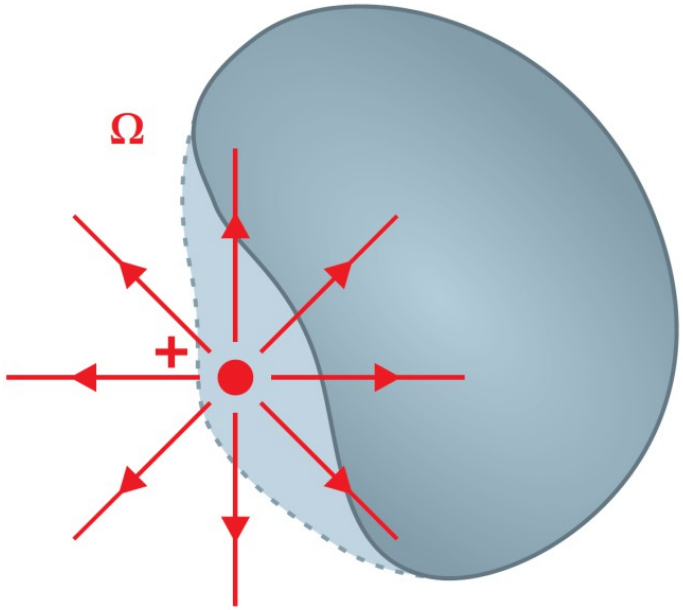
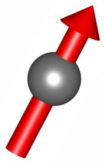
Introduction

Alexander Tsirlin

Division of Quantum Magnetism and Superconductivity
Felix Bloch Institute for Solid State Physics









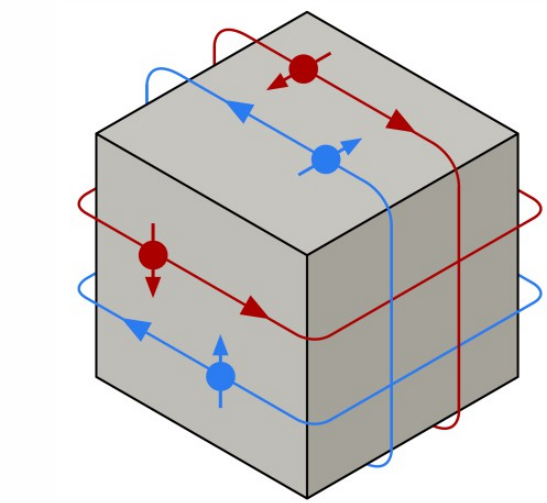
UNIVERSITÄT
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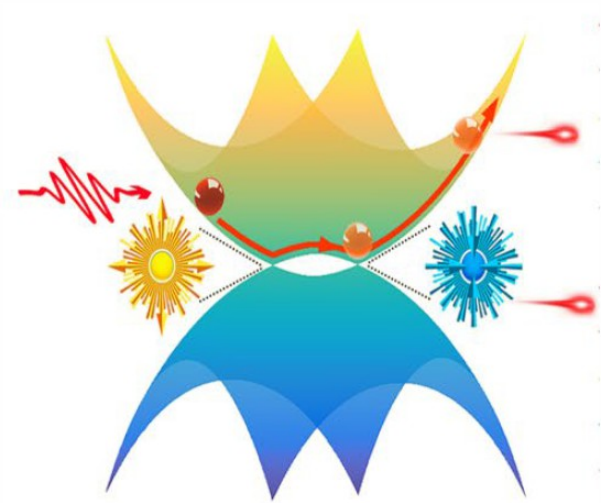
Advanced Solid-State Physics, WS 26/27

I. Band topology

non-interacting electrons in special settings

- integer quantum Hall effect
- Berry curvature and Berry phase
- Chern number
- Topological insulators
- Fermi arcs
- Dirac and Weyl semi-metals





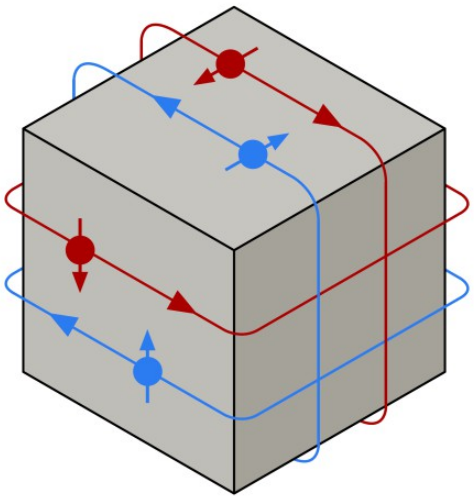
Images from eLight 3, 2 (2023), arXiv:2407.10464, and Phys. Today 73(9), 30 (2020) (title image)

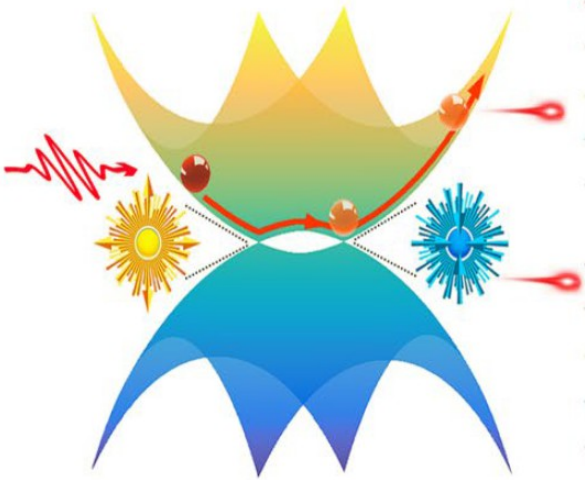
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$\longrightarrow$ paradigm shift in solid-state physics





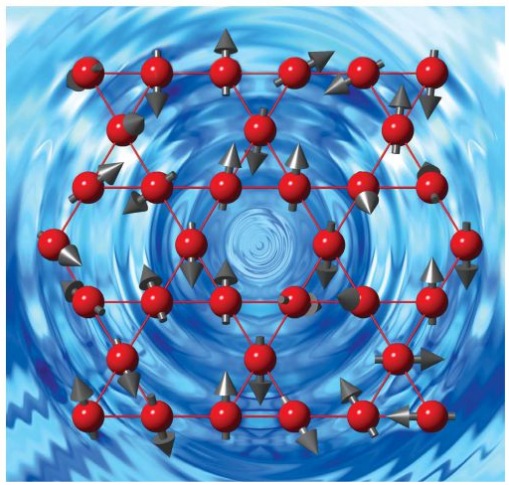
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II. Interacting systems and symmetry breaking

new states arising from interactions between electrons

- Landau Fermi liquid
- superconducting instability (BCS)
- topological superconductors
- electronic correlations and Hubbard model
- Mott and charge-transfer insulators
- spin waves / magnons
- fractionalization and entanglement: quantum Hall again, and spin liquids





Images from Phys. Today 69(8), 30 (2016) and Hunklinger's Solid-State Physics

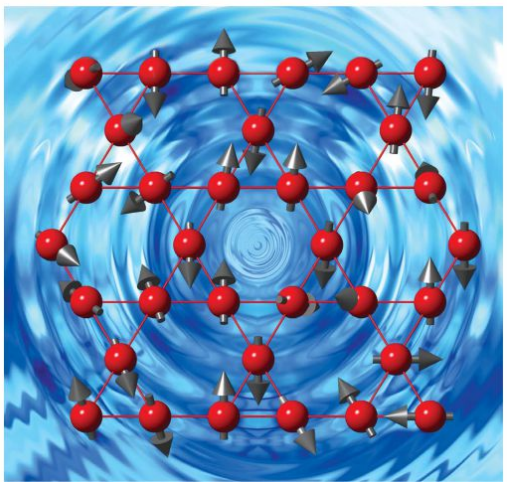
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- fractionalization and entanglement: quantum Hall again, and spin liquids

$\longrightarrow$ tangible properties and functionality





Images from Phys. Today 69(8), 30 (2016) and Hunklinger's Solid-State Physics

Macroscopic quantum effects in condensed-matter systems

(vs. quantization of atomic-like systems: trapped ions, NV-centers...)

