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# Quantum Functionalities of Magnetic Skyrmions

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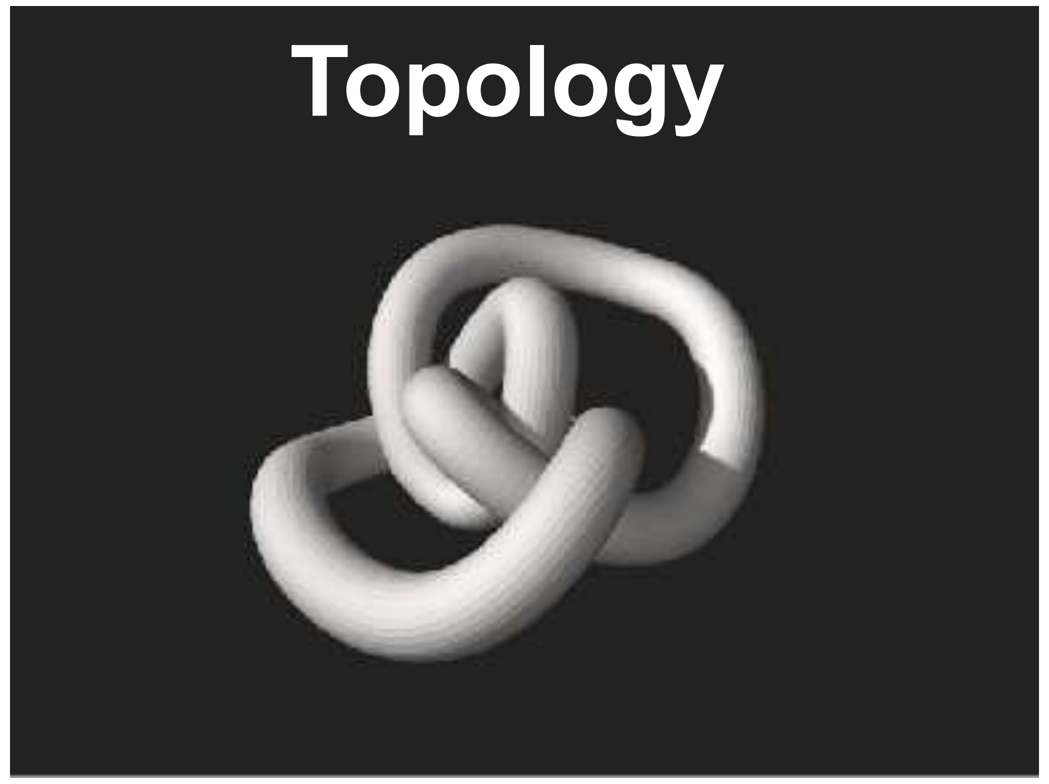
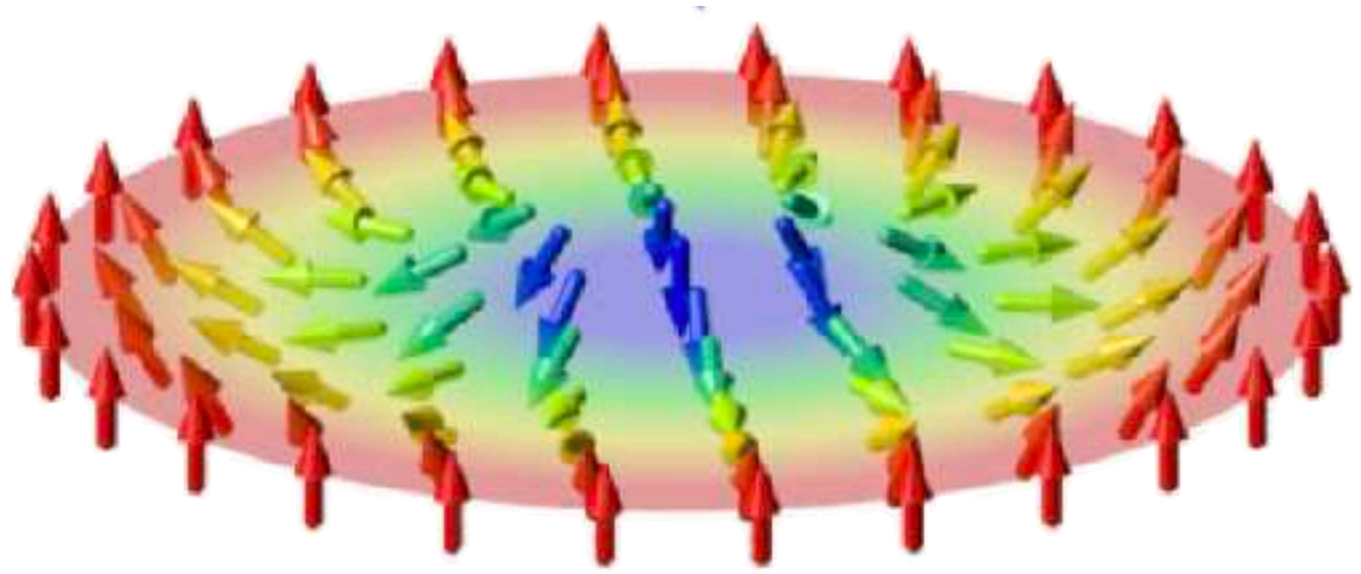
LPENS, Paris

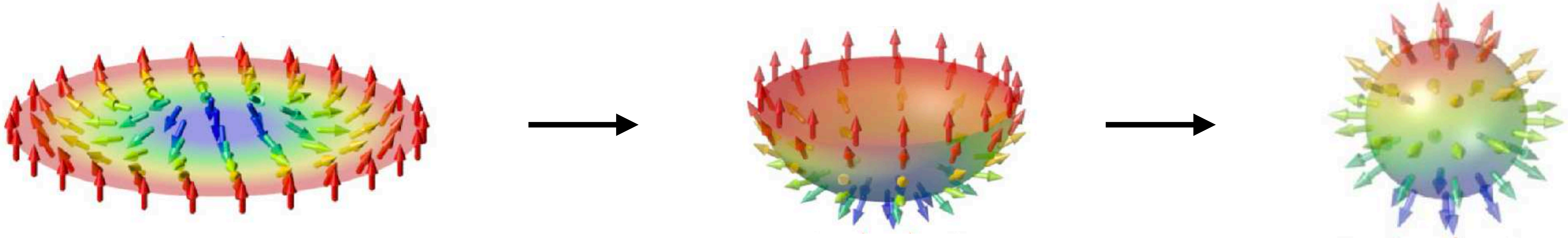
# Topological Solitons in Magnetism



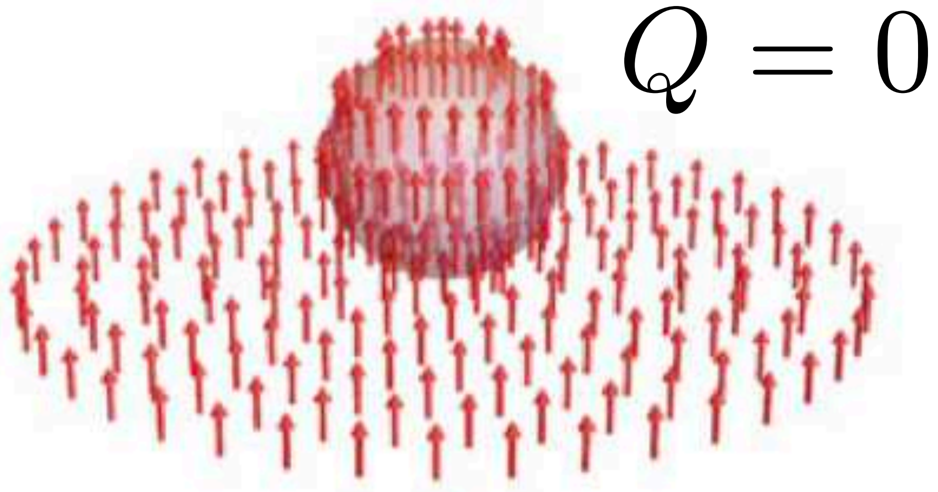



**Topologically protected** magnetization textures





*Real Space* *Spin Space*

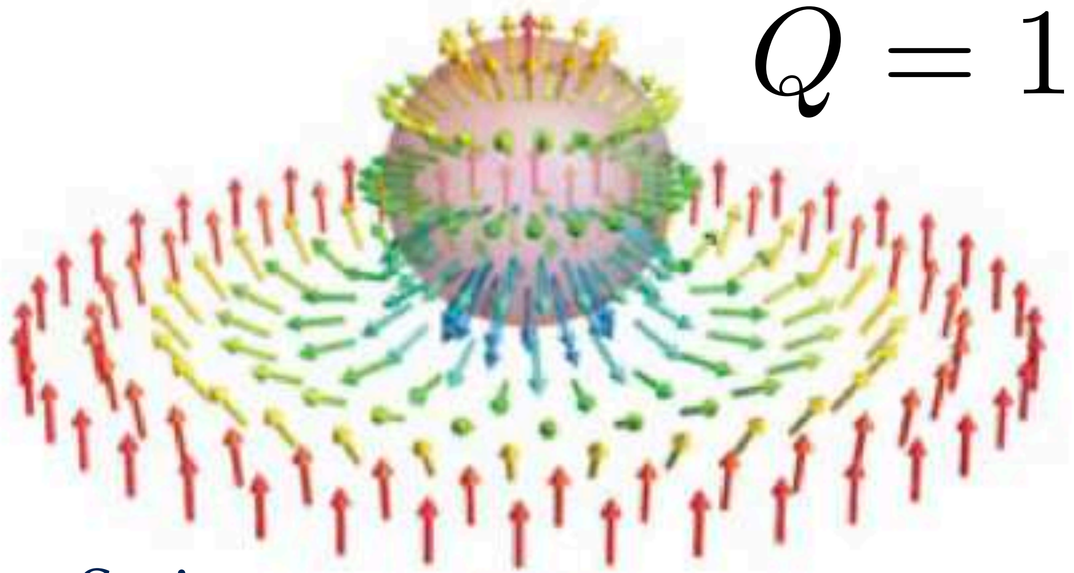


$Q = 0$

Topological number

$$Q = \frac{1}{4\pi} \int d\mathbf{r}\ \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m})$$

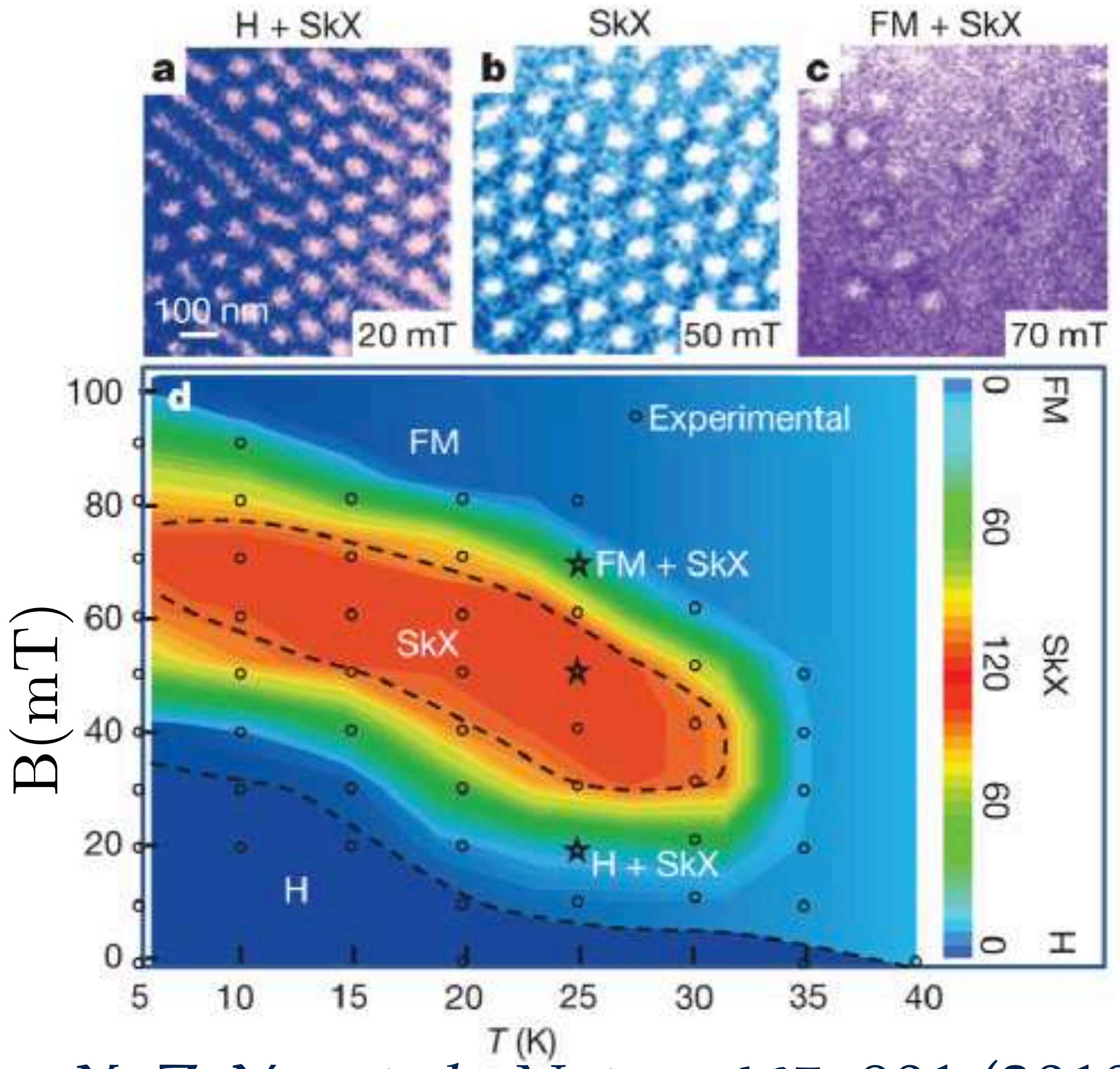
$Q = 1$

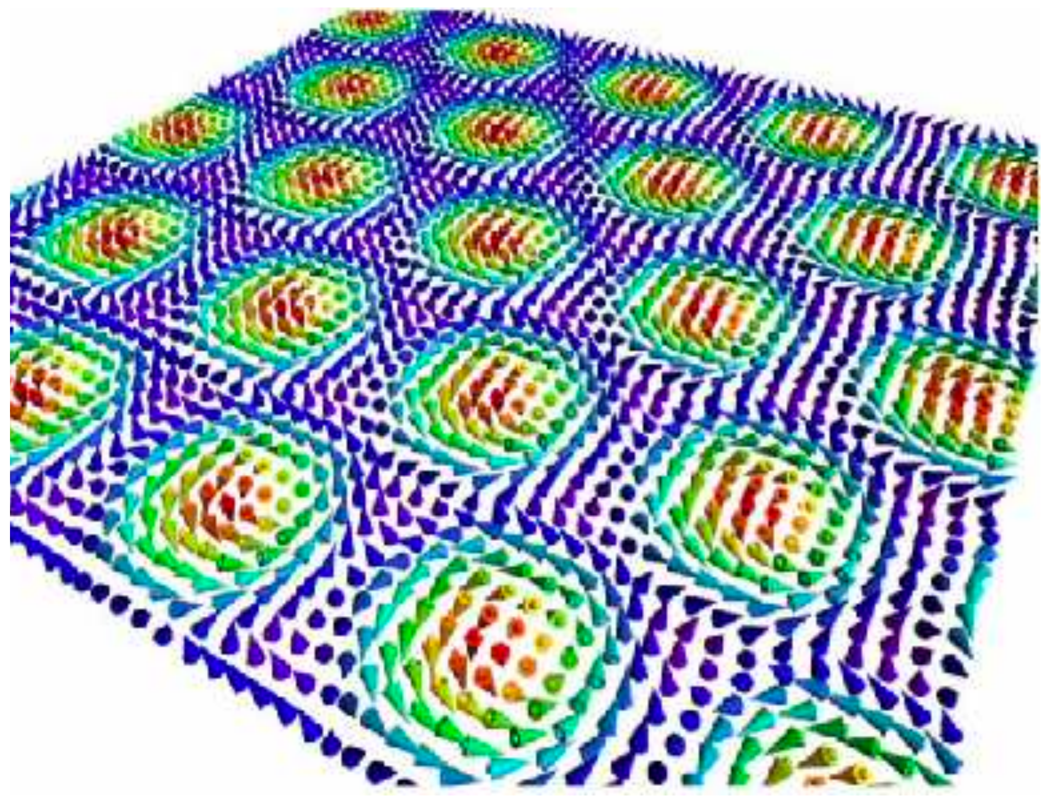


*Topology in Magnetism*, Jiadong Zang, Vincent Cros, and Axel Hoffmann, Springer Series in Solid-State Sciences **192** (2018).

# Topological Solitons

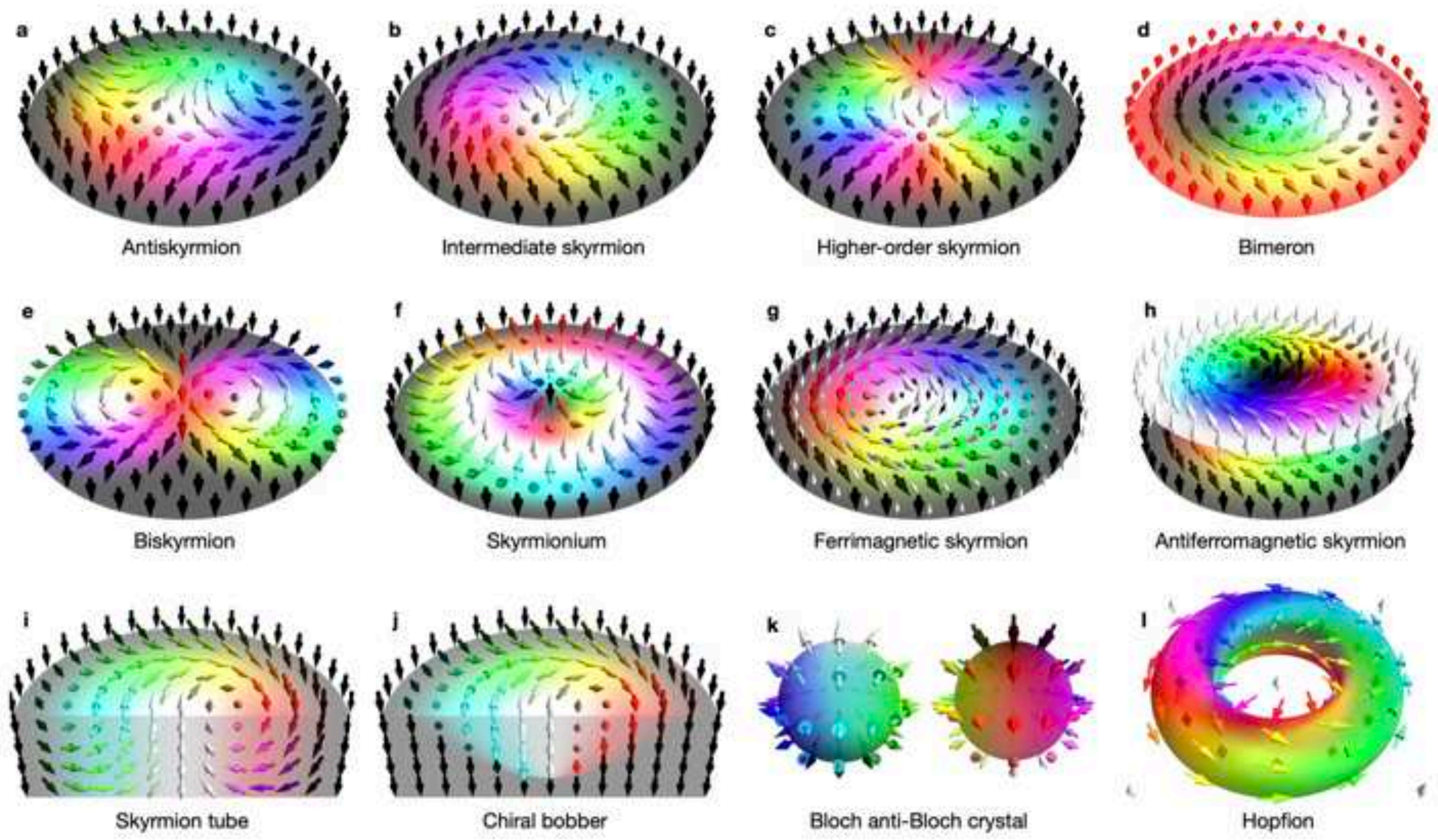
$Fe_{0.5}Co_{0.5}Si$ with lattice spacing 90 nm



X. Z. Yu, *et al.*, *Nature* **465**, 901 (2010).

## Skyrmion Zoo




*Börge Göbel, Ingrid Mertig, and Oleg A.Tretiakov, Physics Reports* ***895****, 1 (2021)*

## Probes for Detection

- **Electrons** (Lorentz TEM, Spin-Polarized EM)
- **Scanning Probes** (MFM, NV, SPSTM)
- **Photons** (soft X-rays, XMCD, XMLD)
- **Scattering Techniques** (Neutron Scattering)

## Skyrmionics

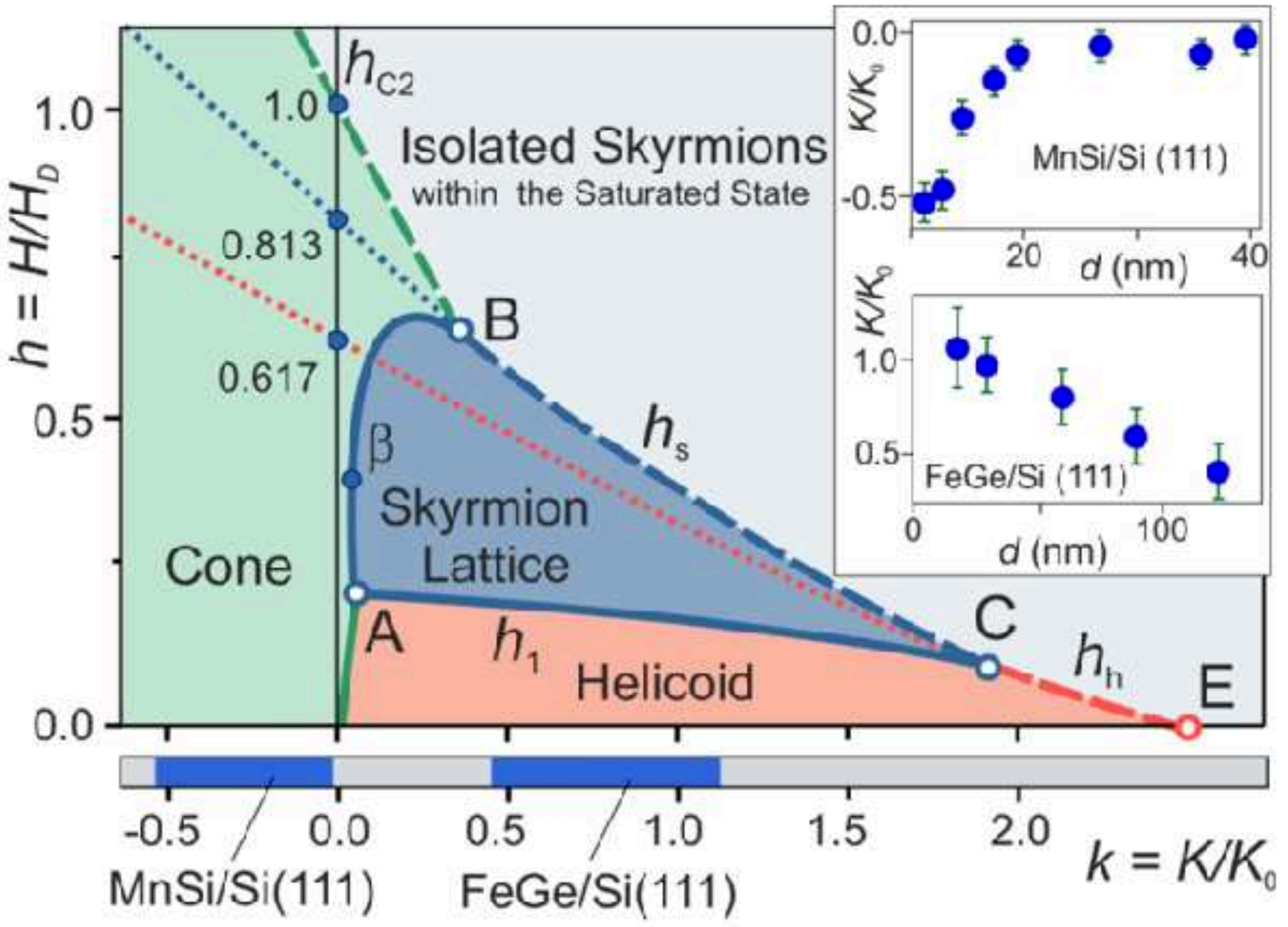
- Nanometric size
- High mobility
- Topological stability
- Controllable properties
- Compact
- Low-energy consumptior

# Chiral Magnets



$$H = -\tilde{J}\mathbf{S}_i \cdot \mathbf{S}_{i+1} - \tilde{\mathbf{D}} \cdot (\mathbf{S}_i \times \mathbf{S}_{i+1}) - \tilde{K}(S_i^z)^2 - HS_i^z$$

## Phase Diagram

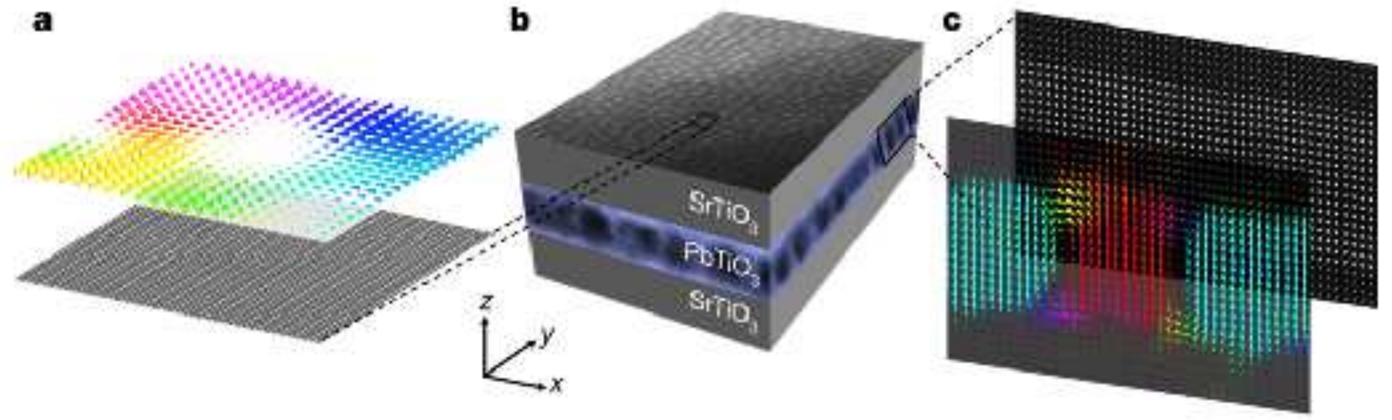



M. N. Wilson, et al., *Phys. Rev. B* **89**, 094411 (2014).

Bulk Compounds

MnSi    MnFeSi / MnCoSi    $GaV_4S_8$    FeGe    $Cu_2OSeO_3$

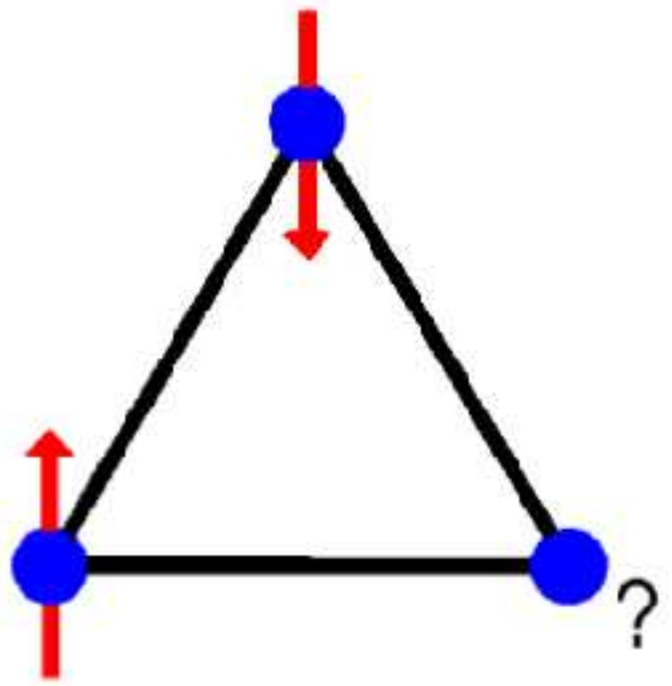
Thin films on magnetic metals



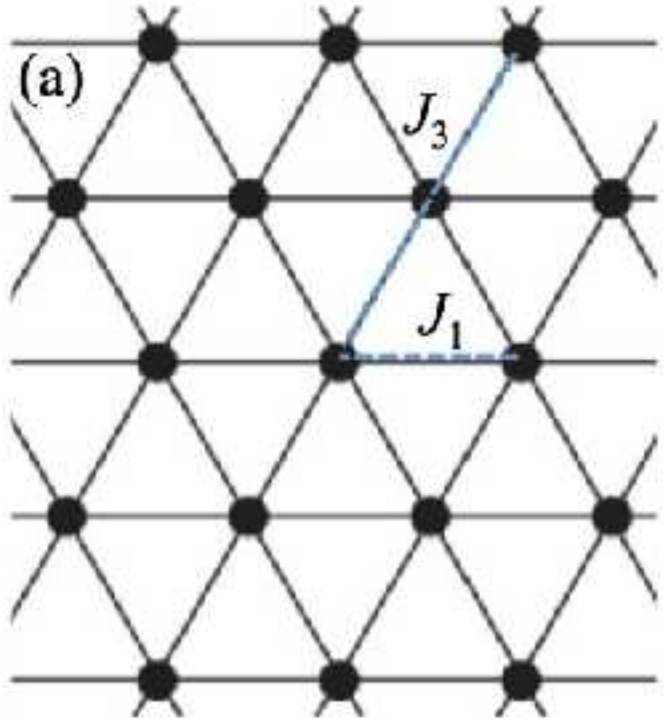

**For a Review**: *Magnetic Skyrmion Materials*, Y. Tokura and N. Kanazawa, Chem. Rev. **121**, 5, 2857 (2021).

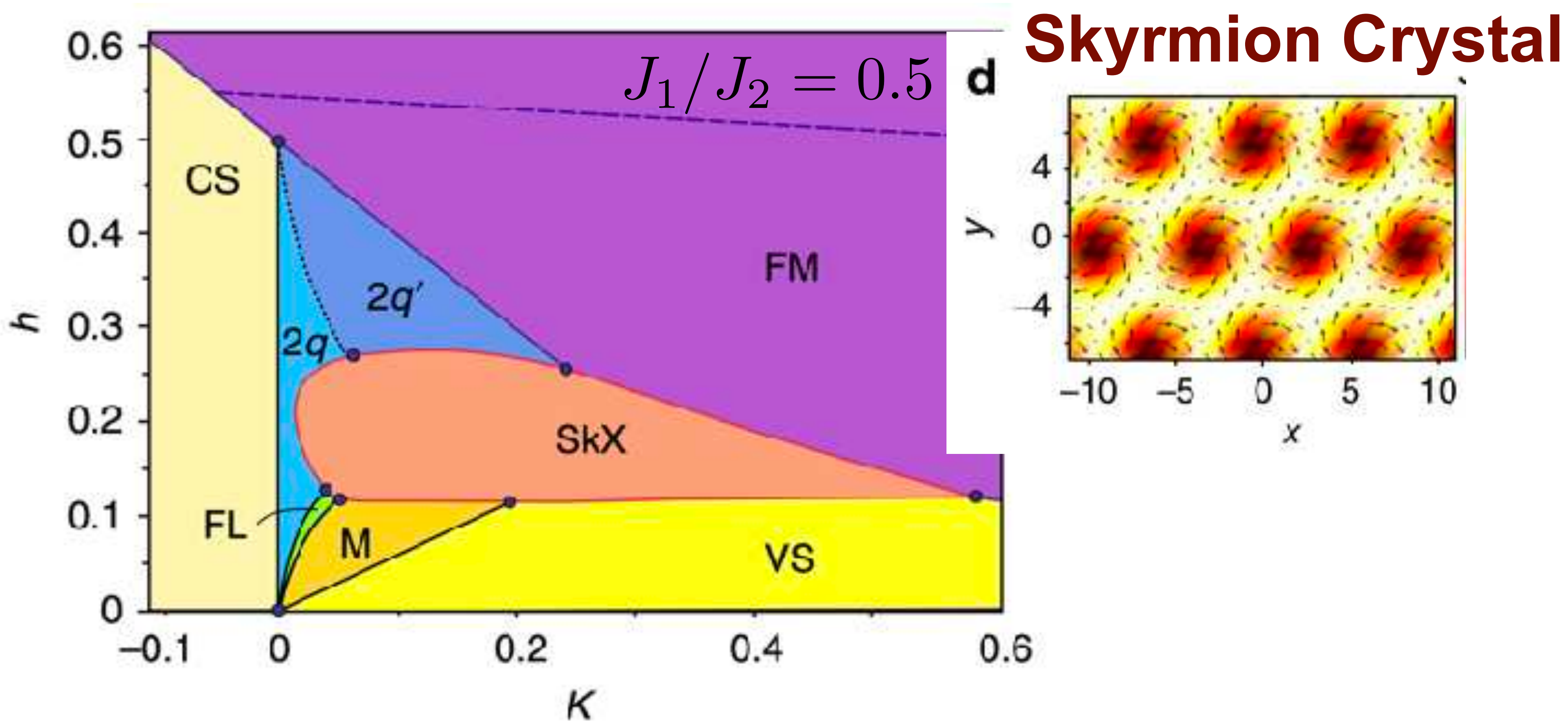
# Frustrated Magnets






$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - J_{2,3} \sum_{\langle\langle i,j \rangle\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - H \sum_i S_{i,z} - \frac{K}{2} \sum_i S_{i,z}^2$$



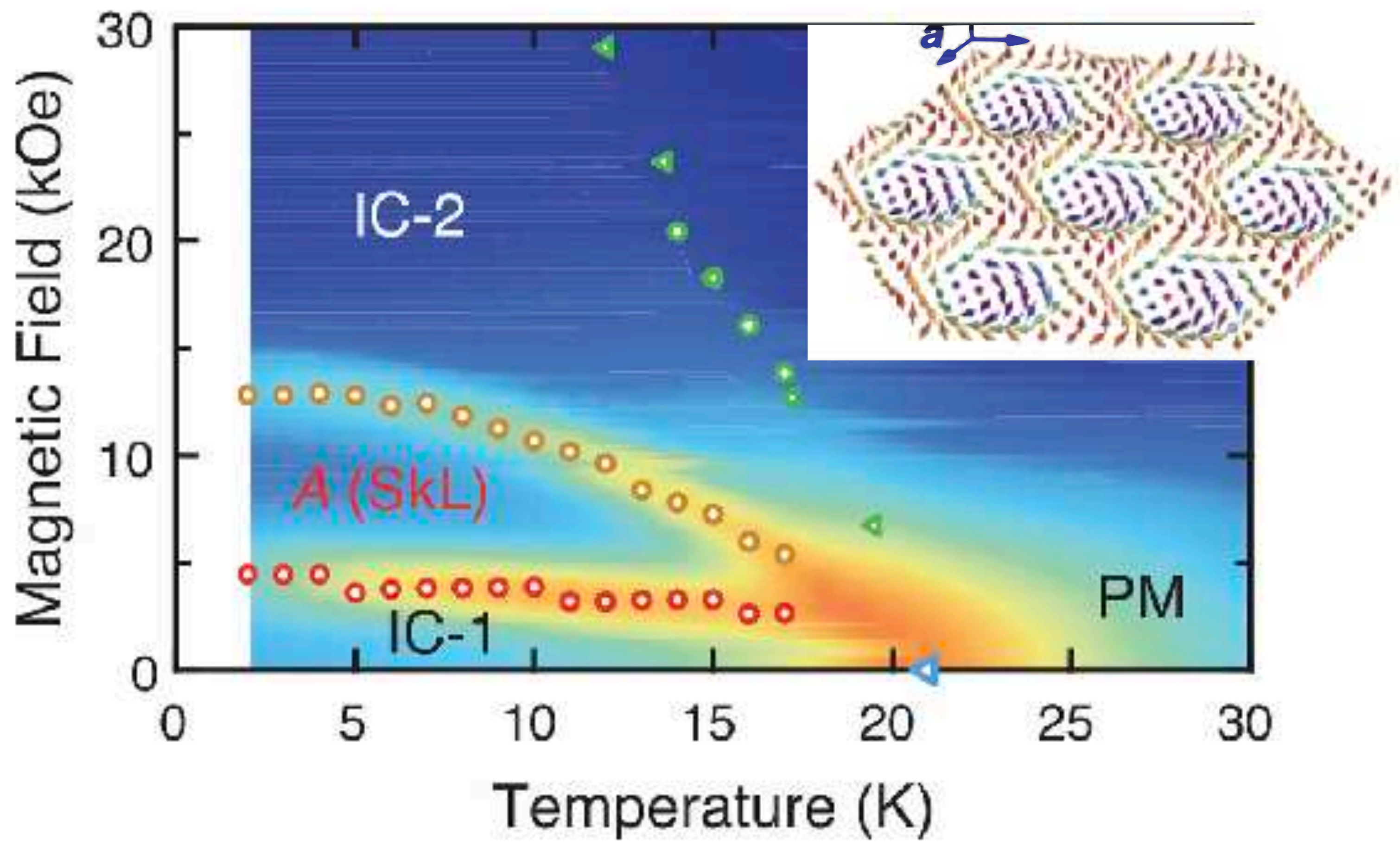




T. Okubo, et al., *Phys. Rev. Lett.* **108**, 017206 (2012).

A. O. Leonov, and M. Mostovoy, *Nature Comm.* **6**, 8275 (2015).

$Gd_2PdSi_3$

$Gd_3Ru_4Al_{12}$



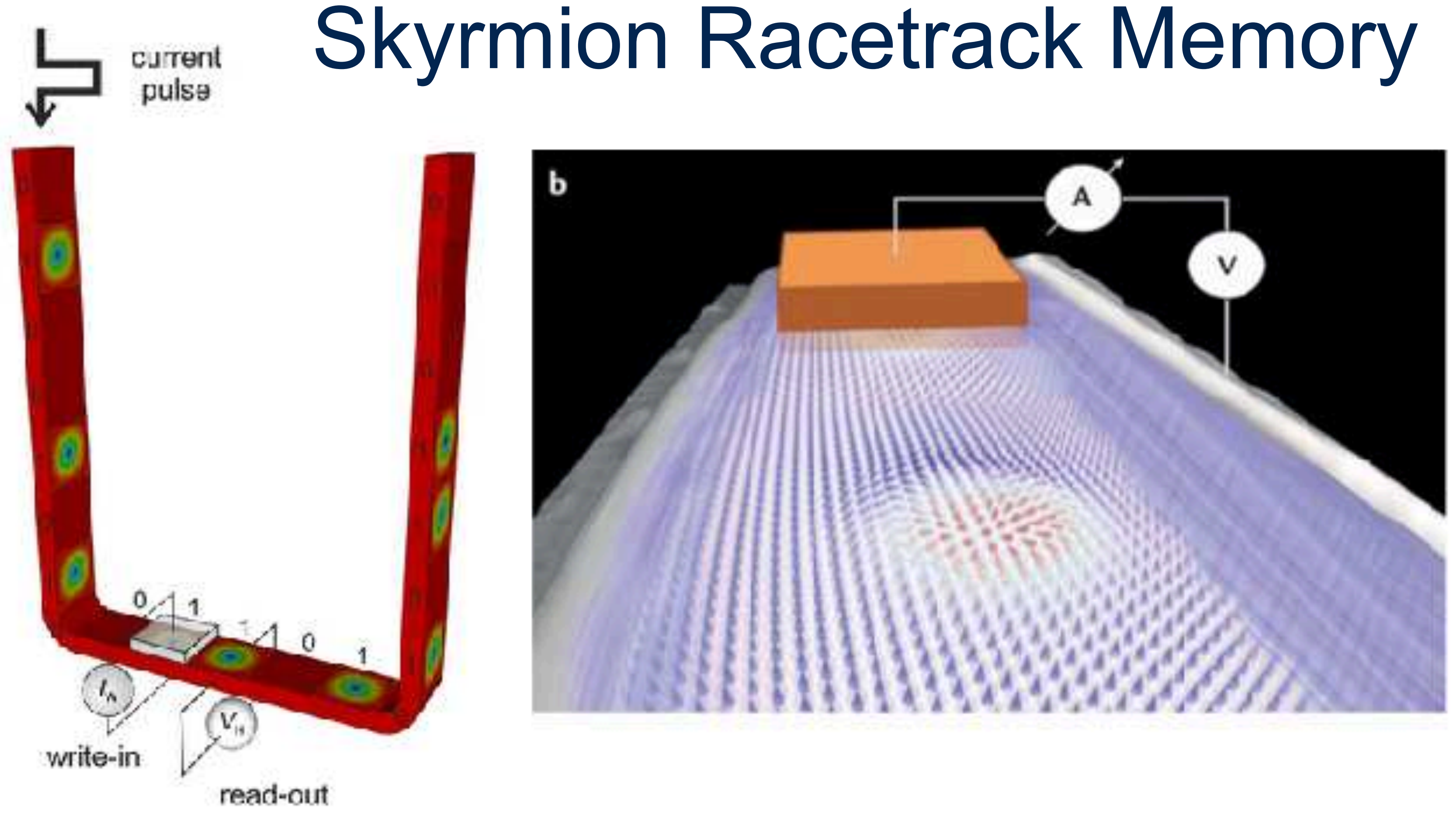

T. Kurumaji, , et al. *Science* 365, 914 (2019)

M. Hirschberger, et al., *Nature Comm.* **10** 5831 (2019)

# Applications

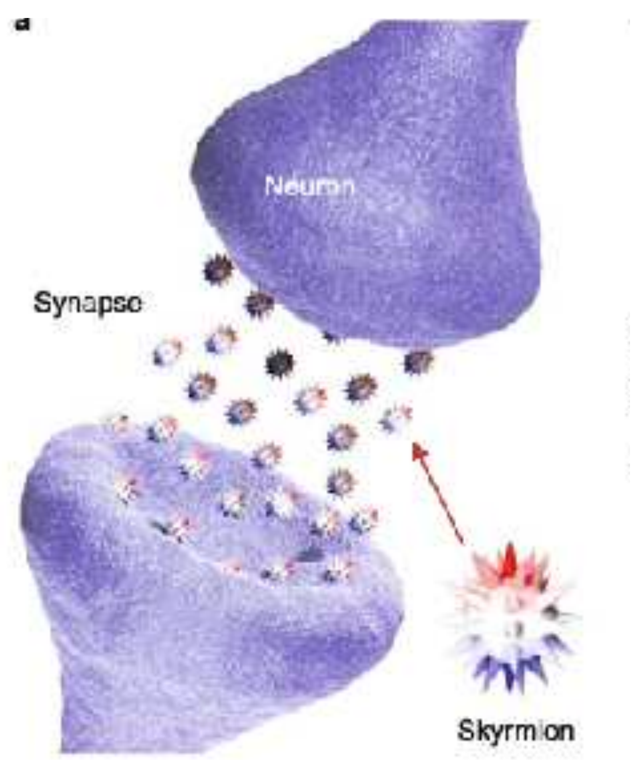


## Skyrmion Racetrack Memory



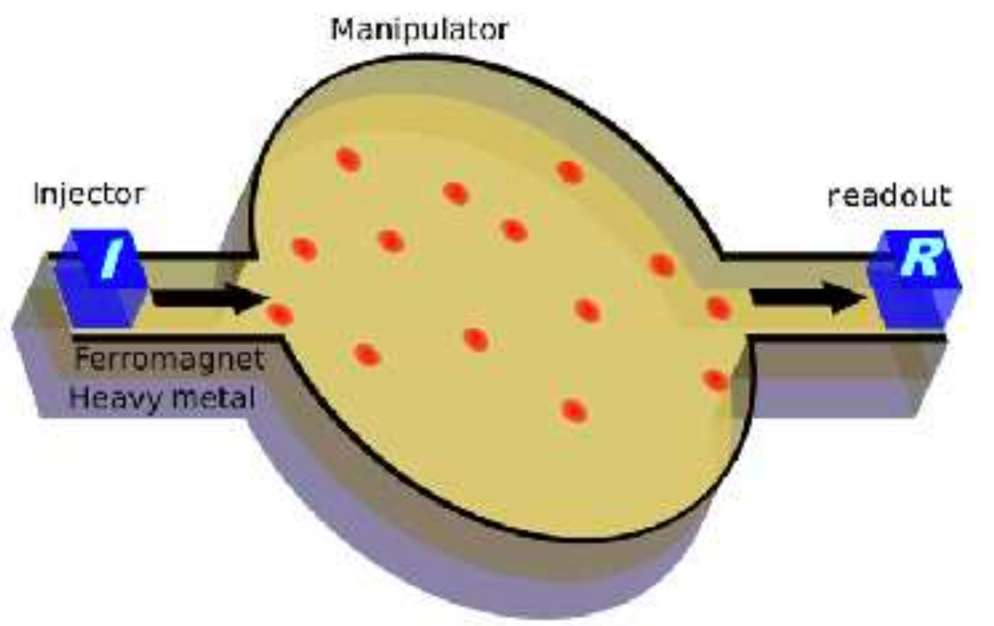

A. Fert, et al., *Nature Nan*. **8**, 152 (2013).
Shilei Zhang, et al., *Sci. Rep*. **5**, 15773 (2015).

## Neuromorphic Computing




K. Mee Song, et al., Nature Electronics **3**, 148–155 (2020).

## Stochastic Computing




D. Pinna et al., Phys. Rev. Applied **9**, 064018 (2018).

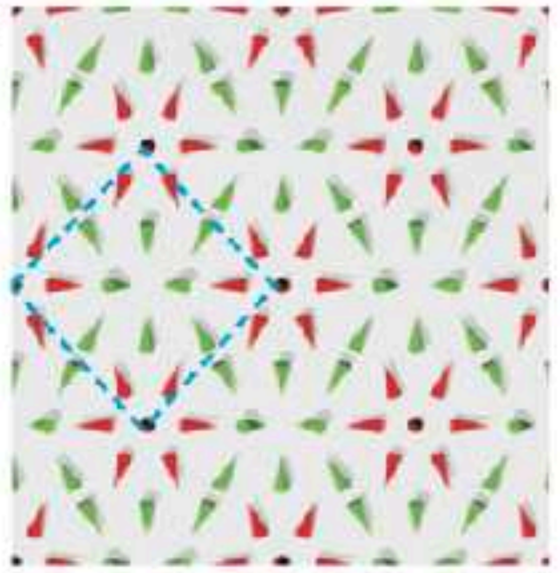
**Stability, formation, and dynamics are well understood to motivate going in the quantum regime!**

