

magnon and ferron in texture

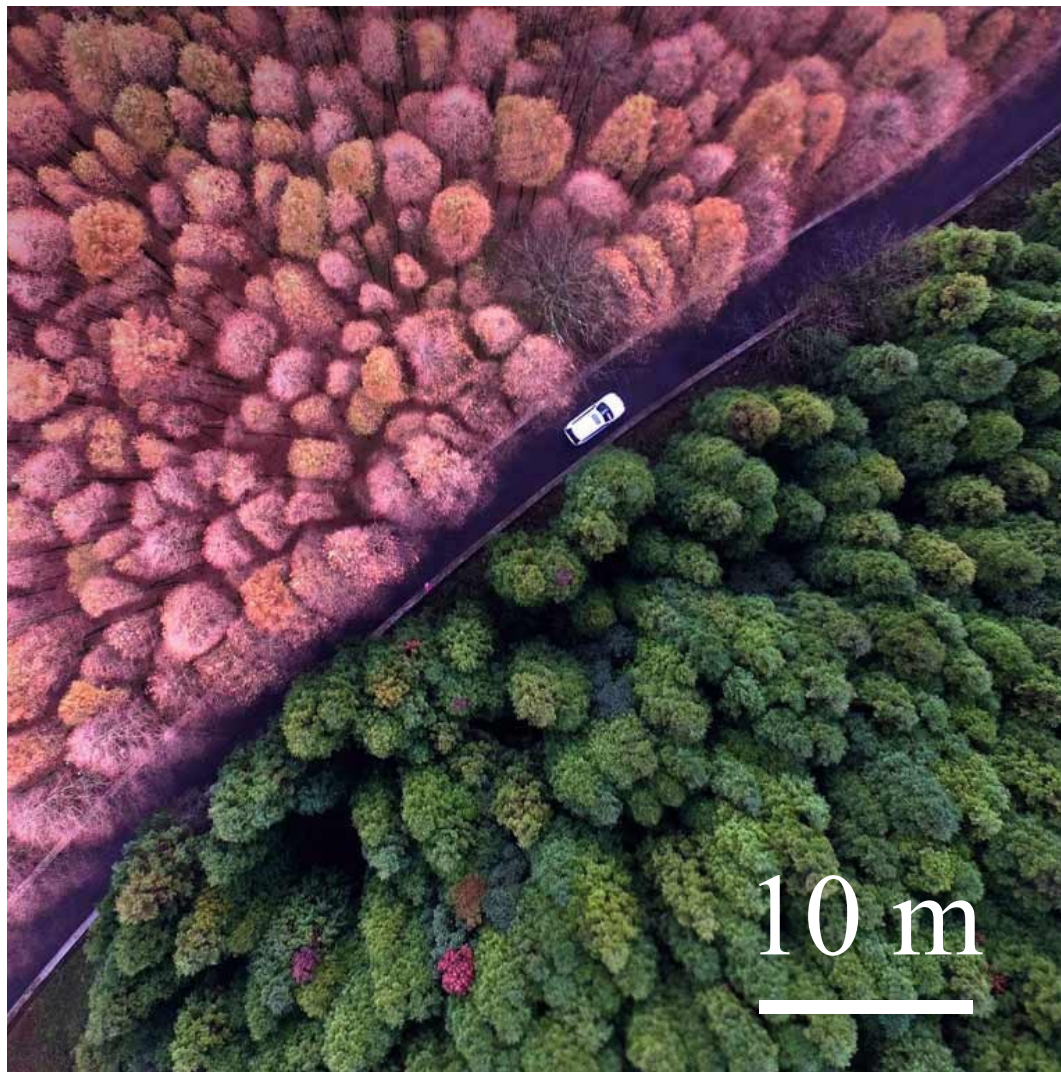


Jiang XIAO

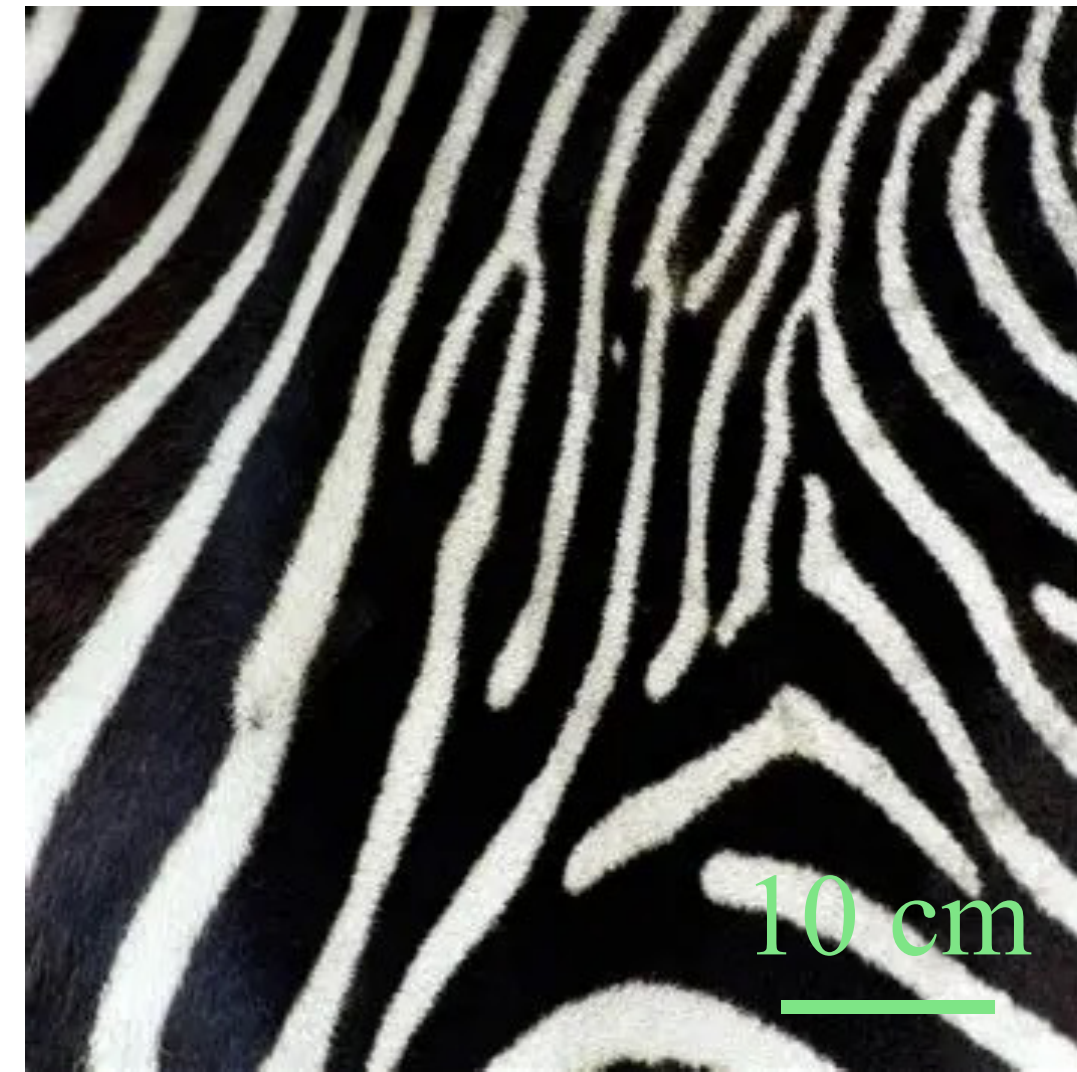
Fudan University, Shanghai, China

SPICE Workshop: FERRONS AND MAGNONS FRIENDS OR FOES?
Ingelheim, Germany, July 7th – 9th, 2026

