International workshop on "Axion physics and dark matter cosmology"   20-21 December 2017, Osaka University, JAPAN

Electromagnetic effect due to axion dynamics in a superlattice of topological insulators

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Topological Materials Science

トポロジーが紡ぐ物質科学のフロンティア

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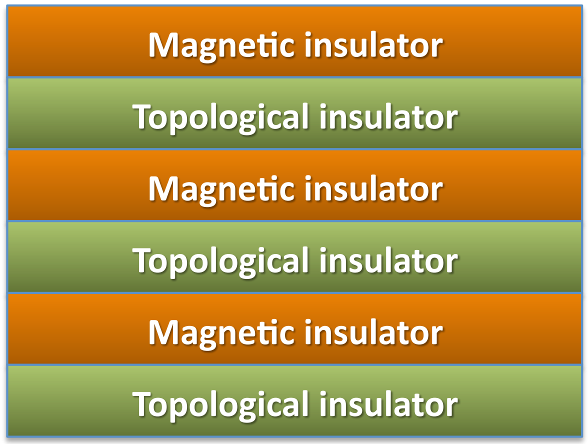
Naoya Kitajima (Nagoya University)

prepare to submit …

Superlattice



Outline

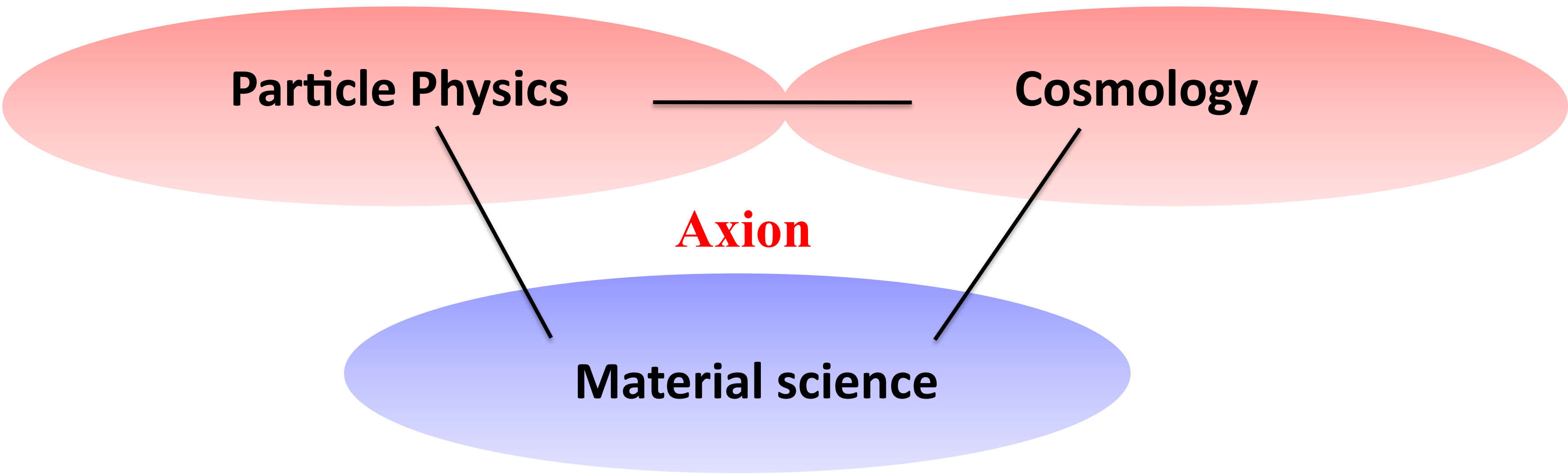
1. Introduction to **“axion” in material science**

2. Our idea to generate the dynamical “axion”
   by an applying magnetic field

3. Summary

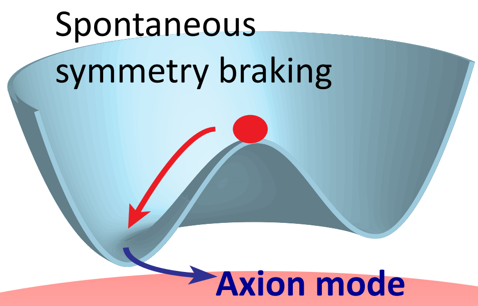
"Axion" in material science

Axion is a common research theme
in the particle physics, cosmology, and material science

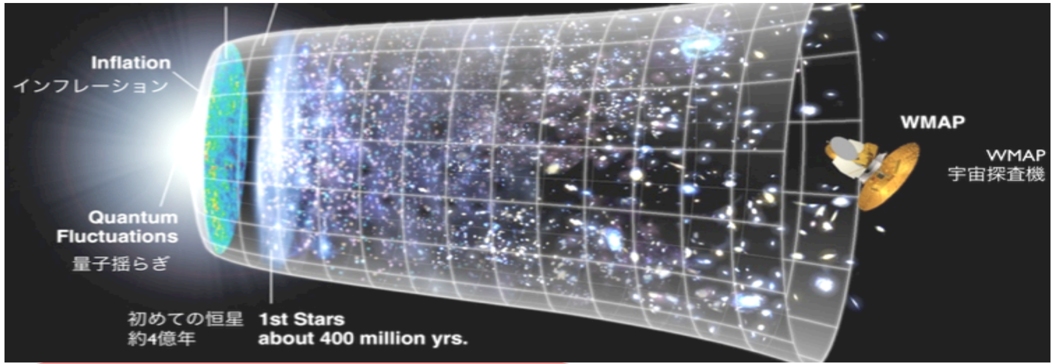


“Axion” in material science

Hypothetical particle
to resolve “strong CP problem”



Candidate for Dark Matter

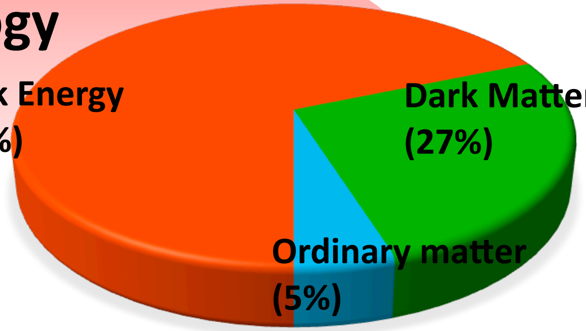


Particle Physics

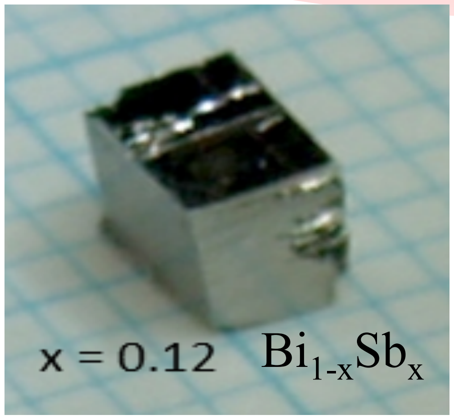
Cosmology

Axion

Material science



Planck 2013 results



“Axion” [axion-like particle]
is hosted in topological materials

Topological materials

It's very hot theme for material science

Theory (~ 2000) ⇒ discovery of theory about "topology" in the condensed matter
2007 : Science 138(2007) 766 [2D topological insulator]
2008 : Nature 452(2008) 970 [3D topological insulator]

2016 Noble Prize in Physics

Mahmoud
David J. Thouless

Mahmoud
F. Duncan M.Haldane

J. Michael Kosterlitz

The Nobel Prize in Physics 2016 was awarded with one half to David J. Thouless, and the other half to F. Duncan M. Haldane and J. Michael Kosterlitz *"for theoretical discoveries of topological phase transitions and topological phases of matter"*.

