Spintronics with magnetic insulators

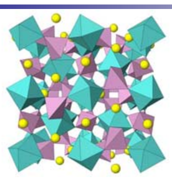
Joe Barker, Yaroslav Blanter, *Mehrdad Elyasi*, *Tao Yu*, & Gerrit Bauer

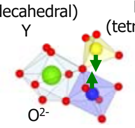
Contents

- Introduction to magnonics of YIG
- (Quantum) non-linearities of YIG in microwave cavities
- Chiral magnon transport

C. Magnon

Yttrium Iron Garnet $Y_3^{(3+)} Fe_2^{(3+)} (Fe^{(3+)} O_4^{(2-)})_3$





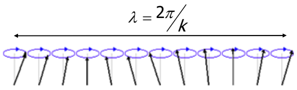
- Curie temperature 550 K
- electrical insulator (band gap 2.8 eV, r@RT>10^{15} Wcm)
- transparent for IR light / large Faraday effect
- switchable by light and currents
- tunable magnetic anisotropy
- superior spin conductor
- high magnetic quality factor, Q=10^5 (single Xtals), Q=10^4 (thin films)
- low acoustic damping ("better than the best quartz")

Spin waves and magnons

Landau-Lifshitz equation: $\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{B}$

Linearized solution (exchange magnons):

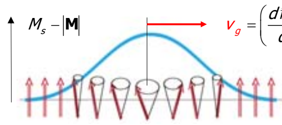
$\lambda = 2\pi/k$



$\hbar\omega_k = \hbar\omega_0 + Ak^2$

$\omega_0 = \gamma B$ Kittel mode

Charles Kittel (1916-2019)



Magnons: Quanta of spin waves with S=1 (Bosons):

$$n_k = \frac{1}{e^{\frac{\hbar\omega_k}{k_B T}} - 1}$$

Magnon interactions

$$H = -J \sum_{\langle ij \rangle}^{nn} \mathbf{S}_i \cdot \mathbf{S}_j + \gamma B \sum_i S_i^{(z)} + H_{anisotropy} + H_{dipole}$$

$$S_i^{(x)} + iS_i^{(y)} = \sqrt{2S}\left(c_i - \frac{c_i^\dagger c_i c_i}{4S}\right) + O\left(\frac{1}{S^{3/2}}\right)$$

$$S_i^{(x)} - iS_i^{(y)} = \sqrt{2S}\left(c_i^\dagger - \frac{c_i^\dagger c_i^\dagger c_i}{4S}\right) + O\left(\frac{1}{S^{3/2}}\right)$$

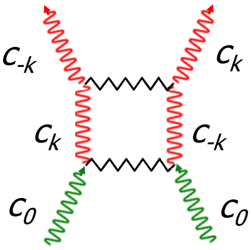
$$S_i^{(z)} = S\left(1 - c_i^\dagger c_i\right)$$

$$\hbar\omega_{\mathbf{k}} = \hbar\omega_0 + JSa^2k^2$$

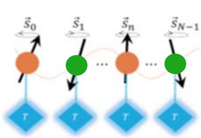
$$H = H^{(4MS)} + H^{(3MS)} + \sum_{\mathbf{k}} \hbar\omega_{\mathbf{k}} c_{\mathbf{k}}^\dagger c_{\mathbf{k}} + \sum_{n>4} H^{(nMS)}$$

increasingly important with magnon density (temperature or external drive)

four magnon scattering



Thermal spin dynamics (J. Barker, 2016,2019)

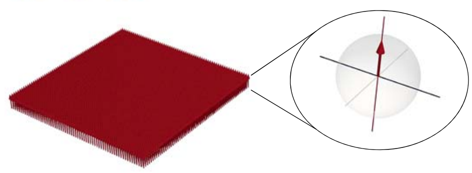


$$\frac{\partial \mathbf{S}_i}{\partial t} = -\frac{\gamma}{\mu_s}\left(\mathbf{S}_i \times \mathbf{H}_i + \eta \mathbf{S}_i \times \left(\mathbf{S}_i \times \mathbf{H}_i\right)\right)$$

