Noninteger-spin excitations: from bosons to fermions

Akashdeep Kamra and Wolfgang Belzig

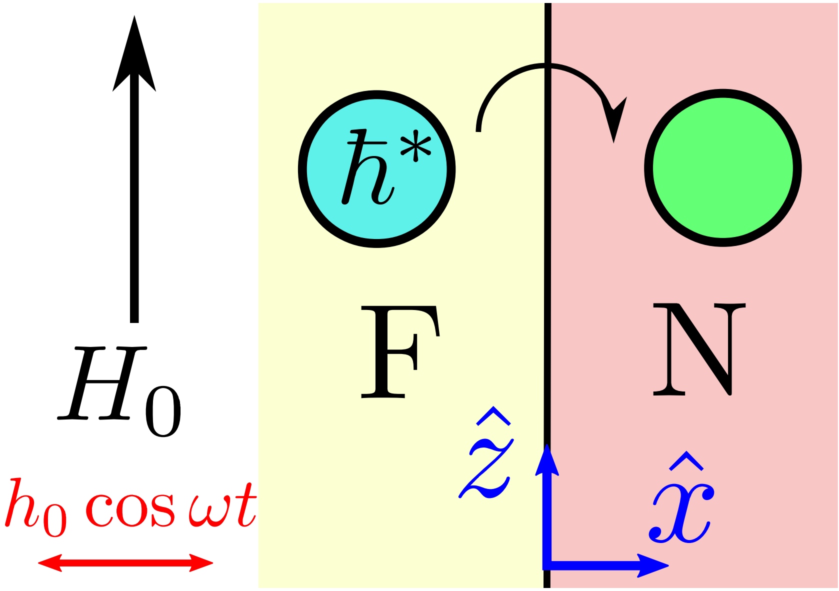
Department of Physics, University of Konstanz, Konstanz, Germany

Collaborator: Utkarsh Agrawal, IIT Bombay, Mumbai, India

Outline/Results

- Introduction and motivation
- Quasiparticles in ferromagnets
- Spin current shot noise and quantum of transport
- Quasiparticles in Ferrimagnets and Antiferromagnets
- Spin pumping in Ferrimagnets and Antiferromagnets
- (Quantum) Fun with squeezed-magnons

Outline/Results



A Kamra and W. Belzig, Super-Poissonian shot noise of squeezed-magnon mediated spin transport, Phys. Rev. Lett. 116, 146601 (2016).

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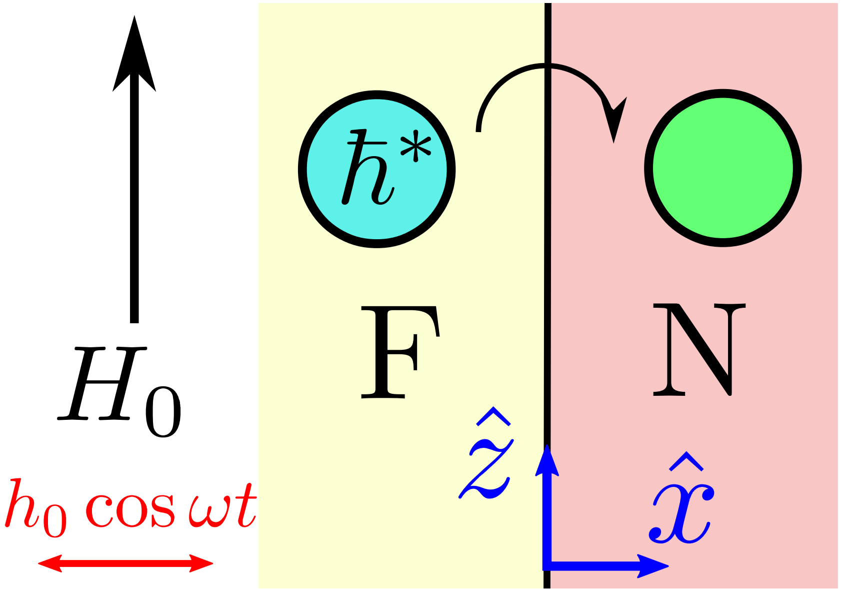

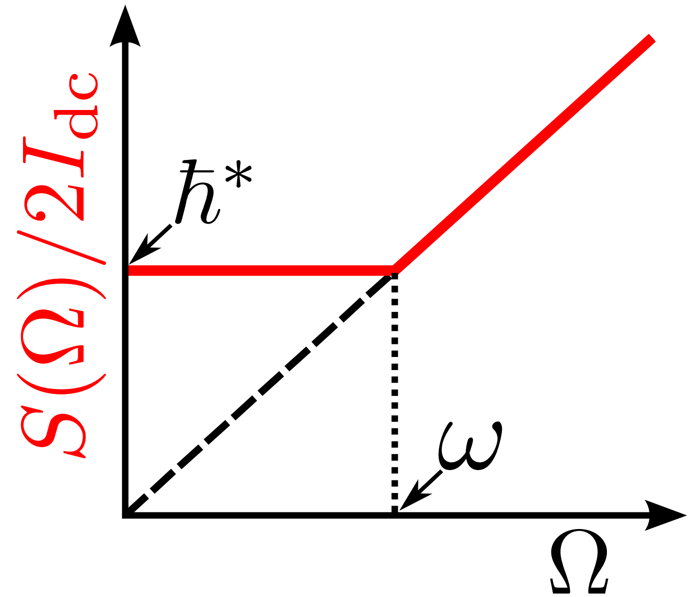

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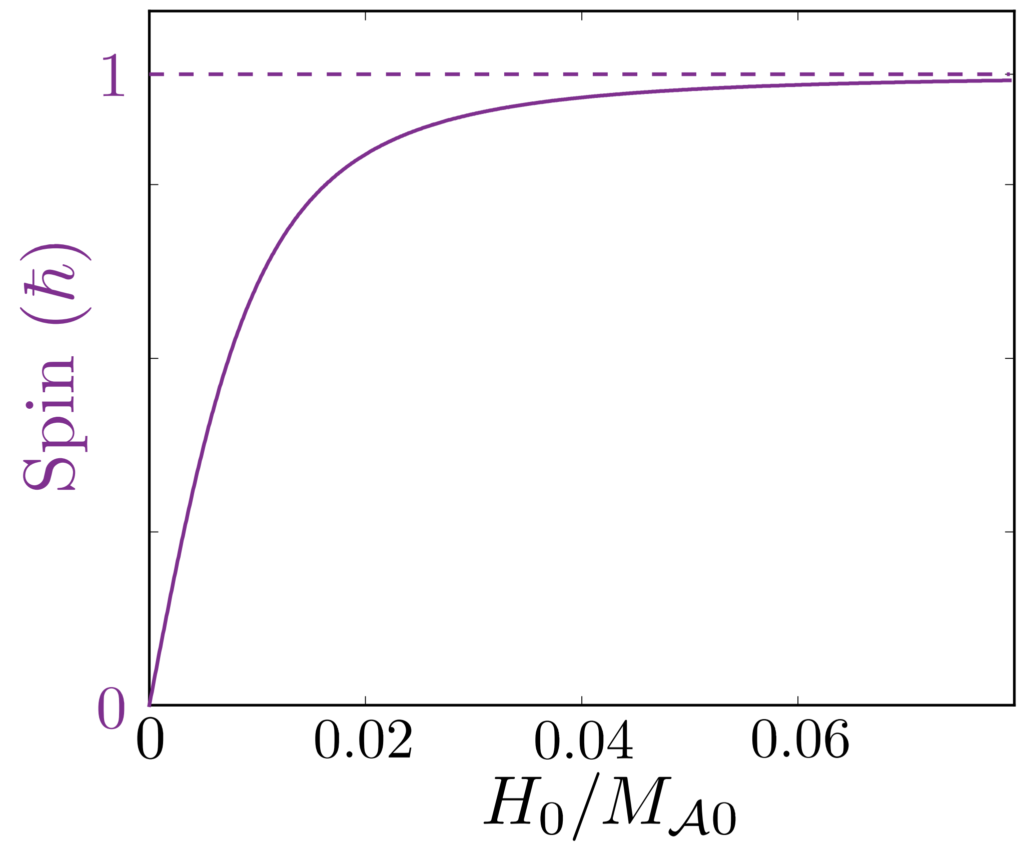
Zero-spin quasiparticles!



A. Kamra, U. Agrawal, and W Belzig, Noninteger-spin magnonic excitations in untextured magnets, Phys. Rev. B, 96, 020411(R) (2017).

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Outline/Results

$$\frac{e}{\hbar} I_{sz} = G_{AA}(\hat{\boldsymbol{m}}_A \times \dot{\hat{\boldsymbol{m}}}_A)_z + G_{BB}(\hat{\boldsymbol{m}}_B \times \dot{\hat{\boldsymbol{m}}}_B)_z$$

$$+ G_{AB}(\hat{\boldsymbol{m}}_A \times \dot{\hat{\boldsymbol{m}}}_B + \hat{\boldsymbol{m}}_B \times \dot{\hat{\boldsymbol{m}}}_A)_z$$

$$\frac{e}{\hbar} I_{sz} = G_{mm}(\boldsymbol{m} \times \dot{\boldsymbol{m}})_z + G_{nn}(\boldsymbol{n} \times \dot{\boldsymbol{n}})_z$$

$$+ G_{mn}(\boldsymbol{m} \times \dot{\boldsymbol{n}} + \boldsymbol{n} \times \dot{\boldsymbol{m}})_z$$

$$\boldsymbol{m} = [\hat{\boldsymbol{m}}_A + \hat{\boldsymbol{m}}_B]/2 \qquad \boldsymbol{n} = [\hat{\boldsymbol{m}}_A - \hat{\boldsymbol{m}}_B]/2$$

A. Kamra and W Belzig, Spin pumping and shot noise in ferrimagnets: bridging ferro- and antiferromagnets, arXiv:1706.07118 (2017).

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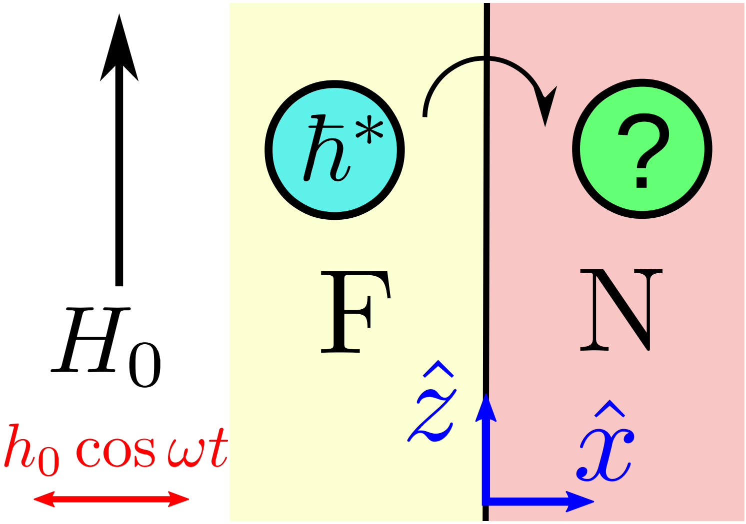
Squeezed-magnons

Mathematical equivalence between squeezed magnons and photons

	Squeezed-light	Squeezed-magnons
Vacuum noise	$\left\langle \left(\Delta \tilde{X}_{1,2} \right)^2 \right\rangle_0 = \frac{1}{4} \exp\left(\mp 2r\right)$	$\left\langle \left(\Delta \tilde{\mathcal{M}}_{x,y} \right)^2 \right\rangle_0 = \frac{\lvert\gamma\rvert \hbar \mathcal{M}_0}{2} \exp\left(\mp 2\xi_{\mathbf{0}}\right)$
Definition in Fock space	$\left(\mu \tilde{a} + \nu \tilde{a}^{\dagger} \right) \lvert 0 \rangle_{\alpha} = 0$	$\left(u_{\mathbf{0}} \tilde{b}_{\mathbf{0}} - v_{\mathbf{0}}^{*} \tilde{b}_{\mathbf{0}}^{\dagger} \right) \lvert 0 \rangle_{\beta} = 0$



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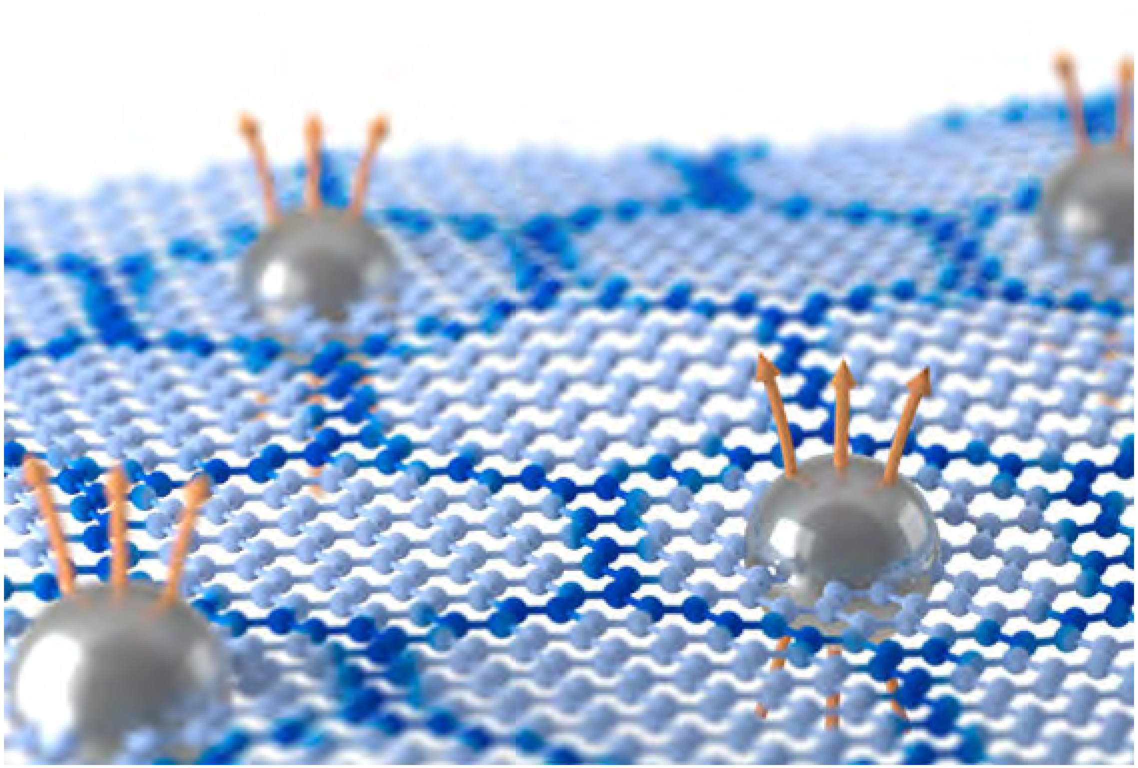
Silicon age: electronics

