New approaches to/from dark matter

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Kanazawa University

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- PRD 106 (2022) 10, 103014 (with S. Ando, N. Hiroshima)

素粒子現象論研究会2022

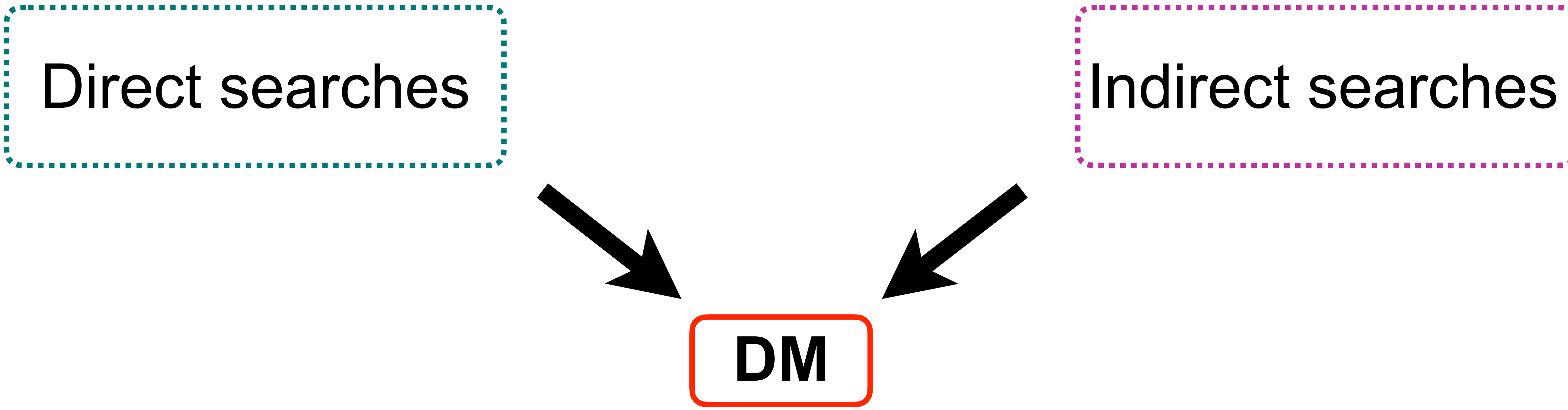
Osaka, March 16, 2023

1. Introduction

Dark matter (DM)

- Electrically neutral
- Non-baryonic
- Stable or sufficiently long-lived
- Non-relativistic
- $\Omega_{\rm DM} \simeq 0.26$
- $10^{-31}\ {\rm GeV} < m_{\rm dm} \lesssim M_{\rm Pl}$ or $10^{-14} < m_{\rm dm}/M_\odot \lesssim 10^{-12}$

Approaches from astro-particle physics and cosmology



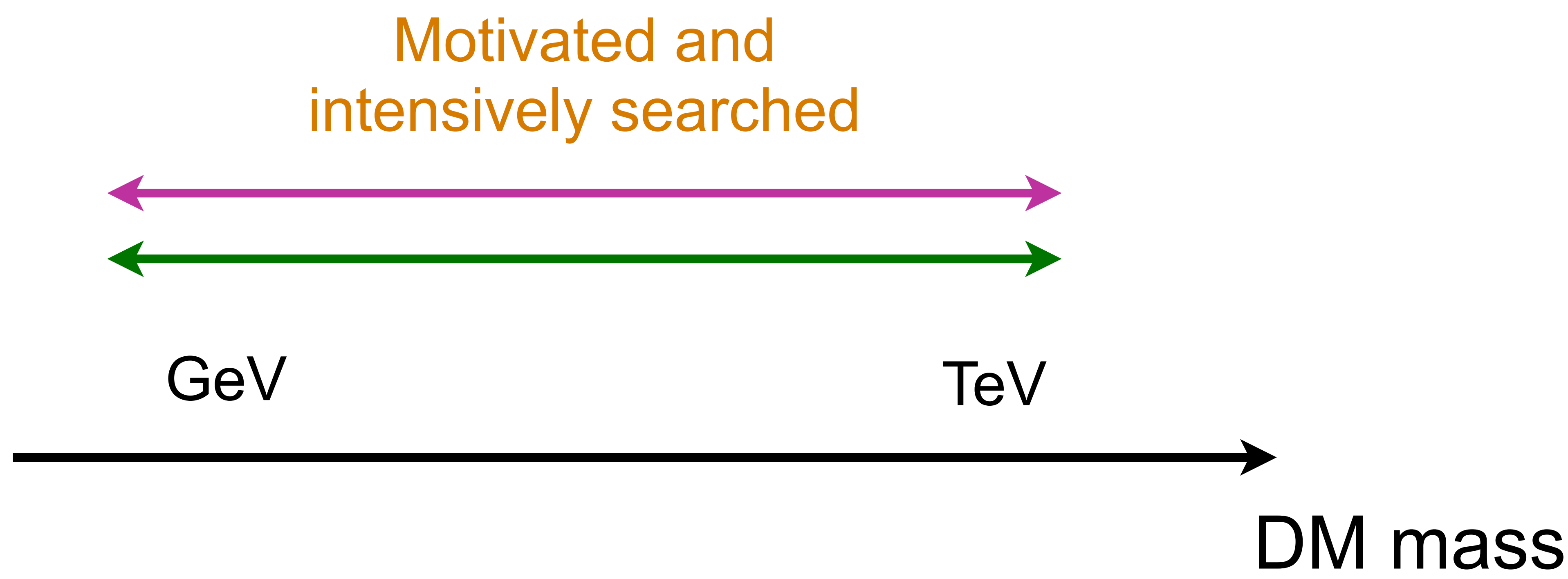
Approaches from astro-particle physics and cosmology

Direct searches

$\mathrm{DM\ SM} \to \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$

Indirect searches

$\mathrm{DM\ (DM)} \to \mathrm{SMs}$



Approaches from astro-particle physics and cosmology

Direct searches

$$\mathrm{DM\ SM} \to \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$$

Indirect searches

$$\mathrm{DM\ (DM)} \to \mathrm{SMs}$$

Motivated and
intensively searched

GeV

TeV

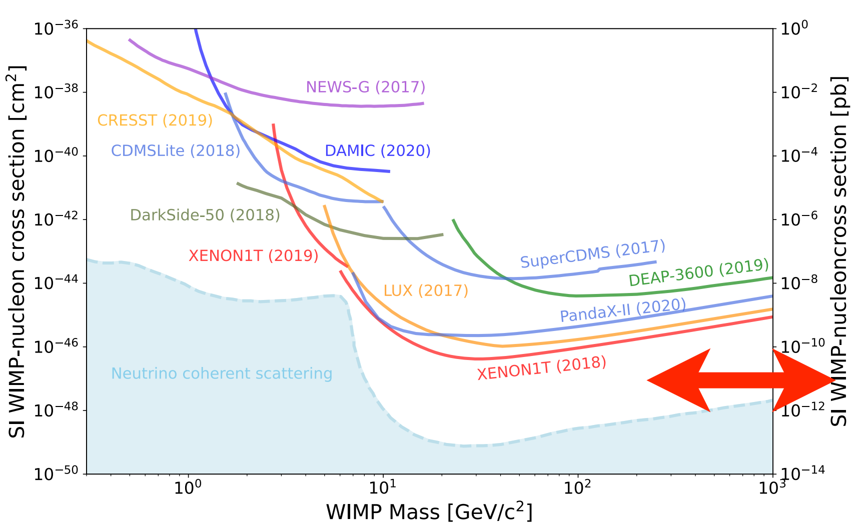
DM mass

e.g., Wino DM

$$\sigma^p_{\mathrm{SI}} = 2.3^{+0.2\ +0.5}_{-0.3\ -0.4} \times 10^{-47}\,\mathrm{cm}$$

Hisano, KI, Nagata '15

PDG '22



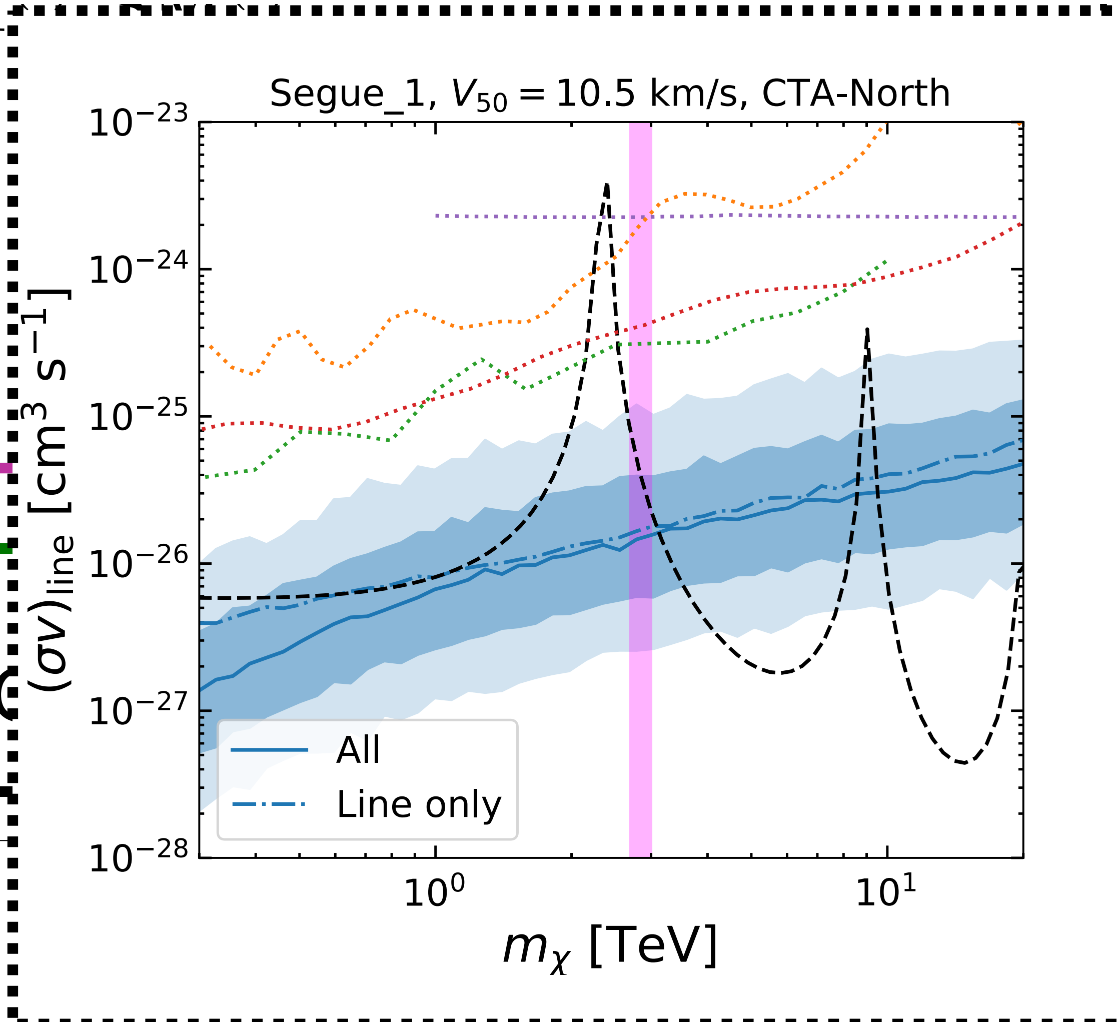
Approaches from astro-particle physics and cosmology

Direct sea

We'll find thermal Wino DM from ultrafaint dSphs

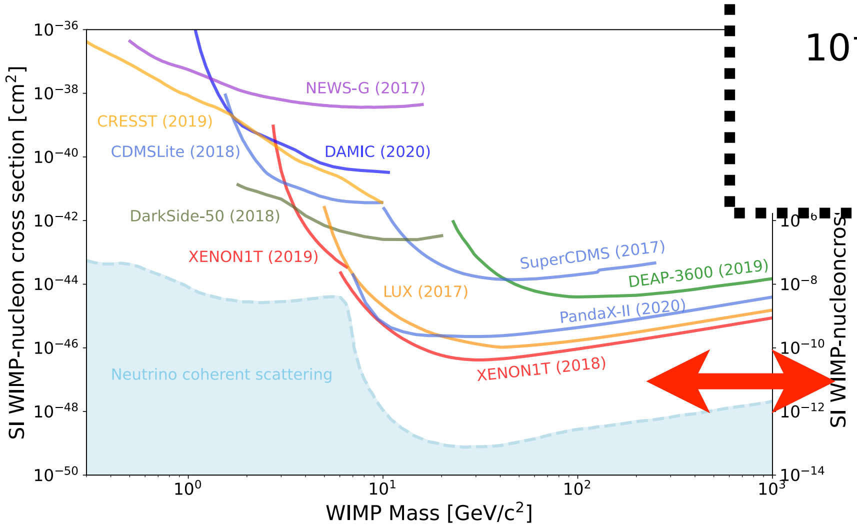
ct searches

$\mathrm{DM\ SM} \to \mathrm{D}$ ... $(\mathrm{DM}) \to \mathrm{SMs}$



Ando, KI '21

PDG '22



DM mass

em

Hisano, KI, Nagata '15

Approaches from astro-particle physics and cosmology

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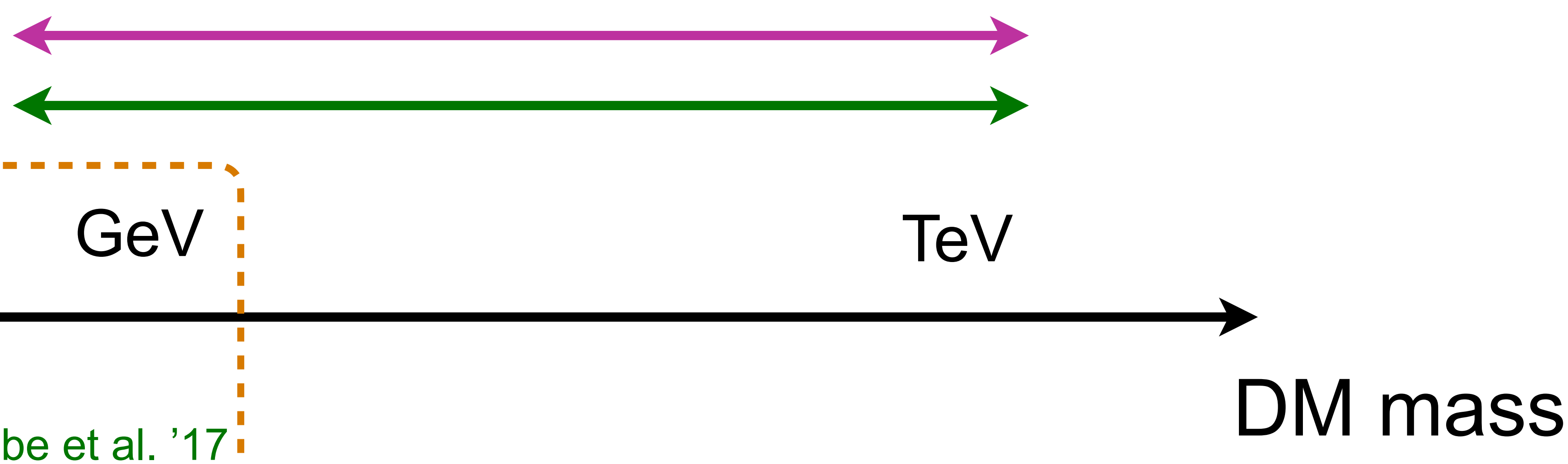

e.g.,

- Migdal effect — Ibe et al. '17
- Upscattering — Bringmann et al. '19, Ema et al. '19

Approaches from astro-particle physics and cosmology

Direct searches

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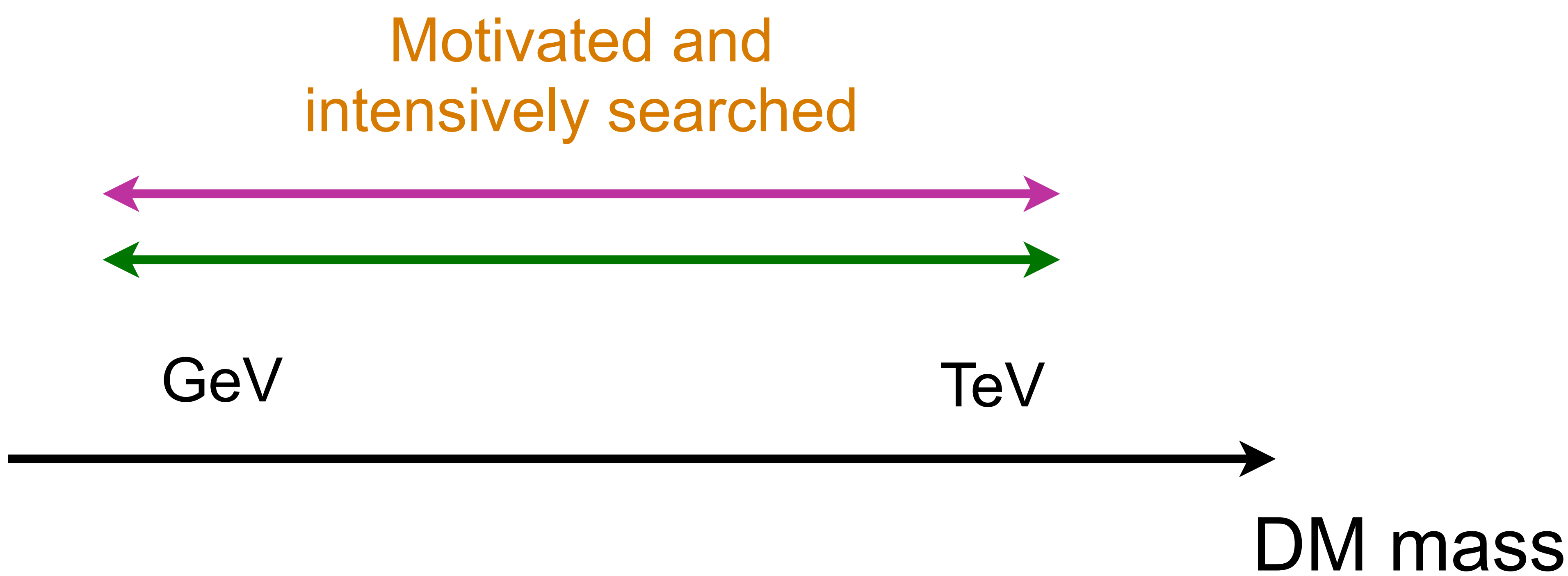

Approaches from astro-particle physics and cosmology

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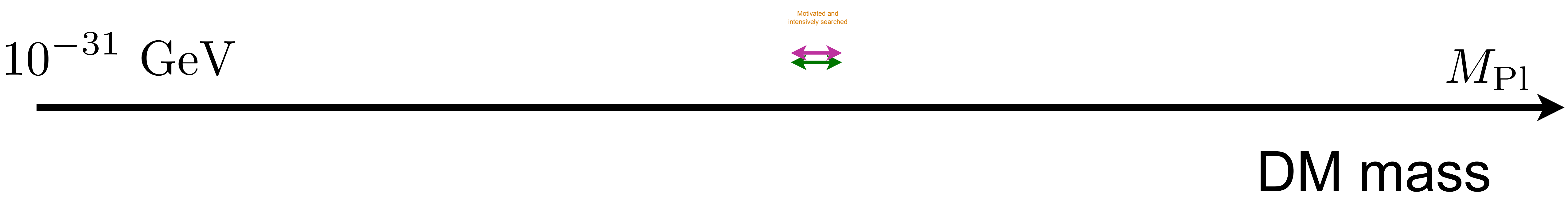

Approaches from astro-particle physics and cosmology

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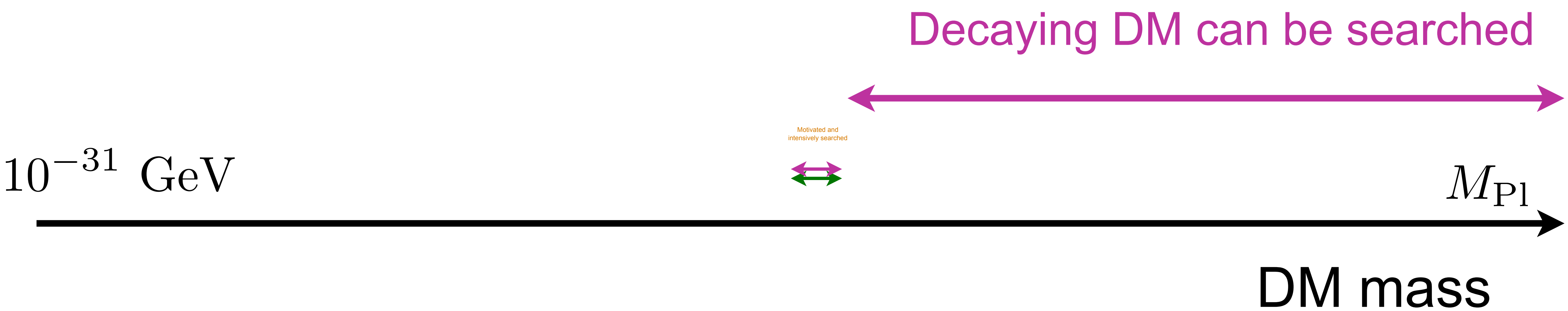
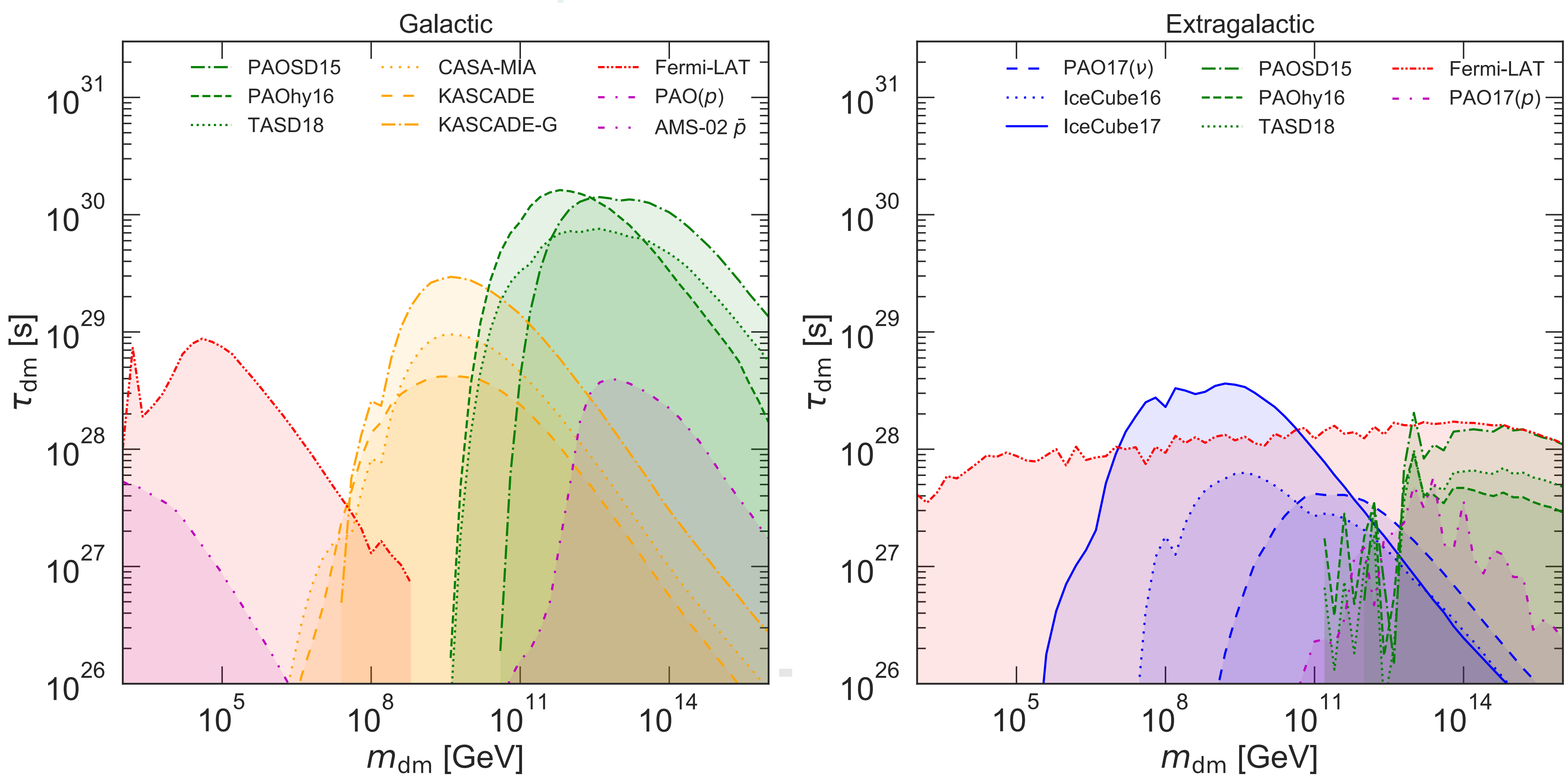


Approaches from astro-particle physics and cosmology

Ando, Arimoto, KI, Macias '20



Past works:

Esmaili, Ibarra, Peres '12
Murase, Beacom '12
Ahlers, Murase '14
Murase, Laha, Ando, Ahlers '15

Aloisio, Matarrese, Olinto '15
Kalashev, Kuznetsov '16
Cohen, Murase, Rodd, Safdi, Soreq '17
Kachelriess, Kalashev, Kuznetsov '18

Sui, Bhupal Dev '18

Approaches from astro-particle physics and cosmology

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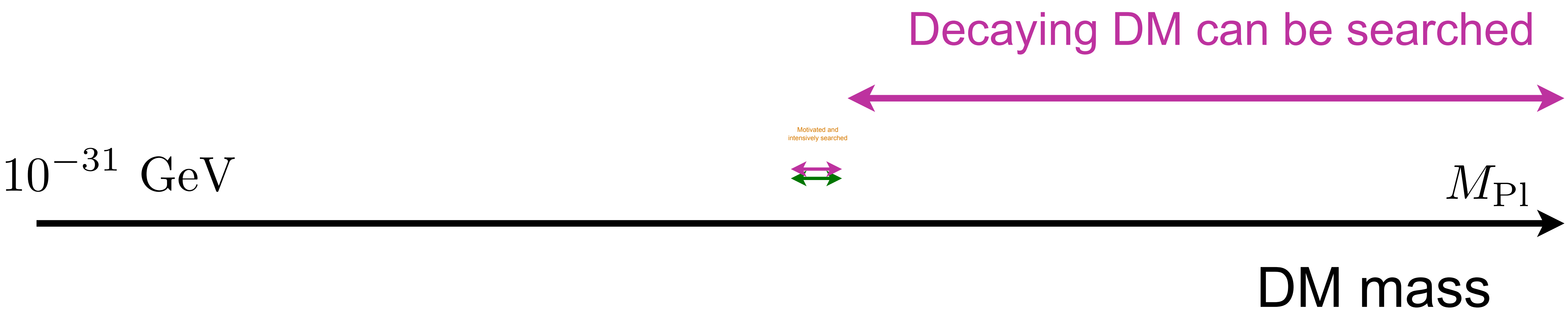


Approaches from astro-particle physics and cosmology

Direct searches

~~$\mathrm{DM}\ \mathrm{SM} \to \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$~~

using **topological insulators**

Axion, Axion-like particles

Indirect searches

$\mathrm{DM}\ (\mathrm{DM}) \to \mathrm{SMs}$

Today's 1st topic

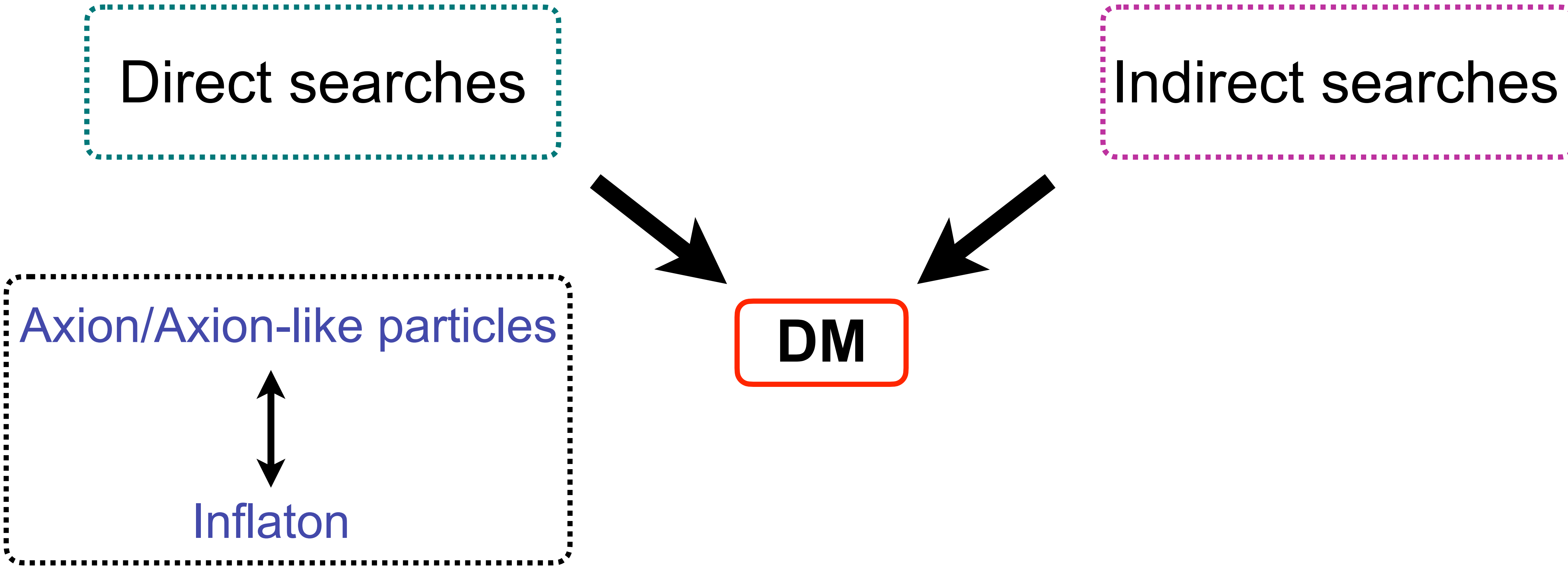
Motivated and intensively searched

10^{-31} GeV

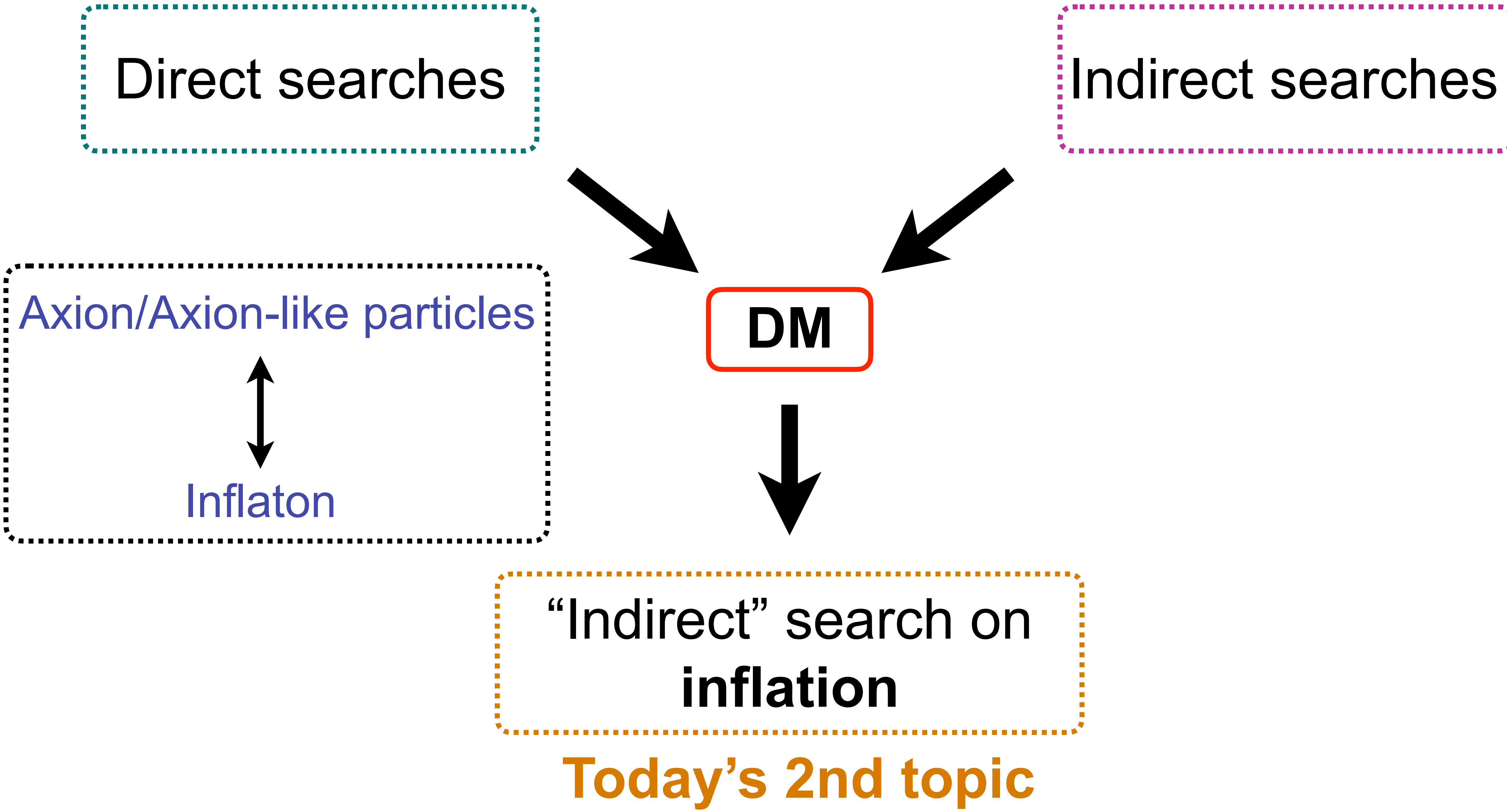
M_{Pl}

DM mass

Approaches from astro-particle physics and cosmology



Approaches from astro-particle physics and cosmology



Outline

1. Introduction

2. Axion in topological insulators

3. Primordial curvature perturbations

4. Conclusion

2. Axion in topological insulators

Axion and axion-like particles (ALPs)

- A solution to the strong CP problem (for axion)
- DM candidates
- Inspired by superstring theory
- Impacts on cosmology (axion strings, domain walls, mini-clusters, etc.)
- Lots of searching using various techniques are ongoing

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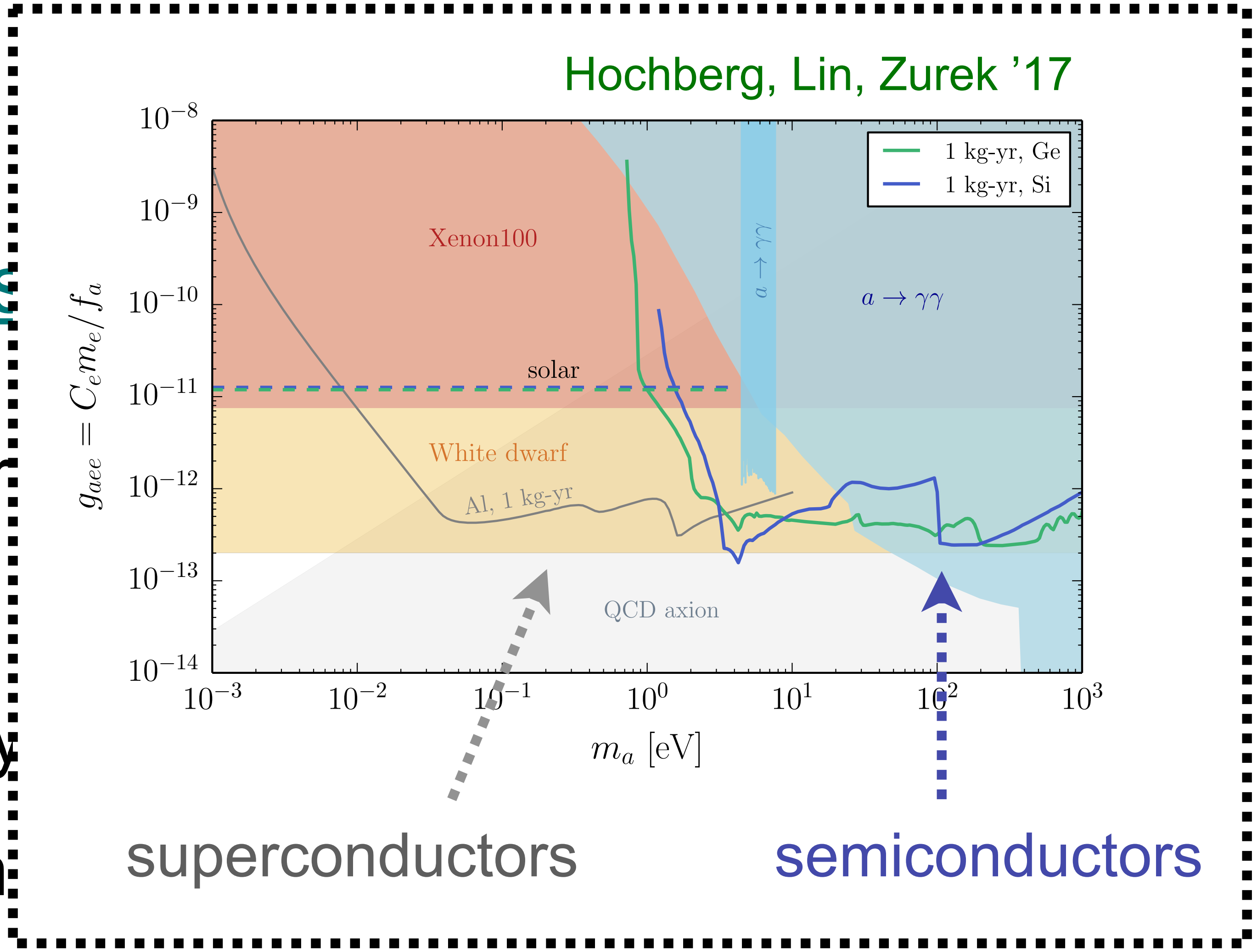

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Axion and axion-like particles (ALPs)

