ISTITUTO ITALIANO
DI TECNOLOGIA
QUANTUM MATERIALS THEORY

Switching magnets with E field: topological aspects

Sergey Artyukhin (IIT Genova, Italy)

Francesco Foggetti, Margherita Parodi, Prof. N. Nagaosa (RIKEN, Tokyo, Japan)

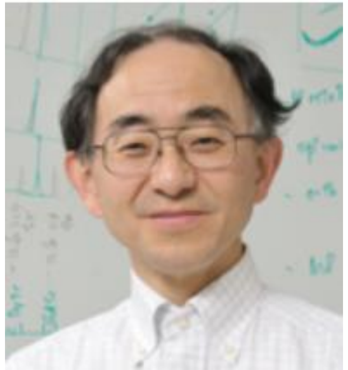
Louis Ponet (IIT), Prof. Andrei Pimenov, (TU Vienna, Austria)

L. Ponet et al, Nature **607**, 81 (2022)

F. Foggetti, M.Parodi, N.Nagaosa, S.Artyukhin, arxiv:2204.09027

L. Maranzana, N. Nagaosa, SA, arxiv:2403.11195

IMPACT-2024, Cargese, France



Prof. Naoto Nagaosa

Louis Ponet

Francesco Foggetti

Andrei Pimenov

Margherita Parodi

Topological aspects of switching in ferroics

Topological switching process

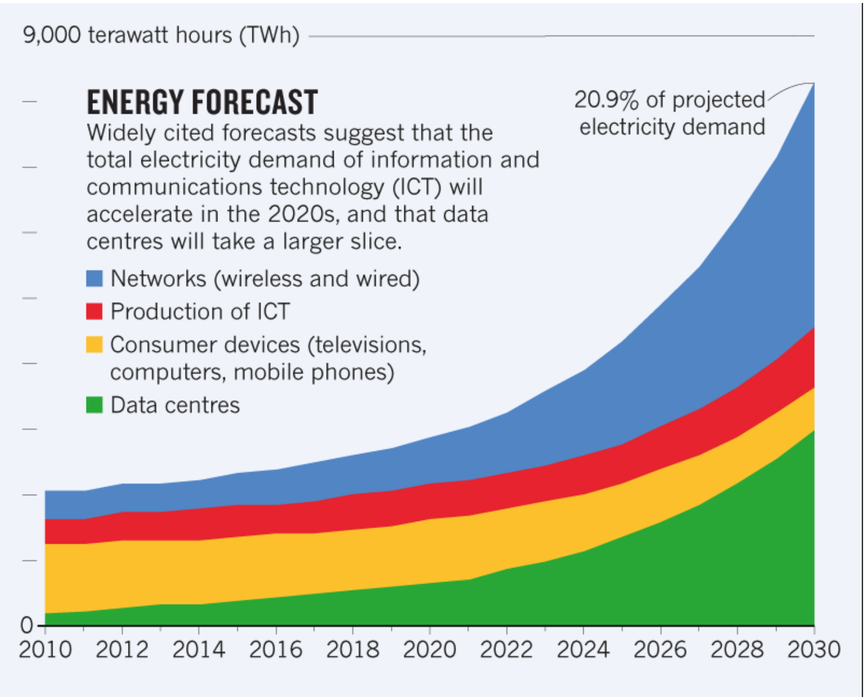
L. Ponet et al, Nat. **607**, 81 (2022)

Role of topology in switching of spiral magnets

F. Foggetti, M.Parodi, N.Nagaosa, S.Artyukhin, arxiv:2204.09027

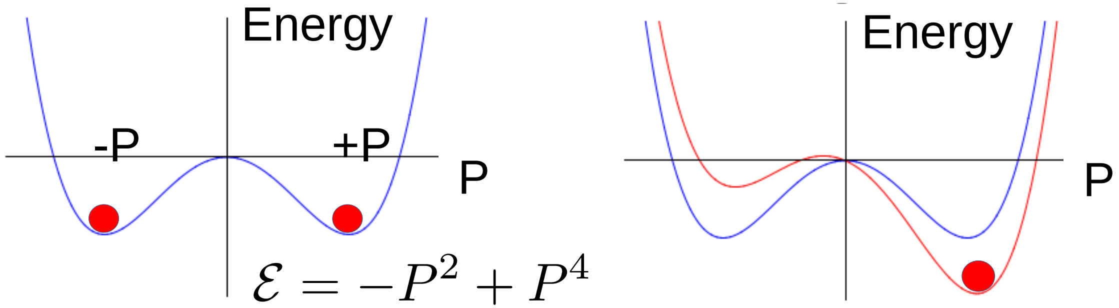
L. Maranzana, N. Nagaosa, SA, arxiv:2403.11195

Why multiferroics?



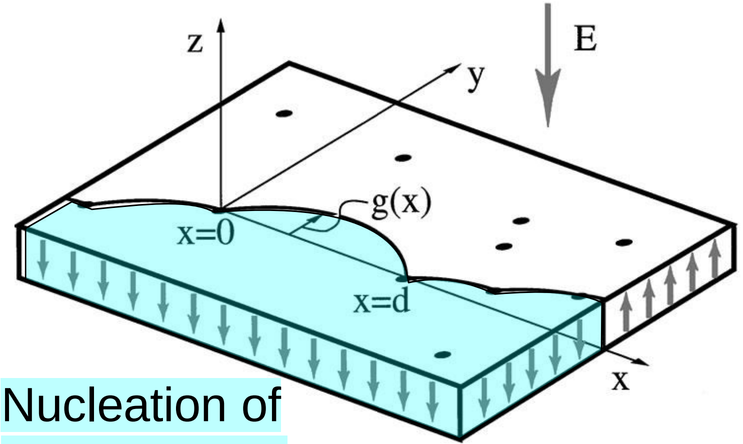
- Data centers consume around 2% of generated electrical energy
- US -> 6M households

Ferroic switching

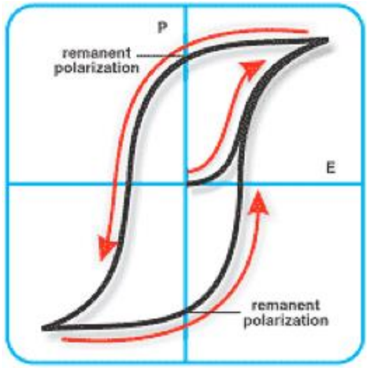


$$\mathcal{E} = -P^2 + P^4$$

switching through propagation of domain walls



Nucleation of down-domain

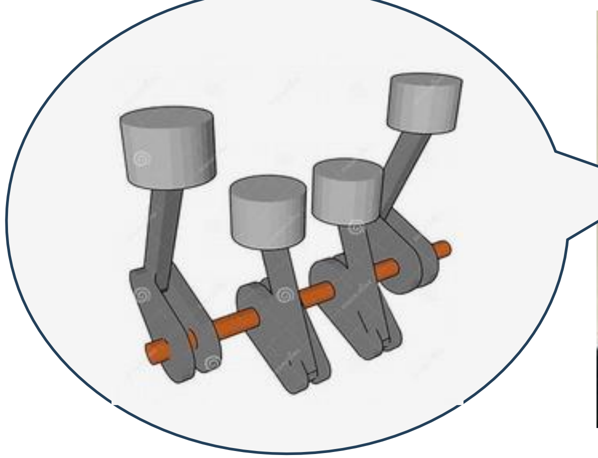


Disorder -> hysteresis

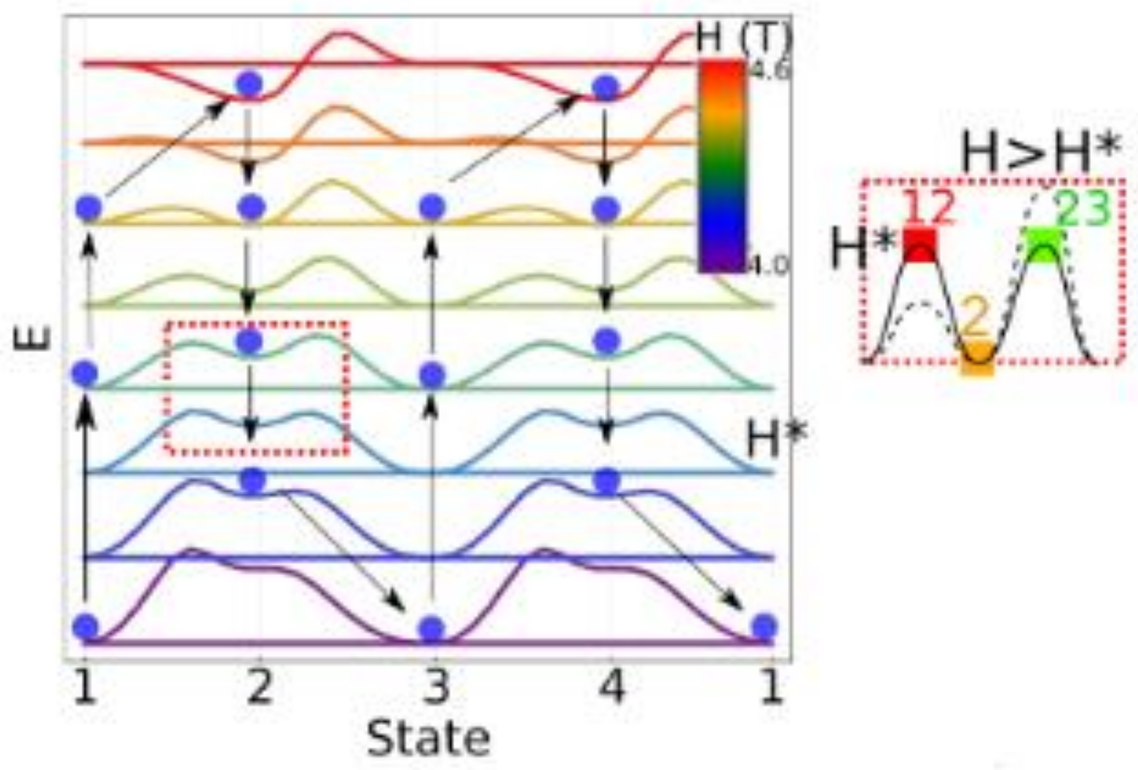
This story: bulk switching, DWs and hysteresis <u>not necessary</u>

Image: Y J Shin et al., Sci. Rep. , **5**, 10485 (2015).