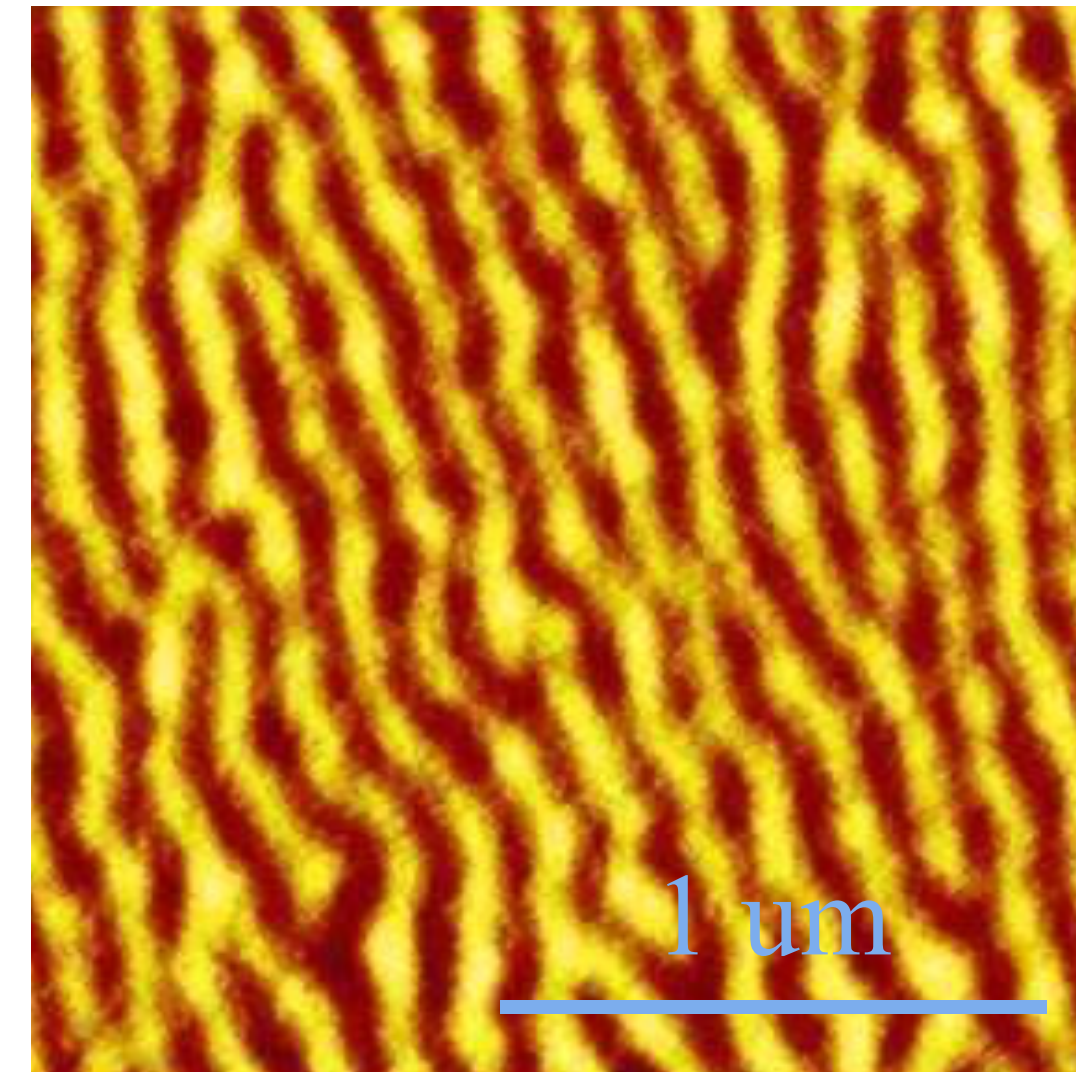
Texture



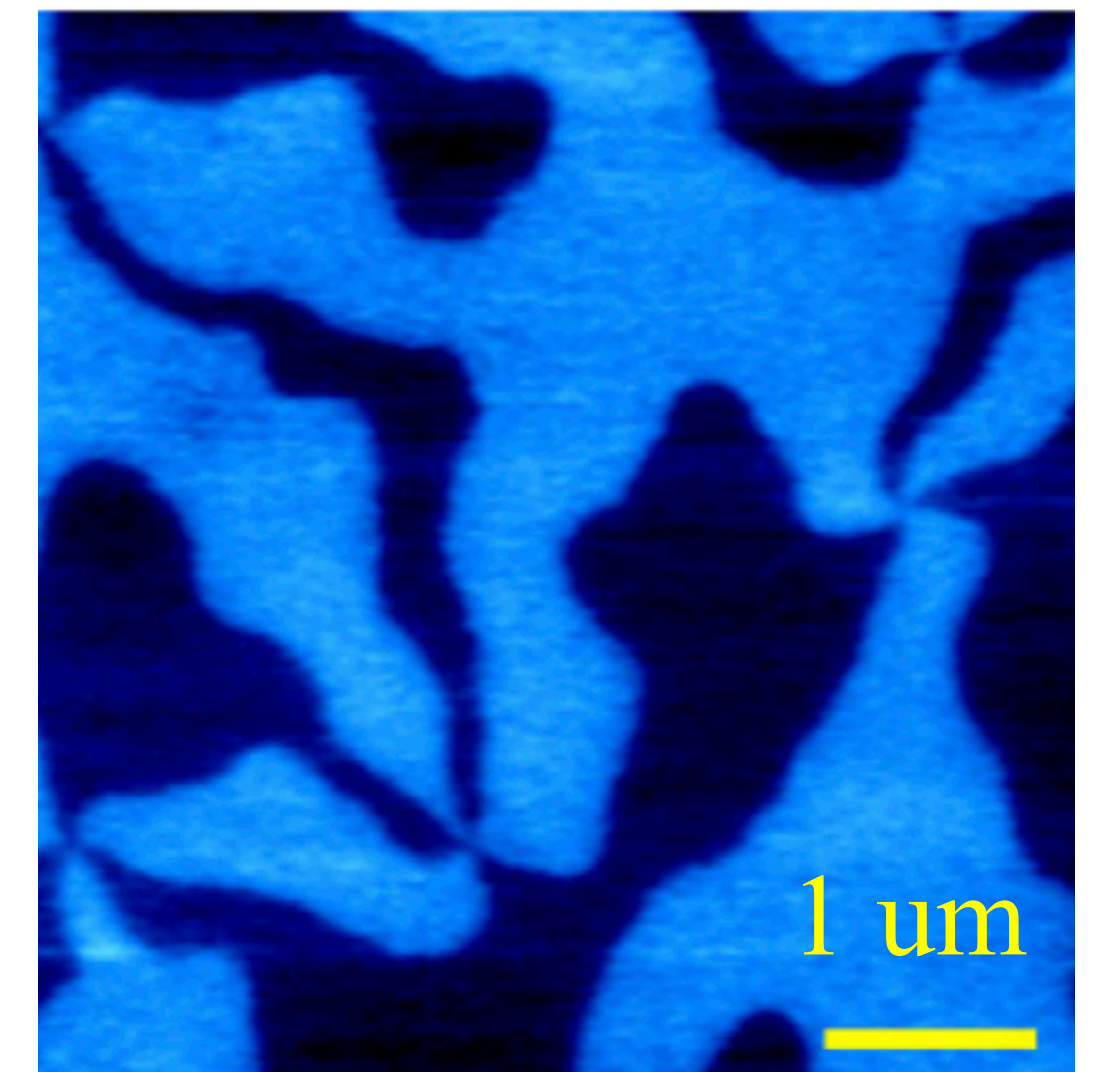
Trees



Zebra

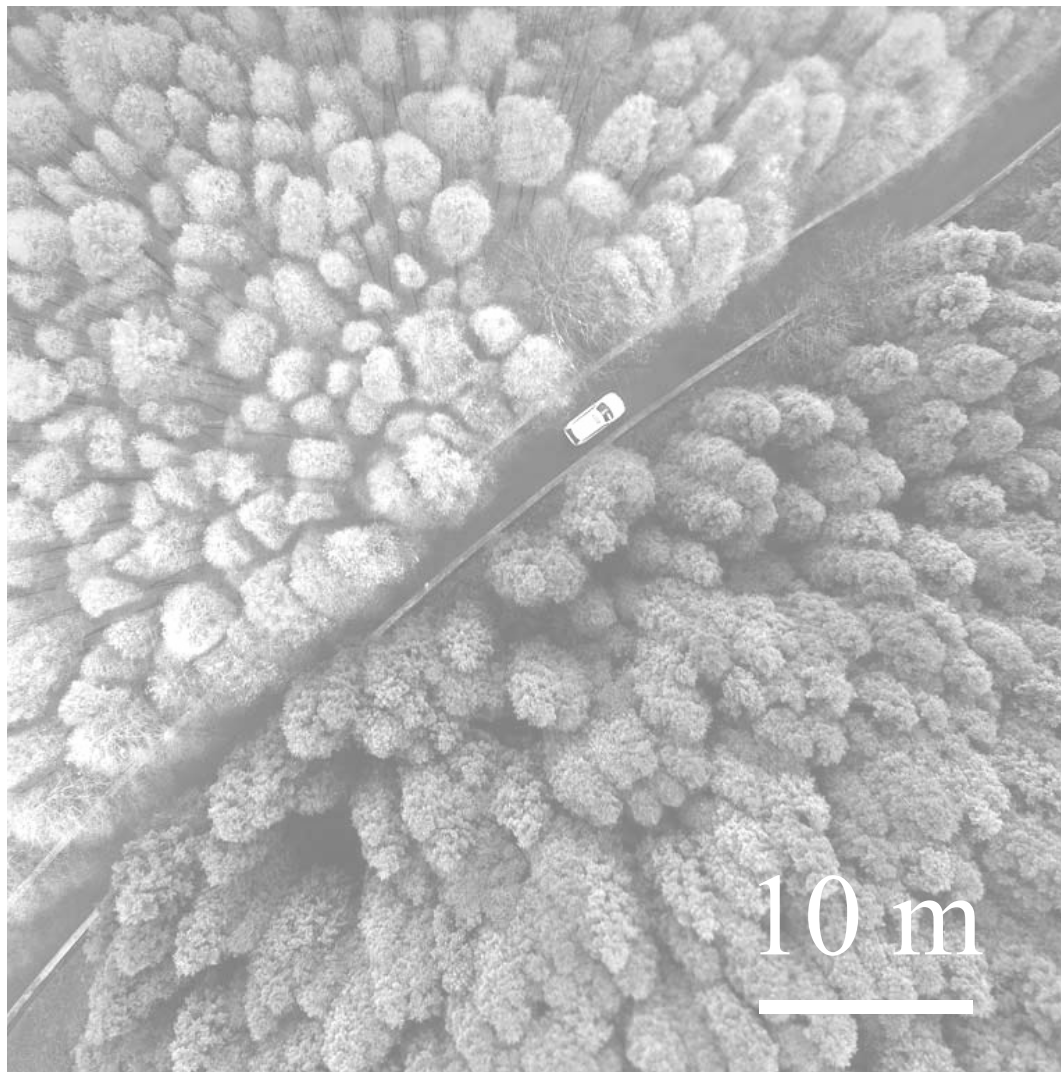


Magnetism

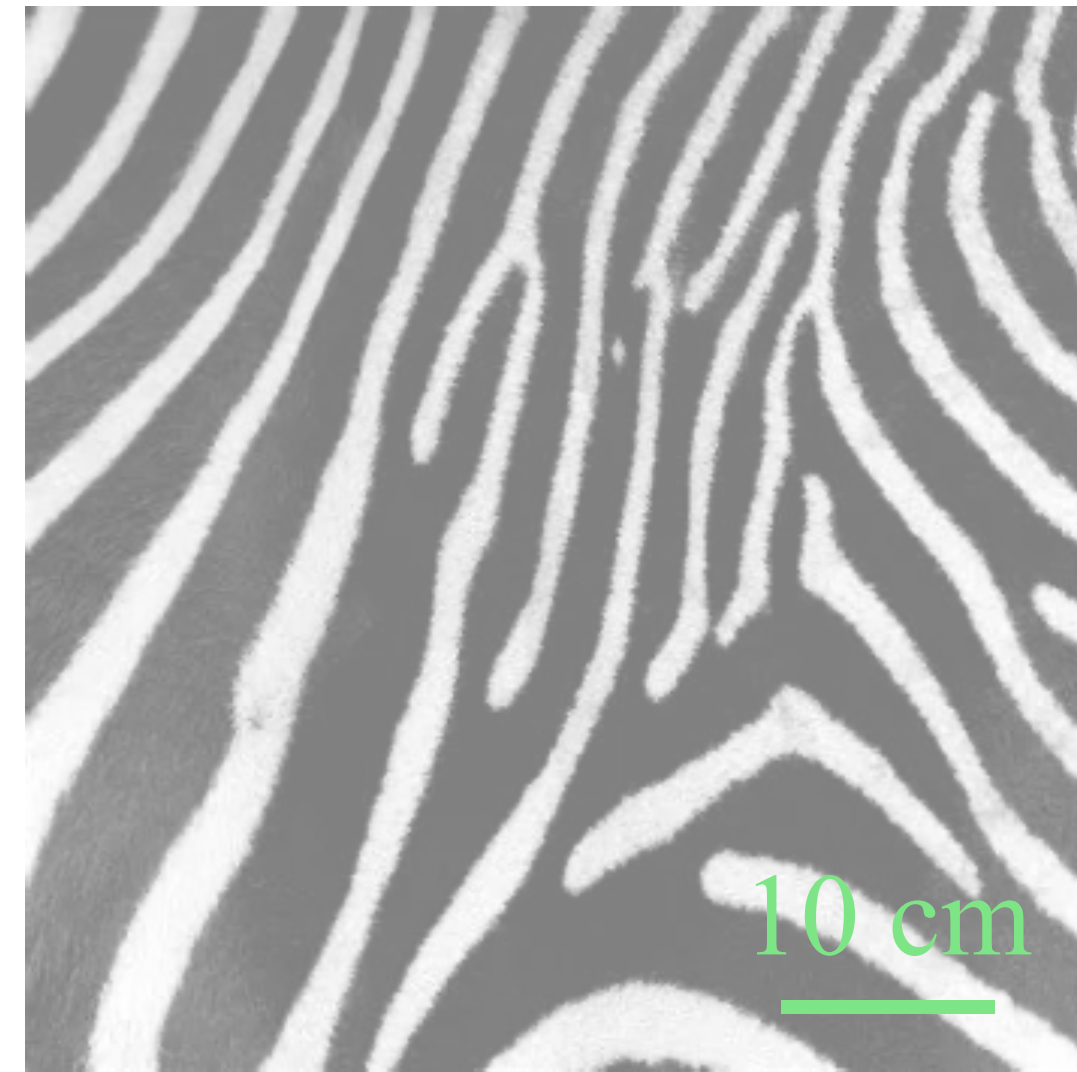


Ferroelectricity

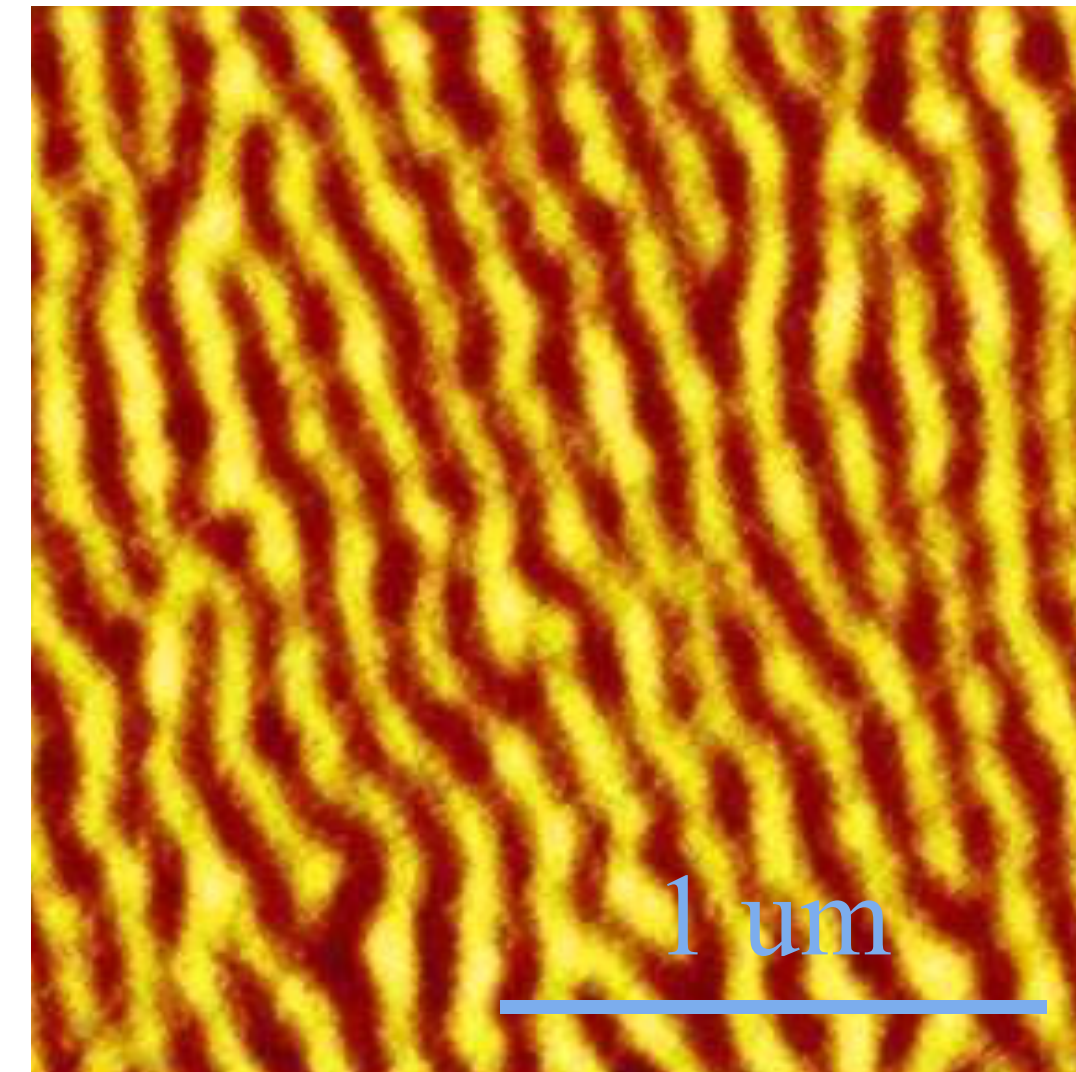
Texture



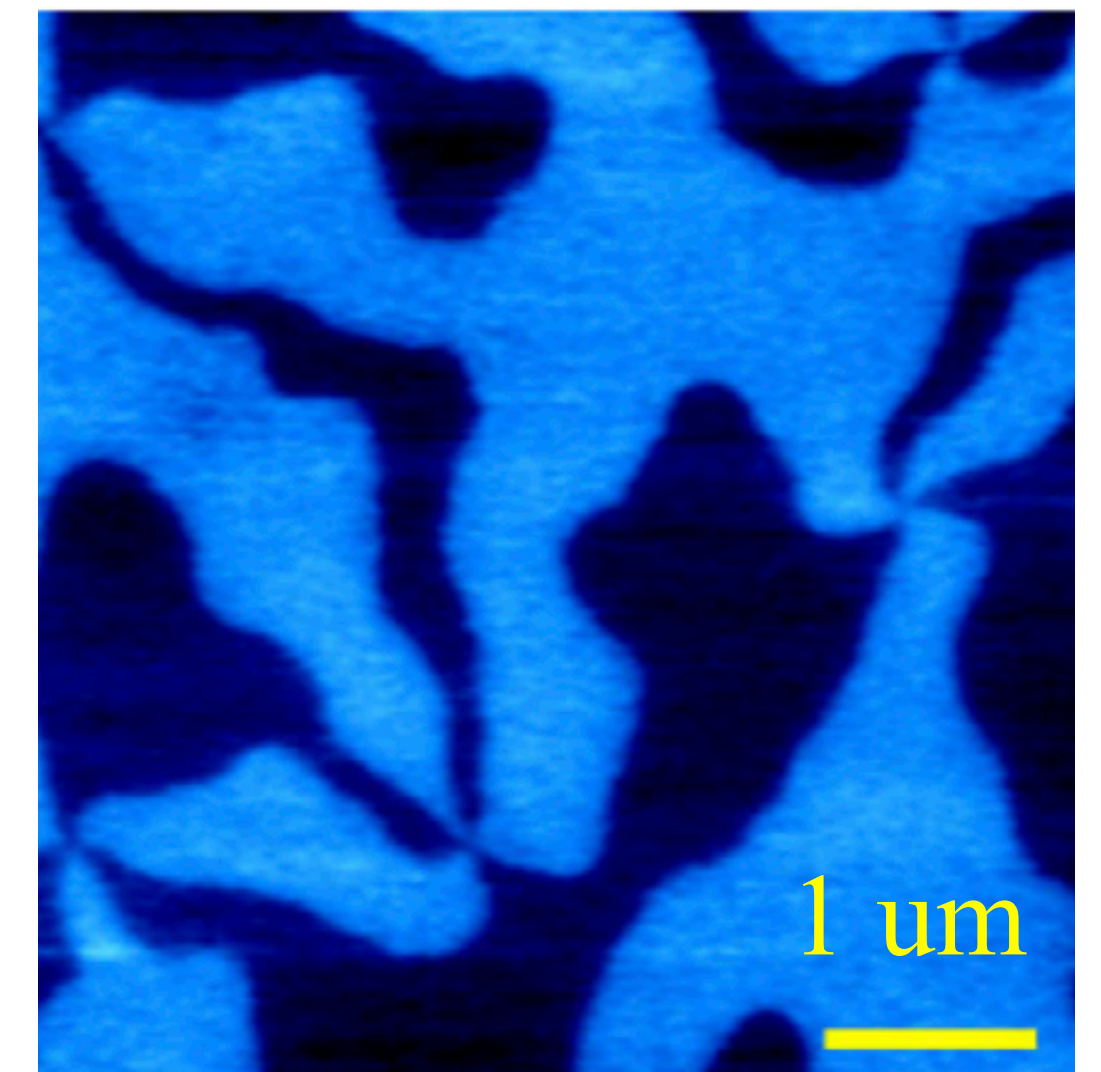
Trees



Zebra

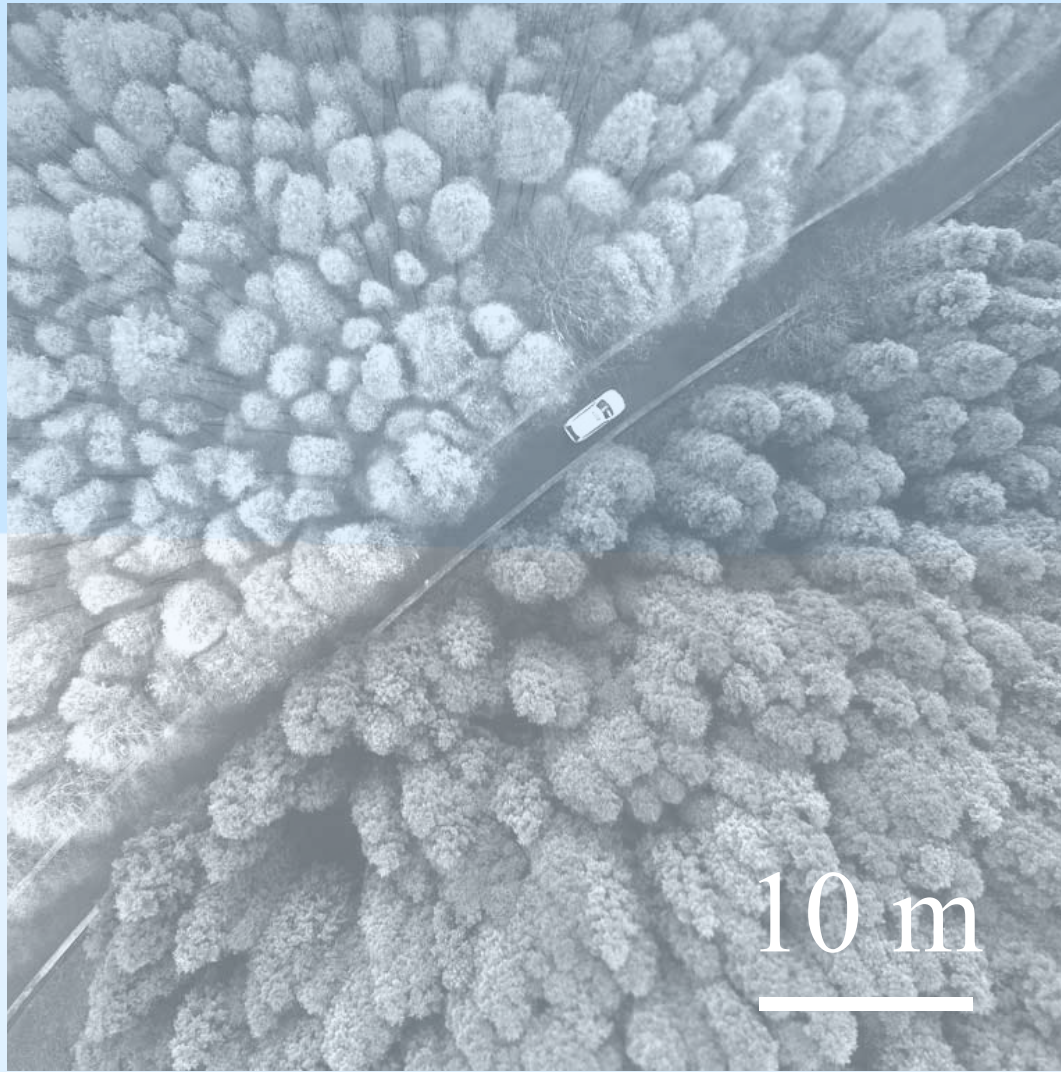


Magnetism

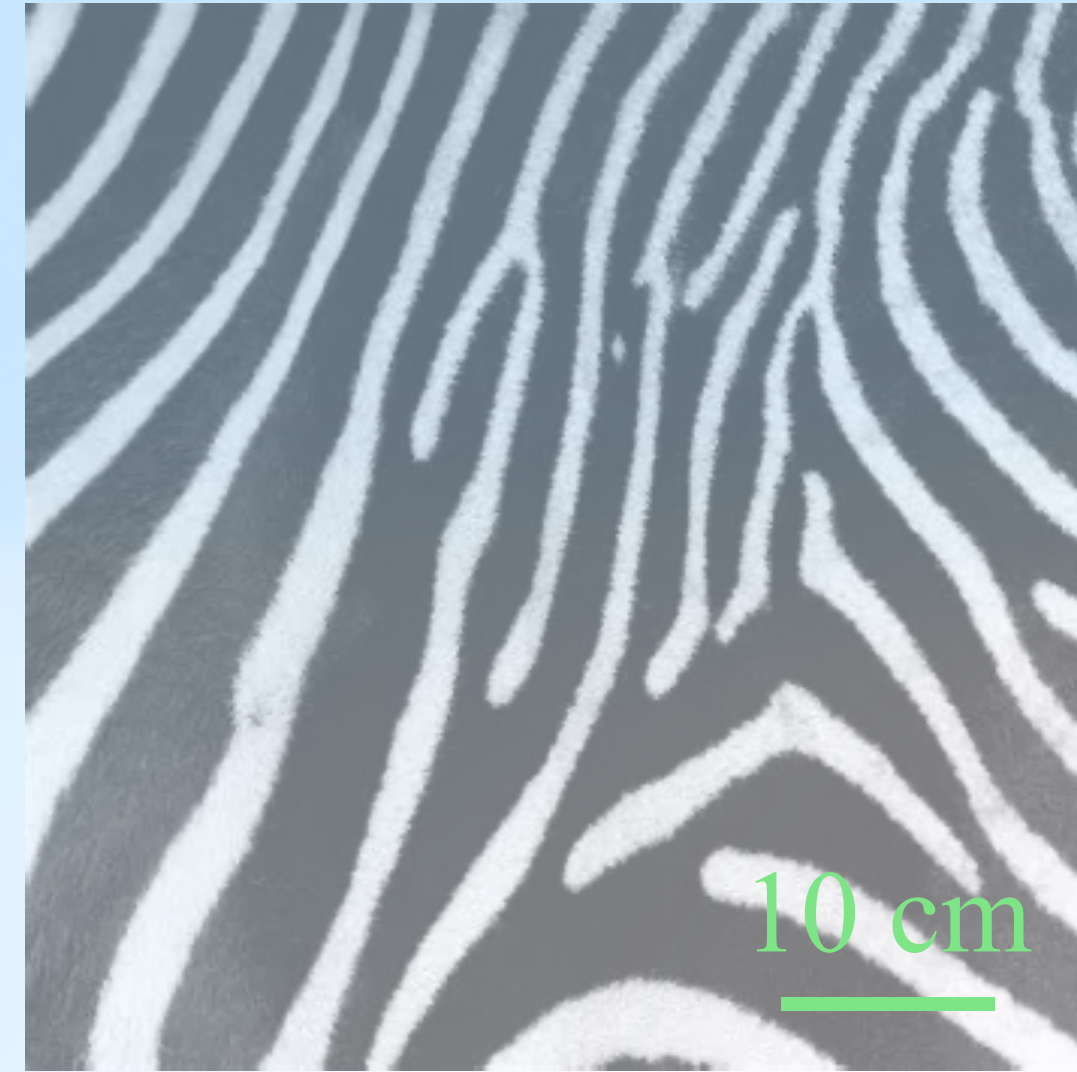


Ferroelectricity

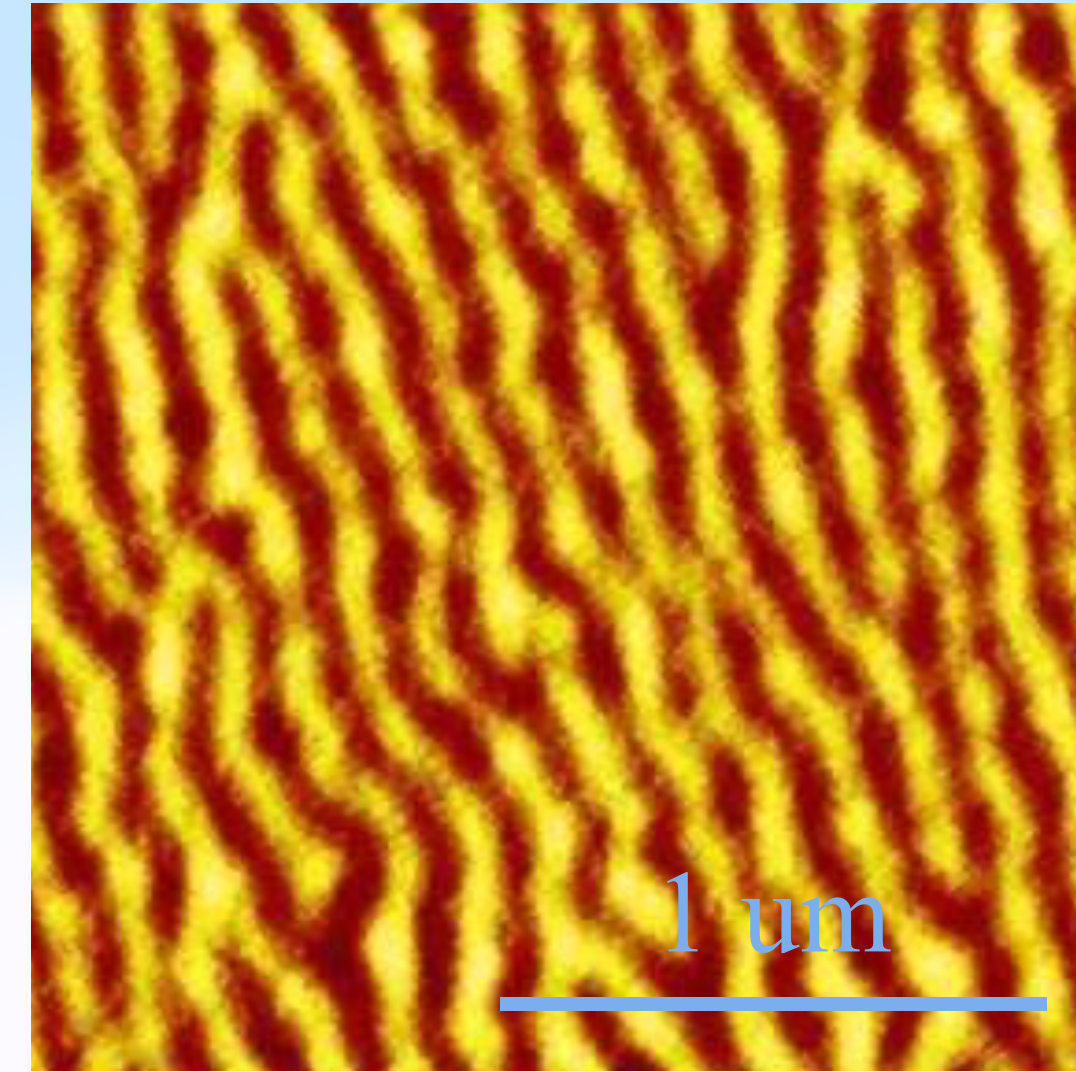
Magnetic Texture



Trees



Zebra

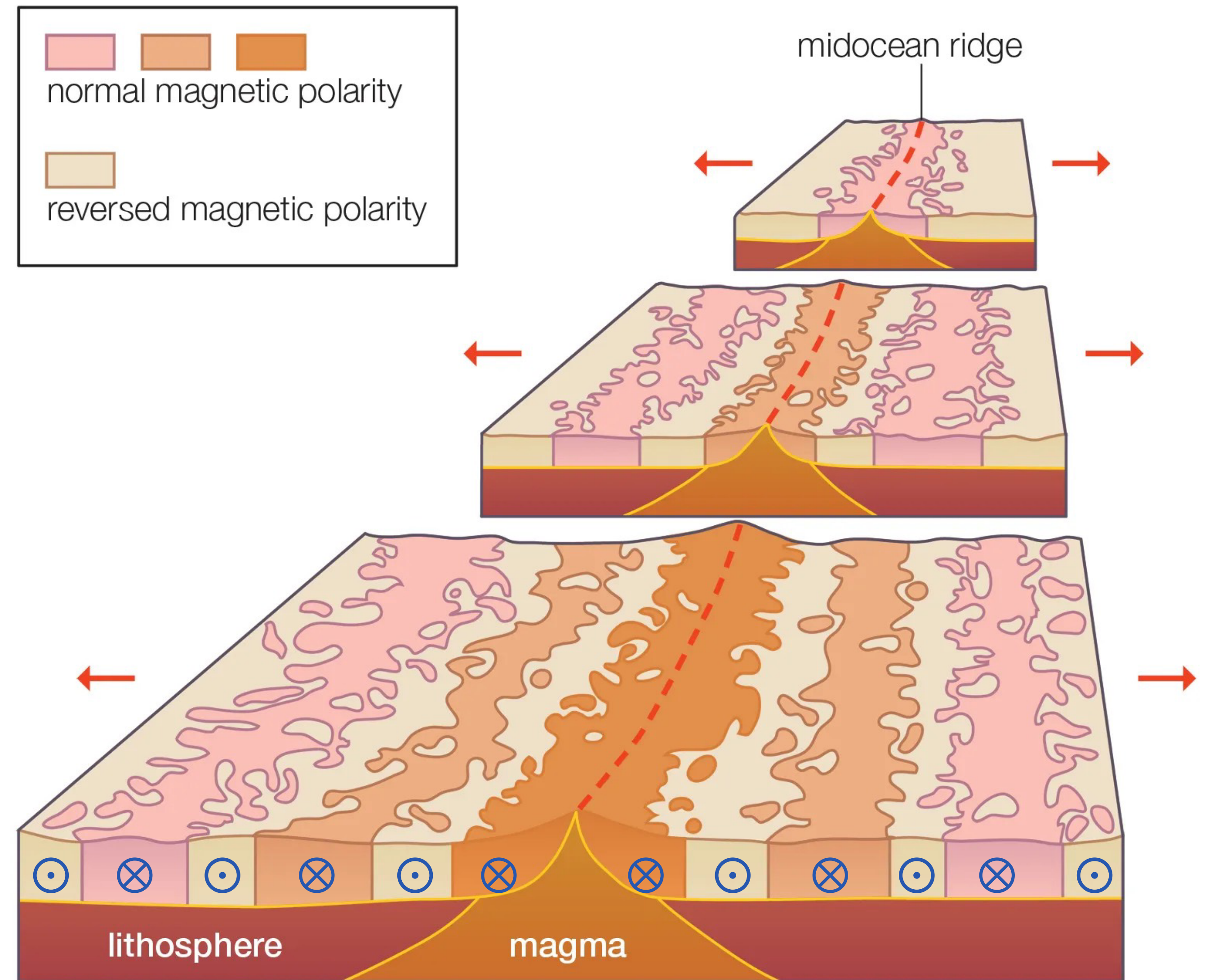
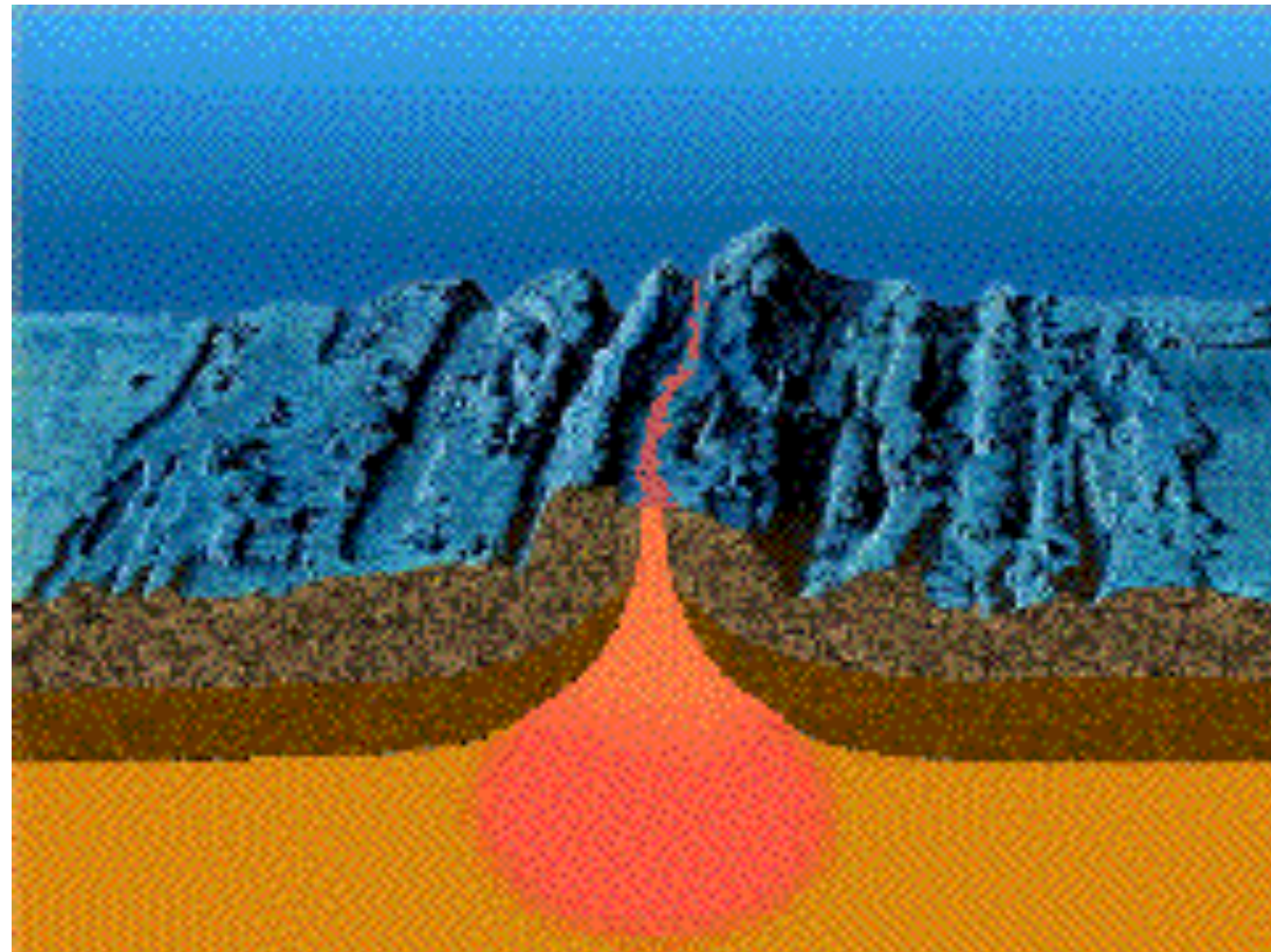


