WMI

Bayerische Akademie der Wissenschaften

Technische Universität München

Spin-Photon Hybrids

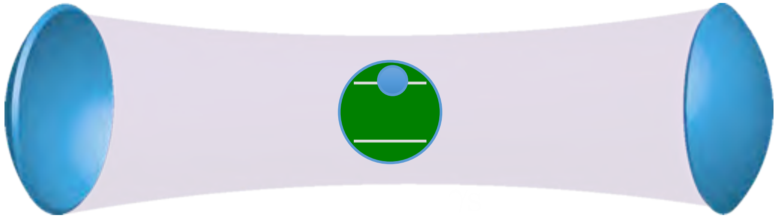
Hans Huebl

Walther-Meißner-Institut d. Bayerischen Akademie der Wissenschaften

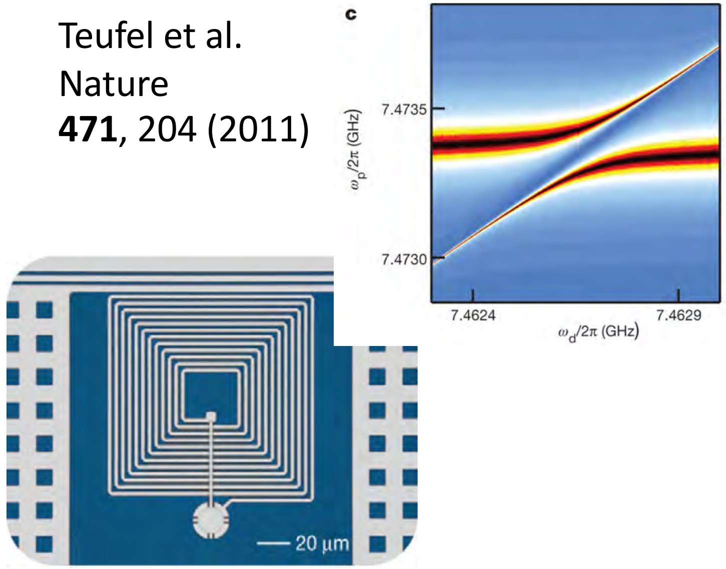
Deutsche Forschungsgemeinschaft DFG

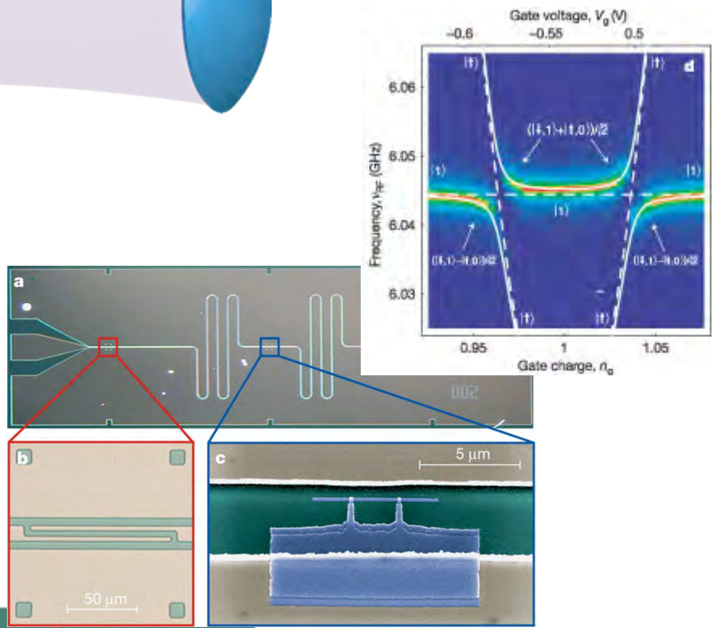
nim nanosystems initiative munich

Quantum optics with solid state systems



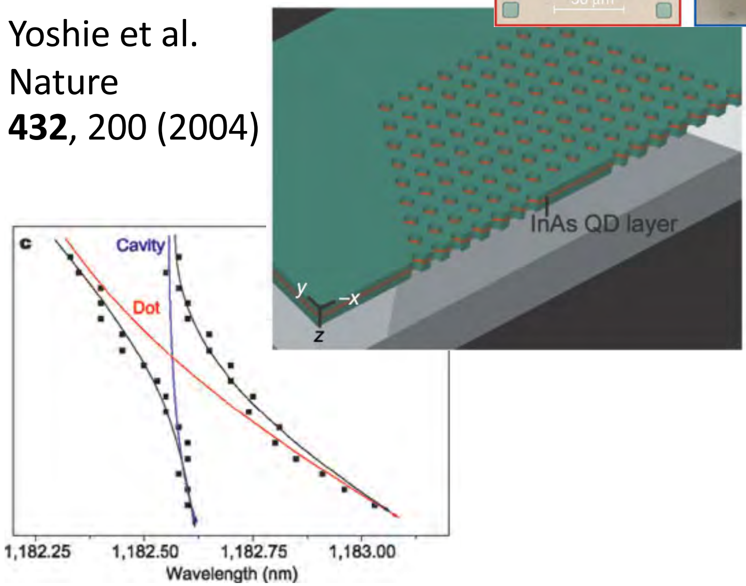
Teufel et al.
Nature
471, 204 (2011)





Wallraff et al.
Nature
431, 162 (2004)

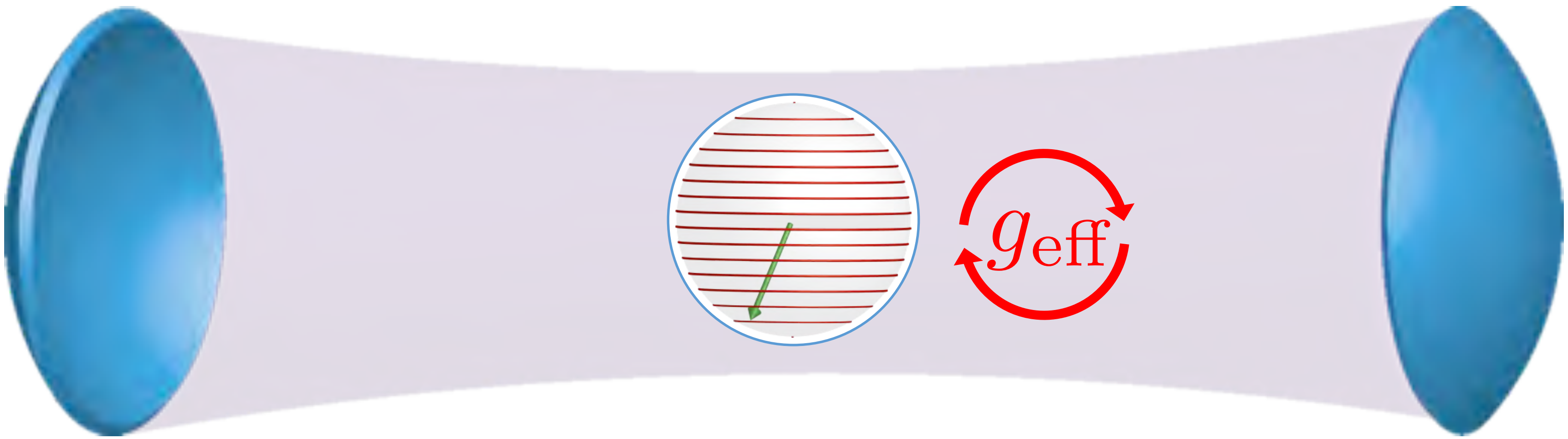
Yoshie et al.
Nature
432, 200 (2004)



