Topological effects in nanomagnetism: from perpendicular recording to monopoles

Hans-Benjamin Braun

UCD Dublin

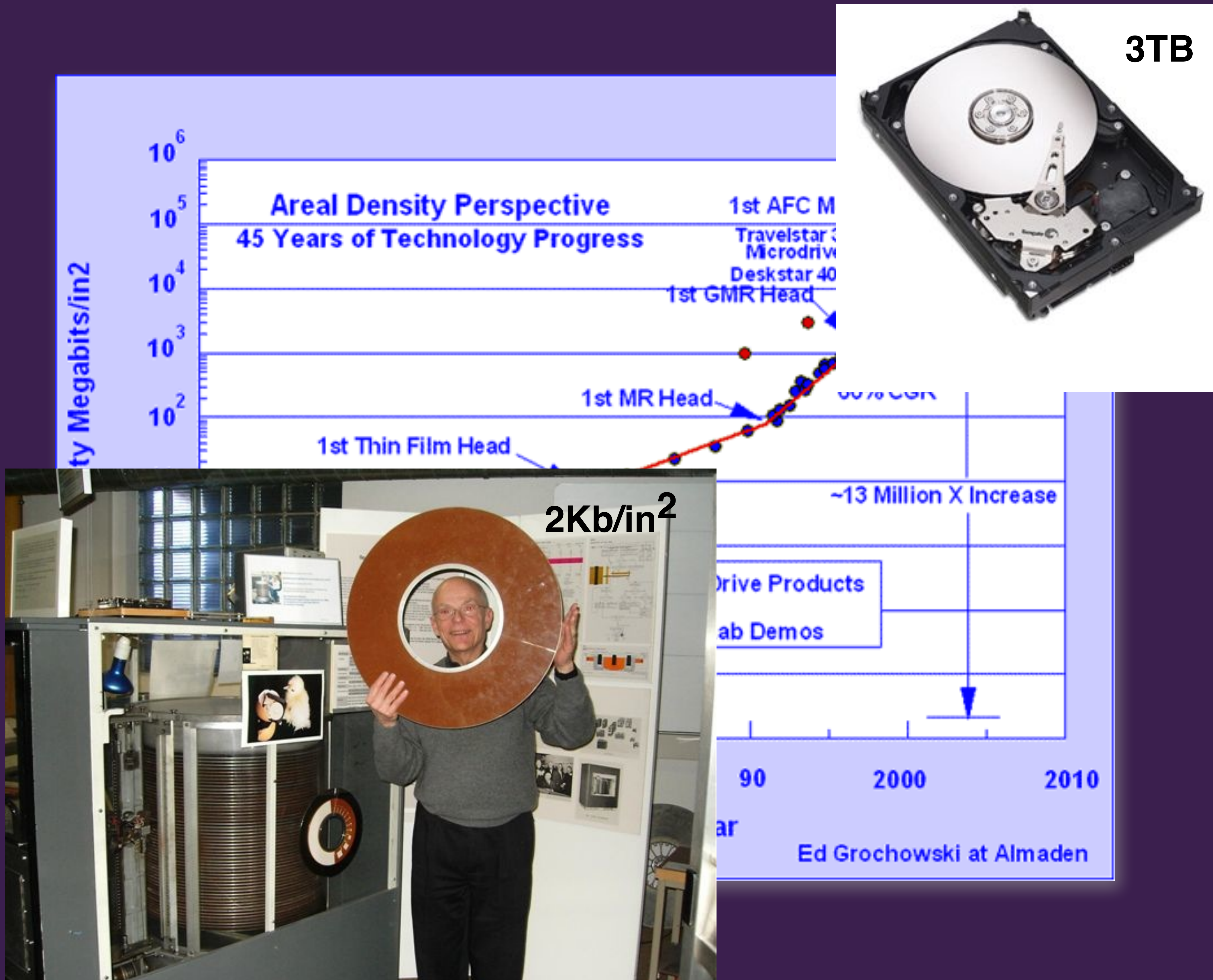
ETH zürich
PAULI CENTER
for Theoretical Studies

sfi Science Foundation Ireland

IEEE MAGNETICS 50 YEARS 1964 2014

IEEE Summer School, CBPF, Rio de Janeiro, Brazil, August 10, 2014

The past 50 years of magnetic data storage



Evolution of storage density

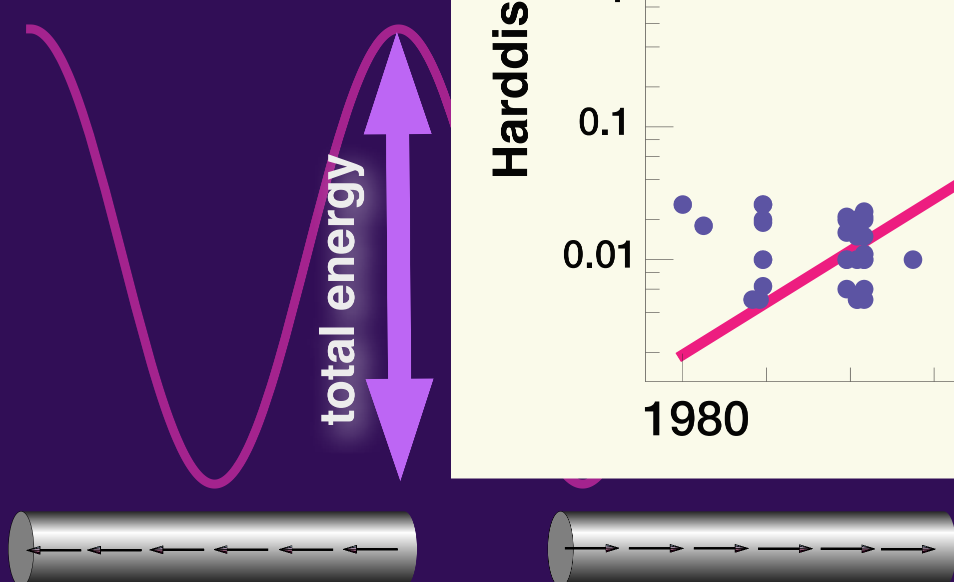
2014: 1.0 Tb/in^2 bit area (25 nm)^2

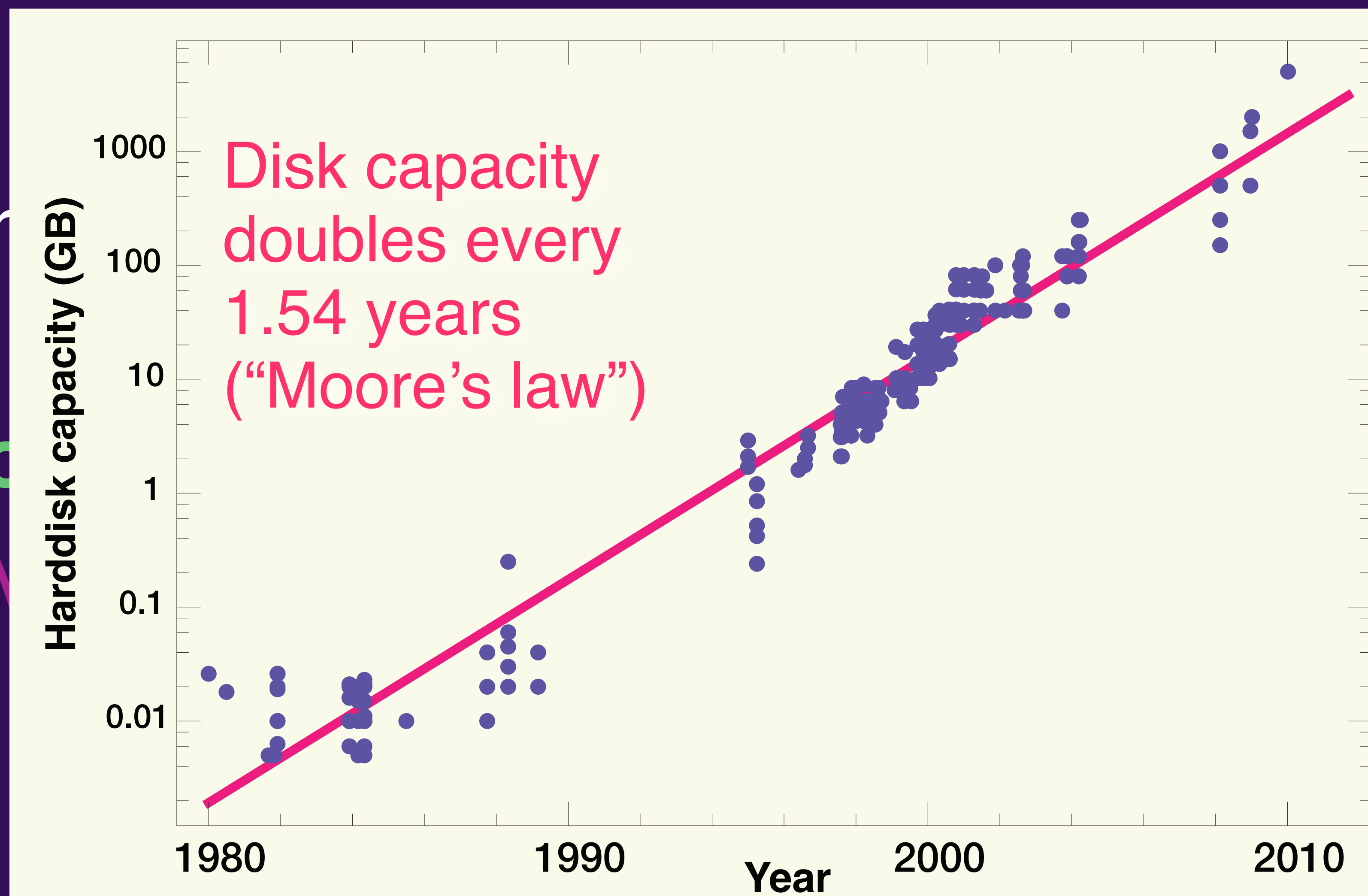
2025: 0.15 Pb/in^2 bit area (2 nm)^2 !!!

Avoid super

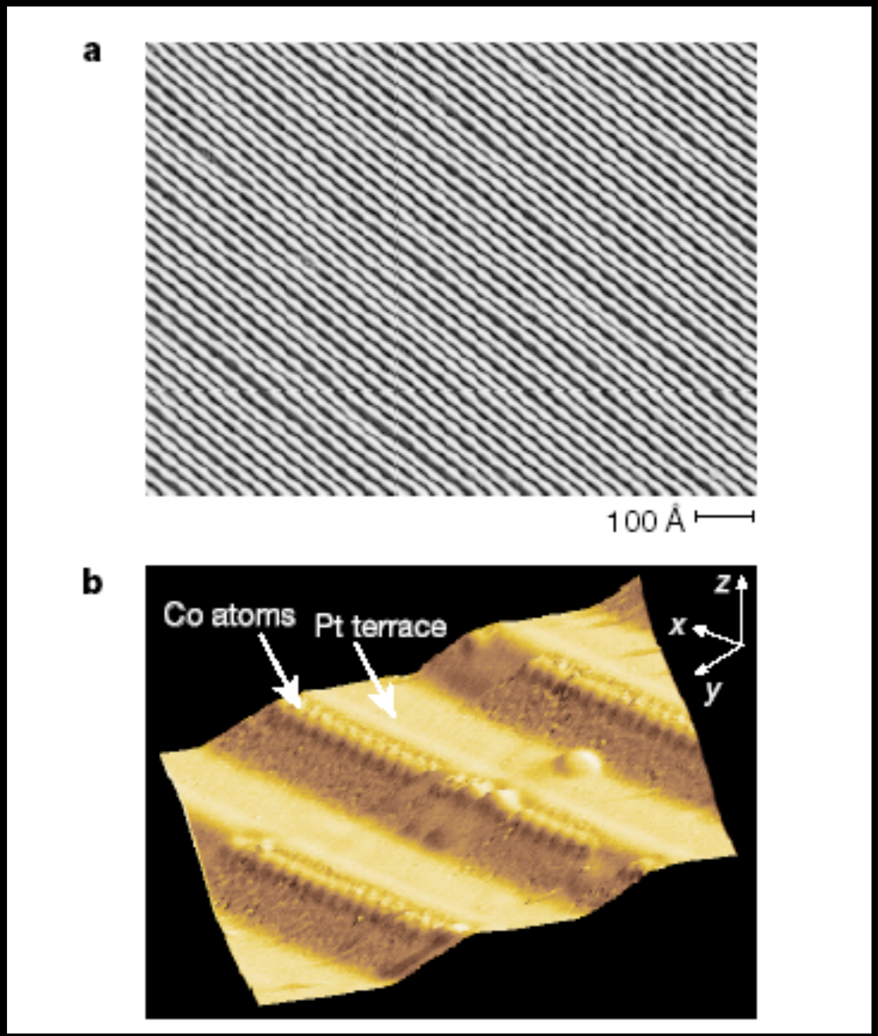
const. =

anisotro

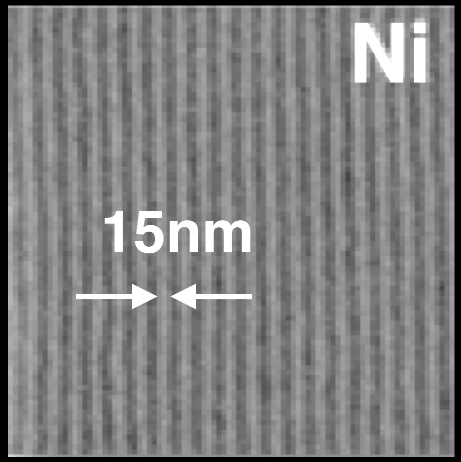




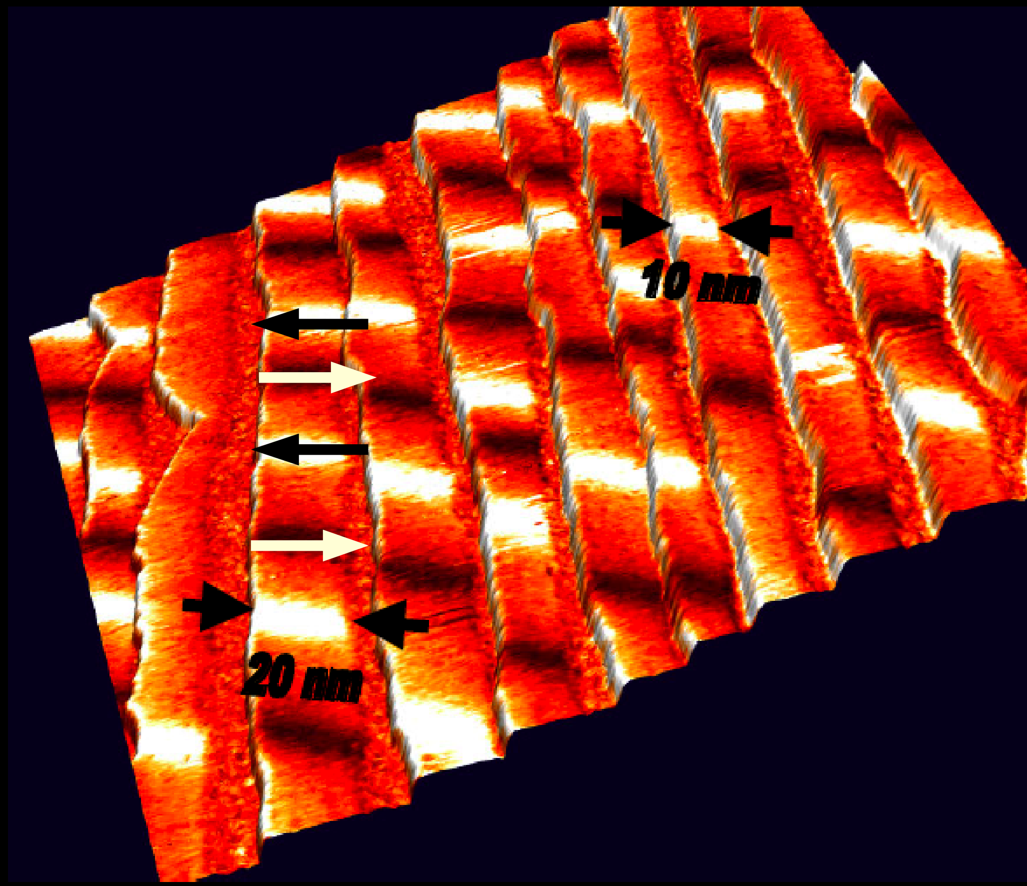
Magnetic nanostructures: quantum vs classical/thermal behaviour



P. Gambardella et al.
Nature ('02)



Y.S. Jung et al.
Nano Lett. ('10)



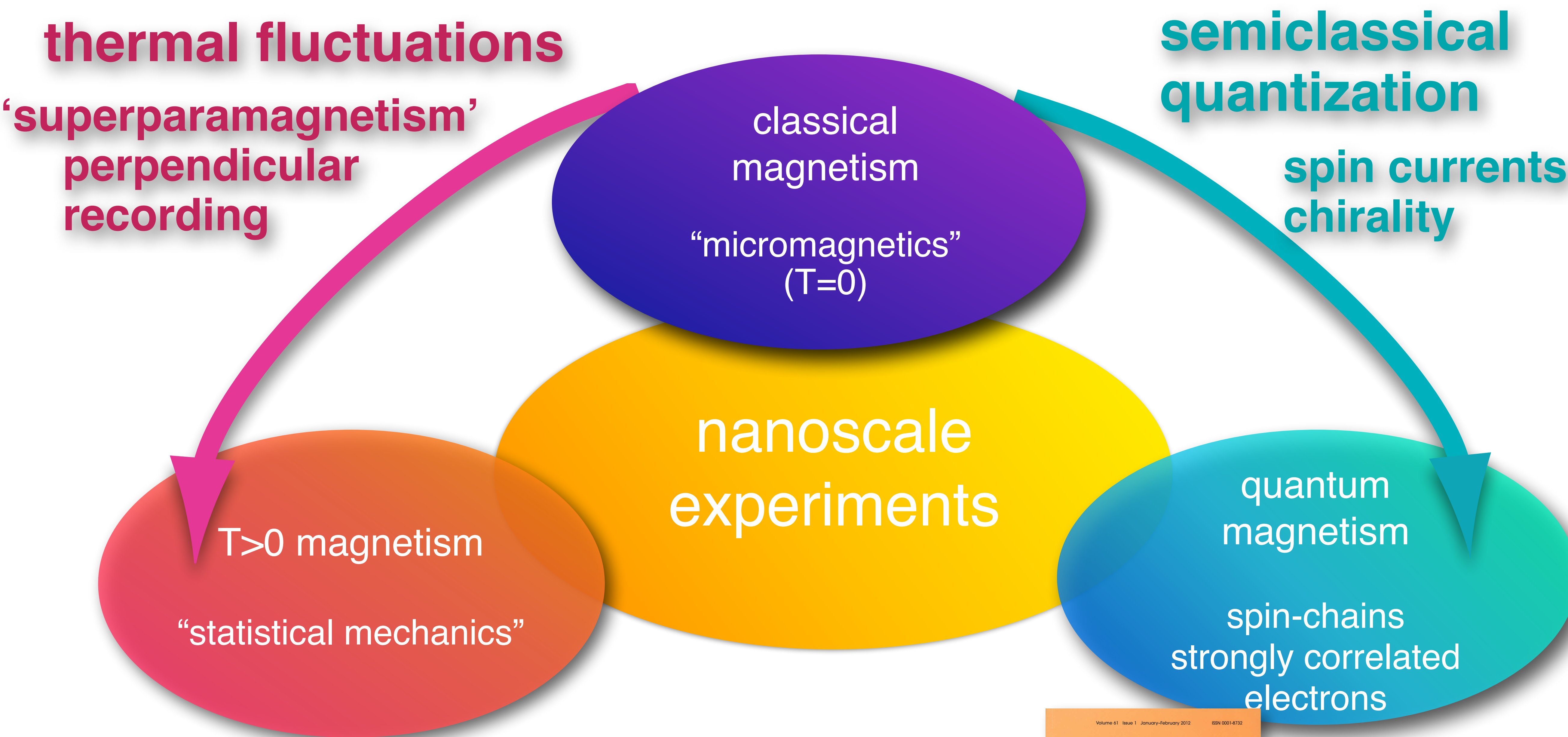
Kubetzka et al.
PRB ('03)

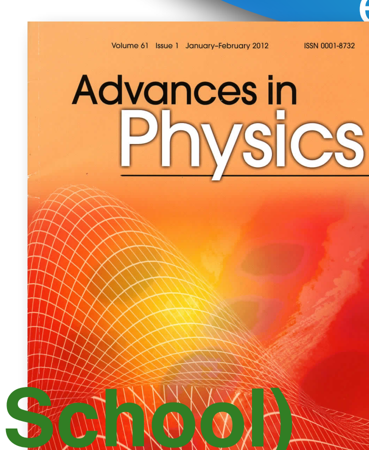
quantum → ← **classical**

"…It's in this no-man's land between quantum and classical physics that a wide array of "emergent" phenomena reveal themselves…"

R.F. Service, Science ('12)

Theoretical descriptions of magnetism





Topological concepts as unifying principle

HBB, Adv. Phys. **61**, 1-116 (2012)

cf. O. Fruchart's & D. Bürgler's lecture (this School)

Overview

I. Topological defects in magnetism (domain walls, vortices, skyrmions, merons, hedgehogs)

II. Superparamagnetism and limits of magnetic data storage

III. Quantization of micromagnetics: emergent chirality and spin currents in quantum spin chains

IV. Dipolar interactions in nanomagnetic arrays - emergent Dirac monopoles and Dirac strings

Why Topology?

- Within the framework of ‘micromagnetics’, one considers a continuous magnetization field $\mathbf{M}(\mathbf{x},t)$

- Magnetic data storage: Are there magnetization configurations that are particularly stable?

- May two magnetization configurations be easily transformed into each other (bit stability)?

What is homotopy about?

$\sim$

$\nsim$

homotopically equivalent

homotopically inequivalent

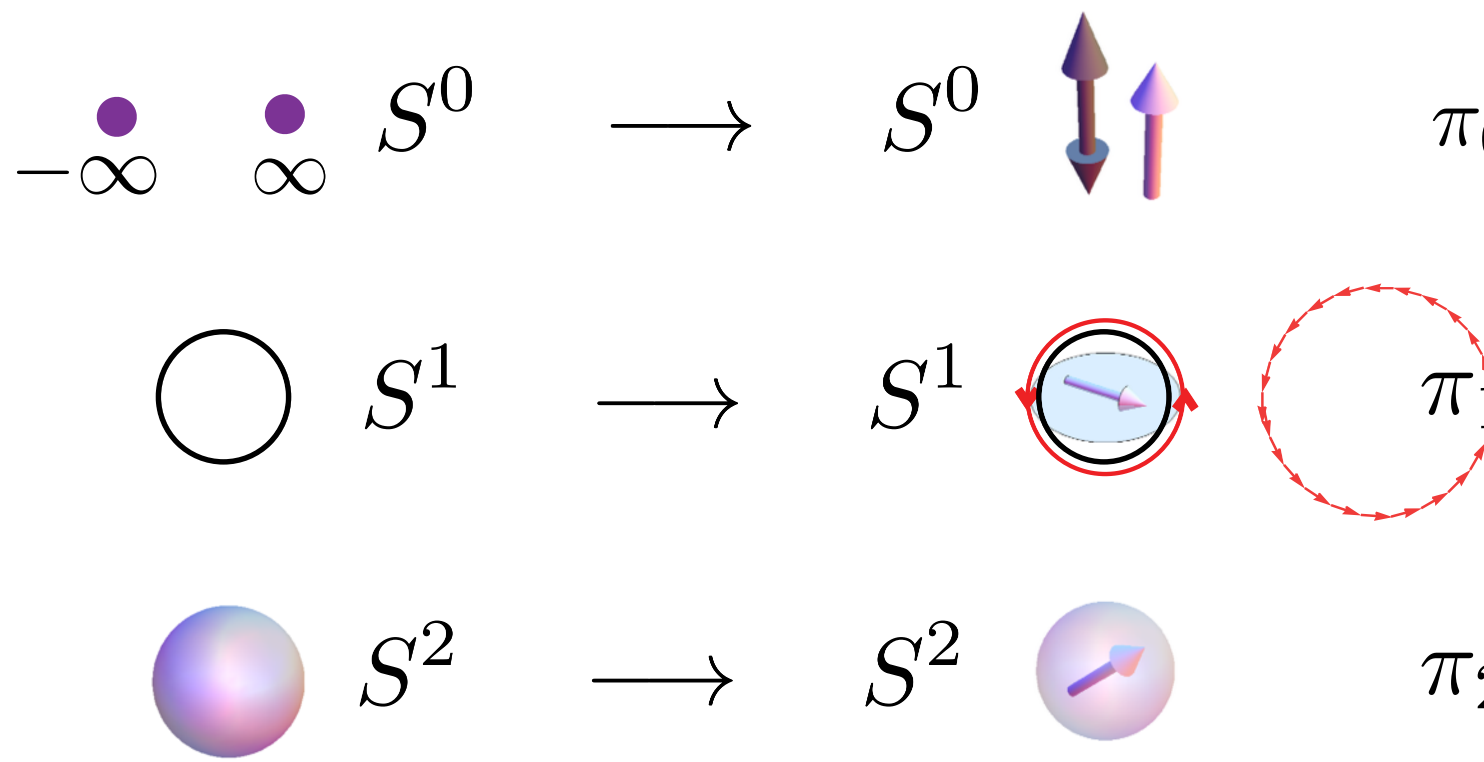
ὁμός	same
τόπος	place

source: Wikipedia

Topology - nontrivial mappings

real space   spin space

mapping:



$\pi_0(S^0) = \mathbb{Z}_2$

$\pi_1(S^1) = \mathbb{Z}$

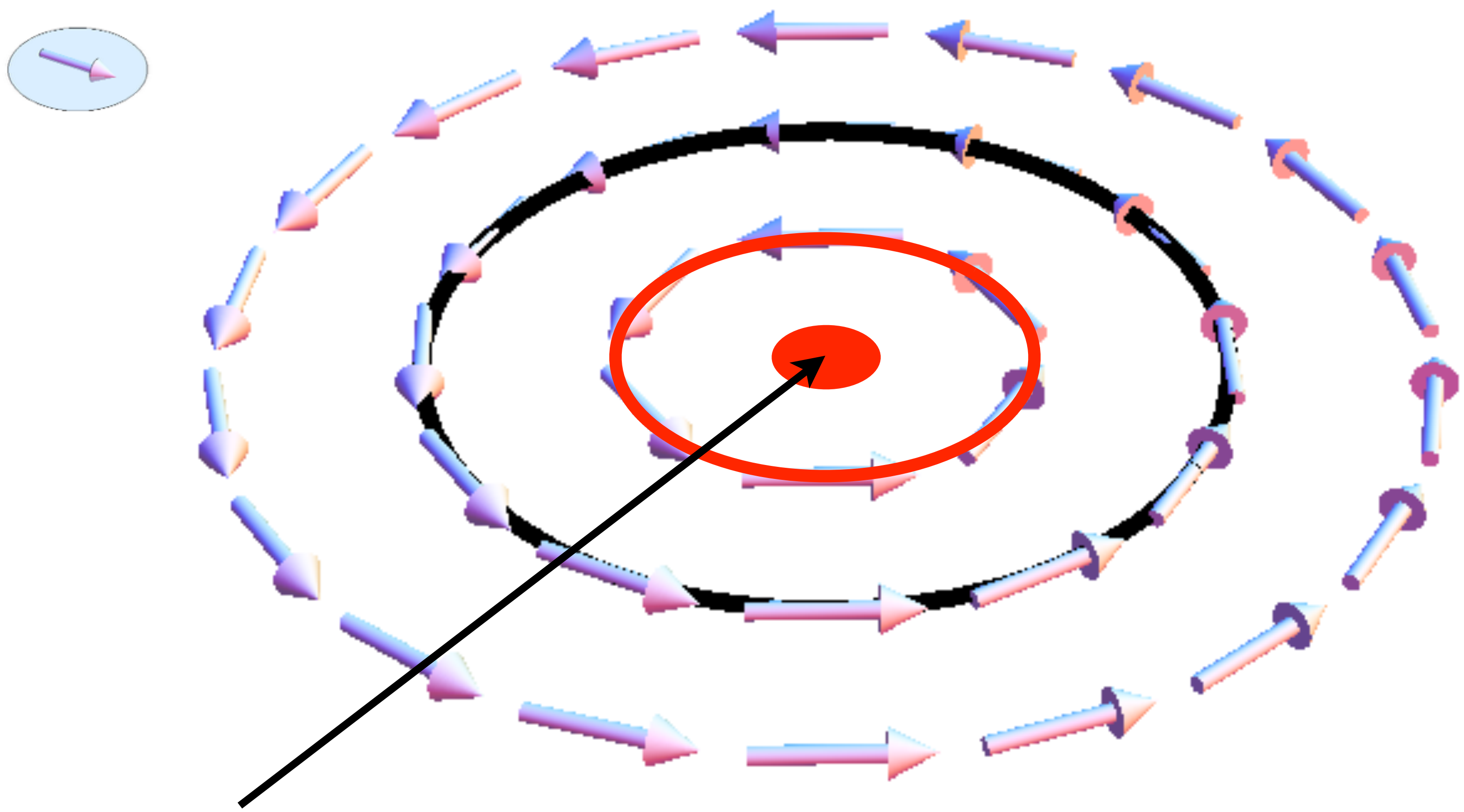
$\pi_2(S^2) = \mathbb{Z}$

Topologically nontrivial mappings exist between spheres of equal dimension

Winding numbers are `fingerprints' of equivalence classes of configurations which are deformable into each other

Topological singular point defects

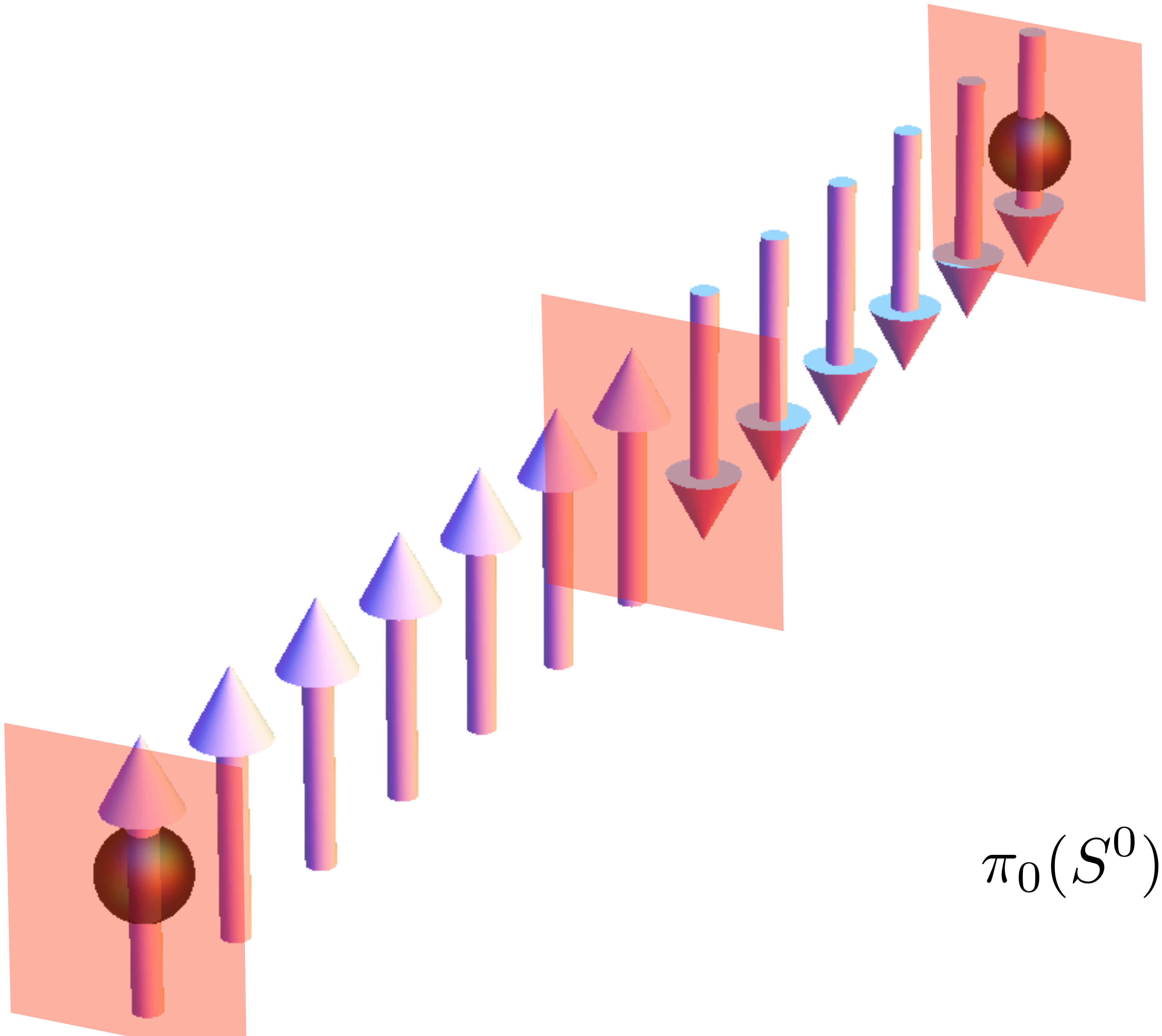
(vs. soliton type topological defects)



