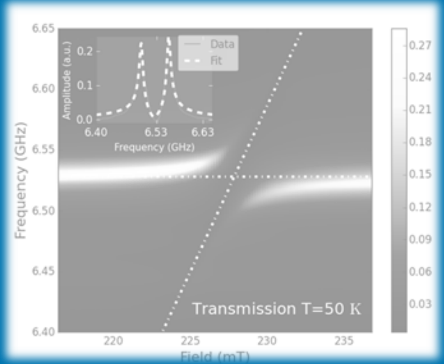
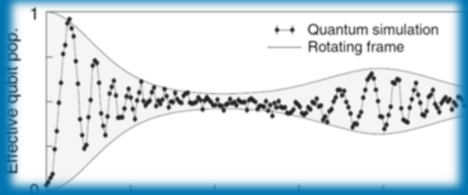
Electro-magnetic and -magnonic cooperativity





May 17th 2018

Martin P. Weides

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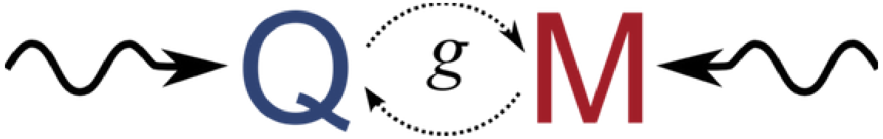
Till 2017: Johannes Gutenberg University Mainz (JGU), Germany



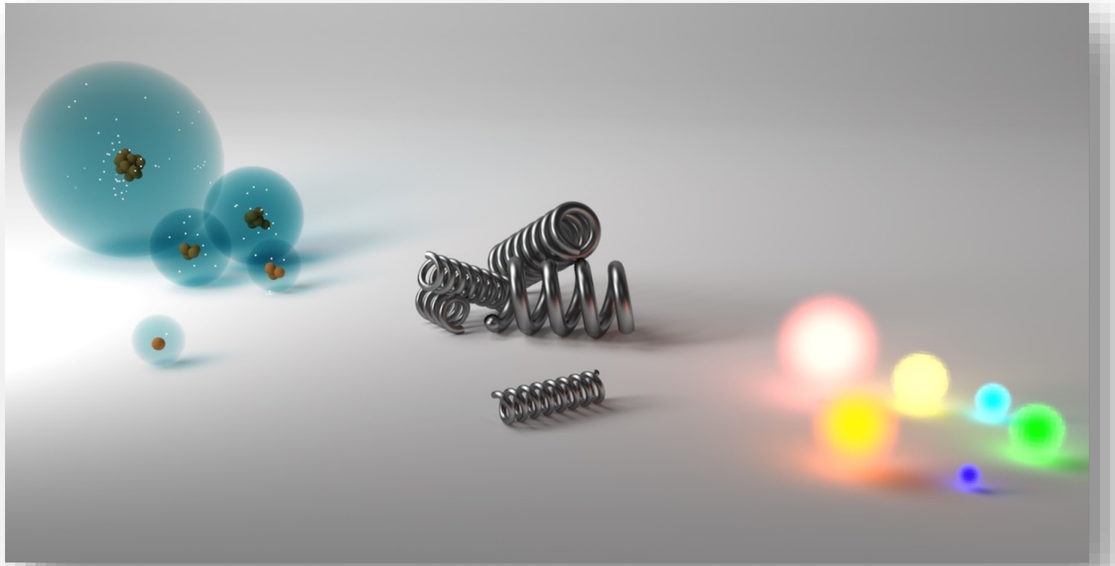
Agenda

1. Analog quantum simulation of ultrastrong coupling

2. Spectroscopic data on YIG
   - From RT to mK
   - mK data
   - Thin film YIG

3. Synchronizing magnons with photons
   - Avoided level crossing and linewidth

Quantum Rabi model



QUTIS Solano

- description of fundamental light-matter interaction

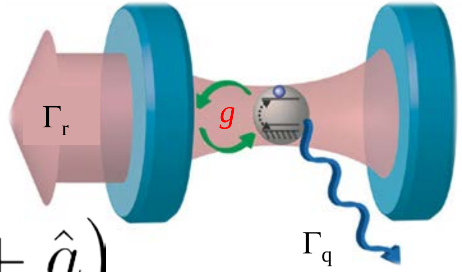
$$\frac{\hat{H}}{\hbar} = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2}\hat{\sigma}_z + g\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

- Ultra/ deep strong coupling regime: $g \approx \omega_r, \omega_q$

Rabi PR **49** (1936); Rabi PR **51** (1937)

WMI 2010, Delft 2016, Waterloo 2017, Tokyo 2017…

Rabi model and coupling regimes



Fundamental light-matter interaction (Rabi)

$$\hat{H}/\hbar = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2}\hat{\sigma}_z + g\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

Creation (annihilation) operator for field mode $\hat{a}^\dagger, \hat{a}$

Qubit operators $\hat{\sigma}_z|\pm\rangle = \pm|\pm\rangle,\ \hat{\sigma}^\pm|\pm\rangle = |\mp\rangle,\ \hat{\sigma}_x = \hat{\sigma}^+ + \hat{\sigma}^-,\ \hat{\sigma}_y = -i\left(\hat{\sigma}^+ - \hat{\sigma}^-\right)$

Coupling strength

- Weak $g \ll \Gamma_r, \Gamma_q, \omega_r, \omega_q$
- Strong $\Gamma_r, \Gamma_q \ll g \ll \omega_r, \omega_q$
- Ultra-strong $\Gamma_r, \Gamma_q, \omega_r/10, \omega_q/10 < g$
- Deep-strong $\Gamma_r, \Gamma_q, \omega_r, \omega_q < g$

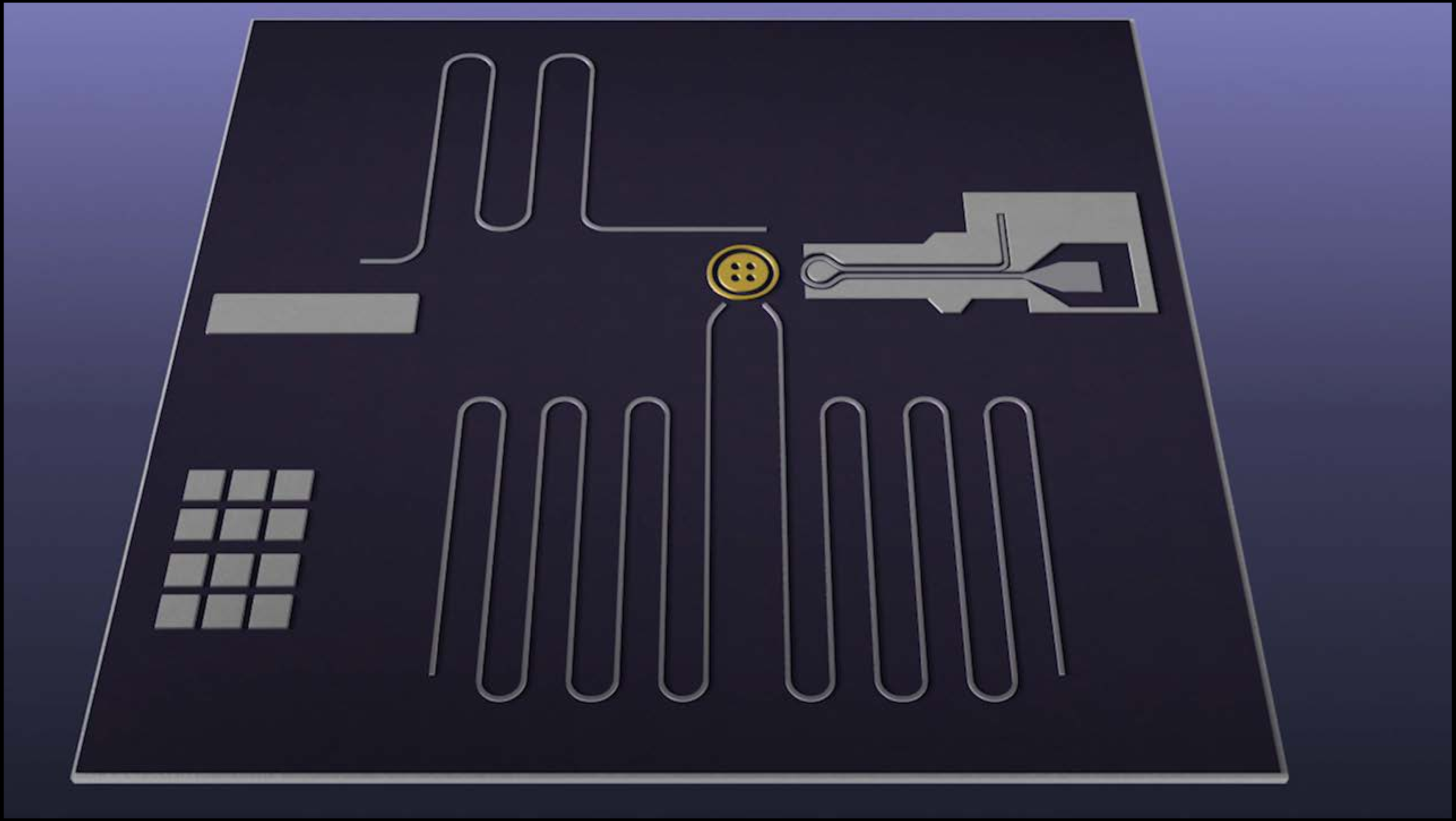
Experimental access complexity

not exactly solvable
(needs 2nd conserved quantity besides energy)

For small coupling ($g \ll \omega_r, \omega_q$) interactions $\cancel{\underbrace{\hat{\sigma}^+\hat{a}^\dagger,\ \hat{\sigma}^-\hat{a}}_{\omega_r+\omega_q}},\ \underbrace{\hat{\sigma}^+\hat{a},\ \hat{\sigma}^-\hat{a}^\dagger}_{|\omega_r-\omega_q|}$

→Jaynes-Cummings $\hat{H}/\hbar = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2}\hat{\sigma}_z + g\left(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+\right)$

From small to ultra / deep - strong coupling



$$|\Psi(t)\rangle = \alpha|R_{\mathrm{g}}g\rangle + \beta|R_{\mathrm{e}}e\rangle$$

Analog quantum simulation of ultra-strong coupling

$$\hat{H}/\hbar = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2}\hat{\sigma}_z + g\left(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+\right) + \hat{\sigma}_x\left(\eta_1 \cos\omega_1 t + \eta_2 \cos\omega_2 t\right)$$

Add two microwave drives

In reference frame rotating with ω_1

$$\hat{H}/\hbar = (\omega_r - \omega_1)\,\hat{a}^\dagger\hat{a} + \frac{\omega_q - \omega_1}{2}\hat{\sigma}_z + g\left(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+\right) + \frac{\eta_1}{2}\hat{\sigma}_x + \frac{\eta_2}{2}\left(\hat{\sigma}^+ e^{i(\omega_1 - \omega_2 t)} + \hat{\sigma}^- e^{-i(\omega_1 - \omega_2 t)}\right)$$

- interaction picture in $\frac{\eta_1}{2}\hat{\sigma}_x$
- basis change via Hadamard transformation
- constraints: $\omega_1 - \omega_2 = \eta_1$, $\omega_{eff} \equiv \omega_r - \omega_1 \approx \mathrm{MHz}$

→ effective Hamiltonian (ultra-strong /deep-strong)

$$\hat{H}_{\mathrm{eff}}/\hbar = \omega_{\mathrm{eff}}\hat{a}^\dagger\hat{a} + \frac{\eta_2}{2}\frac{\hat{\sigma}_z}{2} + \frac{g}{2}\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

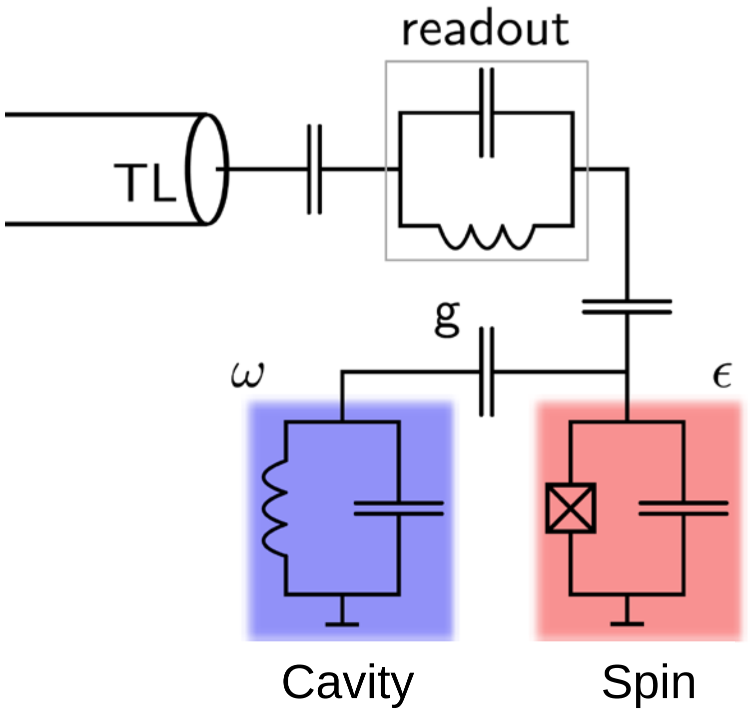
~ MHz ~ MHz 2.5 MHz

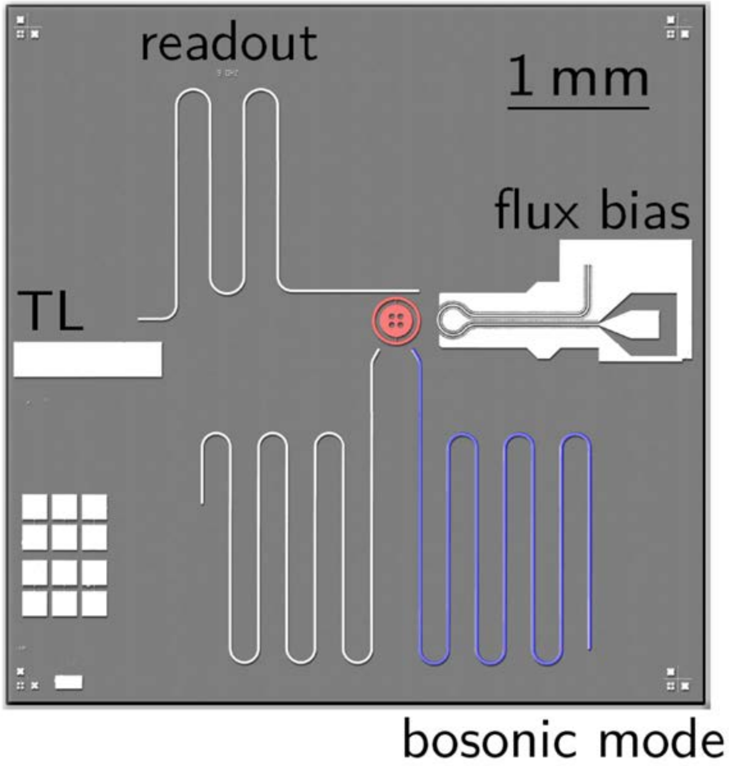
Ballester PRX **2** (2012)

Ultra-strong coupling in rotating frame!

$$\hat{H}_{\text{eff}}/\hbar = \boxed{\omega_{\text{eff}}\hat{a}^\dagger\hat{a}} + \boxed{\frac{\eta_2}{2}\frac{\hat{\sigma}_z}{2}} + \frac{g}{2}\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

