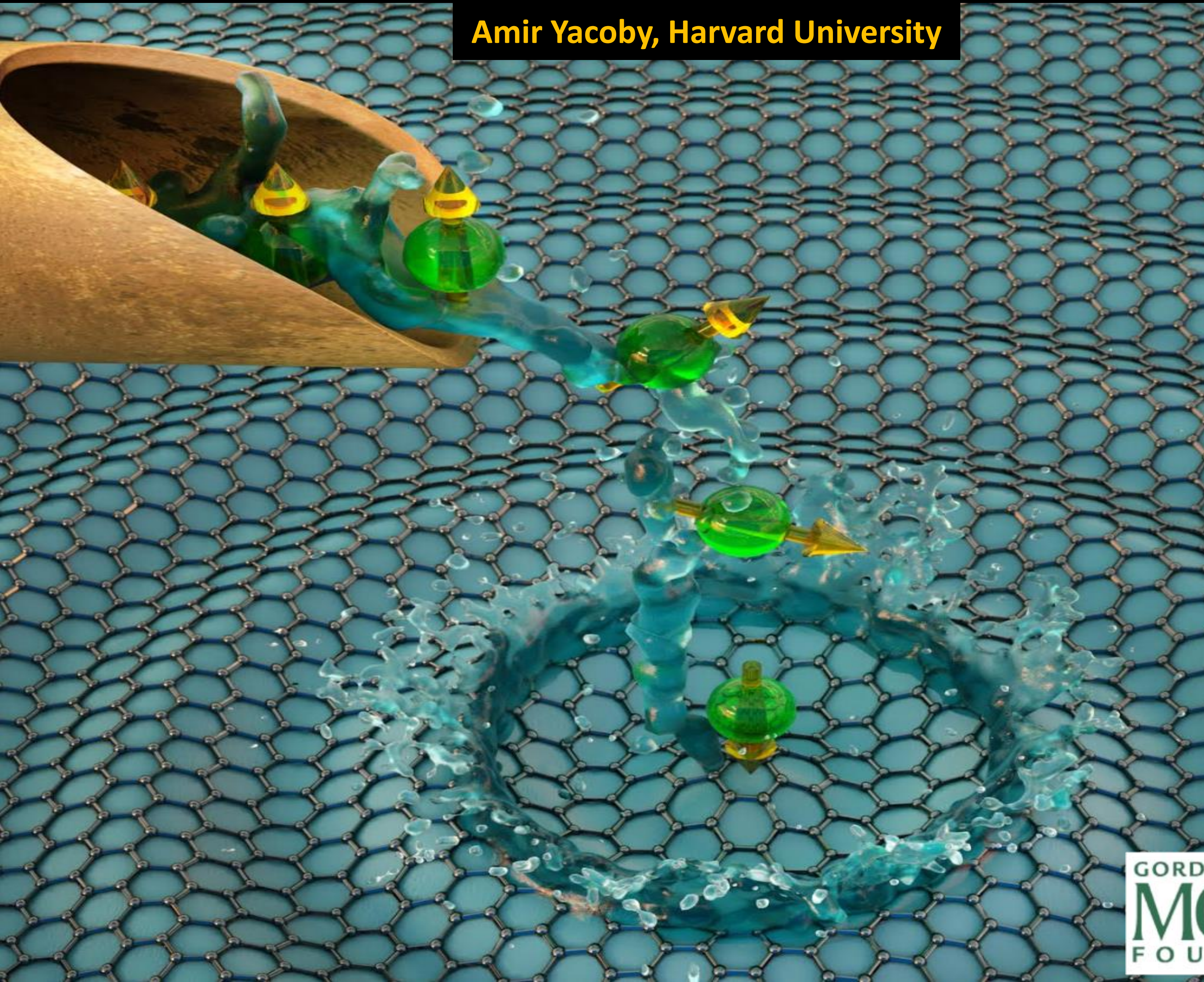
Magnons as a New Probe of Correlated Electron Physics

Amir Yacoby, Harvard University



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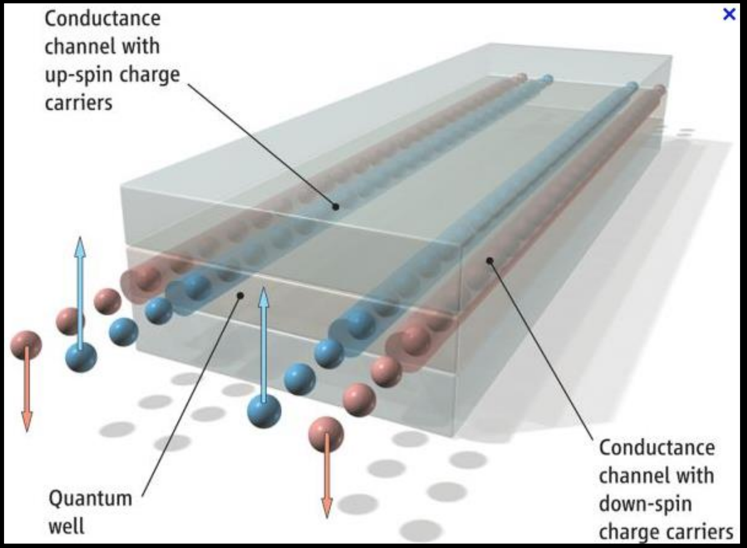
Magnons as a New Probe of Correlated Electron Physics

Spin Momentum Locking: Quantum Spin Hall Effect

Ground state properties

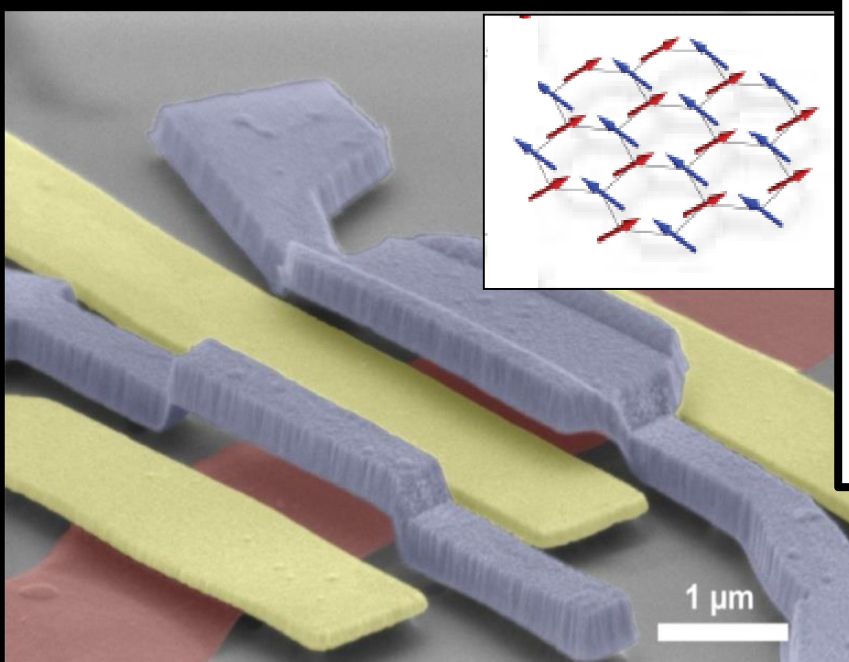


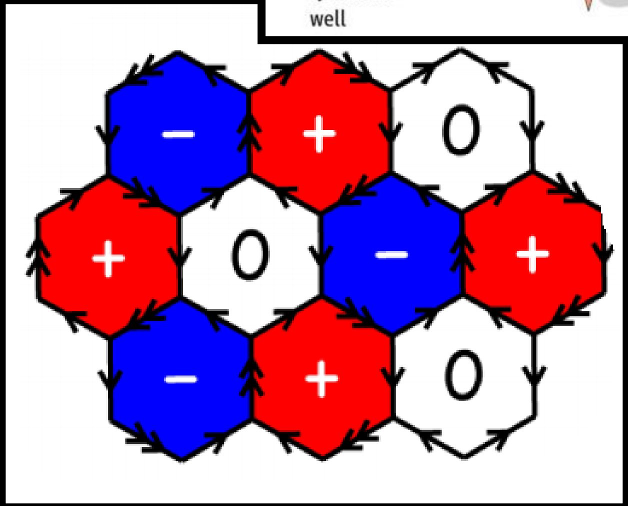
From SC Zhang

Challenges:

- Materials with unique spin and magnetic properties
  nm Length scales and mesoscopic sizes

Canted antiferromagnetic states in graphene





Novel insulating states:
Circulating currents in twisted bilayer graphene

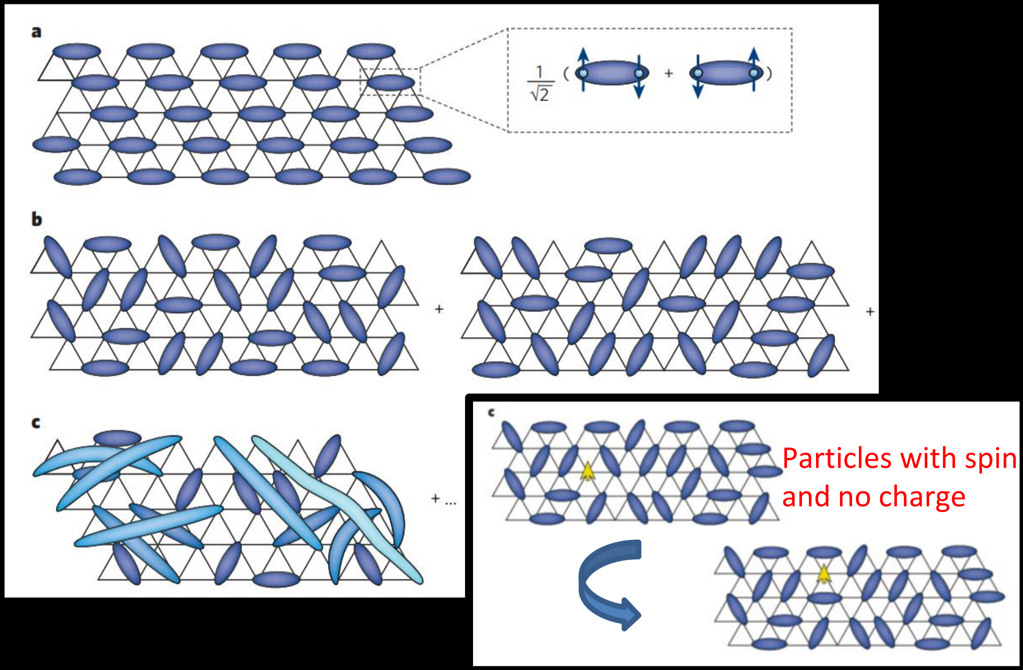
Magnons as a New Probe of Correlated Electron Physics

Novel excitation

Challenges:

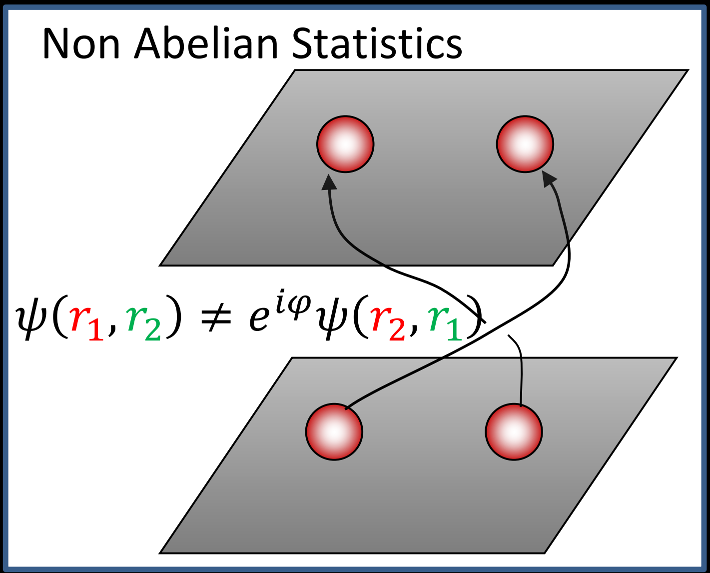
- How to probe dispersion
- Density of states
- Quantum statistics

Spin liquids



Balents – Nature review

Topological
Superconductors



Magnons as a New Probe of Correlated Electron Physics

Transport of novel excitations

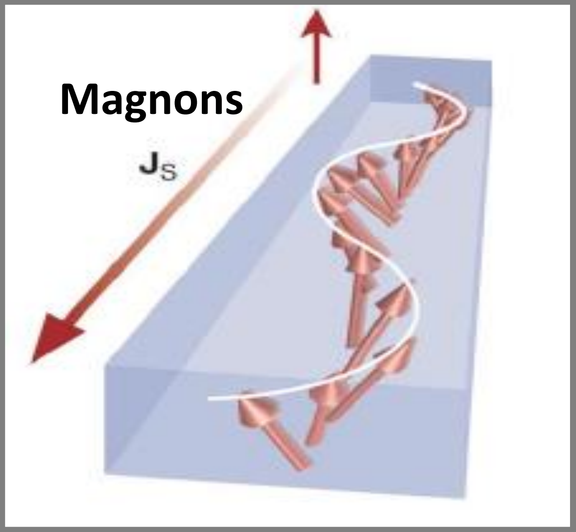
Challenges:

- How to detect spin chemical potential and current

PRL 112, 227201 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

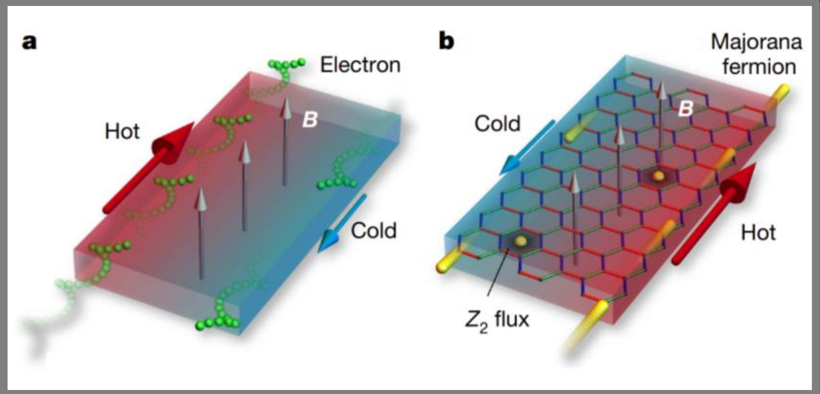
Superfluid Spin Transport Through Easy-Plane Ferromagnetic Insulators

So Takei and Yaroslav Tserkovnyak



Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

Y. Kasahara[1], T. Ohnishi[1], Y. Mizukami[2], O. Tanaka[2], Sixiao Ma[1], K. Sugii[3], N. Kurita[4], H. Tanaka[4], J. Nasu[4], Y. Motome[5], T. Shibauchi[2] & Y. Matsuda[1]*



Quantized thermal Hall effect

Magnons as a New Probe of Correlated Electron Physics

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PRL **112,** 227201 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

Superfluid Spin Transport Through Easy-Plane Ferromagnetic Insulators

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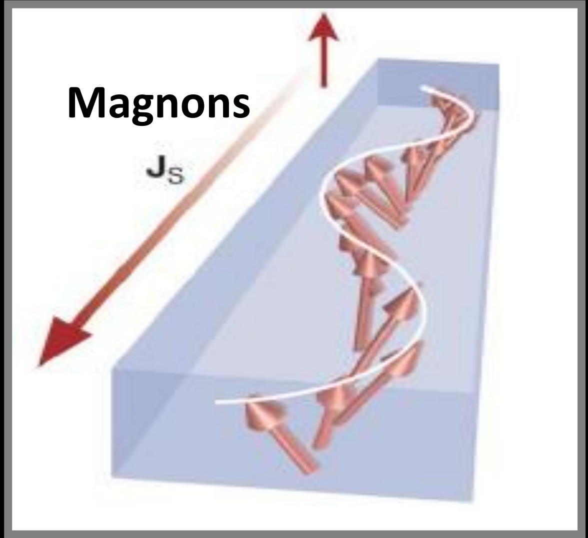

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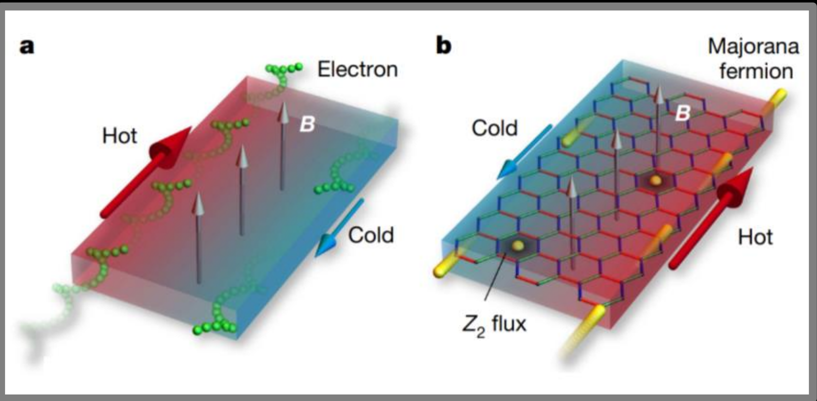

Quantized thermal Hall effect

Need alternatives to electrical measurements

Magnons as a New Probe of Correlated Electron Physics

Transport of novel excitations

Challenges:
- How to detect s
potential and c


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Superfluid Spin Transport Through Easy-Plane Ferromagnetic Insulators


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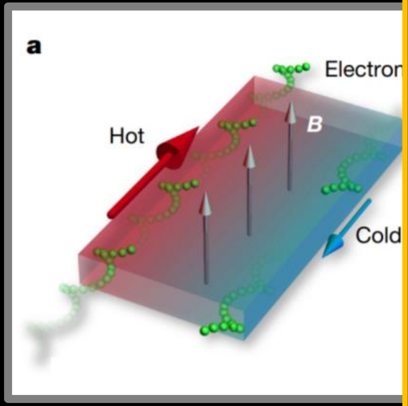
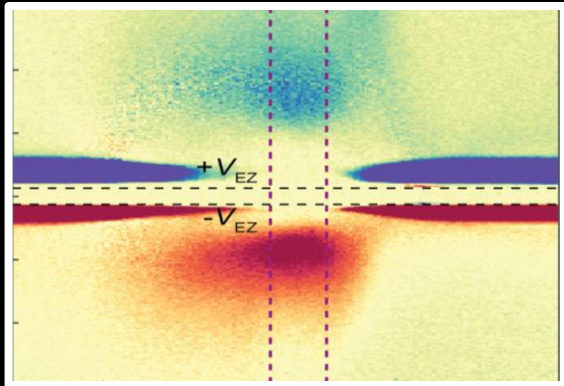


Quantized therm
effect

Today:

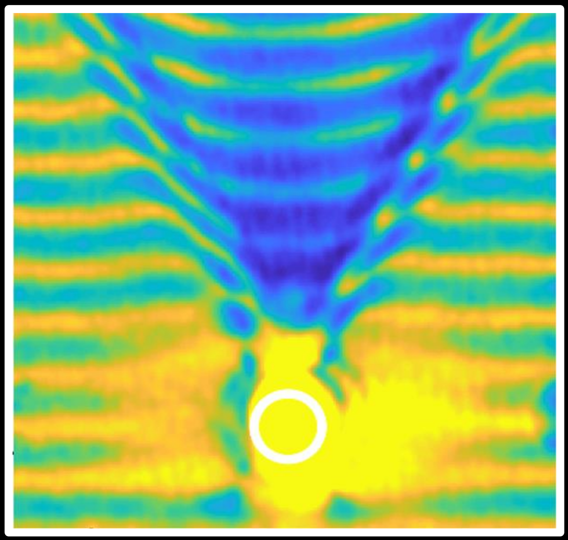
Magnons in Quantum Hall Ferromagnets

Low T – High B

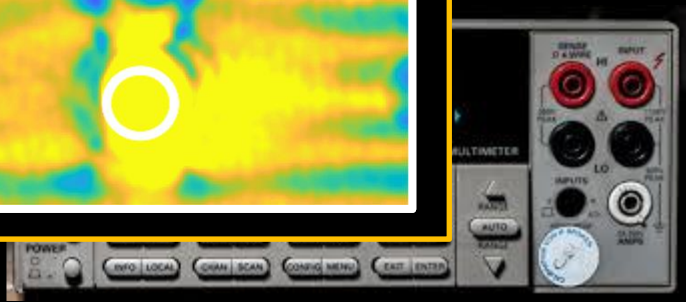


A New Magnon Scattering Platform

Room T – Low B



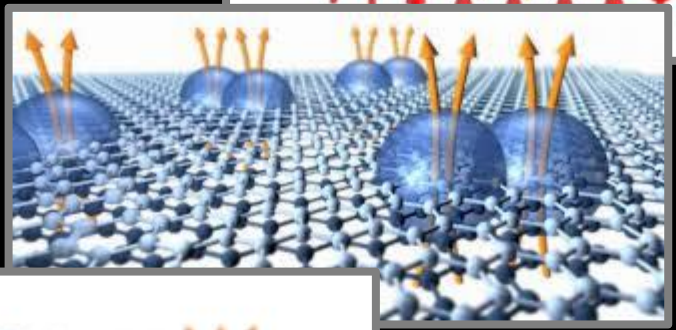
measurements



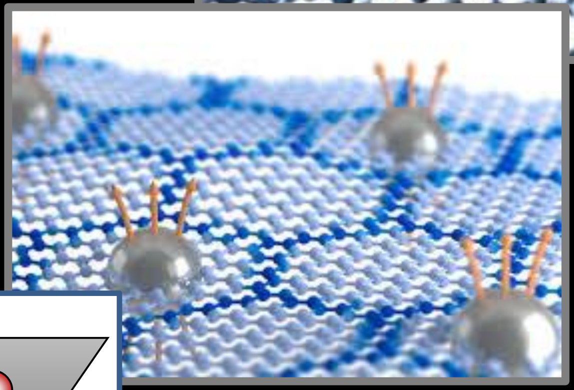
Quantum Hall Systems: Collective Excitations

Skyrmions: charge e

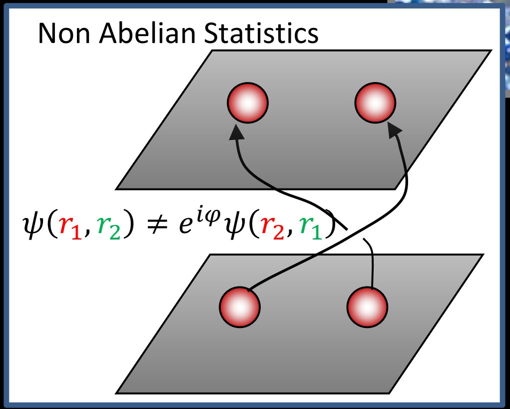
Composite Fermions: charge e



Anyons – Fractional charge



Non-Abelions:
Charge e/4



Quantum Hall Magnons

Spin and Isospin: Exotic Order in Quantum Hall Ferromagnets

Steven M. Girvin

June 2000 Physics Today 39

temperature of a few K, characteristic of the Zeeman gap and the spin stiffness.

