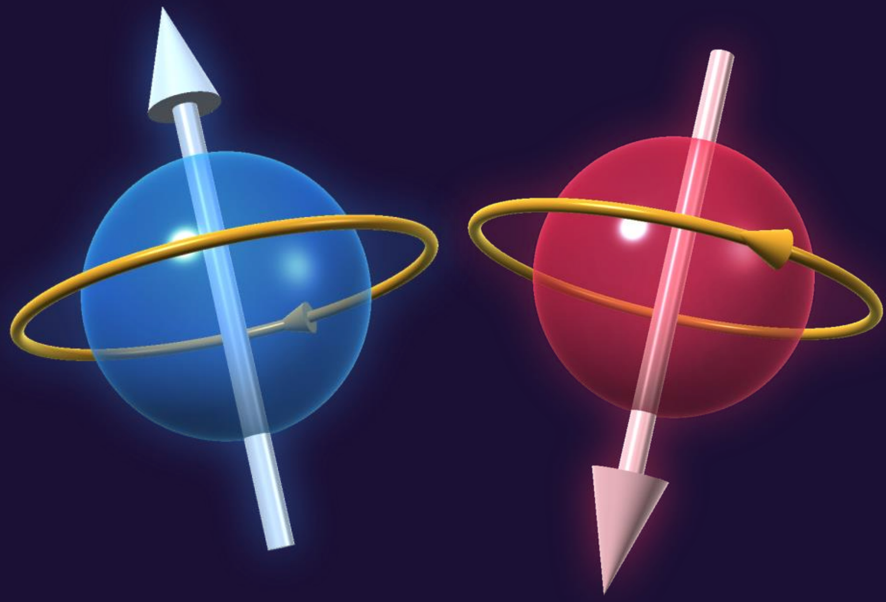
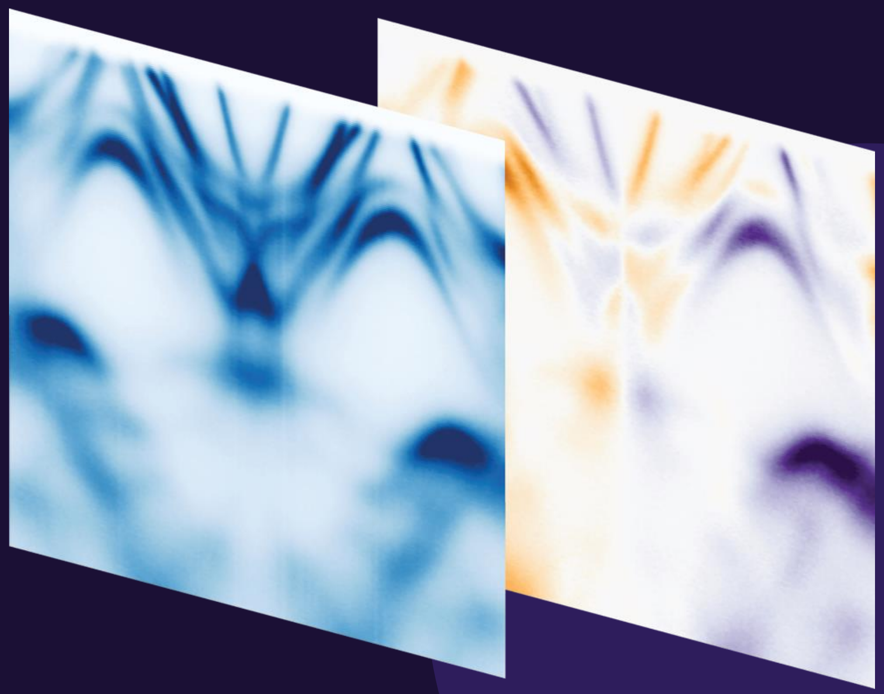
SILS — Società Italiana Luce di Sincrotrone

Spin-resolved ARPES



Reading the spin of the electron, band by band



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ARPES, Spin-ARPES, Circularly-Polarized ARPES, and Spin-and-Circularly-Polarized ARPES

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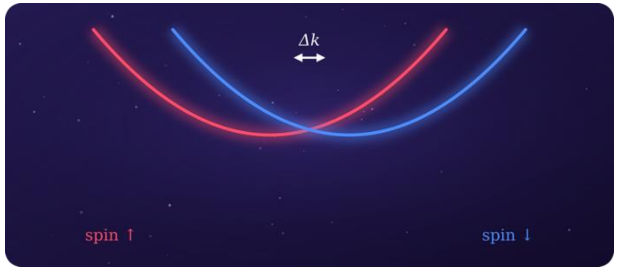
What you should walk out with

Three things to take home.

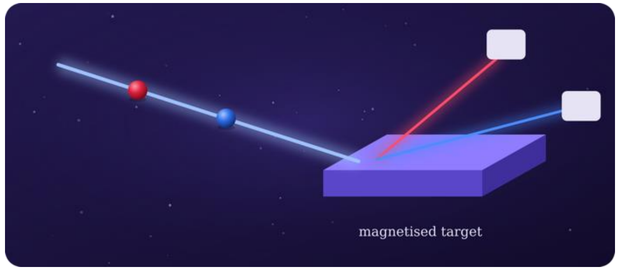
1 The physics

- Why bands split by spin
- What a spin texture is



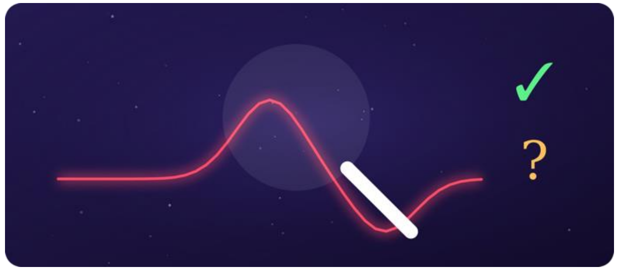
2 The measurement

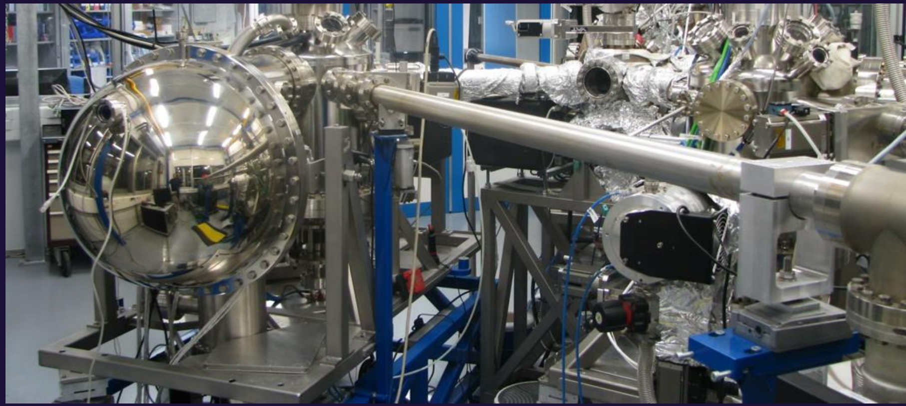
- How to detect electron spin
- Why it is ~100× slower



3 The judgement

- Real texture or artefact?
- When spin beamtime is worth it





1

Why do we want the spin?

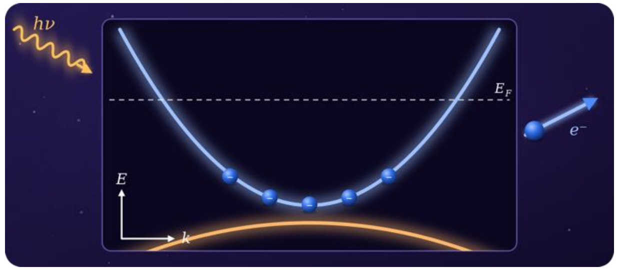
Charge tells you how a material conducts. Spin tells you why — and increasingly, it is the quantity that defines the phase itself.

An electron in a solid carries three labels

Photoemission can measure all three at once.

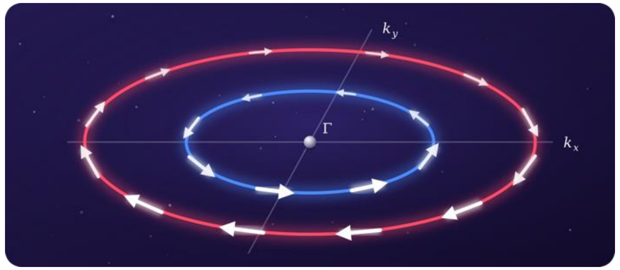
1 Charge → E(k)

- Bands, Fermi surface, gaps
- Standard ARPES



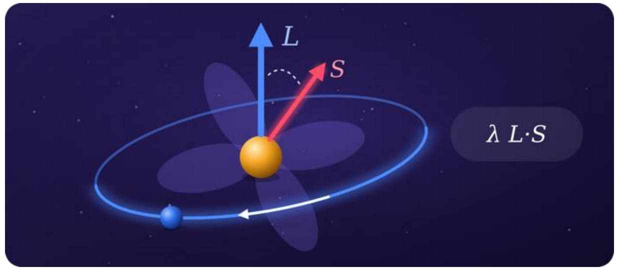
2 Spin → S(k)

- Exchange and spin–orbit splitting
- Needs a spin detector



3 Orbital → L(k)

- Orbital textures
- Often the driver: λL·S

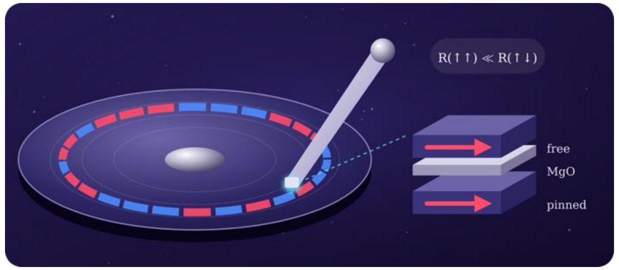


Why anyone outside this room cares

Every device below relies on spin-dependent bands.

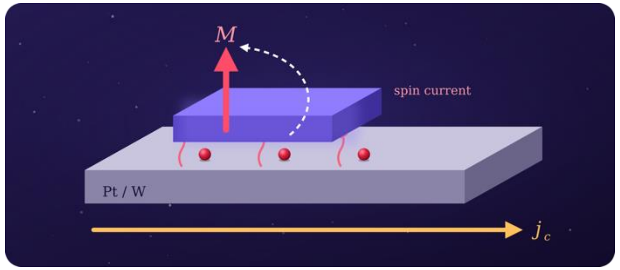
1 Reading and writing bits

- GMR / TMR read heads
- Key number: P at E_F



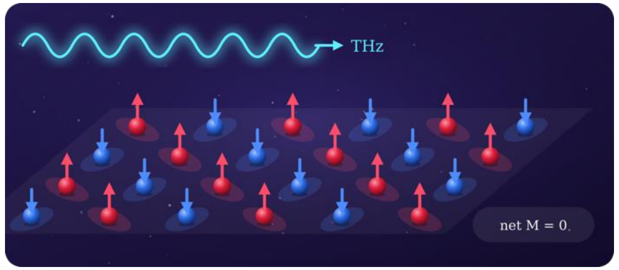
2 Switching without a field

- Spin–orbit torque
- Memory written by current



3 What comes next

- Altermagnetic memory, THz
- Invisible to magnetometry



The two mechanisms this lecture is built on

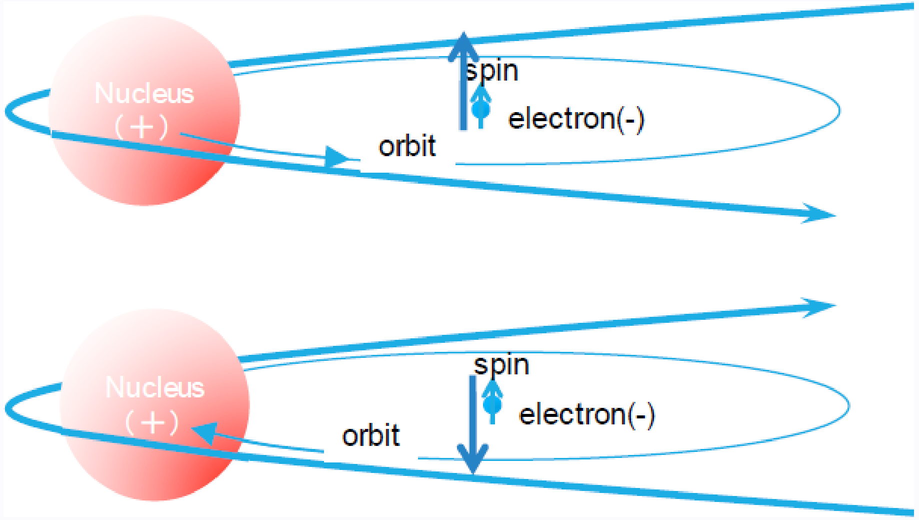
$$H_{\text{ex}} = -J\,\mathbf{S}_i\cdot\mathbf{S}_j \quad\longrightarrow\quad \Delta_{\text{ex}} = E_\uparrow(\mathbf{k}) - E_\downarrow(\mathbf{k})$$

Exchange: non-relativistic, large (0.1–2 eV)

$$H_{\text{SO}} = \lambda\,\mathbf{L}\cdot\mathbf{S}, \qquad \lambda \propto Z^4$$

Spin–orbit: relativistic, grows with Z

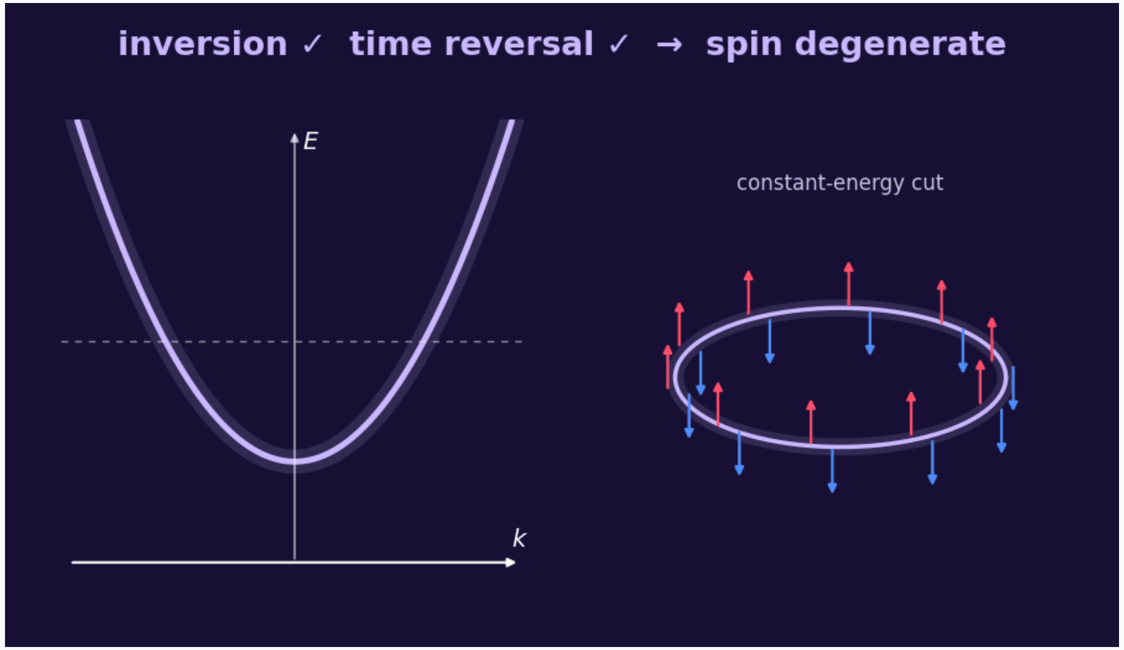
- **Exchange needs magnetic order**
- **Spin–orbit is everywhere**
  - Splits bands only if inversion is broken
- **These two organise everything we measure**



Rest frame of the electron: the nucleus orbits and acts on the spin.

What happens when a symmetry breaks?

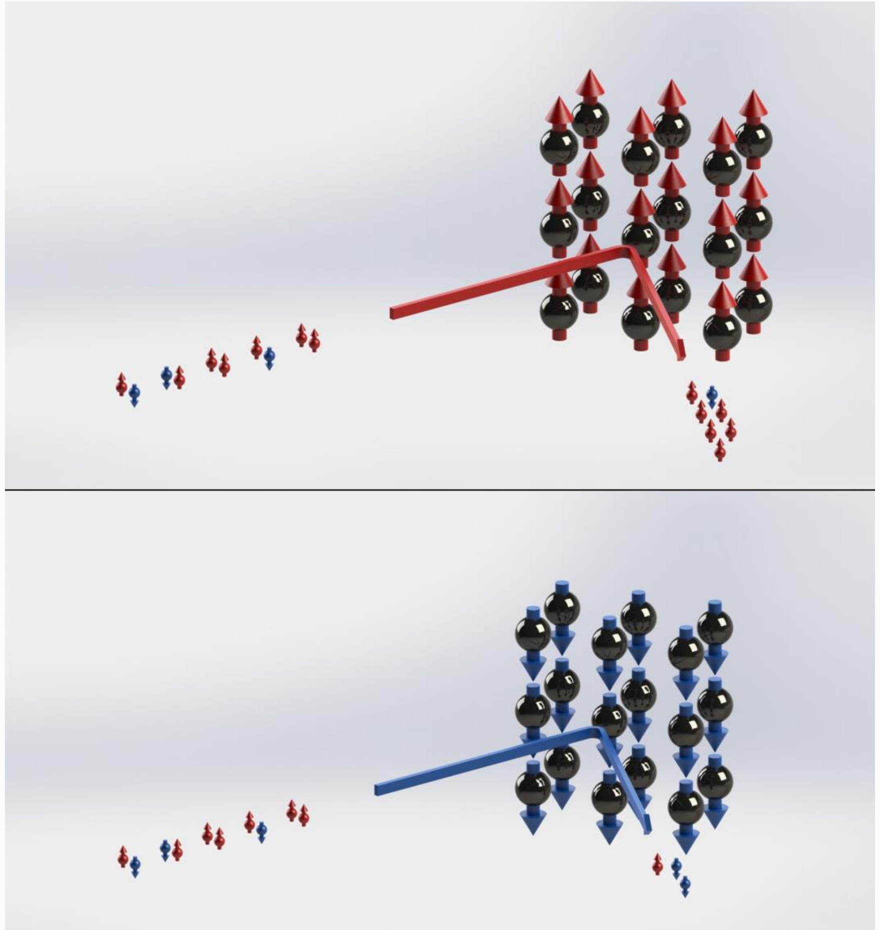
- **Both kept: every band doubly degenerate**
- **Break inversion → split in k**
  - Spin in-plane, helical (Rashba: Au(111))
- **Break time reversal → split in energy**
  - Spin along M (exchange: Fe, Co, Ni)



Left: bands E(k). Right: the same states at fixed energy, with spin arrows.

Case A — exchange splitting in a ferromagnet

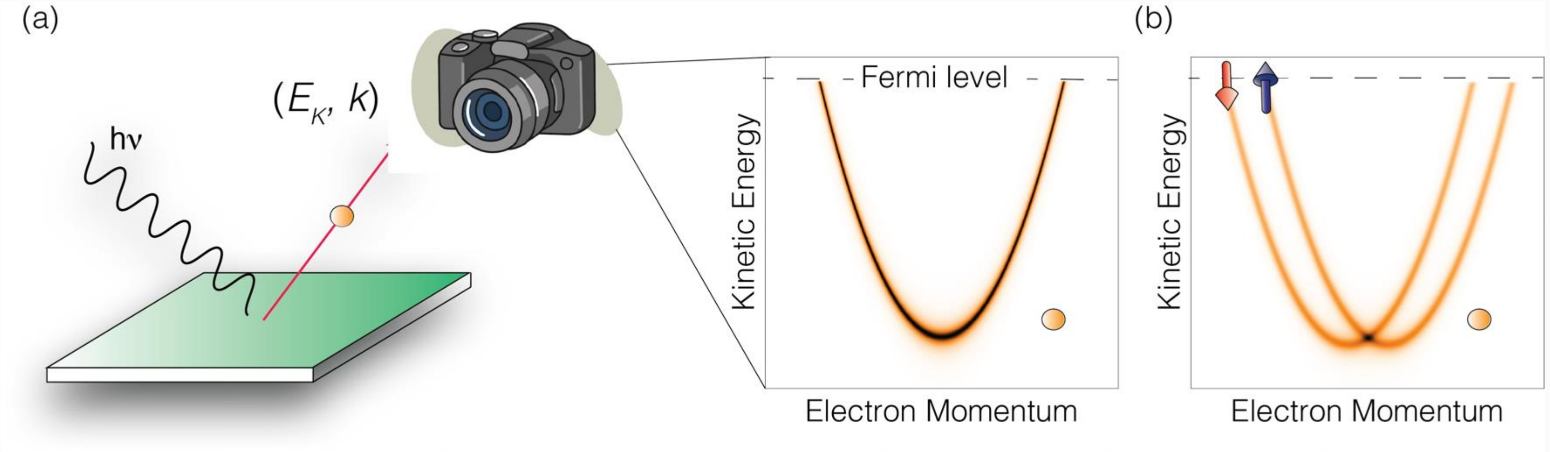
- Spin-up and spin-down bands shifted by Δex
- Fe, Co, Ni: Δex ≈ 0.3–2 eV
- Where spin-ARPES was born (1980s)
- **Sample must be magnetised**



Exchange scattering: ↑ and ↓ reflect differently.

Case B — spin–orbit: the Rashba effect

- Surface breaks inversion
- Two parabolas shifted in k
- Spin ⊥ k, in-plane, helical
- **Au(111): the calibration sample**



$$H_R = \alpha_R\,(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \hat{\mathbf{z}} \quad \longrightarrow \quad E_\pm(k) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha_R |k|$$

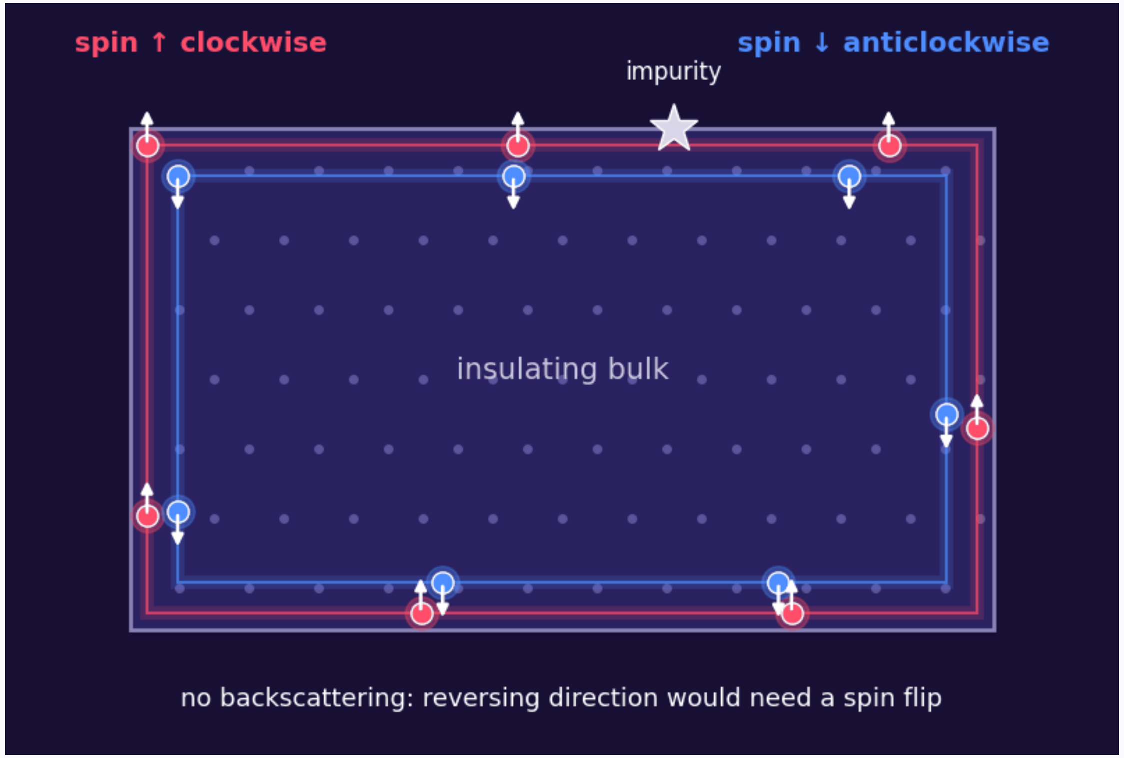
Topology first: when is an insulator topological?

- Insulator: filled bands + a gap
- Strong SOC can invert the bands
- **Undo it only by closing the gap**
- Like a sphere vs a donut

Close the gap, invert, reopen: a surface state appears.

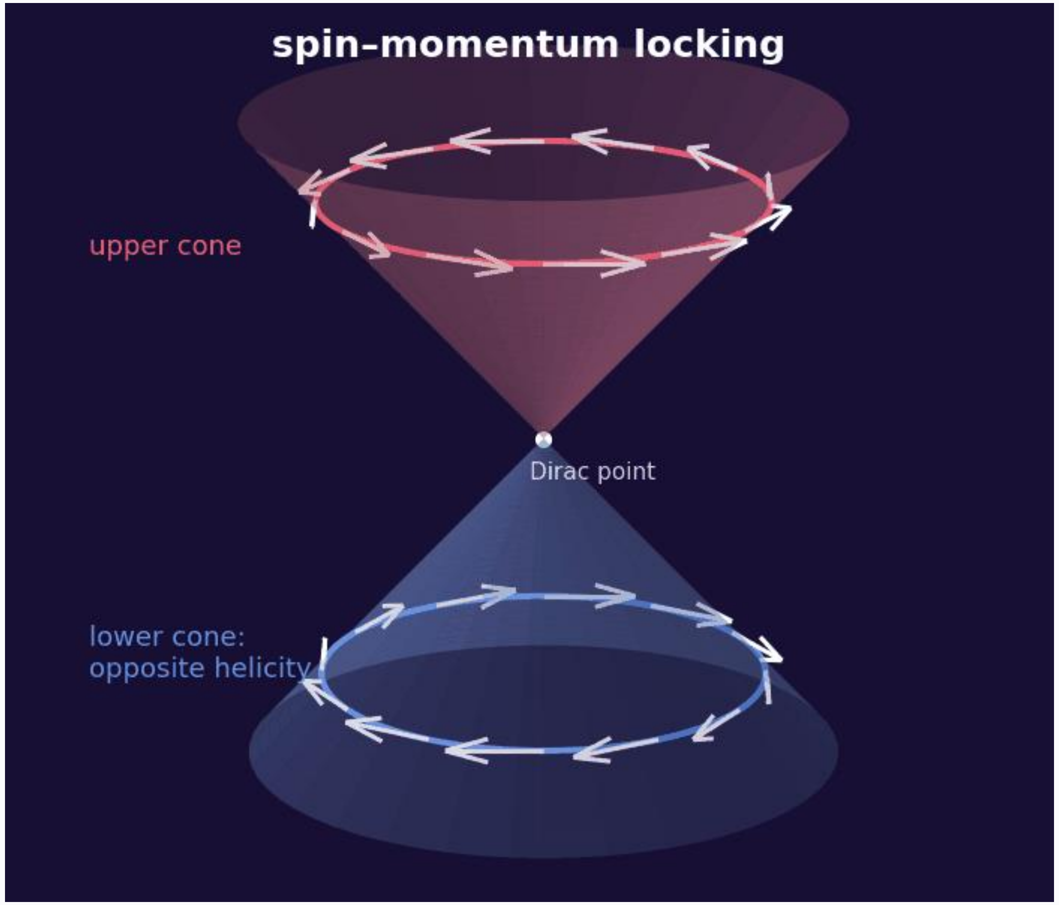
Why the edge must conduct

- Inside: topological
- Outside: vacuum, trivial
- **The gap must close at the boundary**
- **Edge: spin ↑ one way, ↓ the other**
- **U-turn needs a spin flip → forbidden**



2D topological insulator: counter-propagating spin channels.

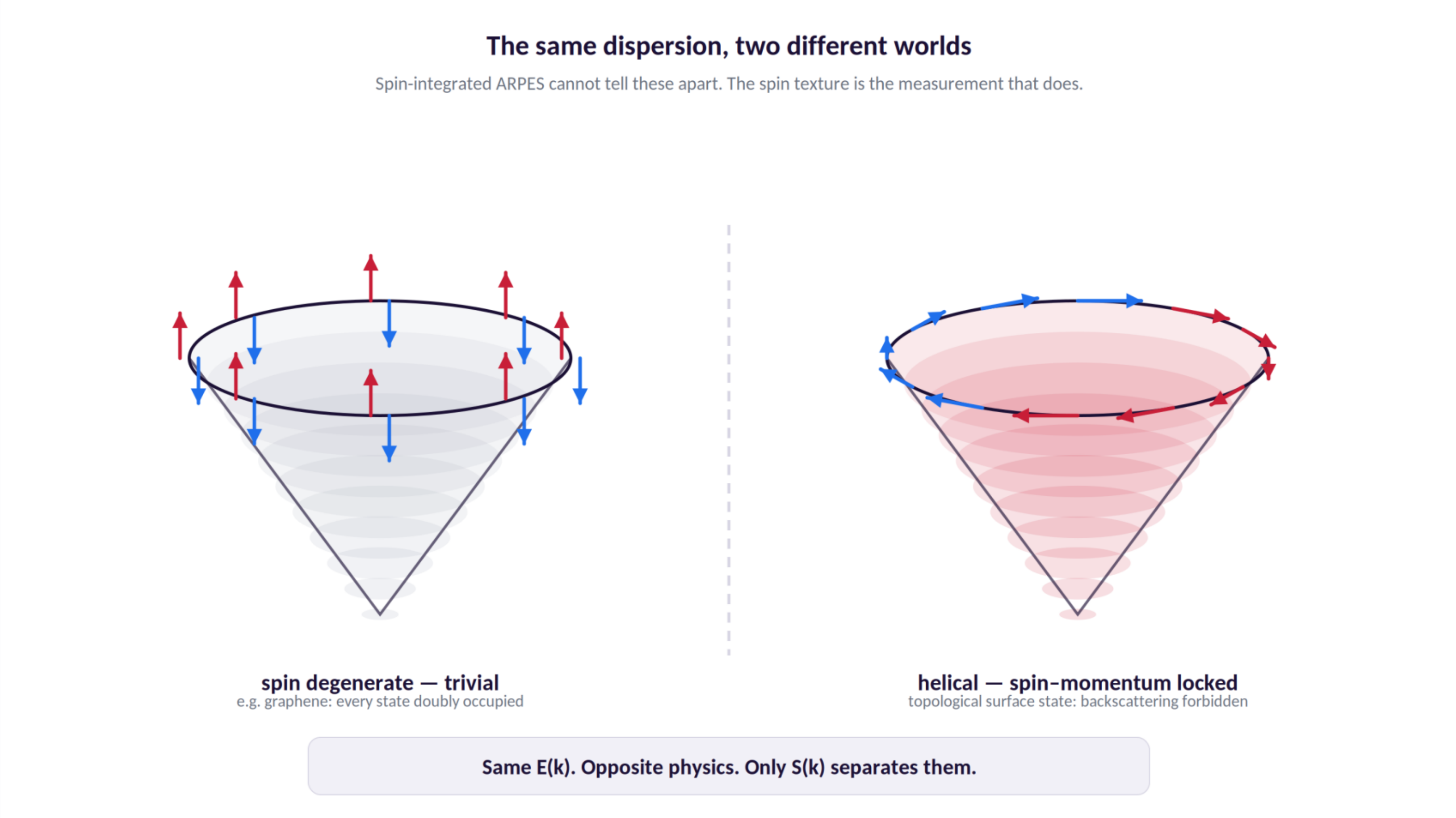
Case C — in 3D: the surface Dirac cone



Spin winds around the cone; helicity reverses across the Dirac point.

- One Dirac cone at the surface
- Spin locked to k by time reversal
- No backscattering +k → −k
- **Spin texture: necessary, not sufficient**
  - Also needs bulk gap + band connectivity

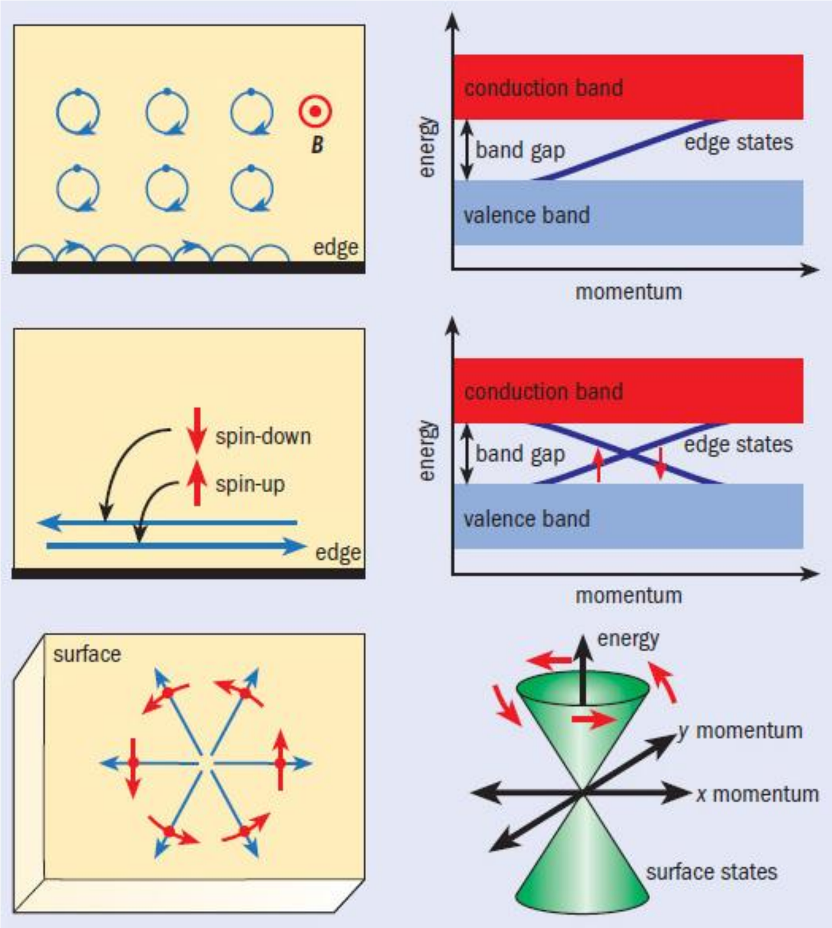
Why the spin texture is the whole argument



Same dispersion. Left: spins cancel. Right: spin winds with k.

And a case that breaks the rules: hidden spin polarisation

- Inversion + time reversal → degenerate bands
- Local sectors still polarised
- **Surface probe sees one sector**
- Polarisation ≠ proof of broken symmetry



The spin lives in the sublattice, not the unit cell.

optional — skip if short on time

THE ONE-SENTENCE MOTIVATION

Spin-ARPES is the only technique that measures energy, momentum and spin of the same electron, at the same time.

Neutrons: no bands. XMCD: no k. Transport: no texture.

2

13 minutes

ARPES in a hurry

Only what we need to add spin.

