Dynamics and transport in quantum spin liquids

Leon Balents, KITP

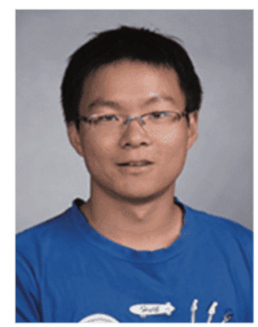
FRUMAG, PCS IBS, October 2019

Collaborators

Oleg Starykh, U. Utah

Urban Seifert, TU Dresden

experimental inspiration

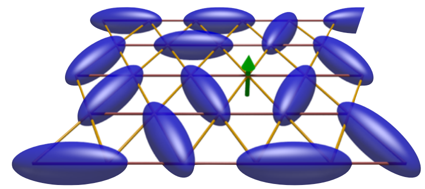


Rick Averitt   Gufeng Zhang

UCSD

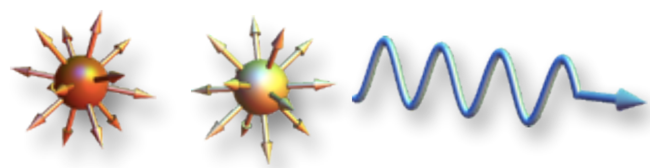
Classes of QSLs

- Topological QSLs



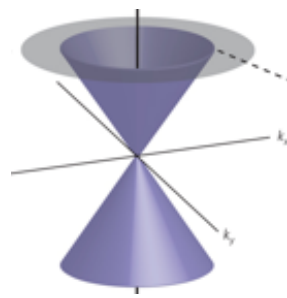
anyons, spinons

- U(1) QSL



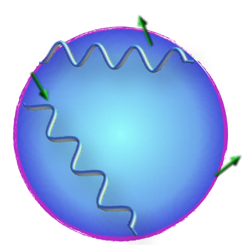
compact U(1)

- Dirac QSLs



QED_3

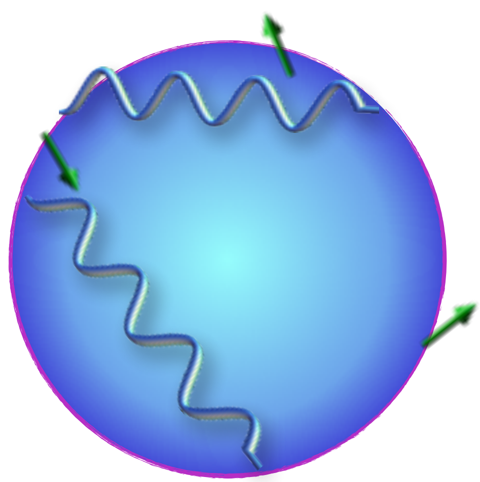
- Spinon Fermi surface



non-Fermi liquid “spin metal”

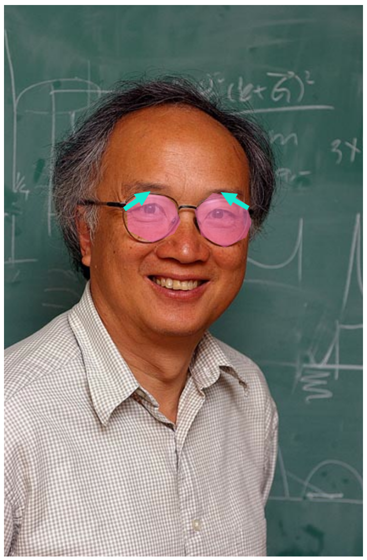
Spinon Fermi surface

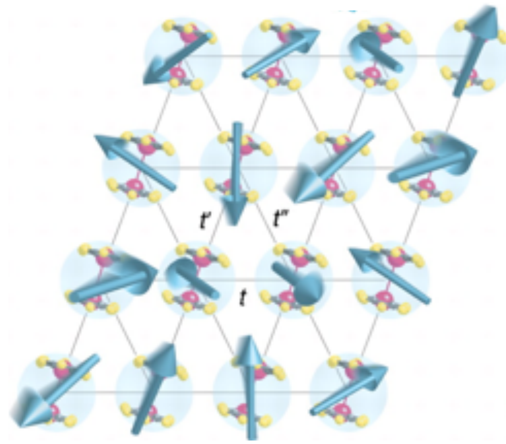
$$|\Psi\rangle = \prod_i \hat{n}_i(2-\hat{n}_i) \prod_{k<k_F} c^\dagger_{k\uparrow} c^\dagger_{k\downarrow}|0\rangle$$



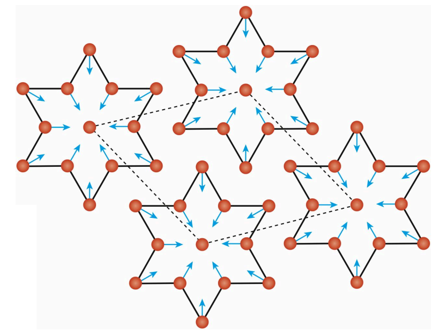
- The most gapless/highly entangled QSL state
- Like a "metal" of neutral fermions w/ a U(1) gauge field
- Prototype "non-Fermi liquid" state of great theoretical interest

Spinon Fermi surface

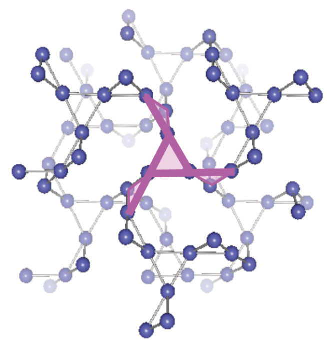




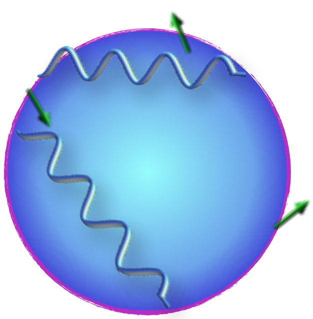
k-ET

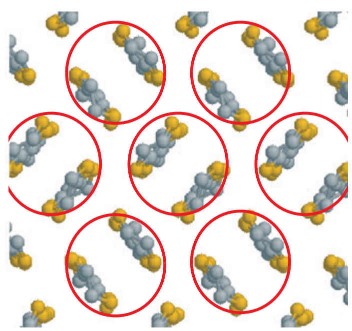


1T-TaS$_2$

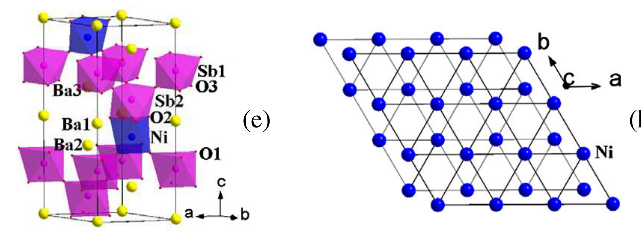


Na$_4$Ir$_3$O$_8$



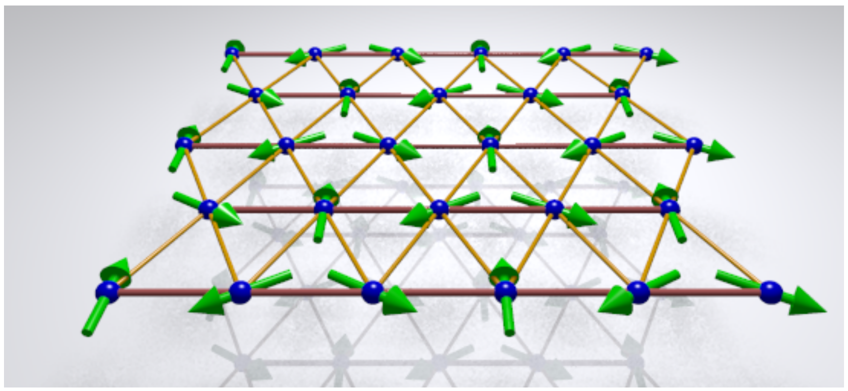


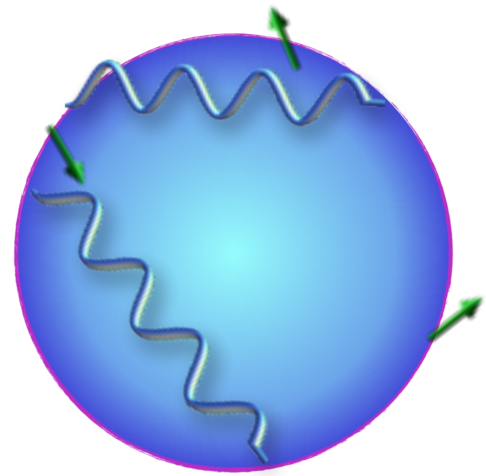
dmit



Ba$_3$NiSb$_2$O$_9$

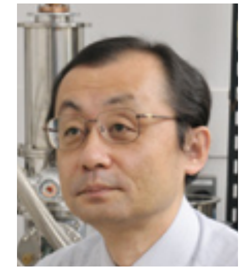
Triangular lattice w/ ring exchange

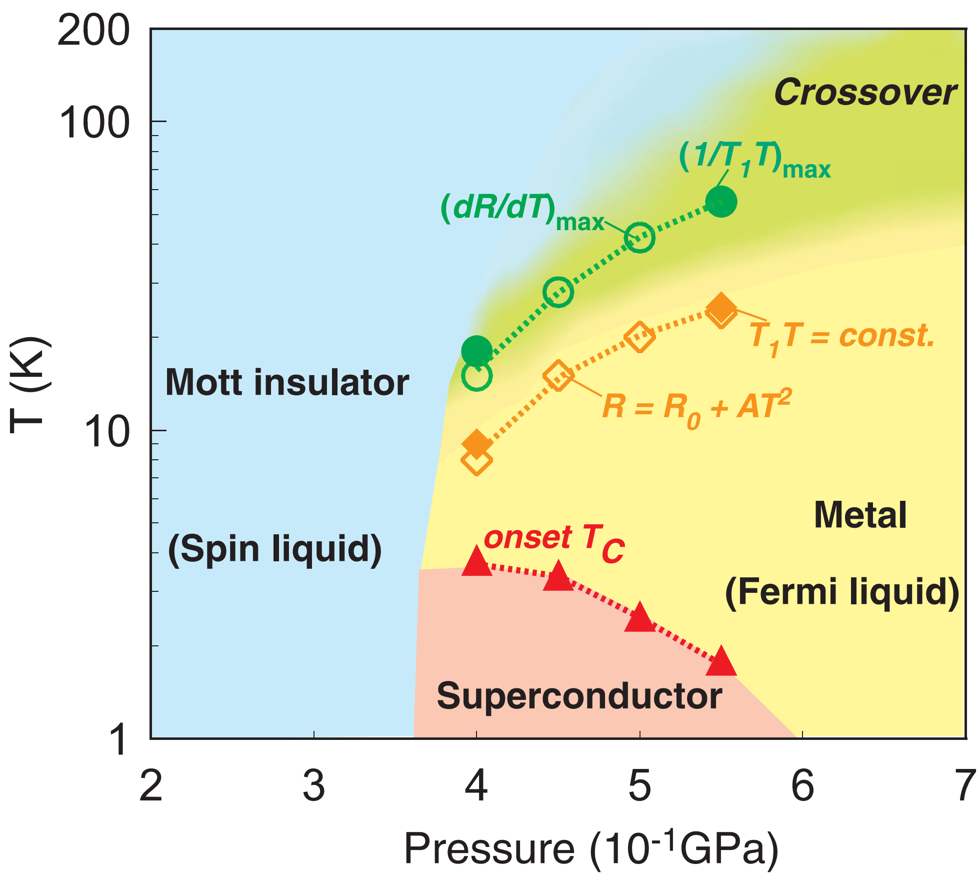


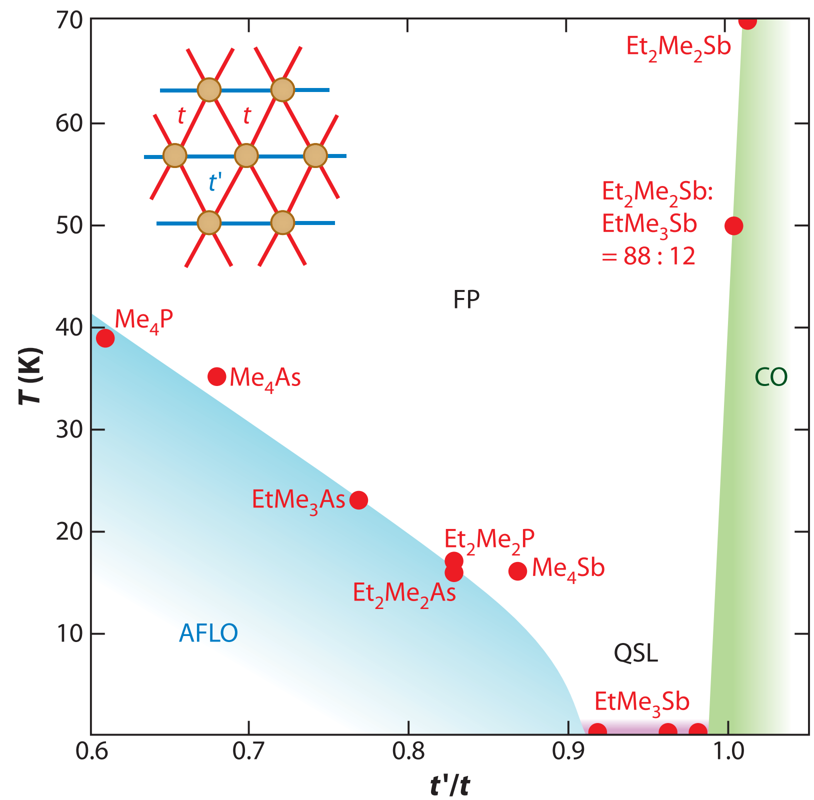


- Motrunich (2005): ring exchange stabilizes a spin liquid
- Motrunich, Lee/Lee: spin liquid state favored by ring exchange is the "spinon Fermi sea" state

triangular organics







κ-$(ET)_2Cu_2(CN)_3$

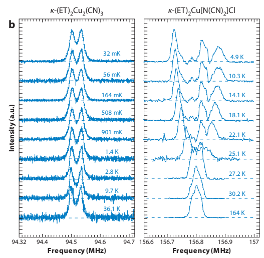
β′-$Pd(dmit)_2$

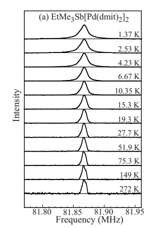
K. Kanoda group (2003-)

