Bayerische Akademie der Wissenschaften

Technische Universität München

Controlling the Collective Coupling in Spin-Photon Hybrids

Hans Huebl

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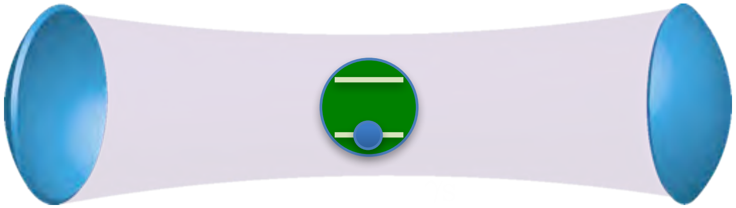
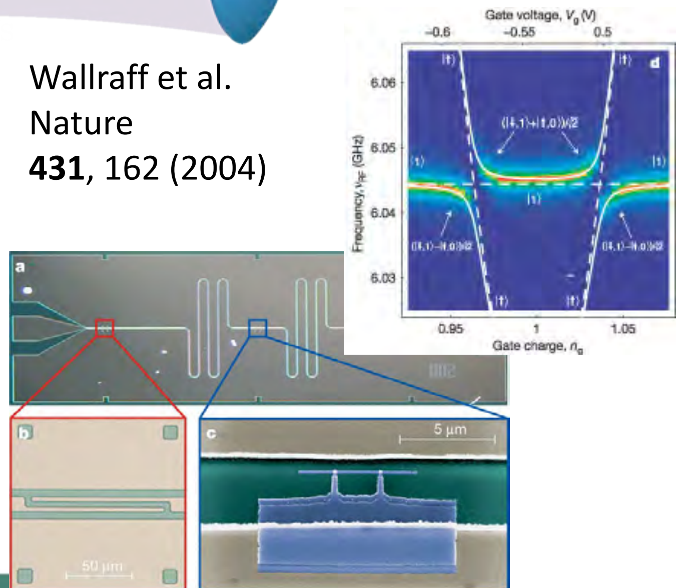
Bayerische Akademie der Wissenschaften

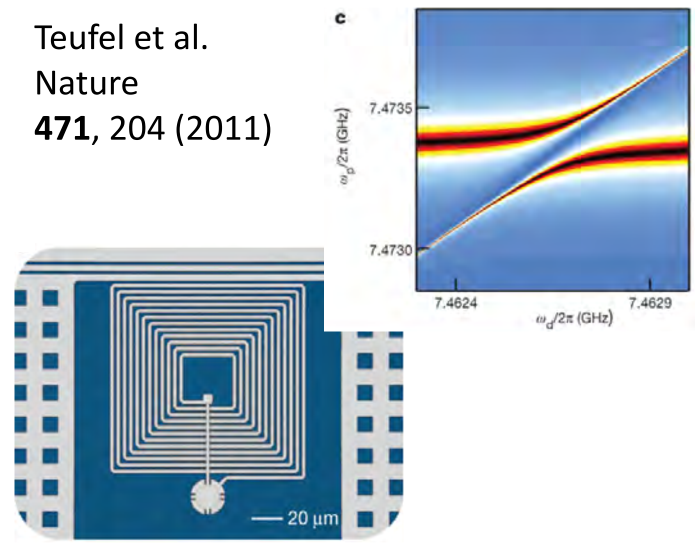
Quantum optics with solid-state systems



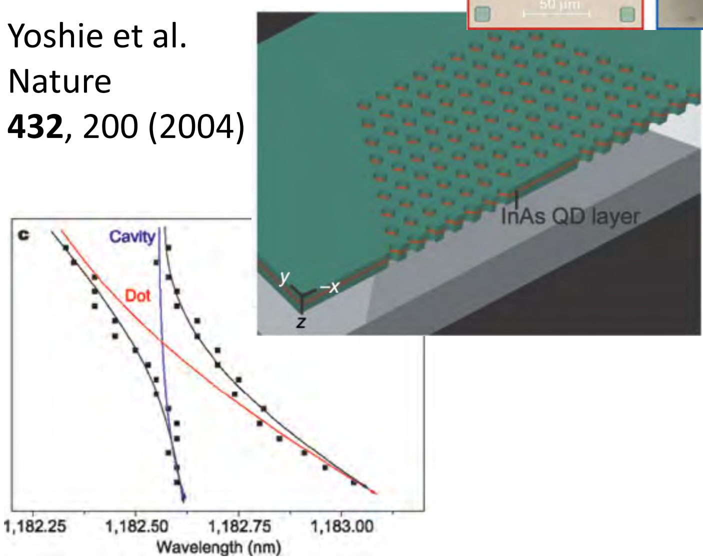
Wallraff et al.
Nature
431, 162 (2004)



Teufel et al.
Nature
471, 204 (2011)



Yoshie et al.
Nature
432, 200 (2004)



Quantum optics experiments in solid state systems

- higher coupling strength
- experimental access to new physics
- investigation of solid state properties

Quantum optics with solid state systems

Magnetism

typical description:

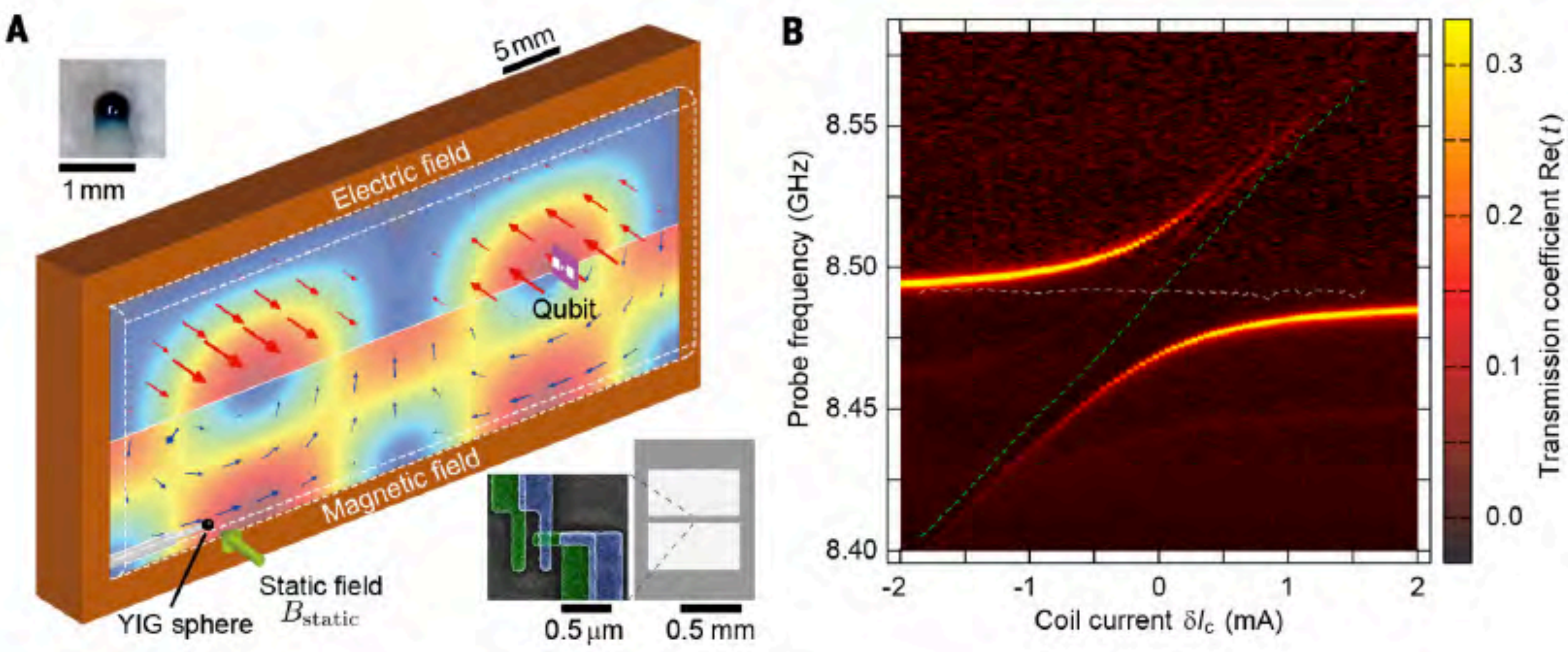
magnetization vector

- quantum effects in large objects
- ground state preparation
- state conversion solid state systems

- Sensing, storage and conversion applications

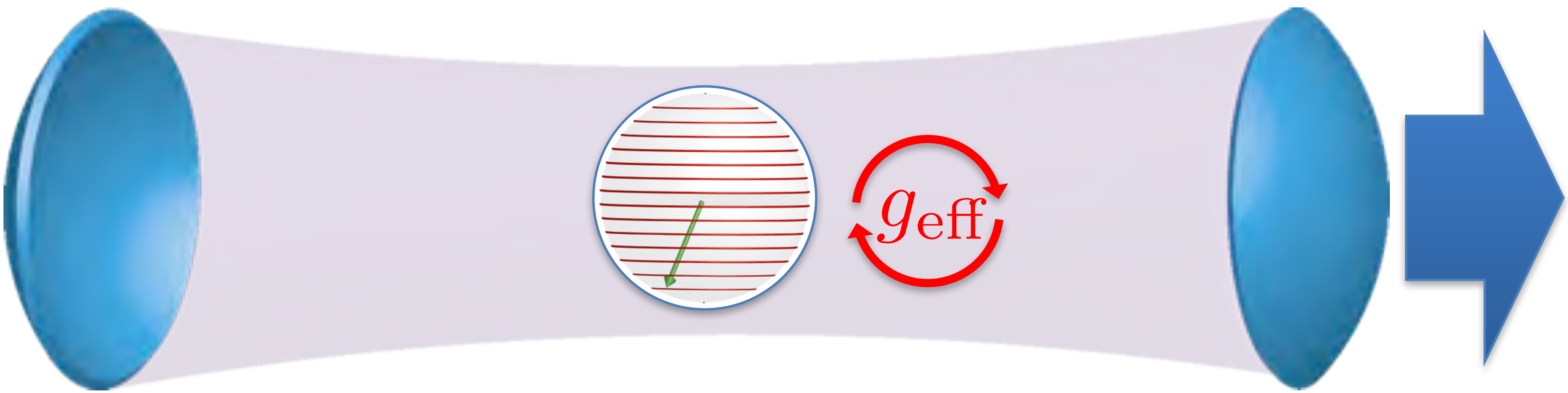
wondermagnet.com

Photons, magnons & quantum

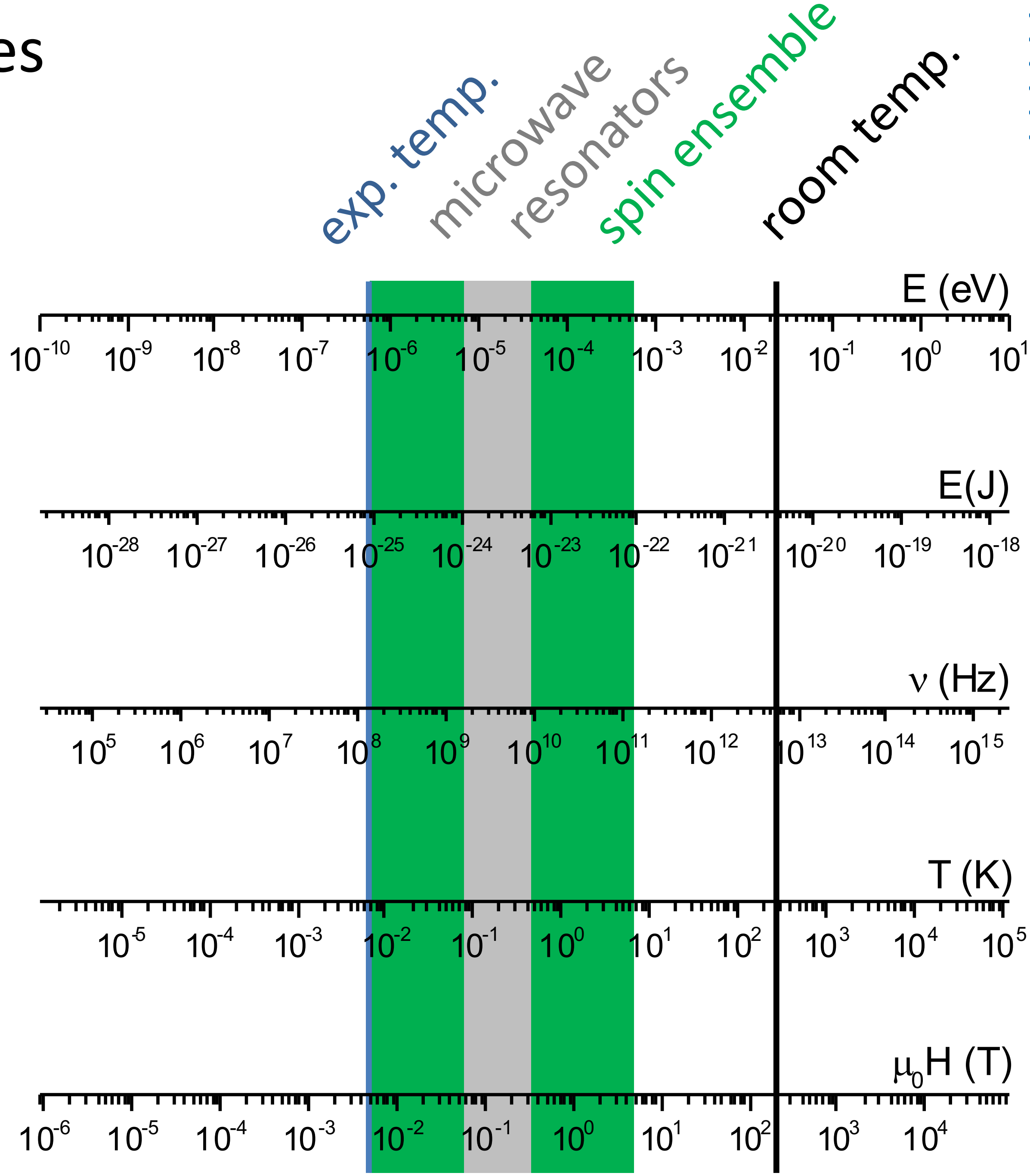


Tabuchi et al., Science **349**, 405 (2015)

Photons & magnons

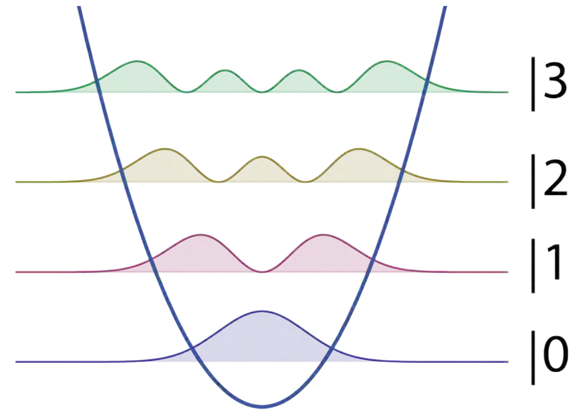


Energy scales

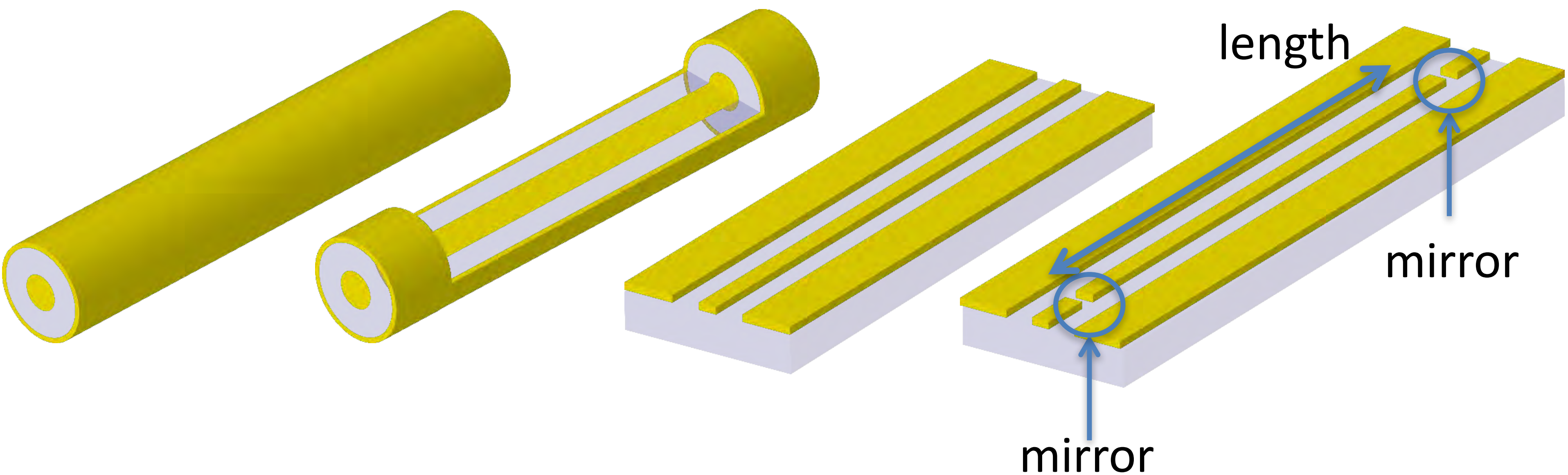


Microwave Cavities and Resonators

- The quantum optics way:
  optical (Fabry-Pérot) cavity



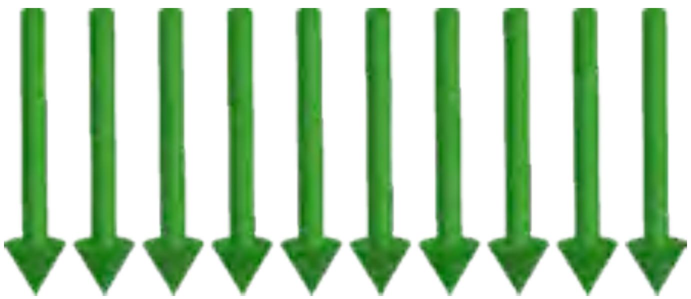
- Integrated resonators on a chip: LC circuits

