Topologically nontrivial excitations and transverse transport in quantum magnets

Judit Romhányi

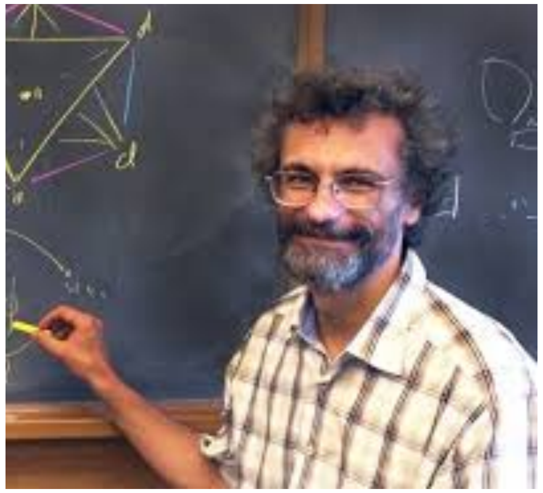
University of California, Irvine

Okinawa Institute of Science and Technology

KITP Conference: Topological Quantum Matter: From Fantasy to Reality

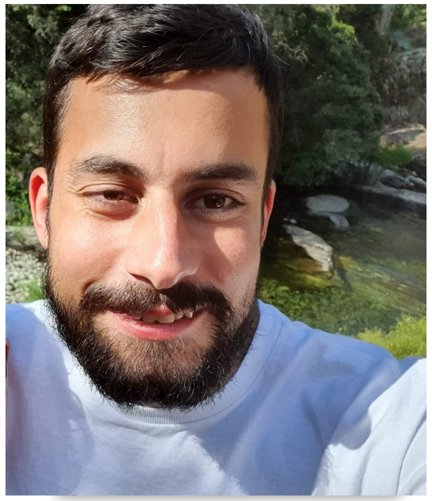
in collaboration with

Karlo Penc



Wigner Research Centre, Budapest

Andreas Thomasen



Okinawa Institute of Science and Technology

R. Ganesh

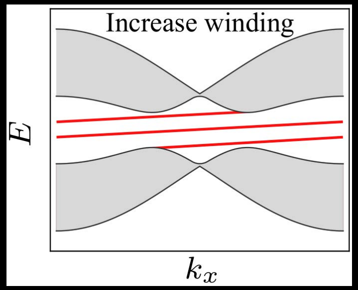
Institute of Mathematical Sciences, Chennai

Nic Shannon

Okinawa Institute of Science and Technology

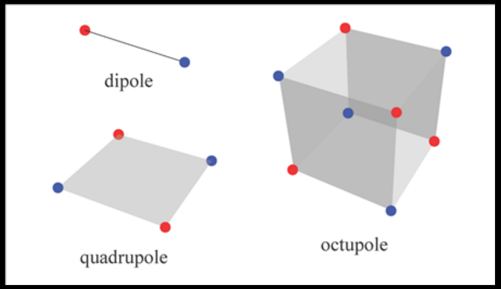
this week's topological physics …

- in photonics

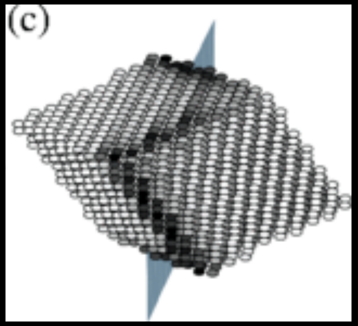


- in metamaterials

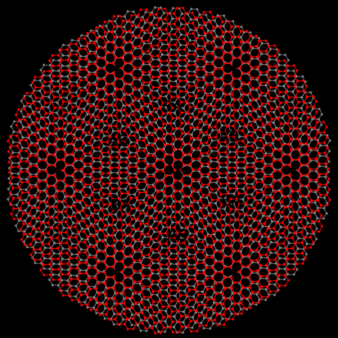
- of electric multipole insulators



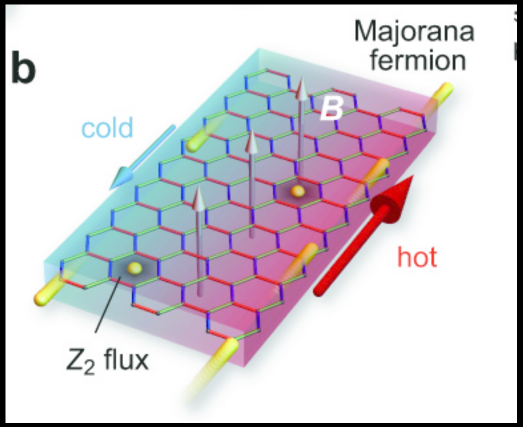
- in Floquet systems



- in twisted bilayer graphene



- in magnetic insulators



and many more..

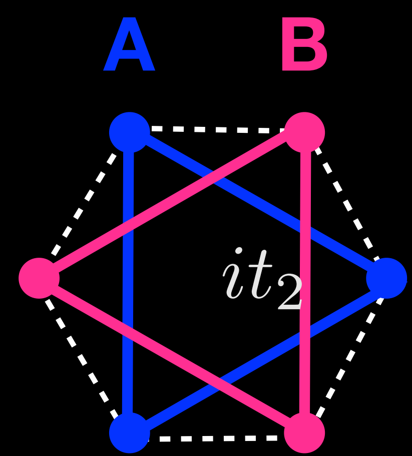
Introduction & Motivation

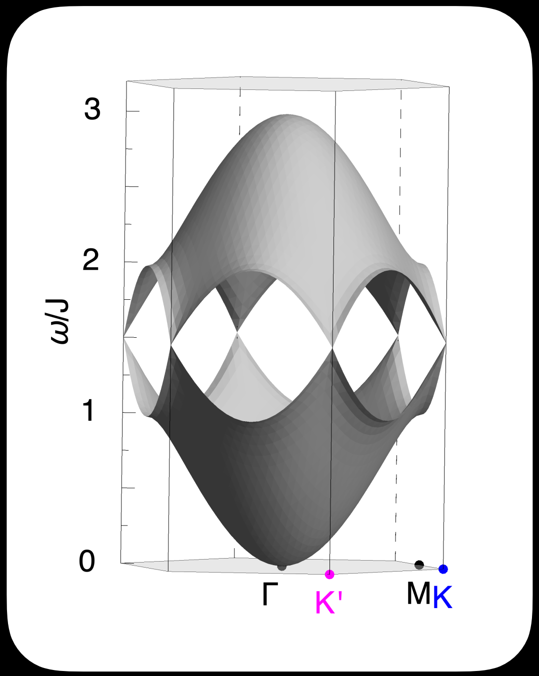
- Haldane's model

PRL 61, (1988)

Honeycomb lattice

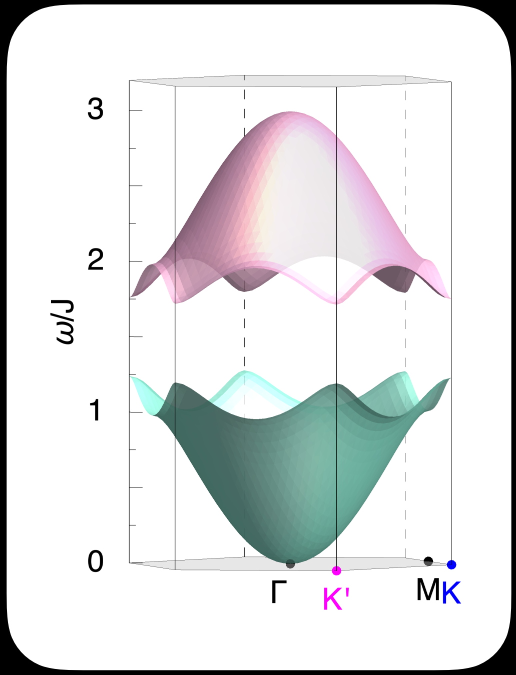
complex 2nd neighbor hopping





Dirac points protected by TR and inversion symmetries

breaking of TR symmetry



a nontrivial gap opens

Chern insulator (QAH) state

realized in

- photonics

Rechtsman et al Nature 496 (2013)

- magnetic TI

Chang et al Science 340 (2013)

- cold atoms

Jotzu et al Nature 515 (2014)

- …

Nontrivial magnon bands

- Haldane's model

PRL 61, (1988)

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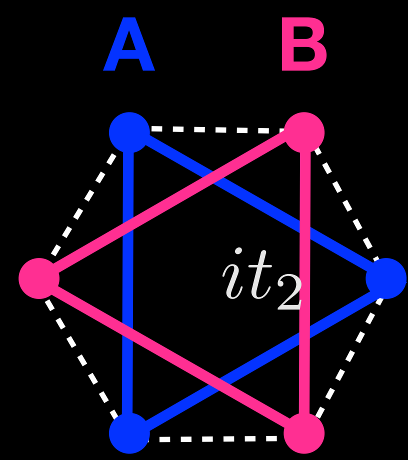


- .. in a ferromagnet

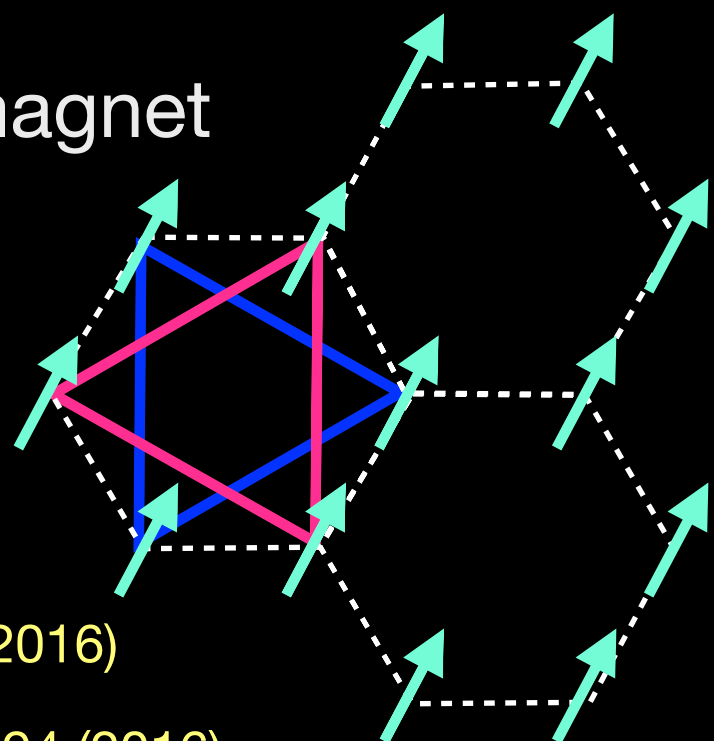
Hirschberger et al PRL 115 (2015)

Chisnell et al PRL 115 (2015)

Kim et al PRL 117 (2016)

Fransson et al PRB 94 (2016)

Kim et al npj Quant Mat 2, (2017)



$$\mathcal{H} = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + D \sum_{\langle\langle i,j \rangle\rangle} (\mathbf{S}_i \times \mathbf{S}_j)_z$$

linear spin waves

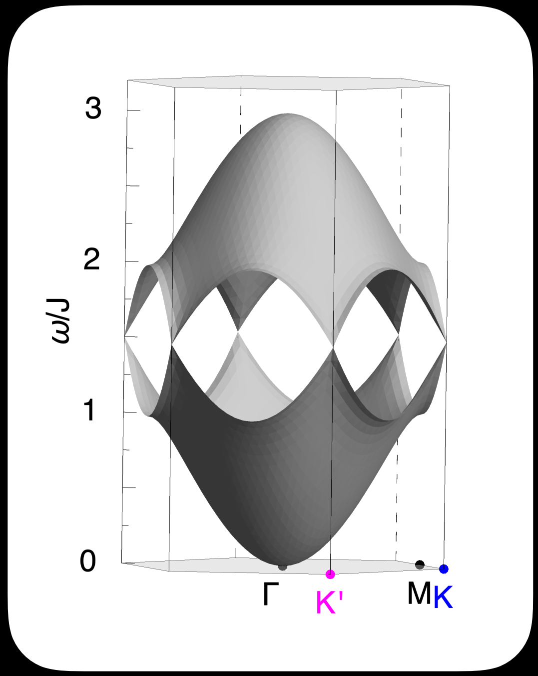
magnon dynamics can be written as

$$\mathcal{H}(\mathbf{k}) = \epsilon(\mathbf{k})\mathbf{1} + \boldsymbol{d}(\mathbf{k})\boldsymbol{\sigma}$$

$$\omega(\mathbf{k}) = \epsilon(\mathbf{k}) \pm d(\mathbf{k})$$

$$d(\mathbf{k}) = |\boldsymbol{d}(\mathbf{k})|$$

Band touching when d-vector is zero somewhere in the BZ



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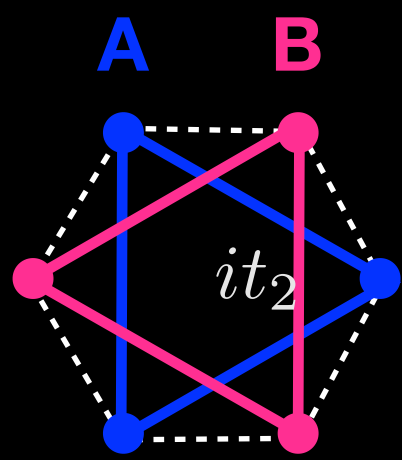

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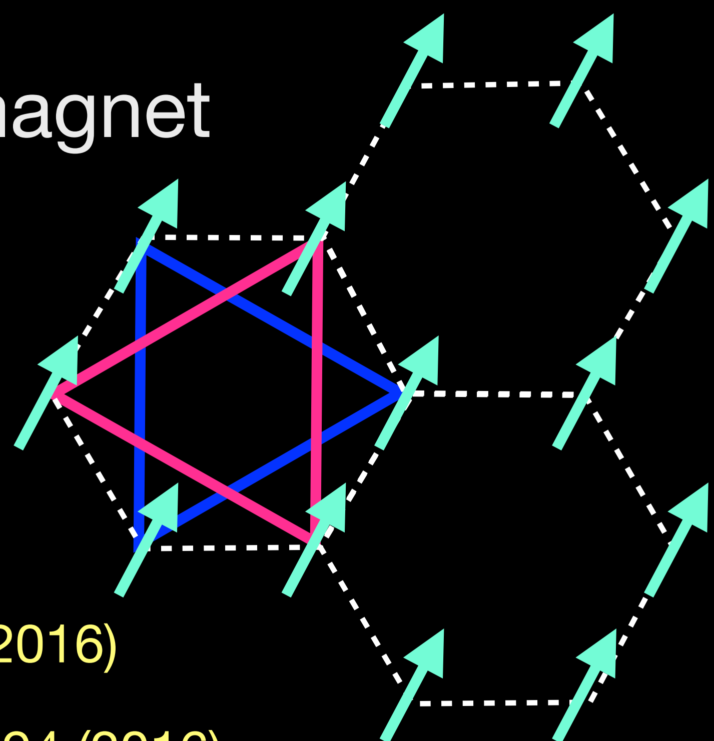

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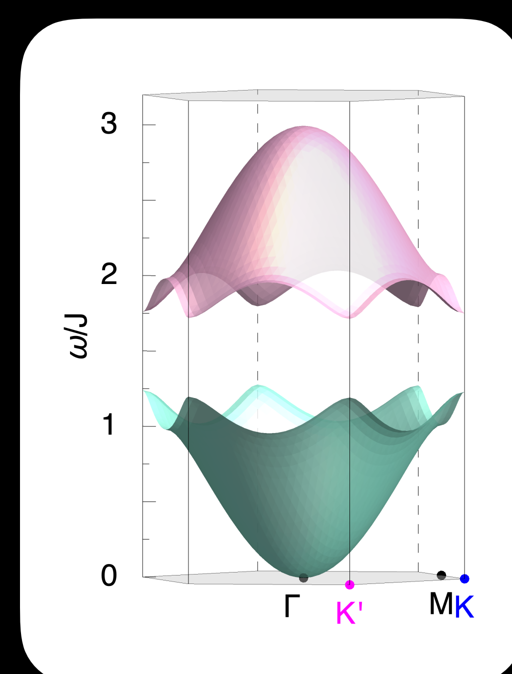

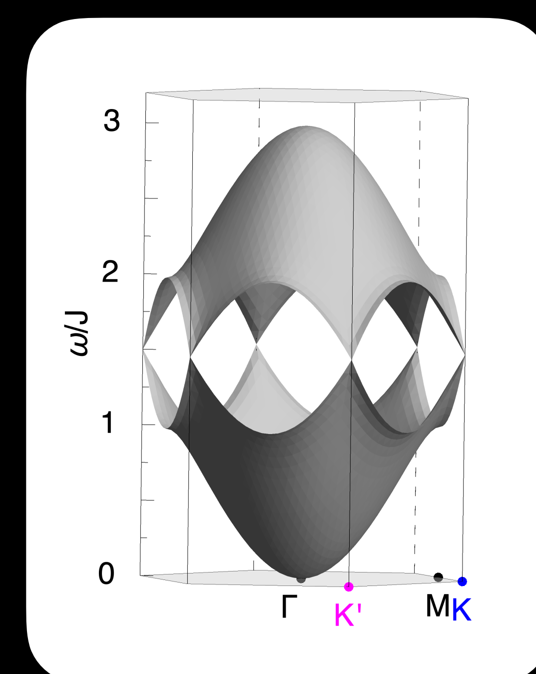

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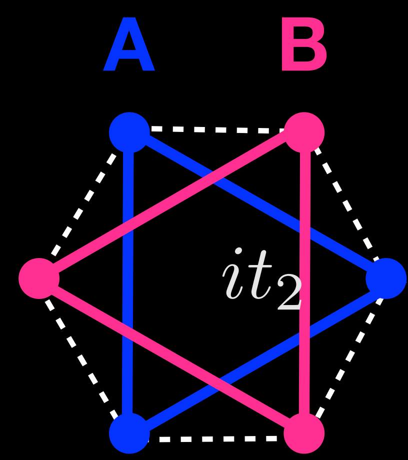

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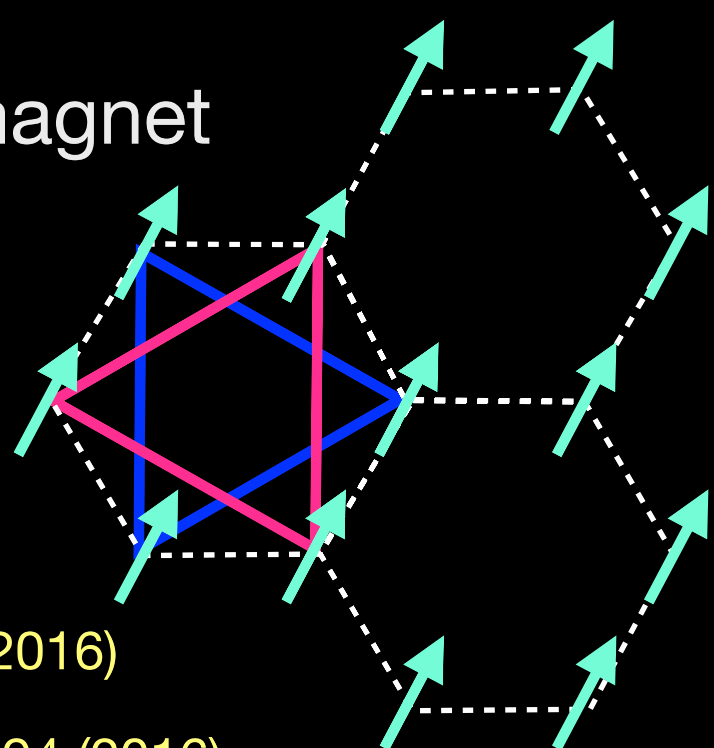

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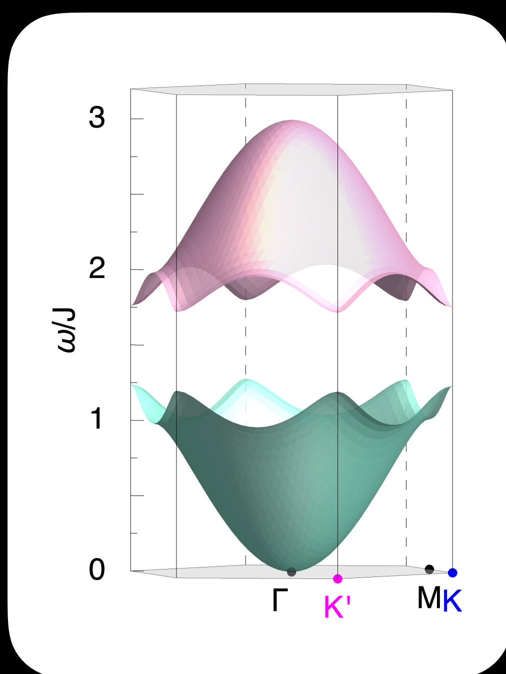