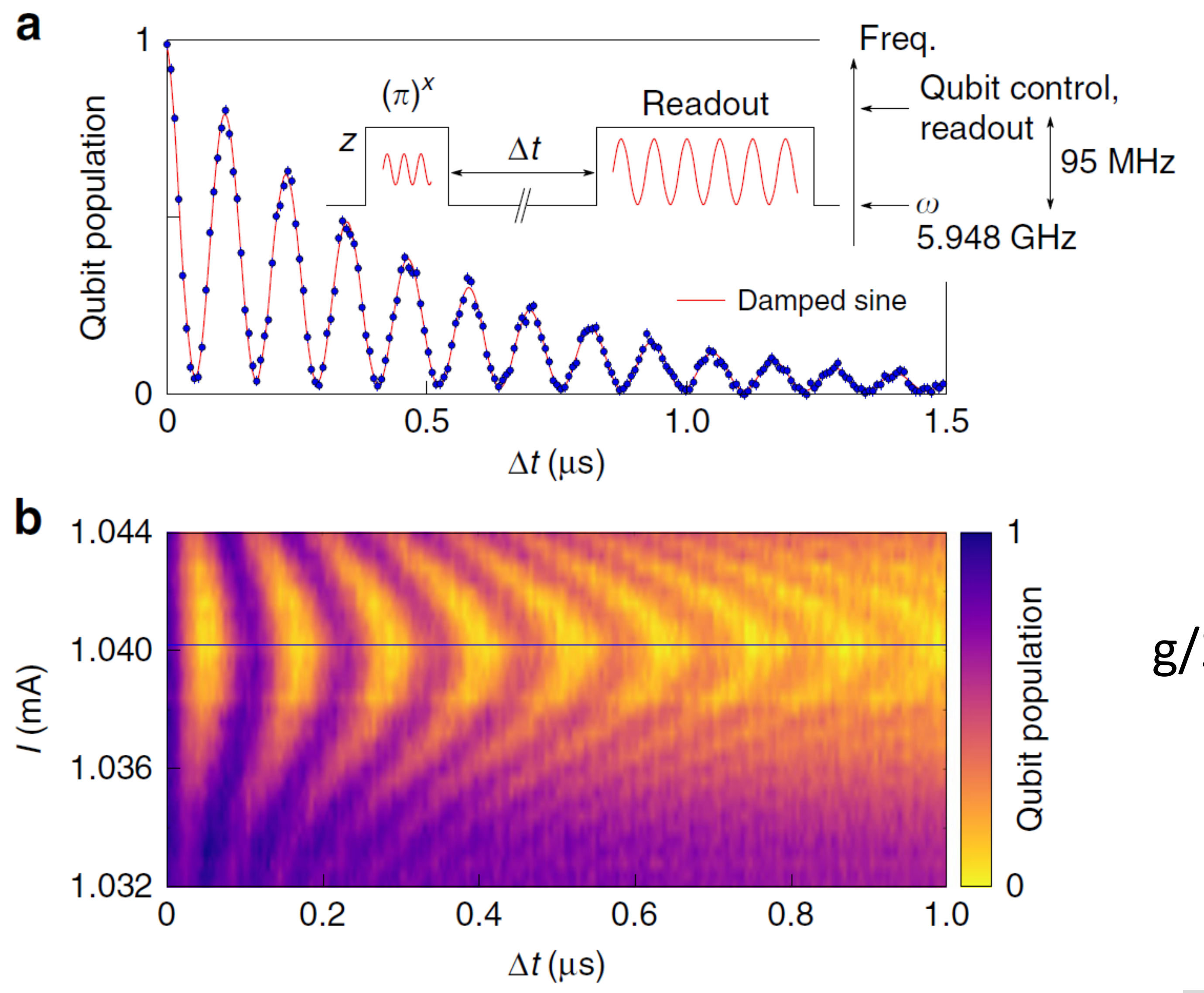
~ MHz ~ MHz 2.5 MHz





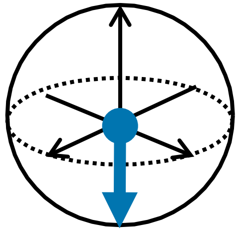
Braumüller *et al.* Nat. Commun. **8**, 779 (2017)

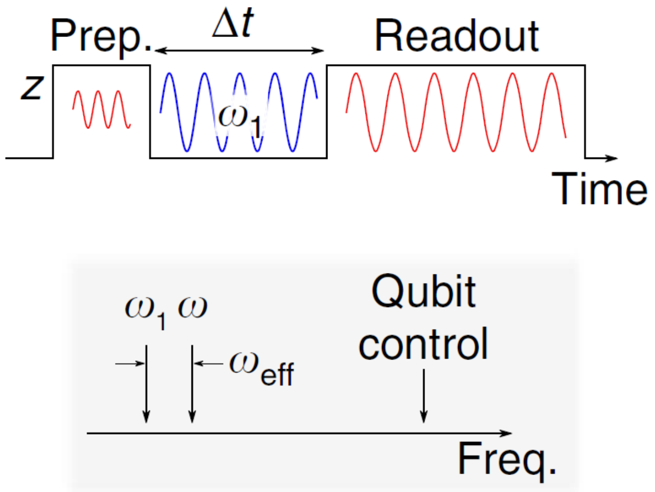
Vacuum Rabi oscillations between qubit and bosonic mode

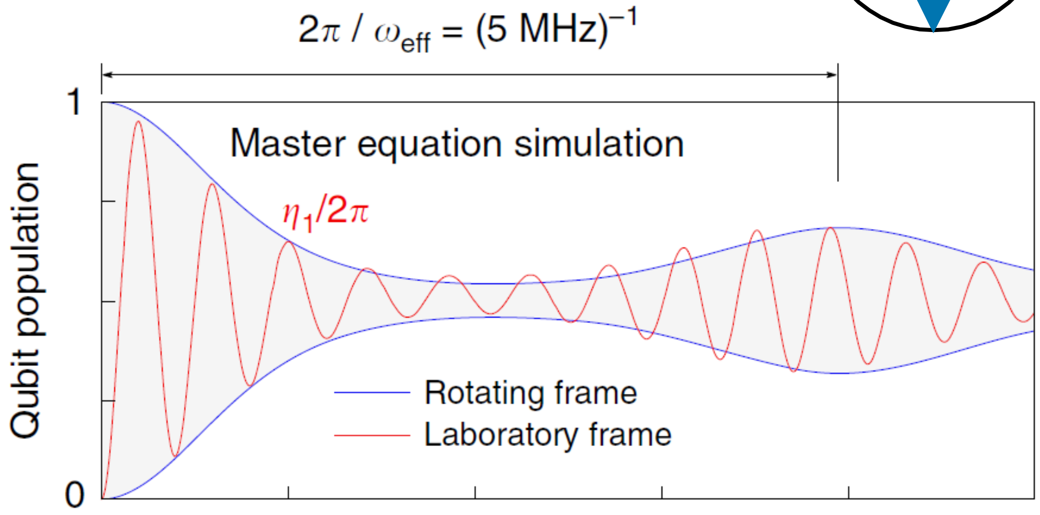


g/2π ≈ 5 MHz

Quantum state collapse, idling and revival







→ Non-classical feature

→ Hallmark of large coupling

Relative coupling ratio

$$\frac{g}{\omega_{\mathrm{eff}}} \sim 0.6$$

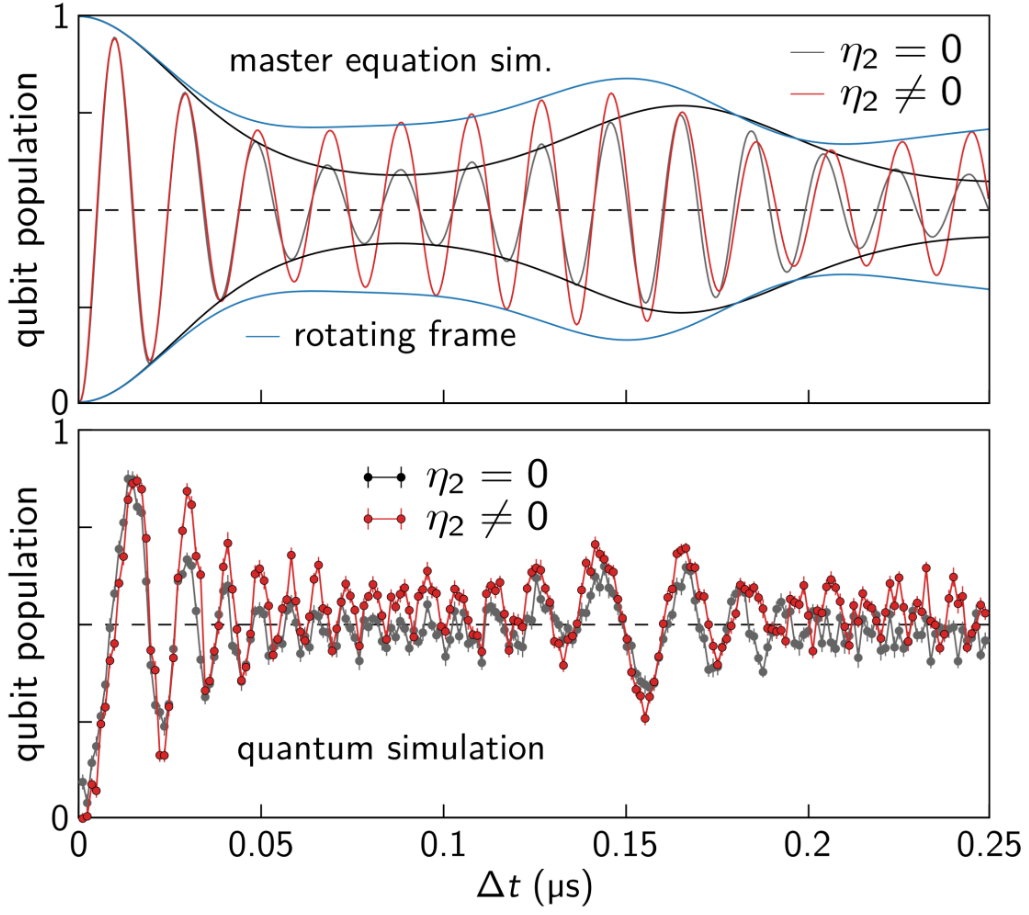
→ Ultra-strong coupling

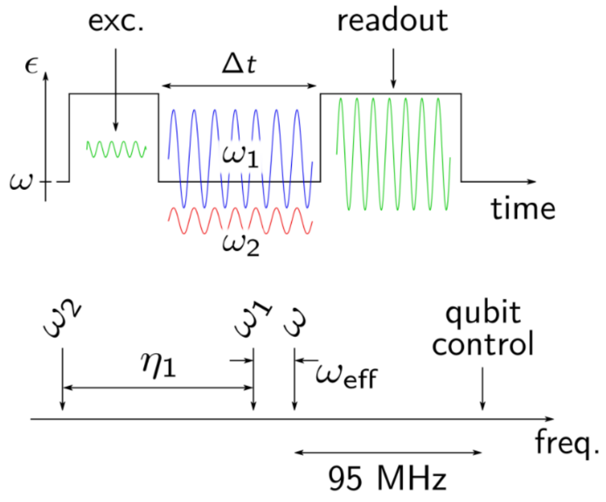
Braumüller *et al.* Nat. Commun. **8**, 779 (2017)

Extend to full quantum Rabi model (i.e. add qubit term)

$$\hat{H}_{\mathrm{eff}}/\hbar = \omega_{\mathrm{eff}}\hat{a}^\dagger\hat{a} + \frac{\eta_2}{2}\frac{\hat{\sigma}_z}{2} + \frac{g}{2}\left(\hat{\sigma}^+ + \hat{\sigma}^-\right)\left(\hat{a}^\dagger + \hat{a}\right)$$

6 MHz 3 MHz 2.5 MHz





- ✓ Main structures captured
- Substructures not → ring up dynamics break constrains

Braumüller *et al.* Nat. Commun. **8**, 779 (2017)

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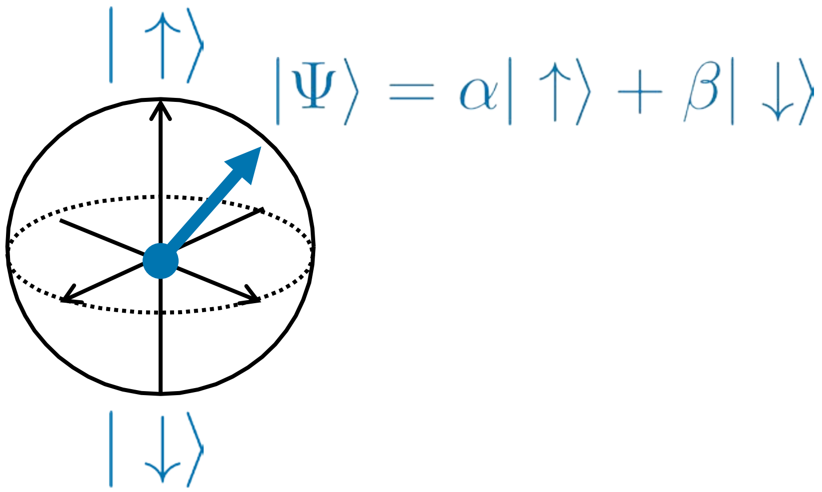
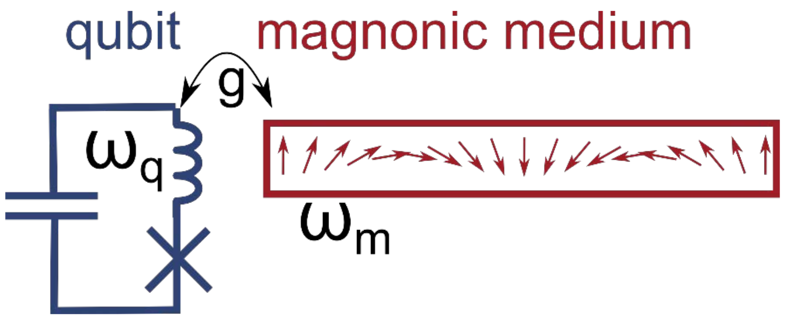
Probing and manipulating single magnons?!

- Quantum ground state (T=10 mK) $\hbar\omega_m \gg k_B T$
- Single quanta spectroscopy, coherent coupling
- **How to achieve?**

Extend magnon to artificial spin!



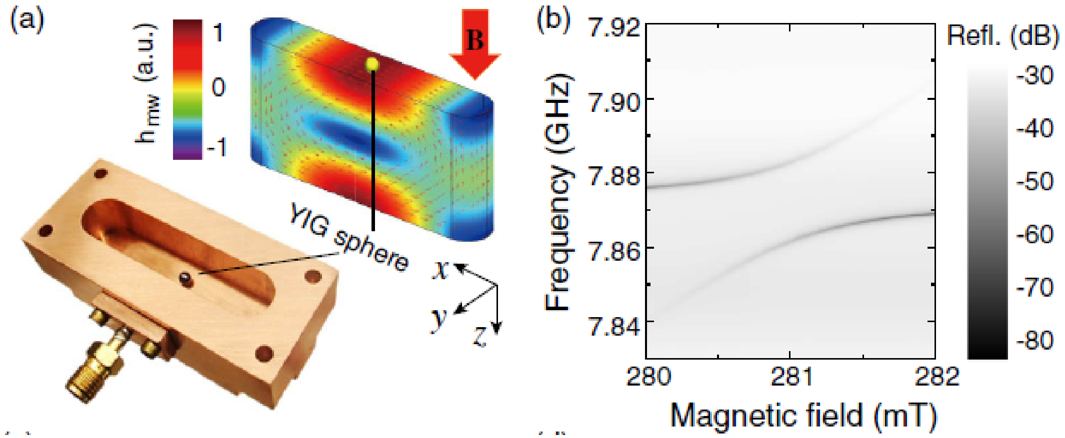


QuantumMagnonics

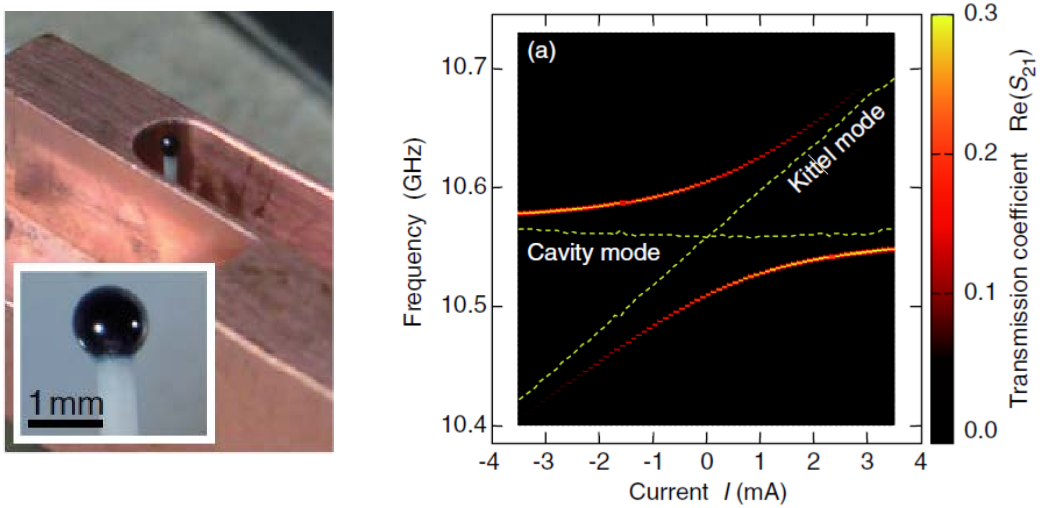
▶ **Access magnon lifetime and coherence via coherent coupling**

Single magnon creation and detection
Quantum-resolved broadband noise spectroscopy

From room temperature to milliKelvin



X. Zhang *et al.*, *Phys. Rev. Lett.* **113**, 156401 (2014)

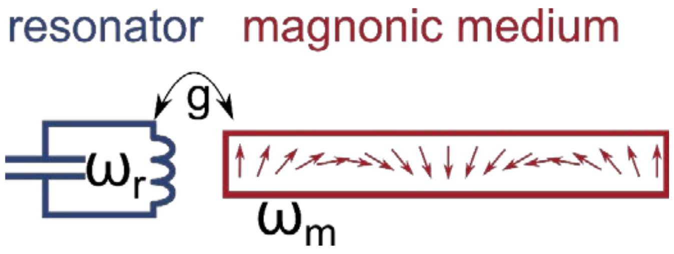


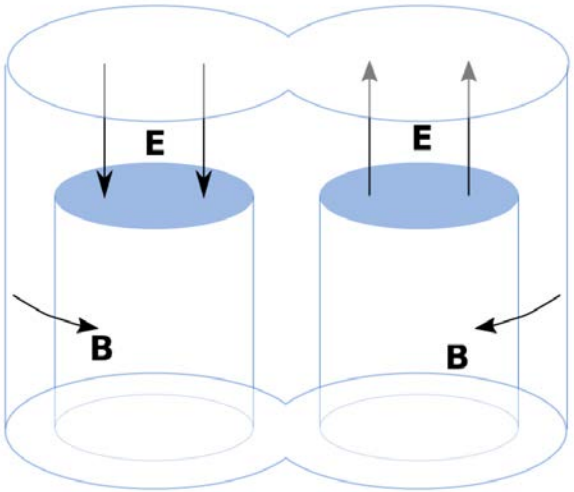
Y. Tabuchi *et al.*, *Phys. Rev. Lett.* **113**, 083603 (2014)

Temperature dependence of hybridized cavity magnon system?

