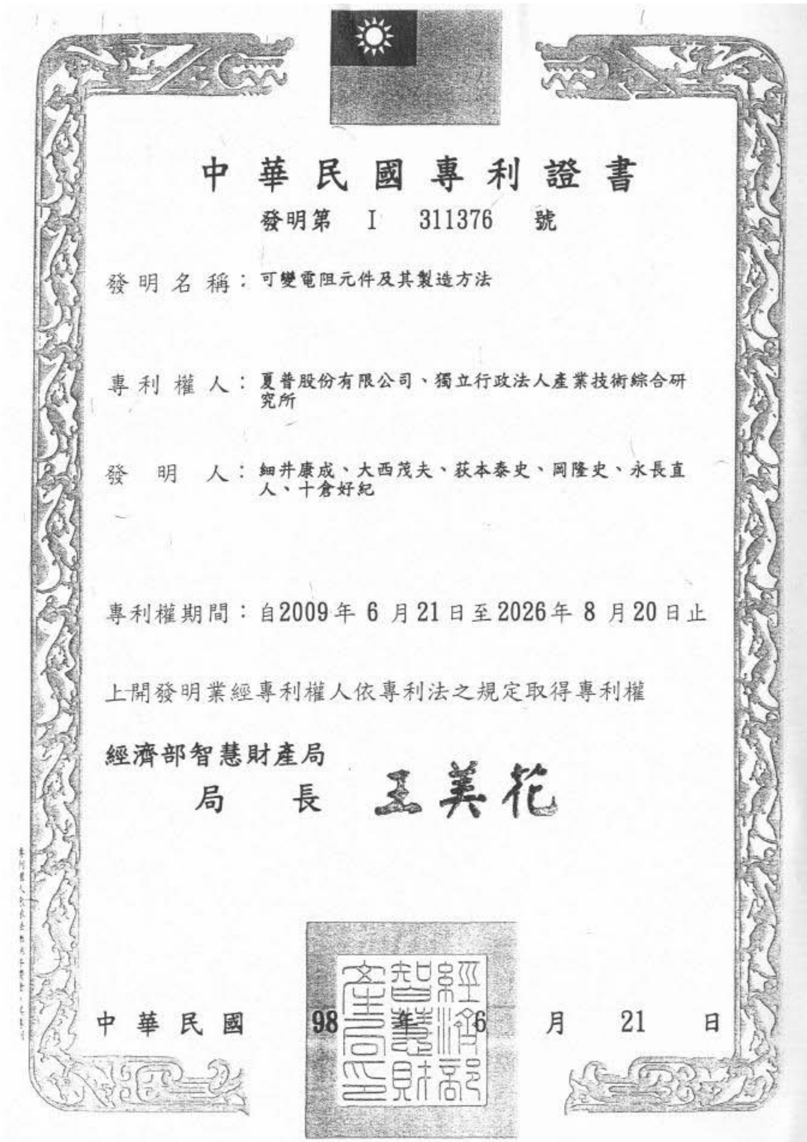
$ Dielectric breakdown

$$E_{th} = \Delta^2/t_{hop}a \sim 1eV/\mathring{A} \sim 10^8 V/cm$$

2. Full of dreams

You may earn $ with your theoretical ideas!

Patent for a new flash memory



中 華 民 國 專 利 證 書

發明第 I 311376 號

發 明 名 稱：可變電阻元件及其製造方法

專 利 權 人：夏普股份有限公司、獨立行政法人產業技術綜合研究所

發　明　人：細井康成、大西茂夫、荻本泰史、岡隆史、永長直人、十倉好紀

專利權期間：自2009年 6 月21日至2026年 8 月20日止

上開發明業經專利權人依專利法之規定取得專利權

經濟部智慧財產局

局　長　王美花

中 華 民 國 98 年 6 月 21 日

in Taiwan

in USA

"Variable Resistor Element and its Manufacturing method"

Y, Hosoi, S. Ohnishi, Y. Ogimoto, T. Oka, N. Nagaosa, Y. Tokura,

United State Patent No US7,978,047B2,

in Japan and Korea as well

I earned 12000¥ (not $)

Might be used in iPadxx

$$$?

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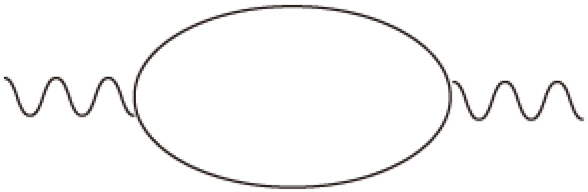
2. Photo-induced quantum Hall effect

Parity anomaly

Niemi Semenoff ‘83, Redlich ‘84, Ishikawa ‘84



vacuum polarization tensor

2+1 Dirac (Weyl) fermion with mass *m*

$$\Pi_{\mu\nu}(p^2,m^2)=(p^2g_{\mu\nu}-p_\mu p_\nu)\Pi_{\rm even}(p^2,m^2)+i\varepsilon_{\mu\nu\alpha}p^\alpha\Pi_{\rm odd}(p^2,m^2)$$

$$\mu(p^2,m^2)=m\Pi_{\rm odd}(p^2,m^2)$$

$$=\frac{e^2m}{4\pi}\int_0^1 dx\frac{1}{[-p^2x(1-x)+m^2]^{1/2}}$$

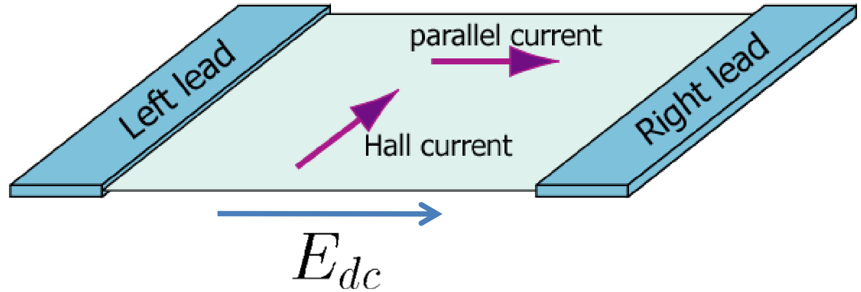
dim. regularization

$$=\begin{cases}\frac{e^2m}{4p} & p\gg m\\ \frac{e^2}{4\pi}\frac{m}{|m|} & p\ll m\end{cases}$$

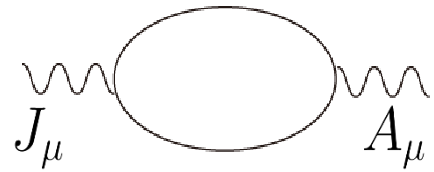
a singular term proportional to the sign of the mass

Mass breaks parity in 2+1 d

Kubo formula and the TKNN formula



$$J^i_{\rm dc} = \sigma_{ij} E^j_{\rm dc}$$



Kubo formula (= polarization tensor) $\boldsymbol{q} \to 0$ and $\omega \to 0$

$$\sigma_{ab} = i \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_{\alpha, \beta \neq \alpha} \frac{[f_\beta(\boldsymbol{k}) - f_\alpha(\boldsymbol{k})]}{E_\beta(\boldsymbol{k}) - E_\alpha(\boldsymbol{k})} \frac{\langle \Phi_\alpha(\boldsymbol{k}) | J_b | \Phi_\beta(\boldsymbol{k}) \rangle \langle \Phi_\beta(\boldsymbol{k}) | J_a | \Phi_\alpha(\boldsymbol{k}) \rangle}{E_\beta(\boldsymbol{k}) - E_\alpha(\boldsymbol{k}) + i\eta}$$

$\Phi_\alpha(\boldsymbol{k})$ Bloch wave function

$$f_\alpha(\boldsymbol{k}) = (\exp(\beta E_\alpha(\boldsymbol{k})) + 1)^{-1}$$

Thouless-Kohmoto-Nightingale-Nijs formula (1982)

in ISSP next door!

$$\sigma_{xy} = e^2 \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_{\alpha} f_\alpha(\boldsymbol{k}) \left[\nabla_{\boldsymbol{k}} \times \boldsymbol{\mathcal{A}}_\alpha(\boldsymbol{k})\right]_z$$

Berry curvature
=Chern density

artificial gauge field

$$\boldsymbol{\mathcal{A}}_\alpha(\boldsymbol{k}) \equiv -i\langle\Phi_\alpha(\boldsymbol{k})|\nabla_{\boldsymbol{k}}|\Phi_\alpha(\boldsymbol{k})\rangle \qquad H|\Phi_\alpha\rangle = E_\alpha|\Phi_\alpha\rangle$$

(TKNN is the Adler-Bell-Jackiw in CM)

Thouless-Kohmoto-Nightingale-Nijs formula (1982)

in ISSP next door!

$$\sigma_{xy} = e^2 \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_{\alpha} f_\alpha(\boldsymbol{k}) \left[\nabla_{\boldsymbol{k}} \times \boldsymbol{\mathcal{A}}_\alpha(\boldsymbol{k})\right]_z$$