singular point defect

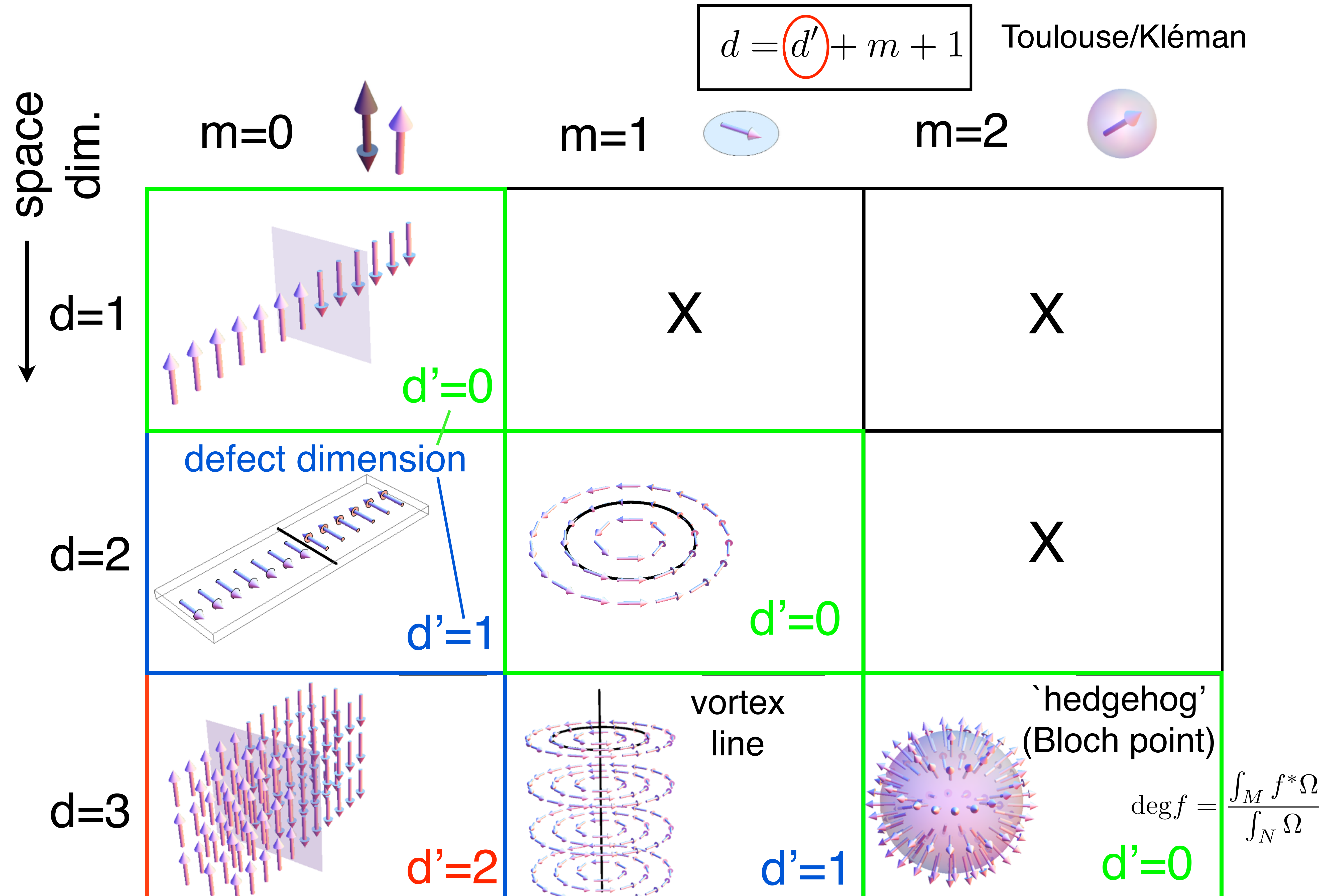
$$\pi_1(S^1) = \mathbb{Z}$$

Topological point defect - domain wall

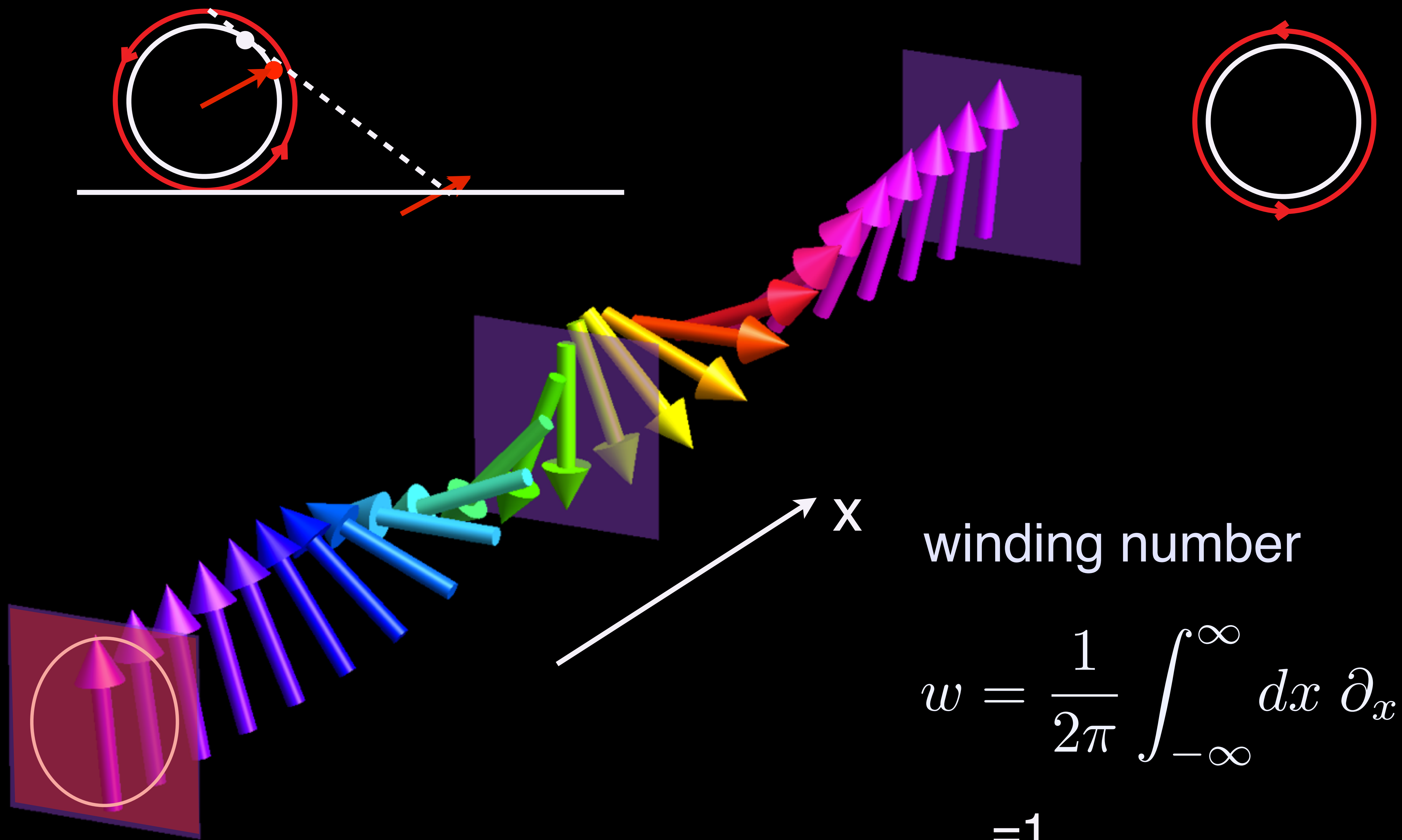


$$\pi_0(S^0) = \mathbb{Z}_2$$

'Zoology' of singular topological defects



Smooth solitary defect in 1D: 2 π domain wall

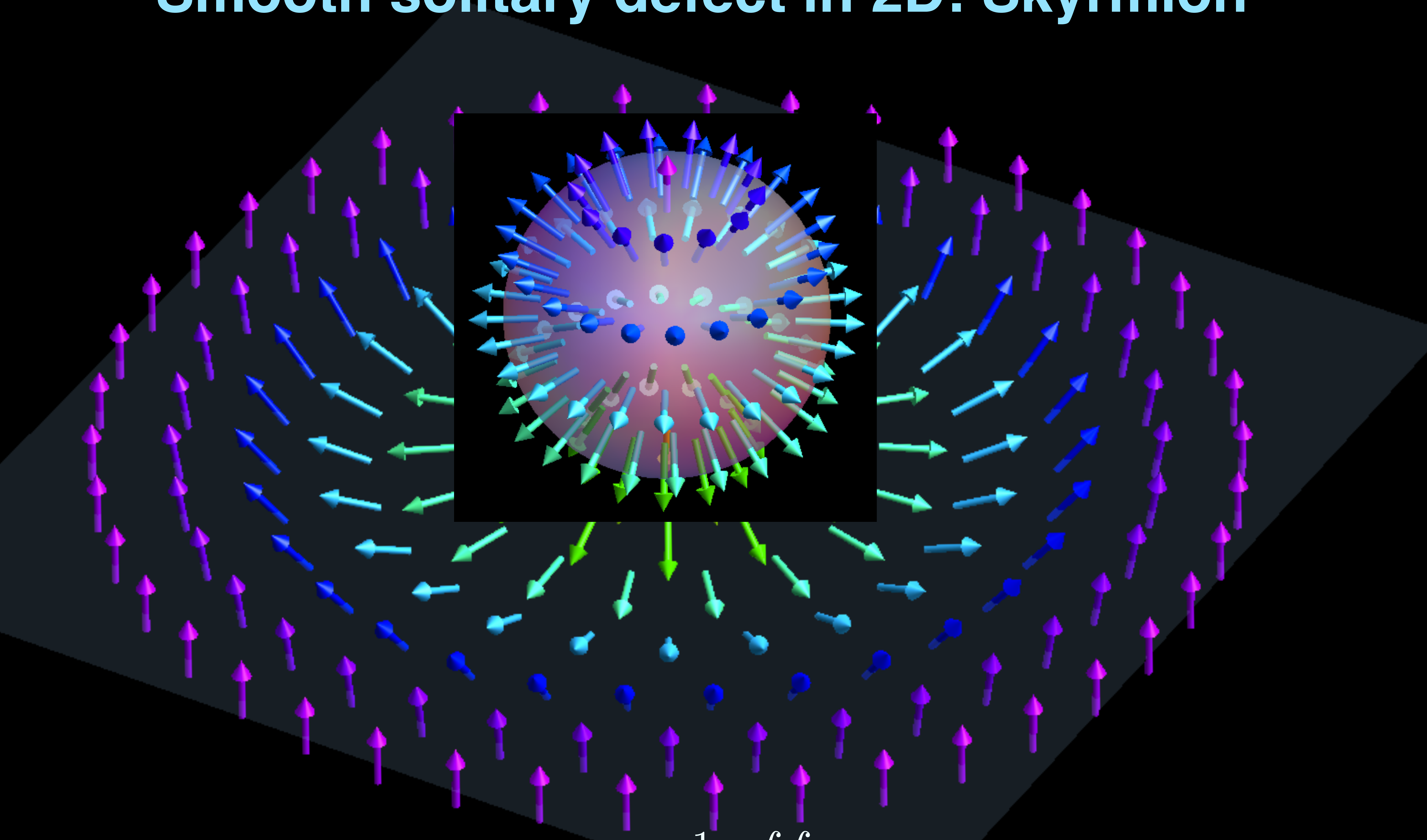


winding number

$$w = \frac{1}{2\pi}\int_{-\infty}^{\infty} dx\, \partial_x \phi$$

=1

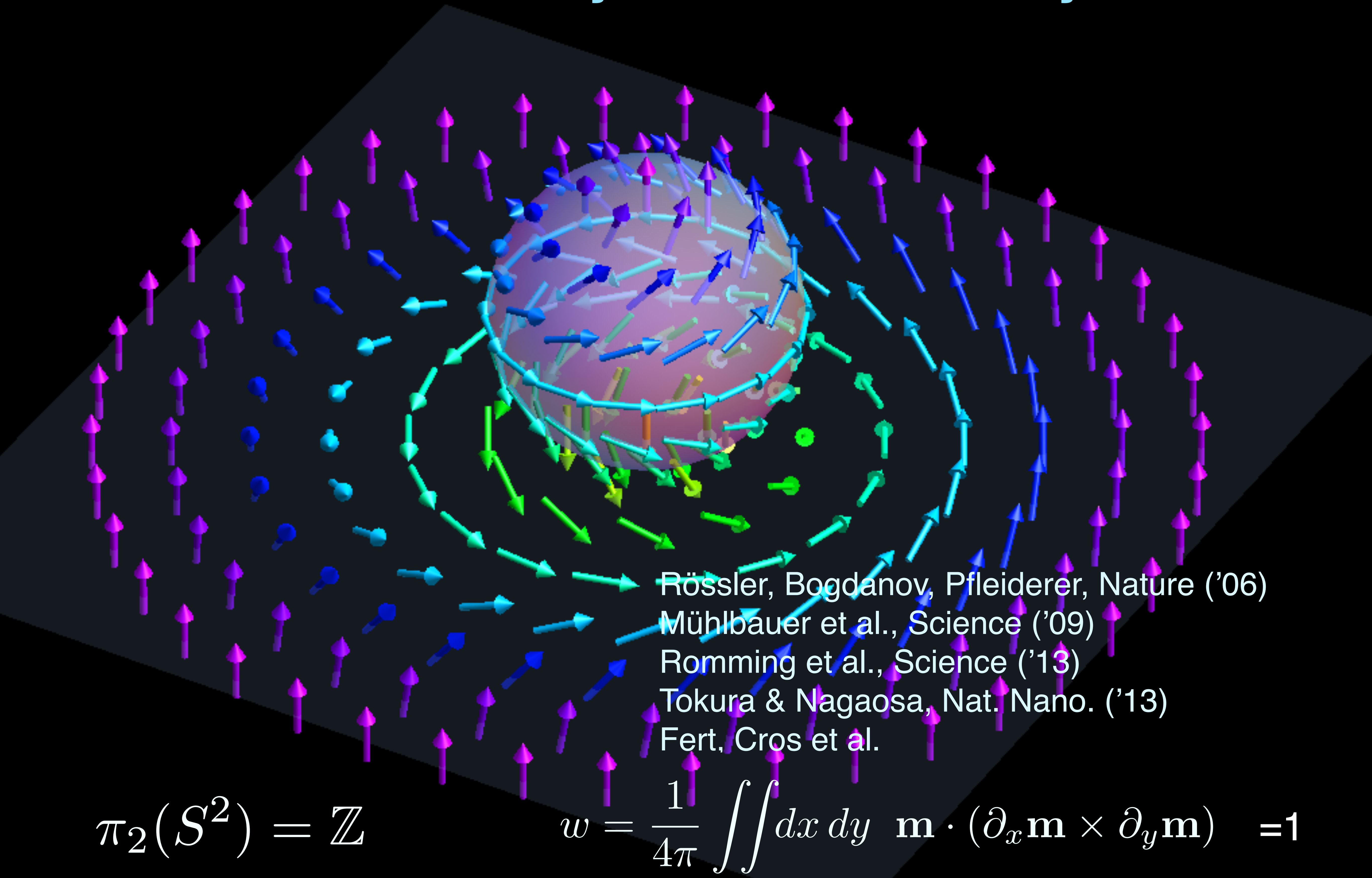
Smooth solitary defect in 2D: Skyrmion



$$\pi_2(S^2) = \mathbb{Z}$$

$$w = \frac{1}{4\pi}\iint dx\, dy \;\; \mathbf{m}\cdot(\partial_x \mathbf{m} \times \partial_y \mathbf{m}) \quad =1$$

Smooth solitary defect in 2D: Skyrmion

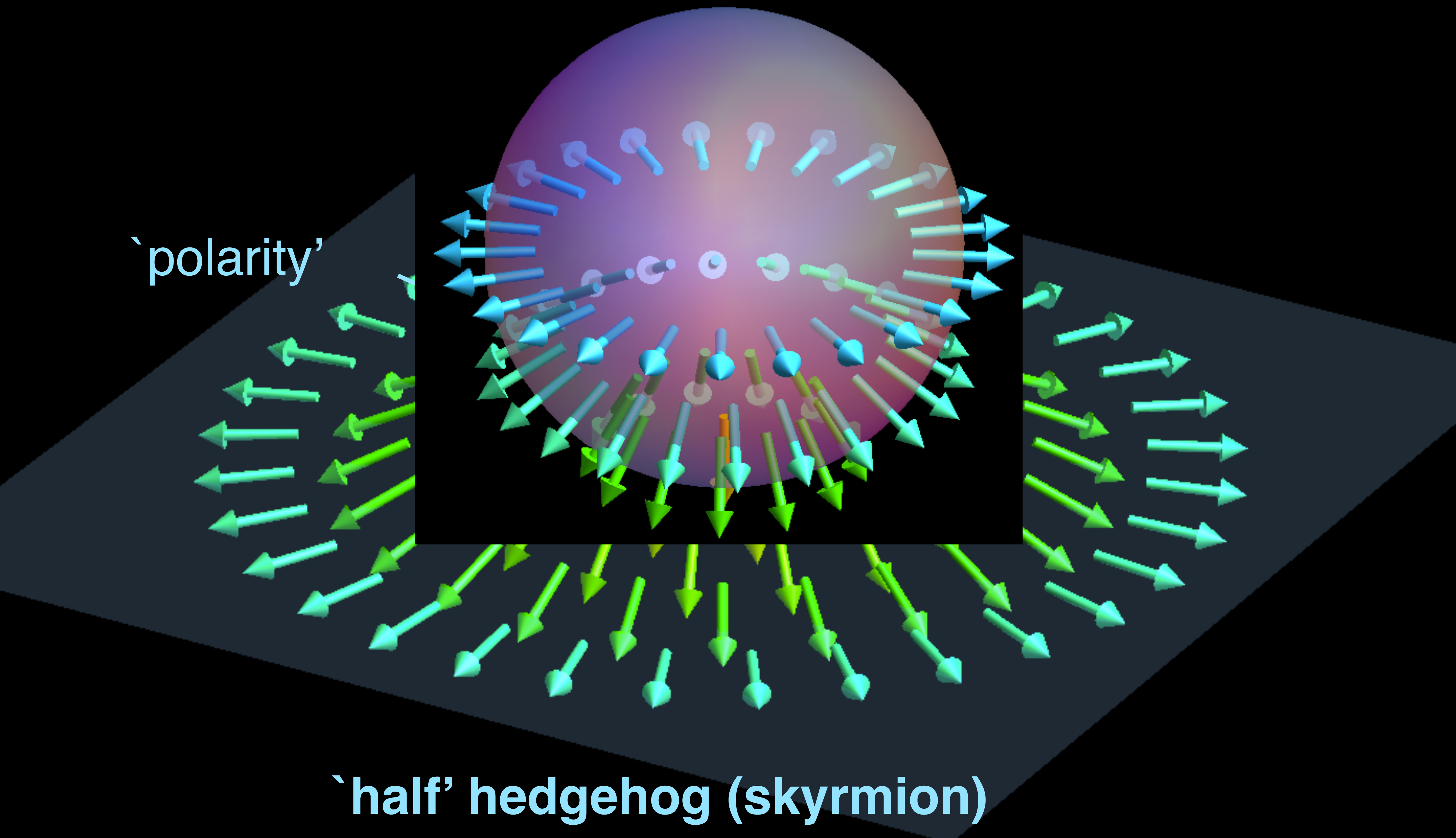


Rössler, Bogdanov, Pfleiderer, Nature ('06)
Mühlbauer et al., Science ('09)
Romming et al., Science ('13)
Tokura & Nagaosa, Nat. Nano. ('13)
Fert, Cros et al.

$$\pi_2(S^2) = \mathbb{Z}$$

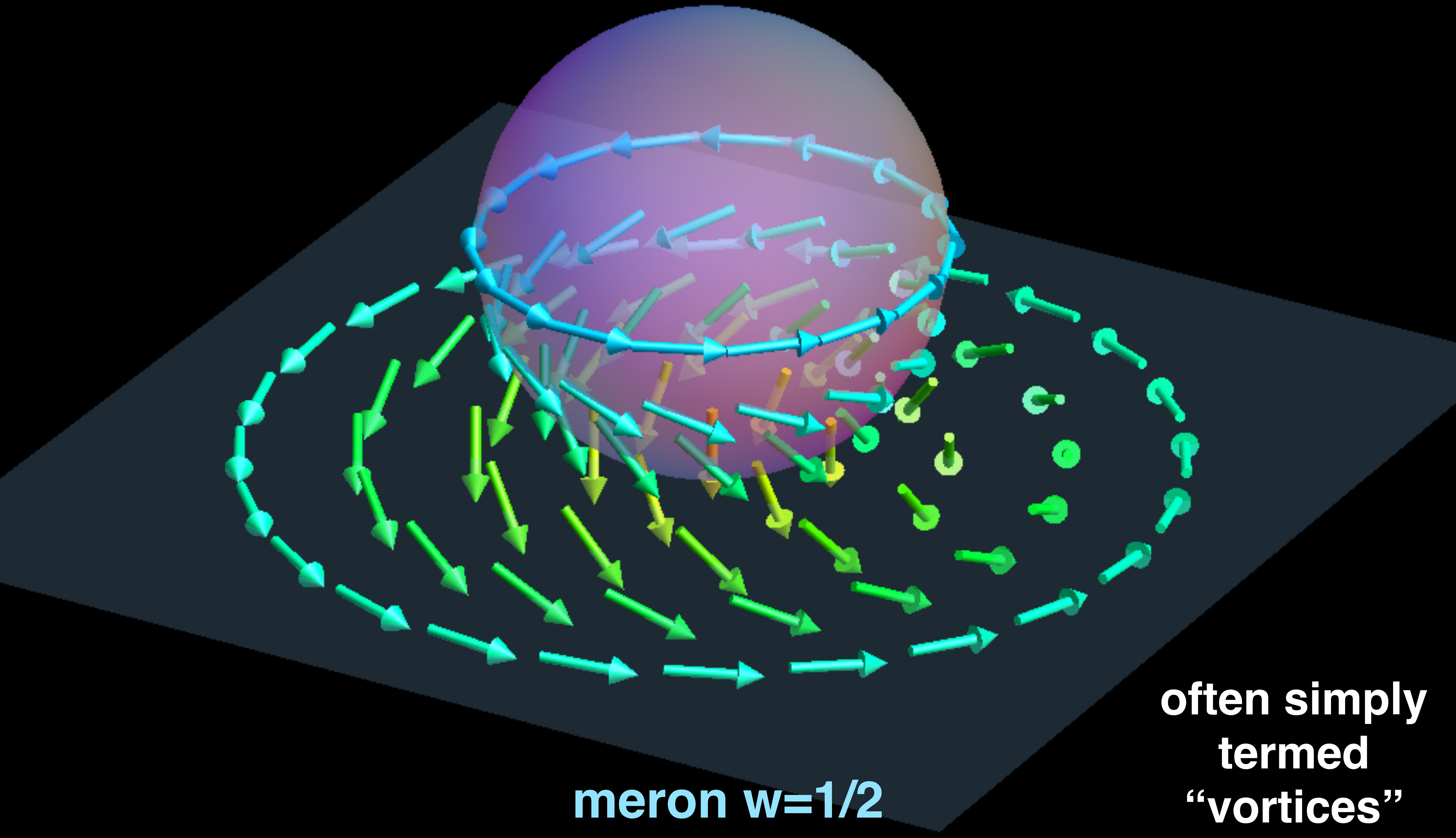
$$w = \frac{1}{4\pi} \iint dx\, dy \;\; \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m}) \quad =1$$

Meron (`vortex' with core)



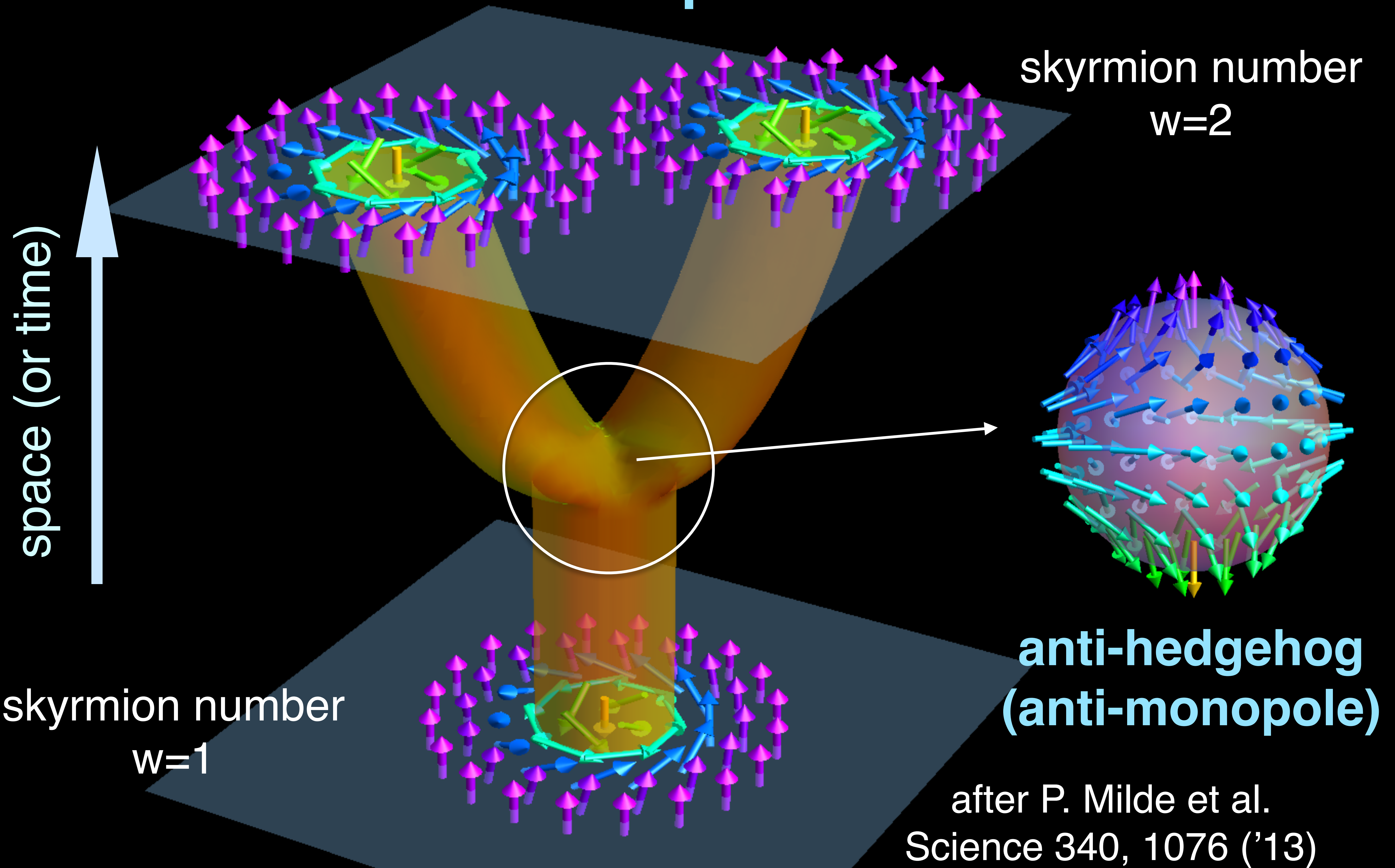
`half' hedgehog (skyrmion)

Meron (`vortex' with core)



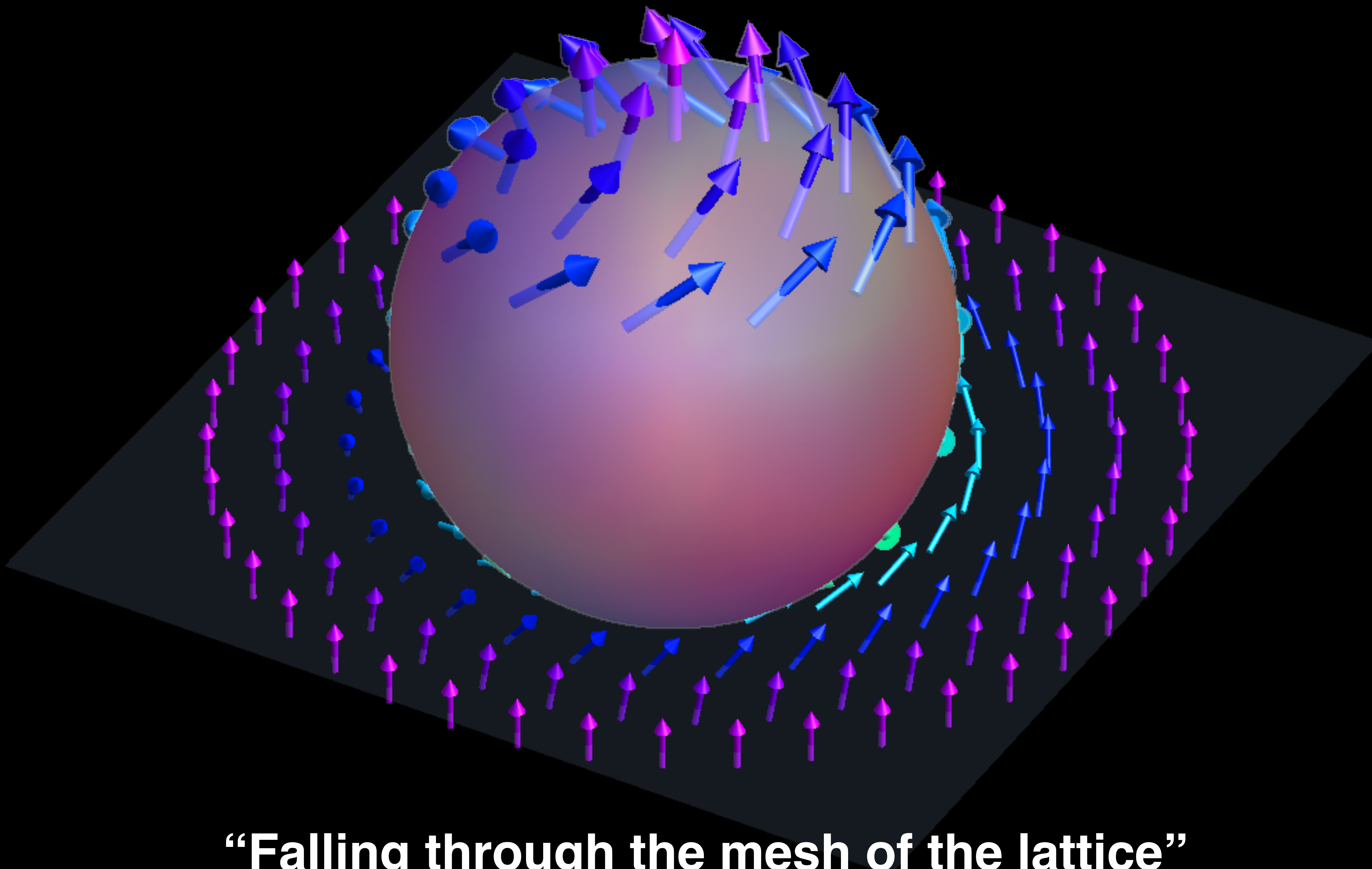
often simply termed "vortices"

Skyrmion creation via hedgehog-monopoles



after P. Milde et al.
Science 340, 1076 ('13)

How to get rid of a skyrmion



"Falling through the mesh of the lattice"

Summary

Topological defects are robust (e.g.Parkin's racetrack memory)
but with the following `caveats':

Winding ('skyrmion') number may be changed:

i) via singular 'hedgehog' monopole topological point defects

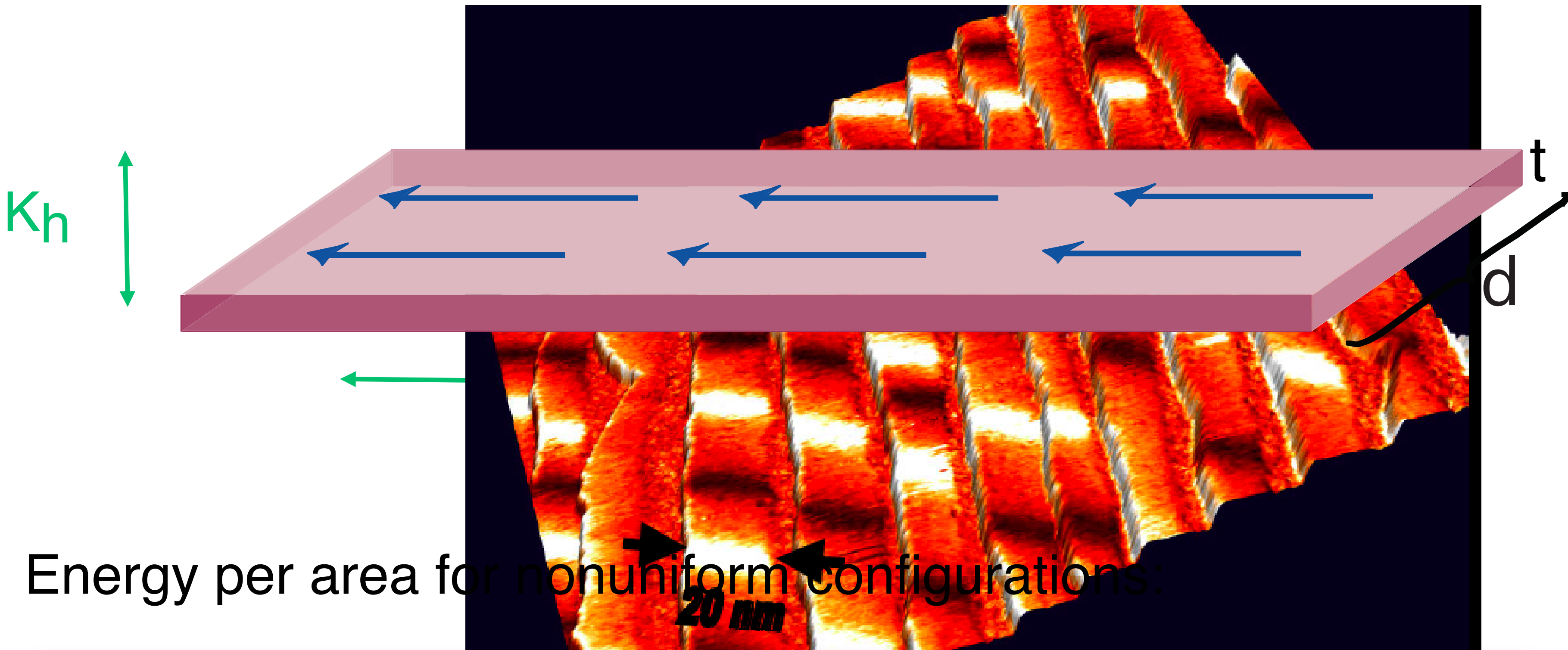
ii) via lattice effects (numerical work, e.g. Hertel et al., Sheka et al., Thiaville et al.)

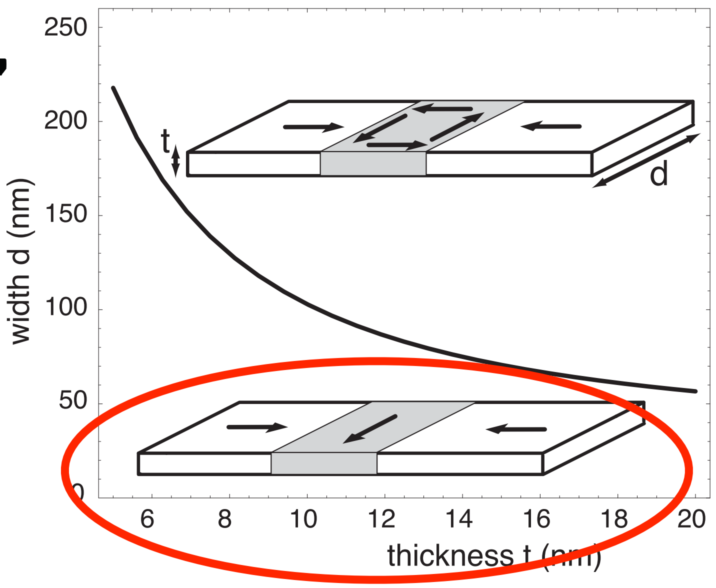
iii) at sample boundaries

Can quantum fluctuations restore smoothness of magnetisation field (cf. part III)?

From topology back to nanomagnets

quasi 1D nanowires





Energy per area for nonuniform configurations:

$$\mathcal{E} = \int dx \Big\{ A(\partial_x \mathbf{m})^2 - K_e m_x^2 + K_h m_z^2 - H M_0 m_x \Big\}$$

$$\mathbf{m}(x) = \mathbf{M}(x)/M_0$$

$$|\mathbf{m}| = 1$$

K_e , K_h **are effective anisotropy constants**

`local approximation'

(includes leading order demag effects)

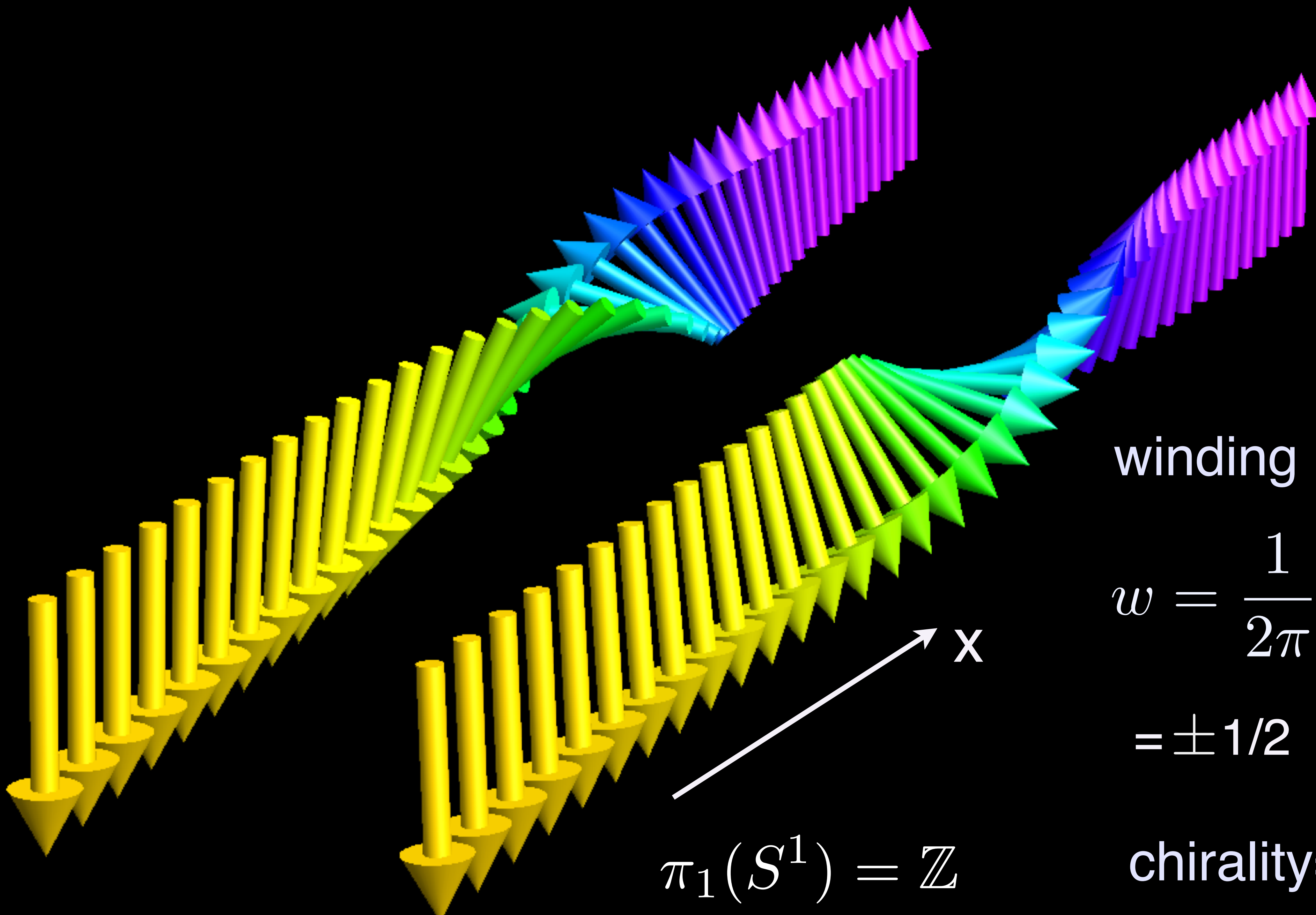
HBB, PRL ('93)

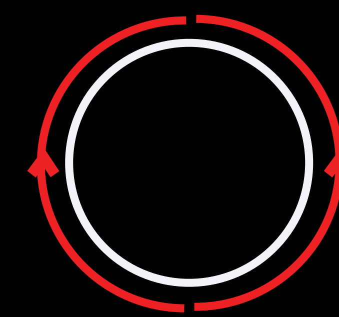
~~Aharoni JAP ('96);~~

HBB, JAP('99)

Kohn, Slastikov ('05)

Topological stability of π domain walls - chirality





winding number

$$w = \frac{1}{2\pi}\int_{-\infty}^{\infty} dx\ \partial_x \phi$$

$= \pm 1/2$

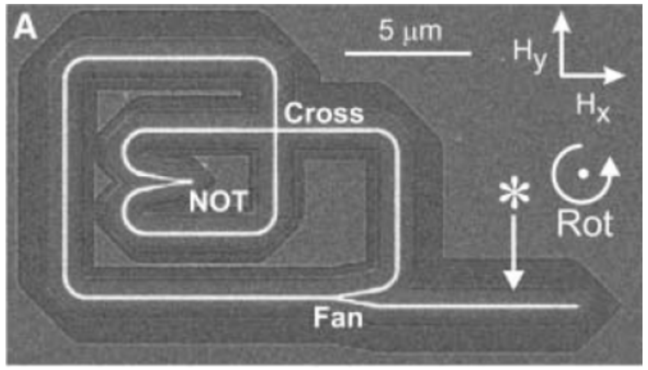
$$\pi_1(S^1) = \mathbb{Z}$$

chirality= $\pm$ 1

Storage & logic using domain walls

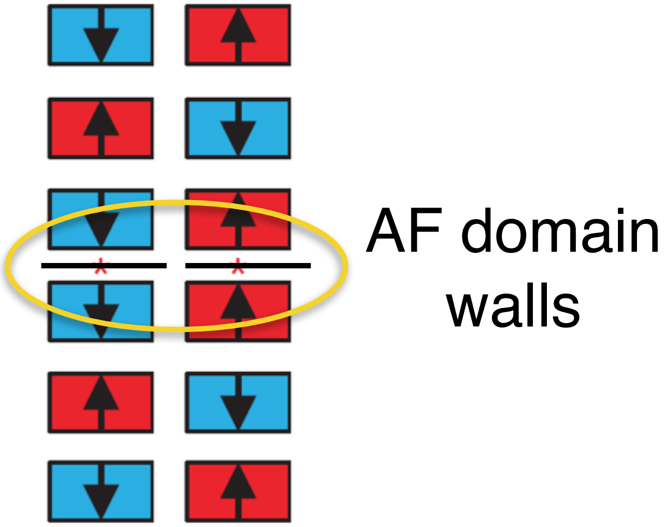
R. Cowburn

Domain wall logic



Allwood *et al.*, Science ('05)