Quantum optics experiments in solid state systems

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

Spins & Photons in a Box

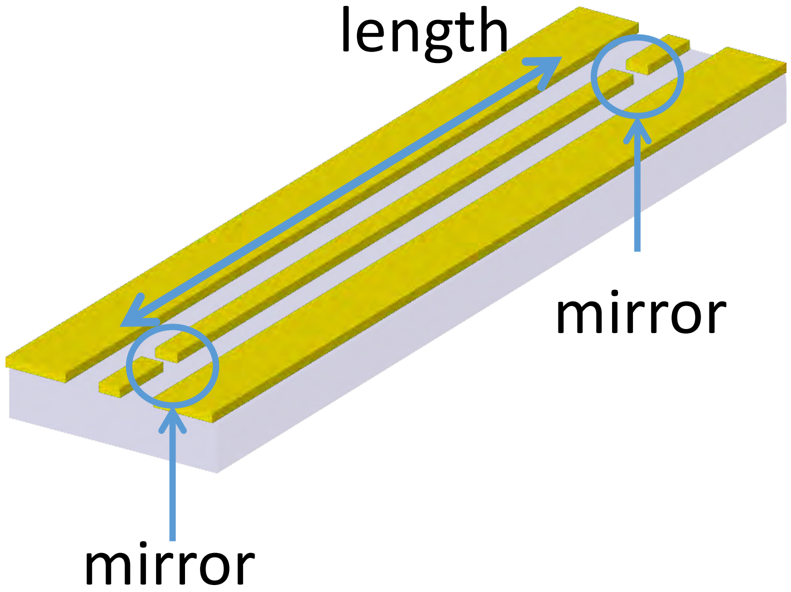


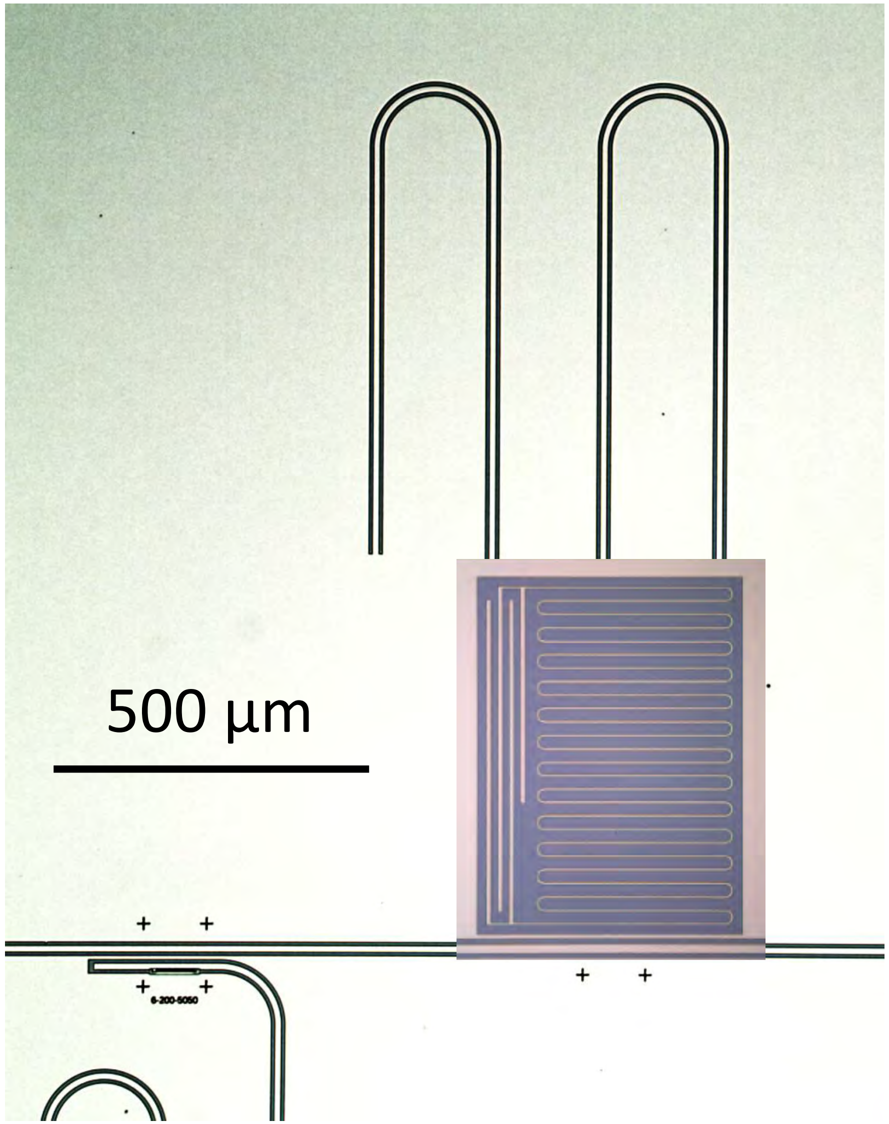
Quantum technology

- Storage and conversion of quantum signals
- Sensing

Photons in a Box

(microwave) Photons in a Box

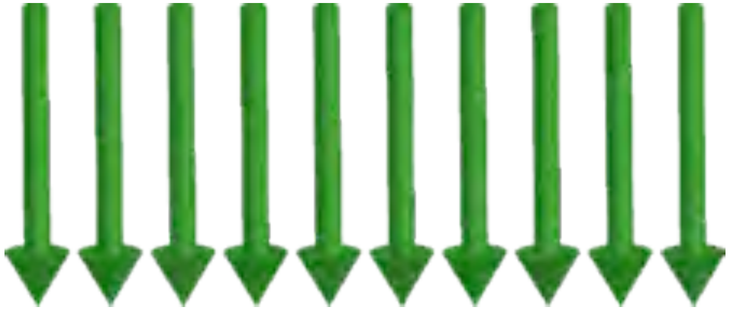


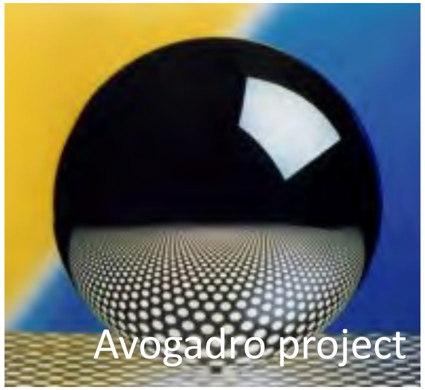


Spins in an Ensemble

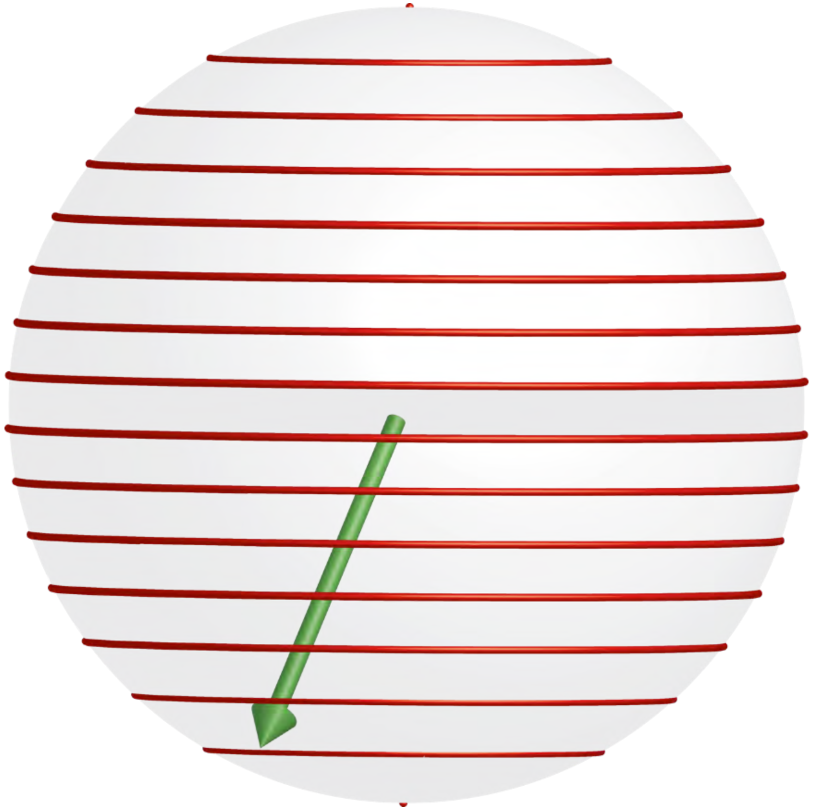