Exotic quasiparticles



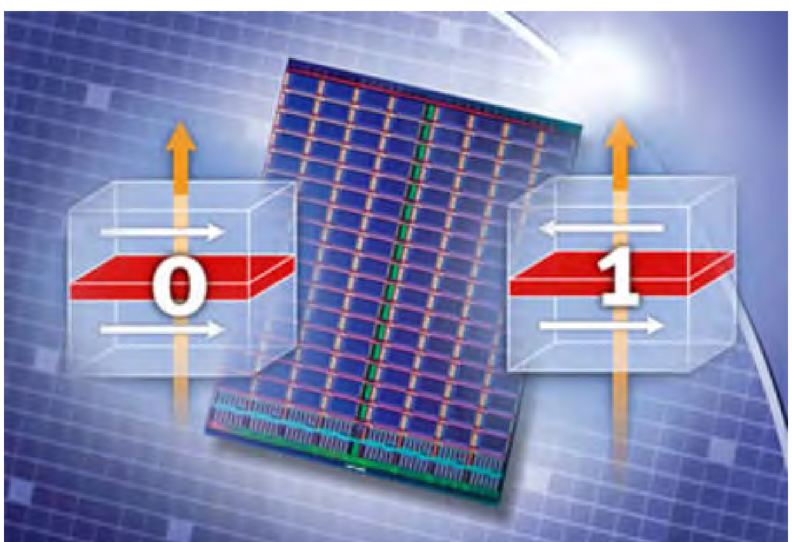
Artistic illustration of Fractional quantum Hall effect
www.nationalmaglab.org

Spintronics

Giant Magnetoresistance (GMR)

Nobel Prize in Physics 2007
P. Gruenberg and A. Fert

A. Fert, Nobel Lecture: Origin, development, and future of spintronics. Rev. Mod. Phys. 80, 1517 (2008).

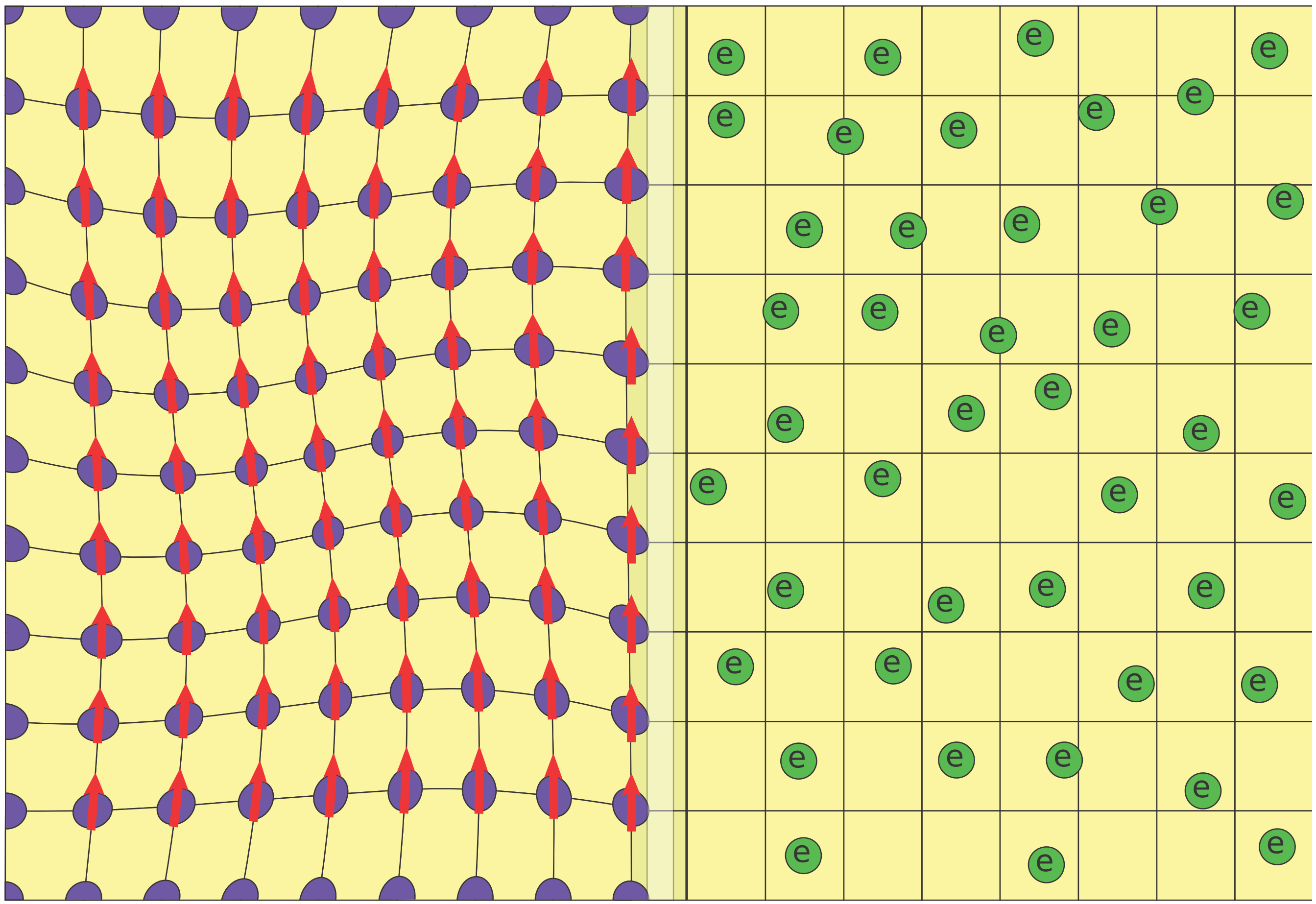


MRAMS

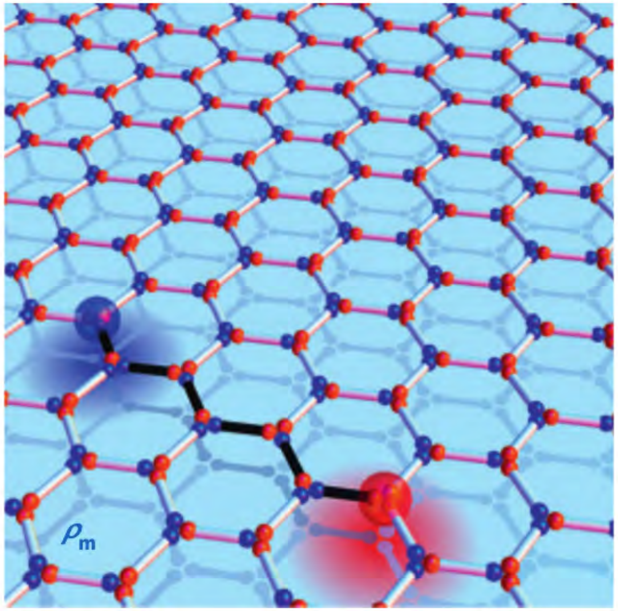
J. Akerman, Toward a Universal Memory, Science 308, 508 (2005).

www.everspin.com
Everspin Technologies
The MRAM company

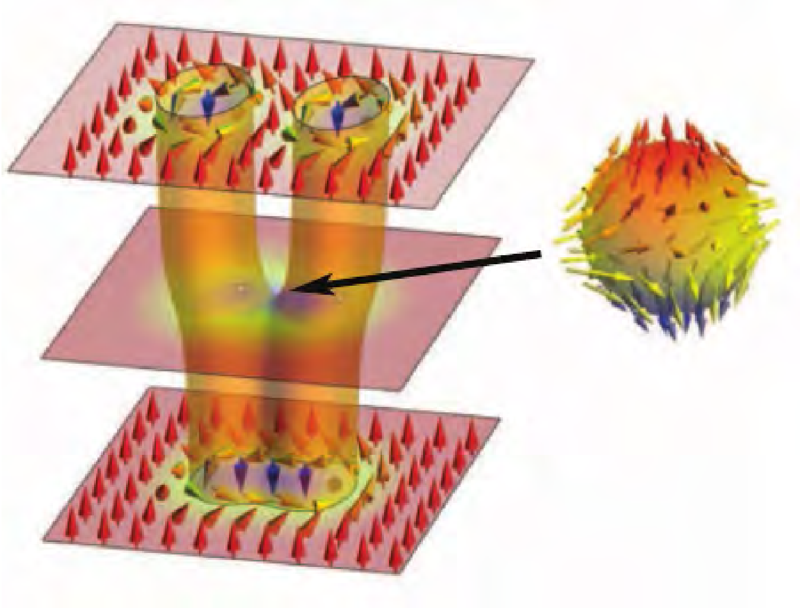
Spintronics with magnetic insulators



Magnetic Monopoles



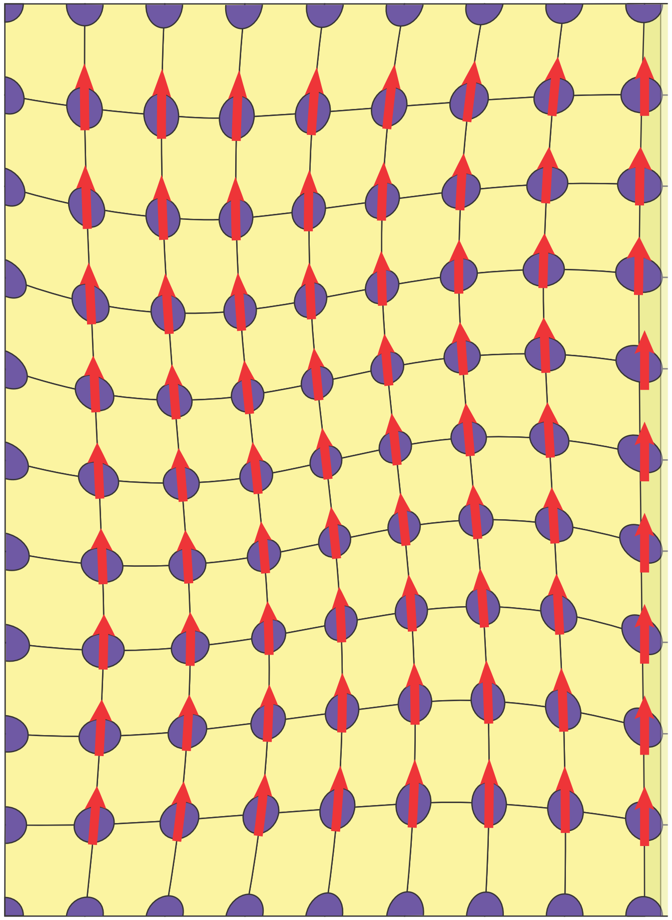
Real space observation of emergent magneic monopoles....
Nature physics, 7, 68 (2011).



Unwinding of a skyrmion lattice by magnetic monopoles, P. Milde, ….
Science, 340, 1076 (2013).

Spintronics with magnetic insulators

Magnetic Insulator



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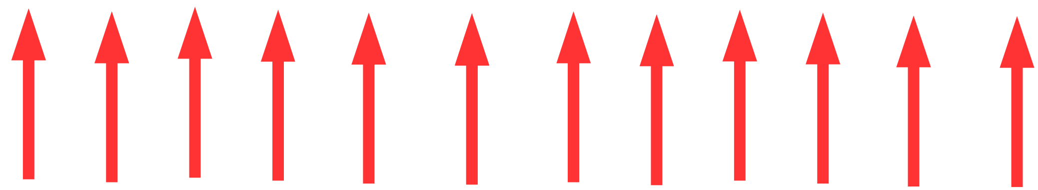
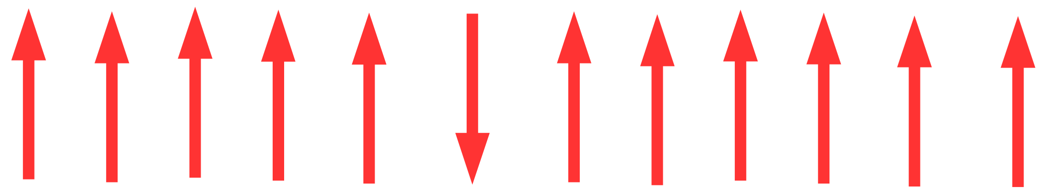
Quasiparticles in a ferromagnet



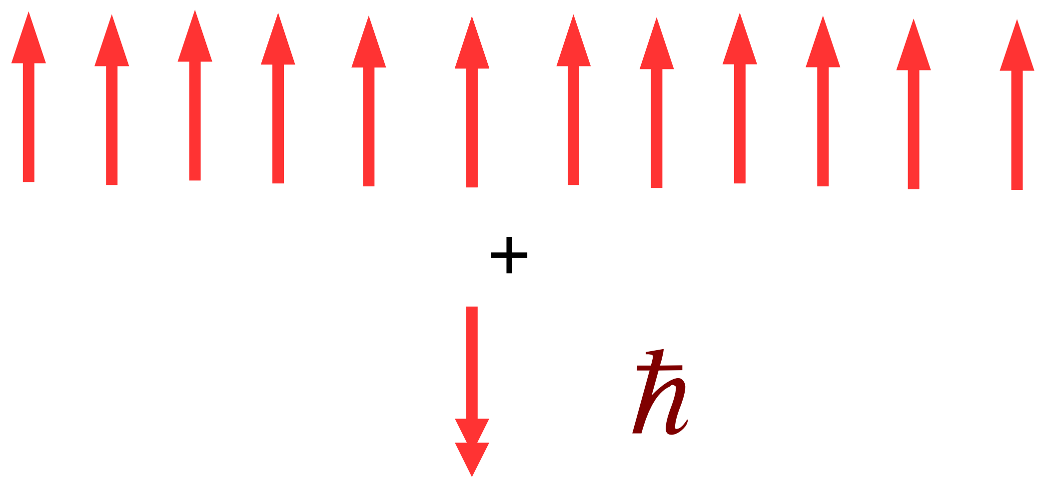
C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 1953)

Quasiparticles in a ferromagnet



C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 1953)