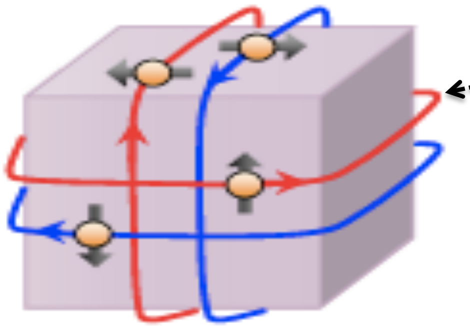
Topological insulators

Hasan and Kane, Rev. Mod. Phys (2010),
Qi and Zhang, Rev. Mod. Phys (2011),
Ando JPSJ (2013)

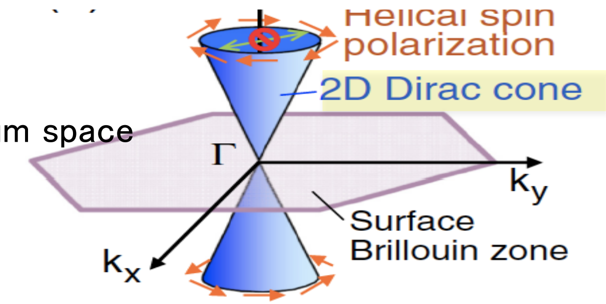
Topological insulator

- Bulk: Insulator
- Surface: Metallic

Helical edge state
・Spin-dependent transport
・2D Dirac cone



Real space



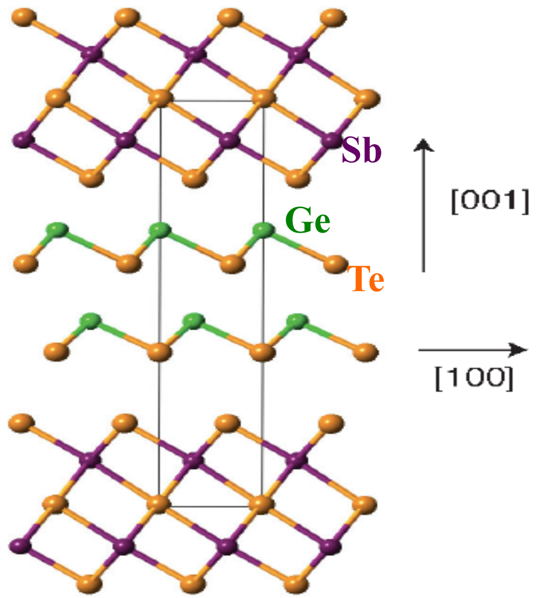
Momentum space

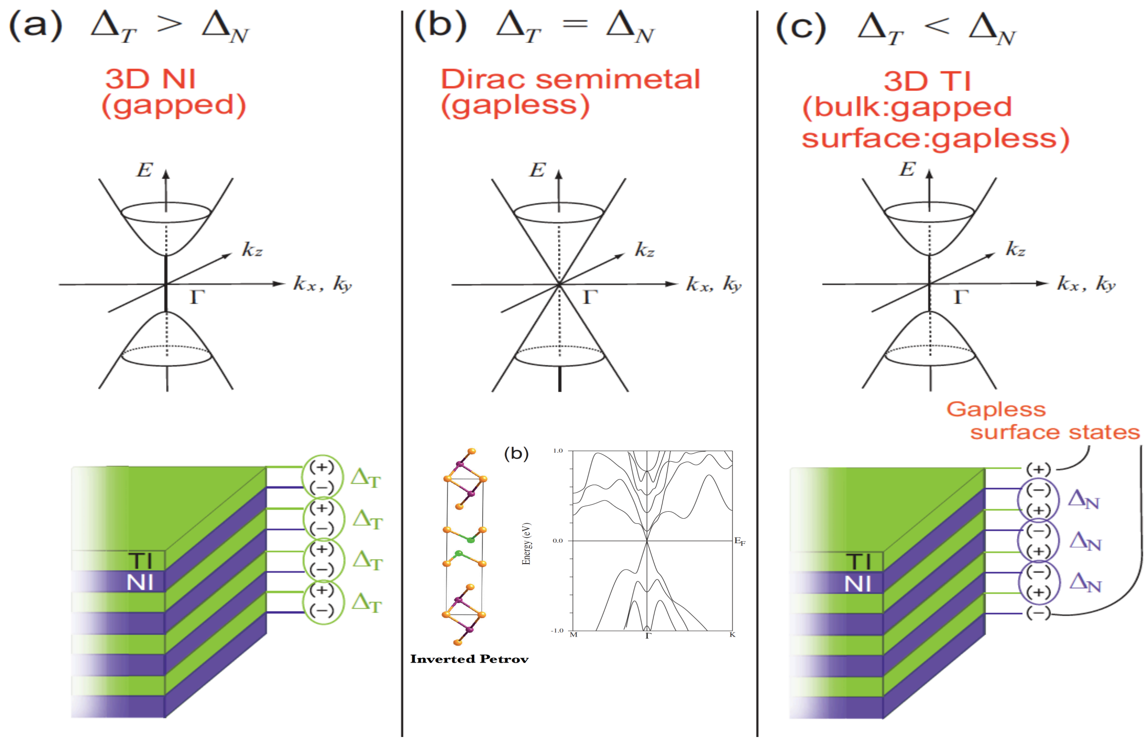
Superlattice

Superlattice of topological insulator (TI) and normal insulator (NI)

Superlattice of GeTe (NI)/ SbTe (TI)

Ref: J. Tominaga, et al., Adv. Mater. Interfaces 1, 1300027(2014)





This material has been already applied in ***interfacial phase change memory***

Lagrangian in a topological insulator

Effective Lagrangian in a topological materials is described by

(Topological insulator, Weyl semimetal, Dirac semimetal, etc…)

Ref: F. Wilczek, PRL 58, 1799 (1987).
X.-L. Qi, T. L. Hughes, and S.-C. Zhang, PRB 78, 195424 (2008).
A. M. Essin, J. E. Moore, and D. Vanderbilt, PRL. 103, 259902 (2009).

$$\mathcal{L}_a = g_{a\gamma\gamma}\alpha\theta(\boldsymbol{x},t)\boldsymbol{E}\cdot\boldsymbol{B}$$

Coupling constant

Fine structure
= 1/137

~ "axion-like"
particle (or field)

Electric field
and magnetic field

This Lagrangian is similar to the Lagrangian in Field theory (QCD-axion)

so

"θ"-term is called as "axion" field

Maxwell equations

Maxwell equation from Euler-Lagrange Equation

$$\nabla \mathrm{E} = 4\pi\left[\rho + \frac{e^2}{2\pi h}\nabla\left(\frac{\theta}{\pi}\right)\boldsymbol{B}\right]$$

Anomalous Hall effect term (Hall effect w/o ***B***)

$$\mathrm{rotB} - \frac{1}{c}\frac{\partial E}{\partial t} = 4\pi\left[j + \frac{e^2}{2h}\nabla\left(\frac{\theta}{\pi}\right)\times E + \frac{e^2}{2\pi h}\frac{\dot{\theta}}{\pi}B\right]$$

Chiral magnetic effect term

j_a : axion induce current

$\nabla\theta$ and $\partial_t\theta$ couple with electromagnetic fields

Trigger characteristic transport:

Ref: F. Wilczek, PRL 58, 1799 (1987).
X.-L. Qi, T. L. Hughes, and S.-C. Zhang, PRB 78, 195424 (2008).
A. M. Essin, J. E. Moore, and D. Vanderbilt, PRL. 103, 259902 (2009).