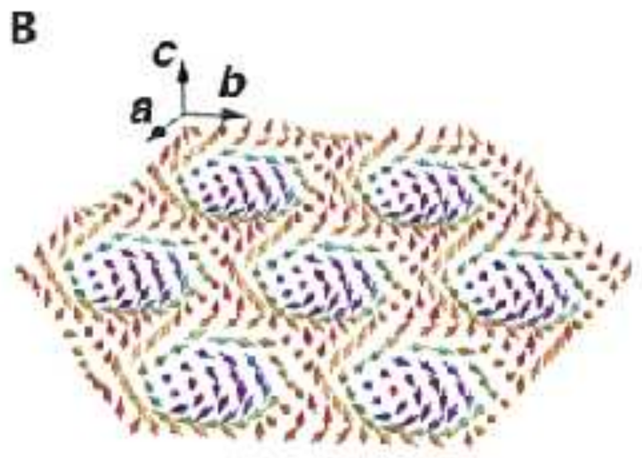
# Skyrmions going quantum

## Atomic Scale Skyrmions

Fe ML on Ir(111) with lattice spacing **1 nm**

Frustrated Magnets with lattice spacing ~ **2.5 nm**



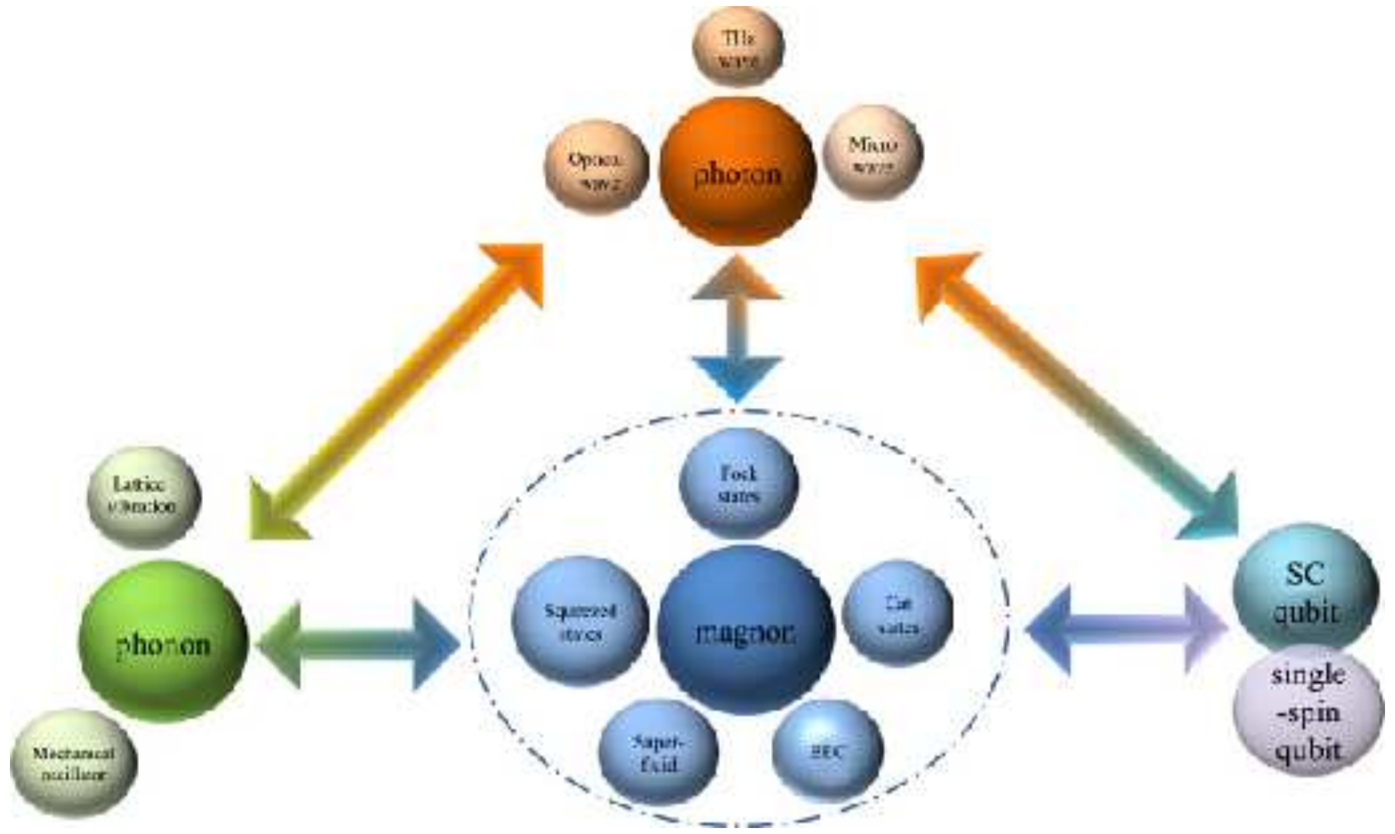




$\mathrm{Gd_2PdSi_3}$

$\mathrm{Gd_3Ru_4Al_{12}}$

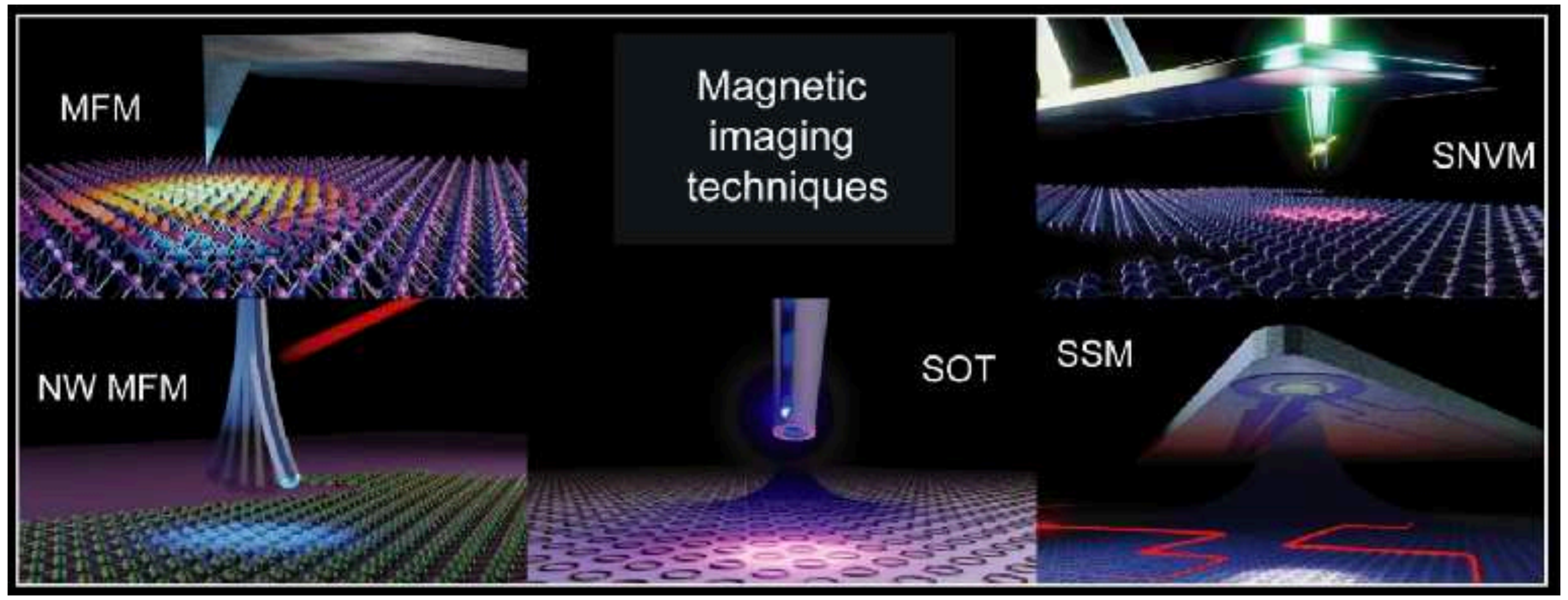
S. Heinze, et al., *Nature Physics* **7**, 713 (2011).
M. Hirschberger, et al., *Nature Comm*. **10** 5831 (2019).

## Quantum Magnonics



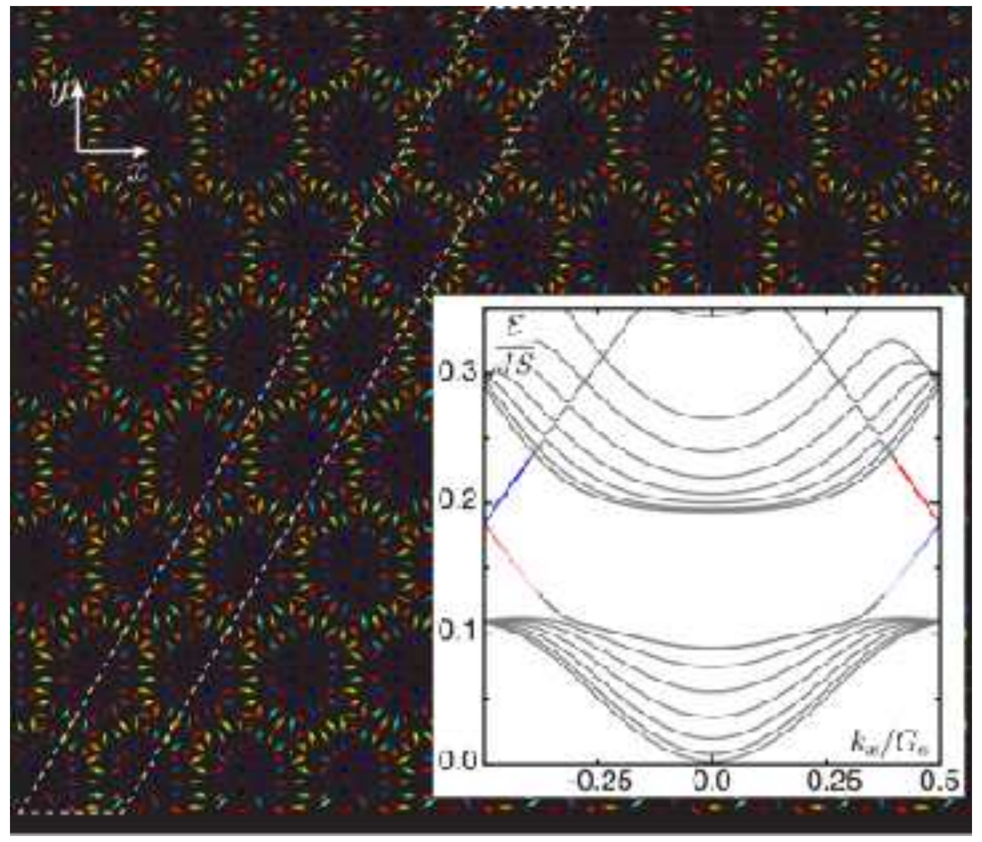

H.Y.Yuan, et al., Physics Reports **965**, 1-74 (2022).

## Quantum Sensing




E. Marchiori, et al., Nat. Rev. Phys. **4**, 49 (2022)

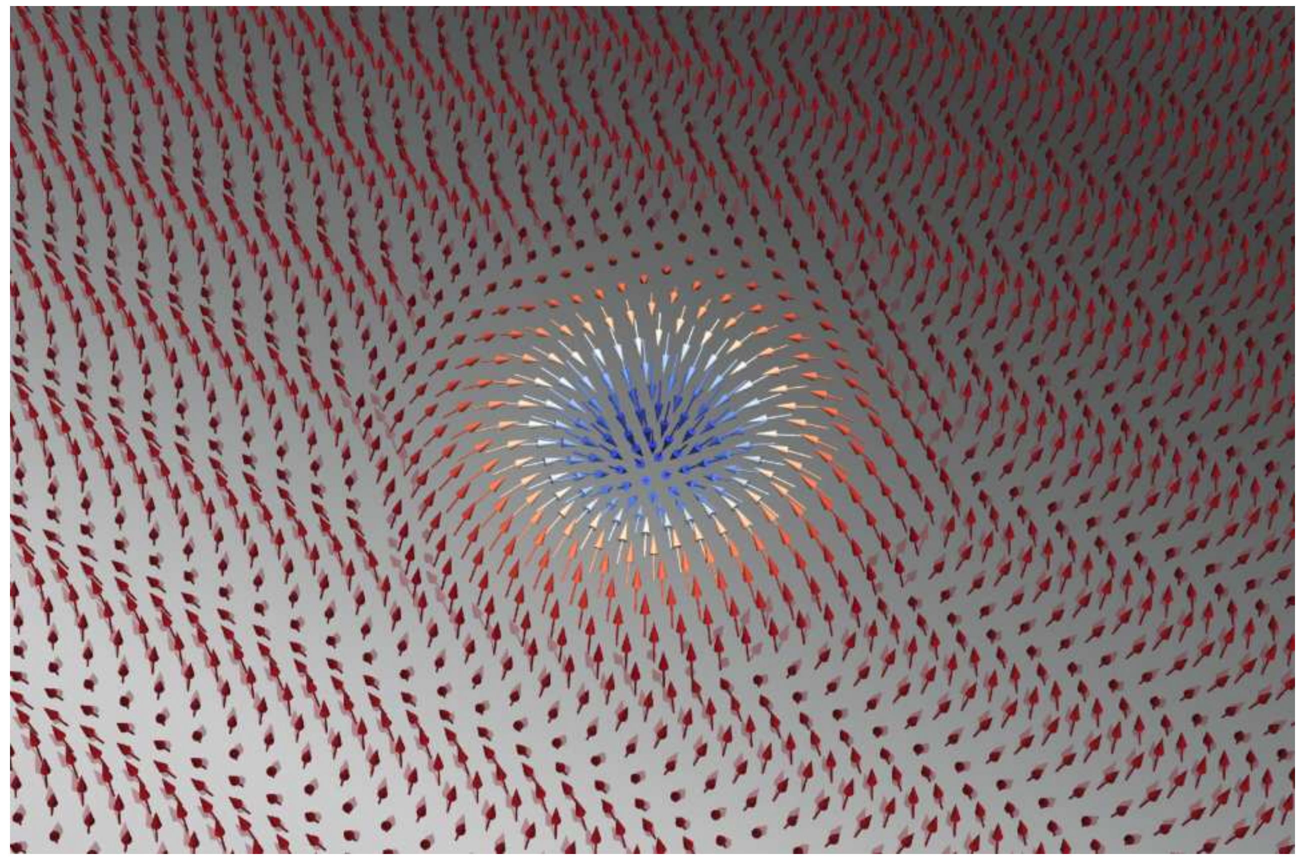
## Topological Magnons




S. A. Diaz, et al., *PRL* **122**, 187203 (2019).

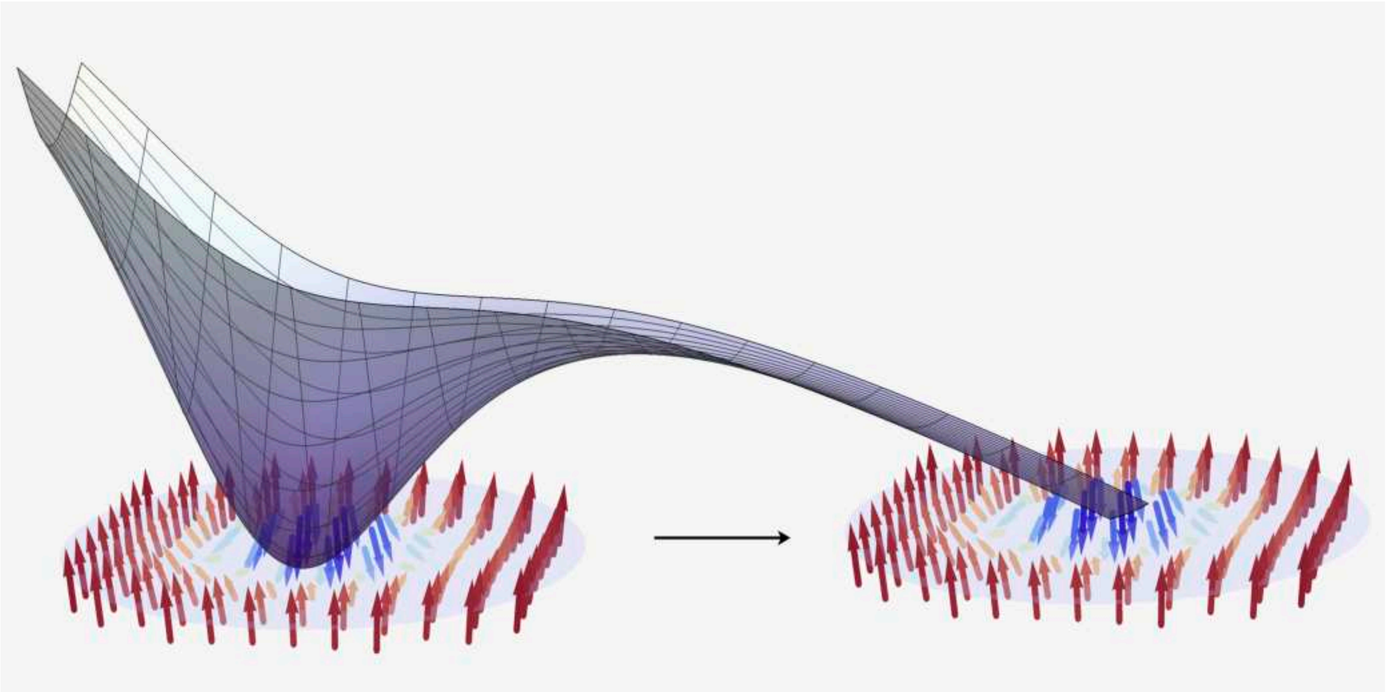
# Quantum Skyrmions





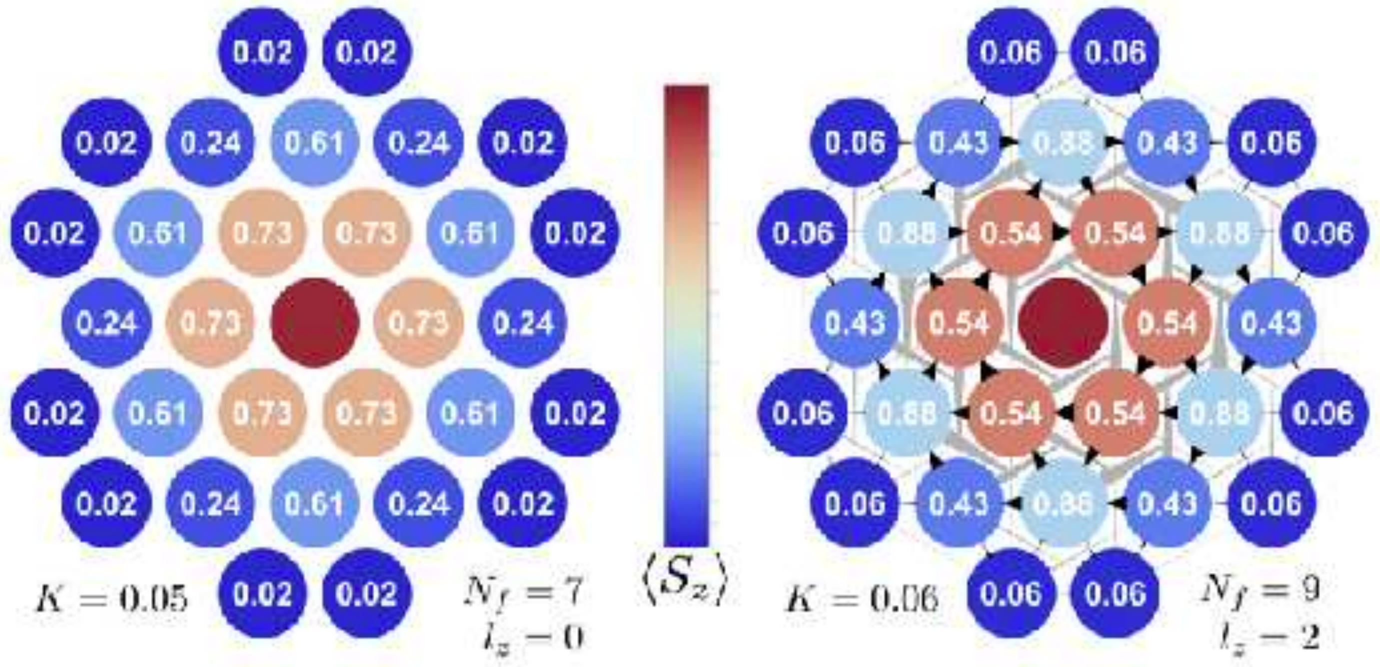
C. Psaroudaki, S. Hoffman, J. Klinovaja, and D. Loss,
*Quantum Dynamics of Skyrmions in Chiral Magnets*,
Phys. Rev. X **7**, 041045 (2017).

*Quantum Mass*



C. Psaroudaki and D. Loss,
*Quantum Depinning of a Magnetic Skyrmion*,
Phys. Rev. Lett. 124, 097202 (2020).

*Macroscopic Quantum Phenomena*

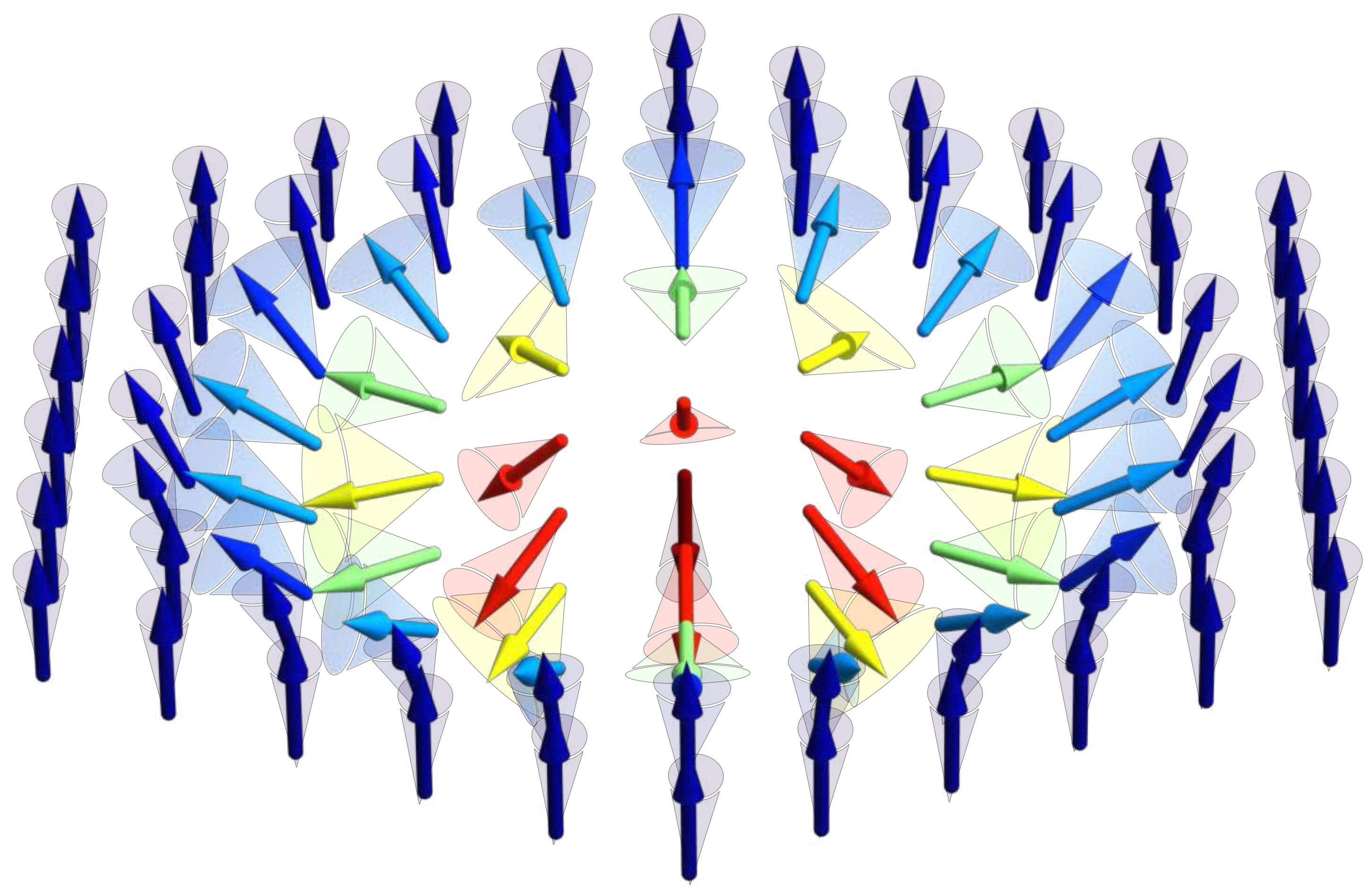



V. Lohani, C. Hickey, J. Masell, and A. Rosch,
*Quantum Skyrmions in Frustrated Ferromagnets*,
Phys. Rev. X 9, 041063 (2019).

*Skyrmions in spin 1/2 frustrated magnets*

# Quantum Skyrmions





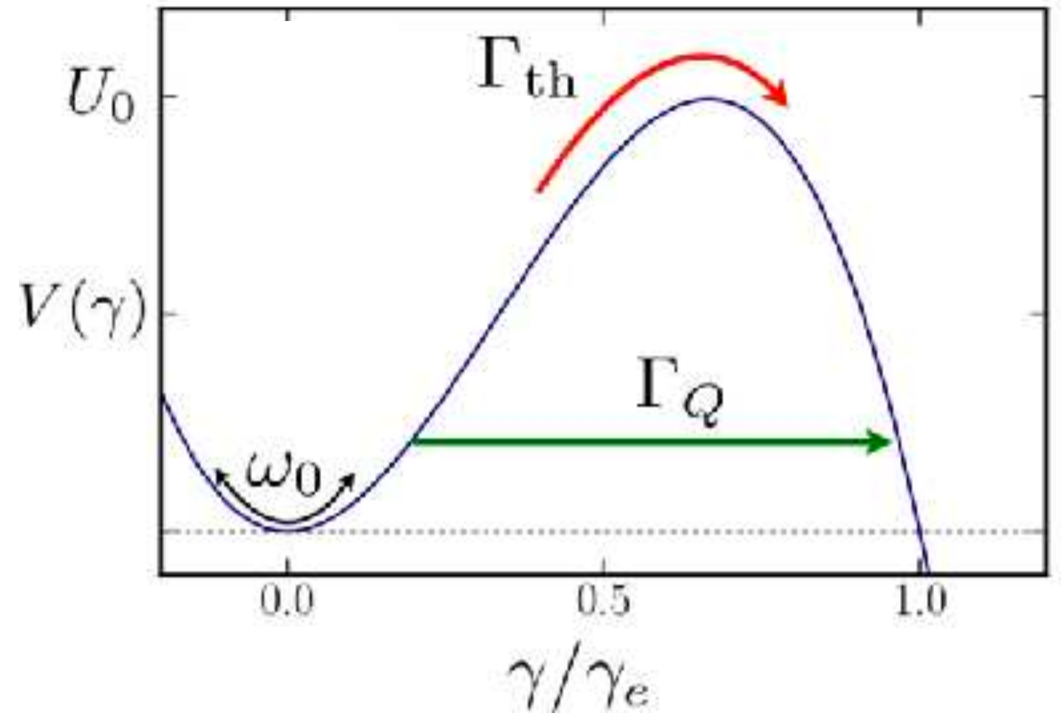
***Strong Quantum Fluctuations***

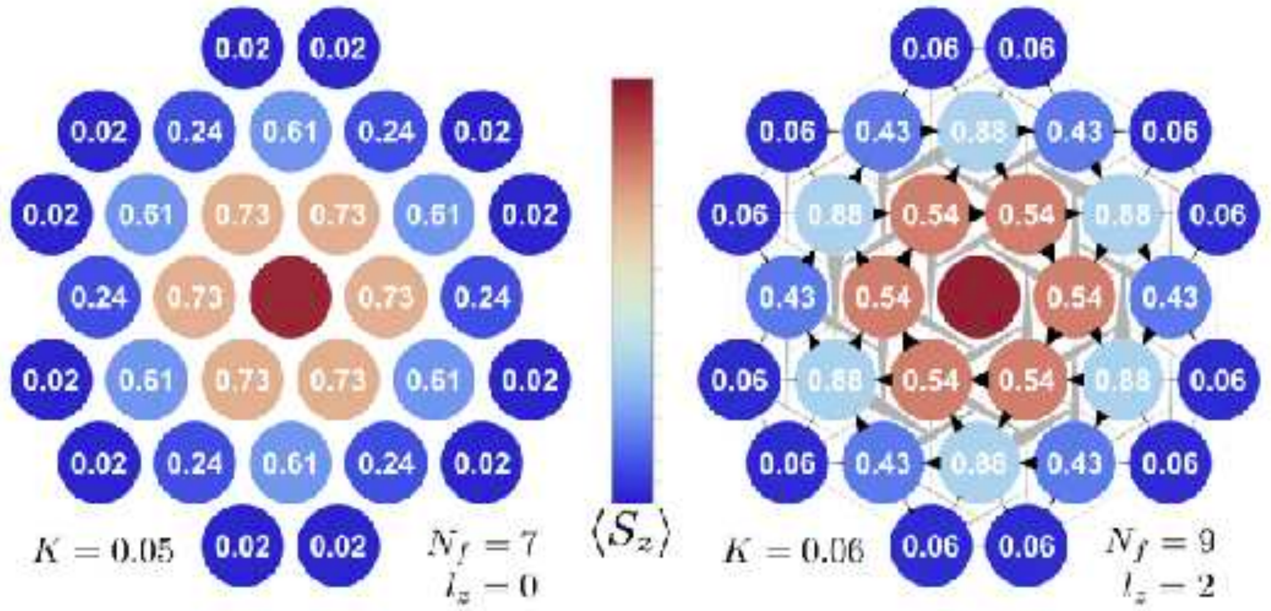
- Collective coordinates $\mathbf{m}(\mathbf{r}, t) \to \mathbf{m}(\mathbf{R}(t)\,, \varphi_0(t), \gamma(t))$
- Collective coordinates canonical quantization

  Particle + fluctuations

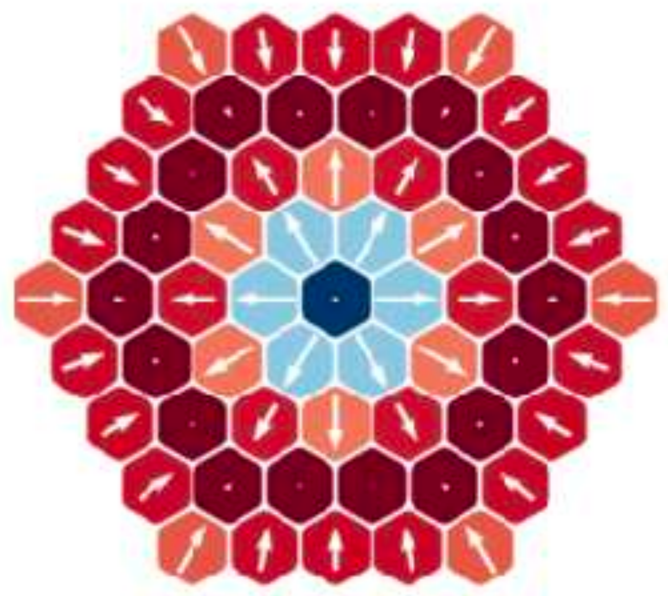
$$\mathbf{R} \to \hat{\mathbf{R}}$$
$$\varphi_0 \to \hat{\varphi}_0$$
$$\gamma \to \hat{\gamma}$$

- Macroscopic quantum tunneling




***Skyrmions in spin 1/2 magnets***



$$\hat{H} = \frac{1}{2}\sum_{\langle \boldsymbol{r},\boldsymbol{r}'\rangle}[J\hat{\boldsymbol{S}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}'} + \boldsymbol{D}_{\boldsymbol{r}'-\boldsymbol{r}} \cdot (\hat{\boldsymbol{S}}_{\boldsymbol{r}} \times \hat{\boldsymbol{S}}_{\boldsymbol{r}'})] + \sum_{\boldsymbol{r}} \boldsymbol{B} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}},$$

A. Haller, et al., Phys. Rev. Res. **4**, 043113 (2022)
V. Lohani, et al., Phys. Rev. X **9**, 041063 (2019).

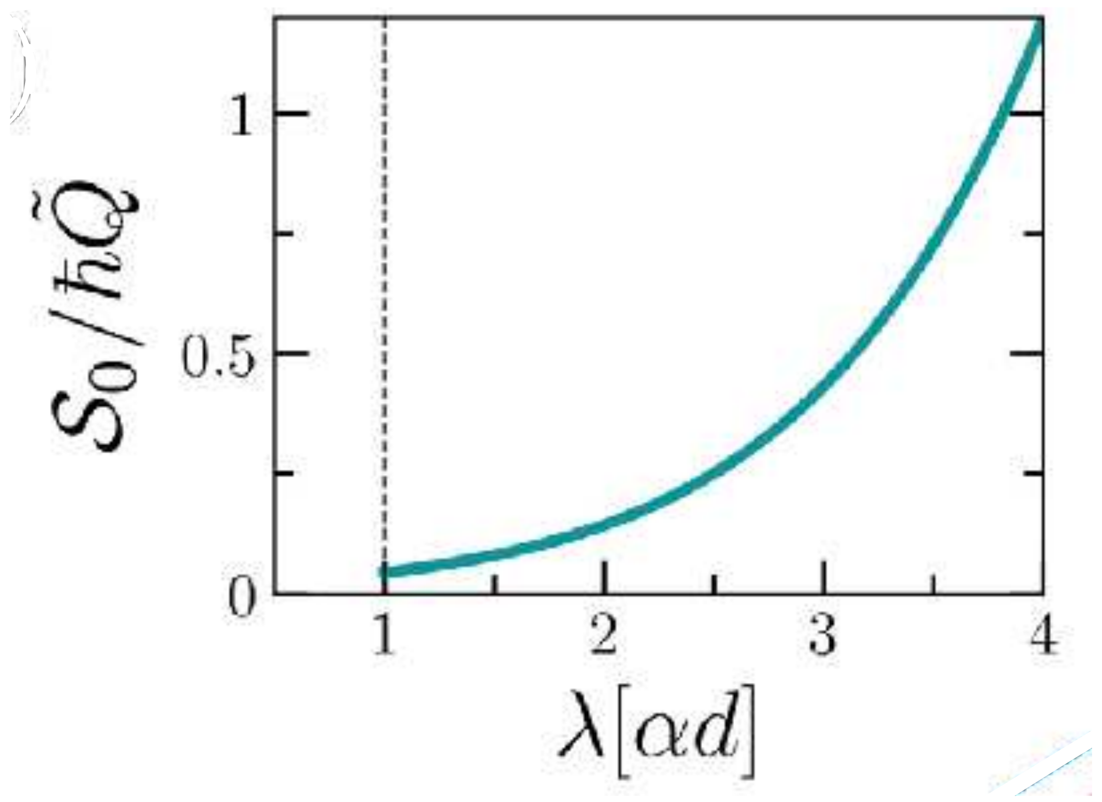
# Quantum Depinning



$$\mathcal{S}_E = \int_0^\beta d\tau[-i\tilde{Q}(\dot{\mathcal{X}}\mathcal{Y} - \dot{\mathcal{Y}}\mathcal{X}) + \frac{1}{2}\mathcal{M}\dot{\mathbf{R}}^2 + U(\mathcal{X},\mathcal{Y})]$$

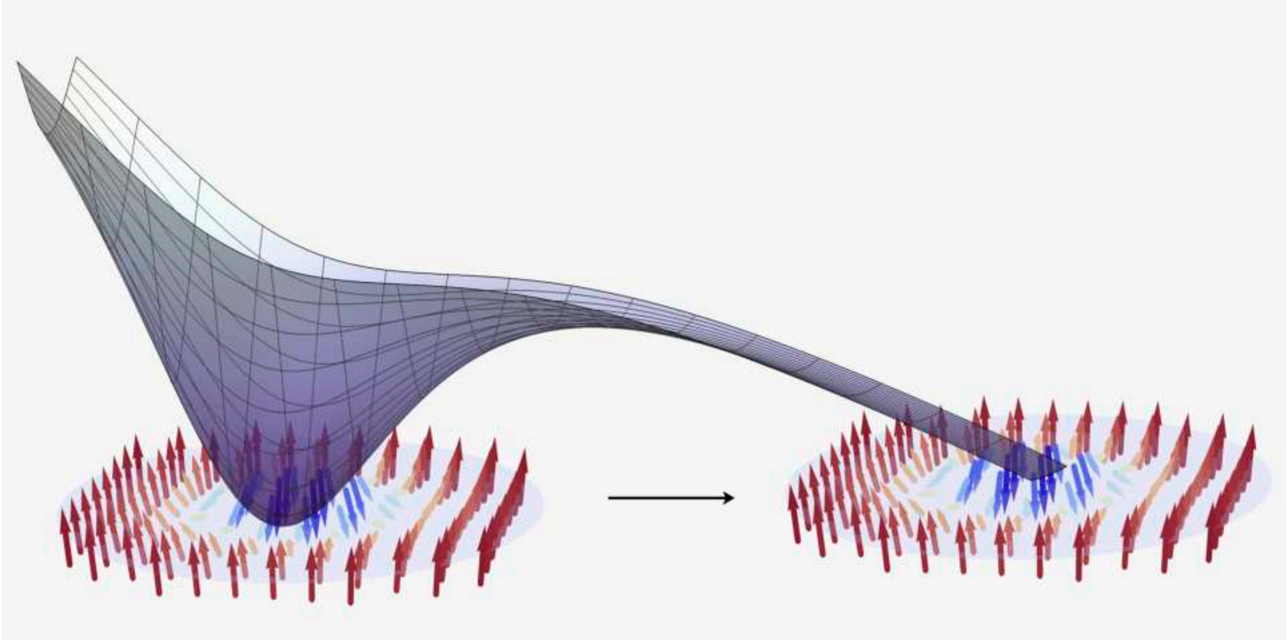
Topological number — Skyrmion Mass — Pinning Potential

**Decay Rate** $\Gamma \simeq \frac{\omega_\tau}{2\pi} e^{-\mathcal{S}_0/\hbar}$

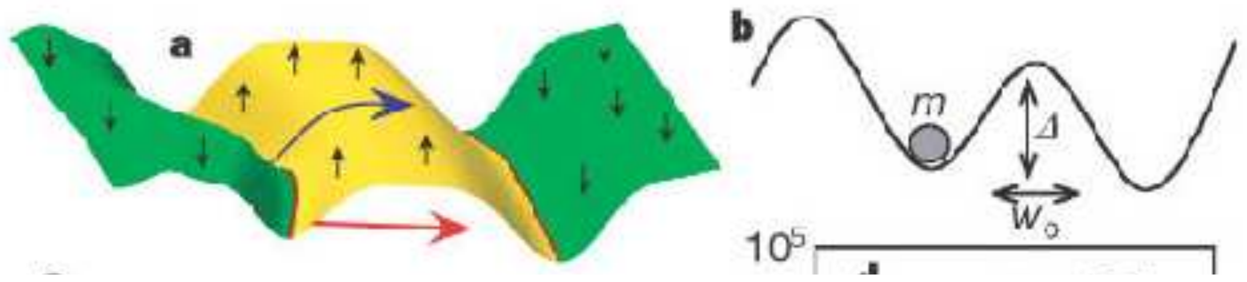



**Crossover Temperature** $T_c = \frac{\hbar U_0}{k_B \mathcal{S}_0}$

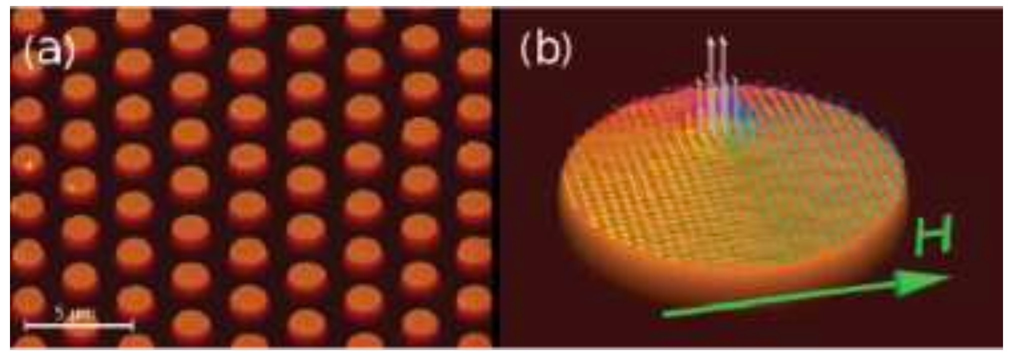
$\Gamma^{-1} \approx 100$ s



*Quantum Depinning of a Magnetic Skyrmion,*
C. Psaroudaki and D. Loss, Phys. Rev. Lett. **124**, 097202 (2020)