$$S = \frac{N}{2}$$

N spins





spin ensemble – Si:P & YIG

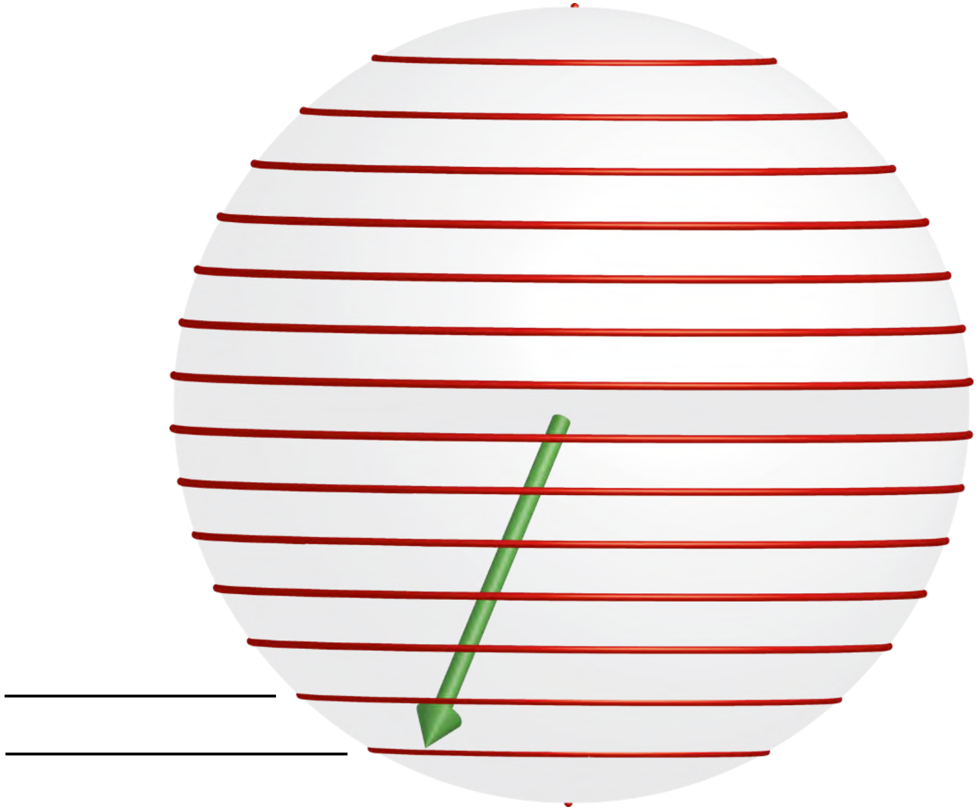


macro-spin model

Spins in an Ensemble

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

$$\Delta S_z = \pm 1$$

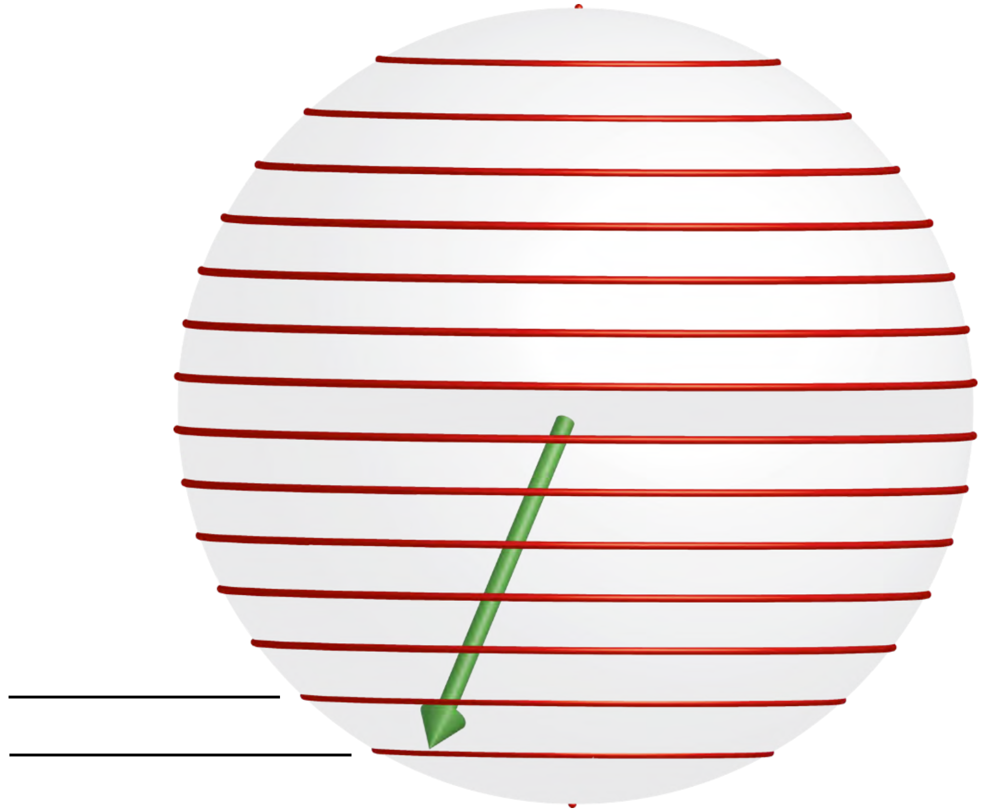


macro-spin model

Spins in an Ensemble

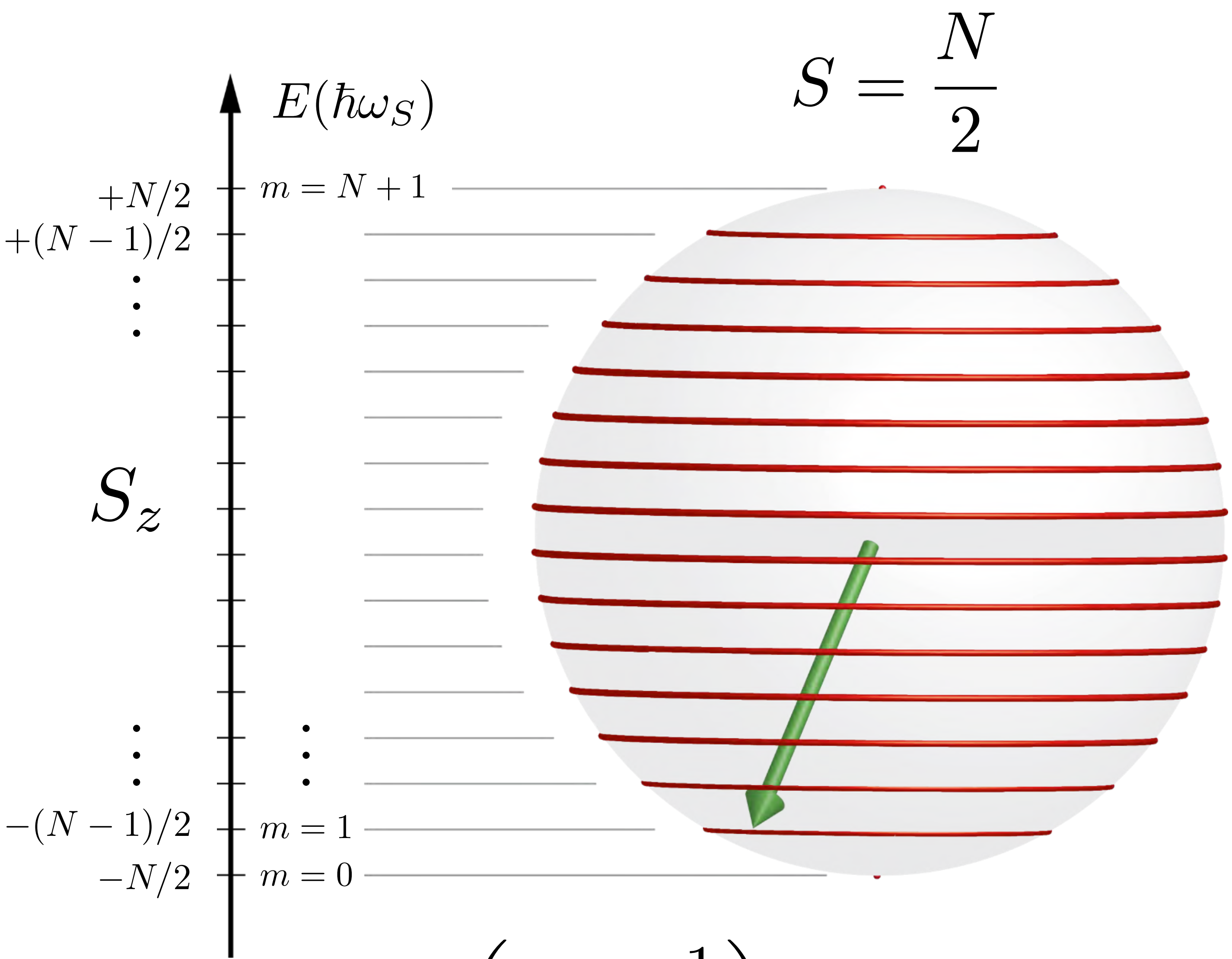
$$S = \frac{N}{2}$$

$$\Delta S_z = \pm 1$$



macro-spin model

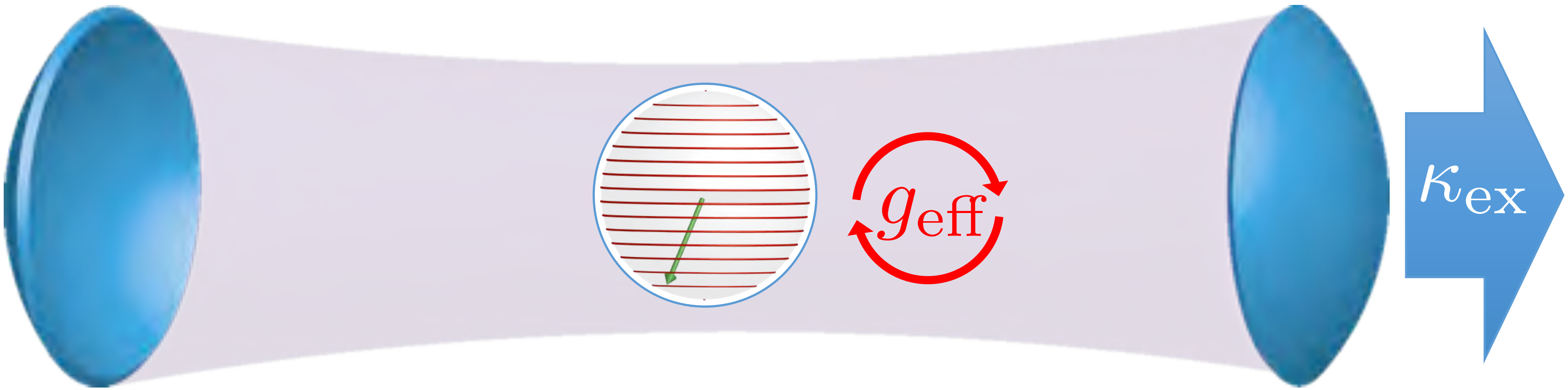
Spins in an Ensemble



low excitation numbers:

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

Spins & Photons (Tavis-Cummings)



coupling mechanism: magnetic dipole interaction

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

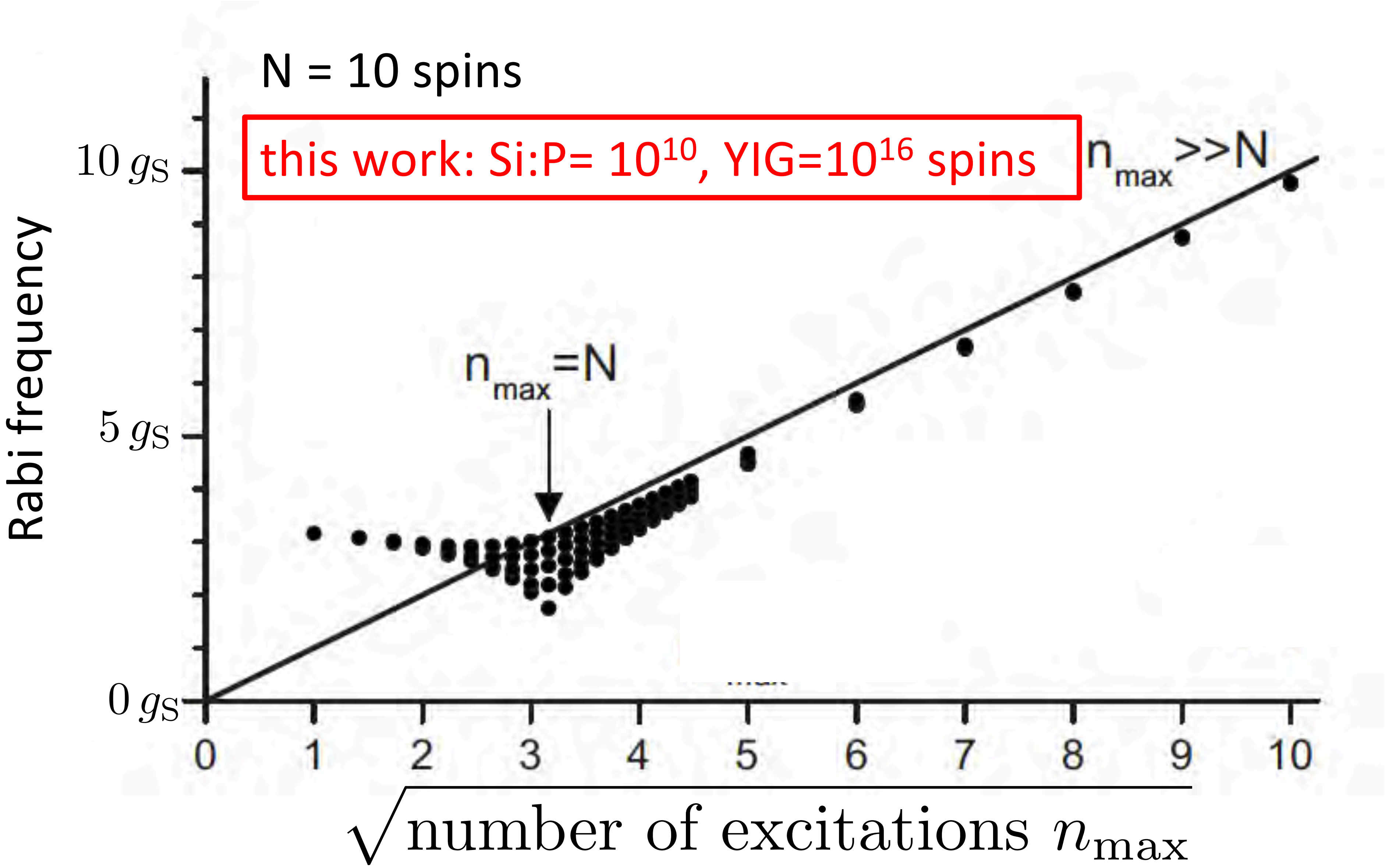
$$\hat{H} = \hbar\omega_{\mathrm{c}}\left(a^\dagger a + \frac{1}{2}\right) + \hbar\omega_{\mathrm{S}}\left(b^\dagger b + \frac{1}{2}\right) + g_{\mathrm{eff}}\left(ab^\dagger + ba^\dagger\right)$$

low excitation: $g_{\mathrm{eff}} \approx g_{\mathrm{S}}\sqrt{N}$

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

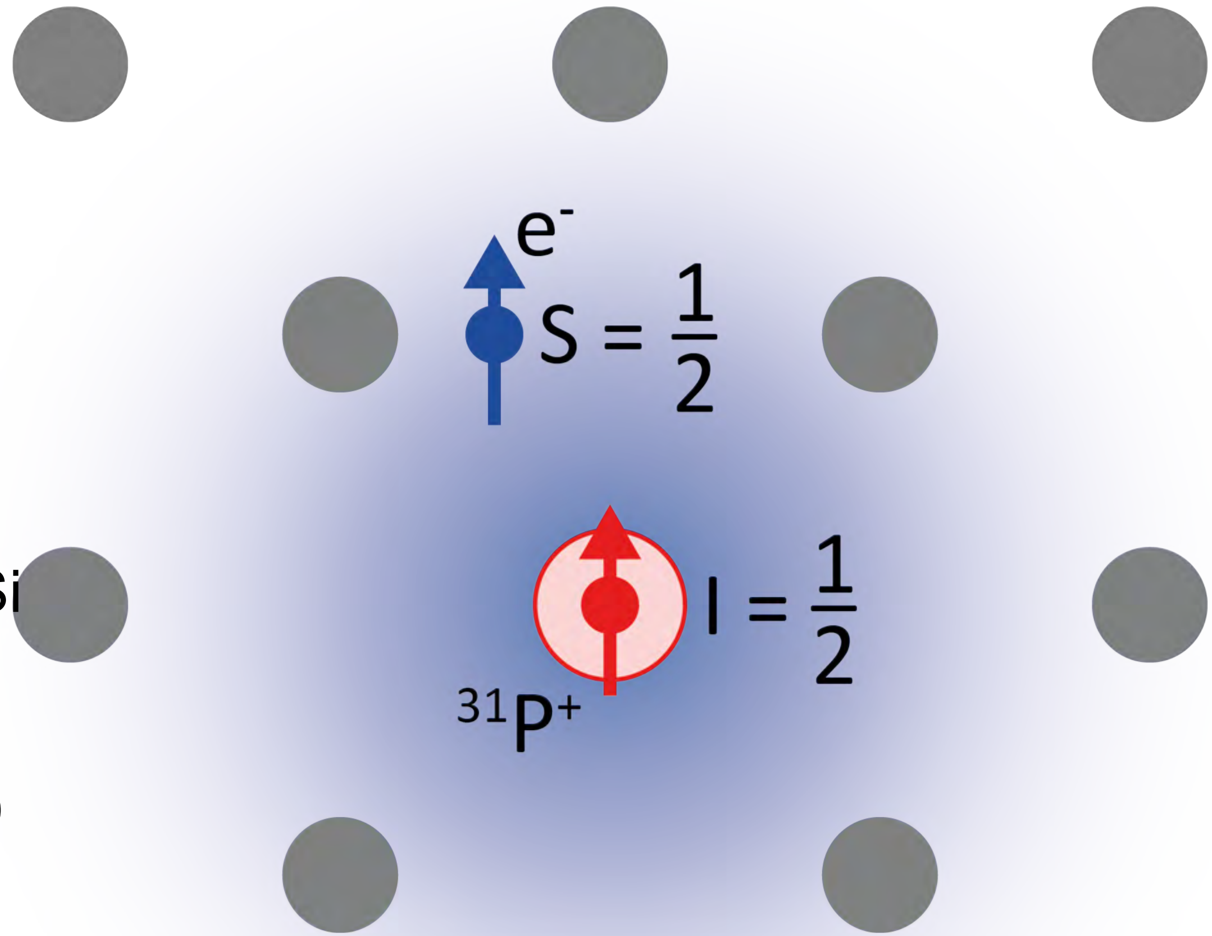
Chiorescu et al., PRB **82**, 024413 (2010)

