Experimental demonstration of a magnetically induced warping transition in a topological insulator mediated by rare-earth surface dopants

Beatriz Muñiz Cano

Spin-ARPES Laboratory, IMDEA Nanociencia, Madrid, Spain

AUSE Meeting 2024

Muñiz Cano, B., et al. *Nano Lett*. **2023**, 23, 13, 6249–6258

Introduction: topological insulators (TIs)

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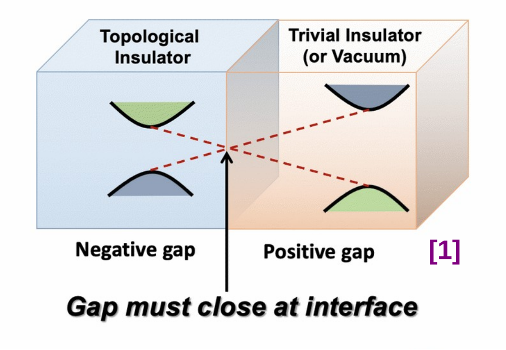

- Topological insulators (TIs) → bulk insulators + **conducting linearly dispersing Dirac edge (surface) states**

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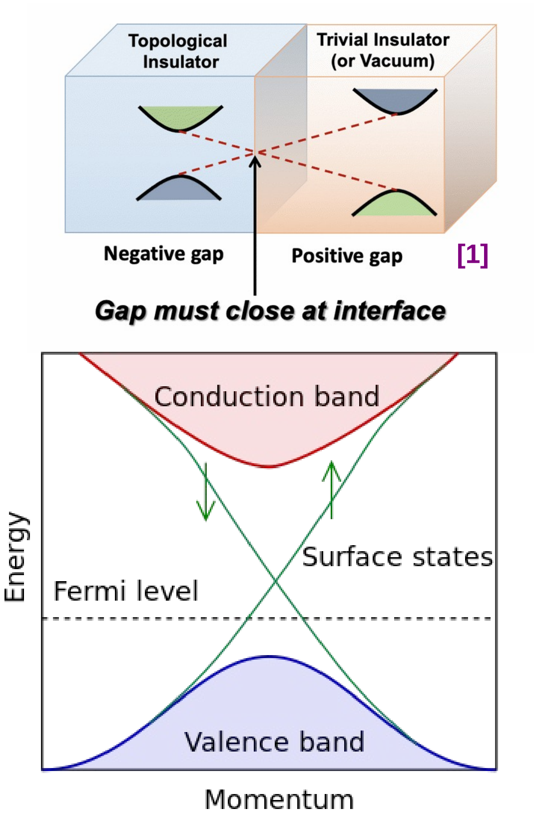

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- **Surface states** (SS) are **topologically protected by time-reversal symmetry** (TRS) → topological SS (**TSS**)

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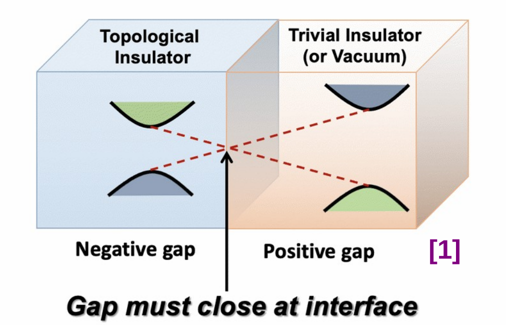

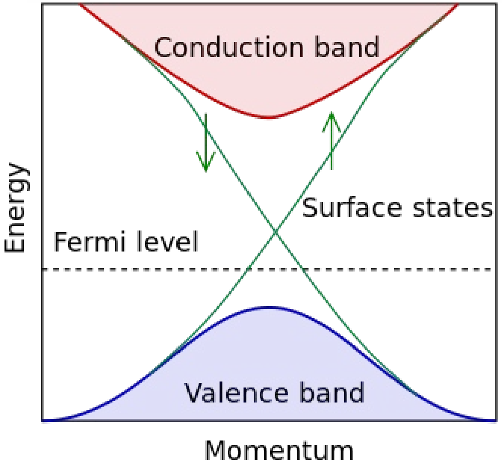

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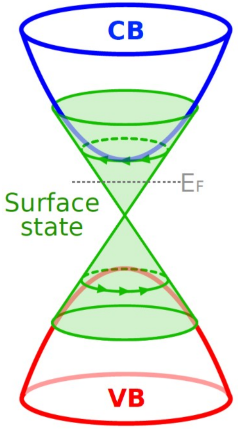

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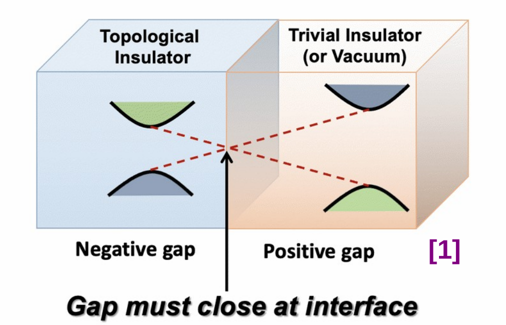

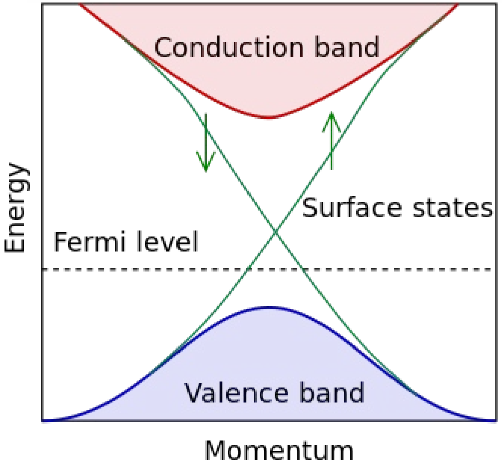

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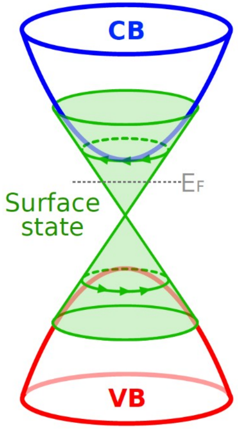

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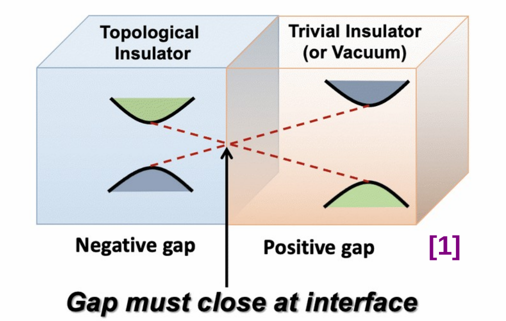

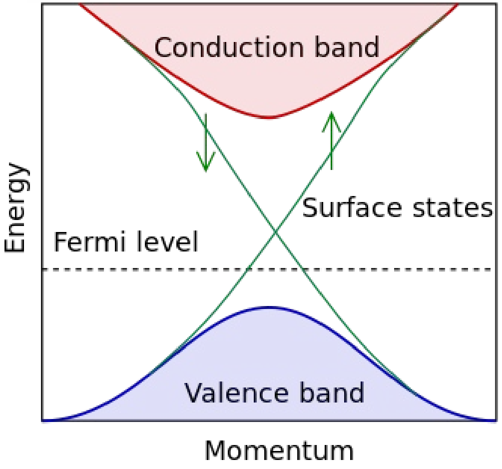

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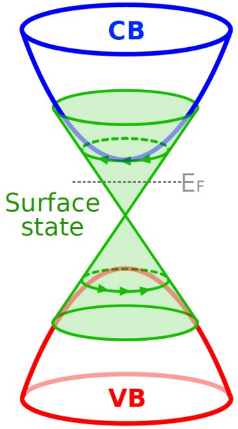
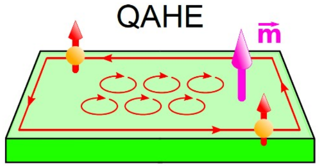


Disipationless spin-polarized currents
(insulating inside y conductive en el edge)



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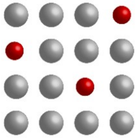

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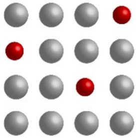

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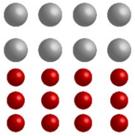

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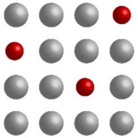

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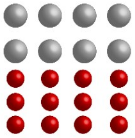

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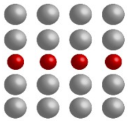

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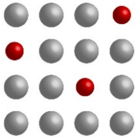

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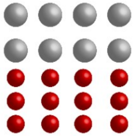

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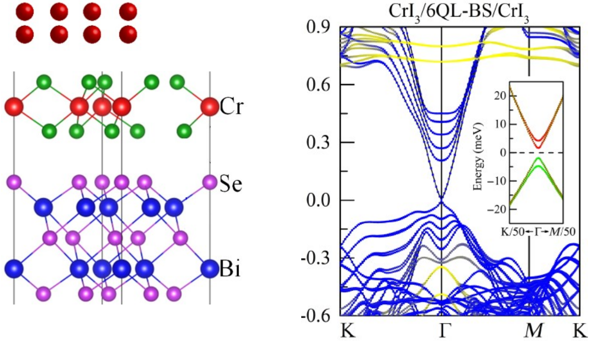

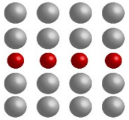

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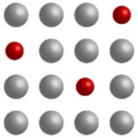

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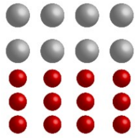

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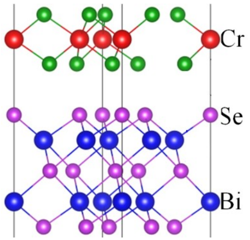

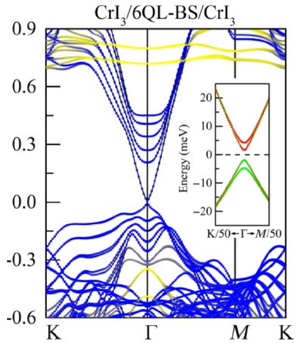

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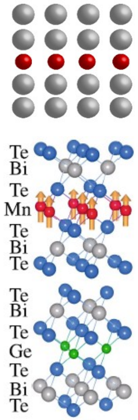

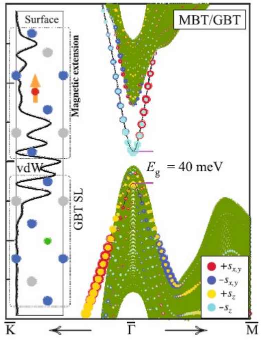

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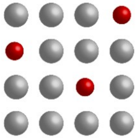

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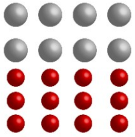

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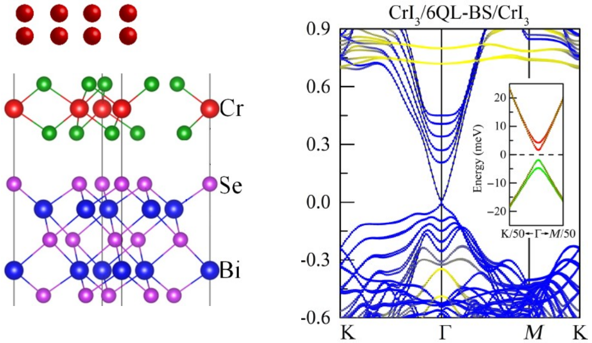

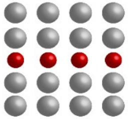

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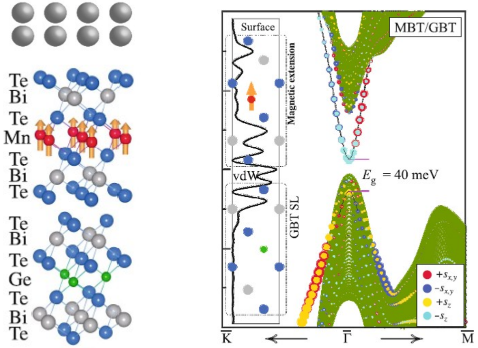

Prediction and observation of an antiferromagnetic topological insulator [5]

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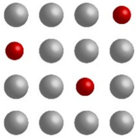

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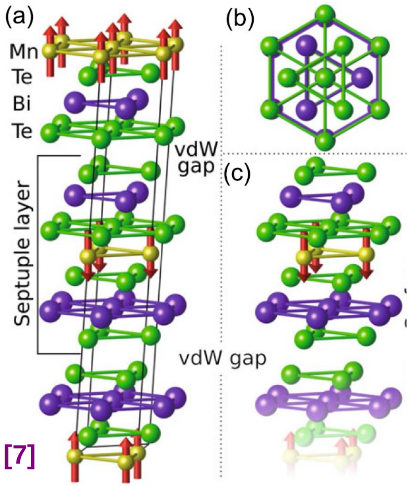

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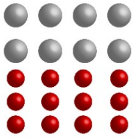

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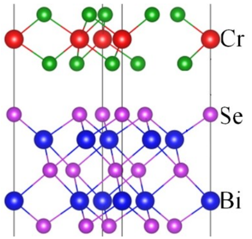

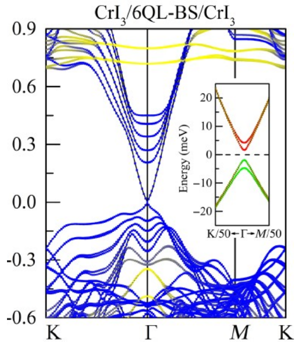

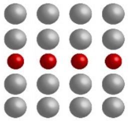

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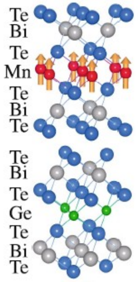

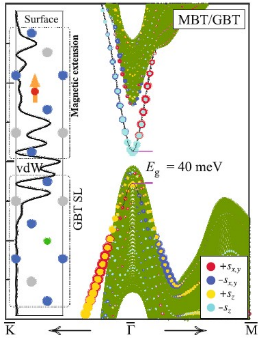

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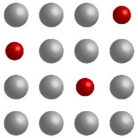

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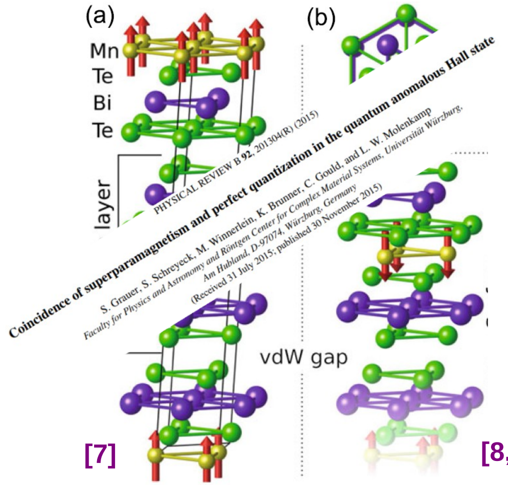

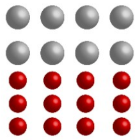

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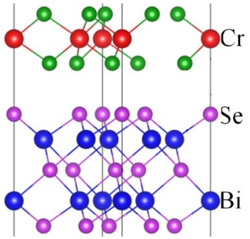

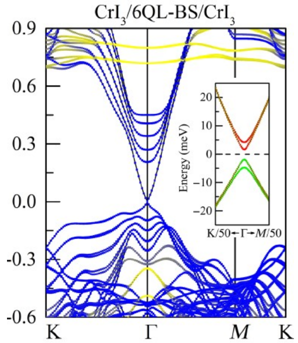

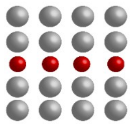

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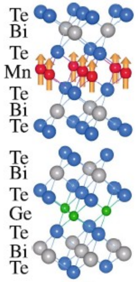

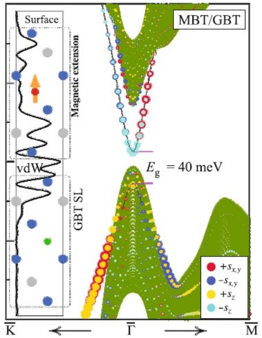

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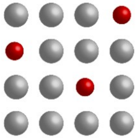

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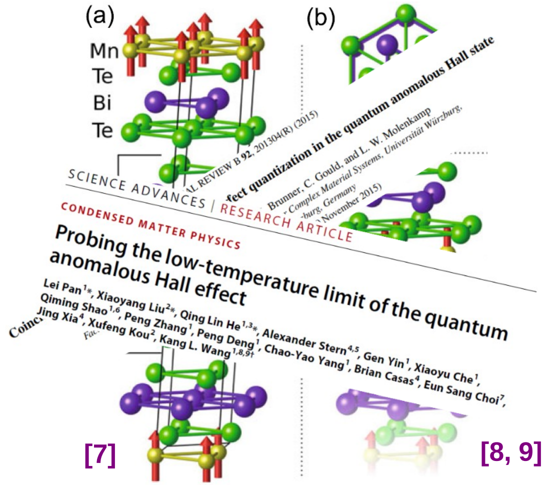

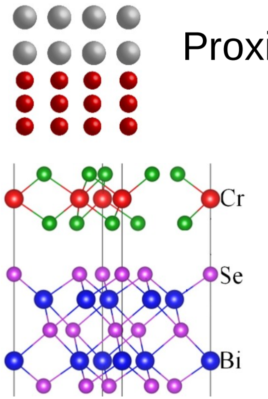

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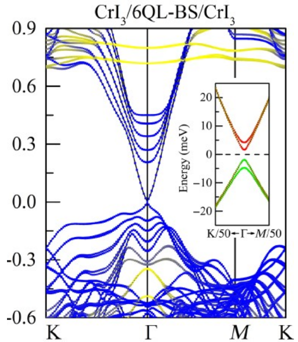

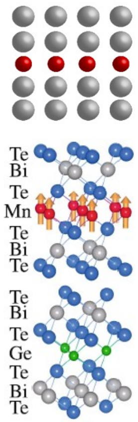

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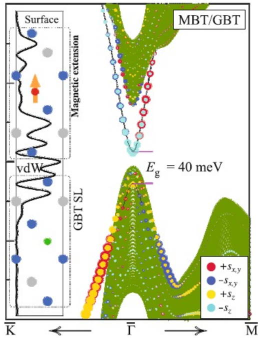

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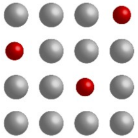

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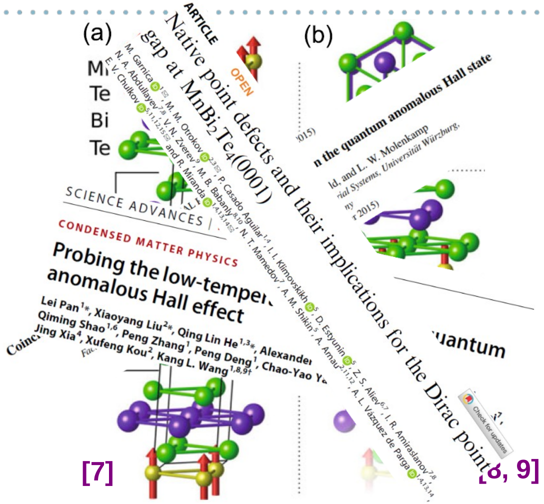