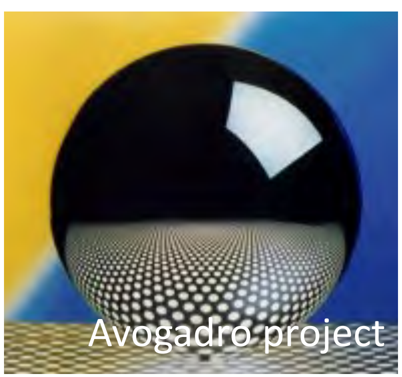


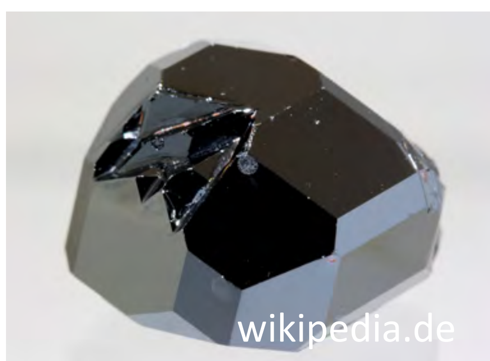
Spin ensemble

$$S = \frac{N}{2}$$

N spins







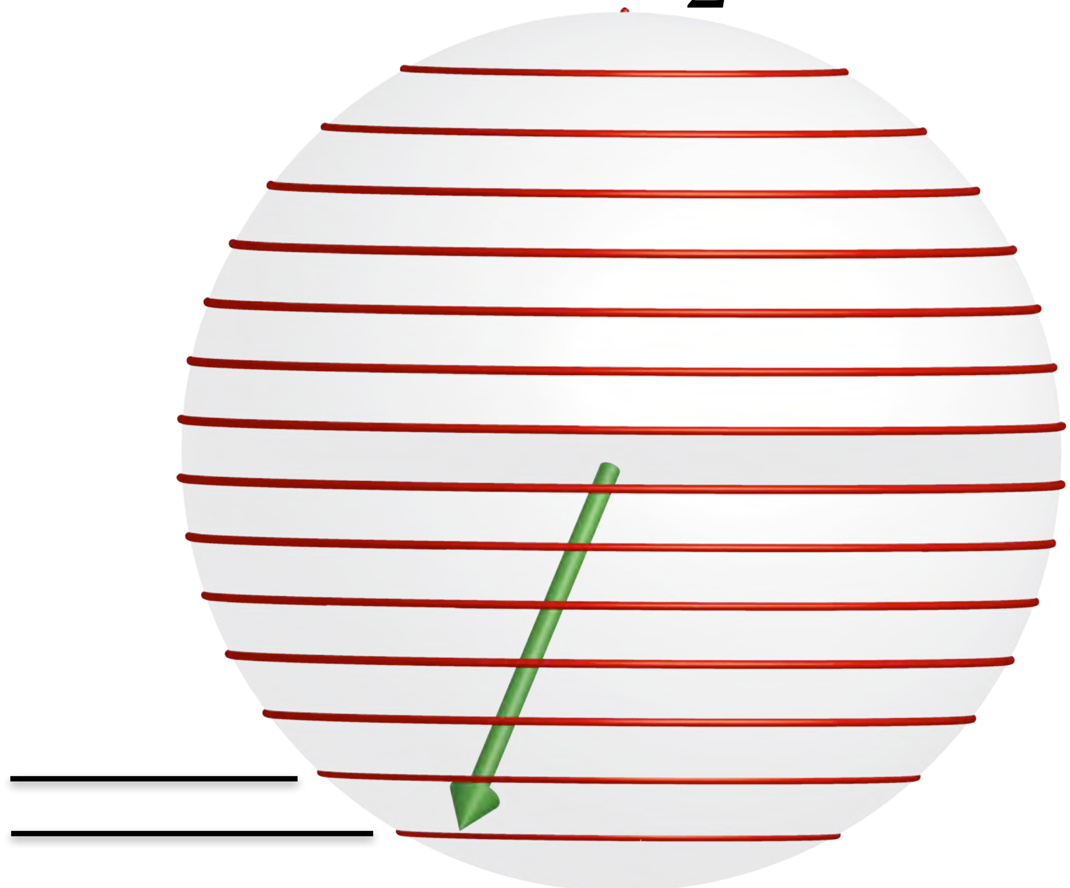
spin ensembles – Si:P & YIG

macro-spin model

Spin ensemble

$$S = \frac{N}{2}$$

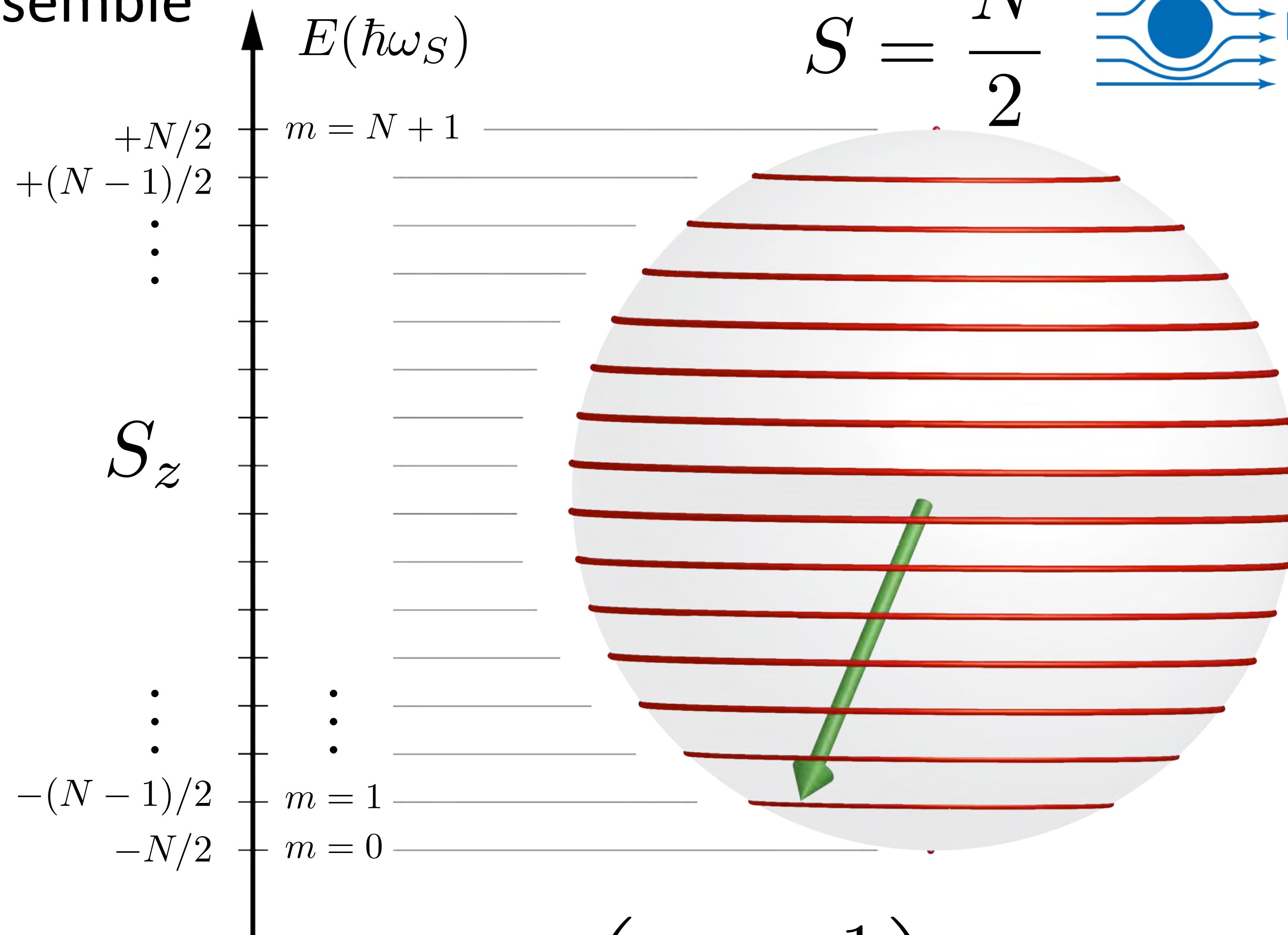
$$\Delta S_z = \pm 1$$



macro-spin model

Spin ensemble

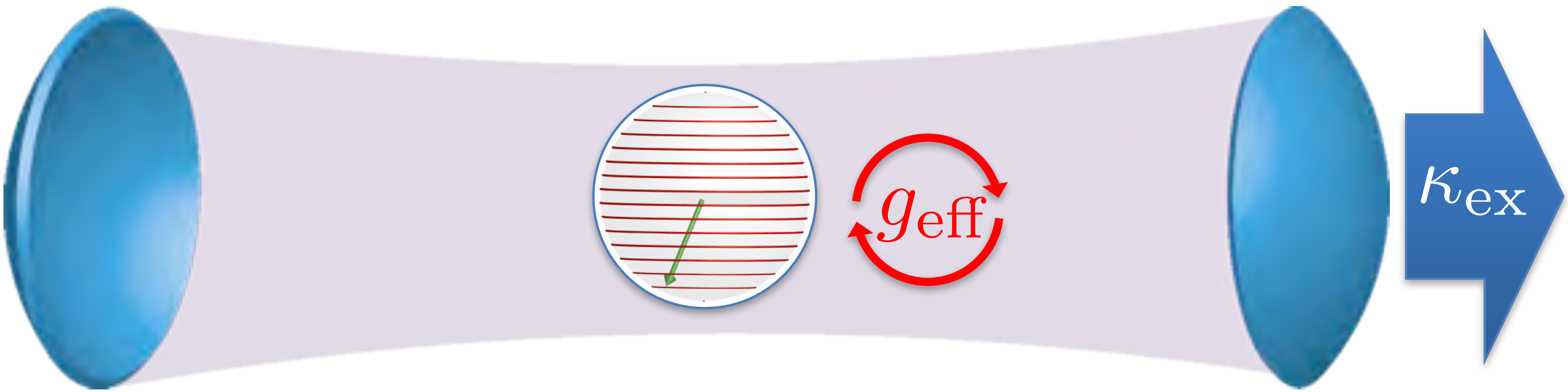
$$S = \frac{N}{2}$$



low excitation numbers:

$$\hat{H} = \hbar\omega_{\mathrm{S}} \left(b^{\dagger} b + \frac{1}{2} \right)$$

Photons & magnons – Jaynes Cummings



coupling mechanism: magnetic dipole interaction

$$-\vec{B}\vec{m} \propto (a + a^\dagger)(b + b^\dagger) \approx (ab^\dagger + ba^\dagger)$$

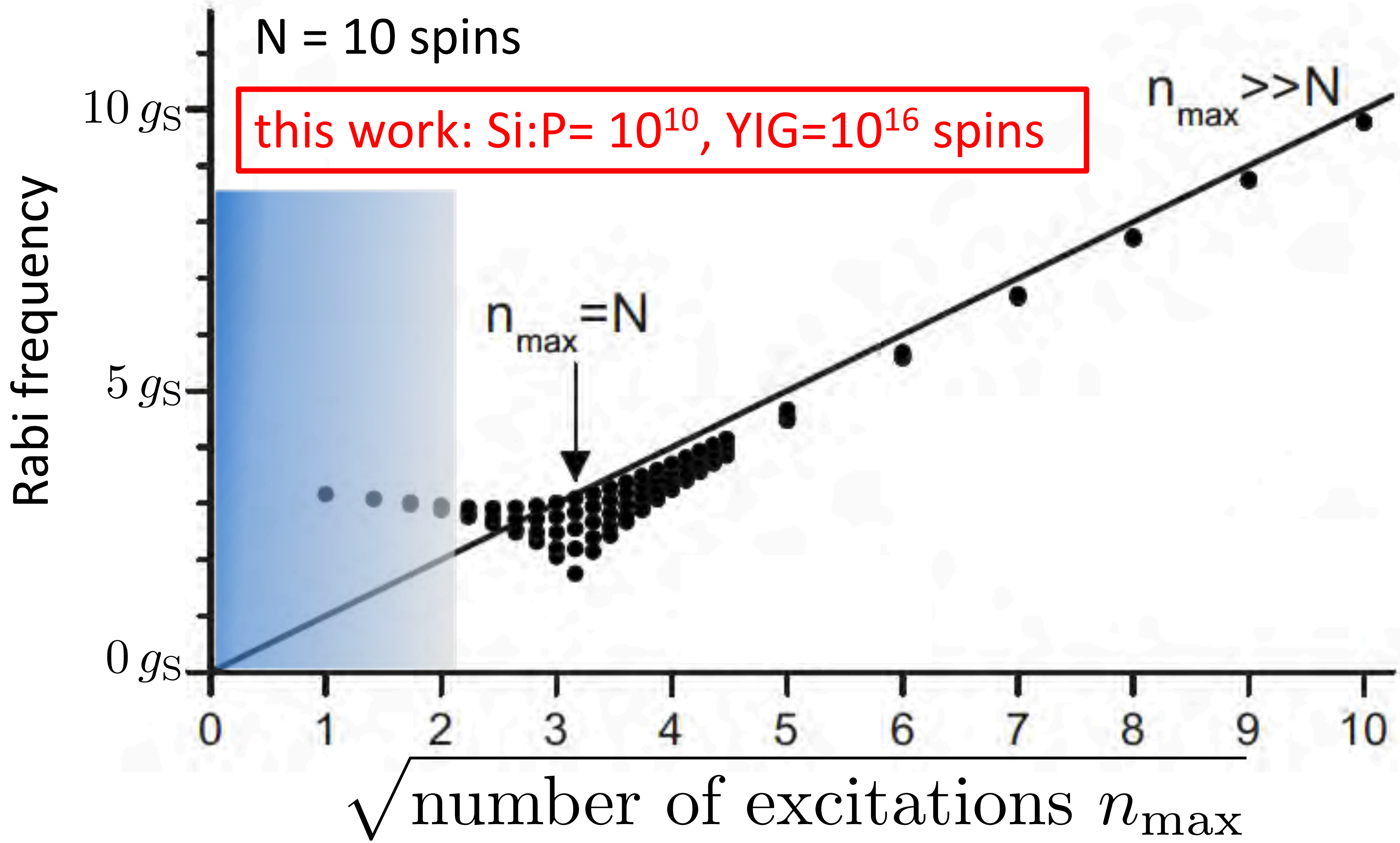
$$\hat{H} = \hbar\omega_c \left(a^\dagger a + \frac{1}{2} \right) + \hbar\omega_S \left(b^\dagger b + \frac{1}{2} \right) + g_{\text{eff}} \left(ab^\dagger + ba^\dagger \right)$$

low excitation: $g_{\text{eff}} \approx g_S \sqrt{N}$

Soykal Phys. Rev. Lett. **104**, 077202 (2010)

