

DC-driven Quantum Matter: Electric Field, Normal Current, Supercurrent

Kazuaki Takasan University of Tokyo

KT, M. Sato, Phys. Rev. B **100**, 060408(R) (2019)

S. C. Furuya, KT, M. Sato, Phys. Rev. Res. **3**, 033066 (2021)

KT, M. Tezuka, arXiv: 2111.03857

KT, T. Morimoto, J. Orenstein, J. E. Moore, Phys. Rev. B **104**, L161202 (2021)

KT, S. Sumita, Y. Yanase, Phys. Rev. B **106**, 014508 (2022)

S. Sumita, KT, J. Phys. Soc. Jpn. **91**, 074703 (2022)



Collaborators

	Masahiro Sato (Chiba U)			
Magnetism	Shunsuke C. Furuya (U Tokyo)			
	Masaki Tezuka (Kyoto U)			
	Takahiro Morimoto (U Tokyo)			
Optical response	Joseph Orenstein (UC Berkeley)			
	Joel E. Moore (UC Berkeley)			
	Shuntaro Sumita (U Tokyo)			
Superconductivity	Youichi Yanase (Kyoto U)			

Outline

Take-home message

DC-drive works as a good tool for controlling states of matter.
There is a rich physics of DC-driven quantum matter.

Introduction: AC-drive vs DC-drive, Why we study DC

Our studies about DC-driven quantum matter

1. Insulating magnets + DC electric field → Control magnetic interaction
2. Topological semimetals + DC electric current → Enhance optical responses
3. Superconductors + DC supercurrent → Topological phase transitions

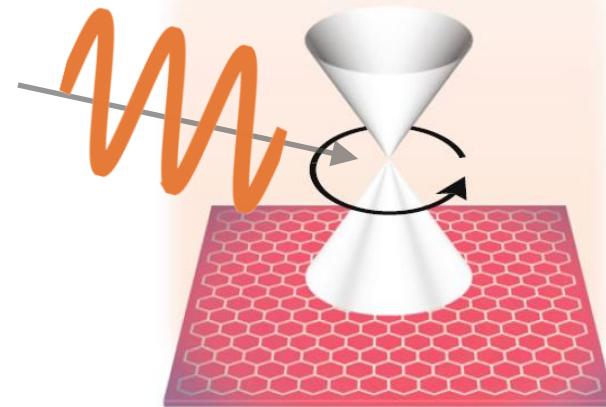
Outlook, Summary

AC-drive control = Floquet engineering

Time-periodic (AC-driven) Hamiltonian

$$H(t) = H(t + T)$$

Design driving protocol



Massless Dirac + Circularly pol. light

$$H(t) = [\mathbf{k} - \mathbf{A}(t)] \cdot \boldsymbol{\sigma}$$

$$\mathbf{k} = (k_x, k_y, 0)$$

$$\mathbf{A}(t) = A (\cos \omega t, \sin \omega t, 0)$$

Floquet theory



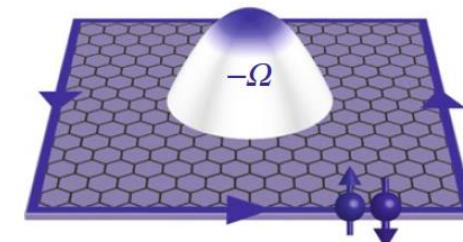
Effective (static) Hamiltonian

$$H_{\text{eff}}$$

Desired Hamiltonian



Topologically non-trivial



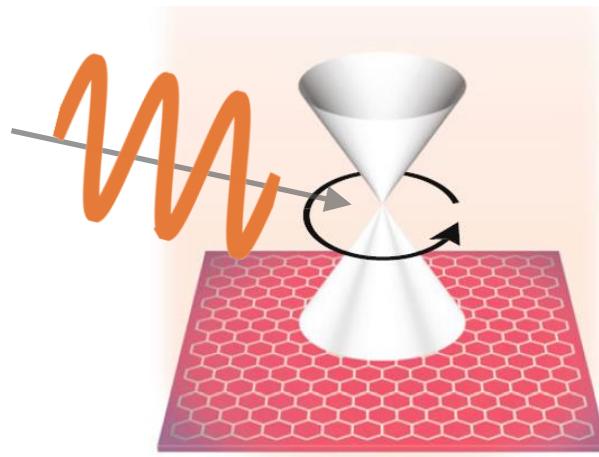
Massive Dirac (Chern ins.)

$$H_{\text{eff}} = H(0) + m_{\text{eff}}(A) \sigma_z$$

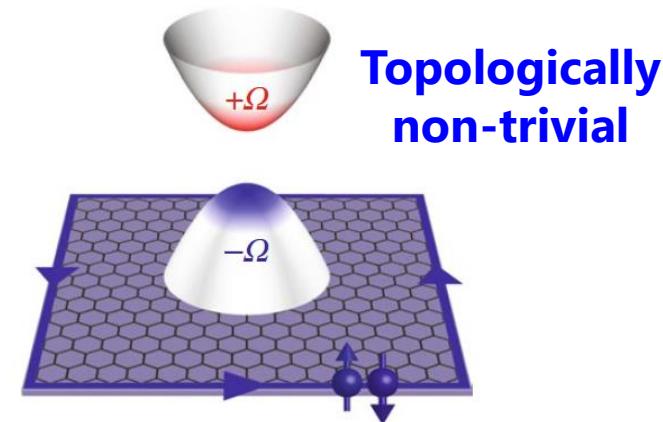
Theory: Oka and Aoki, PRB(R) (2009)

Experiment: McIver *et al.* Nat. Phys. (2020)

AC-drive control = Floquet engineering



Massless Dirac + Circularly pol. light



Massive Dirac (Chern ins.)

Add a new feature/functionality by external **AC** drive

This works as a good technique for realizing novel quantum states of matter

Chiral spin liquid

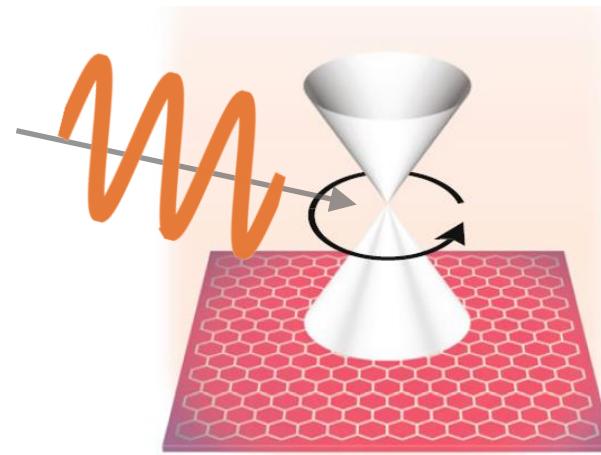
Classen et al. Nat. Comm. (2017); Kitamura et al. PRB (2017).

Topological SC

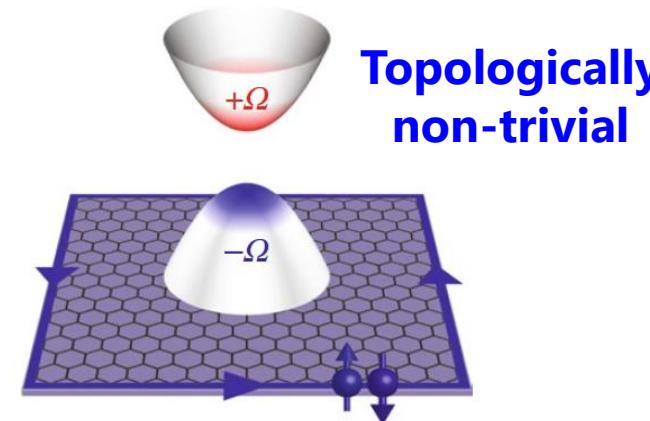
KT et al. PRB (2017); Chono, KT, Yanase PRB (2020).