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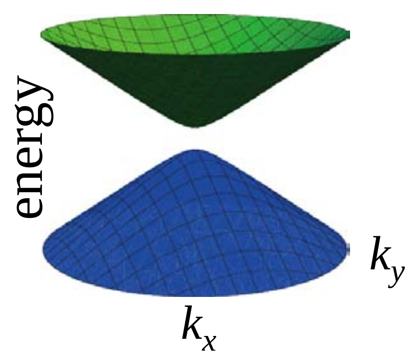
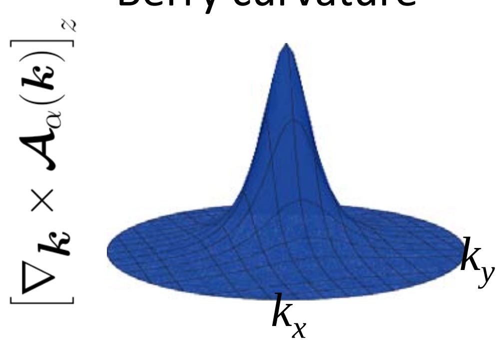
(TKNN is the Adler-Bell-Jackiw in CM)

energy



Berry curvature



2d Dirac system has a non-trivial Chern number

$$H = \begin{pmatrix} m & \pm k_x - ik_y \\ \pm k_x + ik_y & -m \end{pmatrix}$$

$$\sigma_{xy} = e^2 \int \frac{d\boldsymbol{k}}{(2\pi)^d} \left[\nabla_{\boldsymbol{k}} \times \boldsymbol{\mathcal{A}}_1(\boldsymbol{k})\right]_z$$

zero temperature

$$= \pm \frac{1}{2}\frac{e^2}{h}\frac{m}{|m|}$$

1. Dirac cone = half quantum unit
2. Pauli-Villars regularization

Niemi Semenoff '83, Redlich '84, Ishikawa '84

Classification of topological insulators

K-theory: Kitaev 2009
random matrix theory:
(Altland-Zirnbauer 1997), Schnyder-Ryu-Furusaki-Ludwig 2008

Symmetry				d							
AZ	Θ	Ξ	Π	1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	-1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	-1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	-1	-1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	-1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	-1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

2d quantum Hall state

Bott's periodicity

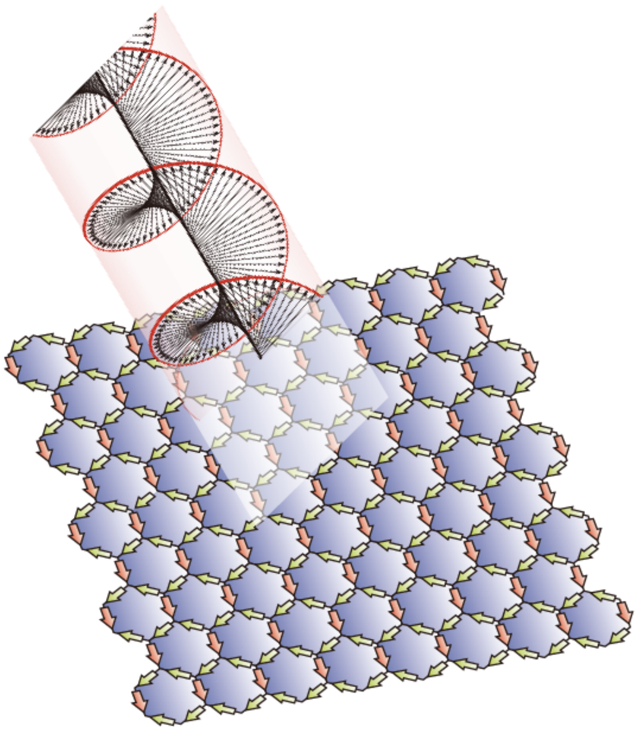
Many CM realizations:
- topological superconductors, e.g., SrRuO
- topological insulators, e.g,. BiSb

review: Hasan-Kane, RMP arXiv1002.389

Q. Can we change the topological number by laser?

2+1 Dirac

$$\sigma_{xy} \propto \mathrm{Ch} = 0, \pm 1$$



A. Yes

Photo-induced Quantum Hall state

TO, H. Aoki, PRB 79, 081406 (R) (2009)

massless Dirac

$$\mathrm{Ch} = 0$$

right-circularly polarized light → $\mathrm{Ch} = -1$

left-circularly polarized light → $\mathrm{Ch} = +1$

Photo-induced Quantum Hall state

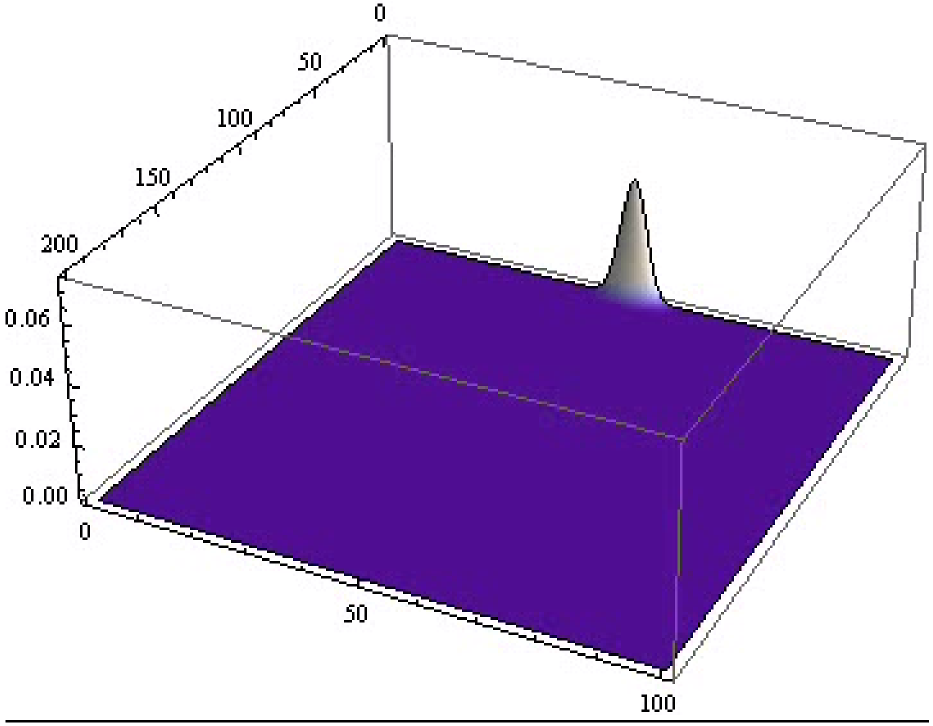
honeycomb lattice
(supports a Dirac cone,
realized in graphene)

$$H = \sum_{\langle ij \rangle} t_{ij} c_i^\dagger c_j$$

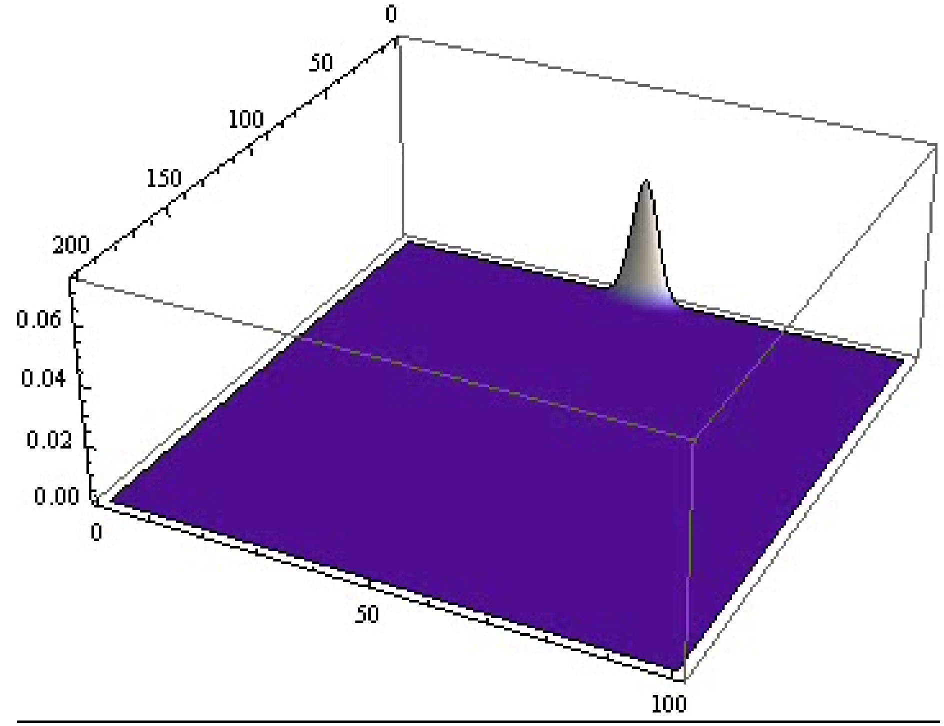
honeycomb lattice
+ circularly polarized light