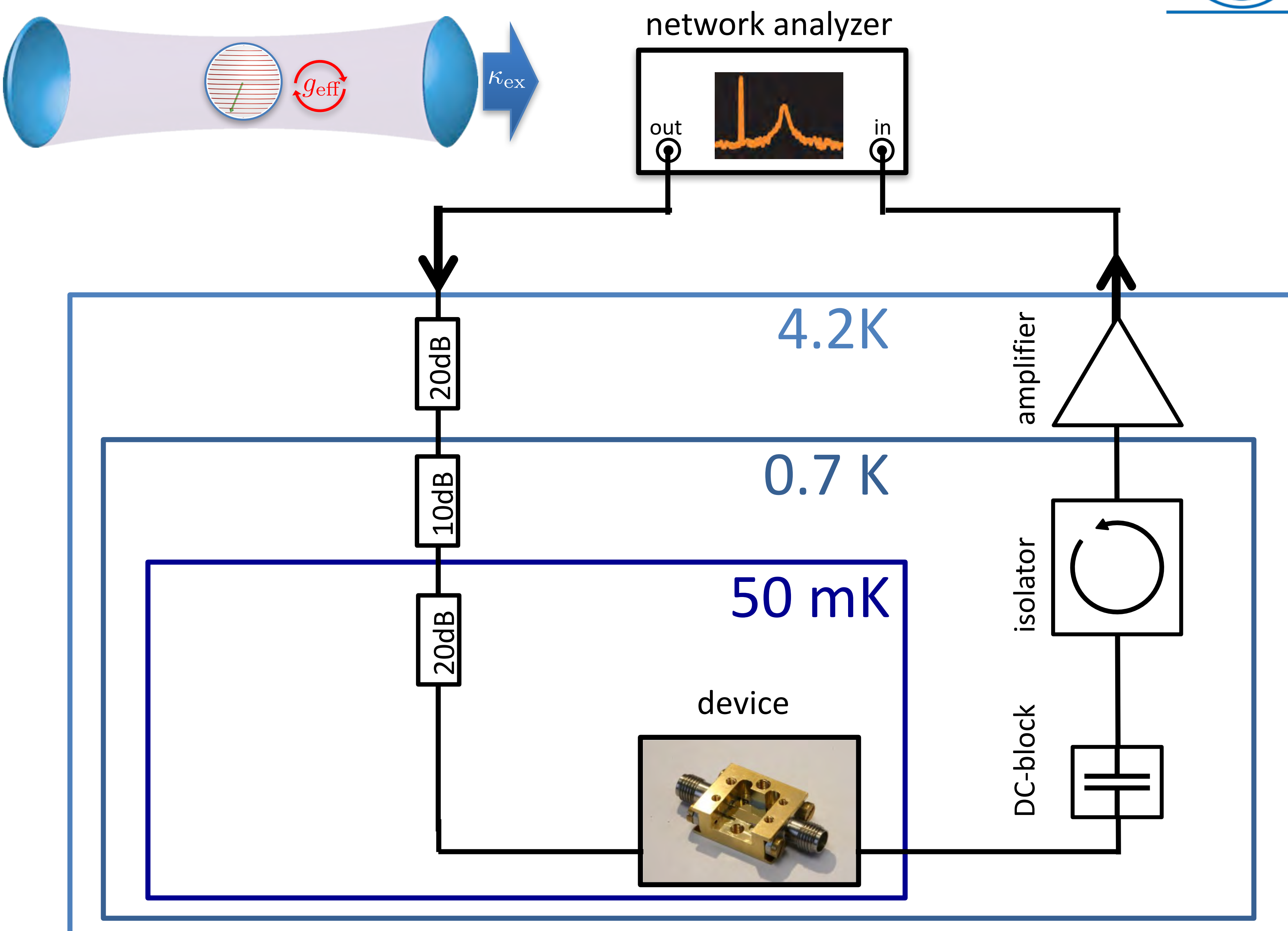
Chiorescu et al., PRB **82**, 024413 (2010)

Rabi frequencies



Chiorescu et al., PRB **82**, 024413 (2010)

Microwave spectroscopy



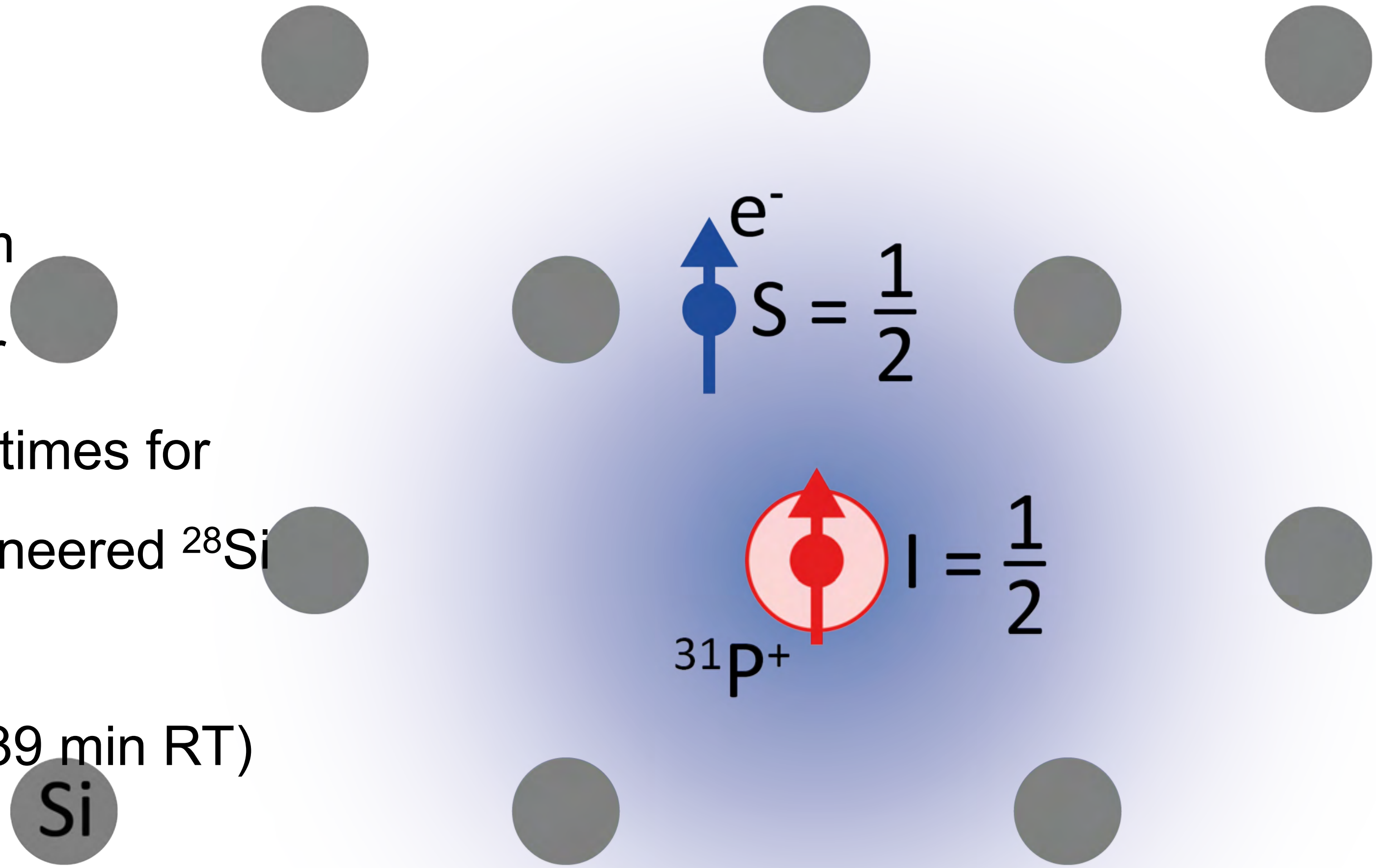
Paramagnetic Spin Ensemble: Phosphorus Donors in Silicon

- atomistic system
- isotrope g-factor
- long coherence times for isotopically engineered ^{28}Si

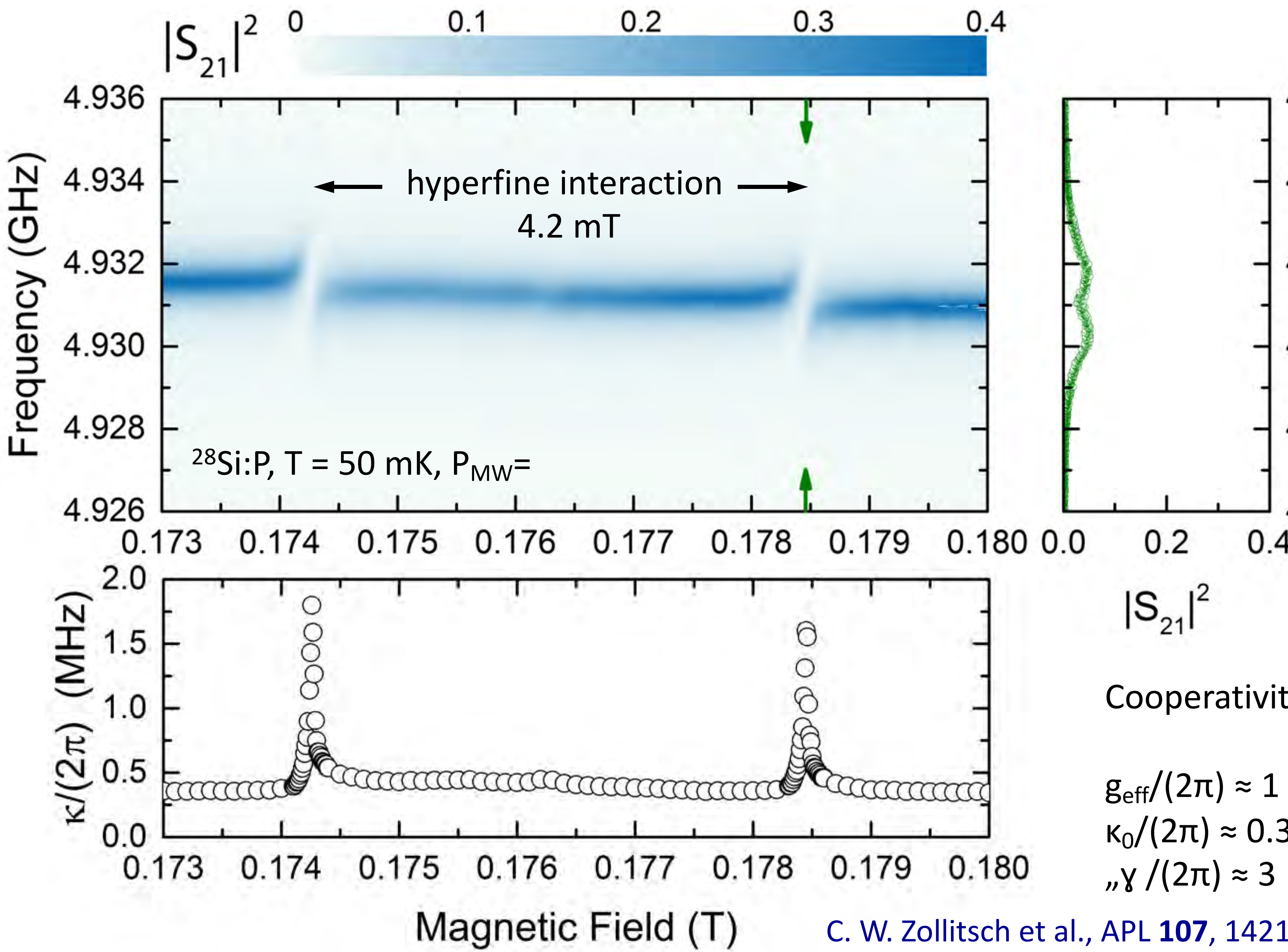
  $T_{2e} =$ seconds

  $T_{2n} =$ 180 min (39 min RT)

- zero field splitting 117 MHz



Phosphorus Donors in Silicon

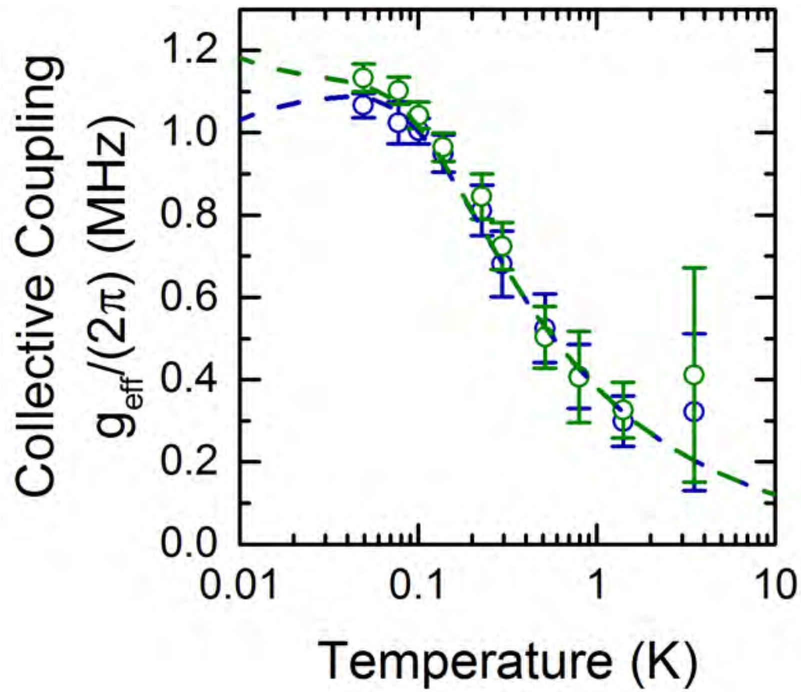


Cooperativity: C ≈ 1

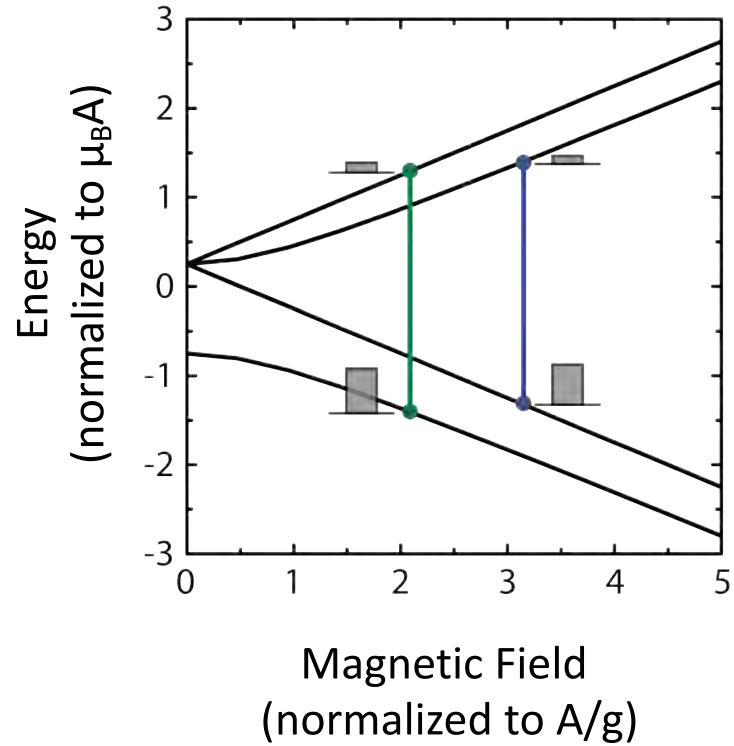
$g_{eff}/(2\pi) \approx 1$ MHz
$\kappa_0/(2\pi) \approx 0.34$ MHz
„$\gamma/(2\pi) \approx 3$ MHz“