Magnetism

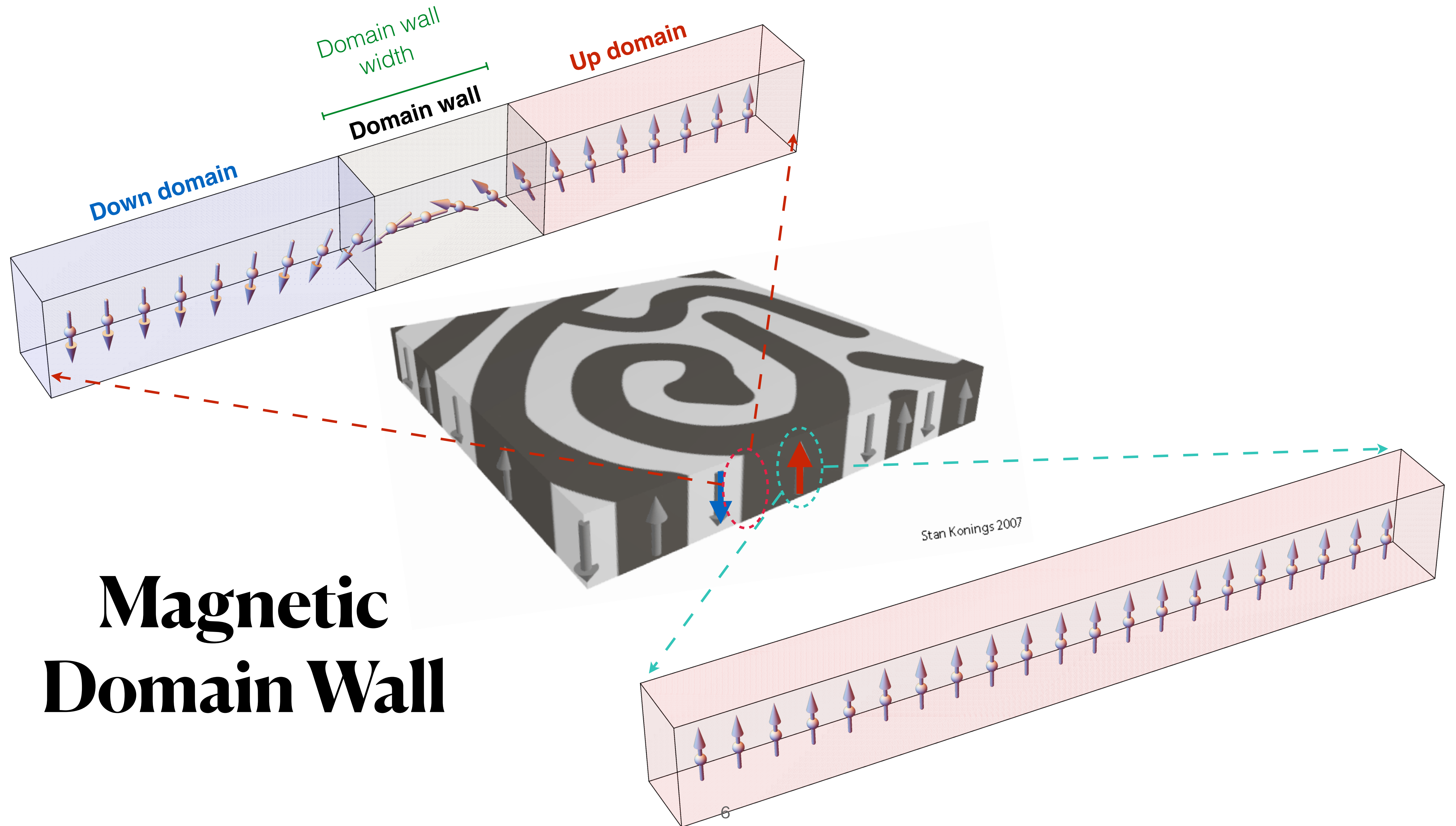


Ferroelectricity

Pre-history magnetism



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Magnetic Domain Wall

Spin wave excitation: LLG to Schrödinger

Landau-Lifshitz Gilbert (LLG) equation

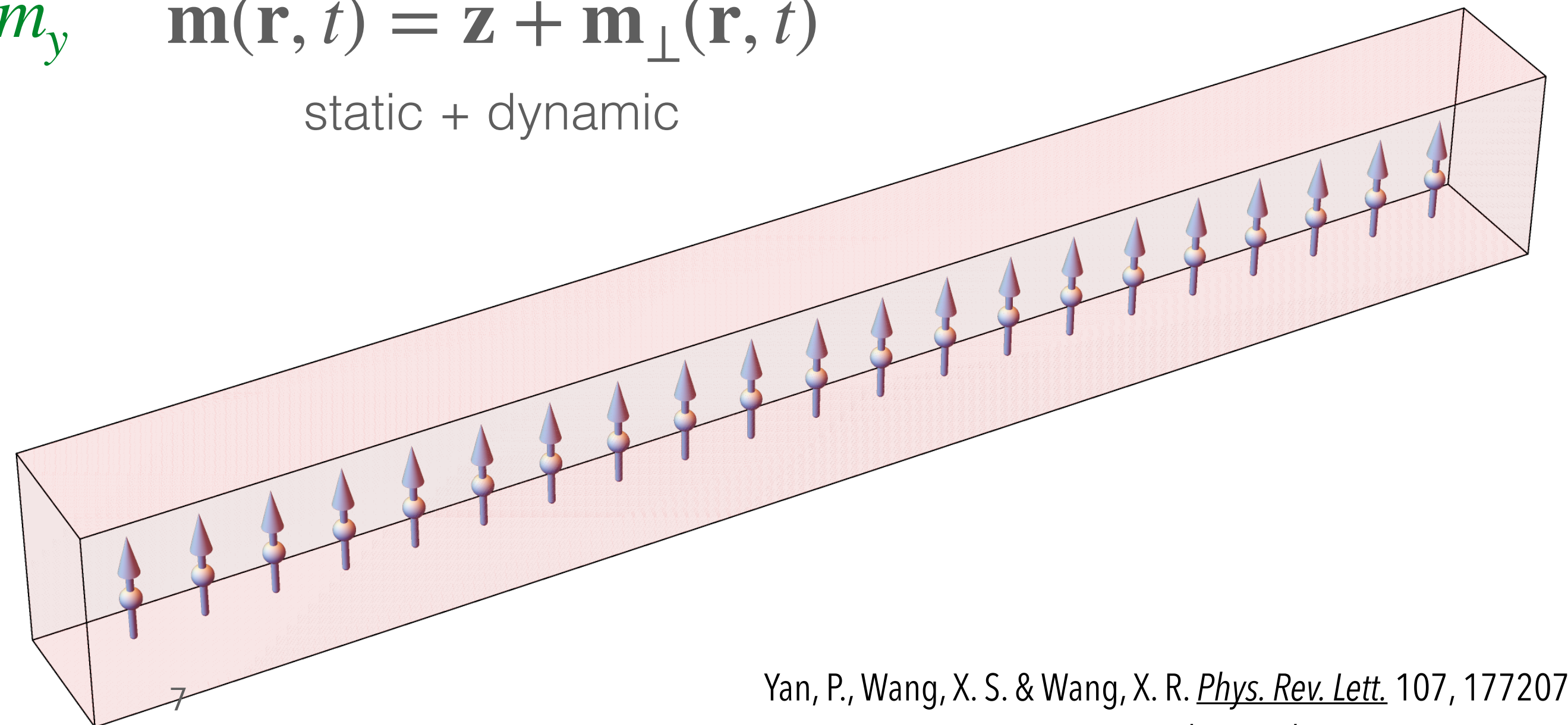
$$\frac{d}{dt}\mathbf{m}(\mathbf{r}, t) = -\mathbf{m} \times \overbrace{(\mathbf{K} + \mathbf{H}_{\text{ext}} + J\nabla^2\mathbf{m})}^{\mathbf{H}_{\text{eff}}} + \alpha\mathbf{m} \times \dot{\mathbf{m}}$$

$$\mathbf{m}_{\perp}(\mathbf{r}, t) \Rightarrow \psi(\mathbf{r}, t) \equiv m_x + im_y \quad \mathbf{m}(\mathbf{r}, t) = \mathbf{z} + \mathbf{m}_{\perp}(\mathbf{r}, t)$$

static + dynamic

$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m^*}\nabla^2\psi$$

Effective Schrödinger Eq.



Yan, P., Wang, X. S. & Wang, X. R. *Phys. Rev. Lett.* 107, 177207 (2011)

J. Lan, W. Yu, R. Wu, and **JX***, *Phys. Rev. X* 5, 041049 (2015)

Spin wave excitation: LLG to Schrödinger

Landau-Lifshitz Gilbert (LLG) equation

$$\frac{d}{dt}\mathbf{m}(\mathbf{r}, t) = -\mathbf{m} \times \overbrace{(\mathbf{K} + \mathbf{H}_{\text{ext}} + J\nabla^2\mathbf{m})}^{\mathbf{H}_{\text{eff}}} + \alpha\mathbf{m} \times \dot{\mathbf{m}}$$

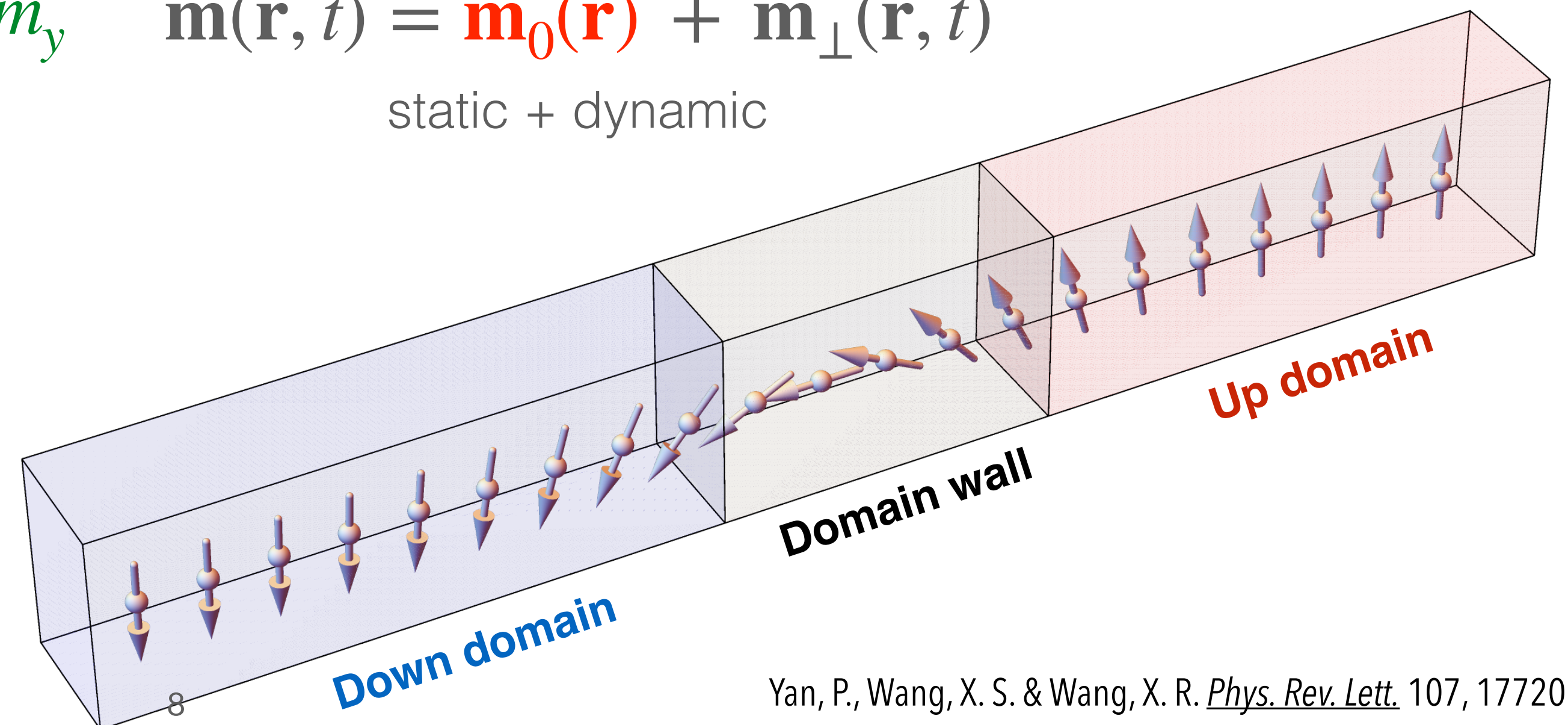
$$\mathbf{m}_{\perp}(\mathbf{r}, t) \Rightarrow \psi(\mathbf{r}, t) \equiv m_x + im_y$$

$$\mathbf{m}(\mathbf{r}, t) = \mathbf{m}_0(\mathbf{r}) + \mathbf{m}_{\perp}(\mathbf{r}, t)$$

static + dynamic

$$i\hbar\frac{\partial}{\partial t}\psi = \left[-\frac{\hbar^2}{2m^*} \left(\nabla + i\frac{q}{\hbar c}\mathbf{A}(\mathbf{r}) \right)^2 + V(\mathbf{r}) \right] \psi$$

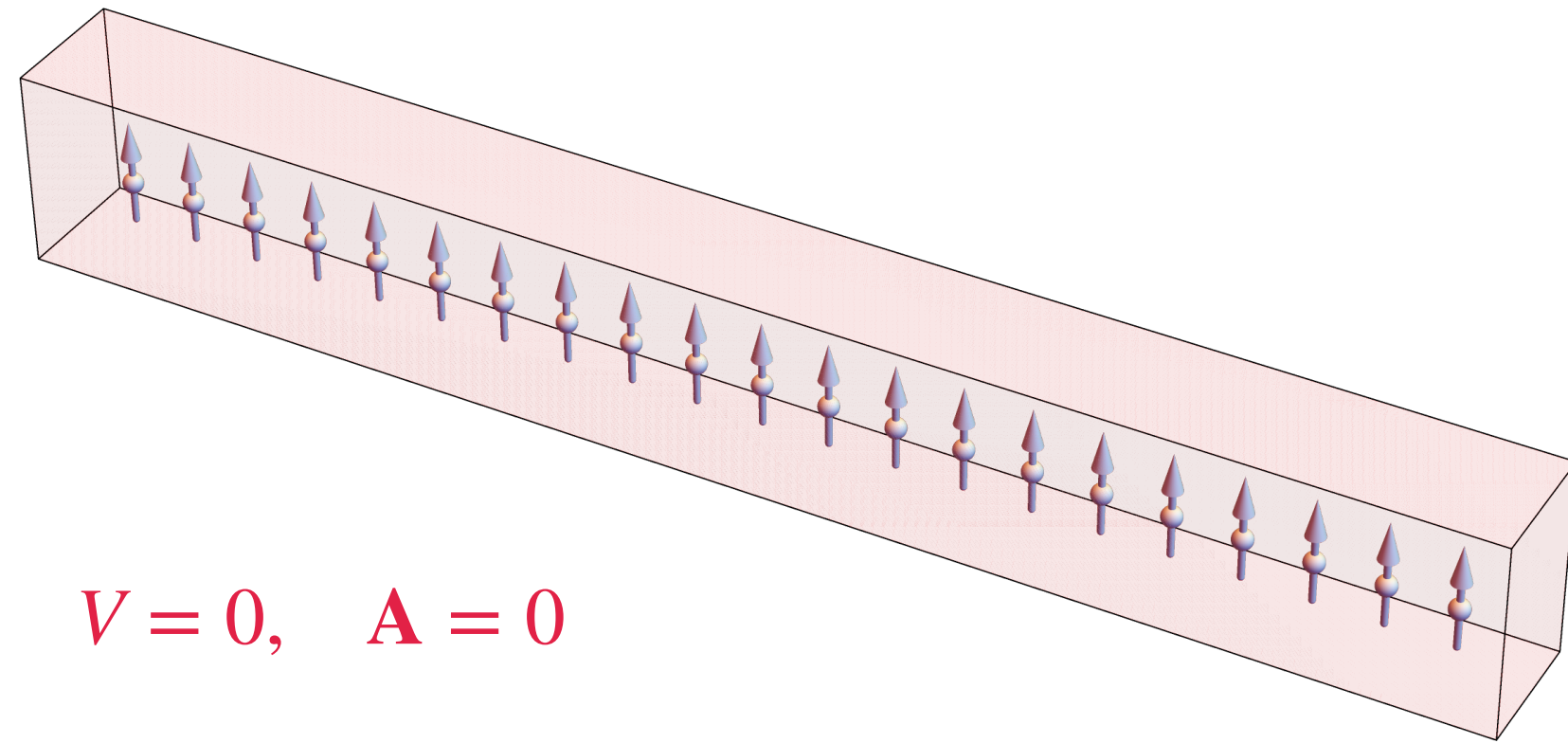
Effective Schrödinger Eq.



Yan, P., Wang, X. S. & Wang, X. R. *Phys. Rev. Lett.* 107, 177207 (2011)

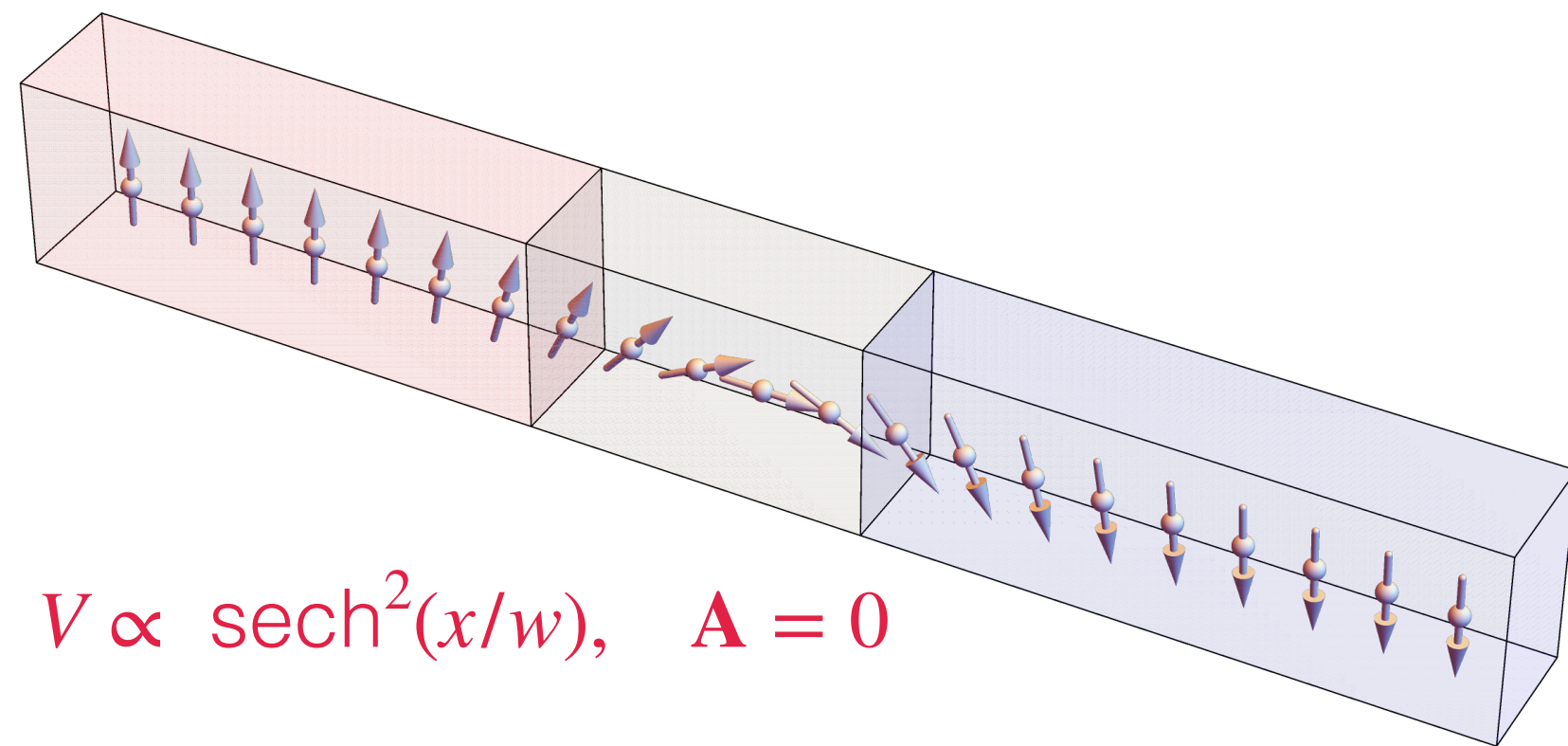
J. Lan, W. Yu, R. Wu, and **JX***, *Phys. Rev. X* 5, 041049 (2015)

Spin wave excitation: LLG to Schrödinger



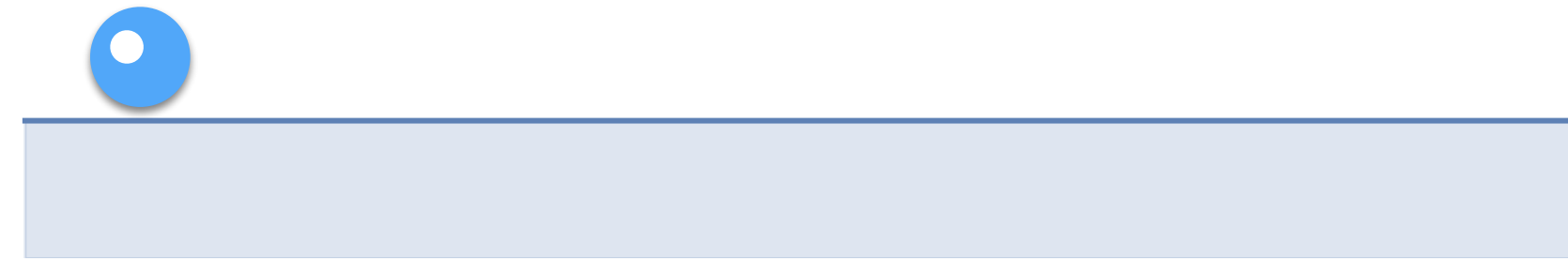
$$V = 0, \quad \mathbf{A} = 0$$

A homogeneous domain



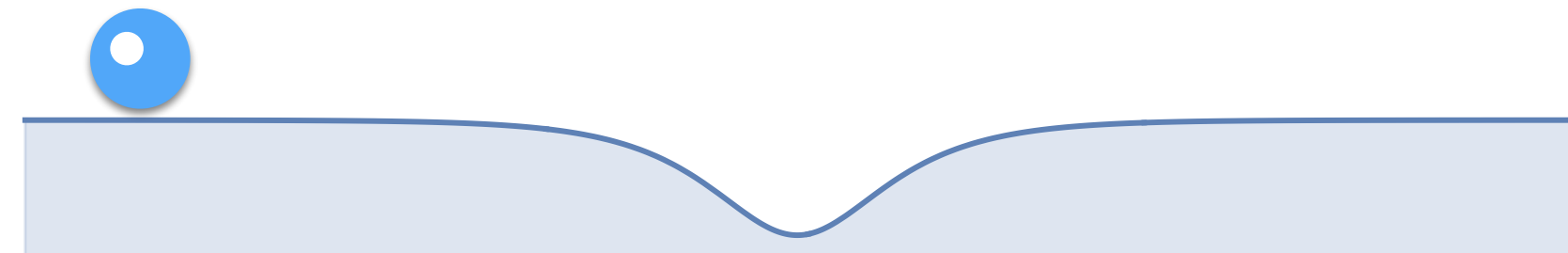
$$V \propto \text{sech}^2(x/w), \quad \mathbf{A} = 0$$