$$H(t) = \sum_{\langle ij \rangle} t_{ij} e^{-i\phi_{ij}(t)} c_i^\dagger c_j$$

Wave packet dynamics



2+1 d Dirac system

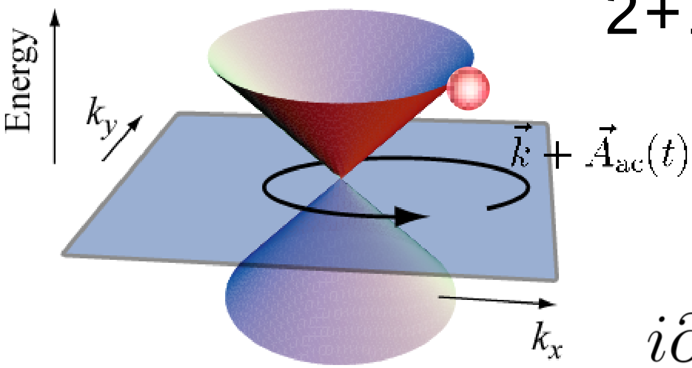


gapped 2+1 d Dirac system

chiral edge state

cf) boundary index theorem

2+1 Dirac + circular polarized light



$$k_i \to k_i + A_i(t)$$

$$A_i = (A\cos(\Omega t), A\sin(\Omega t))$$

$$i\partial_t|\psi_k\rangle = \begin{pmatrix} 0 & k + Ae^{i\Omega t} \\ \bar{k} + Ae^{-i\Omega t} & 0 \end{pmatrix}|\psi_k\rangle$$

$$k = k_1 - ik_2 \quad A = F/\Omega$$

Floquet method

Fourier transformation with $e^{im\Omega t}$

$$|\psi_k(t)\rangle = e^{-i\varepsilon t}|\Phi(t)\rangle = e^{-i\varepsilon t}\sum_m |\Phi_m\rangle e^{im\Omega t}$$

$$H^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} \qquad T = 2\pi/\Omega$$

Floquet equation

$$\sum_n H^{mn}|\Phi_\alpha^n\rangle = (\varepsilon_\alpha + m\Omega)|\Phi_\alpha^m\rangle$$

Floquet spectrum

TO, H. Aoki (2009)

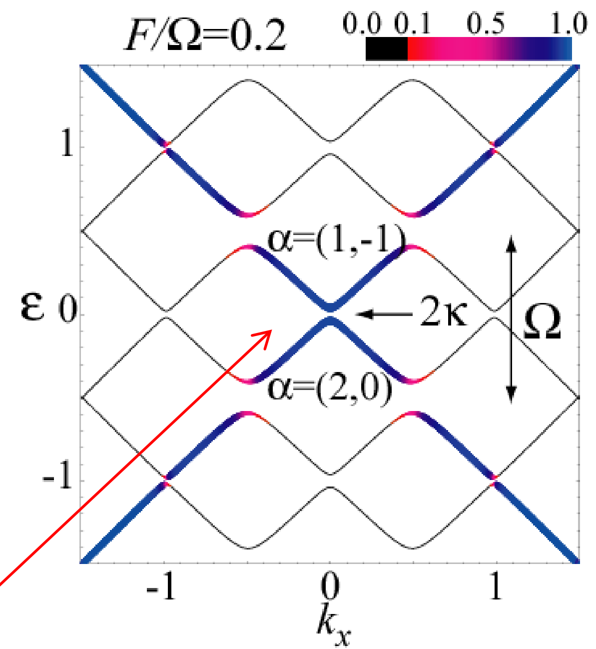
m=-1 m=0 m=+1

$$H^{\mathrm{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

n=-1
n=0
n=+1

* truncated to m=0,+1, -1 for display

quasi-energy spectrum

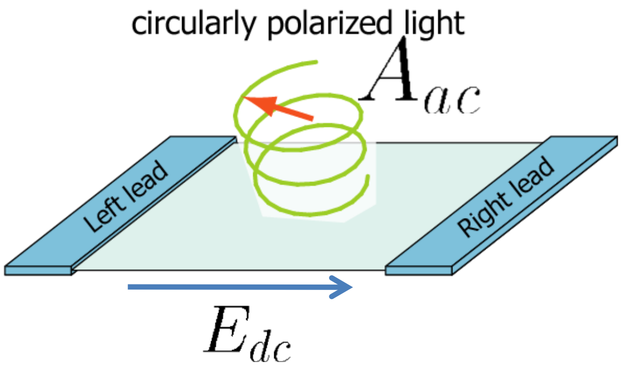


1. Dynamical topological gap

$$\kappa = \frac{\sqrt{4A^2 + \Omega^2} - \Omega}{2} \sim A^2/\Omega$$

2. Resonant gaps

Kubo-formula for photo-induced transport



Large A_{ac} small E_{dc}

$$J^i_{\mathrm{dc}} = \sigma_{ij}(\boldsymbol{A}_{\mathrm{ac}}) E^j_{\mathrm{dc}}$$

$$\sigma_{ab}(\boldsymbol{A}_{ac}) = i \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_{\alpha,\beta\neq\alpha} \frac{[f_\beta(\boldsymbol{k}) - f_\alpha(\boldsymbol{k})]}{\varepsilon_\beta(\boldsymbol{k}) - \varepsilon_\alpha(\boldsymbol{k})} \frac{\langle\langle\Phi_\alpha(\boldsymbol{k})|J_b|\Phi_\beta(\boldsymbol{k})\rangle\rangle\langle\langle\Phi_\beta(\boldsymbol{k})|J_a|\Phi_\alpha(\boldsymbol{k})\rangle\rangle}{\varepsilon_\beta(\boldsymbol{k}) - \varepsilon_\alpha(\boldsymbol{k}) + i\eta}$$

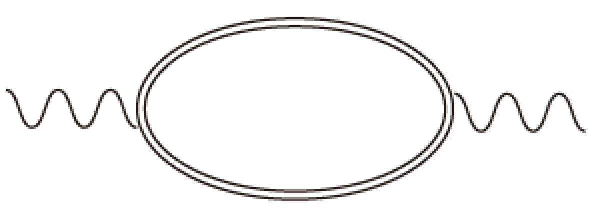
ε_α Floquet's quasi-energy

f_α occupation fraction

inner product = time average

$$\langle\langle\Phi_\alpha|\Phi_\beta\rangle\rangle = \frac{1}{T}\int_0^T \langle\Phi_\alpha(t)|\Phi_\beta(t)\rangle$$

Floquet state



TO and H. Aoki, Phys. Rev. B 79, 081406 (R) (2009)

Extended Thouless-Kohmoto-Nitingale-Nijis formula for photo-induced Hall conductivity (photo-induced Chern form)

$$\sigma_{xy}(\boldsymbol{A}_{\rm ac}) = e^2 \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_\alpha f_\alpha(\boldsymbol{k}) \left[\nabla_{\boldsymbol{k}} \times \boldsymbol{A}_\alpha(\boldsymbol{k})\right]_z$$

photo-induced gauge field $\boldsymbol{A}_\alpha(\boldsymbol{k}) \equiv -i\langle\langle\Phi_\alpha(\boldsymbol{k})|\nabla_{\boldsymbol{k}}|\Phi_\alpha(\boldsymbol{k})\rangle\rangle$

Floquet states (time-dependent solution)

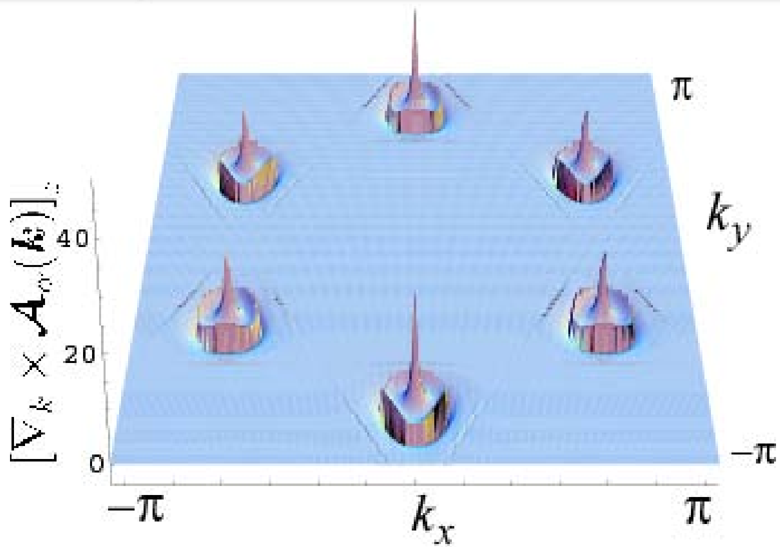
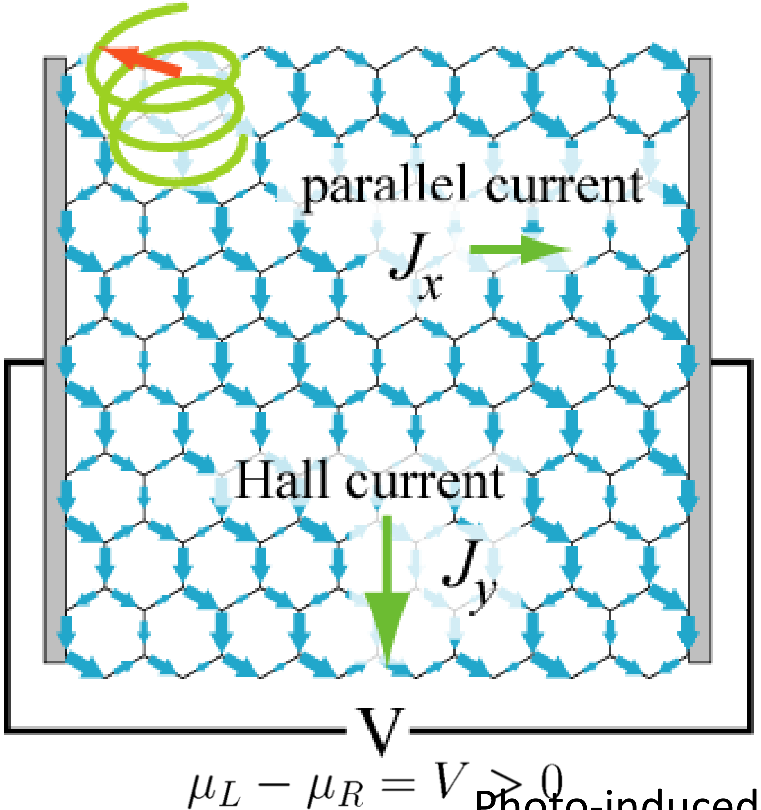


