固体電子中の強電場物理 --- 多体Schwinger機構、光誘起ホール効果

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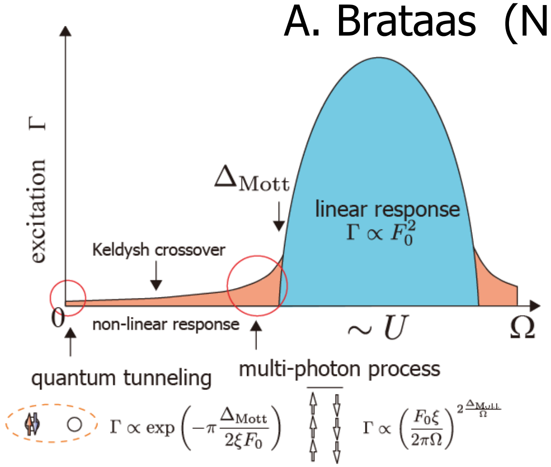
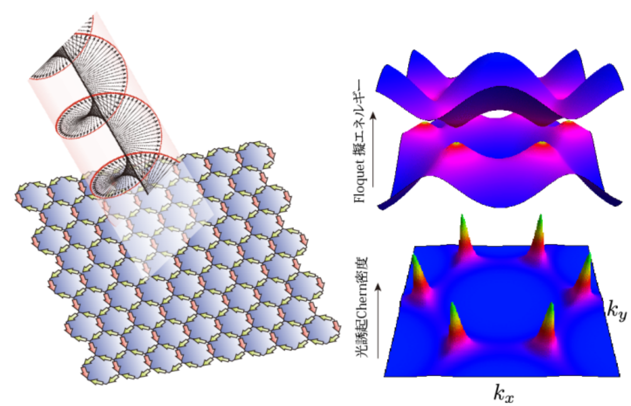


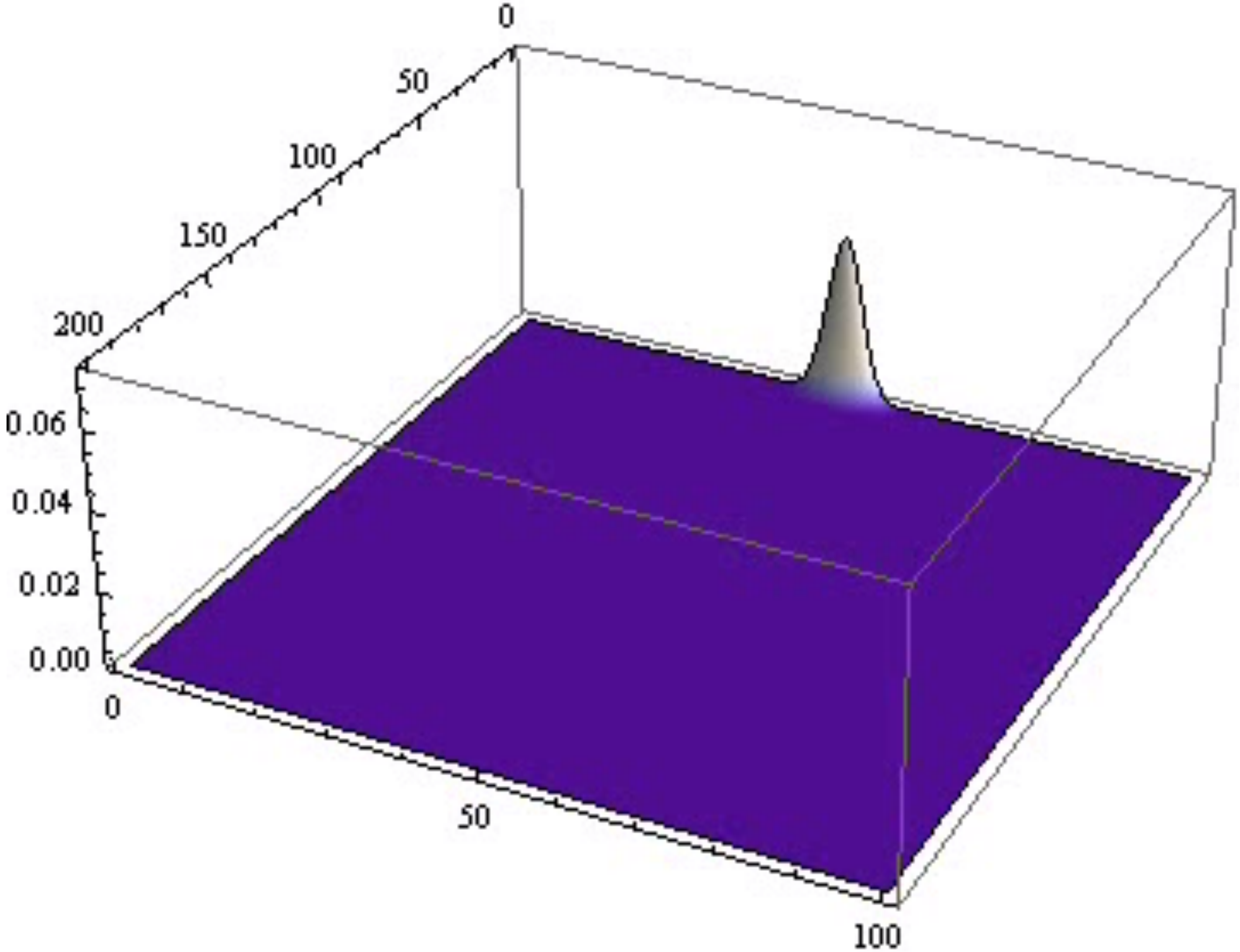


解説:
岡、青木、日本物理学会2012出版予定「強相関系の非平衡現象」
岡、北川、固体物理2011, 11月号「光誘起トポロジカル相転移の理論--Floquet描像の立場から--」
Aoki, TO, Tsuji, Eckstein, Werner RMP in prep.

2+1d Dirac equation

$$\mathcal{L} = \bar{\psi} i \gamma_\mu \partial^\mu \psi$$

wave packet dynamics, with a boundary

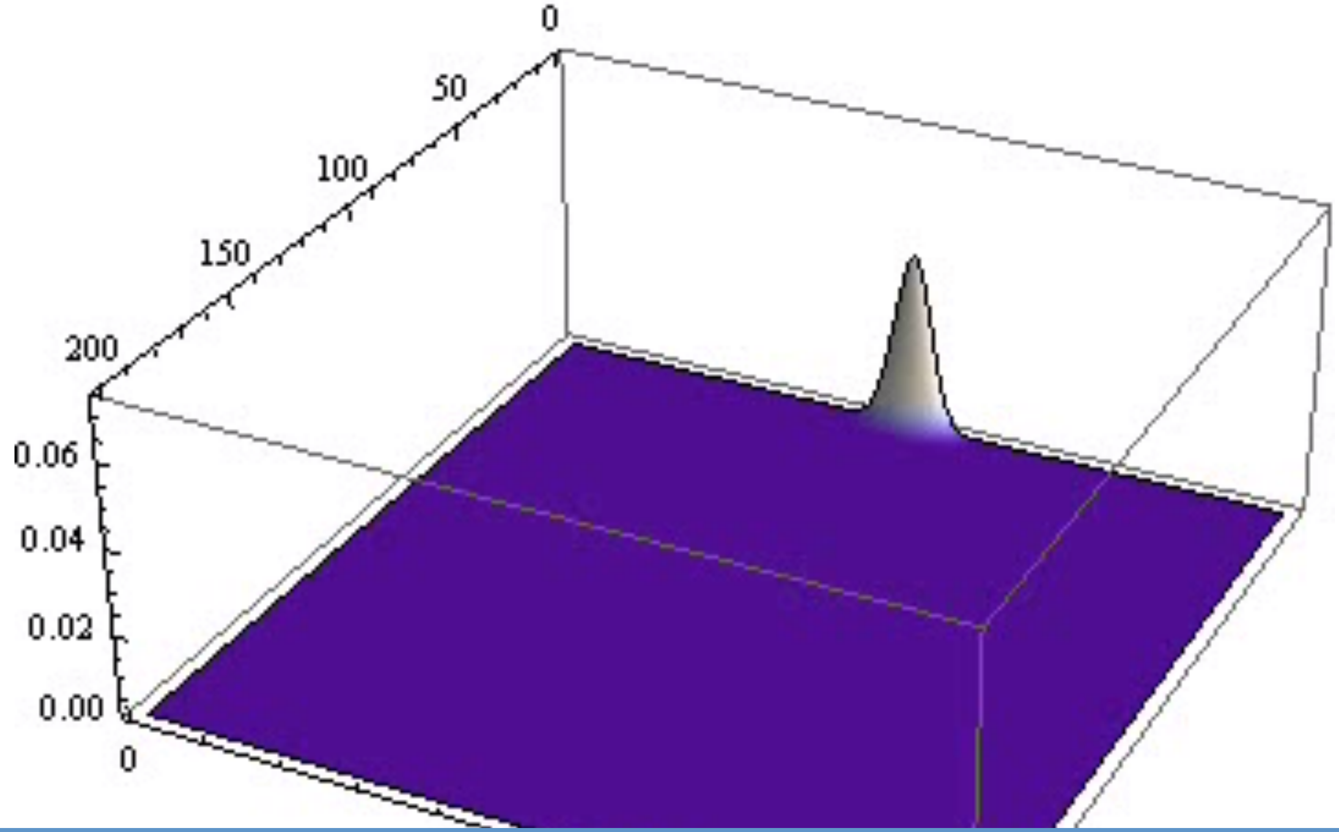


calculation is done in graphene (honeycomb lattice)

2+1d Dirac equation + circularly polarized light

$$\mathcal{L} = \bar{\psi}\gamma_\mu(i\partial^\mu - A^\mu(t))\psi$$

$$A^\mu = (0, \frac{F}{\Omega}\cos\Omega t, \frac{F}{\Omega}\sin\Omega t)$$



Aim of Strong field physics
= "**Control**" of Quantum states

1. Introduction

1.1 Condensed matter VS Hadron Physics

Mott transition ⟷ confinement

topological phase transition ⟷ quantum anomaly

1.2 (Old, New) Strong field physics

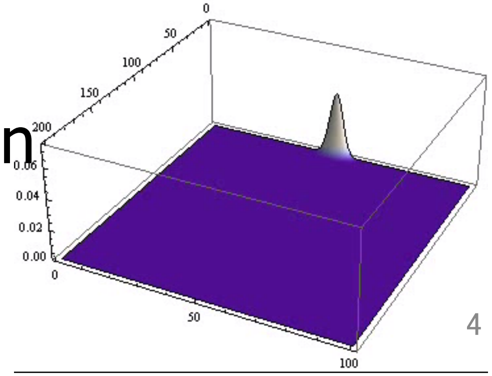
1.3 Numerical methods for non-equilibrium

2. Many-body Schwinger mechanism

Nonlinear transport/Photo-induced Mott transition

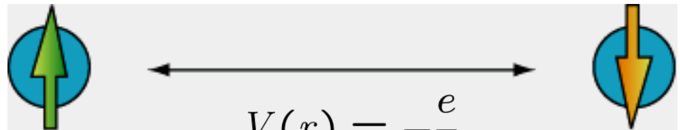
3. Photo-induced Hall effect

Floquet topological phase transition



Introduction： Strongly Correlated Electron Systems

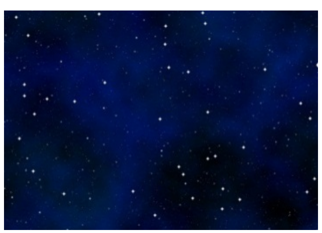
What are strongly correlated electrons?