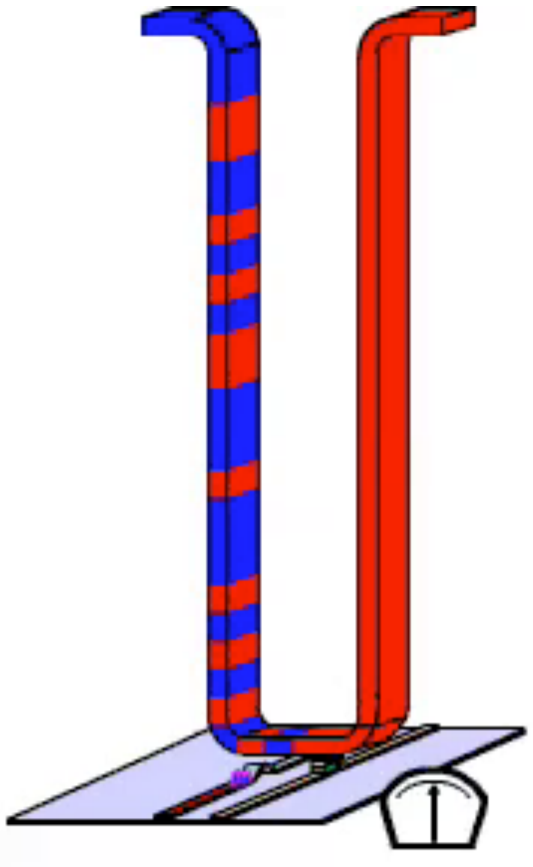
Magnetic ratchet



Lavrijsen, Cowburn *et al.*, Nature ('13)

S. Parkin

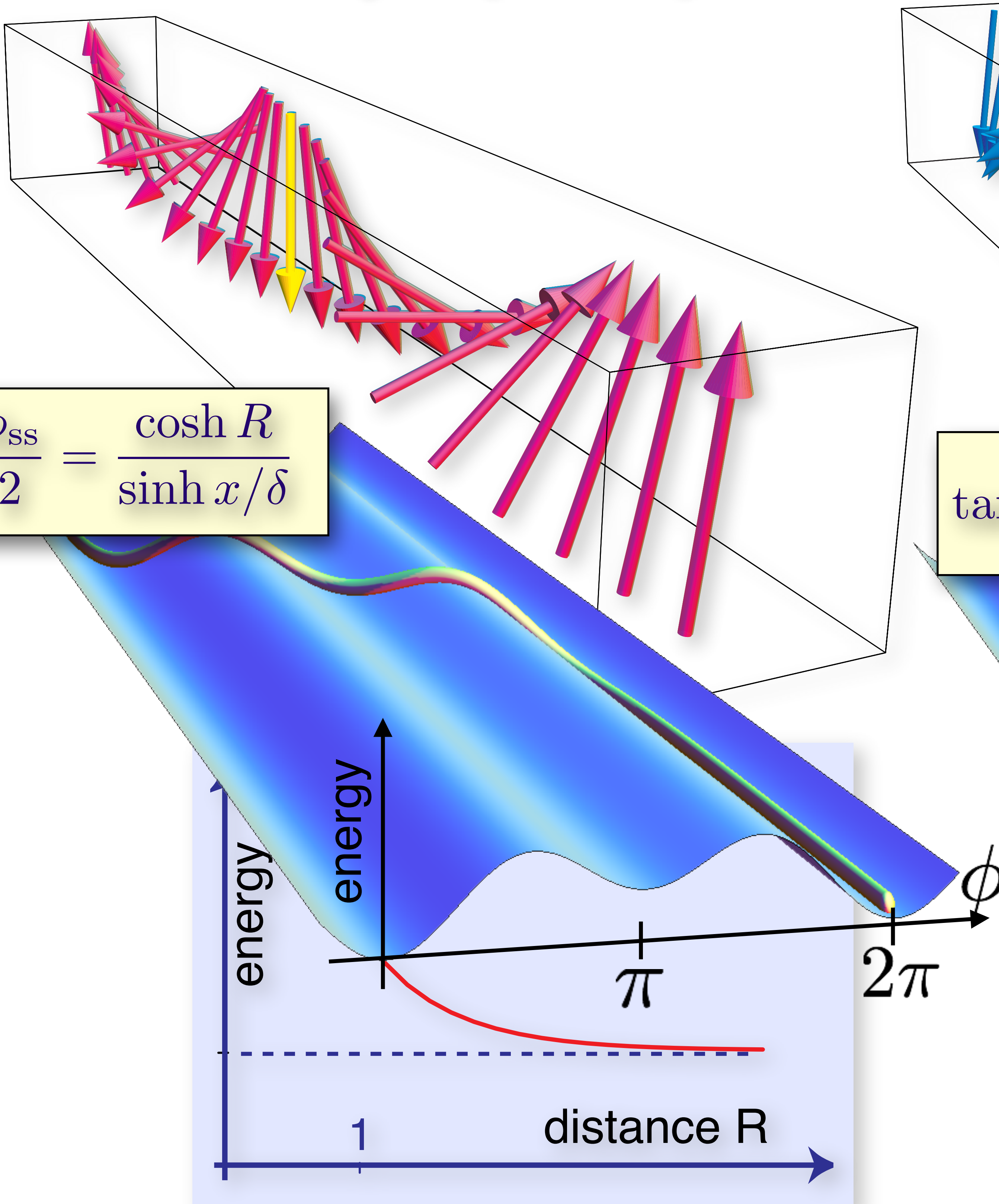
Racetrack memory



Parkin *et al.*, Science ('08)

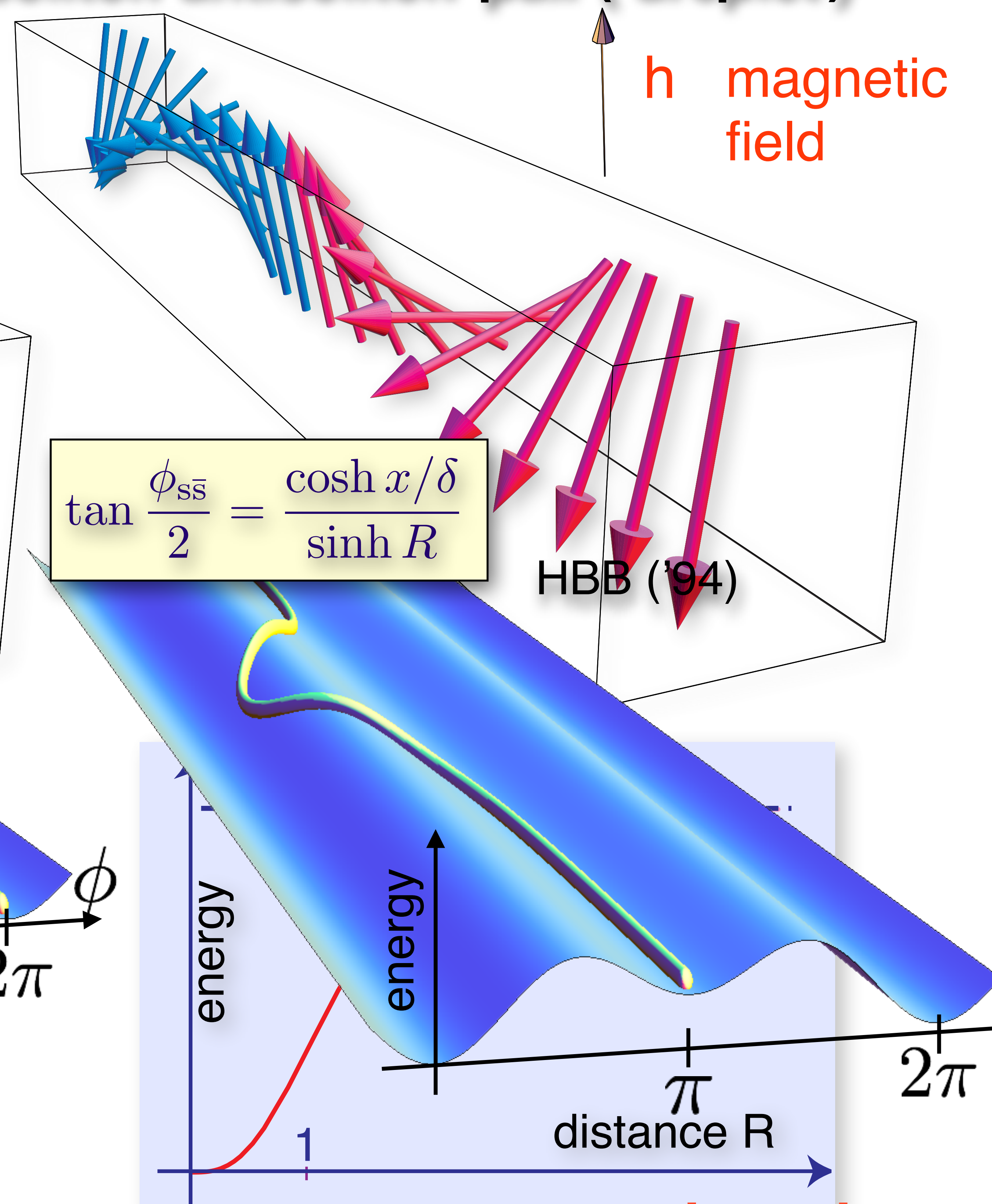
Pairs of solitons

'soliton-soliton' pair (2π wall)



$$\tan\frac{\phi_{ss}}{2} = \frac{\cosh R}{\sinh x/\delta}$$

'soliton-antisoliton' pair ('droplet')



$$\tan\frac{\phi_{s\bar{s}}}{2} = \frac{\cosh x/\delta}{\sinh R}$$

Finite temperature generalization of micromagnetics

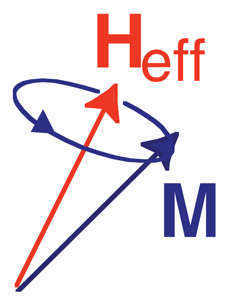
LL or LLG equations form basis of micromagnetism, **but** both are at variance with fluctuation-dissipation theorem (i.e. damping, but no noise!)

unable to describe superparamagnetism and related phenomena (important for data storage)

Remedy: introduce fluctuating fields

$$\mathbf{H}_{\text{eff}} \rightarrow \mathbf{H}_{\text{eff}} + \zeta$$

$$\langle \zeta_i(\mathbf{x},t)\zeta_j(\mathbf{0},0) = g_{ij} D_0 \delta_{ij} \delta(t)\delta(\mathbf{x})$$
$$D_0 = 2\alpha k_B T/\gamma M_0$$



$$\partial_t \mathbf{M} = -\gamma \mathbf{M} \times (\mathbf{H}_{\text{eff}} + \zeta) + \frac{\alpha}{M_0} \mathbf{M} \times \partial_t \mathbf{M}$$

$$(1+\alpha^2)\partial_t \mathbf{M} = -\gamma \mathbf{M} \times (\mathbf{H}_{\text{eff}} + \zeta) - \frac{\alpha\gamma}{M_0} \mathbf{M} \times [\mathbf{M} \times (\mathbf{H}_{\text{eff}} + \zeta)]$$

$$\mathbf{H}_{\text{eff}} = -\delta E/\delta \mathbf{M}$$

Finite temperature generalization of micromagnetics

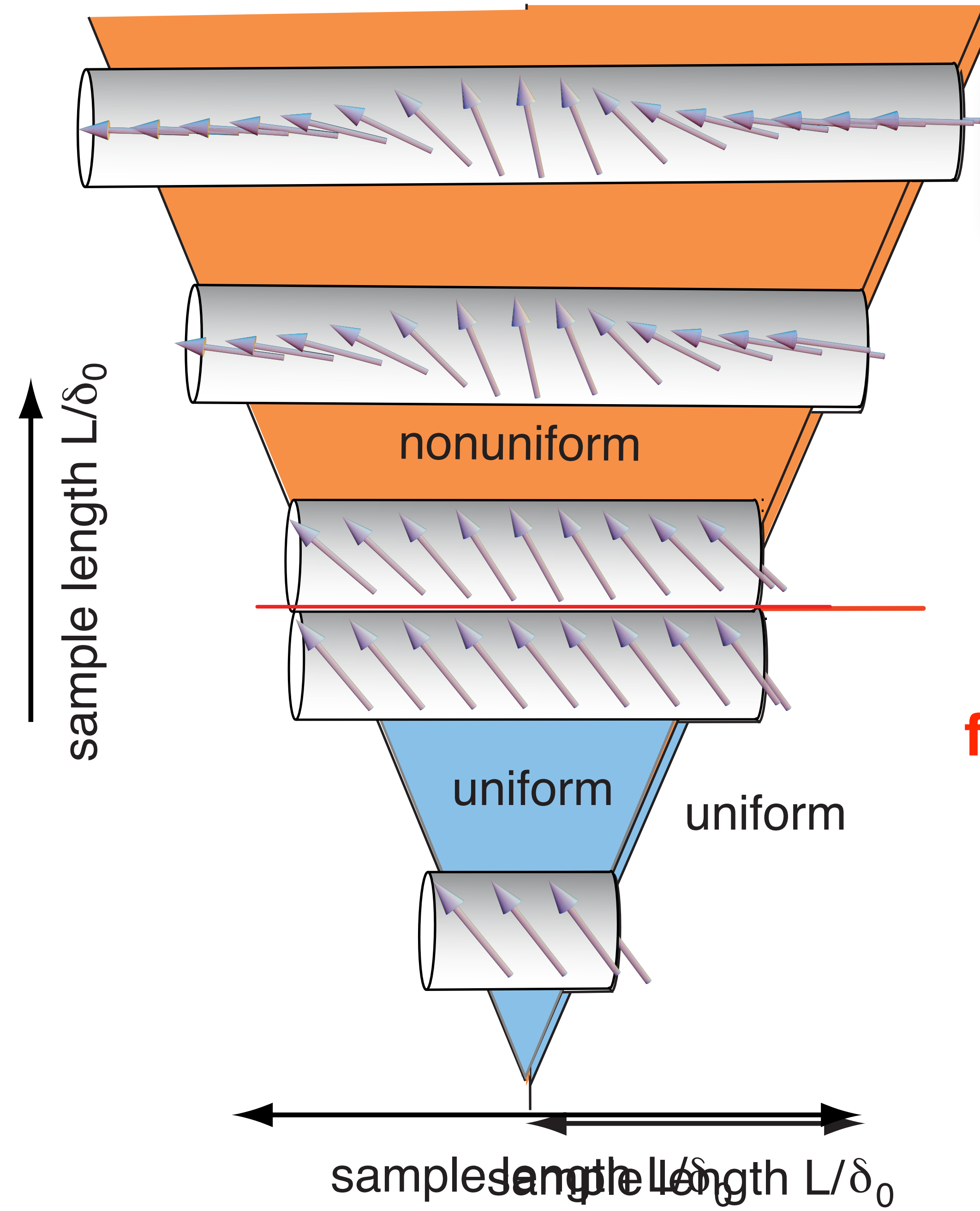
Consequences:
Superparamagnetism in single domain clusters (Néel-Brown);
Nucleation of domain walls in nanowires (HBB ’93, Adv Phys ‘12)

II.Superparamagnetism & limits of magnetic data storage

Nanowires: superparamagnetism via soliton-antisoliton nucleation & perpendicular magnetic recording

Energy barriers and Arrhenius prefactors

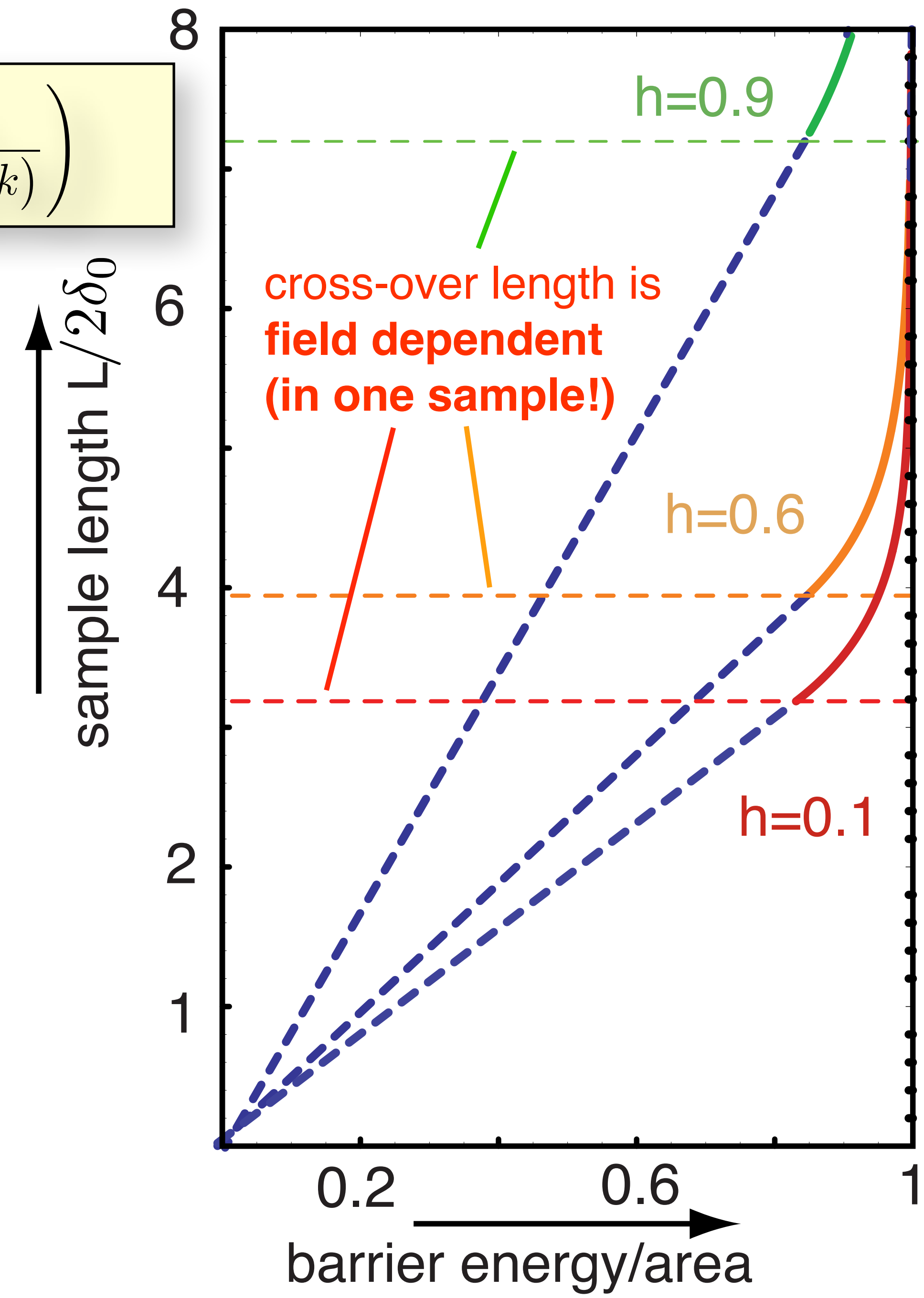
Crossover between Néel-Brown mechanism and soliton nucleation



$$\phi_{\text{s}\bar{\text{s}}}^{L} = 2\arctan\left(\frac{w_1}{\text{dn}\left(\frac{x}{\delta}, k\right)}\right)$$

$$L_{\text{crit}} = \frac{\pi\delta_0}{\sqrt{1-h^2}}$$

field dependent!



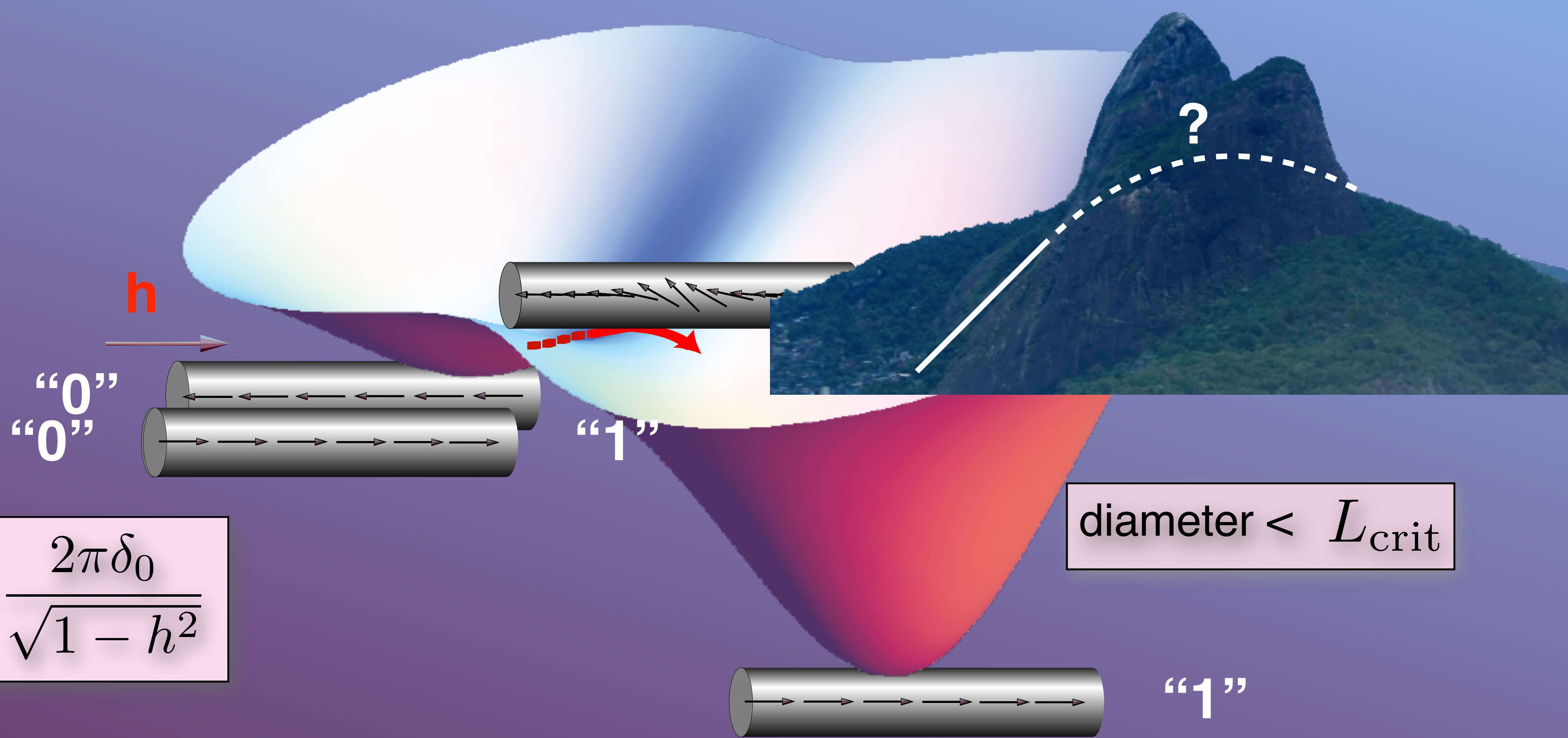
barrier energy / area:

HBB (*JAP (`06), Adv. Phys. ('12)*)

$$\mathcal{E}_m = 8\sqrt{AK_e}\frac{\delta_0}{\delta}\left\{E(k) + (1-\frac{k^2}{\alpha^2})K(k) + (\alpha^2 + \frac{k^2}{\alpha^2} - 2)\Pi(\alpha^2, k)\right\} + \\ -2K_e L(c+h)$$

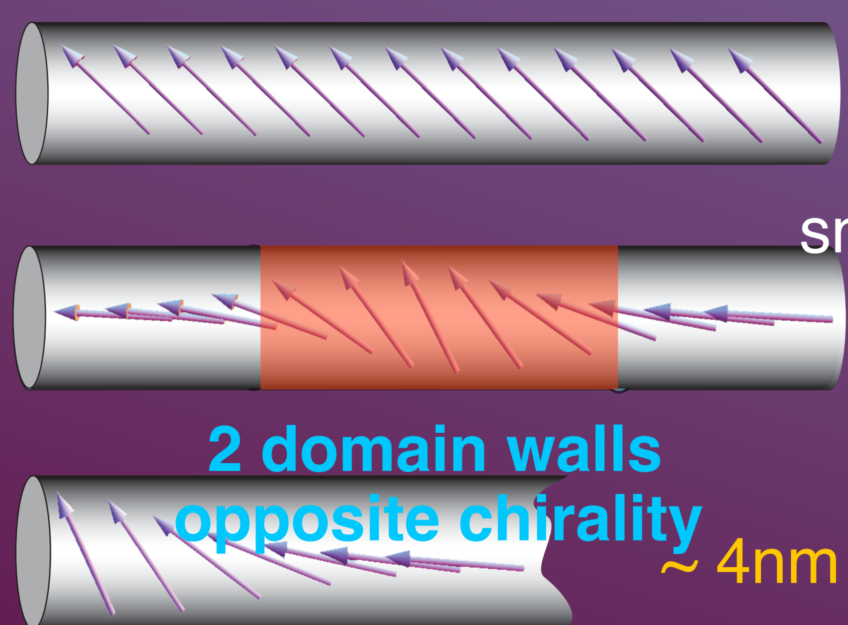
Cross-over has "critical" character

Soliton-antisoliton pairs and thermal energy barriers



diameter < L_{crit}

$$L_{\text{crit}} = \frac{2\pi\delta_0}{\sqrt{1-h^2}}$$



$L < L_{\text{crit}}$ uniform (Néel-Brown)

small fields

$L > L_{\text{crit}}$ soliton-antisoliton mechanism (HBB 93)

~~'activation volume'~~

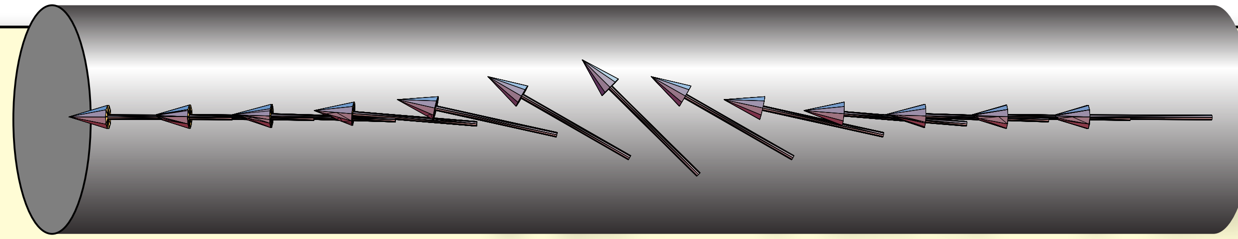
$L > L_{\text{crit}}/2$ ~ 4nm (FePt) !!

Switching rates for soliton-antisoliton nucleation

switching rate $\Gamma = \Omega e^{-\beta \mathcal{A}\mathcal{E}_s}$

(HBB, PRL'93, PRB '94, JAP'06
Adv Phys.'12),
cf. P. Loxley, R. Stamps, '06

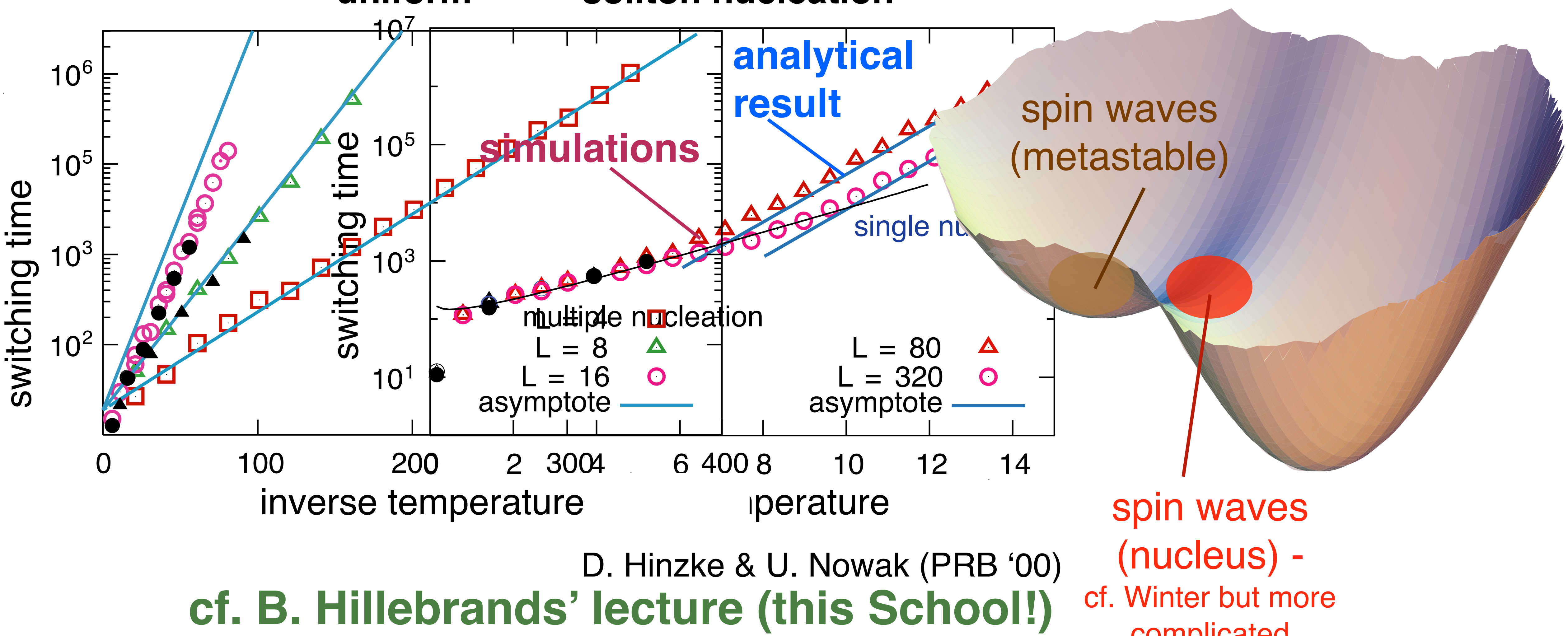
prefactor Ω



$\mathcal{H}^{mp}$ / $\mathcal{H}^{sp}$

= *escape frequency* x *zero modes (symmetry)* x $\left(\frac{\textit{curvature (M)}}{\textit{curvature (S)}}\right)^{1/2}$

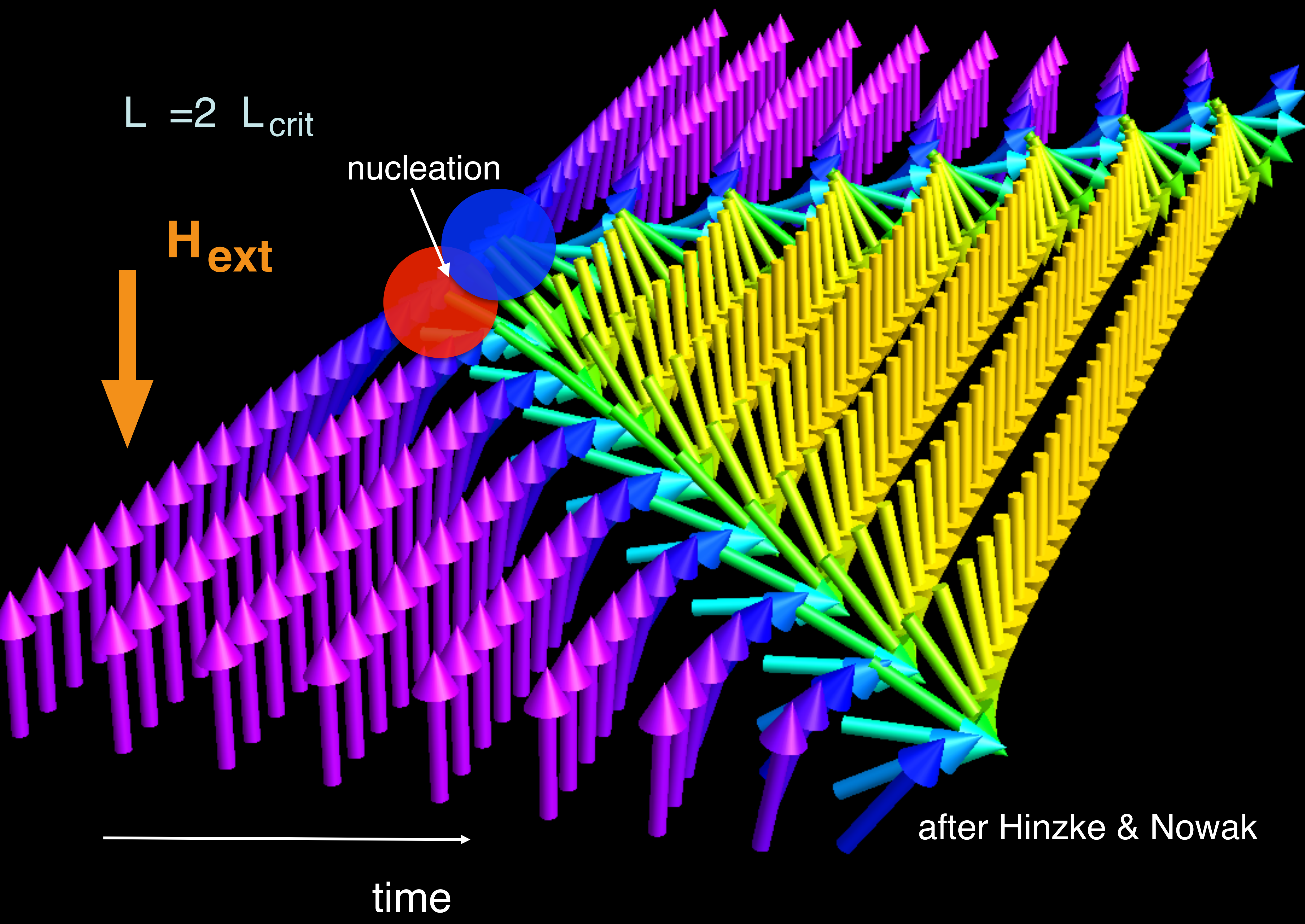
uniform **soliton nucleation**



D. Hinzke & U. Nowak (PRB '00)

cf. B. Hillebrands' lecture (this School!)