- A solution to the strong CP problem (for axion)
- DM candidates
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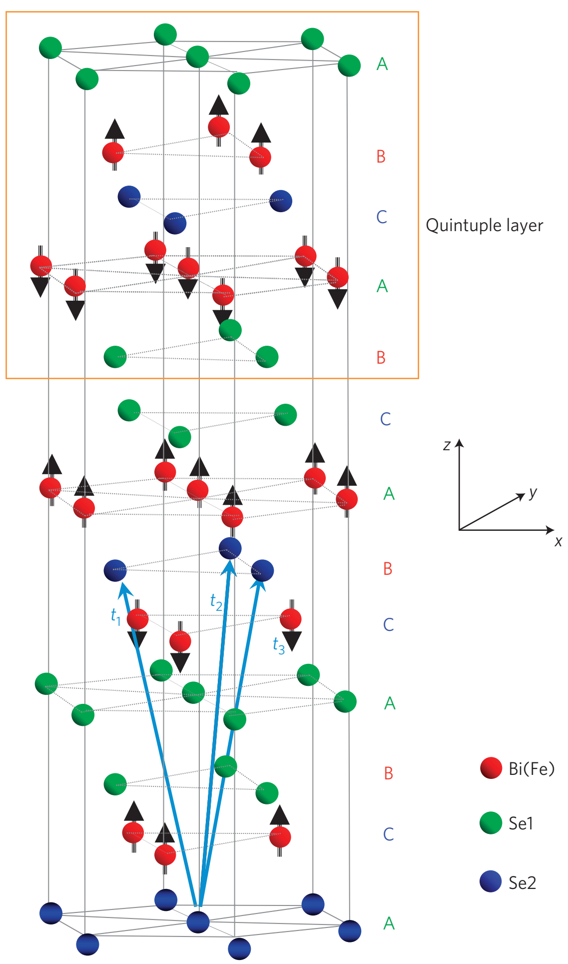
- Impacts on cosmology (axion strings, domain walls, mini-clusters, etc.)
- Lots of searching using various techniques are ongoing
- ‘Axion’ is predicted in topological insulators
- ‘Axion’ in insulators can be used for axion detection

Axion is predicted in topological magnetic insulators

ARTICLES
PUBLISHED ONLINE: 7 MARCH 2010 | DOI: 10.1038/NPHYS1534
nature physics

Dynamical axion field in topological magnetic insulators

Rundong Li[1], Jing Wang[1,2], Xiao-Liang Qi[1] and Shou-Cheng Zhang[1]*



Bi_2Se_3

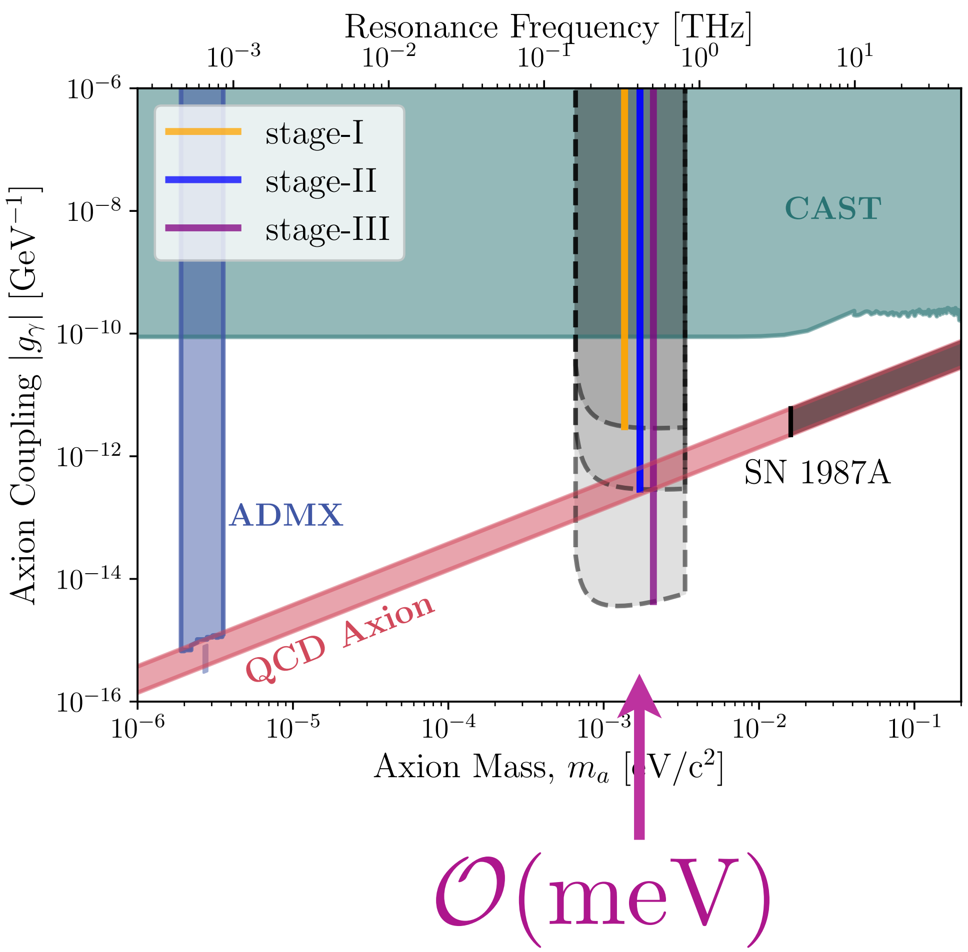
(Topological insulator)

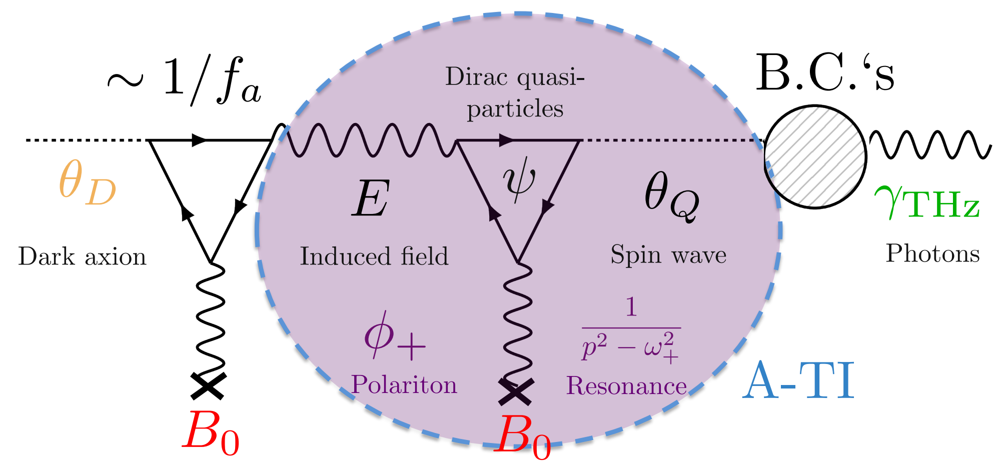
$$\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\begin{aligned} \mathcal{S}_{\text{tot}} &= \mathcal{S}_{\text{Maxwell}} + \mathcal{S}_{\text{topo}} + \mathcal{S}_{\text{axion}} \\ &= \frac{1}{8\pi}\int d^3x\,dt\left(\epsilon \mathbf{E}^2 - \frac{1}{\mu}\mathbf{B}^2\right) + \frac{\alpha}{4\pi^2}\int d^3x\,dt(\theta_0 + \delta\theta)\mathbf{E}\cdot\mathbf{B} \\ &\quad + g^2 J\int d^3x\,dt[(\partial_t\delta\theta)^2 - (v_i\partial_i\delta\theta)^2 - m^2\delta\theta^2] \end{aligned} \qquad (4)$$

Axion mass ~ $\mathcal{O}(\text{meV})$

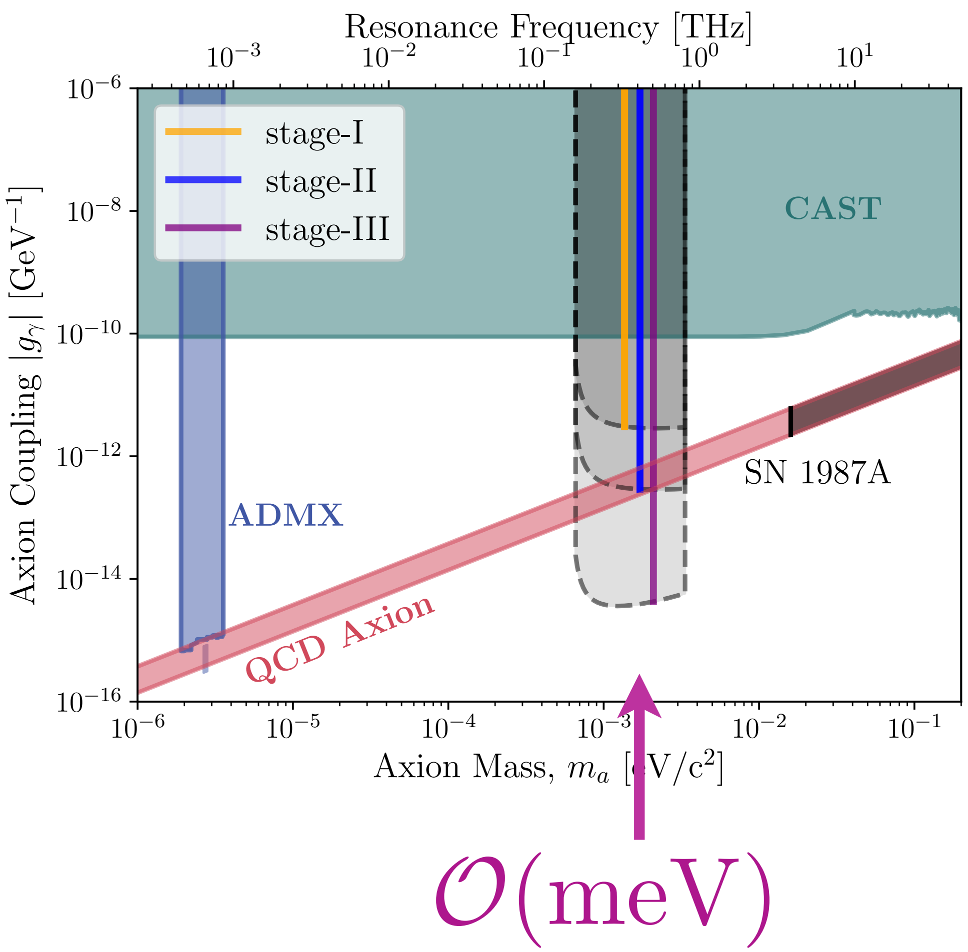
Proposals for axion/ALPs search using 'axion' in insulators

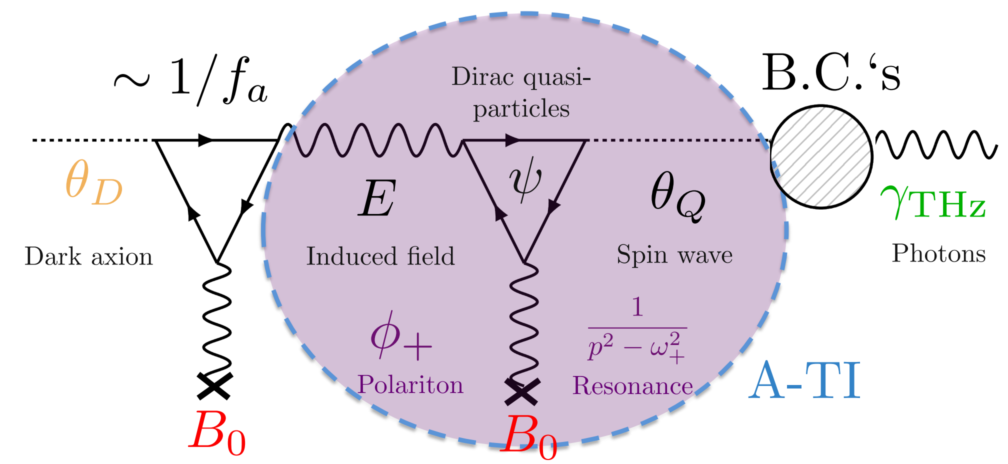




Marsh, Fong, Lentz, Smejkal, Ali '19

Proposals for axion/ALPs search using ‘axion’ in insulators





Marsh, Fong, Lentz, Smejkal, Ali ’19

Only meV range?

Basics to axion in insulators

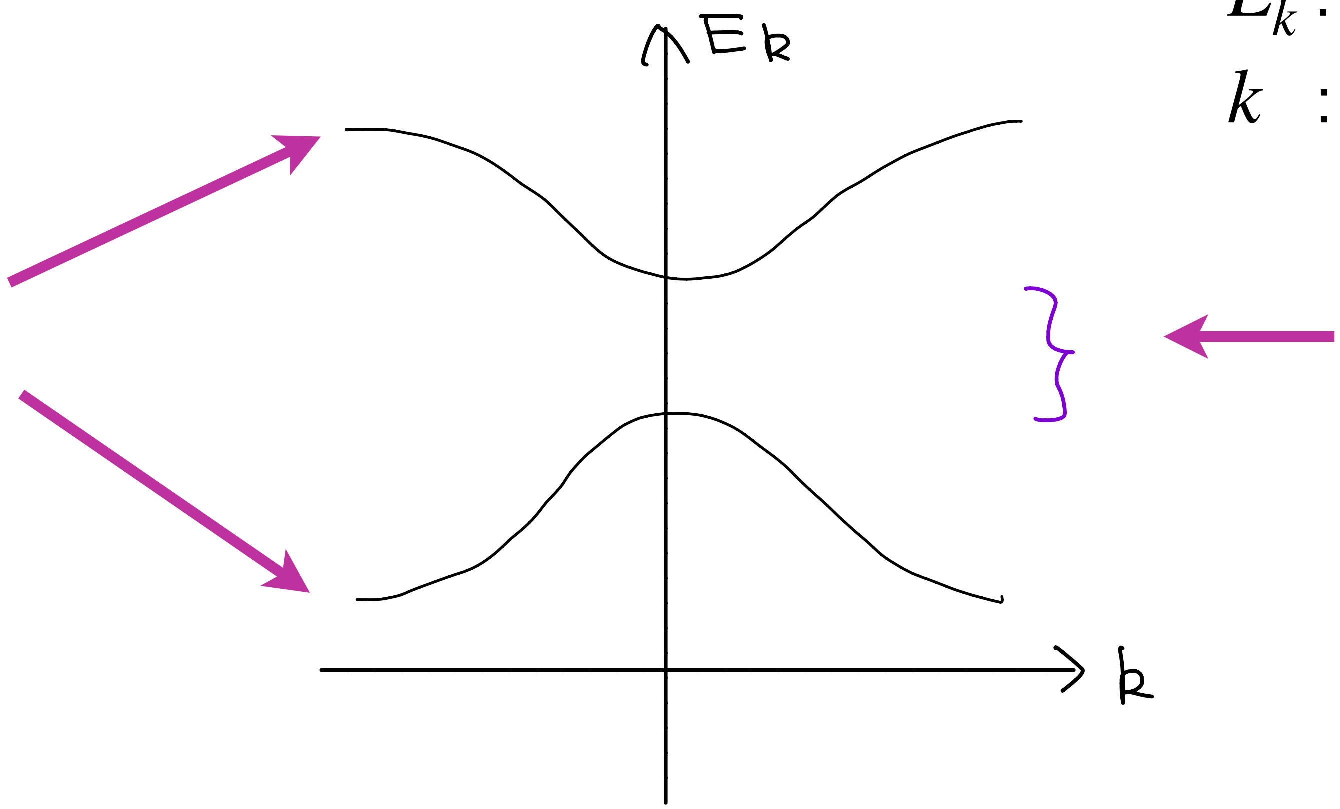
a). Insulators

b). Quantum Hall effect

a). Insulators

E_k : energy of electron

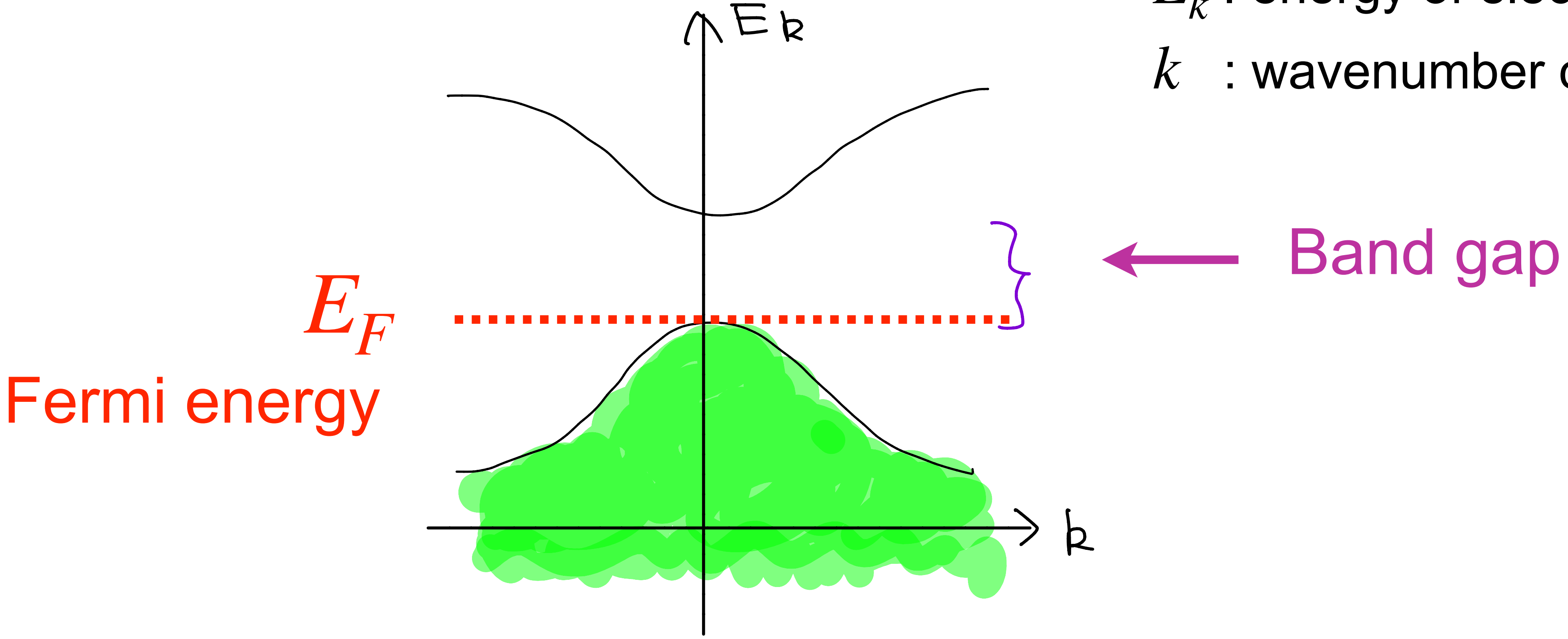
k : wavenumber of electron



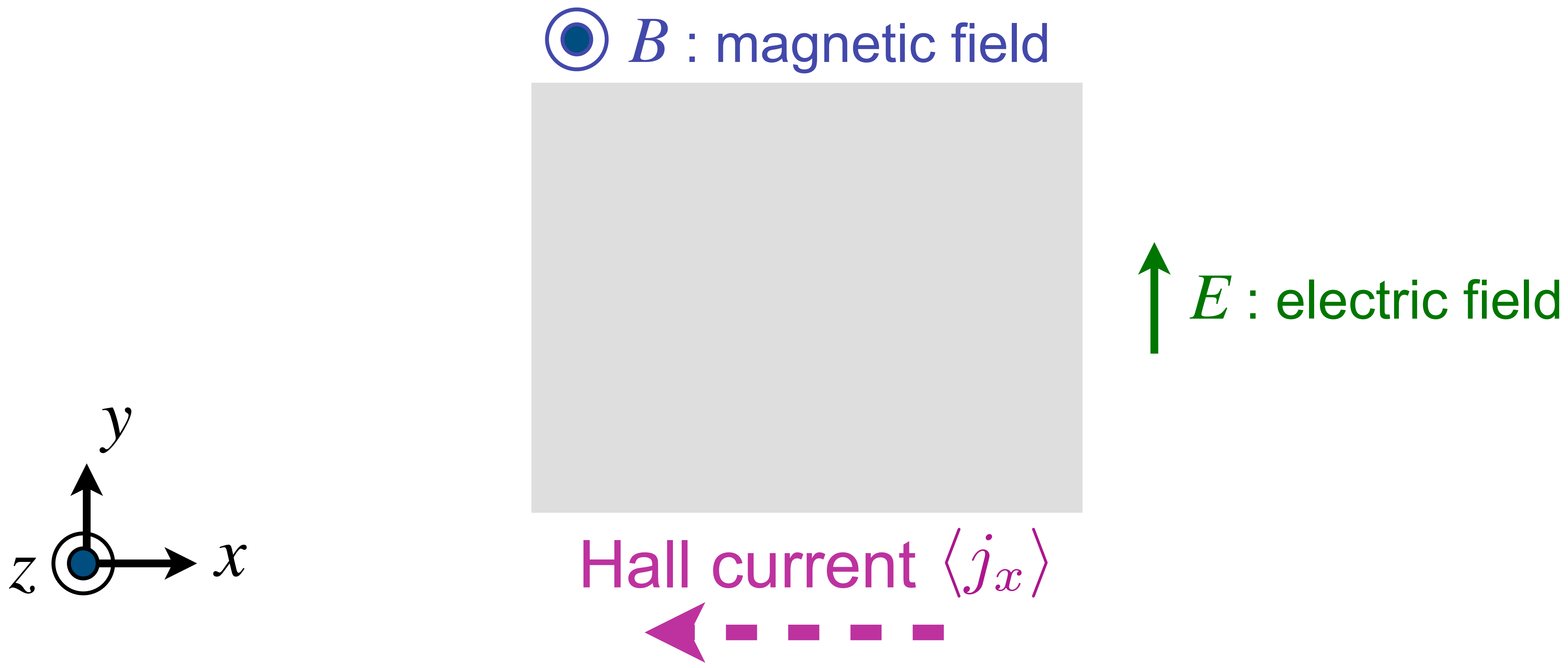
a). Insulators

E_k : energy of electron

k : wavenumber of electron



e.g., 2D insulator



Quantized electric current is induced in x direction e.g., a toy model in 2D

$$H = \begin{pmatrix} m & k_x - ik_y \\ k_x + ik_y & -m \end{pmatrix} = \boldsymbol{d} \cdot \boldsymbol{\sigma}$$

$$\boldsymbol{d} = (m, k_x, k_y)$$

$\longrightarrow$

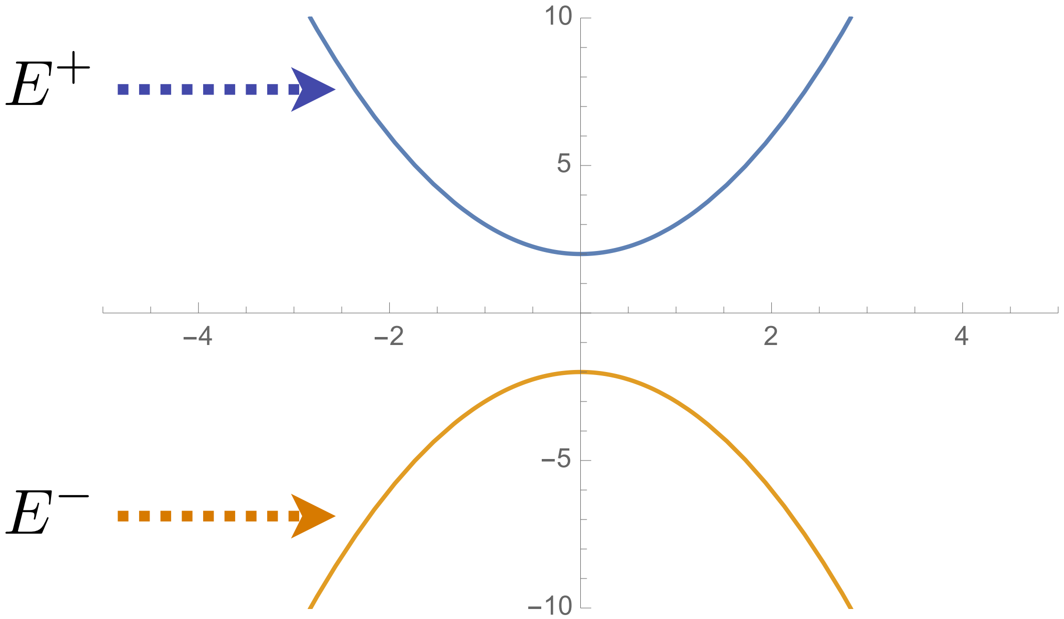
$$E^+ \simeq m + \frac{|\boldsymbol{k}|^2}{2|m|}$$