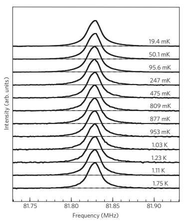
R. Kato group (2008-)

Evidence

- NMR



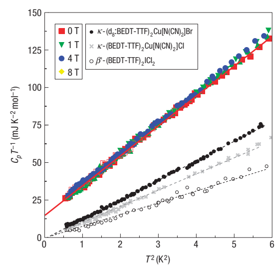


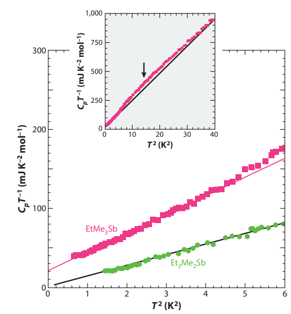


Y. Shimizu *et al*, 2003 T. Itou *et al*, 2008,2010

no magnetic order

- Specific heat

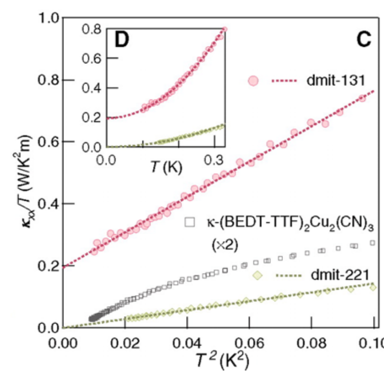




S. Yamashita *et al*, 2008

Sommerfeld law

- Thermal conductivity

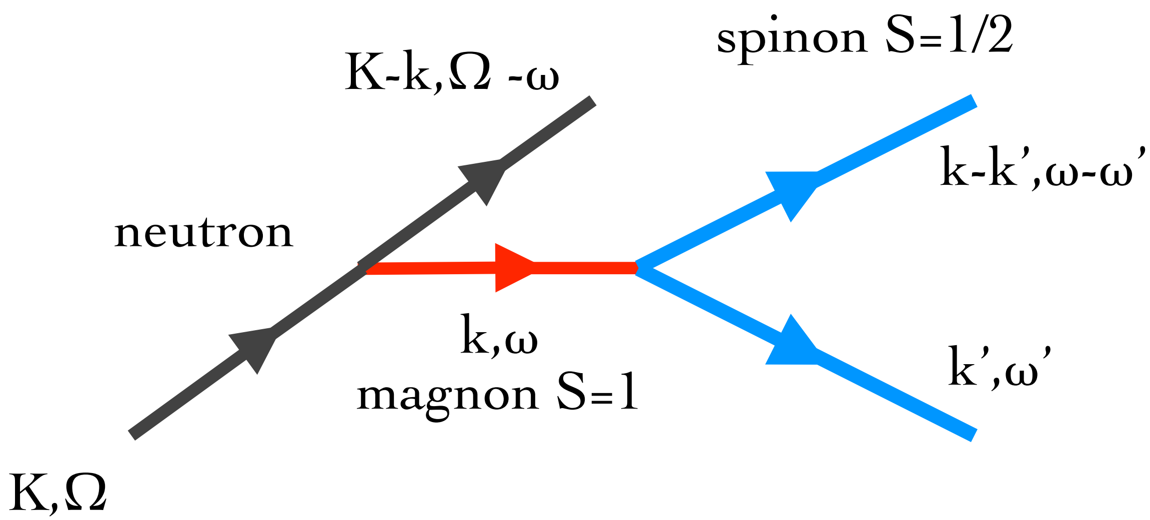


M. Yamashita *et al*, 2010

itinerant fermions?

Spectra

Common expectation in a QSL:
broad continuum scattering

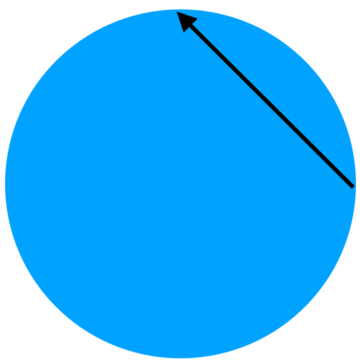


broad peak with
$\omega = \varepsilon(k') + \varepsilon(k-k')$

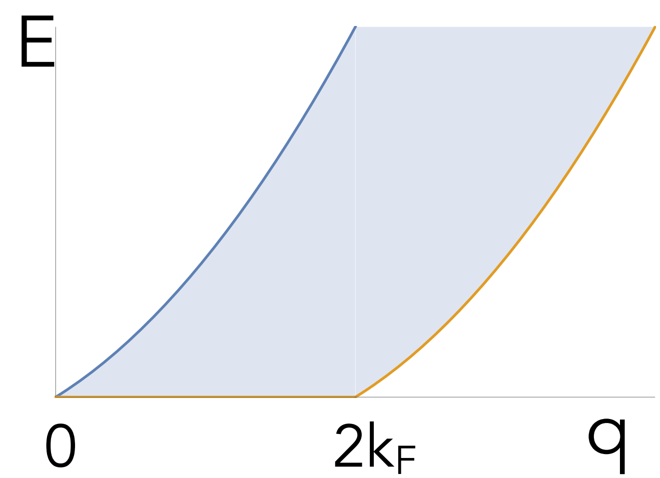
Not very inspiring?

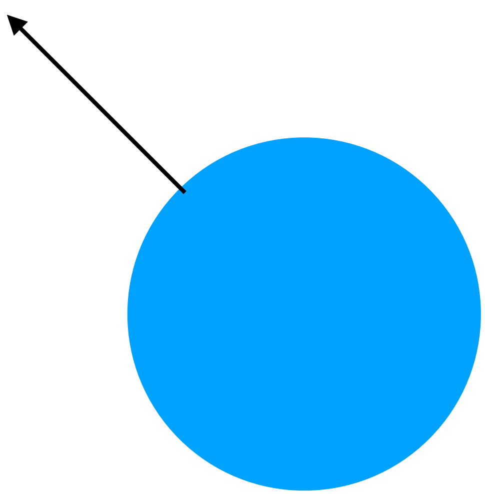
particle-hole continuum

Free fermions



lowest energy for $k<k_F$



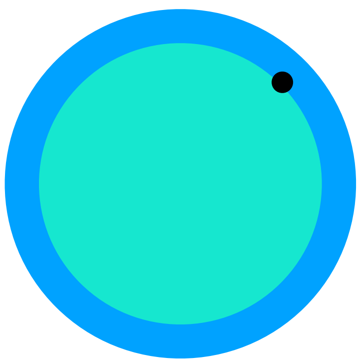


maximum energy

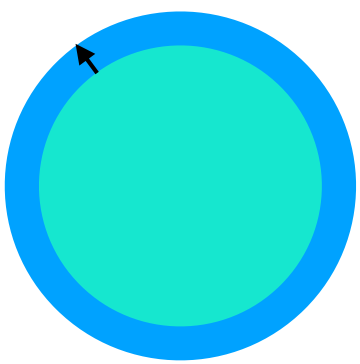
particle-hole continuum

With Zeeman field

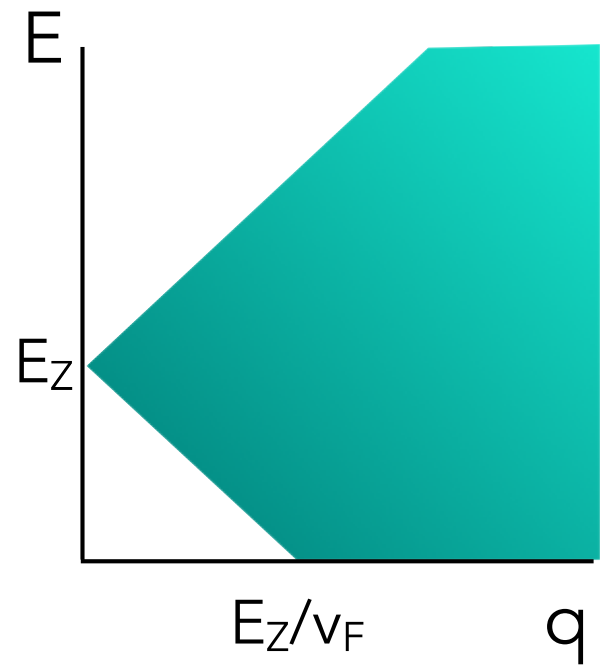
$$\chi_{\pm}(\boldsymbol{q},\omega) = i\int_0^{\infty} dt\langle [S^{\dagger}_{\mathbf{q}}(t), S^{-}_{-\mathbf{q}}(0)]\rangle e^{i\omega t}$$



q=0 costs Zeeman energy



zero energy when $v_F q$
= Zeeman



Inorganic analogs?

$YbMgGaO_4$

Letter | Published: 05 December 2016

Evidence for a spinon Fermi surface in a triangular-lattice quantum-spin-liquid candidate

Yao Shen, Yao-Dong Li, Hongliang Wo, Yuesheng Li, Shoudong Shen, Bingying Pan, Qisi Wang, H. C. Walker, P. Steffens, M. Boehm, Yiqing Hao, D. L. Quintero-Castro, L. W. Harriger, M. D. Frontzek, Lijie Hao, Siqin Meng, Qingming Zhang, Gang Chen & Jun Zhao

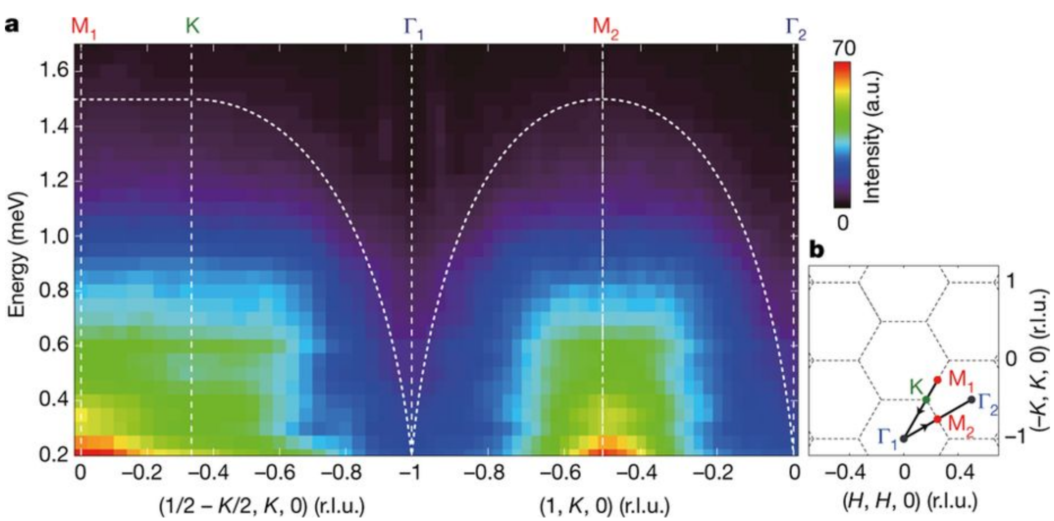
Nature **540**, 559–562 (22 December 2016) | Download Citation

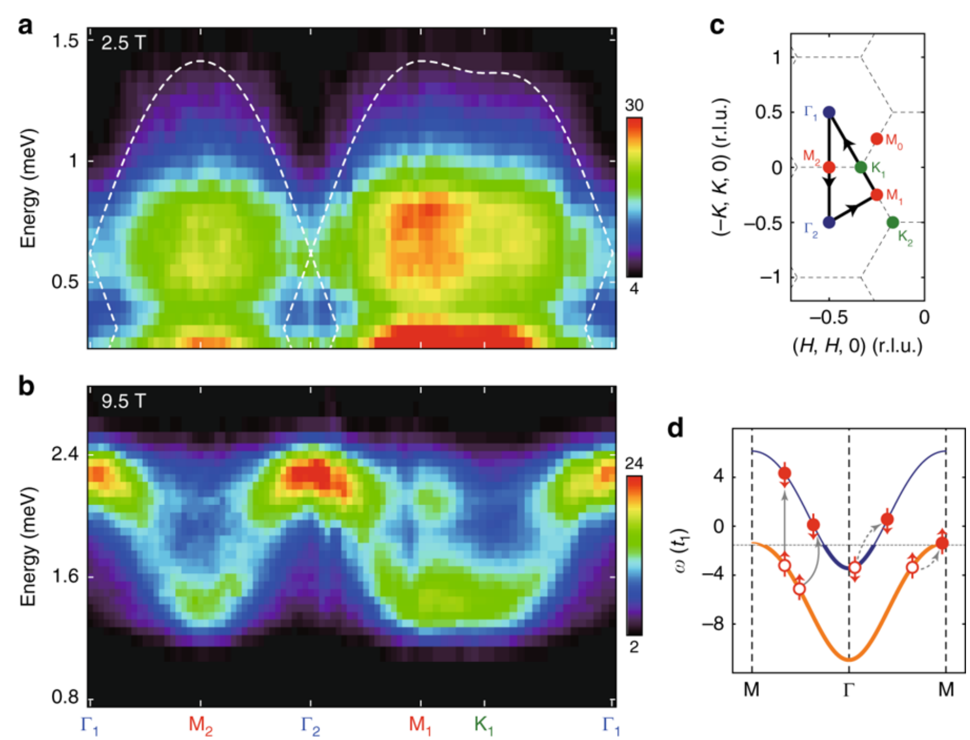
Article | OPEN | Published: 08 October 2018

Fractionalized excitations in the partially magnetized spin liquid candidate $YbMgGaO_4$

Yao Shen, Yao-Dong Li, H. C. Walker, P. Steffens, M. Boehm, Xiaowen Zhang, Shoudong Shen, Hongliang Wo, Gang Chen & Jun Zhao

Nature Communications **9**, Article number: 4138 (2018) | Download Citation



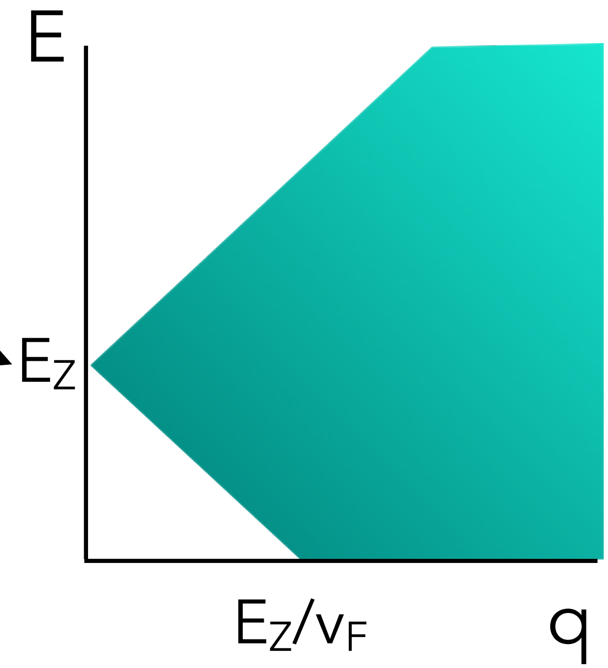


particle-hole continuum

With Zeeman field

q=0: ESR

Larmor theorem fixes response



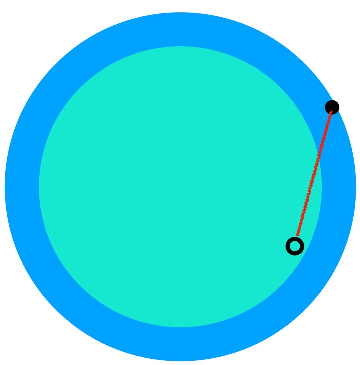
Effects of interactions?