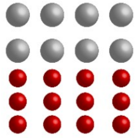

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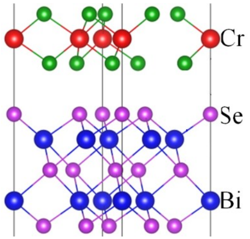

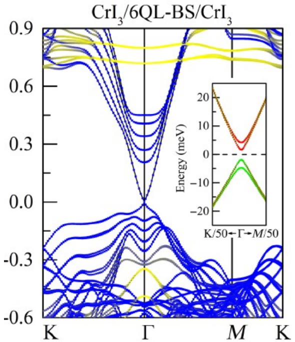

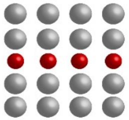

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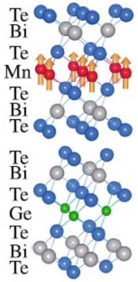

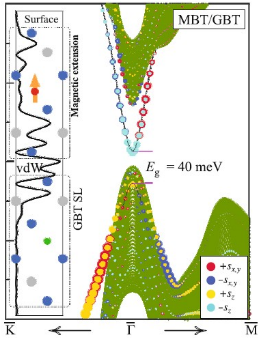

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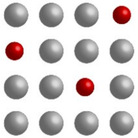

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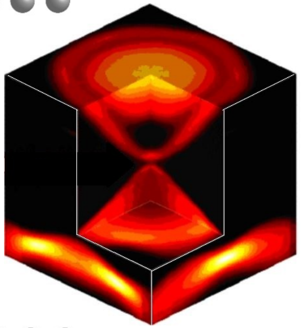

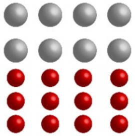

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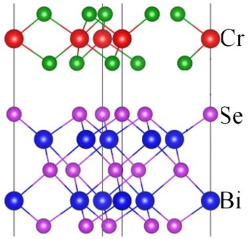

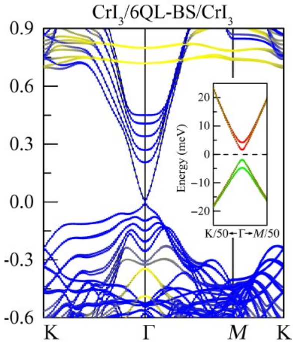

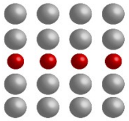

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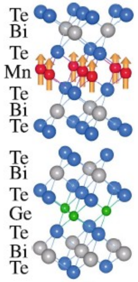

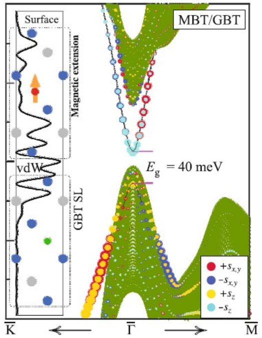

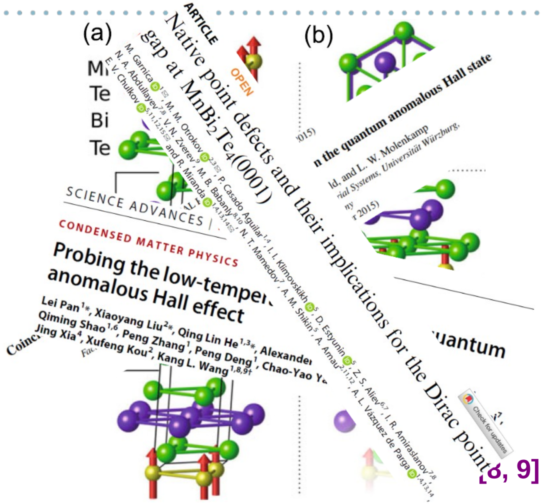

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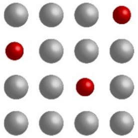

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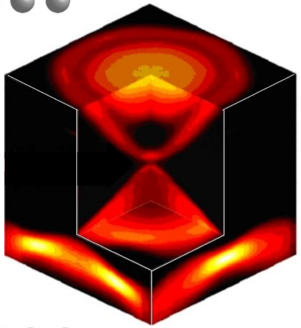

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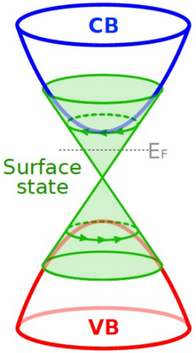

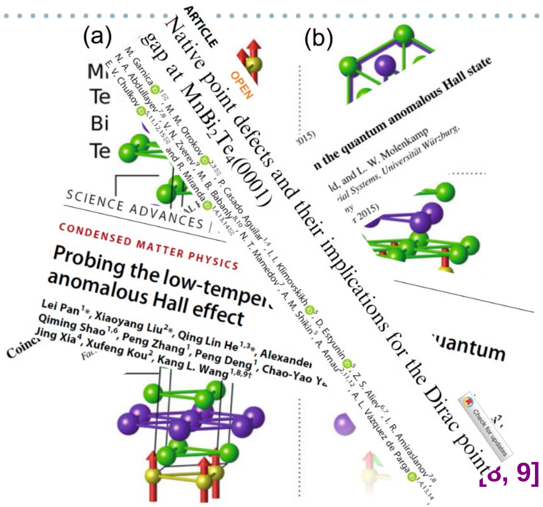

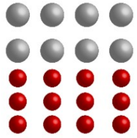

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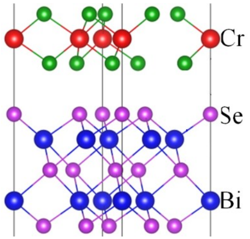

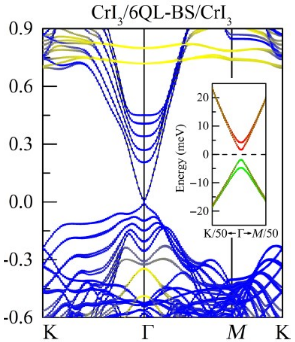

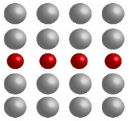

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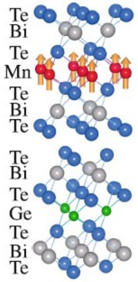

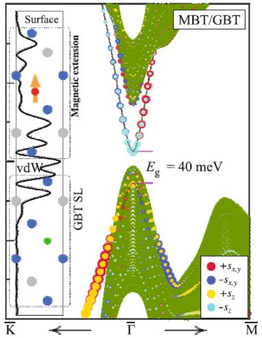

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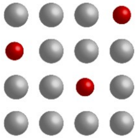

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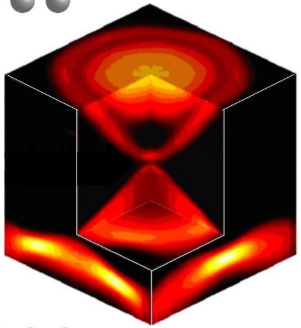

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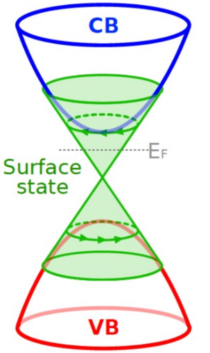

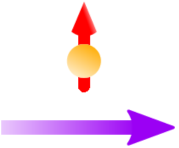

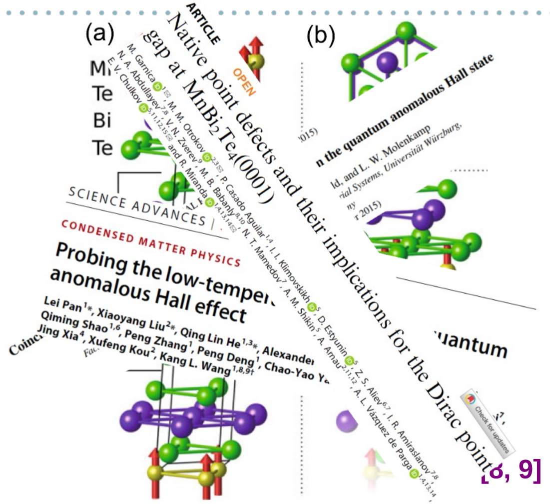

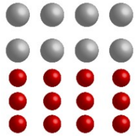

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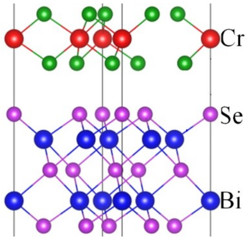

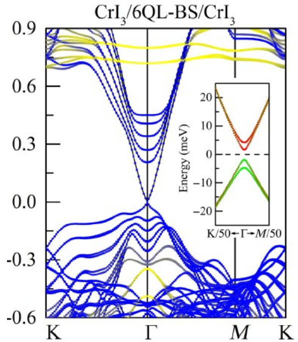

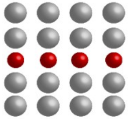

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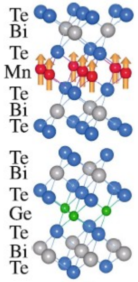

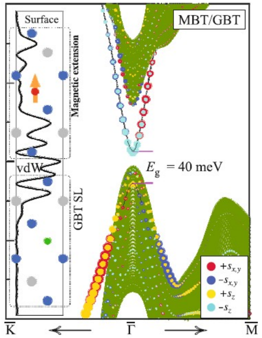

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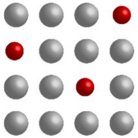

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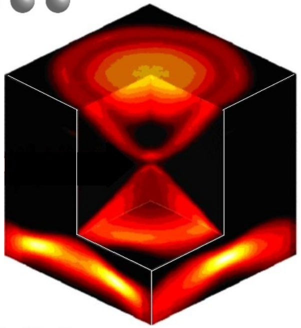

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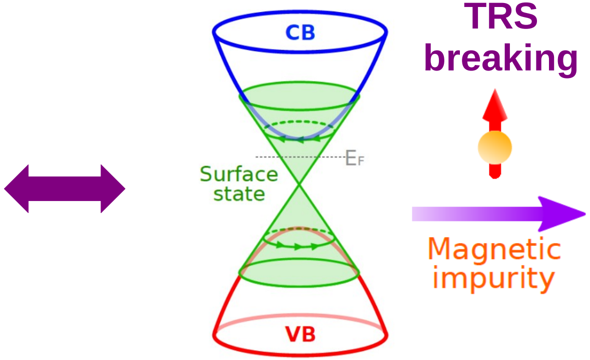

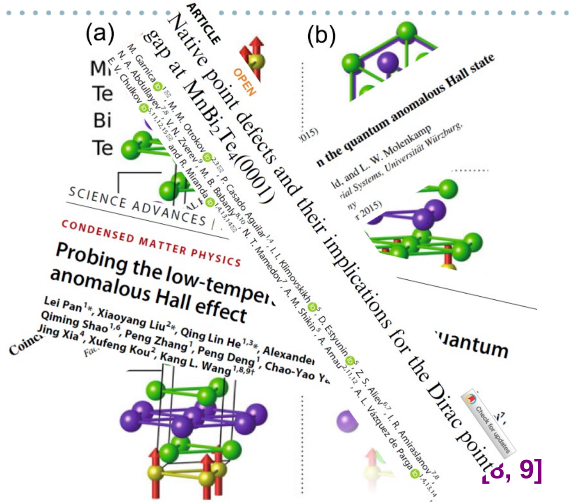

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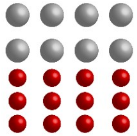

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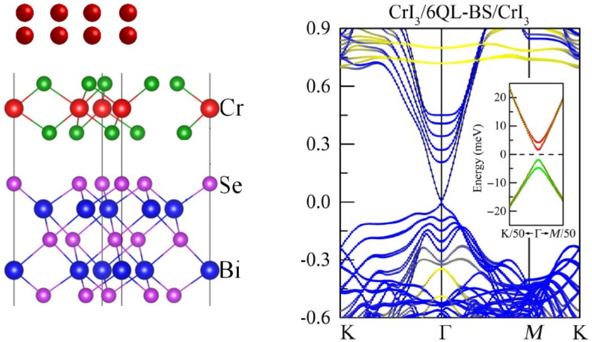

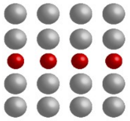

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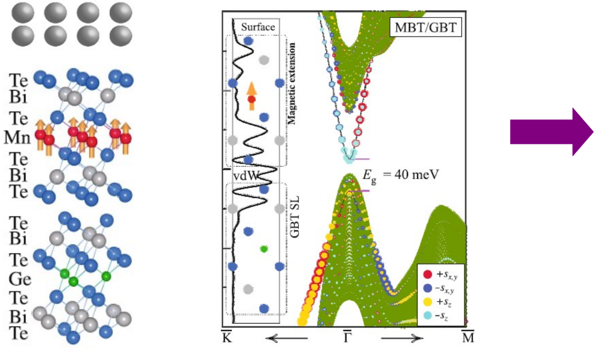

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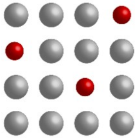

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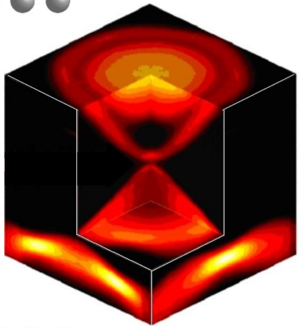

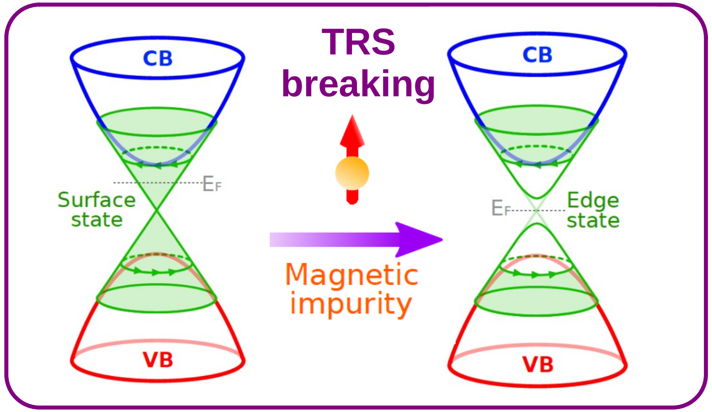

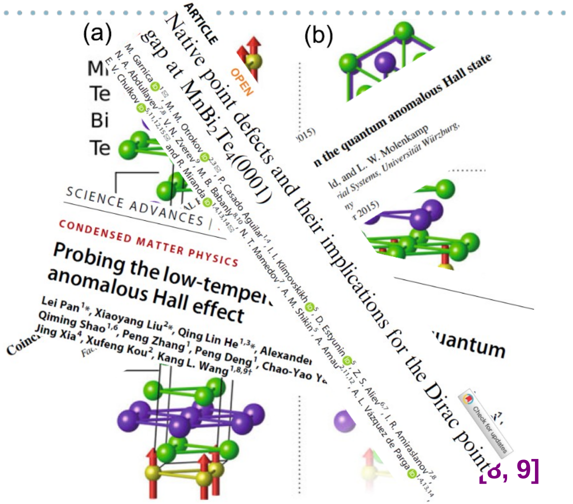

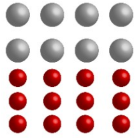

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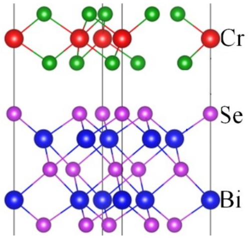

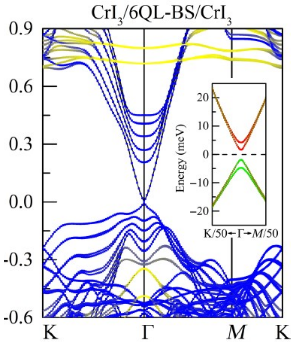

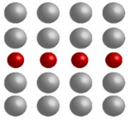

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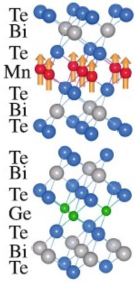

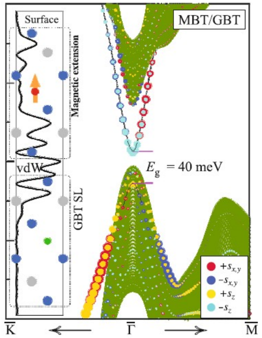

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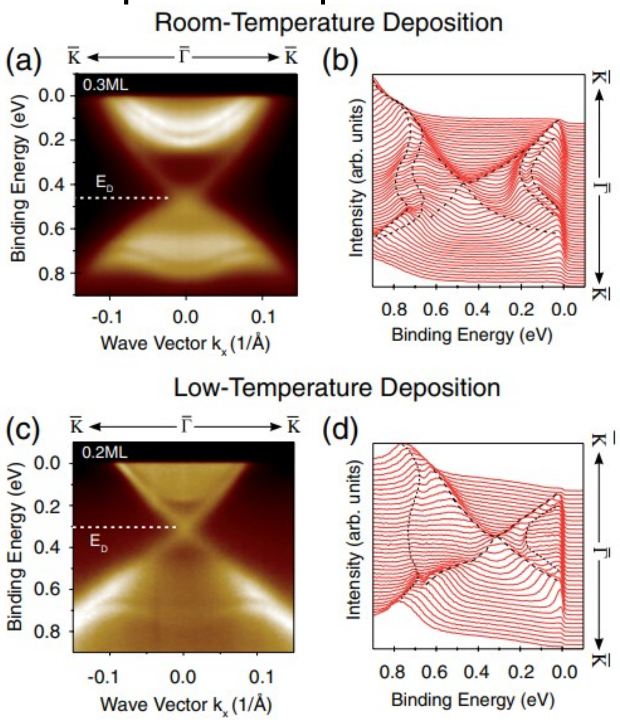

