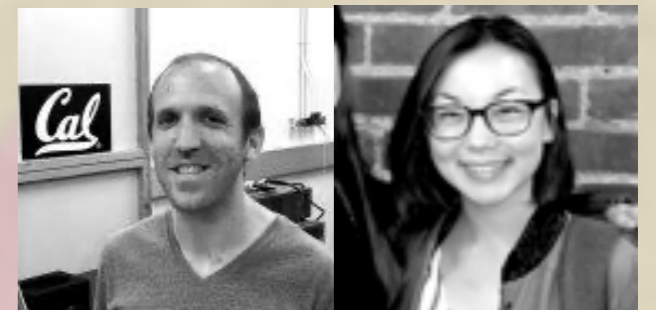


Collective dynamics of coexisting spin textures: the antiferromagnetic switching of Fe_xNbS_2

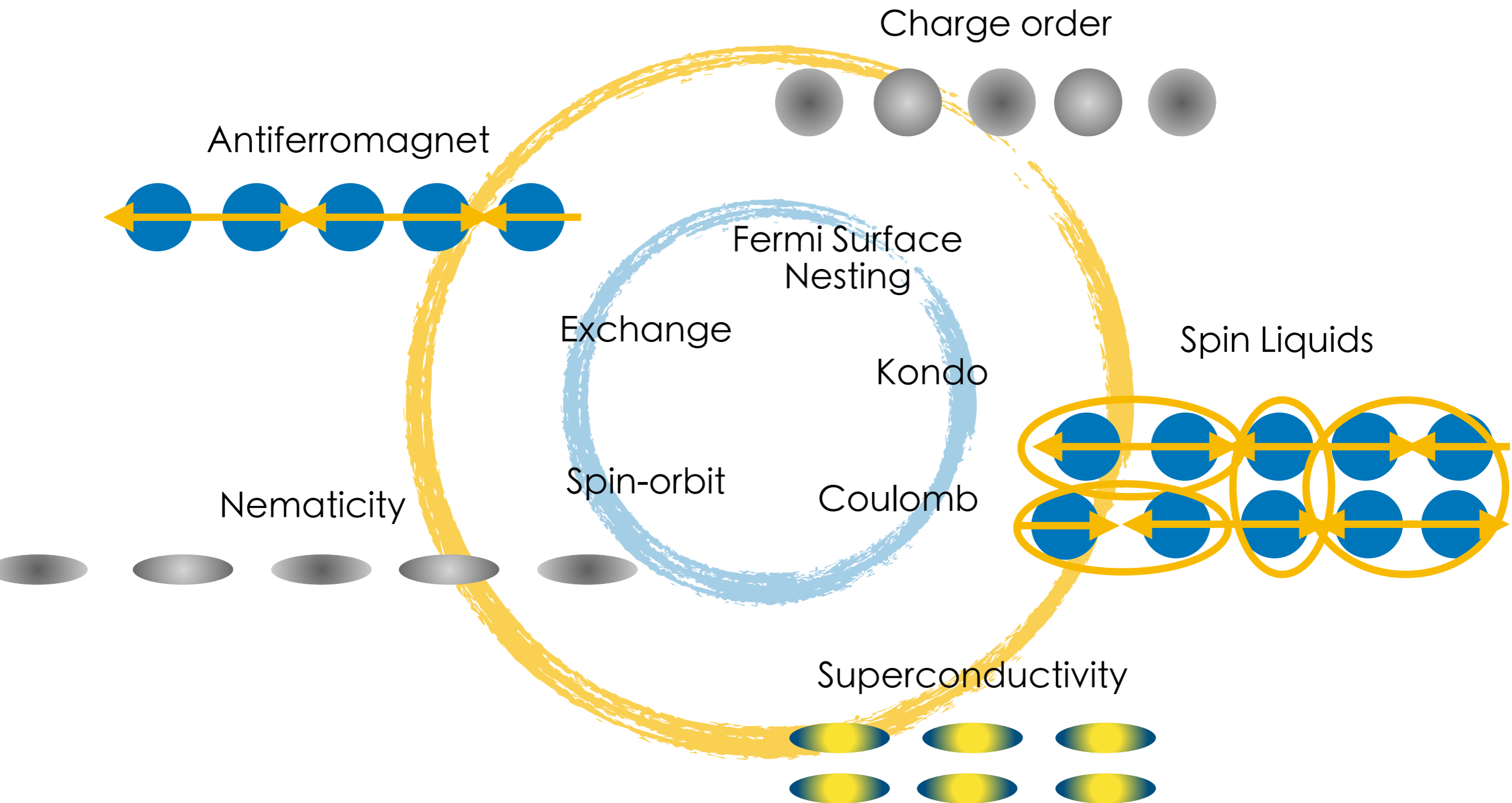
Eran Maniv, Nityan Nair, Shannon Haley
Shan Wu, Robert Birgeneau
Caolan John, Spencer Doyle
Yaroslav Tserkovnyak
James G. Analytis



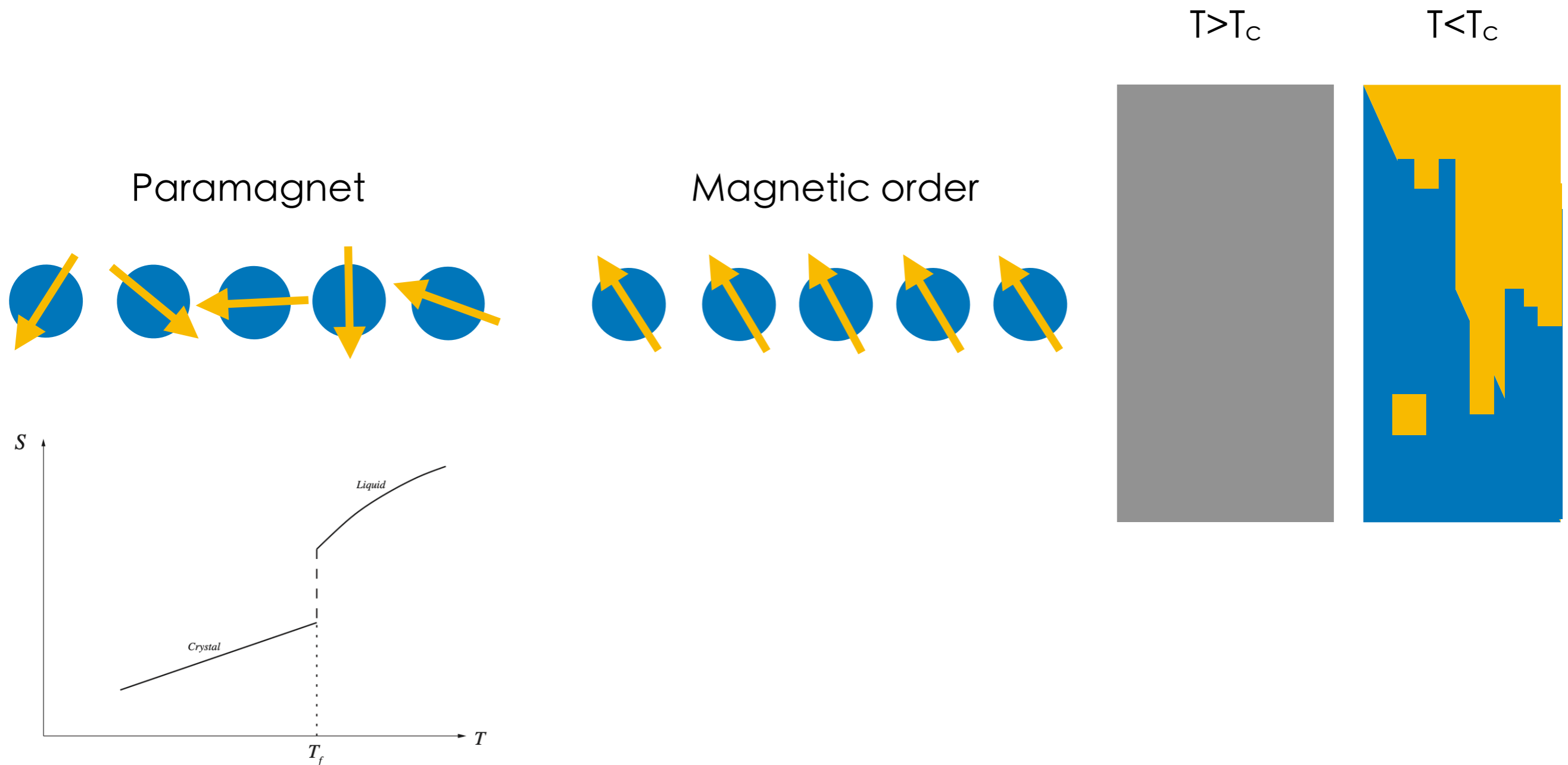
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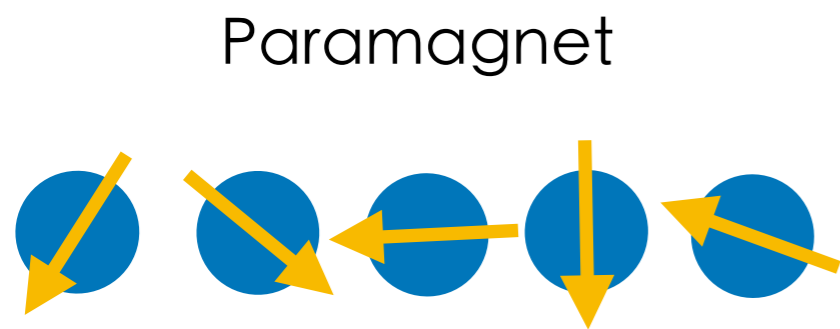
Frustration, Rigidity and Disorder



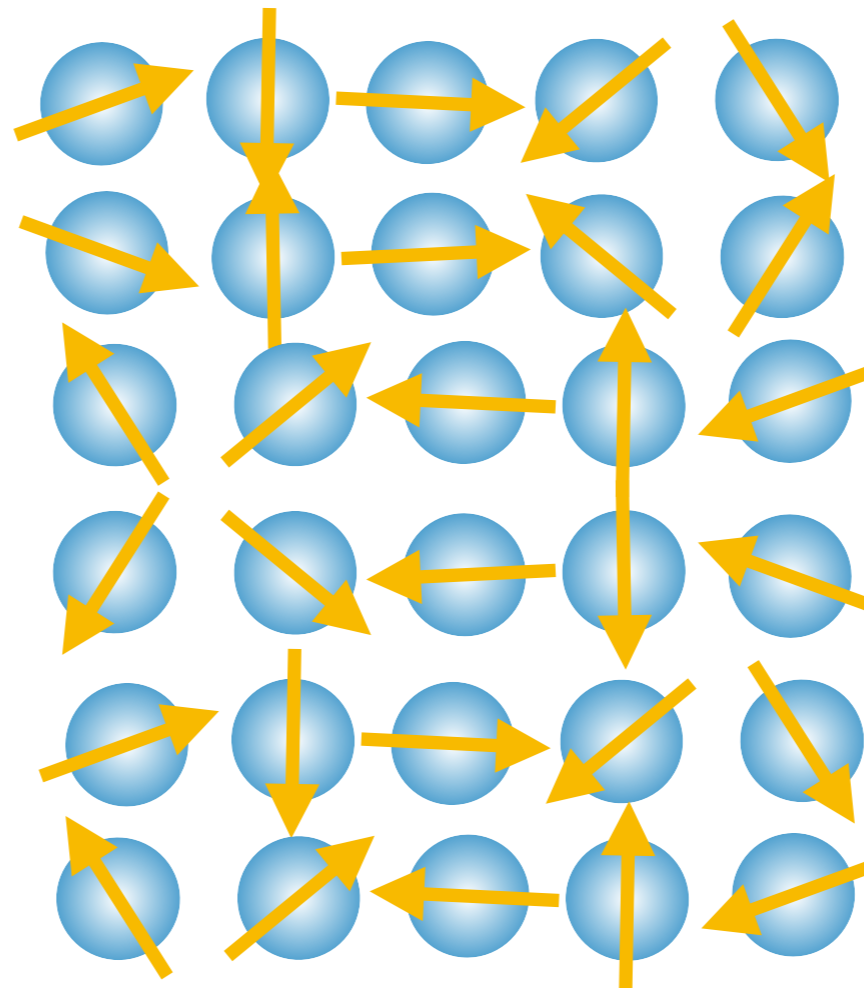
Frustration, Rigidity and Disorder



Frustration, Rigidity and Disorder

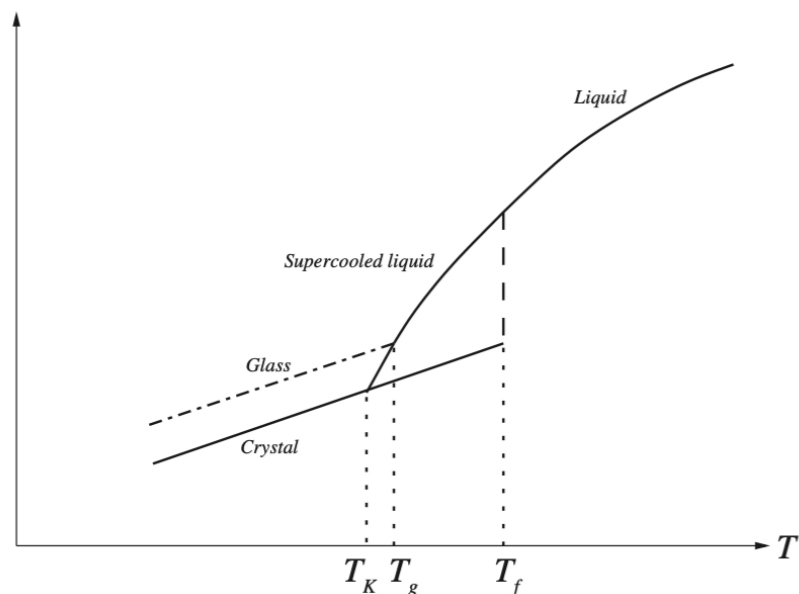
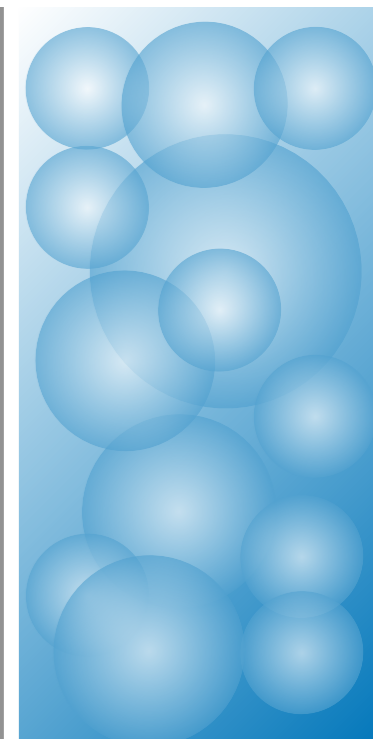