Everything follows from two conservation laws

$$E_{\mathrm{kin}} = h\nu - \Phi - |E_B|$$

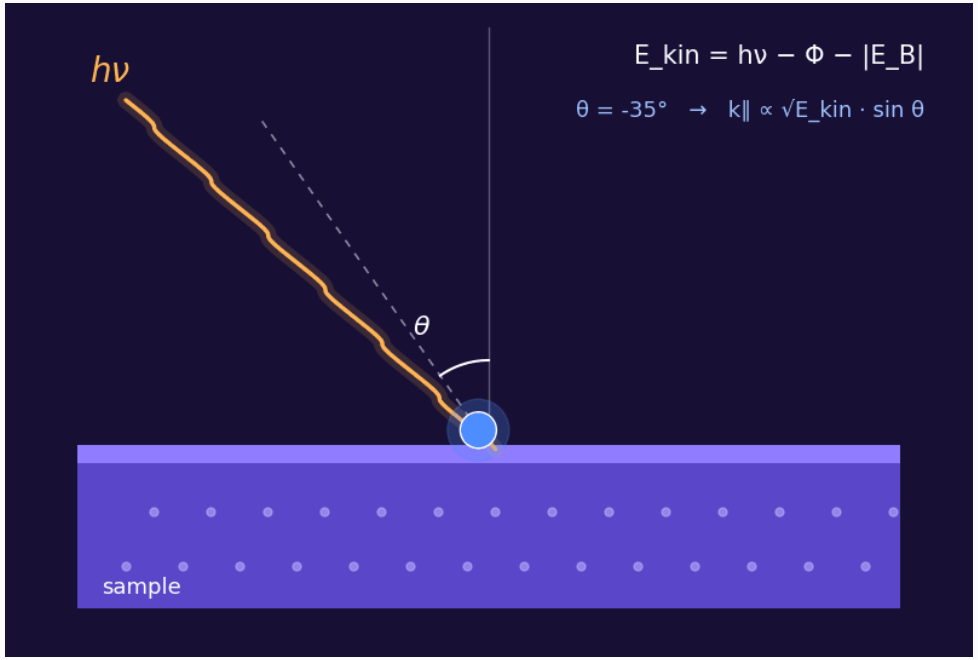
Energy conservation — Einstein, 1905.

$$k_{\|} = 0.5123\,\sqrt{E_{\mathrm{kin}}\,[\mathrm{eV}]}\;\sin\theta \quad [\mathrm{Å}^{-1}]$$

In-plane momentum is conserved across the surface.

$$k_{\perp} = 0.5123\,\sqrt{E_{\mathrm{kin}}\cos^2\theta + V_0}$$

$k_\perp$ is not conserved: needs V_0.



Photon in, electron out: energy and k∥ are conserved.

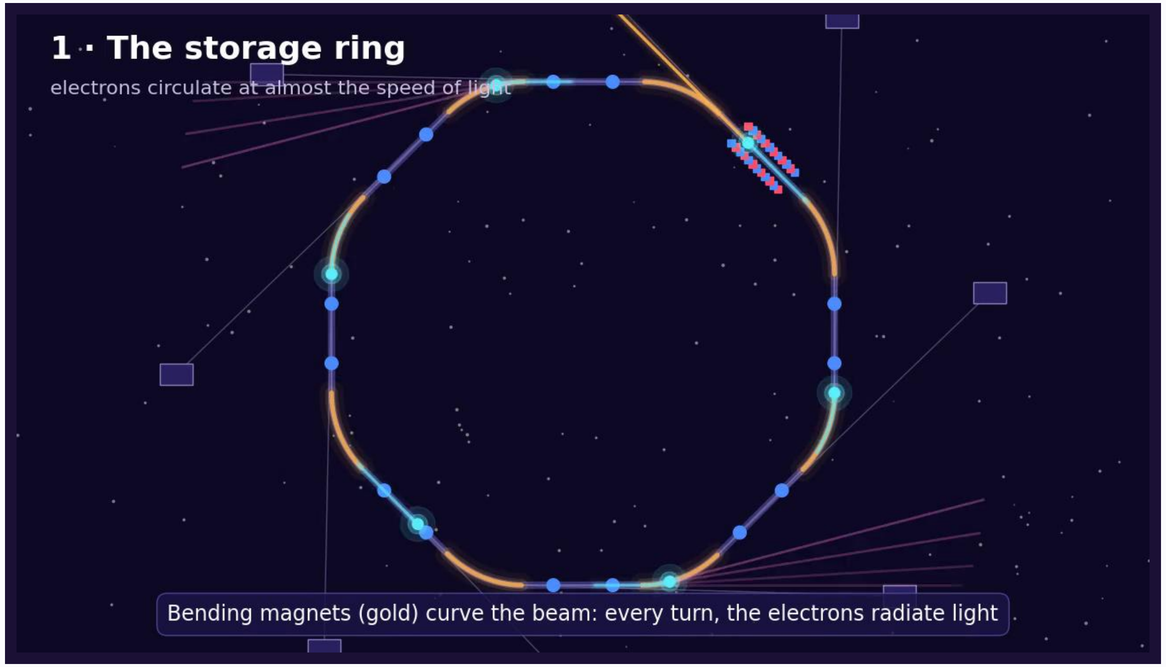
- Measure E_kin and θ → E(k)
- **k_z is the weakest axis**

2a

Where do the photons come from?

The source decides resolution, k range and polarisation.

The synchrotron: relativistic electrons, tunable light



Ring → undulator → APPLE polarisation → beamline to the sample.

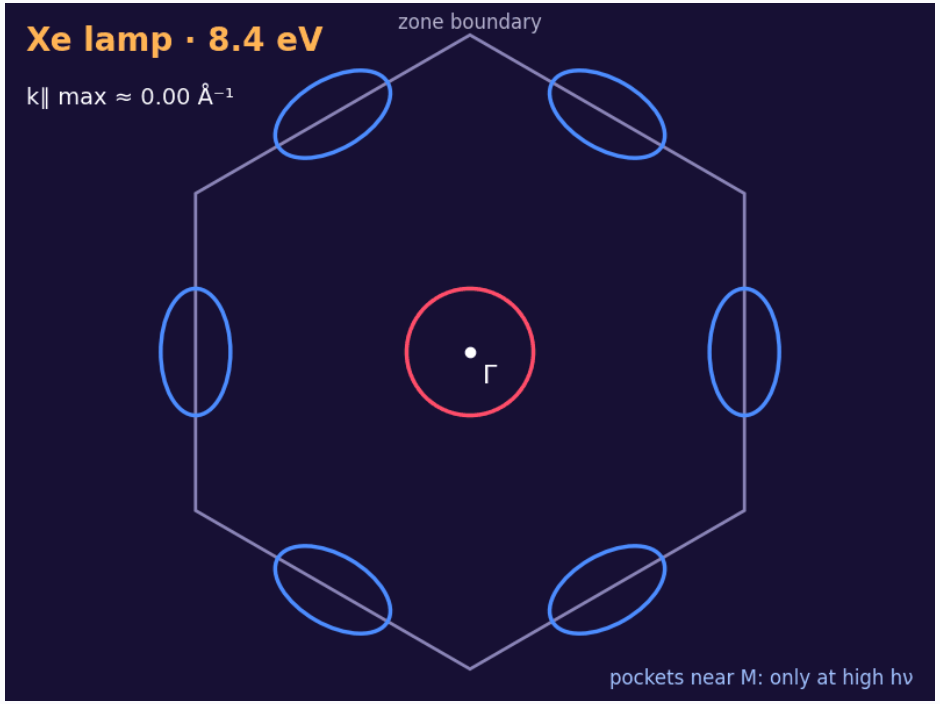
- Relativistic electrons radiate when bent
- **Undulator gap → photon energy**
- **APPLE undulator → any polarisation**
  - Our main weapon against artefacts

How much of the Brillouin zone can you actually reach?

$$k_{\parallel}^{\max} = 0.5123\,\sqrt{h\nu - \Phi}\ \sin\theta_{\max} \quad [\text{Å}^{-1}]$$

Low hv: better resolution, smaller k range.

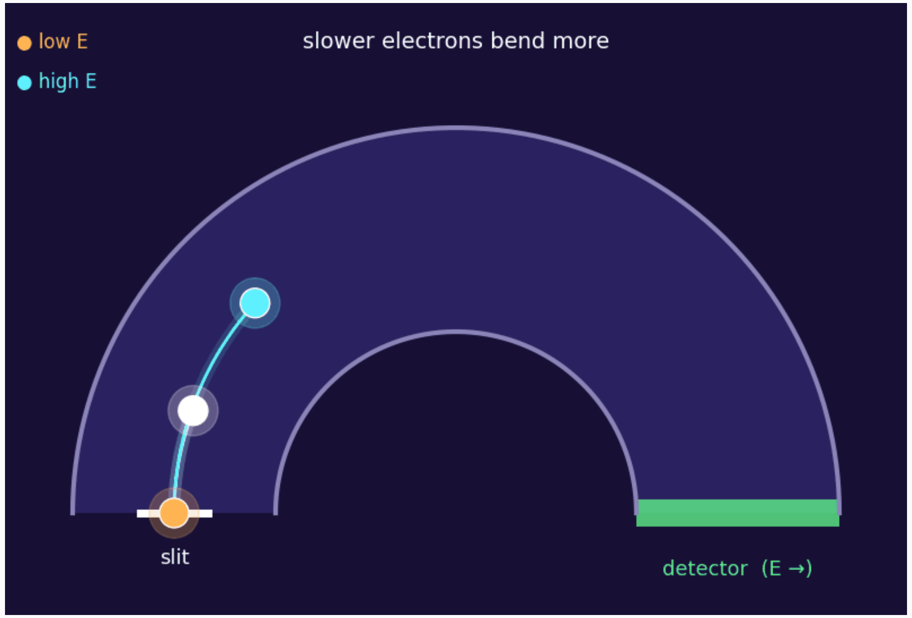
- Xe 8.4 eV → 0.32 $Å^{-1}$
- He I 21.2 eV → 0.65 $Å^{-1}$
- Zone boundary ≈ 0.8–1.0 $Å^{-1}$
- **Lab sources: zone centre only**

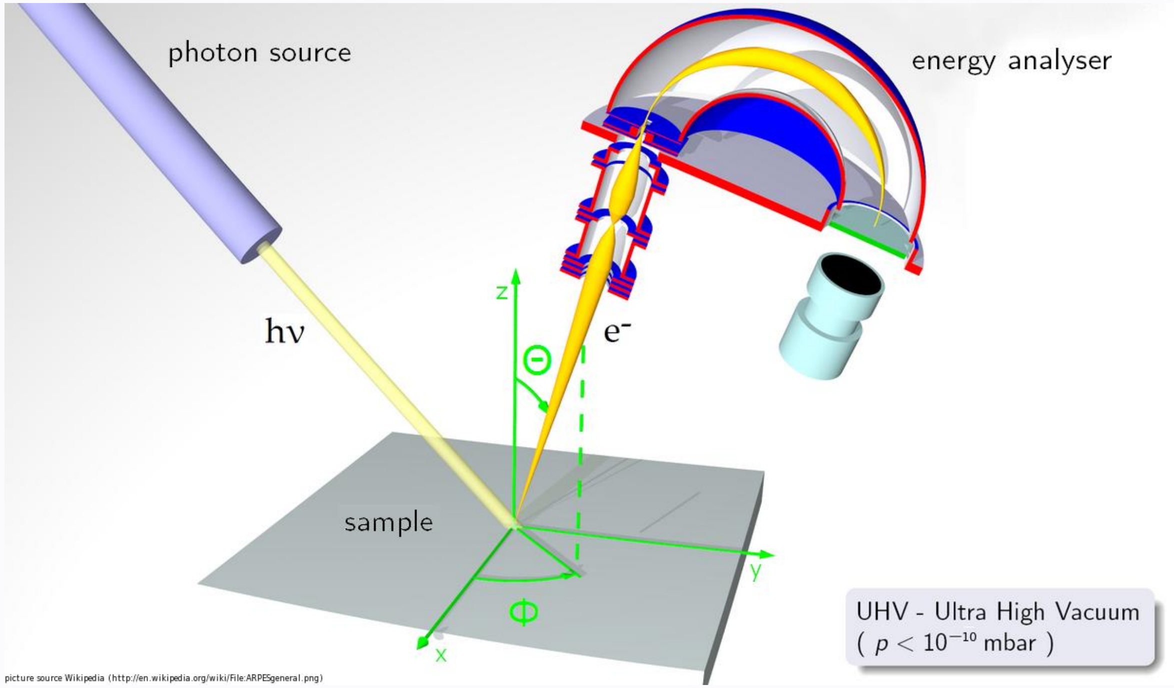


Reachable k∥ grows with photon energy.

The instrument: hemispherical analyzer

- Lens → hemisphere → 2D detector
- One shot = full E vs θ image
- $\Delta E \lesssim 2$ meV, $\Delta\theta \approx 0.1°$
- **Its exit feeds the spin detector**

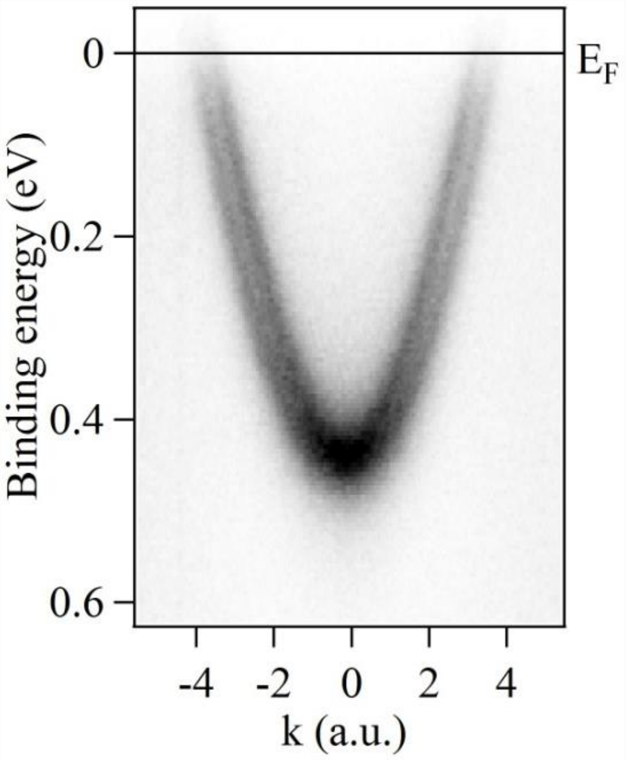




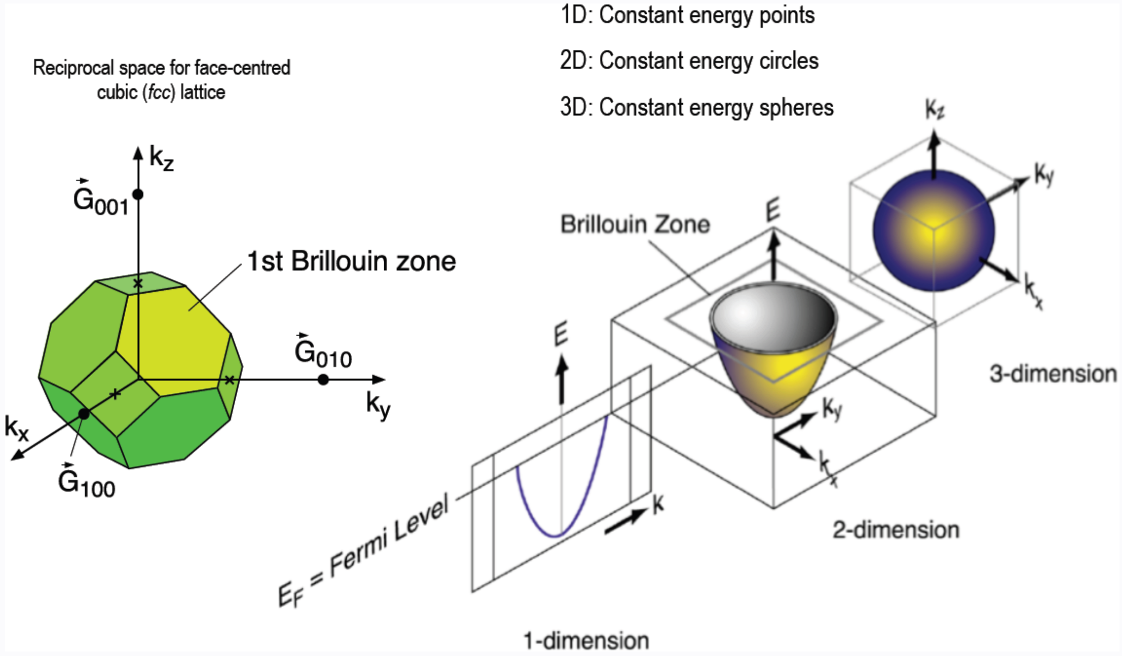
Energy and angle dispersed at once.

What a band map looks like

Au(111) surface state: our first spin target.



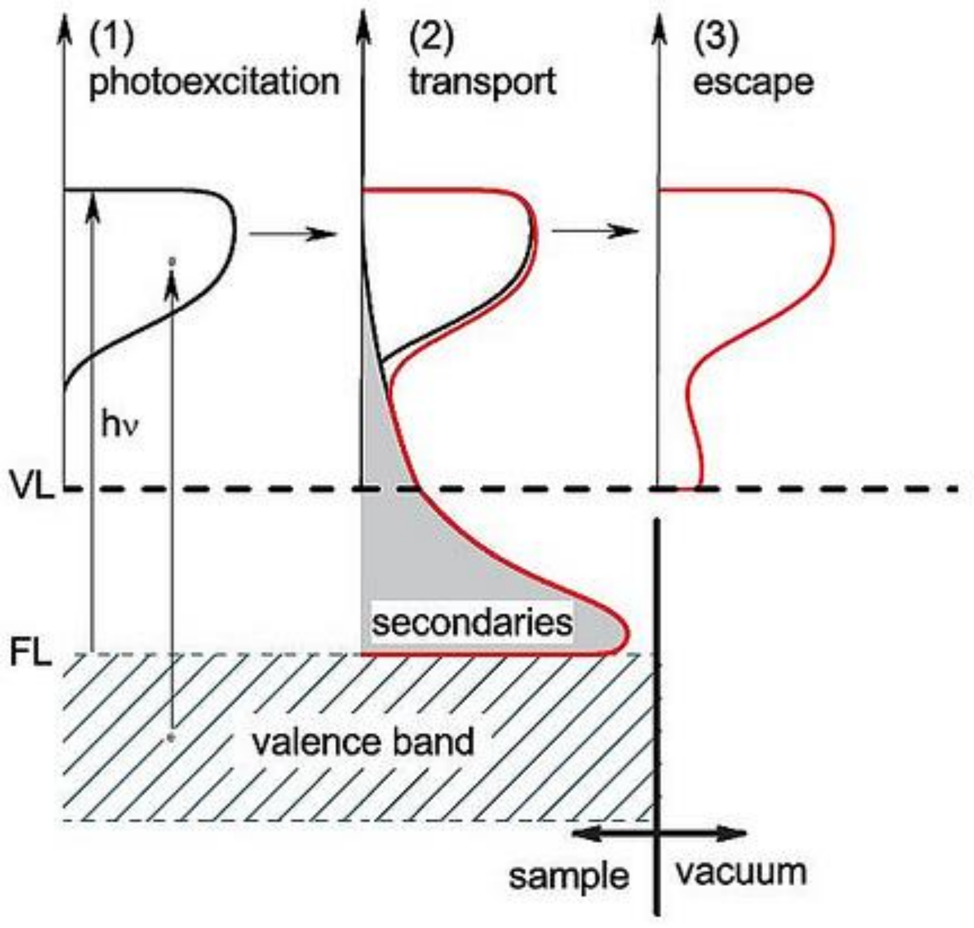
Spin integrated: splitting barely visible.



Constant-energy cuts: 1D, 2D, 3D.

The three-step model — and why step 3 matters for spin

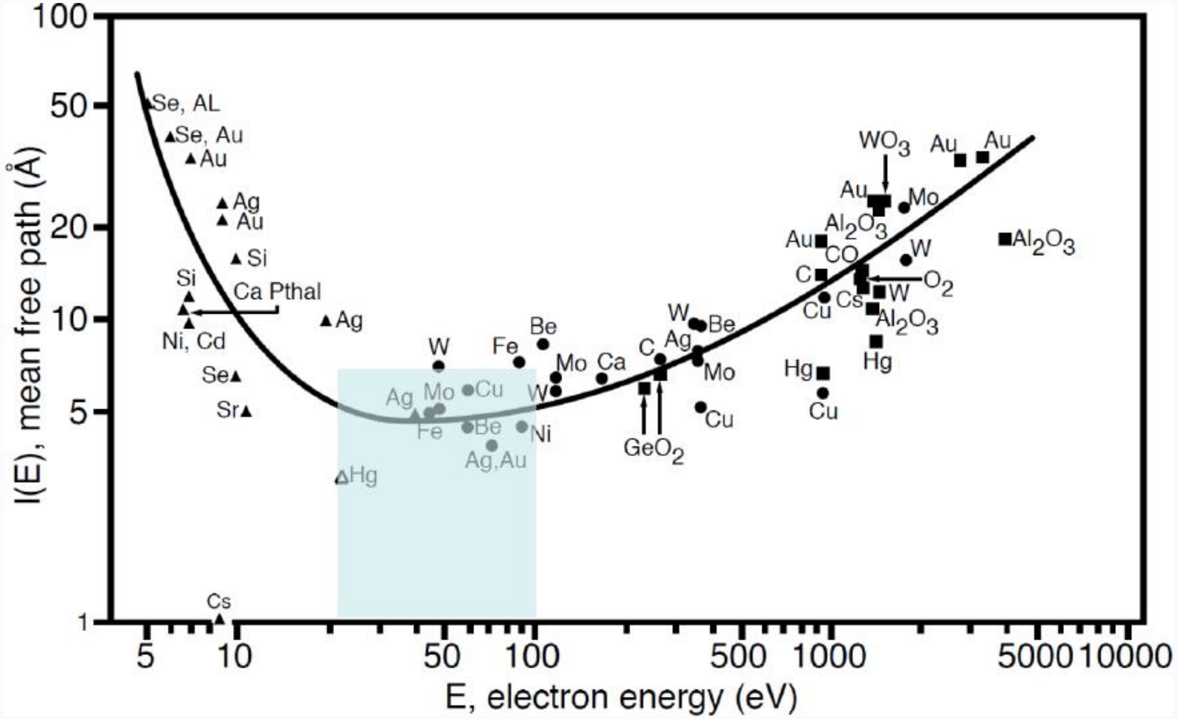
- 1. Excitation
- 2. Transport
- 3. Escape
- Steps 1 and 3 can create spin



Three-step model (one-step is the rigorous version).

Surface sensitivity — the universal curve

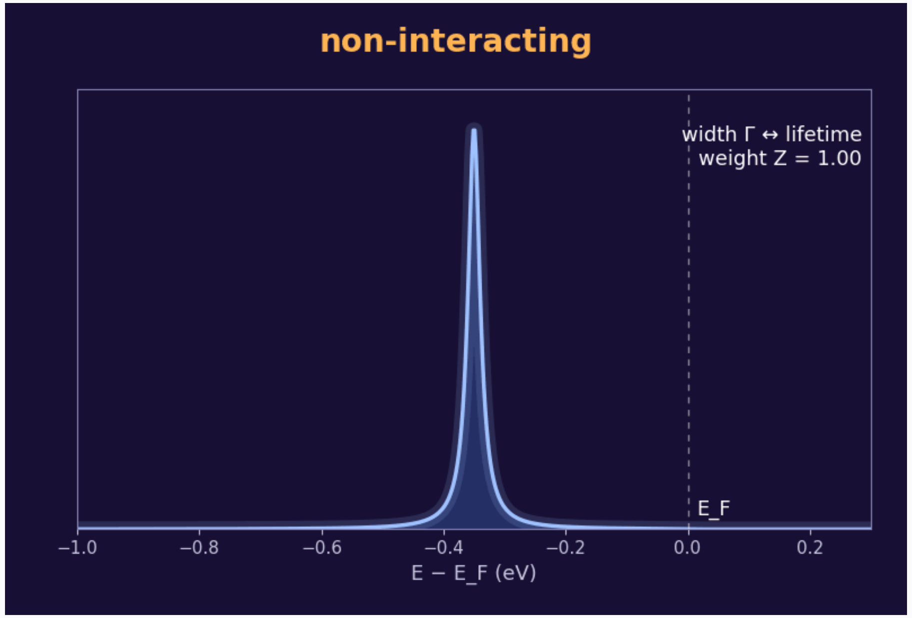
- Mean free path: 5–10 Å
- You see the top few layers
- **UHV and clean surfaces, for hours**

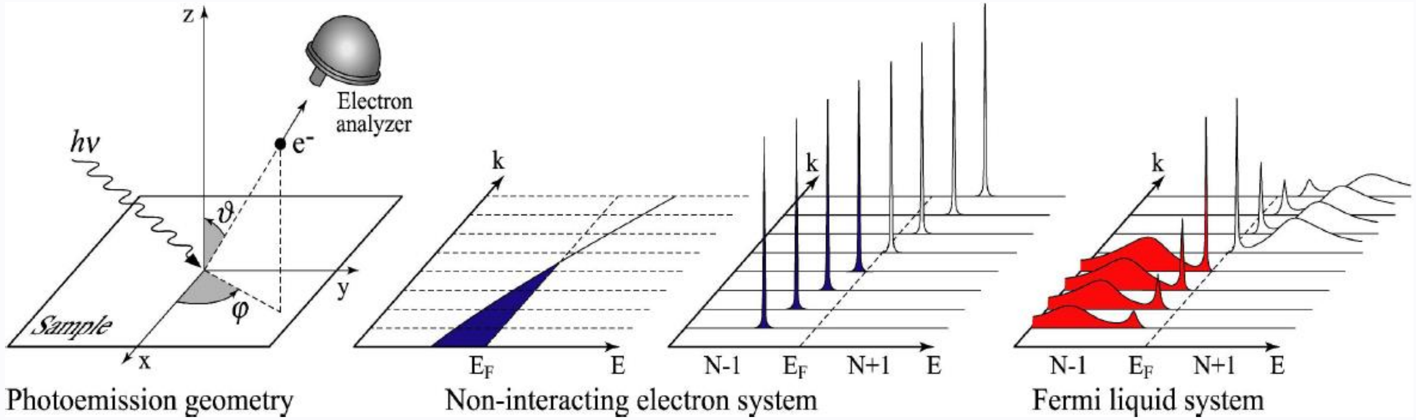


The universal curve.

Beyond the image: the spectral function

- $I \propto |M|^2 \cdot f \cdot A(k,\omega)$
- Width → lifetime
- Shift → mass (kinks)
- **|M|² cannot be ignored**

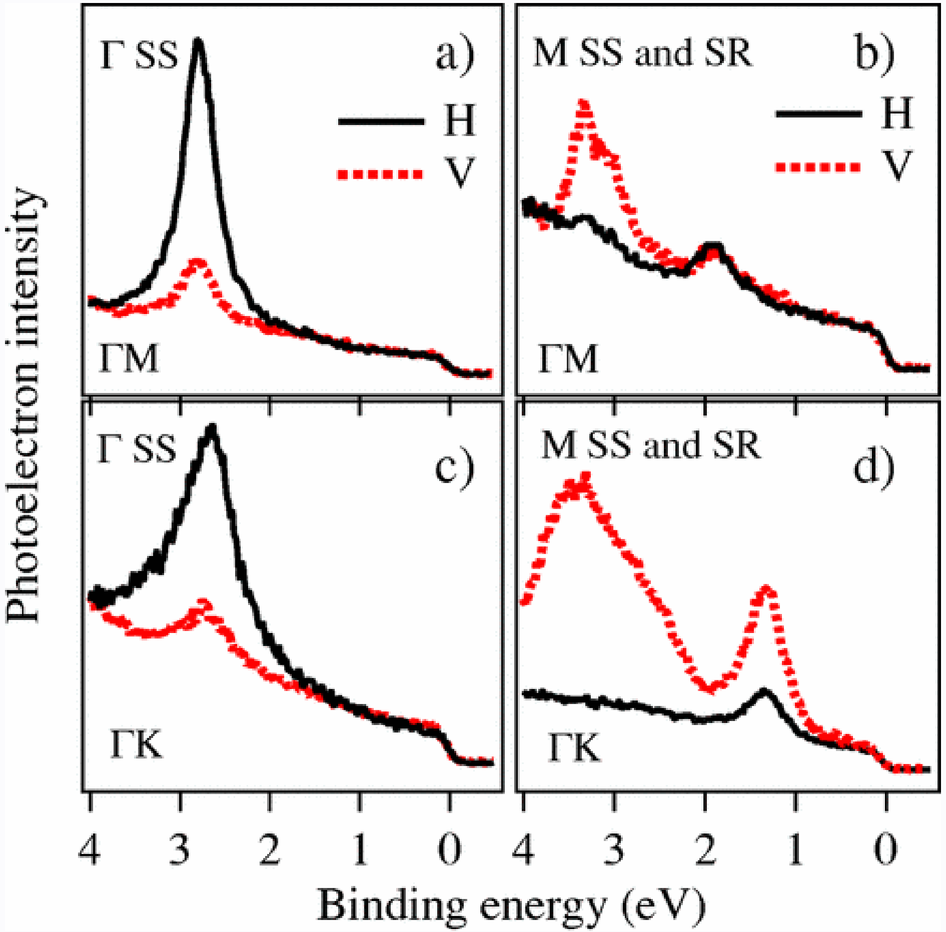




Free electrons vs Fermi liquid.

Matrix elements and light polarisation

- Light polarisation → selection rules
- Same band, different intensity
- **With SOC: different measured spin**



Horizontal vs vertical light: same sample, new pattern.

END OF PART 2

ARPES gives you E and k. It gives you the spin only as an average — weighted by matrix elements you did not choose.

To get $S(E,k)$ you must separate ↑ and ↓ after the analyzer.

3

26 minutes

How do you measure the spin of a free electron?

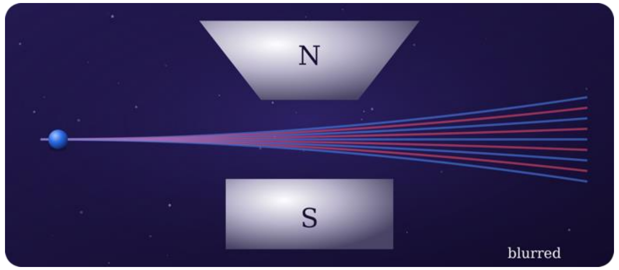
The heart of the lecture.

First, the bad news

You cannot do a Stern–Gerlach experiment on free electrons.

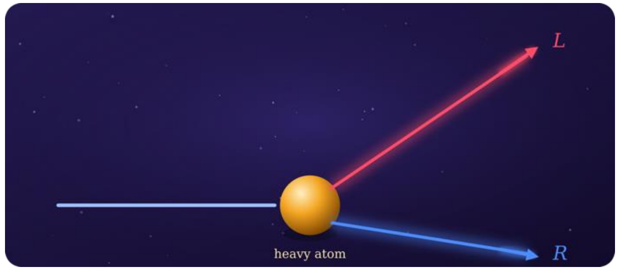
1 Why not

- No Stern–Gerlach for electrons
- Lorentz force blurs it



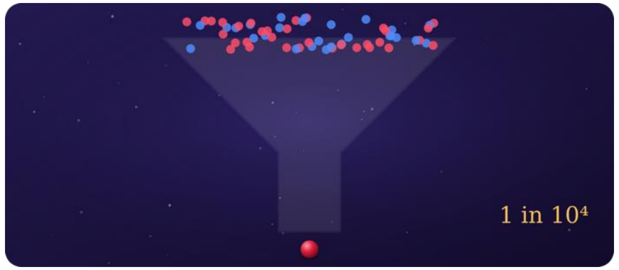
2 So what is left

- Spin-dependent scattering
- Only two mechanisms



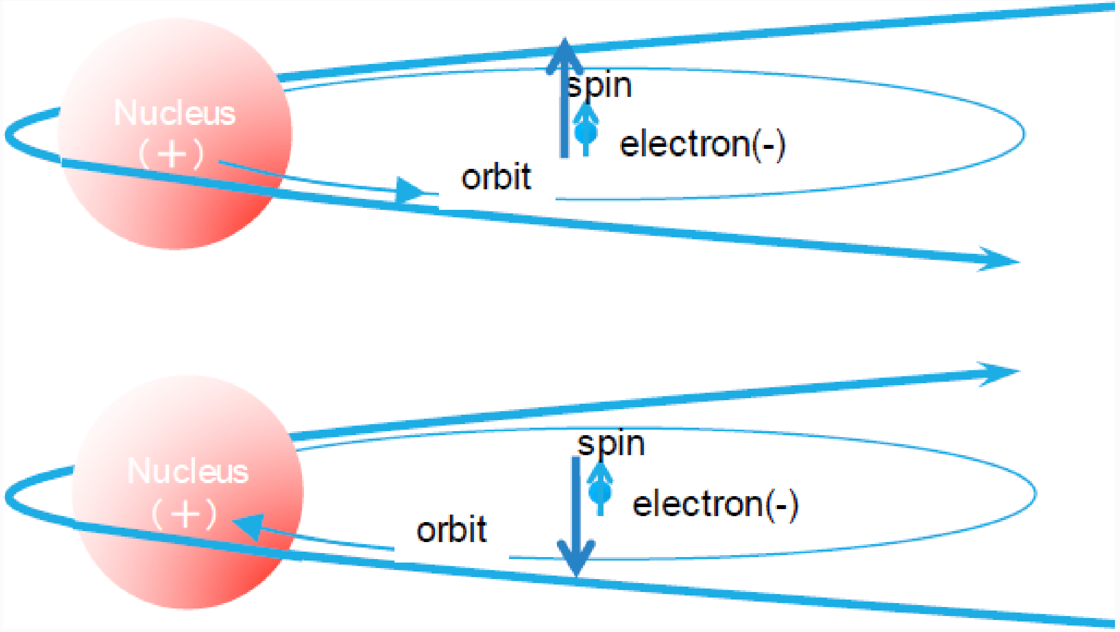
3 The price

- Most electrons are lost
- Drives every design

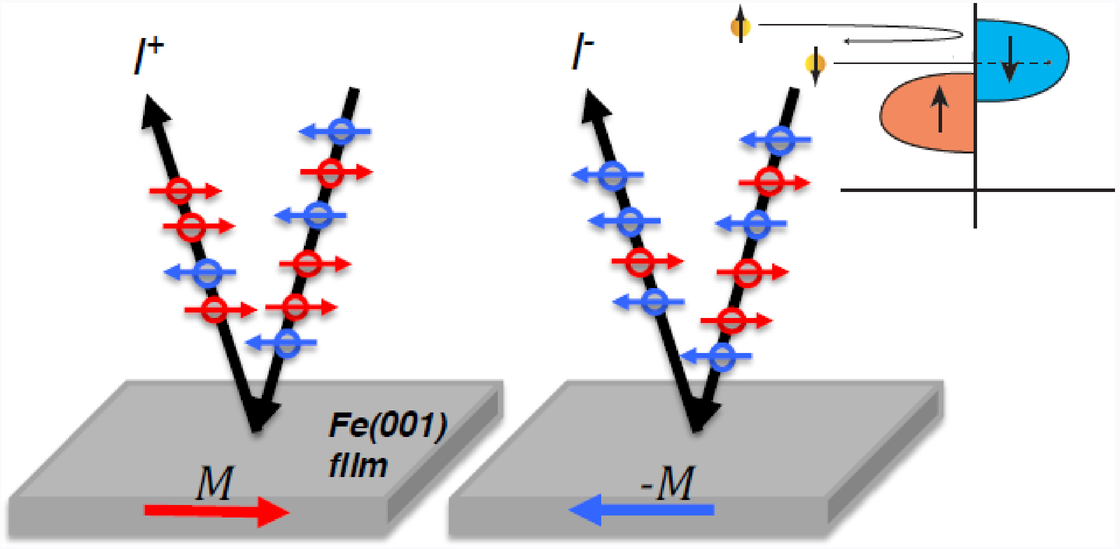


The two mechanisms

Heavy nucleus, or magnetised target.