C. W. Zollitsch et al., APL **107**, 142105 (2015)

Collective Coupling



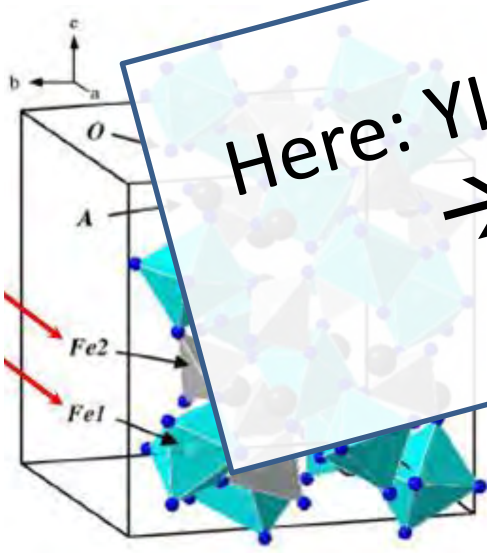
Breit Rabi diagram



$$g_{\mathrm{eff}} \approx g_S \sqrt{N(T)} = g_S \sqrt{N_0 P(T)}$$

C. W. Zollitsch et al., APL **107**, 142105 (2015)

Ingredients: (pure) yttrium iron garnet



Gilleo and Geller, PR **110**, 73 (1958)
Coey, *Magnetism and Magnetic Materials Cambridge University Press (2010)*
Van Uitert, JAP **27**, 723 (1956)

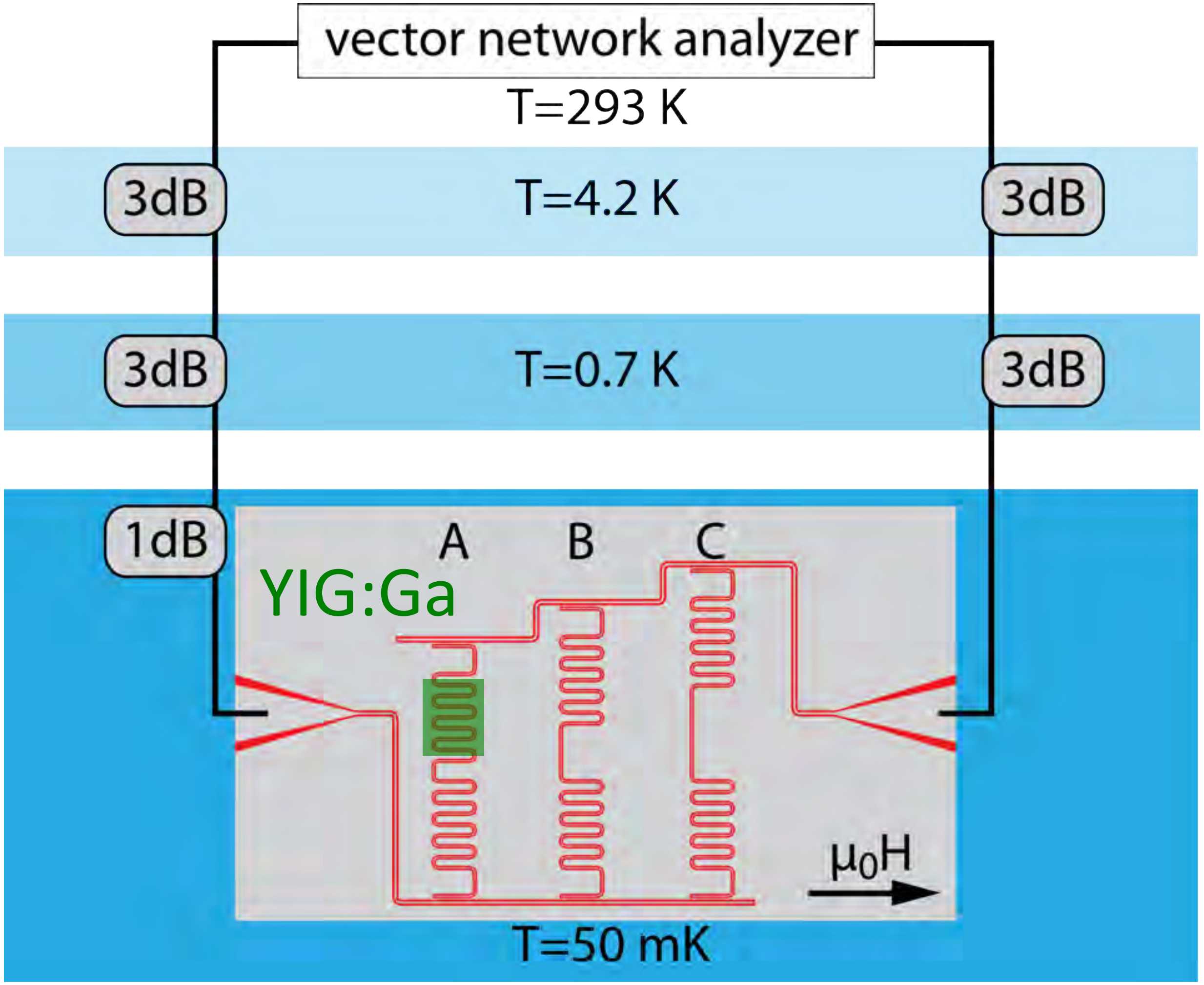
chemical formula:
- $Y_3Fe_2(FeO_4)_3$ or $Y_3Fe_5O_{12}$
- lattice constant: 1.2376 nm

magnetic properties:
- ferrimagnet
- 40 μ_B per unit cell
  - → 2.1 x 10^{22} $\mu_B cm^{-3}$
- saturation magnetization 143 kA/m
- FMR linewidth:
  - fundamental mode : 1mT ≡ 28 MHz
  - spin wave modes: 10µT ≡ 280 kHz
    - ≡ µsec coherence times

Here: YIG:Ga
→ linewidth: 28 MHz
Rachford, et al. JAP **87**, 6253

electrical/optical properties:
$\sigma = 10^{-11}\ \Omega cm^{-1}$ (at RT)
Bandgap 2.8 eV

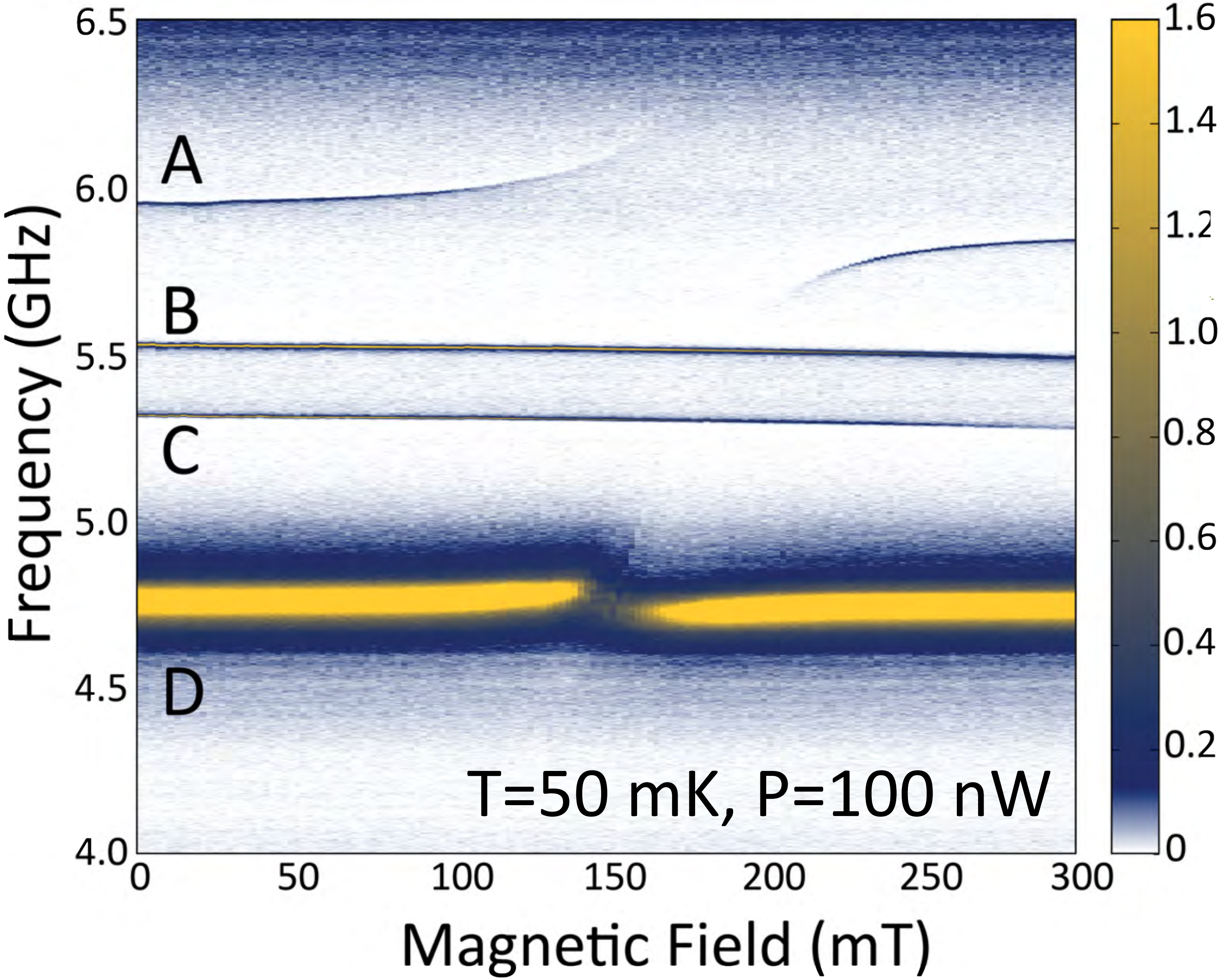
Experimental setup and coupling strategy

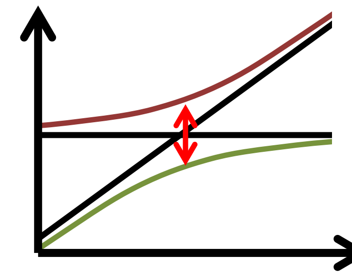


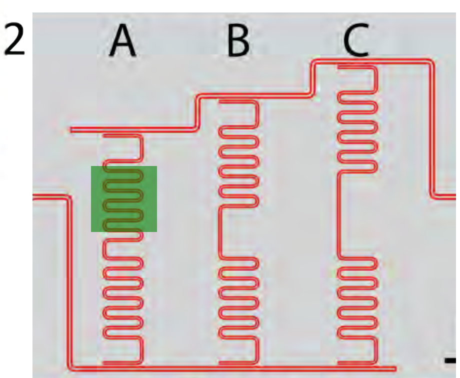
Estimate:

$$
\begin{aligned}
N &= \rho \text{ length width height} \\
&= 2 \times 10^{22}\,\mathrm{cm}^{-3} \cdot 2.5\,\mathrm{mm} \cdot (30\,\mu\mathrm{m})^2 = 4.5 \times 10^{16}
\end{aligned}
$$

Transmission spectrum

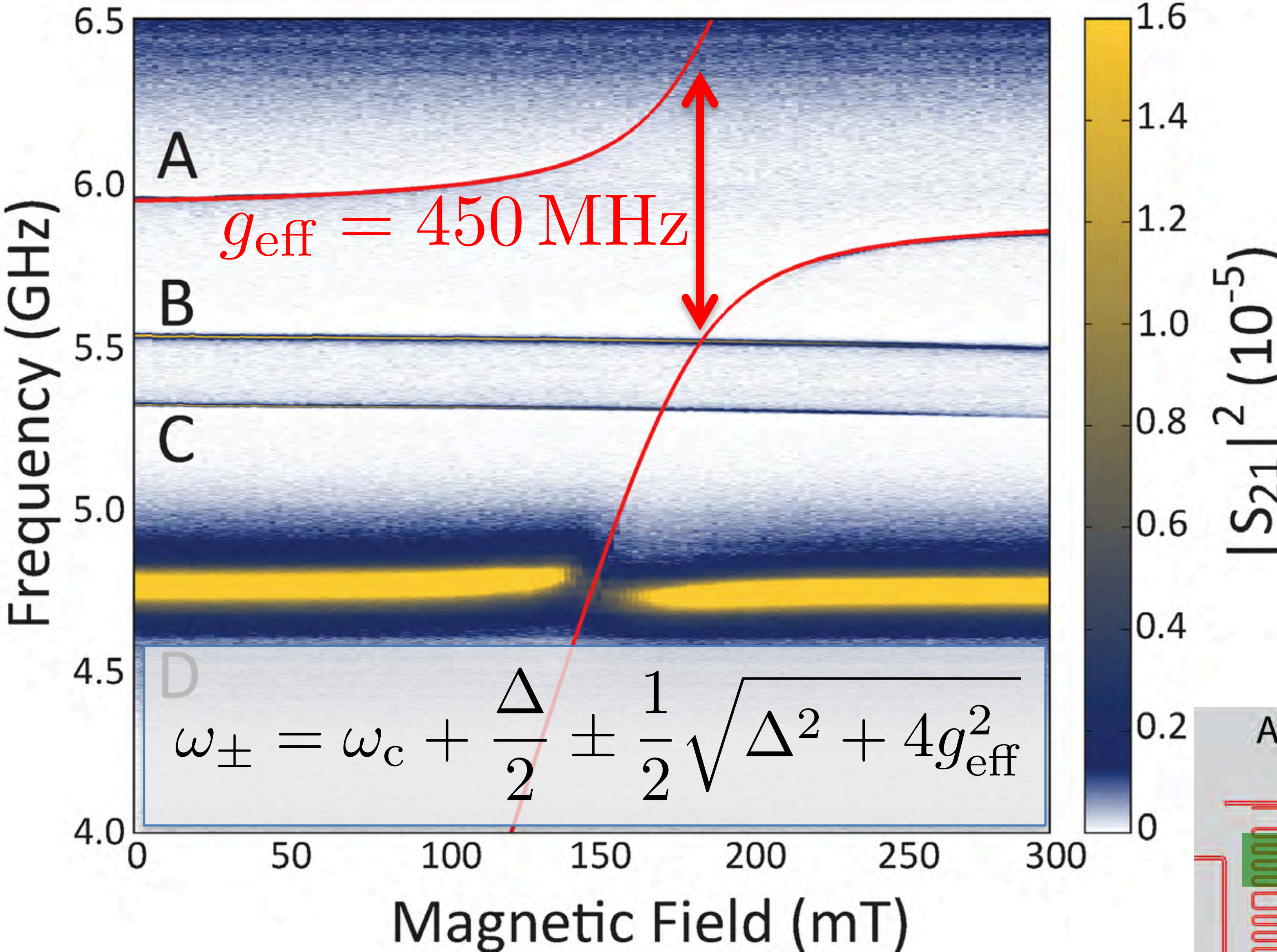


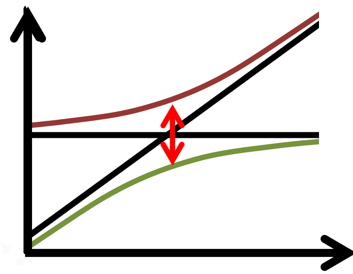


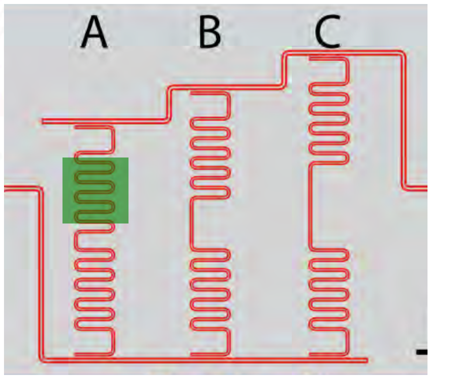


Huebl et al., Phys. Rev. Lett. **111**, 127003 (2013)