Interactions

- Longitudinal

$$a_0 \psi^\dagger \psi$$

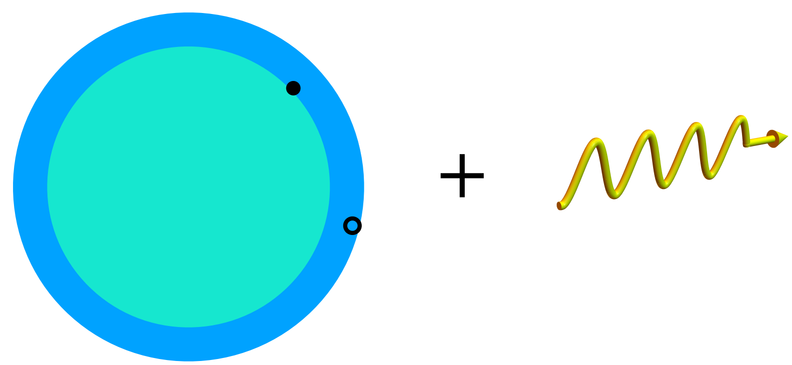
screened Coulomb interaction



- Transverse

$$i\boldsymbol{A} \cdot \left(\psi^\dagger \boldsymbol{\nabla} \psi - \boldsymbol{\nabla} \psi^\dagger \psi\right)$$

coupling to dynamical photons



Interactions

- Longitudinal $a_0\psi^\dagger\psi$ $\Rightarrow$ $u\psi_\uparrow^\dagger\psi_\uparrow\psi_\downarrow^\dagger\psi_\downarrow$

$$= -um\left(\psi_\uparrow^\dagger\psi_\uparrow - \psi_\downarrow^\dagger\psi_\downarrow\right) + \; u :\psi_\uparrow^\dagger\psi_\uparrow\psi_\downarrow^\dagger\psi_\downarrow:$$

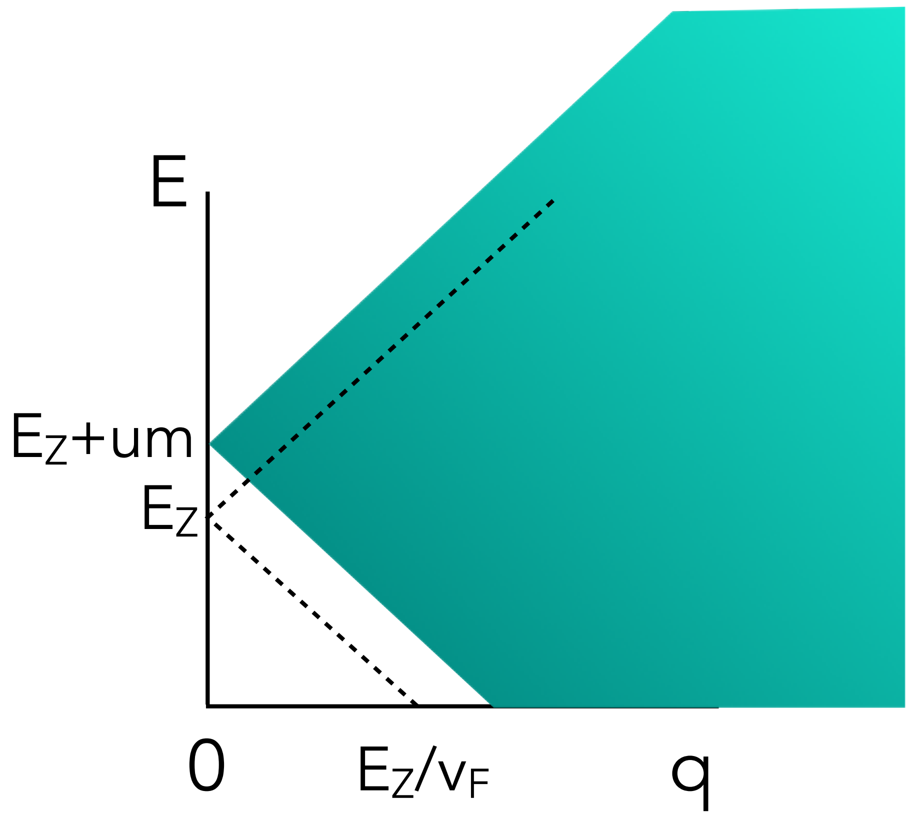
self-energy interaction

Self energy

- Longitudinal $a_0\psi^\dagger\psi$ $\rightarrow$ $u\psi^\dagger_\uparrow\psi_\uparrow\psi^\dagger_\downarrow\psi_\downarrow$

$$= -um\left(\psi^\dagger_\uparrow\psi_\uparrow - \psi^\dagger_\downarrow\psi_\downarrow\right)$$

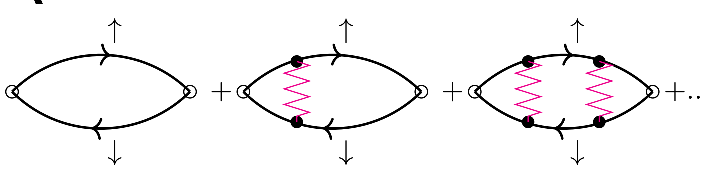
mean field shift



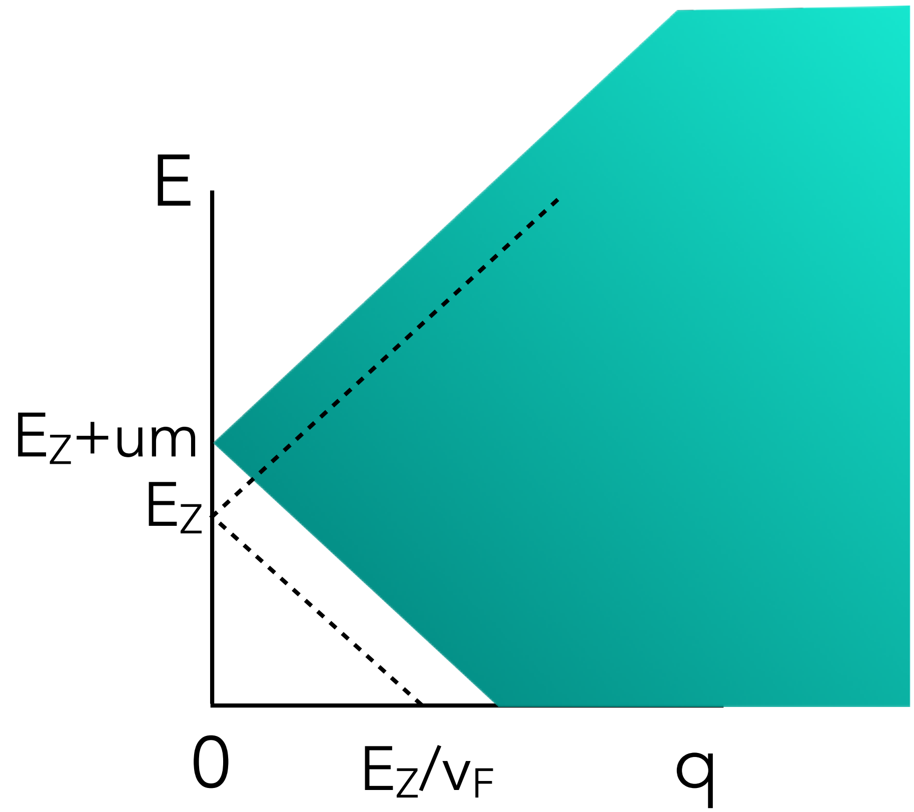
Interaction

<u>Larmor theorem</u>: q=0 excitation *must* be at E_Z

RPA



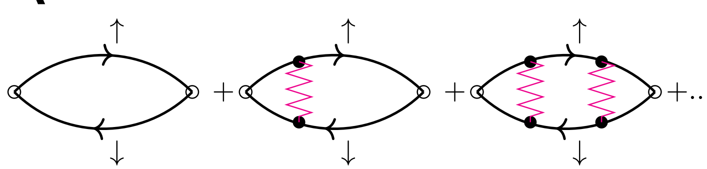
$$\chi(\boldsymbol{q}, i\omega_n) = \frac{\chi^0(\boldsymbol{q}, i\omega_n)}{1 + u\chi^0(\boldsymbol{q}, i\omega_n)}$$



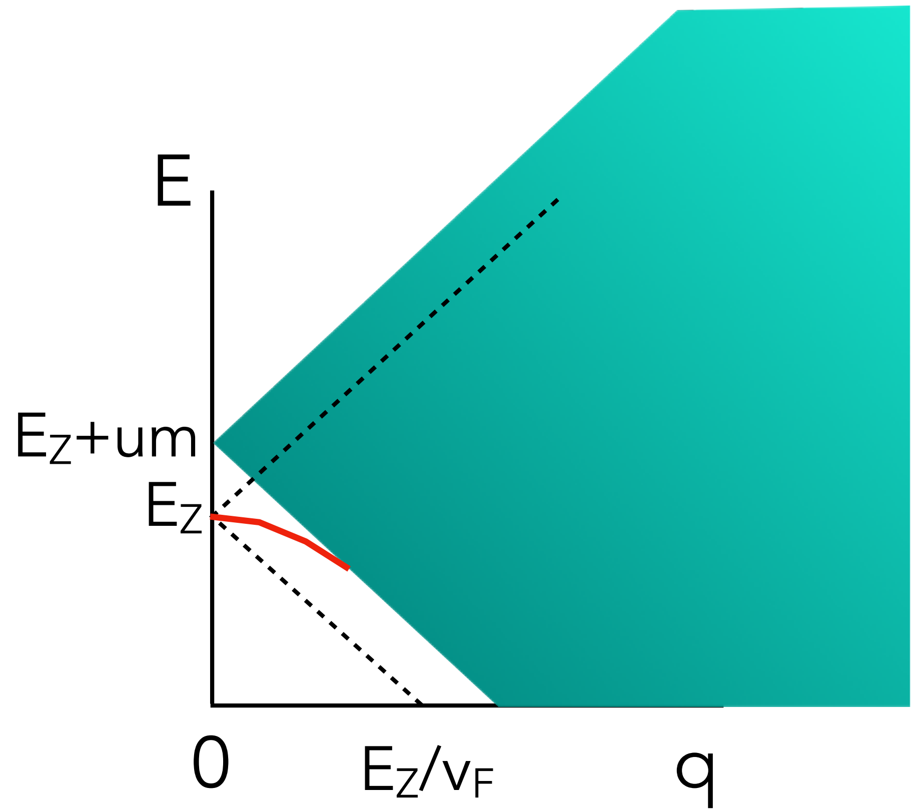
Silin spin wave

<u>Larmor theorem</u>: q=0 excitation *must* be at E_Z

RPA



$$\chi(\boldsymbol{q}, i\omega_n) = \frac{\chi^0(\boldsymbol{q}, i\omega_n)}{1 + u\chi^0(\boldsymbol{q}, i\omega_n)}$$

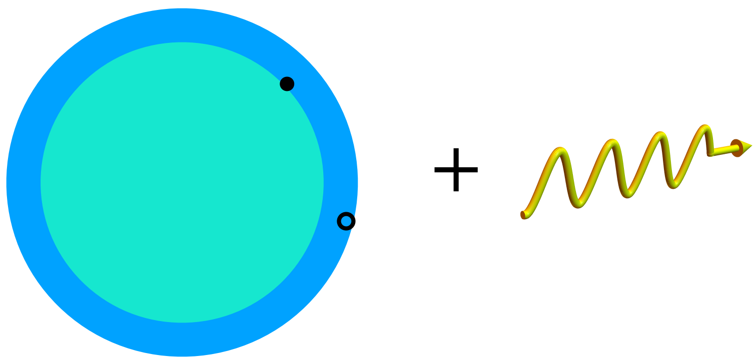


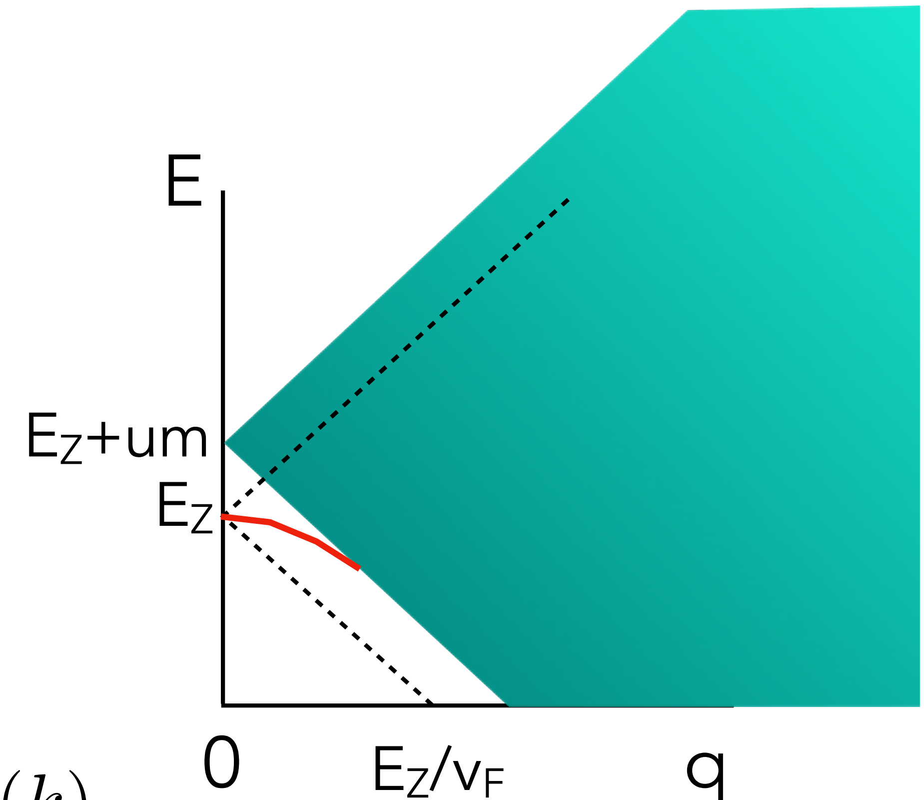
pole: collective mode

$$\omega = E_Z + um - \sqrt{u^2 m^2 + v_F^2 q^2}$$

"Silin spin wave"

