# Topological order and interplay with real space textures

Leon Balents, KITP

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# Collaborators


Jianpeng Liu

Interplay of band topology and topological magnetic textures in an antiferromagnet

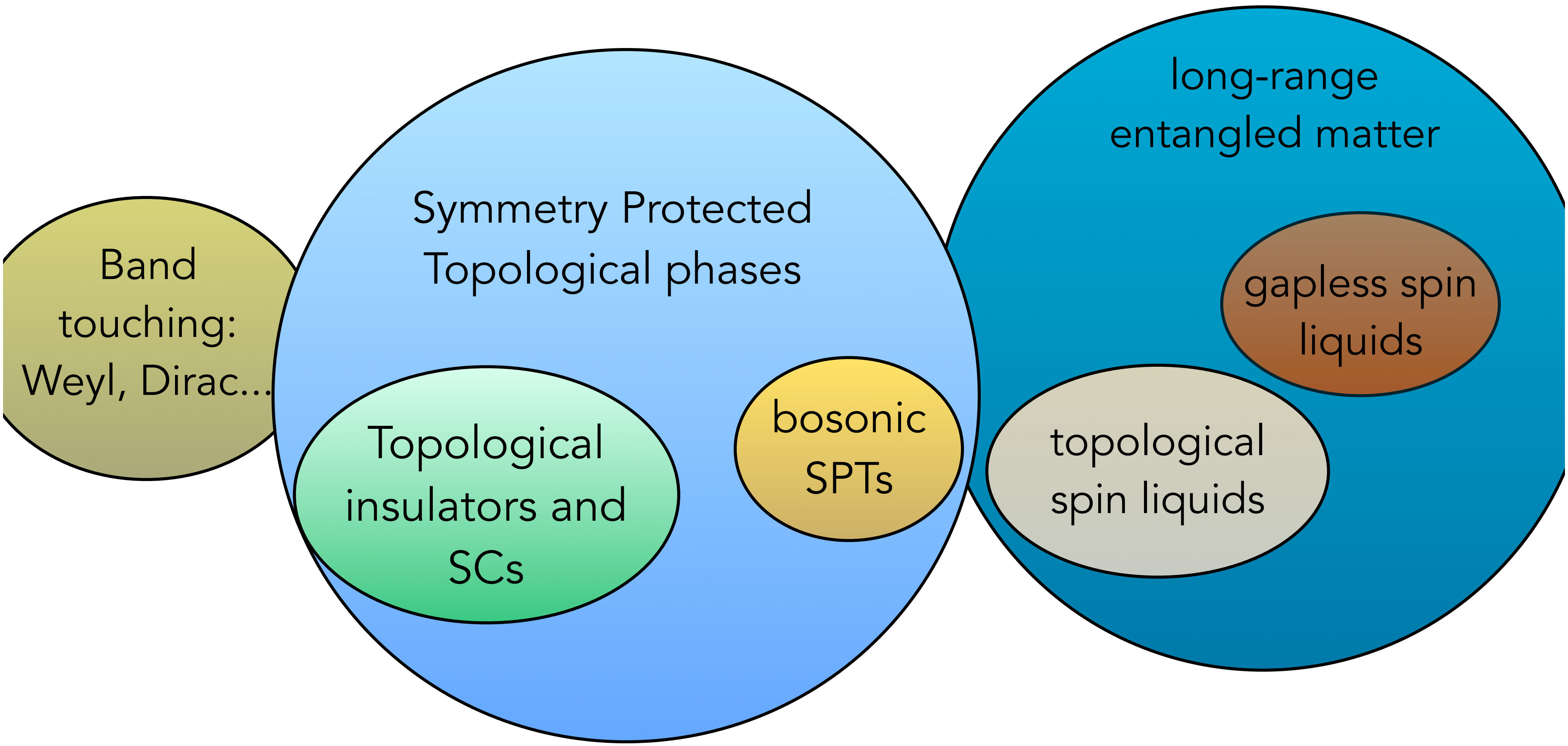

Chaoming Jian


Lucile Savary

Intrinsic topological order and local measurements

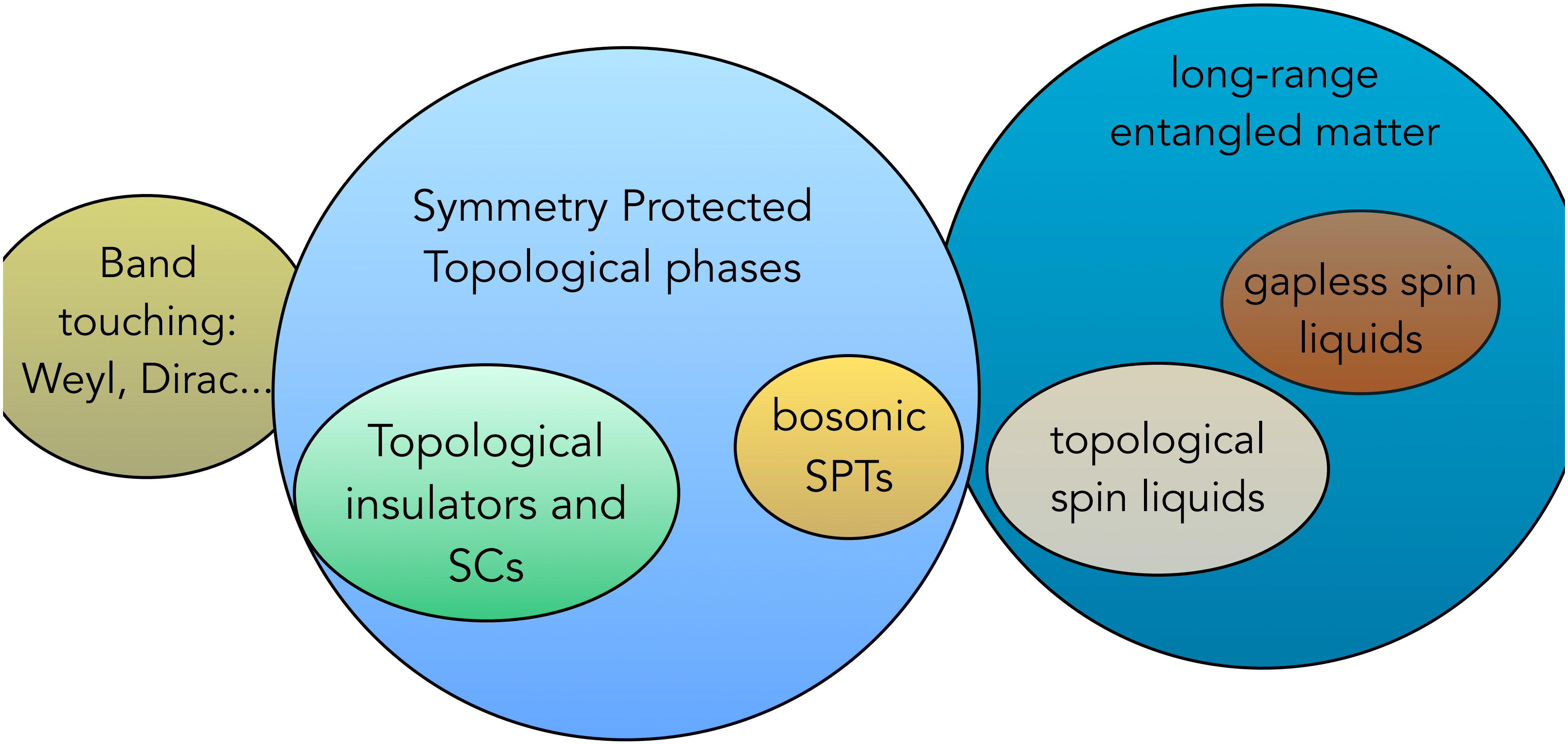

RANDY'S
DONUTS
Topology is big

# Topology++



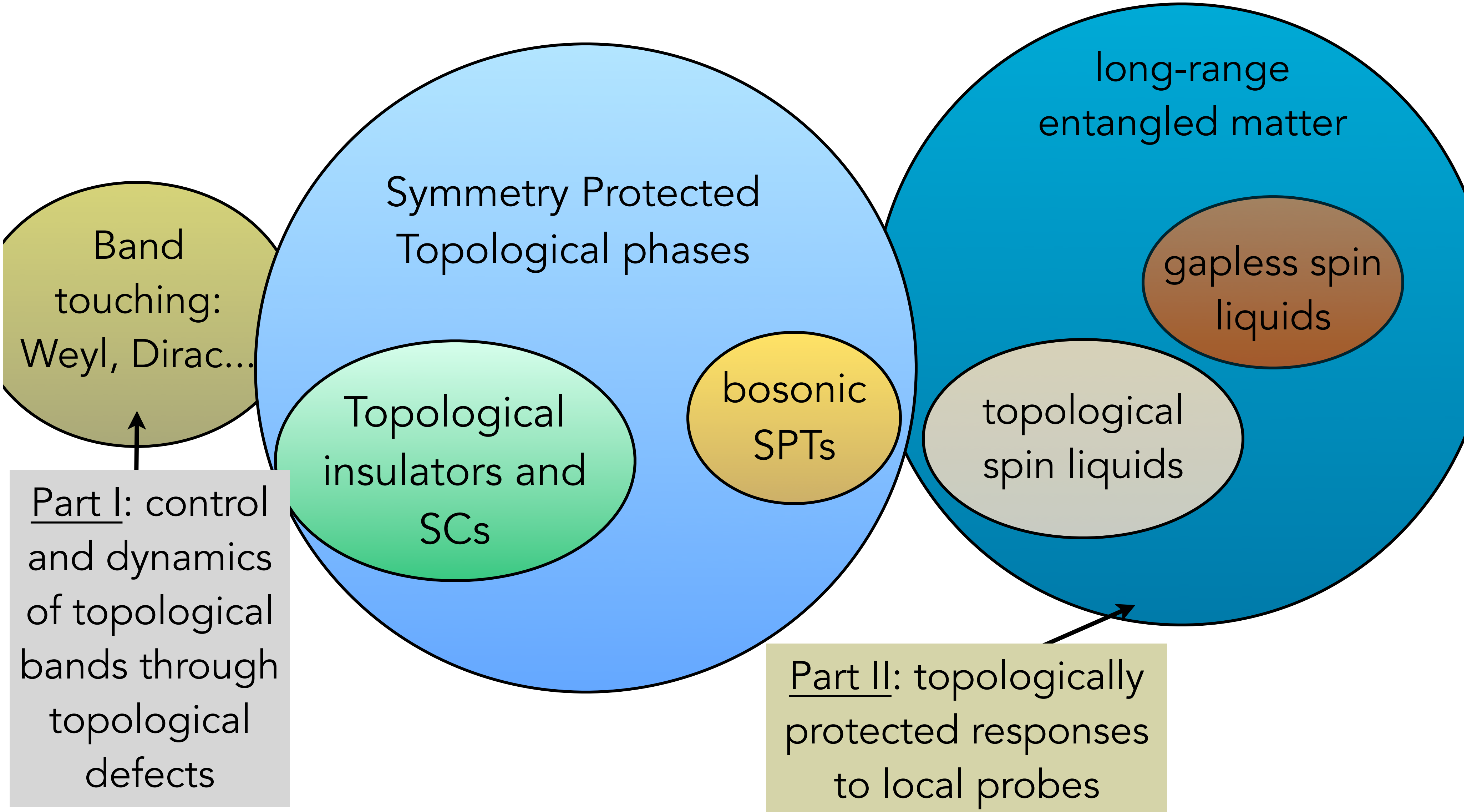
Band touching: Weyl, Dirac...
Symmetry Protected Topological phases
Topological insulators and SCs
bosonic SPTs
long-range entangled matter
gapless spin liquids
topological spin liquids

# Topology++




This talk: theoretical speculations on new experimental prospects

# Topology++


Band
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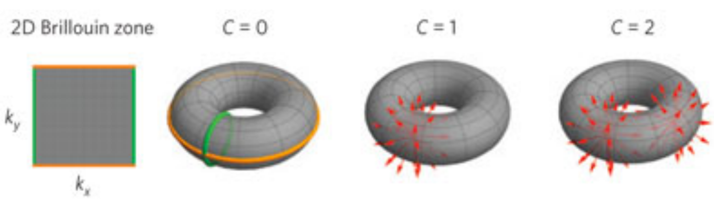
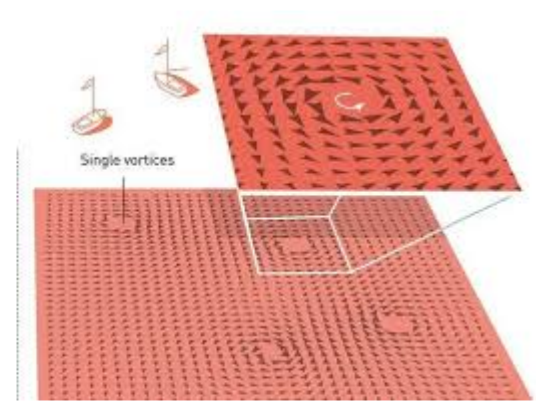
spin liquids
Part I: control and dynamics of topological bands through topological defects
Part II: topologically protected responses to local probes