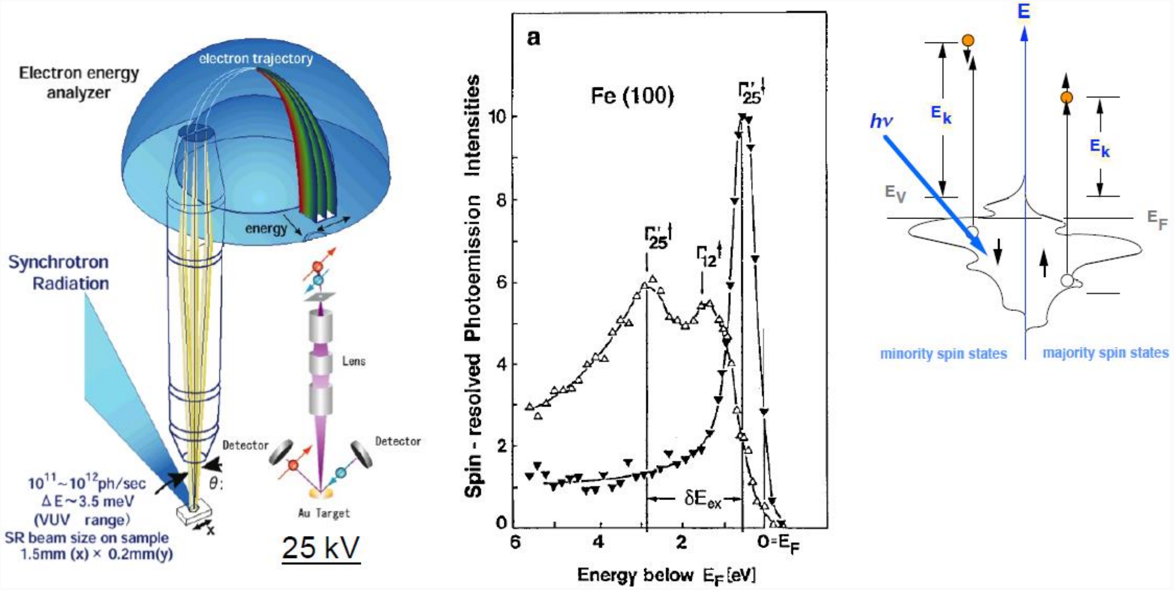
Spin–orbit: left–right asymmetry (Au, W).



Exchange: flip M, intensity changes (Fe–O).

The classical solution: the Mott polarimeter

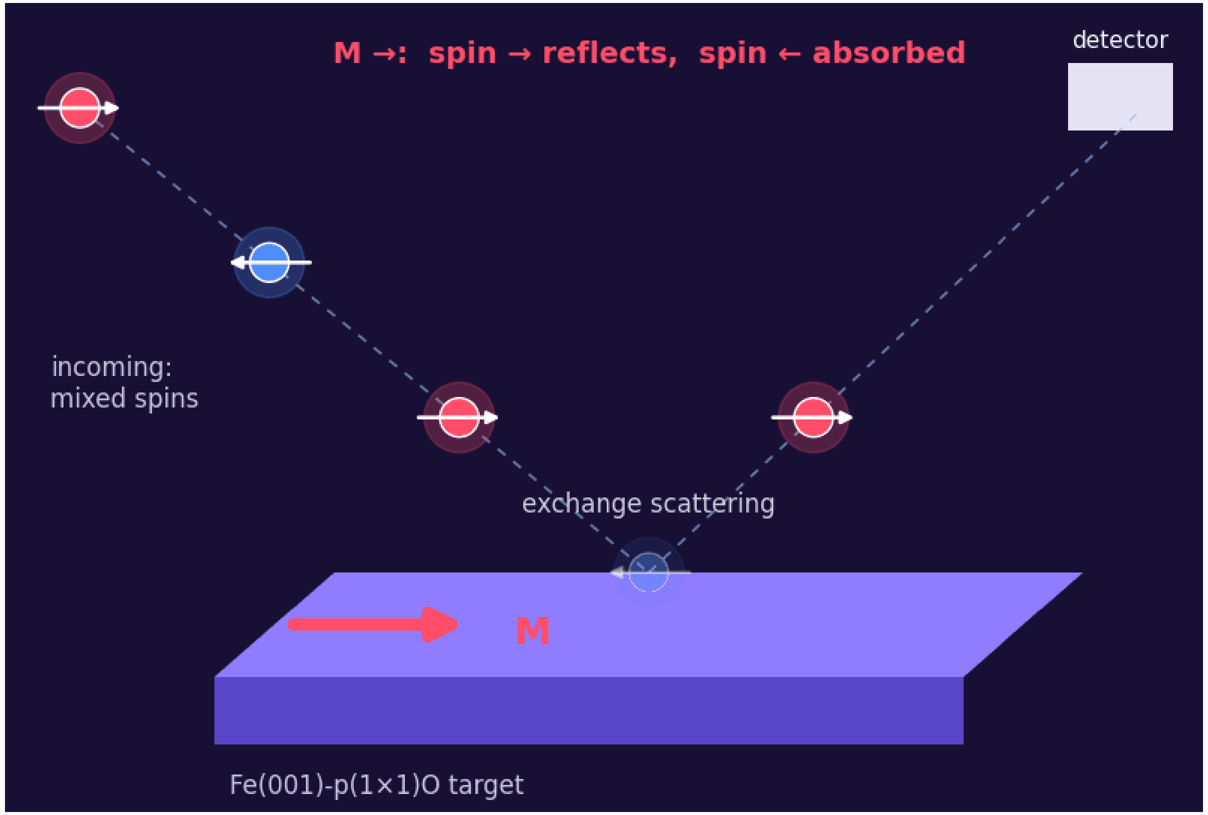
- 25–100 keV onto a gold foil
- Left–right asymmetry
- **FOM ≈ 10^{-4}: 1 in 10 000 counts**
- Robust, commercial



Mott chamber and spin-resolved Fe(100).

The modern solution: VLEED

- 5–15 eV onto Fe(001)-O
- Flip M, measure the change
- **100× better than Mott**
    - Target ages, needs reactivation



Flip M: the change is the spin signal.

The observable: asymmetry, Sherman function, polarisation

$$A = \frac{I_+ - I_-}{I_+ + I_-}$$

What the detector gives you.

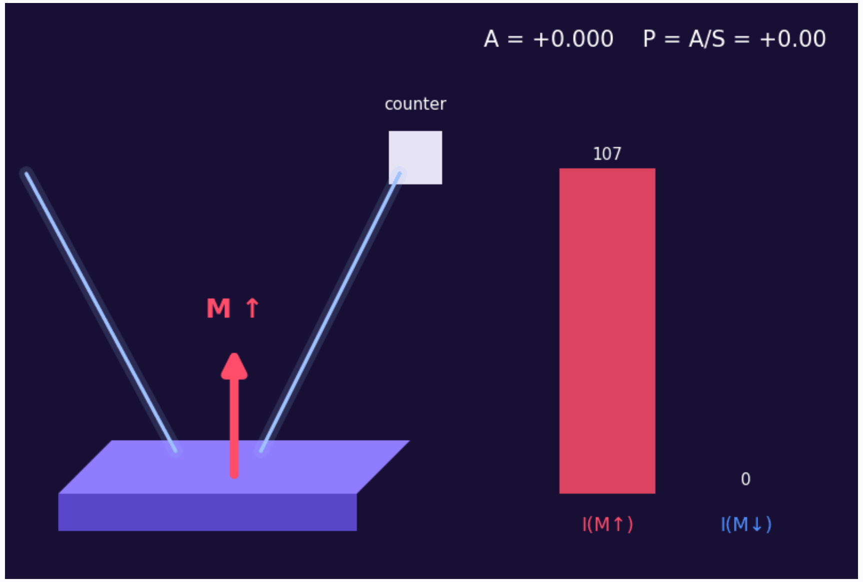
$$P = \frac{A}{S_{\mathrm{eff}}}$$

Sherman function: asymmetry → polarisation.

- **S is a calibration, not a constant**
- **20% error in S = 20% error in P**
- Calibrate on Au(111) every beamtime

$$P = \frac{1}{S}\,\frac{\mathrm{EDC}_{M\uparrow} - \mathrm{EDC}_{M\downarrow}}{\mathrm{EDC}_{M\uparrow} + \mathrm{EDC}_{M\downarrow}}$$

P from the two magnetisation states.



From polarisation to spin-resolved spectra

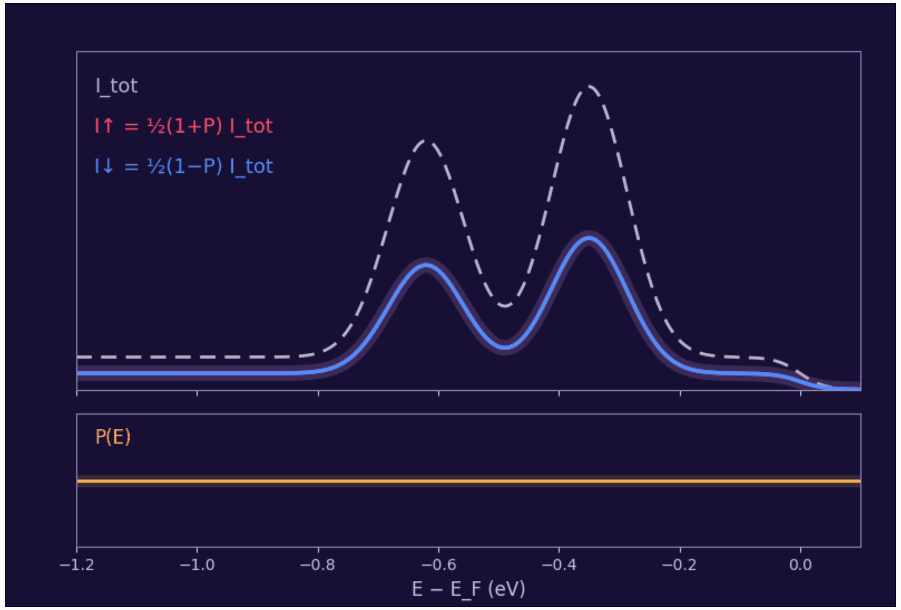
$$I_{\uparrow,\downarrow}(E) = \tfrac{1}{2}\left[1 \pm P(E)\right] I_{\mathrm{tot}}(E)$$

↑ and ↓ are reconstructed, not measured.

$$\mathrm{EDC}_{\uparrow,\downarrow} = \frac{(1 \pm P)\left(\mathrm{EDC}_{M\uparrow} + \mathrm{EDC}_{M\downarrow}\right)}{2}$$

Rebuilding the two spin channels.

- **Most misreadings happen here**
- Weak where I_tot is small
- **Publish asymmetry, S, error bars**



The figure of merit — why spin-ARPES is slow

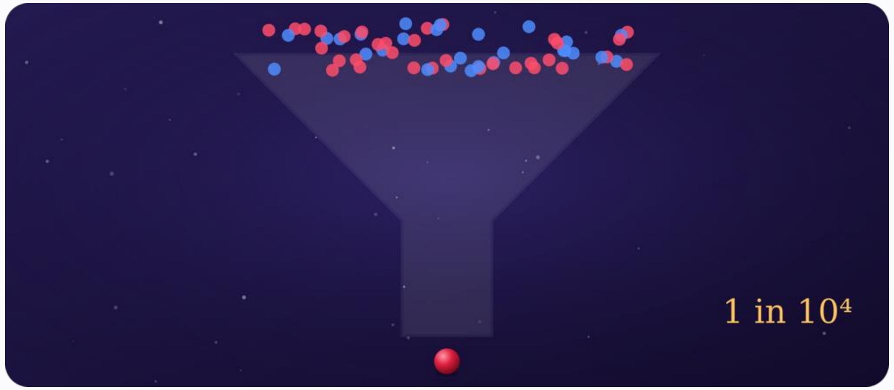
$$\mathrm{FOM} = S^2 \, \frac{I}{I_0}$$

The only number that matters.

$$\Delta P = \frac{1}{S\sqrt{N}}$$

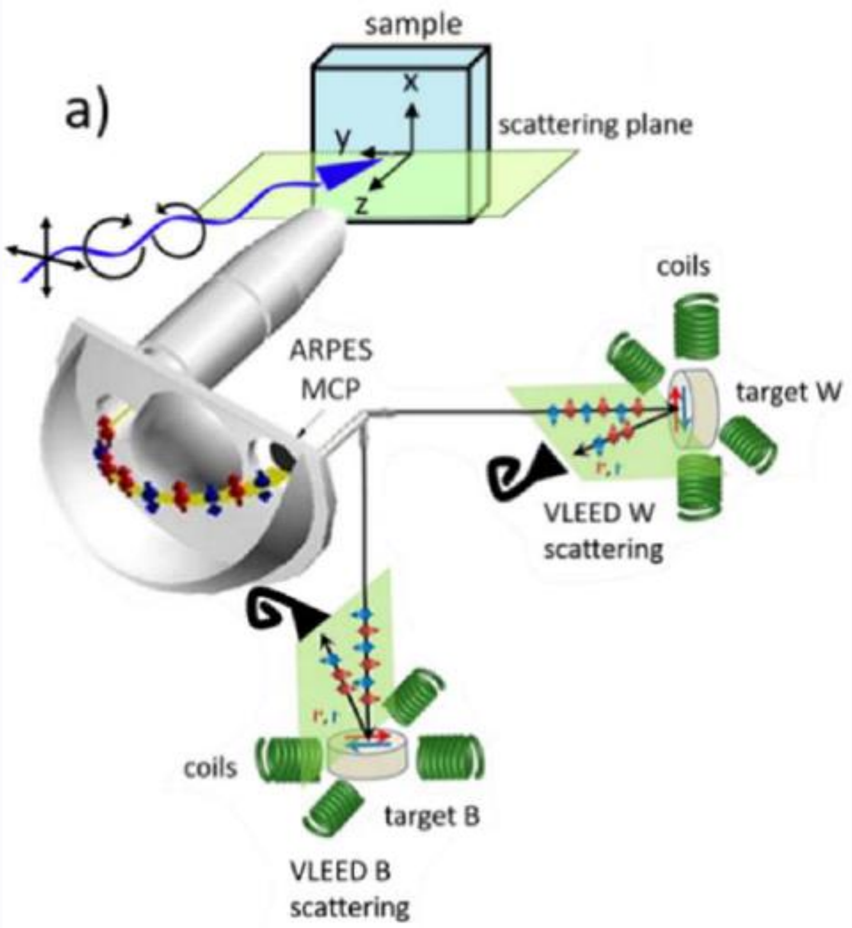
Error on P for N electrons.

- **$\Delta P = 0.05$ needs ~4000 counts per point**
- Half the error = 4× the time
- **Penalty: 10^4 (Mott), 10^2 (VLEED)**



Getting all three spin components

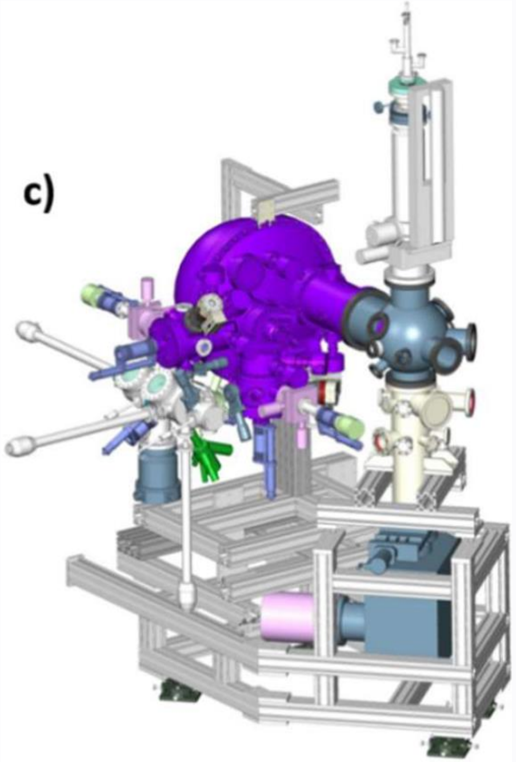
- One detector = one axis
- Spin is a vector
- **Two chambers → Px, Py, Pz**
- **Always ask: which frame?**



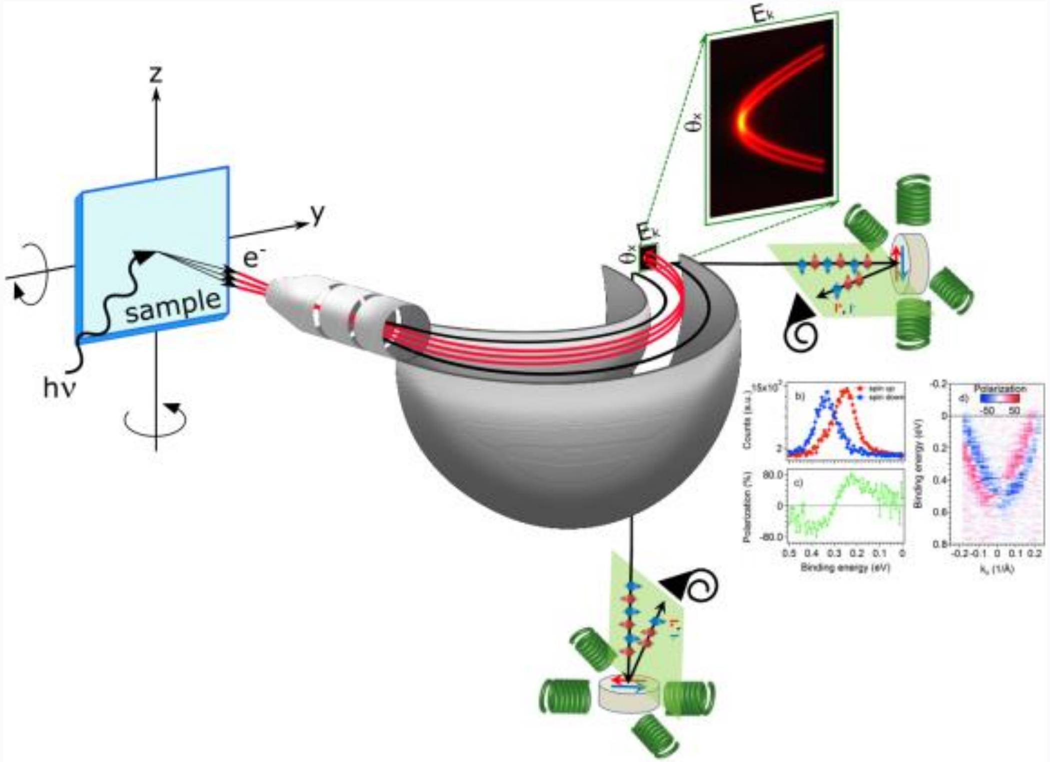
Two VLEED chambers: 3D spin analysis.

A real instrument: VESPA at APE-LE, Elettra

Built in Trieste, running since 2015.



Two VLEED units on the analyzer exit.



DA30 analyzer, 8–120 eV, any polarisation.

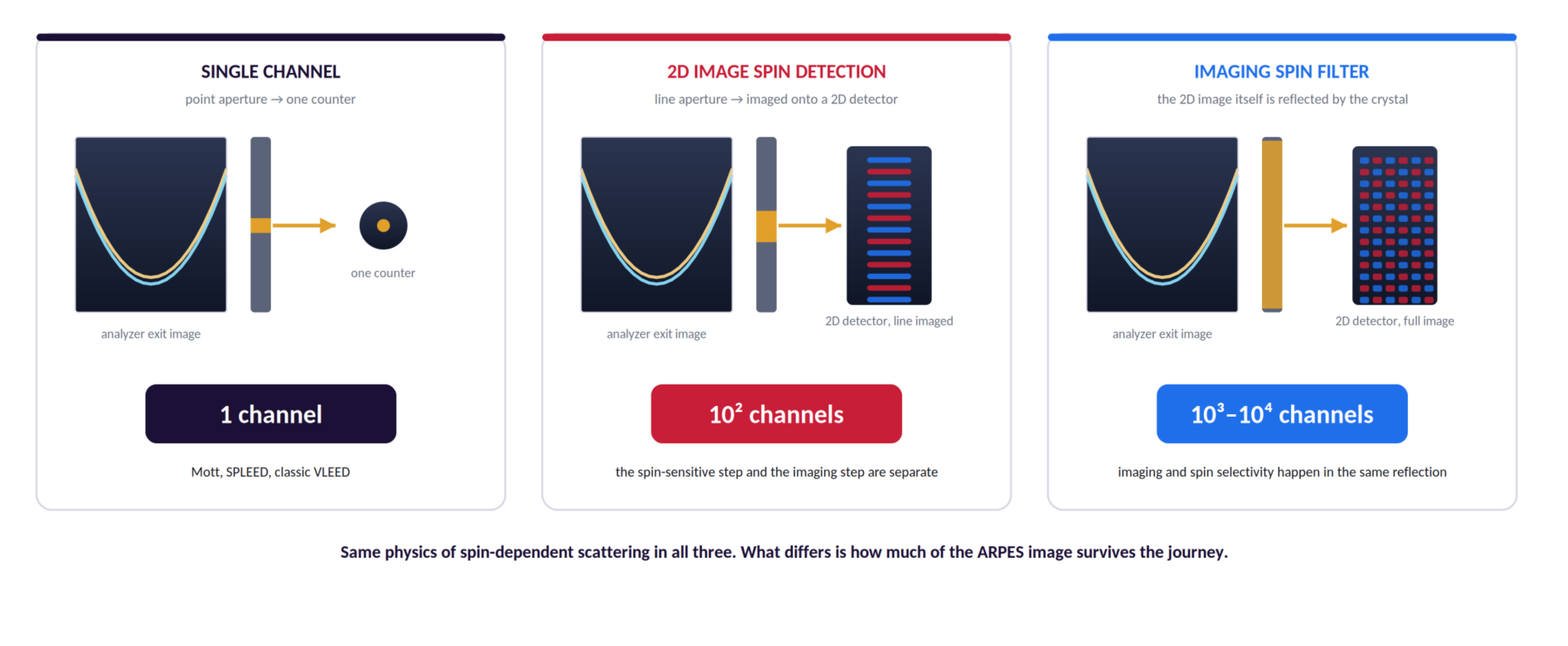
THE BIG RECENT CHANGE

A single-channel polarimeter throws away the whole ARPES image and keeps one point of it.

Recovering that parallelism beats any gain in the Sherman function.

Three ways to keep more than one channel

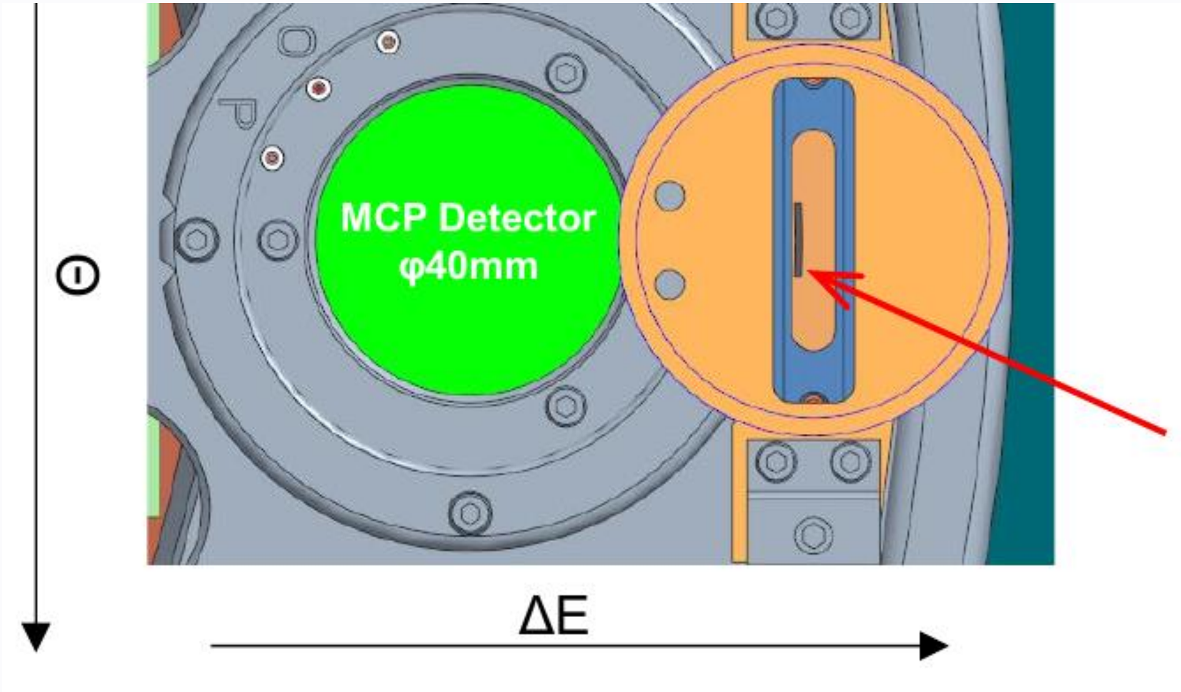
Same physics. Different amount of image kept.



1 point → 1 line → the full image.

Two-dimensional image spin detection

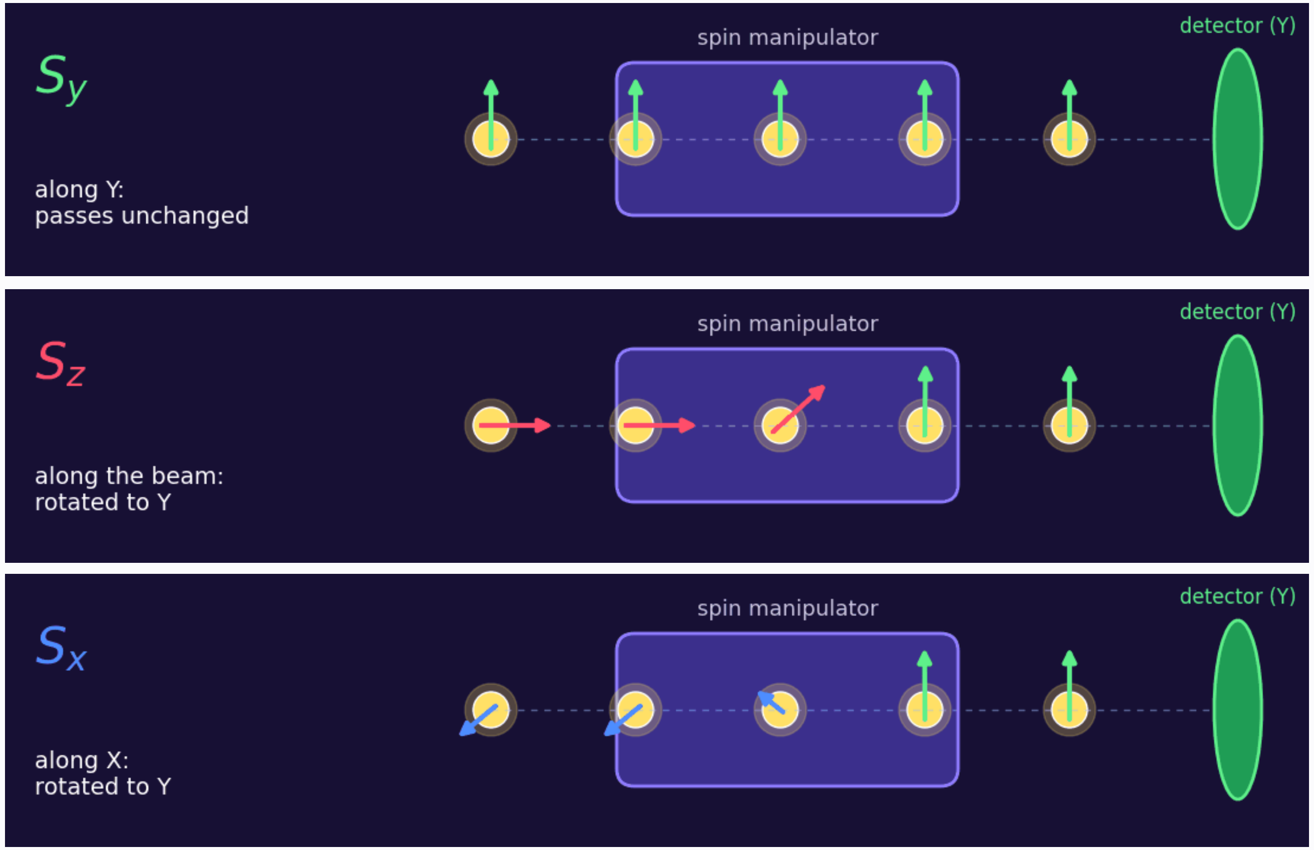
- A slit keeps a whole line
- The line stays imaged
- **Not a filter: optics do the imaging**
- **Gain: 10–100×**



The spin slit at the analyzer exit. Figure: MB Scientific AB.

Rotate the spin, not the detector

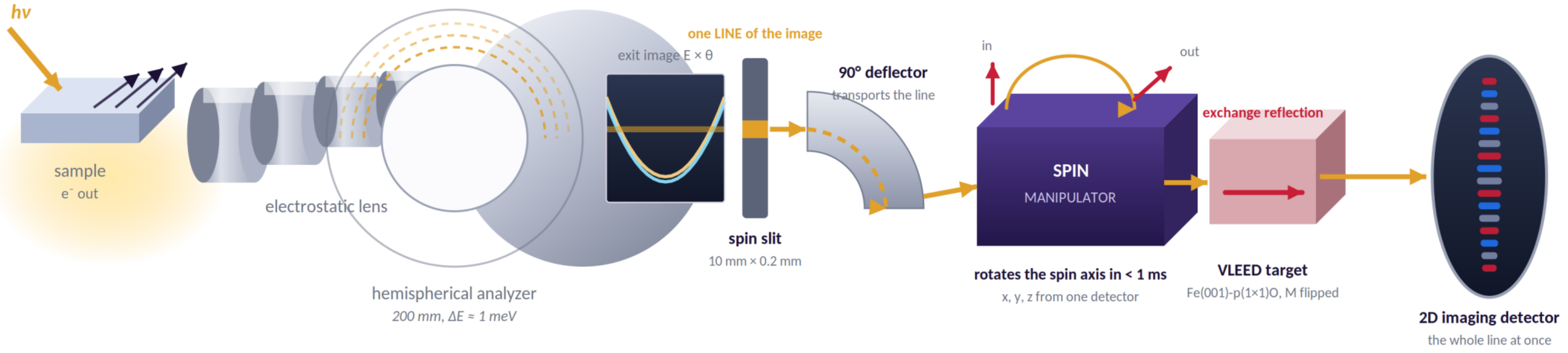
Precess the spin instead of adding a detector.



Three settings of the same manipulator: one target, one detector, all three components.

The whole column, end to end

Sample → analyzer → spin slit → manipulator → target → detector.



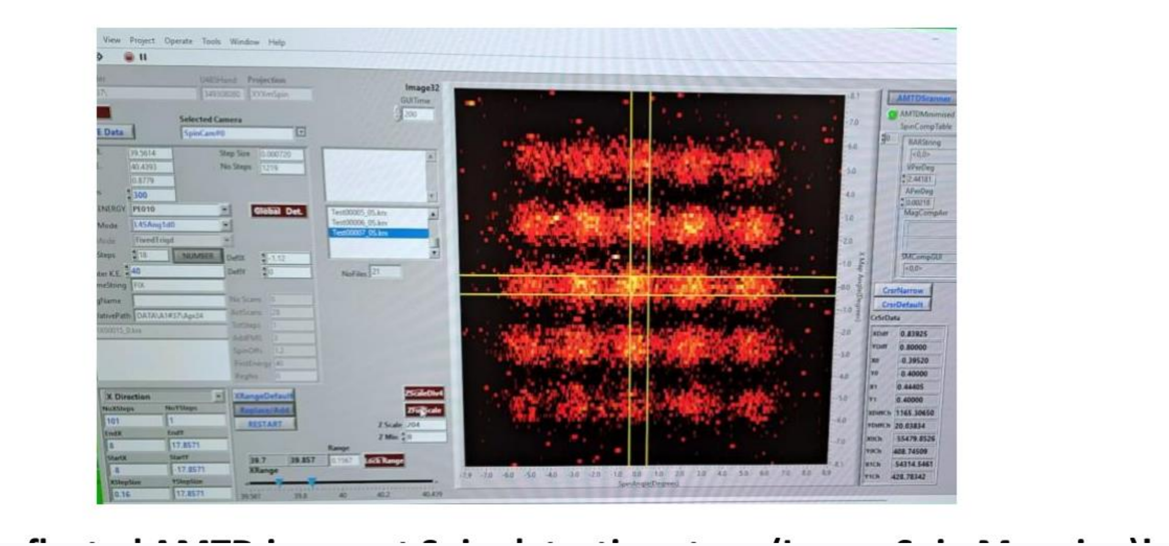
The spin selectivity happens at the VLEED target. The imaging is done by the electron optics before and after it.

Nothing is “filtered out” of the image — a whole line of the band map is transported, spin-analysed and read in parallel.

All inside mu-metal: < 500 nT at the sample.

What this changes in the control room

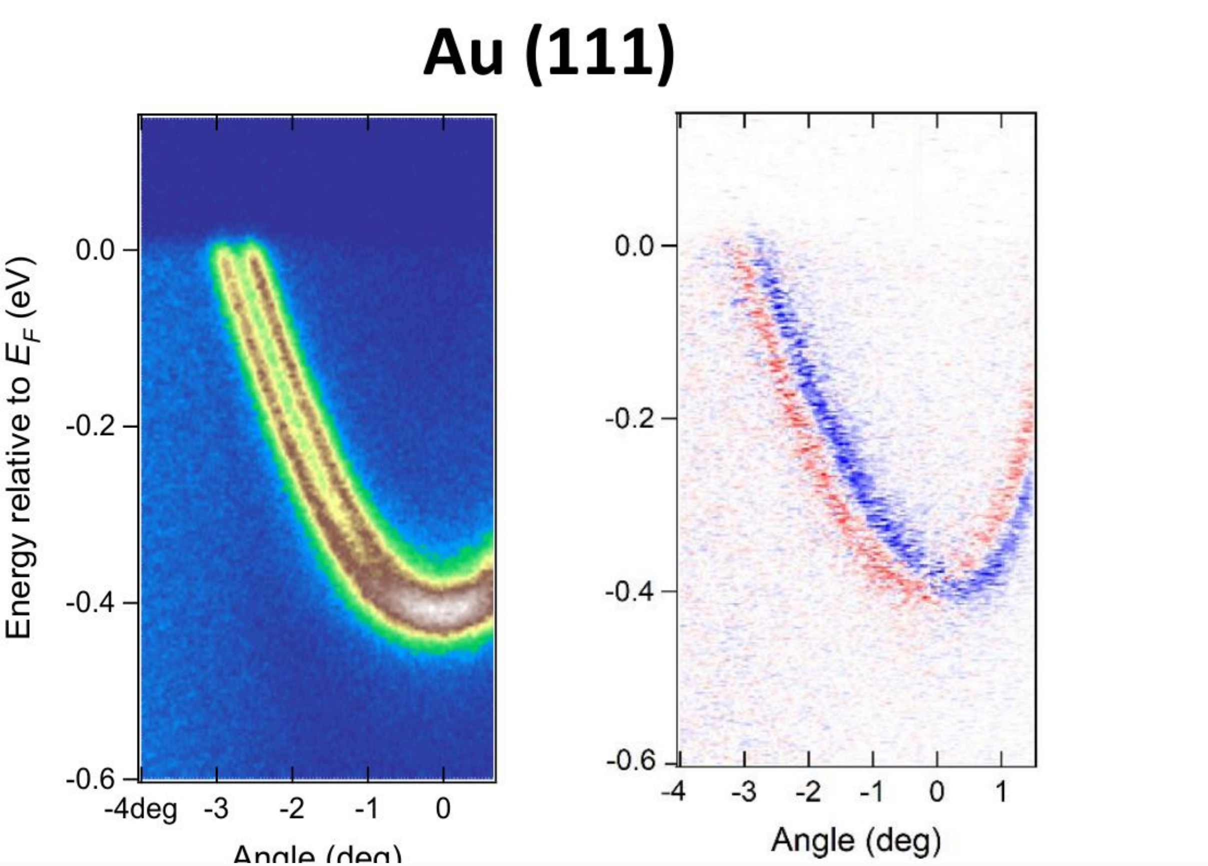
- Spin becomes an image
- **Flip M thousands of times**
- **Cheapest control: automate it**



Spin-filtered line on the detector. Figure: MB Scientific AB.

