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nanoelectronics

Optical Readout of Reconfigurable Layered Magnetic Domain Structure in CrSBr

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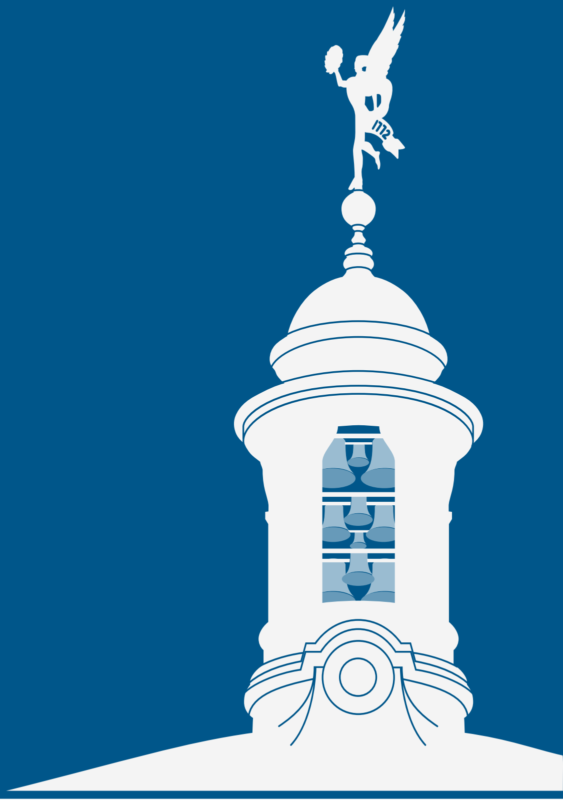
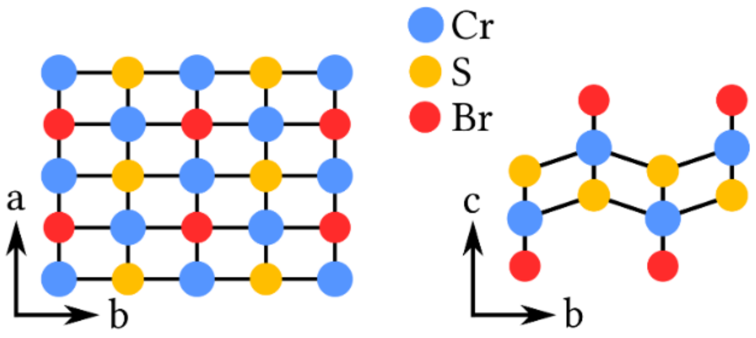
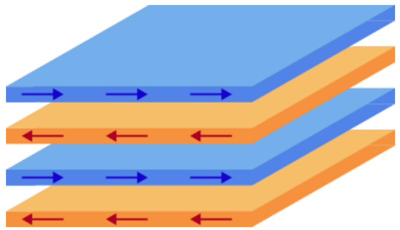


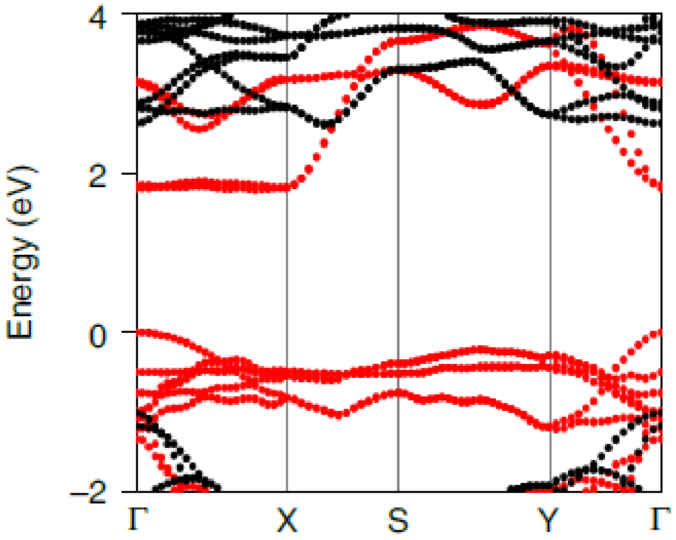
living.knowledge

Chromium sulfide bromide (CrSBr)

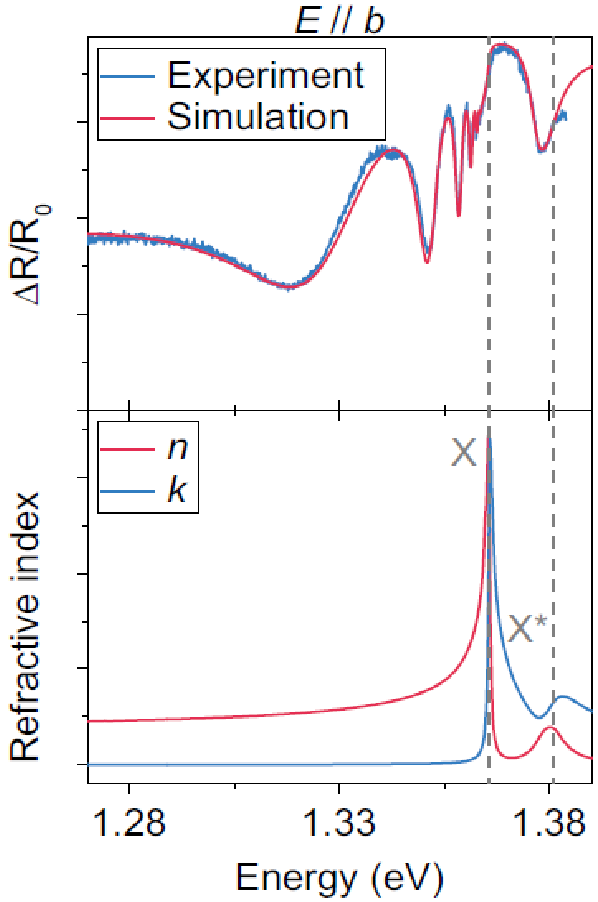
- layered **magnetic** semiconductor
- high anisotropy (optical, magnetic...)
- direct bandgap – $E_A \approx 1.3$eV
- **strong exciton** → dispersive ε(ω)







N. Wilson, et al. *Nature Materials* 20.12 (2021): 1657-1662



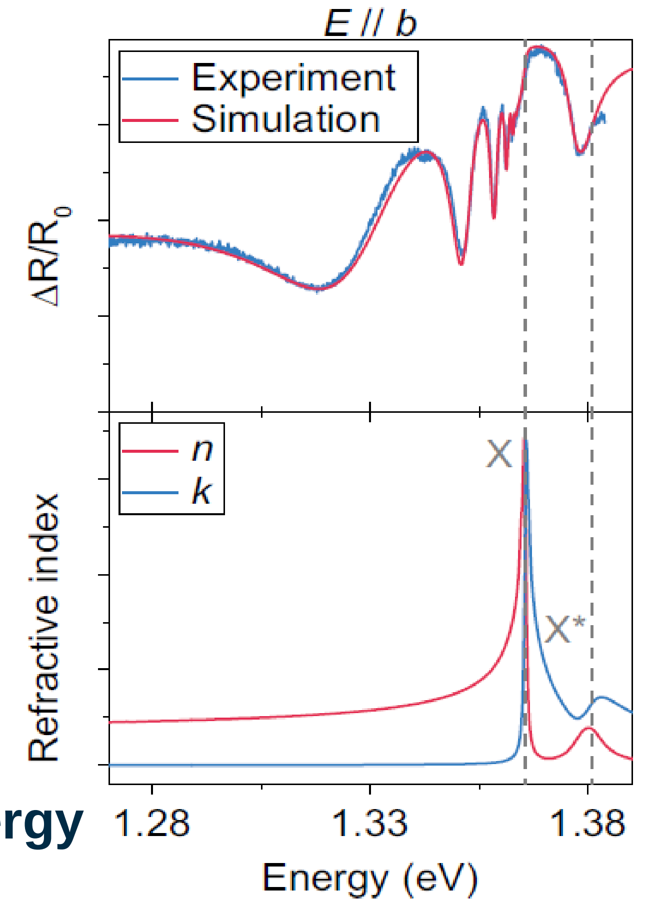
Magnetically-dressed CrSBr excitonpolaritons in ultrastrong coupling regime, Nat. Comm. | (2023) 14:5966

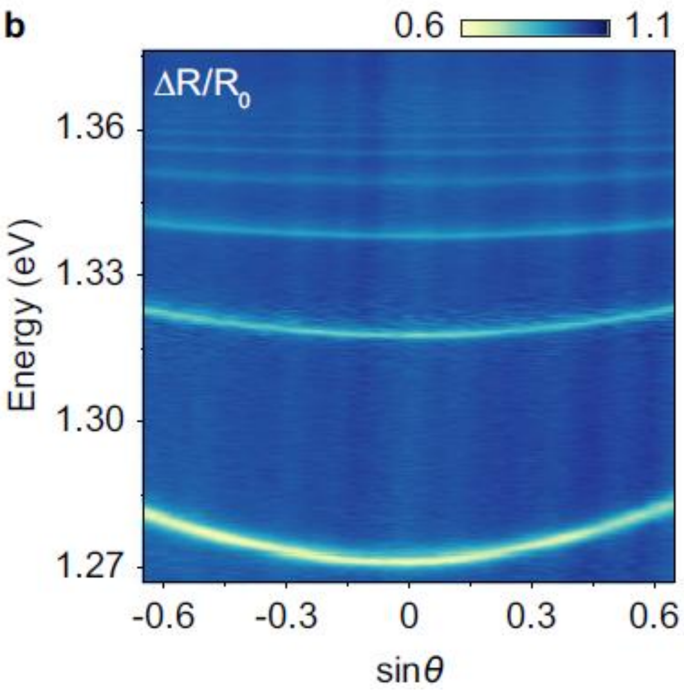
Strong excitonic resonance in CrSBr

A-exciton (≈1.34 eV):
high oscillator amplitude $\hbar^2 f \approx$ 1.7-2 eV^2 and small linewidth: 0.68 $\hbar\gamma \approx$ 0.68 meV [1]

high refractive index of CrSBr in the range of the excitonic resonance

bulk CrSBr crystals create self-sufficient optical microcavities with self-hybridized exciton-polaritons [2]

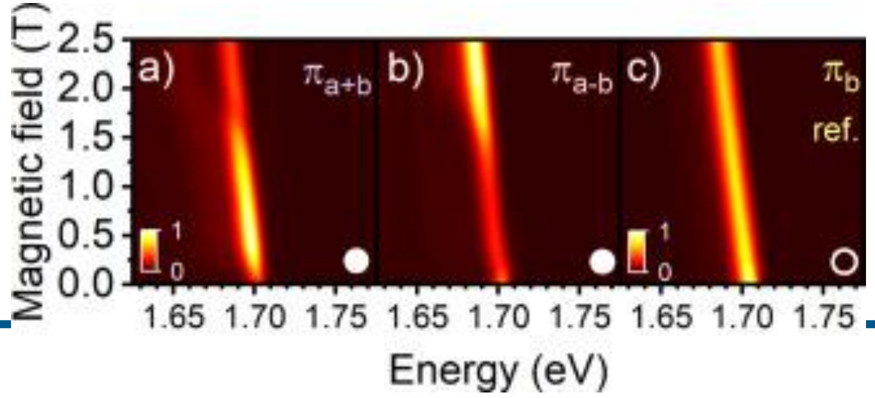




Magnetically-dressed CrSBr excitonpolaritons in ultrastrong coupling regime, Nat. Comm. | (2023) 14:5966

+ magnetic field dependence of exciton energy
(different for AFM and FM ordering)

we can think about magnetic switching of the optical properties



R.Komar, AŁ et al., Solid State Communications 397 (2025): 115798.

[1] [3] T. Wang et al., Nature Communications, 14(1), 2023.
[2] F. Dirnberger, et al., Nature, 620(7974):533–537, 2023.

