Slides are available on
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Accessing topological magnonic excitations in non-equilibrium

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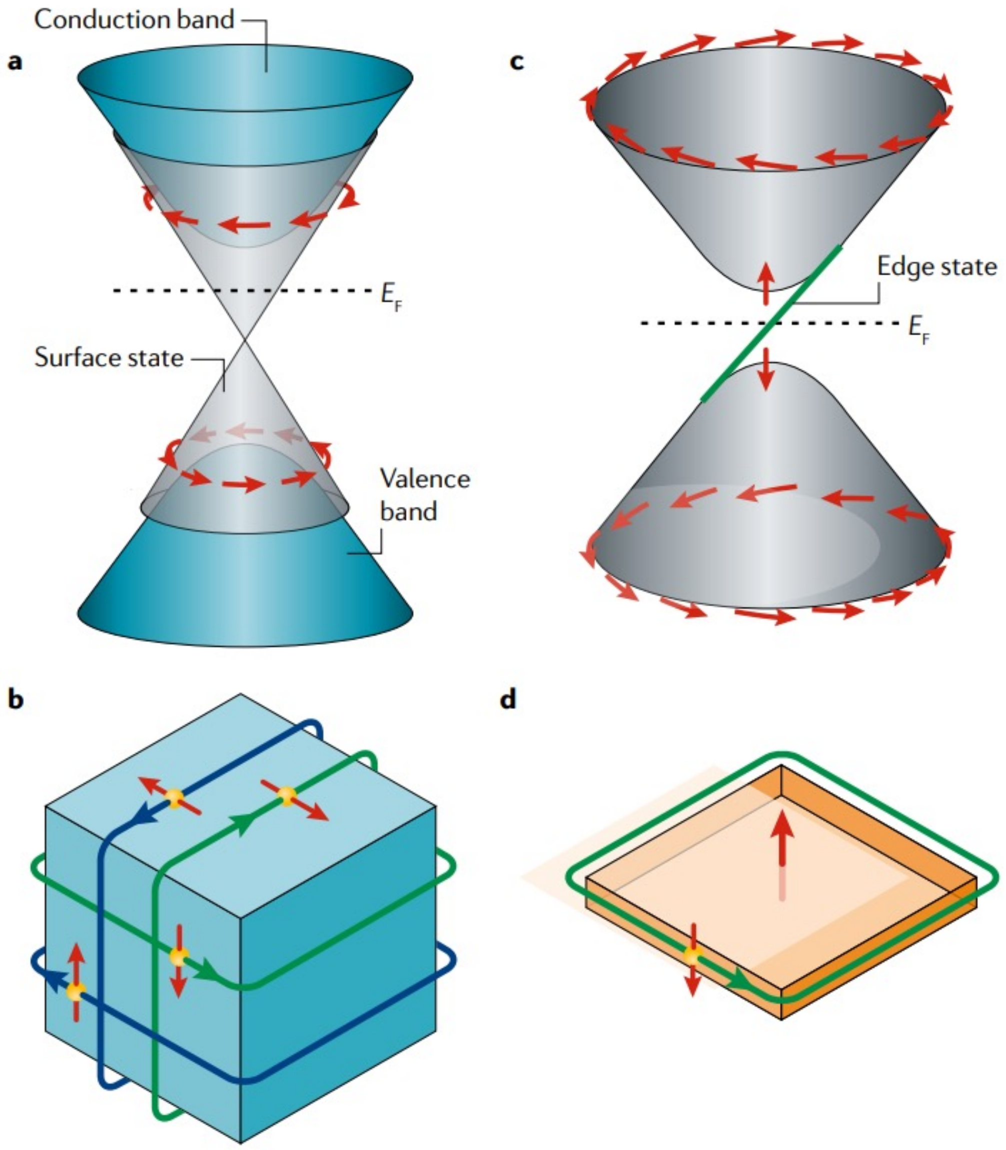
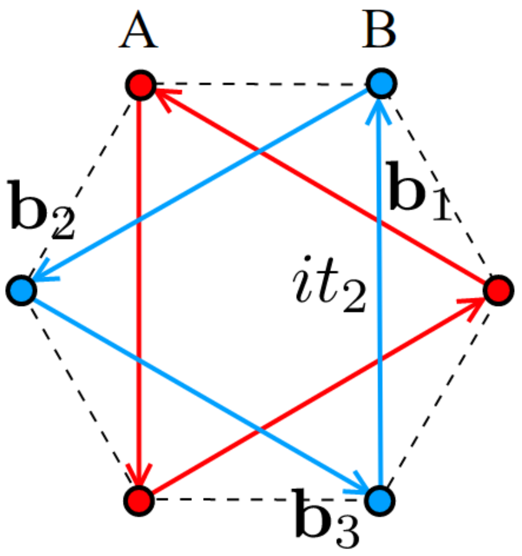
CONTENTS

TOPOLOGY

https://topocondmat.org/w4_haldane/haldane_model.html



Tokura et al., Nature Reviews Physics, **1**, 126



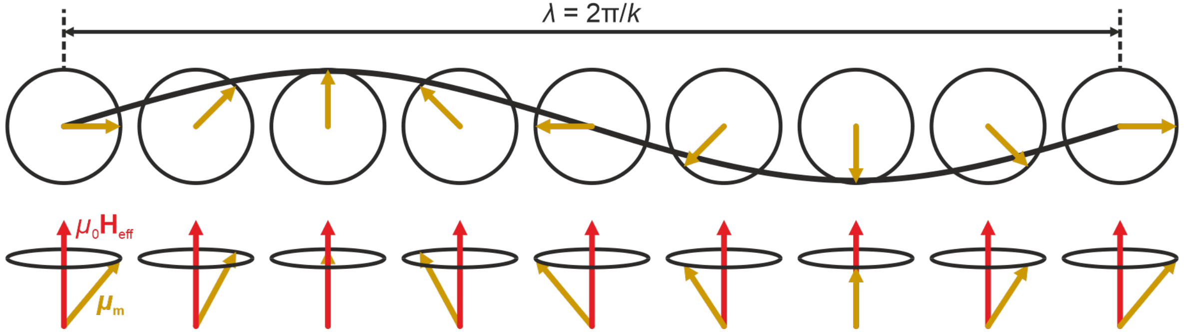
Topological insulators:
- Bulk band gap
- Protected edge states

Chern insulator:
- 2D insulator
- Chiral edge modes
- Haldane model

[Haldane, PRL, **61** 2015 (1988)]

TOPOLOGY IN MAGNON SYSTEMS

https://mandmems.eu/spin-waves/



Magnetic systems:

$$\hat{H} = -\sum_{i,j} J_{ij}\, \boldsymbol{S}_i \cdot \boldsymbol{S}_j - \boldsymbol{H}_e \cdot \sum_i \boldsymbol{S}_i$$

Linearize around uniform state $\boldsymbol{S}_i = S\hat{z}$

$$m_i = (S_i^x - iS_i^y)/S$$

$$H_{\boldsymbol{k}} = \sum_{\boldsymbol{k}} m_{\boldsymbol{k}}^* [H + 2JS(1 - \cos ka)] m_{\boldsymbol{k}}$$

Bloch Hamiltonian → topology!

Bosons vs fermions

TOPOLOGY IN MAGNON SYSTEMS: EXAMPLES

Many "electronic" phases have been found:

- Quantum spin Hall effect [Kondo *et al.*, *PRB* **99**, 041110(R)]
- Weyl magnons [Mook *et al.*, PRL **117**, 157204]
- Higher order (skyrmion lattice) [Hirosawa *et al.*, PRL. **125**, 207204]

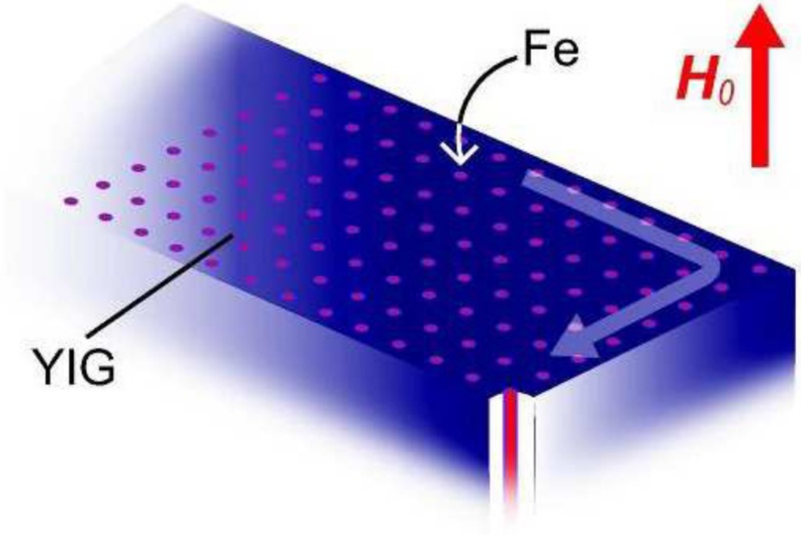
Recent reviews: [McClarty, Annu. Rev. Condens. Matter Phys. 2022. 13:171–90; Wang and Wang, J. Appl. Phys. 129, 151101 (2021)]

Chern insulators (requires no additional symmetries)

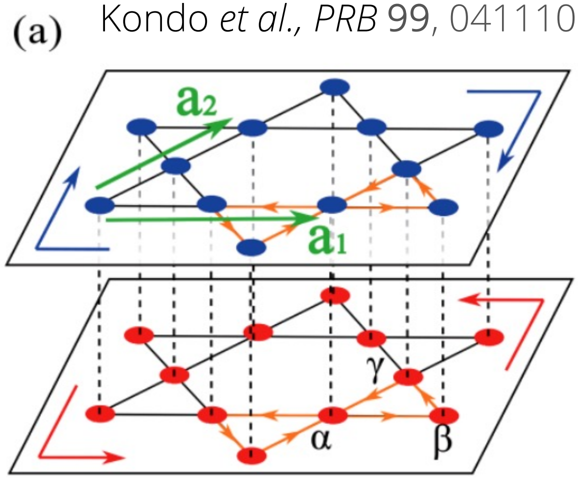
Several proposals:

- Cu(1,3-bdc) [Katsura *et al.*, PRL **104**, 066403]
- CrI_3 [S. A. Owerre 2016 *J. Phys.: Condens. Matter* **28** 386001, Kim *et al.*, PRL **117**, 227201 (2016)]
- $CrBr_3$ [Cai *et al.*, PRB **104**, L020402]
- Magnon metamaterials [Shindou *et al.*, PRB **87**, 174427]

Shindou *et al.*, PRB **87**, 174427



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



MAGNON CHERN INSULATOR

Requires no additional symmetries

Chiral edge states

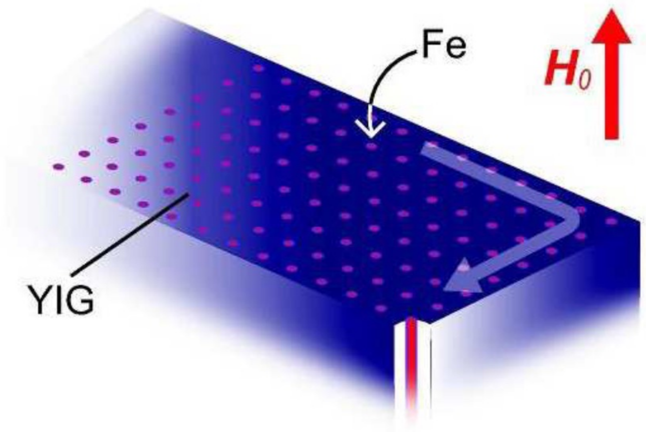
Multiple predictions based on neutron scattering of bulk spectrum

But no direct evidence of edge states yet!