$$V(r) = -\frac{e}{r}$$

Strong effects of Coulomb interaction

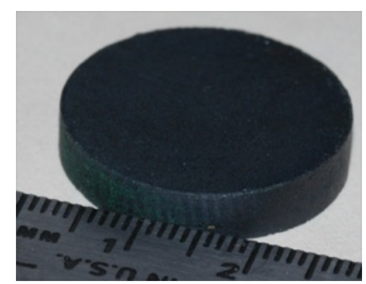
space



plasma

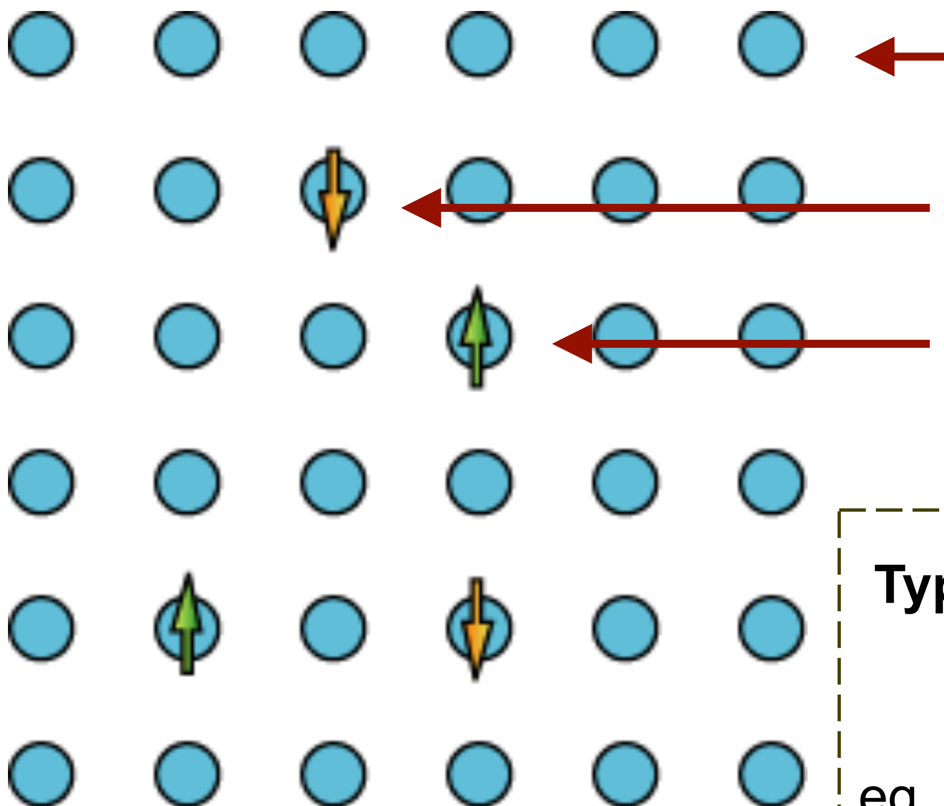
semiconductor

strongly correlated material



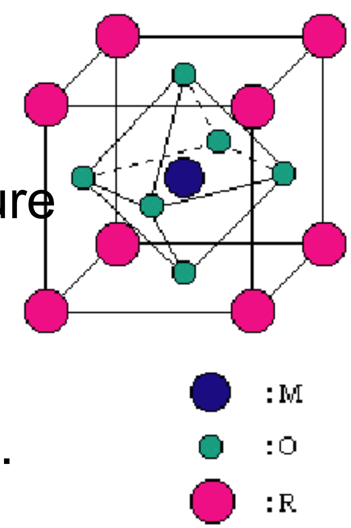
density of electrons **large**

Basic degrees of freedom



Typical structure

eg. perovskite structure
of manganite oxides

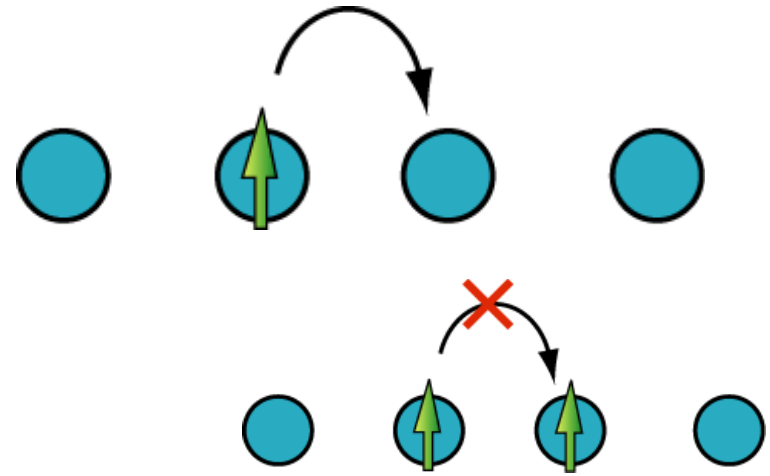


The electrons exist
on the R-atom =site.

Basic rules

1. Hopping between lattice sites

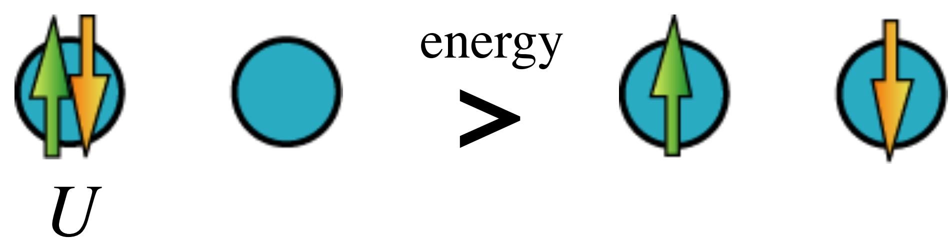
$$-t\sum_{ij}\left(c^{\dagger}_{i\sigma}c_{j\sigma}+\text{h.c.}\right)$$



Fermi statistics: Pauli principle

2. On-site Coulomb interaction

$$U\sum_{i}n_{i\uparrow}n_{i\downarrow}$$



Hubbard Hamiltonian:

minimum model of strongly correlated electron system.

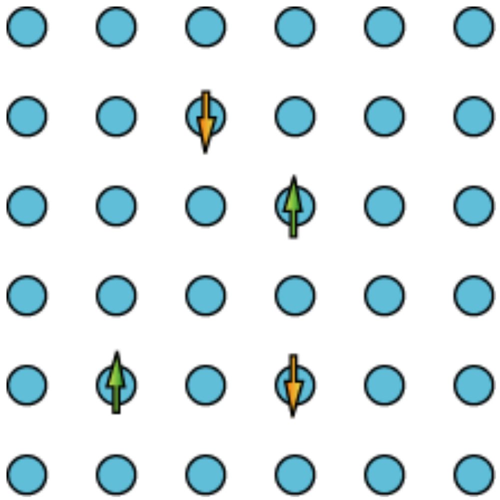
$$H=-t\sum_{\langle ij\rangle}\left(c^{\dagger}_{i\sigma}c_{j\sigma}+\text{h.c.}\right)+U\sum_{i}n_{i\uparrow}n_{i\downarrow}$$

Other parameters

3. Band filling

n **=フィリング(filling)**

= number of electrons per lattice site



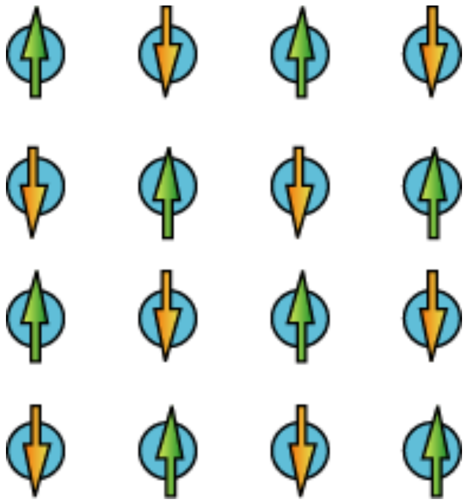
4. Temperature

typical temp. range: T = 0.1-1 eV = 1000-10000K

Magic filling

When the filling takes certain values, the groundstate show non-trivial orders.

$n = 1$ (half-filling)

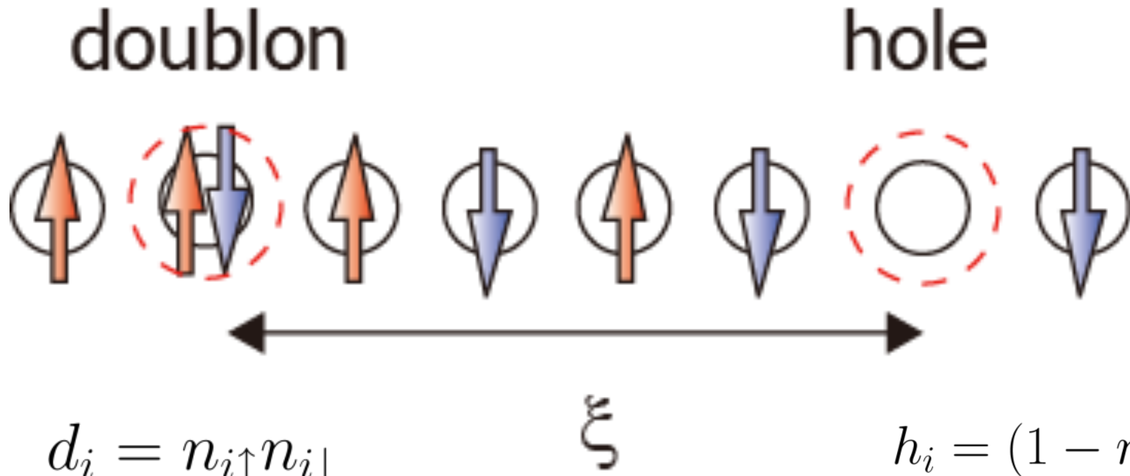


Mott Insulator

1. **Insulator:**
   no free carriers

2. **Anti-ferromagnetic order**

Doublon-hole “confinement”