Why excitons are useful in CrSBr: they sense spin order

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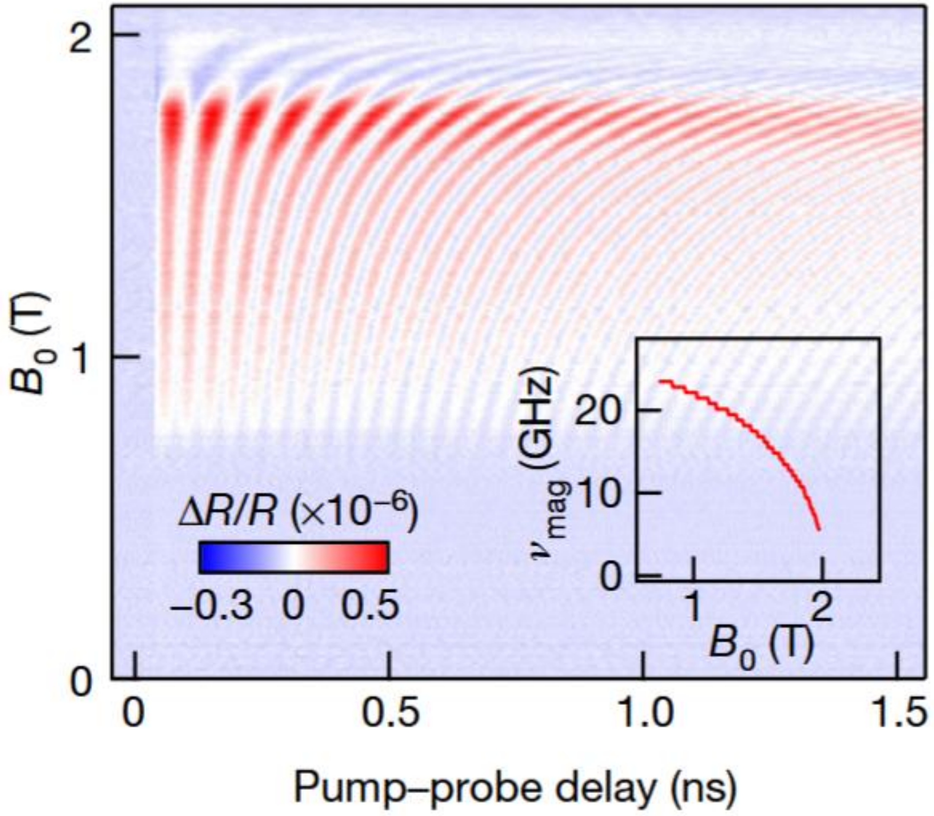
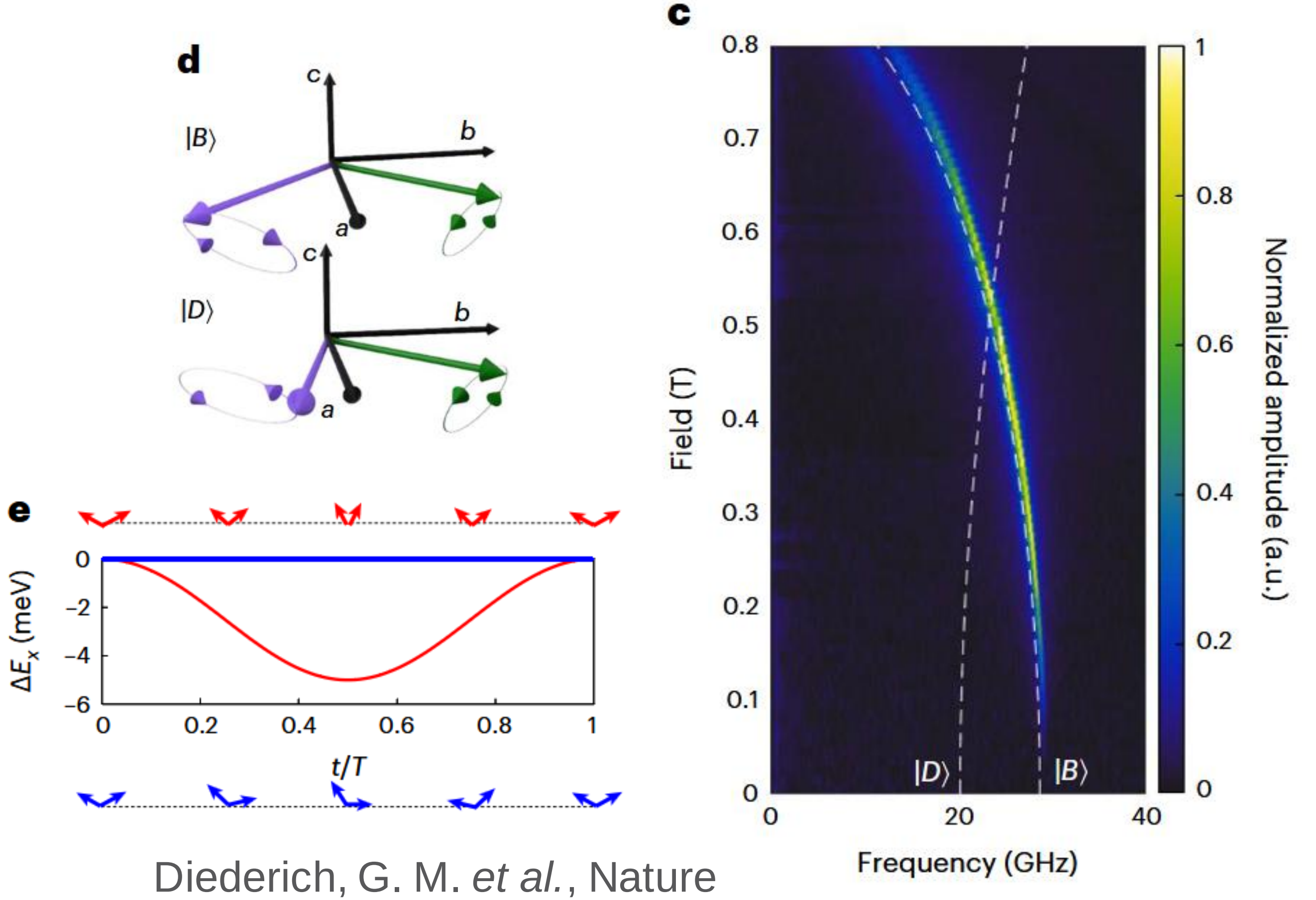
coherent magnons modulate exciton energy



Bae, Y. J. *et al.*, Nature 609, 282–286 (2022)

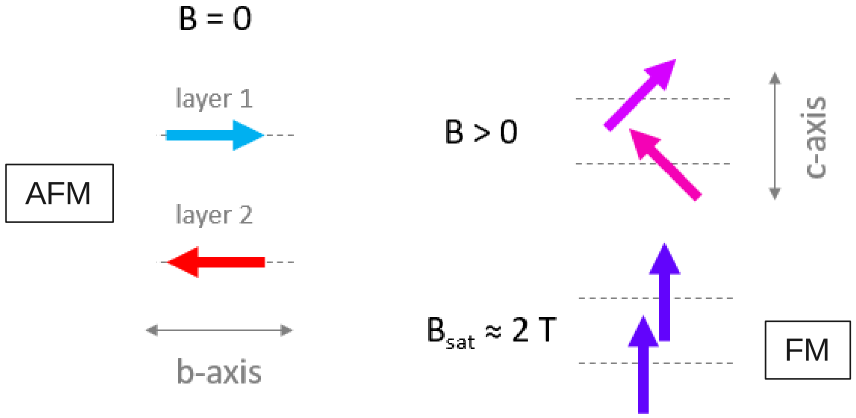
exciton–magnon coupling tunable by field direction / strain

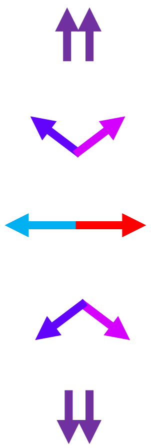


Diederich, G. M. *et al.*, Nature Nanotechnology 18, 23–28 (2023)

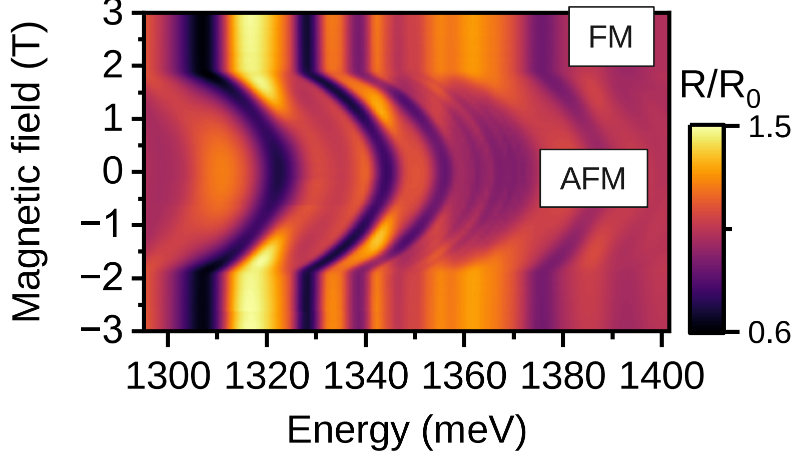
Why optics is sensitive to magnetism in CrSBr

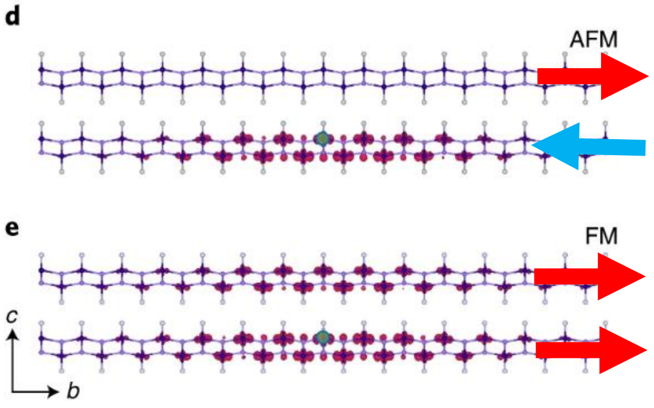
magnetic alignment tunes interlayer hybridization → excitonic dielectric response





Komar, R., AŁ et al. https://arxiv.org/pdf/2409.00187





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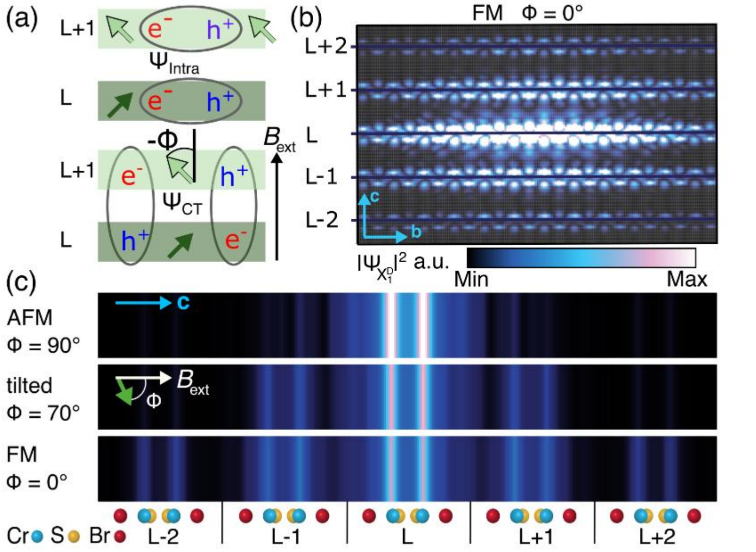

M.-Ch. Heißenbüttel et al Phys. Rev. B 111, 075107 (2025)

strong coupling between optical and magnetic propeties

Higher energy excitons

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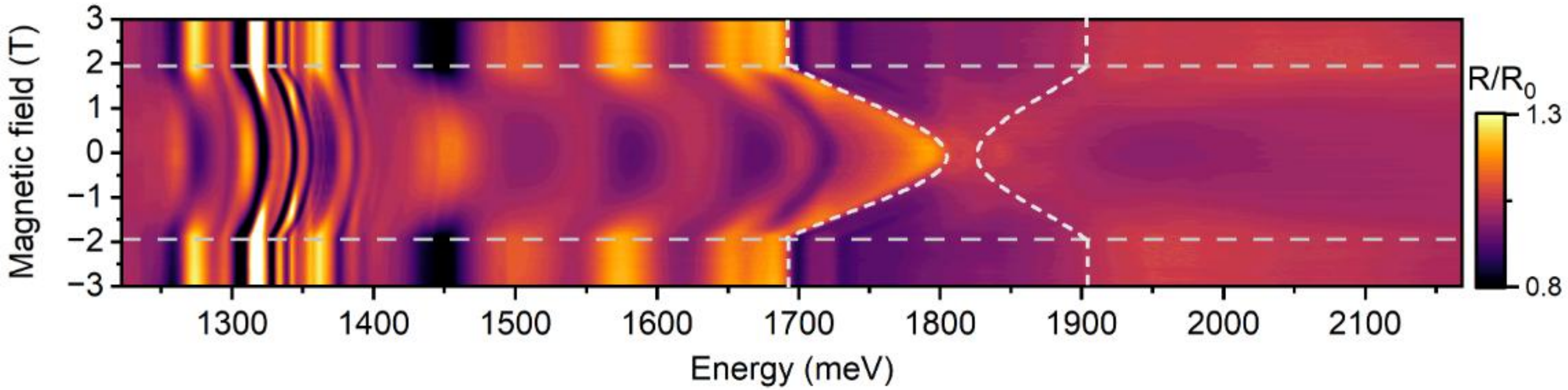