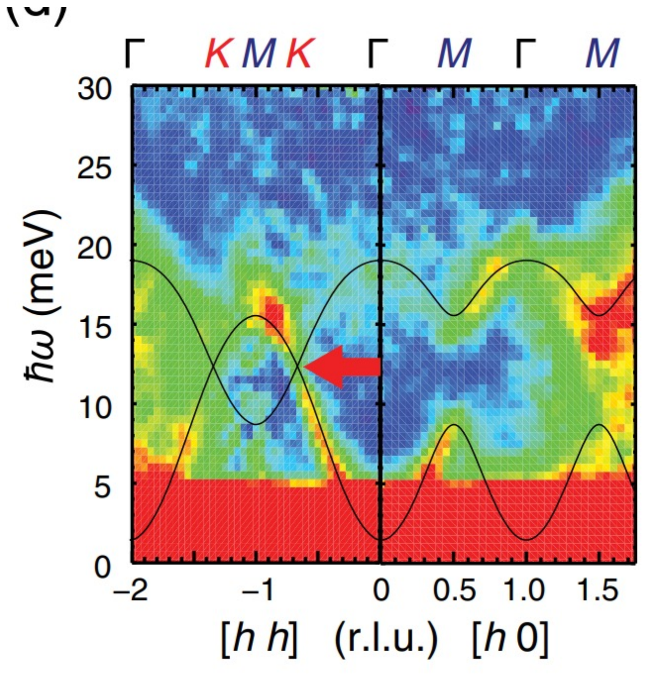
Robust spin transport [Xu et al., PRB 94 220403 (2016); Rückriegel et al., PRB 081106(R) (2018); Wang et al., PRL 125, 217202 (2020)]

Useful for magnon computing [Shindou et al. 87.174427; Wang et al. PRAppl. 9, 024029 (2018)]

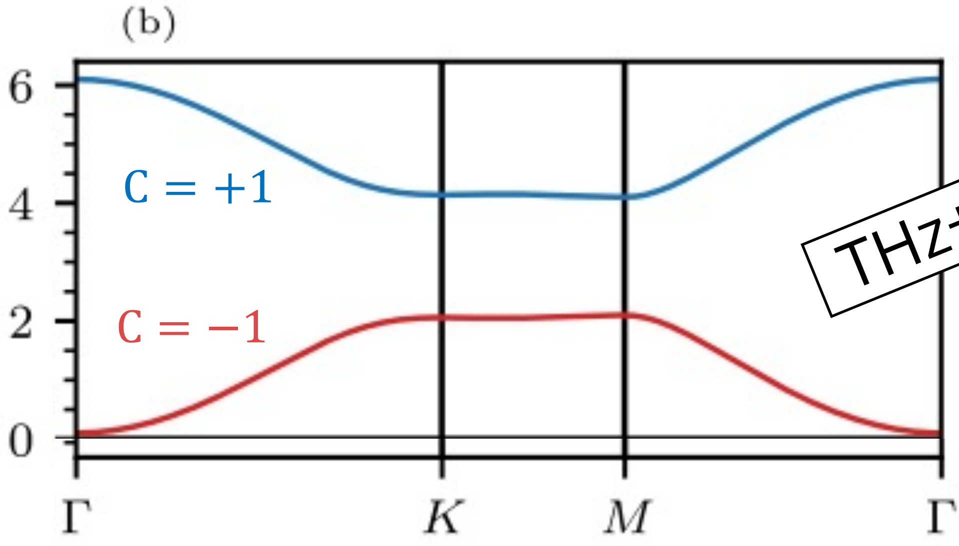
Shindou *et al.*, PRB **87**, 174427



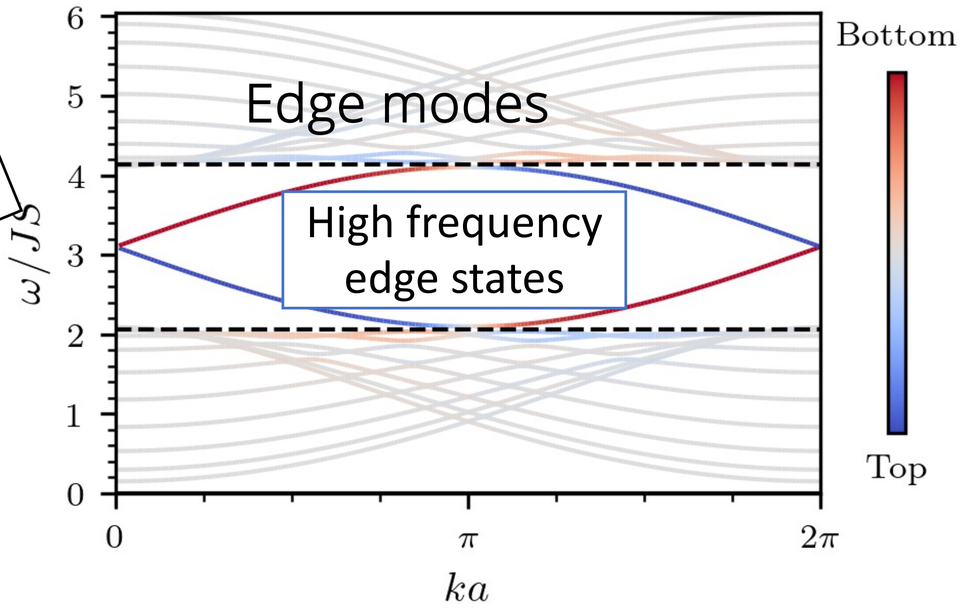
Inelastic neutron scattering CrI_3
Chen *et al.*, PRX **8**, 041028



MAGNON HALDANE MODEL



THz+

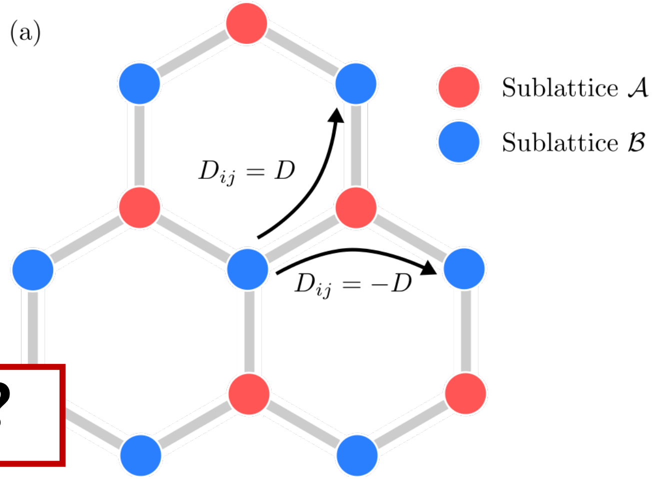


Edge modes

High frequency edge states

Dzyaloshinskii-Moriya interaction

$$\hat{H} = \frac{1}{2}\sum_{ij}[-J\boldsymbol{S}_i \cdot \boldsymbol{S}_j + D_{ij}\hat{\boldsymbol{z}} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)] - \boldsymbol{H} \cdot \sum_{\boldsymbol{i}} \boldsymbol{S}_i$$



- Edge states are above the first band
- Energy scale of first band is set by exchange (meV)

How to access these THz edge states?

Accessing chiral magnon edge states protected by non-equilibrium topology

Pieter M. Gunnink, Joren S. Harms, Rembert A. Duine, Alexander Mook,

Phys. Rev. Lett. **131**, 126601

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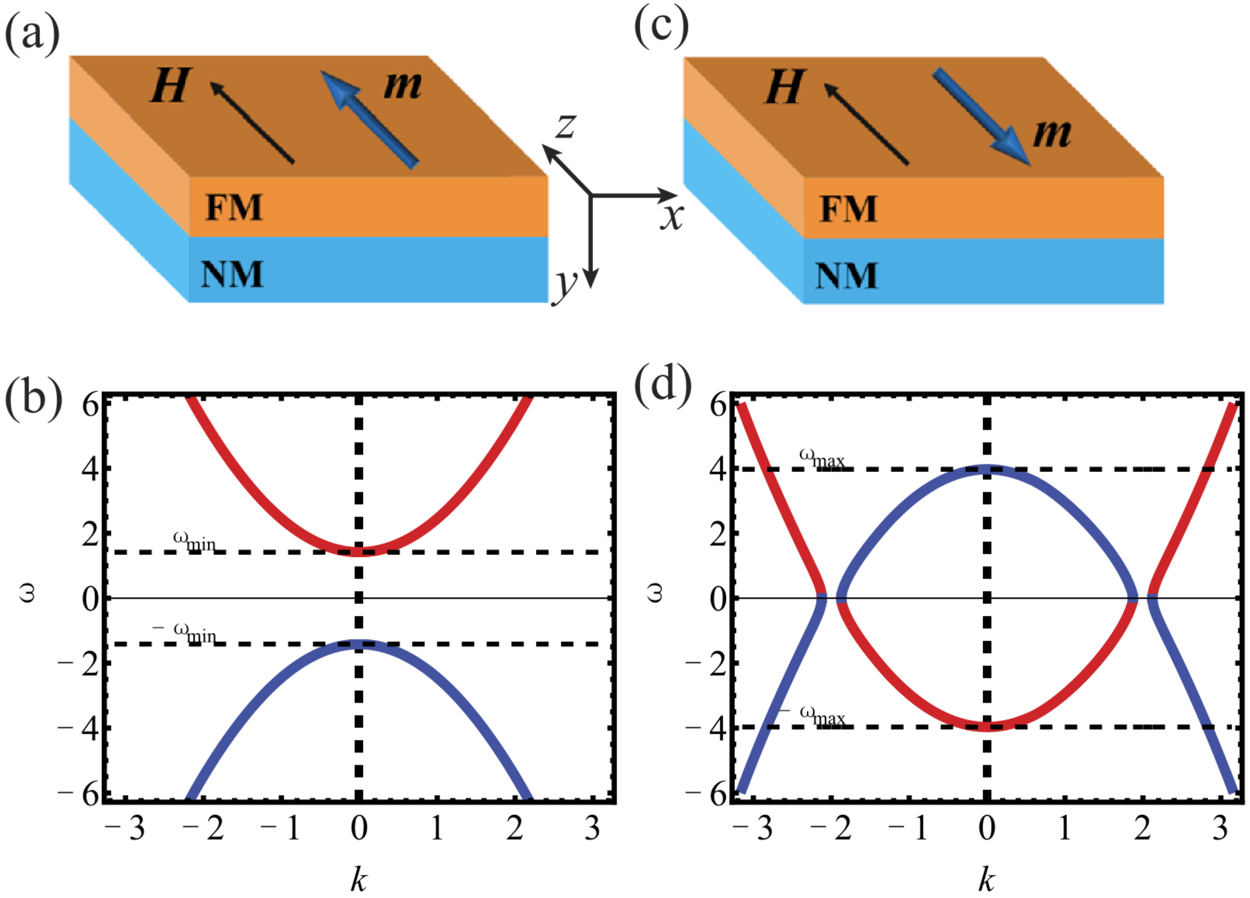
ANTIMAGNONICS

Magnon is excitation of ground state

But what if we keep another ground state stable? [Doornenbal et al. , PRL. 122, 037203 (2019); Harms et al. PRB 103 144408 (2021); Errani et al. arXiv:2405.04996 (2024)]

Magnonic excitation still exist, but shifted in energy

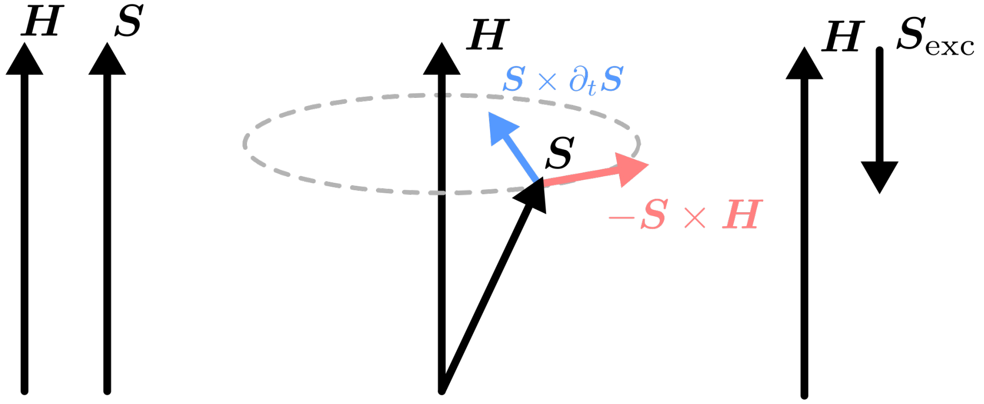
Kept stable by spin-orbit torque



Harms, Yuan, Duine, *AIP Advances* 14, 025303 (2024)

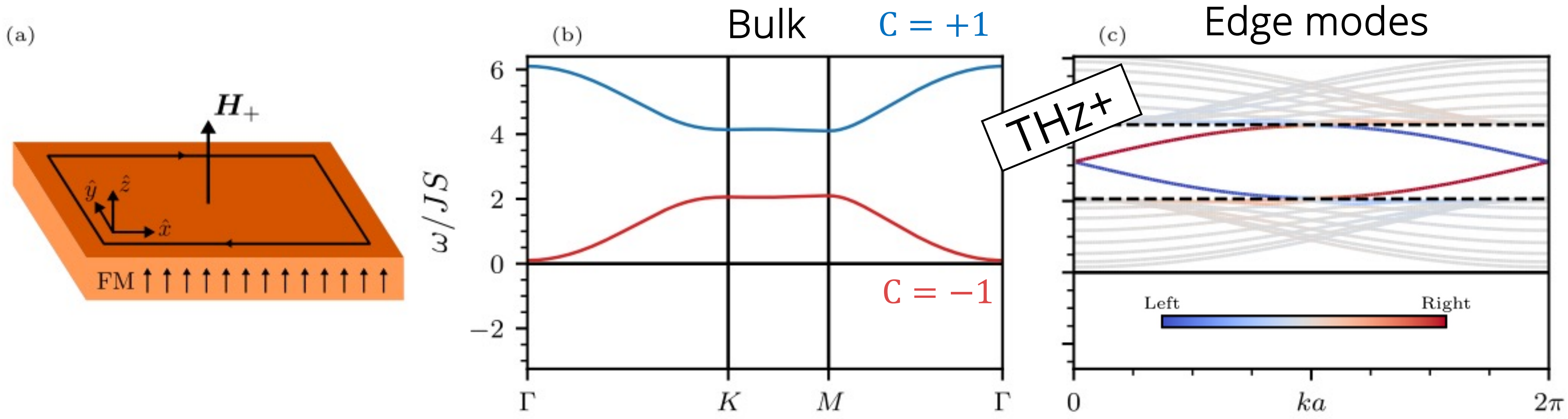
NON-EQUILIBRIUM MAGNON STATES

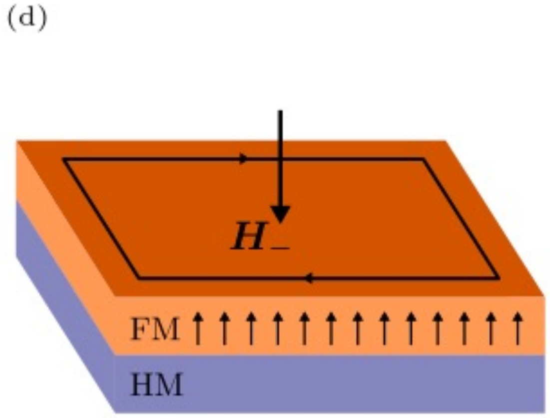
$$E_z = -\mu \boldsymbol{H} \cdot \boldsymbol{S}_{\text{exc}} > 0$$