Soliton-antisoliton nucleation



Application:
'Perpendicular Magnetic Recording' (PMR)

TOPICAL REVIEW

The transition from longitudinal to perpendi

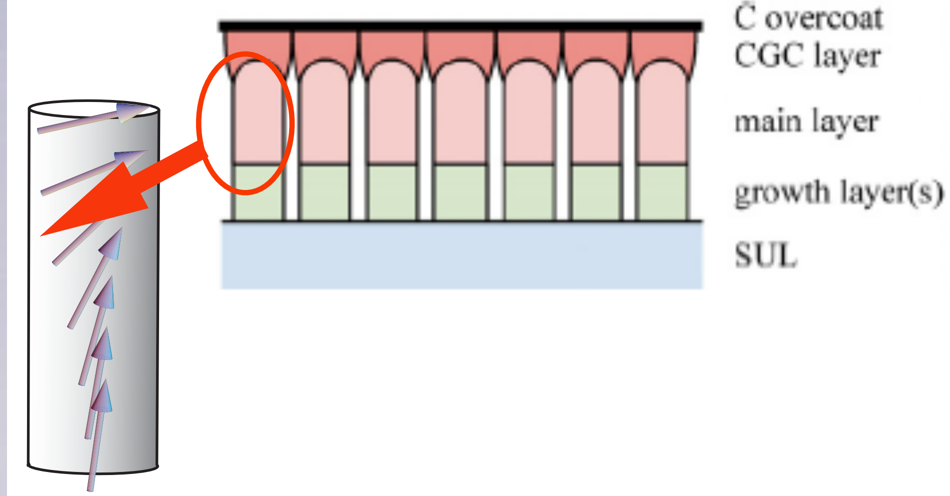
H J Richter

Seagate Technology, 47010 K

Received 7 February 20
Published 19 April 2007
Online at stacks.iop.org/

6. Perpendicul

6.1. Media structu



However, it also ha
to the tallness of t
the thermal energy
The energy barrie
$4\sqrt{AK}$ where K is
stiffness. For a cyl
barrier becomes

$$\Delta E_{DW} = \pi D^2 \sqrt{AK}. \quad (29)$$

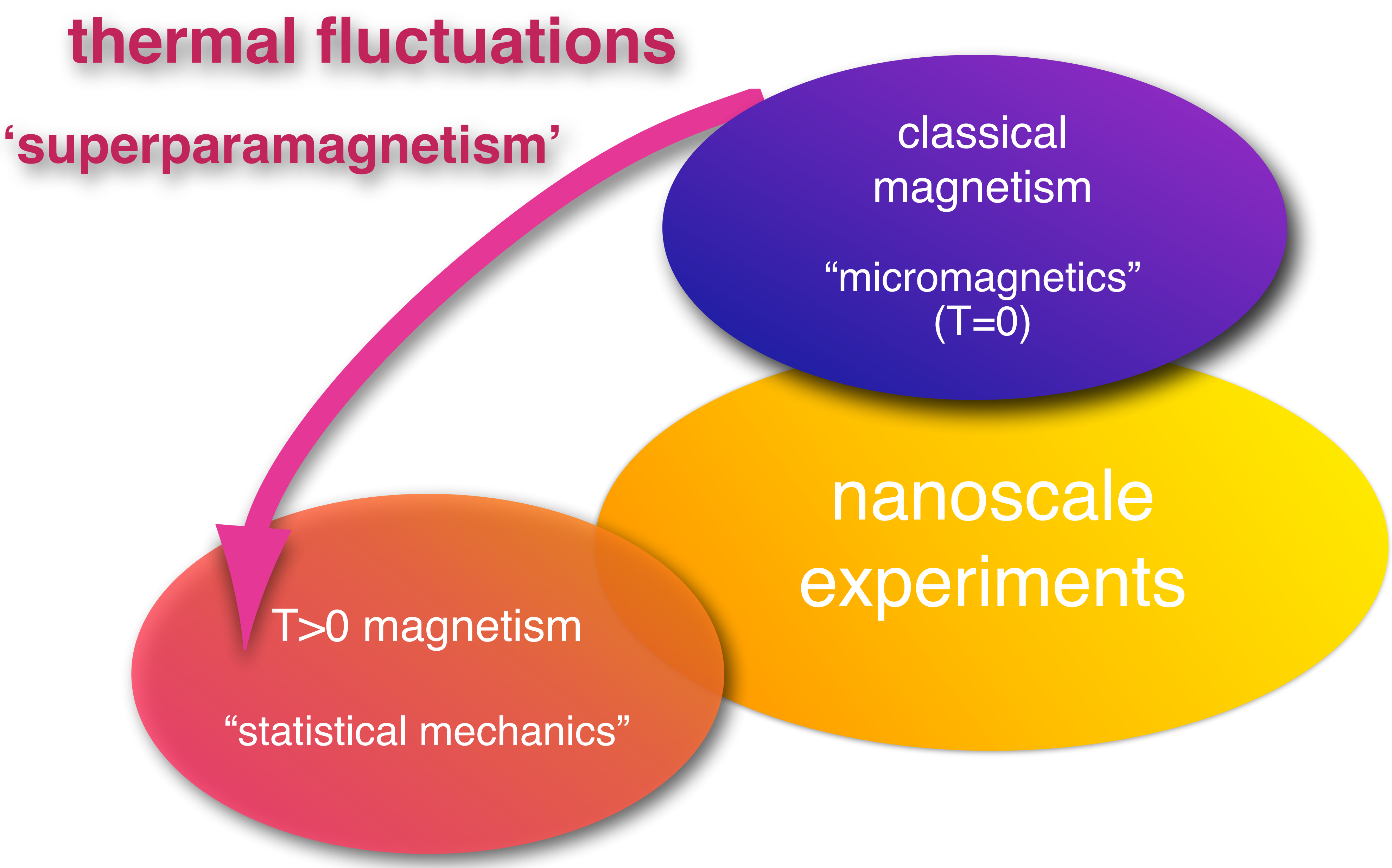
T at which the reversal process transitions
coherent:

$$\ell_T = 4\sqrt{\frac{A}{K}}. \quad (30)$$

Typical values for current perpendicular recording media are $K \approx 4 \times 10^5\,\mathrm{J\,m^{-3}}$ and $A \approx 10^{-11}\,\mathrm{J\,m^{-1}}$ and hence $\ell_T \approx 20\,\mathrm{nm}$, which has been confirmed experimentally [94]. It is important to note that materials with higher K lead to smaller transition thicknesses ℓ_T. This has an important implication for possible SNR gains that can be achieved by a reduction of grain size. As long as the medium thickness is less than the transition length ℓ_T, maintaining thermal stability (that is KV) requires that the anisotropy K has to be scaled according to $K \propto 1/D^2$. However, if the medium thickness is equal to ℓ_T,

cf. J. Coker's lecture (this School!)

Theoretical descriptions of magnetism

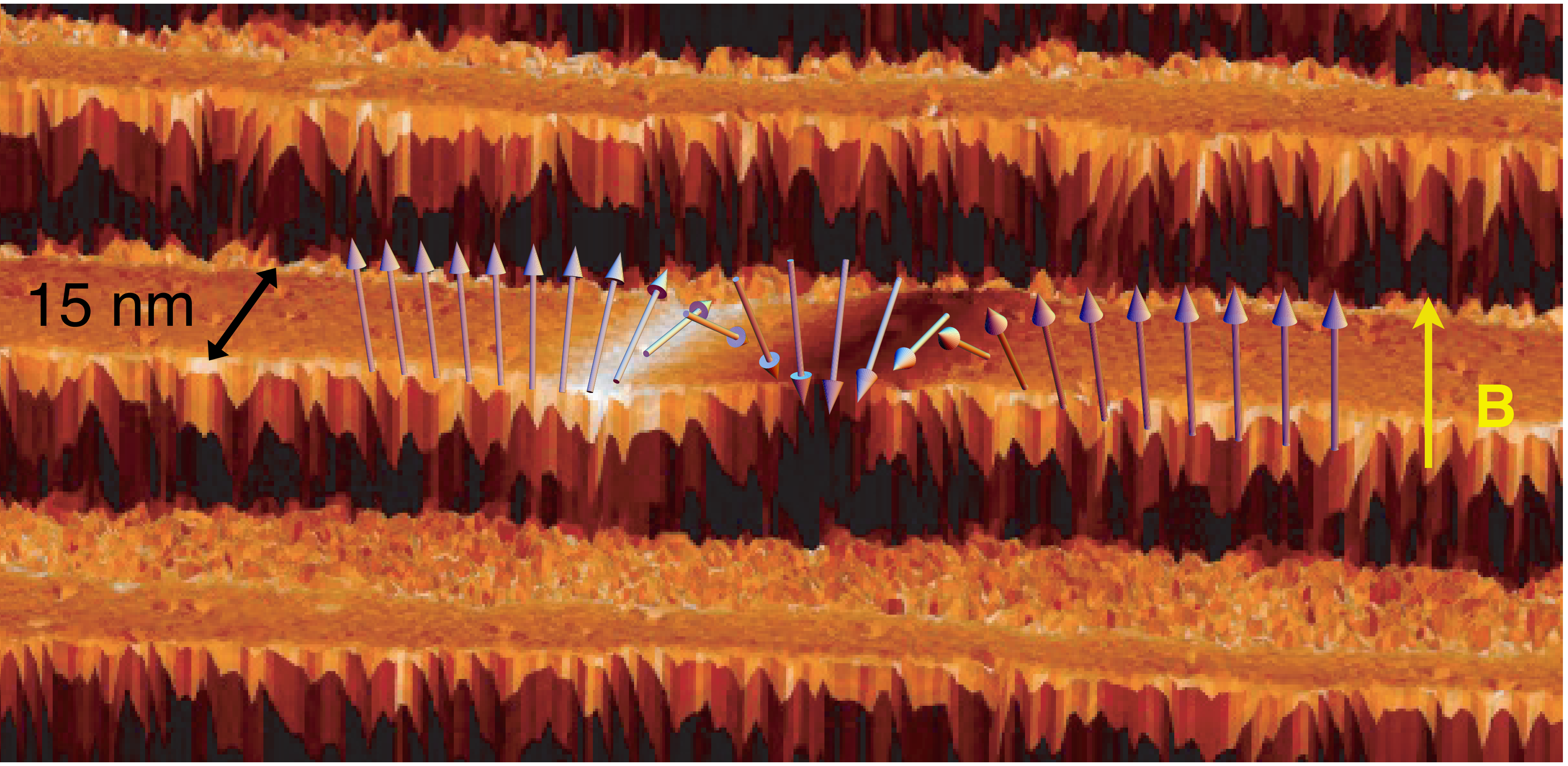


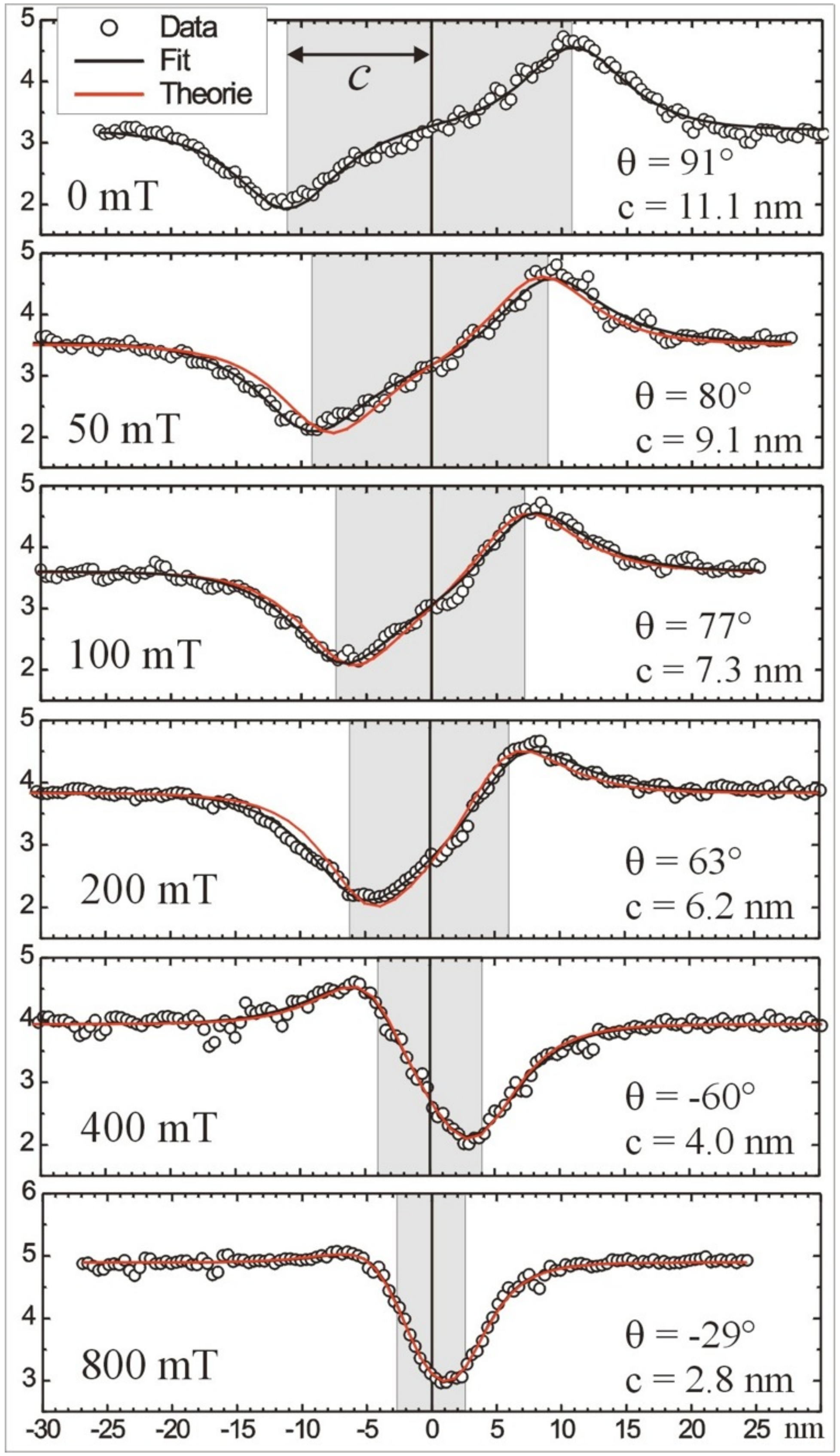
III.Quantization of micromagnetics

Semiclassical quantization of micromagnetics, Berry phase and topology

How to derive excitations of anisotropic XYZ-Heisenberg spin chains from micromagnetics

Soliton-soliton pairs in nanowires

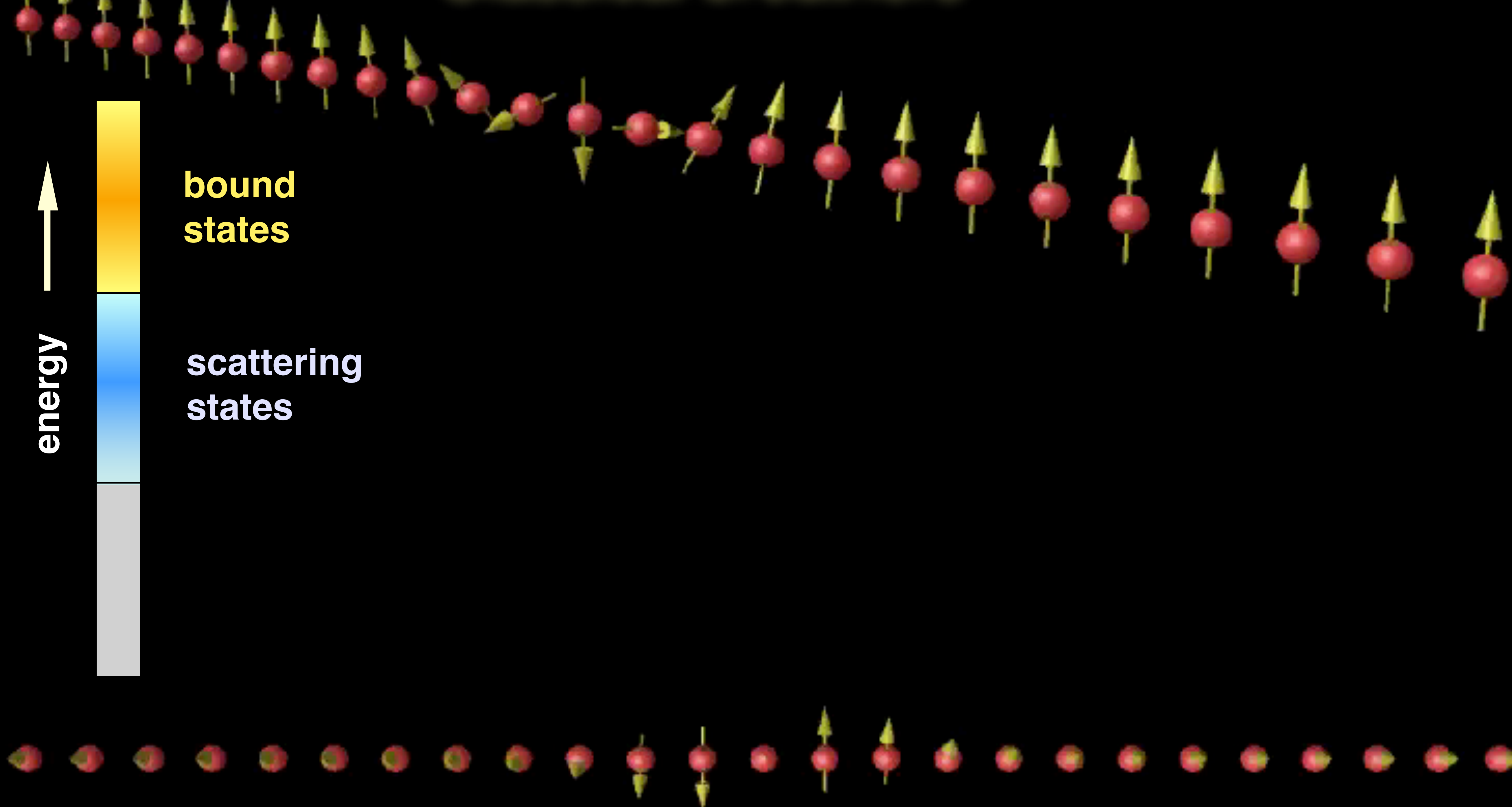




expts: Kubetzka, Pietzsch, Bode, Wiesendanger (PRB '03)

theory: HBB (PRB '94)

Classical breathers

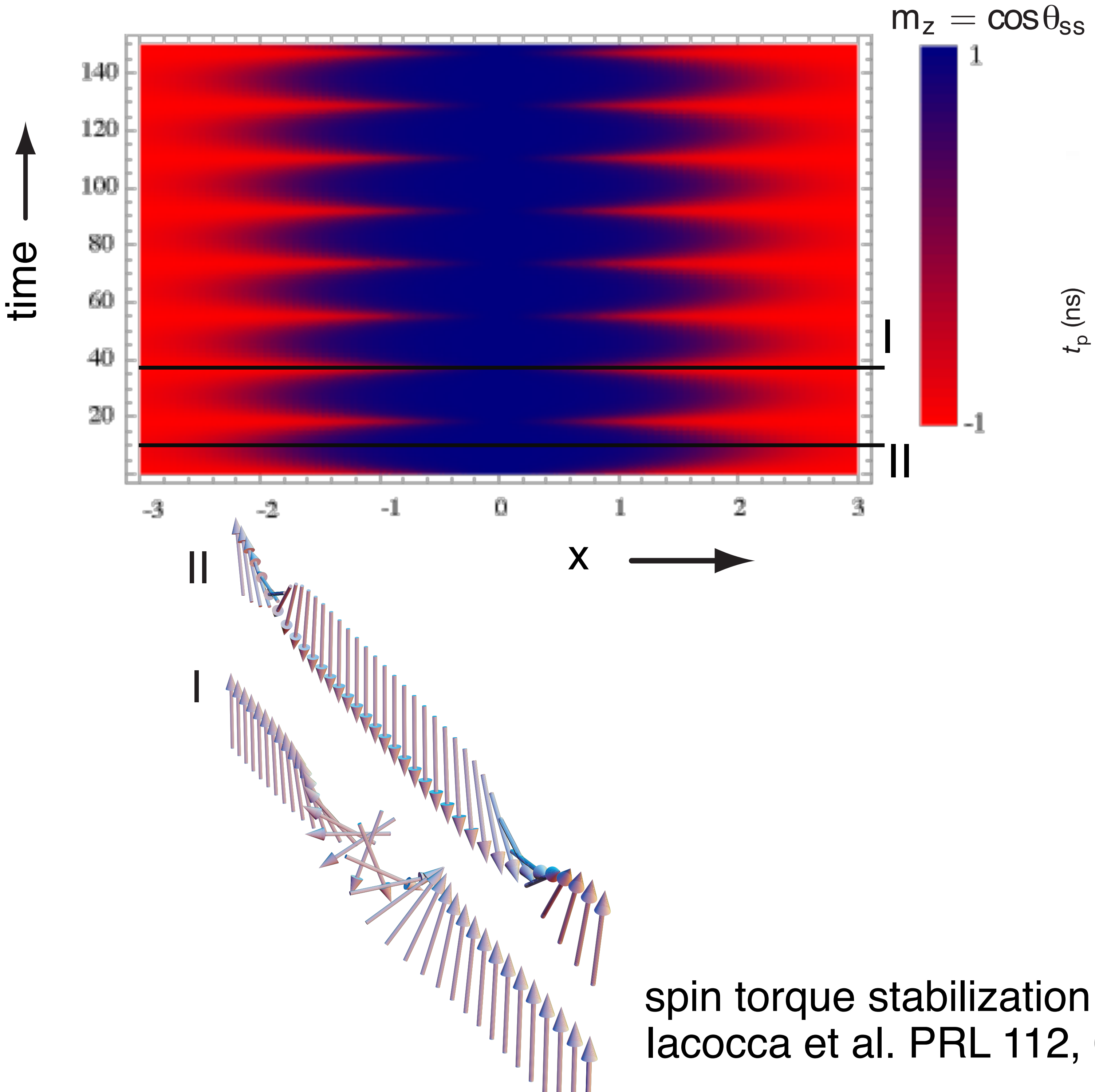


exact solutions: HBB & Brodbeck, PRL ('93),
J. Eves et al. ('10)

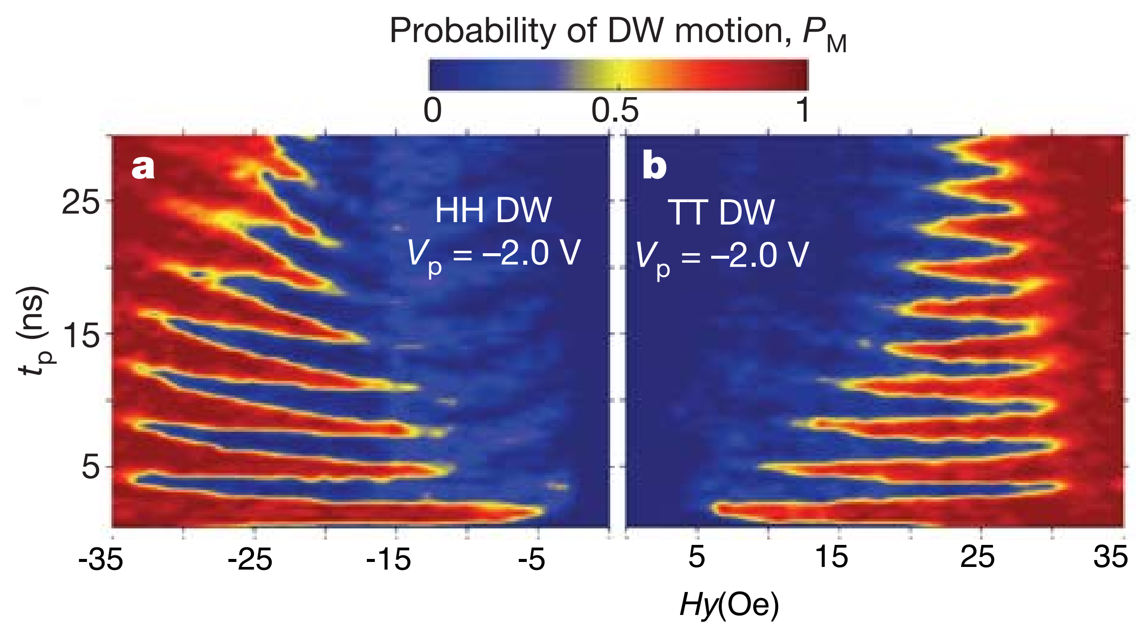
Are breathers observable ?

predicted breather oscillations

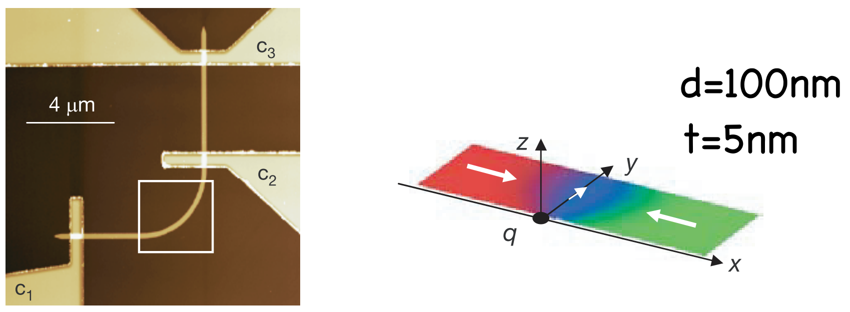
J. Eves et al. ('10)



Depinning und induced wall oscillations in nanowires



L. Thomas et al, Nature (06)



spin torque stabilization:
Iacocca et al. PRL 112, 047201 ('14)

Importance of quantum effects

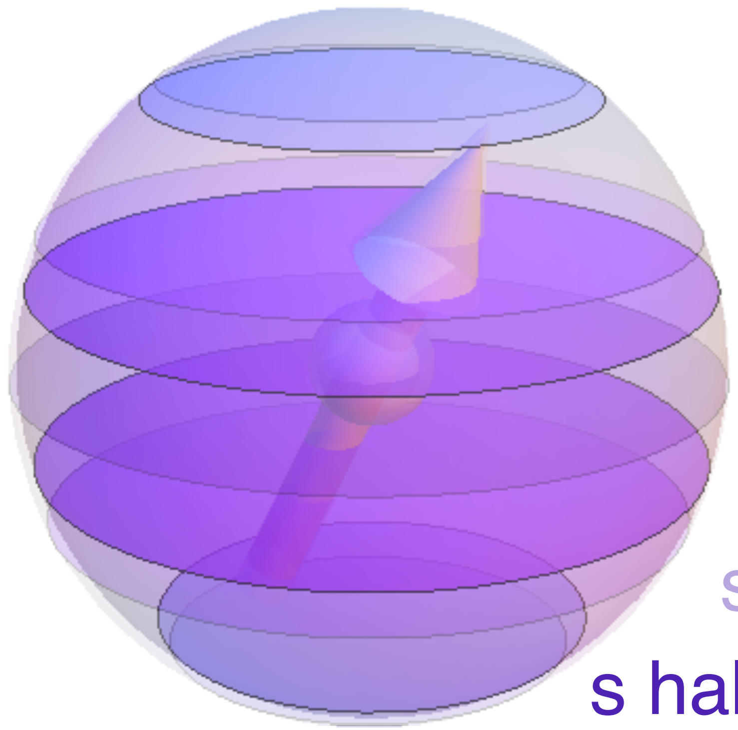
classical spin

$$\mathbf{S} = s(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$0 \leq \theta \leq \pi$$
$$0 \leq \phi < 2\pi$$

real

quantum spin



s integer

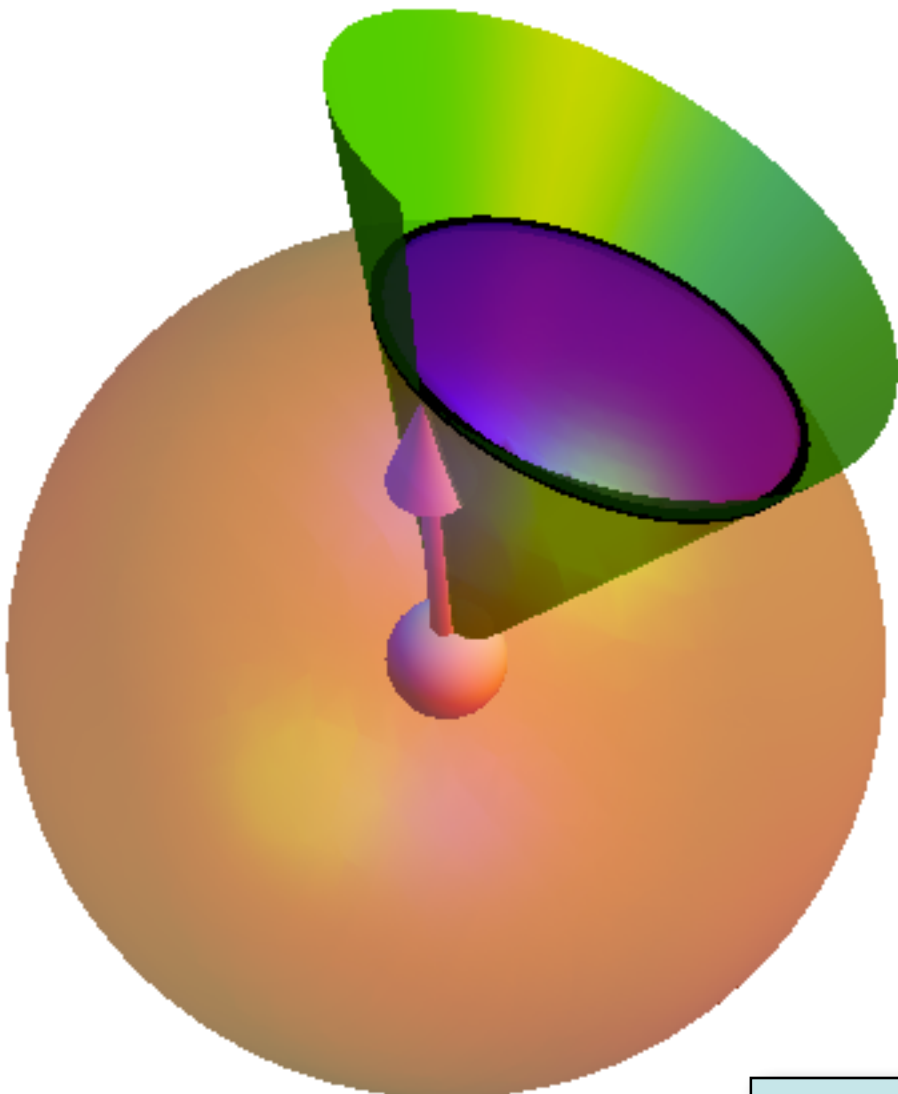
s half integer

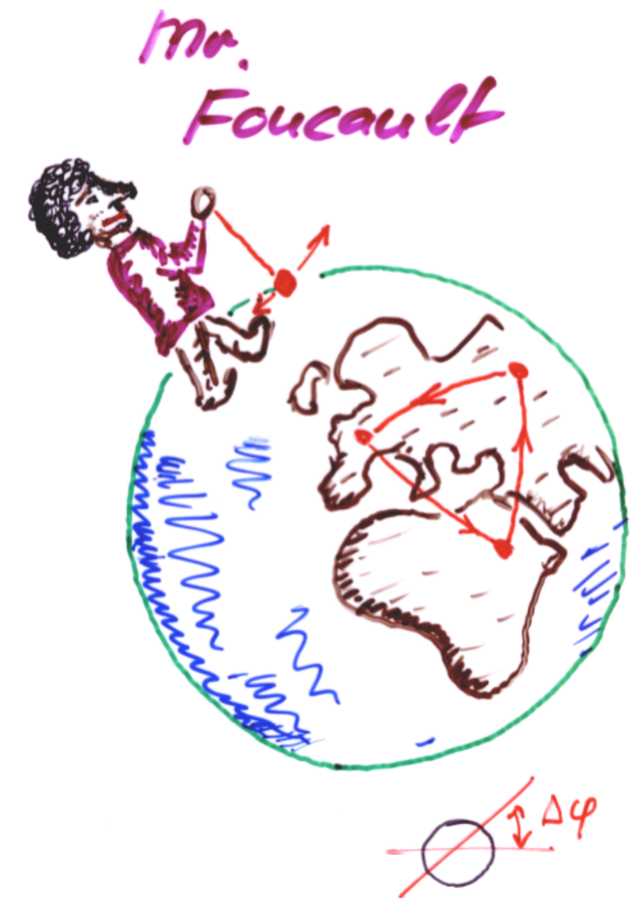
$$|s\ m_s\rangle$$

$$m_s = -s, \ldots, s$$

discrete

Key concept - Berry phase





$$|\psi(T)\rangle = e^{i\gamma(T)} e^{-i\int_0^T dt E_n(t)} \, |\psi(0)\rangle$$

$$\gamma(T) = s \oint d\mathbf{n} \cdot \mathbf{A} = s \int_0^T dt \partial_t \phi (1 - \cos\theta) = s \; \text{area}$$

monopole vector potential (!)

Quantized breathers

Quantization condition $(\hbar = 1)$

$$\mathcal{S}_B[\mathbf{n}_{\mathrm{ss},\mathrm{s\bar{s}}}] = 2\pi N$$

Berry-phase

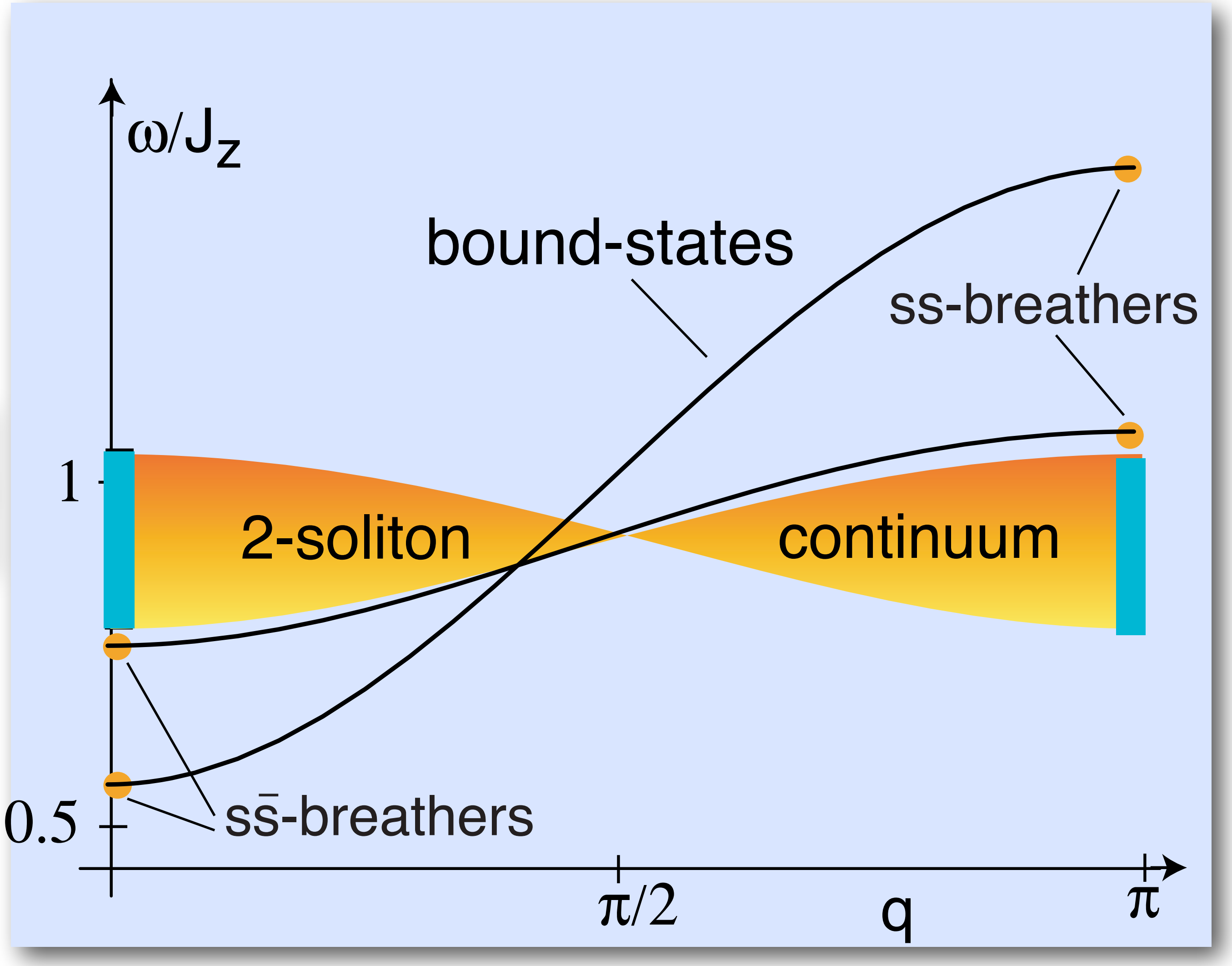
ss-breather

$$E_{\mathrm{ss}}^{\mathrm{bound}}(N)/2E_0 = 1/\{\tilde{m}\ \mathrm{sn}((N/2\tilde{s}\tilde{m}),\tilde{m})\}$$

s$\bar{\text{s}}$-breather

$$E_{\mathrm{s\bar{s}}}^{\mathrm{bound}}(N)/2E_0 = \mathrm{sn}((N/2\tilde{s}\tilde{m}),\tilde{m})$$

cf. sine-Gordon model



HBB & N. Fettes, JAP 85 ('99)
HBB & O. Brodbeck, PRL ('93)

$$0 < N/2\tilde{s}\tilde{m} < K(\tilde{m})$$

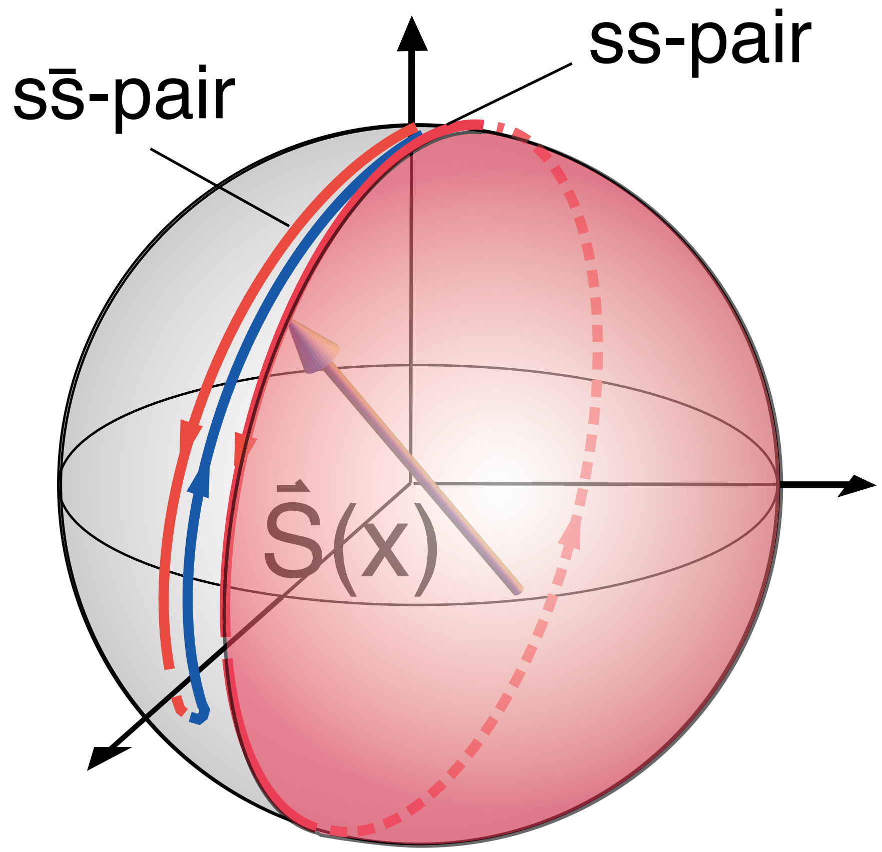
easy-plane limit $\tilde{m} \to 0$

Ising limit $\tilde{m} \to 1$

excitation spectrum agrees with that of discrete spin-1/2 xyz-chain:

$$H_{xyz} = \sum_i J_x S_i^x S_{i+1}^x + J_y S_i^y S_{i+1}^y + J_z S_i^z S_{i+1}^z$$

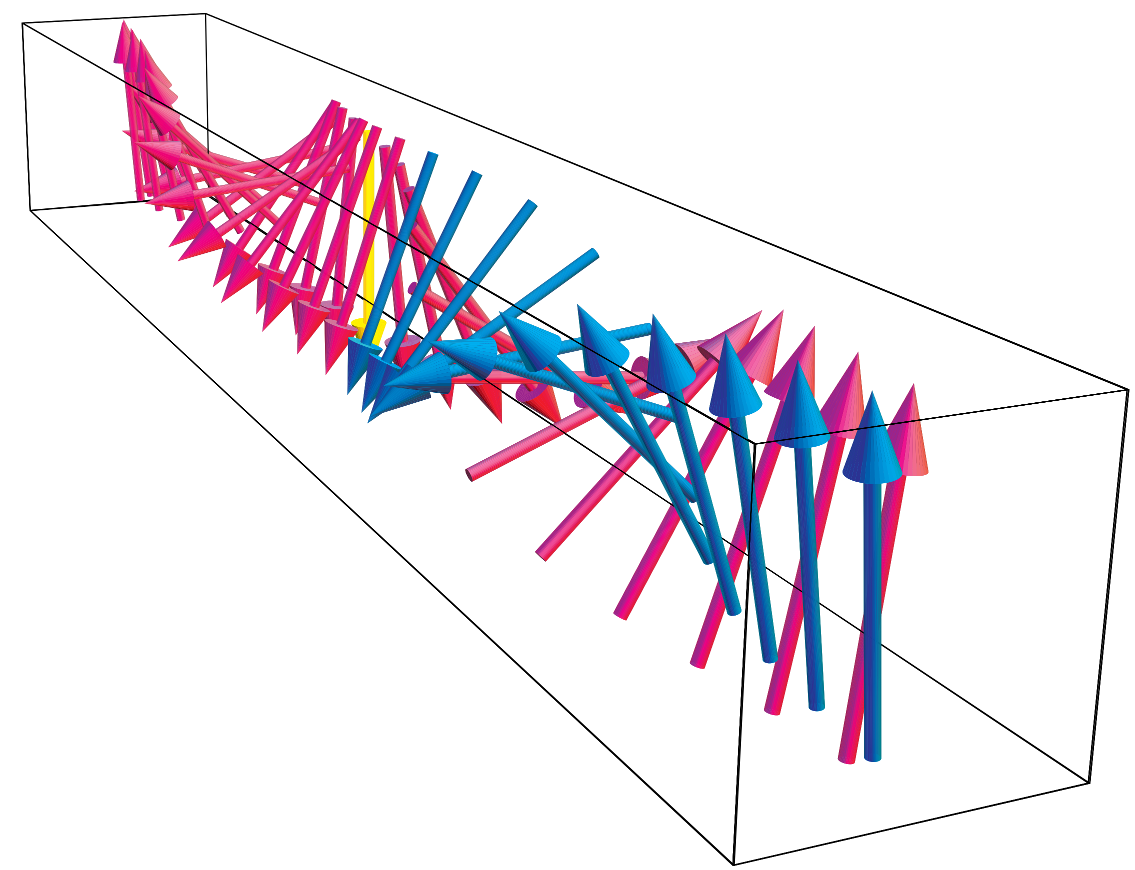
Spin momentum and solitons



momentum (Haldane)

$$\mathcal{P} = \oint dx\, \partial_x \mathbf{n} \cdot \mathbf{A}$$

monopole



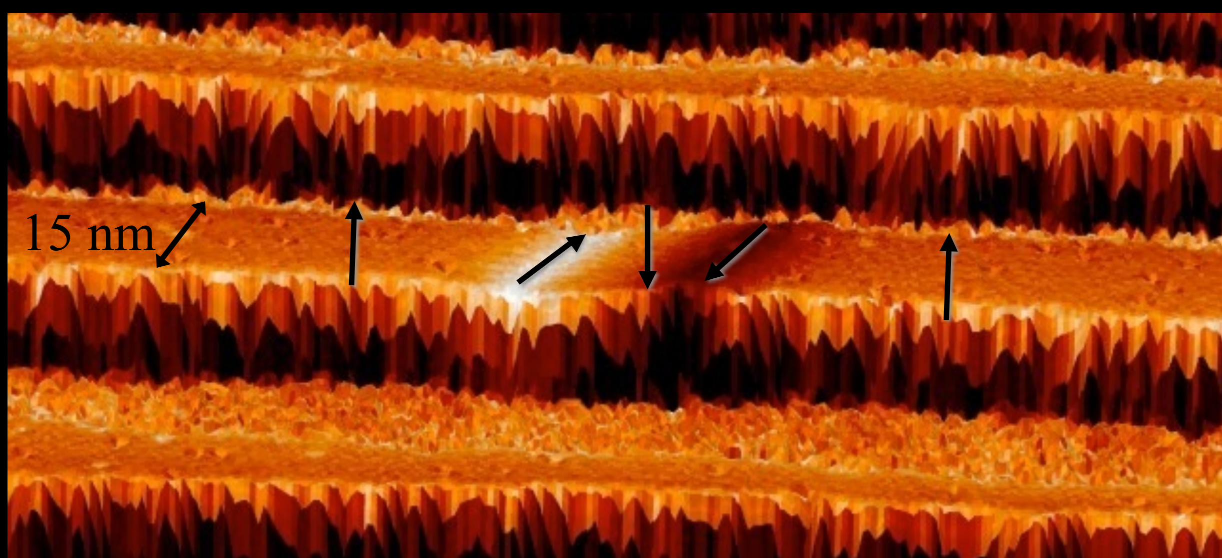
wavevector k=0 k=π

$$k = s\mathcal{P}$$

Relative wave vector of solitons with opposite chirality is π !