A magnetic domain wall

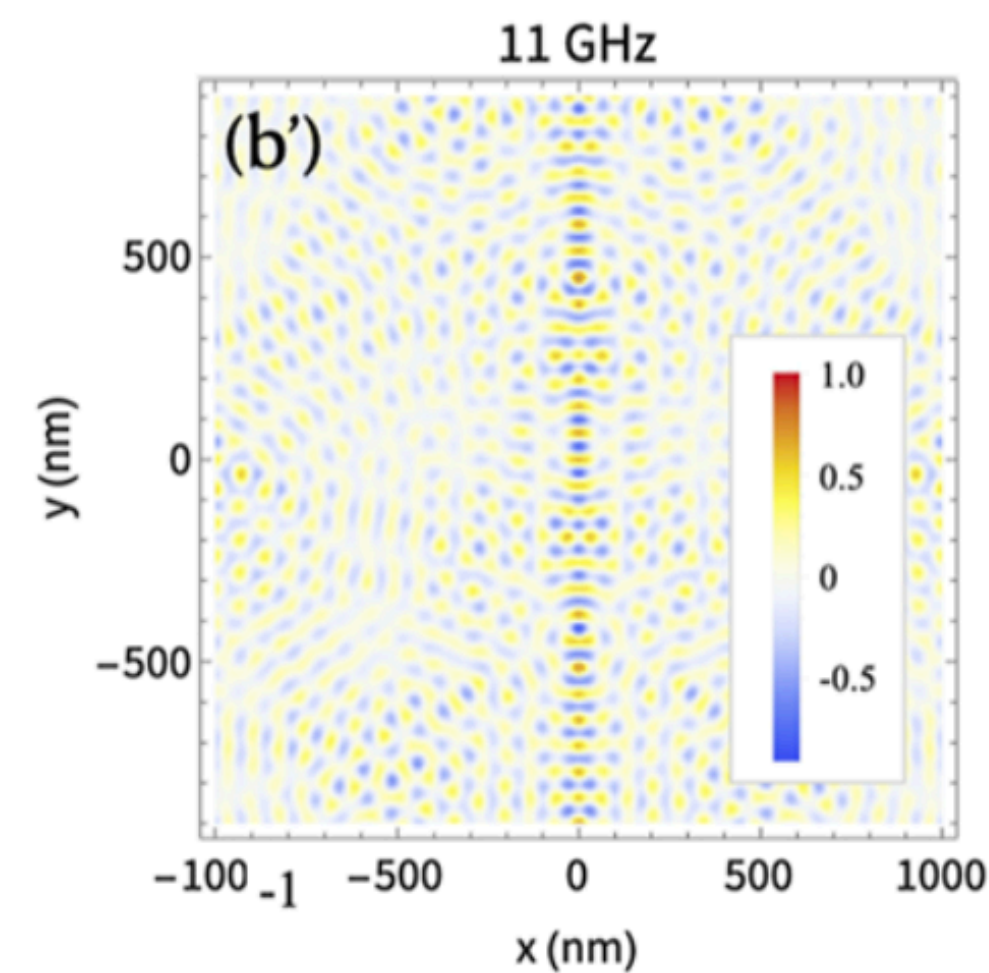
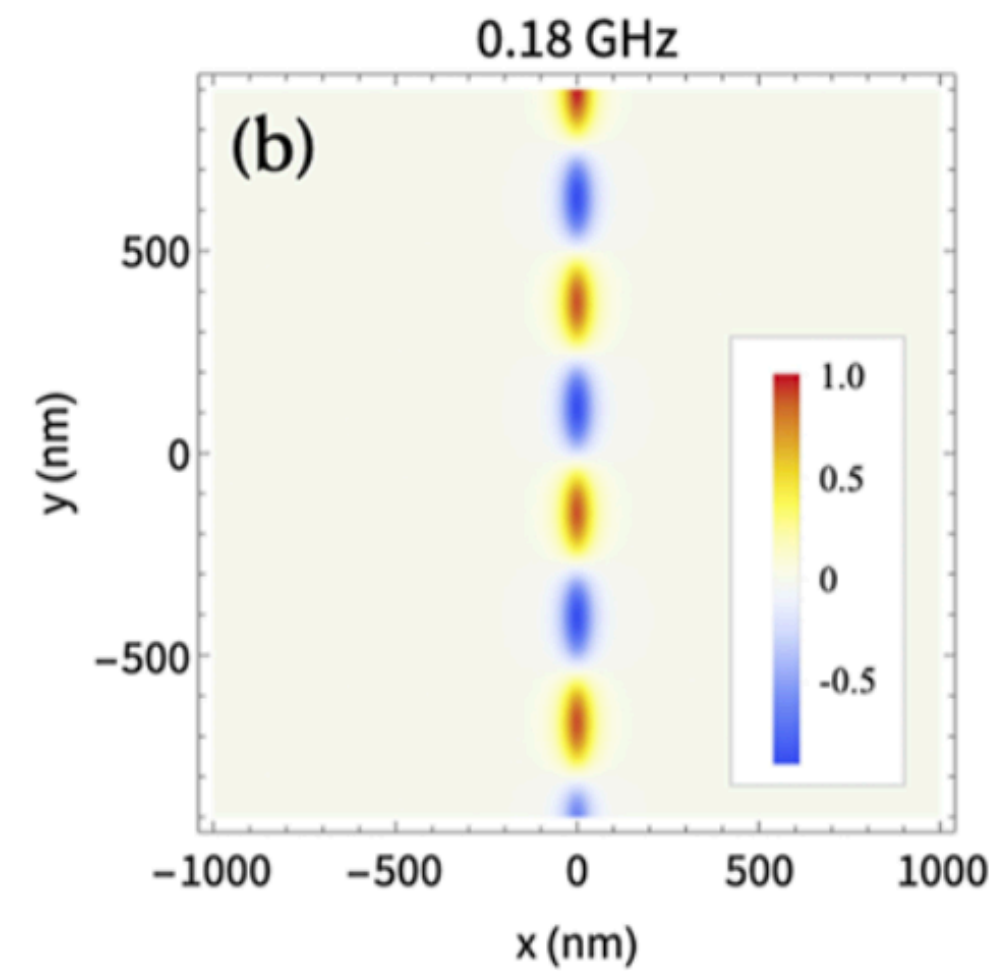
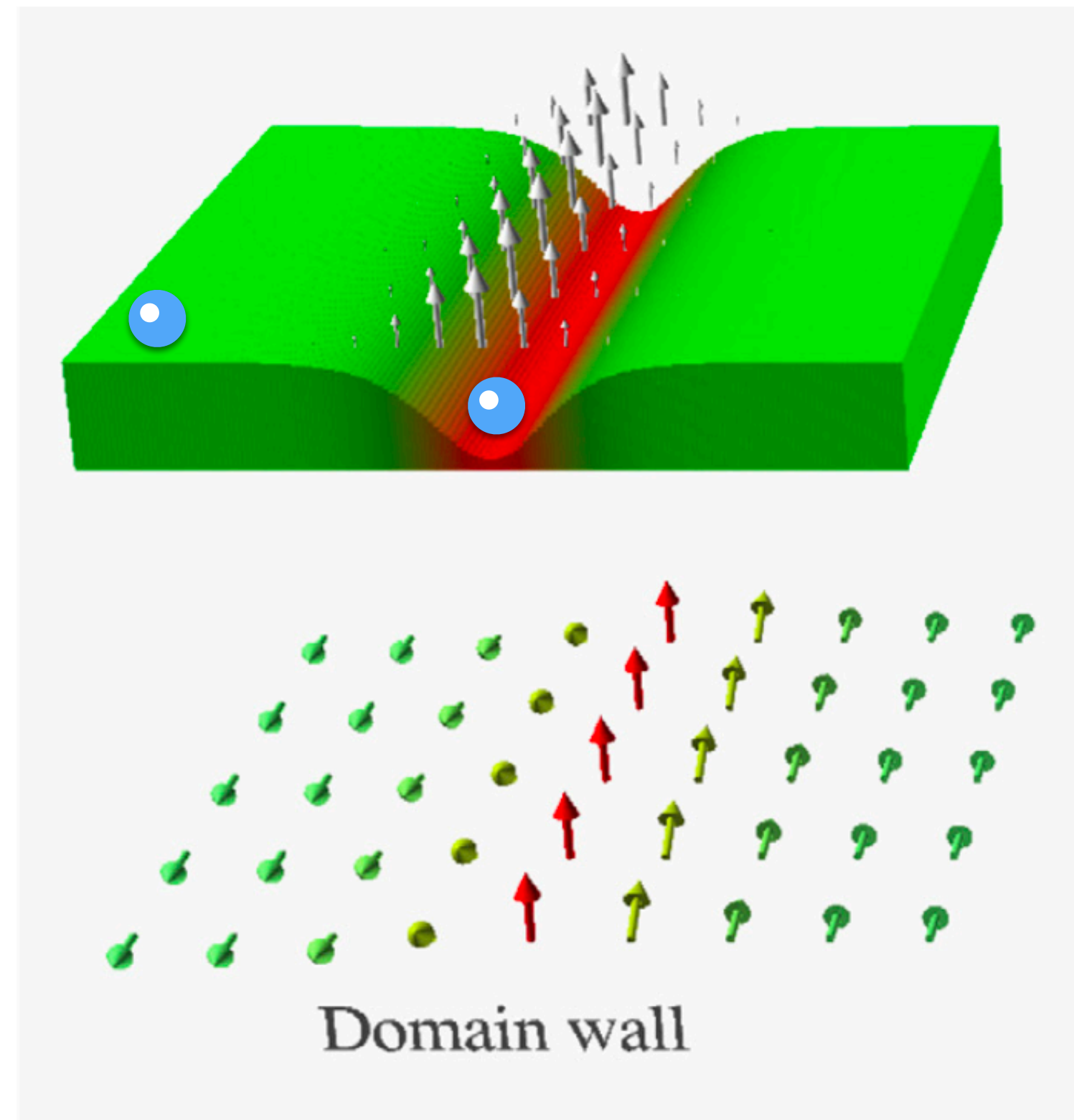


$$i\hbar \frac{\partial}{\partial t} \psi = \left[-\frac{\hbar^2}{2m^*} \left(\nabla + i \frac{q}{\hbar c} \mathbf{A}(\mathbf{r}) \right)^2 + V(\mathbf{r}) \right] \psi$$

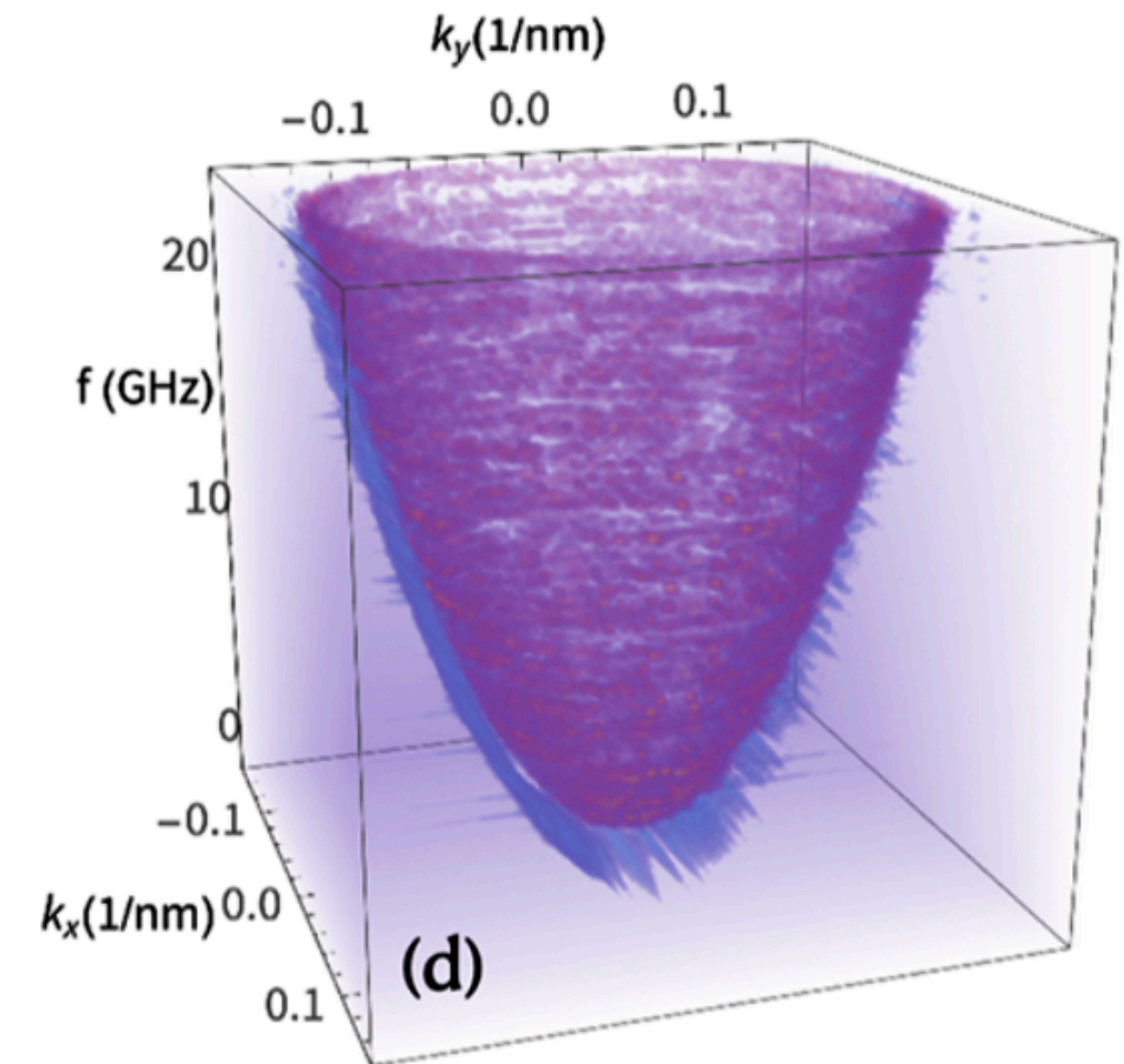
Effective Schrödinger Eq.



Domain wall: waveguide

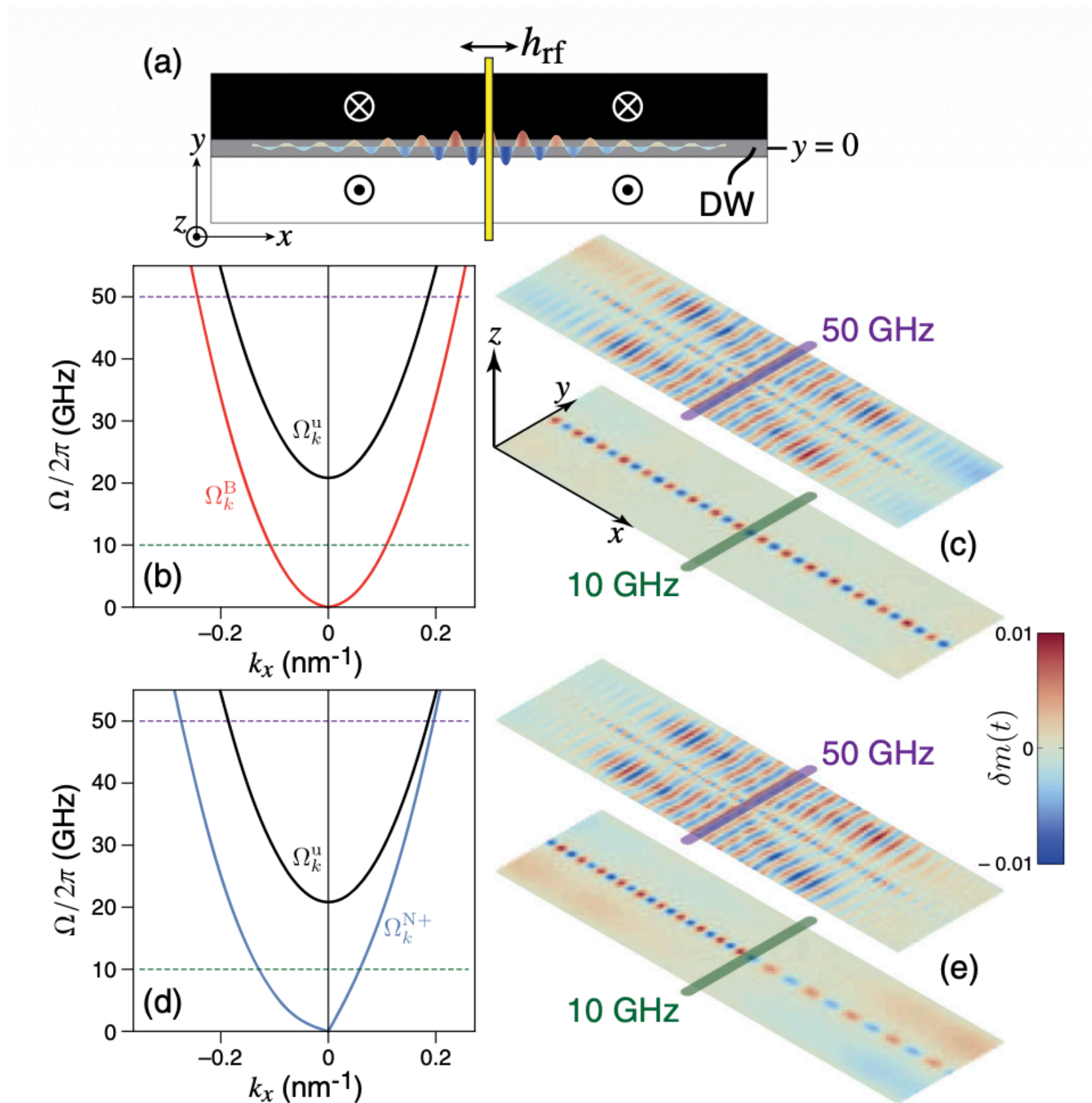


Spin wave dispersion

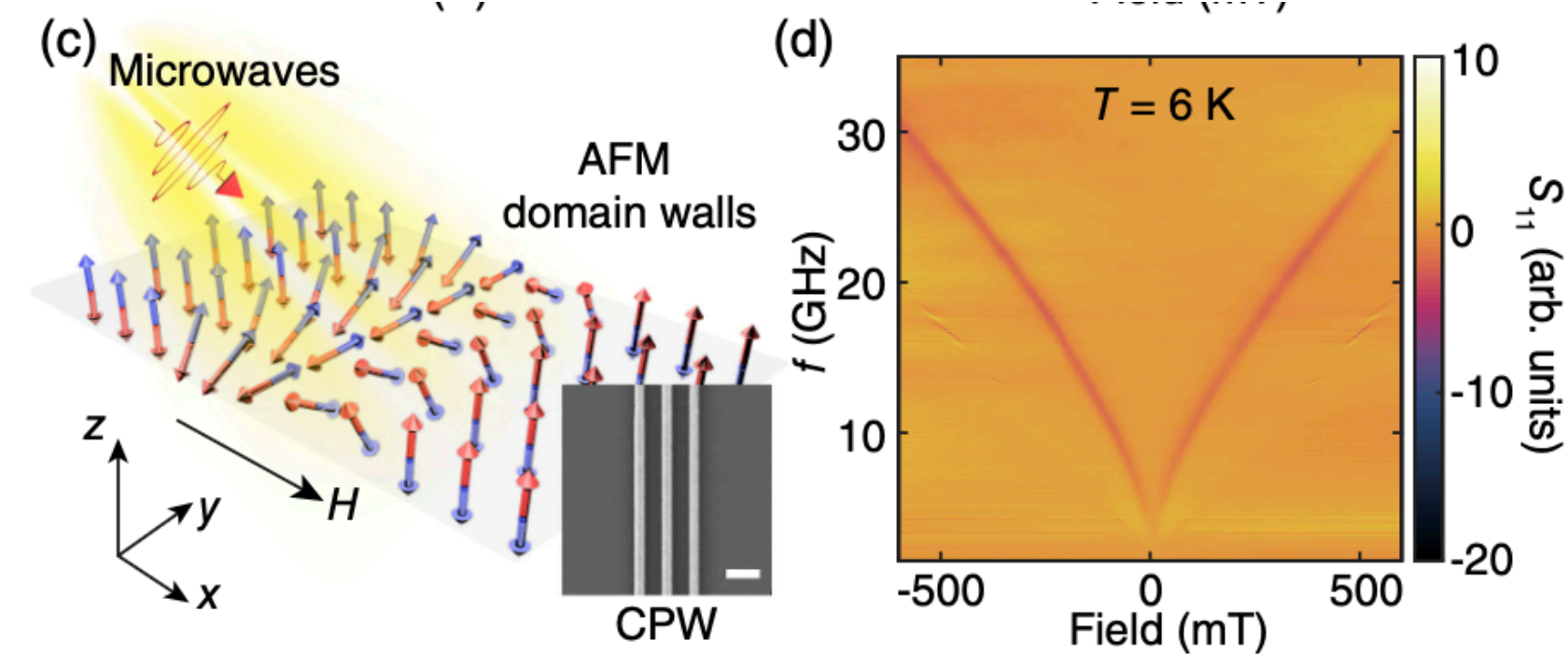


$$E = \frac{\mathbf{p}^2}{2m} = \frac{\hbar^2 \mathbf{k}^2}{2m}$$

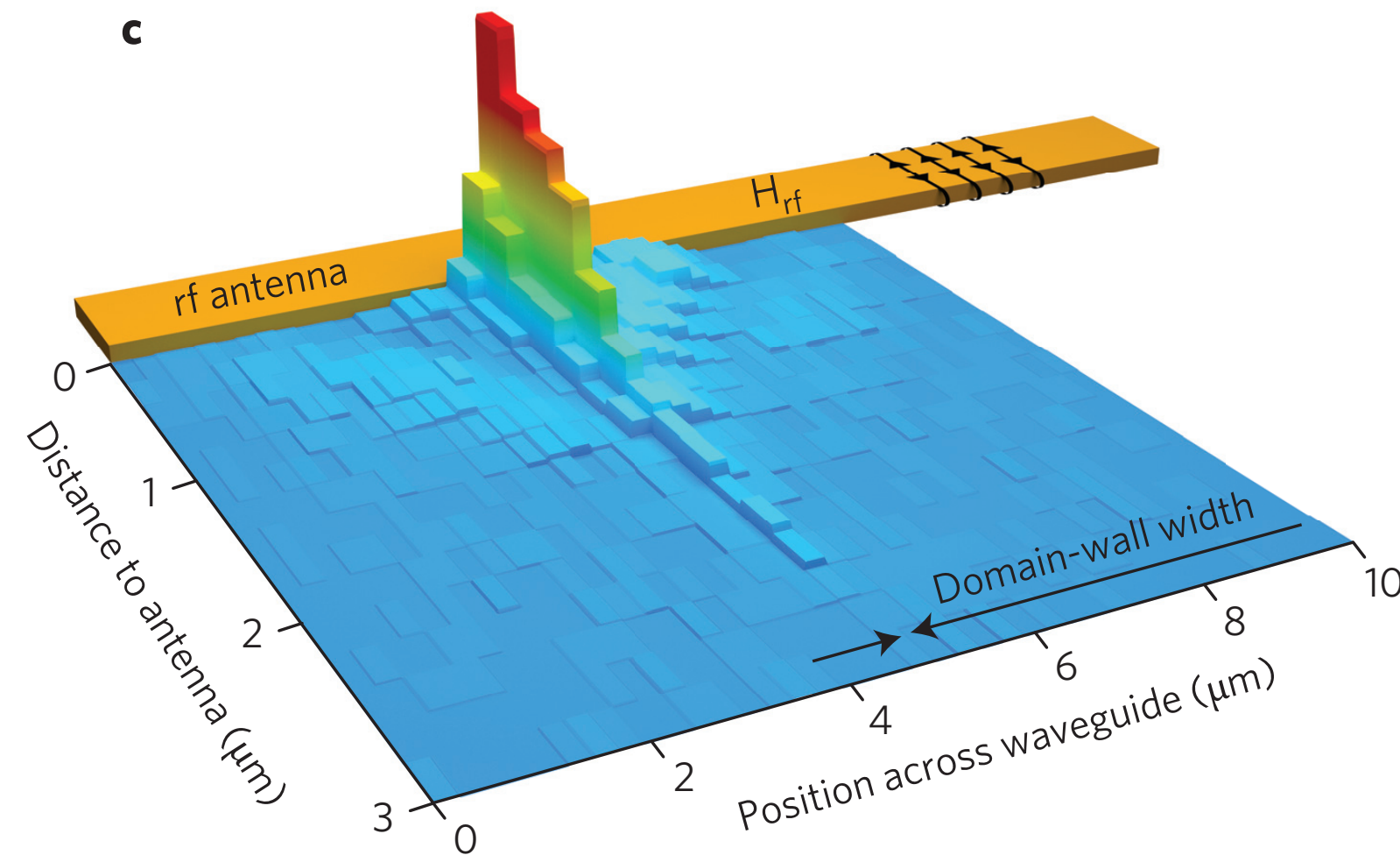
Domain wall: waveguide



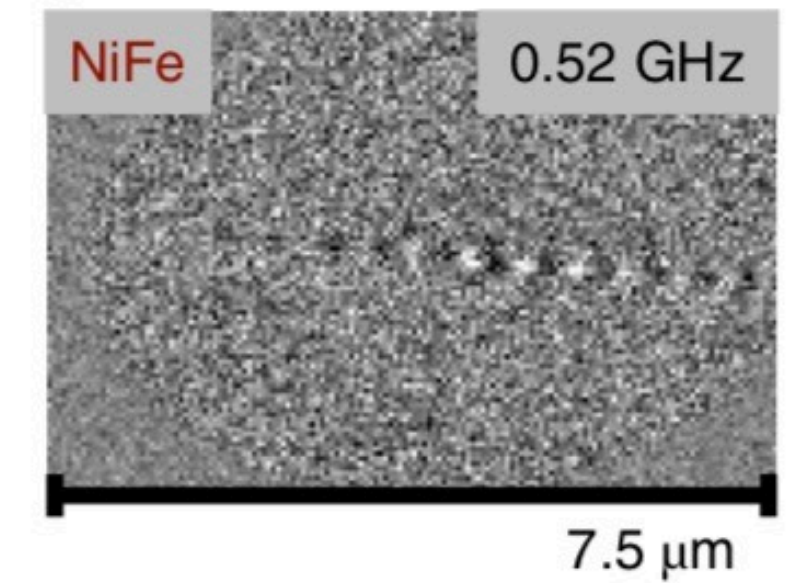
Garcia-Sanchez, F. et al. Phys. Rev. Lett. (2015).