Rabi frequencies



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

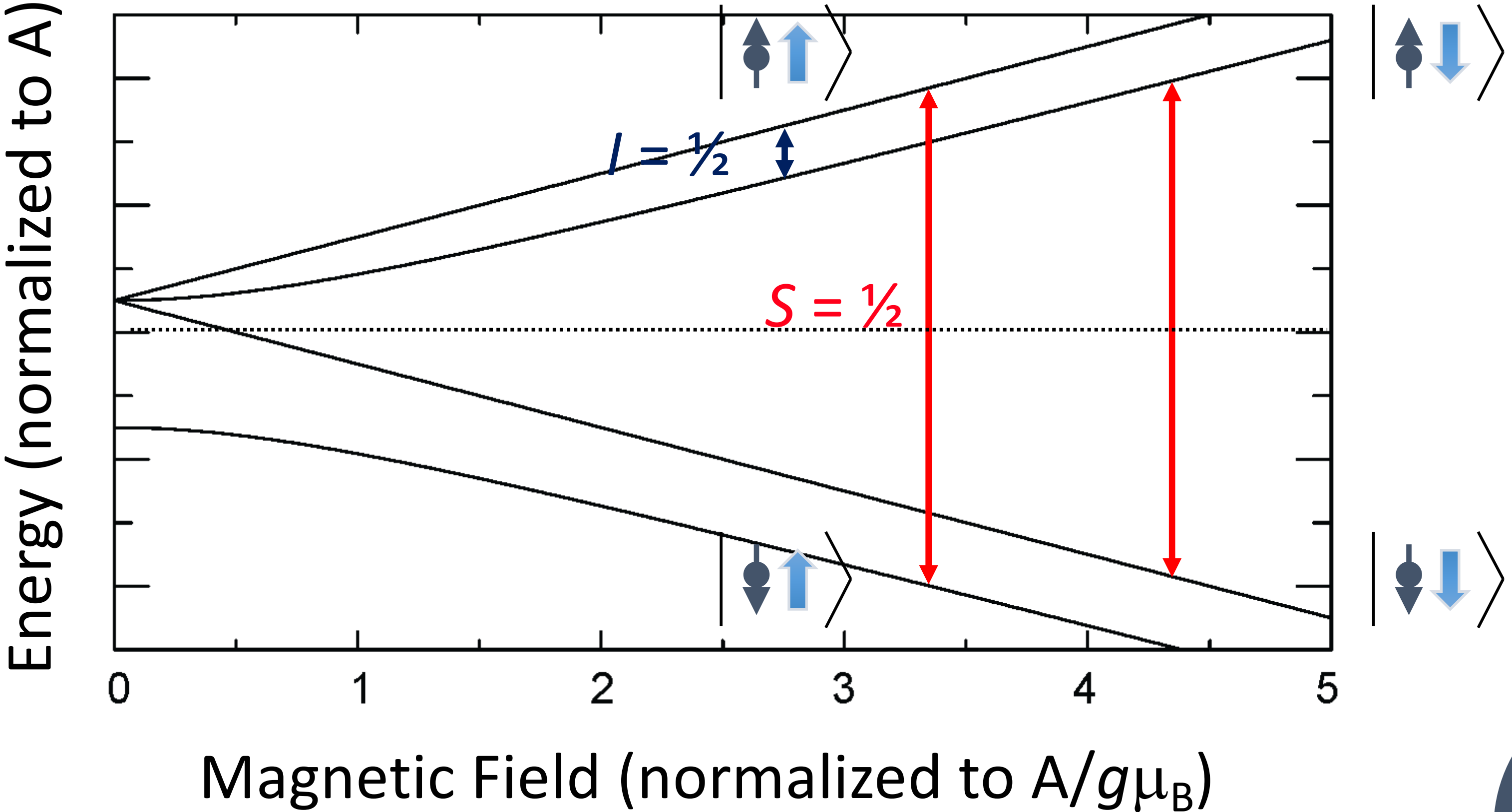
Paramagnetic Spin Ensemble: Phosphorus Donors in Silicon



- 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

A. Tyryshkin et al., Nat. Mat. **11**, 143 (2012),
M. Steger et al. Science **336**, 1280 (2012),
K. Saeedi et al., Science **342**, 830 (2013),
G. Feher et al., *Phys. Rev.* **100,** 1784–1786 (1955).

Magnetic level scheme of ^{31}P in silicon

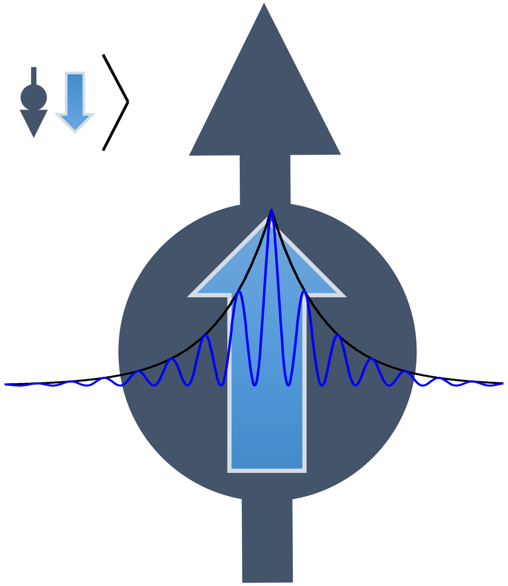


Spin- Hamiltonian:

$$\mathbf{H} = g\,\mu_B\,B\,S + A\,S\,I$$

Zeeman interaction

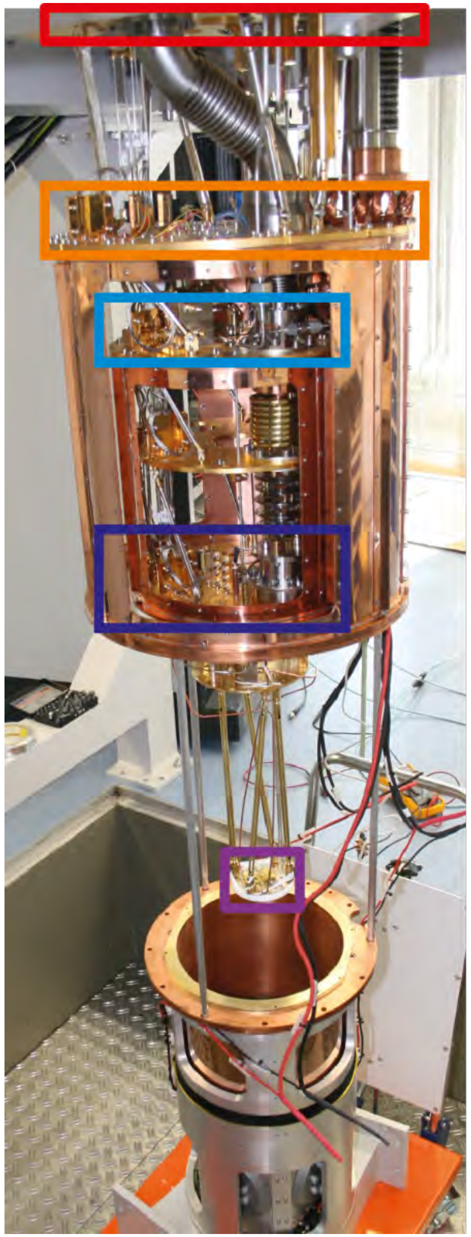
Hyperfine interaction nuclear spin I=1/2

