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Microscopic Insights into Magnetic Warping and Time-Reversal Symmetry Breaking in Topological Surface States of Rare-Earth-Doped Bi_2Te_3

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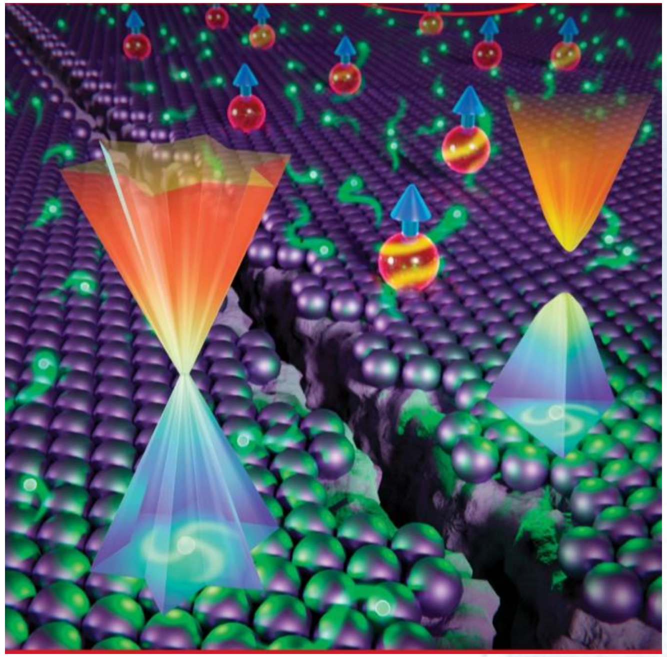
EXCELENCIA SEVERO OCHOA 2017-2021

AGENCIA ESTATAL DE INVESTIGACIÓN

Spin-ARPES Lab



Miguel Angel Valbuena

IMDEA Nanociencia (Madrid)

ALBA Users Meeting

3rd—4th September 2026

UNIÓN EUROPEA FONDOS ESTRUCTURALES

Comunidad de Madrid

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Summary

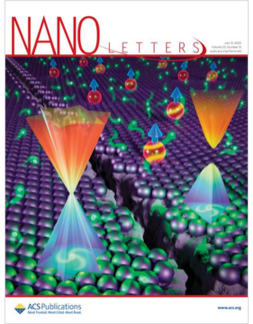
✓ **Why magnetically dope topological insulators?**
✓ **Rare-earth surface doping as an alternative strategy**

✓ **From Er/Bi_2Se_2Te to Er/Bi_2Te_3**

- Structural and chemical characterization: **STM and XPS**
- Magnetic properties: **XMCD**
- Topological surface state: **ARPES**
- Modelling of **time-reversal symmetry breaking**

Magnetic warping transition and gap opening at the topological surface state

Rare-earth surface doping of topological insulators: from the first LOREA user publication to microscopic insight into TRS breaking



Volume 23, Issue 13
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Letter | May 08, 2023 Open Access

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Beatriz Muñiz Cano; Yago Ferreiros; Pierre A. Pantaleón; Ji Dai; Massimo Tallarida; Adriana I. Figueroa; Vera Marinova; Kevin García-Díez; Aitor Mugarza; Sergio O. Valenzuela; Rodolfo Miranda; Julio Camarero; Francisco Guinea; Jose Angel Silva-Guillén; Miguel A. Valbuena *

+ Author & Article Information

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ADVANCED MATERIALS

Research Article | Open Access

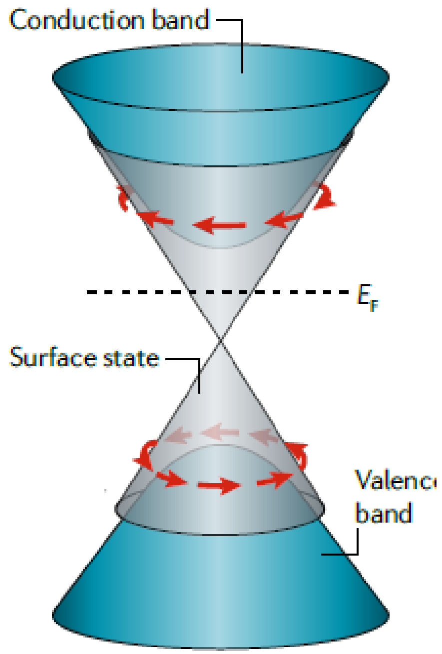
Microscopic Insights into Magnetic Warping and Time-Reversal Symmetry Breaking in Topological Surface States of Rare-Earth-Doped Bi_2Te_3

Beatriz Muñiz Cano, Fabián Calleja, Ji Dai, Massimo Tallarida, Vera Marinova, Alessandro Barla, Marc G. Cuxart, Pierluigi Gargiani, Gonzalo N. Molina, José Angel Silva-Guillén, Adriana I. Figueroa, Kevin García-Díez, Sergio O. Valenzuela, Aitor Mugarza, Amadeo L. Vázquez de Parga, Rodolfo Miranda, Francisco Guinea, Manuela Garnica, Miguel A. Valbuena ... See fewer authors

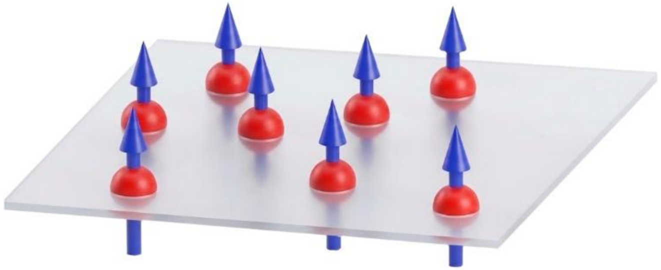
First published: 04 November 2025 | https://doi.org/10.1002/adma.202510877 | VIEW METRICS

Why magnetically dope topological insulators?

Pristine TSS:
- Gapless Dirac surface state
- Spin–momentum locking
- Protection by time-reversal symmetry



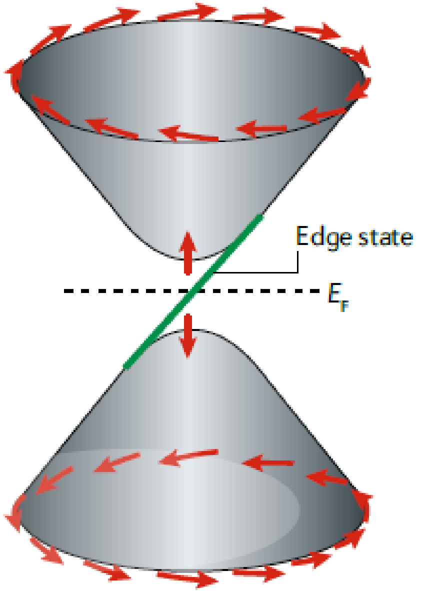
Magnetic doping

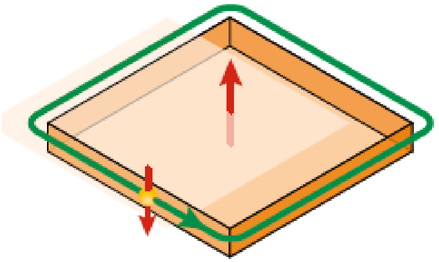


Out-of-plane exchange field
Breaks time-reversal symmetry

Nature Reviews Physics **1**, 126 (2019)

Magnetically gapped surface state:
- Exchange gap at the Dirac point
- Chiral edge-state transport
- Quantum anomalous Hall effect



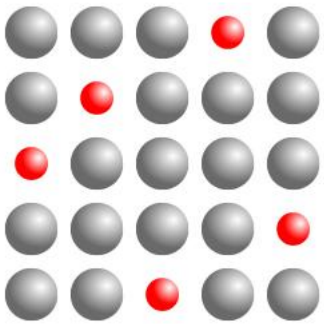


Requirements for the QAHE: an exchange gap, the Fermi level inside the gap, and robust magnetic order

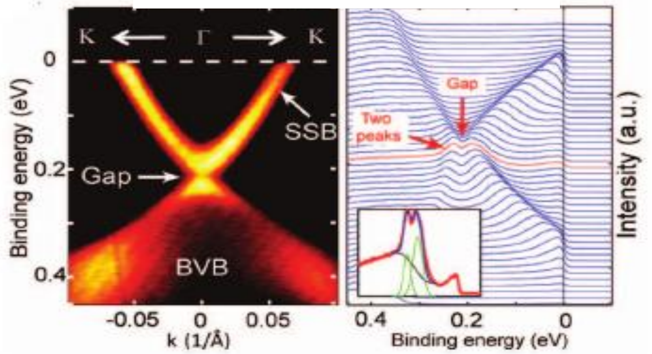
Experimentally challenging: the QAHE generally emerges only at very low temperatures

Magnetic doping in topological insulators

Surface doping



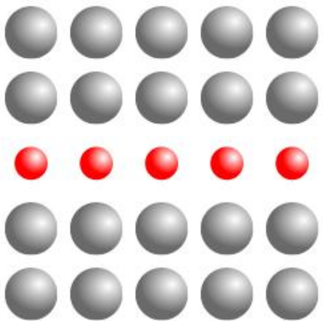
Fe-doped Bi_2Se_3

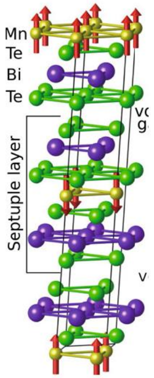


Science **329**, 659 (2010)

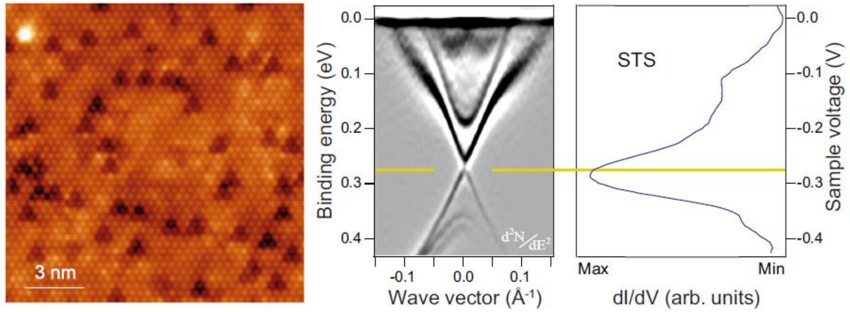
- Multiple adsorption sites.
- Clustering and inhomogeneities.
- Lack of control of the magnetic anisotropy

Magnetic extension





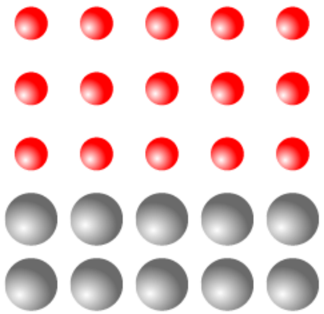
$MnBi_2Te_4$

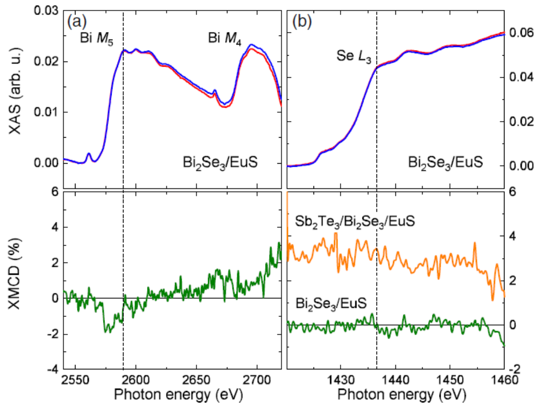


Npj Quant. Mat. 2022, **7**, 1–9

- Defects concentration can drastically alter the electronic properties and magnetic order

Proximity to magnetic layers





EuS/TIs

PRL **125**, 226801 (2020)

- Neither significant induced magnetism within the TI nor an enhancement of the Eu magnetic moment

Lack of experimental reproducibility

Rely on sophisticated and complex growing methods

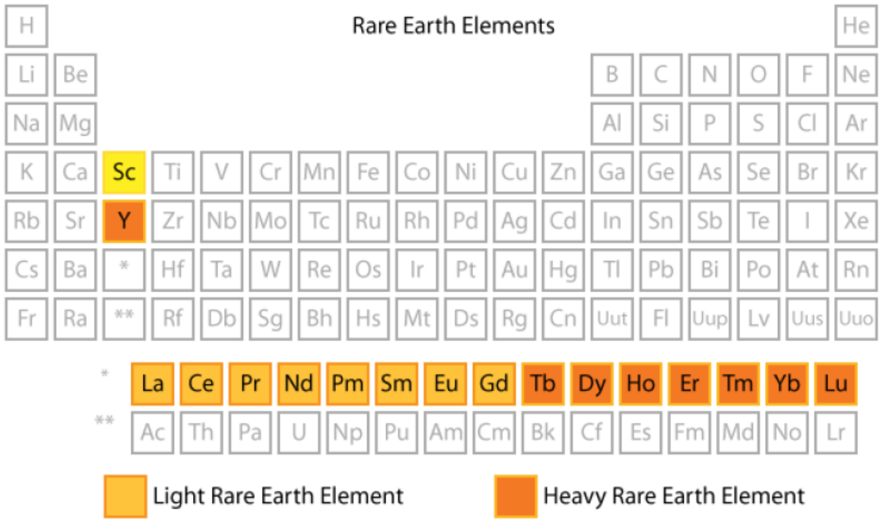
Rare-Earths as magnetic surface dopants in topological insulator substrates

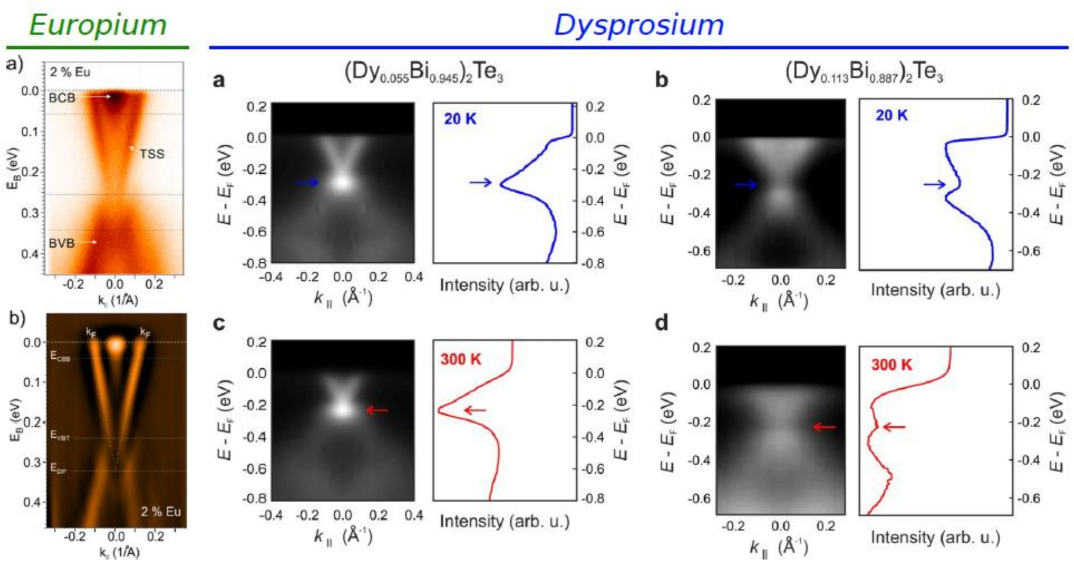
- **Larger size** → prevents from substitutional sites → reduced the multiplicity of adsorption configurations → better control of magnetic anisotropy

- Unpaired 4f electrons → **large magnetic moments** → enhanced magnetic anisotropy and allow a lower doping concentration and eventually maximize gap opening

- High Curie Temperatures

- Previous results on REs as **bulk substitutional dopants** on Tis showed contradictory and non-conclusive results.

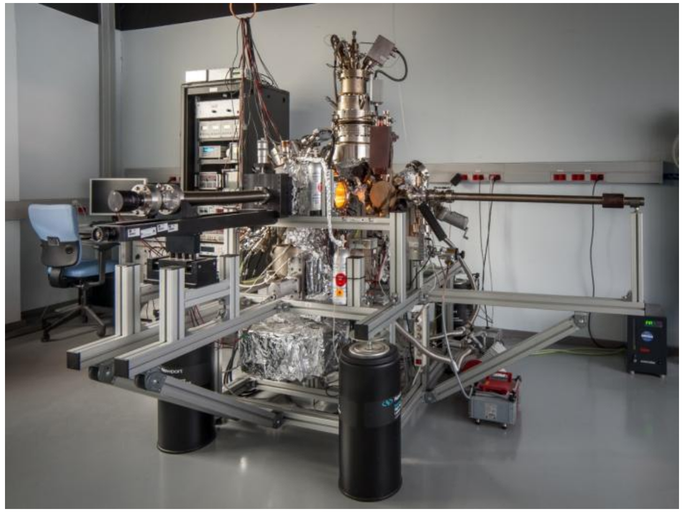




B. Muñiz Cano PhD thesis and references therein

Experimental Approach: STM-XPS-XMCD-ARPES

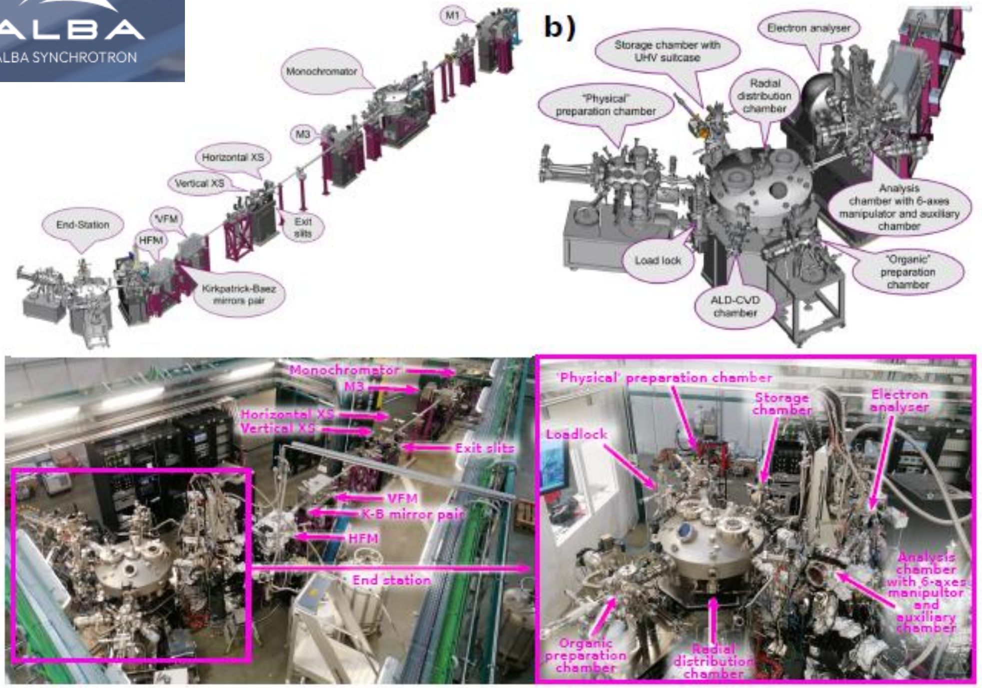
LT-STM (1.2 K)



✓ STM Structural defect characterization
✓ Local electronic properties (STS/QPIs)

ALBA SYNCHROTRON

LOREA beamline



✓ XPS: Chemical characterization
✓ ARPES: TSS characterization

BOREAS beamline
HECTOR endstation

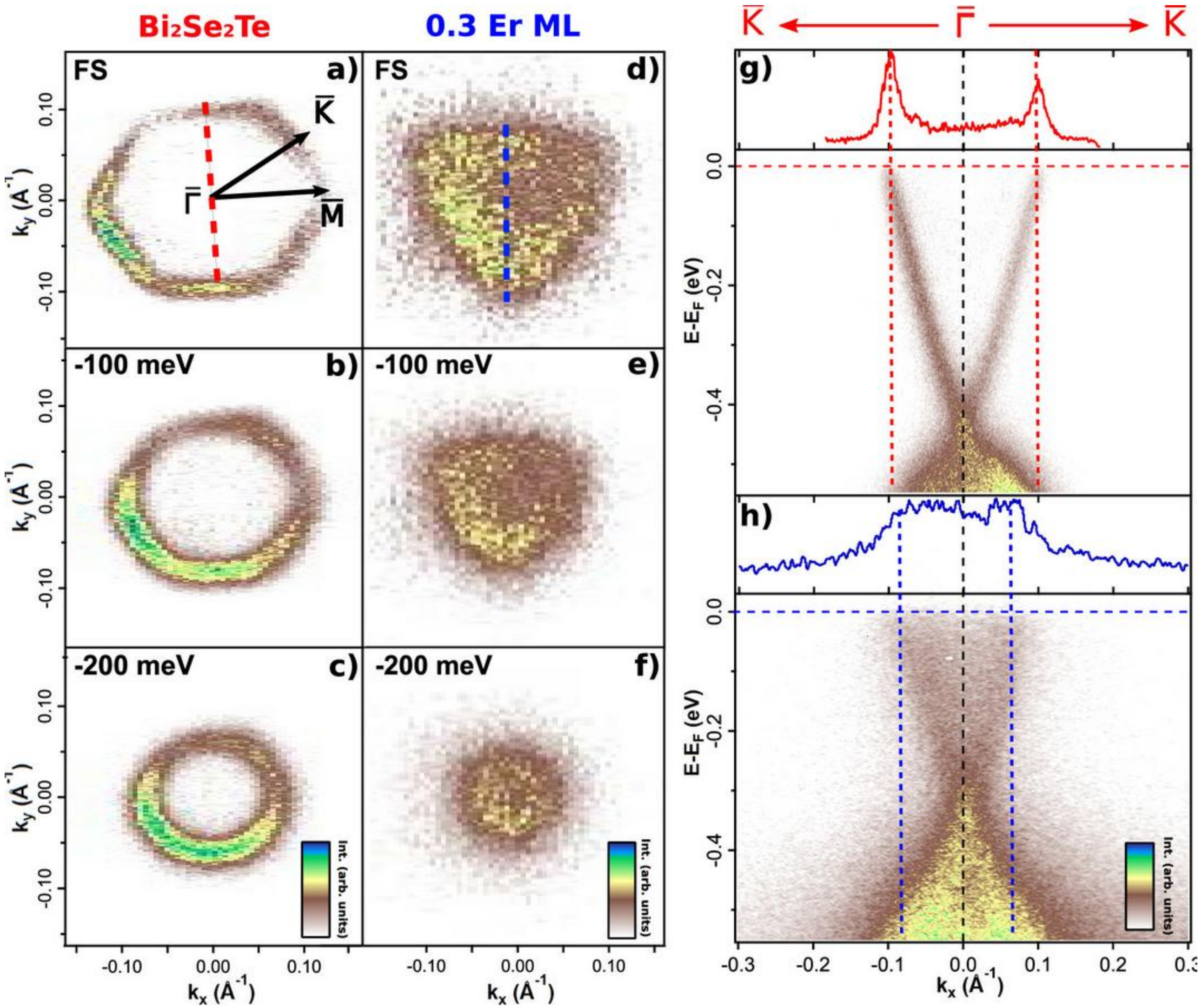
✓ XAS-XMCD: magnetic characterization

- **Bulk single crystal. Exfoliated in-situ** (UHV) at T = 15 K
- **Er impurities** deposited by means of an e-beam evaporator.
- ARPES/XPS @ T = 15 K. XMCD @ T = 7.5 K

ARPES Er/Bi_2Se_2Te: Fermi surface and TSS band dispersion

FS transition from warped hexagonal to trigonal pattern

T = 15 K hν = 52 eV

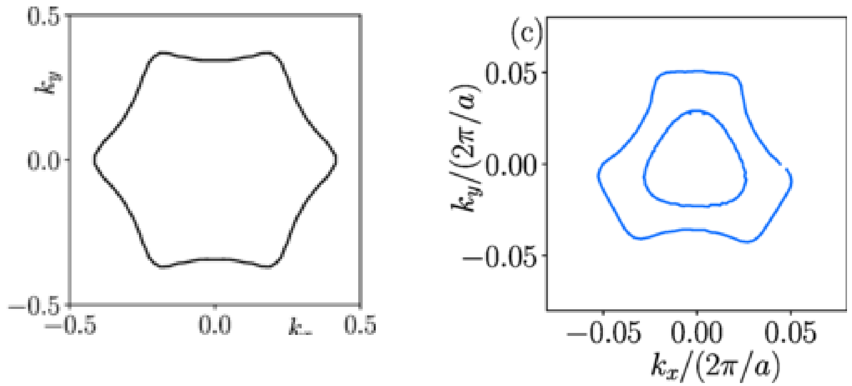


B. Muñiz Cano et al., Nano Lett. 2023, **23**, 13, 6249

Pristine sample shows the typical **hexagonal warping FS pattern** (less pronounced than in Bi_2Te_3) derived from high-order spin-orbit coupling effects.