$d_i = n_{i\uparrow} n_{i\downarrow}$

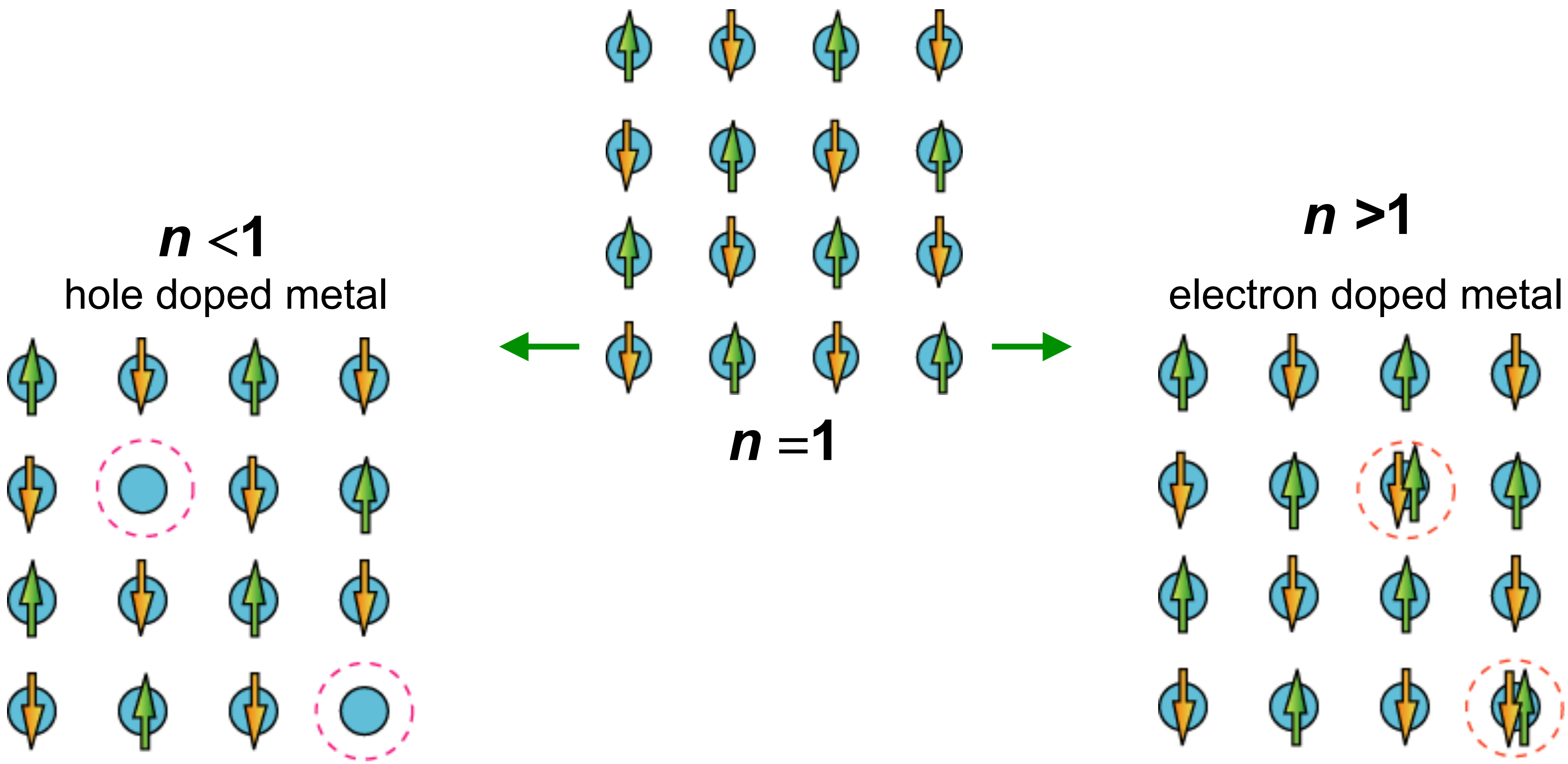
$h_i = (1 - n_{i\uparrow})(1 - n_{i\downarrow})$

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

ξ: correlation length

doublons and holes are bound to each other

Metal-insulator transition due to doping



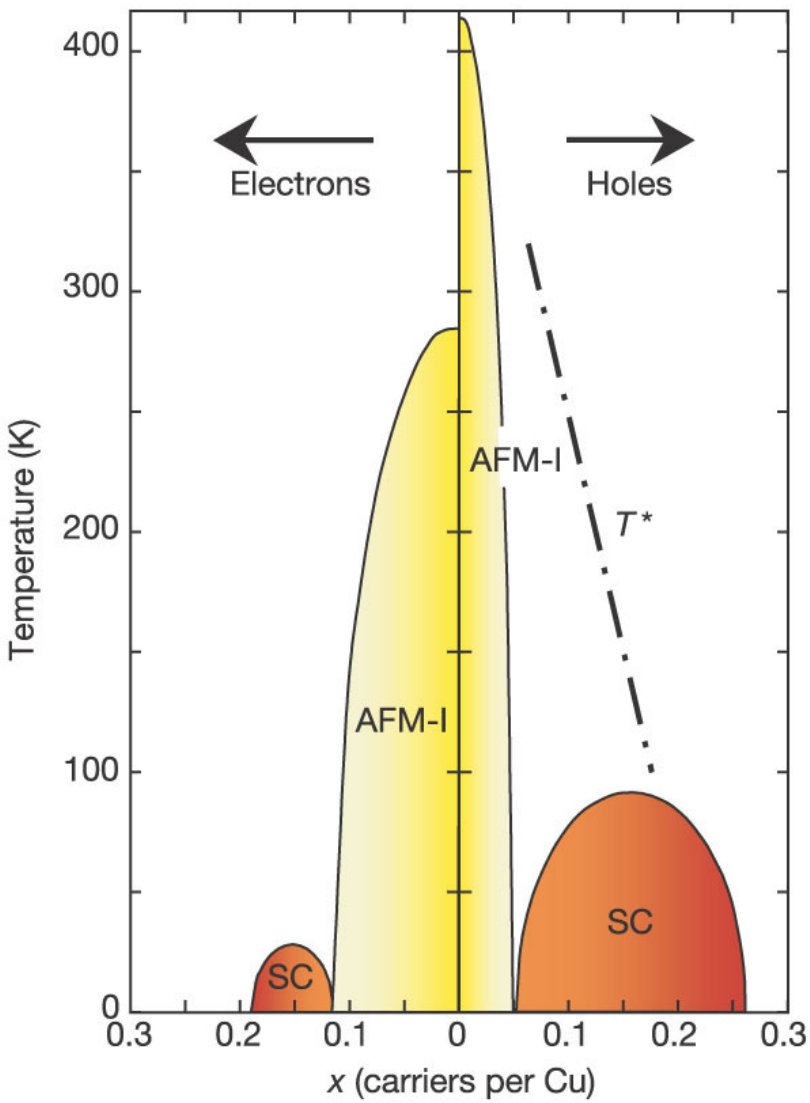
carrier = hole

$$h_i = \langle (1 - n_{i\uparrow})(1 - n_{i\downarrow}) \rangle \neq 0$$

carrier = double occupied state (doublon)

$$d_i = \langle n_{i\uparrow} n_{i\downarrow} \rangle \neq 0$$

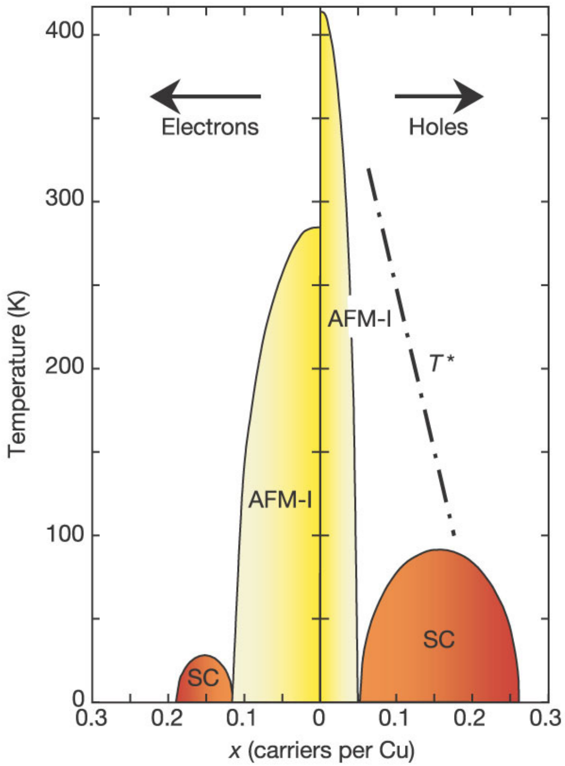
Equilibrium phase diagram

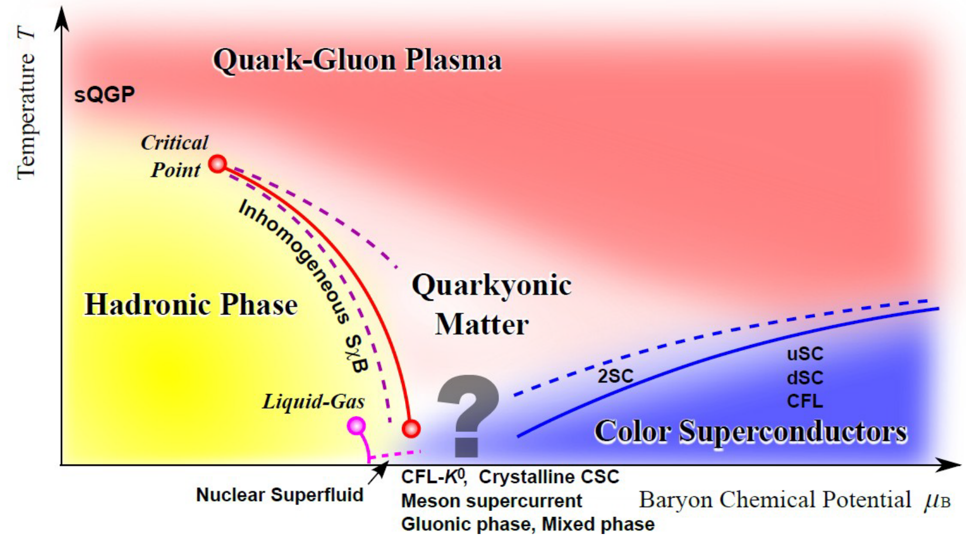


Phase diagram of copper oxides (2 dim material)

1. **AFM = Mott insulator with anti-ferromagnetic order**
2. **Metal-insulator transition due to doping**
3. **Superconductivity (SC) near the Mott insulator phase**

Condensed matter VS Hadron Physics





from Fukushima-Hatsuda (2010)

Hatsuda-Kunihiro ('94)

electron+Coulomb interaction

Hubbard model

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

QCD (quark-gluon)

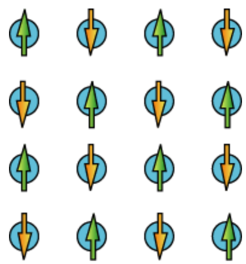
Nambu-Jona Lasinio (NJL) model

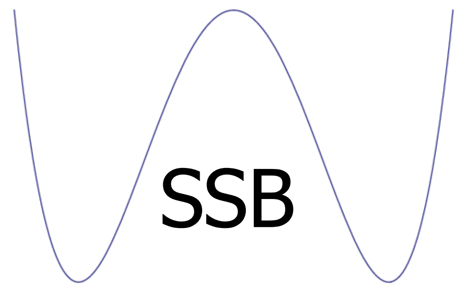
$$\mathcal{L} = \bar{q} i \gamma \cdot \partial q + g/2[(\bar{q}q)^2 + (\bar{q} i \gamma_5 \boldsymbol{\tau} q)^2].$$

Condensed matter VS Hadron Physics 2

magnetic phase transition

chiral phase transition



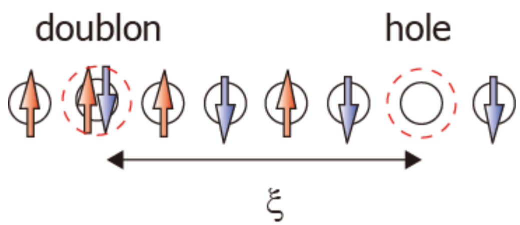


$$\langle \bar{q}q \rangle \neq 0$$

$$M = \sum_i \langle (-1)^i s_{iz} \rangle$$

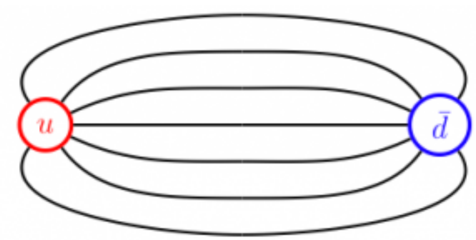
Mott transition

confinement



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

No Mean Field!