J. Brooke, *et al.*, Nature **413**, 610 (2001).

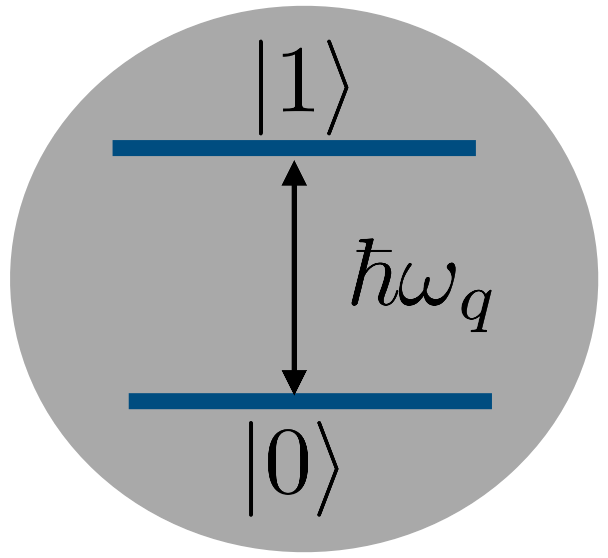


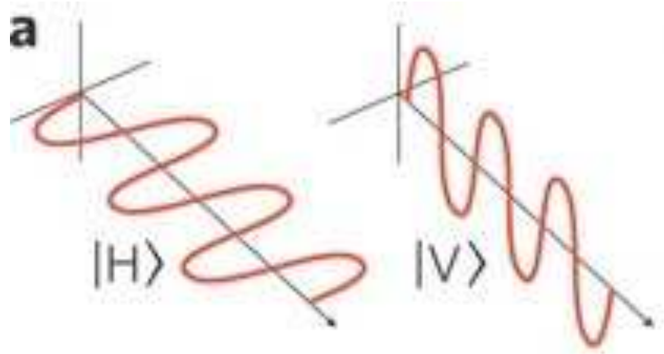

R. Zarzuela, et al.,
Phys. Rev. B **85**, 180401(R) (2012).

# Quantum Computing

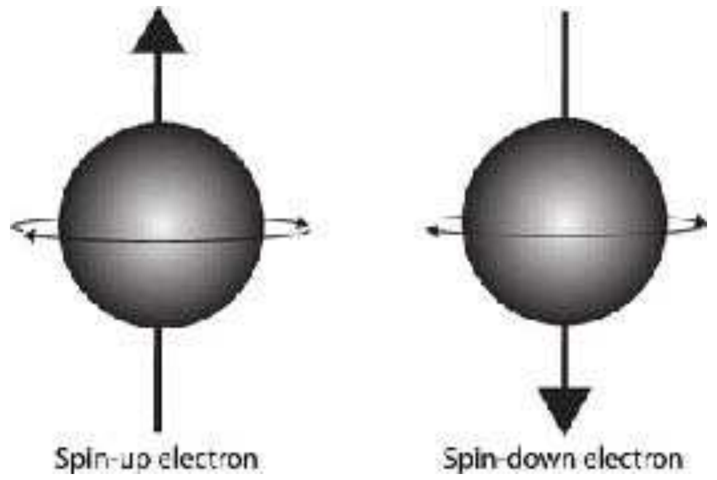


## Two-level System

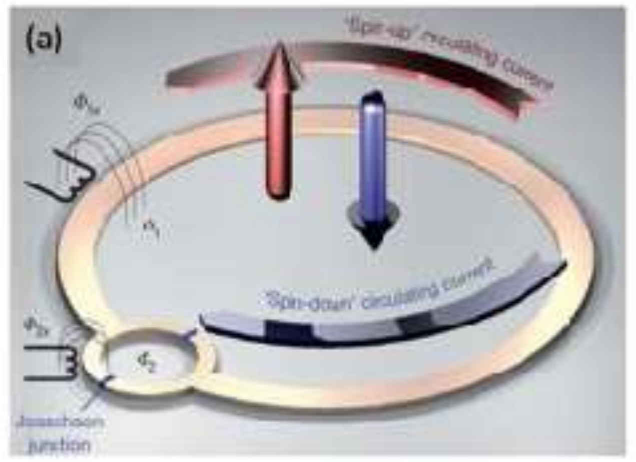



*Photon Polarization*

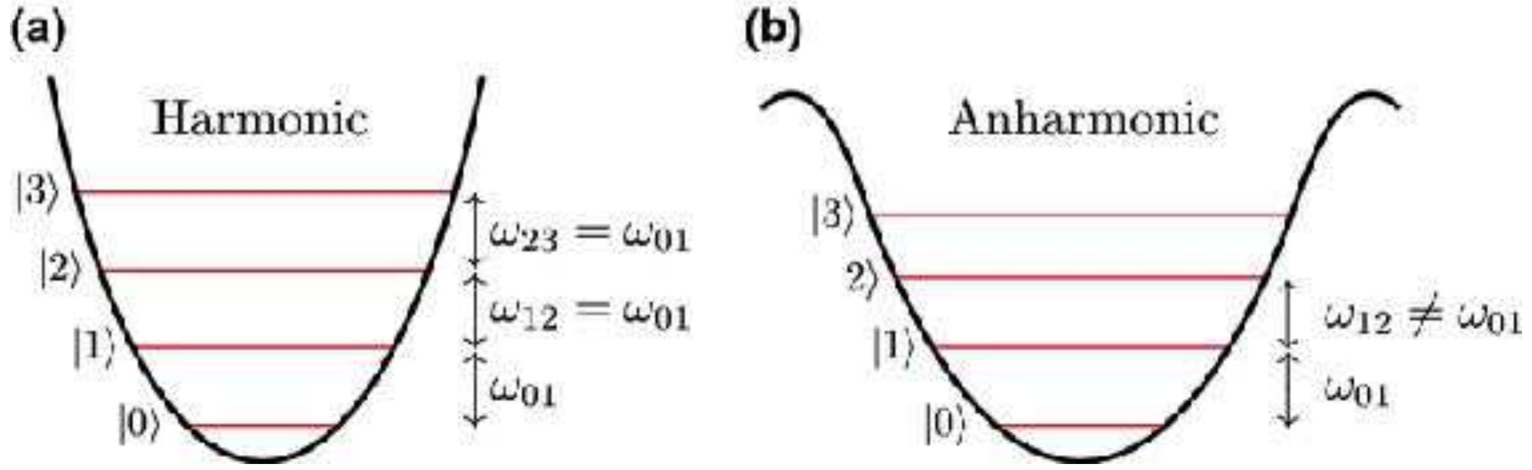



*Electronic Spin*

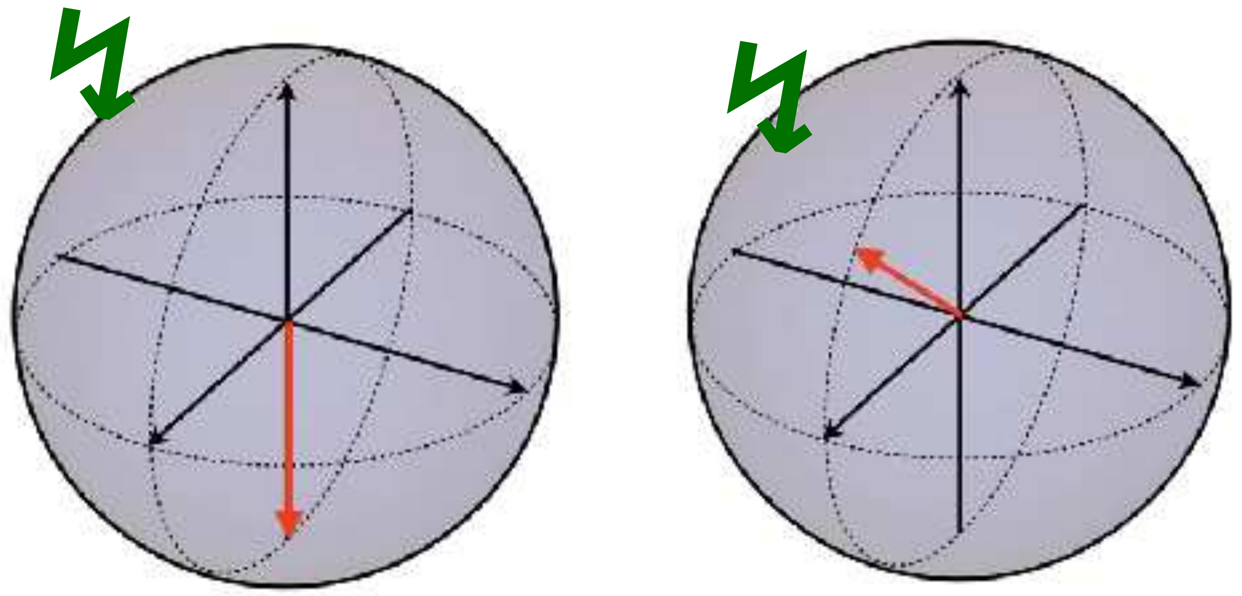



*Superconducting Flux*

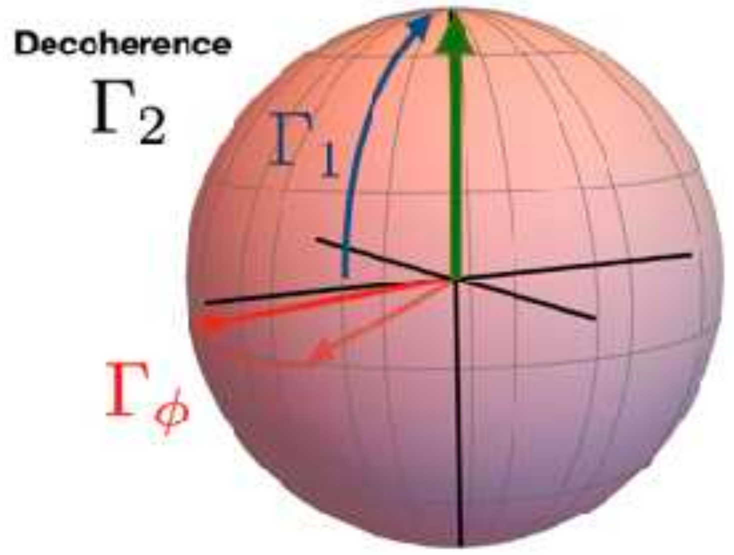
*Skyrmion Helicity*



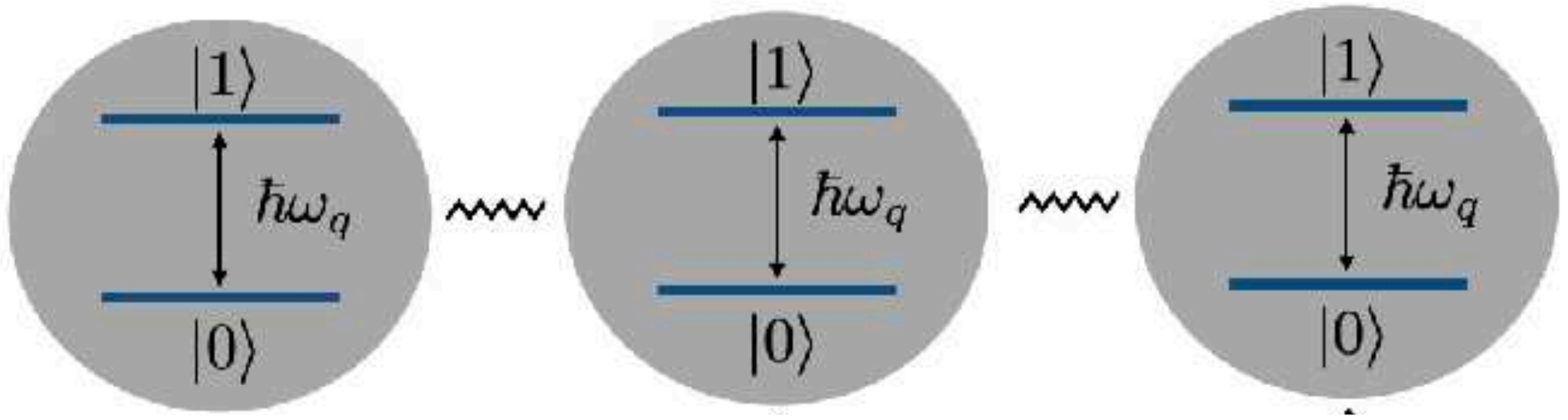

*Anharmonicity*



*Initialization and Control*




*Decoherence*




*Scalability*

$$\mathcal{G}_0 = \{U_x, U_y, U_z, U_{\mathrm{ph}}, U_{\mathrm{CNOT}}\}$$

$$\mathcal{G}_1 = \{U_H, U_S, U_T, U_{\mathrm{CNOT}}\}$$

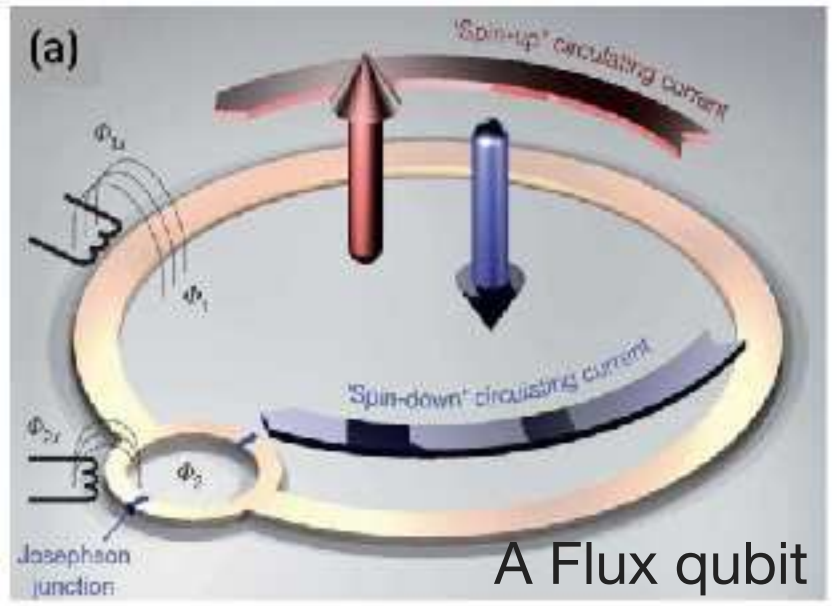
*Universal Set of Quantum Gates*

# Physical Qubits



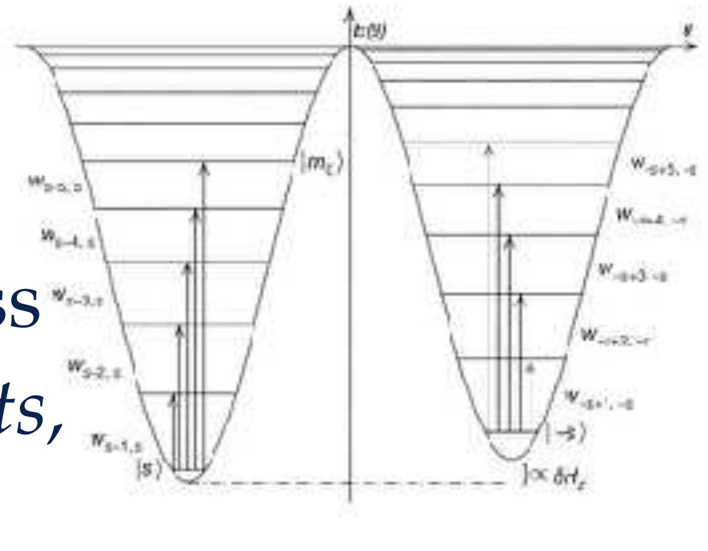
- Superconducting Qubits

John Clarke & Frank K. Wilhelm,
*Superconducting quantum bits, Nature* ***453*** *(2008)*



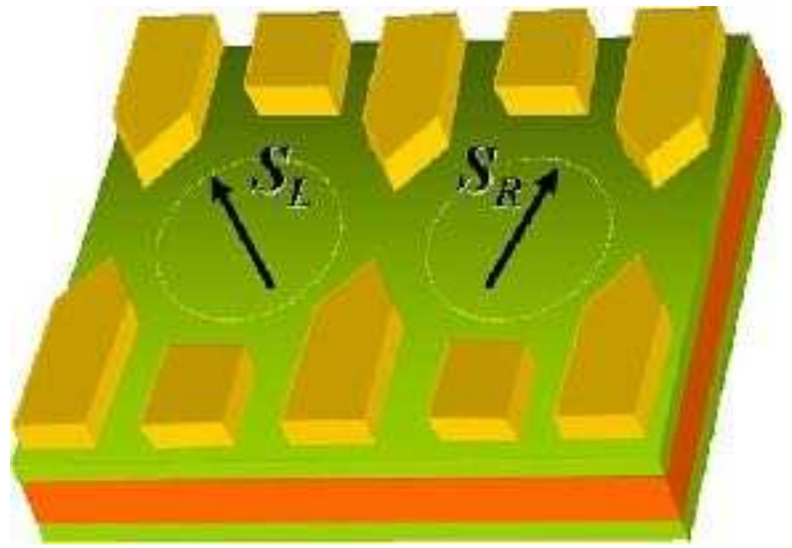

- Molecular Magnets

Michael N. Leuenberger & Daniel Loss
*Quantum computing in molecular magnets,*
*Nature* ***410****, 789 (2001)*



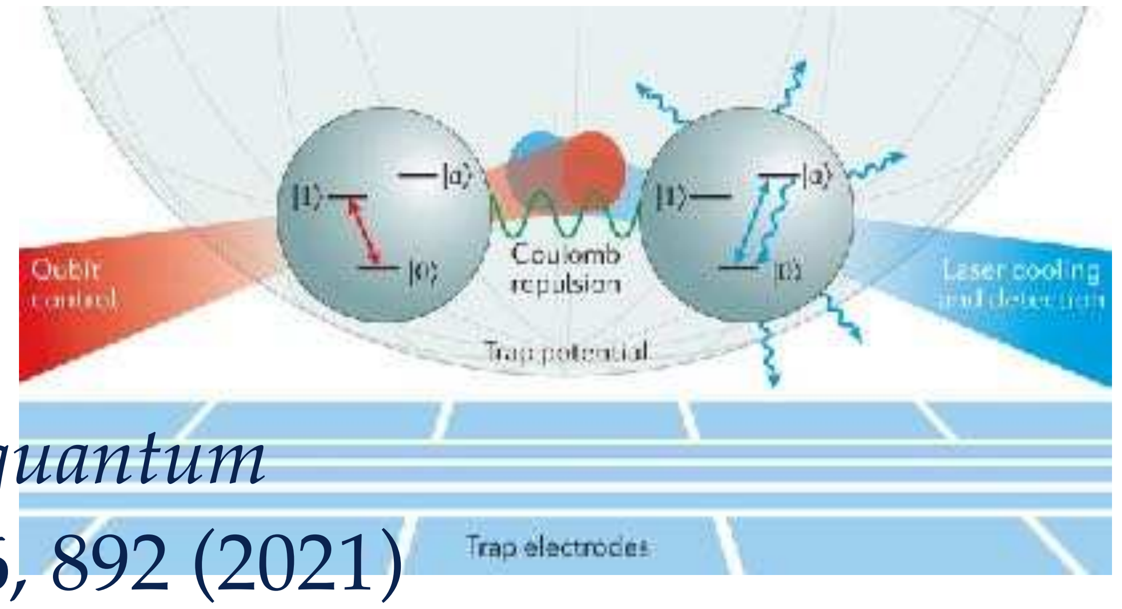
- Quantum Dot Qubit

Daniel Loss and David P. DiVincenzo,
*Quantum computation with quantum dots,*
*Phys. Rev. A* **57***, 120 (1998)*




- Ion Traps

K. R. Brown, et al.,
*Materials challenges for trapped-ion quantum computers,* Nature Reviews Materials **6**, 892 (2021)




- Photon Qubits

J. L. O'Brien, et al.,
*Photonic quantum technologies,*
*Nature Photonics* **3** 687 (2009)

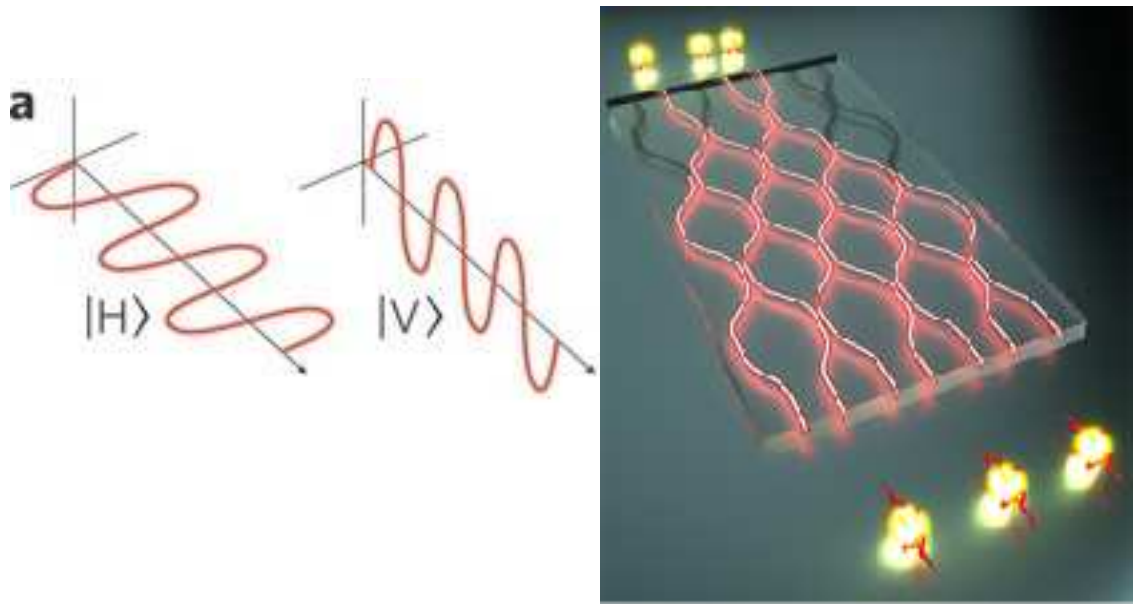
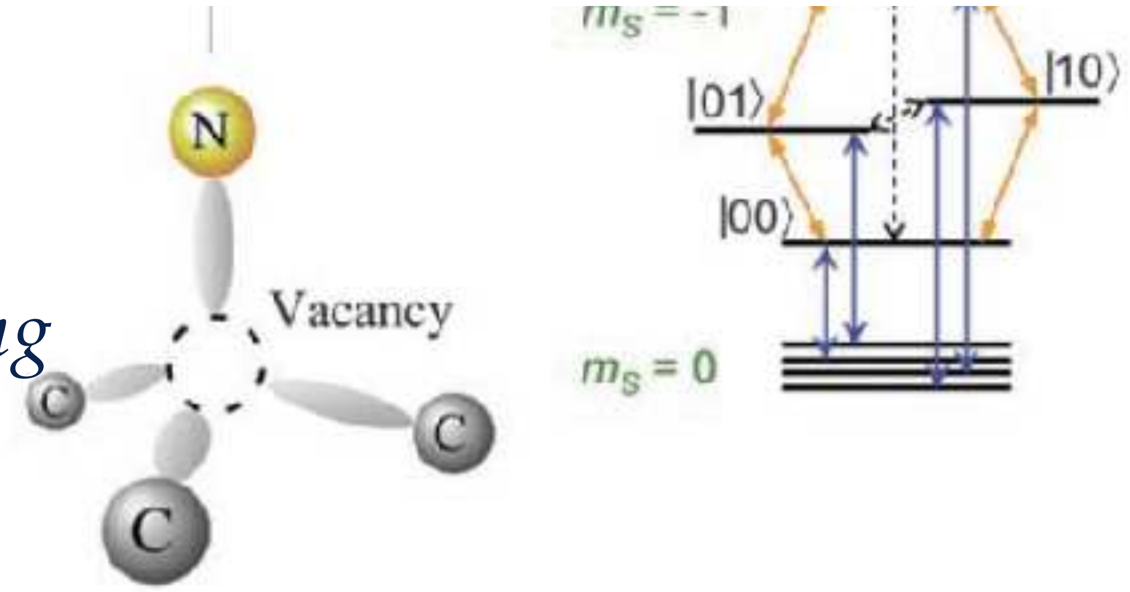



*Figure from: Ernesto Galvão/ Quantum and linear-optical computation/INL*

- Nitrogen Vacancies in Diamond

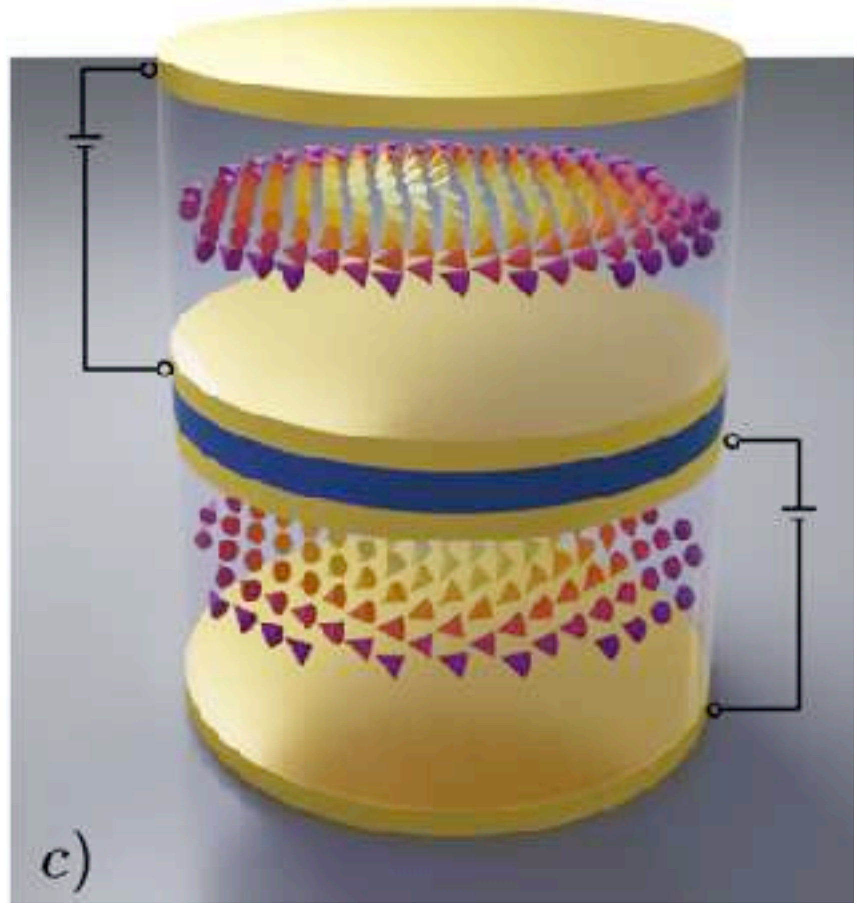
P. Neumann, et al.,
*Multipartite Entanglement Among Single Spins in Diamond,*
*Science* ***320****, 1326 (2008)*



# Novel Platform: Skyrmion Qubit



## Roadmap for new qubit development




- Identify a degree of freedom that can be quantum-coherently controlled

  ↳ *Skyrmion Helicity in frustrated magnets*

- Check if a few traditional requirements are met

  ↳ *Coherence time, scalability, control and gate operations*

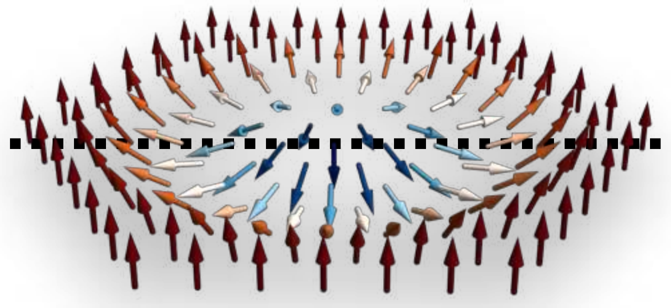
- Readout Measurements

## Advantages

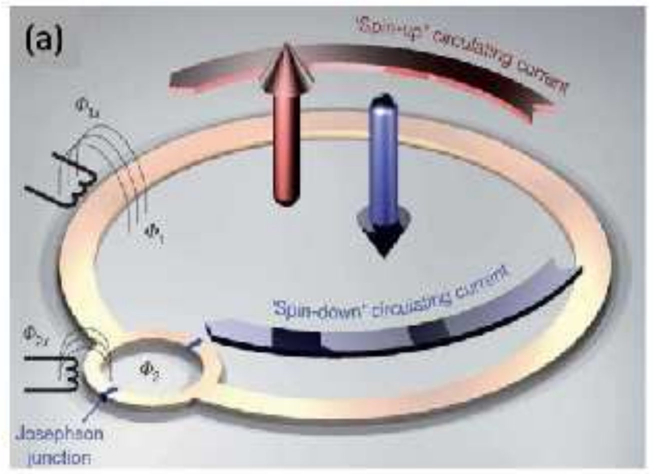
- Compact, high density, and low-energy devices

Single-Spins

Skyrmions



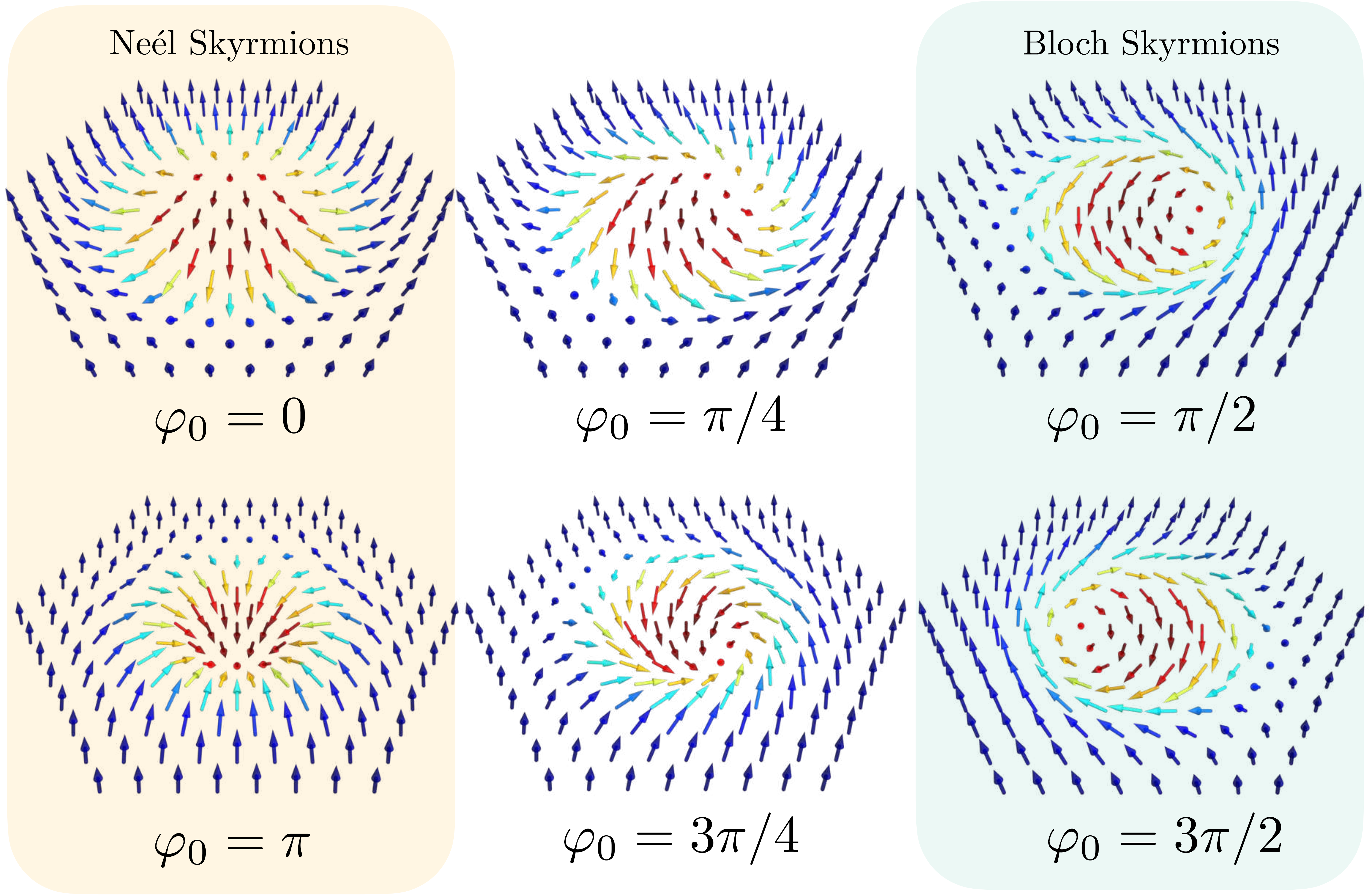
Circuits




- Ability to individually address qubits and tune external parameters
- Transferable state-of-the-art technology from skyrmionics

# Stabilizing Mechanisms






$$\mathbf{m} = (\sin\Theta(\mathbf{r})\cos\Phi(\mathbf{r}), \sin\Theta(\mathbf{r})\sin\Phi(\mathbf{r}), \cos\Theta(\mathbf{r}))$$

$$\Phi(\mathbf{r}) = \phi + \varphi_0$$ Helicity

$$\Theta(\mathbf{r}) = \Theta(\rho)$$

Dipole Interactions: $\propto \cos(2\varphi_0)$ — $\ell_{\rm typ} = J/V$ — $\ell_{\rm sky} = 100\text{nm} - 1\mu\text{m}$

Dzyaloshinskii- Moriya Interactions: $\propto \cos(\varphi_0)$ (Bulk), $\sin(\varphi_0)$ (Interfacial) — $\ell_{\rm typ} = J/D$ — $\ell_{\rm sky} = 10 - 100\text{nm}$

Geometrical frustration: Global Symmetry: No intrinsic potential term — $\ell_{\rm typ} = \sqrt{J_2/J_1}$ — $\ell_{\rm sky} = 2 - 10\text{nm}$

# Skyrmion Helicity Quantization



$$Z = \int \mathcal{D}\mathbf{m} e^{i\mathcal{S}(\mathbf{m},\dot{\mathbf{m}})}$$

Path integral quantization

$$\mathbf{m} = \mathbf{m}_0(\mathbf{r}, \varphi_0(t)) + \boldsymbol{\chi}(\mathbf{r}, t, \varphi_0(t)) \longrightarrow$$

$$Z = \int \mathcal{D}\varphi_0 \mathcal{D}S_z e^{i\mathcal{S}_{\text{eff}}(\varphi_0, S_z)} \tilde{Z}$$

**Faddeev-Popov techniques** *δ-constraints*

$$\int \mathcal{D}\varphi_0 \mathcal{D}S_z J_{\varphi_0} J_{S_z} \delta(F_1)\delta(F_2) = 1$$

*Integrate out zero mode* ($\delta(F_1)$) *Momentum Conservation* ($\delta(F_2)$)

**Canonical Forms** $\{\Phi(\mathbf{r}), \Pi(\mathbf{r}')\}_D = \delta(\mathbf{r} - \mathbf{r}')$

$$\int dr^2 dt \; \dot{\Phi}(1 - \cos\Theta) = \int dt[S_z\dot{\varphi}_0 + \int dr^2 \boldsymbol{\chi}^* \dot{\boldsymbol{\chi}}]$$

$$\mathcal{S}_{\text{eff}} = \int dt[\bar{S} \; S_z\dot{\varphi}_0 - H(\varphi_0, S_z)]$$

**Conjugate Momentum**

Conjugate momentum $S_z = \int d\mathbf{r}(1 - m_z)$

Generator of rotations $\{S_z, \Phi\} = -\partial_\phi \Phi$

**Collective Coordinate Operators**

$\hat{\varphi}_0 \, , \hat{S}_z \quad [\hat{\varphi}_0, \hat{S}_z] = i/\bar{S}$

$\hat{S}_z|s\rangle = (s/\bar{S})|s\rangle$

$\hat{\varphi}_0|\varphi_0\rangle = \varphi_0|\varphi_0\rangle \, , \text{with } |\varphi_0\rangle = |\varphi_0 + 2\pi\rangle$

# Skyrmion Helicity Quantization



$$Z = \int \mathcal{D} \ldots$$

$$\ldots e^{i\mathcal{S}_{\text{eff}}(\varphi_0, S_z)}\tilde{Z}$$

PHYSICAL REVIEW D VOLUME 11, NUMBER 10 15 MAY 1975

**Extended particles in quantum field theories***

J.-L. Gervais
*Laboratoire de Physique Theorique de l'Ecole Normale Superieure 75005 Paris, France*

B. Sakita
*Department of Physics, The City College of The City University of New York, New York, New York 10031*

(Received 13 January 1975)

The method of collective coordinates developed in the study of strong-coupling theory is used for the quantization of the kink solution of a two-dimensional nonlinear field theory. The position of the kink is treated as a collective coordinate, which represents the position of a particle. It is separated from the rest of the coordinates, which represent the internal degrees of freedom of an extended particle. Two similar but different methods are presented; the one is nonrelativistic and suited for the weak-coupling limit, while the other is relativistic.

**Faddeev-Popo**

$$\int \mathcal{D}\varphi_0 \mathcal{D}S_z \ldots \qquad \ldots{}_D = \delta(\mathbf{r} - \mathbf{r}')$$

$$\ldots\dot{\varphi}_0 + \int dr^2 \boldsymbol{\chi}^* \dot{\boldsymbol{\chi}}]$$

*Integrate*

$$\mathcal{S}_{\text{eff}} = \int dt[\bar{S}\ S_z\dot{\varphi}_0 - H(\varphi_0, S_z)]$$

### Conjugate Momentum

Conjugate momentum $\quad S_z = \int d\mathbf{r}(1 - m_z)$

Generator of rotations $\quad \{S_z, \Phi\} = -\partial_\phi \Phi$

### Collective Coordinate Operators

$$\hat{\varphi}_0\,, \hat{S}_z \qquad [\hat{\varphi}_0, \hat{S}_z] = i/\bar{S}$$

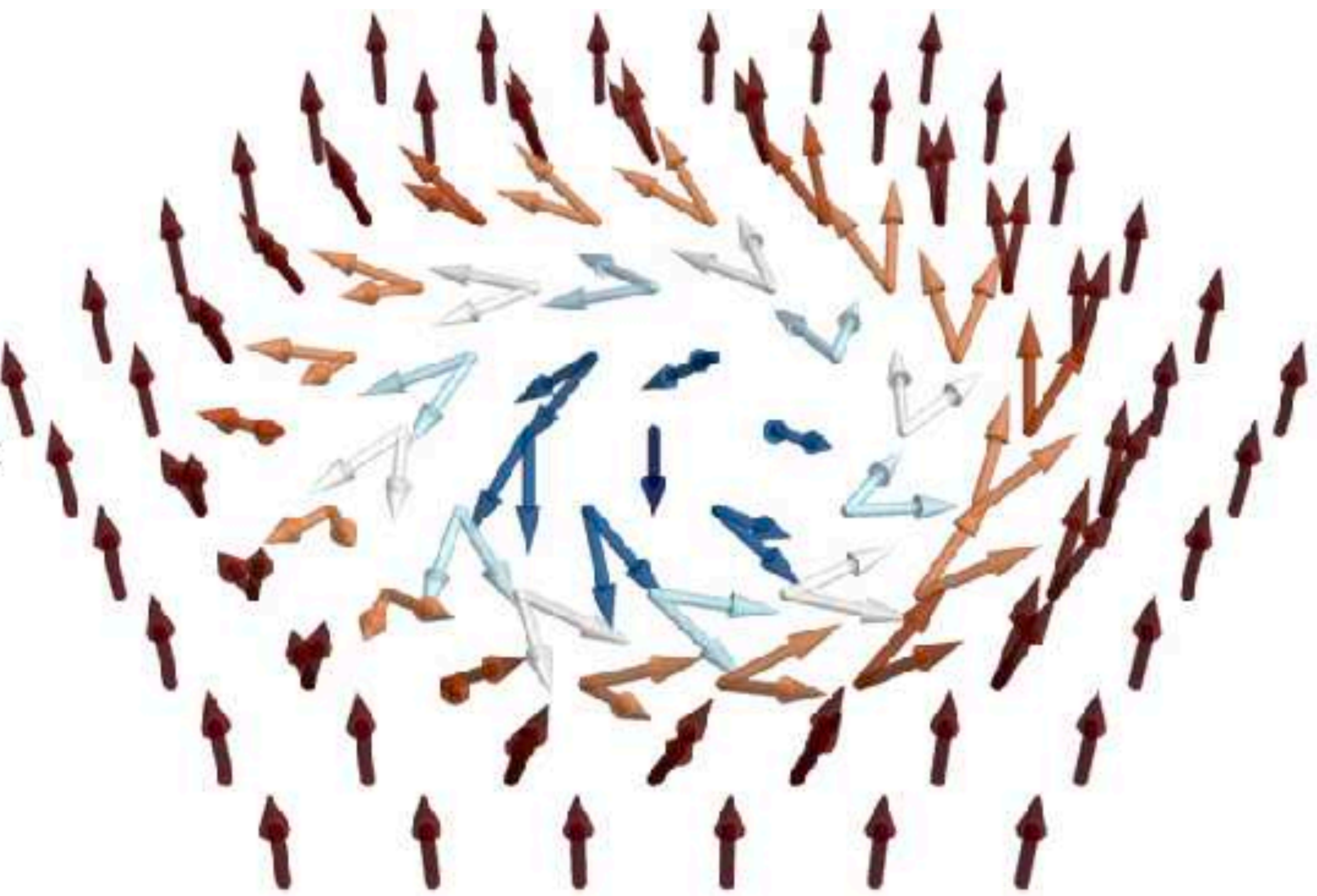
$$\hat{S}_z|s\rangle = (s/\bar{S})|s\rangle$$

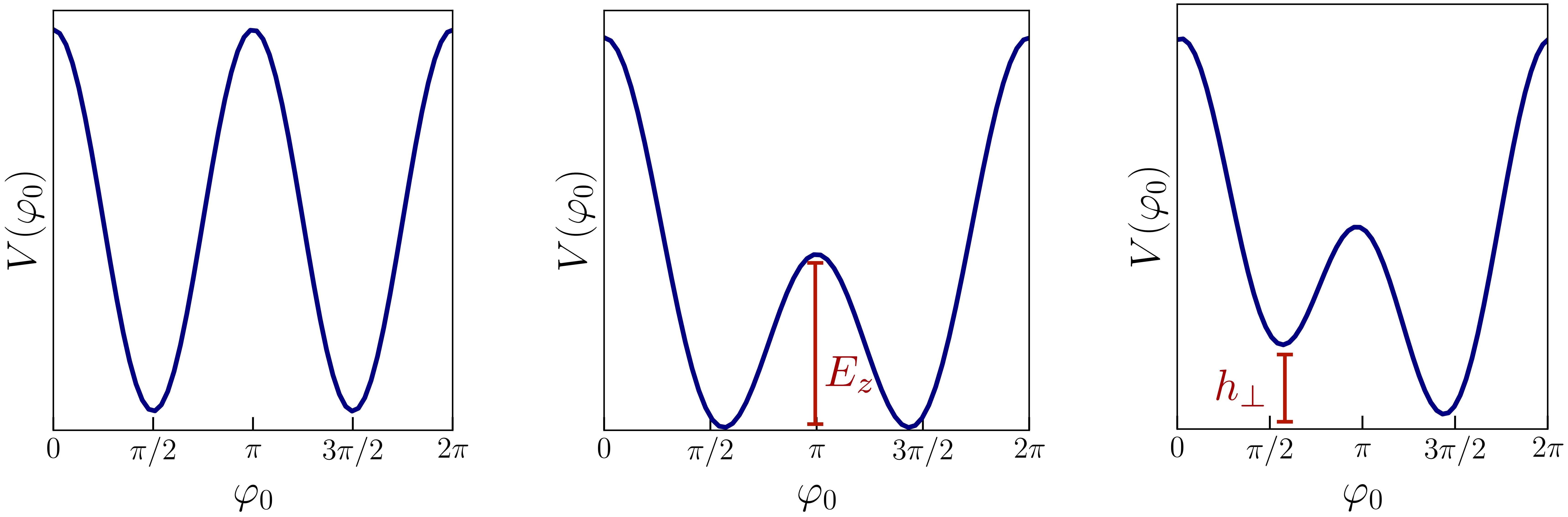
$$\hat{\varphi}_0|\varphi_0\rangle = \varphi_0|\varphi_0\rangle\,, \text{with } |\varphi_0\rangle = |\varphi_0 + 2\pi\rangle$$

# Quantum Hamiltonian

$$H = \frac{\hat{S}_z^2}{2\mathcal{M}} + h\hat{S}_z + \kappa_x \cos 2\hat{\varphi}_0 - E_z \cos \hat{\varphi}_0 + h_\perp \sin \hat{\varphi}_0$$

- $\frac{\hat{S}_z^2}{2\mathcal{M}}$: *Magnetic anisotropy*
- $h\hat{S}_z$: *Magnetic field*
- $\kappa_x \cos 2\hat{\varphi}_0$: *Dipole interactions/Strain*
- $E_z \cos \hat{\varphi}_0$: *Electric field*
- $h_\perp \sin \hat{\varphi}_0$: *Magnetic field gradient/DMI*