photo-induced Berry's curvature for graphene

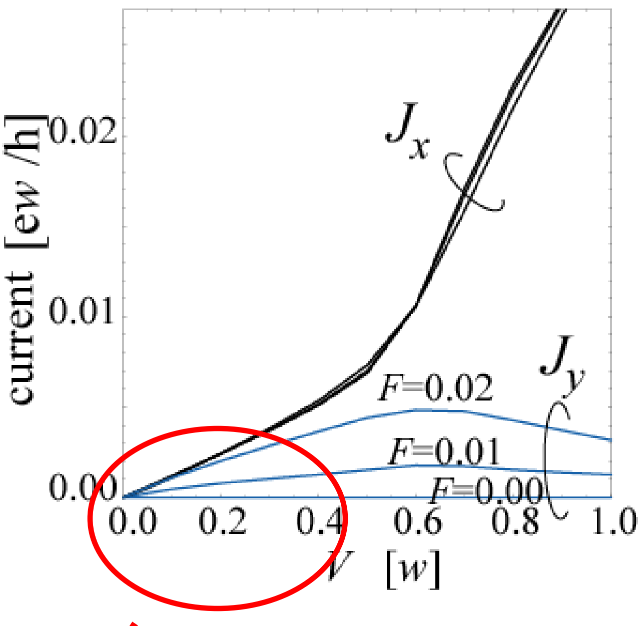
TO and H. Aoki, Phys. Rev. B **79**, 081406 (R) (2009)

Static current in circularly polarized light

DC-component of the current



IV-characteristics



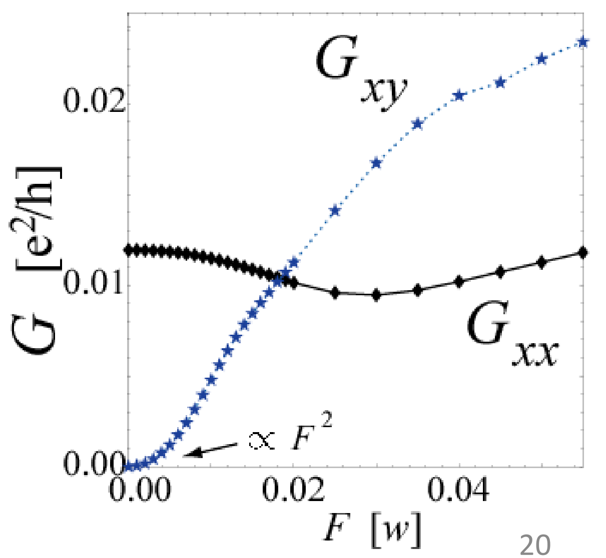


Photo-induced Hall conductivity

$$J_y = G_{xy} V$$

$$G_{xy} \propto F^2$$

Experimentally observable!

Difference between the Floquet state in CM and the Volkov state

Electrons + circularly polarized light

Condensed matter

gapped Dirac system

Quantum Hall state

TO, H. Aoki (2009)

High energy

Volkov's solution

$$\Psi_{p,r}(x) = \sqrt{\frac{m}{QV}} \sum_{s=-\infty}^{\infty} \left[J_s(\bar{\alpha})\, e^{is\varphi} + \frac{e\,\hat{\varkappa}\,\hat{a}_1}{2\varkappa\cdot p} J_s^{+}(\bar{\alpha},\varphi) + \frac{e\,\hat{\varkappa}\,\hat{a}_2}{2\varkappa\cdot p} J_s^{-}(\bar{\alpha},\varphi) \right] u_r(p)\, e^{-i(q-s\varkappa)\cdot x}.$$

D. M. Volkov, Z. Phys. **94**, 250 1935

The two are different: in graphene,
speed of massless fermion ~1/300 c << c

momentum of light $l^{\mu} = (1, 0, 0, \cancel{1})$

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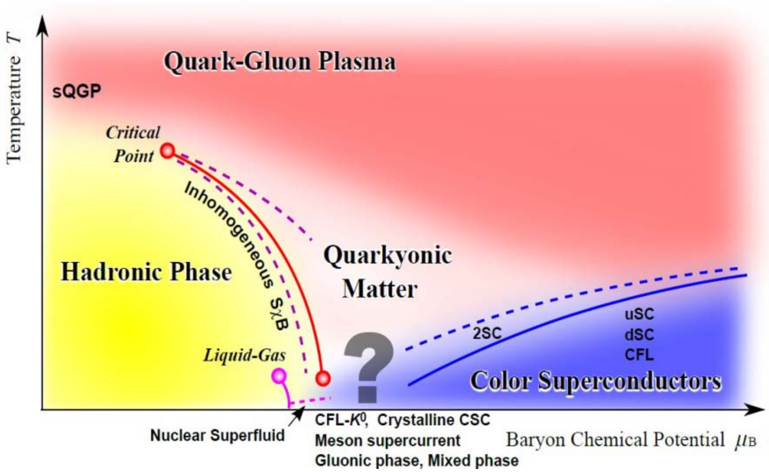
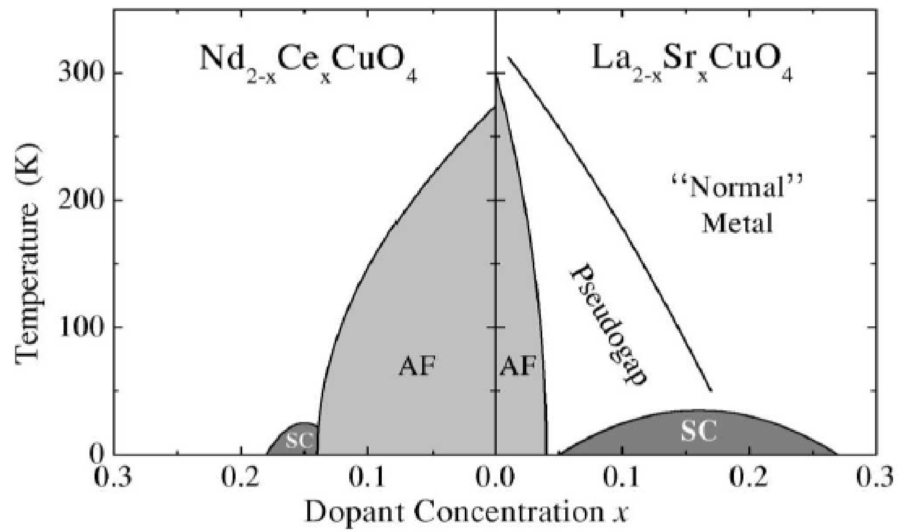
Mott insulator

proposed QCD phase diagram



from Fukushima-Hatsuda (2010)
(early version Hatsuda-Kunihiro ('94))

High Tc superconductor



Hadronic phase

confinement

chiral symmetry breaking

Strongly correlated insulator

Mott state

anti-ferromagnetic order

Nambu-Jona Lasinio (NJL) model

$$\mathcal{L} = \bar{q} i \gamma \cdot \partial q + g/2[(\bar{q}q)^2 + (\bar{q} i \gamma_5 \boldsymbol{\tau} q)^2].$$

