Exploiting antiferromagnetic magnons for strong coupling and condensation phenomena

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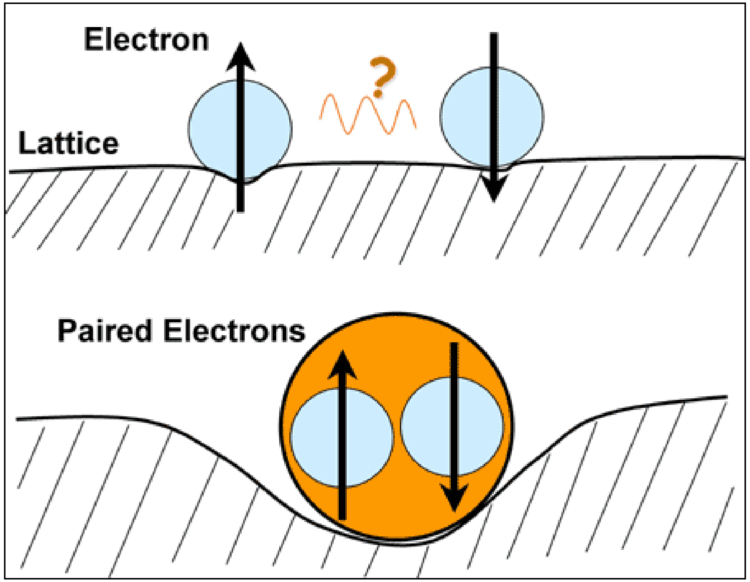
Norwegian University of Science and Technology, Trondheim

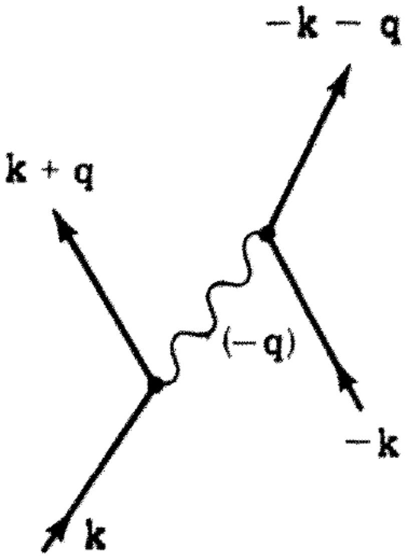
Néel ordered state is not the “true ground state” of an antiferromagnet!

“Classical” antiferromagnets exhibit various exchange-enhancement effects!

Antiferromagnetic quantum fluctuations may underlie superconductivity!

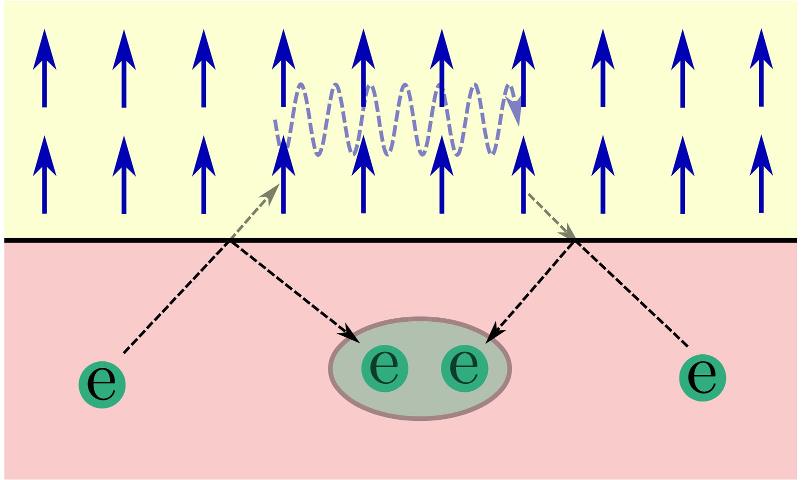
Superconductivity





$$k_B T_c = \hbar \omega_c \exp\left(-\frac{1}{\lambda}\right)$$

Magnon-mediated Superconductivity



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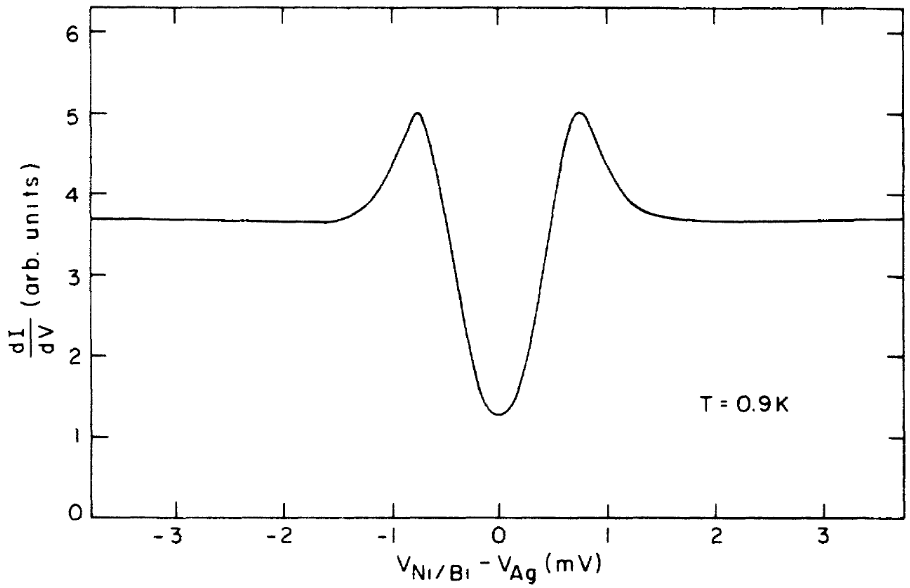
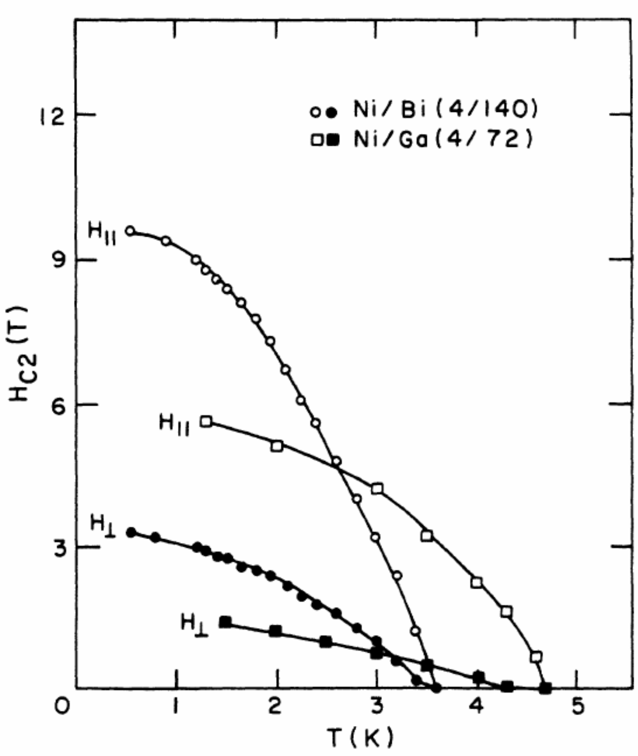
Kargarian et al., PRL 117, 076806 (2016).
Gong et al., Sci. Adv 3, e1602579 (2017).
Rohling et al., PRB 97, 115401 (2018).
Hugdal et al., PRB 97, 195438 (2018).
...

$$k_B T_c = \hbar \omega_c \exp\left(-\frac{1}{\lambda}\right)$$

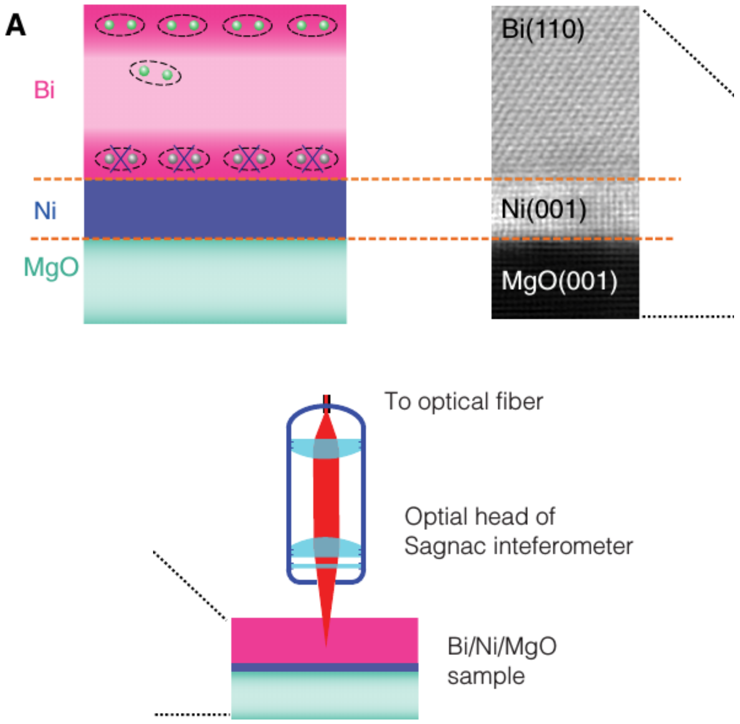
Superconductivity in Magnet/Metal Bilayers