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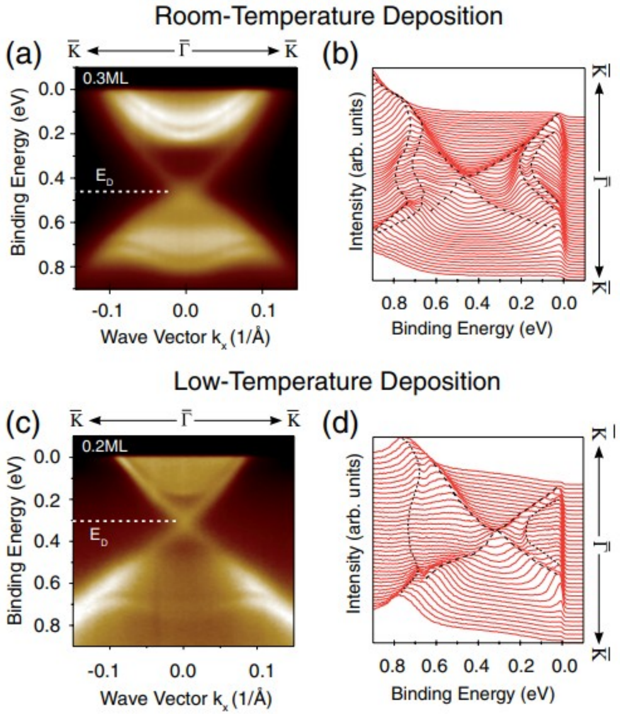
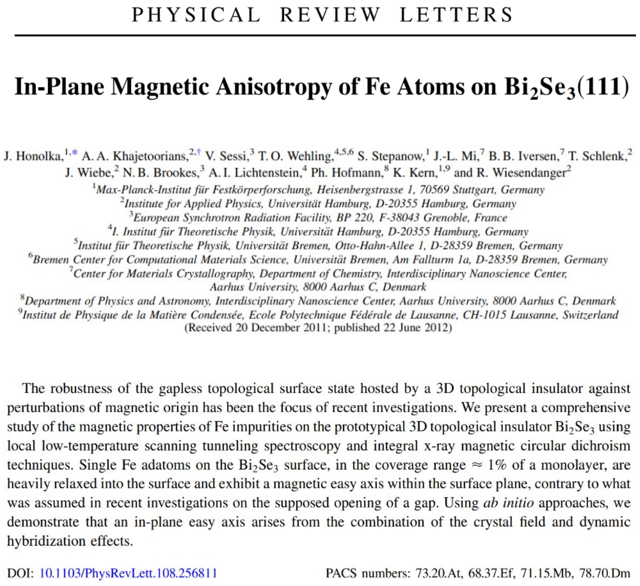


Strong surface relaxations [12]



PHYSICAL REVIEW LETTERS

In-Plane Magnetic Anisotropy of Fe Atoms on $Bi_2Se_3(111)$

J. Honolka,[1,*] A. A. Khajetoorians,[2,†] V. Sessi,[3] T. O. Wehling,[4,5,6] S. Stepanow,[1] J.-L. Mi,[7] B. B. Iversen,[7] T. Schlenk,[2] J. Wiebe,[2] N. B. Brookes,[3] A. I. Lichtenstein,[4] Ph. Hofmann,[8] K. Kern,[1,9] and R. Wiesendanger[2]

[1]*Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany*
[2]*Institute for Applied Physics, Universität Hamburg, D-20355 Hamburg, Germany*
[3]*European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble, France*
[4]*I. Institut für Theoretische Physik, Universität Hamburg, D-20355 Hamburg, Germany*
[5]*Institut für Theoretische Physik, Universität Bremen, Otto-Hahn-Allee 1, D-28359 Bremen, Germany*
[6]*Bremen Center for Computational Materials Science, Universität Bremen, Am Fallturm 1a, D-28359 Bremen, Germany*
[7]*Center for Materials Crystallography, Department of Chemistry, Interdisciplinary Nanoscience Center, Aarhus University, 8000 Aarhus C, Denmark*
[8]*Department of Physics and Astronomy, Interdisciplinary Nanoscience Center, Aarhus University, 8000 Aarhus C, Denmark*
[9]*Institut de Physique de la Matière Condensée, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*
(Received 20 December 2011; published 22 June 2012)

The robustness of the gapless topological surface state hosted by a 3D topological insulator against perturbations of magnetic origin has been the focus of recent investigations. We present a comprehensive study of the magnetic properties of Fe impurities on the prototypical 3D topological insulator Bi_2Se_3 using local low-temperature scanning tunneling spectroscopy and integral x-ray magnetic circular dichroism techniques. Single Fe adatoms on the Bi_2Se_3 surface, in the coverage range ≈ 1% of a monolayer, are heavily relaxed into the surface and exhibit a magnetic easy axis within the surface plane, contrary to what was assumed in recent investigations on the supposed opening of a gap. Using *ab initio* approaches, we demonstrate that an in-plane easy axis arises from the combination of the crystal field and dynamic hybridization effects.

DOI: 10.1103/PhysRevLett.108.256811 PACS numbers: 73.20.At, 68.37.Ef, 71.15.Mb, 78.70.Dm

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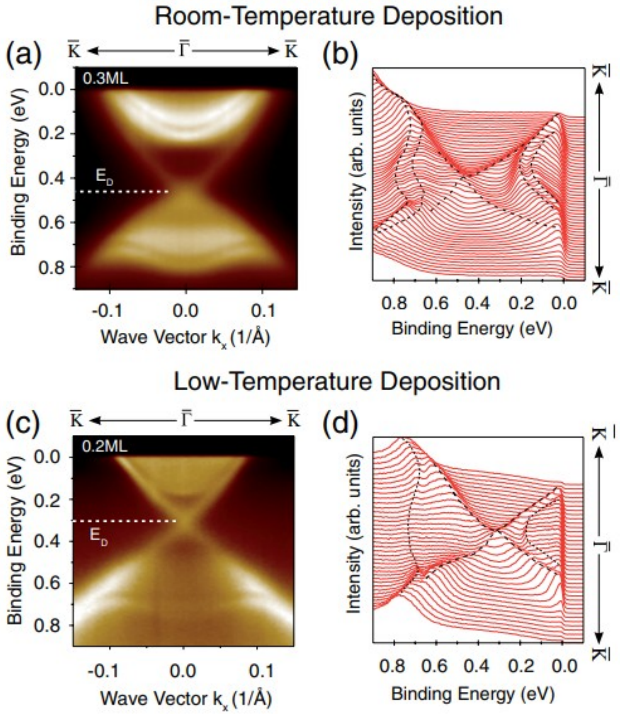

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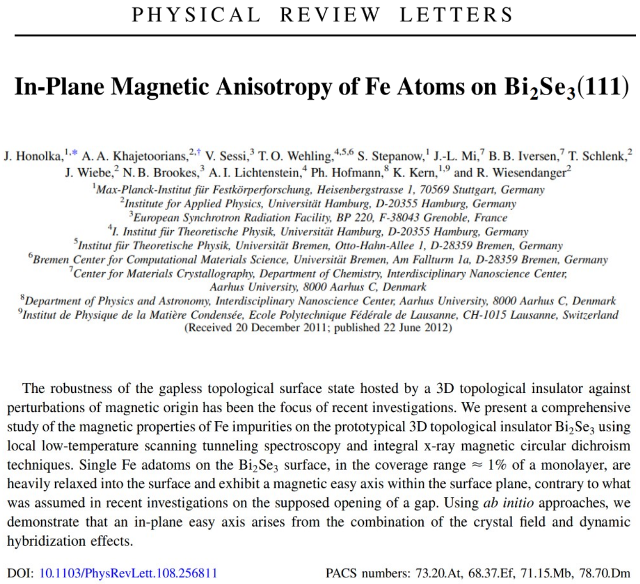
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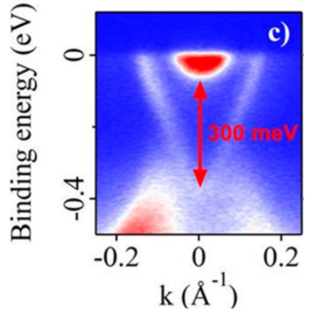
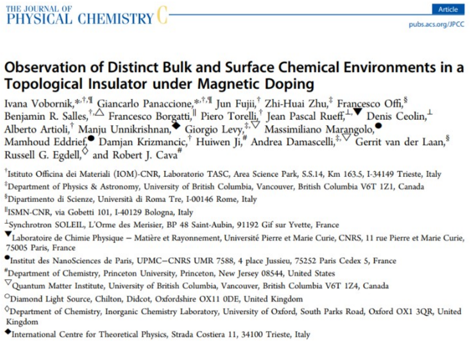
Bulk states doping [13]




THE JOURNAL OF PHYSICAL CHEMISTRY C — Article — pubs.acs.org/JPCC

Observation of Distinct Bulk and Surface Chemical Environments in a Topological Insulator under Magnetic Doping

Ivana Vobornik,*,†,¶ Giancarlo Panaccione,*,†,¶ Jun Fujii,† Zhi-Huai Zhu,‡ Francesco Offi,§ Benjamin R. Salles,†,△ Francesco Borgatti,‖ Piero Torelli,† Jean Pascal Rueff,⊥,▼ Denis Ceolin,⊥ Alberto Artioli,† Manju Unnikrishnan,◆ Giorgio Levy,‡,▽ Massimiliano Marangolo,● Mamhoud Eddrief,● Damjan Krizmancic,† Huiwen Ji,# Andrea Damascelli,‡,▽ Gerrit van der Laan,§ Russell G. Egdell,◇ and Robert J. Cava#

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●Institut des NanoSciences de Paris, UPMC–CNRS UMR 7588, 4 place Jussieu, 75252 Paris Cedex 5, France
#Department of Chemistry, Princeton University, Princeton, New Jersey 08544, United States
▽Quantum Matter Institute, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
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◇Department of Chemistry, Inorganic Chemistry Laboratory, University of Oxford, South Parks Road, Oxford OX1 3QR, United Kingdom
◆International Centre for Theoretical Physics, Strada Costiera 11, 34100 Trieste, Italy

[10] Gambardella, P. et al. Science, **2003**, 300(5622), 1130-1133. [11] Scholz, M. R. et al. Physical Review Letters, **2012**, 108(25), 256810. [12] Honolka, J. et al. Physical review letters, **2012**, 108(25), 256811. [13] Vobornik, I. Et al. The Journal of Physical Chemistry C, **2014**, 118(23), 12333-12339.

Introduction: rare-earth (RE) surface magnetic doping

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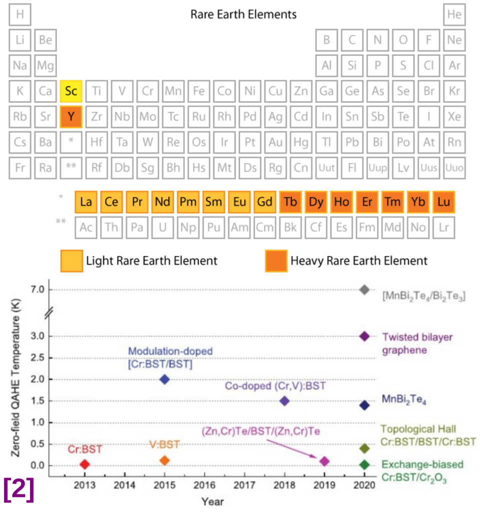

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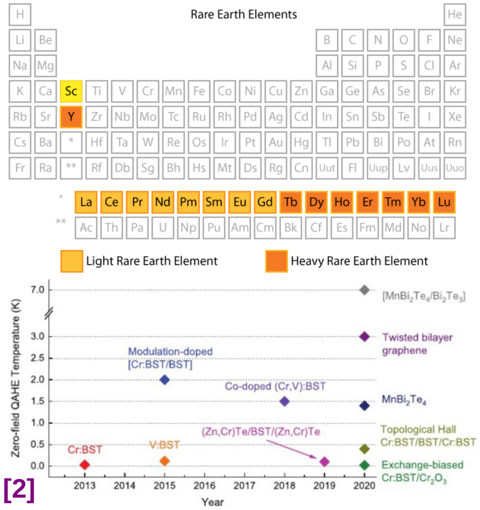

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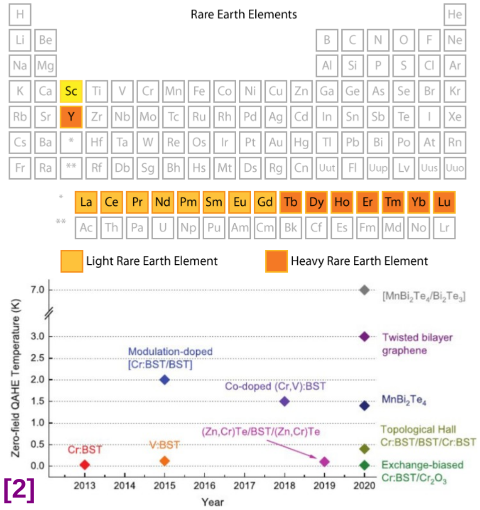

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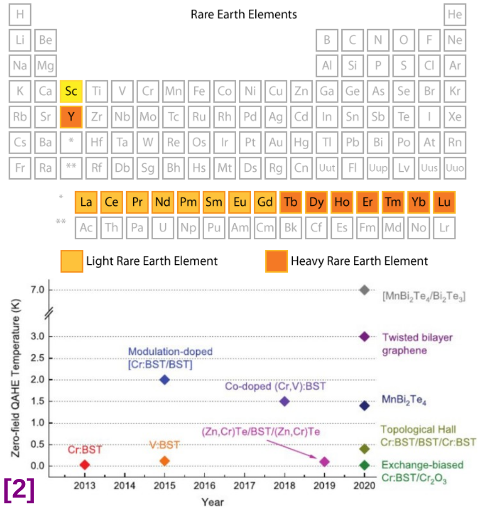

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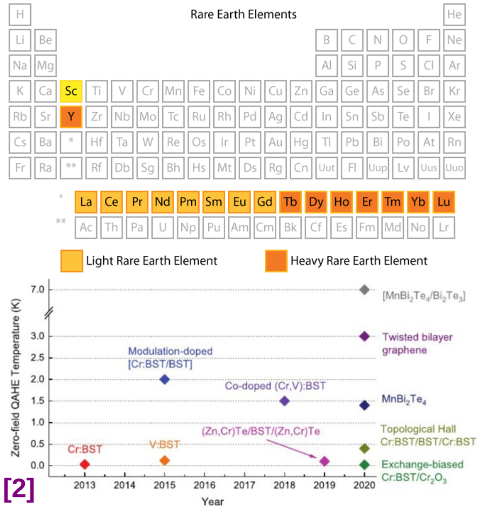

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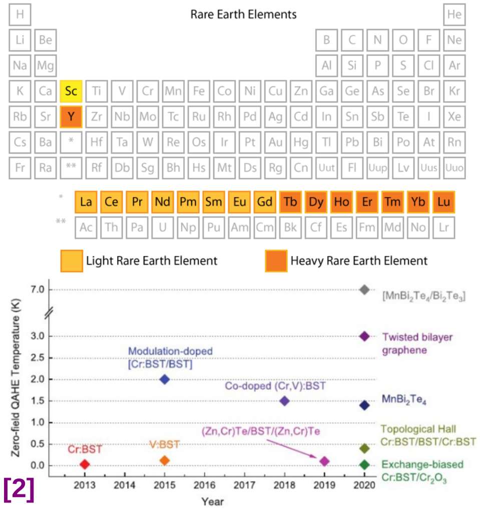

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Magnetic order in MTIs

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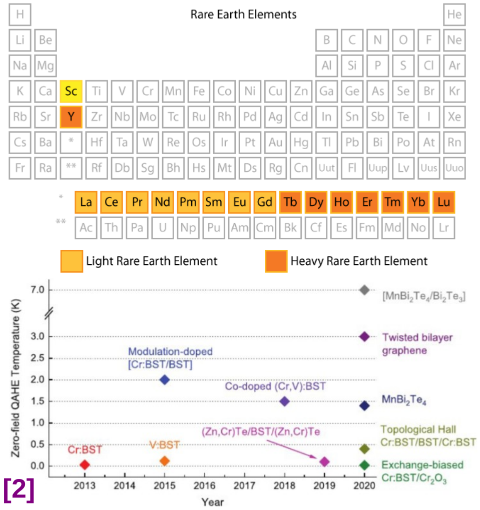

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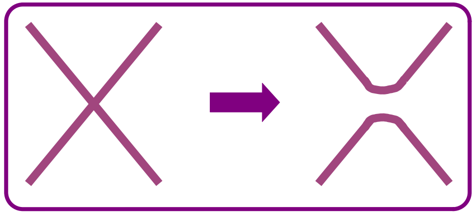

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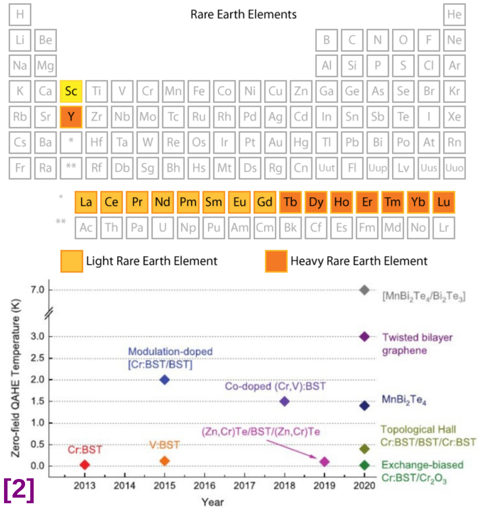

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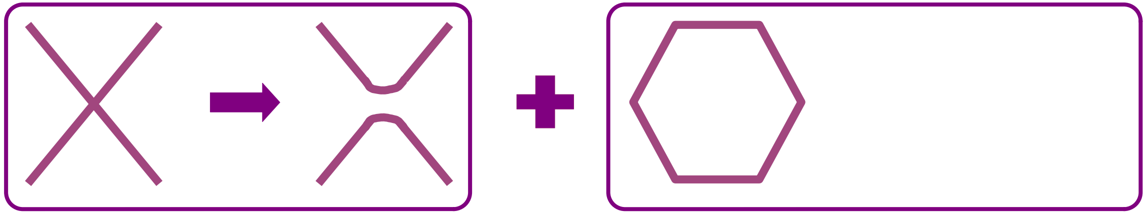

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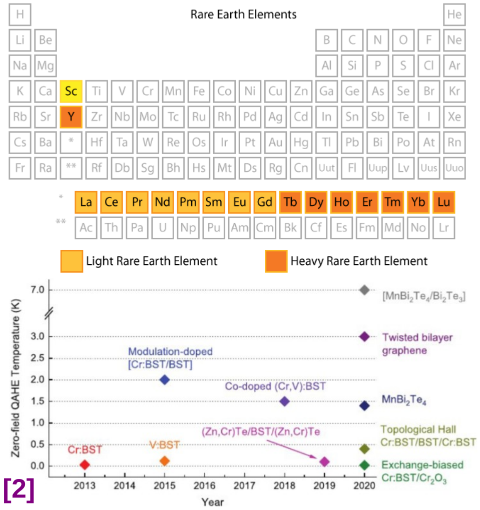

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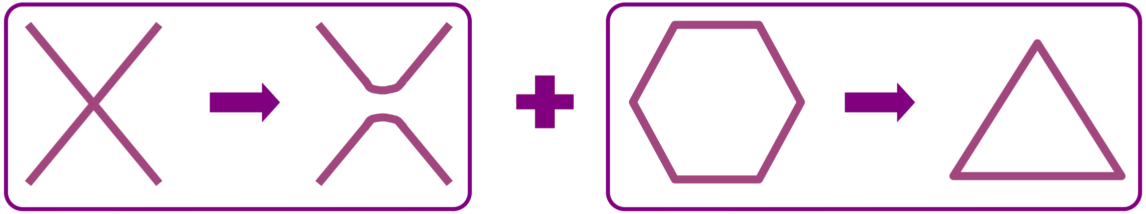