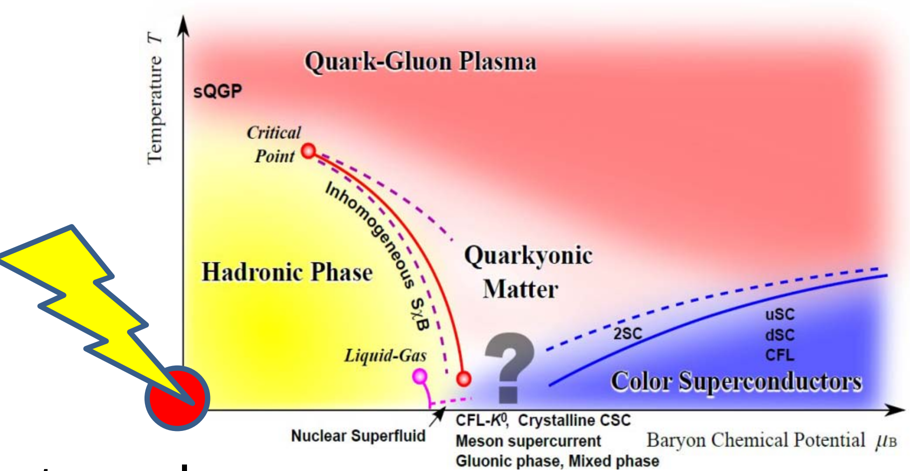
Hubbard model

$$H = -t \sum_{\langle ij \rangle} \left(c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

$$n_i \uparrow = c^\dagger_{i\uparrow} c_{i\uparrow}$$

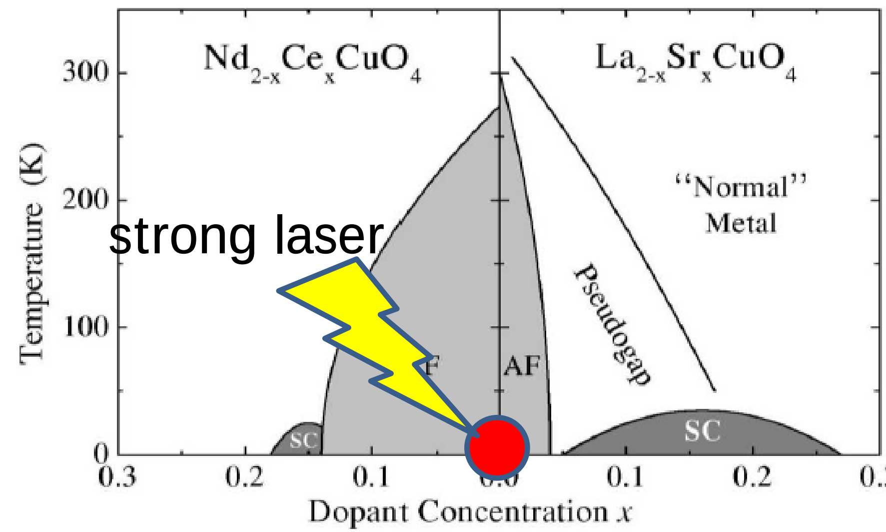
Strong field physics in strongly correlated systems

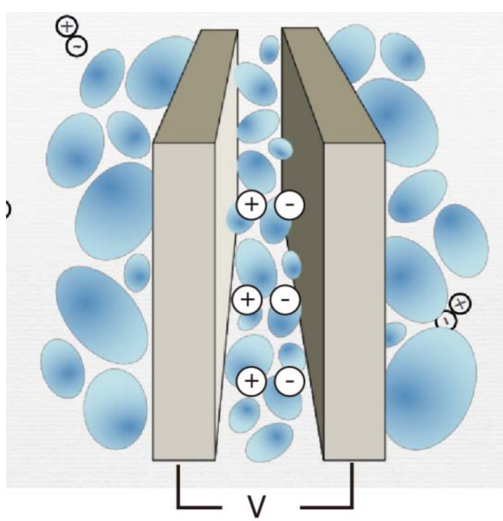
proposed QCD phase diagram



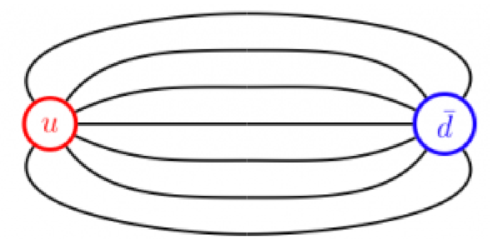
strong laser

High Tc superconductor





Pair creation of charge from the vacuum by quantum tunneling confinement



(color) electric fields

creation of quarks, gluons

QCD: nightmare problem

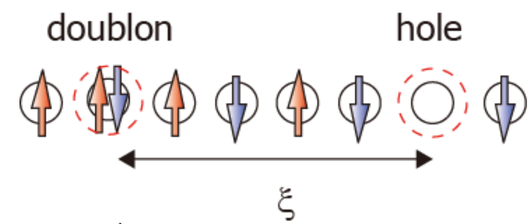
effective model

Tanji 2008 (refs. to older paper), Tanji-Itakura 2011

cf) Heisenberg-Euler 1936, Weiskopf 1936
Schwinger 1951

Mott insulator

(single particle charge excitation exists)



$$\langle d_x^\dagger h_0 \rangle = \exp(-x/\xi)$$

electric fields

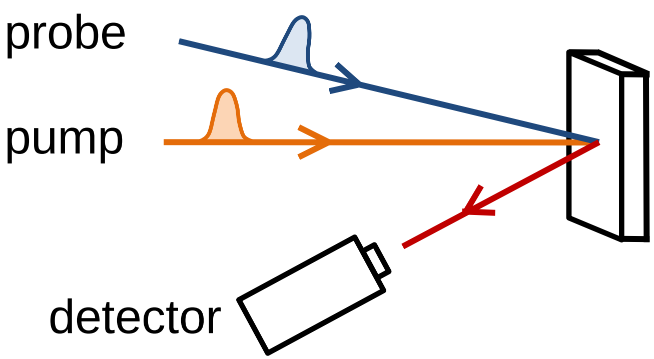
creation of doublons and holes

1d Hubbard model

analytic calculation possible

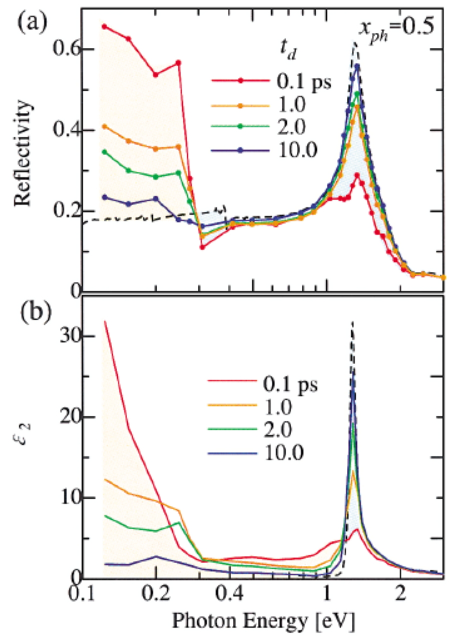
Oka Aoki 2010, Oka 2011

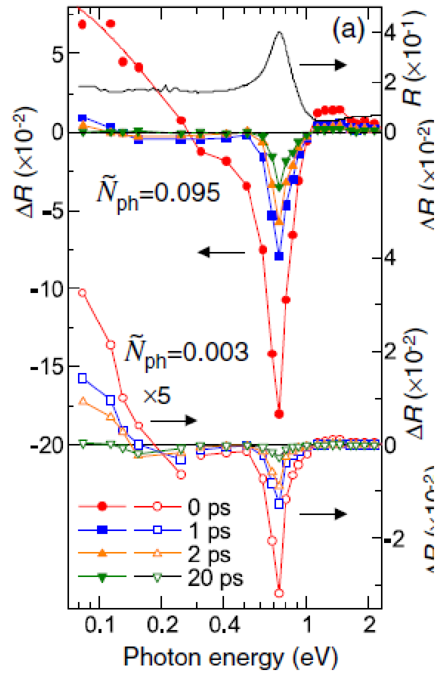
Experiments in CM: photo-induced Mott transition



- time-dependent reflectivity

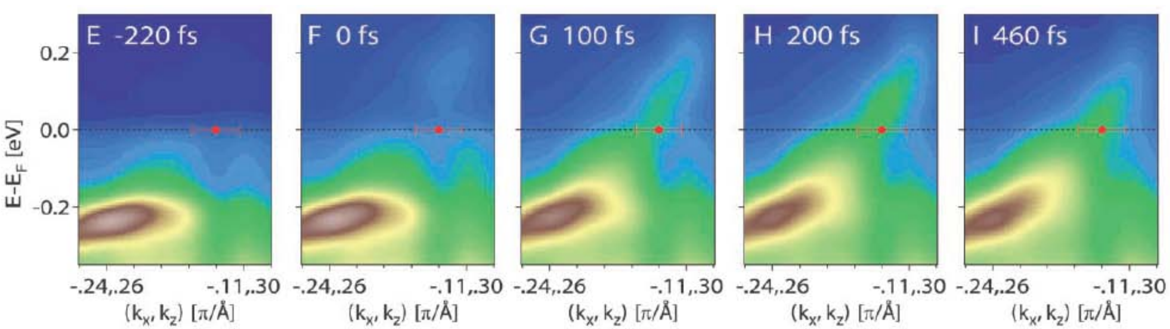
  $[Ni(chxn)_2Br]Br_2$ Iwai *et al.*, PRL '03.
  1D charge transfer Mott insulator.





$ET\text{-}F_2TCNQ$ Okamoto *et al.*, PRL '07.

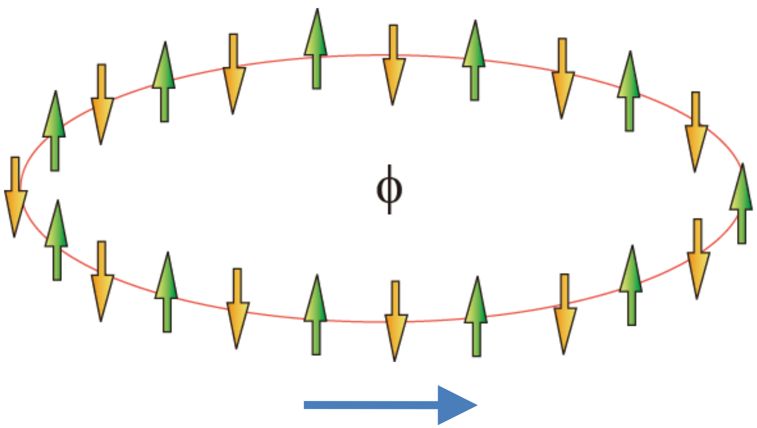
- time-dependent spectrum (PES/ARPES)



melting of order
Schmitt *et al.*, Science '08.

