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ANTIFERROMAGNETIC SKYRMIONICS

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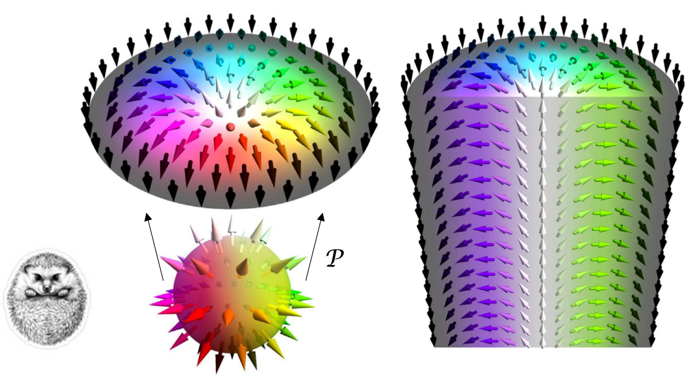
SPICE SPIN+X – NOV 2021

SKYRMIONS

$$\hat{n}(\boldsymbol{r}) = [\sin\theta(r)\cos\phi\,,\ \sin\theta(r)\sin\phi\,, \cos\theta(r)]$$



Courtesy: B. Göbel et al. (Physics Rep 2021)

$$Q = \frac{1}{4\pi}\iint d^2\boldsymbol{r}\,\underbrace{\hat{n}\cdot\left[\frac{\partial\hat{n}}{\partial x}\times\frac{\partial\hat{n}}{\partial y}\right]}_{\text{Solid Angle}}$$

Solid Angle

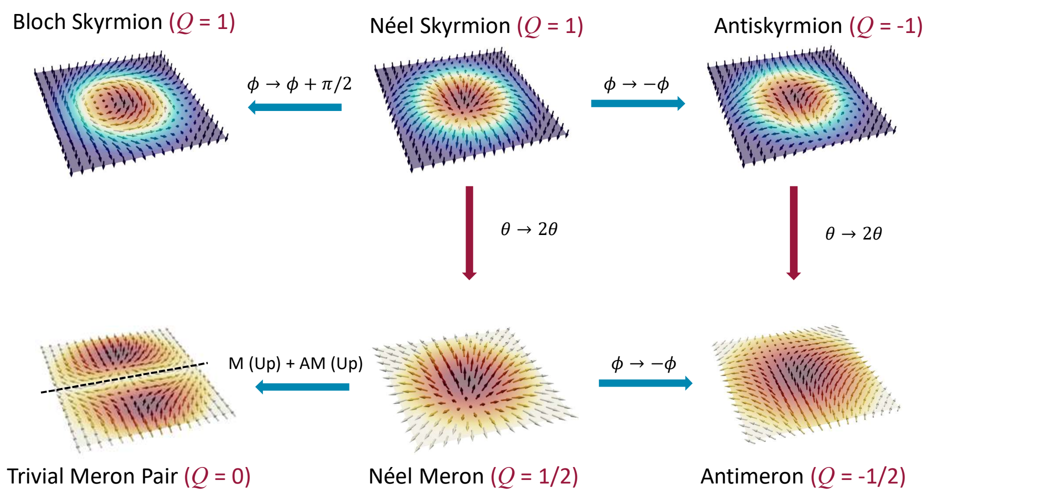
Q = 1 (wrapping a unit sphere)

Q = 1/2 (wrapping a unit hemi-sphere)

.
.
.

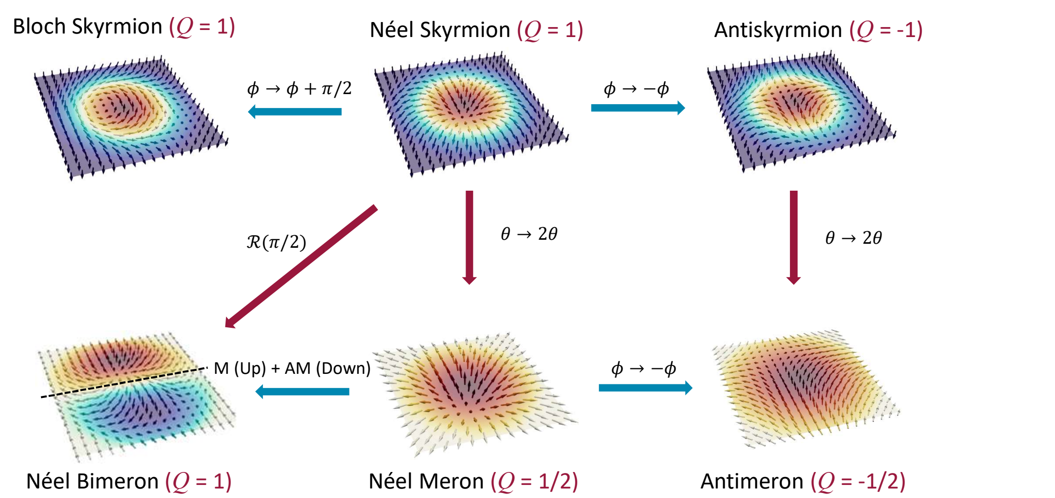
TOPOLOGICAL ZOO

$\hat{n}(\boldsymbol{r}) = [\sin\theta(r)\cos\phi\,,\ \sin\theta(r)\sin\phi\,, \cos\theta(r)]$



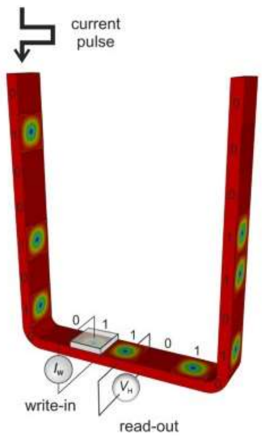
TOPOLOGICAL ZOO

$\hat{n}(\boldsymbol{r}) = [\sin\theta(r)\cos\phi\,,\ \sin\theta(r)\sin\phi\,, \cos\theta(r)]$



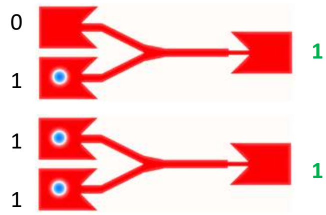
WHY SKYRMIONICS?

Racetracks

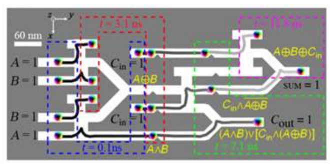


S Parkin et al., Science **320** (2008)
S Zhang et al., Sci Rep **5** (2015)

Logic-in-Memory

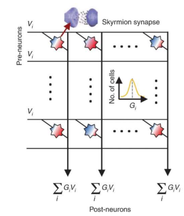


X Zhang et al., Sci Rep **5** (2015)

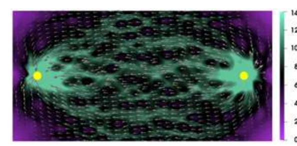


M Chauwin et al., PRA **12** (2019)

Neuromorphic/Reservoir Computing



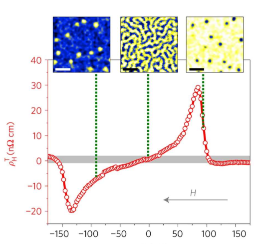
KM Song et al., Nat Elec **3** (2020)



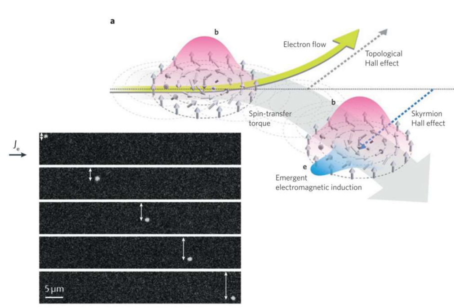
G Bourianoff et al., AIP Adv **8** (2018)

DRAWBACKS OF FM SKYRMIONICS

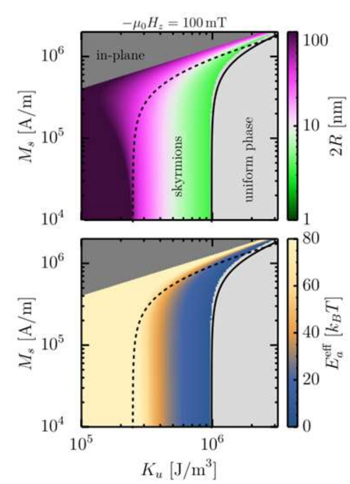
- × **Susceptible to external magnetic fields**
- × **Skyrmion Hall effect (gyromagnetic torques)**
- × **Strong dipolar fields limit scaling**