A-exciton band

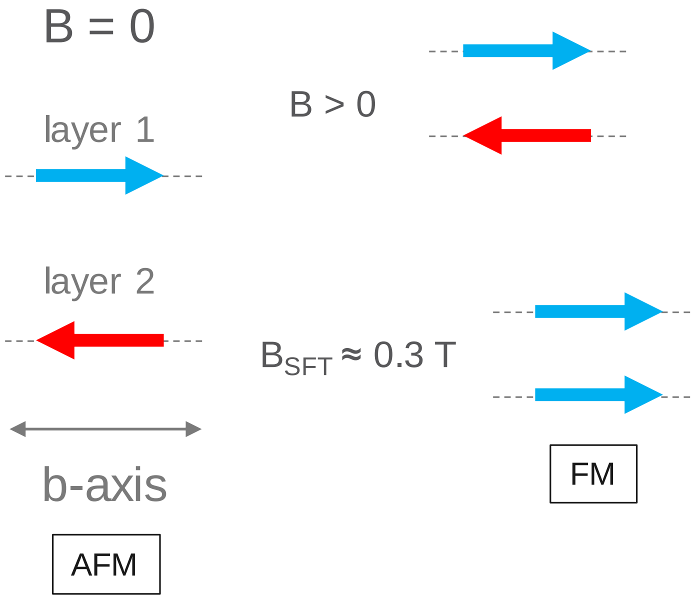
Beyond the A-exciton:
higher-energy excitons
different spin–exciton coupling channels
→ giant magneto-optical shifts

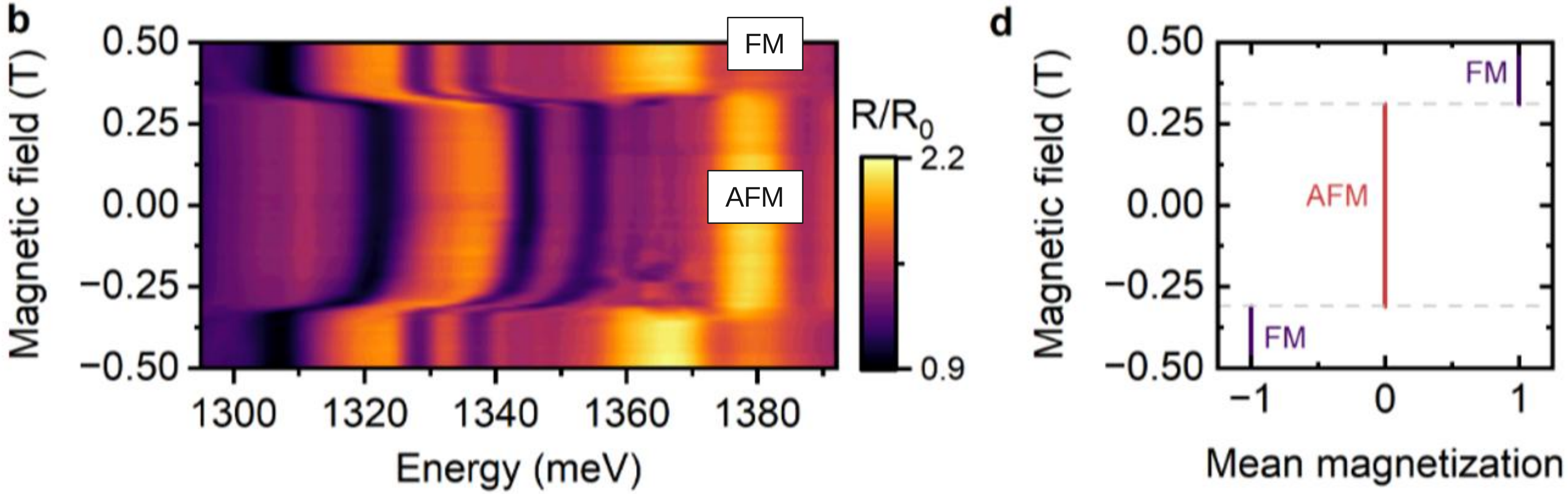
Komar, R., AŁ. et al.
accepted in Nat. Commun.
arXiv:2409.00187

See also: Śmiertka, M. et al., Nat. Commun. 17, 1777 (2026)

Easy-axis field is special: switching vs canting

- B⊥b (hard/intermediate axes): canting → smooth spectral shifts
- B∥b (easy axis): discrete switching between configurations

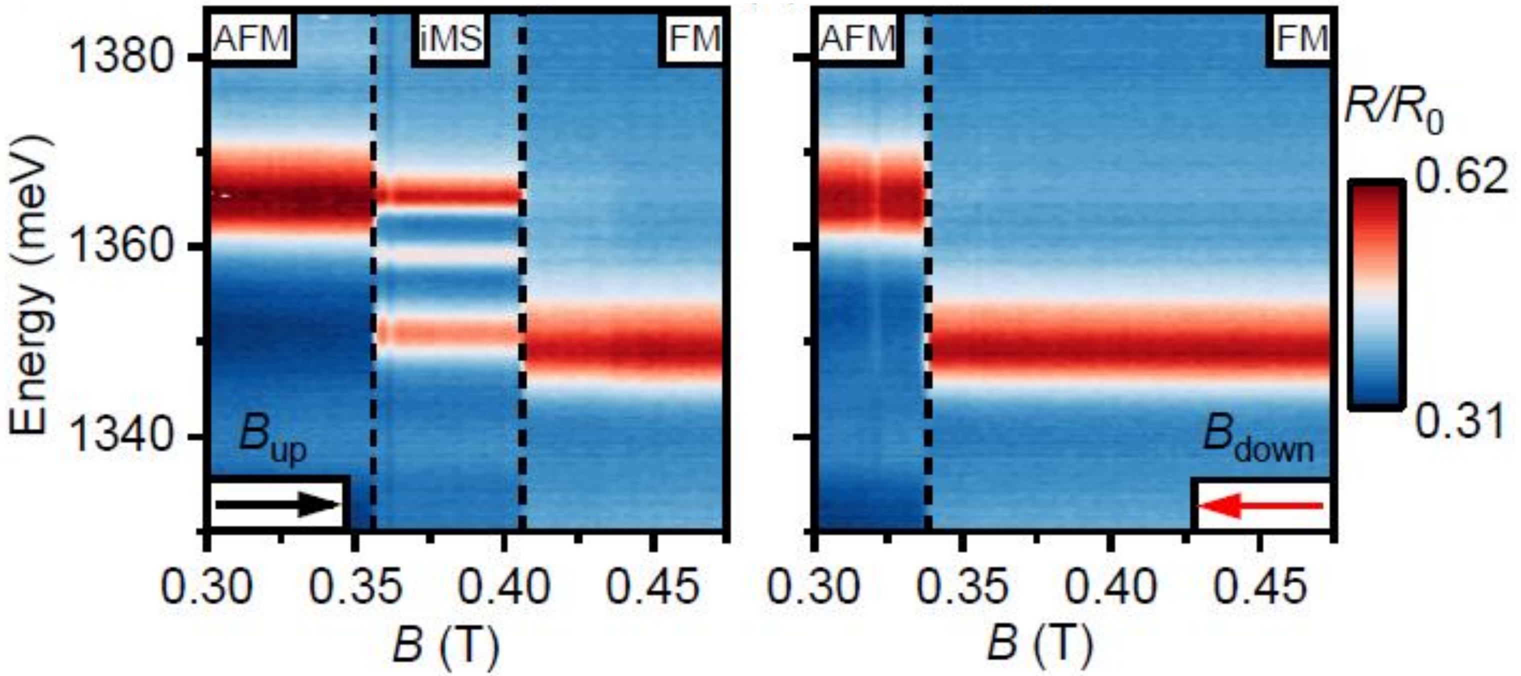




Komar, R, AŁ., et al. https://arxiv.org/pdf/2409.00187

Next: intermediate configurations and sweep-history dependence for B∥*b*

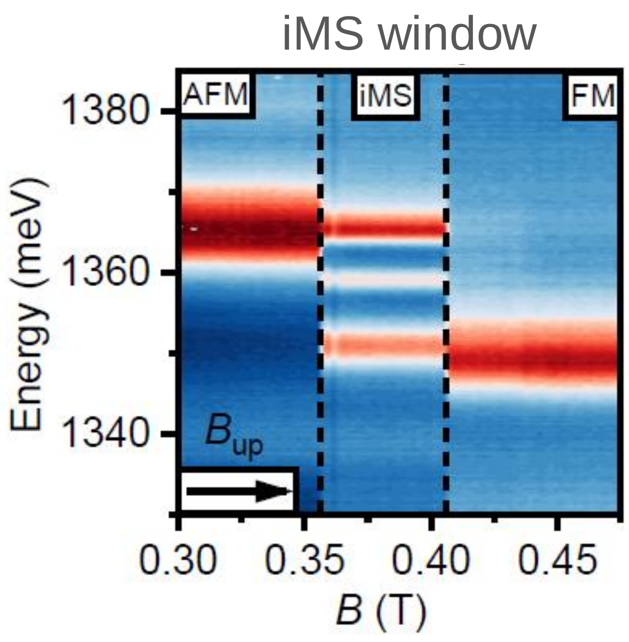
Non-binary switching (7L): multi-level intermediate states

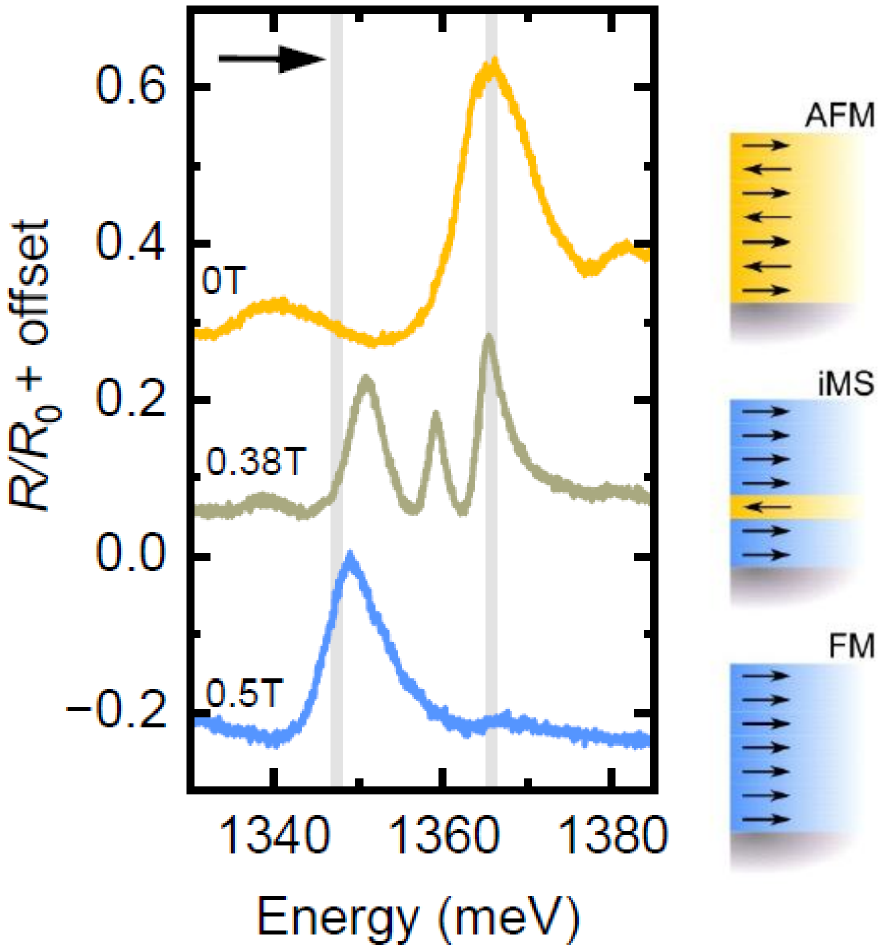


- multi-level states
- reconfigurable,
  path-dependent (B↑ vs B↓)
- stable intermediate configurations

Intermediate magnetic states (iMS): out-of-plane domains

- layer-by-layer switching
- mixed AFM/FM sequence (variable domain thickness)