Quenched disorder

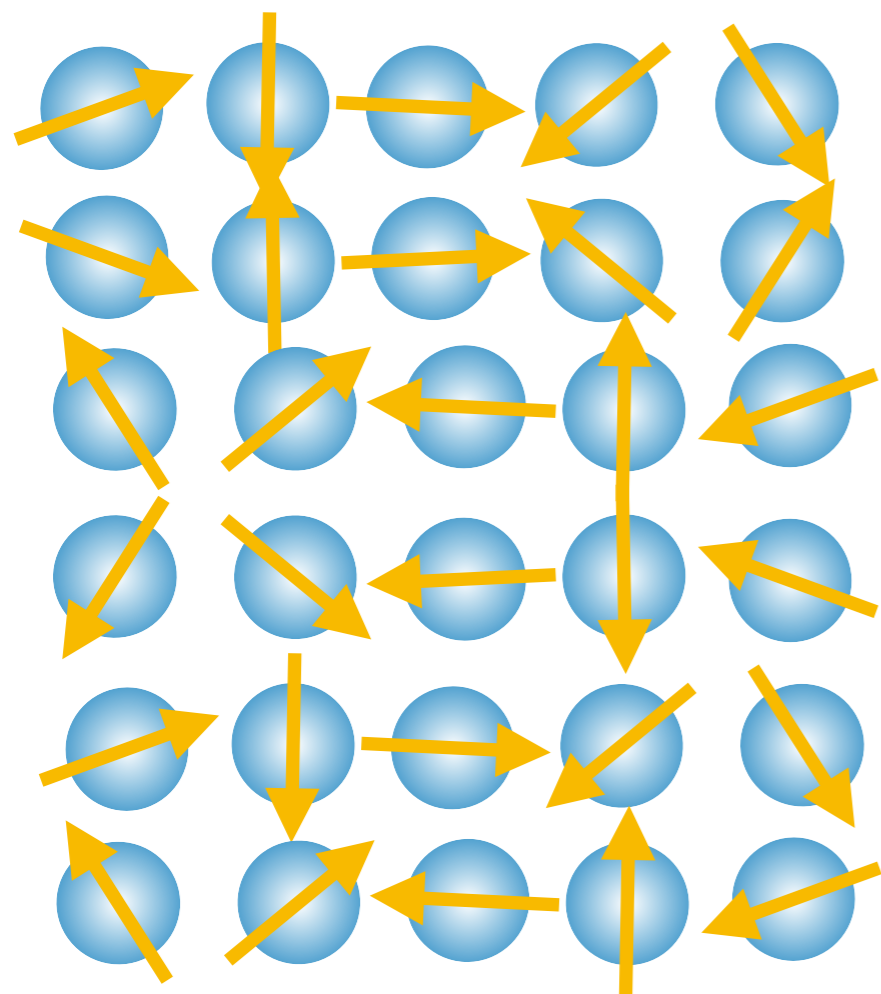


$T > T_f$

$T < T_f$



Frustration, Rigidity and Disorder



Spin susceptibility

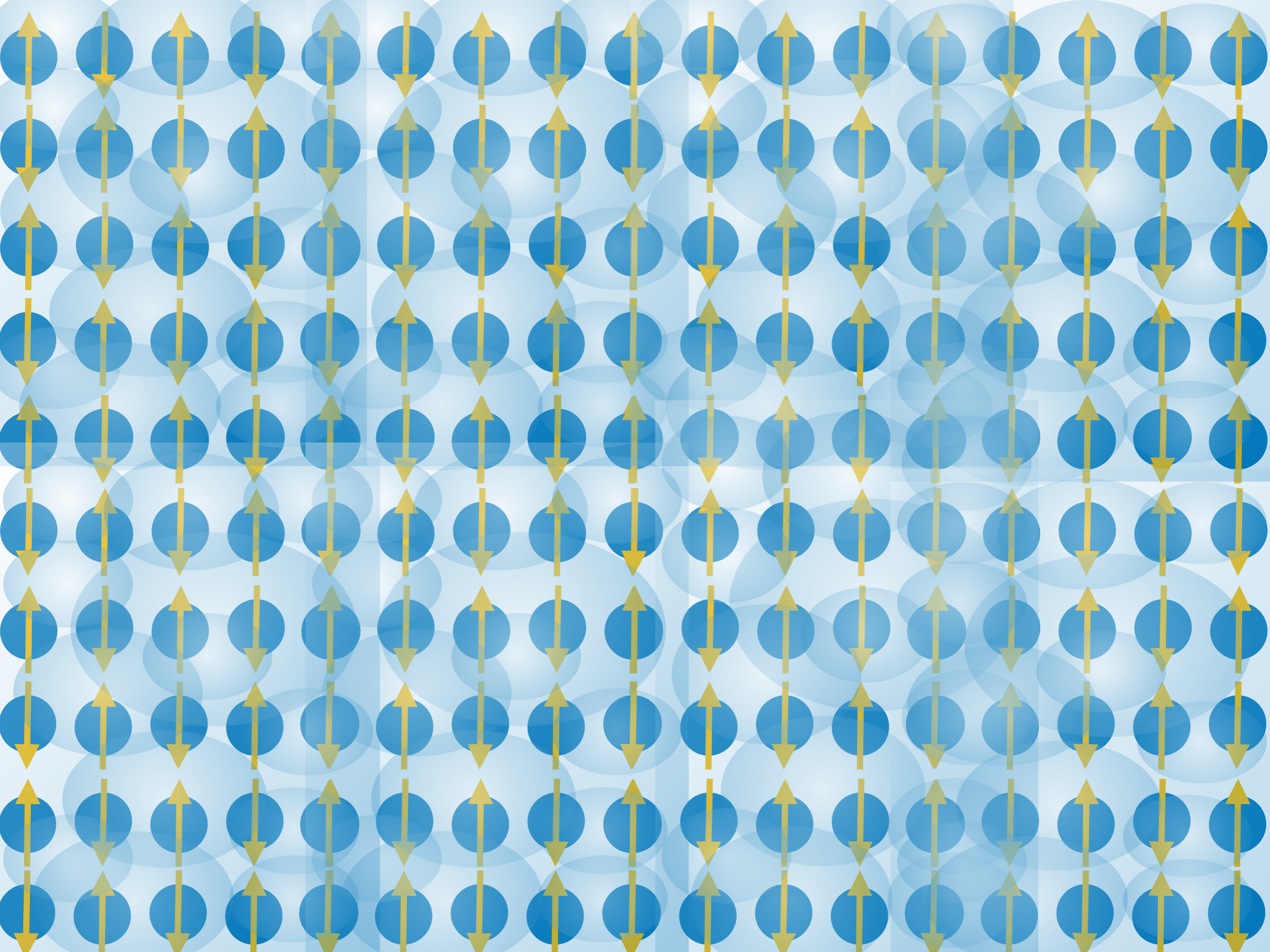
Local rotation

$$[m_{\alpha}^2 \chi^{-1} + \rho_s (\nabla \theta_{\alpha})^2]$$

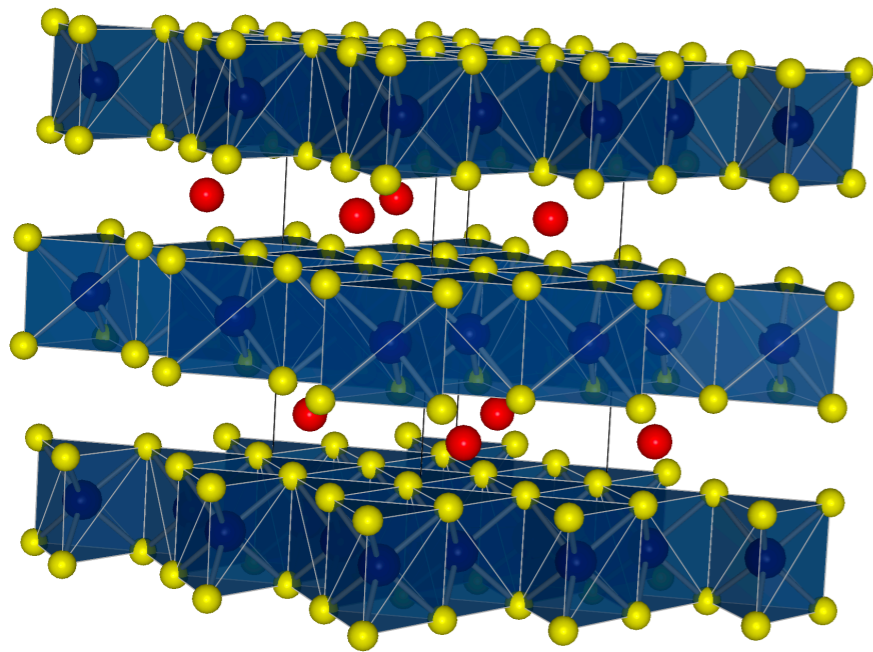
Stiffness

Local magnetization density

Halperin & Saslow, PRL 16, 2154 (1977)



Intercalated TMDs - $M_x\text{NbS}_2$



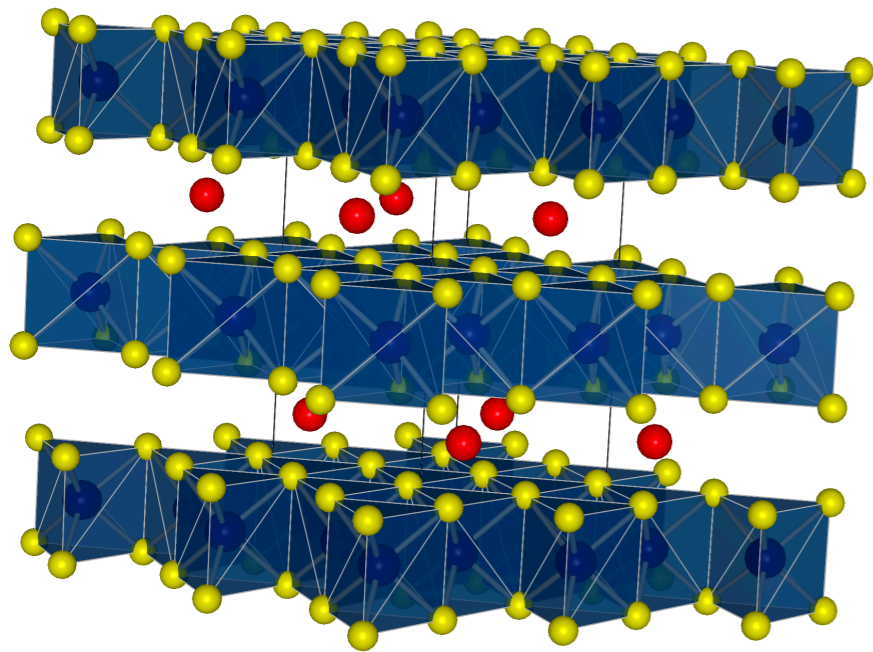
Layered 2H-NbS₂
Centrosymmetric at 1/4 filling
Becomes chiral at 1/3 filling

Periodic Table of the Elements

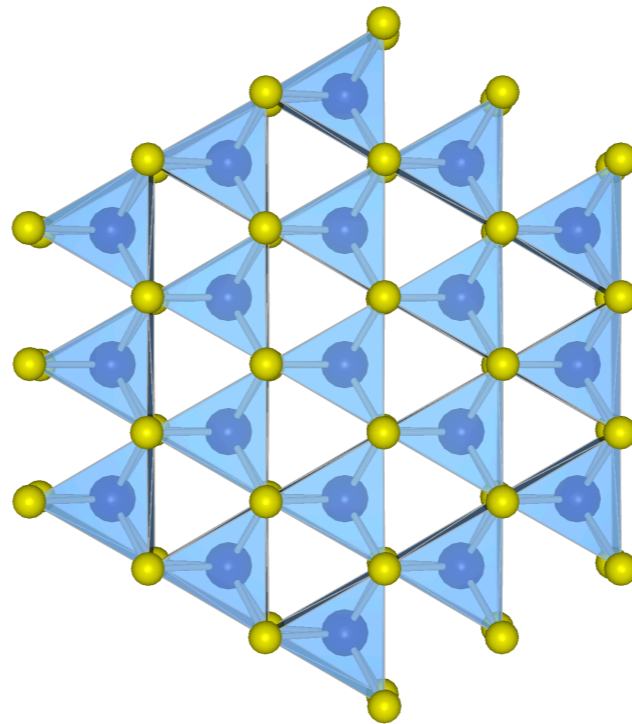
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.992	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanum series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon 222.018
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinide series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium [144.913]	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967			
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]			

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sciencenotes.org

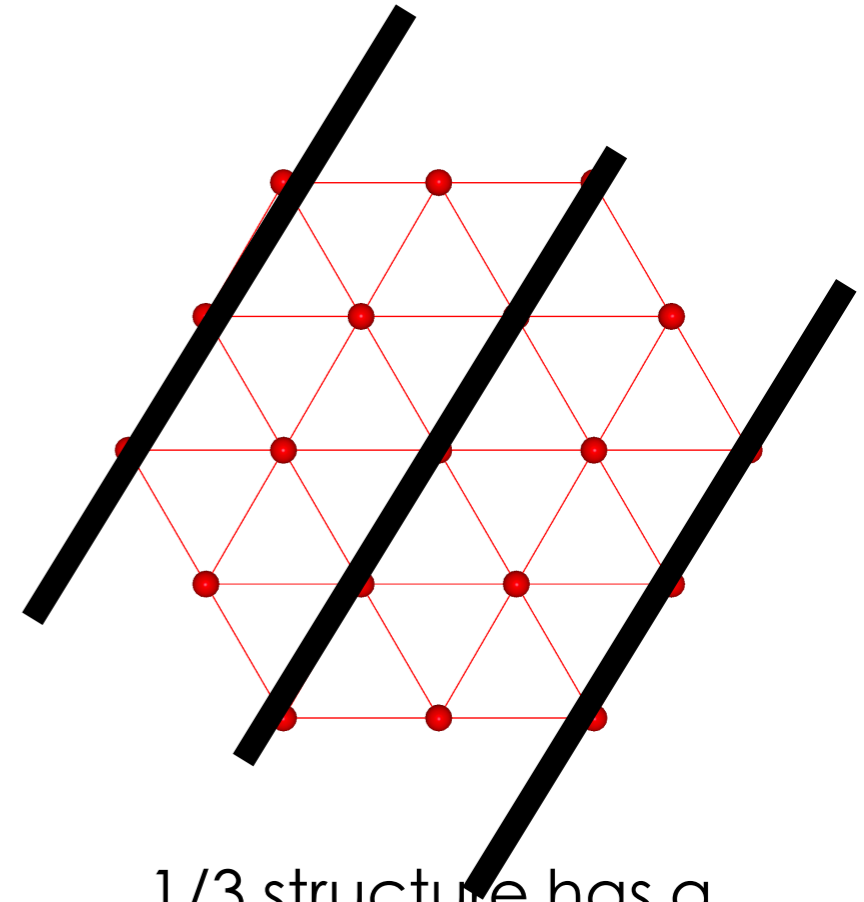
Intercalated TMDs - Fe_xNbS_2



Layered 2H-NbS₂
Centrosymmetric at 1/4 filling
Becomes chiral at 1/3 filling



Triangular prism co-ordination of Nb
Octahedral co-ordination of Fe



1/3 structure has a
triangular lattice of Fe

Magnetic structure

PHILOSOPHICAL MAGAZINE B, 1980, VOL. 41, No. 1, 65-93

JOURNAL OF SOLID STATE CHEMISTRY 3, 154-160 (1971)

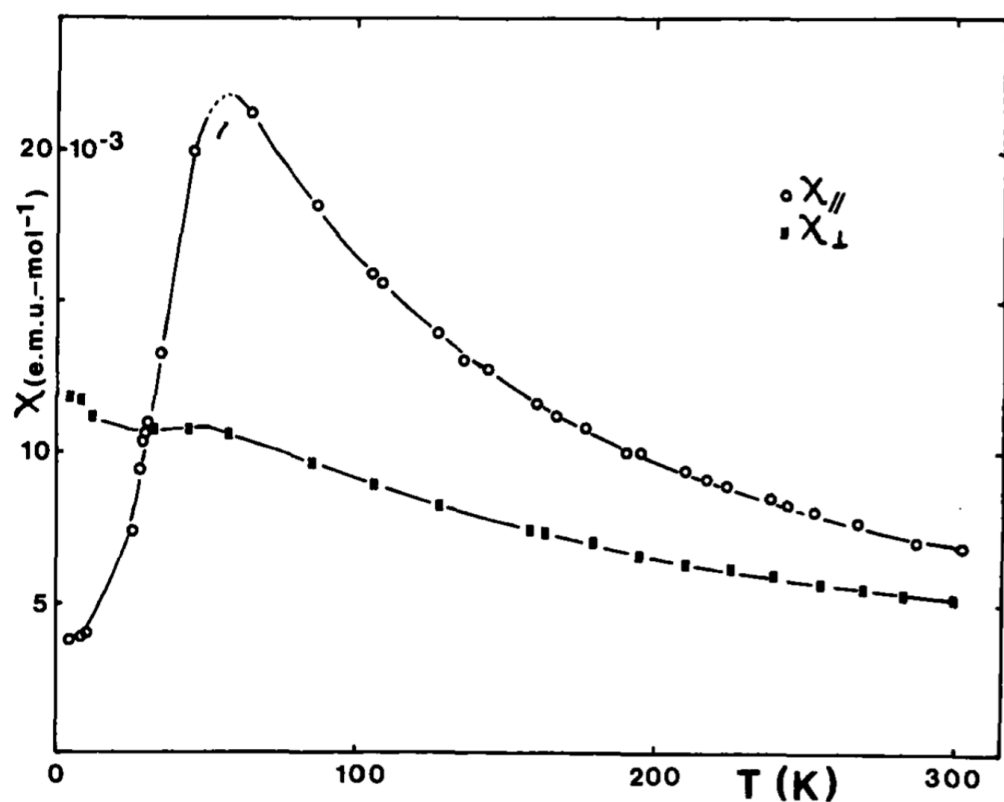
3d transition-metal intercalates of the niobium and tantalum dichalcogenides

I. Magnetic properties

By S. S. P. PARKIN and R. H. FRIEND

Cavendish Laboratory, Madingley Road, Cambridge, England

Fig. 3



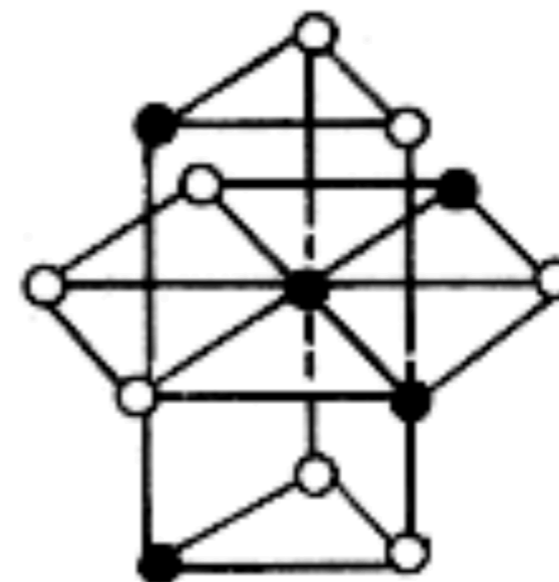
Magnetic susceptibility of a single crystal of $\text{Fe}_{0.33}\text{NbS}_2$ versus temperature. Black squares: χ_{\perp} c axis. Open circles: χ_{\parallel} c axis.

Magnetic and Crystallographic Structures of Me_xNbS_2 and Me_xTaS_2

B. VAN LAAR, H. M. RIETVELD

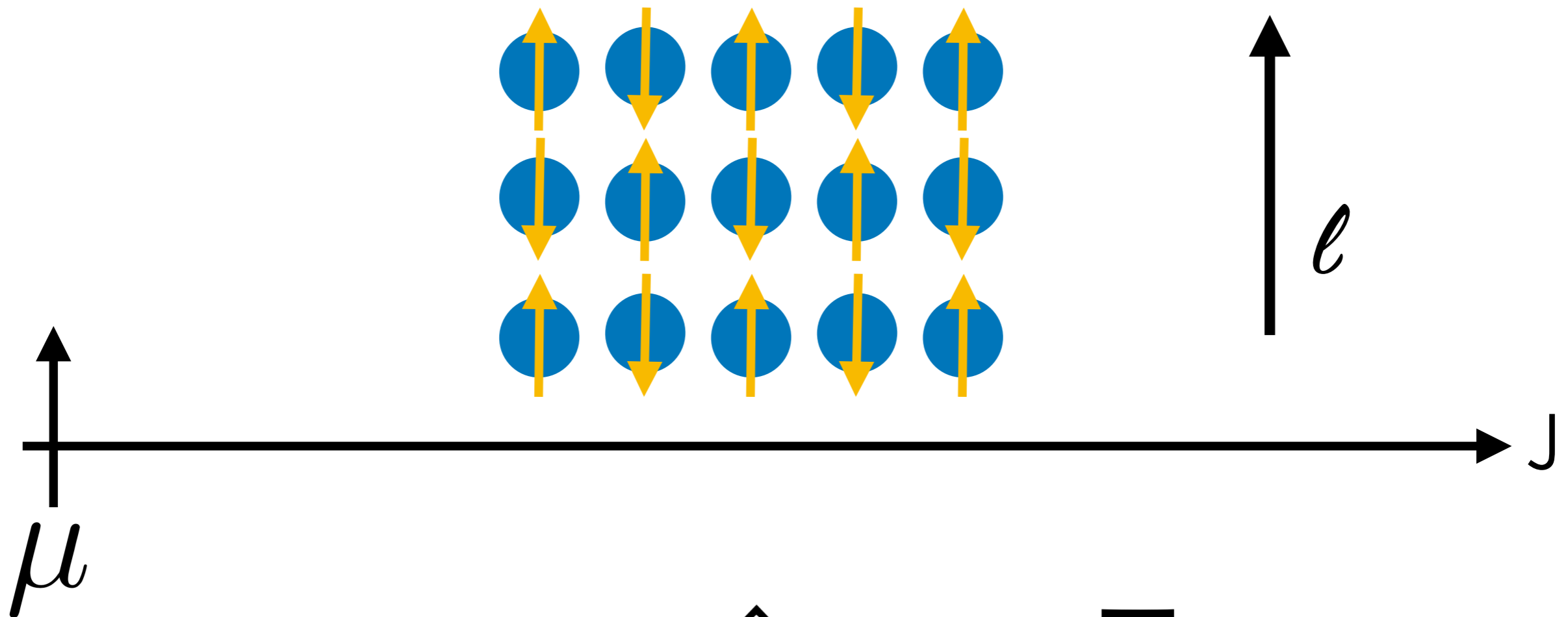
Reactor Centrum Nederland, Petten, The Netherlands

Wurtzite



Aside: What is an
antiferromagnetic
switch?

What is an antiferromagnetic switch?