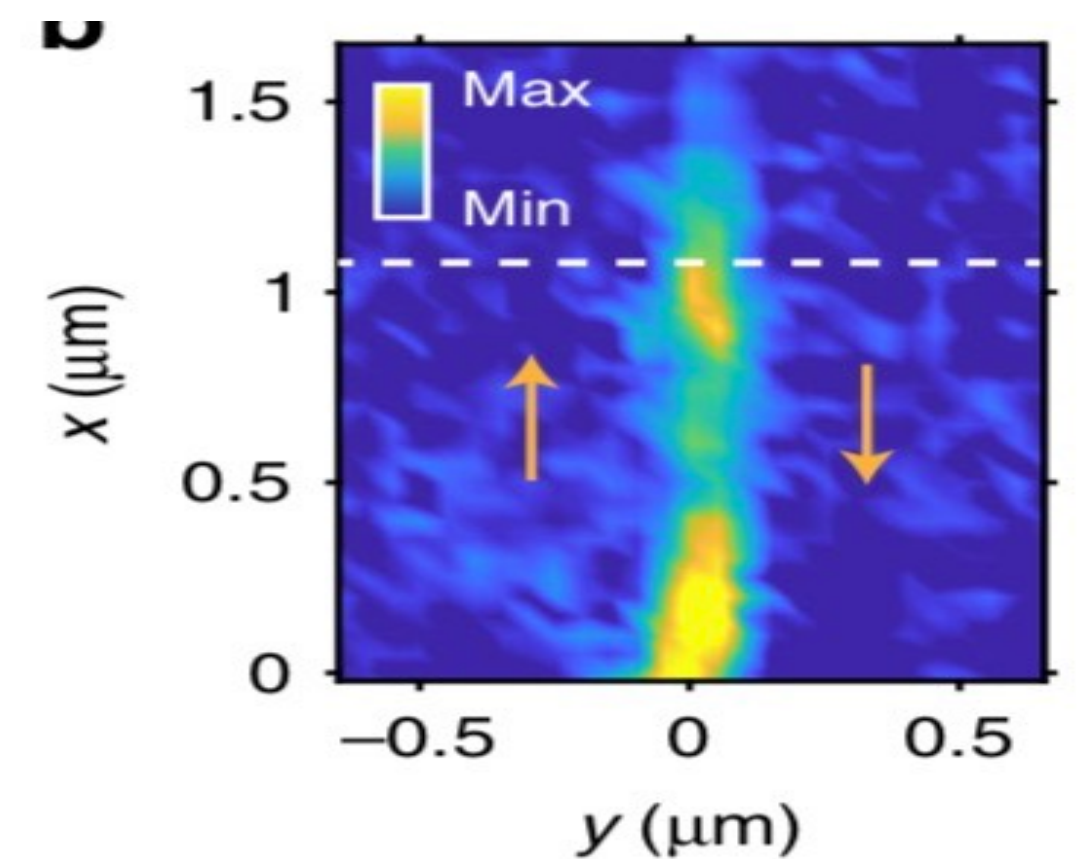
Chen, J. et al. Phys. Rev. Lett. (2025).



Wagner, K. et al. Nature Nano. (2016)



Sluka, V. et al. Nature Nanotechnology (2019)



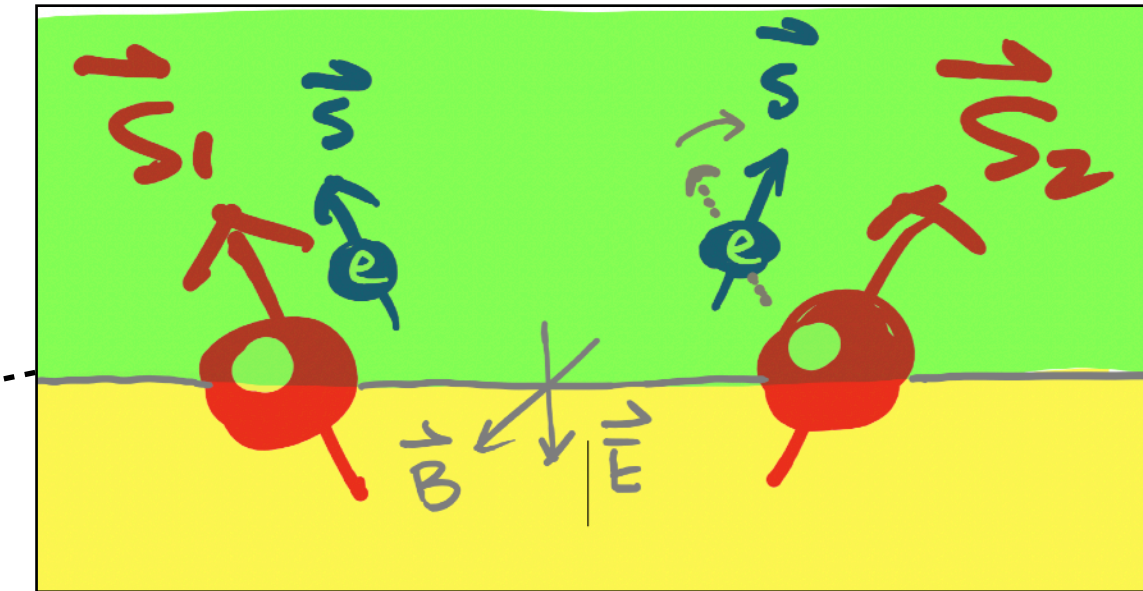
Albisetti, E. et al. Communications Physics 1, (2018)

LLG to Schrödinger

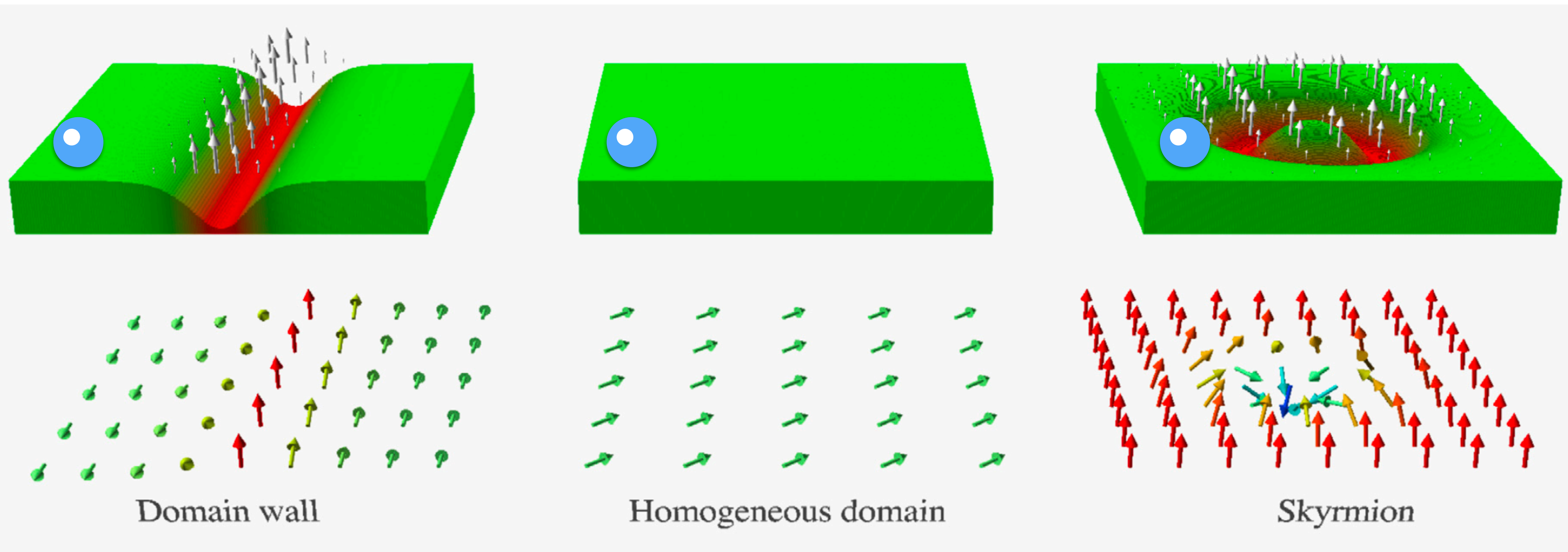
$$i\hbar \frac{\partial}{\partial t} \psi = \left[-\frac{\hbar^2}{2m^*} \left(\nabla + i \frac{q}{\hbar c} \mathbf{A}(\mathbf{r}) \right)^2 + V(\mathbf{r}) \right] \psi$$

due to inhomogeneous texture

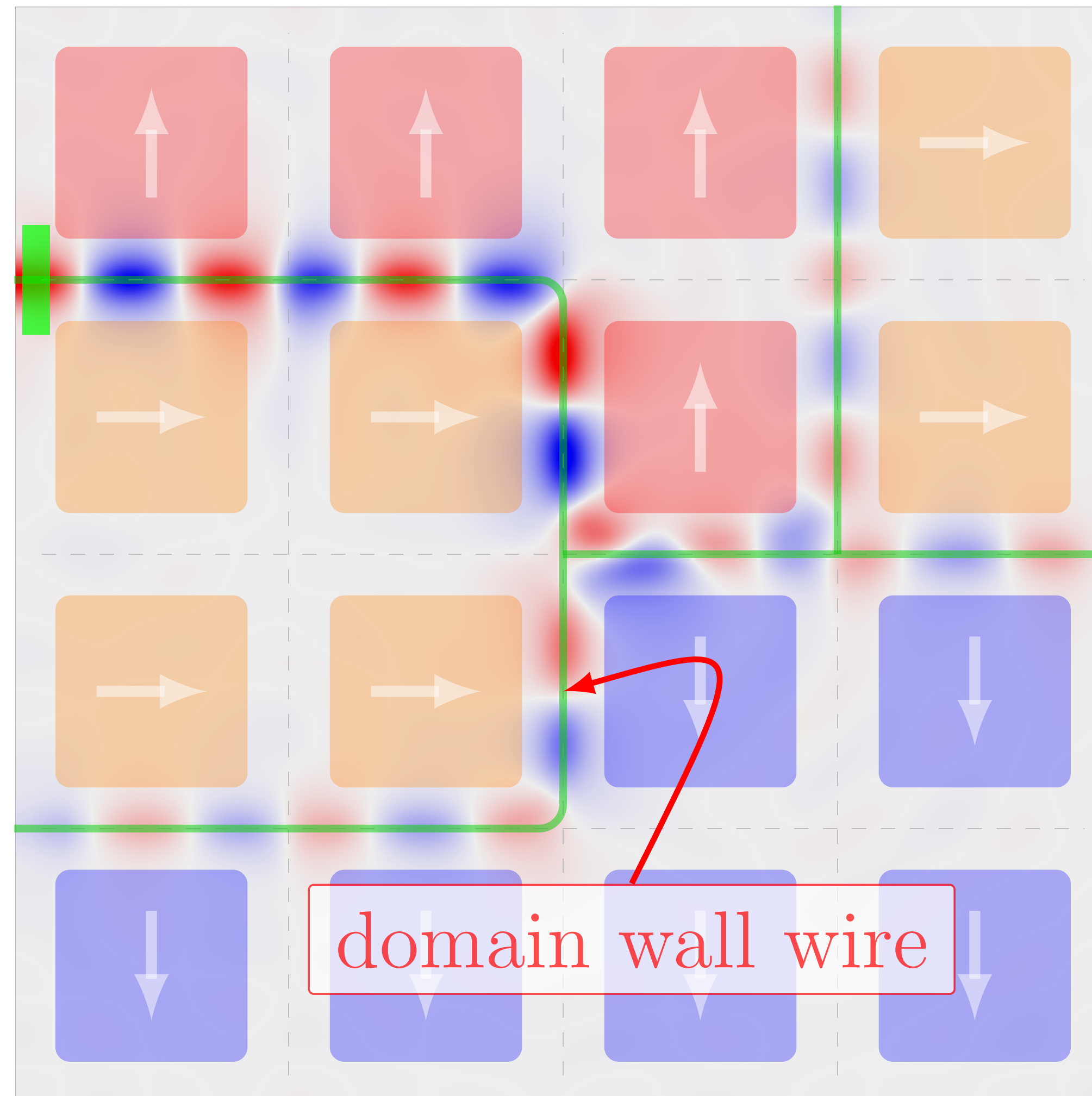
due to **DMI** & inhomogeneous texture



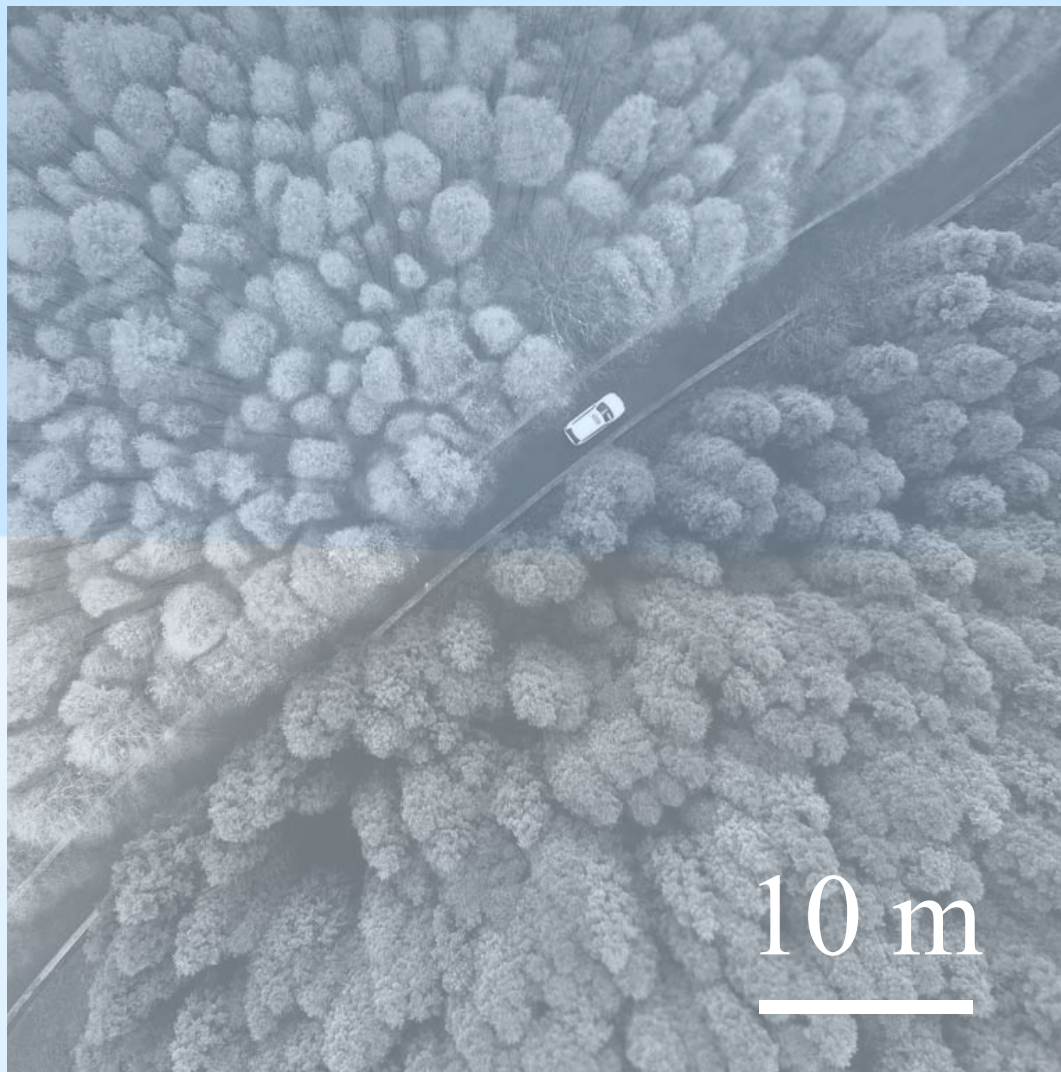
Dzyaloshinskii-Moriya interaction
(**DMI**) $F = \mathbf{D} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$