Transmission spectrum







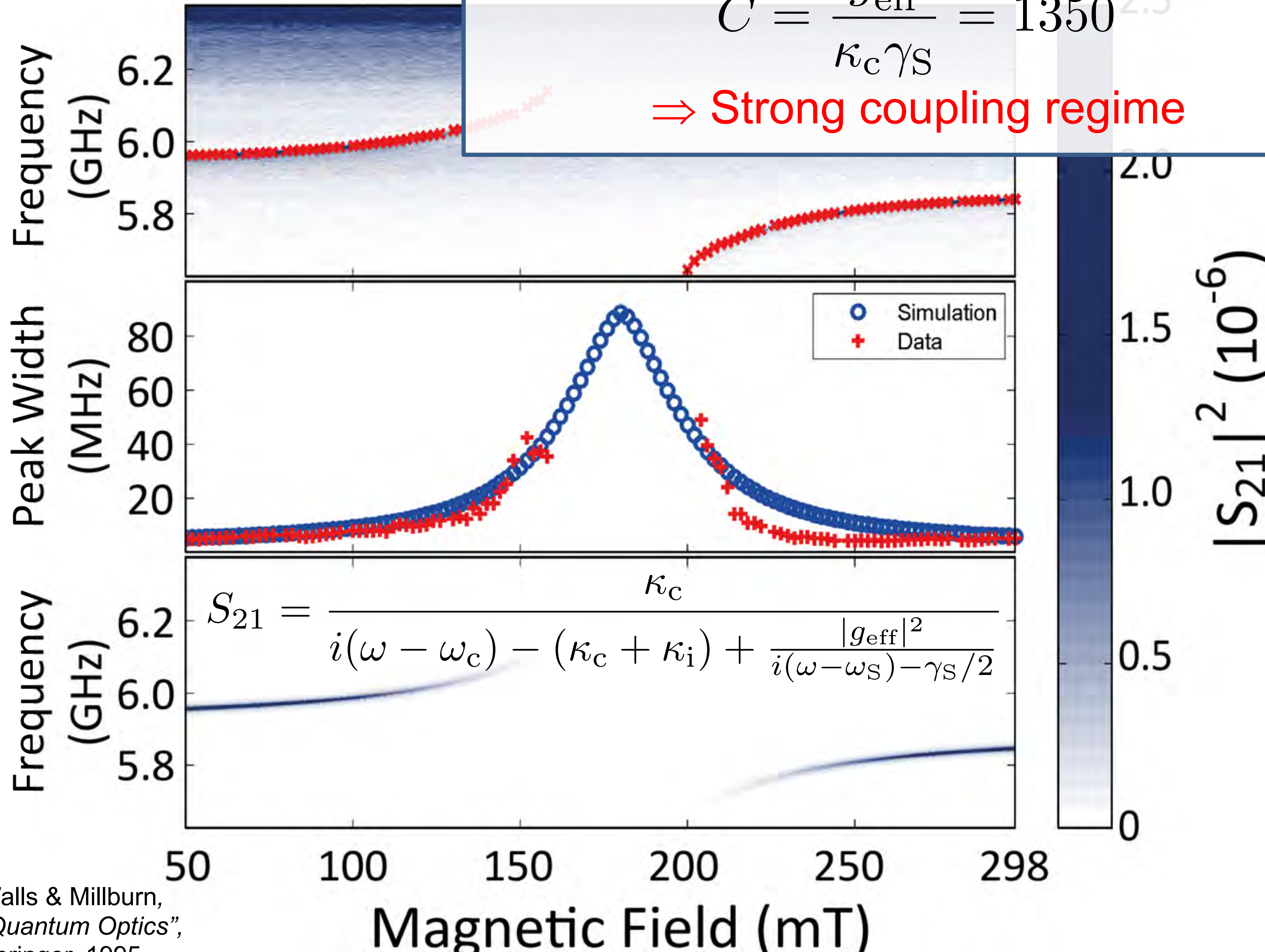
Huebl et al., Phys. Rev. Lett. **111**, 127003 (2013)

Relaxation rate

$$\kappa_c/2\pi = 3\,\mathrm{MHz},\ \ \gamma_S/2\pi = 50\,\mathrm{MHz}$$

$$C = \frac{g_{\mathrm{eff}}^2}{\kappa_c \gamma_S} = 1350$$

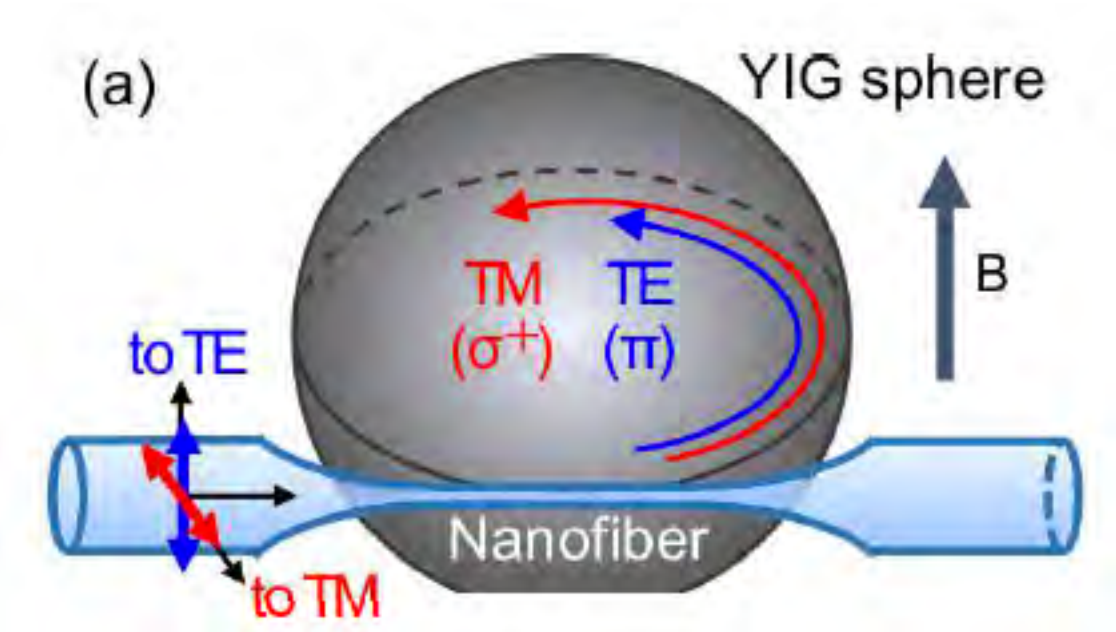
$\Rightarrow$ Strong coupling regime



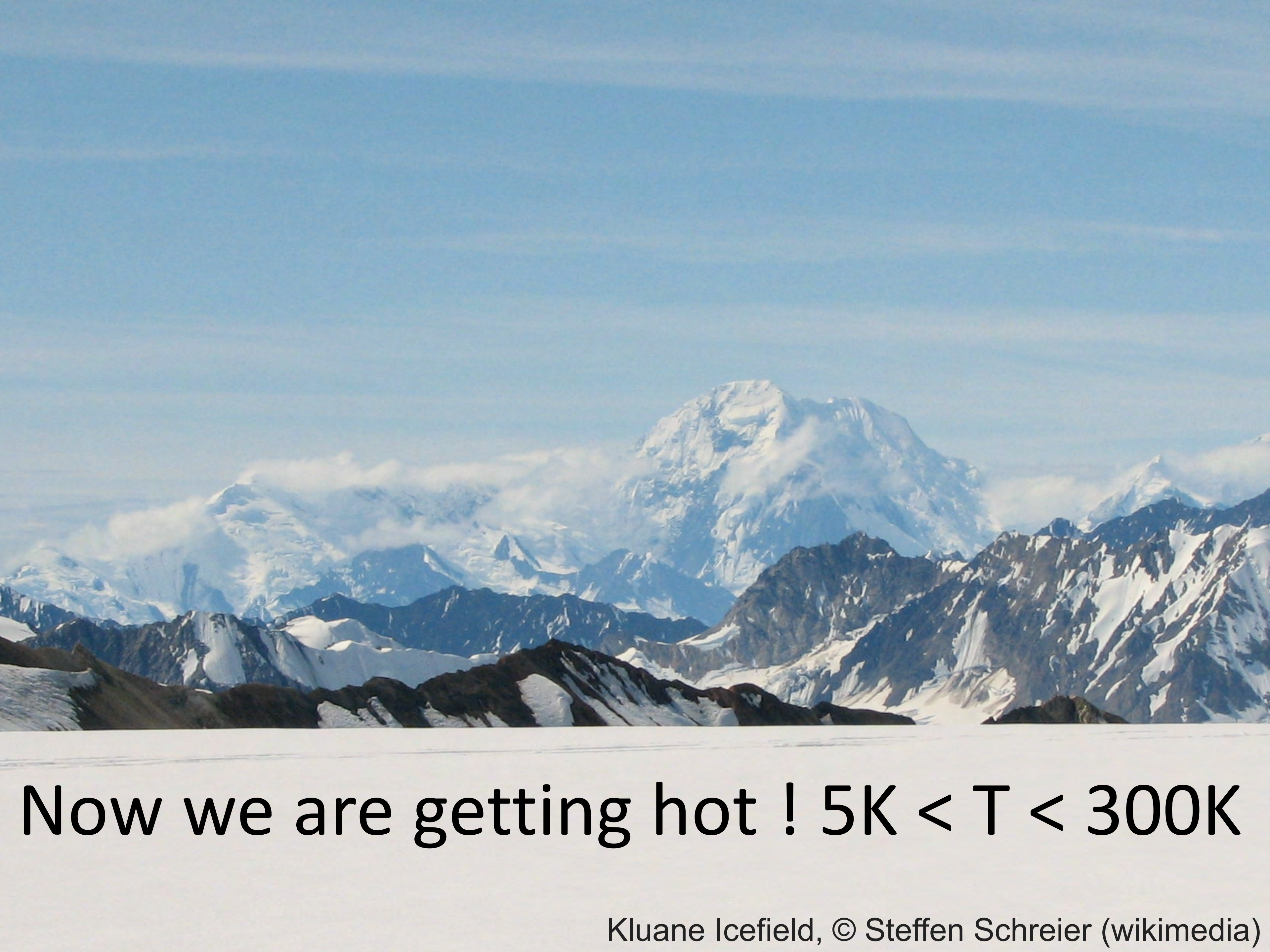
$$S_{21} = \frac{\kappa_c}{i(\omega - \omega_c) - (\kappa_c + \kappa_i) + \frac{|g_{\mathrm{eff}}|^2}{i(\omega - \omega_S) - \gamma_S/2}}$$

Walls & Millburn,
"Quantum Optics",
Springer, 1995

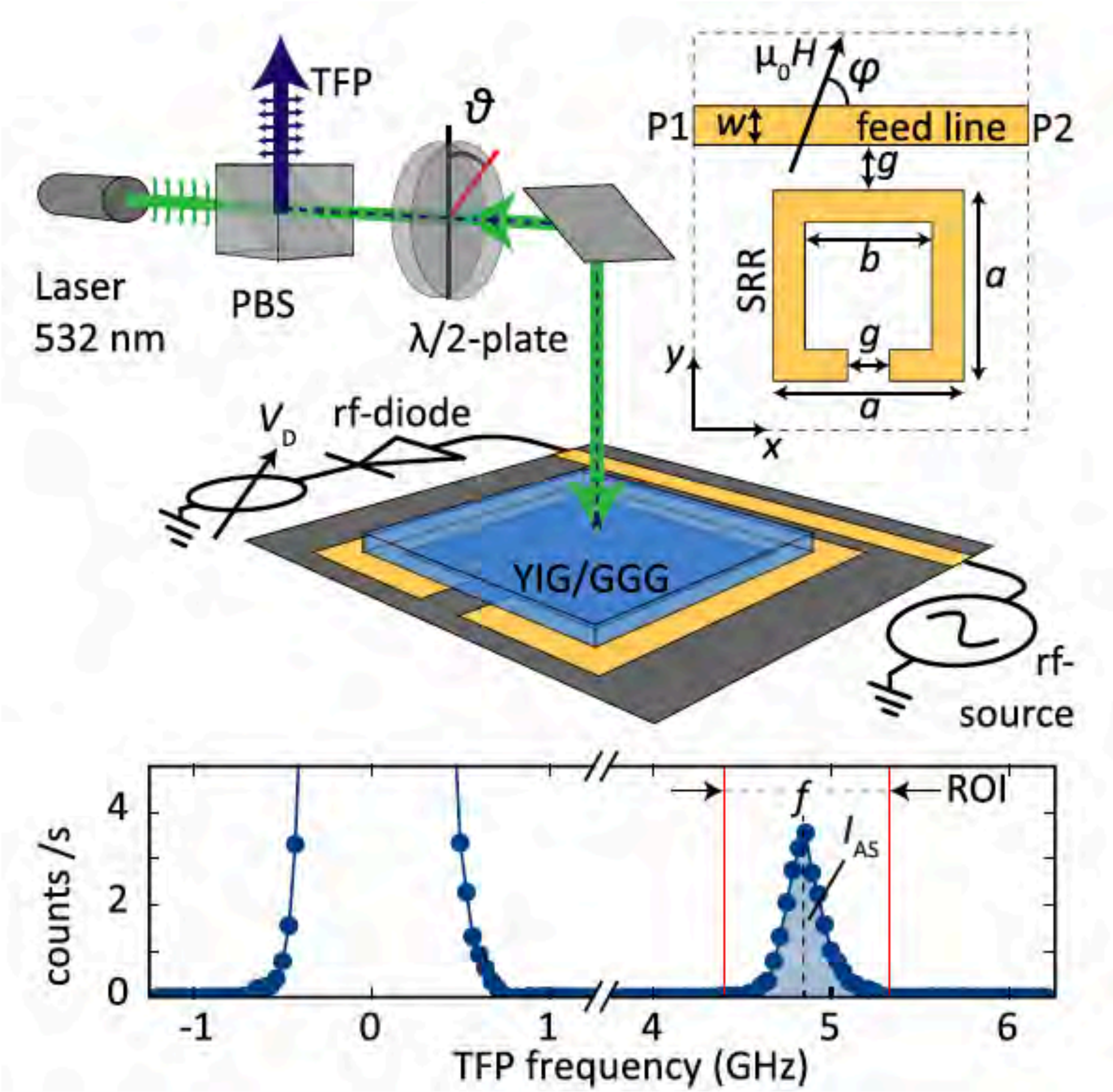
Optical Detection of Spin Excitations



Hisatomi, Phys Rev B **93**, 174427 (2016)
Osada, Phys. Rev. Lett. **116**, 223601 (2016)
Sharma, arXiv: 1706.04106
Liu, Phys Rev B **94**, 060405(R) (2016)
Viola-Kusminskiy, Phy Rev A **94**, 033821 (2016)
Haigh, Phys. Rev. Lett. **117**, 133602 (2016)
Demokritov, Phys. Rep. **348**, 441 (2001)
+ many more


Now we are getting hot ! 5K < T < 300K
Kluane Icefield, © Steffen Schreier (wikimedia)