Thouless:
Chern number

$$q_n = \frac{1}{2\pi} \int d^2k\, \mathcal{B}_n^z$$




Kosterlitz+ Thouless:
Vortices



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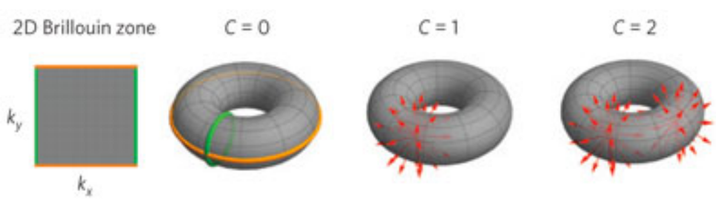


Kosterlitz+ Thouless:
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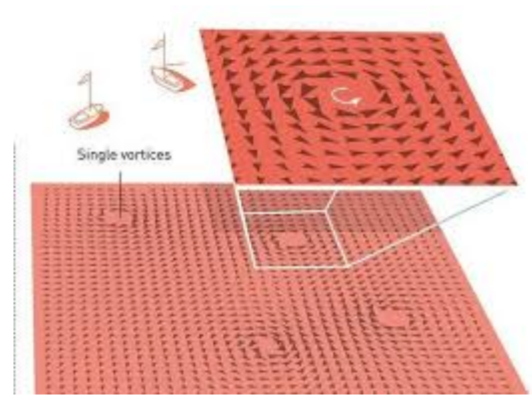
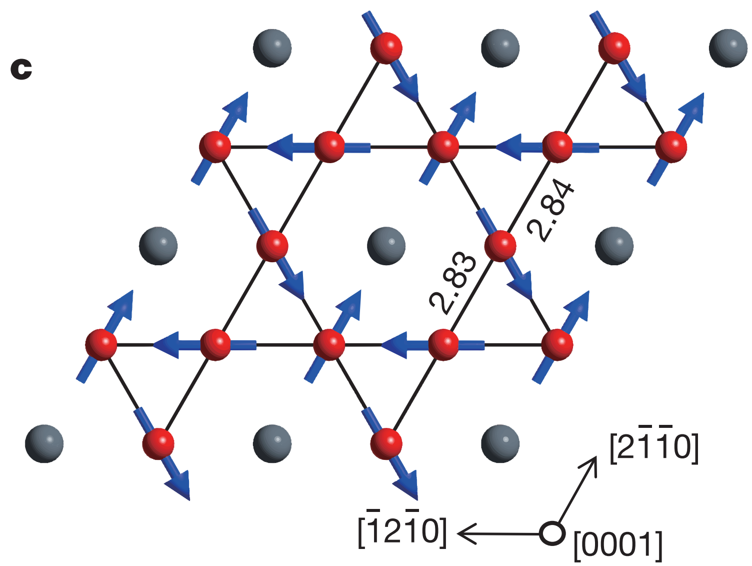



To control the interplay, we want a soft magnet

# $Mn_3Sn$ family




two kagomé layers of
Mn, related by inversion

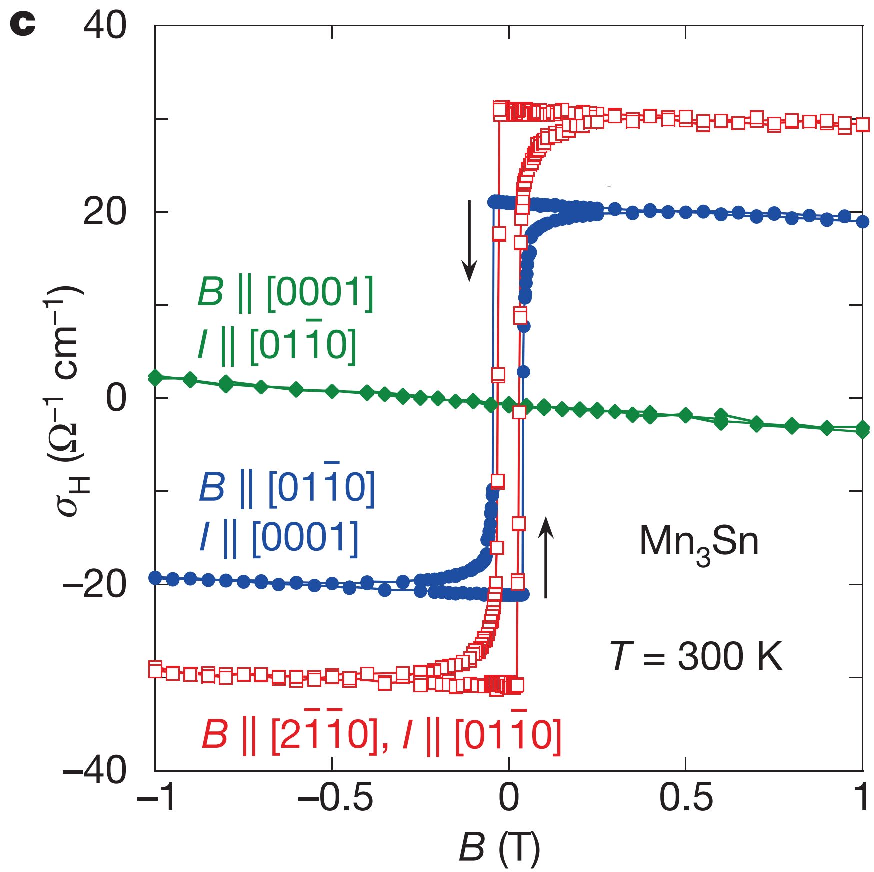
large ordered
*antiferromagnetic*
moment
~ 3 $\mu_B$ /Mn