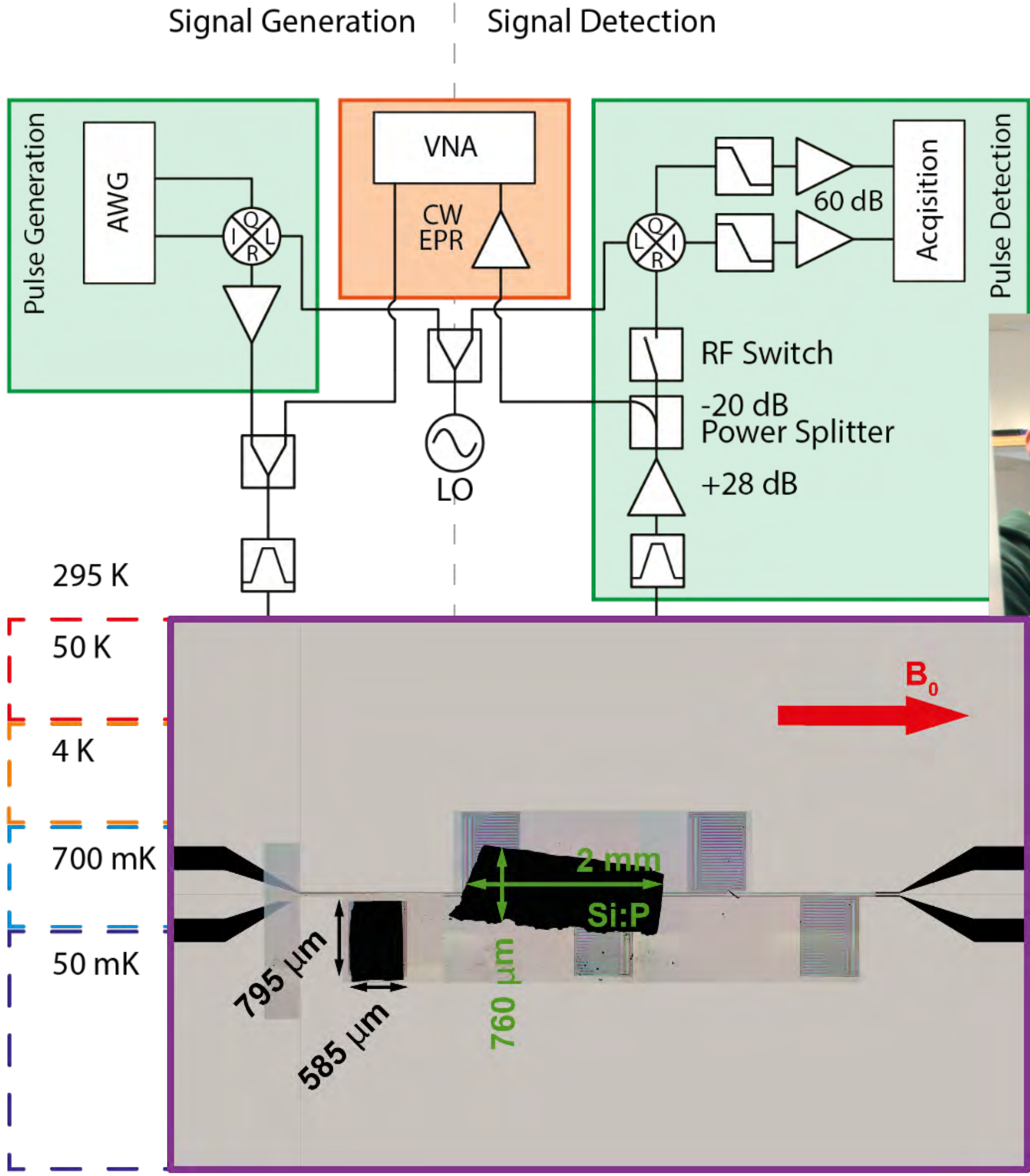


A = 4.2 mT = 484 neV

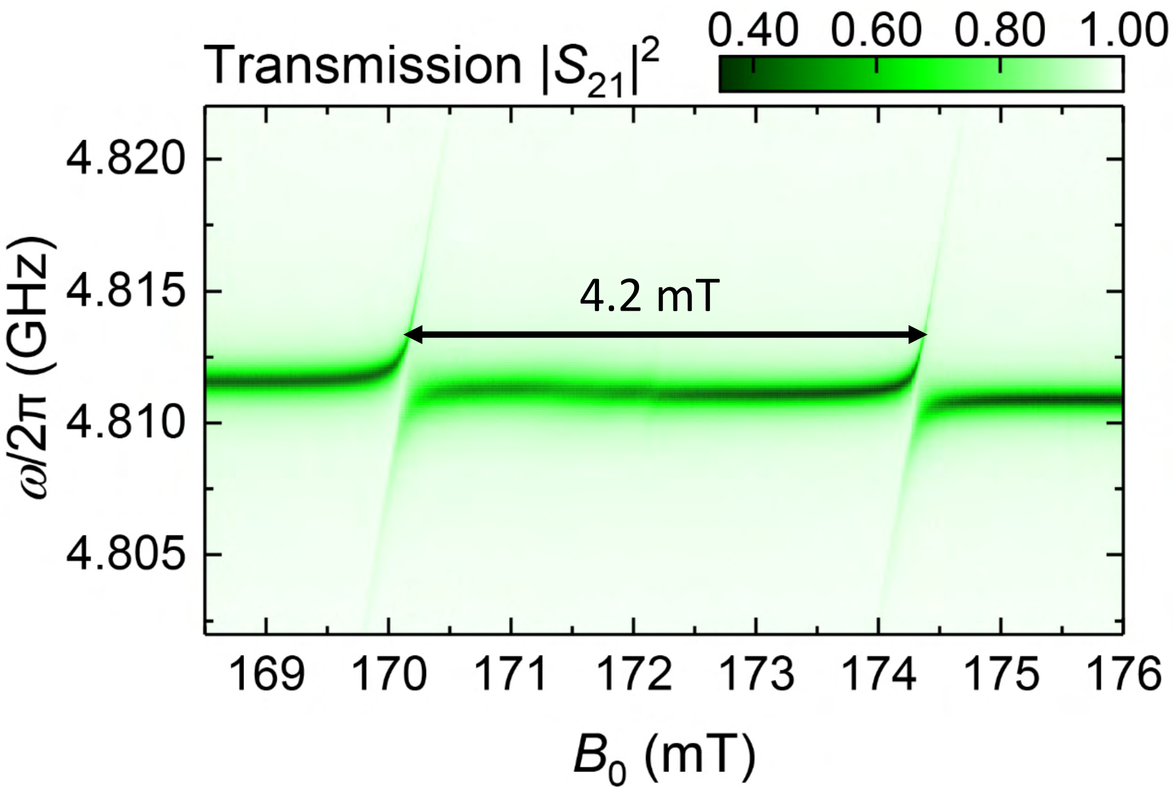
$\propto |\Psi(\vec{r}=0)|^2$

Setup




Signal Generation
Signal Detection
Pulse Generation
AWG
VNA
CW
EPR
LO
Acqisition
60 dB
Pulse Detection
RF Switch
-20 dB
Power Splitter
+28 dB
295 K
50 K
4 K
700 mK
50 mK
B0
2 mm
Si:P
795 µm
585 µm
760 µm