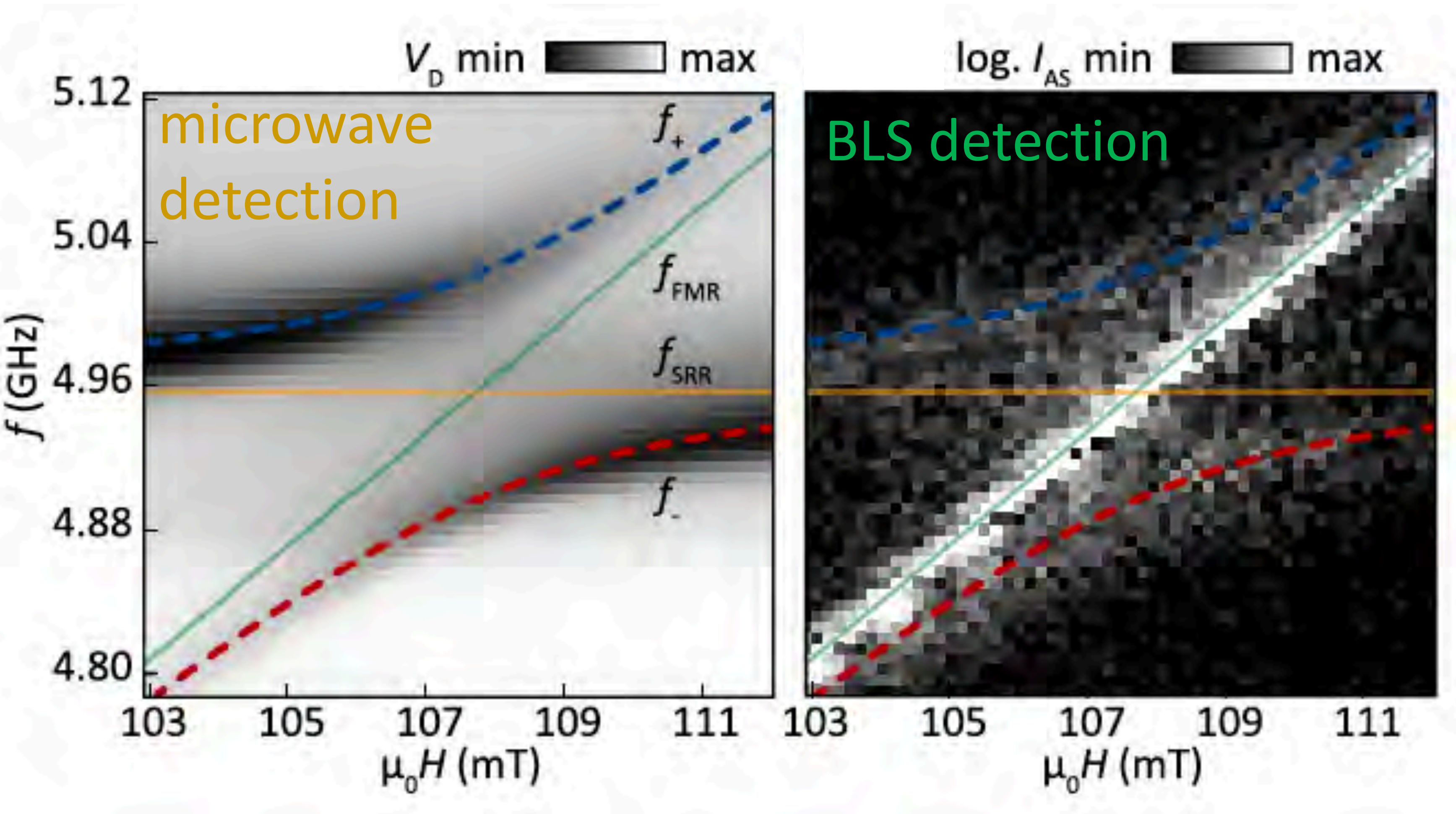
Optical Detection of Strong Coupling



In situ detection:
magnons via BLS
and
microwave photons
via detection diode

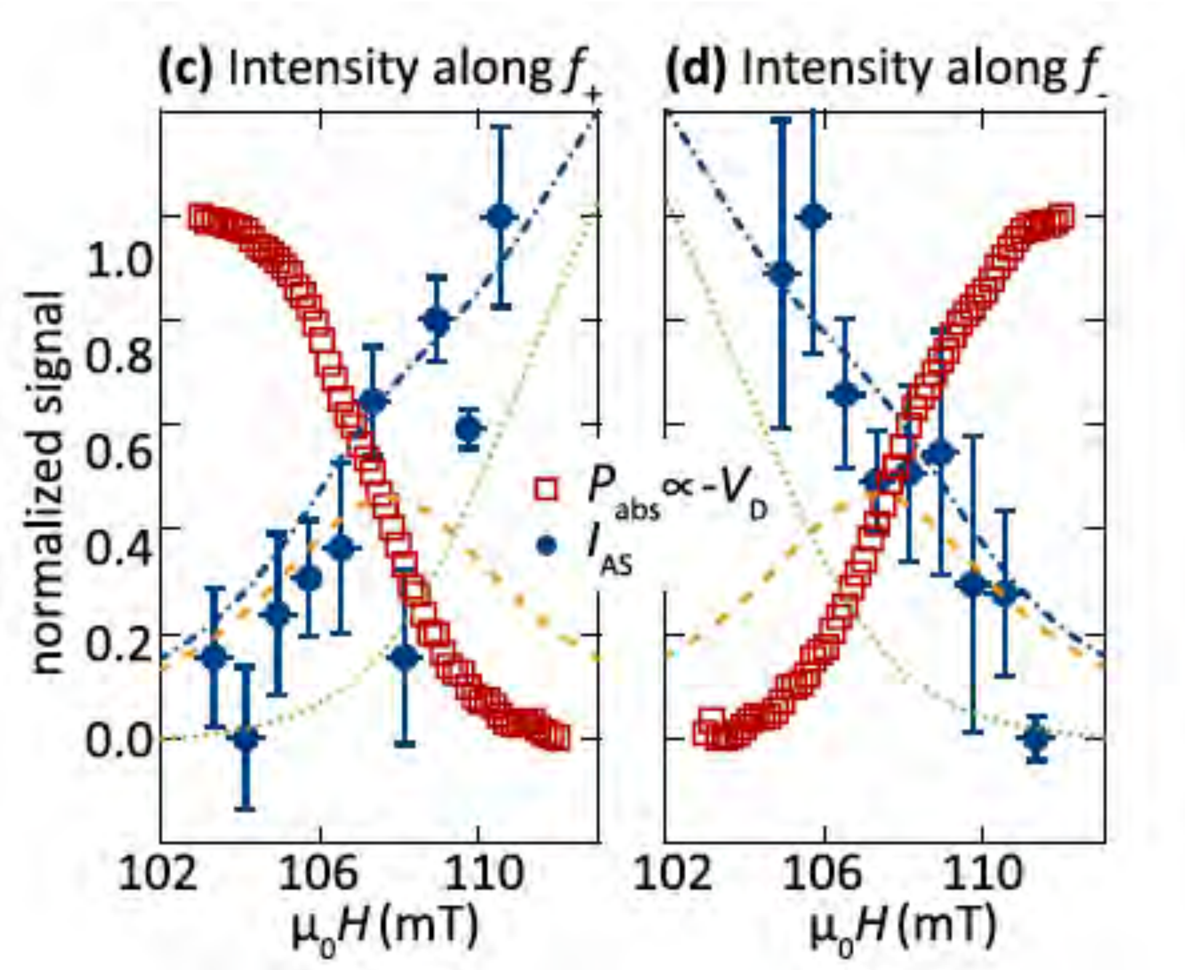
S. Klingler, Appl. Phys. Lett. **109**, 072402 (2016)

Optical Detection of Strong Coupling



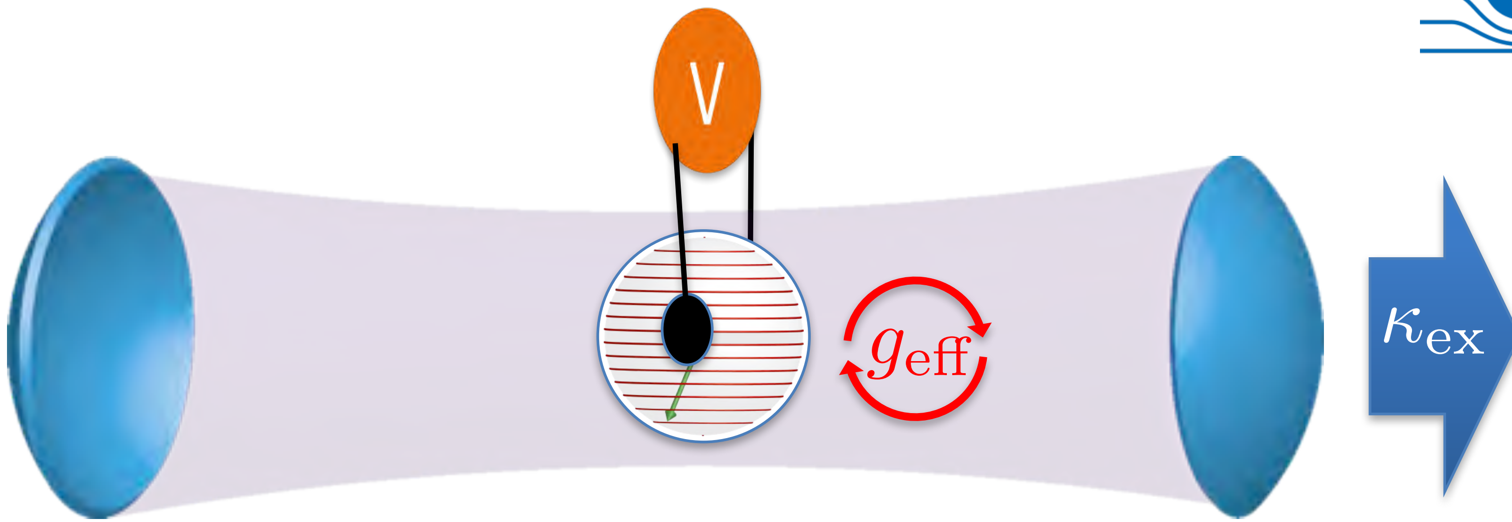
S. Klingler, Appl. Phys. Lett. **109**, 072402 (2016)

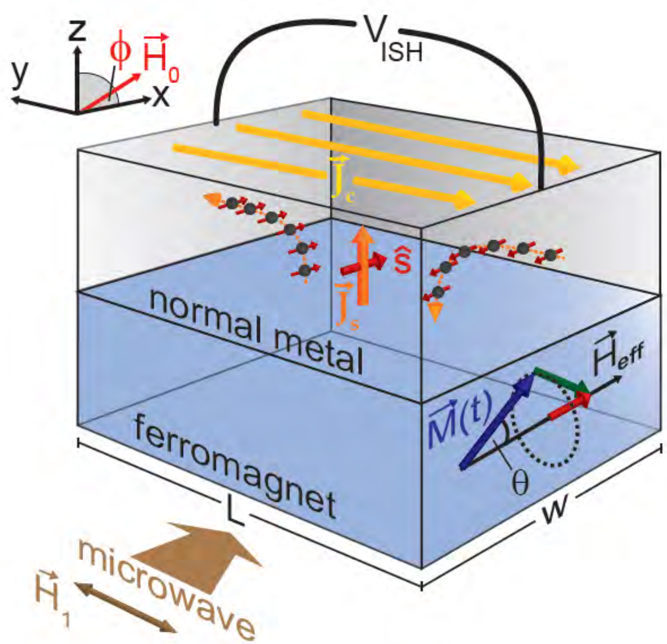
Optical Detection of Strong Coupling



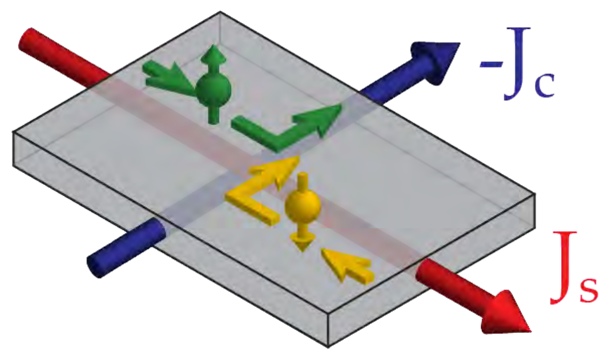
S. Klingler, Appl. Phys. Lett. **109**, 072402 (2016)

Spin pumping – a different viewpoint





Czeschka PhD Thesis, TUM



inverse spin Hall effect (ISHE)

spin current ➡ charge current

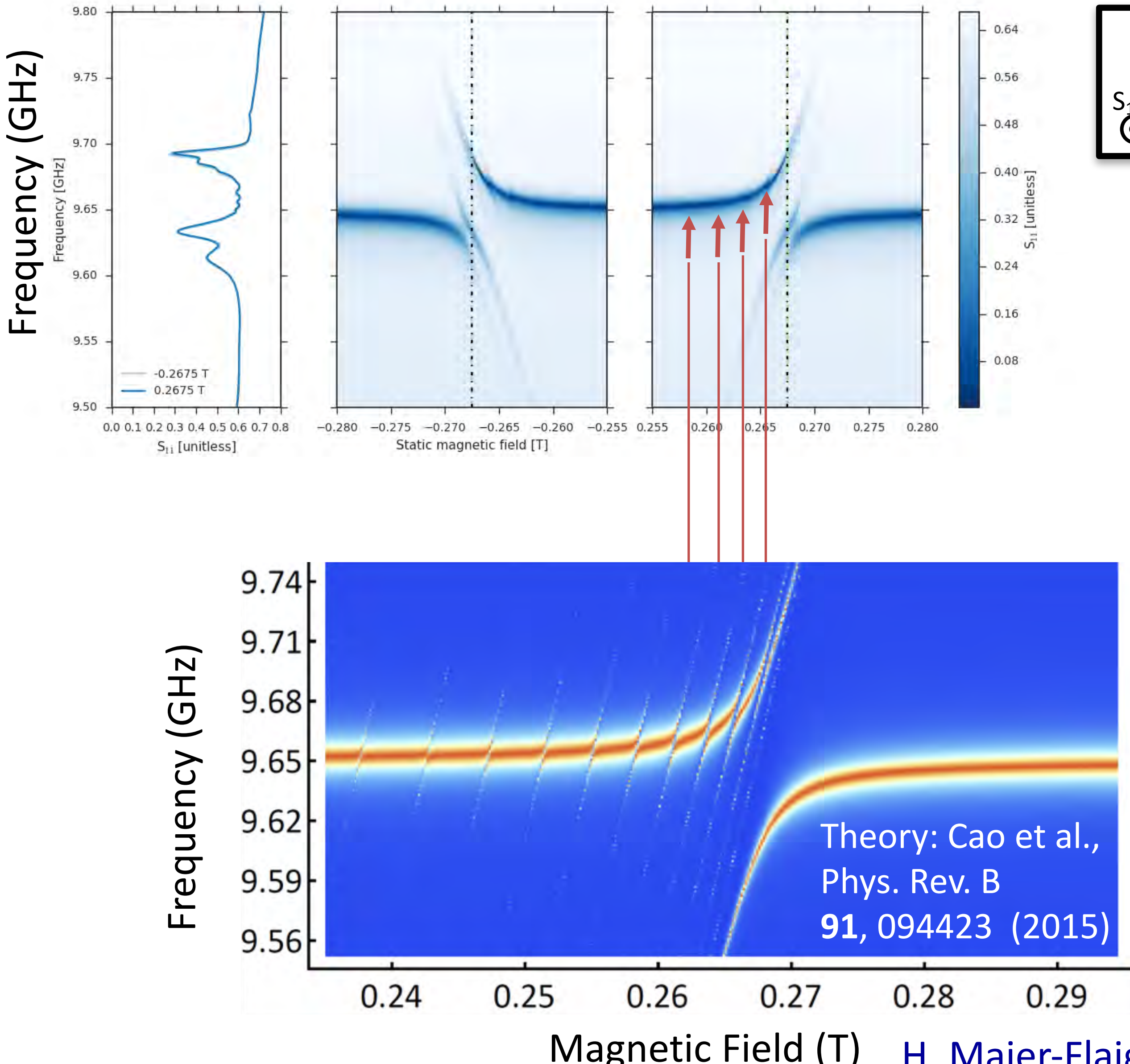
Cao et al., Phys. Rev. B **91**, 094423 (2015)

Bai et al., Phys. Rev. Lett. **114**, 227201 (2015)

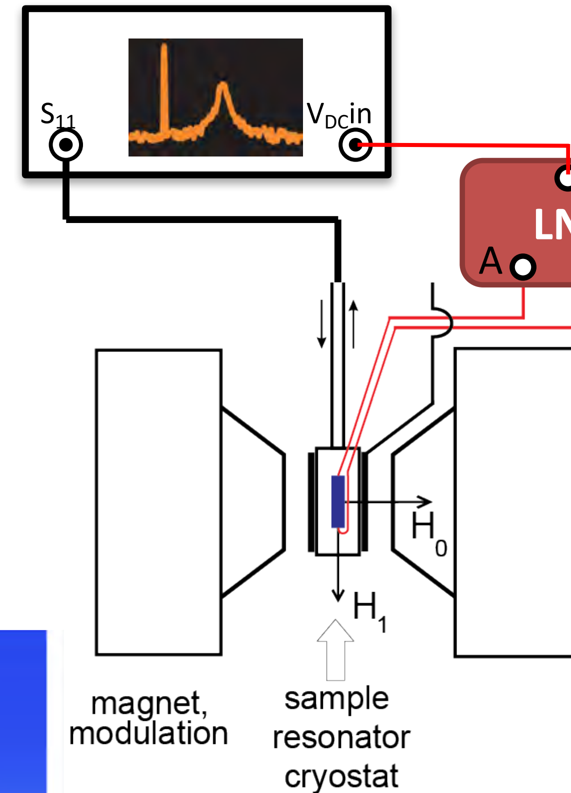
H. Maier-Flaig, Phys. Rev. B **94**, 054433 (2016)