Soumyanarayanan, A. et al. Nat Mat **16** (2017)



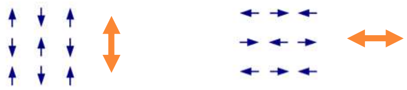
Jiang, W. et al. Nat. Phys **13** (2016)
Litzius K., et al. Nat. Phys **13** (2016)



Buttner, F. et al. Sci. Rep. **8** (2018)

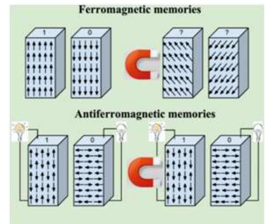
ENTER ANTIFERROMAGNETS

- Order Parameter is **Néel Vector** not Magnetization:



$$\vec{L} \equiv \vec{M}_1 - \vec{M}_2$$

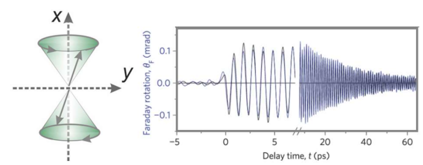
- Therefore they cannot be influence by stray fields:



- Exchange Amplification of AFM Dynamics

ω_{AFM} ~ **0.1-10 THz**

Baltz et al., Rev Mod Phys **90** (2018)



Kampfrath et al., Nat Phot **5** (2011)

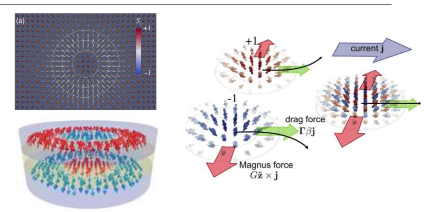
AFM SKYRMIONICS

☑ **Evolution/stabilization without fields**

☑ **No transverse deviations for Néel objects**

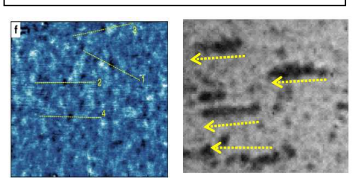
☑ **Absence of dipolar fields allows down-scaling**

☑ **Ultrafast current driven motion**

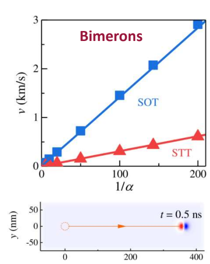


J Barker et al., PRL **116** (2016); Zhang et al., Nat Commun **7** (2016)

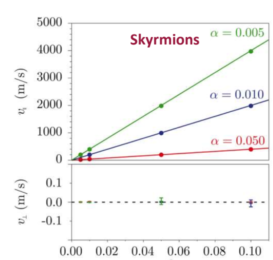
Skyrmions in Synthetic AFMs



W Legrand et al., Nat Mater **19** (2020)
T Dohi et al., Nat Commun **10** (2019)



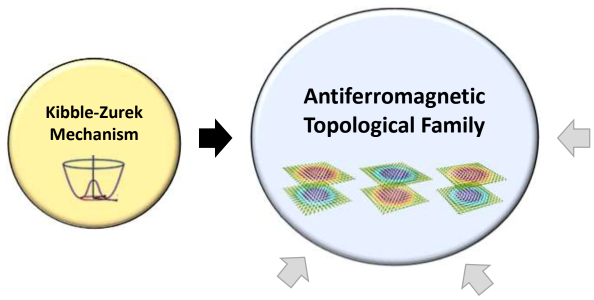
L Shen et al., PRL **124** (2020)



$$v \propto \frac{j}{\alpha}$$

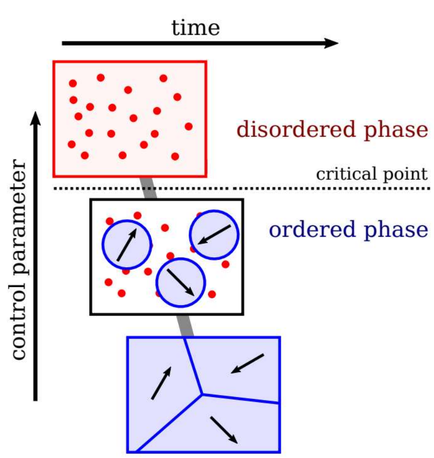
H Velkov et al., New J Phys **18** (2016)
C Jin et al., APL **109** (2016)
A Salimath et al., PRB **101** (2020)

DISCOVERY & CONTROL

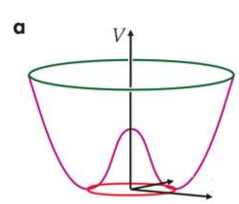


H Jani, et al. Nature **590** (2021)

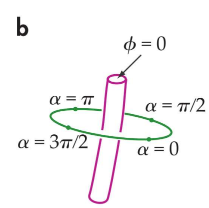
KIBBLE-ZUREK QUENCH



Courtesy: S. Donadello (PhD dissertation, 2016)



'Mexican Hat' Potential



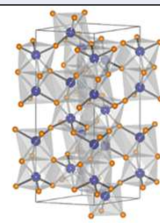
Topological defect

Observed in:
- Liquid crystals
- BECs
- Multiferroics…

Kibble, J. Phys. A **9** (1976)
Zurek, Nature **317** (1985)
Kibble, Phys Today **47** (2007)

KEY MATERIAL REQUIREMENTS

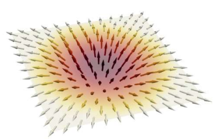
Properties	Benefits	α-Fe_2O_3
Fully/Significantly compensated magnetic sublattice	More robust against perturbations	Weakly Canted AFM
	Weakened dipolar interactions	
Easy-plane Anisotropy	Favor U(1)-like symmetry	RT State
Accessible Phase transition	Perform Kibble-Zurek Quench	Néel & Morin
Low Gilbert Damping (α)	Unlock ultrafast dynamics	10^{-4}
Correlated degrees of freedom	Tunable via external perturbations	Spin-charge-lattice
Spin Injection via currents	Current-driven motion	Pt overlayer



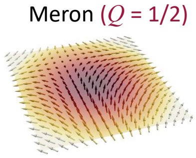
α-Fe_2O_3

FJ Morin, Phy Rev **78** (1950)
AH Morrish, World Scientific (1994)
R Lebrun et al., Nature **561** (2018)
R Lebrun et al., Nat Commun **11** (2020)
T Nakau, J Phys Soc Japan **15** (1960)
L Carneiro, Nat Mater **16** (2017)

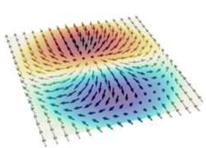
SIMULATING KIBBLE-ZUREK



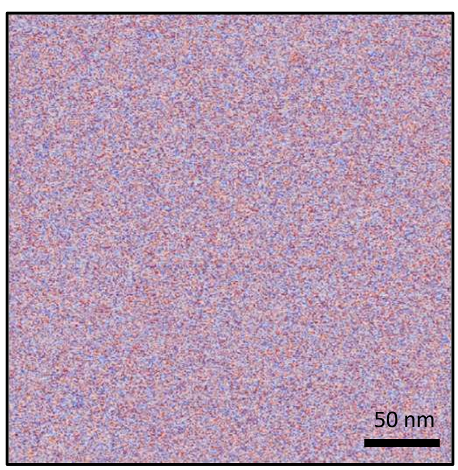
Meron (Q = 1/2)



Antimeron (Q = -1/2)



Bimeron (Q = 1)

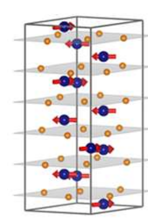


Time Steps: 500 fs

Top Layer M_z

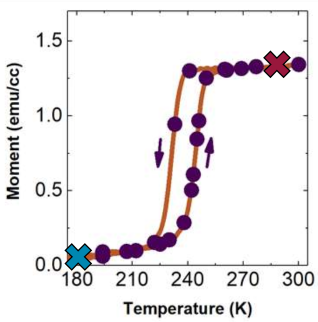
Atomistic Simulations

J Chen



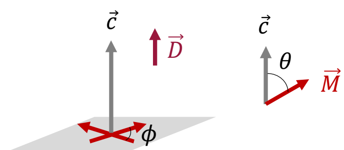
(A, K_{eff})