Transverse gauge coupling





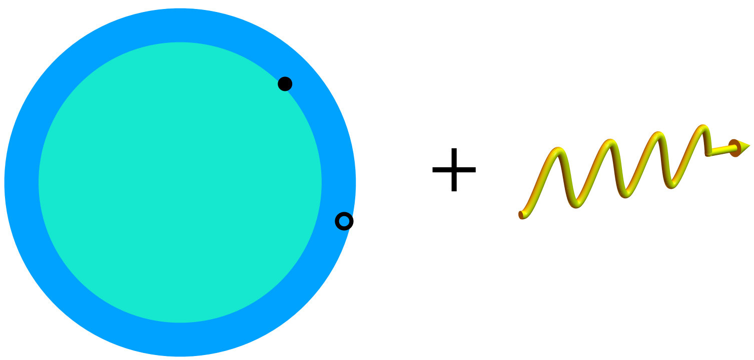
Simple picture:

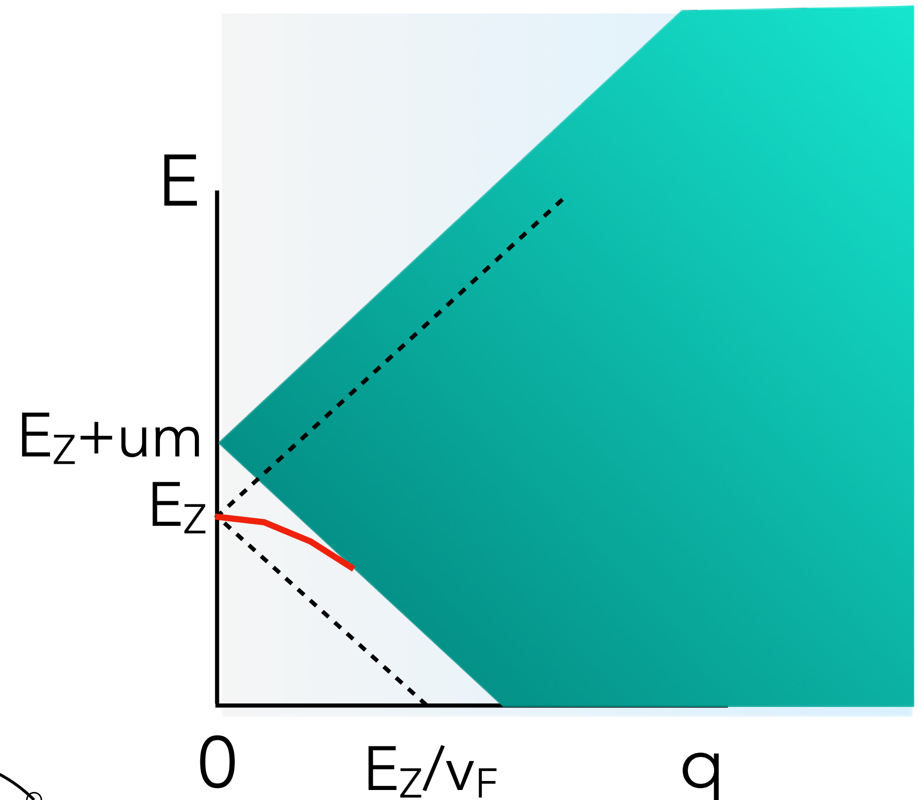
3-particle process:

$$E = E_{\mathrm{p/h}}(q-k) + \underbrace{E_{\mathrm{photon}}(k)}_{\sim c\,k^3}$$

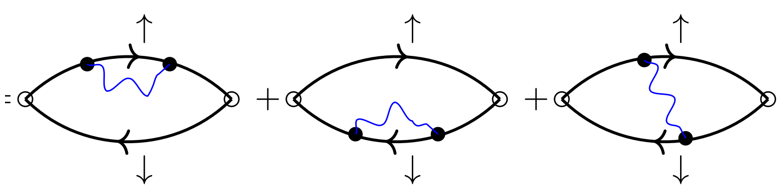
Does this smear out all the Fermi liquid structure?

Transverse gauge coupling





Actual calculation:



c.f. Y. B. Kim, A. Furusaki, X.-G. Wen, and P. A. Lee, Phys Rev. B **50**, 17917 (1994).

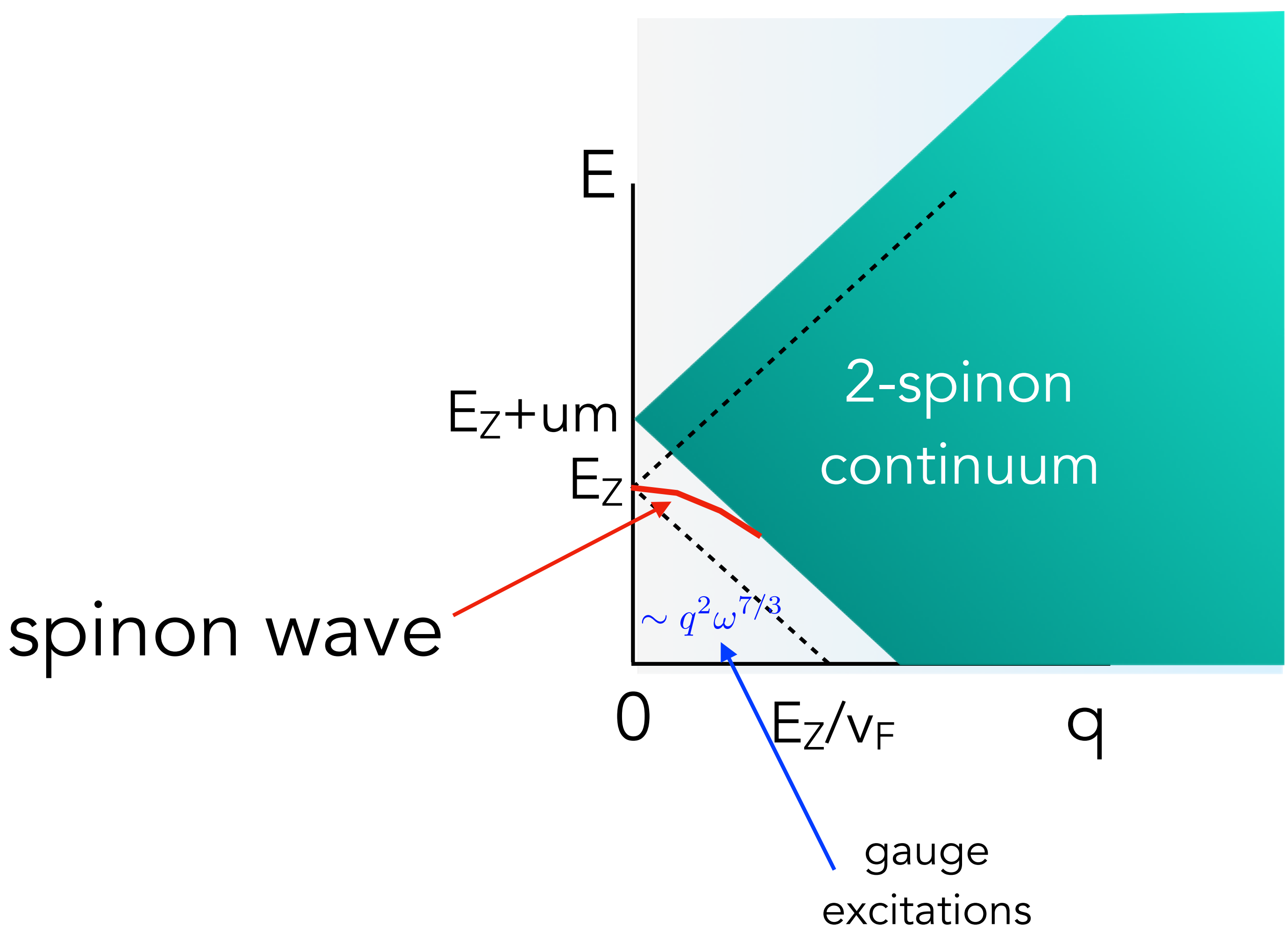
$$\mathrm{Im}\chi_{\pm} \sim q^2 \omega^{7/3}$$

weight at all q != 0

but weak enough to preserve structure

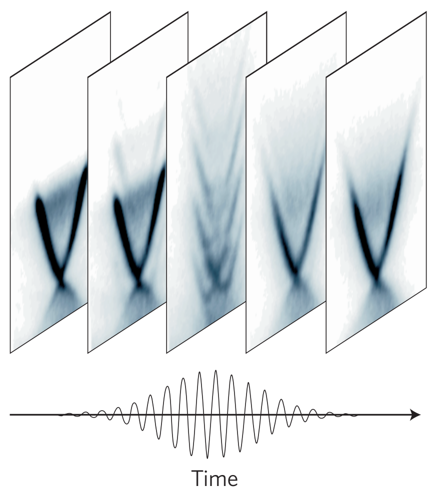
Summary

Distinct signatures of spinons, interactions, and gauge fields



O.Starykh + LB,
arXiv:1904.02117

Ultra-fast Manipulation of Quantum Matter



Floquet-Bloch states in Bi_2Se_3

Wang *et al*, Science 2013

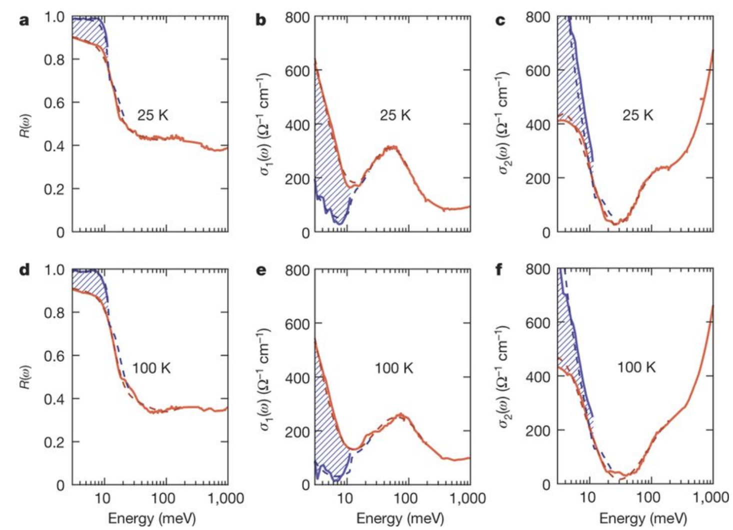


Photo-induced conductivity changes in K_3C_{60}

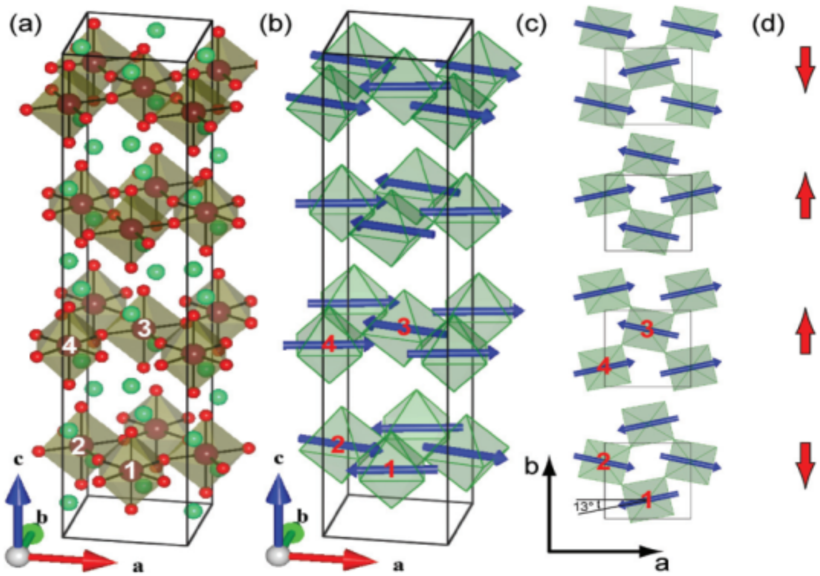
Mitrano *et al*, Nature 2016

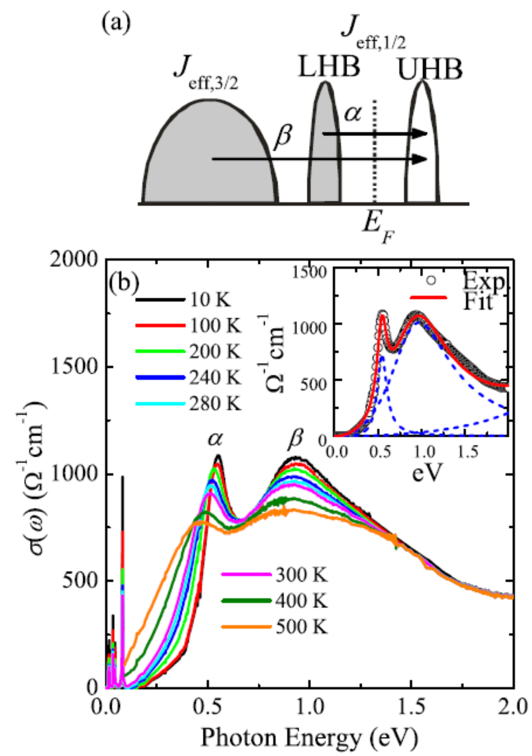
Couple to electrons

Couple to phonons?