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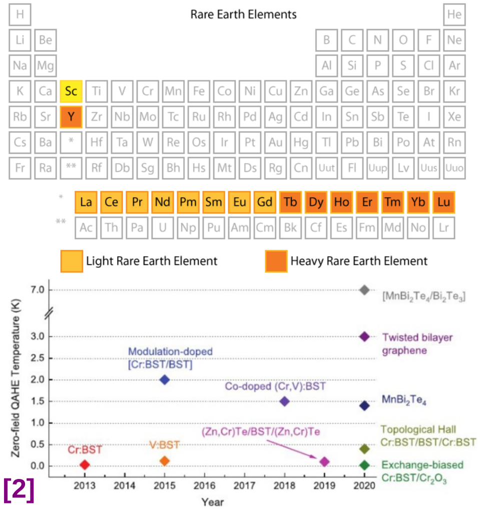

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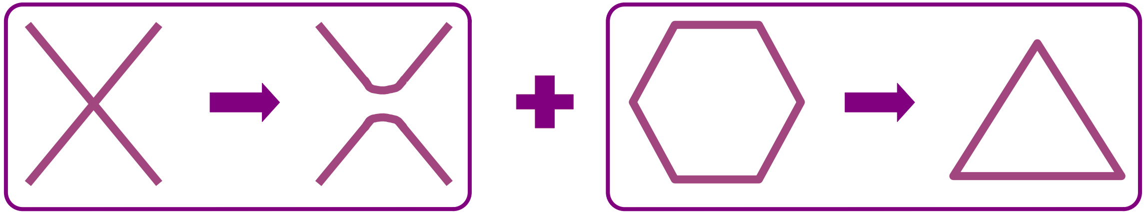

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Experimental methods

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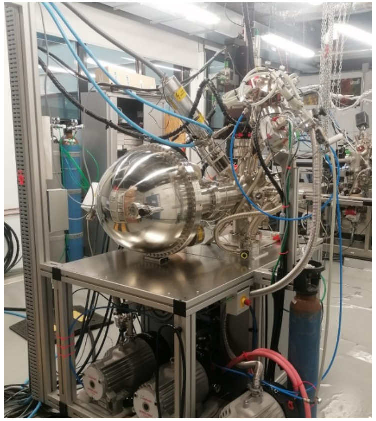

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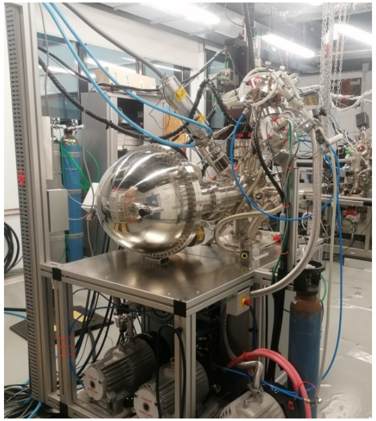
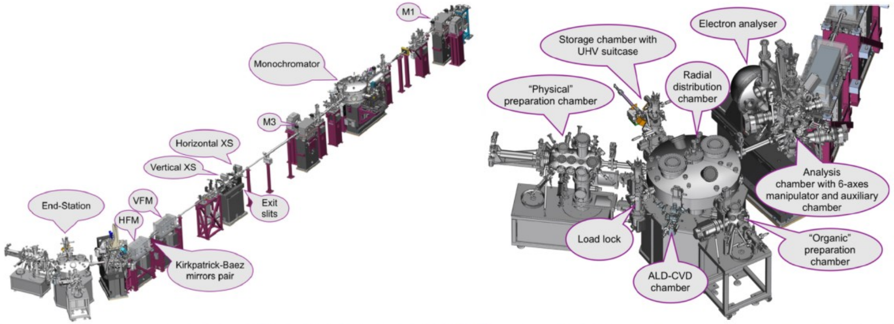
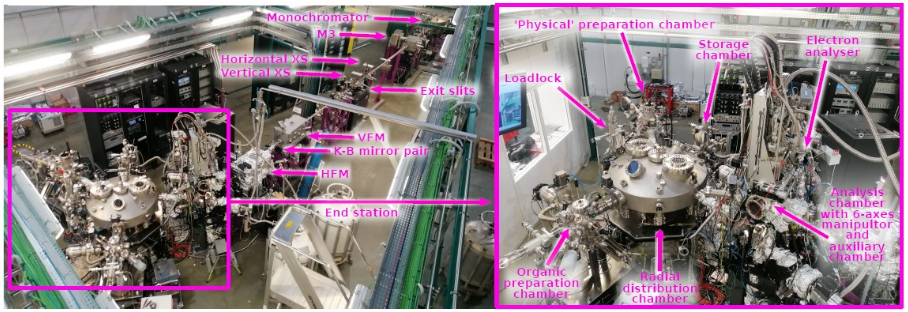


LOREA beamline





Analyser:
- MBS A-1 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.

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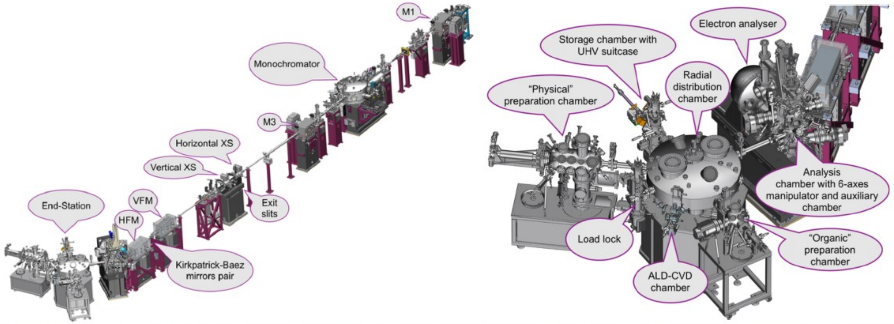

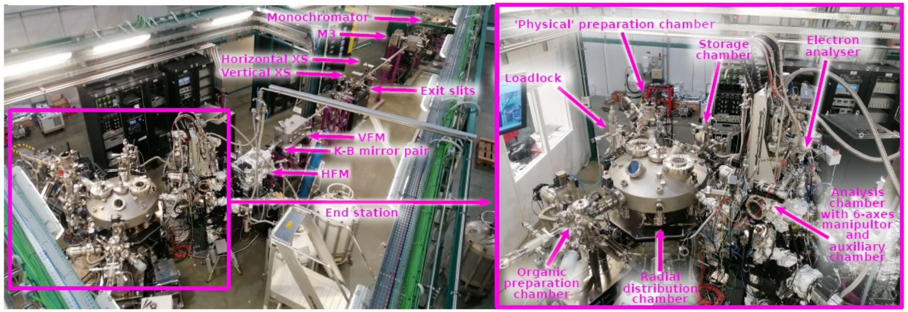

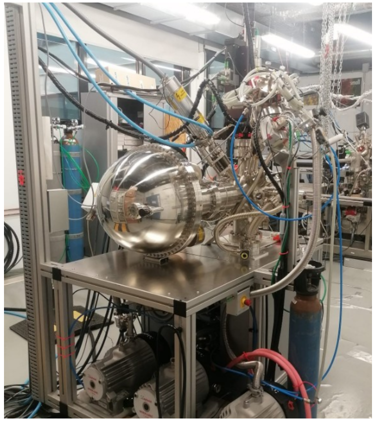

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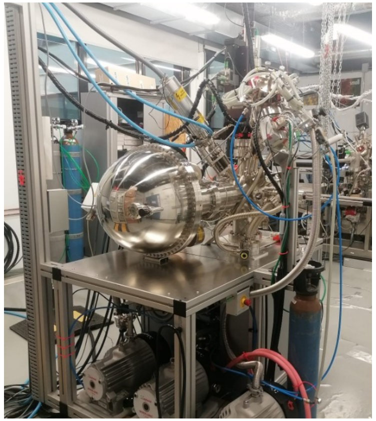

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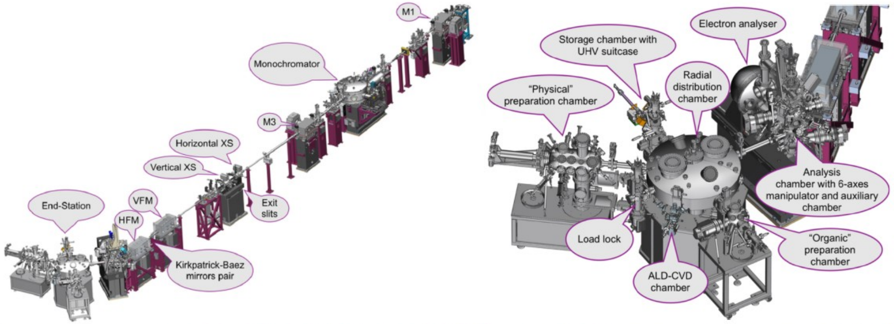

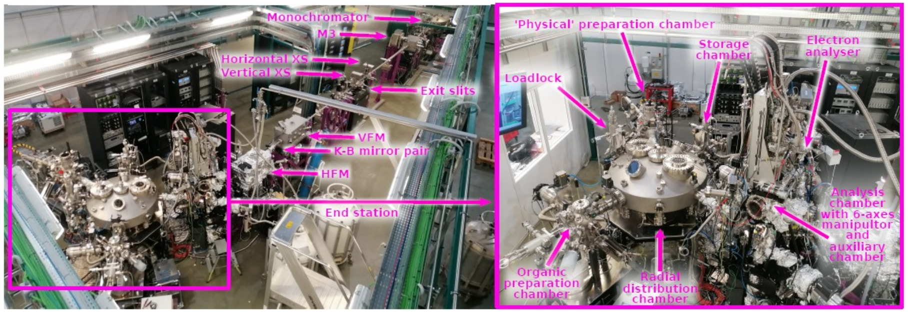

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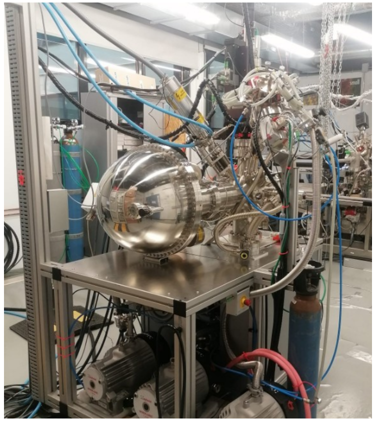

- **Bulk single crystal**
- **Er impurities** deposited by means of an e-beam evaporator.
- XPS and ARPES performed at a **T = 15 K**
- **Exfoliated in-situ** (UHV) at T = 15 K
- **Linear horizontal** polarization
  hν = **100** (XPS) and **52** (ARPES) **eV**

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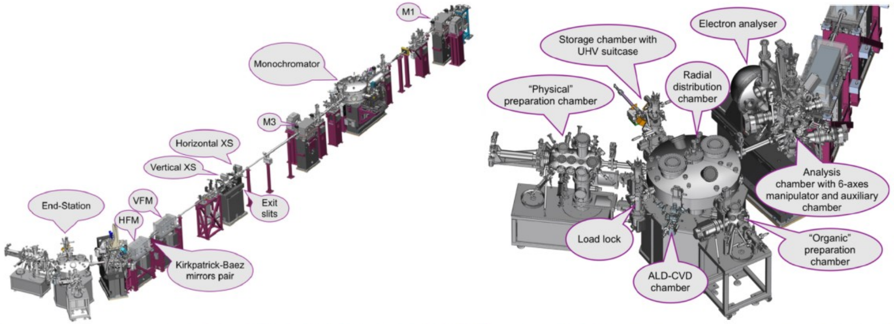

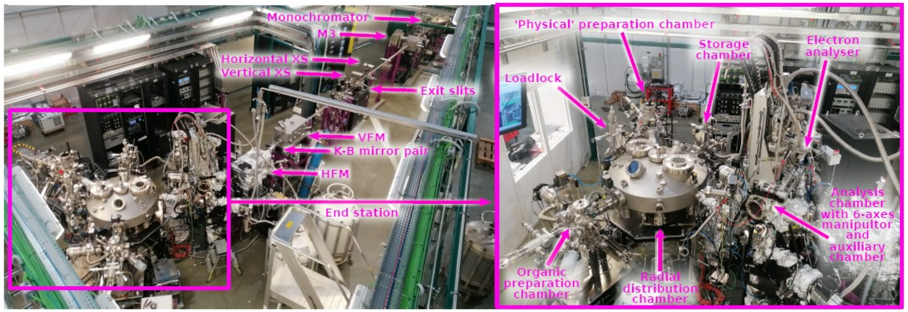

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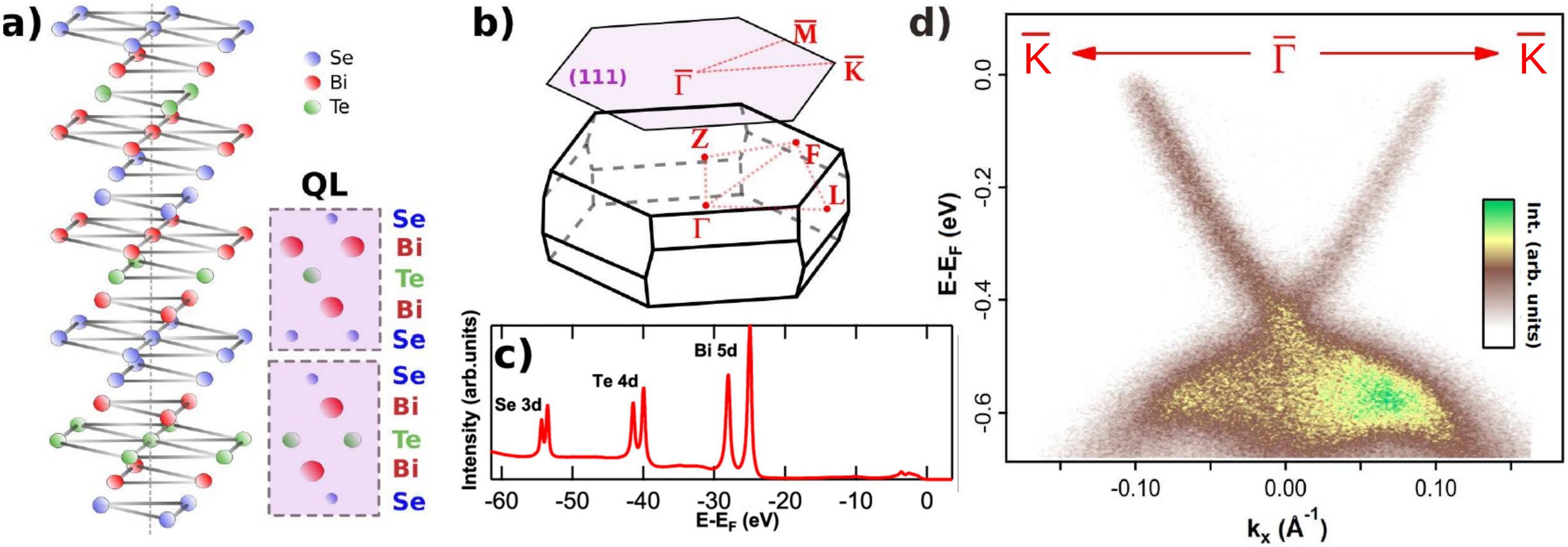
Results: pristine Bi_2Se_2Te



Muñiz Cano, B., et al. *Nano Lett*. **2023**, 23, 13, 6249–6258

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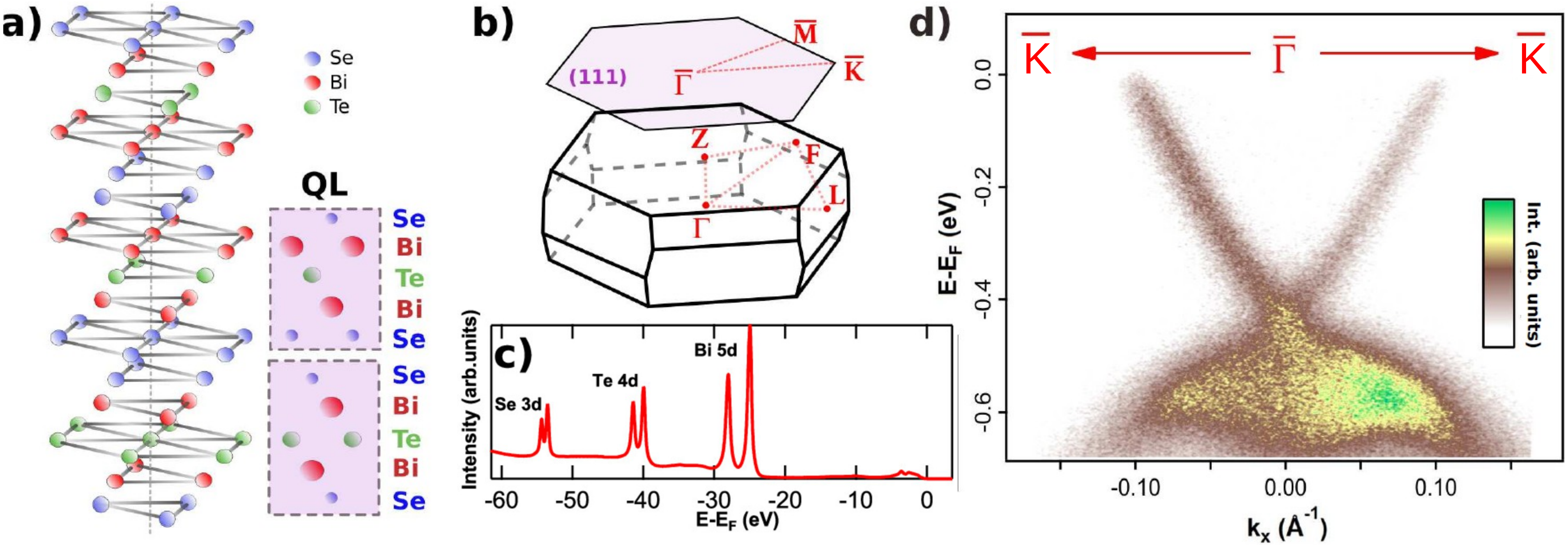

- **3D quintuple layer crystal** structure.