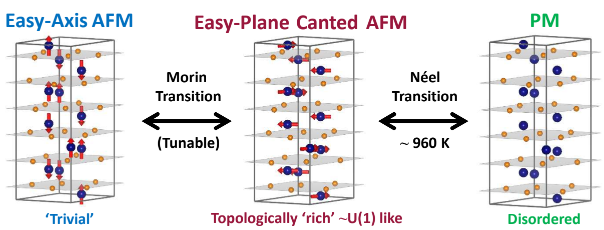
MORIN TRANSITION



$$F_{TOT} = F_{EX} + F_{DMI} + F_{MC} + \cdots$$

$$F_{MC} = K_1 \sin^2 \theta$$

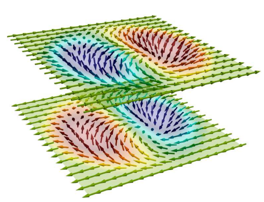




Magnetic Dipolar: $K_{MD} = K_{MD}^{0} \langle S_z \rangle^2 < 0$ **In-Plane**

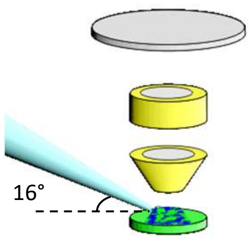
Single-Ion: $K_{SI} = K_{SI}^{0} \langle S_z^2 \rangle > 0$ **Out-of-Plane**

Artman, et al. Phys Rev **138** (1965)



EXPERIMENTAL TECHNIQUES

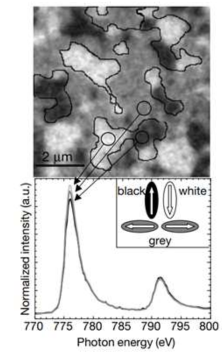
HOW TO IMAGE AFM ORDER?



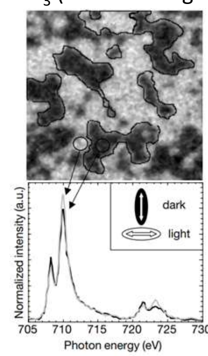
Courtesy: ALS PEEM Tutorial

X-ray Photoemission Electron Microscopy

Co (Ferromagnet)



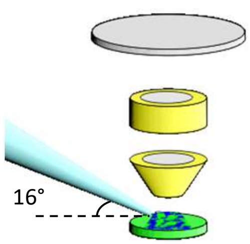
$LaFeO_3$ (Antiferromagnet)



	Co (Ferromagnet)	$LaFeO_3$ (Antiferromagnet)
Polarization:	Circular	Linear
Process:	1^{st} order	2^{nd} order
Order Parameter:	$\vec{M}$	$\vec{L}$

F Nolting, et al. Nature **405** (2000)
A Scholl et al, Science **287** (2000)

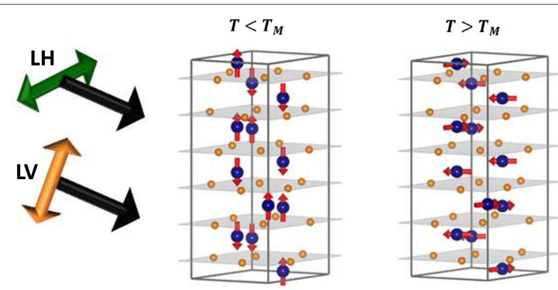
AFM VECTOR MAPPING



Courtesy: ALS PEEM Tutorial

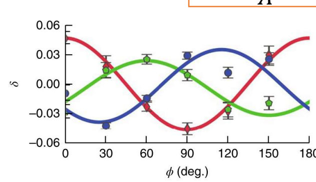
X-ray Photoemission Electron Microscopy

Also works with
X-ray Transmission Microscopy & Holography



PG Radaelli Group

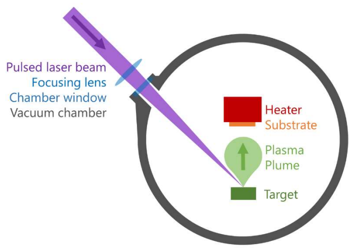
$$I = I_A + I_B \cos^2 \phi$$



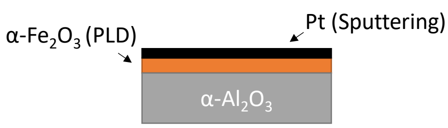
F Nolting, et al. Nature **405** (2000)
A Scholl et al, Science **287** (2000)

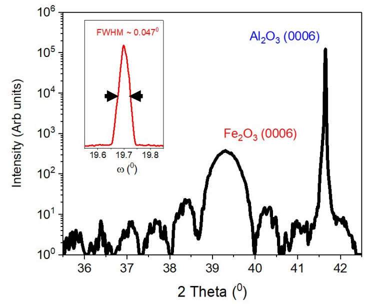
FP Chmiel et al. Nat Mater **17** (2018)
NW Price et al., PRL **117** (2016)

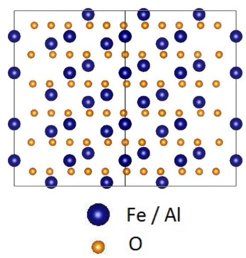
SAMPLE GROWTH

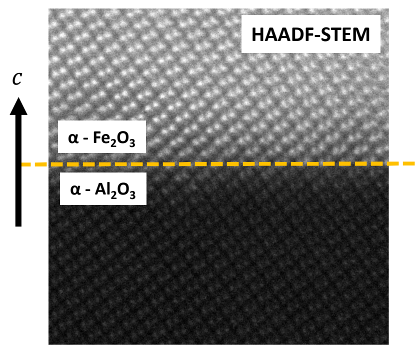


Courtesy: Wiki Tedsanders (2016)



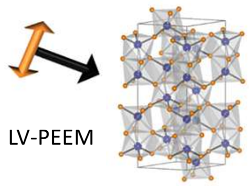


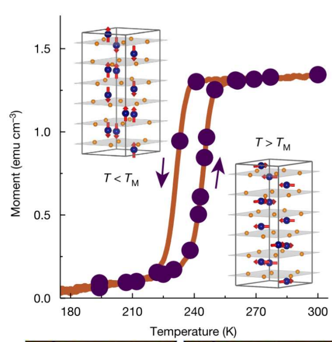


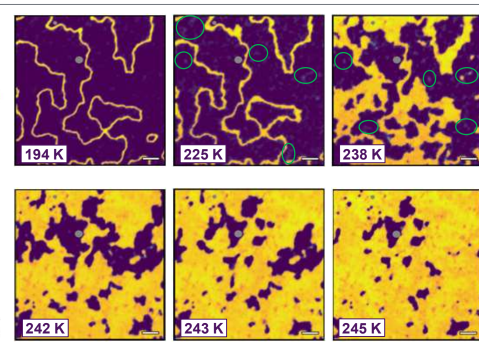


H Jani et al., Nat Commun **12**, 1668 (2021)