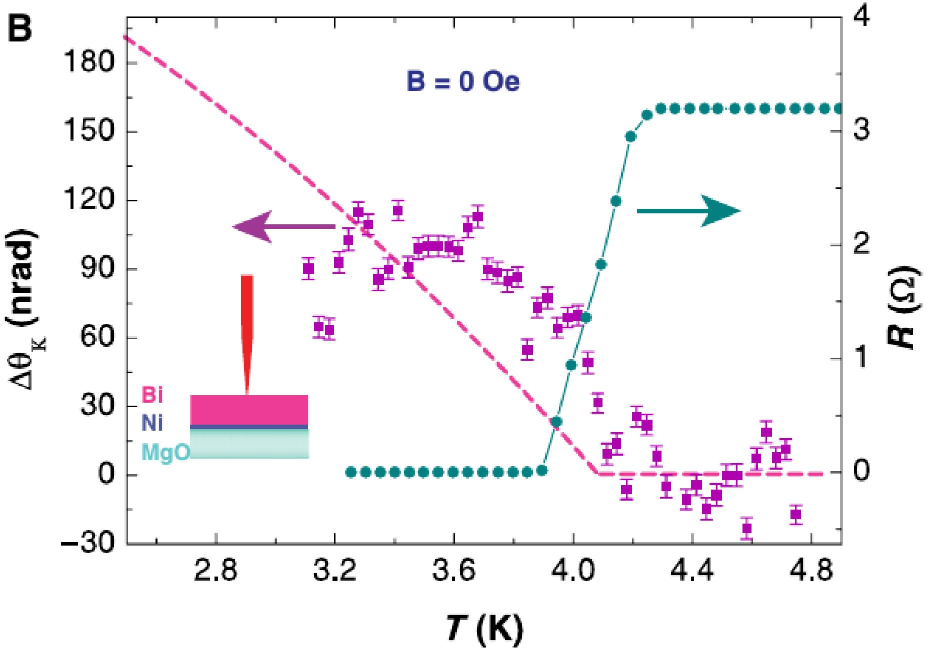




J. S. Moodera and R. Meservey. Phys. Rev. B 42, 179 (1990).

Superconductivity in Magnet/Metal Bilayers





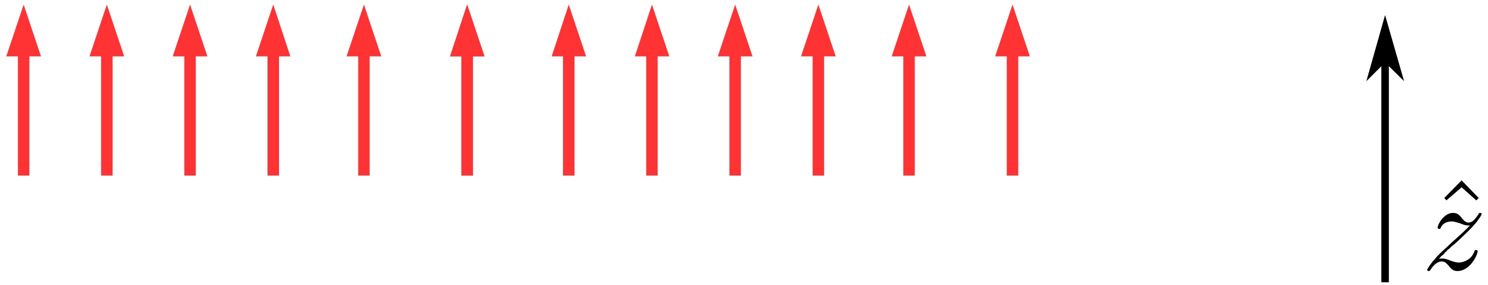
Gong et al., Sci. Adv 3, e1602579 (2017).

Outline

- ~~Brief introduction~~
- Magnons in ferromagnets
- Antiferromagnetic magnons
- Exploiting squeezing-mediated quantum fluctuations
- Superconductivity enhancement due to squeezing
- Magnon-mediated indirect exciton condensation

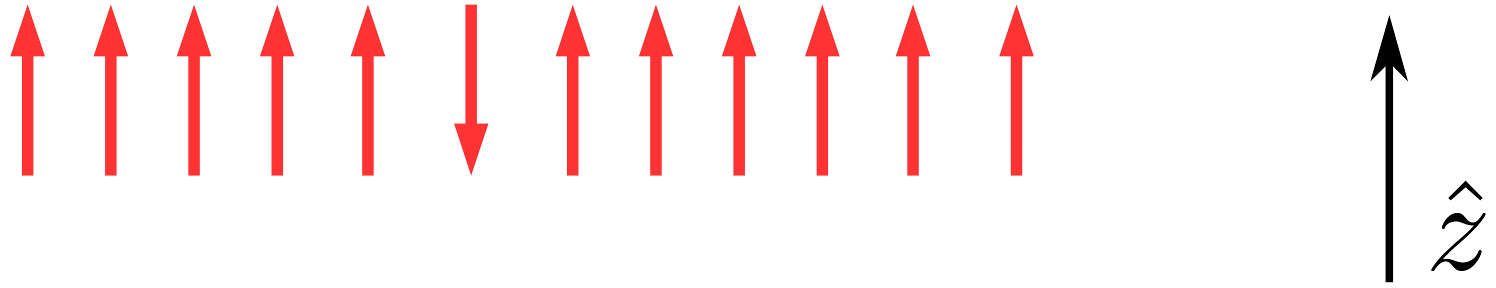
Ferromagnet

Ferromagnet Ground State



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

Ferromagnet Excited State



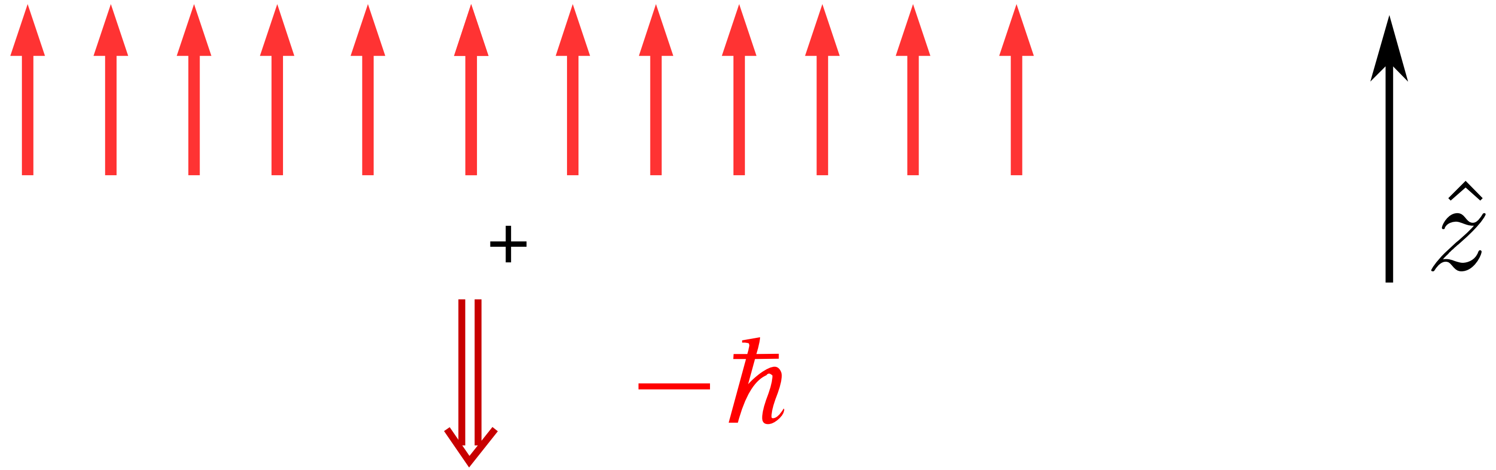
C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 1953)

Ferromagnet Excited State

Ground State

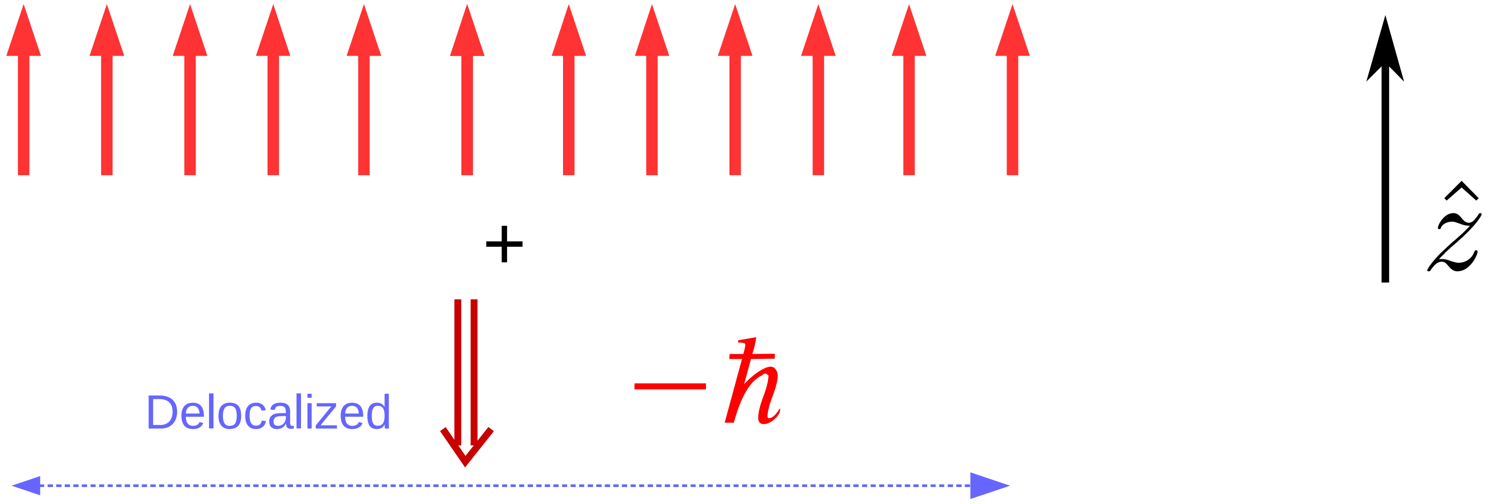
+

Magnon



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

Magnon



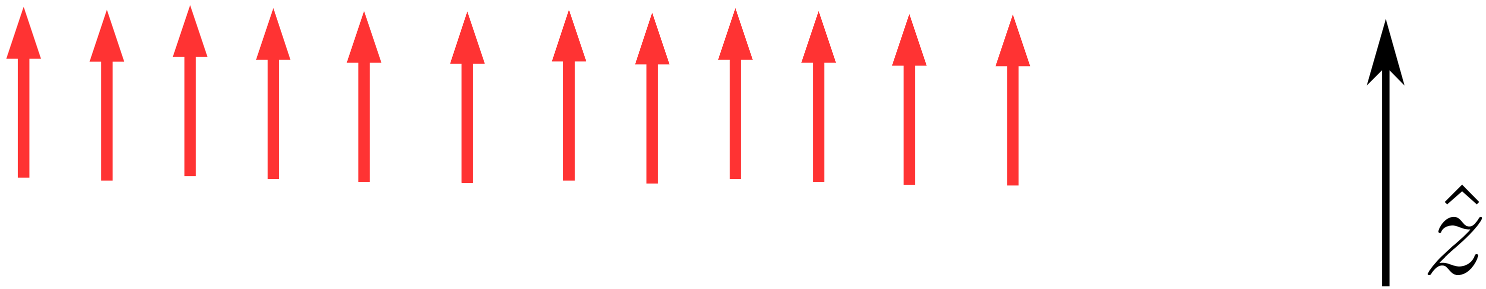
Considering only exchange interaction and Zeeman energy!