tiny canting moment:
.002 $\mu_B$/Mn

$T_N$ ~ 420K

Nagamiya *et al*, 1982

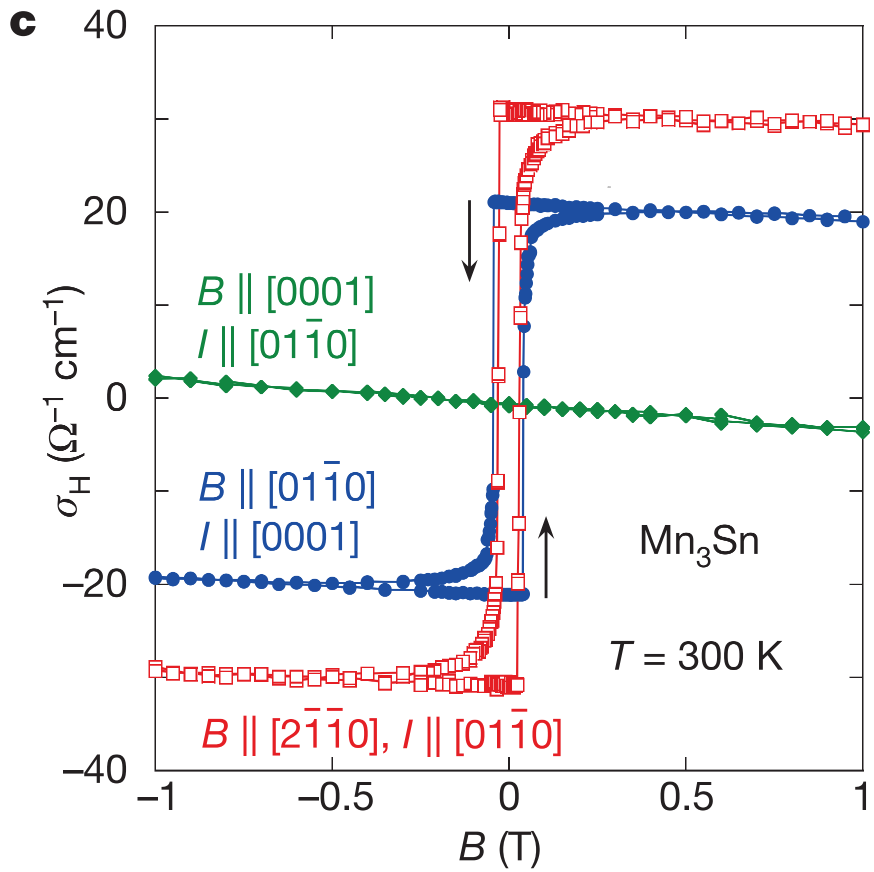
# anomalous Hall effect

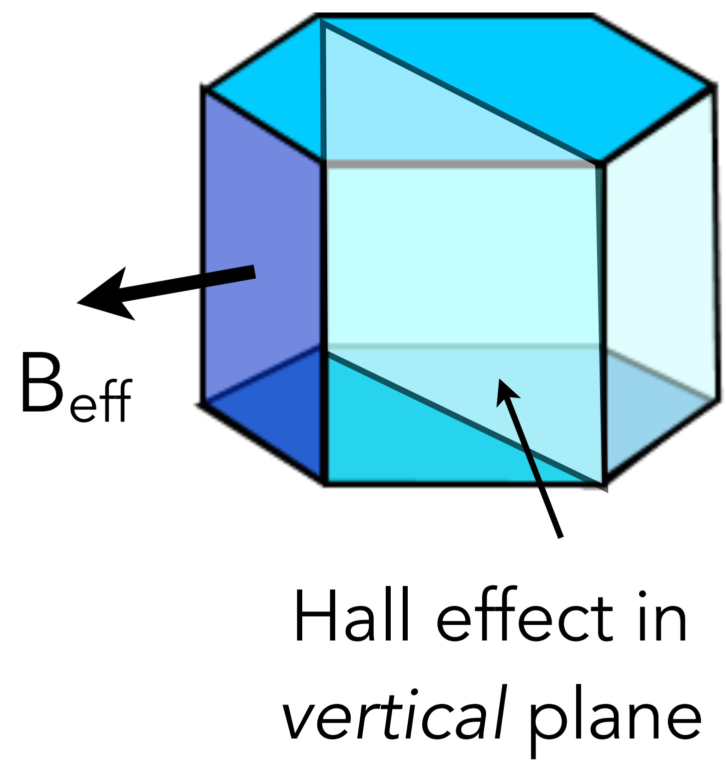



comparable to metallic FMs

switchable because of small magnetic moment and small anisotropy

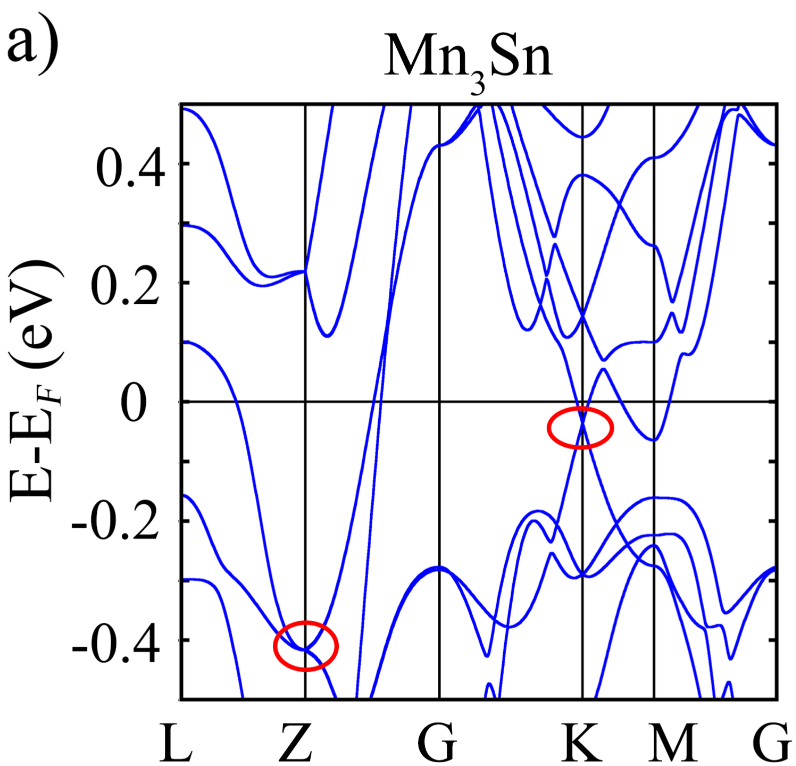
# anomalous Hall effect

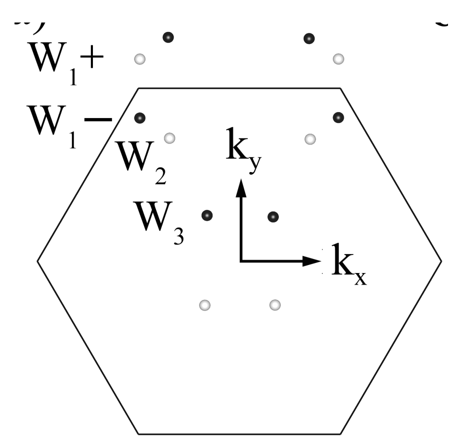


# Weyl

## *ab initio* finds Weyl points and surface Fermi arcs



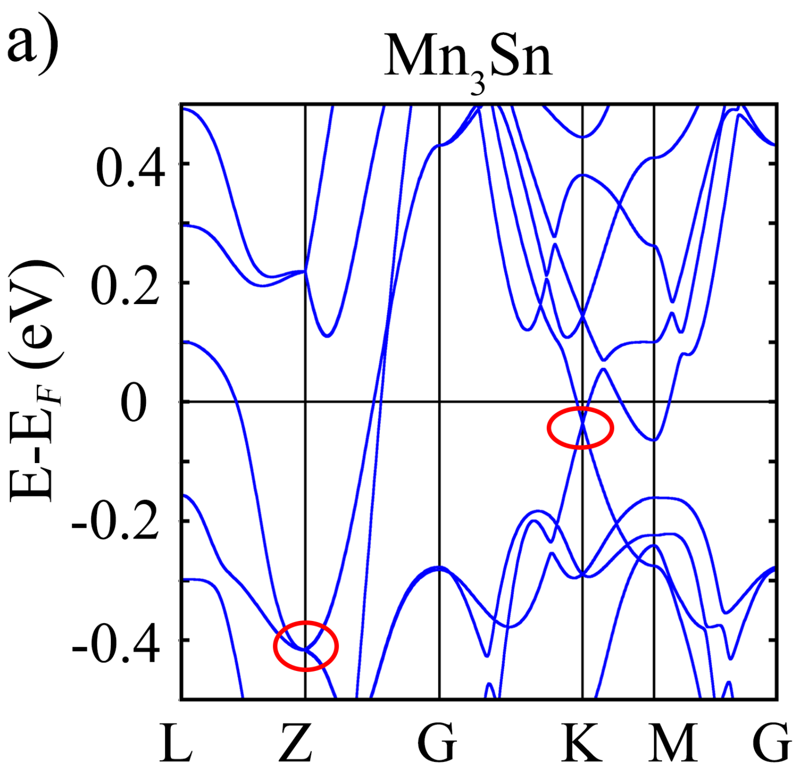



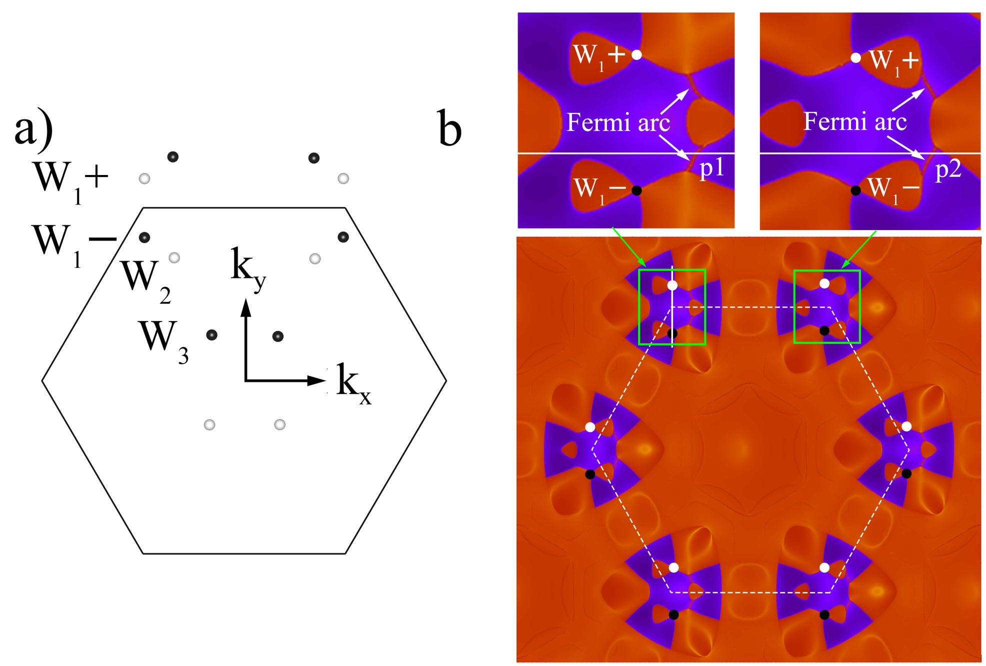

notice lack of 6-fold symmetry: due to direction of AF order

Hao Yang *et al*, arXiv:1608.03404

# Weyl

## *ab initio* finds Weyl points and surface Fermi arcs

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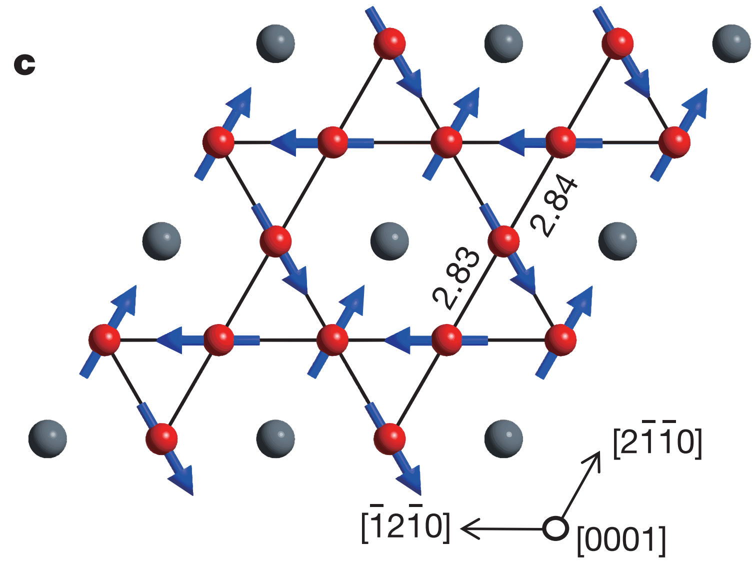
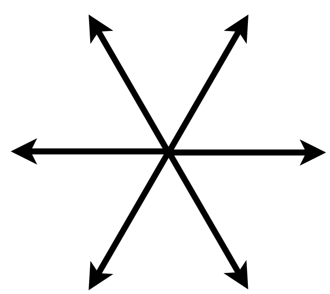
# Textures

Magnetic order has $Z_6$ structure




direction of inward-pointing spin



$$\psi = |\psi| e^{2\pi i n/6}$$

3 pairs of time-reversed domains

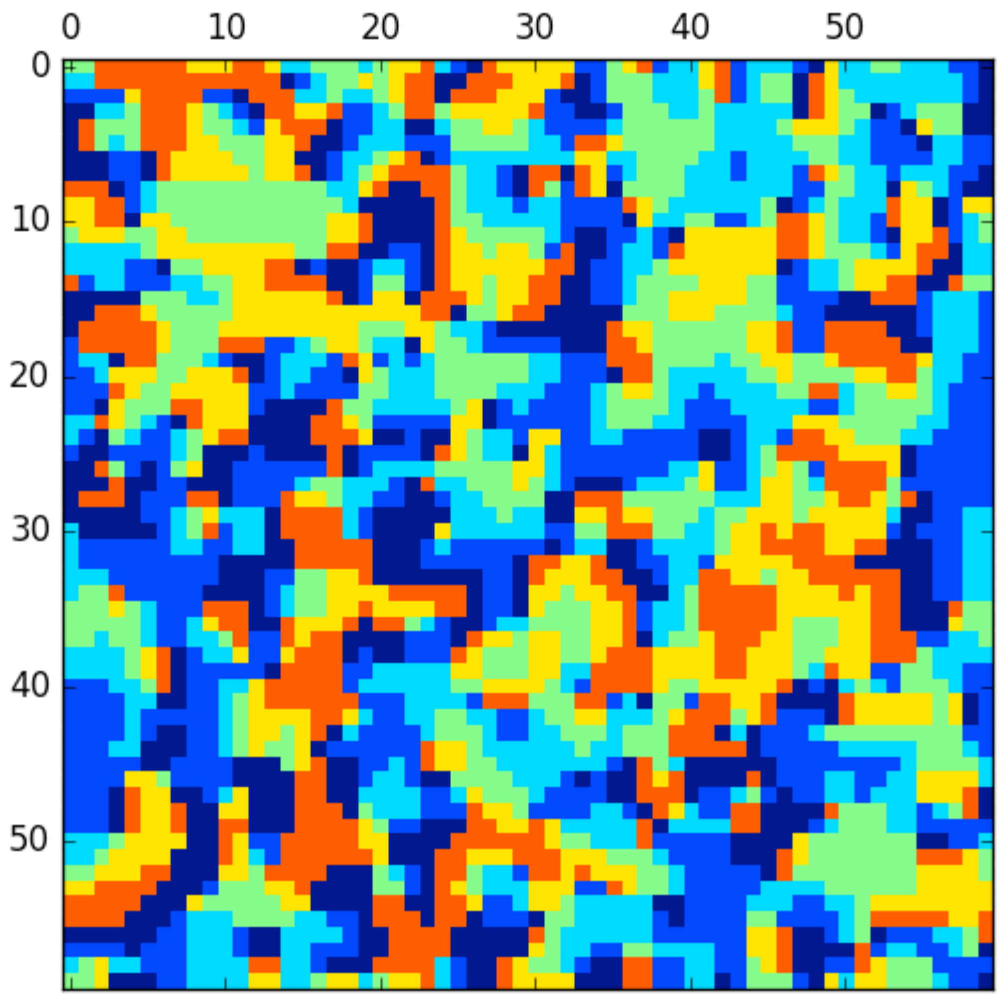
# Textures

$$\psi = |\psi| e^{i\theta} \qquad\qquad F \sim \int d^3x \left\{ \frac{\rho}{2} (\nabla\theta)^2 - \lambda \cos 6\theta \right\}$$

sine-Gordon model with 6-fold anisotropy

- Minimal energy domain walls are *not* between time-reversed states
- Magnetization,Hall vector, location of Weyl points are all determined by domain choice, not by field in general
- Stable $Z_6$ vortices exist