Topological switching

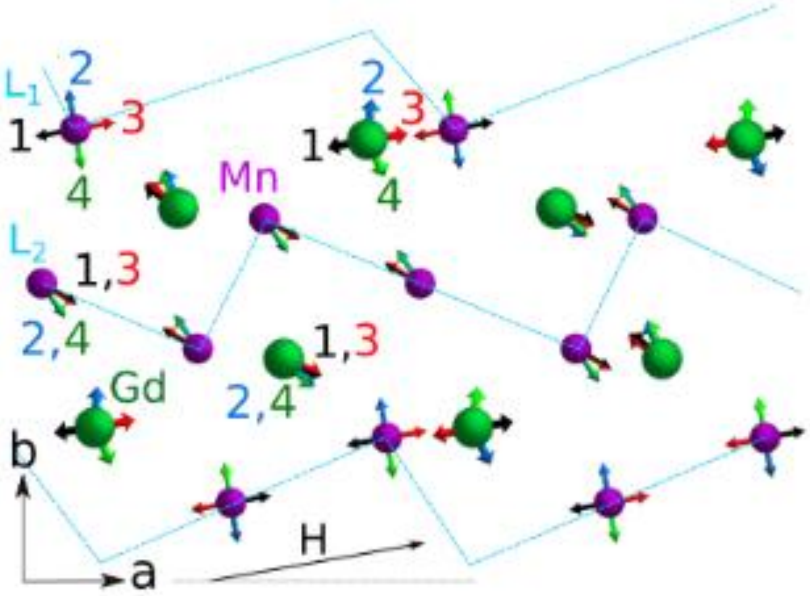


Louis Ponet



Asymmetric barrier change – rather general at low symmetry

$$E_{23}(H) - E_{12}(H) \approx (H - H_*)(M_{12} - M_{23})$$



Topological invariant – winding number

$$Q = \frac{1}{2\pi} \oint dt (l_x \partial_t l_y - l_y \partial_t l_x)$$

Thouless pump

Thouless PRB 27, 6083 (1983) “Quantization of Particle Transport”

pumped charge for one cycle T:

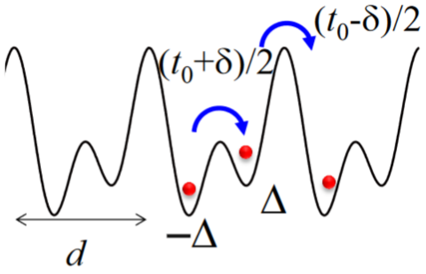
$$C = \frac{i}{2\pi}\sum_{\lambda} f_{\lambda}\int_0^T dt\int_0^{2\pi/L} dk\left[\left\langle\frac{\partial\psi_{\lambda k}}{\partial t}\middle|\frac{\partial\psi_{\lambda k}}{\partial k}\right\rangle - \left\langle\frac{\partial\psi_{\lambda k}}{\partial k}\middle|\frac{\partial\psi_{\lambda k}}{\partial t}\right\rangle\right]$$

topological invariant
Chern number

f_{λ}=1 for filled bands
=0 for empty bands

λ: band index

Rice & Mele, PRL (1982): One-Dimensional Dimerized Lattice Model



Su-Schrieffer-Heeger model

$$\mathcal{H} = \boxed{\sum_i\left(\frac{t_0}{2} + (-1)^i\frac{\delta}{2}\right)(c_i^{\dagger}c_{i+1} + \text{h.c.})}$$

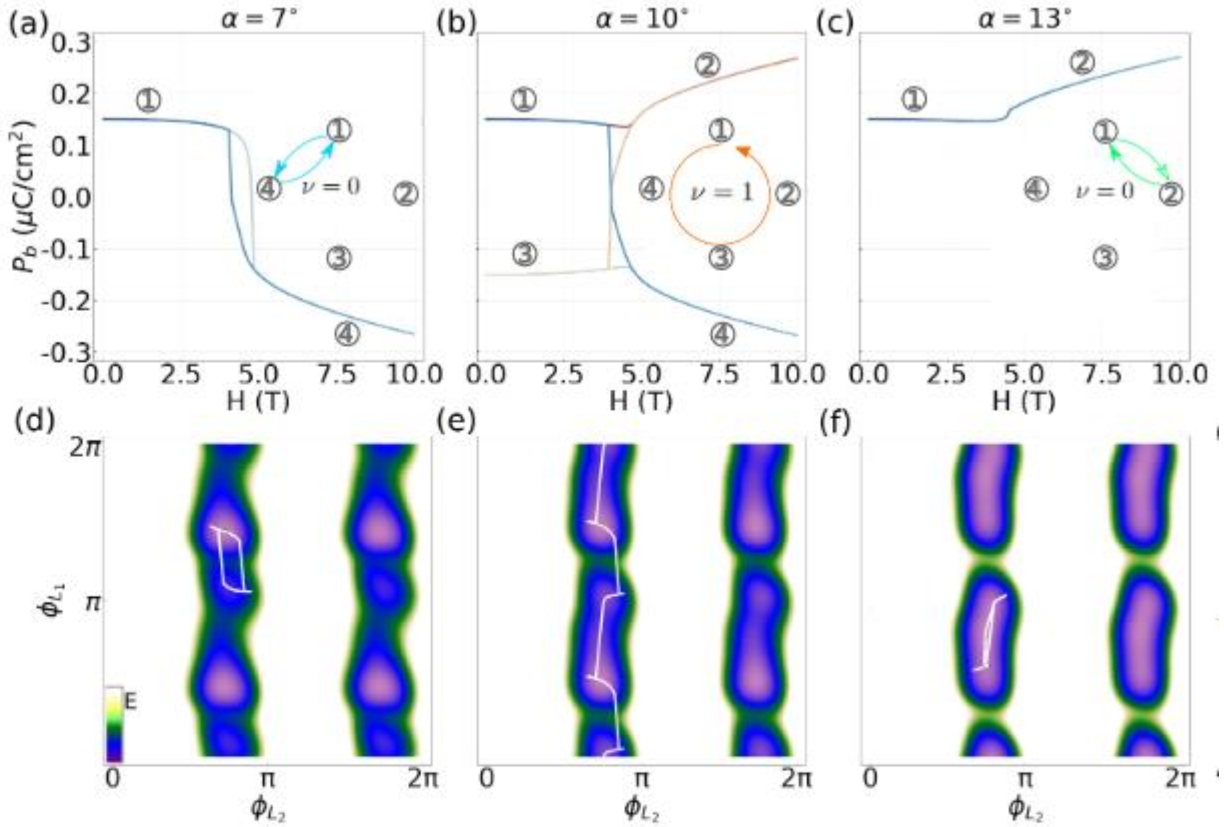
$$+\boxed{\Delta\sum_i(-1)^i c_i^{\dagger}c_i}$$

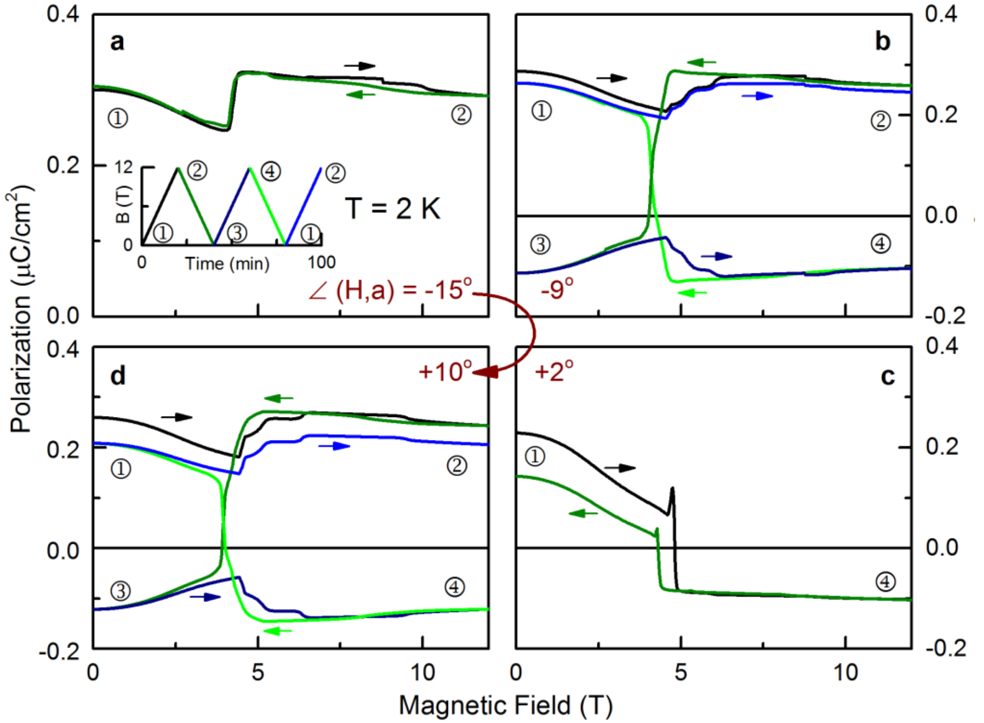
Staggered Potential

Precision Graphics

Topologically protected regime

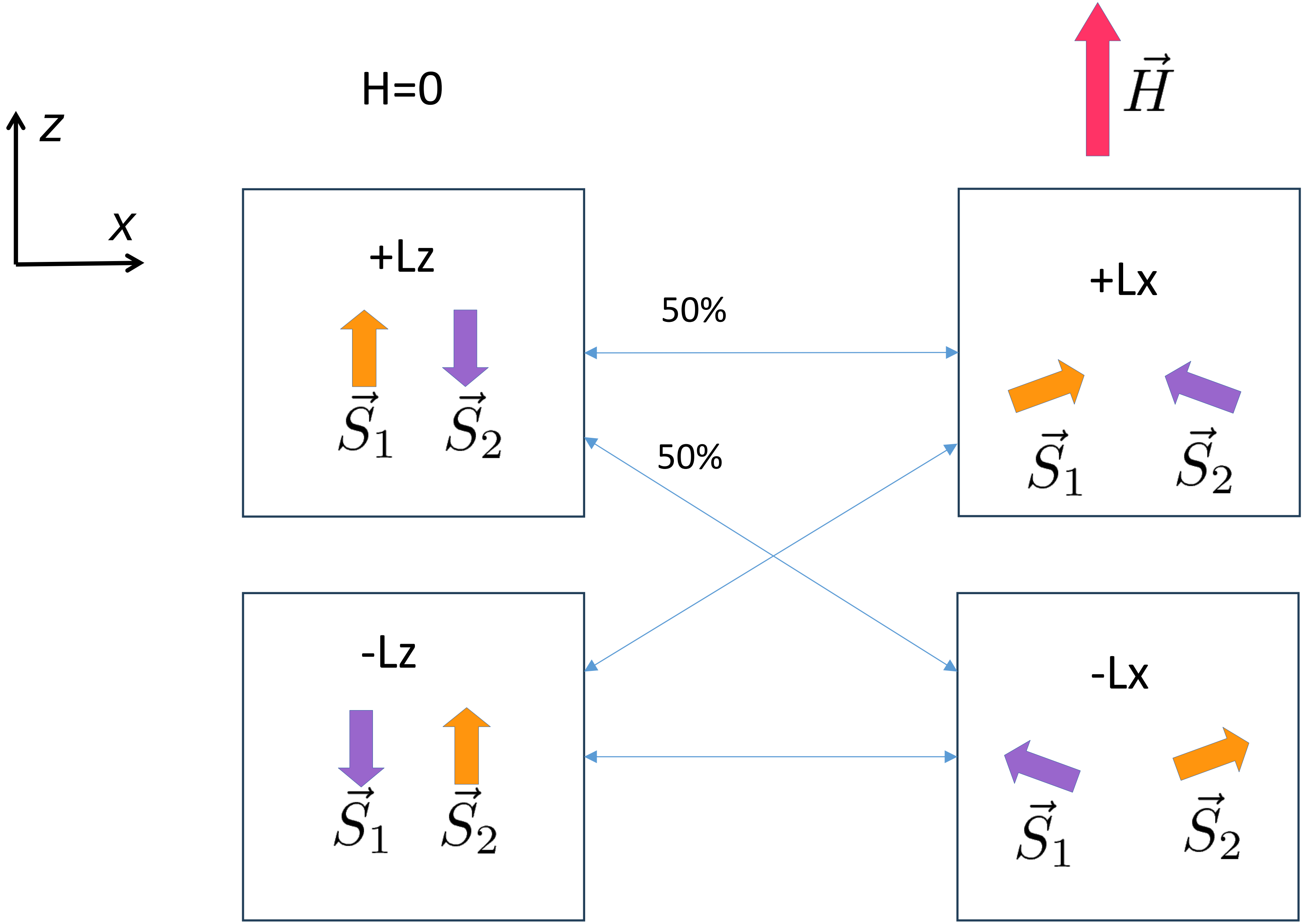
Andrei Pimenov



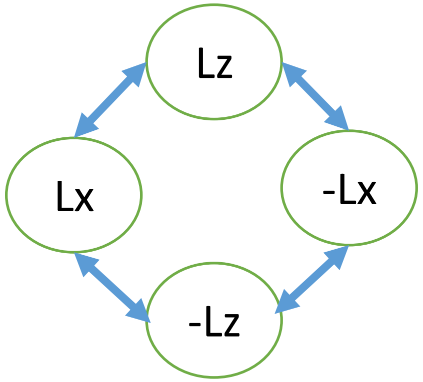


L. Ponet, SA, Th. Kuhn et al., Nature **607**, 81 (2022)

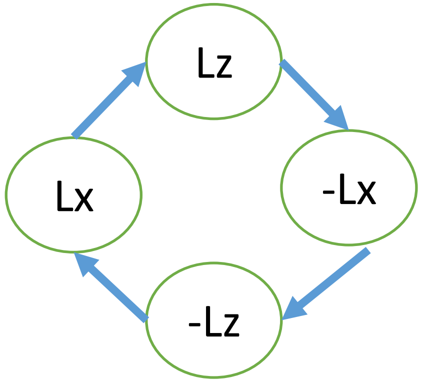
Microscopic intuition: Spin-flop transition