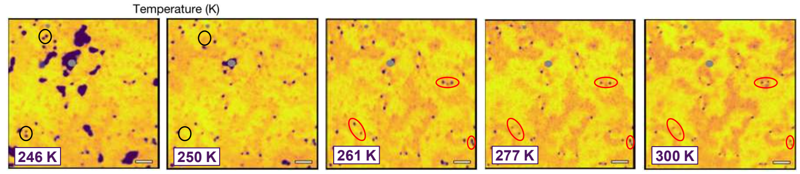
KIBBLE-ZUREK TRANSITION





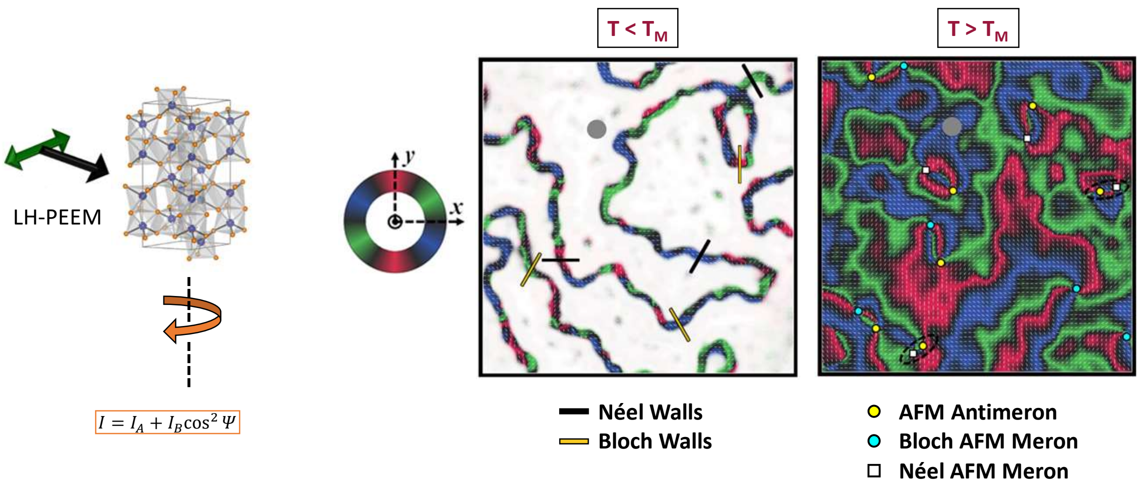


Yellow/Orange – In-Plane
Purple – Out-of-Plane

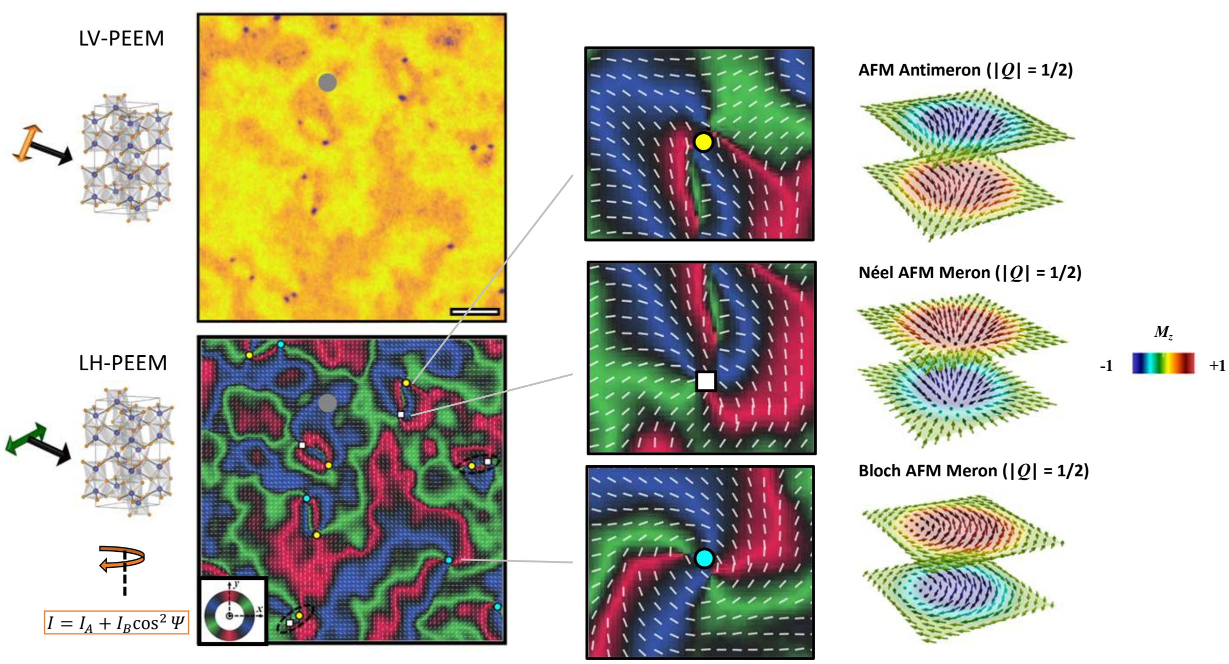


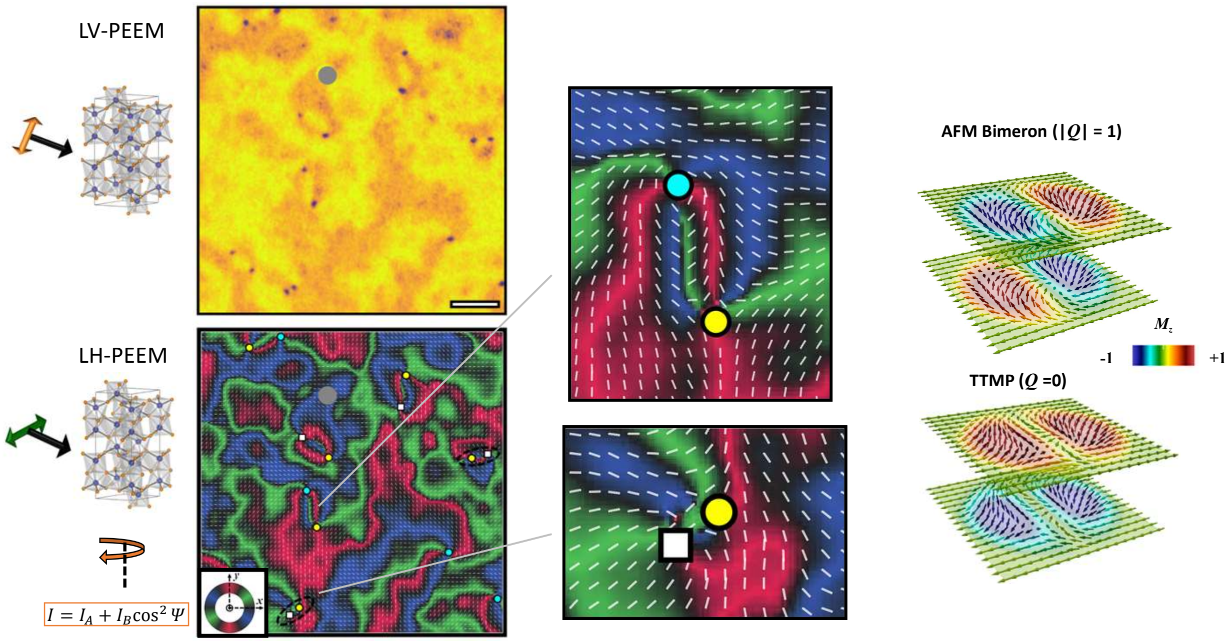
H Jani et al., Nature **590**, 74 (2021)

KIBBLE-ZUREK TRANSITION

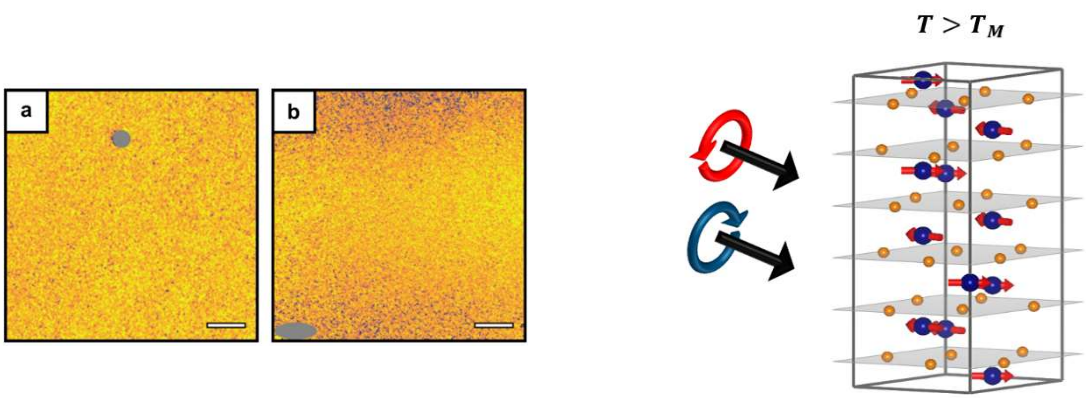


H Jani et al., Nature **590**, 74 (2021)

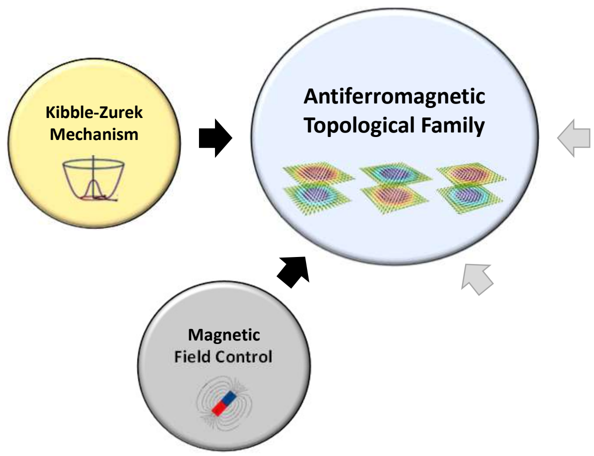




ABSENCE OF XMCD CONTRAST

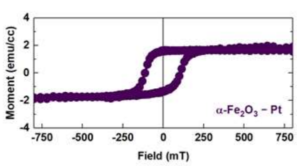


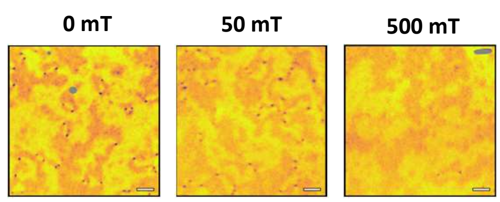
DISCOVERY & CONTROL



H Jani, et al. Nature **590** (2021)