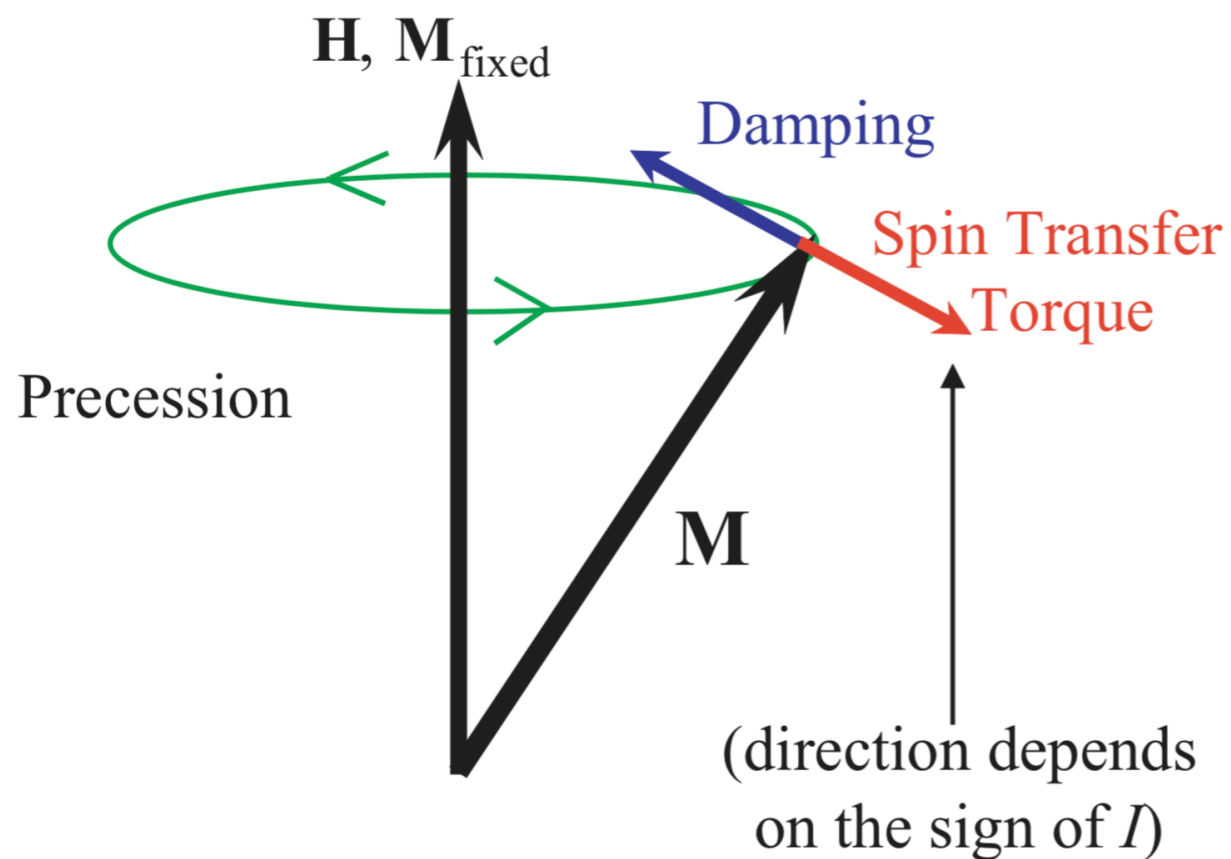


$$\mu = \hat{\mathbf{z}} \times \mathbf{J}$$

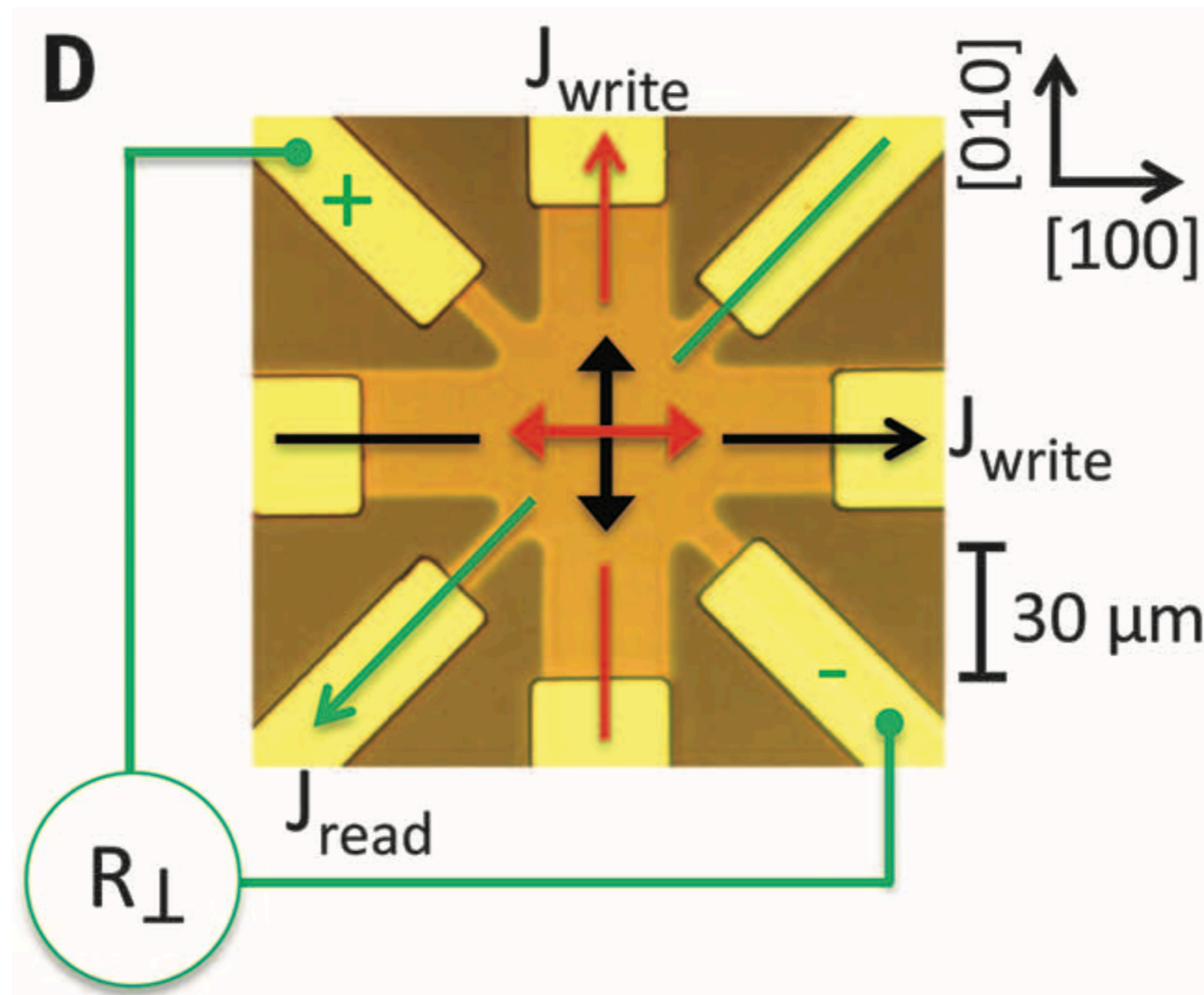
In the presence of spin orbit coupling and broken inversion symmetry, an applied current can attain a partial spin polarization due to the Edelstein/Spin Hall effect

Landau-Lifshitz-Gilbert

$$d\mathbf{M}/dt = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times d\mathbf{M}/dt$$

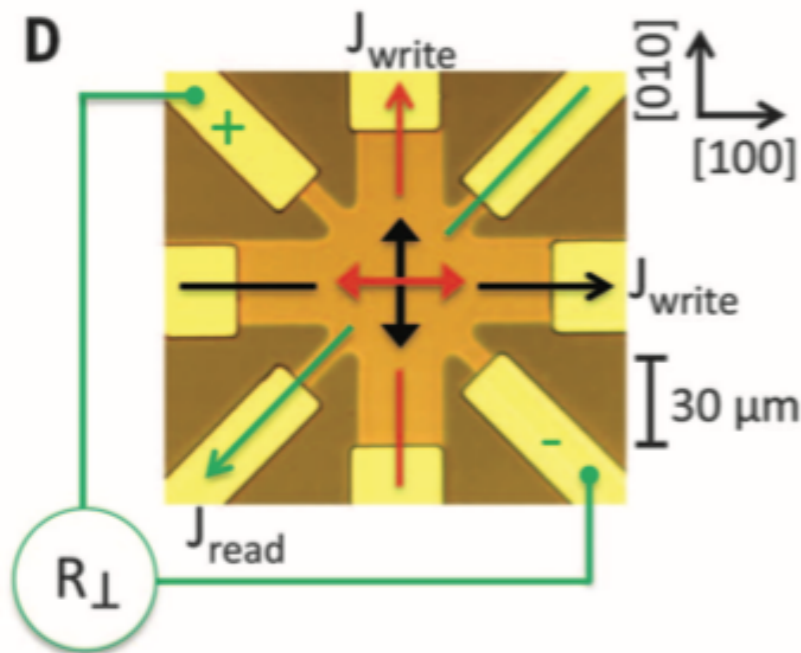


What is an antiferromagnetic switch?

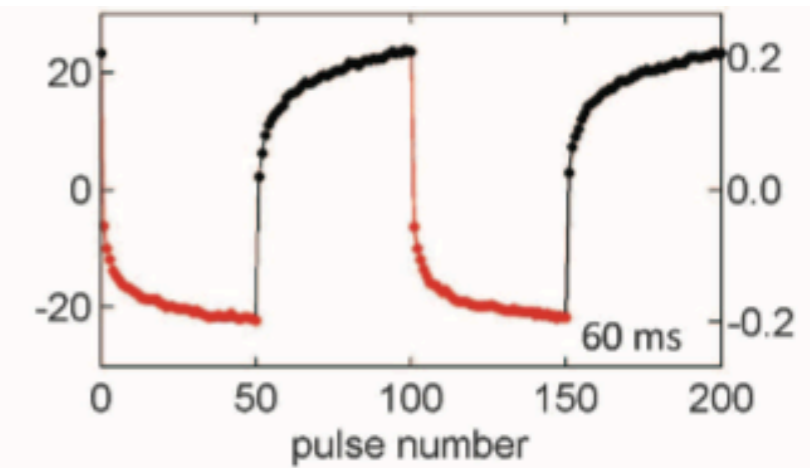
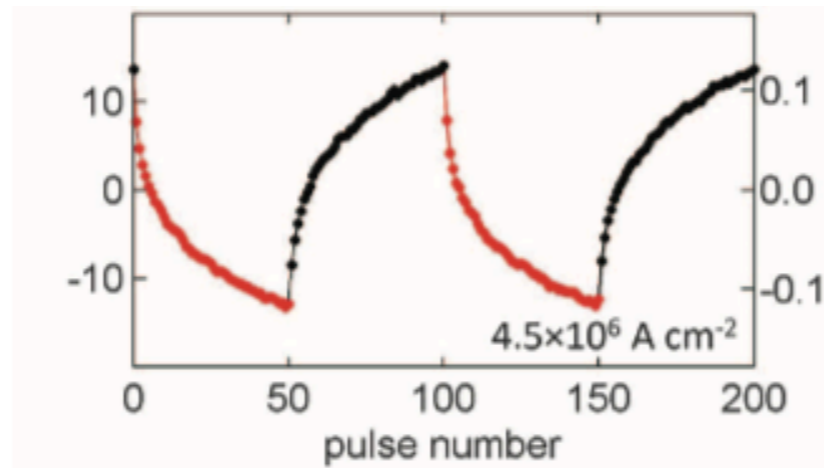


CuMnAs (Wadley et al.
Science 2016)

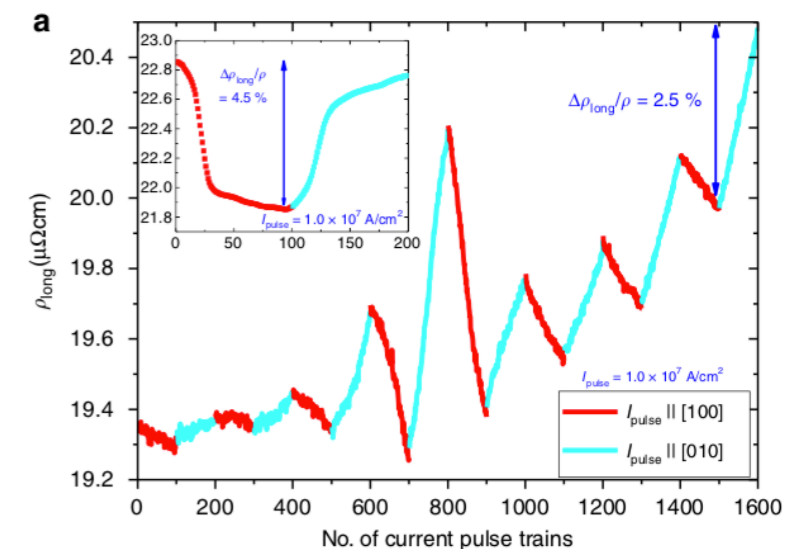
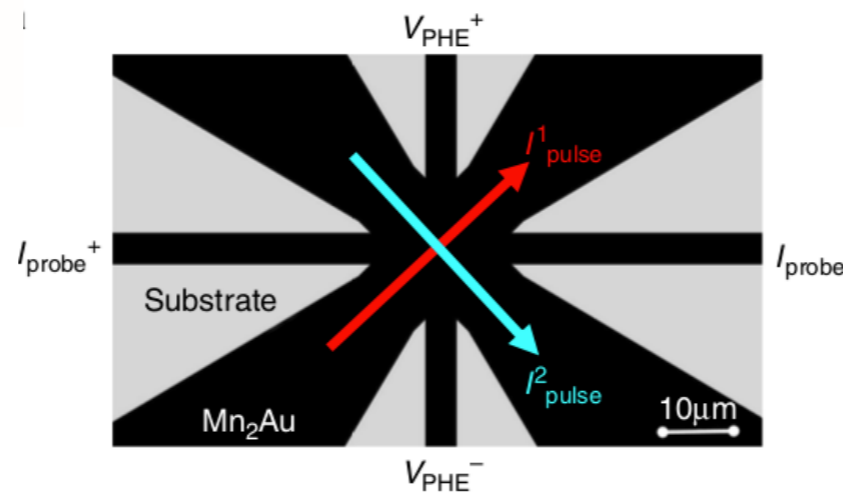
What is an antiferromagnetic switch?



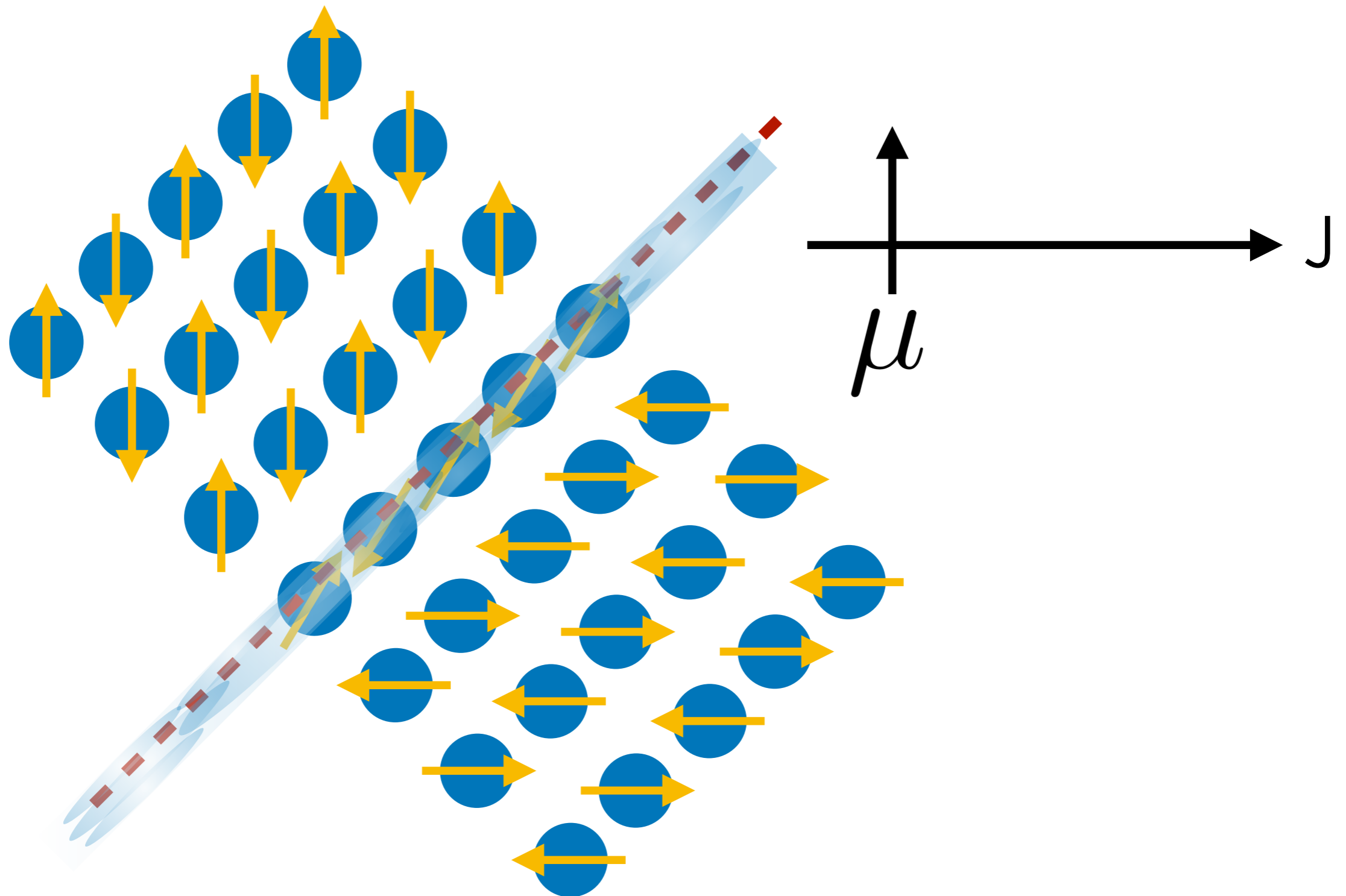
Mn₂Au (Bodnar et al, Nature Comm. 2018)