Study from 290 K down to 10mK

3d split ring resonator

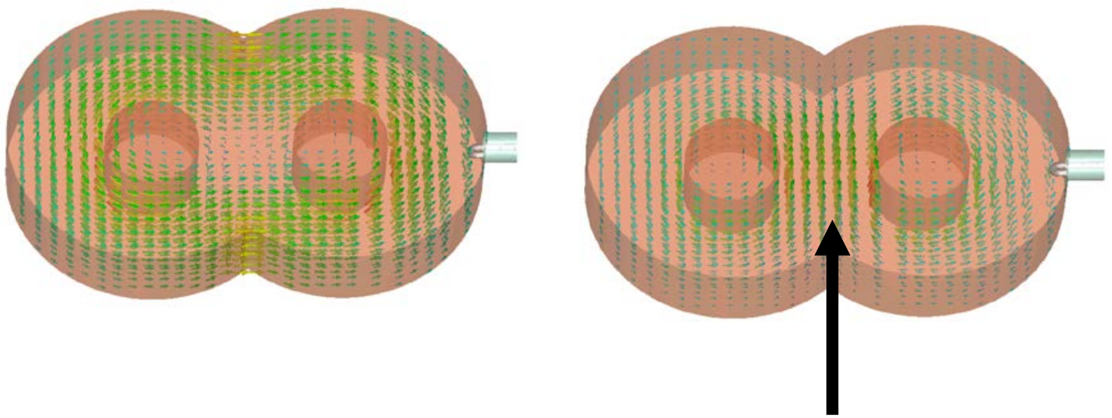




Magnetic field distribution

Parallel

Antiparallel



Magnetic sphere (YIG) placed in center

Reentrant cavity: M. Goryachev *et al., Phys. Rev. Appl.* ,**2,** 054002 (2014)

Avoided crossing: Spectrum

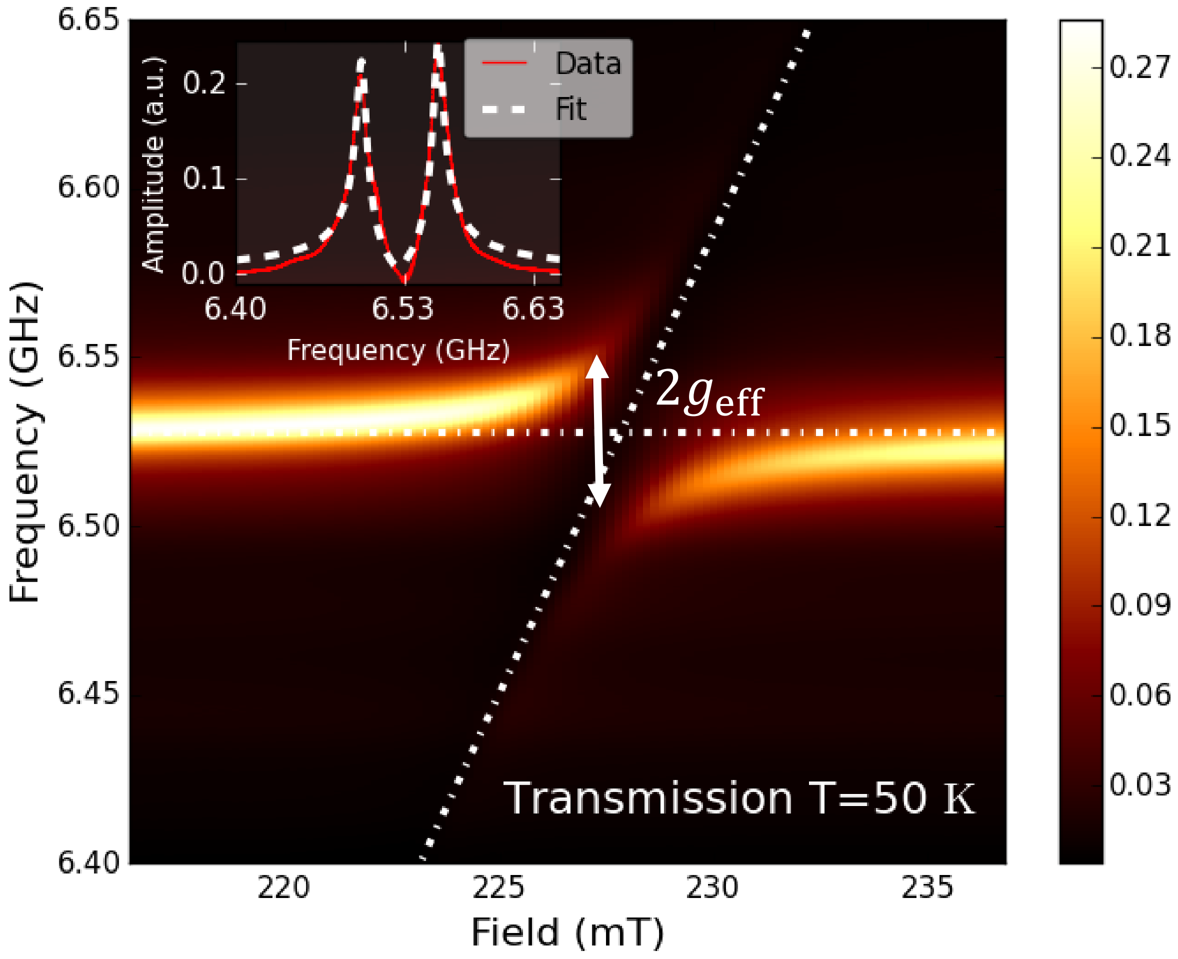
Consider coupling to Kittel mode only

- **Cavity:** field independent

- **YIG:** field dependent

Sphere: $\omega_{res} = \gamma\mu_0\overrightarrow{\mathrm{H}_{eff}}$

- **At resonance:** $\omega_{res} = \omega_r = \omega_m$



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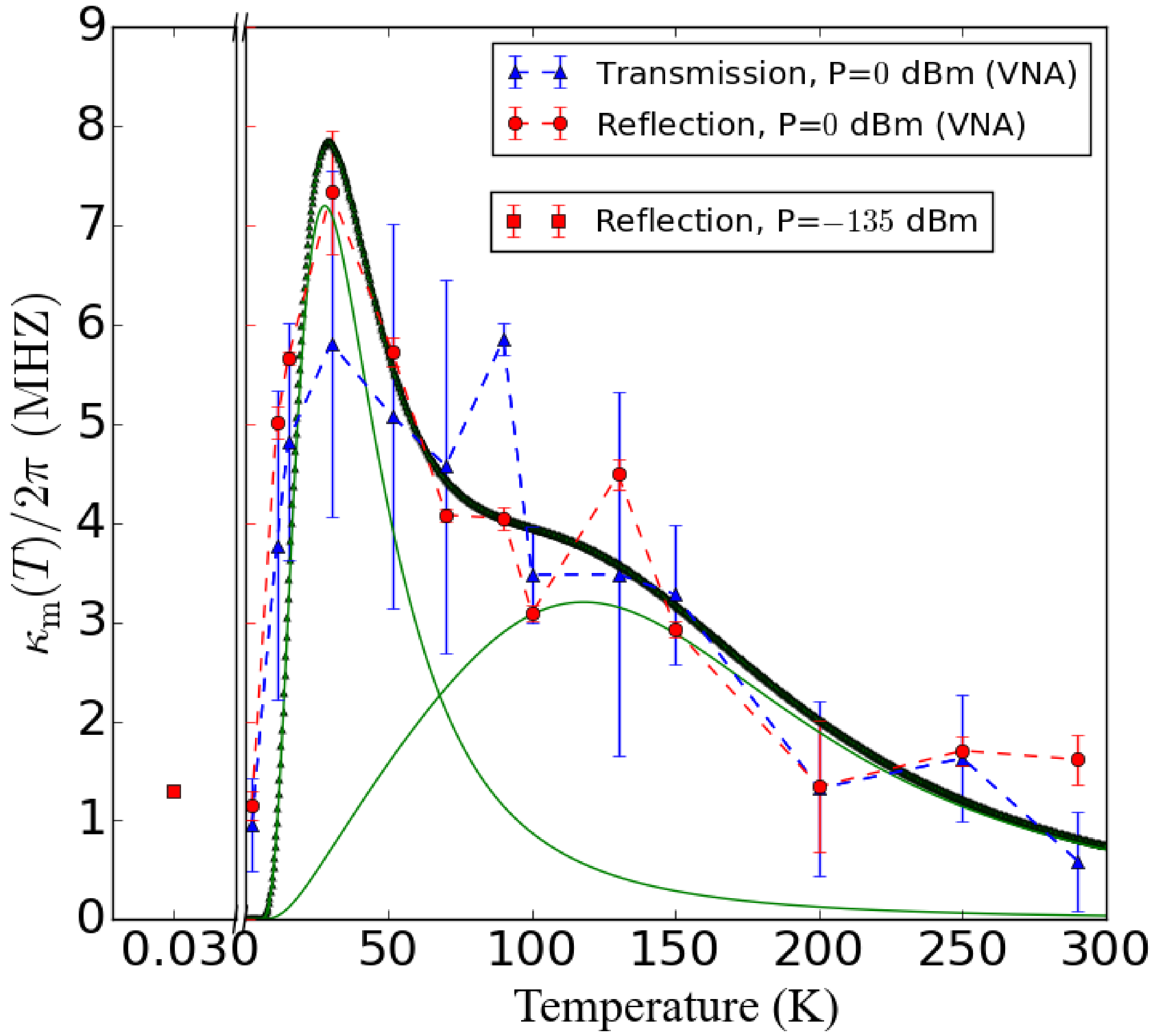
Magnon linewidth $\kappa_m(T)$



Rare earth impurity scattering

- Dominant peak at 43 K
- ‚Broad shoulder' at 90 K
- Offset of ~1 MHz from intrinsic damping & surface scattering

Model well the temperature behaviour of our system

Boventer *et al.* Phys. Rev. B **97**, 184420

Approaching the quantum regime

- Excitation energy: $$\hbar\omega \gg k_{\mathrm{B}} T$$

$$T = 50\,\mathrm{mK} \Leftrightarrow \omega/2\pi = 1\,\mathrm{GHz}$$

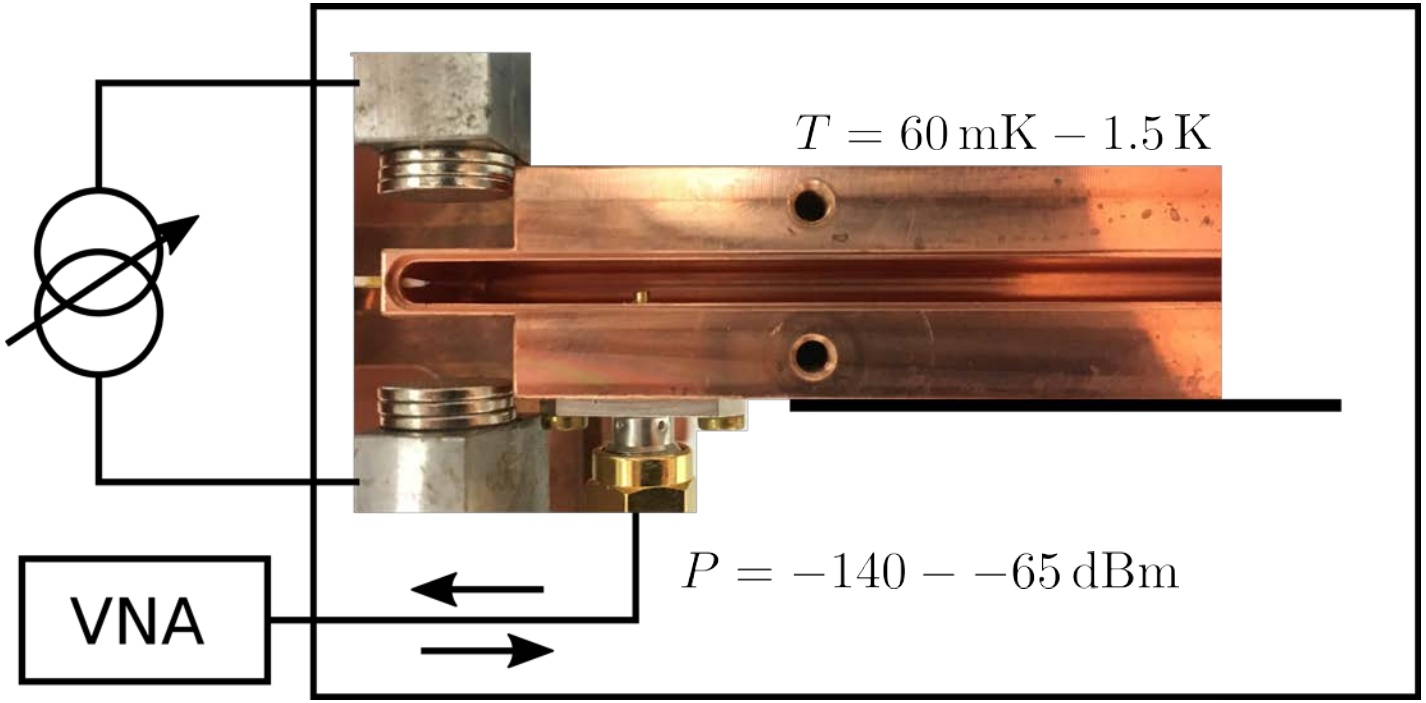
- Excitation power: $$\langle n \rangle \approx 1$$

- Non-linear system, anharmonic level structure

Coherent limitations and quantum applications?