Usual spin-flop transition



$GdMn_2O_5$



Topological aspects of switching in ferroics

Topological switching process

L. Ponet et al, Nat. **607**, 81 (2022)

E-field switching of spiral magnets: role of topology

F. Foggetti, M.Parodi, N.Nagaosa, S.Artyukhin, arxiv:2204.09027

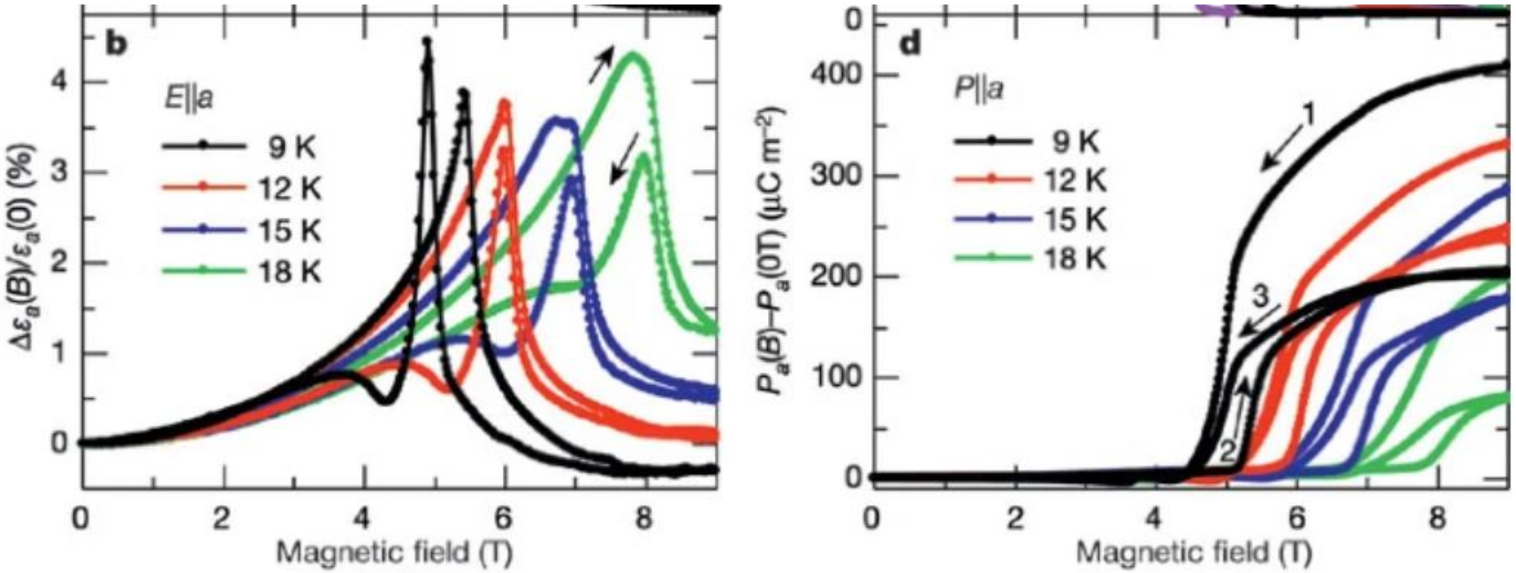
L. Maranzana, N. Nagaosa, SA, arxiv:2403.11195

+ topological ferroic switching

- very low temperature (2 K), H-control, we want electric control!

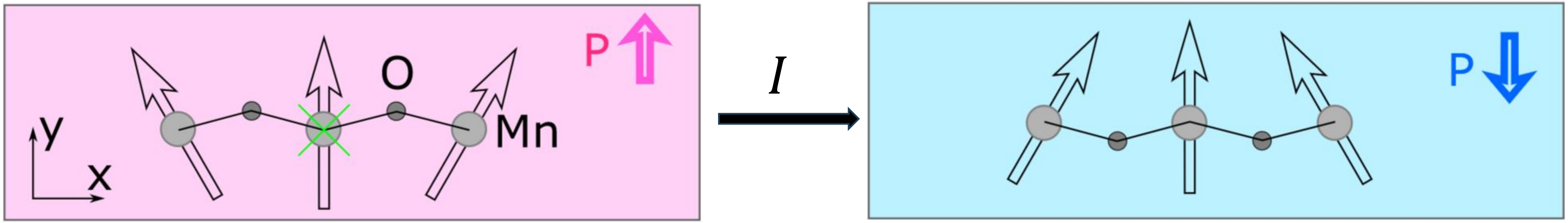
Spiral magnets?

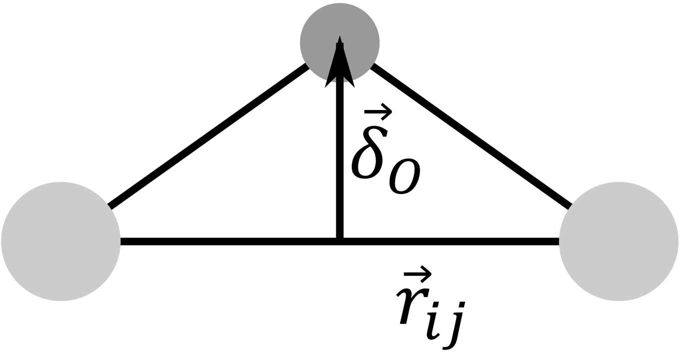
- KBN Electromagnons
- Emergent Inductance
- E control of natural optical activity
- E field switching?



Magnetic control of ferroelectric polarization
T. Kimura, T. Goto, H. Shintani, K. Ishizaka, T. Arima, Y. Tokura, Nature **426**, 55–58 (2003)

Polarization induced by spiral





$$H = \vec{\delta}_O \cdot [\vec{r}_{ij} \times [\vec{S}_i \times \vec{S}_j]]$$

Inverse DM/shift current mechanism:

H. Katsura, N. Nagaosa, and A.V. Balatsky, Phys. Rev. Lett. 95, 057205 (2005)

M. Mostovoy, PRL 96, 067601 (2006)

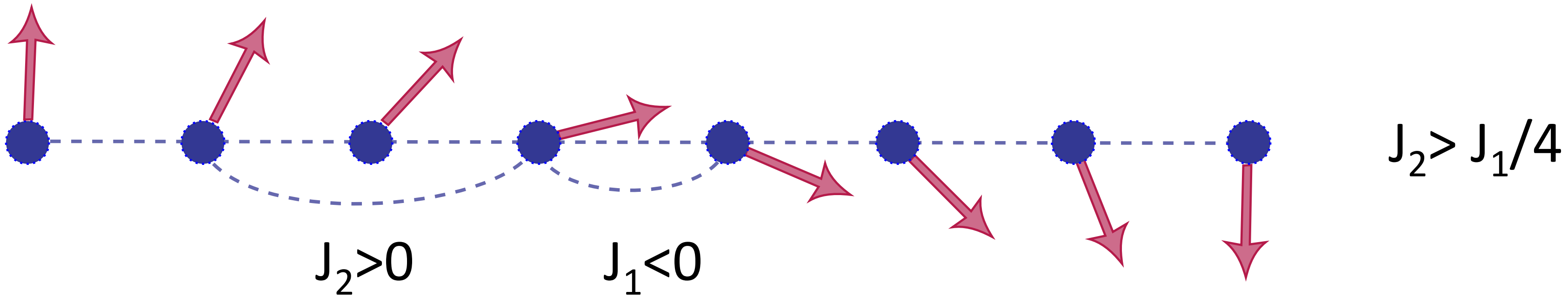
I. A. Sergienko and E. Dagotto. Phys. Rev. B 73, 094434 (2006)

Model

$$H = \sum_n J_1 S_n \cdot S_{n+1} + J_2 S_n \cdot S_{n+2} + K_z S_z^2 + [E \times r_{12}][S_1 \times S_2]$$

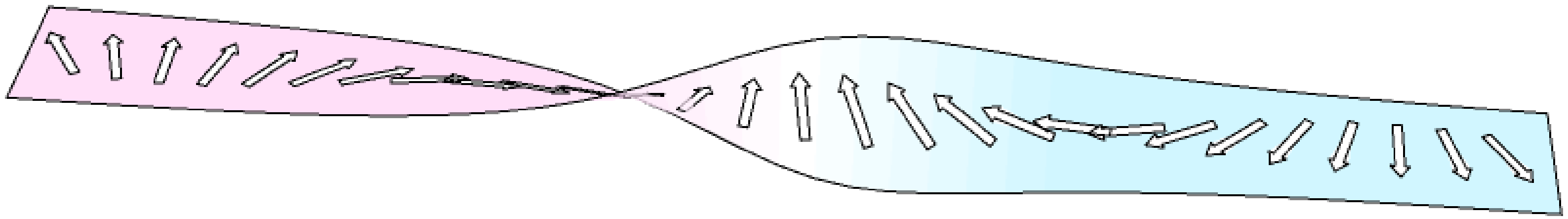
Continuous model – Lagrangian:

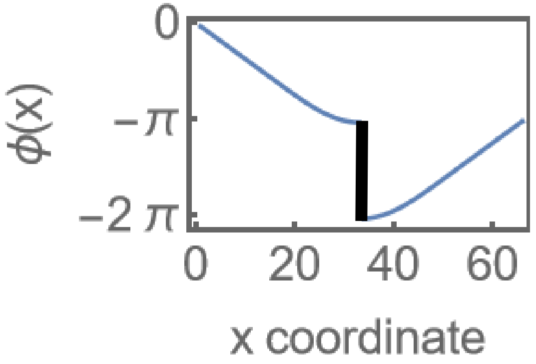
$$\begin{aligned}\mathcal{L} =& \alpha \mathbf{A}(\mathbf{M}) \cdot \dot{\mathbf{M}} - J(\nabla \mathbf{M})^2 - J'(\nabla^2 \mathbf{M})^2 + \\ &+ \gamma [\mathbf{E} \times \mathbf{x}] \cdot [\mathbf{M} \times \nabla \mathbf{M}] - K_z M_z^2,\end{aligned}$$