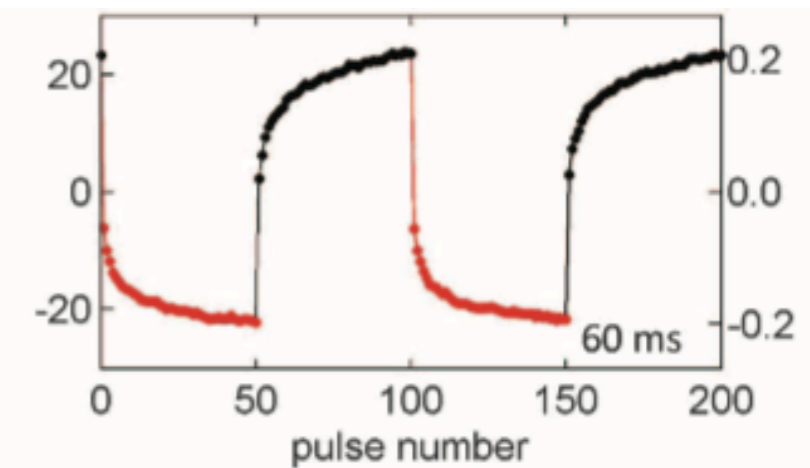
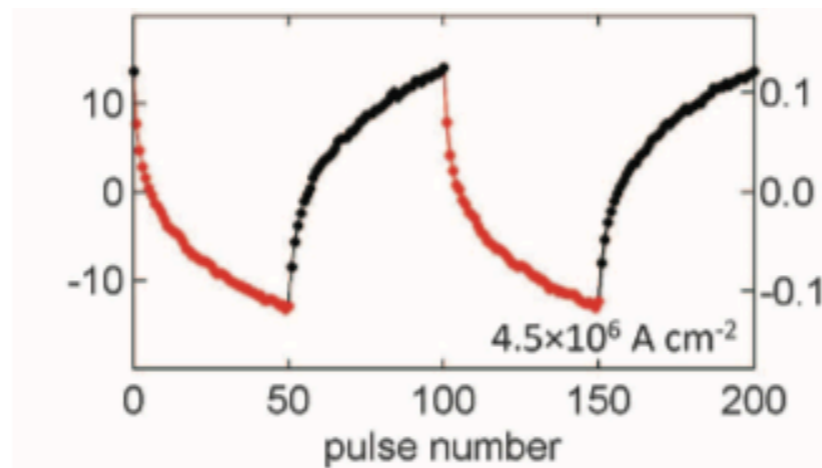
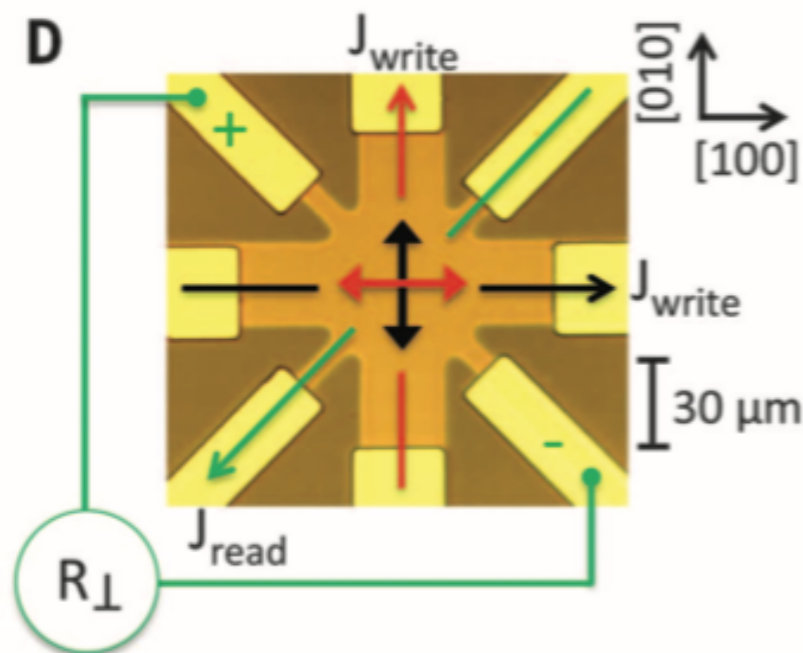
CuMnAs (Wadley et al. Science 2016)



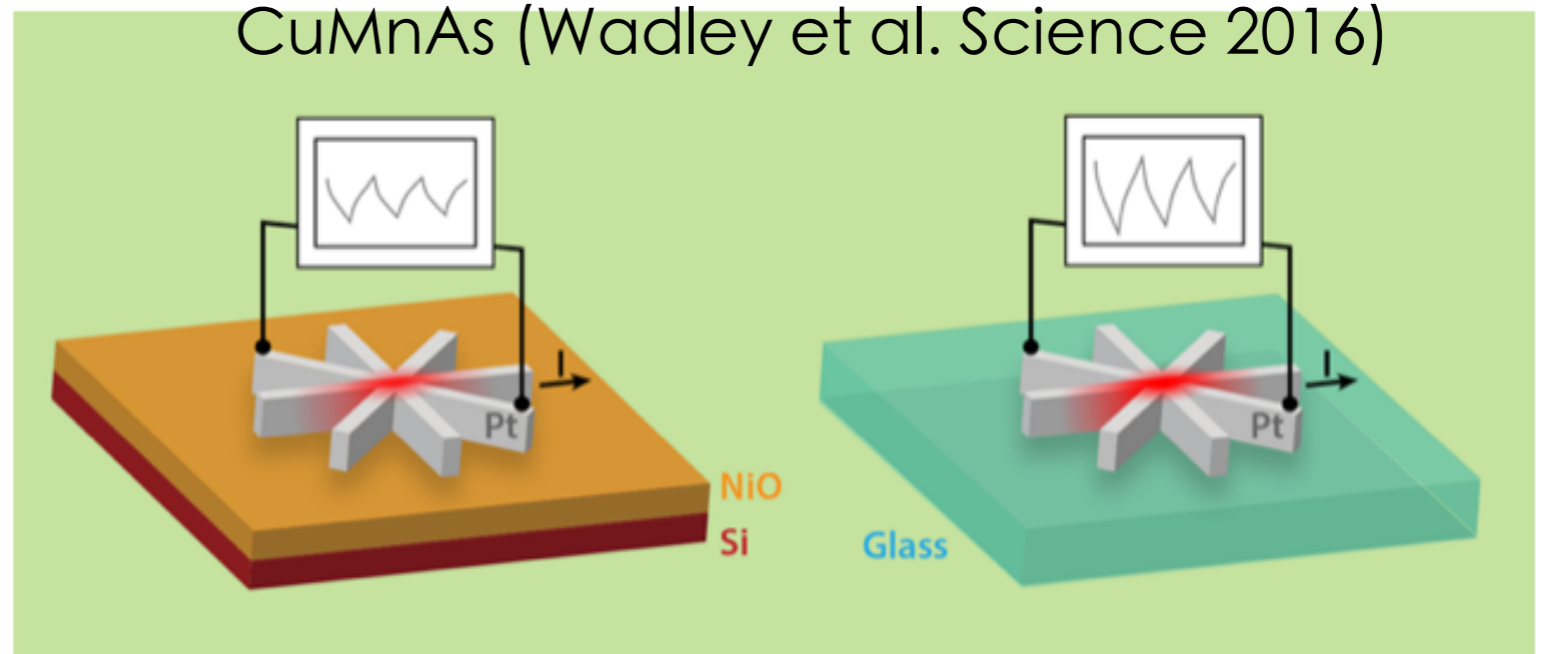
Domain boundary motion
moves an average ℓ



What is an antiferromagnetic switch?

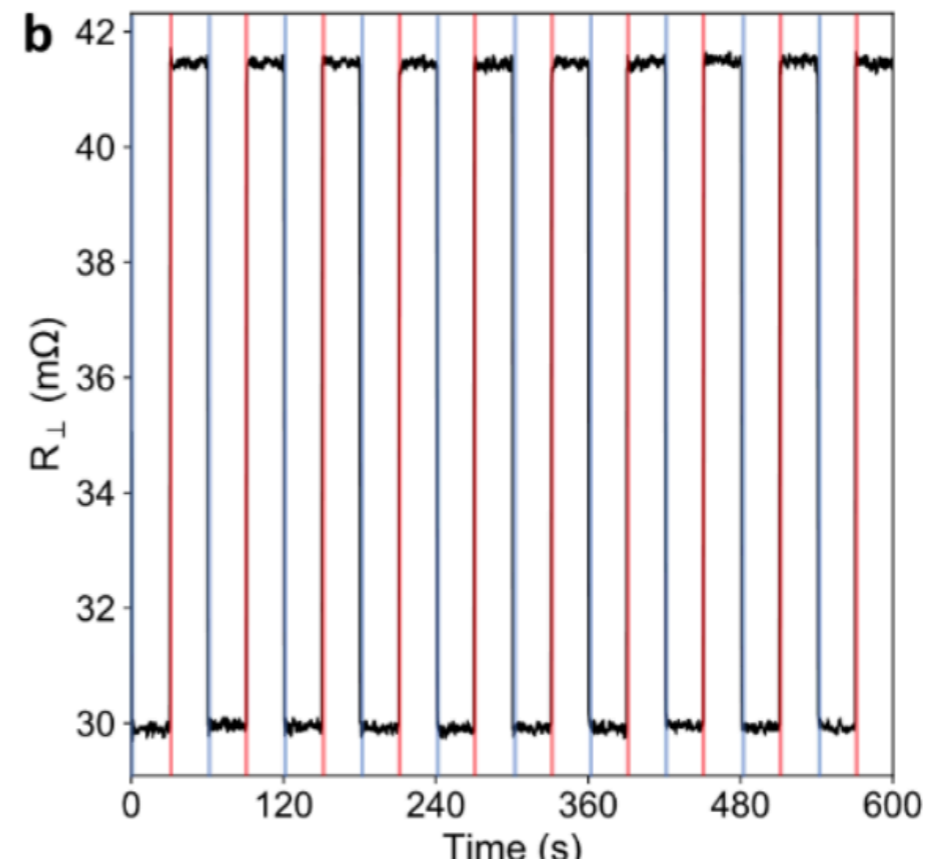
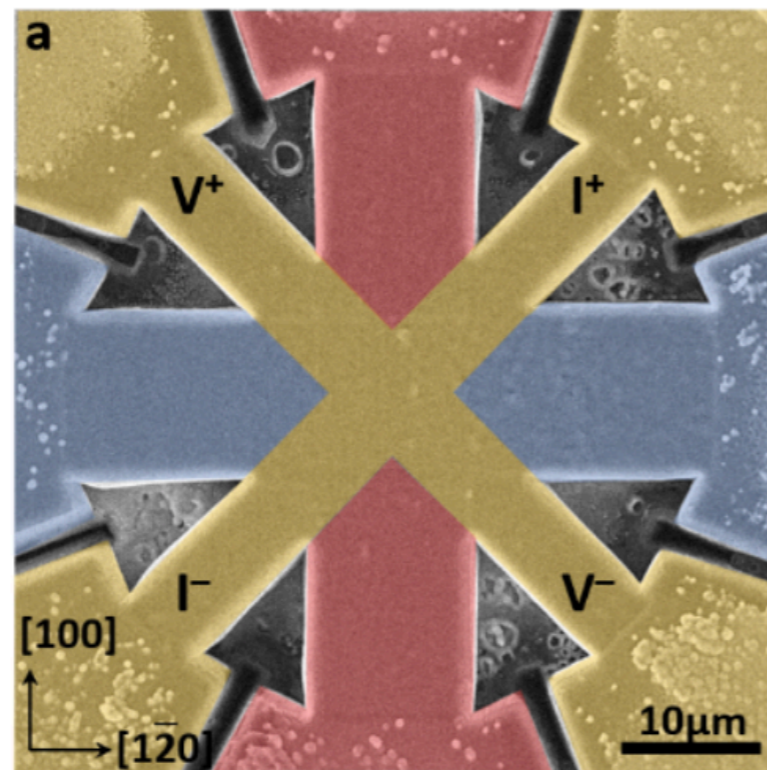


CuMnAs (Wadley et al. Science 2016)

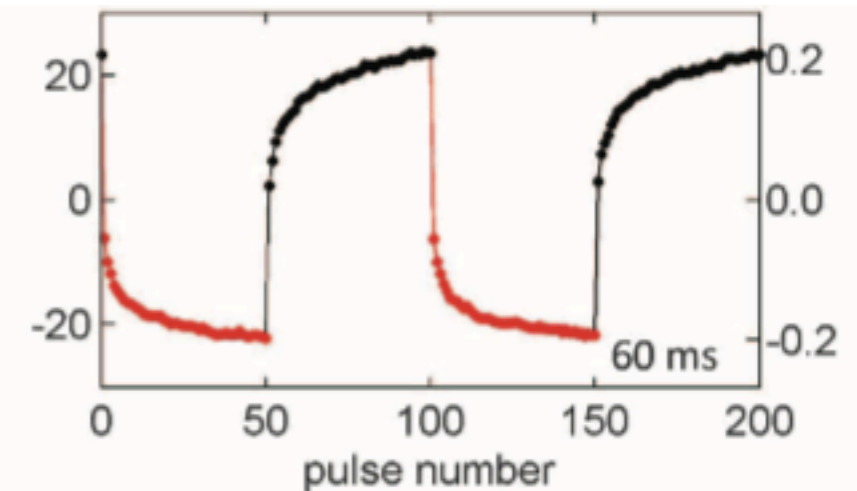
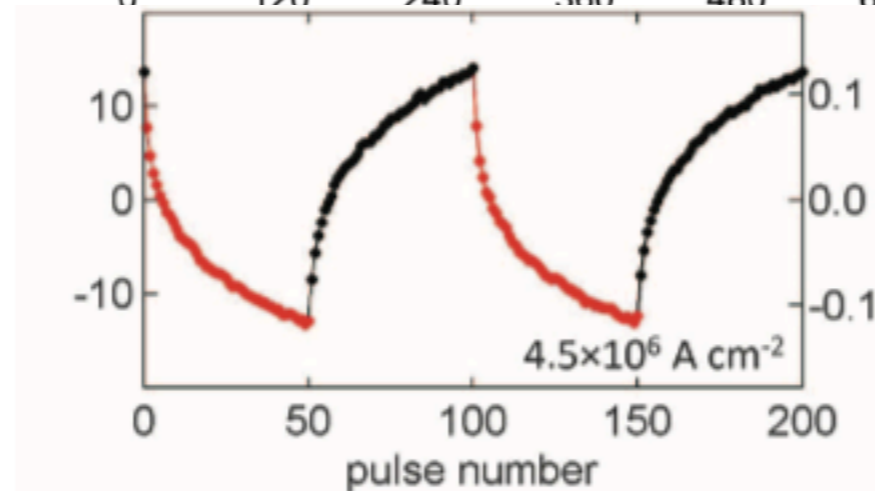
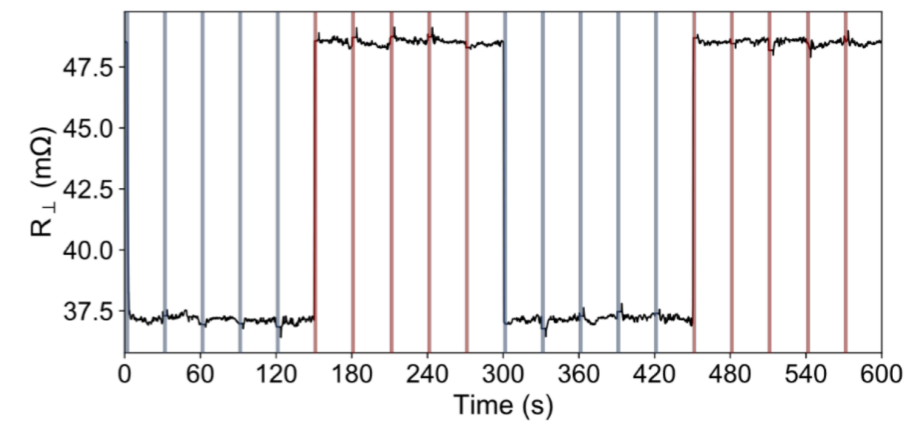
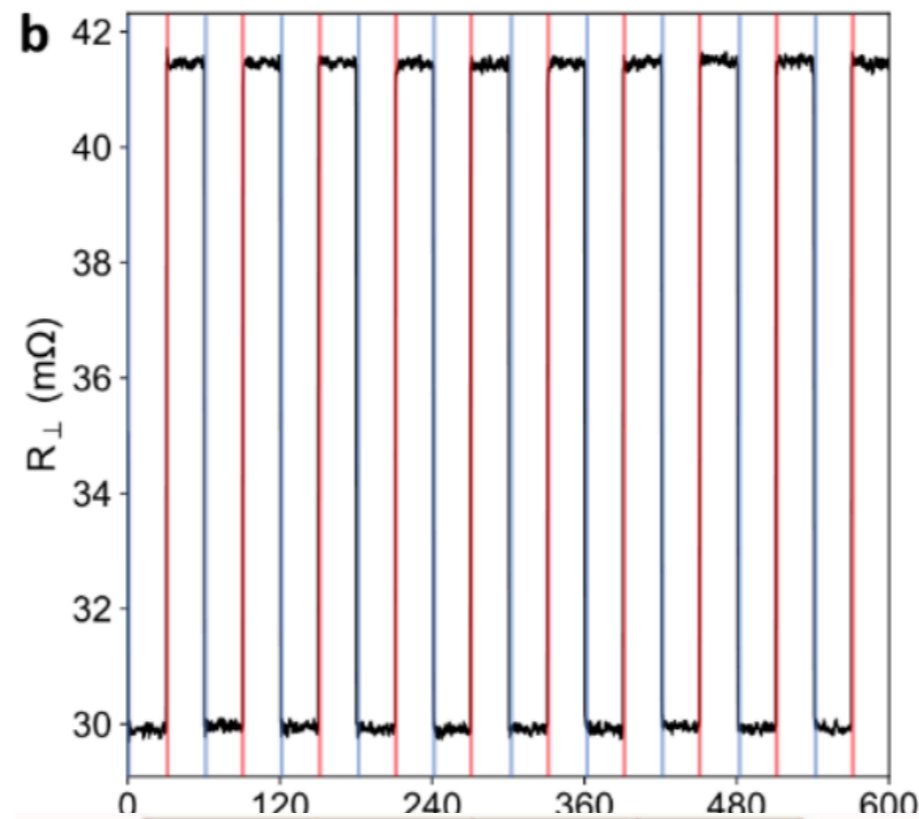
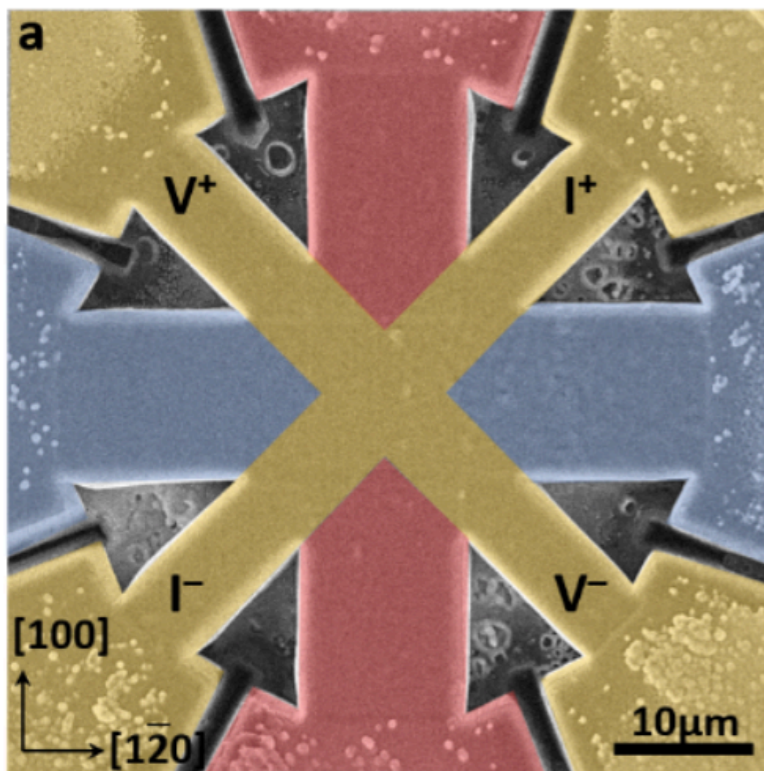