Image credit: Nobel Prize Outreach

Macroscopic quantum effects in condensed-matter systems

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Nobel prize in physics 2025:

for the discovery of macroscopic quantum mechanical tunnelling and energy quantization in an electric circuit

John Clarke

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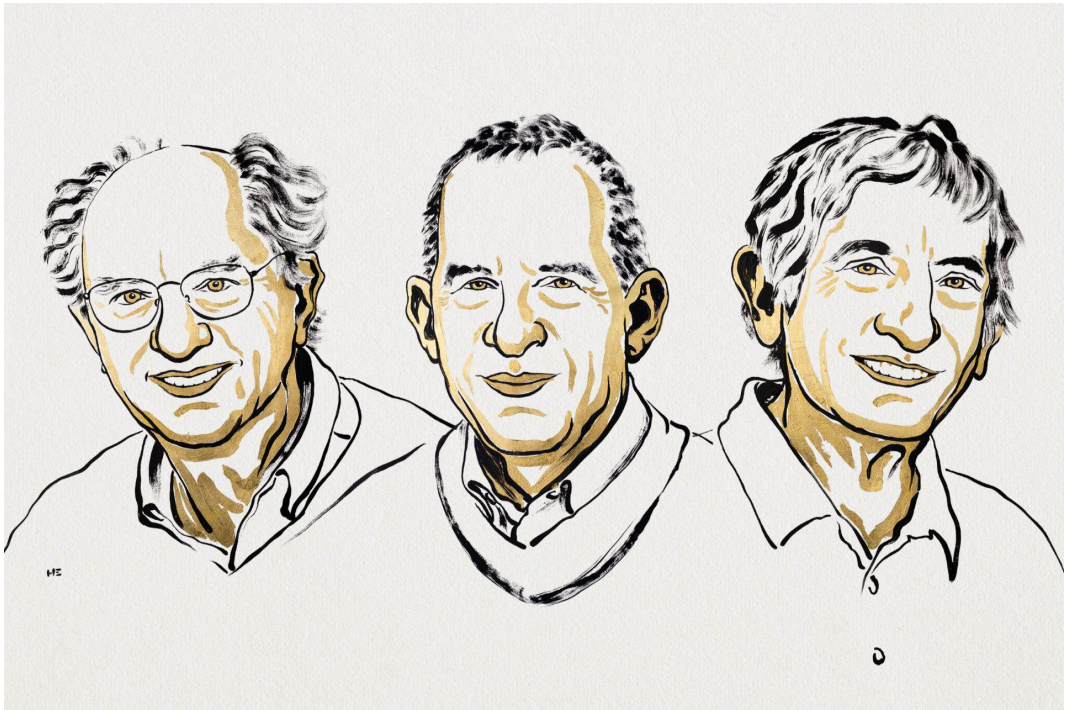


Image credit: Nobel Prize Outreach

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superconducting qubits

quantum computer

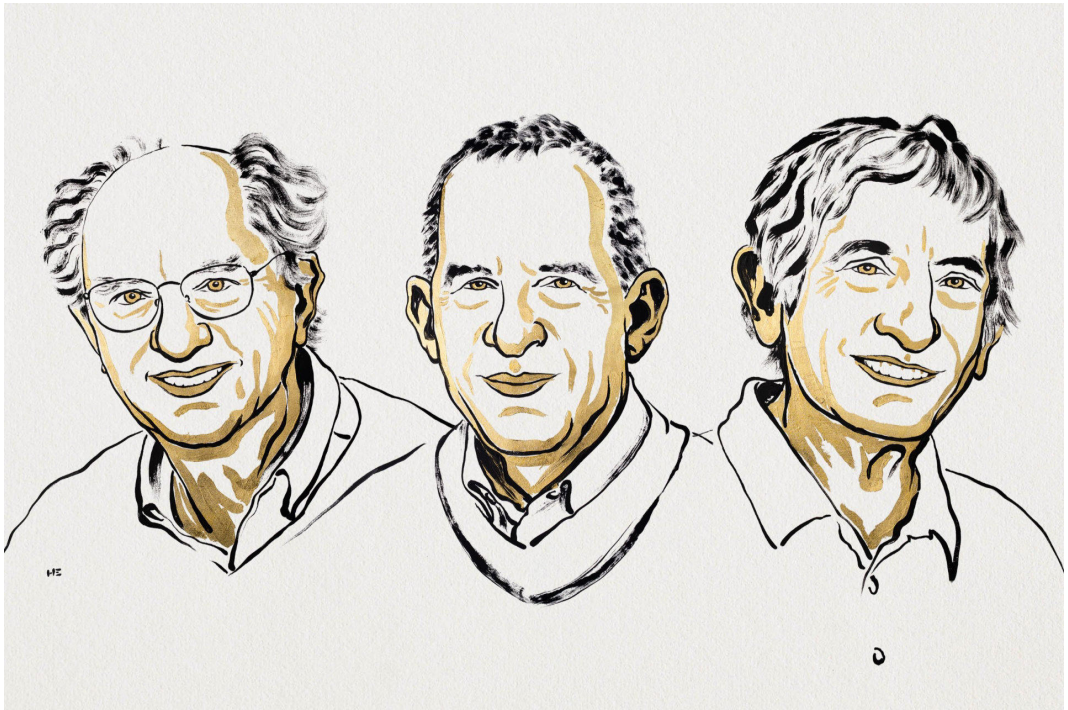


Image credit: Nobel Prize Outreach

Expect rapid shifts: new concepts and topics every week

don't be discouraged: solid-state physics is diverse

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learn to grasp concepts and navigate through the math

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May seem deep in the weeds of theory: brace yourself
that's life; in solid state, you have to be friends with theory

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- Your semester-long **crash course** in modern solid-state physics

It's an open-end graduate-level lecture. You will not learn everything, but try to identify your own reference points:

what is studied? on which materials? why?

Refresh your basic solid-state knowledge

newer textbooks may have some bits and pieces of what we will study here:

- S. Simon, The Oxford Solid State Basics
- R. Gross, A. Marx. Festkörperphysik
  latest German reading for solid-state physics, e-book available

but do not expect them to cover too much...

- D. Vanderbilt, Berry phases in electronic structure theory
  paper copy only
- B.A. Bernevig, Topological insulators and topological superconductors
  e-book available
- David Tong, Lecture notes on The Quantum Hall effect
  available from his web site
- Topology in condensed matter: tying quantum knots
  Online course on topology in condensed matter: Topocondmat

+ review articles that will be suggested on the web page

Literature to part II

- P. Fazekas,
  Lecture notes on electronic correlations and magnetism
  paper copy only

- D. Khomskii, Transition metal compounds
  D. Khomskii, Basic aspects of the quantum theory of solids
  e-books available

+ review articles that will be suggested on the web page

Mo 13:15 and Tu 9:15, SR 532

Web page of the course:

- list of key terms/concepts
- problem sheets
- schedule changes
- additional literature



Mo 13:15 and Tu 9:15, SR 532



Key concept



Open problem

Web page of the course:

- list of key terms/concepts
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W 15:15, SR 224 and Th 11:15, SR 218 *every week!*

first classes: 21.10 and 22.10

- 3 problems every week
- written solution to *one of the problems*
  should be submitted at the beginning of the exercise class
- solutions to *two other problems*:
  indicate how much you accomplished,
  and be ready to present the solution in the class

Training in problem solution is essential
for succeeding in the written exam!

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Do not expect detailed homework corrections!

Mo 11:15, SR 221

kick-off meeting: 26.10, then bi-weekly

Volunteer to make a seminar presentation

20-30 min talks introducing individual materials or applications

Examples of topics:

- quantum metrology
- topological transistors
- room-temperature superconductivity
- superconducting qubits

- full list is available on the web page
- select your topic and send it to alexander.tsirlin@uni-leipzig.de, or discuss at the first meeting on 26.10

Admission criterion:

- 50% of the homework points

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Written exam (3 hours)

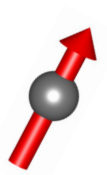
- first attempt: February
- second attempt: March

- several problems (resembling the homeworks)
- questions on the main concepts introduced during the lectures
- only topics covered in the homeworks may appear in the exam

How to handle band structures?