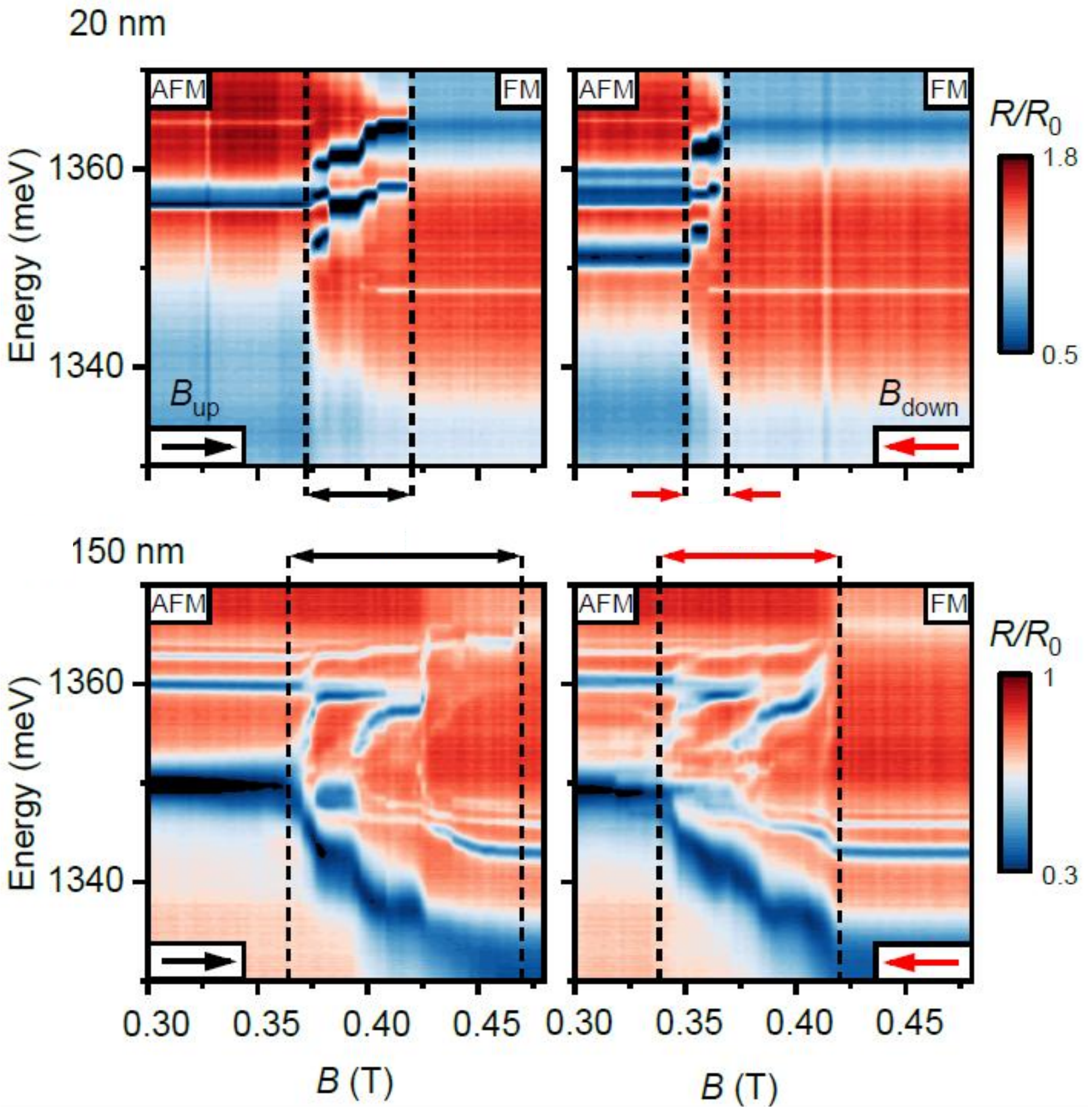


iMS = layered AFM/FM domain stack (out-of-plane)

Non-binary switch: thicker flakes

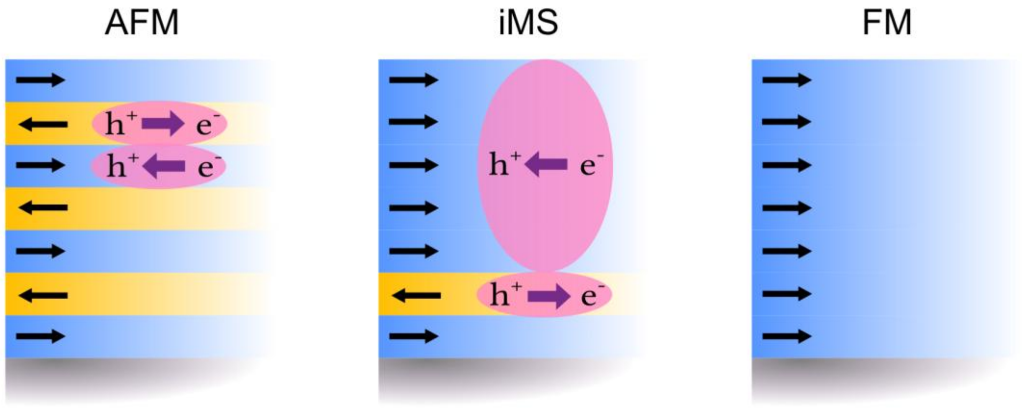
- thicker flakes → richer multi-level landscape.
- path-dependent access (B↑ vs B↓)

more accessible intermediate configurations

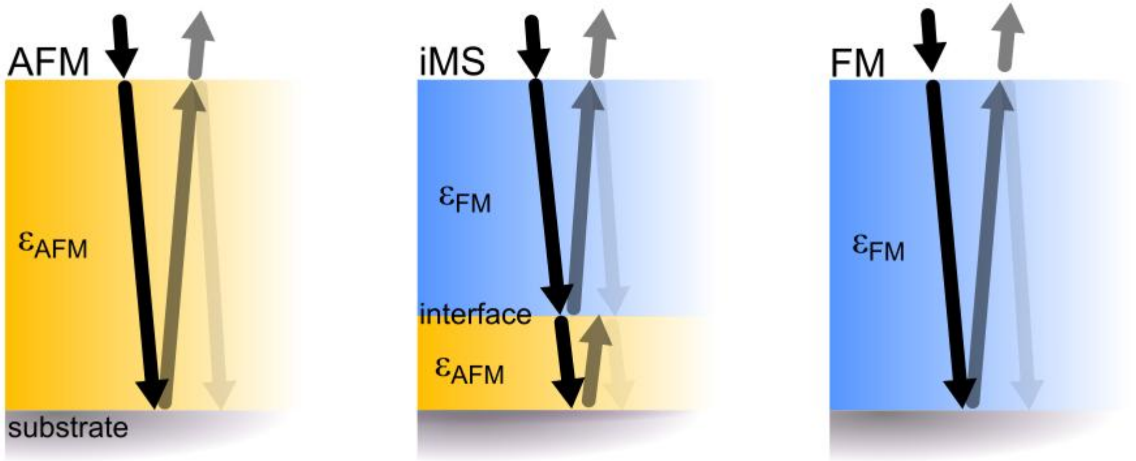


Mechanism

layer alignment → interlayer hybridization → excitonic ε(ω)

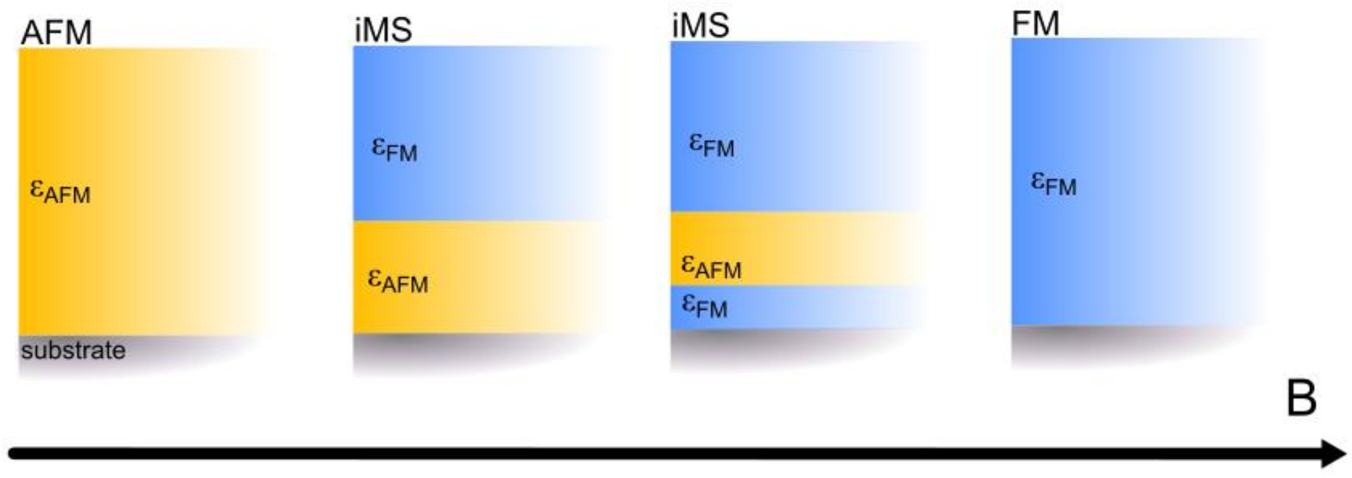


domain stack → multilayer interference conditions



combined → configuration-specific spectral signatures (readout)

Why spectra change: configuration-dependent interference



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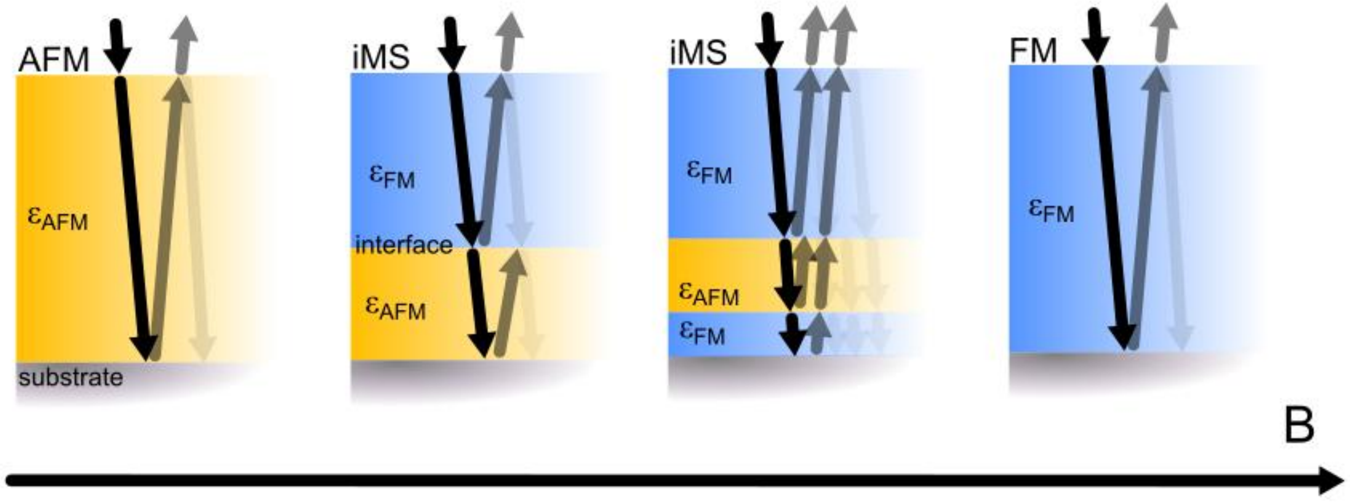
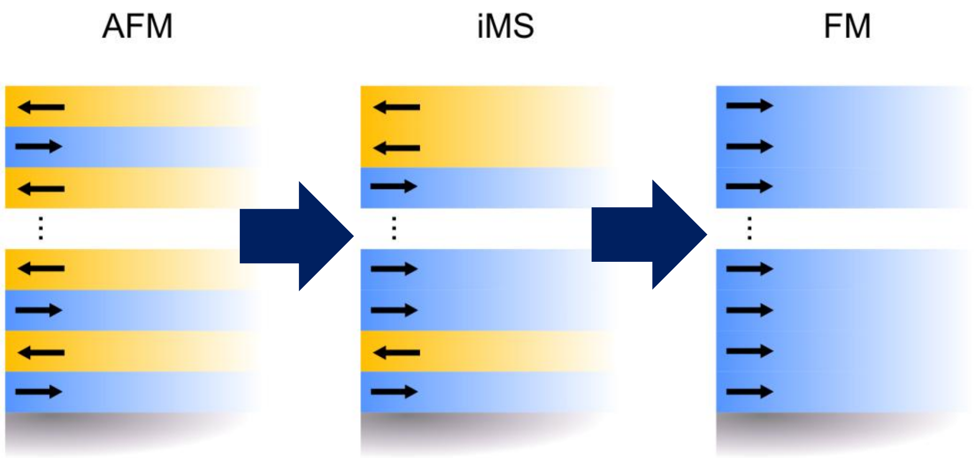