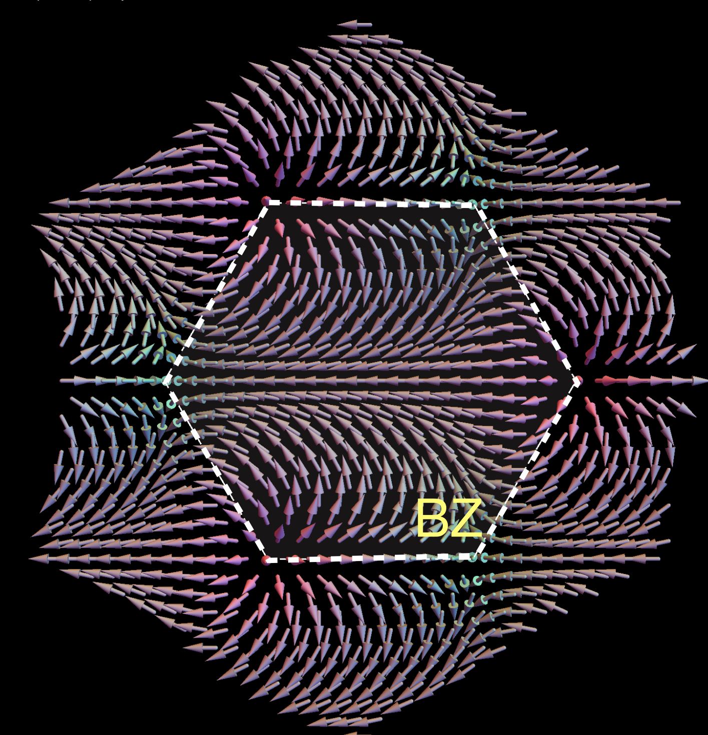

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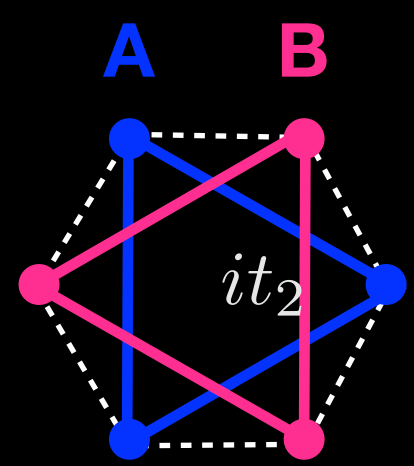

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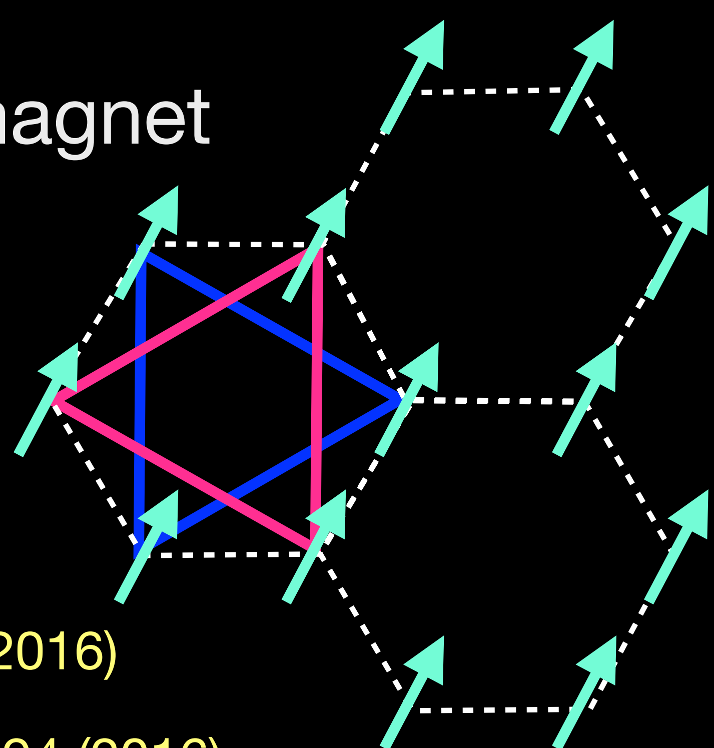

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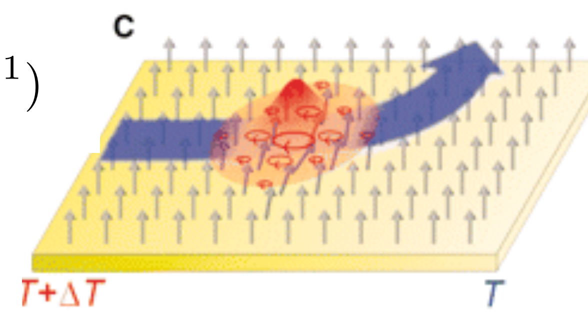
Thermal Hall effect

$$\kappa^{xy} = \frac{1}{\beta} \sum_n \int_{\mathrm{BZ}} d^2\mathbf{k}\; c_2(\rho_n) \frac{F_n^{xy}(\mathbf{k})}{i}$$

$$c_2(\rho) = \int_0^\rho dt\; \ln^2(1+t^{-1})$$

$$\rho_n = \frac{1}{e^{\omega_n \beta} - 1}$$

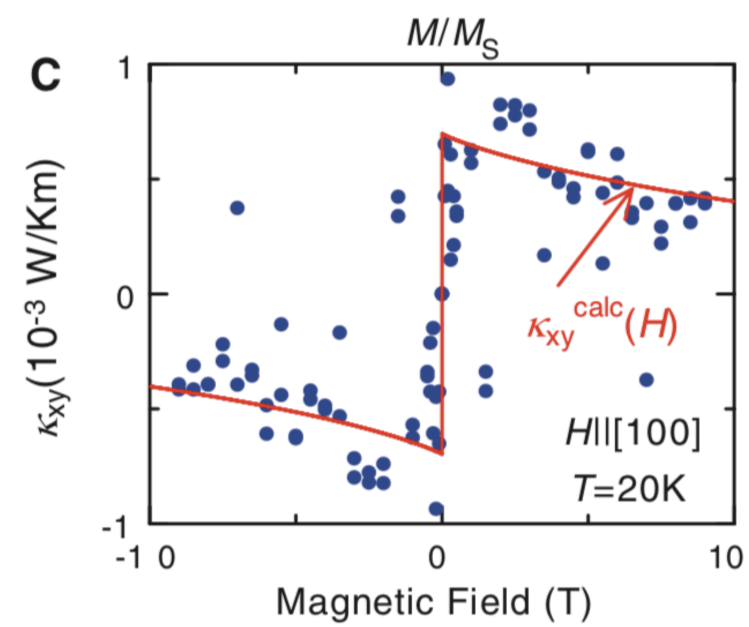


Katsura et al PRL **104** (2010)

Matsumoto et al PRL **106** and PRB **84** (2011)

Onose et al., Science **329**, (2010)

$Lu_2V_2O_7$ FM insulator



Nontrivial magnon bands

is there more?

what about the excitations of magnetically disordered states?

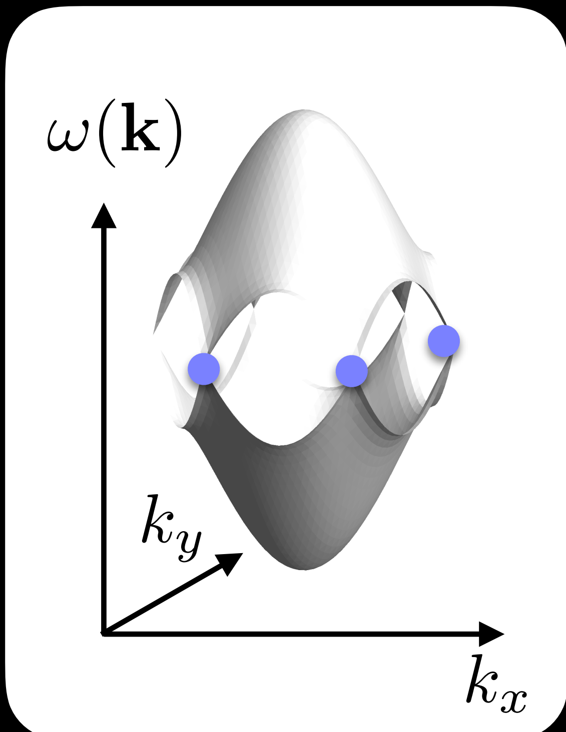
- spin liquid
- singlet product state
- quadrupolar phase

⋮

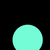
Topological boson systems

general (2S+1)-band Hamiltonian

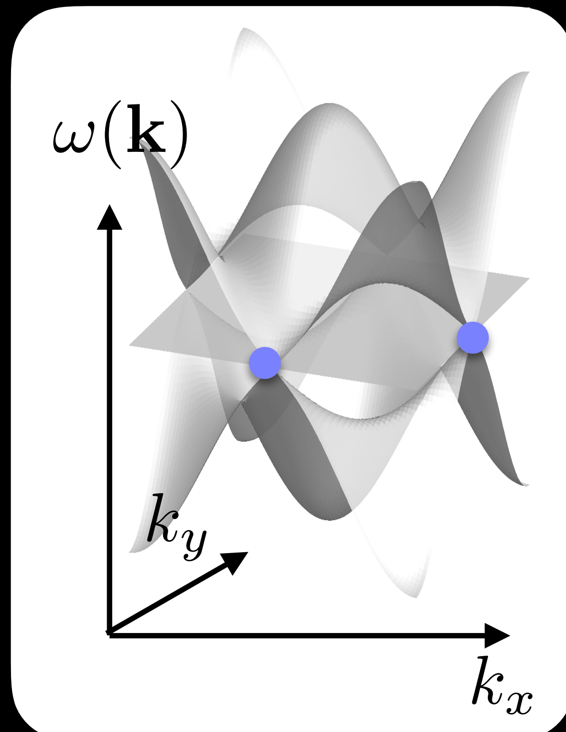
JR et al *Nat Comm* **6**, (2015) JR PRB **99**,(2019)



S=1/2 Dirac cone

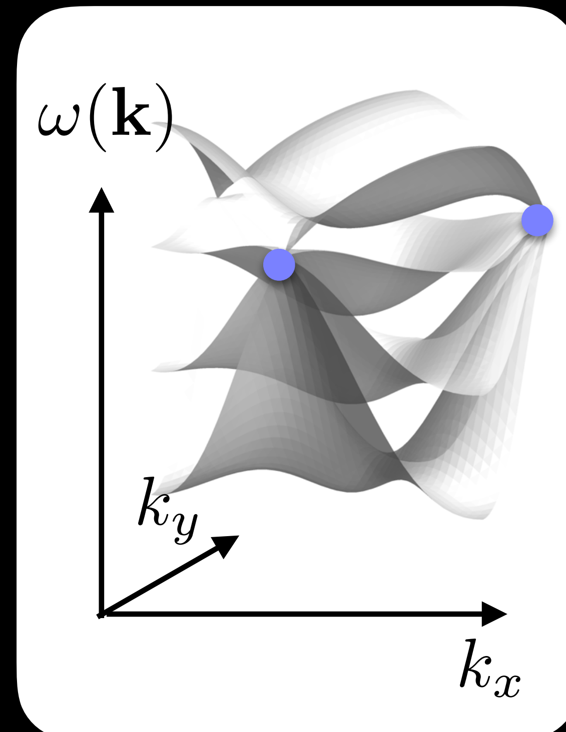


single site

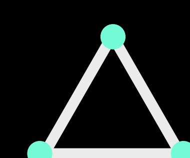


S=1 Dirac cone

dimer



S=3/2 Dirac cone



trimer

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$$m = -S, \ldots, S$$

S is a pseudo spin representing the **2S+1** levels

generalization to **larger spins**

Topological boson systems

general (2S+1)-band Hamiltonian

JR et al *Nat Comm* **6**, (2015)

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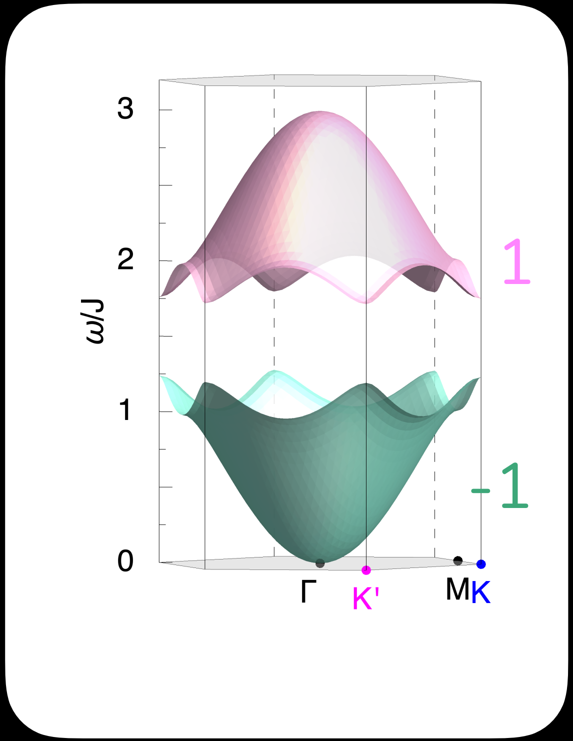
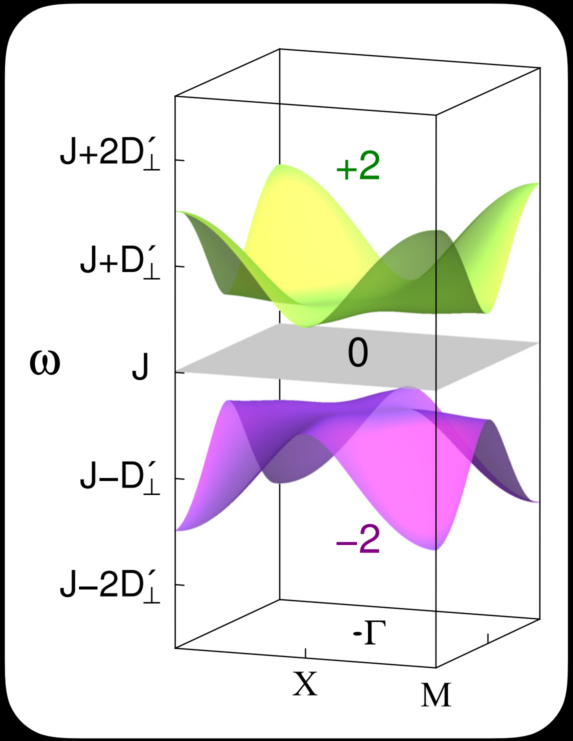
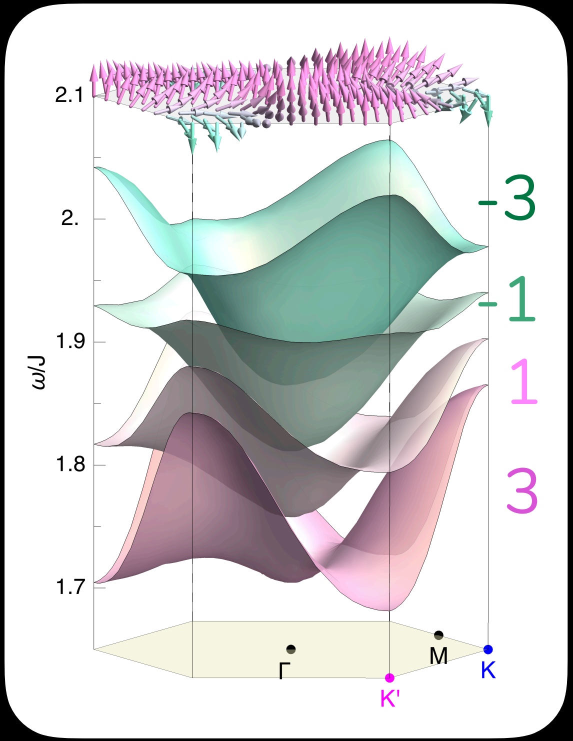






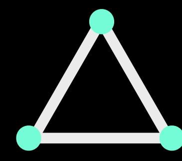
S=1/2 Dirac cone

S=1 Dirac cone

S=3/2 Dirac cone

single site

dimer



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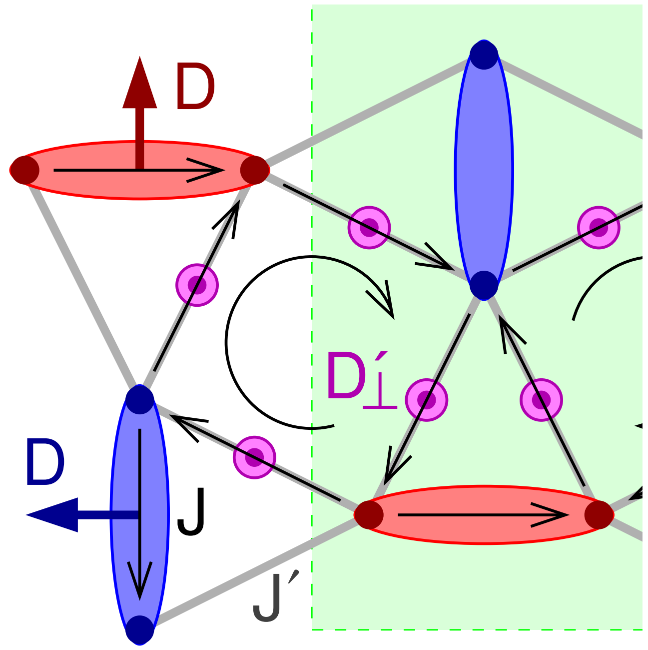
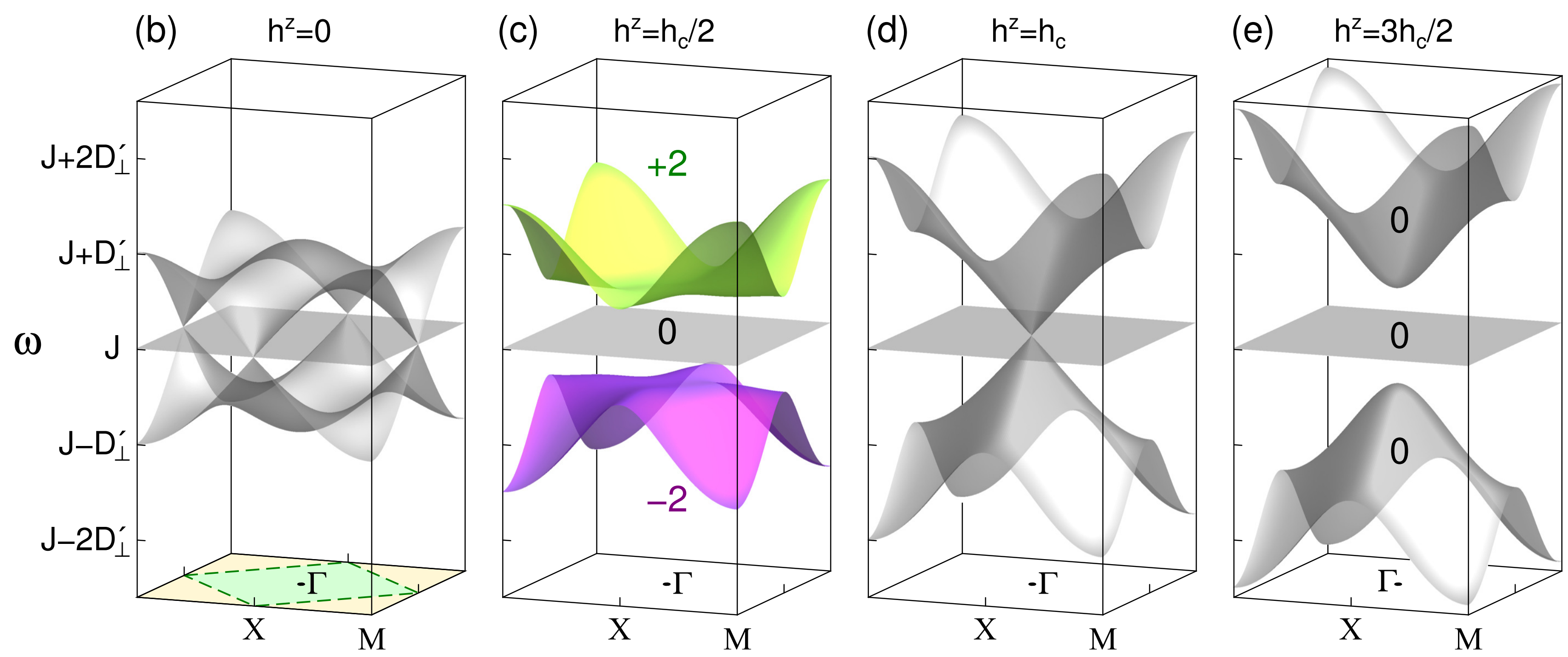
Chern number:

$$C_m = -\mathbf{2}mN_s$$

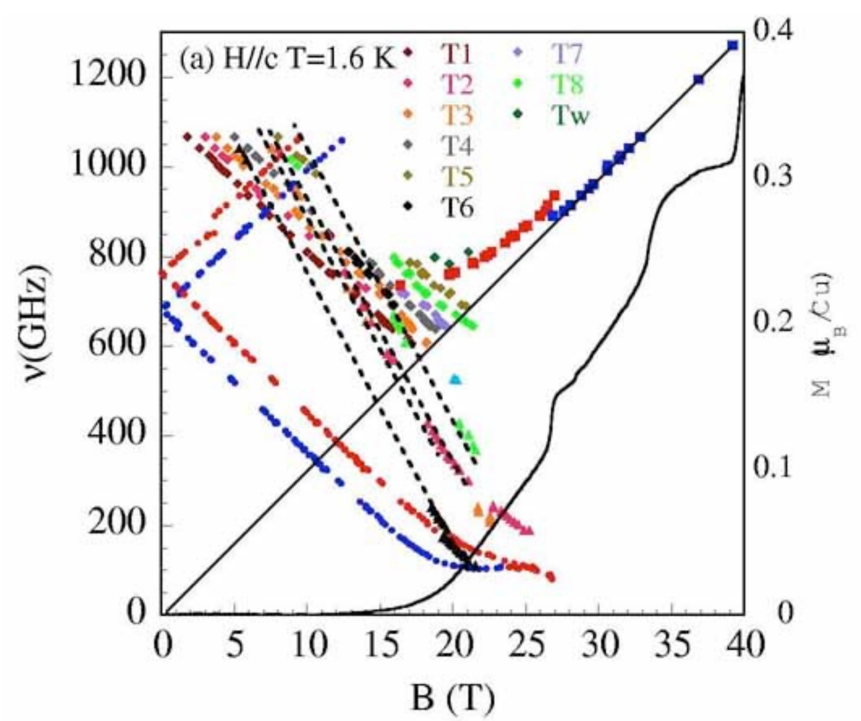
generalization to **larger spins**

From Fantasy to Reality - $SrCu_2(BO_3)_2$





$$\mathcal{H}(\mathbf{k}) = J\mathbf{I} + \mathbf{d}(\mathbf{k}) \cdot \mathbf{L}$$