**Potential Engineering is experimentally feasible with current technology**

# Potential Engineering

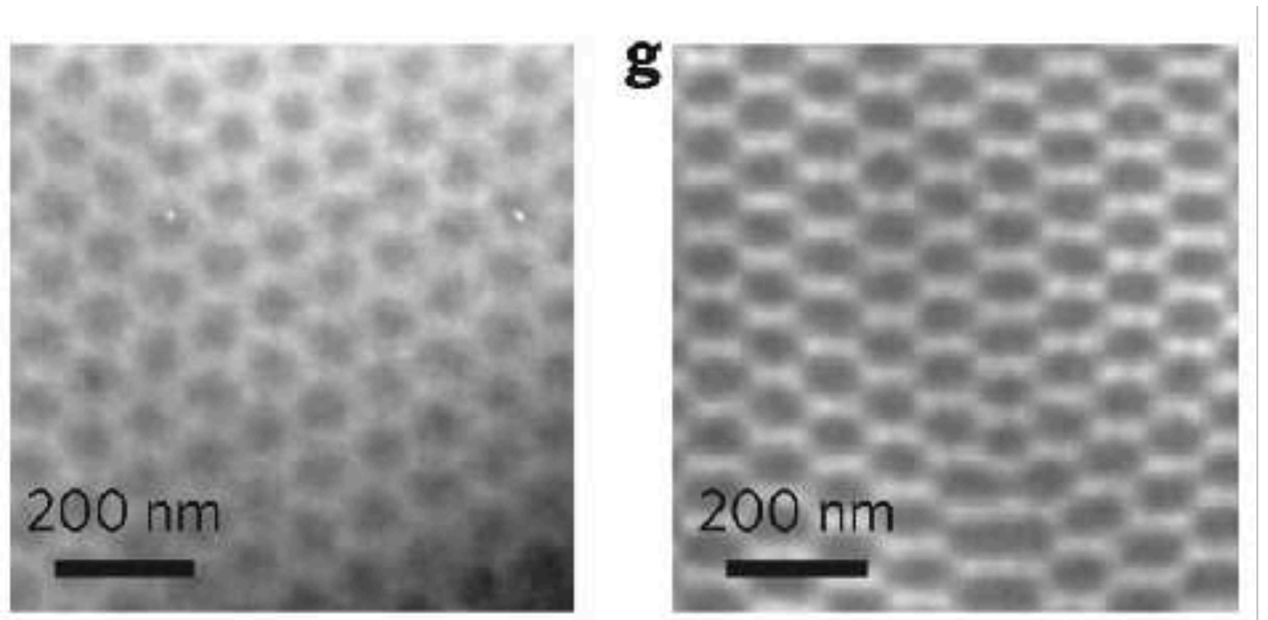


## Magnetic anisotropy

**In-plane magnetic anisotropy**

$$\mathcal{F}_x = \bar{S}K_x/a^2 \int d\mathbf{r}\; m_x^2$$

FeGe thin plate under uniaxial tensile strain




K. Shibata, et al., *Nature Nanotech.* **10**, 589 (2015).

MnSi thin films

M. N. Wilson, et al., *Phys. Rev. B* **86**, 144420 (2012).

## Electric Field

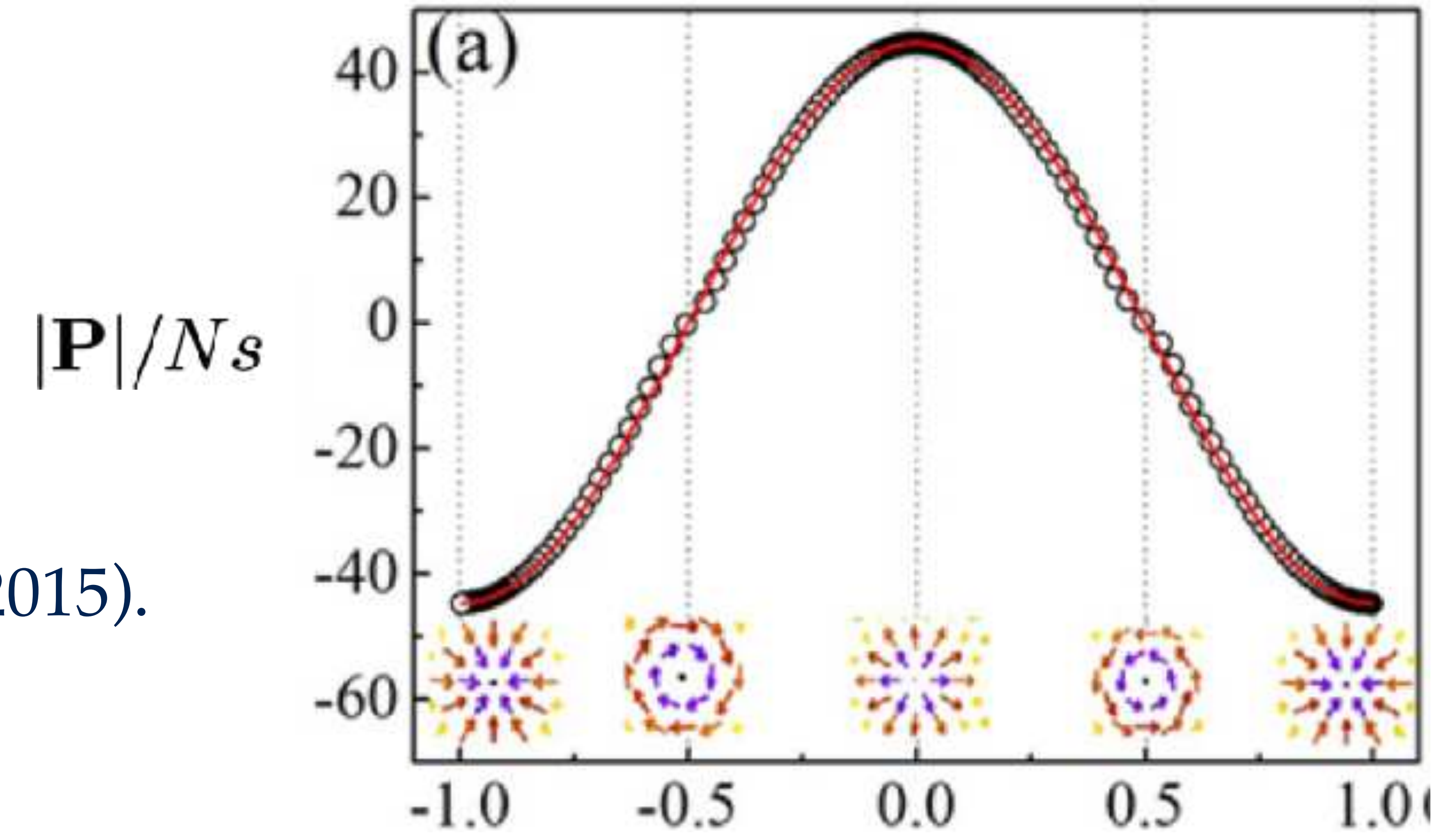
Electric dipole

$$\mathbf{p}_{ij} = -\mathbf{e}_{ij} \times (\mathbf{S}_i \times \mathbf{S}_j)$$

H. Katsura , et al., *Phys. Rev. Lett.* **95** 057205 (2005)

Electric Polarization

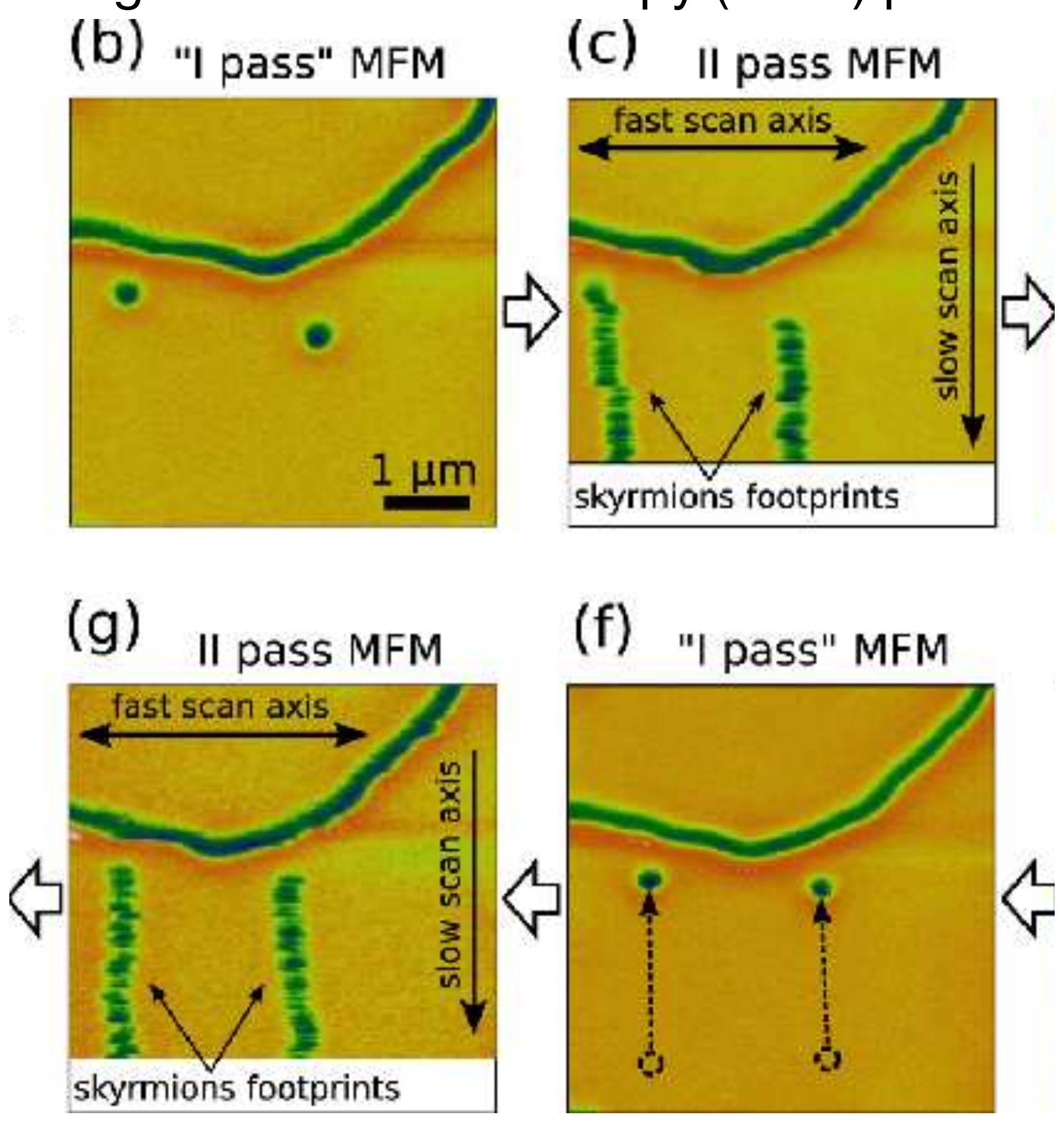
$$\mathbf{P} = \sum_i \mathbf{p}_i$$




X. Yao, et al., *New J. Phys.* **22** 083032 (2020)

## Magnetic Field Gradient

Magnetic force microscopy (MFM) probe

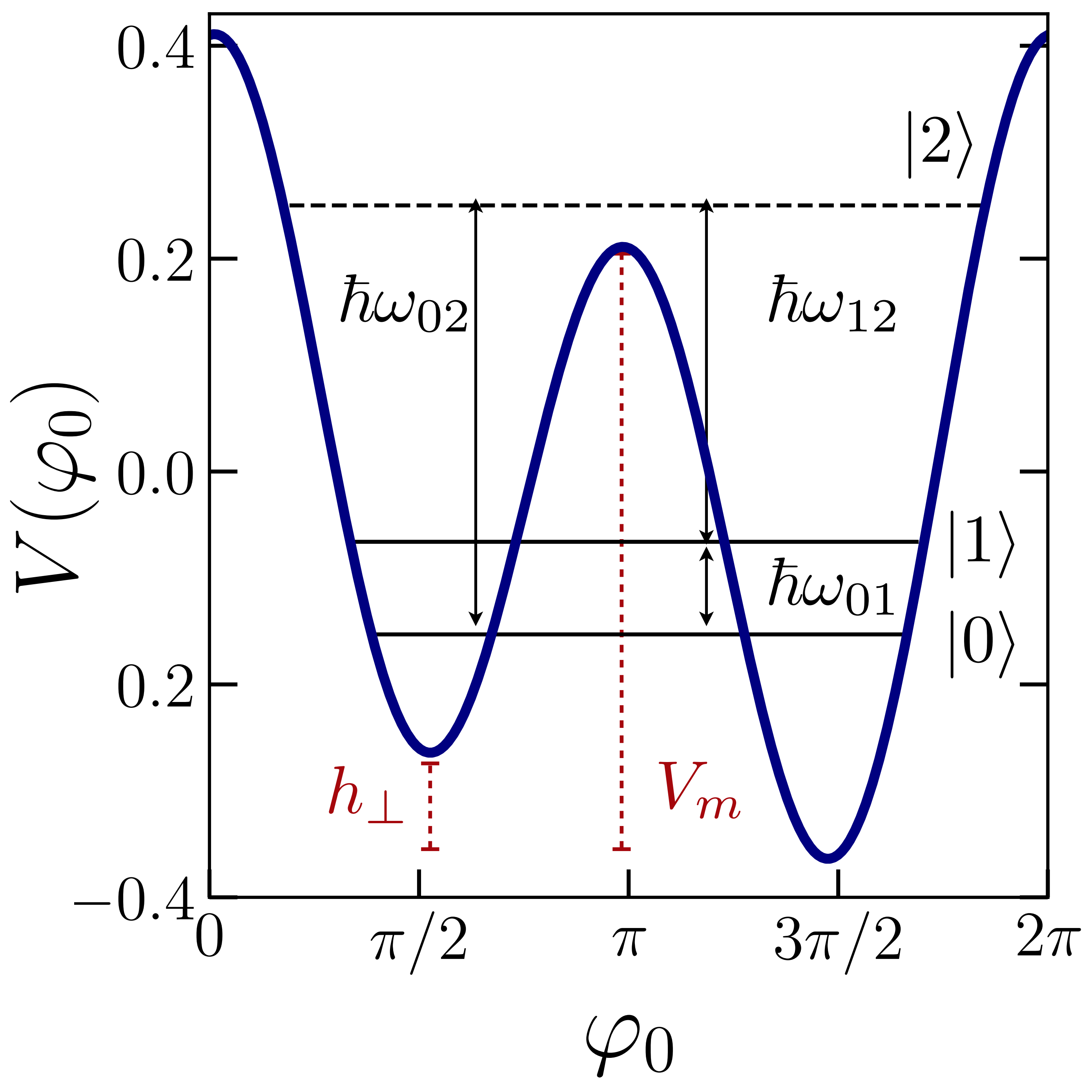


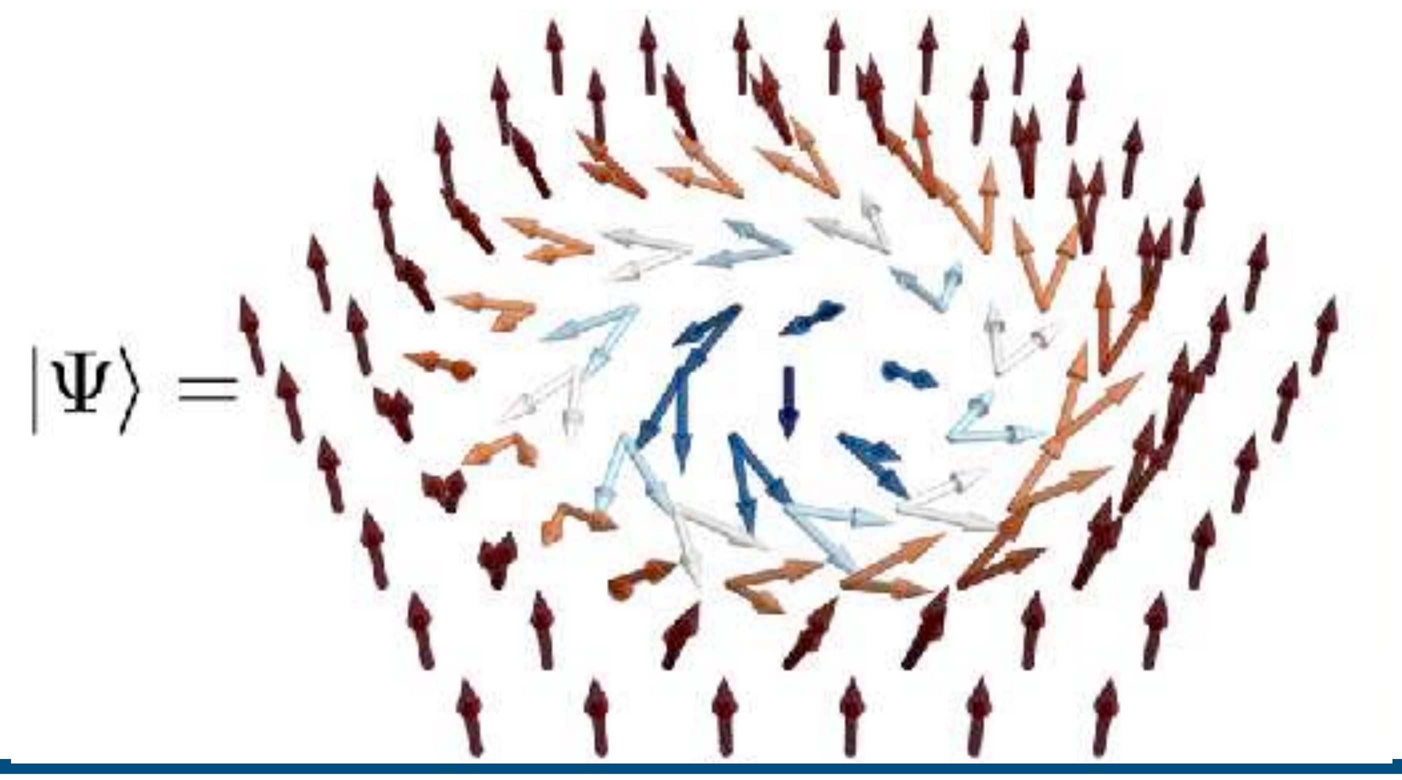

A. Casiraghi, et al. *Commun. Phys.* **2,** 145 (2019)

# Helicity-Qubit



$$V(\varphi_0) = \kappa_x \cos 2\hat{\varphi}_0 - E_z \cos\hat{\varphi}_0 + h_\perp \sin\hat{\varphi}_0$$

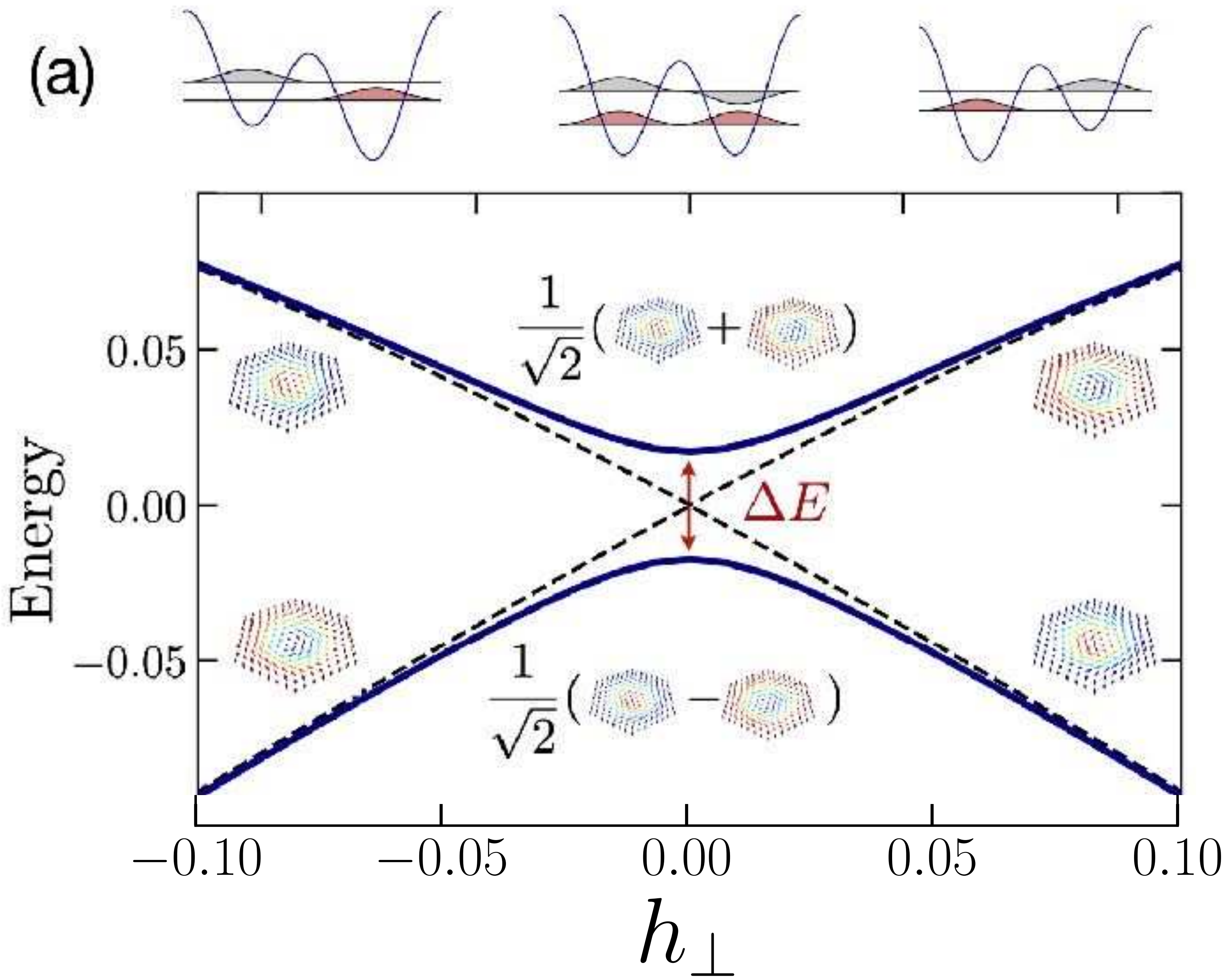



## Requirements

- High Anharmonicity $|\omega_{12} - \omega_{01}| > 20\% \omega_{01}$
- Suppressed Thermal Excitations $k_B T \ll \hbar\omega_{12}\,, \hbar\omega_{02}$

## Universal Level Repulsion Diagram

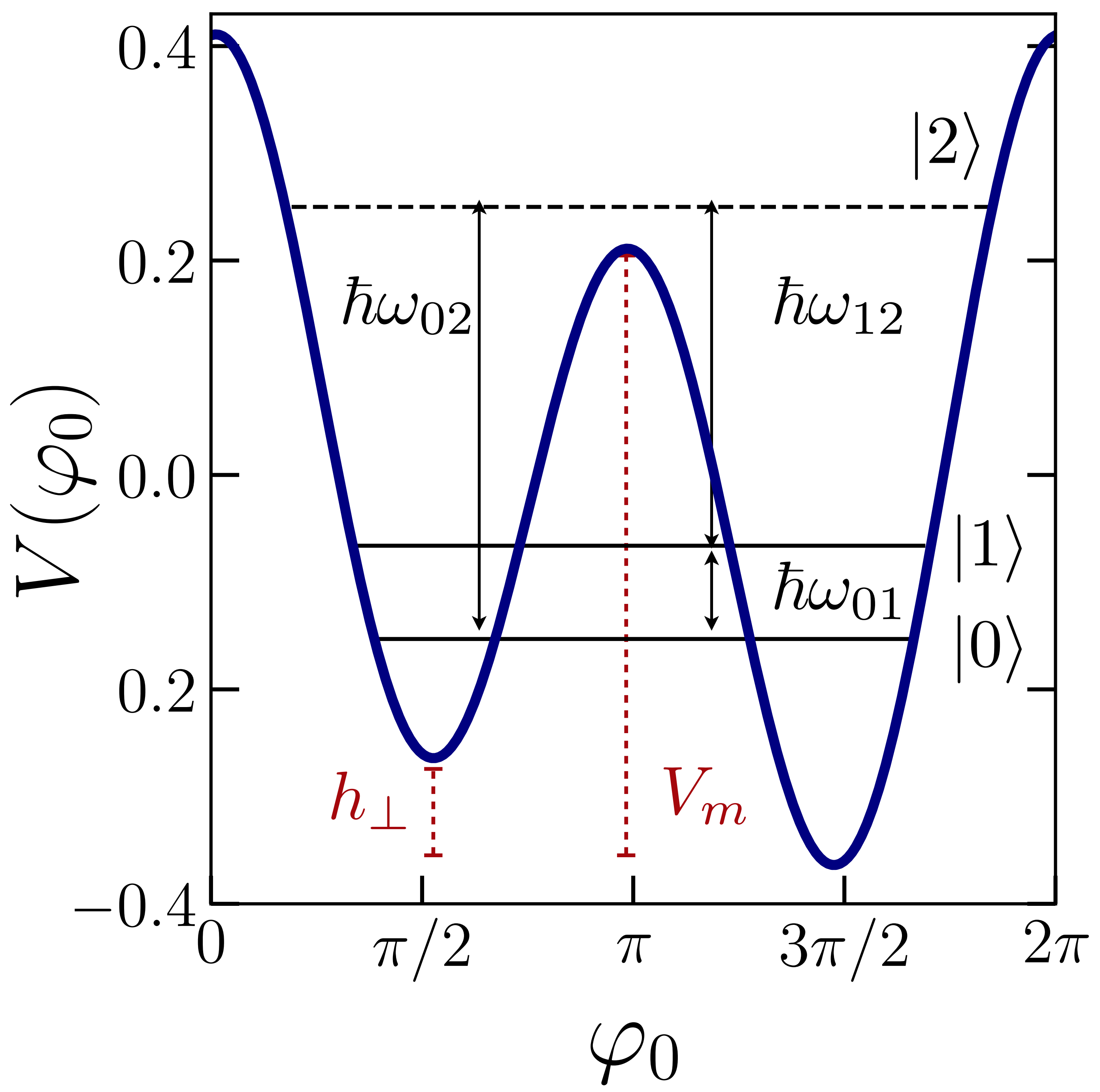


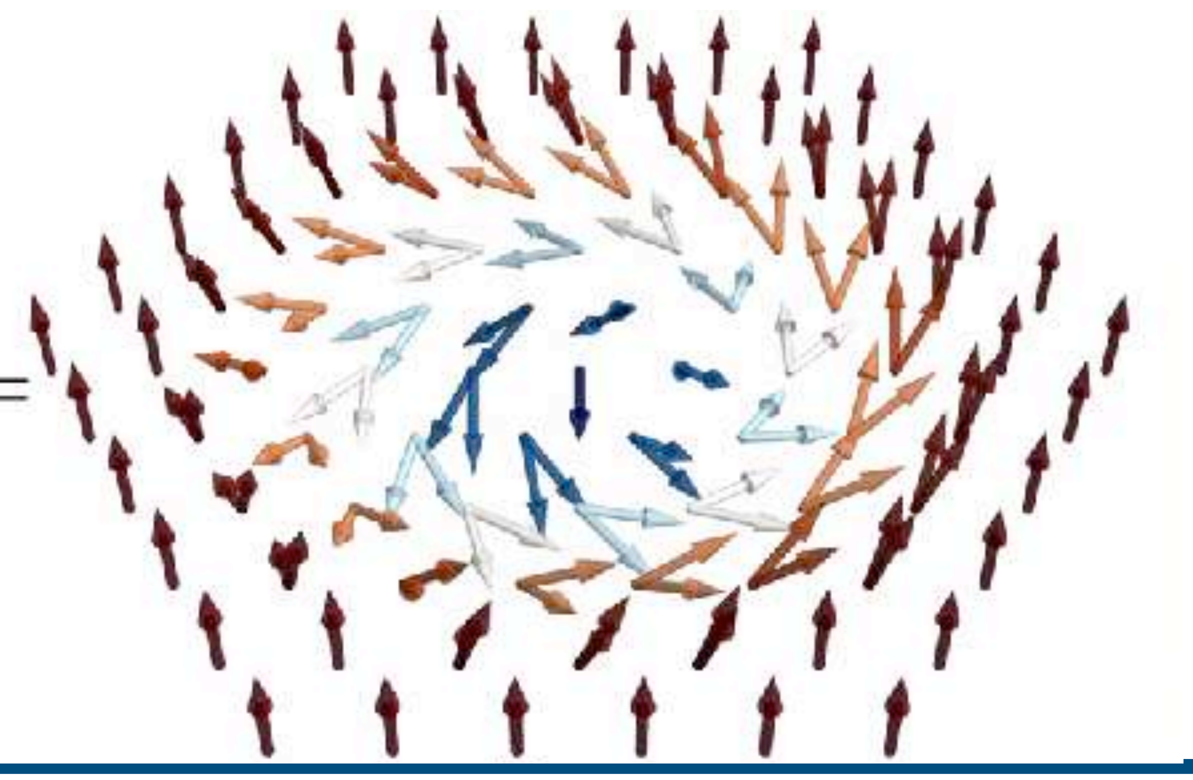

C. Psaroudaki and C. Panagopoulos, Phys. Rev. Lett. **127**, 067201 (2021)

# Helicity-Qubit

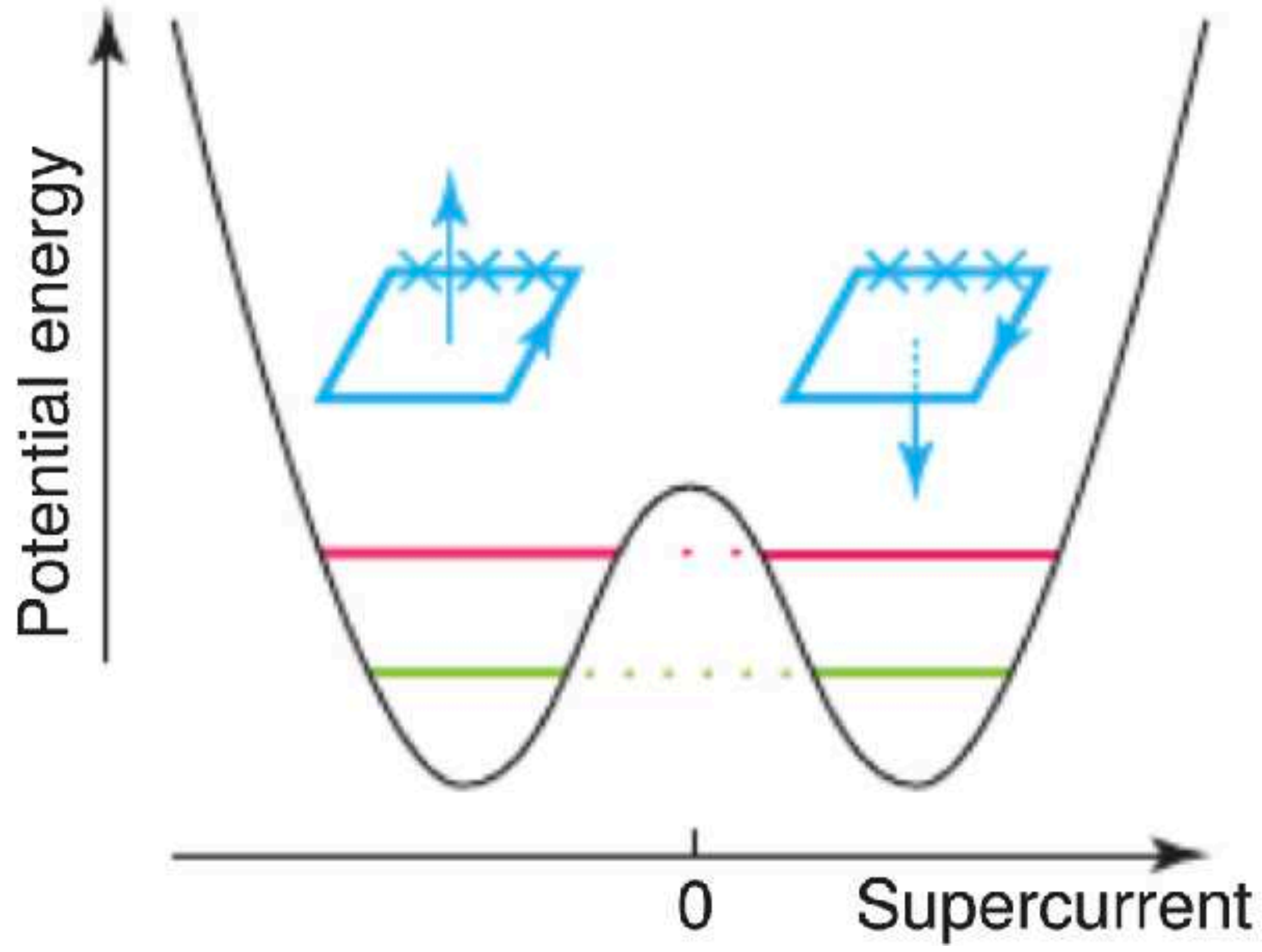


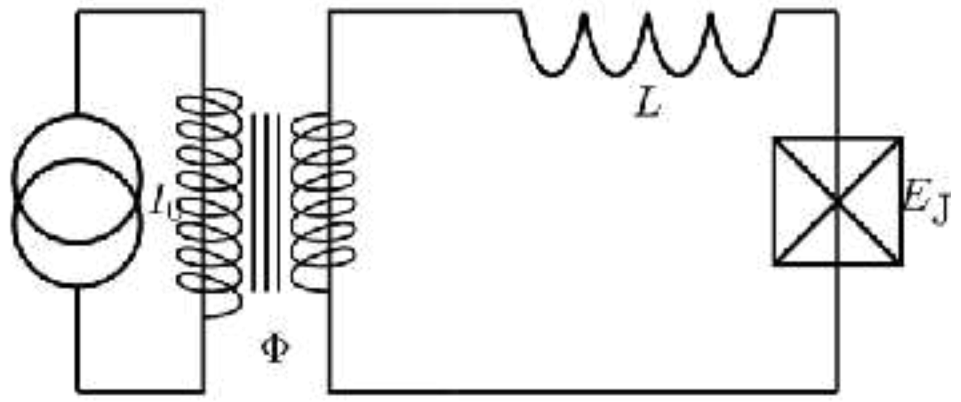
$$V(\varphi_0) = \kappa_x \cos 2\hat{\varphi}_0 - E_z \cos \hat{\varphi}_0 + h_\perp \sin \hat{\varphi}_0$$

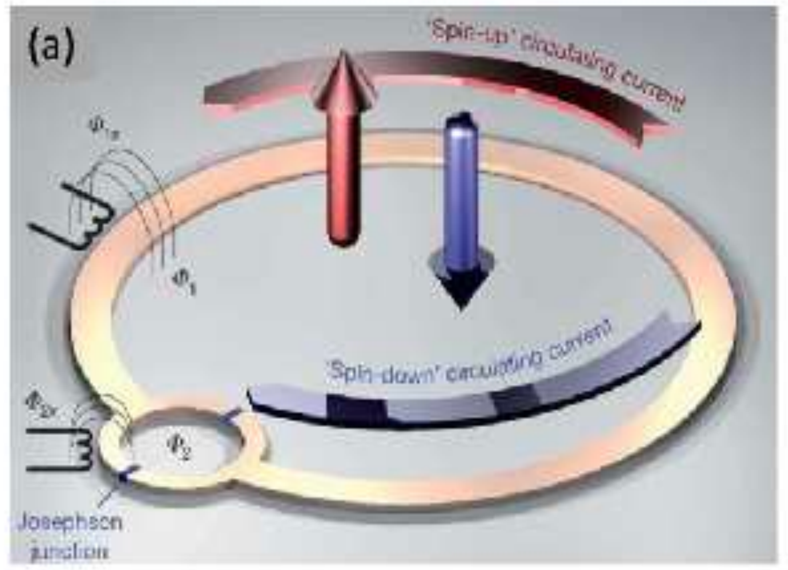



$|\Psi\rangle =$ 

## RF-SQUID "Flux" Qubit



# $S_z$-Qubit

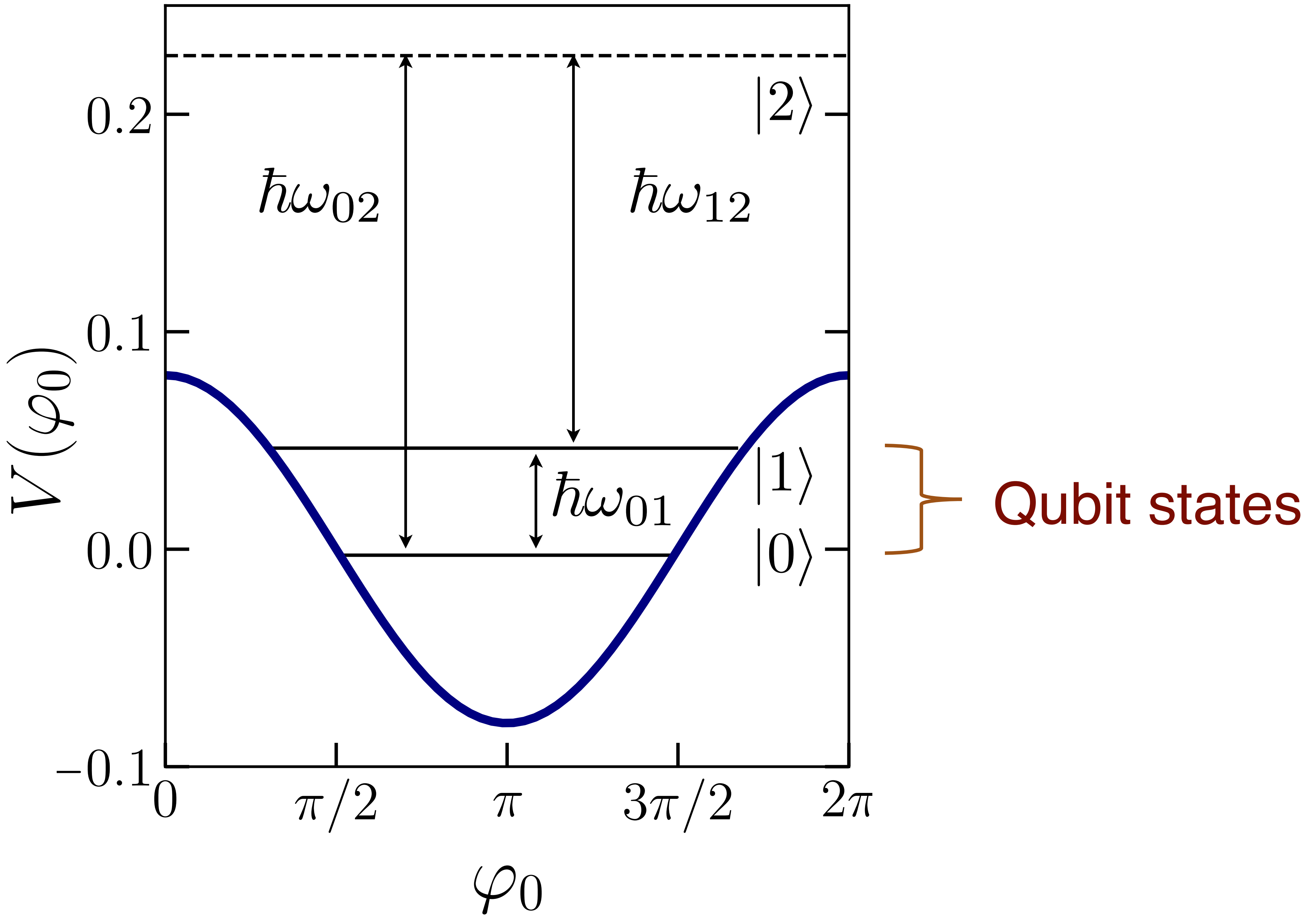


magnetic anisotropy — magnetic field — electric field

$$H_{S_z} = \kappa(\hat{S}_z - h/\kappa)^2 - E_z \cos\hat{\varphi}_0$$

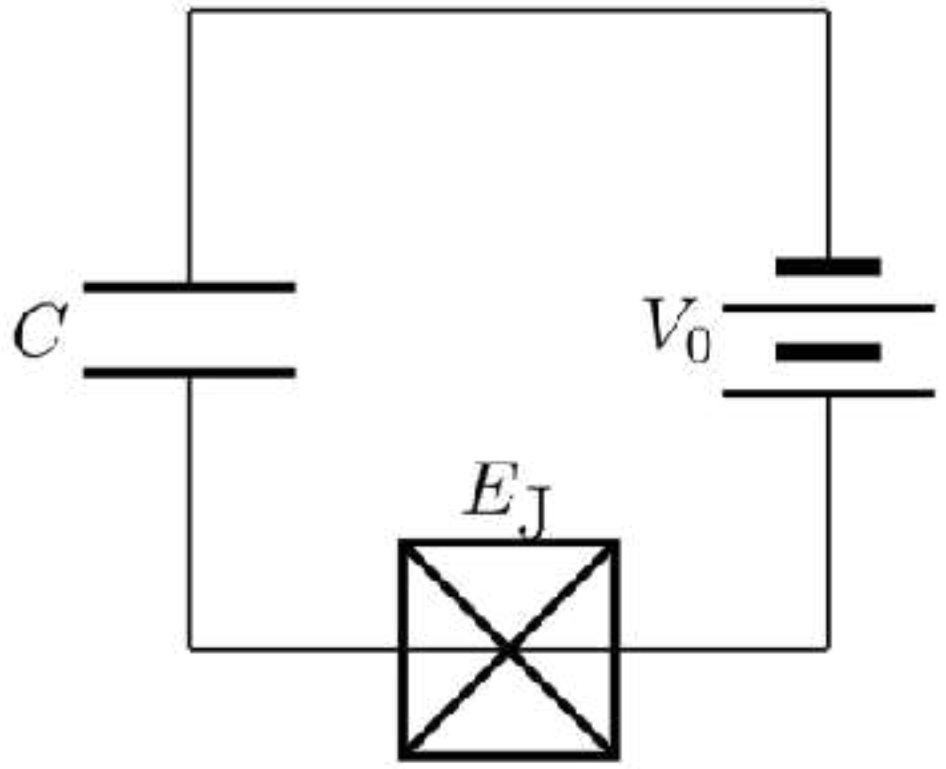
$S_z$- Qubit

$$E_z \ll \kappa$$

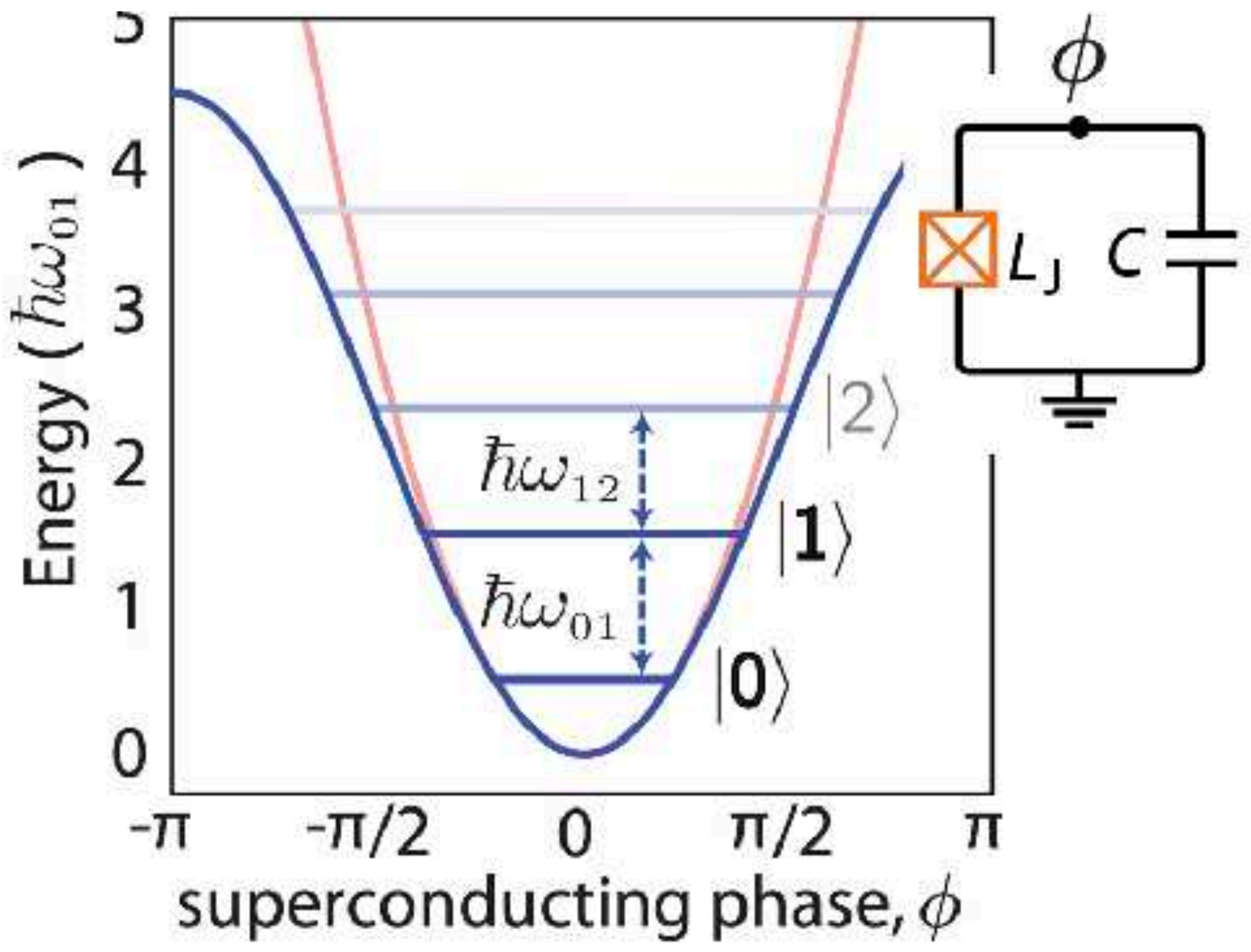



$$\hat{H} = 4E_C\left(\hat{N} - n_g\right)^2 - E_J\cos\hat{\phi}$$

$$[\hat{\phi}, \hat{N}] = i$$



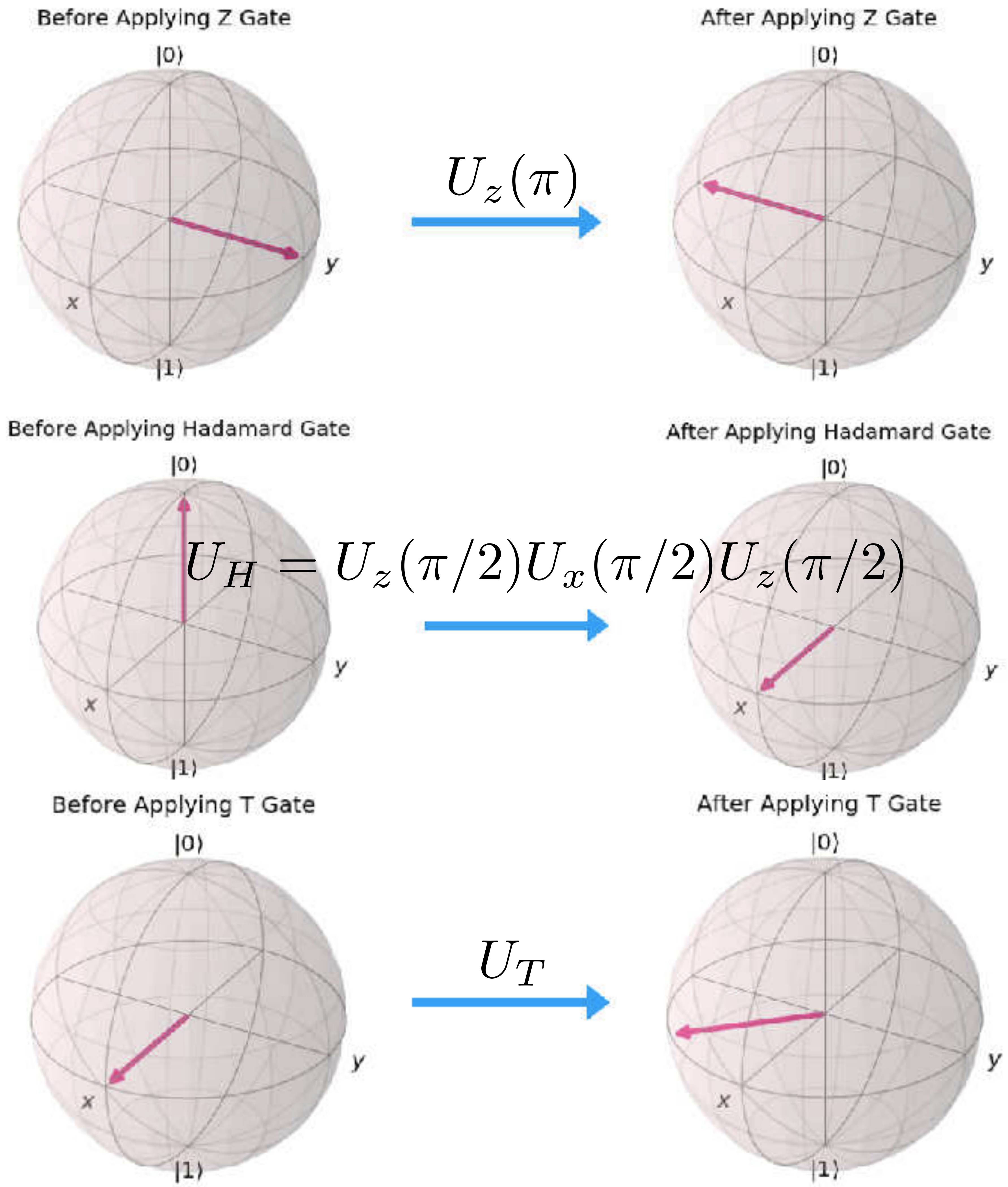

Charge Qubit



# Universal Quantum Computing



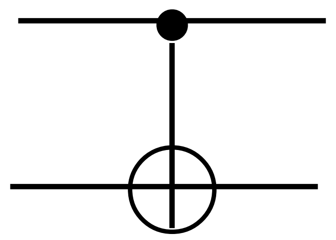
## Single-qubit unitary operations $U_i(\theta)$