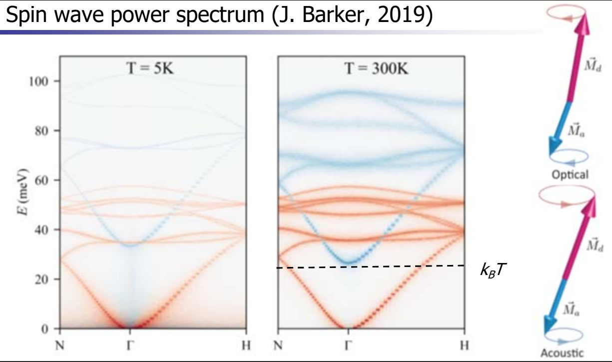
$$\mathbf{H}_i = \mathbf{H}_0 + \mathbf{h}_i(t)$$

$$\mu_s = g\mu_B S$$

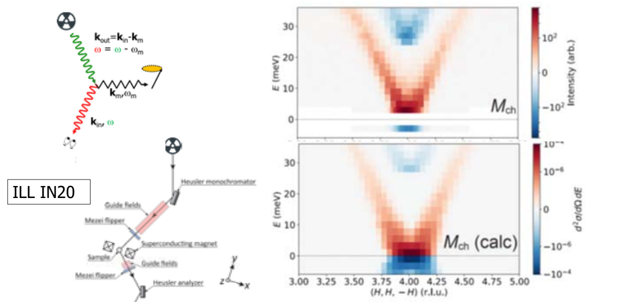
$$\left\langle h_{i,\alpha}(t) h_{j,\beta}(0) \right\rangle_\omega = \frac{2\eta}{\mu_s} \frac{\hbar\omega\delta_{ij}\delta_{\alpha\beta}}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1} \xrightarrow{kT \gg \hbar\omega} \frac{2\eta}{\mu_s} kT\delta_{ij}\delta_{\alpha\beta}$$



Spin wave power spectrum (J. Barker, 2019)

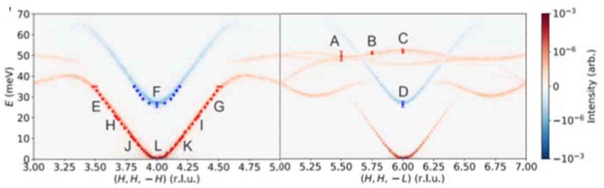


Feynman has been joking!



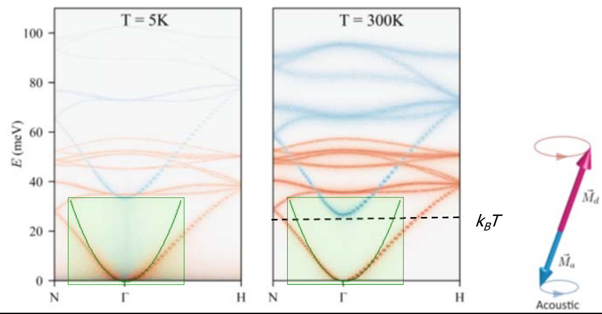
Y. Nambu, J. Barker, K. Kakurai, et al. (2019)

Polarized inelastic neutron scattering cross section



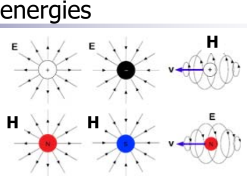
Y. Nambu, J. Barker, et al. (2019)

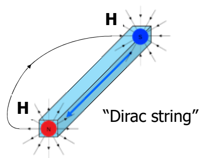
Parabolic exchange model



Magnetic charges and energies

magnetic vs. electric monopoles (Wikipedia)