$$E^- \simeq -m - \frac{|\boldsymbol{k}|^2}{2|m|}$$

around $\boldsymbol{k} = 0$

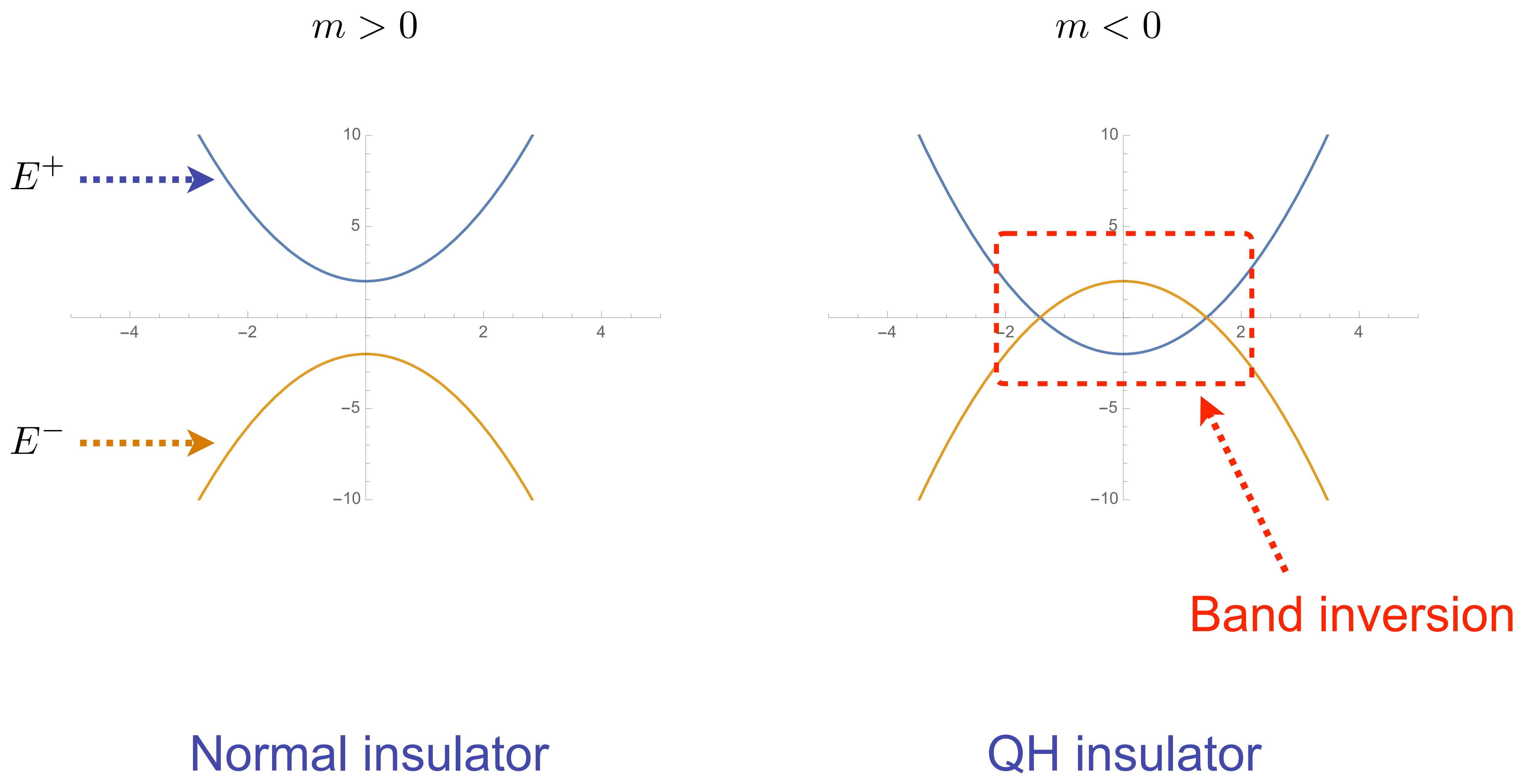
The band structure

$m > 0$

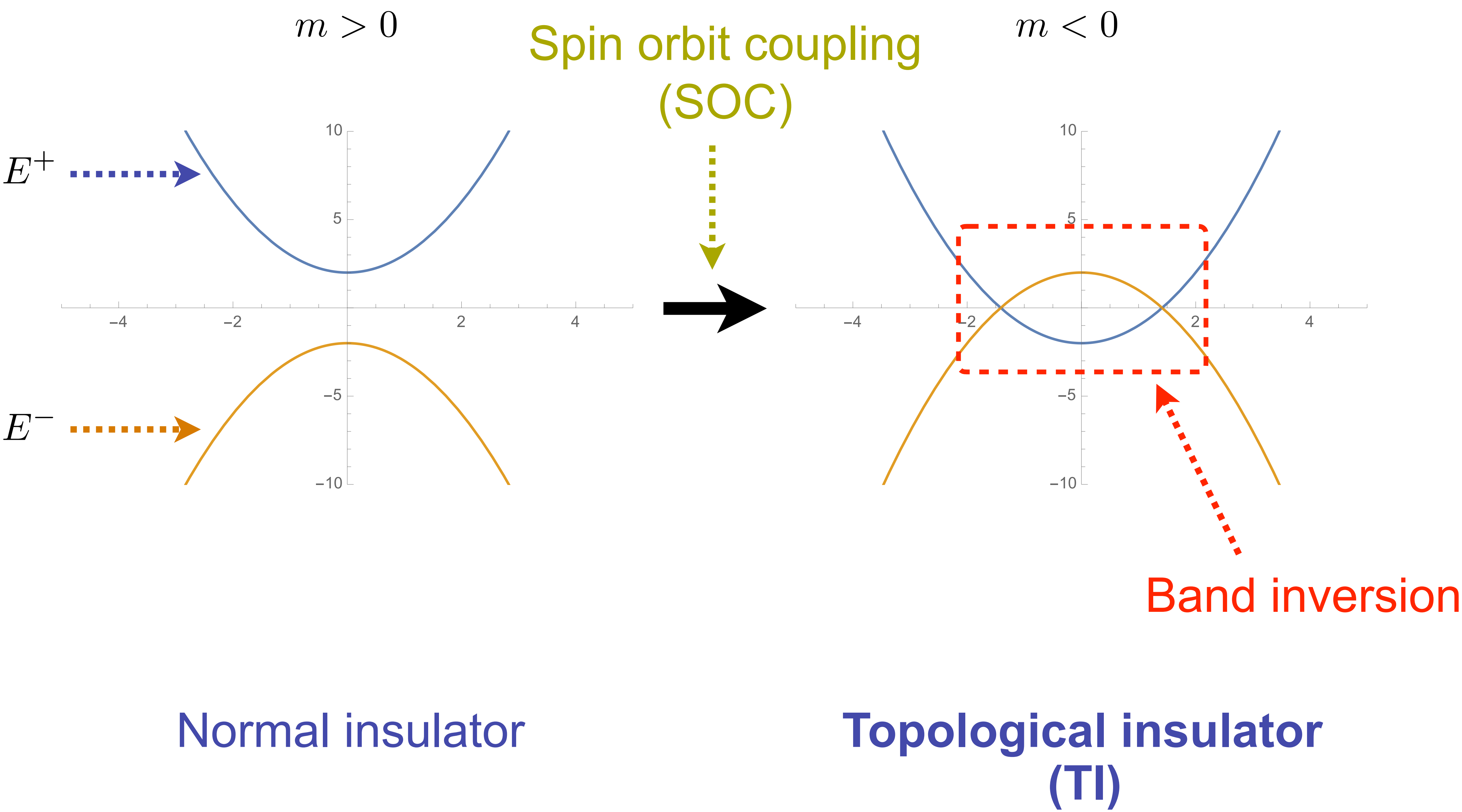


Normal insulator

The band structure

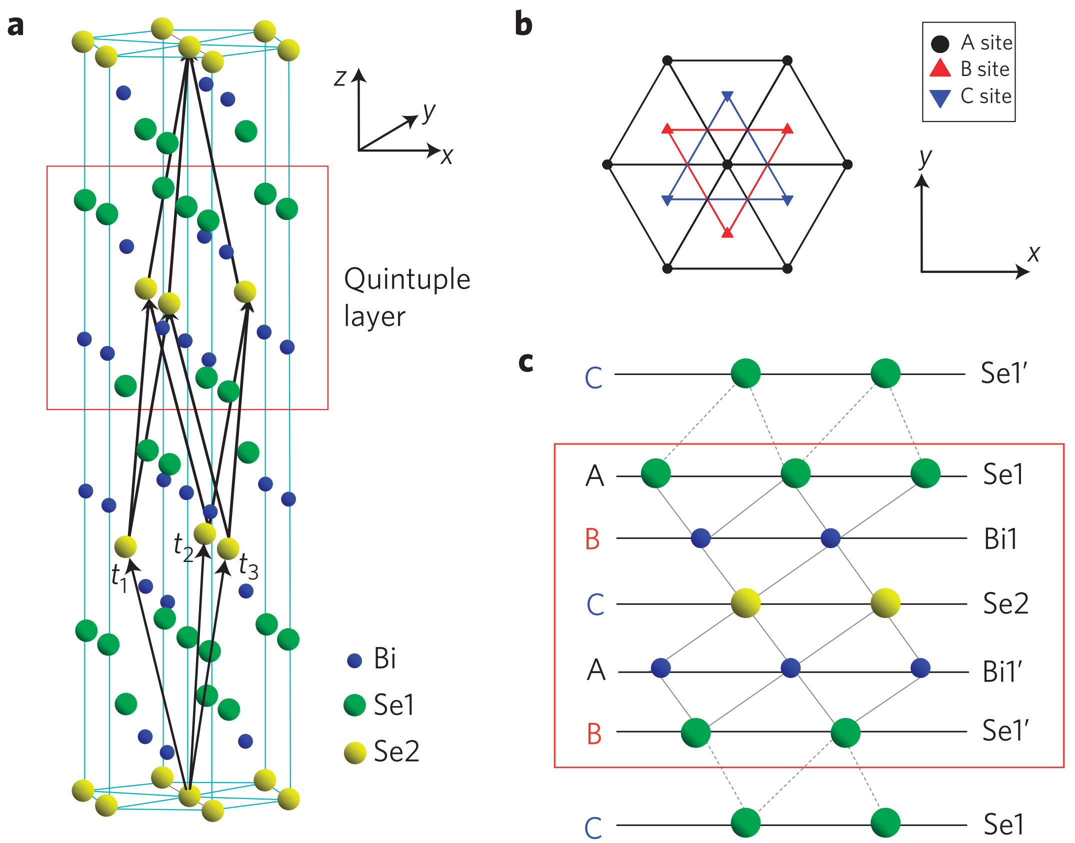


The band structure

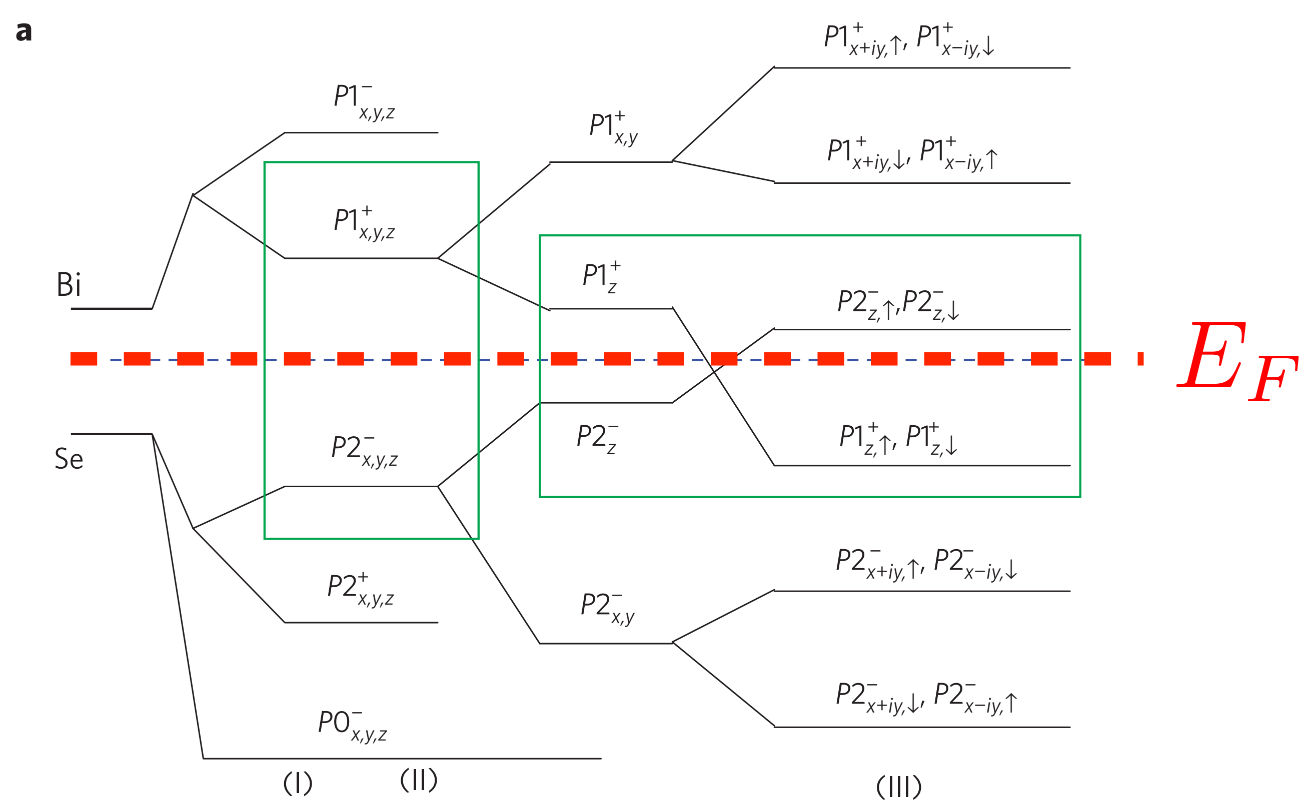


3D TI, Bi_2Se_3

H. Zhang et al. '09



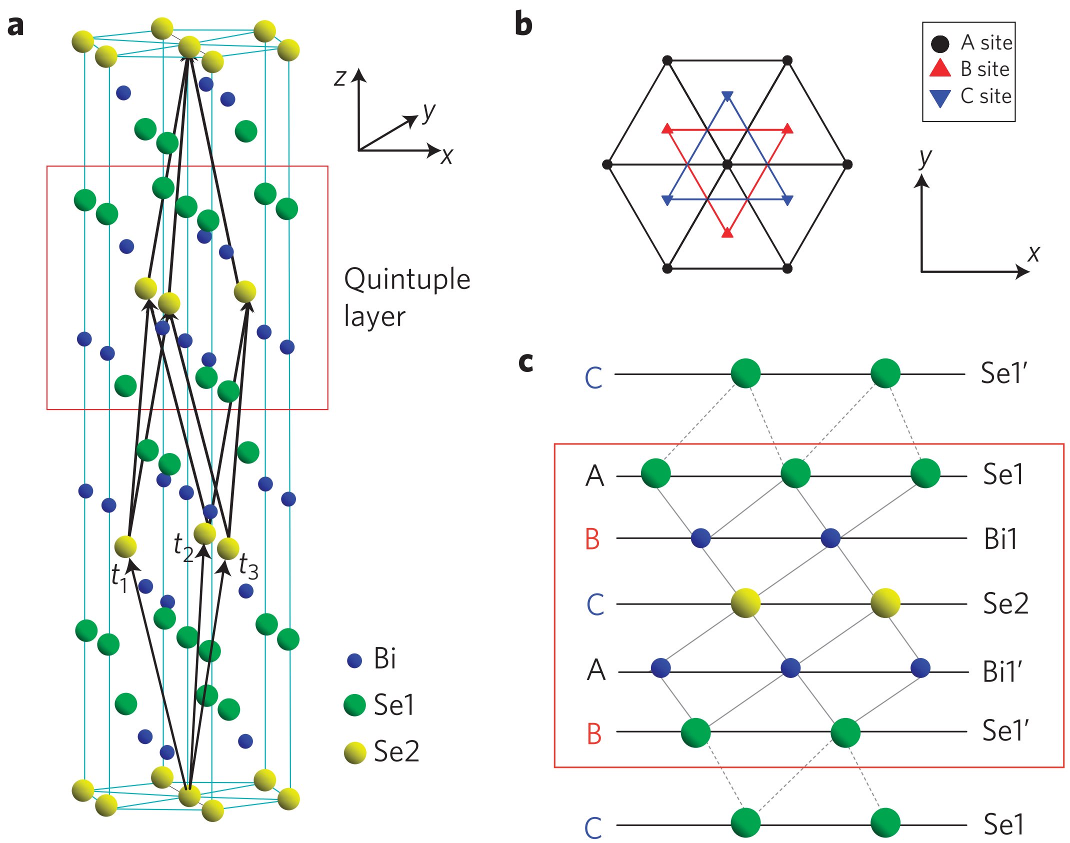
Cristal structure



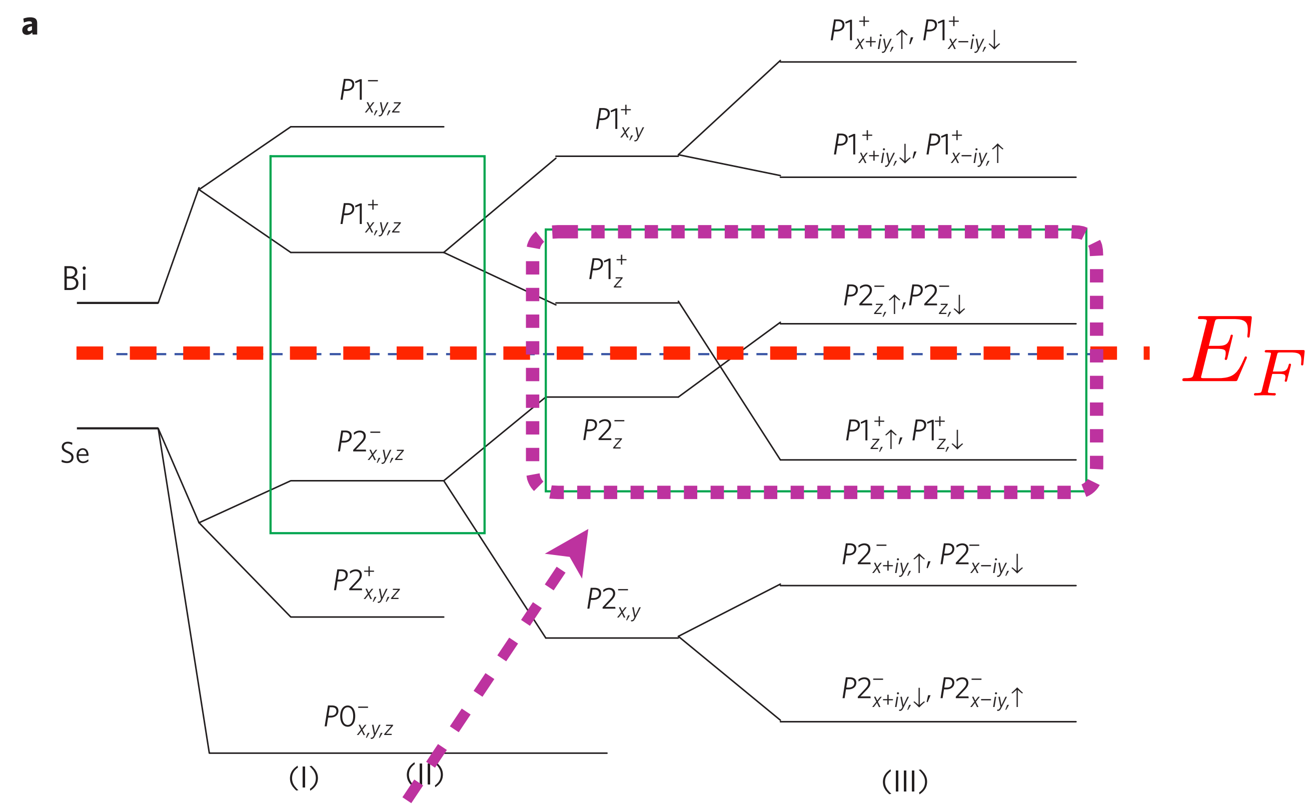
Energy levels

3D TI, Bi_2Se_3

H. Zhang et al. '09

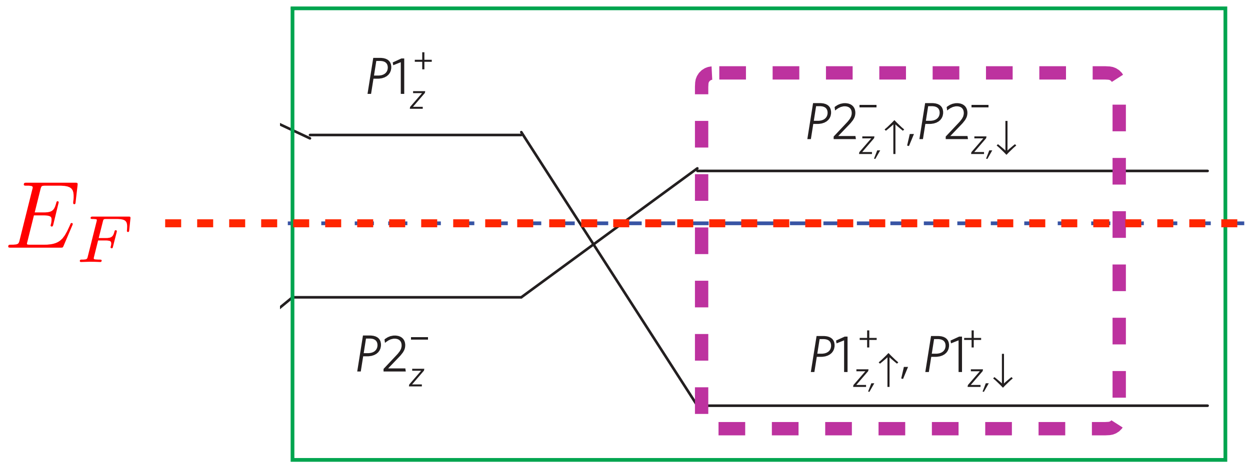


Cristal structure



Energy levels

Band inversion due to strong SOC



→ 4 by 4 matrices

$$H_0(\boldsymbol{k}) = \epsilon_0 \mathbf{1}_{4\times 4} + \sum_{a=1}^{5} d^a \Gamma^a$$

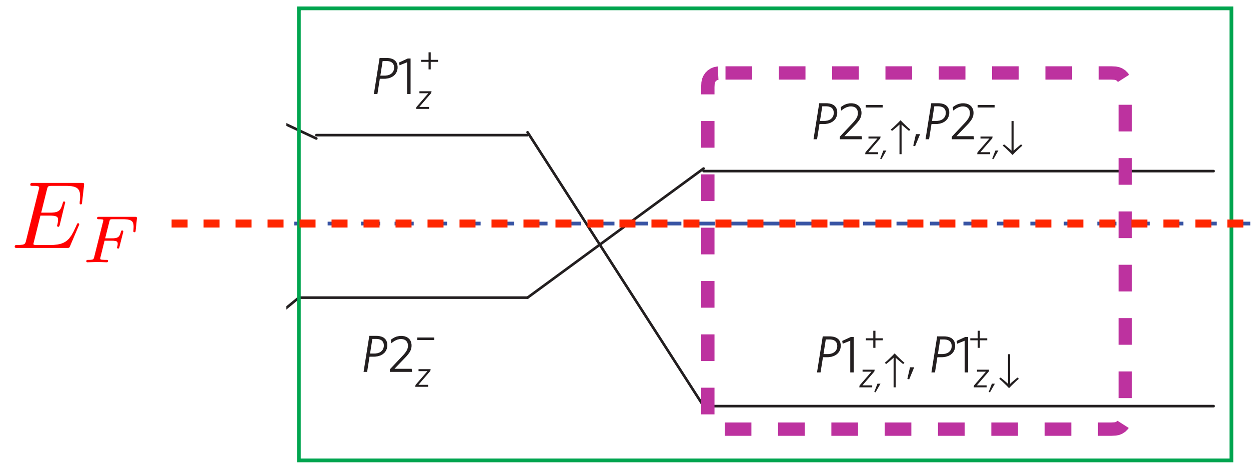
$$(d^1, d^2, d^3, d^4, d^5) = (A_2 \sin k_x,\ A_2 \sin k_y,\ A_1 \sin k_z,\ \mathcal{M}(\boldsymbol{k}), 0)$$

$$\mathcal{M}(\boldsymbol{k}) = M - 2B_1 - 4B_2 + 2B_1 \cos k_z + 2B_2(\cos k_x + \cos k_y)$$

$$\Gamma^1 = \begin{pmatrix} 0 & \sigma^x \\ \sigma^x & 0 \end{pmatrix} \quad \Gamma^2 = \begin{pmatrix} 0 & \sigma^y \\ \sigma^y & 0 \end{pmatrix} \quad \Gamma^3 = \begin{pmatrix} 0 & -i\mathbf{1} \\ -i\mathbf{1} & 0 \end{pmatrix}$$

$$\Gamma^4 = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix} \quad \Gamma^5 = \begin{pmatrix} 0 & \sigma^z \\ \sigma^z & 0 \end{pmatrix}$$

"Effective Hamiltonian for 3D TI"



→ 4 by 4 matrices

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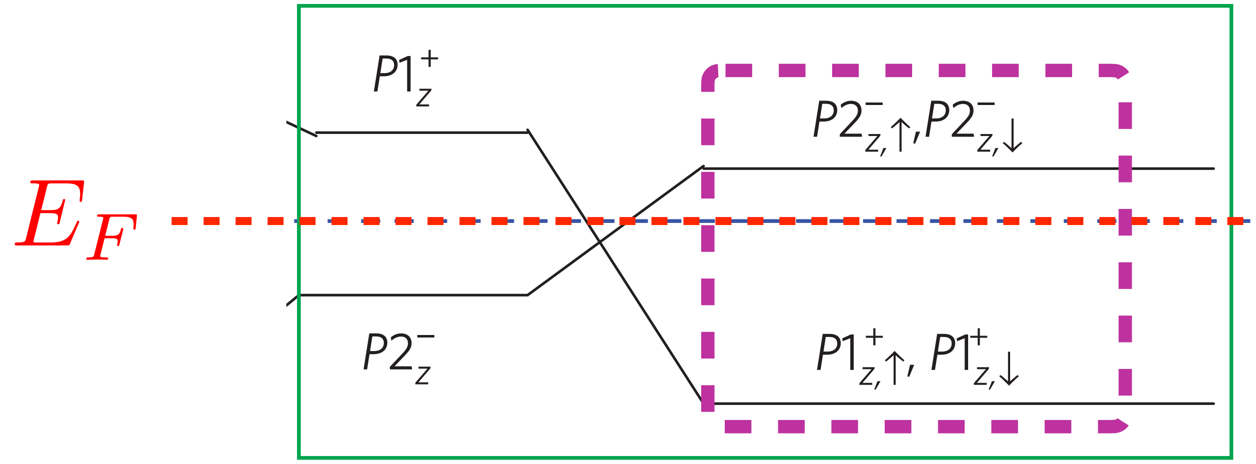
$d_5 = 0$

(see later discussion)

"Effective Hamiltonian for 3D TI"



→ 4 by 4 matrices

important for topological state

$$H_0(\boldsymbol{k}) = \epsilon_0 \mathbf{1}_{4\times 4} + \sum_{a=1}^{5} d^a \Gamma^a$$

cf. 2D toy model

$$H = \boldsymbol{d}\cdot\boldsymbol{\sigma}$$

$$\boldsymbol{d} = (m, k_x, k_y)$$

$$(d^1, d^2, d^3, d^4, d^5) = (A_2 \sin k_x,\ A_2 \sin k_y,\ A_1 \sin k_z,\ \mathcal{M}(\boldsymbol{k}), 0)$$

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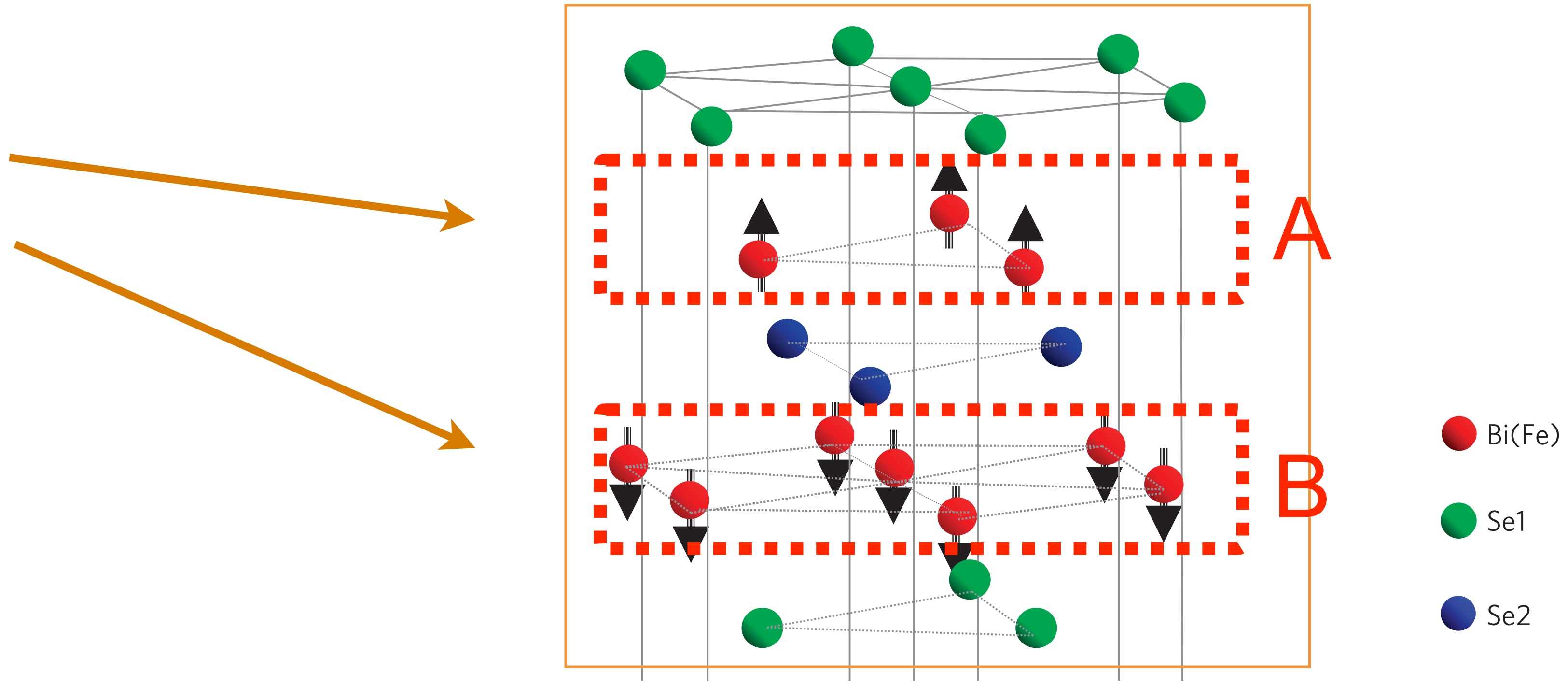
"Effective Hamiltonian for 3D TI"

In addition we consider *antiferromagnetism (AFM)*

R. Li et al. '10

Suppose electrons at Bi are AFM order



In addition we consider *antiferromagnetism (AFM)*

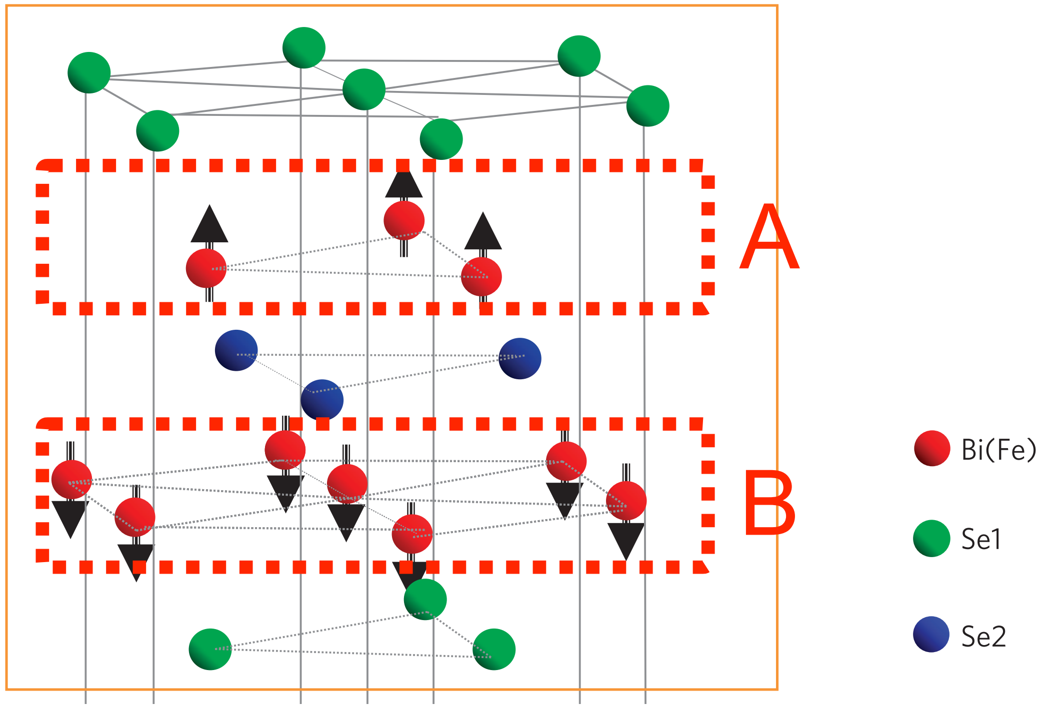
R. Li et al. '10

$$\mathcal{H}_{\rm int} = \frac{UV}{N} \int d^3x \, (n_{\rm A\uparrow} n_{\rm A\downarrow} + n_{\rm B\uparrow} n_{\rm B\downarrow})$$

"Hubbard term"

U : parameter to give AFM

Large U ⟶ AFM



V : volume

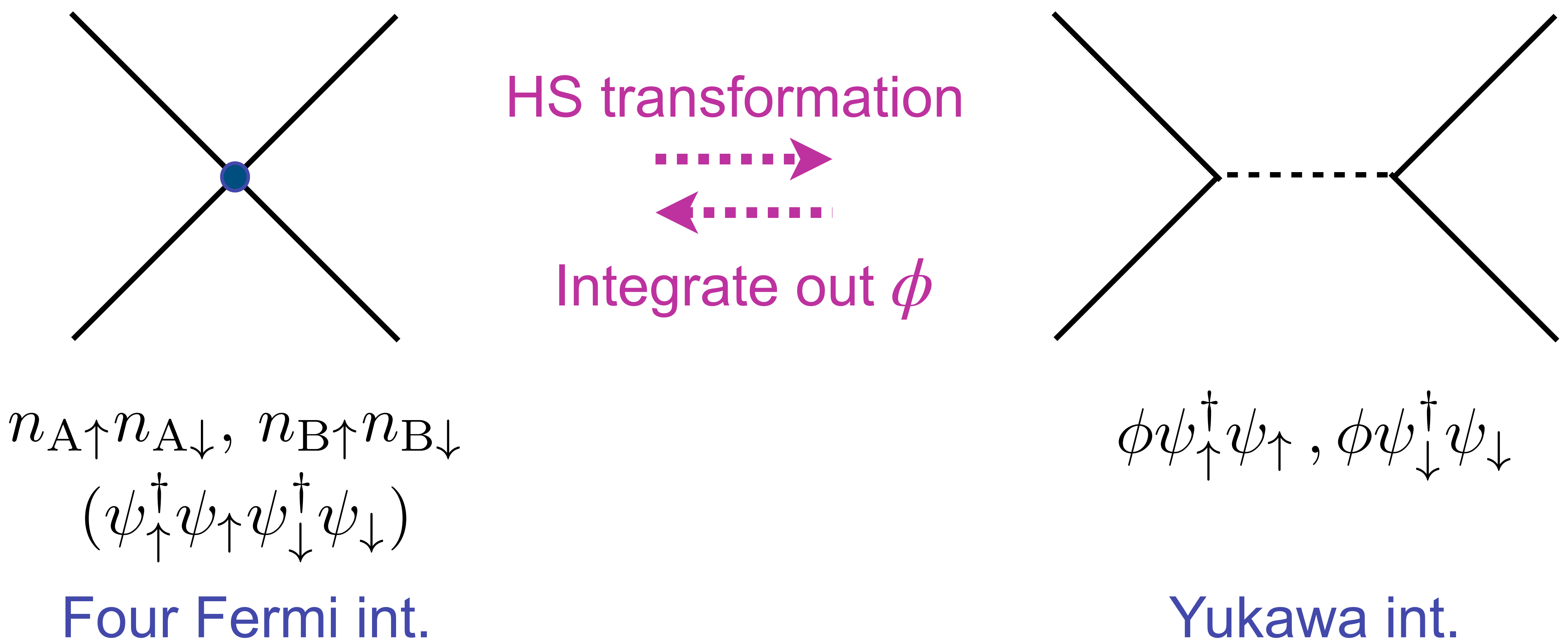
N : number of site

$$n_{\rm A\sigma} = \psi^\dagger_{\rm A\sigma} \psi_{\rm A\sigma}$$

$$n_{\rm B\sigma} = \psi^\dagger_{\rm B\sigma} \psi_{\rm B\sigma}$$

$$\mathcal{H}_{\rm int} = \frac{UV}{N} \int d^3x \; (n_{\rm A\uparrow} n_{\rm A\downarrow} + n_{\rm B\uparrow} n_{\rm B\downarrow})$$

$\downarrow$ Hubbard-Stratonovich (HS) transformation


HS transformation
Integrate out ϕ
$n_{A\uparrow}n_{A\downarrow}$, $n_{B\uparrow}n_{B\downarrow}$
$(\psi^\dagger_\uparrow\psi_\uparrow\psi^\dagger_\downarrow\psi_\downarrow)$
Four Fermi int.
$\phi\psi^\dagger_\uparrow\psi_\uparrow$, $\phi\psi^\dagger_\downarrow\psi_\downarrow$
Yukawa int.

$$\mathcal{H}_{\text{int}} = \frac{UV}{N} \int d^3x \; (n_{\mathrm{A}\uparrow} n_{\mathrm{A}\downarrow} + n_{\mathrm{B}\uparrow} n_{\mathrm{B}\downarrow})$$

↓ Hubbard-Stratonovich (HS) transformation

- A dynamical scalar ϕ that gives $\Gamma^5 d_5$ $(d_5 = \phi)$
- Mass term of ϕ ← missed in

Sekine, Nomura '16

Sekine, Nomura '20

Schütte-Engel '21

(confirmed by private communication with Sekine-san)

$$\mathcal{H}_{\rm int} = \frac{UV}{N}\int d^3x \, (n_{A\uparrow}n_{A\downarrow} + n_{B\uparrow}n_{B\downarrow})$$

↓ Hubbard-Stratonovich (HS) transformation

- A dynamical scalar ϕ that gives $\Gamma^5 d_5$ ($d_5 = \phi$)
- Mass term of ϕ
- ϕ relates to the axion field

$$\theta = \frac{1}{4\pi}\int d^3k \frac{2|d| + d^4}{(|d| + d^4)^2 |d|^3} \epsilon^{ijkl} d^i \partial_{k_x} d^j \partial_{k_y} d^k \partial_{k_z} d^l$$

R. Li et al. '10

Derivation as chiral anomaly

$$H(\boldsymbol{k}) = \sum_{a=1}^{5} d^a(\boldsymbol{k})\Gamma^a$$

$$(d^1,\, d^2,\, d^3,\, d^4,\, d^5) = (A_2 \sin k_x,\; A_2 \sin k_y,\; A_1 \sin k_z,\; \mathcal{M}(\boldsymbol{k}),\; \phi)$$

$$\mathcal{M}(\boldsymbol{k}) = M - 2B_1 - 4B_2 + 2B_1 \cos k_z + 2B_2(\cos k_x + \cos k_y)$$

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$$\mathcal{M}(\boldsymbol{k}) = M - 2B_1 - 4B_2 + 2B_1 \cos k_z + 2B_2(\cos k_x + \cos k_y)$$

- expand around $\boldsymbol{k} = 0$
- redefine $\boldsymbol{k}$

$$H(\boldsymbol{k}) = k_x\Gamma^1 + k_y\Gamma^2 + k_y\Gamma^3 + M\Gamma^4 + \phi\Gamma^5$$

"Dirac model"

$$H(\boldsymbol{k}) = k_x\Gamma^1 + k_y\Gamma^2 + k_y\Gamma^3 + M\Gamma^4 + \phi\Gamma^5$$

Unitary transformation of the basis

$$\tilde{U}H(\boldsymbol{k})\tilde{U}^\dagger = \beta(\boldsymbol{\gamma}\cdot\boldsymbol{k} + M + \phi\gamma_5)$$

$$S = \int d^4x\ \bar{\psi}[i\gamma^\mu(\partial_\mu - ieA_\mu) - M - i\phi\gamma_5]\psi$$

$\Gamma^5\phi$ reduces to $i\gamma^5\phi$

$i\gamma^5\phi$ term can be rotated away, which gives rise to θ term:

$$S_\Theta = -\frac{\alpha}{4\pi}\int \mathrm{d}^4x\,\Theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Theta = \frac{\pi}{2}[1-\mathrm{sgn}(M)]\mathrm{sgn}(\phi) + \tan^{-1}\frac{\phi}{M}$$

it is consistent with

$$\theta = \frac{1}{4\pi}\int d^3k \frac{2|d| + d^4}{(|d| + d^4)^2|d|^3}\epsilon^{ijkl} d^i \partial_{k_x} d^j \partial_{k_y} d^k \partial_{k_z} d^l$$

Partition function (TI + AFM)

$$Z = \int \mathcal{D}\psi \mathcal{D}\psi^\dagger \mathcal{D}\phi \; e^{iS + iS_\phi^{\mathrm{mass}}}$$

$$S = \int d^4x \; \psi^\dagger(x) \left[i\partial_t - H \right] \psi(x)$$

$$H = H_0 + \delta H$$

$$S_\phi^{\mathrm{mass}} = -\int d^4x \; M_\phi^2 \phi^2$$

$$M_\phi^2 = \int \frac{d^3k}{(2\pi)^3} \frac{2}{U}$$

Partition function (TI + AFM)

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$$\Gamma^5 \phi$$

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$\Gamma^5 \phi$

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$$S = \int d^4x \; \psi^\dagger(x) \left[i\partial_t - H \right] \psi(x)$$

$$S_\phi^{\mathrm{mass}} = -\int d^4x \; M_\phi^2 \phi^2$$

$$M_\phi^2 = \int \frac{d^3k}{(2\pi)^3} \frac{2}{U}$$

Summing over ψ , $\psi^\dagger$

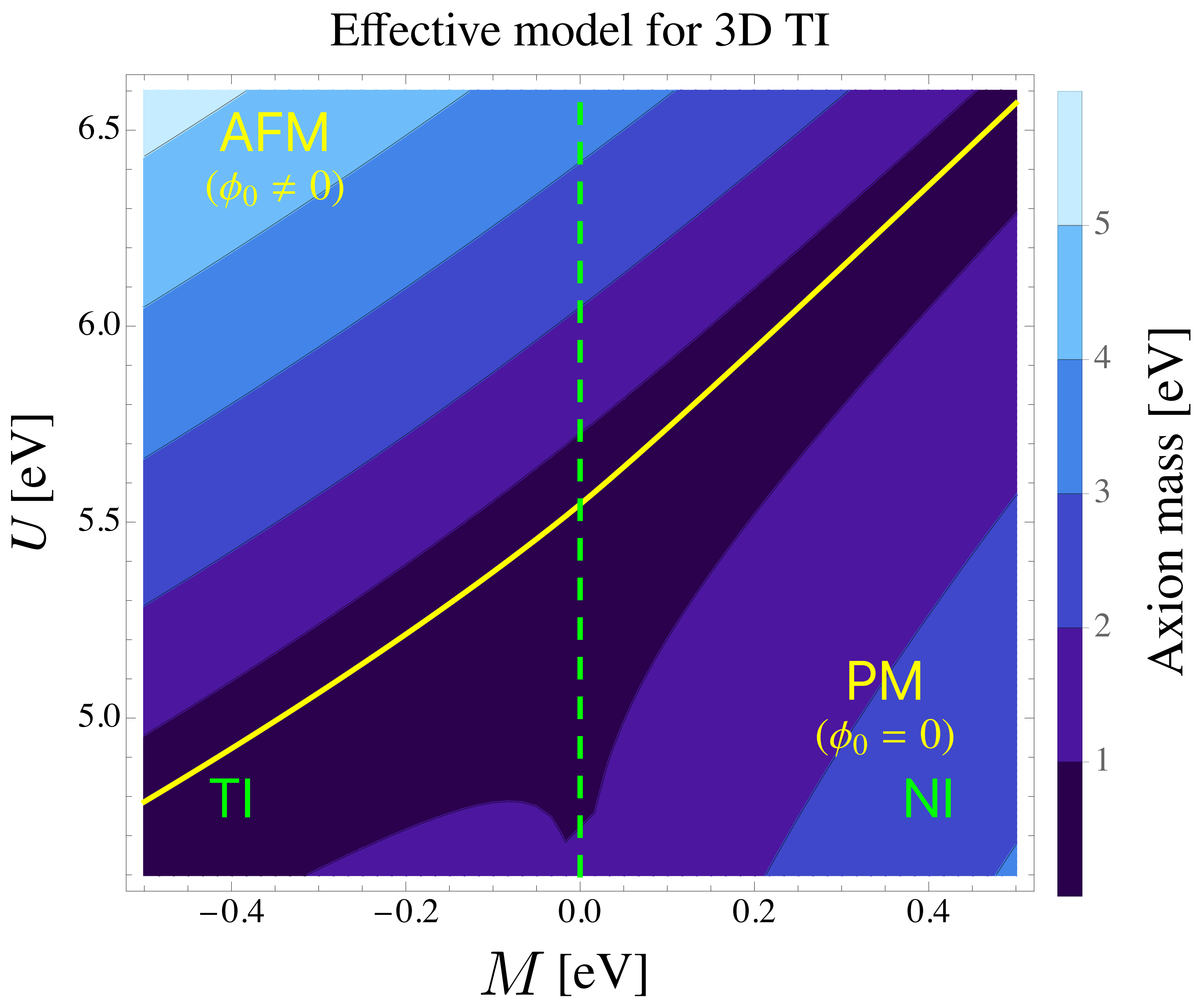
→ Effective potential for ϕ

→ Effective potential for θ

$$\theta = \frac{1}{4\pi} \int d^3k \frac{2|d| + d^4}{(|d| + d^4)^2 |d|^3} \epsilon^{ijkl} d^i \partial_{k_x} d^j \partial_{k_y} d^k \partial_{k_z} d^l$$

Axion mass

KI '21



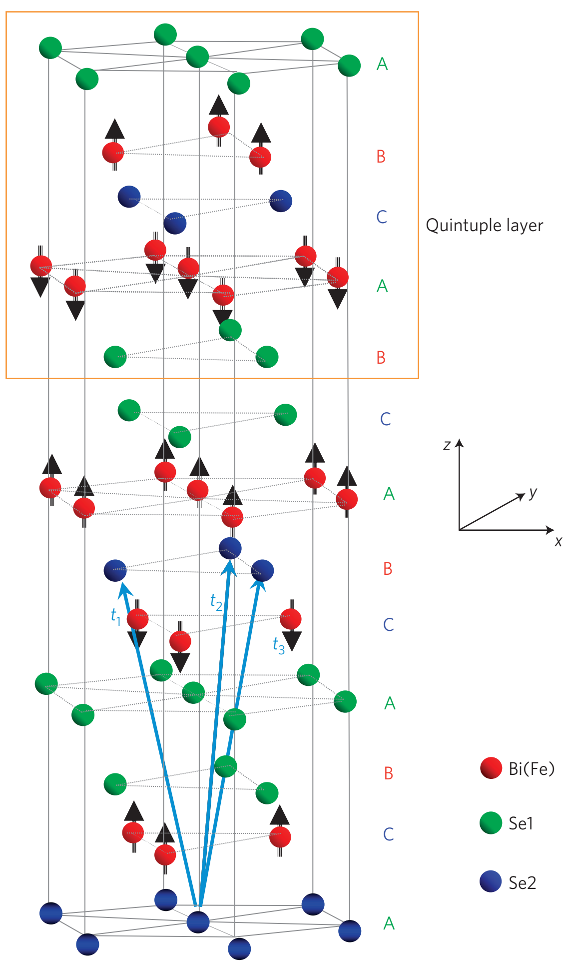
Axion mass is $\mathcal{O}(\mathrm{eV})$

Dynamical axion is predicted in topological magnetic insulators

ARTICLES
PUBLISHED ONLINE: 7 MARCH 2010 | DOI: 10.1038/NPHYS1534
nature physics

Dynamical axion field in topological magnetic insulators

Rundong Li[1], Jing Wang[1,2], Xiao-Liang Qi[1] and Shou-Cheng Zhang[1]*



Bi_2Se_3

$$\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\begin{aligned}\mathcal{S}_{\rm tot} &= \mathcal{S}_{\rm Maxwell}+\mathcal{S}_{\rm topo}+\mathcal{S}_{\rm axion}\\ &= \frac{1}{8\pi}\int d^3x\,dt\left(\epsilon\mathbf{E}^2-\frac{1}{\mu}\mathbf{B}^2\right)+\frac{\alpha}{4\pi^2}\int d^3x\,dt\,(\theta_0+\delta\theta)\mathbf{E}\cdot\mathbf{B}\\ &\quad+g^2J\int d^3x\,dt[(\partial_t\delta\theta)^2-(v_i\partial_i\delta\theta)^2-m^2\delta\theta^2] \qquad (4)\end{aligned}$$

Axion mass ~ $\mathcal{O}(\mathrm{meV})$

Dynamical axion is predicted in topological magnetic insulators

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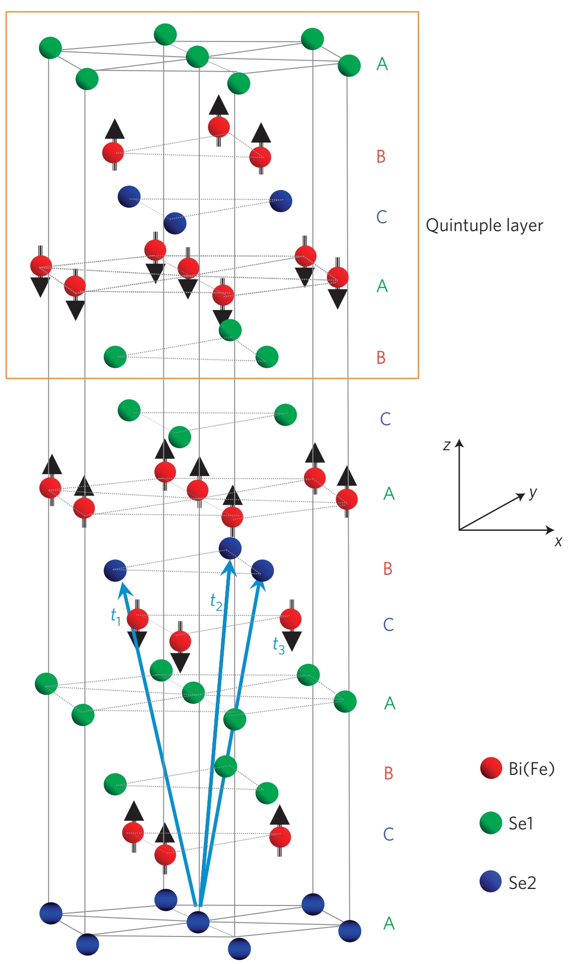

Bi_2Se_3

$$\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\begin{aligned}\mathcal{S}_{\mathrm{tot}} &= \mathcal{S}_{\mathrm{Maxwell}} + \mathcal{S}_{\mathrm{topo}} + \mathcal{S}_{\mathrm{axion}} \\ &= \frac{1}{8\pi}\int d^3x dt \left(\epsilon \mathbf{E}^2 - \frac{1}{\mu}\mathbf{B}^2\right) + \frac{\alpha}{4\pi^2}\int d^3x dt (\theta_0 + \delta\theta)\mathbf{E}\cdot\mathbf{B} \\ &\quad + g^2 J \int d^3x dt [(\partial_t \delta\theta)^2 - (v_i \partial_i \delta\theta)^2 - m^2 \delta\theta^2] \qquad (4)\end{aligned}$$

Axion mass ~ $\mathcal{O}(\mathrm{meV})$

?