Magnon



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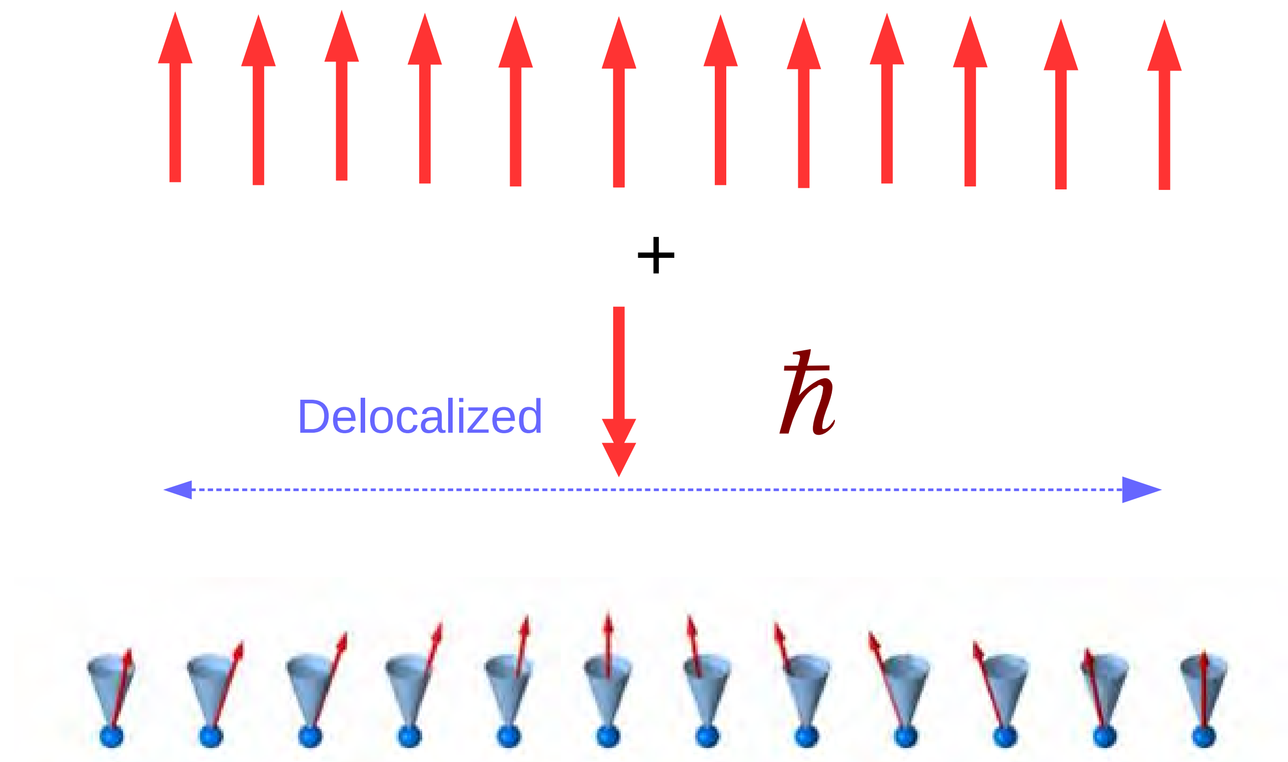
Magnon



Considering only exchange interaction and Zeeman energy!

C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 1953)

Quasiparticles in a ferromagnet

With magnon annihilation operators $\tilde{b}_{\boldsymbol{q}}$

$$\tilde{\mathcal{H}}_{\mathrm{F}} = \sum_{\boldsymbol{q}} A_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}}^{\dagger} \tilde{b}_{\boldsymbol{q}}$$

Classical Hamiltonian

$$\mathcal{H}_{\mathrm{F}} = \int_{V_{\mathrm{F}}} d^3 r \left(H_{\mathrm{Z}} + H_{\mathrm{aniso}} + H_{\mathrm{ex}} + H_{\mathrm{dip}} \right)$$

C. Kittel, *Quantum Theory of Solids* (John Wiley & Sons, London 1963).

Classical Hamiltonian

$$\mathcal{H}_{\mathrm{F}} = \int_{V_{\mathrm{F}}} d^3r \, (H_{\mathrm{Z}} + H_{\mathrm{aniso}} + H_{\mathrm{ex}} + H_{\mathrm{dip}})$$

Linearization about equilibrium orientation:
Magnetization saturated along z direction

C. Kittel, *Quantum Theory of Solids* (John Wiley & Sons, London 1963).

Classical Hamiltonian

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Linearization about equilibrium orientation:
Magnetization saturated along z direction

$$H_{\mathrm{Z}} + H_{\mathrm{aniso}} = \frac{\omega_{\mathrm{za}}}{2|\gamma|M_s} \left(M_x^2 + M_y^2\right)$$

$$H_{\mathrm{ex}} = \frac{A}{M_s^2} \left[(\boldsymbol{\nabla} M_x)^2 + (\boldsymbol{\nabla} M_y)^2 \right]$$

C. Kittel, *Quantum Theory of Solids* (John Wiley & Sons, London 1963).

Classical Hamiltonian

Mean-field description of dipolar interaction:
Demagnetization field

$$H_{\mathrm{dip}} = -\frac{1}{2}\mu_0 \boldsymbol{H}_m \cdot \boldsymbol{M}$$

C. Kittel, *Quantum Theory of Solids* (John Wiley & Sons, London 1963).

Classical Hamiltonian

Mean-field description of dipolar interaction:
Demagnetization field

$$H_{\text{dip}} = -\frac{1}{2}\mu_0 \boldsymbol{H}_m \cdot \boldsymbol{M}$$

$$\boldsymbol{H}_m = \boldsymbol{H}_u + \boldsymbol{H}_{nu} \qquad \boldsymbol{M} = \boldsymbol{M}_u + \boldsymbol{M}_{nu}$$

$$\boldsymbol{H}_u = -N_x M_{ux}\,\hat{\boldsymbol{x}} - N_y M_{uy}\,\hat{\boldsymbol{y}} - N_z M_{uz}\,\hat{\boldsymbol{z}}$$

C. Kittel, *Quantum Theory of Solids* (John Wiley & Sons, London 1963).

Quantization: HP transformations

With $\tilde{a}^\dagger(\boldsymbol{r}), \tilde{a}(\boldsymbol{r})$ the magnon ladder operators in real space

$$\tilde{M}_\pm = \tilde{M}_x \pm i(\gamma/|\gamma|)\tilde{M}_y$$

$$\tilde{M}_+ = \sqrt{2|\gamma|\hbar M_s}\left(1 - \frac{|\gamma|\hbar}{2M_s}\tilde{a}^\dagger\tilde{a}\right)^{\frac{1}{2}}\tilde{a}$$

$$\tilde{M}_- = \sqrt{2|\gamma|\hbar M_s}\tilde{a}^\dagger\left(1 - \frac{|\gamma|\hbar}{2M_s}\tilde{a}^\dagger\tilde{a}\right)^{\frac{1}{2}}$$

$$\tilde{M}_z = M_s - |\gamma|\hbar\tilde{a}^\dagger\tilde{a}.$$

T. Holstein and H. Primakoff, *Field Dependence of the Intrinsic Domain Magnetization of a Ferromagnet*, Phys. Rev. 58, 1098 (1940).

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T. Holstein and H. Primakoff, *Field Dependence of the Intrinsic Domain Magnetization of a Ferromagnet*, Phys. Rev. 58, 1098 (1940).

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Quantum Hamiltonian

With $\tilde{b}_{\boldsymbol{q}}$ the magnon annihilation operators in Fourier space

$$\tilde{\mathcal{H}}_{\mathrm{F}} = \sum_{\boldsymbol{q}} \left[A_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}}^{\dagger} \tilde{b}_{\boldsymbol{q}} + B_{\boldsymbol{q}}^{*} \tilde{b}_{\boldsymbol{q}}^{\dagger} \tilde{b}_{-\boldsymbol{q}}^{\dagger} + B_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}} \tilde{b}_{-\boldsymbol{q}} \right]$$

$$A_{\boldsymbol{q}} \ = \ A_{-\boldsymbol{q}} = \hbar \left(\omega_{\mathrm{za}} - \omega_s N_z + D q^2 + \frac{\omega_s}{2} (N_x + N_y) \delta_{\boldsymbol{q},\boldsymbol{0}} + \frac{\omega_s}{2} \sin^2 \theta_{\boldsymbol{q}} \right)$$

$$B_{\boldsymbol{q}} \ = \ B_{-\boldsymbol{q}} = \hbar \left(\frac{\omega_s}{4} N_{xy} \delta_{\boldsymbol{q},\boldsymbol{0}} + \frac{\omega_s}{4} \sin^2 \theta_{\boldsymbol{q}} \ e^{i 2 \phi_{\boldsymbol{q}}} \right)$$

$$D \ = \ 2A|\gamma|/M_s \qquad \omega_s \ = \ |\gamma| \mu_0 M_s \qquad N_{xy} \ = \ N_x - N_y$$

Quantum Hamiltonian

With $\tilde{b}_{\boldsymbol{q}}$ the magnon annihilation operators in Fourier space

$$\tilde{\mathcal{H}}_{\mathrm{F}} = \sum_{\boldsymbol{q}} \left[A_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}}^{\dagger} \tilde{b}_{\boldsymbol{q}} + B_{\boldsymbol{q}}^{*} \tilde{b}_{\boldsymbol{q}}^{\dagger} \tilde{b}_{-\boldsymbol{q}}^{\dagger} + B_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}} \tilde{b}_{-\boldsymbol{q}} \right]$$

$$A_{\boldsymbol{q}} \;=\; A_{-\boldsymbol{q}} = \hbar \left(\omega_{\mathrm{za}} - \omega_s N_z \qquad + \frac{\omega_s}{2} (N_x + N_y) \delta_{\boldsymbol{q},\mathbf{0}} \qquad \right)$$

$$B_{\boldsymbol{q}} \;=\; B_{-\boldsymbol{q}} = \hbar \left(\frac{\omega_s}{4} N_{xy} \delta_{\boldsymbol{q},\mathbf{0}} \qquad \right)$$

$$\omega_s \;=\; |\gamma| \mu_0 M_s \qquad N_{xy} \;=\; N_x - N_y$$

Squeezed-magnons

Bogoliubov transformation to new quasi-particles

$$\tilde{\beta}_{\boldsymbol{q}} = u_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}} - v_{\boldsymbol{q}}^{*} \tilde{b}_{-\boldsymbol{q}}^{\dagger}$$

$$\tilde{\mathcal{H}}_{\mathrm{F}} = \sum_{\boldsymbol{q}} \hbar \omega_{\boldsymbol{q}} \tilde{\beta}_{\boldsymbol{q}}^{\dagger} \tilde{\beta}_{\boldsymbol{q}}$$

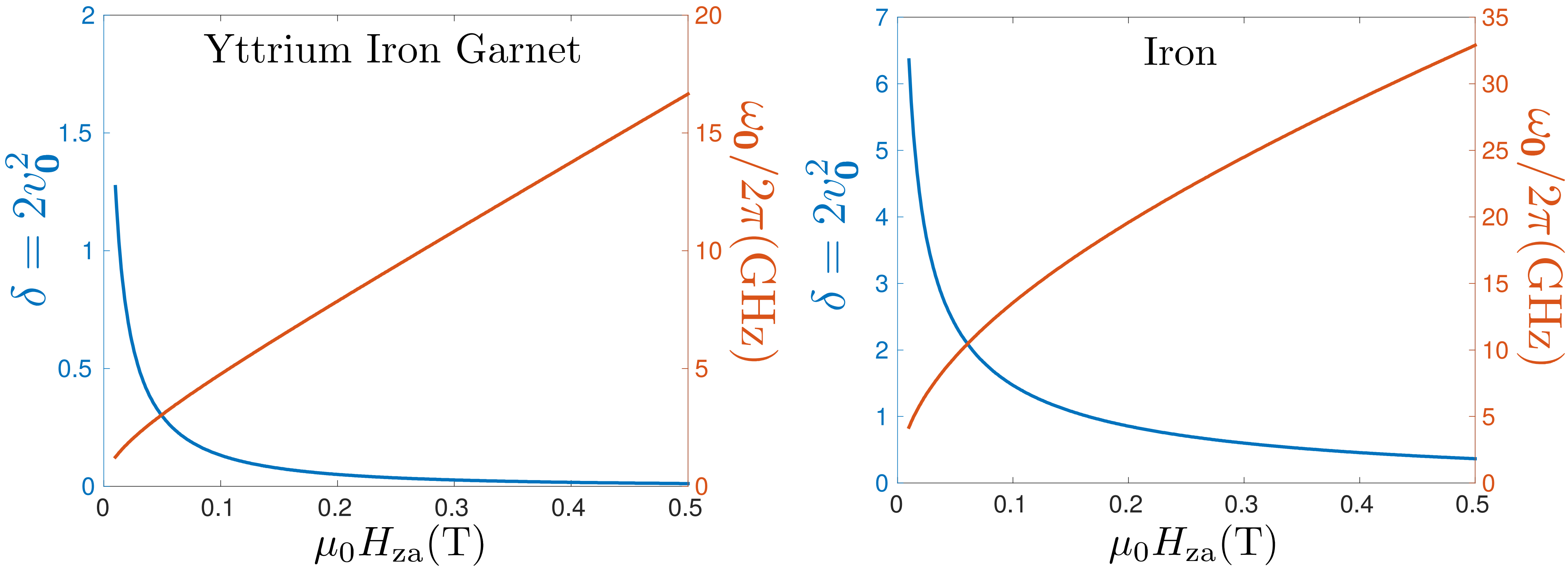
Spin of squeezed-magnon

$$\int_{V_{\mathrm{F}}} \langle \tilde{S}_{\mathrm{F}}^{z}(\boldsymbol{r}) \rangle d^3 r = -\frac{\mathcal{M}_0}{|\gamma|} + \sum_{\boldsymbol{q}} \boxed{\hbar(1 + 2|v_{\boldsymbol{q}}|^2)} n_{\boldsymbol{q}}^{\beta} + \sum_{\boldsymbol{q}} \hbar |v_{\boldsymbol{q}}|^2$$

A Kamra and W. Belzig, Super-Poissonian shot noise of squeezed-magnon mediated spin transport, Phys. Rev. Lett. 116, 146601 (2016).