Er-doped BST TSS → FS warping symmetry: **hexagonal → trigonal**

Theoretically predicted for intrinsic magnetic topological insulators (MnBiTe) with long-range FM order

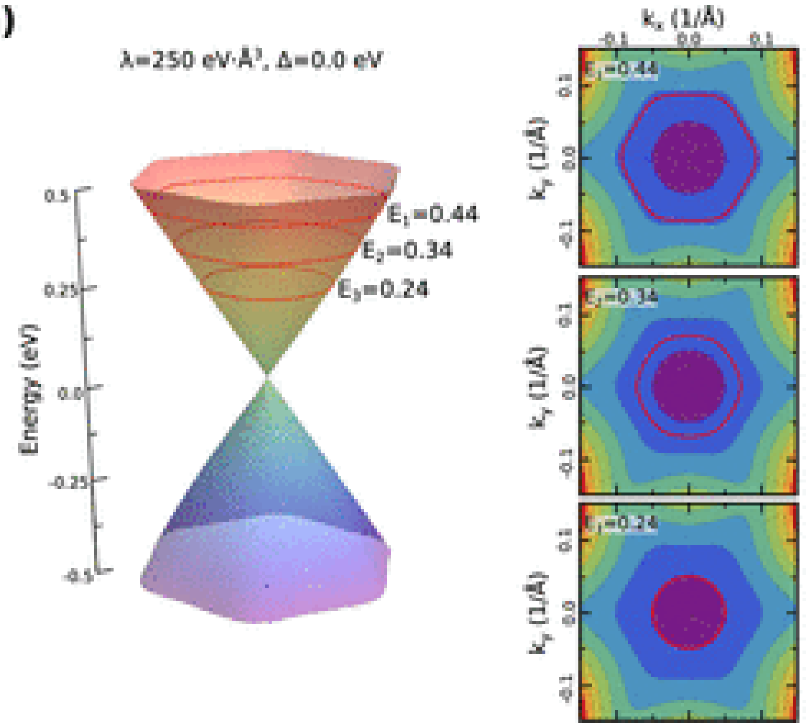


Phys. Rev. Research **4**, 033198 (2022)

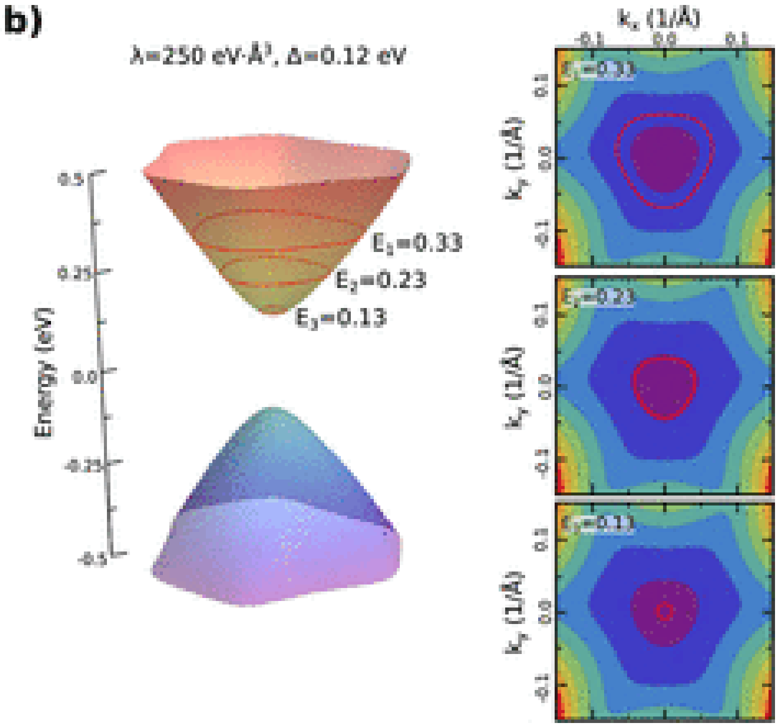
Er/Bi_2Se_2Te: Fermi surface and TSS band dispersion

Modelling FS transition from warped hexagonal to trigonal pattern

a)



b)



$$H = \hbar v_{\mathrm{F}}(k_{\mathrm{x}}\sigma_{\mathrm{y}} - k_{\mathrm{y}}\sigma_{\mathrm{x}}) + \frac{\lambda}{2}(k_+^3 + k_-^3)\sigma_{\mathrm{z}}$$

Expected hexagonal warping of prototypical 3D topological insulators as Bi_2Te_3

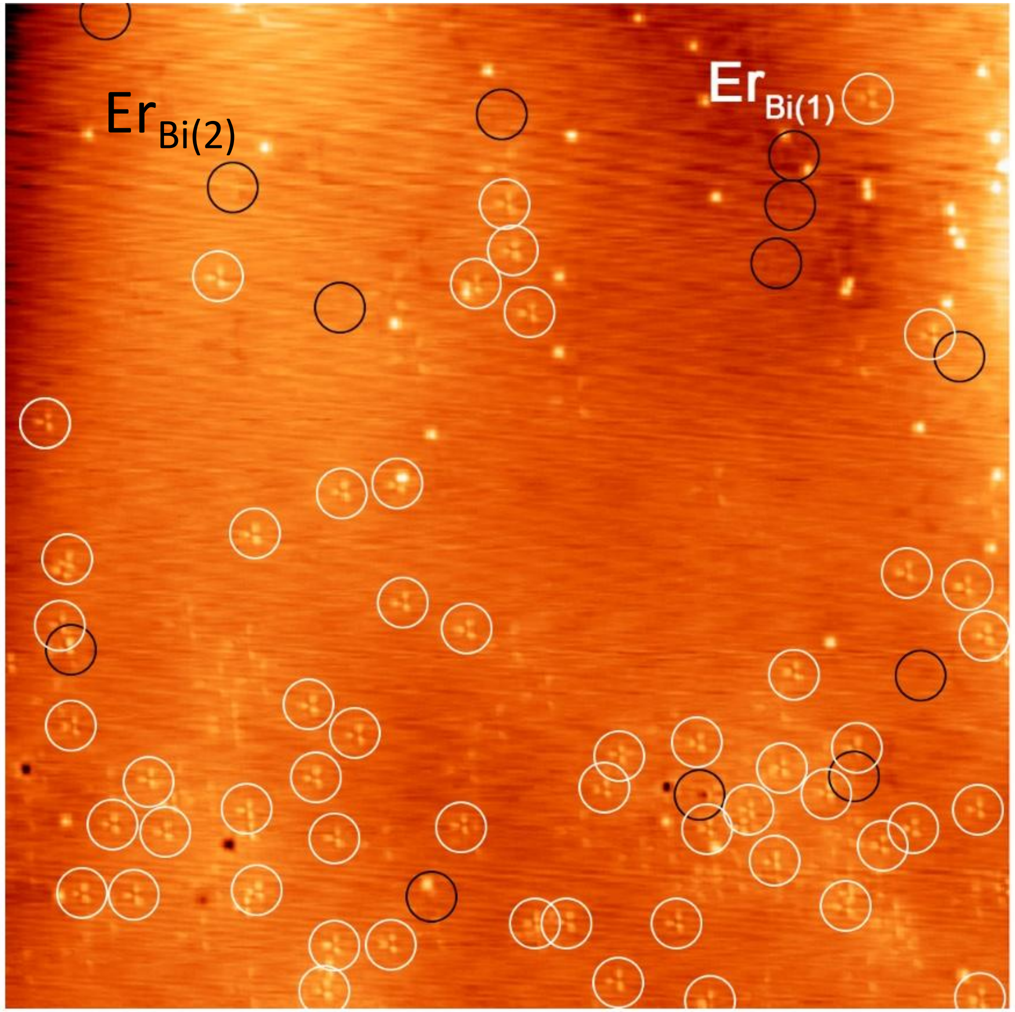
B. Muñiz Cano et al., Nano Letters
Nano Lett. 2023, **23**, 13, 6249

$$H = \hbar v_{\mathrm{F}}(k_{\mathrm{x}}\sigma_{\mathrm{y}} - k_{\mathrm{y}}\sigma_{\mathrm{x}}) + (\lambda k^3 \cos 3\theta - \Delta)\sigma_{\mathrm{z}}$$

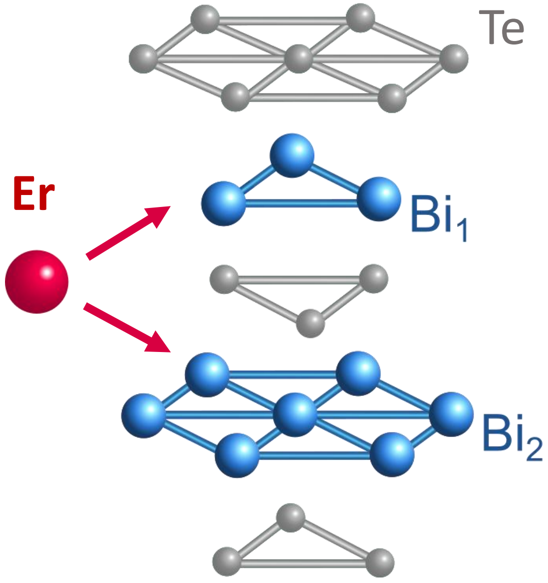
Introducing a **Zeeman magnetic out-of-plane term with** a large **exchange coupling of $\Delta \sim$ 0.1 eV** in the Hamiltonian, describes the experimental band dispersion:

- **FS transition from hexagonal to trigonal**
- **Gap opening at the DP**

Er/Bi_2Te_3: STM Structural defect characterization



1V, 70 pA



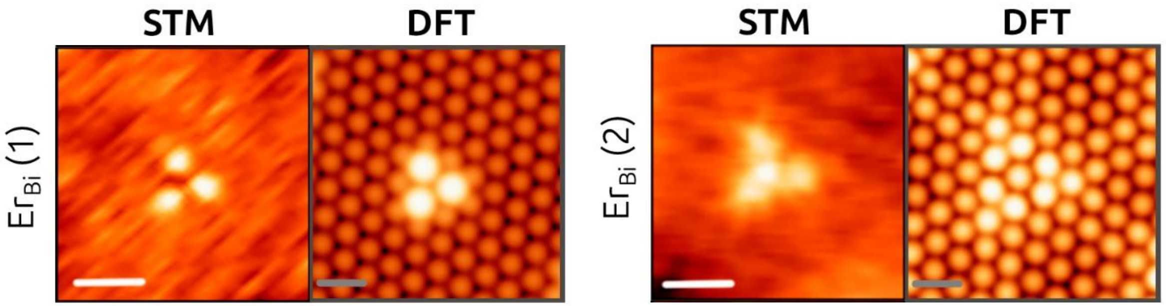
Bi_2Te_3 crystal

Bridgman method

Er deposition

Islands

New defects not reported in pristine samples



STM–DFT comparison identifies Er substitutional defects in both Bi layers of the first quintuple layer

B. Muñiz-Cano *et al.,* Advanced Materials e10877 (2025)

XPS: Surface and Chemical Characterization

Enery shift at Te 4d

- charge transfer from Er islands to substrate.
- No new components appearing
- p-type doping consistent with ARPES).

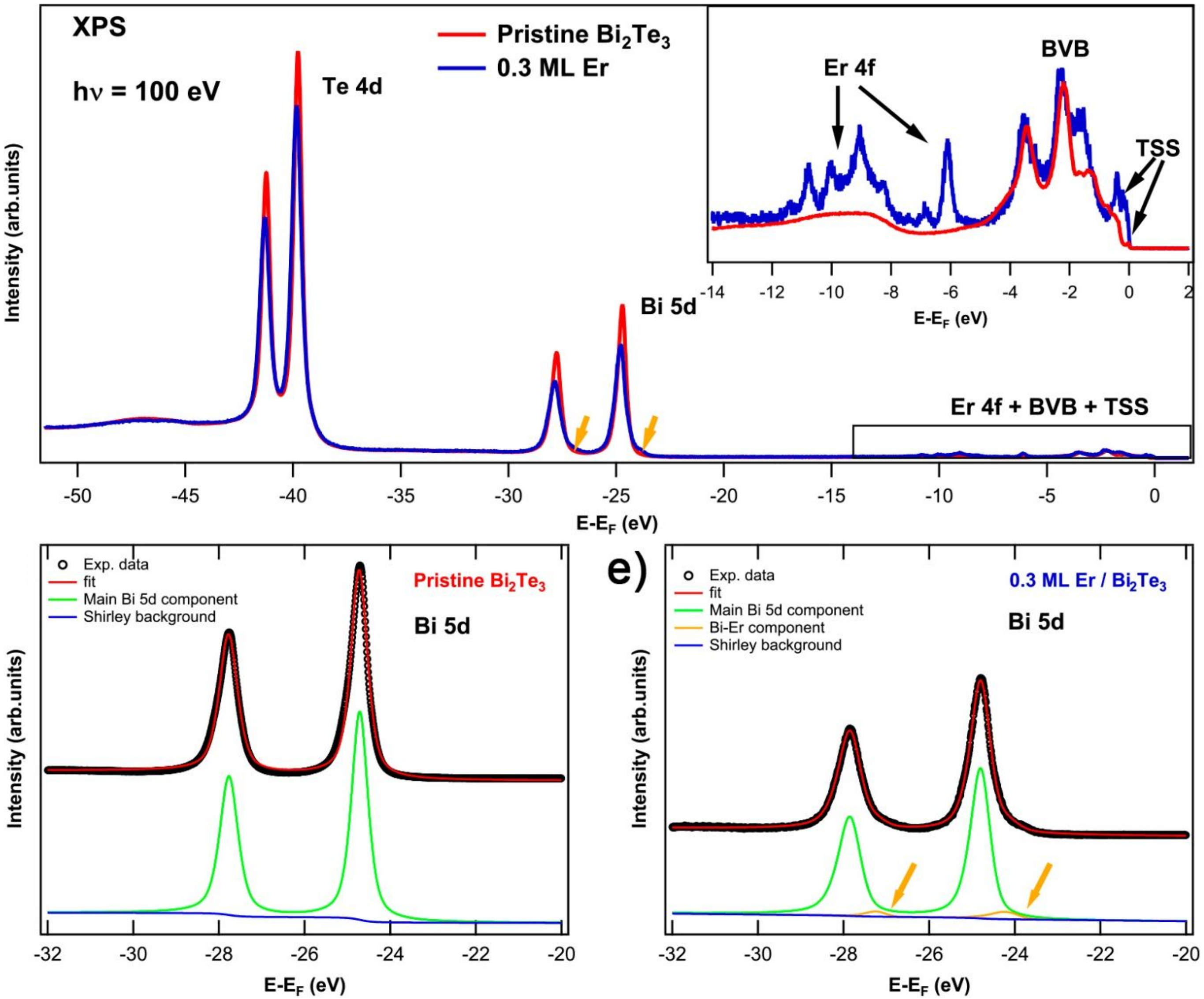
New Bi 5d component

- Er–Bi interaction. Corroborates STM defect characterization

Intensity of new component

- Increases with Er coverage
- Not proportional to total Er

Direct evidence of Er–Bi interaction



B. Muñiz-Cano *et al.,* Advanced Materials e10877 (2025)

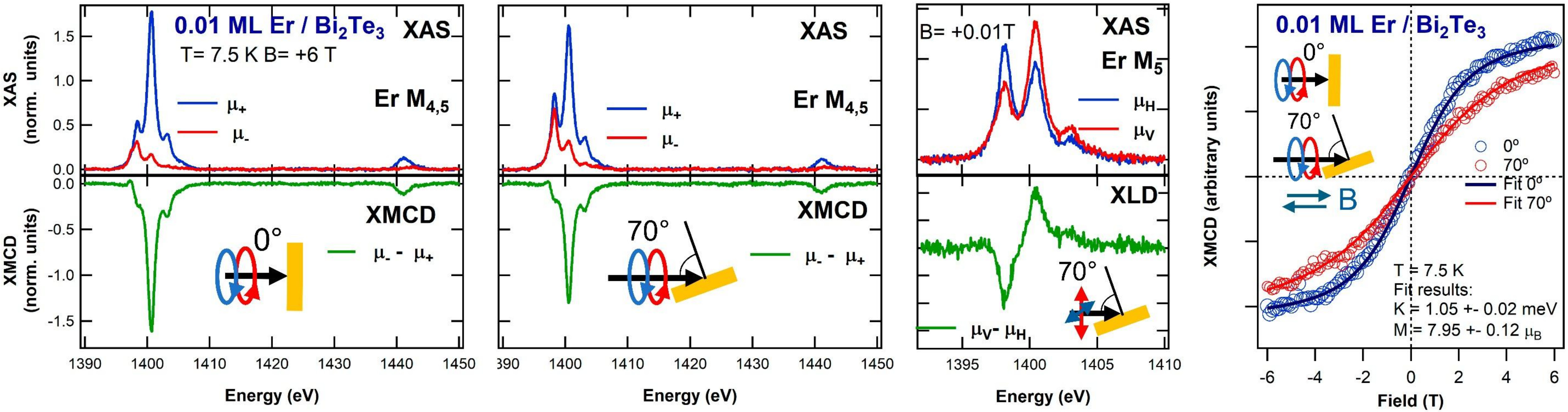
Magnetic anisotropy of Er impurities probed by XMCD

Stronger **XMCD** signal and higher saturation magnetization @ normal incidence

→ out-of-plane magnetic anisotropy

XLD line-shape → reported for other atomic or molecular Er systems with out-of-plane magnetic anisotropy

7.5 K



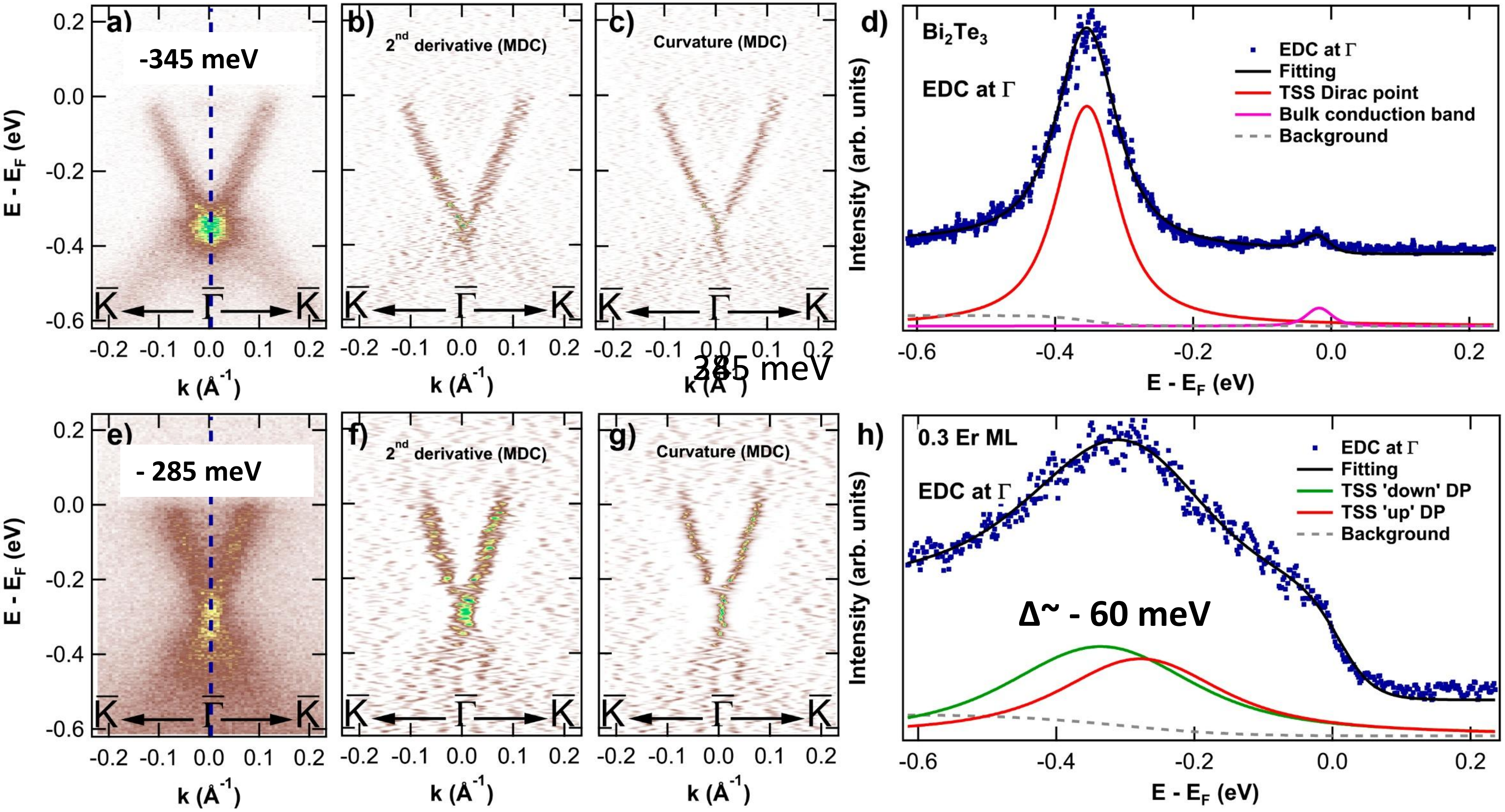
B. Muñiz-Cano *et al.,* Advanced Materials e10877 (2025)