MAGNETIC FIELD CONTROL

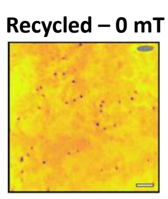




Field applied ex-situ

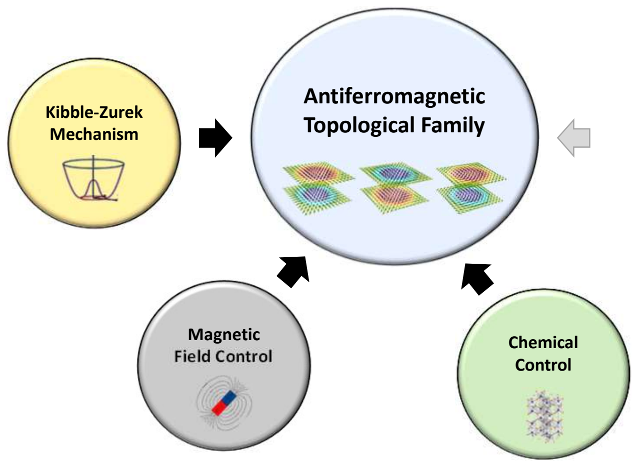
Imaged in Remanence

Annihilation of textures



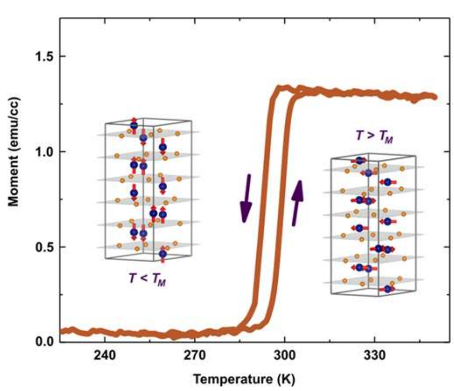
Regeneration of textures

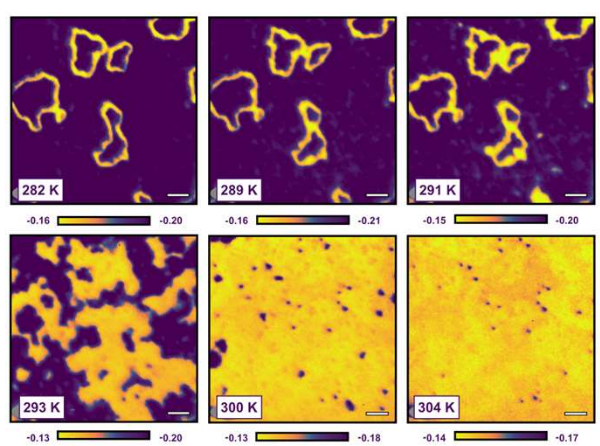
DISCOVERY & CONTROL



H Jani, et al. Nature **590** (2021)

NUCLEATING TEXTURES AT ROOM TEMP

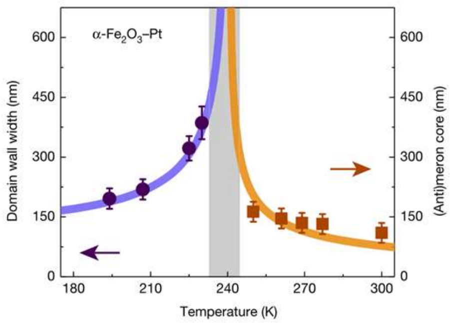




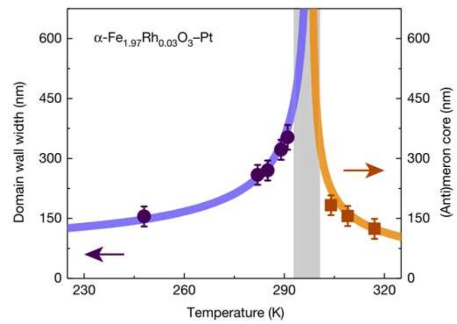
Tuning T_M via doping : Rh-substituted α-Fe_2O_3

H Jani et al., Nature **590**, 74 (2021)

CONTROL OF TEXTURE DIMENSIONS



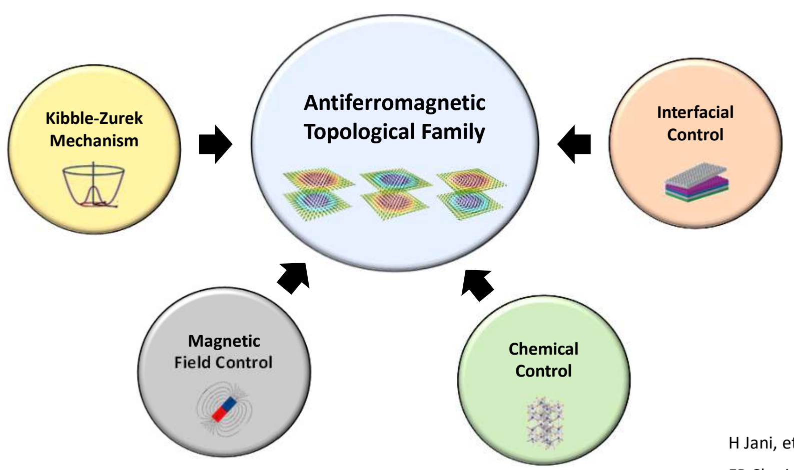
Rh doping



Core size of (anti)merons

$$R = \frac{4}{3}\sqrt{\frac{2\pi^2}{(\pi^2-4)}\frac{A_{ex}}{|K|}}$$

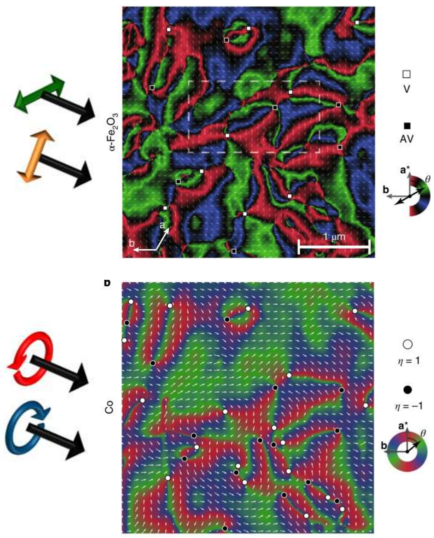
DISCOVERY & CONTROL

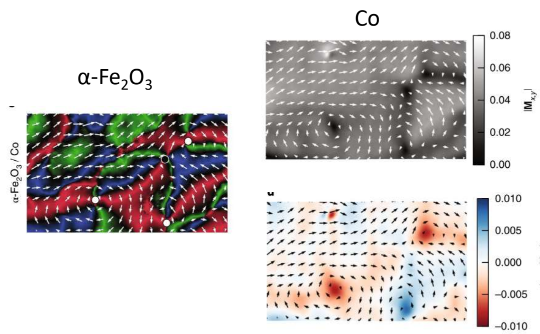


H Jani, et al. Nature **590** (2021)

FP Chmiel et al., Nat Mater **17** (2018)

INTERFACIAL CONTROL

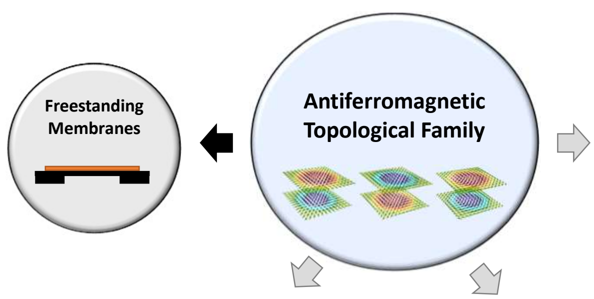




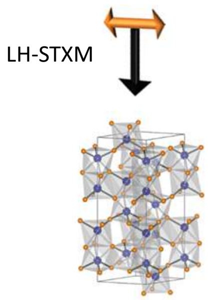
Imprinting textures by exploiting interfacial exchange

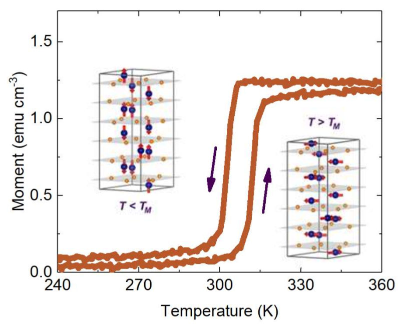
FP Chmiel et al., Nat Mat **17**, 581 (2018)

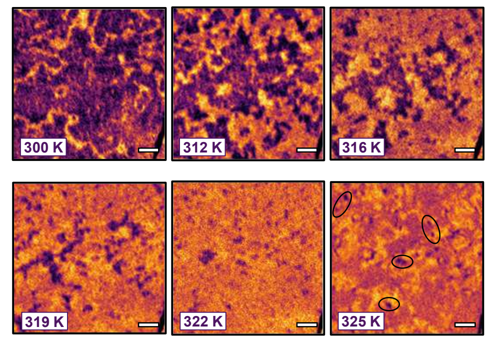
WHAT LIES AHEAD?