*theoretical proposals

AC-drive control = Floquet engineering



Massless Dirac + Circularly pol. light



Massive Dirac (Chern ins.)

Add a new feature/functionality by external **AC** drive

This works as a good technique for realizing novel quantum states of matter

My question: Is **AC drive** necessary? Other external drive?

Engineering by “DC drive”



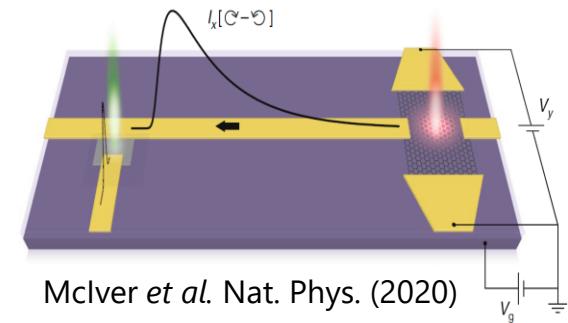
from AC/DC official website

Why DC drive?

There are reasons beyond just curiosity!

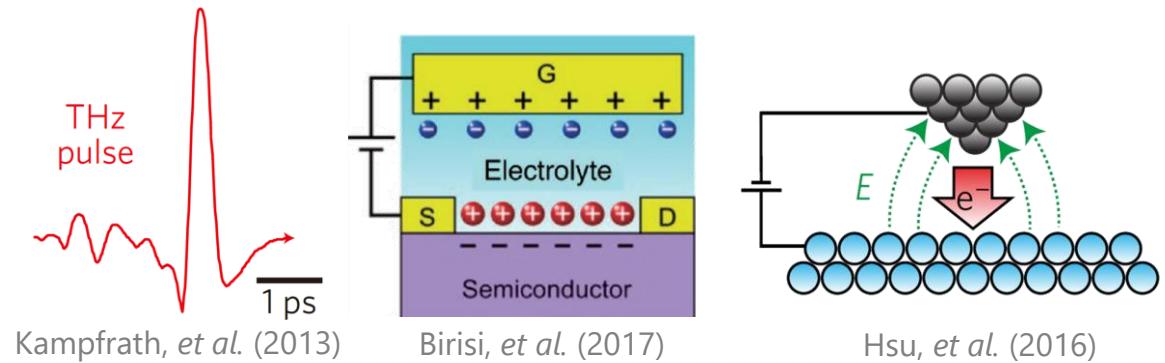
1. DC drive does *NOT* need sophisticated optical techniques

Time-resolved probe, Strong pump



2. Developing techniques for generating a strong DC E-field

THz pulse, EDLT, STM-like devise, ...



3. Features not expected in the case of AC drive



Our works: DC-driven quantum matter

Theoretical proposals for controlling states of matter using DC drive

Insulator

1. Insulating magnets + DC electric field → Control magnetic interaction

KT, M. Sato, Phys. Rev. B **100**, 060408(R) (2019).

S. C. Furuya, KT, M. Sato, Phys. Rev. Res. **3**, 033066 (2021).

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3. Superconductors + DC supercurrent → Topological phase transitions

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Our works show that DC drive also works as a good tool for controlling states of matter, like (beyond?) AC (Floquet) drive

Our works: DC-driven quantum matter

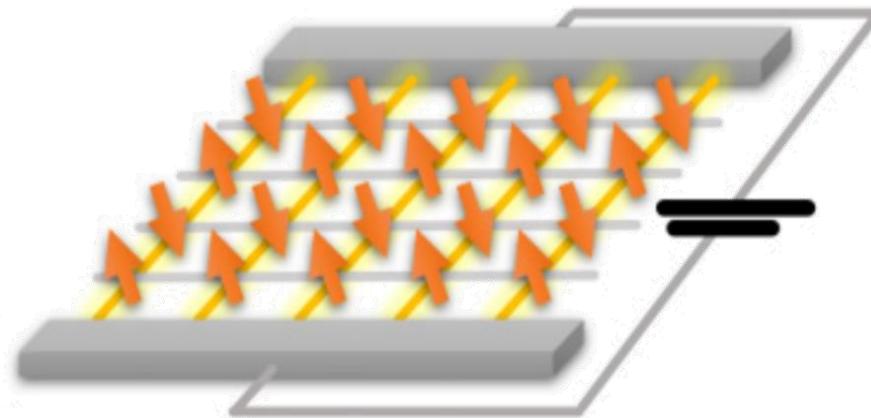
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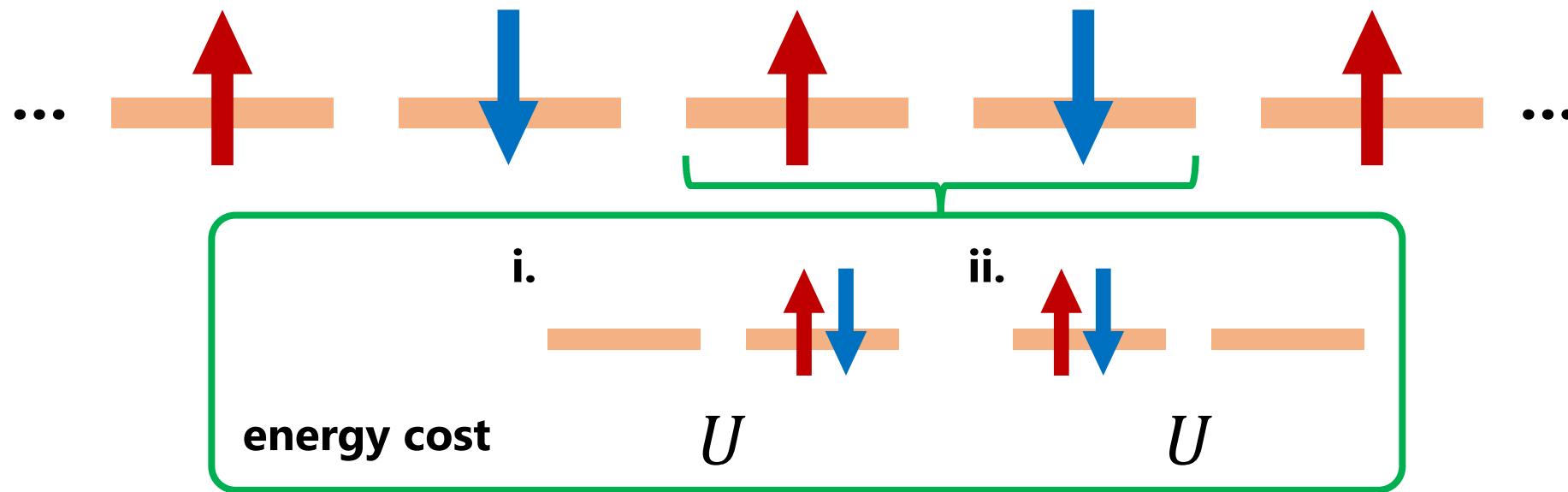
KT, M. Tezuka, arXiv: 2111.03857