Chiang et al. Phys. Rev. Lett. 123, 227203

Antiferromagnetic Switching in $\text{Fe}_{1/3-\delta}\text{NbS}_2$



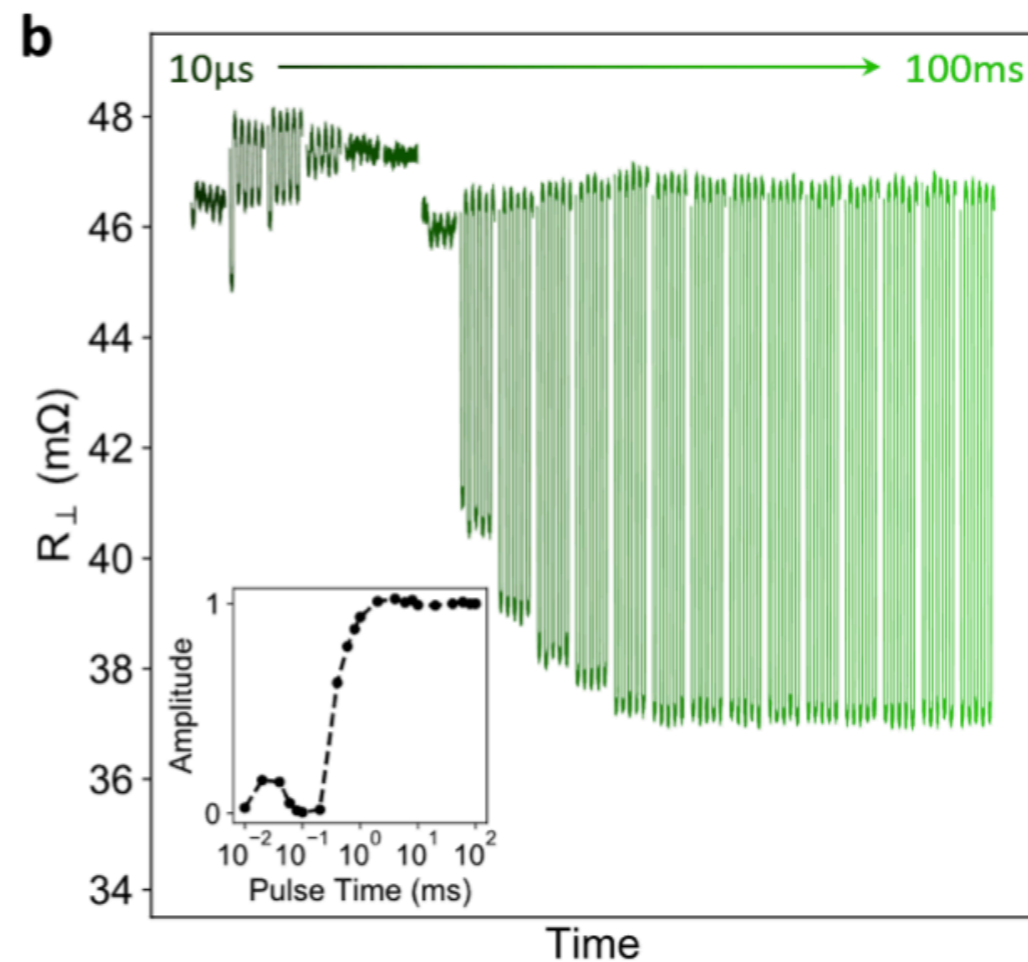
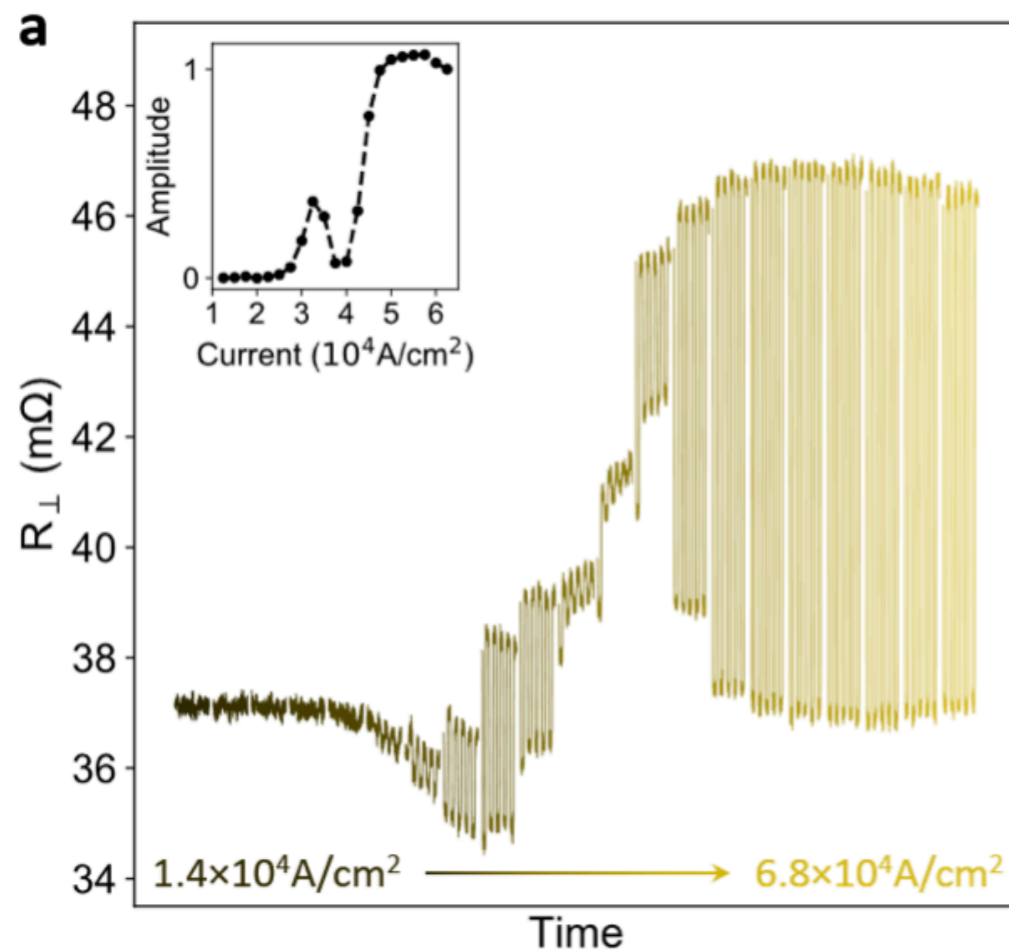
Antiferromagnetic Switching in $\text{Fe}_{1/3-\delta}\text{NbS}_2$



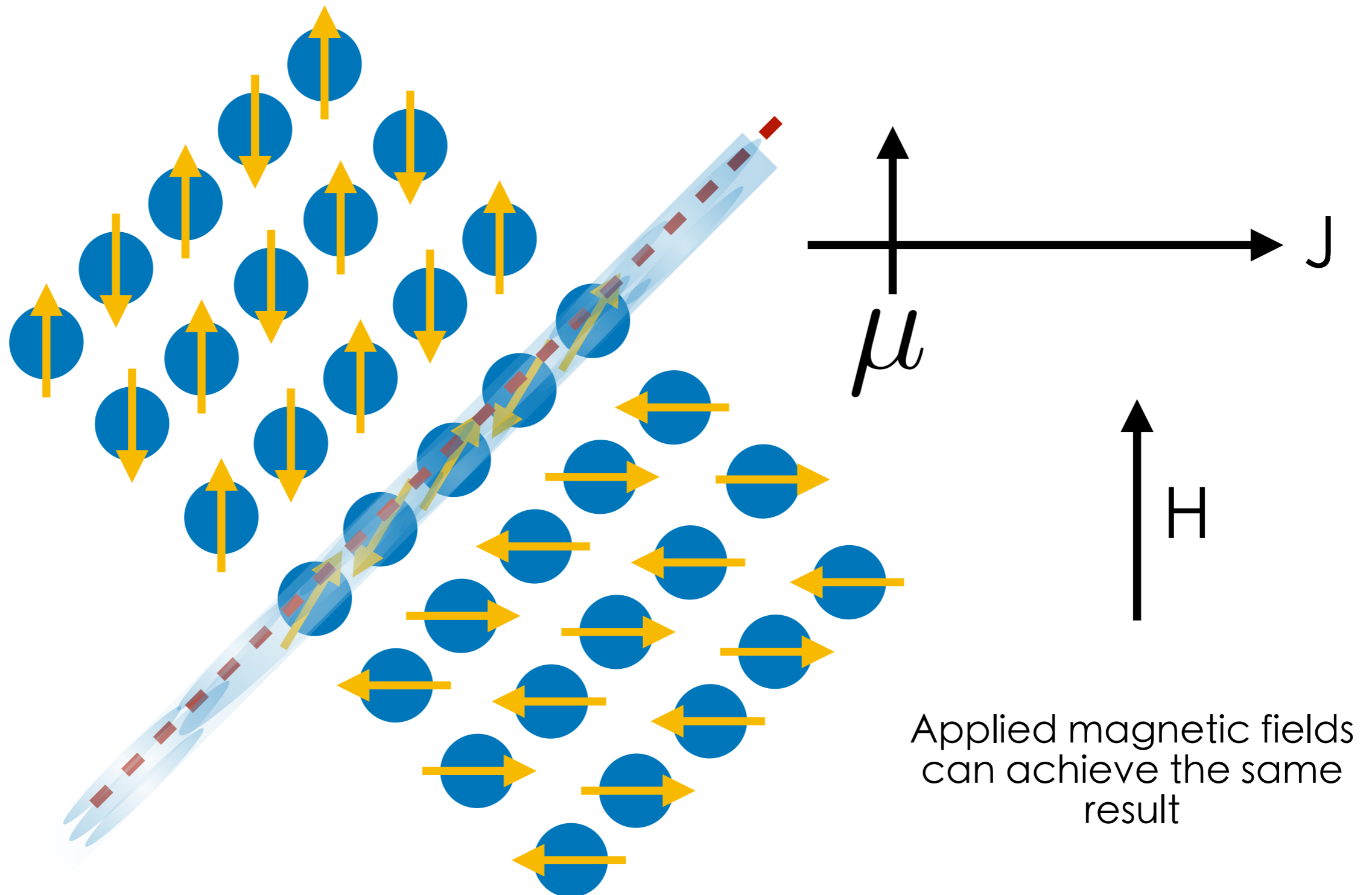
Extremely low current densities and pulse durations

$$J \sim 10^4 \text{A/cm}^2$$

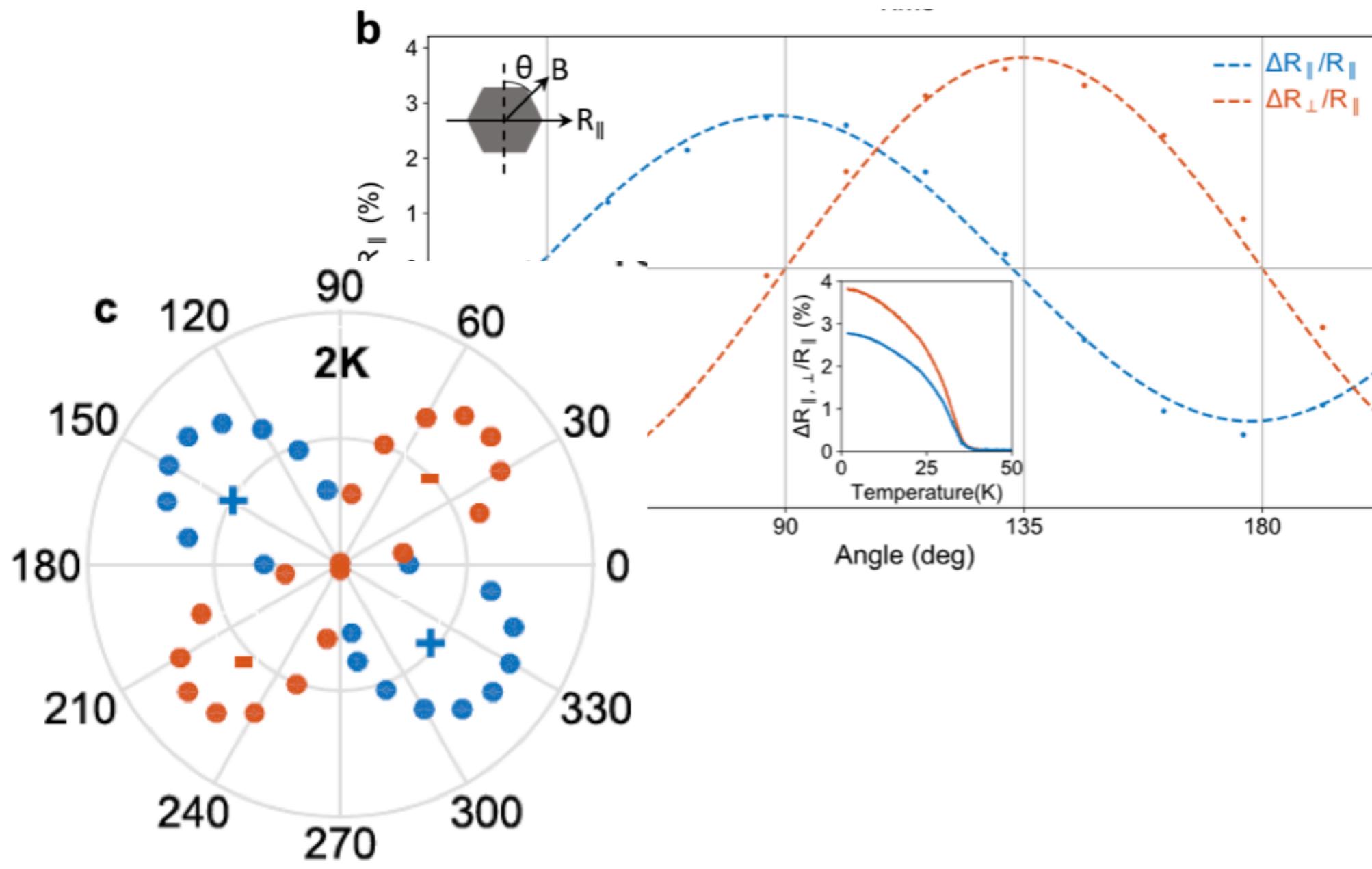
$$\Delta t \sim 1 \text{ms}$$



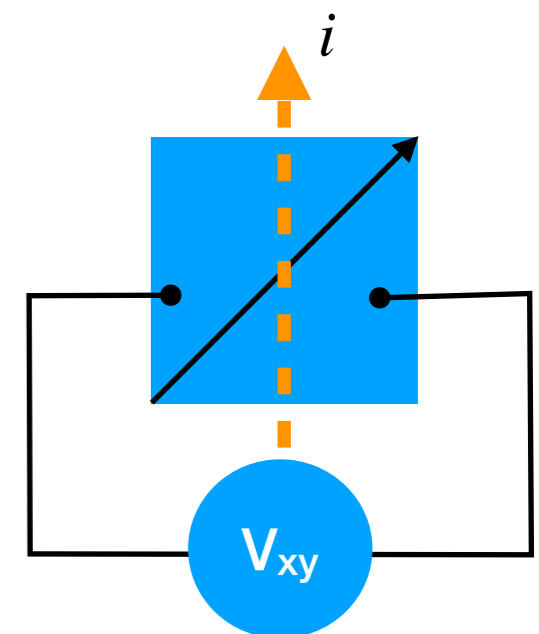
Domain boundary motion moves an average ℓ



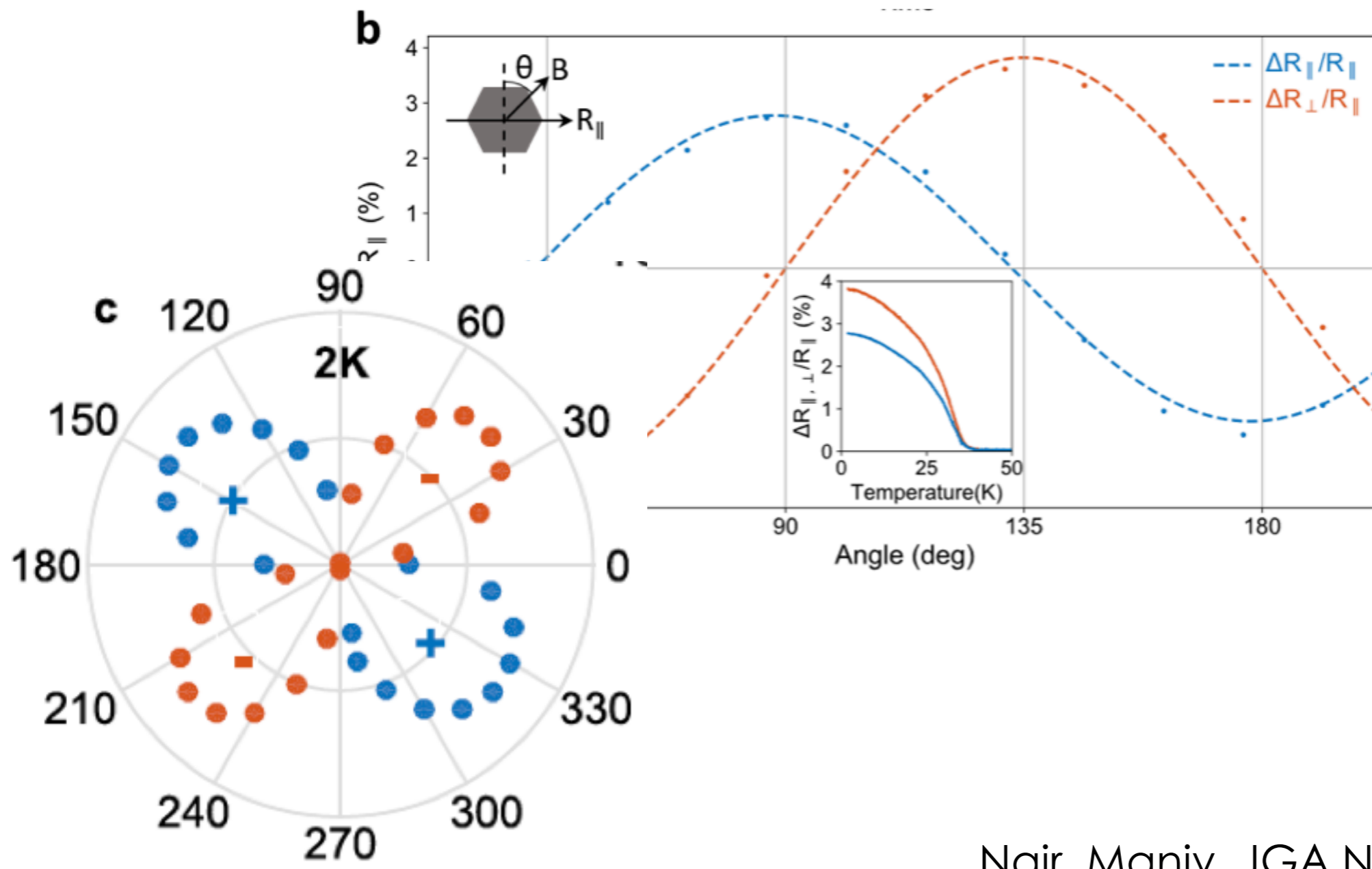
Anisotropic MagnetoResistance & switching in $\text{Fe}_{1/3+\delta}\text{NbS}_2$