magnetic wire, spin ice

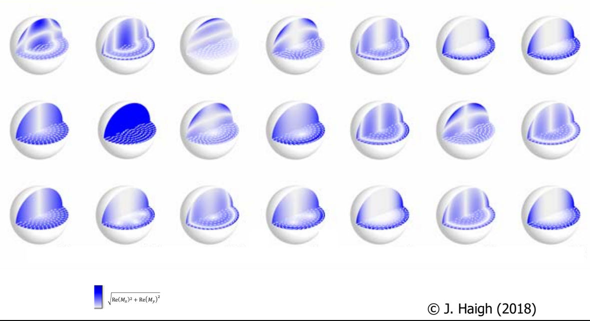
$$\rho_m = \nabla \cdot \mathbf{M}$$

uncompensated magnetic dipoles

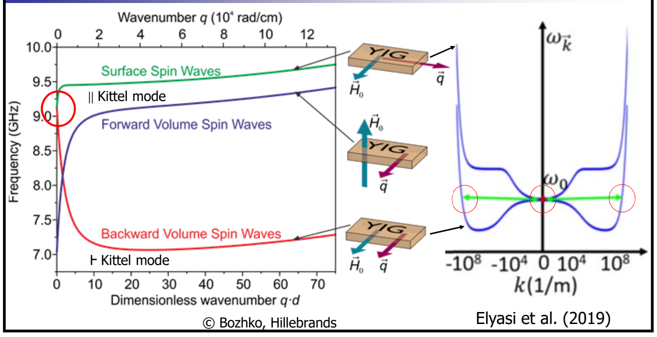
$$\mathbf{H}_m(\mathbf{r}) = \nabla \int \frac{\rho_m(\mathbf{r}')}{4\pi|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$$

Coulomb's Law

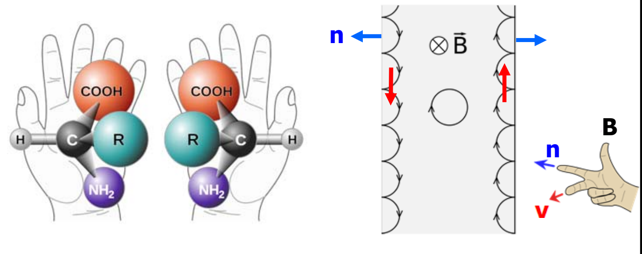
Magnetostatic hydrogen



Magnon dispersion of a d = 5μm YIG film



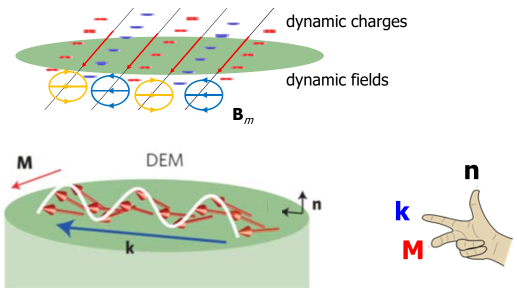
Chirality in chemistry and transport



chemistry

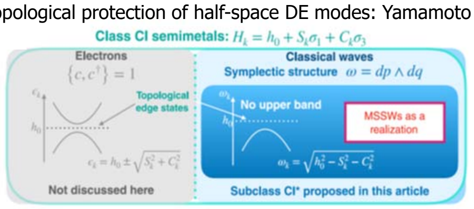
quantum (spin) Hall effects

Magnetostatic surface waves (Damon & Eshbach, 1959)



Magnetostatic surface waves

+ Topological protection of half-space DE modes: Yamamoto et al. (2019)



Tao et al. (2019)

- Small group velocity
- Dephasing by weak disorder
- Efficient backscattering to opposite surface in films

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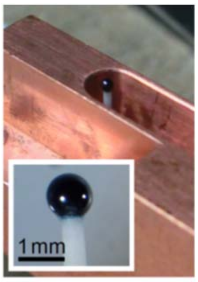
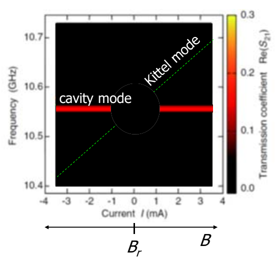
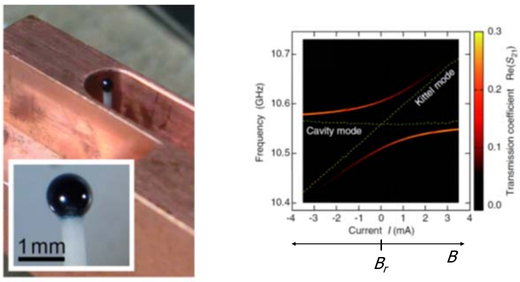
YIG sphere in a microwave cavity





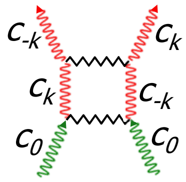
Very strong coupling: magnon polariton quasiparticle

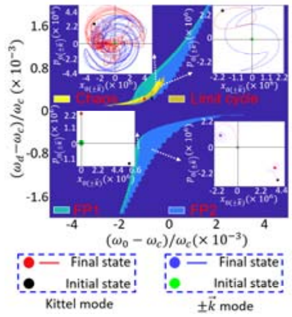


Huebl et al. (2013), Tabuchi et al. (2014) Y. Cao et al. (2015)

M. Elyasi et al., arXiv:1910.11130

Classical dynamics of YIG in resonantly driven microwave cavity.