Performance: Au(111), spin resolved as an image

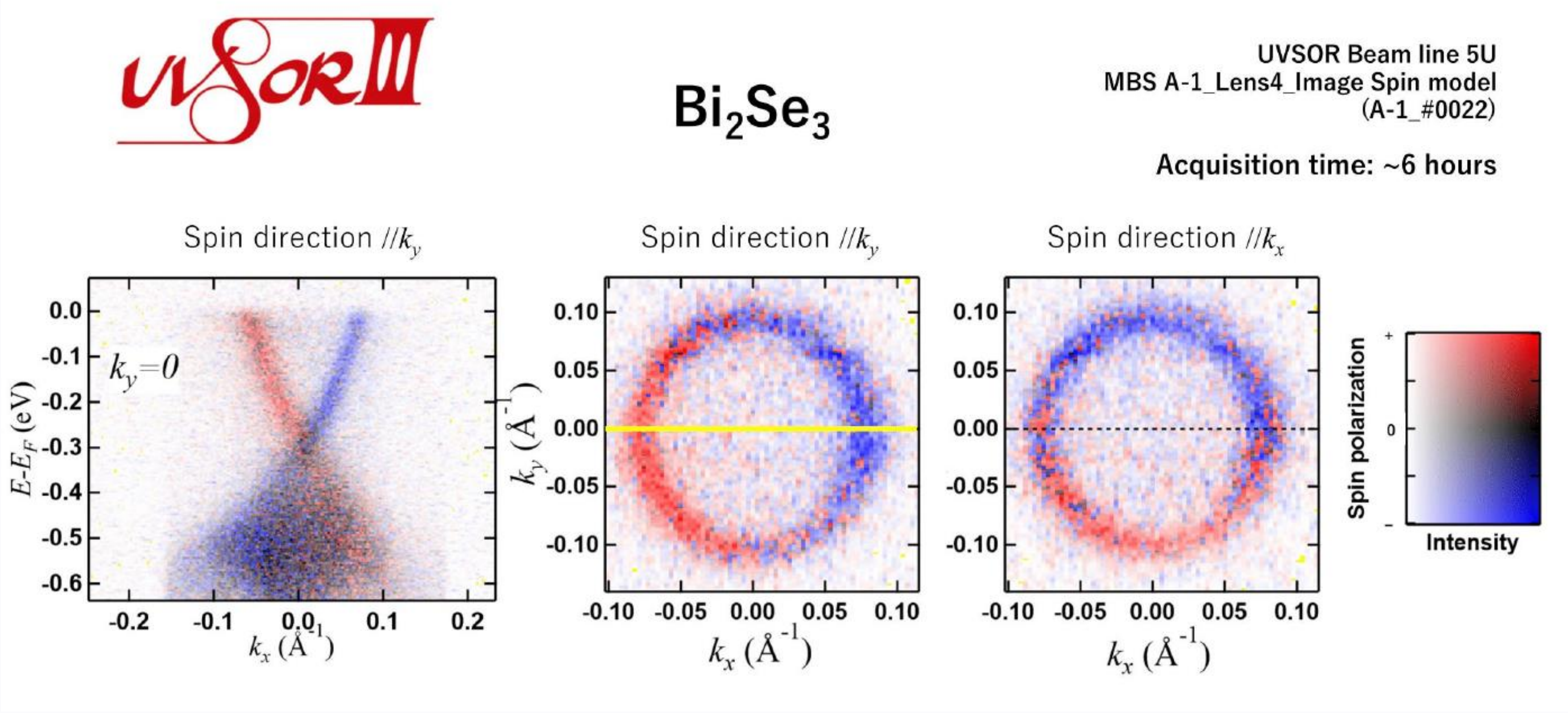
A spin-resolved band map, not a series of EDCs.



Left: band map. Right: spin asymmetry. UVSOR 5U, courtesy K. Tanaka; figure MB Scientific AB.

Performance: a full topological spin texture in one shift

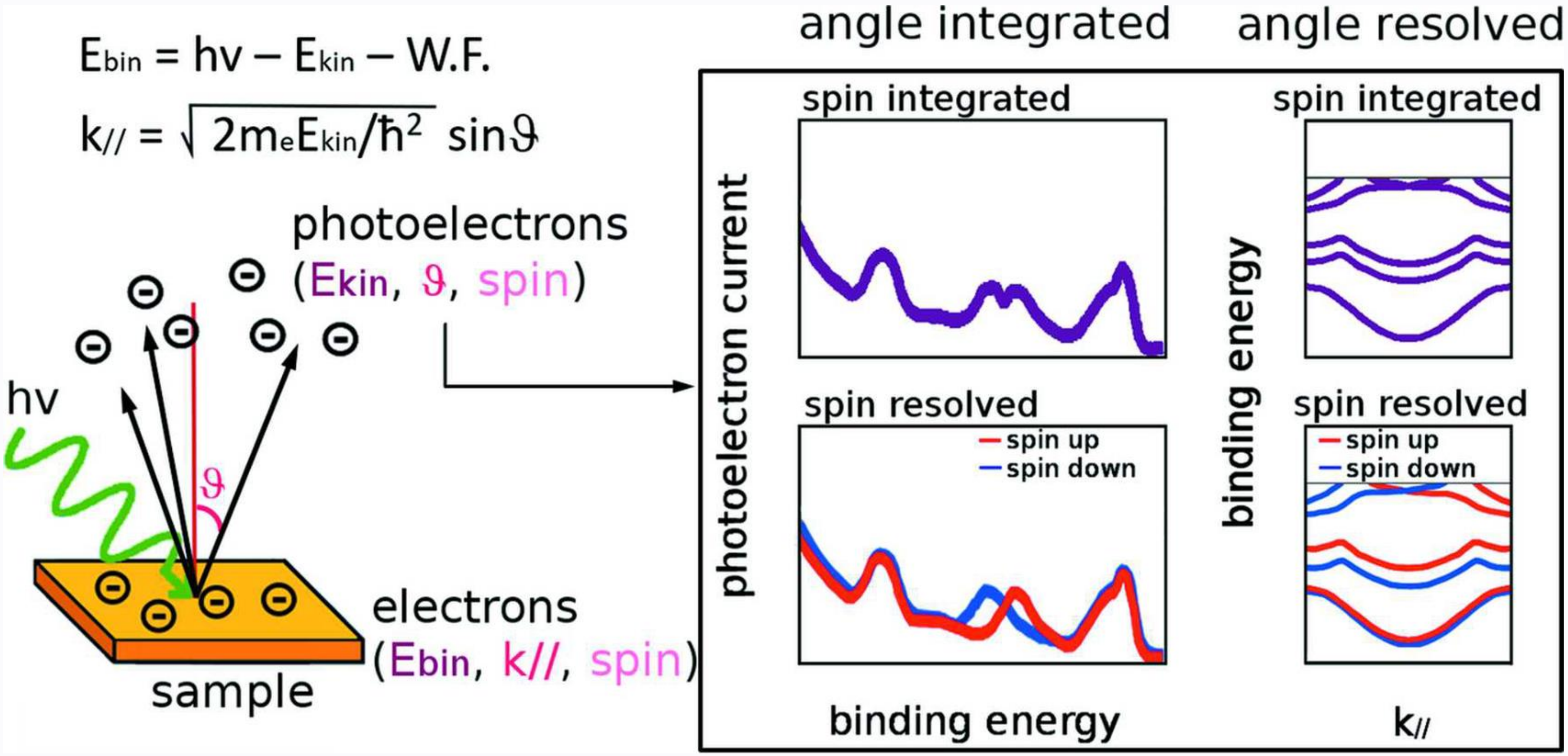
Bi_2Se_3: Dirac cone and spin texture, ~6 hours.



Two in-plane spin components. UVSOR 5U, courtesy K. Tanaka; figure MB Scientific AB.

What the added spin channel actually buys you

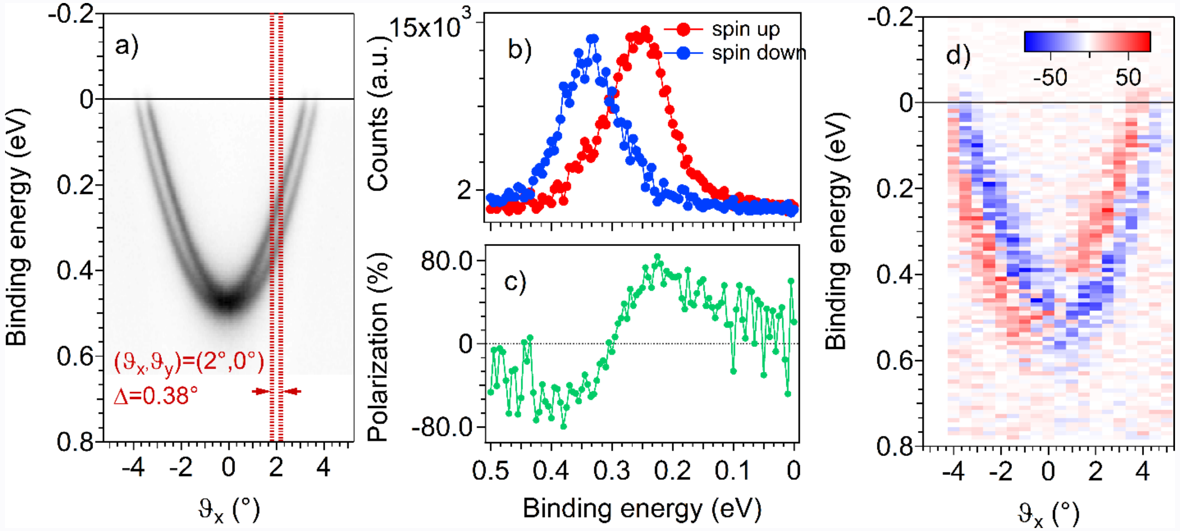
Spin integrated vs spin resolved.



Each step removes an average that hid the physics.

What good spin data look like

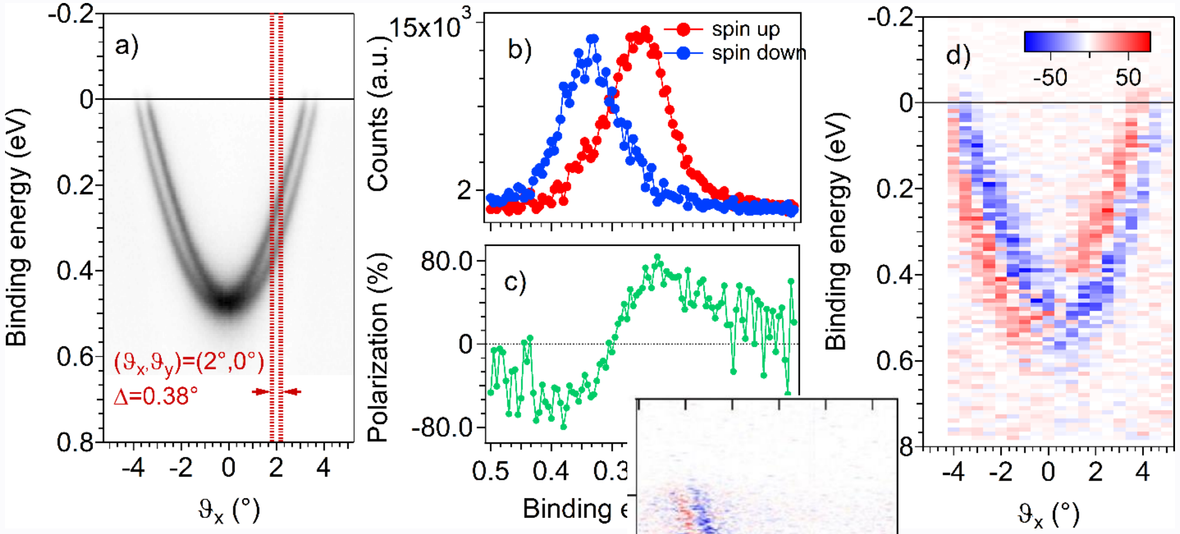
- Band map
- Spin EDCs with error bars
- Polarisation P(E)
- Spin texture
- **Only the last? Can't judge it**



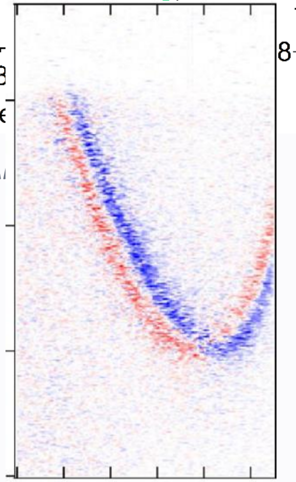
A complete spin-ARPES figure.

What good spin data look like

- Band map
- Spin EDCs with error bars
- Polarisation P(E)
- Spin texture
- **Only the last? Can't judge it**



A complete spin-A



4

13 minutes

Doing the experiment — and not fooling yourself

The part your referees will care about.

THE CENTRAL CAVEAT

You do not measure the spin of the electron in the solid. You measure the spin of the photoelectron.

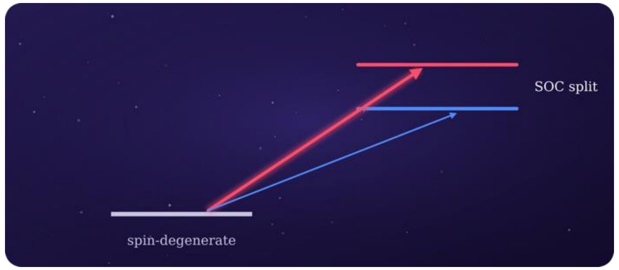
Same only if excitation and escape keep the spin. With strong SOC they may not.

Three ways the photoemission process creates spin polarisation

None of these is the spin of the band.

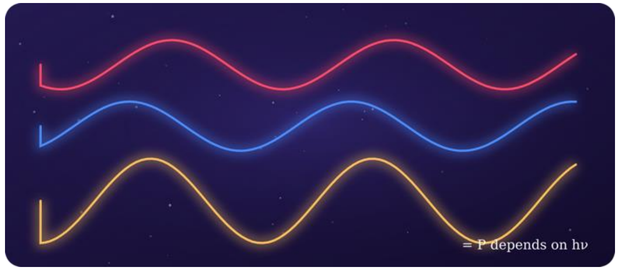
1 Final-state SOC

- Final state is SOC split
- Spin from spin-degenerate states



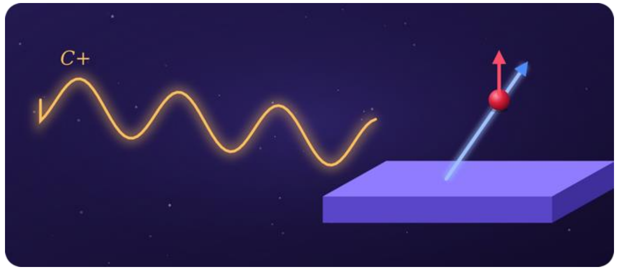
2 Interference

- Several initial states interfere
- P changes with hν



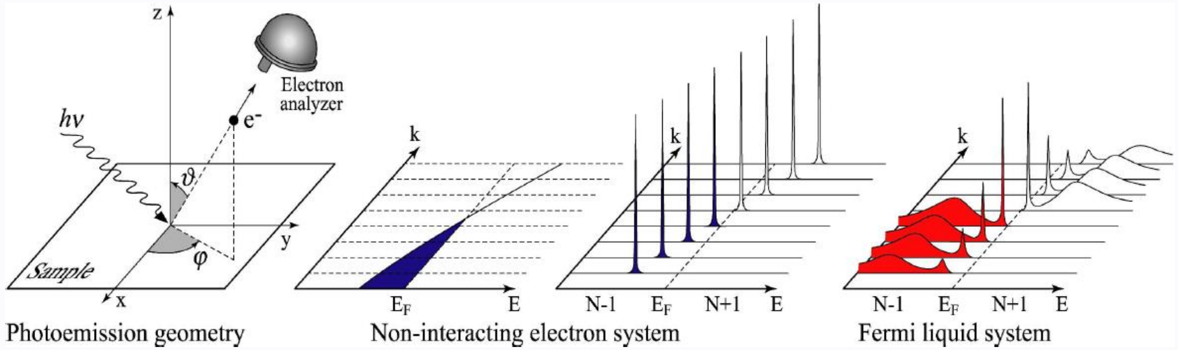
3 Light helicity

- Circular light steers spin
- Jozwiak 2013



Reference frames: say which one you mean

- **Three frames: sample, detector, light**
- Rotating the sample mixes them
- **State the frame when you publish**



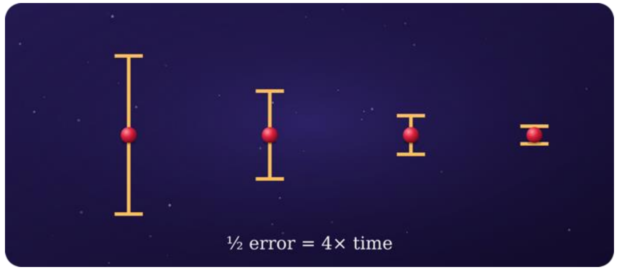
Each part of the geometry has its own axes.

Planning a spin run: the arithmetic you must do first

Before the proposal, not on the first night.

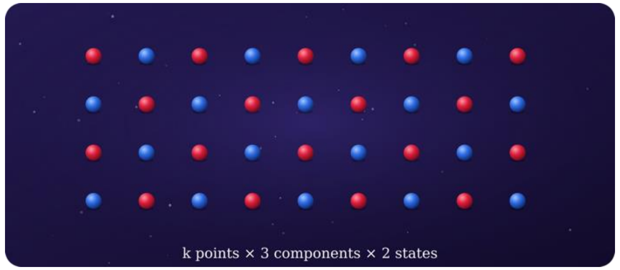
1 Decide the precision

- ±0.1: polarised at all?
- ±0.02: quantitative



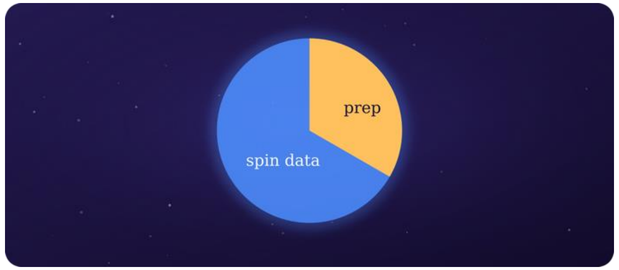
2 Count the points

- k points × energies
- × 3 components × 2 states

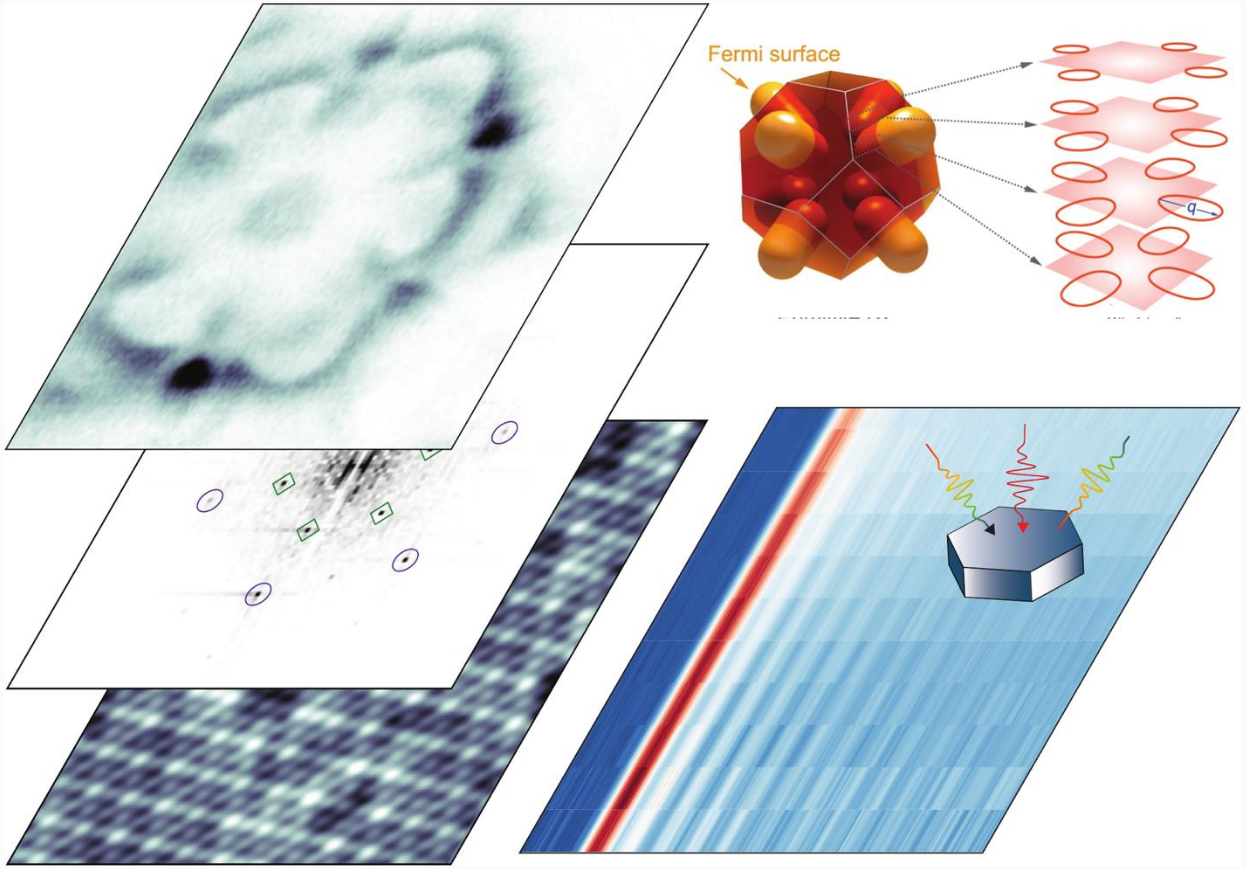


3 Protect the budget

- ⅓ of time for prep
- Band map first, always



Complementary techniques — know when not to use spin-ARPES



Only one probe resolves spin in momentum space.

- **SQUID: net moment**
- **XMCD: element moments**
- **Neutrons: q and ω**
- **SP-STM: real space**
- **Spin-ARPES: S(E,k)**

5

8 minutes

The complete photoemission experiment: S, L and L·S

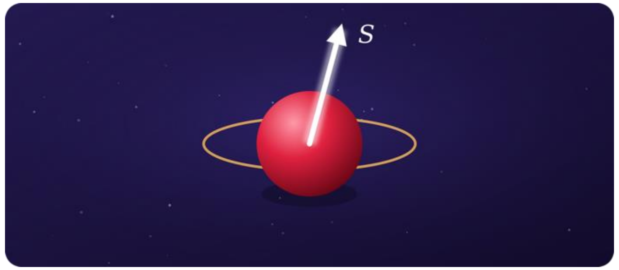
Spin is only half the angular momentum story.

Three observables, one photoelectron

The organising idea of the last part.

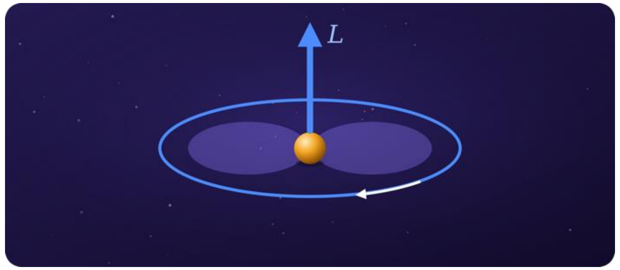
1 S — spin

- Spin detector
- Slow but direct



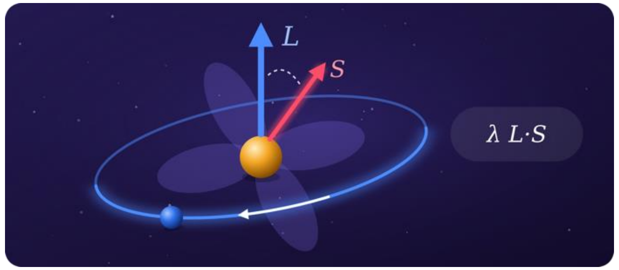
2 L — orbital

- Circular dichroism
- Fast, model dependent



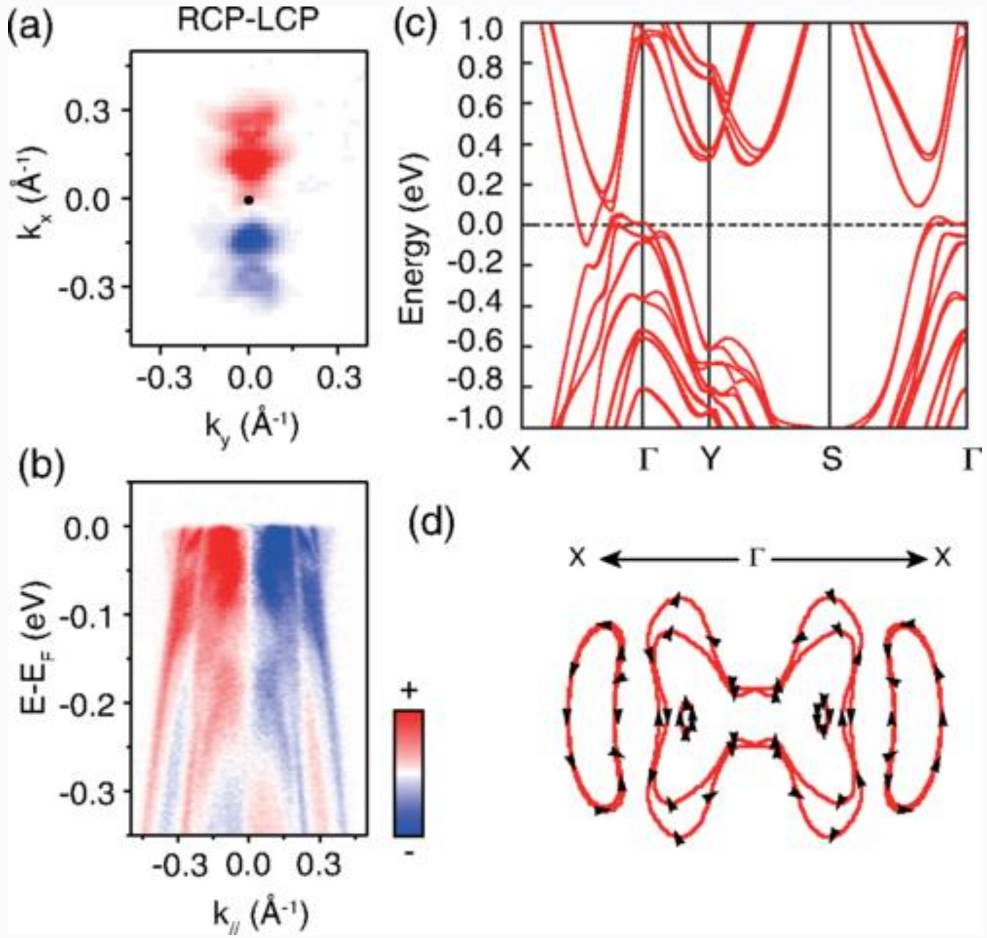
3 L·S — correlation

- Spin + light helicity
- Answers what S or L can't



Circular dichroism as a window on L

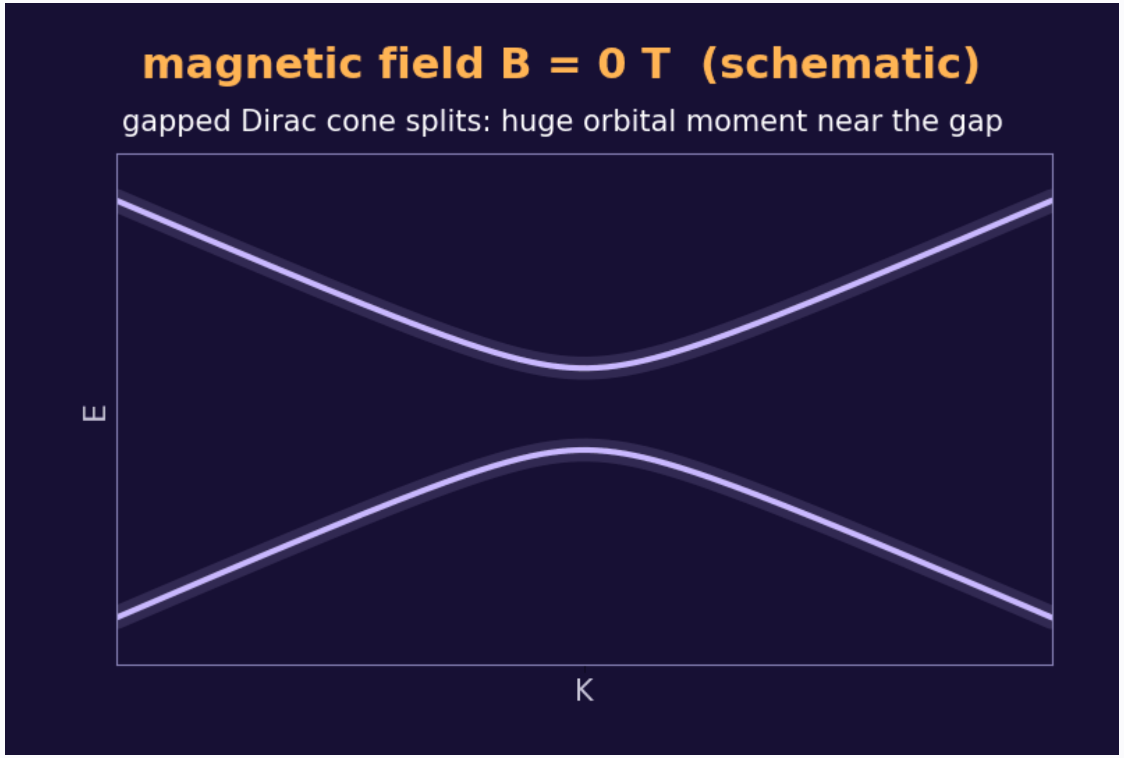
- CD = I(C+) − I(C−)
- Tracks orbital texture
- Sign flip k ↔ −k
- **Not a direct measure of L**



Opposite signs at opposite momenta.

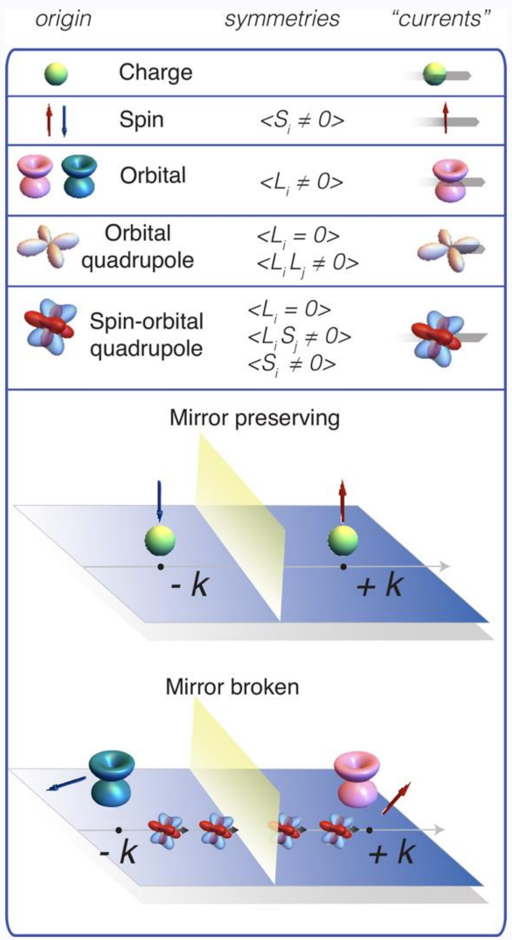
Putting S and L together: the kagome metal TbV_6Sn_6

- Spin Berry curvature ↔ orbital moments
- **Gapped Dirac cone at K**
- **A magnetic field splits it: orbital Zeeman**
- **Orbital moments up to ~200 μB**
  - Li, …, Mazzola, … Nat. Phys. 20, 1103 (2024)



Schematic: the splitting is largest near the gap, where the orbital moment peaks.

Symmetry bookkeeping: multipoles



Multipoles classified by inversion, time reversal and mirrors.

- Each multipole has a symmetry
- Symmetry → which experiment sees it
- **Check before the beamtime**

6

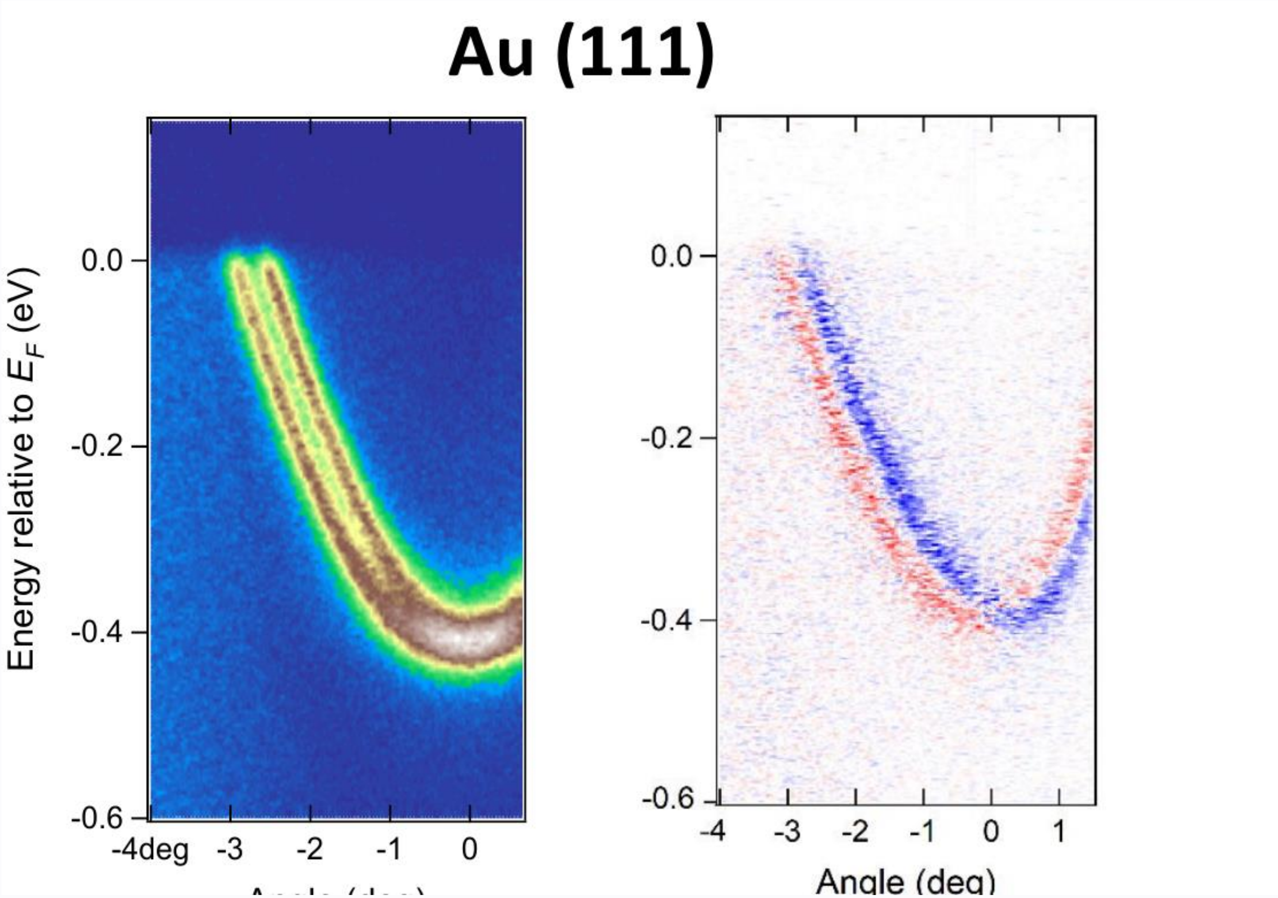
12 minutes

Case studies: from the calibration sample to the frontier

Question → what spin added → what would be wrong without it.