- Mott transition w/o magnetic phase transition is possible (1d Hubbard)
- confinement w/o chiral phase transition is possible (e.g., 1+1d QED)

(old) Strong field physics

1935 Volkov

sol. of Dirac equation in electro-magnetic fields

1936 Heisenberg Euler

Effective Lagrangian for static fields
vacuum instability (electron-positron pair creation)

1951 Schwinger

Heisenberg-Euler's result by path integral

Schwinger mechanism = vacuum instability (electron-positron pair creation)
Schwinger limit = threshold for e-p pair creation

1965 Keldysh

tunneling problem in time-periodic potential

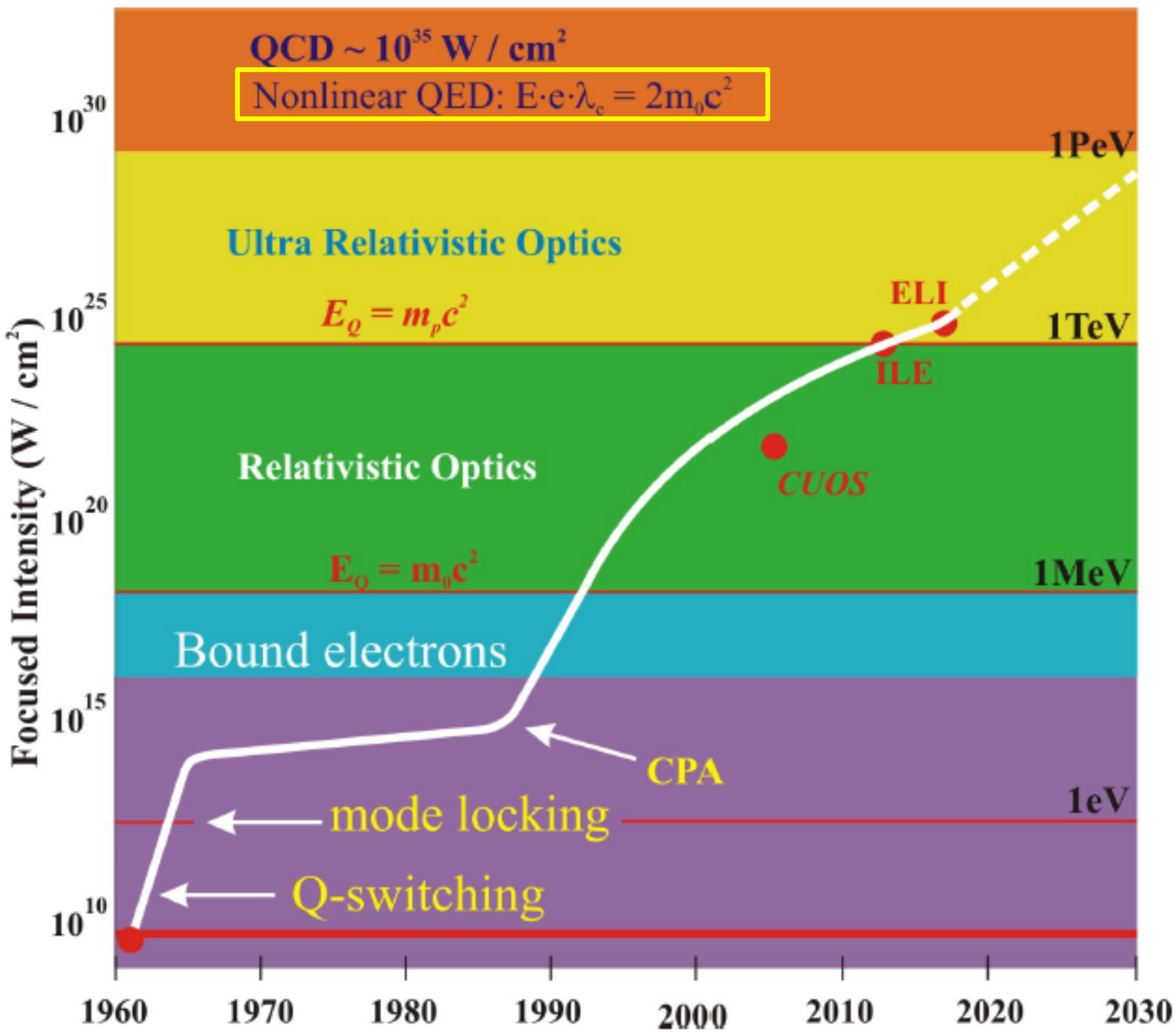
1970 Brezin Itzykson

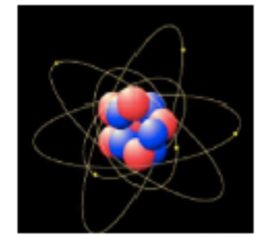
1972, 1974 V.S. Popov

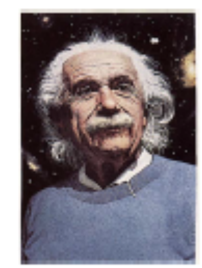
Schwinger mechanism in time-periodic potential

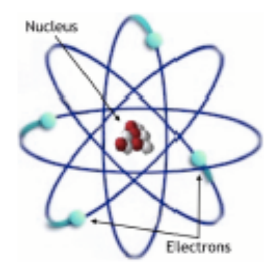
Keldysh, Brezin-Itzykson, Popovの仕事はPIF2010でDunneさんに教えてもらいました。

Laser elementary particle physics









From a talk at PIF2010 by
Gerard A. Mourou (Institut de Lumiere Extreme, ILE) Physics Today 51 (1998)

NEW Strong field physics

Strong correlation/interaction

Non-linear doublon-hole excitation in Mott insulators

RHIC

Gauge/gravity duality (S. Nakamura's talk)

Topology (quantum anomaly)

Photo-induced topological phase transition

Control of phase transitions by light

New Strong field physics

1935 Volkov

↓

Oka Aoki PRB 2009
"photovoltaic Hall effect"
*This is a non-relativistic effect

1936 Heisenberg Euler

1951 Schwinger

↓

Oka, Aoki PRL 2003, 2005,PRB2011

1965 Keldysh

1970 Brezin Itzykson
1972, 1974 V.S. Popov

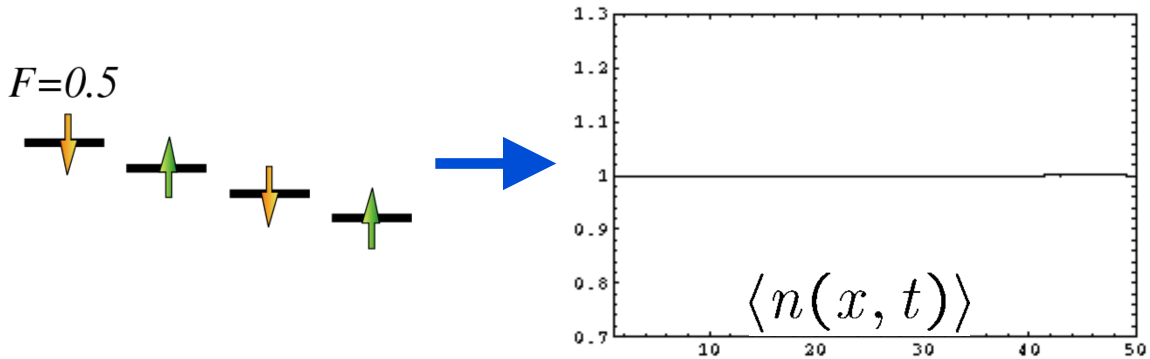
↓

Oka arXiv2011

Numerically exact methods to study real time dynamics

one dimension

Time-dependent density matrix renormalization group (Feiguin, White 2004)



TO, Aoki 2005

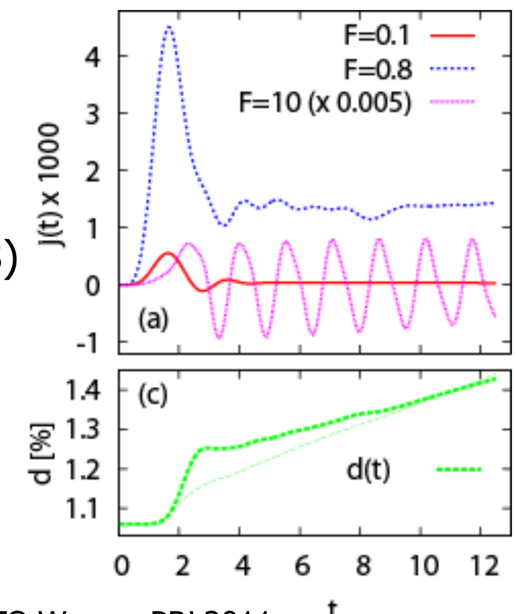
infinite dimension

Non-equilibrium dynamical mean field theory
(Freericks 2008, Eckstein,TO,Werner 2011)

real time diagramatic QMC (Werner, TO, Millis 2008)

$$\Sigma(k;t,t') \to \Sigma(0;t,t')$$

Simplification of Feynman diagrams



Eckstein,TO,Werner PRL2011

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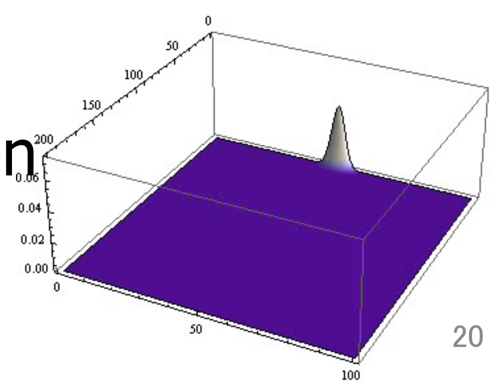
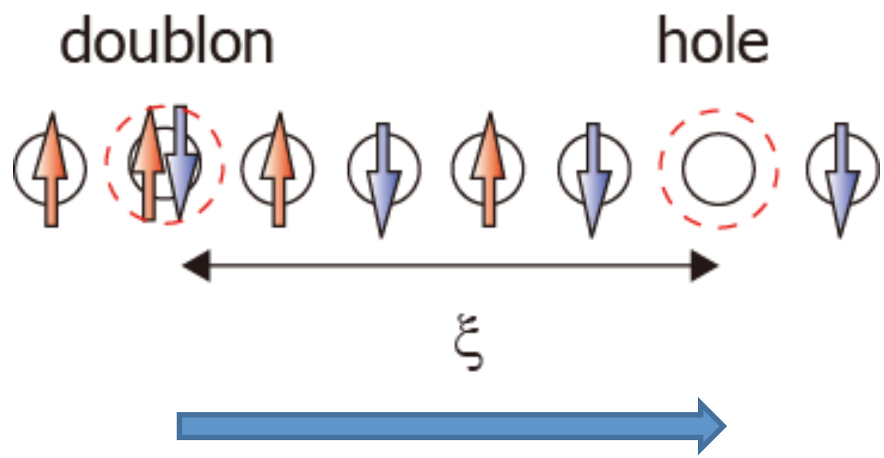
Floquet topological phase transition