Today's topic

Study of "Axion" in **material science**

Why ?

The reasons are …

1. **Interaction** between "Axion" and electromagnetic fields in materials science could be large (compared with that in QCD-axion)

2. **Controllable** "Axion" by using knowledge of material science

3. There are some analogy between particle physics (cosmology) and material science
(e.g., majorana fermion, axion ..)

Material science v.s. particle physics & cosmology

particle physics & cosmology		Material science
High energy physics	**energy scale**	Low energy physics 0.1 meV ～1 eV
Strong CP Dark matter	**context**	**Unconventional electromagnetic effects**
Pure research	**Pure or applied**	Pure & **Device application via the electromagnetic effects**

Material science v.s. particle physics & cosmology

Property of “Axion” in the particle physics vs that in the material science

$$\mathcal{L}_a = g_{a\gamma\gamma}\alpha\theta(\boldsymbol{x},t)\boldsymbol{E}\cdot\boldsymbol{B}$$

	Partciel physics + cosmology	Material science
Type of axion	QCD axion, ALPs	Topological axion
Interaction strength	Very small (~10^{-19})	Large (~1)
Character	Dynamical	**Not dynamical**
Detection	Halo scope (cavity) + Primakoff effect	In this topic

Dynamical Axion signals in the both field have not seen yet!!
First, let’s try to consider about the axion response in material science.

Take-home message

Topological materials are …

good experimental platforms for testing axion physics,

because of

Controllable parameters such as coupling constant and axion mass

“Axion” is controllable in lab…
We can challenge a low-energy physics

so

axion is **not** “dark” in material science!

Naively question:

Is there true of the effective Lagrangian even in material science ?

$$\mathcal{L}_a = g_{a\gamma\gamma}\,\alpha\,\theta(\boldsymbol{x}, t)\,\boldsymbol{E}\cdot\boldsymbol{B}$$

Coupling constant

Fine structure = 1/137

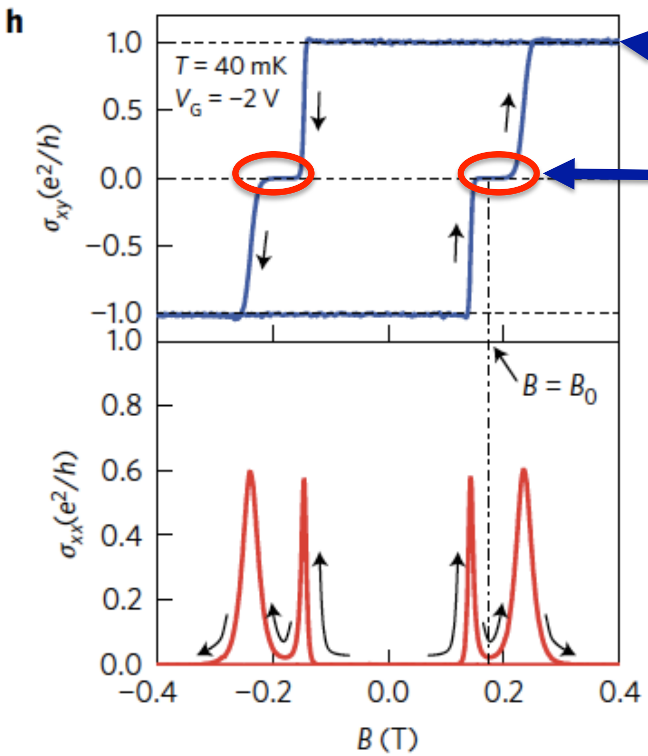
~ "axion-like" particle (or field)

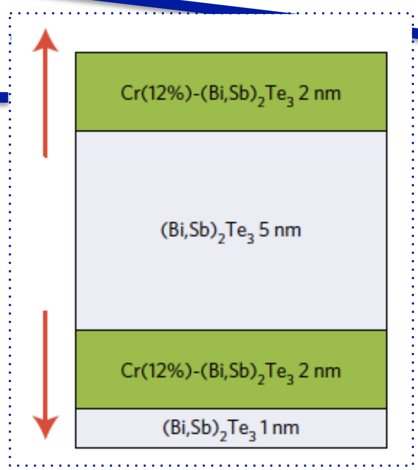
Electric field and magnetic field

Evidence of static axion in material science

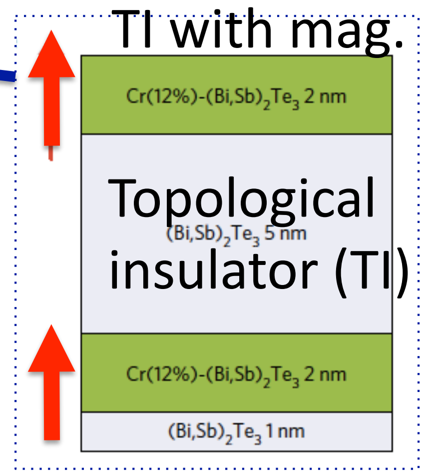
Electrical evidence: Quantum Hall effect

M. Mogi, et al., Nat Mater advance on, (2017).





Anti-parallel
magnetic configuration



Parallel
magnetic configuration

There is cancelation (=1/2 - 1/2) of each half-quantum Hall effect on top and bottom surface of TIs

There is no-cancelation half-quantum Hall effect (=1/2 + 1/2)

Optical evidence in TIs : Giant (half-quantized) Kerr effect

"Quantized Faraday and Kerr rotation and axion electrodynamics of a 3D topological insulator"
Liang Wu et al.,

Maxwell equation include axion field

Maxwell equation from Euler-Lagrange Equation

$$\nabla E = 4\pi[\rho + \frac{e^2}{2\pi h}\nabla\left(\frac{\theta}{\pi}\right)\boldsymbol{B}]$$

$$\mathrm{rot}B - \frac{1}{c}\frac{\partial E}{\partial t} = 4\pi[j + \frac{e^2}{2h}\nabla\left(\frac{\theta}{\pi}\right)\times E + \frac{e^2}{2\pi h}\frac{\dot{\theta}}{\pi}B]$$

Chiral magnetic effect

j_a : axion induce current

However…

In usual TI, as θ is static, it does not have time-dependence. (and θ = π)

You can not see the electromagnetic effect following Maxwell equation!!

We dare to think the dynamical θ from the analogy of particle physics

However, There is the source term generated by the time-dependent axion field

➡ How can we make such dynamical axion field ?