Comparison – Microwave Spectroscopy / Spin Pumping

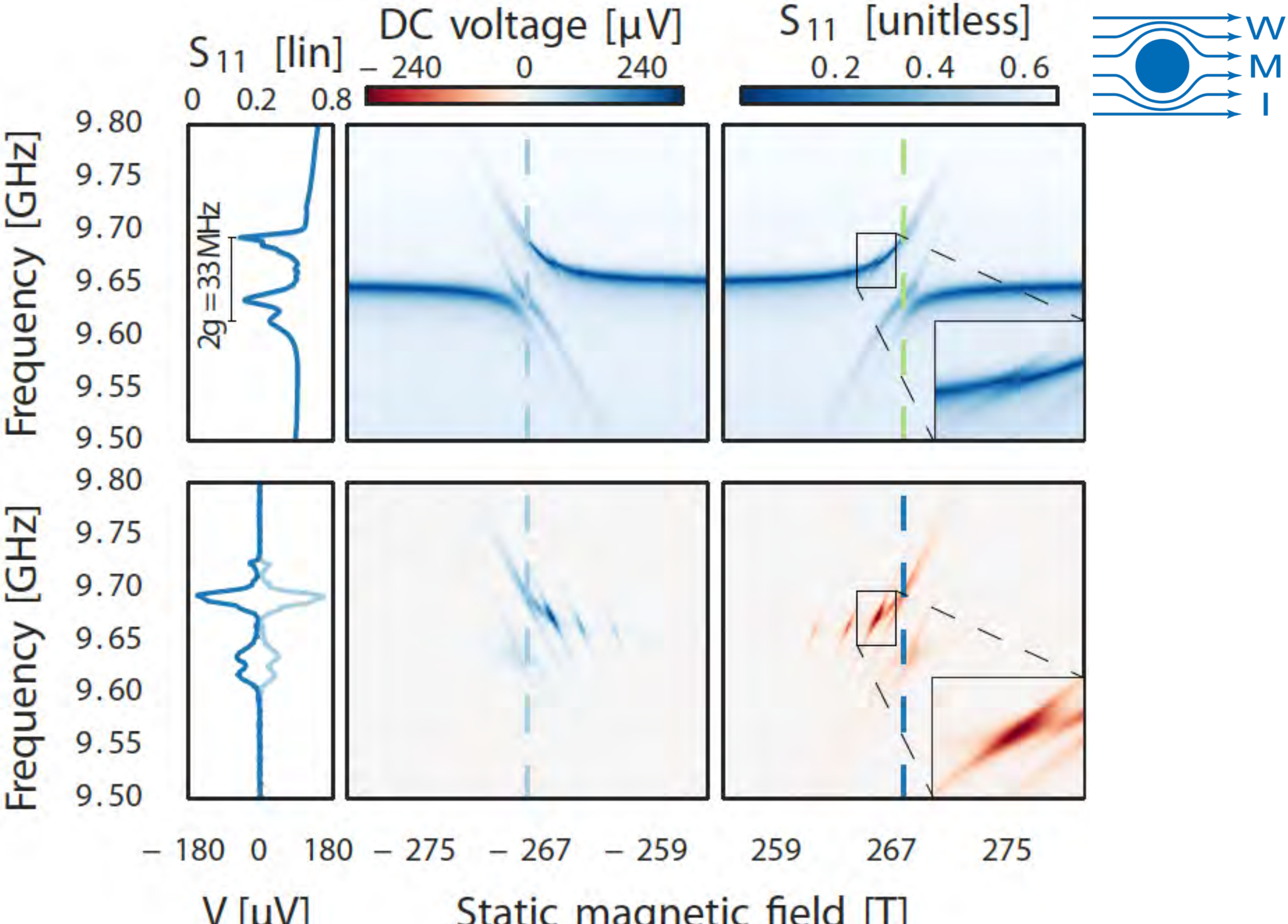
Microwave Detecton



network analyzer

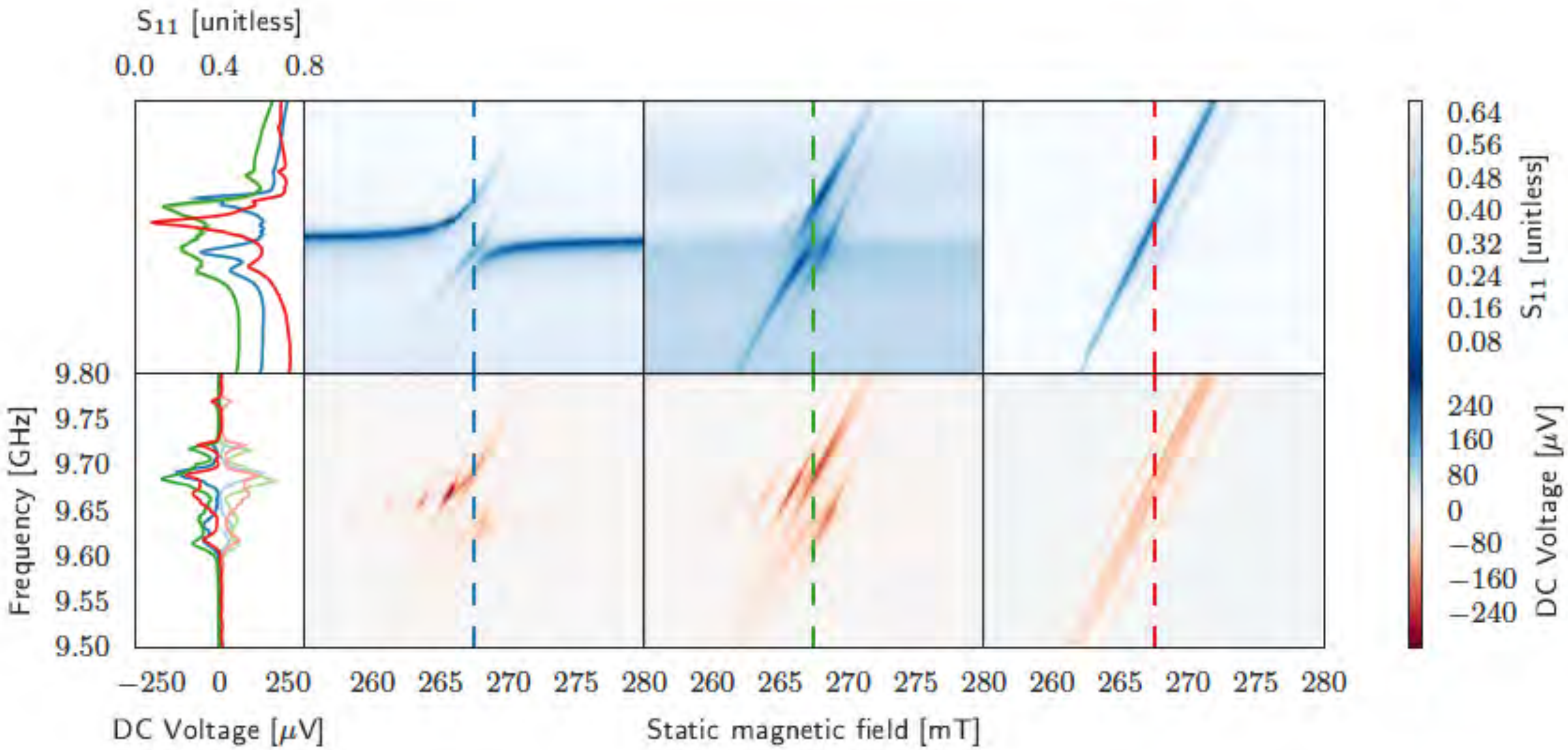


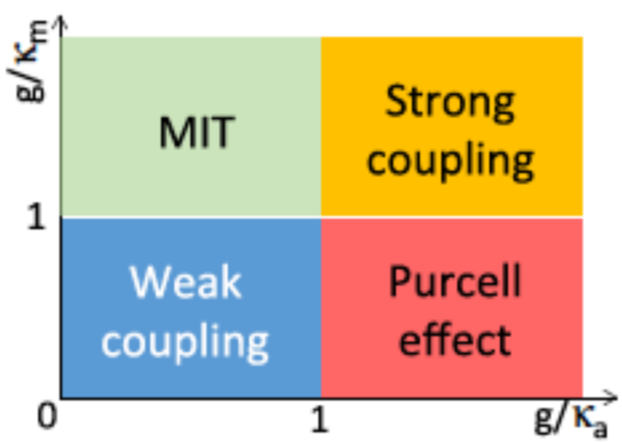
H. Maier-Flaig, Phys. Rev. B **94**, 054433 (2016)



H. Maier-Flaig, Phys. Rev. B **94**, 054433 (2016)

Strong coupling → overcoupled cavity



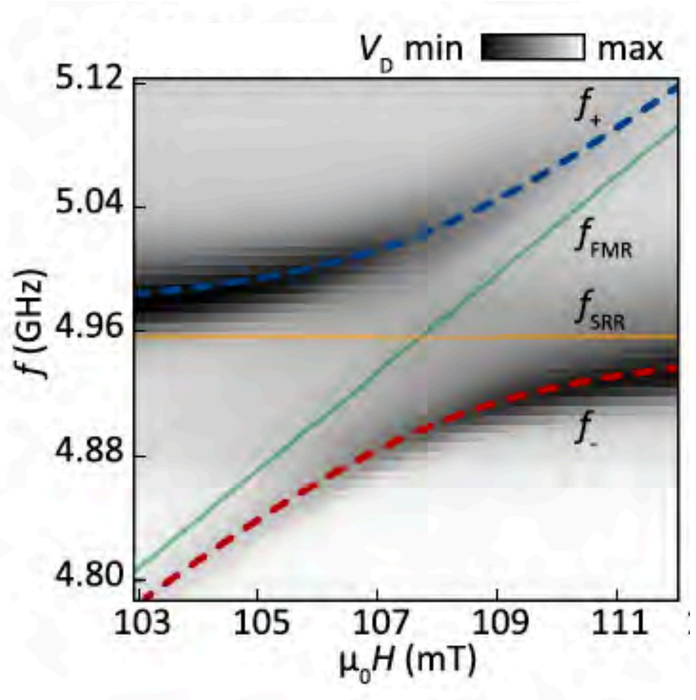


Zhang et al., PRL **113**, 156401 (2015)

- From strong coupling to transmission line like behavior

H. Maier-Flaig, Phys. Rev. B **94**, 054433 (2016)

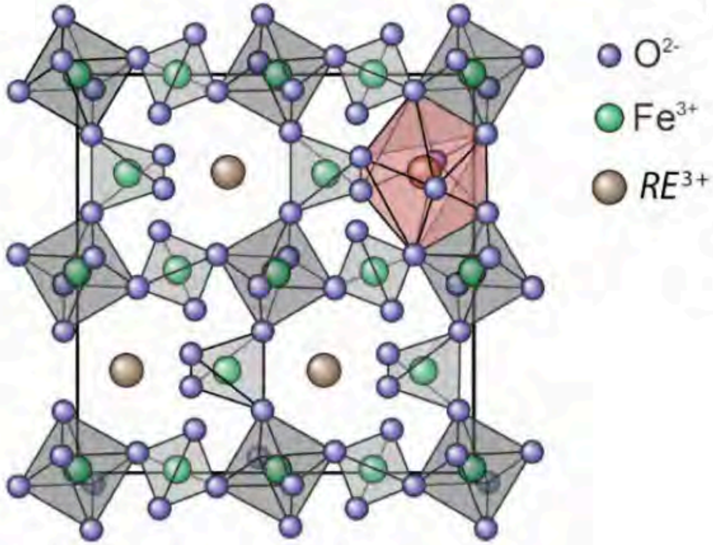
Tunable Coupling GdIG

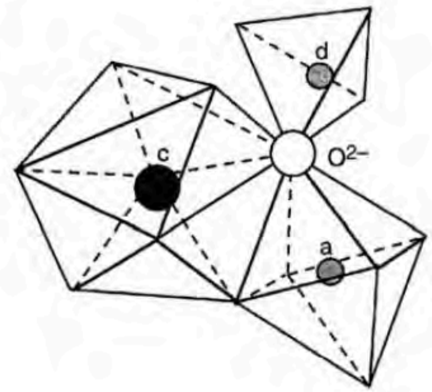


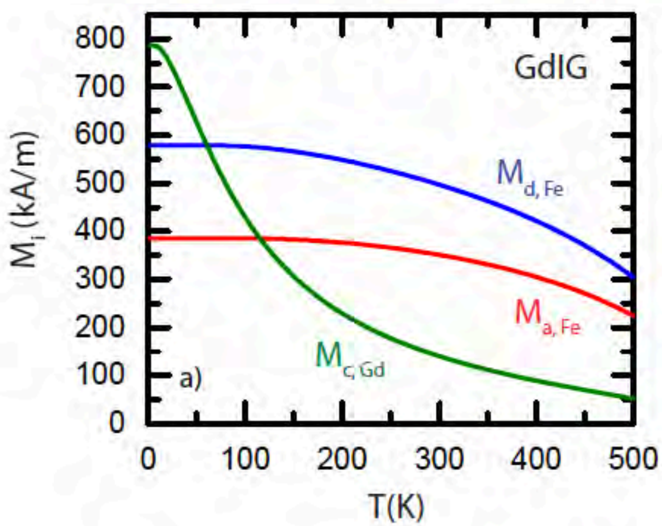
$$g_{\text{eff}} \approx g_{\text{S}} \sqrt{N} \propto \sqrt{M}$$

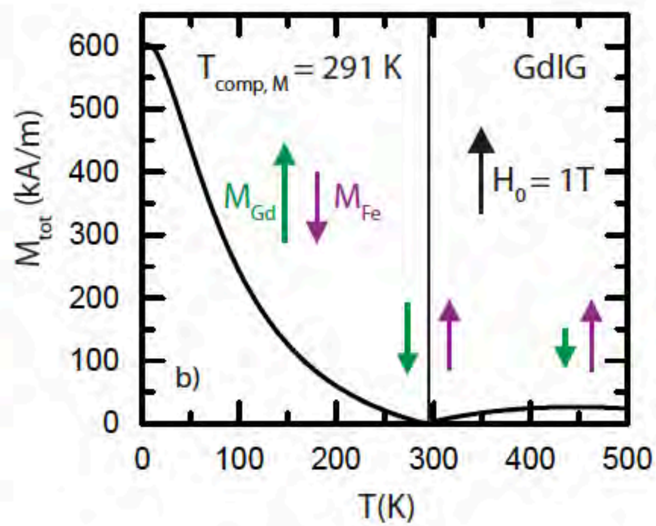
H. Maier-Flaig, Appl. Phys. Lett. **110**, 132401 (2017)