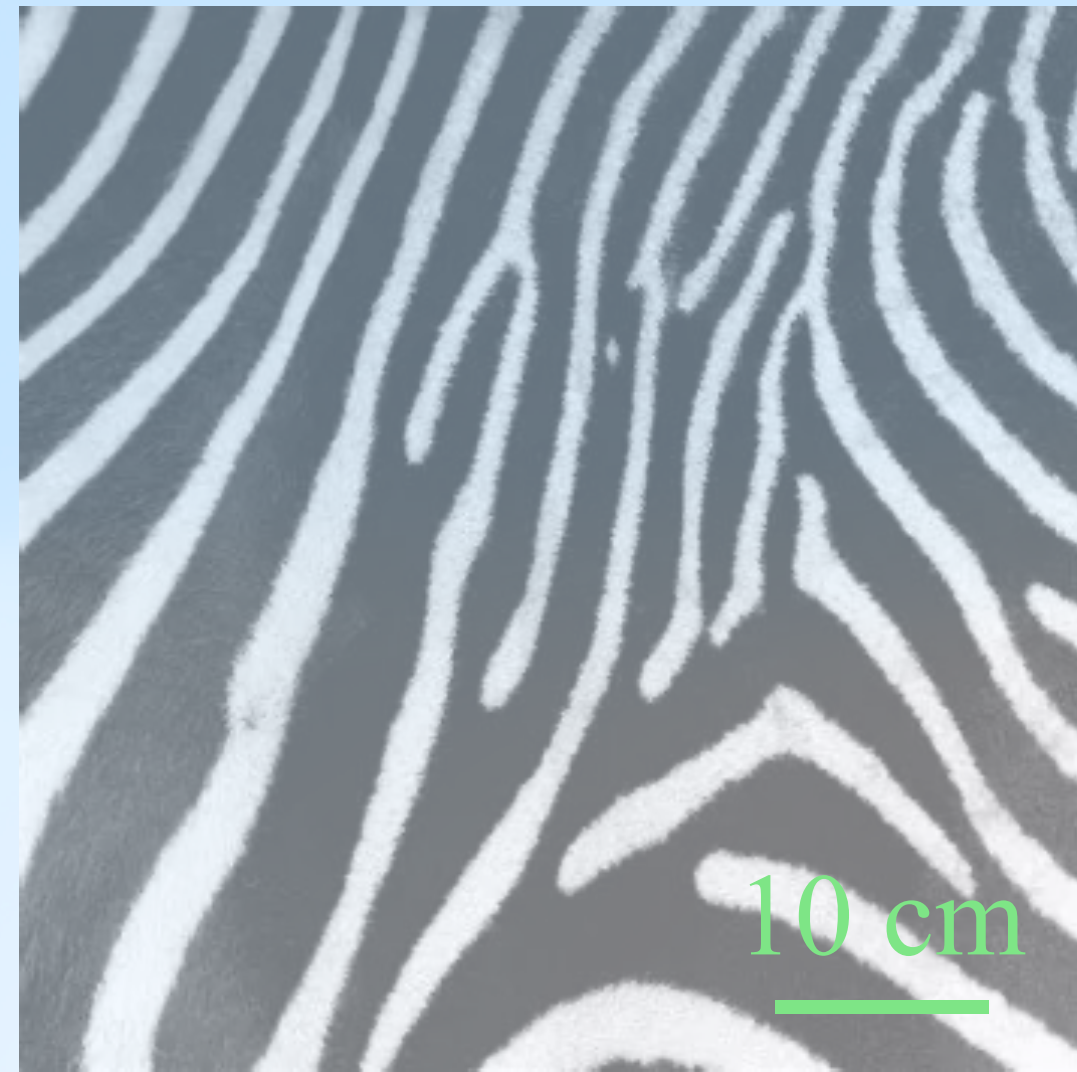
Domain wall circuit: reconfigurable



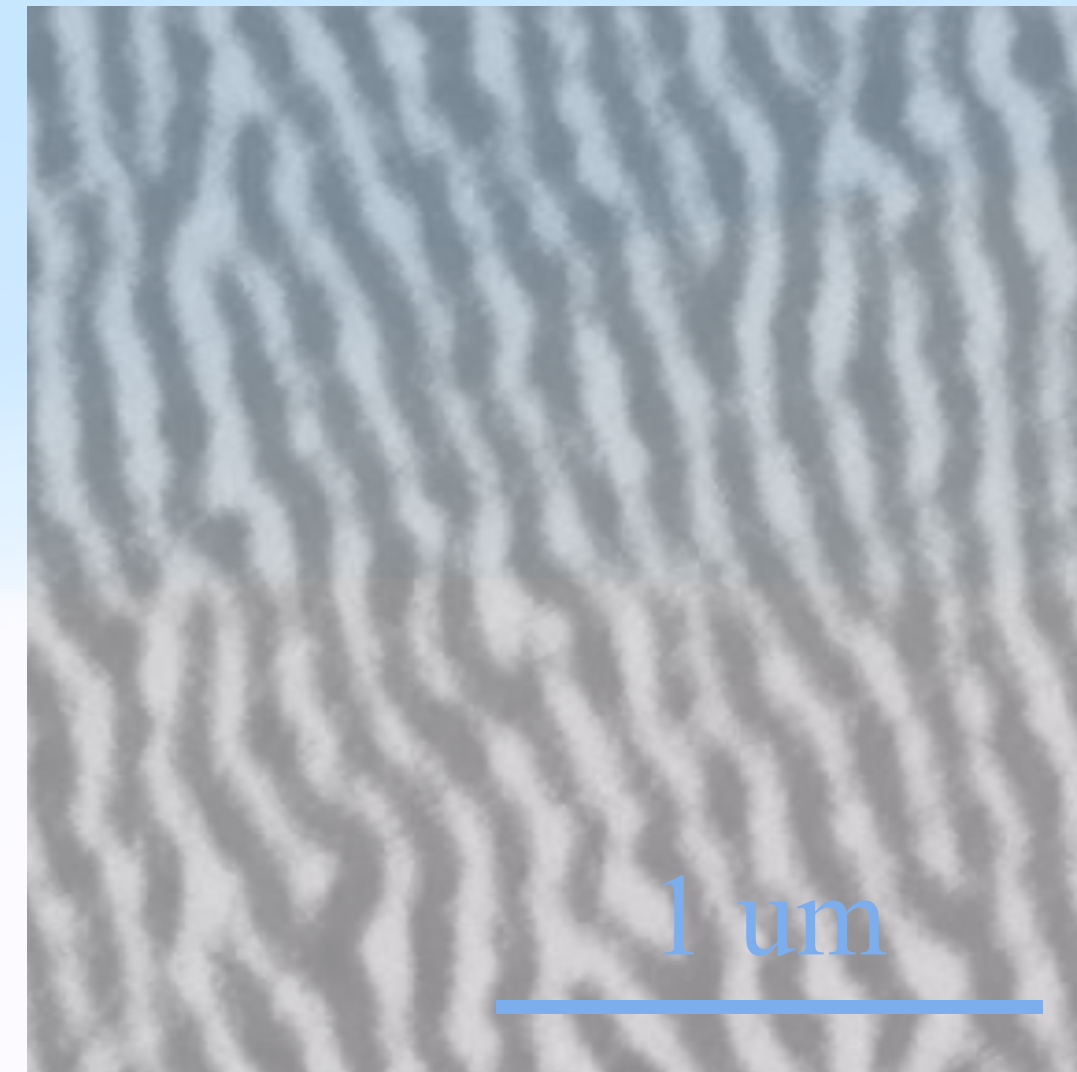
Ferroelectric Texture



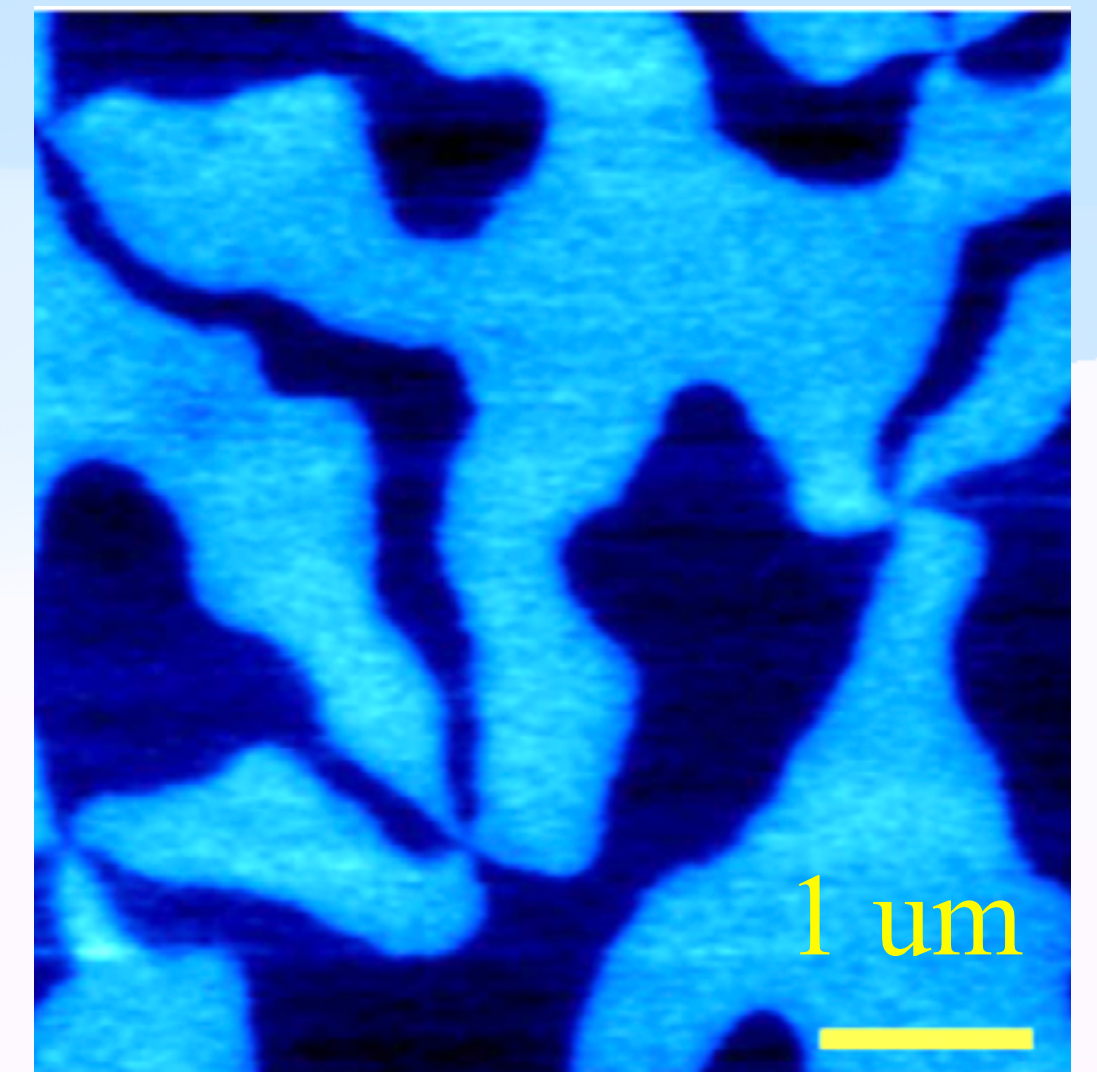
Trees



Zebra

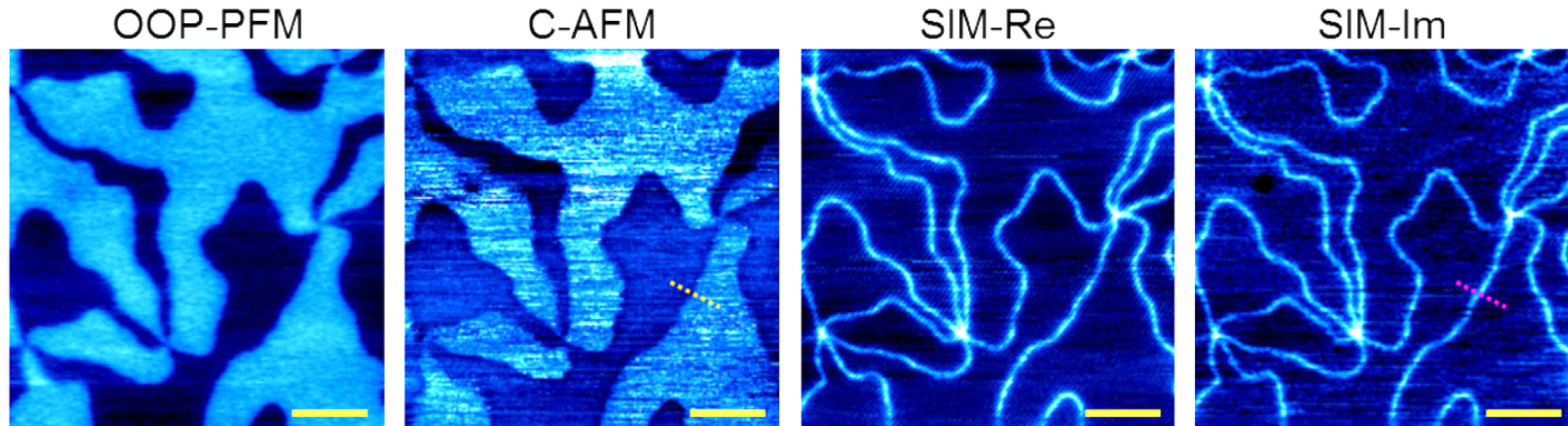


Magnetism



Ferroelectricity

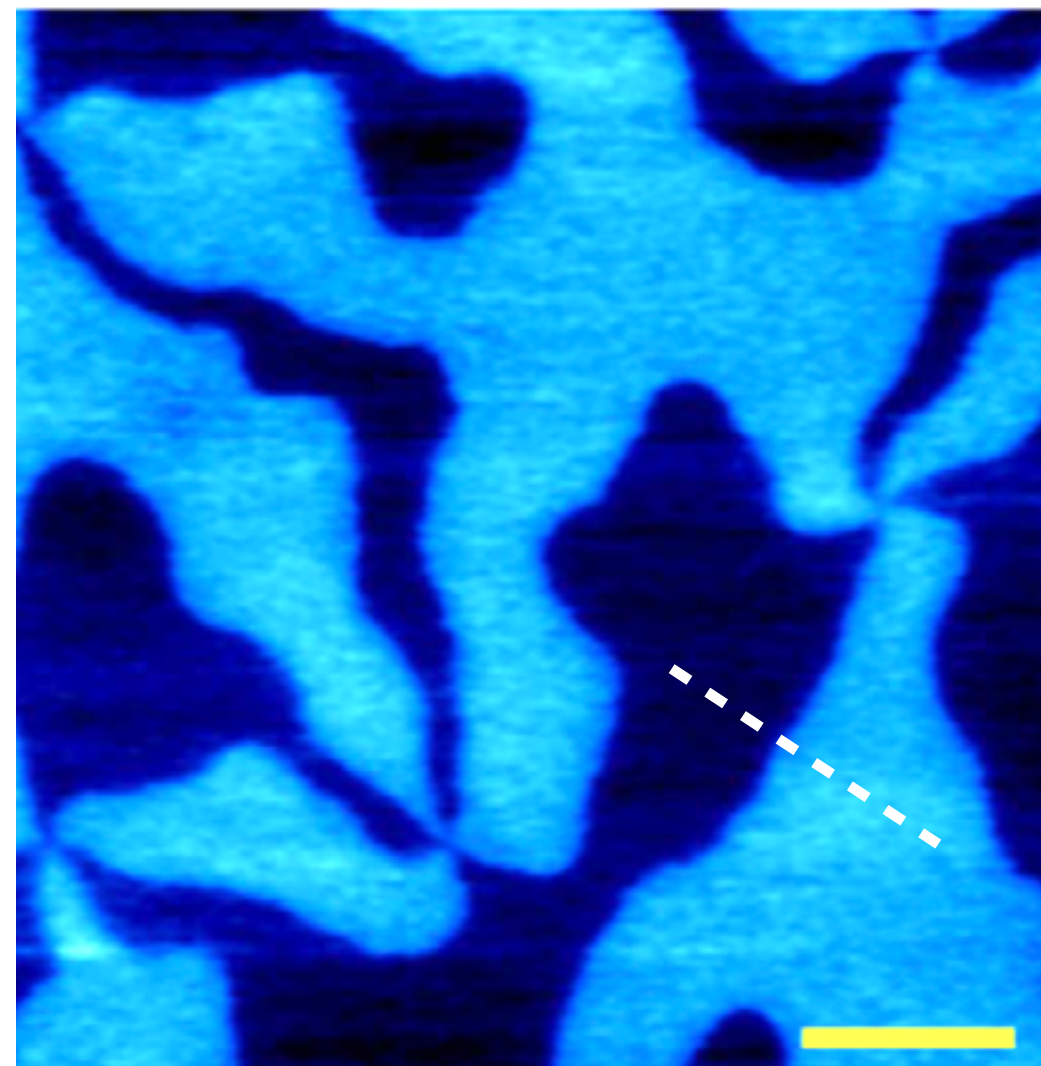
Ferroelectric domains



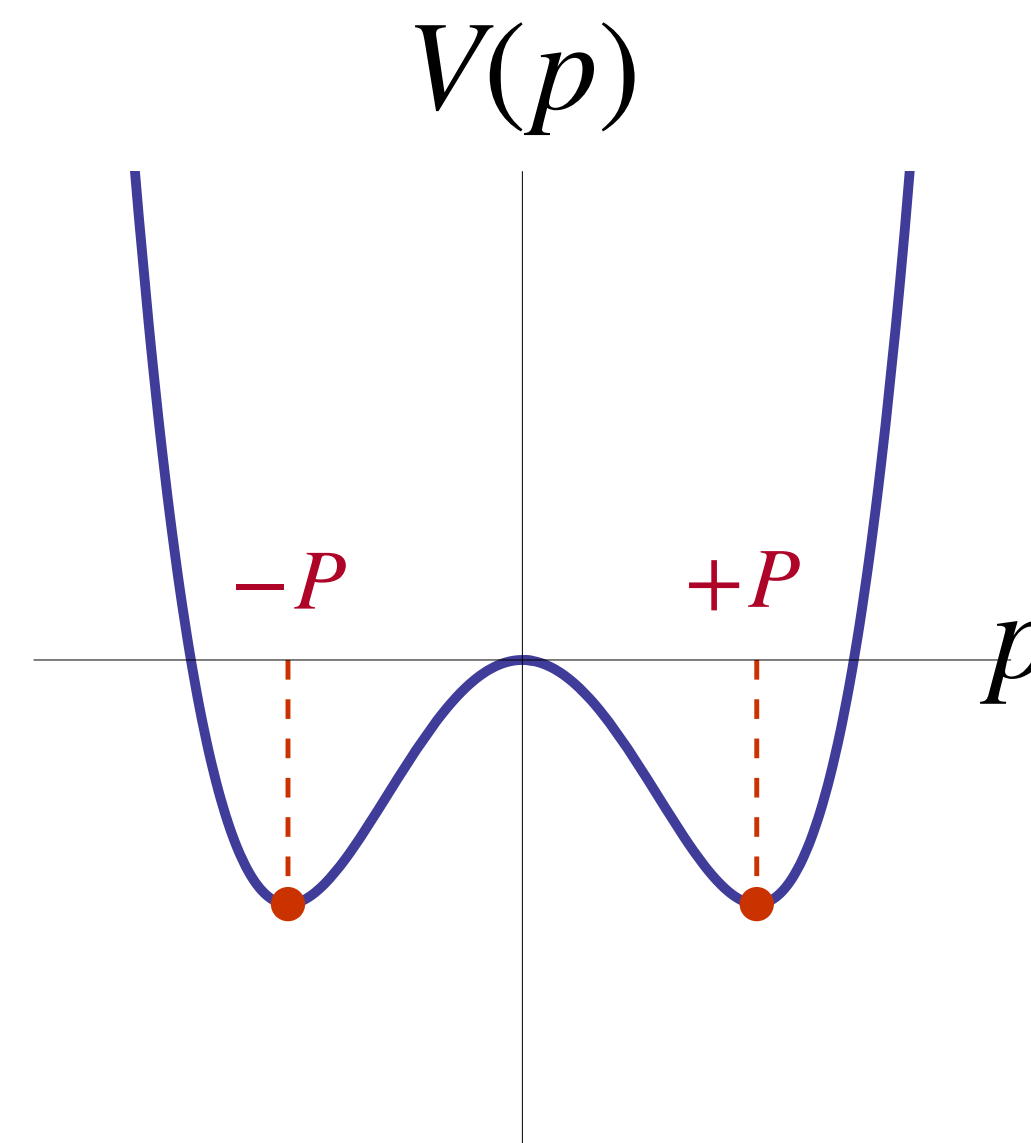
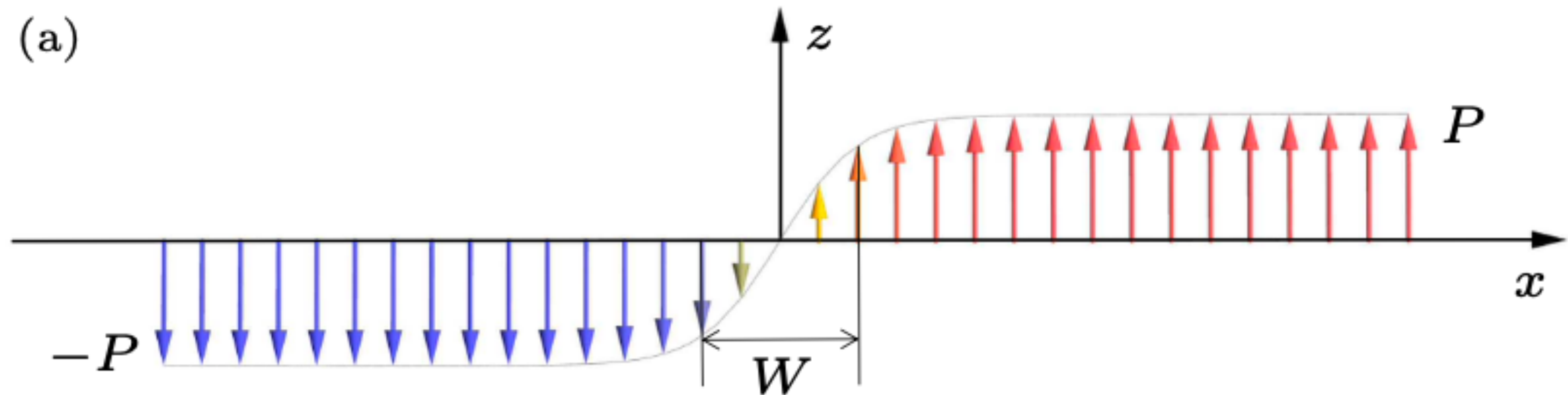
Wu, X. et al. Science Advances (2017). SIM: Scanning Impedance Microscope (@ 1GHz). *Hexagonal rare-earth manganites ($h\text{-RMnO}_3$)*

Ferroelectric domain walls are (locally) electrically conductive (AC).

Ferroelectric domain wall



Ferroelectricity

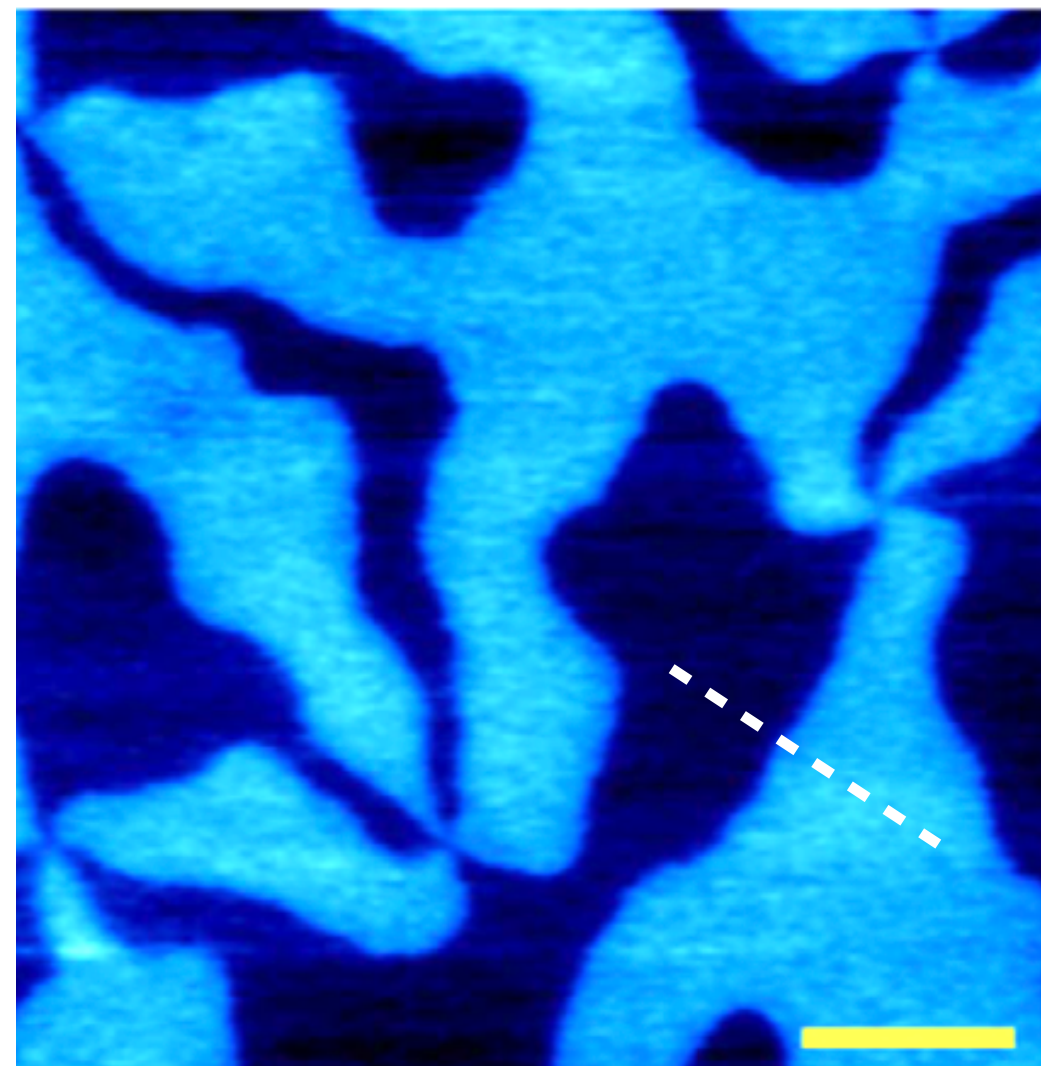


Landau potential (ϕ^4 model):

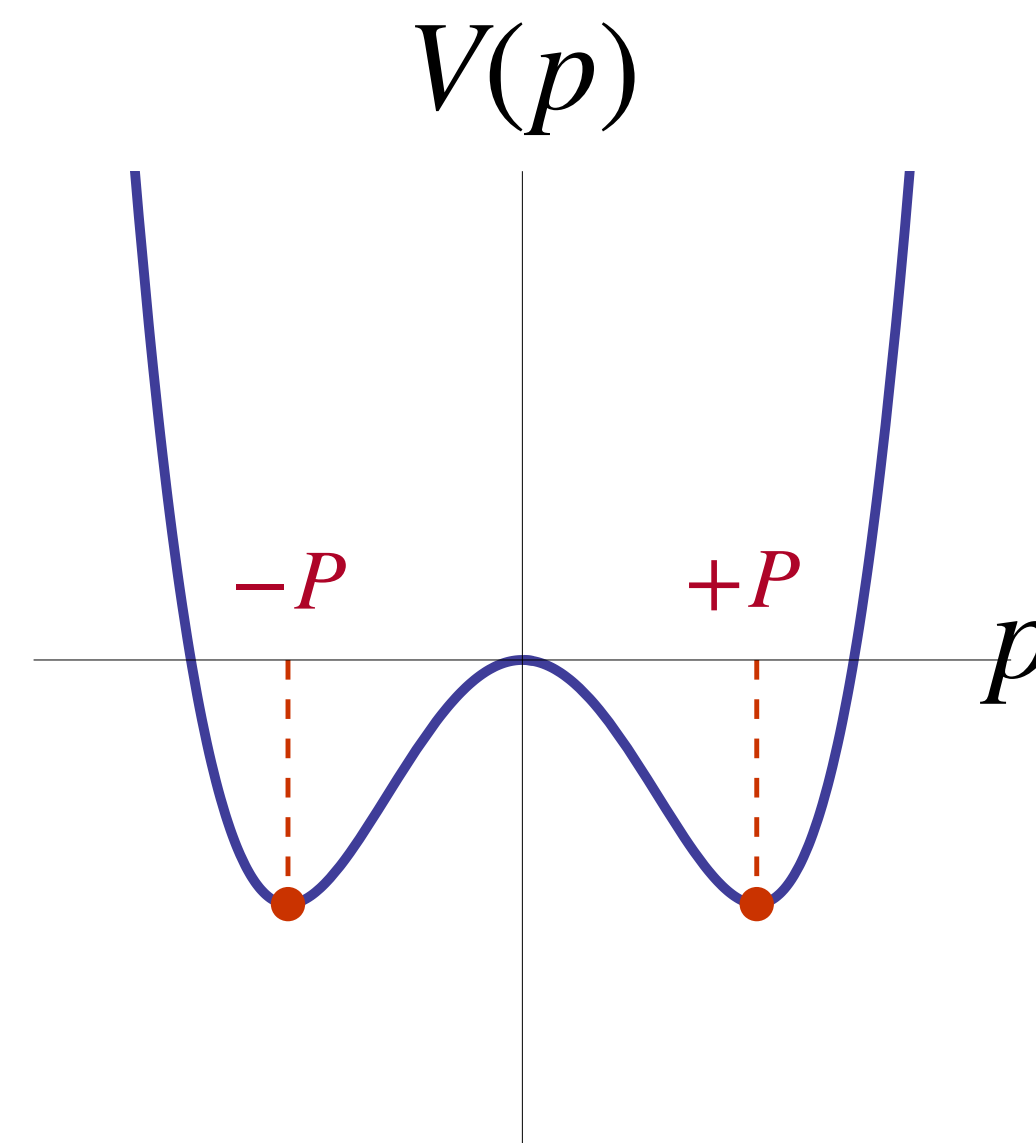
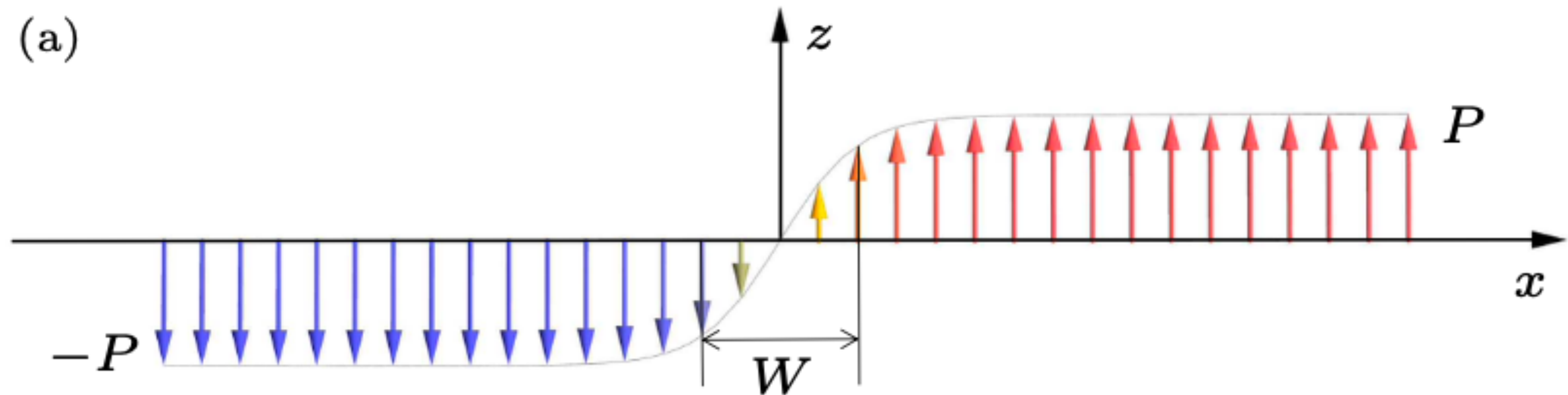
$$V(p) = -\frac{\alpha}{2}p^2 + \frac{\beta}{4}p^4, \quad \alpha, \beta > 0$$

- Two minima: $p = \pm P = \pm\sqrt{\alpha/\beta}$
- Spontaneous ferroelectricity