Doublon-hole “de-confinement”

In strong electric fields, doublon-hole pair production leads to instability of the Mott phase



Electric field F

Many-body Schwinger mechanism

What let’s calculate the dh-pair production rate

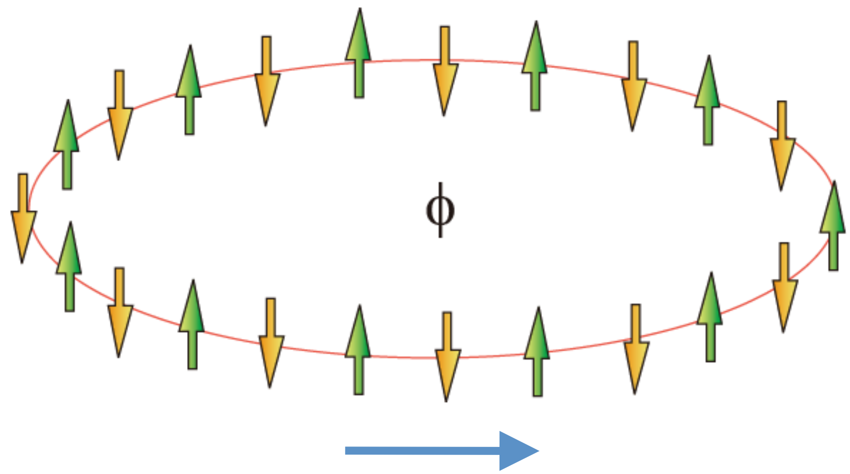
use the integrability of the 1dHubbard model

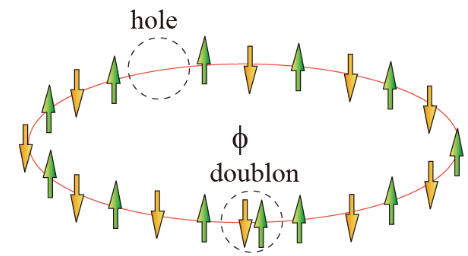
Electric fields applied to a Mott insulator

(1dim) TO, Aoki: PRL (2003), PRL(2005)
(DMFT) Eckstein, TO, Werner: PRL (2010)

half-filled Hubbard model (1-dim)

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





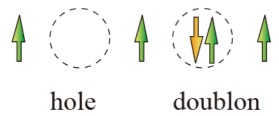
electric field F

$$F(t) = -\frac{d\Phi(t)}{dt}$$

Bethe ansatz solution in the 1d half-filled Hubbard model

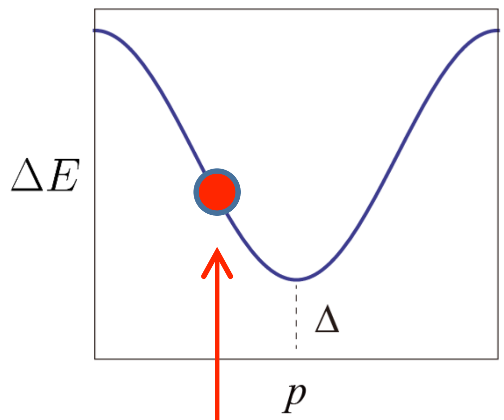
doublon-hole (holon-antiholon) excitations

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



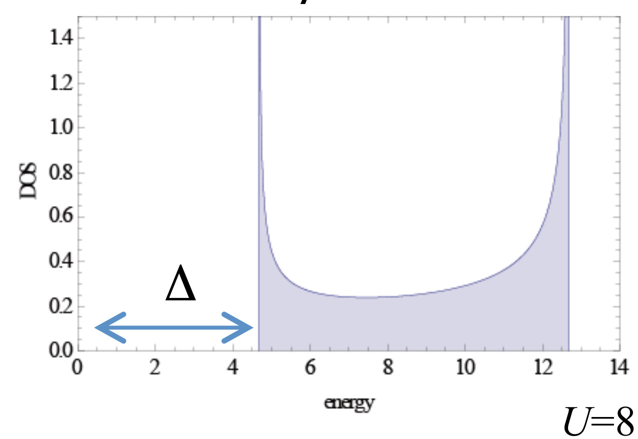
we neglect these contributions

spectrum of d-h pairs



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

Density of states



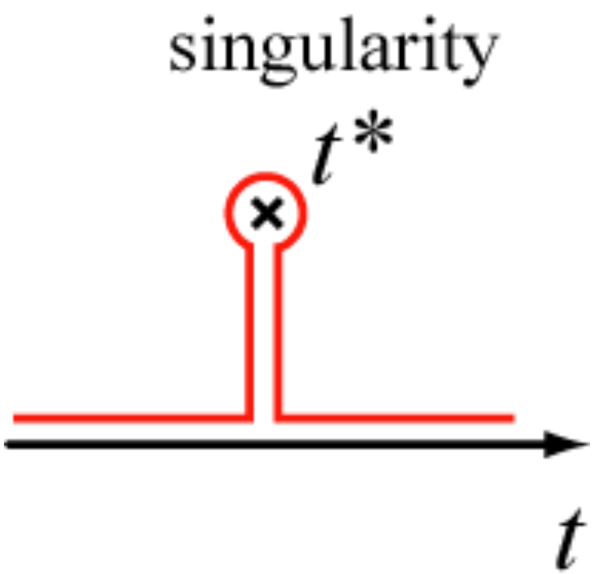
We want to calculate the tunneling probability $\mathcal{P}_p$

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

Landau-Dykhne theory of tunneling

Dykhne JETP (1962), Daviis, Pechukas, J.Chem.Phys. (1976)
Landau-Lifshitz *Quantum mechanics*

generalization of Landau-Zener formula



1. Use complex time
2. Find the singular point

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

3. Tunneling probability

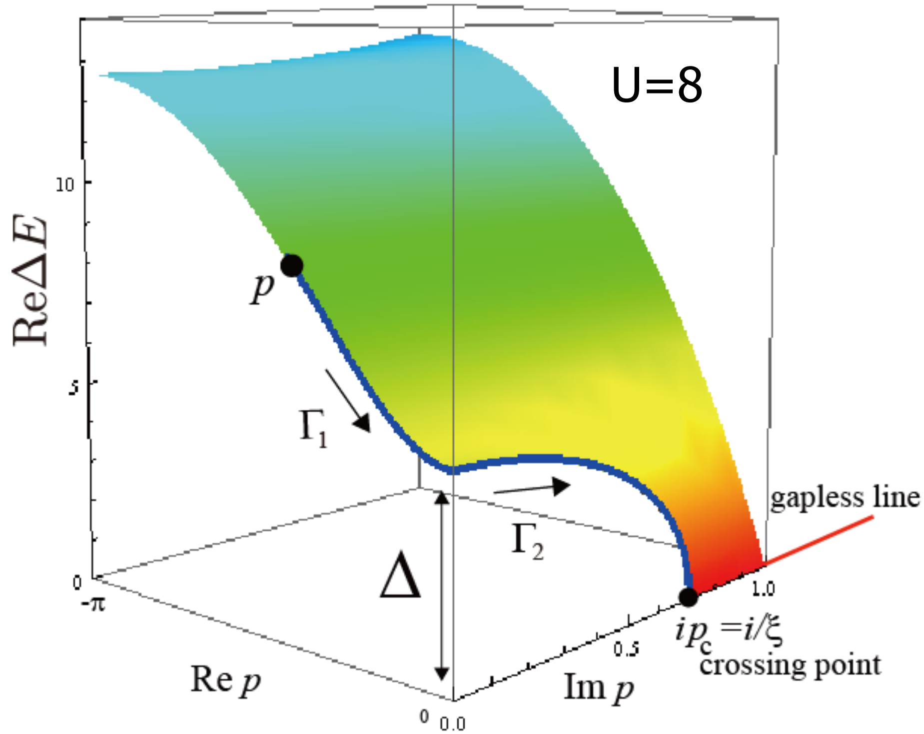
$$p = \exp\left(-2\mathrm{Im}S_{1,2}/\hbar\right)$$

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

imaginary part of the dynamical phase

Singular point in the 1d Hubbard model

Fukui Kawakami 1998, TO Aoki 2010



$\Phi \longrightarrow i\Psi$ Non-Hermitian Hubbard model

$$H(t) = -\sum_i \left[e^{\Psi} c_{i+1}^{\dagger} c_i + e^{-\Psi} c_i^{\dagger} c_{i+1} \right] + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

dh-pair production rate

tunneling probability

$$\mathcal{P}_p = \exp\left(-2\mathrm{Im}\int_0^{\Phi_c} \Delta E(p-\Phi)\frac{-1}{F(\Phi)}d\Phi\right)$$

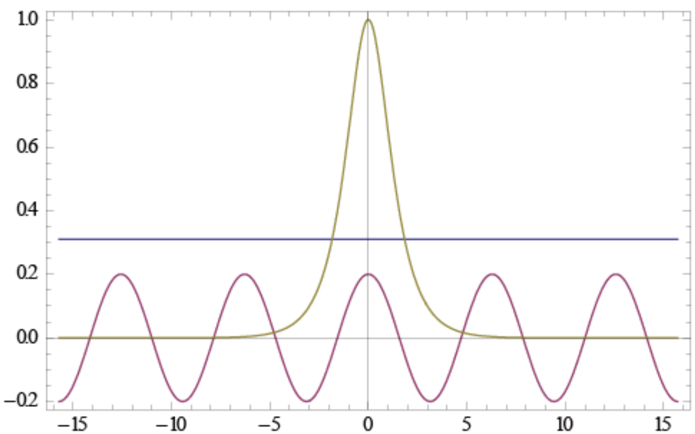
production rate

$$\Gamma_p = f\mathcal{P}_p$$

TO arXiv:1105.3145

Dirac model: Popov (1972)

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-result: Schwinger limit

$$\Gamma_p = \frac{F_0}{2\pi} \exp(-\pi \frac{F_{\rm Sch}}{F_0}) \qquad F_{\rm Sch} = \frac{2}{\pi} \int_0^{p_c = 1/\xi} \Delta E(il) dl$$

strong/weak coupling limits

$$\Gamma_p = \frac{F_0}{2\pi} \exp\left(-\frac{\pi}{2} \frac{(\Delta_{\rm Mott})^2}{c_{\rm eff} F_0} \right) \quad \text{(DC, Small } U\text{)}$$

$$\Gamma_p = \frac{F_0}{2\pi} \left(\frac{g\tau}{U} \right)^{\frac{\pi}{2} \frac{U}{F_0}} \quad \text{(DC, Large } U\text{)}$$