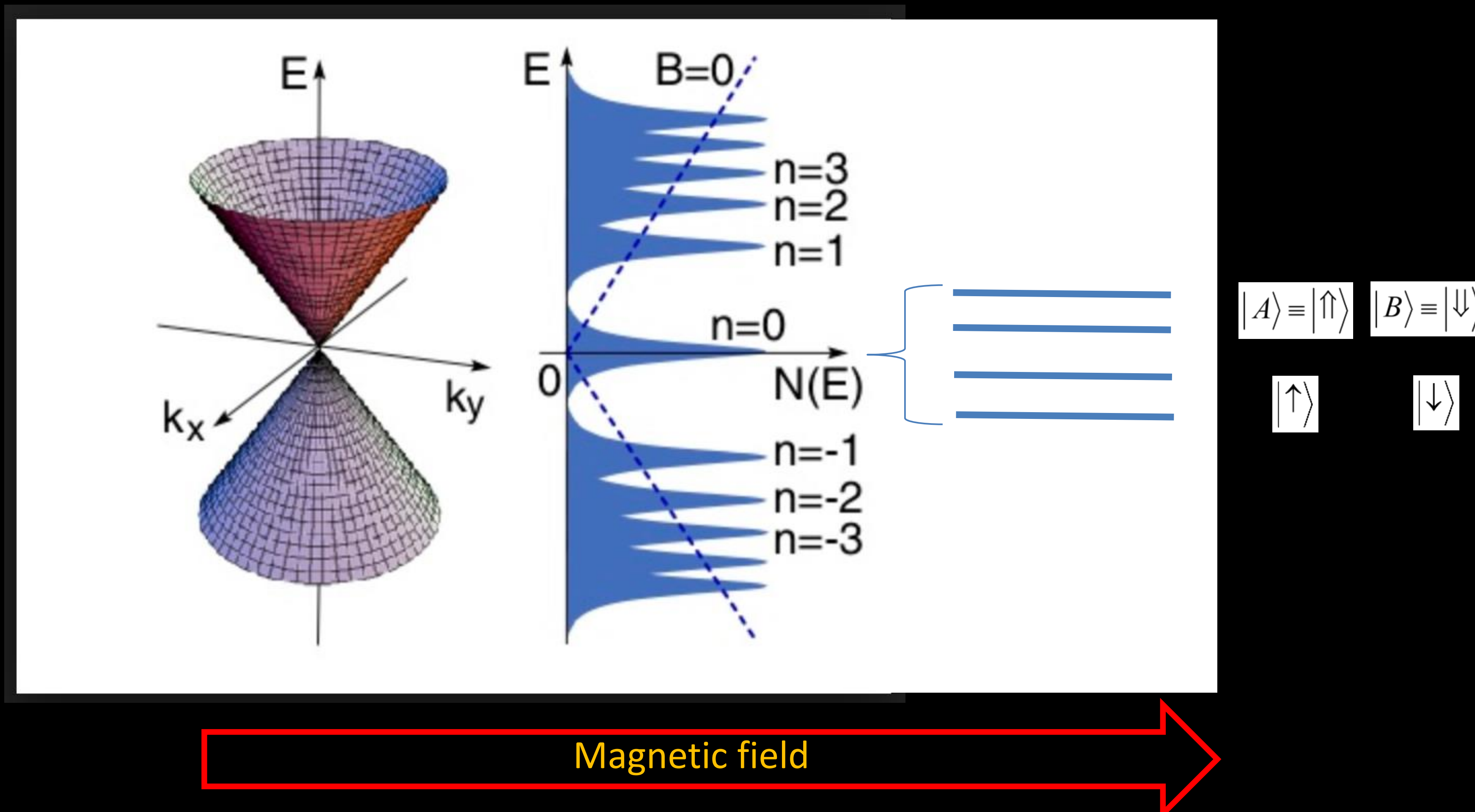
At filling factor $\nu = 1$, spin waves are the lowest energy excitations. But because they do not carry charge, they do not have a large impact on the electrical transport properties. Since the lowest spin state of the lowest Landau level is completely filled at $\nu = 1$, the Pauli exclusion principle tells us that we can add more charge, as illustrated in figure 1, only with reversed spin. In the absence of strong Coulomb interactions, the energy cost of this spin flip is simply the Zeeman energy, which is very small. So one might not expect to see a quantized Hall plateau near $\nu = 1$, because there would be a high density of thermally excited charges. However, the Coulomb interaction exacts a large exchange-energy penalty for having a reversed spin in a ferromagnetic state.[2,7] Thus magnetic order induced by Coulomb interactions turns out to be essential to the integer quantum Hall effect.

Extremely low Magnetization

Quantum Hall Ferromagnets

Formation of Landau Levels.
Each level is 4 fold degenerate for spin and valley

Breaking of spin and valley degeneracy



Quantum Hall Ferromagnets

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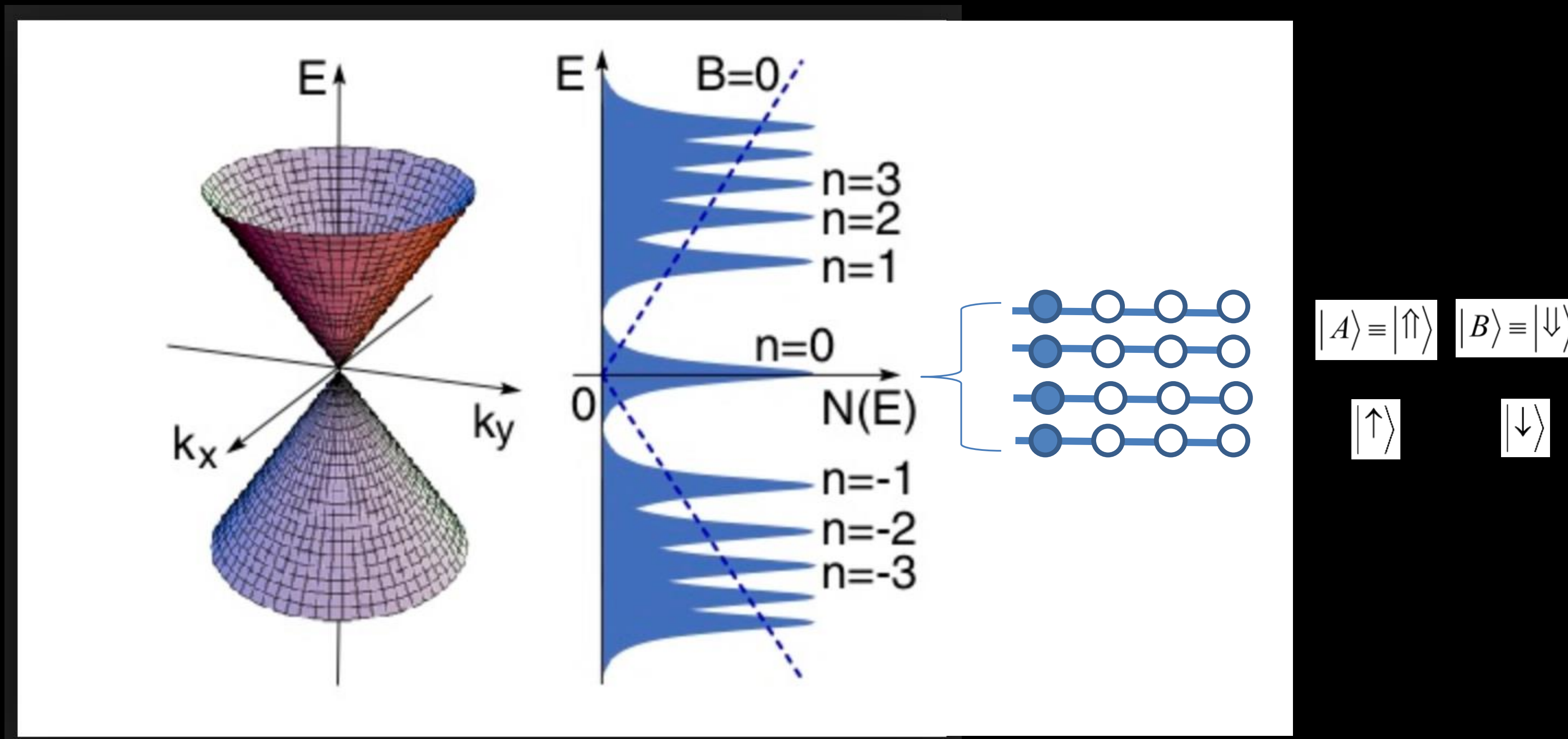
Breaking of spin and valley degeneracy

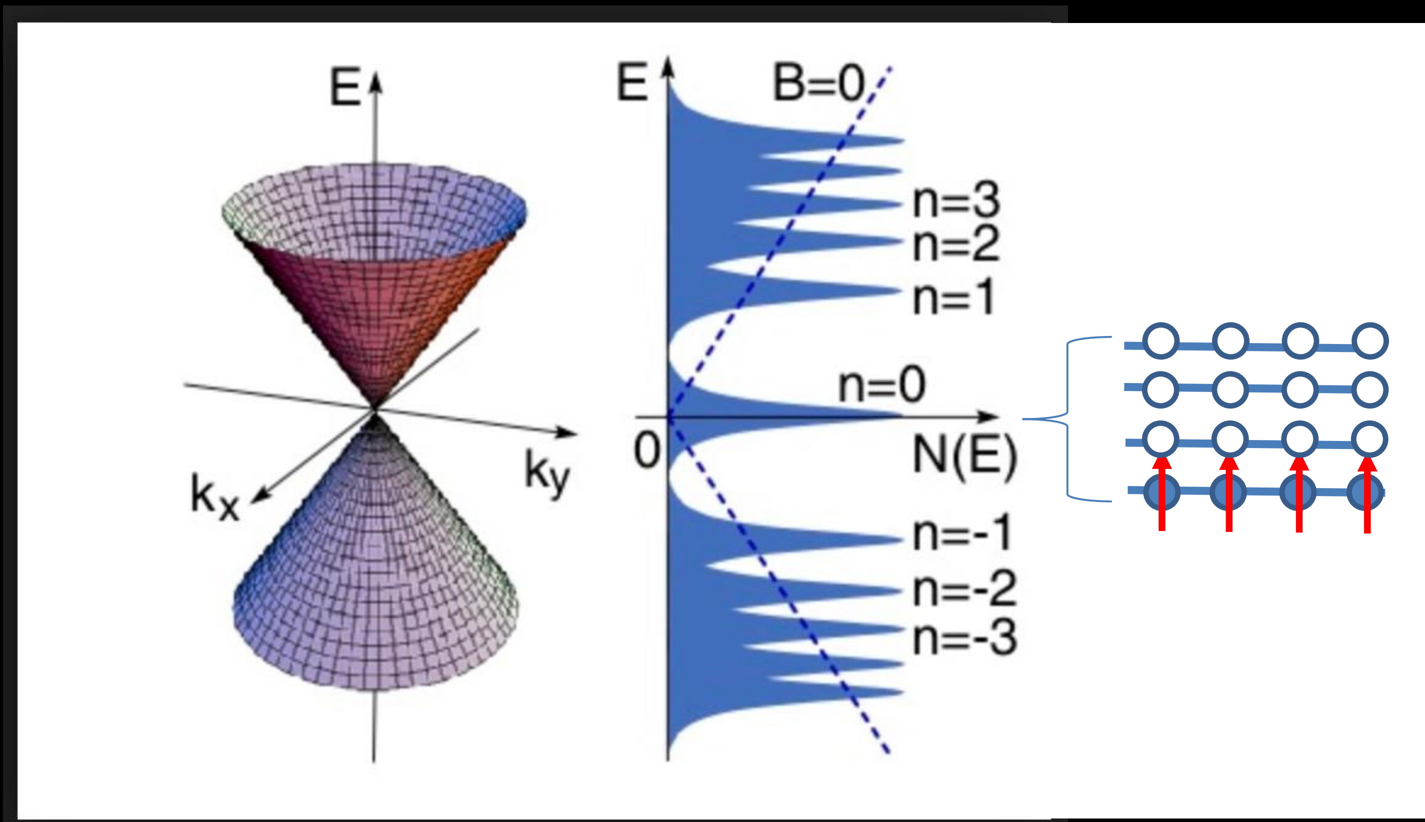


Magnetic field

Quantum Hall Ferromagnets

Formation of Landau Levels.
Each level is 4 fold degenerate for spin and valley

Breaking of spin and valley degeneracy



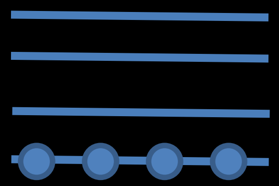
$$|A\rangle \equiv |\Uparrow\rangle \quad |B\rangle \equiv |\Downarrow\rangle$$

$$|\uparrow\rangle \quad |\downarrow\rangle$$

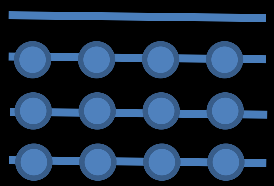
Magnetic field

Quantum Hall Magnons

ν=-1



ν=1



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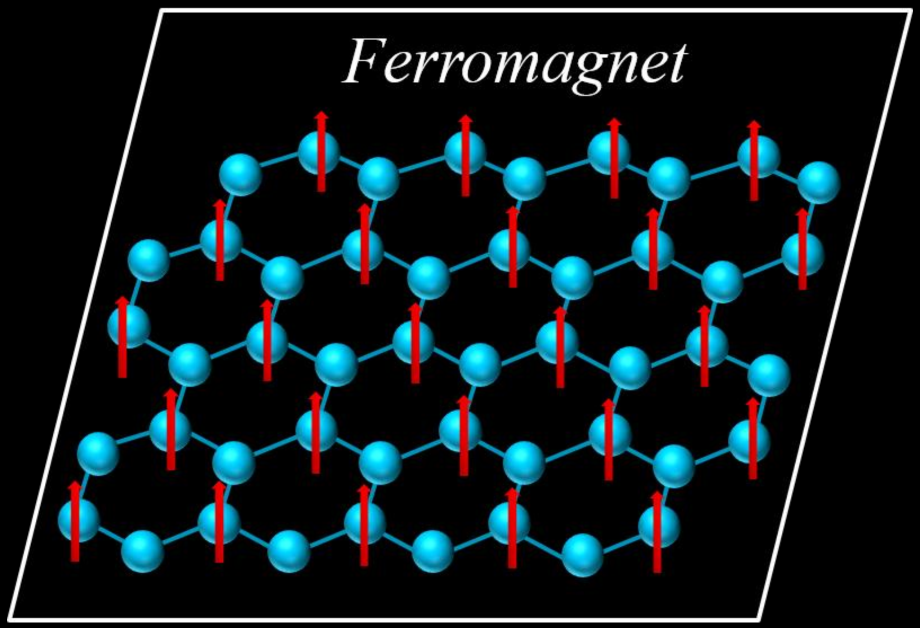
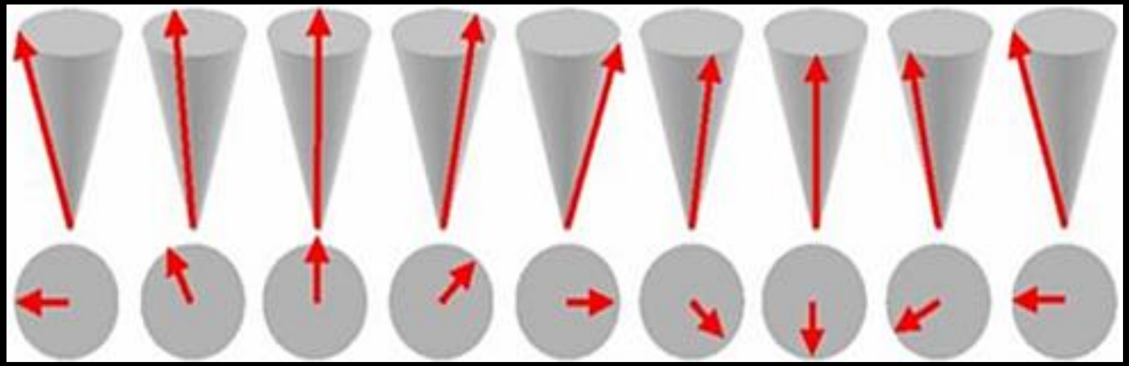
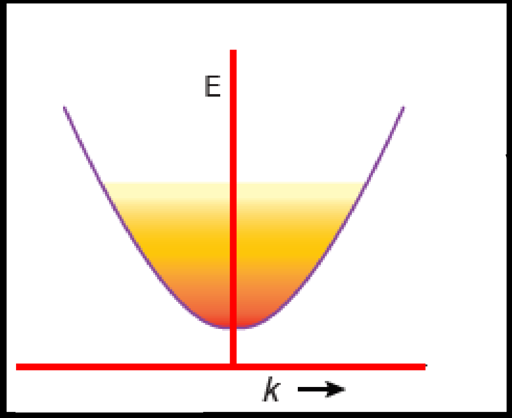
$|\uparrow\rangle$ $|\downarrow\rangle$

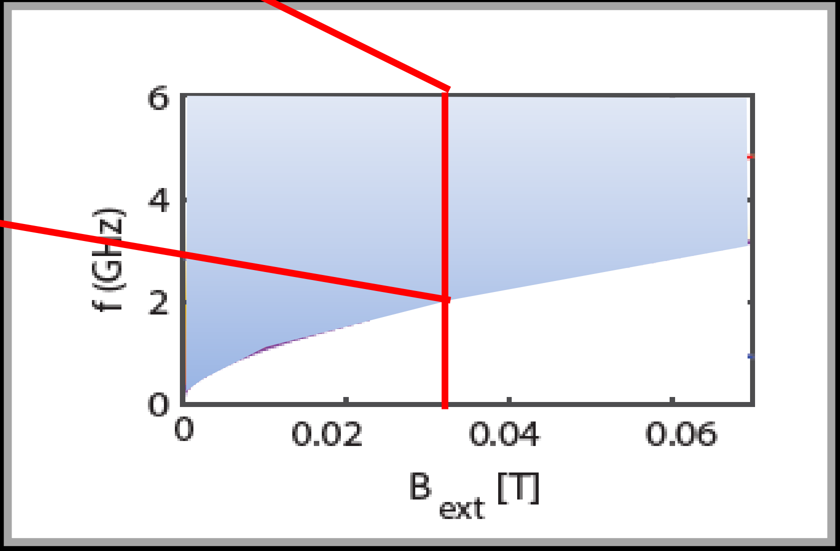


Magnons

Spin wave





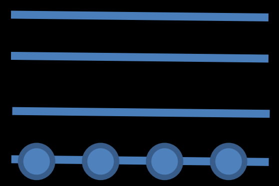


Kittel Law

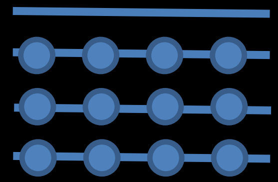
$$\omega = g\mu\sqrt{B(B+M)}$$

Quantum Hall Magnons

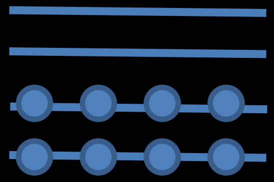
ν=-1



ν=1



ν=0



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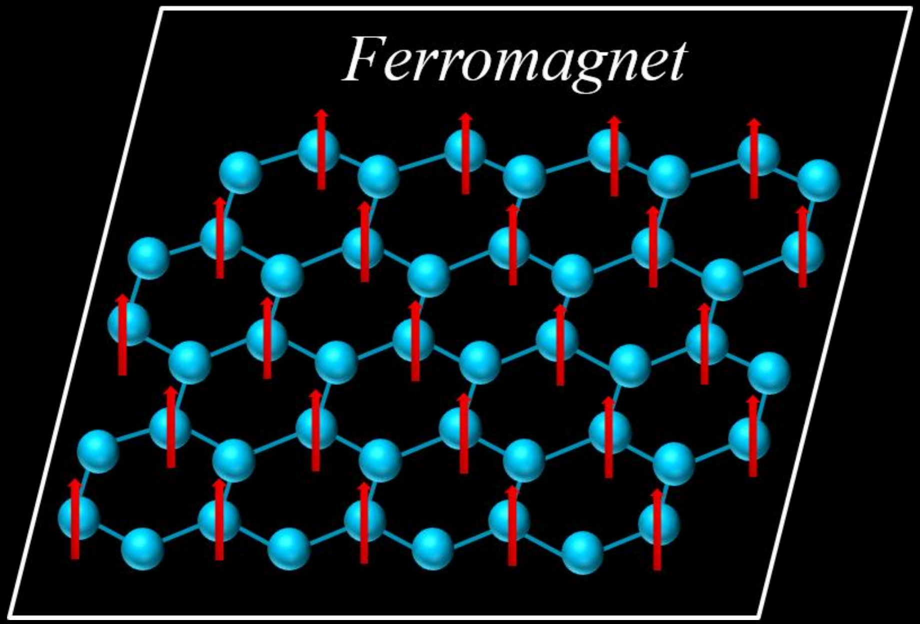
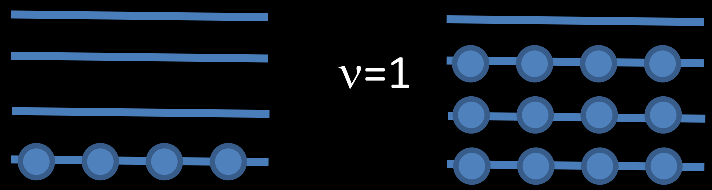