H. Nojiri et al JPSJ **72**,(2003)

JR, K. Penc and R. Ganesh *Nat Comm* **6**, (2015)

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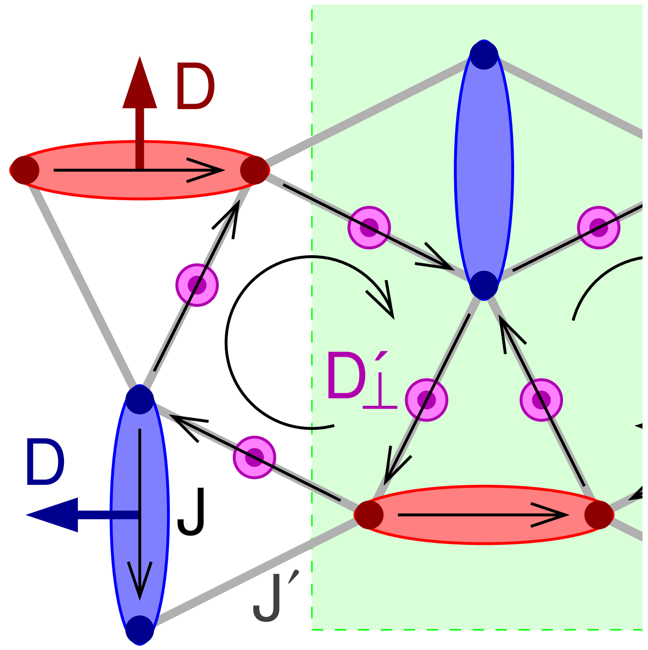

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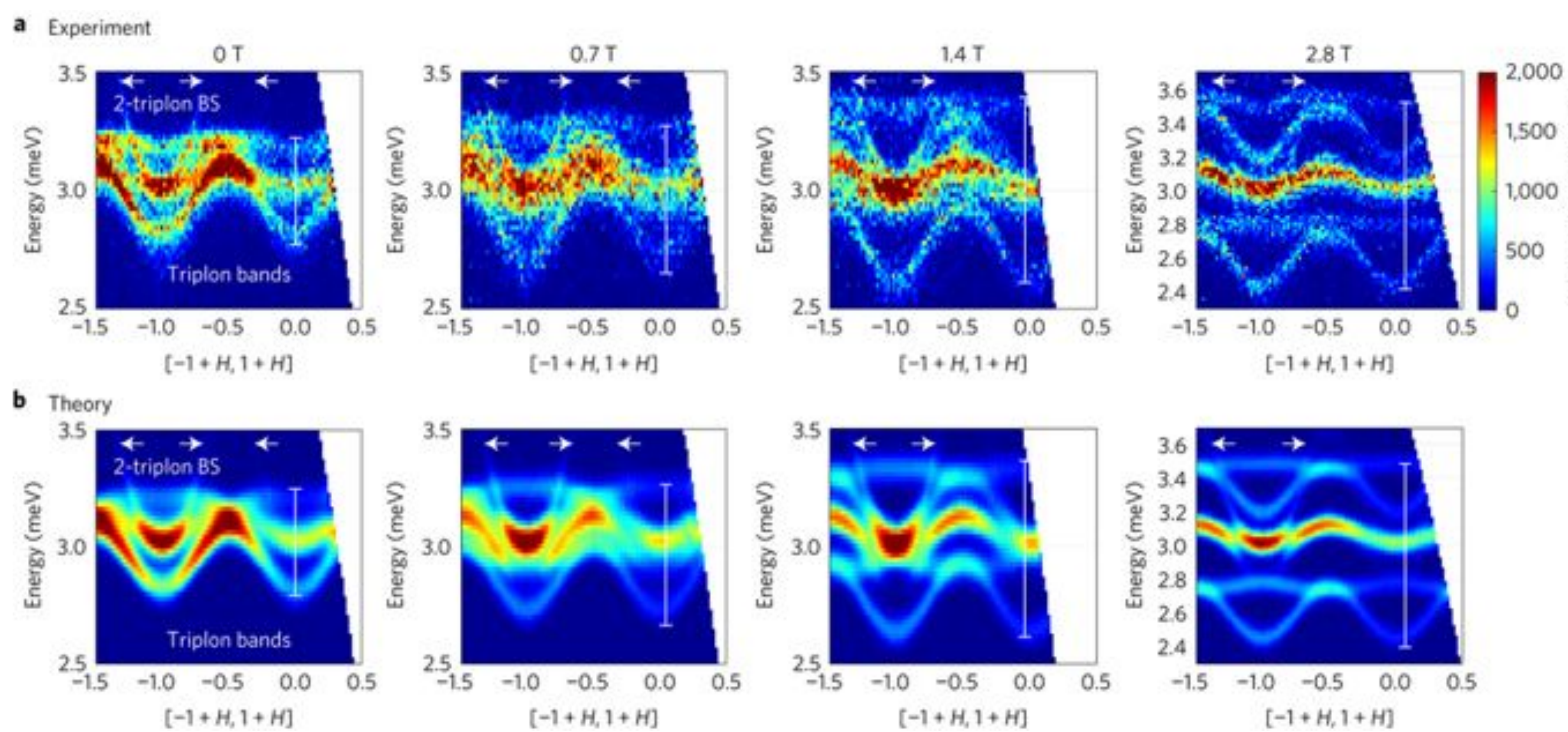
LETTERS
PUBLISHED ONLINE: 8 MAY 2017 | DOI: 10.1038/NPHYS4117
nature physics

Topological triplon modes and bound states in a Shastry–Sutherland magnet

P. A. McClarty[1,2]*, F. Krüger[1,3]*, T. Guidi[1], S. F. Parker[1], K. Refson[1,4], A. W. Parker[5], D. Prabhakaran[6] and R. Coldea[6]



JR, K. Penc and R. Ganesh *Nat Comm* **6**, (2015)

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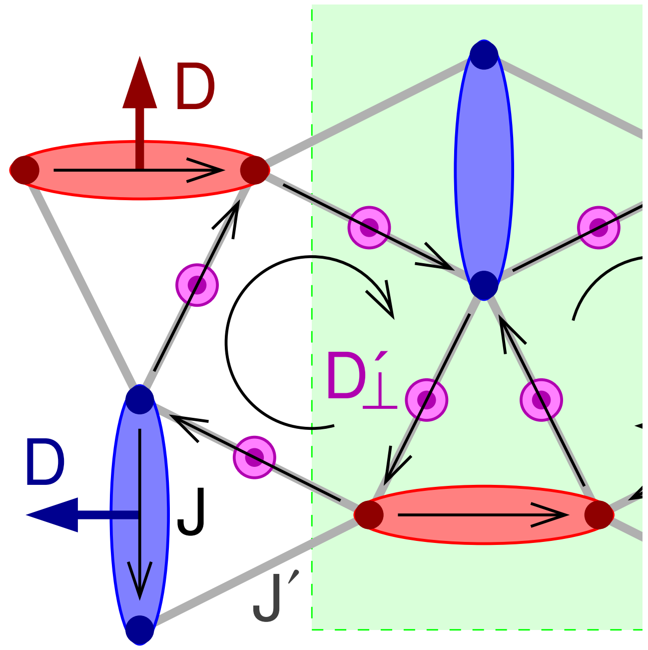

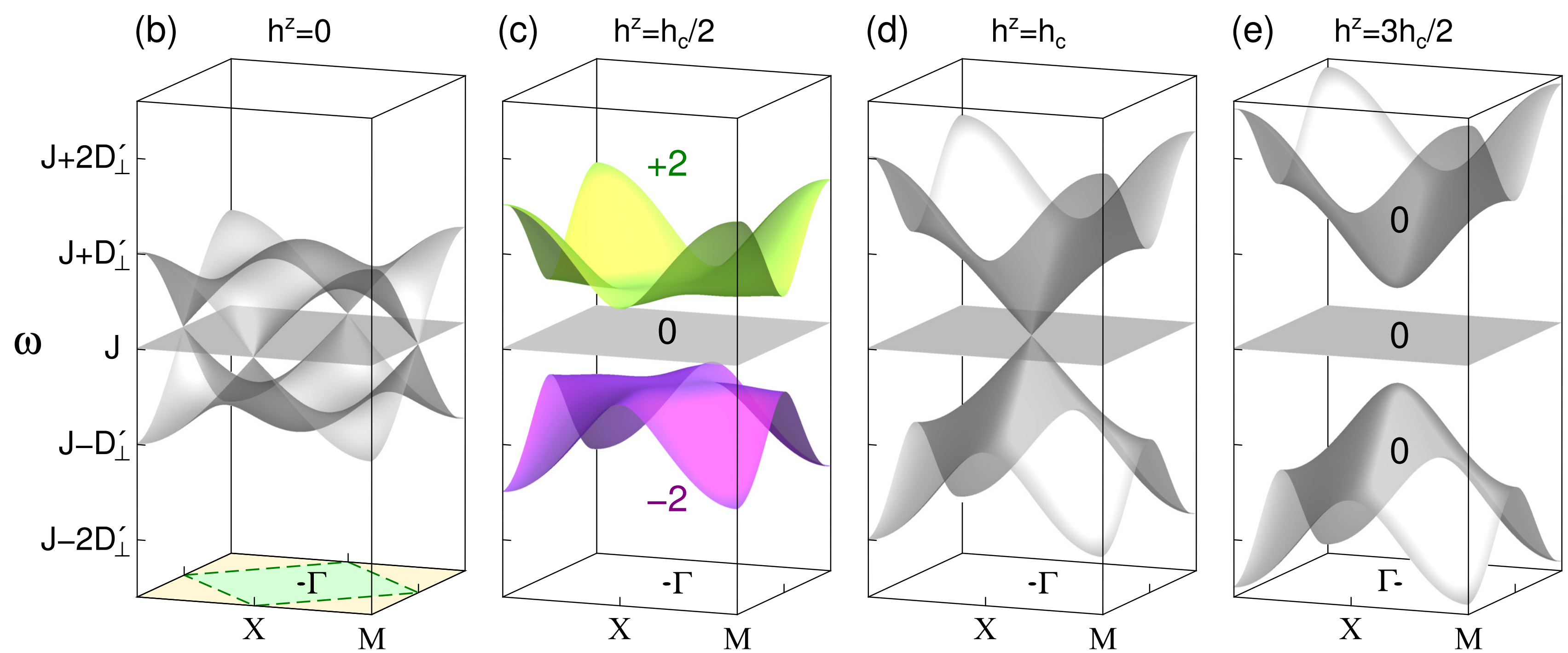

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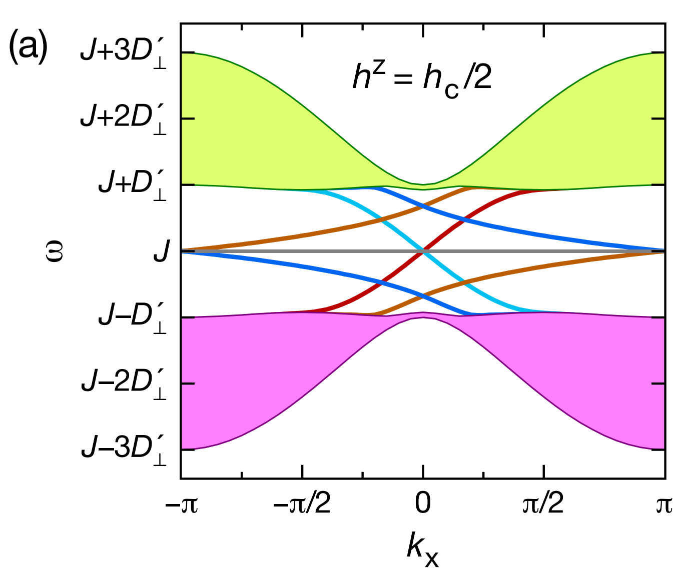
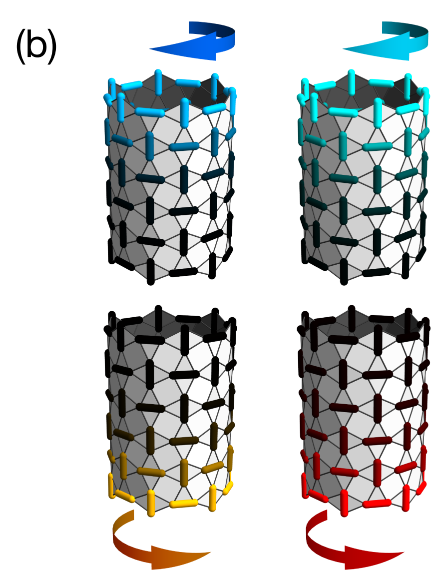
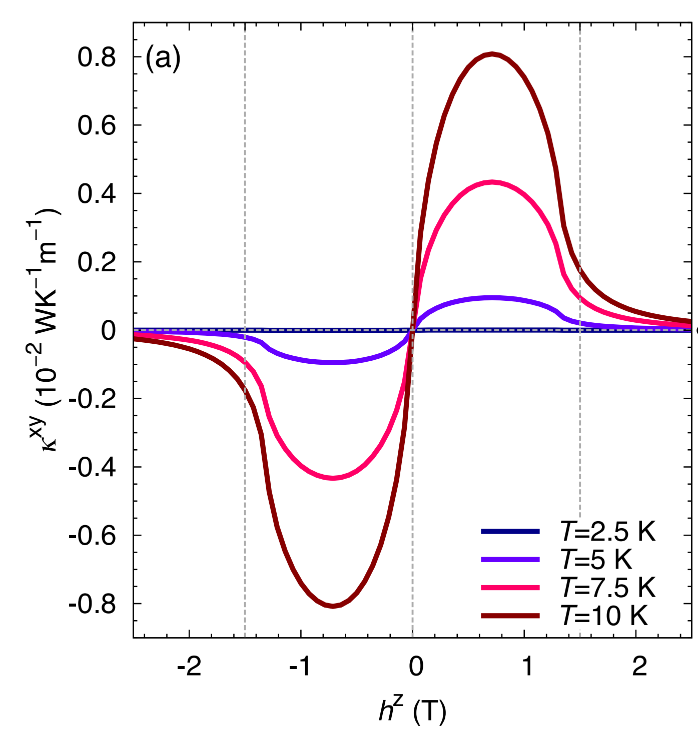


edge states is given by the Chern numbers



edge state carry energy current

Thermal Hall effect of triplets



JR, K. Penc and R. Ganesh *Nat Comm* **6**, (2015)

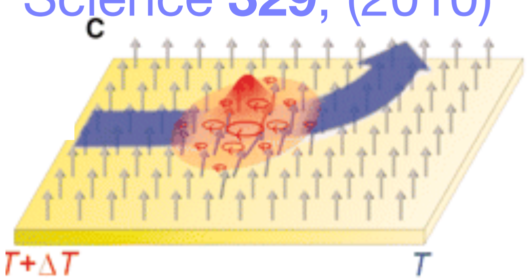
… back to fantasy

magnons 2D

- Topological magnon insulator

TKNN invariant
for bosons

Onose et al.,
Science **329**, (2010)



thermal Hall effect

Katsura et al PRL **104**;

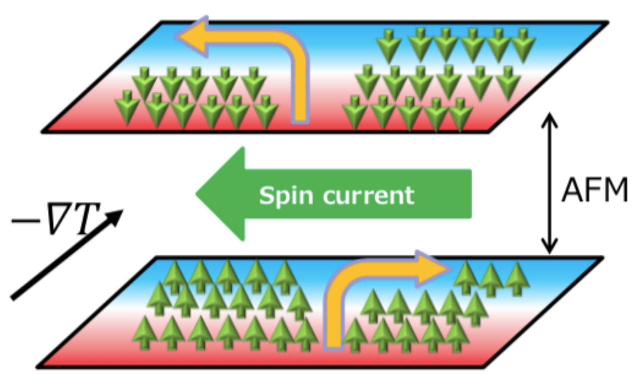
Matsumoto et al PRL 106 and
PRB 84, 184406 (2011)

+ spin degrees of freedom

- Magnon QSH insulator

Z2 invariant
for bosons

Magnon spin
Nernst effect

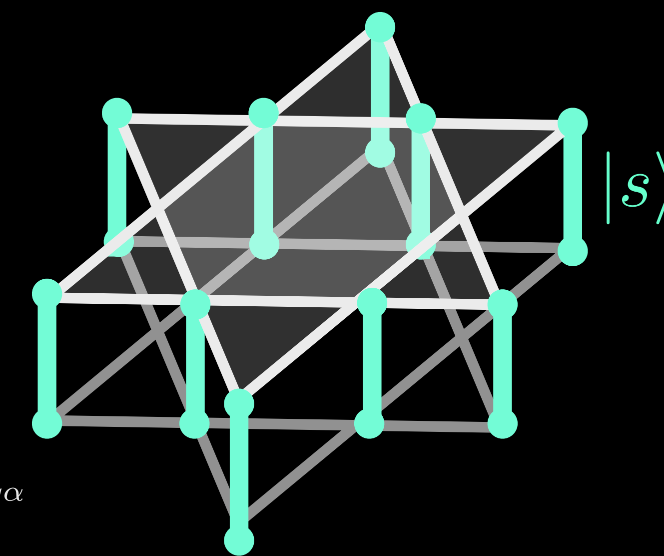


Kondo et al PRB **99**, 041110(R)

also in Kim et al PRL 117 (2016) with spinons

additional DOF

bilayer kagome
antiferromagnet



singlet ground
state

triplet dynamics:

$$J\mathbf{1}_3 + J' \sum_\alpha \cos\frac{\boldsymbol{\delta}_\alpha \cdot \mathbf{k}}{2} S^\alpha$$

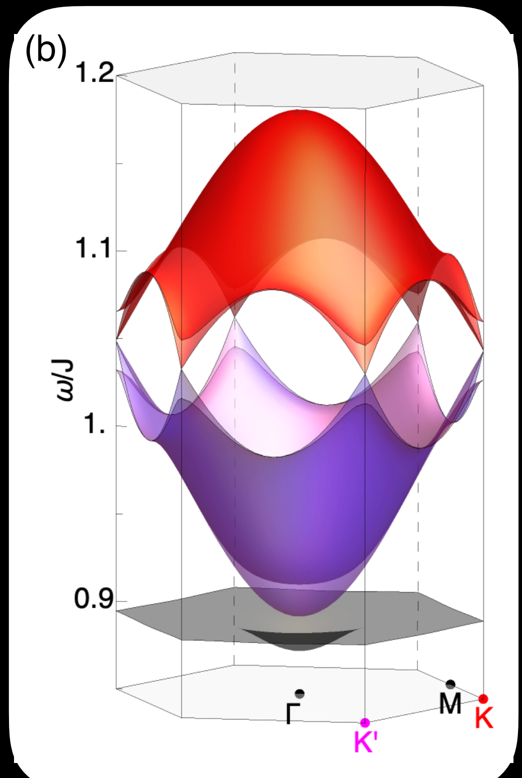
$$+ m \sum_\alpha \left[D' \cos\frac{\boldsymbol{\delta}_\alpha \cdot \mathbf{k}}{2} + D'' \cos\frac{(\boldsymbol{\delta}_\beta - \boldsymbol{\delta}_\gamma)\cdot \mathbf{k}}{2} \right] L^\alpha$$

$$m = -1, 0, 1$$

TR pairs m=1 and -1

Nernst effect of triplets

work by Andreas



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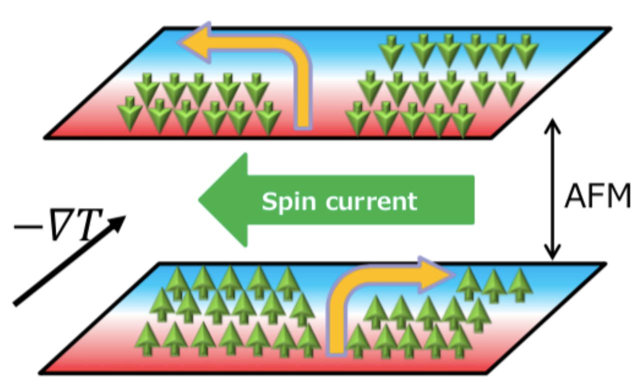