Quantum fluctuations, point defects & emergence of chirality

Fe-nanowires



Kubetzka et al. PRB (‘03)

quantum spin-chains

$$|\uparrow\uparrow\uparrow\uparrow|\downarrow\downarrow\ldots\downarrow\downarrow\ldots\downarrow\downarrow|\uparrow\uparrow\uparrow\rangle$$

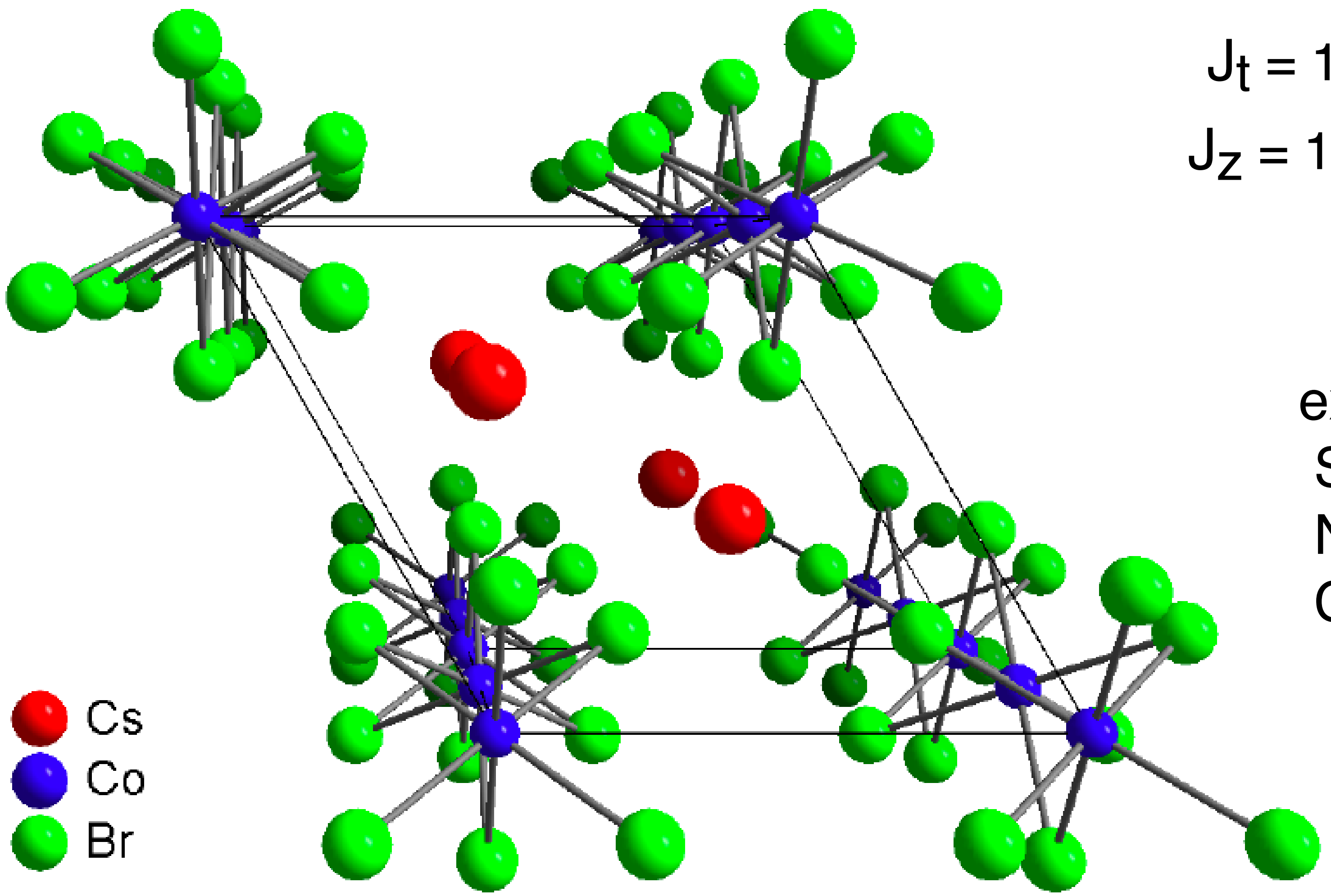
$$|\uparrow\downarrow\uparrow\downarrow|\downarrow\uparrow\ldots\downarrow\uparrow\downarrow\uparrow\ldots\uparrow\downarrow|\downarrow\uparrow\downarrow\rangle$$

Ising domain wall
point defects

$CsCoBr_3$ - a quasi 1D Heisenberg-Ising chain

$$H_{xxz} = \sum_i J_z S_i^z S_{i+1}^z + J_t \left(S_i^x S_{i+1}^x + S_i^y S_{i+1}^y \right)$$

Ising-term XY-term



J_t = 1.9 meV

J_z = 13.8 meV

T_N=28 K

J'/J ~ 10^{-2}

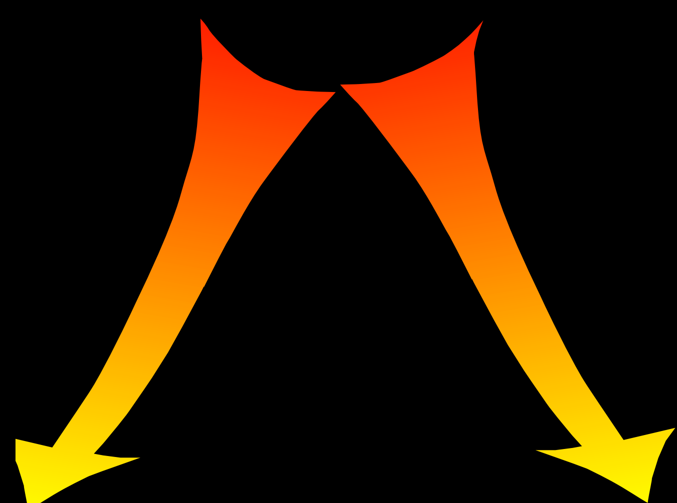
extensively studied:
Shirane
Nagler, Tennant, Goff, Gaulin,
Cowley, Regnault, Boucher

Chirality and Solitons

Ising limit,
no chirality

$|\uparrow\downarrow\ldots\uparrow\downarrow\uparrow\downarrow\vdots\downarrow\vdots\downarrow\uparrow\downarrow\uparrow\ldots\uparrow\downarrow\rangle$

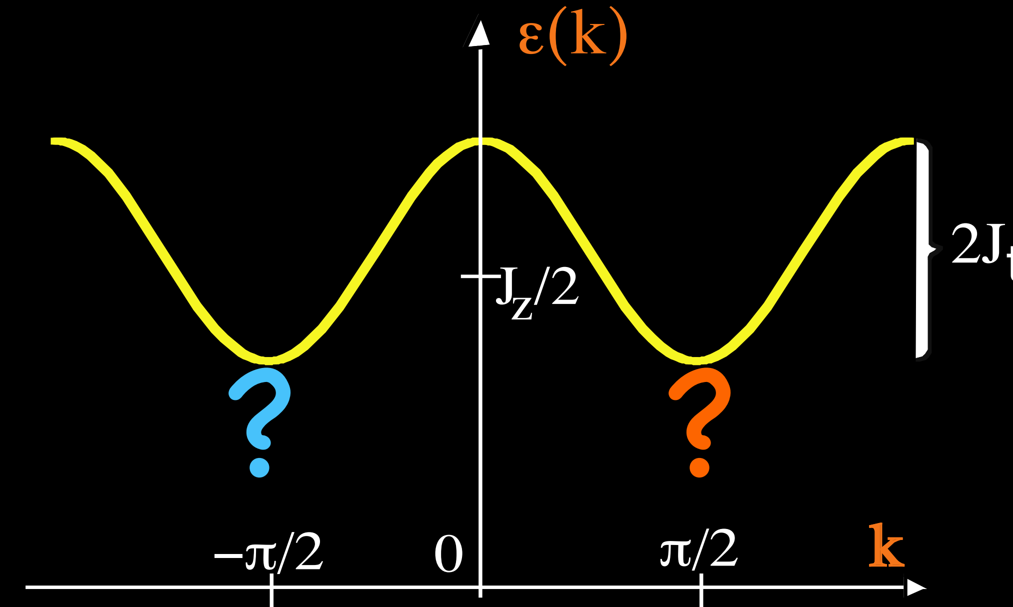
$|\uparrow\downarrow\ldots\uparrow\downarrow\vdots\downarrow\uparrow\downarrow\vdots\downarrow\uparrow\downarrow\uparrow\ldots\uparrow\downarrow\rangle$



$|\uparrow\downarrow\uparrow\downarrow\vdots\downarrow\uparrow\ldots\downarrow\uparrow\downarrow\uparrow\ldots\uparrow\downarrow\vdots\downarrow\uparrow\downarrow\rangle$

magnon decays into 2 solitons

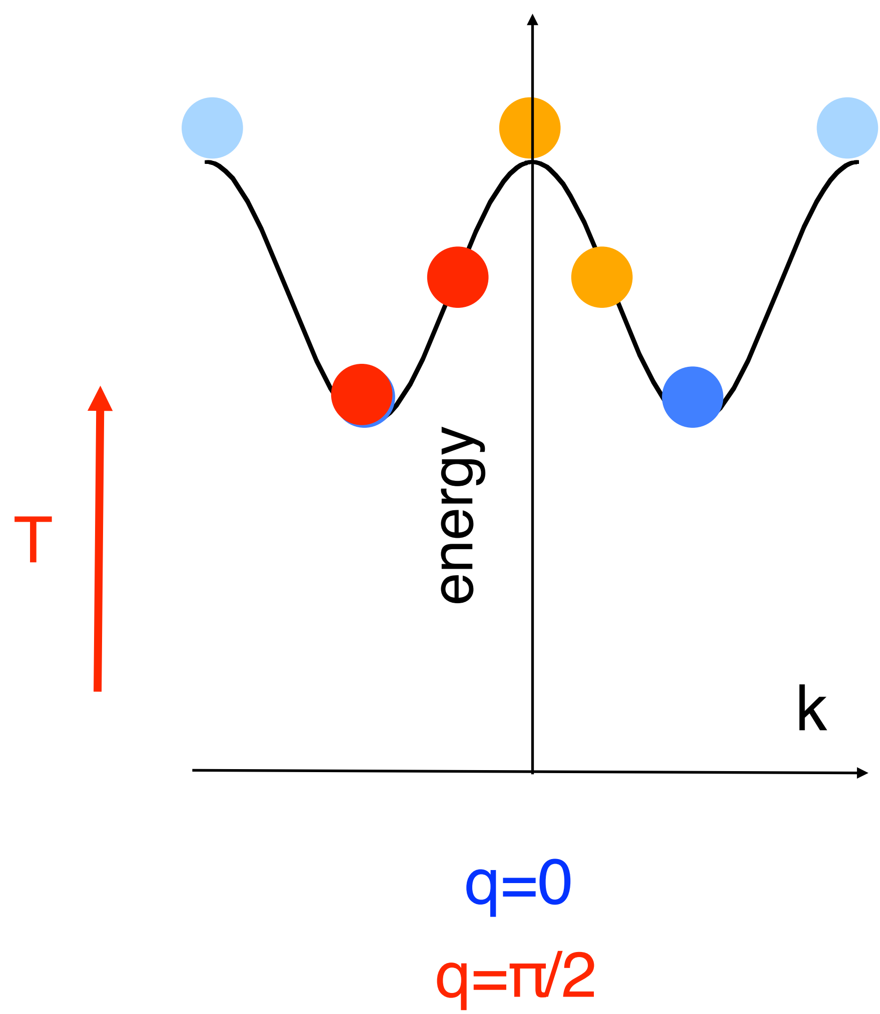
quantum fluctuations (XY-term)

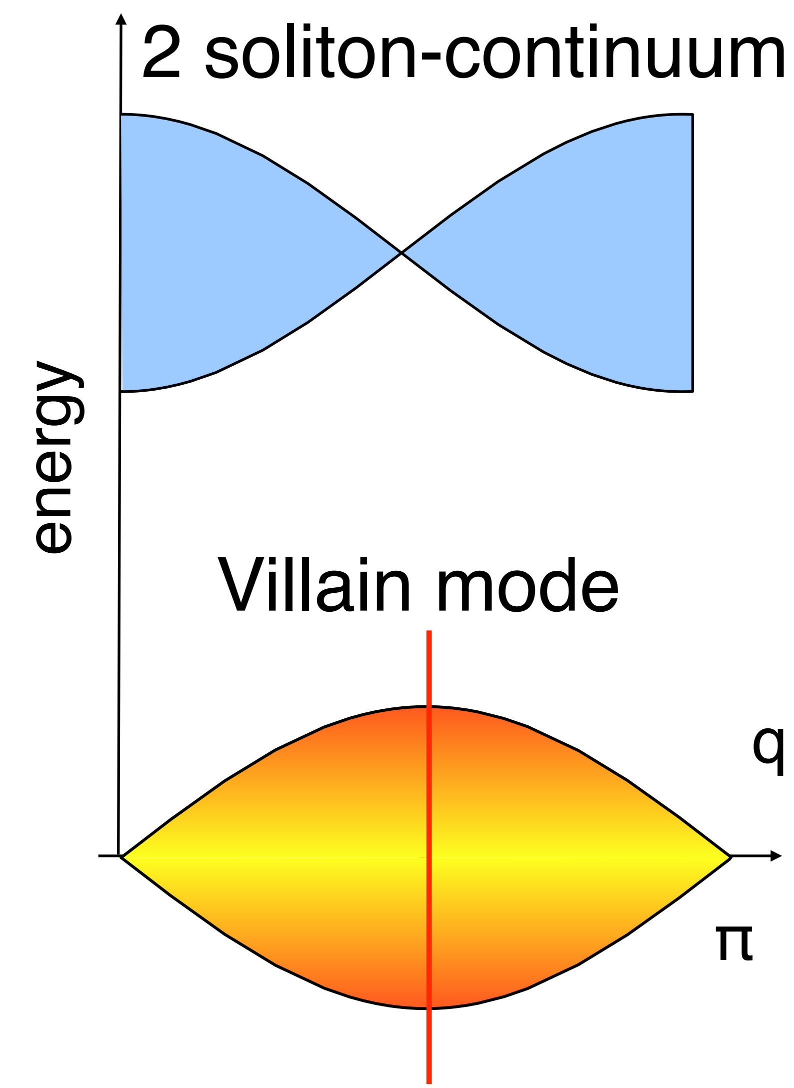


Are the two bandminima equivalent?

$$\langle\sum_i(\mathbf{S}_i\wedge\mathbf{S}_{i+1})_x\rangle=\pm1$$

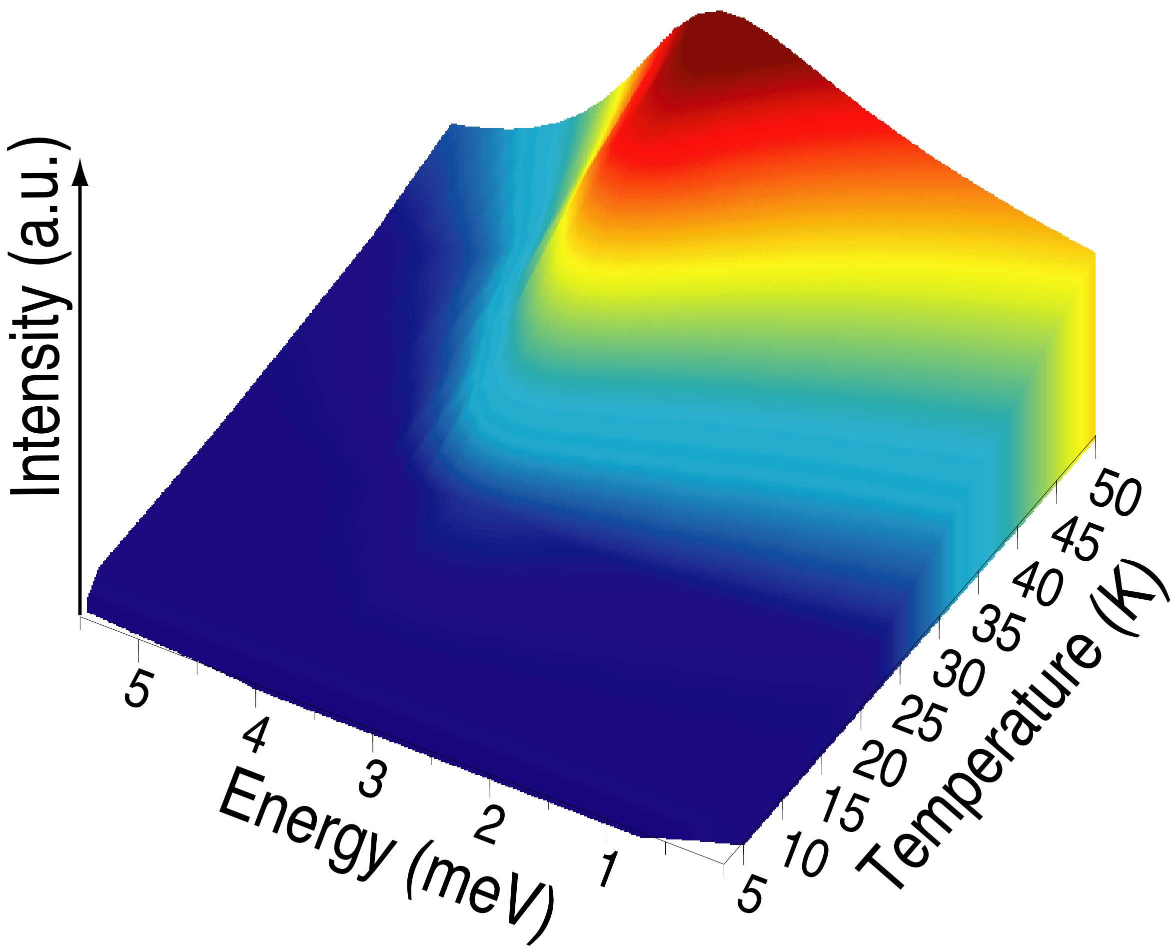
How neutrons couple to solitons



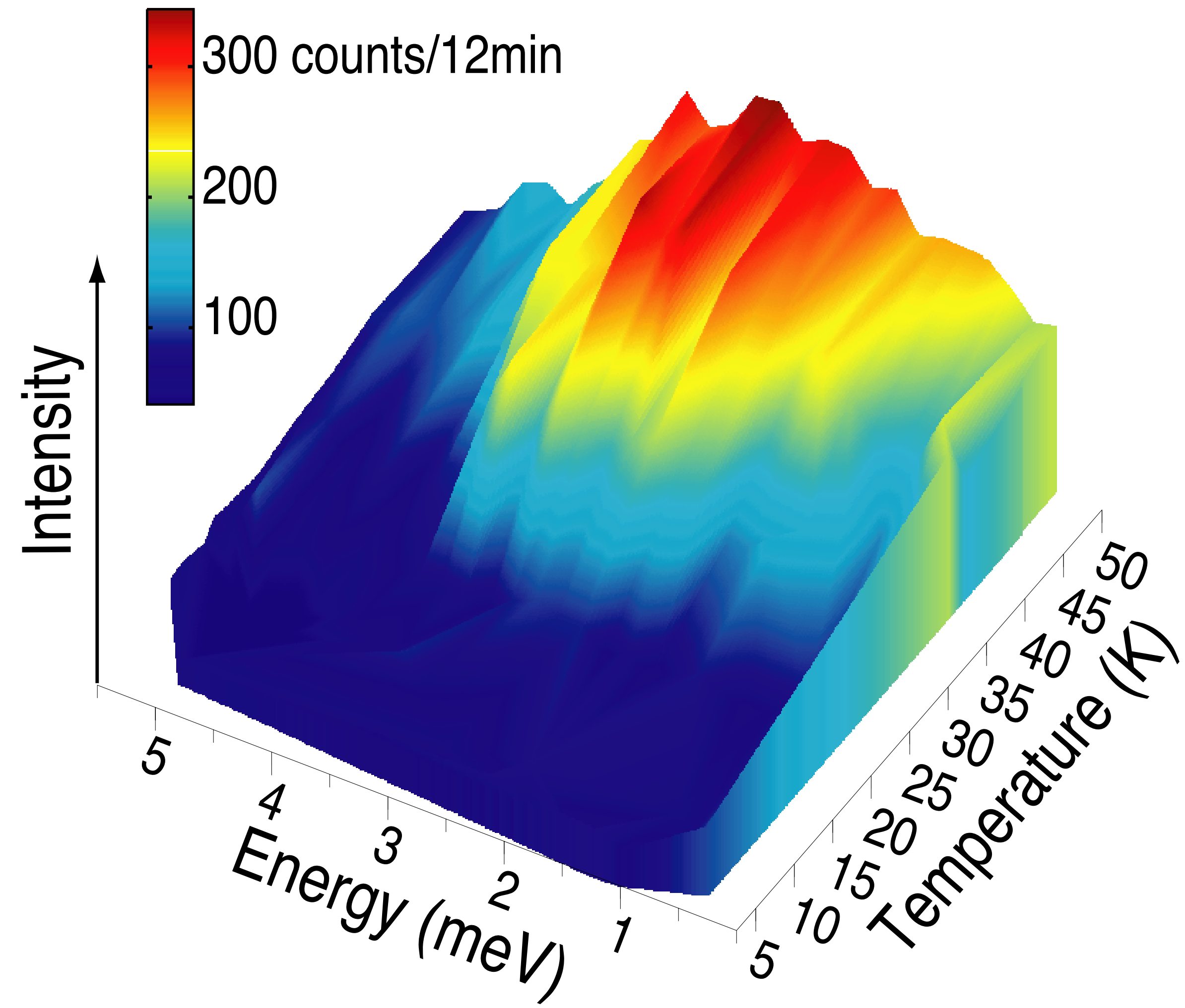


Villain mode

theory



experiment $CsCoBr_3$



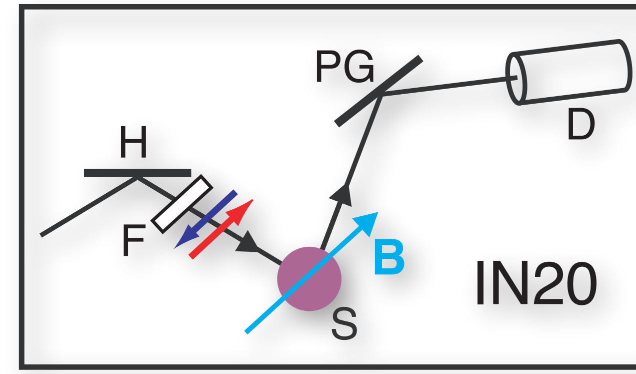
Polarized neutrons and chirality

$$I_+ - I_- \propto 2i \int dt\, e^{-i\omega t} \sum_k e^{-\beta\epsilon_k} \langle k | S^\perp_{-\mathbf{Q}} \wedge S^\perp_{\mathbf{Q}}(t) | k \rangle$$

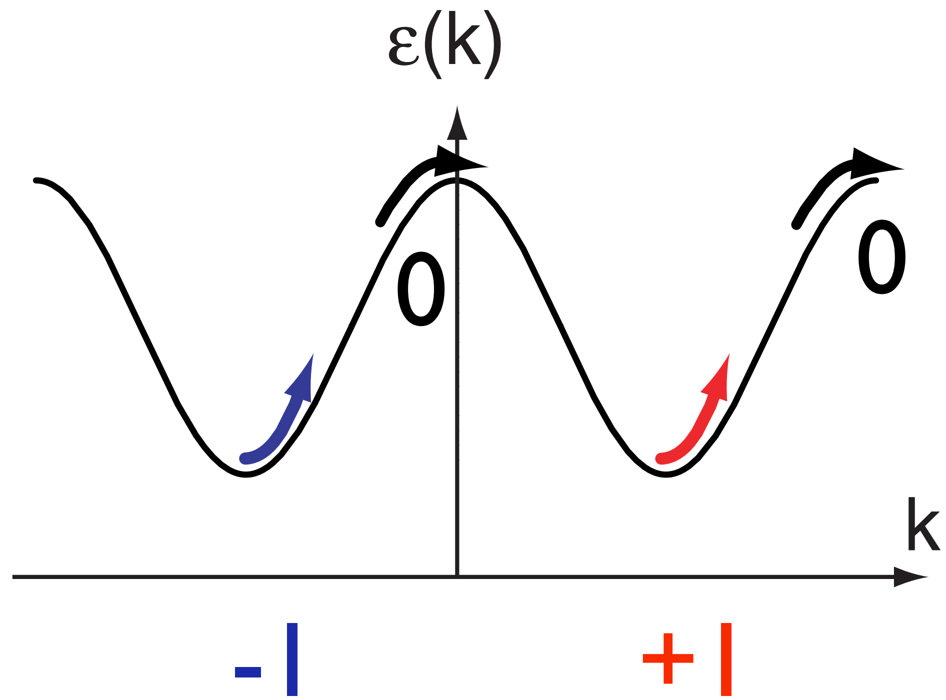
$$I_{\mathbf{P}} = \ldots + i\,\mathbf{P} \cdot \int dt\, e^{-i\omega t} \langle S^\perp_{-\mathbf{Q}} \times S^\perp_{\mathbf{Q}}(t) \rangle$$

$$\propto \frac{1}{\cos(q/2)} \ldots e^{-\beta\epsilon_k} \sin\left(\frac{k+k'}{2}\right) \delta(\hbar\omega - \epsilon_k + \epsilon_{k'})$$

Maleyev, Blume,...



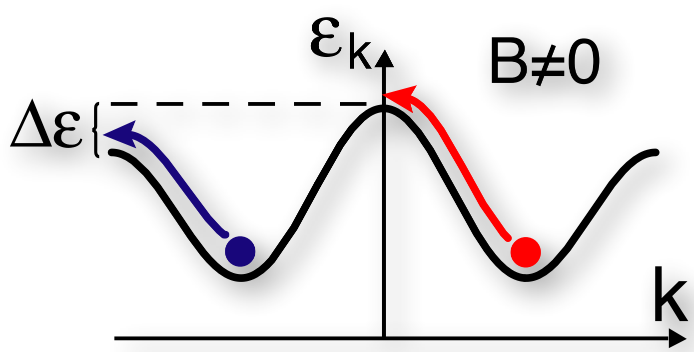
$$k' = k + q - \pi$$



Chirality is hidden !!

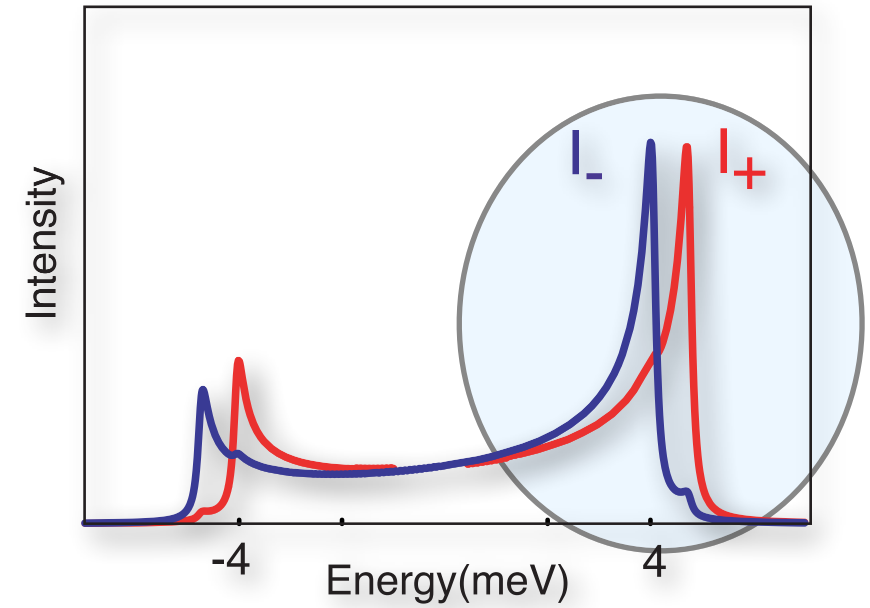
Institute Laue Langevin Grenoble

Chirality and spin-currents in $CsCoBr_3$

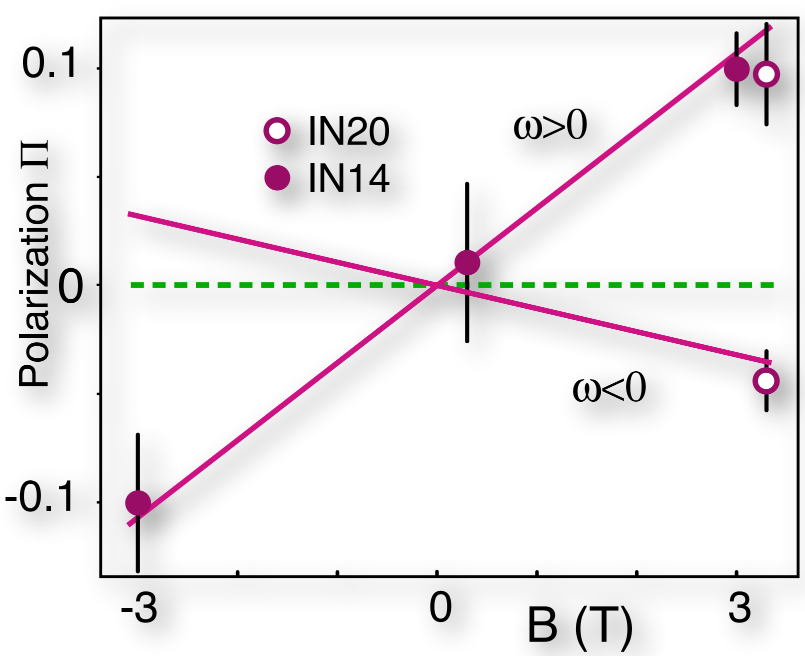


weak field !