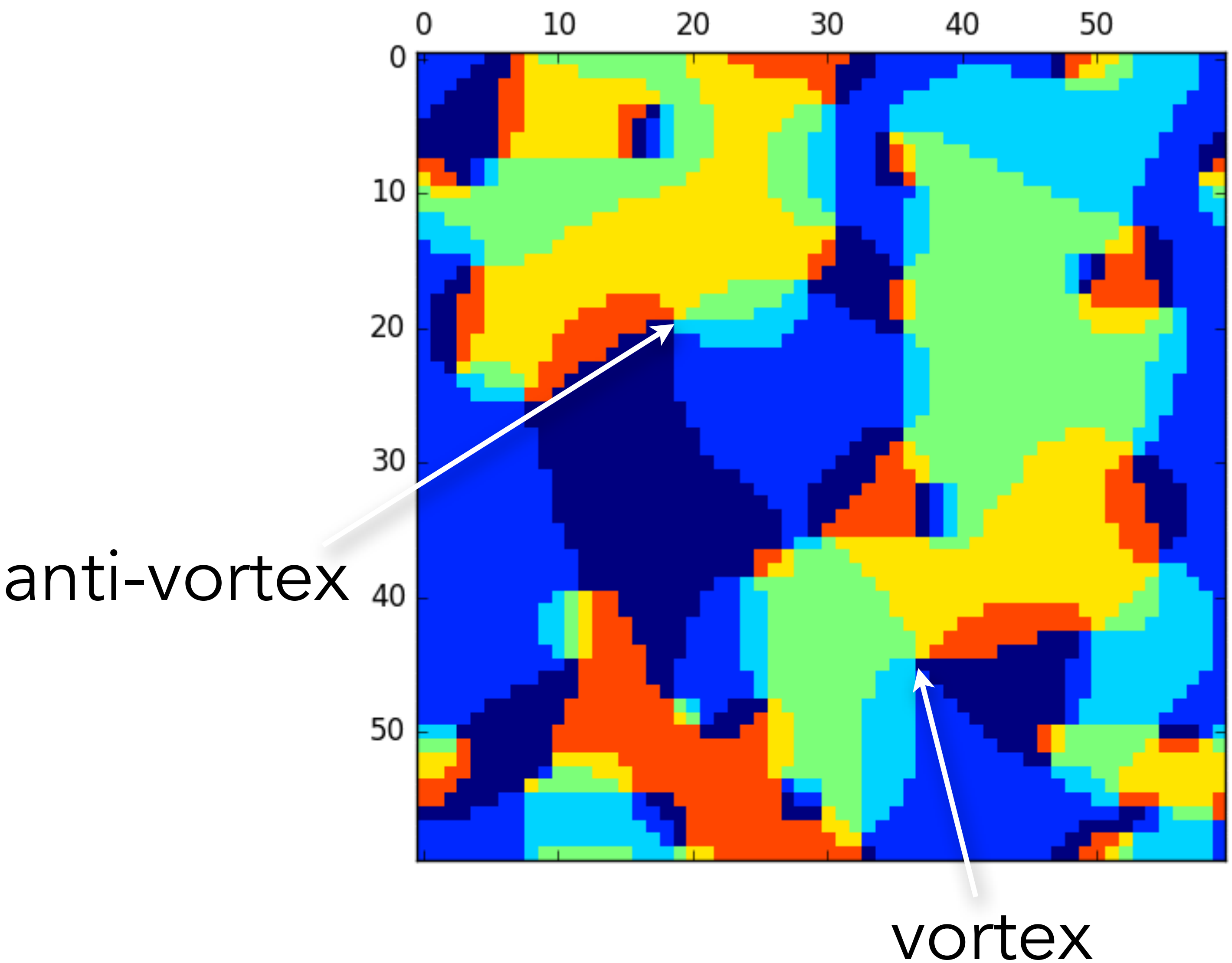
# Domain formation




quench

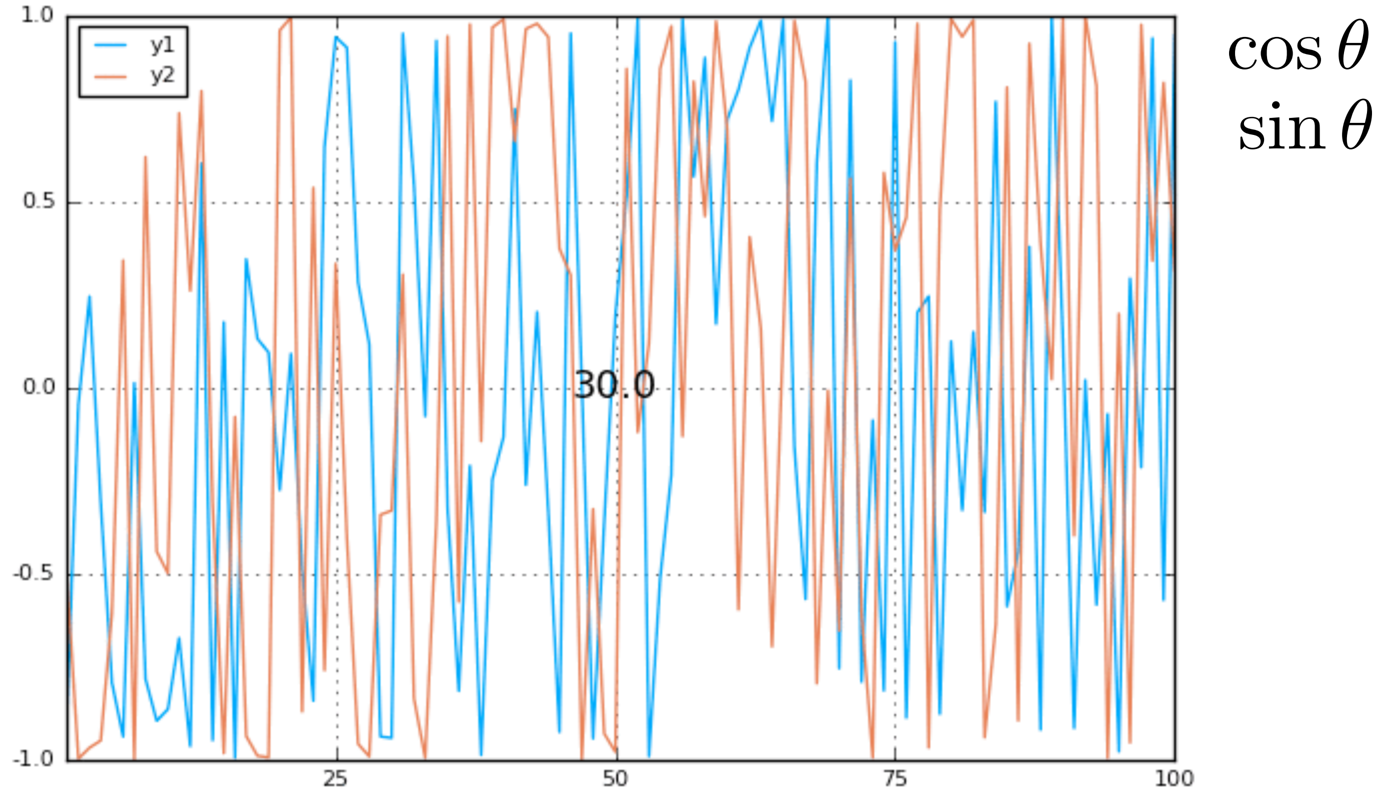
(model A dynamics)

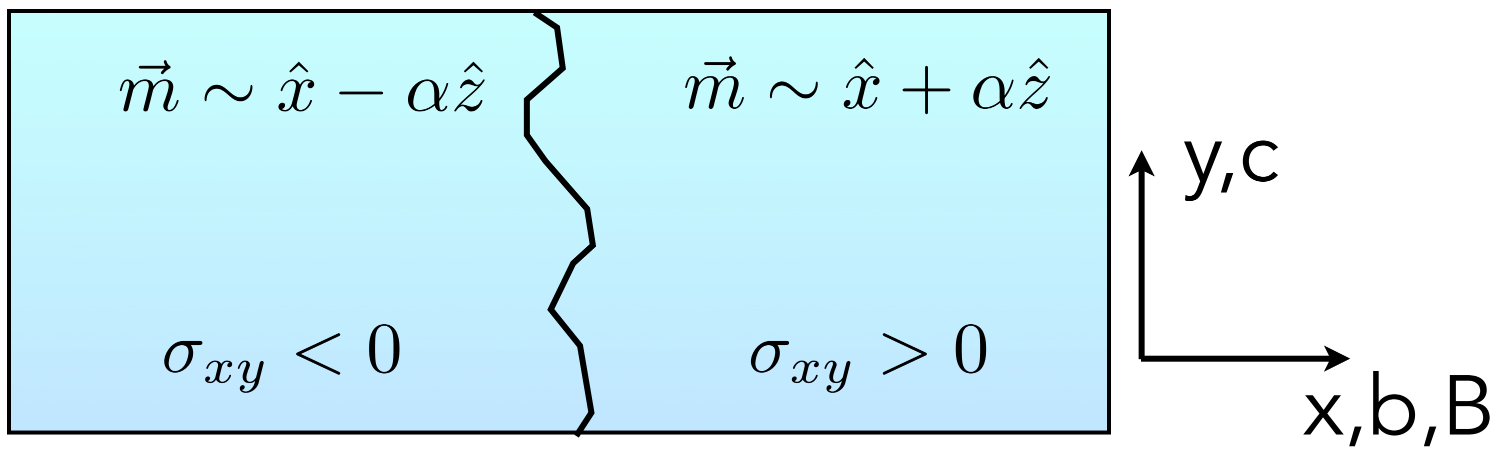
# Domain formation



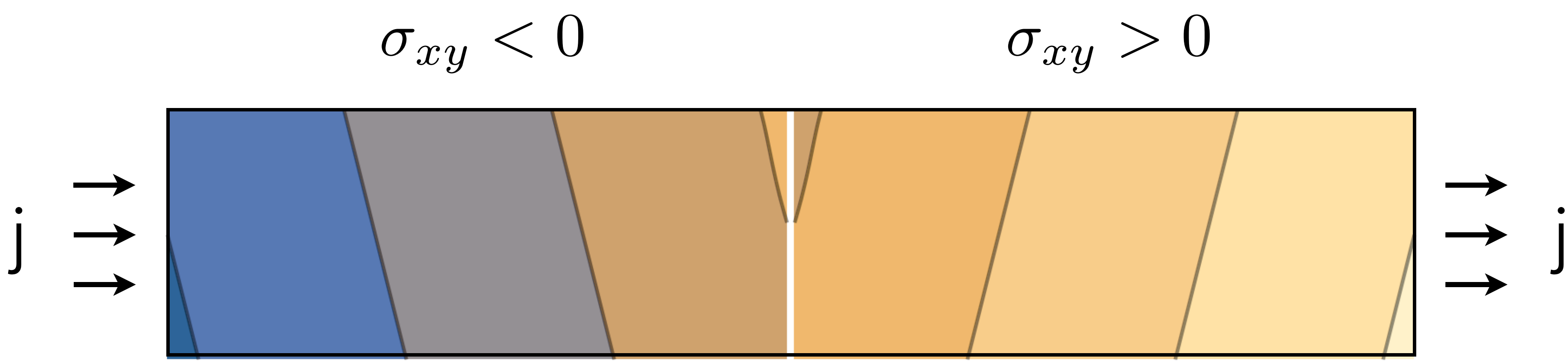
controllable
domain walls
in narrow
Hall bar

(triangle wave of $B_z(t)$)

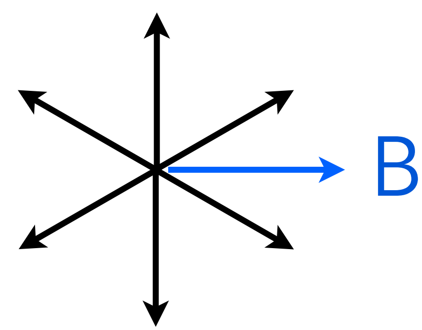



B || x

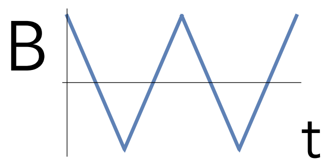


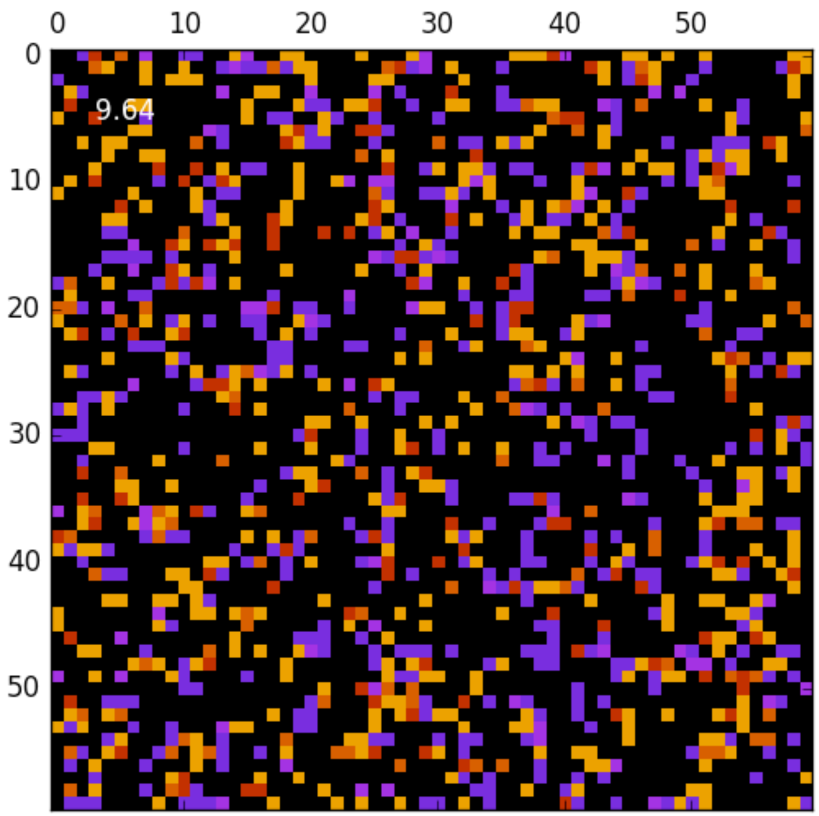

equipotentials from solution of Laplace's equation for a Hall bar with two domains