Kondo et al PRB **99**, 041110(R)

also in Kim et al PRL 117 (2016) with spinons

additional DOF

- Magnets with S>1/2 spin

larger local Hilbert space

↓

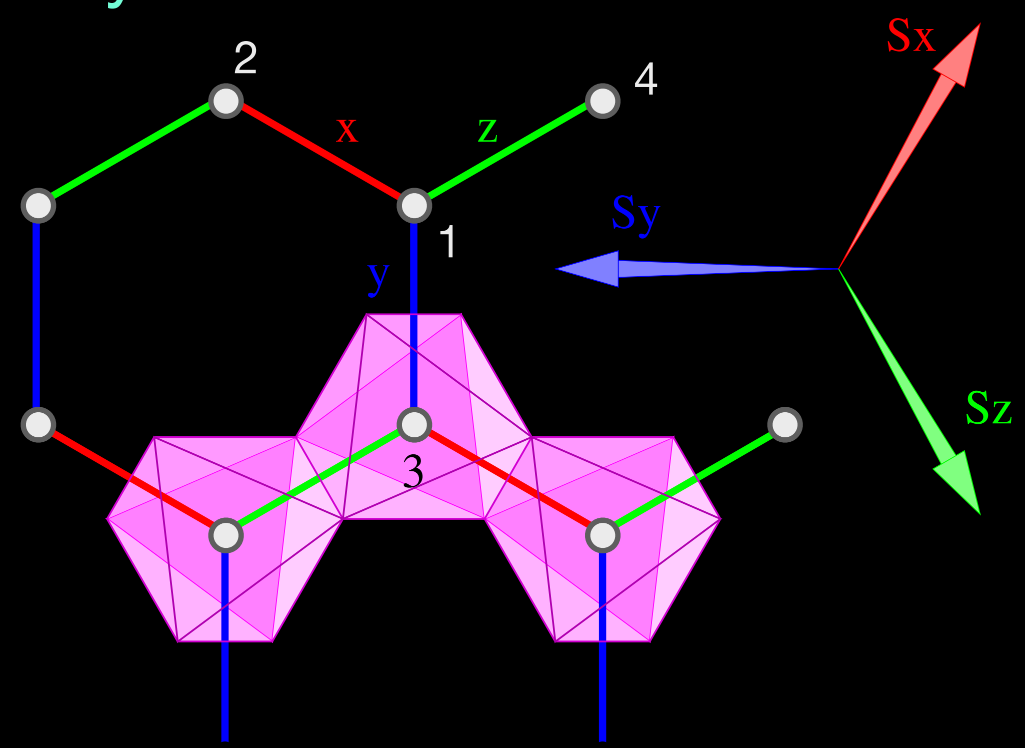
onsite “spin degree of freedom”

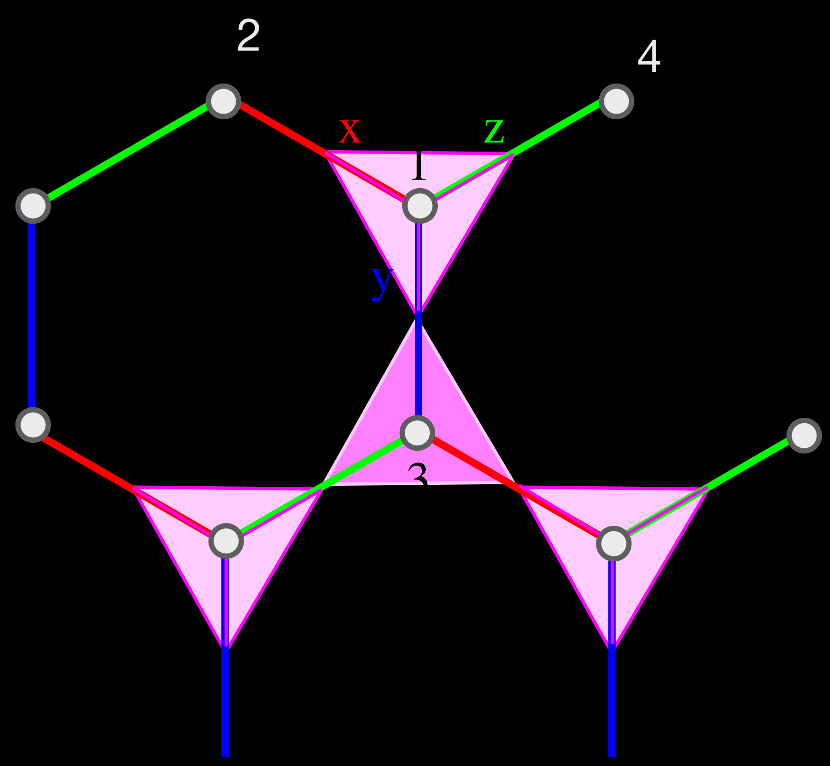
S=1

- Spin Hall insulator state
- Kitaev induced topological magnons
- onsite polarization + E field

… back to fantasy

honeycomb lattice





additional DOF

- Magnets with S>1/2 spin

larger local Hilbert space

↓

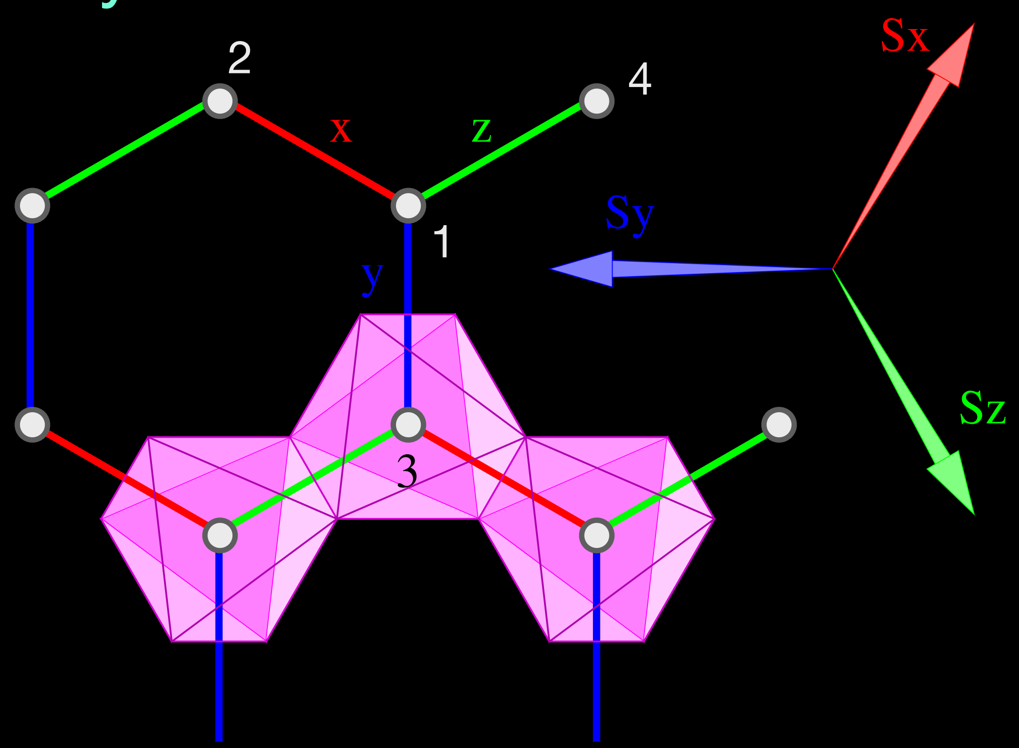
onsite “spin degree of freedom”

S=1

- Spin Hall insulator state
- Kitaev induced topological magnons
- onsite polarization + E field

… back to fantasy

honeycomb lattice



additional DOF

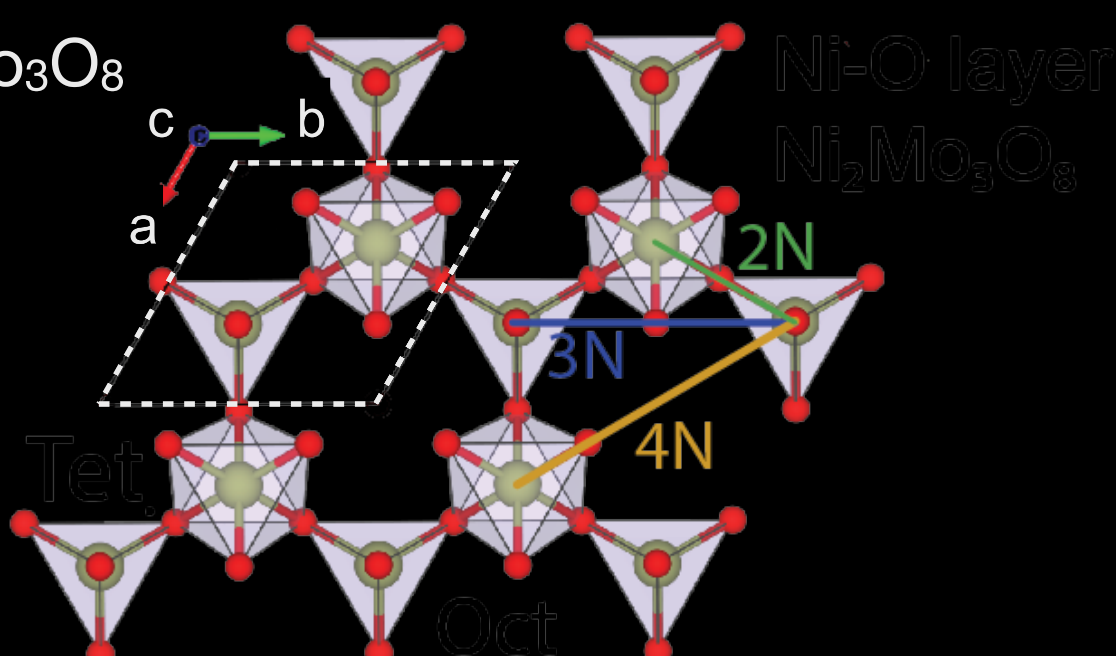
- Magnets with S>1/2 spin

larger local Hilbert space

↓

onsite “spin degree of freedom”

$Ni_2Mo_3O_8$



S=1

- Spin Hall insulator state
- Kitaev induced topological magnons
- onsite polarization + E field

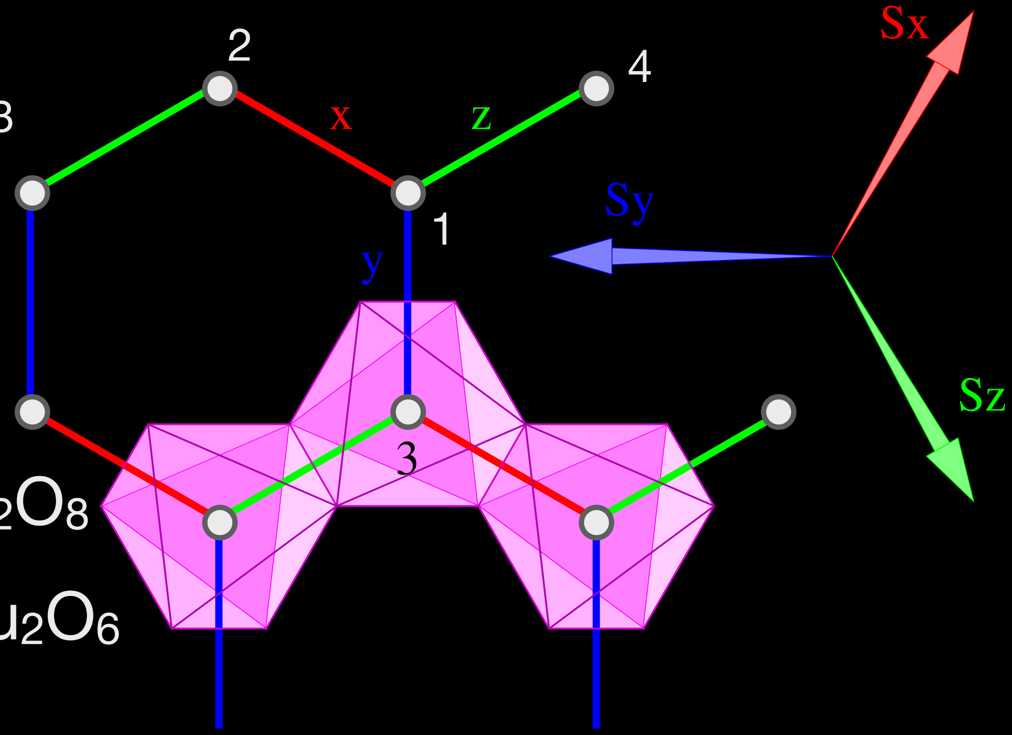
... back to fantasy

honeycomb lattice

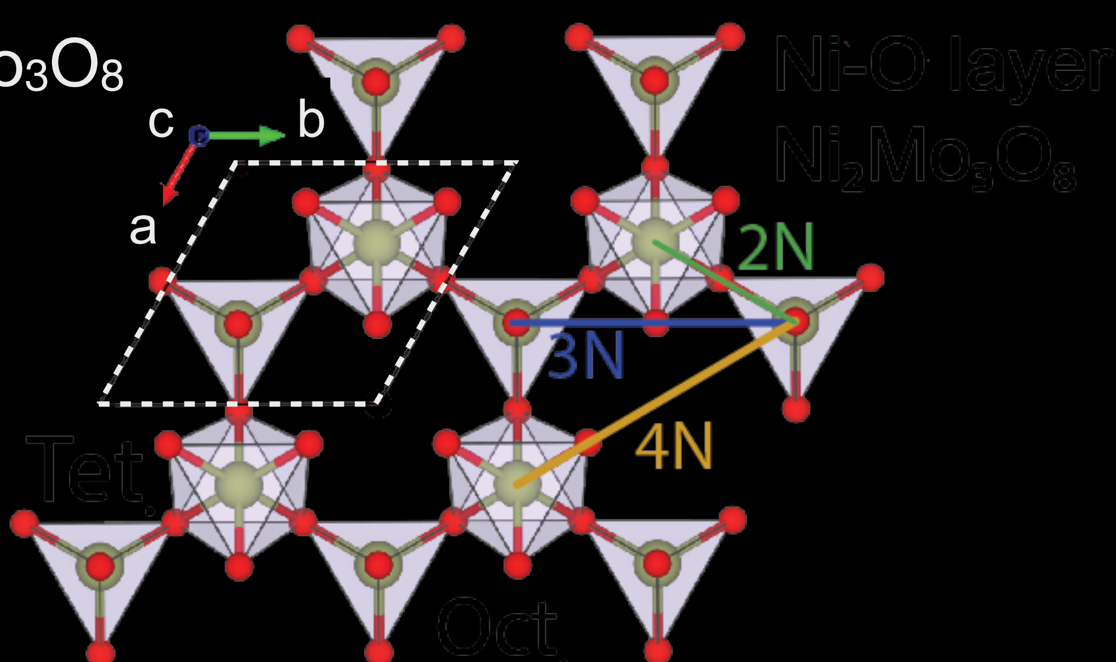
Li_2RuO_3

$BaNi_2V_2O_8$

$Ag_3LiRu_2O_6$



$Ni_2Mo_3O_8$



honeycomb & S=1

- $Ag_3LiRu_2O_6$ unconventional magnetism

  R. Kumar et al PRB 99, (2019)

- $BaNi_2V_2O_8$ ordered magnet

  N. Rogado et al PRB 65 (2002)

- $Ni_2Mo_3O_8$ zig-zag order

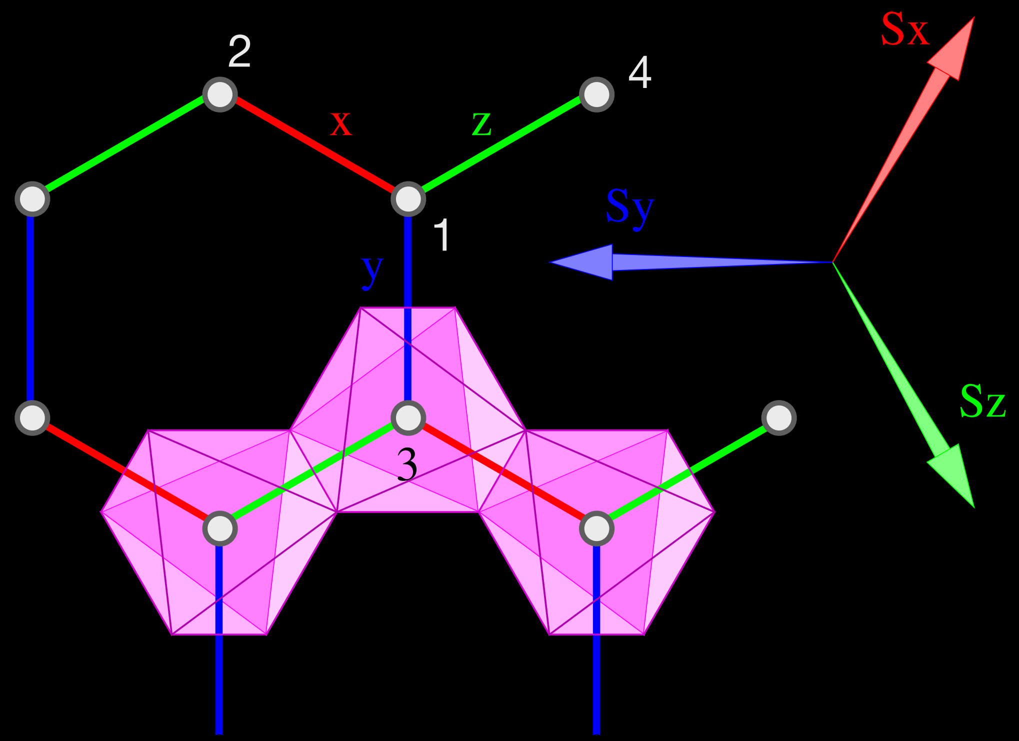
  J. Morey et al PR Mat 3, 014410 (2019)