Er dopants provide the out-of-plane magnetic component required to break TRS at the topological surface state

Spin-ARPES Lab

ARPES: gap opening at the DP in the TSS of Bi2Te3

T = 15 K hν = 52 eV



Bi_2Te_3

Gapless TSS with a single peak at the Dirac point

0.3 Er ML

The Dirac point shifts by ~60 meV towards E_F
→ **p-type doping,** consistent with XPS
The EDC requires two TSS components separated by $\Delta \approx 60$meV
→ **gap opening at the Dirac point**

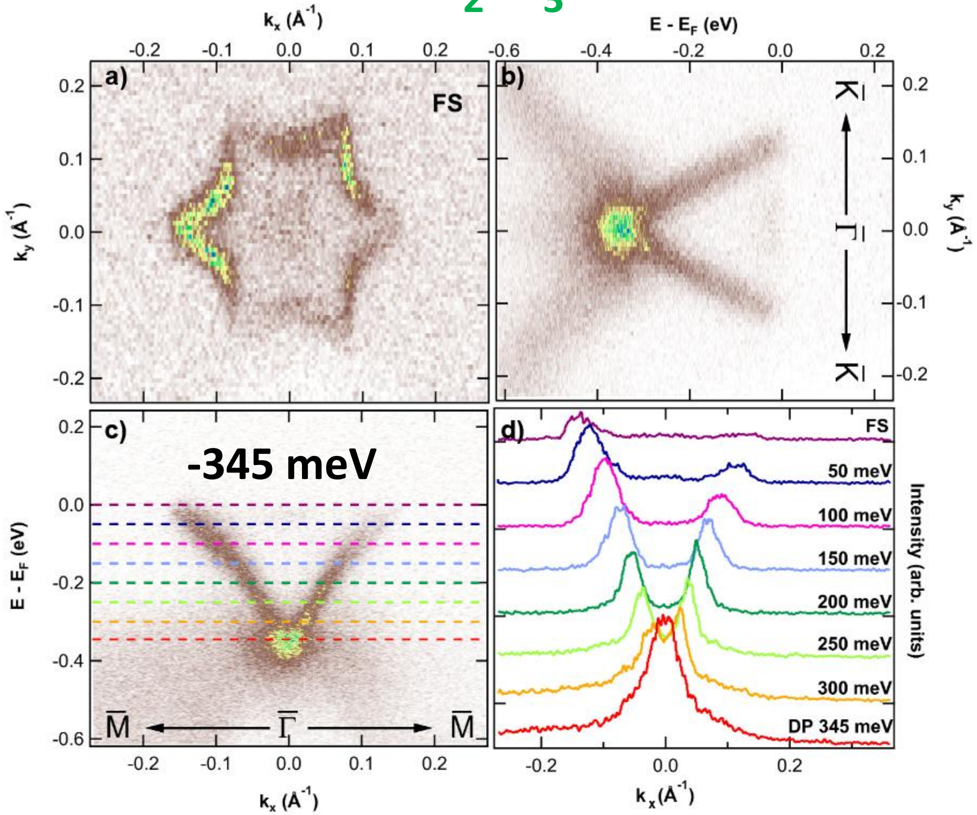
B. Muñiz-Cano *et al.,* Advanced Materials e10877 (2025)

Together with XMCD, the gap is consistent with magnetically induced TRS breaking

ARPES: FS magnetic warping transition from “snow-flake” to “star-of-David” pattern

T = 15 K hν = 52 eV

Bi_2Te_3



B. Muñiz-Cano *et al.,* Advanced Materials e10877 (2025)

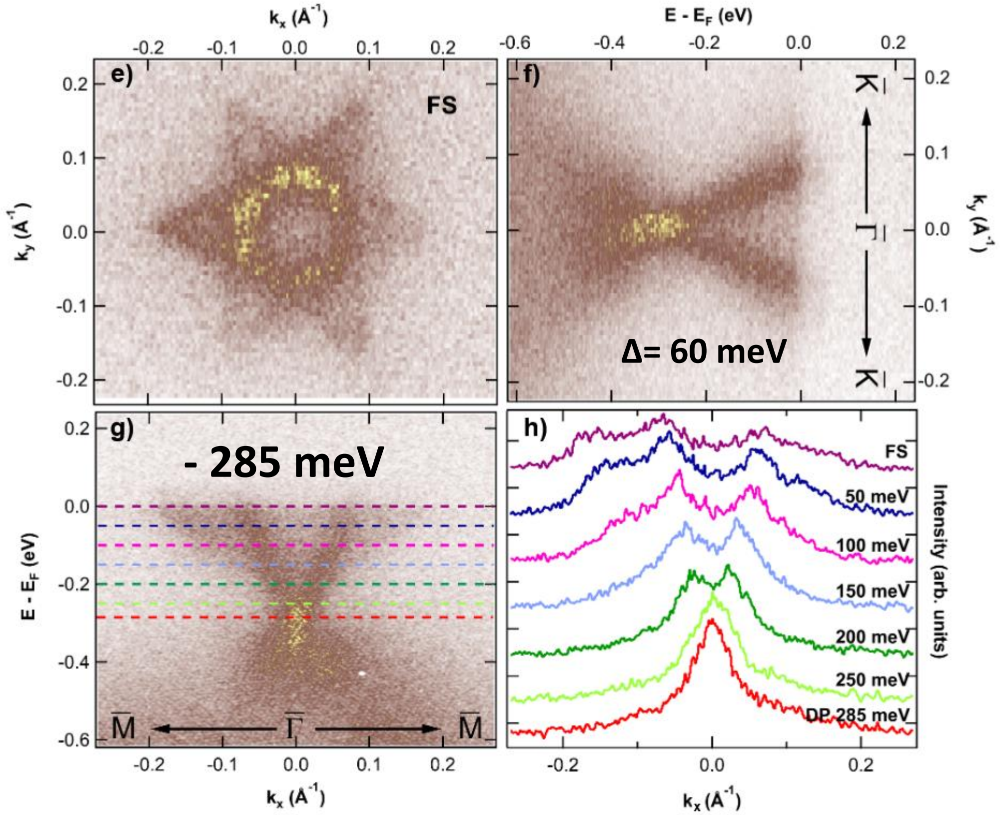
Er deposition produces:

→ p-type doping

→ Dirac-gap opening

→ Strong **FS reshaping**

0.3 Er ML / Bi_2Te_3

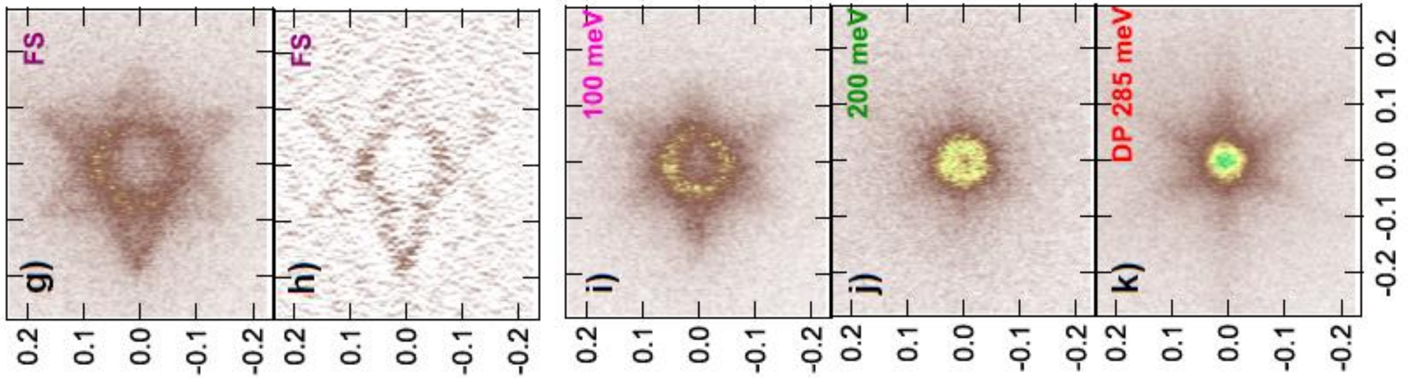


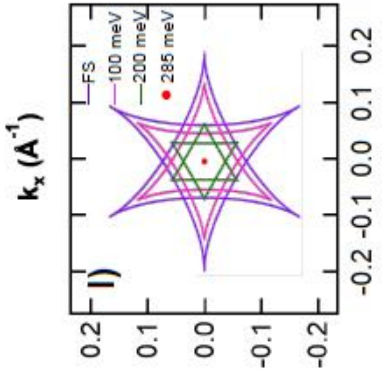
Er transforms the snowflake-like Fermi surface into a Star-of-David pattern

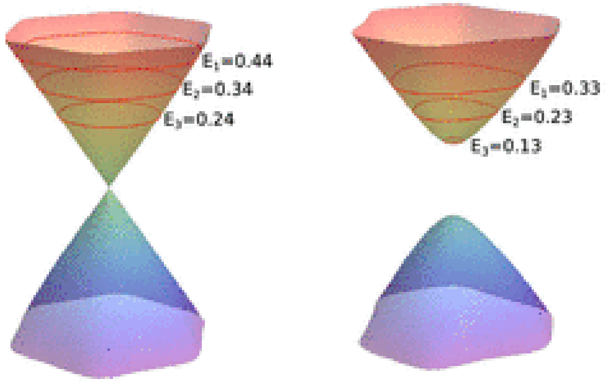
Magnetic origin of the Star-of-David Fermi surface

15 K

Fermi Surface and constant energy contours



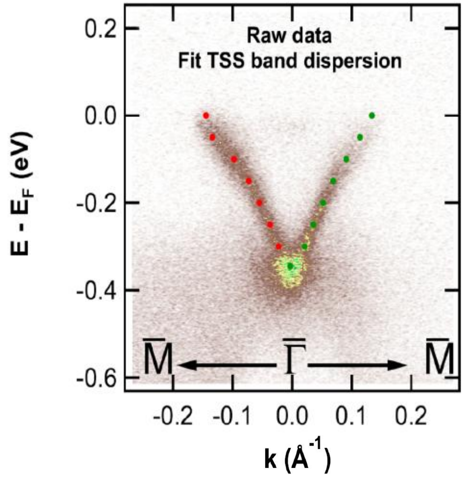




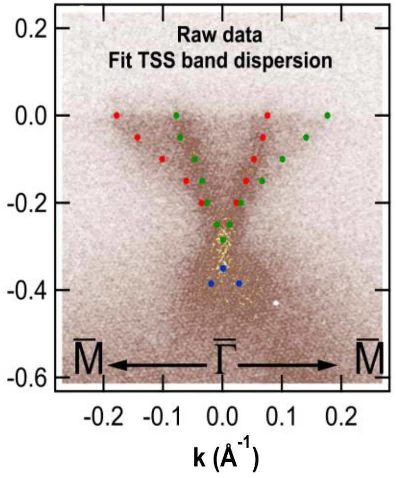
T = 15 K hν = 52 eV

B. M. Cano., Nano Letters 2023

Bi_2Te_3



0.3 Er ML / Bi_2Te_3



Asymmetric double-branch dispersion of the TSS

The Star-of-David pattern can be described as the superposition of two oppositely oriented trigonal TSS contours

TSS composed of two opposite trigonal Dirac cones

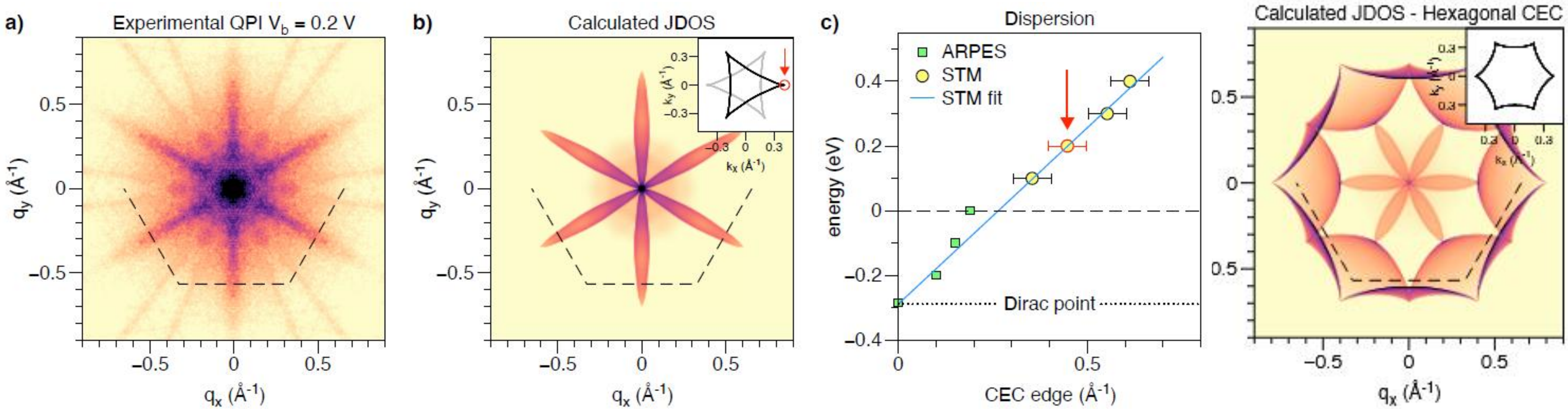
Two magnetic Zeeman terms with opposite sign

B. M. Cano., Adv. Ma. e10877 (2025)

QPI locally resolves a trigonal TSS contour in Er/Bi_2Te_3

ARPES provides a momentum-resolved but spatially averaged view of the occupied electronic structure. QPI offers a complementary local probe of the proposed interpretation.

Elastic scattering of surface electrons by defects produces quasiparticle interference patterns whose Fourier transform is related to the constant-energy electronic structure at the energy selected by the STM bias voltage.

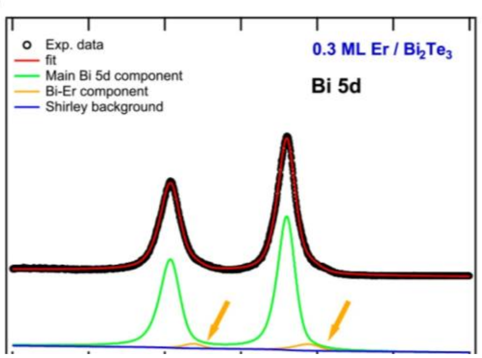


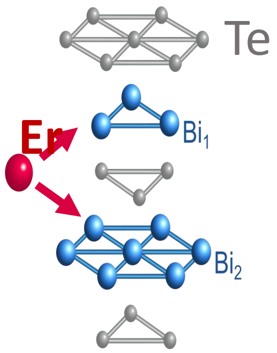
B. Muñiz-Cano *et al.*, Advanced Materials e10877 (2025)

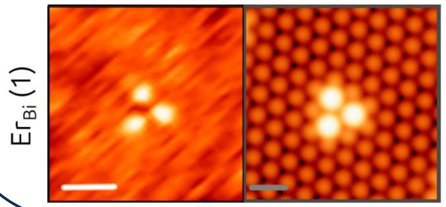
The experimental asterisk-like QPI pattern is reproduced by one of the two trigonal TSS contours, rather than by the hexagonally warped contour expected for pristine Bi_2Te_3

Conclusions

STM/XPS



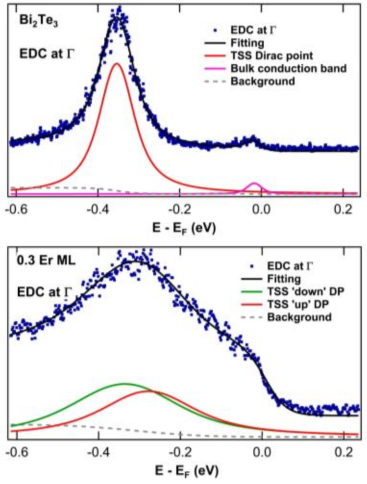




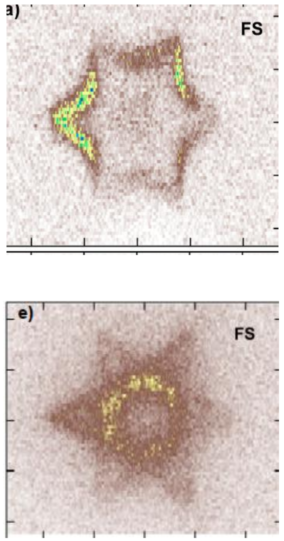
Direct microscopic evidence Er-Bi interaction

Consistent picture of magnetically induced TRS breaking

ARPES

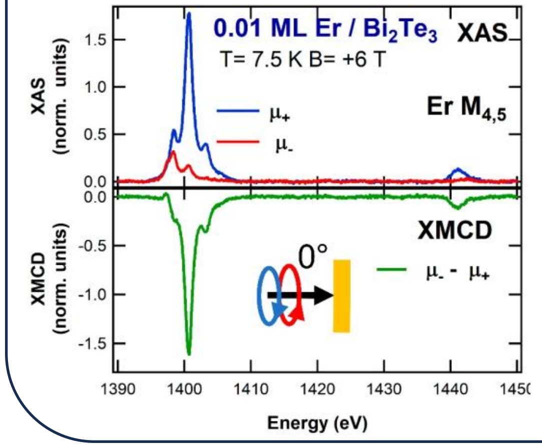


Gap opening at DP



Magnetically induced FS transition from “snow-flake” to a “star-of-David”

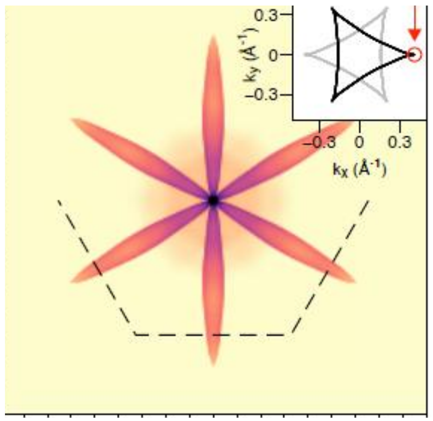
XMCD



Out-of-plane magnetic anisotropy

Rare-earth surface doping provides key ingredients toward the QAHE: out-of-plane magnetism, p-type doping and Dirac-gap opening

STS/QPIs



QPI locally resolves a trigonal TSS component, supporting the superposition of two opposite Zeeman contributions

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Pierluigi Gargiani

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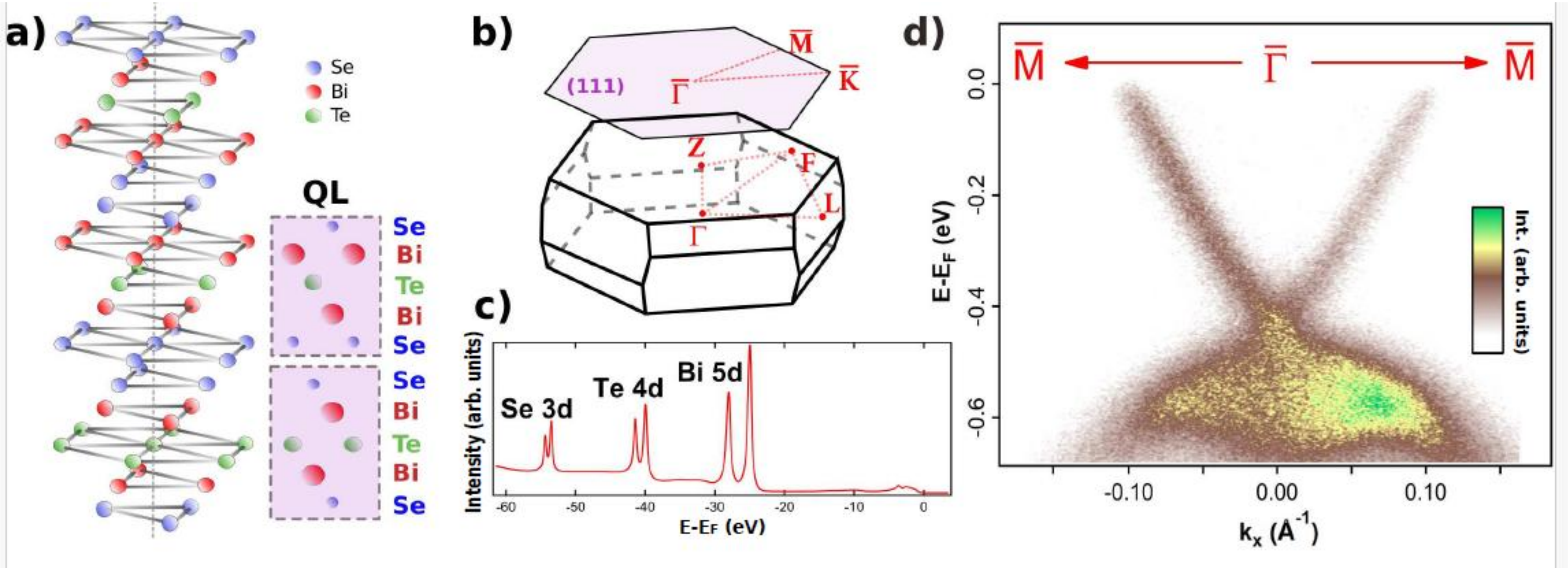
CONPHASETM PID2021-123776NB-C21
TeQMAT PID2024-157655NB-I00 FCM

Thank you for your attention!

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: pristine Bi_2Se_2Te



3D quintuple layer crystal structure.

XPS spectrum: **intense and narrow peaks**, very well-defined **spin-orbit doublets** prove the **surface quality** after *in situ* exfoliation.