Ferroelectric domain wall



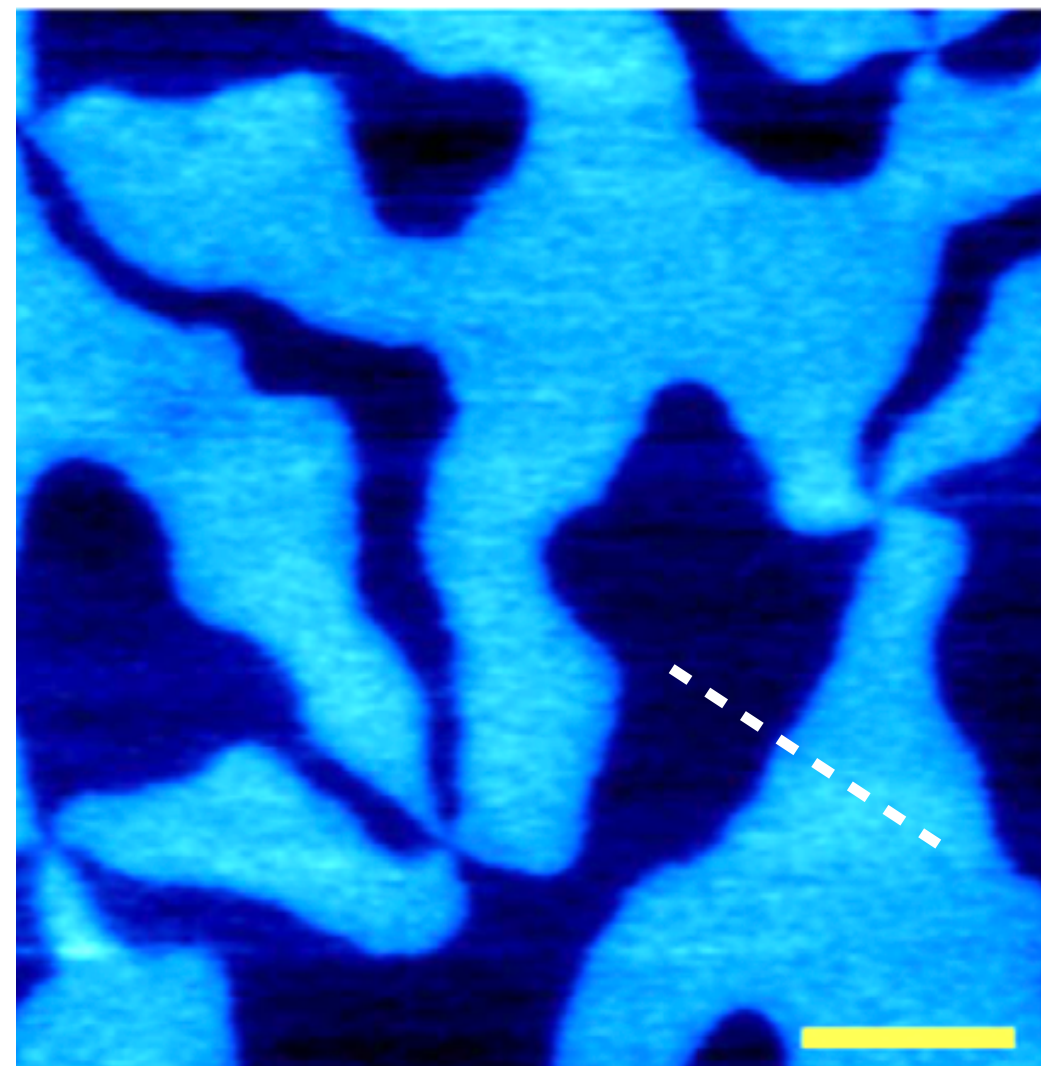
Ferroelectricity



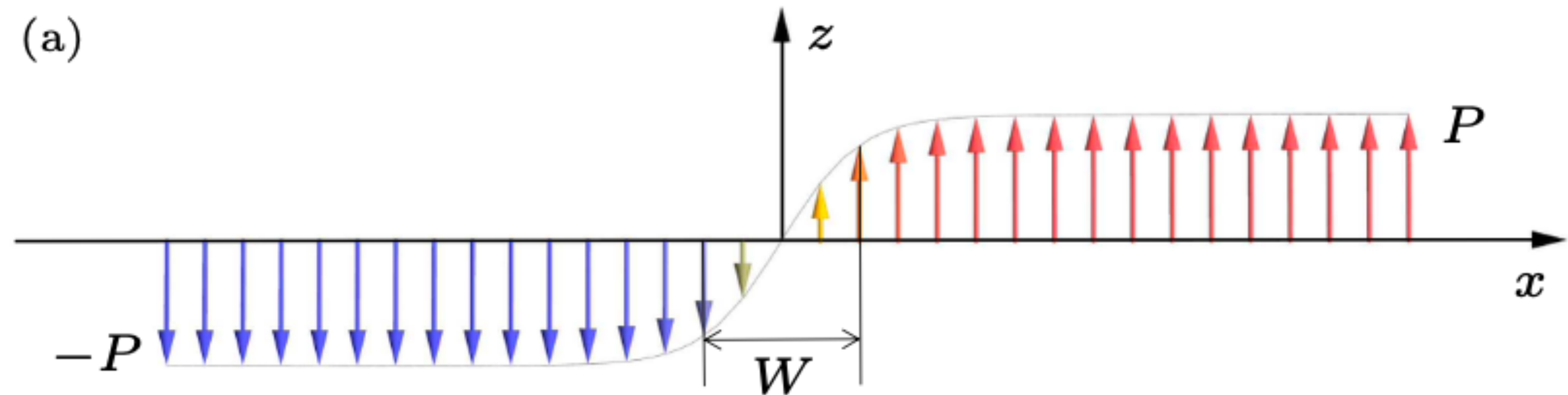
$$p_0(x) = P \tanh \left(\frac{x - X}{W_0} \right)$$

- X : DW center position
- $W_0 = \sqrt{2\kappa/\alpha}$: characteristic width

Ferroelectric domain wall



Ferroelectricity



Landau–Khalatnikov–Tani (LKT) equation

$$m \frac{d^2 p}{dt^2} = -\gamma \frac{dp}{dt} + \kappa \nabla^2 p - \frac{\partial V}{\partial p} + E$$

- m : effective mass (inertial dynamics)
- γ : damping constant
- κ : Ginzburg gradient coupling

LKT vs. LLG

2nd order

$$m \frac{d^2 p}{dt^2} = -\gamma \frac{dp}{dt} + \kappa \nabla^2 p - \frac{\partial V}{\partial p} + E$$

Landau-Khalatnikov-Tani (LKT) equation

1st order

$$\frac{d}{dt} \mathbf{m}(\mathbf{r}, t) = -\mathbf{m} \times (\mathbf{K} + \mathbf{H}_{\text{ext}} + J \nabla^2 \mathbf{m}) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

Landau-Lifshitz Gilbert (LLG) equation

Polar wave: Linearized excitation

Separate static and dynamic components: $p(x, t) = p_0(x) + p'(x, t)$, with $|p'| \ll P$

Landau–Khalatnikov–Tani equation

$$m \frac{d^2 p}{dt^2} = -\gamma \frac{dp}{dt} + \kappa \nabla^2 p - \frac{\partial V}{\partial p} + E \quad \Rightarrow \quad -m \frac{\partial^2 p'}{\partial t^2} = \left[-\kappa \frac{\partial^2}{\partial x^2} + 2\alpha + U(x) \right] p'.$$

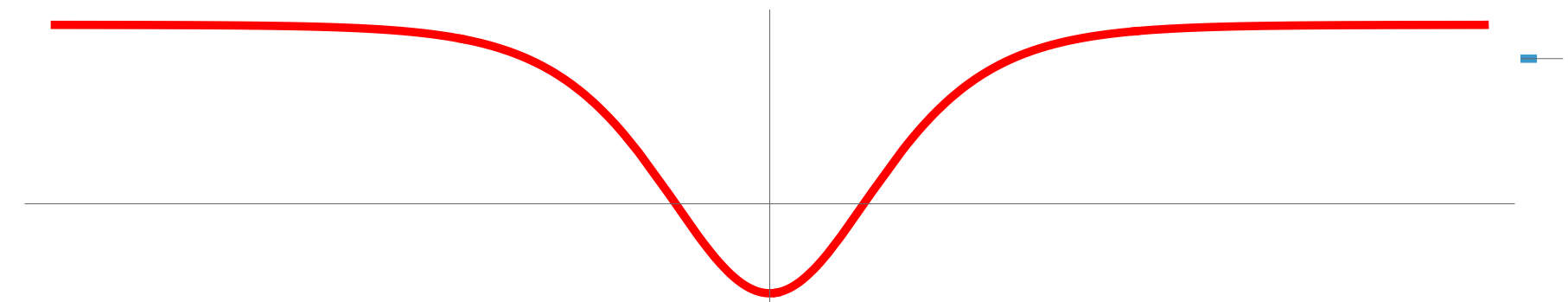
Without DW (Bulk)

$$\omega_k^2 = \omega_0^2 + \frac{\kappa}{m} k^2, \quad \omega_0 = \sqrt{\frac{2\alpha}{m}}$$

Bulk gap

With DW

$$\blacksquare \quad U(x) = -3\alpha \operatorname{sech}^2(x/W_0)$$



Polar wave: Linearized excitation

Separate static and dynamic components: $p(x, t) = p_0(x) + p'(x, t)$, with $|p'| \ll P$

Anti-symmetric (breathing) mode

$$\omega_a = \frac{\sqrt{3}}{2} \omega_0$$

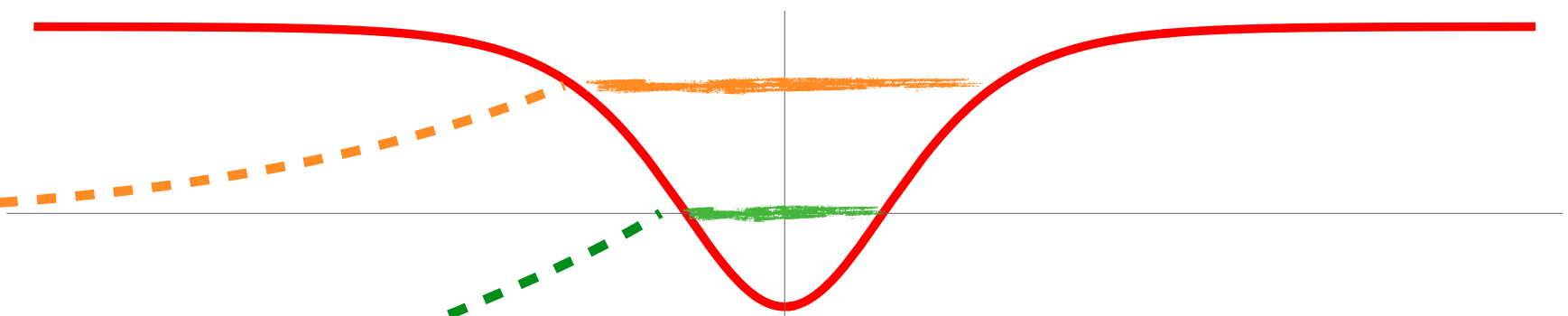
$$p'_a \propto \operatorname{sech}\left(\frac{x}{W_0}\right) \tanh\left(\frac{x}{W_0}\right)$$

Symmetric (vibration) mode

$$\omega_s = 0 \quad \text{Goldstone!}$$

$$p'_s \propto \operatorname{sech}^2\left(\frac{x}{W_0}\right)$$

$$-m \frac{\partial^2}{\partial t^2} p' = \left[-\kappa \frac{\partial^2}{\partial x^2} + 2\alpha + U(x) \right] p'.$$



With DW

- $U(x) = -3\alpha \operatorname{sech}^2(x/W_0)$
- Index-2 Pöschl–Teller potential
- Exactly solvable! $m(m+1)\operatorname{sech}^2(x)$
- Hosts two bound states below ω_0

Polar wave: Linearized excitation

Anti-symmetric (breathing) mode

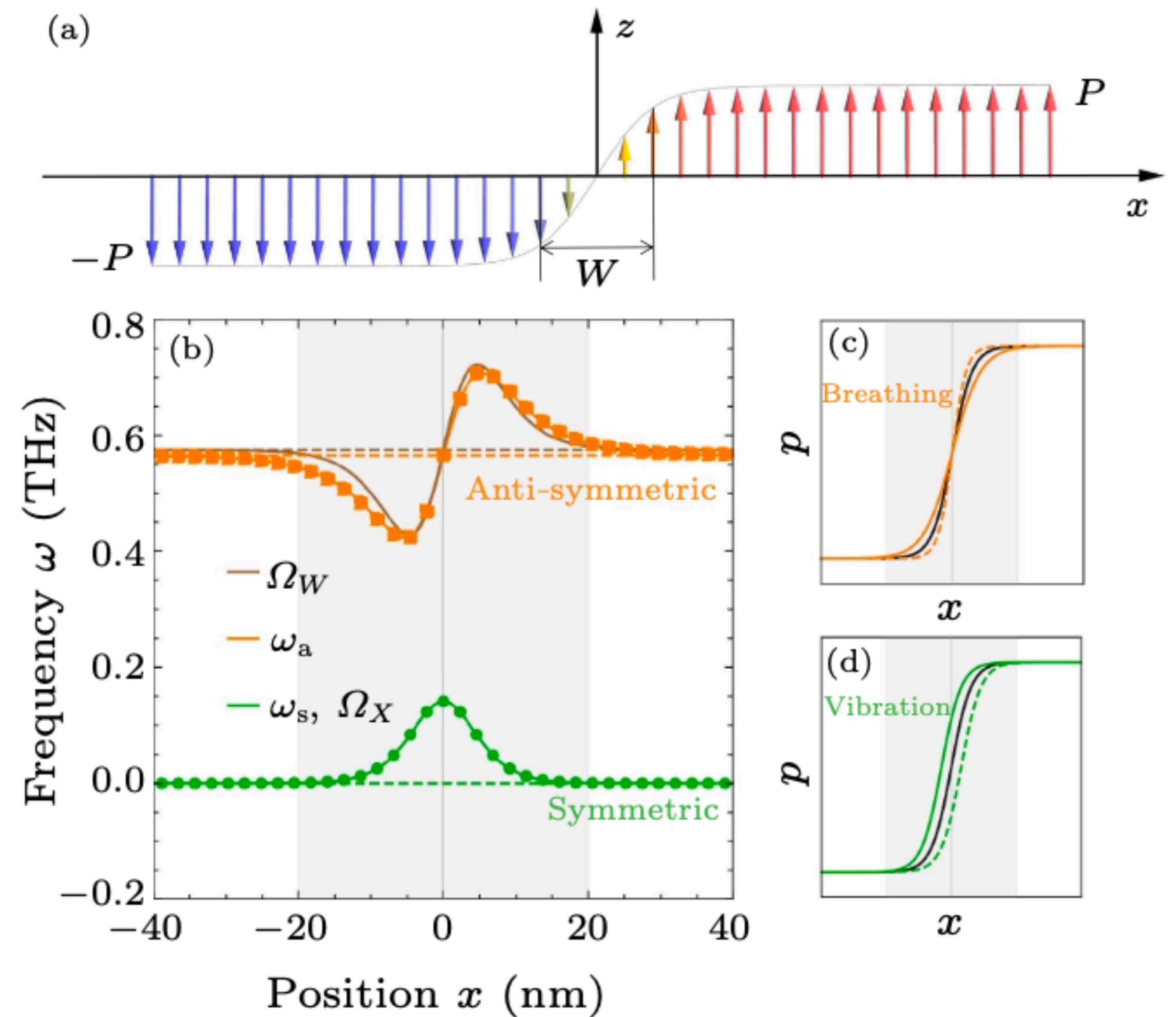
$$\omega_a = \frac{\sqrt{3}}{2} \omega_0$$

$$p'_a \propto \operatorname{sech}\left(\frac{x}{W_0}\right) \tanh\left(\frac{x}{W_0}\right)$$

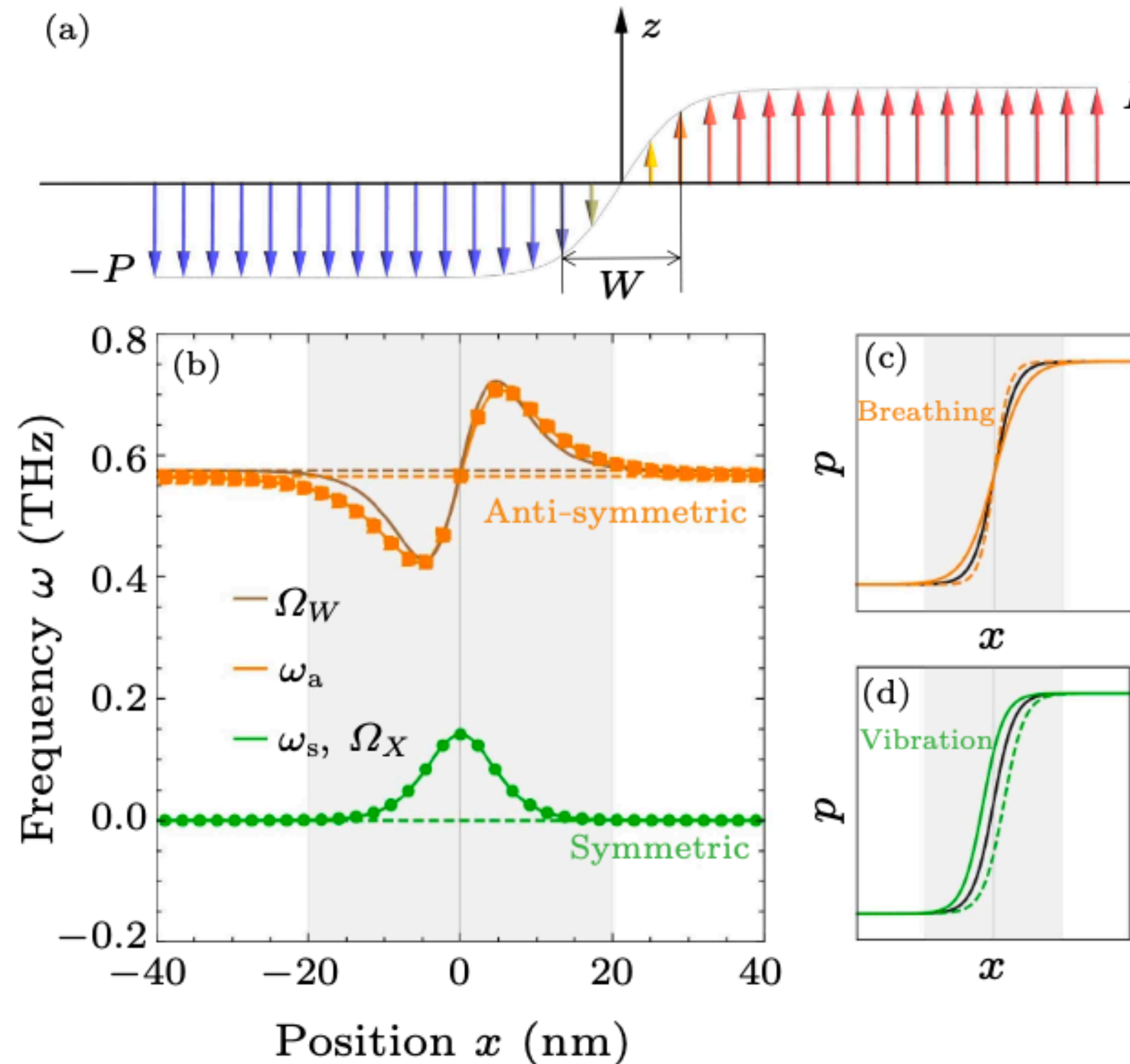
Symmetric (vibration) mode

$$\omega_s = 0 \quad \text{Goldstone!}$$

$$p'_s \propto \operatorname{sech}^2\left(\frac{x}{W_0}\right)$$



Soft modes of ferroelectric domain wall



Landau–Khalatnikov–Tani equation

$$m \frac{d^2 p}{dt^2} = -\gamma \frac{dp}{dt} + \kappa \nabla^2 p - \frac{\partial V}{\partial p} + E$$

$$p(x, t) = P \tanh \left(\frac{x - X(t)}{W(t)} \right)$$

Collective coordinates description ($X(t), W(t)$)

$$m_x \frac{\partial^2 X}{\partial t^2} + \gamma_x \frac{\partial X}{\partial t} = 0,$$

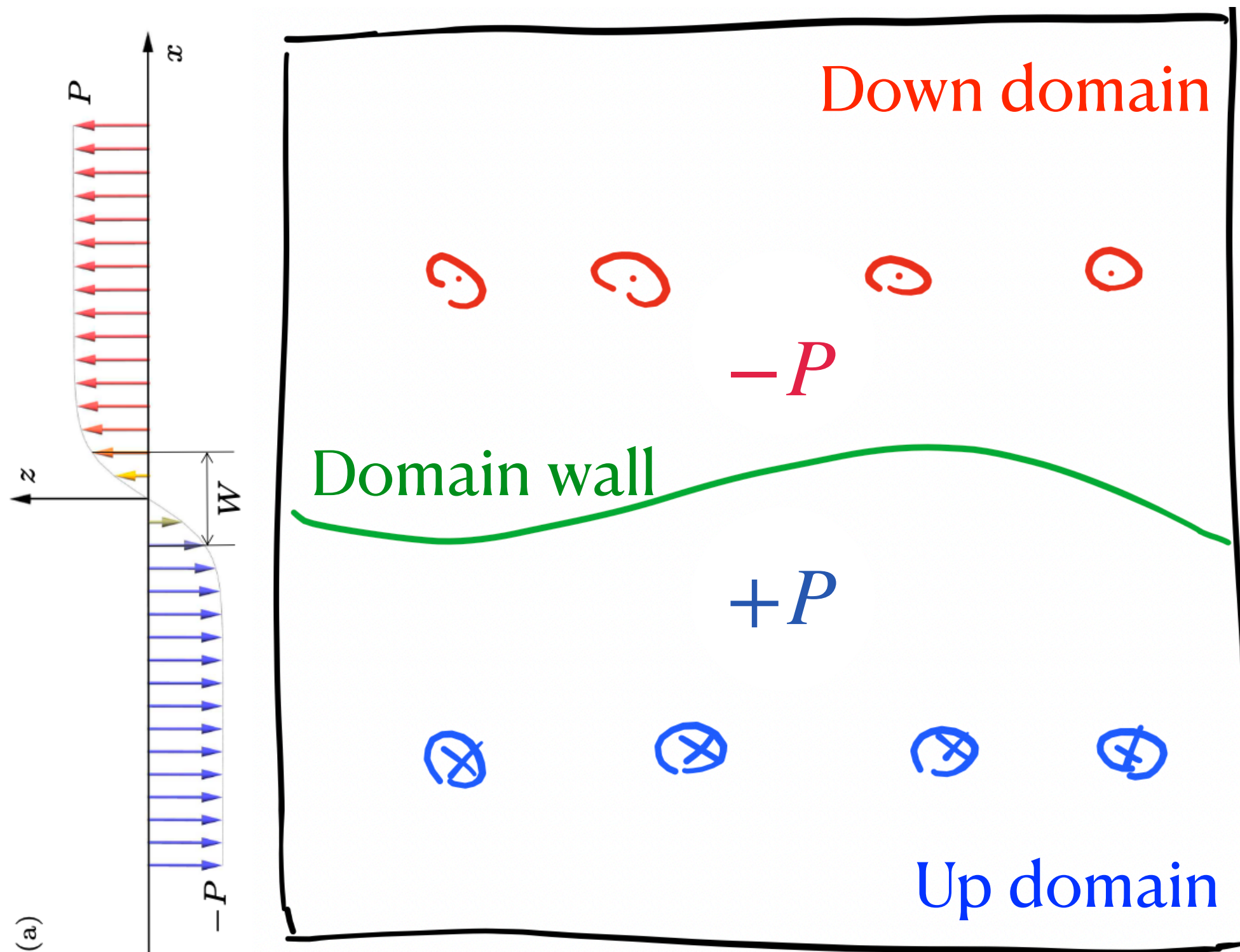
$$m_w \frac{\partial^2 W}{\partial t^2} + \gamma_w \frac{\partial W}{\partial t} = \frac{\alpha^2}{3\beta} \left(\frac{W_0^2}{W^2} - 1 \right) \equiv R(W),$$