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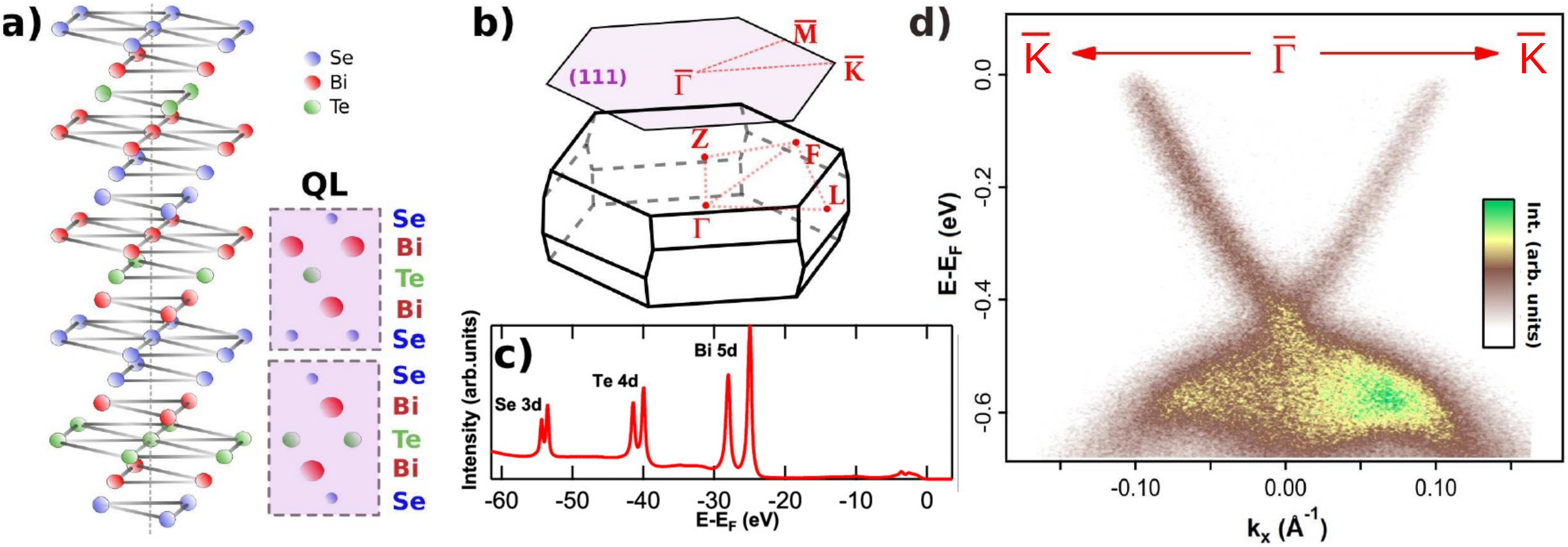

- 3D quintuple layer crystal structure.
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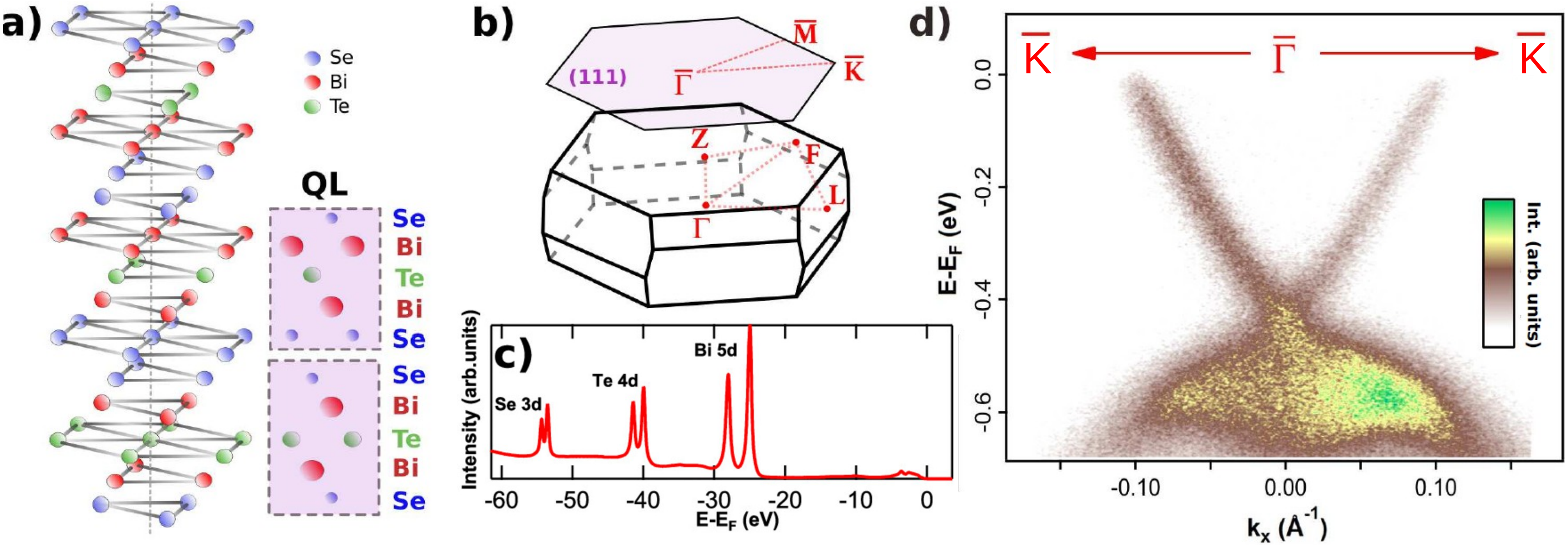

- 3D quintuple layer crystal structure.
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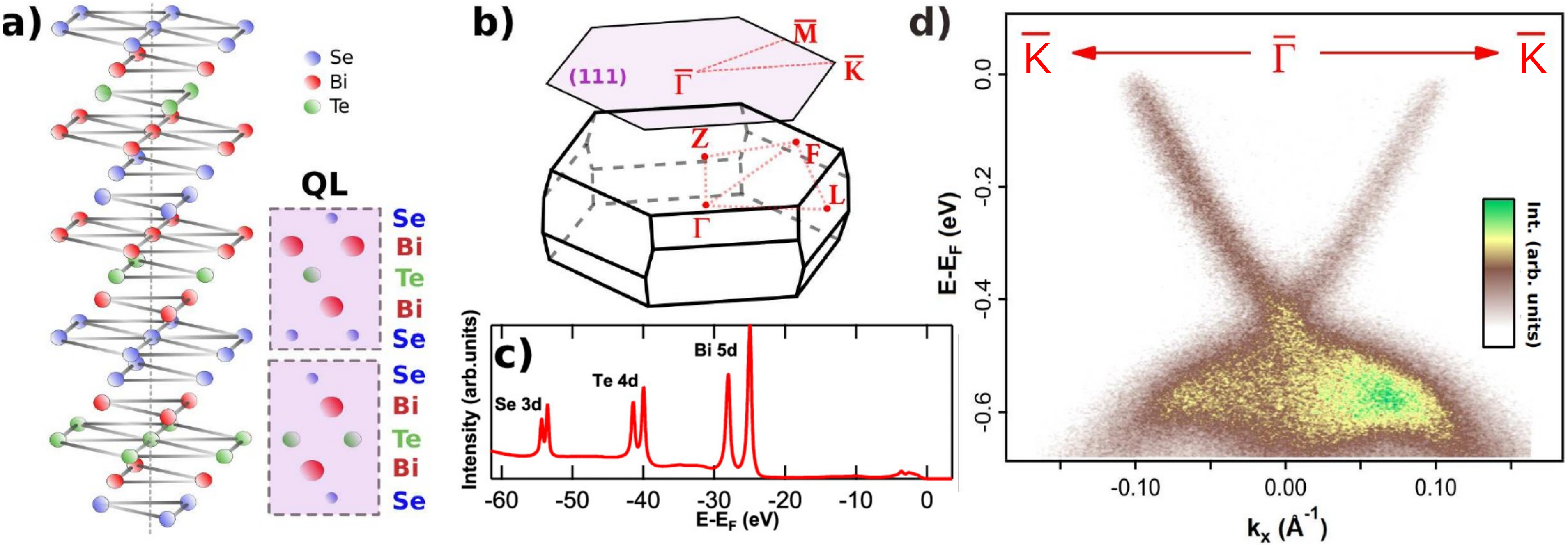

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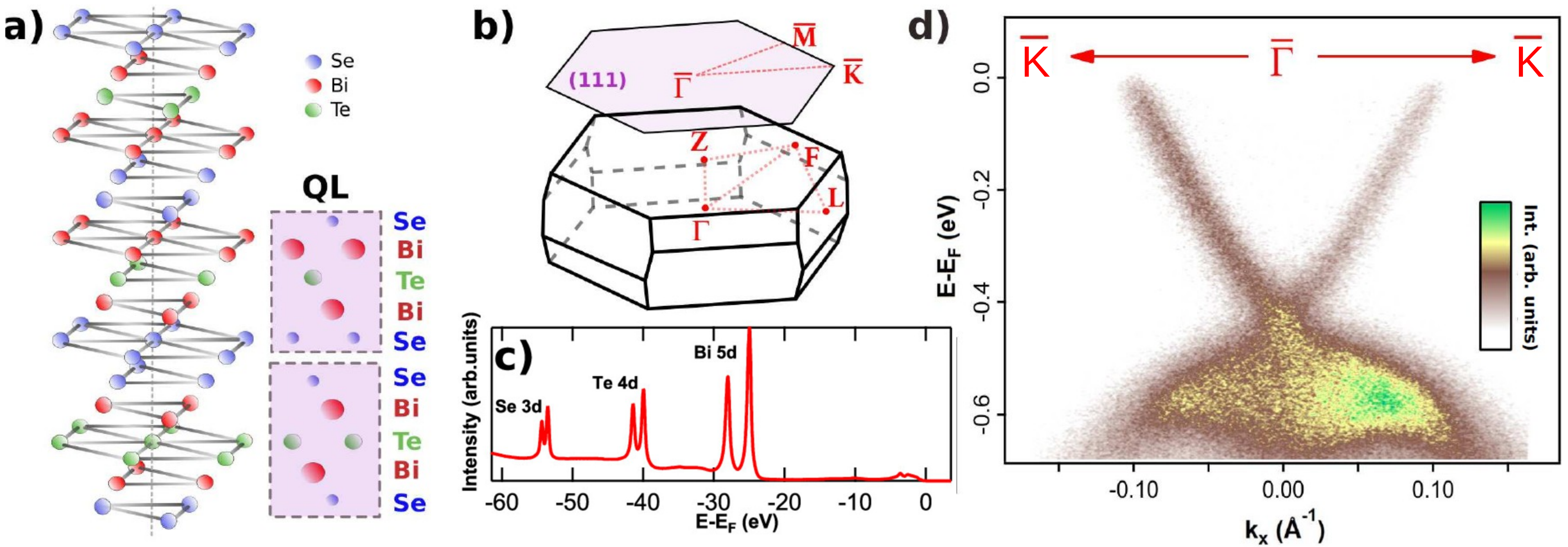

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E_{DP} = 440 meV
No gap
$V_F = (7.1 \pm 0.1)\cdot 10^5$ m/s

Muñiz Cano, B., et al. *Nano Lett*. **2023**, 23, 13, 6249–6258

Results: Er-doped Bi_2Se_2Te XPS

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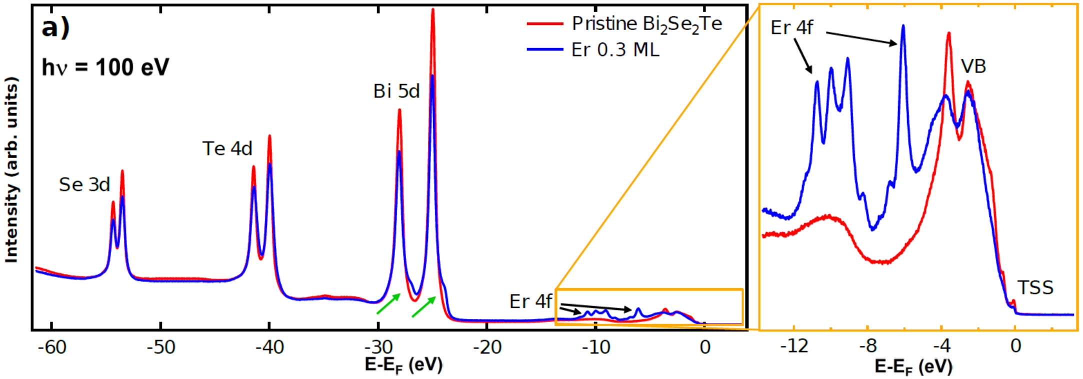

Muñiz Cano, B., et al. *Nano Lett*. **2023**, 23, 13, 6249–6258

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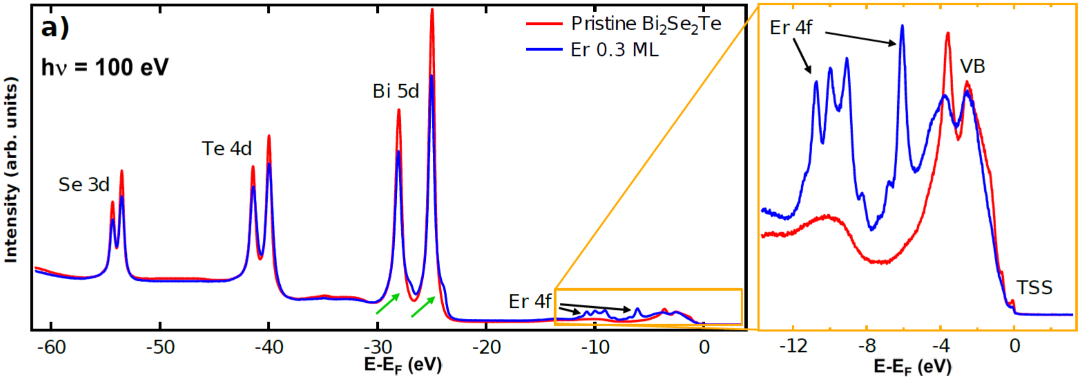

- Se 3d, Te 4d, Bi 5d → **attenuated**.

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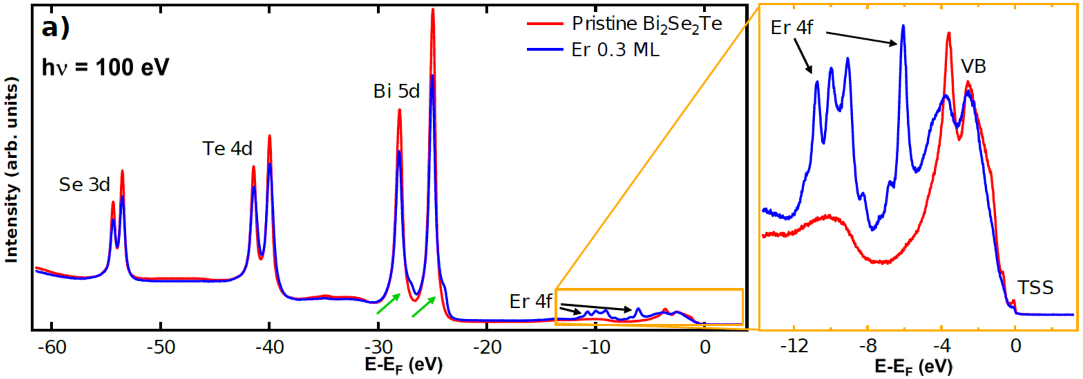

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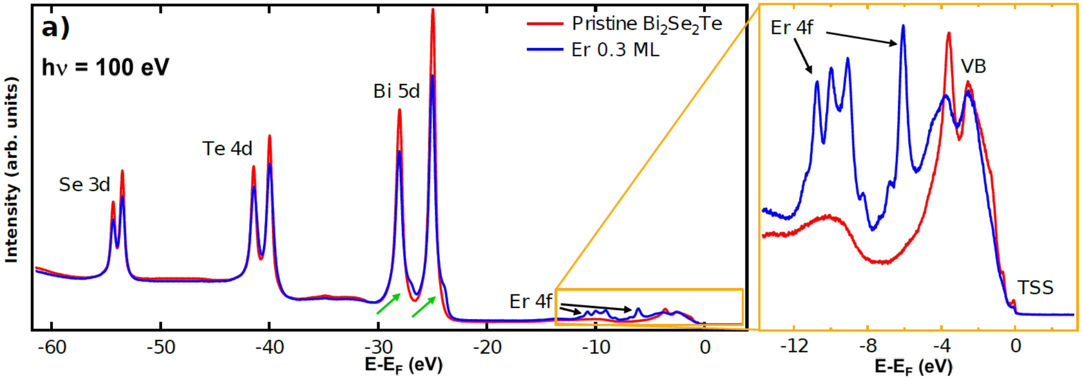

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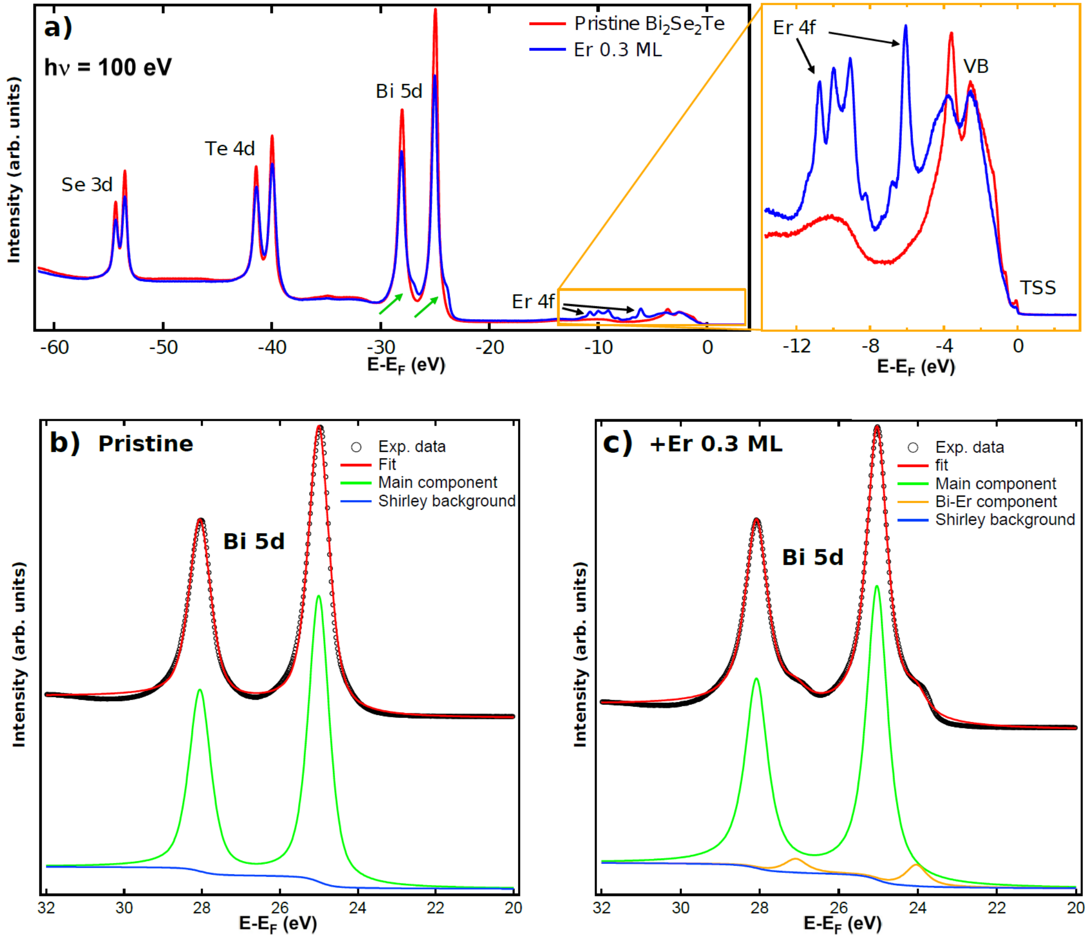