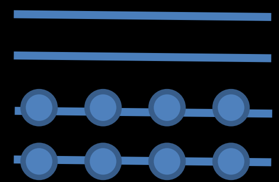
Gapped spin excitations below Zeeman energy

Quantum Hall Magnons

ν=-1 ν=1



ν=0



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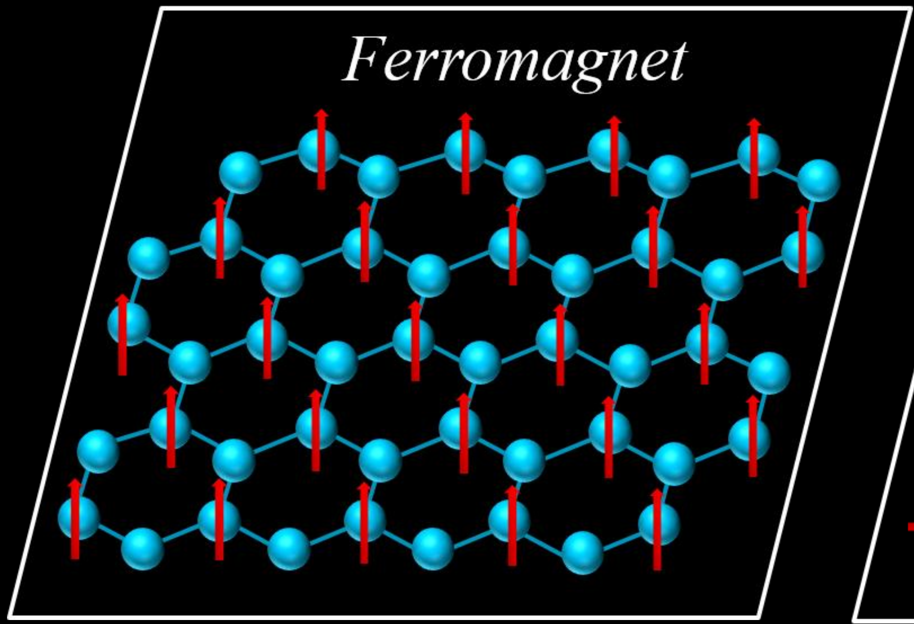
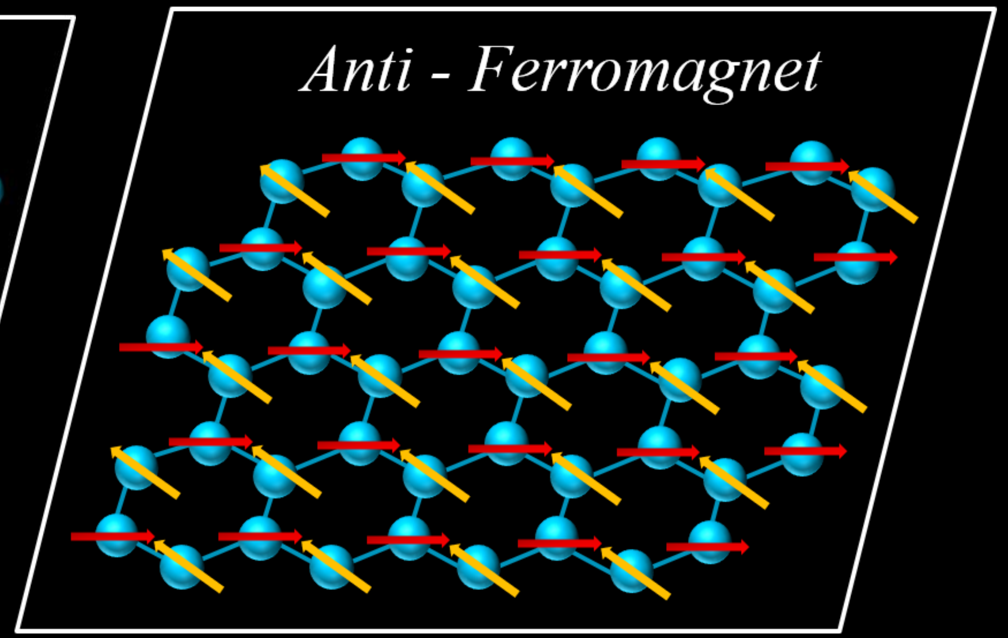


Gapped spin excitations below Zeeman energy

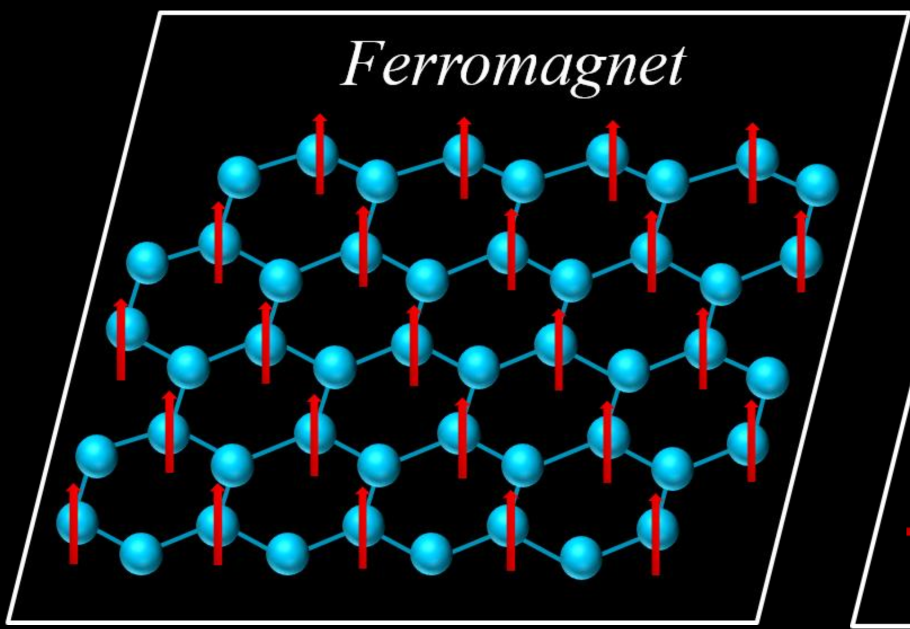


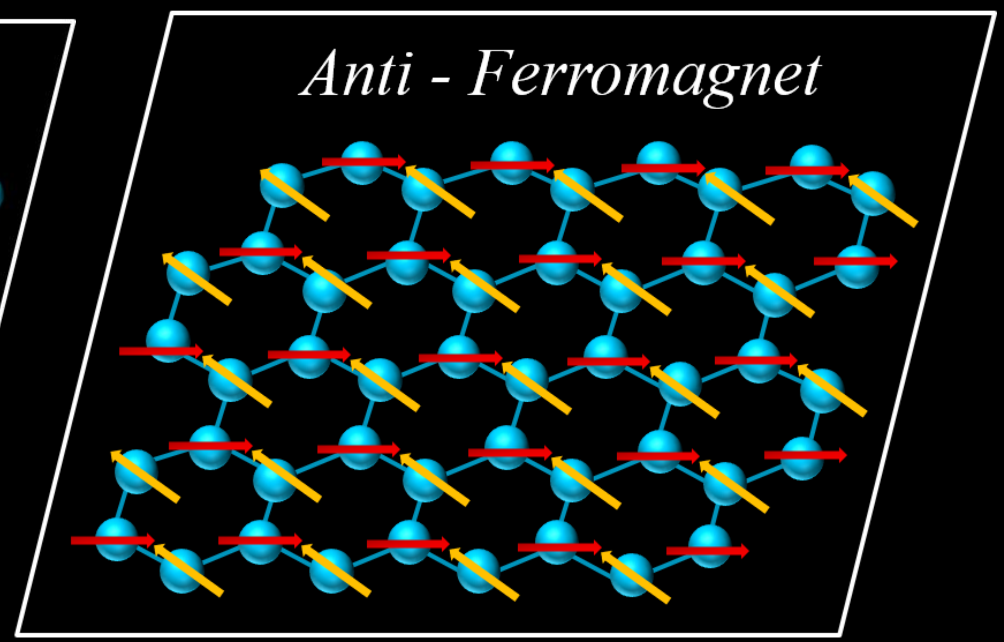
Spontaneous breaking of U(1) symmetry
Gapless spin excitations

M. Kharitonov, Phase diagram for the ν=0 quantum Hall state in monolayer graphene. *Phys. Rev. B.* **85**, 155439 (2012).

D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)
See also P. Stepanov et al, Nat. Phys. 2018

Quantum Hall Magnons





Gapped spin excitations below Zeeman energy

Spontaneous breaking of U(1) symmetry
Gapless spin excitations

- Electrically Tunable Magnetic Order
- Weak spin orbit interaction – long lived spin excitations

Quantum Hall Magnons

Transport of novel excitations

PRL **112**, 227201 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

Superfluid Spin Transport Through Easy-Plane Ferromagnetic Insulators

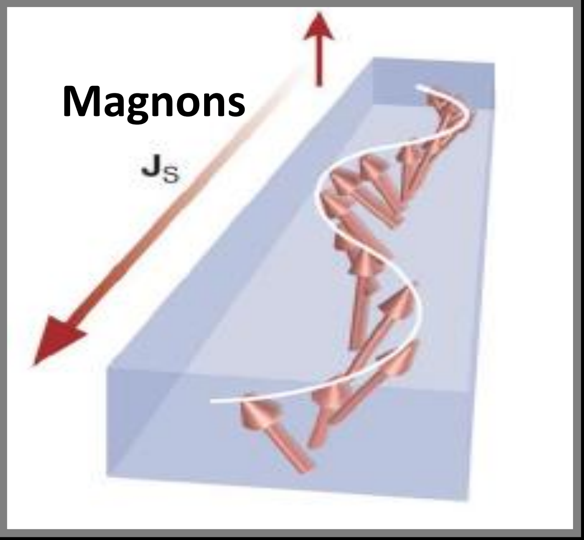
So Takei and Yaroslav Tserkovnyak

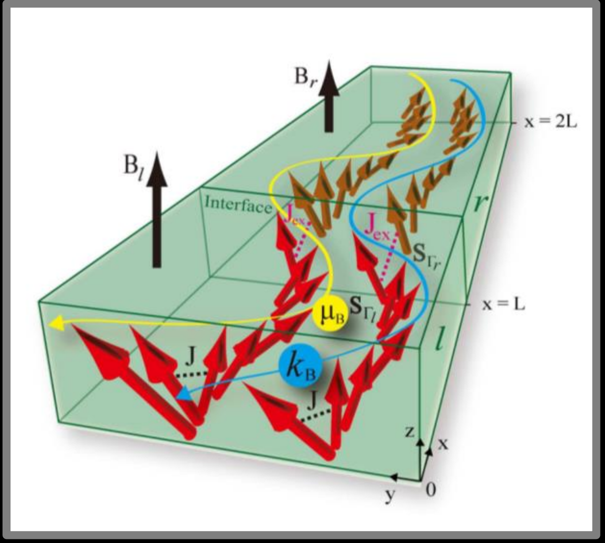
Wiedemann-Franz law for magnon transport

Kouki Nakata,[1] Pascal Simon,[2] and Daniel Loss[1]
[1] *Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2] *Laboratoire de Physique des Solides, CNRS UMR-8502, Université Paris Sud, 91405 Orsay Cedex, France*
(Dated: November 4, 2015)

Magnetization Transport and Quantized Spin Conductance

Florian Meier and Daniel Loss





Universal Peltier and Seebeck coefficieAnts

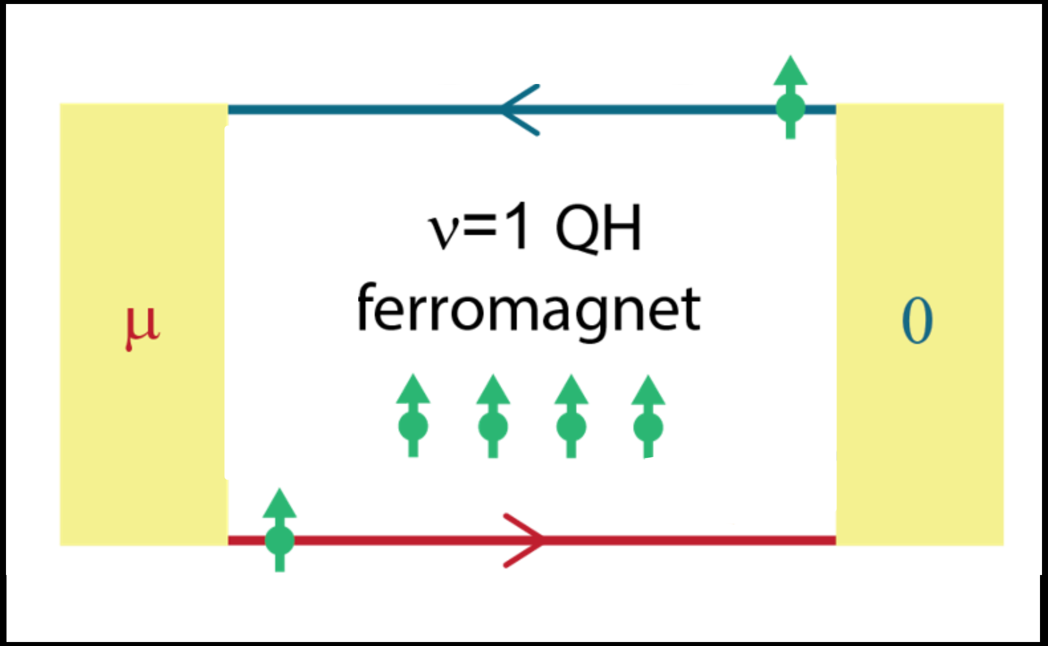
Challenges:

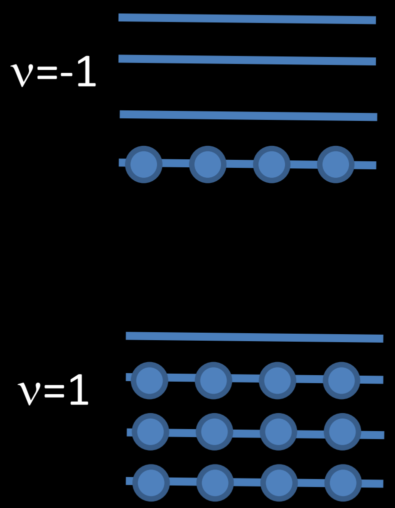
- How to generate and detect spin transport in quantum Hall ferromagnets?

Quantum Hall Magnons

Magnons:

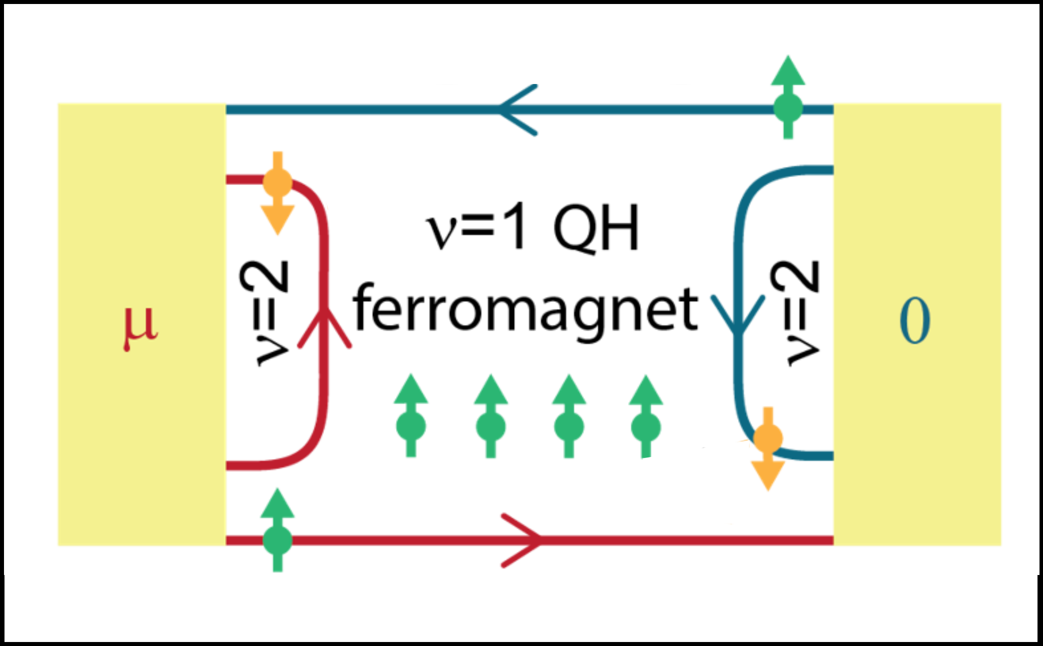
- Collective spin excitations
- Gapped at finite field
- In QH systems, gap energy equals BARE Zeeman energy

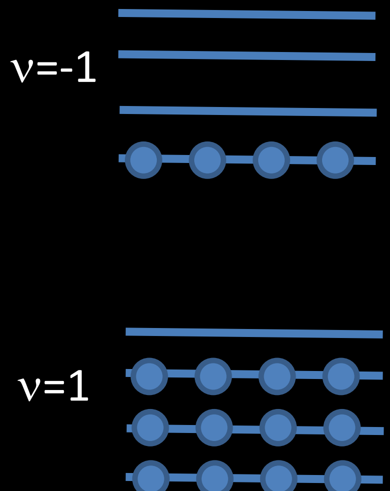




D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Quantum Hall Magnons





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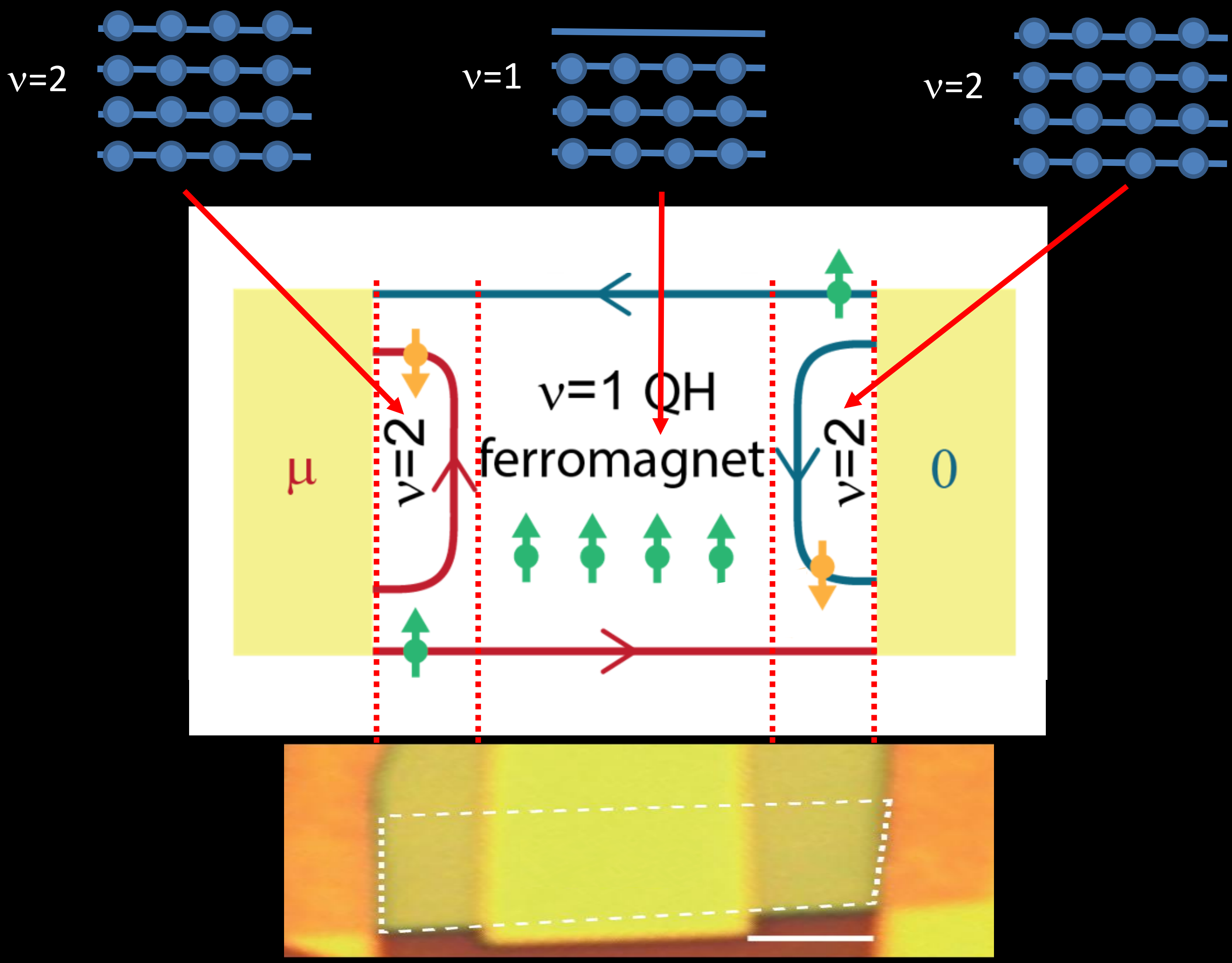
Quantum Hall Magnons