Spin of squeezed-magnon

$$\hbar^* = \hbar(1 + \delta)$$



Specimen in the shape of a film

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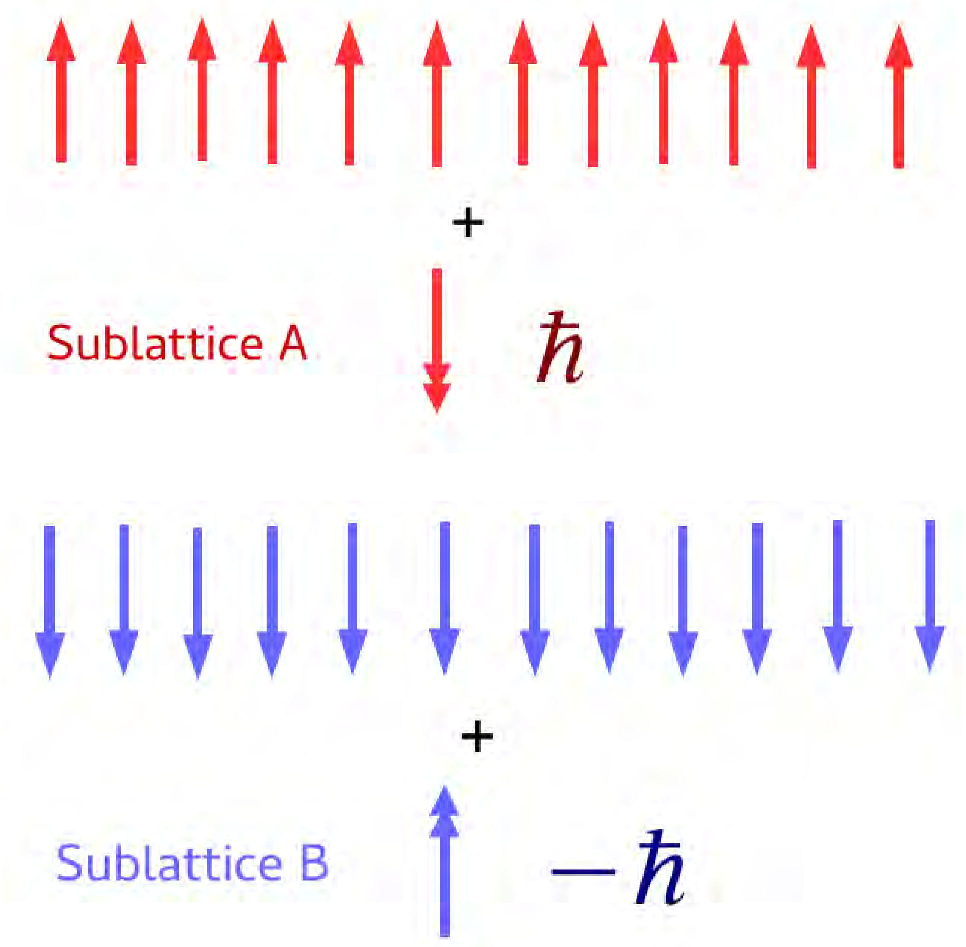
Effect of dipolar interaction in Ferri- and Antiferromagnets?

Two interpenetrating sublattices



A. Kamra, U. Agrawal, and W Belzig, Noninteger-spin magnonic excitations in untextured magnets, Phys. Rev. B, 96, 020411(R) (2017).

4-D Bogoliubov Transform

Ferromagnet:

$$\tilde{\beta}_{\boldsymbol{q}} = u_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}} - v_{\boldsymbol{q}}^{*} \tilde{b}^{\dagger}_{-\boldsymbol{q}}$$

Ferrimagnet:

$$\tilde{\alpha}_{\boldsymbol{q}} = u_{\boldsymbol{q}} \tilde{a}_{\boldsymbol{q}} + v_{\boldsymbol{q}} \tilde{b}^{\dagger}_{-\boldsymbol{q}} + w_{\boldsymbol{q}} \tilde{a}^{\dagger}_{-\boldsymbol{q}} + x_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}}$$

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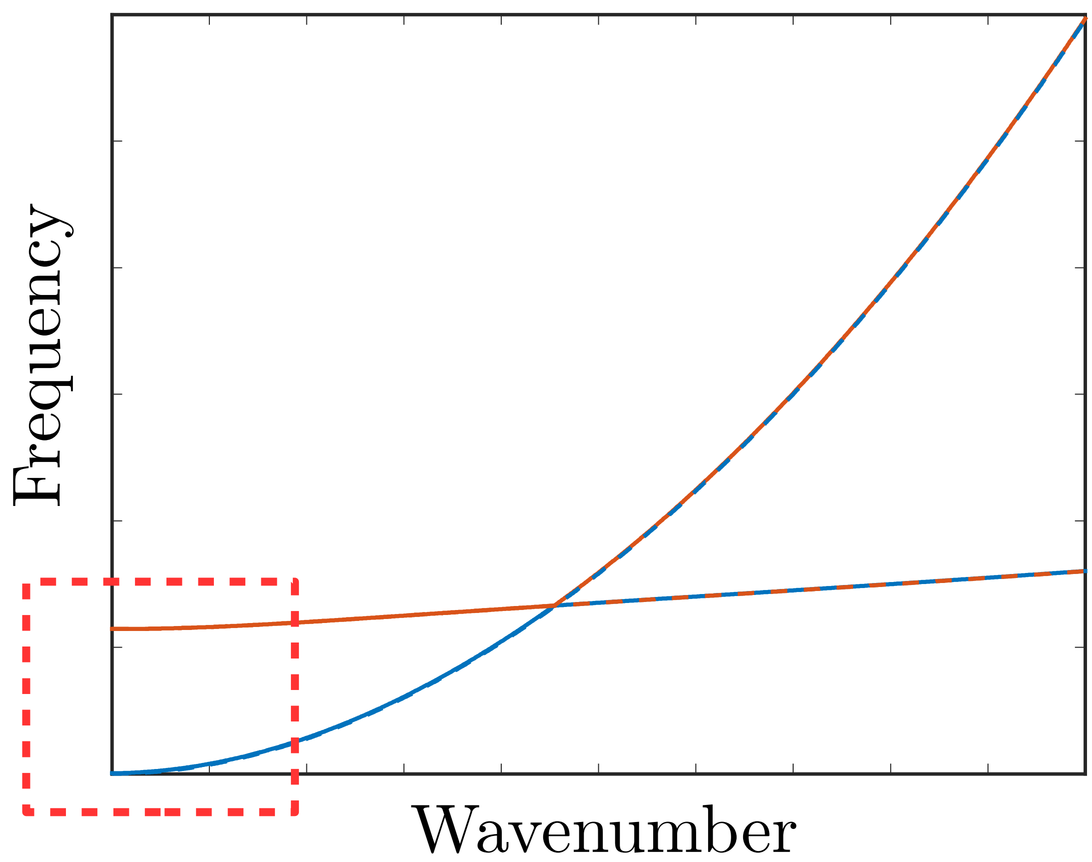
Ferrimagnets



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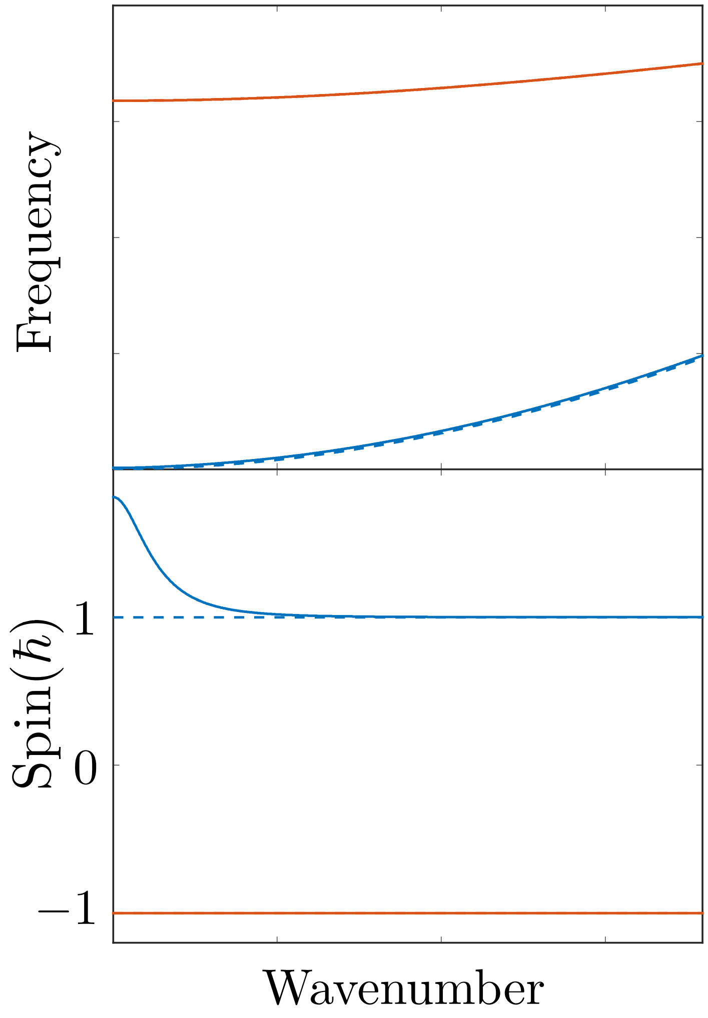
Ferrimagnets



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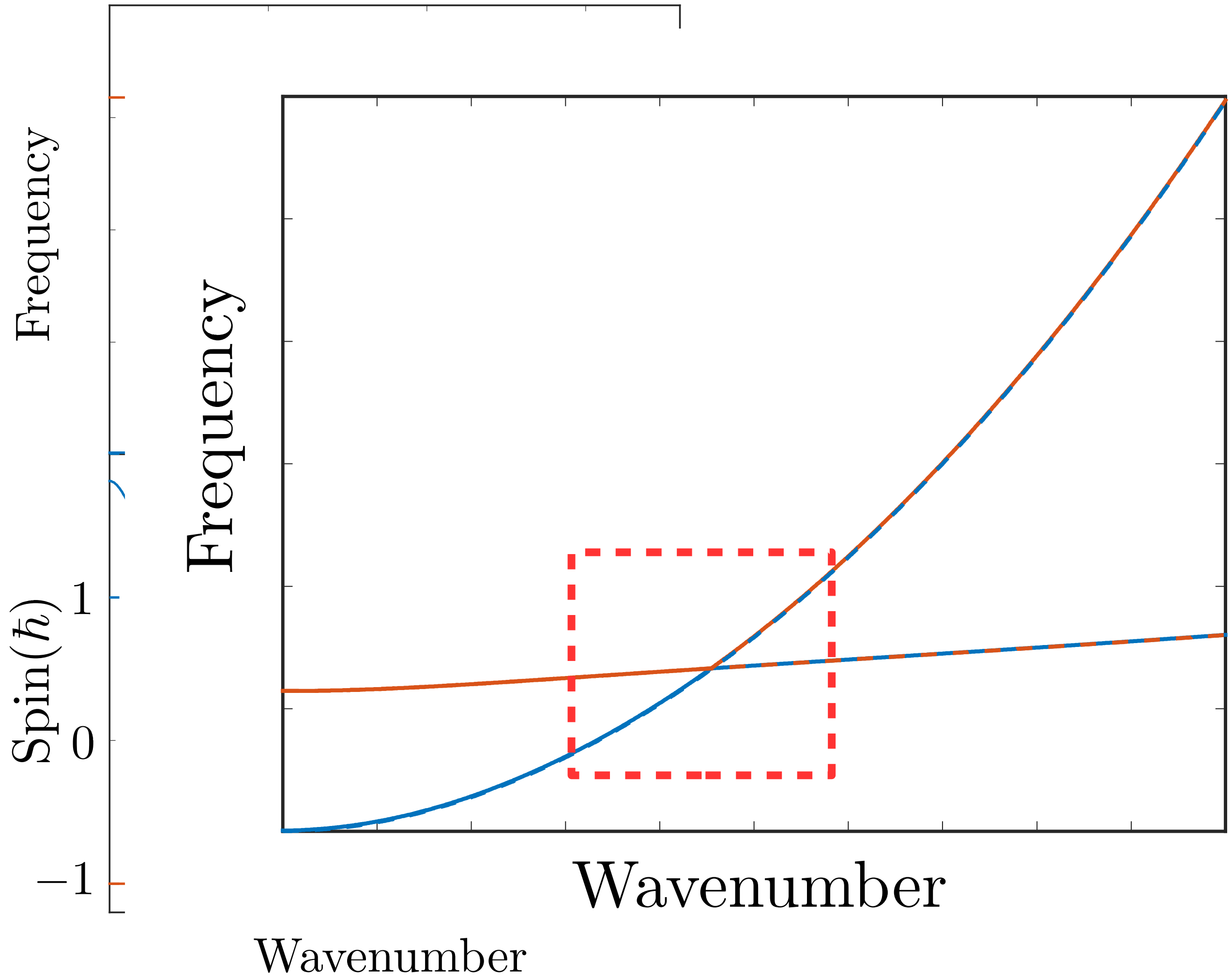

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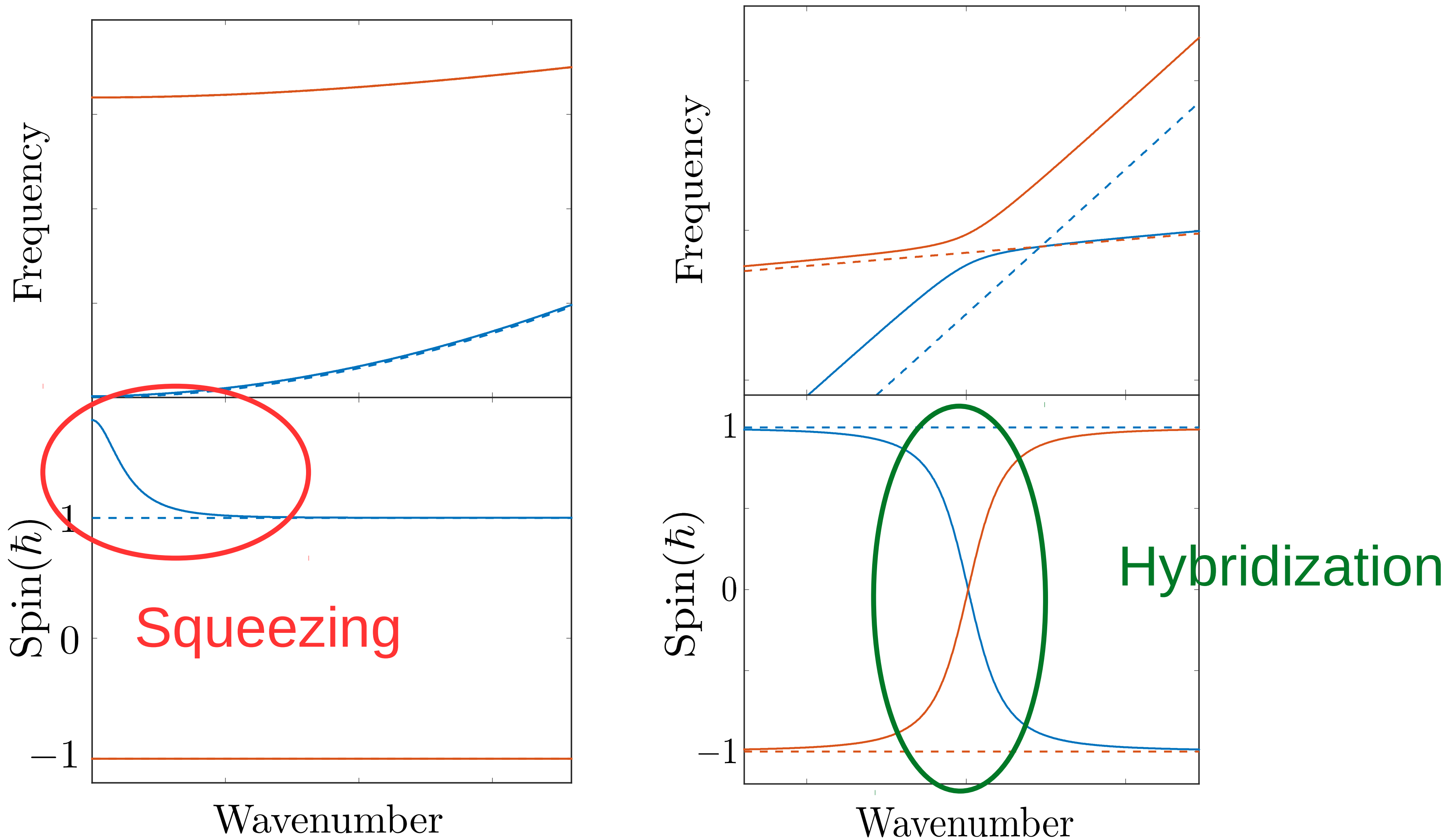