Tight-binding model



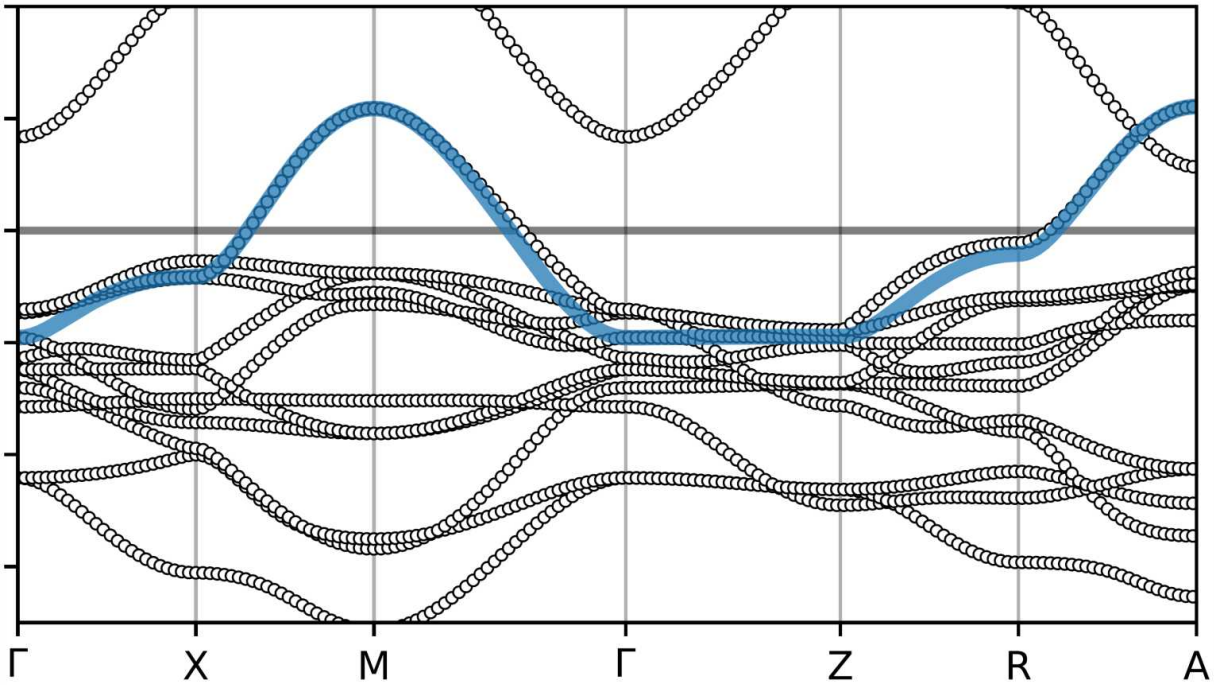
by Alexander Tsirlin, Leipzig University

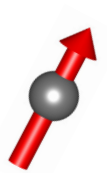
Lecture 1: October 12, 2026

How to handle band structures?



Tight-binding model





by Alexander Tsirlin, Leipzig University

Lecture 1: October 12, 2026

Band structure of NaCl

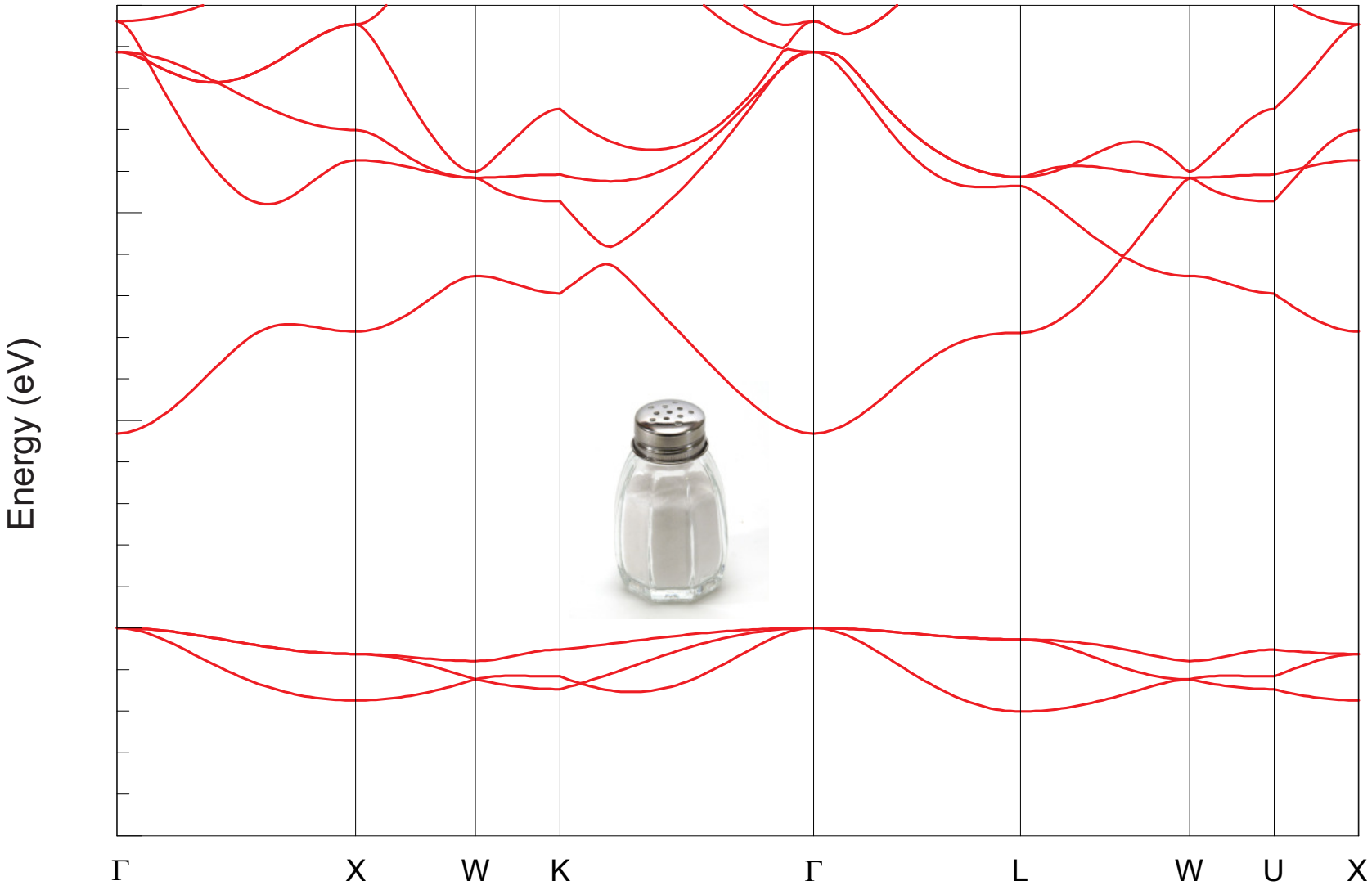


Image credit (salt): Dubravko Sorić (CC-BY)