Magnetism in Mott insulators (1D)

K. M. S. D., Phys. Rev. B **100**, 060408(R) (2019)

$$H_{\text{eff}} = \sum_{\langle i,j \rangle} J_0 \mathbf{S}_i \cdot \mathbf{S}_j \quad J_0 = \frac{4t_h^2}{U}$$



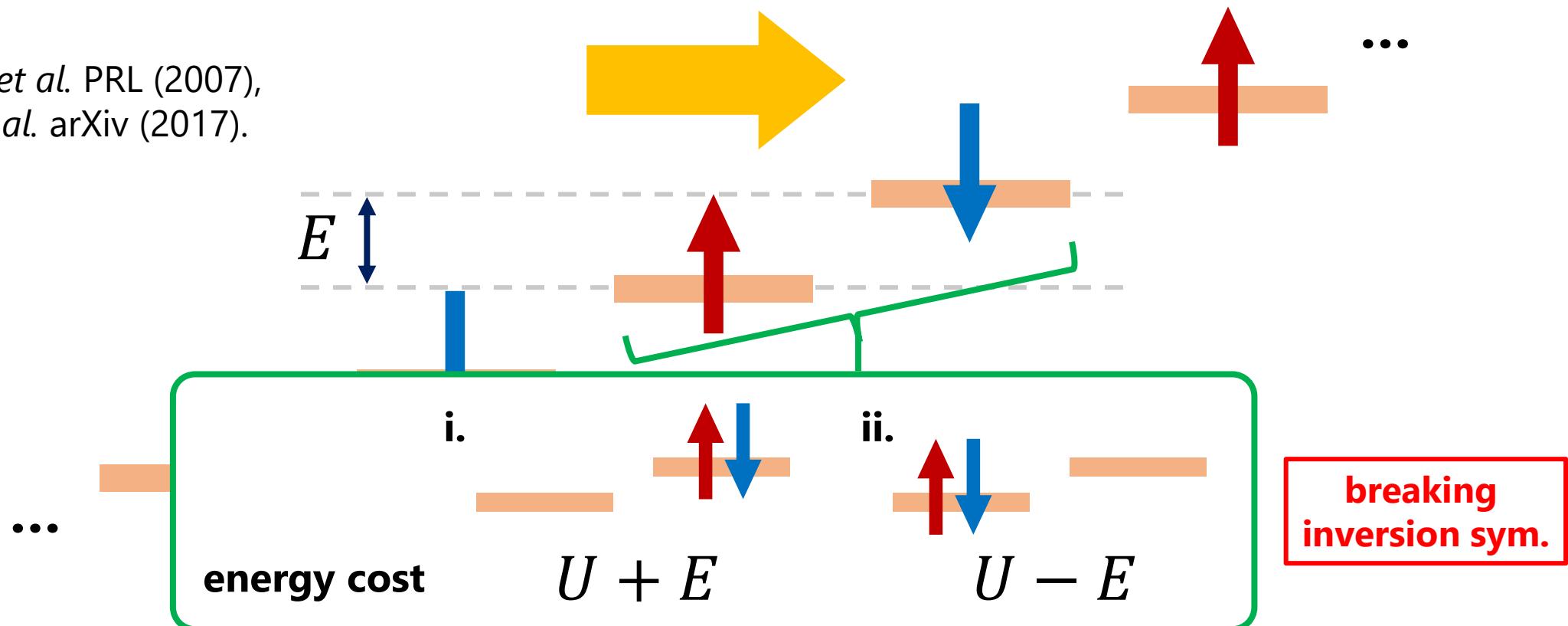
Mott insulators + DC electric field (1D)

$$H_{\text{eff}} = \sum_{\langle i,j \rangle} J_{\text{eff}}(E) \mathbf{s}_i \cdot \mathbf{s}_j$$

KTF-MSC-PR-100-000100(R) (2019)

$$J_{\text{eff}}(E) = \frac{2t_h^2}{U - E} + \frac{2t_h^2}{U + E} = \frac{J_0}{1 - \left(\frac{E}{U}\right)^2}$$

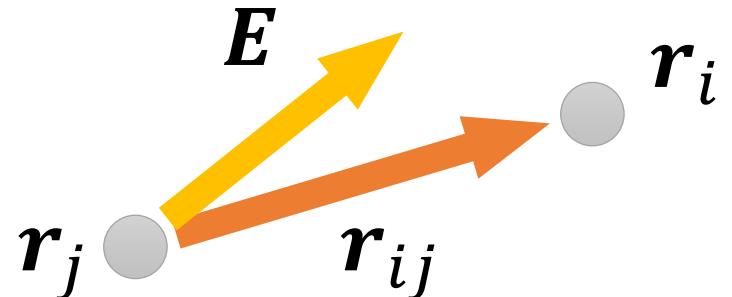
cf. Katsura *et al.* PRL (2007),
Eckstein *et al.* arXiv (2017).



Mott insulators + DC electric field (General)

[KT](#), M. Sato, Phys. Rev. B **100**, 060408(R) (2019)

$$H_{\text{eff}} = \sum_{\langle i,j \rangle} \frac{J_0}{1 - \left(\frac{\mathbf{E} \cdot \mathbf{r}_{ij}}{U} \right)^2} \mathbf{S}(\mathbf{r}_i) \cdot \mathbf{S}(\mathbf{r}_j)$$



$\mathbf{r}_{ij} \parallel \mathbf{E} \rightarrow \mathbf{Enhance !}$ $\mathbf{r}_{ij} \perp \mathbf{E} \rightarrow \mathbf{No enhance}$