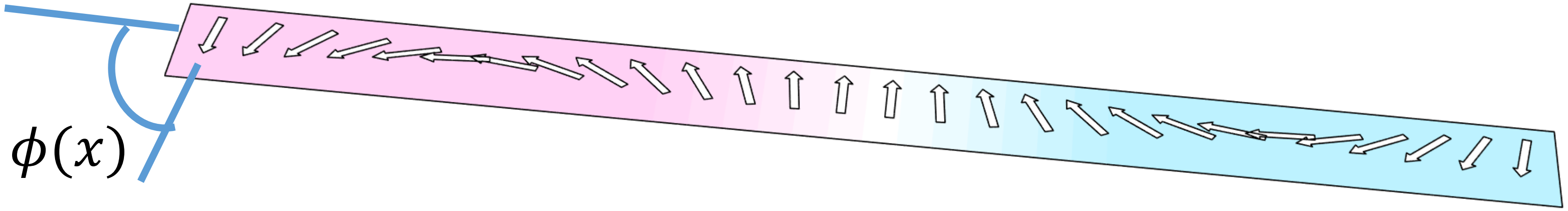
Domain wall types and topology

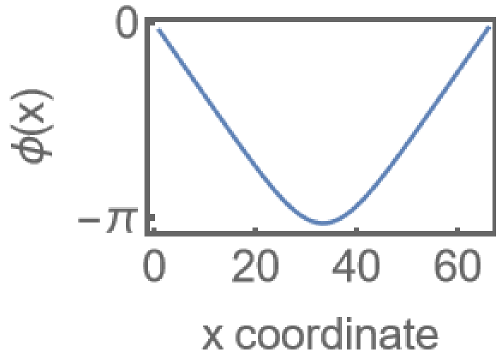
Type II

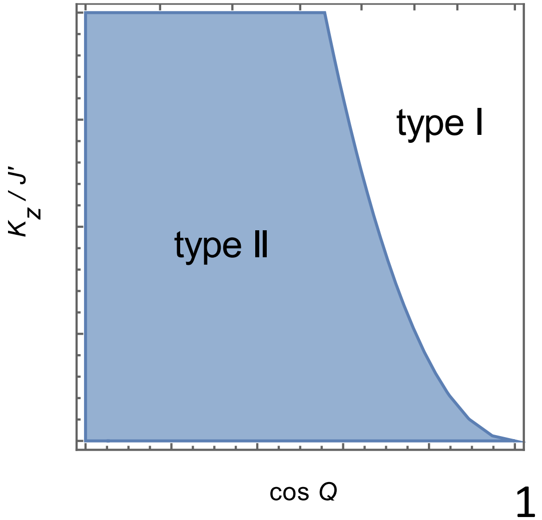




Type I







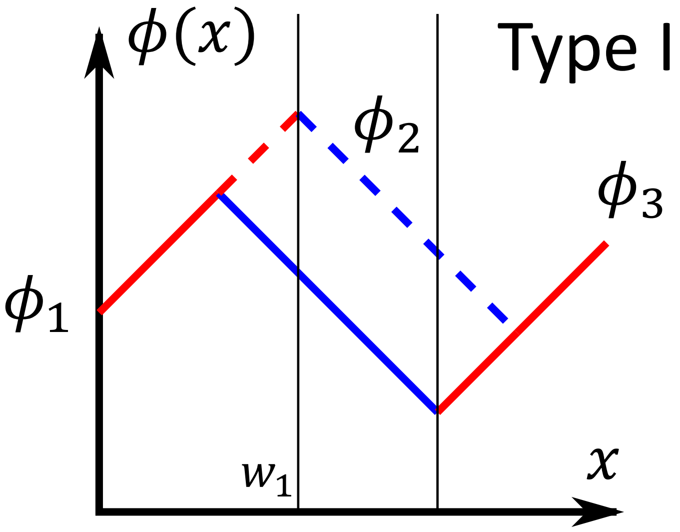
Two basic types of walls:

Type II: spins get almost vertical, ~~winding number~~

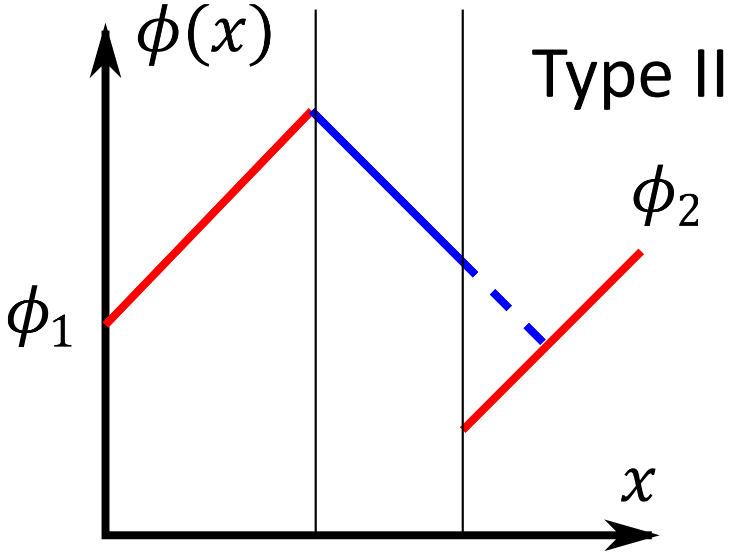
Type I: spins lie in the plane, winding number!

Winding number, is it important?

- Total polarization = winding number: $P = \int dx\, [S \times \nabla S] = \int d\phi = \phi_R - \phi_L$
- Nonlocal dynamics



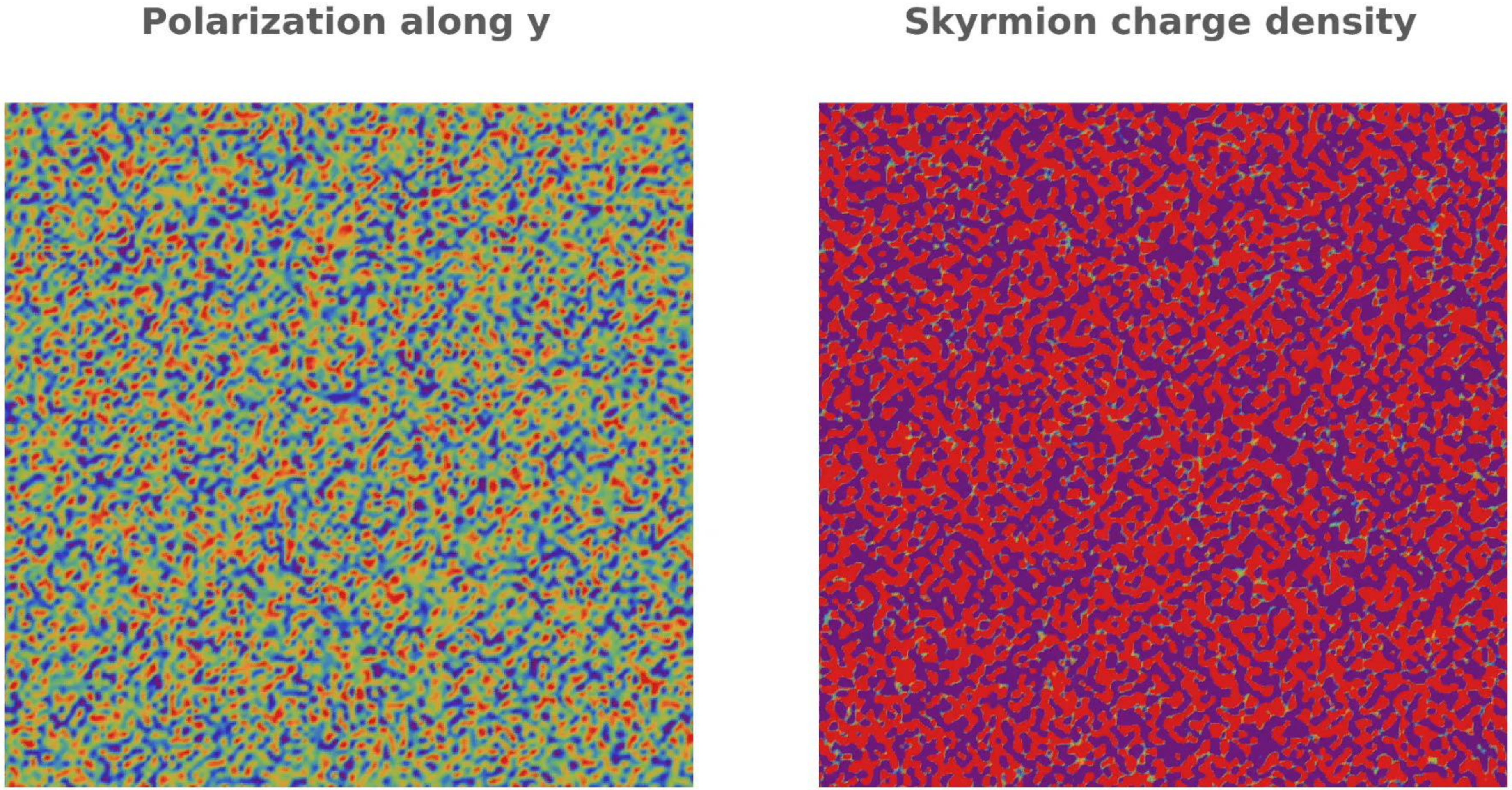
P+ P-



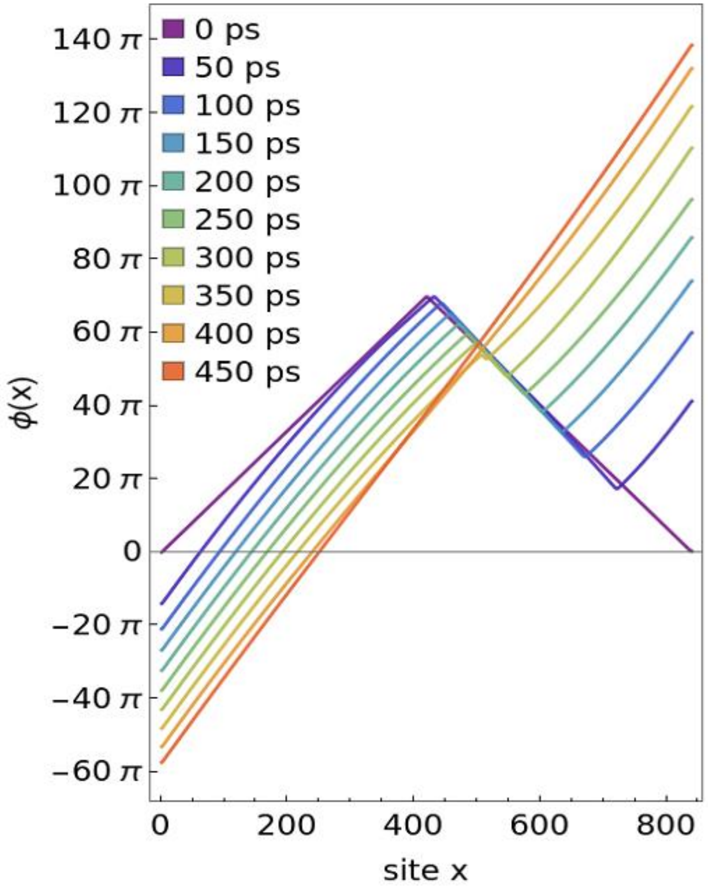
- Domain wall motion <=> phason
- No dielectric response in termodyn. limit!
- Damping~domain width, $v_1 \sim E/\alpha w_1 Q$
- Pinning ~ sqrt(domain width), $E_T = k(nw)^{1/2}$

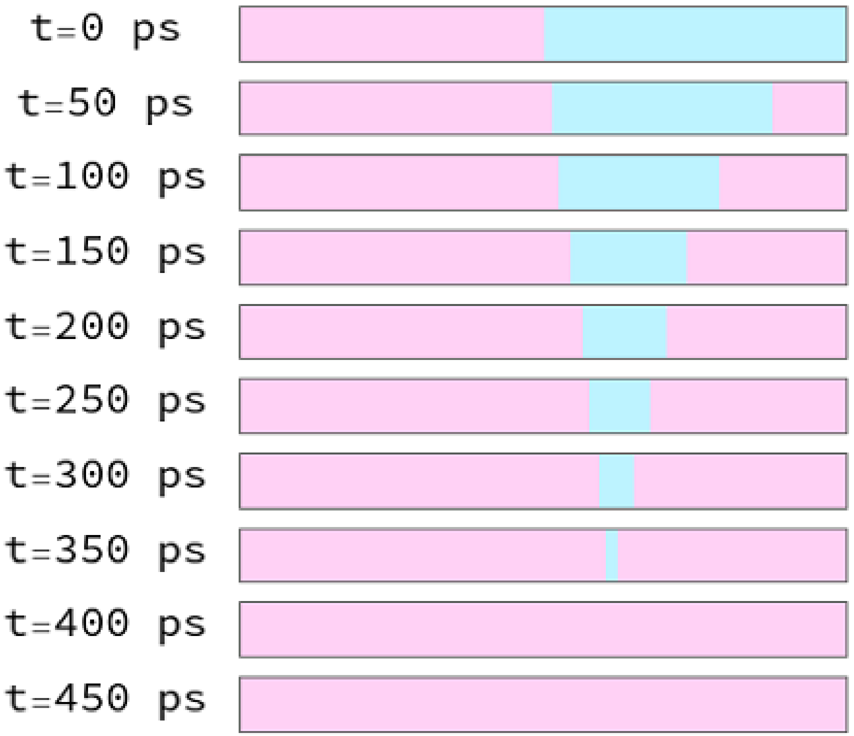
- Domain wall motion: local
- Damping~DW width, $v_1 \sim E/\alpha$
- Pinning ~ sqrt(DW width)