Our idea

“Generating the time-dependent θ using the spin-flip “

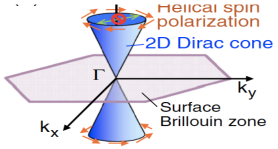
Our motivation and purpose

Conventional works consider static “axion”-response

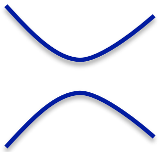
Our work shows that …
[1] how to drive dynamical “axion”-response
[2] the electromagnetic effect via dynamical “axion”-response

θ term is mathematically described when there is gap

X.-L. Qi, T. L. Hughes, and S.-C. Zhang, PRB 78, 195424 (2008). [See Eq.
P. Hosur, S. Ryu, and A. Vishwanath, PRB 81, 45120 (2010).
R. Li, J. Wang, X.-L. Qi, and S.-C. Zhang, Nat Phys 6, 284 (2010).



Gapless (massless)



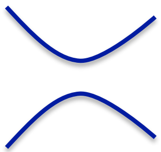
Gap

θ term is obtained from Hamiltonian with PT-symmetry

$$H(\boldsymbol{k}) = \boldsymbol{k} \cdot \boldsymbol{\Gamma} + \phi_4 \Gamma_4 + \phi_5 \Gamma_5,$$

$$\{\Gamma_i, \Gamma_j\} = 2\delta_{ij}$$

φ_4 corresponding the band gap in $\varphi_5=0$



Gap

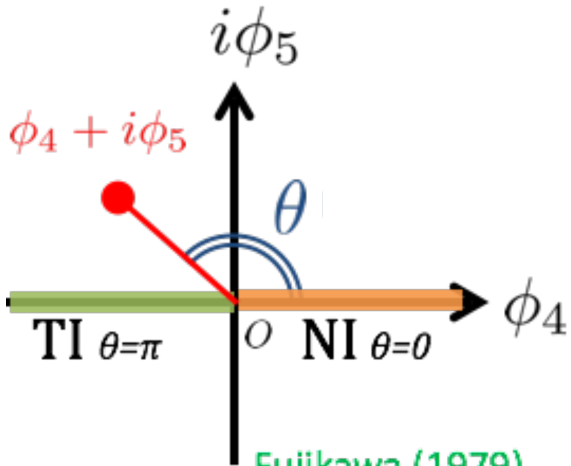
φ_5 corresponding the breaking P and T simultaneously

Hamiltonian with PT-symmetry

$$H(\boldsymbol{k}) = \boldsymbol{k}\cdot\boldsymbol{\Gamma} + \phi_4\Gamma_4 + \phi_5\Gamma_5,$$

Theta term

$$\theta = \mathrm{Arctan}(\varphi_5/\varphi_4)$$



Fujikawa (1979)
Wang, Lian, Zhang (2016)

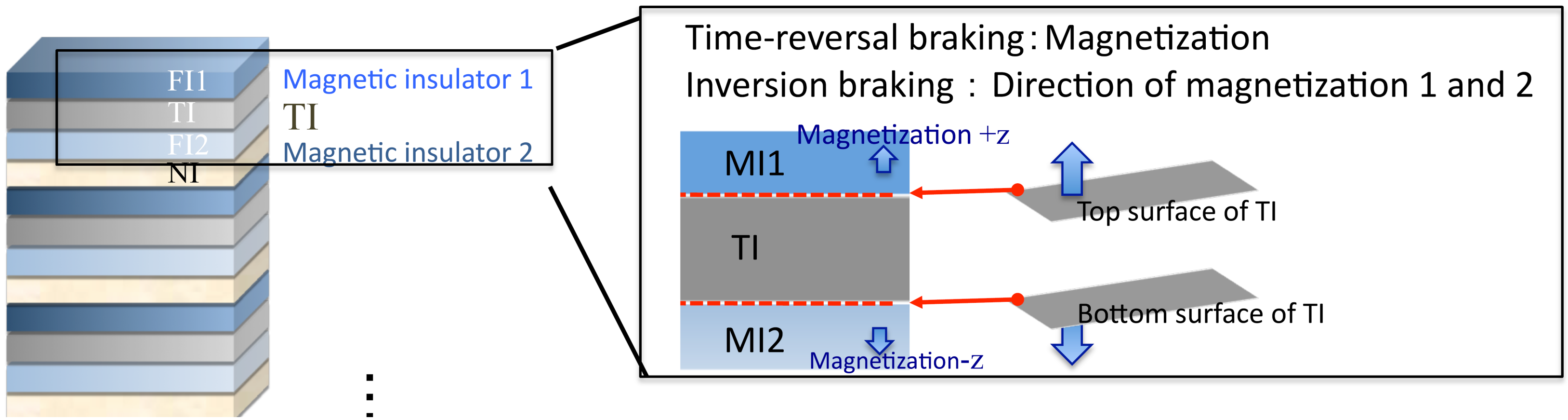
[Review] P. Hosur, S. Ryu, and A. Vishwanath, PRB 81, 45120 (2010).
K. Fujikawa and H. Suzuki, "Path Integrals and Quantum Anomalies" Clarendon Press, Oxford, 2004

Model

To control $\theta = \mathrm{Arctan}(\varphi_5 / \varphi_4)$

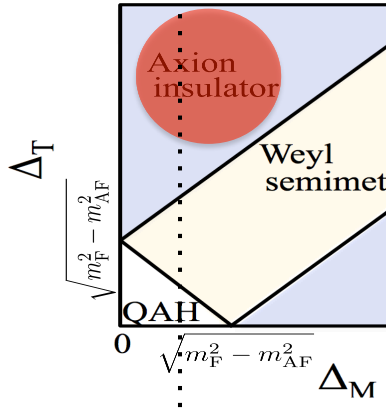
we consider the superlattice of topological insulators (TIs) and magnetic insulators (for P and T symmetry breaking)

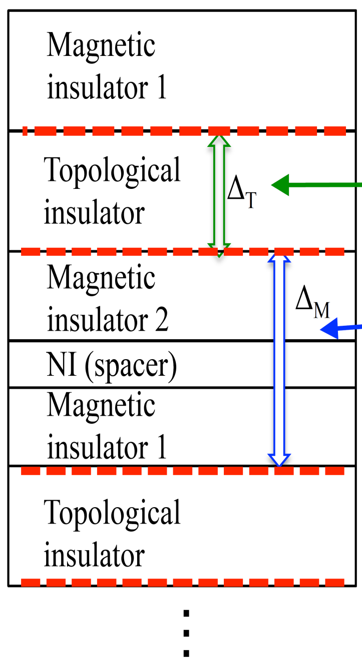
Superlattice of magnetic-topological insulator (TI) and magnetic insulator (MI1 and 2)



Consider thin film of the TIs and tunneling between TIs

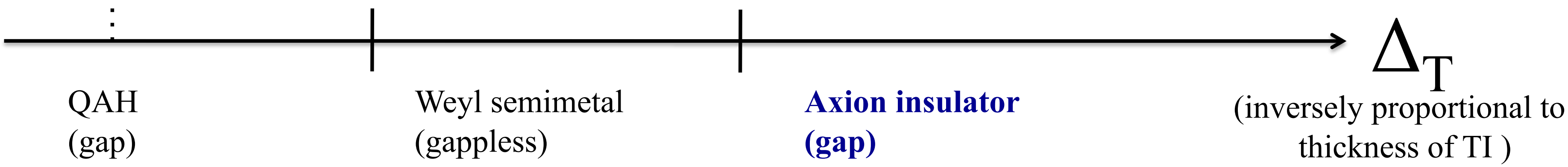
Ref: A. A. Burkov and L. Balents, PRL 107, 127205 (2011).