Spatial structure of the magnetic interaction can be controlled

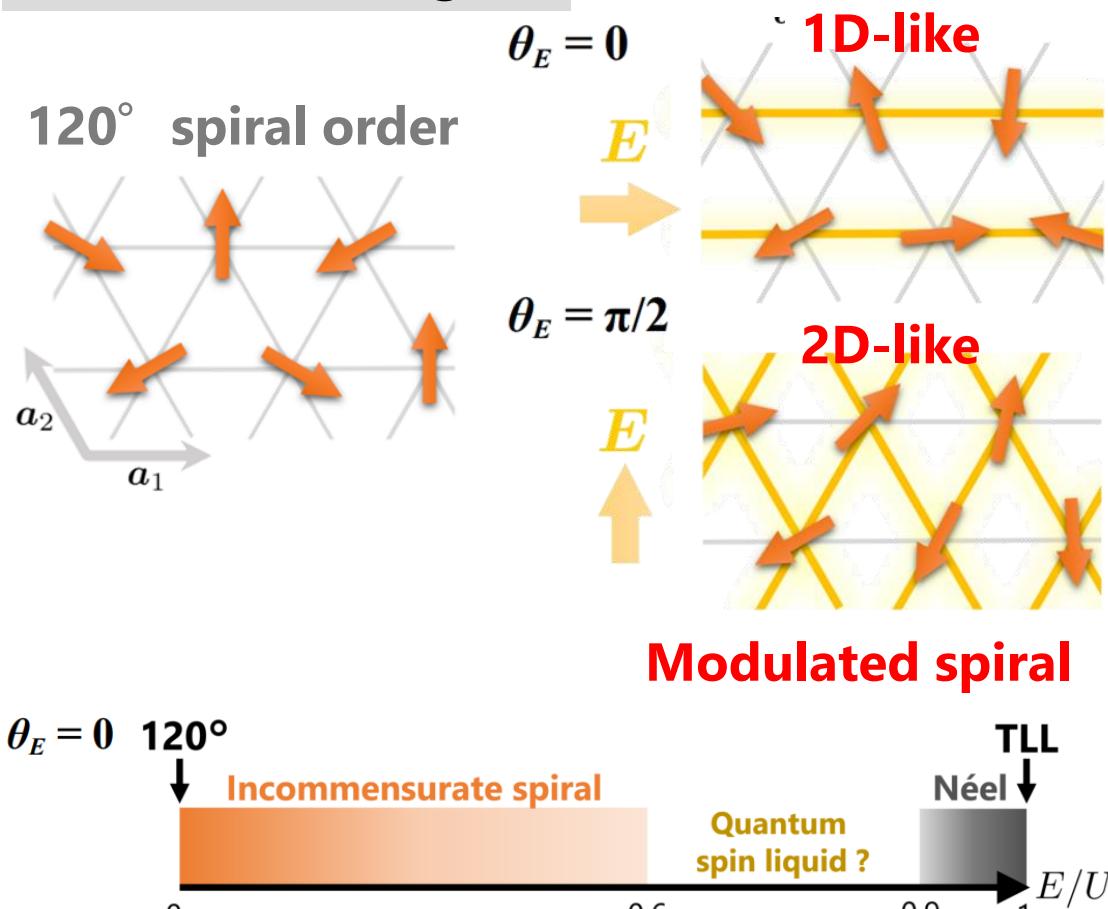
Application: Control of dimensionality

Control of dimensionality by DC E-field

AFM coupling is enhanced in E-field direction

KT, M. Sato, Phys. Rev. B **100**, 060408(R) (2019)

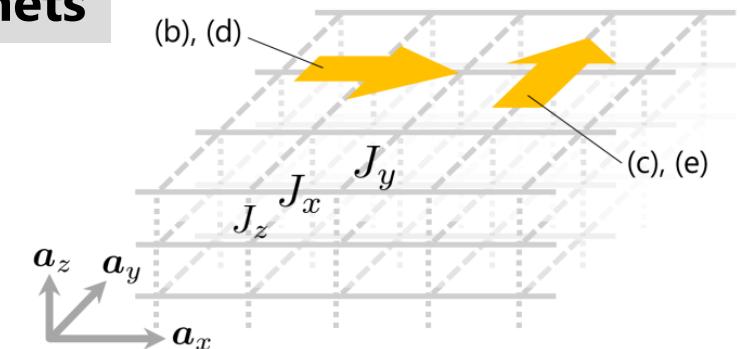
1. Frustrated magnet



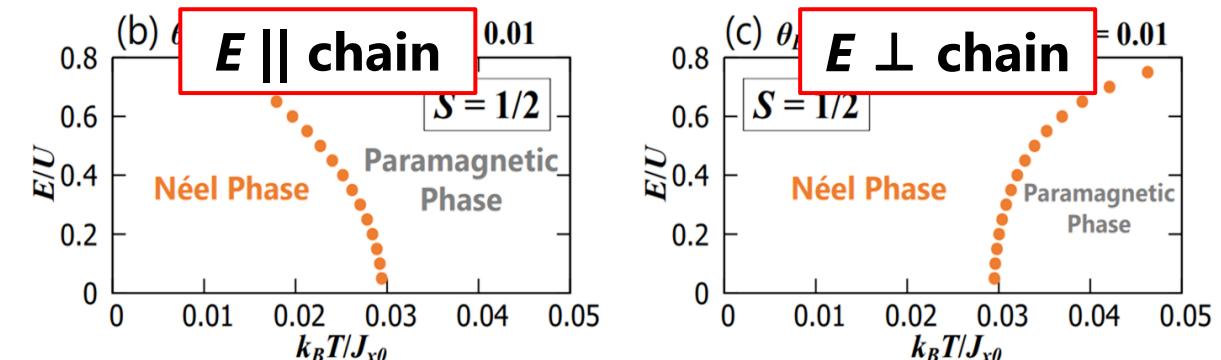
DC-field-induced Quantum spin liquid

2. Quasi-1D magnets

= Ensemble of spin chains



$E \perp$ chain 2D-ness is enhanced
 $E \parallel$ chain 1D-ness is enhanced



DC-field-induced AFM order

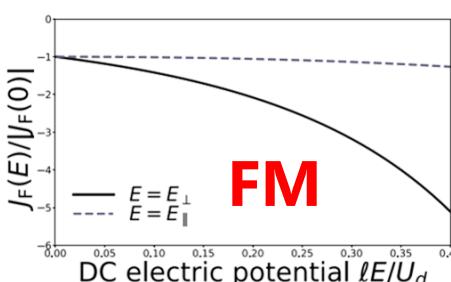
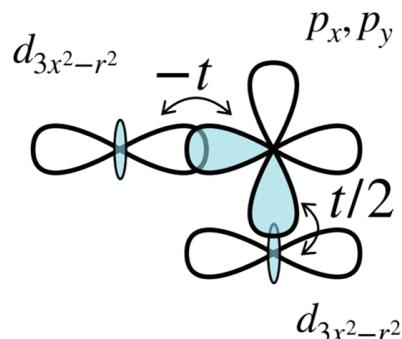
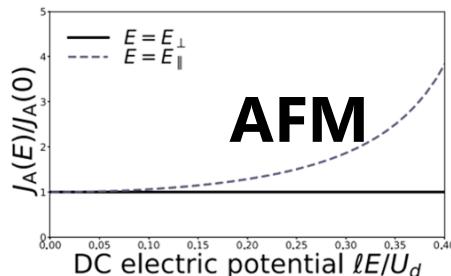
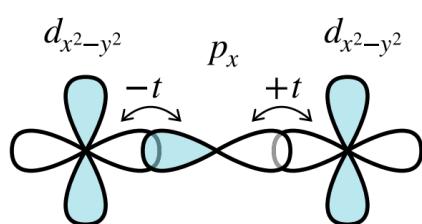
Recent development: Ferromagnetism

Ferromagnetism is also enhanced in a similar way

S. C. Furuya, [KT](#), M. Sato, PRR 3, 033066 (2021)

Extension to superexchange mechanism

FM enhancement $\propto \mathbf{E}$ (c.f. AFM $\propto \mathbf{E}^2$)

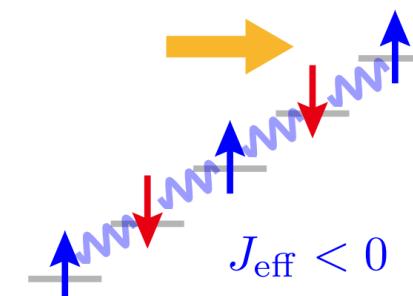


AFM-to-FM switch is possible using Wannier-Stark localization

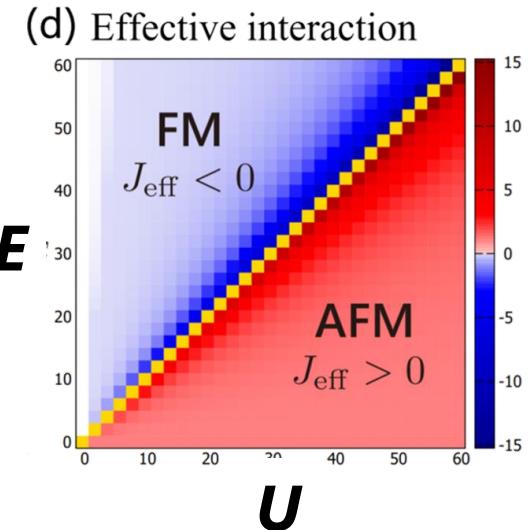
[KT](#), M. Tezuka, arXiv: 2111.03857

Extreme strong field induces **localization**
→ Effective localized spin systems

$U \ll E$ (Wannier-Stark)



$$J_{\text{eff}} = \frac{J_0}{1 - \left(\frac{E}{U}\right)^2}$$



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2. Topological semimetals + DC electric current → Enhance optical responses