AMR

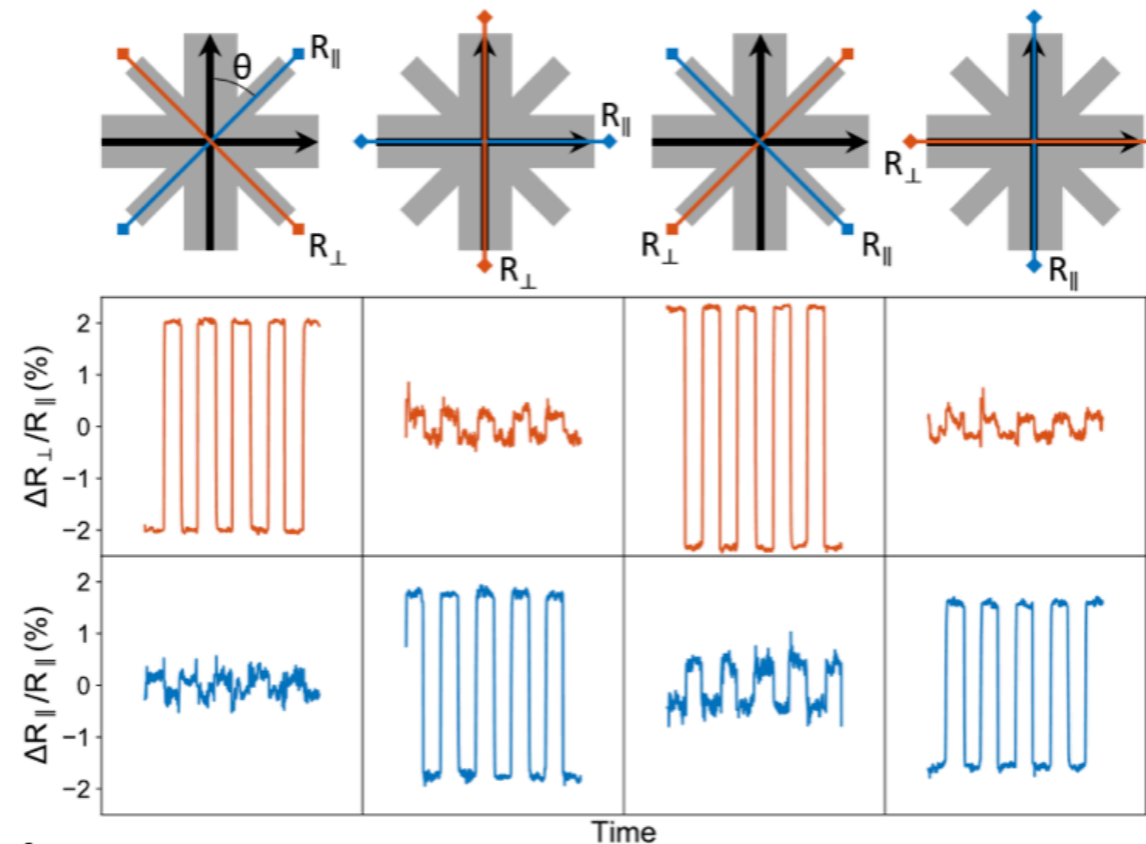


Zero-Field Anisotropic MagnetoResistance & switching in $\text{Fe}_{1/3+\delta}\text{NbS}_2$

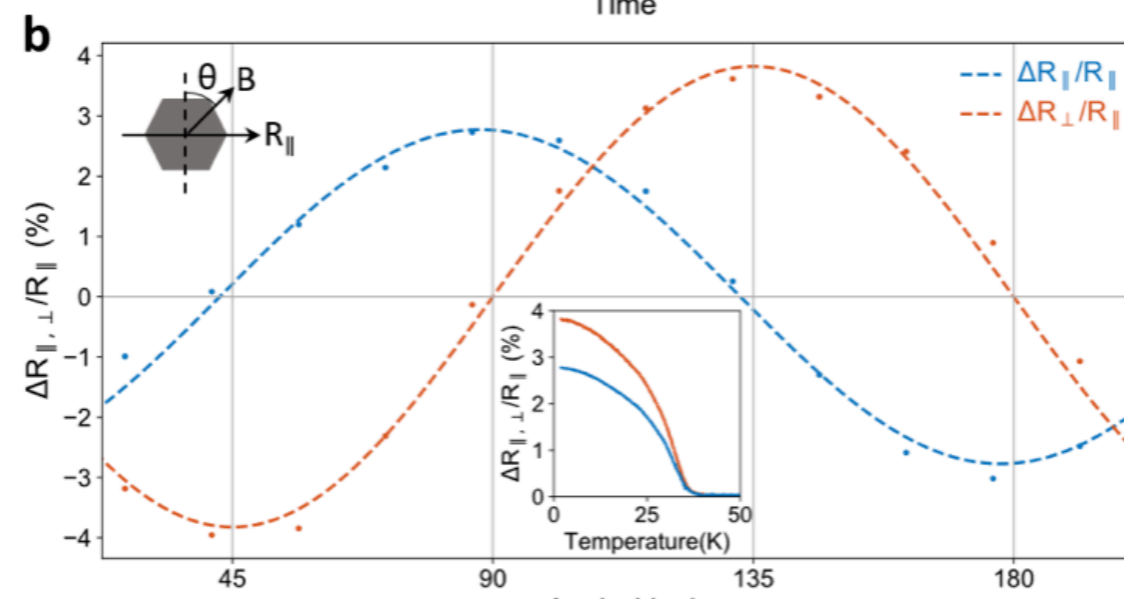


ZAMR

Zero-Field Anisotropic MagnetoResistance & switching in $\text{Fe}_{1/3+\delta}\text{NbS}_2$

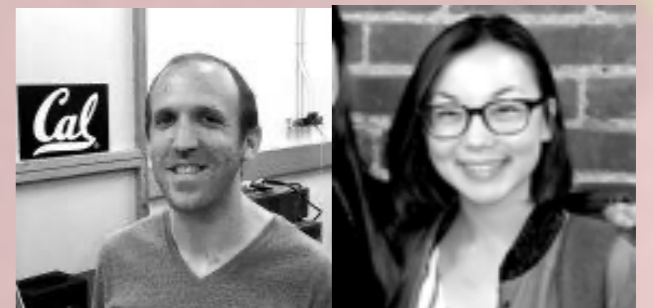


This provides evidence that the AFM switching follows the AFM order parameter.



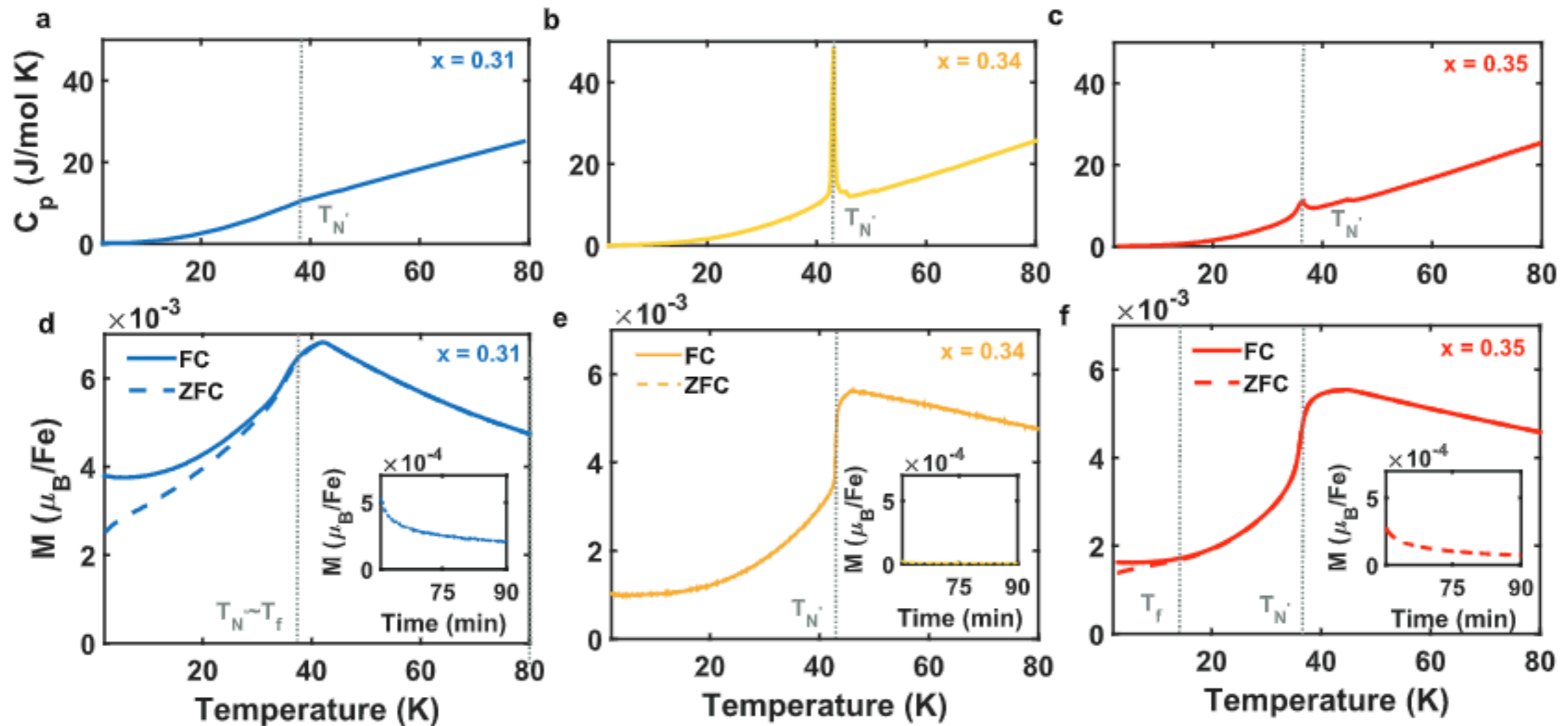
Or does it?

Collective dynamics of the coexisting spin glass



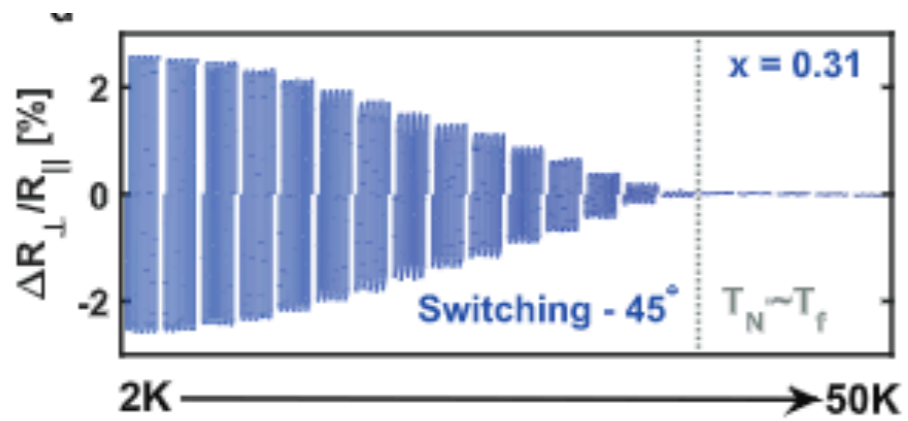
Eran Maniv, Shannon Haley

Sample “improvements”

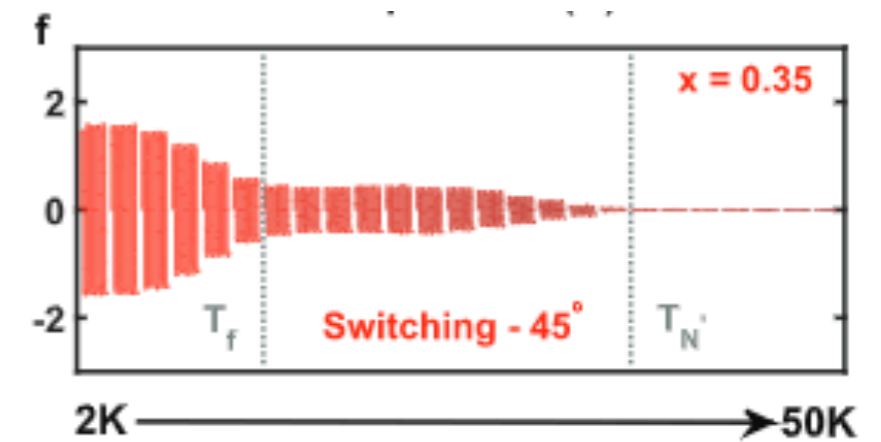


Eran Maniv, Shannon Haley

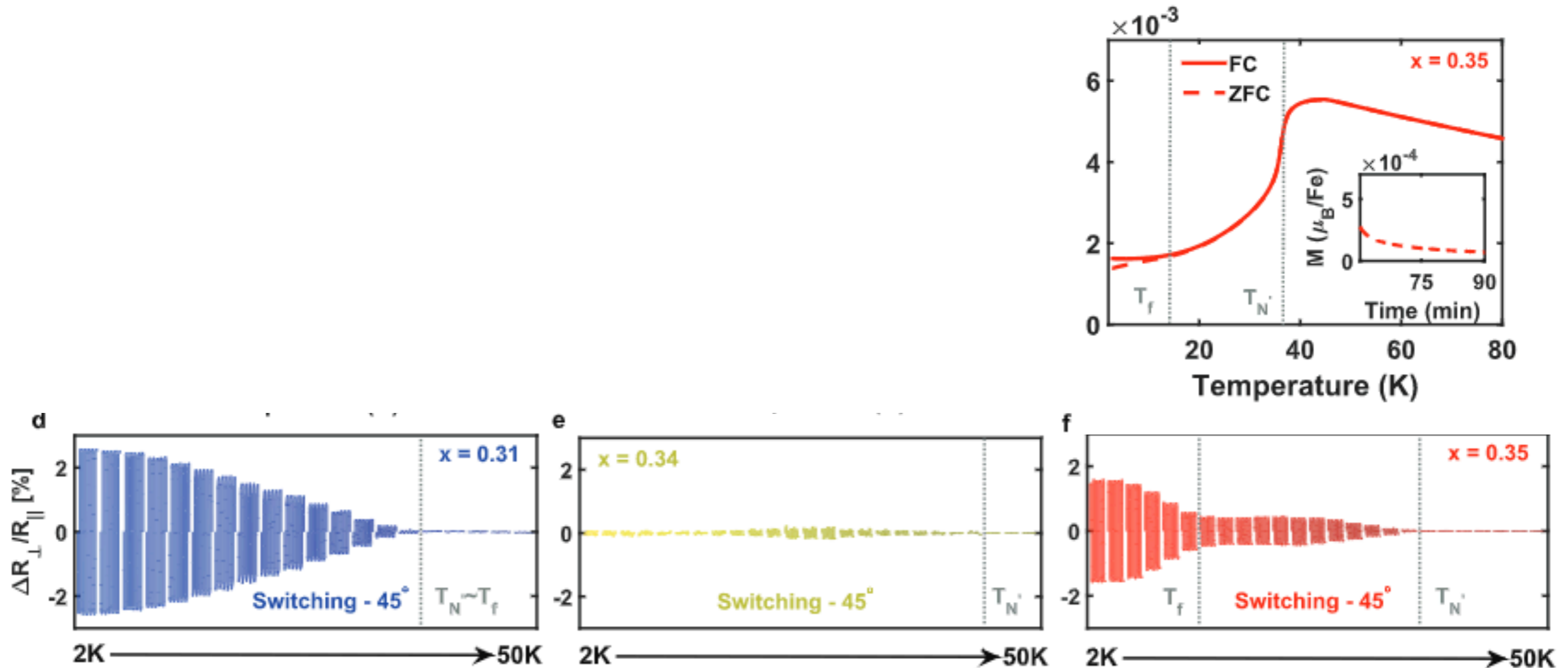
Sample “improvements”



Sample “improvements”

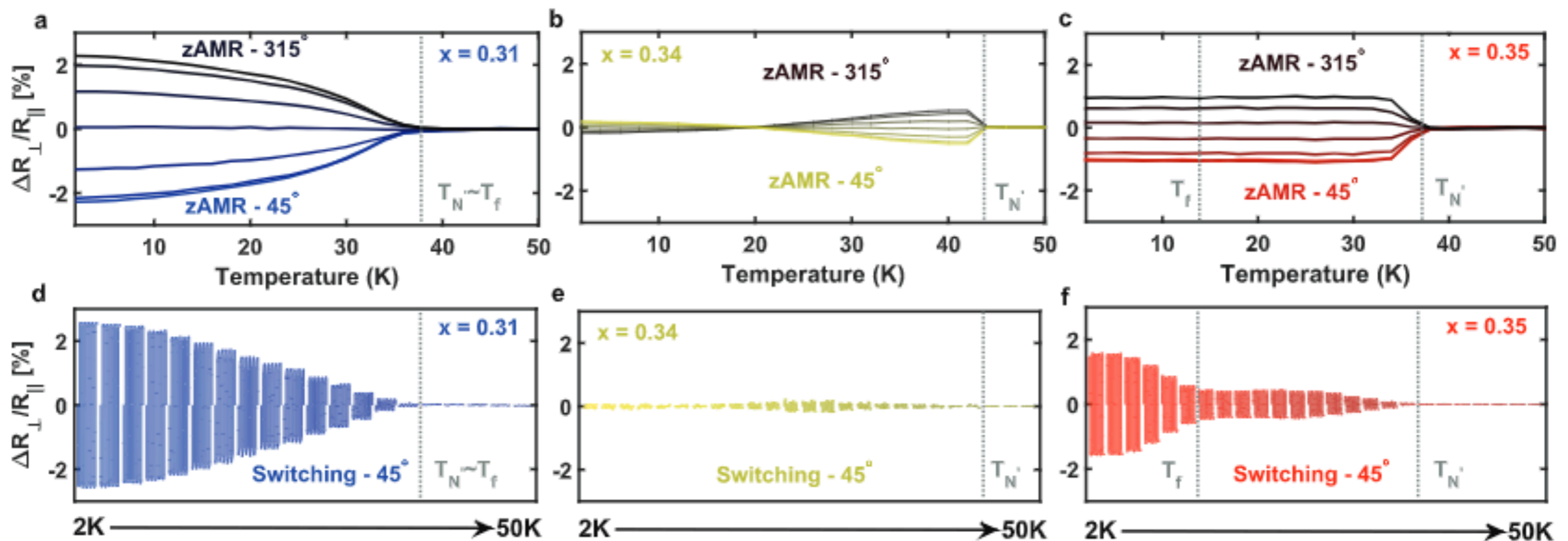


Sample “improvements”



The presence of the spin glass is essential in facilitating the switching

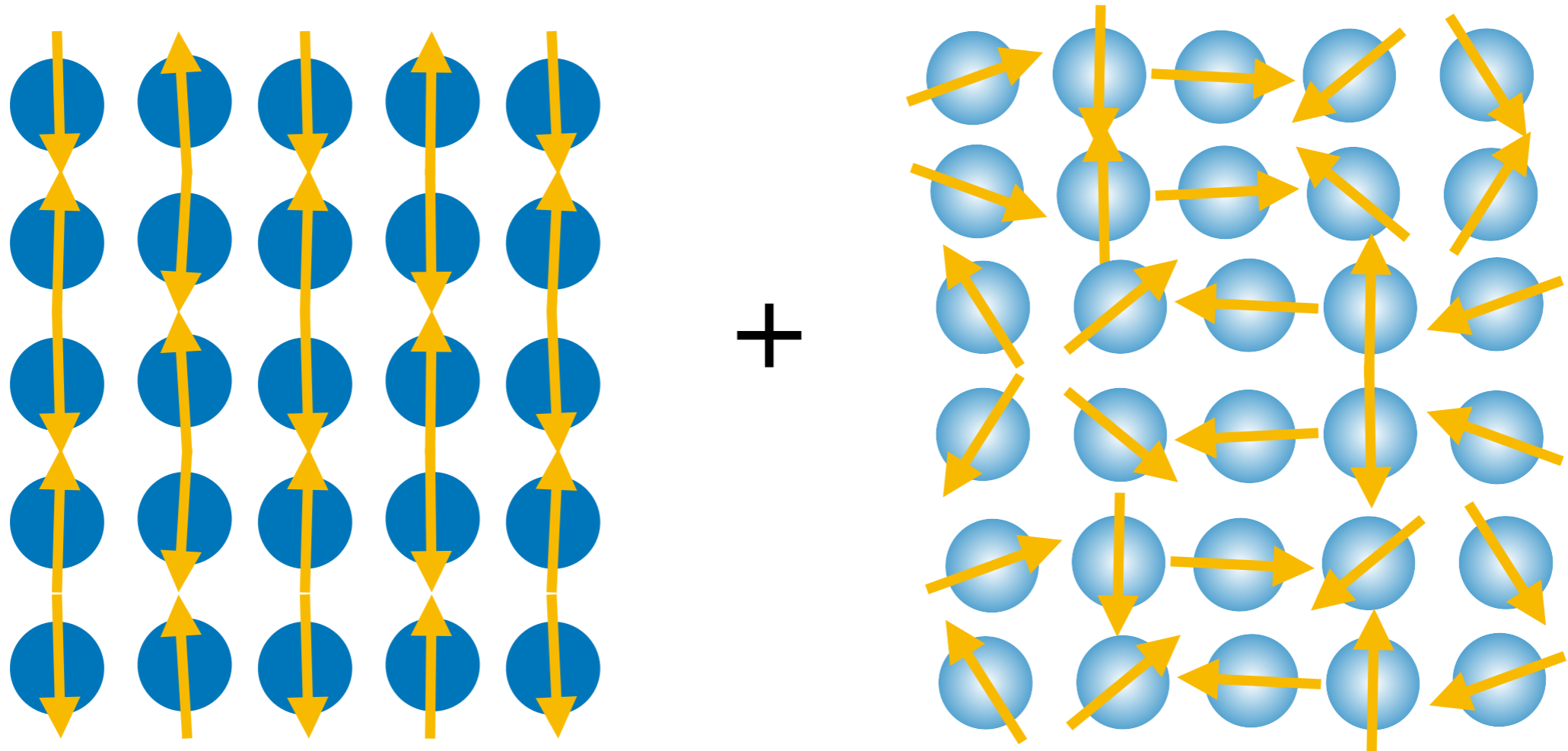
AFM Switching and AMR



The AMR is completely indifferent to the presence of the spin glass, and there is no change of sign.