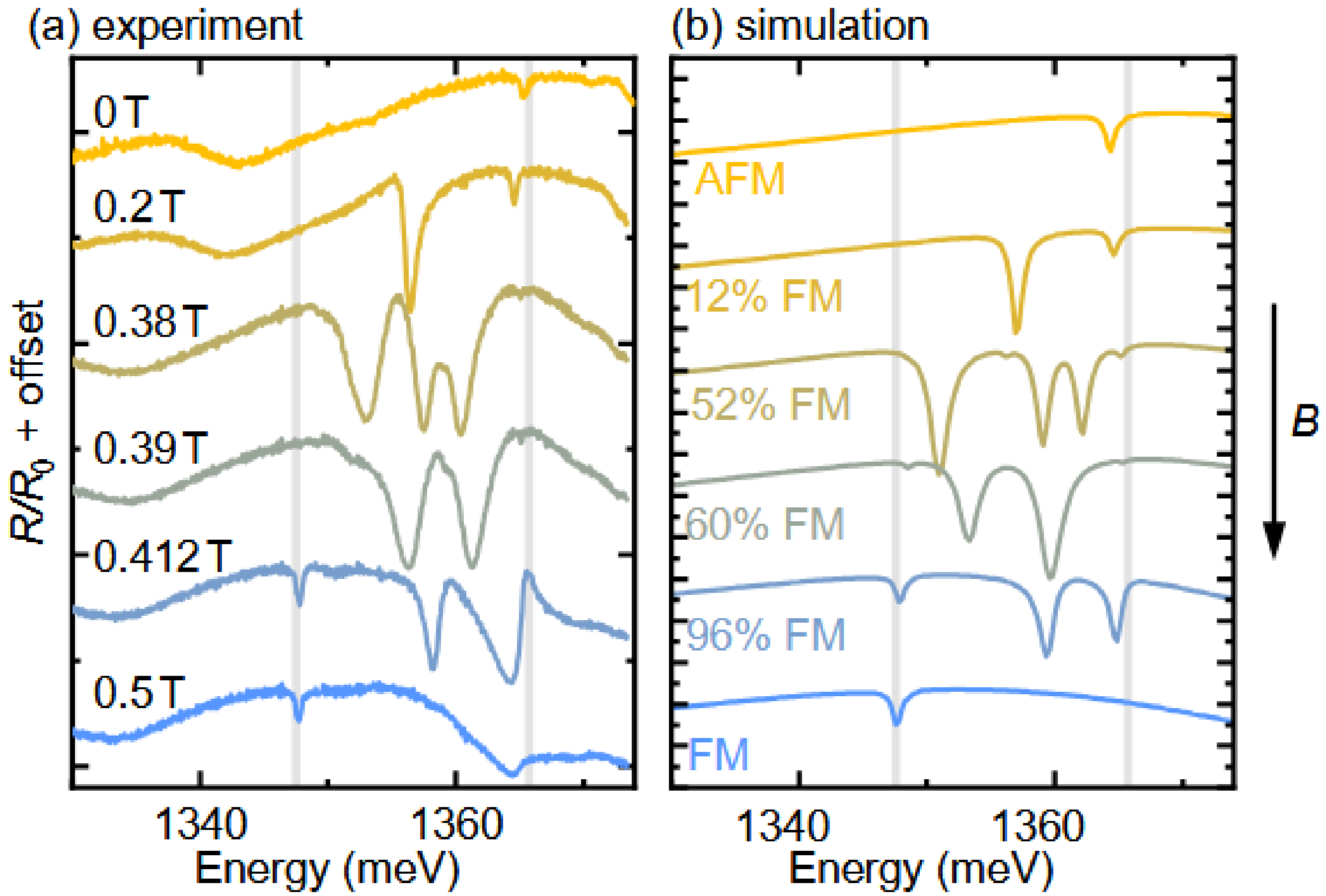
Minimal transfer-matrix model



- single exciton resonance with different **AFM vs FM** energies → different ε(ω)

- layer-by-layer switching → mode multiplication

Spectral complexity = interference of one tunable exciton with layered stack



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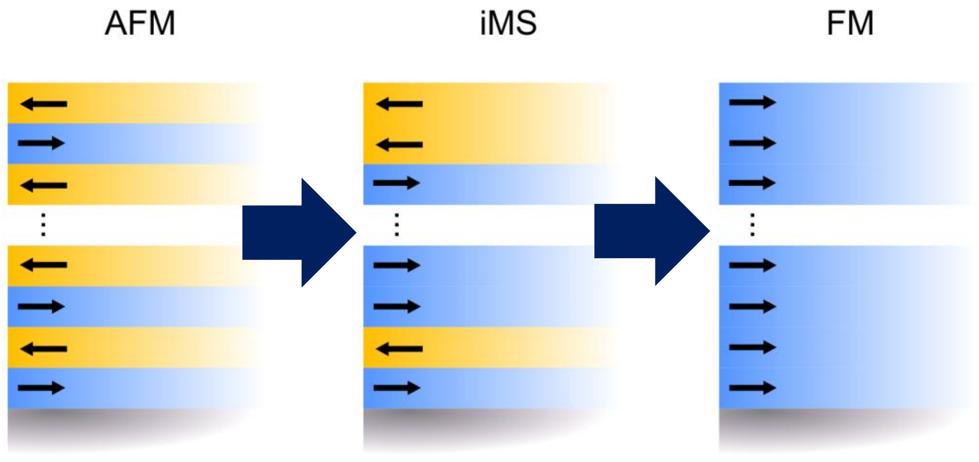

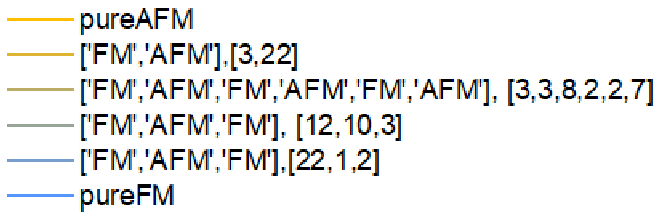

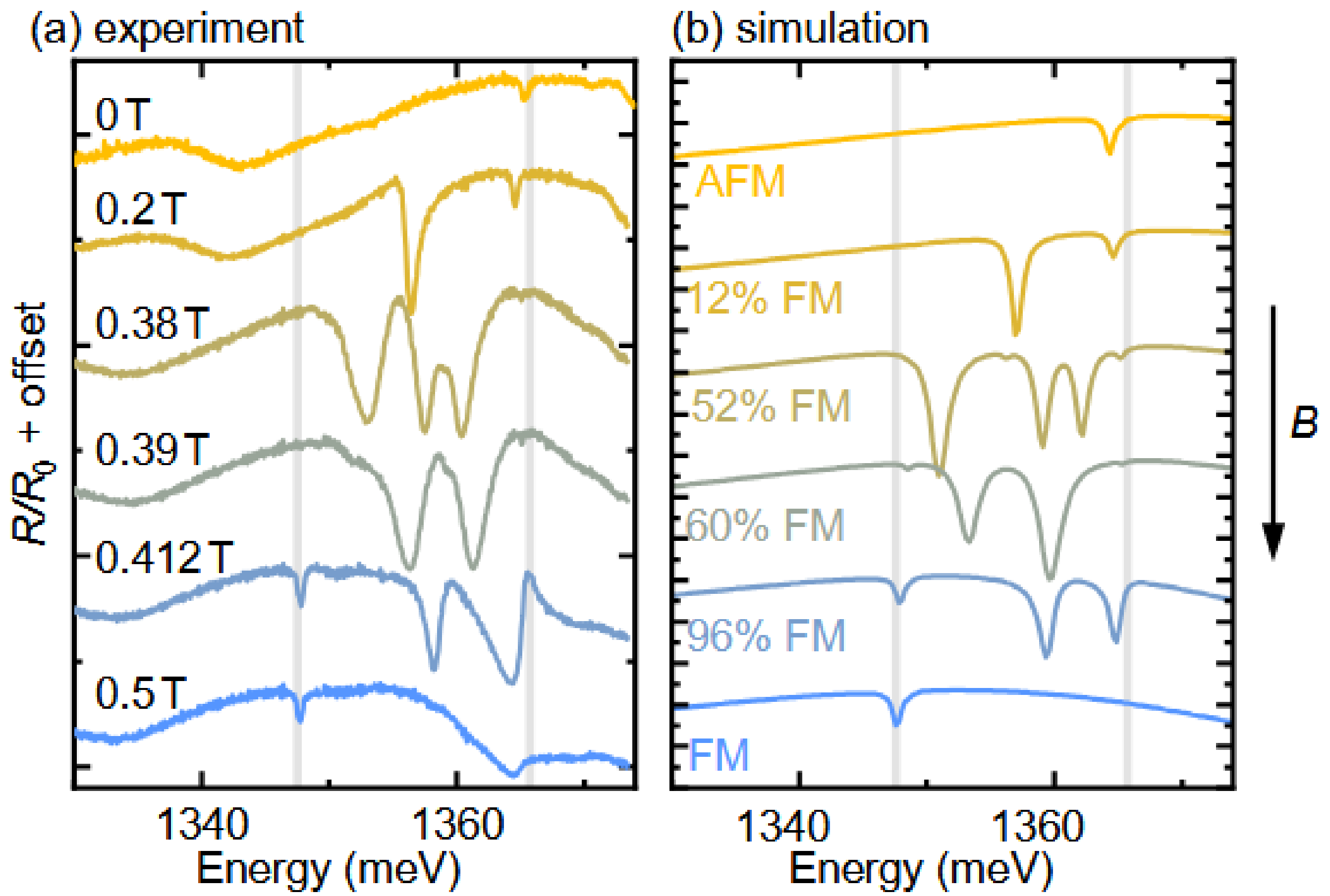

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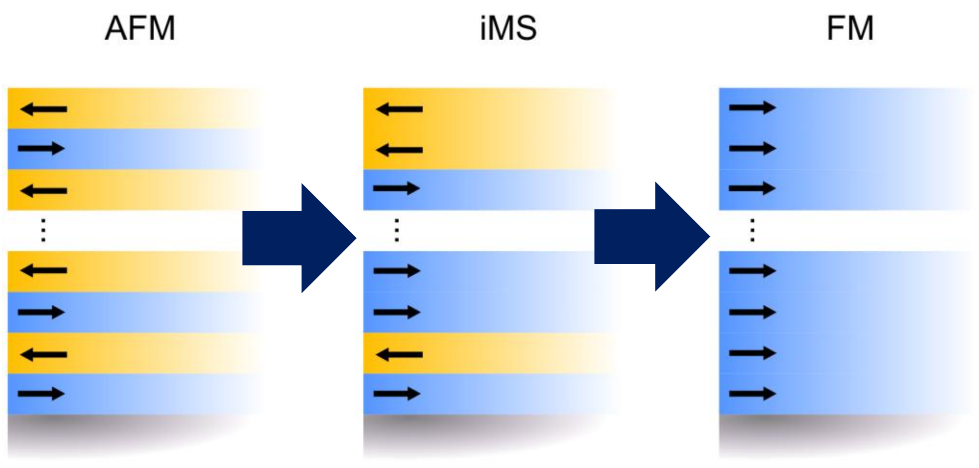