The thing would be …

R. Li et al. ’10

- $\langle \phi \rangle \ (= m_5) \ = 1 \ \mathrm{meV}$ is taken

  (i.e., $\langle \phi \rangle$ is considered to be a free parameter)

- AFM order is *assumed*

The thing would be …

R. Li et al. '10

- $\langle\phi\rangle\ (= m_5)\ = 1\ \mathrm{meV}$ is taken

  (i.e., $\langle\phi\rangle$ is considered to be a free parameter)

  → Axion mass ~ $\mathcal{O}(\mathrm{meV})$ $(\because\ m_a^2 \propto m_5^2)$

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The thing would be …

R. Li et al. '10

- $\langle \phi \rangle \ (= m_5) \ = 1 \ \mathrm{meV}$ is taken

  (i.e., $\langle \phi \rangle$ is considered to be a free parameter)

→ Axion mass ~ $\mathcal{O}(\mathrm{meV})$ $\quad (\because \ m_a^2 \propto m_5^2)$

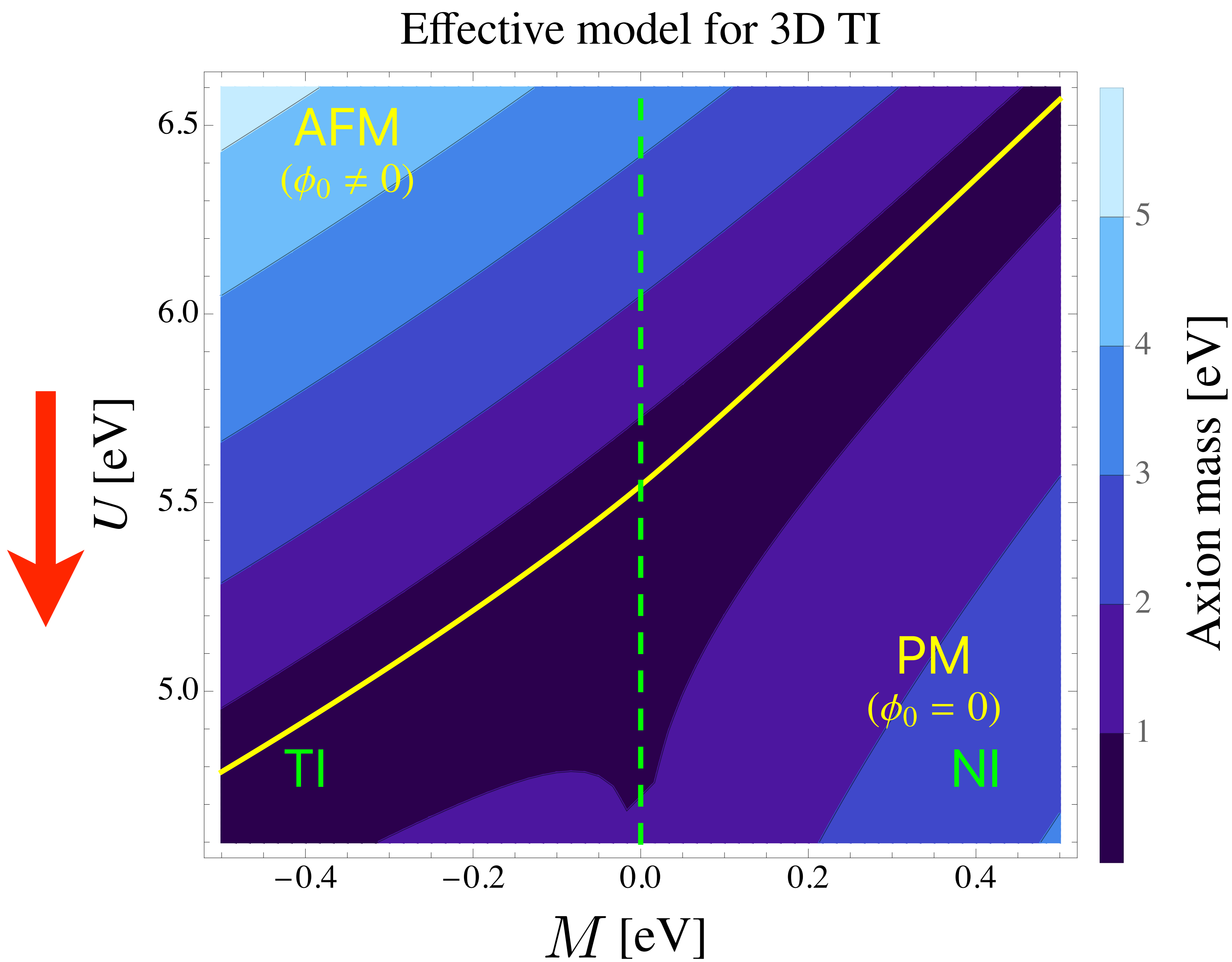
But this is not naively possible since

- AFM order is *assumed*

$m_5 \sim U \sim \mathrm{eV}$ (in AFM order)

Axion mass

KI '21



Suppressed U → No AFM

The thing would be …

R. Li et al. '10

- $\langle\phi\rangle\ (= m_5) = 1\ \mathrm{meV}$ is taken

  (i.e., $\langle\phi\rangle$ is considered to be a free parameter)

  ⟶ Axion mass ~ $\mathcal{O}(\mathrm{meV})$ $\quad (\because\ m_a^2 \propto m_5^2)$

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The thing would be …

R. Li et al. '10

- $\langle\phi\rangle\ (= m_5) = 1\ \mathrm{meV}$ is taken

  (i.e., $\langle\phi\rangle$ is considered to be a free parameter)

  → Axion mass ~ $\mathcal{O}(\mathrm{meV})$ $(\because\ m_a^2 \propto m_5^2)$

- AFM order is *assumed*

  No AFM in TI in the first place

  → Fe-doped $\mathrm{Bi_2Se_3}$ is considered

- Fe -doped $\mathrm{Bi_2Se_3}$, $\mathrm{Bi_2Te_3}$

  "likely to be AFM" J.M. Zhang et al. '13

  (by first-principles calculation)

  → It looks unlikely to be realized …

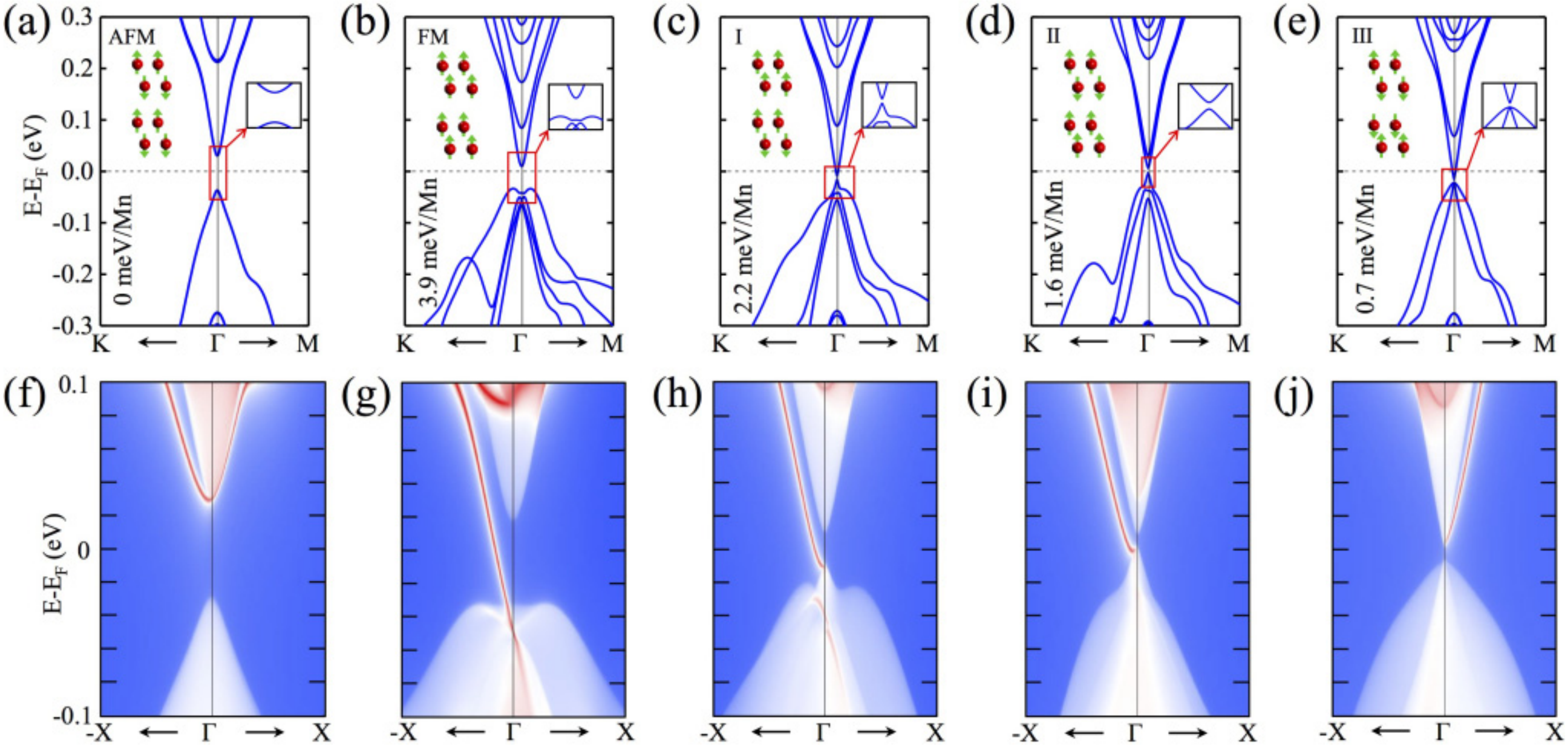
- $\mathrm{Mn_2Bi_2Te_5}$ J. Zhang et al. '19

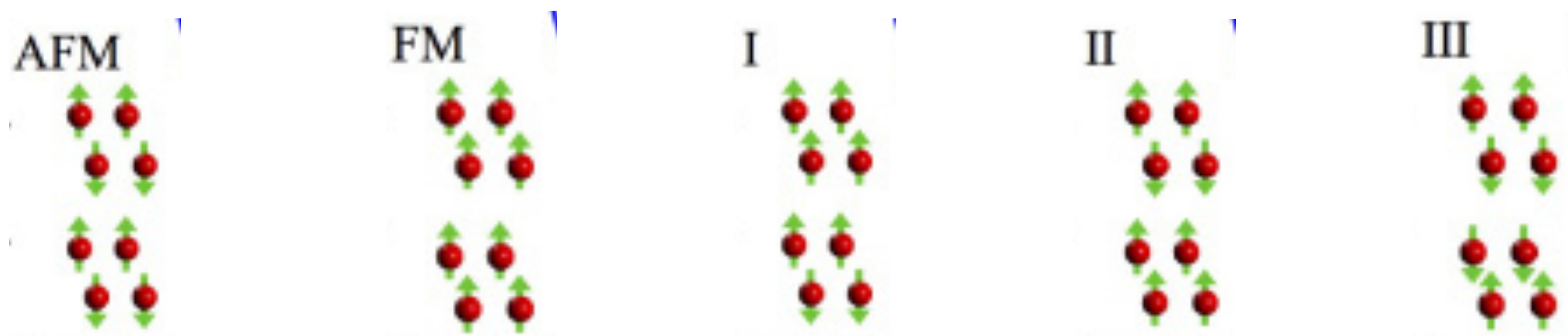
  "rich magnetic topological quantum states" Y. Li et al. '20

  (by first-principles calculation)

First-principles calculation

Y. Li et al. ’20



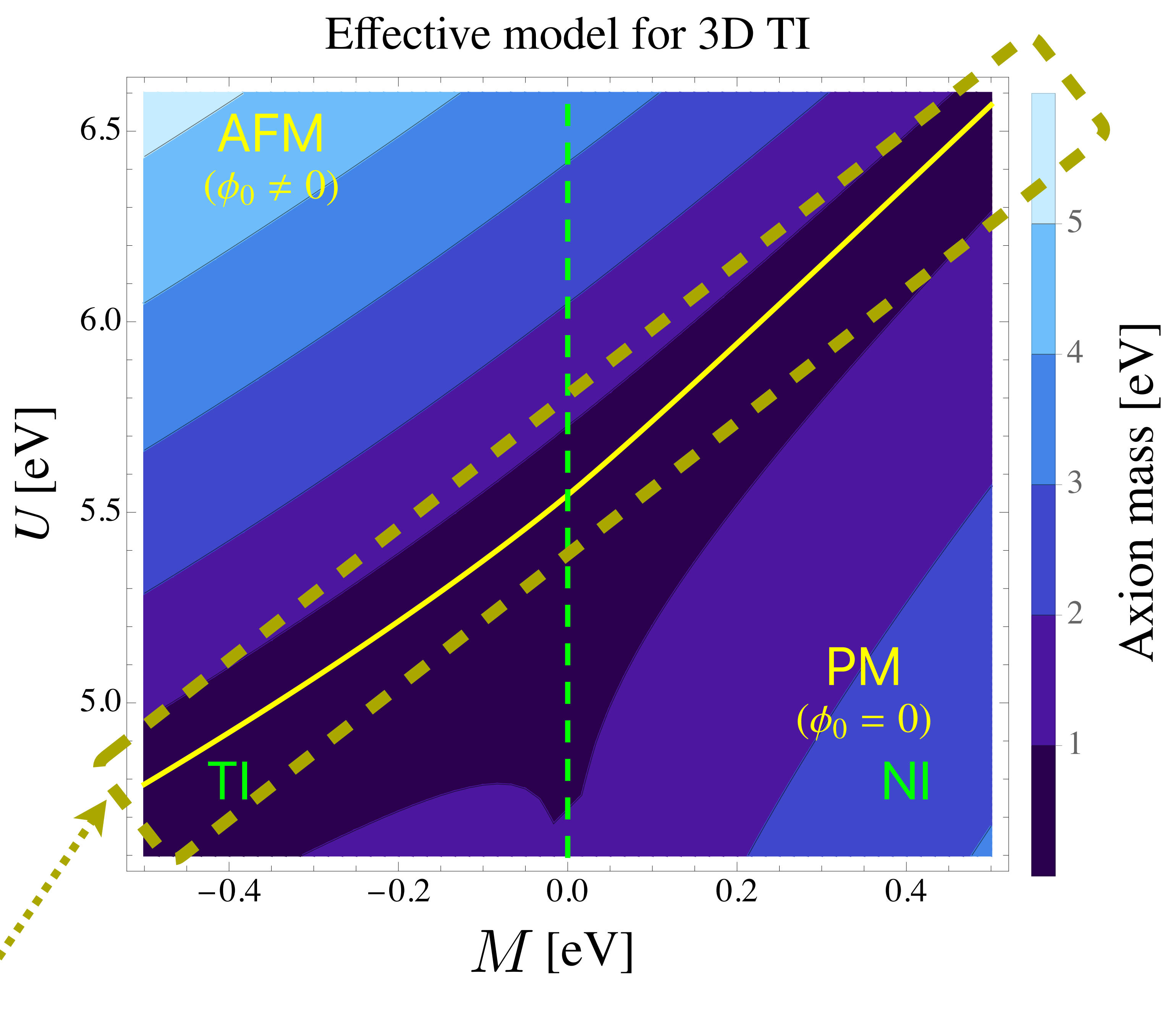


$Mn_2Bi_2Te_5$ is synthesized

L. Cao et al. ’21

Axion mass

KI '21



It can be suppressed near the phase boundary

Rich magnetic topological states in that region?

Discussion

- How do we describe axion in $\mathrm{Mn_2Bi_2Te_5}$?
- What about axion in NI ?
- Dynamical axion in ferromagnetic state or other magnetic states?

Interaction between impurity and electron

$$H^{\mathrm{TI}} = \sum_{\boldsymbol{k}} c_{\boldsymbol{k}}^{\dagger} \mathcal{H}_{\boldsymbol{k}}^{\mathrm{TI}} c_{\boldsymbol{k}}$$

$$H_J = \sum_{I}^{N_s} \left[J^A \boldsymbol{S}^A(\boldsymbol{x}_I) \cdot \boldsymbol{s}_I^A + J^B \boldsymbol{S}^B(\boldsymbol{x}_I) \cdot \boldsymbol{s}_I^B \right]$$

Interaction between impurity and electron

$$H^{\mathrm{TI}} = \sum_{\boldsymbol{k}} c^{\dagger}_{\boldsymbol{k}} \mathcal{H}^{\mathrm{TI}}_{\boldsymbol{k}} c_{\boldsymbol{k}}$$

Spin of electron

$$H_J = \sum_{I}^{N_s} \left[J^A \boldsymbol{S}^A(\boldsymbol{x}_I) \cdot \boldsymbol{s}^A_I + J^B \boldsymbol{S}^B(\boldsymbol{x}_I) \cdot \boldsymbol{s}^B_I \right]$$

Spin of impurity

Interaction between impurity and electron

$$H^{\mathrm{TI}} = \sum_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k}} \mathcal{H}^{\mathrm{TI}}_{\boldsymbol{k}} c_{\boldsymbol{k}}$$

Spin of electron

$$H_J = \sum_{I}^{N_s} \left[J^A \boldsymbol{S}^A(\boldsymbol{x}_I) \cdot \boldsymbol{s}^A_I + J^B \boldsymbol{S}^B(\boldsymbol{x}_I) \cdot \boldsymbol{s}^B_I \right]$$

Spin of impurity

Mean field approximation →

$$H_e = \sum_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k}} \mathcal{H}_{e\boldsymbol{k}} c_{\boldsymbol{k}}$$

$$\mathcal{H}_{e\boldsymbol{k}} = \mathcal{H}^{\mathrm{TI}}_{\boldsymbol{k}} + \mathcal{H}^{m}_{\boldsymbol{k}}$$

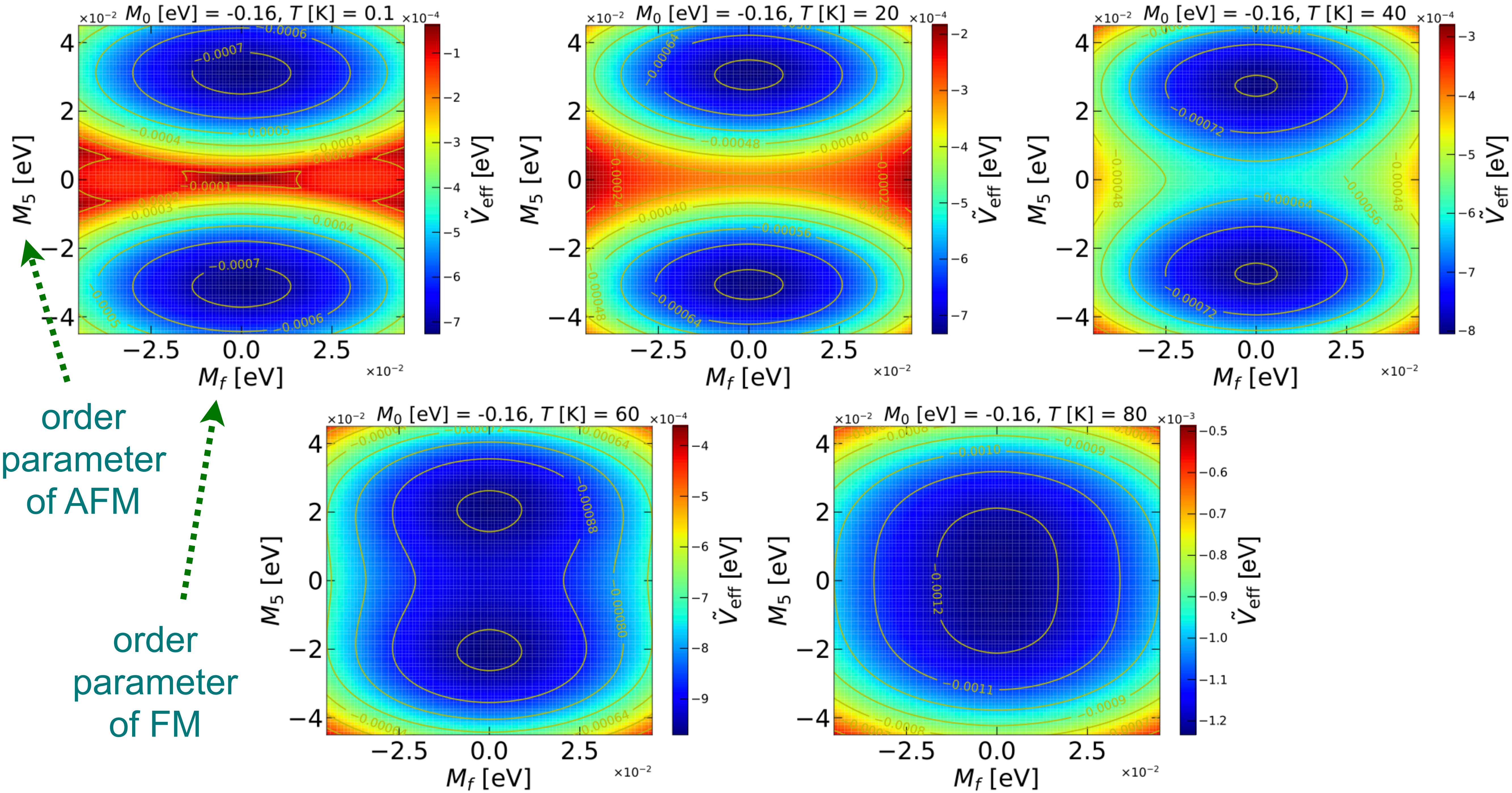
$$\mathcal{H}^{m}_{\boldsymbol{k}} = M_f \Gamma^{12} + M_5 \Gamma^5$$

M_f : order parameter of FM

M_5 : order parameter of AFM

Effective potential

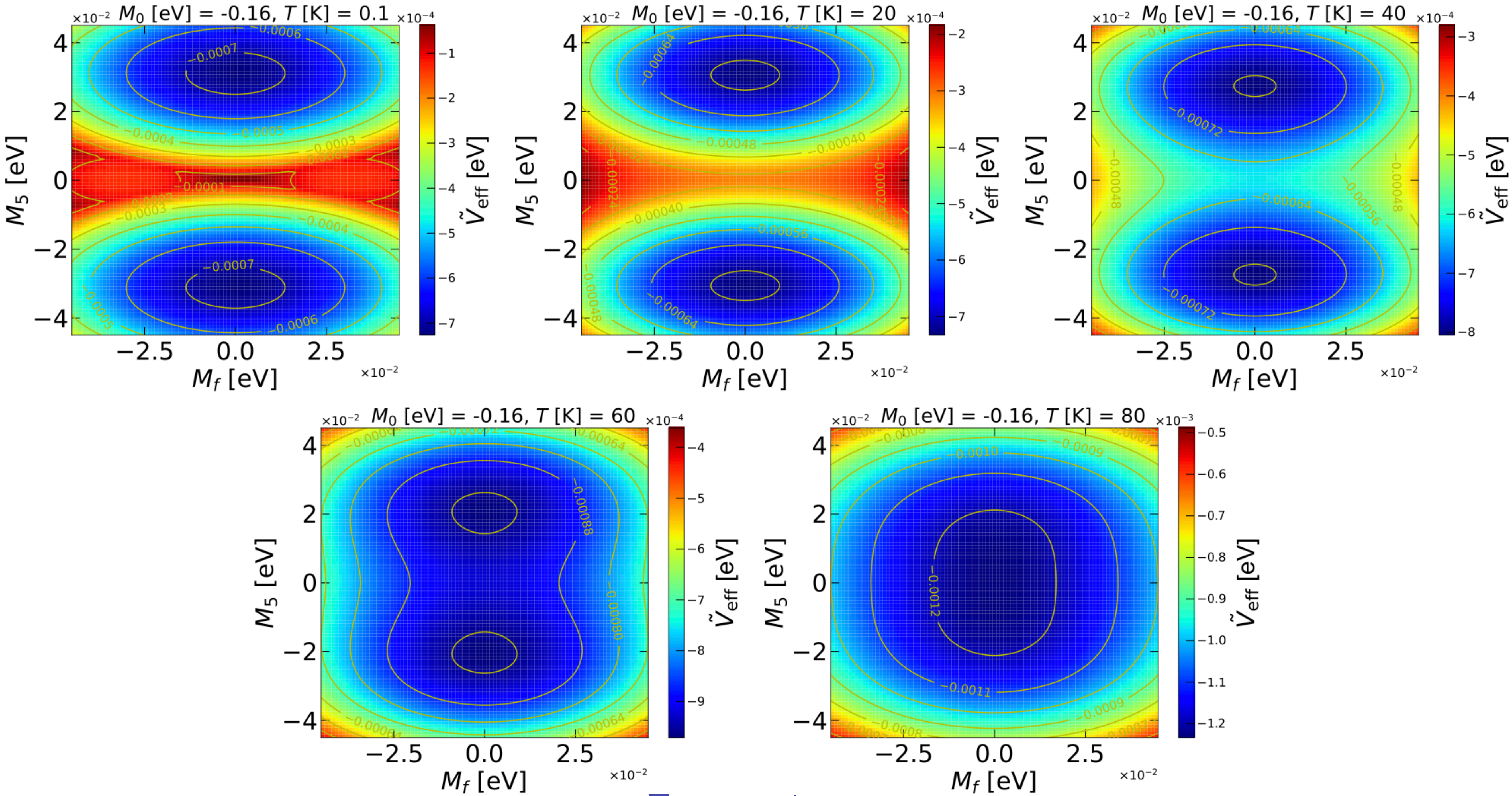
KI '22



Effective potential

KI '22

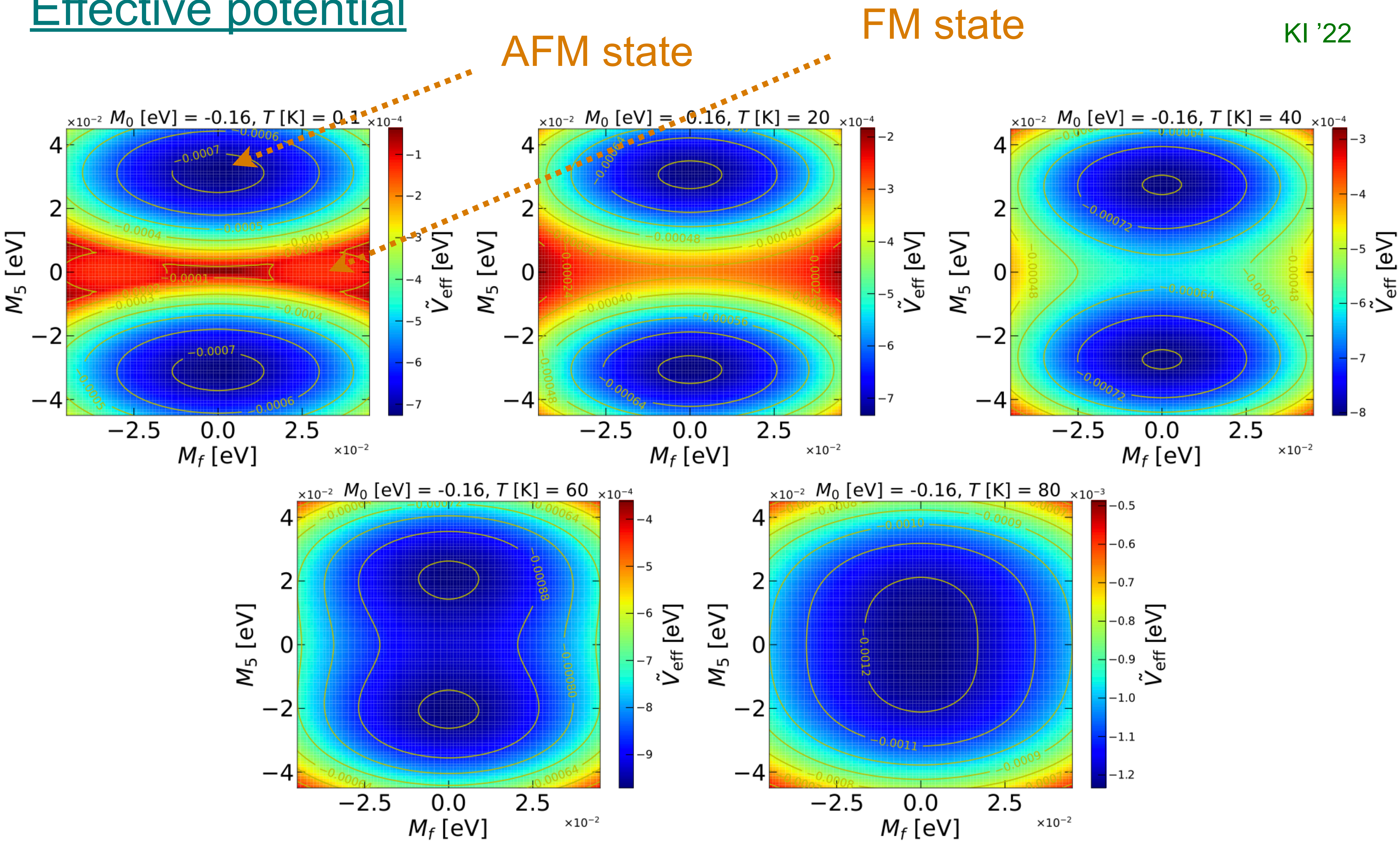
Temperature



Temperature

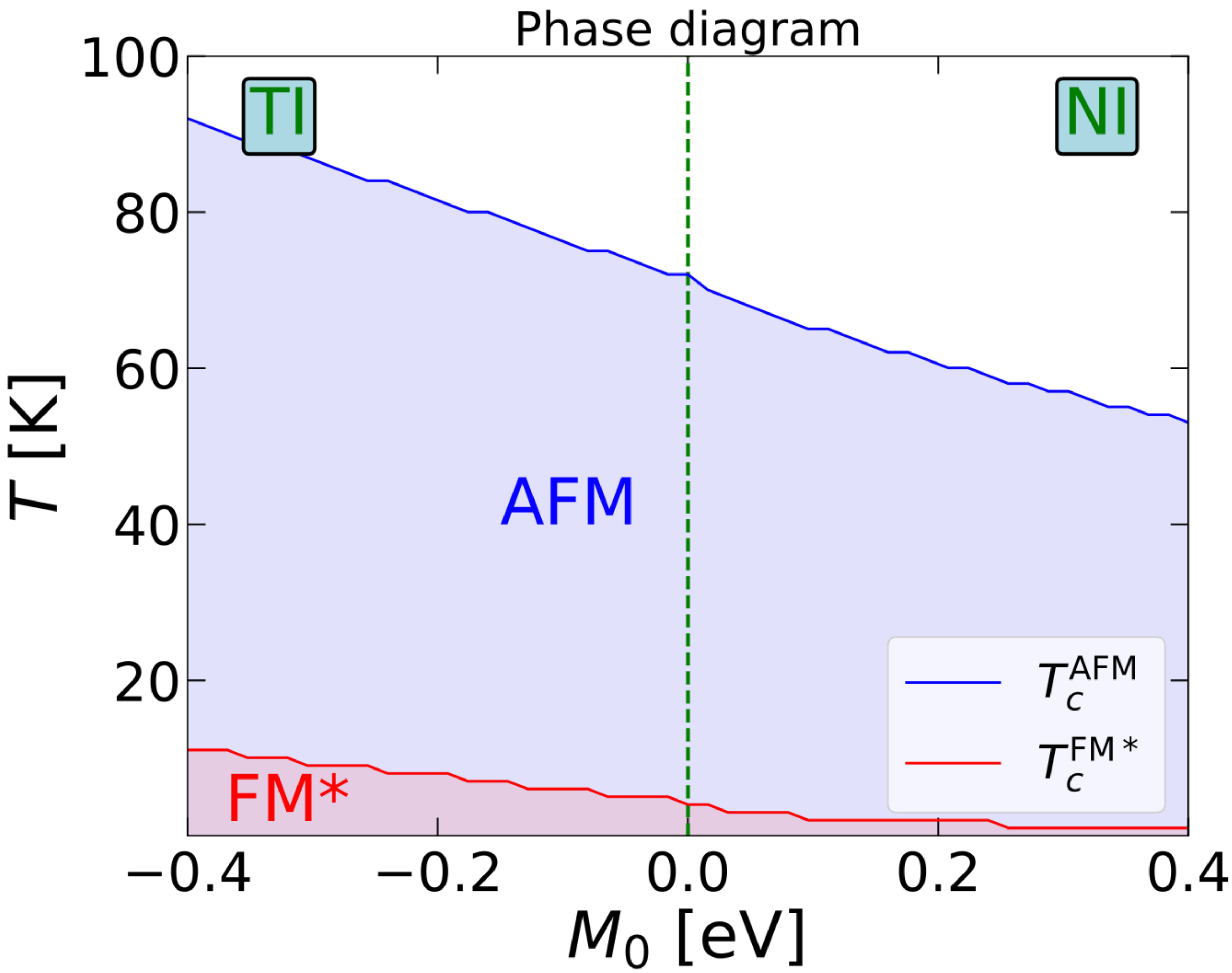
Effective potential

KI '22



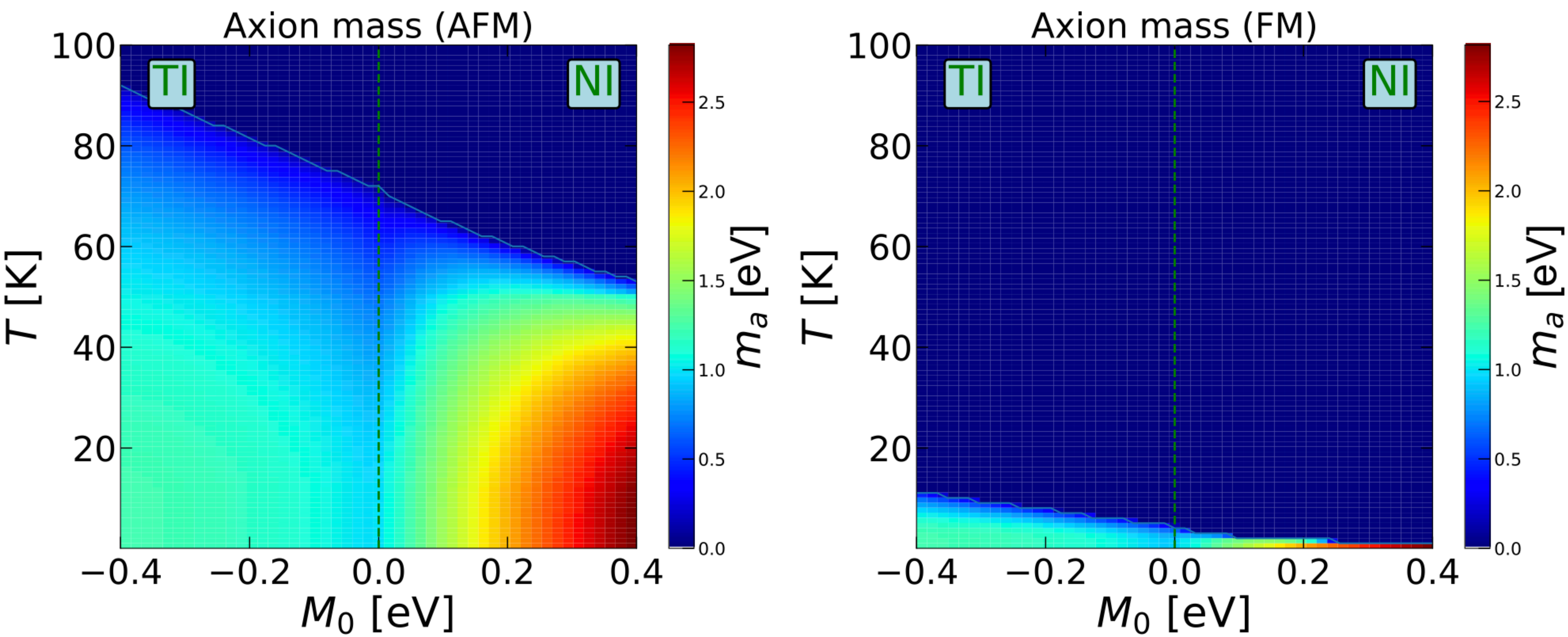
Phase diagram

KI ’22



Axion mass

KI ’22

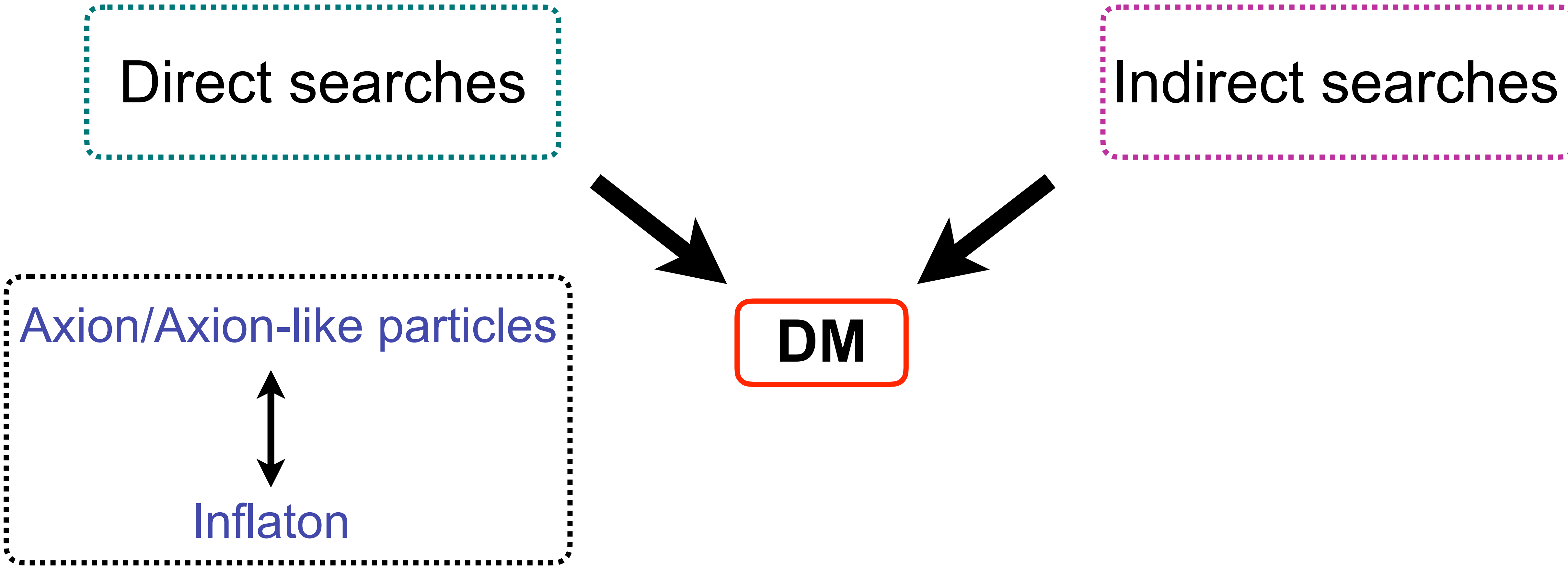


Axion mass is $\mathcal{O}(\mathrm{eV})$ except for the phase boundaries

Quick summary

- Axion mass is $\mathcal{O}(\mathrm{eV})$ while it can be suppressed around the phase boundaries in the magnetic TIs
- Material search is crucial for the particle axion detection