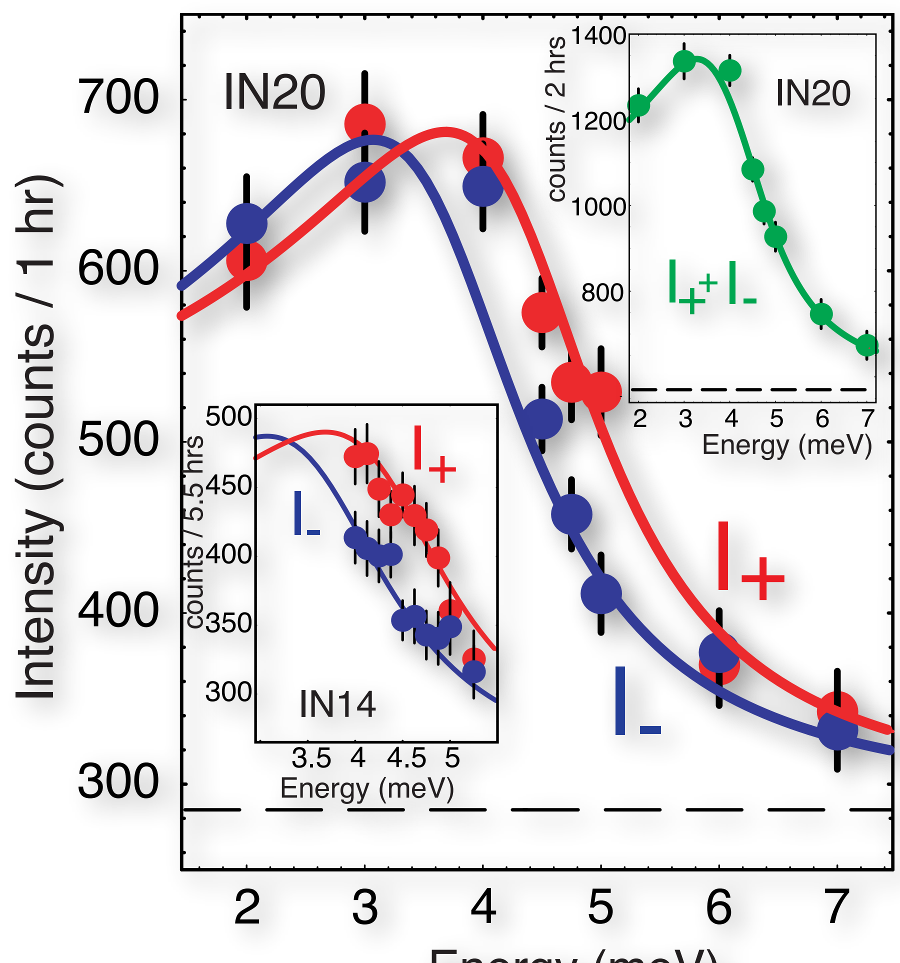
theory



magnetic field



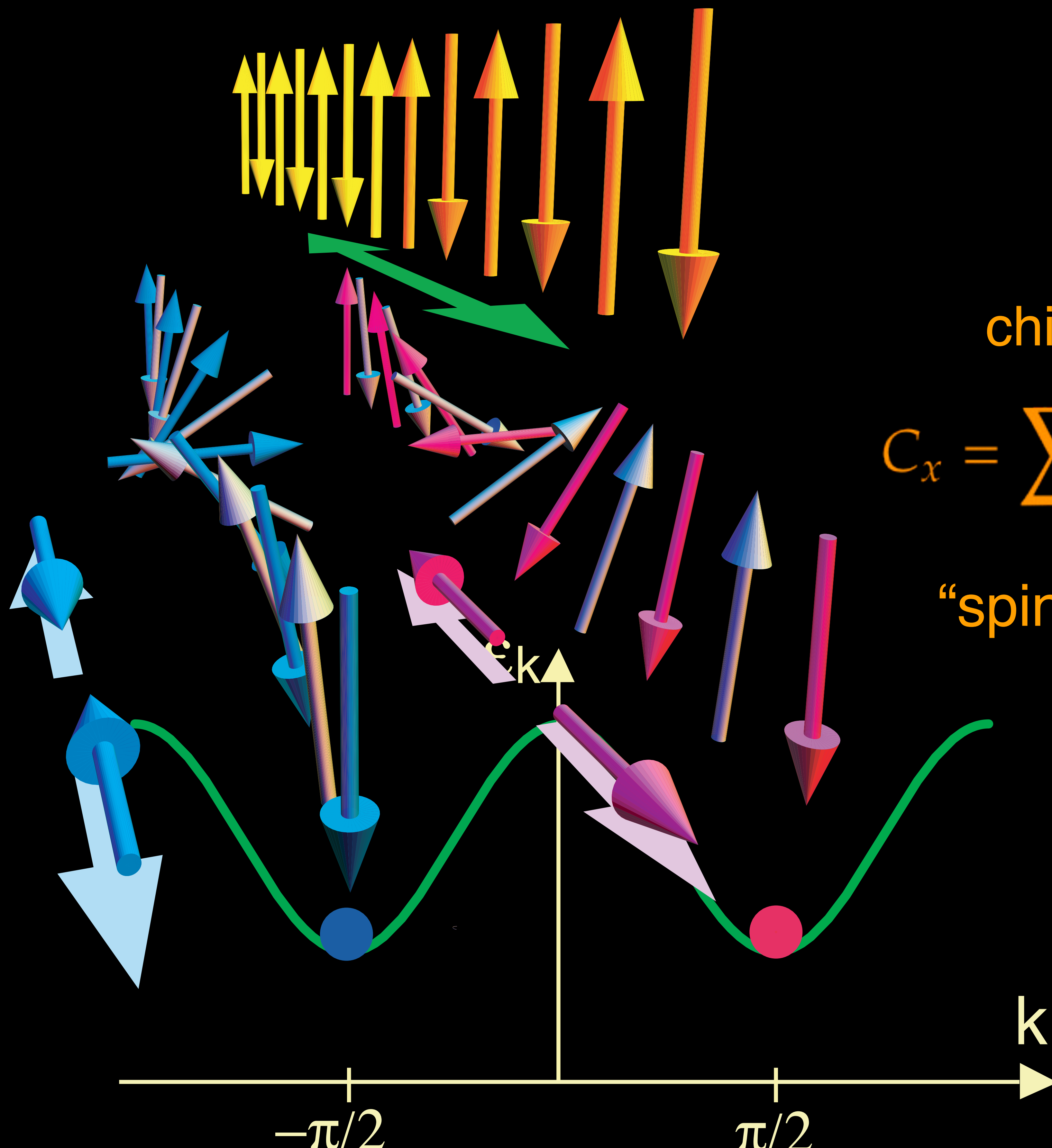
expts (ILL)



First detection of (chargeless) spin currents due to solitons:

HBB et al. *Nature Phys.* **1**, 159 ('05)

Emergence of soliton chirality



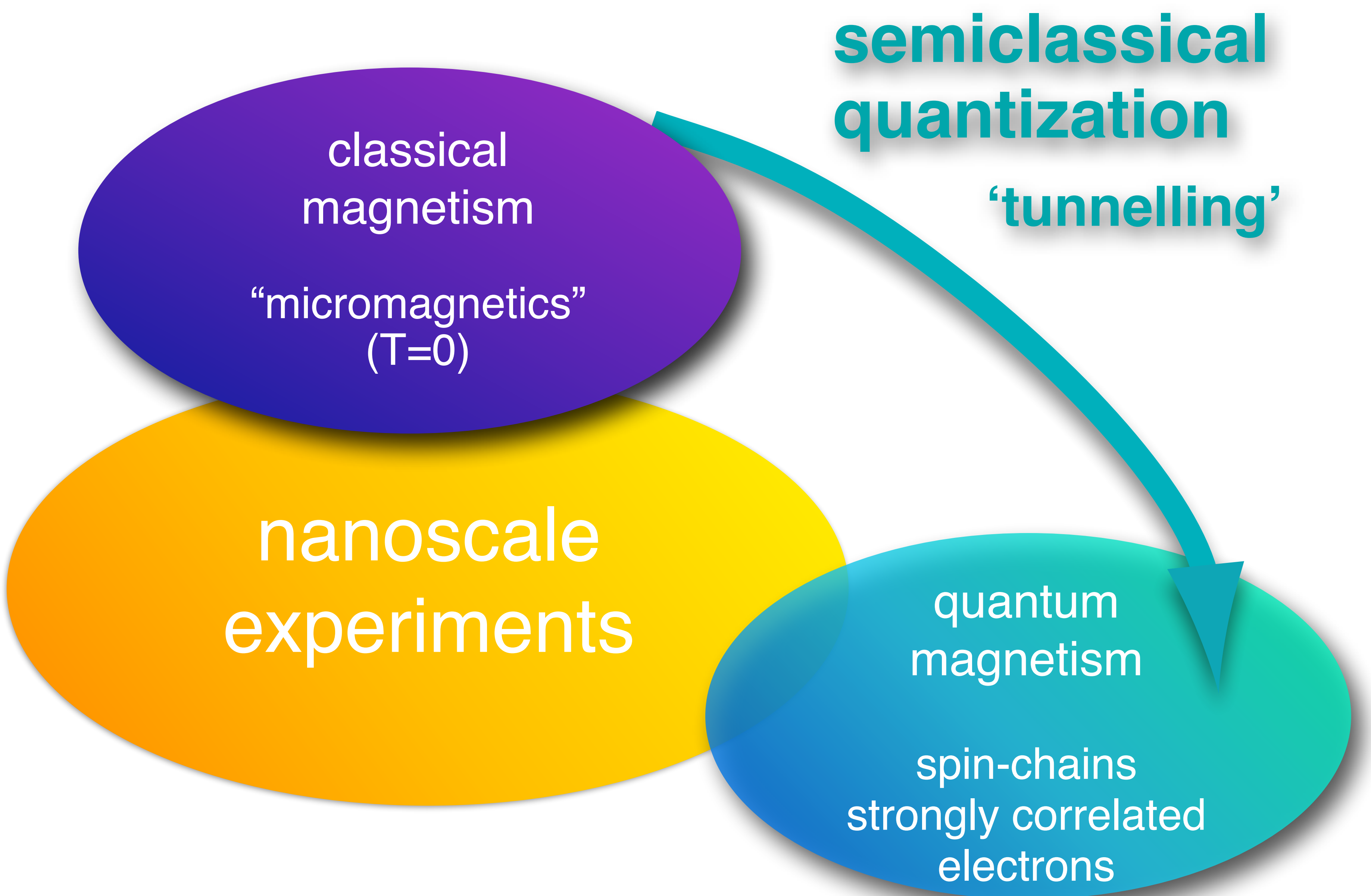
chirality

$$C_x = \sum_i (\mathbf{S}_i \wedge \mathbf{S}_{i+1})_x$$

"spin current"

cf. R. Jansen, this School (spin currents with charge)

Theoretical descriptions of magnetism

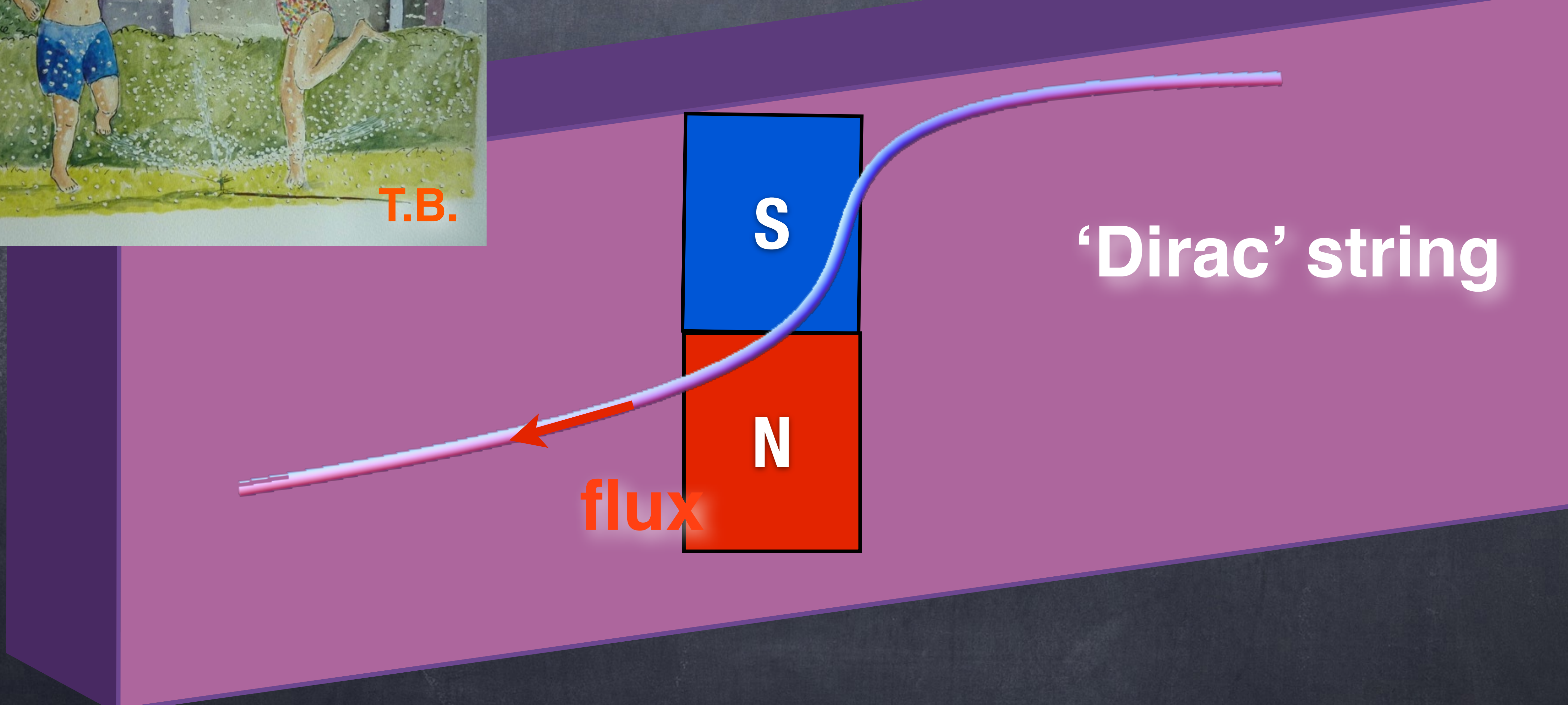


IV. Dipolar interactions in nanomagnetic arrays

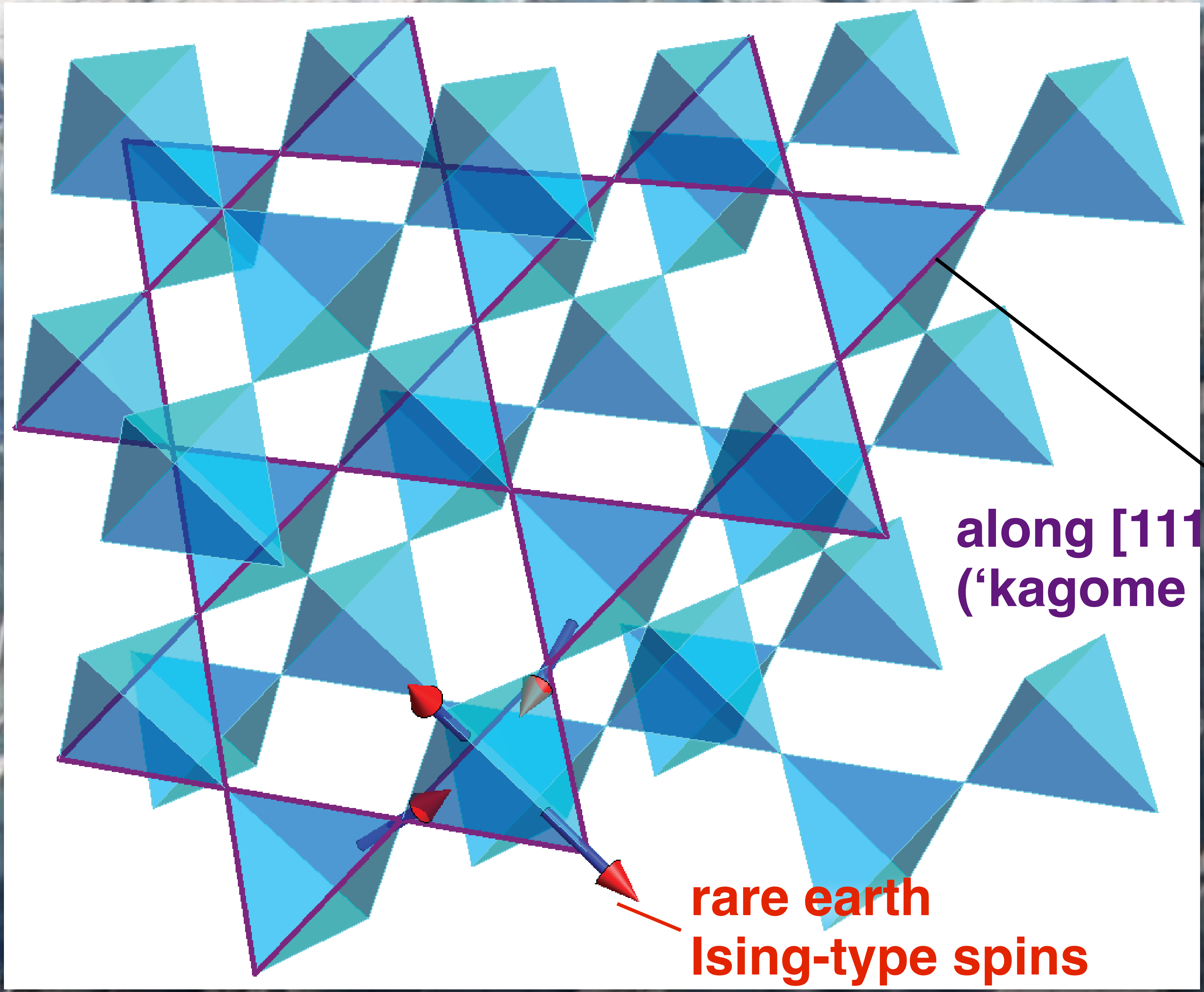
Emergent `monopoles' & `Dirac strings' in pyrochlore spin ice

Emergent `monopoles' and Dirac string avalanches in artificial spin ice - nanolithographic arrays of nanomagnets

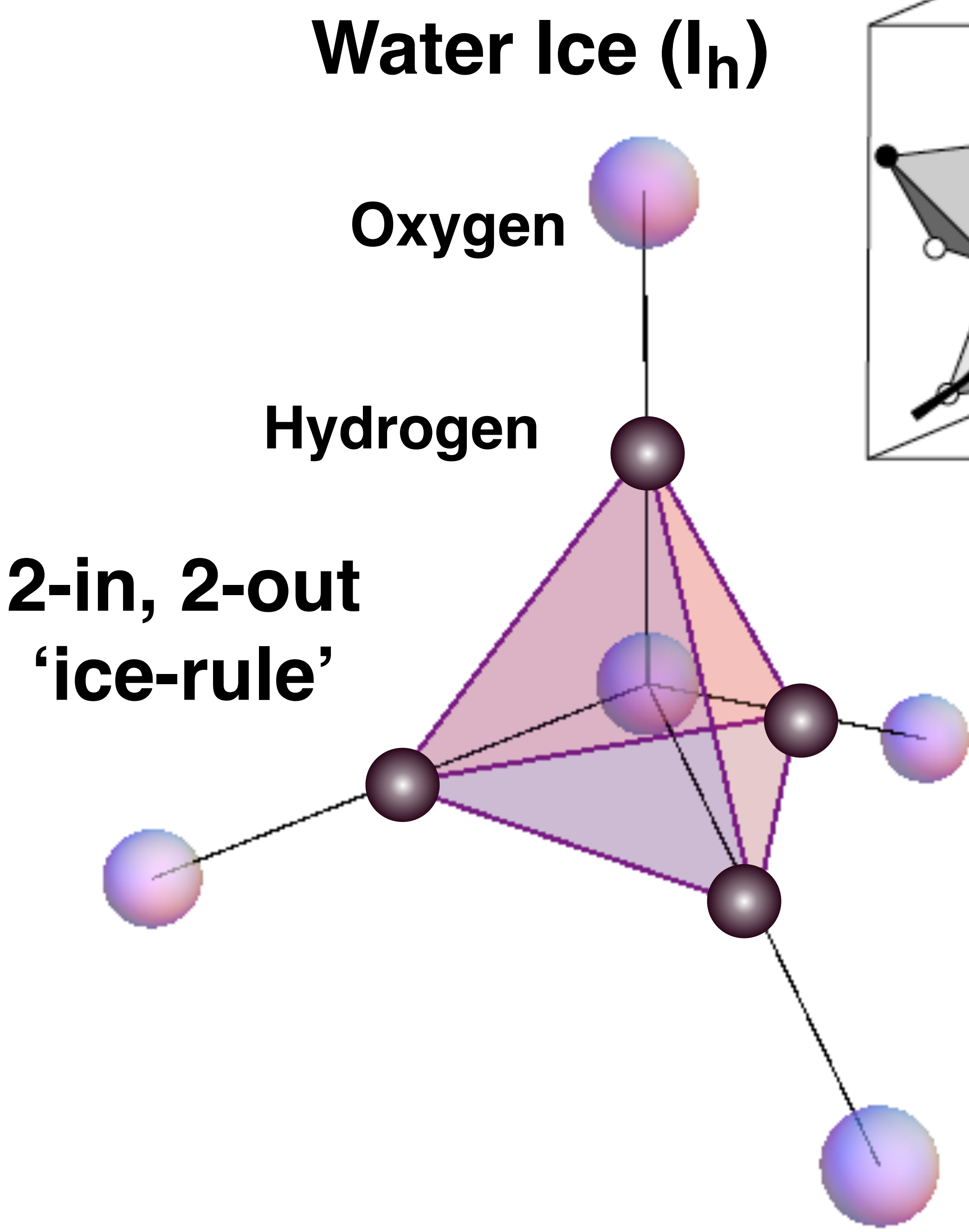
Magnetic Monopoles - Can they exist as emergent quasiparticles?



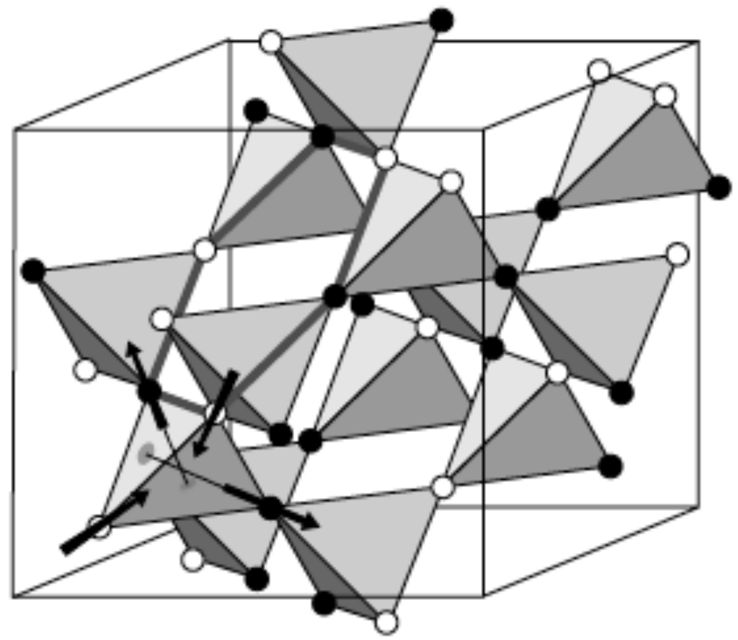
Pyrochlore spin-ice

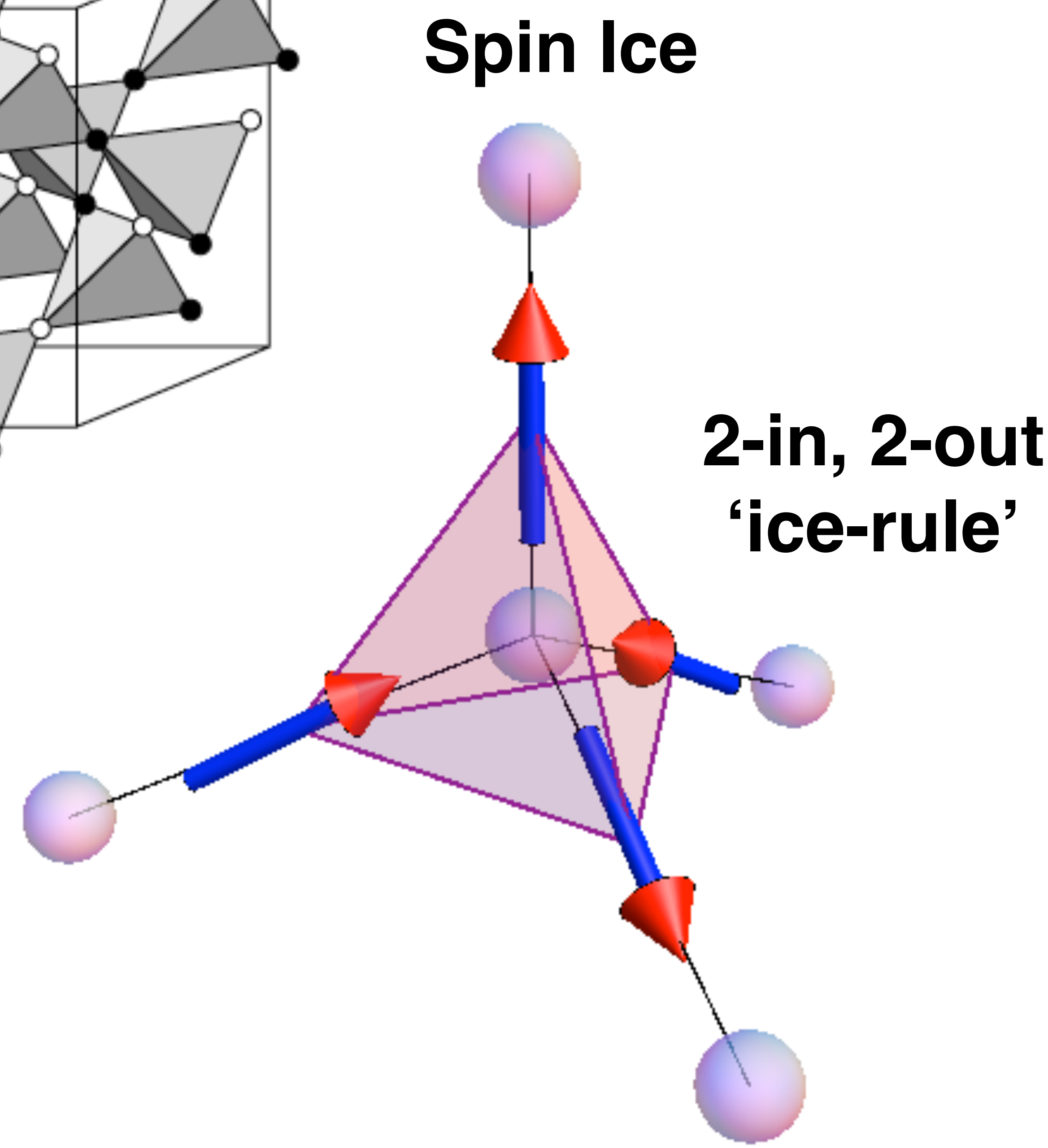


Why `spin-ice' ?



Water Ice (I_h)
Oxygen
Hydrogen
2-in, 2-out
'ice-rule'





Spin Ice
2-in, 2-out
'ice-rule'

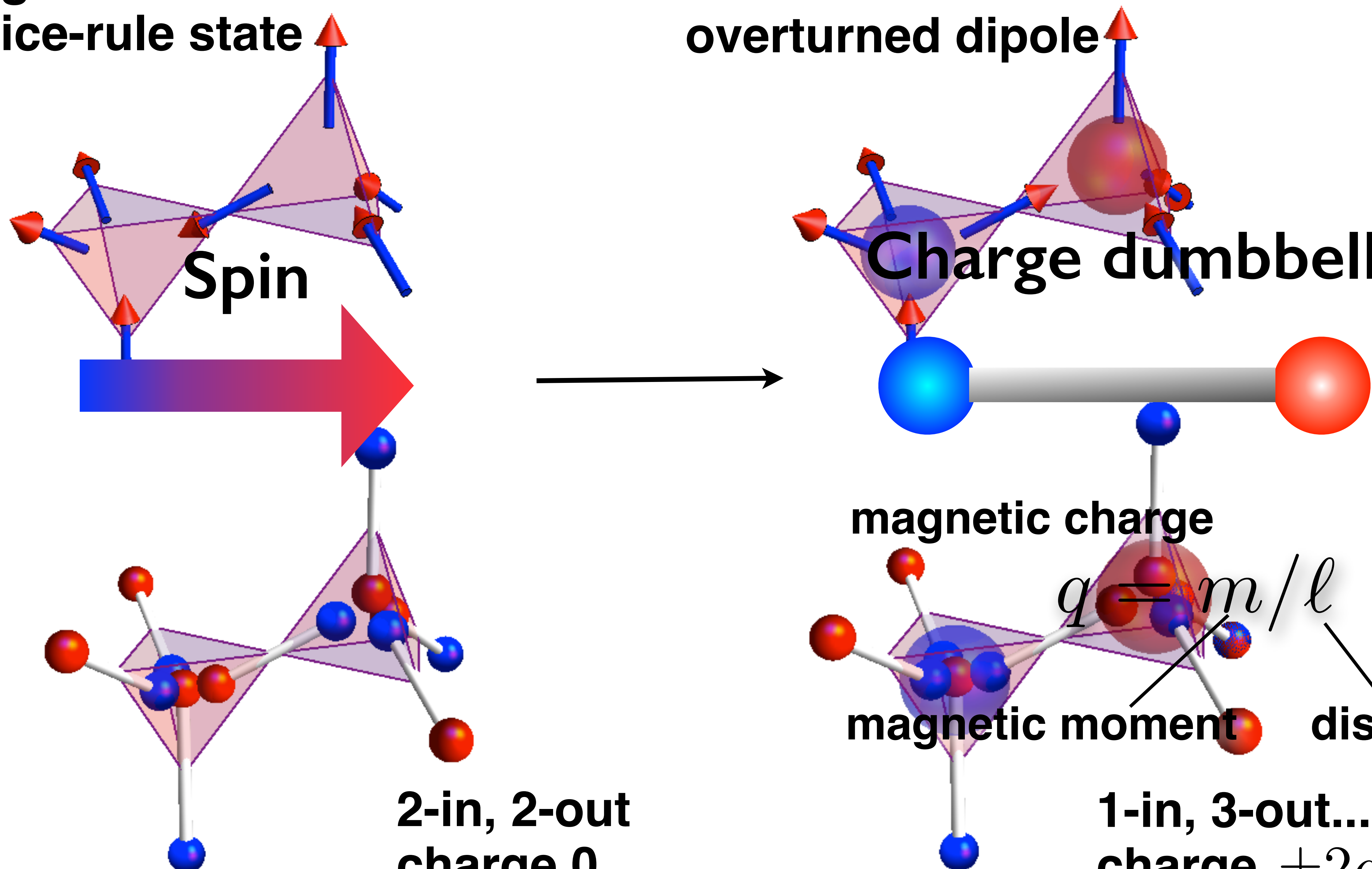
Excitations - dipoles as charge dumbbells

Castelnovo, Moessner, Sondhi, Nature ('08)

Ryzhkin ('05)

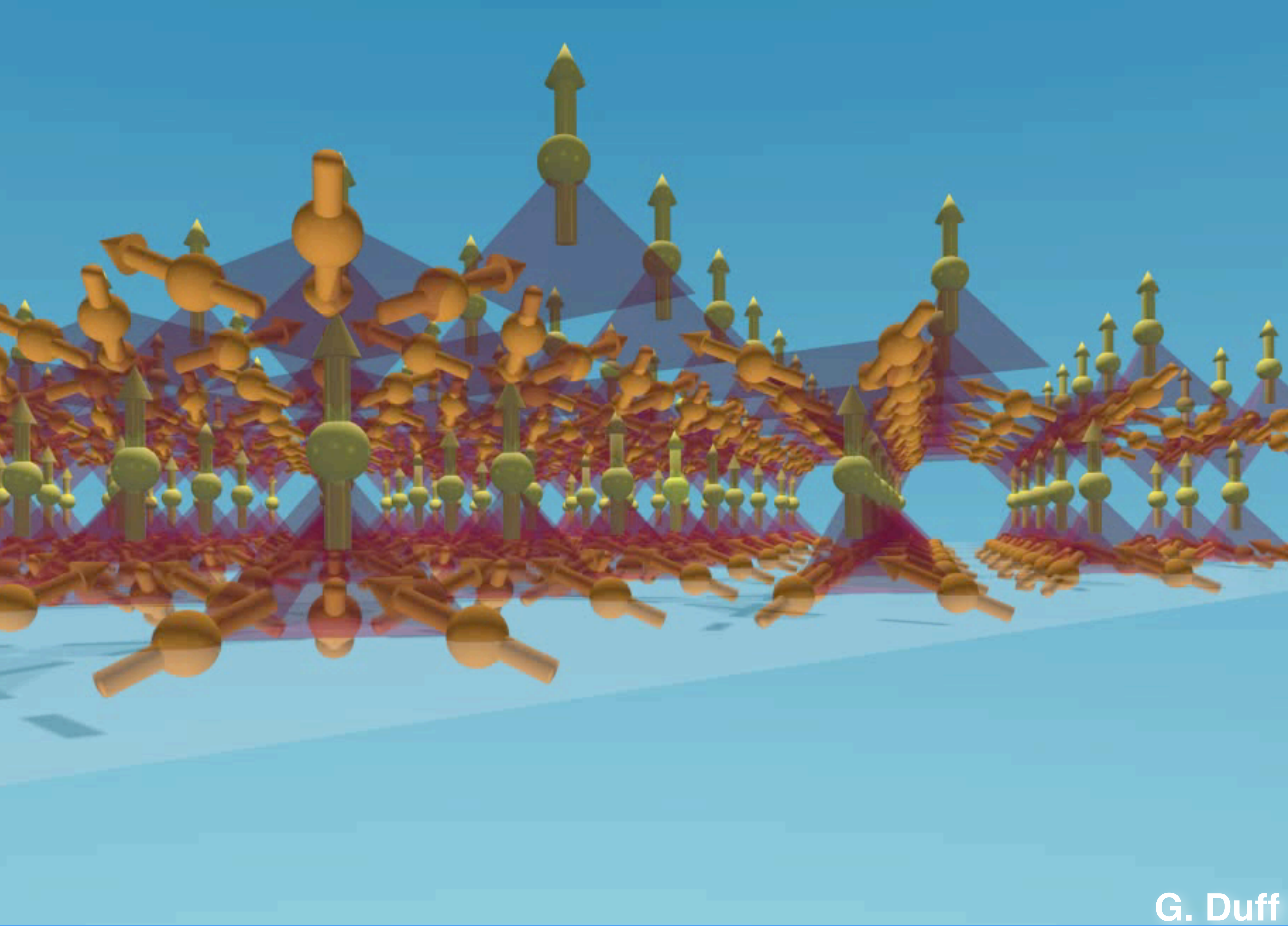
ground state
ice-rule state

excited state
overturned dipole

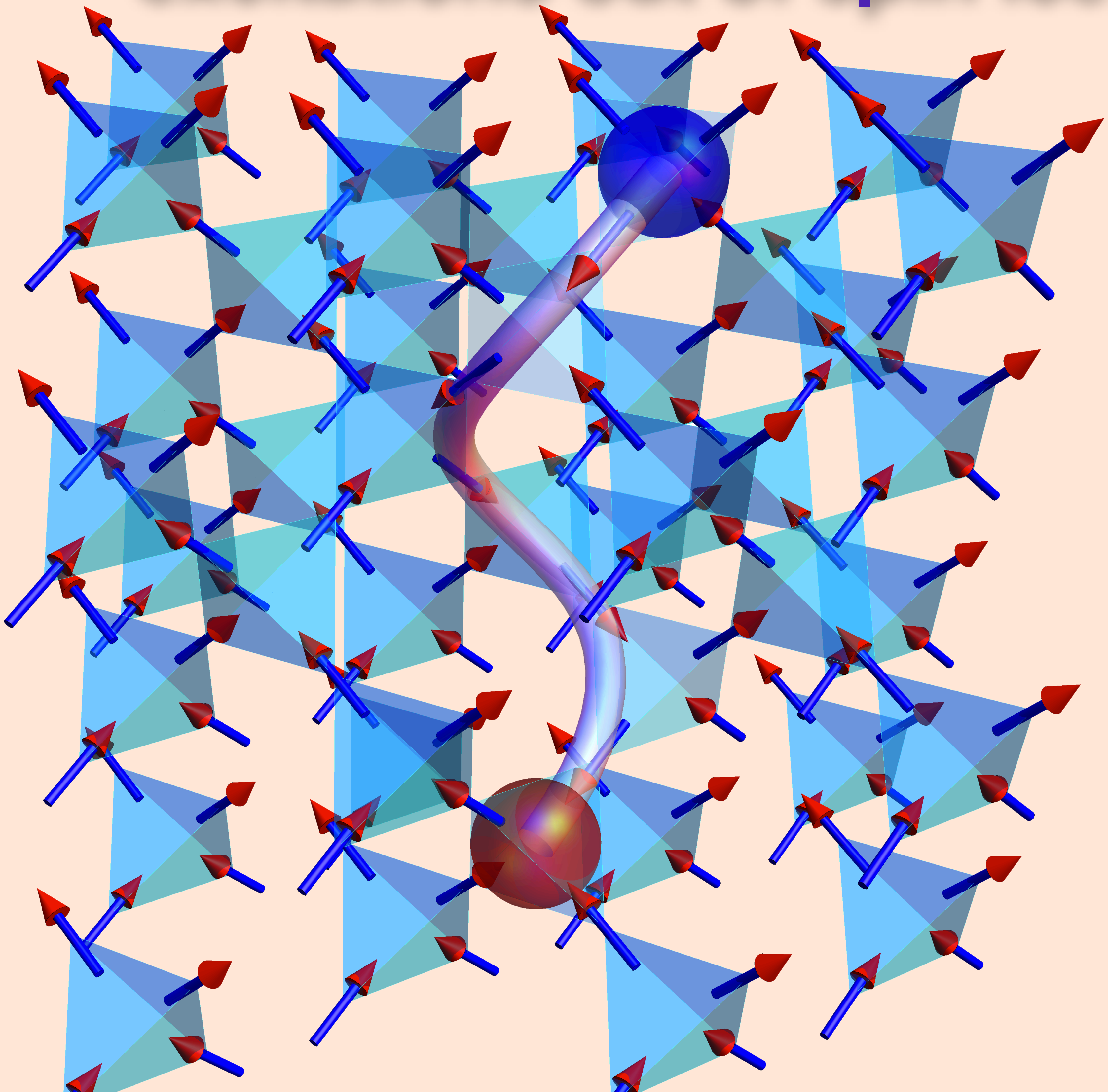


2-in, 2-out
charge 0

1-in, 3-out.....
charge $\pm 2q$


G. Duff

Monopoles and (unquantized) Dirac strings as excitations out of spin ice ground state

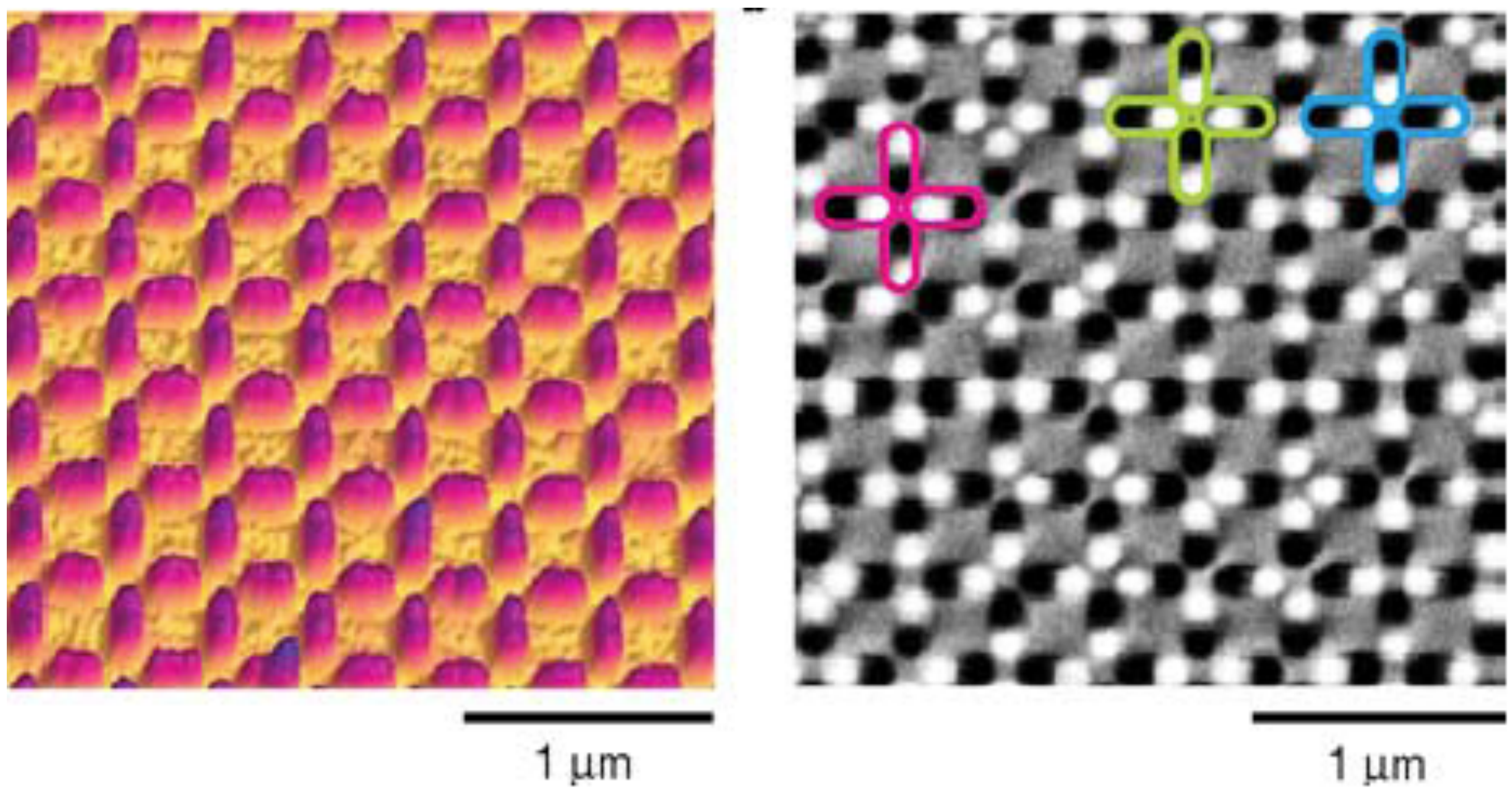


Neutron scattering expts:
Morris et al, Science ('09)
Kadowaki et al. ('09)
Fennell et al. ('09)

$$T \lesssim 1\mathrm{K}\,!$$

Low T and reciprocal space - can one do better?