How about spins?

Sr_2IrO_4





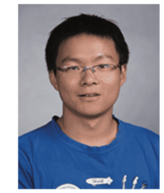
Square lattice antiferromagnet

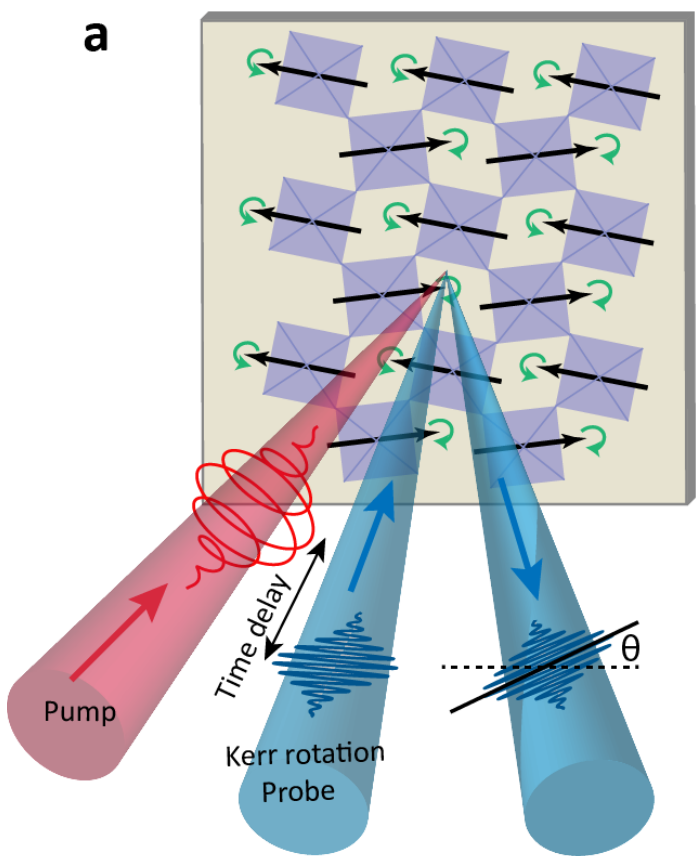
Strong SOC

Good venue for light-spin interactions

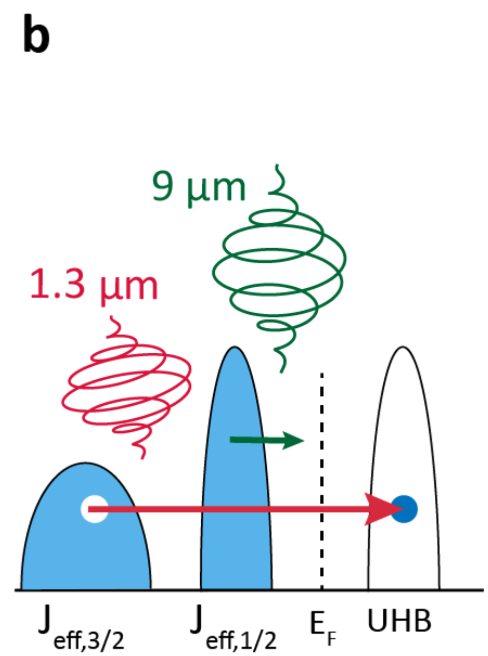
Ultrafast experiments

Gufeng Zhang *et al*, Averitt group, UCSD, in preparation





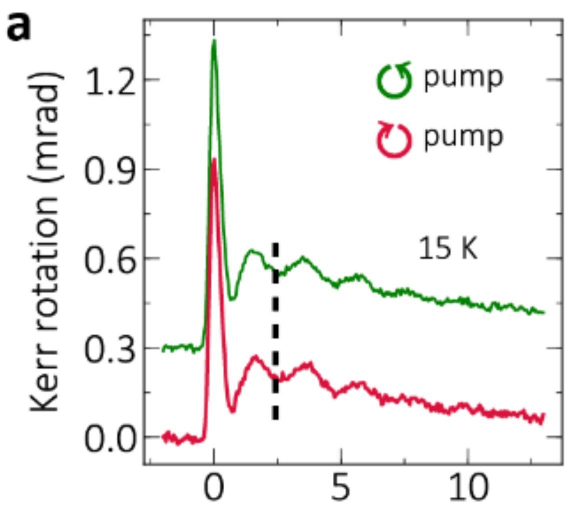
Kerr angle ~ magnetization

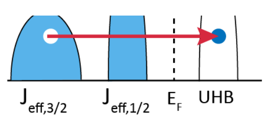


"Resonant" versus "non-resonant"

Phenomena

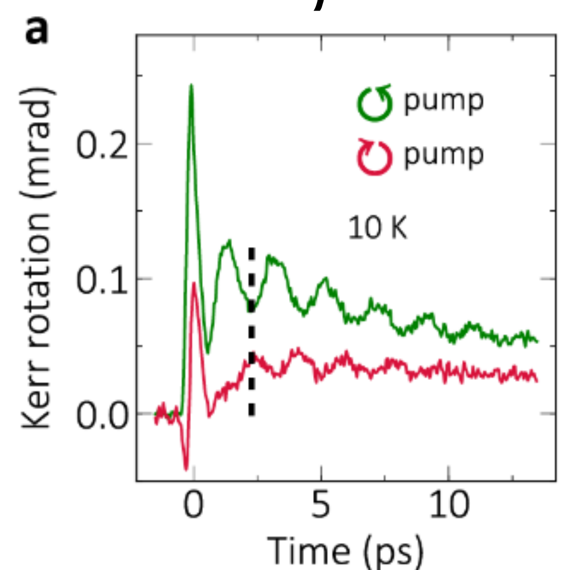
1.3 μm

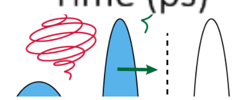




θ_K =.029 mrad mJ^{-1} cm^2

9 μm

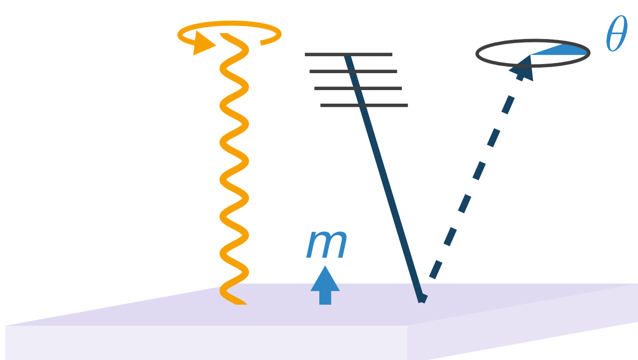


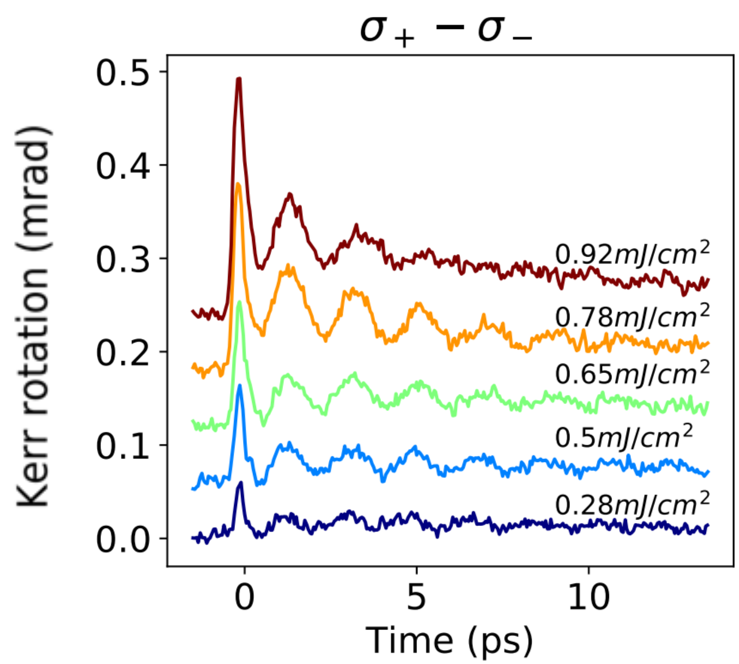


θ_K =.24 mrad mJ^{-1} cm^2

- Oscillation frequency 0.57THz = 2meV independent of details of pump: intrinsic magnon energy
- Pumping <u>much more efficient</u> for 9micron light.

Phenomena

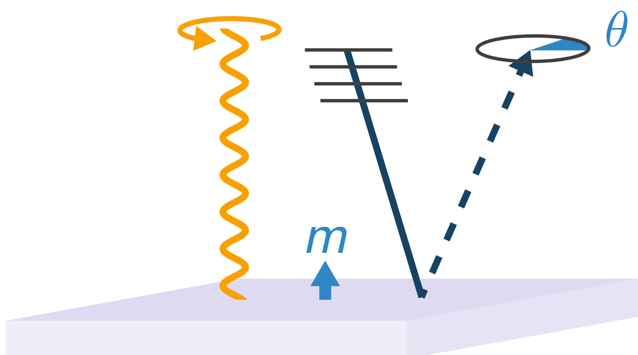


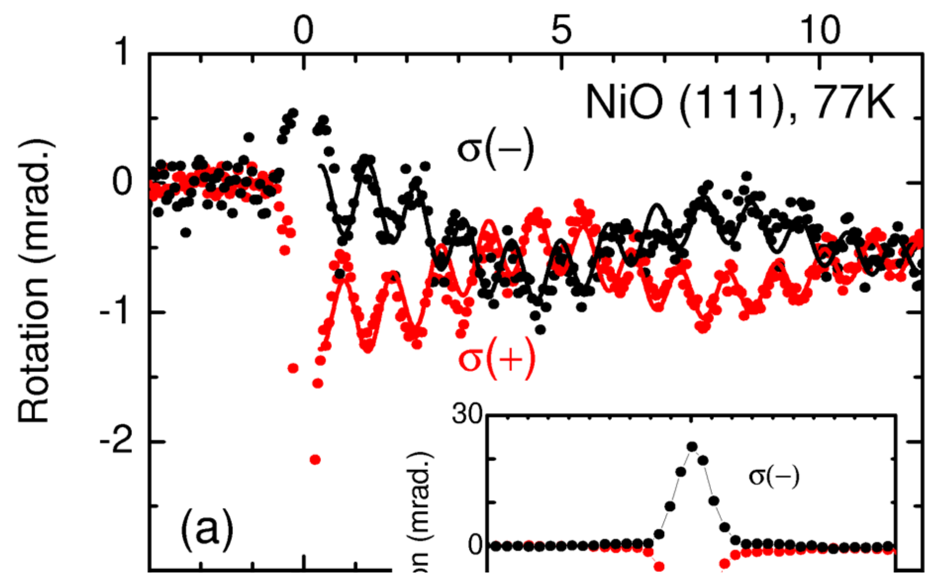


Questions

- What is the magnon oscillation and why is it visible?
- How is the magnon excited by sub-gap light?

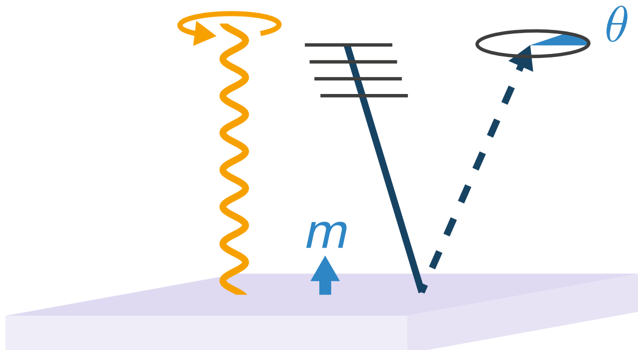
Phenomena

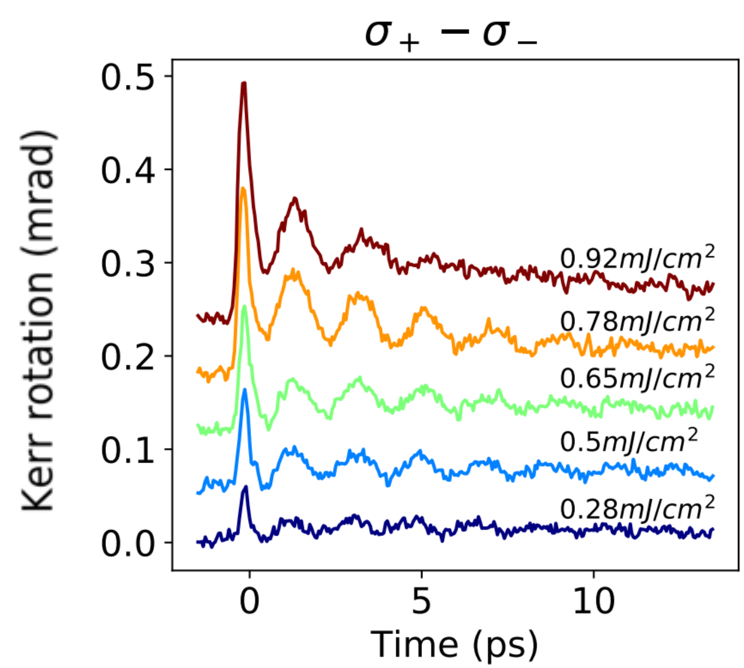




c.f. T. Satoh *et al*, 2010 - NiO

Phenomena



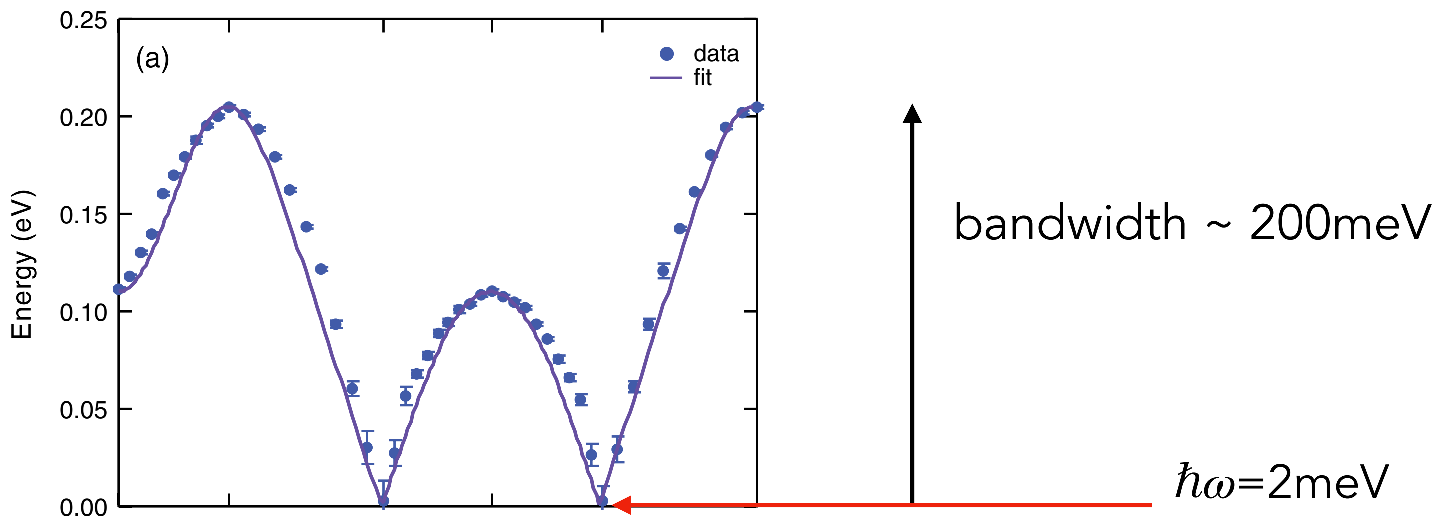


Questions

- What is the magnon oscillation and why is it visible?
- How is the magnon excited by sub-gap light?