Estimate for 1d Mott insulators

	τ(eV)	U(eV)	a(Å)	Δ(eV)	$\xi(a)$	$F_{\rm Sch}$(V/Å)
ET-F_2TCNQ	0.1	1	10	0.7	1.1	0.06
[Ni(cnxn)$_2$Br]Br_2	0.22	2.4	5	1.6	1.0	0.3
Sr_2CuO_3	0.52	3.1	4	1.5	2.1	0.18

$$F_{\rm Sch}^{\rm QED} = m^2 c^3 / e\hbar \ \sim 10^6 \ {\rm V/Å}$$

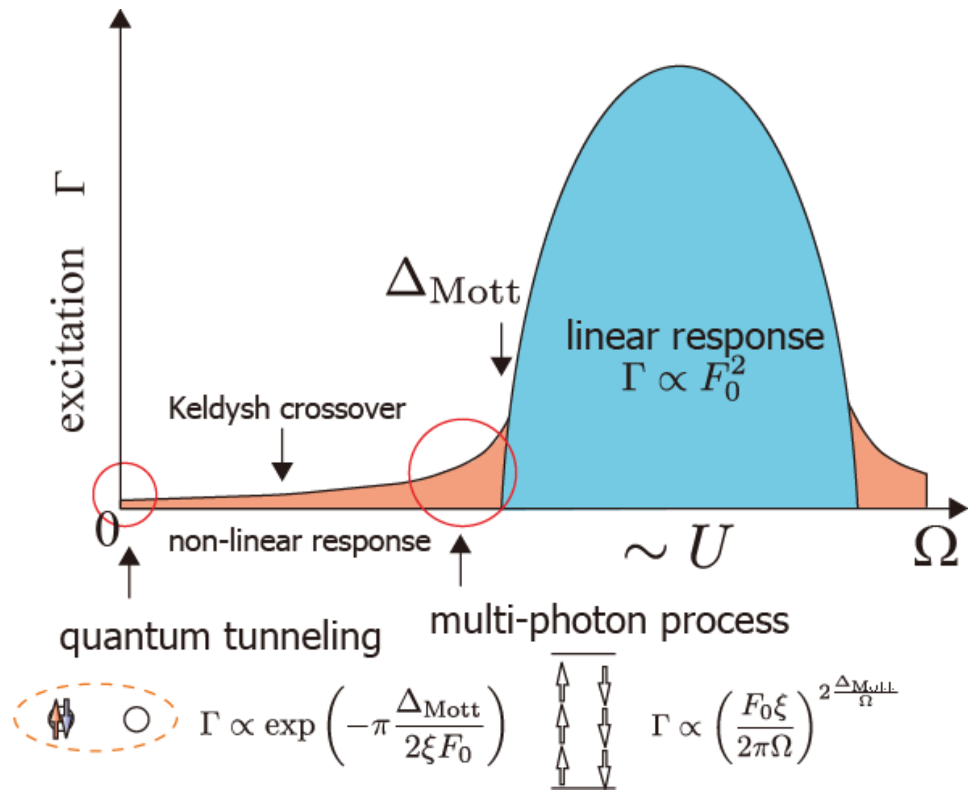
Easily accessible with ultra-short pulse lasers!

AC-result: Keldysh Crossover

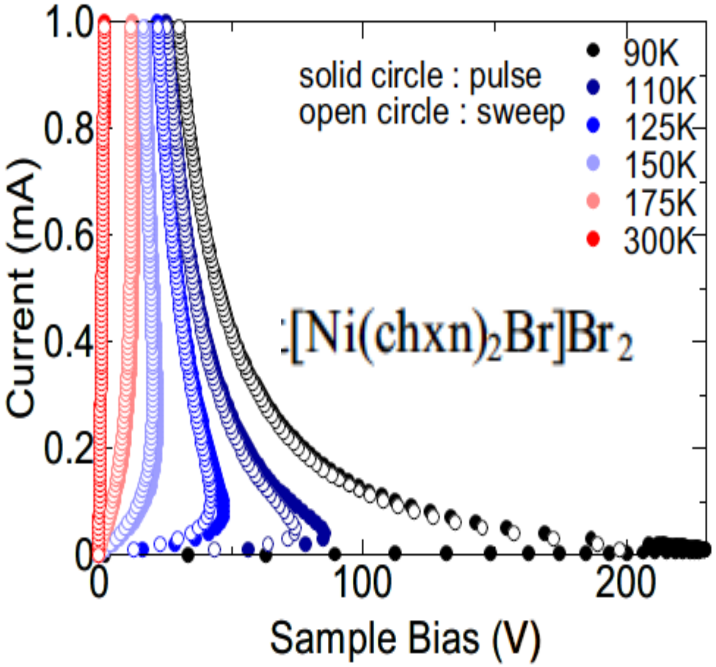
AC-field $\phi(t) = F_0 \sin(\Omega t)$

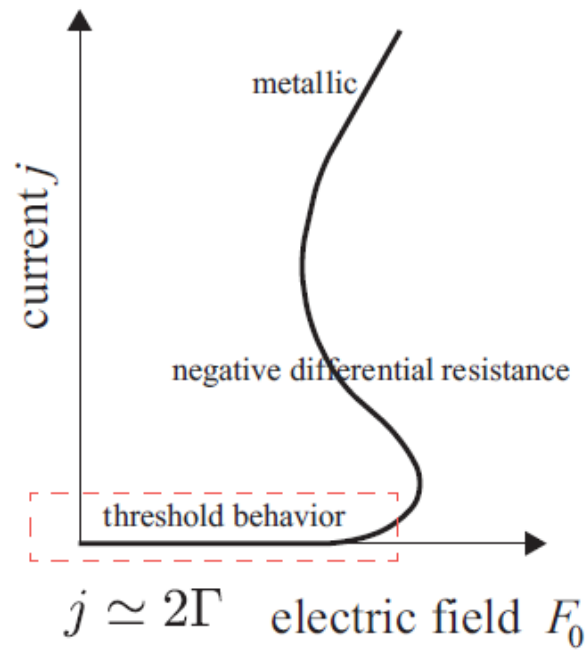
$$\mathcal{P}_{p=0} \to \begin{cases} \left(\frac{F_0\xi}{b\Omega}\right)^{2\frac{\Delta_{\rm Mott}}{\Omega}} & \gamma \gg 1, \quad \text{mulit-photon} \\ \exp\left(-\frac{\pi}{2}\frac{\Delta_{\rm Mott}}{\xi F_0}\left(1 - \frac{\pi}{16}\gamma^2 + \dots\right)\right) & \gamma \ll 1, \quad \text{tunneling}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

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



Comparison with Experiments (DC)





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

possible origin of negative differential resistance

1. Heat transfer between fermion/bosons: phonon=heat resovoir.

c.f.) Altshuler et al. PRL 102 (2009)
Mori et al. PRB (2009)

2. non-equilbrium phase transition c.f.) Ajisaka et al. (2009)

see S. Nakamura's talk

1. Introduction

1.1 Condensed matter VS Hadron Physics

Mott transition ⟷ confinement
topological phase transition ⟷ quantum anomaly

1.2 (Old) Strong field physics

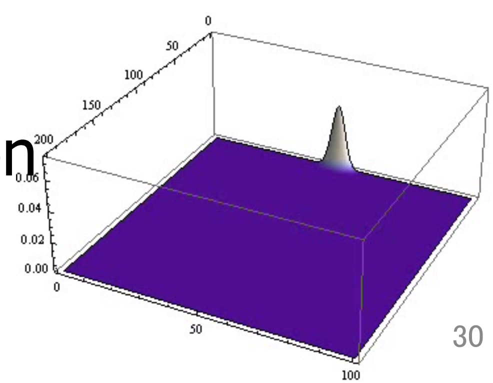
1.3 Numerical methods for non-equilibrium

2. Many-body Schwinger mechanism

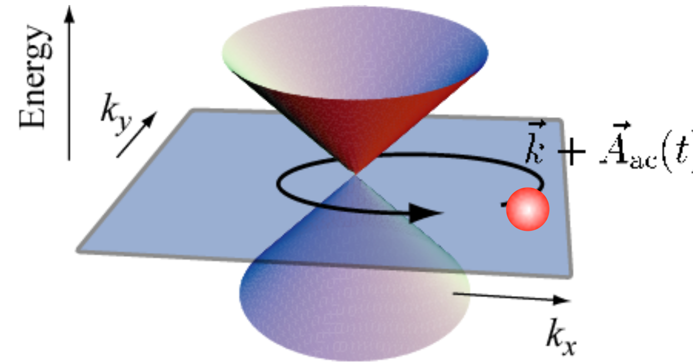
Nonlinear transport/Photo-induced Mott transition

3. Photo-induced Hall effect

Floquet topological phase transition



Question:
What happens to Dirac particles in circularly polarized light?



High energy answer:

the Volkov state

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

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

Condensed matter answer:

A dynamical gap opens at the Dirac point of graphene making it a photo-induced quantum Hall state.

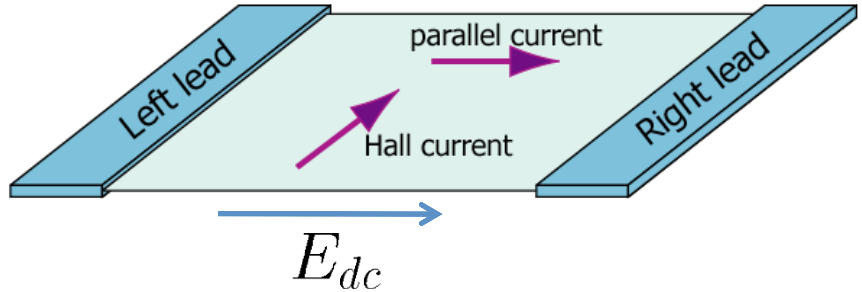
TO, H. Aoki, PRB 79, 081406 (R) (2009)

The two are different:

in graphene, speed of massless fermion << speed of light

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

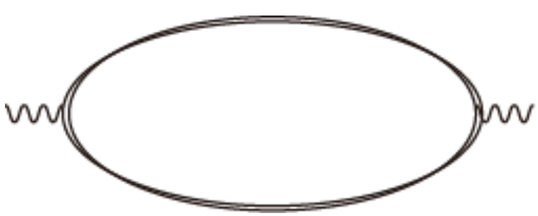
Topology and Transport:
Kubo formula and the TKNN formula



$$J_{\mathrm{dc}}^{i} = \sigma_{ij} E_{\mathrm{dc}}^{j}$$

Kubo formula（linear response）

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



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

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

Party anomaly diagram for 2+1 d Dirac model

TKNN formula in a 2d Dirac system

Thouless, Kohmoto, Nightingale, Nijs 1982

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

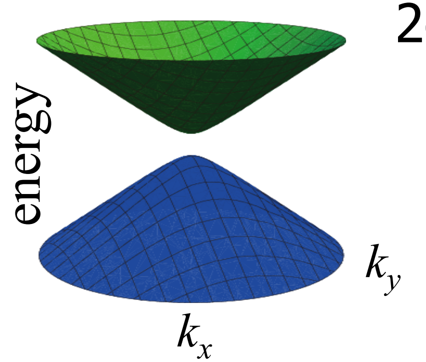
Berry curvature

artificial gauge field

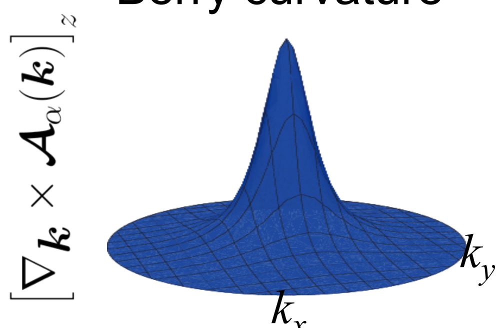
$$\boldsymbol{\mathcal{A}}_\alpha(\boldsymbol{k}) \equiv -i \langle \Phi_\alpha(\boldsymbol{k}) | \nabla_{\boldsymbol{k}} | \Phi_\alpha(\boldsymbol{k}) \rangle$$