Case 1 — Au(111): the calibration standard

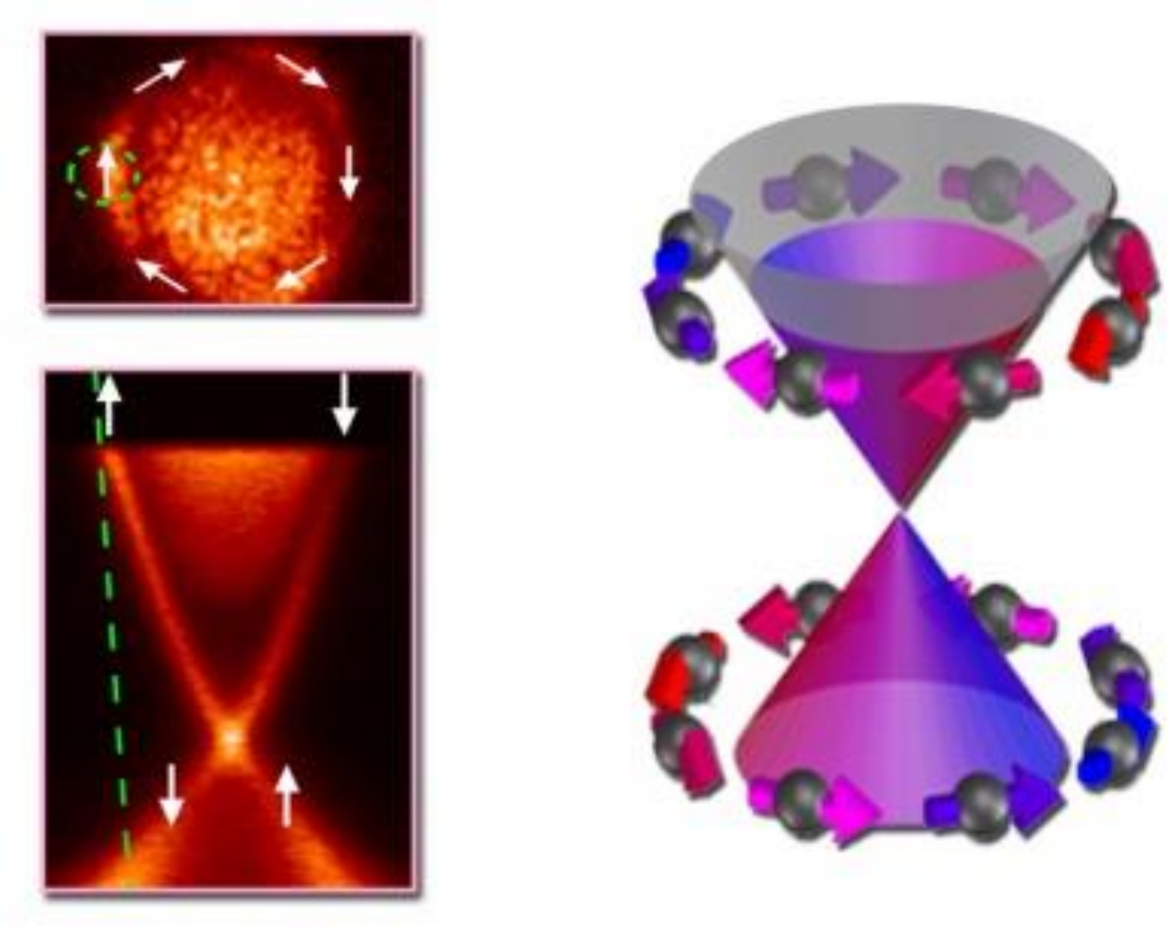
- **Question: Rashba split?**
- **Answer: two helical branches**
- **Use: calibrate S every time**



Same surface state, integrated and resolved.

Case 2 — topological insulators: proof by spin

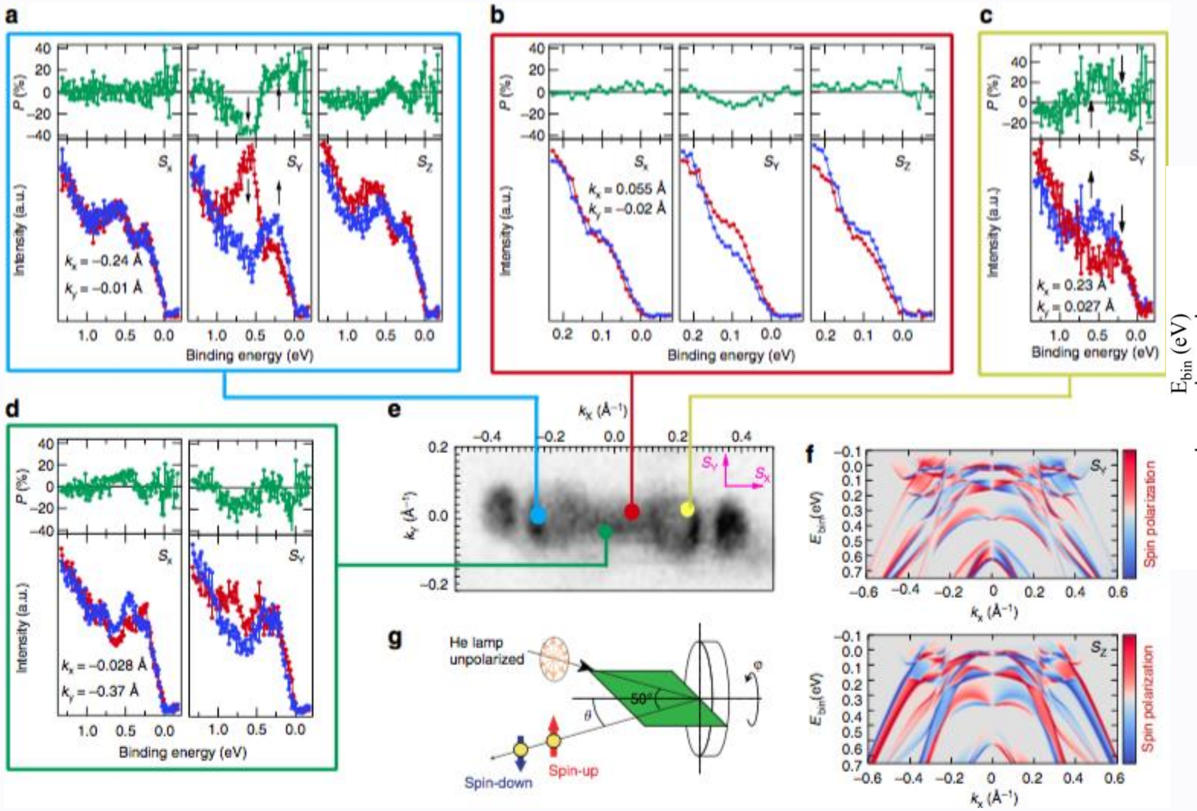
- **Question: topological or trivial?**
- **Answer: one helical cone**
- **Limit: Rashba is helical too**
  - Also needs bulk gap + connectivity

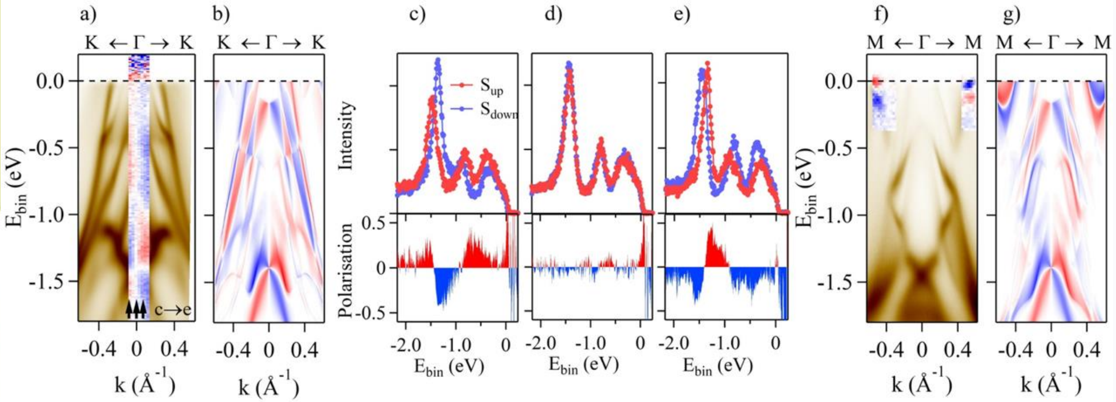


Helical spin texture of a topological surface state.

Case 3 — dichalcogenides: textures that are not simple Rashba

Low symmetry: in-plane and out-of-plane spin.



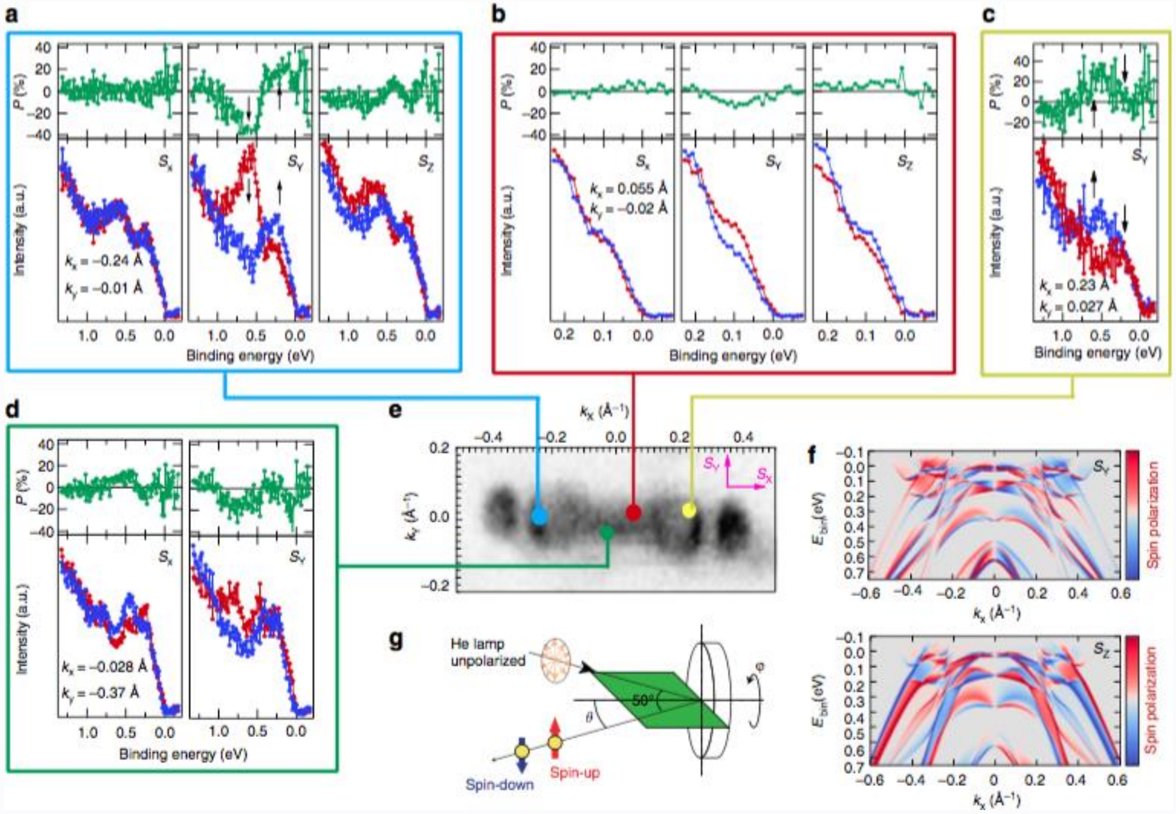


NiTe₂: spin texture of topological surface states.

WTe₂: canted textures. Das et al., Nat. Commun. 7, 10847 (2016).

Case 3b — hidden spin polarisation in a centrosymmetric crystal

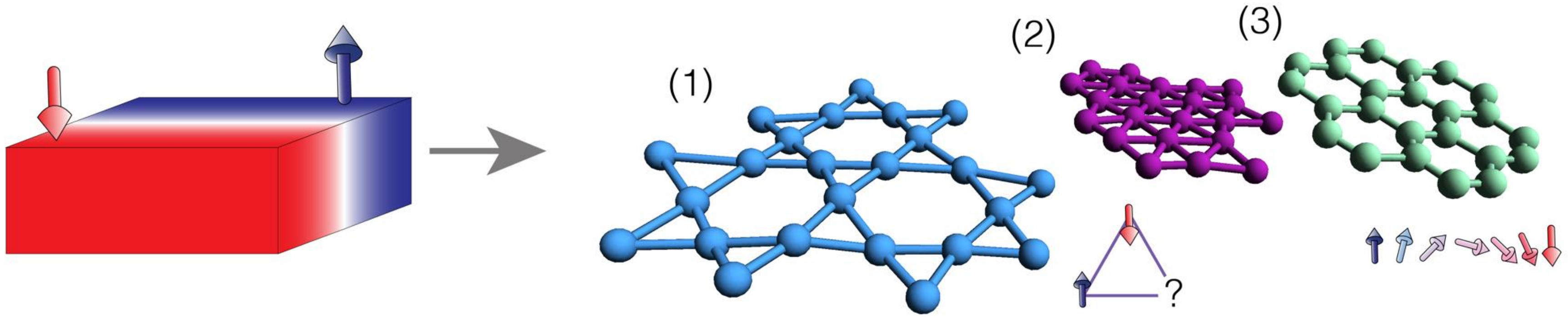
- **Question: polarised yet centrosymmetric?**
- **Answer: local layer polarisation**
- **Lesson: ask where the electron came from**



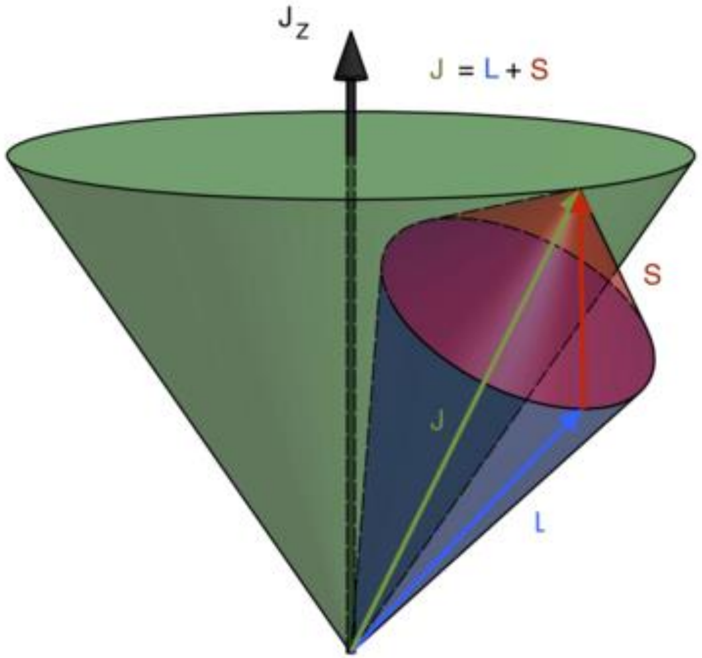
Spin-polarised states in WSe_2.

Little parenthesis

OC can mediate spin-patterns different from standard ones and the topology of the magnetic orders is often affected by it.

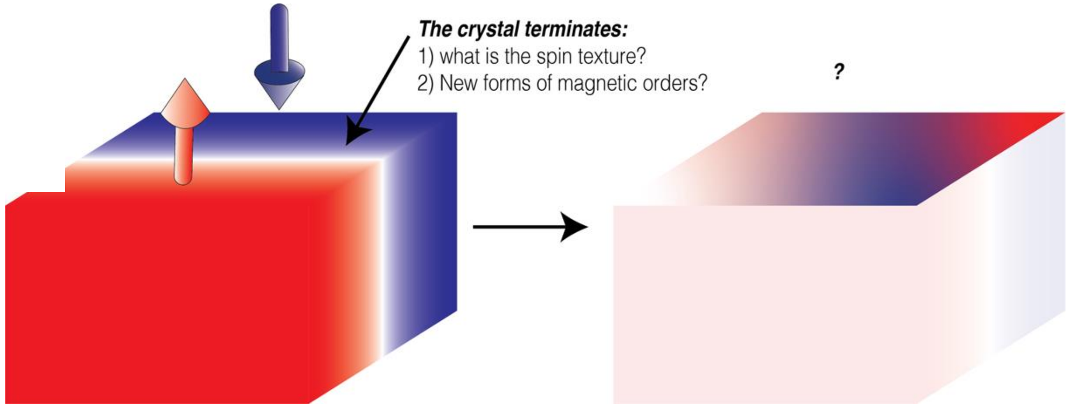


Frustration is found to be a very favourable element for the appearance of chiral orders and "loops"

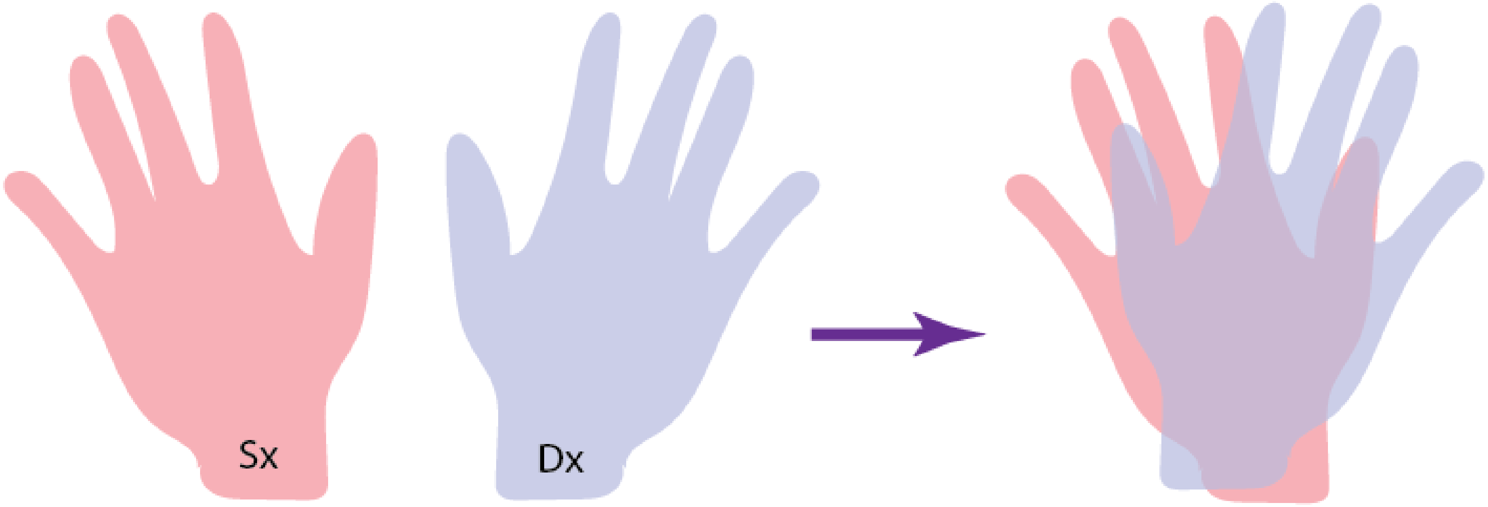


Spin-Orbit Coupling (SOC)

Effect that described the coupling between orbital motion and electron spin



Chirality (loop currents) is one of the most elusive phases

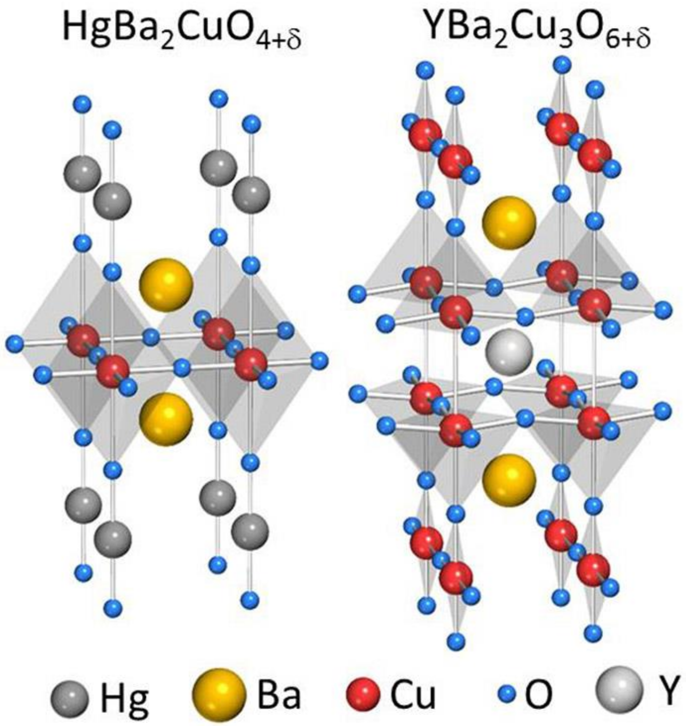


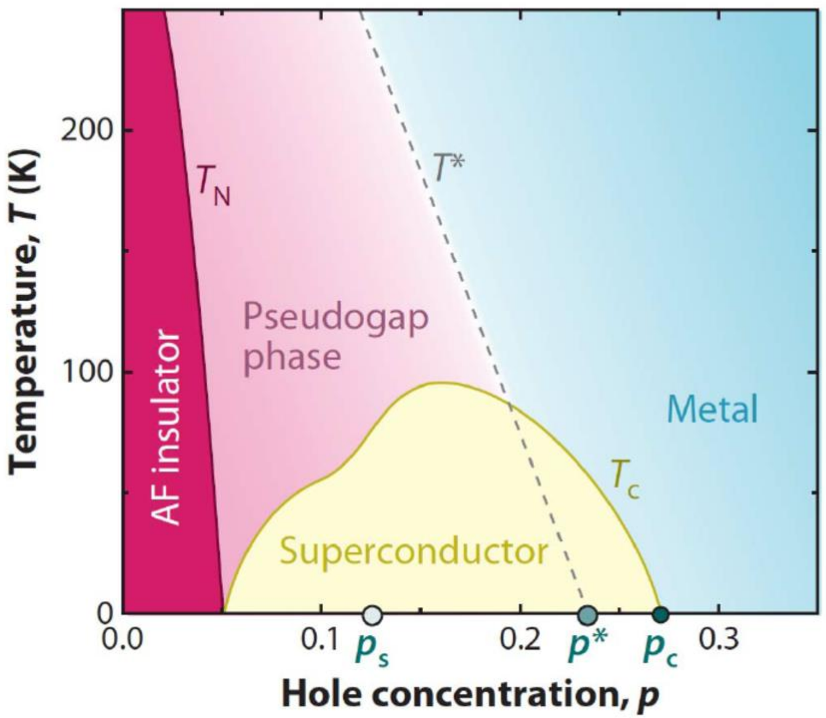
The left hand is the mirror image of the right one, but they cannot be superimposed.

Chirality, loop currents, not easily explainable magnetic phenomena..

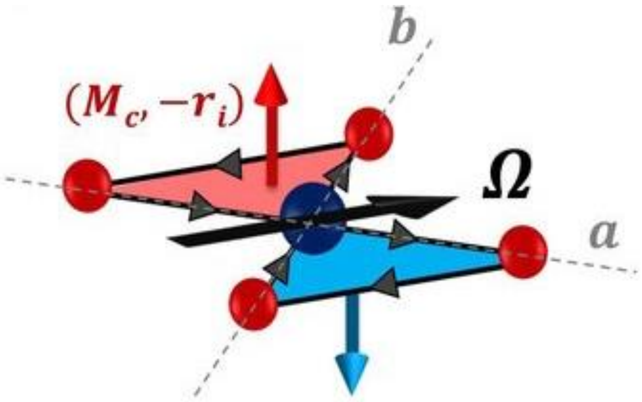
From the AF case to the most strongly doped, two models were developed:

1) Hubbard Model with AF fluctuations
2) Unusual ordered phase / QC fluctuations





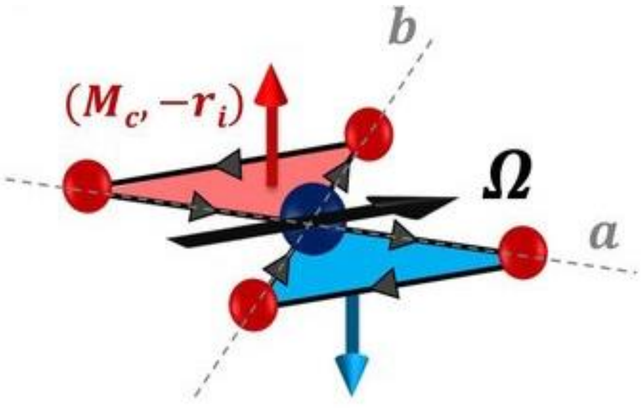
The proposal was to study also a more complex object



$$\mathbf{B} = \mathbf{B}_s + \mathbf{B}_L = \frac{\mu_0}{4\pi}\left[2\mu_B \nabla \times \left(\frac{\mathbf{s} \times \mathbf{R}}{R^3}\right) + I\, d\mathbf{l} \times \frac{\mathbf{R}}{R^3}\right]$$

Neutrons and muons can only detect **bulk** TRS breaking through ***L*** and ***S***.

The proposal was to study also a more complex object



$$\mathbf{B} = \mathbf{B}_s + \mathbf{B}_L = \frac{\mu_0}{4\pi}\left[2\mu_B \nabla \times \left(\frac{\mathbf{s} \times \mathbf{R}}{R^3}\right) + I\, d\mathbf{l} \times \frac{\mathbf{R}}{R^3}\right]$$

Neutrons and muons can only detect **bulk** TRS breaking through ***L*** and ***S***.

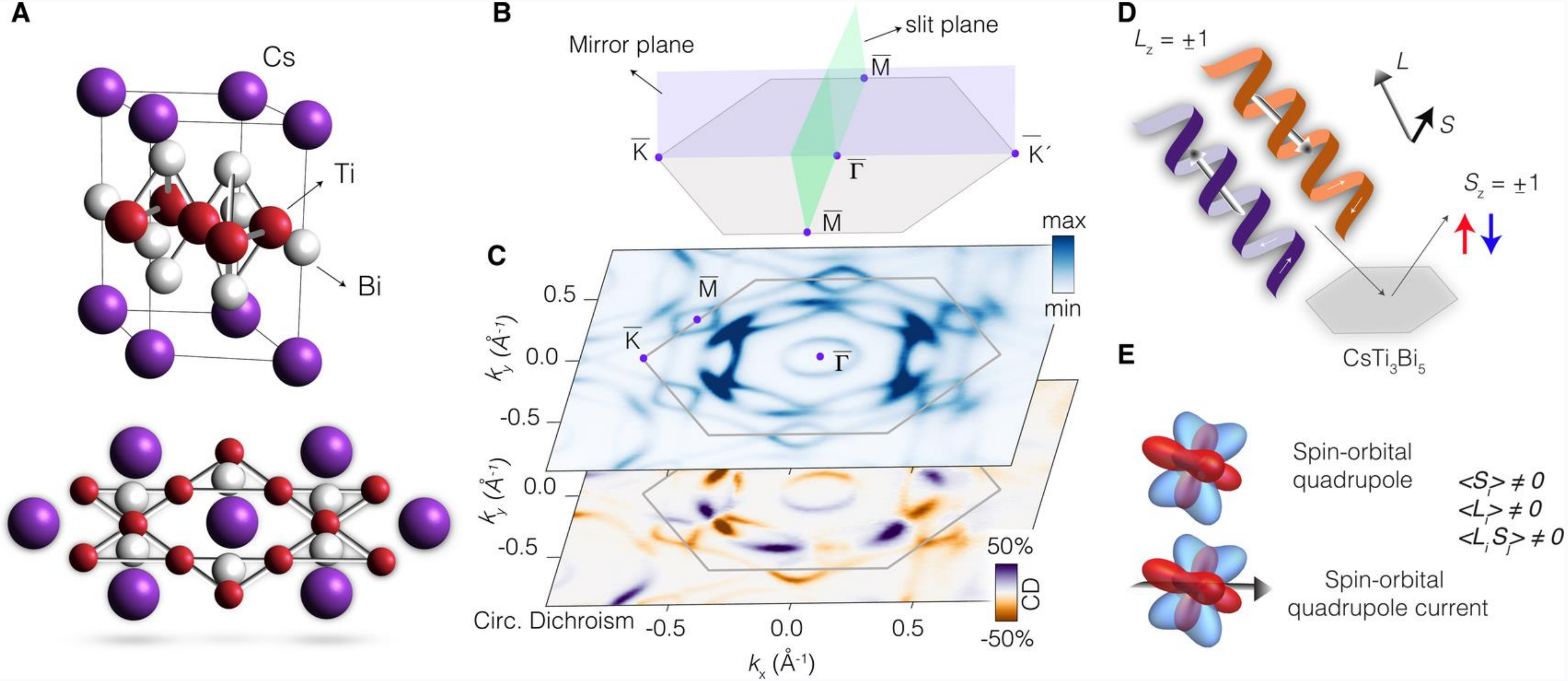
But what about ***LS***? (and also, why?)

- Magnetic textures (like skyrmions) have topological properties that make them stable and robust
- Spin–orbit coupling links magnetic order to the electronic band structure
- Berry curvature acts as a “magnetic field” in momentum space, shaping electron motion
- Complex spin textures create Berry curvature, leading to effects such as the anomalous Hall response
- Plus.. we would like this into low dimensional systems, ideally.

Therefore…

Case 4 — kagome metals and quantum geometry

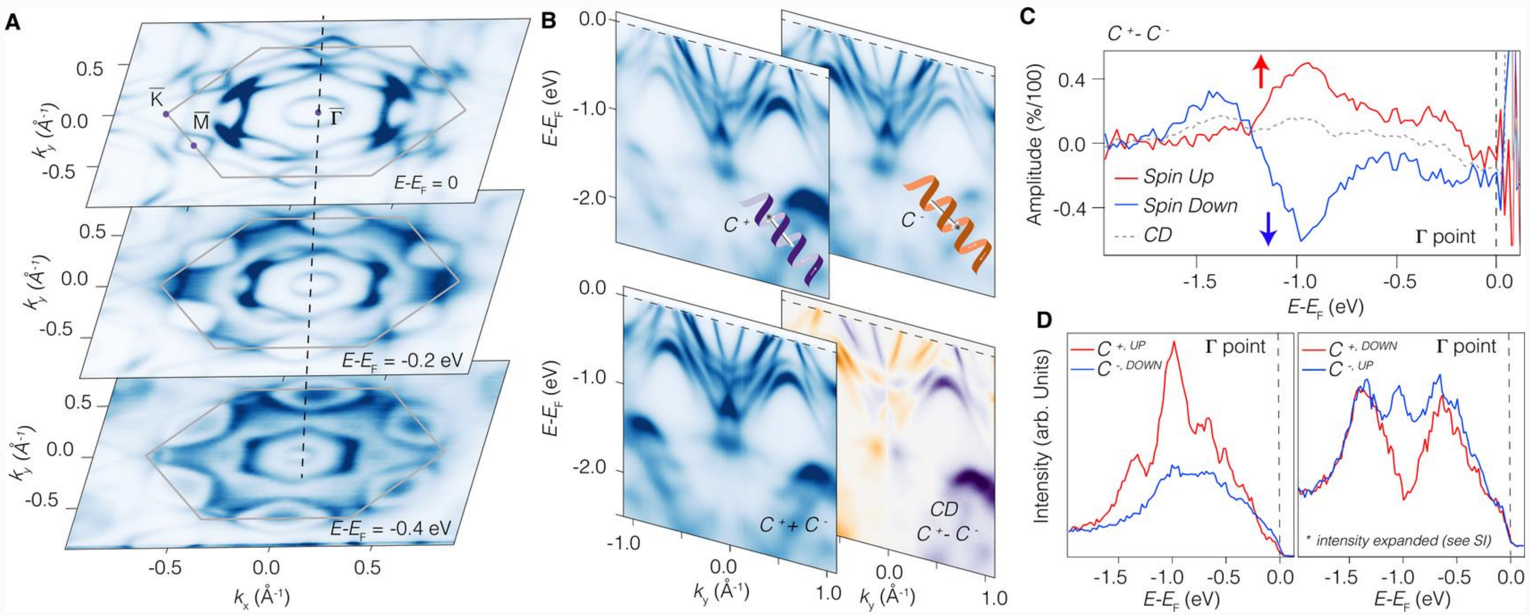
Dirac points, flat band, van Hove, and spin–orbital order.



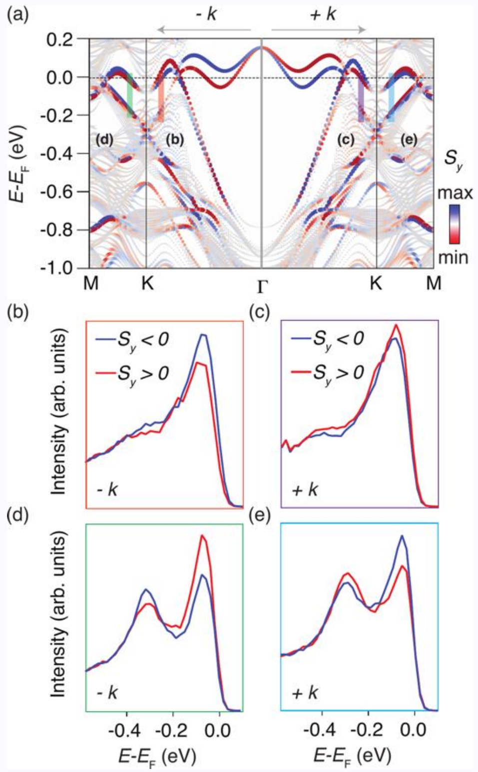
$CsTi_3Bi_5$: structure, CD map, spin–orbital quadrupole.

Case 4 continued — reading the quantum geometry

CD + spin → the geometry of the wavefunctions.



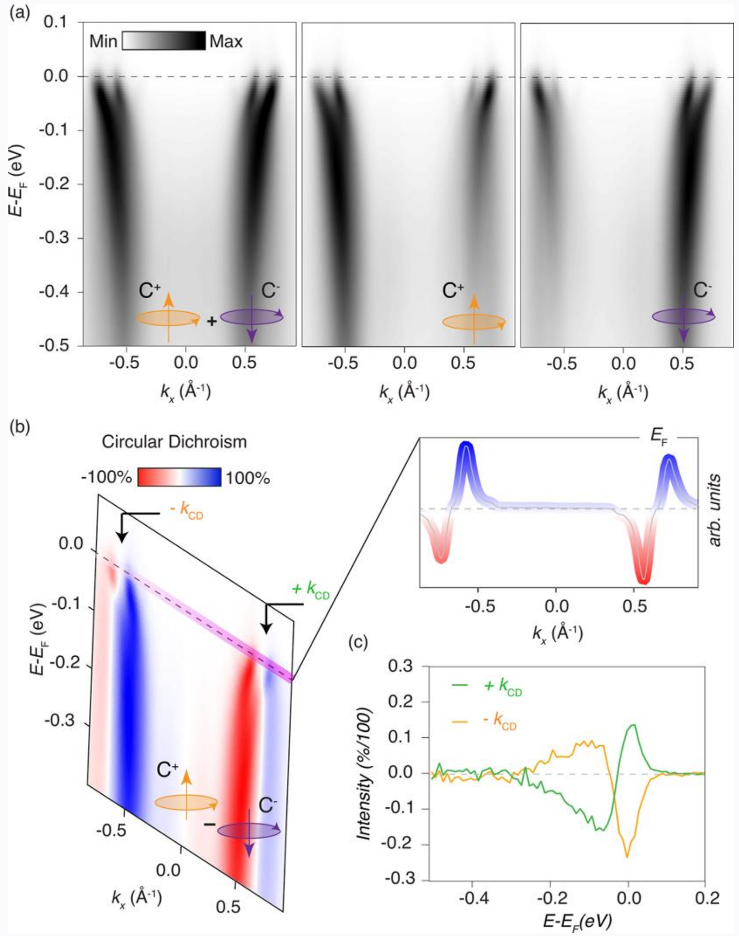
Constant-energy maps with circular light.