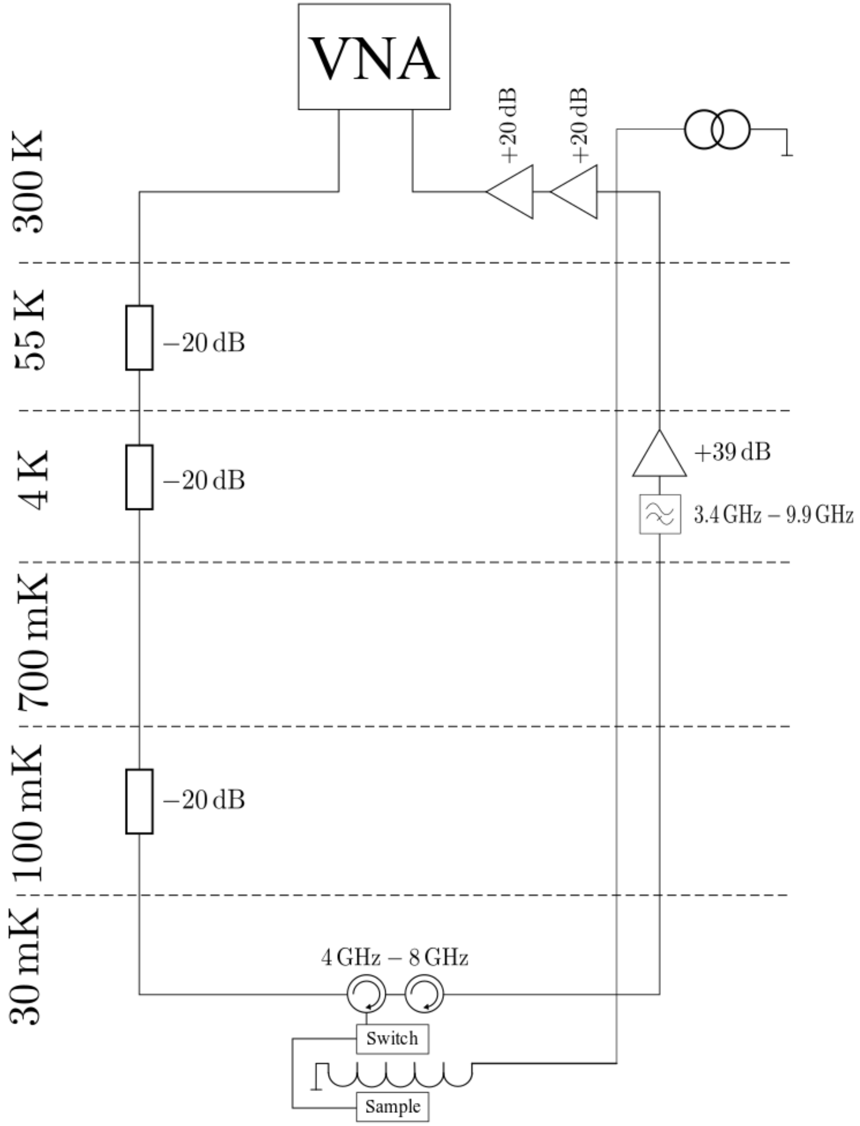
Experimental setup

- Yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) sphere,
  $$\varnothing = 0.5\,\mathrm{mm}$$
- 3d copper cavity resonator
  $$\omega_{\mathrm{TE102}}/2\pi = 5.24\,\mathrm{GHz}$$
- Static magnetic field: tune magnon frequency



- $$S_{11}(\omega) = -1 + \frac{2\kappa_{\mathrm{e}}}{\mathrm{i}(\omega_{\mathrm{r}} - \omega) + \kappa_{\mathrm{l}} + \frac{g^2}{\mathrm{i}(\omega_{\mathrm{m}} - \omega) + \kappa_{\mathrm{m}}}}$$

Cryogenic wiring



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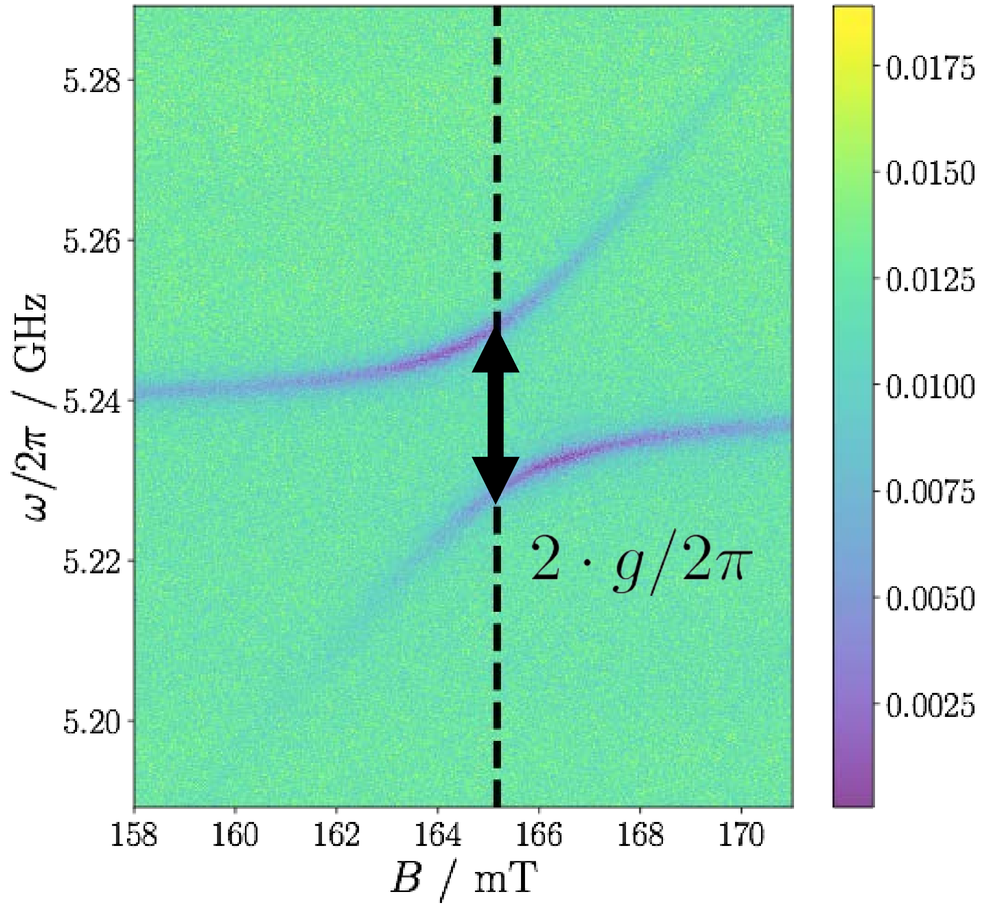
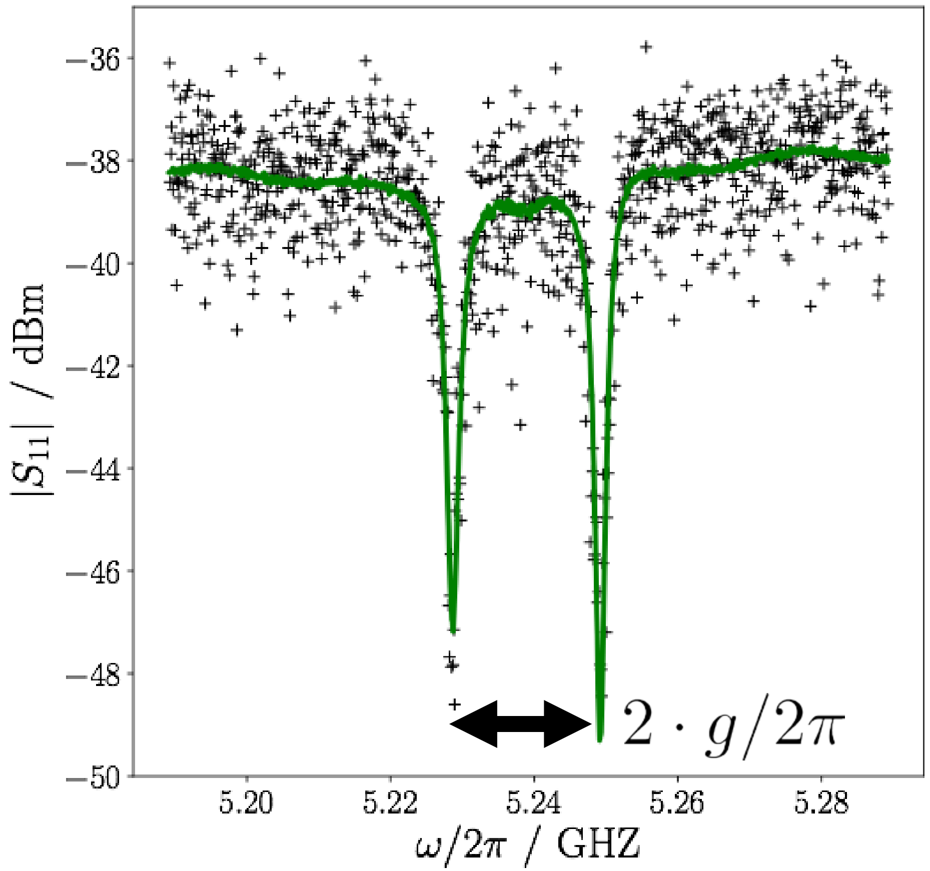
Spectroscopic measurement; 60 mK, -140 dBm





Magnon - photon coupling: $g/2\pi \approx 10.5\,\mathrm{MHz}$

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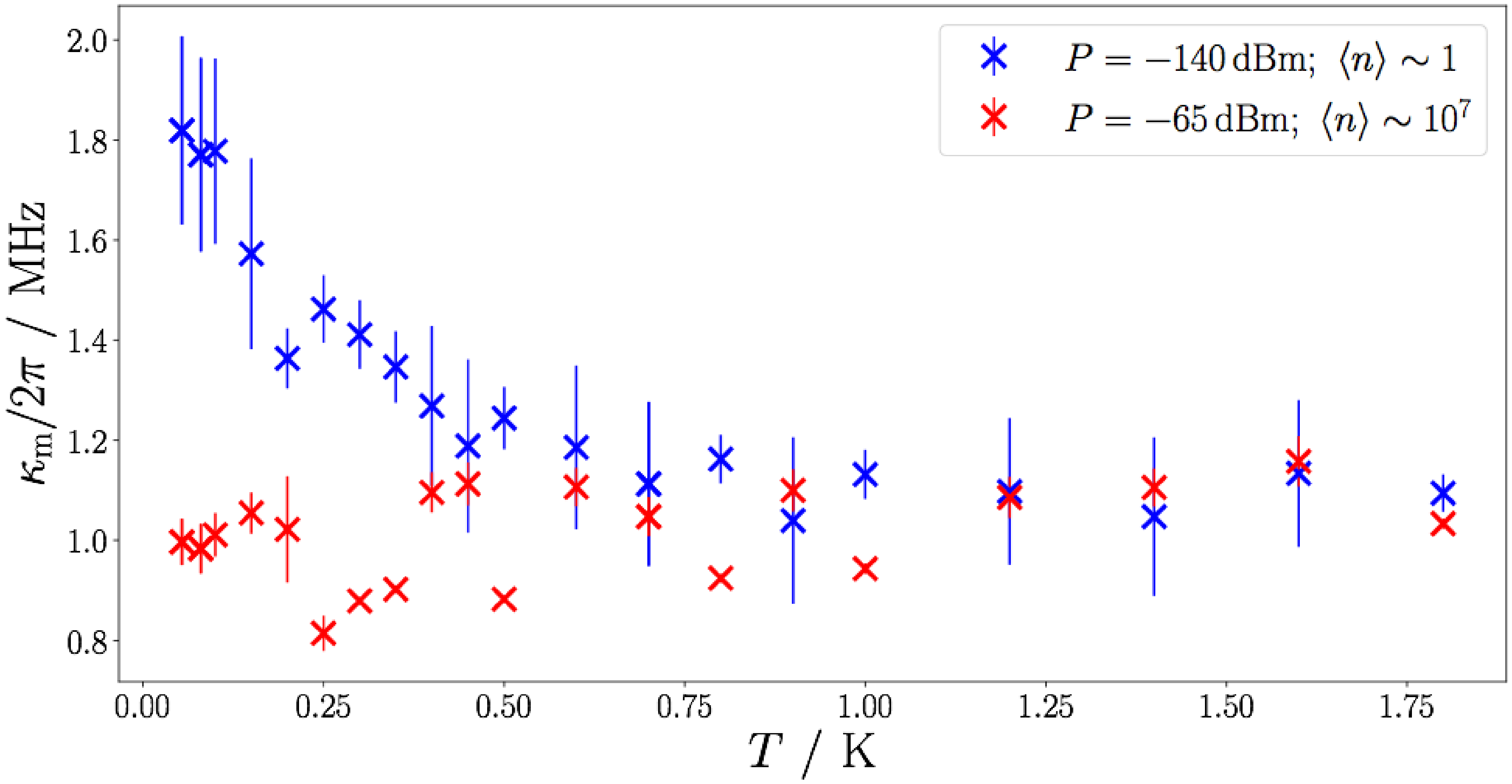
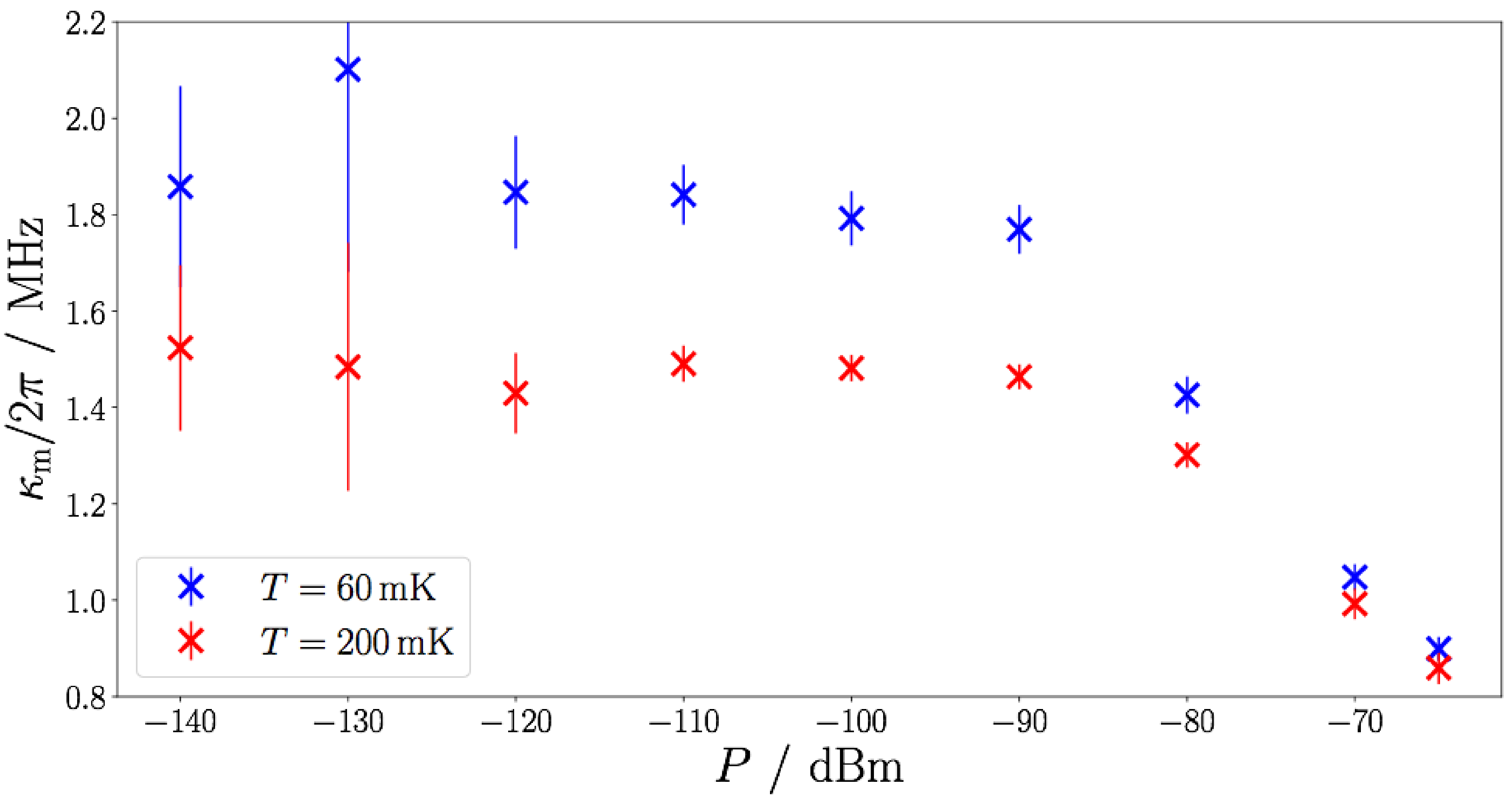
Magnon linewidth: temperature dependence