Nonlinear transport in the 1d Hubbard model

$$H(t) = -\sum_{i\sigma}\left[e^{i\phi(t)}c^\dagger_{i+1\sigma}c_{i\sigma} + e^{-i\phi(t)}c^\dagger_{i\sigma}c_{i+1\sigma}\right] + U\sum_i n_{i\uparrow}n_{i\downarrow}$$



electric field $F(t)$

1. Electric field via Faraday's law

$$F = -\frac{d}{dt}\phi(t) = F_0\cos\Omega t$$

2. Start from the groundstate at half-filling = Mott insulator

3. Closed system

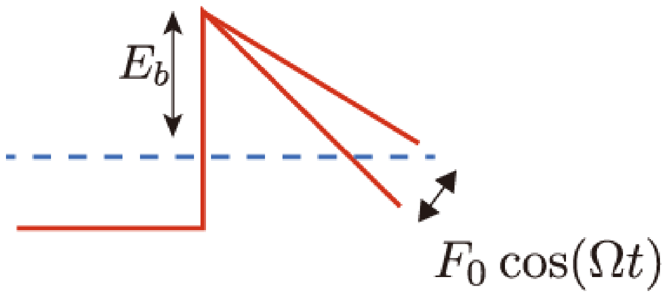
$$\frac{d}{dt}E(t) = JF$$

increase of energy by Joule heating

Quantum tunneling, multi-photon absorption and Keldysh crossover

Keldysh's theory (1964）

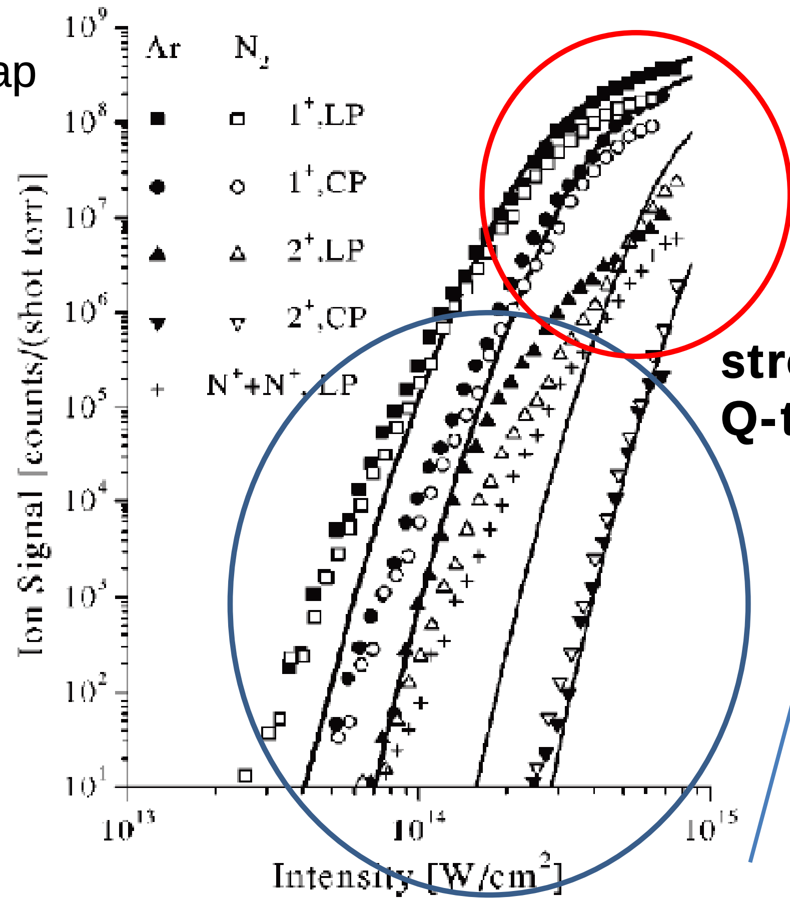
escape of a particle from a oscillating trap



1. atom ionization
2. carrier creation in semiconductors

atom ionization

G. Gibson et al. 1998



strong field：Q-tunneling

Keldysh crossover

weak field：multi-photon

Keldysh's theory (1964)

⇩

extension to infinite degrees of freedom

1. QED

Brezin-Itzykson 1970, Popov 1971

electron-positron creation by laser

2. Doublon-hole excitation in a Mott insulator

TO, Aoki 2010, TO arXiv:1105.3145

Key

1. Calculation of the tunneling probability

Landau-Dykhne's method (Popov 1971)

2. Decomposition by good a quantum number

Bethe ansatz

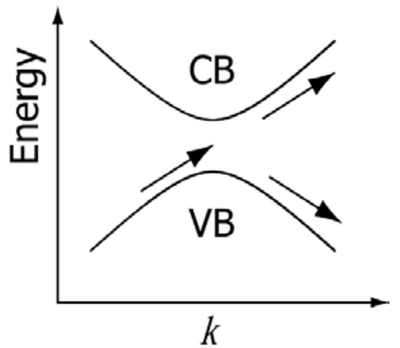
cf) Callan-Coleman: WKB + mode expansion

Landau-Dykhne theory (imaginary time method)

Dykhne JETP (1962), Daviis, Pechukas, J.Chem.Phys. (1976)

Landau-Lifshitz *Quantum mechanics*

WKB for a matrix tunneling problem



$$H(t) = \begin{pmatrix} A(t) & B(t) \\ C(t) & D(t) \end{pmatrix}$$

1. Use complex time

2. Find the singular point

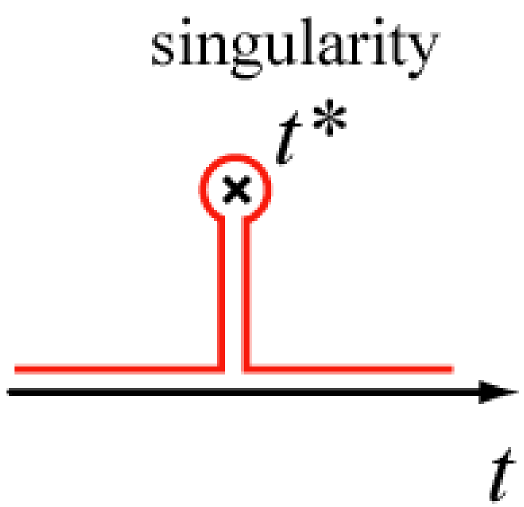
$$E_2(t^*) = E_1(t^*)$$

3. Tunneling probability

$$p = \exp\left(-2\mathrm{Im}S_{1,2}/\hbar\right)$$

$$S_{1,2} = \int_{t_0}^{t^*} dt'[E_2(\Phi(t')) - E_1(\Phi(t'))]$$

imaginary part of the dynamical phase

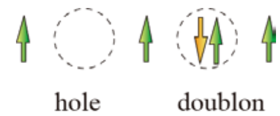


generalization of the Landau-Zener formula

Bethe ansatz of the 1d Hubbard model

doublon-hole exciation
(holon-antiholon;string state)

$|0\rangle$ "$d^\dagger(p)h^\dagger(p)|0\rangle$"

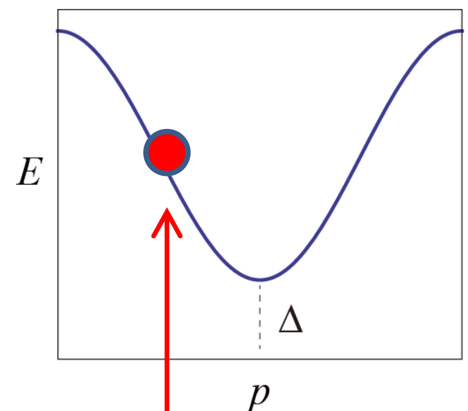


"$d^\dagger(p_1)d^\dagger(p_2)h^\dagger(p_3)h^\dagger(p_4)|0\rangle$"

we neglect these contributions

two level problem

Spectrum of d-h pairs



$$E = \varepsilon_h(p) + \varepsilon_{\overline{h}}(p)$$

We want to calculate the tunneling probability $\mathcal{P}_p$

Landau-Dykhne theory + Bethe ansatz

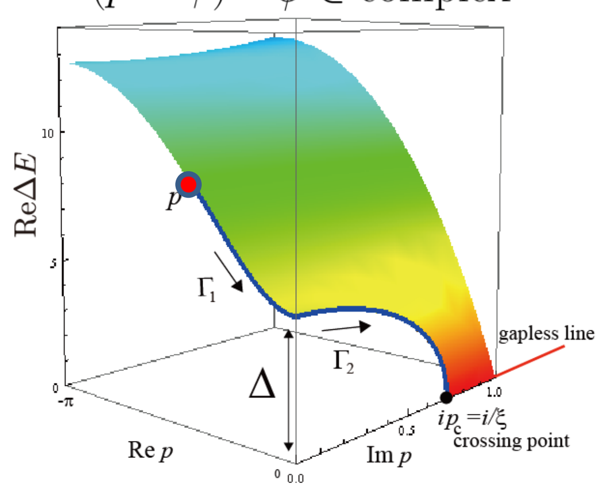
momentum-resolve dh-pair creation rate

$$\mathcal{P}_p = \exp\left(-2\mathrm{Im}\int_\Gamma \Delta E(p-\Phi)\frac{-1}{F(\Phi)}d\Phi\right)$$