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

Wavefunctions Notation

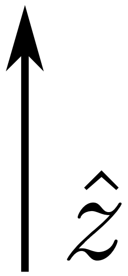
Fully Ordered State	$\lvert \ \rangle$
1 Magnon	$\lvert \Downarrow \rangle$
2 Magnons	$\lvert \Downarrow \Downarrow \rangle$

Ferromagnet Ground State



$$| \quad \rangle$$

Ferromagnet Ground State



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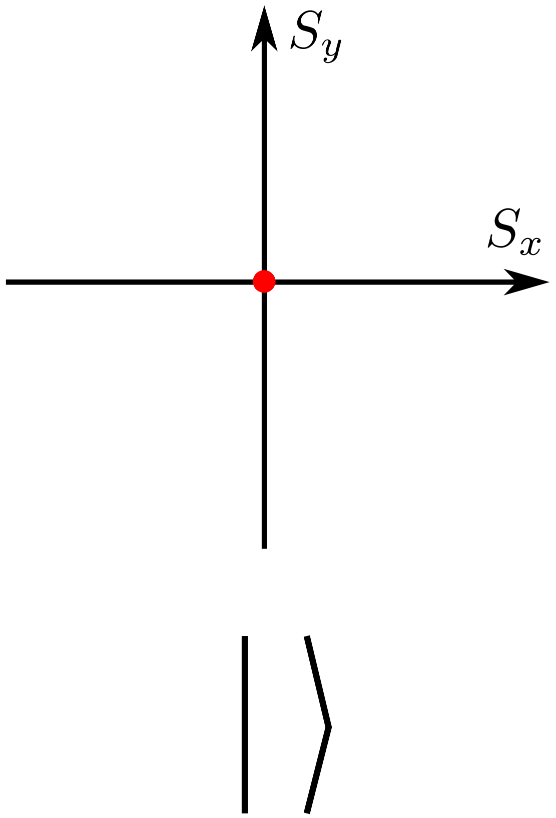
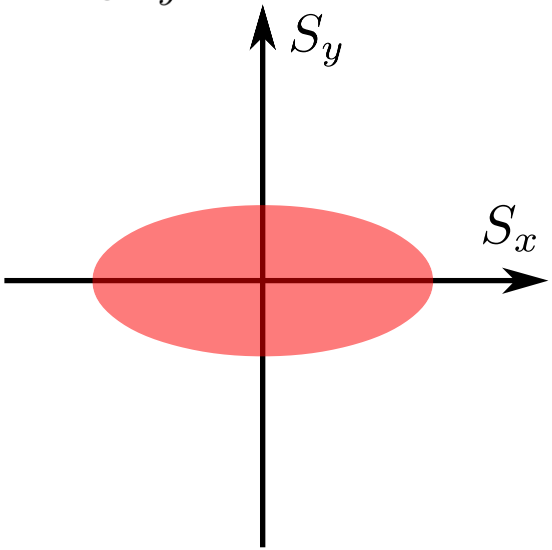
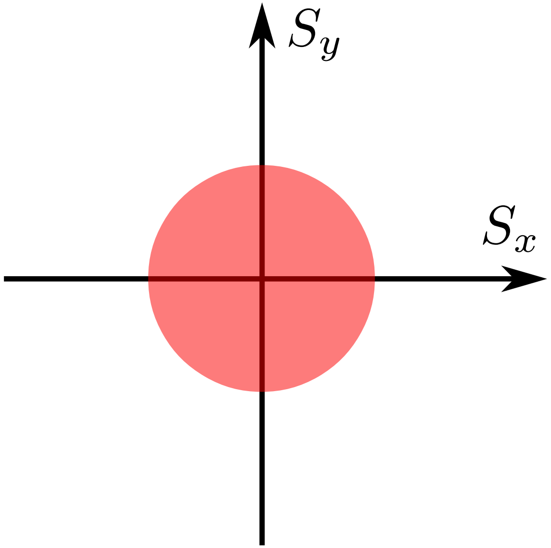
Ferromagnet Ground State



Ferromagnet Ground State

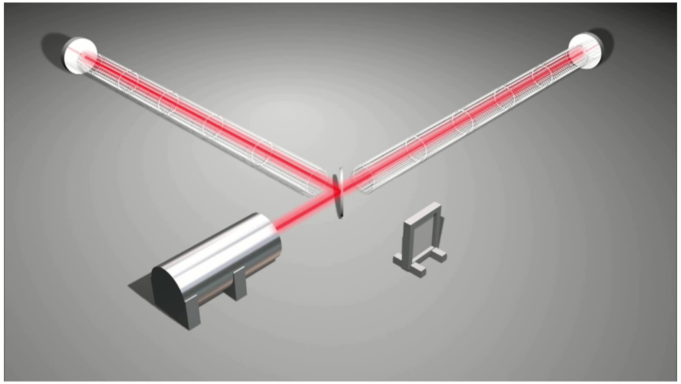
$$H = K_x S_x^2 + K_y S_y^2 + \cdots$$

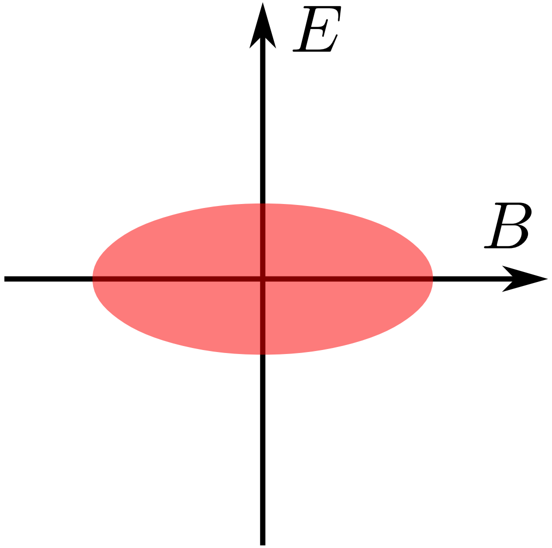




$$|\ \rangle + |\Downarrow\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\Downarrow\rangle + \ldots = S(r)\,|\ \rangle$$

Squeezed Optical Vacuum



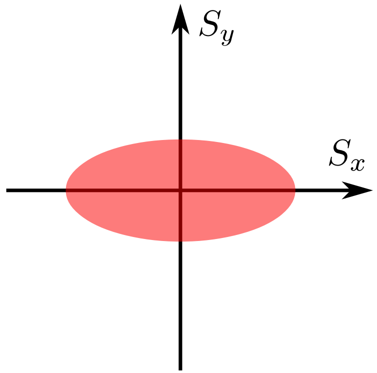


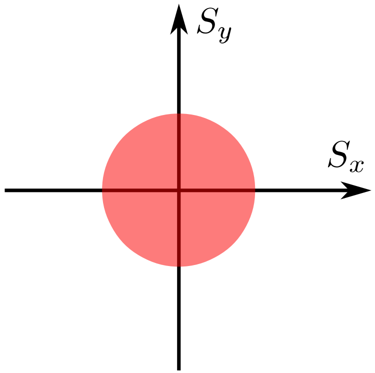
Nonequilibrium state!
Not an eigenstate!

$$| \; \rangle + |\Downarrow\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\Downarrow\rangle + \ldots$$

Chapter 7: Nonclassical light
C. C. Gerry and P. L. Knight, *Introductory Quantum Optics* (Cambridge University Press, 2005).

Ferromagnetic Eigenmodes





Ground State

$$|\ \rangle + |\Downarrow\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\Downarrow\rangle + \ldots = S(r)\,|\ \rangle$$

Excitation

$$|\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow\rangle + \ldots = S(r)\,|\Downarrow\rangle$$

Ferromagnet Summary

- Magnon-squeezing mediated by “weak” spin-nonconserving interactions such as anisotropy
- Net effect of the order of unity
- Bogoliubov transform causes squeezing

Squeezed magnon

$$|\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\rangle + |\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow\rangle + \dots = S(r)\,|\Downarrow\rangle$$

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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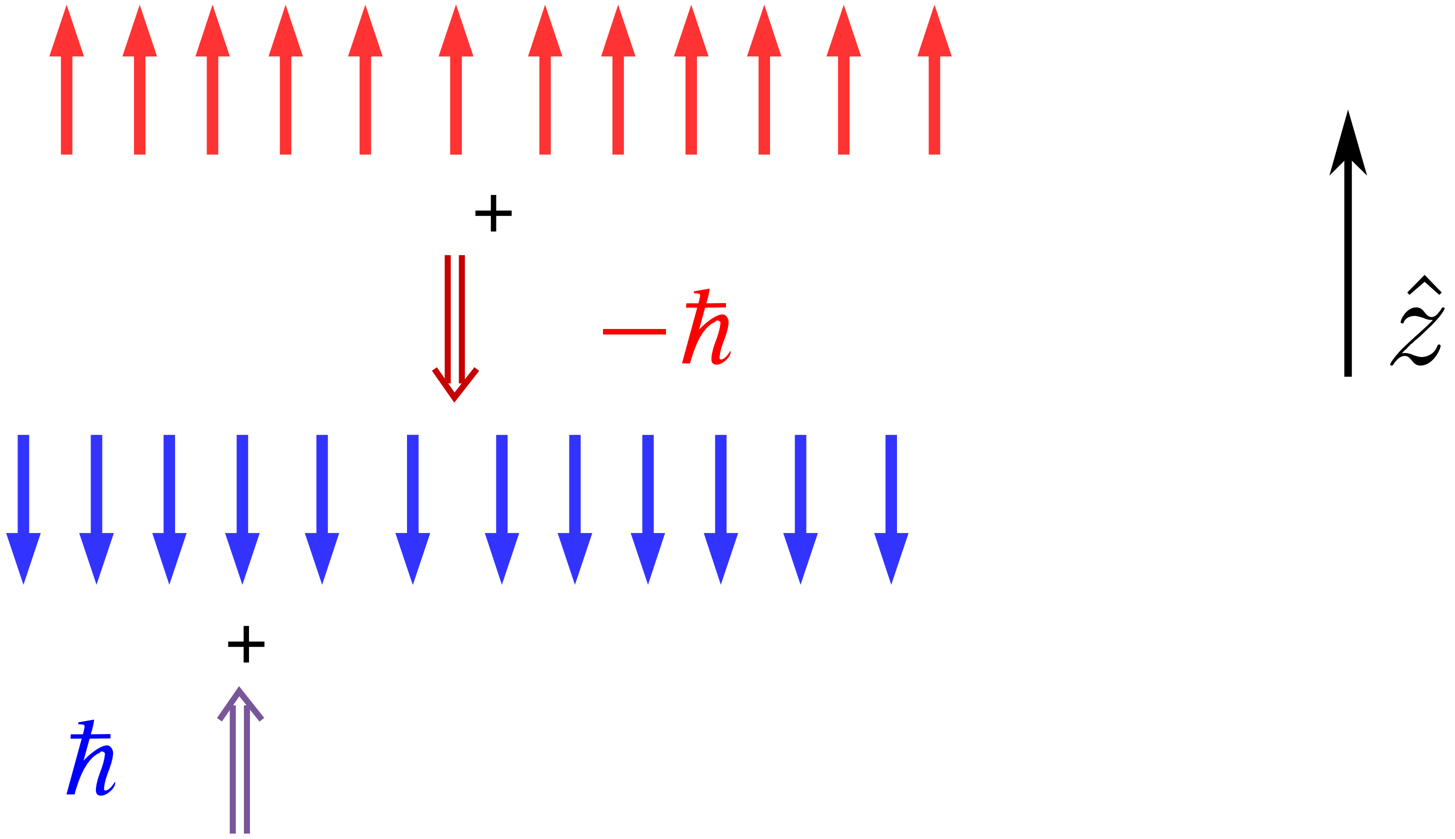
Antiferromagnet