Magnon linewidth: power dependence



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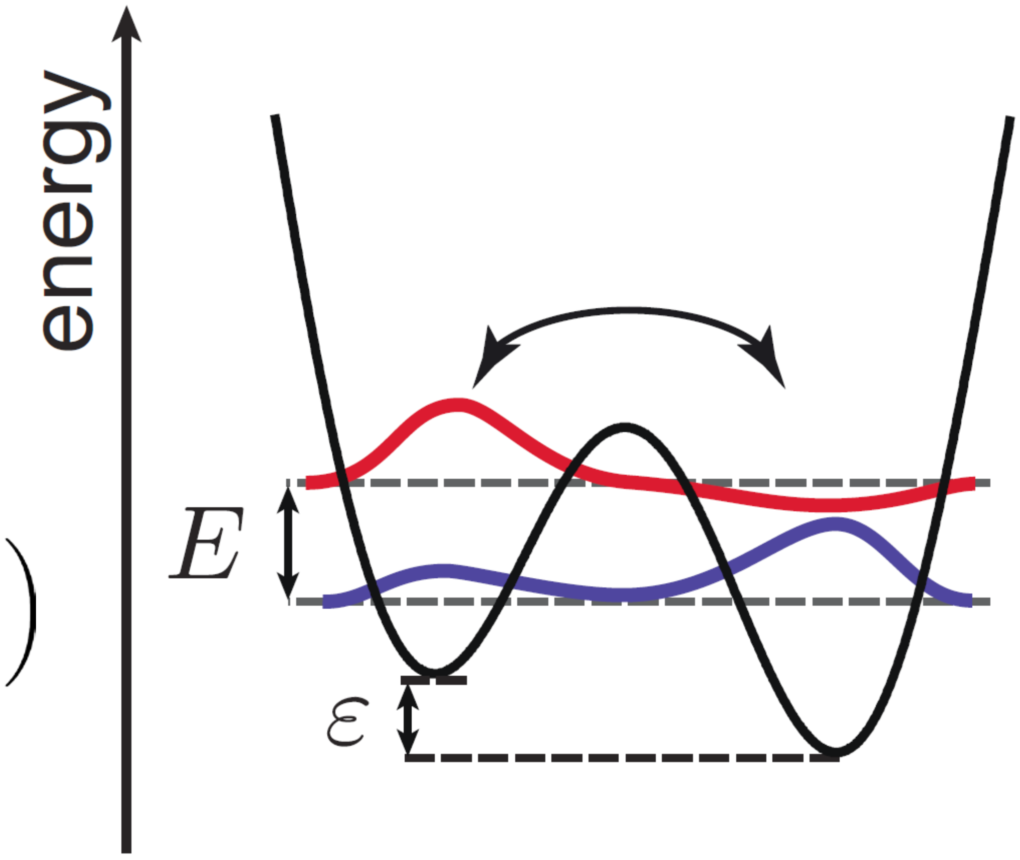
Two-Level system (TLS) model

- Bistable energy level

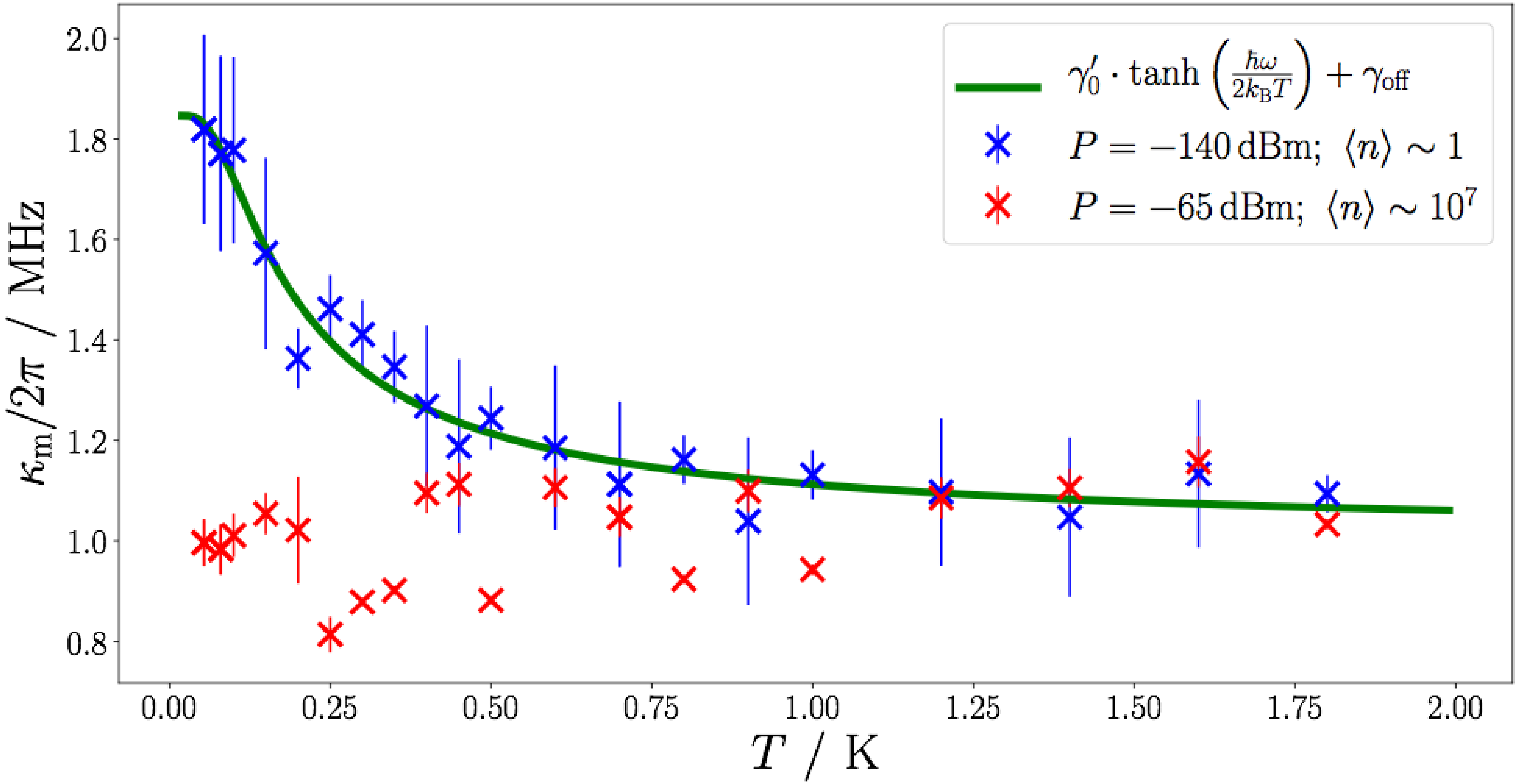
- Loss of excitation

- $$\gamma_{\mathrm{TLS}} = \gamma_0 \cdot \underbrace{\frac{1}{\sqrt{1+\frac{P_{\mathrm{in}}}{P_{\mathrm{c}}}}}}_{\gamma_0'} \cdot \tanh\left(\frac{\hbar\omega}{2k_{\mathrm{B}}T}\right)$$



Y. Tabuchi *et al., Phys. Rev. Lett.* **113**, 083603 (2014)

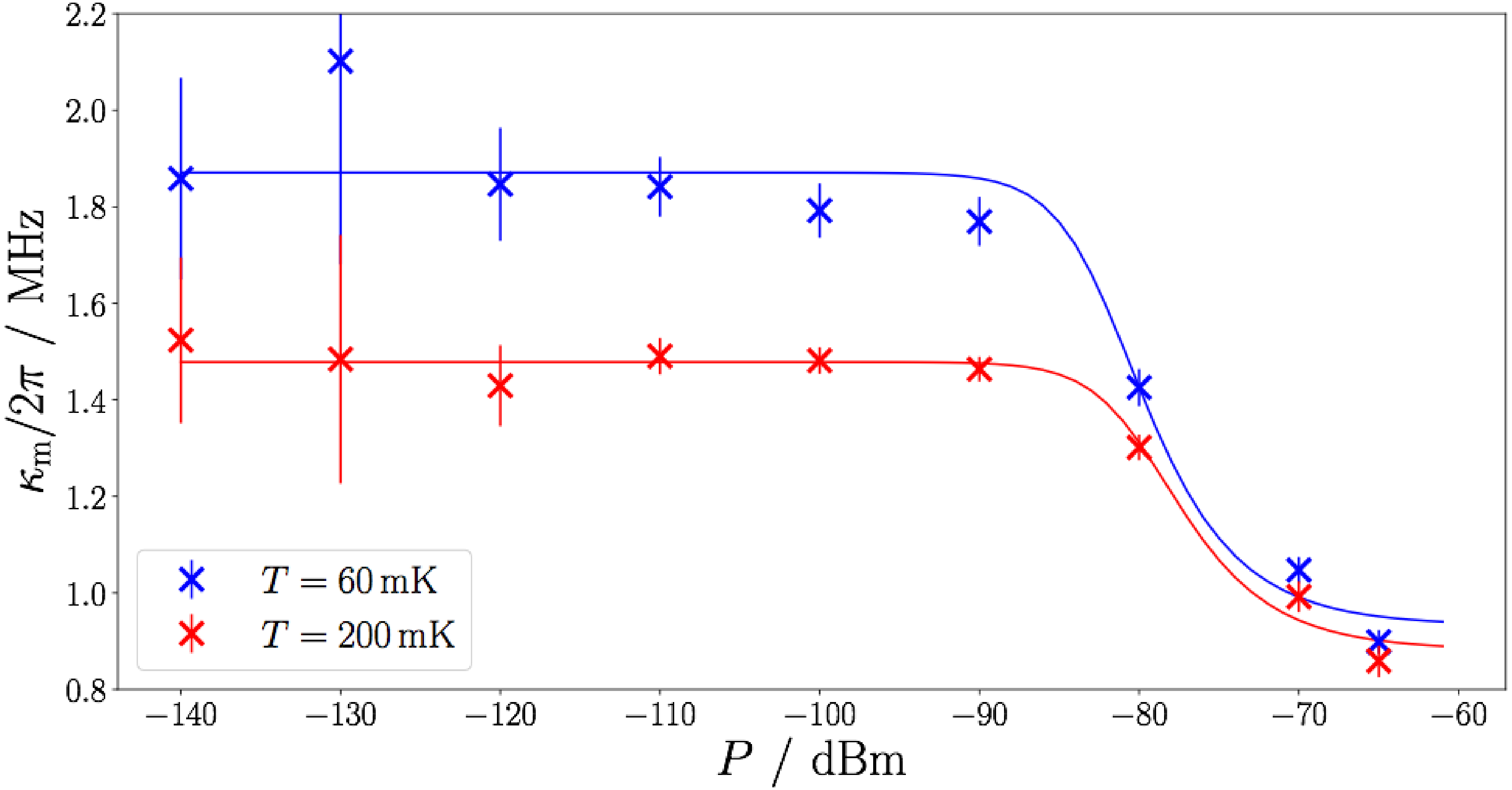
Magnon linewidth below 1.5 K



Fit to TLS model: $\gamma_0' = 0.84\,\text{MHz},\ \gamma_{\text{off}} = 1.01\,\text{MHz}$

Magnon linewidth below 1.5 K

$$\gamma_{\mathrm{TLS}} = \gamma_0 \cdot \tanh\left(\frac{\hbar\omega}{2k_{\mathrm{B}}T}\right) \cdot \frac{1}{\sqrt{1+\frac{P_{\mathrm{in}}}{P_{\mathrm{c}}}}} + \gamma_{\mathrm{off}}$$

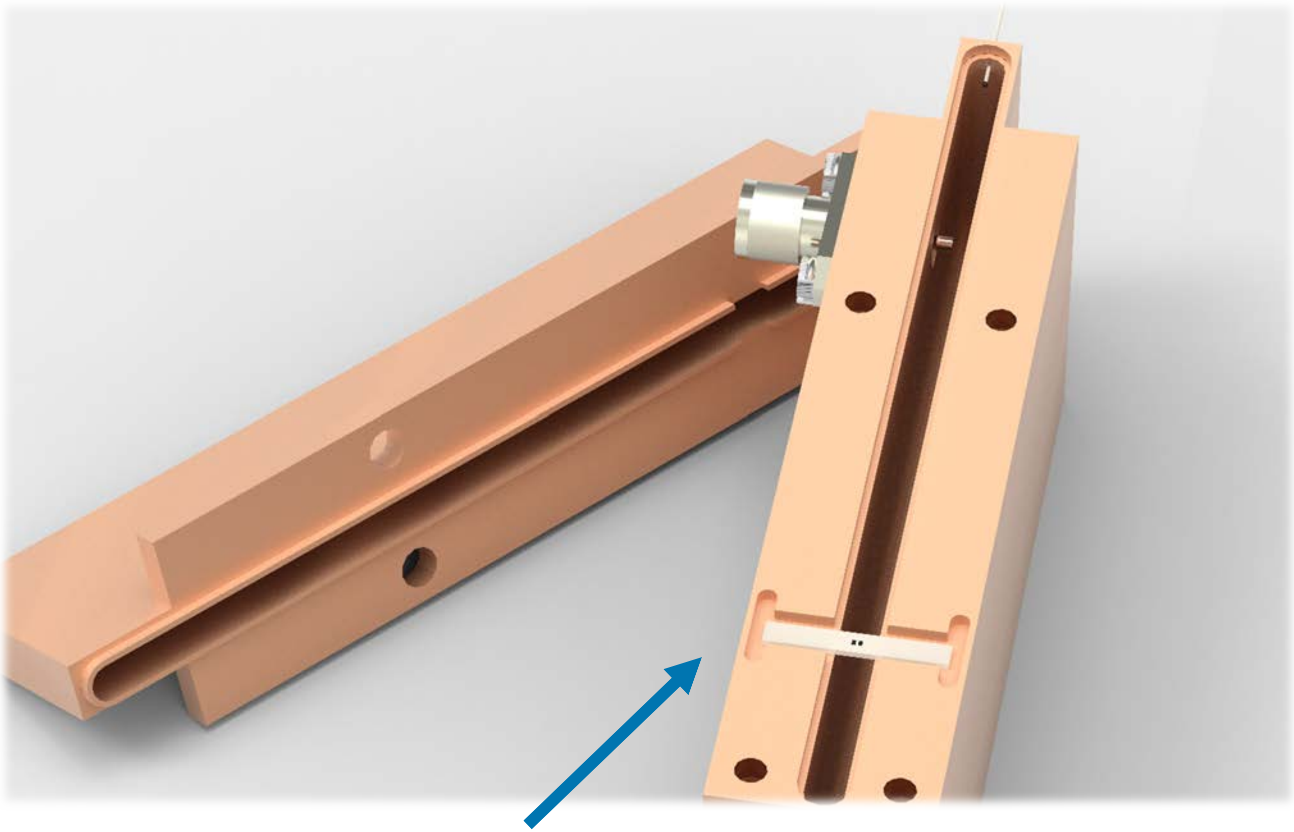


$$\gamma_0 = 1.02 \pm 0.15\,\mathrm{MHz}$$

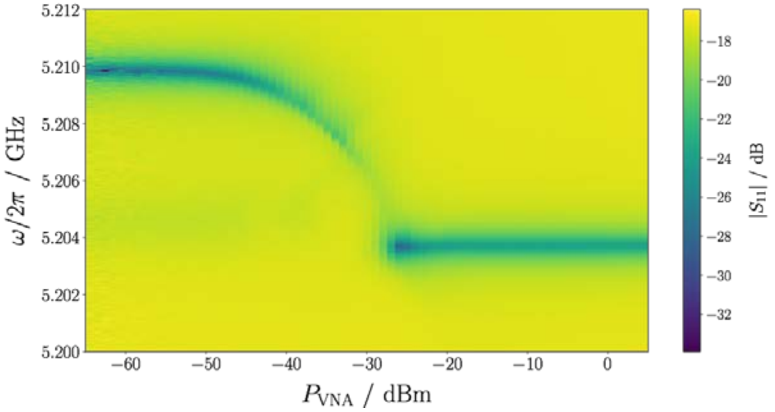
$$P_{\mathrm{c}} = -80.98 \pm 6.33\,\mathrm{dBm}$$

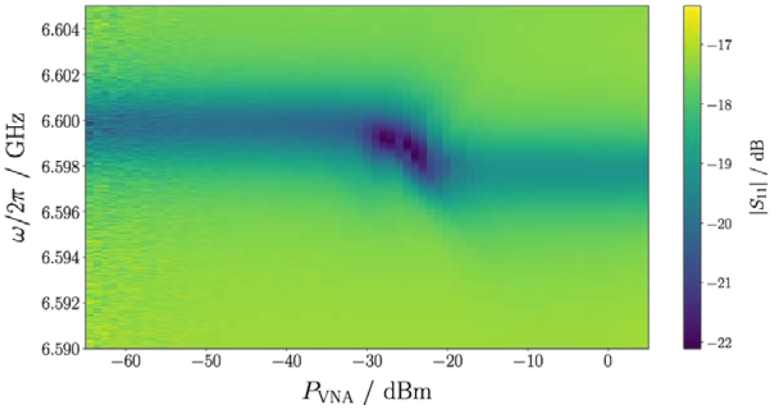
$$\gamma_{\mathrm{off}} = 0.91 \pm 0.11\,\mathrm{MHz}$$