Tunable Coupling GdIG



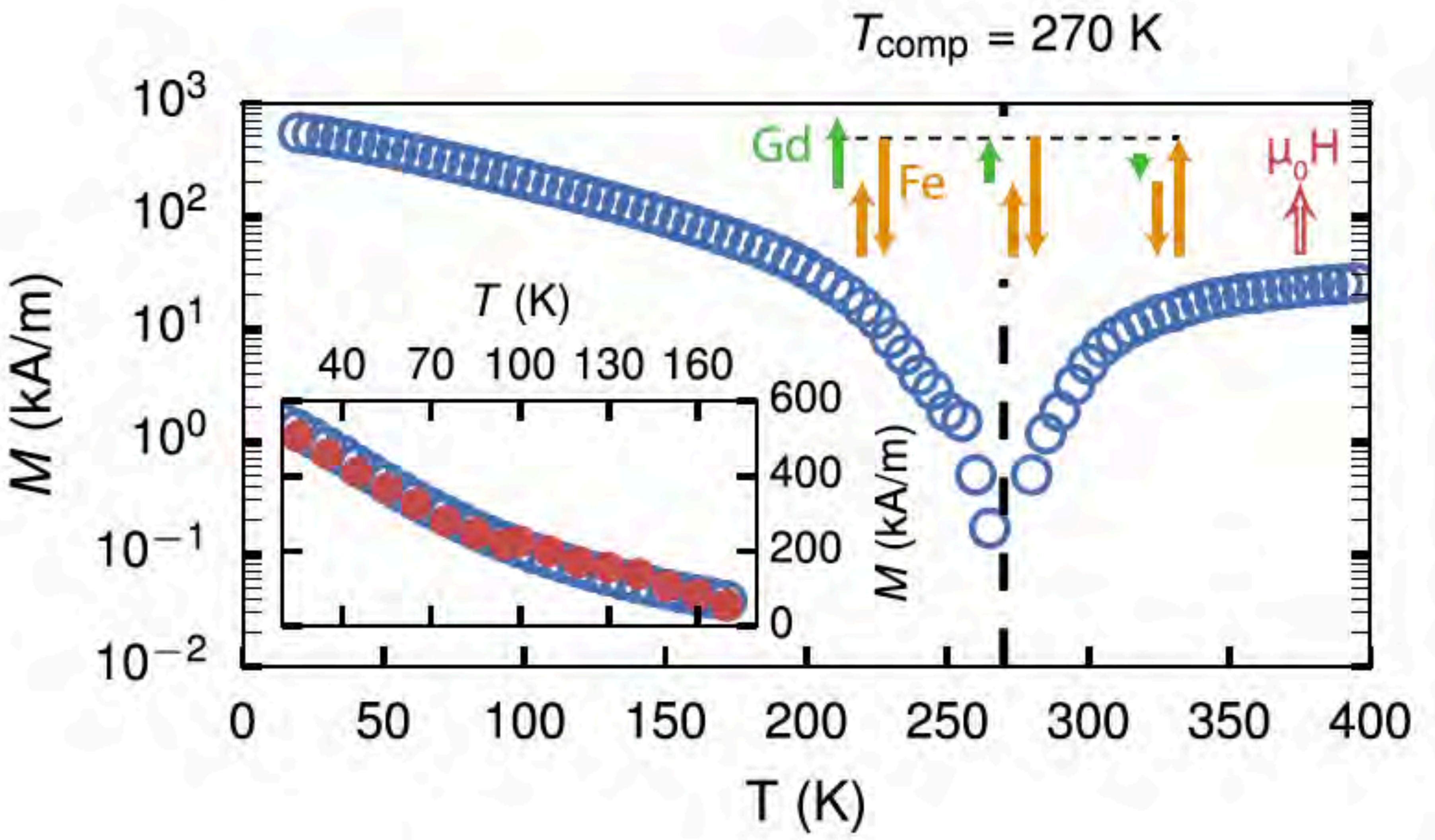






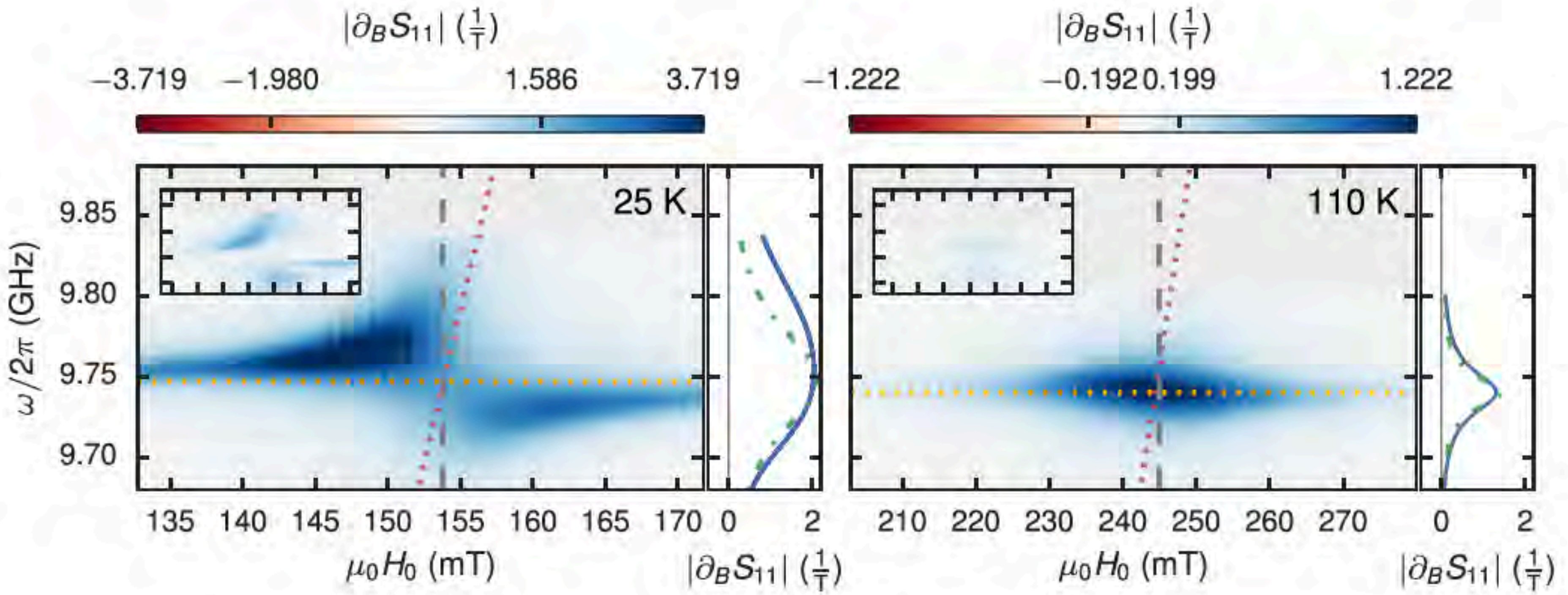
K. Ganzhorn, Masterthesis, TUM 2014
Dionne, *Magnetic Oxides* (Springer, 2009)
Janiak, *Riedel Moderne Organische Chemie* (De Gruyter, 2012)

Tunable Coupling GdIG



H. Maier-Flaig, Appl. Phys. Lett. **110**, 132401 (2017)

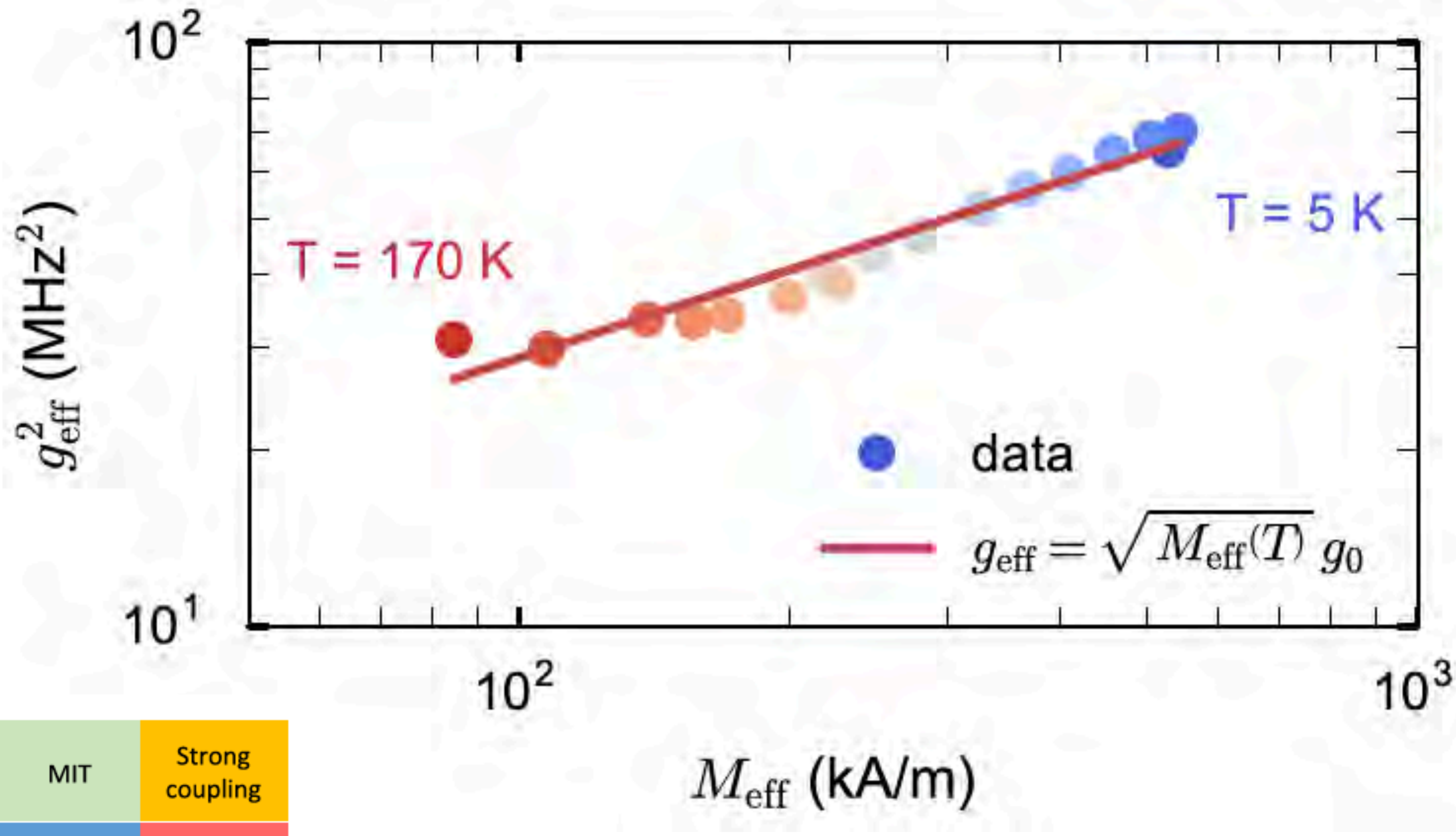
Tunable Coupling GdIG

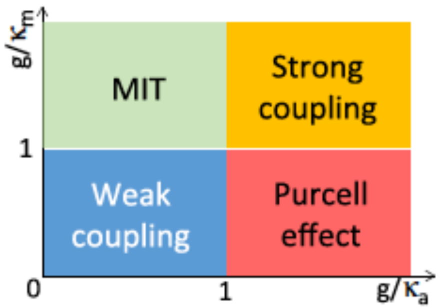


$$S_{11} = \frac{A(1-\kappa_c)}{i(\omega-\omega_c)-\kappa_c-ig_{\text{eff}}^2(\omega-\omega_{\text{FMR}}+i\gamma_s)^{-1}}$$

H. Maier-Flaig, Appl. Phys. Lett. **110**, 132401 (2017)

Tunable Coupling GdIG

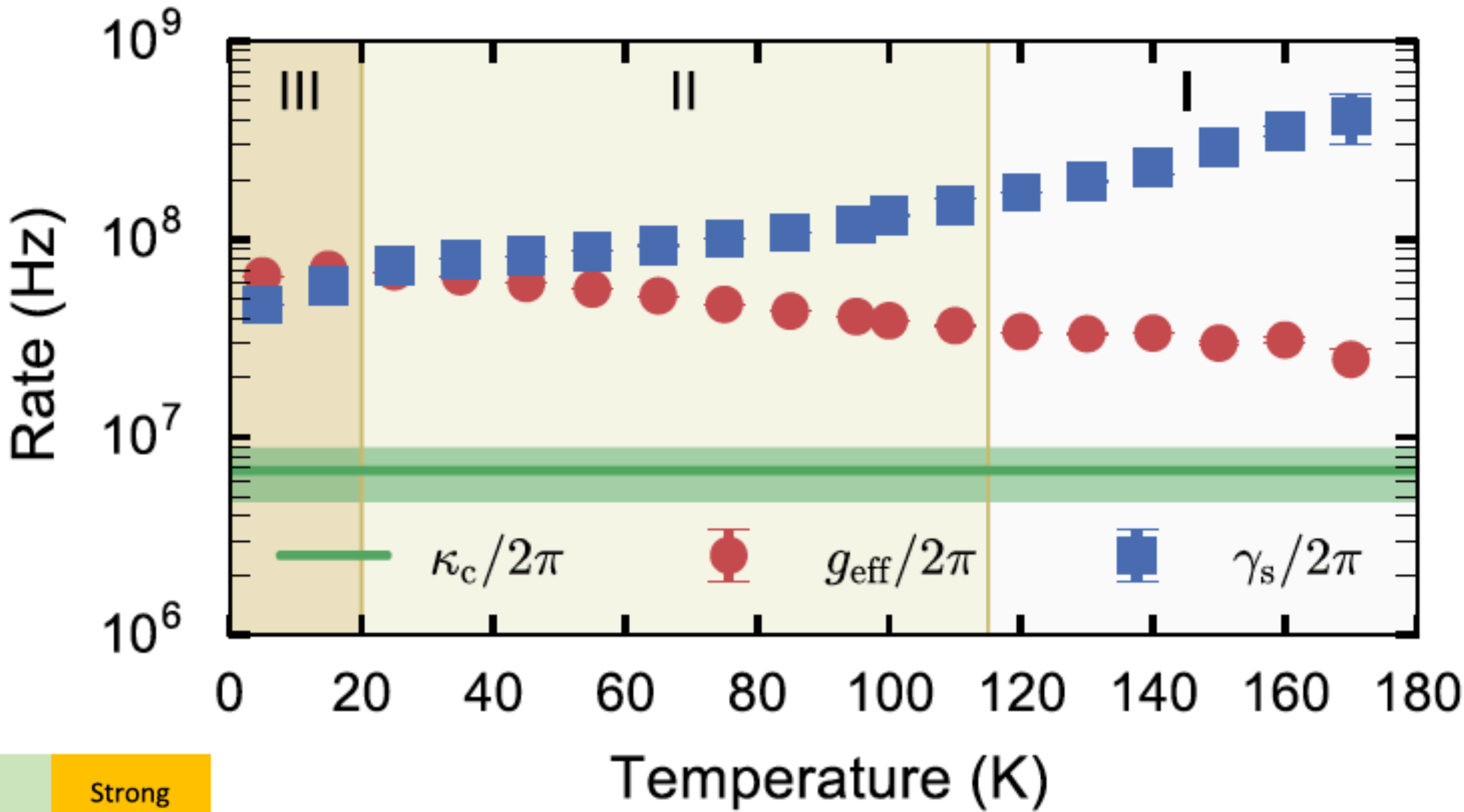


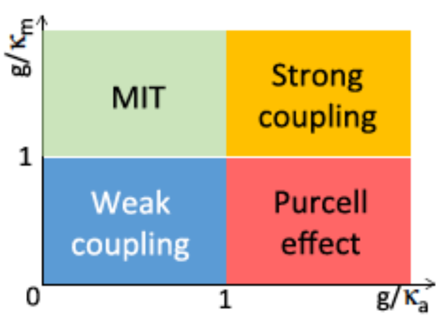


Zhang et al., PRL **113**, 156401 (2015)

H. Maier-Flaig, Appl. Phys. Lett. **110**, 132401 (2017)

Tunable Coupling GdIG





Zhang et al., PRL **113**, 156401 (2015)

H. Maier-Flaig, Appl. Phys. Lett. **110**, 132401 (2017)

Acknowledgements

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Rudolf Gross
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Mathias Weiler

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Yunshan Cao
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Eiji Saitoh
Zhiyong Qiu

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David Fanke

Kathrin Ganzhorn
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Can-Ming Hu
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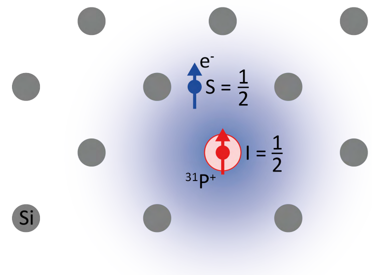
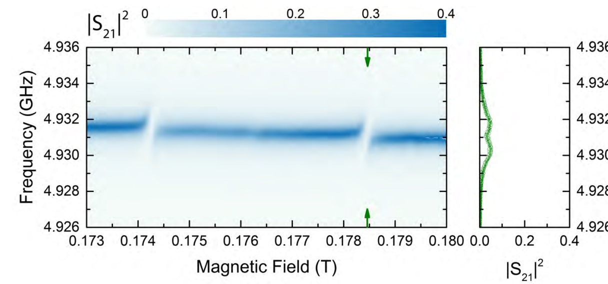
Controlling the Collective Coupling in Spin-Photon Hybrids

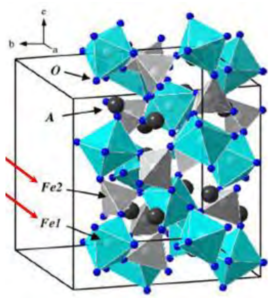
Si:P

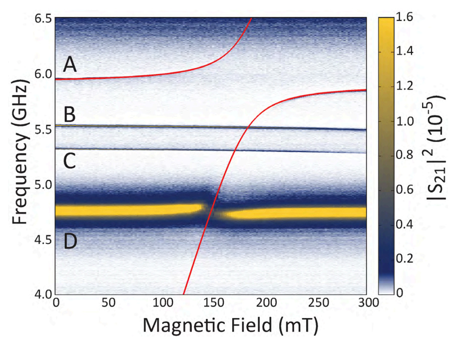
$$g_{\mathrm{eff}} \propto \sqrt{P(T)}$$

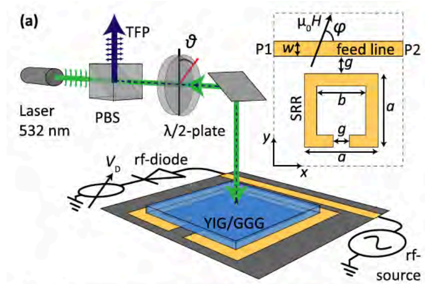


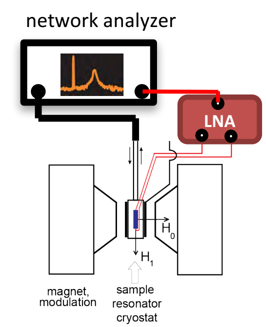


YIG









readout concepts, MW, optical, DC electrical

GdIG

$$g_{\mathrm{eff}} \propto \sqrt{M}$$