Pristine Bi_2Se_2Te TSS ARPES bandmap along the ΓK direction **yields**:

E_{DP} = 440 meV
No gap
$V_F = (7.1 \pm 0.1)\cdot 10^5$ m/s

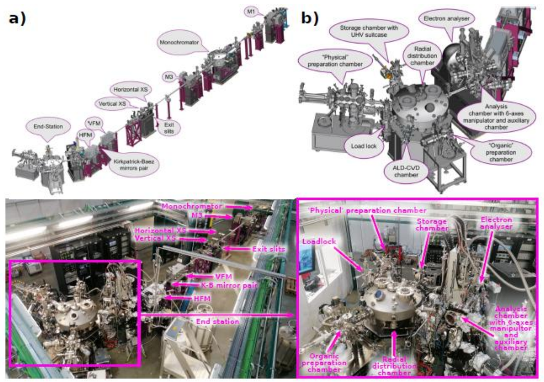
B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Sample Preparation:

- **Bulk single crystal**

Er (Dy) impurities deposited by means of an e-beam evaporator.

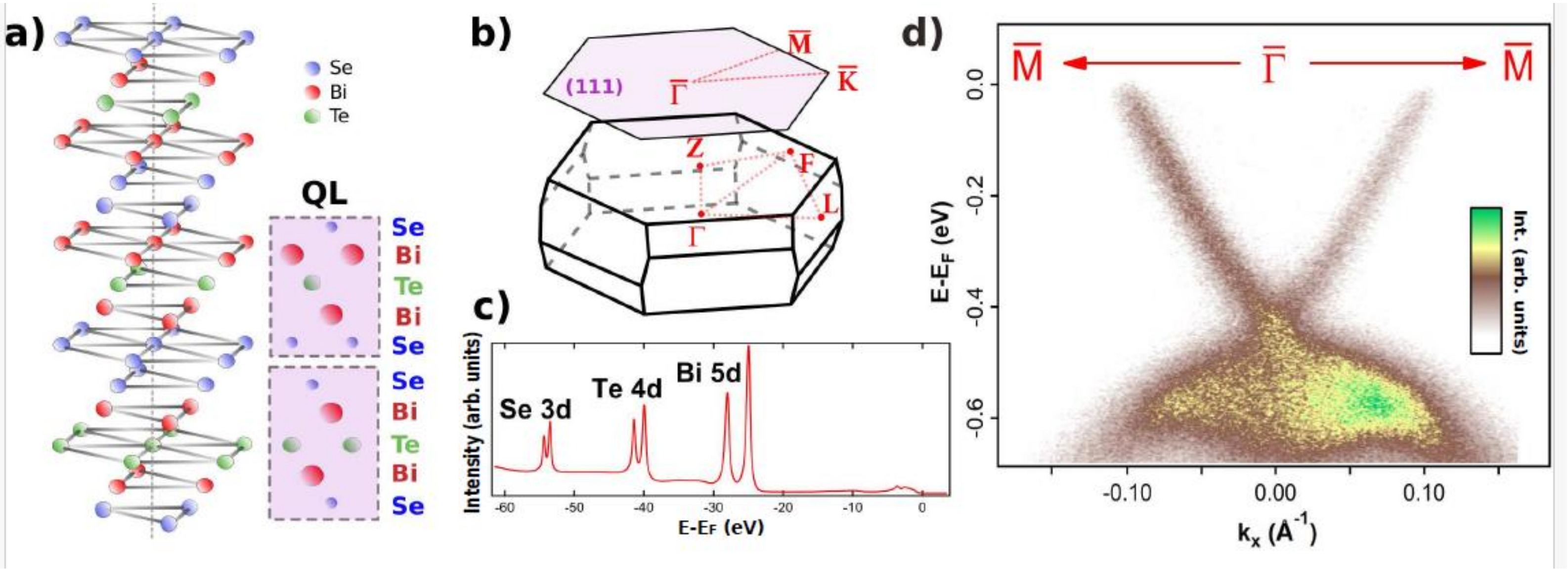
- XPS and ARPES performed at a **T = 15 K**
- **Exfoliated in-situ** (UHV) at T = 15 K
- **Linear horizontal** polarization with **hv** = **100** (XPS) and **52** (ARPES) **eV**



LOREA beamline (ALBA synchrotron)

Results: pristine Bi_2Se_2Te

2D Brillouin Zone



3D quintuple layer crystal structure.

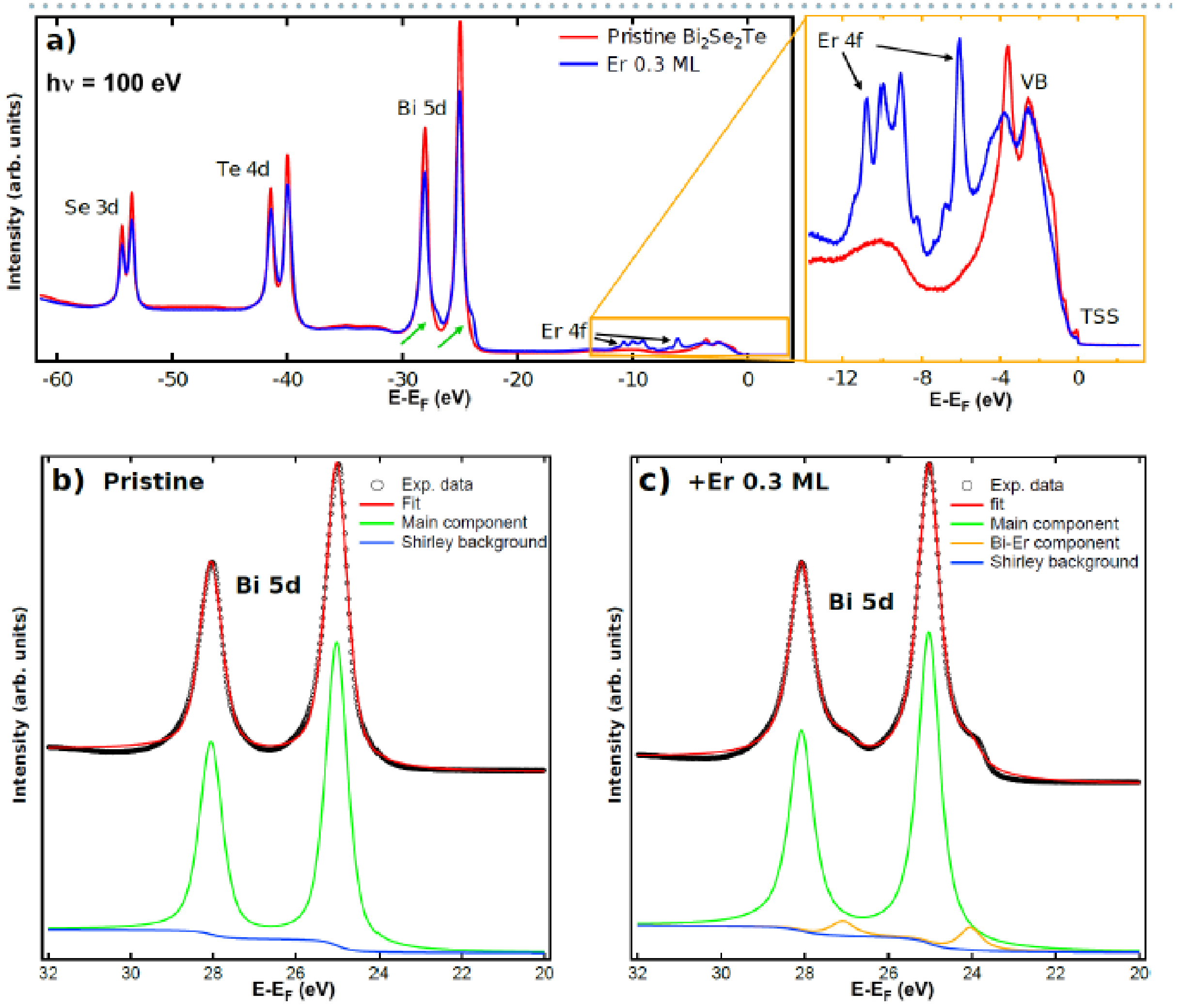
XPS spectrum: **intense and narrow peaks**, very well-defined **spin-orbit doublets** prove the **surface quality** after *in situ* exfoliation.

Pristine Bi_2Se_2Te TSS ARPES bandmap along the ΓK direction **yields**:

E_{DP} = 440 meV
No gap
$V_F = (7.1 \pm 0.1) \cdot 10^5$ m/s

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: 0.3 Er ML doped Bi_2Se_2Te XPS

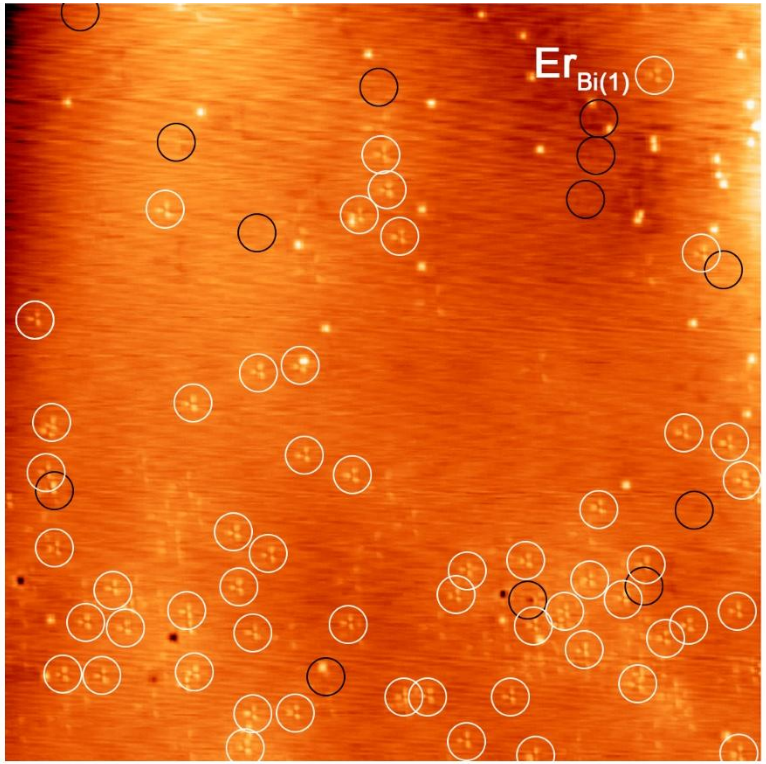


- Se 3d, Te 4d, Bi 5d → attenuated.
- Bi 5d peak attenuation → **Er coverage estimation**
- No extra components at higher BEs → no surface oxidation or contamination
- No widening of the peak + very sharp and well resolved multipeak structure Er 4f states → no further disorder Introduced
- Second Bi 5d component → intensity linearly increases with the Er coverage → related to superficial Bi-Er bond + interaction at the RE-TI interface

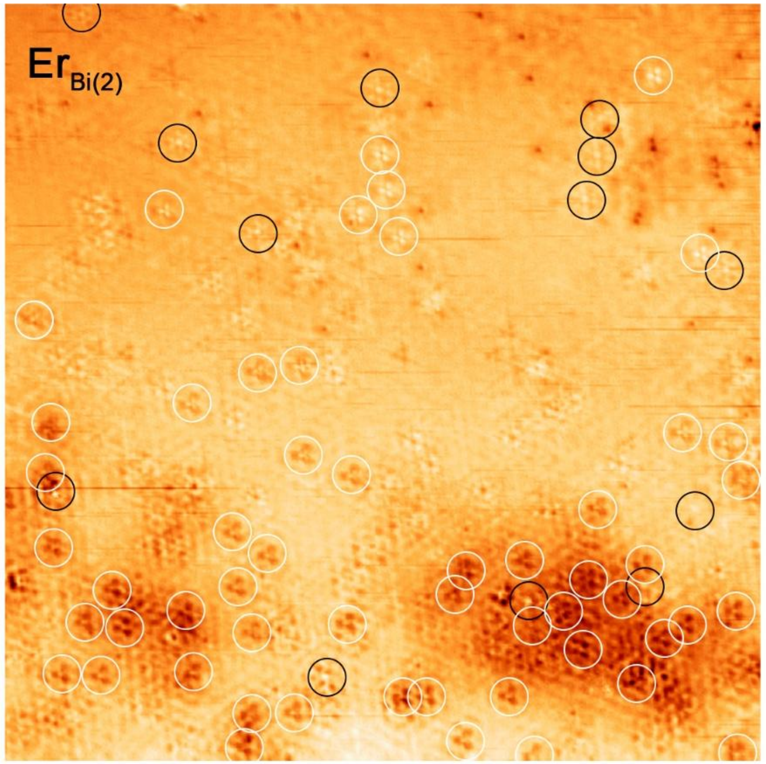
B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