^{31}P in Si: the Strong Coupling Regime

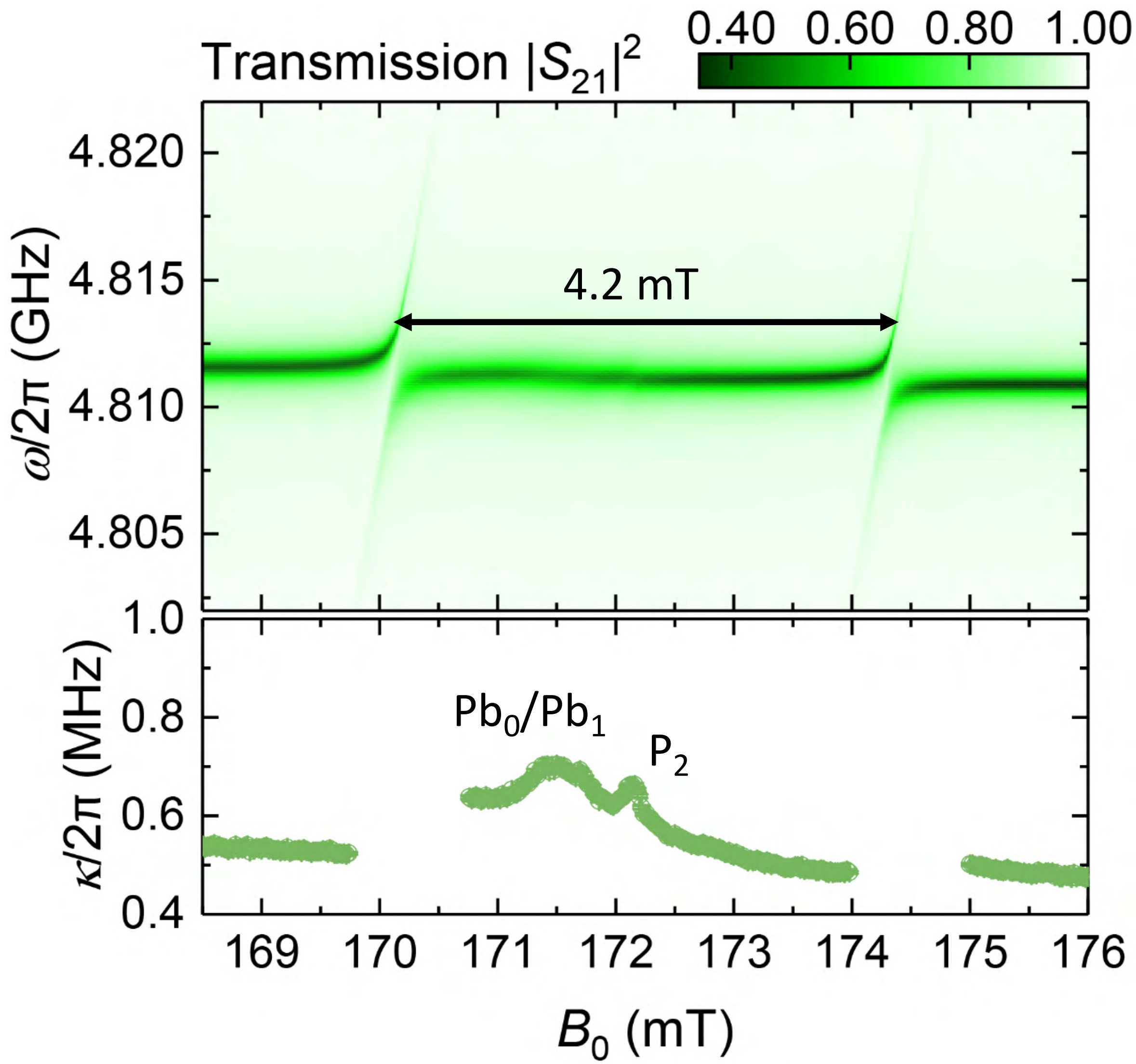


- **P-donor low field transition:**
  - $\kappa = 0.53\ \mathrm{MHz}$
  - $\gamma_s = 0.38\ \mathrm{MHz}$
  - $g_{\mathrm{eff}} = 1.60\ \mathrm{MHz}$

$$\rightarrow C = \frac{g_{\mathrm{eff}}^2}{\kappa\gamma_s} \approx 13$$

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

^{31}P in Si: the Strong Coupling Regime



- **P-donor low field transition:**
  - $\kappa = 0.53$ MHz
  - $\gamma_s = 0.38$ MHz
  - $g_{\text{eff}} = 1.60$ MHz

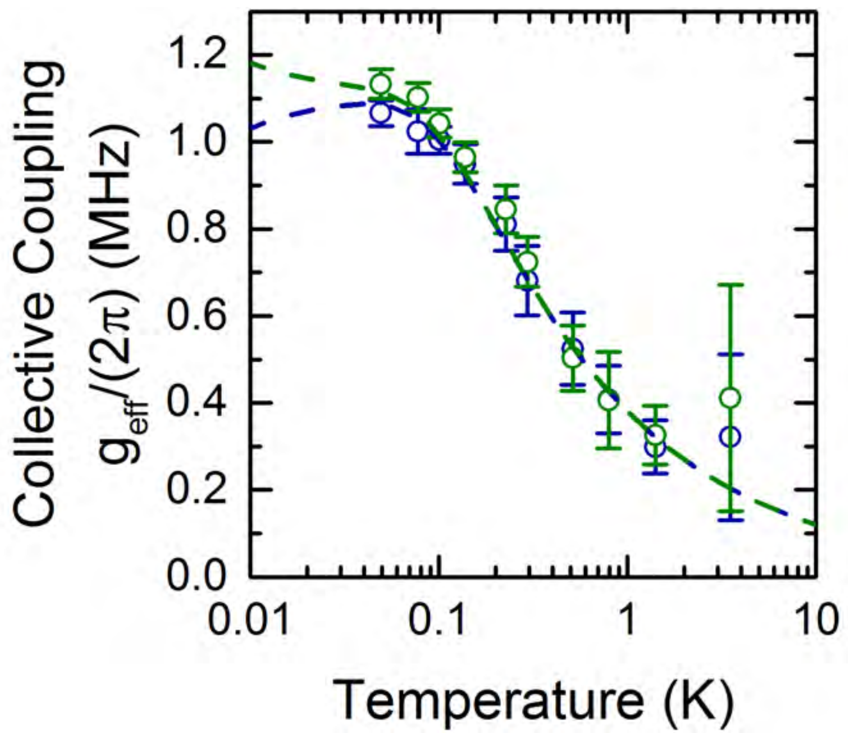
$$\rightarrow C = \frac{g_{\text{eff}}^2}{\kappa\gamma_s} \approx 13$$

- **P_2 dimer transition:**
  - $\kappa = 0.53$ MHz
  - $\gamma_s = 2.82$ MHz
  - $g_{\text{eff}} = 0.49$ MHz

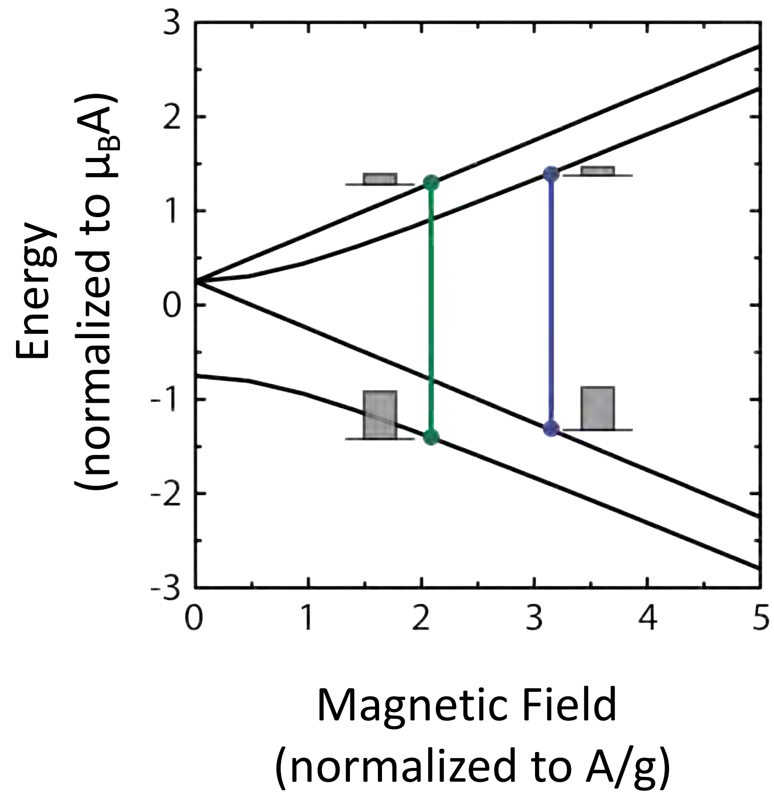
$$\rightarrow C = \frac{g_{\text{eff}}^2}{\kappa\gamma_s} \approx 0.16$$