Type I domain walls



E-field induced motion – type 1 DW

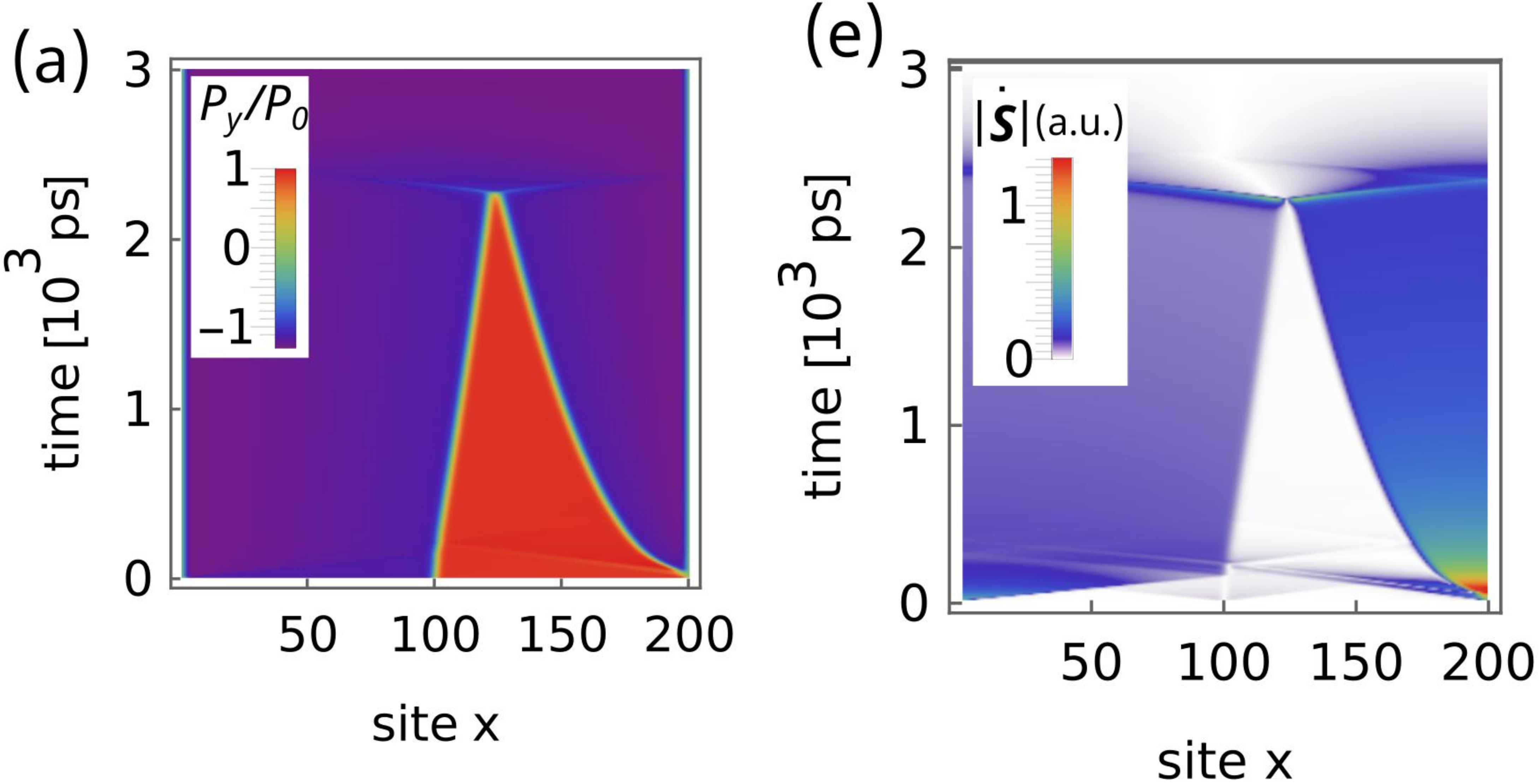




$$\mathcal{L}=\sum_i^N \mathcal{L}_i+\mathcal{L}_E,\quad \mathcal{L}_i=\left[\alpha\dot{\phi}_i\delta_i+\frac{1}{2m}\delta_i^2\right]L_i^{(0)}$$

$$\dot{\phi}_0=-\frac{\gamma E}{2\beta X_1},\ \dot{X}_1=-\frac{\gamma E}{4Q\beta X_1},\ \dot{X}_2=\frac{\gamma E}{4Q\beta(L-X_2)}$$

E-field induced motion – type 1 DW

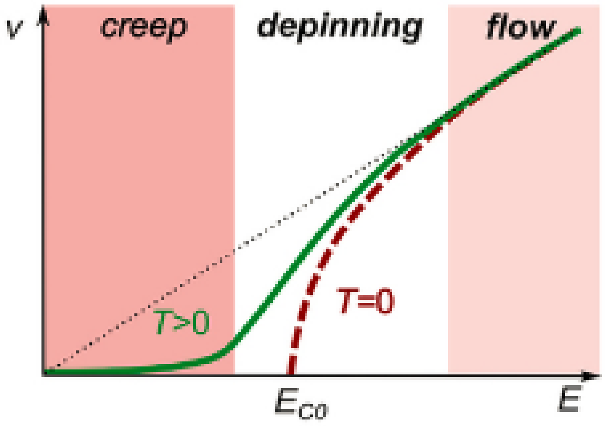


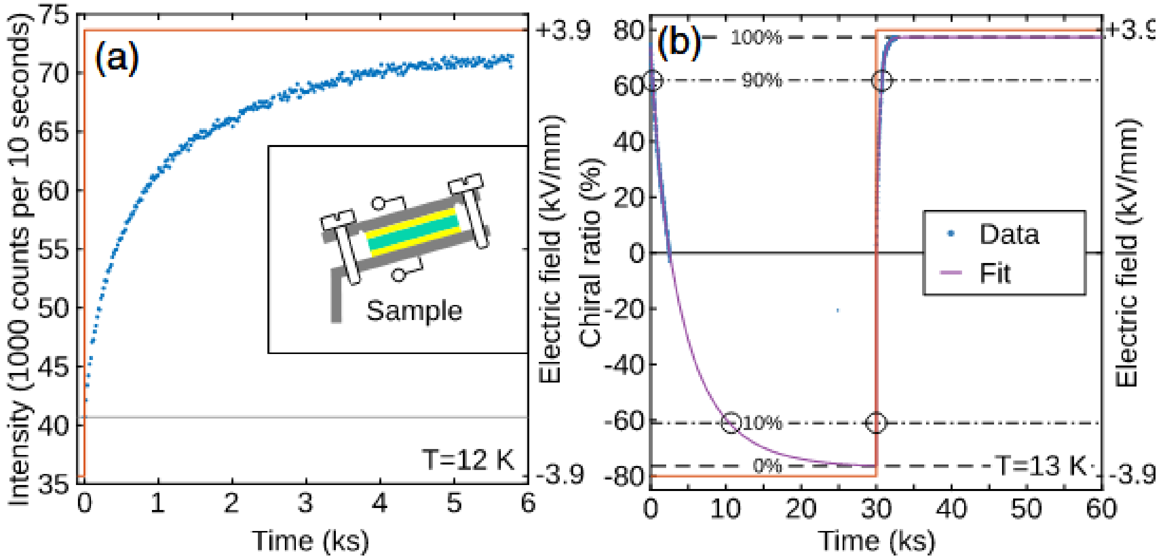
Unusual domain inversion in spiral magnets

- Usual switching: independent of the domain structure

- Switching in spiral magnets: strongly dependent on the geometry

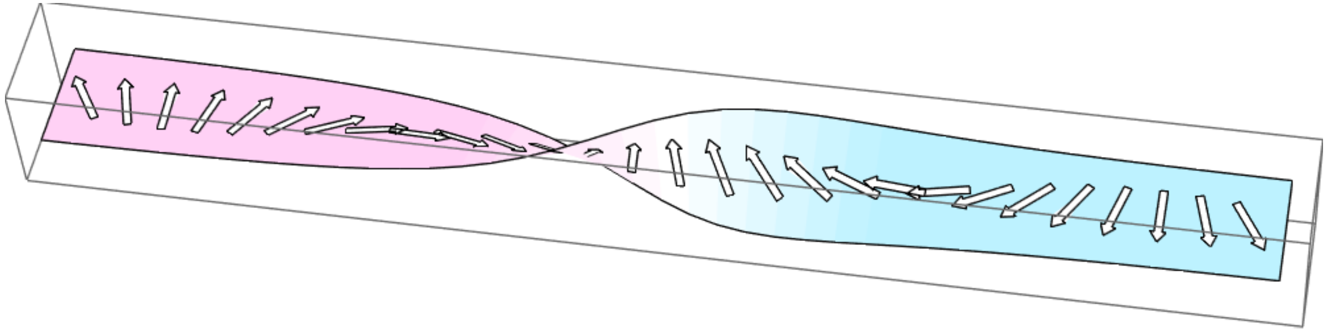
$$\dot{X} = -\frac{\gamma E}{4\beta Q}\frac{L}{X(L-X)}$$



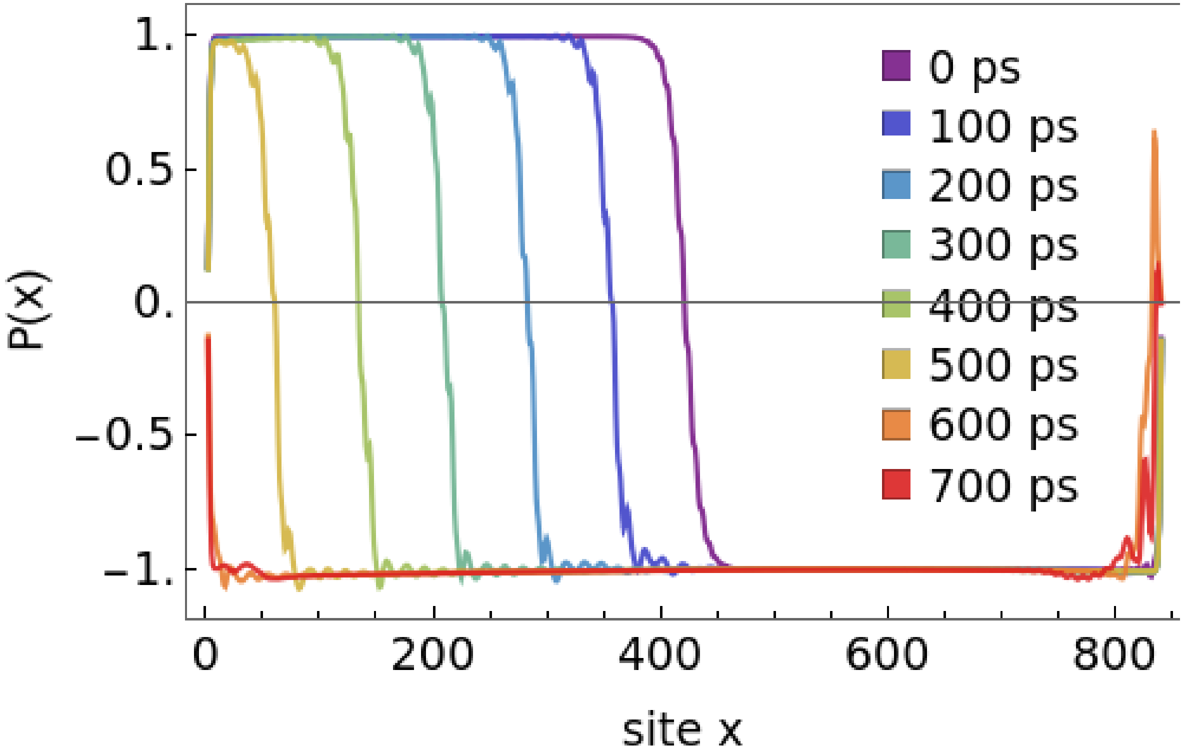


J Stein … M. Braden, Phys. Rev. Lett. **127** 097601 (2021)