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3. Superconductors + DC supercurrent → Topological phase transitions

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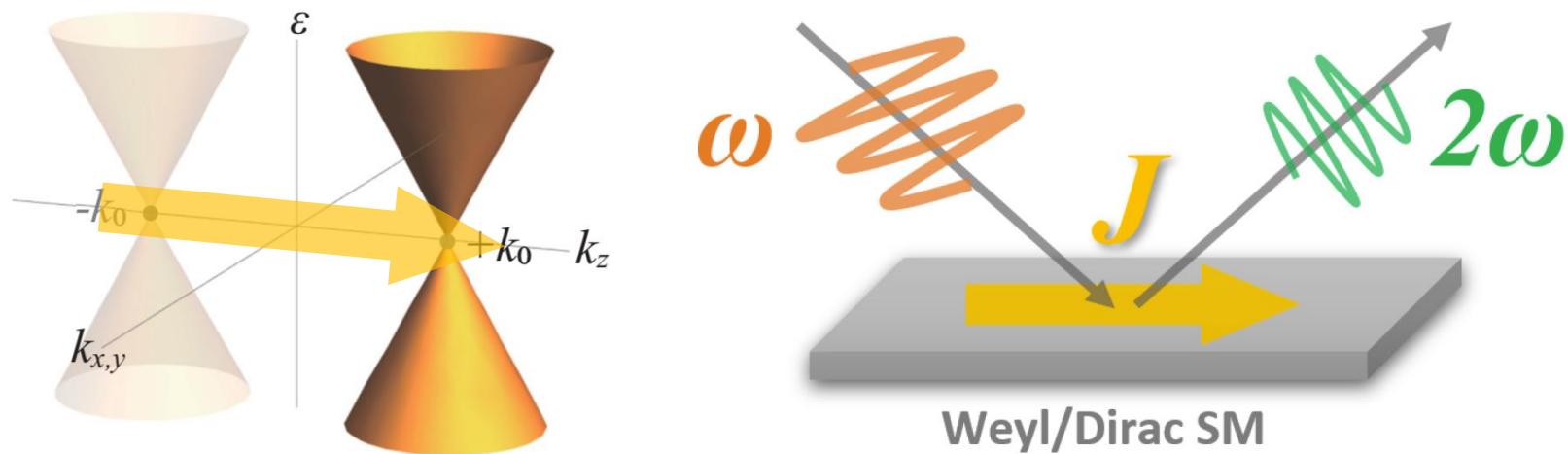
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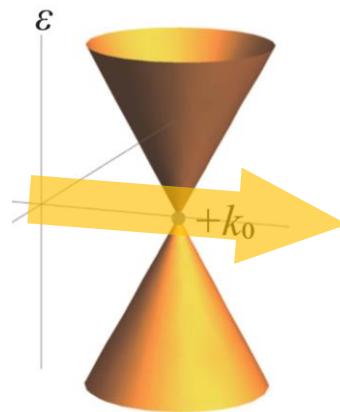
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Topological semimetals + DC electric current



cf. H_{eff}

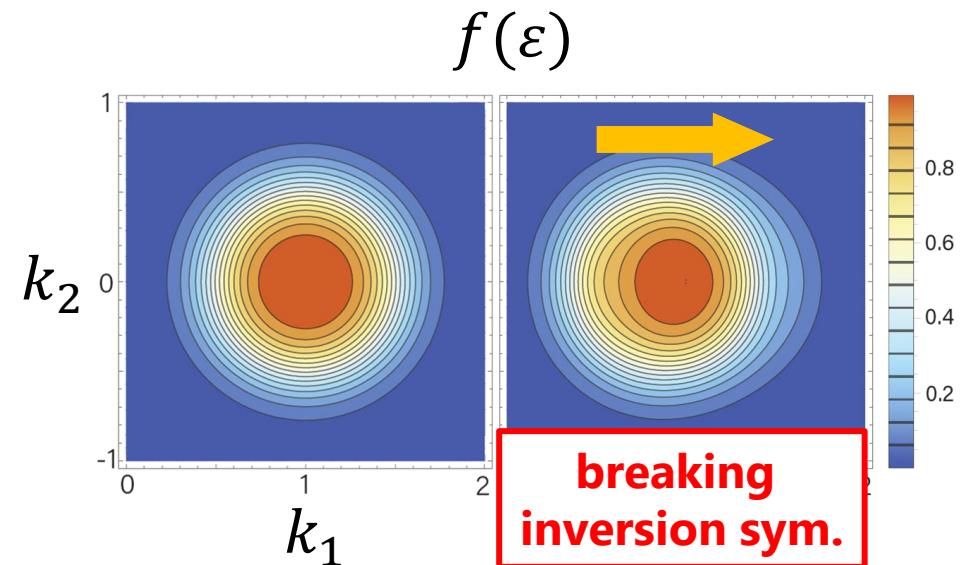
Metal + DC electric field

→ **Nonequilibrium steady state w/ finite current** $f(\varepsilon)$

Boltzmann equation + Relaxation time approximation

$$-E \cdot \frac{\partial f}{\partial k} = \left(\frac{df}{dt} \right)_{\text{coll.}} = -\frac{f - f_{\text{eq.}}}{\tau}$$

$$f = f_{\text{eq.}} + \tau E_a \frac{\partial f}{\partial k_a} + \tau^2 E_a E_b \frac{\partial^2 f}{\partial k_a \partial k_b} + \dots$$



Application : **Current-induced nonlinear optical response**

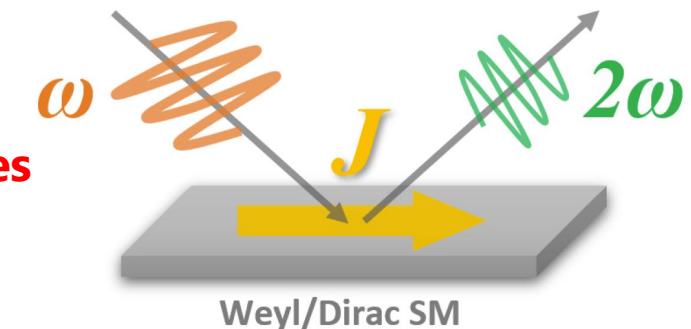
Application: Current-induced nonlinear optical response

Nonlinear response $j = \sigma^{(1)}E + \sigma^{(2)}E^2 + \sigma^{(3)}E^3 + \dots$

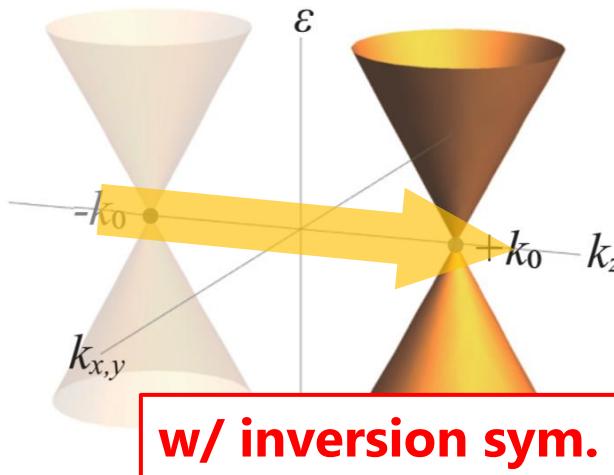
Even order is prohibited under **inversion symmetry**