Band structure of NaCl

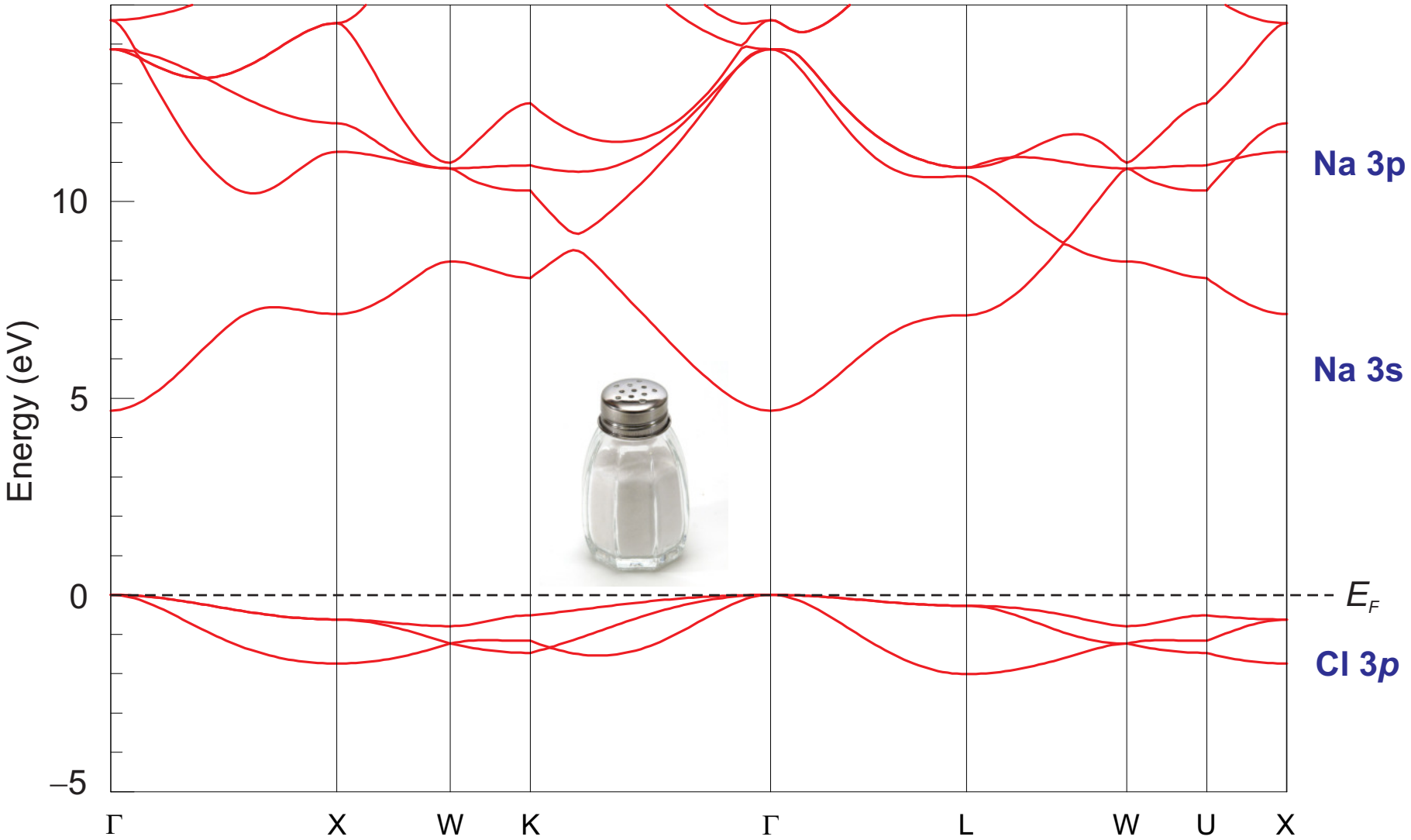
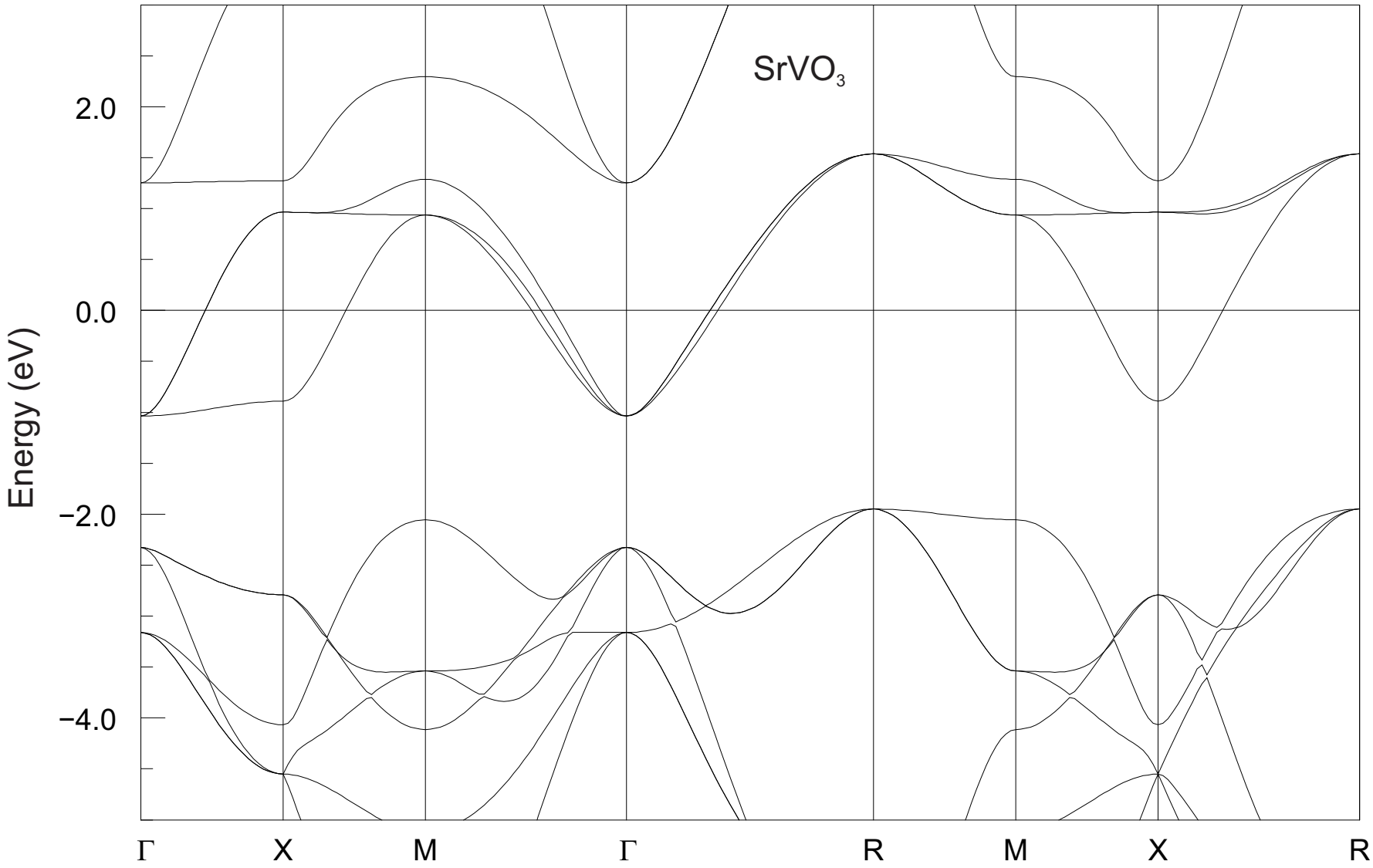
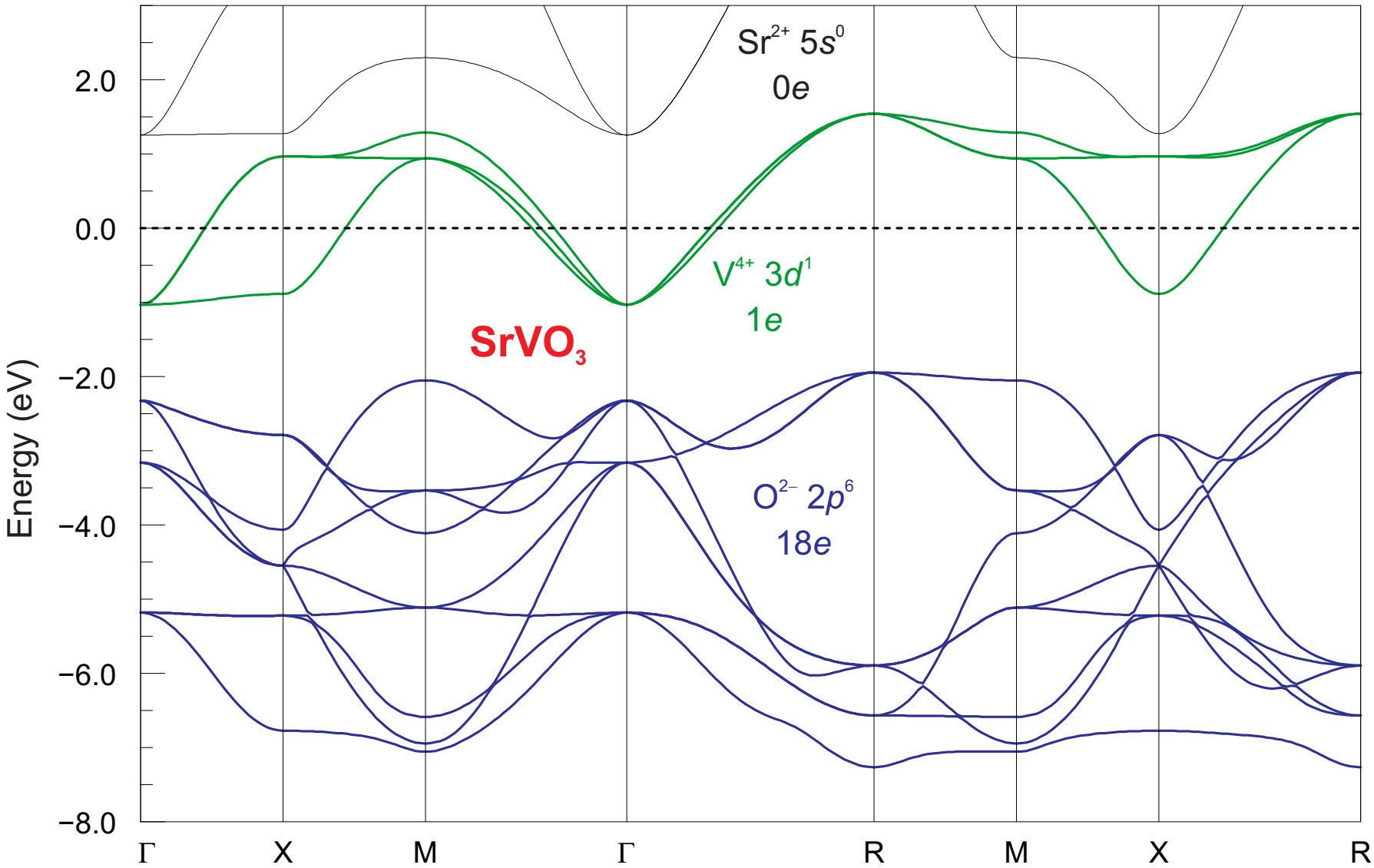