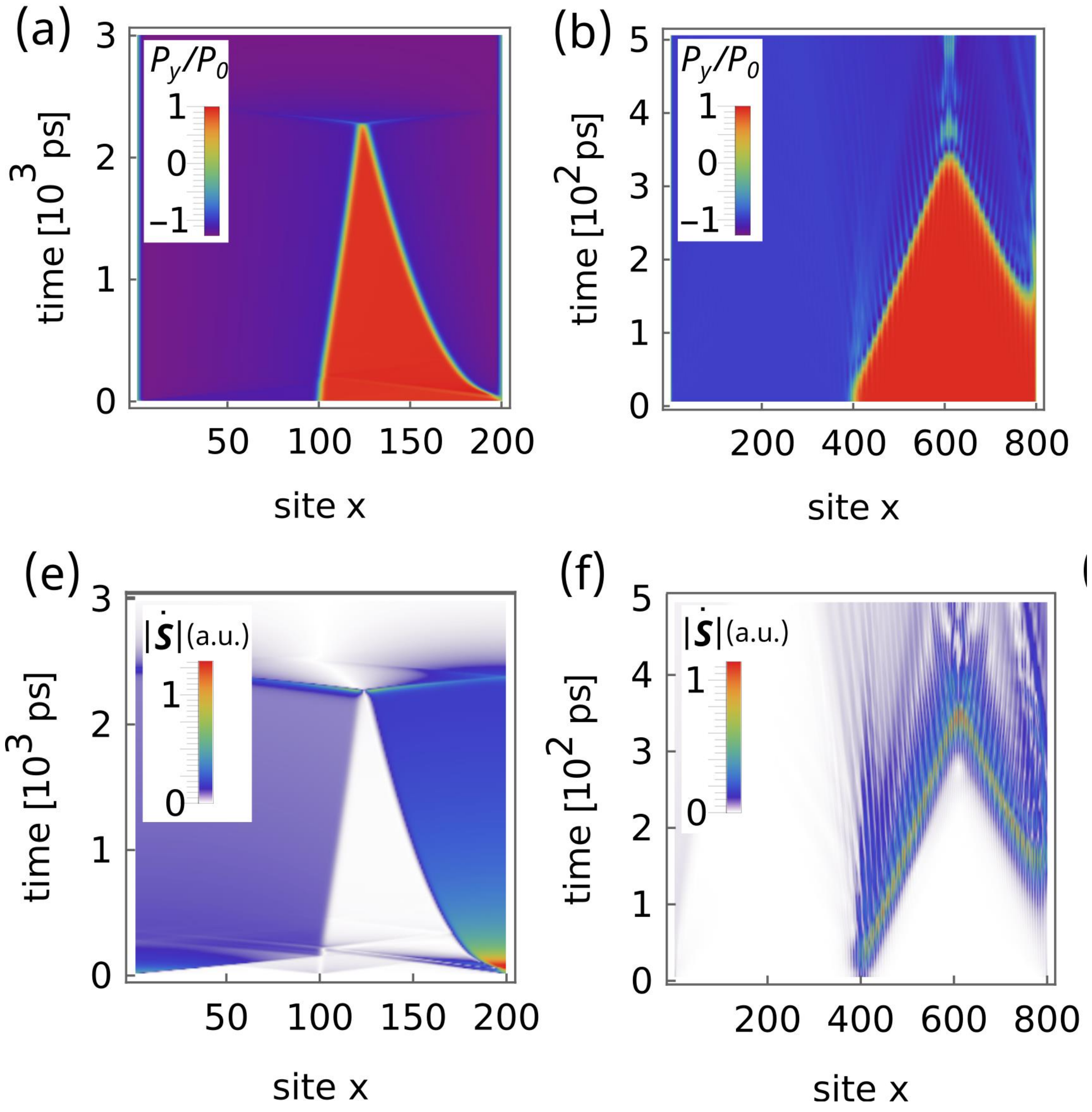
Type 2 domain wall under E-field



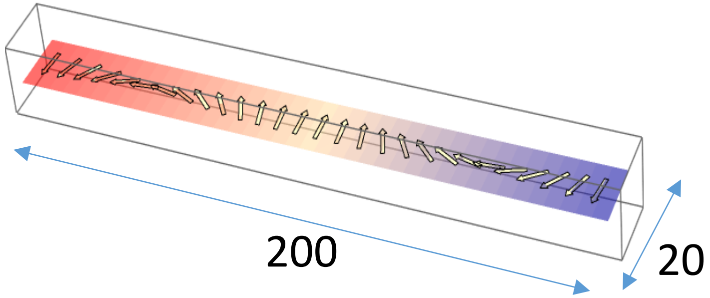
$$F = \int dx\ \left(\frac{J_2 \sin^2 Q}{2} \nabla_i n_j \nabla_i n_j + K_z n_z^2\right)$$



Type I and type II domain wall motion

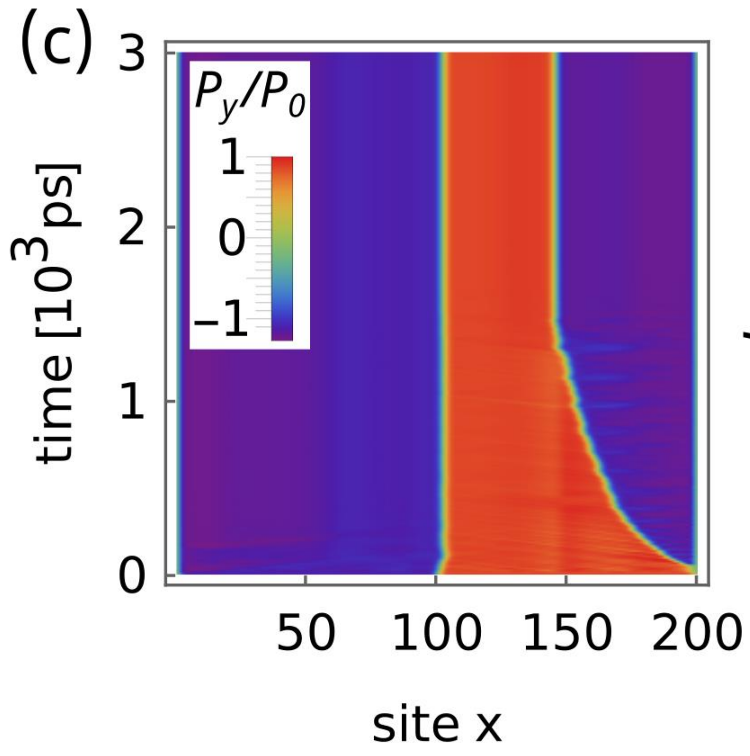


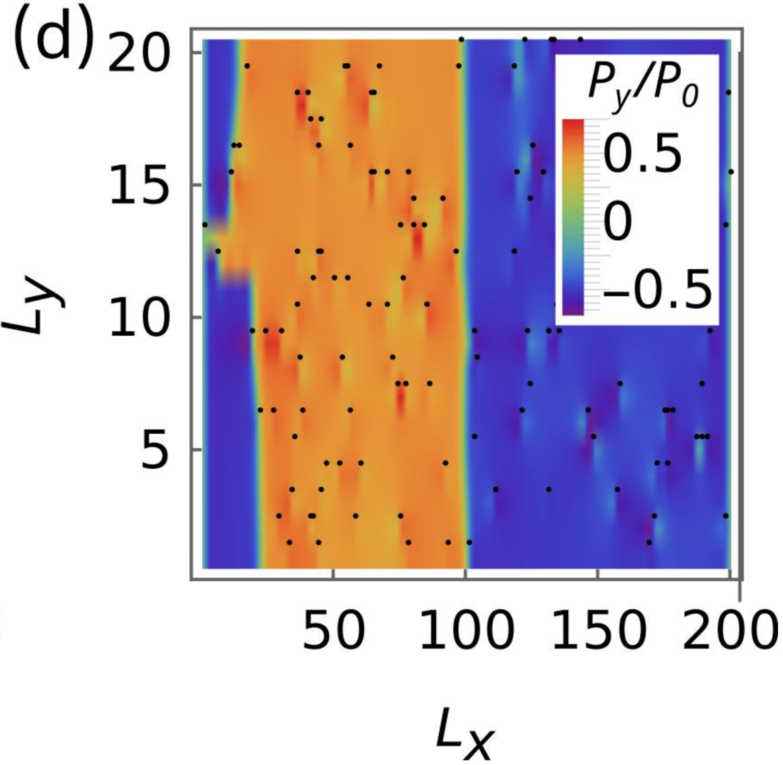
Disorder for type I walls

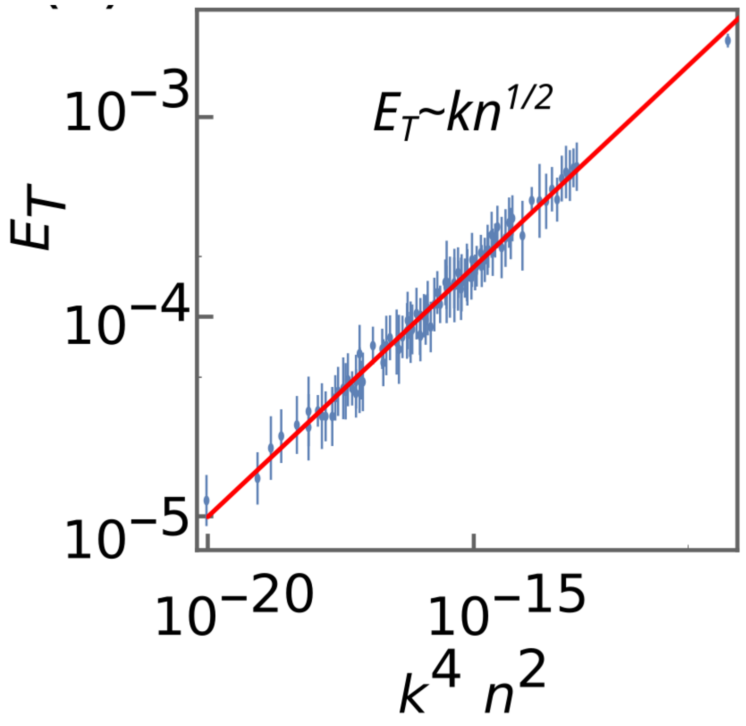



Margherita Parodi

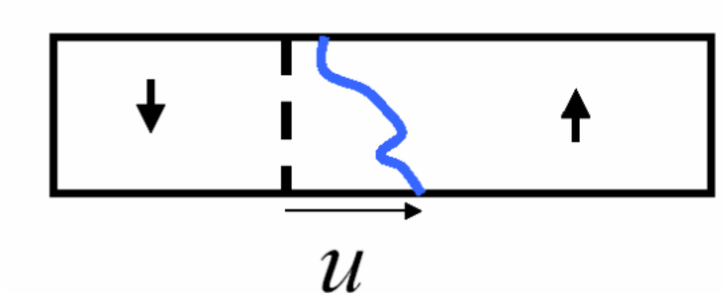
$$H = \sum_n (J_1 \boldsymbol{S}_n \cdot \boldsymbol{S}_{n+1} + J_2 \boldsymbol{S}_n \cdot \boldsymbol{S}_{n+2} + D_z[\boldsymbol{S}_n \times \boldsymbol{S}_{n+1}]_z + K_{n,z} S_z^2) - \sum_{i \in A} K_x S_{i,x}^2$$







Loss of long-range order in d<4 (Larkin length)



$$H_{elastic} = \int c\,(\nabla u)^2\,dy = \int dk\,c\,k^2 |u_k|^2 \qquad H_{dis} = \int V(r)\rho(r)d^dr$$

$$\downarrow \qquad\qquad \downarrow$$

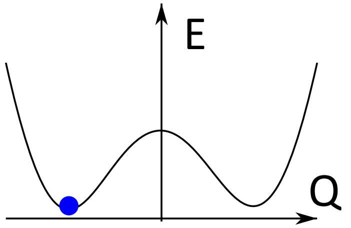
$$cR^{d-2}a^2 \qquad VR^{d/2}\rho_o \qquad R \sim \left(\frac{ca}{V\rho}\right)^{\frac{2}{4-d}}$$

$$C(r) \approx e^{-r^{4-d}}$$

$$H = \int c\left((\nabla\phi)^2 - Q^2\right)^2 dy = c\int (\nabla\phi - Q)^2(\nabla\phi + Q)^2 dy \approx c\int dy\left((\nabla\phi)^2 - 2Q\nabla\phi\right)(2Q)^2$$