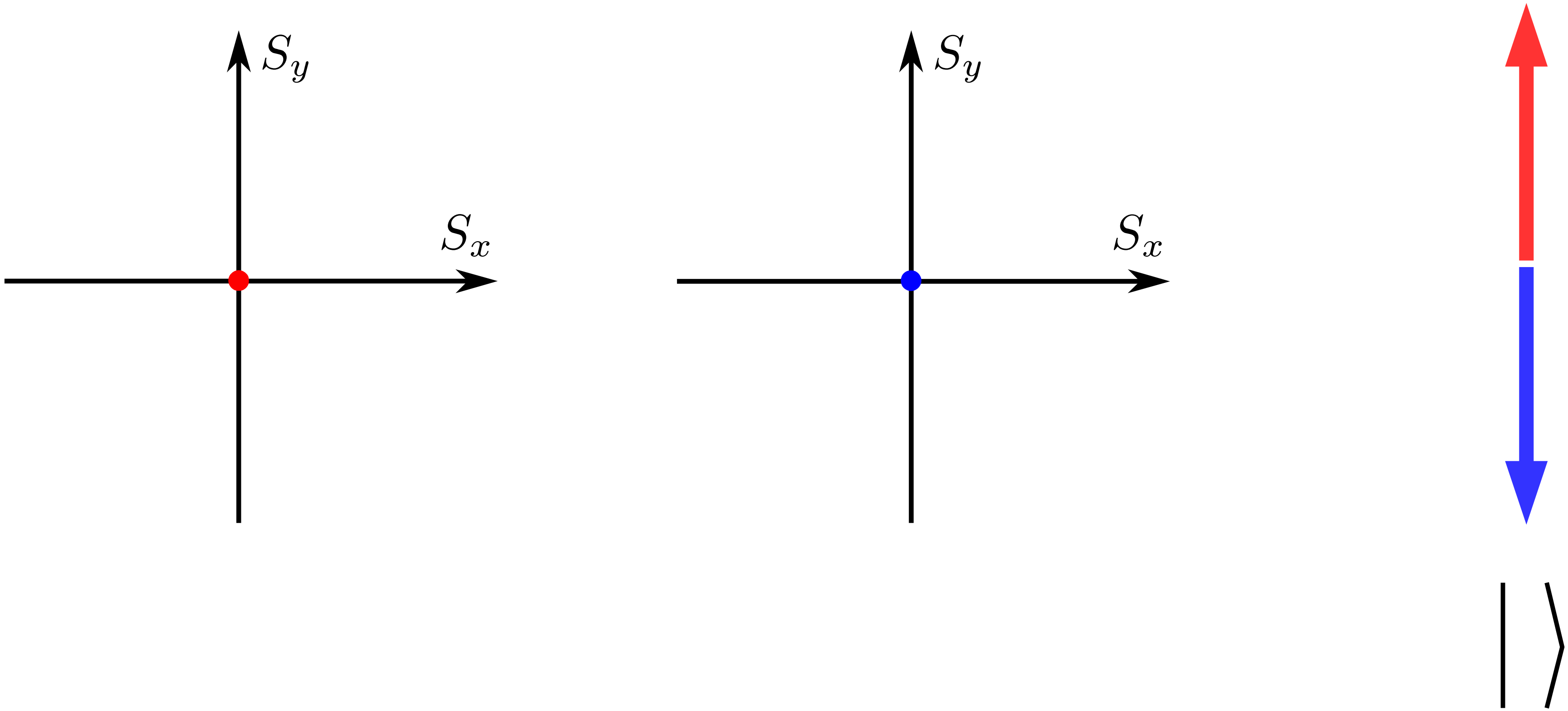
Two Interpenetrating Sublattices



Néel Ordered State

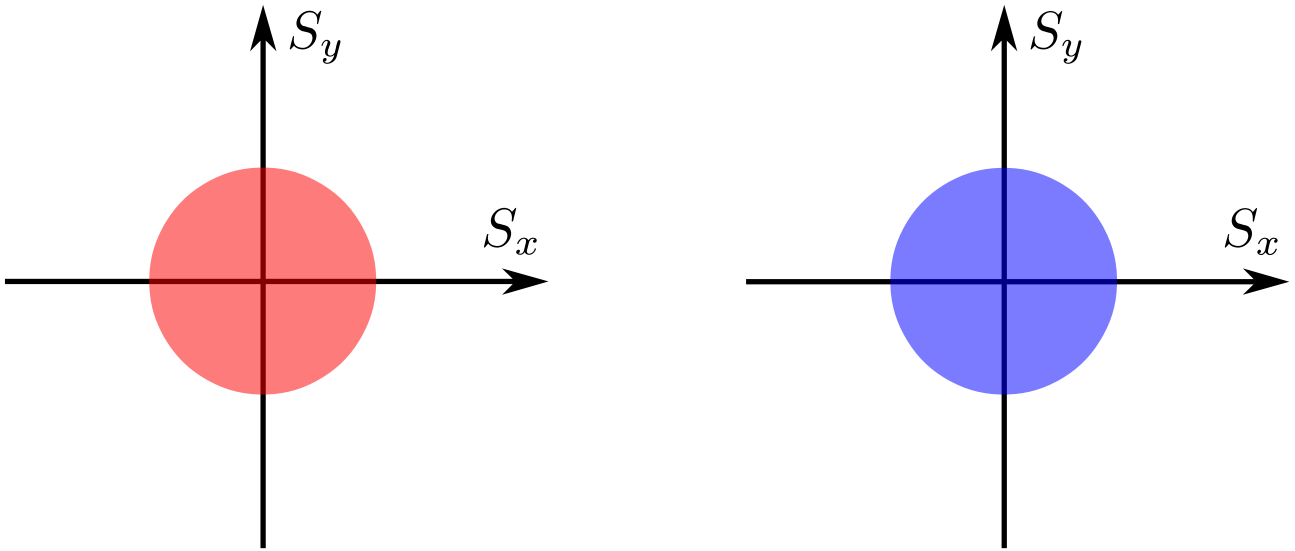
$| \ \rangle$

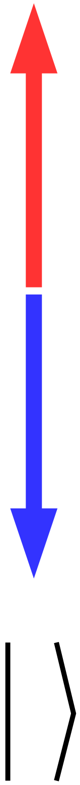
Néel Ordered State



Néel Ordered State

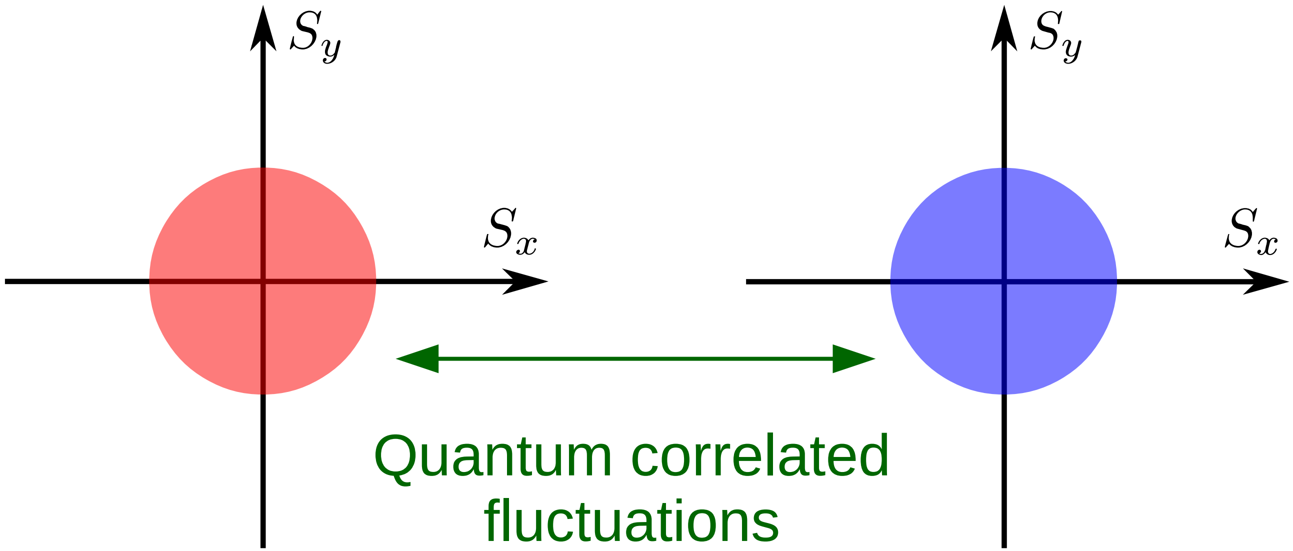
$$H = J\vec{S}_{\mathrm{A}} \cdot \vec{S}_{\mathrm{B}} + \cdots$$

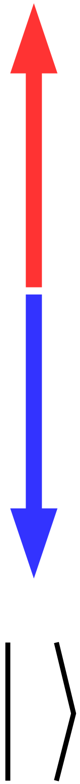




Antiferromagnetic Ground State

$$H = J\vec{S}_{\mathrm{A}} \cdot \vec{S}_{\mathrm{B}} + \cdots$$





Antiferromagnetic Eigenmodes

Ground State

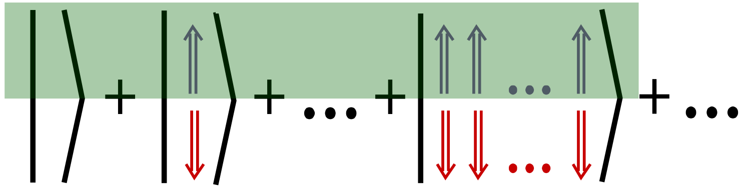
$$\left|\,\right\rangle + \left|\begin{matrix}\Uparrow\\ \Downarrow\end{matrix}\right\rangle + \ldots + \left|\begin{matrix}\Uparrow & \Uparrow & \cdots & \Uparrow\\ \Downarrow & \Downarrow & \cdots & \Downarrow\end{matrix}\right\rangle + \ldots = S_2(r)\left|\,\right\rangle$$