Image credit (salt): Dubravko Sorić (CC-BY)

Band structure of $SrVO_3$



Band structure of $SrVO_3$



Bands vs. DOS

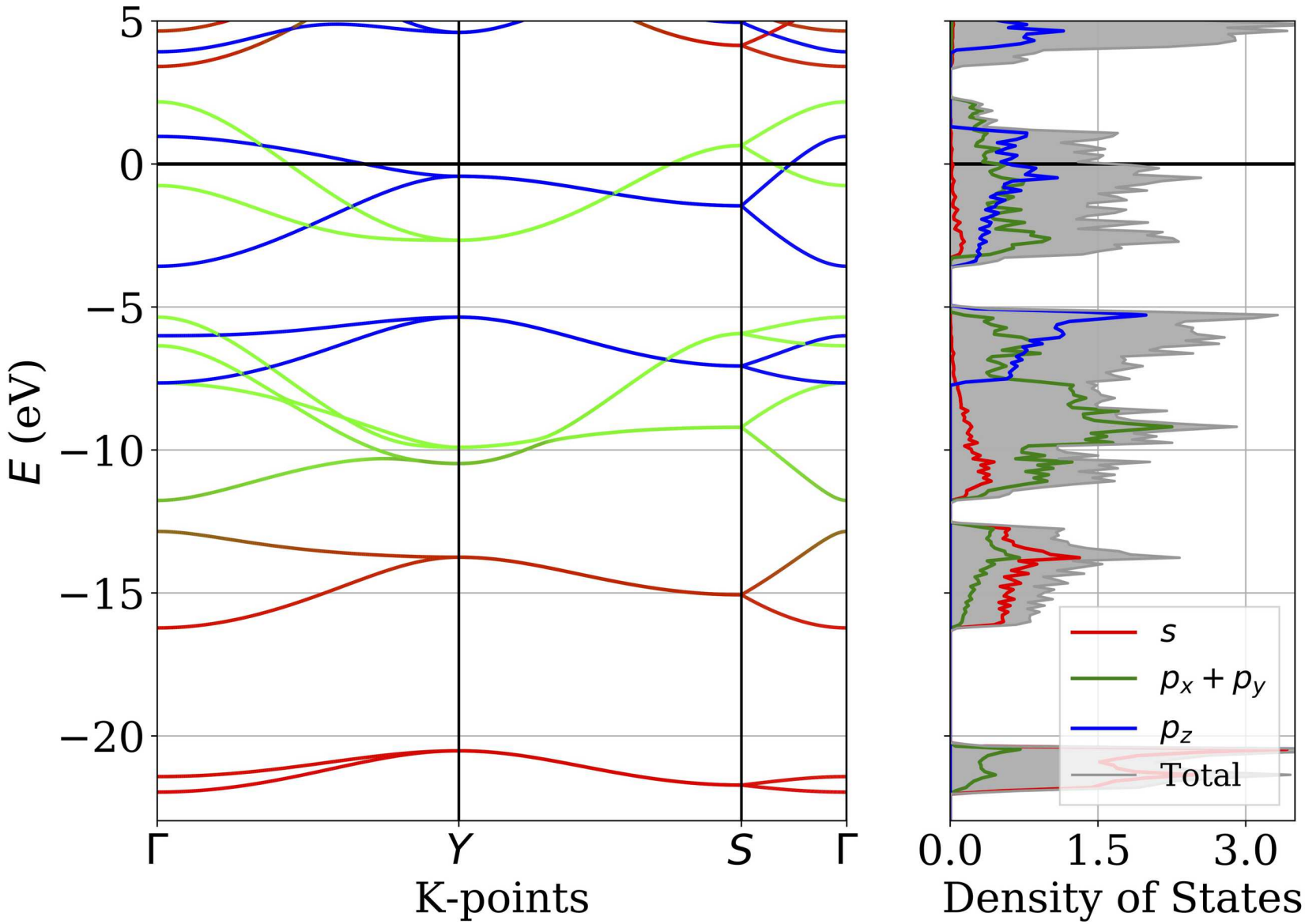
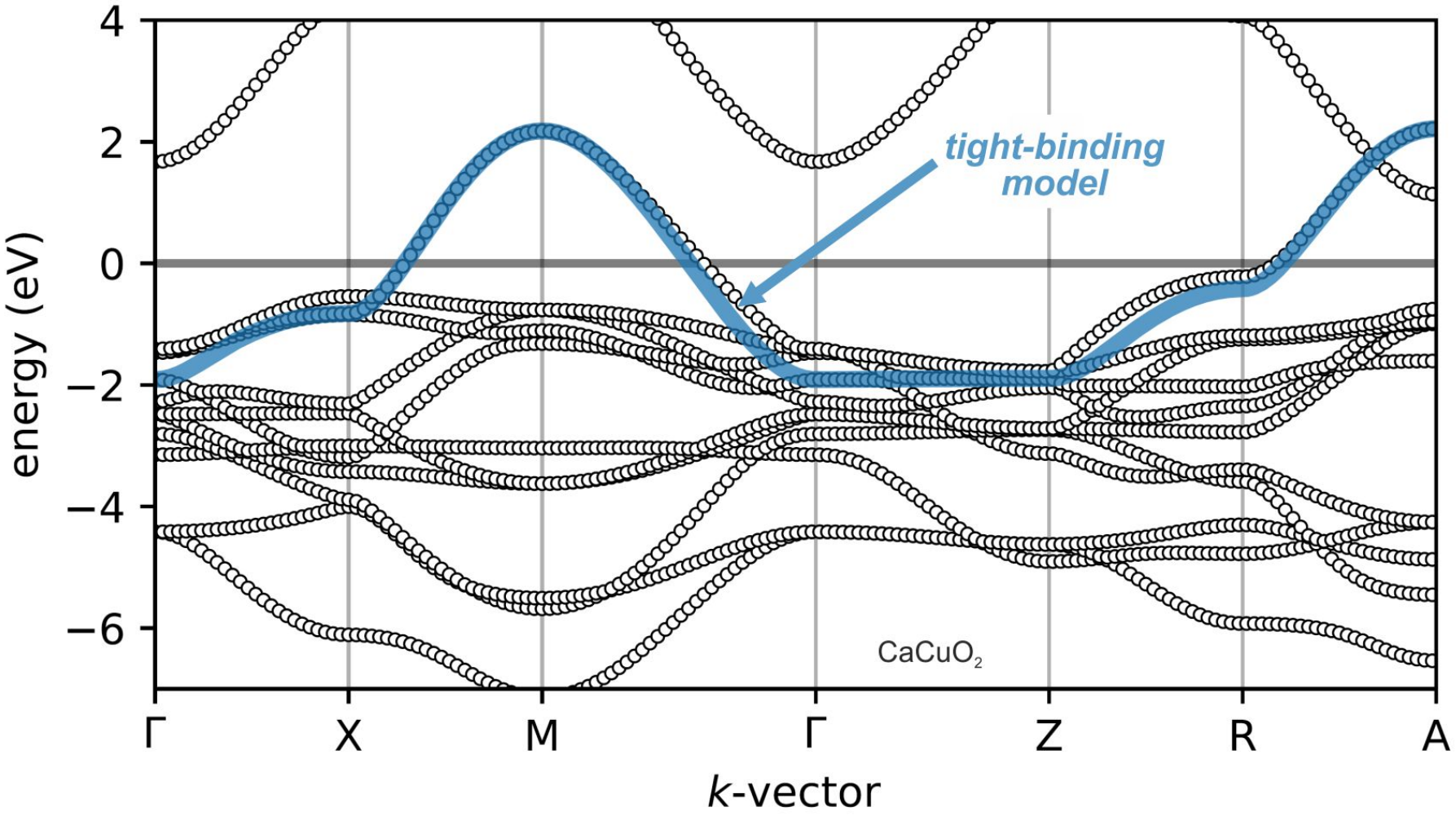