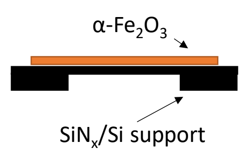
AFM TEXTURES ON MEMBRANES



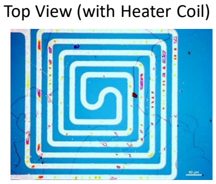




Yellow/Orange – In-Plane
Purple – Out-of-Plane



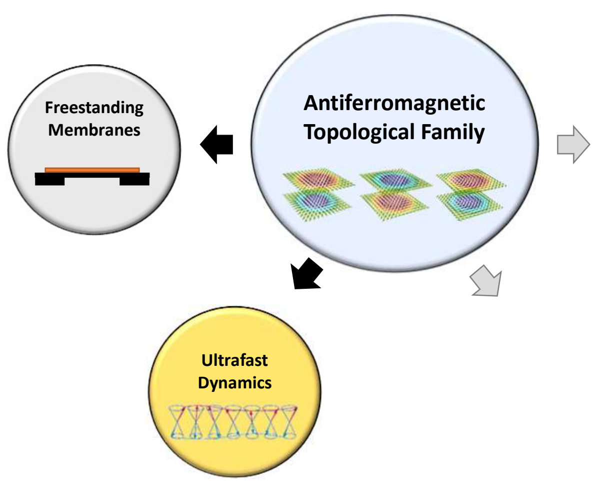
Top View (with Heater Coil)



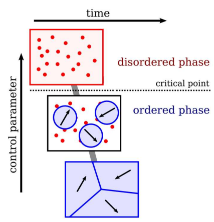
Membranes can be transferred to desired platforms **(Si-compatible)**

H Jani et al., (To be submitted)

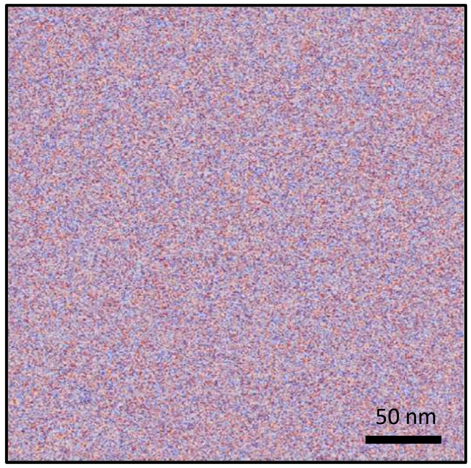
WHAT LIES AHEAD?



REVISITING KIBBLE-ZUREK



Courtesy: S. Donadello
(PhD dissertation, 2016)

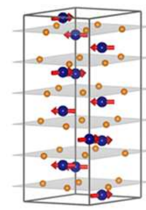


Time Steps: 500 fs

Top Layer
M_z

Atomistic Simulations

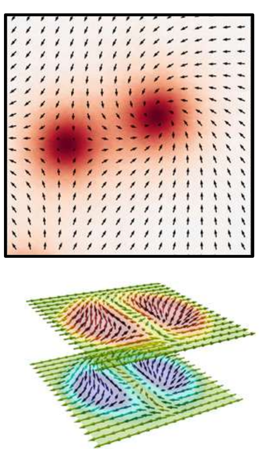
J Chen



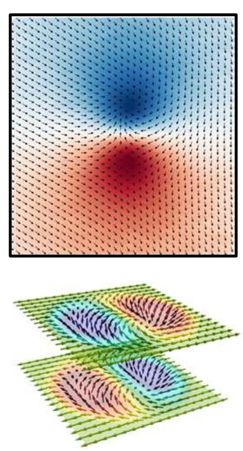
(A, K_{eff})

REVISITING KIBBLE-ZUREK

Emission of Ultra-fast ~1-10 THz spin-waves



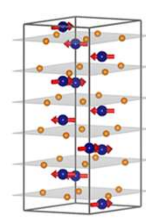
Trivial Meron Pair (Q = 0)



Bimeron Pair (Q = 1)

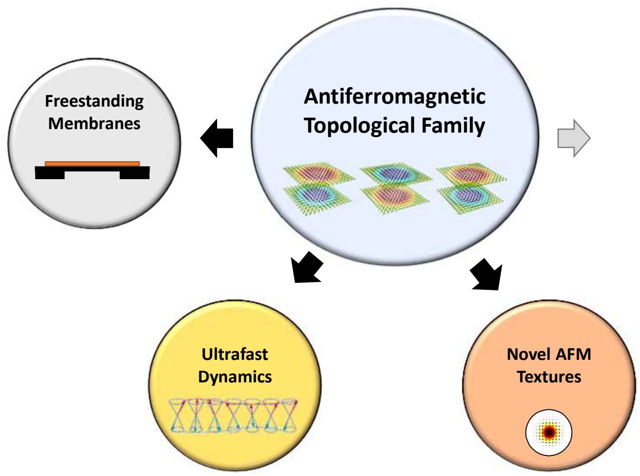
Atomistic Simulations

J Chen

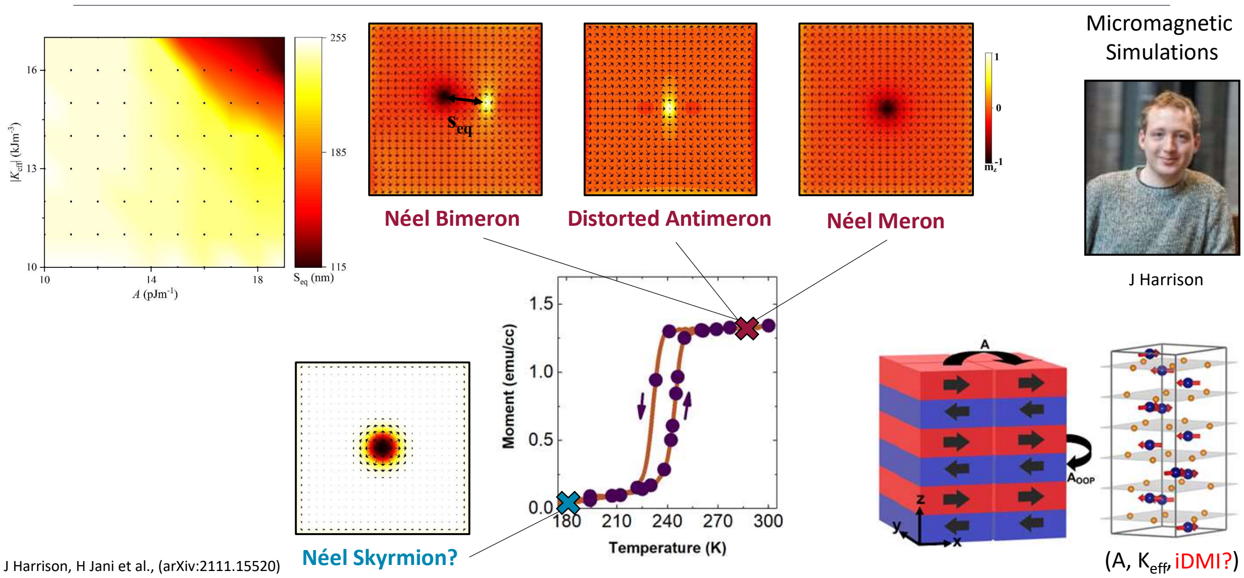


(A, K_{eff})

WHAT LIES AHEAD?