Spin-up Excitation

$$\left|\Uparrow\right\rangle + \left|\begin{matrix}\Uparrow & \Uparrow\\ \Downarrow & \end{matrix}\right\rangle + \ldots + \left|\begin{matrix}\Uparrow & \Uparrow & \Uparrow & \cdots & \Uparrow\\ \Downarrow & \Downarrow & \cdots & & \Downarrow\end{matrix}\right\rangle + \ldots = S_2(r)\left|\Uparrow\right\rangle$$

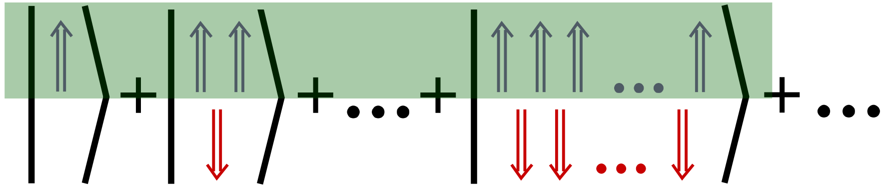
Antiferromagnetic Eigenmodes

$\sinh^2 r$

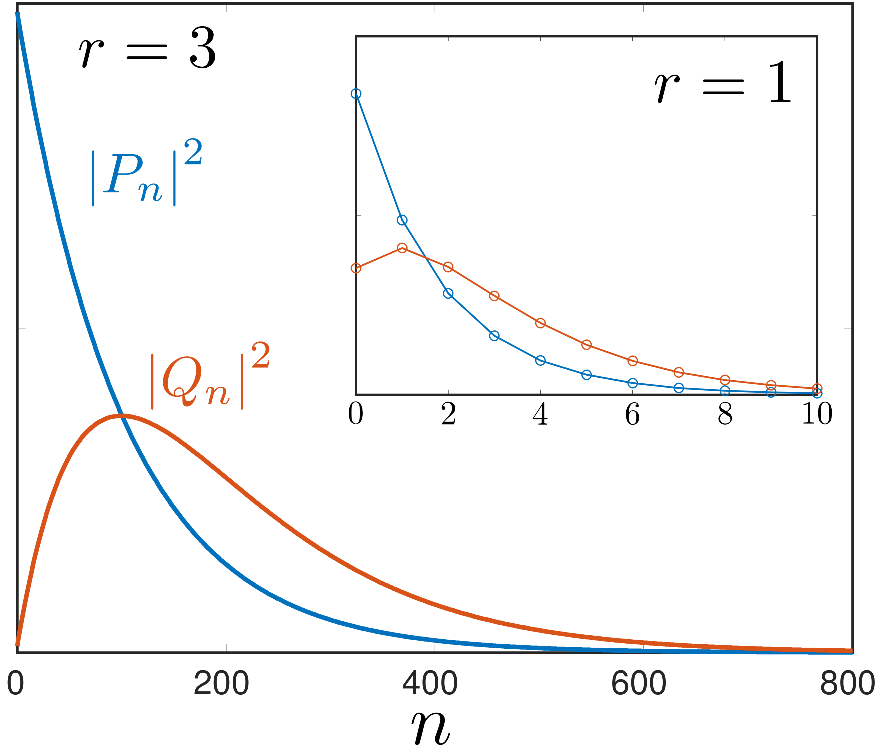


$$|0\rangle_{\text{sq}} = \sum_n P_n \, |n, n\rangle_{\text{sub}}$$

$\sinh^2 r + \cosh^2 r$



$$|\uparrow\rangle_{\text{sq}} = \sum_n Q_n \, |n+1, n\rangle_{\text{sub}}$$



Degree of Squeezing

$$\tilde{H}_{\text{uni}} = \frac{J}{\hbar^2} \sum_{i,\boldsymbol{\delta}} \tilde{\boldsymbol{S}}_{\text{A}}(\boldsymbol{r}_i) \cdot \tilde{\boldsymbol{S}}_{\text{B}}(\boldsymbol{r}_i + \boldsymbol{\delta}) - \frac{K}{\hbar^2} \sum_i \left[\tilde{S}_{\text{A}z}(\boldsymbol{r}_i) \right]^2 - \frac{K}{\hbar^2} \sum_j \left[\tilde{S}_{\text{B}z}(\boldsymbol{r}_j) \right]^2$$

$$\cosh^2 r \sim \sqrt{\frac{J}{K}}$$

$$\frac{J}{K} = 10^4 \implies \cosh^2 r \approx 100 \text{ and } r \approx 3$$

Most squeezed state of light achieved thus far corresponds to $r \approx 1.7$!

Antiferromagnet Summary

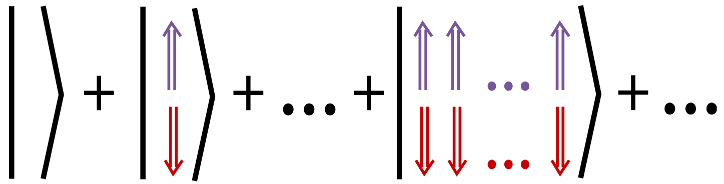
- Classical: Néel ordered ground state and sublattice-magnon
- Quantum (Actual): Squeezed vacuum and magnons
- Squeezing caused by exchange
- Large net effect (~ 100 for typical AFM)
- Bogoliubov transform causes squeezing

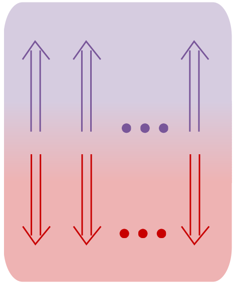
A. Kamra, U. Agrawal, and W. Belzig. *Noninteger-spin magnonic excitations in untextured magnets*. Phys. Rev. B 96, 020411(R) (2017).

A. Kamra, E. Thingstad, G. Rastelli, R. A. Duine, A. Brataas, W. Belzig, and A. Sudbø. *Antiferromagnetic magnons as highly squeezed Fock states underlying quantum correlations*. arXiv:1904.04553.

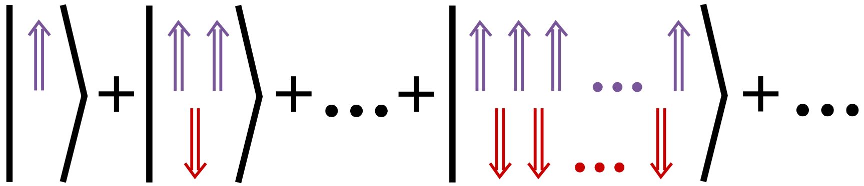
Antiferromagnet Summary

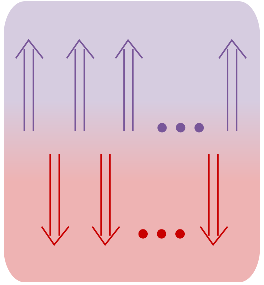
Ground State





Spin-up Excitation





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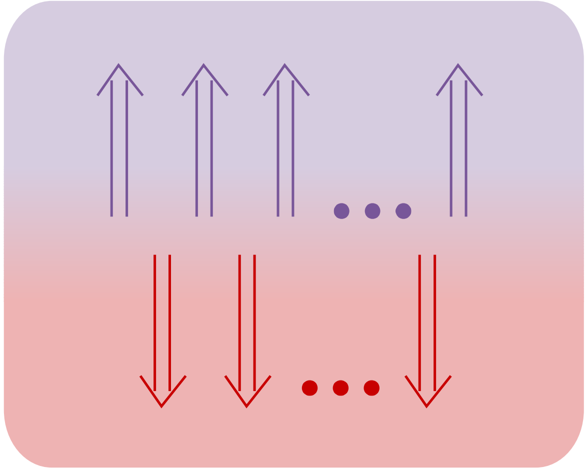
Exploiting Magnon-Squeezing

Coupling Amplification



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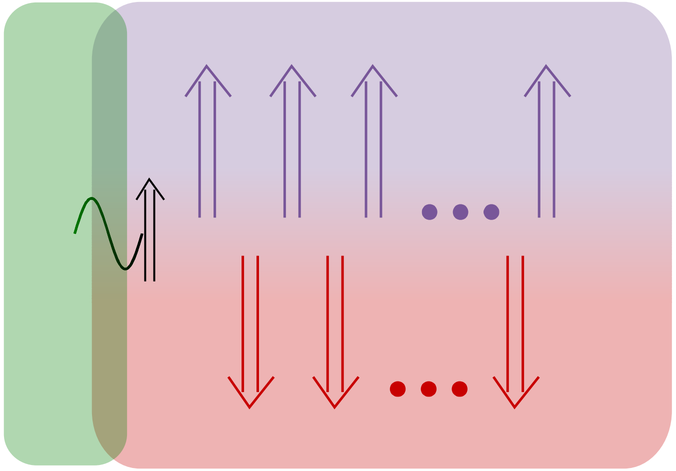

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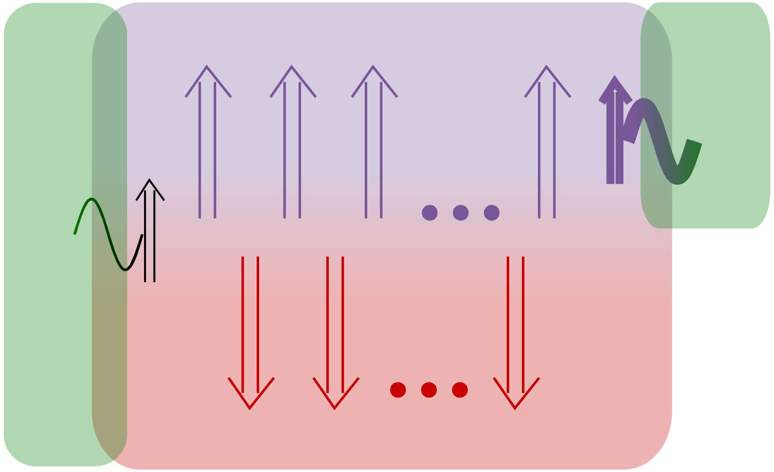
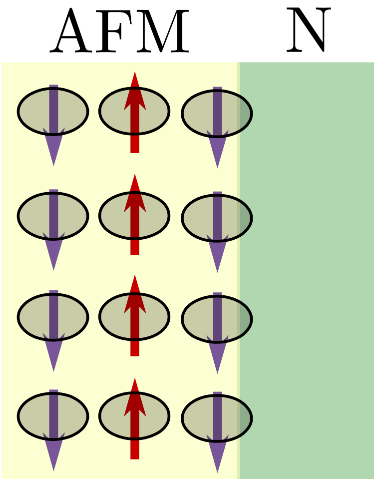
Coupling Amplification