Break inv. sym. by current → **Activate the even order responses**

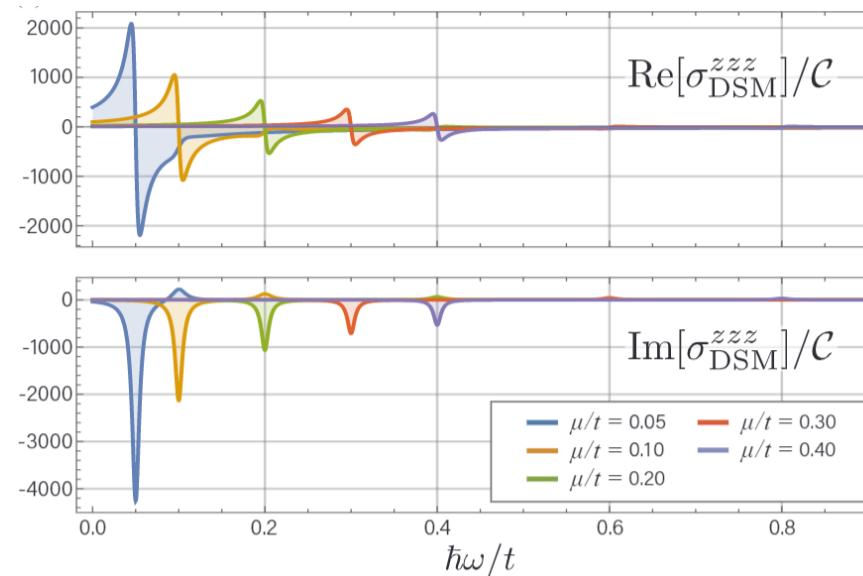
Ex: **Second harmonic generation (SHG)** $E^2 \rightarrow e^{2i\omega t}$



Dirac (Weyl) semimetal



Second order optical conductivity



Finite SHG response!

Very large!

e.g. $\text{Cd}_3\text{As}_2, \text{Co}_3\text{Sn}_2\text{S}_2$

$10^2\text{-}10^4$ times larger
than typical ones

DC-driven topological SMs work as useful nonlinear optical materials

cf. HHG in DC-driven graphene, Kanega-san's poster (B-1)

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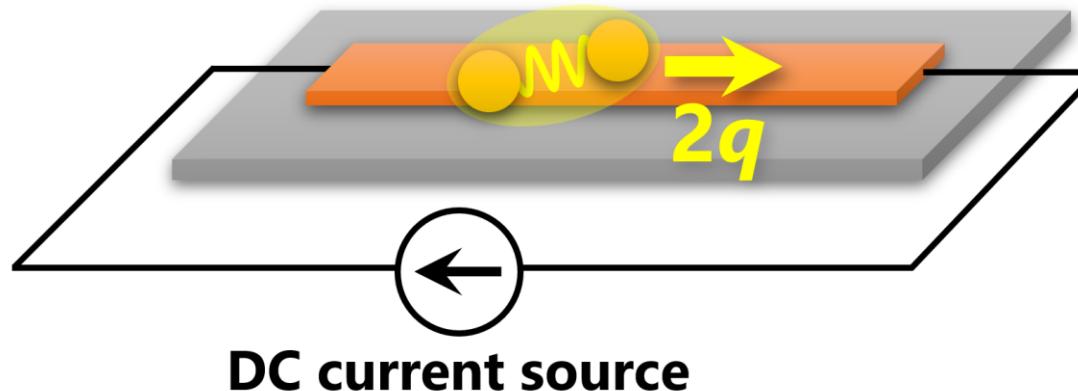
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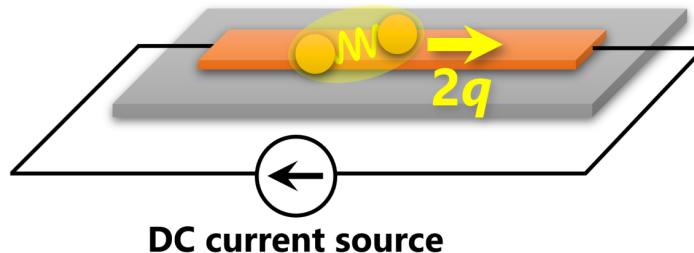
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Superconductors + DC supercurrent



Supercurrent is *equilibrium current* $f(\varepsilon)$ = Fermi dist.

Described as **COM momentum of Cooper pairs**

Mean-field Hamiltonian
$$H = \sum_{\mathbf{k}, s, s'} c_{\mathbf{k}, s}^\dagger [H_N(\mathbf{k})]_{s, s'} c_{\mathbf{k}, s'} + \frac{1}{2} \sum_{\mathbf{k}, s, s'} \left\{ c_{\mathbf{k}+\mathbf{q}, s}^\dagger [\Delta(\mathbf{k})]_{s, s'} c_{-\mathbf{k}+\mathbf{q}, s'}^\dagger + \text{h.c.} \right\}$$

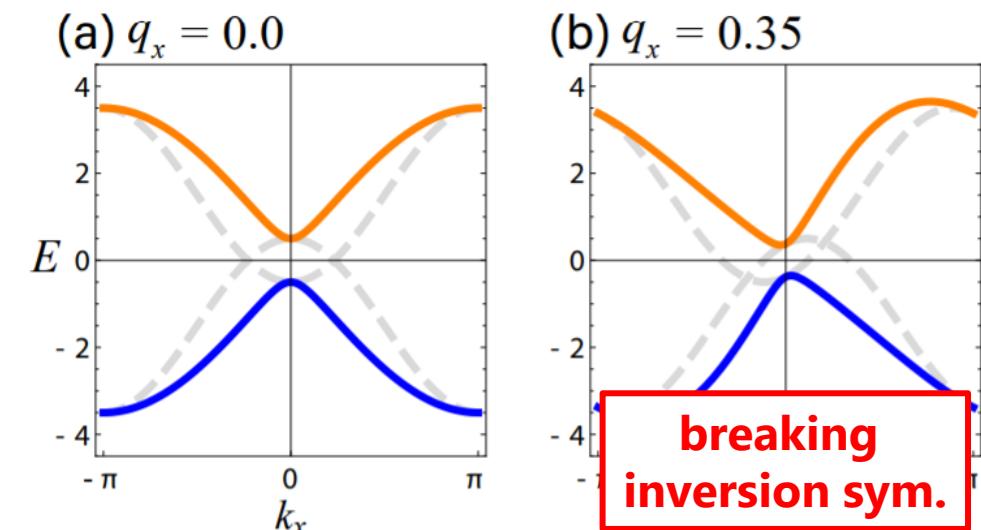
$$H = \frac{1}{2} \sum_{\mathbf{k}} \Psi_{\mathbf{k}; \mathbf{q}}^\dagger H_{\text{BdG}}(\mathbf{k}; \mathbf{q}) \Psi_{\mathbf{k}; \mathbf{q}}, \quad \Psi_{\mathbf{k}; \mathbf{q}} = (c_{\mathbf{k}+\mathbf{q}, \uparrow}, c_{\mathbf{k}+\mathbf{q}, \downarrow}, c_{-\mathbf{k}+\mathbf{q}, \uparrow}^\dagger, c_{-\mathbf{k}+\mathbf{q}, \downarrow}^\dagger)^T$$

$$H_{\text{BdG}}(\mathbf{k}; \mathbf{q}) = \begin{pmatrix} H_N(\mathbf{k} + \mathbf{q}) & \Delta(\mathbf{k}) \\ \Delta^\dagger(\mathbf{k}) & -H_N^T(-\mathbf{k} + \mathbf{q}) \end{pmatrix}$$

cf. H_{eff}

Example: Kitaev chain (1D p-wave SC)