QPI Signatures of TRS Breaking in Er/Bi_2Te_3

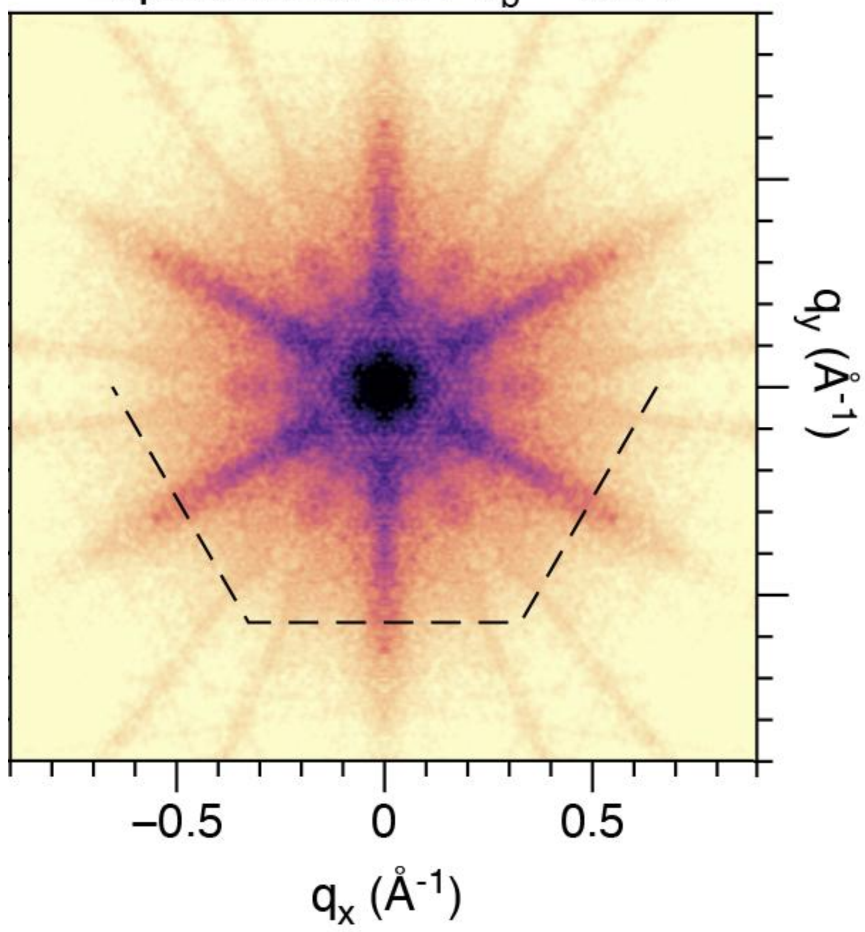
TOPO



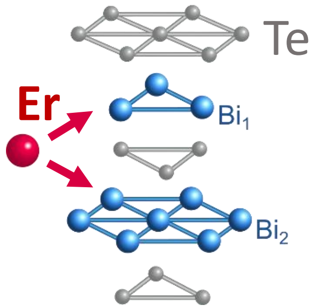
d*I*/d*V* map

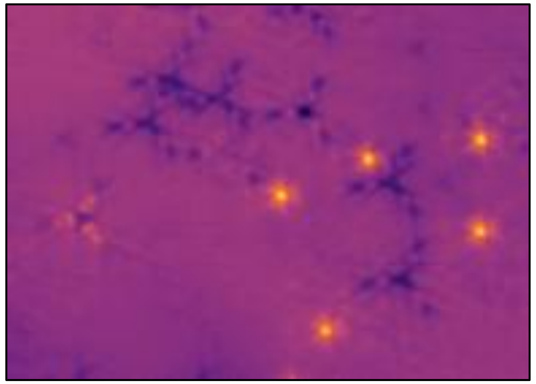


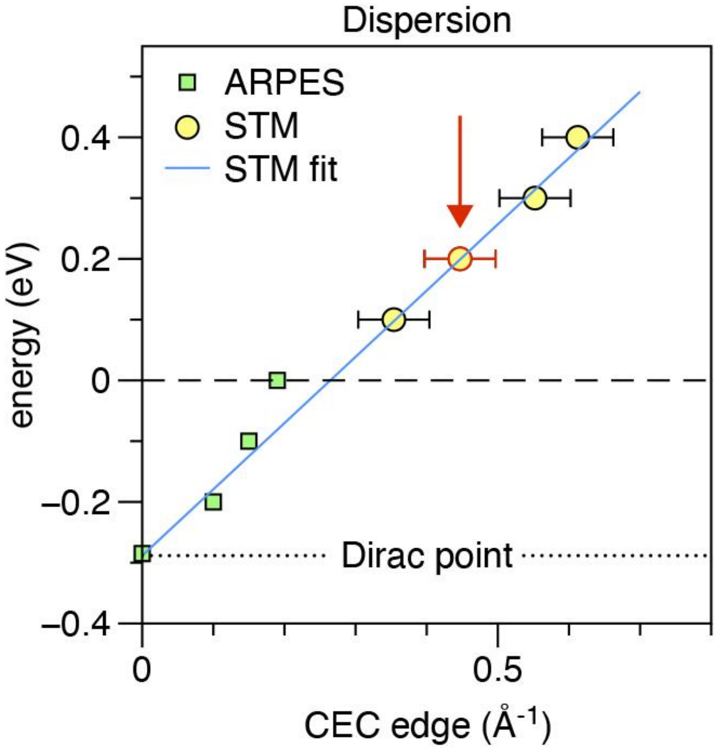
Experimental QPI $V_b = 0.2$ V

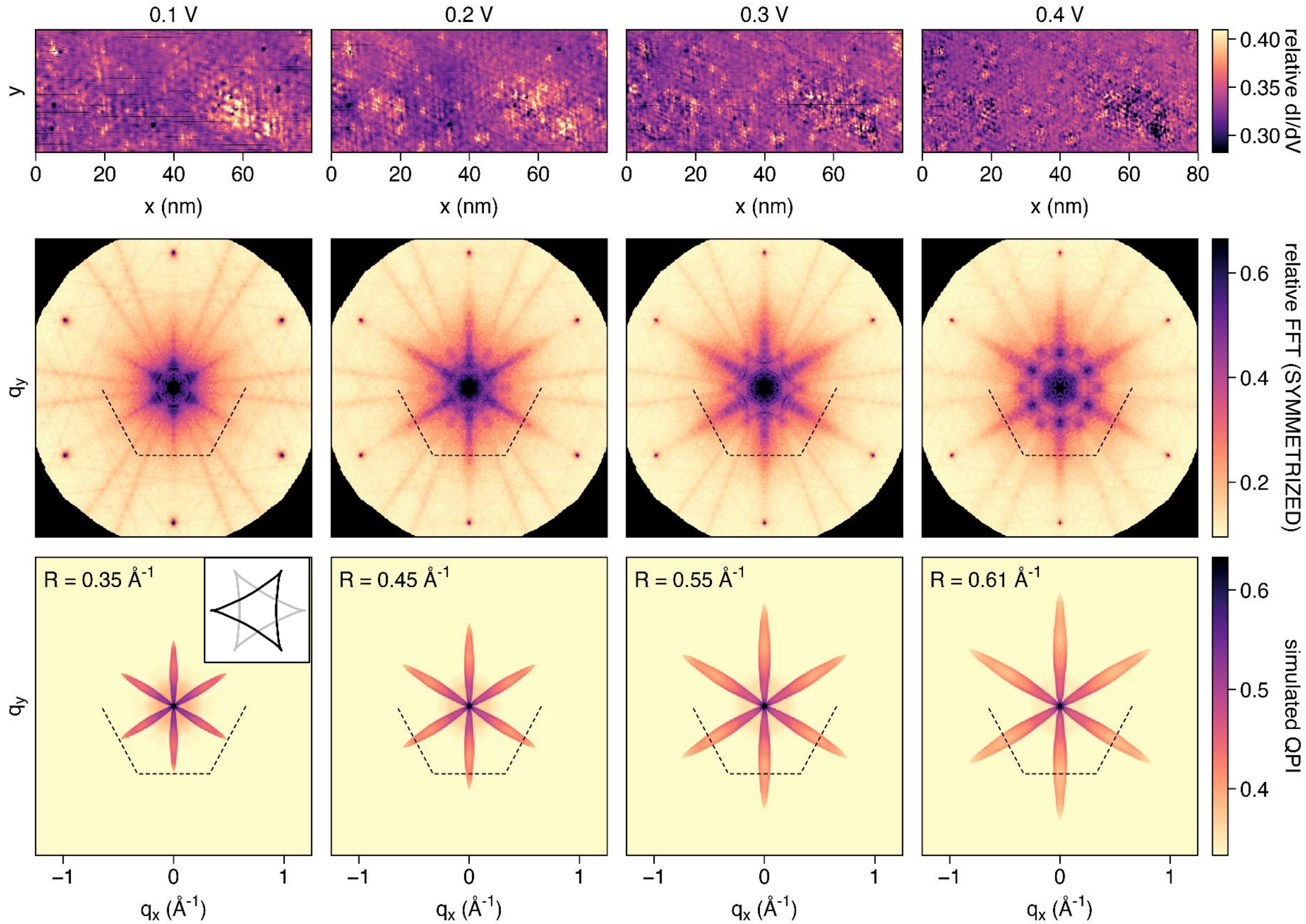


QPI Signatures of TRS Breaking in Er/Bi_2Te_3

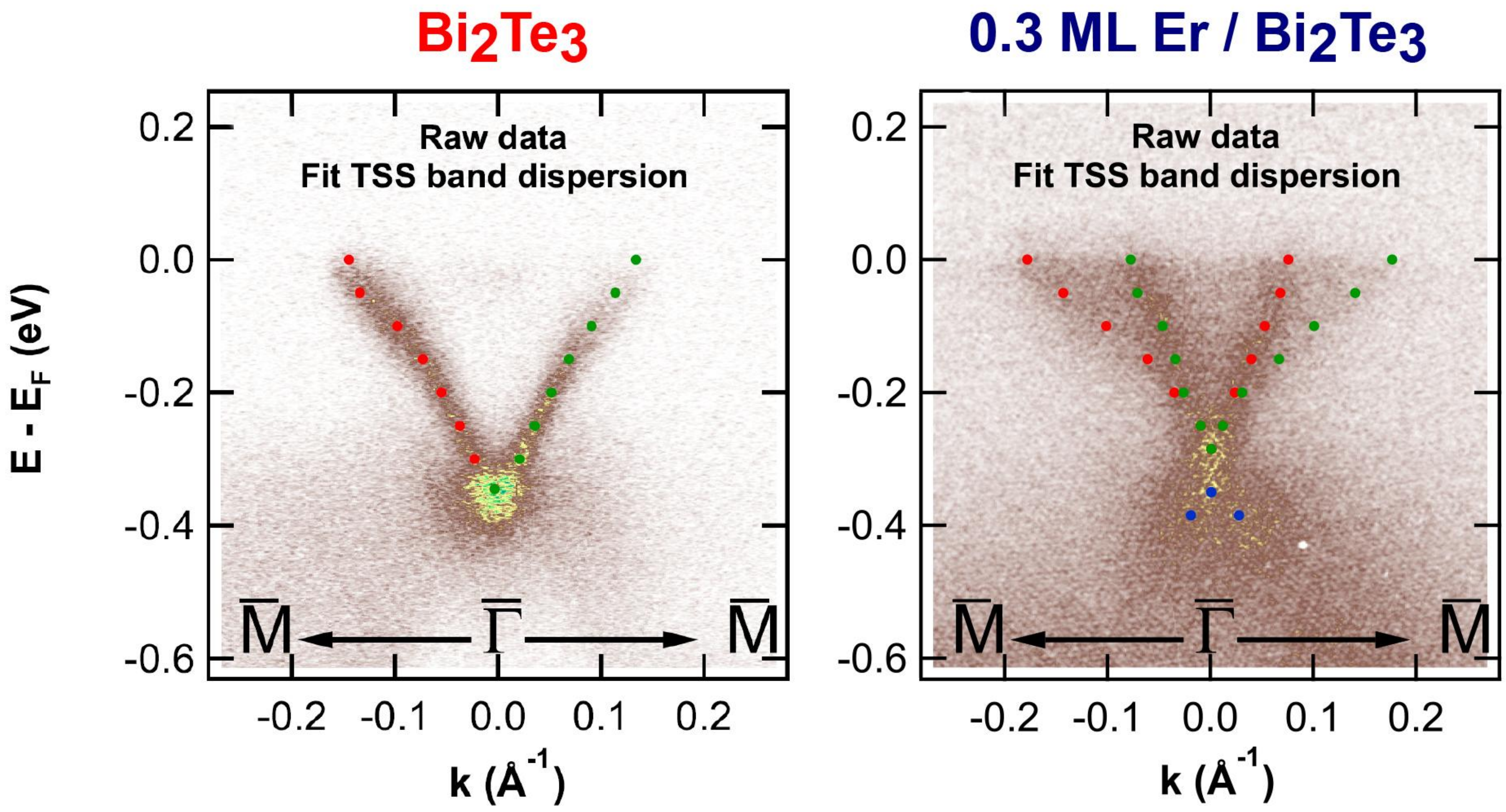






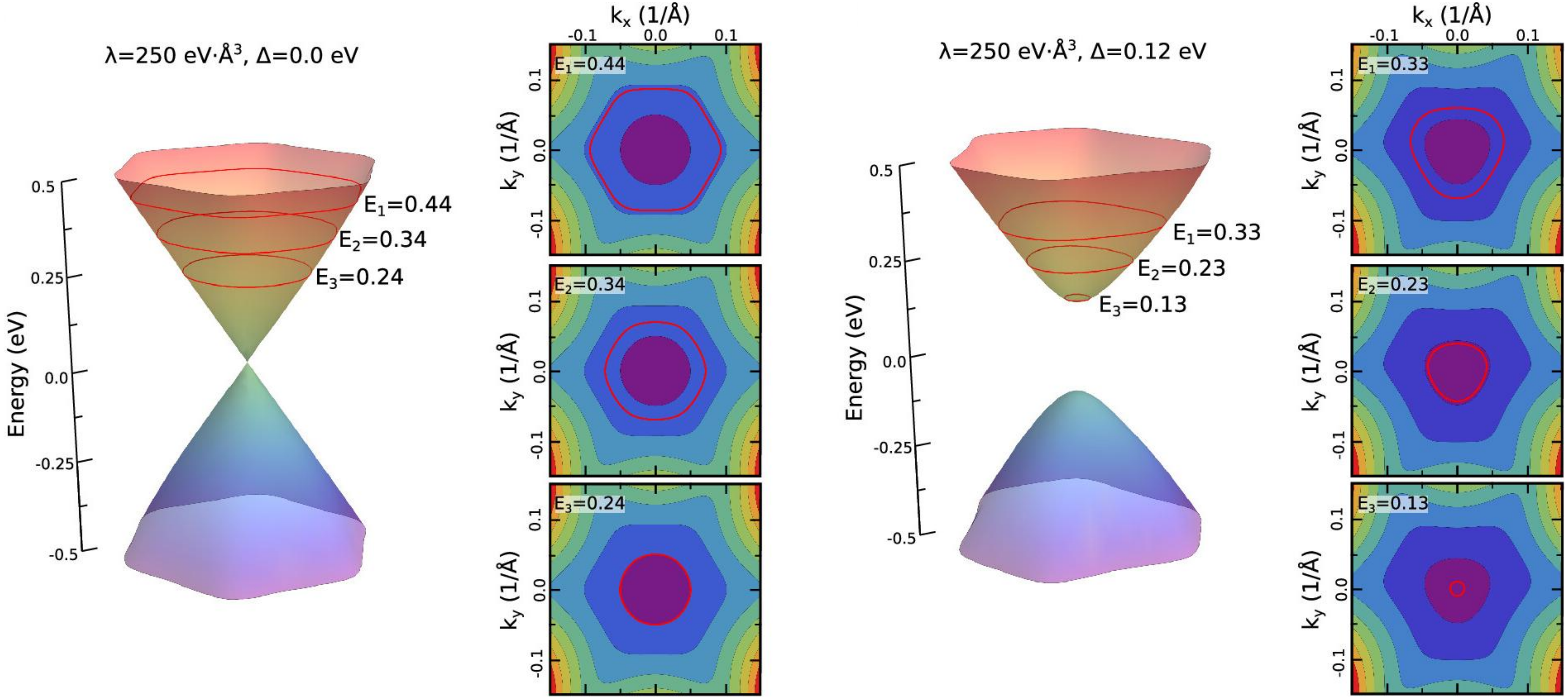


ARPES evidence of the warping transition



Theoretical modeling of the warping transition

Calculations by Paco Guinea's group

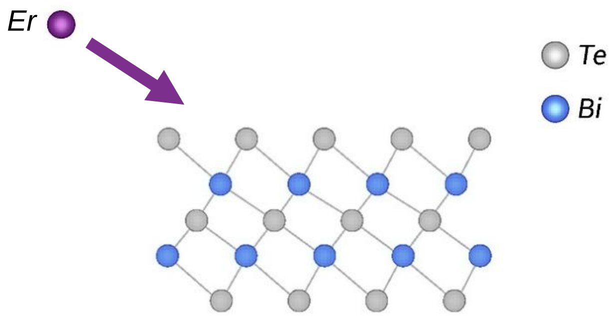


$$E^2 = \hbar^2 v^2 k^2 + \lambda^2 k^6 cos^2 3\theta$$

$$E^2 = \hbar^2 v^2 k^2 + (\lambda k^3 cos 3\theta - \Delta)^2$$

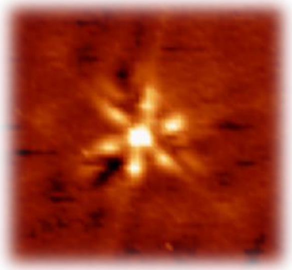
Nano Lett. **23**, 6249 (2023)

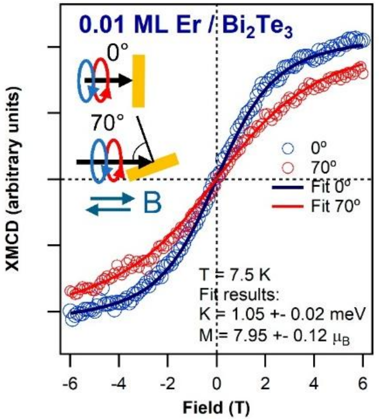
Magnetic doping of Bi_2Te_3

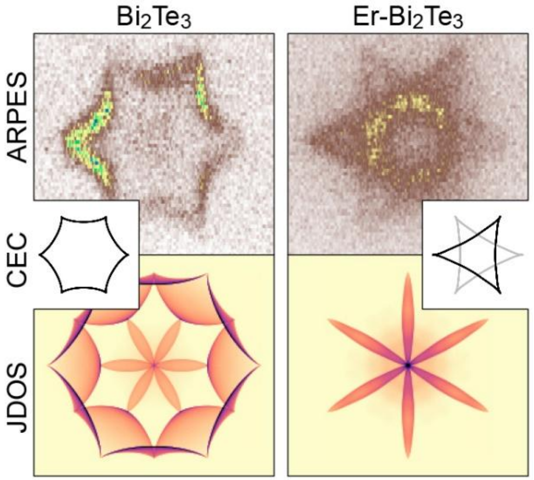


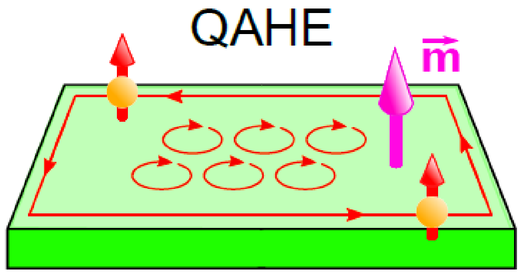
Magnetic doping of Bi_2Te_3

Direct evidence of microscopic mechanisms of TRS breaking









Induce long range FM order

Out of plane magnetization

Open gap at Dirac point

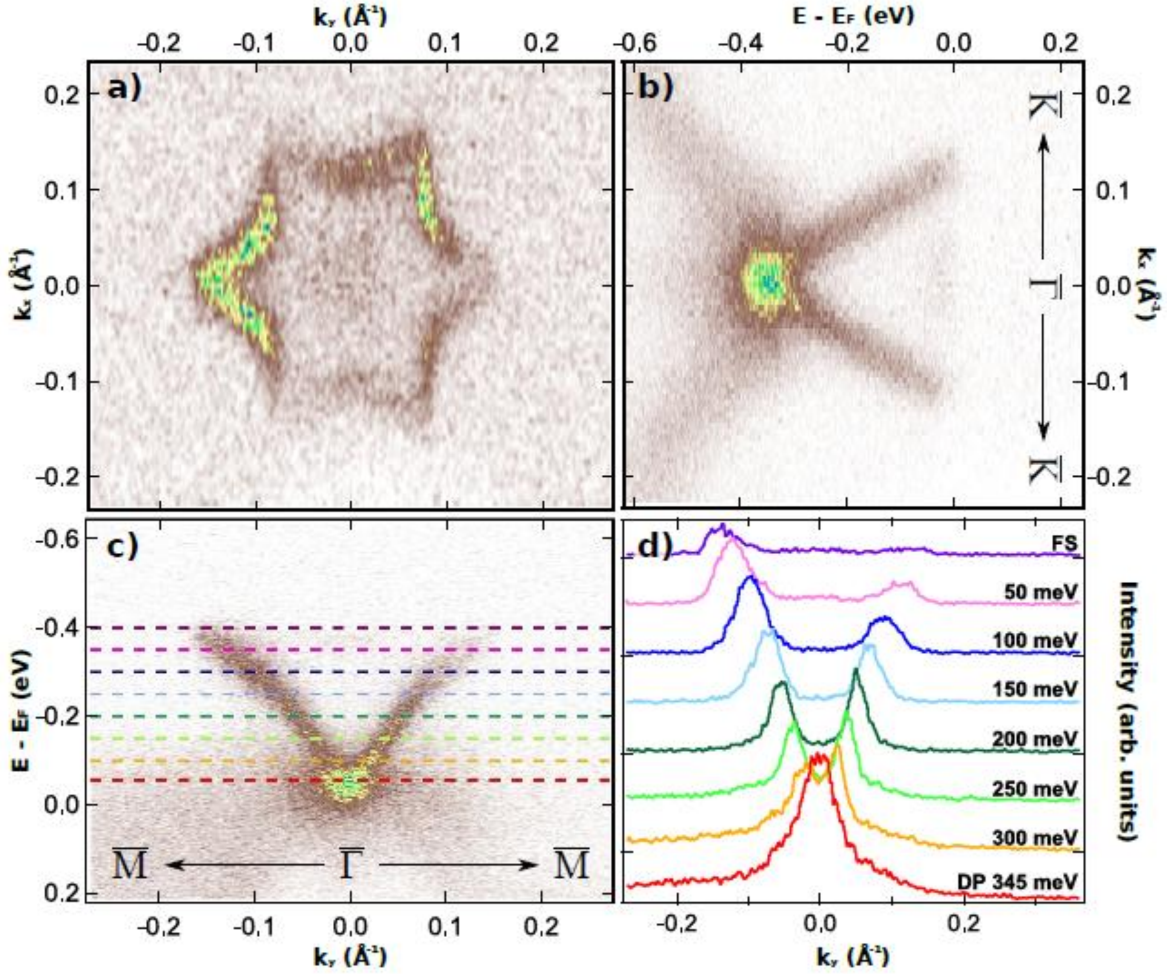
Transformation of the TSS

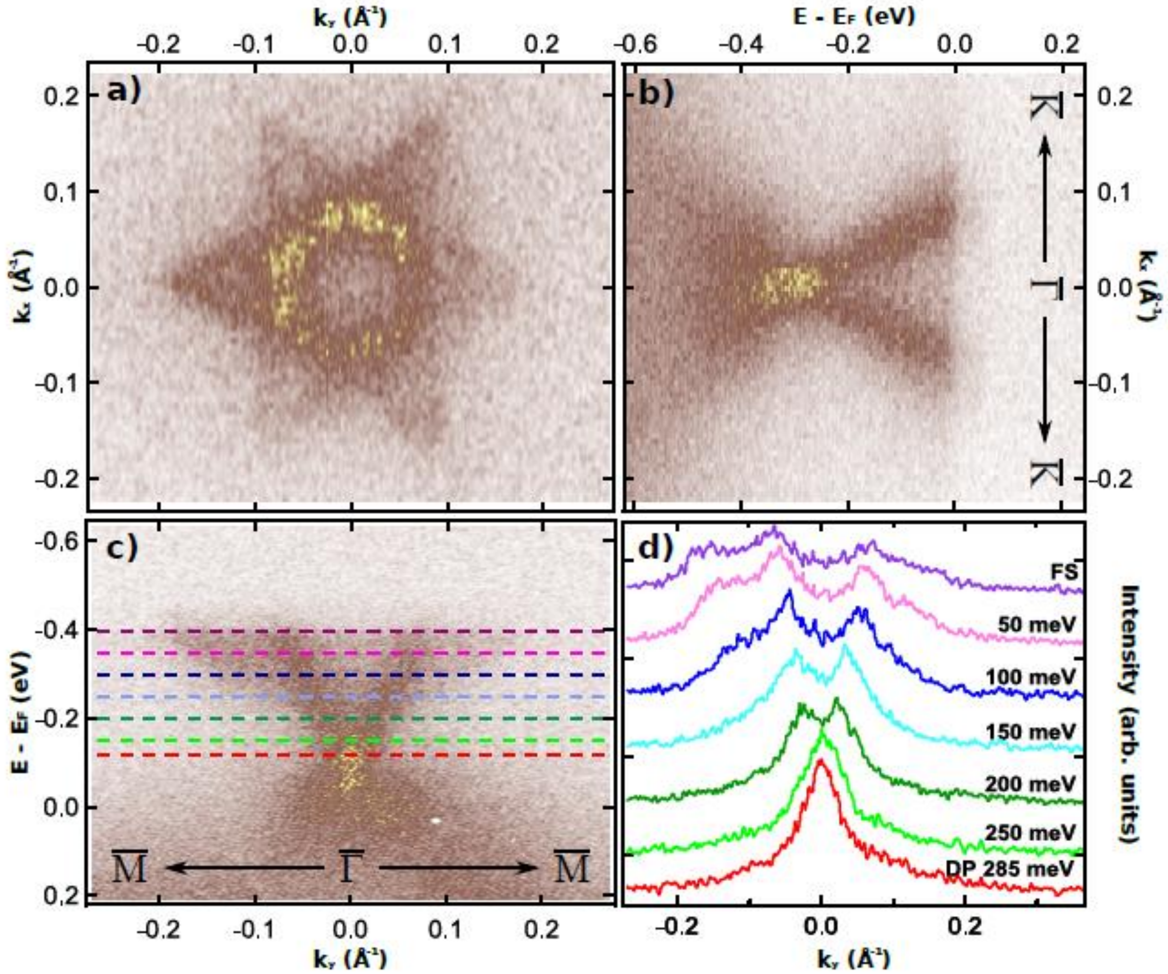
Possibility to realize new phenomena

B. Muñiz-Cano *et al.*, Advanced Materials e10877 (2025)

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Bi_2Te_3 vs Er/Bi_2Te_3





B. Muñiz Cano PhD thesis 2024

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

NANO LETTERS

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Letter

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Beatriz Muñiz Cano, Yago Ferreiros, Pierre A. Pantaleón, Ji Dai, Massimo Tallarida, Adriana I. Figueroa, Vera Marinova, Kevin García-Díez, Aitor Mugarza, Sergio O. Valenzuela, Rodolfo Miranda, Julio Camarero, Francisco Guinea, Jose Angel Silva-Guillén, and Miguel A. Valbuena*

Cite This: *Nano Lett.* 2023, 23, 6249–6258

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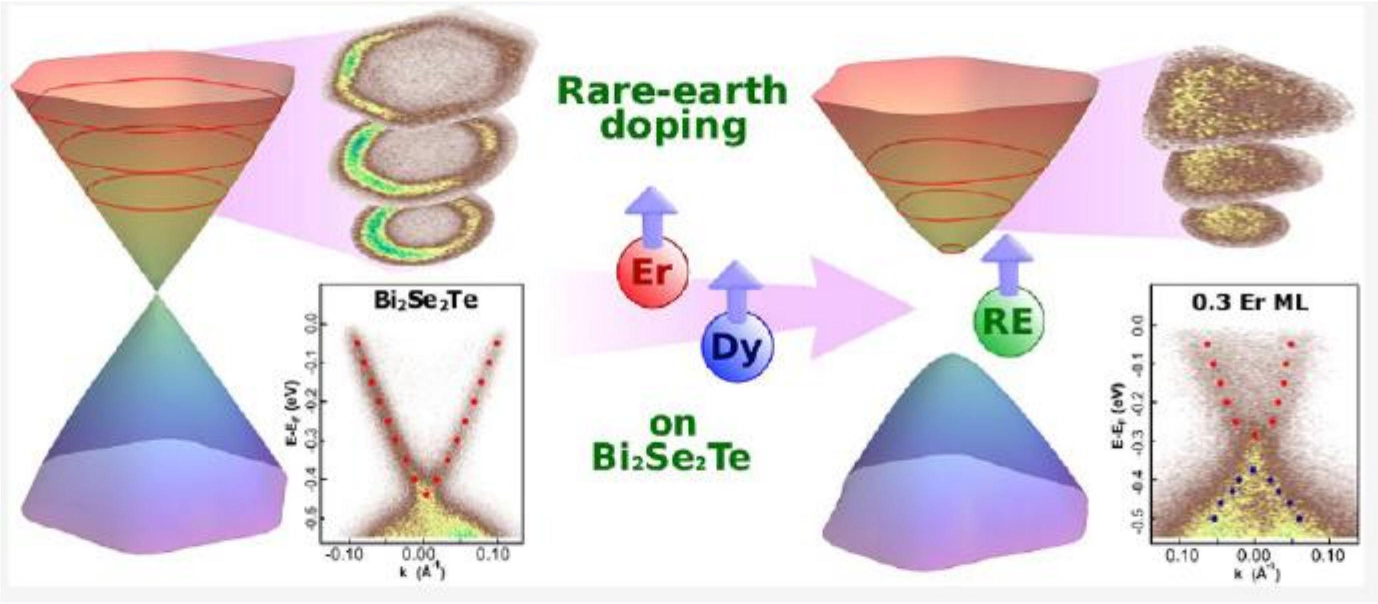

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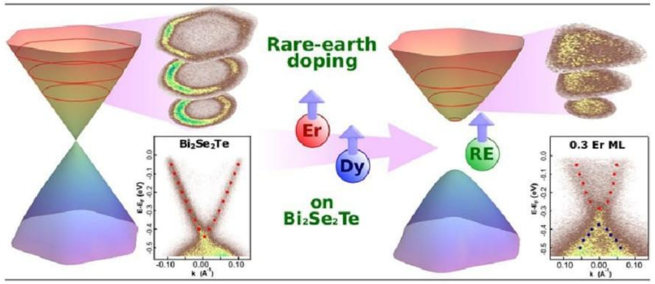

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Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insula...

18:30 · 12 jun 23 · **4.420** Visualizaciones

15 Republicaciones **35** Me gusta

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

- **First scientific publication of Spin-ARPES group**

IMDEA Nanociencia | Investigación | Colaboraciones | Servicios | Empleo | Transparencia

EN ES | buscar...

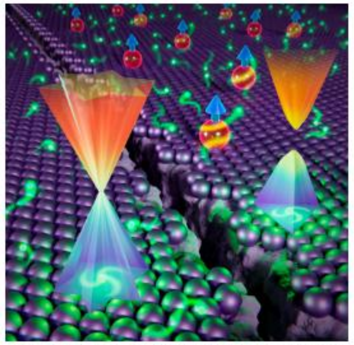
EXCELENCIA SEVERO OCHOA

Inicio / Noticias /

Una nueva huella espectroscópica de interacciones magnéticas entre estados topológicos y dopantes magnéticos de tierras raras, primer artículo del laboratorio Spin-ARPES en IMDEA Nanociencia

Una nueva huella espectroscópica de interacciones magnéticas entre estados topológicos y dopantes magnéticos de tierras raras, primer artículo del laboratorio Spin-ARPES en IMDEA Nanociencia

23.05.2023



Apertura de *gap* y posterior transición de deformación en Bi2Se2Te inducida por dopaje superficial de tierras raras con impurezas magnéticas Er y Dy.

Imagen: Patricia Bondía.