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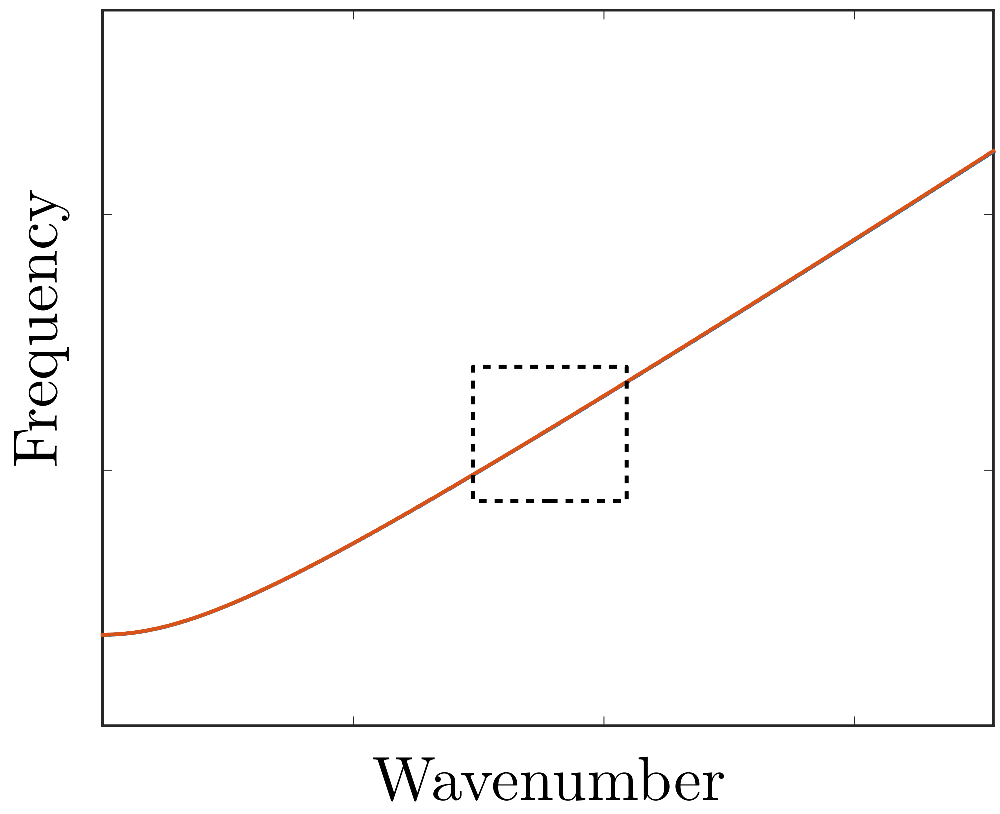
Antiferromagnets



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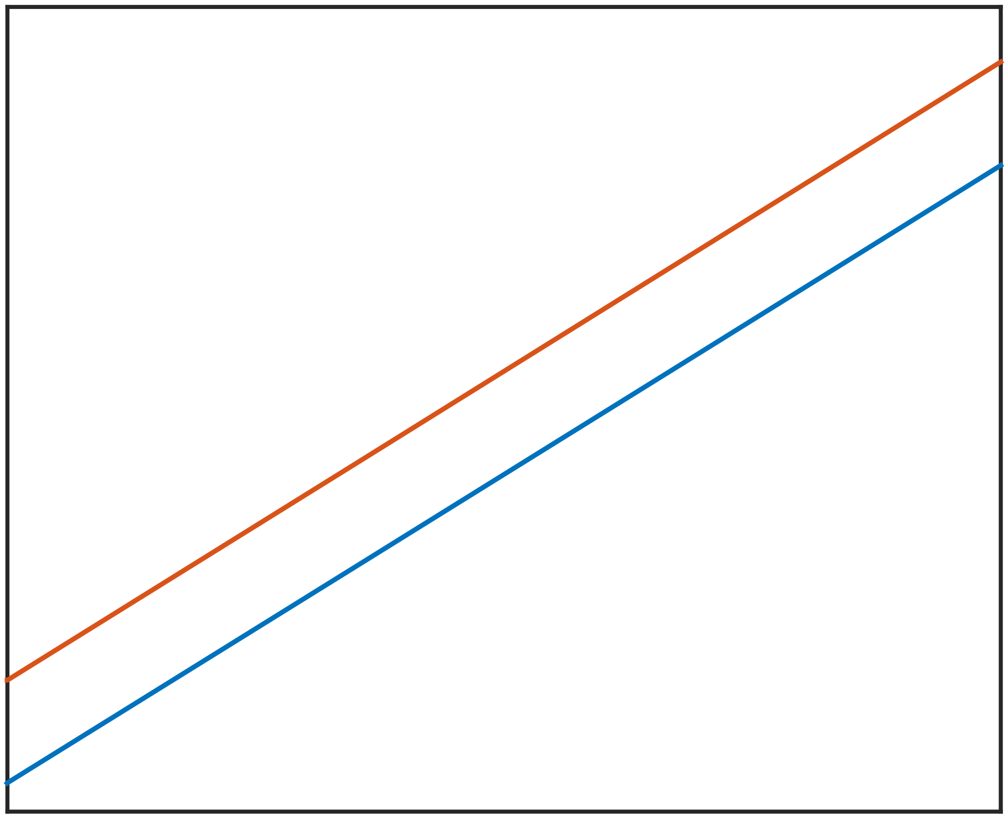
Antiferromagnets

Zero-spin quasiparticles!



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Antiferromagnets

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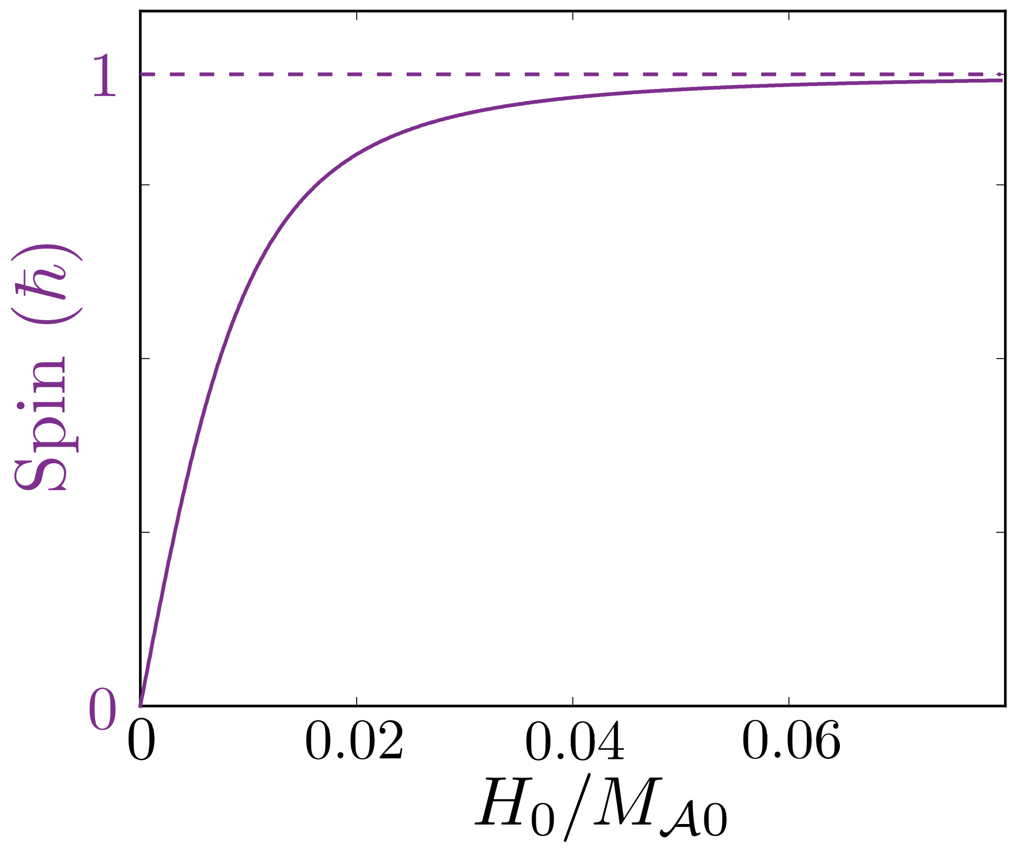

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Squeezing vs. Hybridization

Squeezing:

$$\tilde{\beta}_{\boldsymbol{q}} = u_{\boldsymbol{q}} \tilde{b}_{\boldsymbol{q}} - v_{\boldsymbol{q}}^{*} \tilde{b}_{-\boldsymbol{q}}^{\dagger}$$

Hybridization:

$$\tilde{\alpha}_{\boldsymbol{q}} = u_{\boldsymbol{q}} \tilde{a}_{\boldsymbol{q}} - v_{\boldsymbol{q}}^{*} \tilde{b}_{\boldsymbol{q}}$$

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Squeezing

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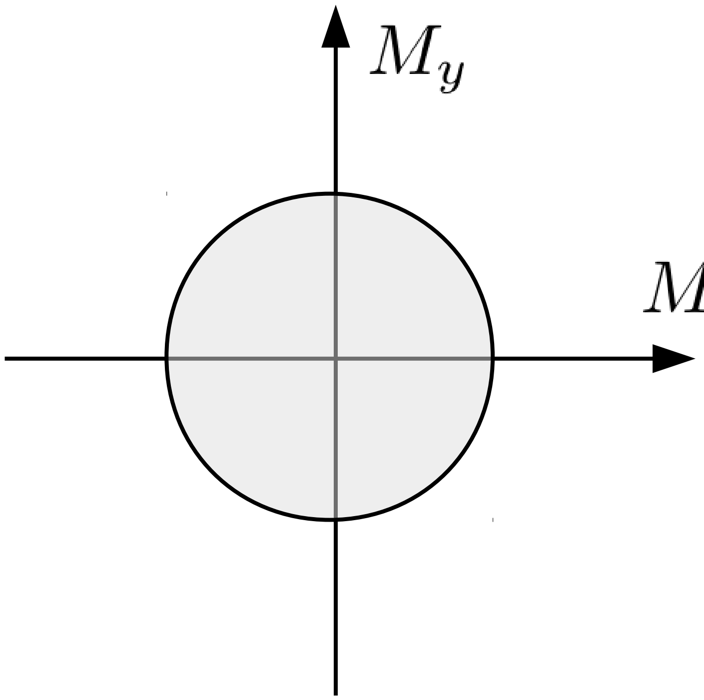
C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Squeezed Vacuum

$$\left\langle (\Delta \tilde{M}_x)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} \qquad \left\langle (\Delta \tilde{M}_y)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2}$$



$$|0\rangle$$

$$\tilde{H} = \hbar\omega a^{\dagger} a$$

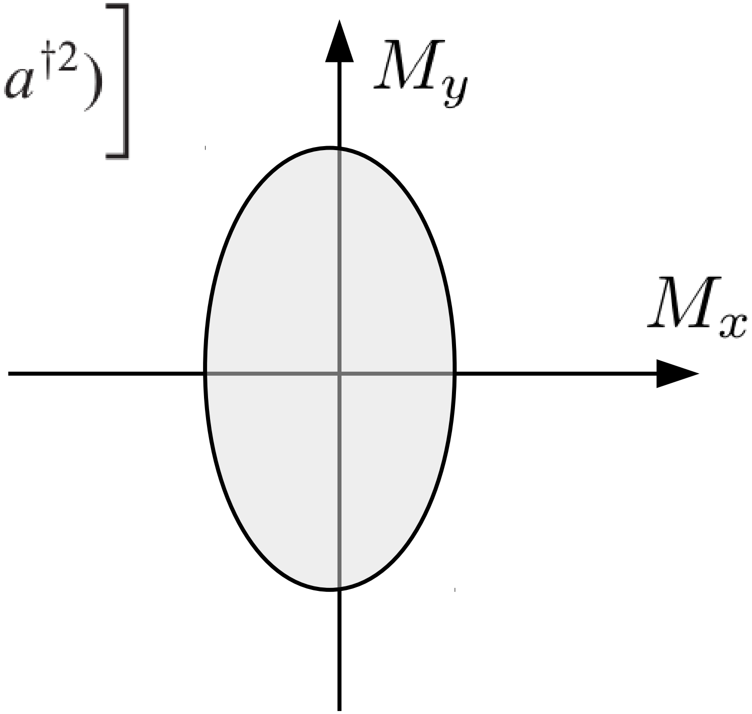
C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Squeezed Vacuum

$$\left\langle (\Delta \tilde{M}_x)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{-2r} \qquad \left\langle (\Delta \tilde{M}_y)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{2r}$$

$$\hat{S}(\xi) = \exp\left[\frac{1}{2}(\xi^* a^2 - \xi a^{\dagger 2})\right]$$

$$\xi = r\ e^{i\ \theta}$$

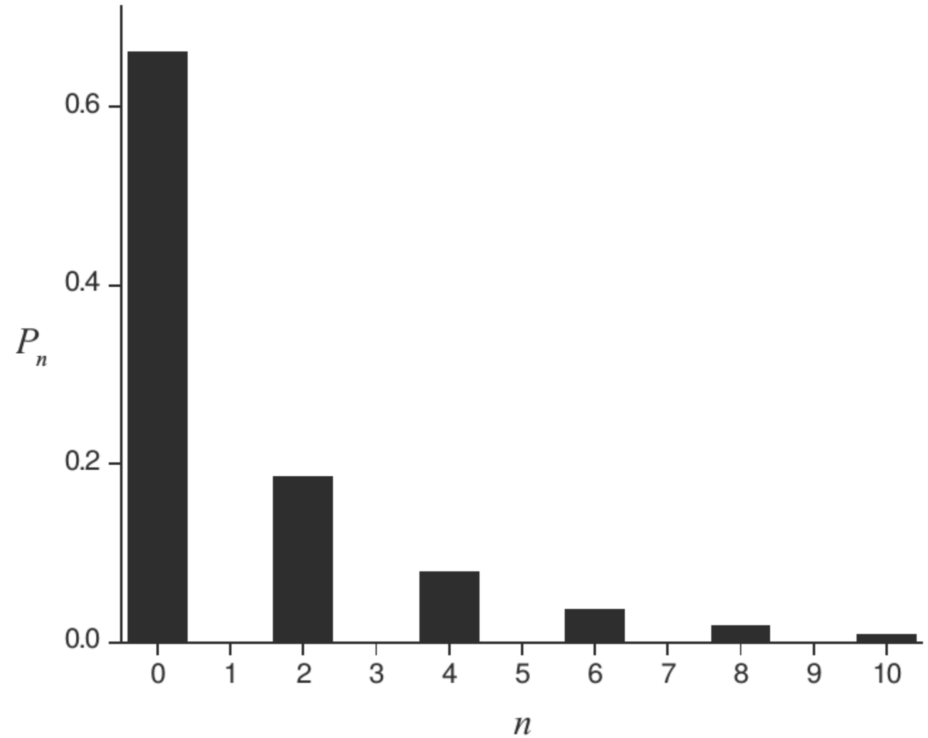


$$|\xi\rangle = \hat{S}(\xi)\,|0\rangle$$

$$\tilde{H} = \hbar\omega a^\dagger a$$

C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Squeezed Vacuum



$$|\xi\rangle = \sum_{n=0}^{\infty} P_n |n\rangle \qquad \tilde{H} = \hbar\omega a^{\dagger} a$$