Fresh data: qubit coupled to YIG



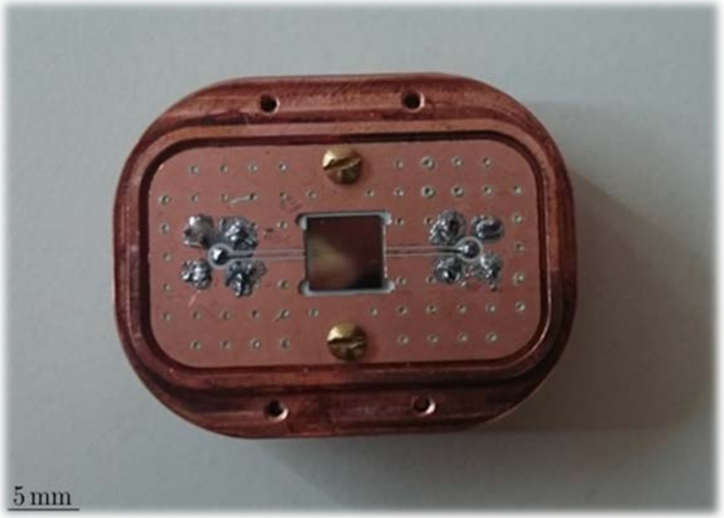
Transmon qubit

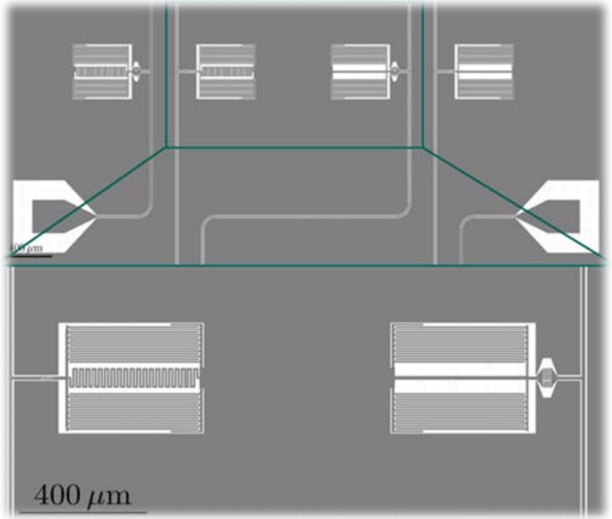




→ (de) couple from qubit

Go thin film





- Sputtered NbN (150 nm) on Si substrate
- Frequency division mux‘ed lumped element resonators
- Flip-chip: 310nm YIG/GGG (Carsten Dubs, Innovent, LPE) face-down on (some) resonators and transmission line

→ Resonator loss, YIG loss and coupling g

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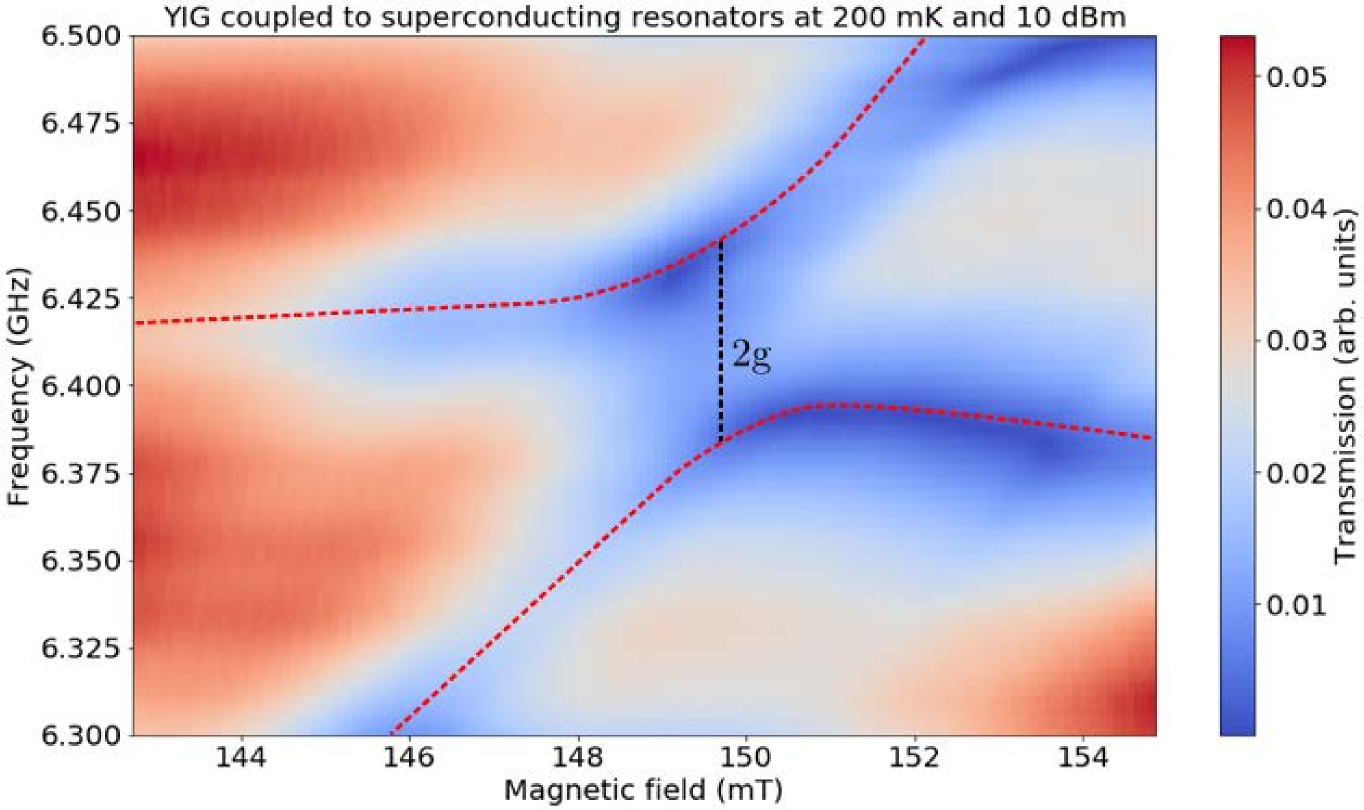
Measurement results: at cryogenic temperatures



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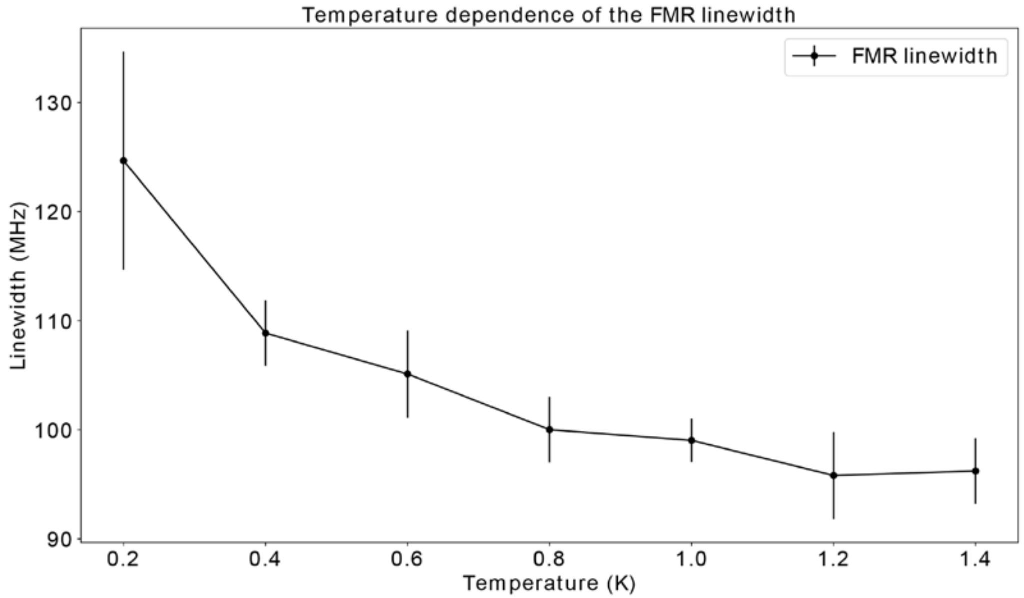
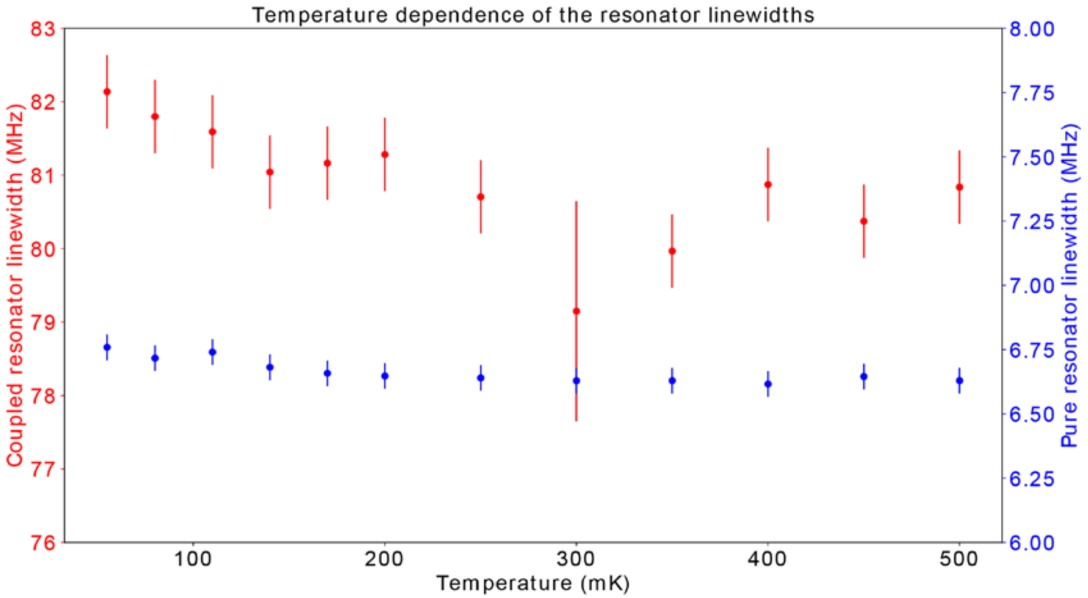
Thin film YIG on NbN transmission line / resonator





- YIG resonance strongly damped
- Superconducting resonator strongly damped

→ Weak coupling. Keep sampling different magnets....

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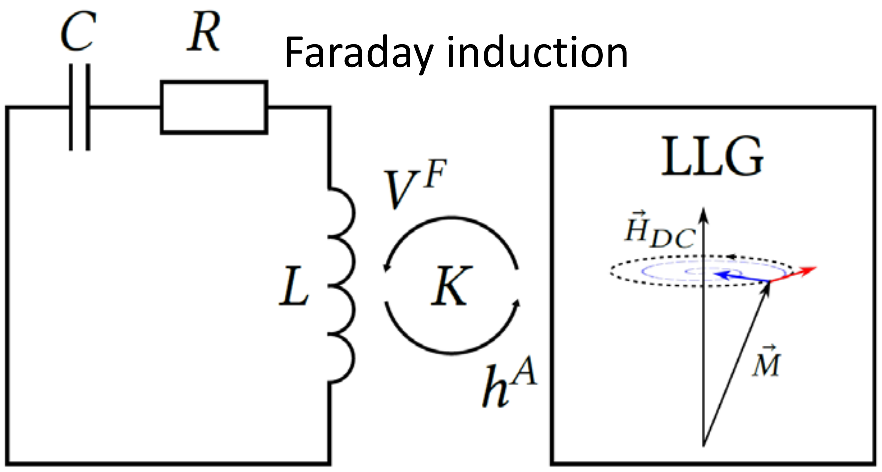
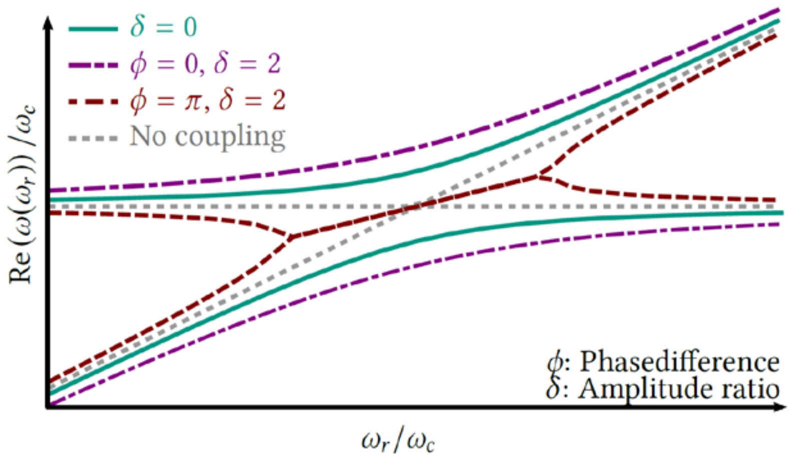
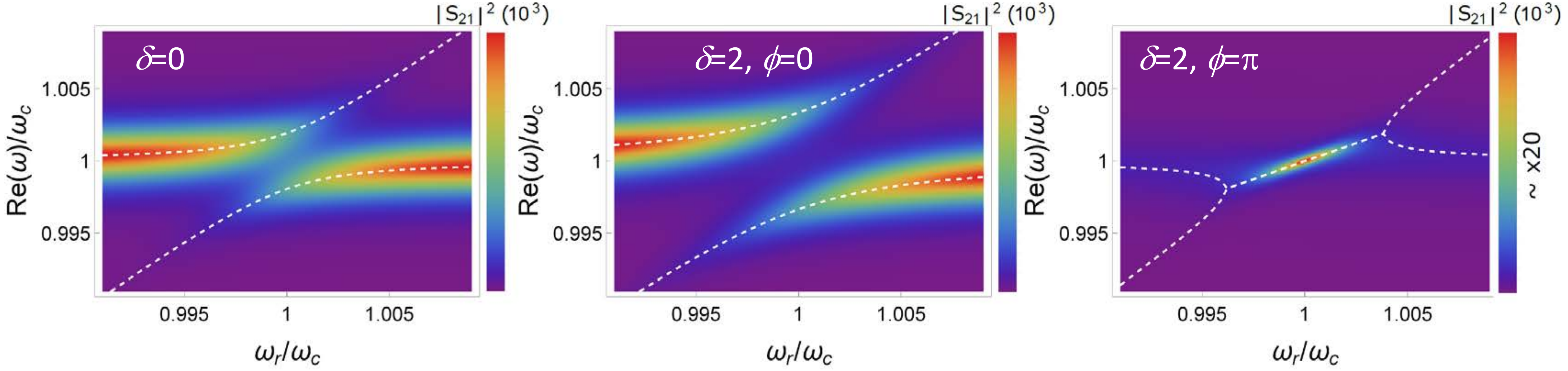
Synchronized spin-photon coupling in a microwave cavity