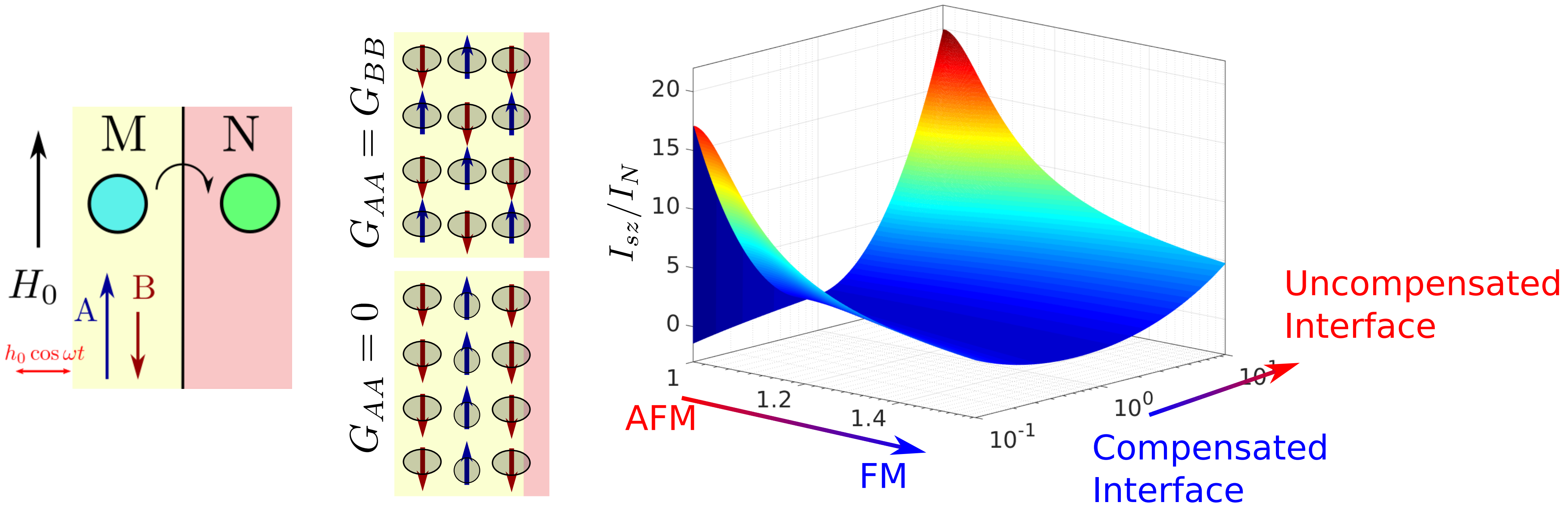




Amplification of sublattice-spin mediated interactions!

A. Kamra, E. Thingstad, G. Rastelli, R. A. Duine, A. Brataas, W. Belzig, and A. Sudbø. *Antiferromagnetic magnons as highly squeezed Fock states underlying quantum correlations*. arXiv:1904.04553.

Enhancement in Spin Pumping Current



A. Kamra and W. Belzig. *Spin pumping and shot noise in ferrimagnets: bridging ferro- and antiferromagnets*. Phys. Rev. Lett. 119, 197201 (2017).

Sublattice-spin-mediated Coupling

PHYSICAL REVIEW LETTERS **120,** 093602 (2018)

Enhancing Cavity Quantum Electrodynamics via Antisqueezing: Synthetic Ultrastrong Coupling

C. Leroux,[1] L. C. G. Govia,[2] and A. A. Clerk[2]
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[2]*Institute for Molecular Engineering, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA*

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PHYSICAL REVIEW LETTERS **120,** 093601 (2018)

Exponentially Enhanced Light-Matter Interaction, Cooperativities, and Steady-State Entanglement Using Parametric Amplification

Wei Qin,[1,2] Adam Miranowicz,[2,3] Peng-Bo Li,[2,4] Xin-You Lü,[5] J. Q. You,[1,6] and Franco Nori[2,7]
[1]*Quantum Physics and Quantum Information Division, Beijing Computational Science Research Center, Beijing 100193, China*
[2]*CEMS, RIKEN, Wako-shi, Saitama 351-0198, Japan*
[3]*Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
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[5]*School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*
[6]*Department of Physics, Zhejiang University, Hangzhou 310027, China*
[7]*Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*

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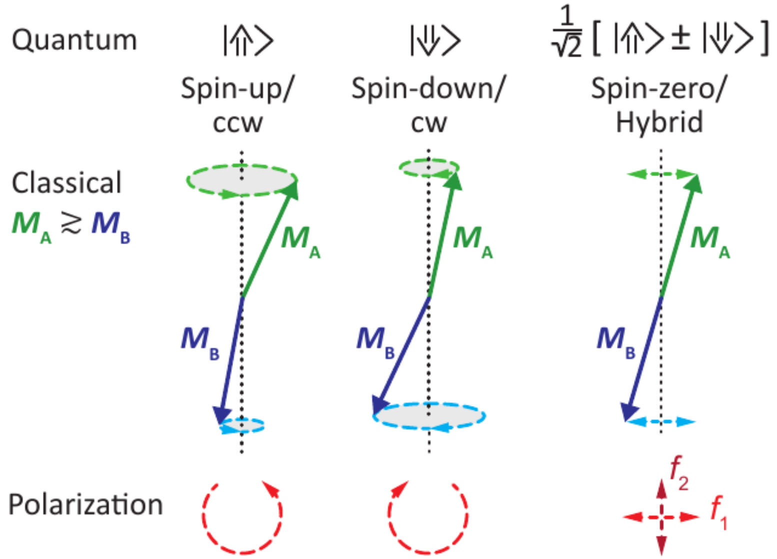
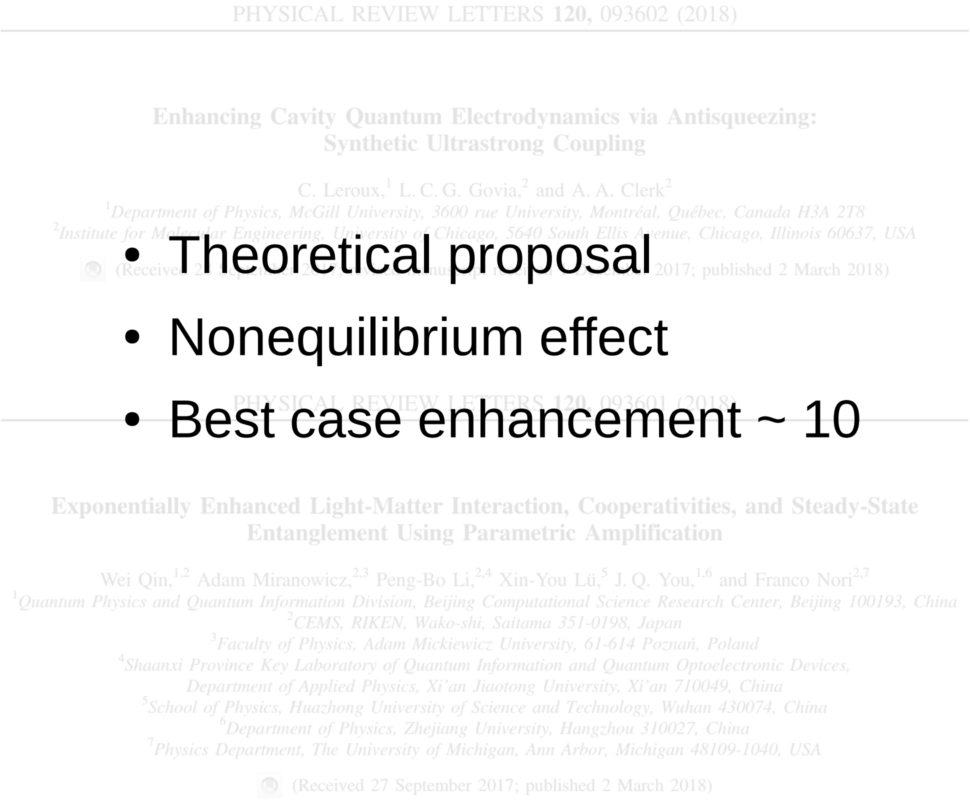


Experiments @ ~ 280 K

L. Liensberger, A. Kamra, H. Maier-Flaig, S. Gepraegs, A. Erb, S. T. B. Goennenwein, R. Gross, W. Belzig, H. Huebl, and M. Weiler. *Exchange-enhanced ultrastrong magnon-magnon coupling in a compensated ferrimagnet*. Phys. Rev. Lett. 123, 117204 (2019).