Magnons

- Gross features: square lattice Heisenberg antiferromagnet



RIXS: BJ Kim *et al*, PRL 2012

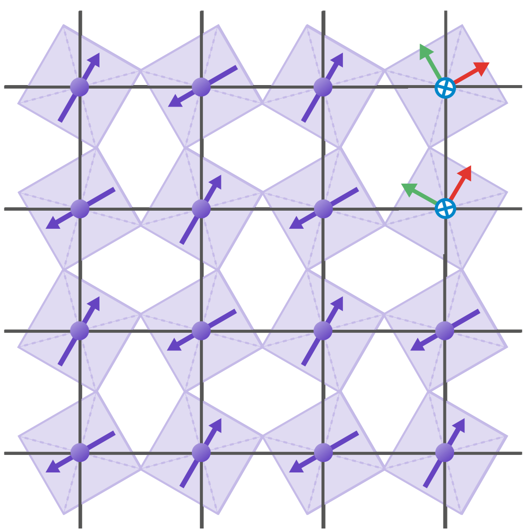
Magnon is a *very* low energy feature

Anisotropy

Unit cell doubled by octahedral rotation

$$\mathcal{H}_{\text{eq}} = \sum_{i \in A} \sum_{\mu = \pm x, \pm y} \left[J_{xy} \left(S_i^x S_{i+\mu}^x + S_i^y S_{i+\mu}^y \right) + J_z S_i^z S_{i+\mu}^z + D \hat{z} \cdot \vec{S}_i \times \vec{S}_{i+\mu} \right]$$

XXZ+DM



DM is removed in local frame

G. Jackeli+G.Khaliullin, 2009

$$\rightarrow \sum_{i \in A} \sum_{\mu = \pm x, \pm y} J \left[S_i^x S_{i+\mu}^x + S_i^y S_{i+\mu}^y + (1 - \delta) S_i^z S_{i+\mu}^z \right]$$

Fits to RIXS give J~60meV and δ~.05

Small easy-plane anisotropy

Spin wave theory

- Holstein-Primakoff

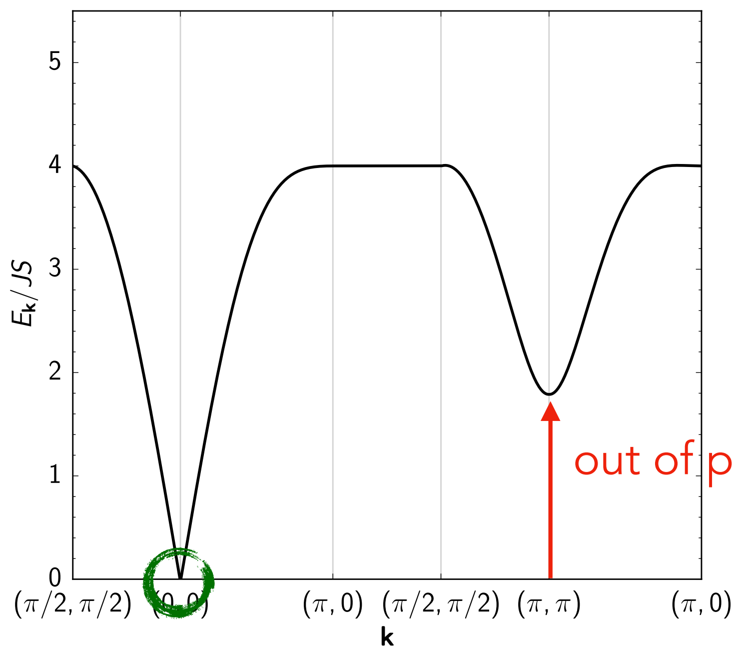
$$S^+ = S^z - \mathrm{i}S^y = \sqrt{2S - a^\dagger a}\, a$$

$$S^- = (S^+)^\dagger \qquad S^x = S - a^\dagger a$$

$$\mathcal{H}_{\text{eq}} = \mathcal{H}^{(0)}_{\text{eq}} + \mathcal{H}^{(2)}_{\text{eq}} + \mathcal{H}^{(4)}_{\text{eq}} + \mathcal{O}(1/S)$$

E_{cl} $\quad$ E_{sw} $\quad$ magnon interactions

$$\mathcal{H}^{(2)}_{\text{eq}} = \sum_{\mathbf{k}} E_{\mathbf{k}}\, \alpha^\dagger_{\mathbf{k}} \alpha_{\mathbf{k}}$$

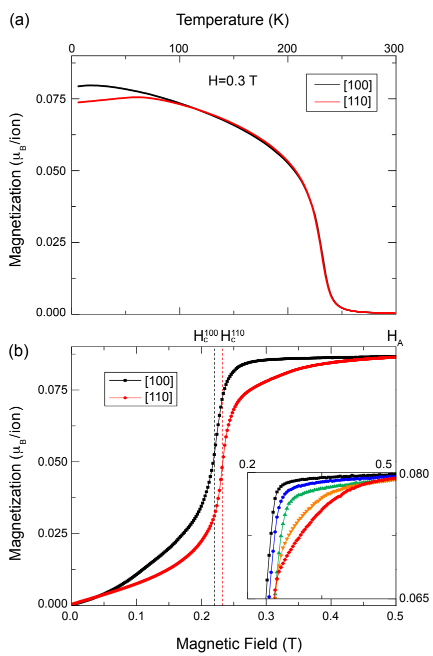


out of plane mode. Gap ~ 30meV! Too big to be the oscillating magnon

gapless Goldstone mode of in-plane rotations

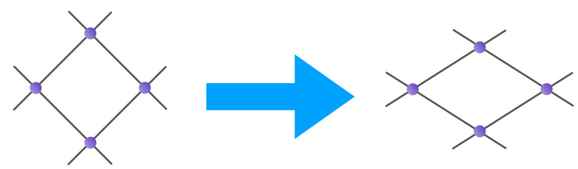
In-plane anisotropy

- Even weaker effect gives tiny gap to in-plane magnon



Porras *et al*, 2019

argue due to lattice distortion induced by spin order



$$\tilde{\mathcal{H}}_{\mathrm{JT}} = \Gamma \sum_{\langle ij \rangle} S_i^x S_j^x - S_i^y S_j^y$$

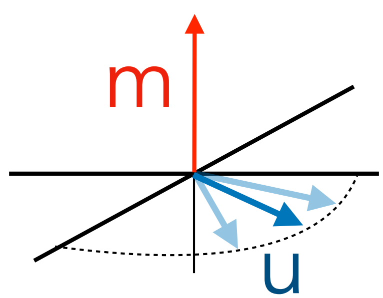
$\boldsymbol{\Gamma}$~6μeV (!) $\omega_0 \simeq 8S\sqrt{\Gamma J}$ ~2meV

Oscillation matches in-plane magnon.

Magnetization oscillation

- Q: Why does Kerr angle oscillate if magnon is in-plane??

In-plane spin rotation $\longleftrightarrow$ out of plane torque



$$\vec{S}_i = \begin{pmatrix} (-1)^i S \\ (-1)^i u(x_i) \\ m(x_i) \end{pmatrix}$$

relation to magnons

$$u = \sqrt{S/2}\,\mathrm{i}(a - a^\dagger)$$
$$m = \sqrt{S/2}\,(a + a^\dagger)$$

$$\underset{\text{uniform}}{\frac{dS_i^z}{dt}} = \underset{\text{staggered}}{h_i^x}\,\underset{\text{staggered}}{S_i^y} - h_y S_i^z \quad \Rightarrow \quad \begin{aligned} \partial_t u &= \chi^{-1} m \\ \partial_t m &= -\kappa\, u \end{aligned}$$

slow modes - hydrodynamic equations valid even when magnons scatter

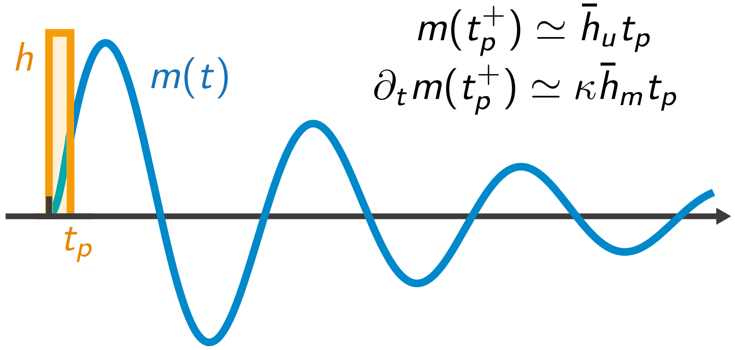
uniform magnetization oscillates out of phase with in-plane angle u

Pumping

- Strategy: light creates *source terms* for EOM

$$\partial_t u = \chi^{-1} m + h_m(t)$$
$$\partial_t m = -\kappa\, u + h_u(t)$$

effective fields drive during pump pulse



decay/relaxation negligible during pump

$$m(t_p^+) \simeq \bar{h}_u t_p$$
$$\partial_t m(t_p^+) \simeq \kappa \bar{h}_m t_p$$

effective initial conditions

Theory: include light-matter interaction and integrate out higher energy modes to obtain h_m, h_u

Coupling to E-field

- Assumption: E-field of light dominates. Strong time-reversal-symmetry constraints

$$\mathcal{T}: \vec{E} \to \vec{E},\ \vec{S} \to -\vec{S} \quad \Rightarrow \quad \mathcal{H}_{\mathrm{E}} \sim g\, E^{\alpha} S_i^{\beta} S_j^{\gamma}$$

- General symmetry allowed couplings

$$\begin{aligned}\mathcal{H}_{\mathrm{E}} = \sum_i \Big[& g_1 \epsilon_i \left[E_x \left(S_i^y S_{i+x}^x + S_i^x S_{i+x}^y\right) - (x \leftrightarrow y)\right] \\ & + g_2 \epsilon_i \left(E_y S_i^x S_{i+x}^x - E_x S_i^y S_{i+y}^y\right) \\ & + g_3 \epsilon_i \left(E_y S_i^y S_{i+x}^y - E_x S_i^x S_{i+y}^x\right) \\ & + g_4 \epsilon_i S_i^z \left(E_y S_{i+x}^z - E_x S_{i+y}^z\right) \\ & + g_5 \left(E_y\, \hat{\mathbf{z}} \cdot \mathbf{S}_i \times \mathbf{S}_{i+x} - E_x\, \hat{\mathbf{z}} \cdot \mathbf{S}_i \times \mathbf{S}_{i+y}\right) \Big]\end{aligned}$$

staggering due to octahedral rotations important!

microscopic calculations confirm these terms

Katsura, Nagaosa, Balatsky, PRL 2005
Bolens, PRB 2018

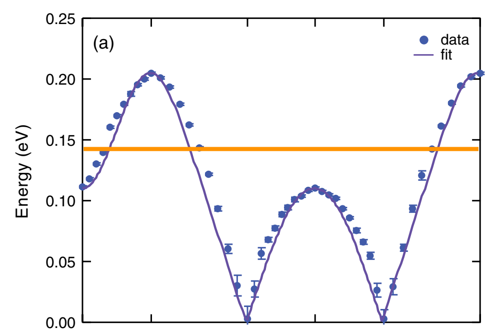
Bosons

- Holstein-Primakoff: $\psi_{\mathbf{k}} = (a_{\mathbf{k}}, a^{\dagger}_{-\mathbf{k}})^T$

$$\mathcal{H}_{\mathrm{E}} = \boxed{E_{\mu}(t)}\left[\Phi^{1,\mu}_{A}\,\psi_A \;+\; \Phi^{2,\mu}_{A,B}\,\psi_A\psi_B \;+\; \Phi^{3,\mu}_{A,B,C}\,\psi_A\psi_B\psi_C \;+\; \mathcal{O}(1/S^0)\right]$$

$$\sim \mathrm{Re}\left(\mathcal{E}_{\mu} e^{i\omega t}\right)$$

Floquet drive



- Cannot excite single magnon due to momentum conservation
- Two magnon process is resonant: generates pairs with **k** and **-k**

?? How is **k=0** magnetization created?