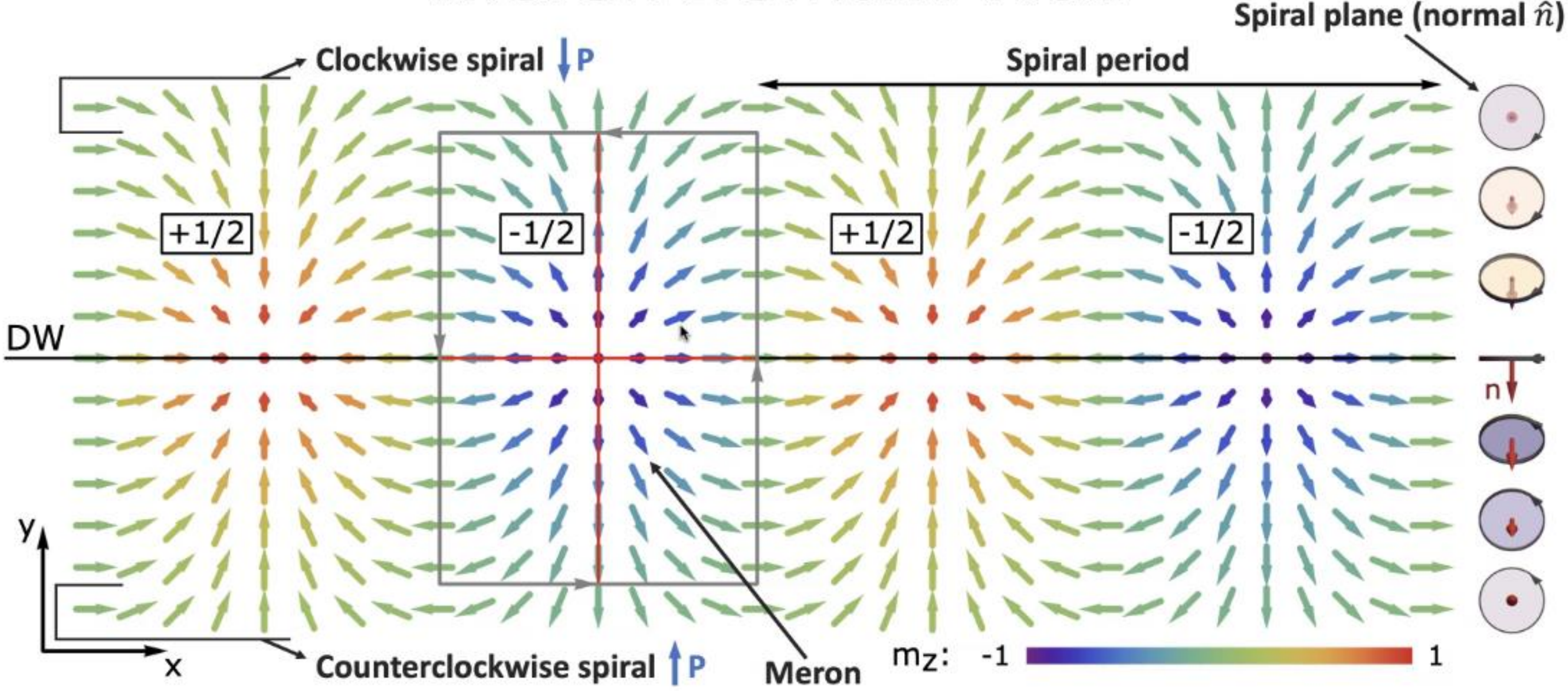
$$\downarrow$$

$$cR^{d-1}a^2 \qquad R \sim \left(\frac{ca}{V\rho}\right)^{\frac{2}{2-d}}$$



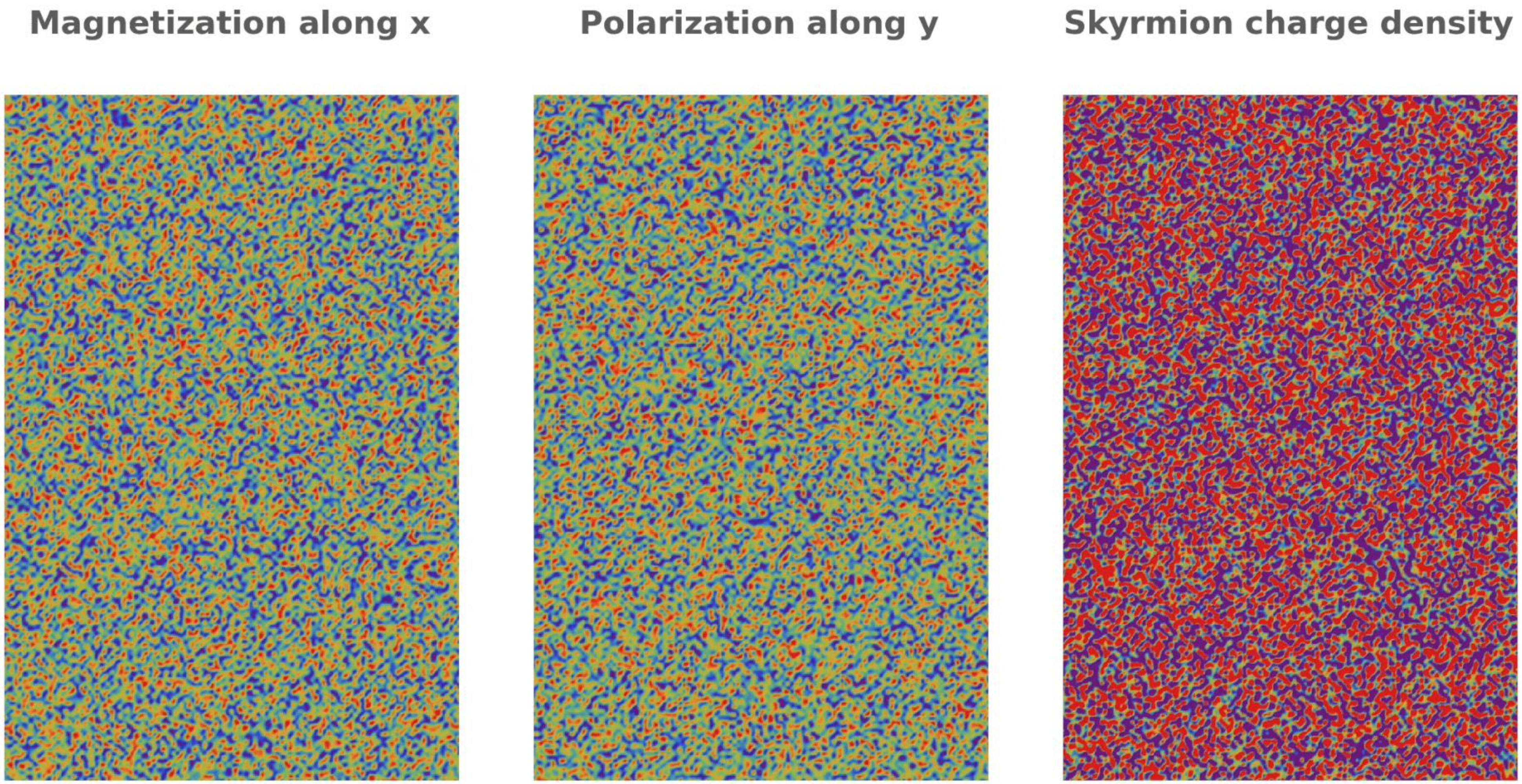
superelasticity

Meron Domain Wall



Domain wall ⟺ Chain of merons with alternating topological charges

Meron domain walls

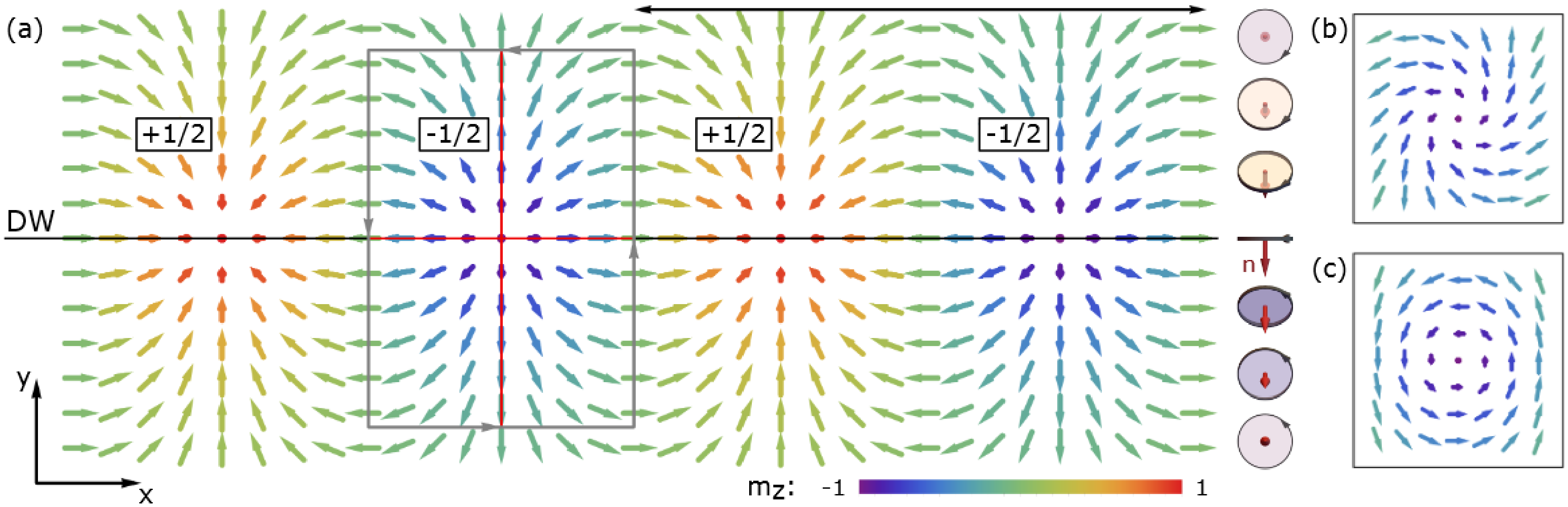


Magnetization along x

Polarization along y

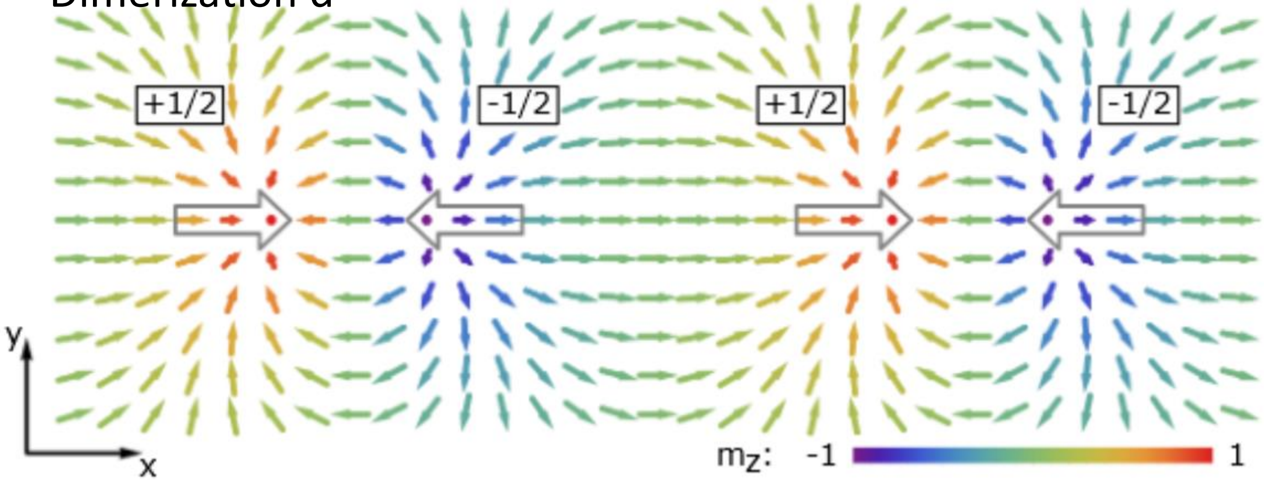
Skyrmion charge density

Meron domain walls



Luca
Maranzana

Dimerization d

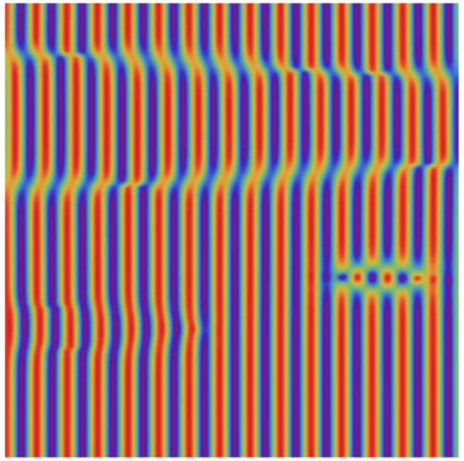


$$L = \dot{\bar{y}} d + qE_y \bar{y} - \frac{d^2}{2m}, \qquad R = \frac{1}{2}\beta\dot{\bar{y}}^2 + \frac{1}{2}\beta\lambda_0^2\dot{d}^2$$