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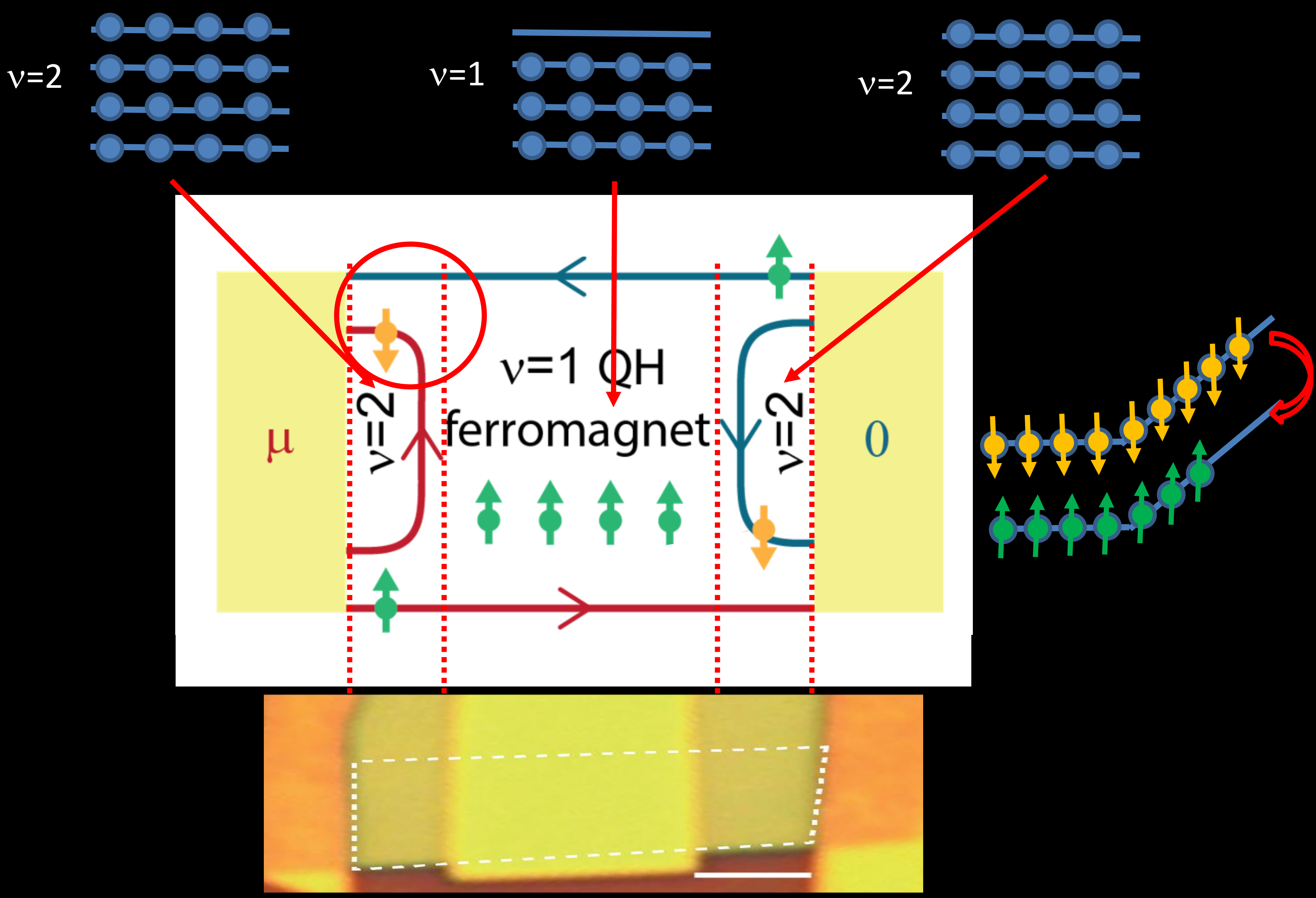

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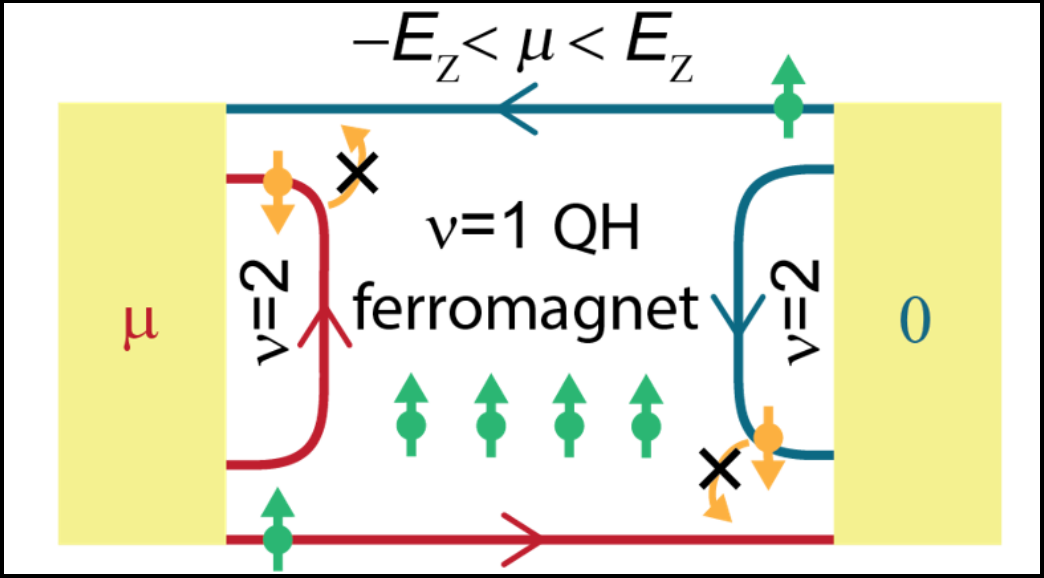
Quantum Hall Magnons



Below the magnon gap

magnon gap at:

$E_z = g\mu_B B$

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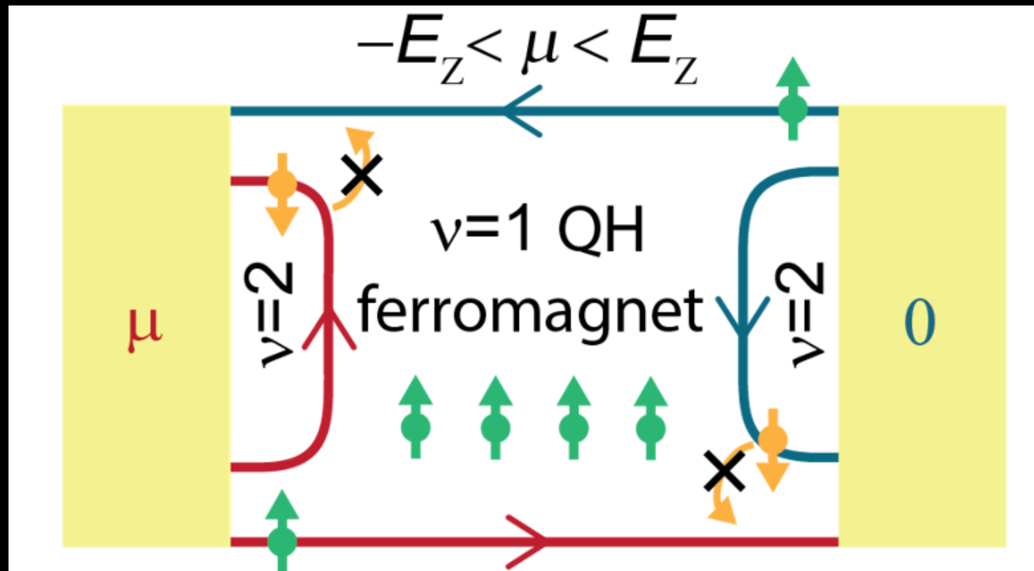
Quantum Hall Magnons



Below the magnon gap

magnon gap at:

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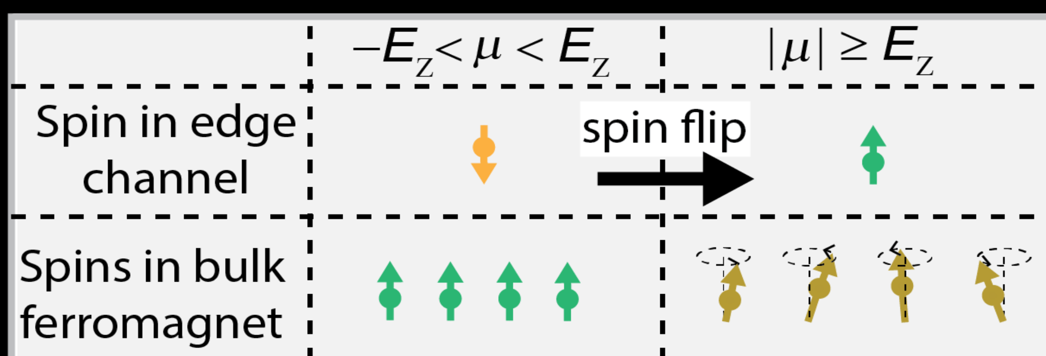

Above the magnon gap

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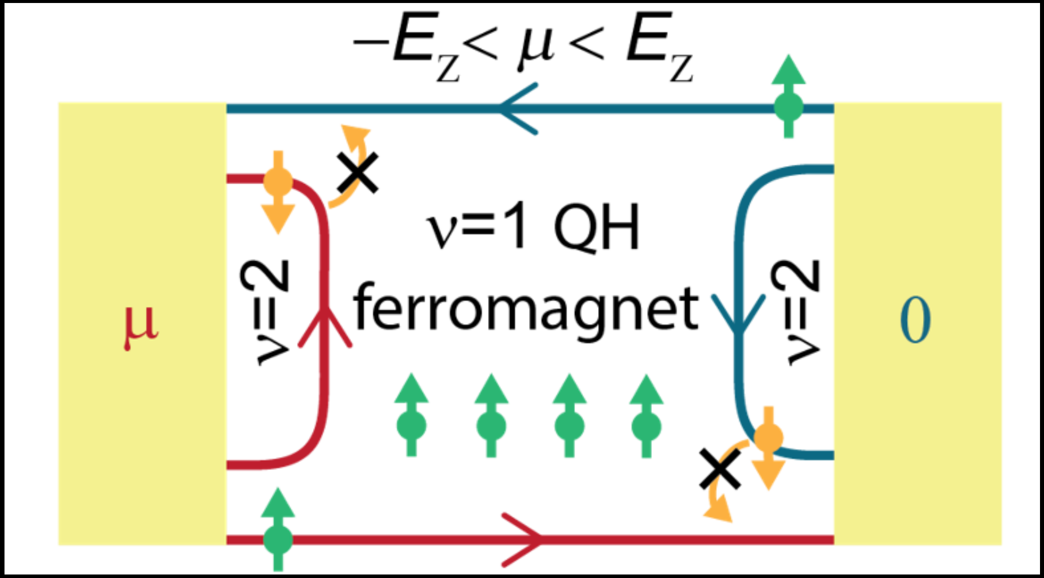
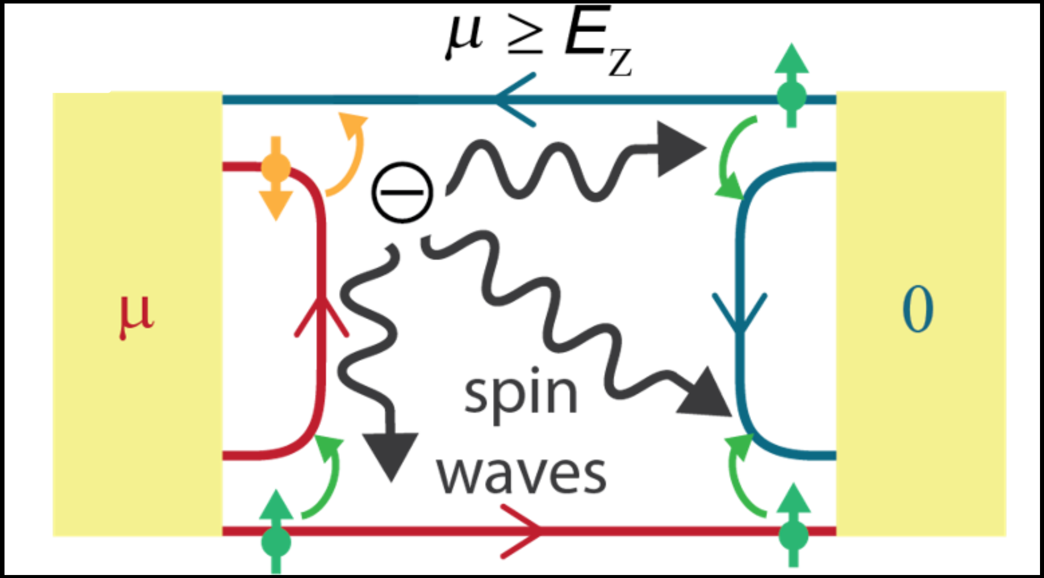
Quantum Hall Magnons



Below the magnon gap

magnon gap at:

$E_z = g\mu_B B$



Above the magnon gap

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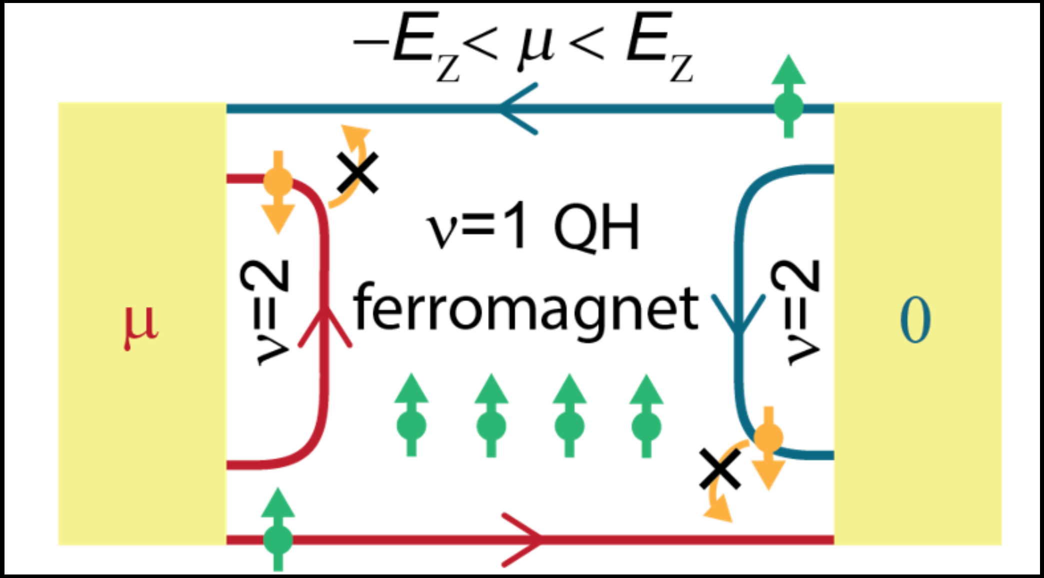
Quantum Hall Magnons



Below the magnon gap

magnon gap at:

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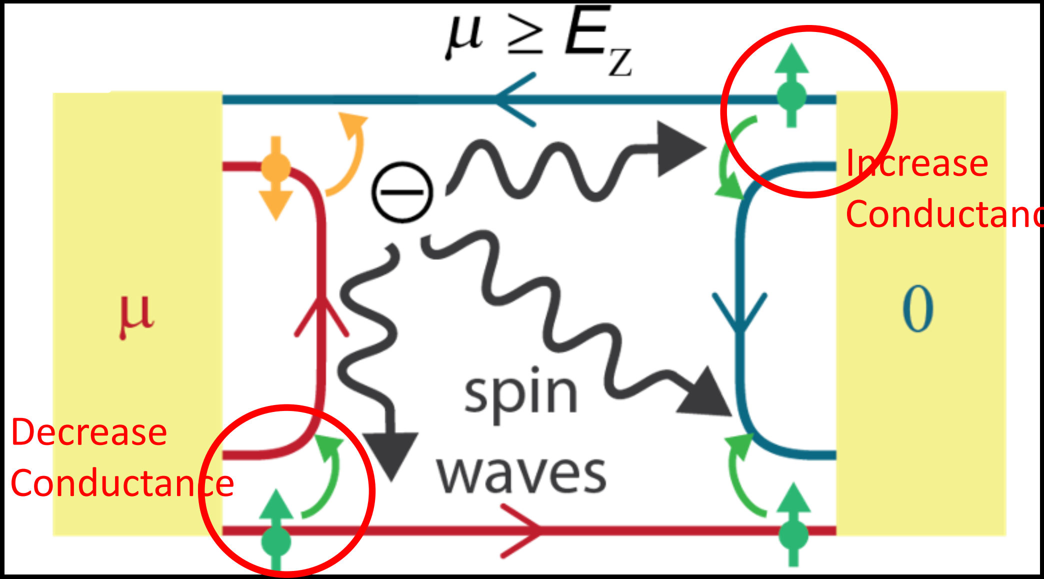

Above the magnon gap

Increase:
Same edge

Decrease:
Opposite edge

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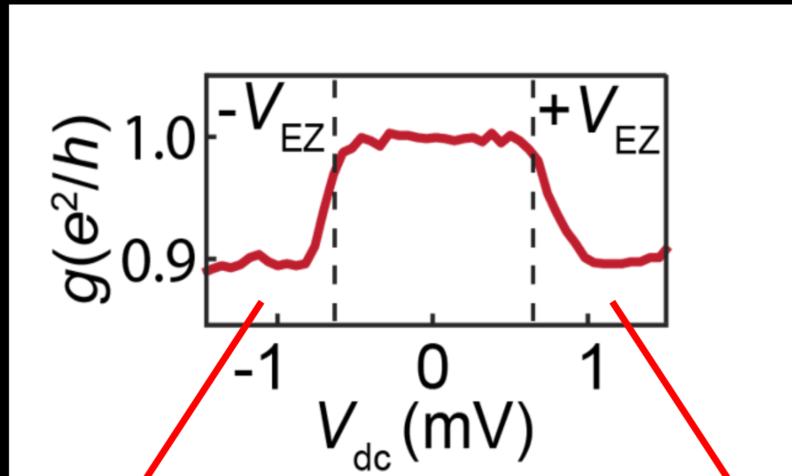
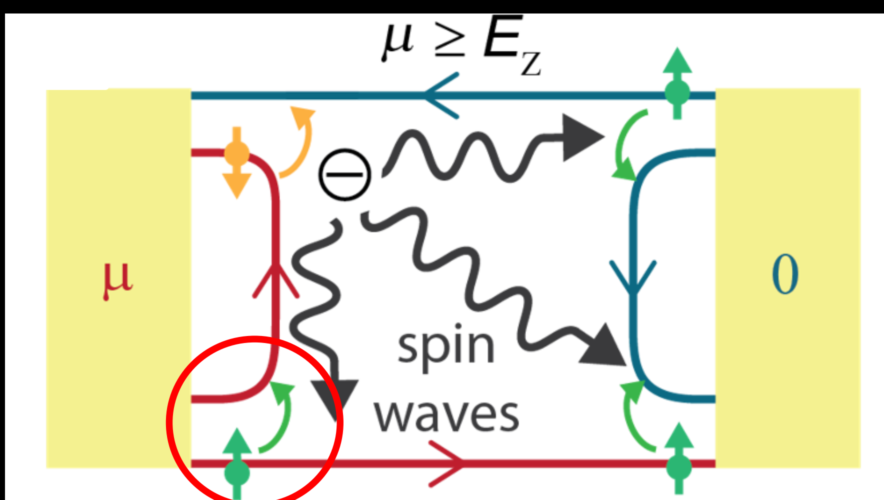
Quantum Hall Magnons

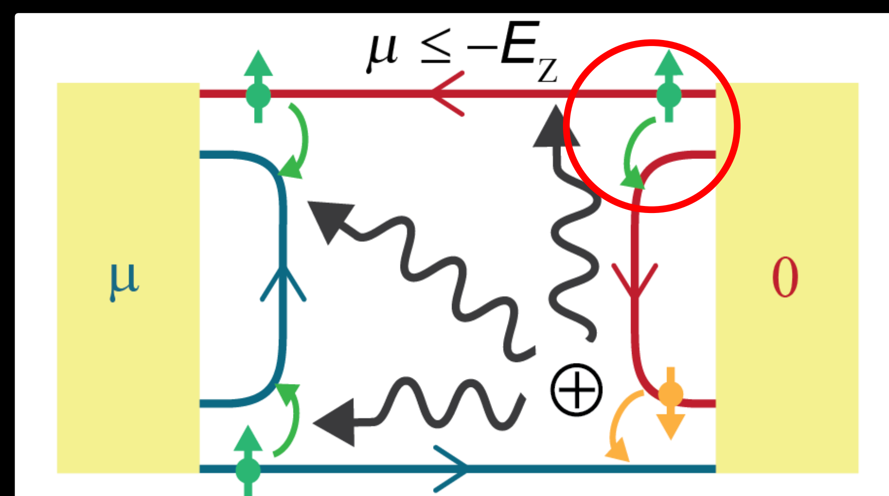


magnon gap at:

$$E_Z = g\mu_B B$$

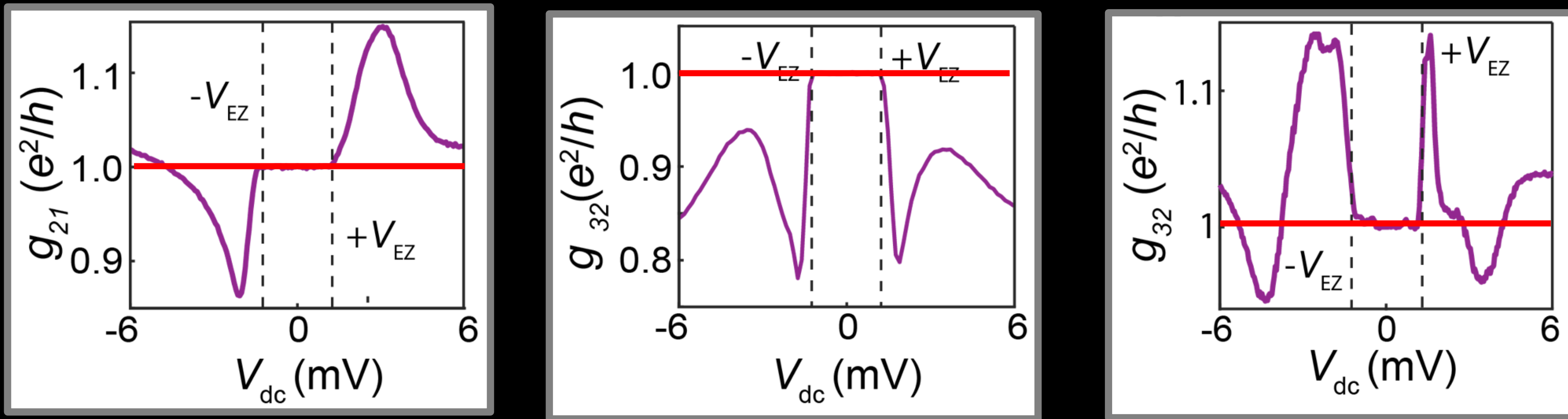
Above the magnon gap





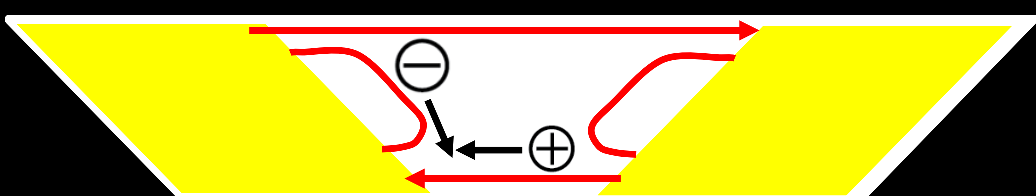
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