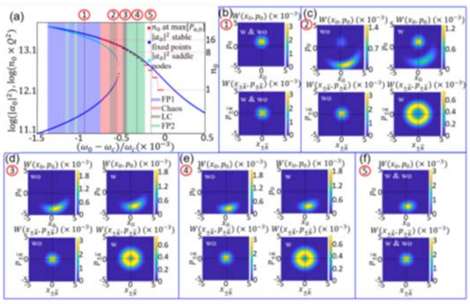


Wigner distribution functions from quantum master equations

Tri-partite system at constant detuning

$$\dot{\hat\rho} = -i[H'^{(T)},\hat\rho] + \sum_{\vec{k}'\in\{0,\vec{k},-\vec{k}\}} L^{(T)}_{\vec{k}'}(\hat\rho, T_{\mathrm{env}})$$

Lindblad operator in Born-Markov approximation



M. Elyasi et al., arXiv:1910.11130

Crash course on entanglement

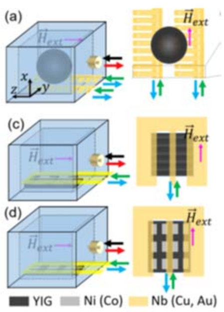
M. Elyasi et al., arXiv:1910.11130

$$\Psi_{\{0,\pm\mathbf{k}\}} \sim \phi_{\{0,p\}}(2)\phi_{\{\pm\mathbf{k}\}}(1) + \phi_{\{0,p\}}(1)\phi_{\{\pm\mathbf{k}\}}(2)$$

① Entanglement is a valuable quantum information "resource".
② For continuous variable systems, the degree of entanglement can be quantified by observable "measures".
③ Not all entanglement is useful ("distillable").
④ The degree of distillable entanglement can be quantified by the E_{LN} "logarithmic negativity" of a bipartite density matrix.
⑤ The "Gaussian" type distillable entanglements around semiclassical fixed points can be observed by homodyne detection schemes.

Conclusions M. Elyasi et al., arXiv:1910.11130

- Driven μ-wave cavity + YIG sphere is massively entangled with distillable E_{LN}~0.3-0.4.
- Quantum squeezing of photon fluctuations by the magnons.
- Entanglement is not Gaussian, but can be made so by "injection locking".
- Heat management can control T~1K.



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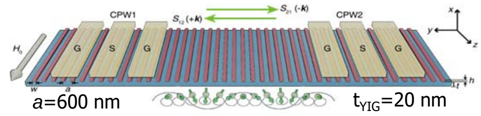
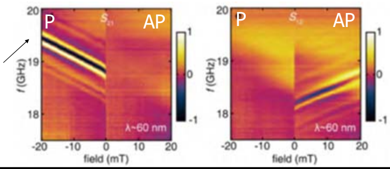
- **Chirality in magnon transport.**

Co nanowire array on YIG film (H. Yu c.s., 2019)

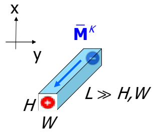


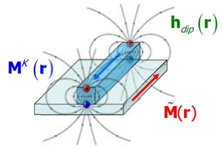
signal transmission by exchange spin waves over 15 μm

Co-FMR $\gg$ YIG-FMR



Magnetic dipole (T. Yu et al., 2019)





magnetostatic charges

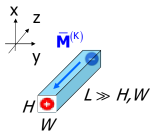
magnetodynamic charges during FMR precession

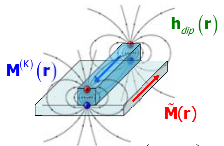
Zeeman interaction: $F_{dip} = -\mu_0 \int \tilde{\mathbf{M}}(\mathbf{r}) \cdot \mathbf{h}_{dip}(\mathbf{r})\, d\mathbf{r}$

Coulomb's Law: $\mathbf{h}_{dip}(\mathbf{r}) = -\mu_0 \nabla_{\mathbf{r}} \int \frac{\rho_m(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}'$