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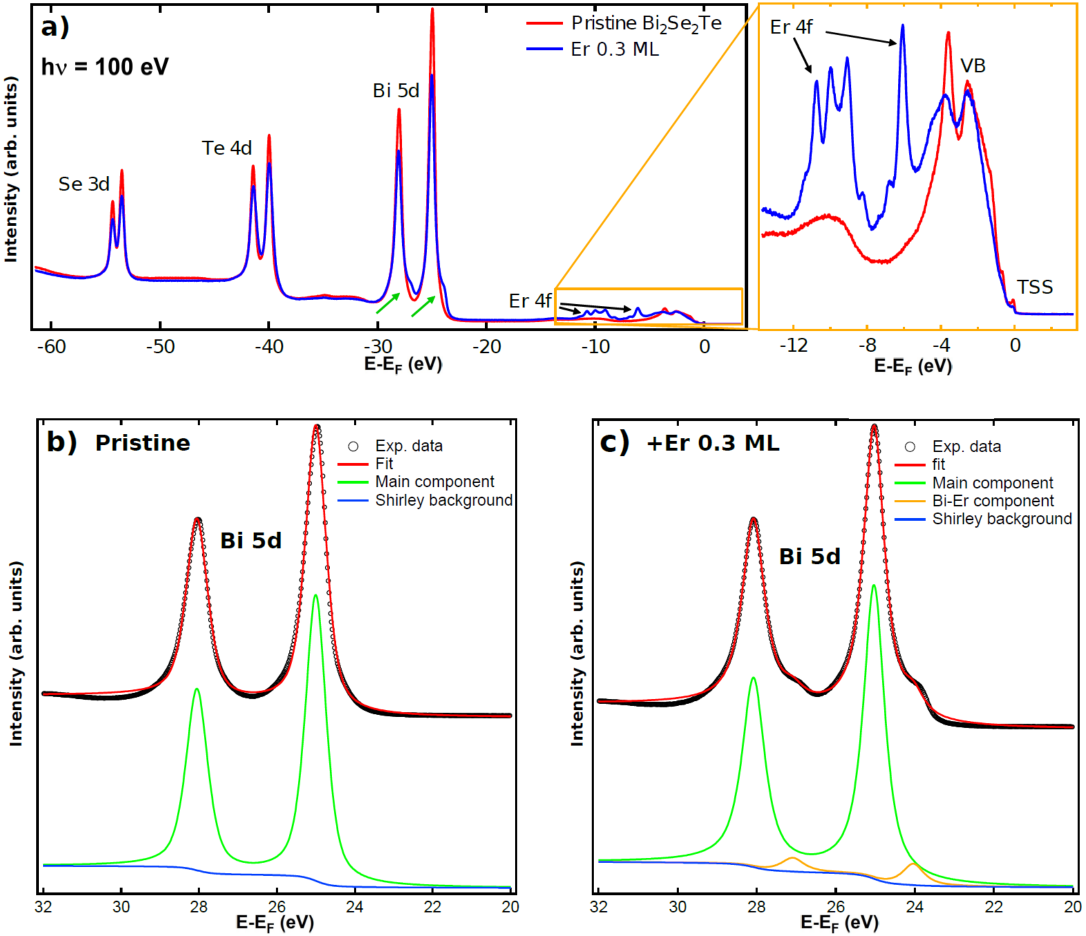

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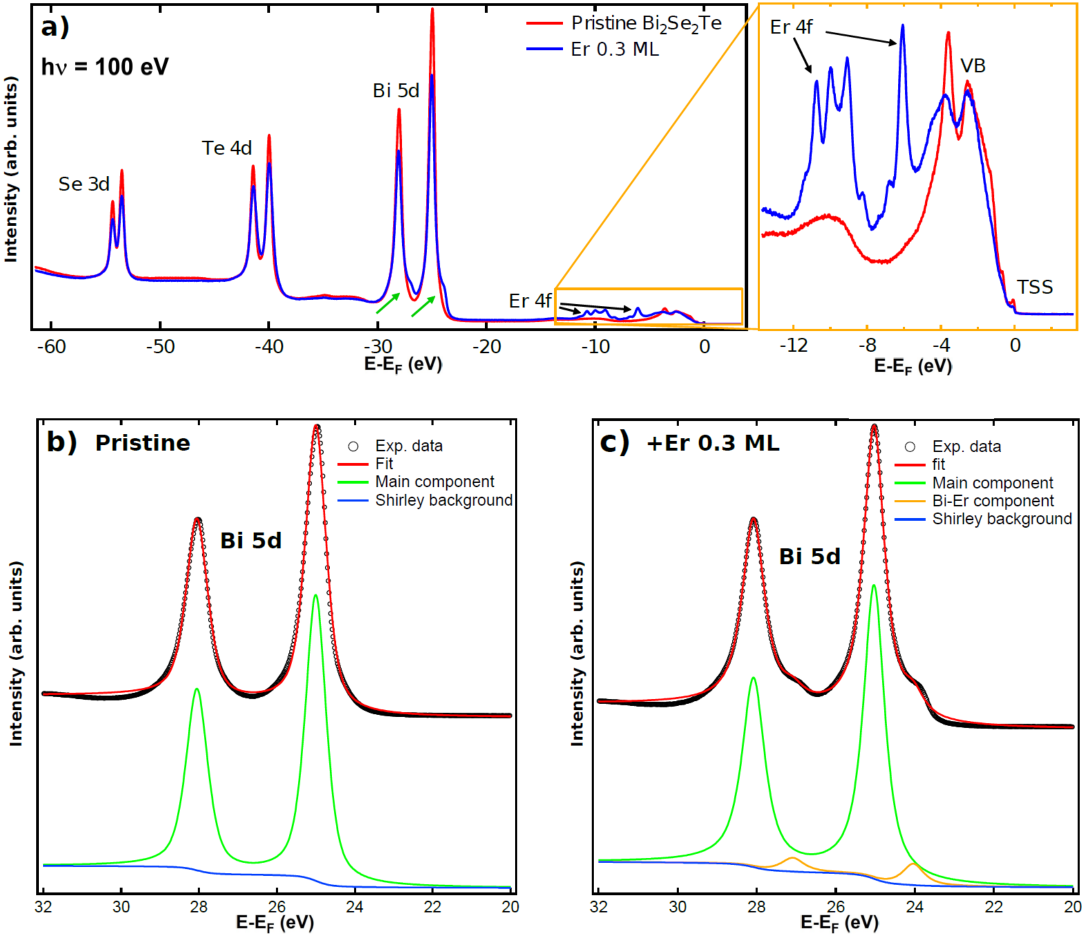

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Results: pristine vs. Er-doped Bi_2Se_2Te Fermi maps

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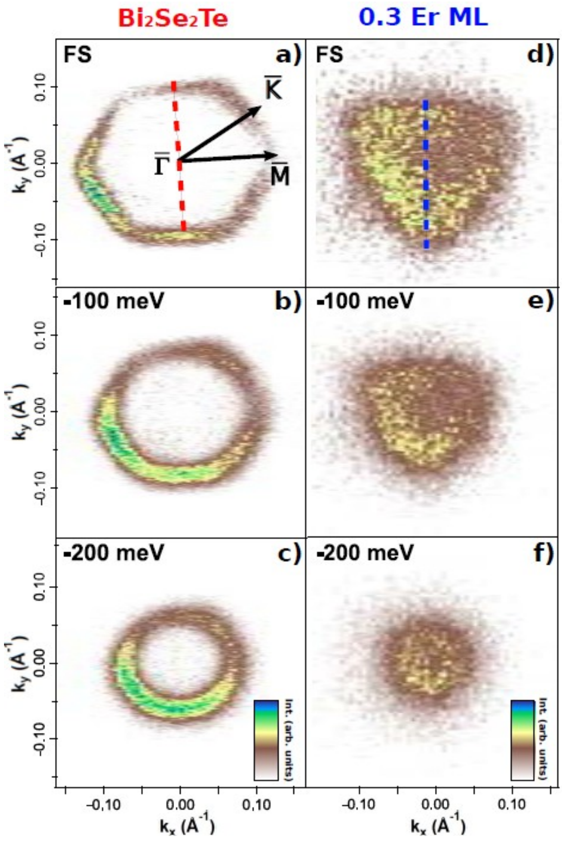

- **Pristine** BST TSS → **hexagonal warped FS** and the circular CE maps.

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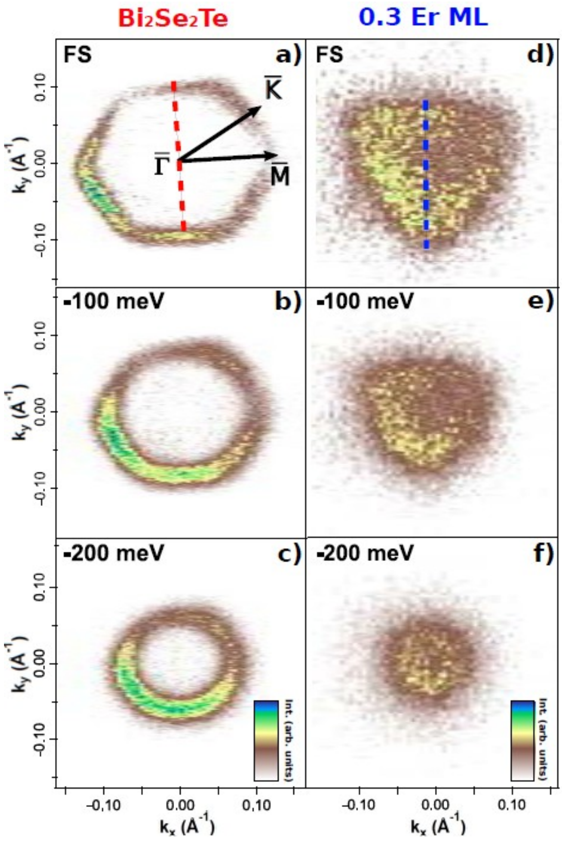

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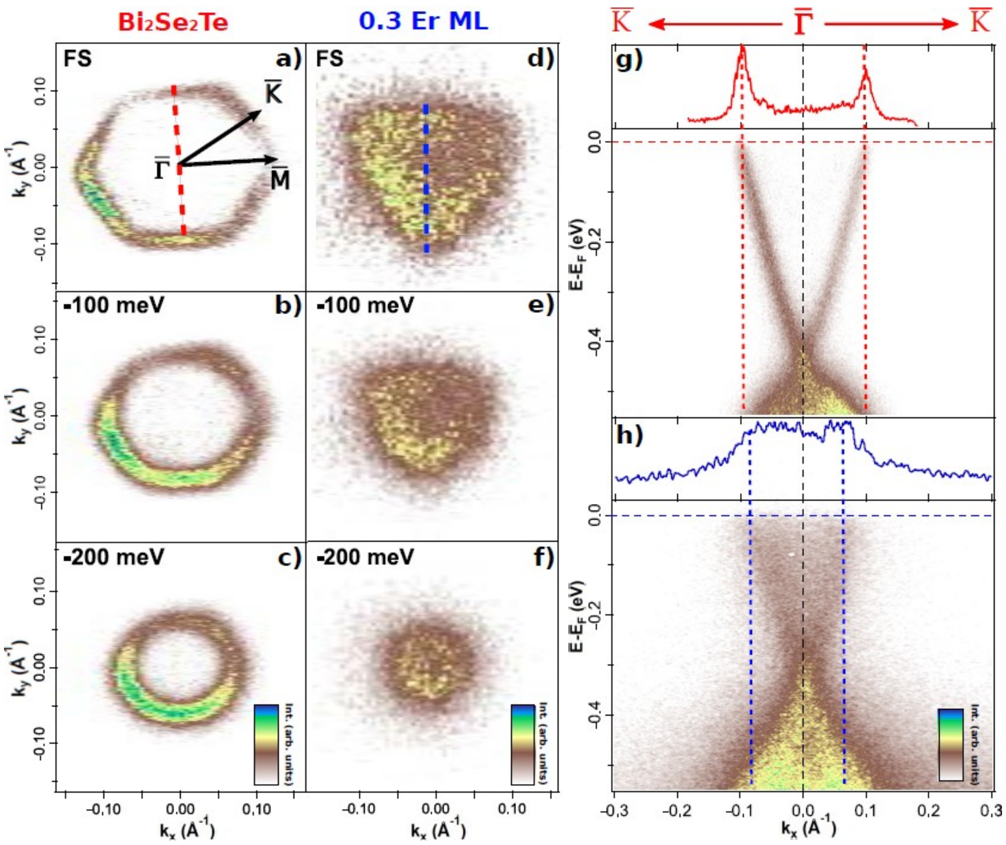

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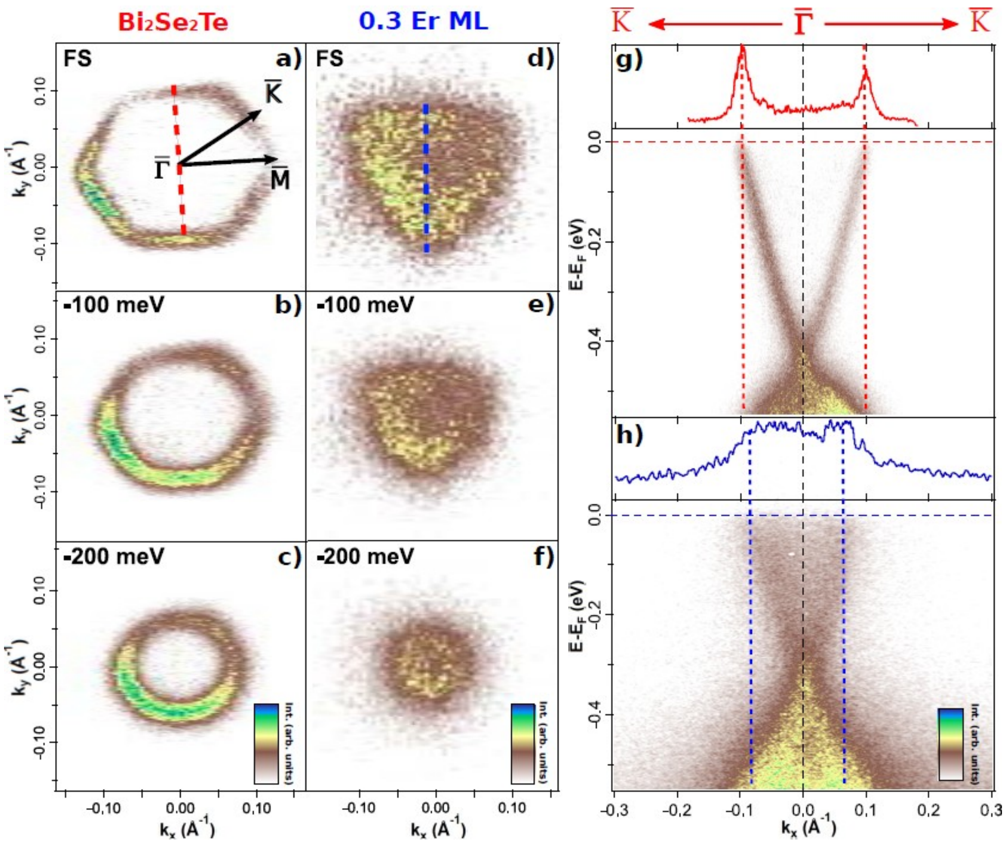

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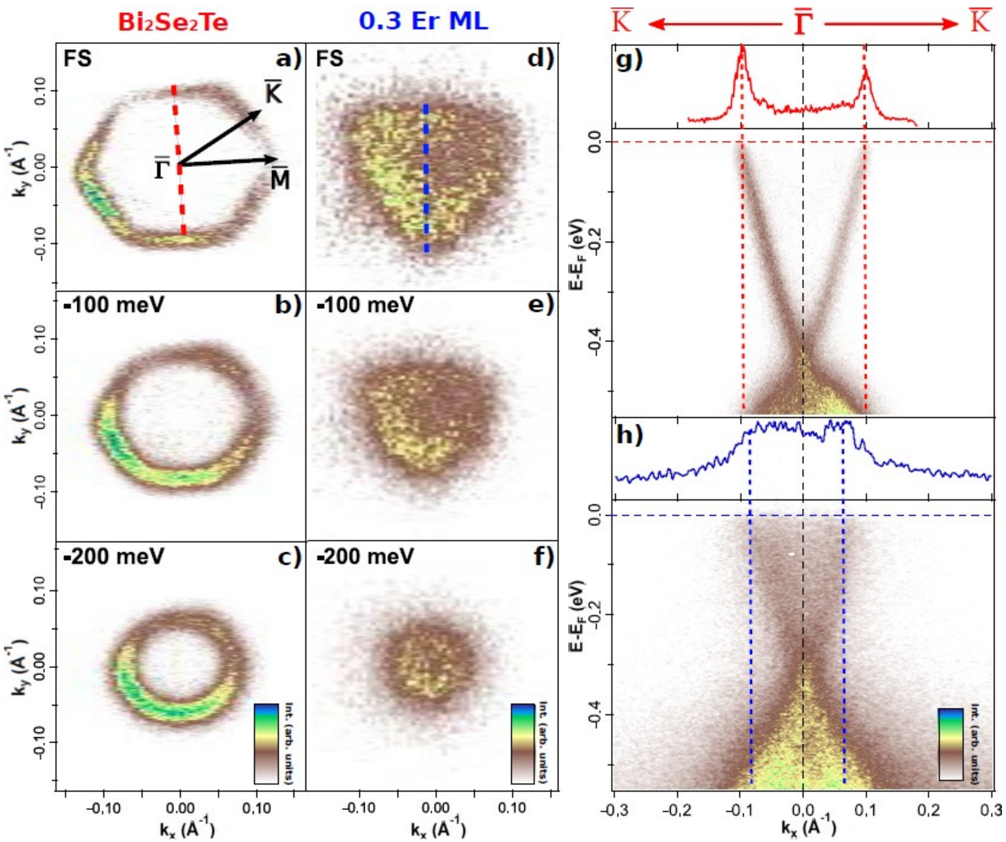