Data vs calculated spin–orbital texture.

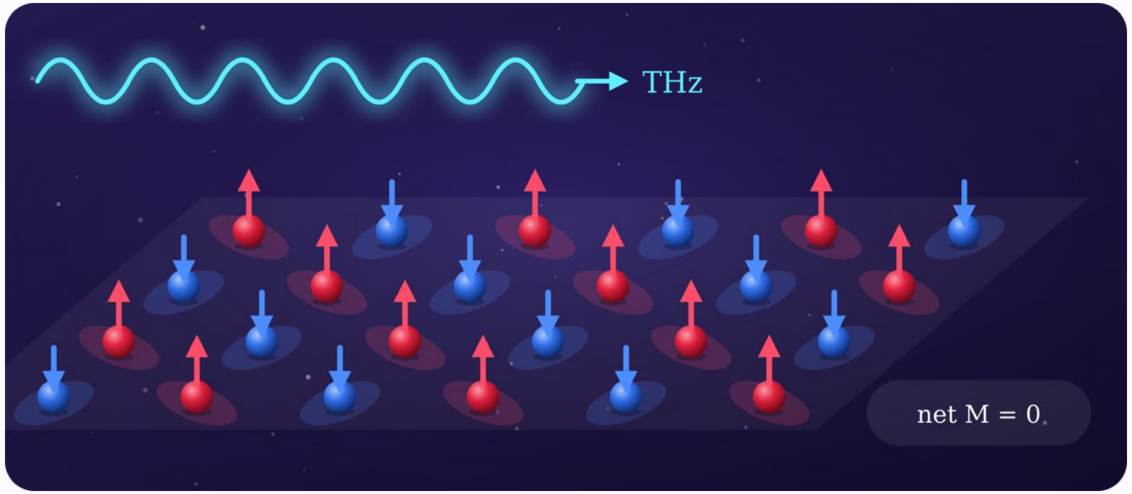
Case 5 — chirality and the surface chiral metal

- **Question: a chiral metal surface?**
- **Answer: handedness in spin × helicity**
- **A correlation, not a quantity**
  - Mazzola et al., Nature 626, 752 (2024)



Handedness appears only when spin and helicity combine.

Case 6 — altermagnets: the new test bed

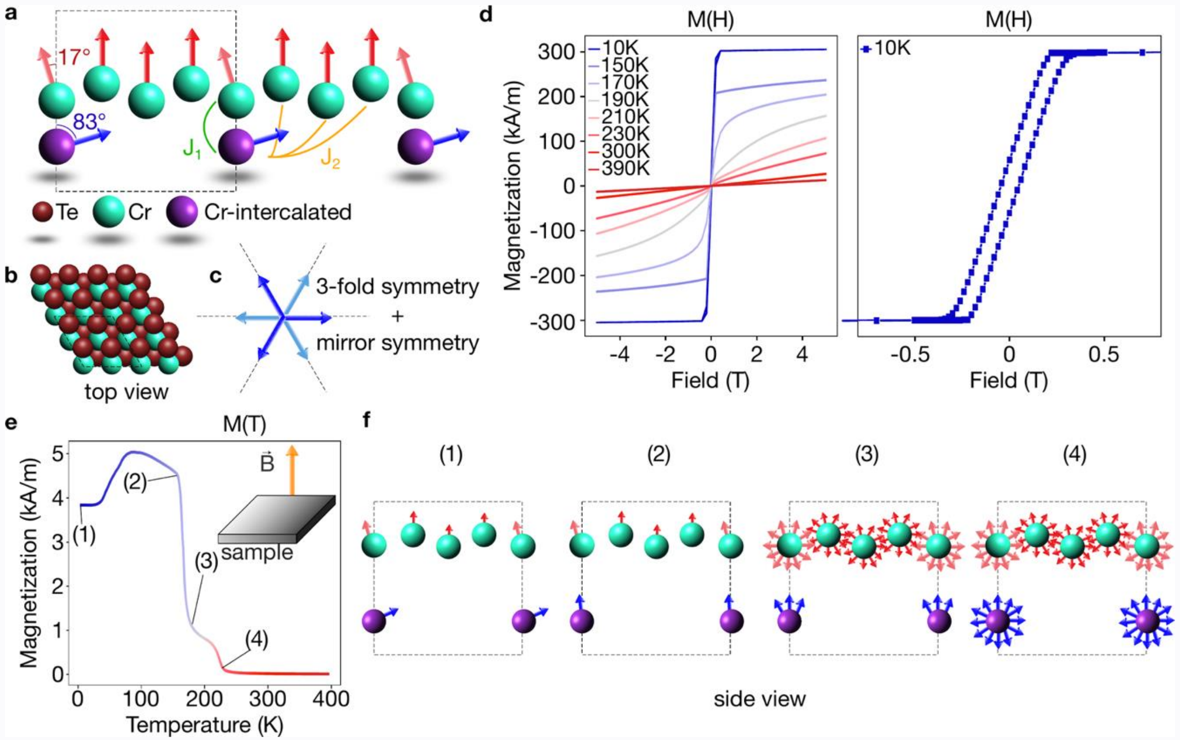


Opposite spins, rotated environments, net M = 0.

- Zero net moment
- Bands still spin split
- **Magnetometry blind, spin-ARPES sees it**
  - Krempaský et al., Nature 626, 517 (2024)

Case 7 — magnetism where you do not expect it

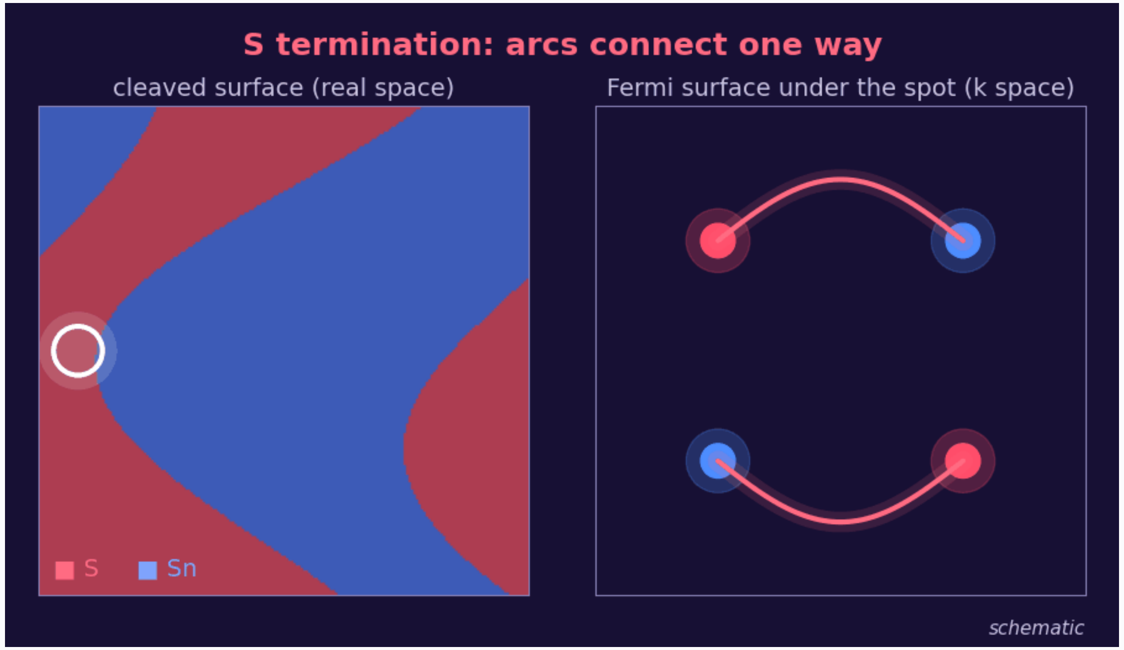
- 2D magnetism in Cr_xTe_2
- **Orthogonal ferromagnet in bilayers**
  - Nat. Commun. 16, 4495 (2025)
- Spin-ARPES + magnetometry + XMCD



Magnetometry and the deduced spin configuration.

Case 8 — the termination decides the topology: $Co_3Sn_2S_2$

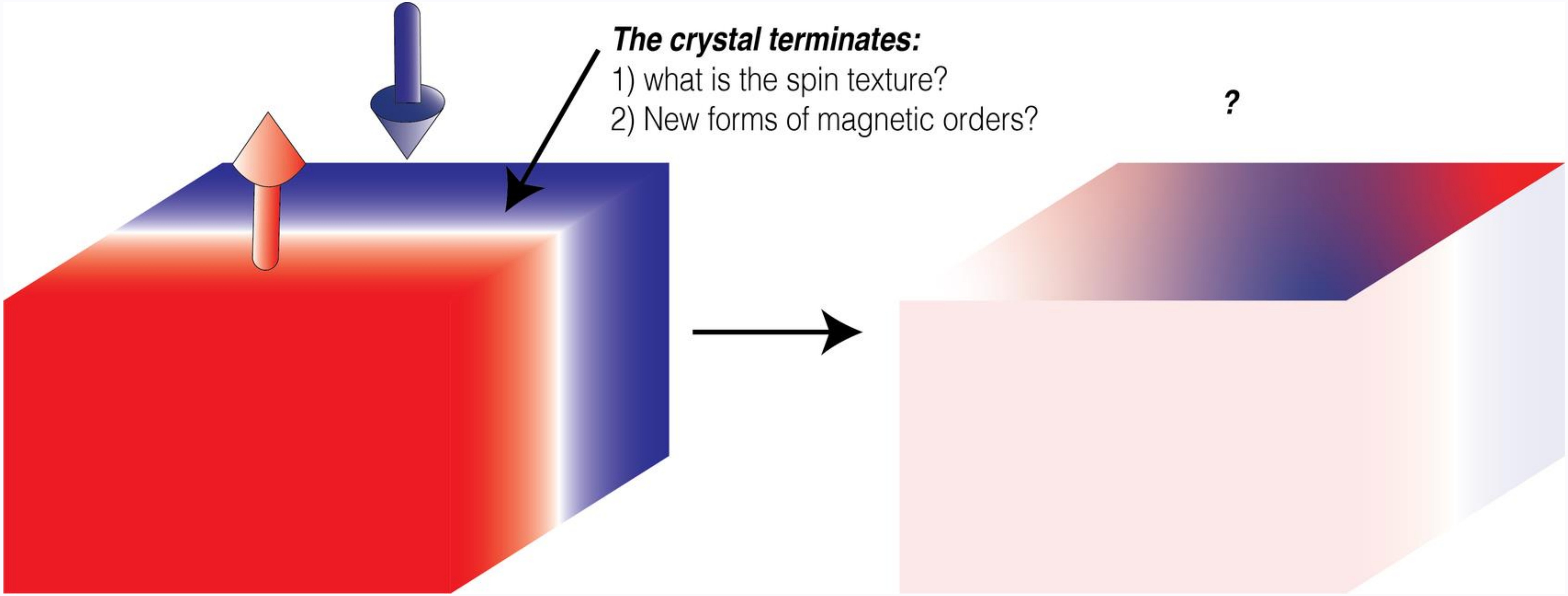
- Magnetic Weyl kagome metal
- Cleave → S and Sn terminations
- **Micro-ARPES: one domain at a time**
- **Weyl points connect differently**
- **The surface potential tunes topology**
  - Nano Lett. 23, 8035 (2023)



Move the spot across the surface: the Fermi arcs reconnect. Schematic.

And the question that is still open

Where a crystal ends, what does its spin do?



The natural question for a surface spin probe.

7

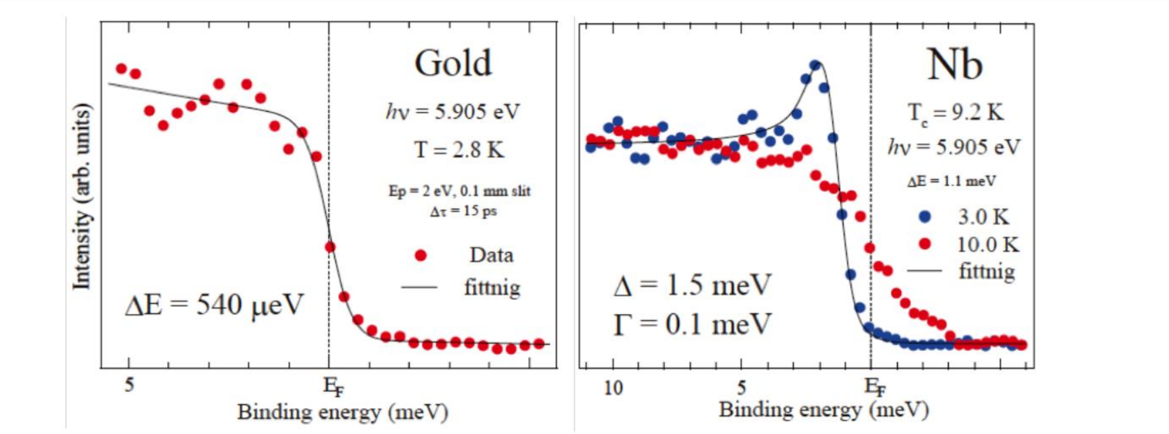
8 minutes

Synchrotron, laser, lab — where should the experiment happen?

Not always a synchrotron any more.

The laboratory came back

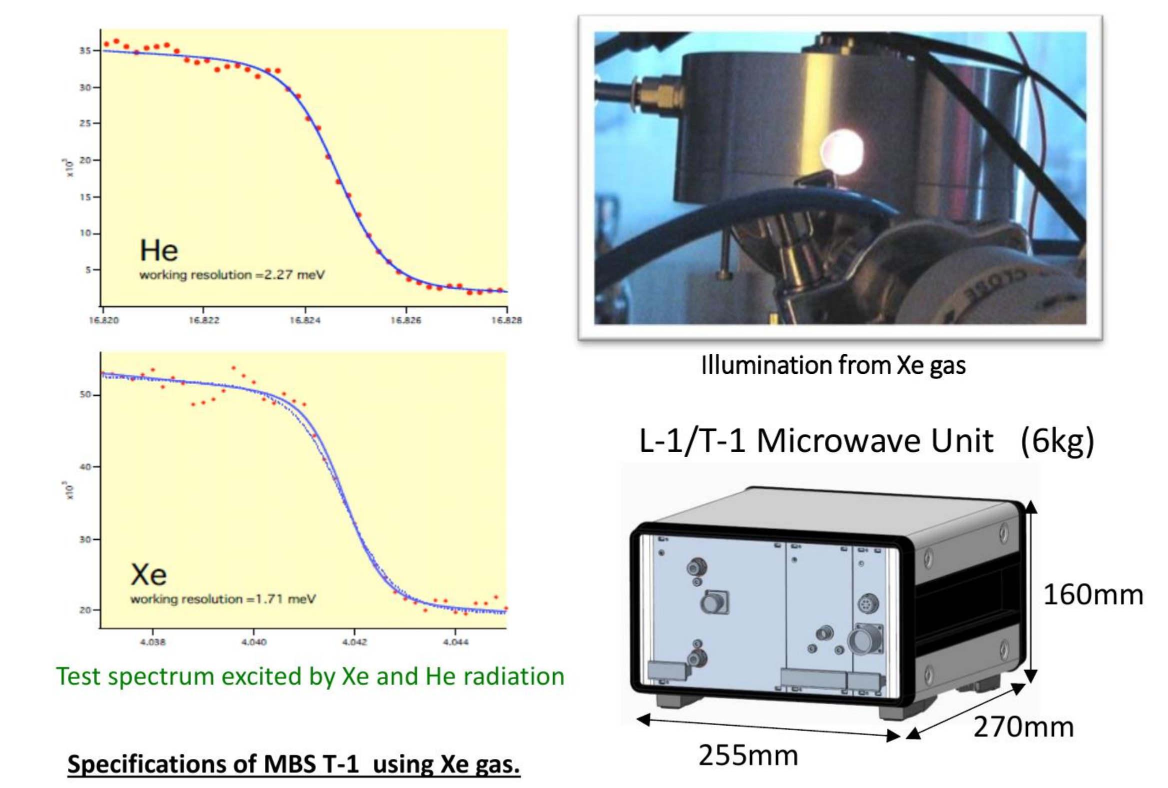
- Sub-meV analyzers and sources
- **Lab wins on resolution and time**
- **No hν, no polarisation, no zone edge**



Gold edge and Nb gap. Figure: MB Scientific AB; data A. Sekiyama, T. Kiss.

The Xe lamp: 8.44 eV and a very narrow line

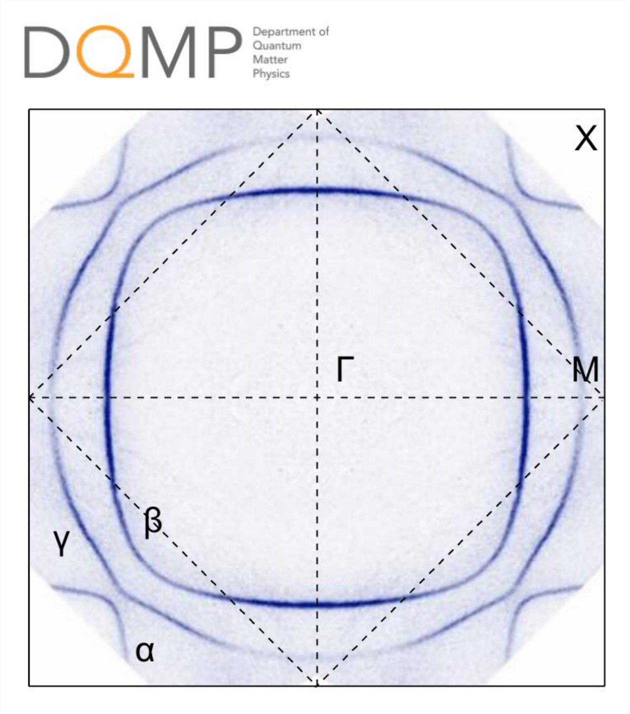
- Xe line at 8.44 eV
- **Linewidth circa 0.95 meV**
- **Fixed hν, unpolarised, zone centre**
- More bulk sensitive



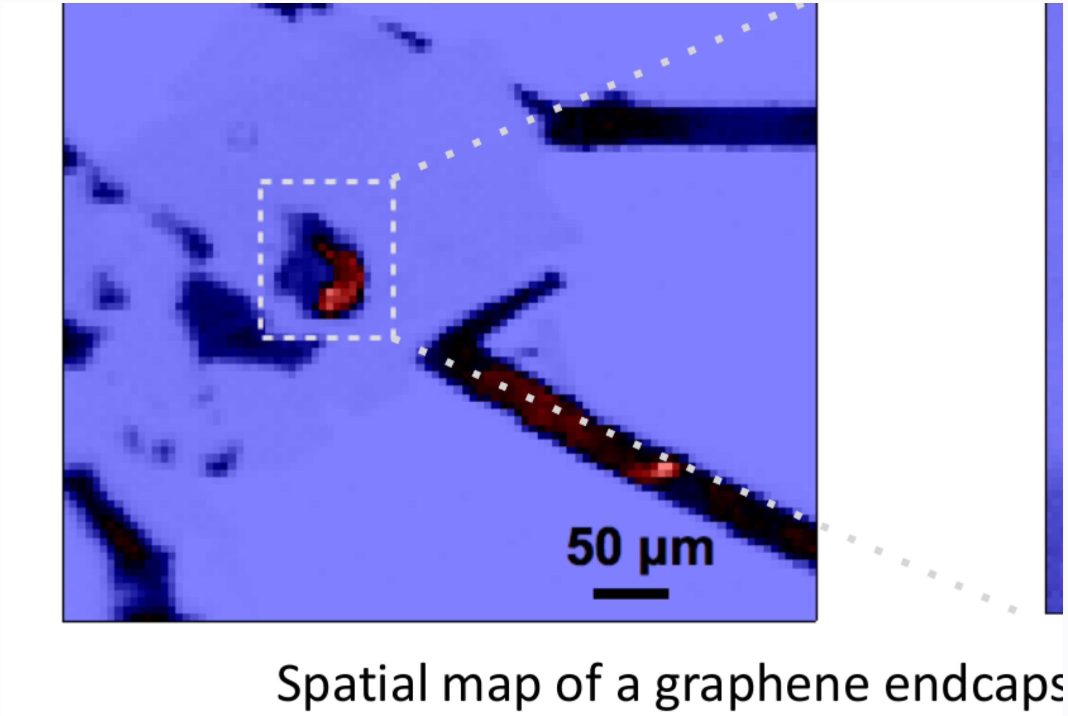
Xe source and test spectra. Figure: MB Scientific AB.

Laser ARPES: resolution and a small spot

6–11 eV lasers: micron spots in the lab.



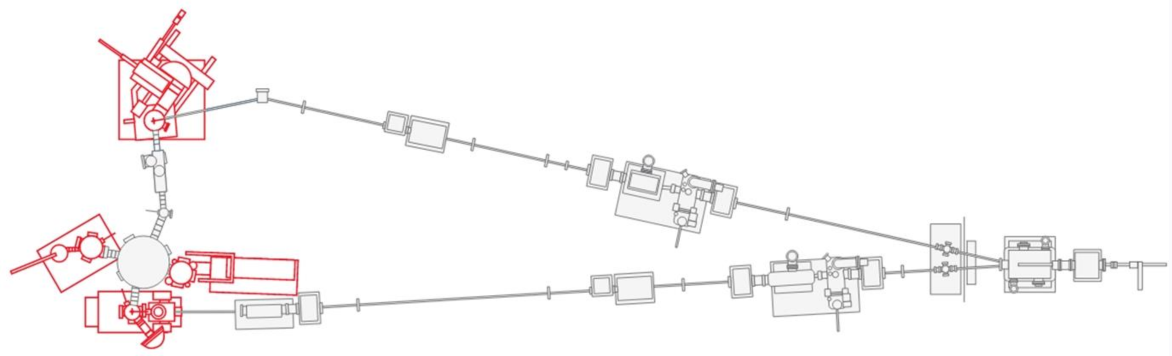
Sr_2RuO_4 Fermi surface, 11 eV. Data A. Tamai, F. Baumberger.



WTe_2 flake, 6 eV, 50 µm scale.

Where to do this

- **APE-LE @ Elettra**
  - 8–120 eV, VESPA 3D spin
- **Elsewhere: SLS, SOLEIL, BESSY, MAX IV…**
- **Lab: laser and HHG spin-ARPES**
- **Talk to the local contact first (if you have doubts!)**



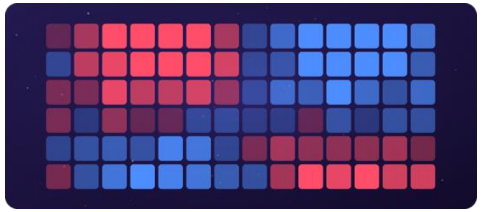
APE: two undulators, two branches.

Where the technique is going

Already producing data.

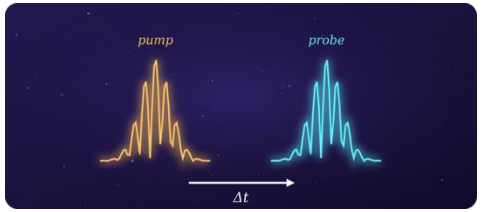
1 Parallel detection

- Imaging spin detectors
- Spin as a map



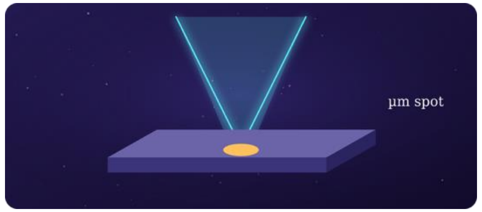
2 Time resolution

- Pump–probe
- Spin dynamics



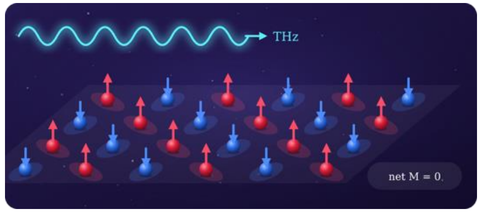
3 Space resolution

- µ-ARPES with spin
- Single domains



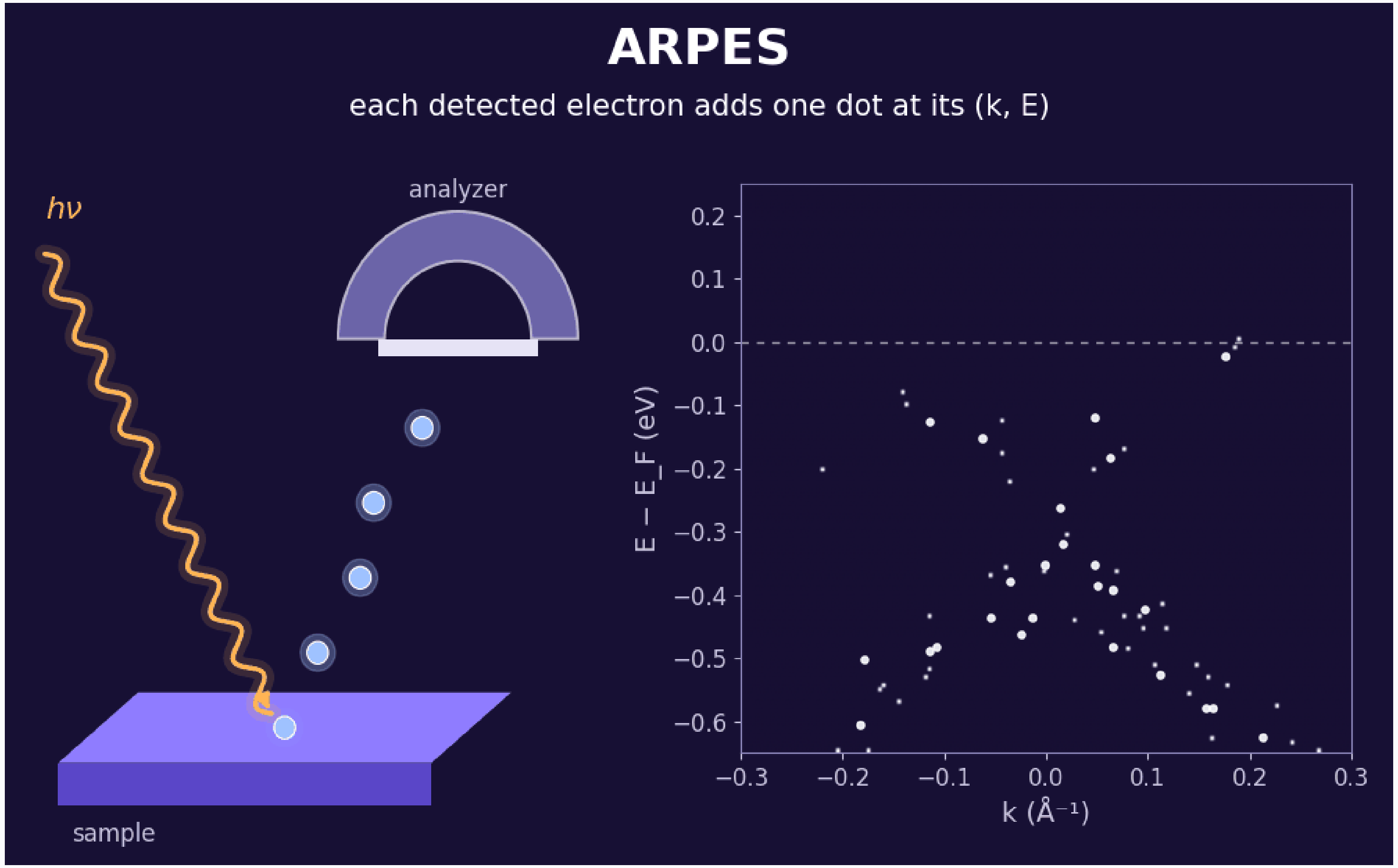
4 New physics to measure

- Altermagnets
- Quantum geometry



ARPES: where are the electrons?

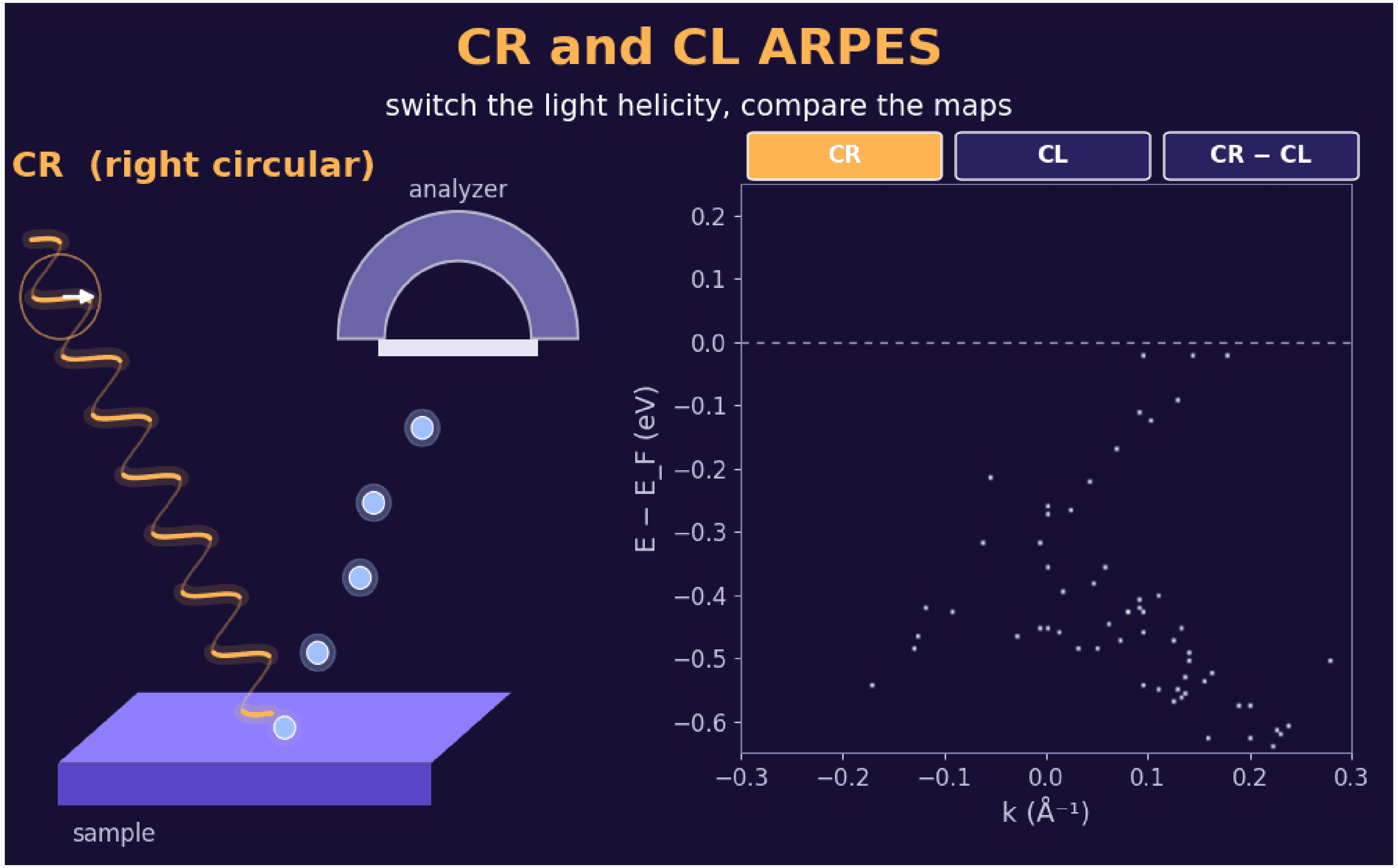
- Photon in, electron out
- Energy + angle → E(k)
- **Each electron = one dot**
- **Bands, Fermi surface, gaps**



Dots accumulate into the band structure (simulated bands).

CR and CL ARPES: what are the orbitals doing?

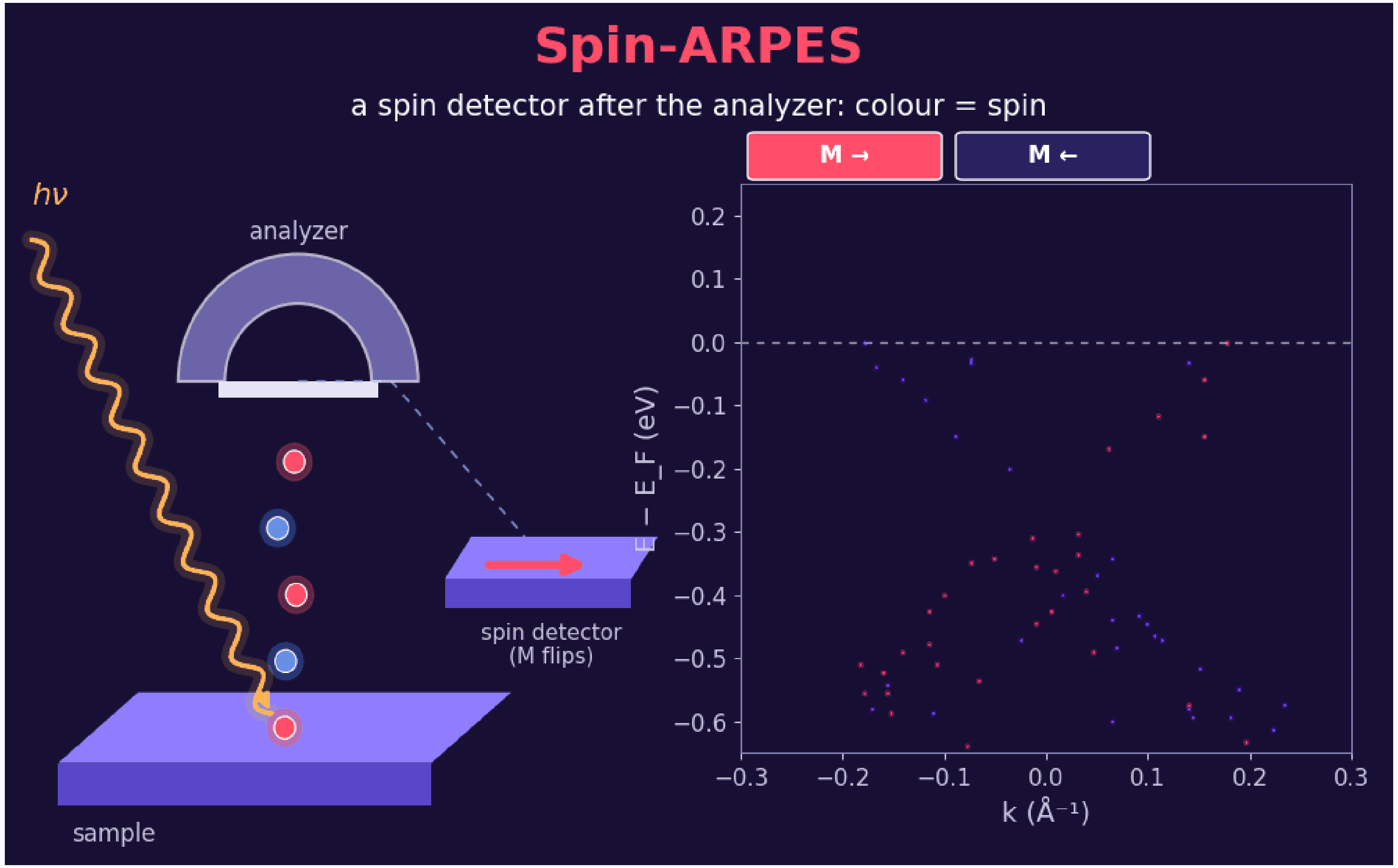
- CR = right circular light
- CL = left circular light
- Intensity moves between +k and −k
- **CR − CL = circular dichroism**
- **Tracks orbital texture, not L directly**



Right, then left circular light, then the difference (simulated bands).