Artificial spin ice - dipolar coupled array of isolated nanoislands

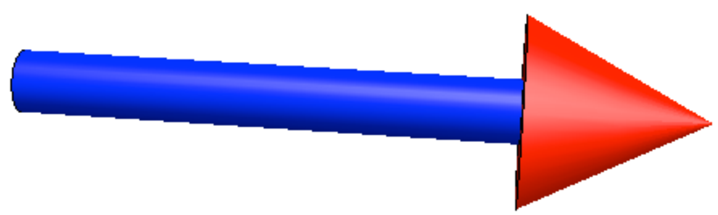


Wang et al. Nature ('06)

Isolated nanoislands as macrospins

Magnetic moments in (artificial) spin ice

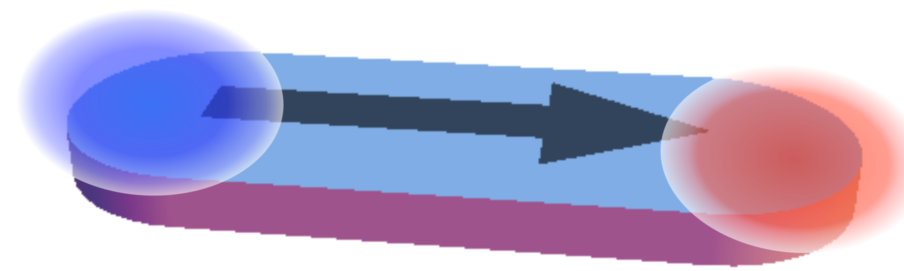
Pyrochlore spin ice



rare earth spin

moment m

Artificial spin ice

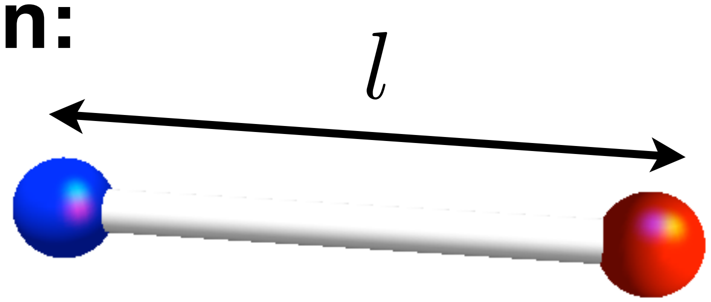


permalloy island
`macrospin’

effective description:

charge
dumbbell

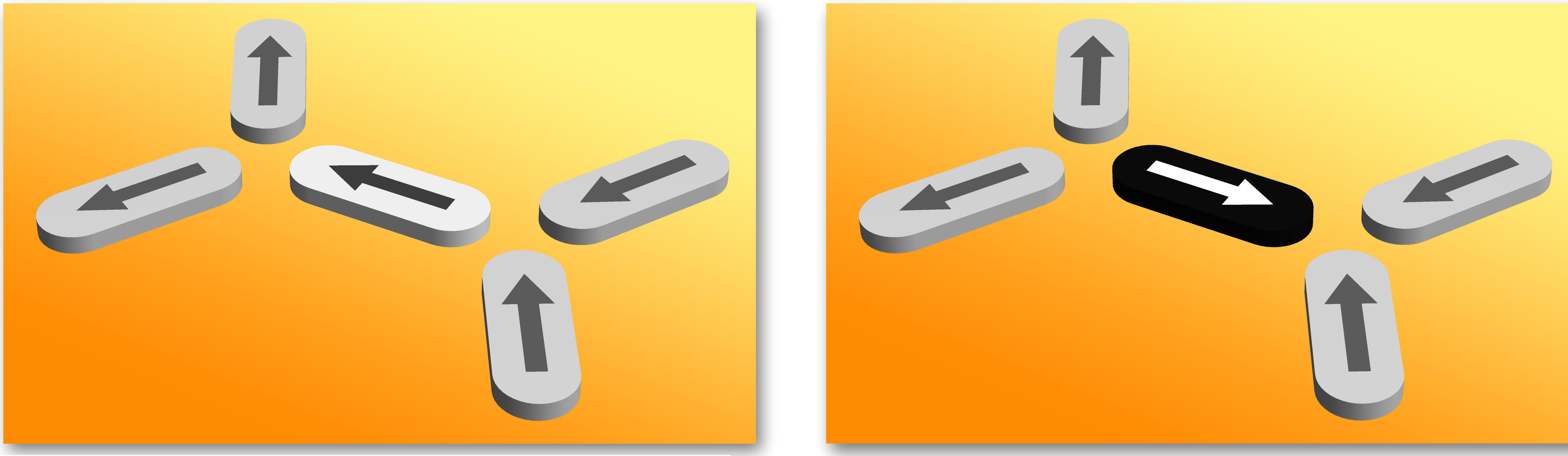
charge

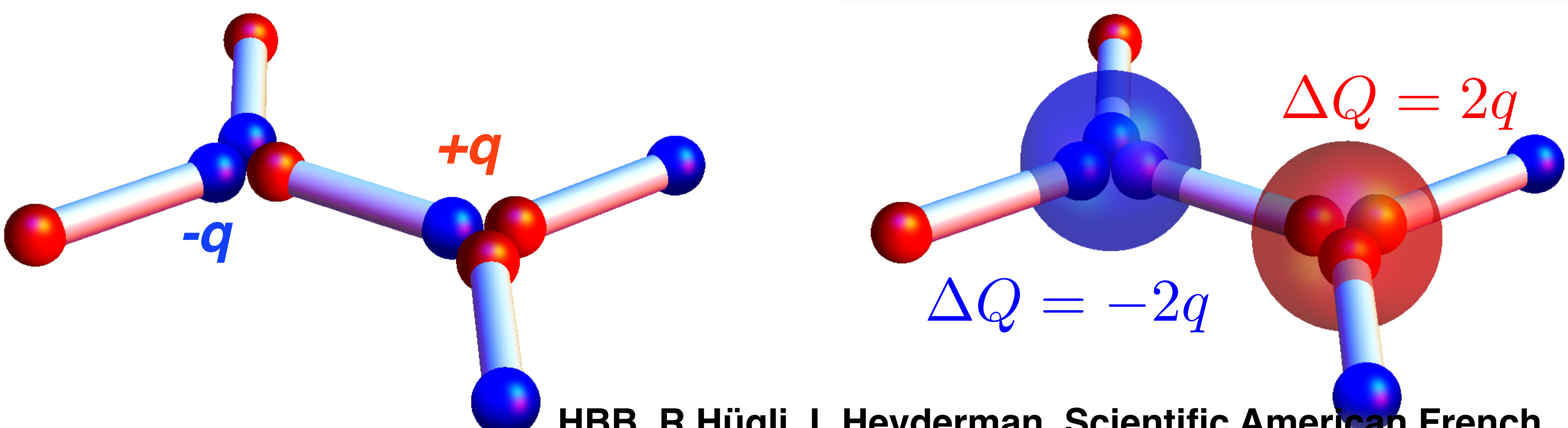


charge
dumbbell

$$q = m/l$$

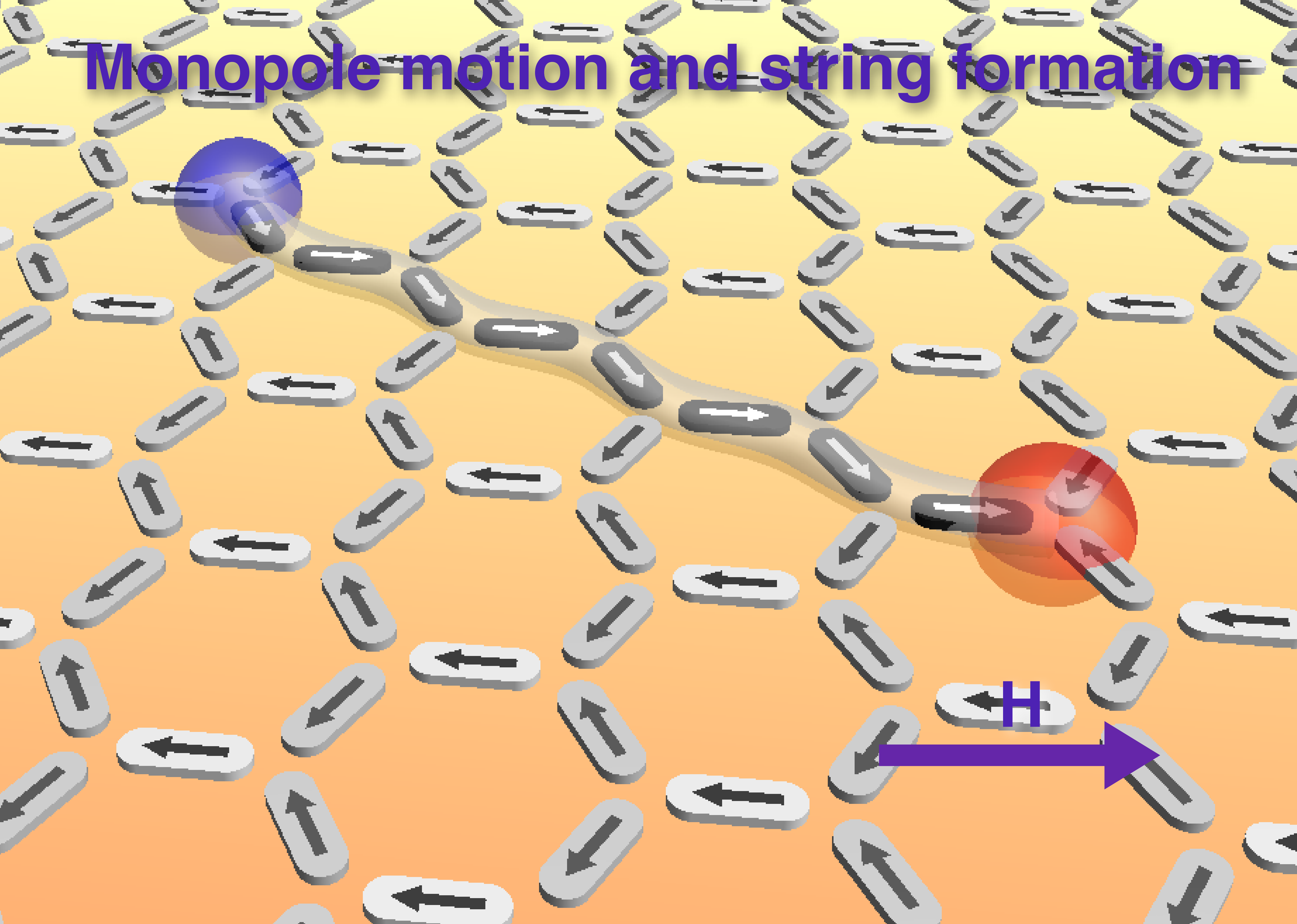
Dumbbell picture





HBB, R Hügli, L Heyderman, Scientific American French Edition ('Pour La Science'), April-June ('13)

Monopole motion and string formation



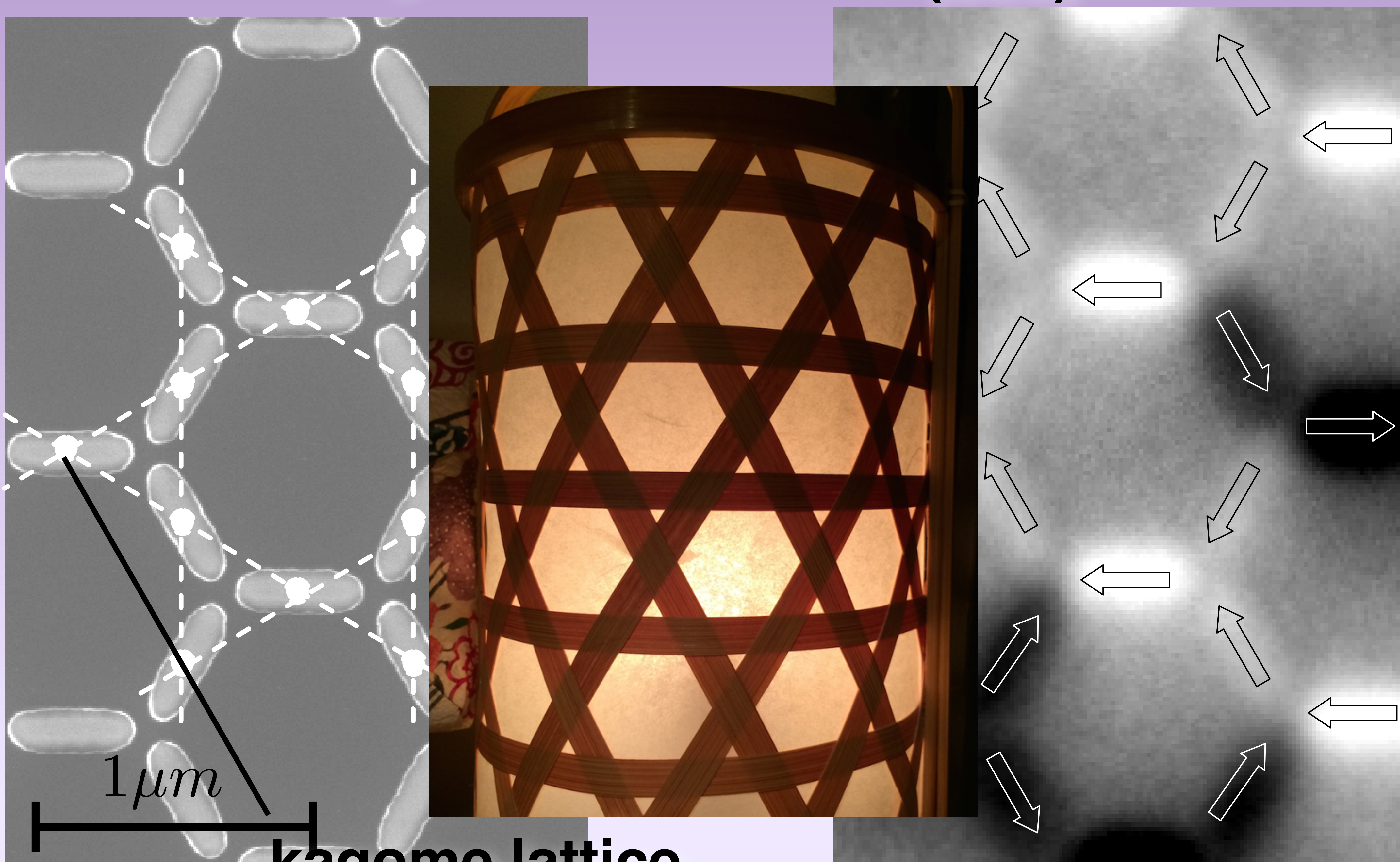

PAUL SCHERRER INSTITUT

Islands on a kagome lattice

with L. Heyderman, F. Nolting, R. Hügli, G.Duff

SEM image

PEEM image (SLS)



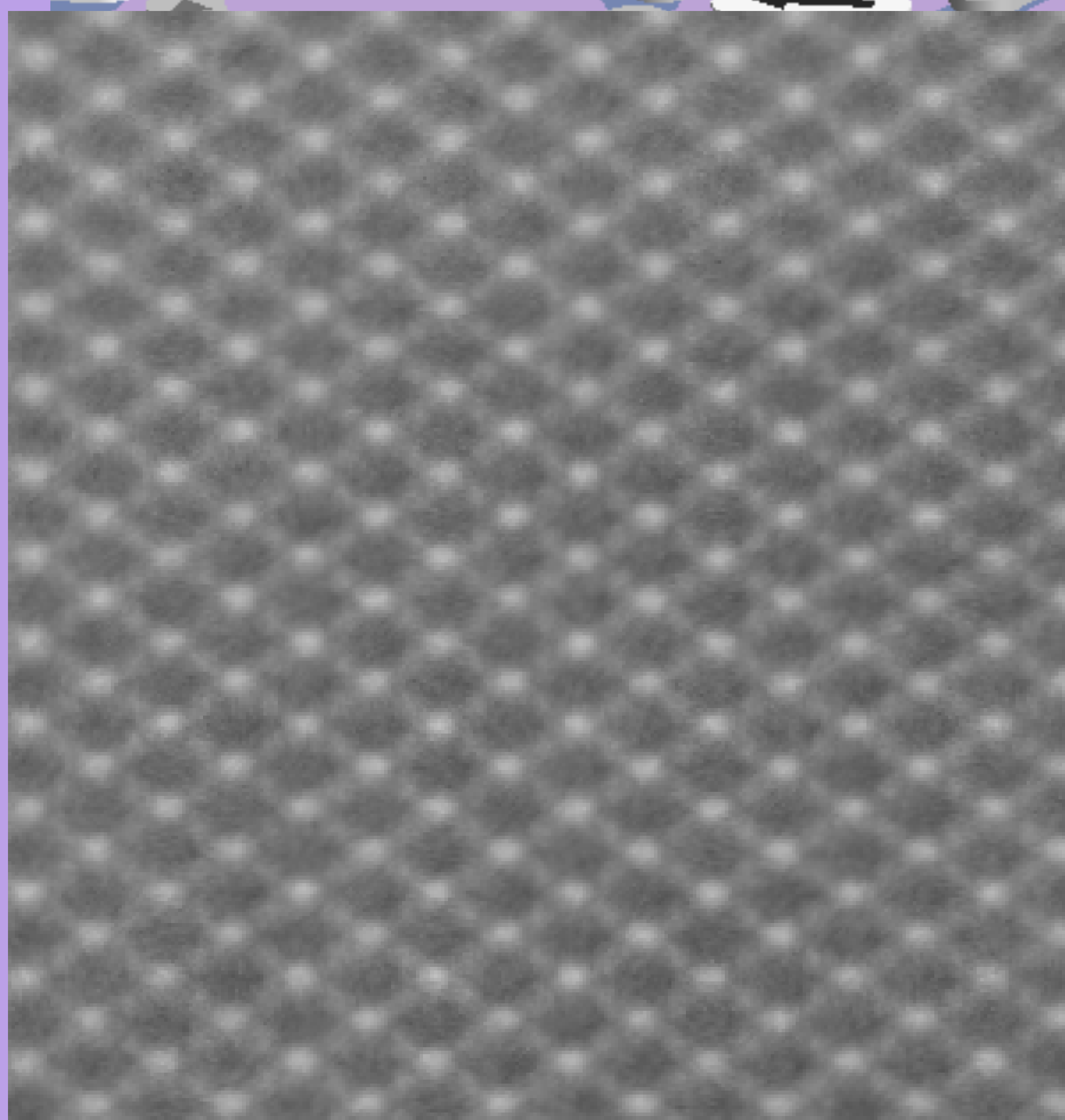
kagome lattice

contrast depends on orientation

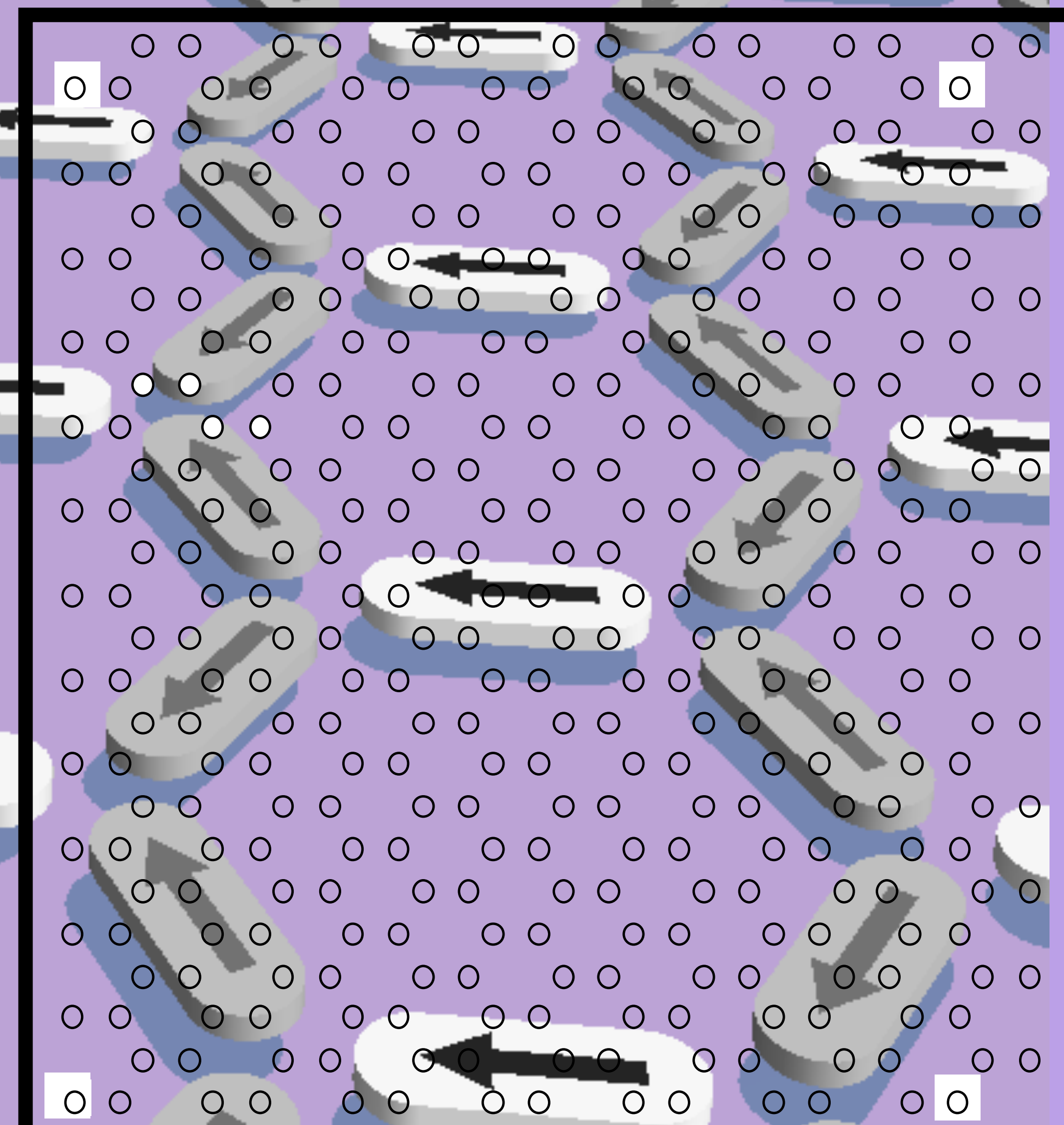
Initial saturation

H< 0.82 H_c

PEEM image



Charge map

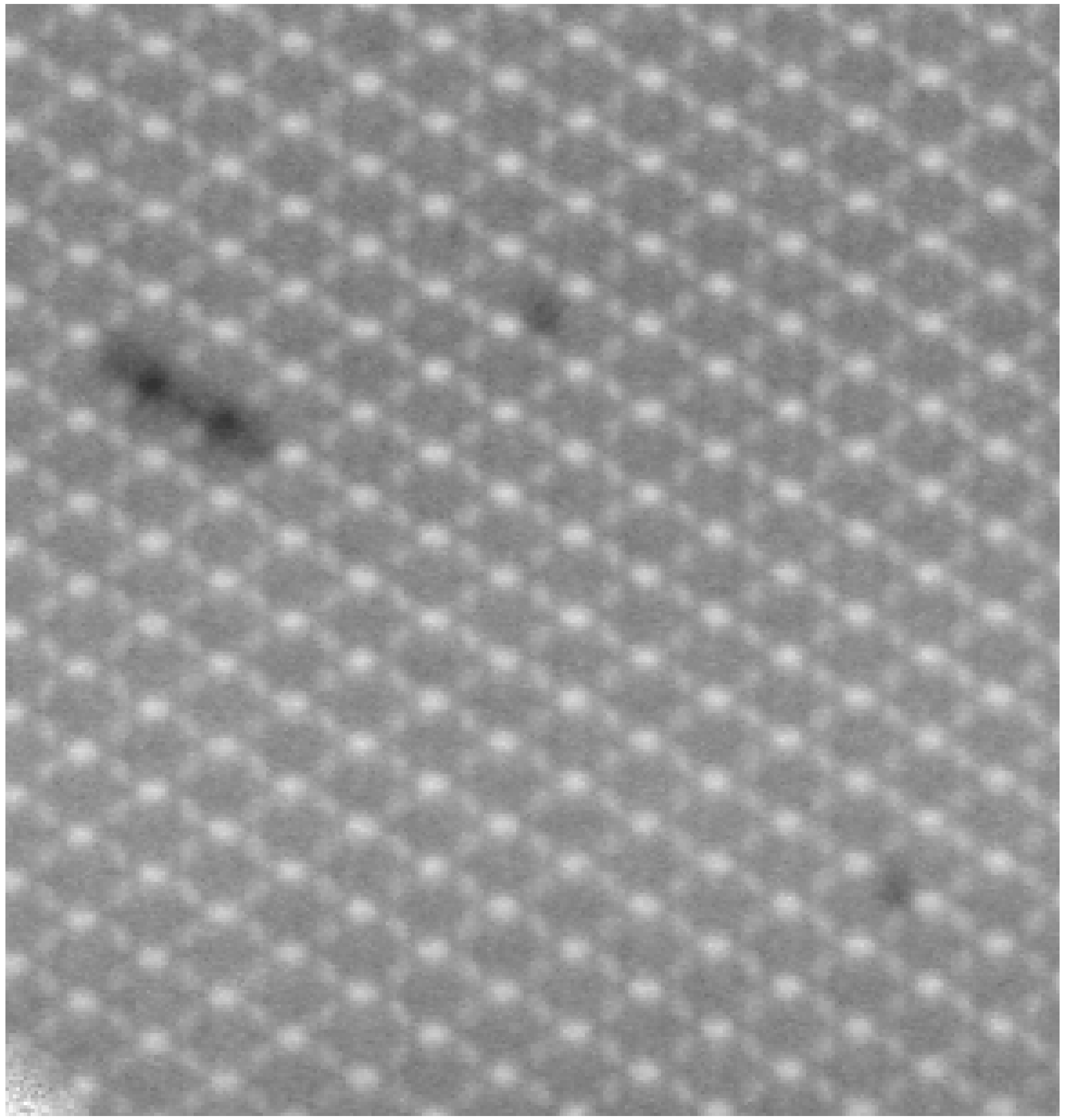


ΔQ map

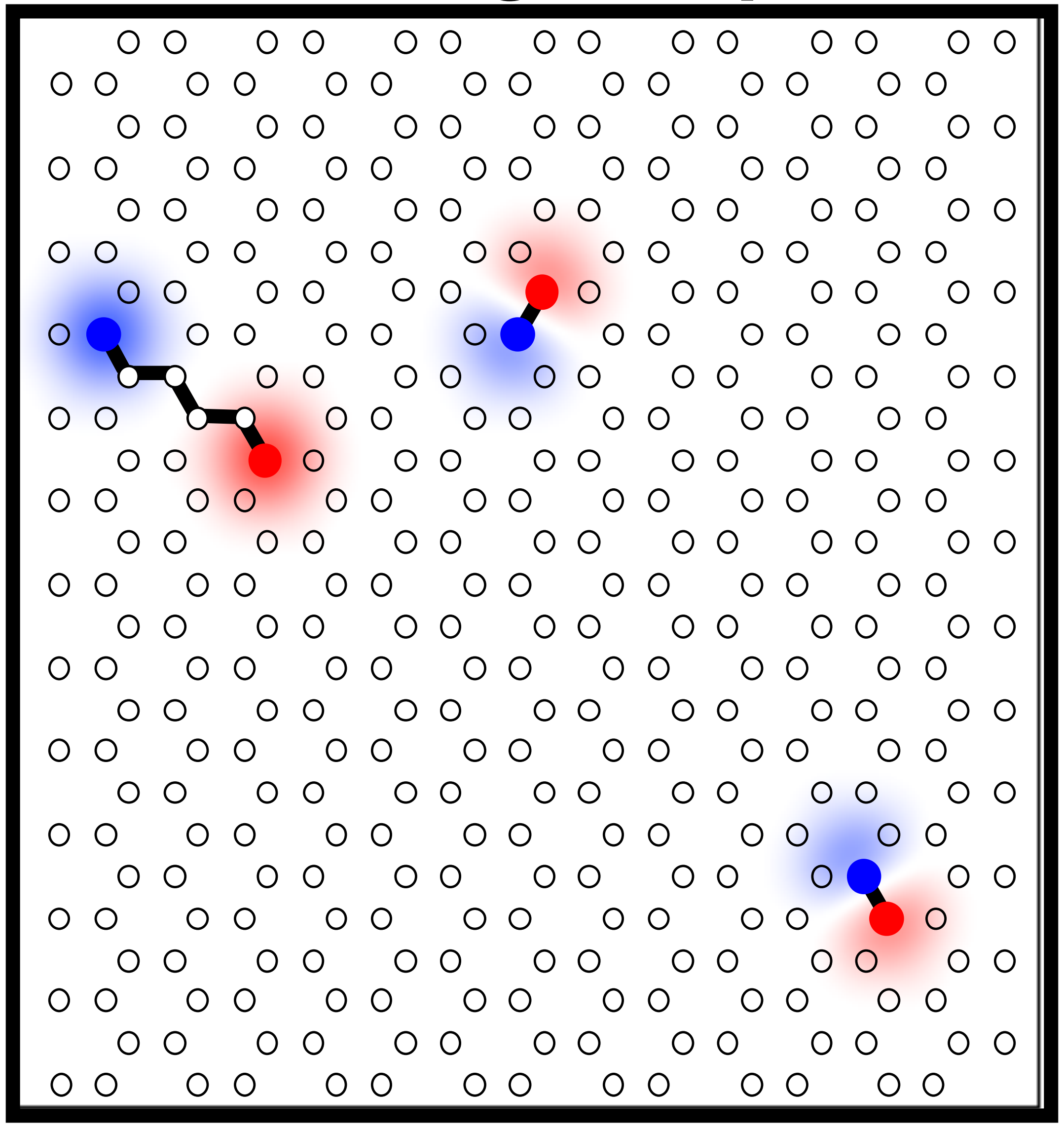
$H=0.85\ H_c$

E. Mengotti *et al.*, Nature Phys. **7**, 68 (2011)

PEEM image



charge map



smeared charge density ('MFM')

Gaussian

$$\rho_m(\mathbf{r}) = \int d^2r'\ f_G(\mathbf{r}-\mathbf{r}')\ \rho_Q(\mathbf{r}')$$

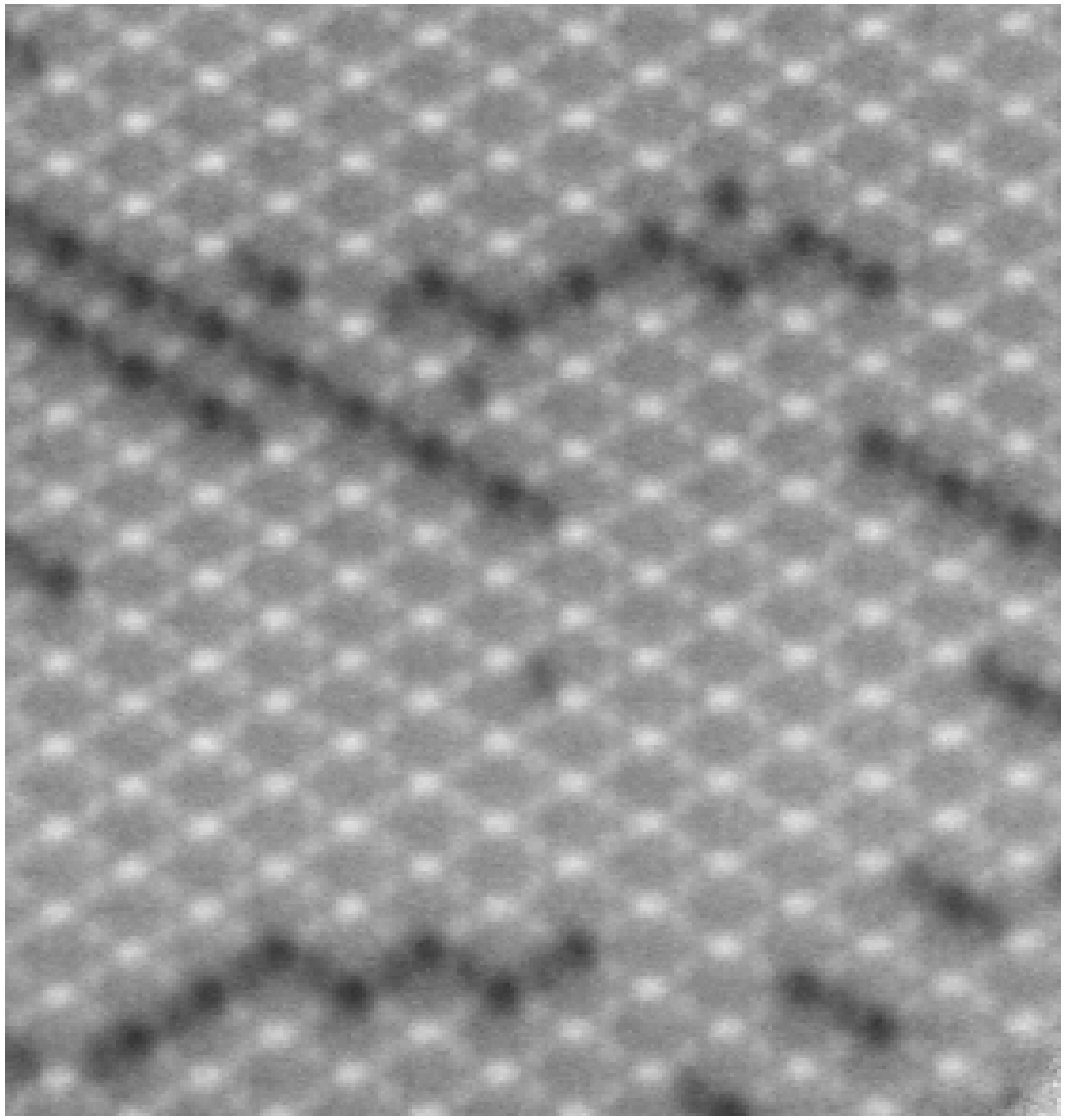
ΔQ **map**

total charge

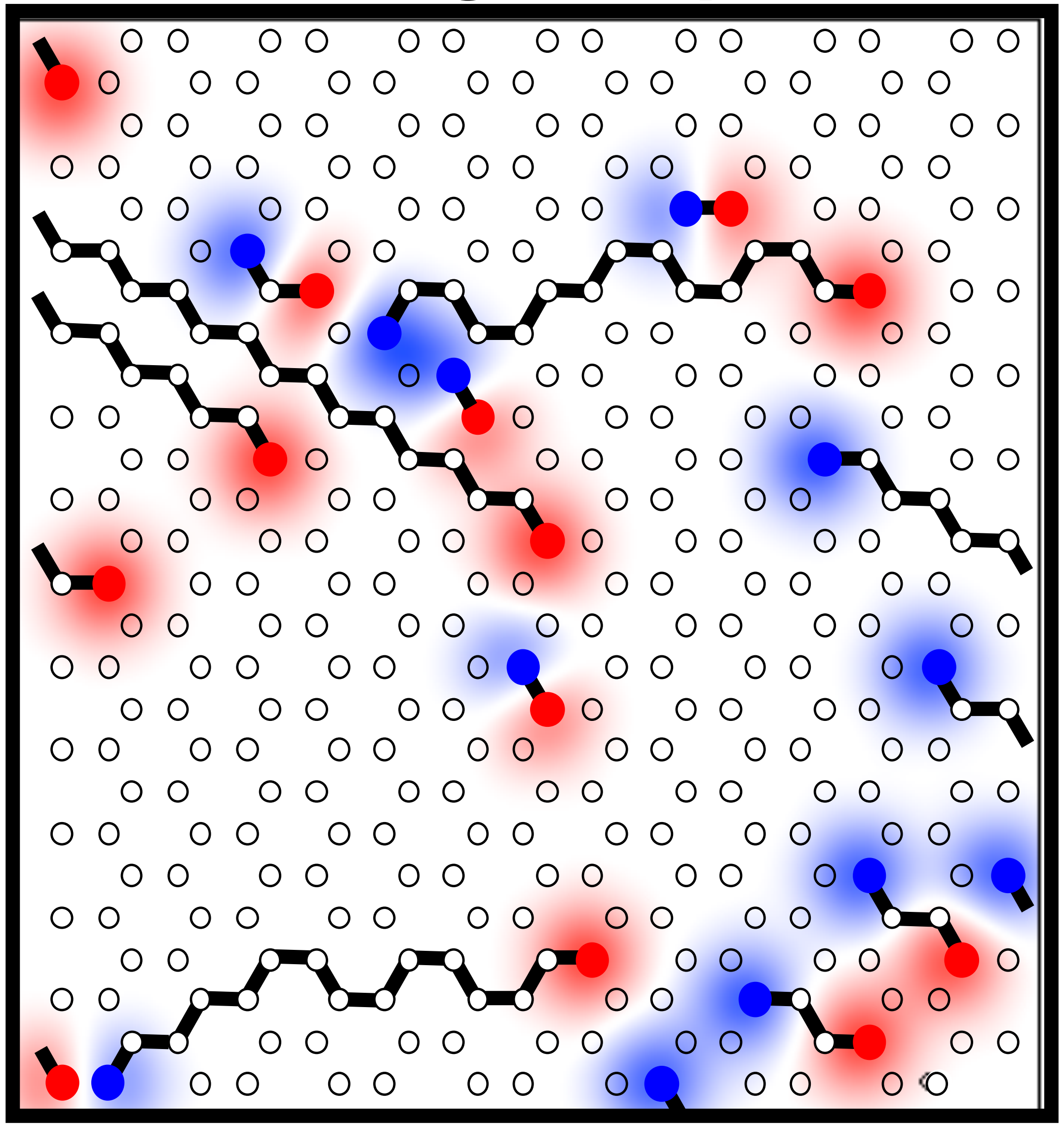
$$\rho_Q(\mathbf{r}) = \sum Q_\alpha\ \delta(\mathbf{r}-\mathbf{R}_\alpha)$$