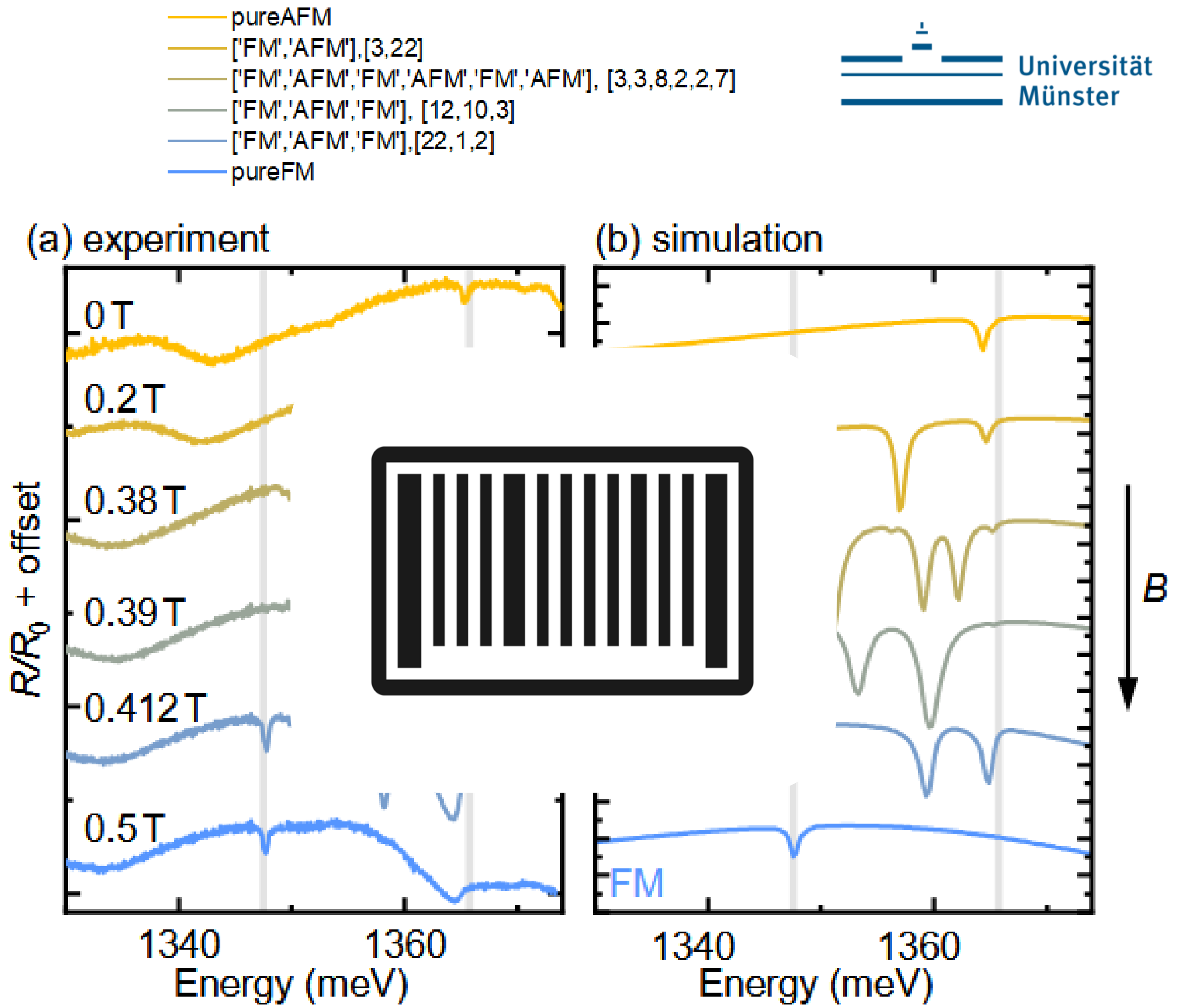

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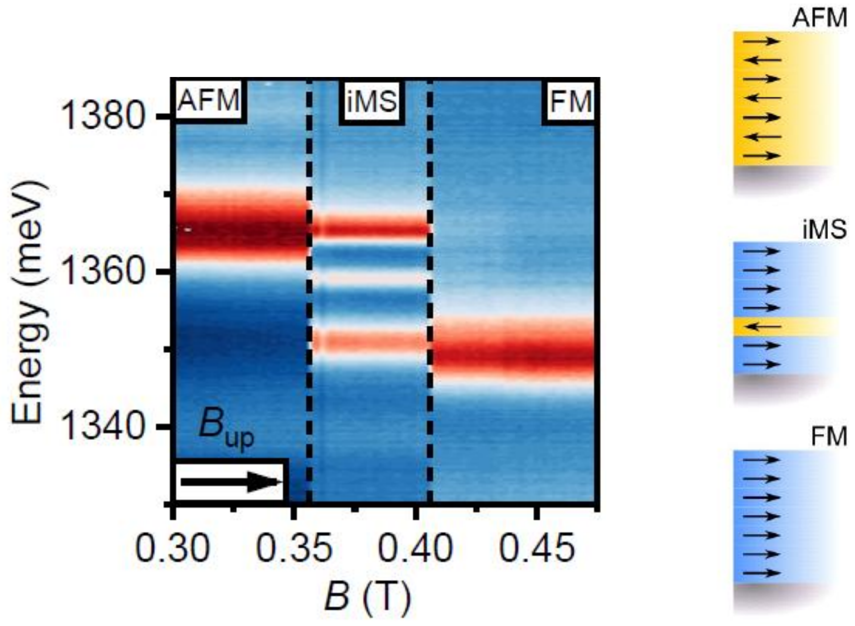
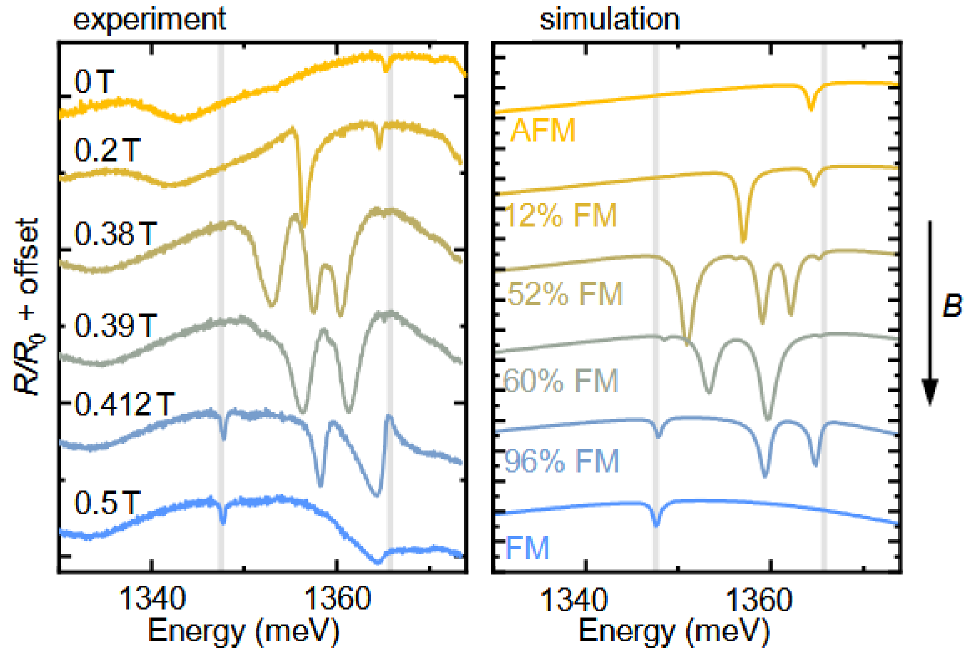
Spectral complexity = interference of one tunable exciton with layered stack

Intermediate magnetic states: stable, readable, multi-level



- distinct out-of-plane domains
- stable intermediate regime
- history dependent (multi-level hysteresis / path dependence)

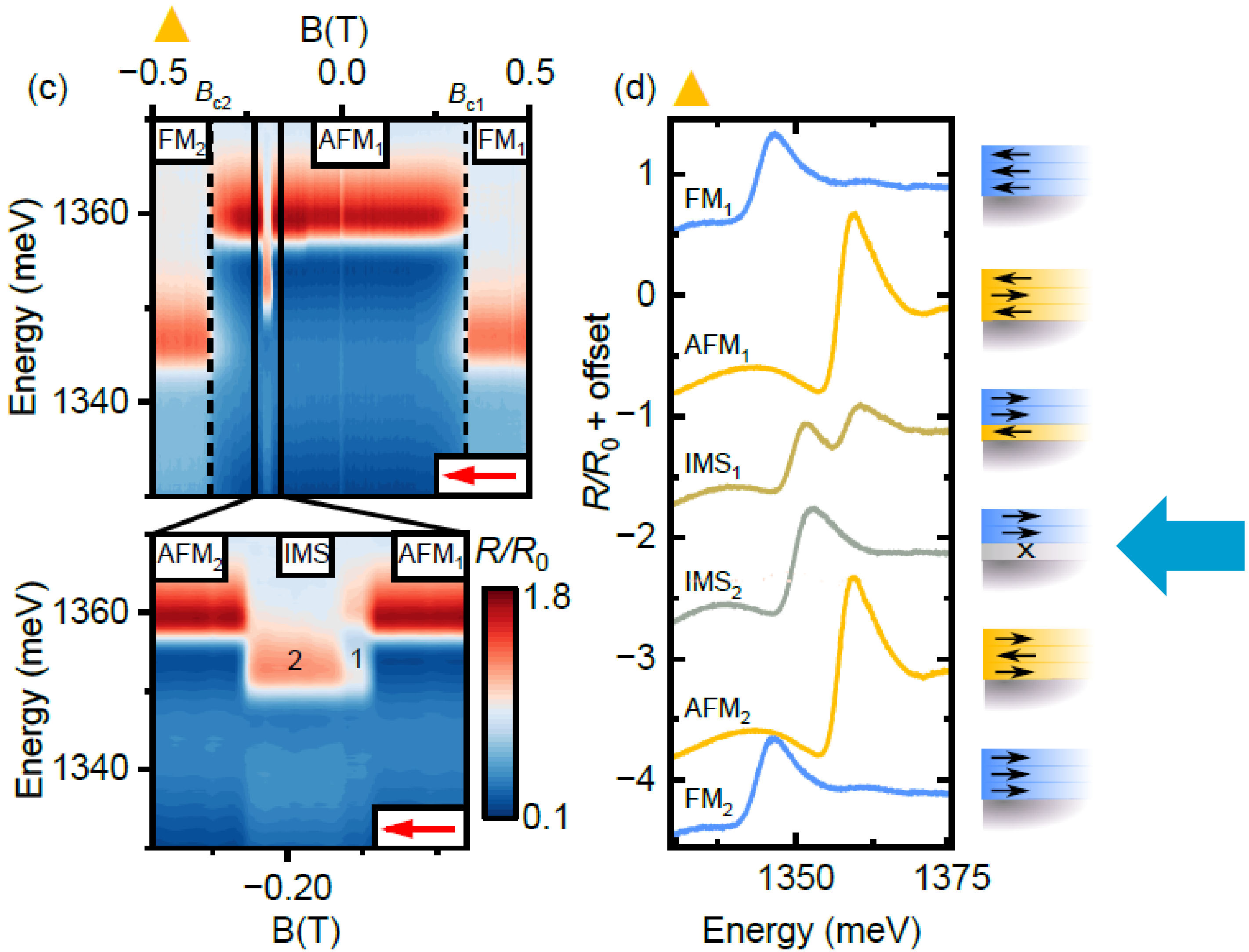


Optical barcode → non-contact **readout**

Next: what could this enable if we gain deterministic selection of configurations?

„Invisible" layer?

3L CrSBr



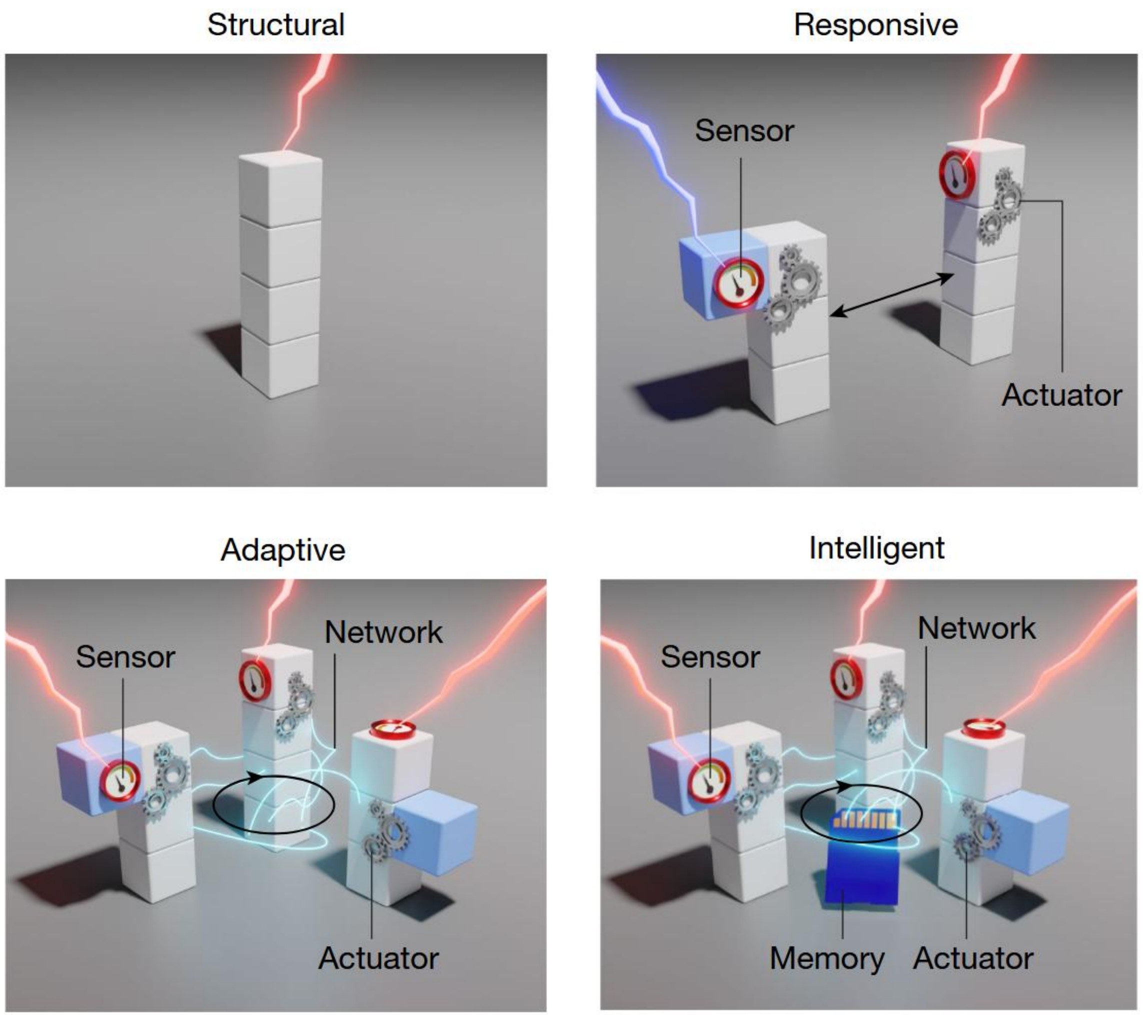
Outlook: towards intelligent matter

- structural: multi-level configurations ✓
- sensing: optical barcode readout ✓
- memory: multistability (partial) ✓ / ?
- actuation: deterministic selection ?