- Li_2RuO_3 orbital dimerization

  Y. Miura et al JPSJ. 76, 033705 (2007)

- VCl_3 coming soon.. G. Nielsen et al

S=1 anisotropic honeycomb magnet

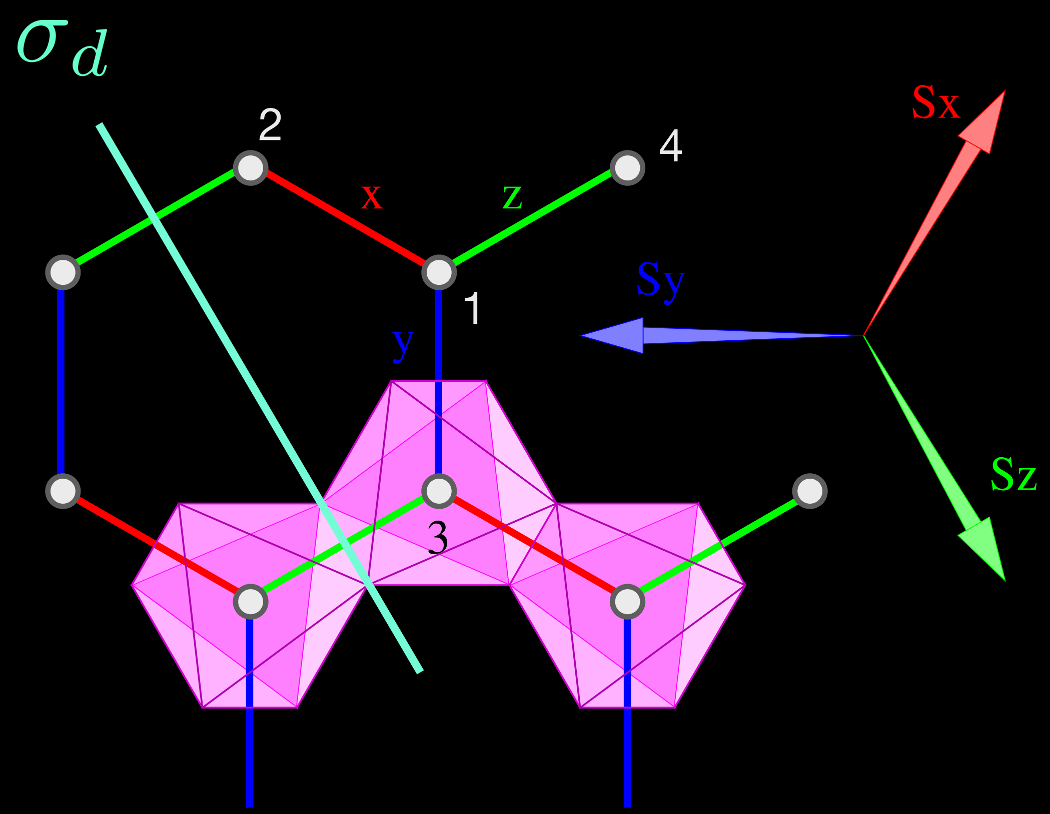


Symmetries

point group isomorphic to D_{3d}

$$\{E, 2C_3, 3C_2', I, 2S_6, 3\sigma_d\}$$

S=1 anisotropic honeycomb magnet



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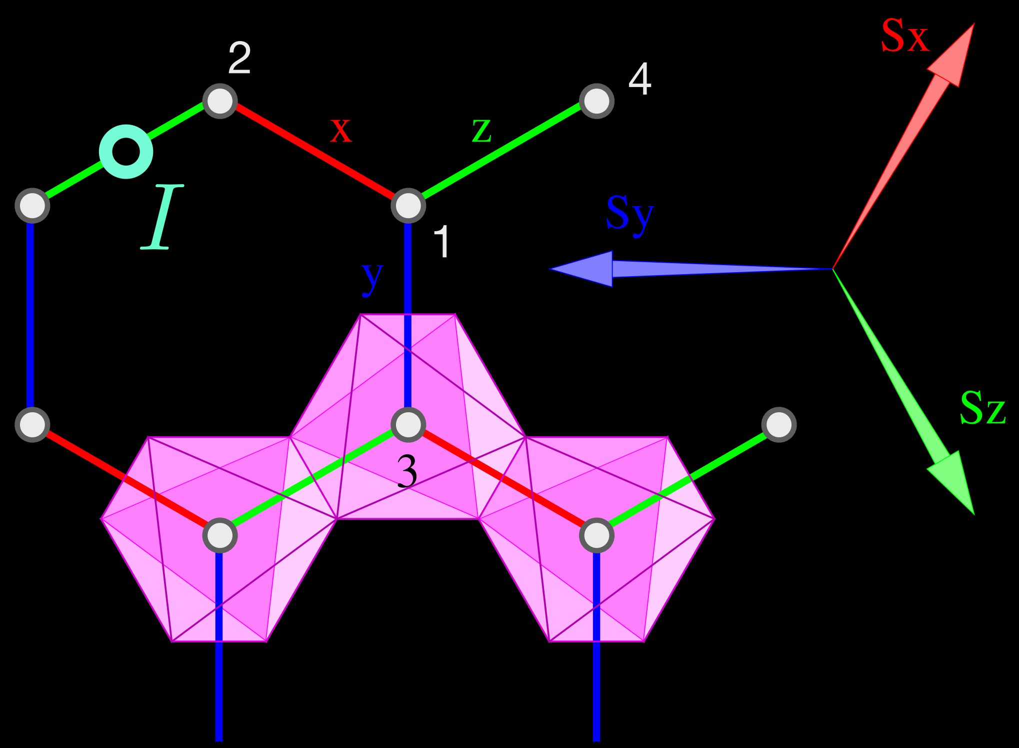
S=1 anisotropic honeycomb magnet



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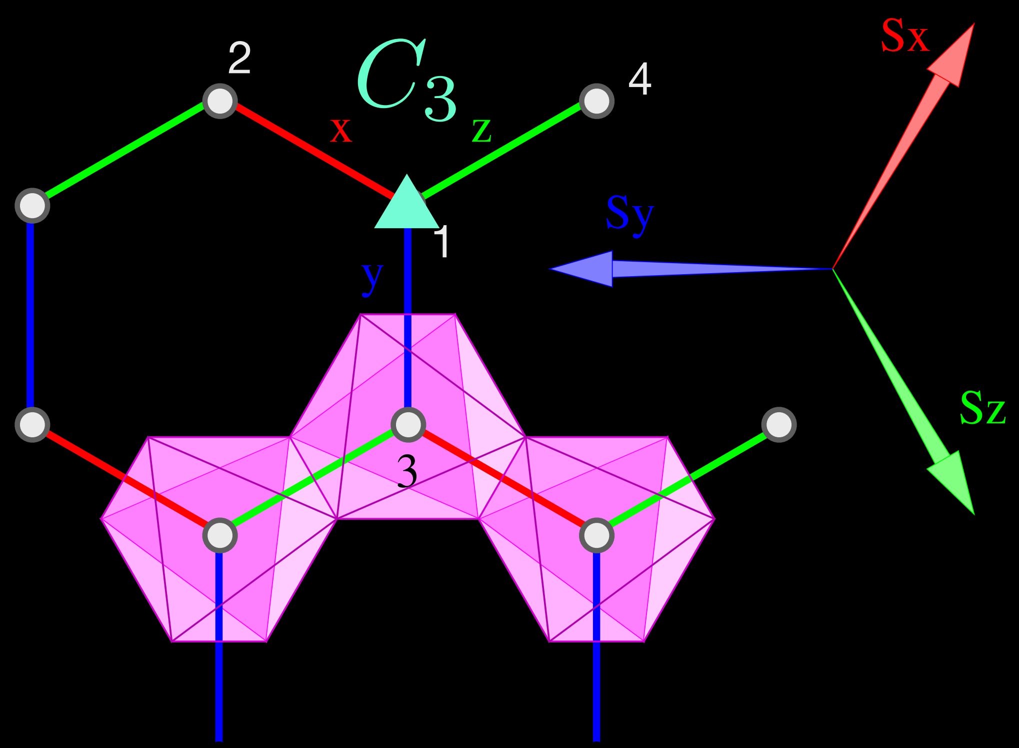

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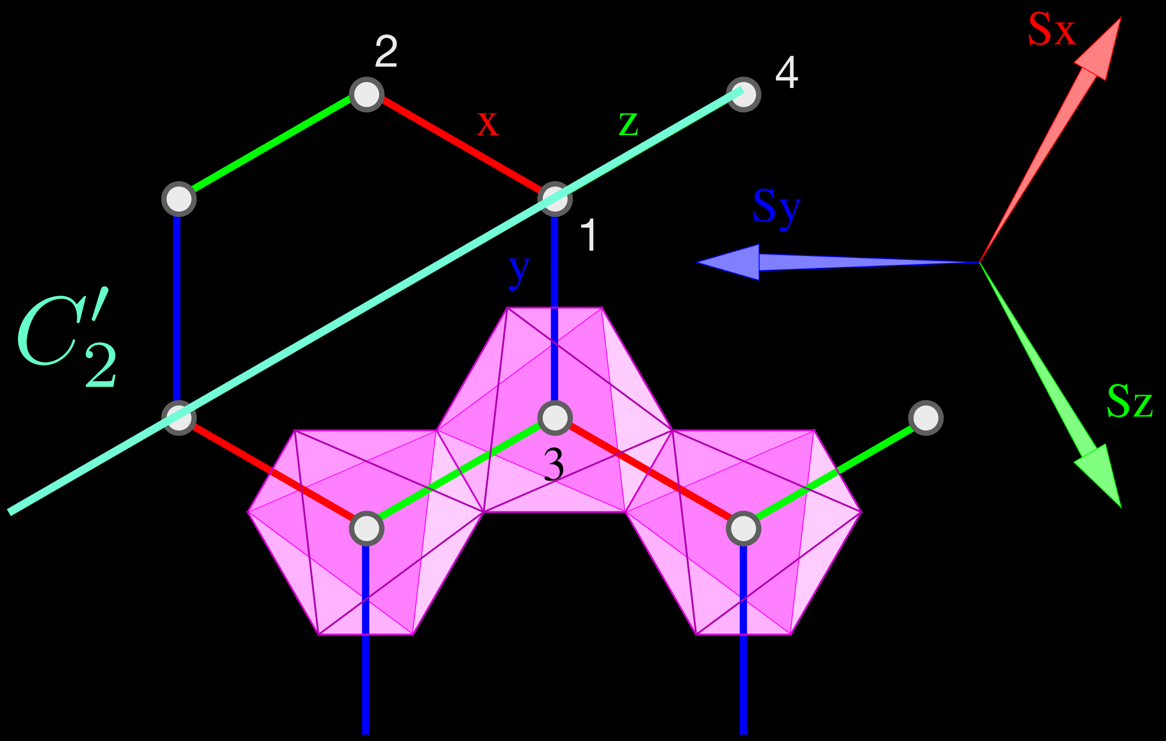

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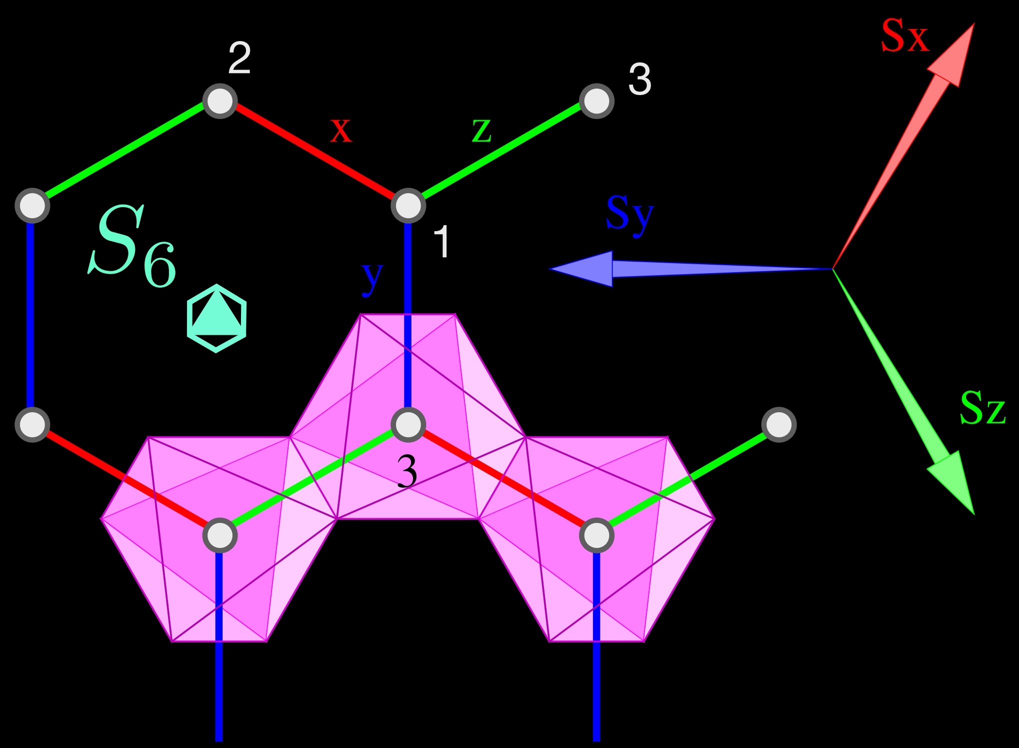

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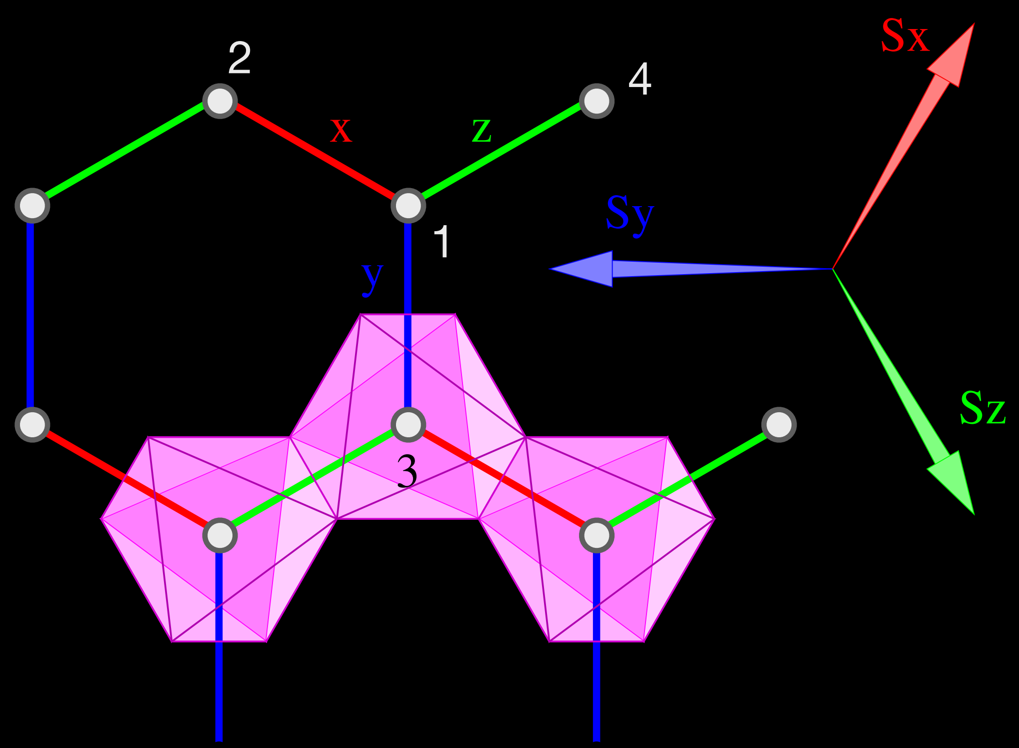


Symmetries

point group isomorphic to D_{3d}

$$\{E, 2C_3, 3C_2', I, 2S_6, 3\sigma_d\}$$

$$\mathcal{H} = J\sum_{\langle i,j\rangle} \mathbf{S}_i \cdot \mathbf{S}_j + K \sum_{\alpha=x,y,z}\sum_{\langle i,j\rangle\in\alpha} S_i^\alpha S_j^\alpha$$
$$+ D'(\boldsymbol{S}_i \times \boldsymbol{S}_j)_{111} + \Lambda \sum_j (S_i^{111})^2 - h\sum_i S_i^{111}$$

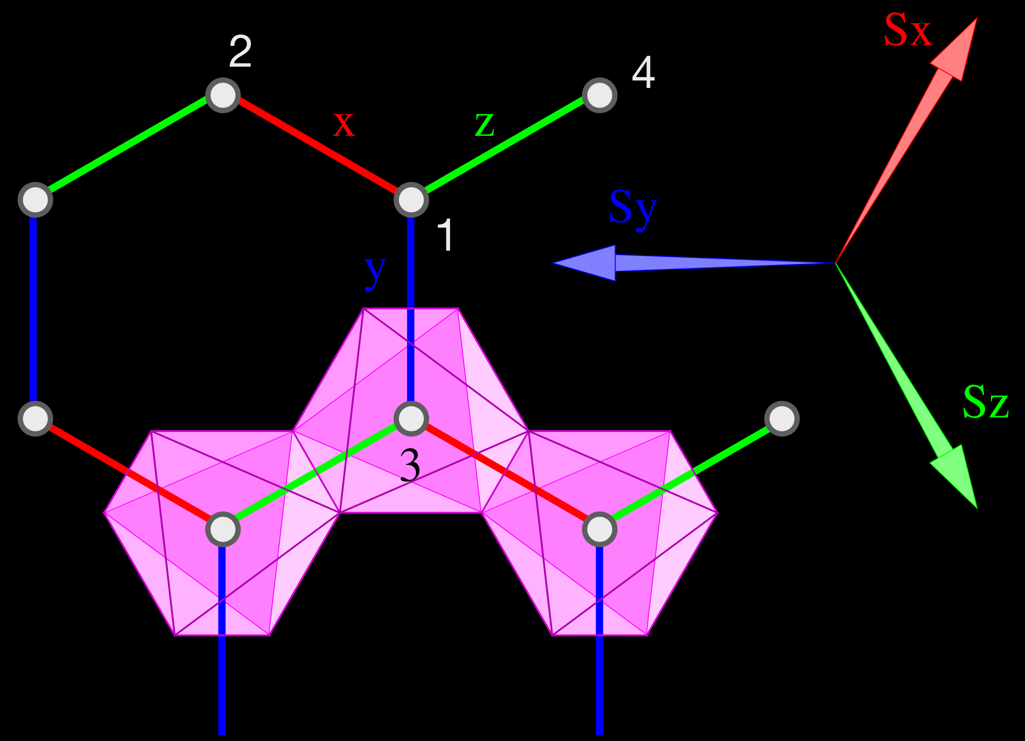
P. A. McClarty et al PRB 98, 060404 (2018)

Hae-Young Kee's talk:

microscopic mechanism for large S
Kitaev model

P. Stavropoulos et al PRL 123, 037203 (2019)

S=1 anisotropic honeycomb magnet



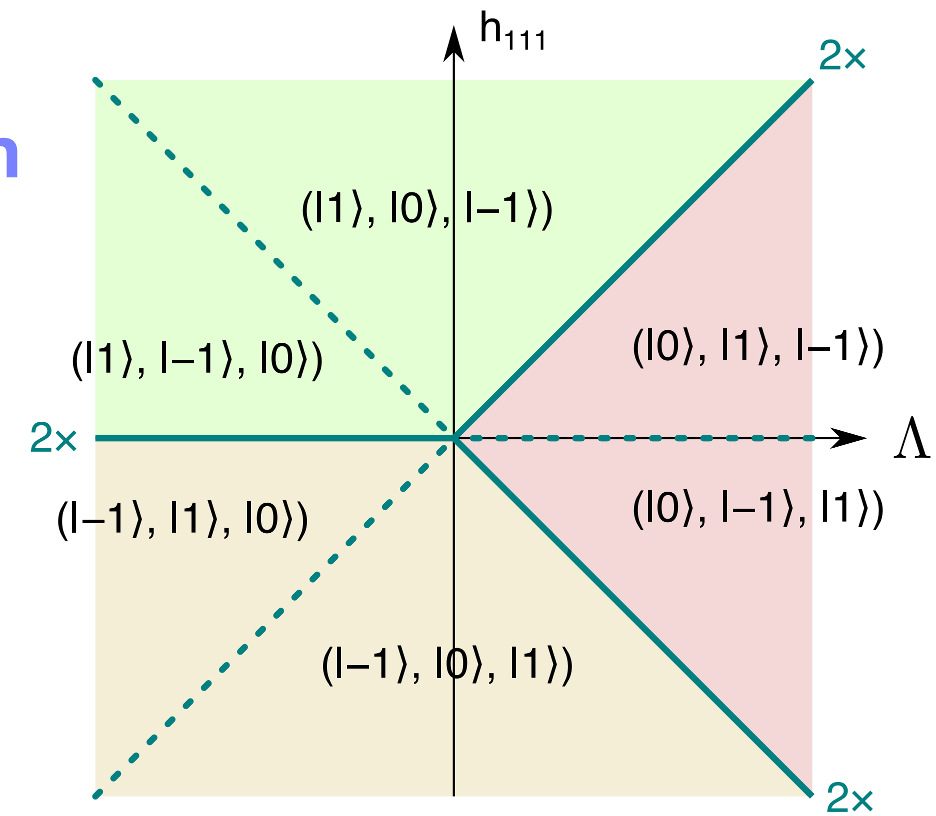
single site phase diagram

3D local Hilbert space:

$|1\rangle$

$|0\rangle$

$|-1\rangle$



$$\mathcal{H} = J\sum_{\langle i,j\rangle} \mathbf{S}_i\cdot\mathbf{S}_j + K\sum_{\alpha=x,y,z}\sum_{\langle i,j\rangle\in\alpha} S_i^\alpha S_j^\alpha + D'\sum_{\langle\langle i,j\rangle\rangle}(\boldsymbol{S}_i\times\boldsymbol{S}_j)_{111} + \Lambda\sum_j (S_i^{111})^2 - h\sum_i S_i^{111}$$

when Λ is large, the ground state is $|\Psi\rangle = \prod_j |0\rangle_j$

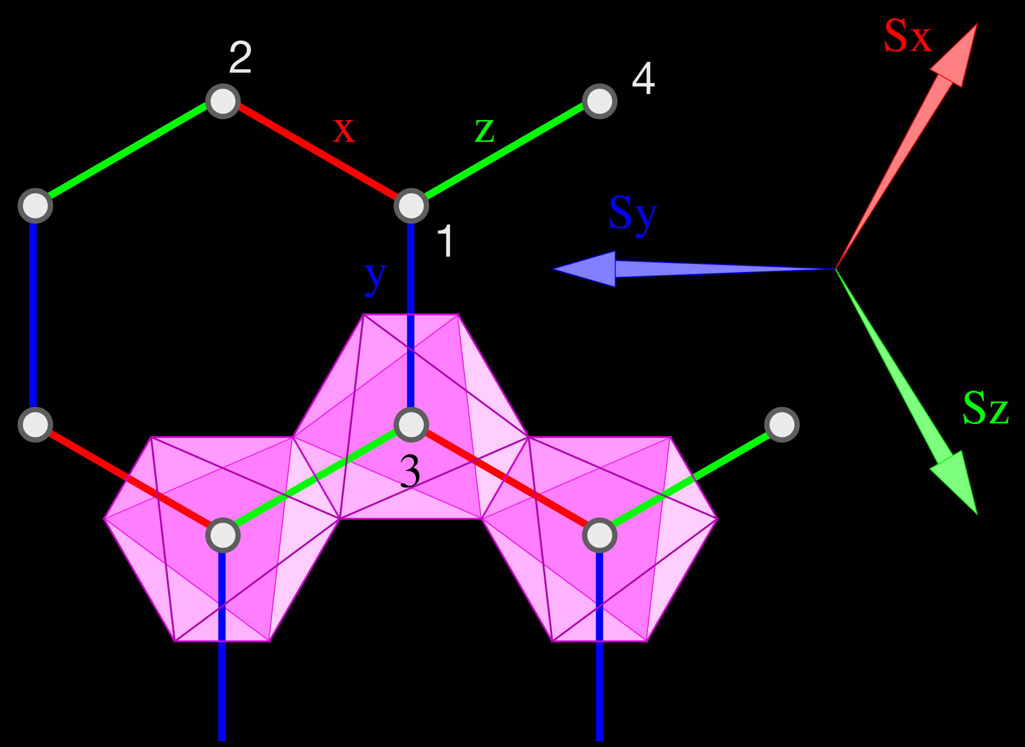
two excitations per site:

$|1\rangle_{i\in A} = a^\dagger_{i,\uparrow}|0\rangle$ & $|-1\rangle_{i\in A} = a^\dagger_{i,\downarrow}|0\rangle$

spin degree of freedom

$|1\rangle_{i\in B} = b^\dagger_{i,\uparrow}|0\rangle$ & $|-1\rangle_{i\in B} = b^\dagger_{i,\downarrow}|0\rangle$

S=1 anisotropic honeycomb magnet



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3D local Hilbert space:

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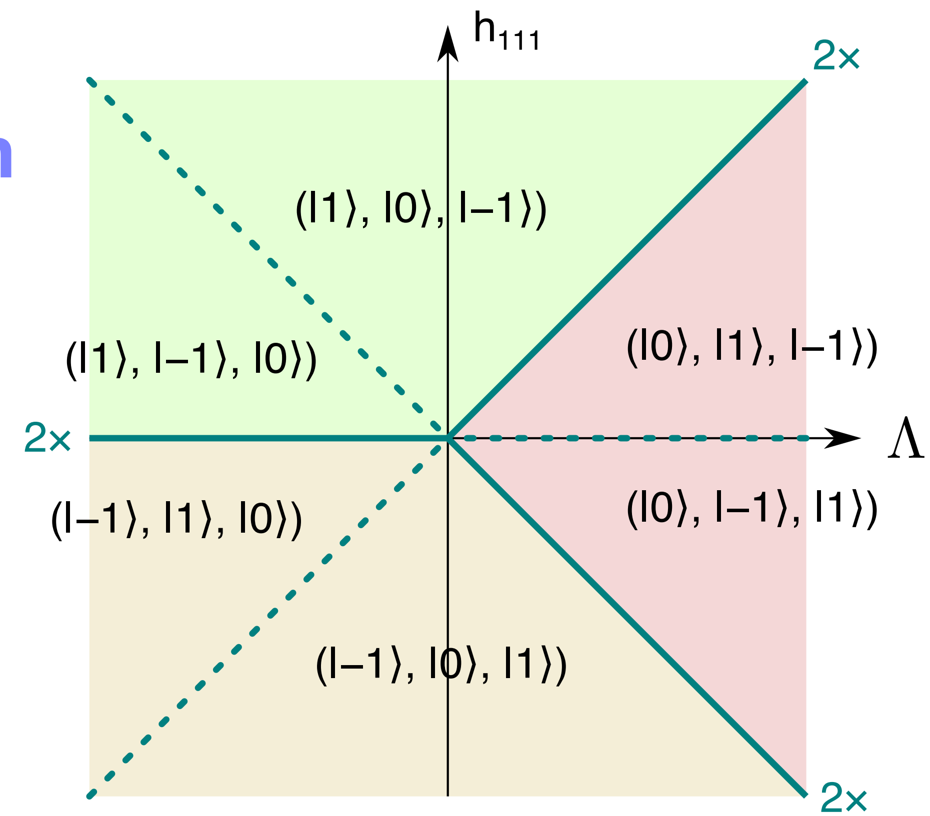


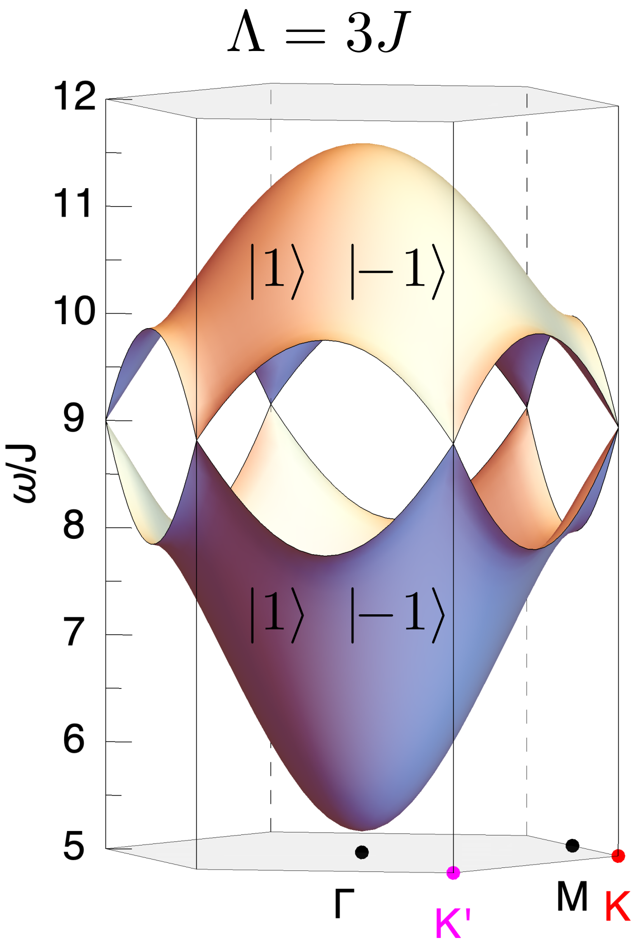
$$\mathcal{H} = J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + K\sum_{\alpha=x,y,z}\sum_{\langle i,j\rangle\in\alpha} S_i^\alpha S_j^\alpha + D'\sum_{\langle\langle i,j\rangle\rangle}(\boldsymbol{S}_i\times\boldsymbol{S}_j)_{111} + \Lambda\sum_j (S_i^{111})^2 - h\sum_i S_i^{111}\,.$$

spin 1 spin -1

$$\mathcal{H} = \begin{pmatrix} a^\dagger_{\uparrow,\mathbf{k}} \\ b^\dagger_{\uparrow,\mathbf{k}} \\ a^\dagger_{\downarrow,\mathbf{k}} \\ b^\dagger_{\downarrow,\mathbf{k}} \end{pmatrix}^T \begin{pmatrix} 3\Lambda-h-6D'\gamma' & (3J+K)\gamma^*_{A1} & 0 & K\gamma^*_{E1} \\ (3J+K)\gamma_{A1} & 3\Lambda-h+6D'\gamma' & K\gamma_{E2} & 0 \\ 0 & K\gamma^*_{E2} & 3\Lambda+h+6D'\gamma' & (3J+K)\gamma^*_{A1} \\ K\gamma_{E1} & 0 & (3J+K)\gamma_{A1} & 3\Lambda+h-6D'\gamma' \end{pmatrix} \begin{pmatrix} a_{\uparrow,\mathbf{k}} \\ b_{\uparrow,\mathbf{k}} \\ a_{\downarrow,\mathbf{k}} \\ b_{\downarrow,\mathbf{k}} \end{pmatrix}$$

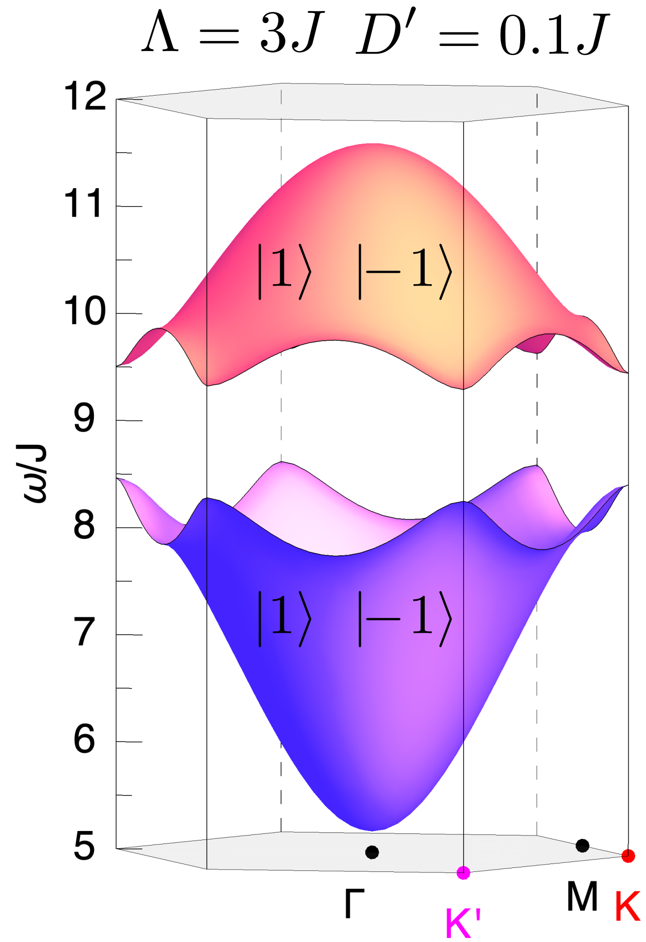
Realization of the Spin Hall system

D’=0



4 (linear) bands touch at K,K’
Dirac magnons

D’> 0



DM opens the gap
bands remain 2-fold deg.

h=0 & K=0

$$\mathcal{H}_{\mathbf{k}} = \begin{pmatrix} \mathcal{H}_{1,\mathbf{k}} & 0 \\ 0 & \mathcal{H}_{-1,\mathbf{k}} \end{pmatrix}$$

$$\mathcal{H}_{m,\mathbf{k}} = 3\Lambda I_2 + \boldsymbol{d}_m(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

$$\boldsymbol{d}_m(\mathbf{k}) = (3J\mathrm{Re}\gamma_{A1}, 3J\mathrm{Im}\gamma_{A1}, m6D'\gamma')$$

$$\omega(\mathbf{k})_m = 3\Lambda \pm |\boldsymbol{d}_m(\mathbf{k})|$$

↑

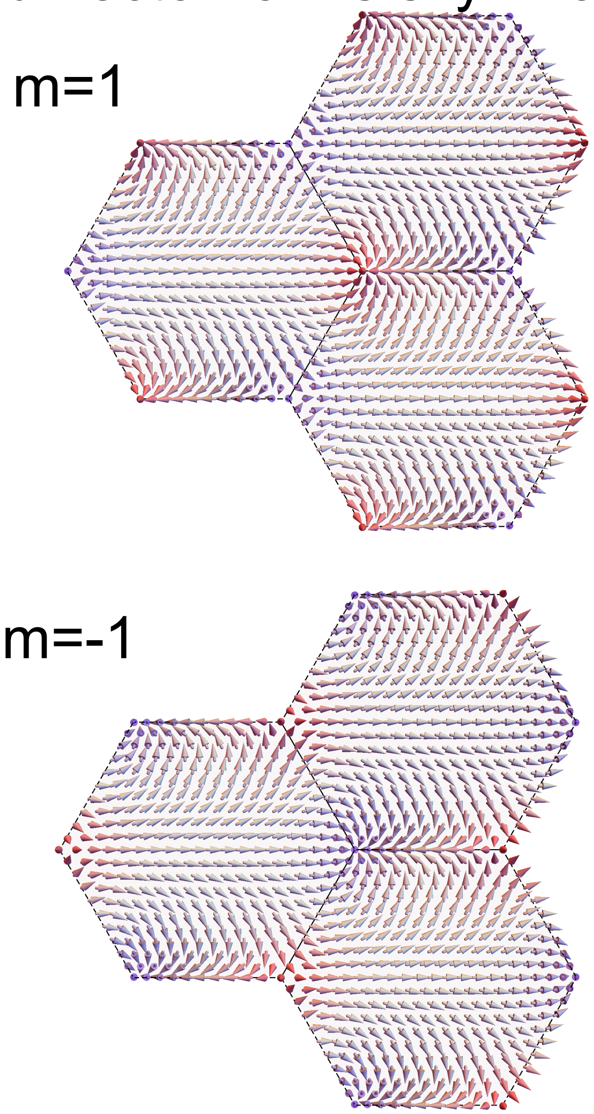
same for m=1 & -1

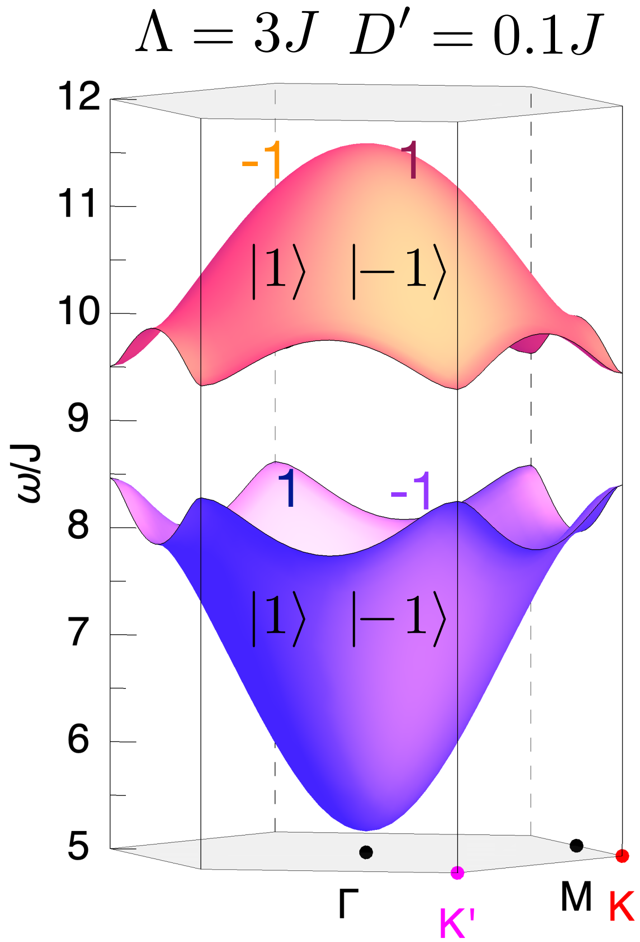
Kane and Mele PRL **95**, (2005)

Realization of the Spin Hall system

h=0 & K=0

d vector forms skyrmion





DM opens the gap

bands remain 2-fold deg.

$$\mathcal{H}_{\mathbf{k}} = \begin{pmatrix} \mathcal{H}_{1,\mathbf{k}} & 0 \\ 0 & \mathcal{H}_{-1,\mathbf{k}} \end{pmatrix}$$

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$$\omega(\mathbf{k})_m = 3\Lambda \pm |\boldsymbol{d}_m(\mathbf{k})|$$

Kane and Mele PRL **95**, (2005)

$$N_s = \frac{1}{4\pi}\int dk_x dk_y d \cdot (\partial_y d \times \partial_x d)$$

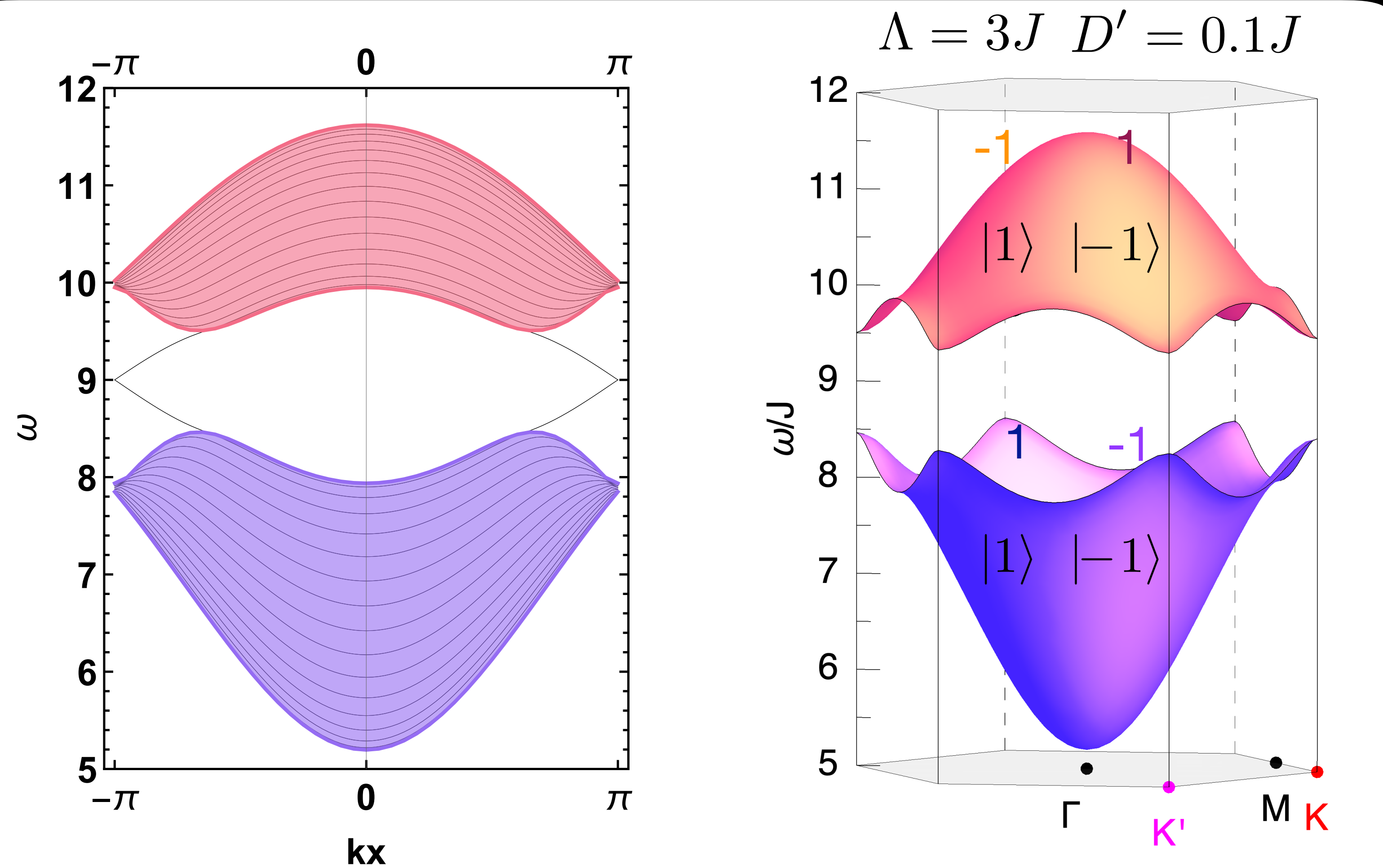
$$F_n^{xy}(\mathbf{k}) = in\boldsymbol{d}(\mathbf{k}) \cdot (\partial_y \boldsymbol{d}(\mathbf{k}) \times \partial_x \boldsymbol{d}(\mathbf{k}))$$

Berry curvature is proportional to the skyrmion number

$$C_{n,m} = \frac{1}{i2\pi}\int dk_x dk_y F_n^{xy} = nmN_s$$

Realization of the Spin Hall system

h=0 & K=0



open geometry

DM opens the gap

bands remain 2-fold deg.

$$\mathcal{H}_{\mathbf{k}} = \begin{pmatrix} \mathcal{H}_{1,\mathbf{k}} & 0 \\ 0 & \mathcal{H}_{-1,\mathbf{k}} \end{pmatrix}$$

$$\mathcal{H}_{m,\mathbf{k}} = 3\Lambda I_2 + \boldsymbol{d}_m(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

$$\boldsymbol{d}_m(\mathbf{k}) = (3J\mathrm{Re}\gamma_{A1}, 3J\mathrm{Im}\gamma_{A1}, m6D'\gamma')$$

$$\omega(\mathbf{k})_m = 3\Lambda \pm |\boldsymbol{d}_m(\mathbf{k})|$$

Kane and Mele PRL **95**, (2005)