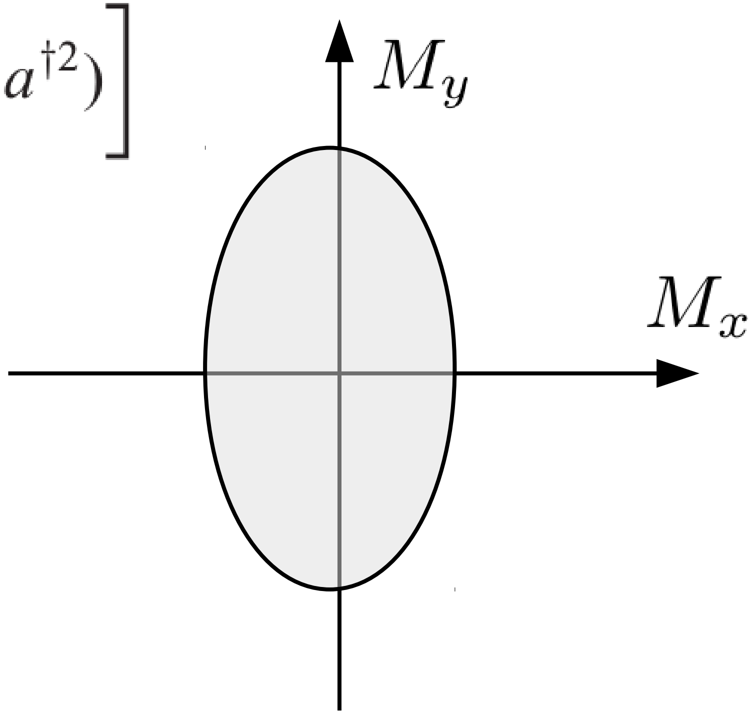
C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Squeezed Vacuum

$$\left\langle (\Delta \tilde{M}_x)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{-2r} \qquad \left\langle (\Delta \tilde{M}_y)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{2r}$$

$$\hat{S}(\xi) = \exp\left[\frac{1}{2}(\xi^* a^2 - \xi a^{\dagger 2})\right]$$

$$\xi = r\ e^{i\ \theta}$$



$$|\xi\rangle = \hat{S}(\xi)\,|0\rangle$$

$$\tilde{H} = \hbar\omega a^\dagger a$$

C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Squeezed Vacuum

$$\hat{S}(\xi)\,\hat{a}\,\hat{S}^{\dagger}(\xi) = \hat{a}\cosh r + e^{i\,\theta}\hat{a}^{\dagger}\sinh r,$$

$$\left(\hat{a}\mu + \hat{a}^{\dagger}\nu\right)|\xi\rangle = 0$$

$$\mu = \cosh r \qquad\qquad \nu = e^{i\theta}\sinh r$$

$$\hat{S}(\xi) = \exp\left[\frac{1}{2}(\xi^{*}a^{2} - \xi a^{\dagger 2})\right]$$

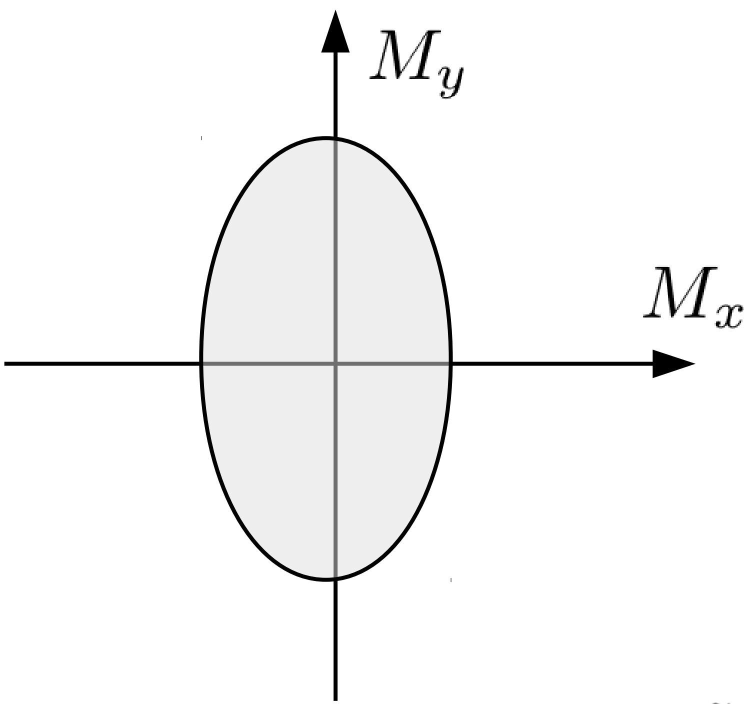
$$\xi = r\ e^{i\,\theta}$$

$$\tilde{H} = \hbar\omega a^{\dagger}a$$

C. Gerry and P. Knight, Introductory Quantum Optics (Cambridge University Press) .

Spontaneously Squeezed Vacuum

$$\left\langle (\Delta \tilde{M}_x)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{-2r} \qquad \left\langle (\Delta \tilde{M}_y)^2 \right\rangle = \frac{|\gamma|\hbar M_0}{2} e^{2r}$$



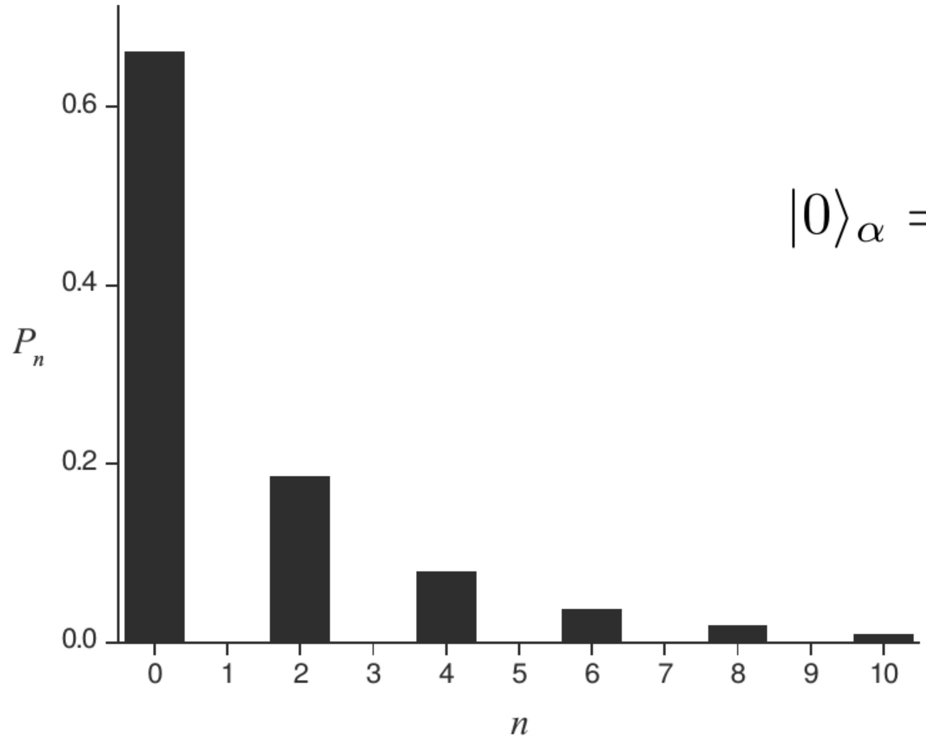
$$|0\rangle_\alpha$$

$$\alpha|0\rangle_\alpha = (ua + va^\dagger)|0\rangle_\alpha = 0$$

$$\tilde{H} = \hbar A a^\dagger a + \hbar B aa + \hbar B^* a^\dagger a^\dagger = \hbar\omega \alpha^\dagger \alpha$$

$$\alpha = ua + va^\dagger$$

Spontaneously Squeezed Vacuum

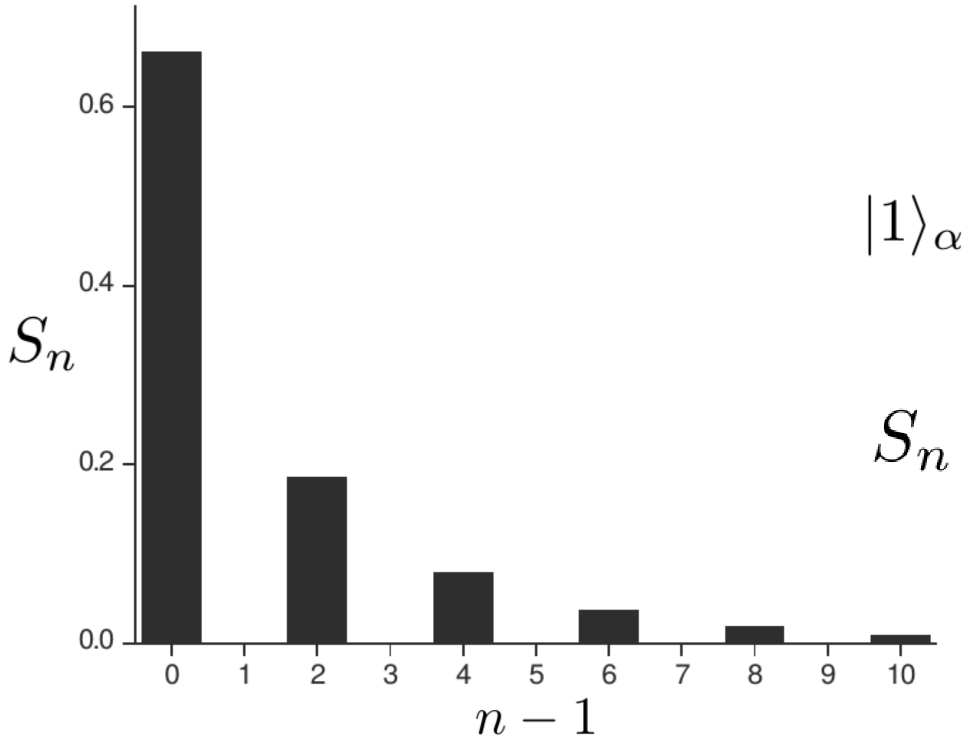


$$|0\rangle_\alpha = \sum_{n=0}^{\infty} P_n |n\rangle$$

$$\tilde{H} = \hbar A a^\dagger a + \hbar B a a + \hbar B^* a^\dagger a^\dagger = \hbar \omega \alpha^\dagger \alpha$$

$$\alpha = u a + v a^\dagger$$

Squeezed-magnon



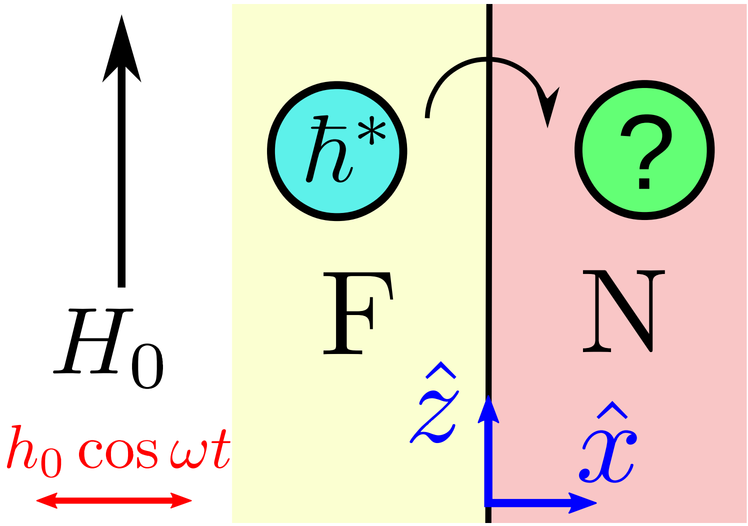
$$|1\rangle_\alpha = \sum_{n=0}^{\infty} S_n |n\rangle$$

$$S_n \neq P_n$$

$$\tilde{H} = \hbar A a^\dagger a + \hbar B a a + \hbar B^* a^\dagger a^\dagger = \hbar \omega \alpha^\dagger \alpha$$