Approaches from astro-particle physics and cosmology



Approaches from astro-particle physics and cosmology

Direct searches

Indirect searches

DM

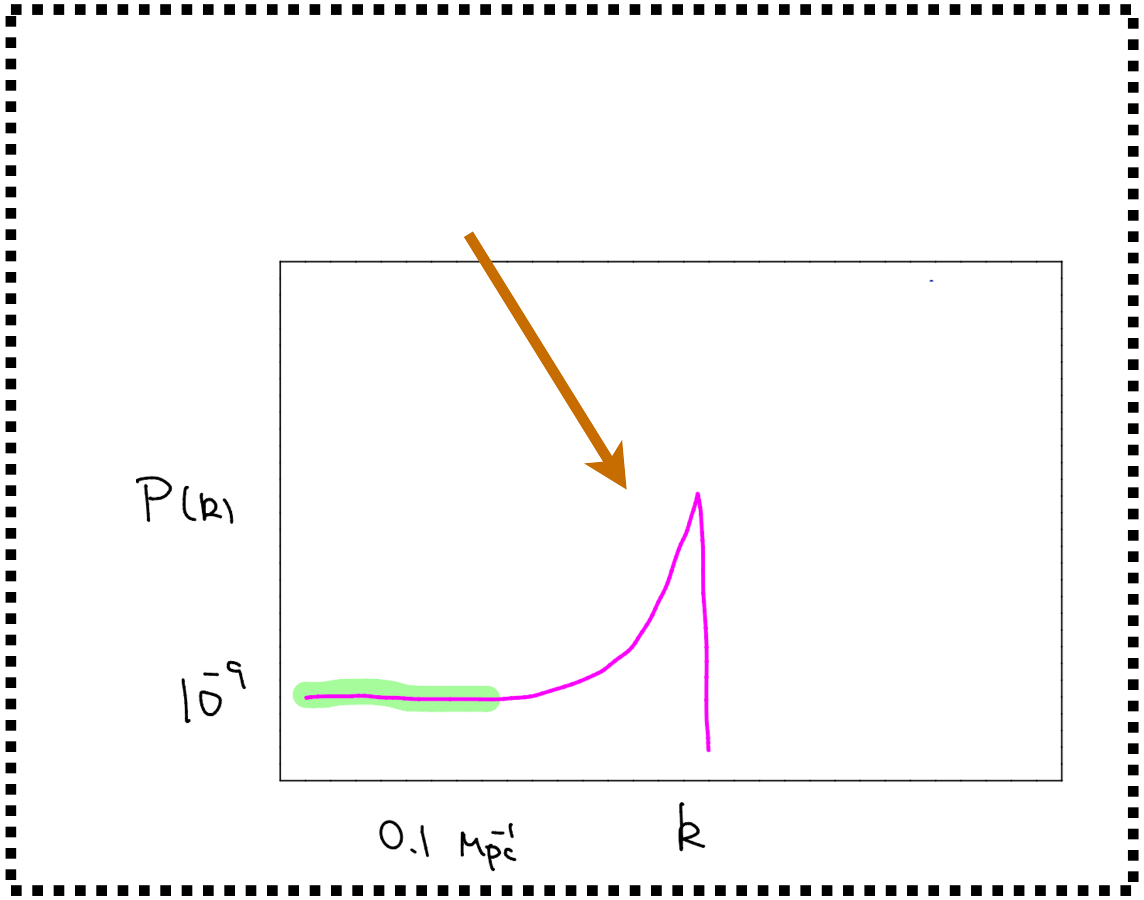
Axion/Axion-like particles

↕

Inflaton

Blue-tilted power spectrum,
e.g., axion-U(1) gauge system

McDonough, Moghaddam, Brandenberger '16



Approaches from astro-particle physics and cosmology

Direct searches

Indirect searches

DM

Axion/Axion-like particles

↕

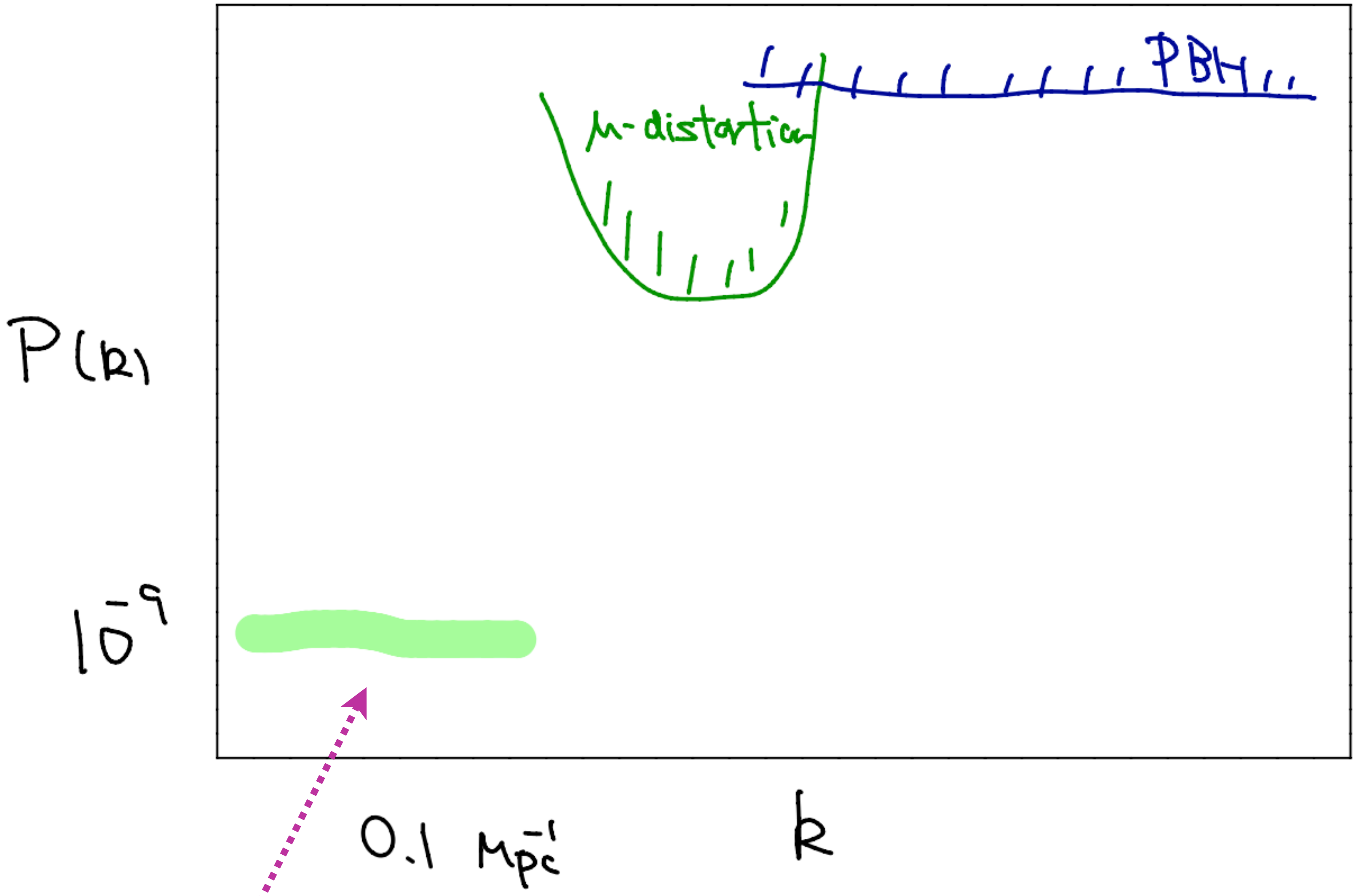
Inflaton

“Indirect” search on **inflation**

Today’s 2nd topic

3. Primordial curvature perturbations

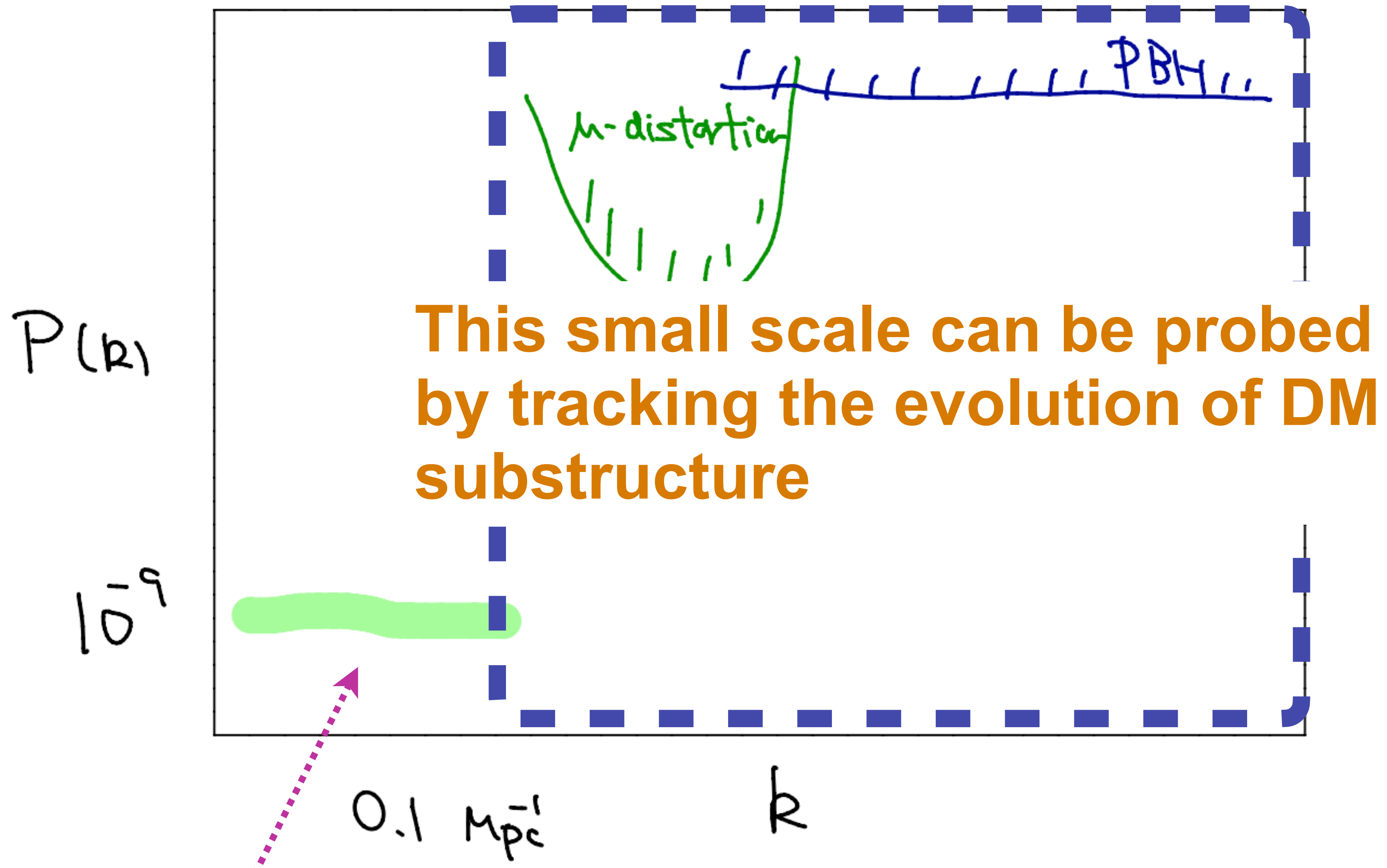
Constraints on primordial curvature power spectrum



$$\mathcal{P}_R = (2.099 \pm 0.029) \times 10^{-9}$$

Planck '18

Constraints on primordial curvature power spectrum



$$\mathcal{P}_R = (2.099 \pm 0.029) \times 10^{-9}$$

Planck '18

Evolution of halo/subhalos

Hiroshima-san's talk in detail

Curvature perturbation

↓

Host halos and subhalos

↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies

Evolution of halo/subhalos

Curvature perturbation

↓

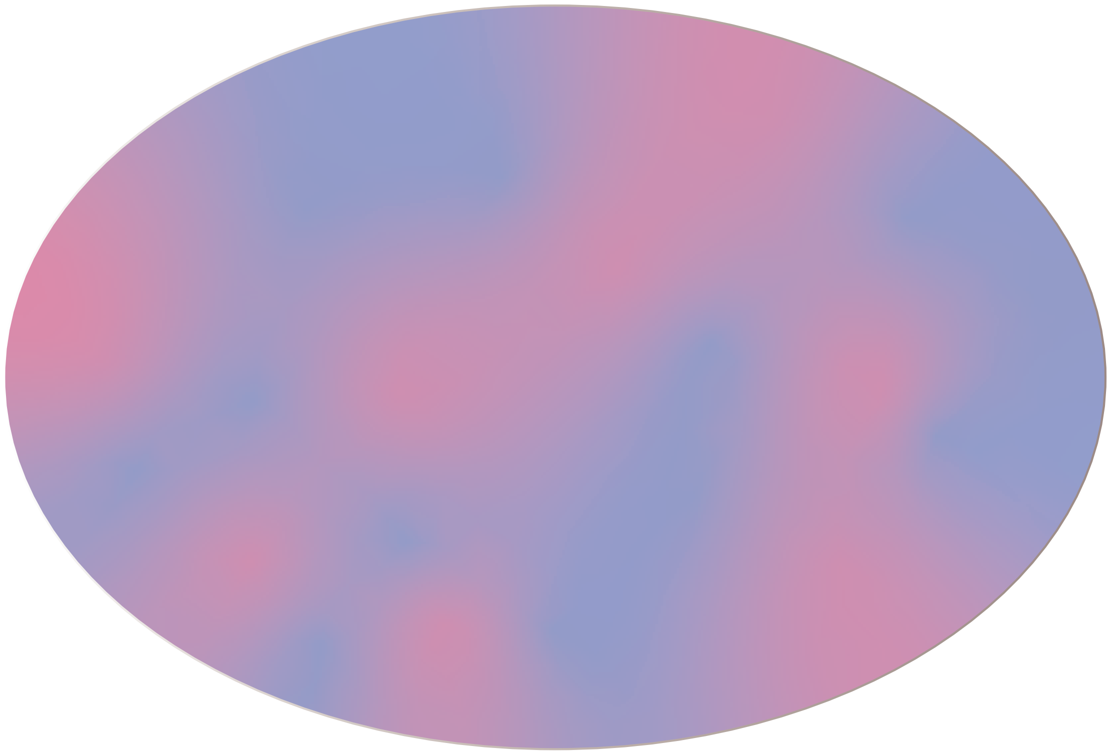
Host halos and subhalos

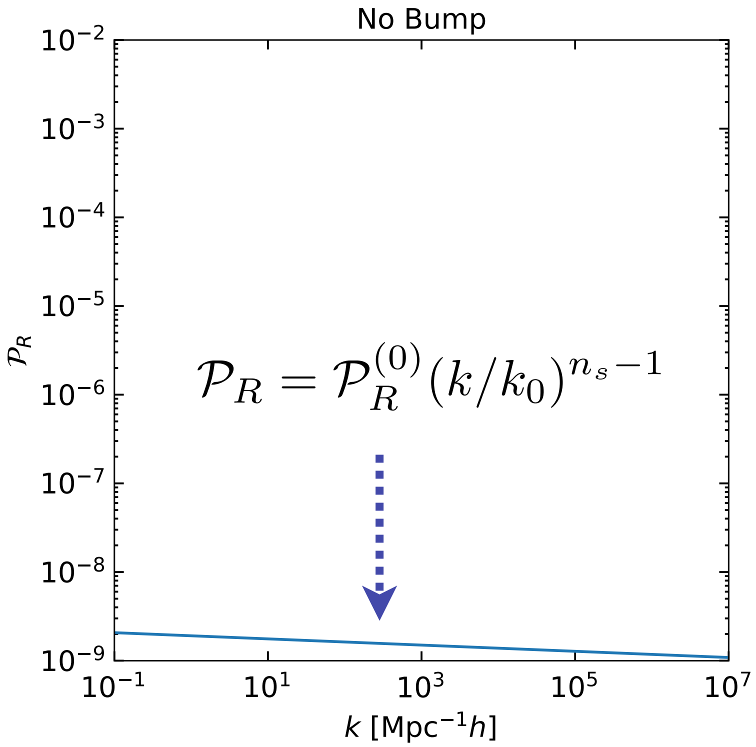
↓

Subhalos accrete on a host halo

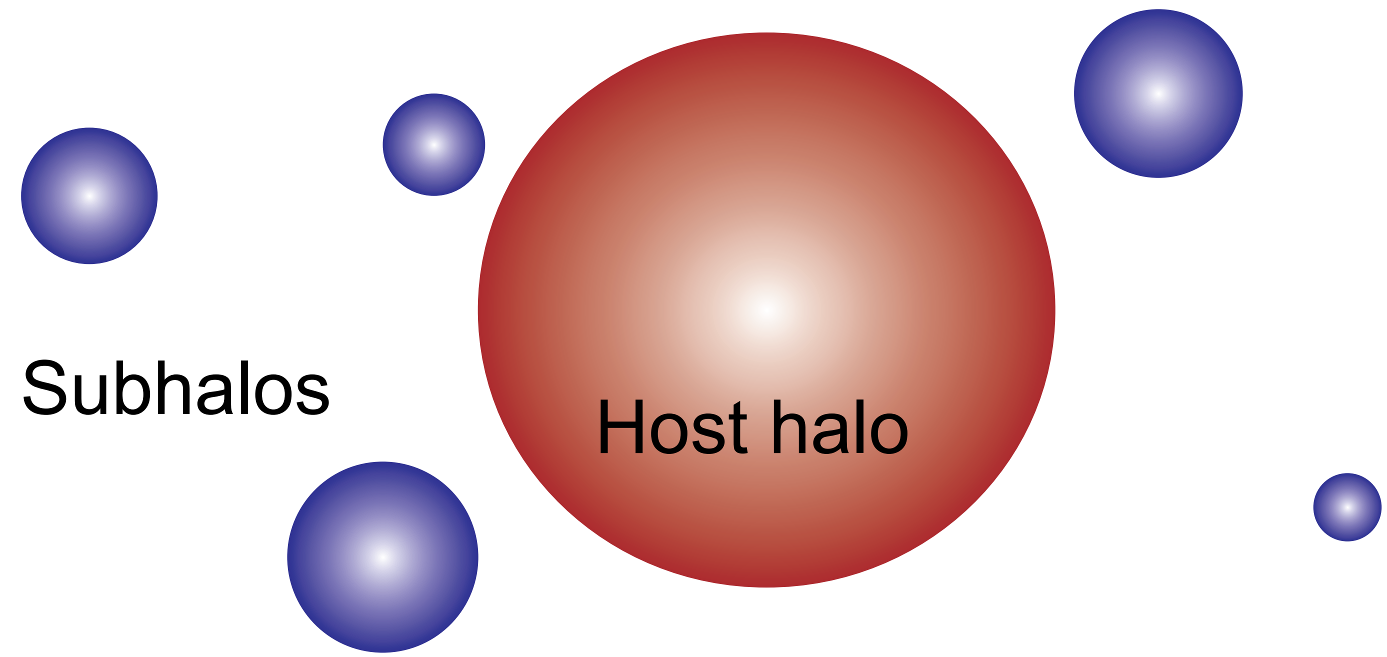
↓

Subhalos or satellite galaxies





Evolution of halo/subhalos



Curvature perturbation

↓

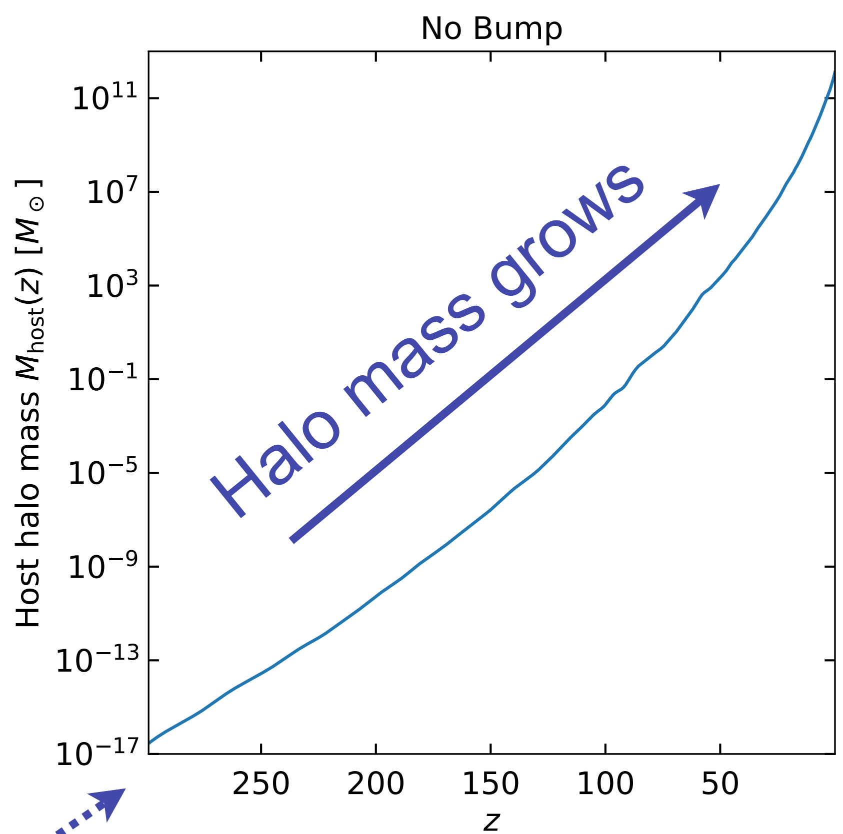
Host halos and subhalos

↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies



Halo mass grows gradually based on the extended Press-Schechter formalism

Bond, Cole, Efstathiou, Kaiser '91
Bower '91
Lacy, Cole '93
Yang, Mo, Zhang, van den Bosch '11

Evolution of halo/subhalos

Curvature perturbation

↓

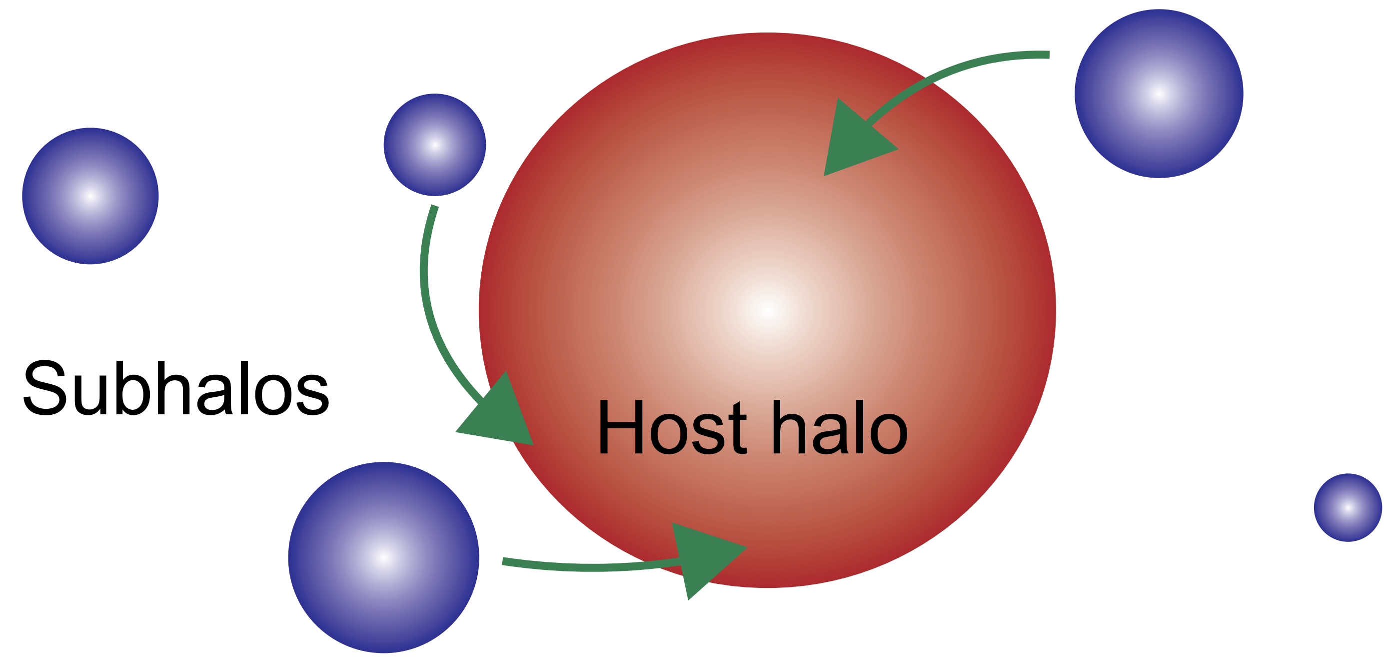
Host halos and subhalos

↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies



Evolution of halo/subhalos

Curvature perturbation

↓

Host halos and subhalos

↓

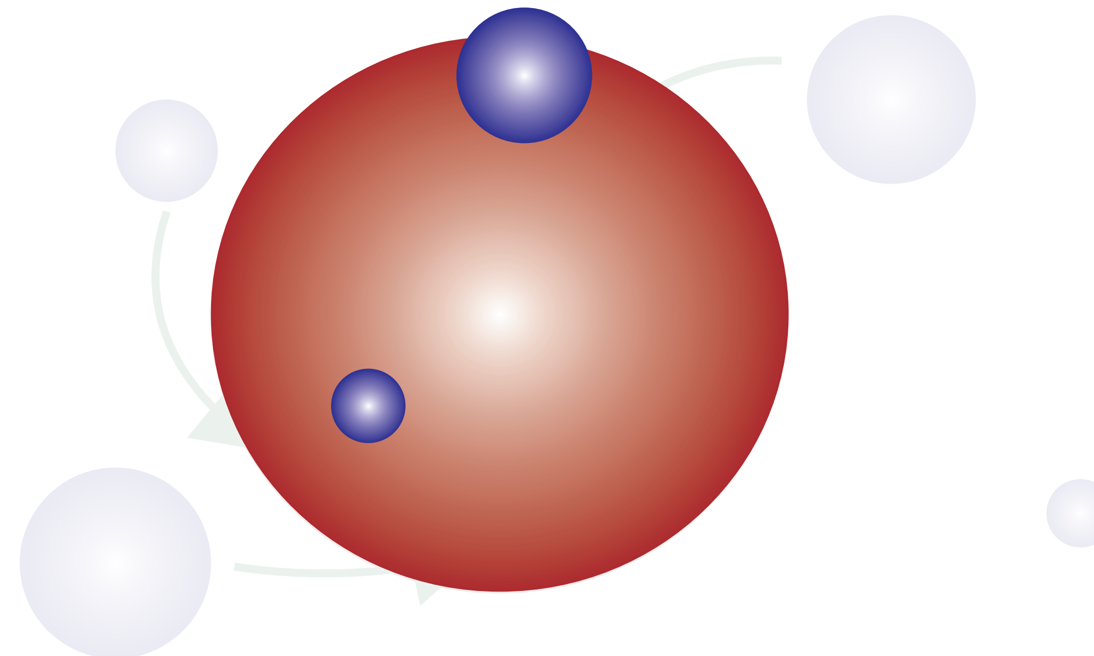
Subhalos accrete on a host halo

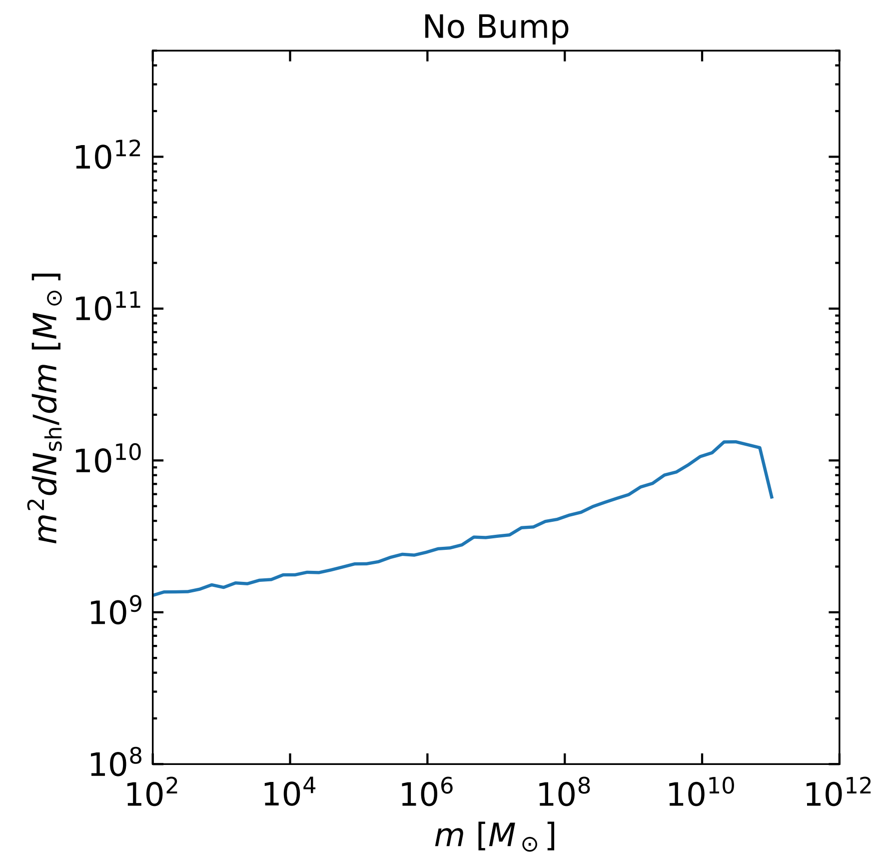
↓ Tidal stripping

Subhalos or satellite galaxies

Studied in semi-analytical way
calibrated by N-body simulation

Hiroshima, Ando, Ishiyama '18

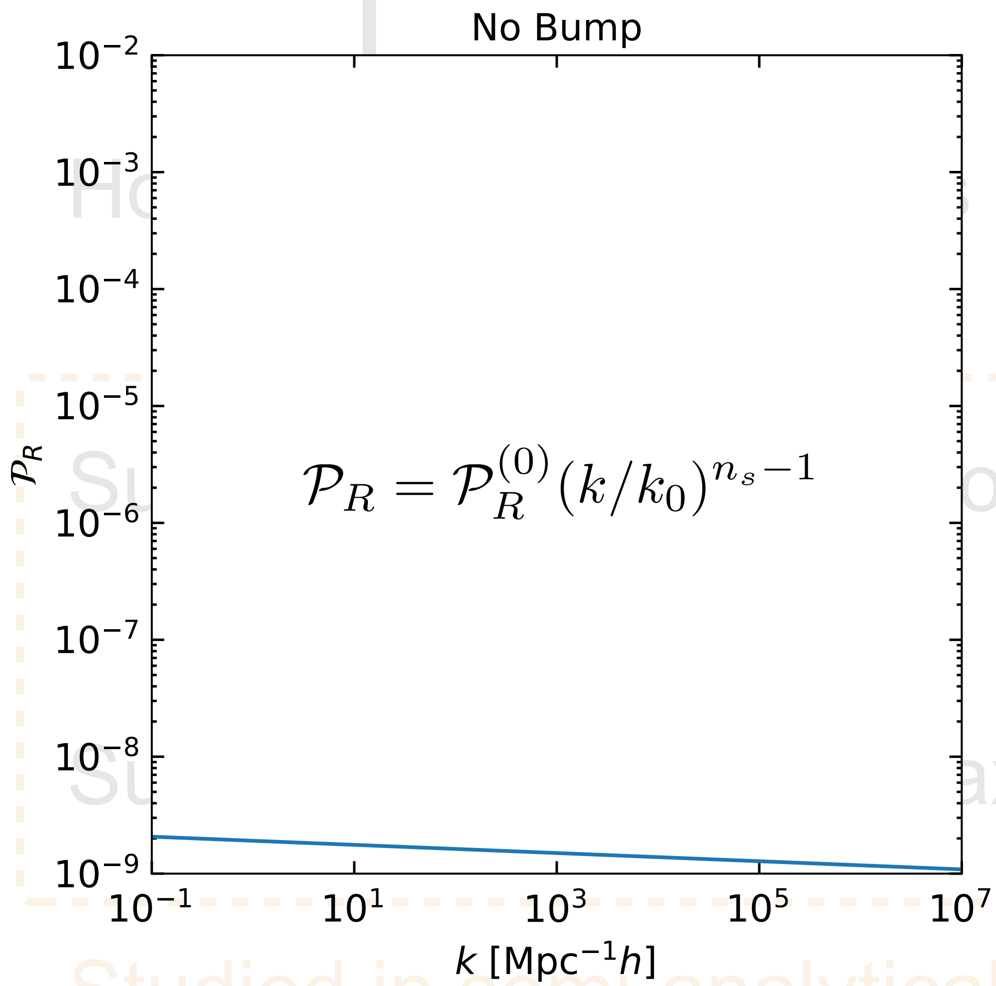


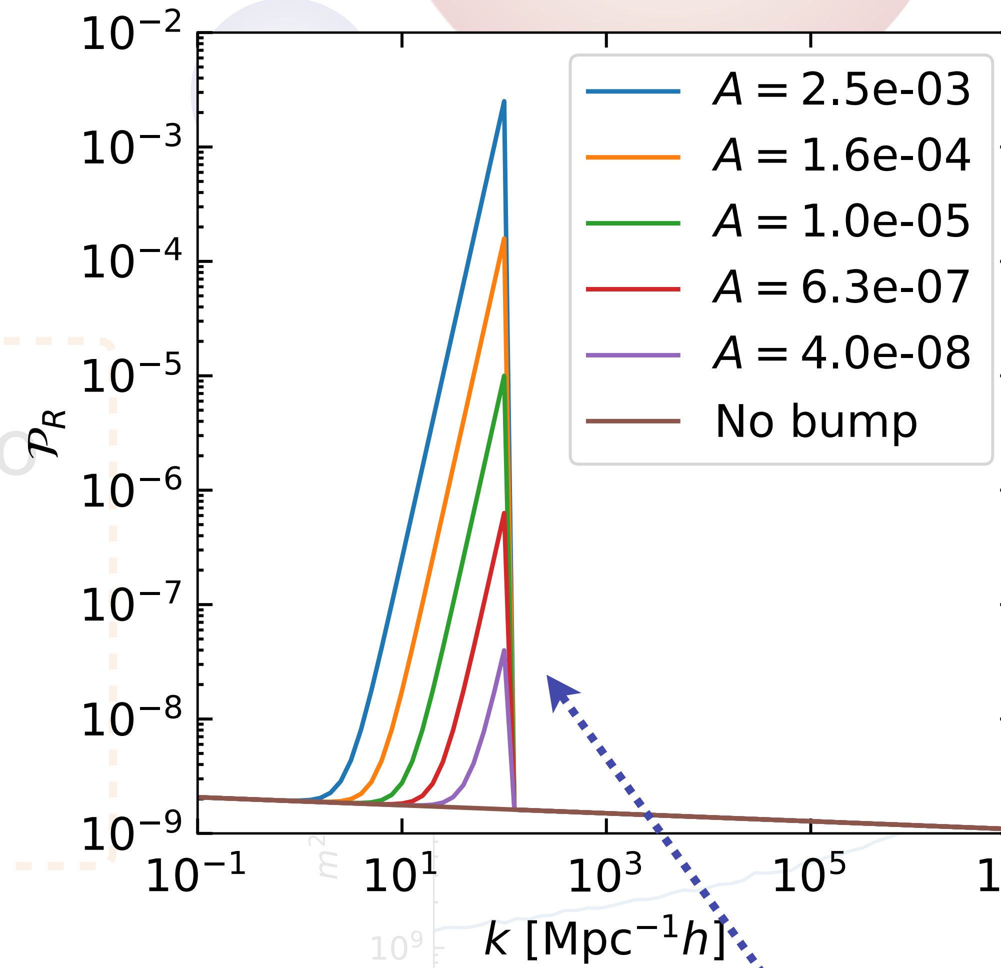


Mass distribution of subhalos

Evolution of halo/subhalos

Curvature perturbation





Additional bump

Studied in semi-analytical way
calibrated by N-body simulation

Hiroshima, Ando, Ishiyama '18

What will happen?