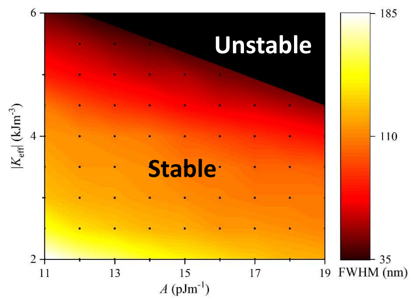


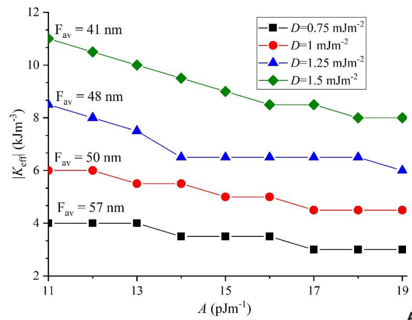
NOVEL AFM TEXTURES



J Harrison, H Jani et al., (arXiv:2111.15520)

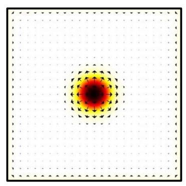
NOVEL AFM TEXTURES

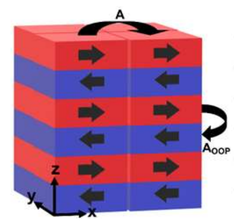


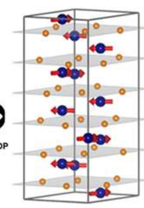


Micromagnetic Simulations

J Harrison





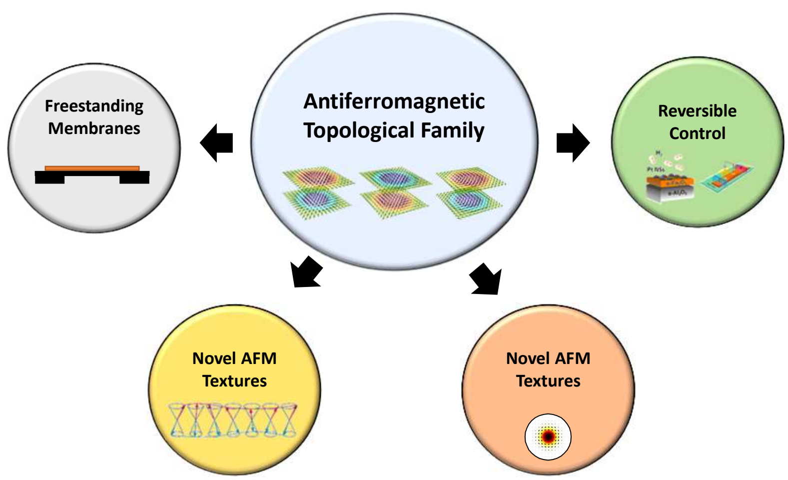


J Harrison, H Jani et al., (arXiv:2111.15520)

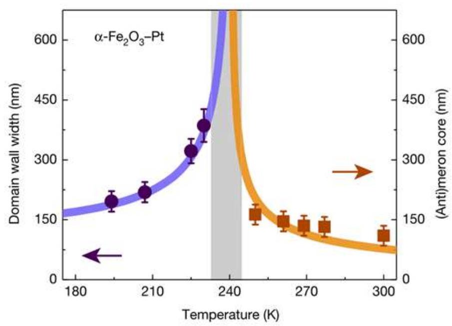
Néel Skyrmion

(A, K_{eff}, iDMI)

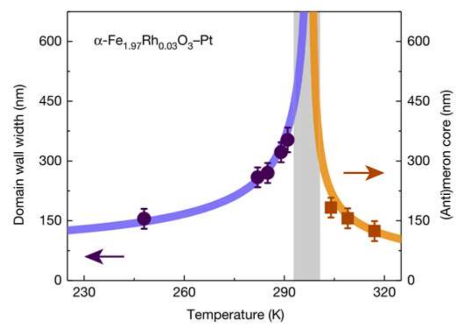
WHAT LIES AHEAD?



CHEMICAL CONTROL



Rh doping

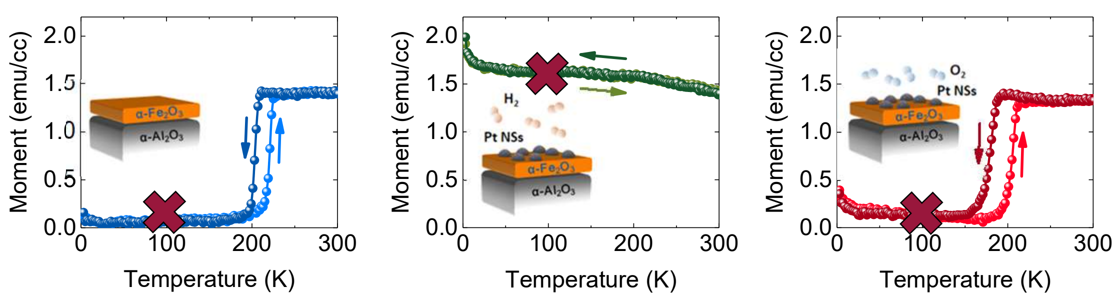


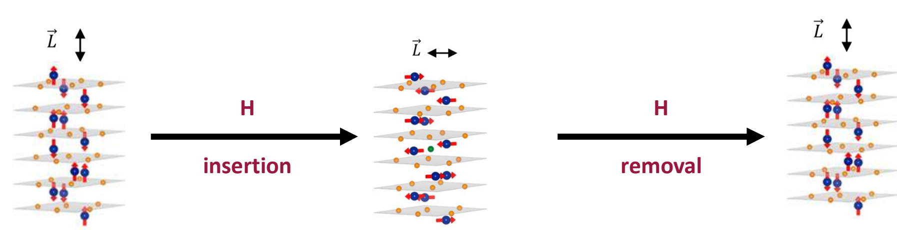
Core size of (anti)merons

$$R = \frac{4}{3}\sqrt{\frac{2\pi^2}{(\pi^2-4)}\frac{A_{ex}}{|K|}}$$

Possible to realize reversible chemical control?

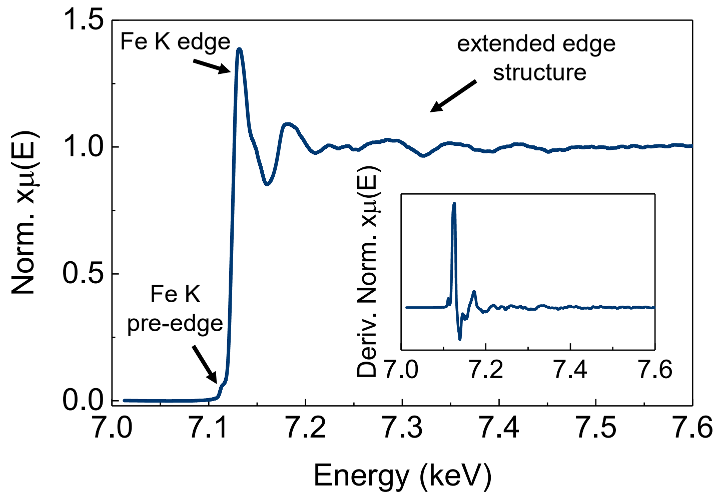
REVERSIBLE IONIC CONTROL





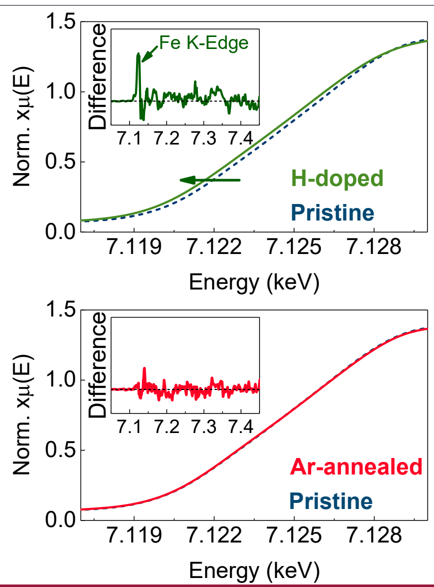
H Jani et al., Nat Commun **12**, 1668 (2021)

ELECTRONIC STRUCTURE: FE K-EDGE



H Jani et al., Nat Commun **12**, 1668 (2021)

H ACTS AS AN ELECTRON DONOR



$$Fe^{3+} \xrightarrow[H]{\delta e^-} (1-\delta)Fe^{3+} + \delta Fe^{2+}$$

$$H \xrightarrow{\delta e^-} O \xrightarrow{\delta e^-} Fe$$

Sample	Fe-K Edge Red-Shift (eV)	Fe^{2+} species (at%)	H-dopants (at%)
Hyd-Treated	0.23 ± 0.02	2.4 ± 0.2	2.47
Ar-Treated	0.03 ± 0.02	0.3 ± 0.2	0.7

H-ions drive an electronic doping effect!