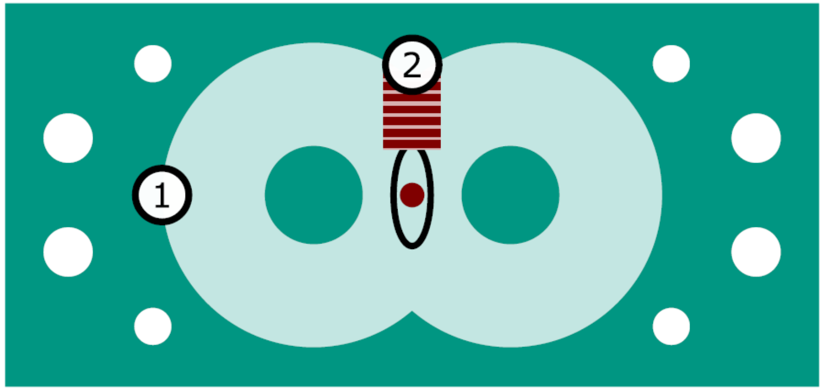


→ two time dependent magnetic fields on M



Grigoryan *et al.* arXiv:1702.07110v2

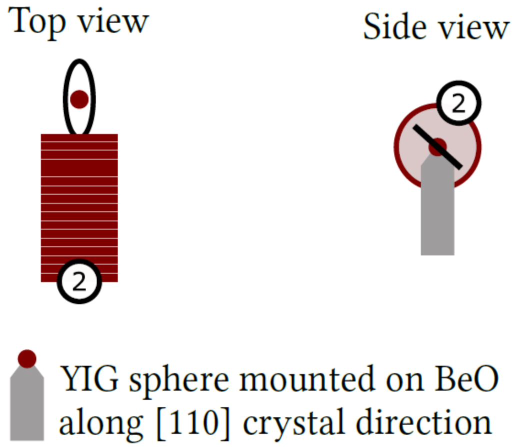
3dimensional approach

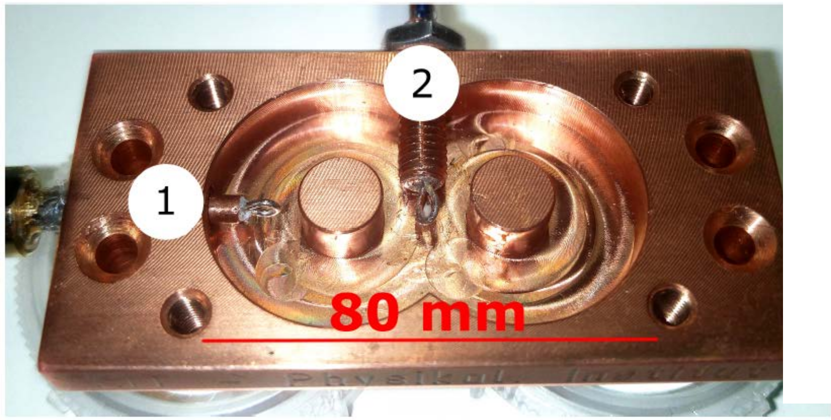


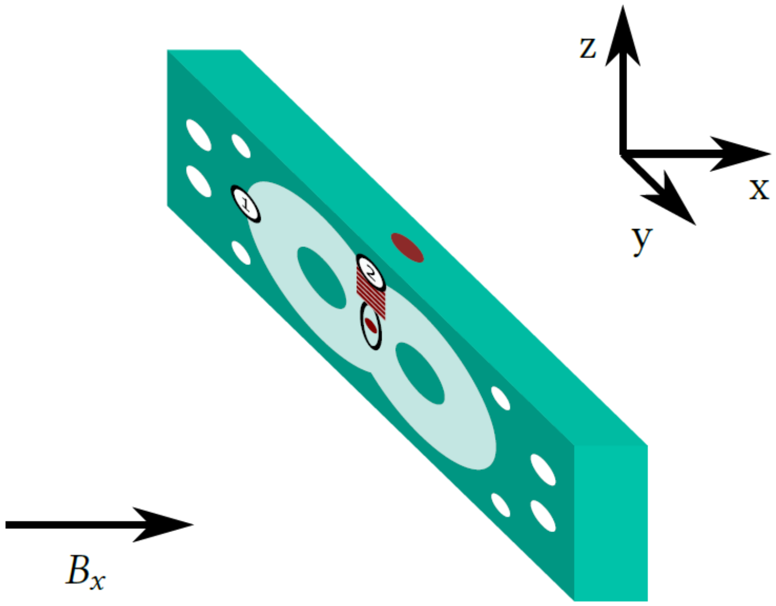
1 Resonator Port

2 Transmission line

● YIG sphere



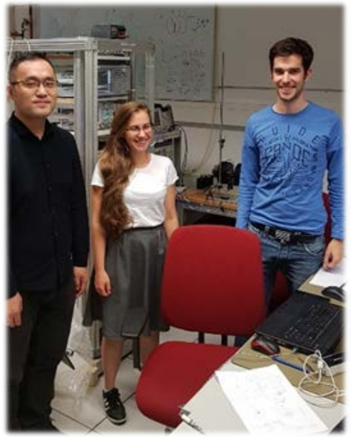


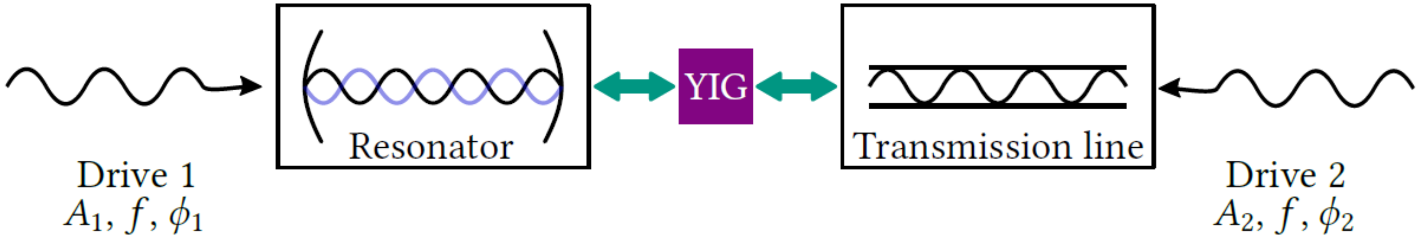


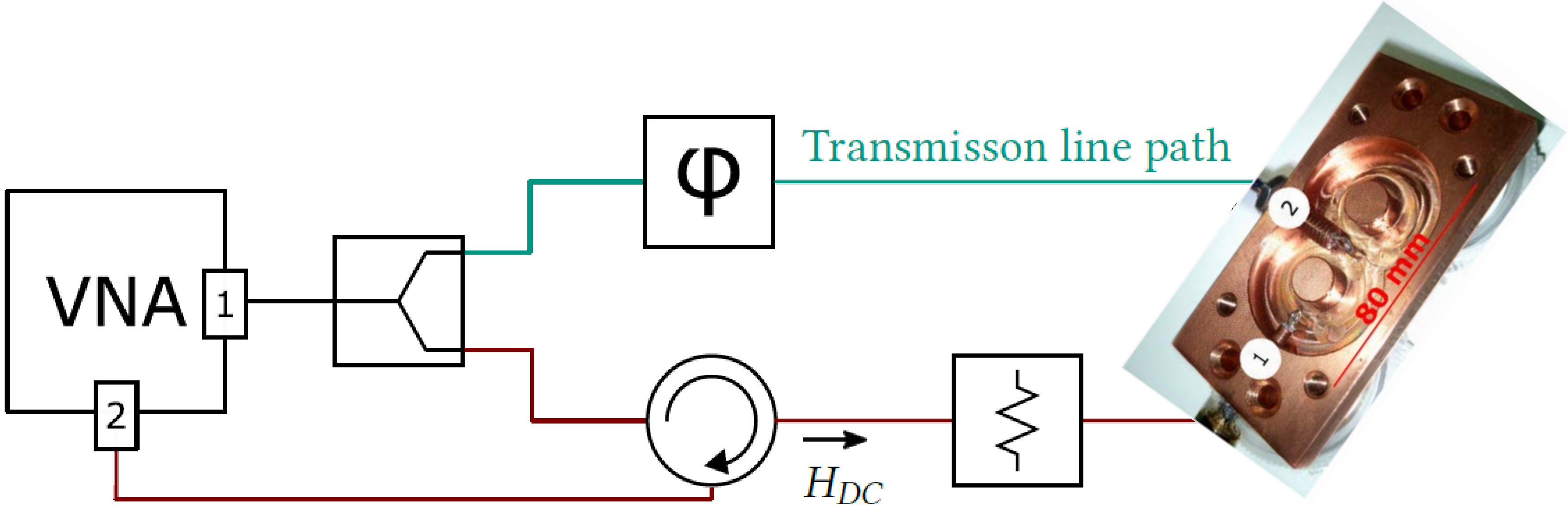
C. Dörflinger MA thesis 2018

Experimental setup

Isabelle Boventer
Tim Wolz
Christine Dörflinger (missing)
Bimu Yao (Hu group)







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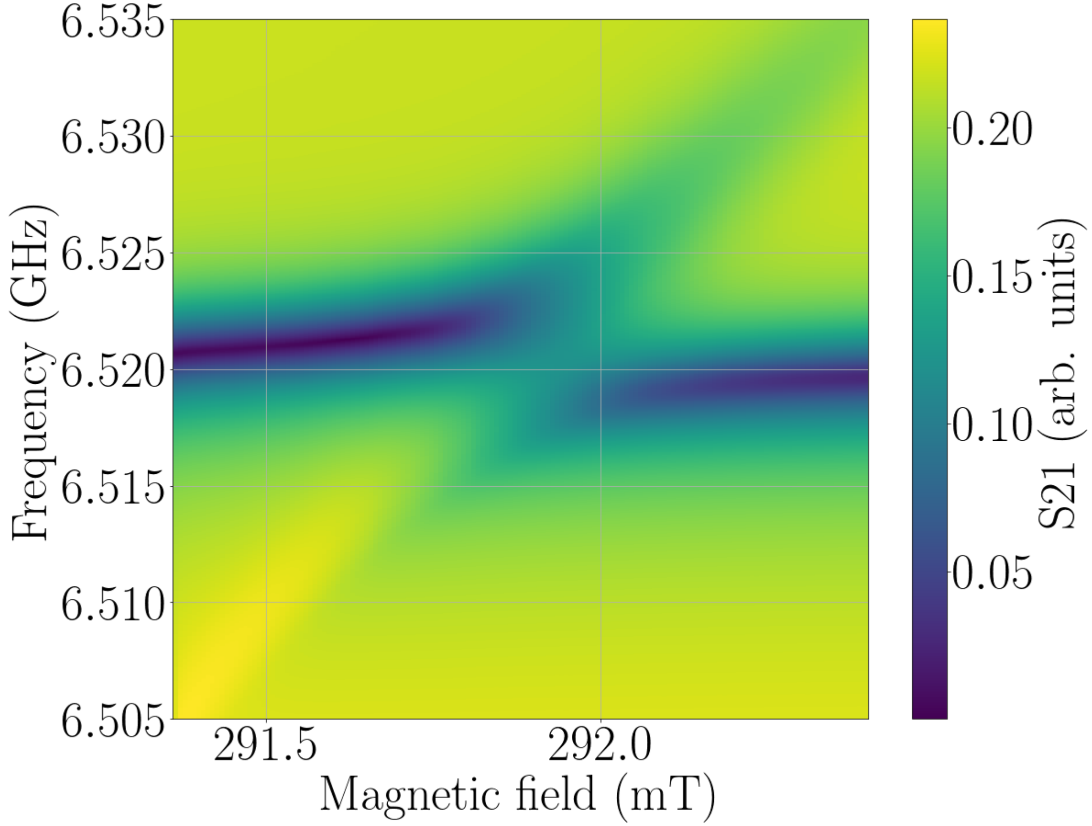
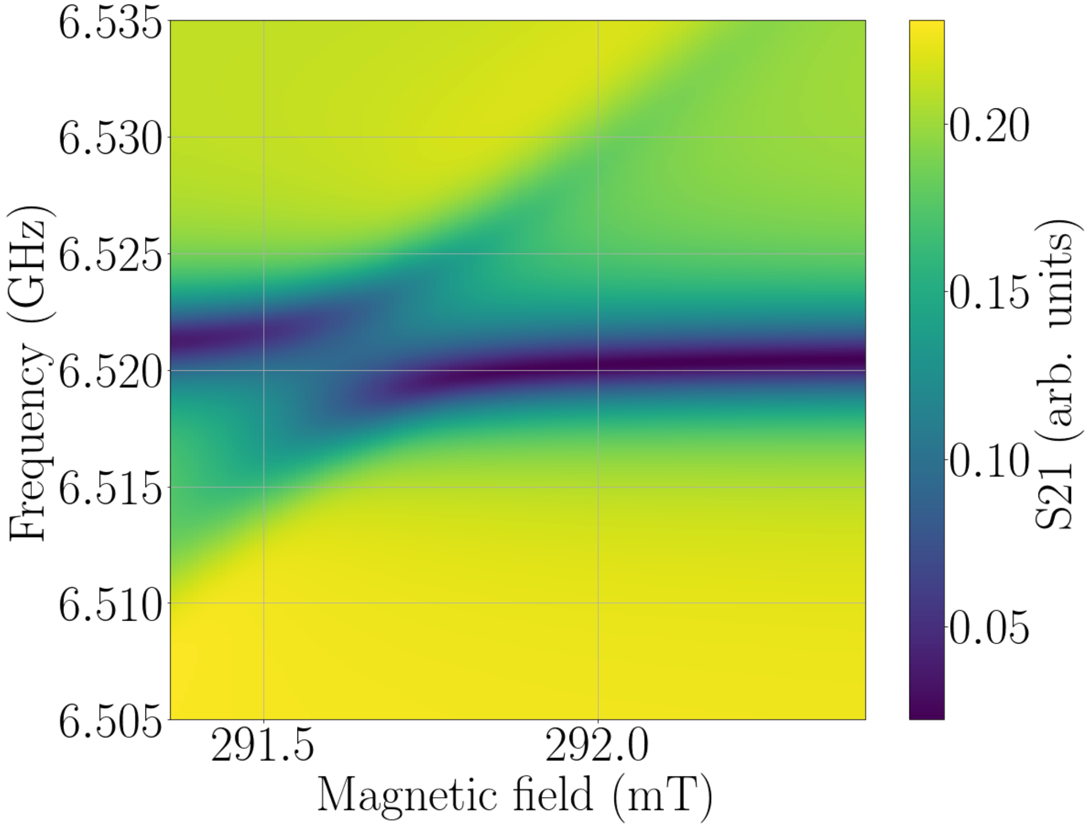
Raw data for 3d cavity





ϕ=0°, Ω=0dB

ϕ=180°, Ω=0dB

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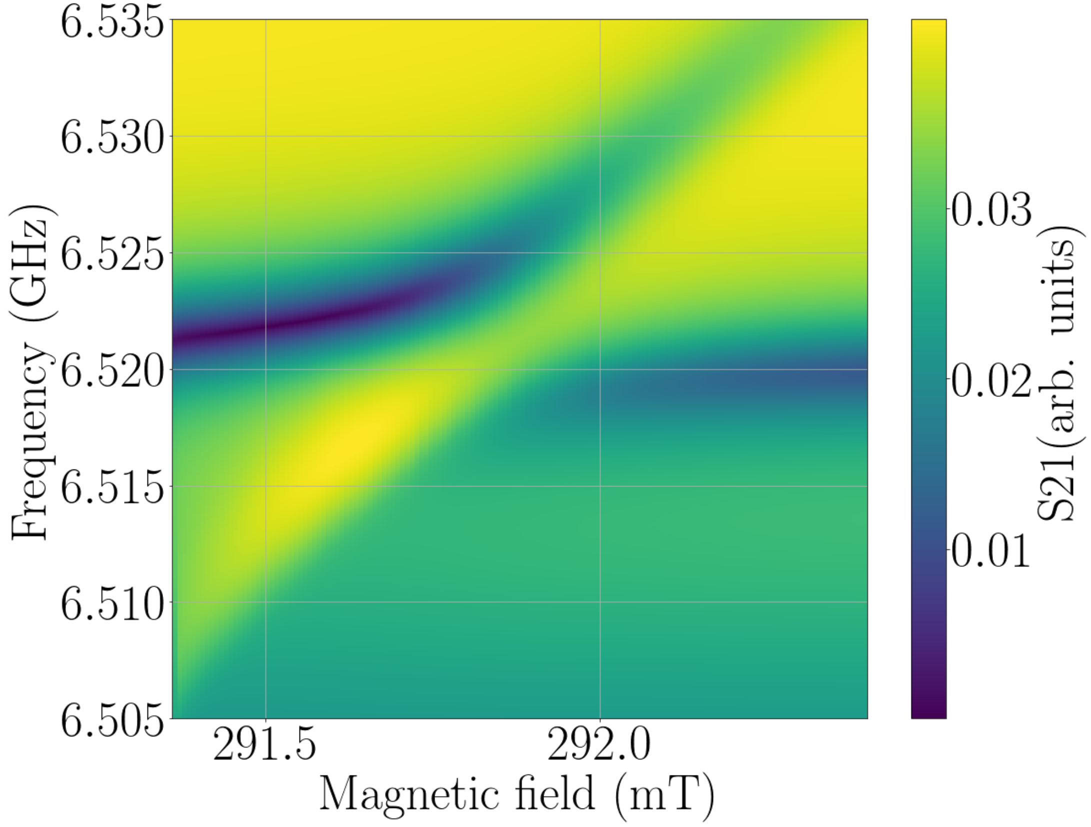
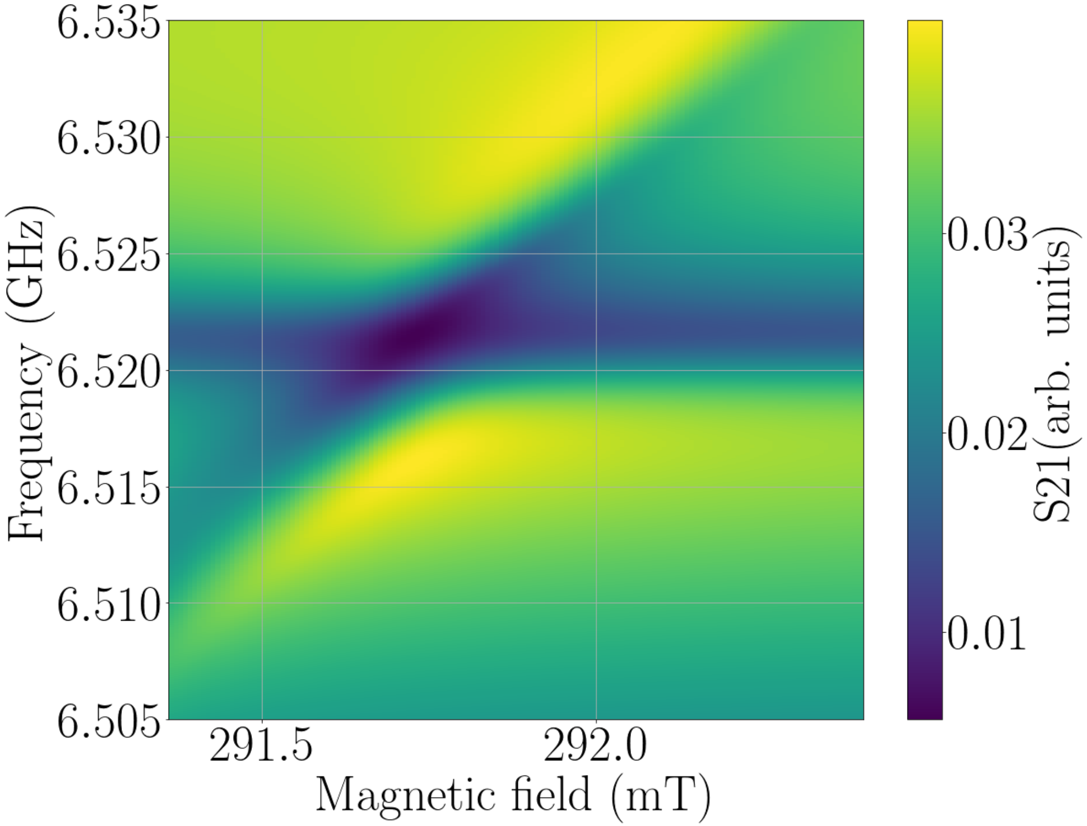
Raw data for 3d cavity, 9dB higher YIG drive