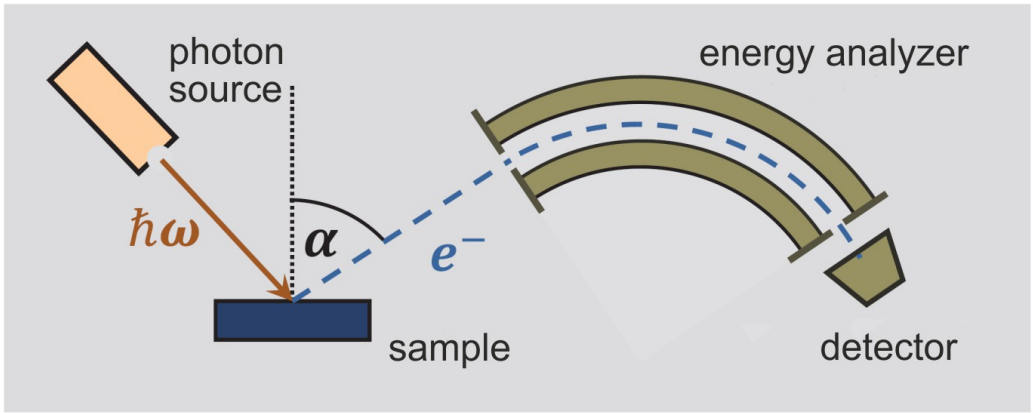
Image credit: Kevin Waters

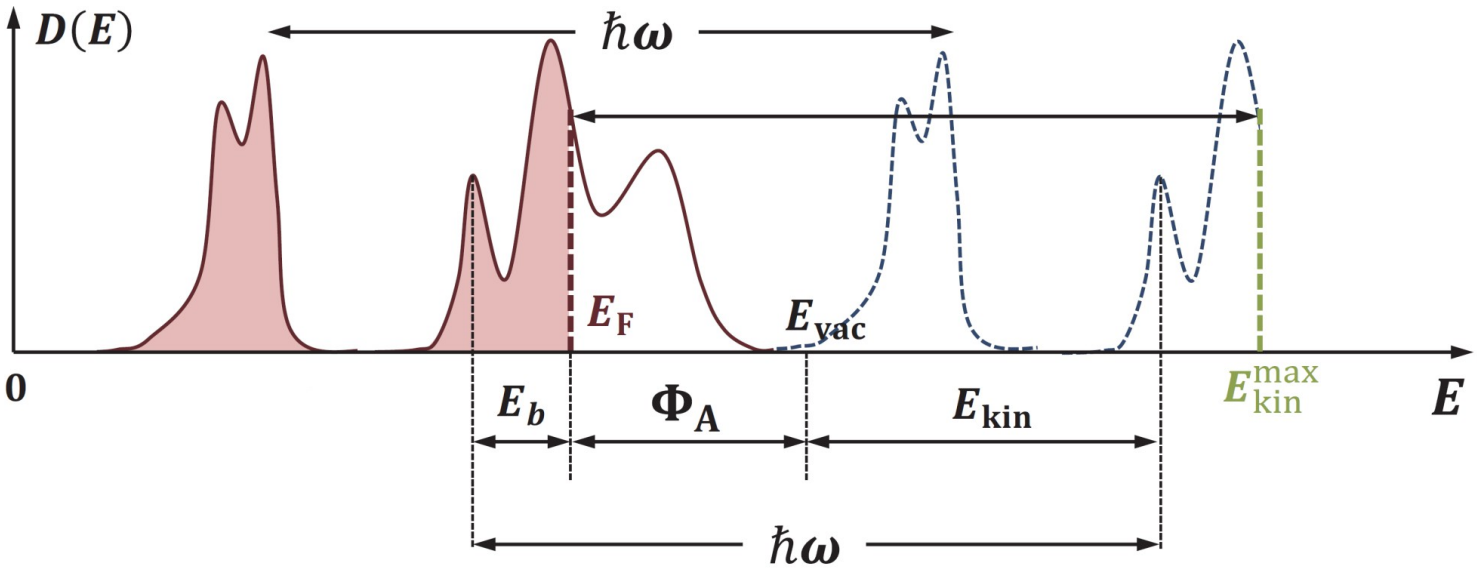


Phys. Rev. B 107, 235135 (2023)