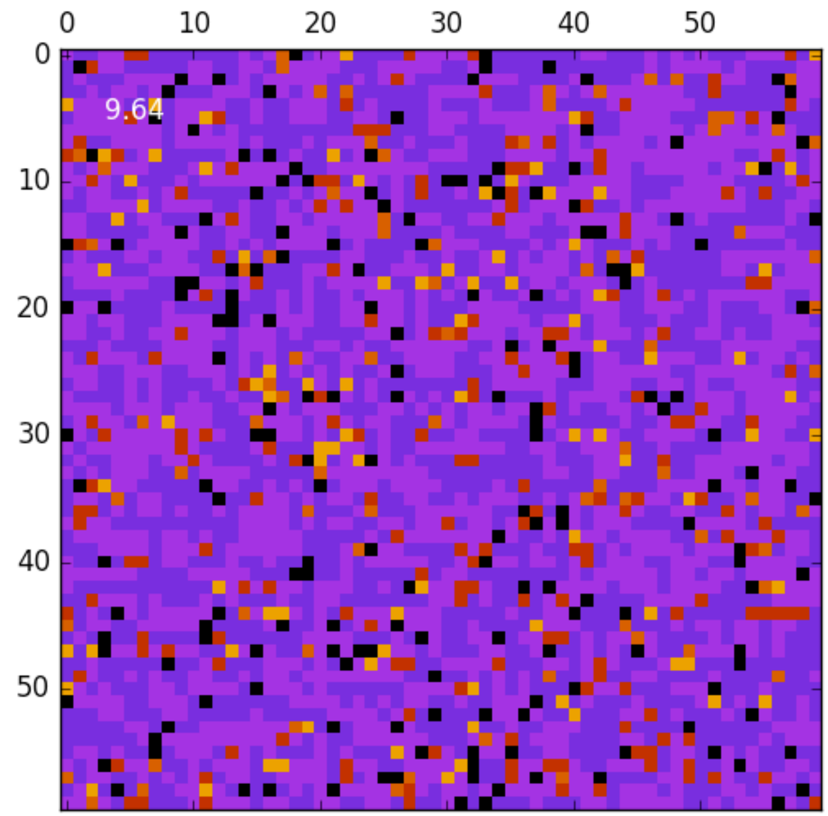

Could use this DW as a switch??

# Wider sample



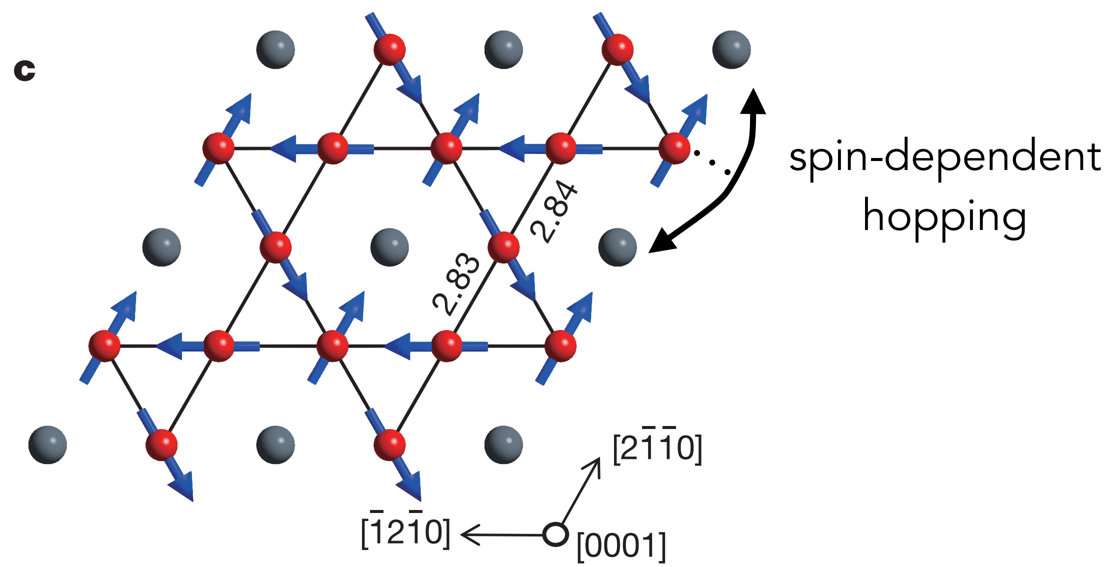

B || easy axis




B ⊥ easy axis

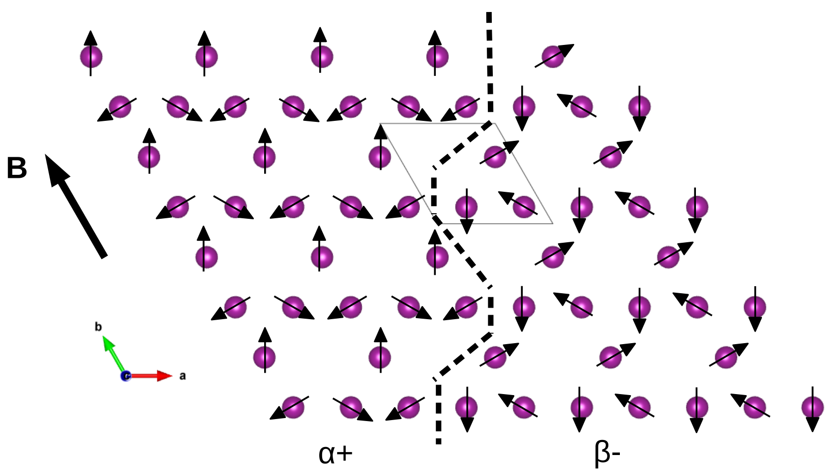
# A model

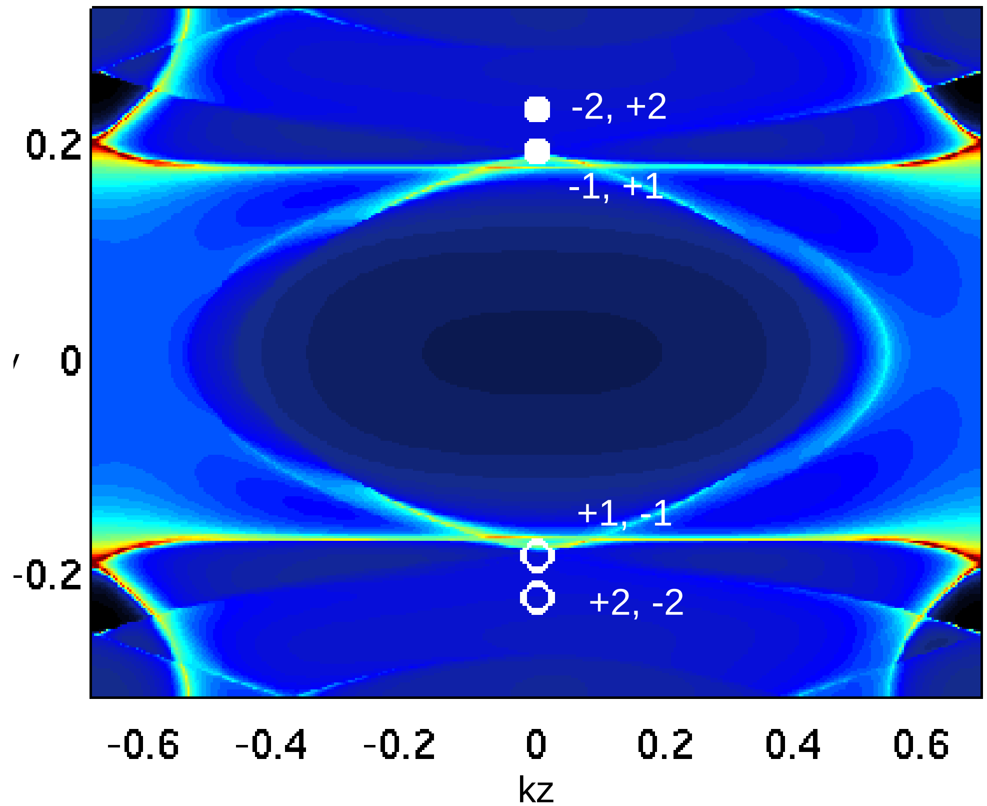
tight-binding of single orbital on Sn sites: a 4 band model




Enables efficient study of domain walls, vortices etc.