- **First scientific publication of LOREA beamline, ALBA Synchrotron.**
- **Among the first users, November 2021**

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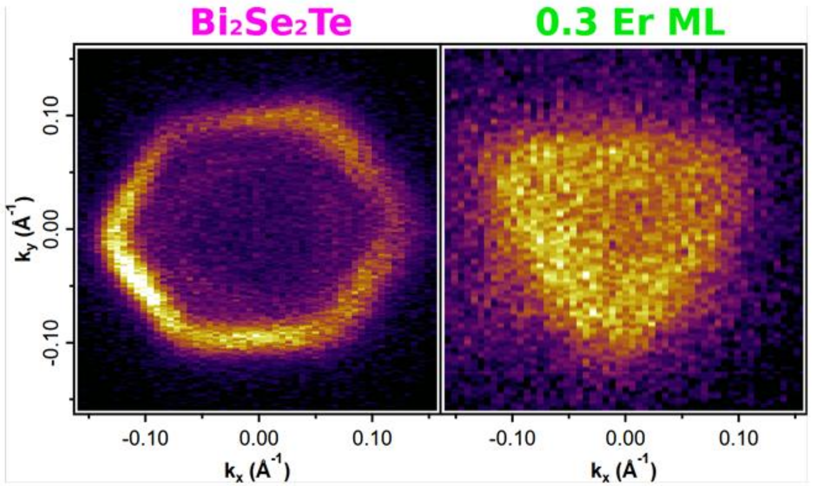
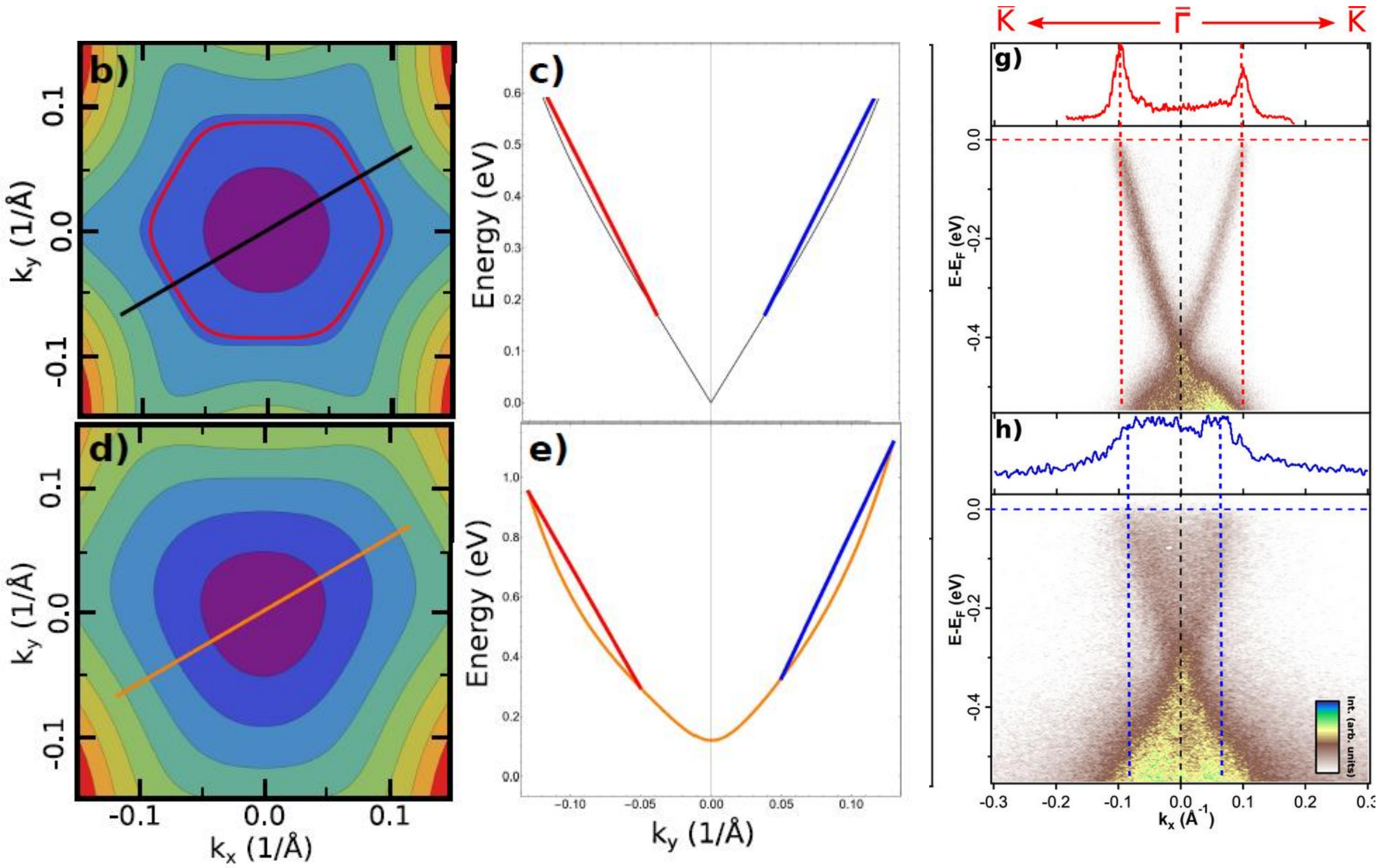
HOME / MEDIA / NEWS / A PAPER ABOUT QUANTUM MATERIALS, FIRST PUBLICATION WITH DATA OBTAINED AT LOREA

One of the latest beamlines of ALBA, performing ARPES (Angle Resolved Photo-Emission Spectroscopy) experiments, has been essential for IMDEA Nanociencia and ICN2 researchers to demonstrate how the conducting surface states of a special class of materials -topological insulators- change due to the introduction of magnetic impurities via doping with a small amount of rare earth elements. These results will help understanding better the quantum anomalous Hall Effect which is essential in the development of spintronics.



Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: TSS Band dispersion: Theoretical modelling



- The experimental Fermi velocity asymmetry is also reproduced

Any doping effects ?

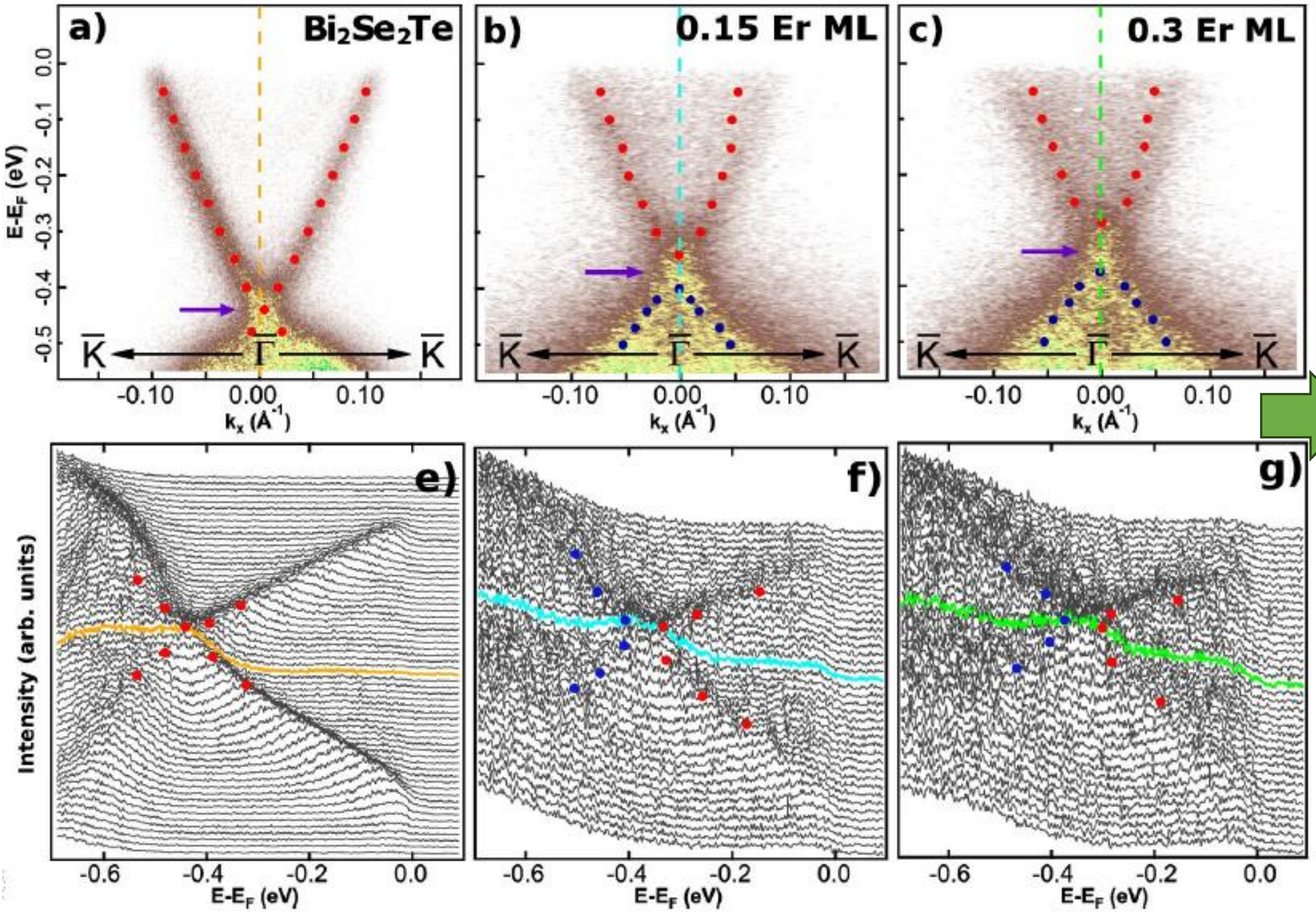
And most importantly…

What about a gap opening at the DP?

B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: p-type doping at TSS. Gap at the DP



p-type doping induced by Er adsorption on the TI surface. It increased linearly with the Er coverage

- **Pristine** BST:

→ **DP defined** as intersection of two linear branches at 440 meV

→ **Punctual maximum** of intensity in the EDC at Γ

- **Er-doped** BST:

→ Linear dispersion renormalized to **parabolic**

→ **Plateau** in the EDC at Γ instead of maximum of intensity

B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

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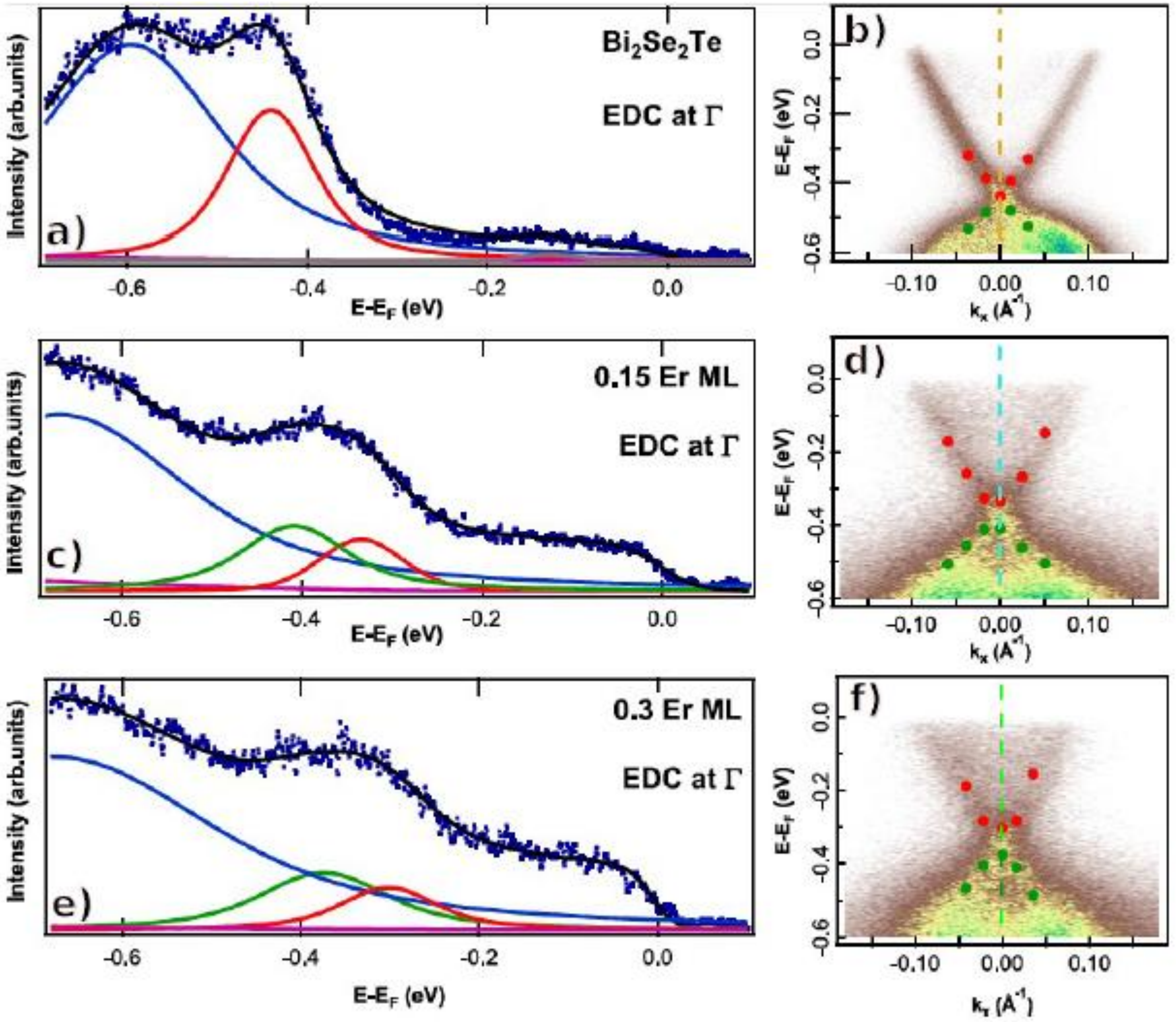

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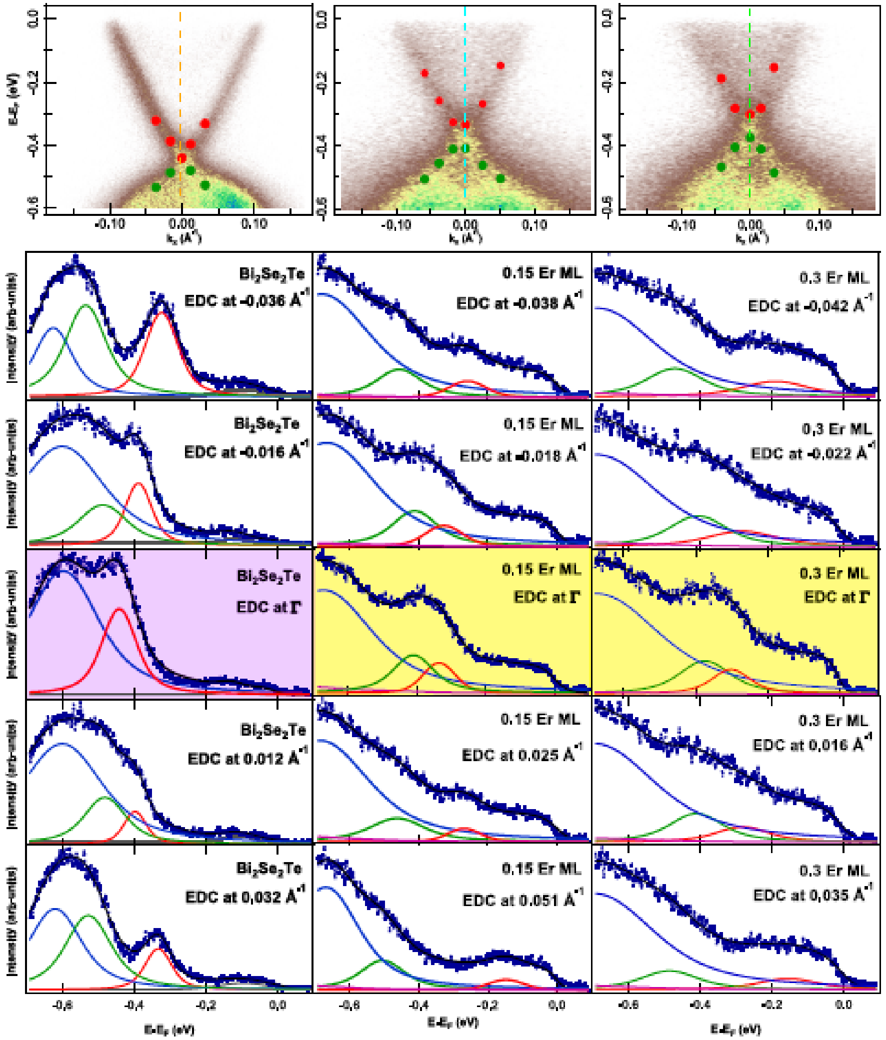
B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

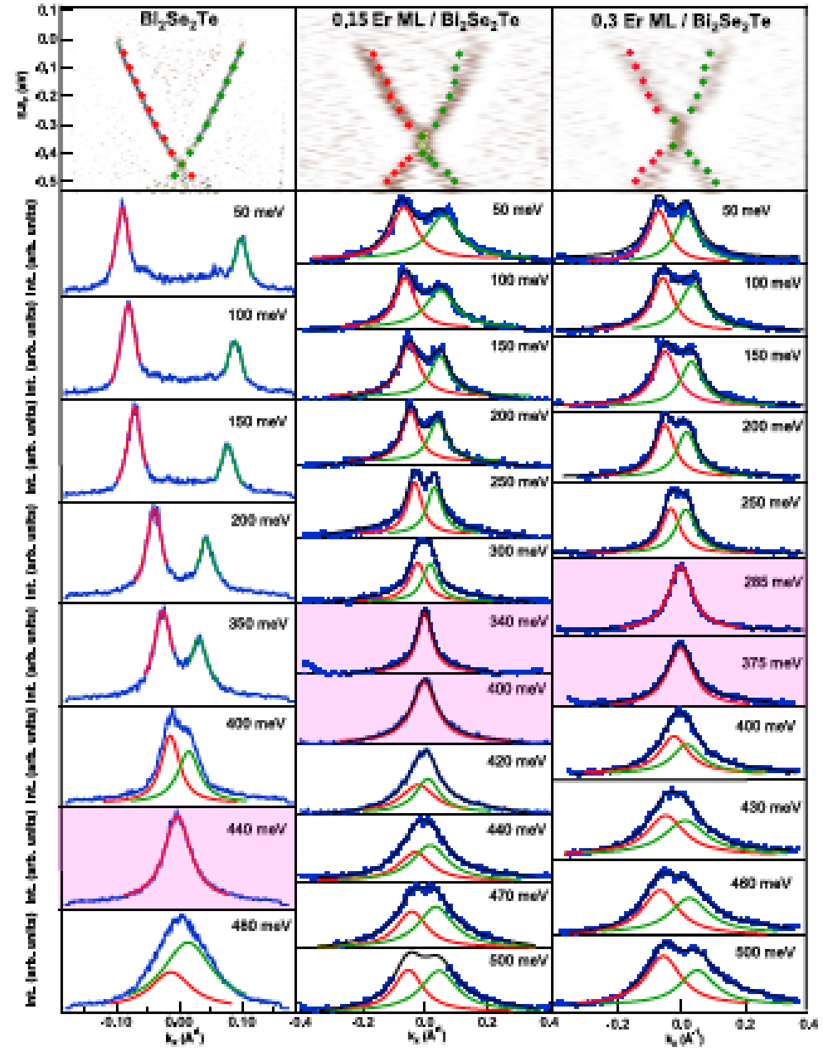
Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: p-type doping at TSS. Gap at the DP

EDCs multipeak fit analysis



MDC multipeak fit analysis

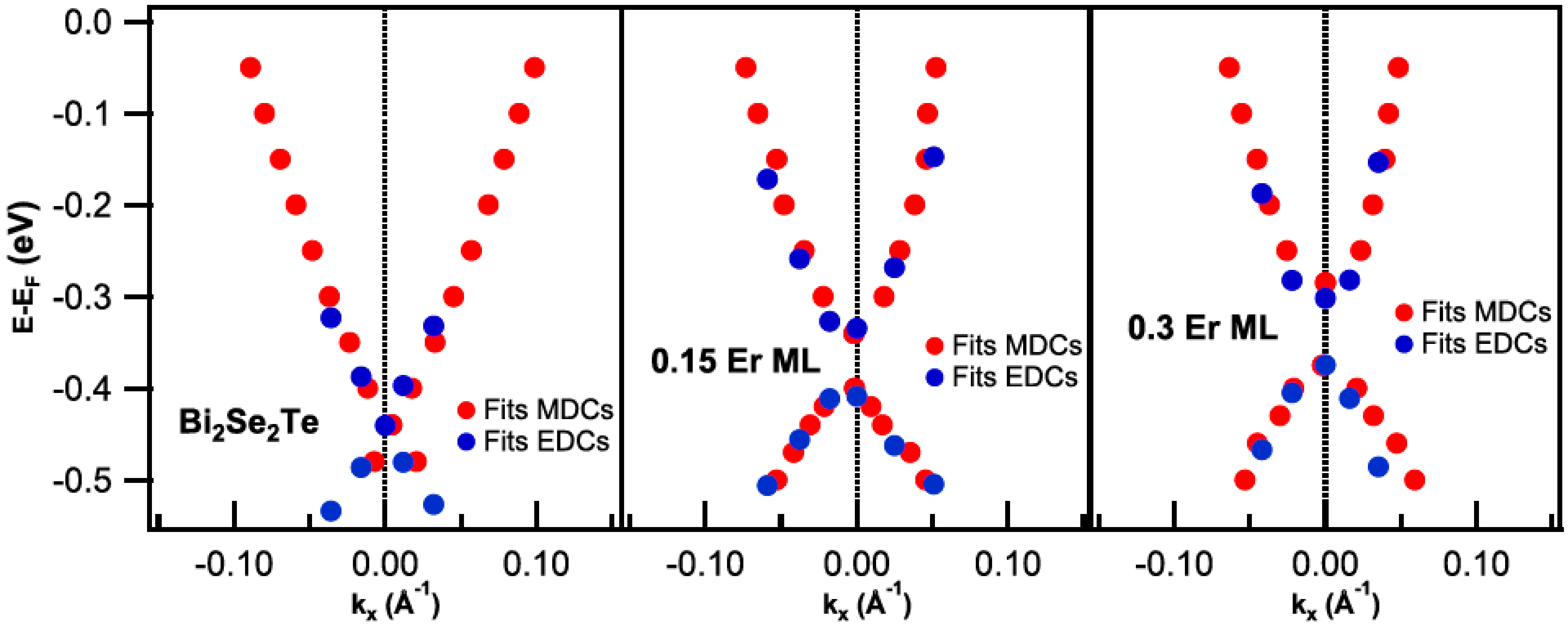


B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Results: p-type doping at TSS. Gap at the DP

Multipeak fit analysis summary



- A gap at the DP is magnetically induced ~ 70 meV
  - P-type doping as a function of Er coverage

B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

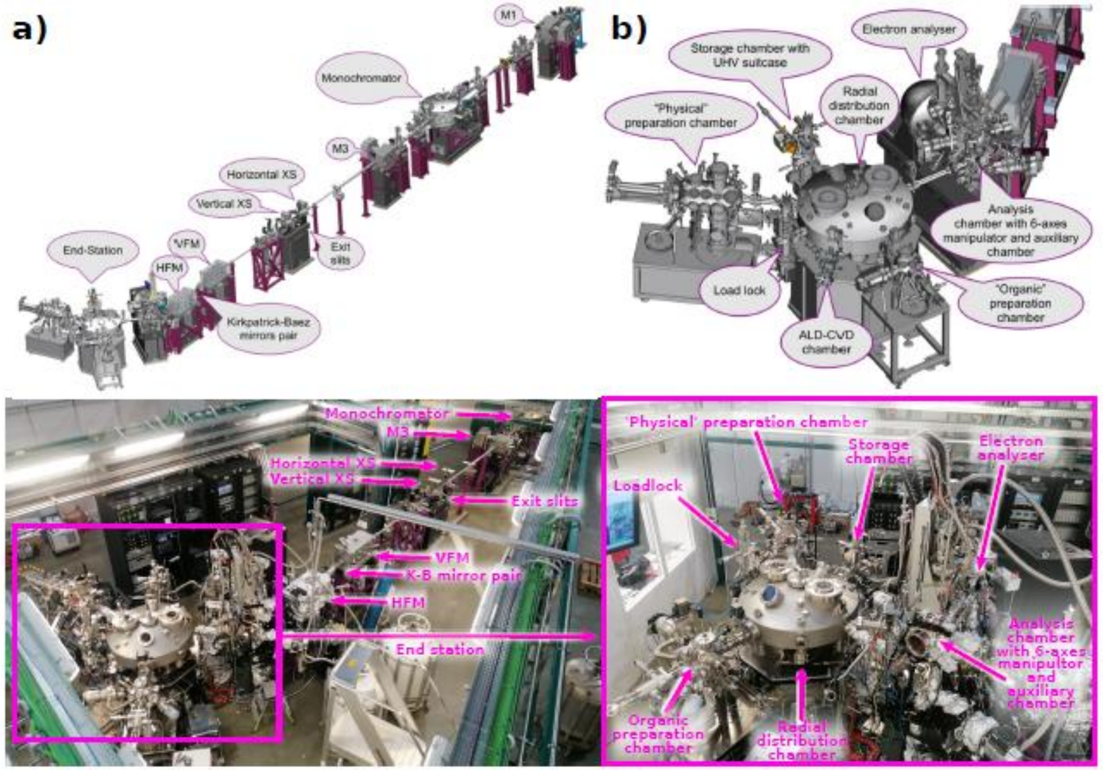
Experimental Methods

- **Bulk single crystal**

Er (Dy) impurities deposited by means of an e-beam evaporator.