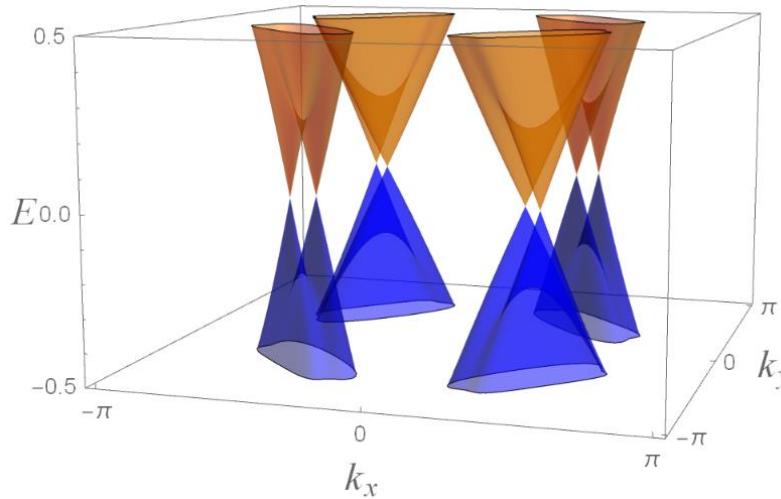
Bogoliubov spectrum becomes asymmetric!



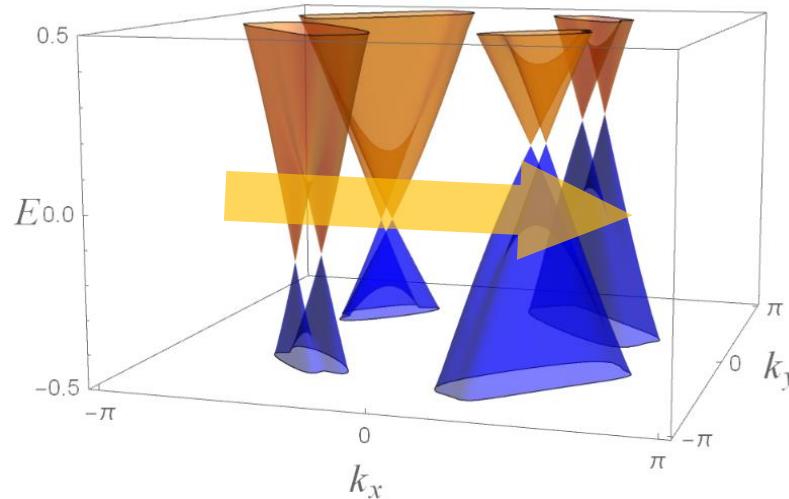
DC-current-induced topological superconductivity (2D)

KT, S. Sumita, Y. Yanase, Phys. Rev. B **106**, 014508 (2022)

w/o supercurrent



w/ supercurrent



2D D+p-wave SC with Rashba-Zeeman SOC

$$H_N(\mathbf{k}) = \xi(\mathbf{k})\sigma_0 + [\alpha\mathbf{g}_R(\mathbf{k}) + \beta\mathbf{g}_Z(\mathbf{k})] \cdot \boldsymbol{\sigma},$$

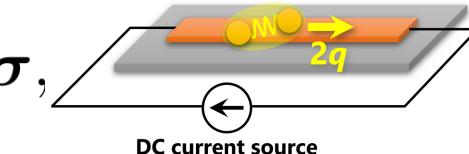
$$\Delta(\mathbf{k}) = \{\psi_d(\mathbf{k})\sigma_0 + \mathbf{d}(\mathbf{k}) \cdot \boldsymbol{\sigma}\}i\sigma_y,$$

$$\mathbf{g}_R(\mathbf{k}) = (-\sin k_y, \sin k_x, 0)$$

$$\mathbf{g}_Z(\mathbf{k}) = (0, 0, \sin k_x)$$

$$\psi_d(\mathbf{k}) = \Delta_d(\cos k_x - \cos k_y)$$

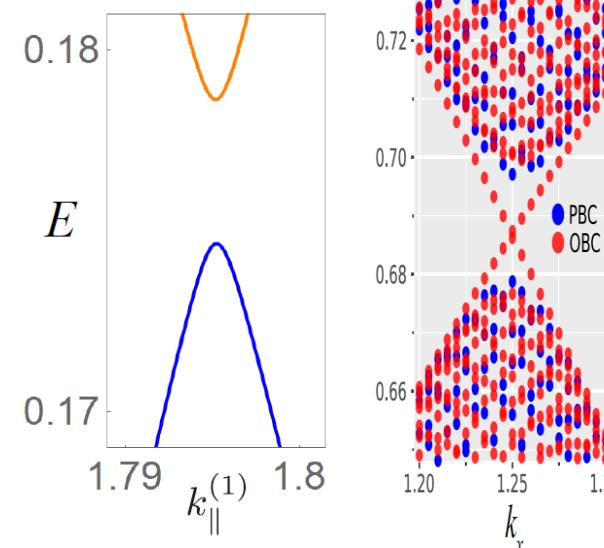
$$\mathbf{d}(\mathbf{k}) = \Delta_p(\sin k_y, \sin k_x, 0)$$



Fully-gapped topological SC
is realized

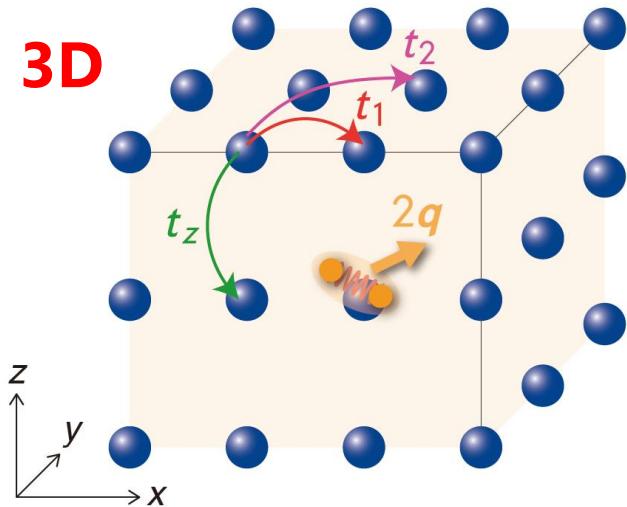
Class D, characterized by
Chern number

Symmetry-protection is lifted



DC-current-induced Weyl superconductivity (3D)