  → extra knobs: gating / strain / heterostructures

- network: coupling between elements ?

CrSBr: a step toward ‘intelligent matter’
(requires deterministic control)

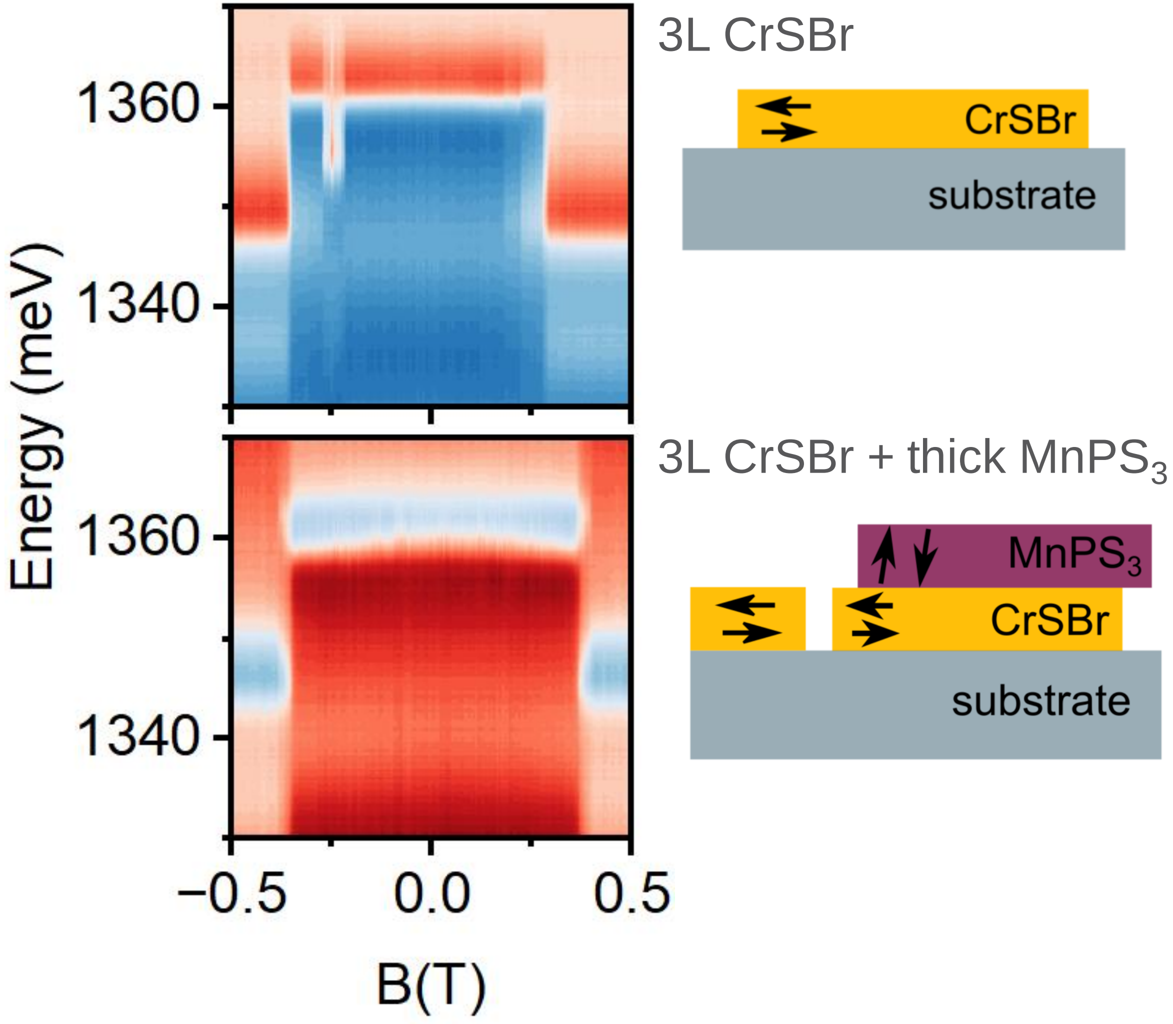


Kaspar *et al.*, “The rise of intelligent matter” (Nature 594, 345–355, 2021)

Outlook: tuning the intermediate regime via interfaces

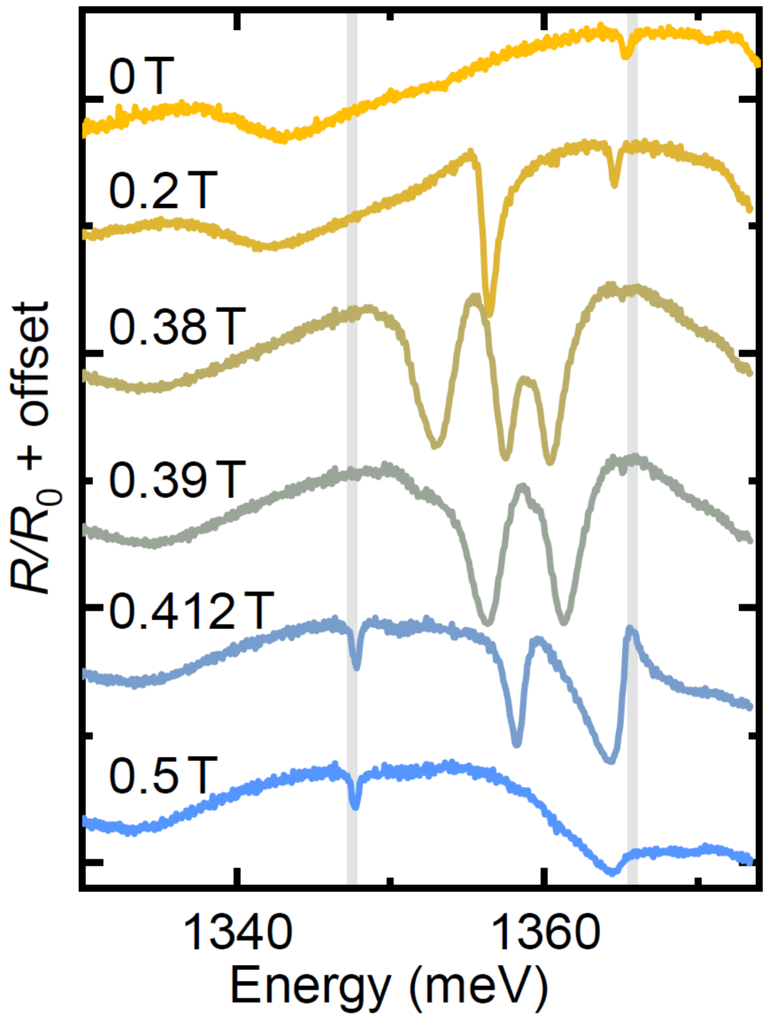
- interfacial coupling may pin and reshape intermediate configurations

- possible stabilization/suppression of iMS (reduced variability)



Take-home message

- **stable intermediate configurations** exist during easy-axis AFM→FM switching.
- **iMS** correspond to layered **out-of-plane domain** stacks formed by layer-by-layer switching.
- **out-of-plane magnetic domain sequence** creates a barcode which can be **readout** by **optics** in non-invasive way
- **interfacial coupling** is a promising handle to tune the intermediate regime (work in progress)



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arXiv:2512.04887

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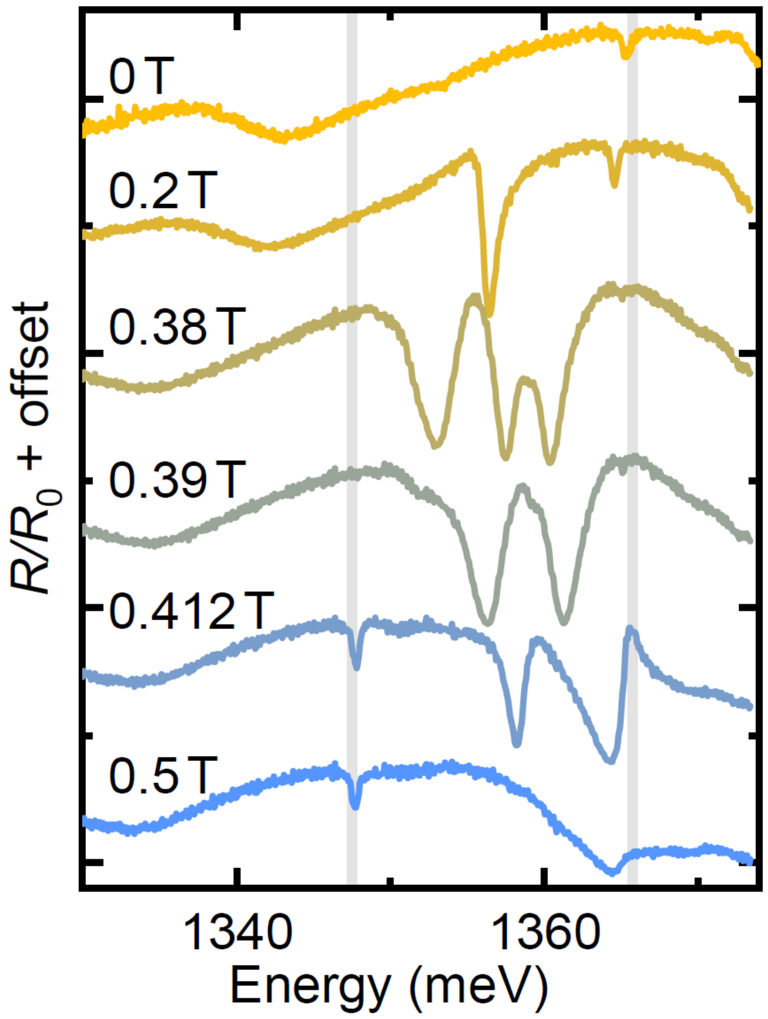