Sublattice-spin-mediated Coupling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[6]*Department of Physics, Zhejiang University, Hangzhou 310027, China*

[7]*Physics Department, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*

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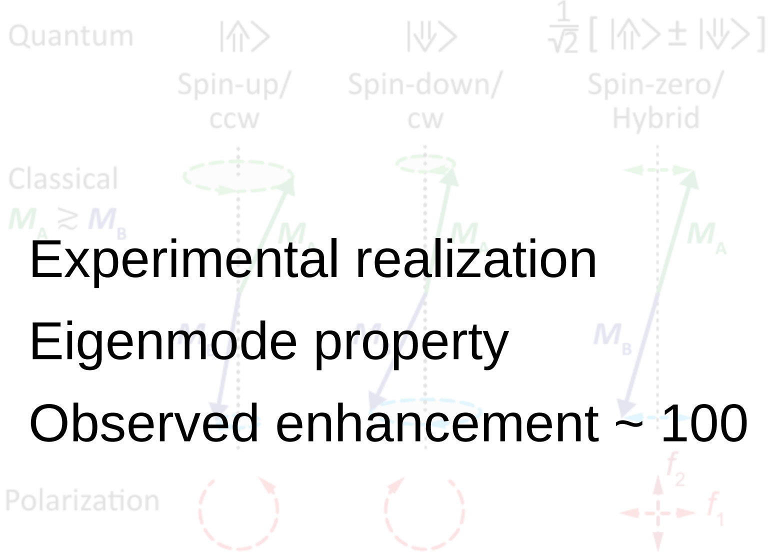
- Theoretical proposal
- Nonequilibrium effect
- Best case enhancement ~ 10

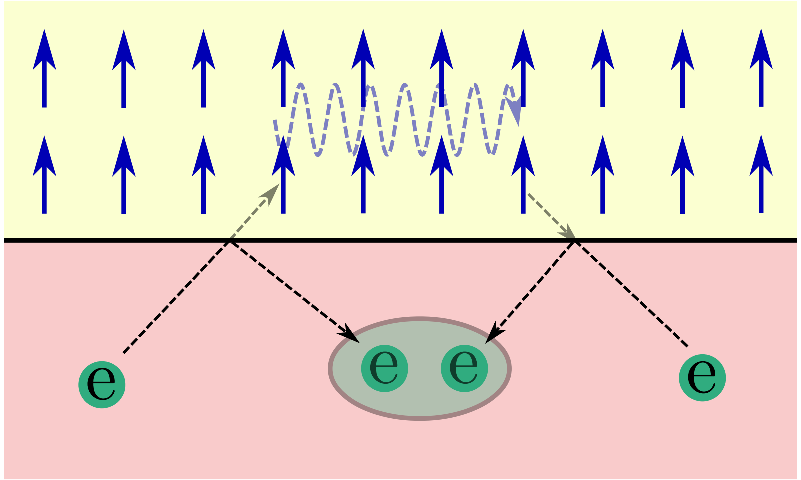


- Experimental realization
- Eigenmode property
- Observed enhancement ~ 100

L. Liensberger, A. Kamra, H. Maier-Flaig, S. Geprägs, A. Erb, S. T. B. Goennenwein, R. Gross, W. Belzig, H. Huebl, and M. Weiler. Exchange-enhanced ultrastrong magnon-magnon coupling in a compensated ferrimagnet. arXiv:1903.04330.

Superconductivity Enhancement

Magnon-mediated Superconductivity



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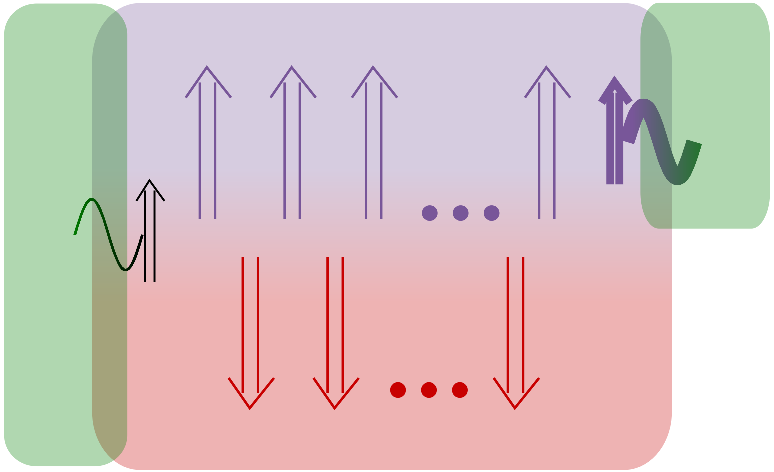
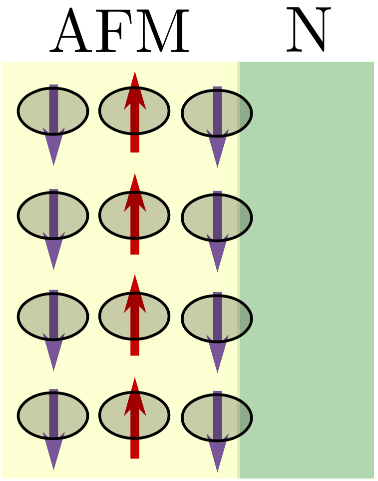
Kargarian et al., PRL 117, 076806 (2016).
Gong et al., Sci. Adv 3, e1602579 (2017).
Rohling et al., PRB 97, 115401 (2018).
Hugdal et al., PRB 97, 195438 (2018).
...

$$k_B T_c = \hbar \omega_c \exp\left(-\frac{1}{\lambda}\right)$$

Squeezed-magnon-mediated Superconductivity





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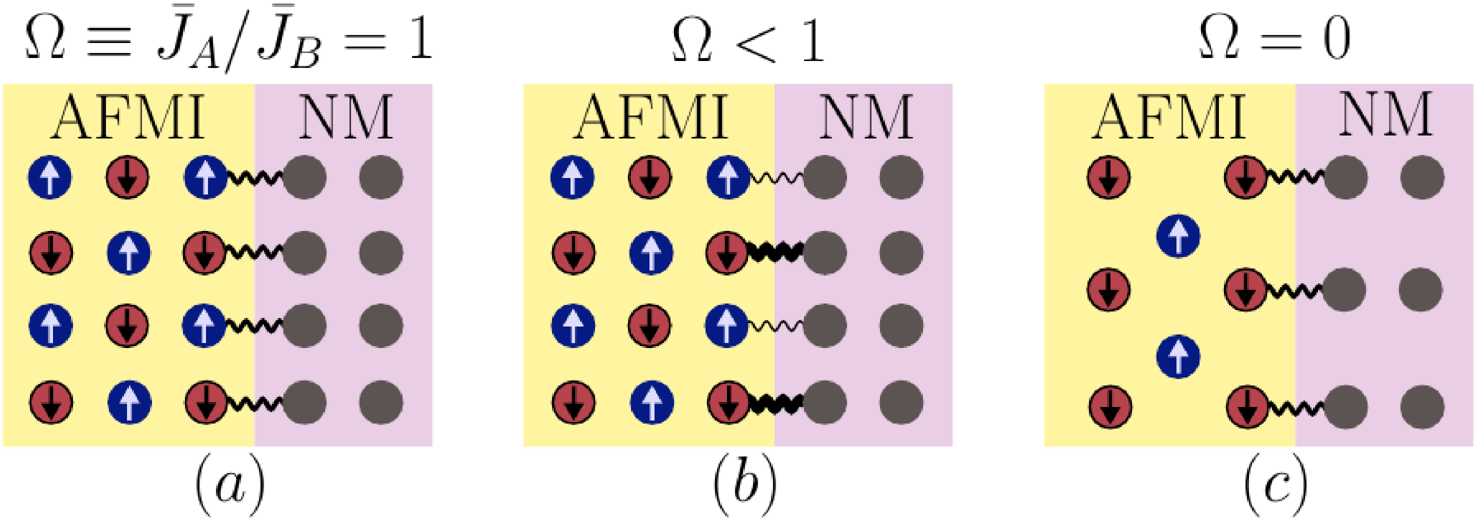
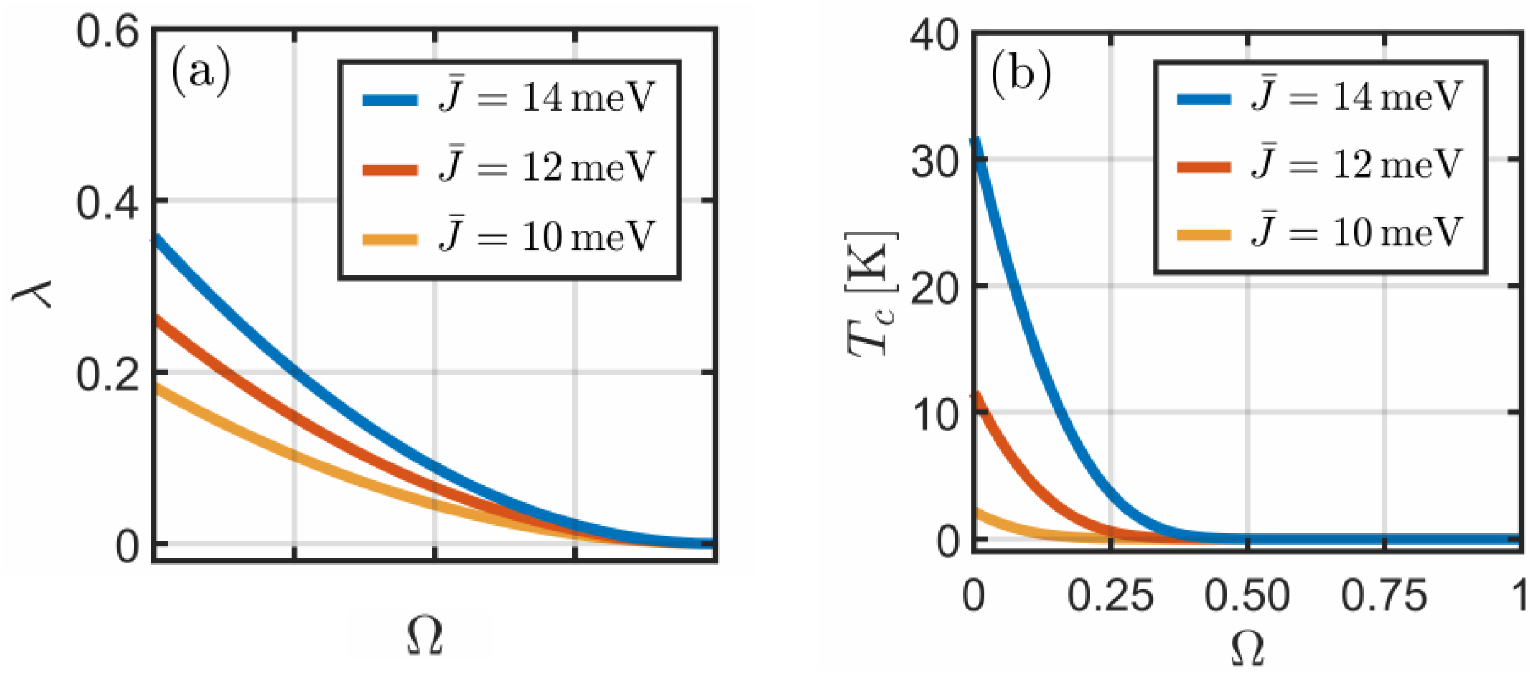
Squeezed-magnon-mediated Superconductivity



E. Erlandsen, A. Kamra, A. Brataas, and A. Sudbø. *Enhancement of superconductivity mediated by antiferromagnetic squeezed magnons*. Phys. Rev. B 100, 100503(R) (2019).