First Chern number if f=1

2d Dirac system has a non-trivial Chern number



Berry curvature



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

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

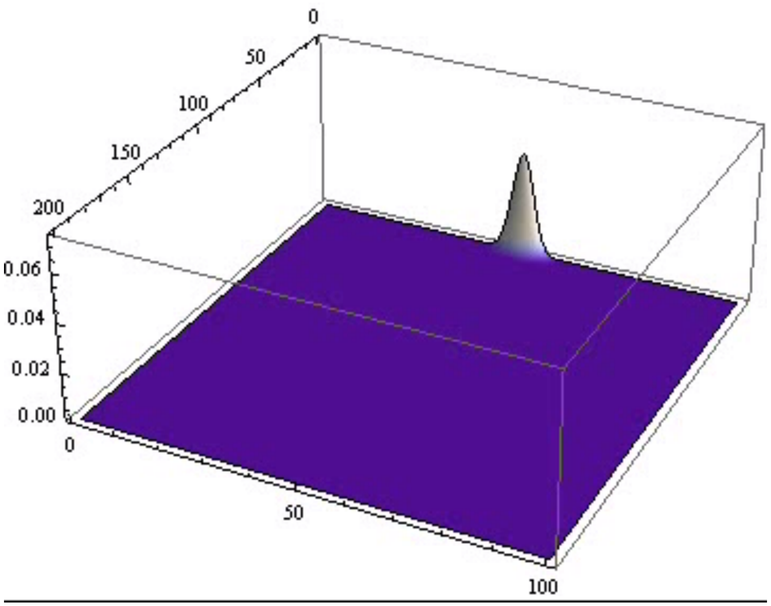
$$\sigma_{xy} = e^2 \int \frac{d\boldsymbol{k}}{(2\pi)^d} \left[\nabla_{\boldsymbol{k}} \times \boldsymbol{\mathcal{A}}_1(\boldsymbol{k}) \right]_z$$

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

1. Sign of the mass = direction of the Hall current
2. Dirac cone = half quantum unit
3. parity anomaly in field theory

photo-induced Chern number

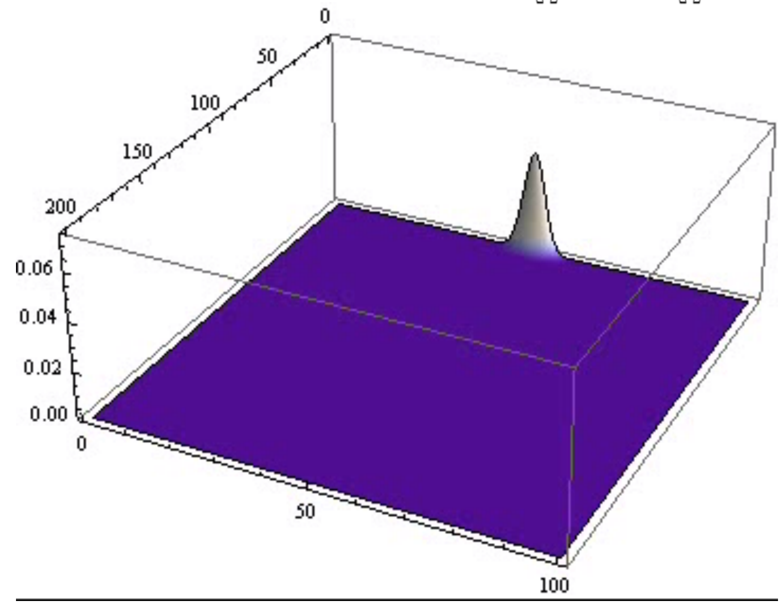
$$\mathcal{L} = \bar{\psi} i \gamma_\mu \partial^\mu \psi$$



$$\text{Chern number} = 0$$

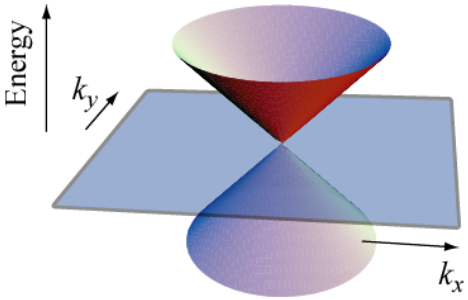
$$\mathcal{L} = \bar{\psi} \gamma_\mu (i\partial^\mu - A^\mu(t))\psi$$

$$A^\mu = (0, \frac{F}{\Omega}\cos\Omega t, \frac{F}{\Omega}\sin\Omega t)$$



$$\text{Chern number} \neq 0$$

2+1 Dirac + circular polarization



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

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

Floquet Hamiltonian (Fourier 変換)

$$H^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} + m\delta_{mn}\Omega I$$

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

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

circular polarization

$$H_{CP} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

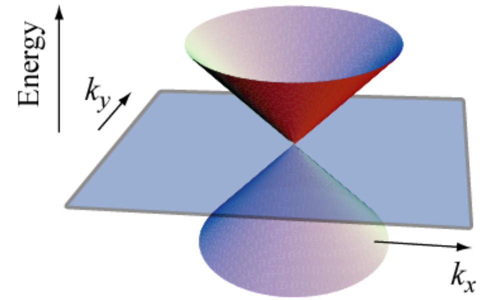
level repulsion with -Ω

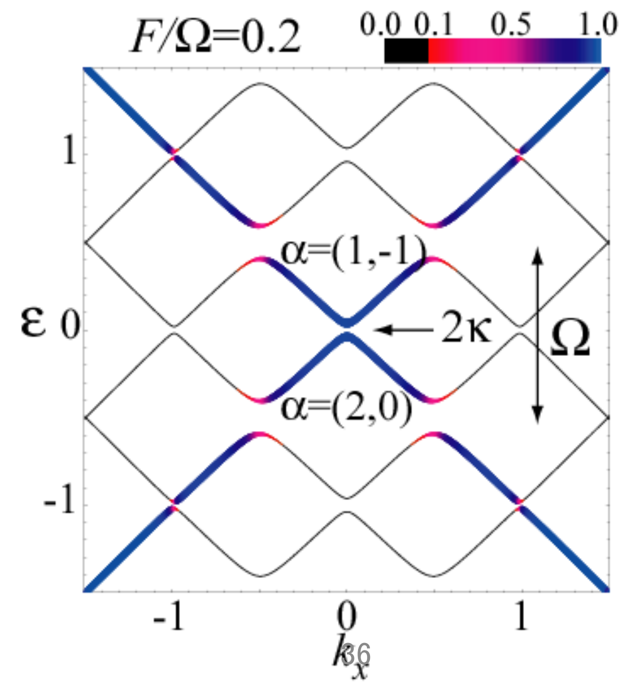
level repulsion with Ω

$$\sim \begin{pmatrix} \kappa/2 & k \\ \bar{k} & -\kappa/2 \end{pmatrix}$$

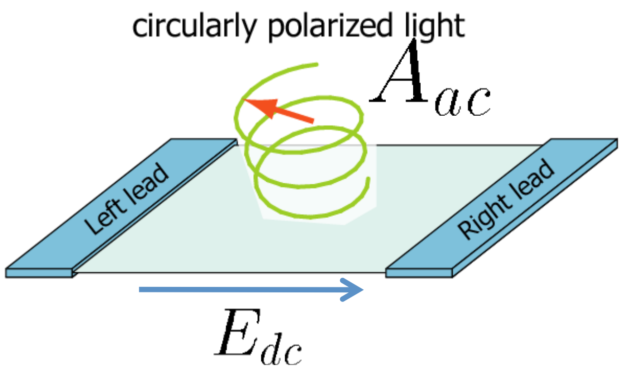
“Dynamical topological gap”

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





Kubo-formula for photo-induced transport



Large A_{ac} small E_{dc}

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

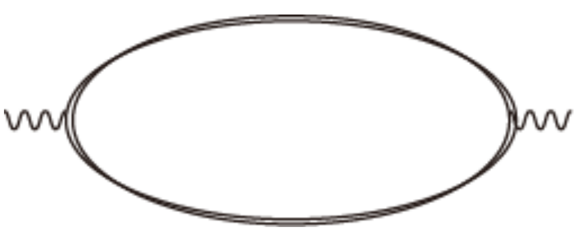
$$\sigma_{ab}(\boldsymbol{A}_{ac}) = i \int \frac{d\boldsymbol{k}}{(2\pi)^d} \sum_{\alpha,\beta\neq\alpha} \frac{[f_\beta(\boldsymbol{k}) - f_\alpha(\boldsymbol{k})]}{\varepsilon_\beta(\boldsymbol{k}) - \varepsilon_\alpha(\boldsymbol{k})} \frac{\langle\langle\Phi_\alpha(\boldsymbol{k})|J_b|\Phi_\beta(\boldsymbol{k})\rangle\rangle\langle\langle\Phi_\beta(\boldsym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

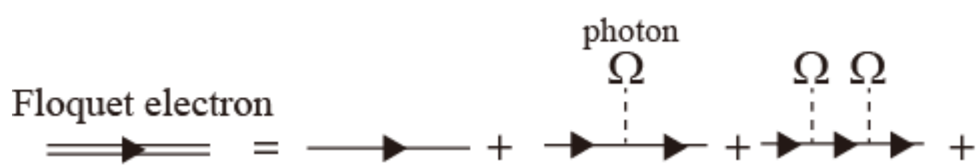
ε_α Floquet's quasi-energy

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 method = “Furry picture” in HEP

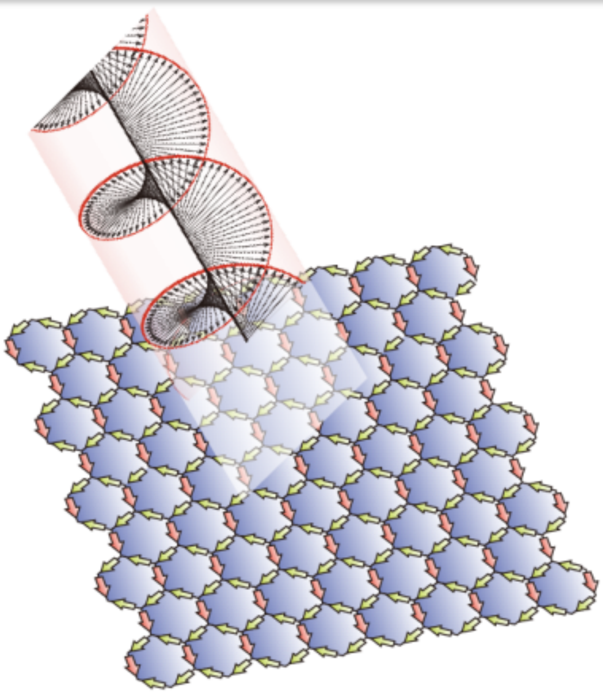
TO and H. Aoki, Phys. Rev. B 79, 081406 (R) (2009)