Why?

Collective dynamics of a correlated spin glass



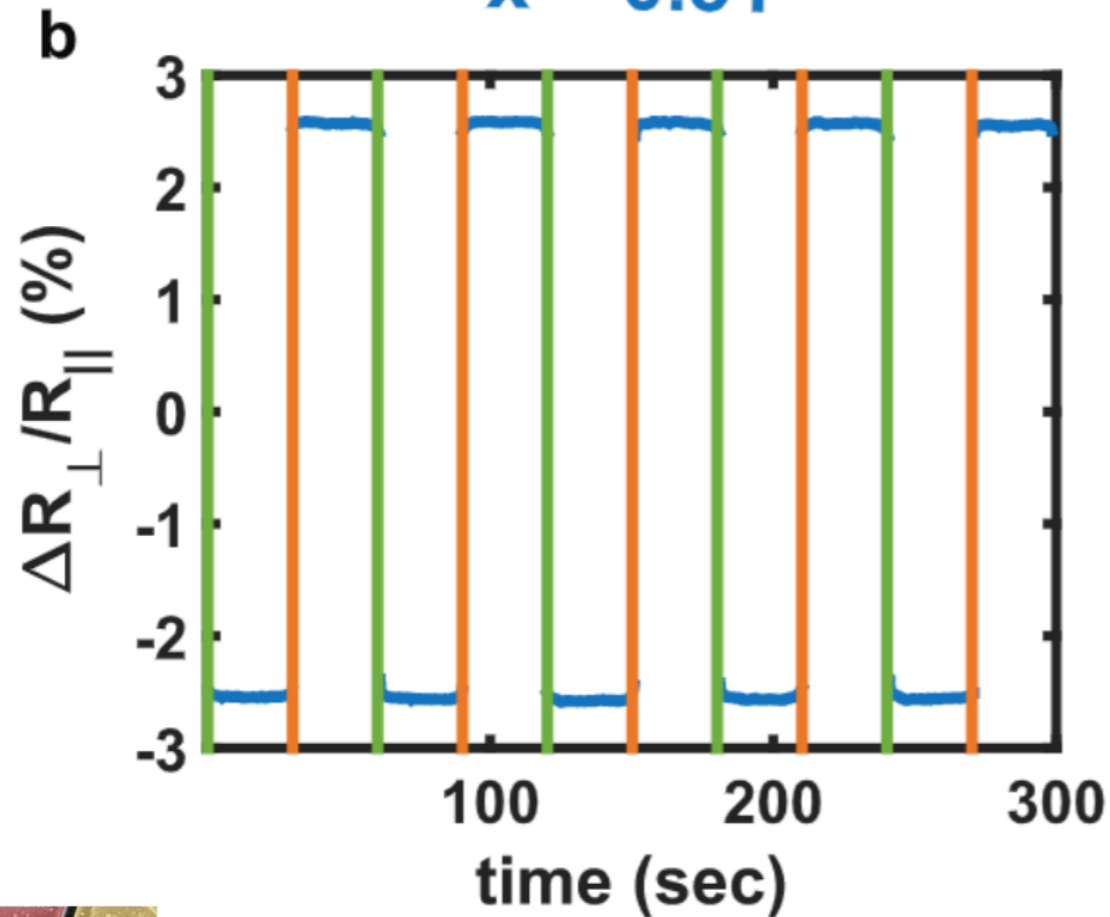
Glassy spin textures form hydrodynamic modes that are locked in phase

Coexisting orders

Anomalous Switching

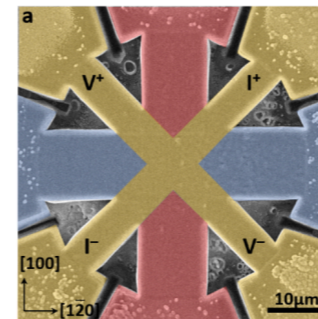
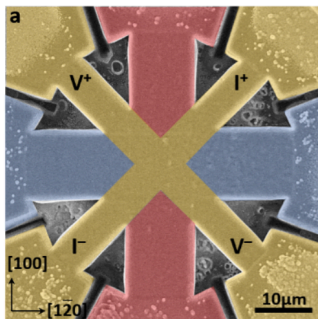
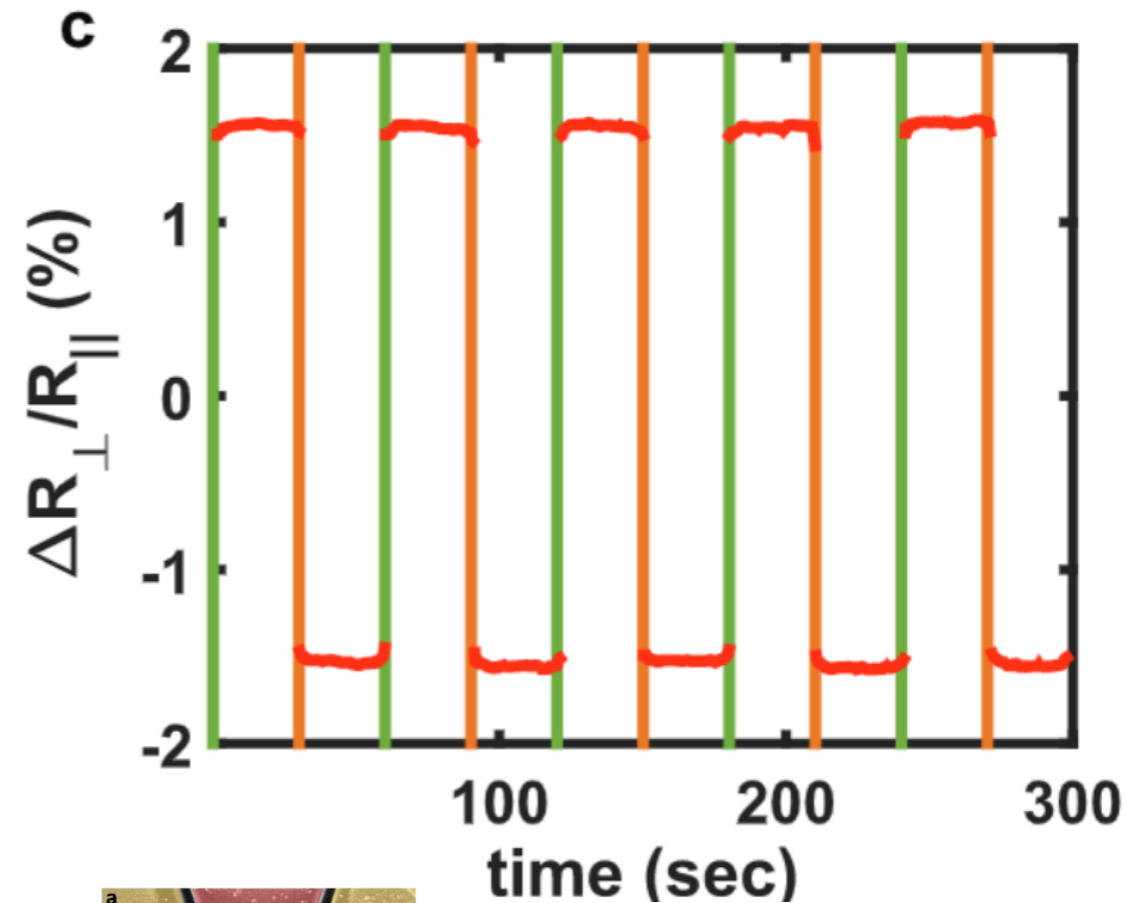
Vacancies