- XPS and ARPES performed at a **T = 15 K**
- **Exfoliated in-situ** (UHV) at T = 15 K
- **Linear horizontal** polarization with **hν = 100** (XPS) and **52** (ARPES) **eV**

LOREA beamline (ALBA synchrotron)



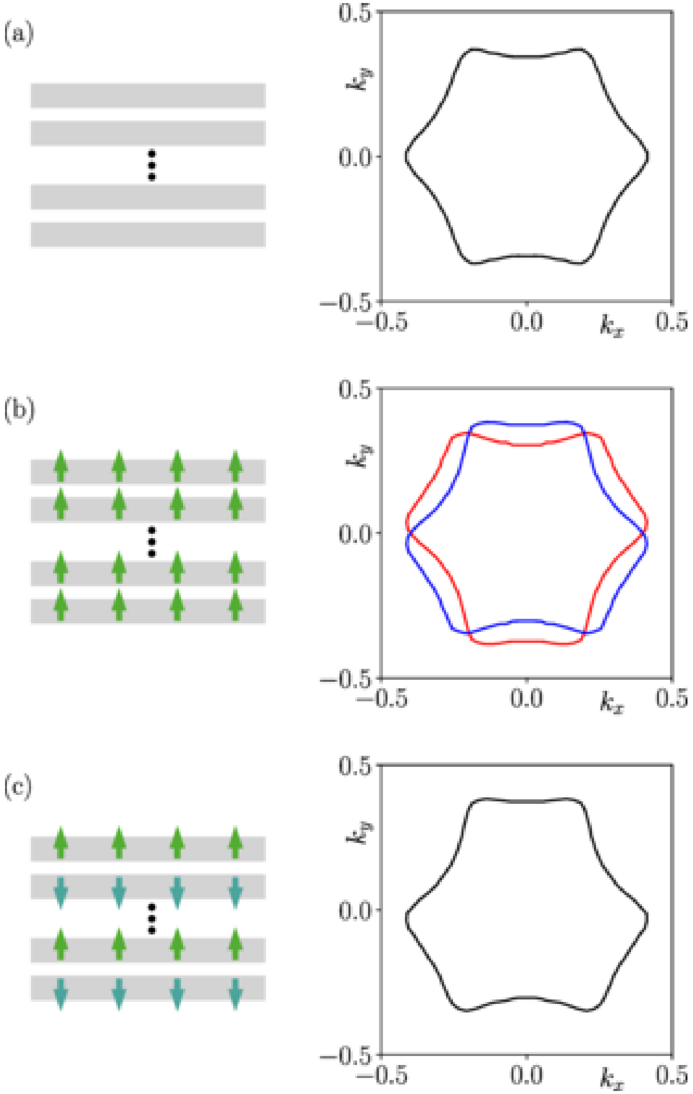
B. Muñiz Cano PhD thesis

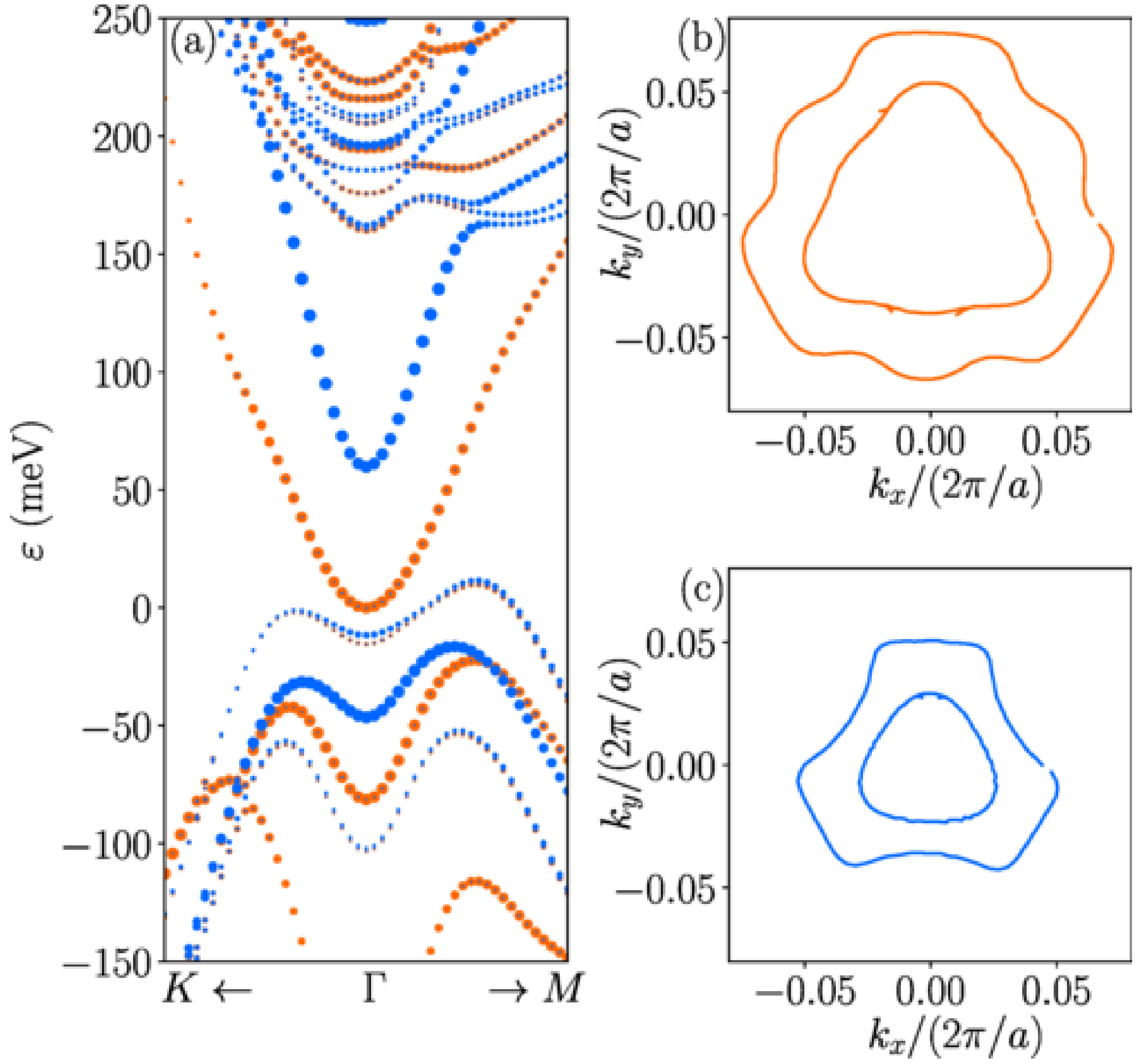
Analyser:
- MBS hemispherical analyser
- Resolution better than 1 meV and 0.1º
- Fast Fermi Surface mapping mode
- Recently added spin detector

Cryo-manipulator:
- 6-axes of movement.
- Allows reaching temperatures lower than 7.5 K

B. Muñiz Cano et al., Nano Letters *Nano Lett.* 2023, 23, 13, 6249

Magnetic warping in $MnBi_{2n}Te_{3n+1}$ family

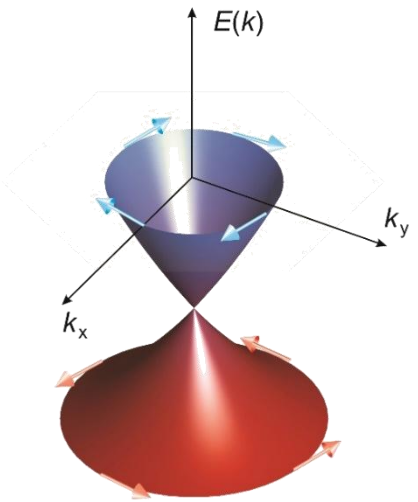




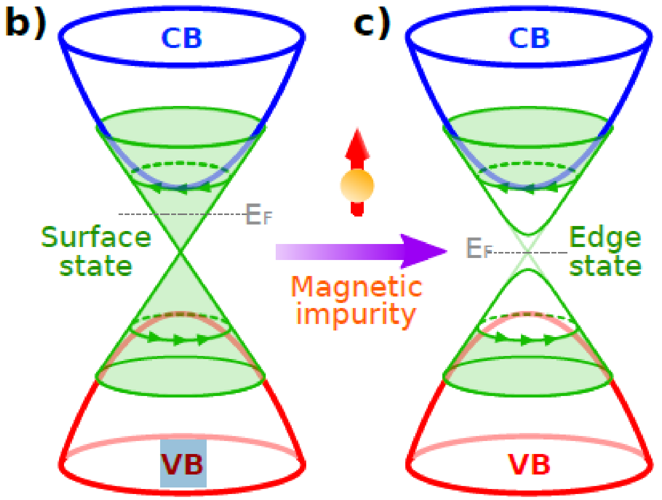
Magnetic doping in topological insulators. Realization of QAHE

Topological surface states (TSS):

- Strong SOC ⇒ Band inversion ⇒ Bulk insulating + **Topological** protected **surface states**
- Dirac relativistic massless Fermions.
- Spin locked to the momentum.
- Topologically protected against back-scattering



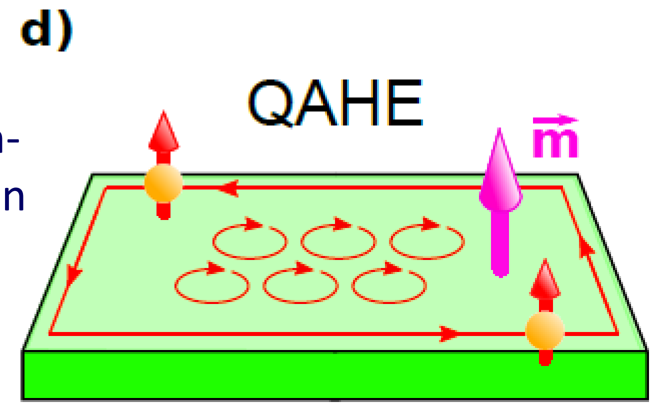
Out-of-plane magnetic moments break TRS symmetry



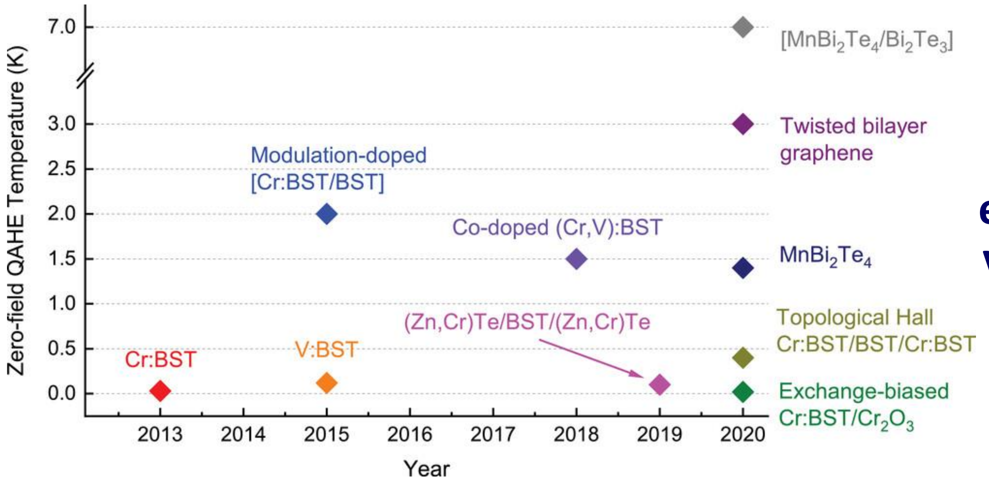
Gap opening at the DP
+
Tuning the gap at the Fermi Level
⇓
Realization of the QAHE

B. Muñiz Cano PhD thesis and references therein

QAHE: Purely dissipationless spin-polarized currents in the absence of a magnetic field



B. Muñiz Cano PhD thesis and references therein

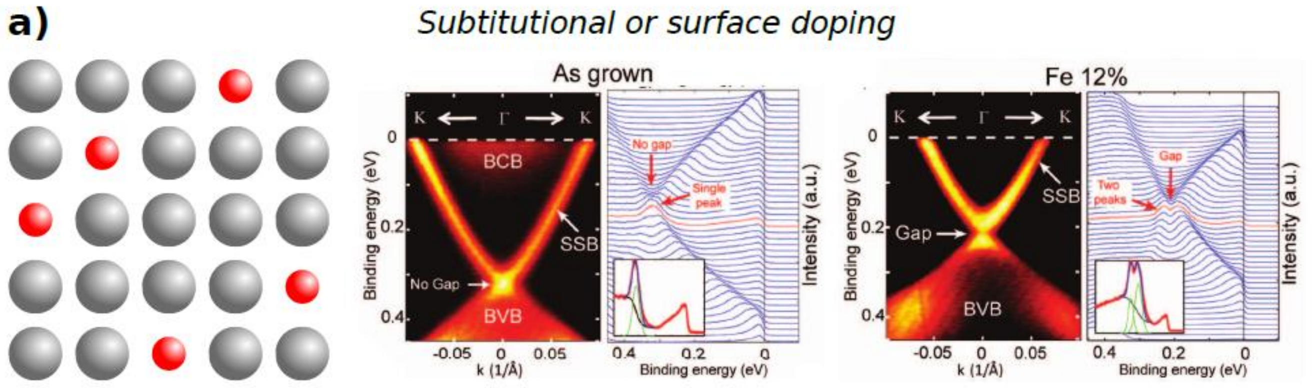


Advanced Materials, 35(27):2102427, 2021

QAHE: Very challenging experimentally. Very extreme T conditions

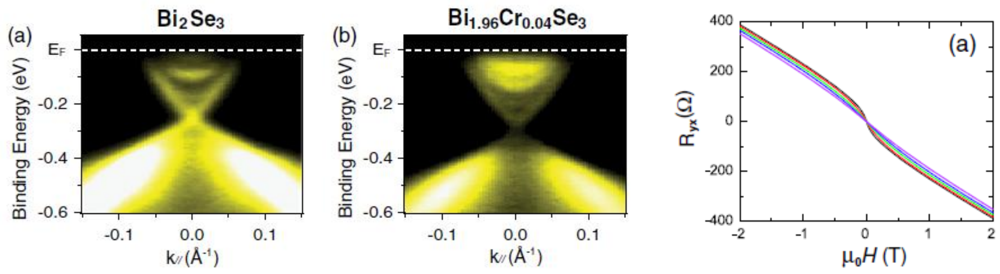
Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Magnetic doping strategies: Substitutional or surface doping 3d FM materials

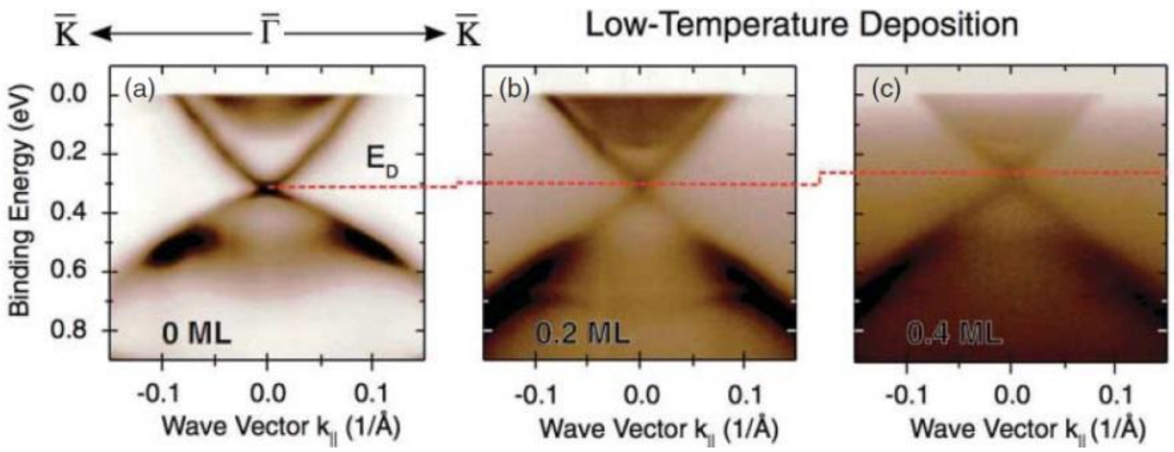


B. Muñiz Cano PhD thesis and references therein

Lack of correlation between gap opening and long-range FM order development



Xue PRL 2014



Advances in Physics . Dirac Materials 2014

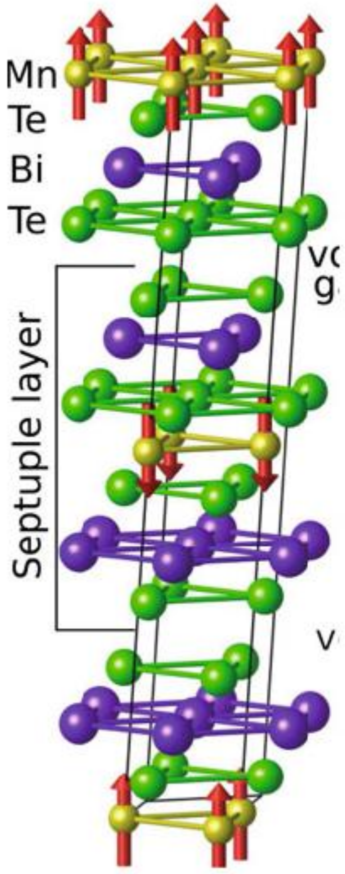
- Multiple adsorption sites. Lack of control of adsorption sites.
- Clustering and inhomogeneities.
- Lack of control of the magnetic anisotropy

Lack of experimental reproducibility

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Magnetic doping strategies: Magnetic extension or proximity coupling to magnetic layers

Mn Bi,Sb Te septuple layer structure



Out-of-plane AFM coupling between Mn adjacent layers

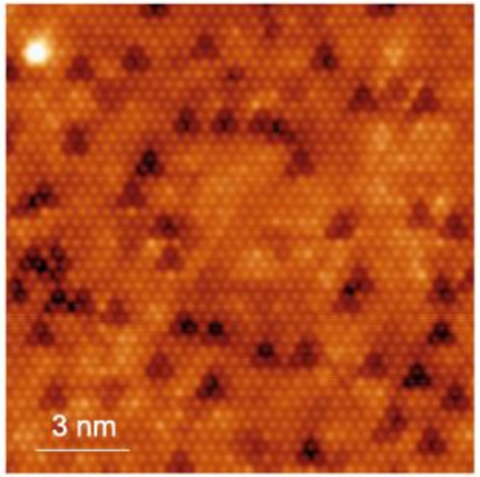
Prediction and observation of an antiferromagnetic topological insulator

Otrokov, M. M.et al. Nature **2019**, 576, 416–422

Large magnetic gap at the Dirac point in $Bi_2Te_3/MnBi_2Te_4$ heterostructures

Rienks, E. D. et al. Nature **2019**, 576, 423–428

Defects concentration can drastically alter the electronic properties and magnetic order