Damped
precession

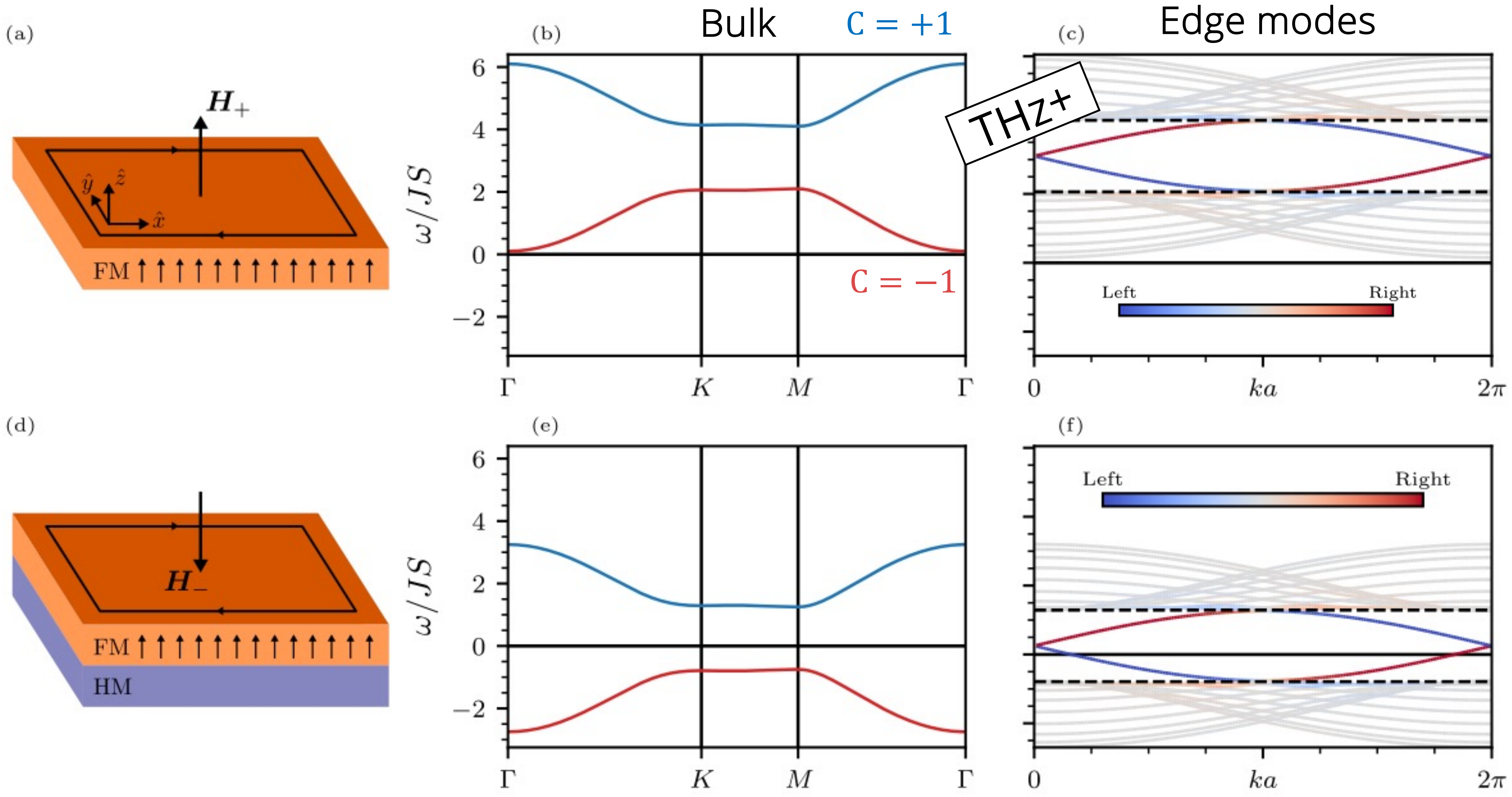
MAGNON HALDANE MODEL





- Haldane model in non-equilibrium
- Can we shift the edge states to zero frequency?
- Are the edge states still stable then?