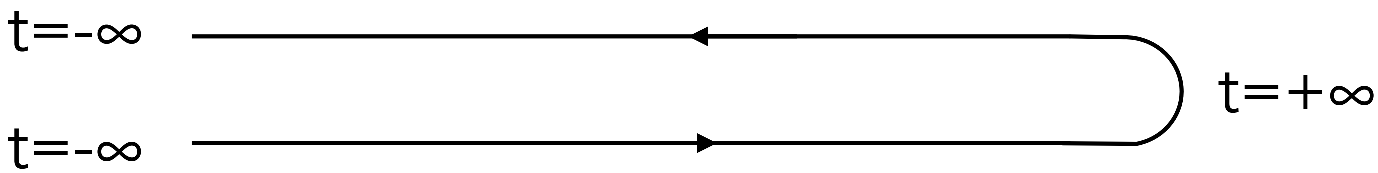
Formalism

- Non-equilibrium Keldysh method: evolve both bra and ket

$$|\Psi(t)\rangle = U(t,-\infty)|\Psi(-\infty)\rangle$$

$$\langle \mathcal{O}(t)\rangle = \langle \Psi(\infty)|U(-\infty,t)\mathcal{O}U(t,-\infty)|\Psi(-\infty)\rangle$$

- Keldysh contour



$$\mathcal{Z} = \int \mathcal{D}[a_+, a_-]\,\exp(\mathrm{i}\mathcal{S})$$

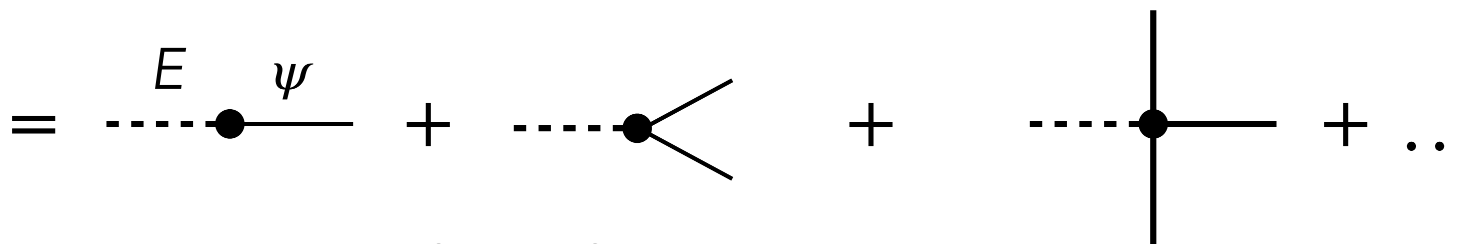
$$\mathcal{S} = \sum_{s=\pm} s \int \mathrm{d}t \left\{ \sum_i \bar{a}_{s,i}\mathrm{i}\partial_t a_{s,i} - \mathcal{H}[\{\bar{a}_{s,i}, a_{s,i}\}] \right\}$$

path integral over doubled fields

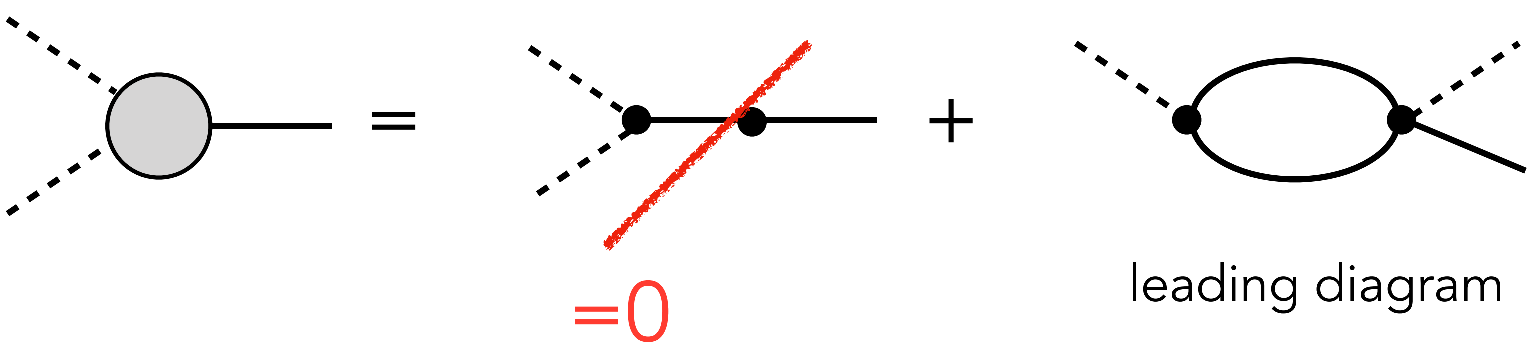
Formalism

- Non-equilibrium Keldysh path integral

$$\mathcal{H}_{\mathrm{E}} = E_\mu(t)\left[\Phi^{1,\mu}_{A}\,\psi_A \;+\; \Phi^{2,\mu}_{A,B}\,\psi_A\psi_B \;+\; \Phi^{3,\mu}_{A,B,C}\,\psi_A\psi_B\psi_C \;+\; \mathcal{O}(1/S^0)\right]$$



- Now integrate out “fast” fields: internal lines



Formalism

- Non-equilibrium Keldysh path integral

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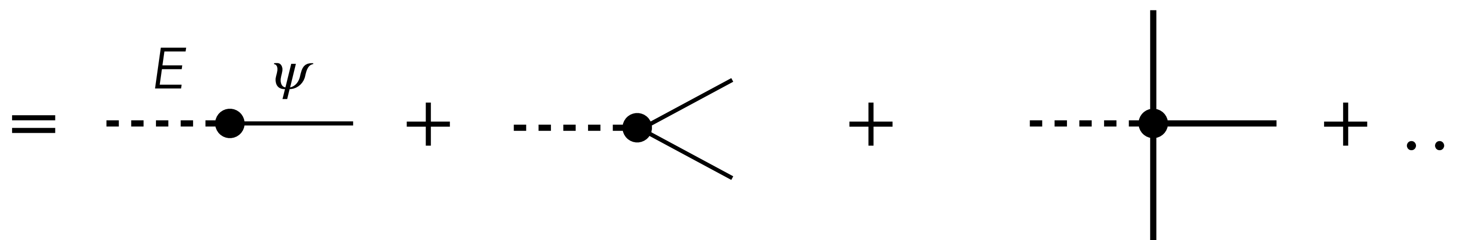

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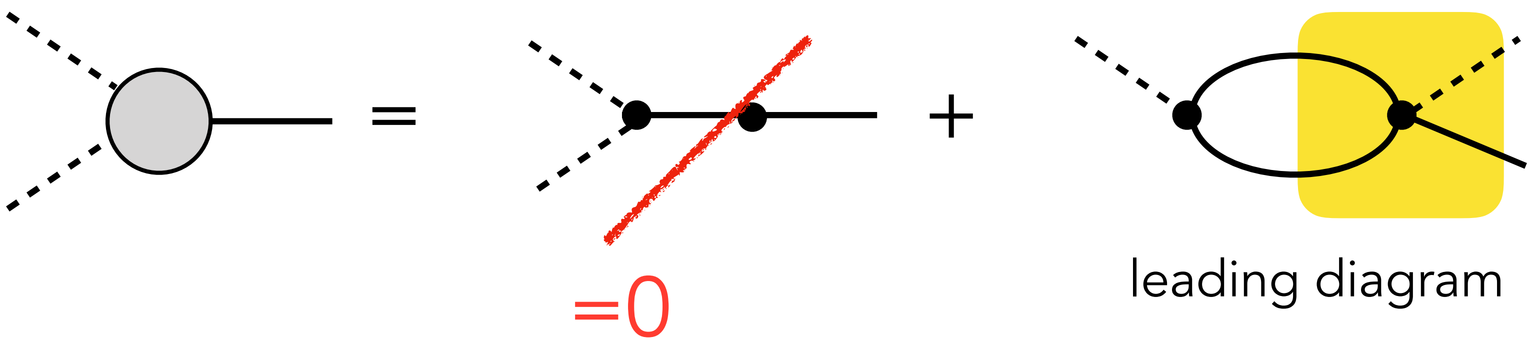


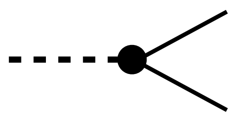
leading diagram

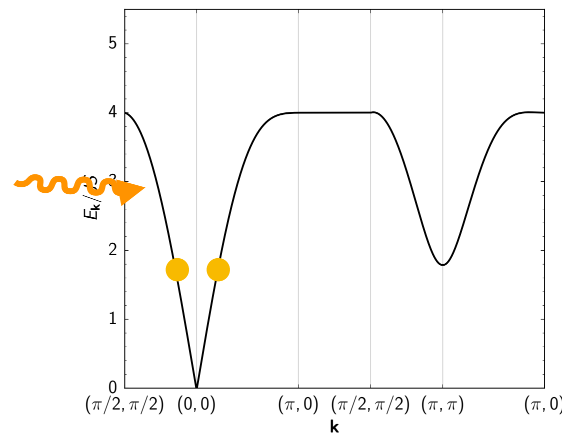
involves boson interactions!

Physical picture

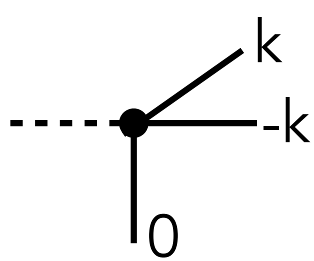
- Step 1:

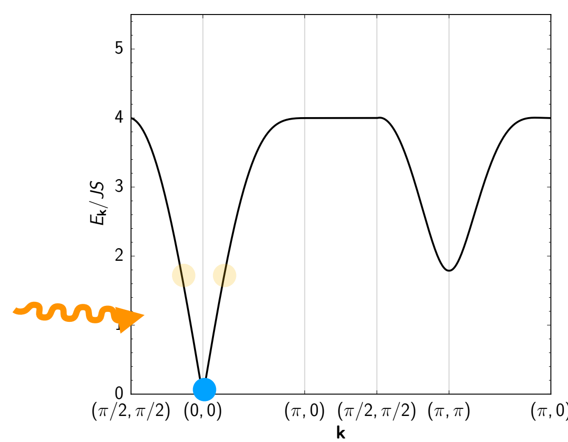
  photon generates coherent pairs





- Step 2: Interaction “proximitizes” low energy condensate = magnons





Results

- Effective fields given by loop integrals

$$h \sim \int \mathrm{d}^2\mathbf{k}\, \mathcal{E}_\mu \bar{\mathcal{E}}_\nu \sum_{\beta,\beta'=\pm 1} \frac{\Phi^{2,\mu}\Phi^{3,\nu}}{\Omega + \beta E_{\mathbf{k}} + \beta' E_{\mathbf{Q}-\mathbf{k}} + \mathrm{i}\eta}$$

separates into:

dissipative	virtual
$\sim \delta(\Omega - E_{\mathbf{k}} - E_{\mathbf{Q}-\mathbf{k}})$	$\sim \frac{P}{\delta - E_{\boldsymbol{k}} - E_{\boldsymbol{Q}-k}}$

Results

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separates into:

dissipative

$$\sim \delta(\Omega - E_{\mathbf{k}} - E_{\mathbf{Q}-\mathbf{k}})$$

virtual

$$\sim \frac{P}{\delta - E_{\boldsymbol{k}} - E_{\boldsymbol{Q}-k}}$$

- Structure of contributions to effective fields

$$\sin 2\phi \times \begin{cases} \mathcal{E}_x\bar{\mathcal{E}}_y + \mathcal{E}_y\bar{\mathcal{E}}_x \\ \mathcal{E}_x\bar{\mathcal{E}}_x - \mathcal{E}_y\bar{\mathcal{E}}_y \end{cases}$$

traceless symmetric

total intensity

$$\sin 4\phi \times \left(\mathcal{E}_x\bar{\mathcal{E}}_x + \mathcal{E}_y\bar{\mathcal{E}}_y\right)$$

identity

chiral intensity

$$\mathrm{i}\left(\mathcal{E}_x\bar{\mathcal{E}}_y - \mathcal{E}_y\bar{\mathcal{E}}_x\right)$$

antisymmetric

Results

- Effective fields given by loop integrals

$$h \sim \int \mathrm{d}^2\mathbf{k}\, \mathcal{E}_\mu \bar{\mathcal{E}}_\nu \sum_{\beta,\beta'=\pm1} \frac{\Phi^{2,\mu}\Phi^{3,\nu}}{\Omega + \beta E_{\mathbf{k}} + \beta' E_{\mathbf{Q}-\mathbf{k}} + \mathrm{i}\eta}$$

separates into:

	dissipative	virtual
	$\sim \delta(\Omega - E_{\mathbf{k}} - E_{\mathbf{Q}-\mathbf{k}})$	$\sim \frac{P}{\delta - E_{\boldsymbol{k}} - E_{\boldsymbol{Q}-k}}$

- Structure of contributions to effective fields

$$\boxed{\sin 2\phi \times \begin{cases} \mathcal{E}_x\bar{\mathcal{E}}_y + \mathcal{E}_y\bar{\mathcal{E}}_x \\ \mathcal{E}_x\bar{\mathcal{E}}_x - \mathcal{E}_y\bar{\mathcal{E}}_y \end{cases} \qquad \overset{\text{total intensity}}{\sin 4\phi \times \left(\mathcal{E}_x\bar{\mathcal{E}}_x + \mathcal{E}_y\bar{\mathcal{E}}_y\right)}}$$

chiral intensity

$$\mathrm{i}\left(\mathcal{E}_x\bar{\mathcal{E}}_y - \mathcal{E}_y\bar{\mathcal{E}}_x\right)$$

linear polarization

Results

- Effective fields given by loop integrals

$$h \sim \int \mathrm{d}^2\mathbf{k}\, \mathcal{E}_\mu \bar{\mathcal{E}}_\nu \sum_{\beta,\beta'=\pm 1} \frac{\Phi^{2,\mu}\Phi^{3,\nu}}{\Omega + \beta E_{\mathbf{k}} + \beta' E_{\mathbf{Q}-\mathbf{k}} + \mathrm{i}\eta}$$

separates into:

	dissipative	virtual
	$\sim \delta(\Omega - E_{\mathbf{k}} - E_{\mathbf{Q}-\mathbf{k}})$	$\sim \frac{P}{\delta - E_{\boldsymbol{k}} - E_{\boldsymbol{Q}-k}}$