$H = 0.92\ H_c$

PEEM image

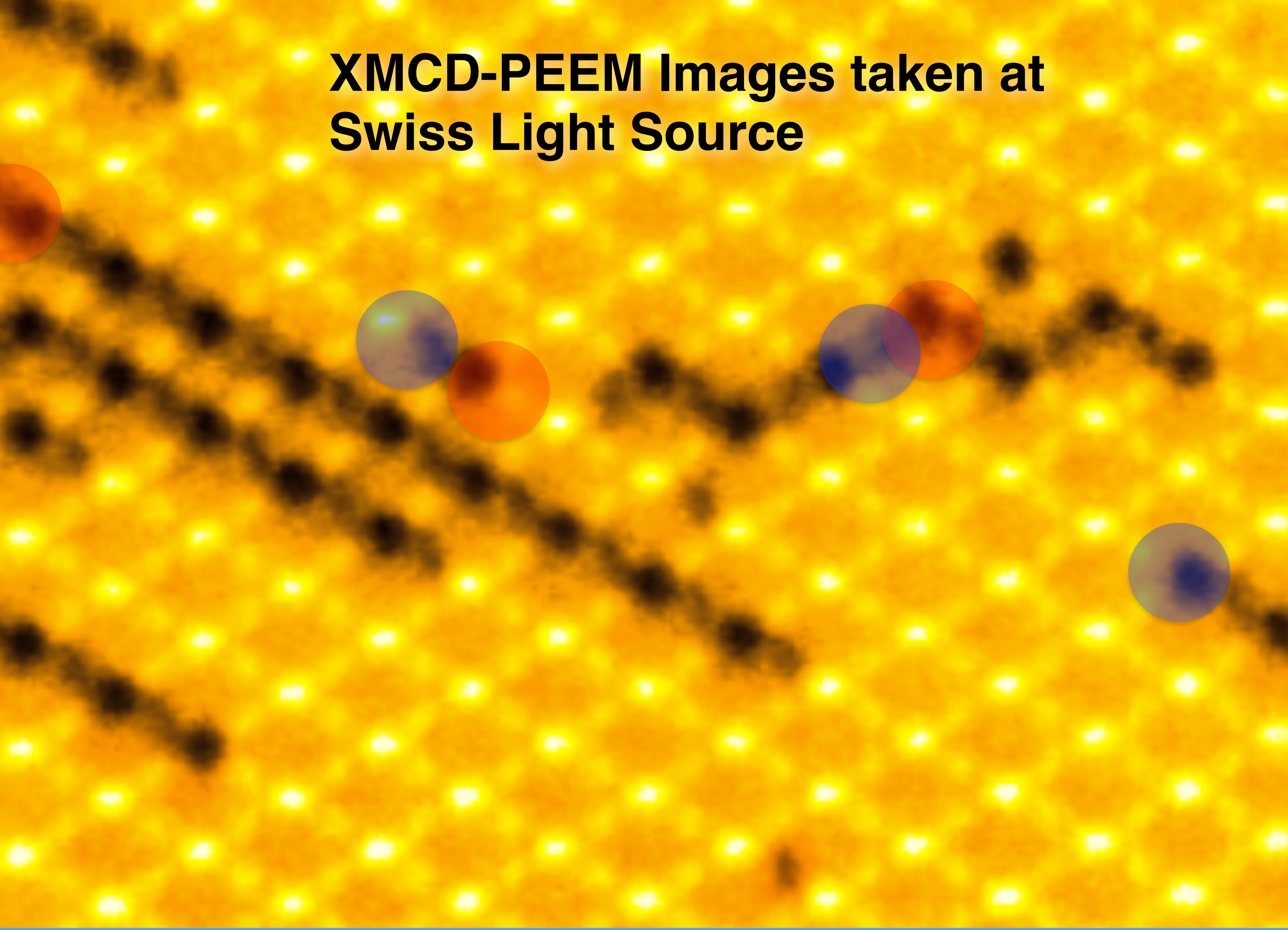


charge map



ΔQ map

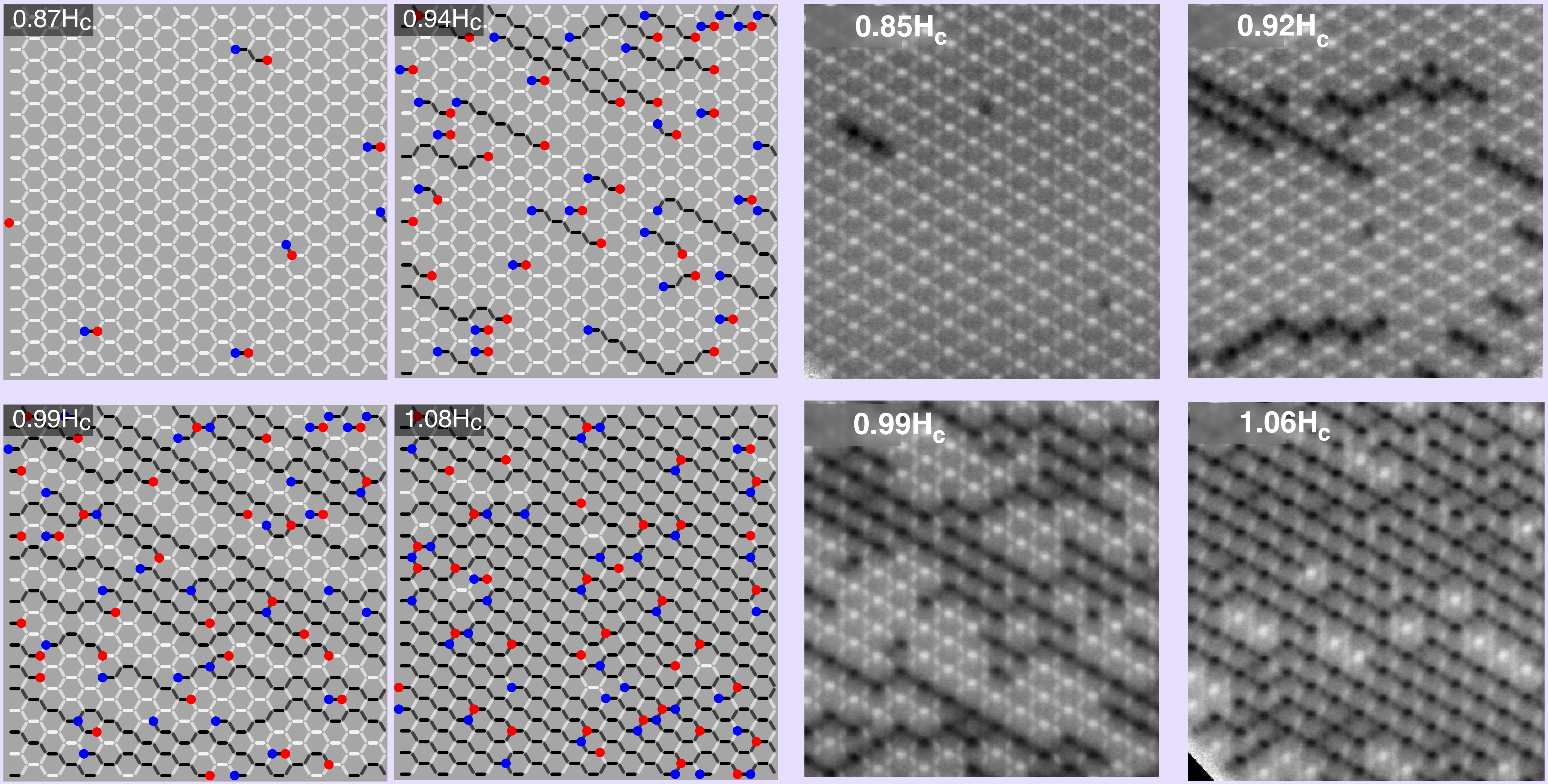
XMCD-PEEM Images taken at Swiss Light Source



Dirac strings and monopoles

Simulations | **PEEM images**

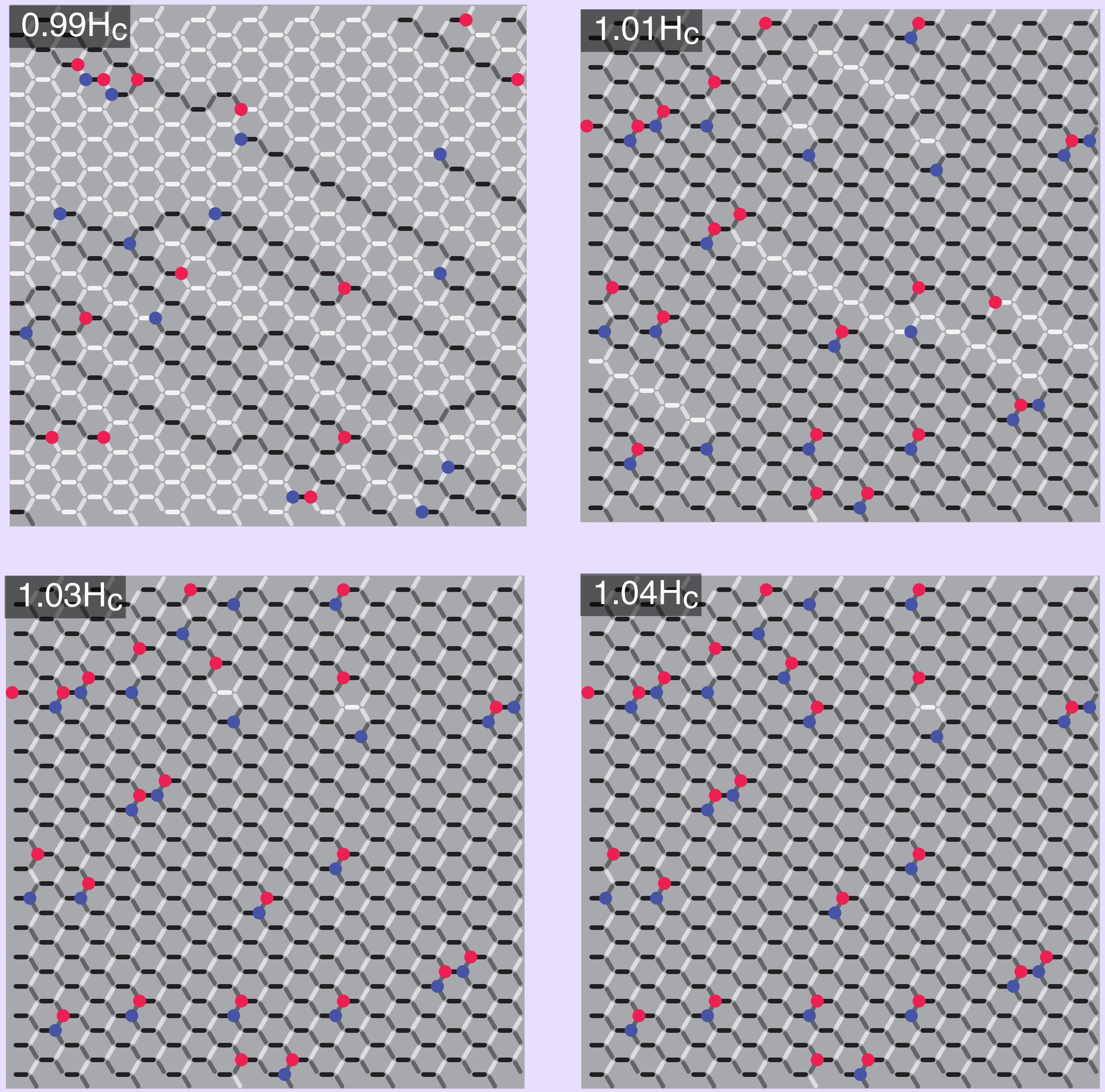
E. Mengotti *et al.*, Nature Phys. **7**, 68 (2011)



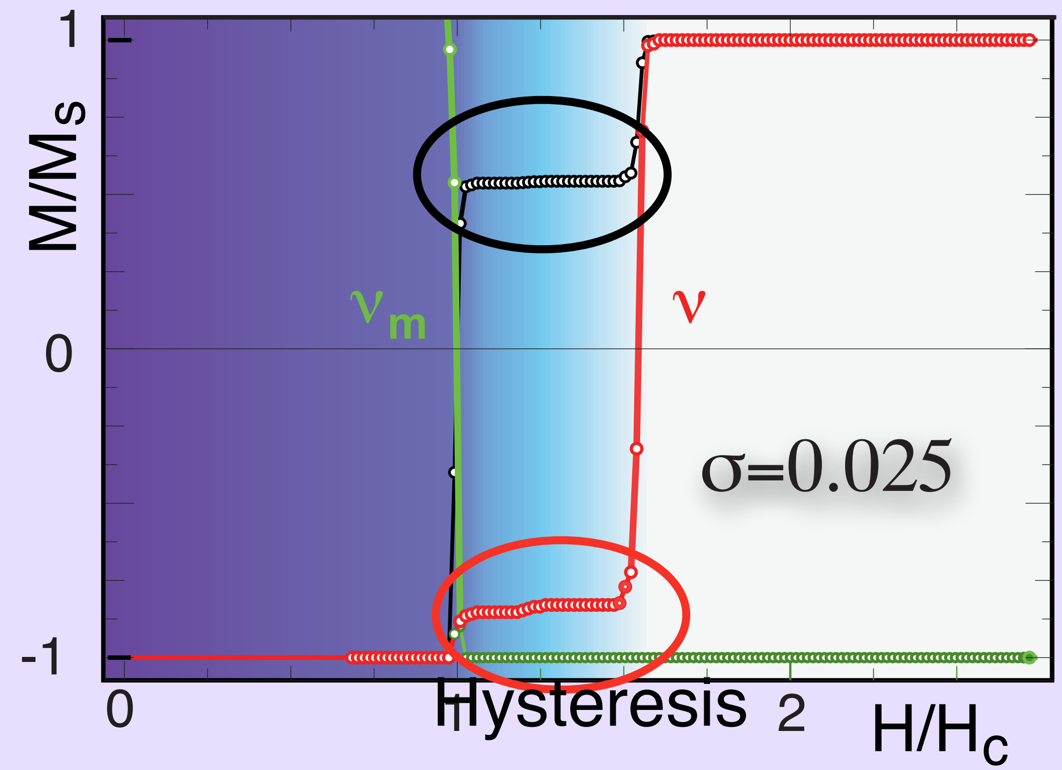
Low Disorder (simulations)

R. Hügli *et al.*, Phil. Trans. R. Soc. A 370, 5767 (2012)

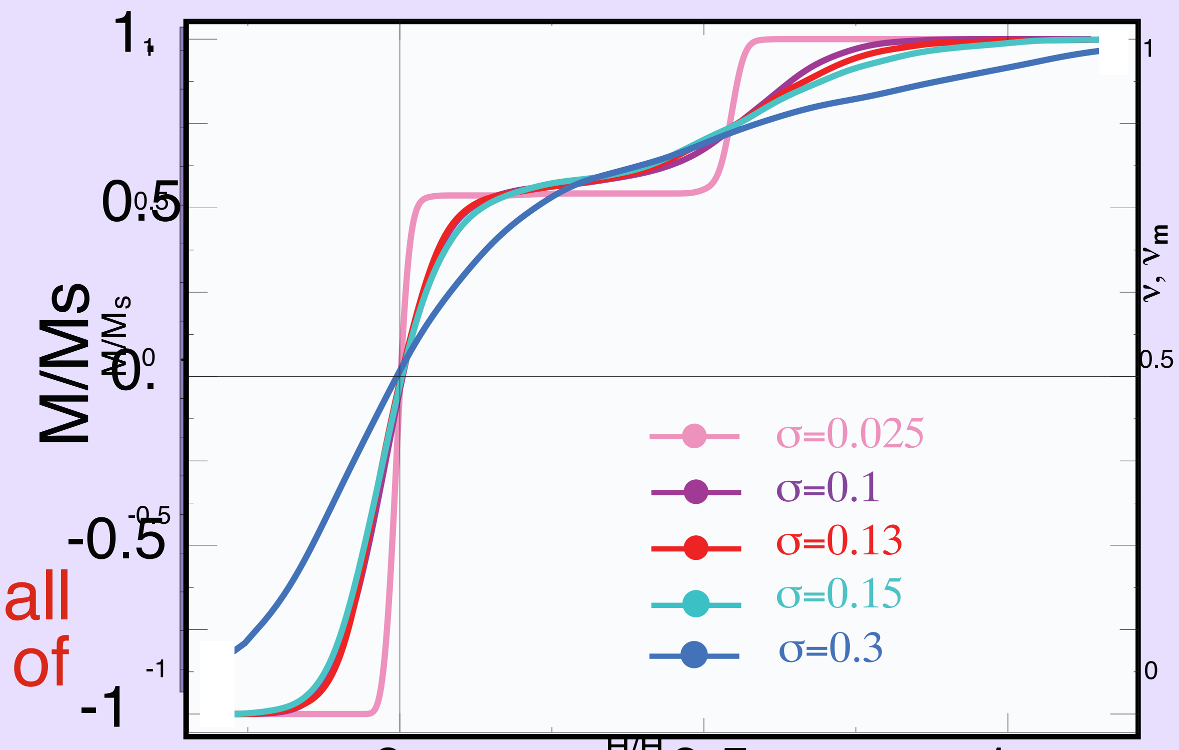
σ=0.025



Distinct stripe phase plateau

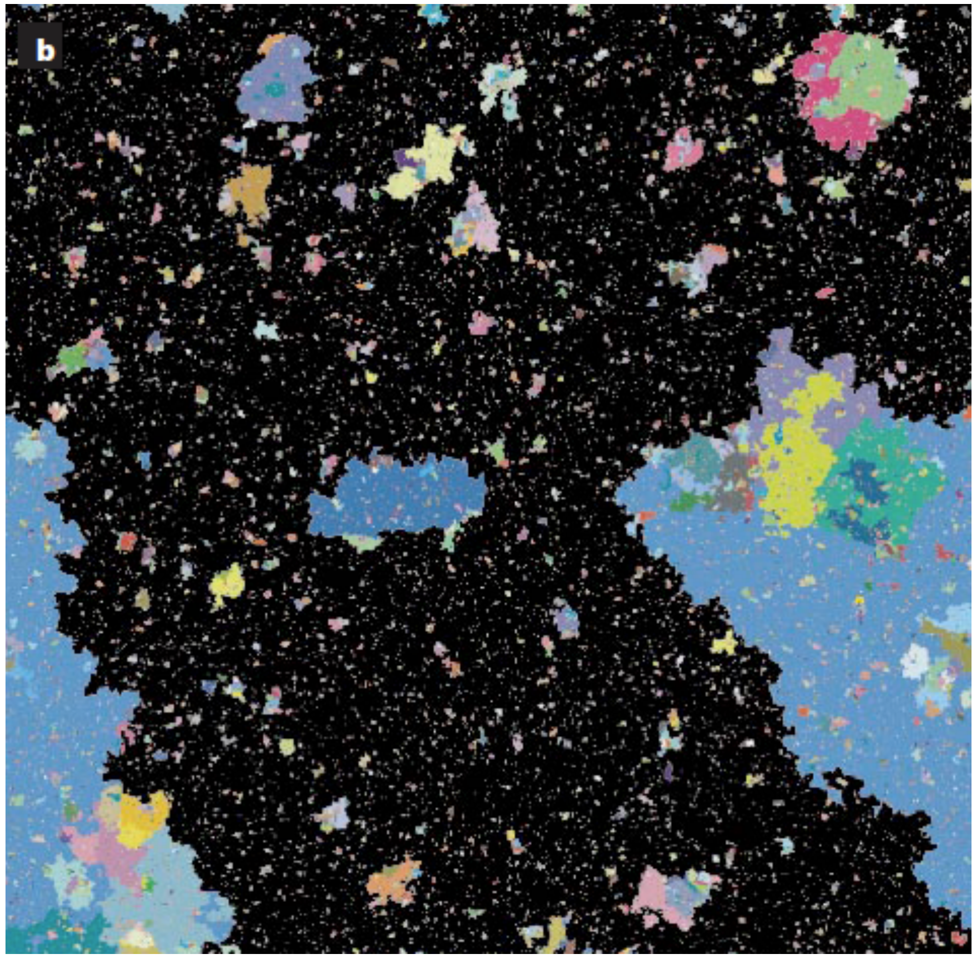


Hysteresis



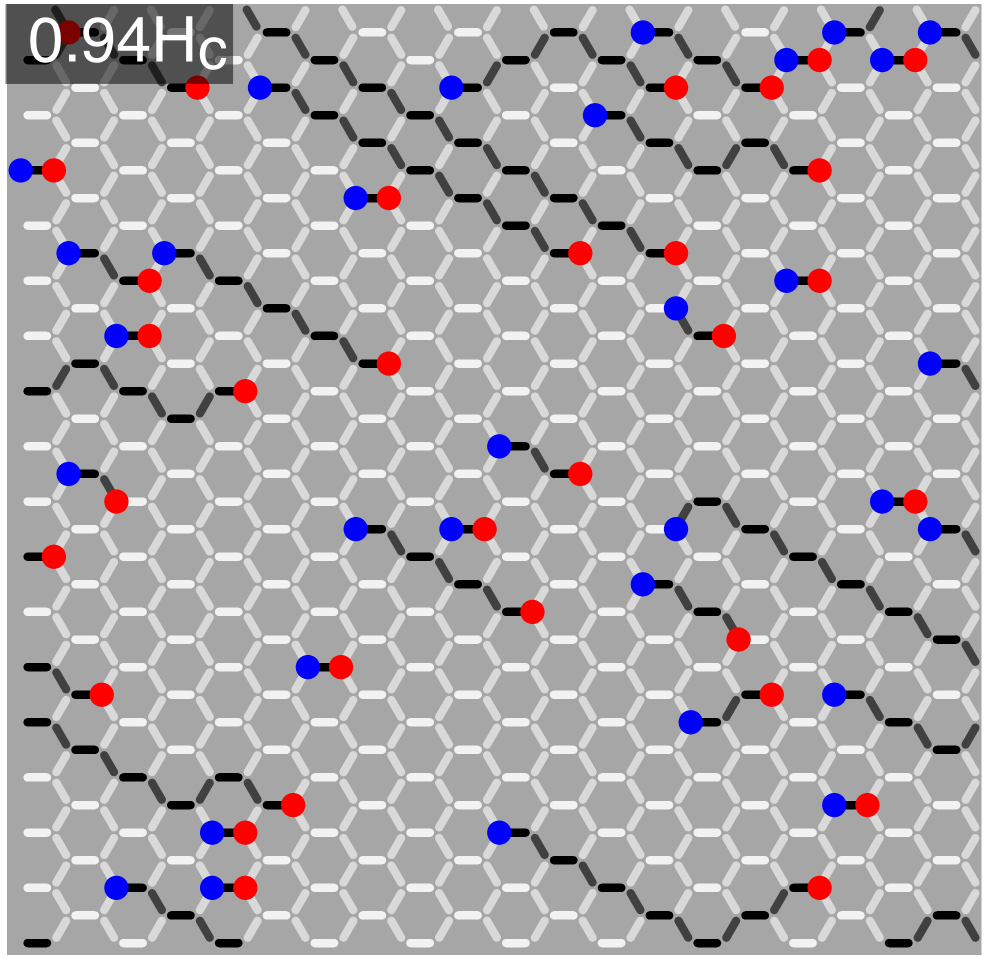
Avalanches grow over large distances -> small monopole concentrations over large regions of hysteresis

Avalanches and dimensional reduction due to frustration



conventional:
2D avalanches
in 2D system
(Sethna, Dahmen et al.)

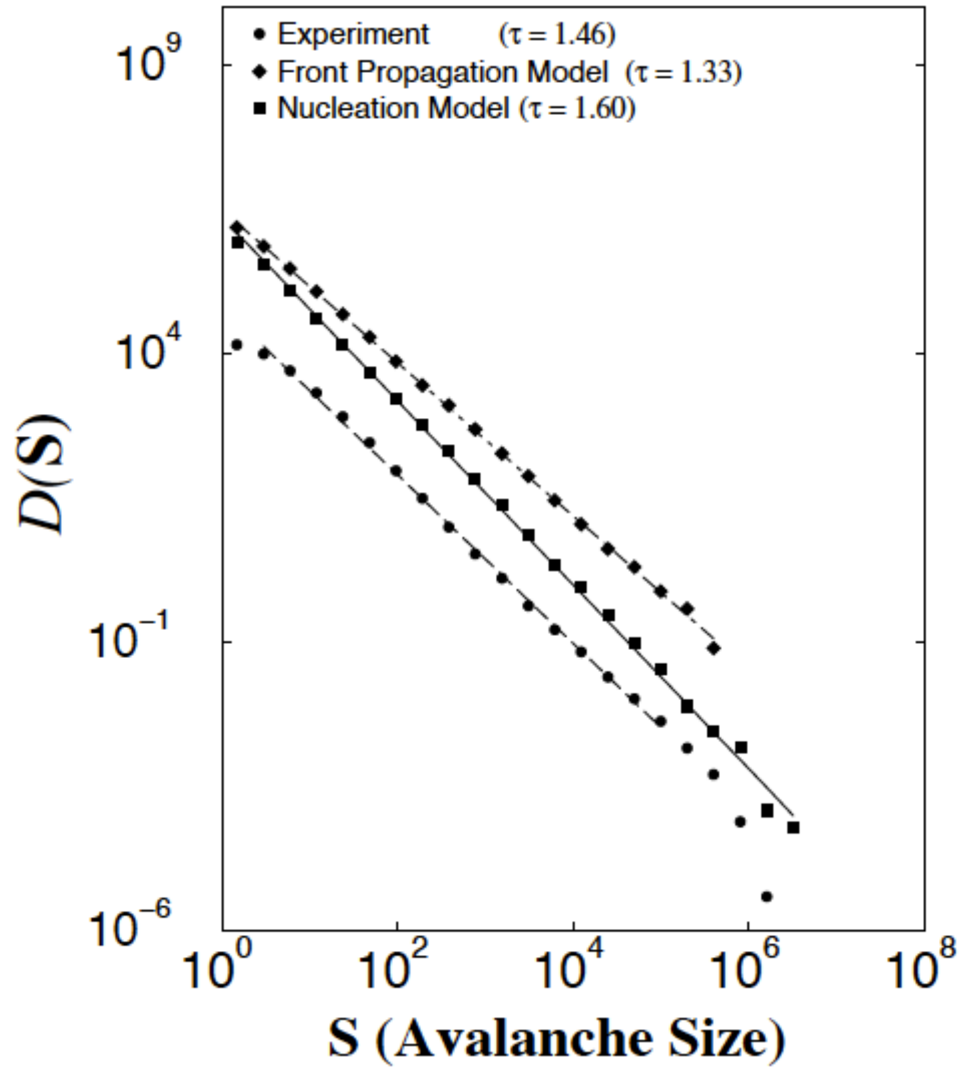
Random Field Ising Model
(RFIM)



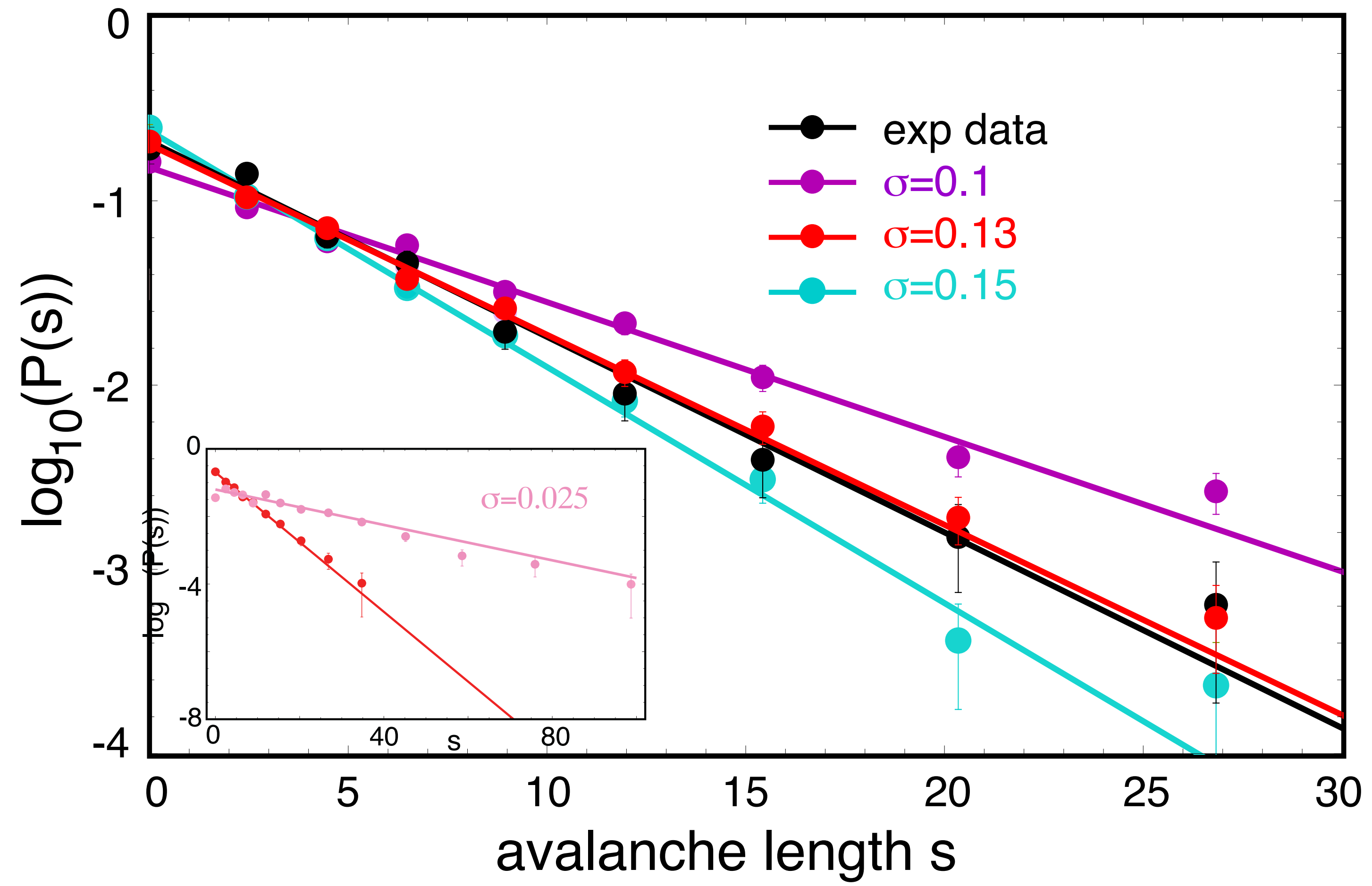
Here:
1D avalanches in 2D system
'dimensional reduction due to frustration'

Random field Ising model vs artificial kagome spin ice

conventional (RFIM):
(power law scaling)



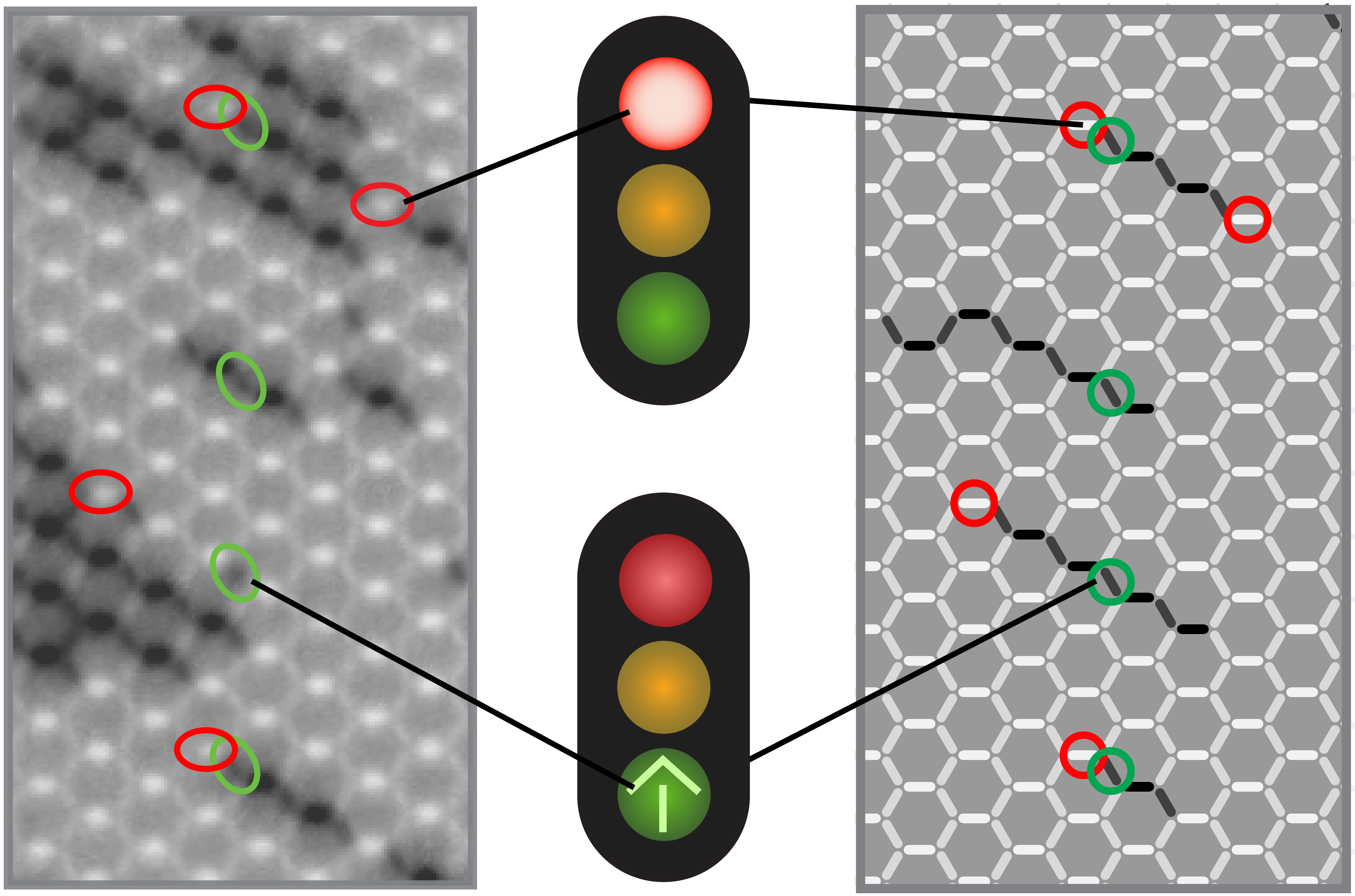
avalanche statistics



$$P(s) \propto p^s$$

cf. avalanches in 1D model
O. Chubykalo et al. (1998)

Control of monopole dynamics - experiments & simulations



R. Hügli *et al.*, Phil. Trans. R. Soc. A 370, 5767 (2012)

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K. Krämer(Bern)

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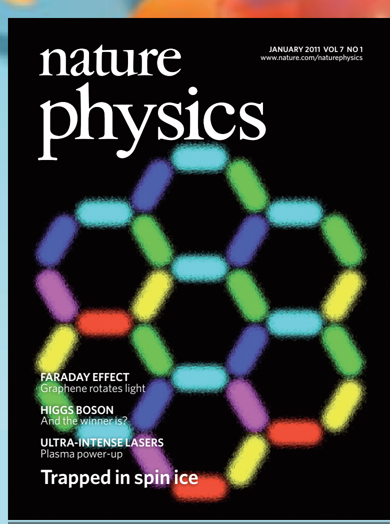
F. Nolting (PSI)
A. Fraile Rodriguez (Barcelona)



SciAm (French) ('13)

SciAm (German) ('14)