MAGNON HALDANE MODEL



Bulk

$C = +1$

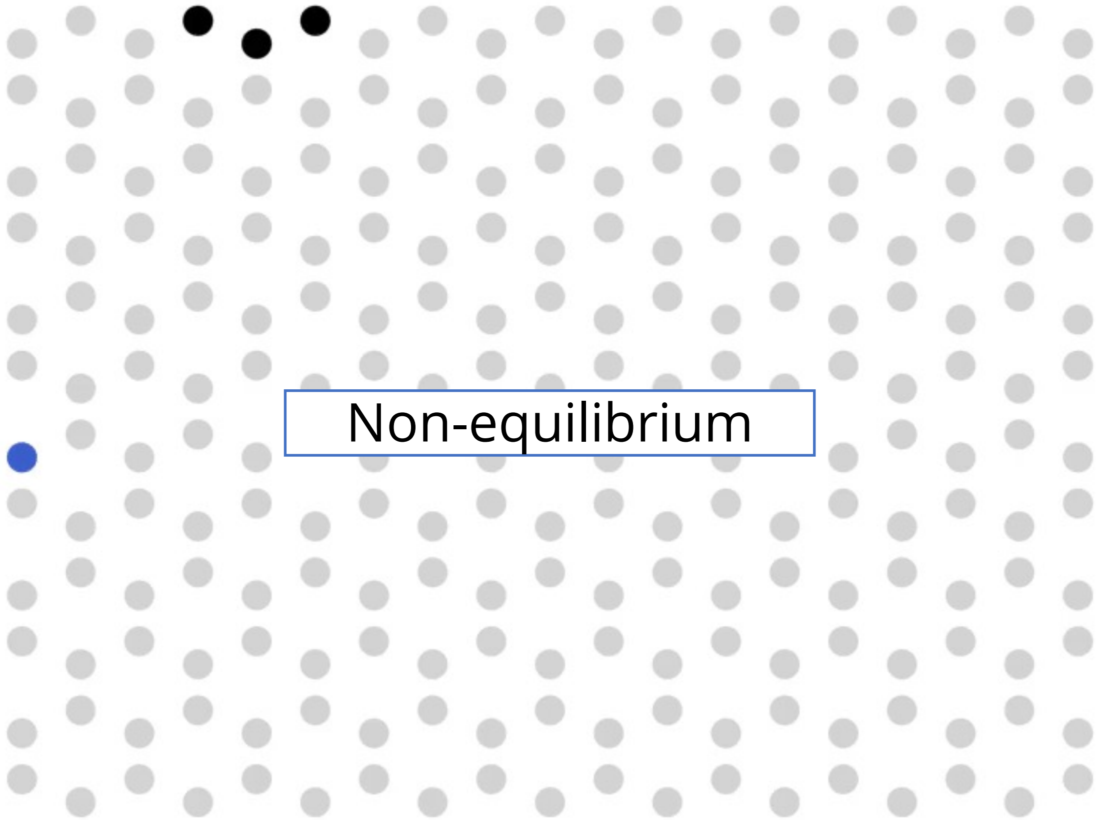
$C = -1$

Edge modes

THz+

NUMERICAL LLG SIMULATION

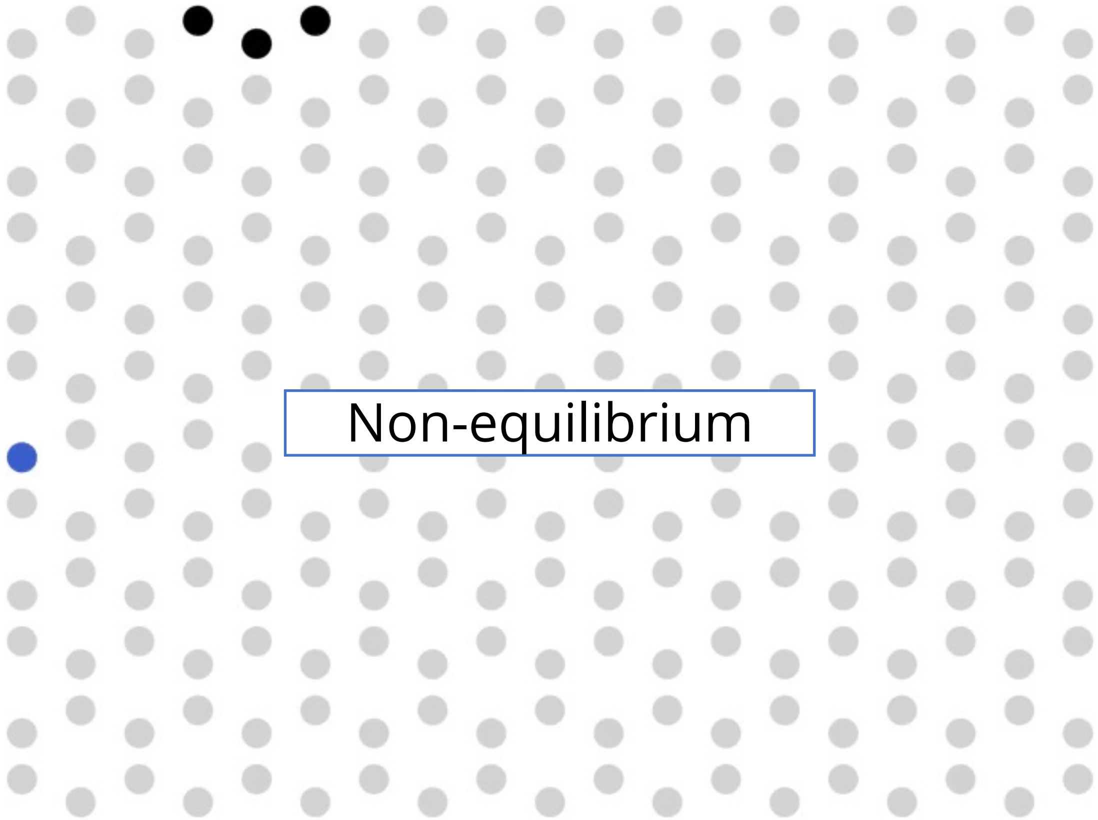
$\omega_0/JS = 0.15$

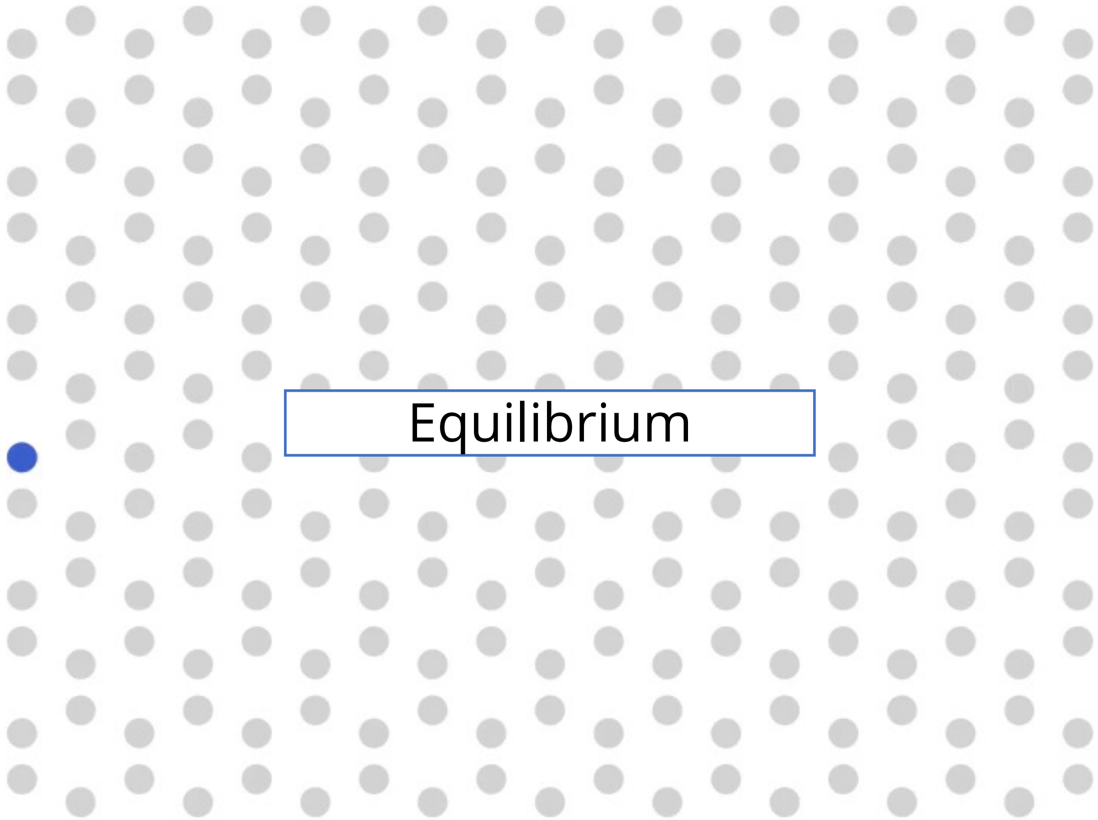


Non-equilibrium

NUMERICAL LLG SIMULATION

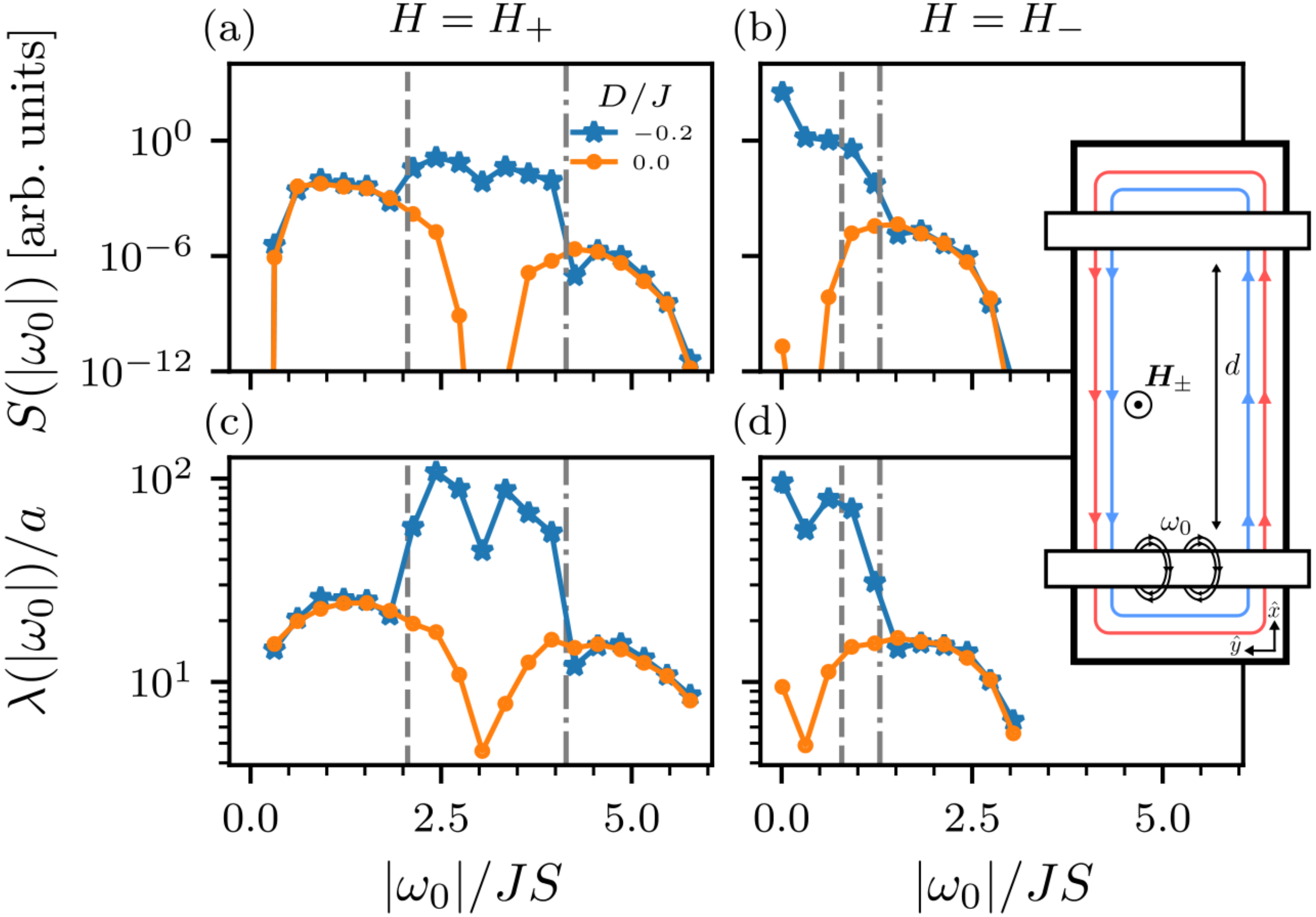
$\omega_0/JS = 0.15$


Non-equilibrium


Equilibrium

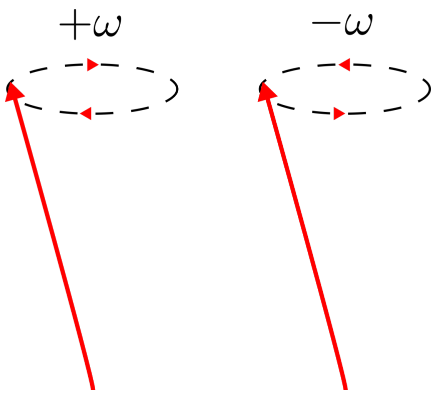
PROPAGATING SPIN WAVE SPECTROSCOPY

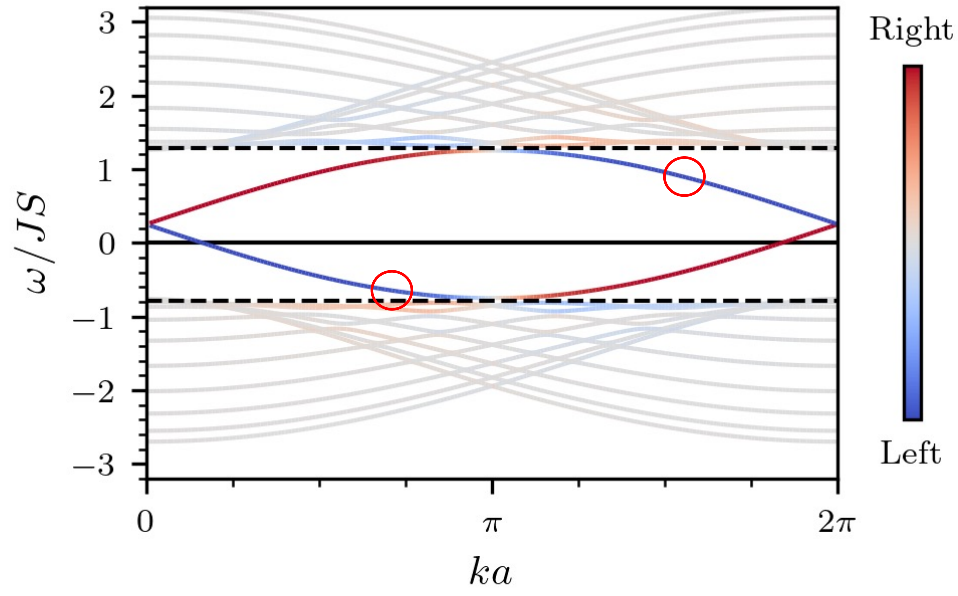
- Linear spin-wave theory
- Including Gilbert damping, spin-transfer torque
- Disorder to see topological protection

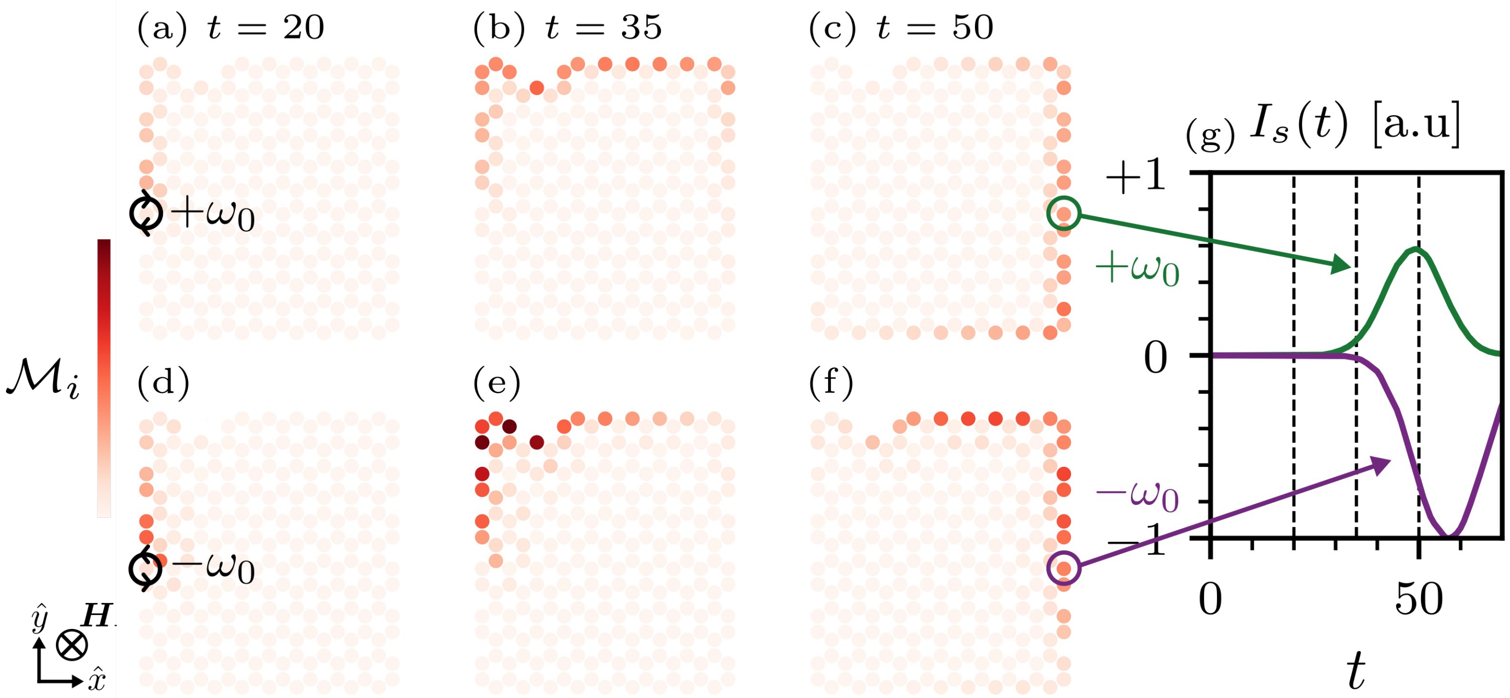


NEGATIVE FREQUENCY?

Negative frequency: precession counterclockwise



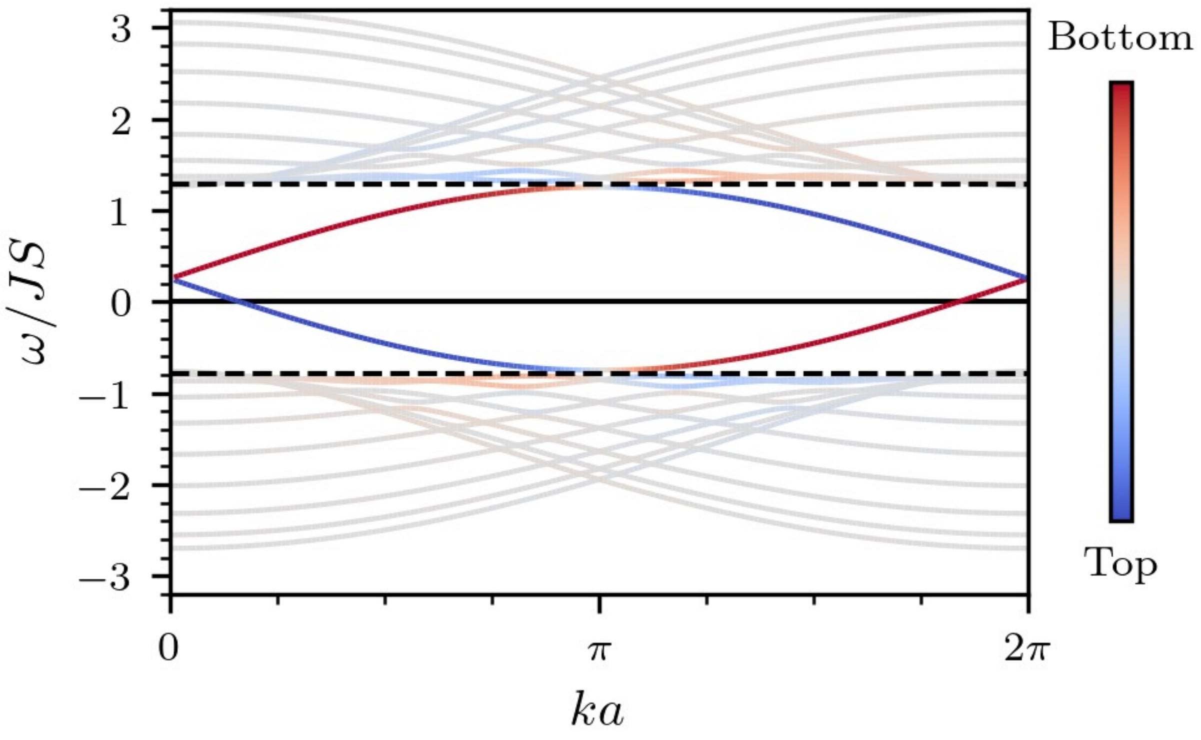




- **Opposite chirality**
- **Different group velocity**
- **Different damping rates**

ACCESSING CHIRAL MAGNON EDGE STATES PROTECTED BY NON-EQUILIBRIUM TOPOLOGY

- Zero-frequency edge modes: GHz range
- Requires large magnetic field and SOT
- Edge modes lower in frequency than bulk modes: Interesting physics!
- Incoherent transport
- Applicable to:
    - Other magnon Chern insulators
    - Other topological magnon phases
    - Other topological bosonic systems (photons etc.)