Z_2 index as “spin Chern number”

$$\frac{1}{2}(C_{n\uparrow} - C_{n\downarrow}) \quad \mathrm{mod}\ 2$$

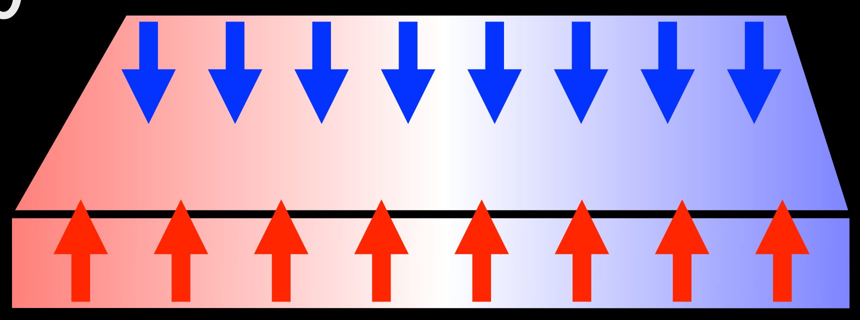
Berry curvature is proportional to the skyrmion number

$$C_{n,m} = \frac{1}{i2\pi}\int dk_x dk_y F_n^{xy} = nmN_s$$

Spin Nernst effect

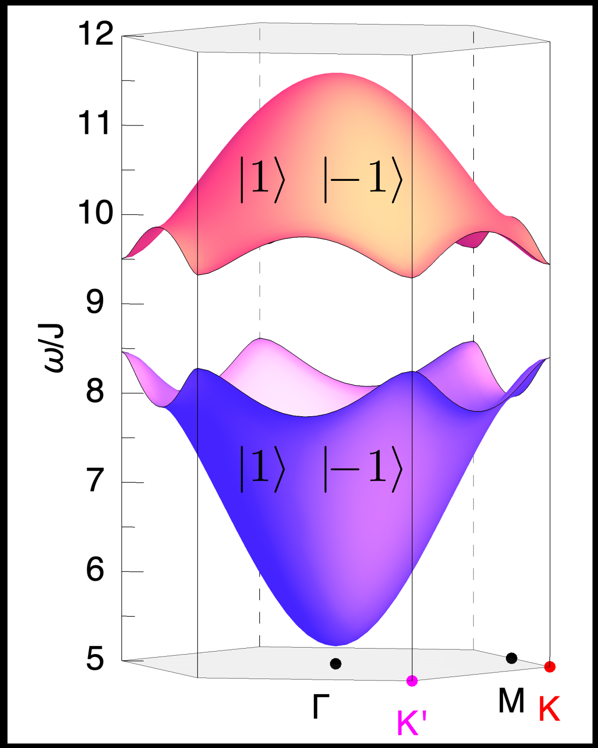
spin separation

B=0



$-\nabla T$ ⟶

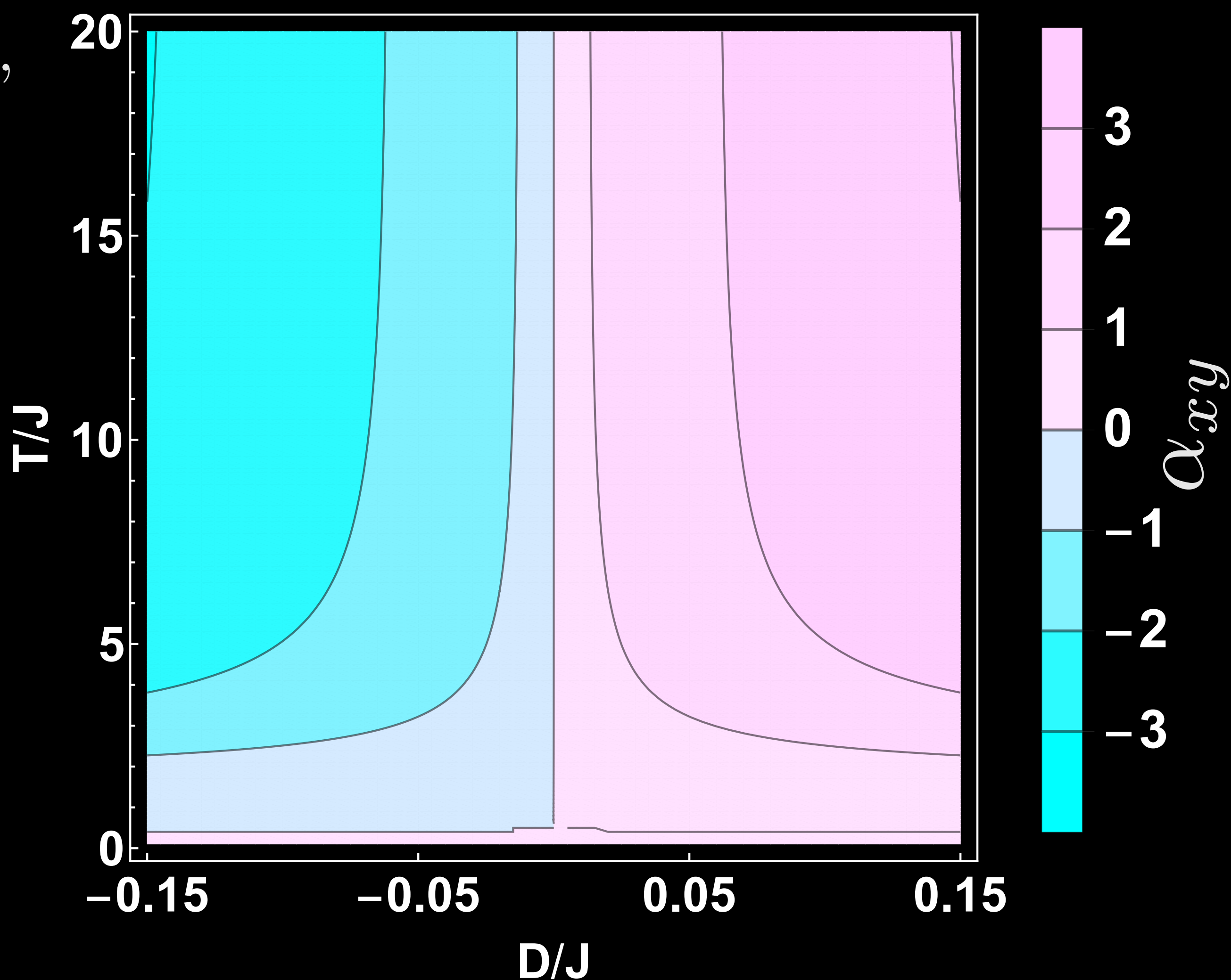
$$j_{\rm SN} = \alpha_{xy}\hat{\boldsymbol{z}} \times \nabla T$$



$$\alpha_{xy} = -i\frac{k_B}{\hbar}\sum_{m,n}\int_{\rm BZ} m\cdot c_1(\rho_{n,m})F^{xy}_{n,m}(\mathbf{k})d^2\mathbf{k}\ ,$$

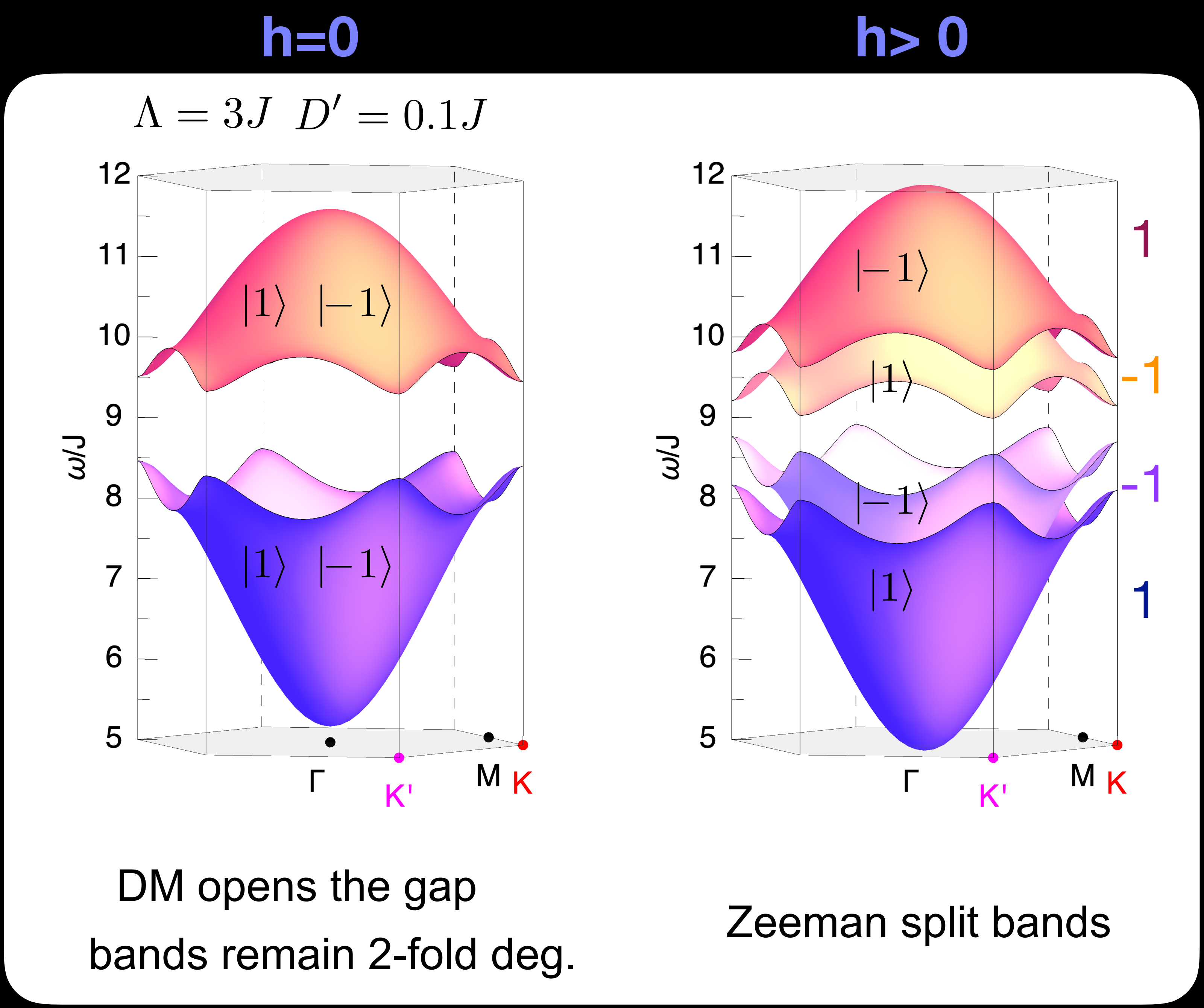
$$c_1(\rho) = \int_0^\rho dt\,\ln(1+t^{-1})$$

$$\rho_{n,\sigma} = \frac{1}{e^{\omega_{n,\sigma}\beta}-1}$$



Nakata et al., PRB **95** 125429 (2017)
Kovalev et al PRB **93** 161106(R) (2016)
Cheng et al PRL **117** 217202 (2016)

Finite magnetic field



K=0

$$\mathcal{H}_{\mathbf{k}} = \begin{pmatrix} \mathcal{H}_{1,\mathbf{k}} & 0 \\ 0 & \mathcal{H}_{-1,\mathbf{k}} \end{pmatrix}$$

$$\mathcal{H}_{m,\mathbf{k}} = (3\Lambda - mh) I_2 + \boldsymbol{d}_m(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

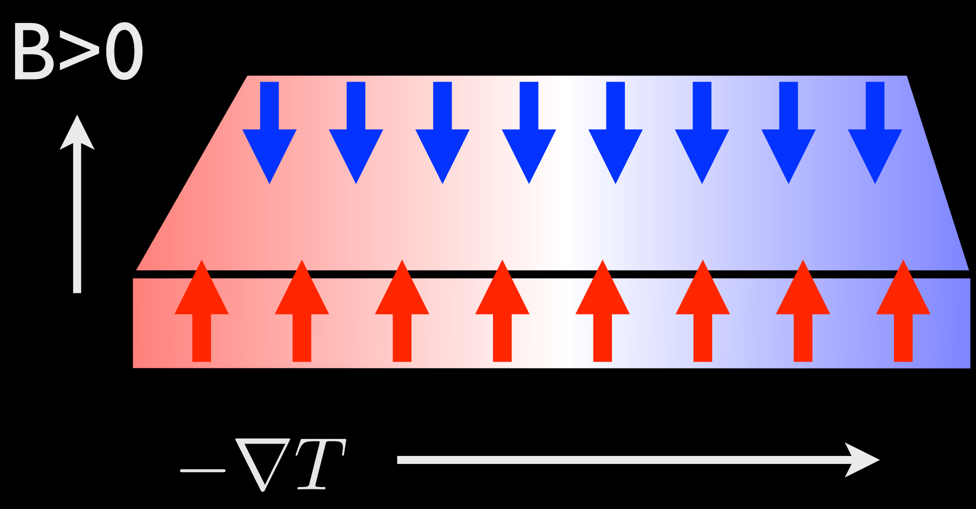
$$\boldsymbol{d}_m(\mathbf{k}) = (3J\mathrm{Re}\gamma_{A1}, 3J\mathrm{Im}\gamma_{A1}, m6D'\gamma')$$

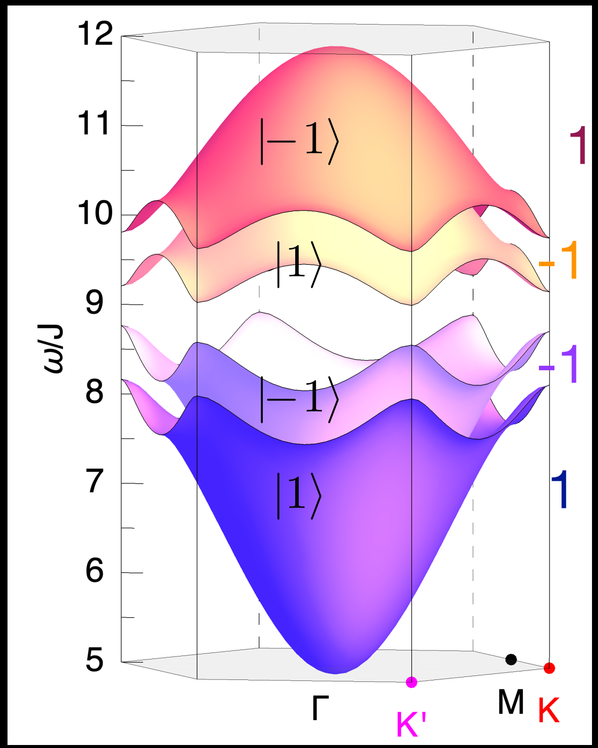
$$\omega(\mathbf{k})_m = (3\Lambda - mh) \pm |\boldsymbol{d}_m(\mathbf{k})|$$

m=1 & -1 Zeeman split

Chern insulator

Thermal Hall effect

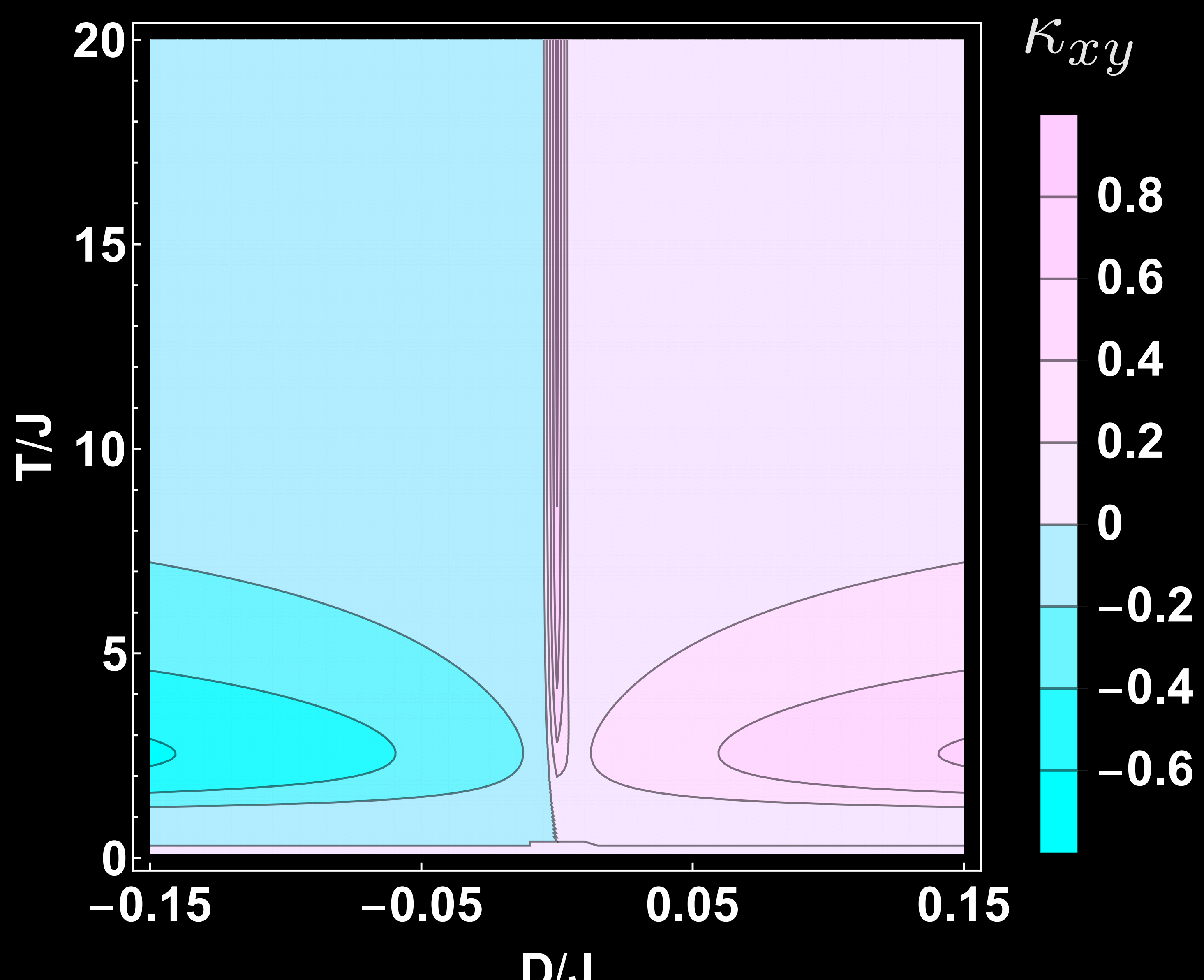




$$\kappa_{xy} = \frac{-i}{\beta} \int_{\mathrm{BZ}} c_2(\rho_n) F_n^{xy}(\mathbf{k}) d^2\mathbf{k} \ ,$$

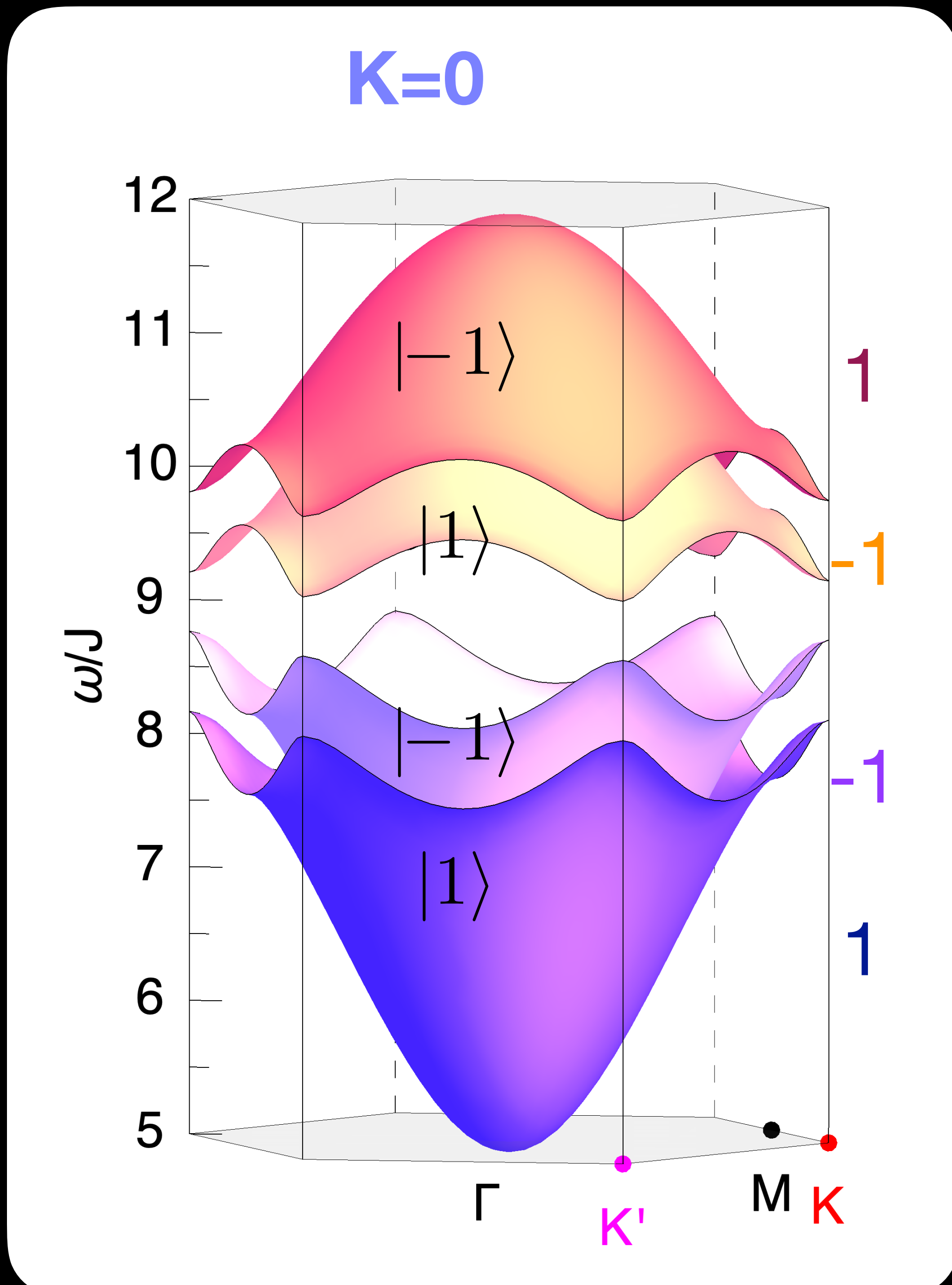
$$c_2(\rho) = \int_0^\rho dt \ln^2(1 + t^{-1})$$