ΔE: d-h energy, Γ: complex path, F: Jacobian   TO arXiv:1105.3145

complex momentum

$\Delta E(p-\phi)$ $\phi \in$ complex

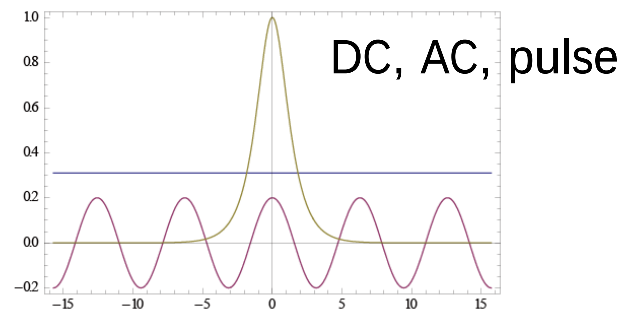


U=8

$$\varepsilon_h(k) = U/2 + 2\cos k + 2\int_0^\infty \frac{d\omega}{\omega}\frac{J_1(\omega)\cos(\omega\sin k)e^{-U\omega/4}}{\cosh(\omega U/4)}$$

$$p_h(k) = \frac{\pi}{2} - k + 2\int_0^\infty \frac{d\omega}{\omega}\frac{J_0(\omega)\sin(\omega\sin(k))}{1+\exp(U\omega/2)}$$

electric field $F(t)$



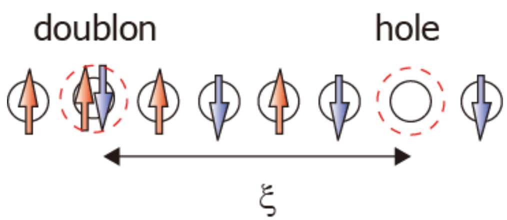
type	$F(t)$	$F(\Phi)$	attempt frequency f
DC-field	F_0	F_0	$F_0/2\pi$
AC-field	$F_0 \sin\Omega t$	$\pm\sqrt{F_0^2 - \Omega^2\Phi^2}$	Ω/π
single pulse	$F_0\cosh^{-2}(t/\sigma)$	$F_0\left(1 - \frac{\Phi^2}{\sigma^2 F_0^t}\right)$	1(single process)

DC fields $F(t)=F_0$

$$\mathcal{P}_p = \exp\left(-\pi \frac{F_{\rm th}}{F_0}\right)$$ no p dependence

tunneling threshold

$$F_{\rm th} \sim \Delta_{\rm Mott}/\xi$$ ξ: d-h pair size



Schwinger limit of QED is recovered if we replace

$$\Delta_{\rm Mott} \to 2m_e,\ \xi \to \text{Compton length}$$

$$F_{\rm Sch} = c^3 m_e^2/e\hbar \sim 10^{16}\text{V/cm}$$

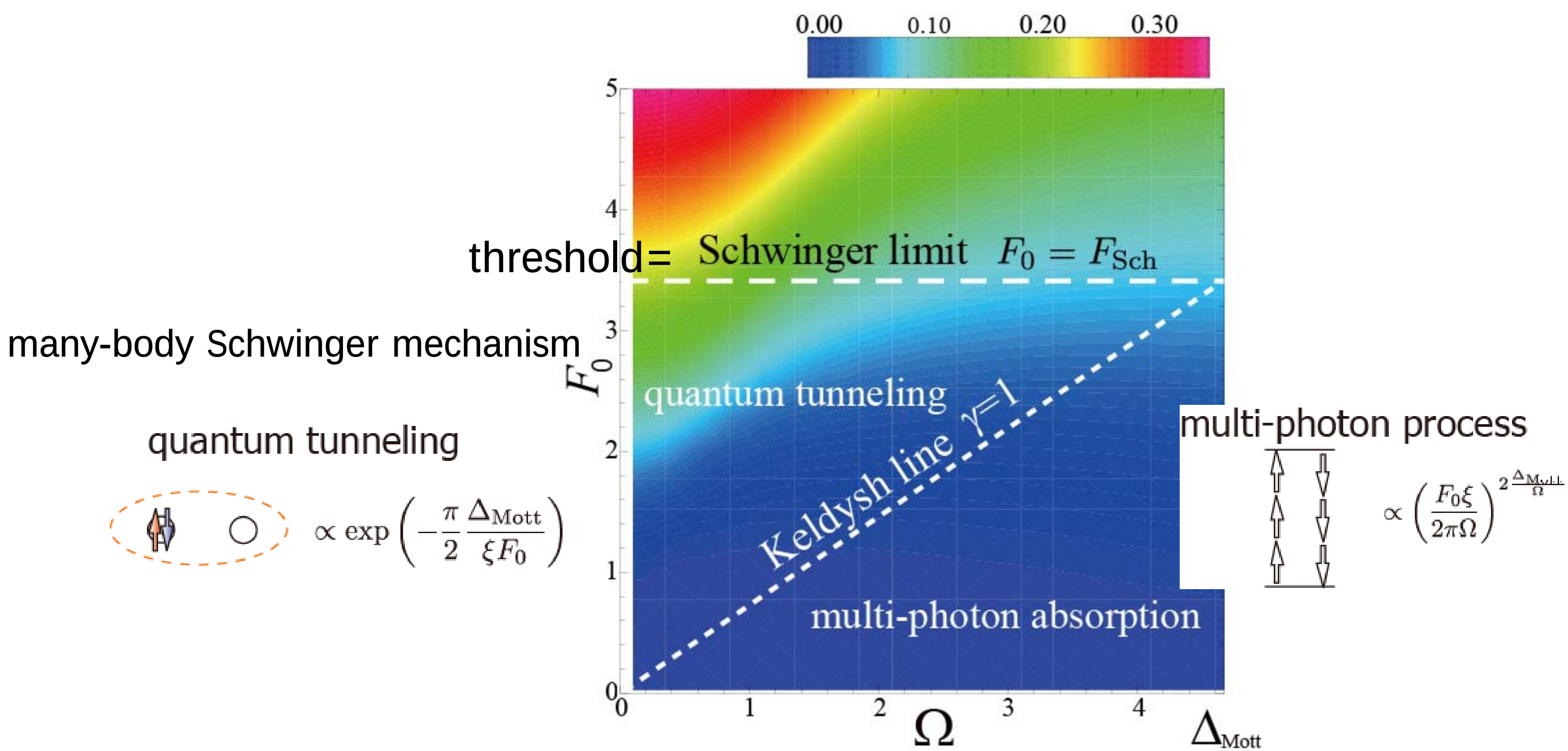
Estimate for 1d Mott insulators

	τ(eV)	U(eV)	a(Å)	$\Delta_{\rm Mott}$(eV)	$\xi(a)$	$E_{\rm th}$(MV/cm)
ET-F_2TCNQ	0.1	1	10	0.7	1.1	6.0
[Ni(cnxn)$_2$Br]Br_2	0.22	2.4	5	1.6	1.0	30
Sr_2CuO_3	0.52	3.1	4	1.5	2.1	18