Pieter M. Gunnink, Joren S. Harms, Rembert A. Duine, Alexander Mook,
Phys. Rev. Lett. **131**, 126601

Electrical Non-Hermitian Control of Topological Magnon Spin Transport

Pieter M. Gunnink, Rembert A. Duine, Alexander Mook,

arXiv:2401.04967

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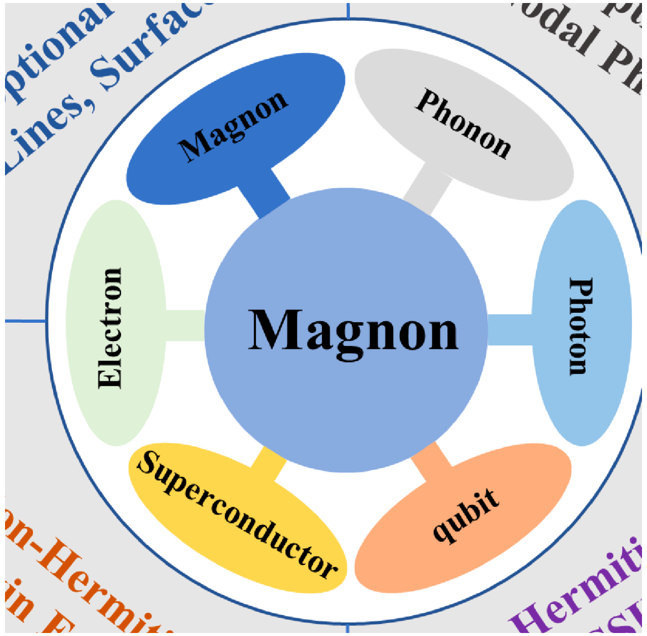
Yu et al., Physics Reports 1062 (2024) 1–86



NON-EQUILIBRIUM IN MAGNONICS

Magnon systems are naturally open tot the environment:

- Gilbert damping
- Non-local damping [Reviews of Modern Physics 77, 1375 (2005)]
- Non-reciprocal couplings [PRB 107, 024418 (2023), arxiv:2307.15792]
- Local driving through spin-transfer [J. Magn. Magn. Mater. 159, L1 (1996); PRB 54, 9353 (1996)] and spin-orbit torques [‘Spintronics and Magnon Bose-Einstein Condensation’, *Universal Themes of Bose-Einstein Condensation*. Cambridge University Press; pp. 505–524]

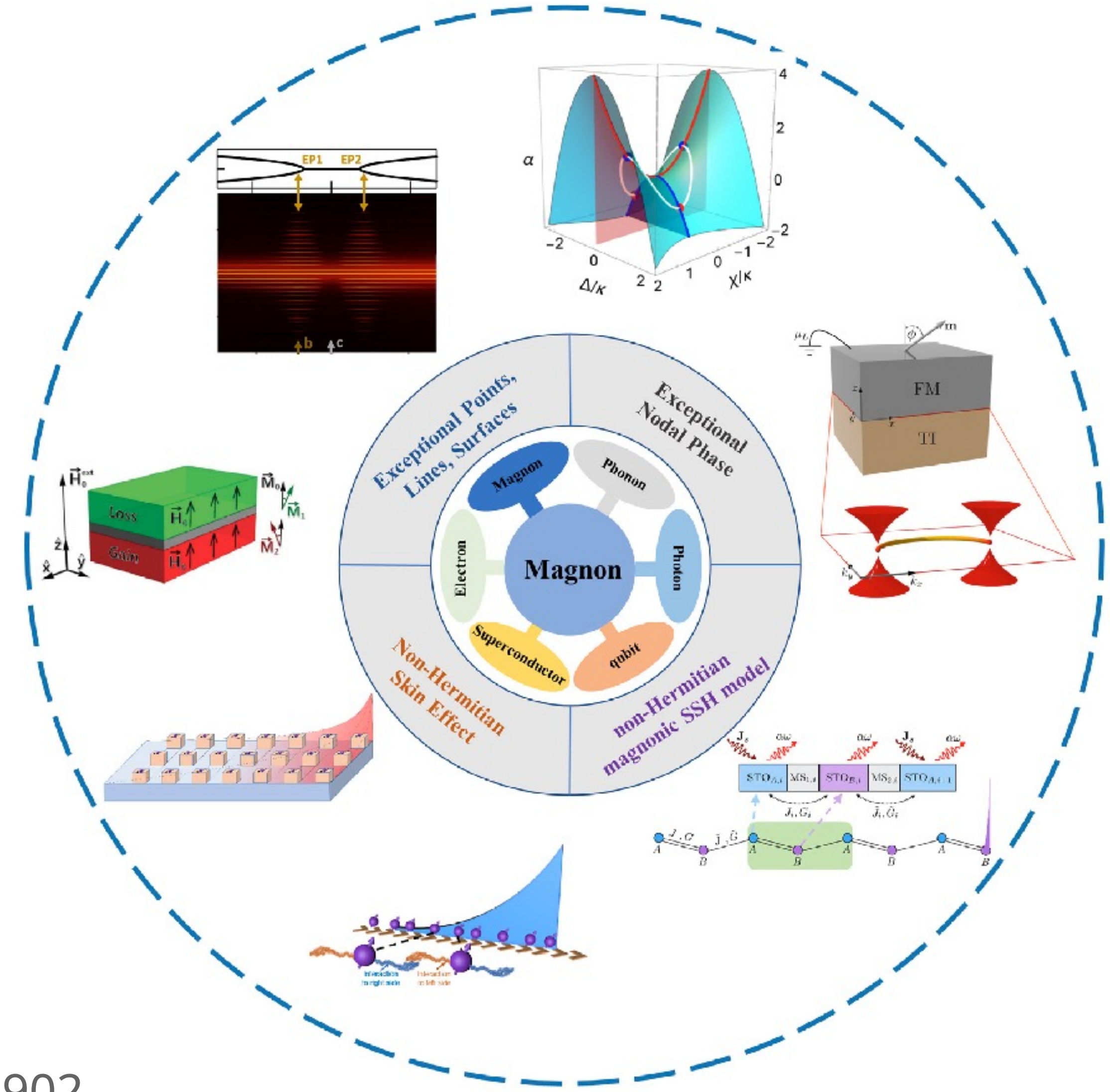
NON-HERMITIAN PHYSICS

Non-Hermitian describes the coupling to the environment as an effective non-Hermitian Hamiltonian: $H^\dagger \neq H$

This allows for novel topological phases:

- Exceptional points
- Non-Hermitian skin effect
- Non-Hermitian lasing modes

Coupling to environment is another engineering degree of freedom!



Yu et al., Physics Reports 1062 (2024) 1–86

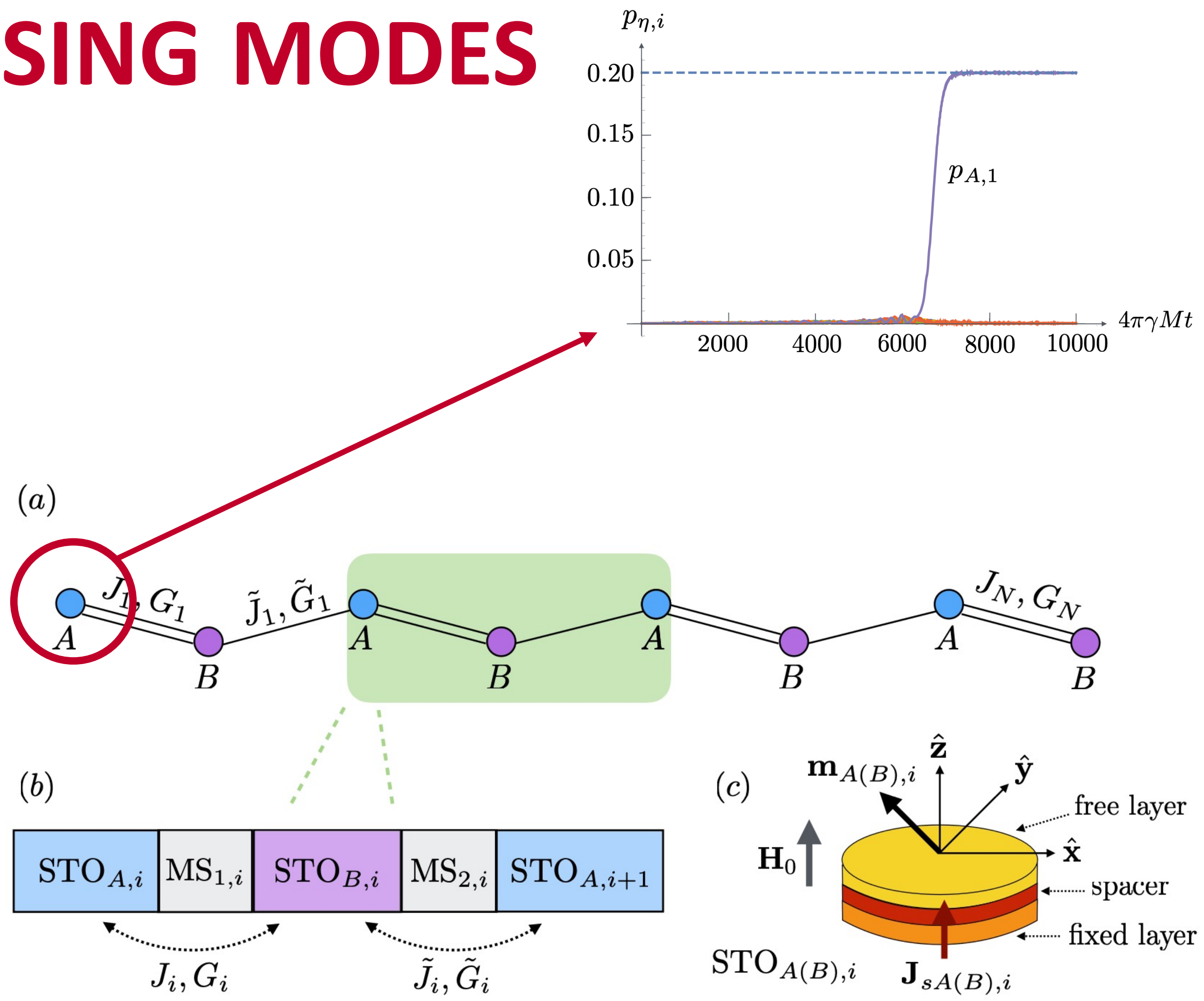
Recent reviews [Hurst and Flebus, J. Appl. Phys. 132, 220902 (2022); Yu et al., Physics Reports 1062 (2024) 1–86]

NON-HERMITIAN LASING MODES

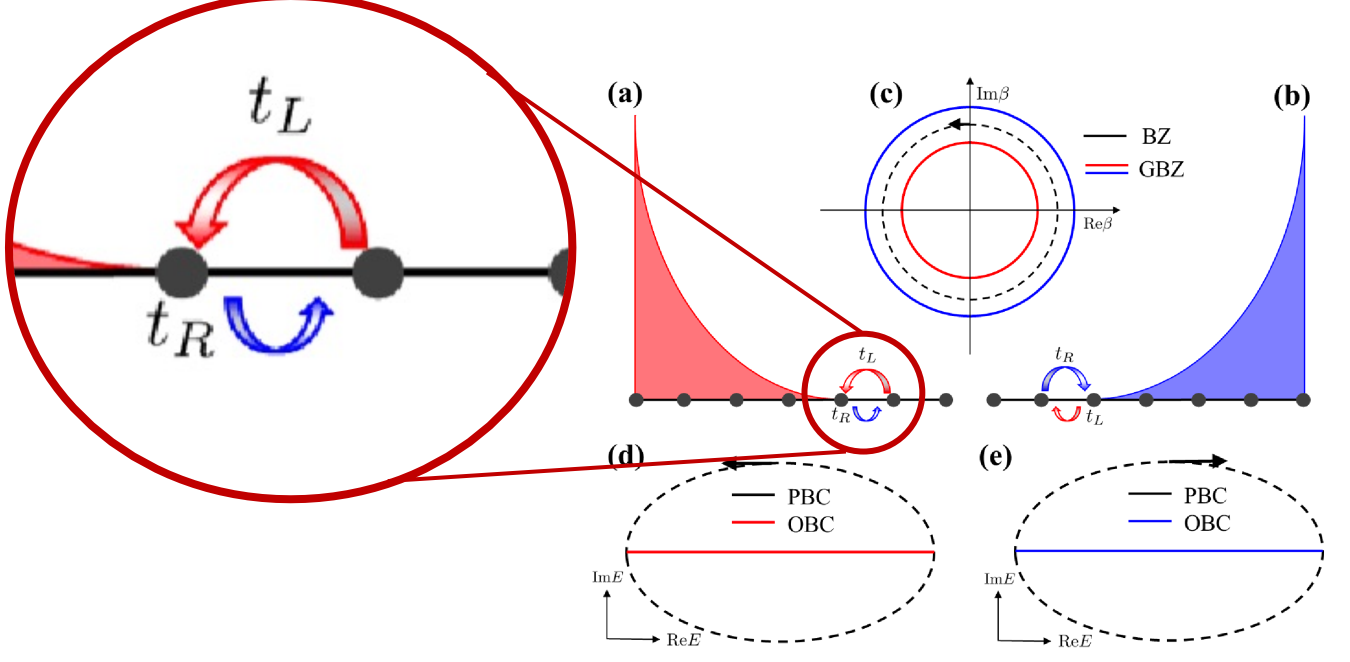
1D SSH model: spontaneous lasing of edge mode [Flebus et al., PRB **102**, 180408(R); Gunnink et al., PRB **105** 104433]