Magnetic charge: $\rho_m(\mathbf{r}) = \nabla_{\mathbf{r}} \cdot \mathbf{M}^K$

Magnetic dipole





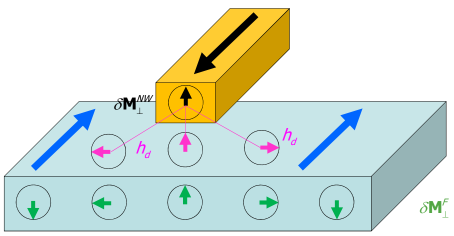
Model: $\mathbf{M}^{(K)}(\mathbf{r},t) = \delta(x-h)\delta(y) M^{(K)} \begin{pmatrix} \cos\omega t \\ \sin\omega t \\ 1 \end{pmatrix}$

Chiral coupling to spin wave with wave vector **k**:

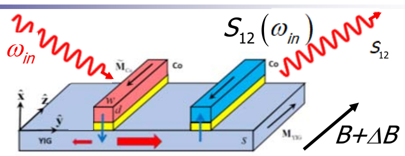
$$F_{\mathrm{dip}} = \frac{\pi \mu_0 M^{(K)}}{\omega} \sum_{k_y} \tilde{M}_{k_y} \begin{cases} k_y e^{-k_y h} & \text{for } k_y > 0 \\ 0 & k_y < 0 \end{cases}$$

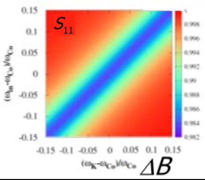
Chiral excitation

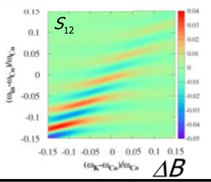
At resonance: $\omega_{FMR}^{NW} = \omega^{film}(\mathbf{k}) = \omega_{FMR}^{film} + \frac{1}{2} A_{ex} \left(k_{\parallel}^2 + k_{\perp}^2 \right)$



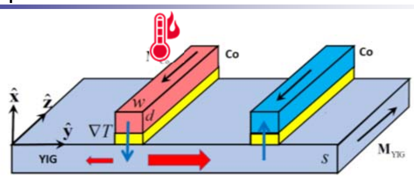
Magnonic diode







Chiral spin Seebeck effect

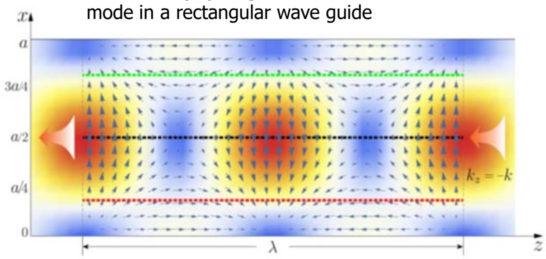


Number of non-equilibrium Kittel magnons in right contact:

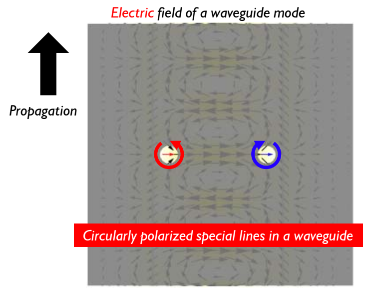
$$\delta\rho_R = \begin{cases} \mathcal{S}_{\mathrm{CSSE}}(T_L - T_R) & \text{when } T_L > T_R \\ 0 & T_L \leq T_R \end{cases}$$

Guided microwaves (TE_{10} mode)

microwave (ac) magnetic field of lowest TE mode in a rectangular wave guide



Chiral optics equivalent



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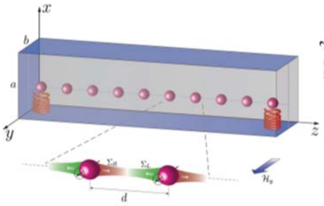
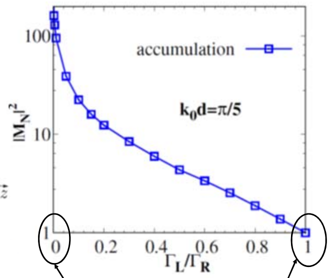
Magnon accumulation by antenna phase array

sub-mm YIG spheres
with local antenna on chiral line





Take home messages on hybrid magnons