Δ_T: Tunneling between top and bottom of the same TI layer

Δ_M: Tunneling between top and bottom of neighboring TI layers



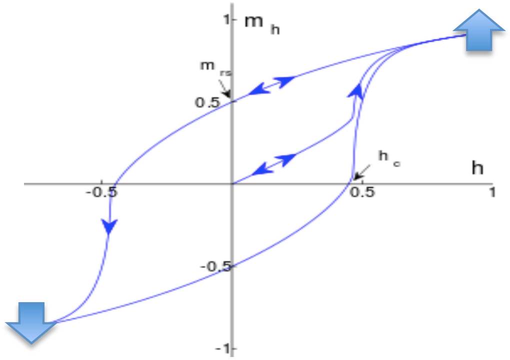
We consider axion insulator

How to derive $\partial_t \theta \neq 0$

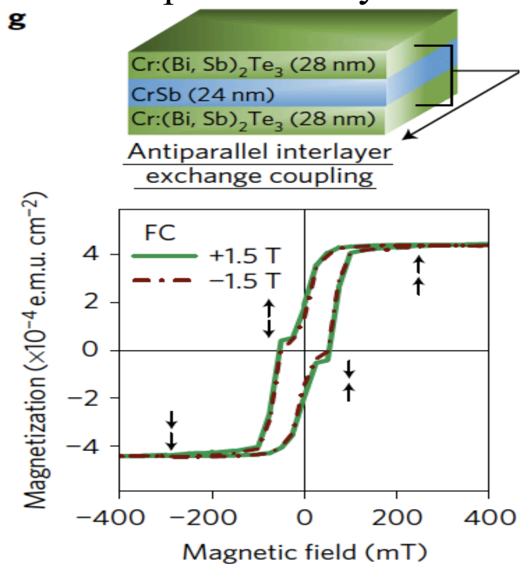
Anti-magnetic configuration is important for manipulation of θ

The magnetic order can be manipulated by an applied magnetic field B_{ex}

"Hard" M-H loop



M-H loop in multilayer



Q. L. He et. al., Nat Mater 16, 94 (2017)

Spin control of super-lattice devi

Assume:

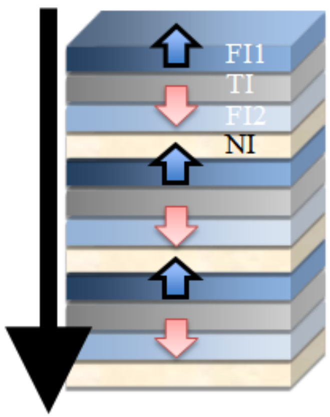
M1 soft

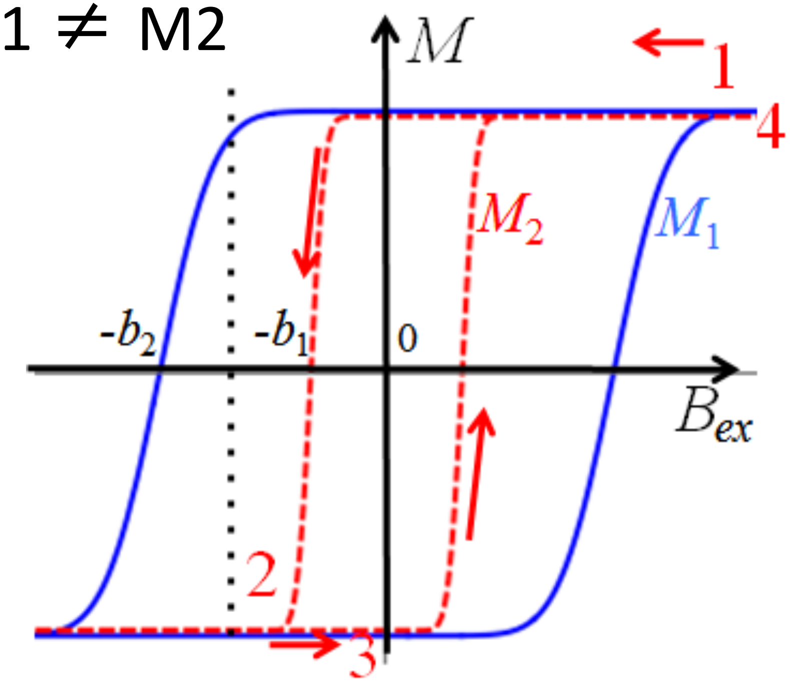
M2 hard

M1 ≠ M2

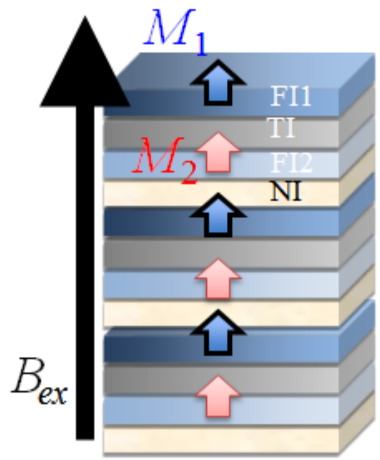
$\theta = \mathrm{Arctan}(\varphi_5 / \varphi_4)$