Spin-ARPES: where do the spins point?

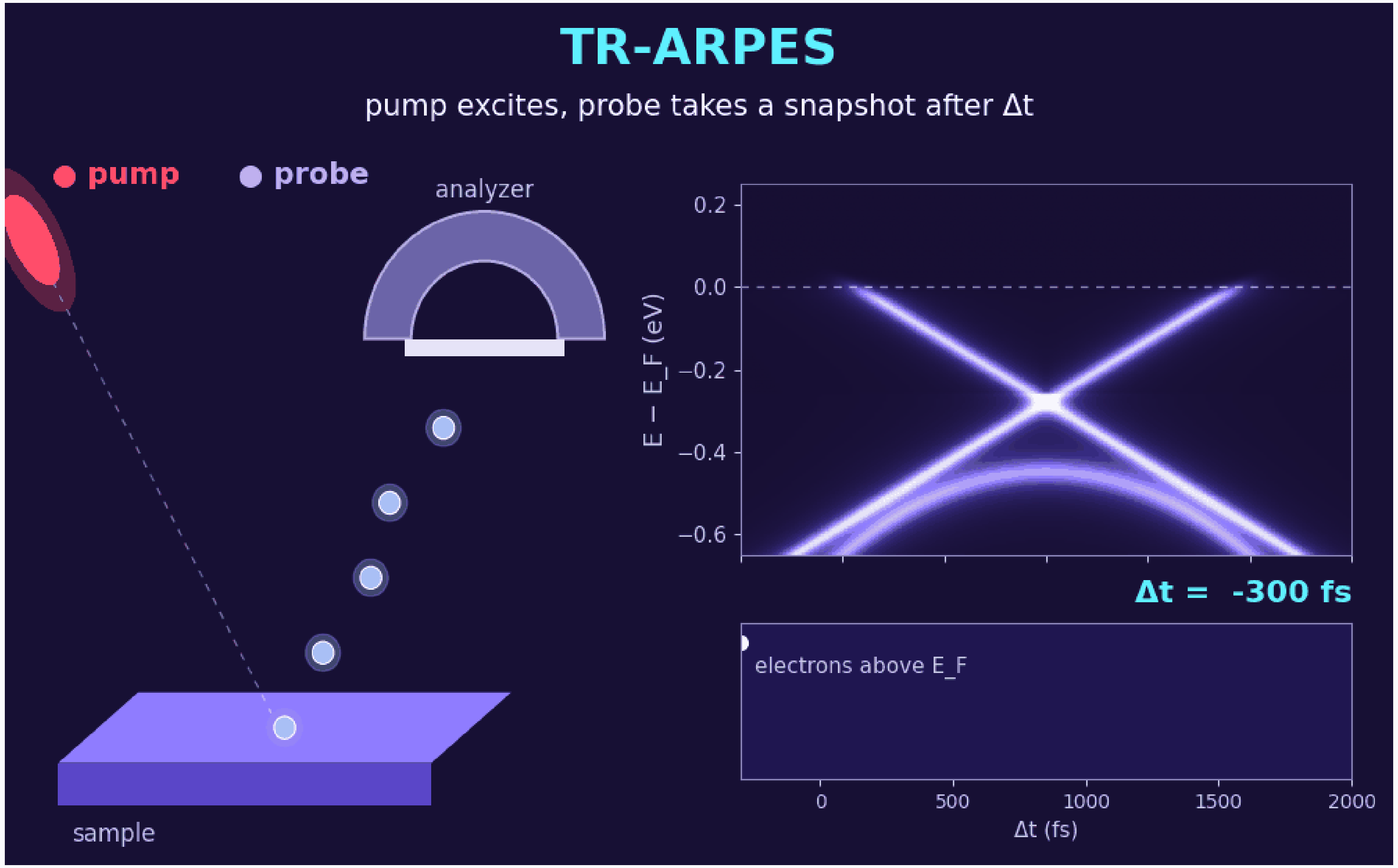
- Spin detector after the analyzer
- Flip the target M: ↑ vs ↓
- **Colour = spin direction**
- **~100× fewer counts**



Every electron counted with its spin: red ↑, blue ↓ (simulated bands).

TR-ARPES: how do electrons move in time?

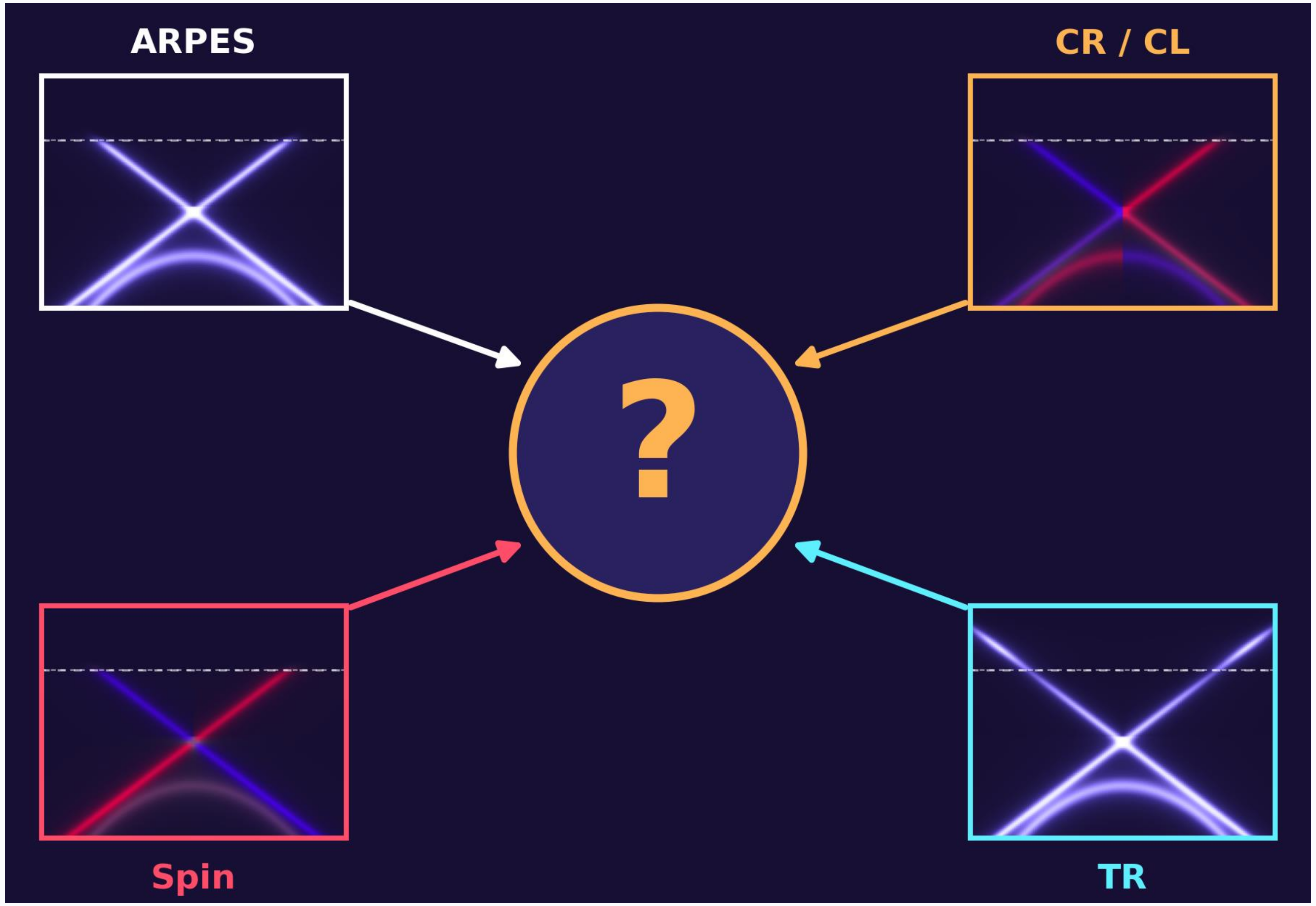
- Pump excites the electrons
- Probe photoemits after Δt
- **Watch them fill and relax**
- **Femtosecond band dynamics**



Electrons pushed above E_F relax back within ~1 ps (simulated bands).

Open question: can we combine them all?

- TR + CR/CL + Spin in one experiment?
- Enough counts? Spin ~10^{-2}, pump–probe limited
- Circular pump, circular probe, or both?
- How to separate dynamics from artefacts?
- **What new physics would we see?**

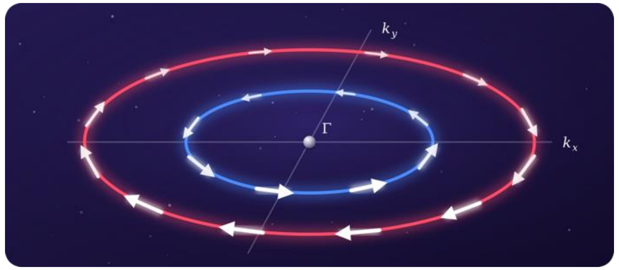


Four measurements on one sample: can they become one experiment?

Take home

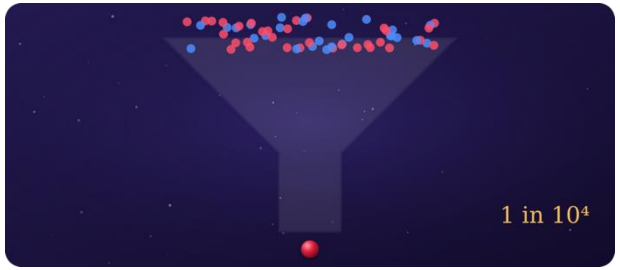
1 Spin is not a detail

- Two sources of splitting
- Band maps can hide it



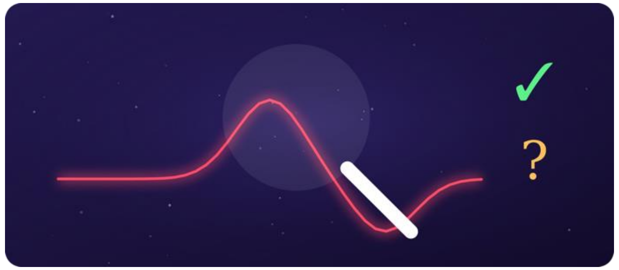
2 The measurement is a budget

- P = A/S
- Plan the counting time



3 Distrust your data first

- Photoelectron spin ≠ band spin
- Vary hν, light, ±k



THANK YOU

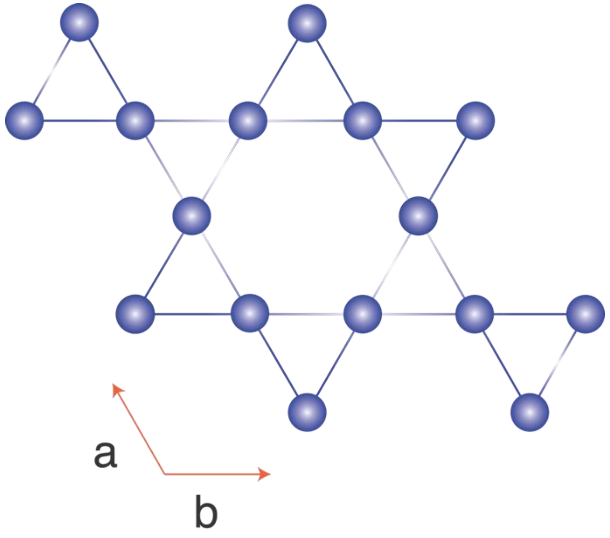
Questions — and if you are thinking of a spin experiment, come and describe it to me during the coffee break.

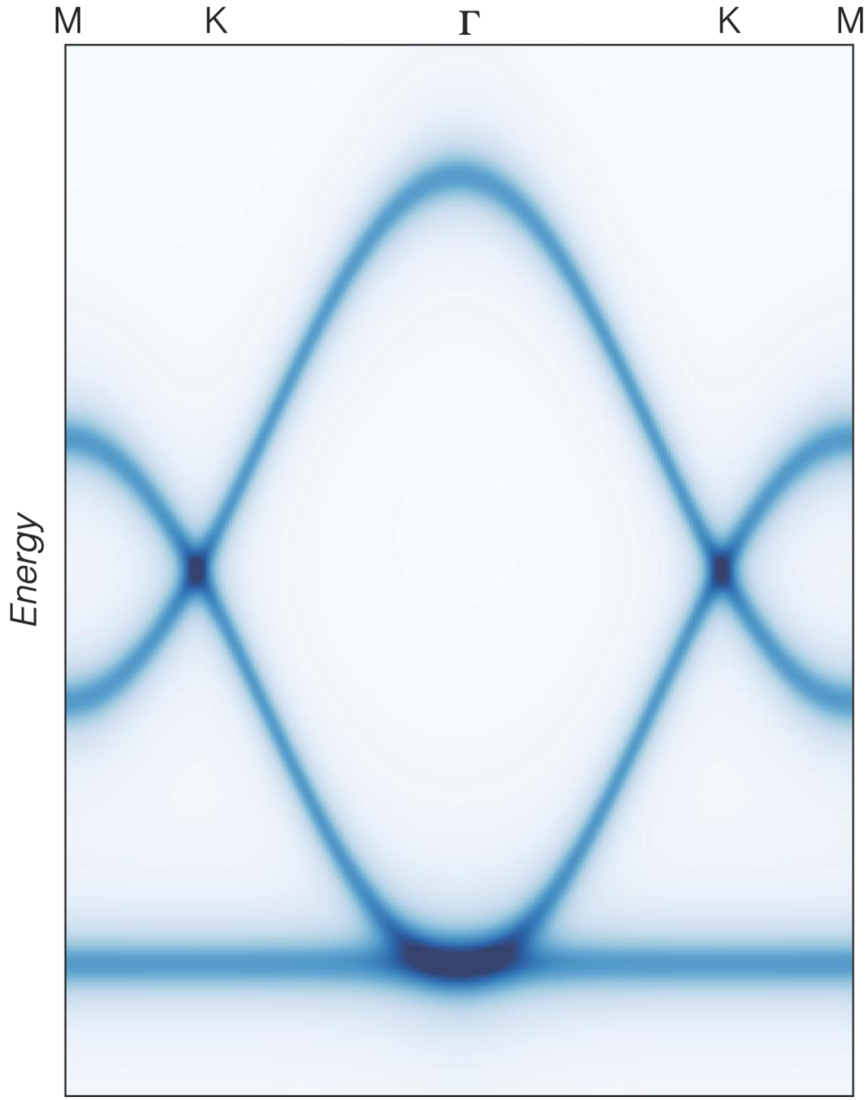
Speaker name · email · APE-LE @ Elettra, CNR-IOM and NFFA-Trieste

With thanks to the beamline staff, the collaborators behind the data shown here, and the SILS organisers.

A full case study

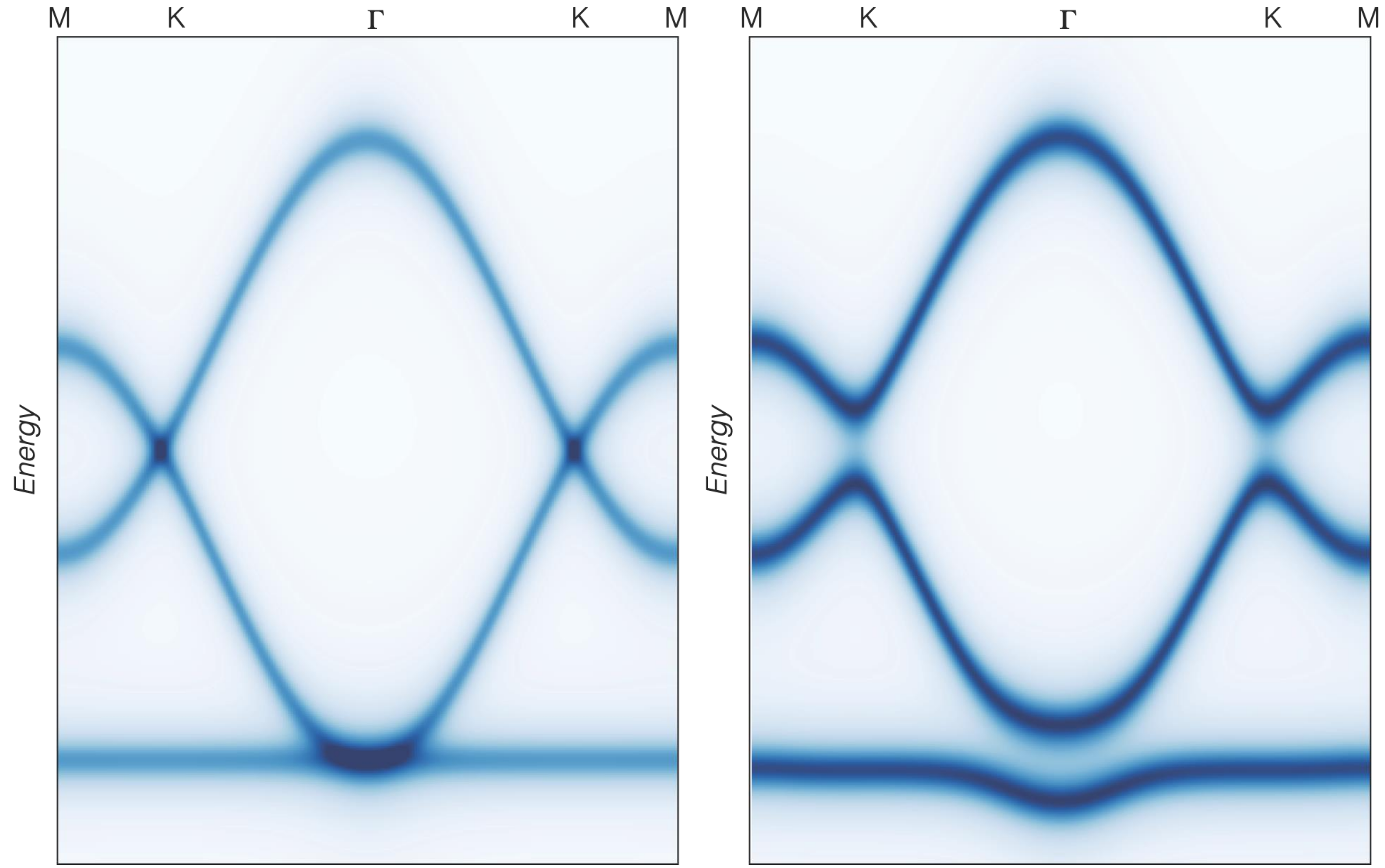
Non-magnetic system - kagome

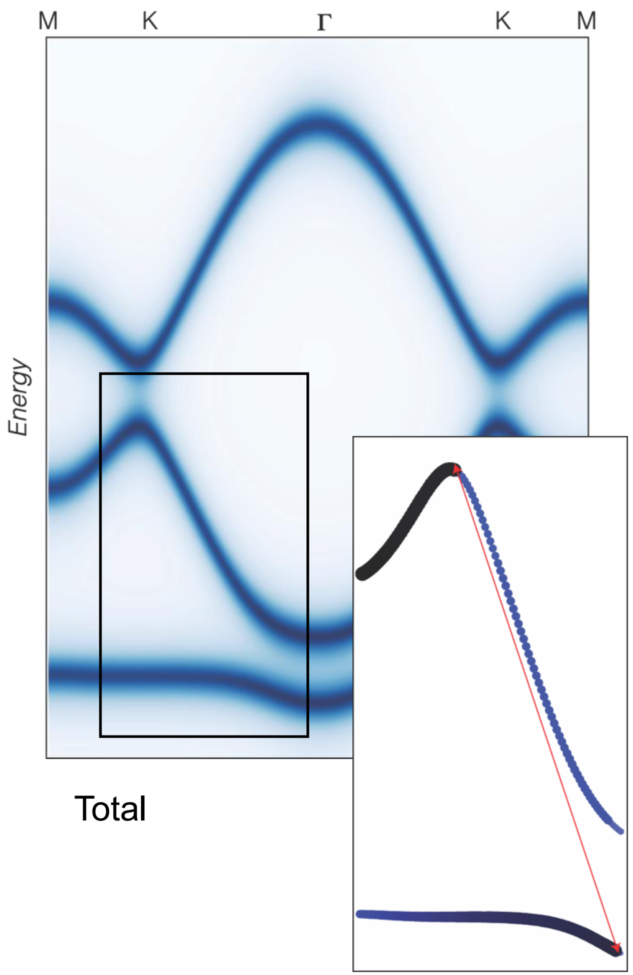




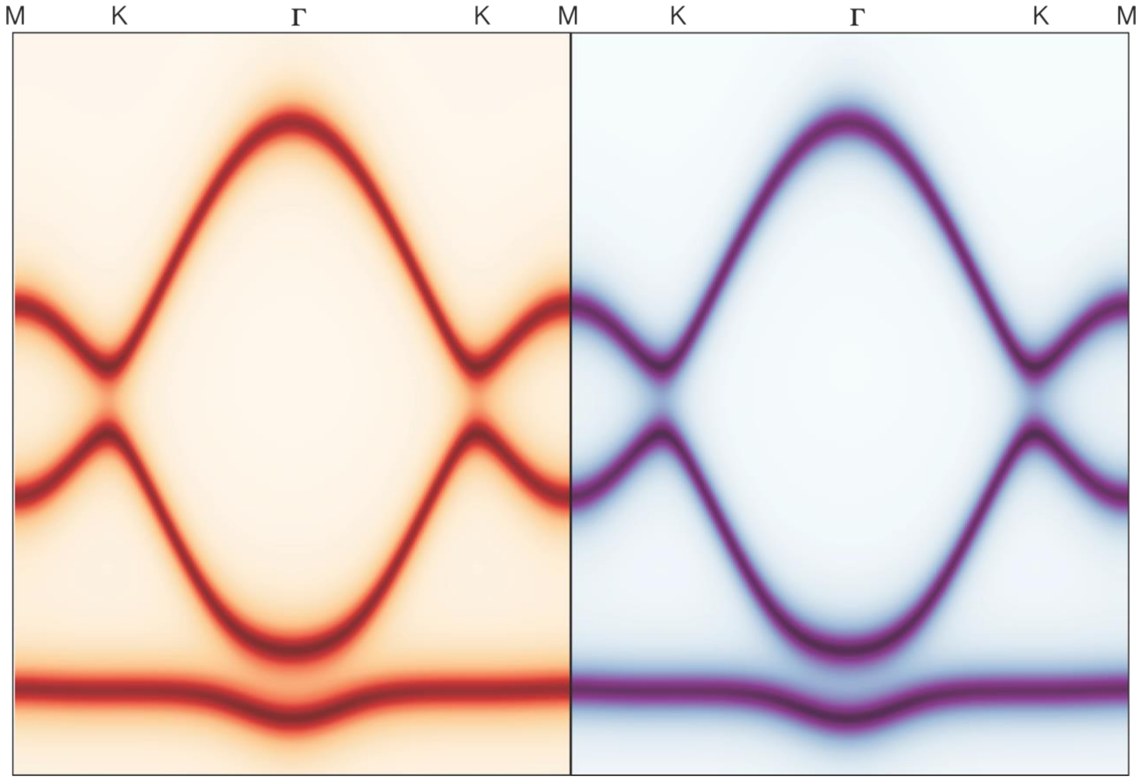
- Dirac bands (like graphene)
- Correlated Flat bands

The effect of SOC gaps the system





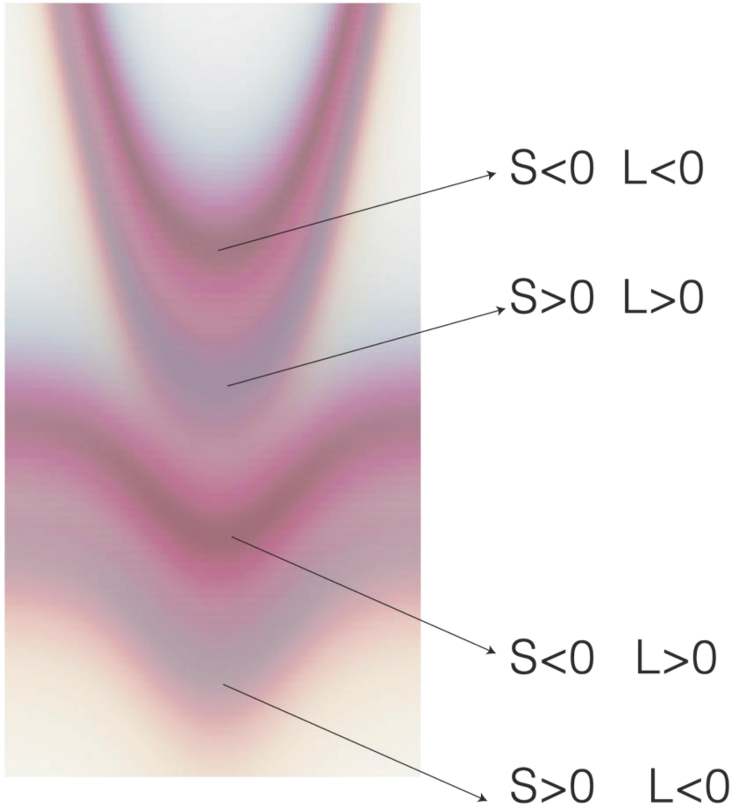
Total



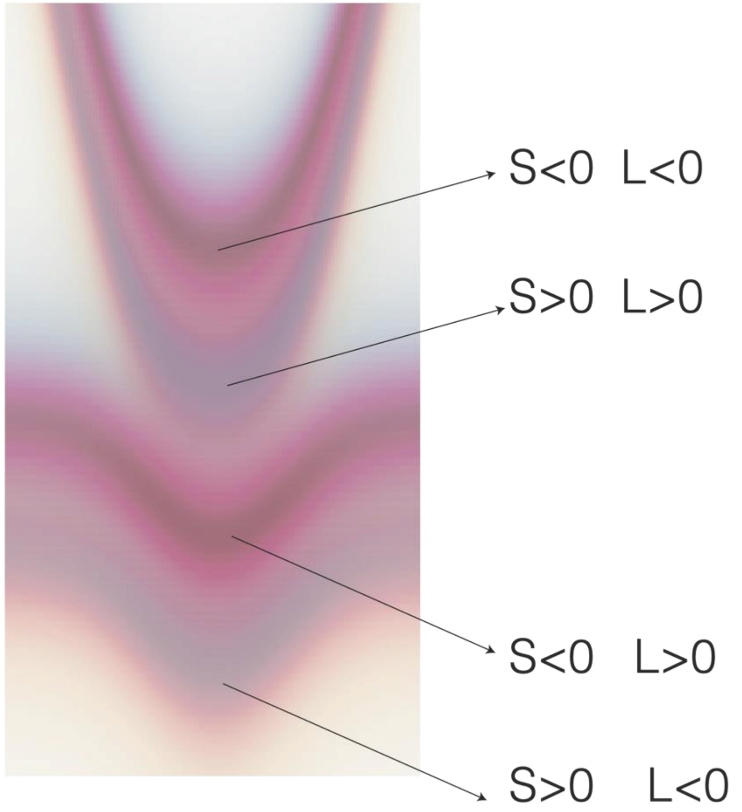
Spin UP

Spin DOWN

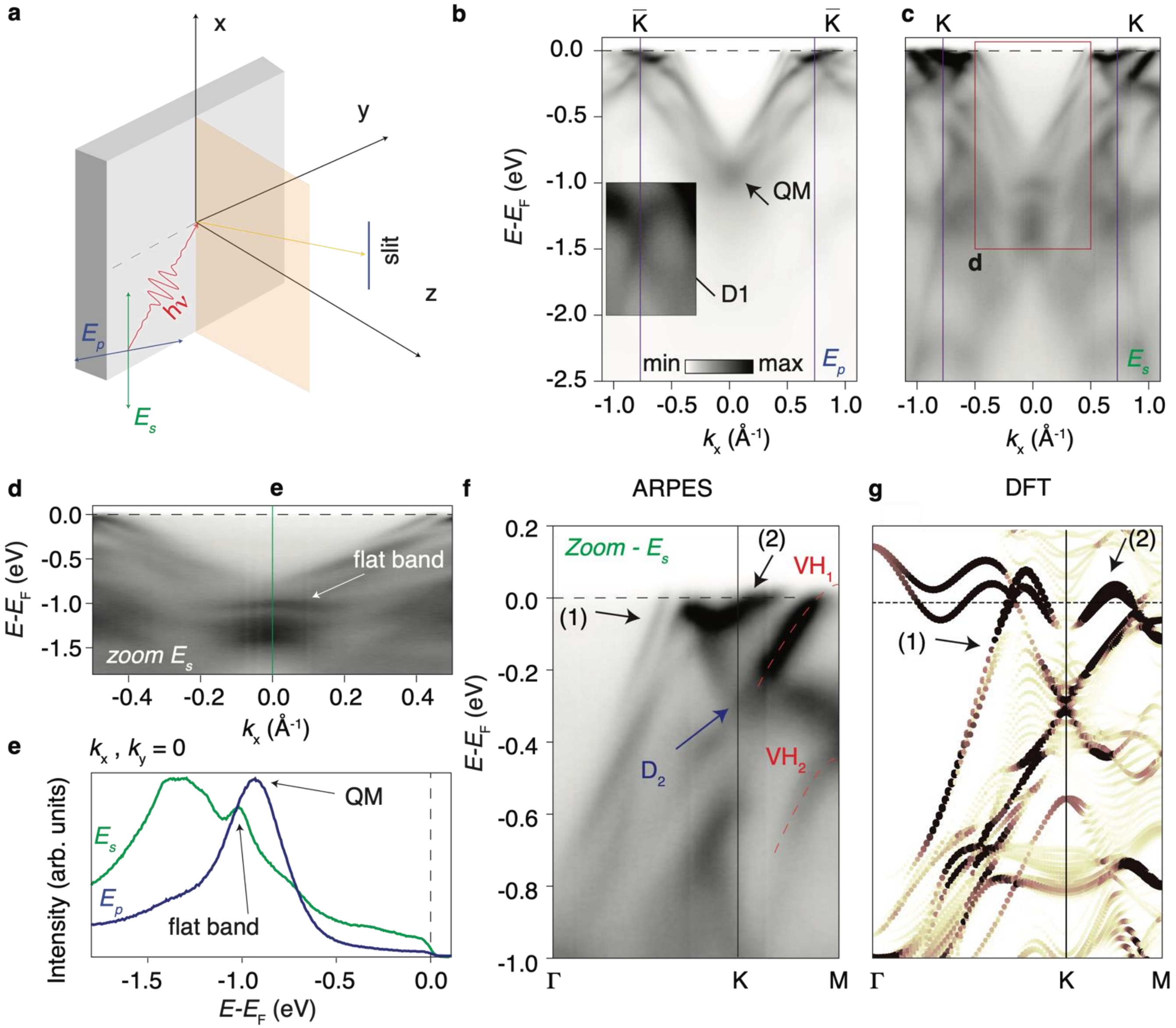
The bands, despite inverted orbital character are spin degenerate



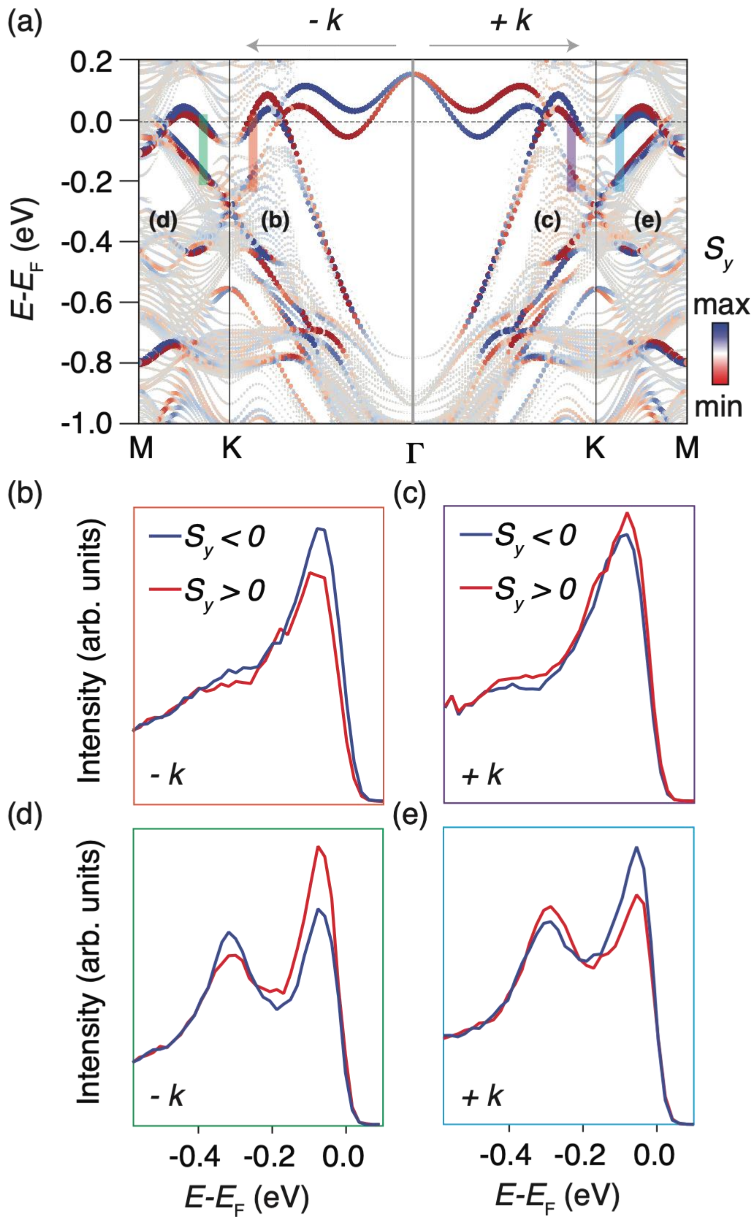
S<0 L<0
S>0 L>0
S<0   L>0
S>0   L<0


S<0 L<0
S>0 L>0
LS positive contribution
S<0 L>0
S>0 L<0
LS negative contribution