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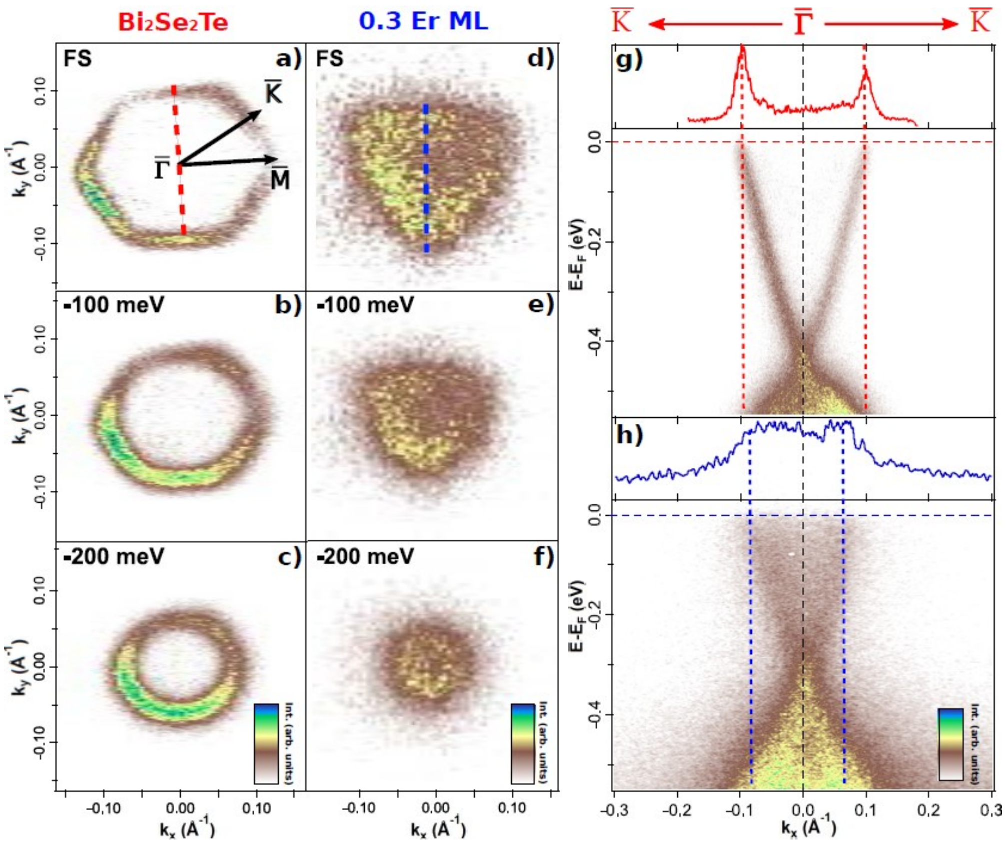
Results: pristine vs. Er-doped Bi_2Se_2Te Fermi maps



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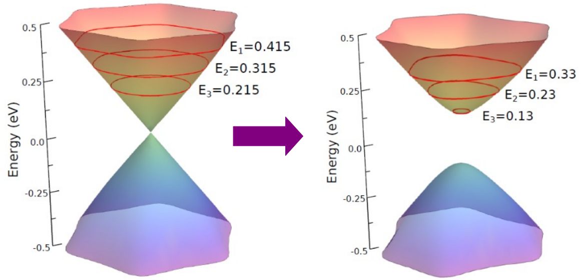
$$H = \hbar v_F(k_x\sigma_y - k_y\sigma_x) + (\lambda k^3 \cos 3\theta - \Delta)\sigma_z$$



- Theoretical model → magnetic **Zeeman out-of-plane term in Hamiltonian**

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Results: bandgap opening at the Dirac point

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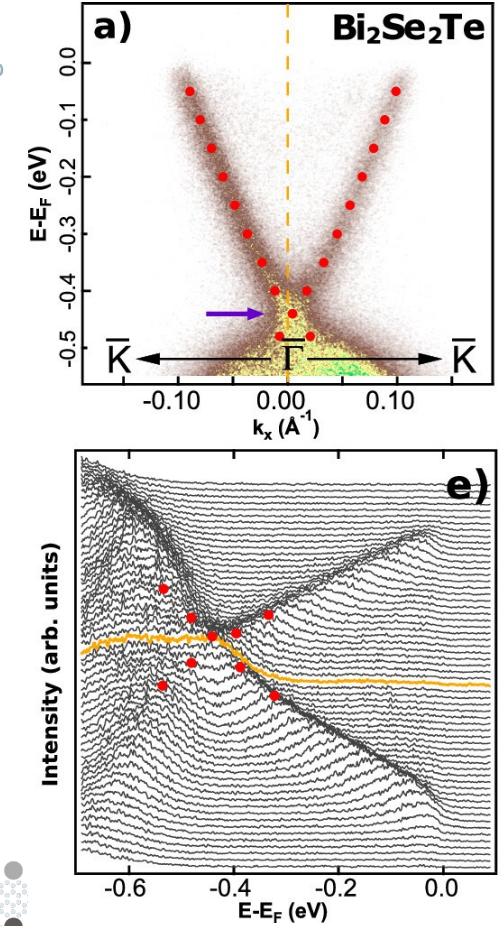

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  → **DP defined** as intersection of two linear branches at 440 meV

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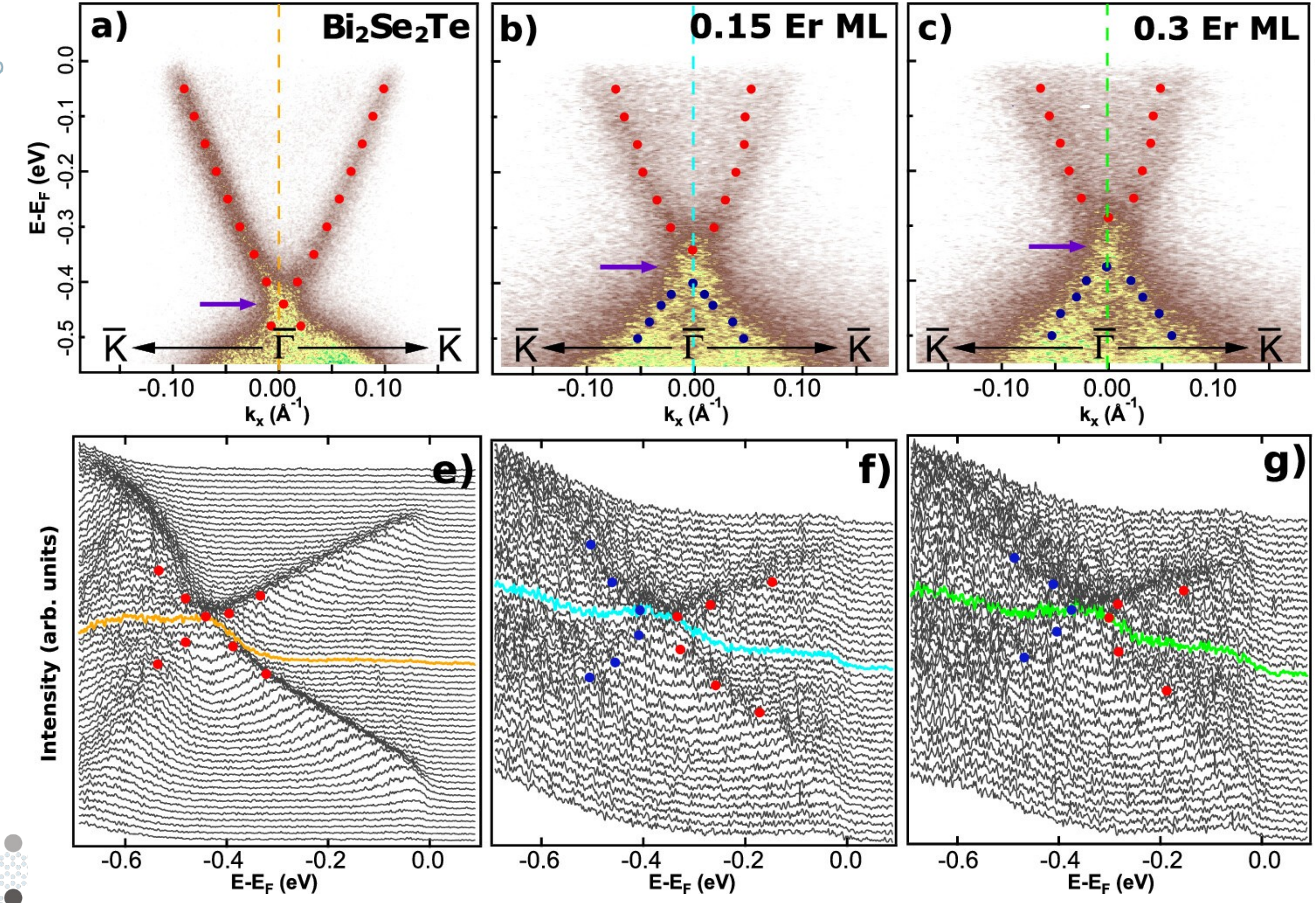

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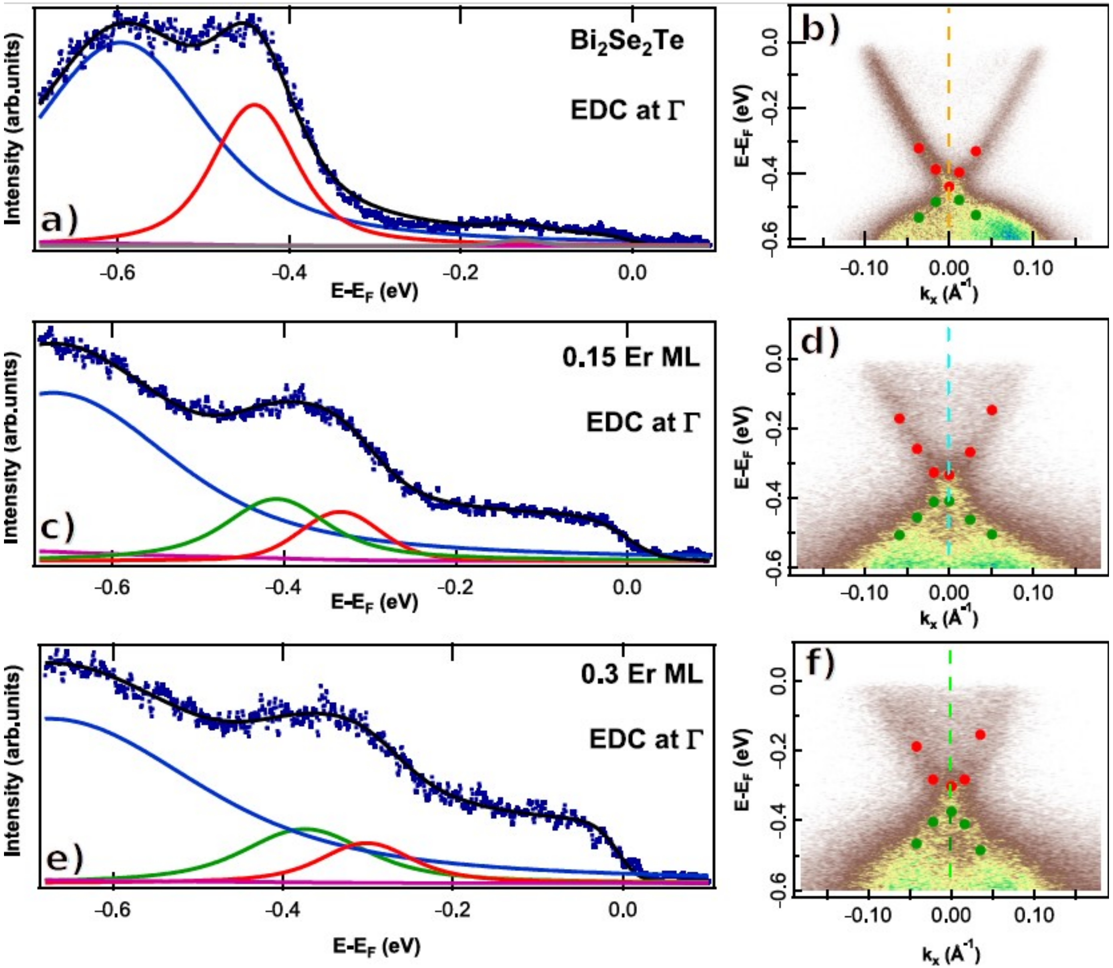

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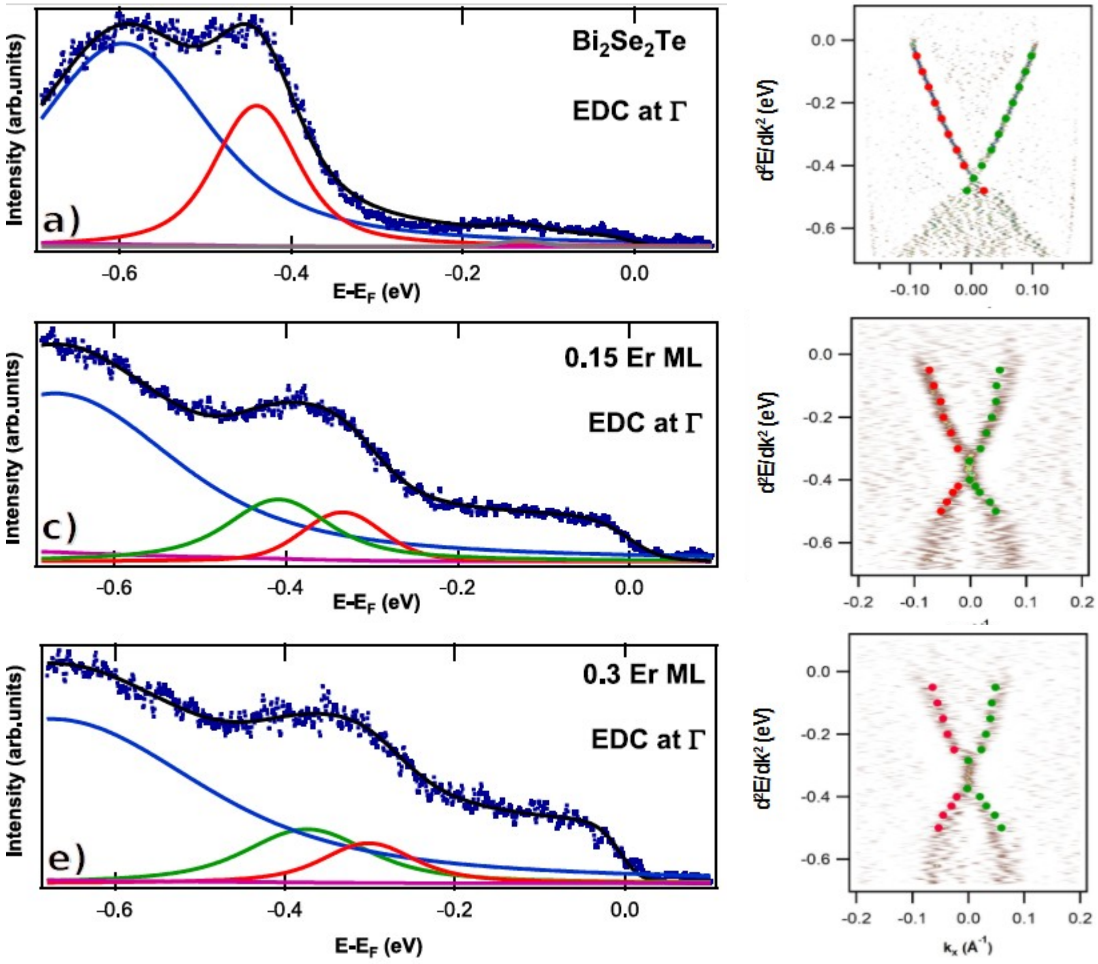

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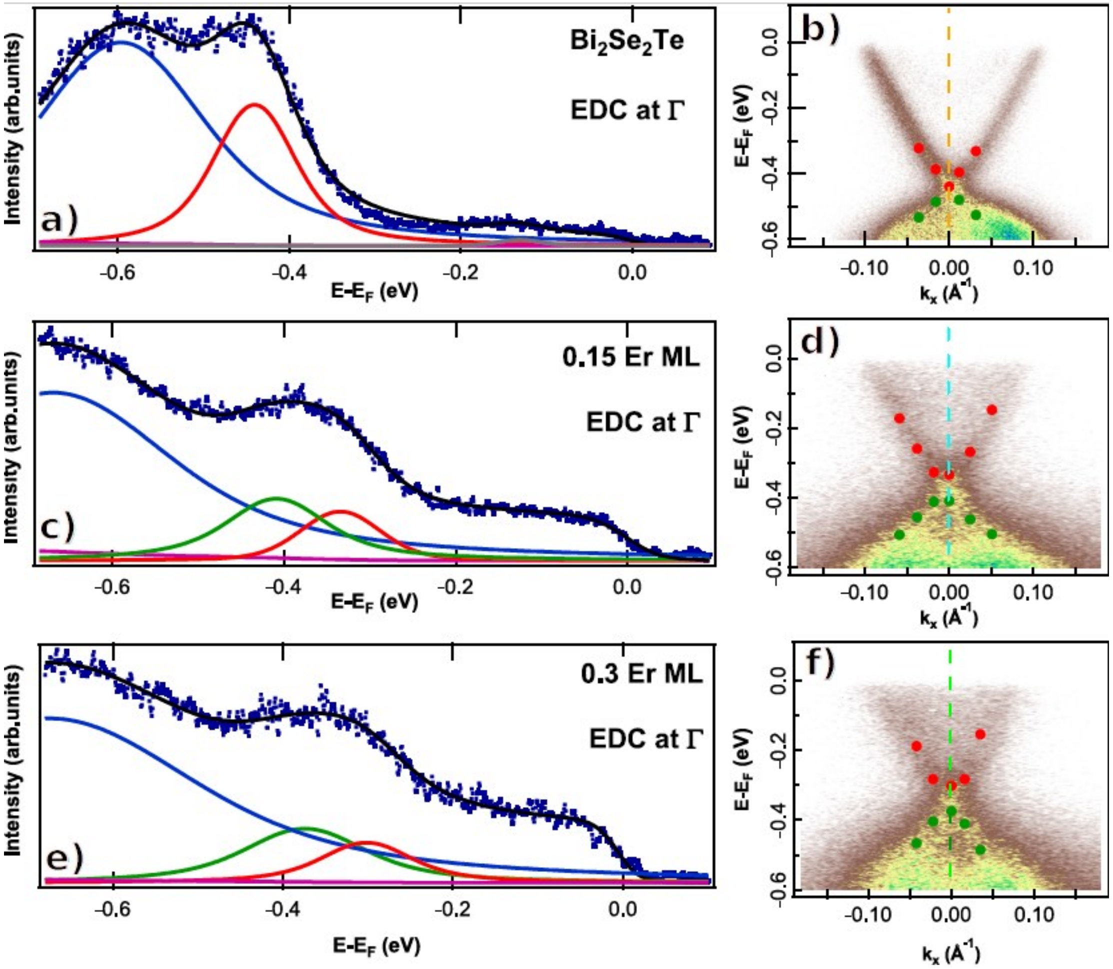

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Gap opening

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Atomic Manipulation and Spectroscopy (AMS)
Kevin García Díez
Aitor Mugarza

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Institució CERCA Centres de Recerca de Catalunya

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Thank you!