ϕ=0°, Ω=9dB



ϕ=180°, Ω=9dB

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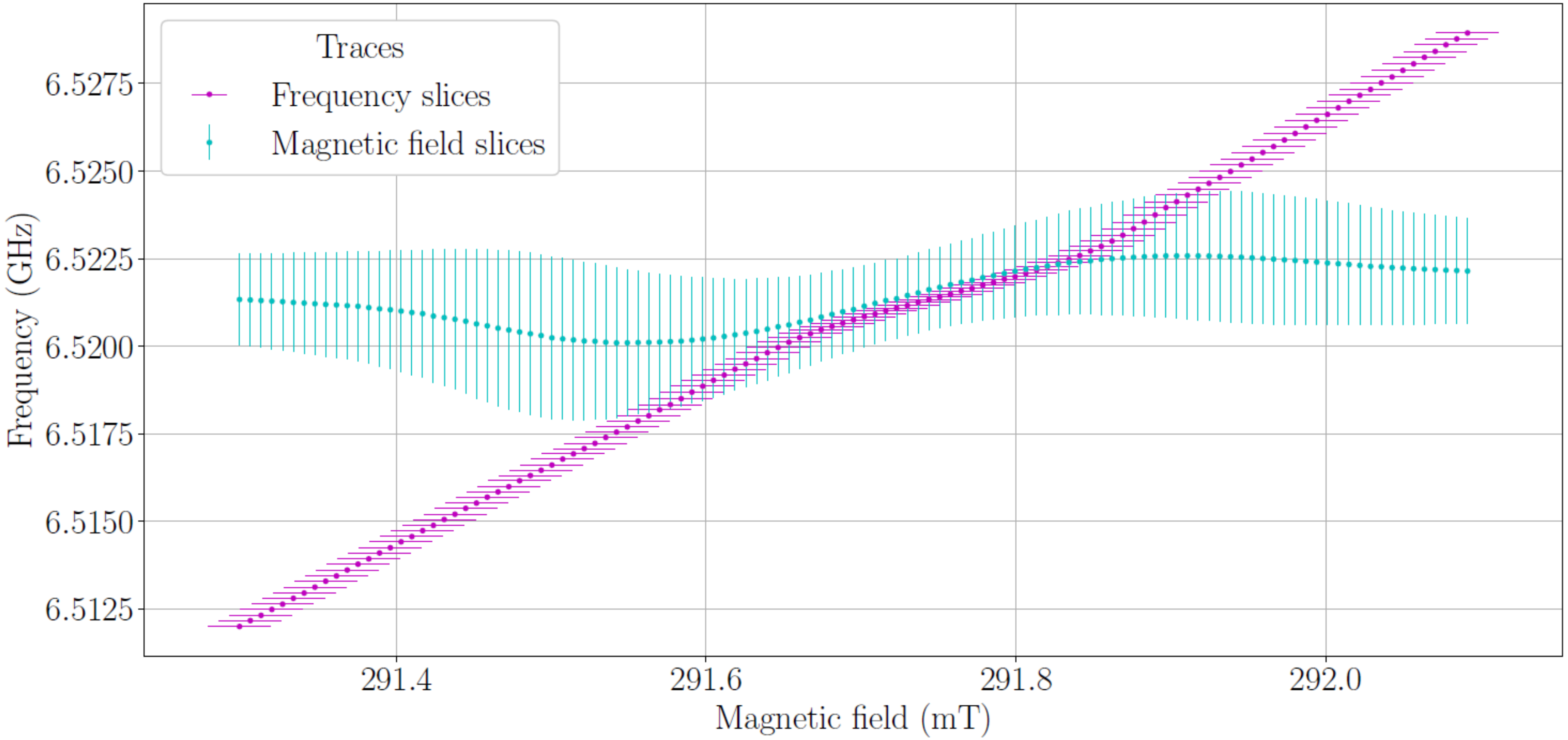
Cavity and Magnon frequencies



→ Synchronization appears

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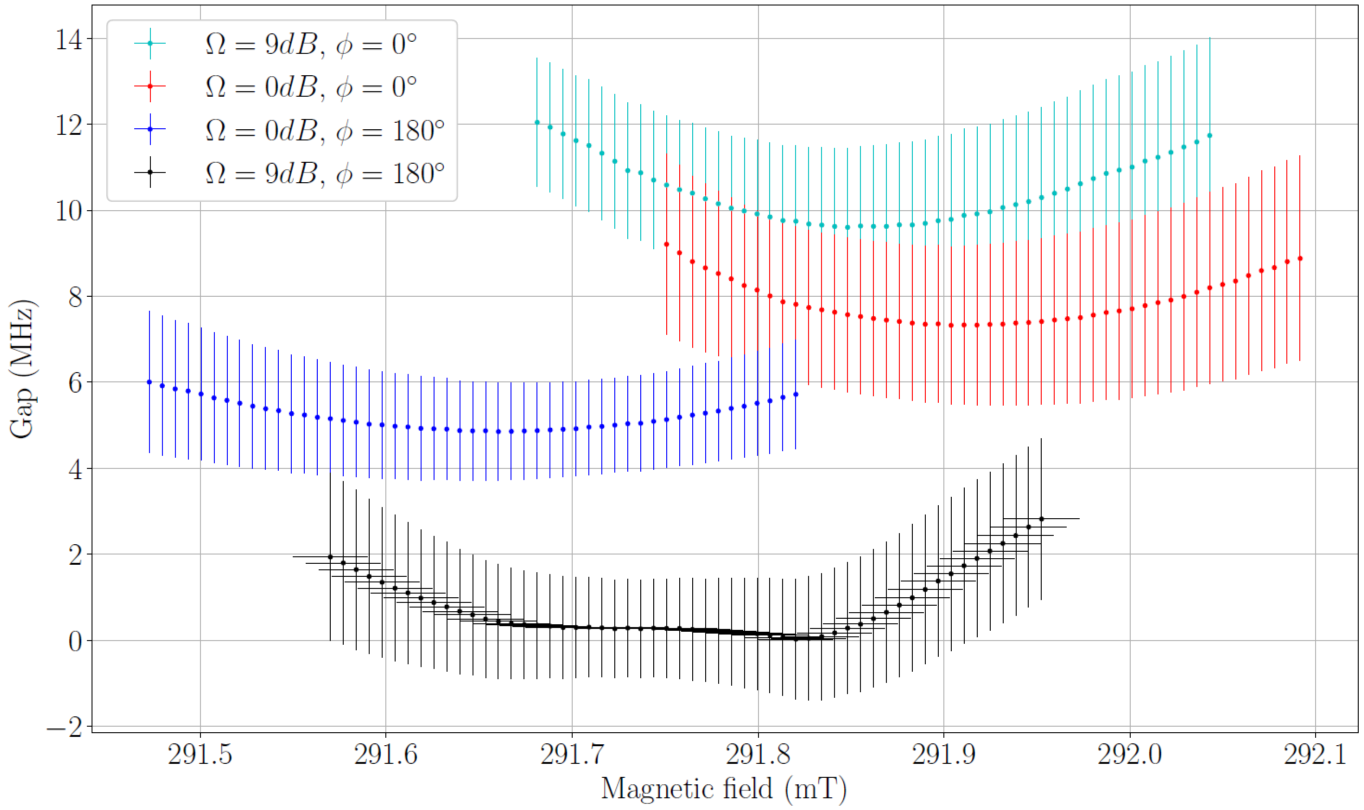
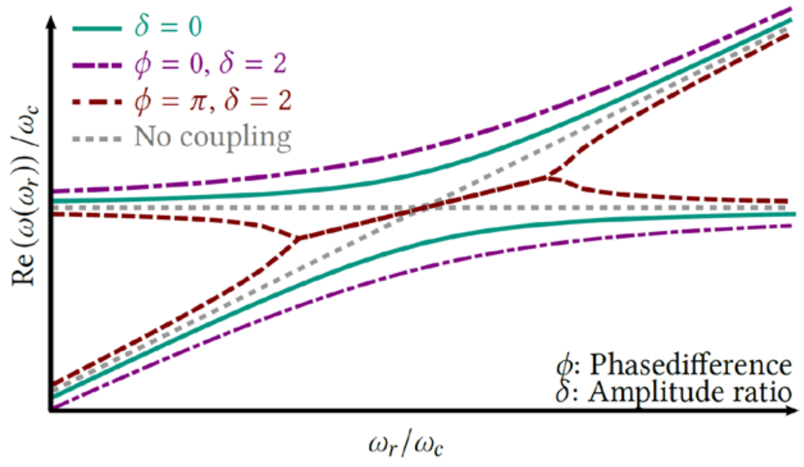
Dispersion data of polariton modes





- Avoided level gap set by phase and relative amplitude

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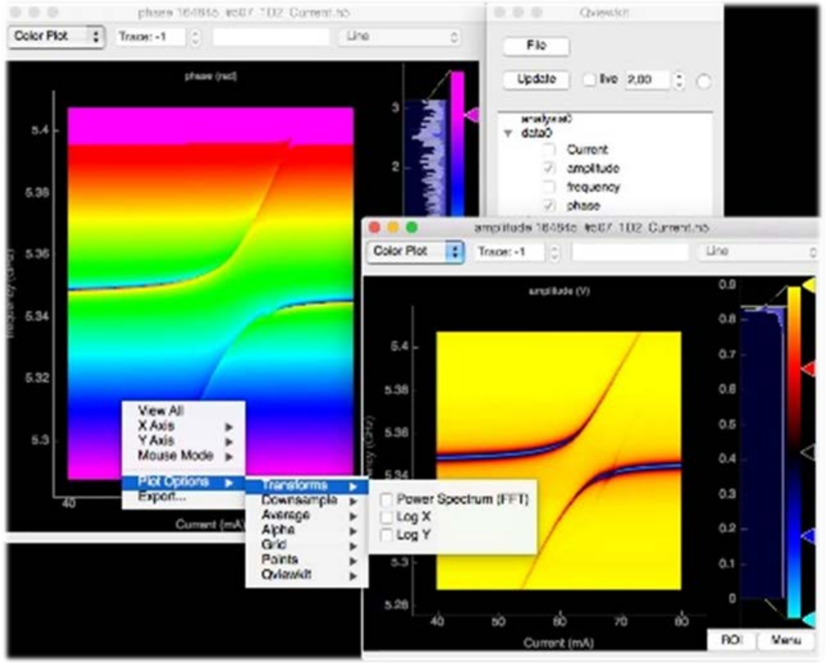
QKIT software

Open-source software QKIT

https://github.com/qkitgroup/qkit

- Python notebooks
- hdf5 data storage
- Instrument drivers, fitting classes
- Flexible data viewer
- Live plotting of measurement data
- Incl. circle fit (Probst *et al.*, Rev. Sci. Instr. 2015)



git.io/qkit

www.phi.kit.edu/weides /
www.gla.ac.uk/schools/engineering/staff/martinweides/

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Christine Dörflinger
Stefan Letzelter
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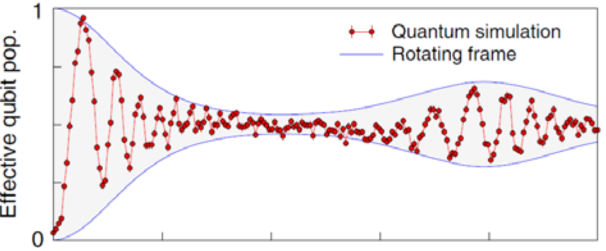
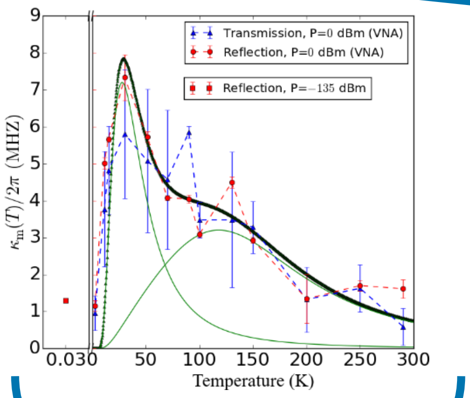
Isabelle Boventer
Mathias Kläui

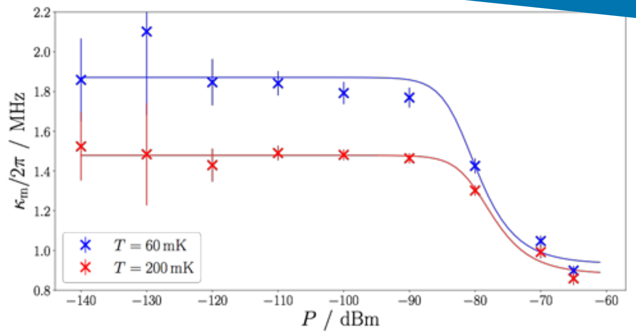
erc

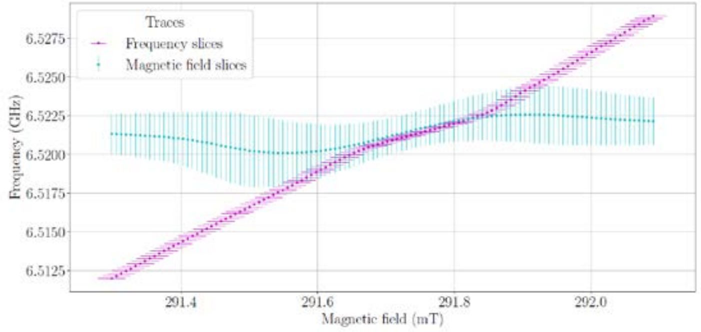
Summary

- Analog simulation of ultra-strong coupling dynamics
- YIG sphere – cavity from 300K to 10mK
  - Power and temperature sweeps indicate additional loss at mK
- Thin film YIG/GGG strongly damped (resonator and FM)
- Controlled synchronization of spin-photon coupling demonstrated
- In progress
  - Coherent coupling to qubit









M. Kläui‘s talk this afternoon