Probe of band structure: APRES

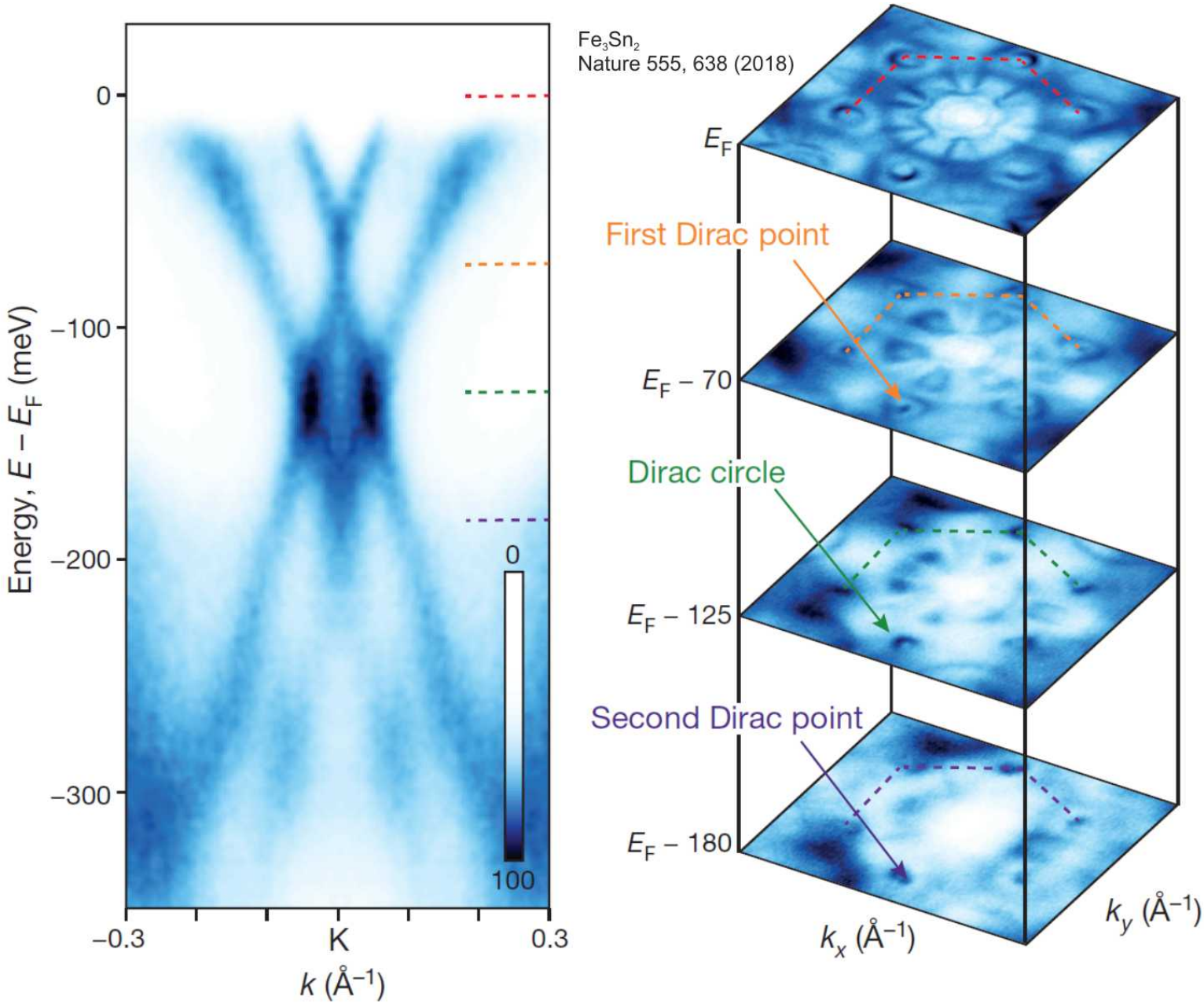
Gross and Marx,
Festkörperphysik



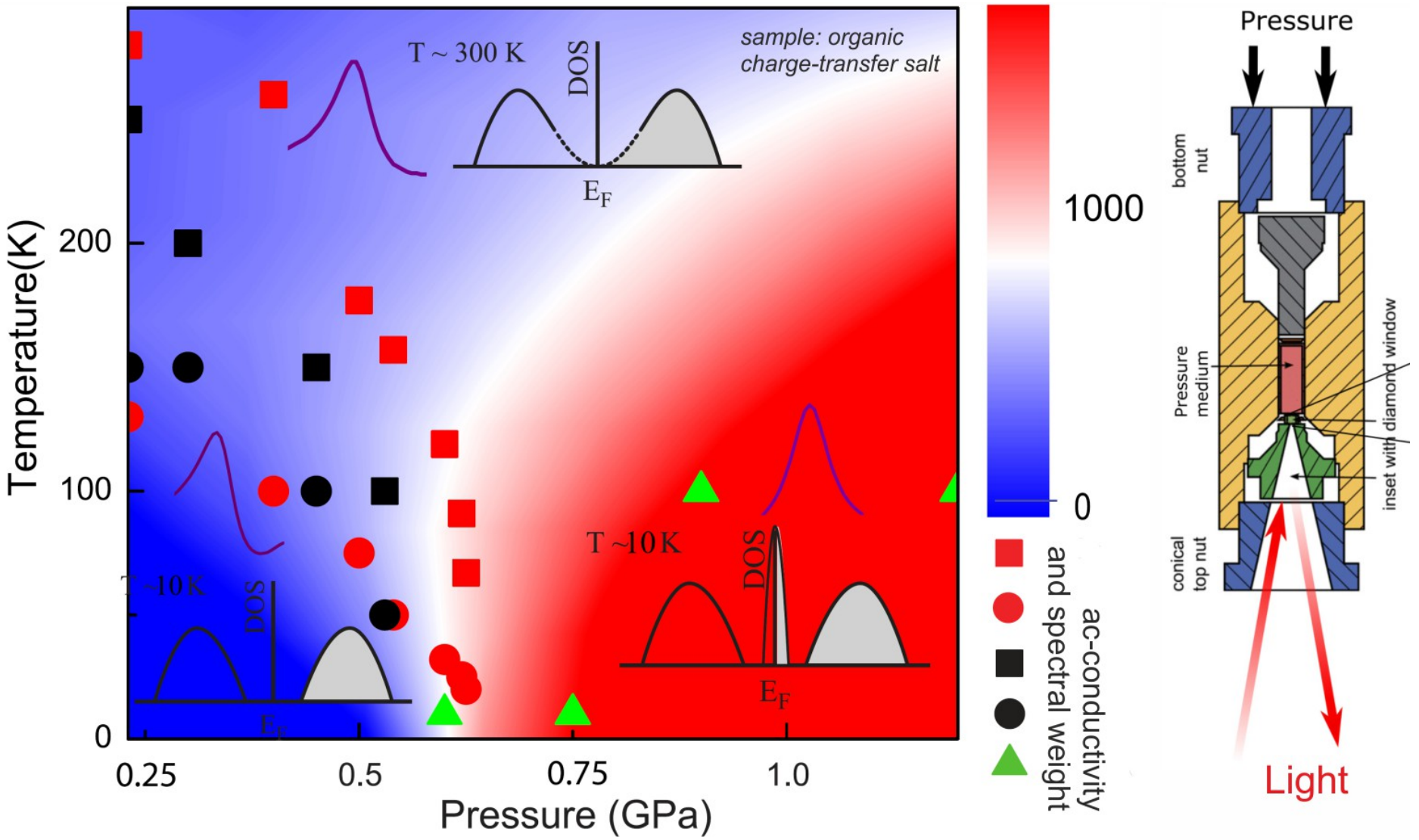


ARPES = angle-resolved photoemission spectroscopy

ARPES spectra

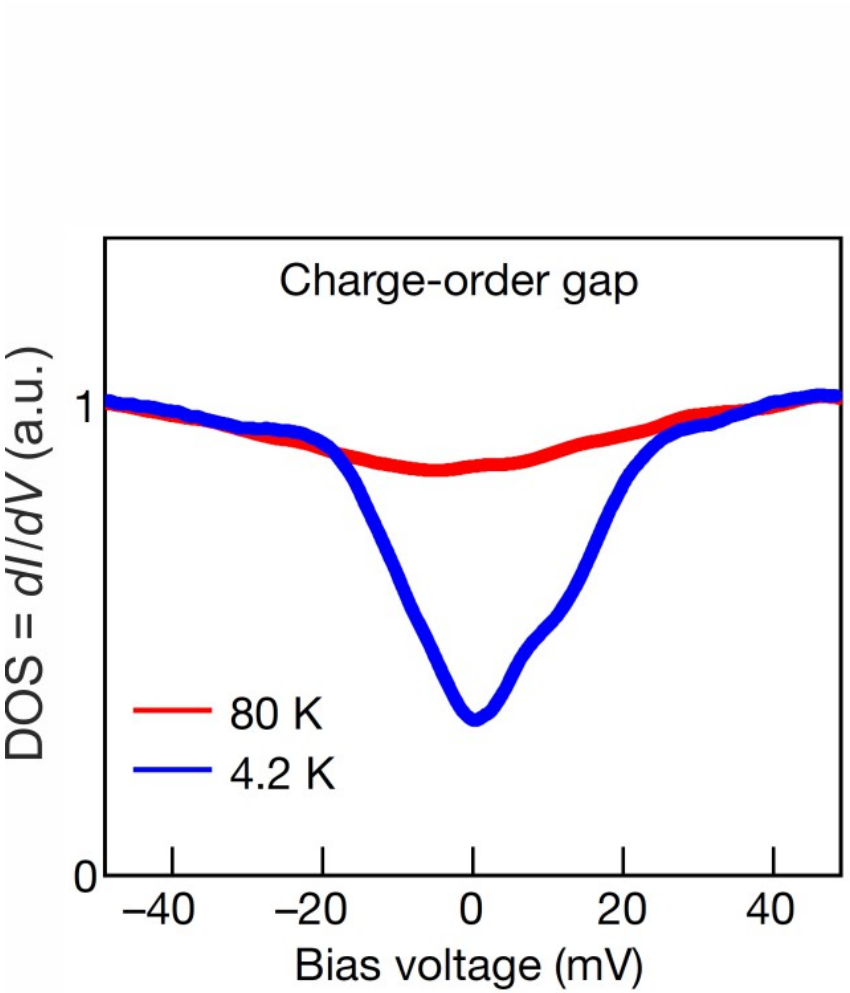


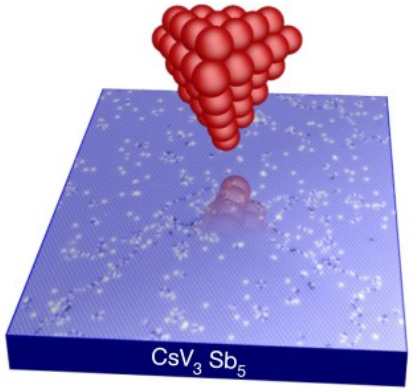
Probe of band structure: optics

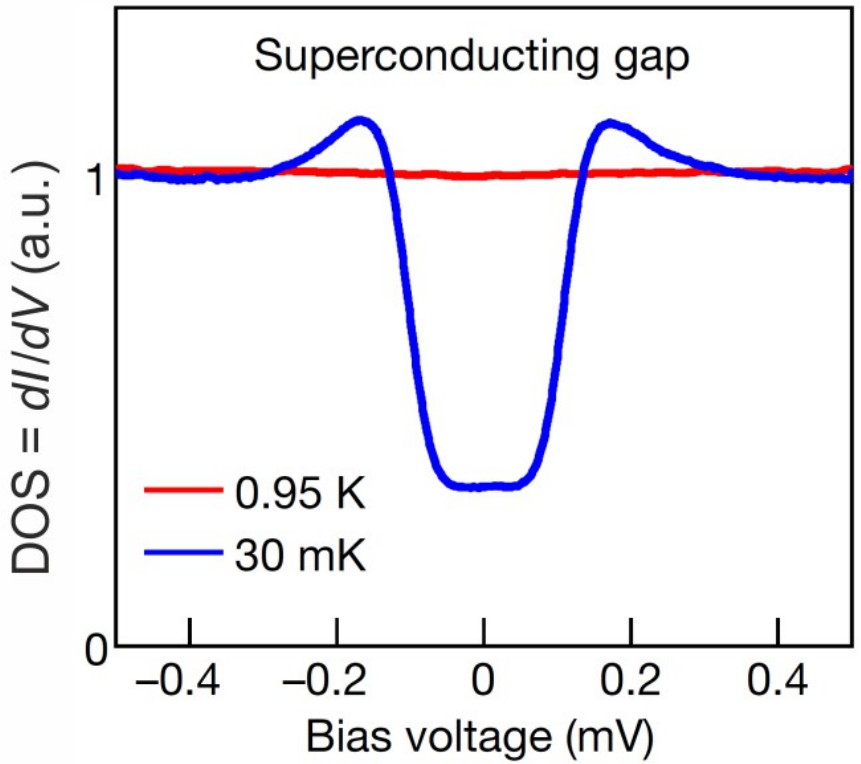


Phys. Rev. B 99, 115137 (2019)