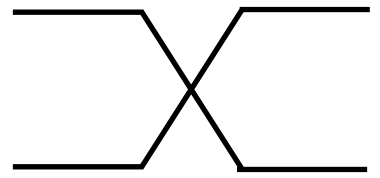


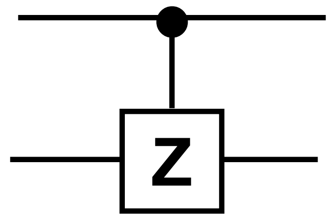

$$\mathcal{G}_0 = \{U_x, U_y, U_z, U_{\text{ph}}, U_{\text{CNOT}}\}$$

$$\mathcal{G}_1 = \{U_H, U_S, U_T, U_{\text{CNOT}}\}$$

## Two-qubit unitary operations

CNOT  Flips the second if first is $|1\rangle$

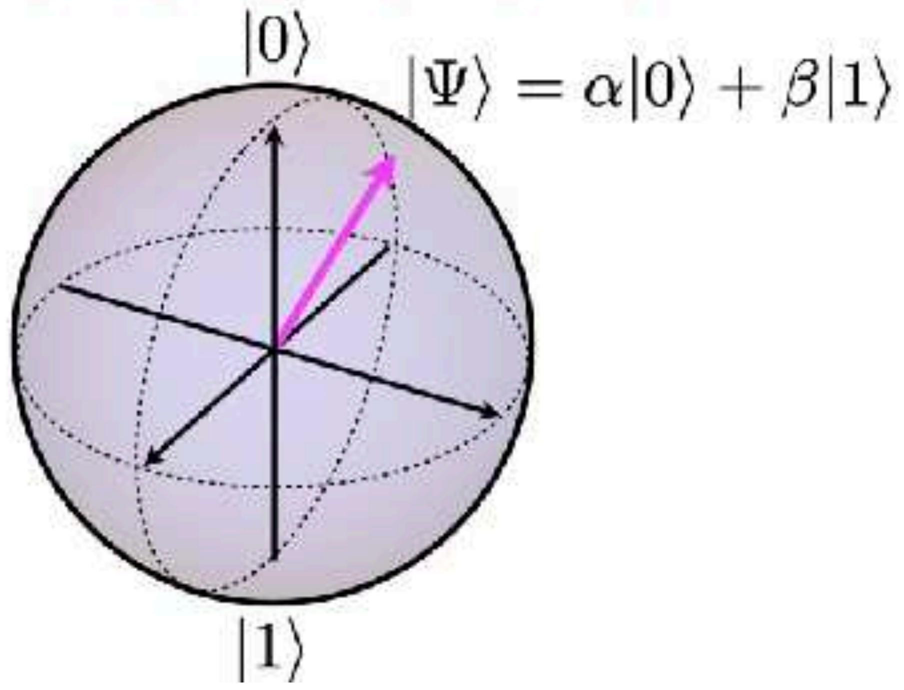
SWAP  Swaps two qubits

CZ 


Applies a phase flip to the second if first is $|1\rangle$

# Single-Qubit Gates






**Microwave Fields** $\mathcal{F}_{\text{ext}} = \int d\mathbf{r}\, \mathbf{B}(\mathbf{r},t) \cdot \mathbf{m}(\mathbf{r},t)$

$$\mathbf{B}(\mathbf{r},t) = B\cos(\omega t + \phi) f(t) x \hat{e}_x \longrightarrow H \sim \cos(\omega t + \phi) f(t) \cos(\hat{\varphi}_0)$$

External frequency — External field amplitude — External phase

**Rotating Frame** $$H_{\text{rot}} = \frac{\omega_q - \omega}{2}\hat{\sigma}_z + \frac{\Omega f(t)}{2}[\cos\phi\hat{\sigma}_x + \sin\phi\hat{\sigma}_y]$$

**In-phase pulses** $\phi = 0$

$$U_x(t) = e^{-\frac{i}{2}\vartheta(t)\hat{\sigma}_x}$$

**Out-of-phase pulses** $\phi = \pi/2$

$$U_y(t) = e^{-\frac{i}{2}\vartheta(t)\hat{\sigma}_y}$$

$$\vartheta(t) = -\Omega \int_0^t f(t')dt'$$

C. Psaroudaki and C. Panagopoulos, *Phys. Rev. Lett.* **127**, 067201 (2021)

**Electric Field Protocol** $H_{\text{EF}} = E_z(t)\hat{\sigma}_z$

$$U_Z(\theta) = \exp\left[-\frac{i}{\hbar}\hat{\sigma}_z \int_0^{t_0} E_z(t)dt\right] = \exp\left[-\frac{i\theta}{2}\hat{\sigma}_z\right]$$

**T-Gate** $U_T = e^{-i\pi/8} U_Z(\pi/4)$

**Hadamard-Gate** $U_H = -iU_Z(\pi/2)U_X(\pi/2)U_Z(\pi/2)$

J. Xia, et al., *Phys. Rev. Lett.* **130** 106701 (2023)

# Two Qubit Gates



Interaction energy

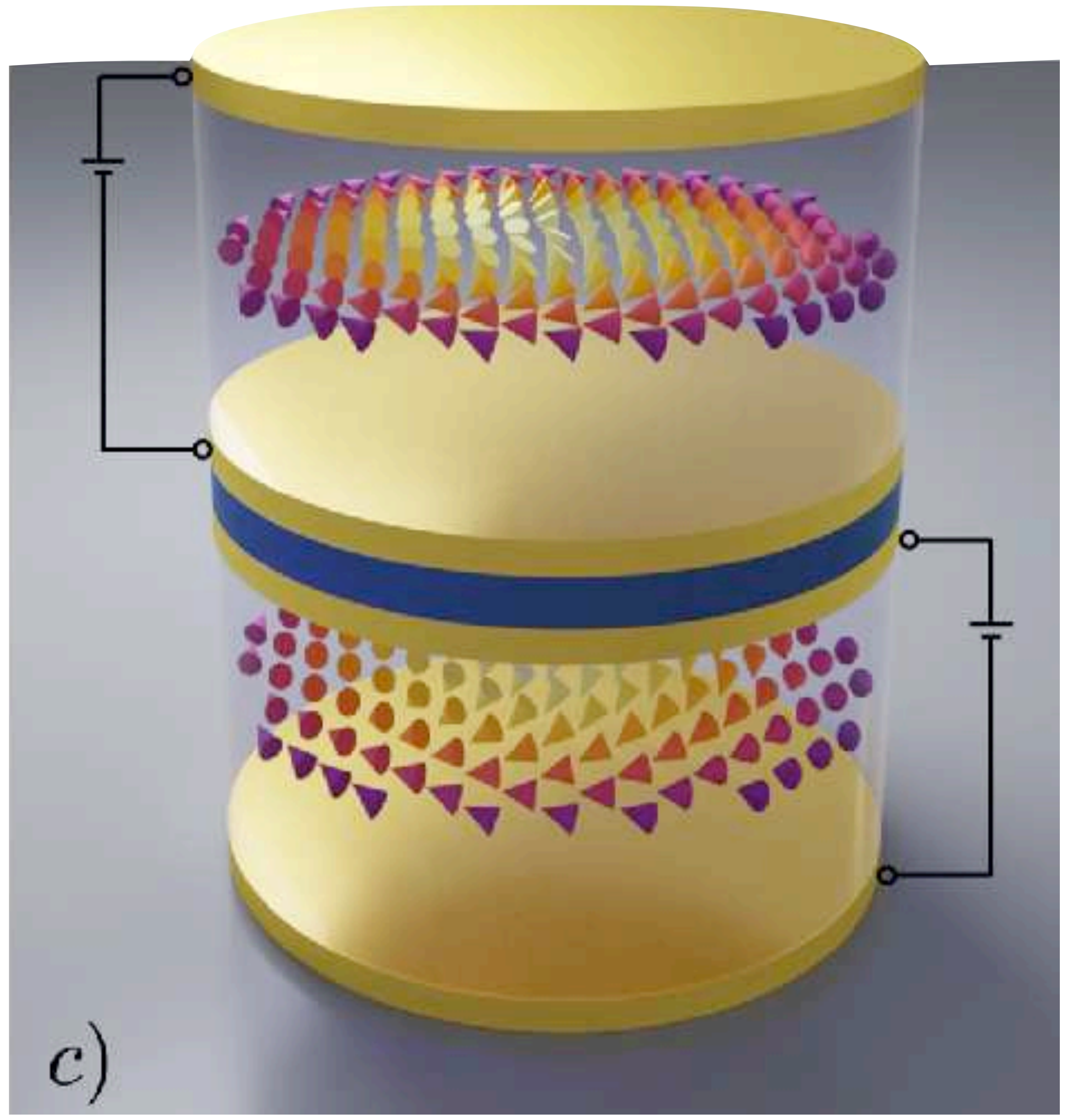
$$\mathcal{F}_{\rm int} = J_{\rm int} \int_{\mathbf{r}} \mathbf{m}_1 \cdot \mathbf{m}_2$$

Qubit Hamiltonian

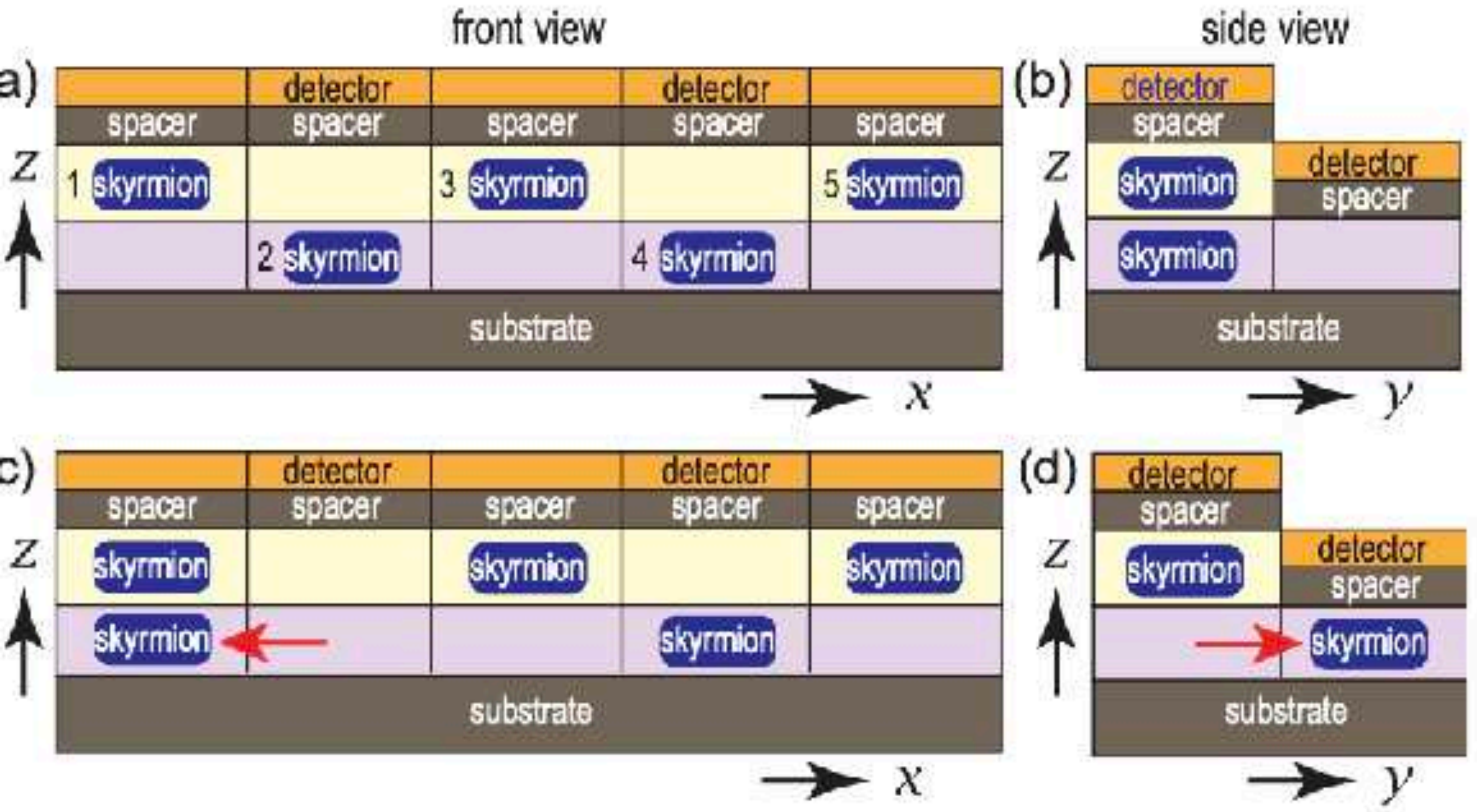
$$H_{\rm int} = -J'_{\rm int} \cos(\varphi_1 - \varphi_2)$$

$$H_{\rm int} = -\mathcal{J}^x_{\rm int} \hat{\sigma}^1_x \hat{\sigma}^2_x - \mathcal{J}^z_{\rm int} \hat{\sigma}^1_z \hat{\sigma}^2_z \qquad \mathcal{J}^x_{\rm int} \ll \mathcal{J}^z_{\rm int}$$

*Time-dependent*




C. Psaroudaki and C. Panagopoulos, *Phys. Rev. Lett.* **127**, 067201 (2021)




J. Xia, et al., *Phys. Rev. Lett.* **130** 106701 (2023)

Ji Zou, et al., Phys. Rev. Research **5**, 033166 (2023)

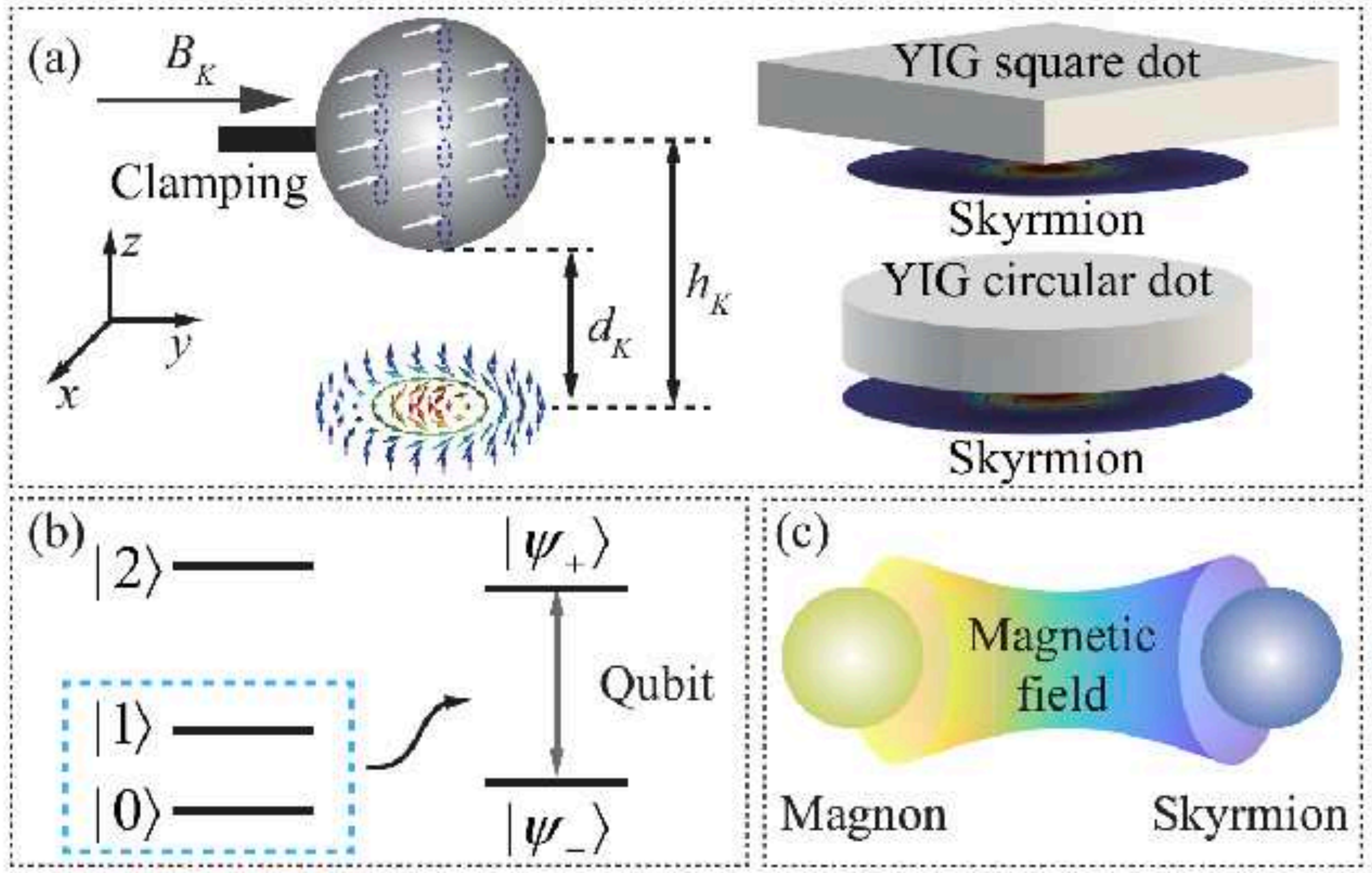
$$U_{ZZ} = \exp\left[\frac{i}{\hbar}\int_0^{t_0} H_{\rm Ising}(t)dt\right] = \exp\left[-\frac{i\theta}{2}\sigma^1_z\sigma^2_z\right] \qquad \boxed{\mathcal{J}^z_{\rm int} = \frac{\hbar\theta}{2t_0} \quad \text{for } 0 \le t \le t_0}$$

CZ $\quad U_{\rm CZ} = e^{i\pi/4} U_Z^{(1)}(\pi/2) U_Z^{(2)}(\pi/2) U_{\rm ZZ}(-\pi/2)$

CNOT $\quad U^{1\to 2}_{\rm CNOT} = U^{(2)}_{\rm H} U_{\rm CZ} U^{(2)}_{\rm H}$

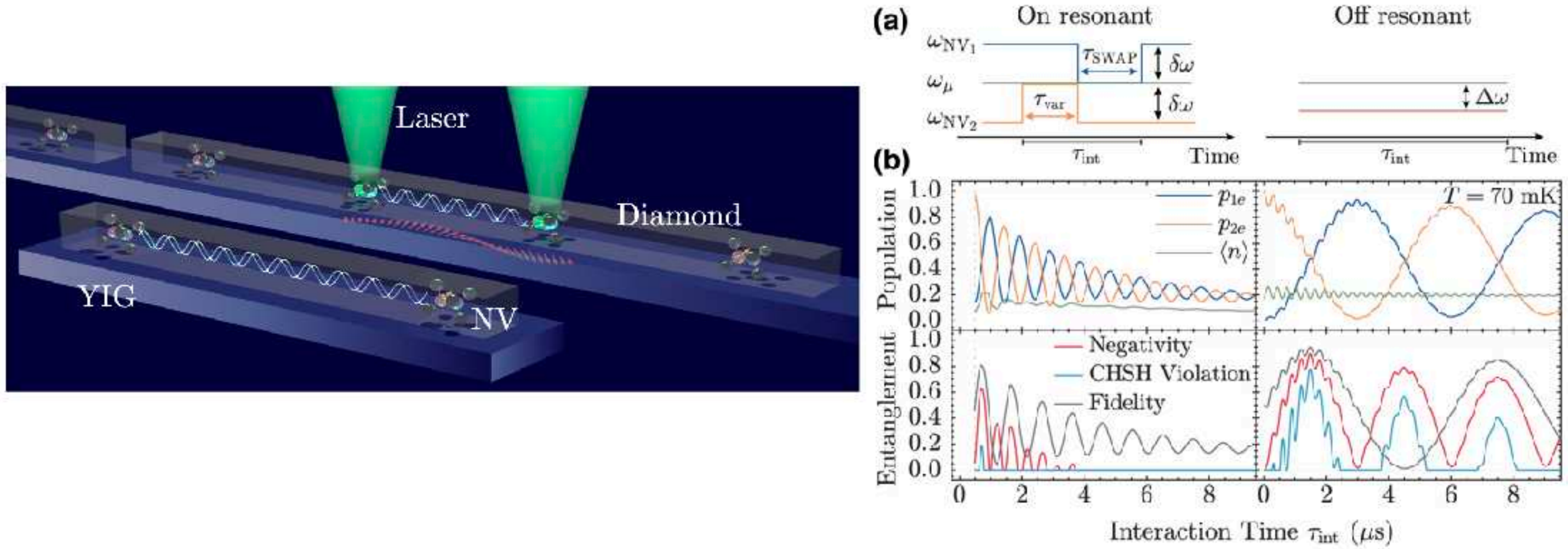
# Two Qubit Gates via Magnons



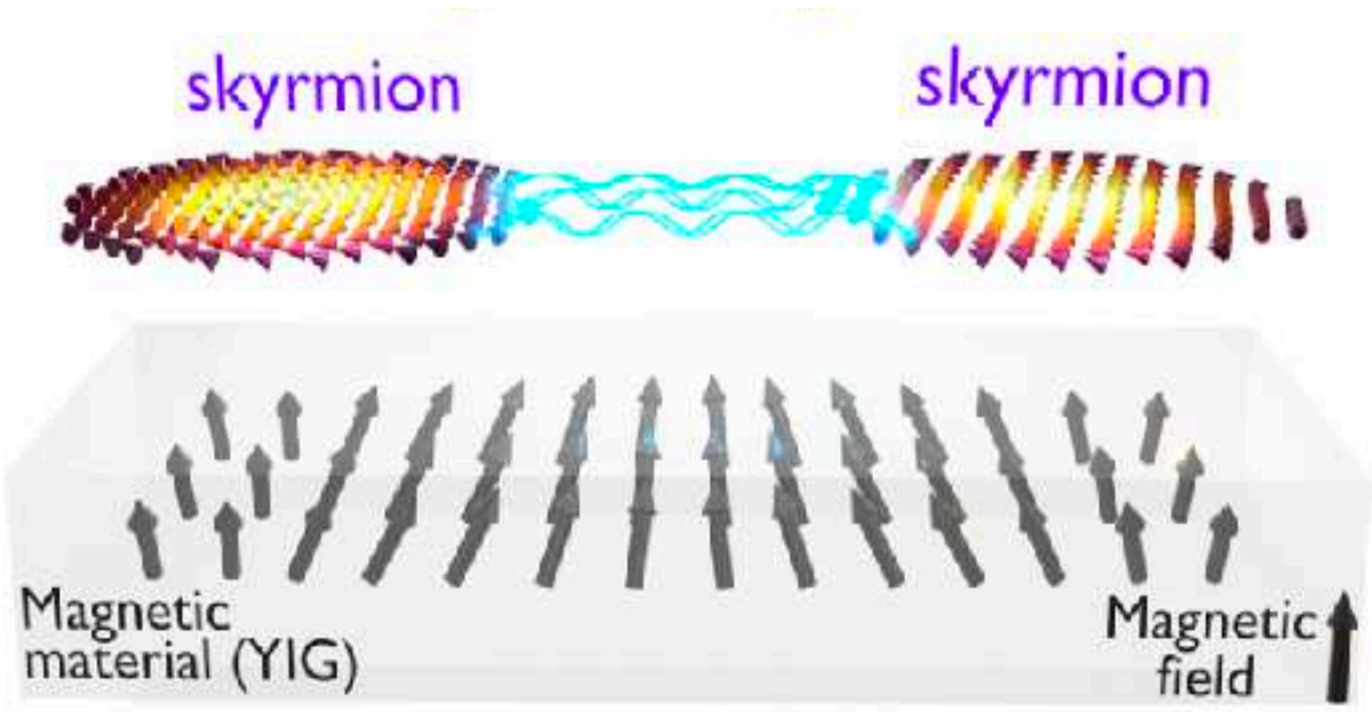



Skyrmion-magnon coupling $\lambda_{\mathrm{KS}} \sim 10\ \mathrm{MHz}$

Xue-Feng Pan, et al., Phys. Rev. Lett. **132**, 193601 (2024)




M. Fukami, D. R. Candido, D. D. Awschalom, and M. E. Flatté
PRX Quantum **2**, 040314 (2021)




C. Psaroudaki and D. R. Candido, in preparation

# Decoherence



**Longitudinal relaxation** $\Gamma_1 = T_1^{-1}$

**Transverse relaxation** $\Gamma_2 = T_2^{-1} = \frac{1}{2}\Gamma_1 + \Gamma_\varphi$

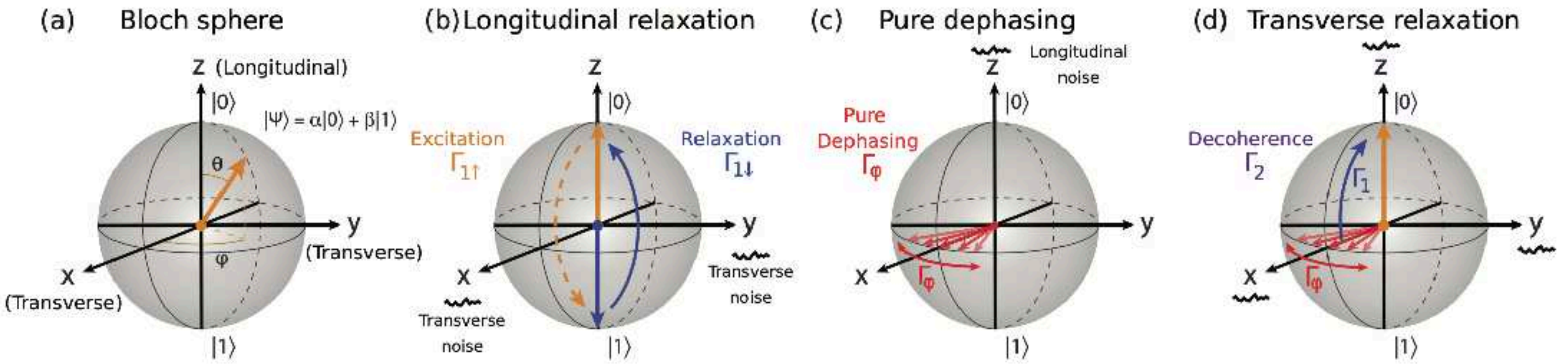



Figure from "Quantum Engineer's Guide to Superconducting Qubits", P. Krantz, et al., Applied Physics Reviews 6, 021318 (2019).

## Landau-Lifshitz-Gilbert Equation

$$\dot{\mathbf{m}} = \gamma(-\delta\mathcal{F}/\delta\mathbf{m}) \times \mathbf{m} + \alpha\mathbf{m} \times \dot{\mathbf{m}}$$

↓

$$-\dot{S}_z + \frac{\partial\mathcal{F}}{\partial\varphi_0} + \alpha_{\varphi_0}\dot{\varphi}_0 = 0$$

$$\dot{\varphi}_0 + \frac{\partial\mathcal{F}}{\partial S_z} + \alpha_{S_z}\dot{S}_z = 0$$

$$\hat{H}_q = -\frac{1}{2}\hbar(\omega_q\hat{\sigma}_z + \xi_z(t)\gamma_z\hat{\sigma}_z + \xi_\perp(t)\gamma_\perp\hat{\sigma}_\perp)$$

$$\Gamma_1 = \frac{\gamma_\perp^2}{\hbar^2}S_\perp(\omega_q)$$

$$\Gamma_\varphi = \frac{\gamma_z^2}{\hbar^2}S_z(0)$$

# Decoherence

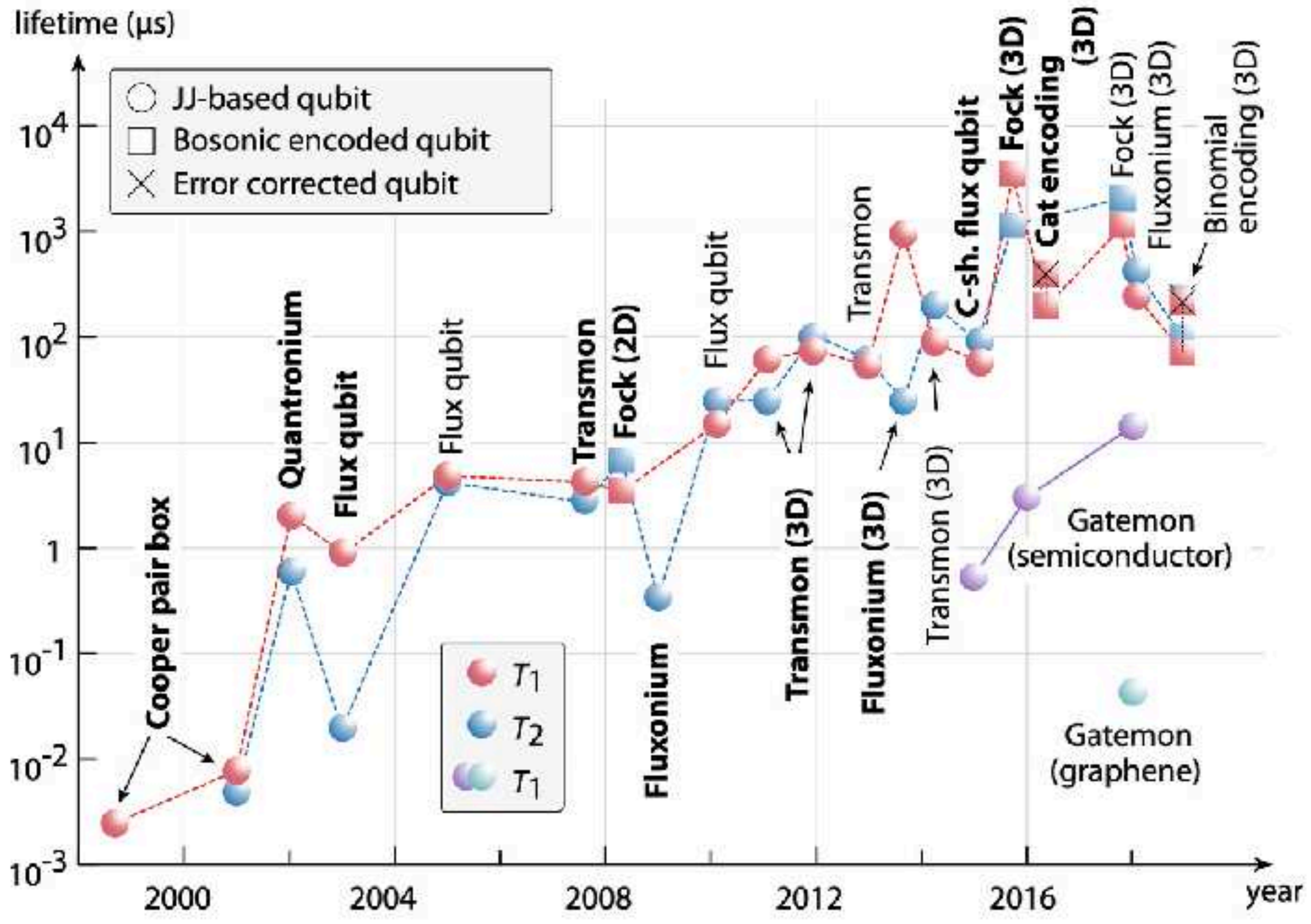


$$H_q = -\omega_q \hat{\sigma}_z + \xi_\perp(t)\gamma_\perp \hat{\sigma}_\perp + \xi_z(t)\gamma_z \hat{\sigma}_z$$

$$\Gamma_1 = \gamma_\perp^2 S_\perp(\omega_q) = \gamma_\perp^2 \omega_q \coth(\frac{\beta\omega_q}{2})$$

$$\Gamma_\varphi = \gamma_z^2 S_z(0) = \gamma_z^2 2/\beta$$

| | |
|---|---|
| **Transition Frequency** | $\omega_q \approx 2 - 25 \text{ GHz}$ |
| **Anharmonicity** | $\omega_{12} \approx 300 \text{ GHz}$ |
| **Decoherence Time** | $T_1\,, T_2 \approx 0.5\ \mu\text{s}$ |
| **Temperature** | $T = 100 \text{ mK}$ |
| **Critical Temperature** | $T_c = 2.5K$ |
| **Gilbert Damping** | $\alpha = 10^{-5}$ |
| **Skyrmion Size** | $\lambda \approx 10a$ |
| **Effective Spin** | $\bar{S} = 10$ |

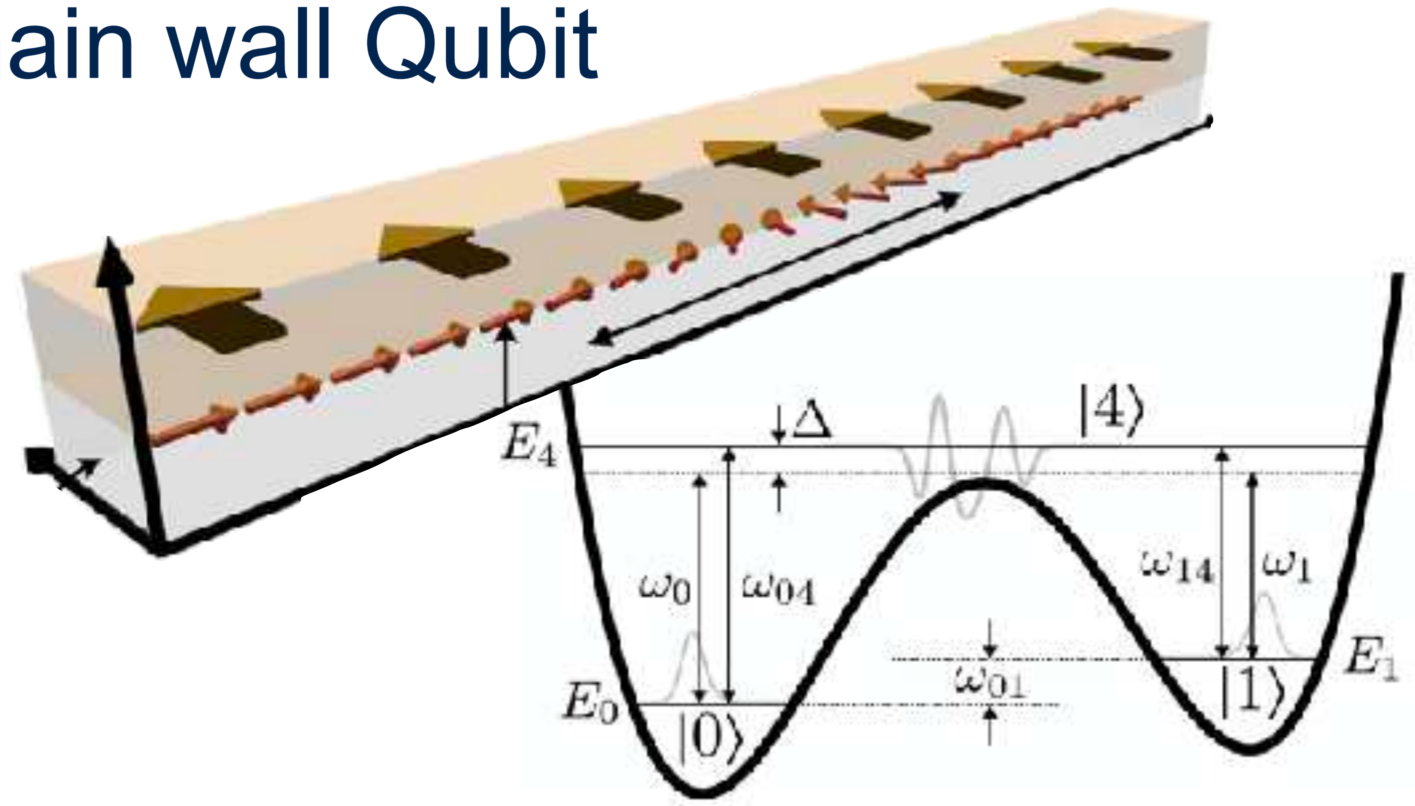



M. Kjaergaard, et al., Annual Reviews of Condensed Matter Physics **11**, 369-395 (2020)

# Magnetic texture qubits

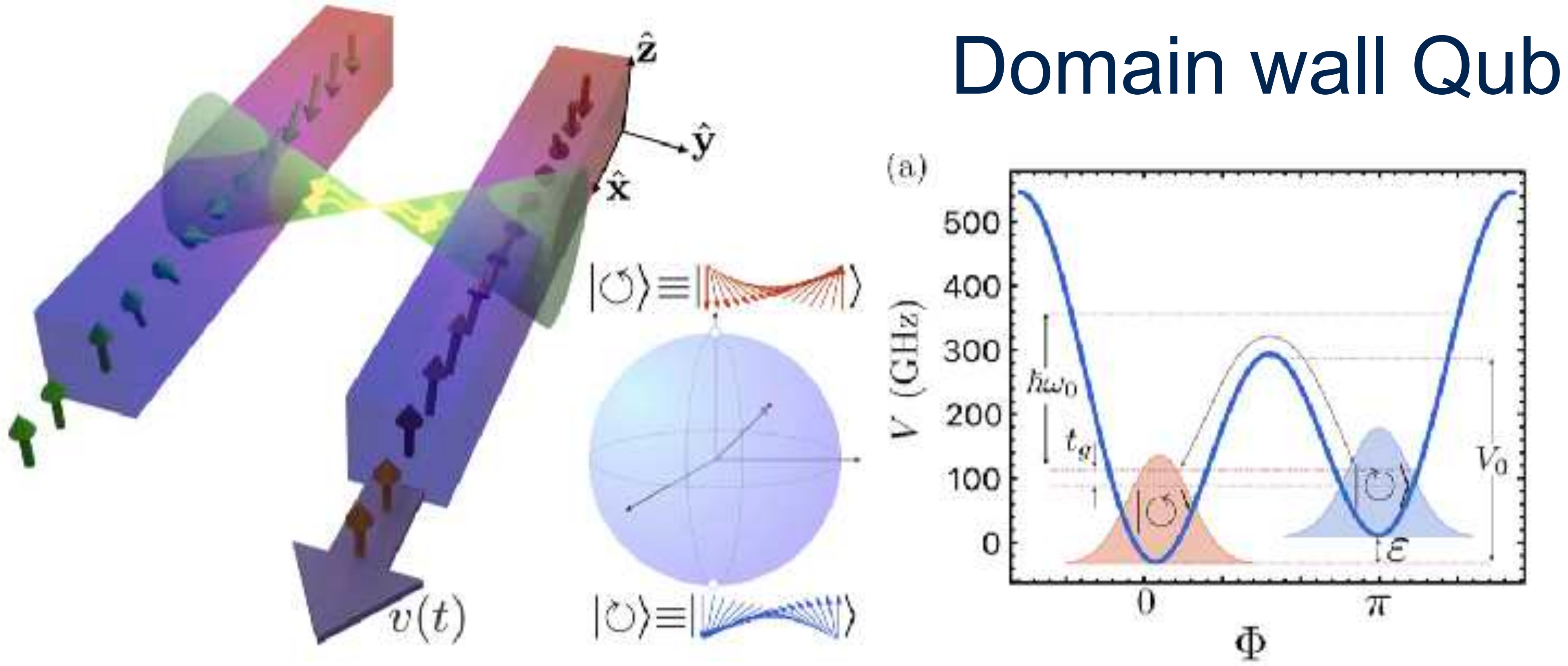


## Domain wall Qubit



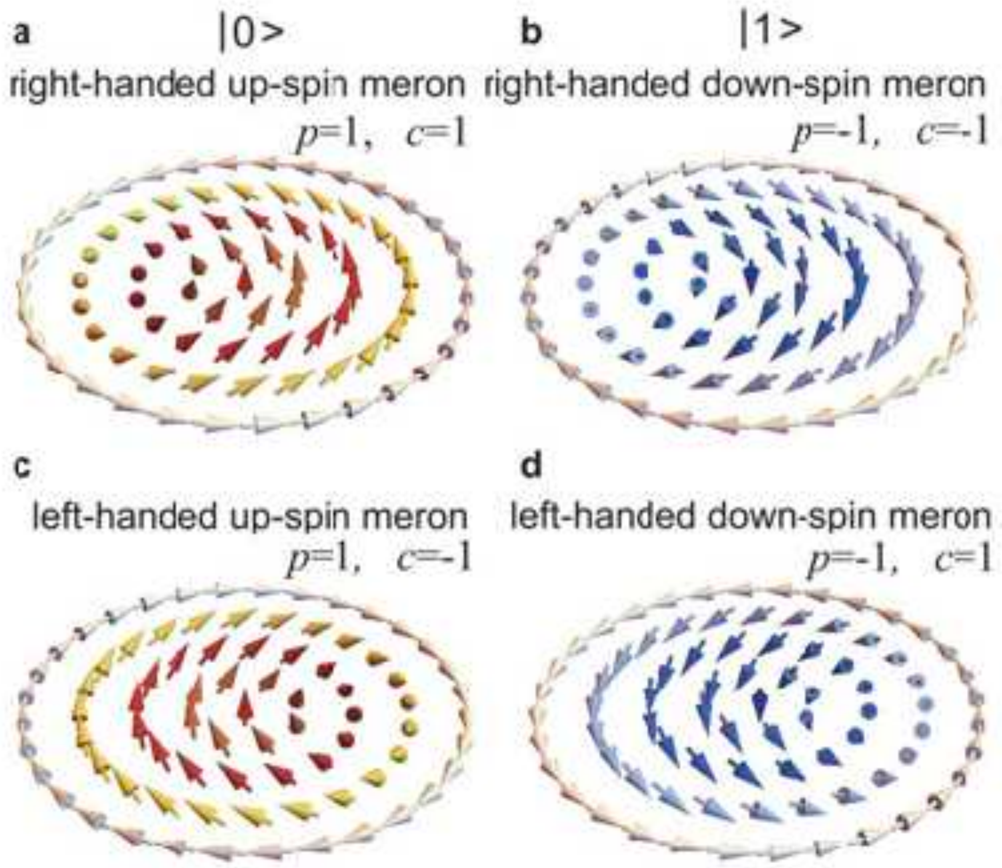

So Takei and Masoud Mohseni, Phys. Rev. B **97**, 064401 (2018)

## Domain wall Qubit




Ji Zou, et al., Phys. Rev. Research **5**, 033166 (2023)