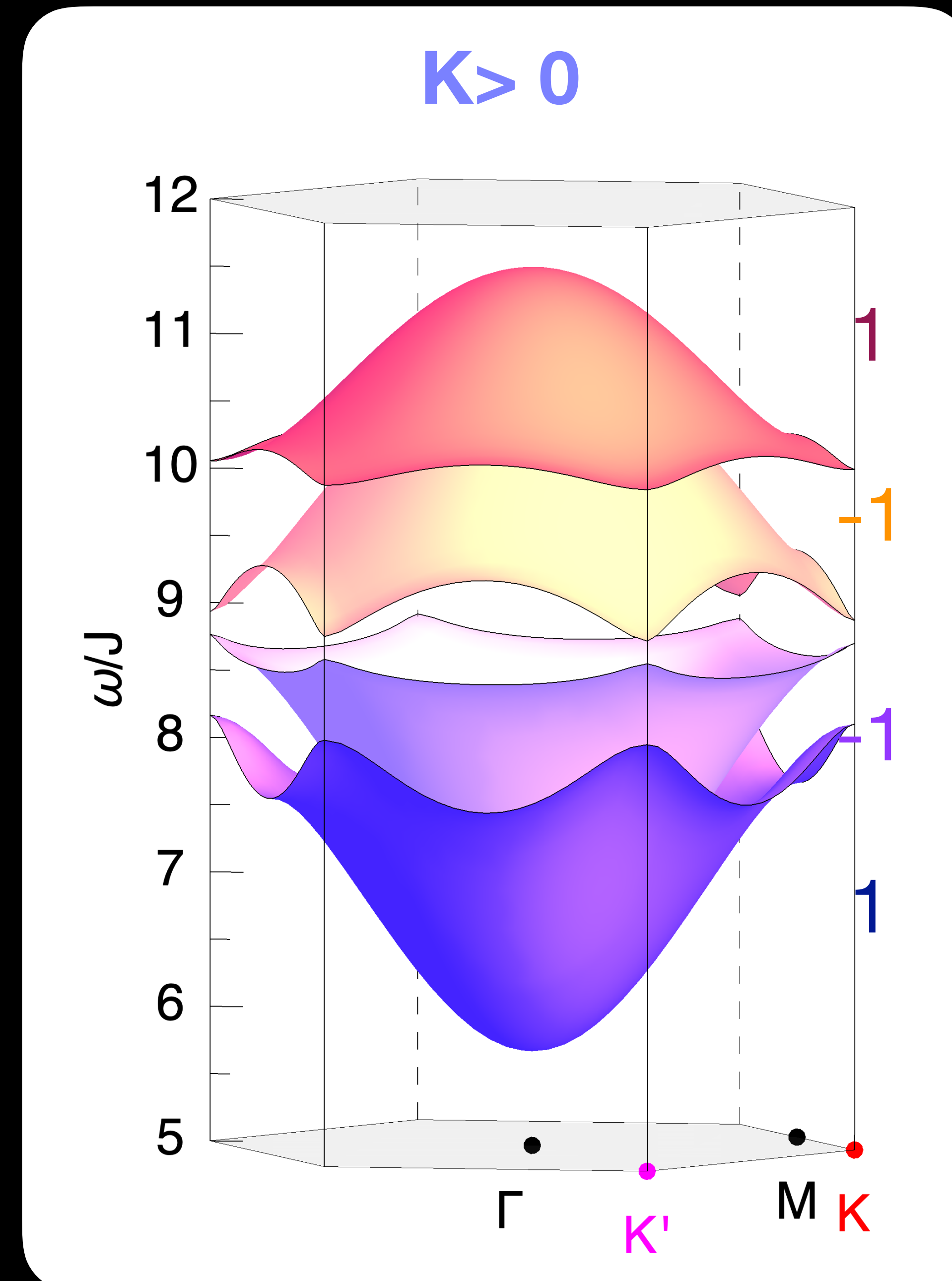
$$\rho_{n,\sigma} = \frac{1}{e^{\omega_{n,\sigma}\beta} - 1}$$



Katsura et al., PRL **104**, 066403 (2010),
Matsumoto et al PRL **106** 197202, (2011)

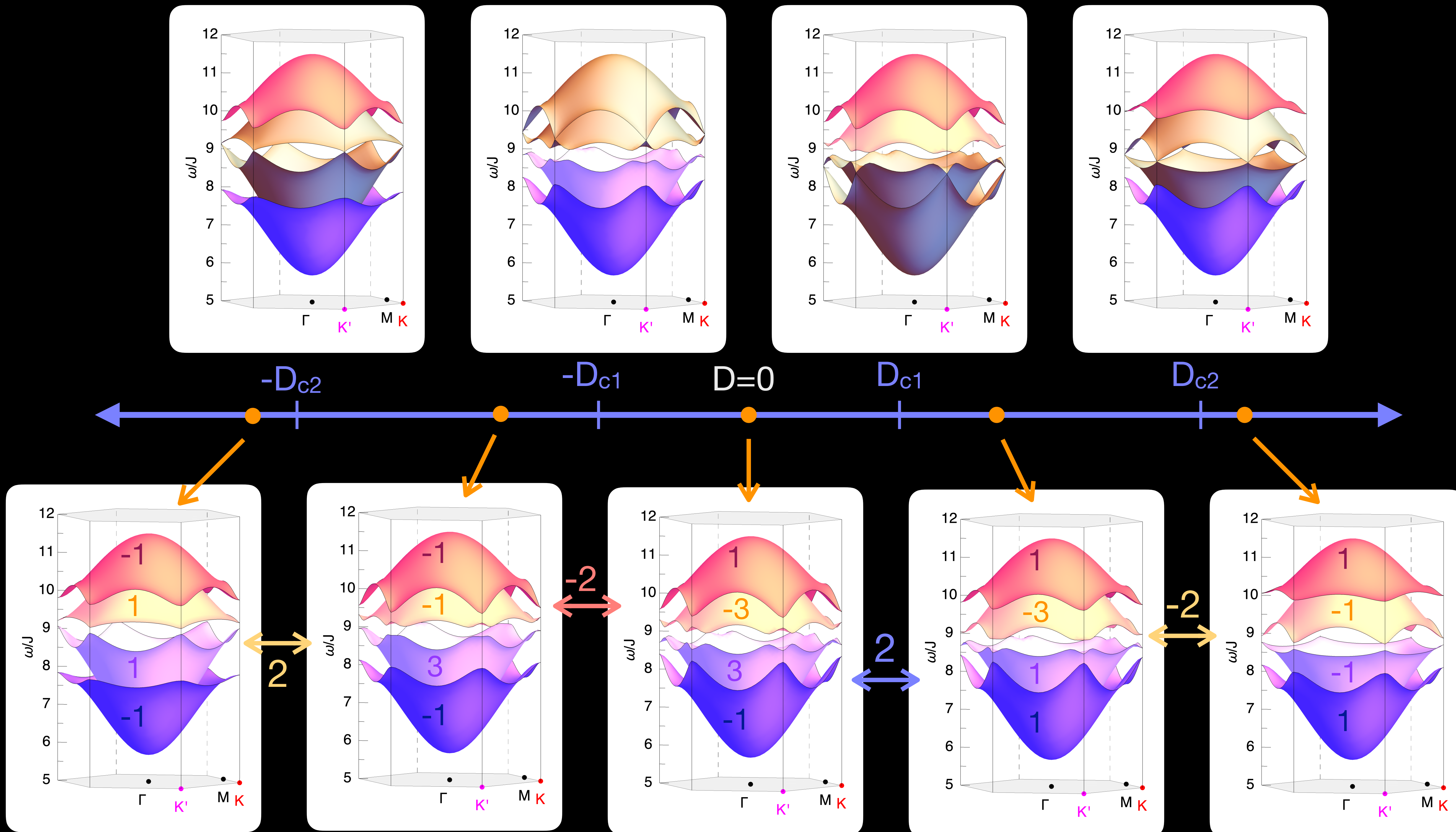
Finite Kitaev interaction



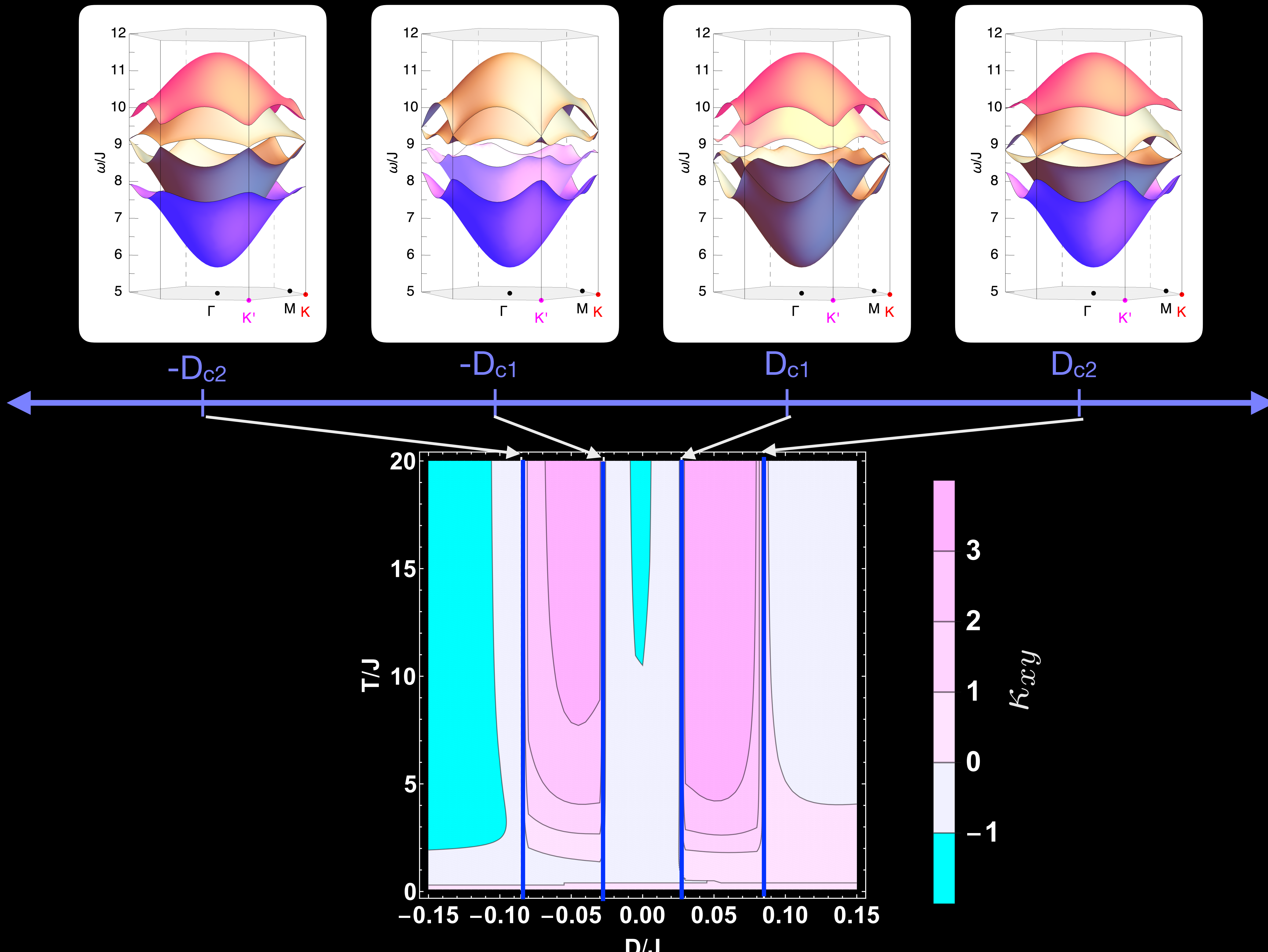


$$\mathcal{H} = \begin{pmatrix} a^\dagger_{\uparrow,\mathbf{k}} \\ b^\dagger_{\uparrow,\mathbf{k}} \\ a^\dagger_{\downarrow,\mathbf{k}} \\ b^\dagger_{\downarrow,\mathbf{k}} \end{pmatrix}^T \begin{pmatrix} 3\Lambda - h - 6D'\gamma' & (3J+K)\gamma^*_{A1} & 0 & K\gamma^*_{E1} \\ (3J+K)\gamma_{A1} & 3\Lambda - h + 6D'\gamma' & K\gamma_{E2} & 0 \\ 0 & K\gamma^*_{E2} & 3\Lambda + h + 6D'\gamma' & (3J+K)\gamma^*_{A1} \\ K\gamma_{E1} & 0 & (3J+K)\gamma_{A1} & 3\Lambda + h - 6D'\gamma' \end{pmatrix} \begin{pmatrix} a_{\uparrow,\mathbf{k}} \\ b_{\uparrow,\mathbf{k}} \\ a_{\downarrow,\mathbf{k}} \\ b_{\downarrow,\mathbf{k}} \end{pmatrix}$$

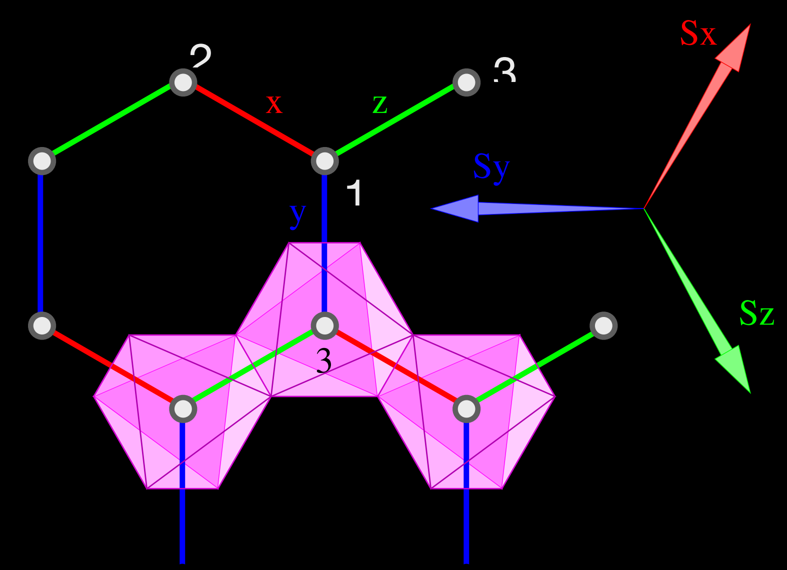
Band touching topological transition



Thermal Hall effect



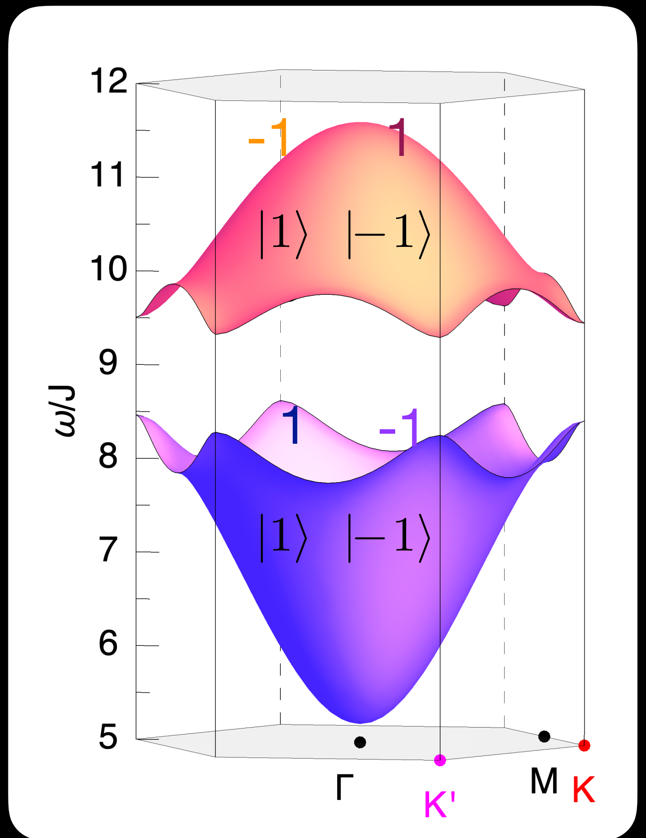
Summary



TR invariance + K=0:

Due to DMI, Z2 topological phase is realized

Spin Nernst effect



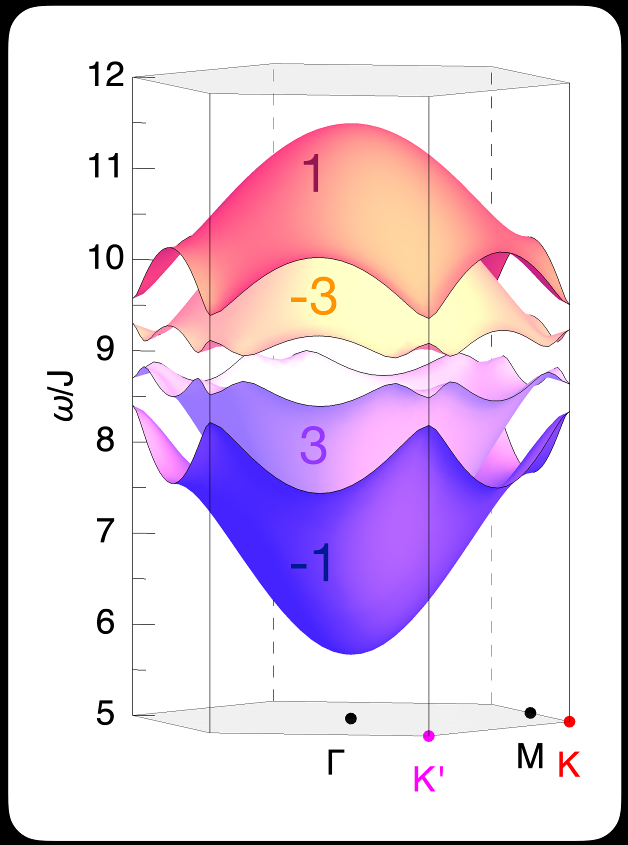
Anisotropic S=1 magnets can have various topologically nontrivial excitations

example: Honeycomb (A)FM

with

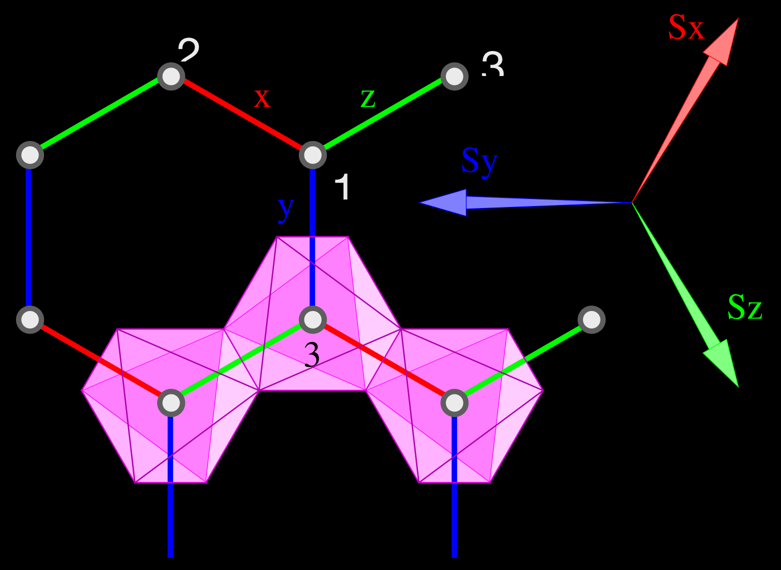
- Kitaev anisotropy
- single-ion anisotropy
- DM interaction

Breaking TR symmetry and/or finite K



Kitaev exchange can lead to the formation of Chern insulator with large Chern numbers.

Outlook



Anisotropic S=1 magnets can have various topologically nontrivial excitations

Magnetoelectric coupling

broken TR and I symmetry

↓

coupling between the electric and magnetic degrees of freedom so that one can be manipulated with the conjugate field of the other.

↓

spin induced polarization from larger spin

$$\mathbf{P} \propto \sum_i (\mathbf{S} \cdot \mathbf{e}_i)^2 \mathbf{e}_i$$

spin quadrupole

T. Arima, J. Phys. Soc. Jpn. **76**, 073702 (2007).

Detection of edge modes (?)

inversion symmetry is broken at the edges → can edge modes couple to electric field/light?

Thank you!