Probe of band structure: STS



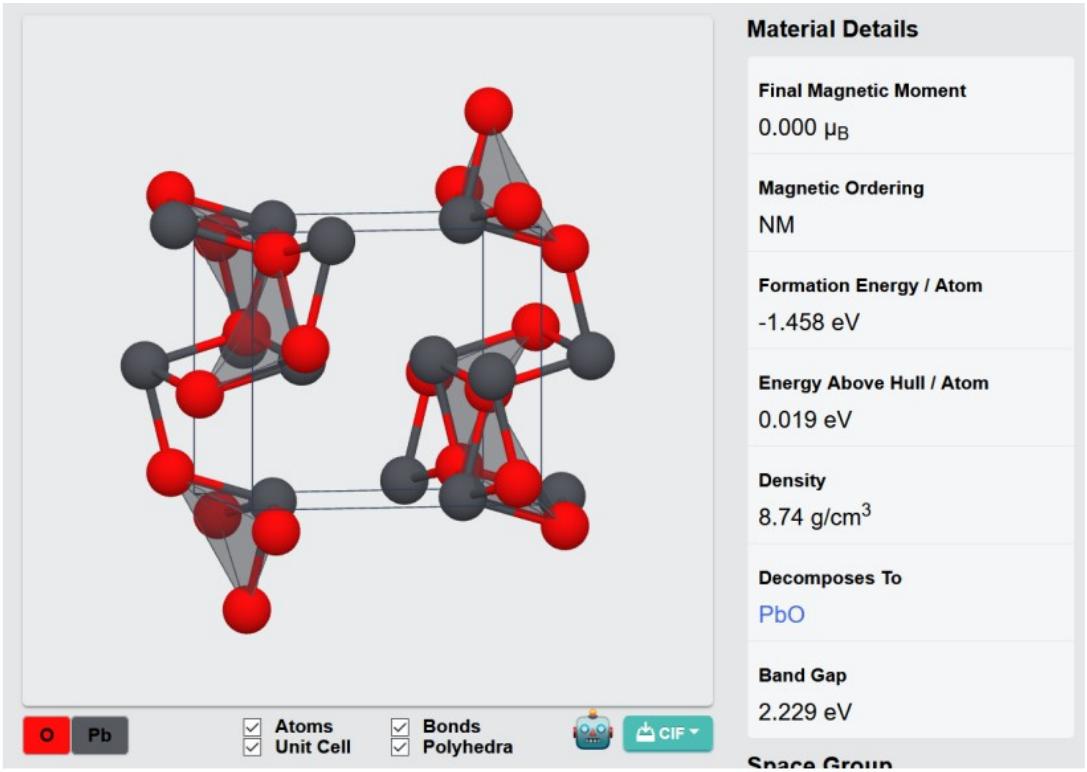




Nature 632, 775 (2024) and Nature 599, 222 (2021)

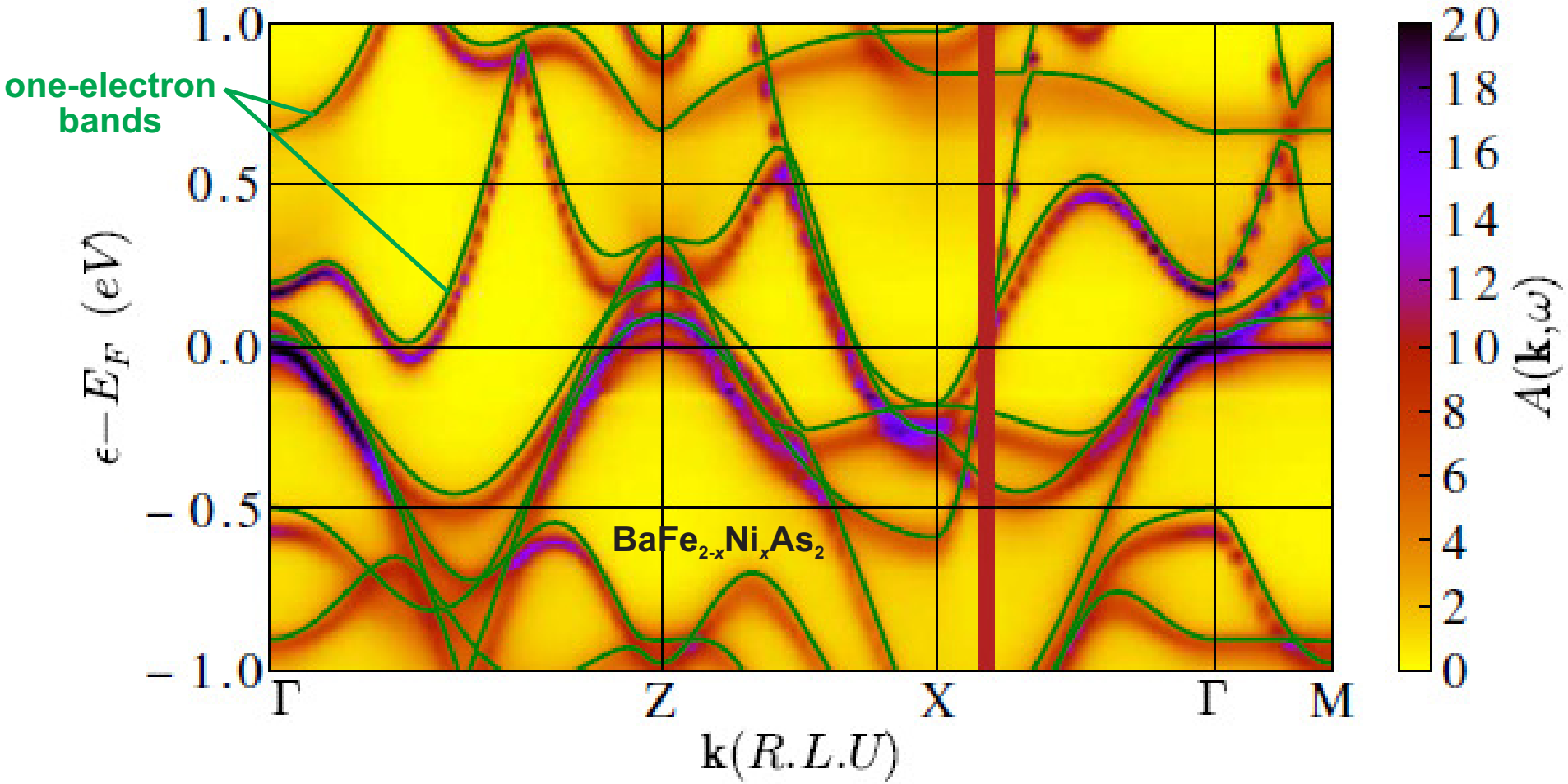
The Materials Project

https://materialsproject.org



Collects band structures for all known and many predicted materials

(the data are **not** experimental)



$A(\mathbf{k}, \omega)$ is known as Bloch spectral function