## Meron Qubit




J. Xia, et al., Commun Mater **3**, 88 (2022)

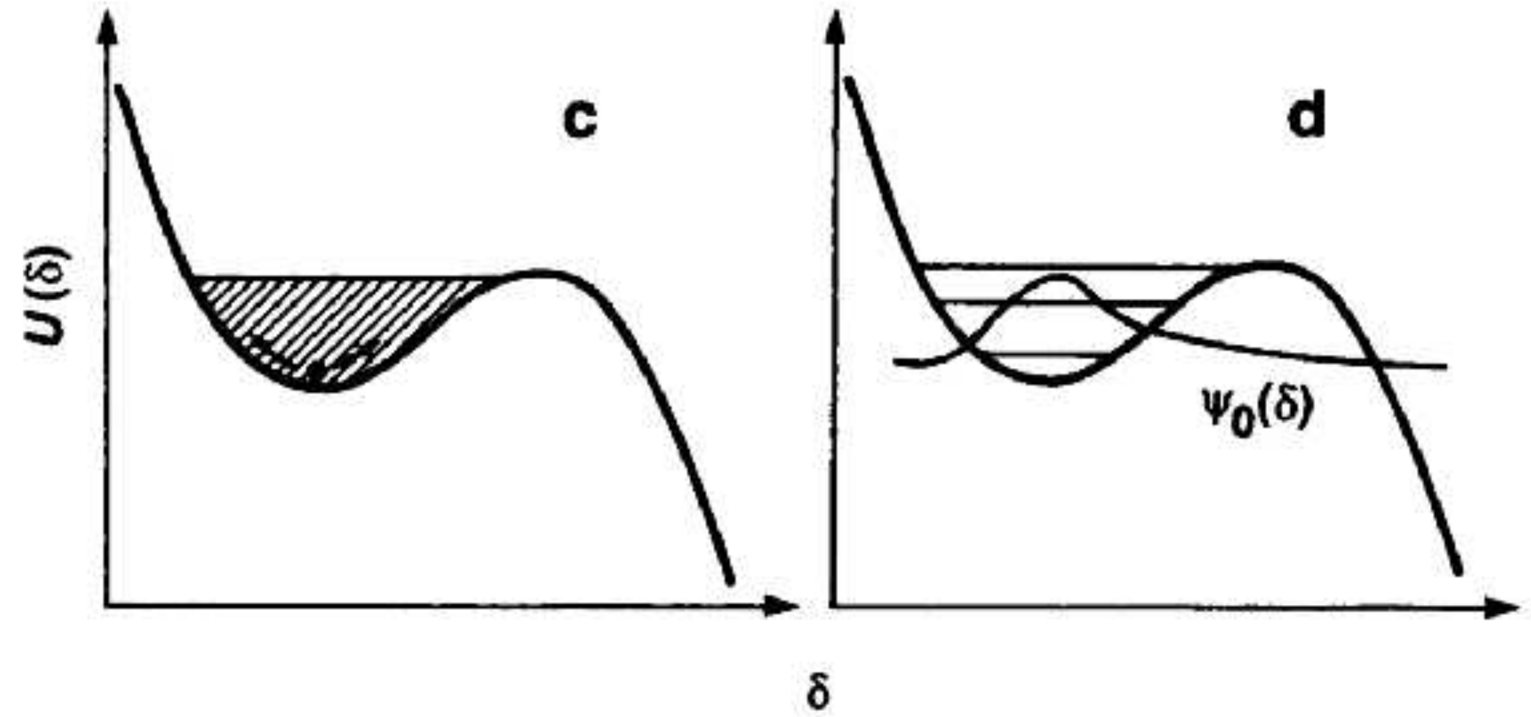
| Host material | Level of maturity | Operational temperature | Number of coupled qubits | Coherence time | Readout method and speed | Refs |
|---|---|---|---|---|---|---|
| Semi-conductors: Defects and III-V nanostructures | High | 1.7 K – 300 K | 7 | ms – mins | Optical, 1 – 100 ns | [1],[2],[3],[4],[5],[6] |
| Semi-conductors: Si/Ge QDs and Si donors | High | 4 K | 6 | ms – s | Electrical, < 1 ns | [7],[8],[9],[10],[11] |
| Spins in superconductors | High | ~10 mK | 2 | ns | Microwave, 10 – 100 ns | [12] |
| Magnetic Skyrmions | Medium | ~ *a few* K | *Concept stage* | *μs* | NV microscopy, scattering, TMR | [13],[14],[15] |
| Emerging 2D materials | Low | ~50 mK | *Concept stage** | Not yet demonstrated | Electrical, 1 μs | [16],[17],[18] |
| Topological materials | Low | ~20 mK | *Concept stage* | *ns* | Electrical or interference | [19],[20],[21],[22] |

**Materials for Quantum Technologies: a Roadmap for Spin and Topology**

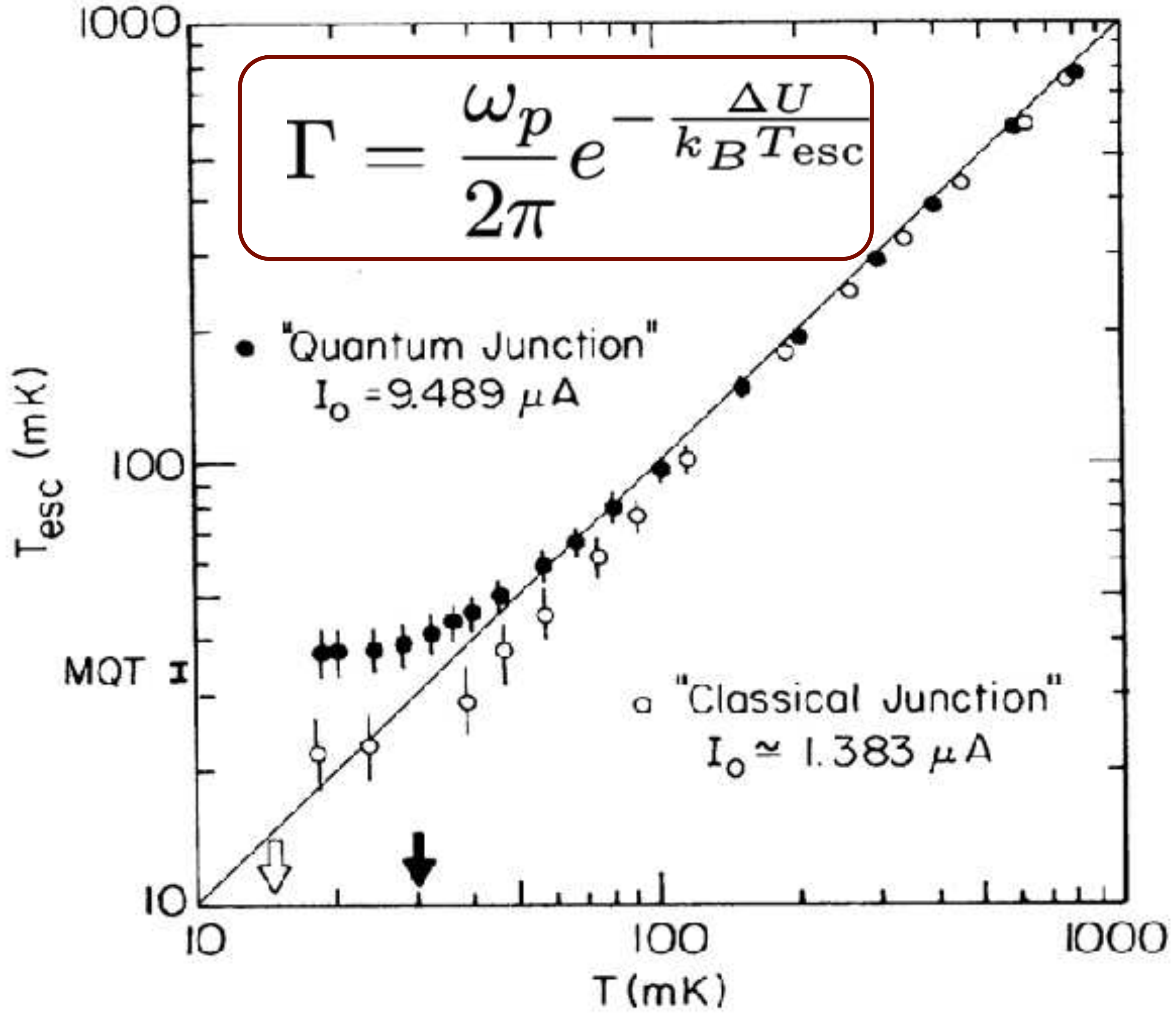
N. Banerjee, et al. arXiv:2406.07720 (2024)

# MQT in Josephson Junctions and Molecular Magnets





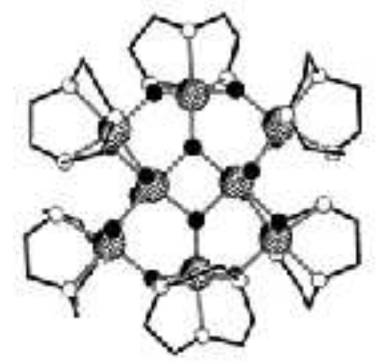

John Clarke, et al., *Science* **239**, 992 (1988).



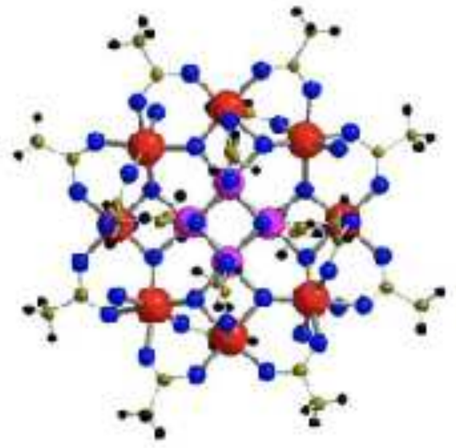

$$\Gamma = \frac{\omega_p}{2\pi} e^{-\frac{\Delta U}{k_B T_{esc}}}$$

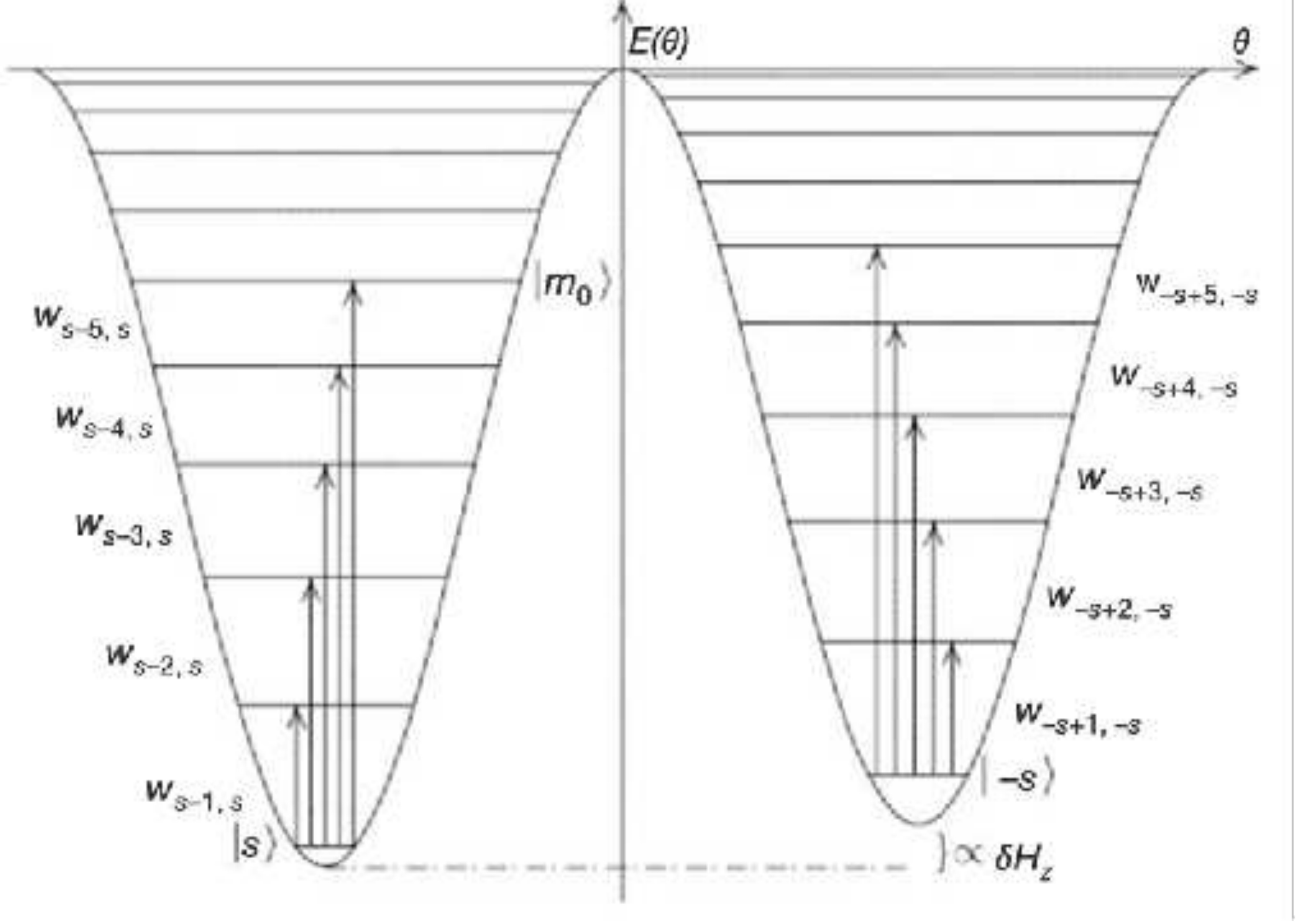
$S = 10$ $\quad H_0 = -D[S_z^2 - S(S+1)/3] + g\mu_B H_z S_z$

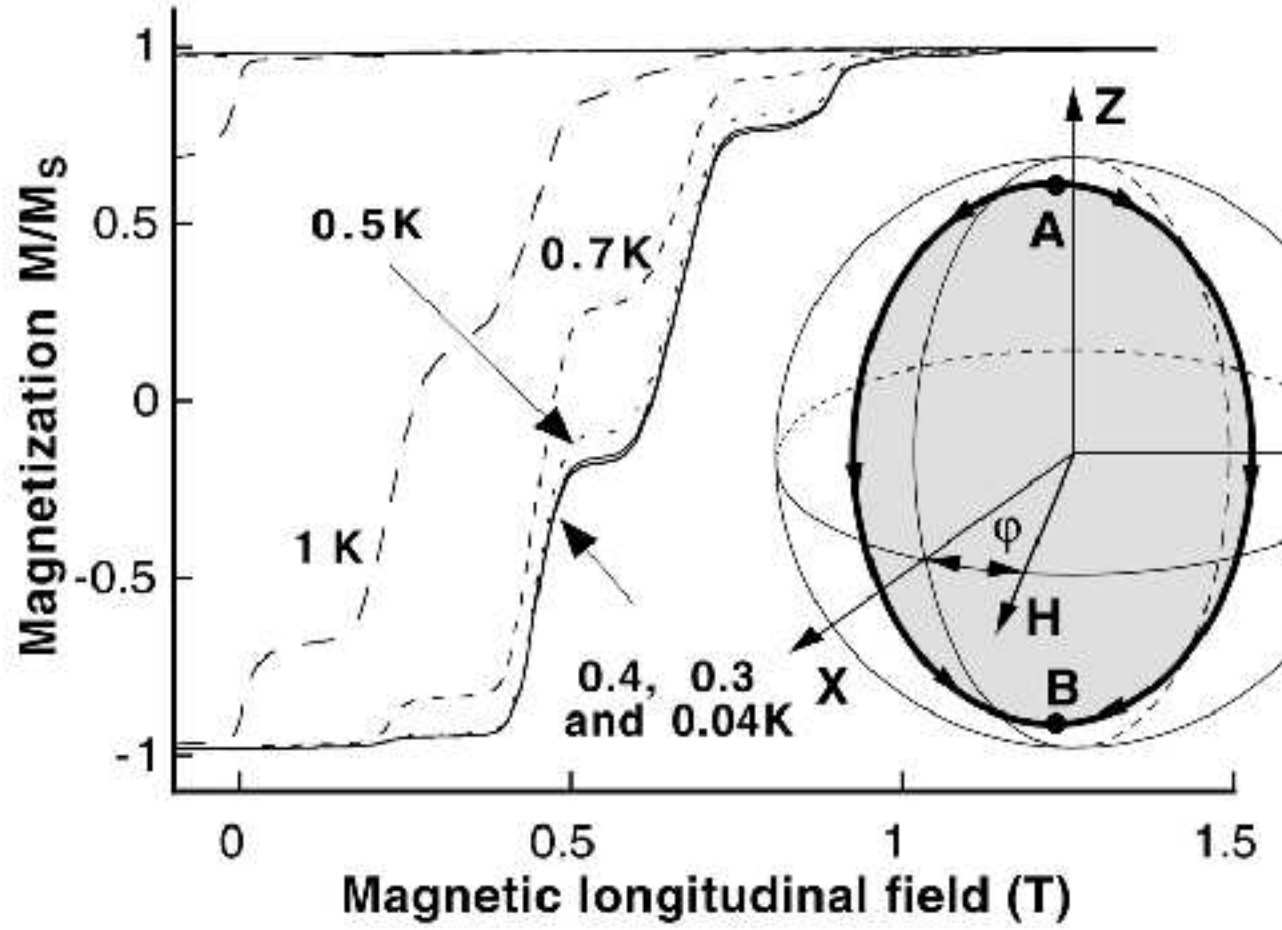
$Fe_8$

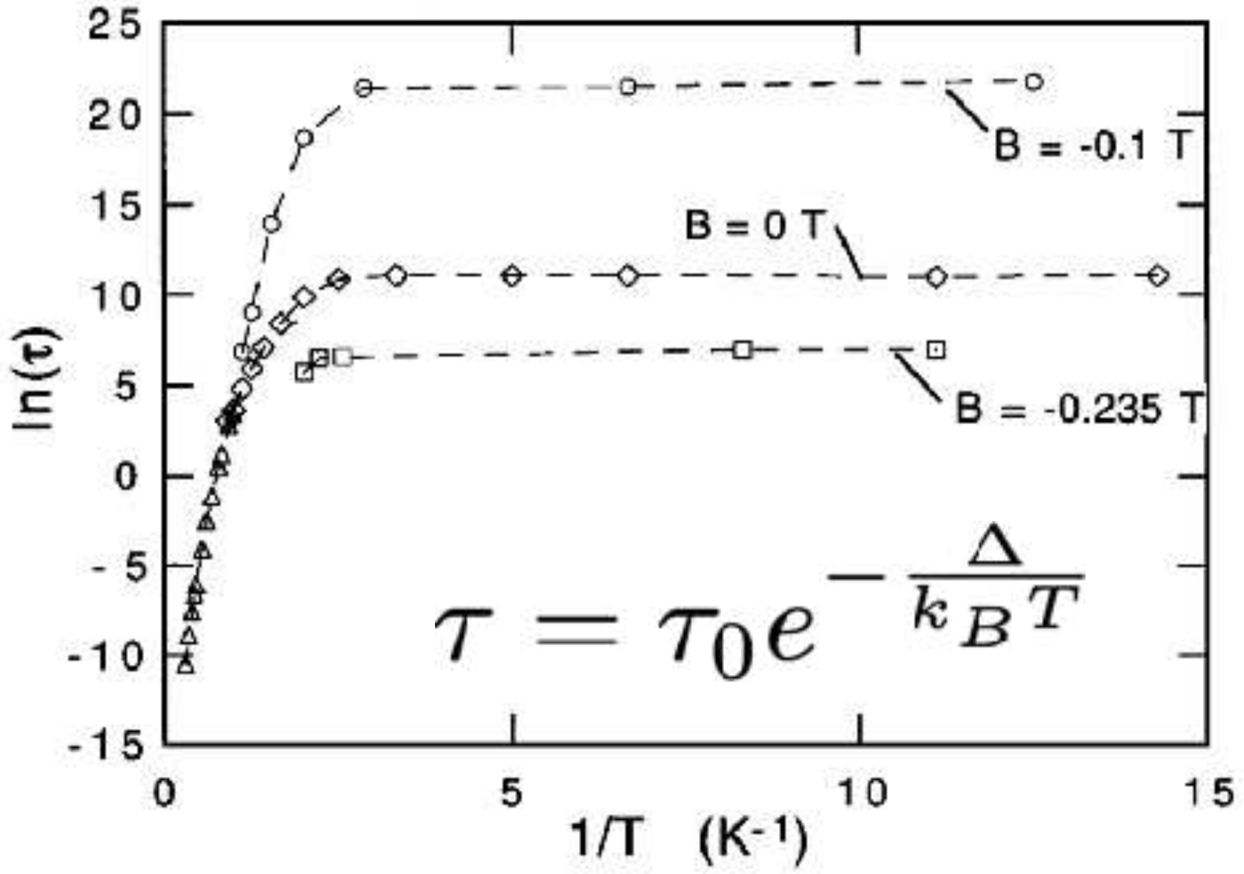


$Mn_{12}$






$$\tau = \tau_0 e^{-\frac{\Delta}{k_B T}}$$

M. H. Devoret, J. M. Martinis, and J. Clarke, *Phys. Rev. Lett*. **55**, 1908 (1985)

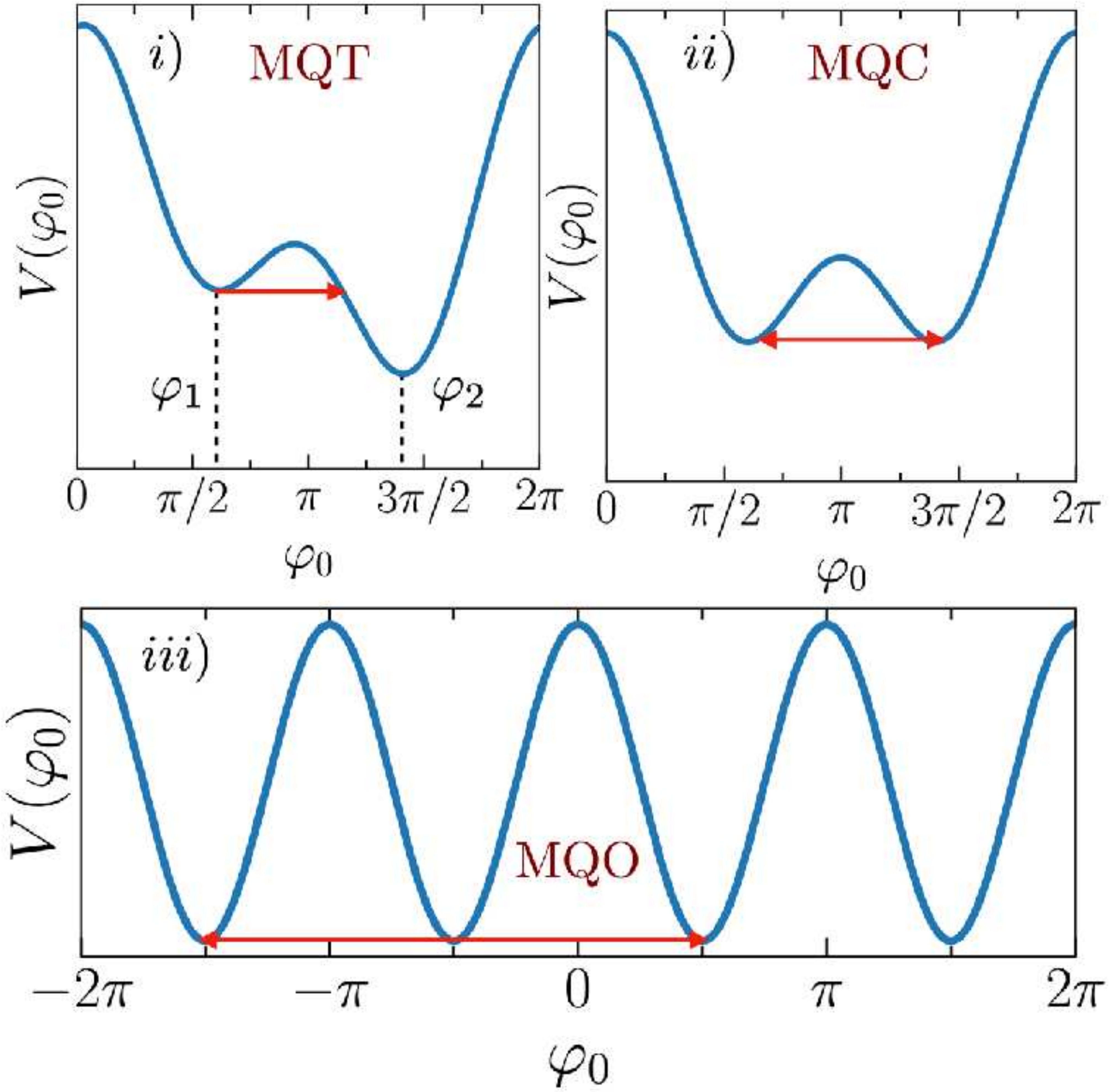
J. M. Martinis, M. H. Devoret, and J. Clarke, *Phys. Rev. Lett*. **55**, 1543 (1985)

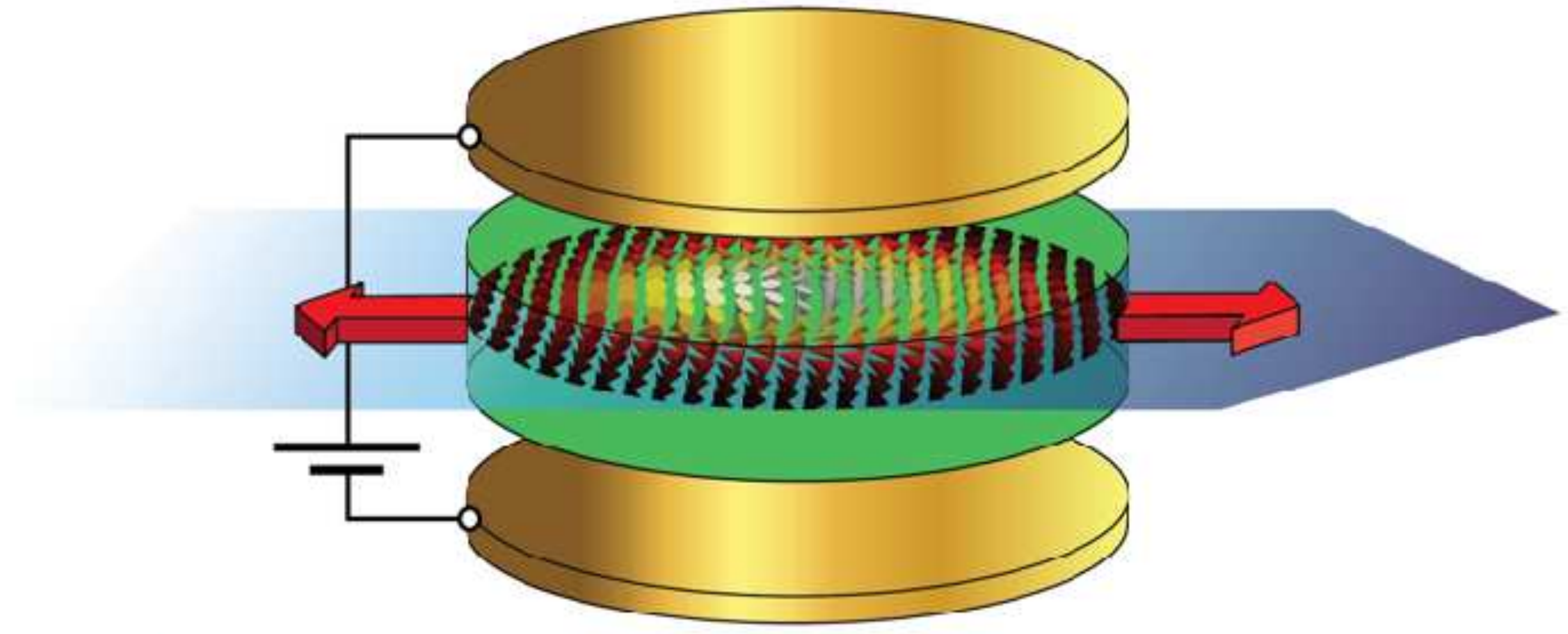
W. Wernsdorfer, and R. Sessoli, *Science* **284** 133 (1999)

C. Sangregorio, et al., *PRL* **78** 4645 (1997).

# Macroscopic Quantum Phenomena





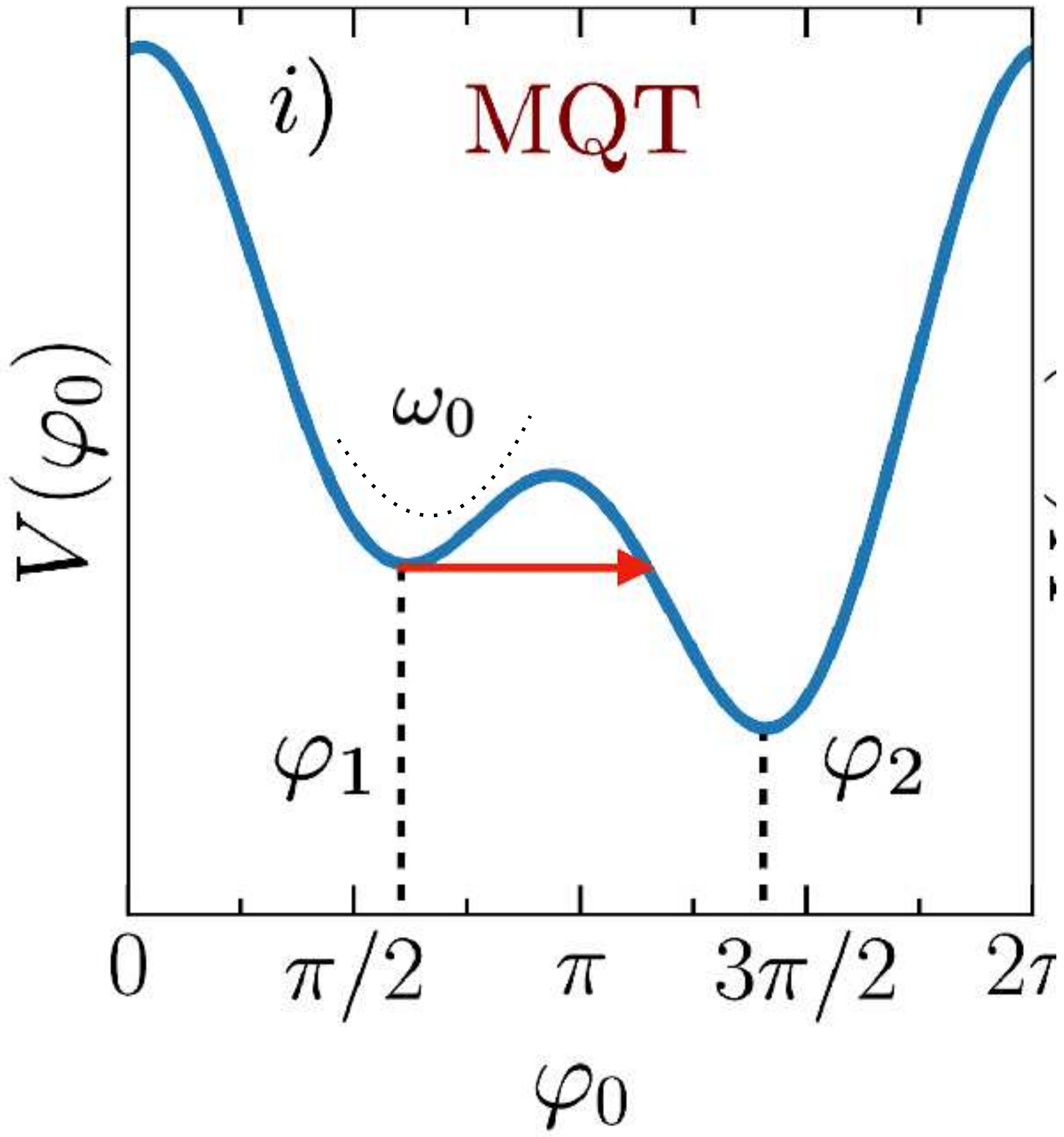
$$Z = \int \mathcal{D}\varphi_0 \tilde{Z} e^{\int_{-\beta/2}^{\beta/2}[\frac{\mathcal{M}}{2}\dot{\varphi_0}^2 - iA\dot{\varphi}_0 + V(\varphi_0) + c]}$$

*Gauge potential* $A = (h_1\mathcal{M}/\bar{S} - \bar{S}\Lambda)$

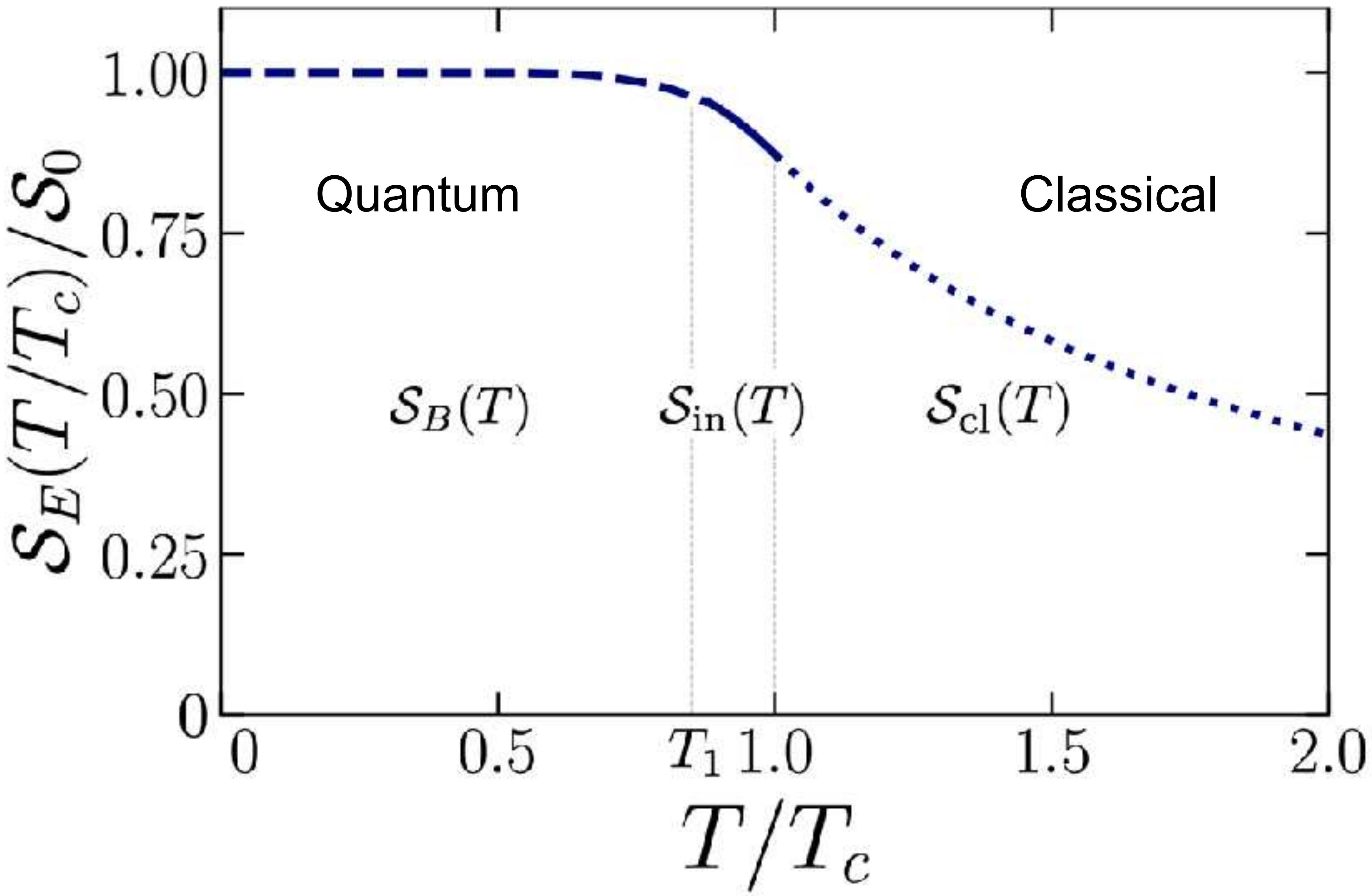
C. Psaroudaki and C. Panagopoulos,
*Skyrmion Helicity: Quantization and Quantum Tunneling Effects* , Phys. Rev. B **106**, 104422 (2022)

# Macroscopic Quantum Tunneling

$$V(\varphi_0) = \kappa_x \cos 2\hat{\varphi}_0 - E_z \cos \hat{\varphi}_0 + h_\perp \sin \hat{\varphi}_0$$




$$\Gamma_Q = 2\omega_0 \sqrt{\frac{15\mathcal{S}_0}{2\pi}} e^{-\mathcal{S}_0}$$



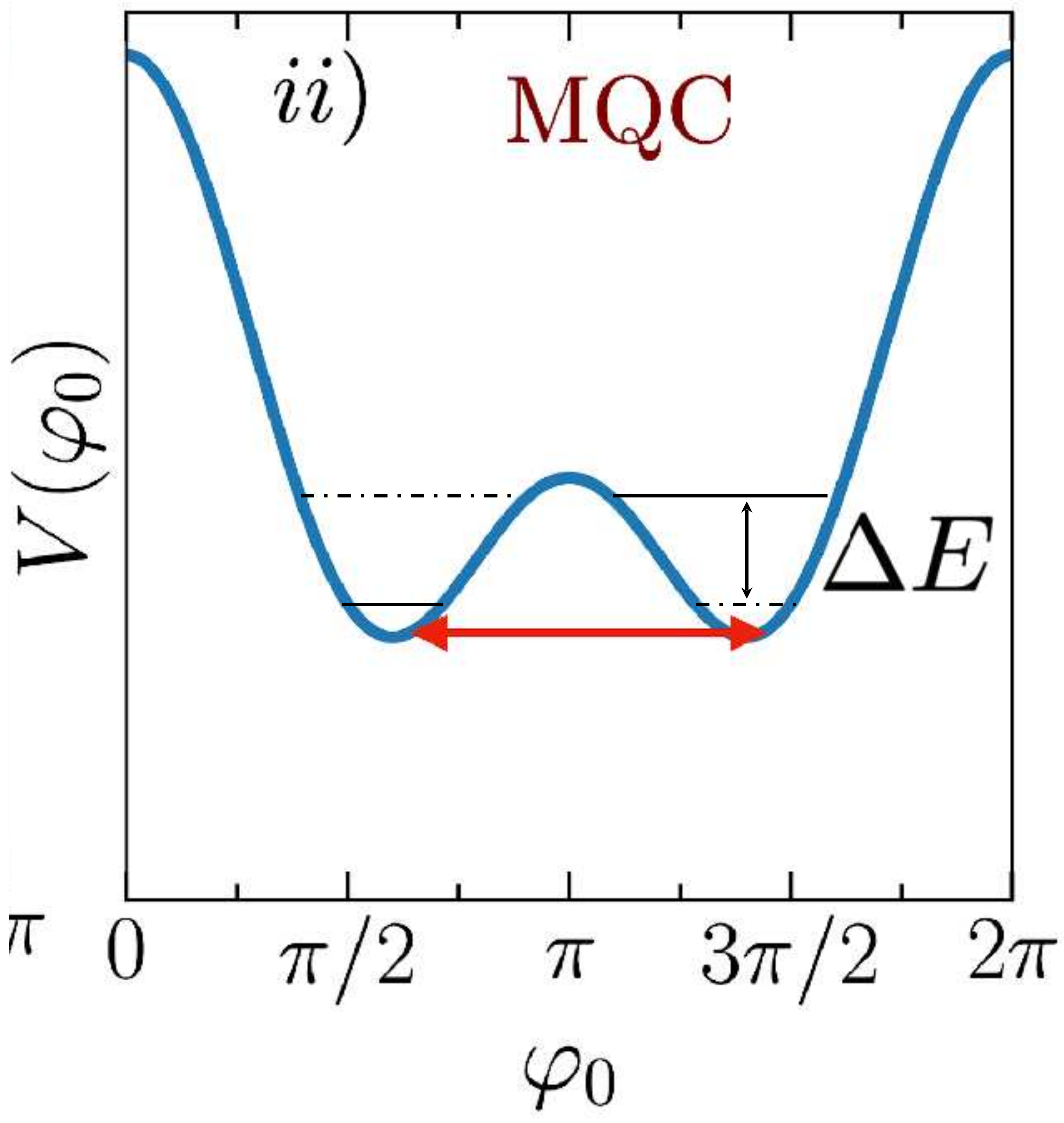

$$T_c \approx 100 \text{ mK}$$

$$\Gamma_Q^{-1} \approx 10 \text{ s}$$

# Macroscopic Quantum Coherence

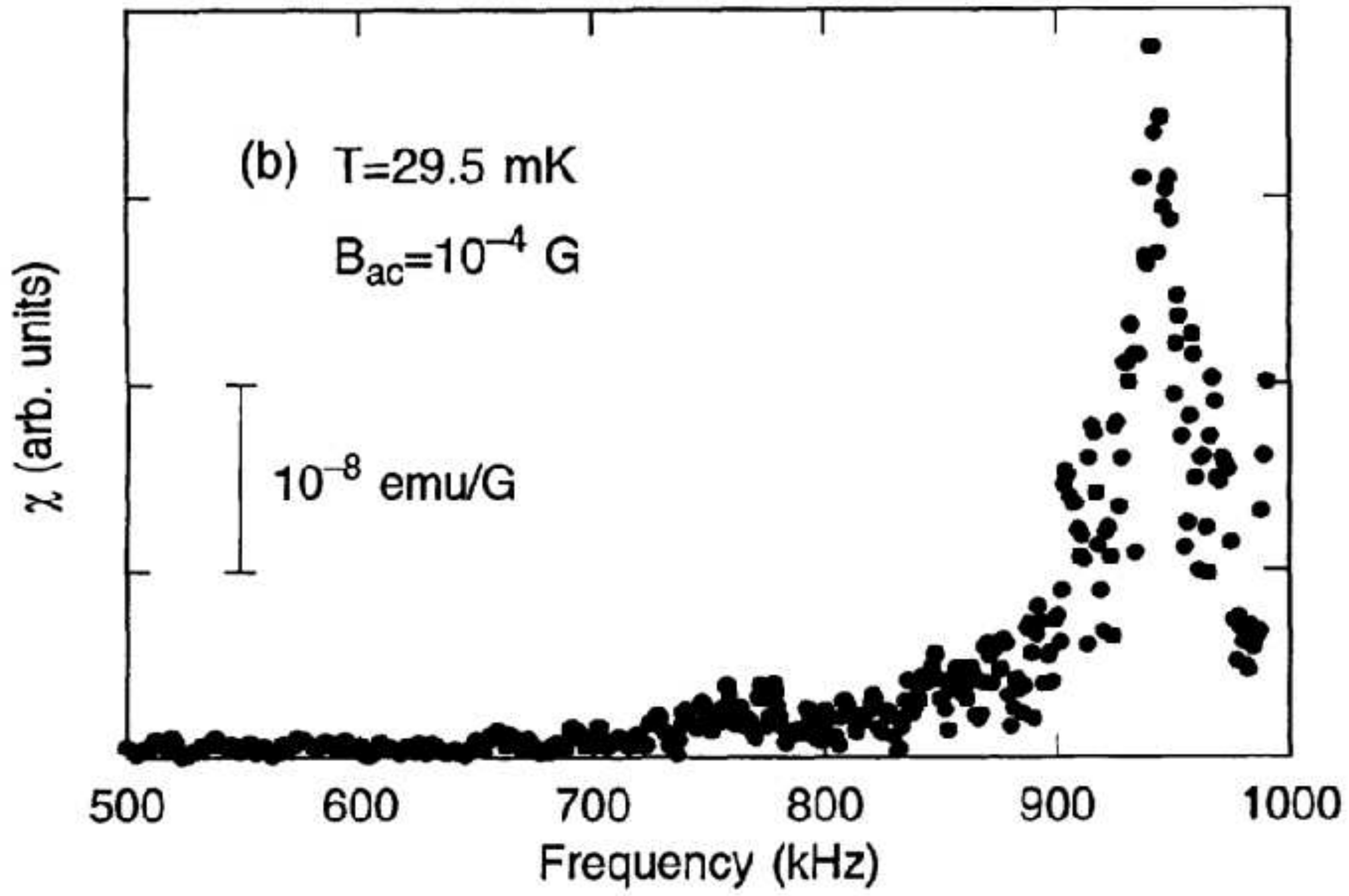


$$V(\varphi_0) = \kappa_x \cos 2\hat{\varphi}_0 - E_z \cos \hat{\varphi}_0$$




$$Z_E(\varphi_s, \varphi_s, \beta) = \sqrt{\frac{2\mathcal{M}\omega_b}{\pi}} e^{-\beta\omega_b} \cosh(\Delta E\beta/2)$$