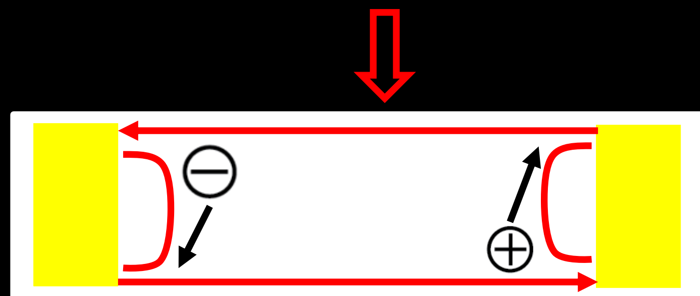
Quantum Hall Magnons

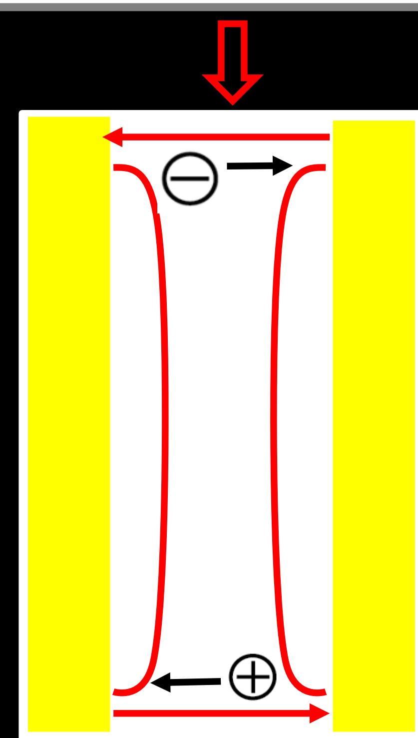


Increase:
Same edge

Decrease:
Opposite edge



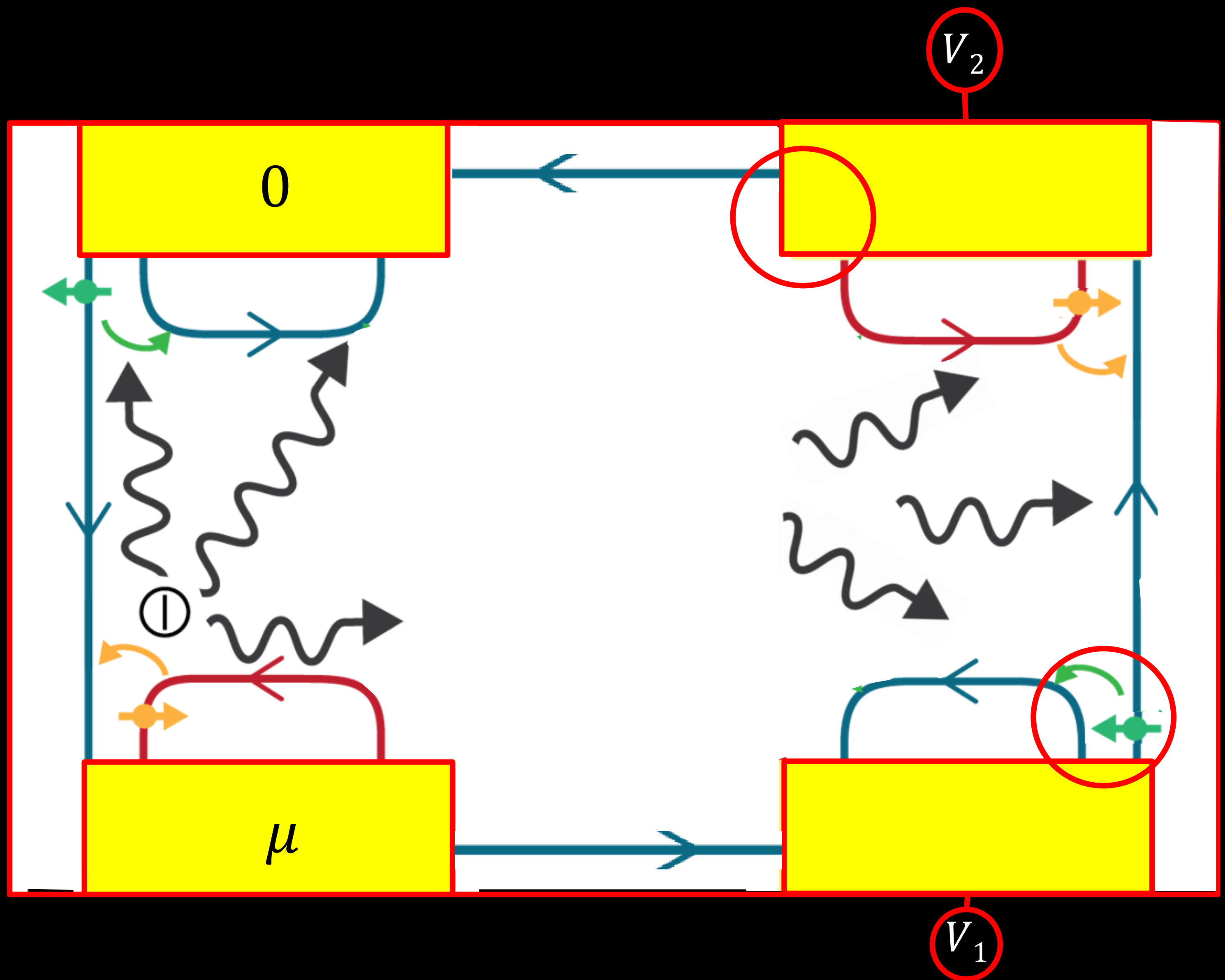




Distance of magnon propagation determines dominant process

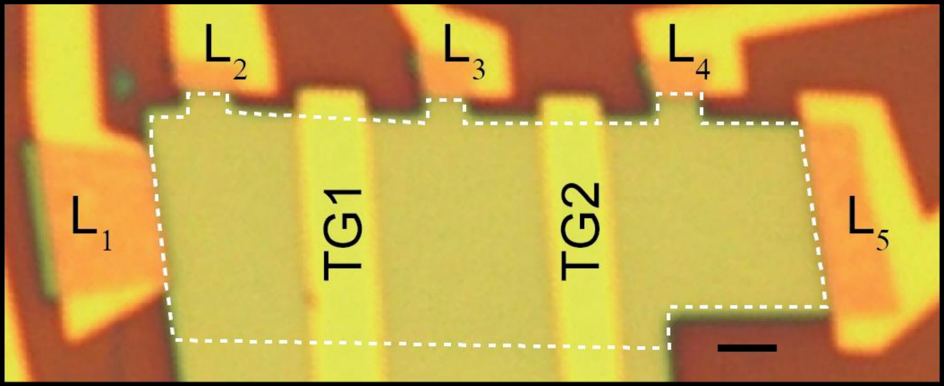
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

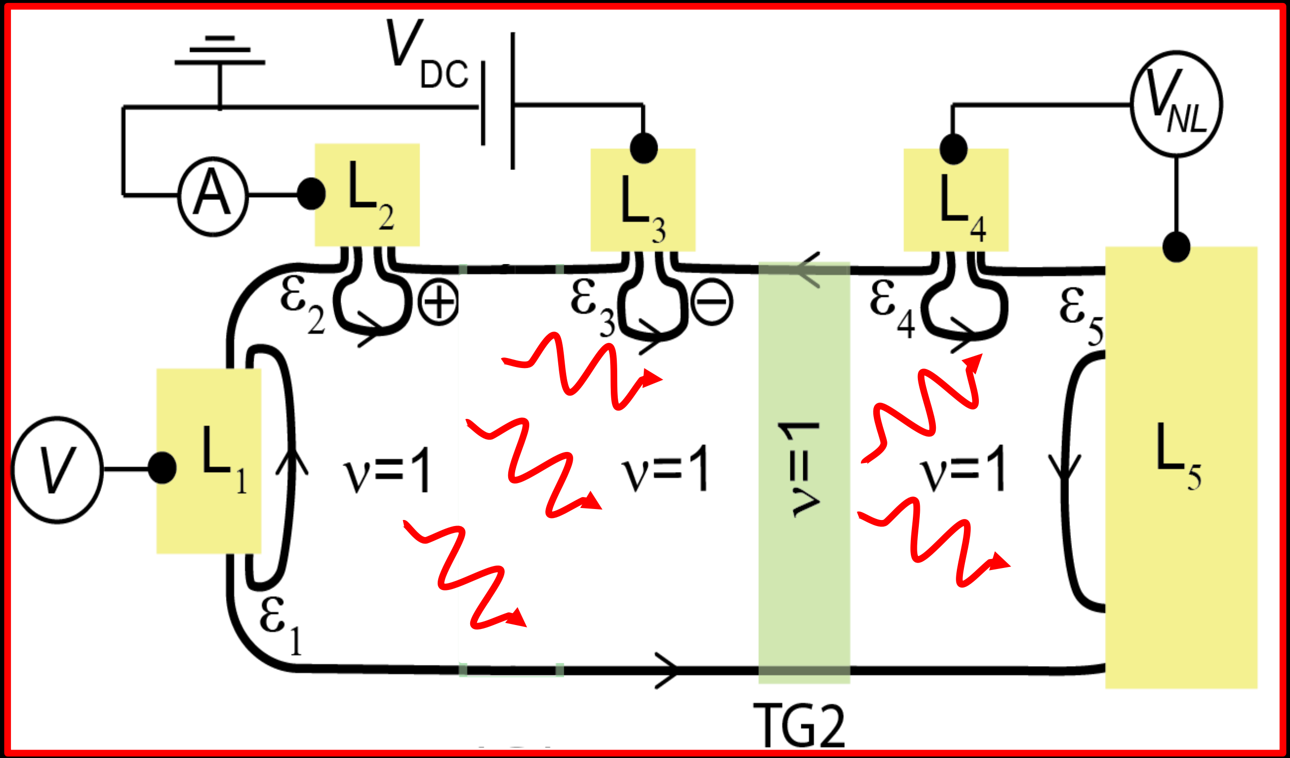
Non Local Experiments



D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

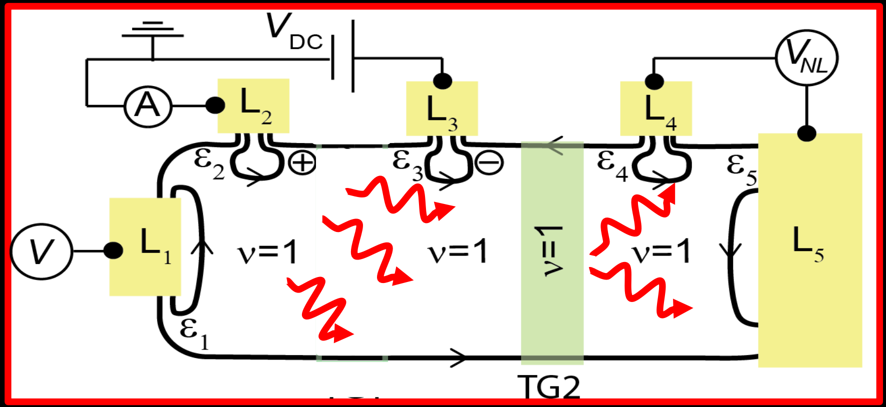
Magnon Scattering Experiments

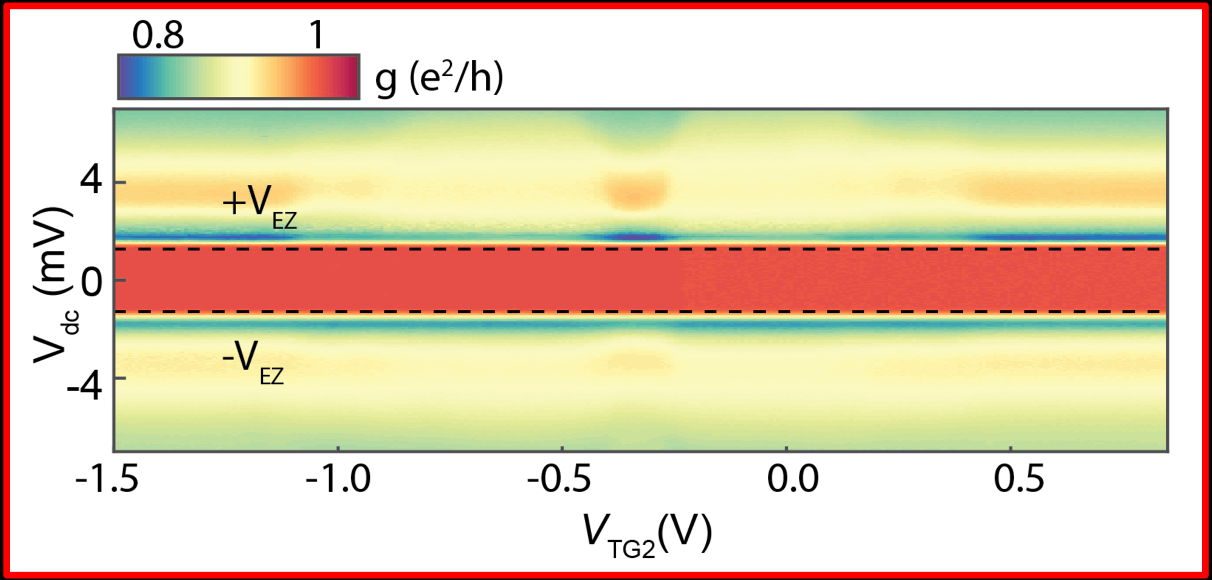




D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

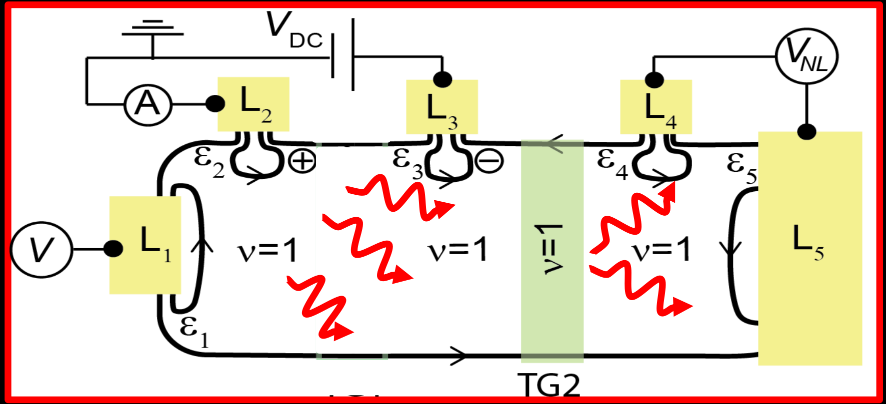
Magnon Scattering Experiments

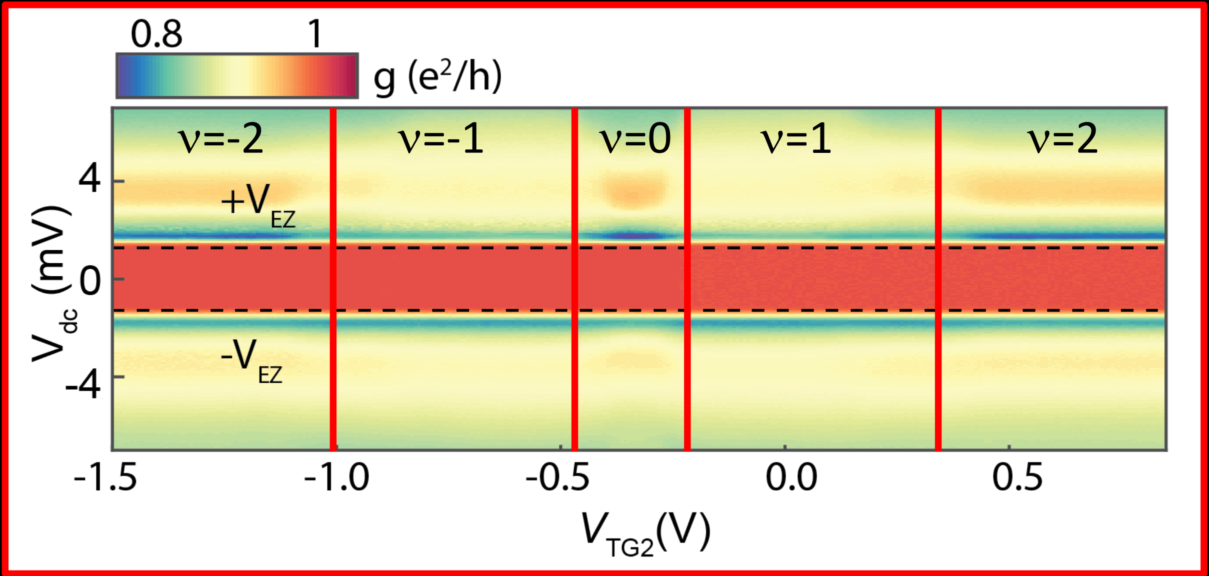




D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

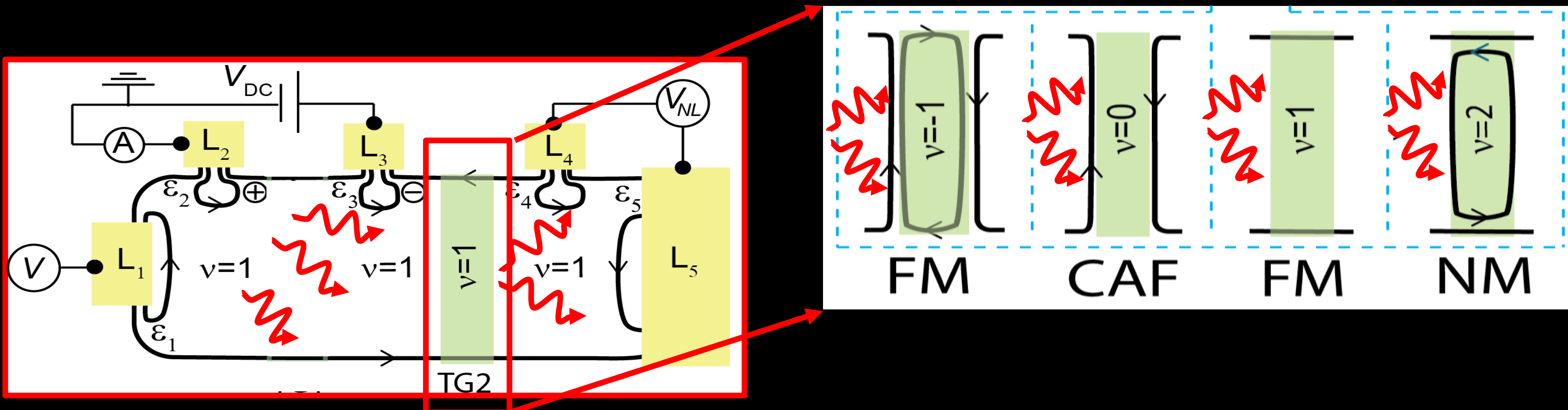
Magnon Scattering Experiments





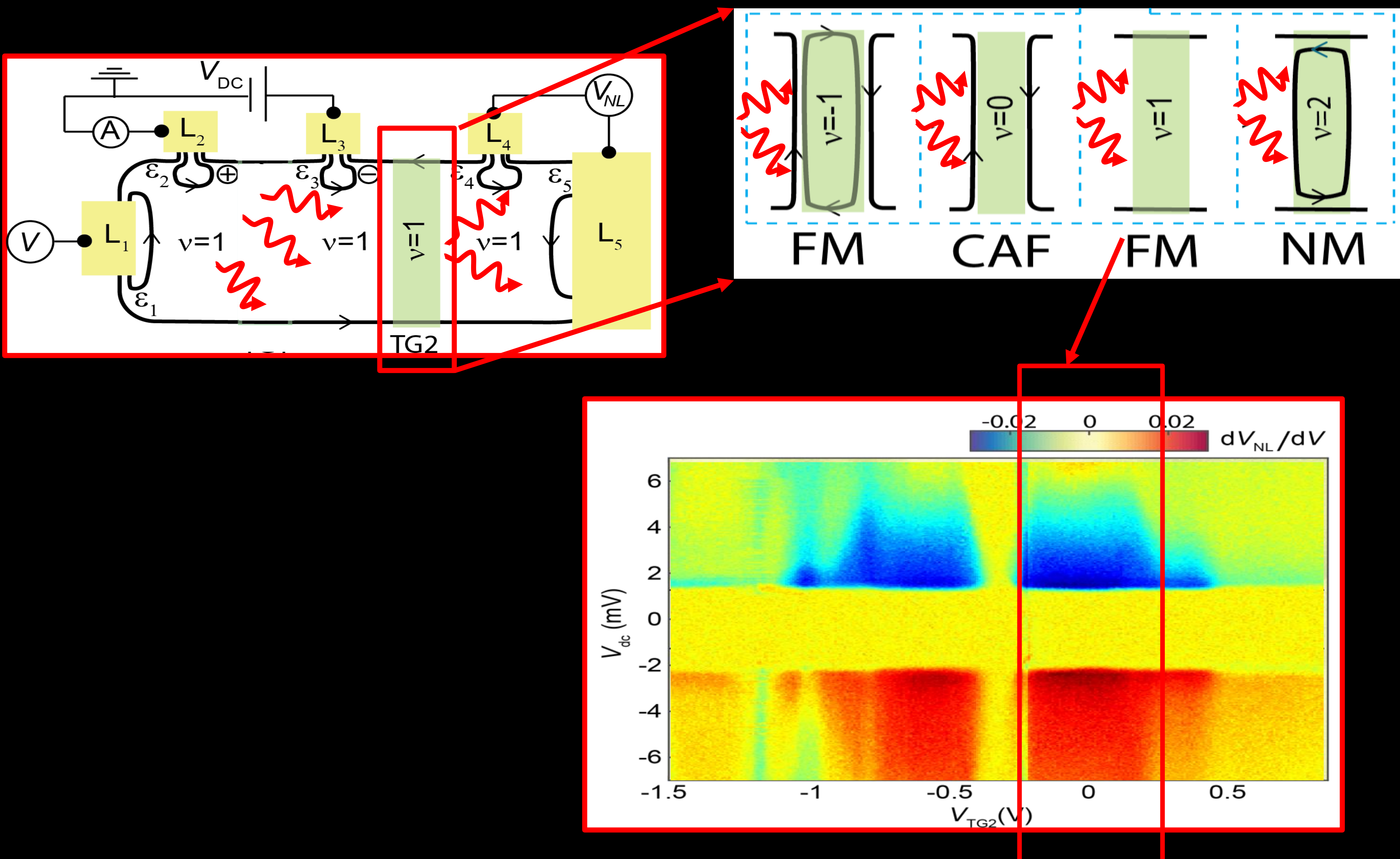
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments



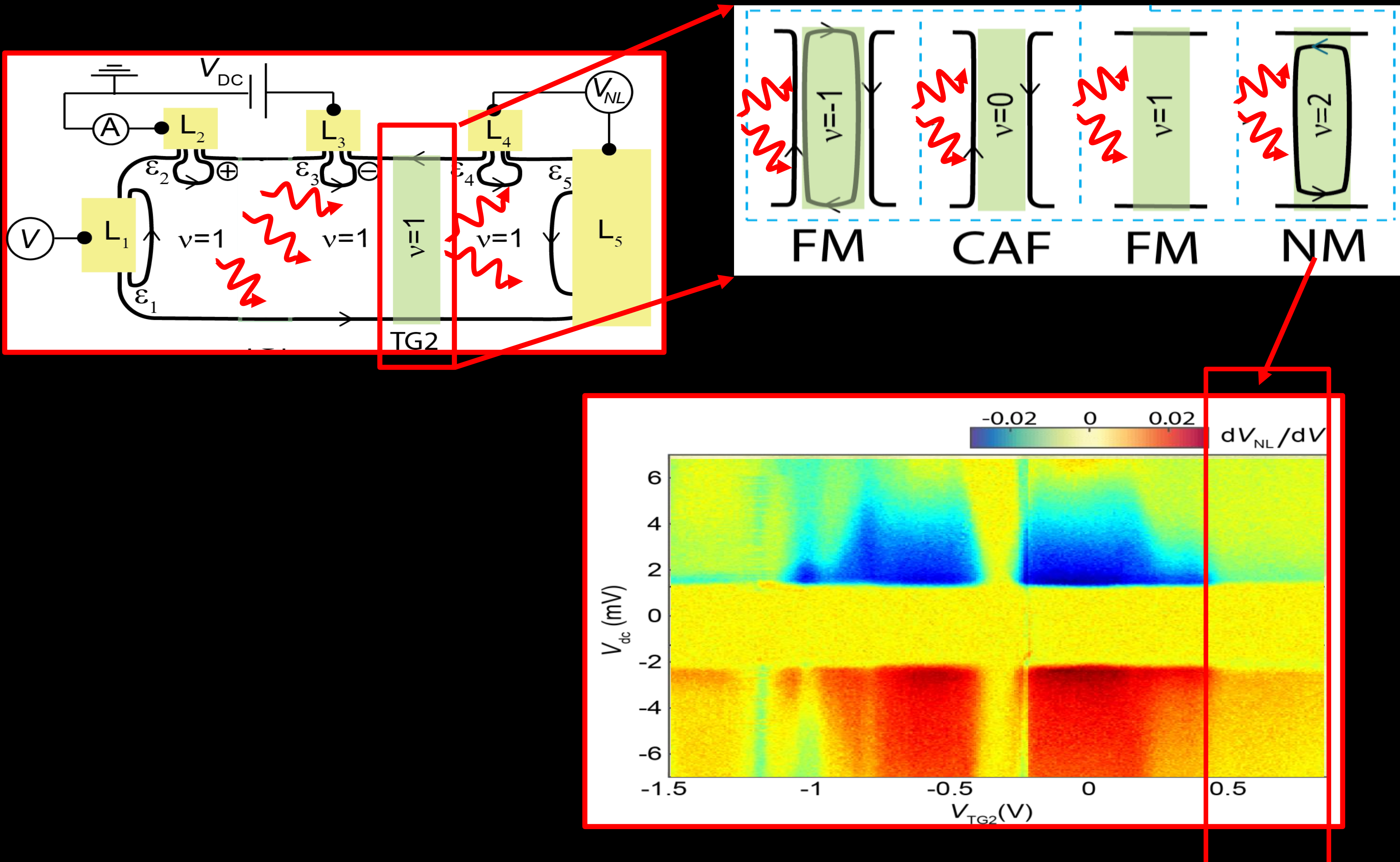
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments



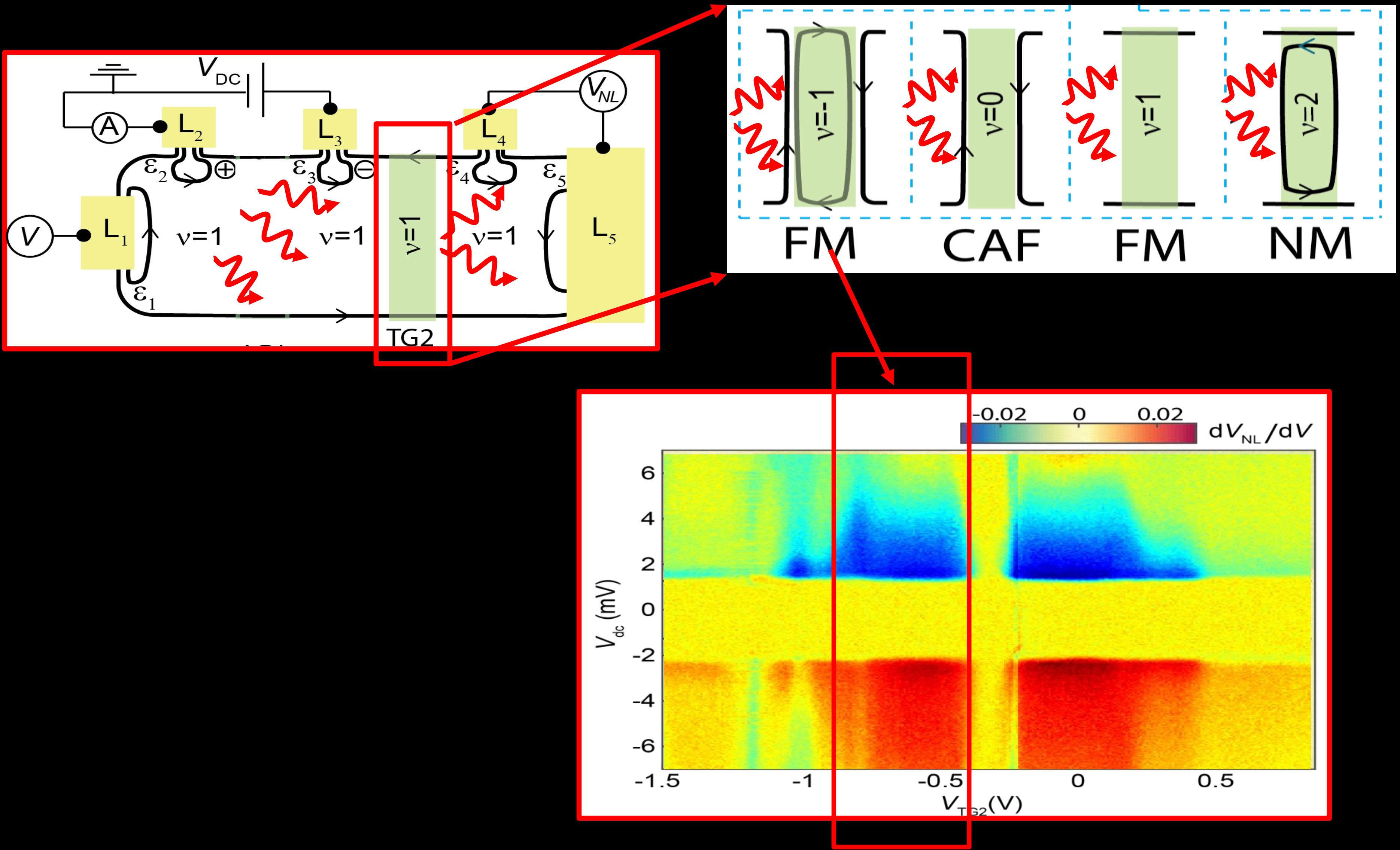
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments



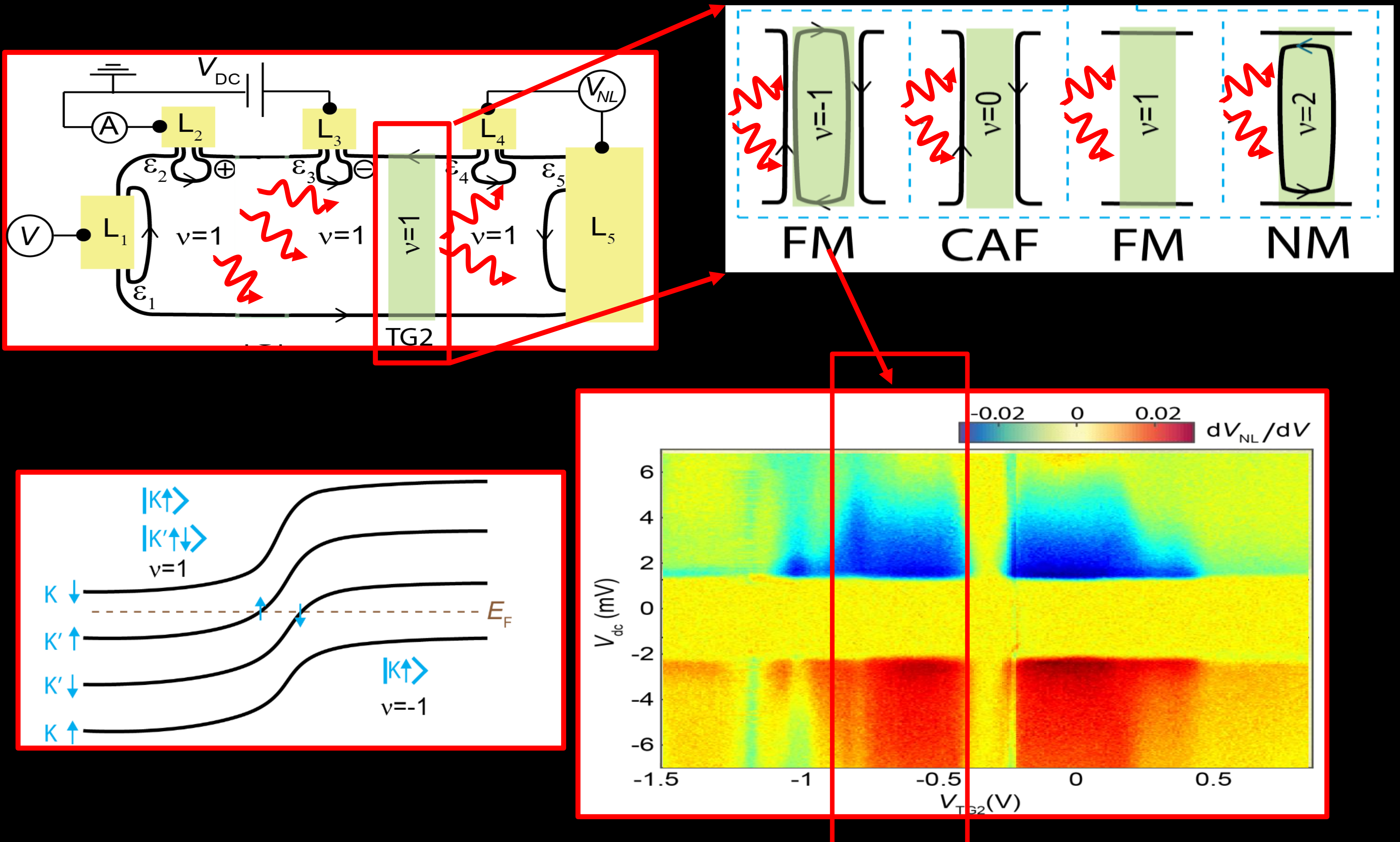
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments



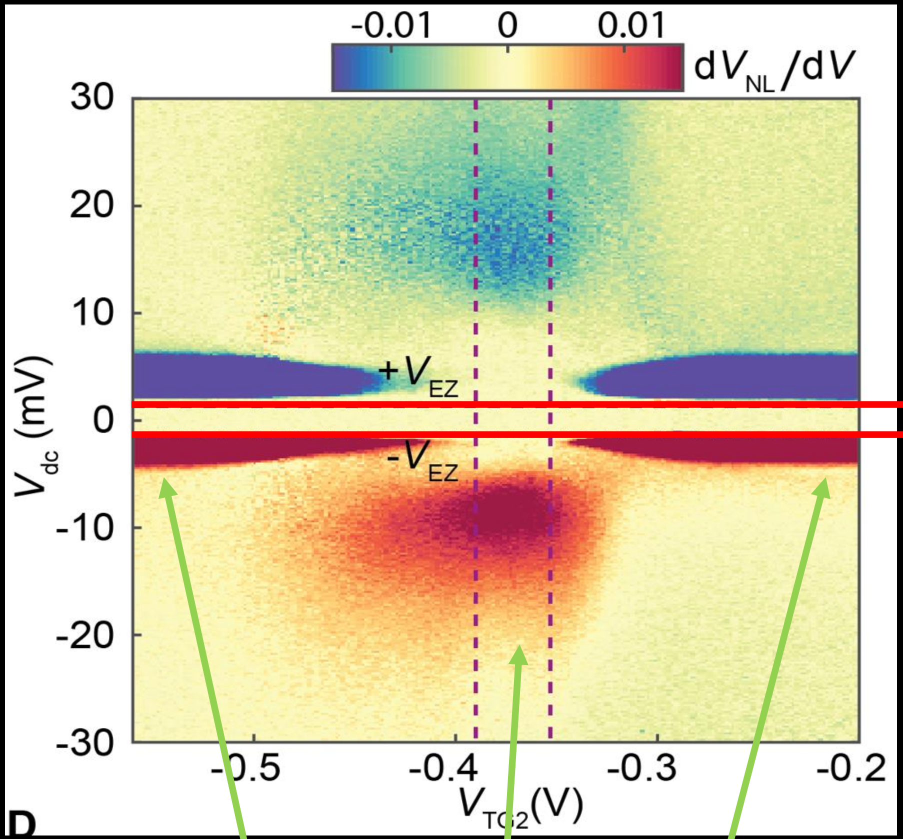
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments



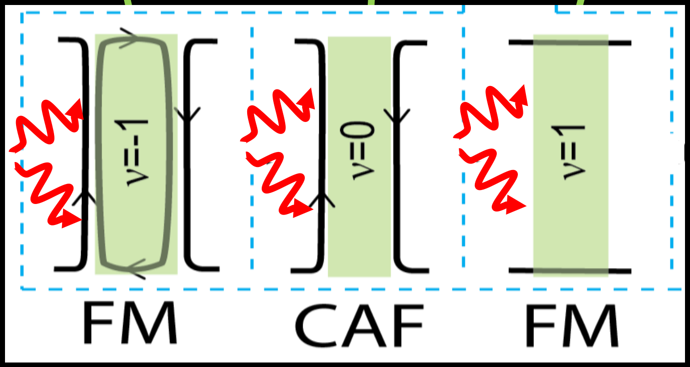
D. Wei. T. van der Sar, B. I. Halperin, AY et al, **Science** (2018)

Magnon Scattering Experiments

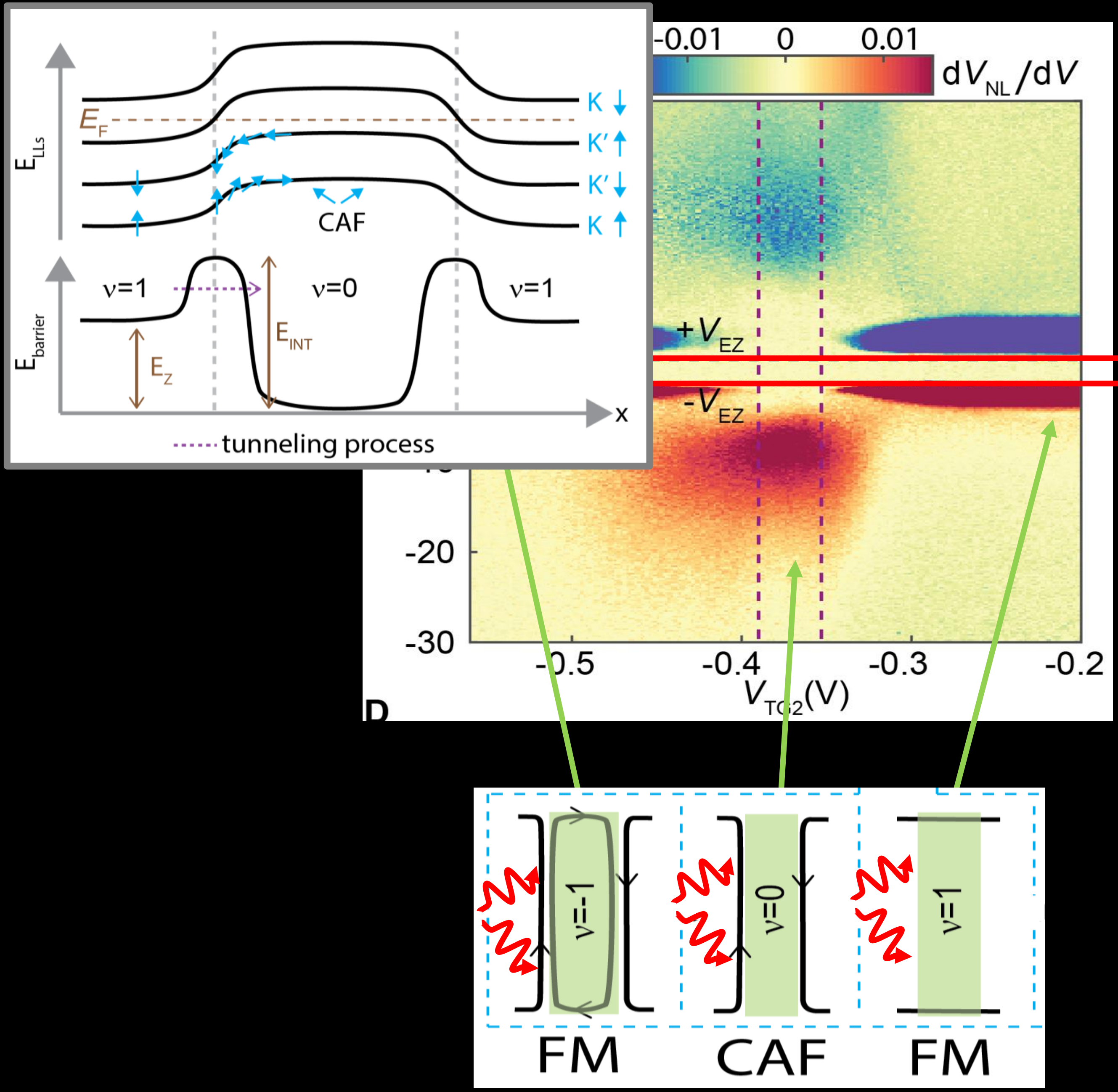


magnon gap at:

$E_z = g\mu_B B$



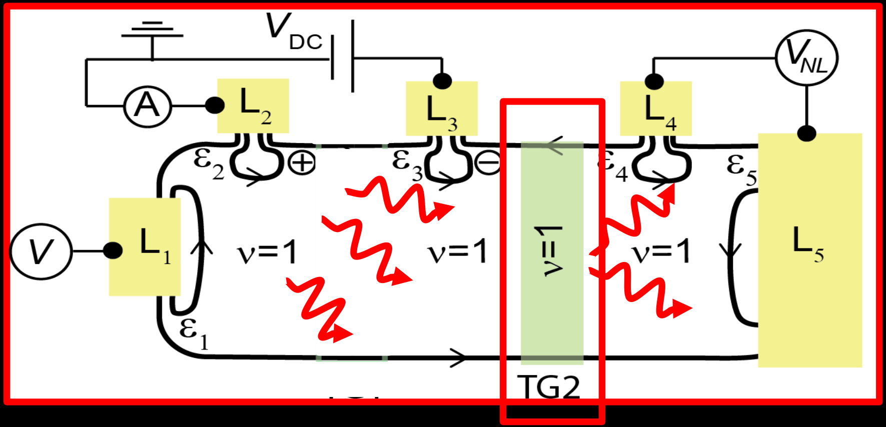
Magnon Scattering Experiments

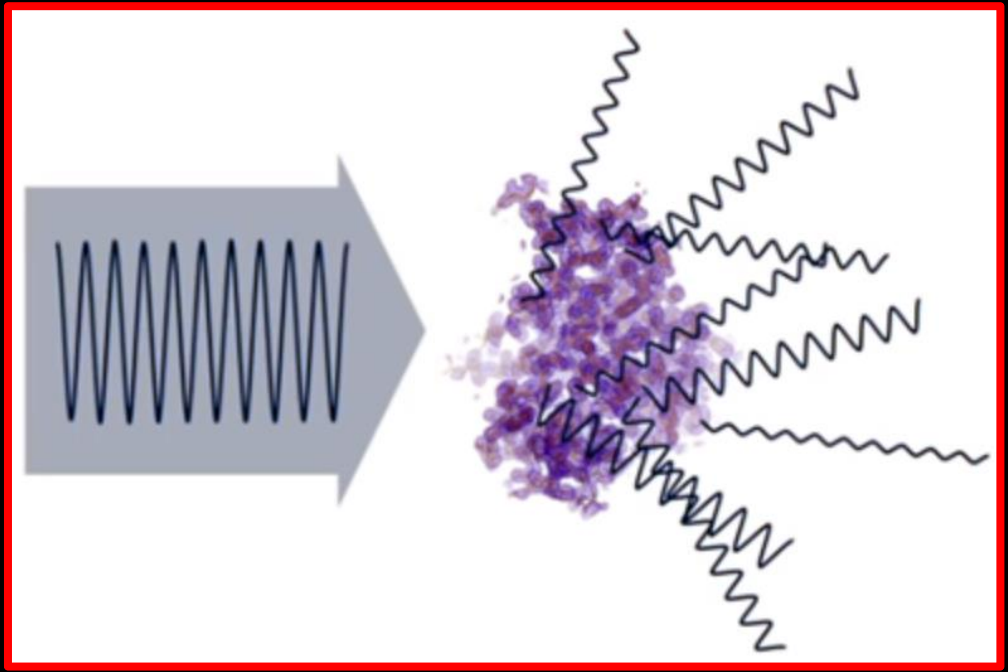


magnon gap at:

$E_z = g\mu_B B$

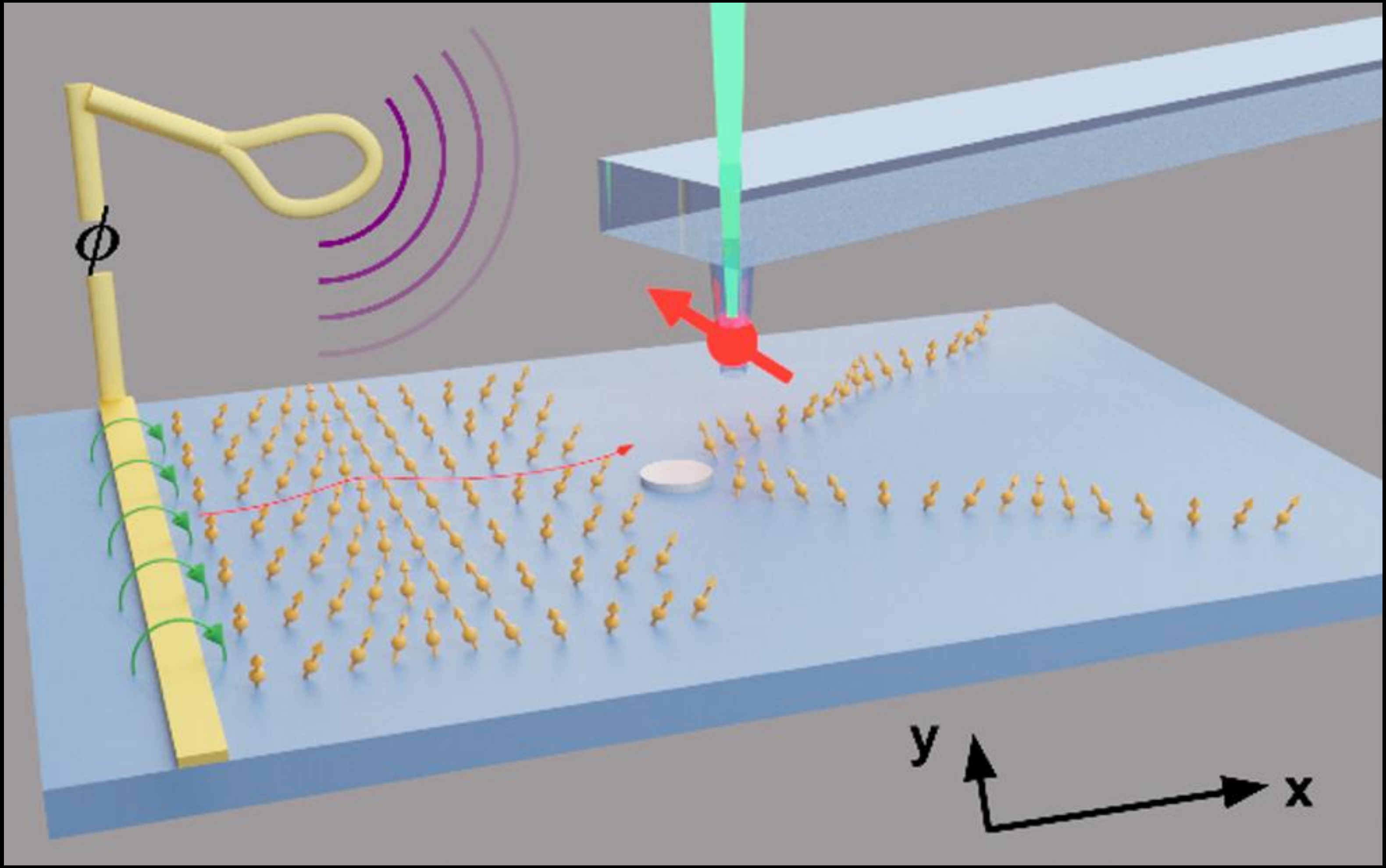
Scattering Platforms





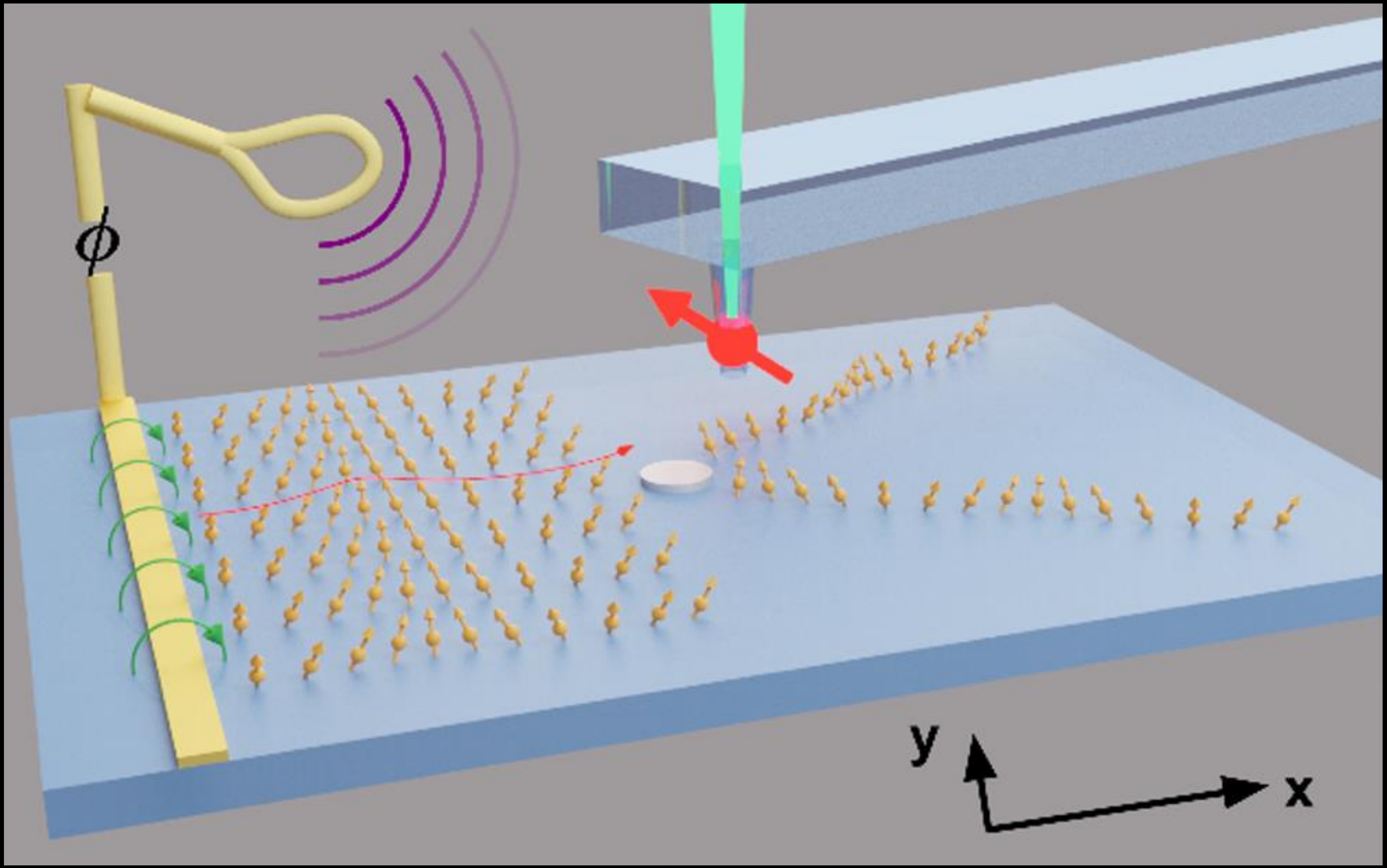
- **Can we perform a scattering experiment with magnons?**

Magnon Scattering Platform



T. Zhou, AY et al, arXiv:2004.07763

Magnon Scattering Platform

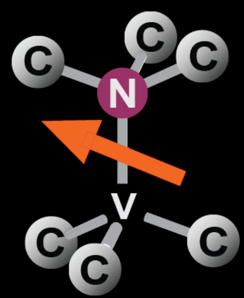


1) Launch coherent waves with well defined energy and momentum
2) Detect scattered waves, ideally, both amplitude and phase
3) Appreciable interaction of magnons with the target material
4) Reliable extraction of target material properties

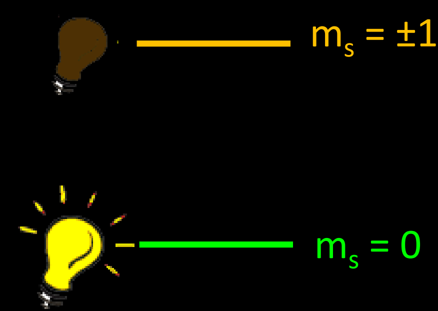
T. Zhou, AY et al, arXiv:2004.07763

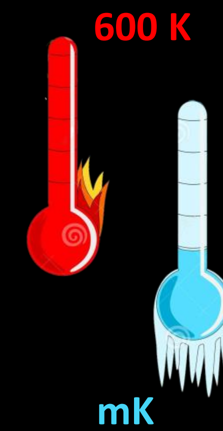
What makes NV-spins in diamond well-suited?

- Atom-sized sensor



- Optical spin initialization and readout

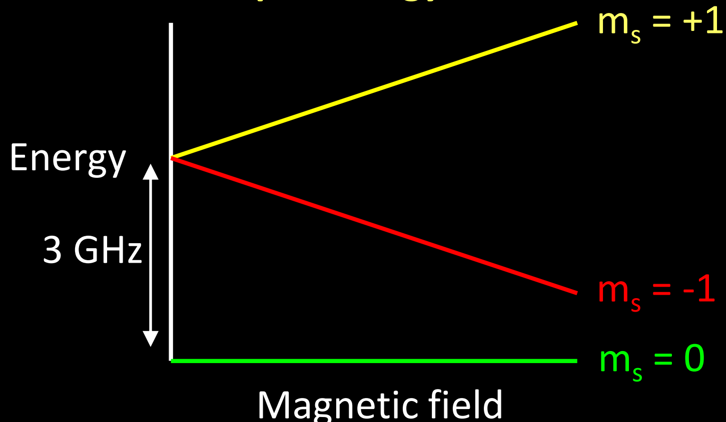




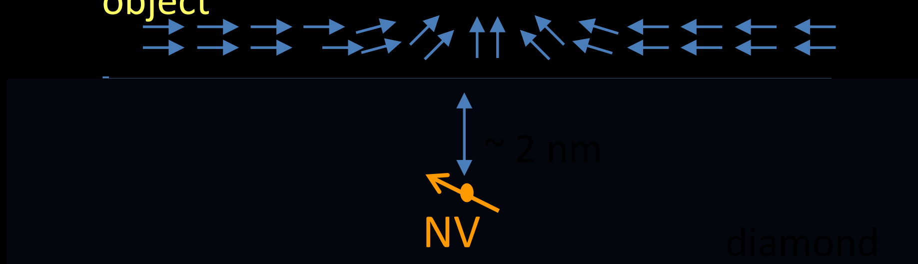
works over a broad temperature range

- Sensitive to magnetic & electric fields, and temperature

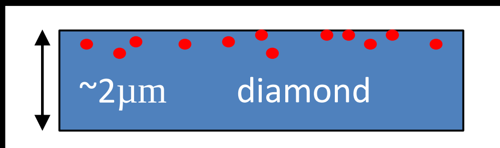
Spin energy levels

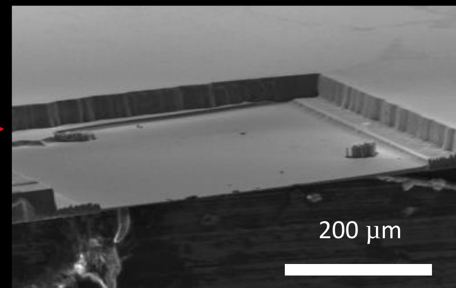


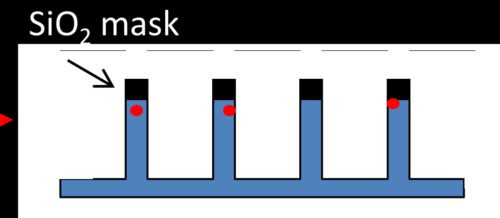
- Can be within a few nm of external object

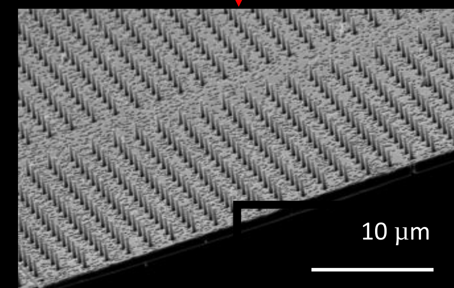


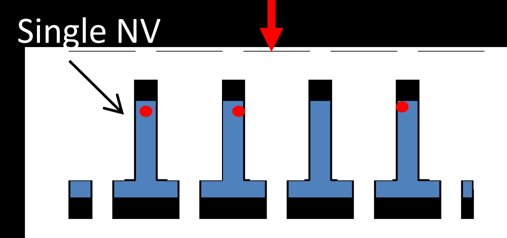
Fabricating Tips

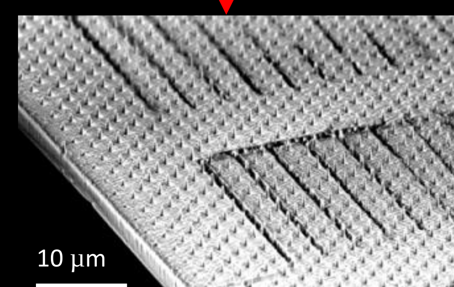


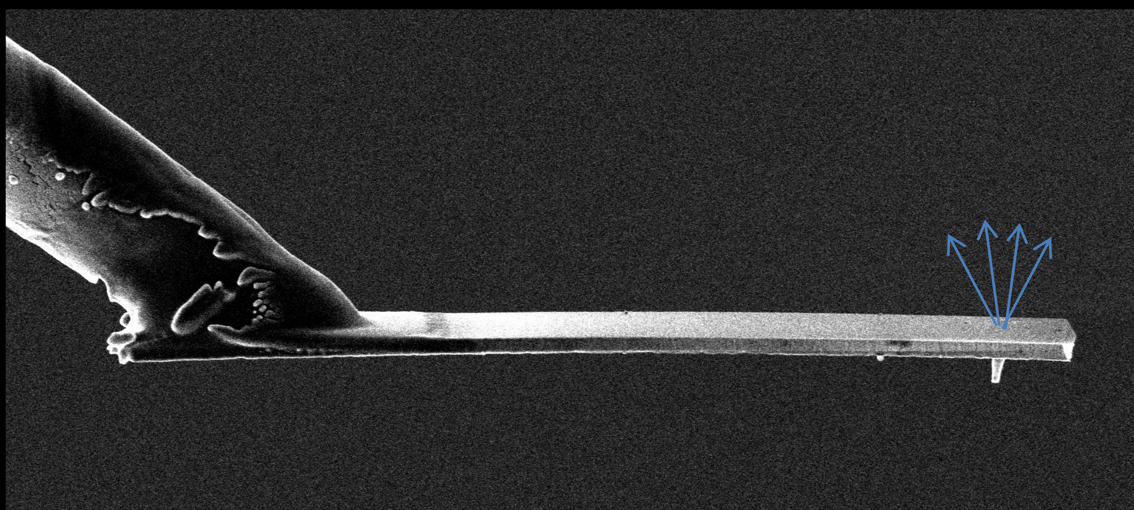










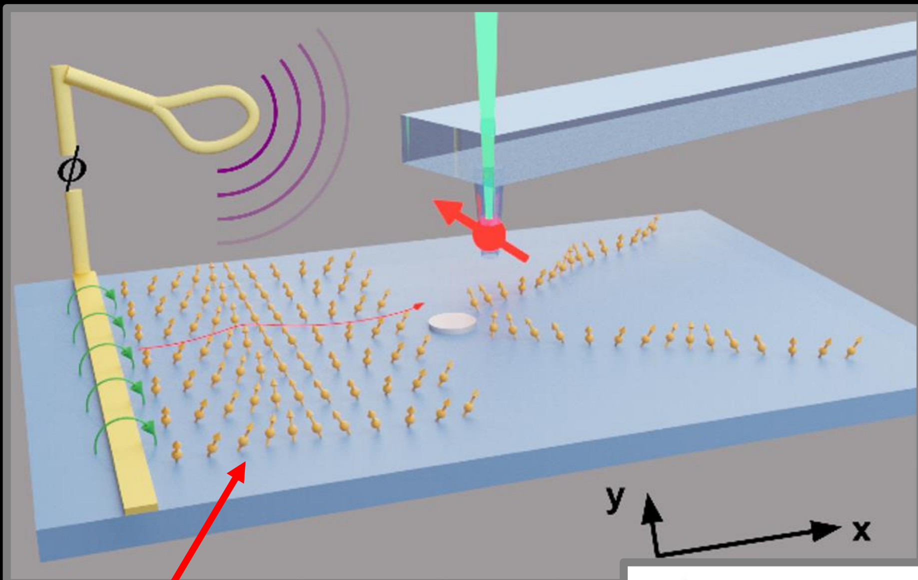


Wave guiding of light

P. Maletinsky, AY et. al. Nature Nano (2012)

Imaging Propagating Magnons

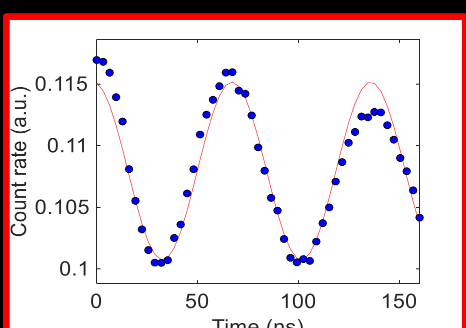
- NV centers are phase sensitive sensors.