Driving all the A-sites

Only the edge site will lase



SKIN-EFFECT



Physics Reports 1062 (2024) 1–86

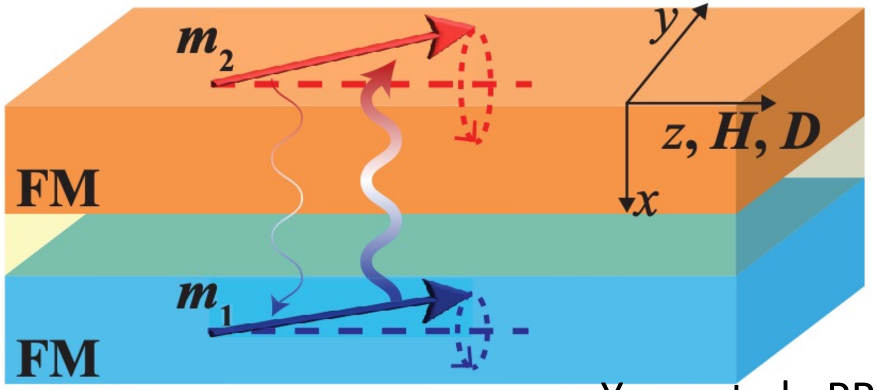
Pile up of modes on the boundary

Requires non-reciprocal couplings (Hatano-Nelson (HN) model):

$$H_{\mathrm{HN}}(k) = (t+\gamma)e^{ik} + (t-\gamma)e^{-ik} ,$$

In magnonic systems possible through:

Non-local damping + chiral couplings [Deng et al., **105**, L180406 ; Yuan et al., PRB **107**, 024418; Li et al., arXiv:2307.15792]

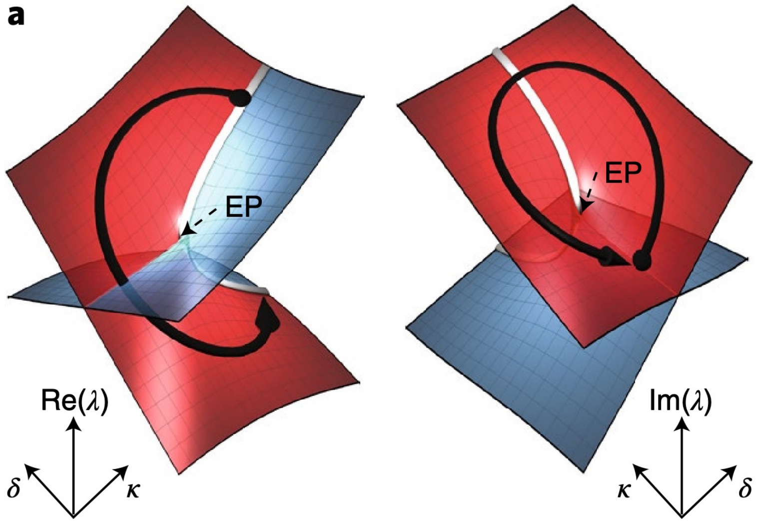


Coupling:
DMI +
non-local
dissipation

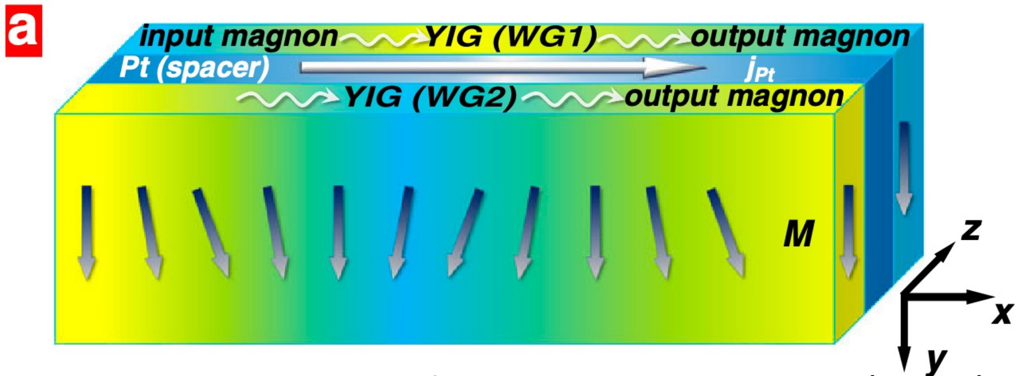
Yuan et al., PRB **107**, 024418

EXCEPTIONAL POINTS

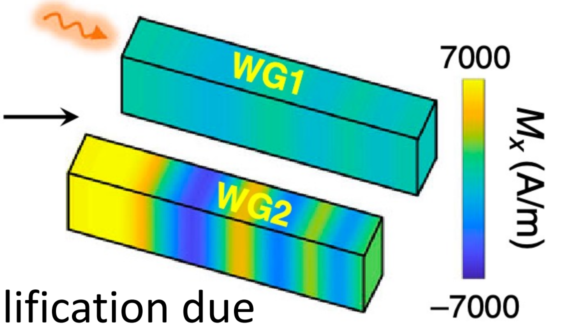
Exceptional point has unique Riemann surface



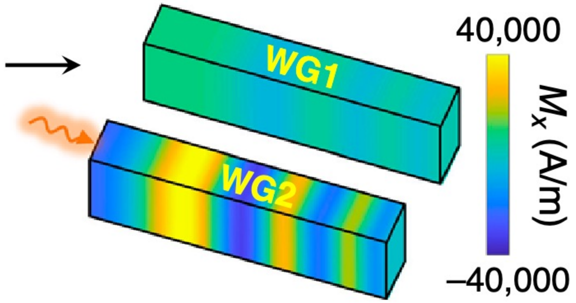
Encircling in parameter space does not bring you back to the same starting point

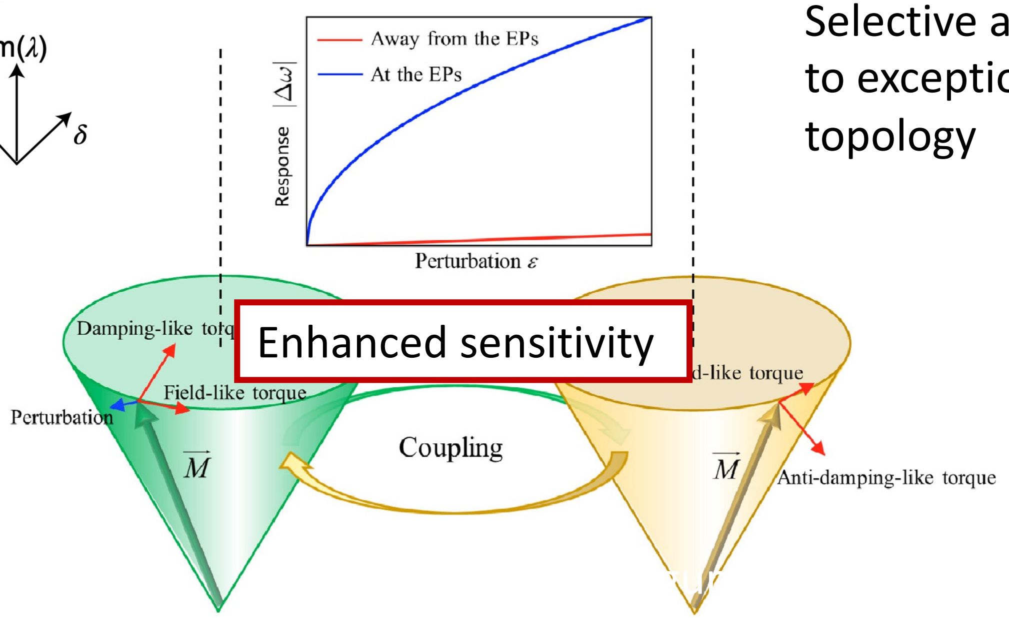


Wang et al., Nat Comm 11 5663 (2020)



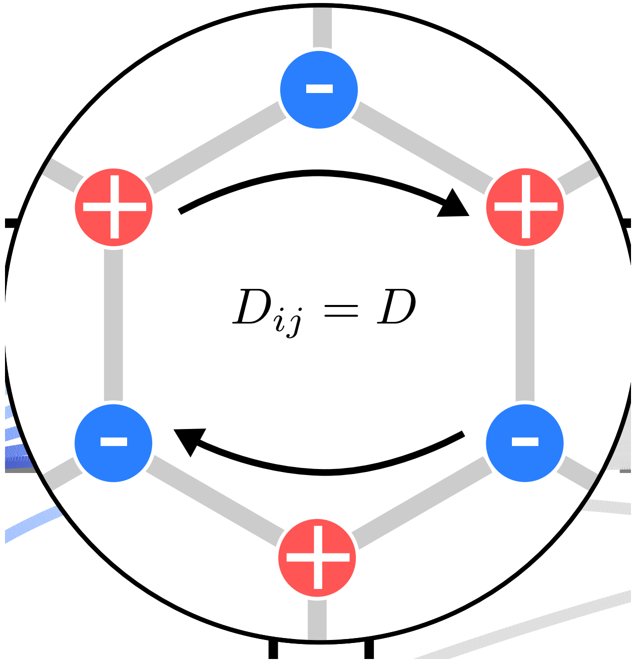
Selective amplification due to exceptional point topology





Enhanced sensitivity

NON-HERMITIAN TOPOLOGICAL MAGNON INSULATOR



Start from magnon Haldane model

Include spin-orbit torque

- Positive on A-sites
- Negative on B-sites

Hamiltonian:

$$\mathcal{H}_{\boldsymbol{k}} = \overset{\text{Hermitian}}{\boxed{(H + 3JS)\sigma_0 + \boldsymbol{h}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}}} + \overset{\text{Non-Hermitian}}{\boxed{\mathrm{i}\gamma\sigma_z}}.$$

Importantly:

- System remains stable (no reversing magnetization)
- Chern number is still well-defined

BAND STRUCTURE

$$\boldsymbol{\mathcal{H}_k} = (H + 3JS)\sigma_0 + \boldsymbol{h_k} \cdot \boldsymbol{\sigma} + \boxed{i\gamma\sigma_z.}$$

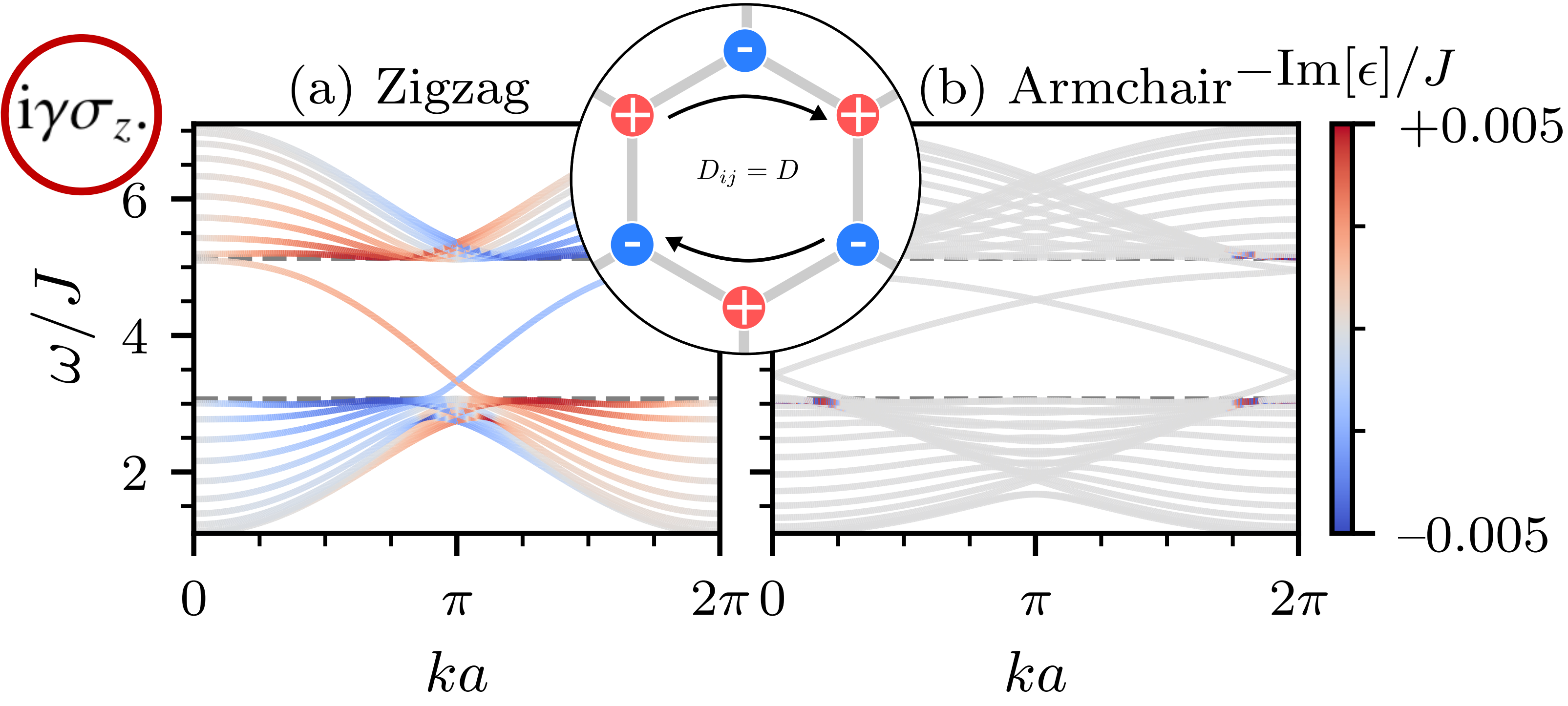
Zigzag:

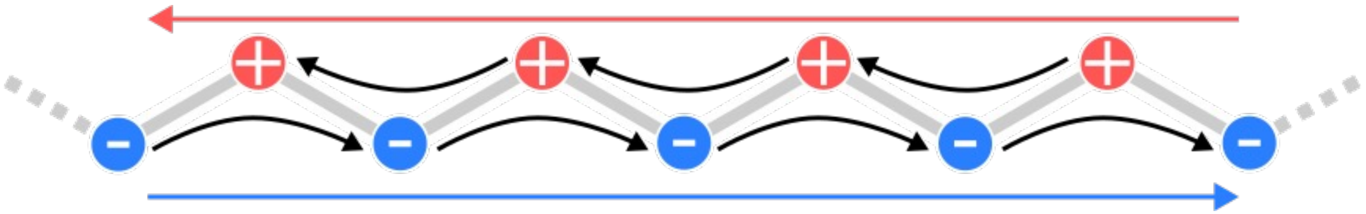
Right-moving modes enhanced

Left-moving modes damped

Armchair:

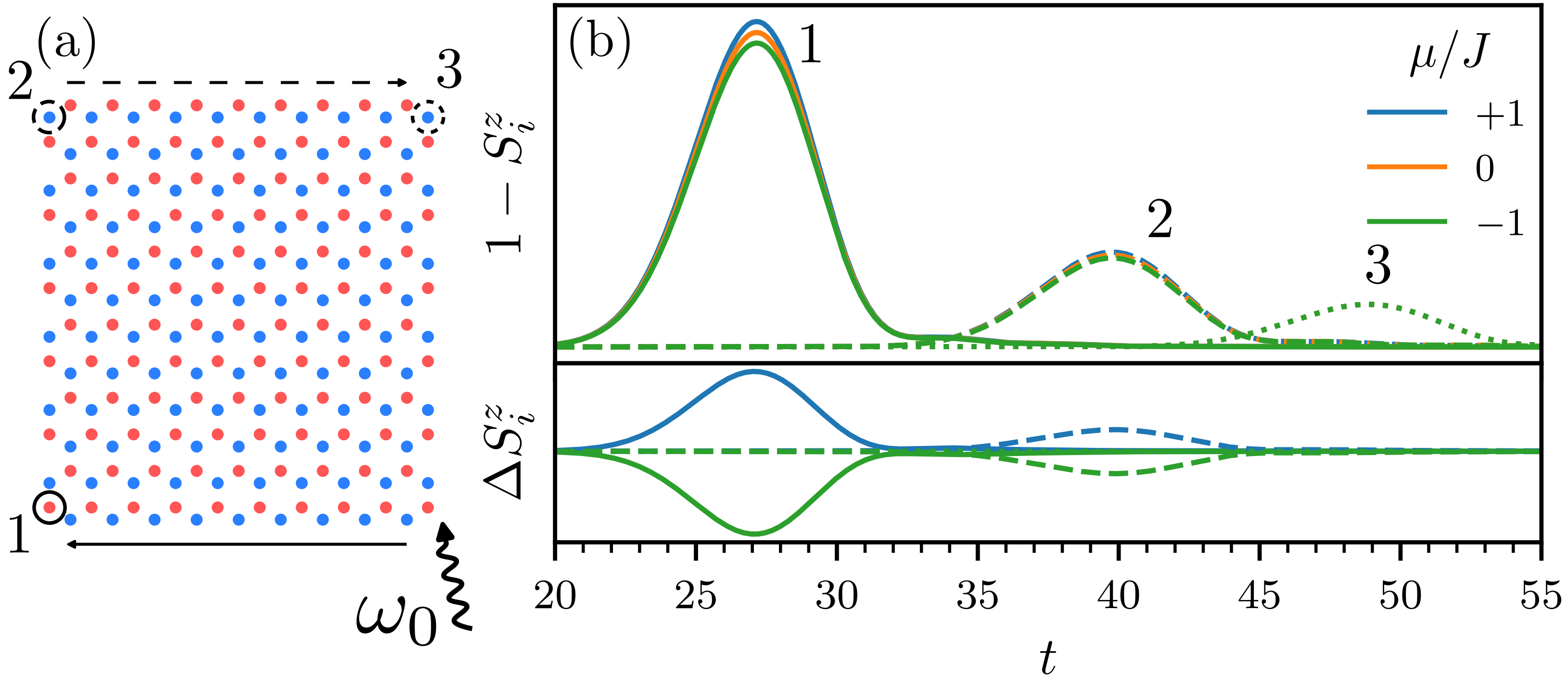
Hybrid skin effect (localization on one side)





AMPLIFICATION OR SUPPRESSING OF EDGE MODES

- Numerical LLG simulations
- Edge mode amplified or suppressed, depending on edge geometry
- But: still stable overall



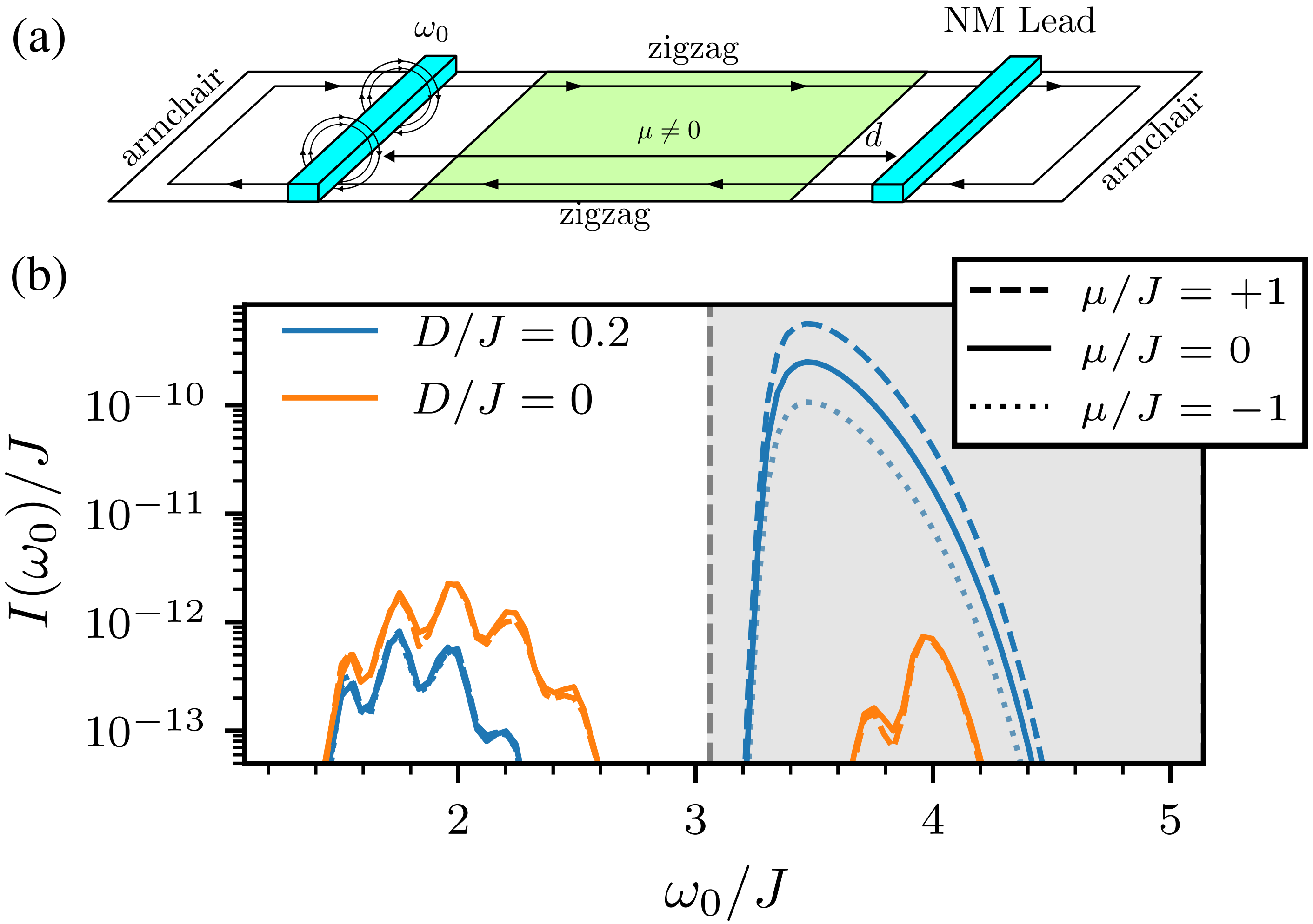
TRANSPORT

Linear spin wave theory

Including disorder to see the topological protection

No amplification for bulk modes

But **robust** amplification of edge modes



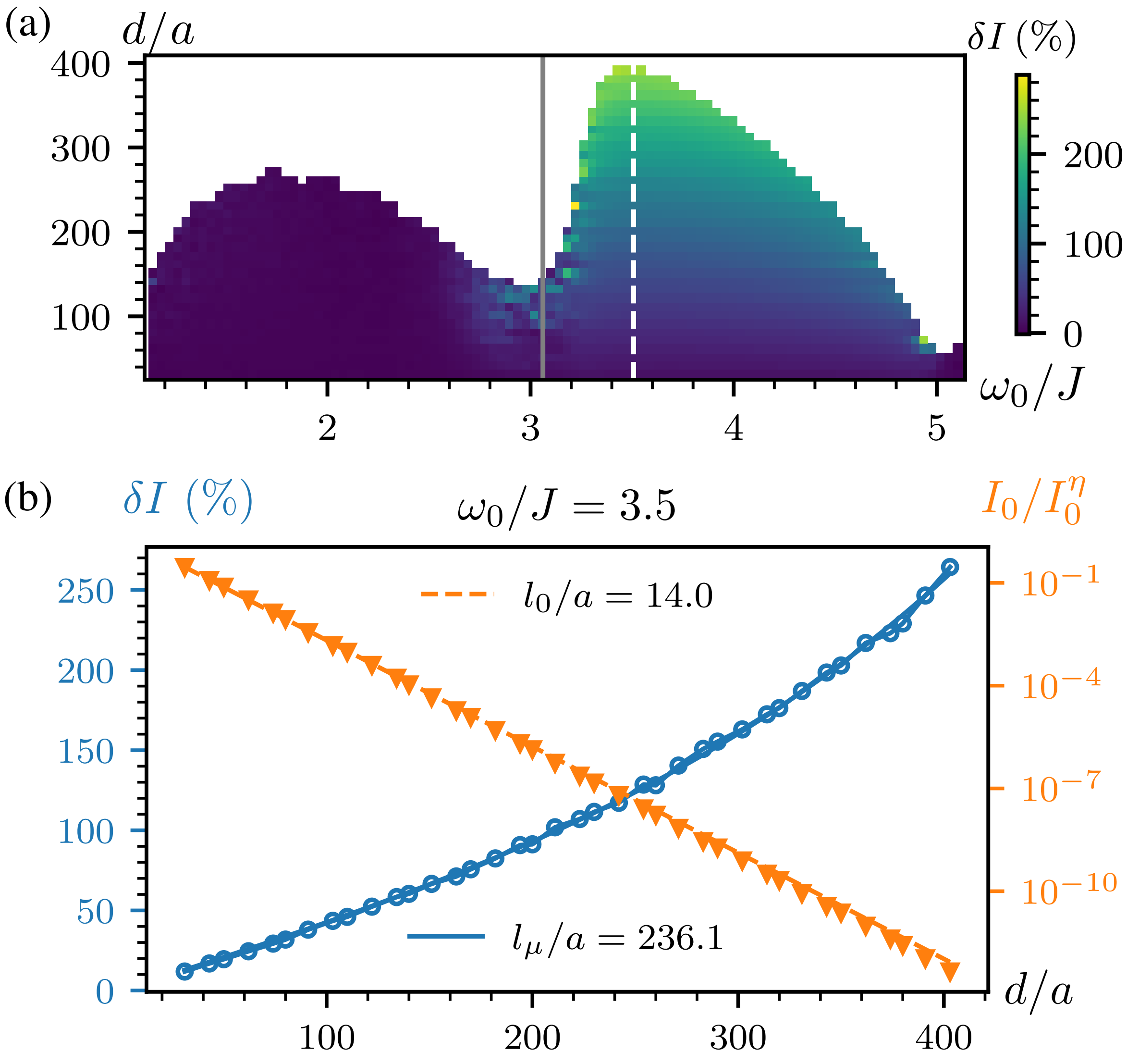
TRANSPORT (2)

Can be modelled with exponential decay: $I_\mu \propto e^{-\frac{d}{l_0}} e^{\pm\frac{d}{l_\mu}}$

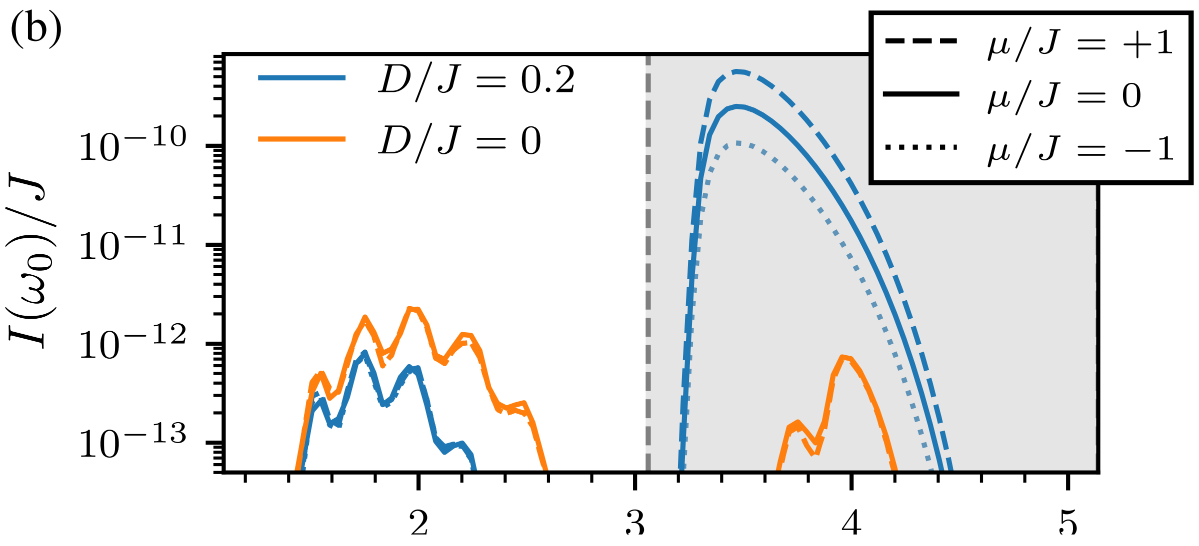
Relative amplification factor:

$$\delta I = \frac{I^{+\mu} - I^{-\mu}}{I^{+\mu} + I^{-\mu}} = \sinh\frac{d}{l_\mu}$$