Mass distribution of subhalos

Evolution of halo/subhalos

Curvature perturbation

↓

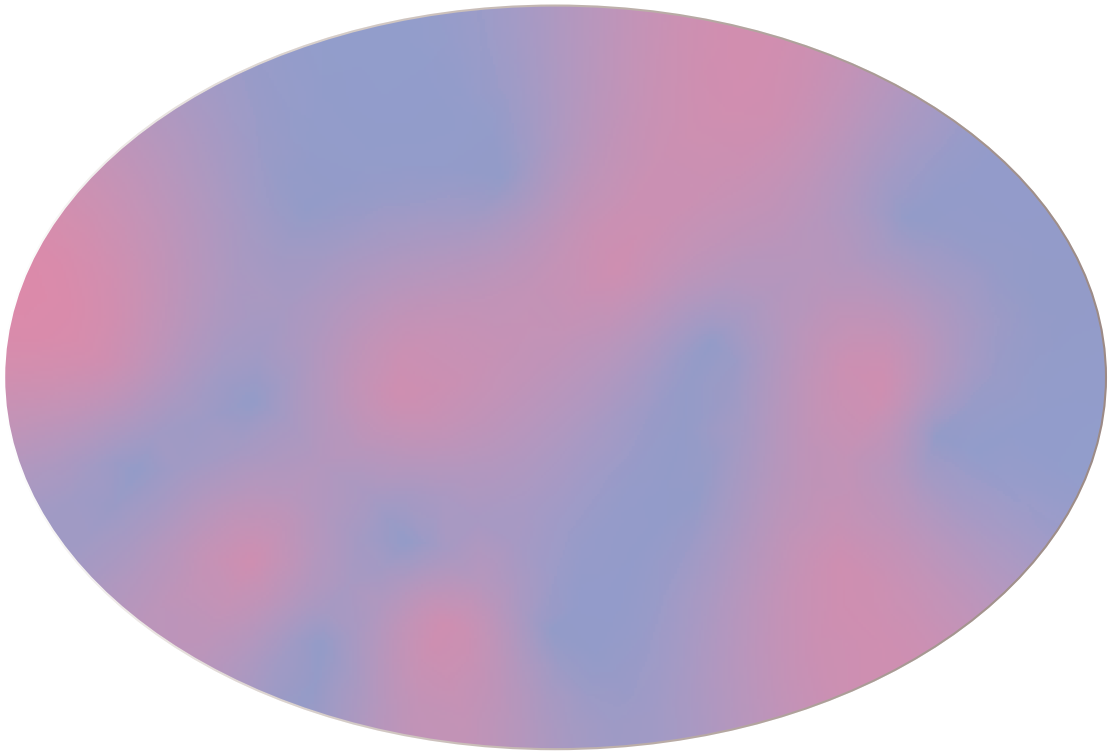
Host halos and subhalos

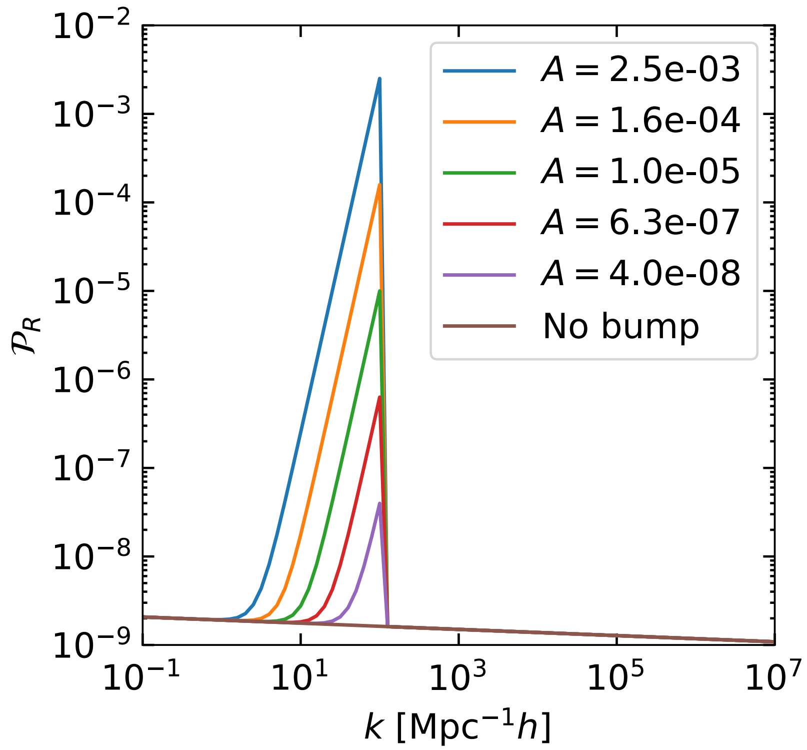
↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies





Evolution of halo/subhalos

Curvature perturbation

↓

Host halos and subhalos

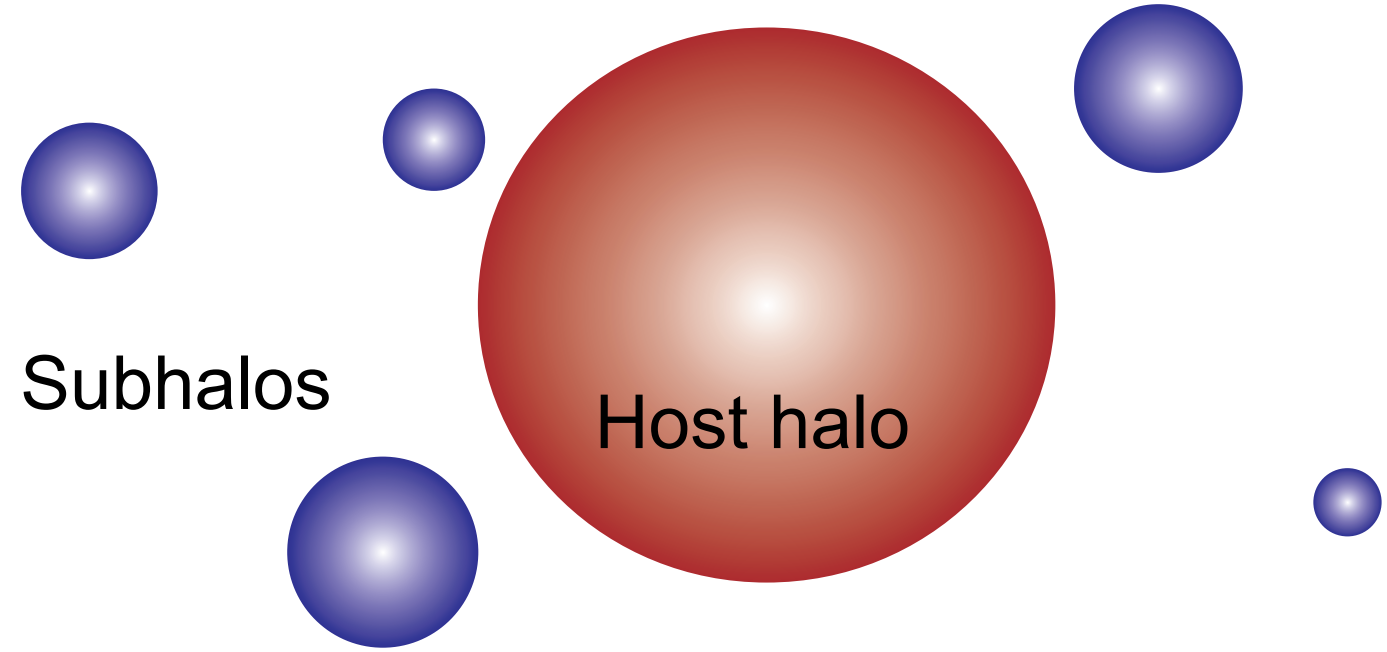
↓

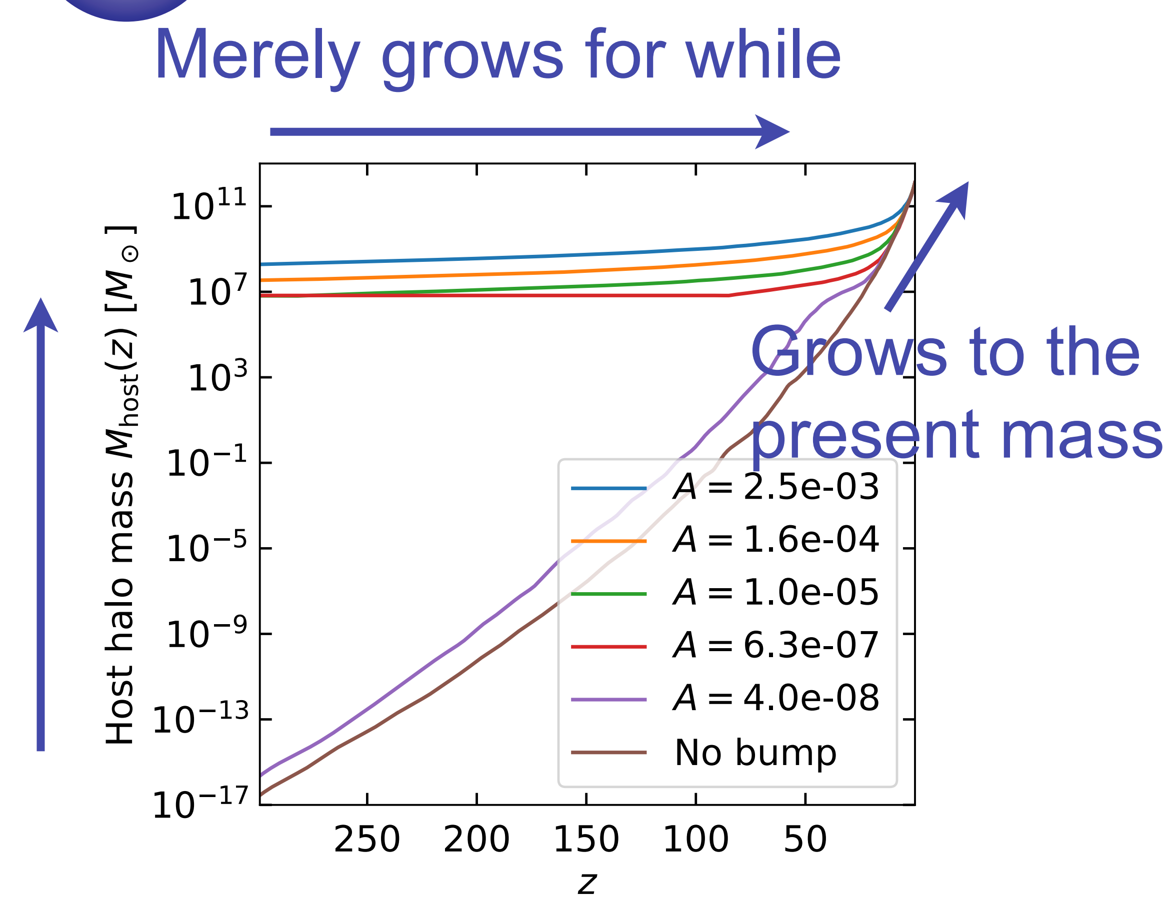
Subhalos accrete on a host halo

↓

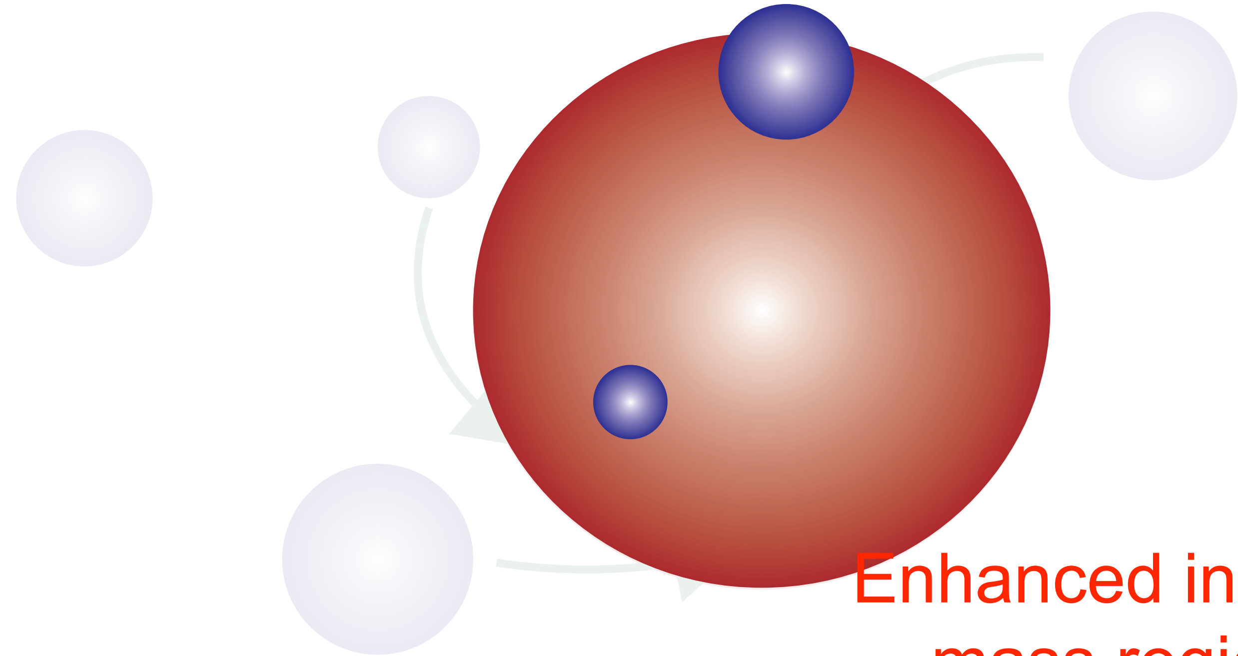
Subhalos or satellite galaxies

Halo grows to a specific scale *at once*





Evolution of halo/subhalos



Curvature perturbation

↓

Host halos and subhalos

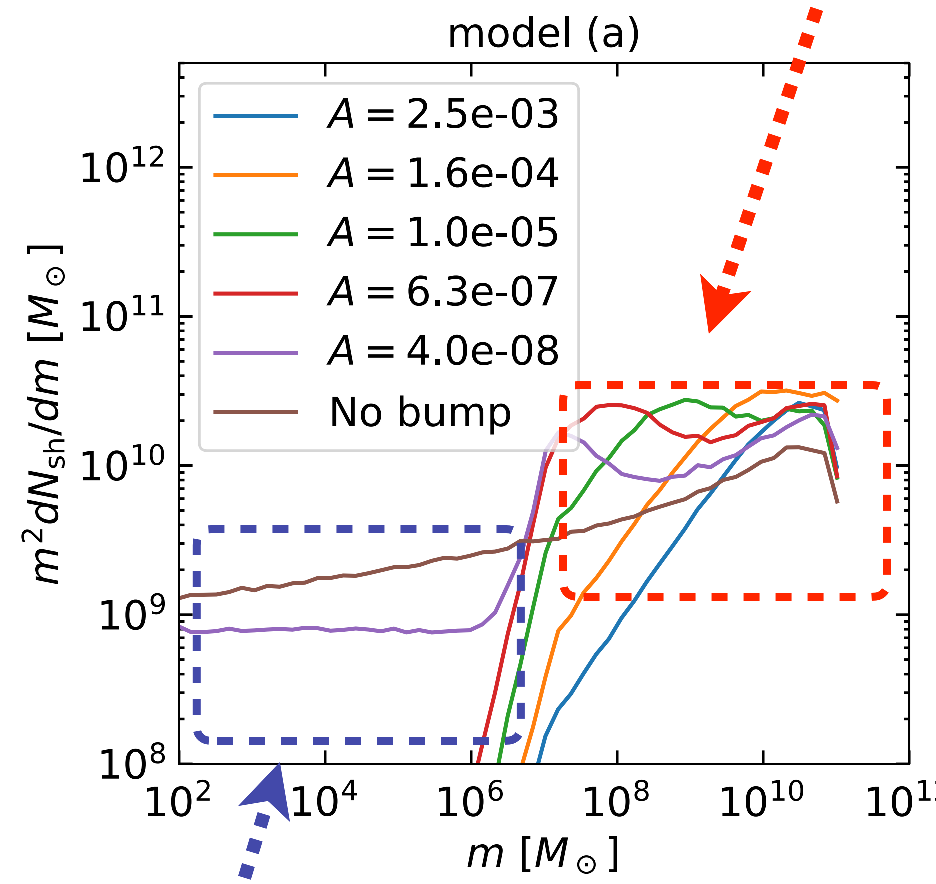
↓

Subhalos accrete on a host halo

↓ Tidal stripping

Subhalos or satellite galaxies

Enhanced in high mass region

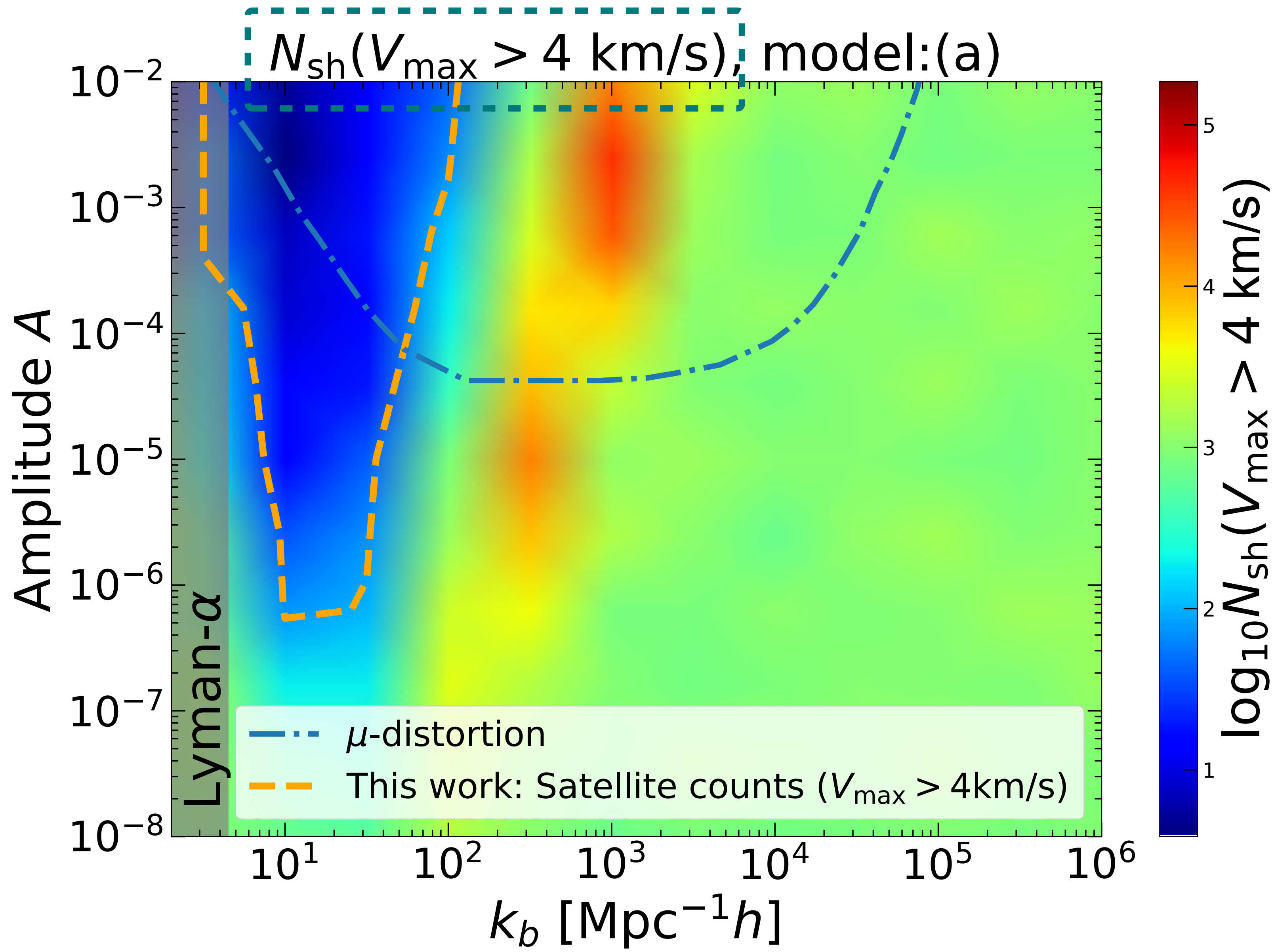


Suppressed in low mass region

Ando, Hiroshima, KI '22

The observable: satellite counts

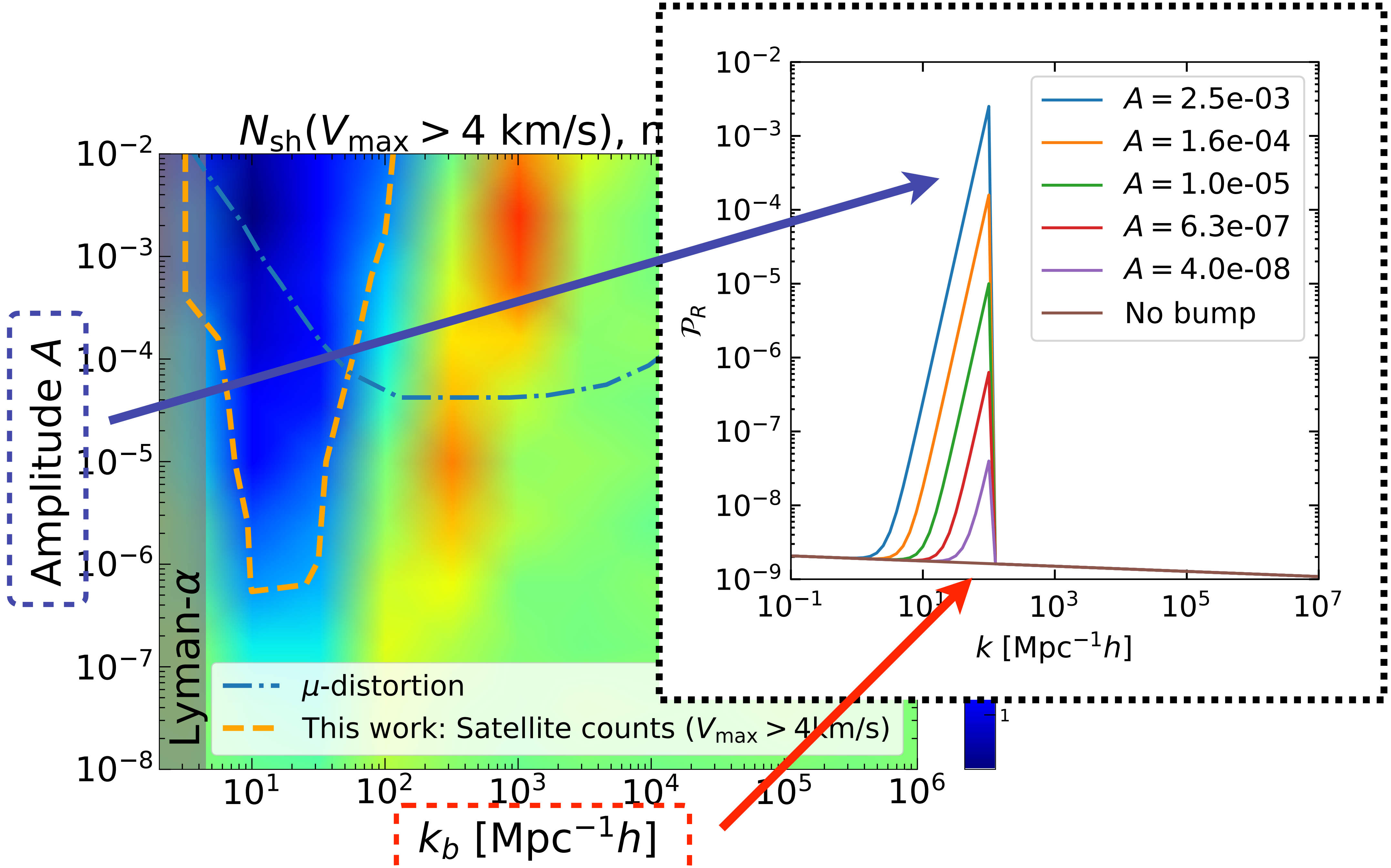
Number of subhalos whose $V_{\max} > 4\ \mathrm{km/s}$



$V_{\max}$: Maximum circular velocity of subhalos

Ando, Hiroshima, KI '22

The observable: satellite counts



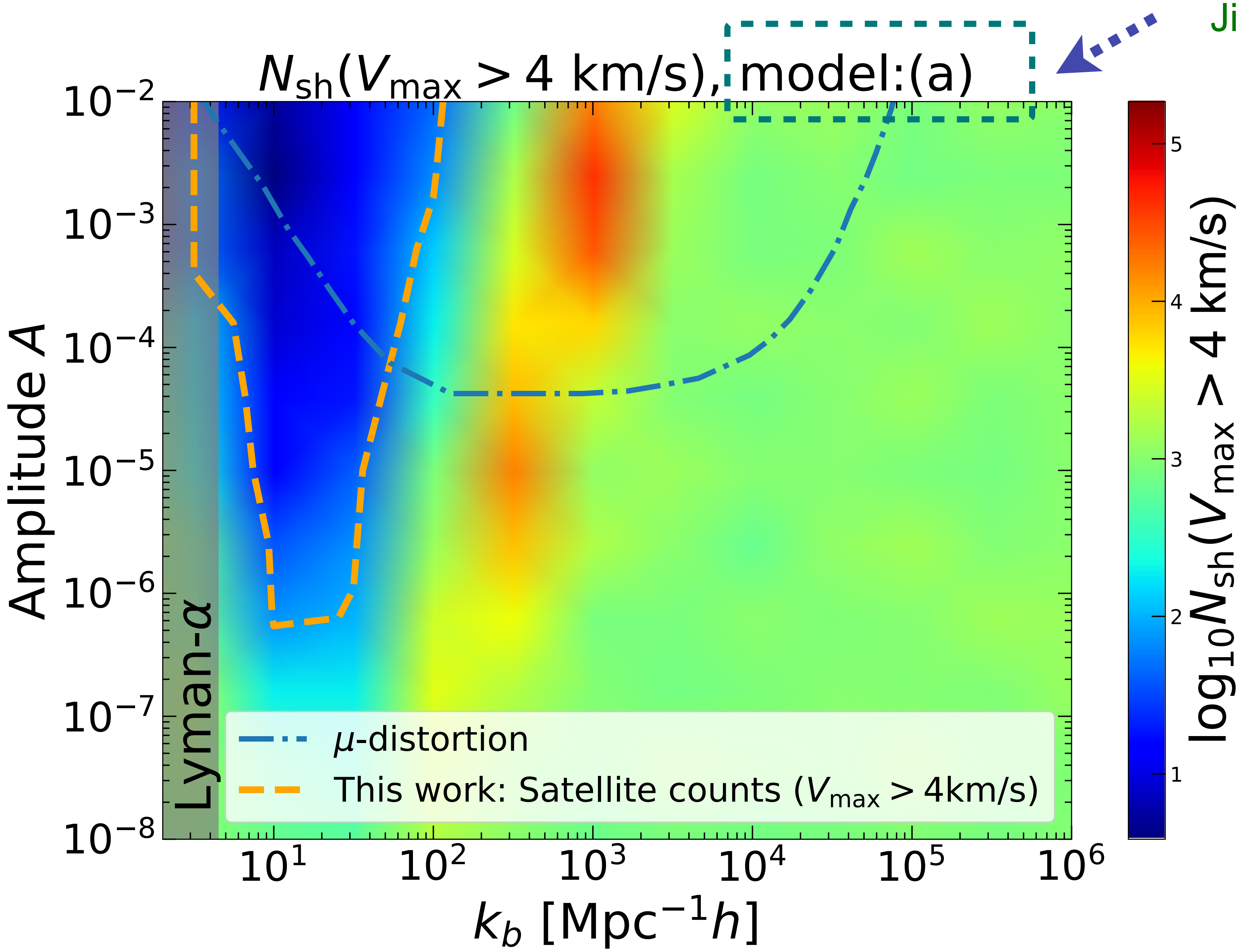
$V_{\rm max}$: Maximum circular velocity of subhalos

Ando, Hiroshima, KI ’22

The observable: satellite counts

Tidal stripping model

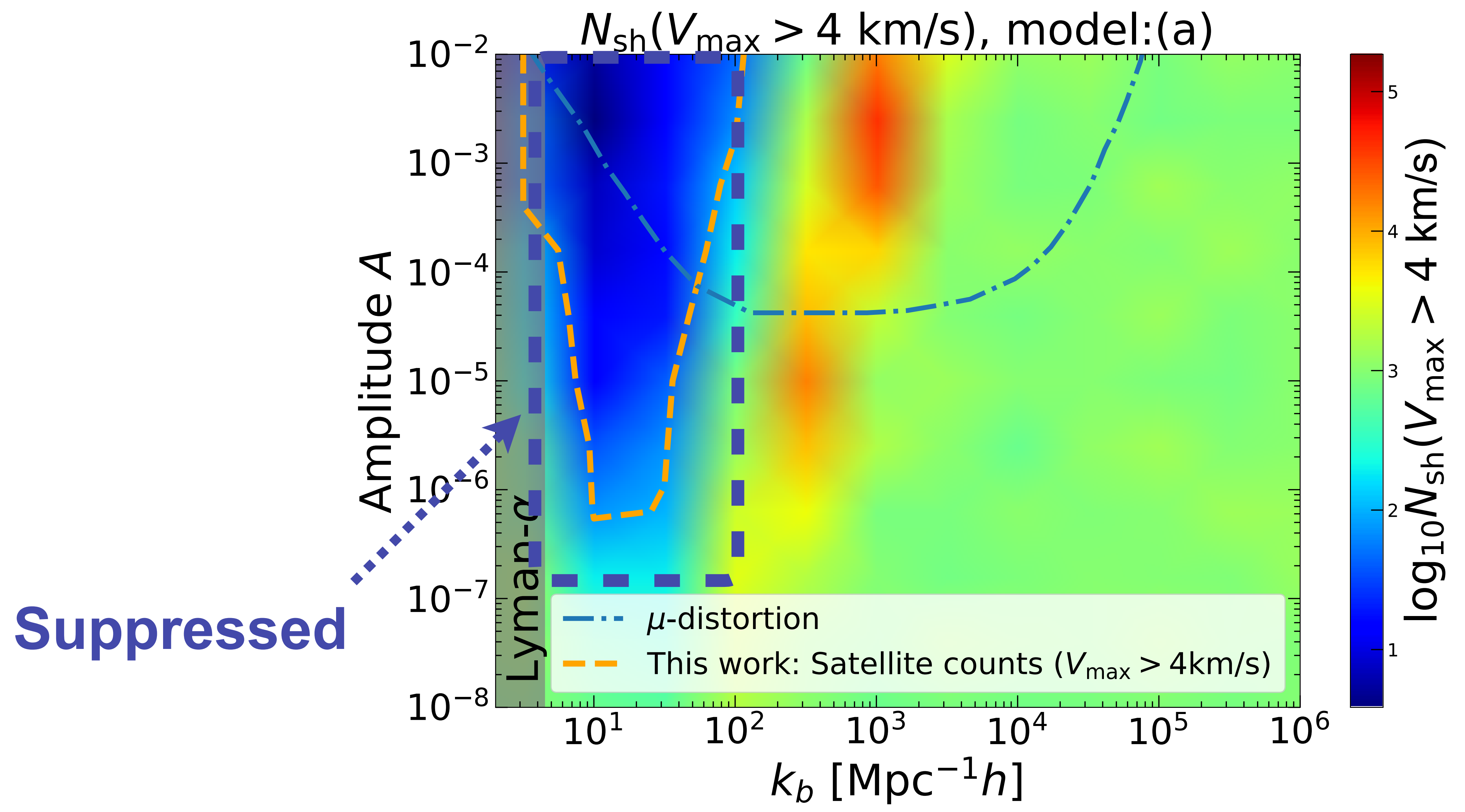
Jiang, van den Bosch ’16



$V_{\rm max}$: Maximum circular velocity of subhalos

Ando, Hiroshima, KI ’22

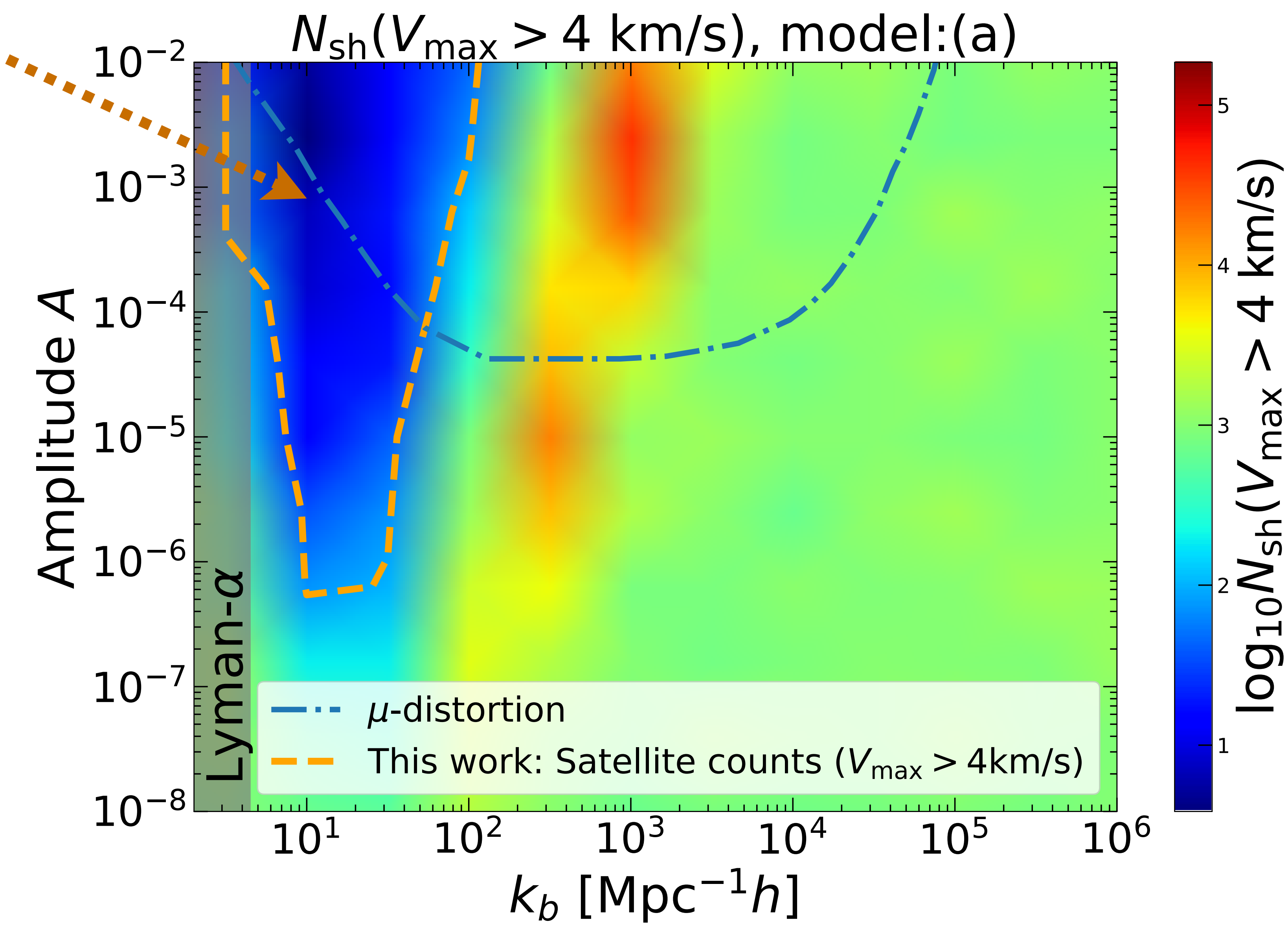
The observable: satellite counts



Ando, Hiroshima, KI ’22

The observable: satellite counts

Excluded



Conservative limit

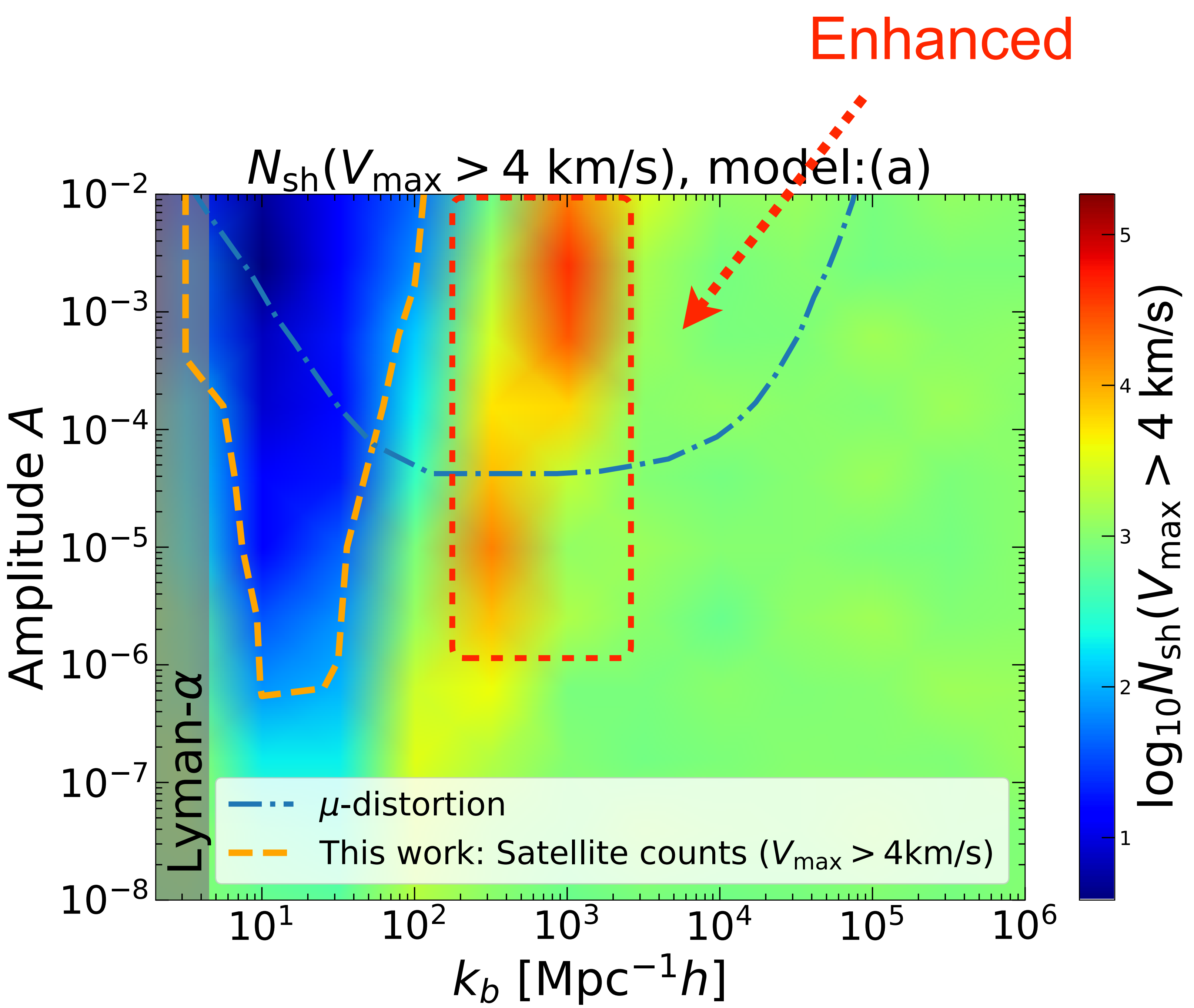
$$N_{\rm dSph}^{\rm low}(V_{\rm max} > 4\ {\rm km/s}) = 94$$