$x = 0.31$

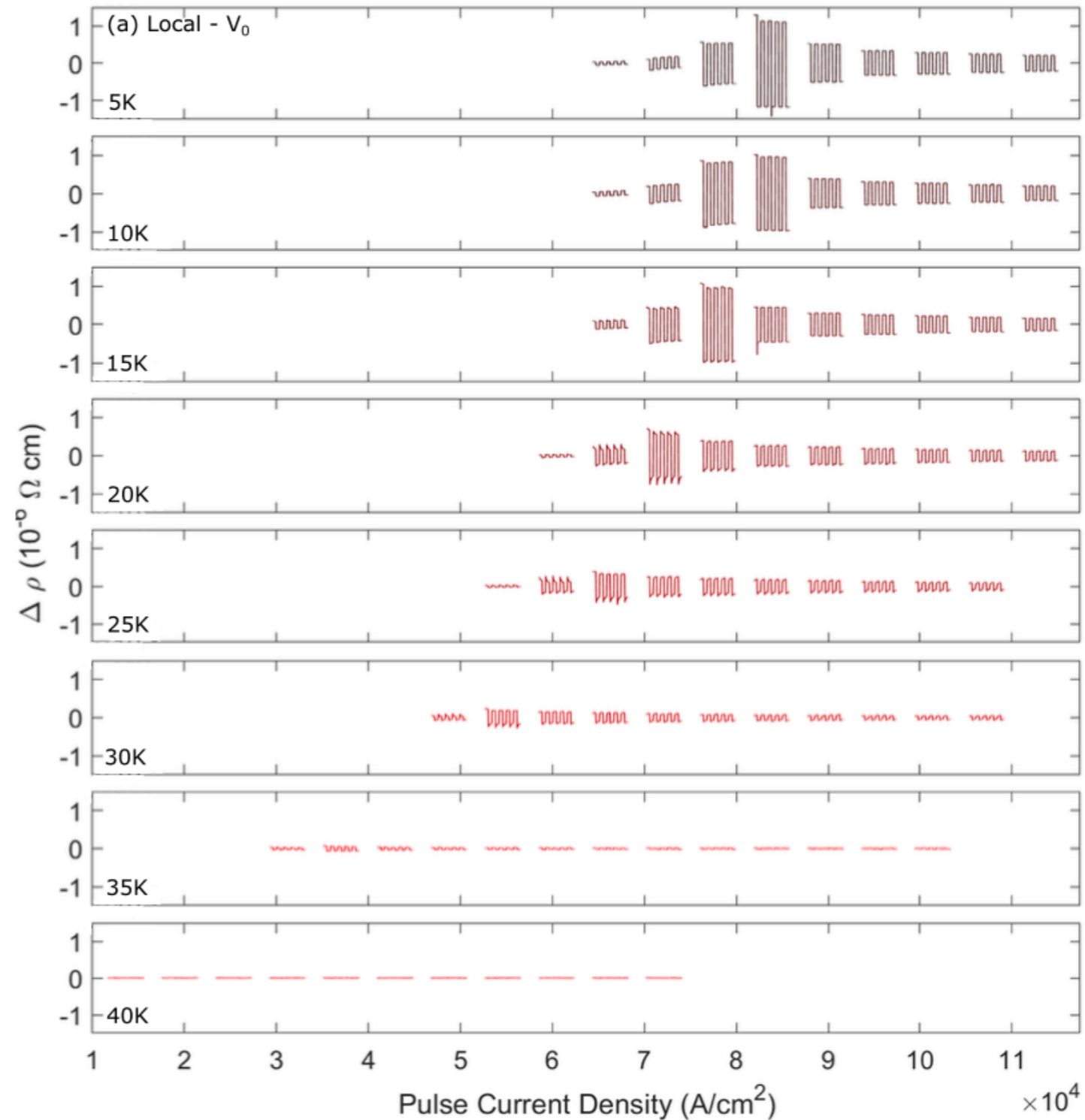


Interstitials

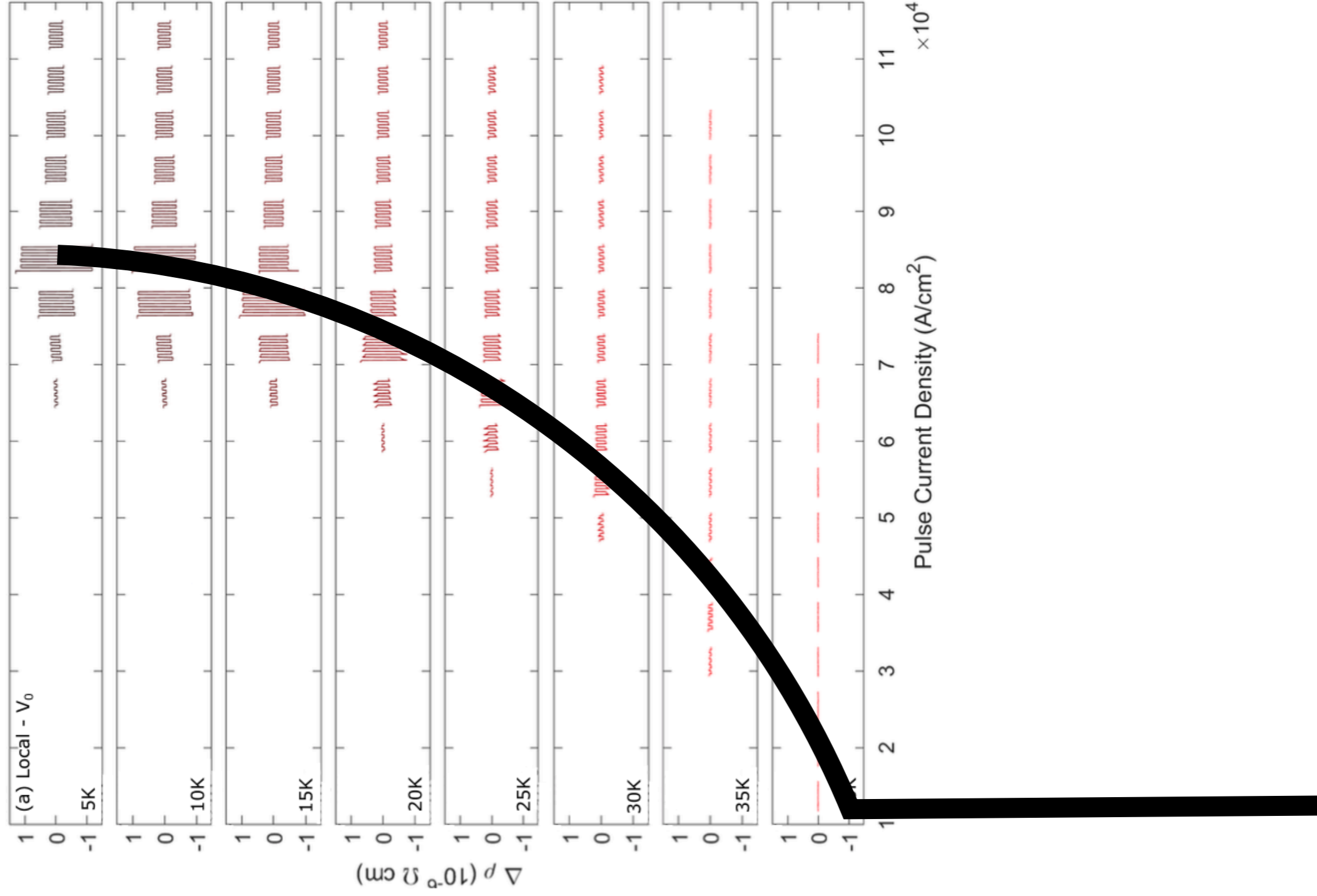
$x = 0.35$



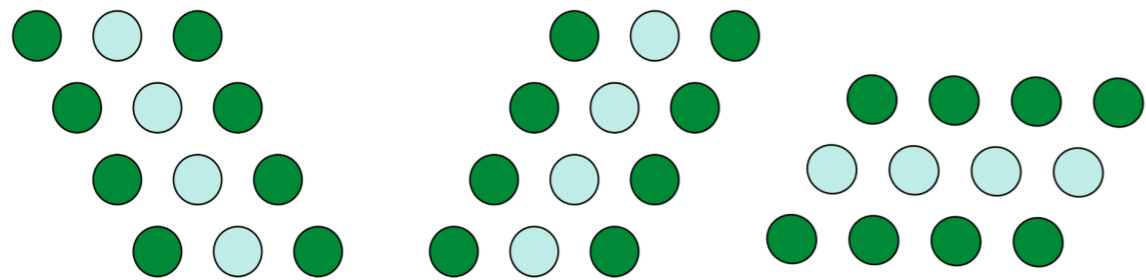
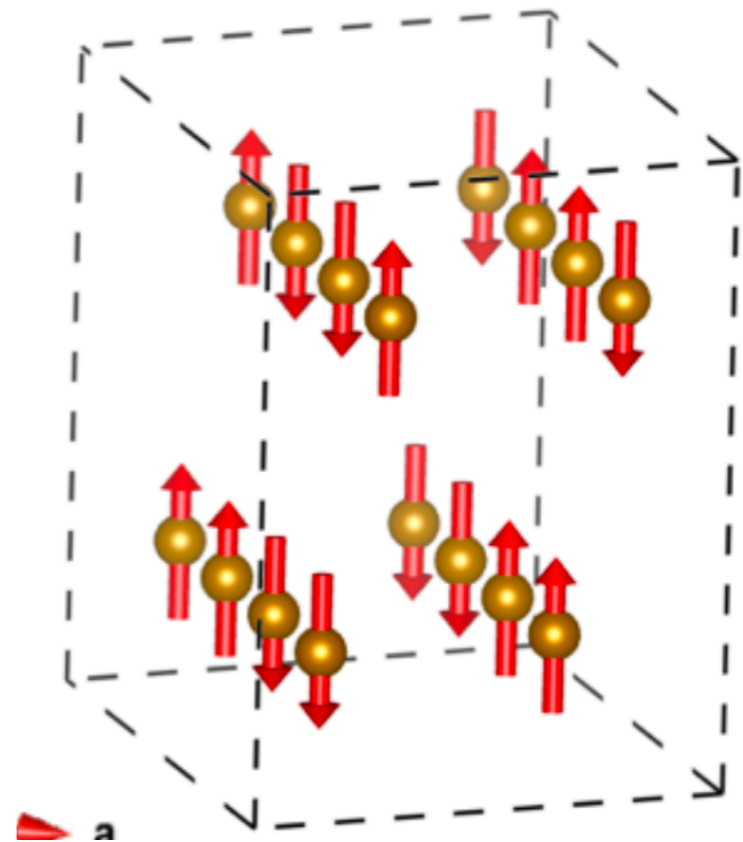
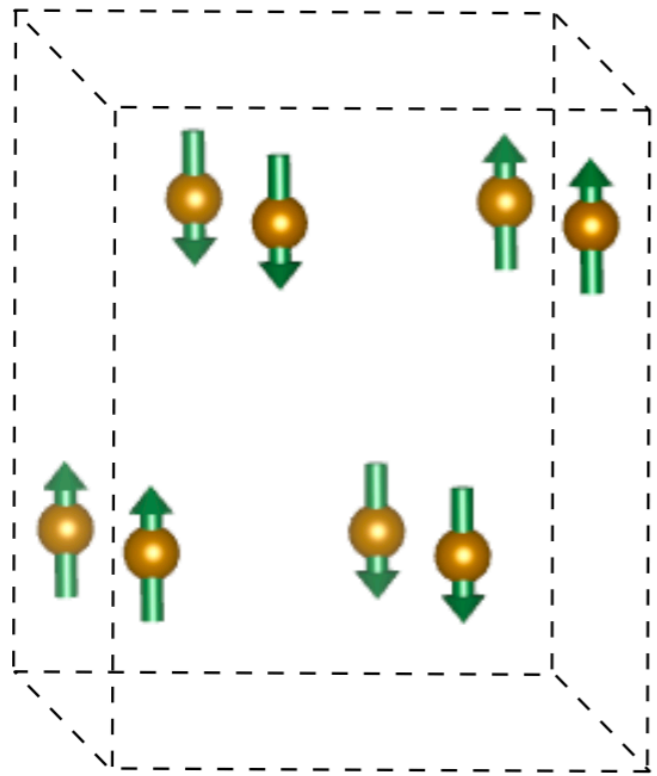
Anomalous switching



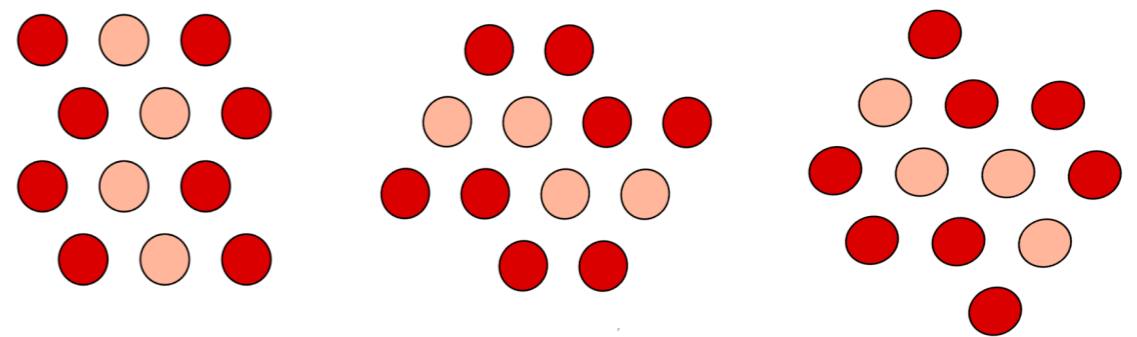
Anomalous Switching



Nearly degenerate magnetic orders

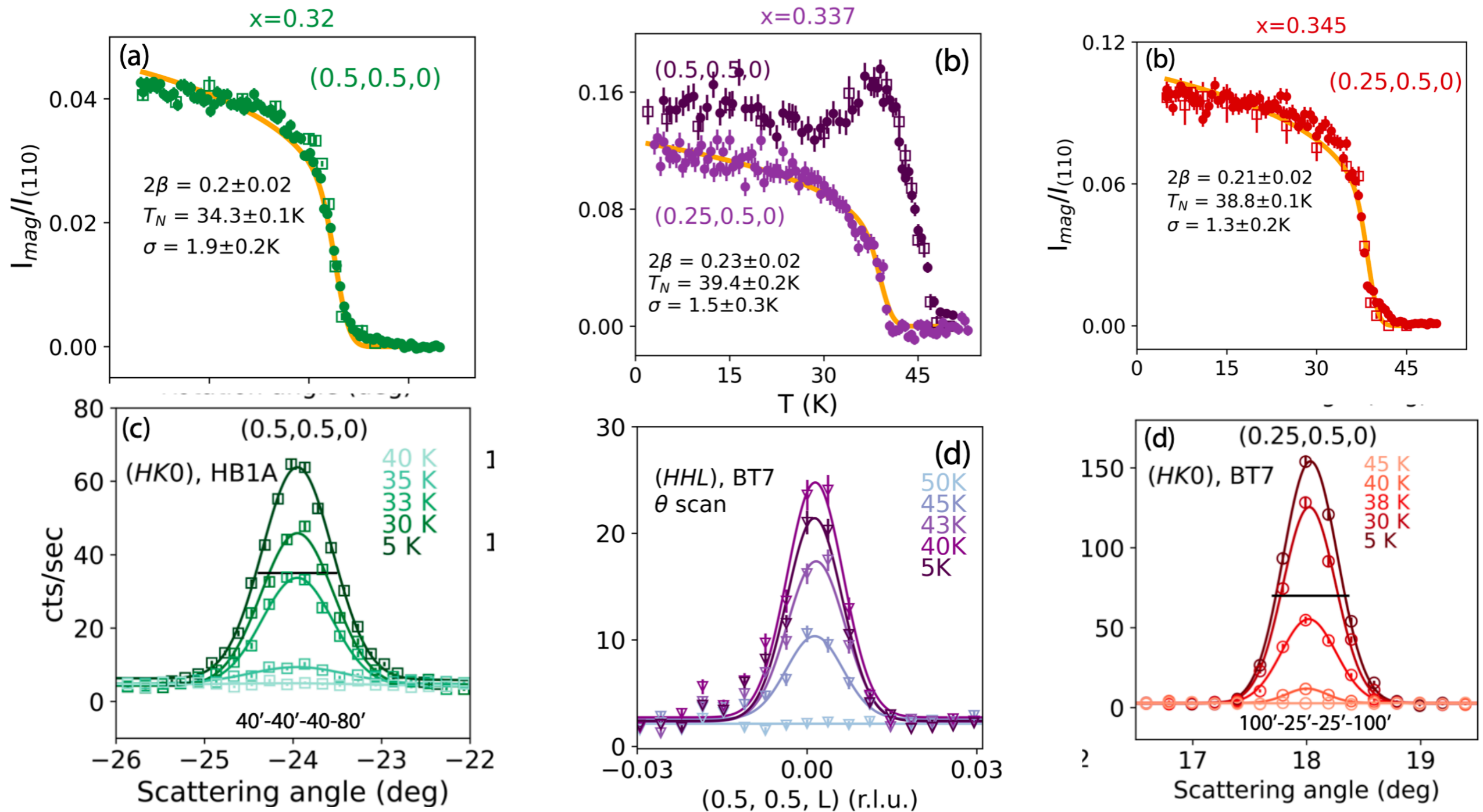


Stripe order

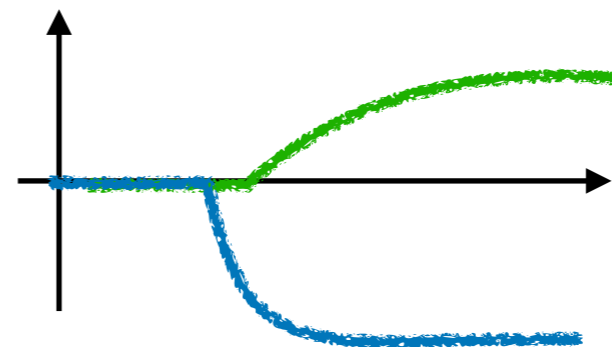
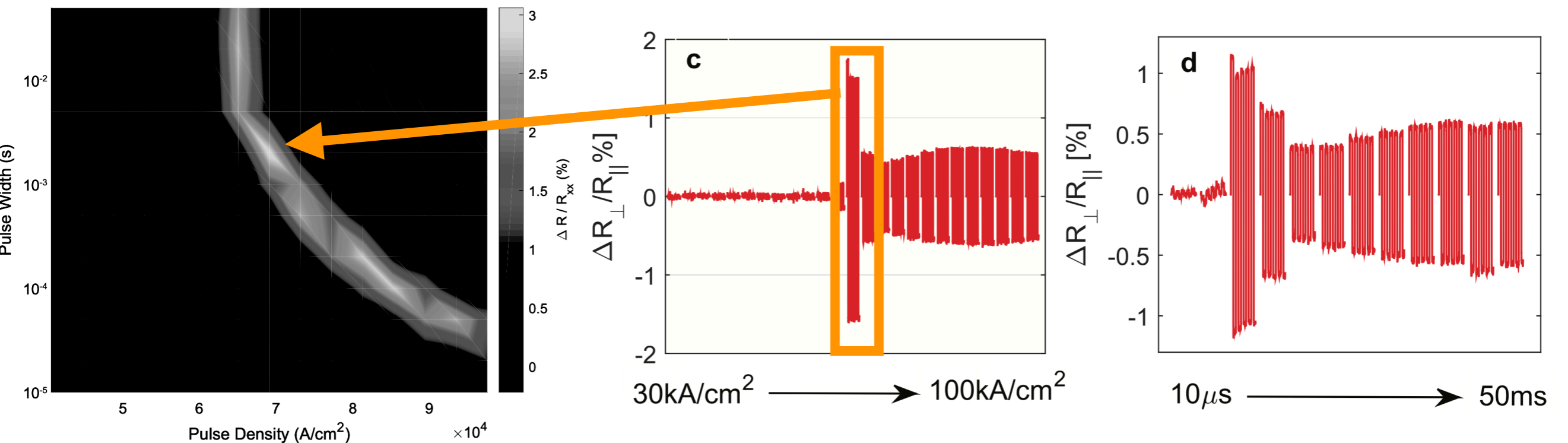


Zig-Zag order

Evolution of the magnetic structure



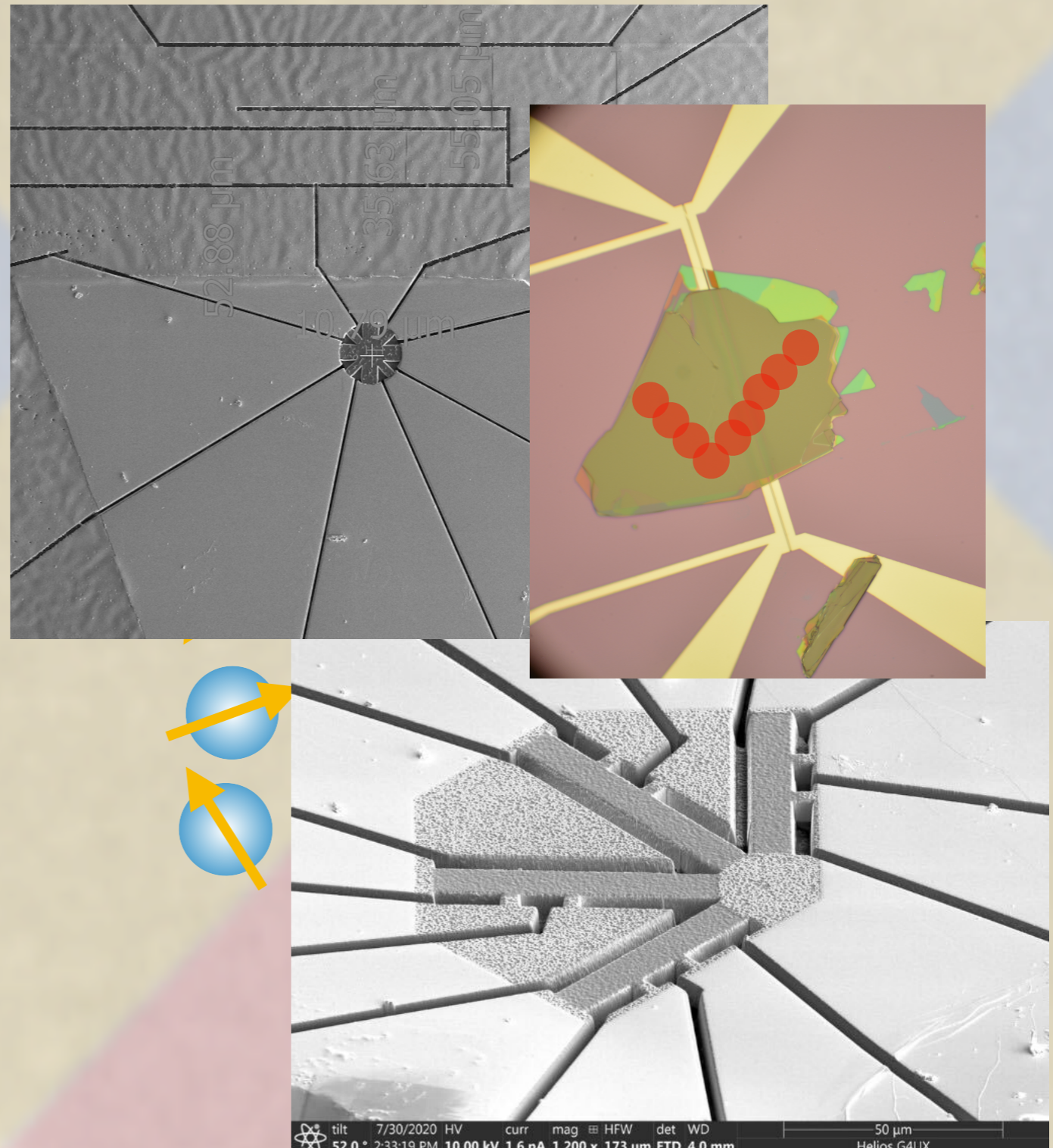
Anomalous current dependence

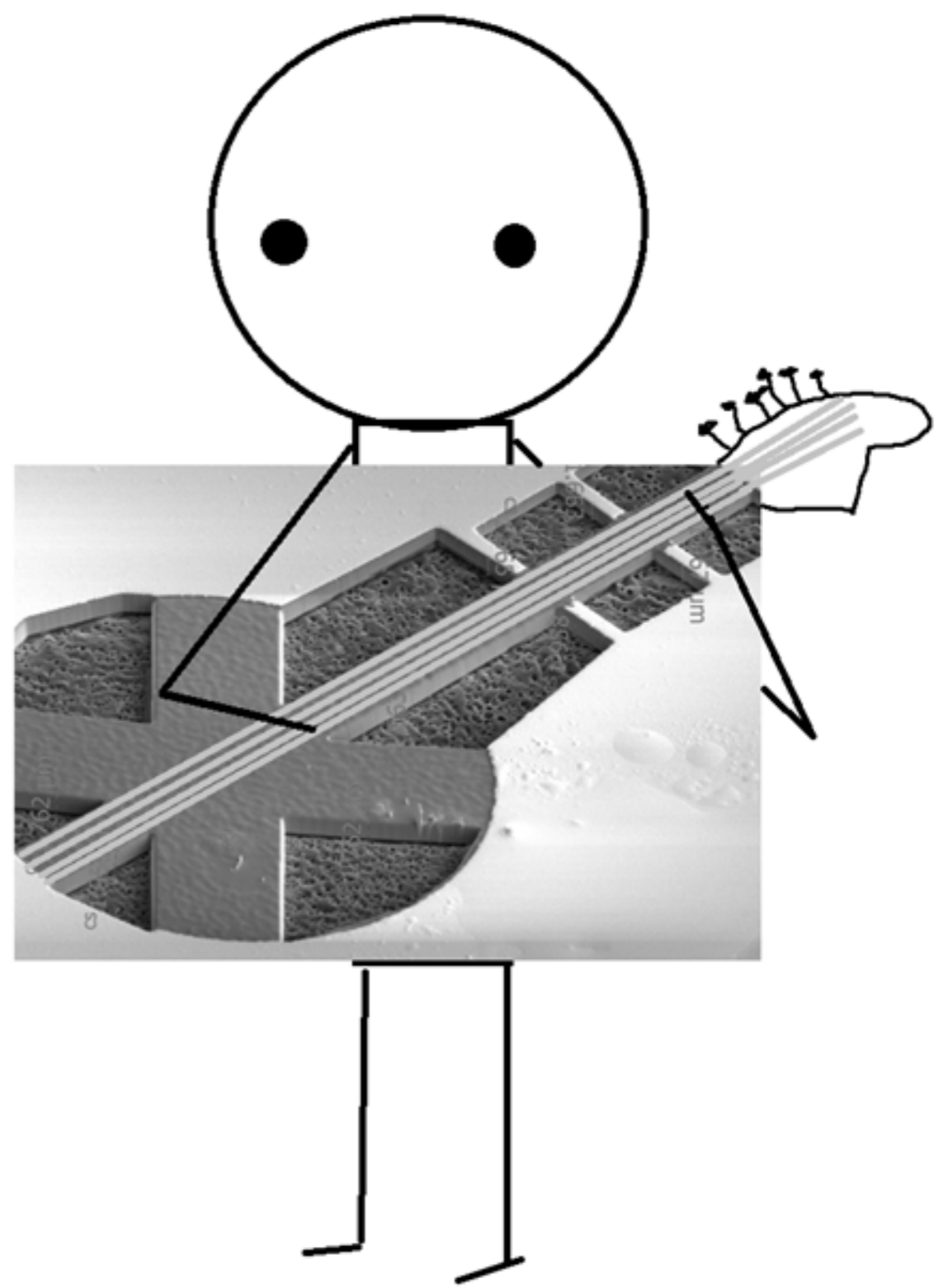


Can be naturally explained by the presence of two order parameters

Summary

- Collective spin-glass dynamic appears to facilitate the better spin transport into the AFM.
- Nearly order degenerate order parameters lead to highly tunable switching with unusual current/pulse width dependence.
- Lots of open questions remain. For example, the magnetic order is entirely in-plane, why is there single pulse saturation?





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