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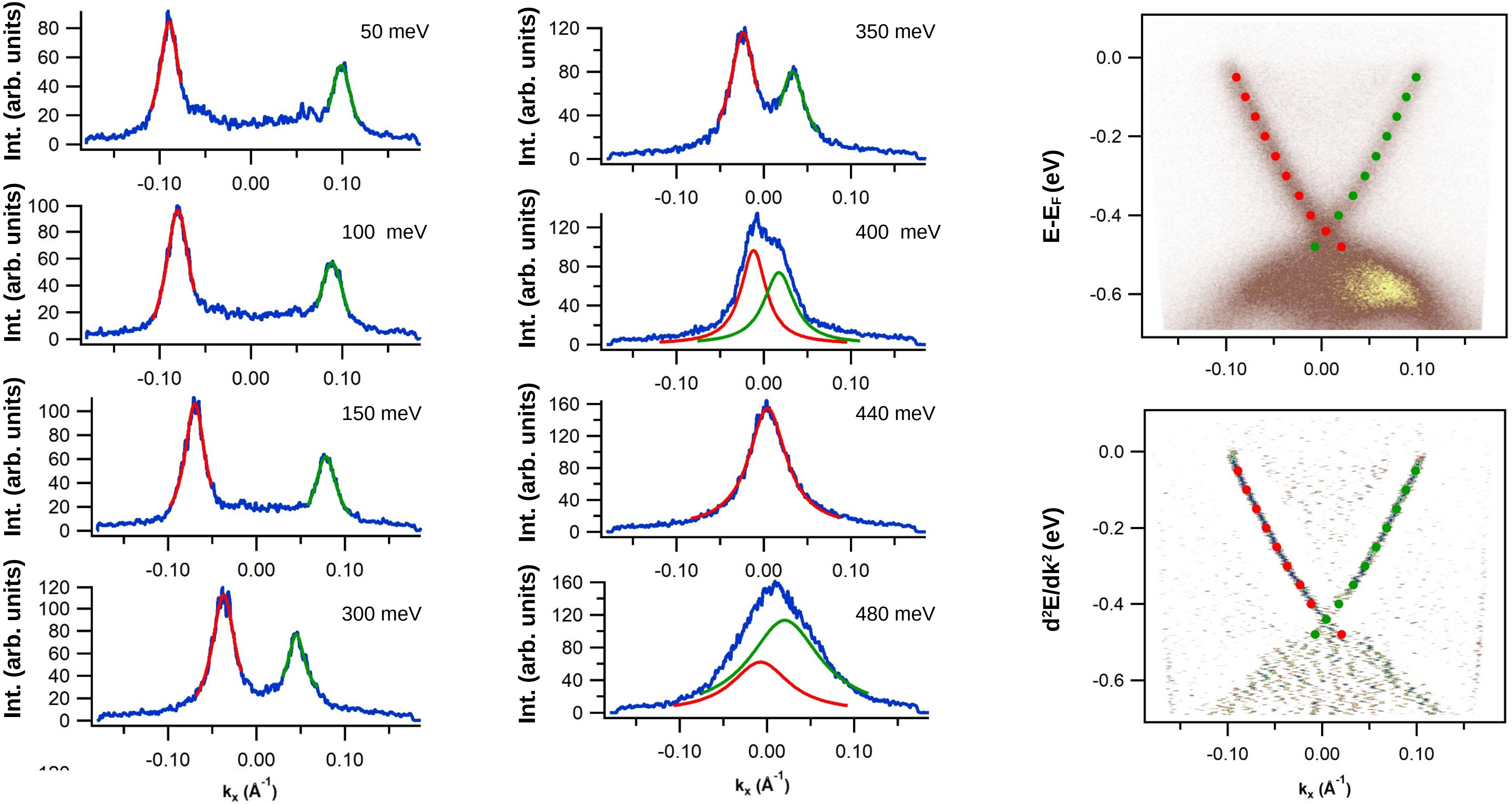
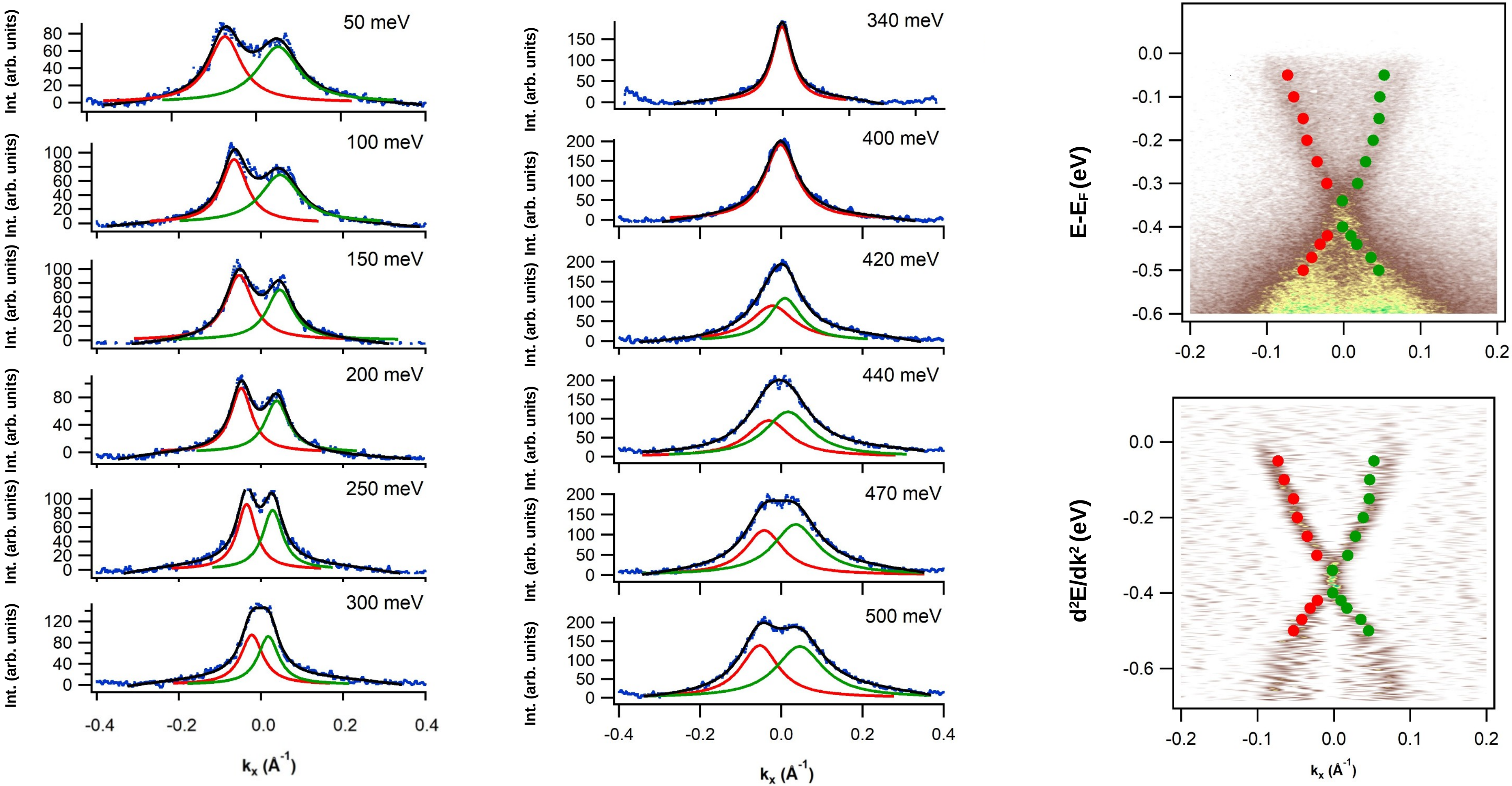
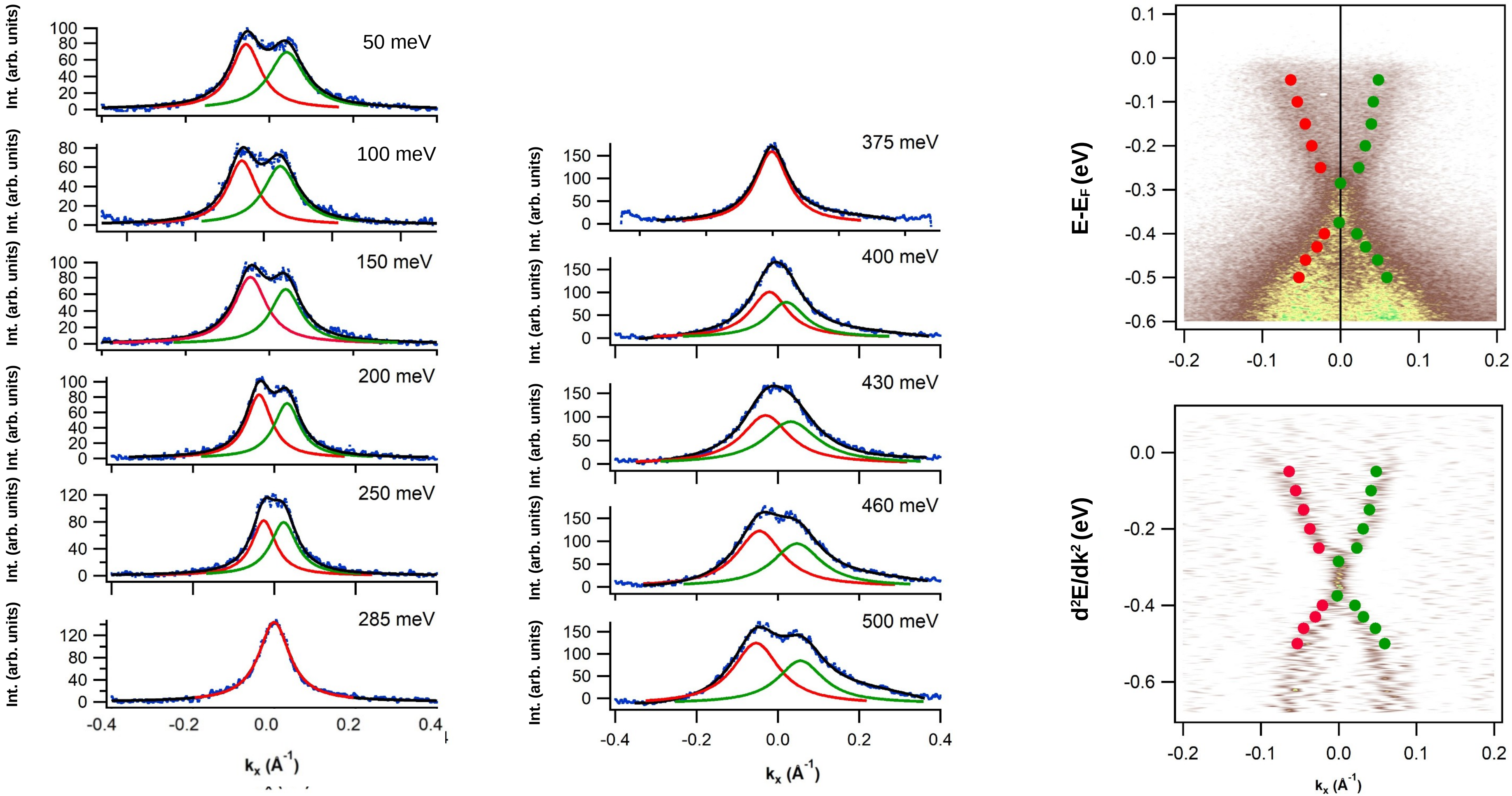
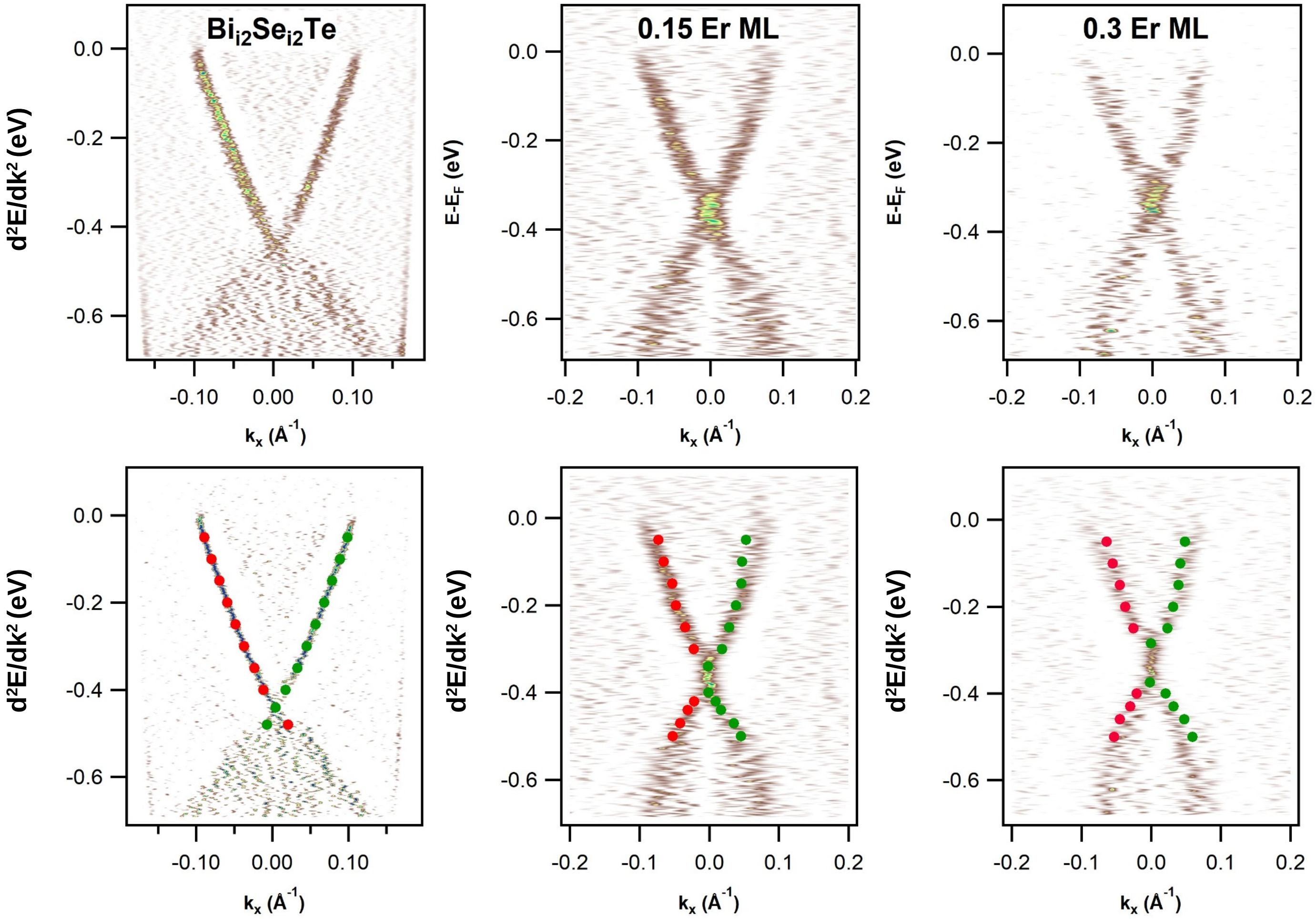
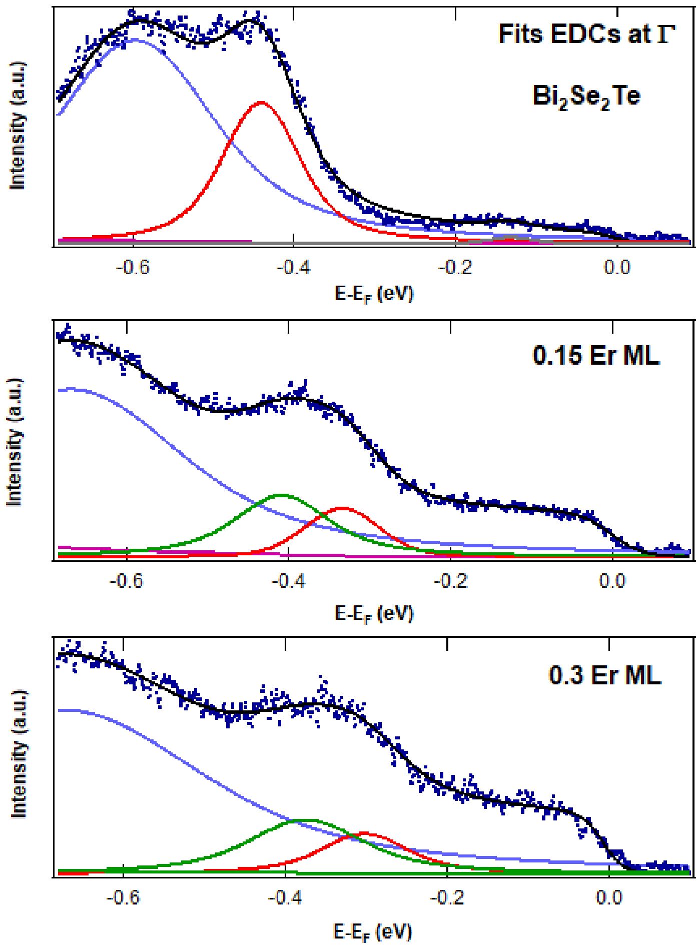

50 meV
100 meV
150 meV
300 meV
350 meV
400 meV
440 meV
480 meV
Int. (arb. units)
-0.10
0.00
0.10
k_x (Å^{-1})
E-E$_F$ (eV)
d^{2}E/dk^2 (eV)
0.0
-0.2
-0.4
-0.6


50 meV
100 meV
150 meV
200 meV
250 meV
300 meV
340 meV
400 meV
420 meV
440 meV
470 meV
500 meV
Int. (arb. units)
k_x (Å^{-1})
$E-E_F$ (eV)
d^2E/dk^2 (eV)
k_x (Å^{-1})


50 meV
100 meV
150 meV
200 meV
250 meV
285 meV
375 meV
400 meV
430 meV
460 meV
500 meV
Int. (arb. units)
k_x (Å^{-1})
$E-E_F$ (eV)
d^2E/dk^2 (eV)


$Bi_{i2}Se_{i2}Te$
0.15 Er ML
0.3 Er ML
d^2E/dk^2 (eV)
$E-E_F$ (eV)
k_x ($Å^{-1}$)


Fits EDCs at Γ
Bi_2Se_2Te
Intensity (a.u.)
-0.6
-0.4
-0.2
0.0
$E-E_F$ (eV)
0.15 Er ML
0.3 Er ML