$b_1 < B_{ex} < b_2$





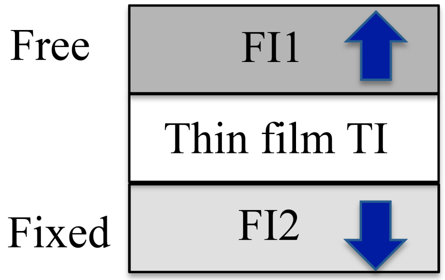
⇒starting point



Simple form

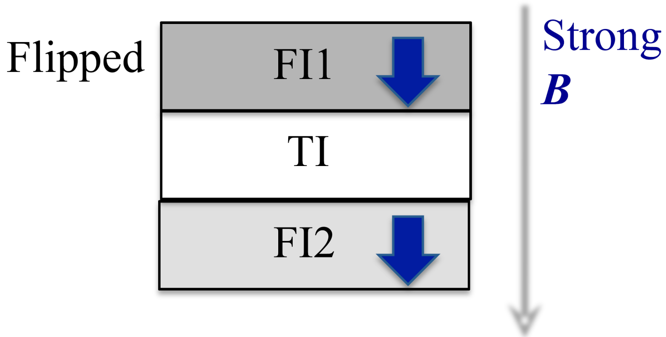
$\theta = 0$

In the absence of $\boldsymbol{B}_{ex}$: $\delta\theta\neq 0$

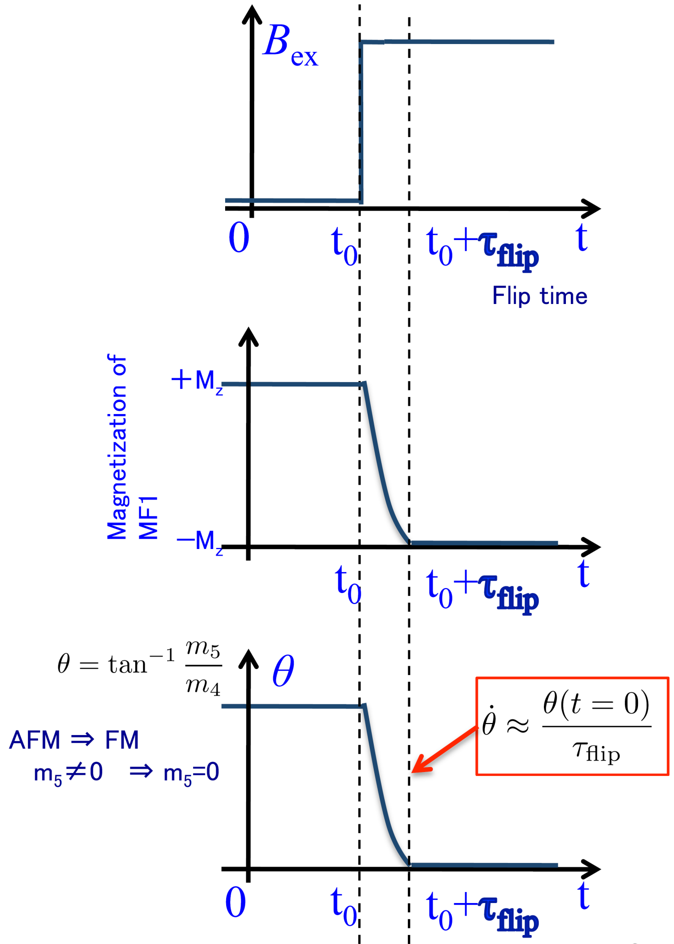


$\boldsymbol{B}_{ex}=0$

$t< t_0$ (initial state)



$t > t_0+\tau_{flip}$



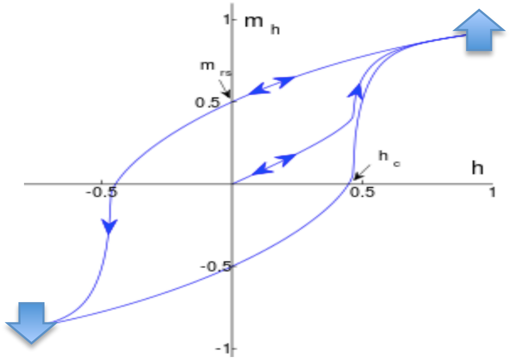
$$m_{AF} = m_{AF}(t=0)\exp(-\frac{t}{\tau_f})$$

How to derive $\partial_t \theta \neq 0$

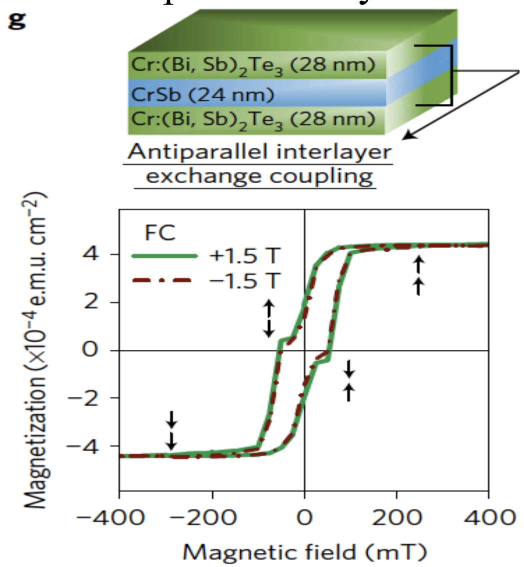
Anti-magnetic configuration is important for manipulation of θ

The magnetic order can be manipulated by an applied magnetic field B_{ex}

"Hard" M-H loop



M-H loop in multilayer



Q. L. He et. al., Nat Mater 16, 94 (2017)

Derivation

We assume the following Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{Maxwell}} + \mathcal{L}_{\mathrm{Axion}} + \mathcal{L}_{\mathrm{e}}$$

$$= \frac{1}{2}\left(\epsilon E^2 - \frac{1}{\mu}B^2\right) + \frac{\alpha}{2\pi\hbar}\theta \boldsymbol{E}\cdot\boldsymbol{B} + \boldsymbol{j}_e\cdot\boldsymbol{A}$$

Electric permittivity and magnetic permeability (ϵ, μ)

charge current ($\boldsymbol{j}_e$)

Assume

$$\boldsymbol{B} = \mu_0(\boldsymbol{H}+\boldsymbol{M}) \rightarrow \mu_0\boldsymbol{H}$$

$$\boldsymbol{D} = \tilde{\epsilon}\epsilon_0\boldsymbol{E} \rightarrow \epsilon_0\boldsymbol{E}$$

Maxwell equations

$$\boldsymbol{\nabla}\times\boldsymbol{E} = -\partial_t\boldsymbol{B}$$

$$\boldsymbol{\nabla}\times\boldsymbol{H} = \partial_t\boldsymbol{D} + \boldsymbol{j}_e + \boldsymbol{j}_a$$

$$\boldsymbol{j}_a = -\frac{c\epsilon_0\alpha}{\pi}\left[(\boldsymbol{\nabla}\theta)\times\boldsymbol{E} + (\partial_t\theta)\boldsymbol{B}\right]$$

α: fine structure, c: velocity of light

We obtain the wave equation for $\boldsymbol{B}$

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\boldsymbol{B}_{\rm ind} = \frac{1}{\epsilon_0}\boldsymbol{\nabla}\times\boldsymbol{j}$$

Induced magnetic field

Source term

$$\frac{1}{\epsilon}\boldsymbol{\nabla}\times\boldsymbol{j} = \frac{1}{\epsilon}\boldsymbol{\nabla}\times\boldsymbol{j}_e - \frac{c\alpha}{\pi}\left[(\boldsymbol{\nabla}\cdot\boldsymbol{E})\boldsymbol{\nabla}\theta - (\boldsymbol{\nabla}\theta)\cdot\boldsymbol{\nabla}\boldsymbol{E}\right] - \frac{c\alpha\mu}{\pi}\partial_t\theta\left(\partial_t\boldsymbol{D} + \boldsymbol{j}_e + \boldsymbol{j}_a\right), \quad (1$$

0 0

Assume

$\boldsymbol{\nabla}\times\boldsymbol{j}_e = 0$ and $\boldsymbol{E}$ is spatial uniform

Result:

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\boldsymbol{B}_{\rm ind} = -\frac{c\alpha\mu_0}{\pi}\partial_t\theta\left(\partial_t\boldsymbol{D} + \boldsymbol{j}_e + \boldsymbol{j}_a\right)$$

$$\boldsymbol{j}_a = -\frac{c\epsilon_0\alpha}{\pi}\left[(\boldsymbol{\nabla}\theta)\times\boldsymbol{E} + (\partial_t\theta)\boldsymbol{B}\right]$$

Main message:

dynamical θ is driven by applied magnetic field (B_{ex})

Result:

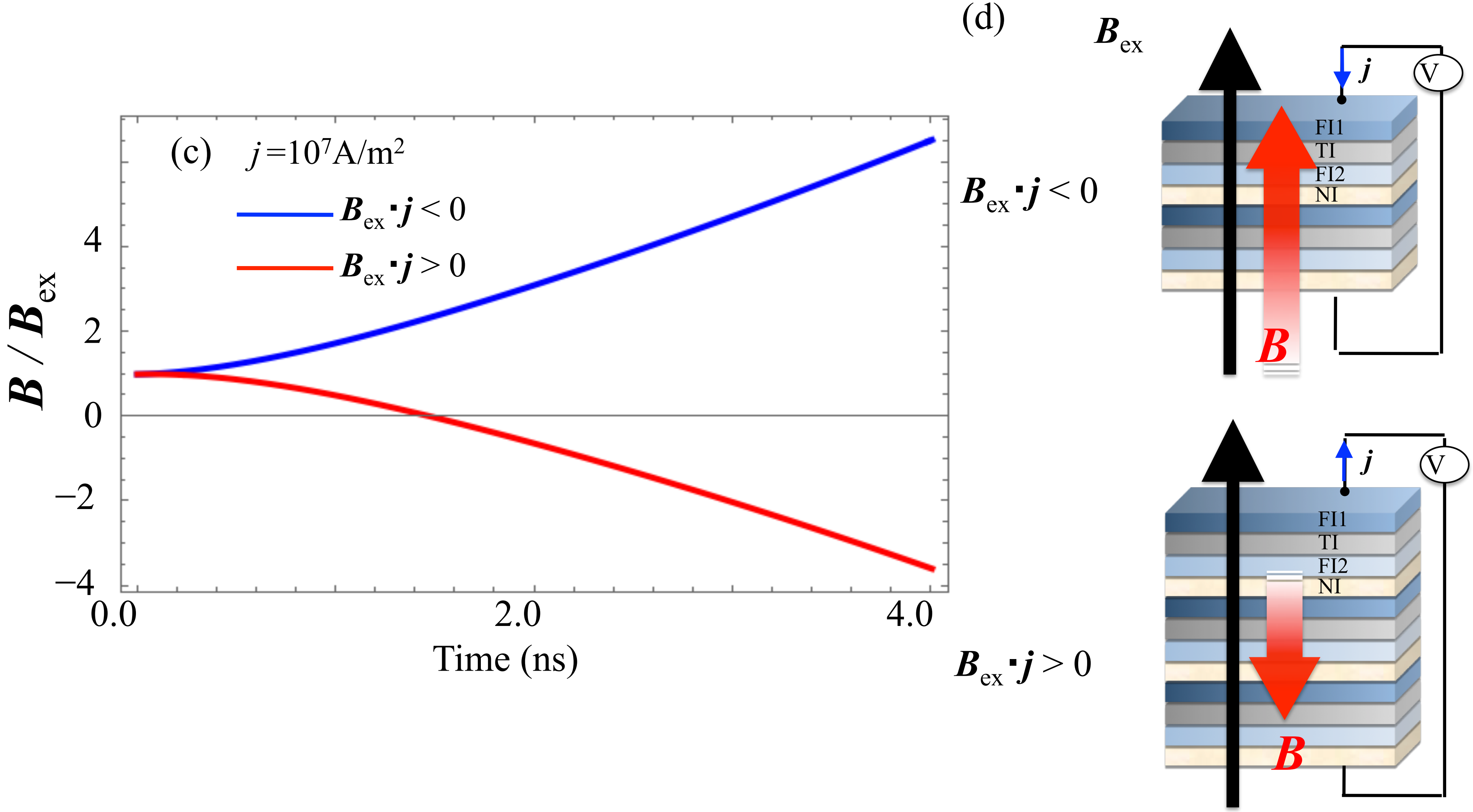
$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\boldsymbol{B}_{\rm ind} = -\frac{c\alpha\mu_0}{\pi}\partial_t\theta\left(\partial_t\boldsymbol{D} + \boldsymbol{j}_e + \boldsymbol{j}_a\right)$$

When we apply the external magnetic field,
the dynamcial θ is induced
and
the dynamical θ drives the electromagnetic effects

(Case 1) in the presence of only the external magnetic field

(Case 2) in the presence of the external magnetic field and charge current (***layered direction***)

(Case 3) in the presence of the external magnetic field and charge current (***inplane***)

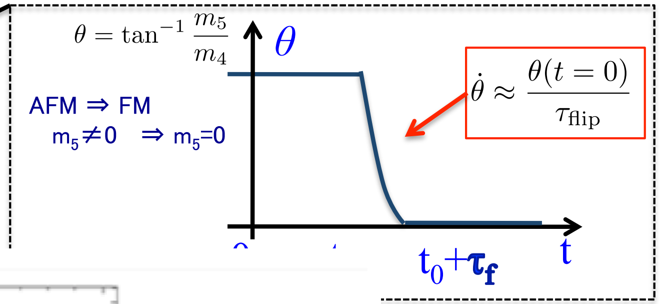


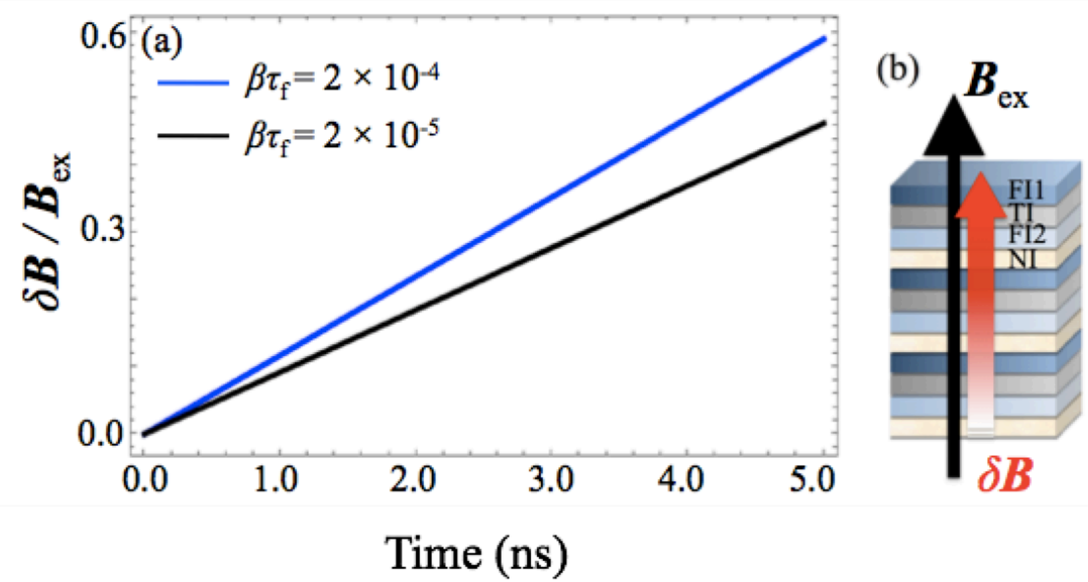
(c) j=10^7A/m^2
Bex·j < 0
Bex·j > 0
B / Bex
4
2
0
−2
−4
0.0
2.0
4.0
Time (ns)
(d)
Bex
j
V
FI1
TI
FI2
NI
B
Bex·j < 0
Bex·j > 0