$$\Delta E \approx 10 \text{ MHz}$$

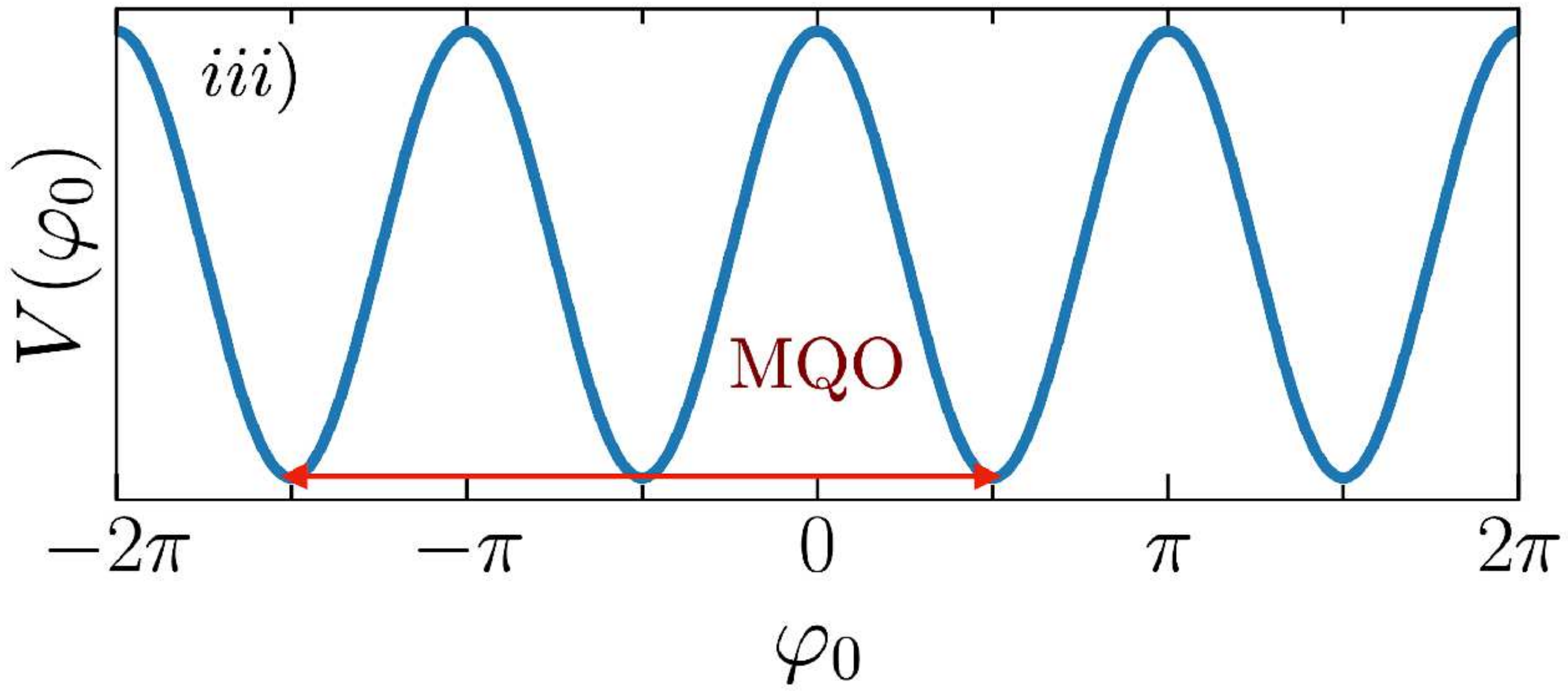



D. D. Awschalom, J. F. Smyth, G. Grinstein,
D. P. DiVincenzo, and D. Loss
*Phys. Rev. Lett.* **71**, 4279 (1993)

# Macroscopic Quantum Oscillation



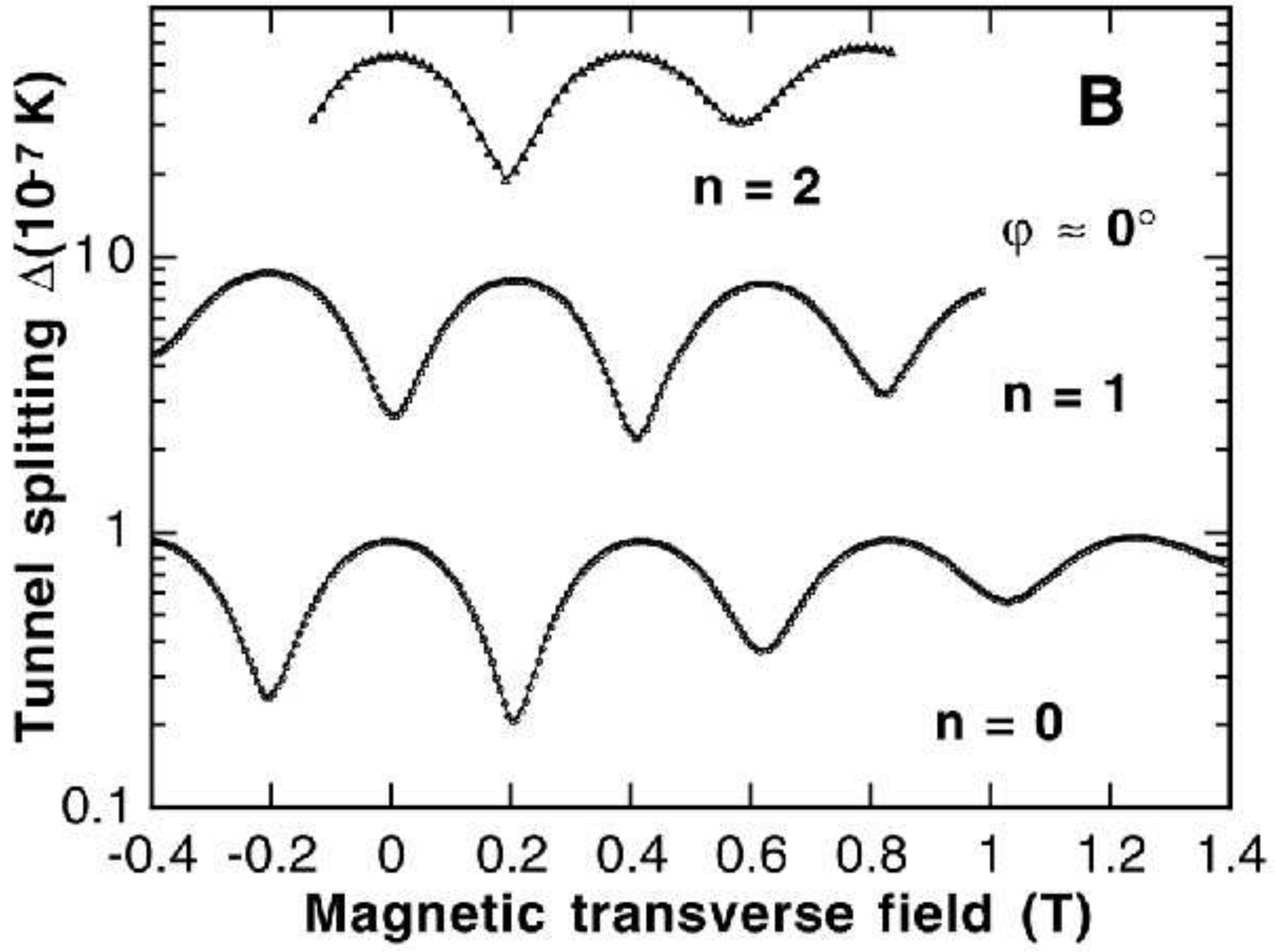
$$V(\varphi_0) = \kappa_x \cos 2\hat{\varphi}_0$$




$$\mathcal{S}_E(\varphi_\pm) = \mathcal{S}_0 \mp iA\pi$$

$$\Delta E \propto |\cos(\pi A)|$$

$$A = h_1 \mathcal{M}/\bar{S} - \bar{S}\Lambda, \;\; \Lambda = \int d\mathbf{r}(1 - \cos\Theta)$$




W. Wernsdorfer and R. Sessoli, *Science* **284**, 133 (1999).

Spin-Parity Effect

D. Loss, D. P. DiVincenzo, and G. Grinstein, Phys. Rev. Lett. **69**, 3232 (1992).

J. von Delft and C. L. Henley, Phys. Rev. Lett. **69**, 3236 (1992).

# Candidate Materials



R&D path

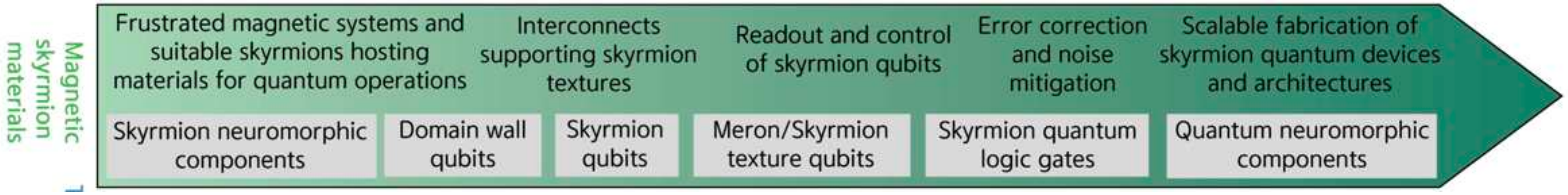



Fig. From N. Banerjee, et al. arXiv:2406.07720 (2024)

| | |
|---|---|
| $Gd_2PdSi_3$<br>$Gd_3Ru_4Al_2$ | *Rare earth-intermetallic, skyrmion hosting* |
| $RGa_2$ $ErSi_2$ | *same space group* |
| $TbGa_2$ | *signatures of nonlinear ground state* |
| $NiGa_2S_4$ | *Mott insulator on a triangular lattice* |
| $\alpha$-$NaFeO_2$ | *frustrated triangular magnet* |
| $Fe_xNi_{1-x}Br_2$ | *frustrated triangular magnet* |
| $Pb_2VO(PO_4)_2$ | *frustrated square lattice* |

Beyond bulk magnets: skyrmions in vdW ferromagnets?

C. Psaroudaki, and C. Panagopoulos., ***Skyrmion Qubits: Challenges For Future Quantum Computing Applications***, Appl. Phys. Lett. **123**, 260501 (2023)

# Magnon Spectrum

**Magnon Spectrum around Skyrmions in Frustrated Magnets***

Adarsh Hullahalli† and Christos Panagopoulos†
Christina Psaroudaki‡

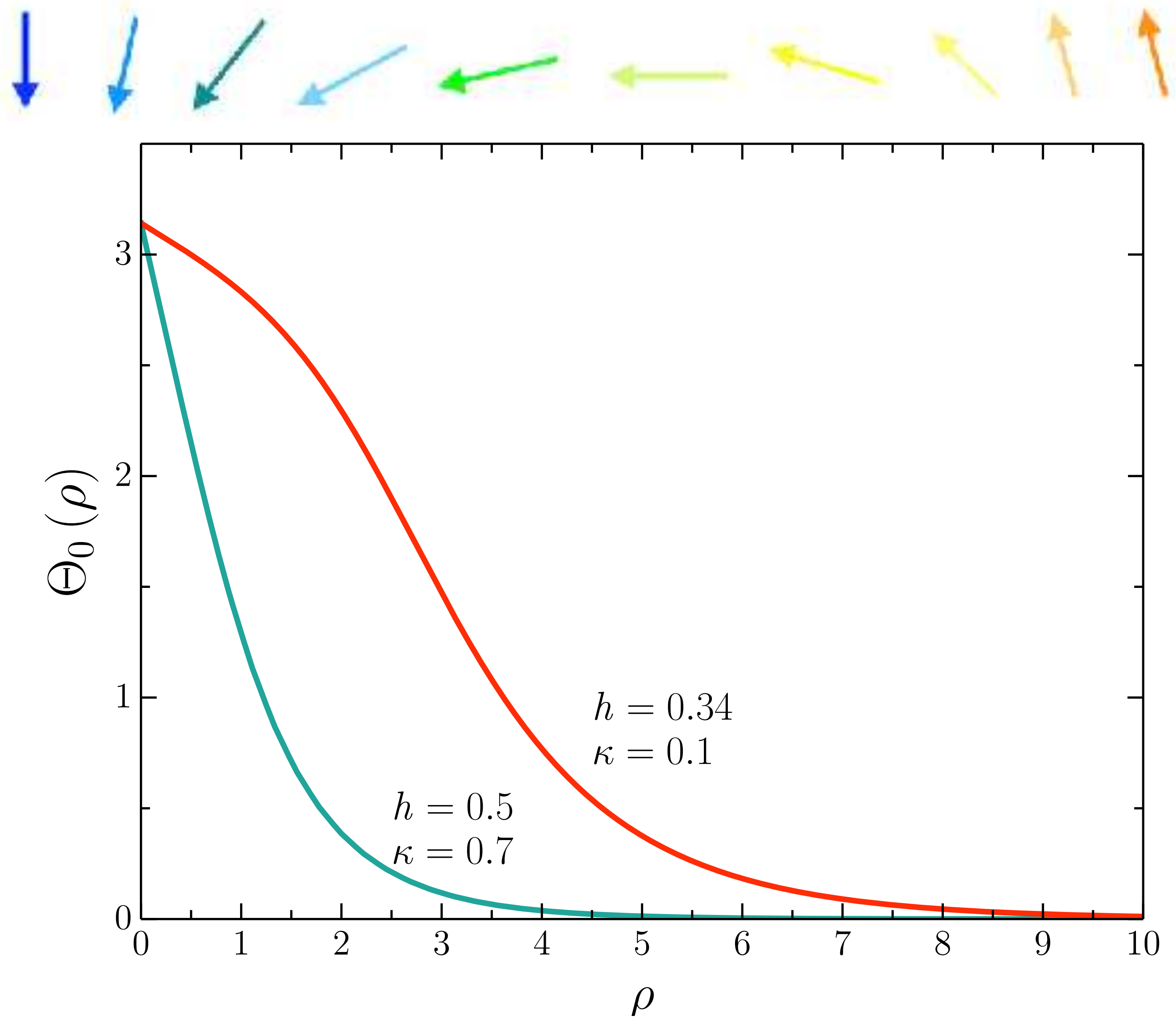

NTU Singapore


NTU Singapore

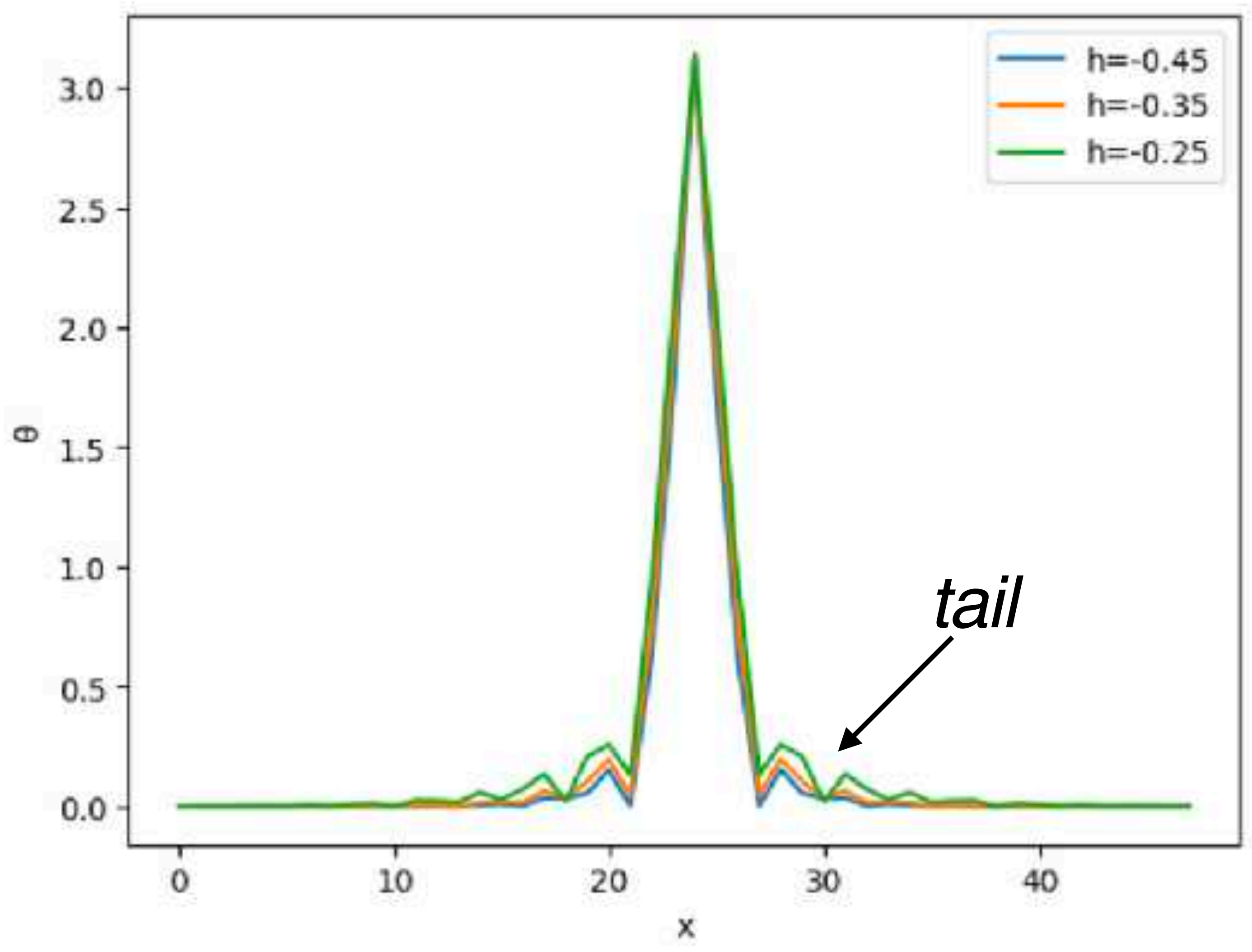
## Skyrmion Profile

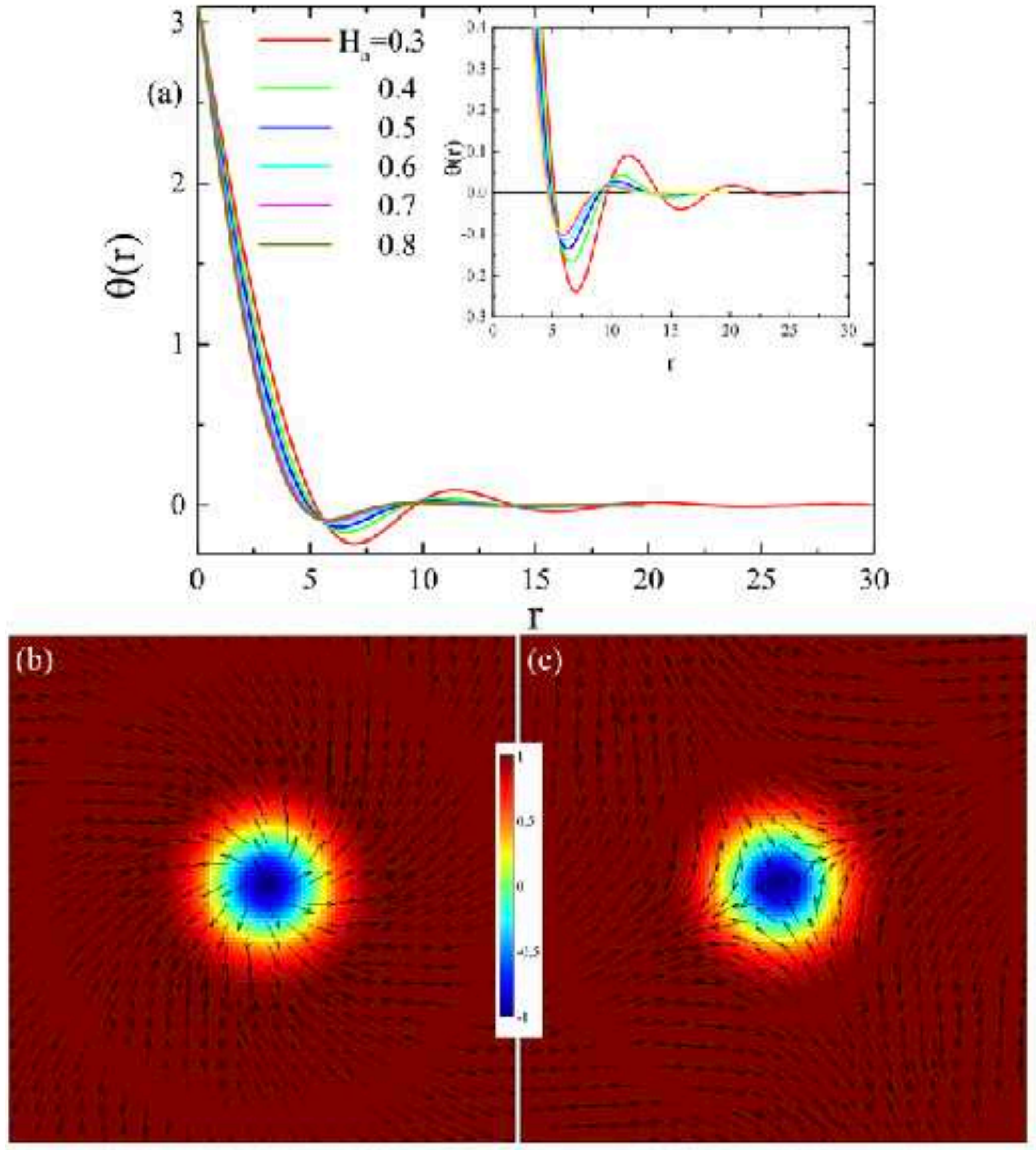
$$m_z = \cos\Theta_0$$

### DMI-systems




### Frustrated-systems

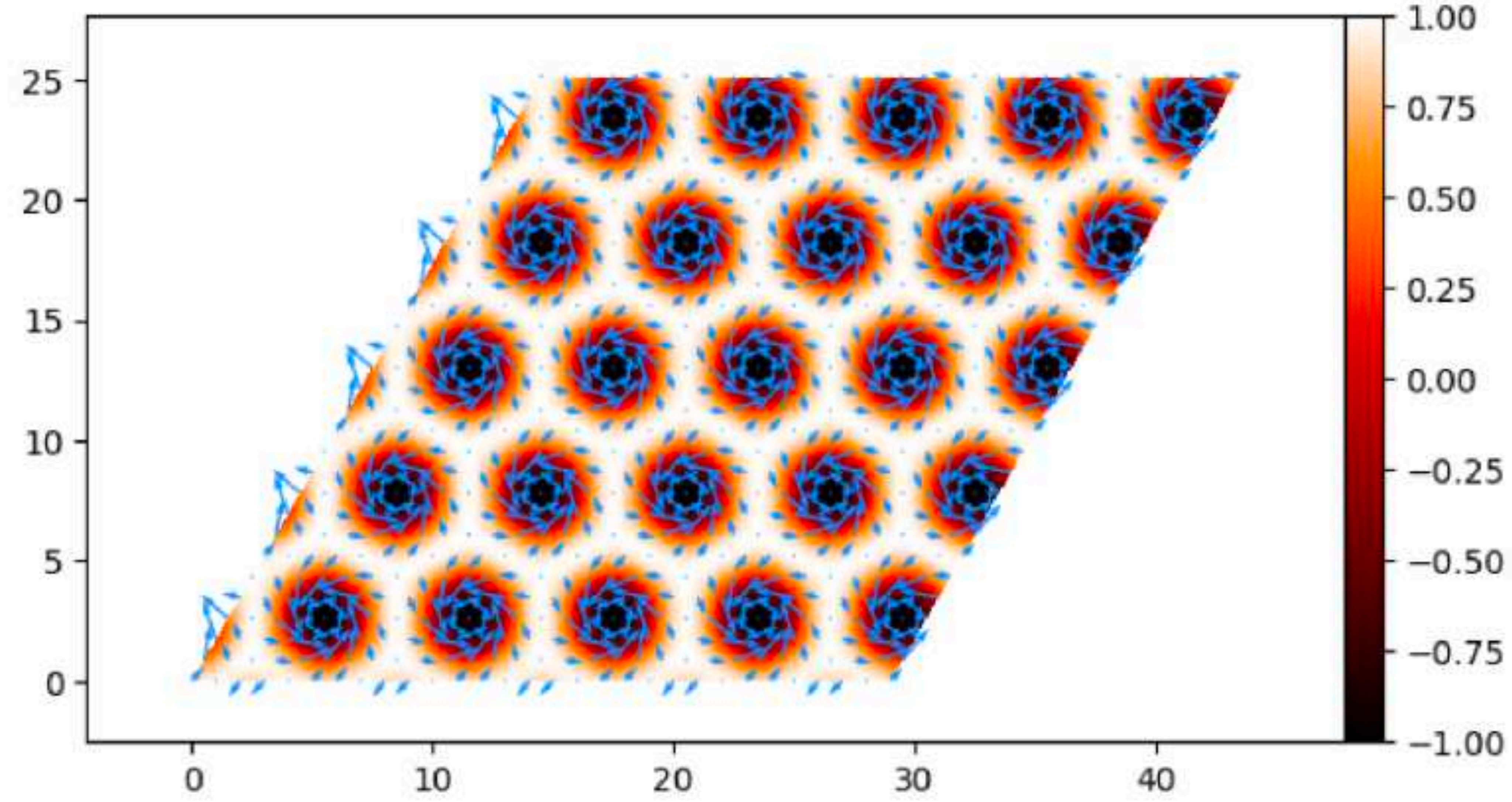


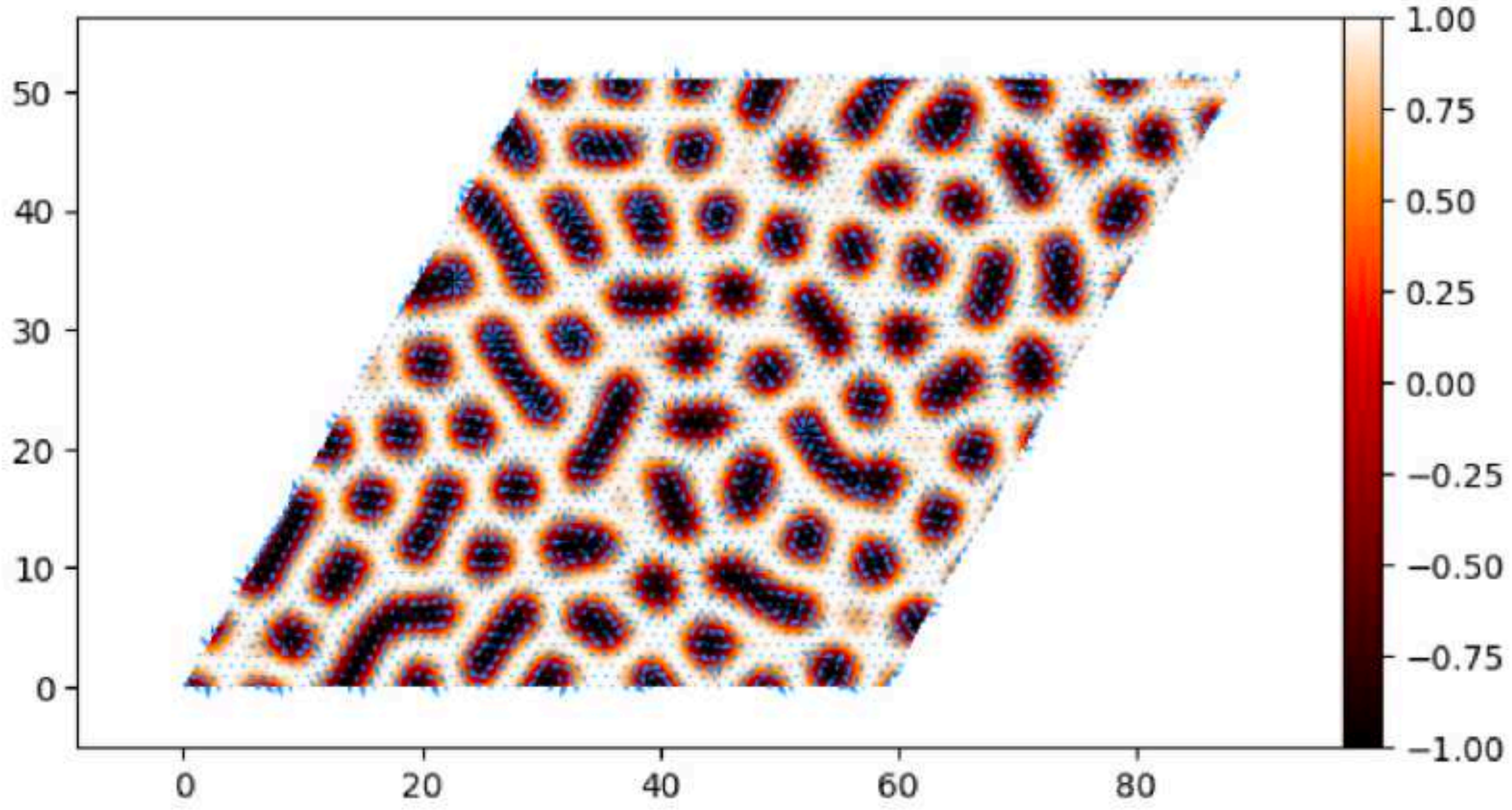

S.-Zeng Lin and S. Hayami, Phys. Rev. B **93**, 064430 (2016)

# Metastable States

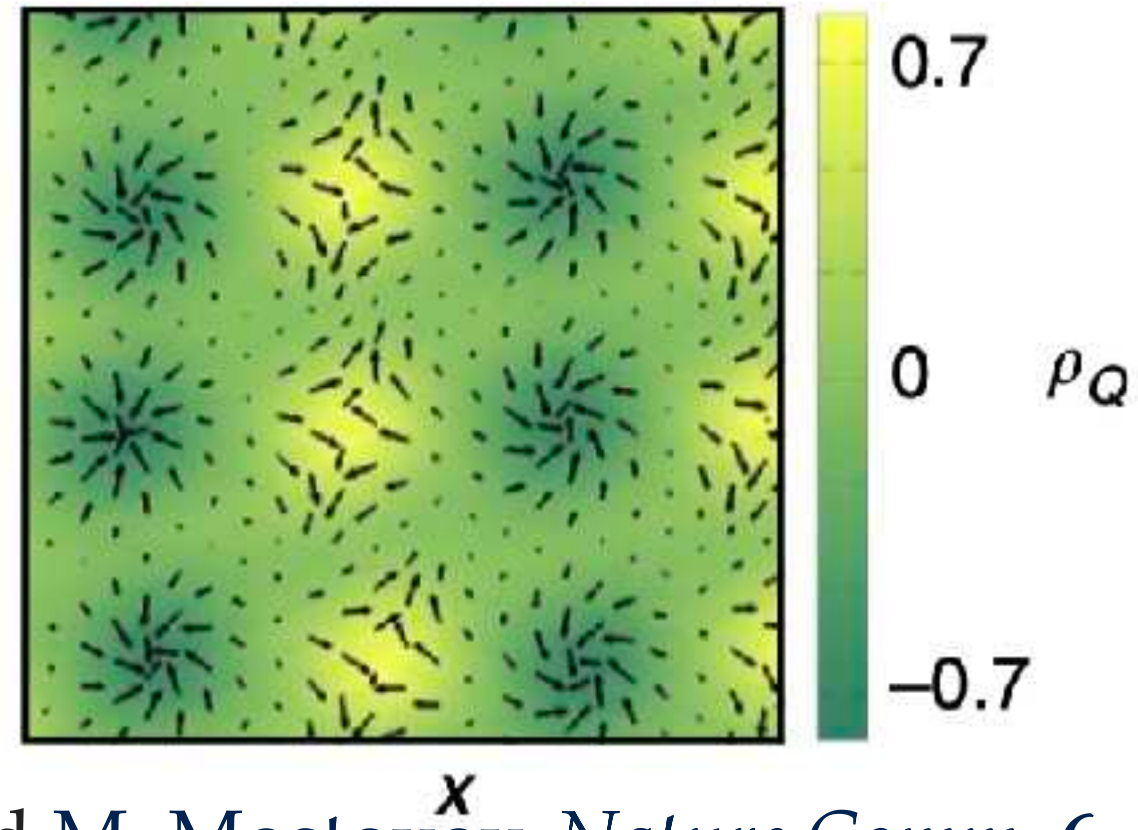
## Skyrmion Lattice Ground State




## Metastable States



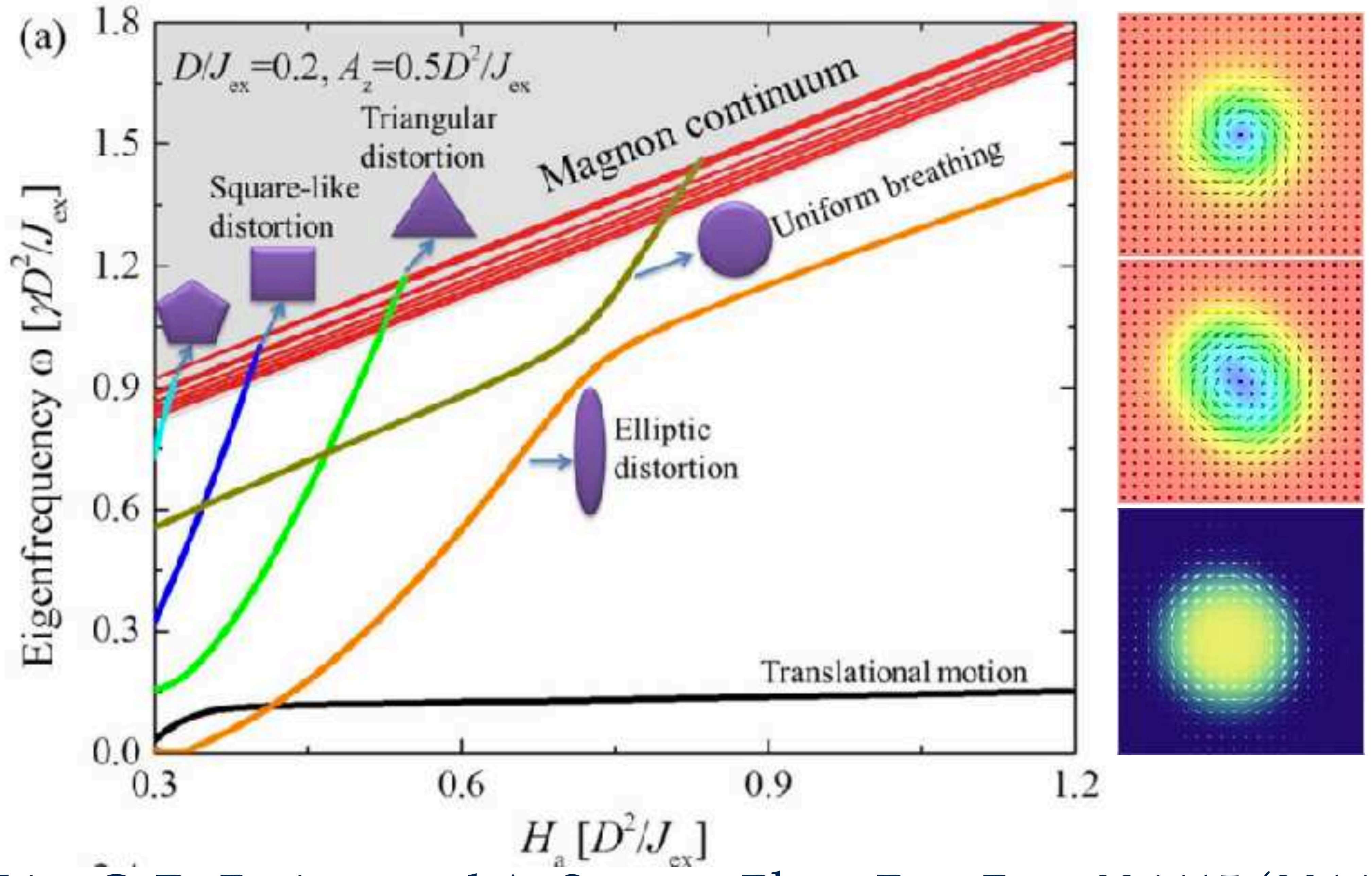

Measurements of the topological Hall effect do not suggest the presence of a specific state type




A. O. Leonov, and M. Mostovoy, *Nature Comm*. **6**, 8275 (2015).

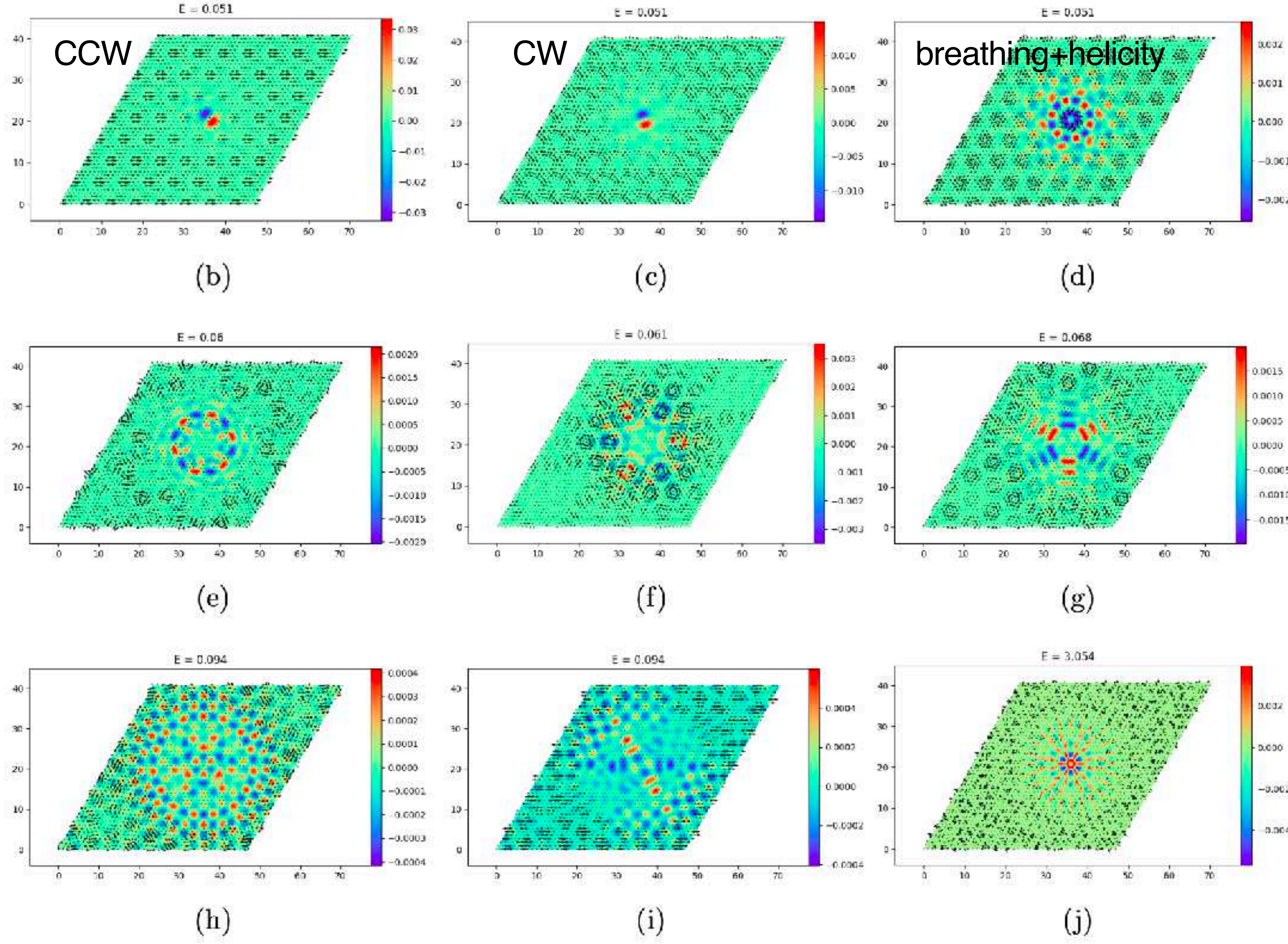
# Magnon modes around Isolated Skyrmions