AC-field: Keldysh crossover $F(t) = F_0 \cos(\Omega t)$

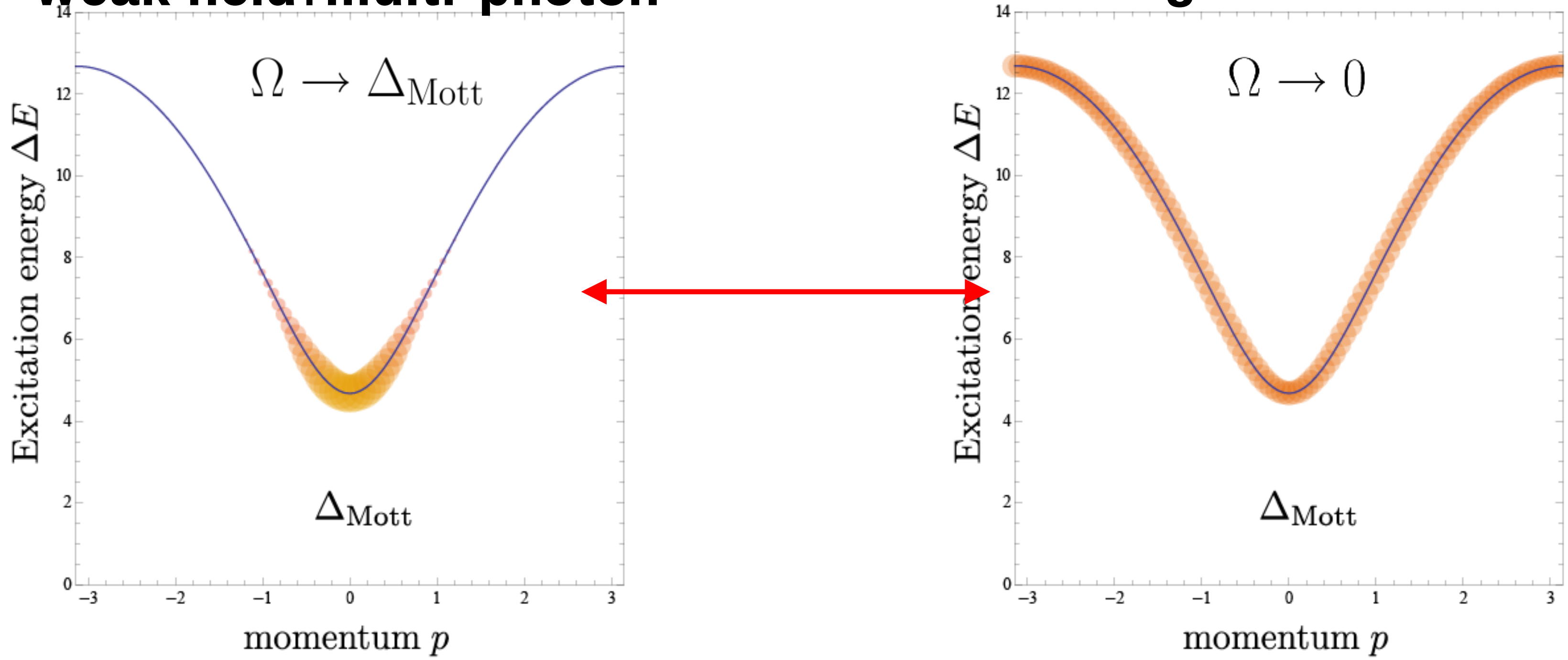
$$\mathcal{P}_{p=0} \rightarrow \begin{cases} \left(\frac{F_0 \xi}{b\Omega}\right)^{2\frac{\Delta_{\mathrm{Mott}}}{\Omega}} & \gamma \gg 1, \quad \text{mulit-photon} \\ \exp\left(-\frac{\pi}{2}\frac{\Delta_{\mathrm{Mott}}}{\xi F_0}\left(1 - \frac{\pi}{16}\gamma^2 + \ldots\right)\right) & \gamma \ll 1, \quad \text{tunneling} \end{cases}$$

Keldysh parameter $\gamma = \Omega / \xi F_0$

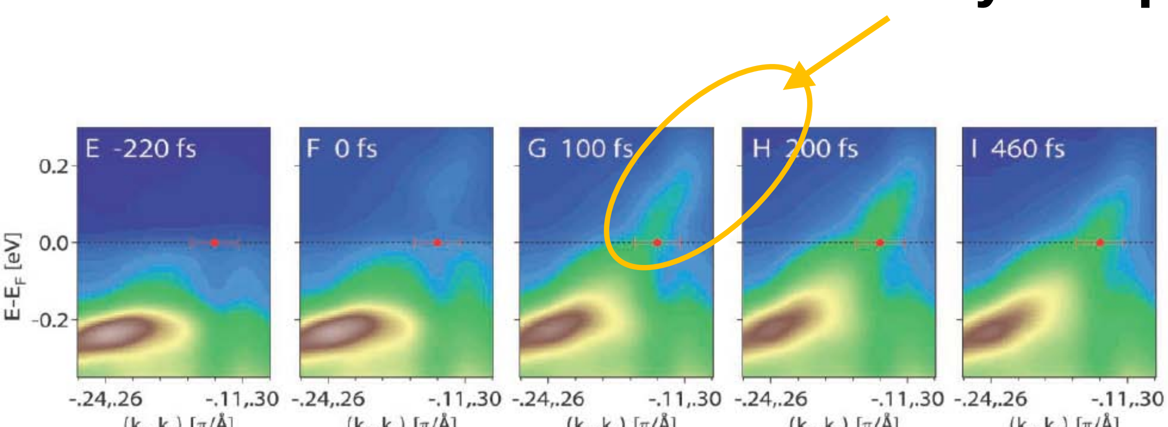


Crossover of the Creation rate

weak field: multi-photon **strong field: tunneling**



Can be seen by THz pump-probe experiments



$TbTe_3$

Schmitt *et al.*, Science '08.

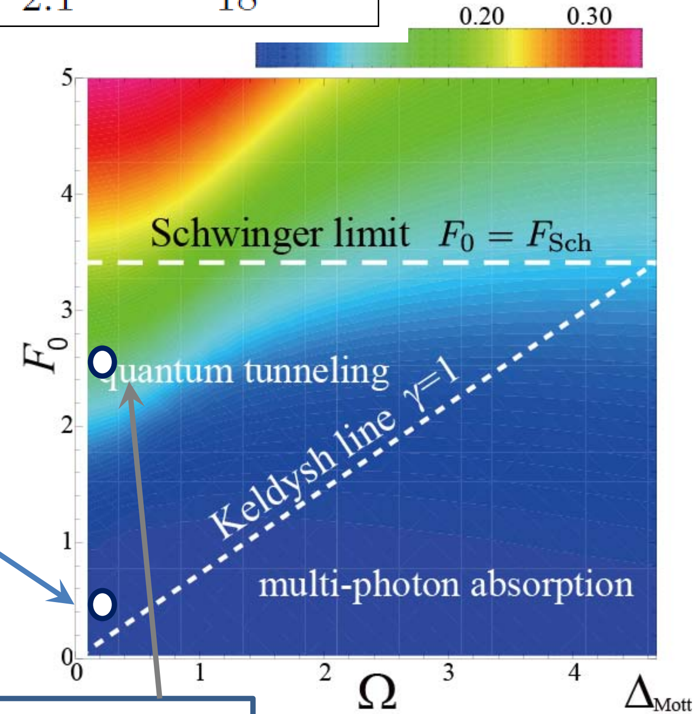
Possible experiments

	τ(eV)	U(eV)	a(Å)	Δ_{Mott}(eV)	$\xi(a)$	F_{th}(MeV/cm)
ET-F_2TCNQ	0.1	1	10	0.7	1.1	6.0
[Ni(cnxn)$_2$Br]Br$_2$	0.22	2.4	5	1.6	1.0	30
Sr_2CuO_3	0.52	3.1	4	1.5	2.1	18

ET-F_2TCNQ dh-distance $\xi \sim 10$ Å

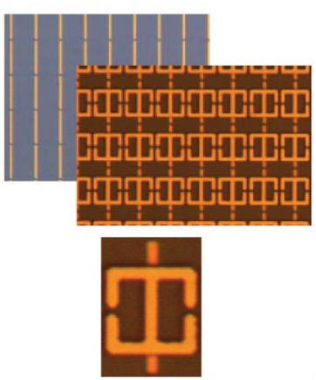
1. crossover field (=Ω/ξ) ~ 0.04 MV/cm

2. threshold ~ 6 MV/cm



THz laser (4 meV) maximum strength>0.7MV/cm

Watanabe, Minami, Shimano, Optics Express 2011



THz laser ＋ meta-material

maximum strength > **4MV/cm**

K. Nelson, R. Averitt et al. (APS March meeting2012)

$$P = e^{-\pi \frac{F_{\mathrm{th}}}{F}} \sim e^{-\pi \frac{6}{4}} \sim 0.01$$

Summary / Perspectives

Simple ideas

1. Photo-induced Quantum Hall state
2. Many-body Schwinger mechanism

interesting outcome

S. Nakamura "Negative Differential Resistivity from Horography" 2010

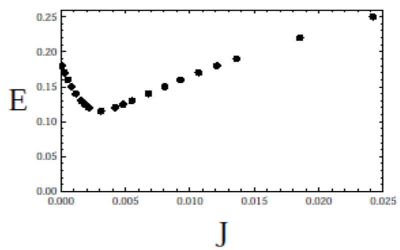
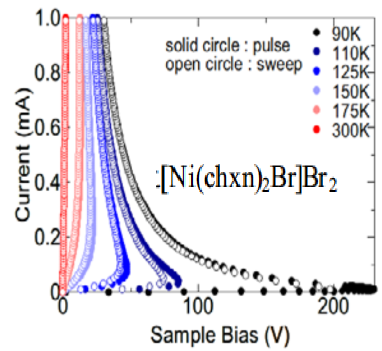
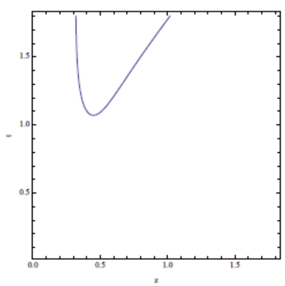


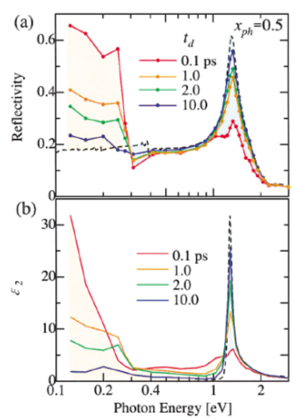
FIG. 2. J-E curve at $m_q = 1.315$. $E_c = 0.11$ in this case. NDR appears in $J \leq 0.0031$, and is absent for $E \geq 0.19$.



H. Kishida, *et al.* J. Appl. Phys. **106**, 016106 (2009);

K. Hashimoto, N. Iizuka, T. Oka "Rapid Thermalization by Baryon Injection in Gauge/Gravity Duality" 2010





apparent horizon ~ metallization

Thank you