Graus, Bullock, Kelley, Boylan-Kolchin, Garrison-Kimmel, Qi ’19

Dekker, Ando, Correa, Ng ’21

Ando, Hiroshima, KI ’22

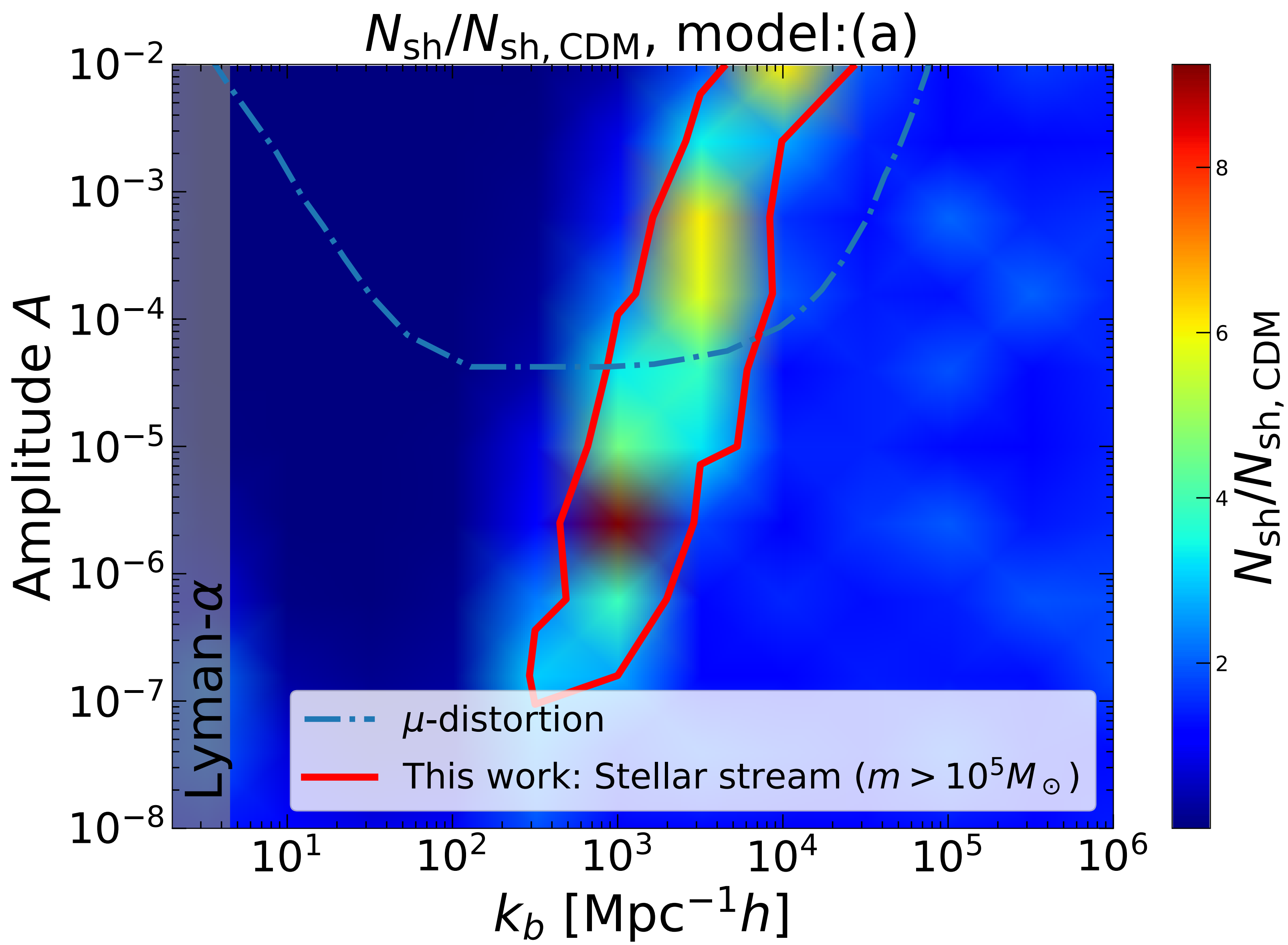
The observable: satellite counts



Ando, Hiroshima, KI '22

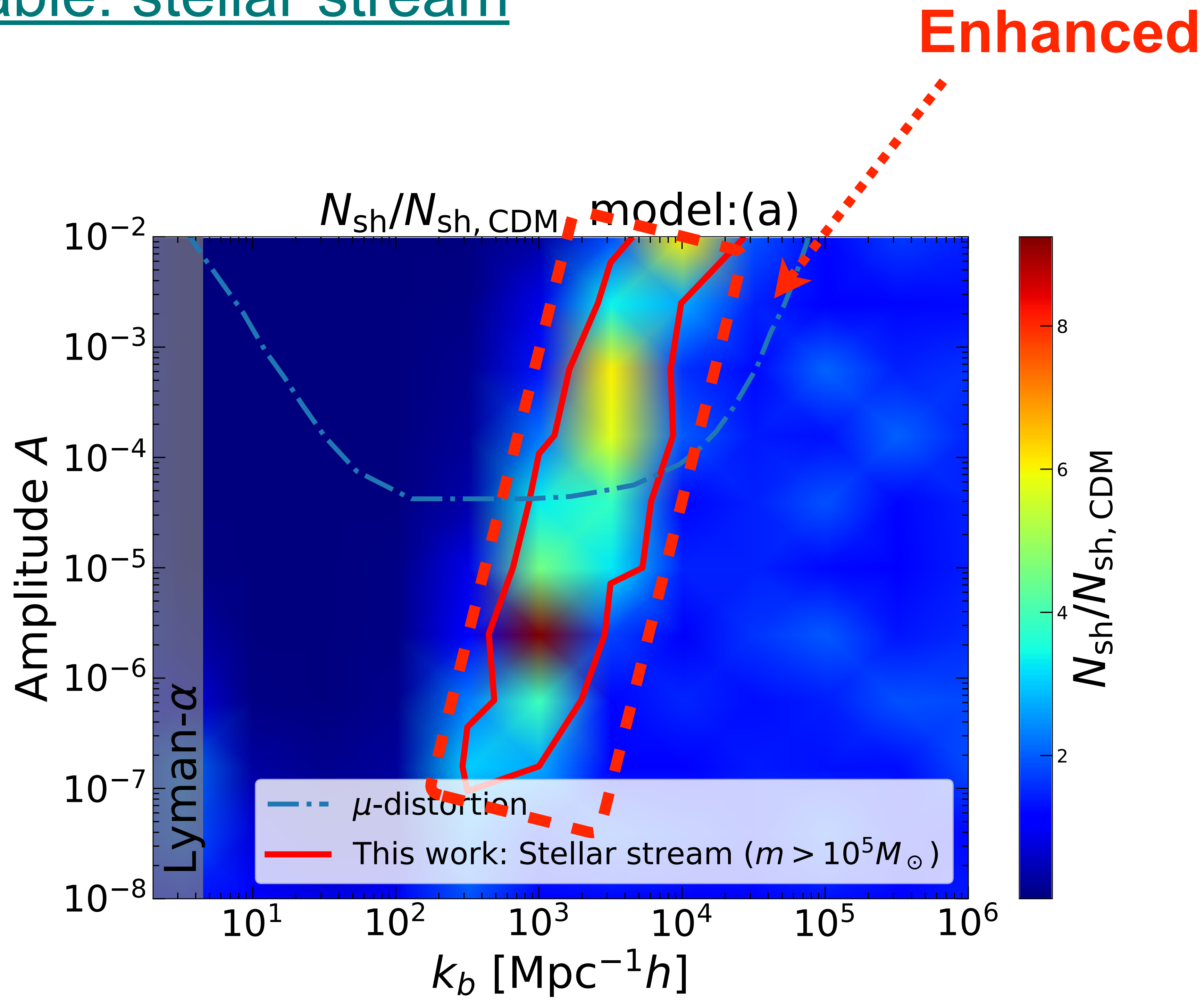
The observable: stellar stream

$N_{\rm sh}$: Number of subhalos whose mass $>10^5 M_\odot$



Ando, Hiroshima, KI '22

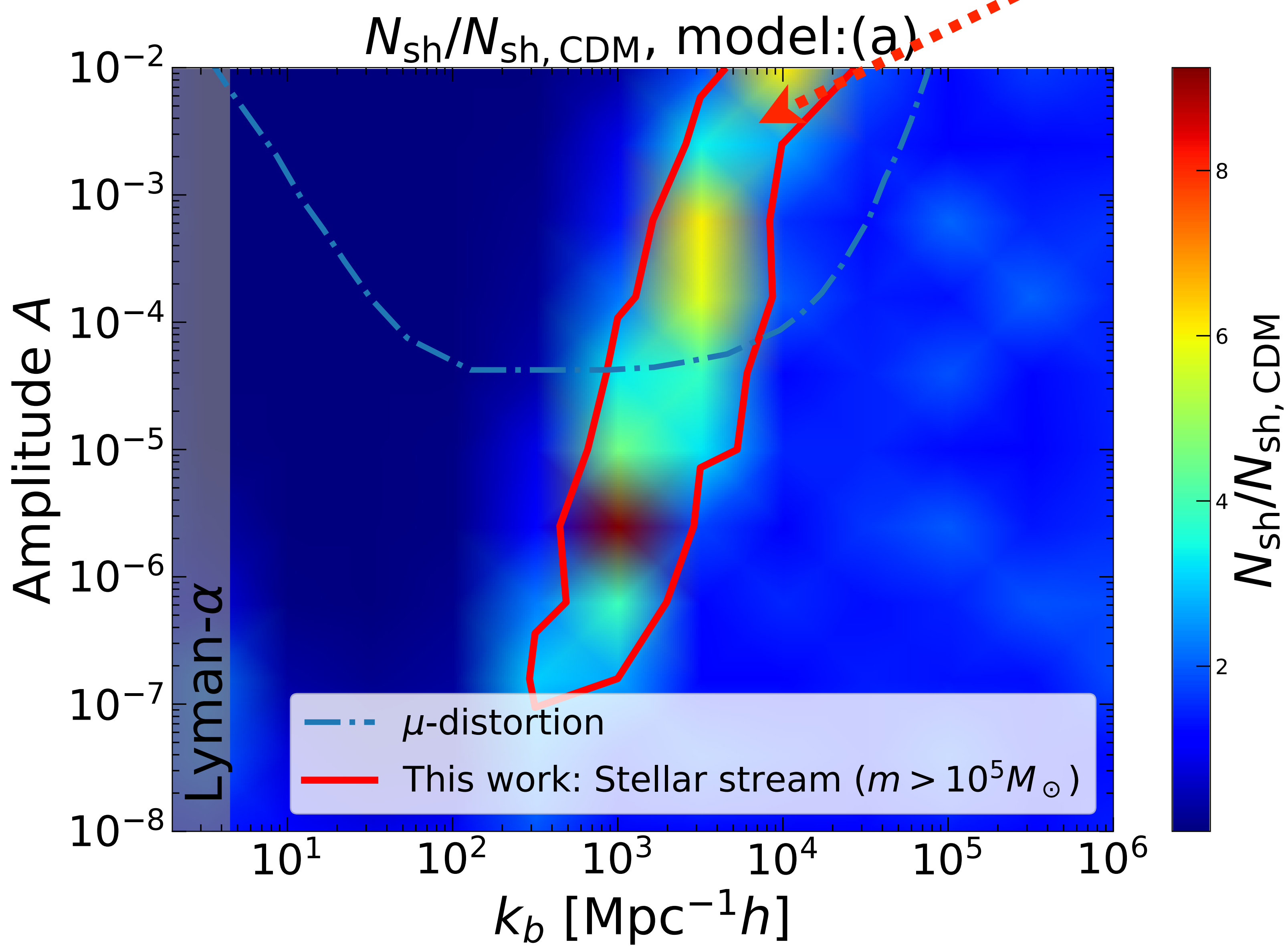
The observable: stellar stream



Ando, Hiroshima, KI ’22

The observable: stellar stream

Excluded



Conservative limit

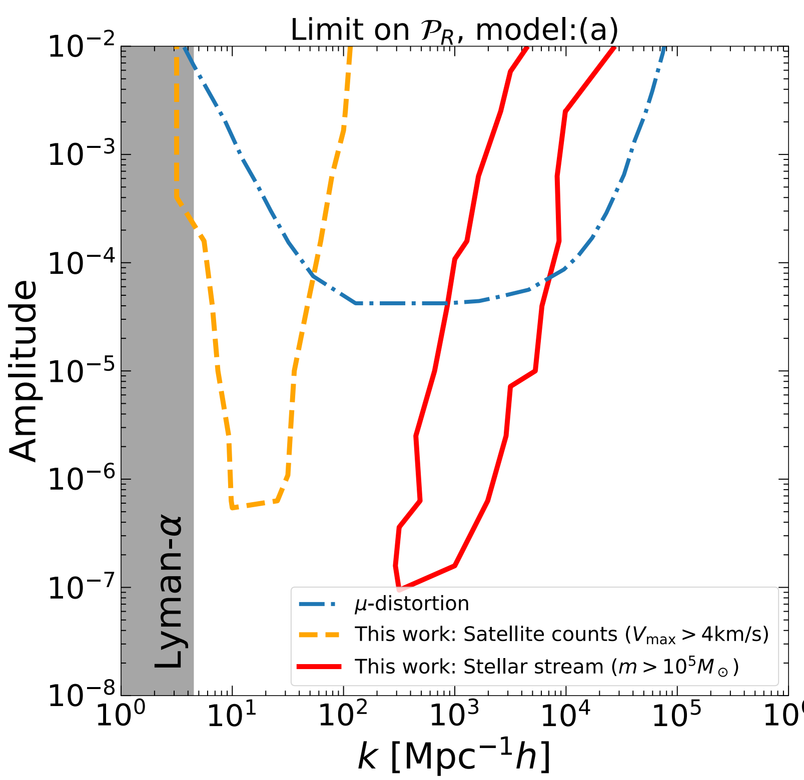
$$N_{\rm sh}/N_{\rm sh,CDM} < 2.7 \ (95\% \ \rm CL)$$

Banik, Bovy, Bertone, Erkal, de Boer ’21

Ando, KI, Hiroshima ’22

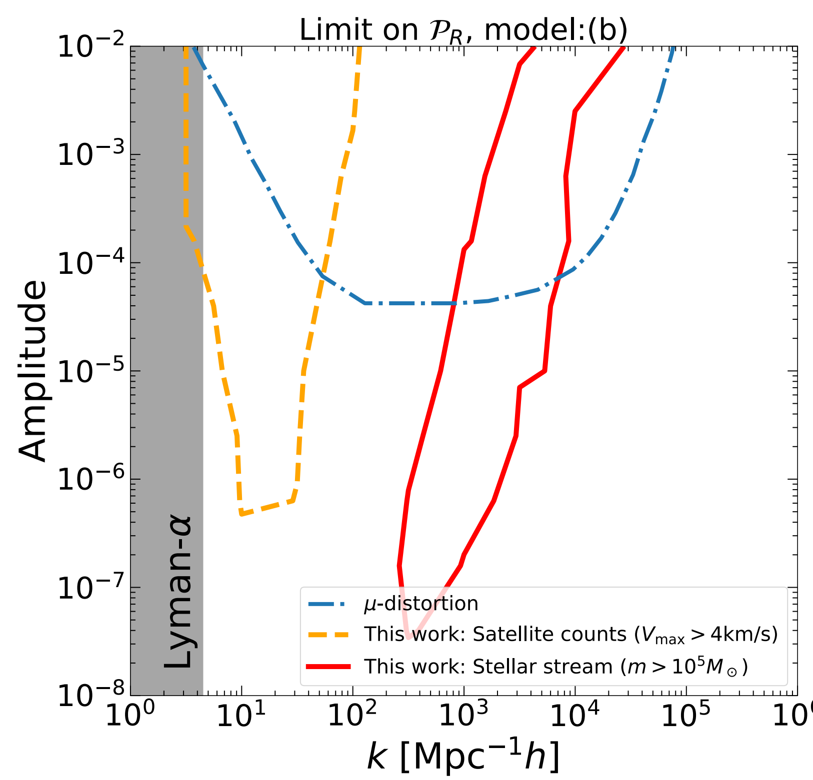
Tidal stripping model

Jiang, van den Bosch ’16

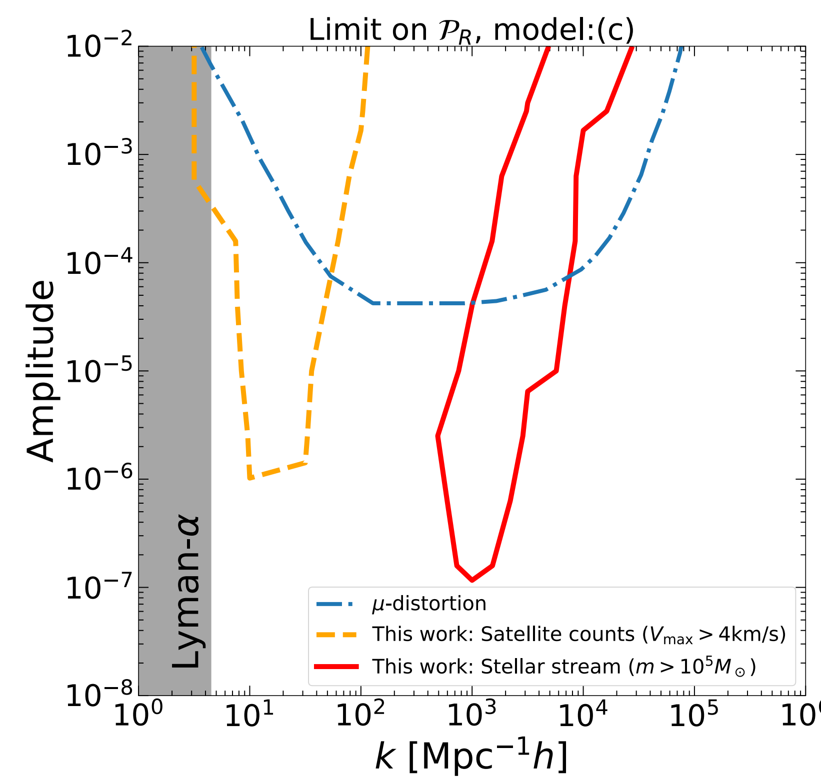


Tidal stripping model

Hiroshima, Ando, Ishiyama ’18



No tidal stripping



No tidal model dependence

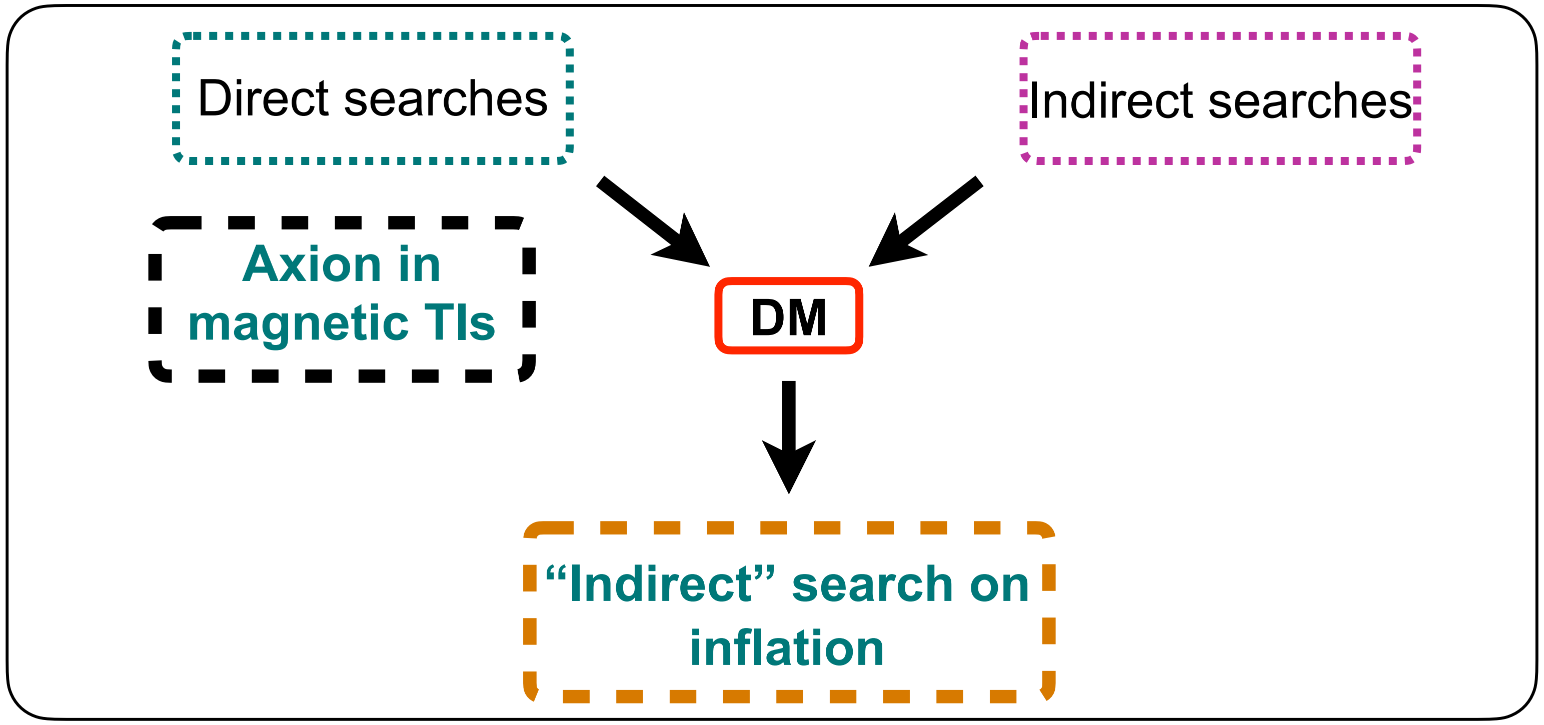
4. Conclusion

Axion in magnetic TIs

- Axion mass is $\mathcal{O}(\mathrm{eV})$ while it can be suppressed around the phase boundary in the magnetic TIs
- Material search is crucial for the particle axion detection

Inflaton sector from DM substructure

- Tracking the evolution of DM substructure is a new technique to probe the primordial curvature perturbation



Backups

Effective potential for ϕ

KI '21

$$V_\phi = -2\int \frac{d^3k}{(2\pi)^3}\left(\sqrt{|d_0|^2+\phi^2} - |d_0|\right) + M_\phi^2\phi^2$$

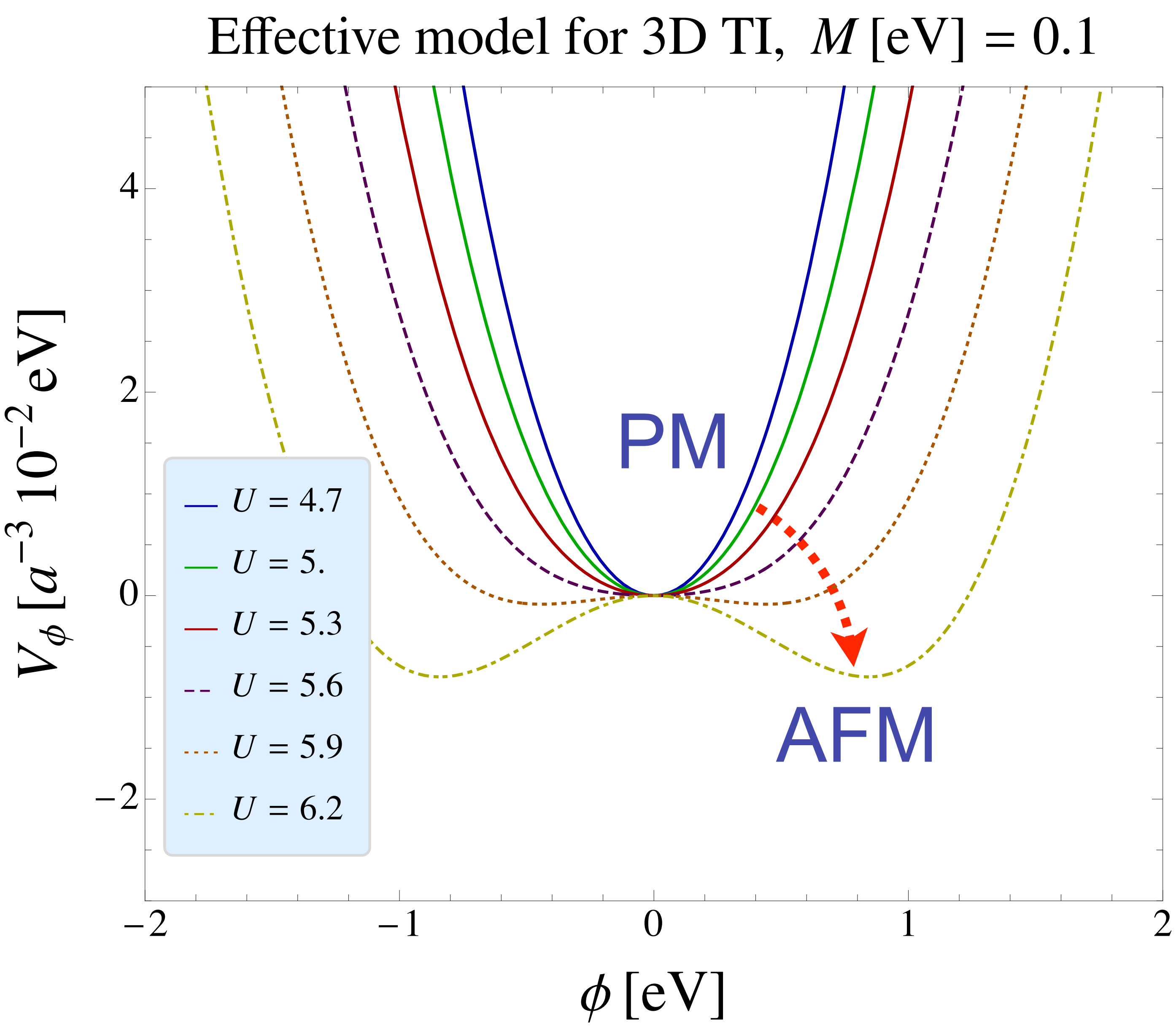
Negative potential

The mass term stabilizes the potential

$$|d_0|^2 = \sum_{a=1}^{4} |d^a|^2$$

$$M_\phi^2 = \int \frac{d^3k}{(2\pi)^3}\frac{2}{U}$$

KI '21



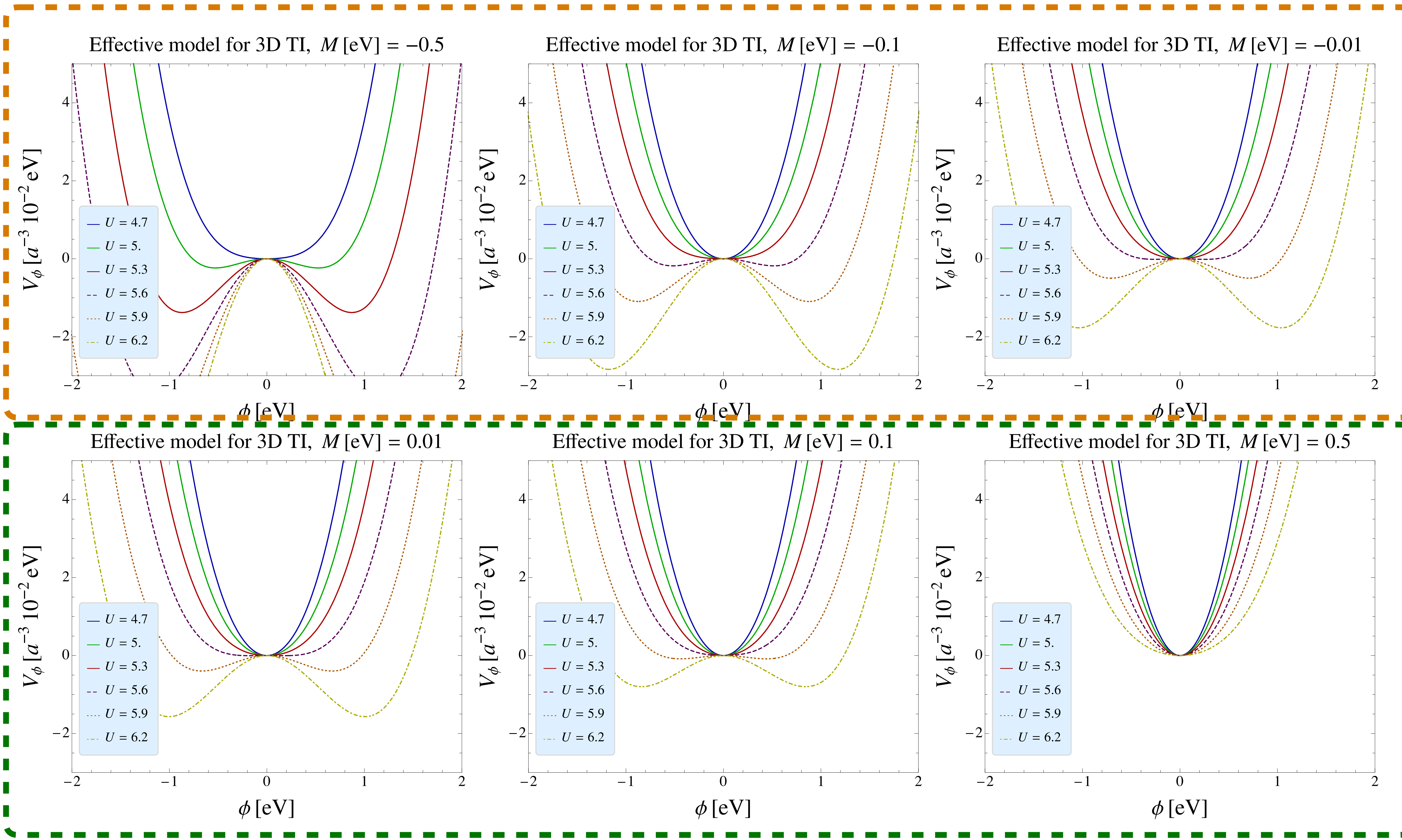
$A_1 = A_2 = 1$

$B_1 = B_2 = -0.5$

M dependence

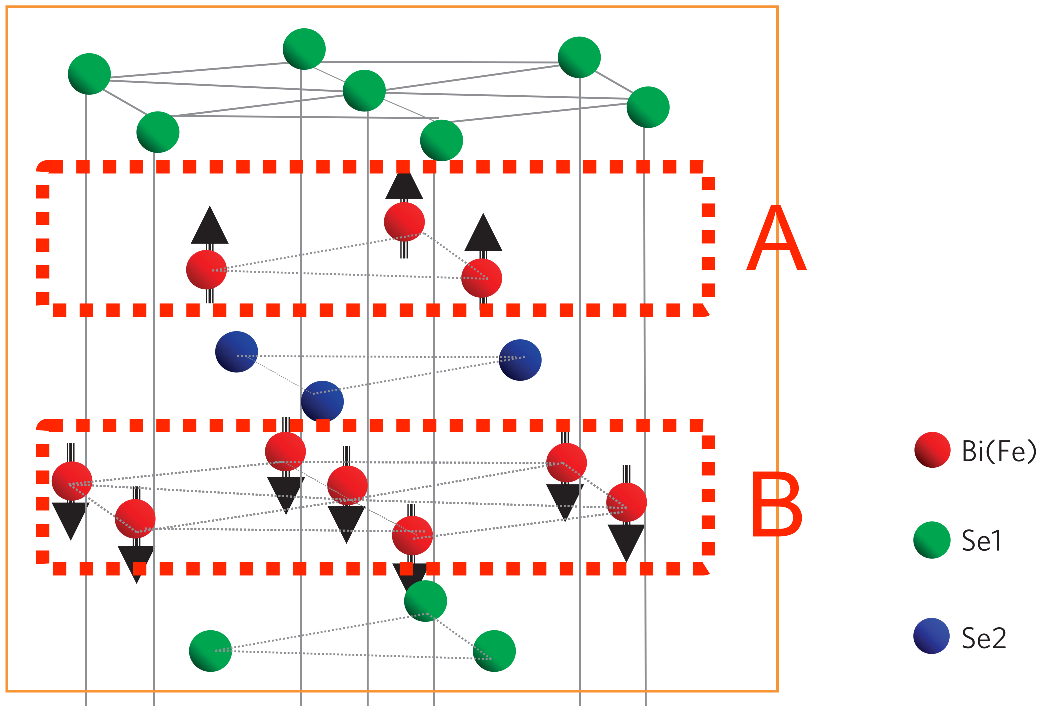
KI ’21

TI



NI

The difference between TI and NI is not clear



$$\langle \phi \rangle \sim \langle S_A \rangle = - \langle S_B \rangle$$

VEV of ϕ is the order parameter of AFM

- $\langle \phi \rangle = 0$ → PM order
- $\langle \phi \rangle \neq 0$ → AFM order

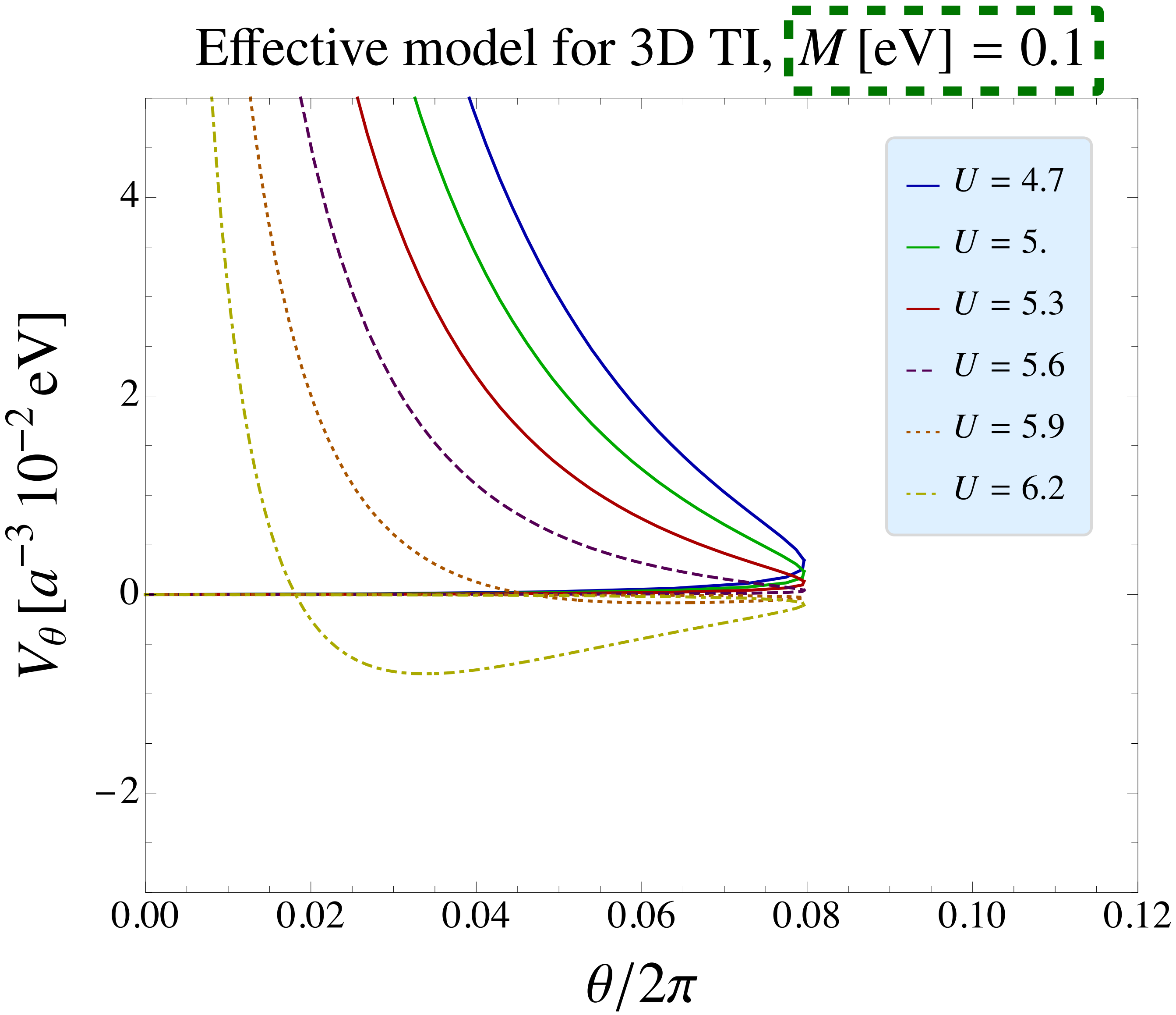
Expected result in the Hubbard model

PM (paramagnetic)

Effective potential in terms of θ

KI '21

NI phase



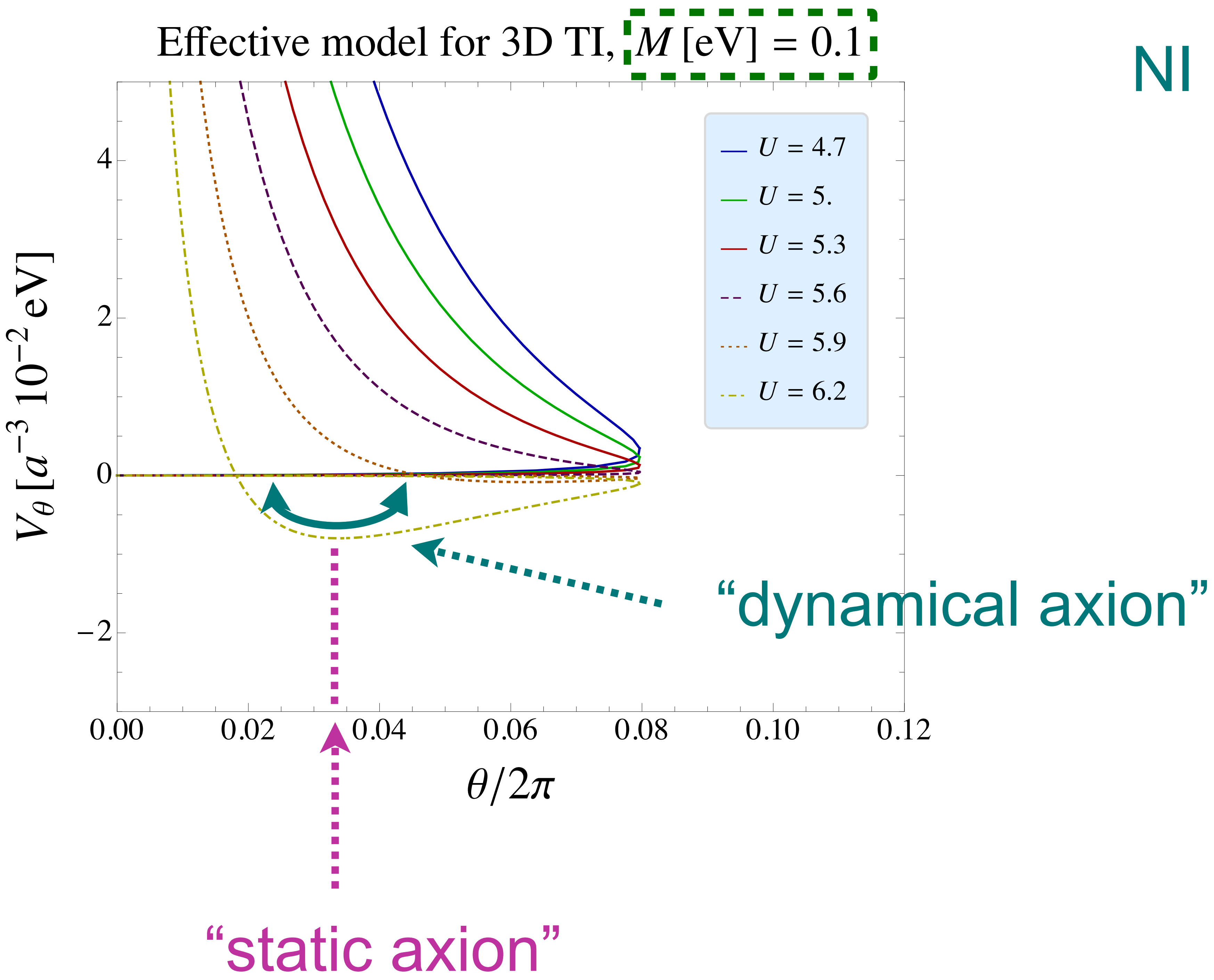
Potential minimum:

- $\theta = 0$ (small U , i.e., PM)
- $\theta \neq 0$ (large U , i.e., AFM)

Effective potential in terms of θ

KI '21

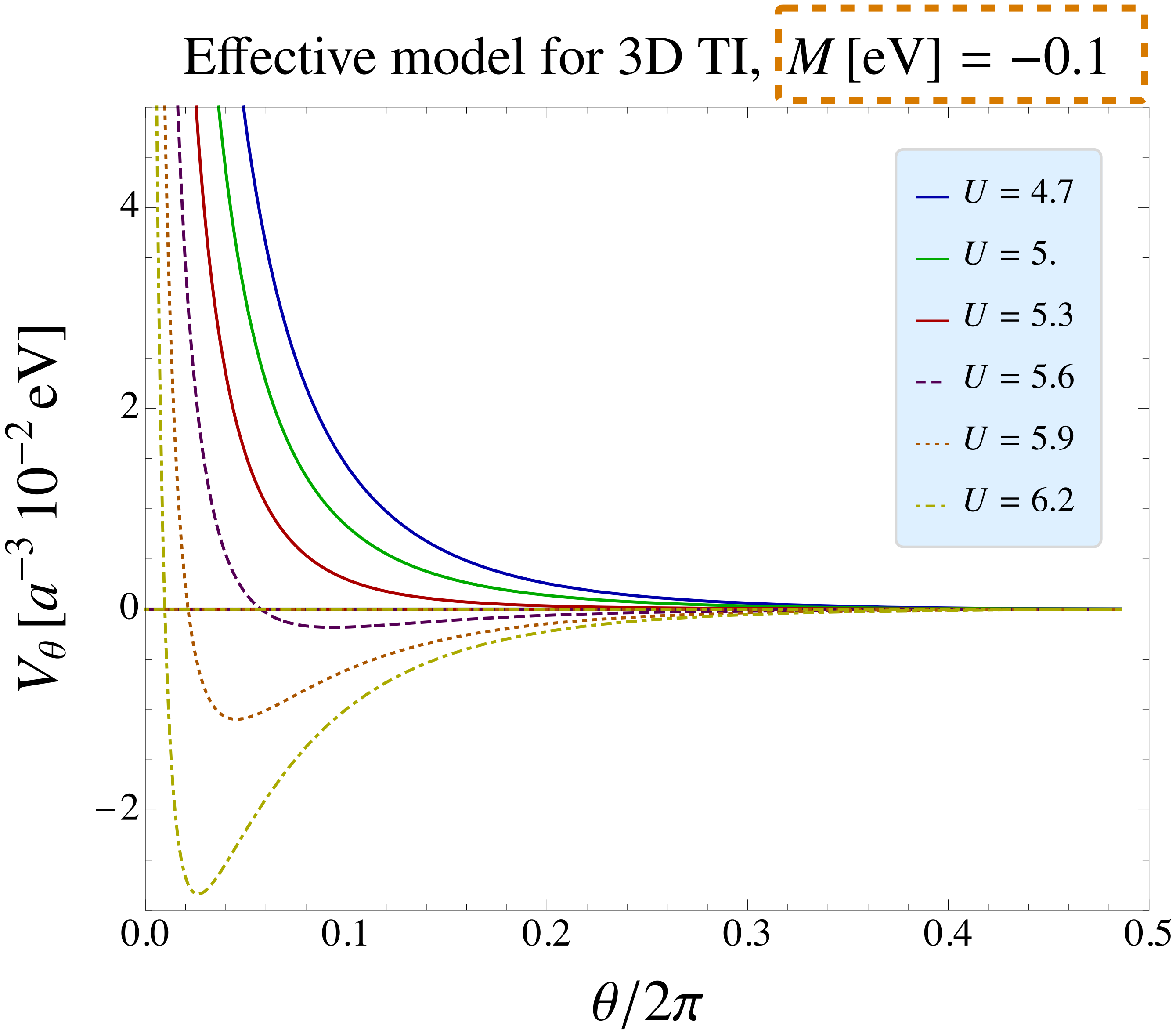
NI phase



Effective potential in terms of θ

KI '21

TI phase



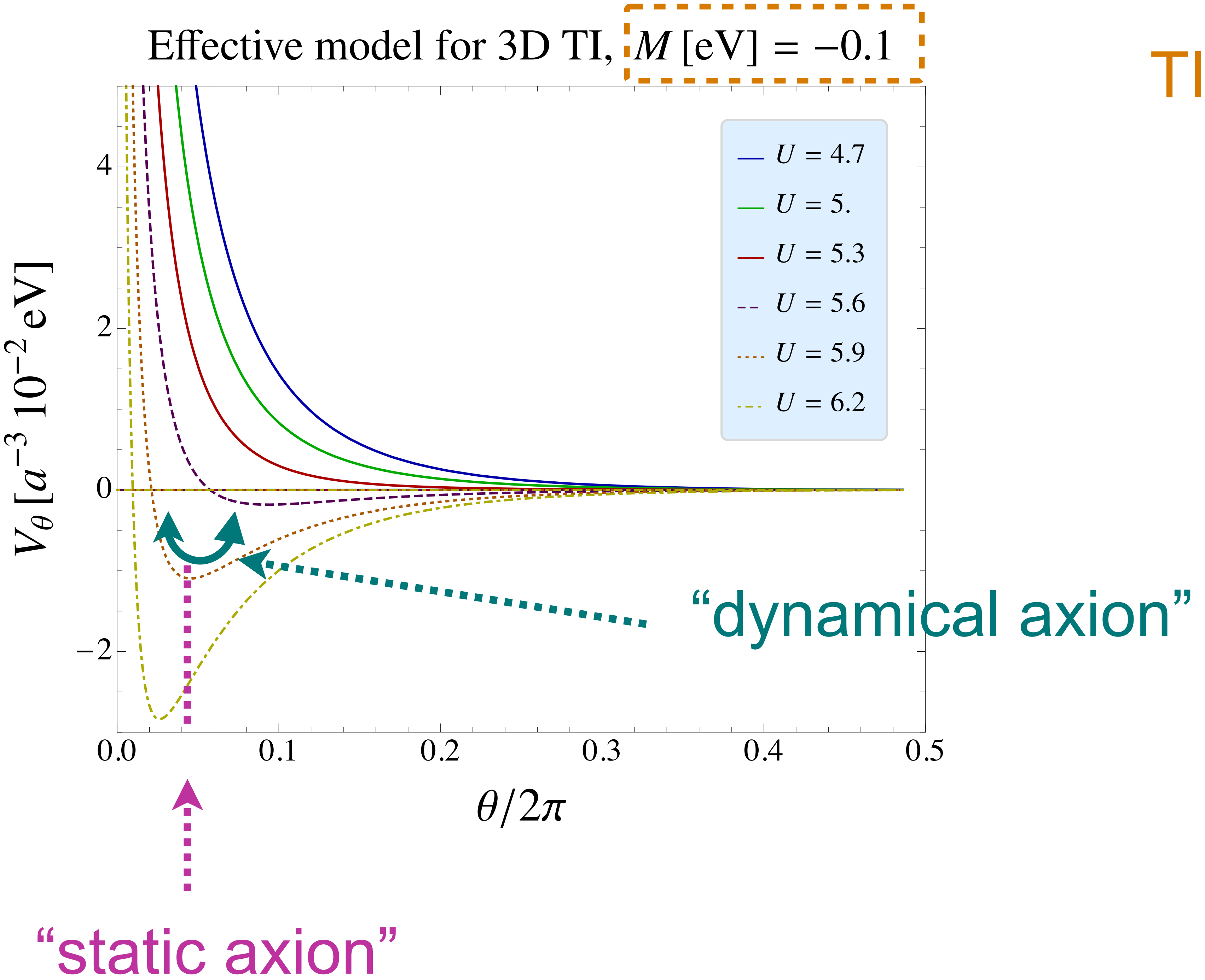
Potential minimum:

- $\theta = \pi$ (small U , i.e., PM)
- $\theta \neq 0$ (large U , i.e., AFM)

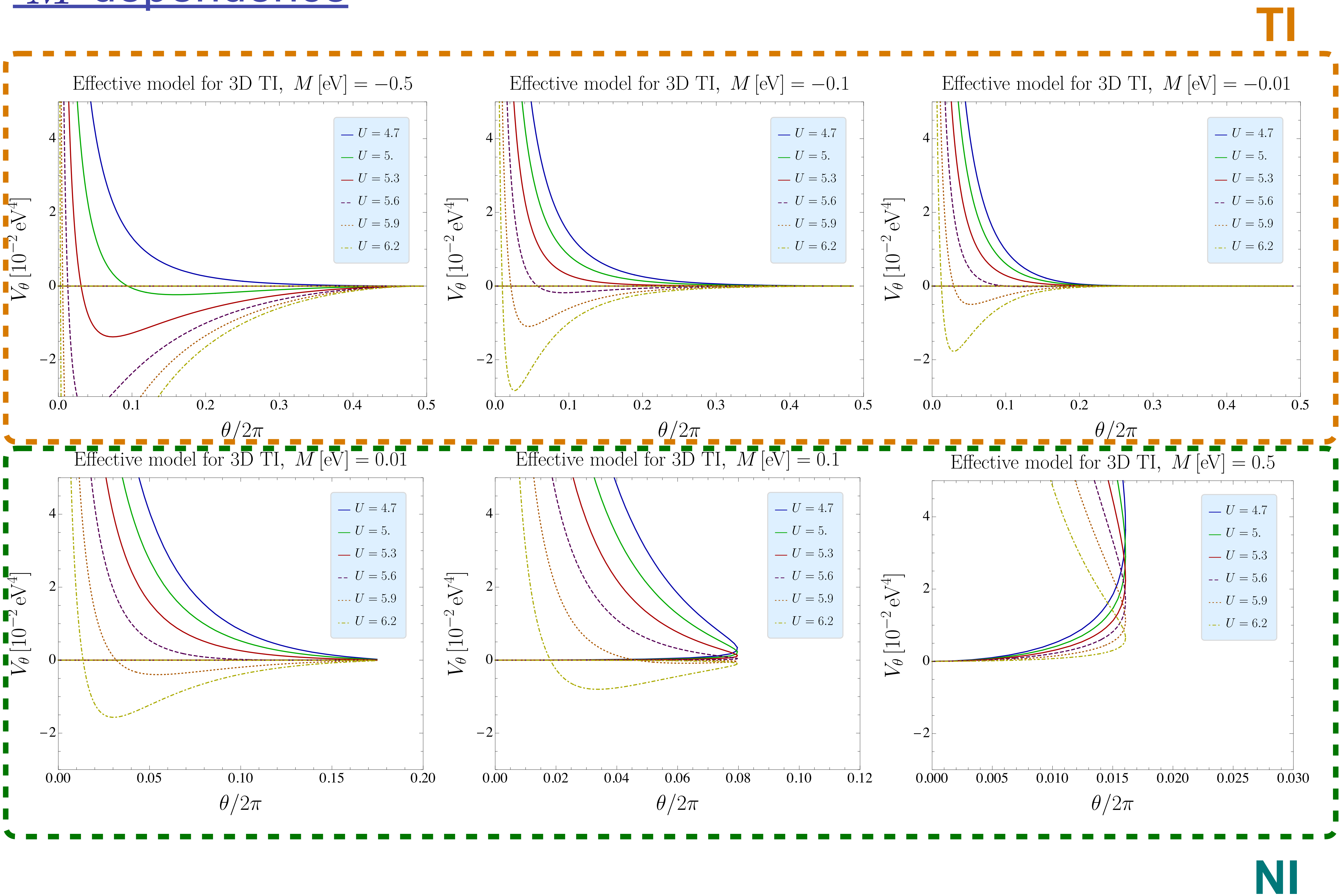
Effective potential in terms of θ

KI '21

TI phase

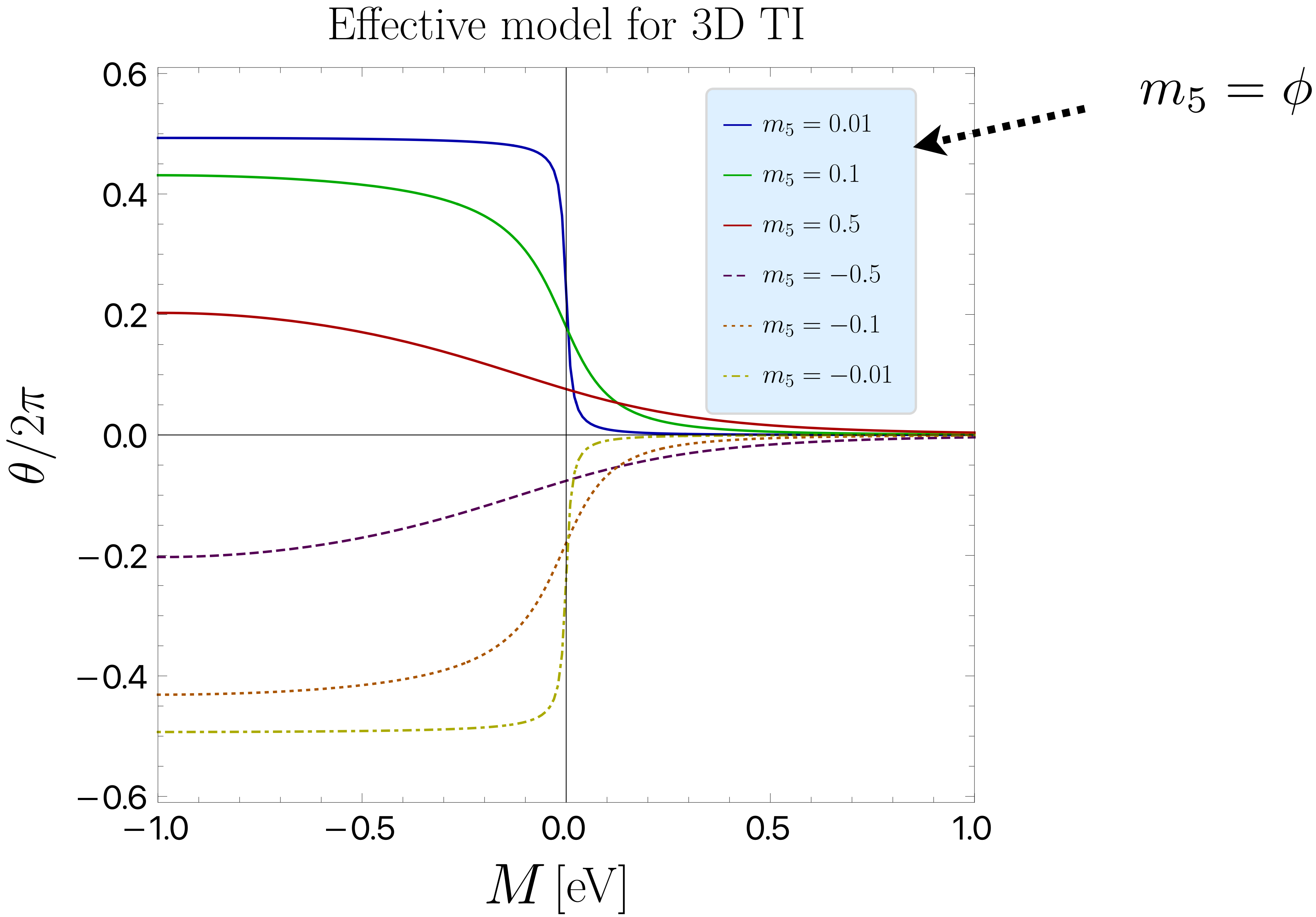


M dependence



θ as function of M

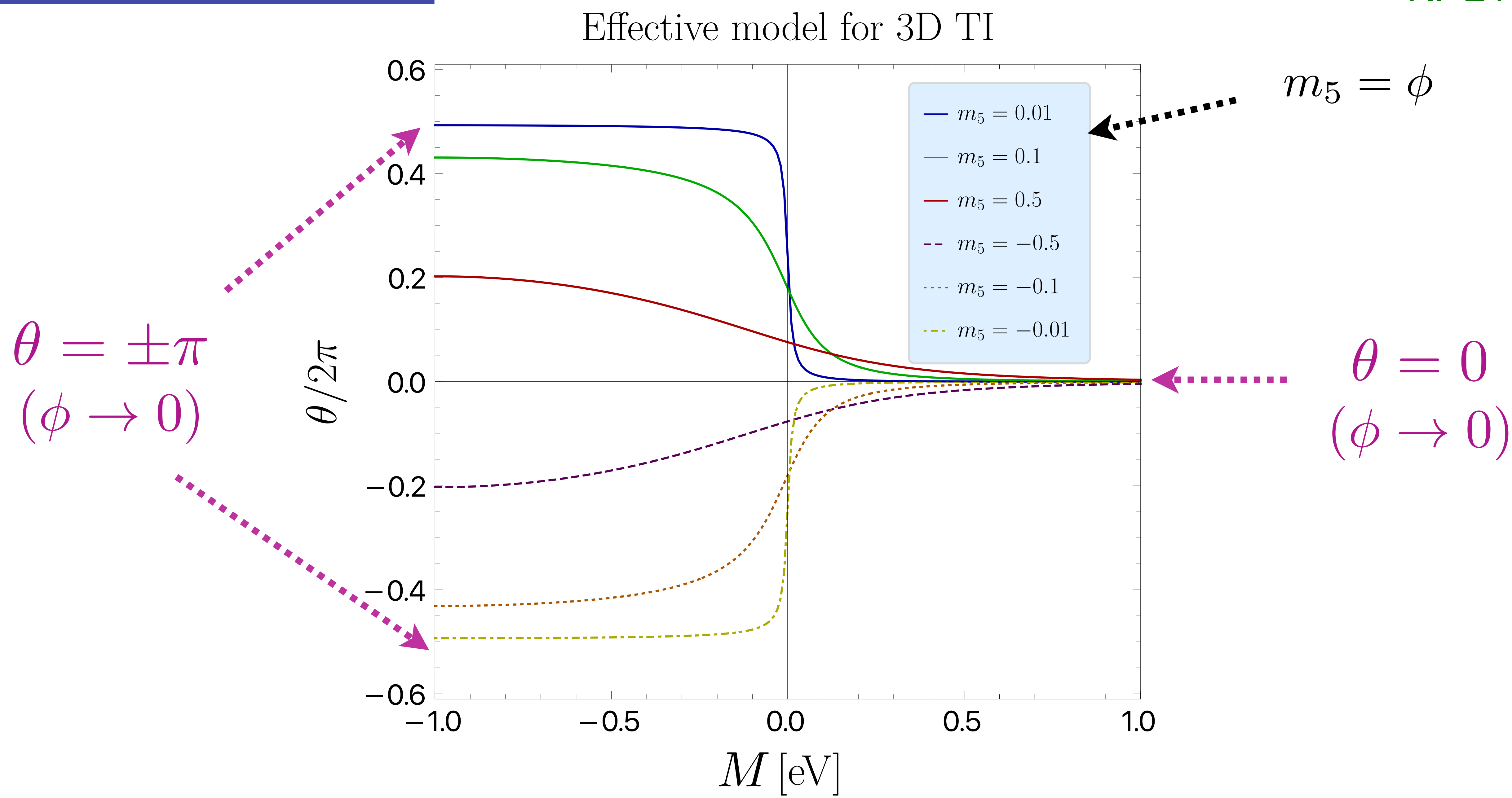
KI '21



calculation for Dirac model is done by Zhang '19

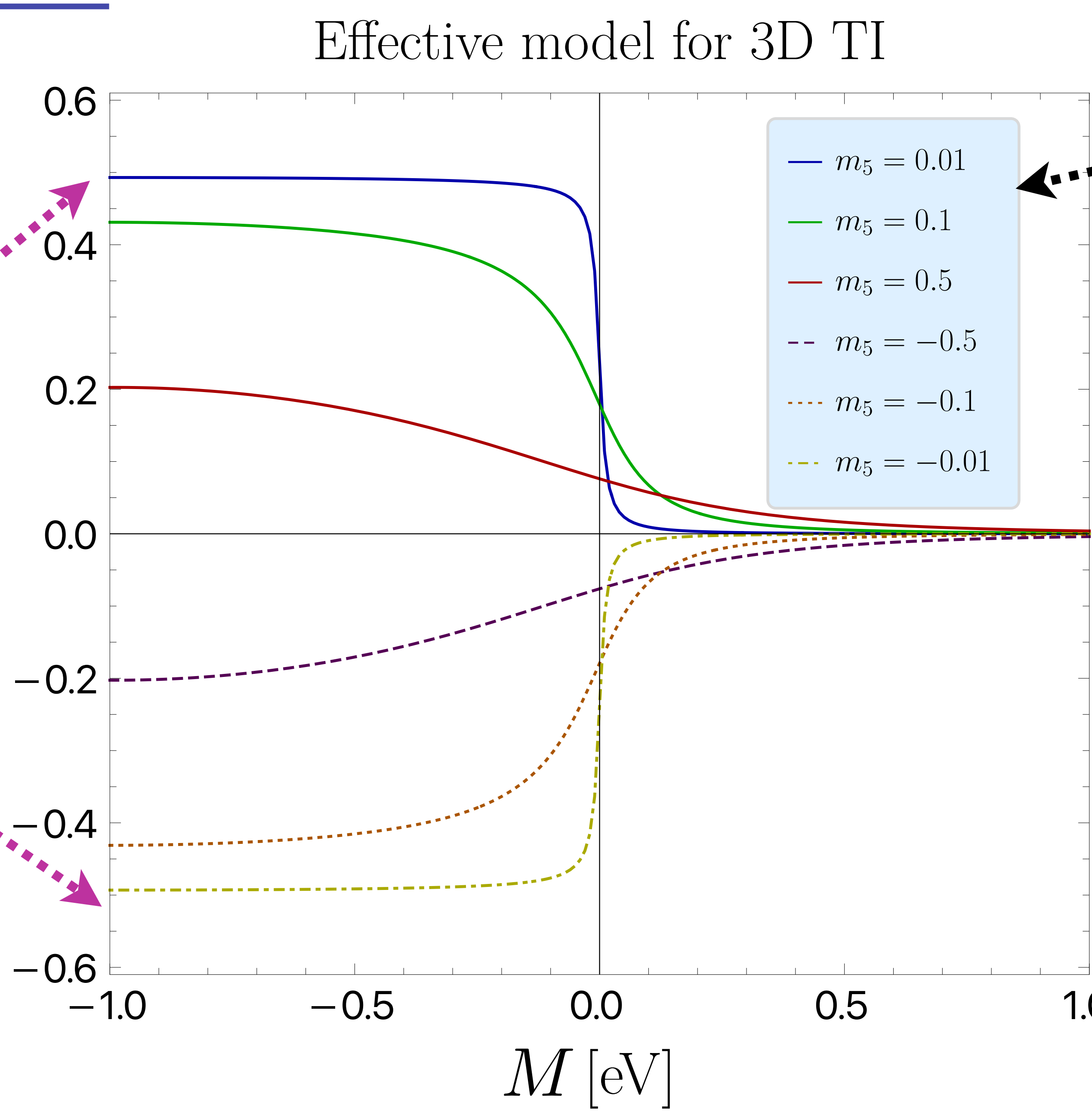
θ as function of M

KI '21



θ as function of M

KI '21



$m_5 = \phi$

$\theta = \pm\pi$
$(\phi \to 0)$

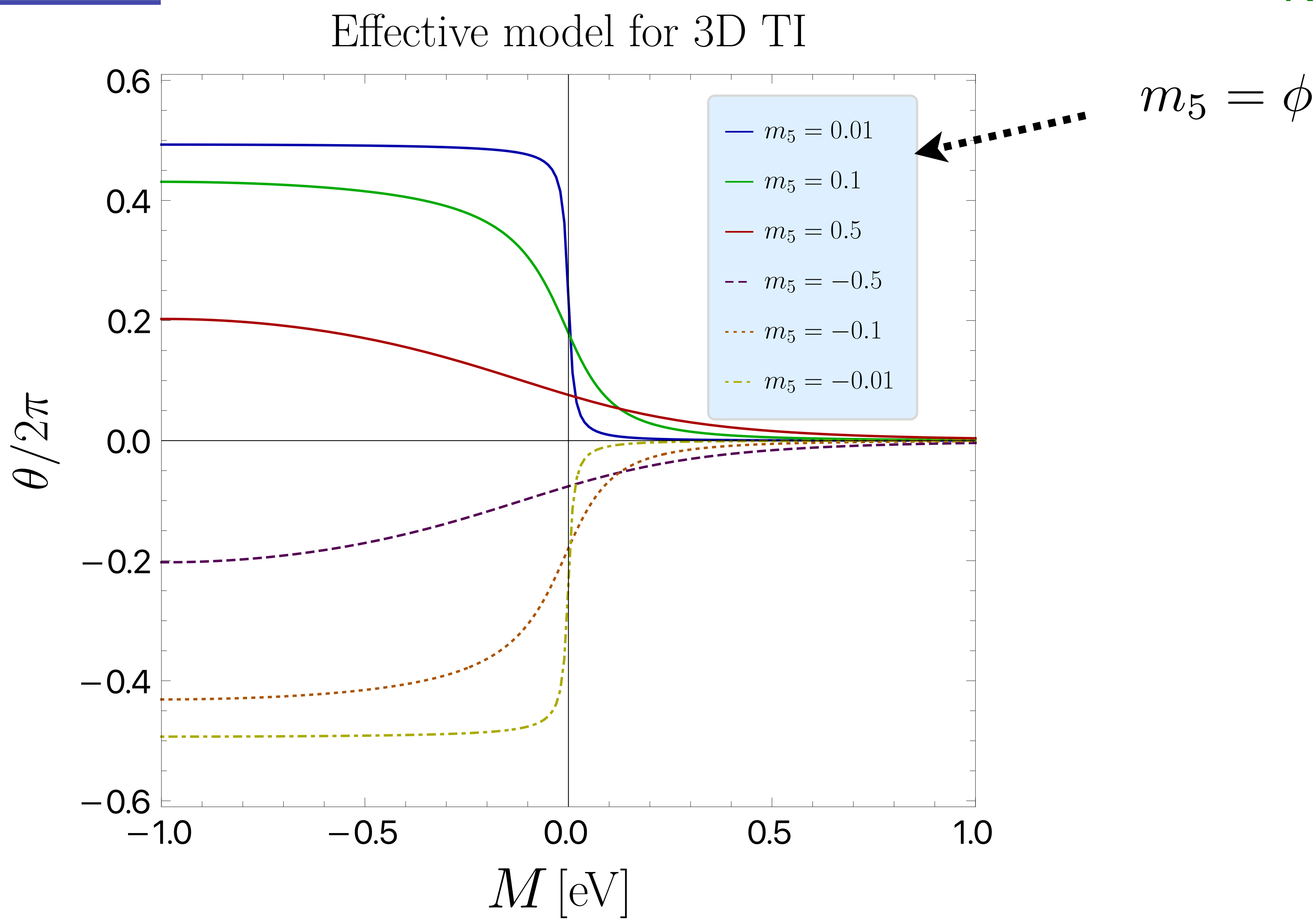
$\theta = 0$
$(\phi \to 0)$

$\phi = 0$ ($\mathcal{T}$) $\leftrightarrow$ PM order $\longrightarrow$

$\theta = \pm\pi$	$M < 0$	(TI)
$\theta = 0$	$M > 0$	(NI)

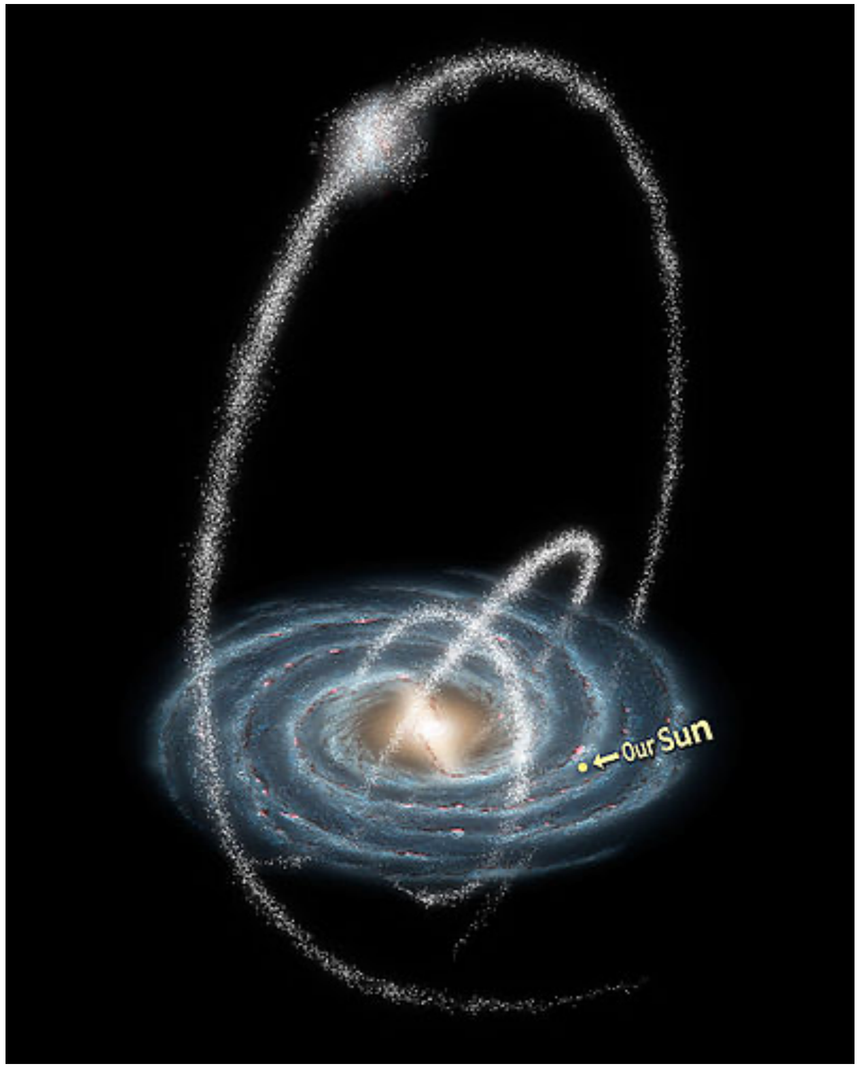
θ as function of M

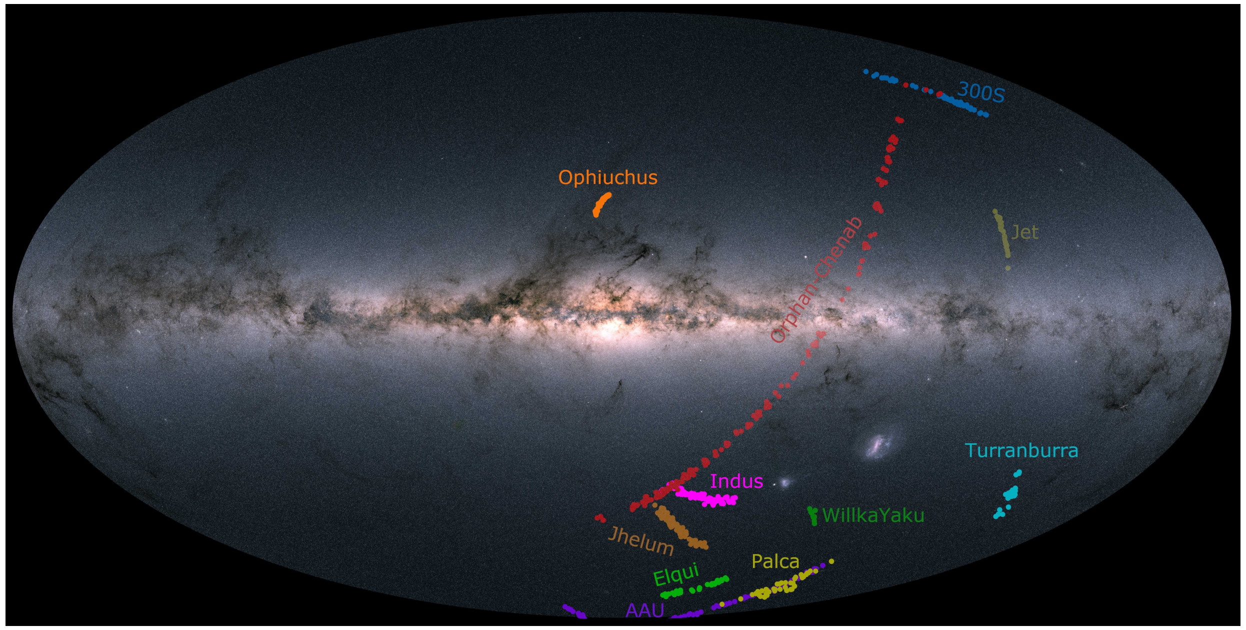
KI '21



$\phi \neq 0$ ($\not{\mathcal{T}}$) $\leftrightarrow$ AFM order $\longrightarrow$ θ takes continuum variable

Stellar stream



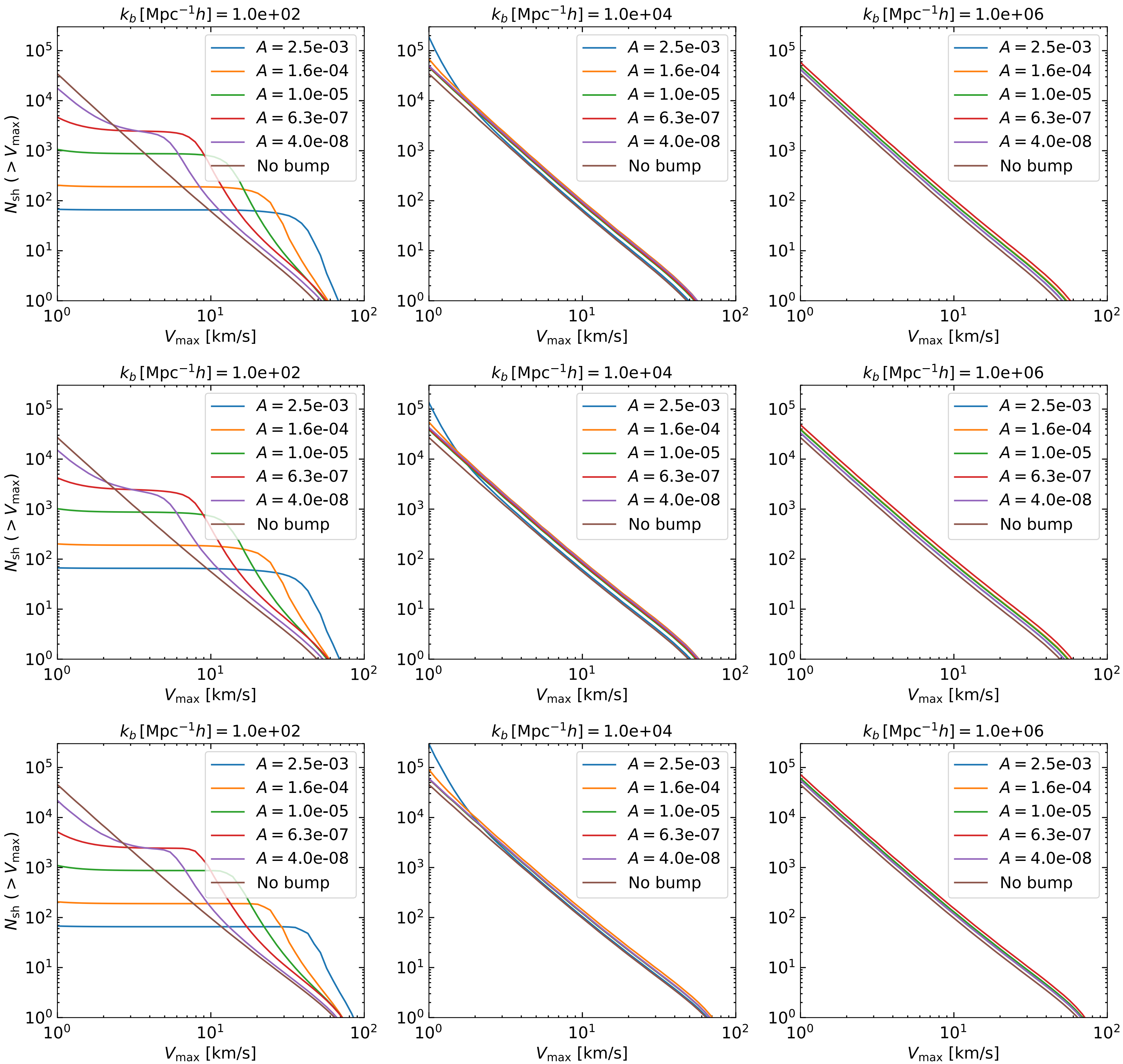


A passage of subhalos ⟶ A gap in the stream

Too small or too large number of subhalos conflict with the observation

Pictures from Wikipedia

Cumulative maximum circular velocity function



Cumulative number of subhalos, maximum circular velocity function, and boost factor