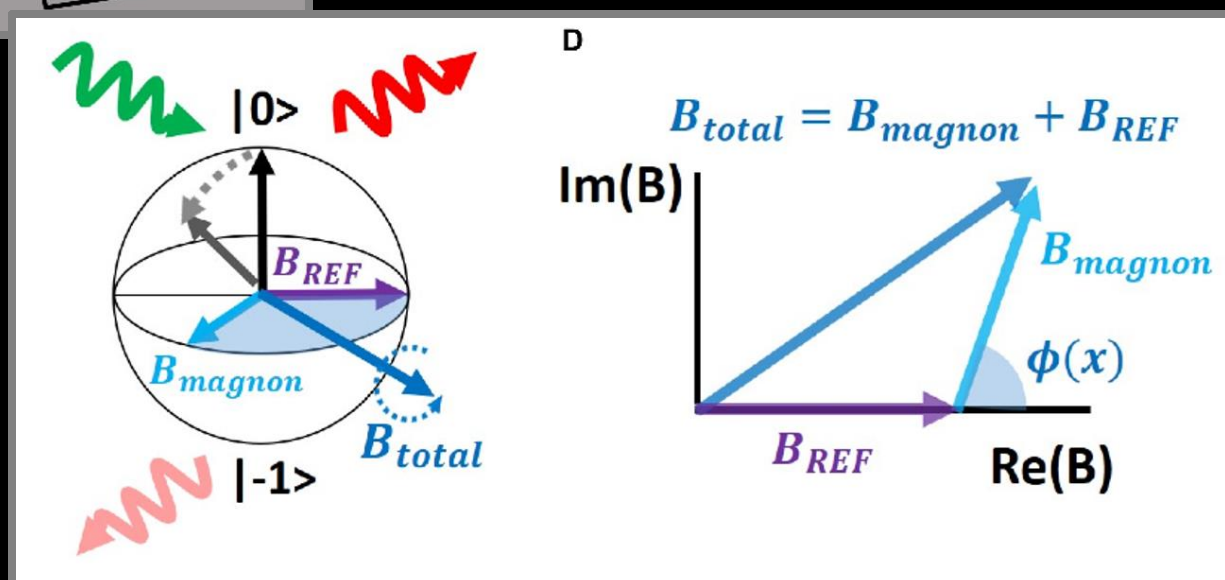


- Frequency set by drive
- Wavelength set by dispersion
- Phase determined from interference

Position dependent phase

$$Be^{i\omega t+ikx}$$

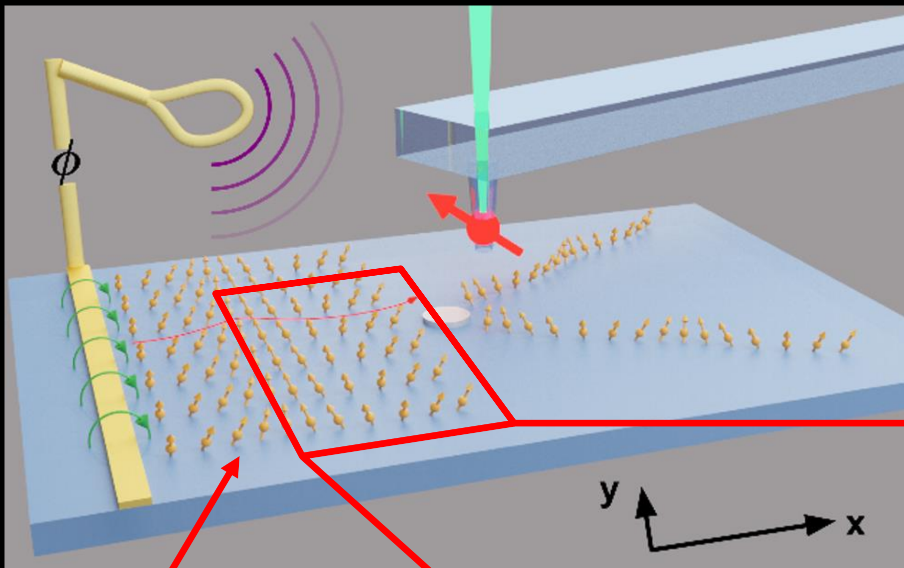




T. Zhou, AY et al, arXiv:2004.07763

Imaging Propagating Magnons

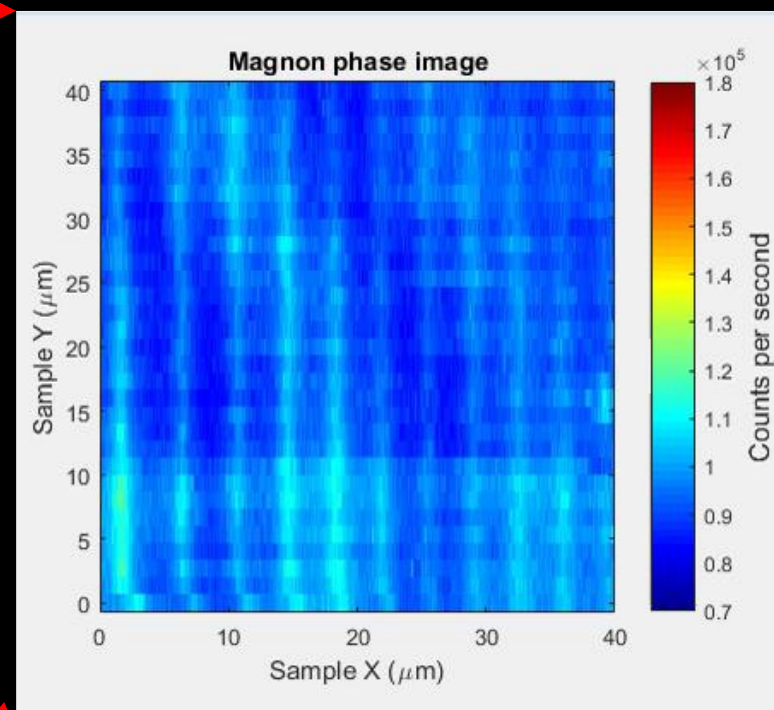
- NV centers are phase sensitive sensors.



- Frequency set by drive
- Wavelength set by dispersion
- Phase determined from interference

Position dependent phase

$$Be^{i\omega t+ikx}$$

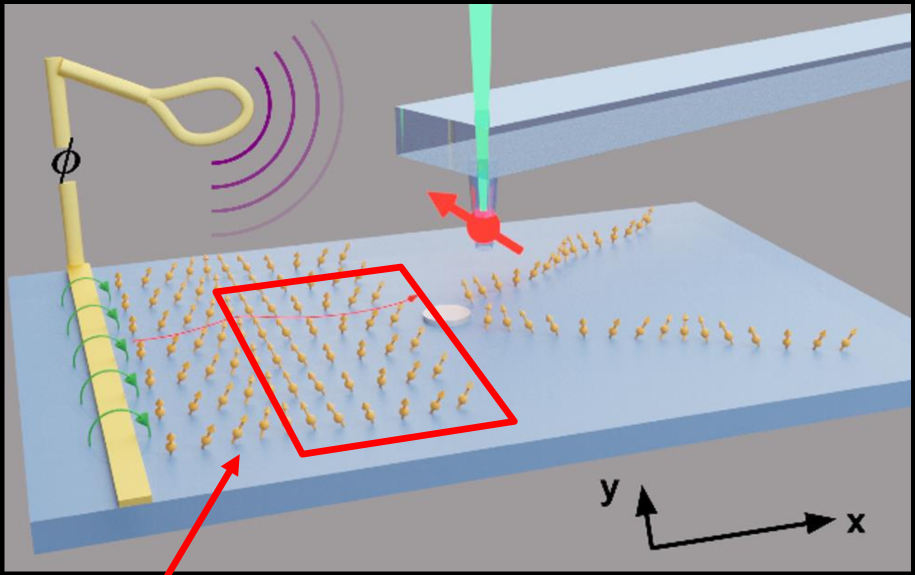


See also experiments using BLS

T. Zhou, AY et al, arXiv:2004.07763

Magnon Dispersion

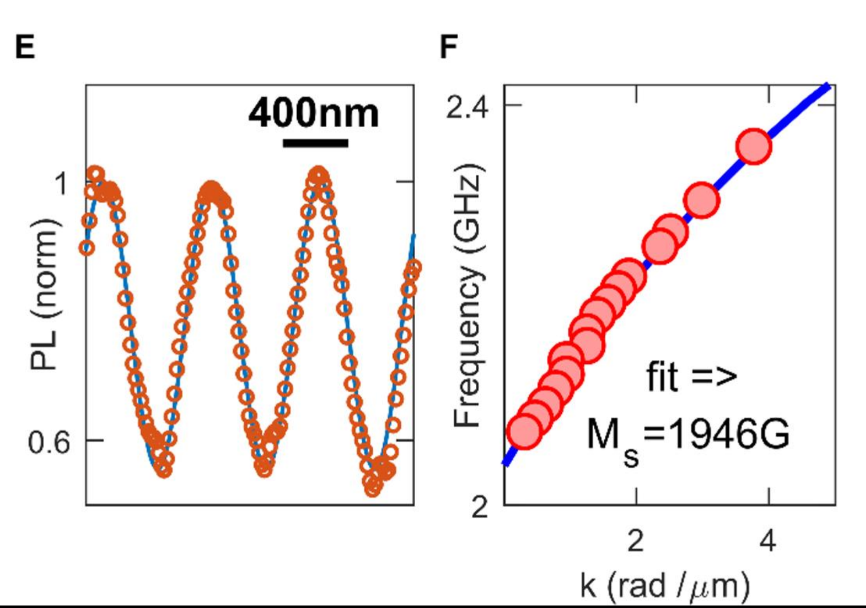
- NV centers are phase sensitive sensors.



- Frequency set by drive
- Wavelength set by dispersion
- Phase determined from interference

Position dependent phase

$$Be^{i\omega t+ikx}$$

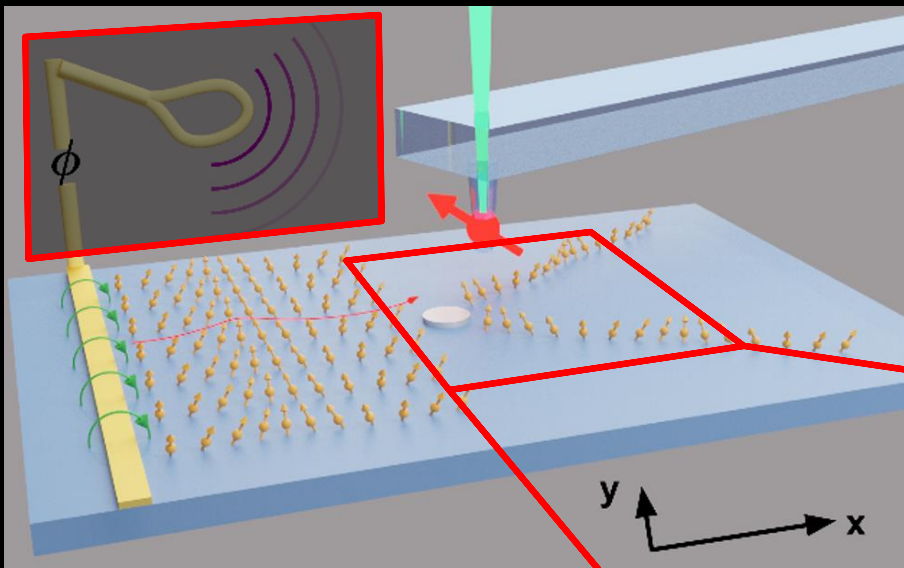


See also experiments using BLS

T. Zhou, AY et al, arXiv:2004.07763

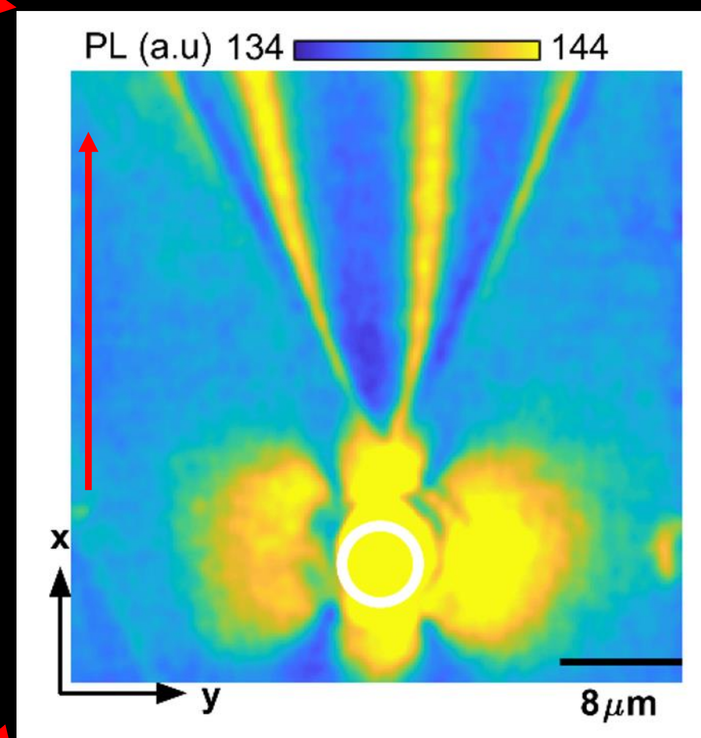
Scattered Amplitude Map

- NV centers are phase sensitive sensors.



Excite only with strip line

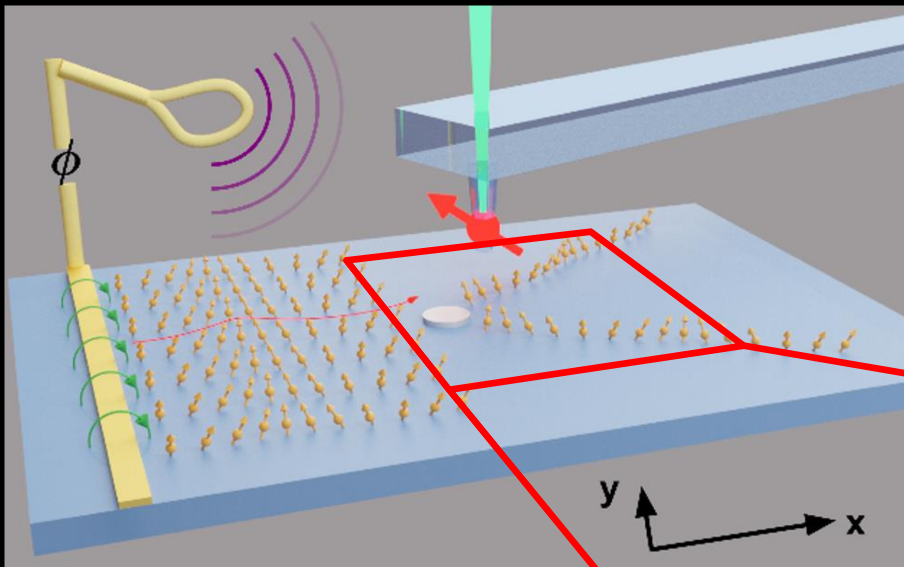
- Frequency set by drive
- Wavelength set by dispersion
- Phase determined from interference



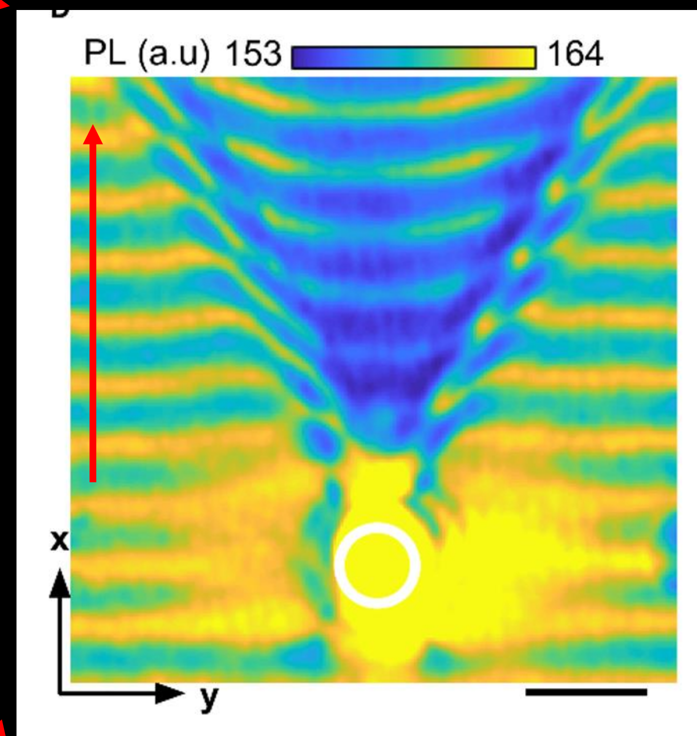
T. Zhou, AY et al, arXiv:2004.07763

Scattered Phase Map

- NV centers are phase sensitive sensors.



- Frequency set by drive
- Wavelength set by dispersion
- Phase determined from interference



Excite Both strip line and Antenna

T. Zhou, AY et al, arXiv:2004.07763

Model and Reconstruction

Looking for the time dependent component

$$\mathbf{H} = H_0\hat{\mathbf{y}} + \mathbf{h}e^{-i\omega t}, \quad \mathbf{M} = M_S\hat{\mathbf{y}} + \mathbf{m}e^{-i\omega t}$$

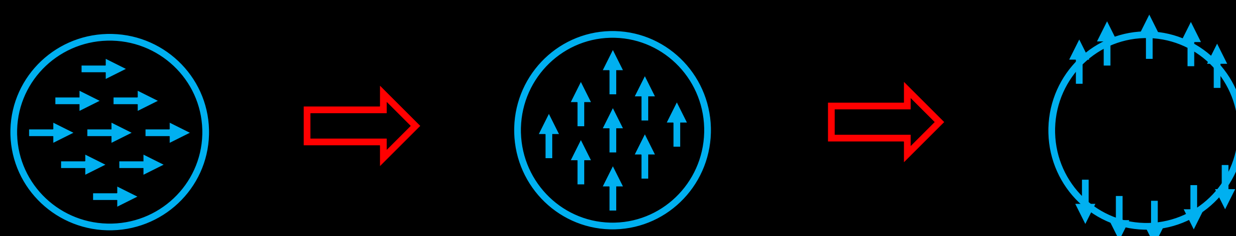
Magnetostatics Maxwell's equations – Valid when $\lambda_{vacuum} \gg \lambda_{medium}$

$$\nabla \times \mathbf{h} = 0, \quad \nabla \cdot (\mathbf{h} + 4\pi\mathbf{m}) = 0 \qquad \mathbf{m} = \mathbf{m}_0 + \delta\mathbf{m}_{target}$$

$$\mathbf{h} = -\nabla\psi$$

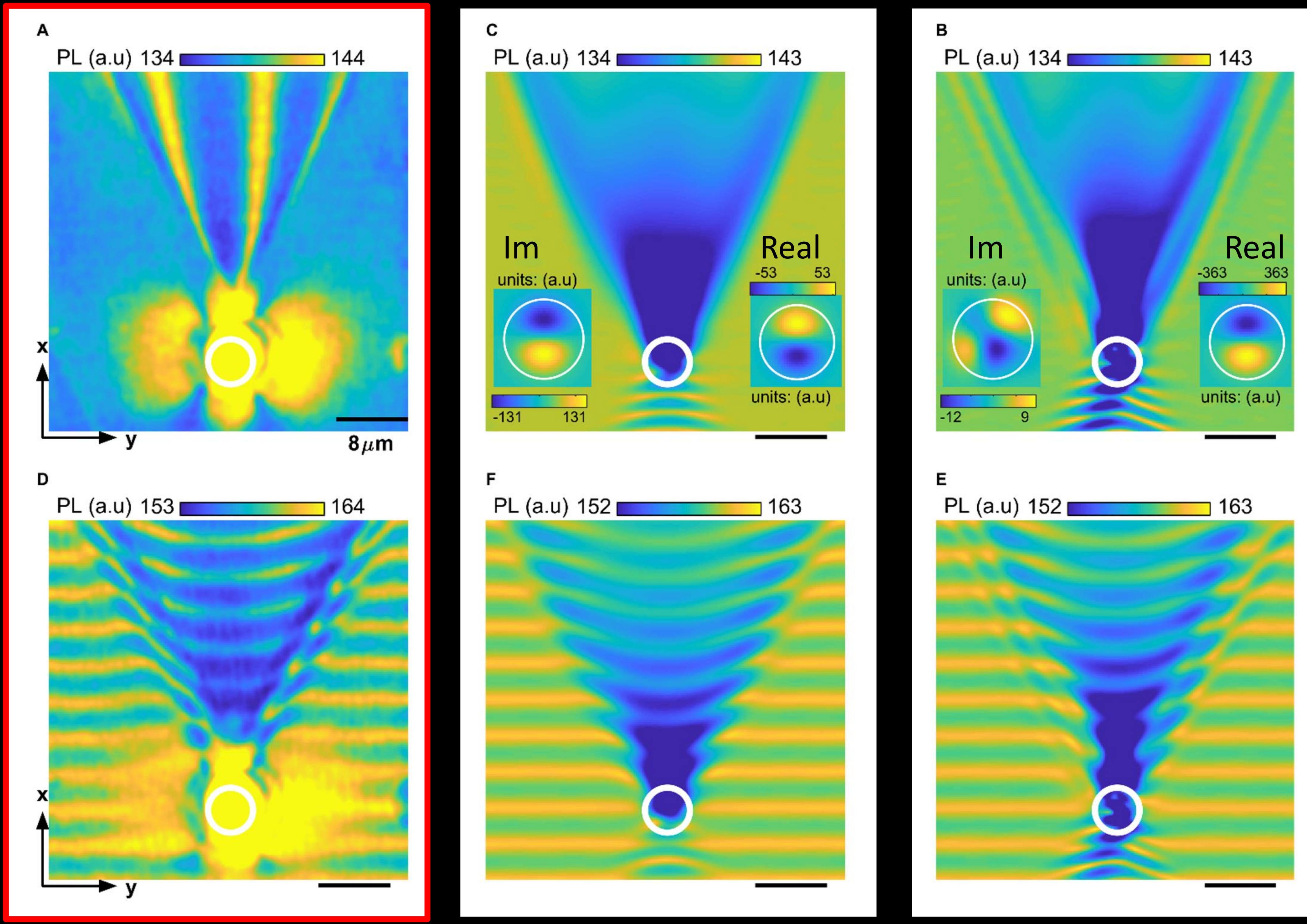
$$\nabla^2\psi = 4\pi\nabla \cdot \delta\mathbf{m}_{target}$$

Example: Magnetized Disc



$\mathbf{m}_0$ $\quad$ $\delta\mathbf{m}_{target}$ $\quad$ $\nabla \cdot \delta\mathbf{m}_{target}$

Model and Reconstruction



Magnons as a New Probe of Correlated Electron Physics

DiDi Wei

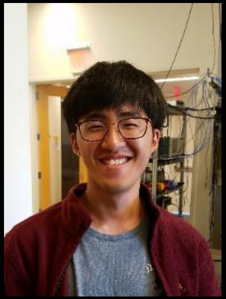
Toeno van der Sar

Tony Zhou

Daniel Fernandez

Andrew Pierce

Seung Hwan Lee



Yonglong Xie

Lisa Gächter

Joris Carmiggelt

Bert Halperin

Eugene Demler

Ilya Esterlis

Dries Sels