(Case 1) in the presence of only the external magnetic field $B_{\rm ex}$

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\boldsymbol{B}_{\rm ind} = -\frac{c\alpha\mu_0}{\pi}\partial_t\theta\,(\partial_t \boldsymbol{D} + \boldsymbol{j}_e + \boldsymbol{j}_a)$$

$$= \frac{\alpha^2}{\pi^2}(\partial_t\theta)^2 \boldsymbol{B}_{\rm ex}.$$





Additionally induced magnetic field δB

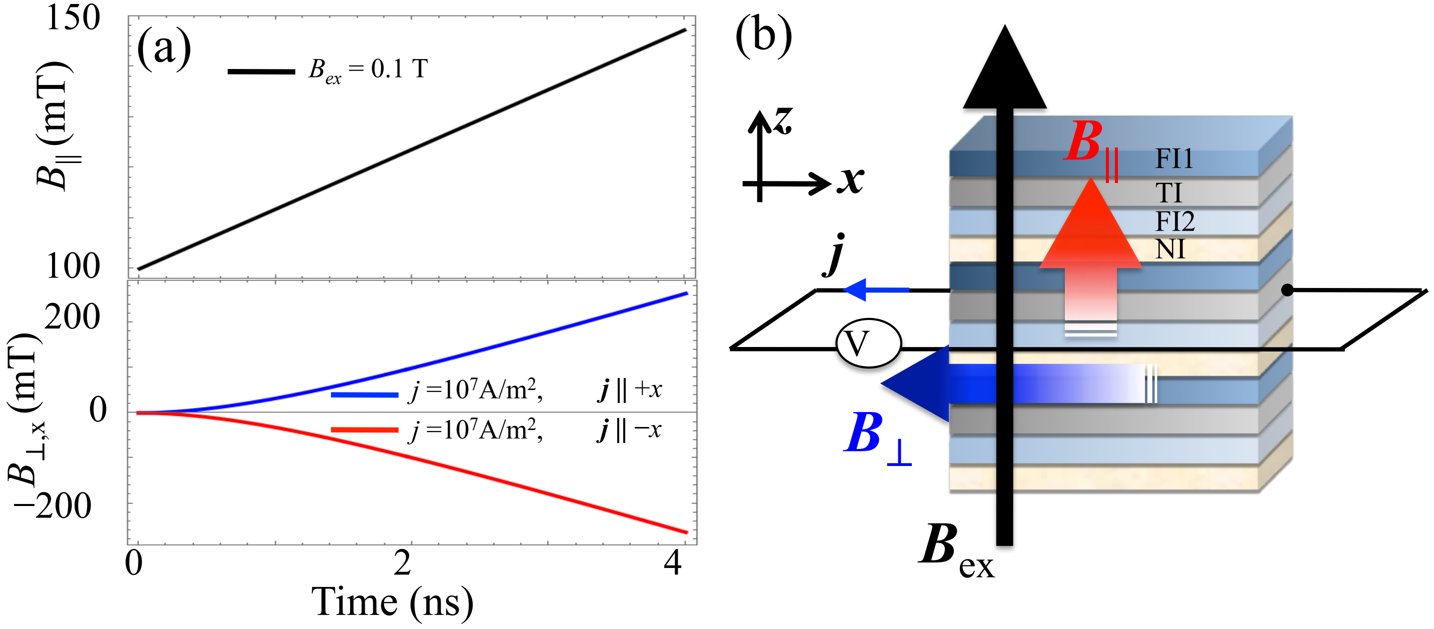
Besides, charge current via ***chiral magnetic effect***

(Case 3) in the presence of the external magnetic field and charge current (***inplane***)

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\boldsymbol{B}_{\mathrm{ind}} = -\frac{c\alpha\mu_0}{\pi}\partial_t\theta\left(\partial_t\boldsymbol{D} + \boldsymbol{j}_e\right) + \frac{\alpha^2}{\pi^2}\left(\partial_t\theta\right)^2\boldsymbol{B}_{\mathrm{ex}}$$

Contribution from ***charge current***

Contribution from $\boldsymbol{B}_{ex}$



How can this effect be detected ?

[1]. Planar hall effect

Planar hall voltage $\propto M^2 \sin\theta$

$\Rightarrow$ provably μV order and it's possible to detect the nsec response

[2]. Chiral magnetic effect

$$\mathrm{rot}B - \frac{1}{C}\frac{\partial E}{\partial t} = 4\pi[j + \frac{e^2}{2h}\nabla\left(\frac{\theta}{\pi}\right) \times E + \frac{e^2}{2\pi h}\frac{\dot{\theta}}{\pi}B]$$

$$j \propto \dot{\theta}B$$

Chiral magnetic effect

Probably, device resistance should be ~MΩ, it's possible to detect < nA current.

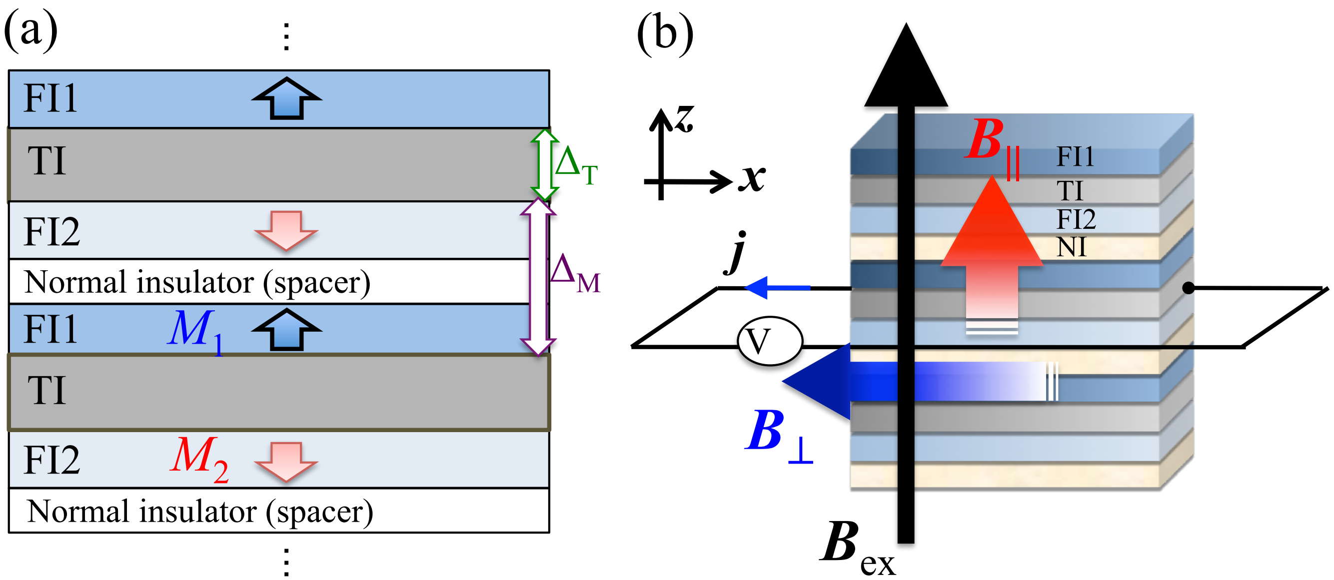
Summary

[1] We study the multilayer of topological insulators (TI) and magnetic insulator (MI)

$$\theta = \mathrm{Arctan}(\varphi_5/\varphi_4)$$

[2] For "axion"-response in materials,
we consider axion insulator and how to drive $\partial_t\theta \neq 0$ ⇒ **Use magnetization flip by B_{ex}**

[3] **Main result** We find that $\partial_t\theta$ and an applied electric field trigger magnetic field [Electromagnetic effect]



Summary

- **Axion is also important in the material science, specially in topological insulator** $\theta = \mathrm{Arctan}(\varphi_5 / \varphi_4)$
- **By this collaboration, we phenomenologically found new method and response for dynamical axion response**
- **Next plan is to first detect this response and connect this collaboration to particle physics and cosmology**

Please join us if you are interested in such activities !!