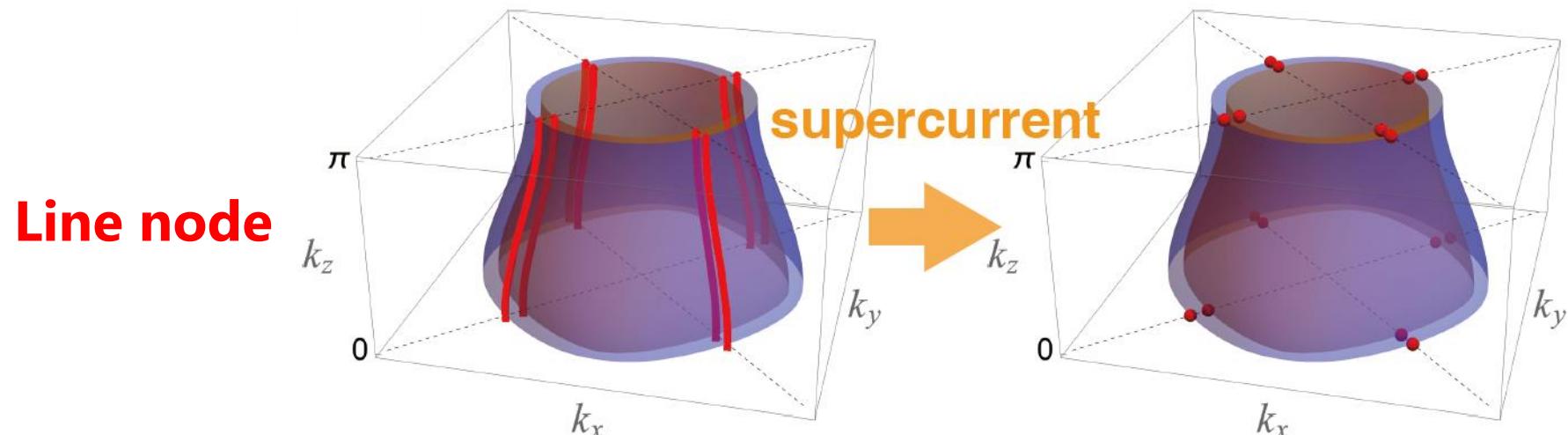
S. Sumita, [KT](#), J. Phys. Soc. Jpn. **91**, 074703 (2022)
 [Editor's Choice, JPS Hot Topics]



$$\xi(\mathbf{k}) = -2t_1(\cos k_x + \cos k_y) - 4t_2 \cos k_x \cos k_y - 2t_z \cos k_z - \mu,$$

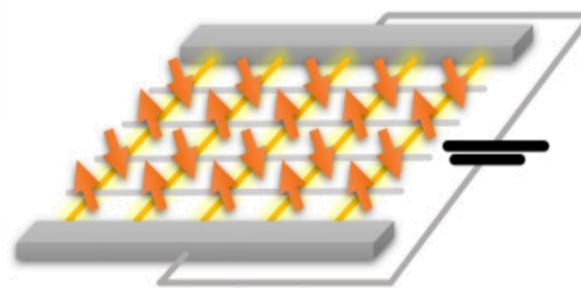
$$\mathbf{g}(\mathbf{k}) = \alpha_1(-\sin k_y \hat{x} + \sin k_x \hat{y}) + \alpha_2 \sin k_x \sin k_y \sin k_z (\cos k_x - \cos k_y) \hat{z},$$

Higer-order SOC

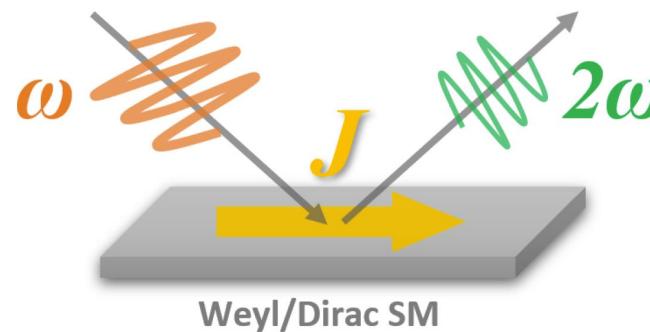


Outlook: Experimentally-feasible proposal, Serious theory

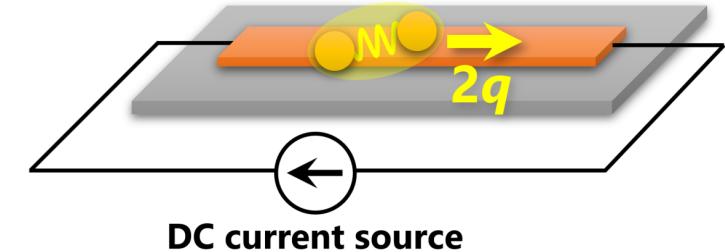
Insulator + DC field



Metal + DC current



Superconductor + DC current



1. More experimentally-feasible proposals

find “tiny current makes a great change”, material-specific calculation

2. More serious theoretical treatments

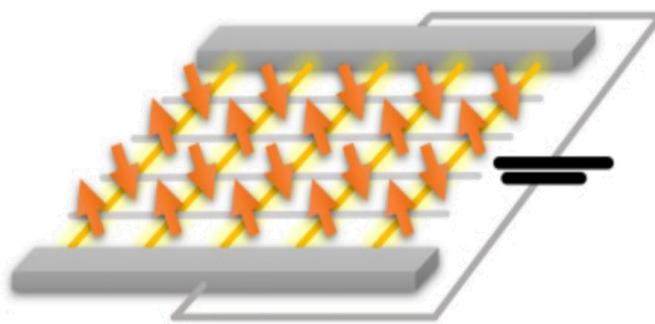
Boltzmann → Keldysh, Q. master eq., Supercurrent → vortex dynamics, beyond m.f., and so on

Understanding of *current-carrying nonequilibrium steady states* is essential

It has just started. Many aspects are still remained to be explored !

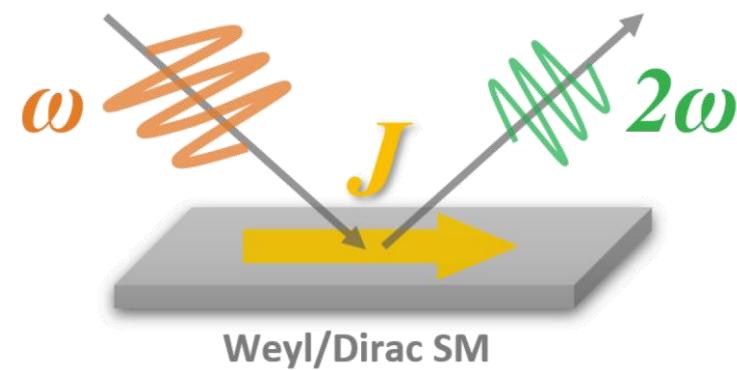
Summary: DC-driven quantum matter

Insulating magnets
+ DC electric field
→ **Control magnetic interaction**



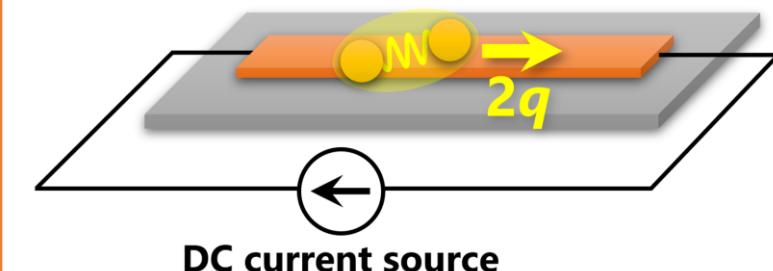
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Topological semimetals
+ DC electric current
→ **Enhance optical responses**



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