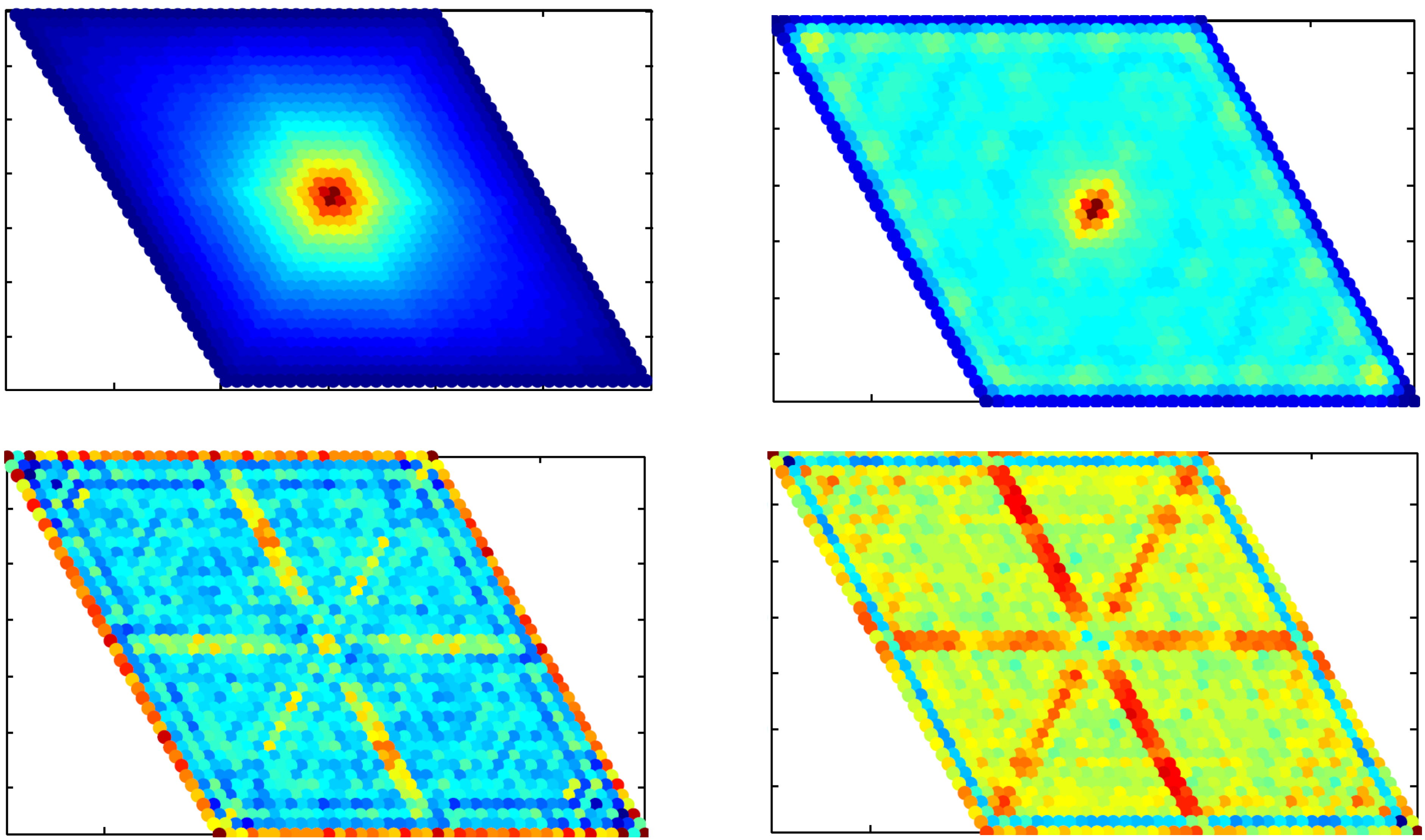
# e.g.: Domain wall




twice as many Fermi arcs as a surface

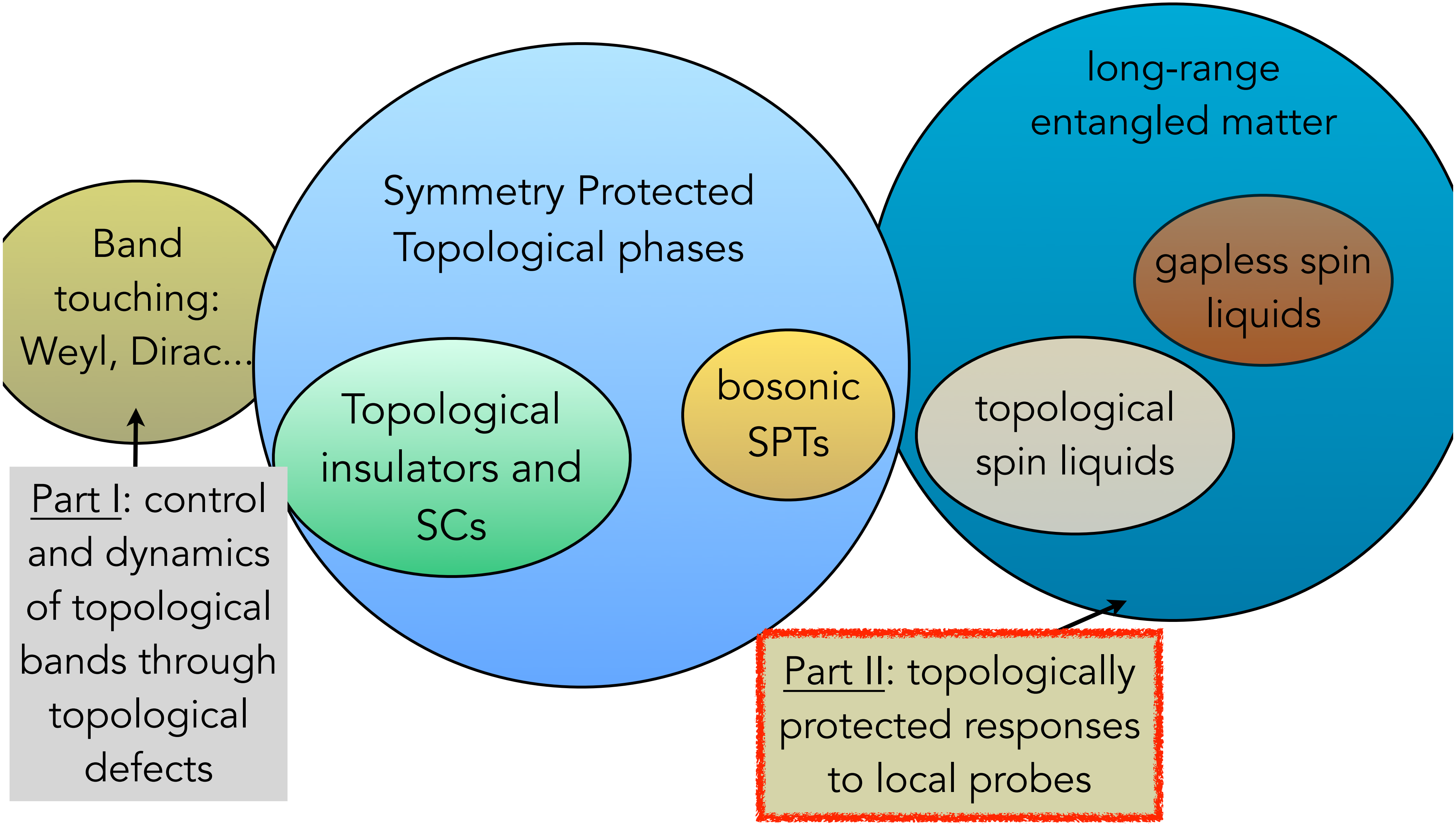
# $Z_6$ vortex



# Summary of Part I

- Ingredients are in place for nano-scale transport studies of non-trivial domain walls (conformational modeling and spatially resolved measurements crucial)
- Q: Are there interesting electronic features of $Z_6$ vortices?
- Q: What is the role of *fluctuations* of magnetic textures?

# Topology++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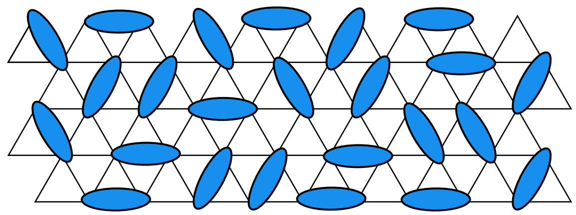
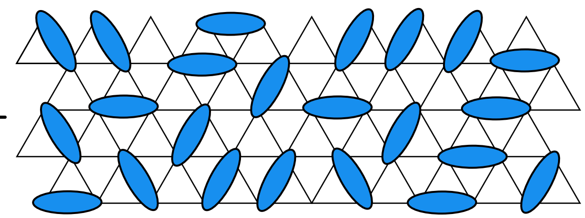
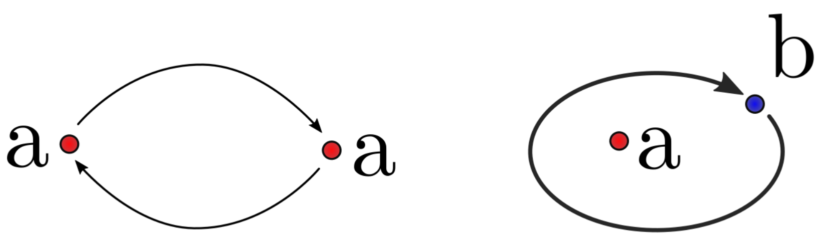
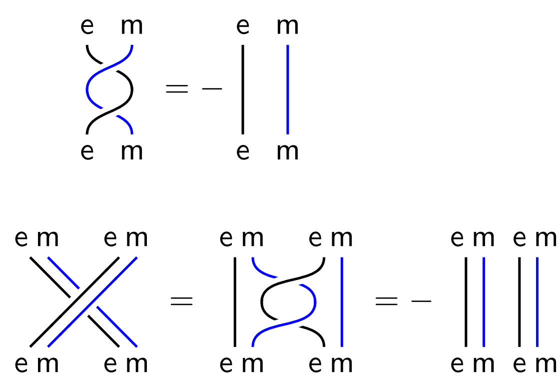
# Quantum Spin Liquids

$|\Psi\rangle =$  $+$  $+ \cdots$

## Simplest examples: *topological* spin liquids




excitations are
*anyons*



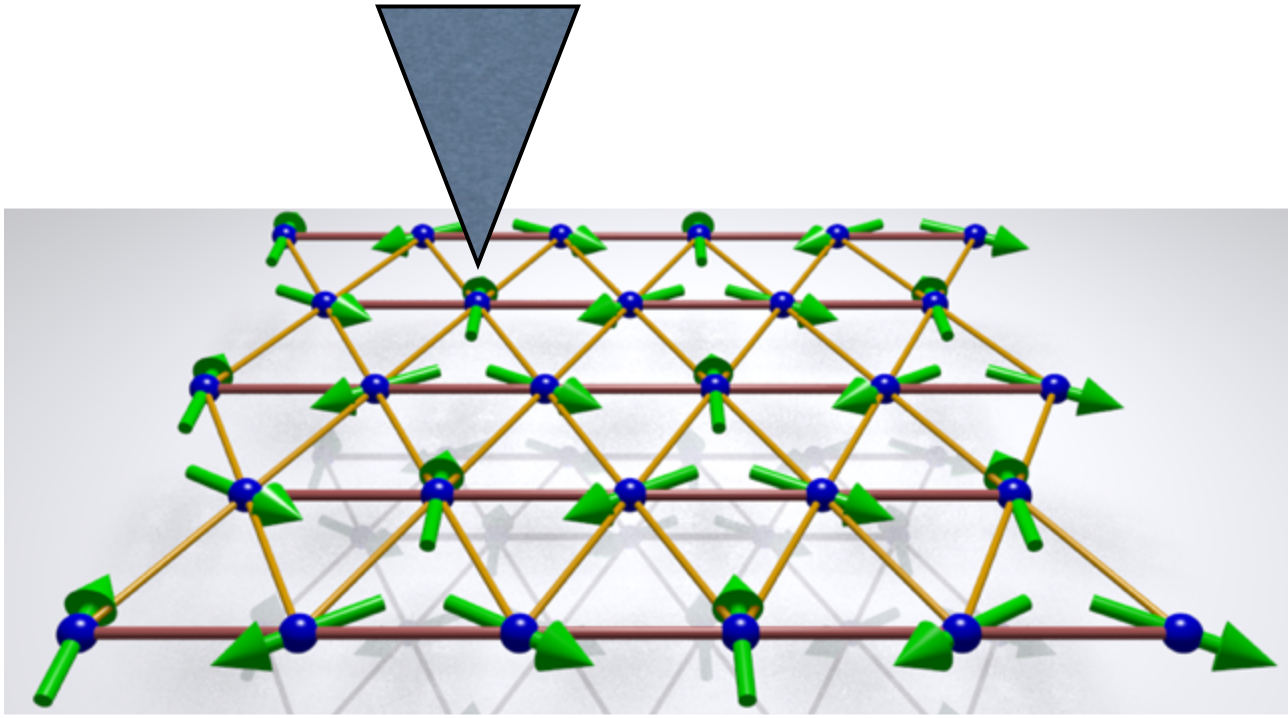

toric code/$Z_2$ QSL

# How do we probe them?

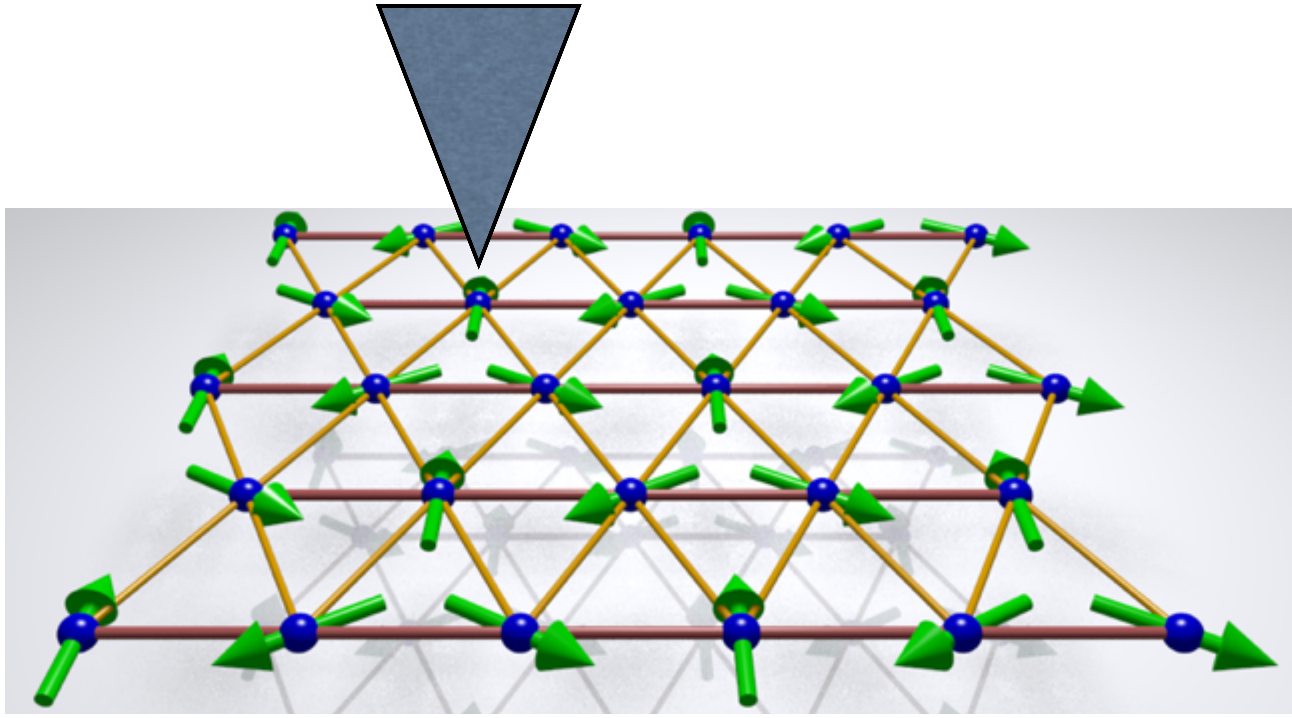
Experimentalist: "I've got this great scanning XXX*"

Theorist: "Pretty picture...but how can a local measurement tell us anything about topology?"

*STM, AFM, SQUID, terahertz STM, SC STM, NV magnetometer, banana, quantum dot, microwave detector,...

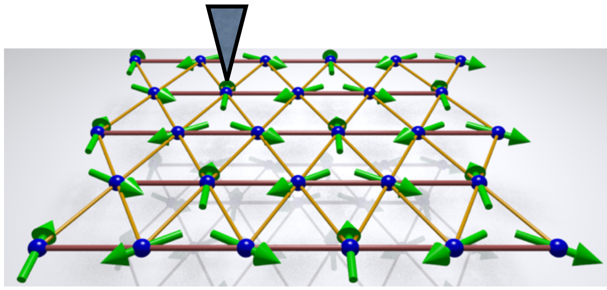


What happens when you apply a local perturbation to a topological system?