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$$\sin 2\phi \times \begin{cases} \mathcal{E}_x\bar{\mathcal{E}}_y + \mathcal{E}_y\bar{\mathcal{E}}_x \\ \mathcal{E}_x\bar{\mathcal{E}}_x - \mathcal{E}_y\bar{\mathcal{E}}_y \end{cases}$$

total intensity	chiral intensity
$\sin 4\phi \times \left(\mathcal{E}_x\bar{\mathcal{E}}_x + \mathcal{E}_y\bar{\mathcal{E}}_y\right)$	$\mathrm{i}\left(\mathcal{E}_x\bar{\mathcal{E}}_y - \mathcal{E}_y\bar{\mathcal{E}}_x\right)$

circular polarization

Results

- Effective fields given by loop integrals

$$h \sim \int \mathrm{d}^2\mathbf{k}\, \mathcal{E}_\mu \bar{\mathcal{E}}_\nu \sum_{\beta,\beta'=\pm 1} \frac{\Phi^{2,\mu}\Phi^{3,\nu}}{\Omega + \beta E_{\mathbf{k}} + \beta' E_{\mathbf{Q}-\mathbf{k}} + \mathrm{i}\eta}$$

separates into:

	dissipative	virtual
	$\sim \delta(\Omega - E_{\mathbf{k}} - E_{\mathbf{Q}-\mathbf{k}})$	$\sim \dfrac{P}{\delta - E_{\boldsymbol{k}} - E_{\boldsymbol{Q}-k}}$

- Structure of contributions to effective fields

$$\sin 2\phi \times \begin{cases} \mathcal{E}_x\bar{\mathcal{E}}_y + \mathcal{E}_y\bar{\mathcal{E}}_x \\ \mathcal{E}_x\bar{\mathcal{E}}_x - \mathcal{E}_y\bar{\mathcal{E}}_y \end{cases}$$

total intensity	chiral intensity
$\sin 4\phi \times \left(\mathcal{E}_x\bar{\mathcal{E}}_x + \mathcal{E}_y\bar{\mathcal{E}}_y\right)$	$\mathrm{i}\left(\mathcal{E}_x\bar{\mathcal{E}}_y - \mathcal{E}_y\bar{\mathcal{E}}_x\right)$

=0 for Sr_2IrO_4
($\phi=\pi/4$)

circular polarization

"inverse Faraday effect"

Prior approach to Inverse Faraday effect

PHYSICAL REVIEW VOLUME 143, NUMBER 2 MARCH 1966

Theoretical Discussion of the Inverse Faraday Effect, Raman Scattering, and Related Phenomena*

P. S. Pershan,† J. P. van der Ziel,‡ and L. D. Malmstrom
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts

(Received 25 October 1965)

- Derived effective thermodynamic potential

$$\mathcal{F} \sim \chi^{ijk} M_i(0) E_j(\omega) E_k(-\omega)$$

$$h^i_{\text{eff}} = -\frac{\partial \mathcal{F}}{\partial M_i(0)} = \chi^{ijk} E_j(\omega) E_k(-\omega)$$

really correct for low frequency magnetization (not short pulse)

- Carried out for quantum mechanical few-level system

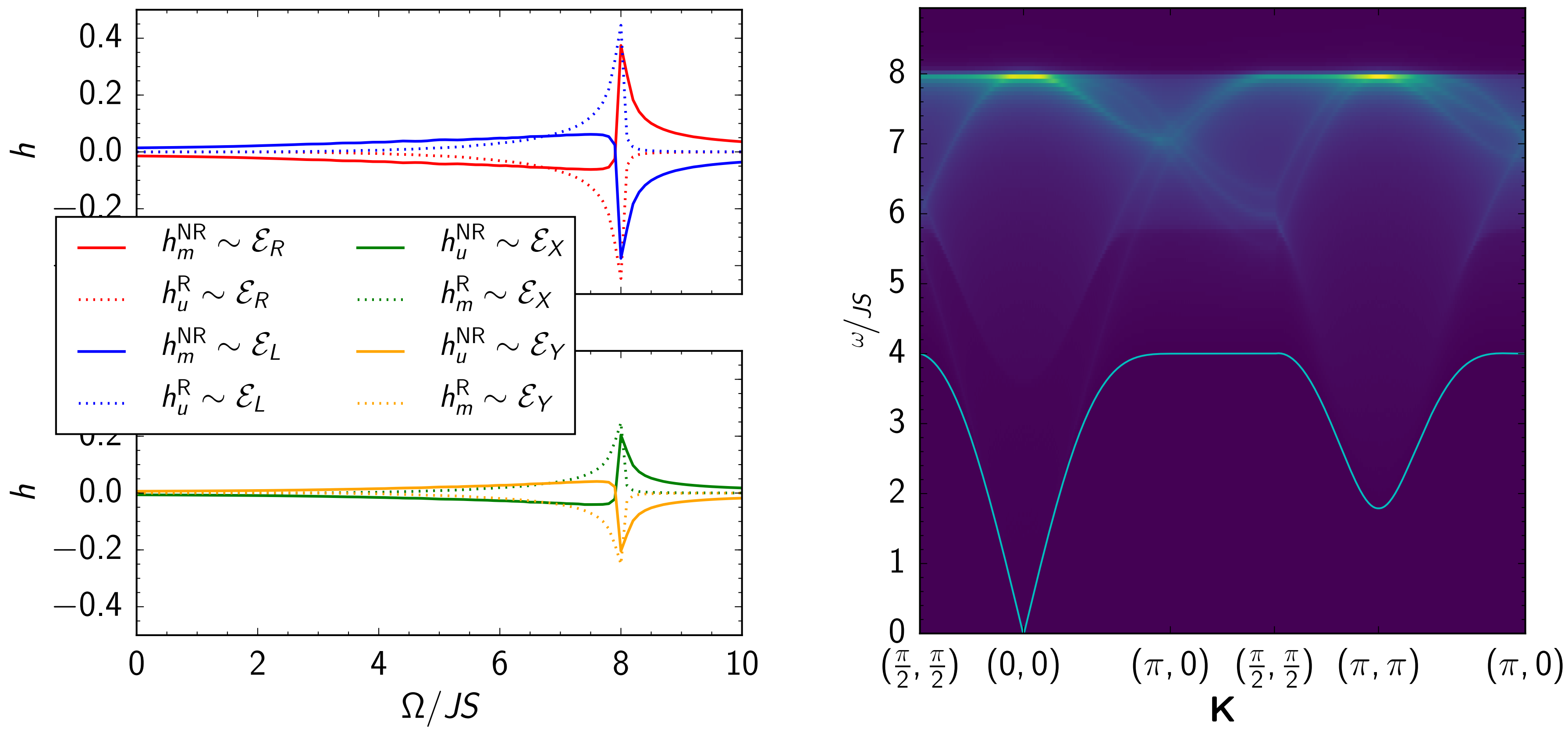
$$\mathcal{H}_{\text{eff}} = (\mathcal{E}_R\mathcal{E}_R^* - \mathcal{E}_L\mathcal{E}_L^*)J_z A + \{(\mathcal{E}_R\mathcal{E}_R^* + \mathcal{E}_L\mathcal{E}_L^*)[J_z^2 - \tfrac{1}{3}J(J+1)] - \mathcal{E}_L\mathcal{E}_R^* J_-^2 - \mathcal{E}_L^*\mathcal{E}_R J_+^2\}C\,,$$

Purely virtual excitations

- Our results treat general many body situation with fast dynamics and both real and virtual excitations

Results

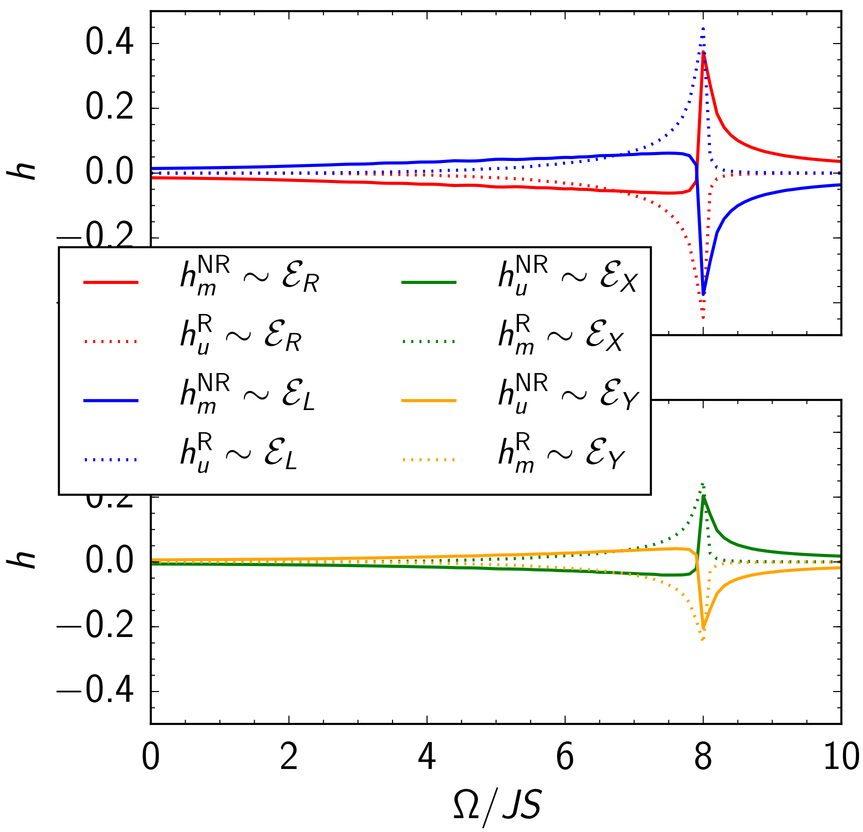
- Effective fields maximized when light is near peak of two-magnon DOS



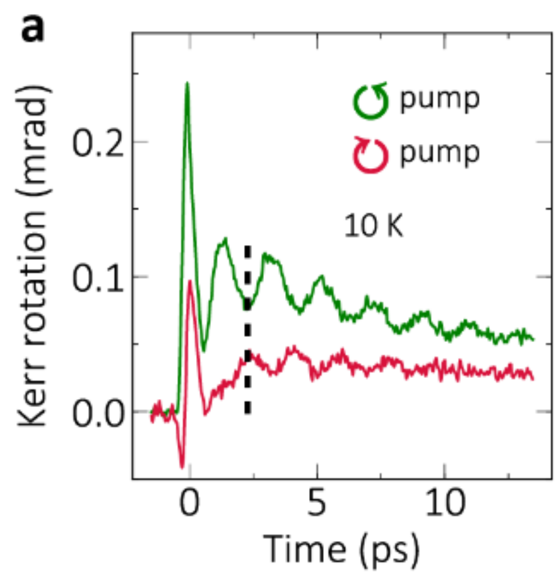
Significant enhancement still possible!

Results

- Effective fields maximized when light is near peak of two-magnon DOS



Gufeng Zhang *et al*



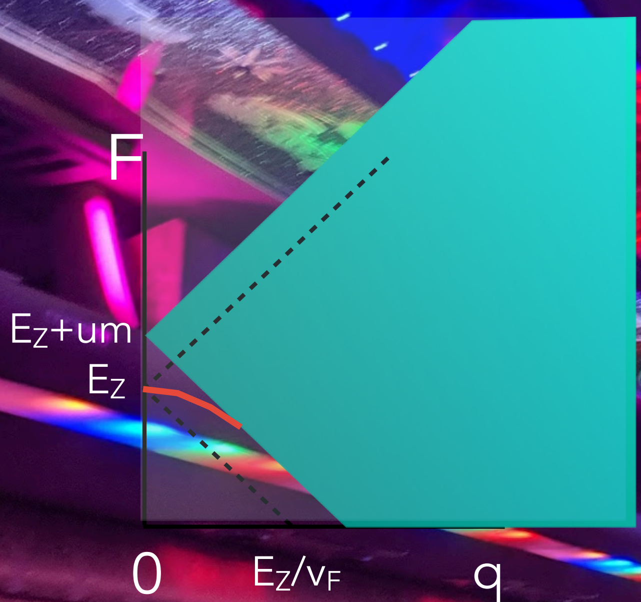
Dominant chiral intensity: magnetization of opposite sign for two circular polarizations

Future directions

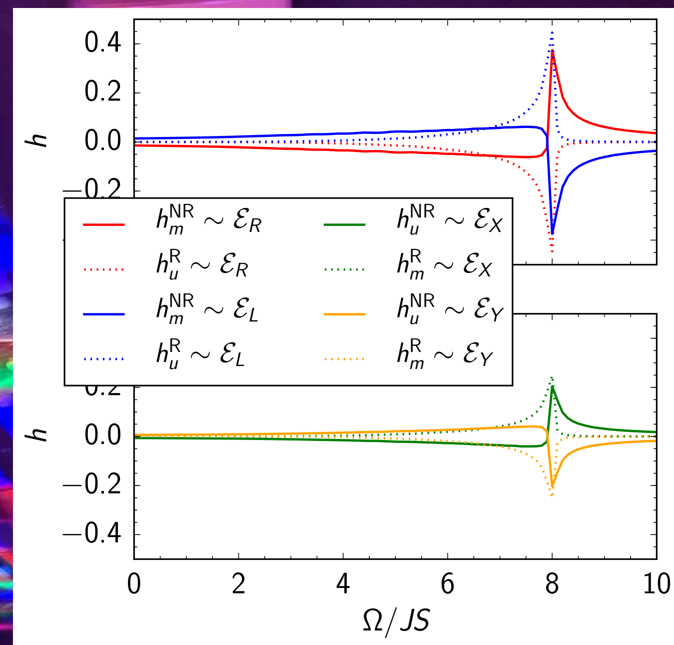
- Experimental test of frequency dependence. Many other materials applications.
- Extension to T>0
- Extension to non-collinear magnets: much larger anharmonic effects
- Topological effects: Pump/probe of Dirac/Weyl magnons, analogies to topological effects in SHG?
- Ultrafast dynamics of quantum spin liquids without magnons?

Recap

O.Starykh + LB, arXiv:1904.02117



U.F.P. Seifert+LB, PRB **100**, 125161 (2019)



- Fermionic two-spinon continuum modified by *Silin spin wave* and *gauge continuum.*
- Further work: modifications near q=0 by anisotropies/ SOC - needed to understand ESR, extension to Dirac spin liquids
- Theory of light-induced magnetization oscillations in an antiferromagnet, with direct application to Sr_2IrO_4

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