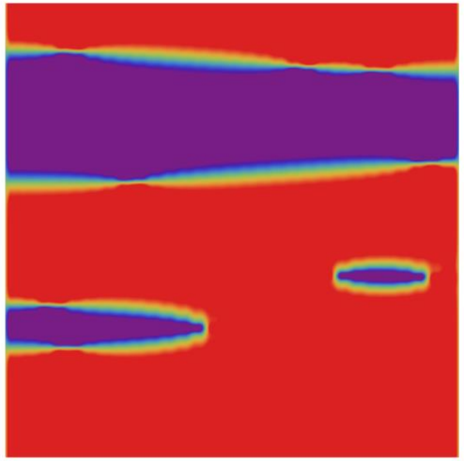
$$m\ddot{\bar{y}} = qE_y - \beta\dot{\bar{y}}, \qquad d = m\dot{\bar{y}}$$

Meron wall defects

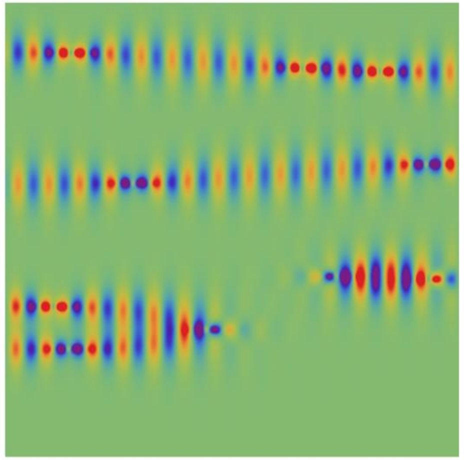
Magnetization along x

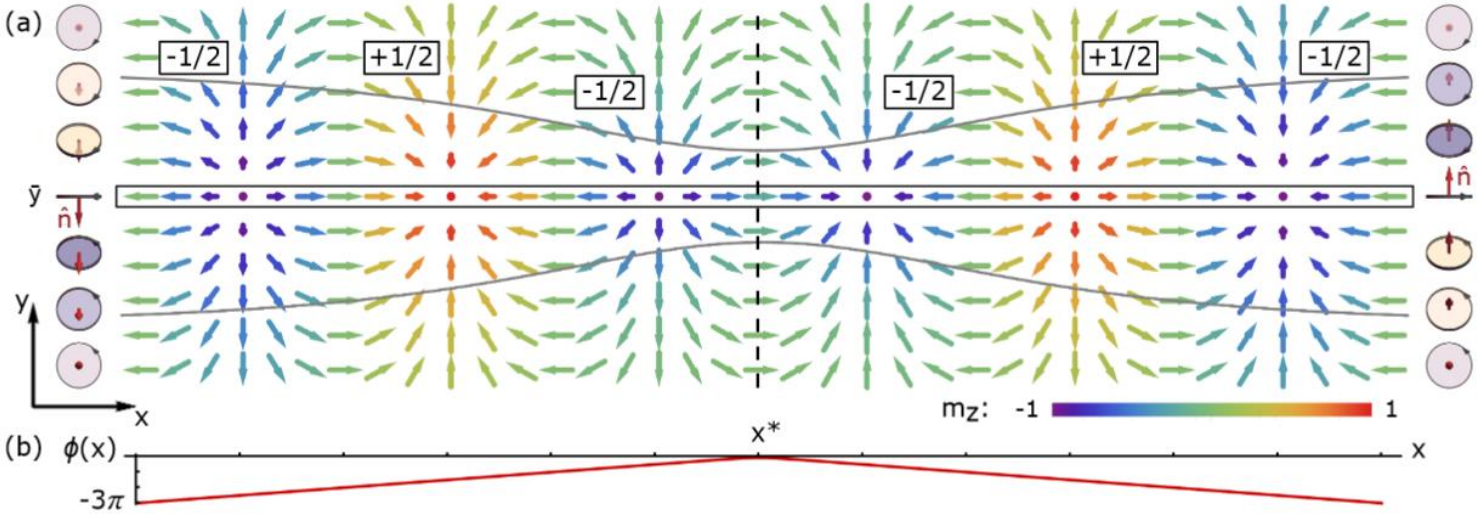


Polarization along y



Skyrmion charge density





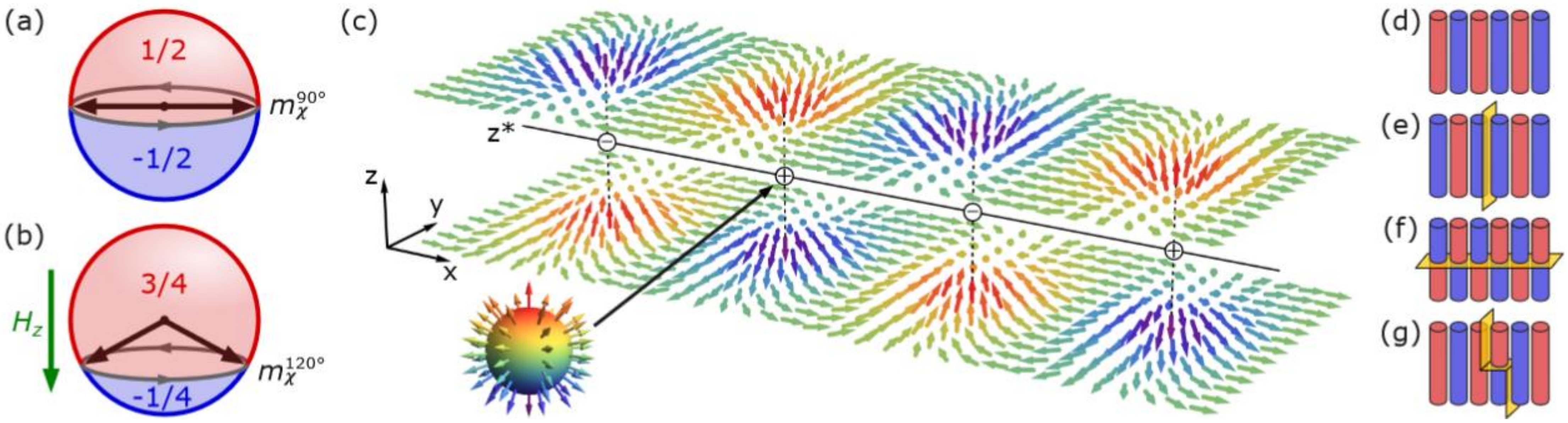
$$\dot{\bar{y}} = v_\infty \left(c + \frac{1}{\alpha^2} \frac{L_y \lambda_0}{\bar{y}(L_y - \bar{y})} \left(\frac{2Q_{\text{tot}}}{N} \right)^2 \right)^{-1}$$

$$\dot{\phi}_+ \equiv \dot{\phi}_t + \dot{\phi}_s = -\frac{2Q_{\text{tot}}}{N} \frac{\dot{\bar{y}}}{\alpha \bar{y}},$$

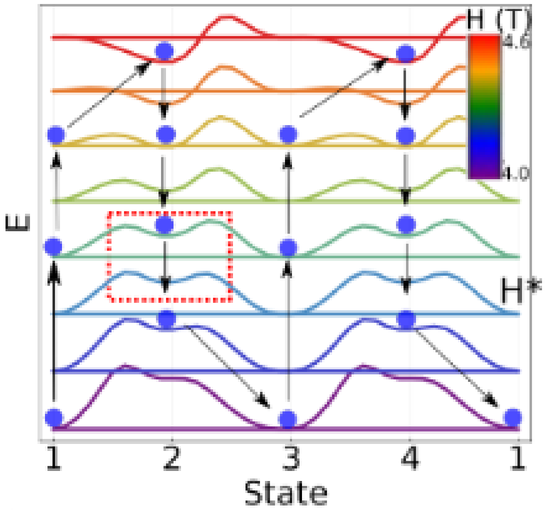
$$\dot{\phi}_- \equiv \dot{\phi}_t - \dot{\phi}_s = -\frac{2Q_{\text{tot}}}{N} \frac{\dot{\bar{y}}}{\alpha (L_y - \bar{y})},$$

Skyrmion charge of the wall controls the nonlocal domain wall dynamics

Bloch lines and hedgehog defects



Conclusions

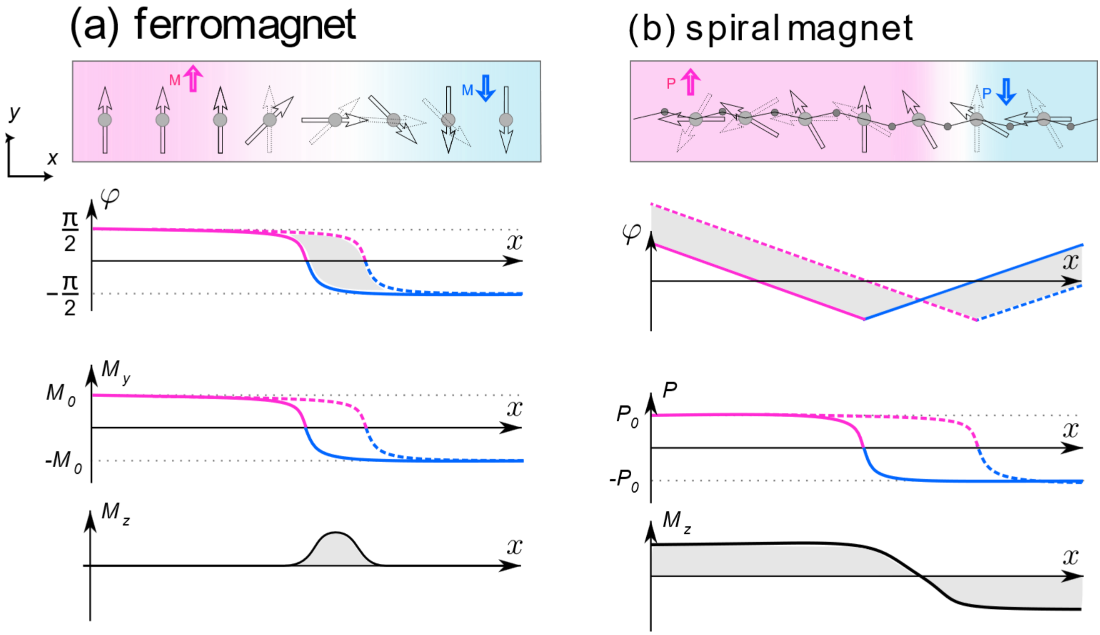


- 4-state unidirectional topological switching in $GdMn_2O_5$
- Key: the evolution of the potential energy surface
- Binary counter: one H sweep – polarization toggles, two sweeps – the system returns to the initial state
- Search for neighboring dissimilar switching regimes!

L. Ponet, SA, Th. Kuhn et al., Nature **607**, 81 (2022)

- Non-local dynamics of type-I walls
- No dielectric response from type I walls in thermodynamic limit
- Wall velocity depends on the domain structure
- Meron walls, defects -> nonlocal dynamics
- F. Foggetti, M.Parodi, N.Nagaosa, SA, arxiv:2204.09027
- L. Maranzana, N. Nagaosa, SA, arxiv:2403.11195

Thank you for your attention!


(a) ferromagnet (b) spiral magnet