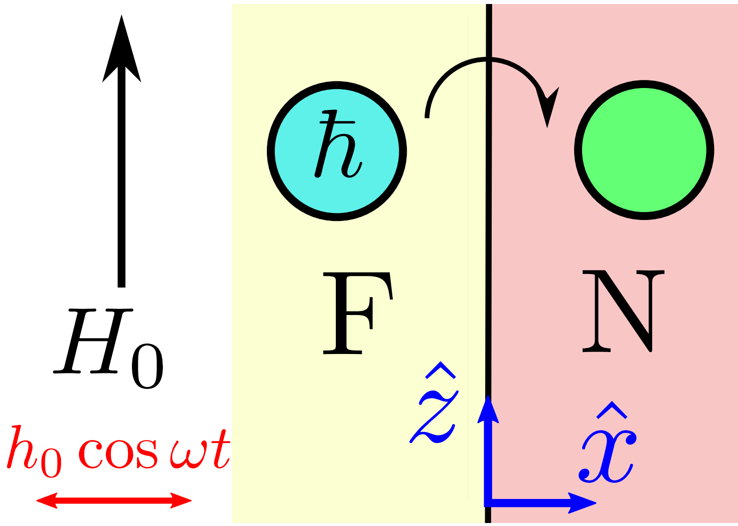
$$\alpha = u a + v a^\dagger$$

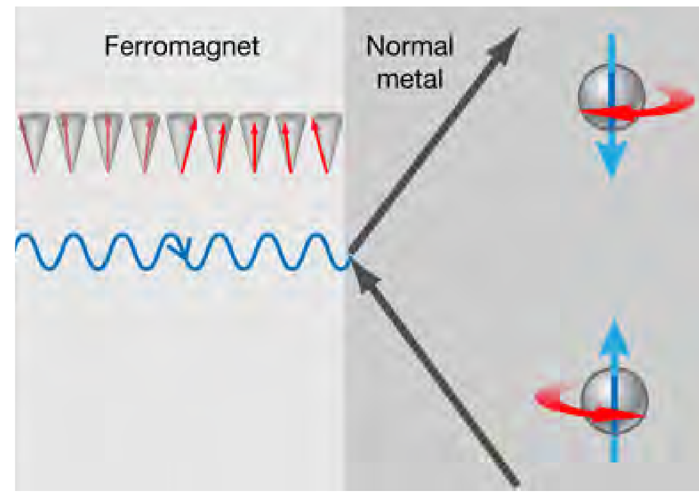
Excitation Transmutation



Excitation Transmutation

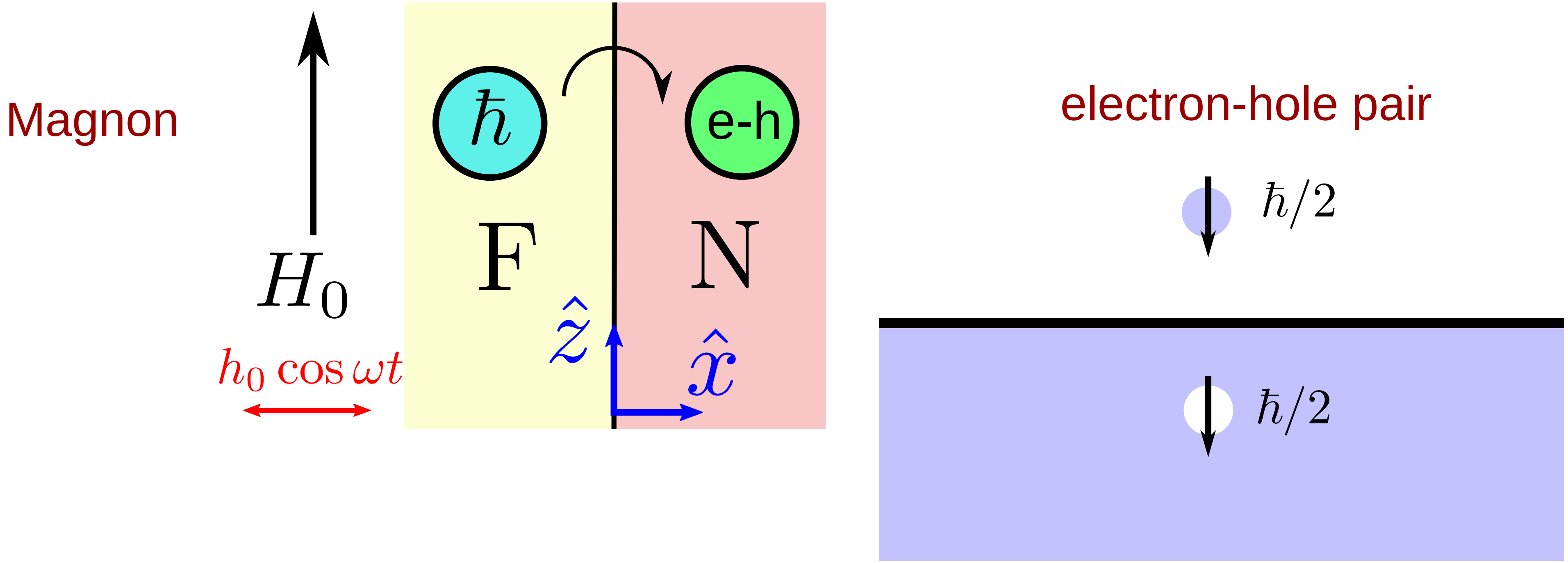
Magnon



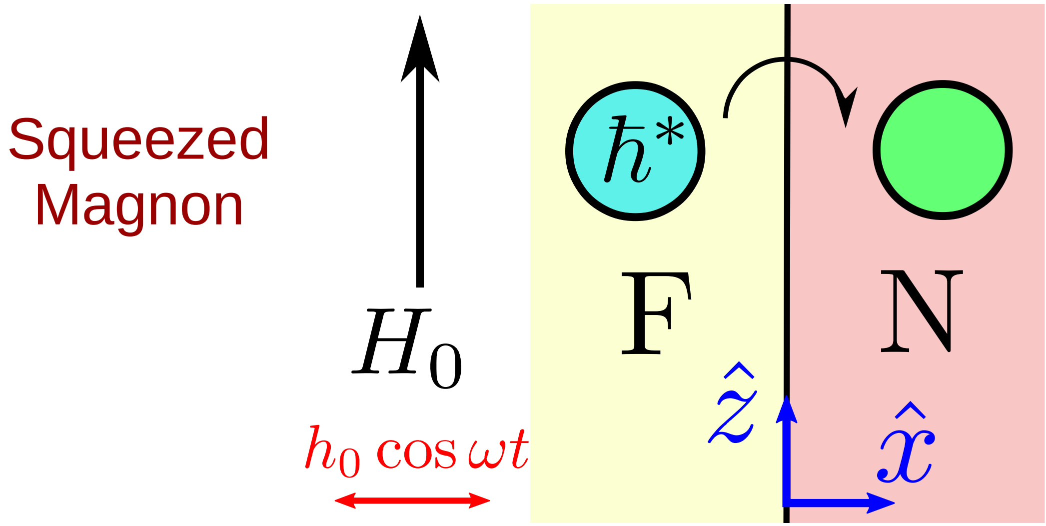


Viewpoint: Spin-magnon transmutation
Bauer and Tserkovnyak

Excitation Transmutation

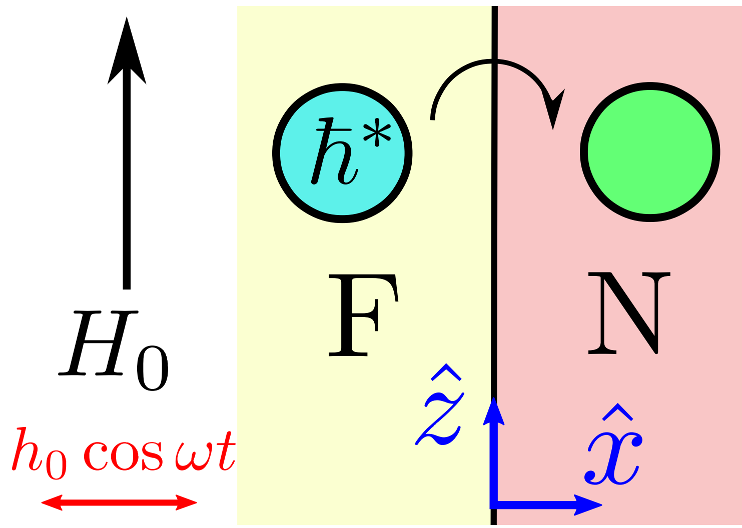


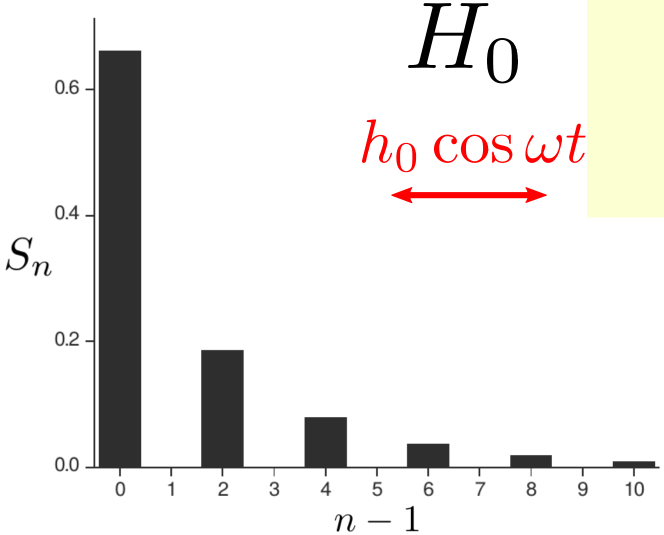
Excitation Transmutation



Excitation Transmutation

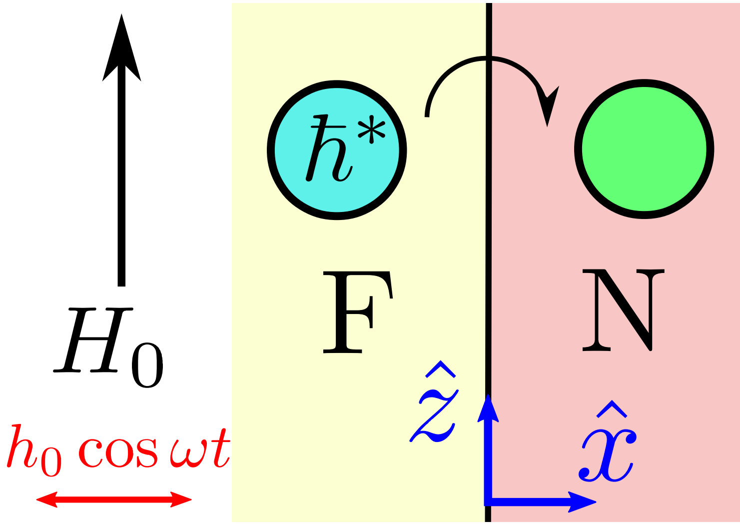
Squeezed Magnon

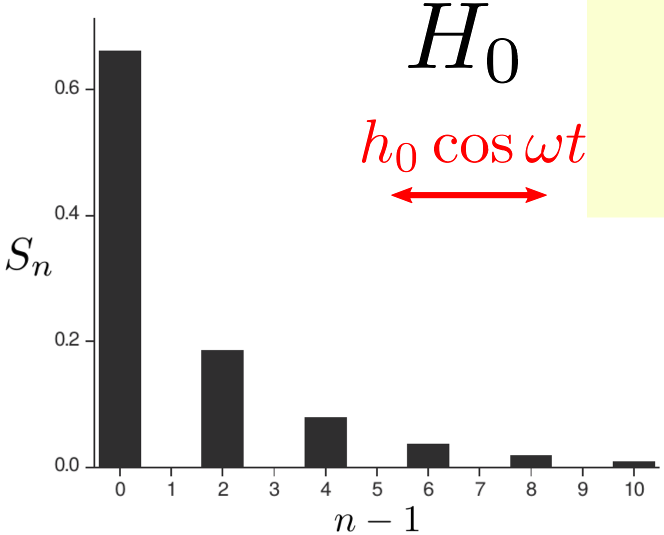




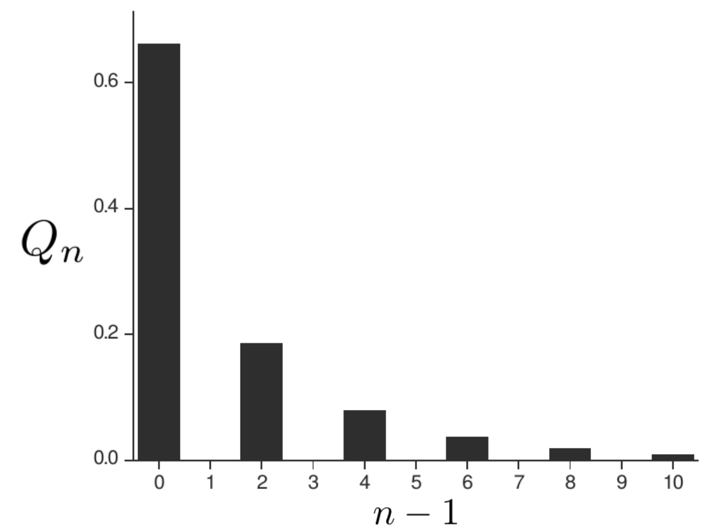
Excitation Transmutation

Squeezed Magnon





Squeezed electron-hole pair



Gordon Research Seminar (GRS)

- Held a day before the Gordon Research Conference and merges into it
- Primarily aimed at “young” scientists
- Keynote speaker
  - One talk giving broad introduction to the field
- Mentorship component
  - Talk/discussion on the non-scientific aspects of a scientific career
- Chairs are also young scientists and elected from within the participants

GRS on Spin Dynamics (2017)

Gordon Research Conferences *frontiers of science*

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Spin Dynamics in Nanostructures (GRS)
Gordon Research Seminar

Generation, Detection and Control of Spin Currents in Solid State Compounds

Dates

July 15-16, 2017

Location

Les Diablerets Conference Center
Les Diablerets, Switzerland

Organizers

Chairs:
Ludo J. Cornelissen & **Davide D. Bossini**

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Meeting Description

The Gordon Research Seminar on Spin Dynamics in Nanostructures is a unique forum for graduate students, post-docs, and other scientists with comparable levels of experience and education to present and exchange new data and cutting edge ideas.

The participants of this affiliated meeting will discuss novel results concerning the manipulation of spins in a broad group of materials and by a wide variety of stimuli (electric currents, temperature gradients, laser pulses). The main topics of the meeting will include antiferromagnetic spintronics, spin caloritronics, magnon spintronics, ultrafast spin dynamics and spin pumping. The phenomena under study will be discussed considering experimental results and theoretical approaches.

The meeting will start off with a general introduction into one of its main topics by one of the experts in the field. Furthermore, some of the challenges and opportunities of pursuing an academic career, in comparison with an employment in the private sector, will be addressed during a mentorship session, given by a senior scientist.

Related Meeting

This GRS was held in conjunction with the **"Spin Dynamics in Nanostructures" Gordon Research Conference (GRC)**. Refer to the **associated GRC program page** for more information.