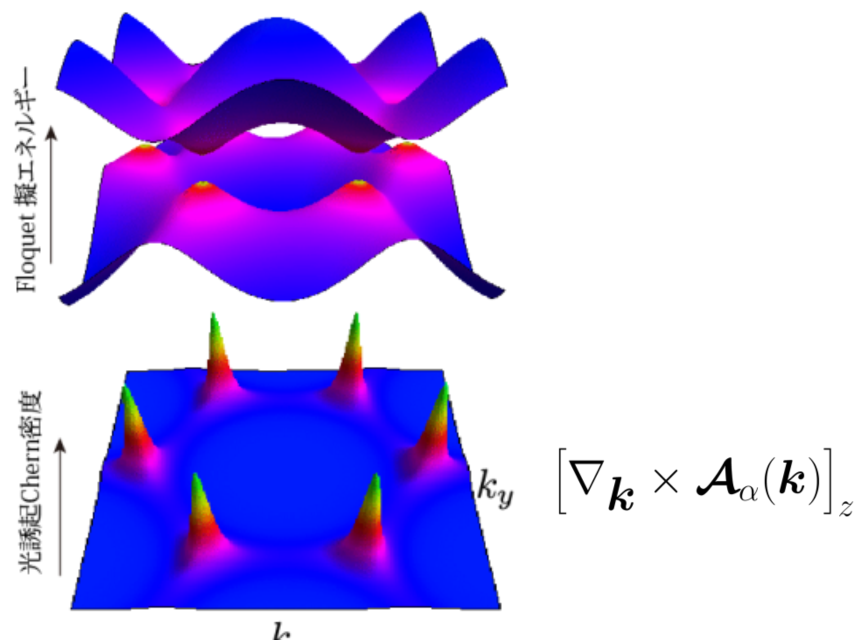
Extended Thouless-Kohmoto-Nitingale-Nijis formula for photo-induced Hall conductivity (photo-induced Chern form)

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

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)

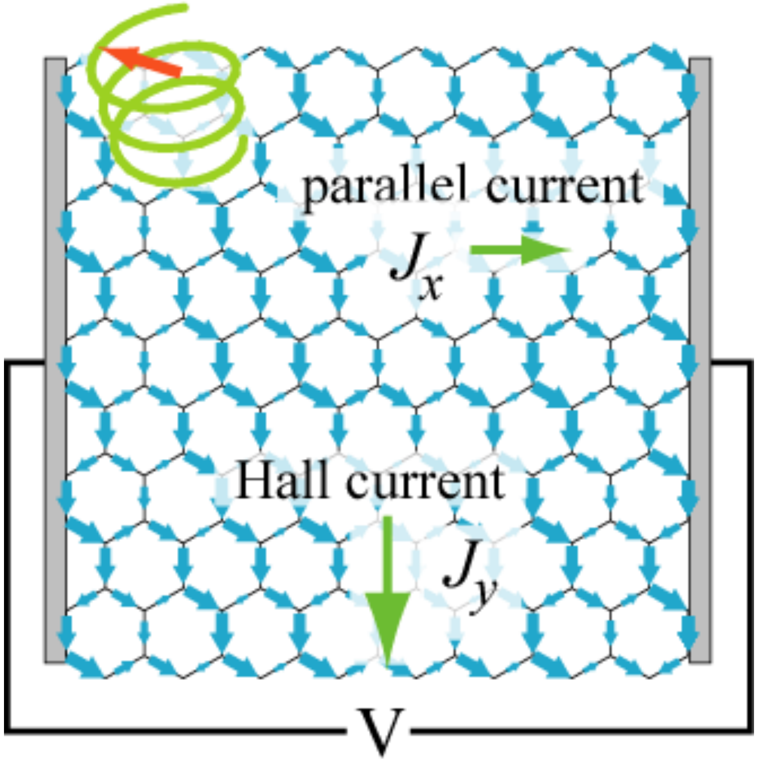




TO and H. Aoki, Phys. Rev. B **79**, 081406 (R) (2009)

Static current in circularly polarized light

DC-component of the current



$\mu_L - \mu_R = V > 0$

IV-characteristics

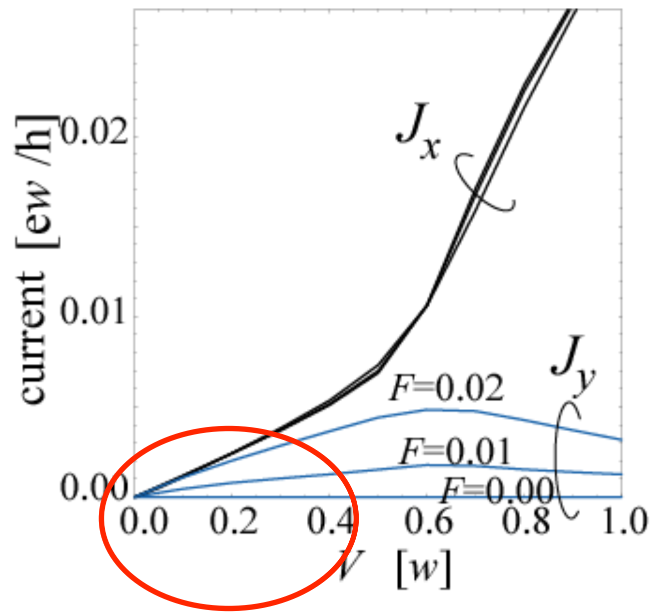
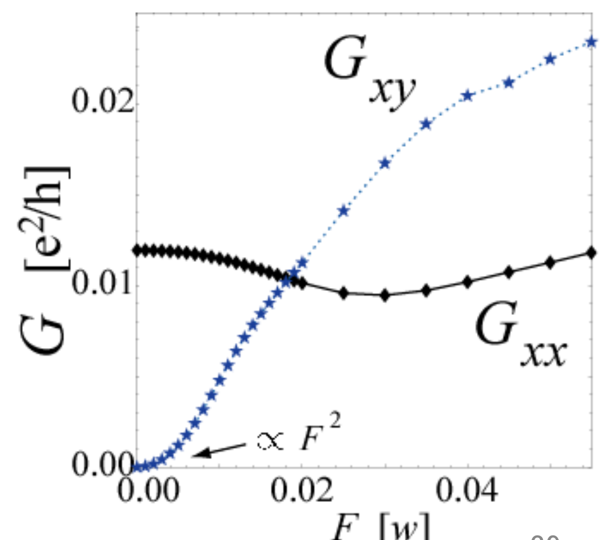


Photo-induced Hall conductivity

$$J_y = G_{xy} V$$

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



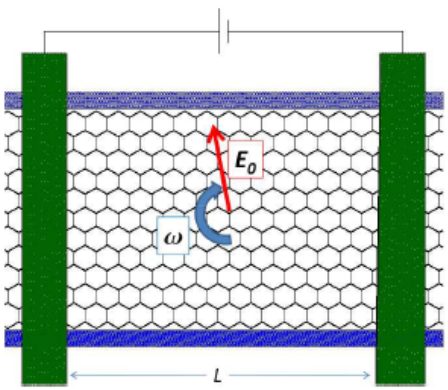
Experimentally observable!

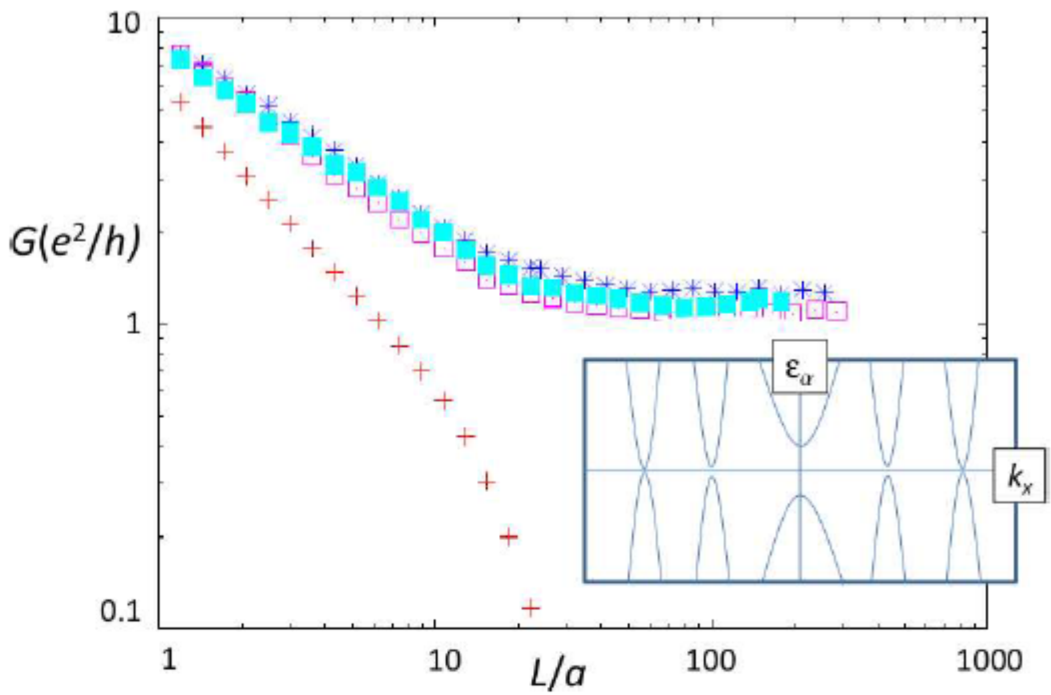
Quantization of the current

Z. Gu, H.A. Fertig, D. P. Arovas, A. Auerbach, PRL 2011

open boundary condition (ribbon geometry)

Floquet Landauer formalism





Quantized transport when size is *large* (Edge state)

Proposals for experimental detection

necessary field strength

$$\Omega \sim 1-3eV \qquad F \sim 10^7 V/m$$

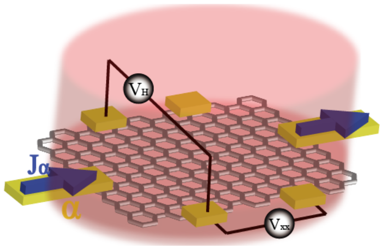
graphene, multilayer-graphene, graphite, surface of TI, etc.

TO, Aoki, arXiv:1007.5399

Gapless is best, but gapped system is OK

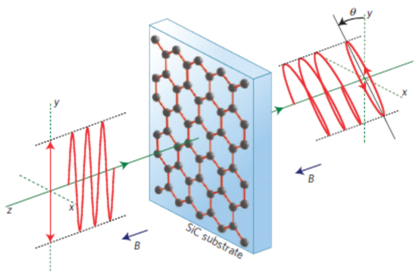
Possible detection

1. Photo-induced Transport



2.Pump-probe (Kerr effect, MOKE)

3.Pump-probe (photoemission)



Summary

Strong field physics in condensed matter

1. Many-body Schwinger mechanism
2. photo-induced topological phase transition

Future problems:

1. Comparison with hadron physics (RHIC, gauge/gravity)
2. Fast thermalization, appearance of a correlated liquid
3. Non-equilibrium superconductor transition

TO Aoki PRB2008