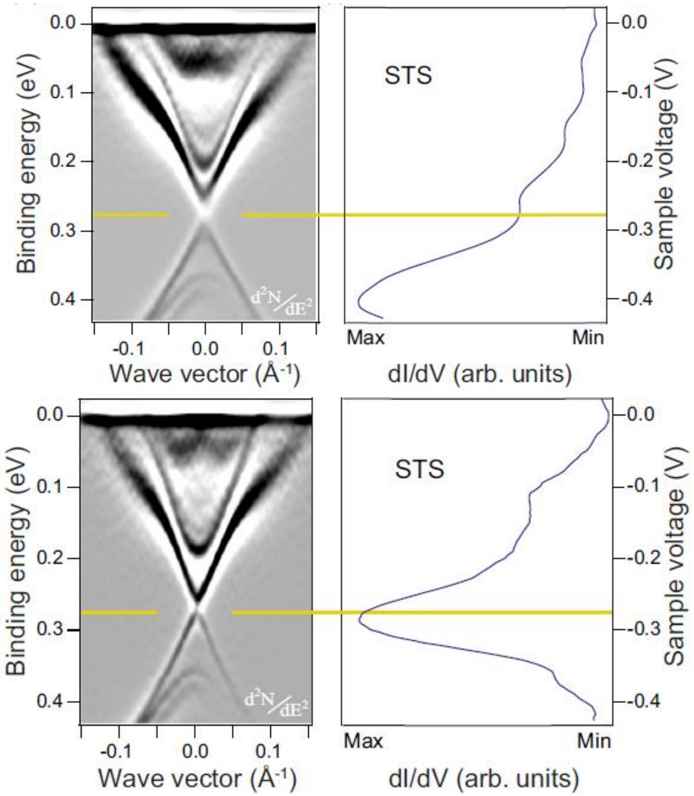


Garnica, M. et al. Npj Quant. Mat. **2022**, 7, 1–9

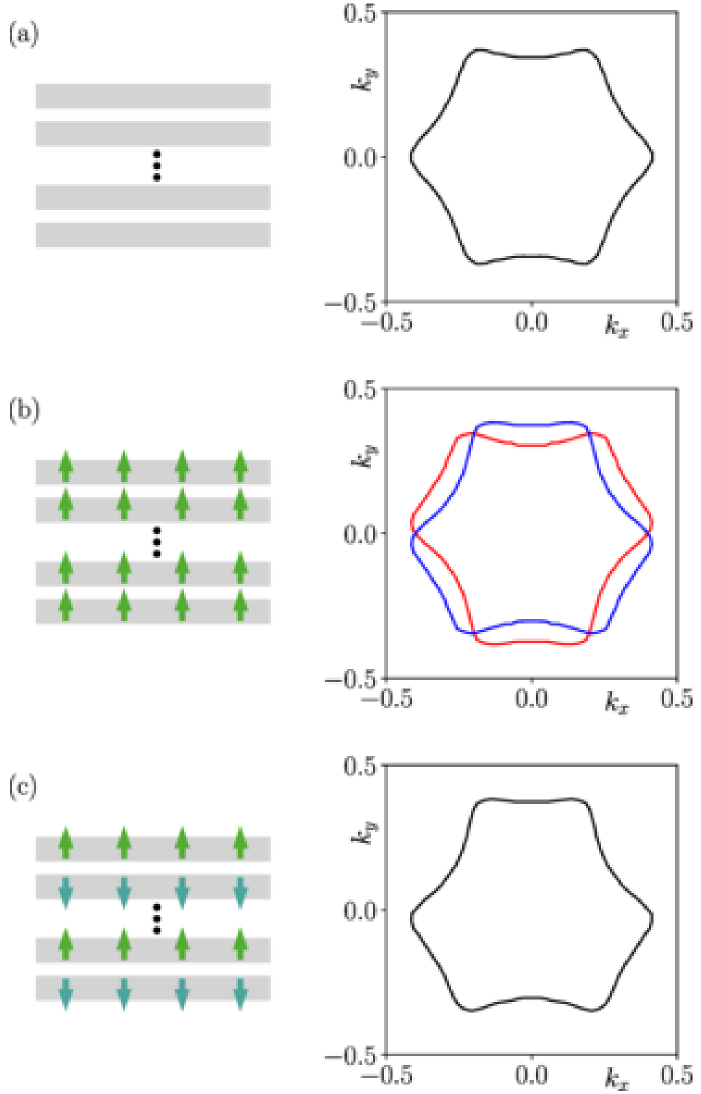
Rely on sophisticated and complex growing methods: Defect concentration is crucial

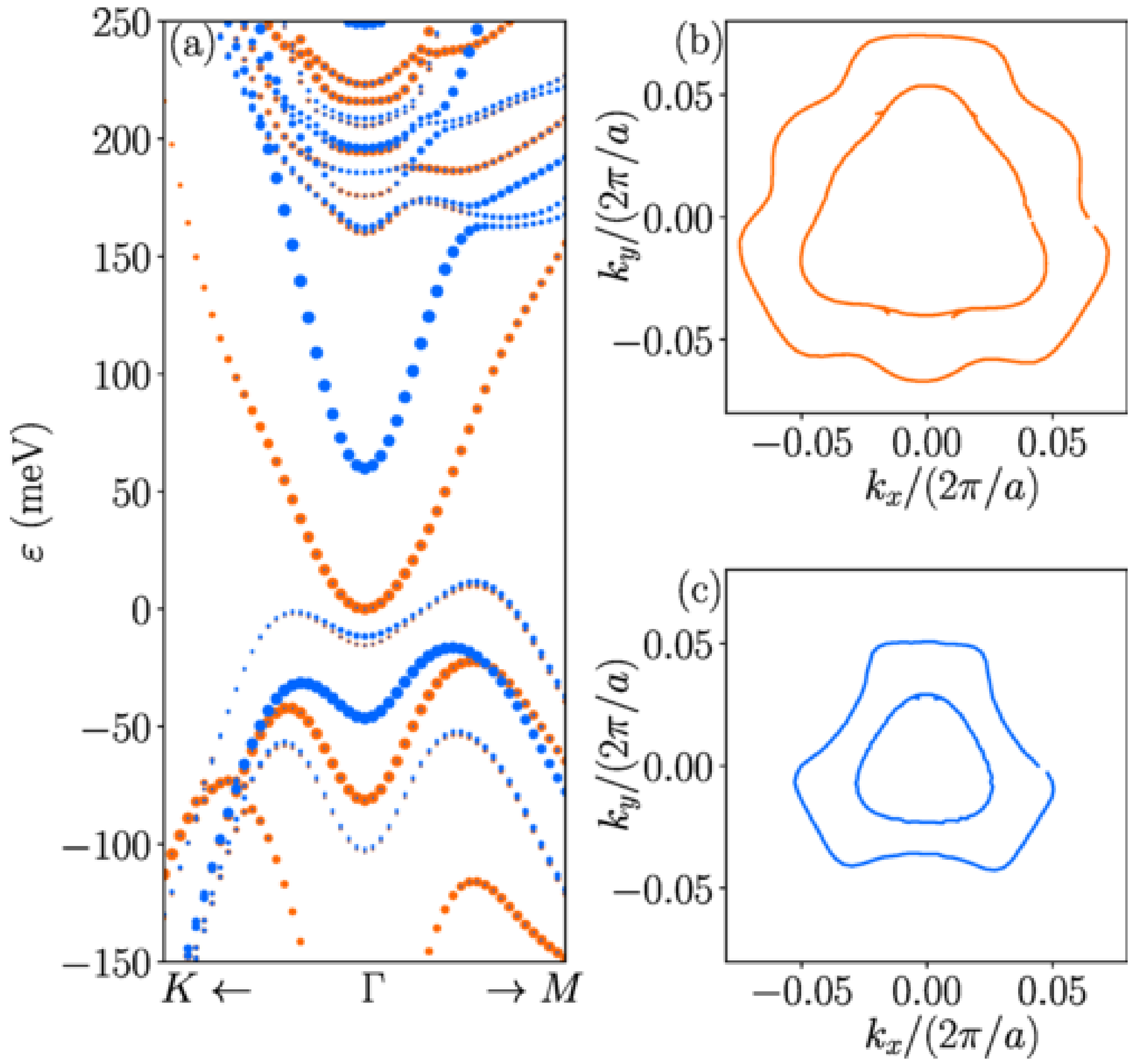
Large gap

Small gap



Magnetic warping in $MnBi_{2n}Te_{3n+1}$ family

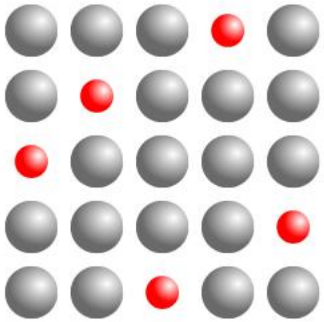




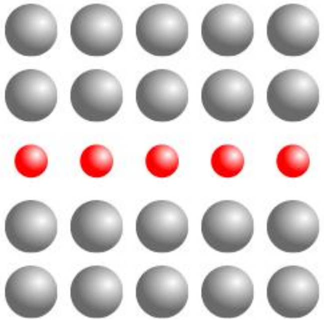
Phys. Rev. Research **4**, 033198 (2022)

Magnetic impurities in Topological Insulators

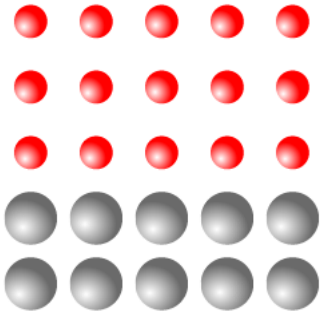
Surface doping



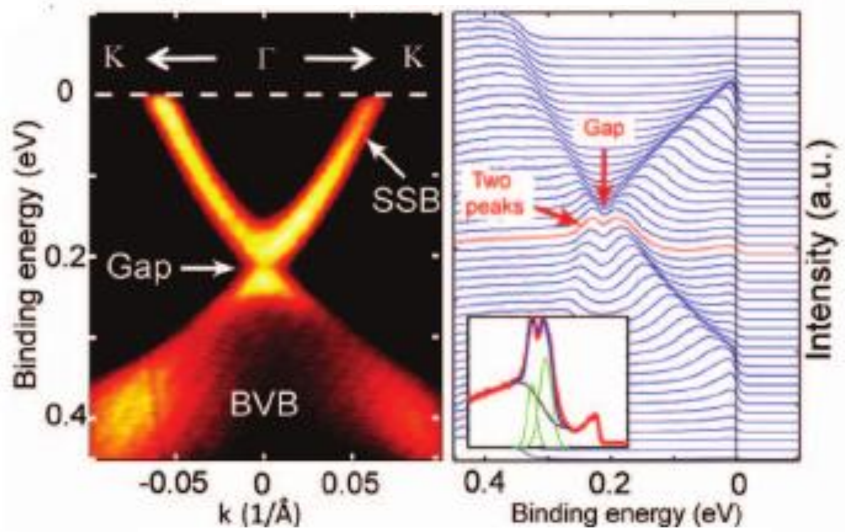
Magnetic extension



Proximity to magnetic layers

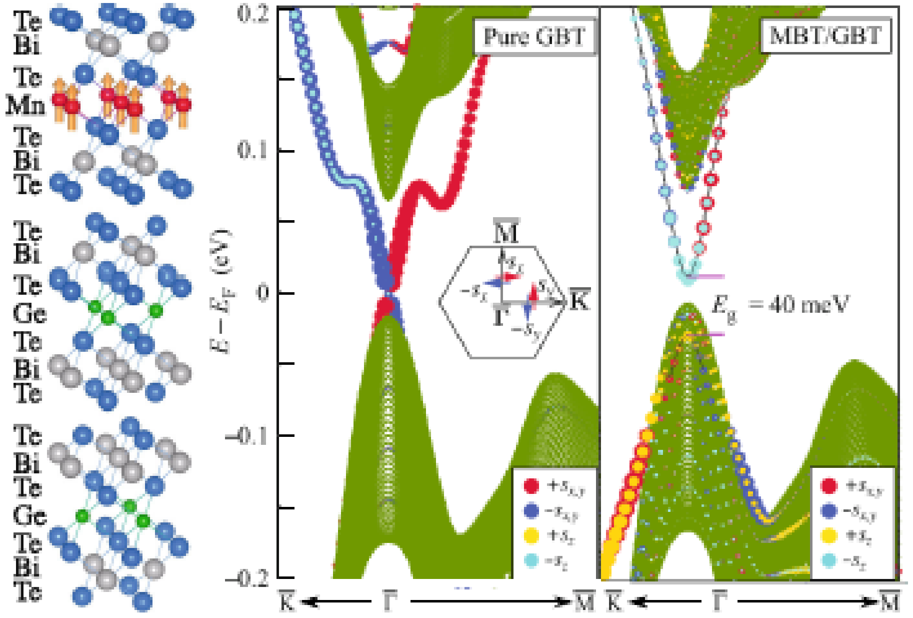


Fe-doped Bi_2Se_3



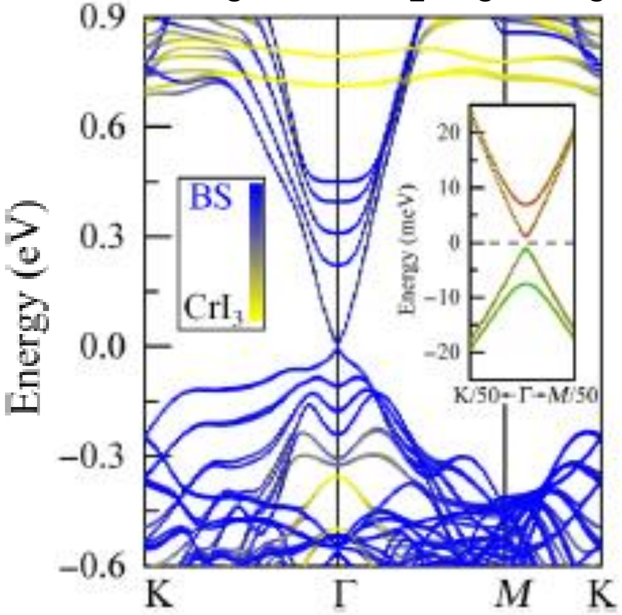
Science **329**, 659 (2010)

$MnBi_2Te_4$



JETP Letters **105,** 297 (2017)

CrI_3/5QL-Bi_2Se_3 /CrI_3

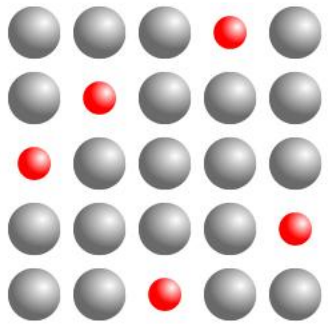


Sci. Adv. **5**, eaaw1874 (2019)

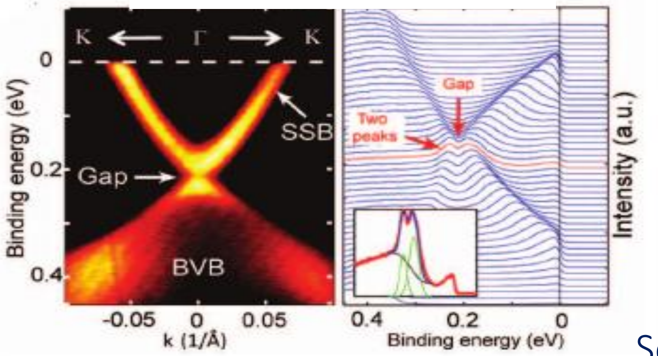
PhD thesis Beatriz Muñiz Cano

Magnetic doping strategies

Surface doping



Fe-doped Bi_2Se_3

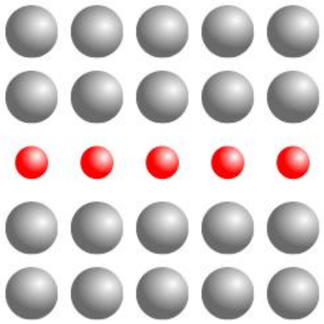


- Multiple adsorption sites.
- Clustering and inhomogeneities.
- Lack of control of the magnetic anisotropy

Science **329**, 659 (2010)

Lack of experimental reproducibility

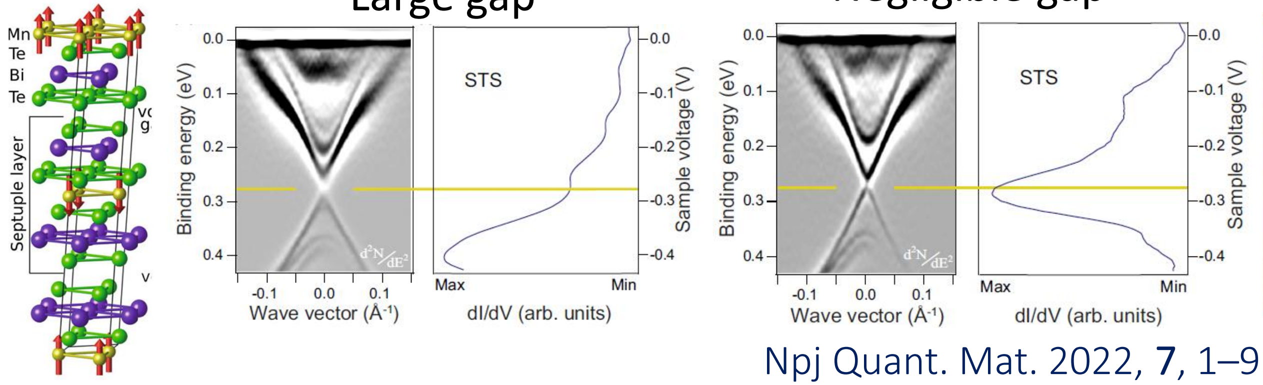
Magnetic extension

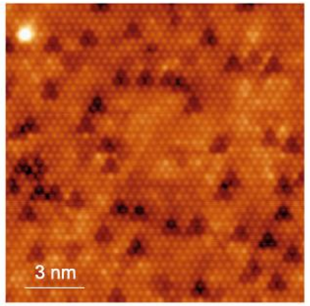


$MnBi_2Te_4$

Large gap

Negligible gap

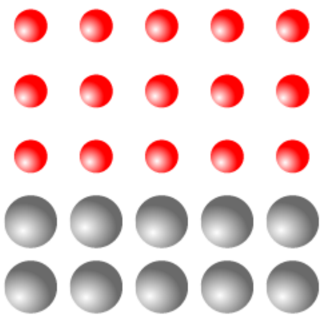




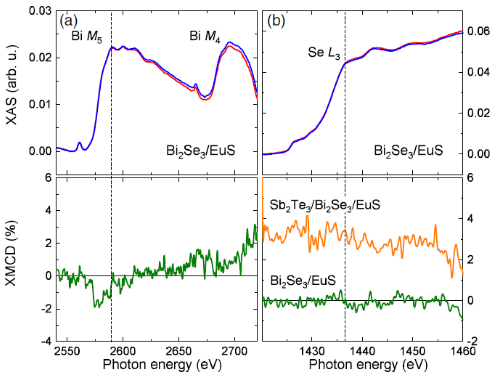
Defects concentration can drastically alter the electronic properties and magnetic order

Npj Quant. Mat. 2022, **7**, 1–9

Proximity to magnetic layers



EuS/TIs



Neither significant induced magnetism within the TI nor an enhancement of the Eu magnetic moment

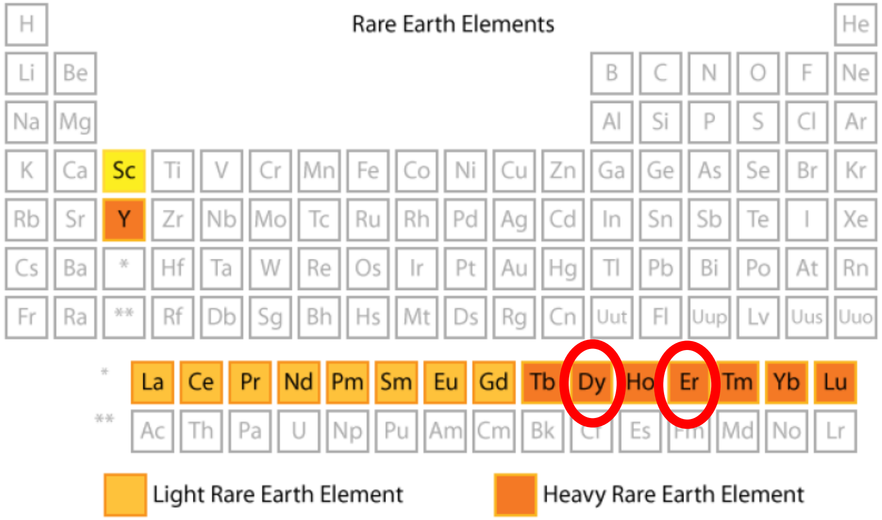
PRL **125**, 226801 (2020)

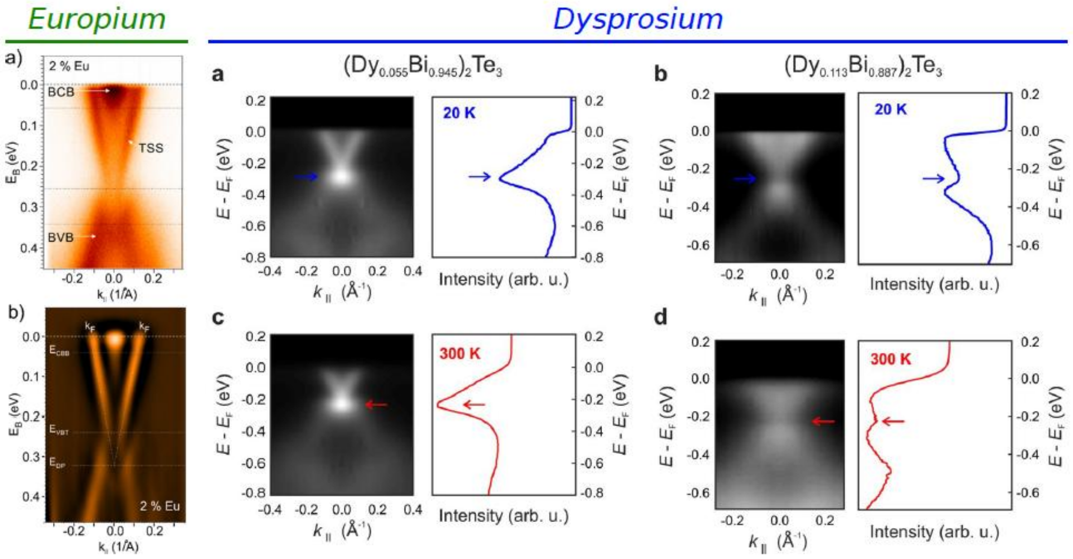
Rely on sophisticated and complex growing methods: Defect concentration is crucial

Experimental Demonstration of a Magnetically Induced Warping Transition in a Topological Insulator Mediated by Rare-Earth Surface Dopants

Rare-Earths as magnetic surface dopants in topological insulator substrates

- **Larger size** → prevents from substitutional sites → reduced the multiplicity of adsorption configurations
- Unpaired 4f electrons → **large magnetic moments** → enhanced magnetic anisotropy and allow a lower doping concentration and eventually maximize gap opening
- Curie temperatures as high as 80K
  - Previous results on REs as **bulk substitutional dopants** on Tis showed contradictory and non-conclusive results.





B. Muñiz Cano PhD thesis and references therein