Warm-up: non-topological system

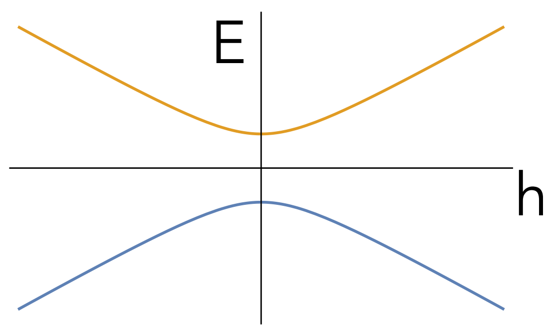
# Transverse-field Ising model



$$H = -J \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z - h_\perp \sum_i \sigma_i^x$$

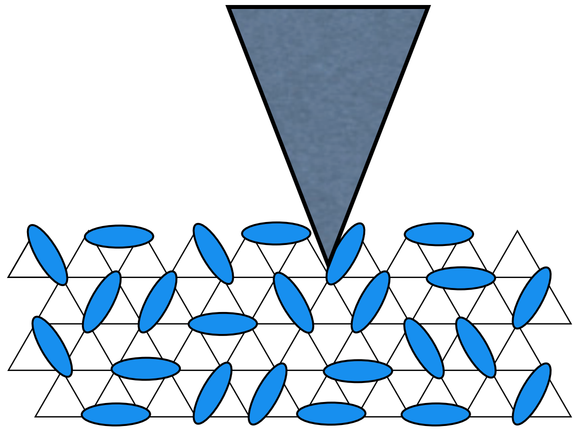
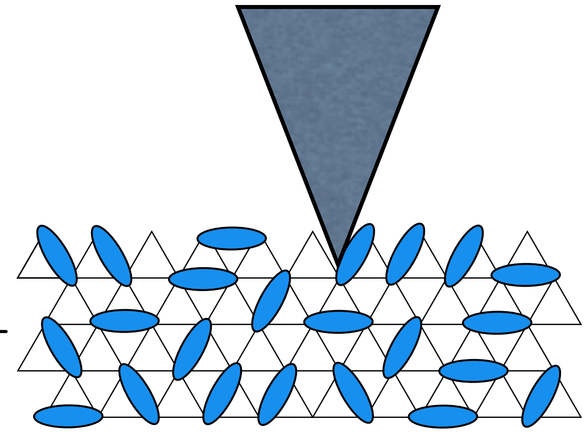
Apply local field $H' = -h\sigma_n^z$

$h_\perp \gg J$ $H_n \approx -h_\perp \sigma_n^x - h\sigma_n^z$



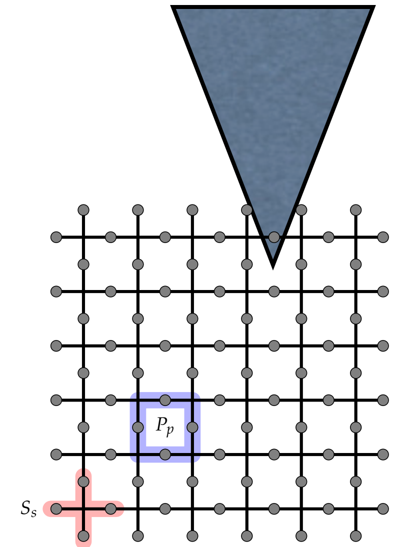

avoided crossing: *smooth response* to applied force.

This is expected for bosonic/spin system whenever local force breaks all symmetries

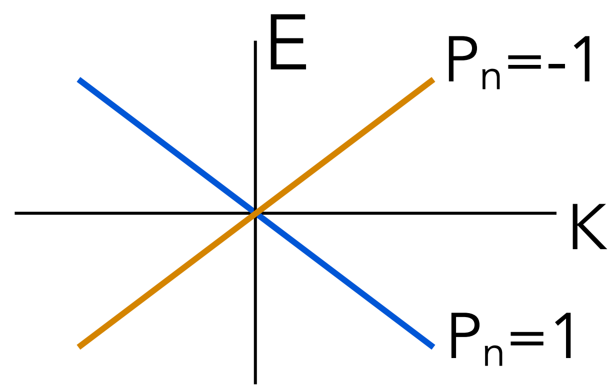
$$|\Psi\rangle = $$  $$+$$  $$+\cdots$$

What happens in a spin liquid?

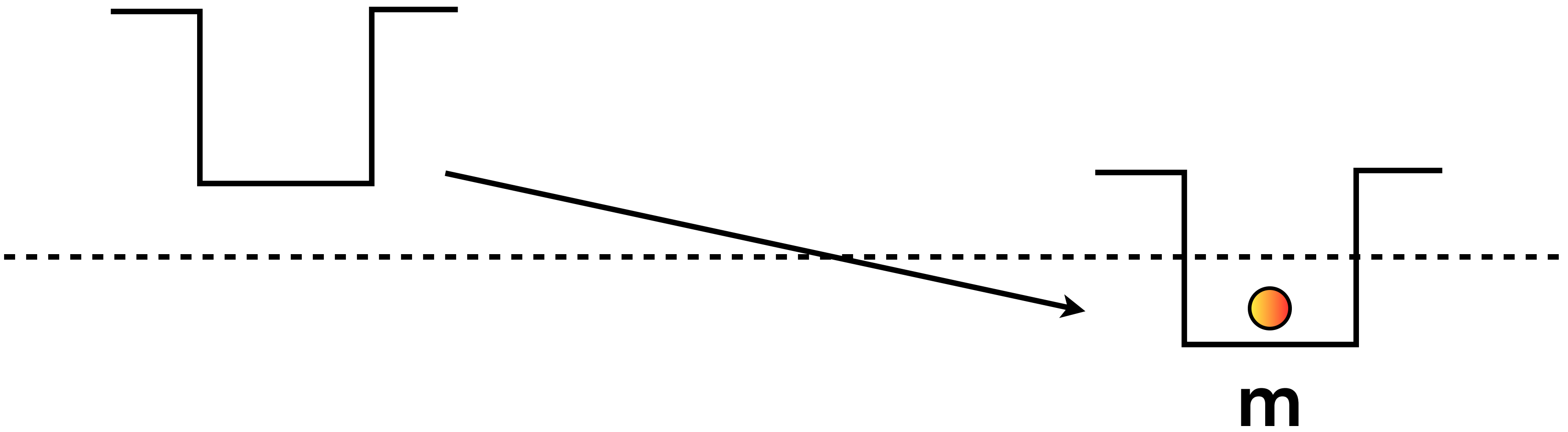
# A model topological spin liquid: Kitaev's toric code




$$H_{\text{tc}} = -K \sum_p P_p - K' \sum_s S_s,$$

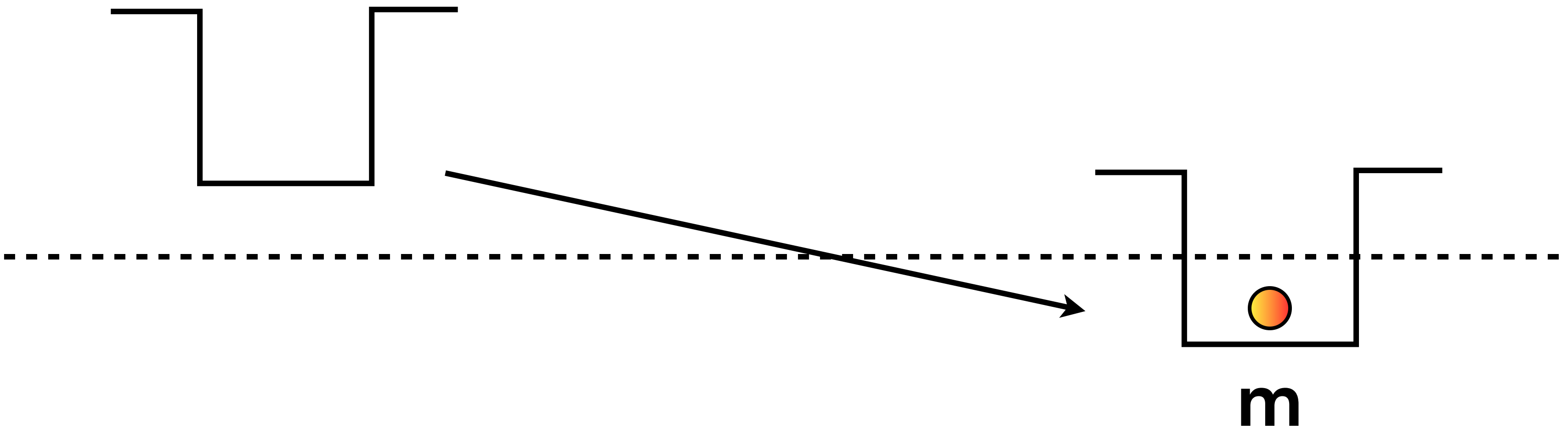



vary one $K_n$ → level crossing



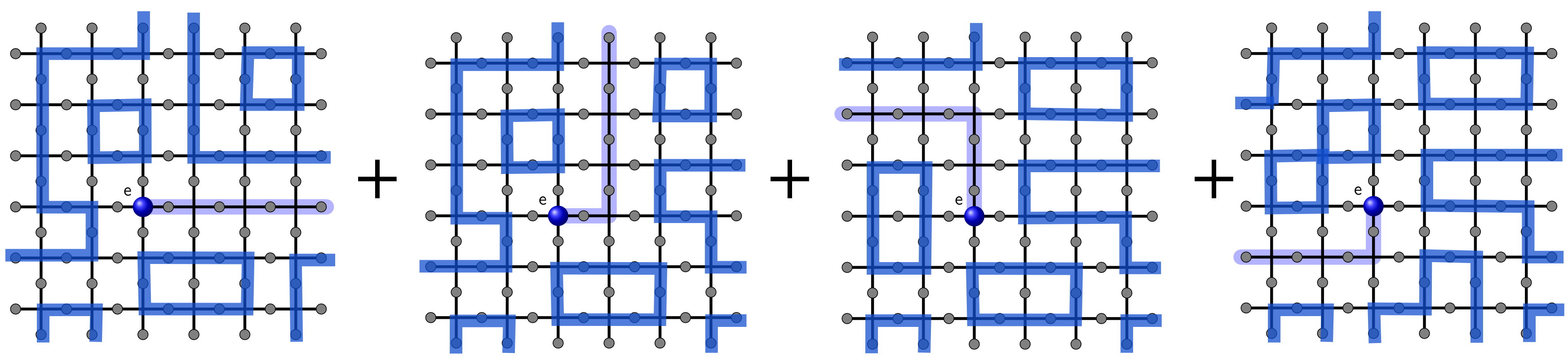

local potential binds an anyon

Level repulsion between state with and without **m** particle is *topologically* forbidden: no local operators can create/annihilate a single anyon. The crossing persists under arbitrary perturbations.