non-linearity

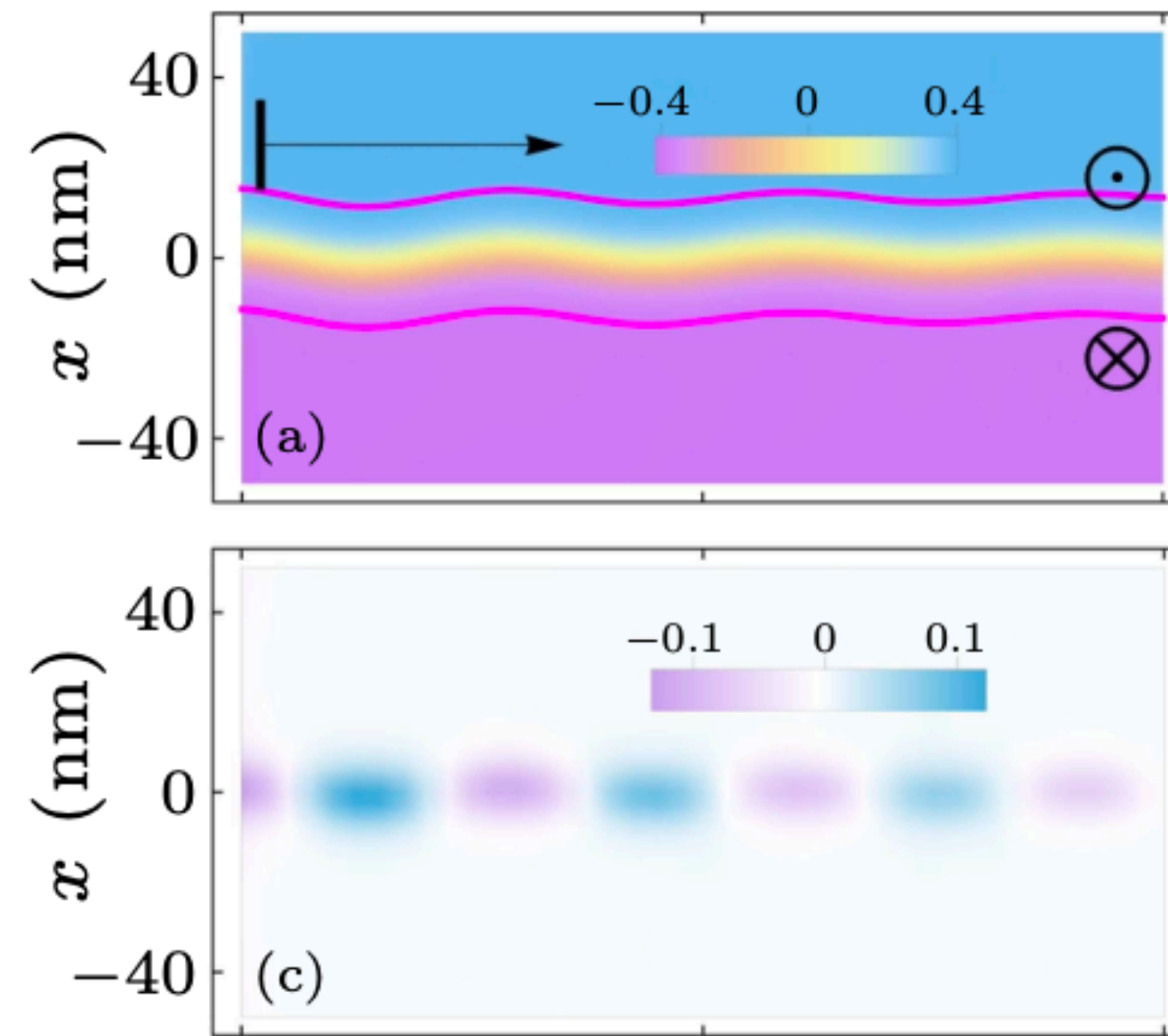
$$m_x = 4mP^2/3W_0 \text{ and } \gamma_x = 4\gamma P^2/3W_0$$

$$m_w = (\pi^2 - 6)mP^2/9W_0 \text{ and } \gamma_w = (\pi^2 - 6)\gamma P^2/9W_0$$

Ferroelectric domain wall: waveguide

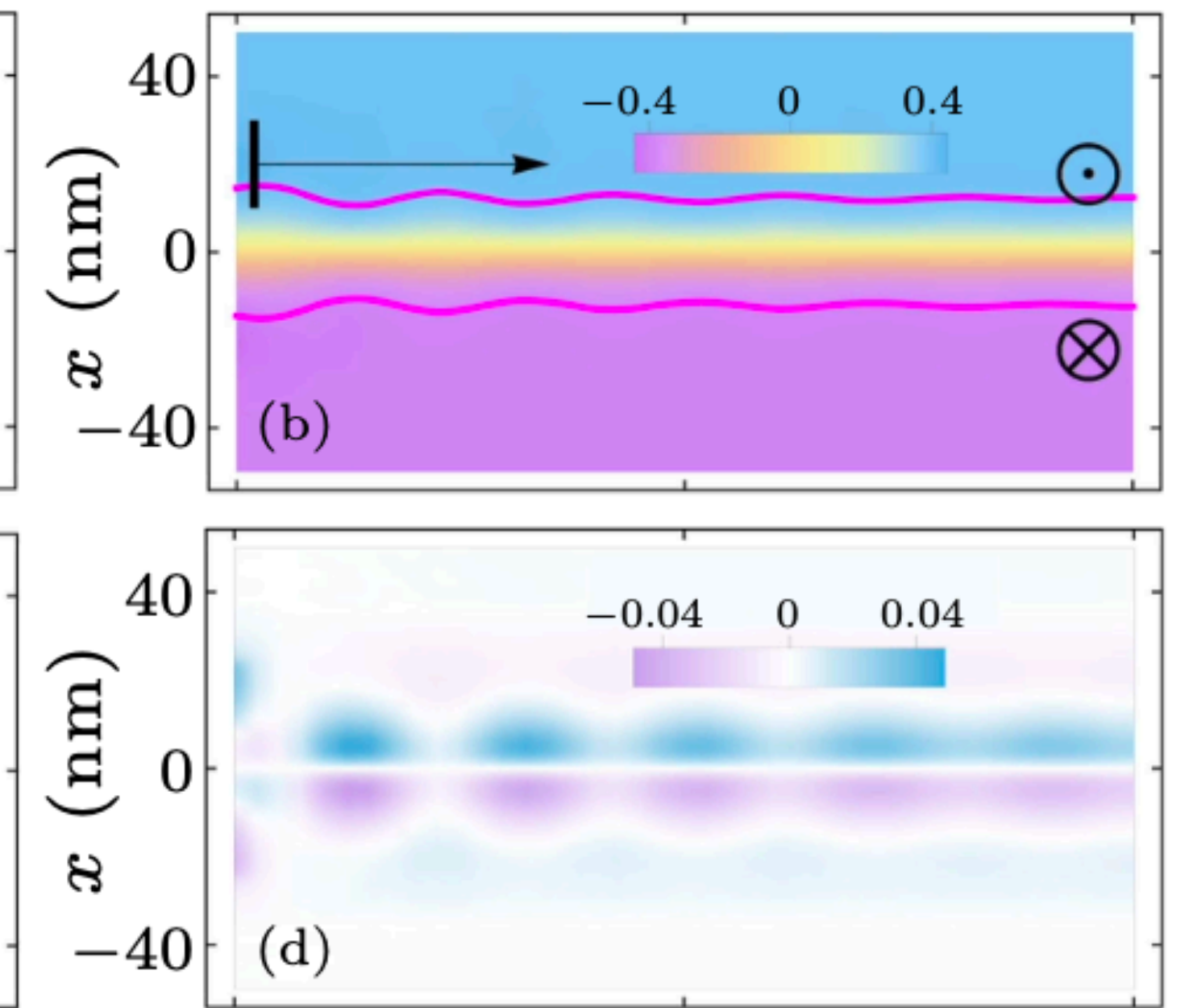


Vibration mode @ 0.2THz



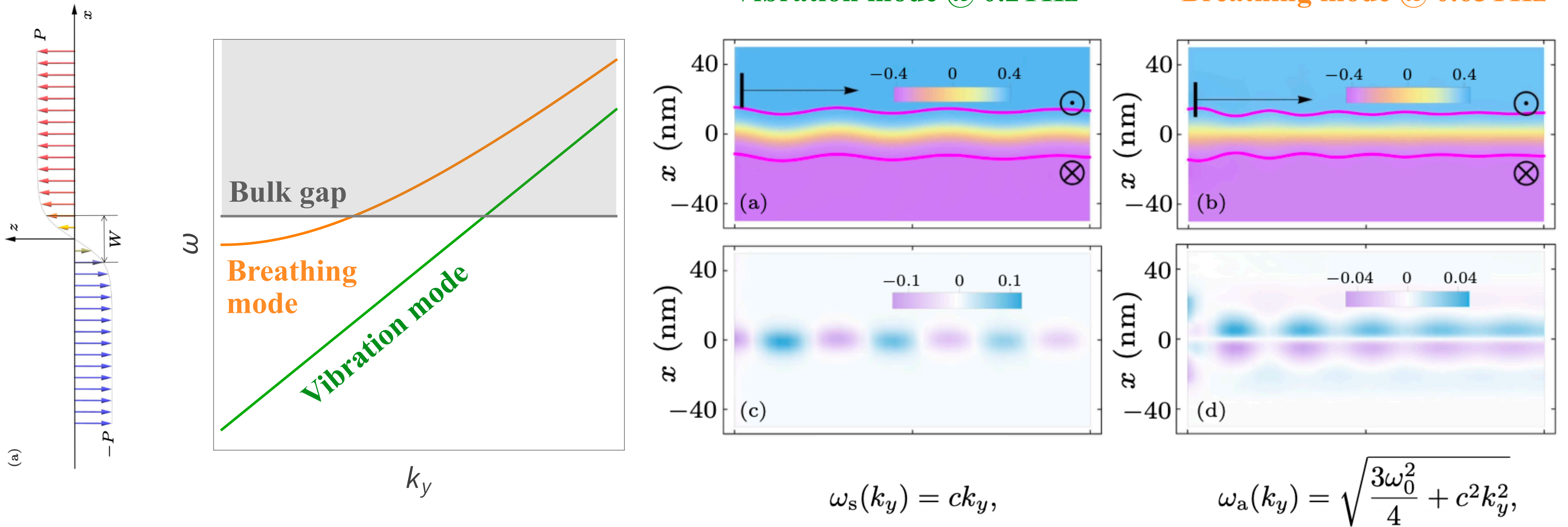
$$\omega_s(k_y) = ck_y,$$

Breathing mode @ 0.65THz

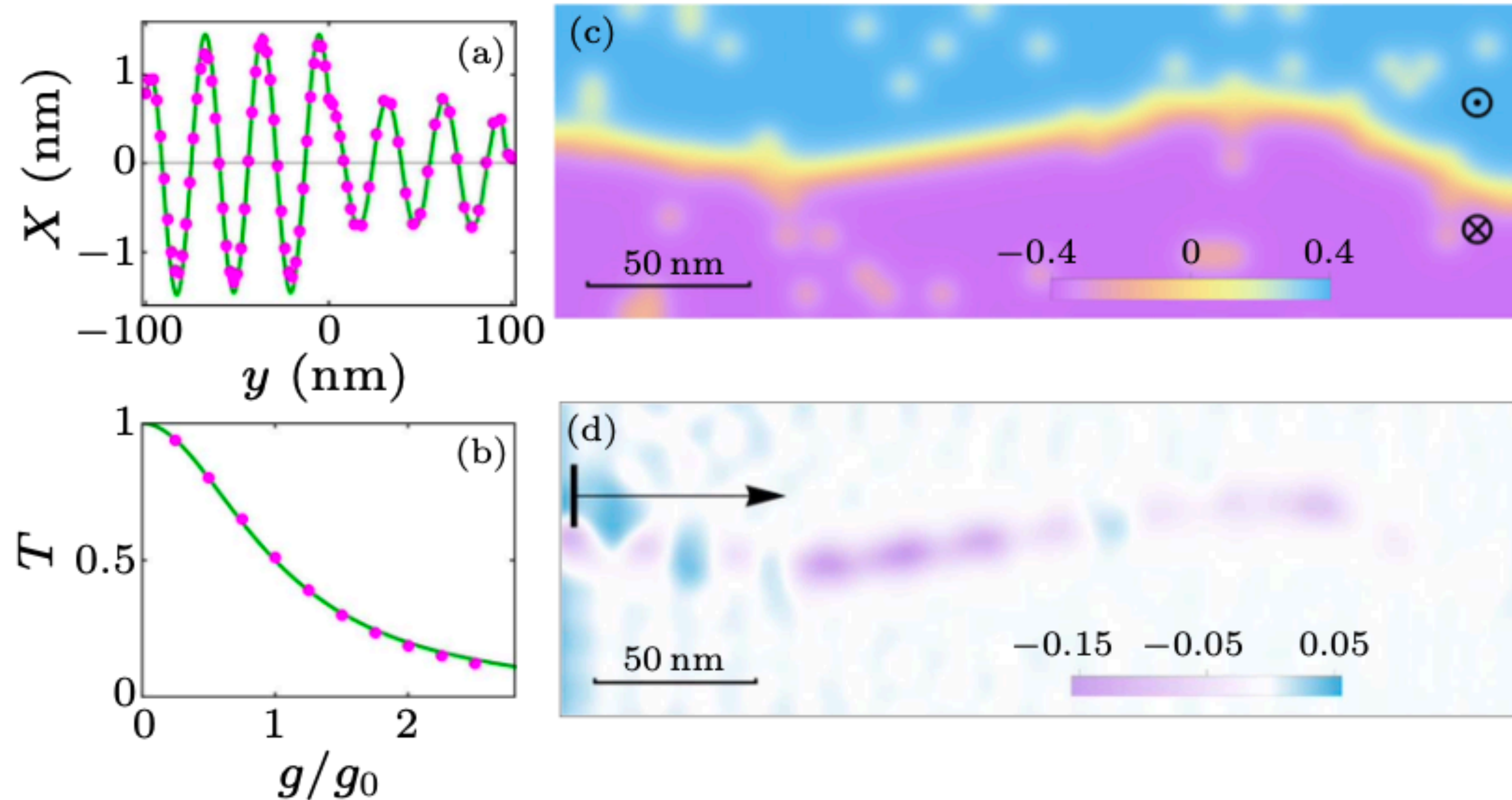


$$\omega_a(k_y) = \sqrt{\frac{3\omega_0^2}{4} + c^2k_y^2},$$

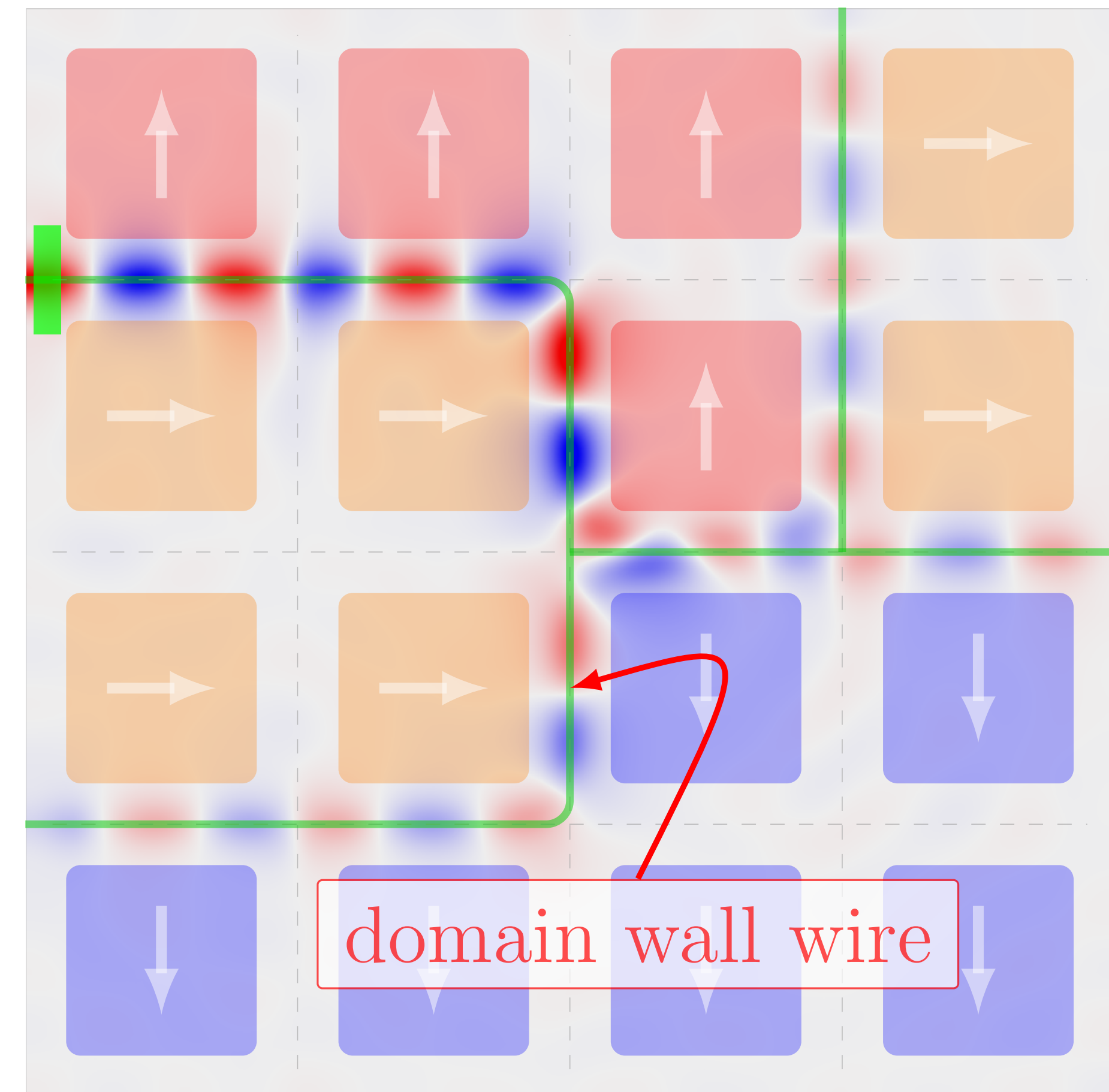
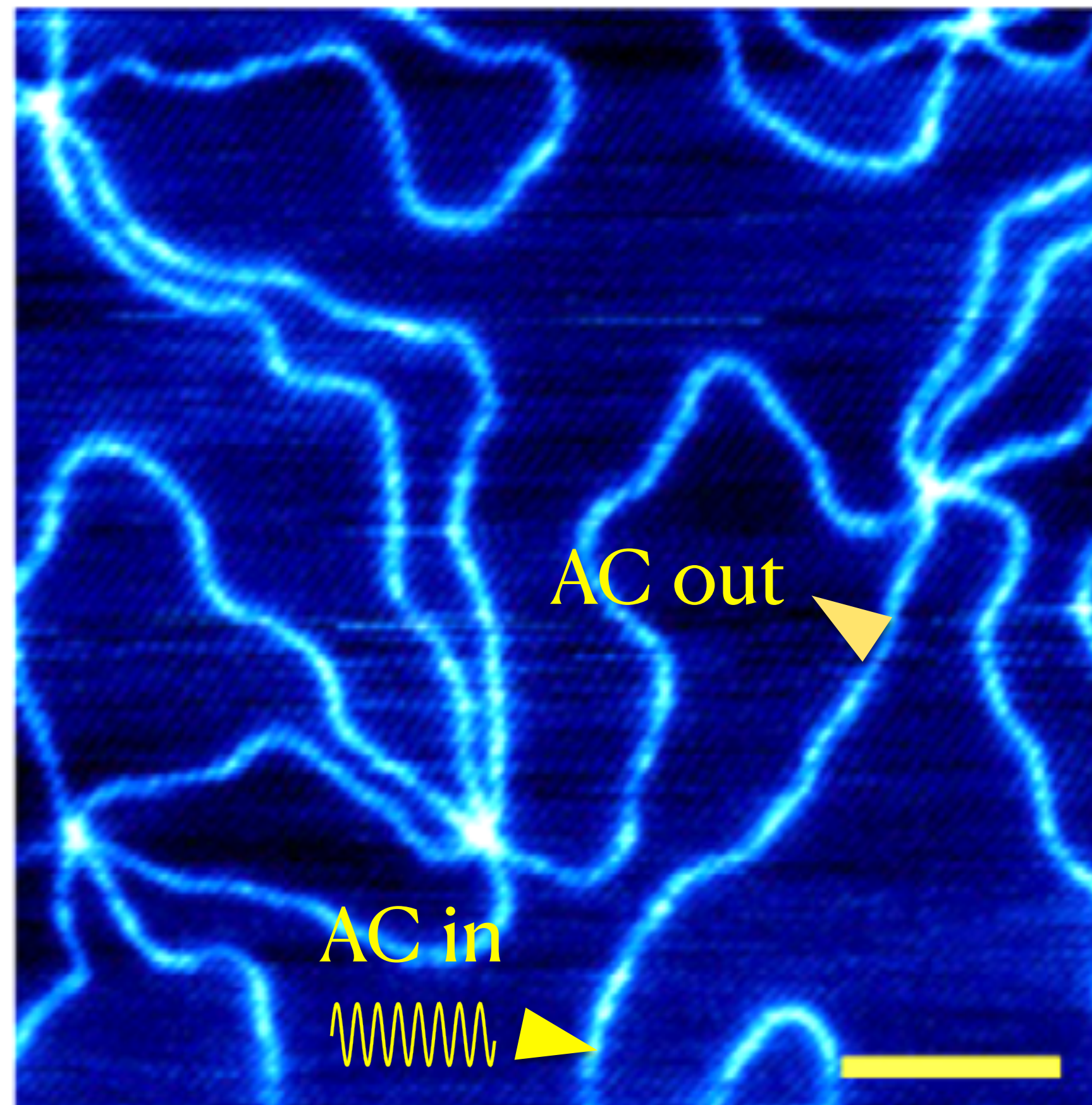
Ferroelectric domain wall: waveguide



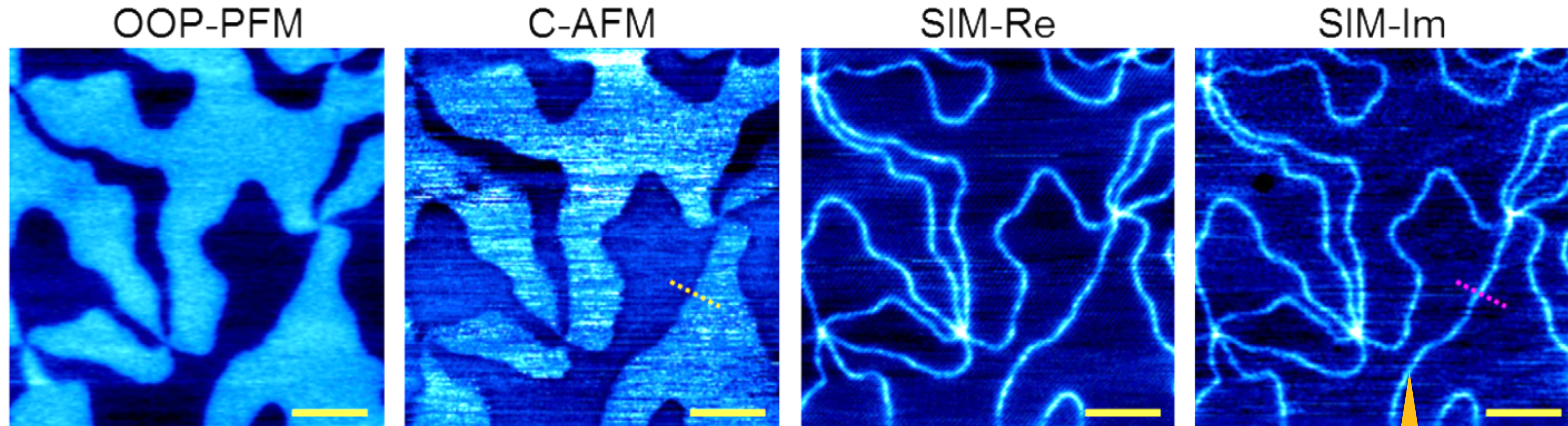
Ferroelectric domain wall: waveguide



Ferroelectric domain wall circuit



Take-home message



Wu, X. et al. Science Advances (2017).

Chen, G., Lan, J., Min, T. & JX
Narrow Waveguide Based on Ferroelectric Domain Wall.
Chin. Phys. Lett. **38**, 87701 (2021).

Ferroelectric domain walls are
electric transmission lines for AC signal
via "ferron" excitation without charge transport.