## DMI-systems



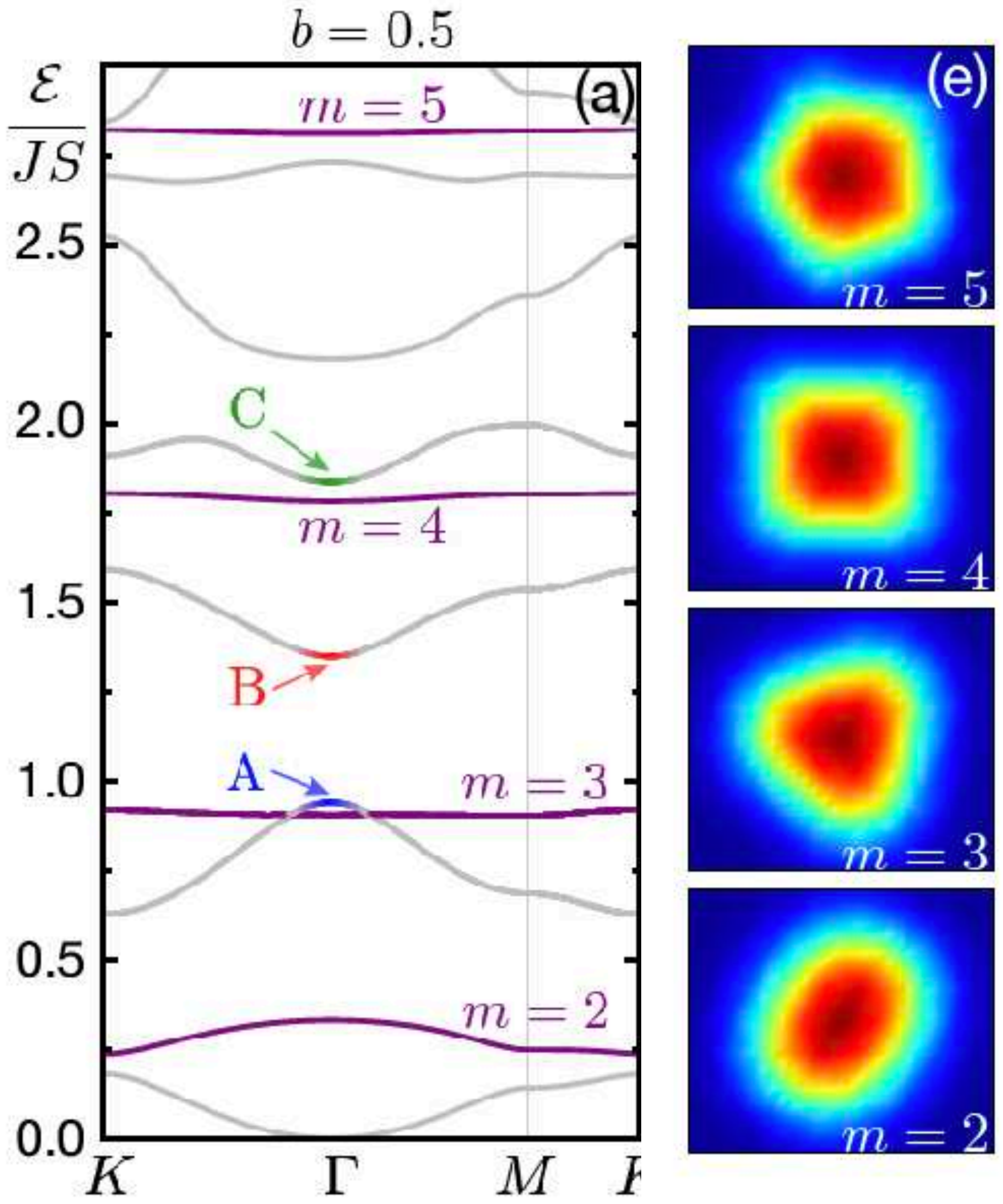

S. Lin, C. D. Batista, and A. Saxena, Phys. Rev. B **89** 024415 (2014)

## Frustrated-systems



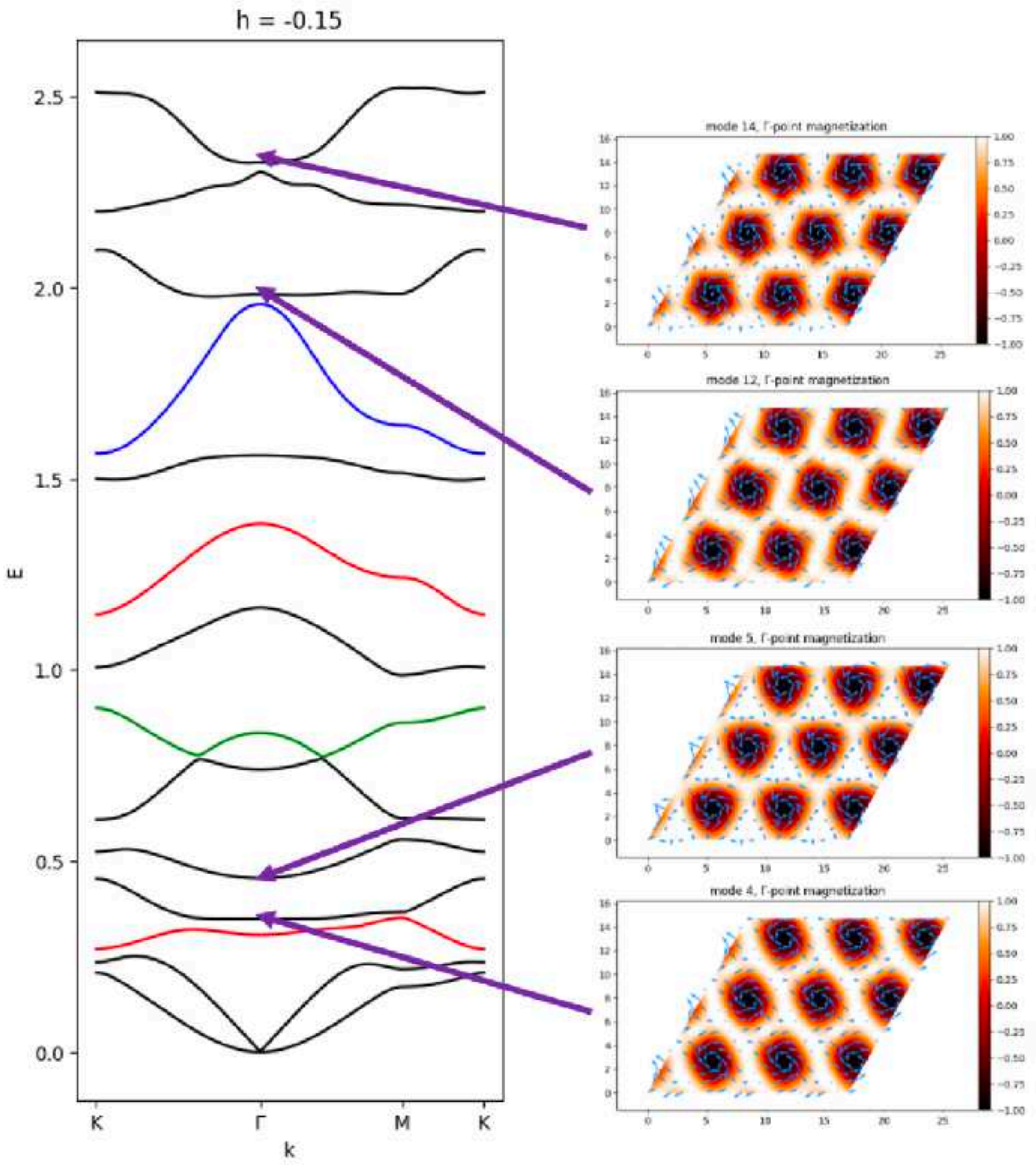
# Magnon modes around Skyrmion Lattices

## DMI-systems




S. Diaz, et al., Phys. Rev. Research **2**, 013231 (2020)

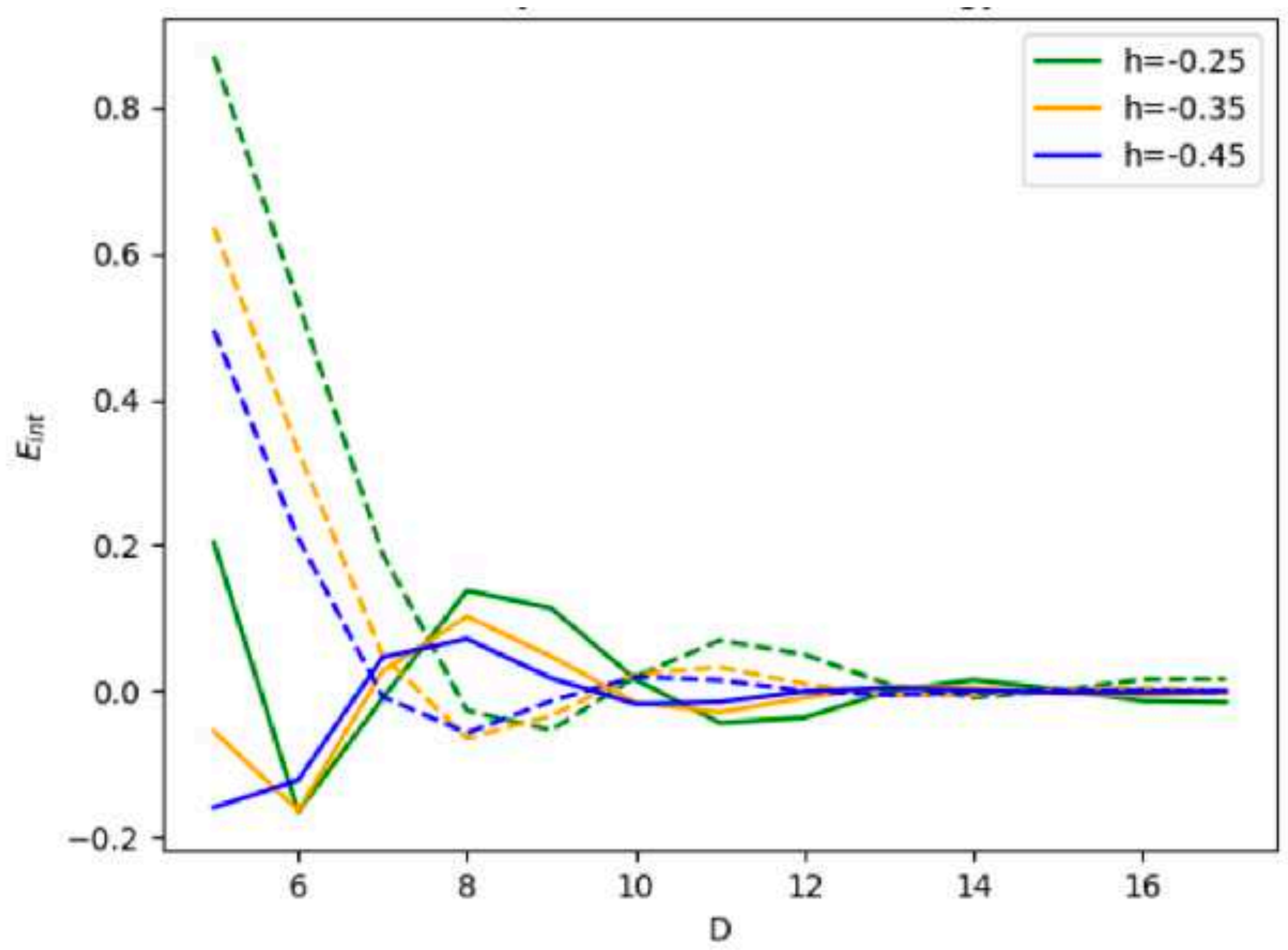
## Frustrated-systems

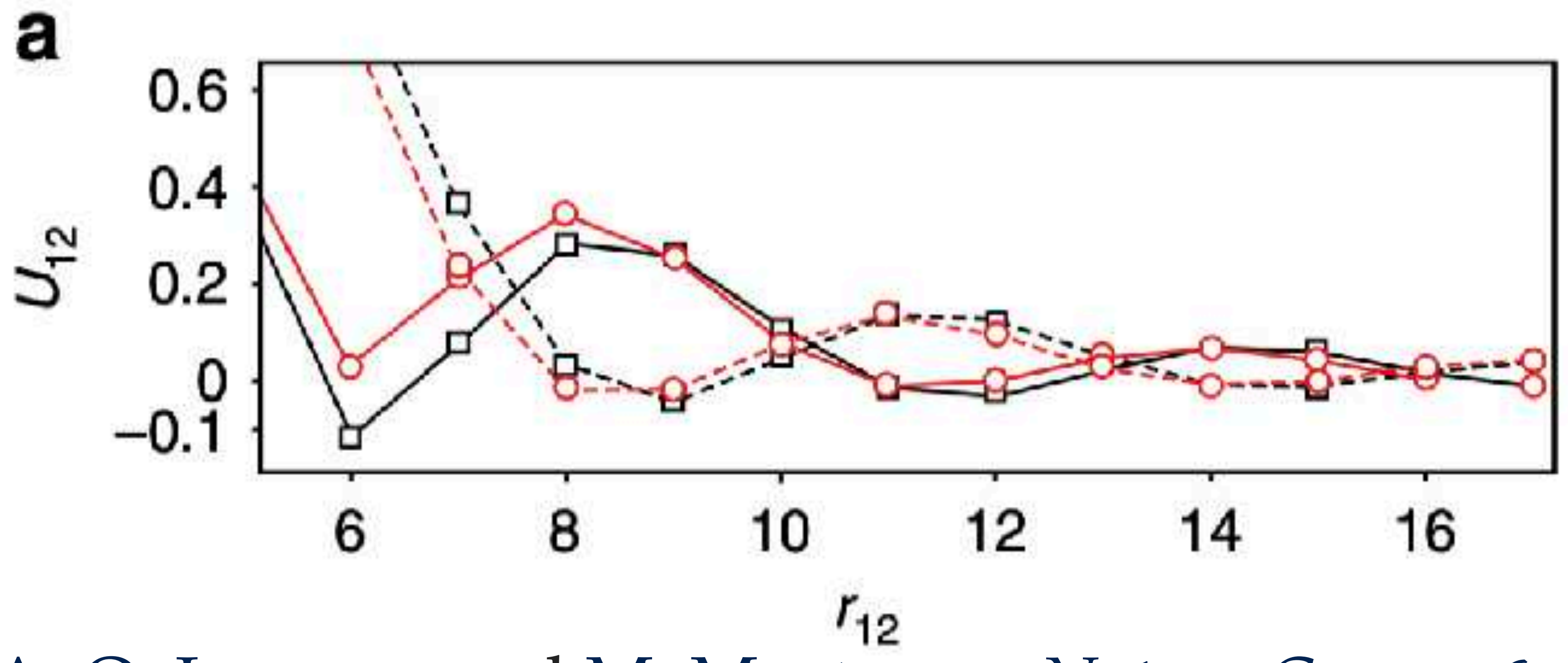


# Magnon modes around Skyrmion Lattices

LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

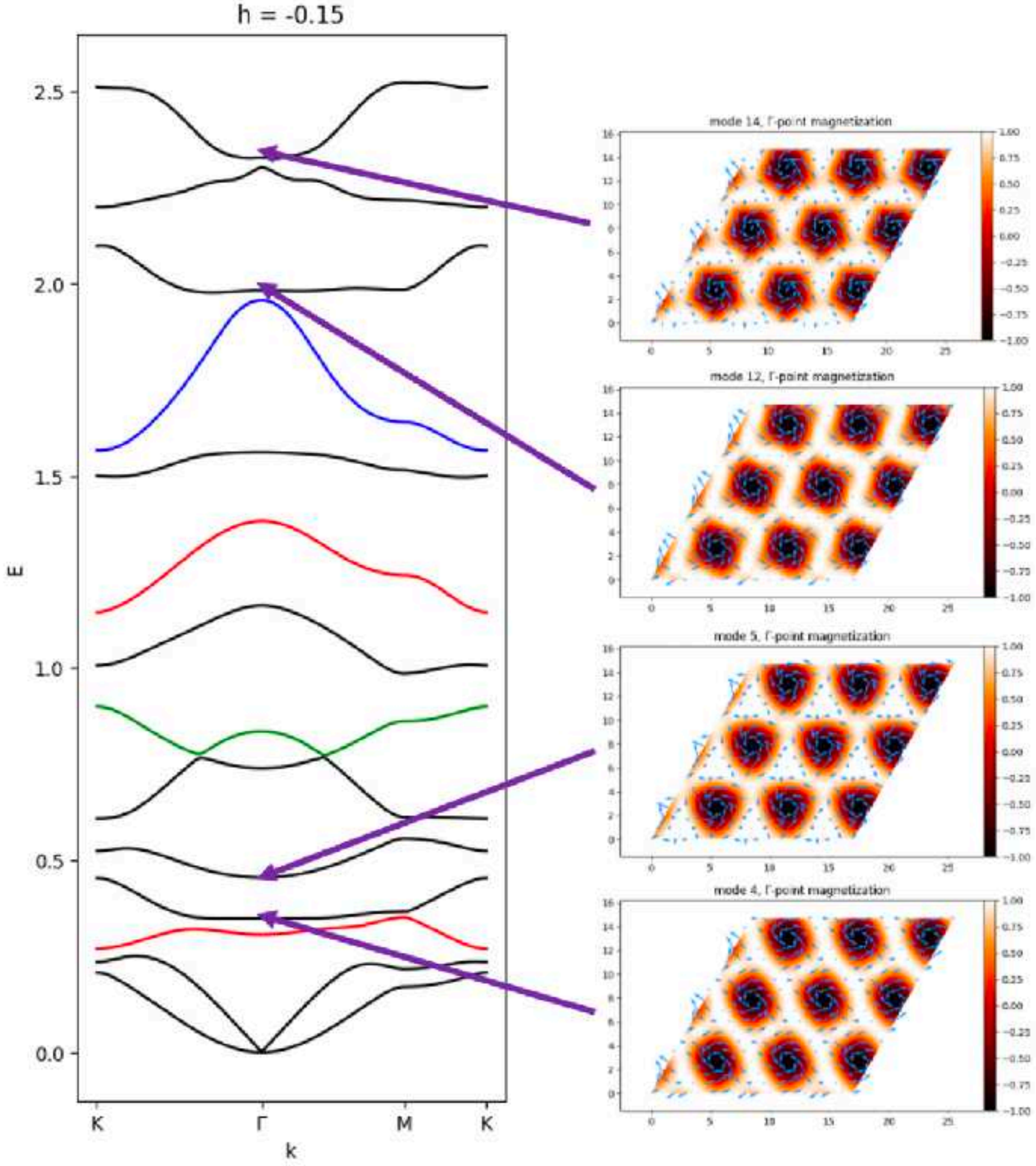
## Skyrmion-Skyrmion Interaction




A. O. Leonov, and M. Mostovoy, *Nature Comm*. **6**, 8275 (2015).

## Frustrated-systems



arXiv > cond-mat > arXiv:2410.11427

Condensed Matter > Mesoscale and Nanoscale Physics

[Submitted on 15 Oct 2024]

## Colloquium: Quantum Properties and Functionalities of Magnetic Skyrmions

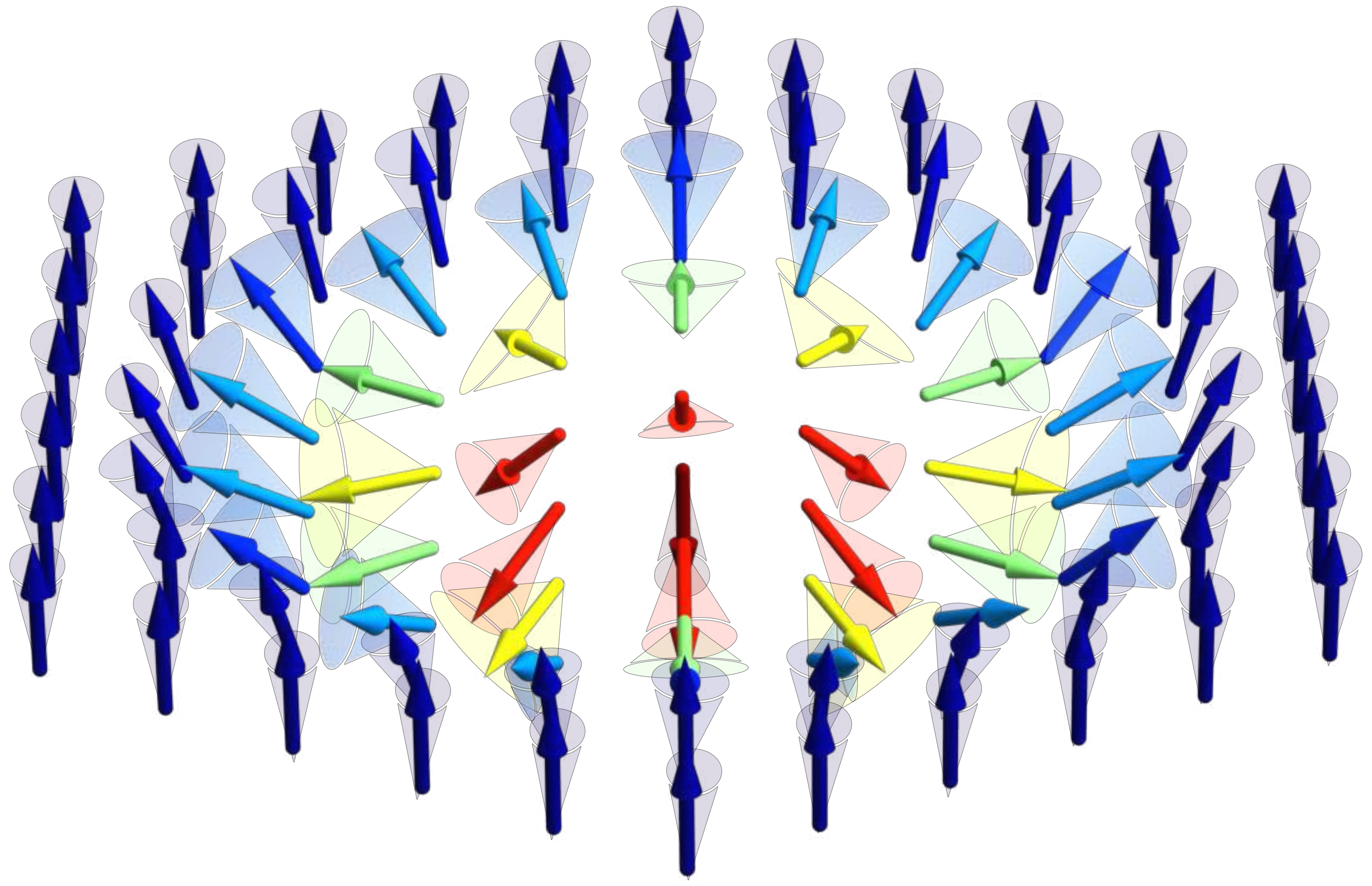
Alexander P. Petrović, Christina Psaroudaki, Peter Fischer, Markus Garst, Christos Panagopoulos

Uni Wyoming

Lawrence Berkeley National Laboratory

ITS Karlsruhe

NTU Singapore



I. Approaching the Quantum Limit with Classical Skyrmions

Low-T phase diagrams and novel centrosymmetric materials

II. Quantum States in the Background of Classical Skyrmions

Magnons, Electrons, Hybrid Superconductor-skyrmions, Cavity Magnonics

III. Quantum Skyrmions

Semiclassical Quantization, Macroscopic Quantum Effects, Skyrmion Qubit, Skyrmions in Quantum Magnetism

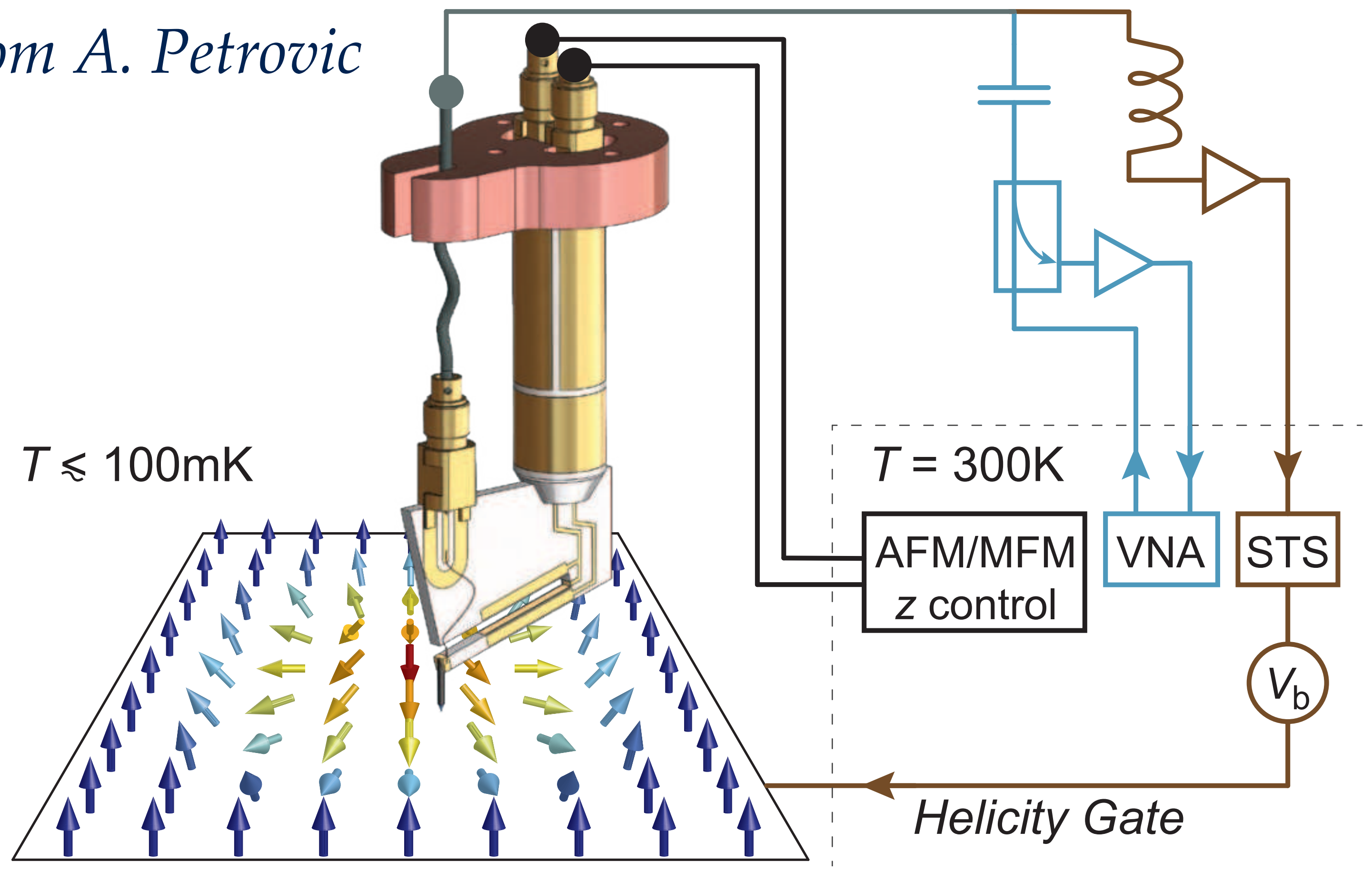
IV. Accessing Quantum Aspects of Skyrmions in the Laboratory

Materials and architectures, Experimental methods, Skyrmion Devices

# Skyrmion Qubit Readout



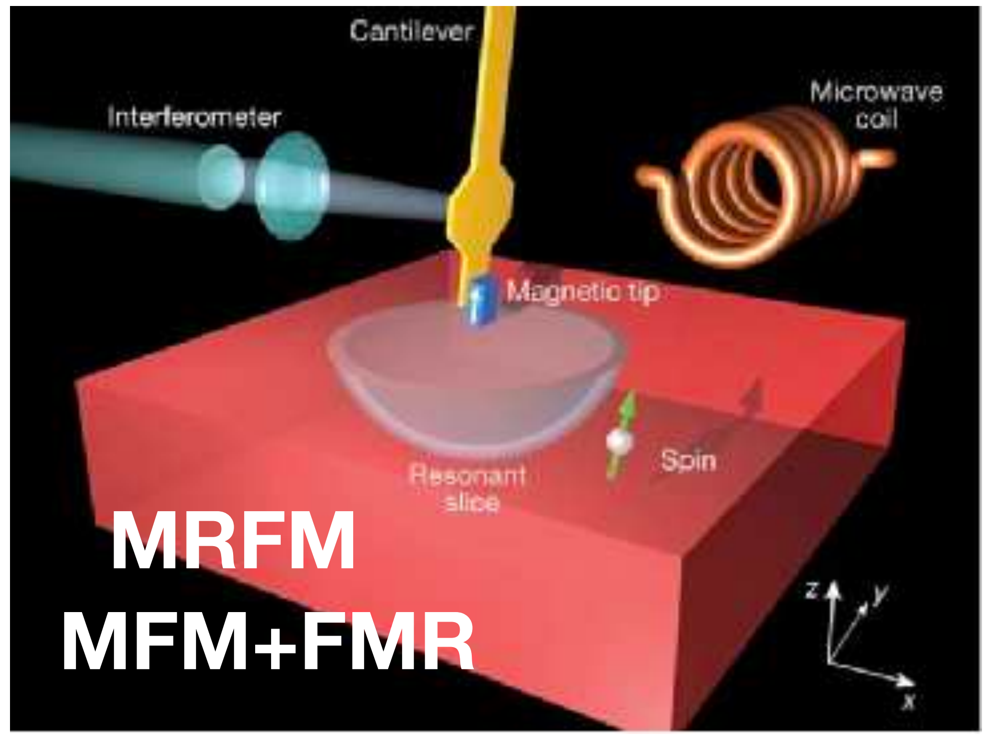
*Figure from A. Petrovic*




**Proposal of a scanning probe with a tuning fork**

A. Petrović, et al., arXiv:2410.11427v1 (2024)

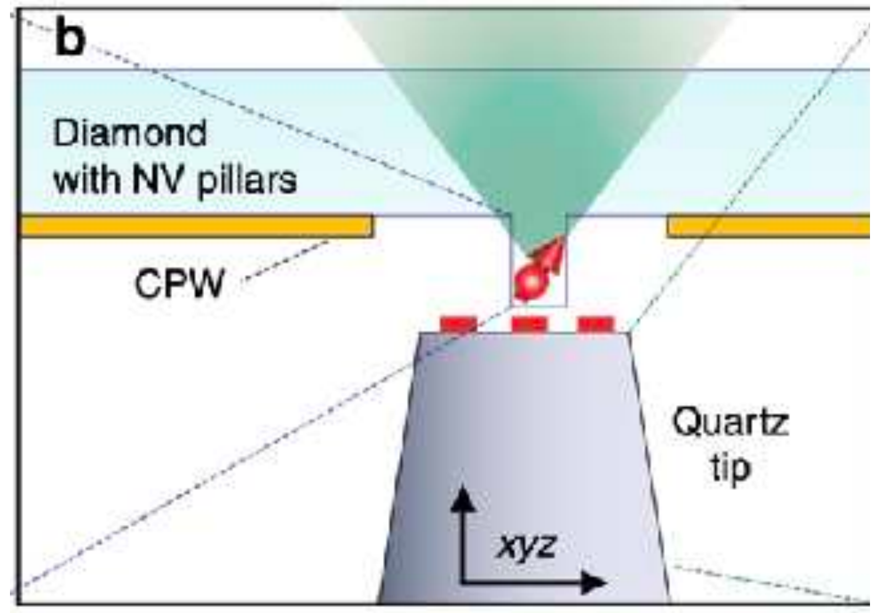
## Magnetic force microscopy




E. Arima, et al., Nanotechnology **26**, 125701 (2015)

D. Rugar, et aal., Nature **430**, 329 (2004).

## NV magnetometry

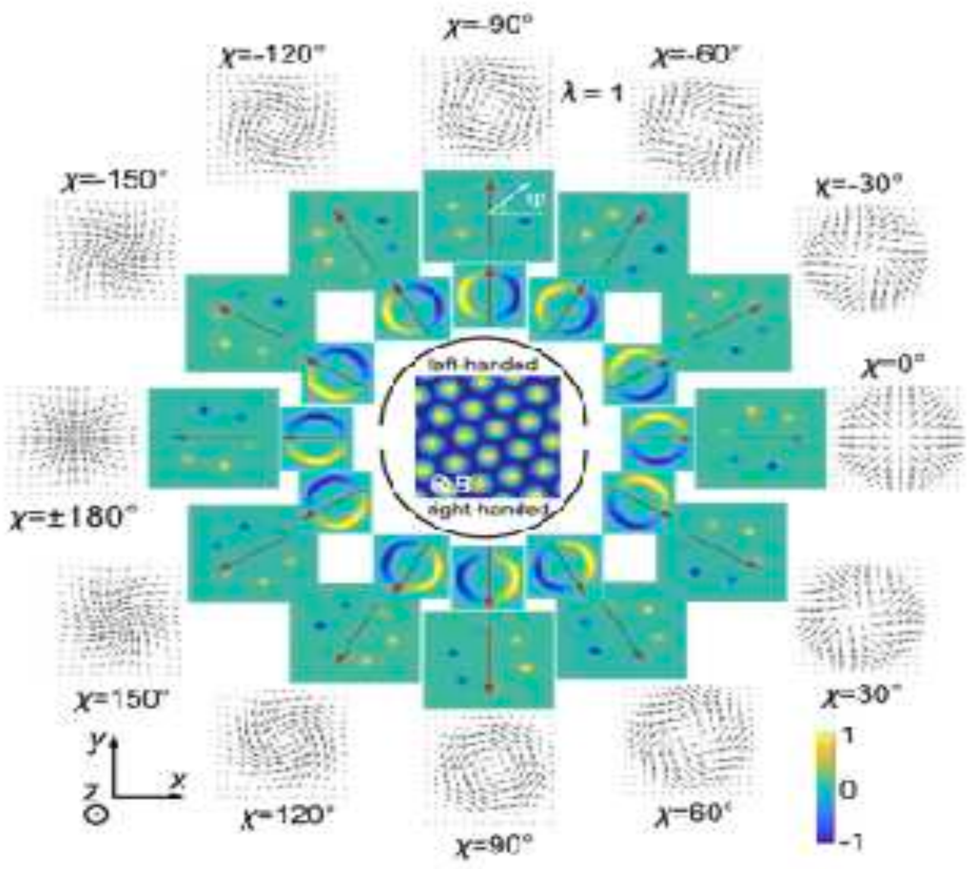



Y. Dovzhenko, et al., *Nature Comm*. 9, 2712 (2018)

# Skyrmion Qubit Readout



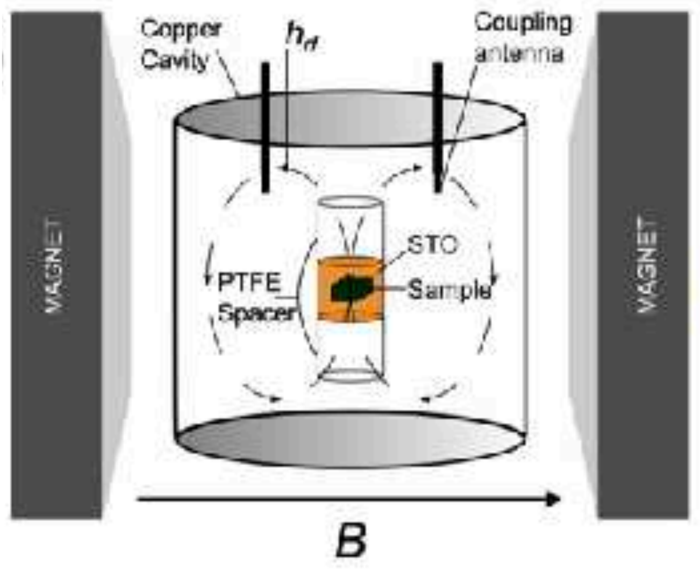
## CD- Resonant elastic X-ray

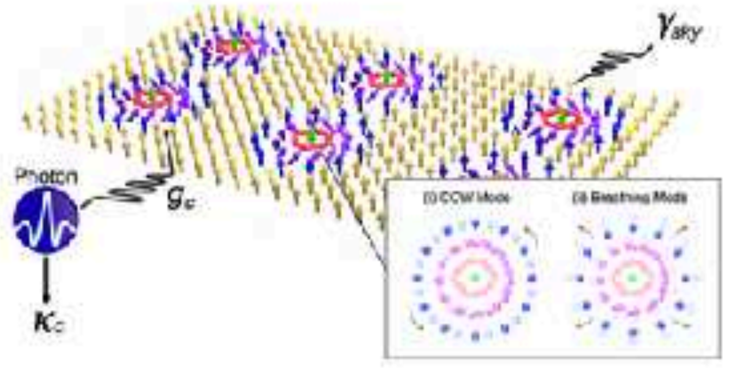


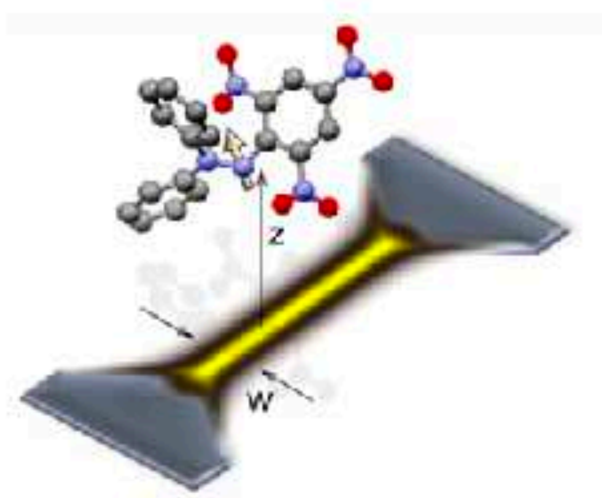
S. L. Zhang, et al., *Phys. Rev. Lett*. 120, 227202 (2018).

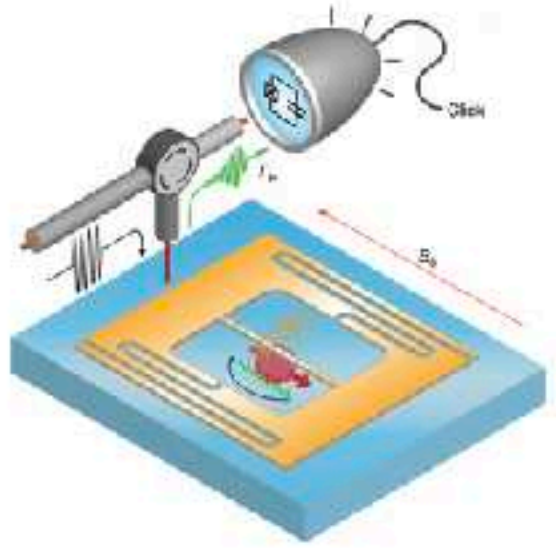
**REXS+ FMR**: S. Pöllath, et al., *Phys. Rev. Lett*. 123, 167201 (2019).

## Microwave Resonators





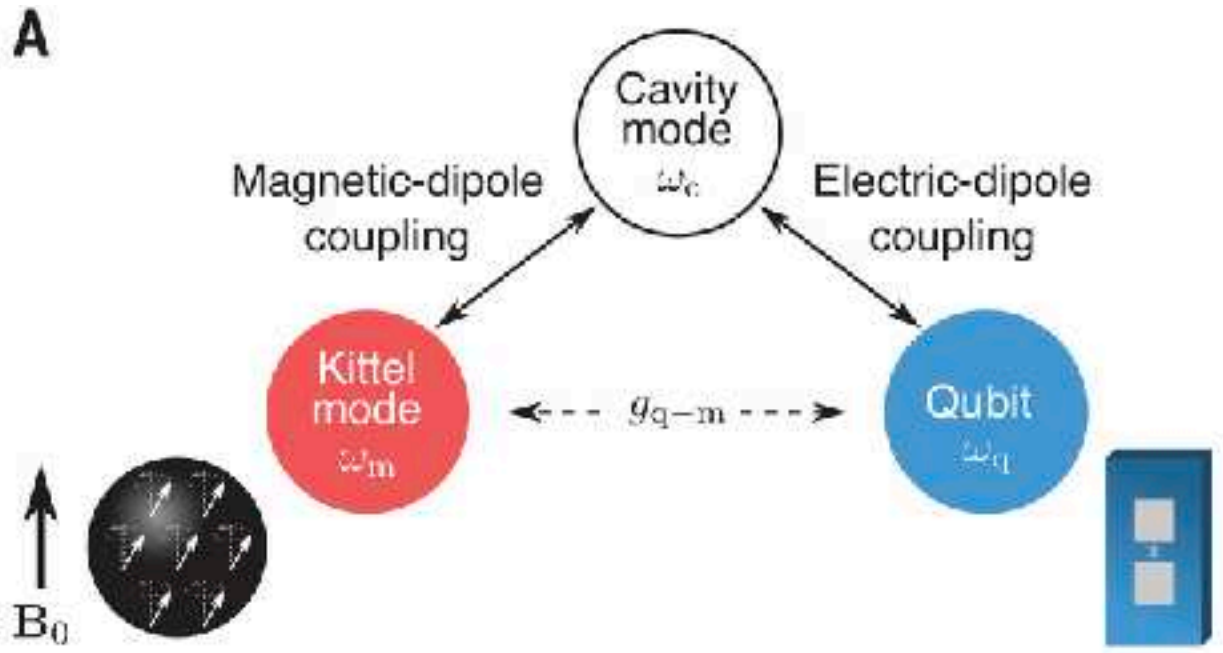


S. Khan, et al., *Phys. Rev. B* **104**, L100402 (2021)

I. Gimeno, et al., ACS Nano, **14**, 8707 (2020)

Z. Wang, et al., Nature **619**, 276 (2023)

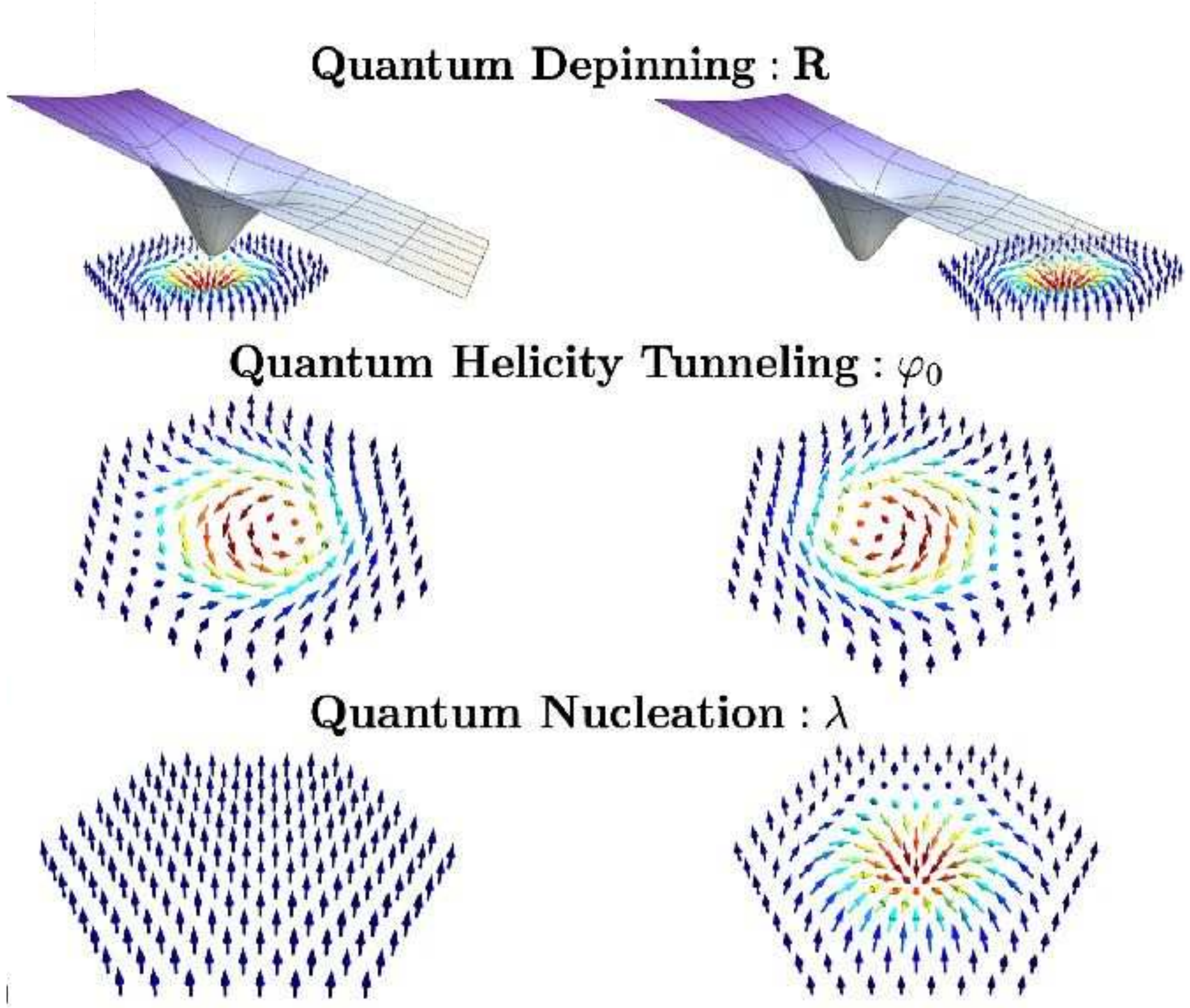
## Hybrid Systems

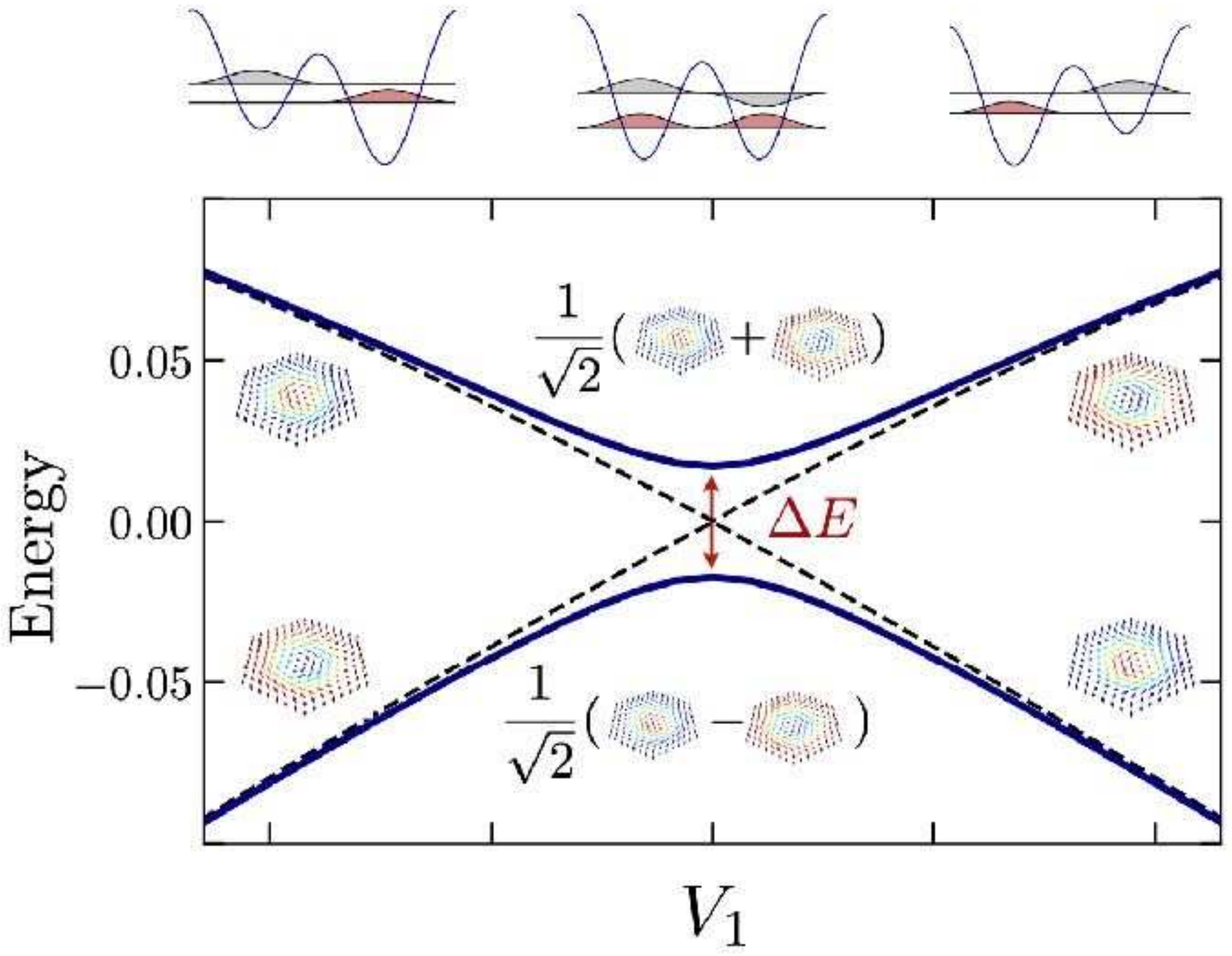


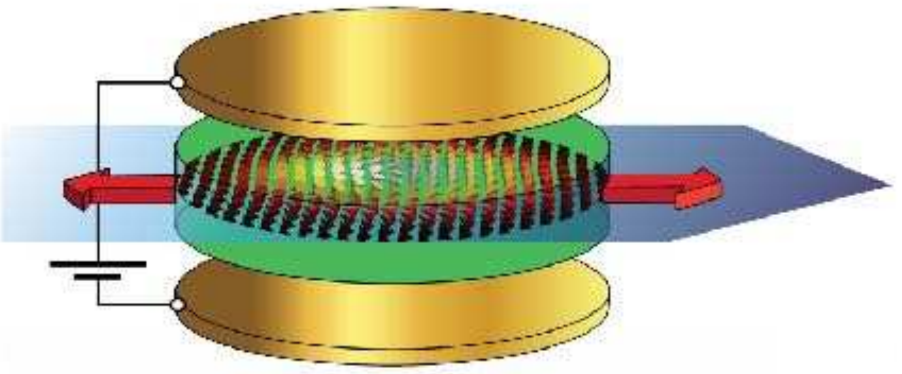

D. Lachance-Quirion, et al., *Science* 367, 425 (2020).

# Discussion





C. Psaroudaki, and C. Panagopoulos.,
***Skyrmion Qubits: Challenges For Future Quantum Computing Applications***, Appl. Phys. Lett. **123**, 260501 (2023)

A Petrovic, C. Psaroudaki, P. Fischer, M. Garst, and C. Panagopoulos,
***Colloquium: Quantum Properties and Functionalities of Magnetic Skyrmions*** arXiv:2410.11427v1 (2024)

anr agence nationale de la recherche AU SERVICE DE LA SCIENCE
Chair of Quantum Information
MITSUBISHI HEAVY INDUSTRIES FRANCE S.A.S.