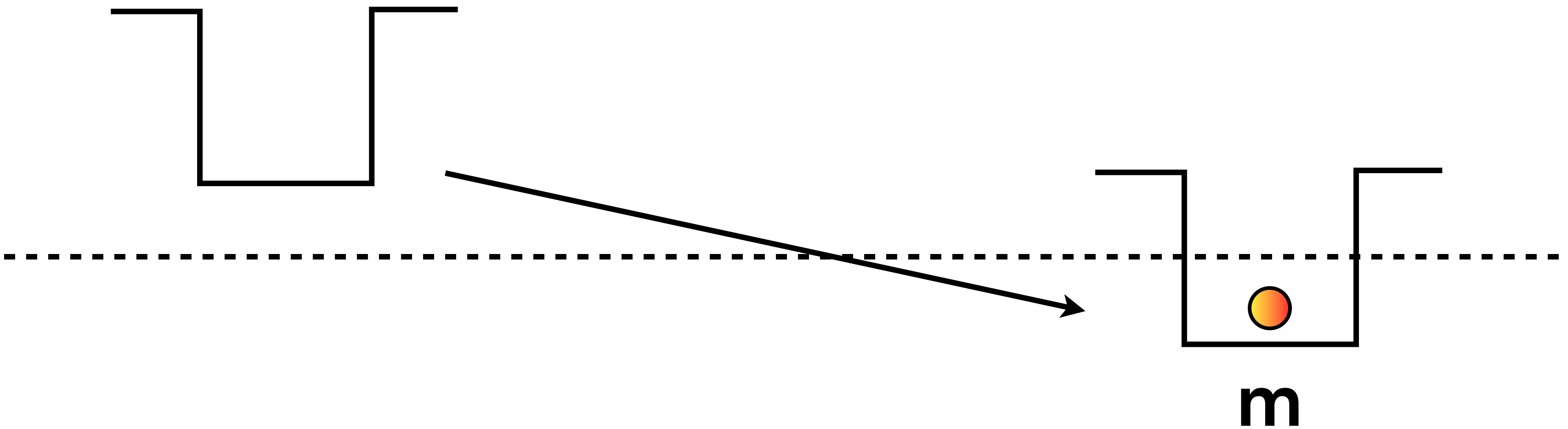



local potential binds an anyon

$|\mathrm{e}_s\rangle =$




robustness due to “field line” emanating from anyon

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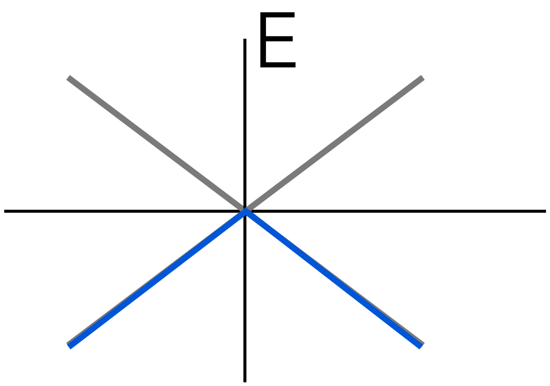
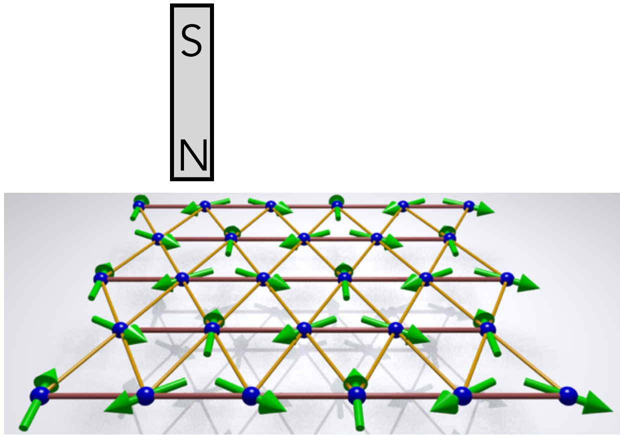



cusp in ground state energy:
a *topologically protected local quantum phase transition* with a discontinuity in local susceptibility

# Weak spin-orbit-coupling

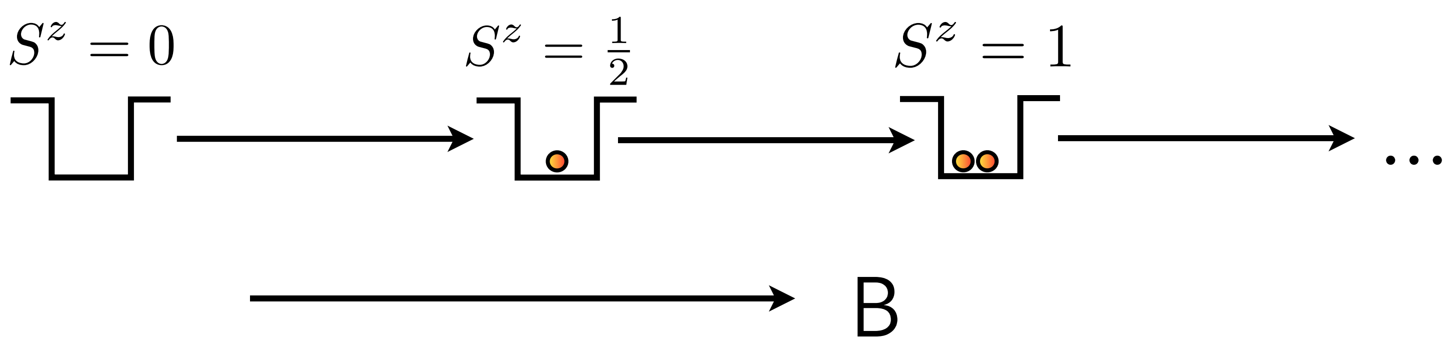



local magnetic field

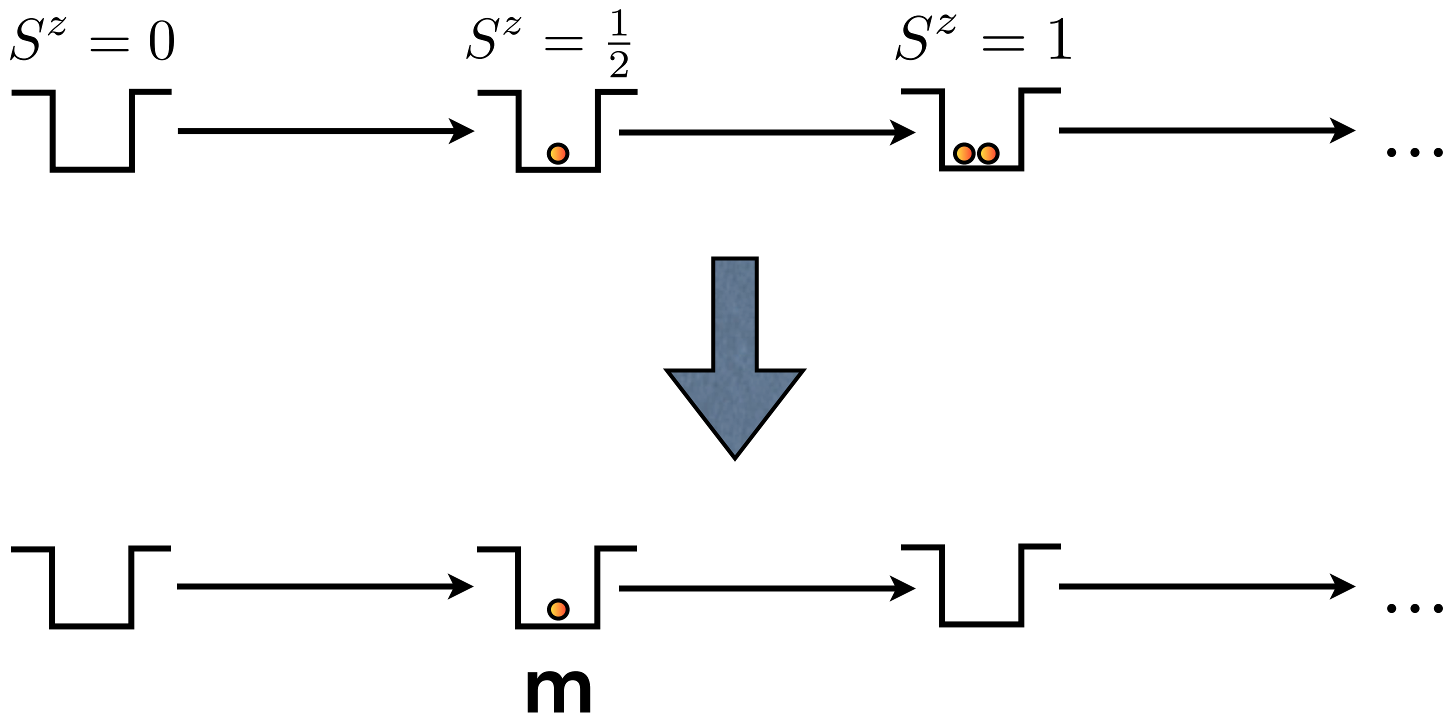
$$H' = -B \sum_i f_i S_i^z$$

lowers energy of excitations with spin

Spinons: anyons of QSL carry spin-1/2

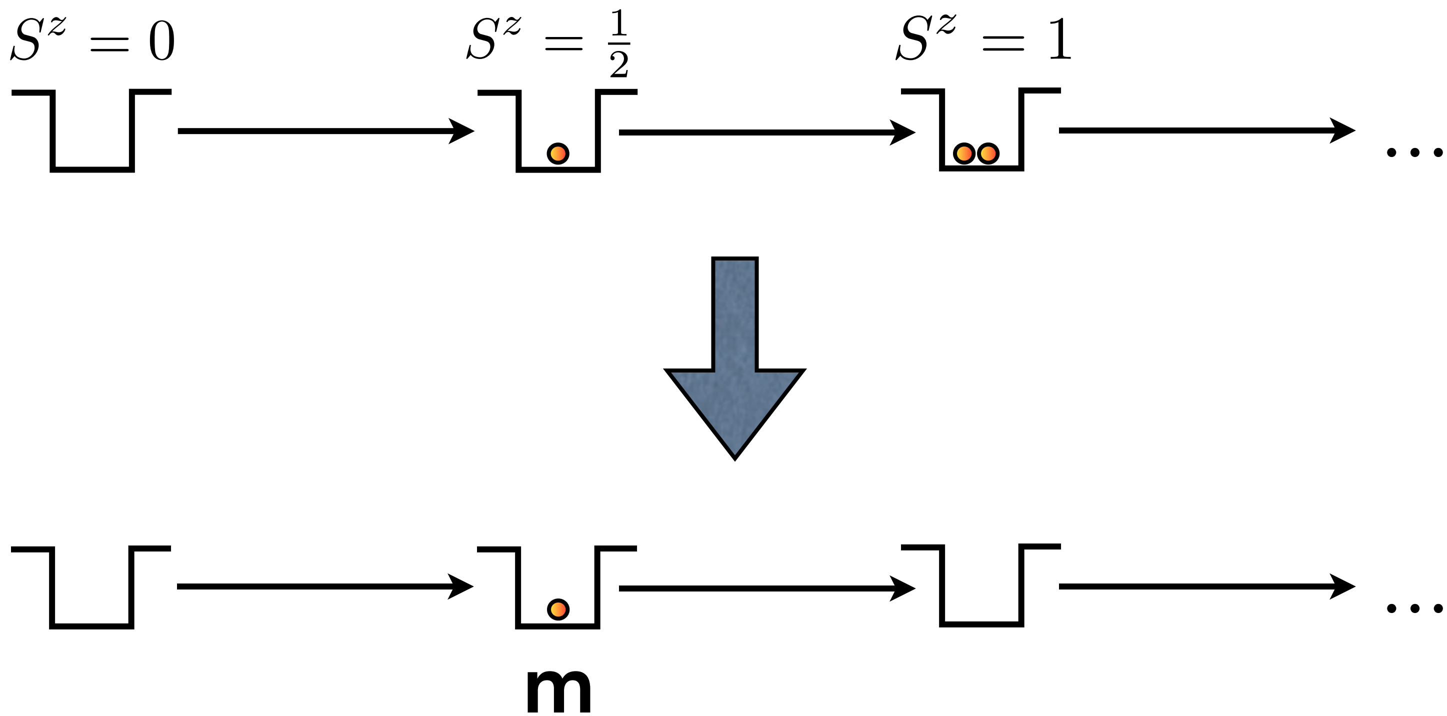


# Spin non-conservation




Periodic level crossings remain robust, and should be expected generically in gapped spin liquids with weak SOC!

# Spin non-conservation



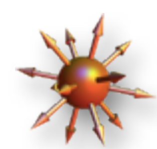

Strong SOC does not affect the protection, but it makes it less obvious what local perturbation creates the level crossing

# Gapless spin liquids

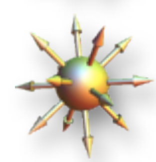
"non-local" excitations are characteristic of most QSLs: so we expect that the local QPT is very general

e.g. Coulomb 3d QSL (quantum spin ice)

- anyons replaced by non-local quasiparticles

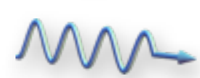


magnetic monopoles



electric monopoles

} cannot be created/ destroyed locally



"photon"

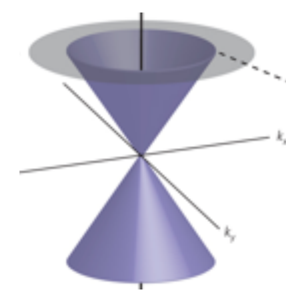
- protected level crossing ✔

# Gapless spin liquids

"non-local" excitations are characteristic of most QSLs: so we expect that the local QPT is very general

e.g. Kitaev honeycomb QSL ($Na_2IrO_3$,$RuCl_3$,...)

- "Fluxes" are non-local and can undergo binding
- Binding becomes non-trivial edge singularity due to gapless Majorana fermions
- But a local QPT persists ✔



# Summary

- Rich interplay of band topology and AHE with real-space topological defects is possible in real AFs. Propose studies of domain walls and vortices in $Mn_3Sn$
- Local studies of QSLs can reveal topological anyons or even more exotic excitations through protected local QPTs

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