166 Family, AV_6Sn_6 (As: Tb, Ho, Gd, Sc)

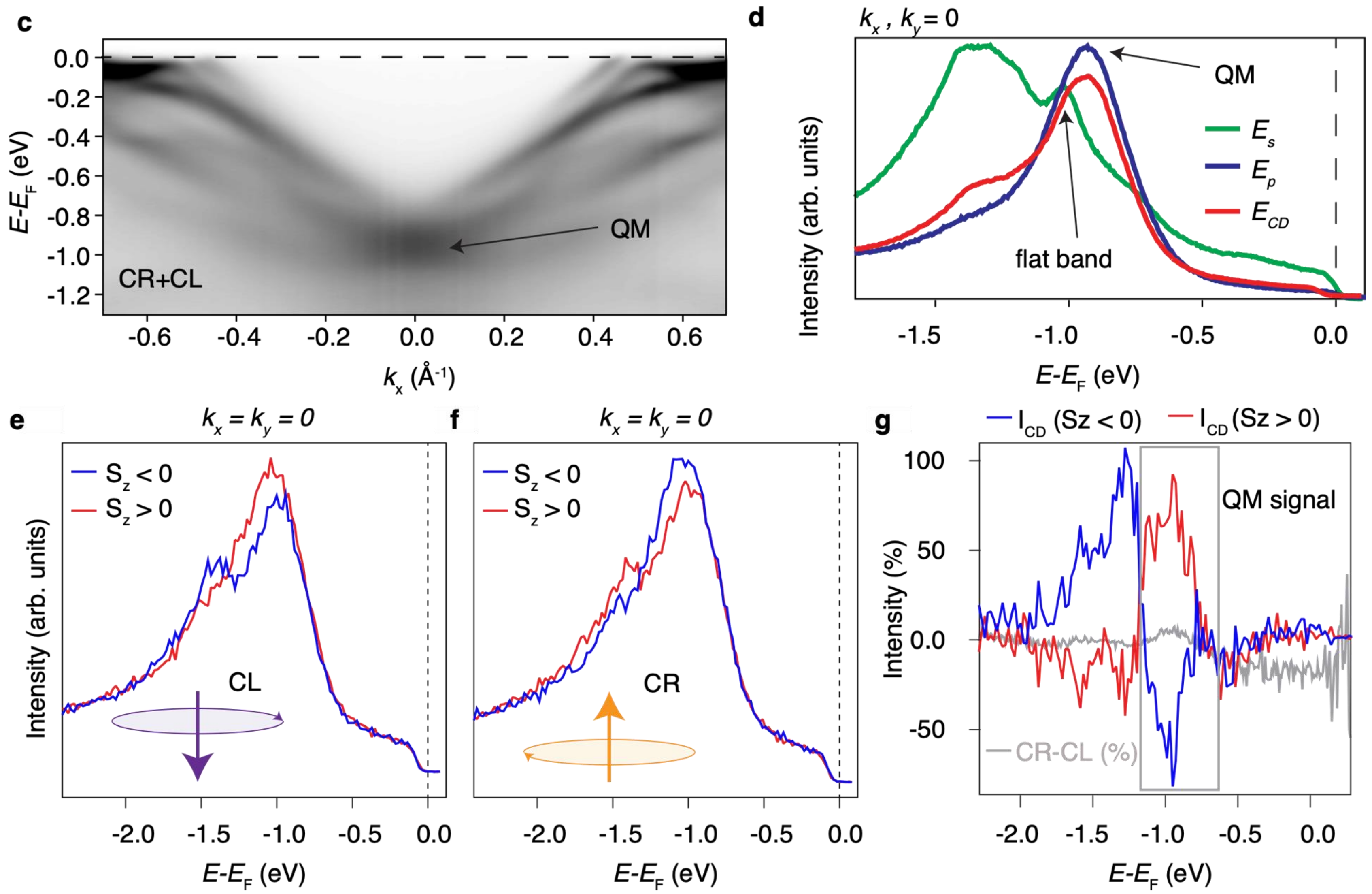


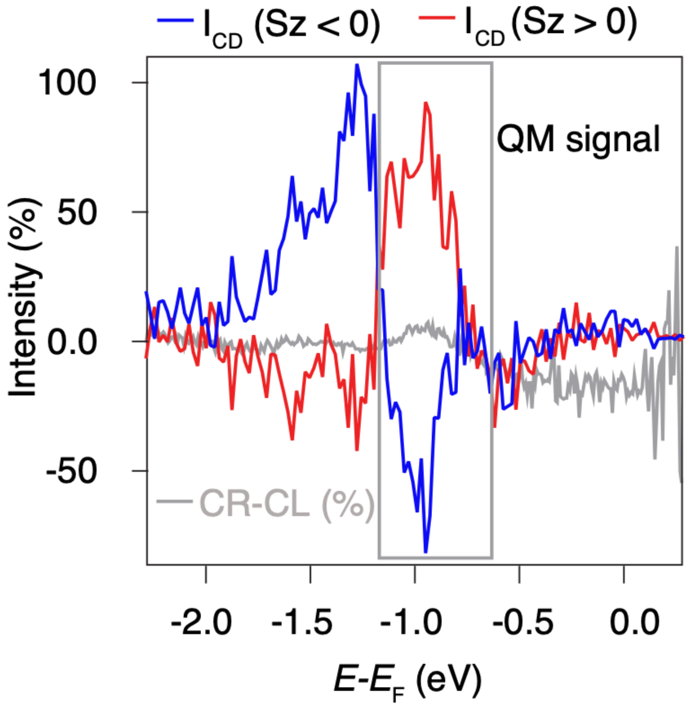
166 Family, AV6Sn6 (As: Tb, Ho, Gd, Sc)



1) Sn surface states are predicted to be topological
2) The have fully Sy polarisation
3) Spin-ARPES verifies this

166 Family, AV_6Sn_6 (As: Tb, Ho, Gd, Sc)





"Flat band separation and robust spin Berry curvature in bilayer kagome metals" ***Nature Physics* 19, 1135–1142, 2023**

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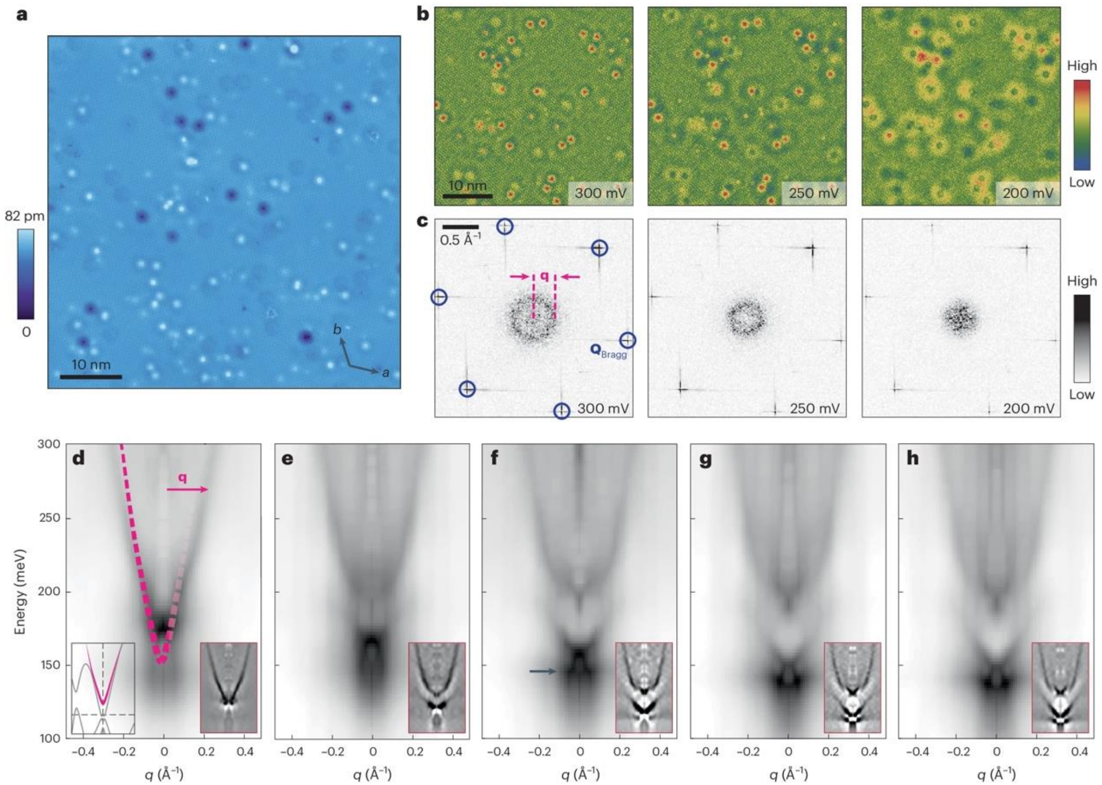

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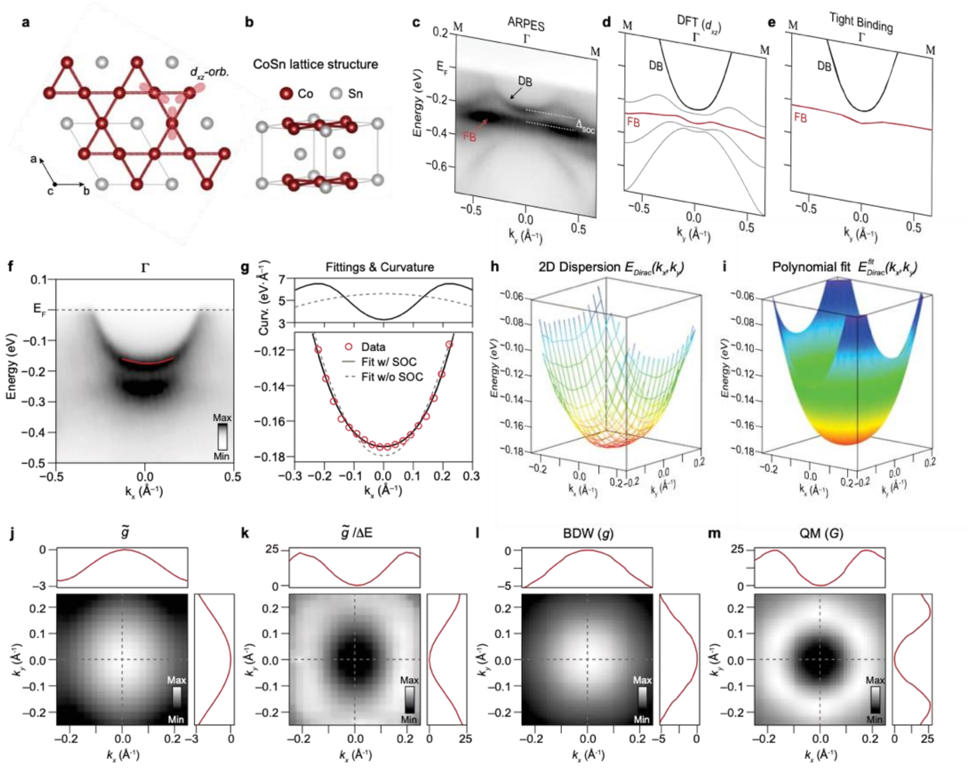

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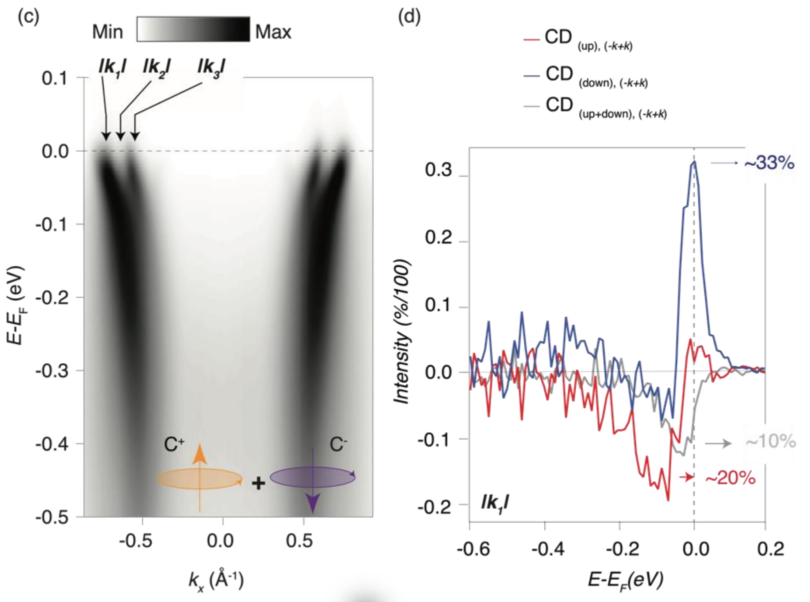
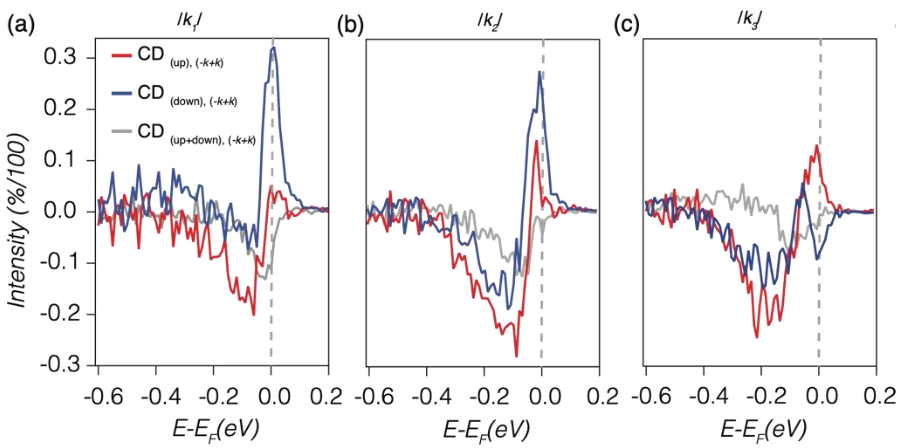
"Measurement of the quantum geometric tensor" ***Nature Physics, 21, 1, 110-117, 2026***





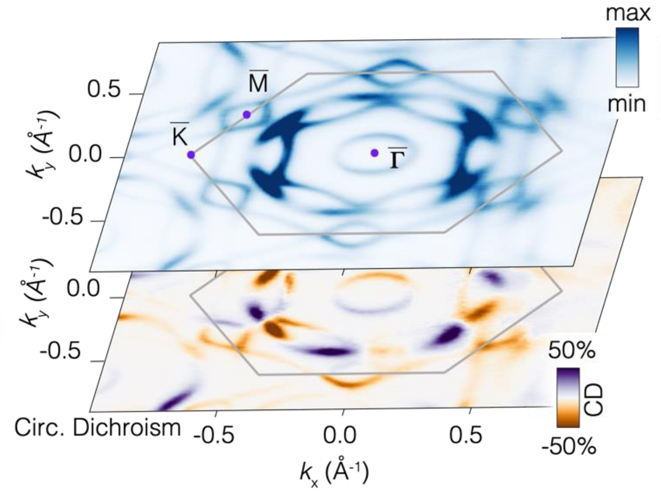
This was our proof of principle, bottom line:

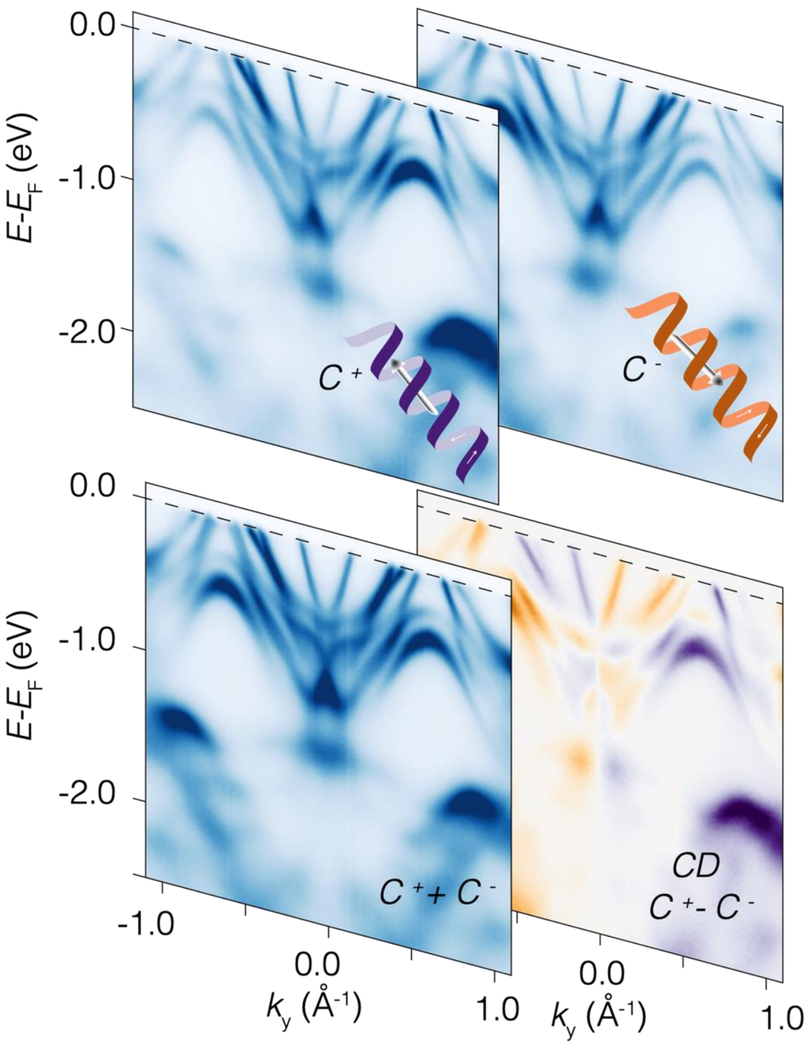
- *E vs k*
- *S (Spin)*
- *L (Orbital and Angular Momentum)*
- *LS (spin-orbital correlations)*

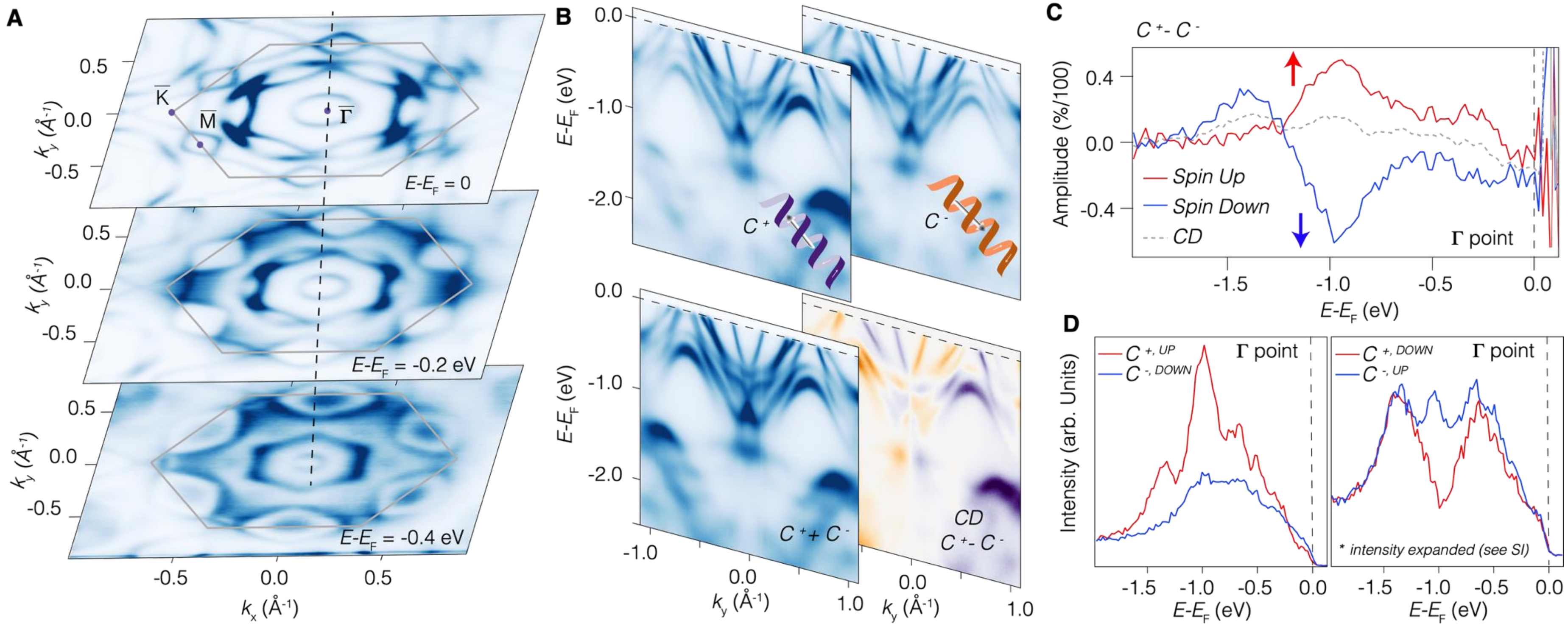
"Signatures of a surface spin-orbital chiral metal"

Nature, 626, 752-758, 2024

The circular dichroism response is well defined and the Fermi surface shows very nice sign-reversal for points in reciprocal space with opposite helicity



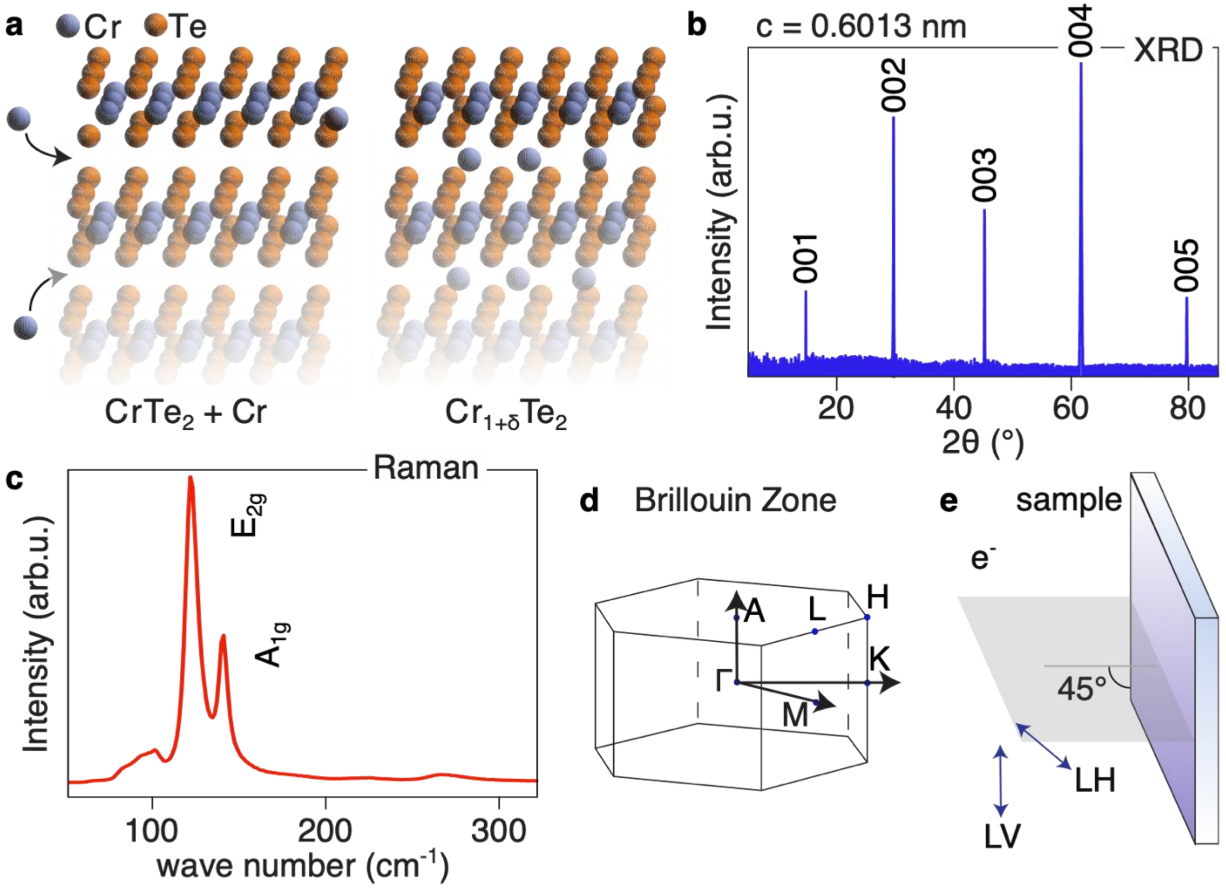




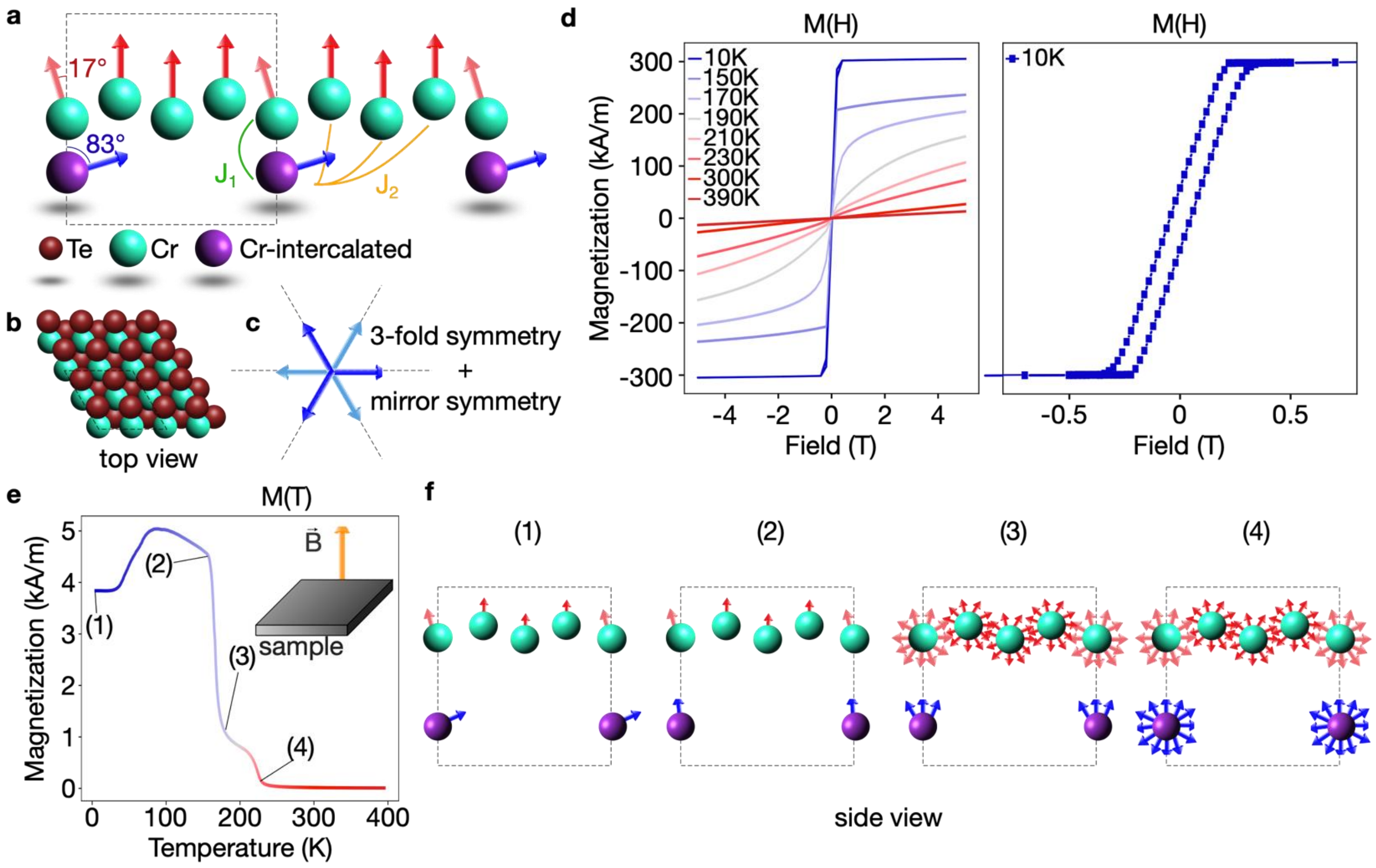
L, S, LS are ineffective, but the single handedness correlated to the spin ($L^{+,-}$ S) reveals the elusive breaking and the evidence of spin optical chiral coupling

"Anomalous spin-optical chiral effect in Ti-based kagome metal", ***Advanced Materials 2026***

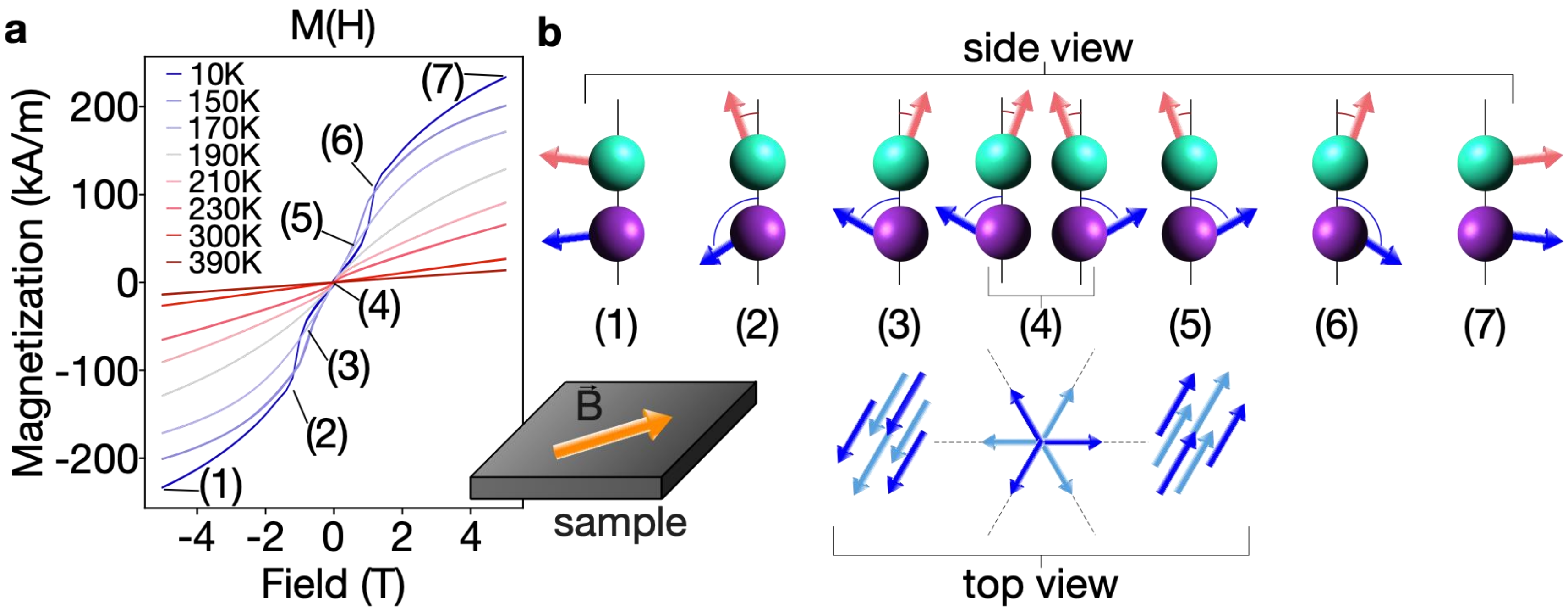
" Pomeranchuk instability from electronic correlations in CsTi3Bi5 kagome metal" ***Nature Communications 2026***



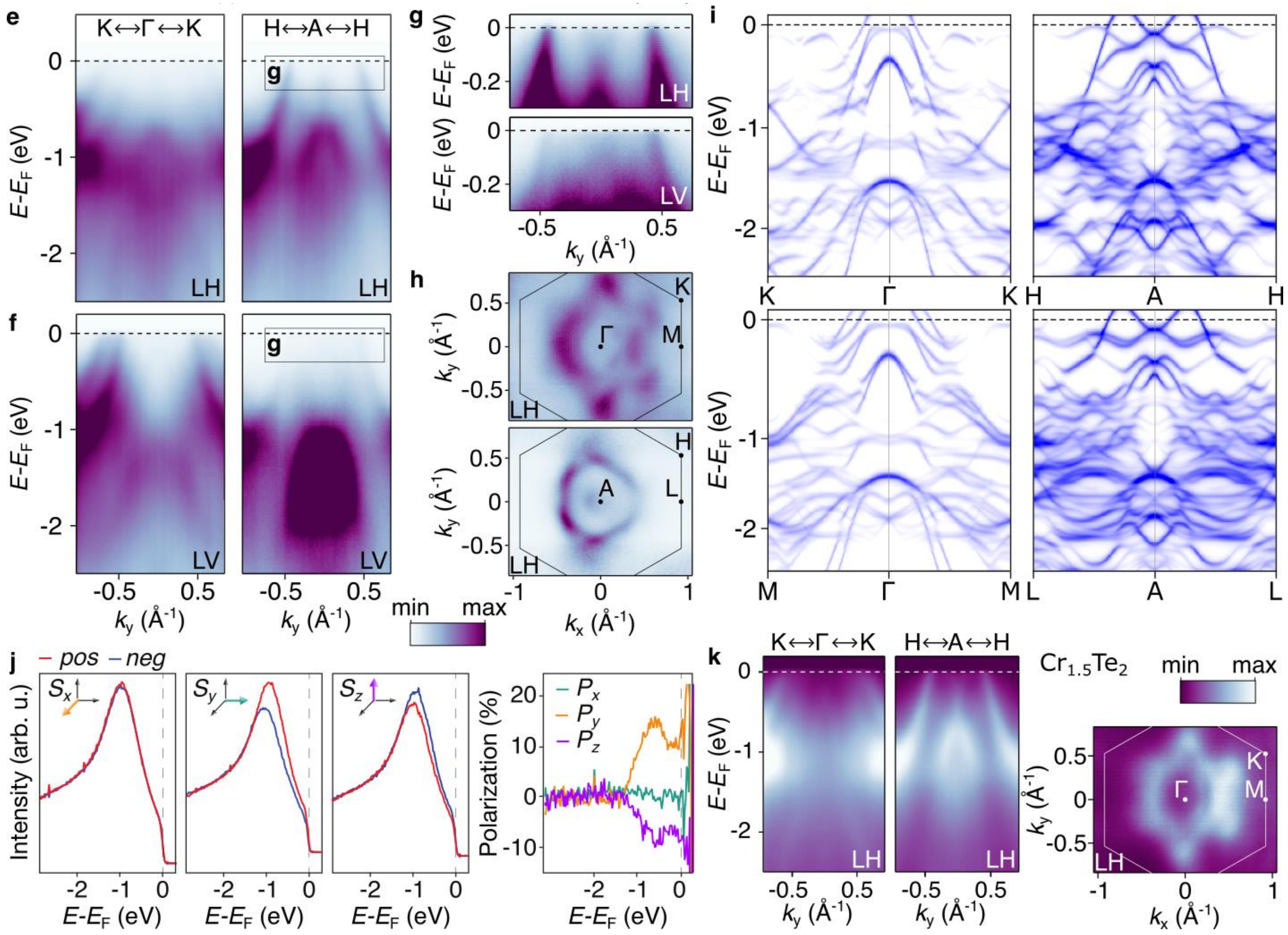
Family of layered magnets: Cr_xTe2



The system exhibit a maximally canted magnetism which we termed "orthogonal ferromagnetism" The mechanism of stabilisation does occur without SO!



In-plane components in addition show typical kinks reminiscent of spin-flip/flop hinting at the real opportunity to control the magnetic properties of this compound via magnetic field and temperature.



[Nature Communications](#) *16, 4495 (2025)*

Some of our work based on Spin ARPES

"Flat band separation and robust spin Berry curvature in bilayer kagome metals" ***Nature Physics* 19, 1135–1142, 2023**

"Spin Berry curvature-enhanced orbital Zeeman effect in a kagome metal" ***Nature Physics, 20, 2203-1109, 2024***

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"Bilayer orthogonal ferromagnetism in $CrTe_2$-based van der Waals system" ***Nature Communications, 16, 4495, 2025***

"Strain-Induced enhancement of the charge density wave in kagome metal ScV6Sn6", ***PRL, 134, 066501, 2025***

"Pomeranchuk instability from electronic correlations in CsTi3Bi5 kagome metal", ***Nature Communications 2026***

"Anomalous spin-optical helical effect in Ti-based kagome metal", ***Advanced Materials 2026***

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