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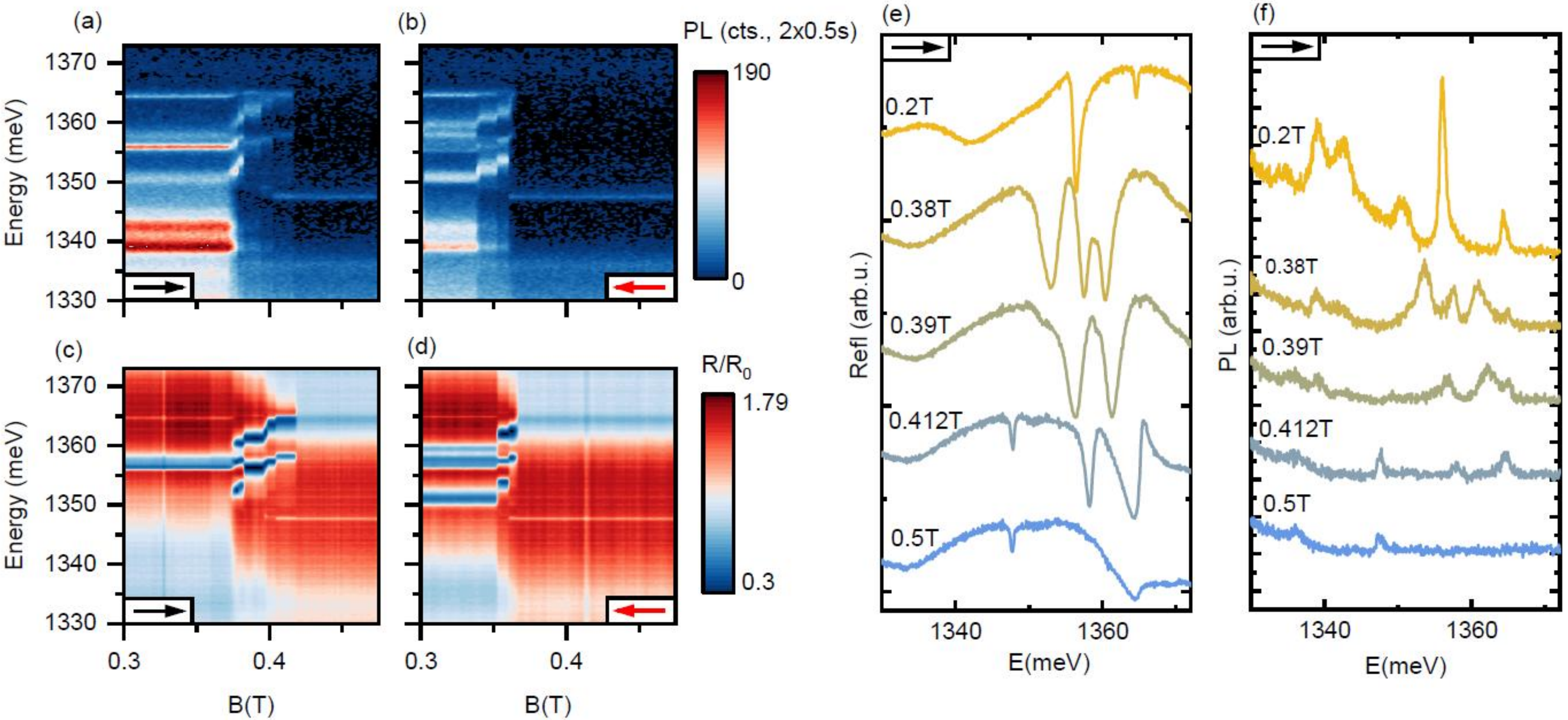
arXiv:2512.04887

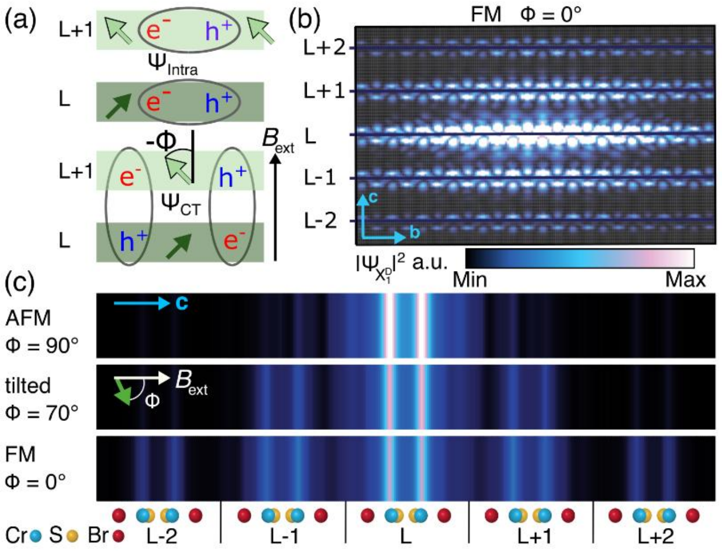
Thank you

Non-binary switch – PL & Reflectance comparison



Microscopic origin

Change of the excitonic energy in AFM/FM states:
localization – delocalization of the exciton wavefunction



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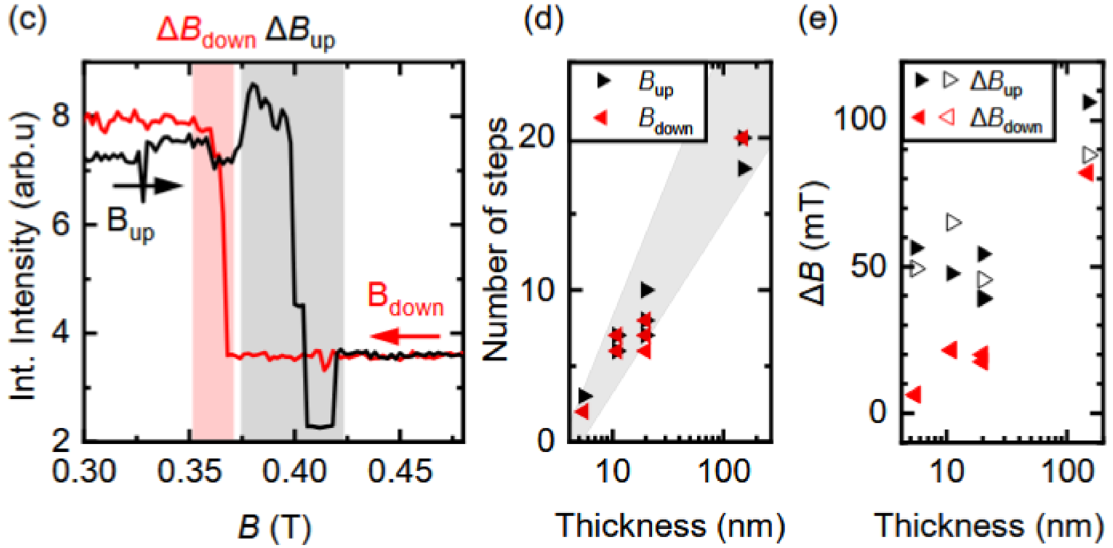
- Relocalization cost may explain asymmetry (FM→AFM vs AFM→FM). (?)



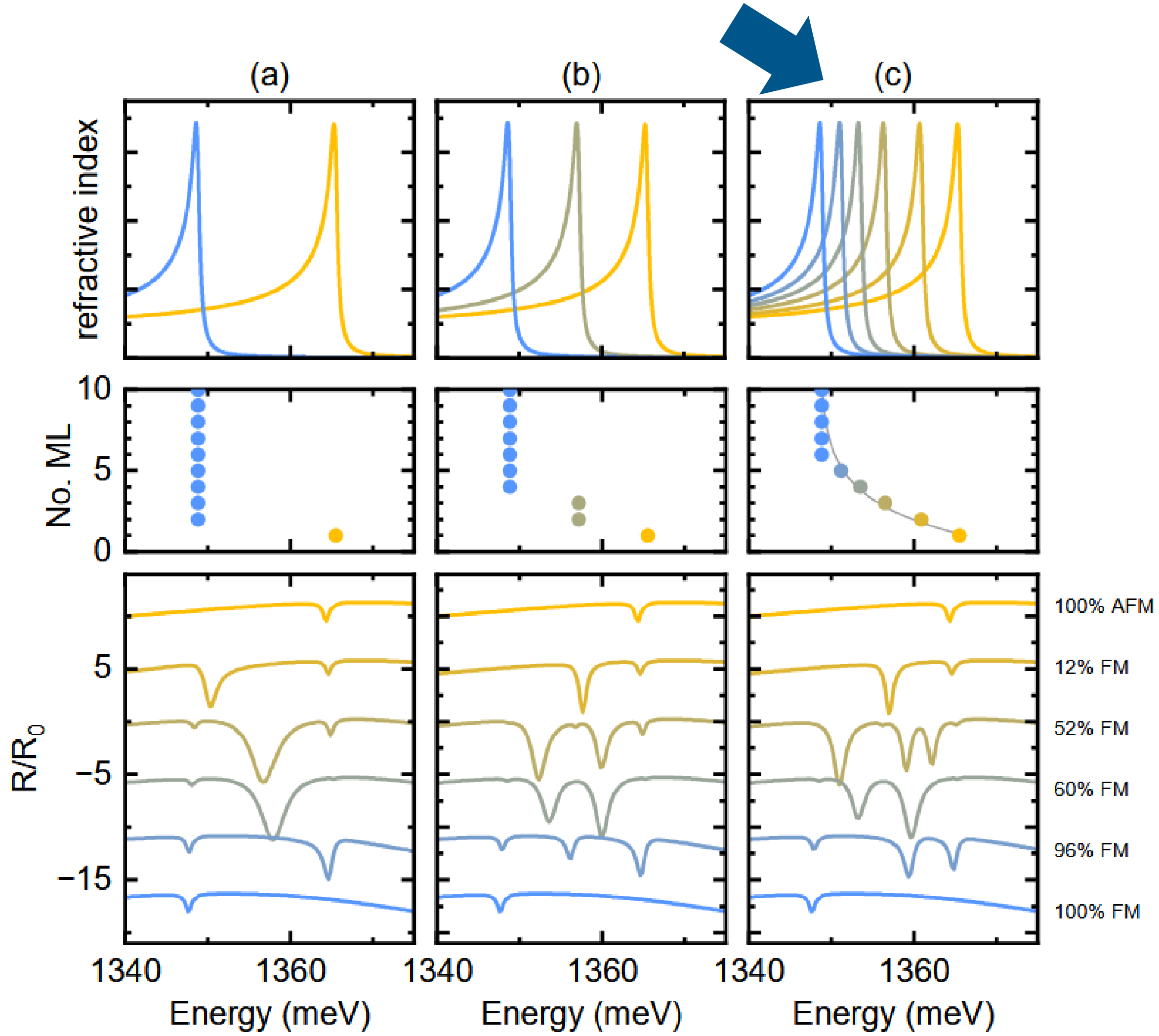
...or this is just magnetism (how spins are switching, spin pinning...)

TMM technicalities

We assume:
- Monolayer have the same n and k (E) as AFM bulk
- FM state (thick flake, in magnetic field) gives minimal energy for FM
- Thinner FM layers – something between

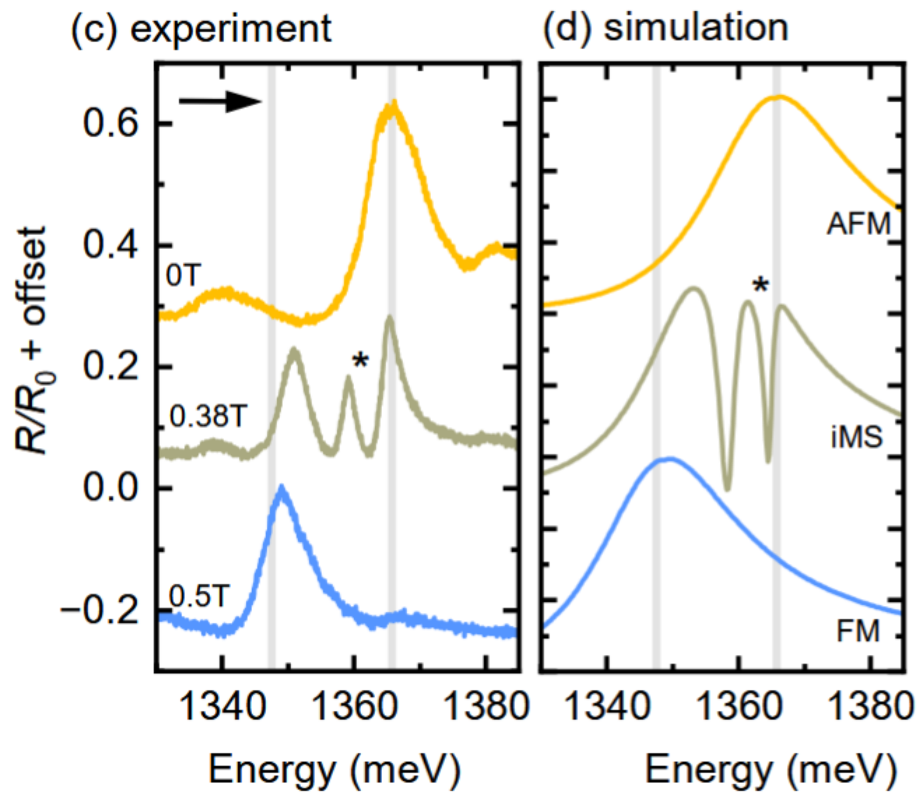
Issues:
- Proper parameters for n,k(E)
- Phase
- Magnetism
- Is confinement enough?

energy change due to confinement in the thinner layer of CrSBr



Phase change

TMM as it is (this is in the paper)



TMM + phase (why it fits better?!)