GRS on Spin Dynamics (2017)

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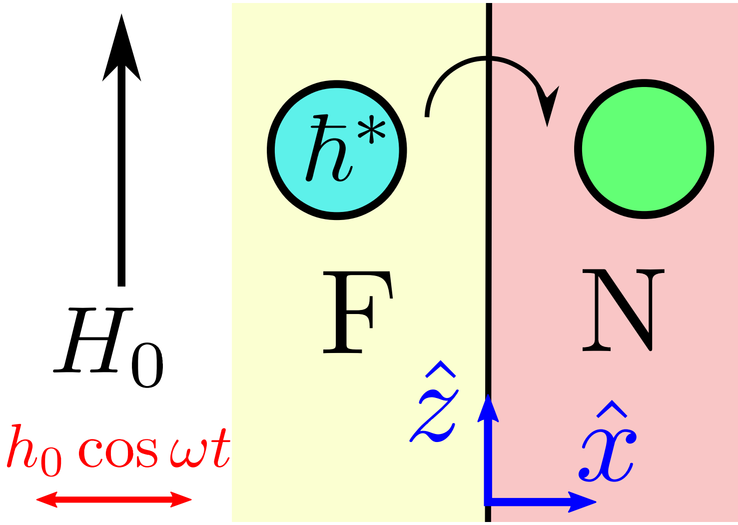
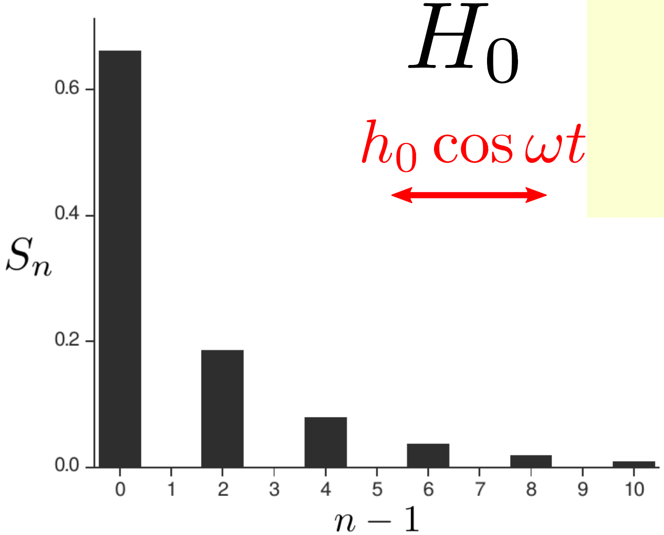
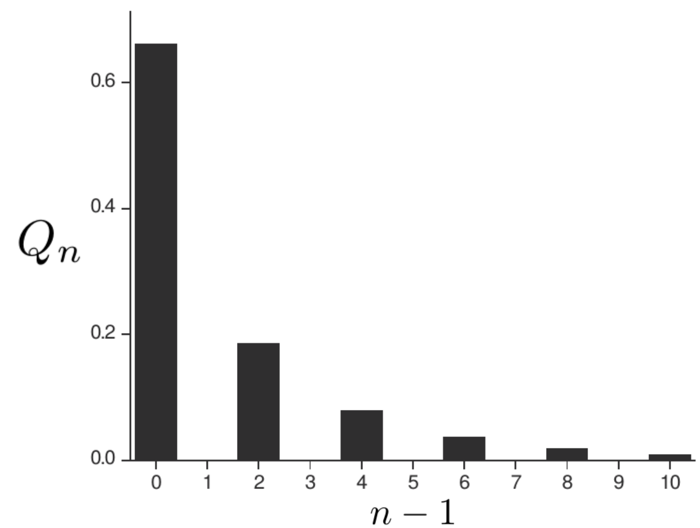
Excitation Transmutation

Squeezed Magnon

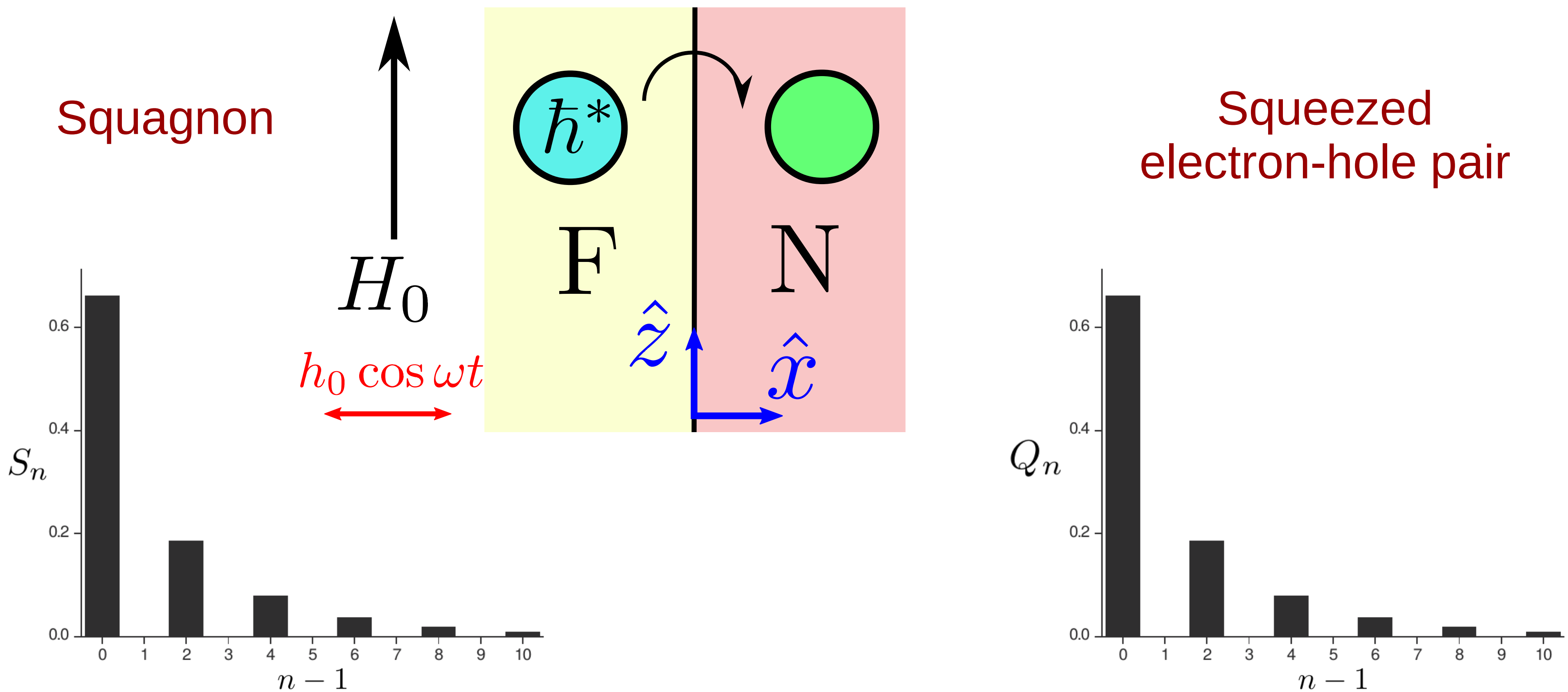


Squeezed electron-hole pair

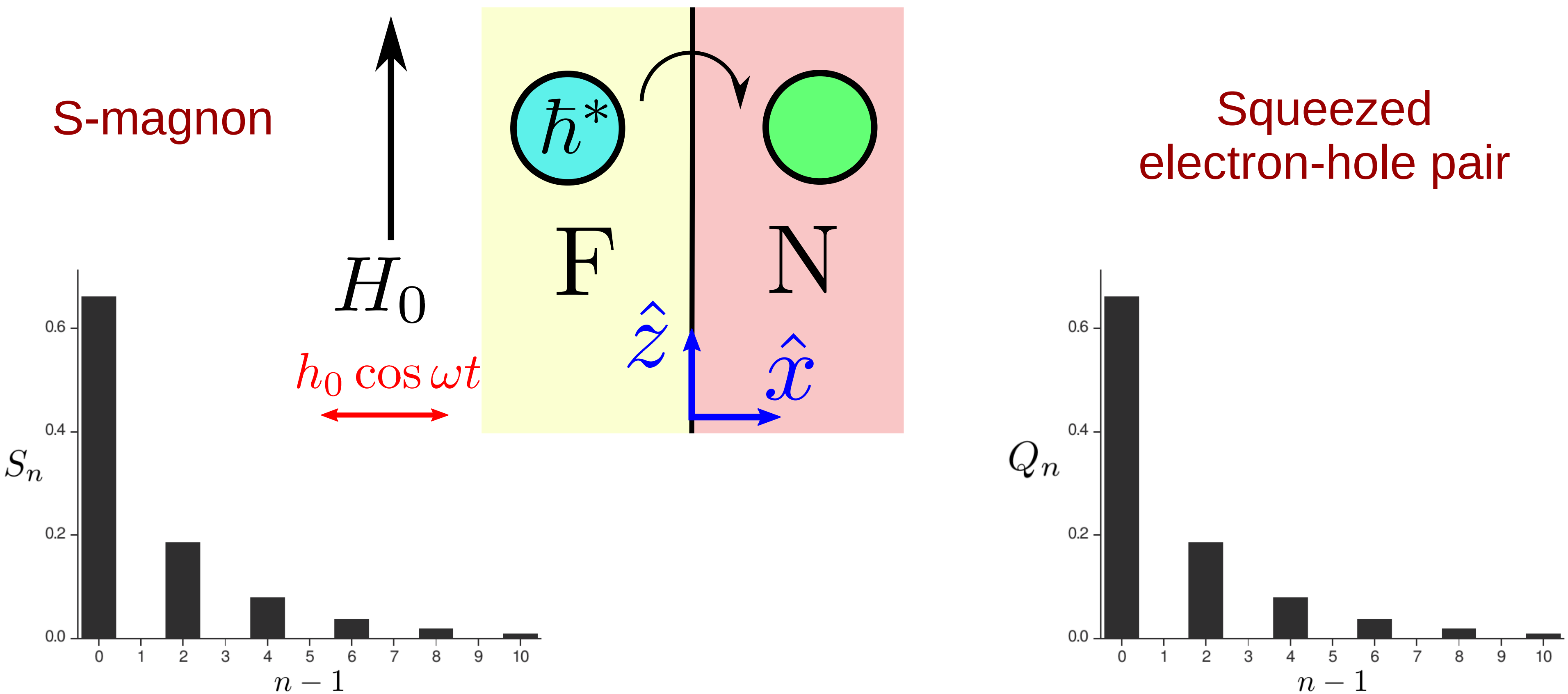




Excitation Transmutation

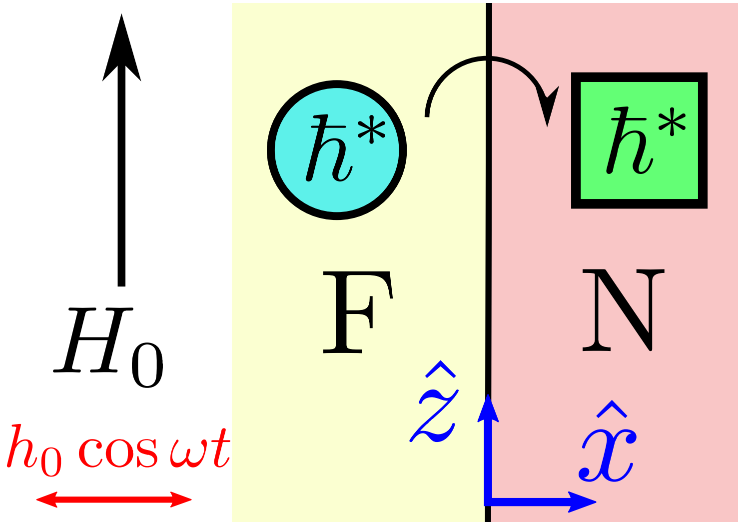


Excitation Transmutation

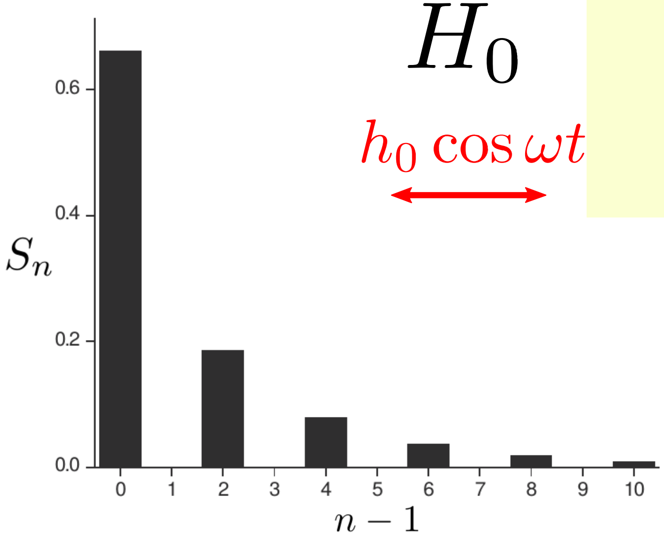


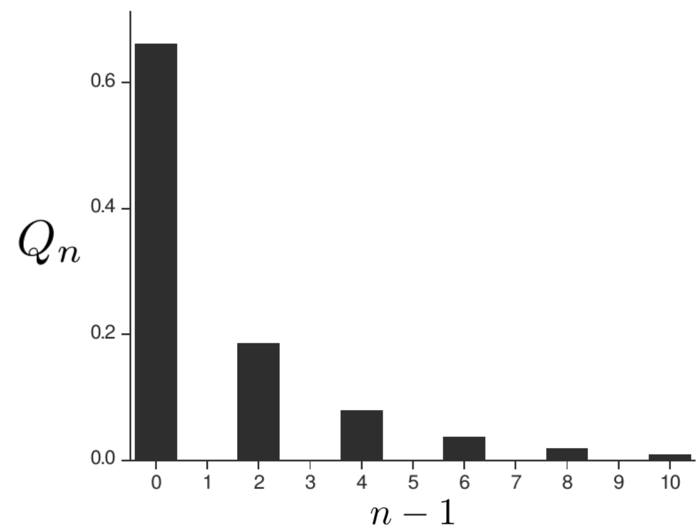
Excitation Transmutation

S-magnon



Sqair





Summary

- Dipolar interaction mediated squeezing and hybridization of magnons
- Greater (Lesser) than 1 spin of squeezed (hybridized) magnons
- Spin-zero excitations in Ferri- and Antiferromagnets
- Squeezed e-h pair (Sqair) quasi-quasiparticle