Squeezed-magnon-mediated Superconductivity



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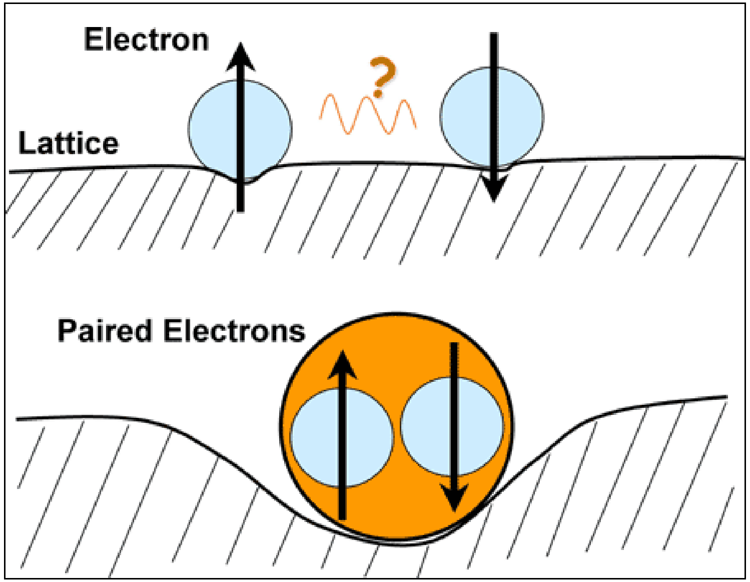
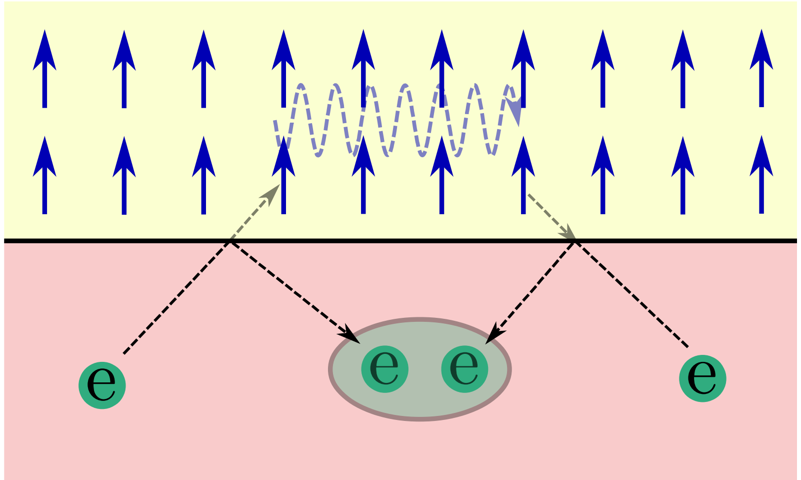
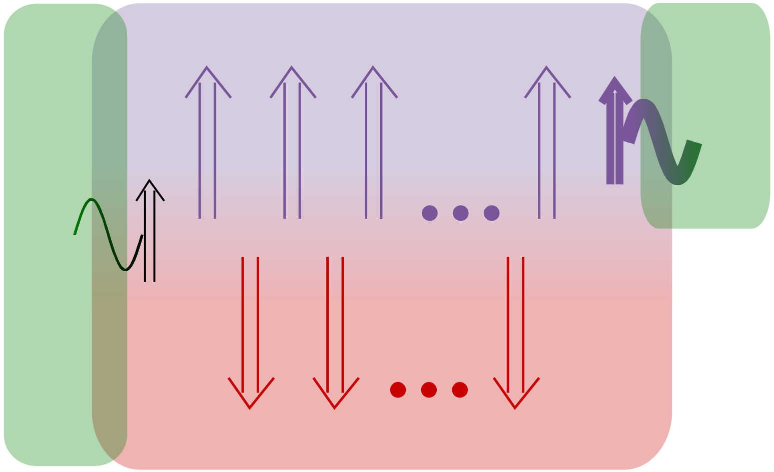
Magnon-mediated Exciton Condensation

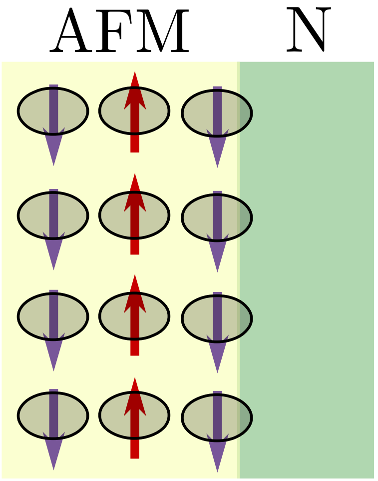
Electron-Electron Attraction



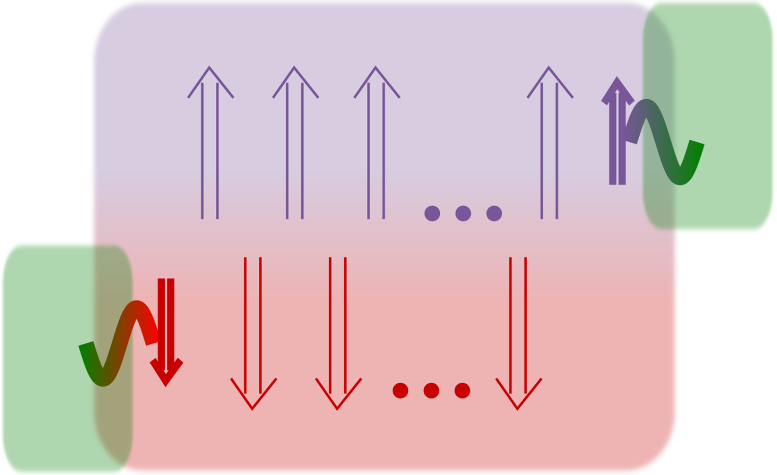


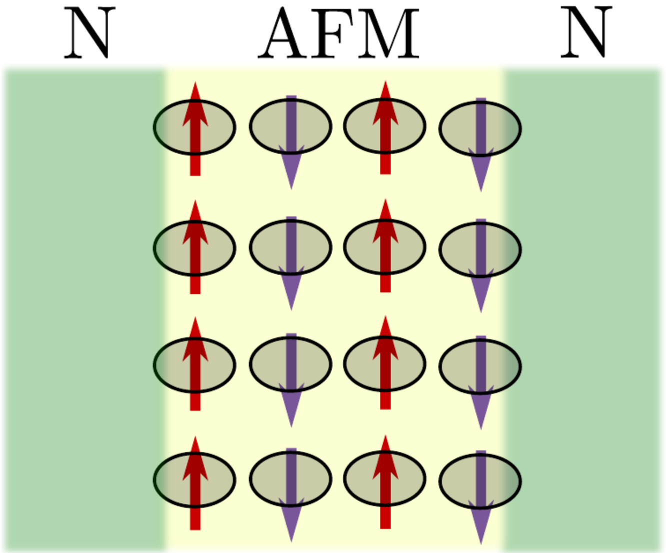
Electron-Electron Attraction





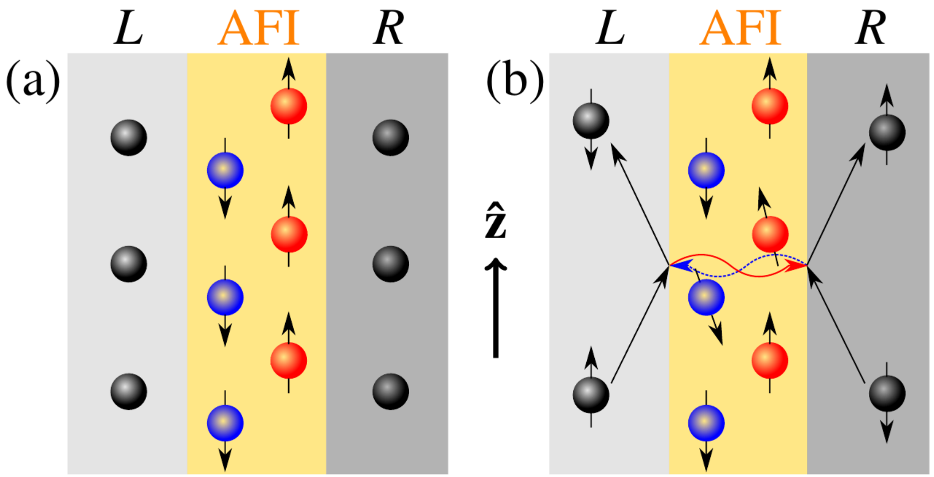
Electron-Electron Repulsion

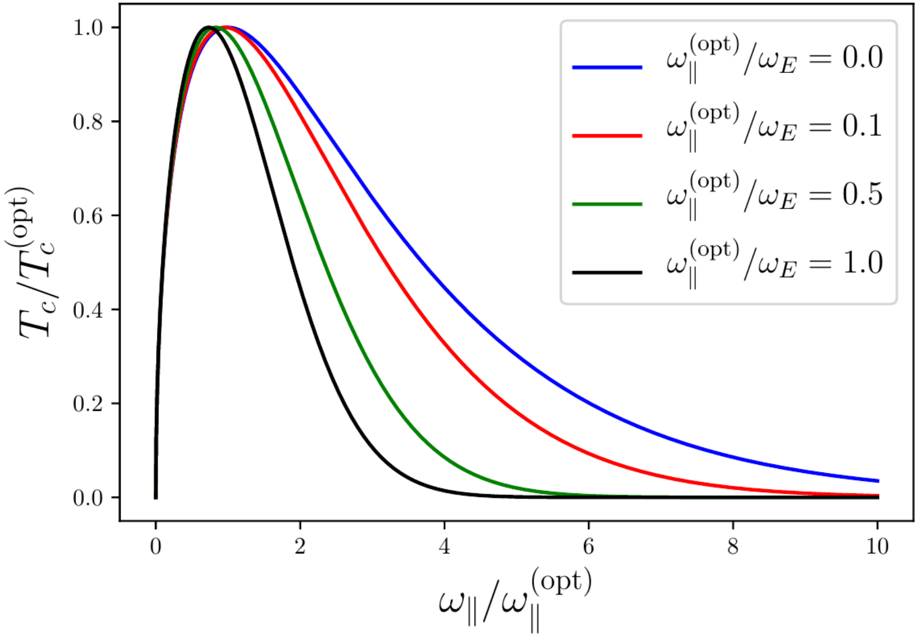




Electron-Electron Repulsion = Electron-Hole Attraction!

Magnon-mediated Exciton Condensation





Ø. Johansen, A. Kamra, C. Ulloa, A. Brataas, and R. A. Duine. *Magnon-mediated indirect exciton condensation through antiferromagnetic insulators*. arxiv:1904.12699.

Collaborators

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- Stephan Gepraegs
- Andreas Erb
- Rudolf Gross
- Hans Huebl
- Mathias Weiler

Squeezing, Strong Coupling and Superconductivity!