Potentially much more efficient because of topological protection [An et al., PRB **89**, 140405(R) (2014); Evelt et al., APL **108**, 172406 (2016); Cornelissen et al., 120, 097702 (2018)]



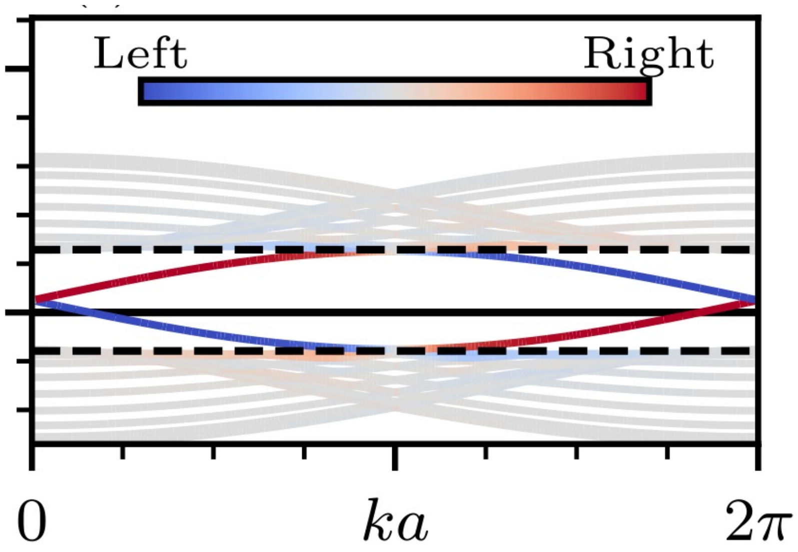
ELECTRICAL NON-HERMITIAN CONTROL OF TOPOLOGICAL MAGNON SPIN TRANSPORT

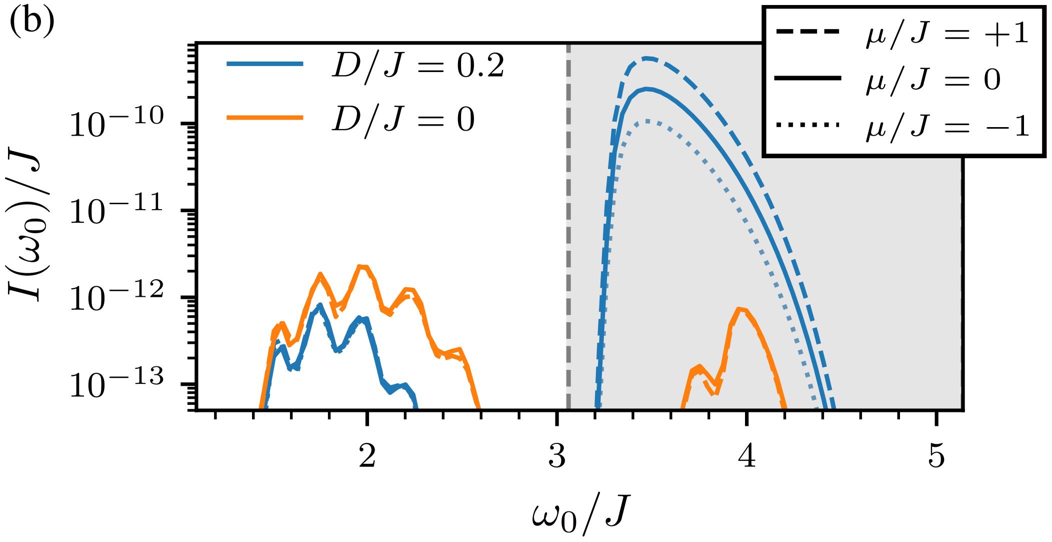


- Effective non-Hermitian magnon Chern insulator through SOT
- Amplification of topological edge modes
- Robust amplification against disorder
- Implementation:
  - *Asymmetric* SOT also possible, as long as $\gamma_A \neq \gamma_B$
  - Possible in specific magnetic compounds (buckled honeycomb, sublattice symmetry breaking spacer layer)
  - Or in artificial magnetic materials

Pieter M. Gunnink, Rembert A. Duine, Alexander Mook,
arXiv:2401.04967

CONCLUSIONS





Magnon insulators are an ideal platform for bosonic topology

Spin-orbit torque offers strong handle for control

Non-Hermitian topology is easily accesible

OUTLOOK

Atomistic magnon topology -> high energies

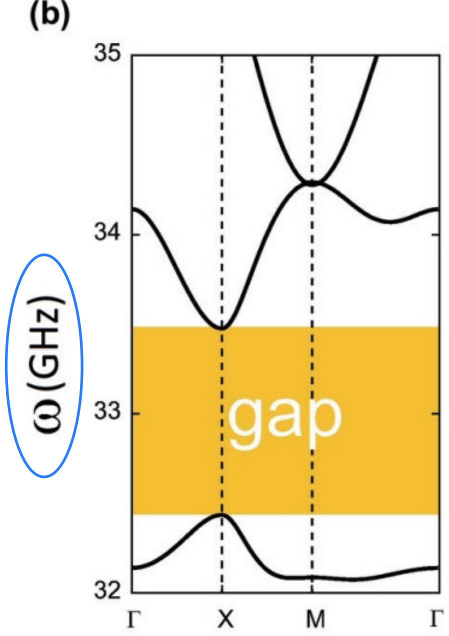
Possible solution:

1. magnonics crystals -> energy scale set by dipole-dipole interaction
2. Coupled magnetic solitons

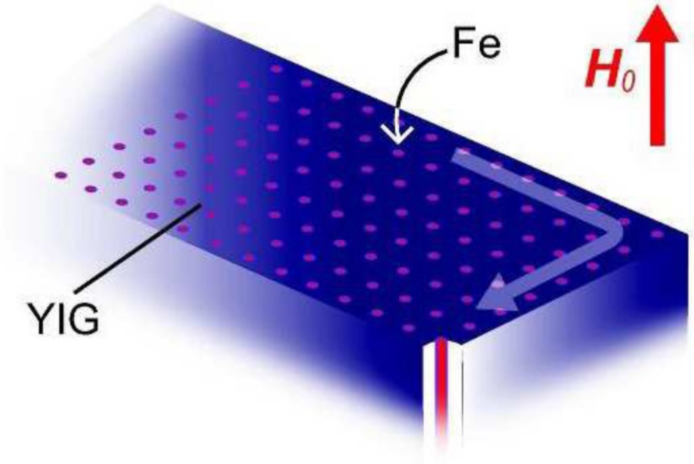
Results shown here “should” translate, so:

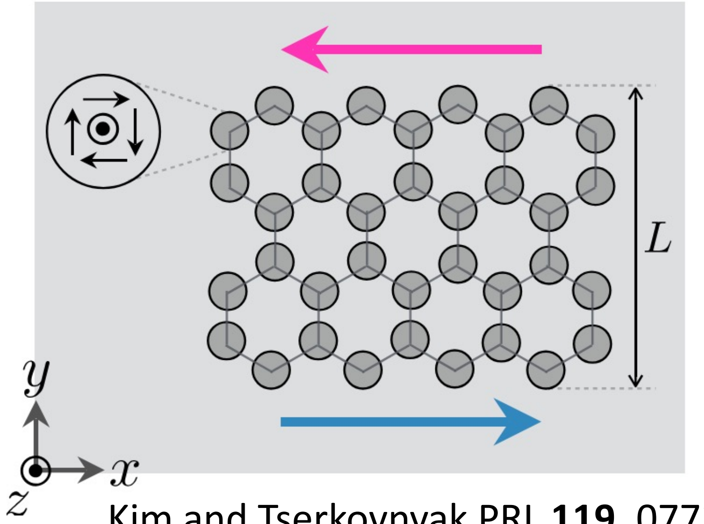
- robust transport through edge modes
- zero-frequency edge modes
- non-Hermitian topology

Would allow close control over spin-orbit torque



Shindou et. al, PRB **87**, 174427





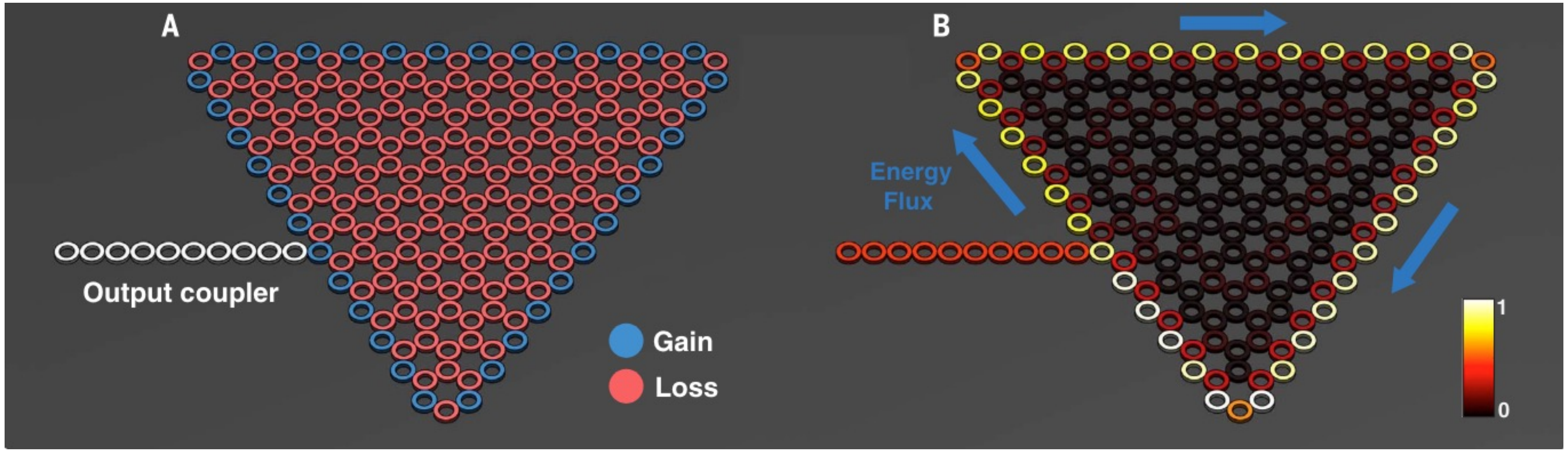
Kim and Tserkovnyak PRL **119**, 077204 (2017)

OUTLOOK

Achieve *true* non-Hermitian magnon laser (on all edges) [Harari et al., Science 359, 1230 (2018); Bandres et al., Science 359, 1231 (2018)]

Possible in photonics platforms

Magnon non-linearities?



Harari et al., Science 359, 1230 (2018)

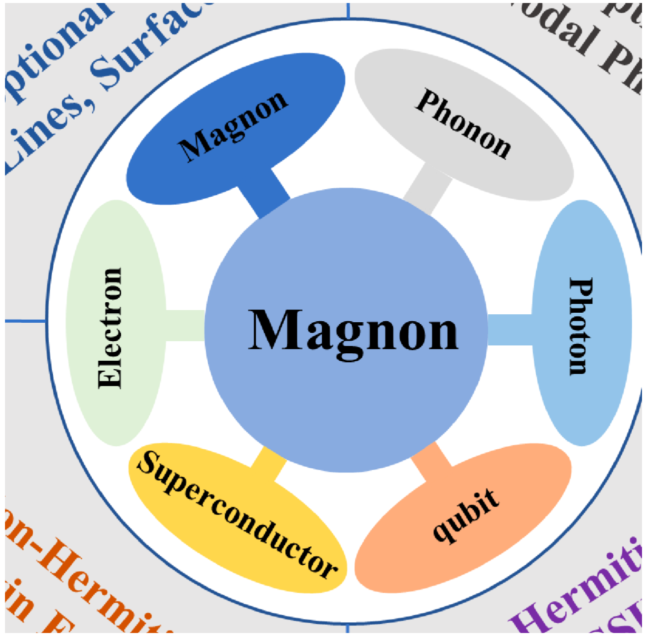
NON-HERMITIAN MAGNONICS: WHAT'S NEXT?

Harness ease of coupling of magnon to environment:

- Control of environment allows for non-Hermitian control (phonons, photons, plasmons, etc.)
- Active driving of environment to realize gain

Extension to compensated magnets:

- Natural high frequency operations
- Would introduce now handle for control



Yu et al., Physics Reports 1062 (2024) 1–86

CONCLUSIONS

Magnon insulators are an ideal platform for bosonic topology

Spin-orbit torque offers strong handle for control

Non-Hermitian topology is easily accesible