H Jani et al., Nat Commun **12**, 1668 (2021)

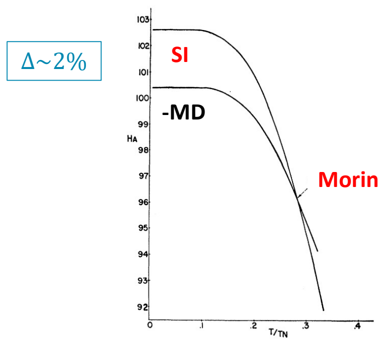
FINE TUNING OF THE MORIN TRANSITION

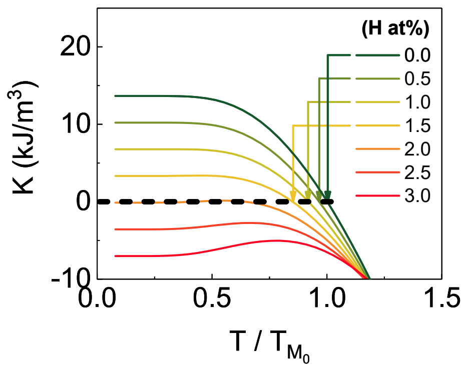
Single-Ion: $K_{SI} = K_{SI}^{0}\left\langle S_z^2 \right\rangle > 0$ Out-of-Plane ↓

Magnetic Dipolar: $K_{MD} = K_{MD}^{0}\left\langle S_z \right\rangle^2 < 0$ In-Plane ↓

$$Fe^{3+} \xrightarrow[H]{\delta e^-} (1-\delta)Fe^{3+} + \delta Fe^{2+}$$

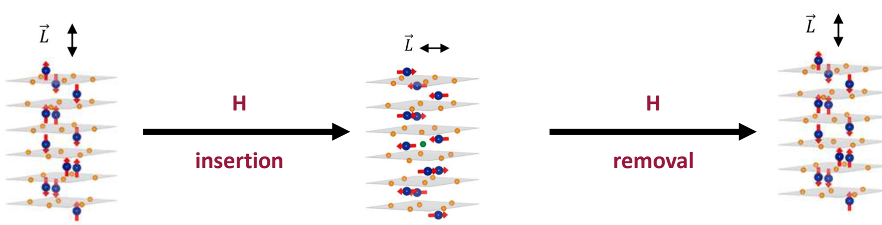
$3d^5$ $3d^6$





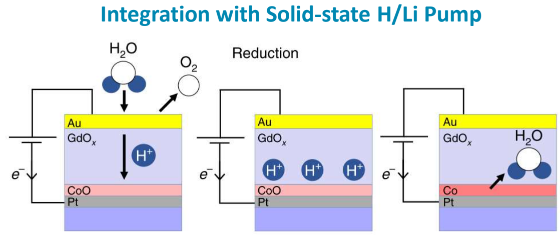
H Jani et al., Nat Commun **12**, 1668 (2021)

NON-VOLATILE FIELD CONTROL



H Jani et al., Nat Commun **12**, 1668 (2021)

Integration with Solid-state H/Li Pump

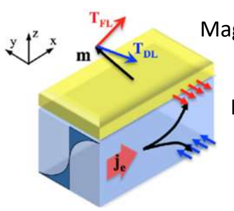


Tan AJ et al., Nat Mater **17** (2018)

Lee K-Y et al., Nano Lett **20** (2020)

ULTRAFAST CURRENT CONTROL

SHE-based Spin Torques

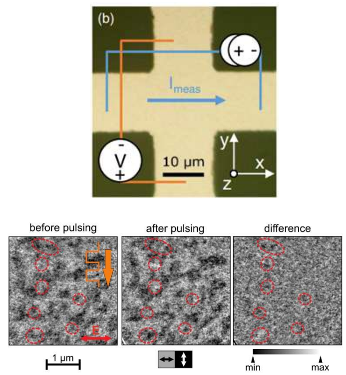


Magnetic Layer

Heavy-Metal

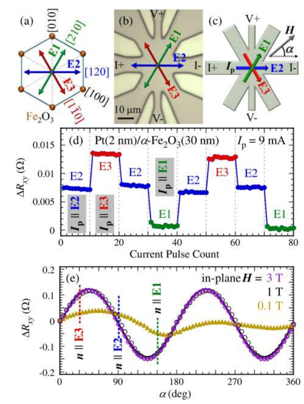
J Sinova et al., Rev Mod Phys **87**, (2015)
A Manchon et al., Rev Mod Phys **91** (2019)
O Gomonay et al., PRL **117** (2016)
T Shiino et al., PRL **117** (2016)

Pt | NiO



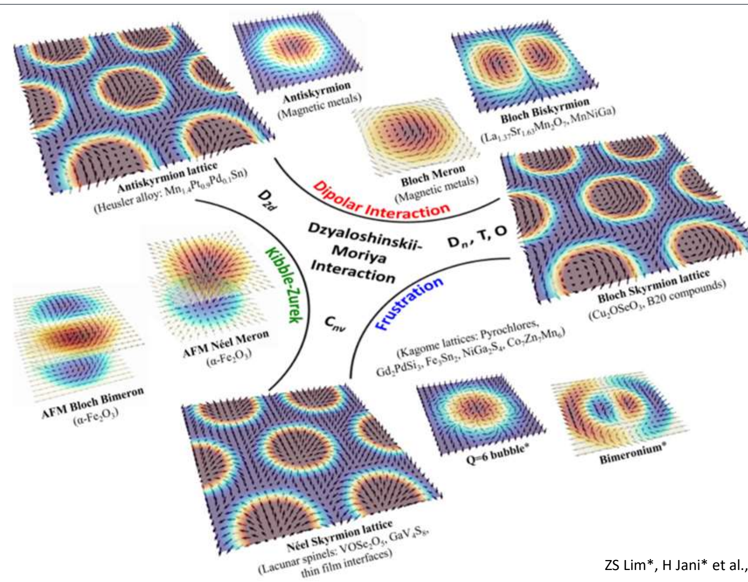
L Baldrati et al., PRL **123** (2019)

Pt | α-Fe_2O_3



Y Cheng et al., PRL **124** (2020)
P Zhang et al., PRL **123** (2019)

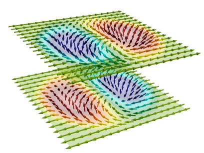
SKYRMIONICS IN CORRELATED OXIDES



ZS Lim*, H Jani* et al., MRS Bulletin (2021) arXiv:2111.10562

KEY TAKEAWAYS

- **α-Fe_2O_3 is a promising platform to build AFM Skyrmionics.**
- **Kibble-Zurek mechanism** can be used to **reversibly generate/destroy** AFM topological textures.
- Tunable **K** and **A** open up **unprecedented control** over texture dimensions and orientation.
- **Free-standing** α-Fe_2O_3 membranes enable **transfer to favourable Si-based platforms**.
- AFM dynamics helps unlock **ultrafast THz physics**.
- Introducing **iDMI** as an ingredient could enable stabilization of a **wide homochiral AFM family** (including Néel merons, bimerons and skyrmions).
- Presence of **correlated** spin-charge degrees opens the possibility of **electric control**.

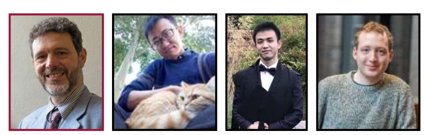


THANKS!

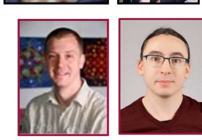
NATIONAL RESEARCH FOUNDATION
EPSRC

NUS Teams:
A Ariando, T Venkatesan, S Prakash, S Hooda, GJ Omar, J Hu, Manohar, ZS Lim, L Changjian, S Ghosh, S Pennycook.

Oxford Teams:
PG Radaelli, J-C Lin, J Harrison, J Chen, T Hesdejal.

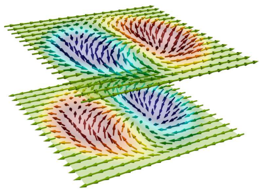


X-ray and Ion Teams:
F Maccherozzi (Diamond), S Finizio (PSI), M Foerster & MA Niño (ALBA), N Jaouen & P Horia (Soleil), R Chopdekar & E Arenholz (ALS), Y Ping, D Yonghua, A & K Banas (SSLS), S Ojha, G Umapathy & D Kanjilal (IUAC).



UWM Team:
C-B Eom, J Schad

Theory and ab-initio Teams:
JMD Coey (TCD-CRANN), L Jiajun & F Yuan Ping (NUS).



QUESTIONS?

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