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

Collective Coupling



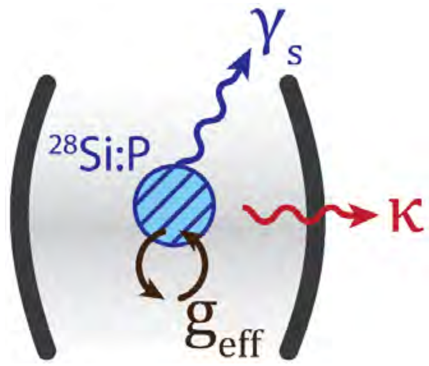
Breit Rabi diagram

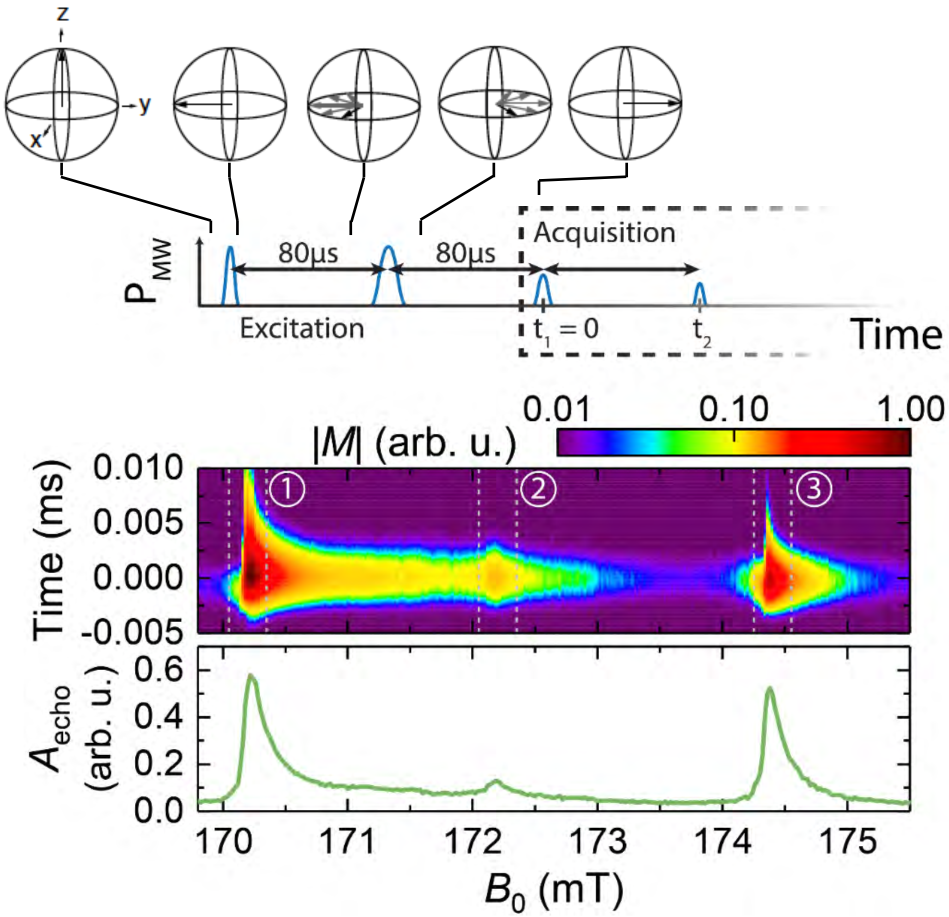


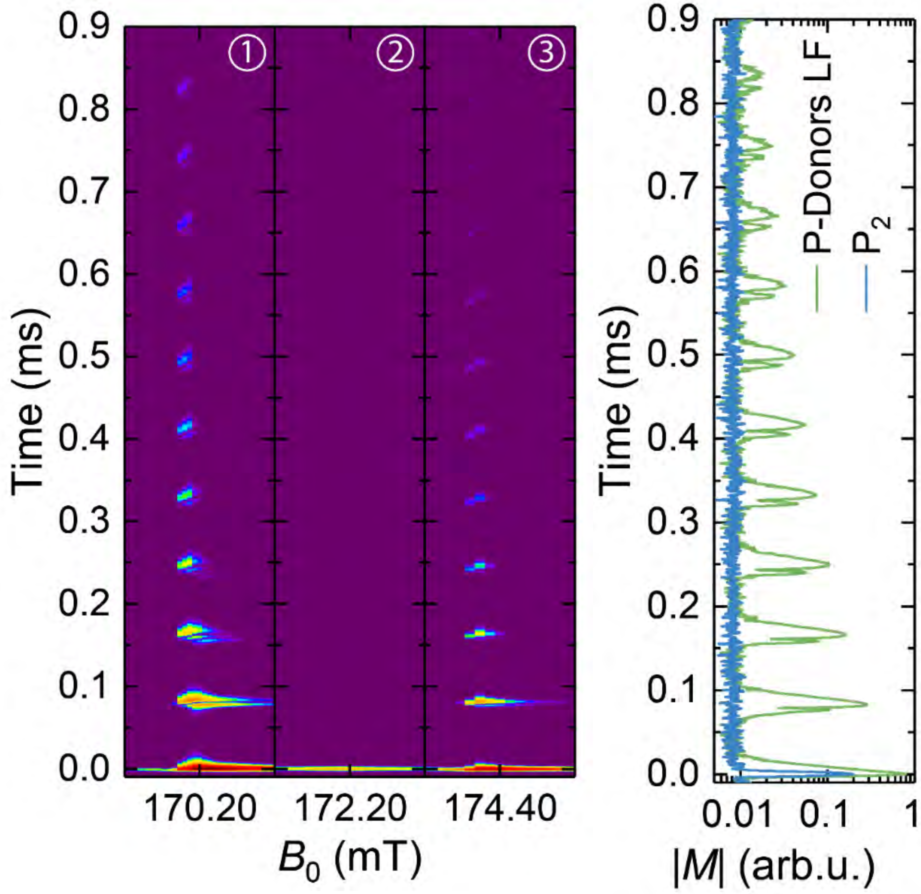
$$g_{\mathrm{eff}} \approx g_S \sqrt{N(T)} = g_S \sqrt{N_0 P(T)}$$

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

Spin Echos in the Strong Coupling Regime

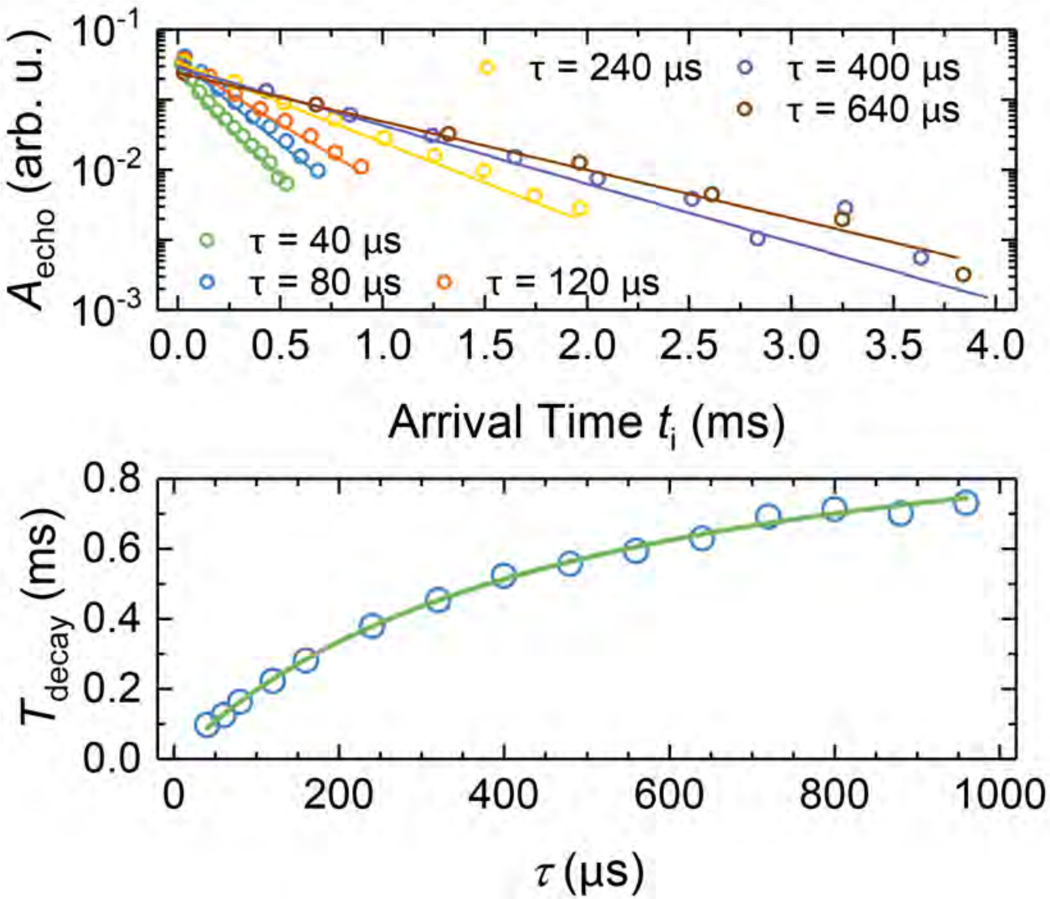


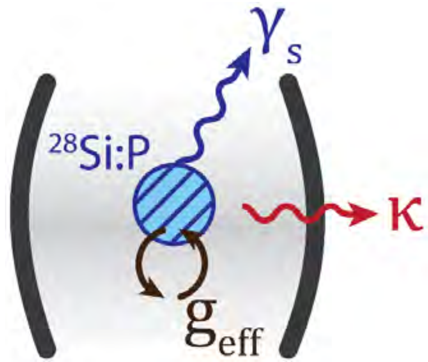




Weichselbaumer (in preparation)

τ-dependent Decay Time



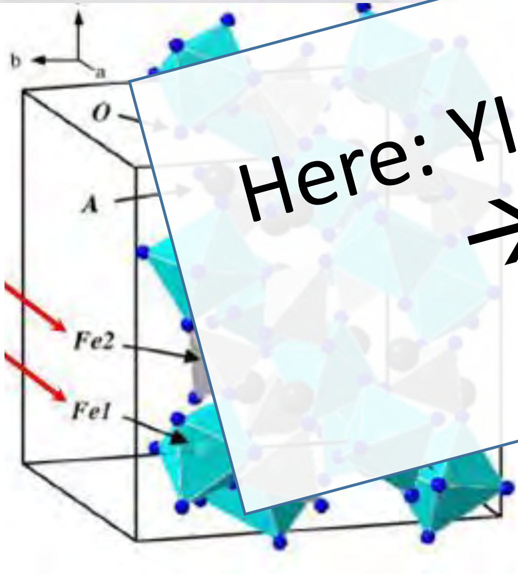


- Two decay channels:
  - T_2 relaxation
  - Loss via resonator (depends on τ, κ, γ)
- Matthiesen Rule:

$$\frac{1}{T_{\mathrm{decay}}} = \frac{2}{T_2} + \frac{\kappa}{\kappa + \gamma}\frac{1}{\tau}$$

Weichselbaumer (in preparation)

Ingredients: (pure) yttrium iron garnet



Here: YIG:Ga

→ linewidth: 28 MHz

Rachford, et al. JAP **87**, 6253

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

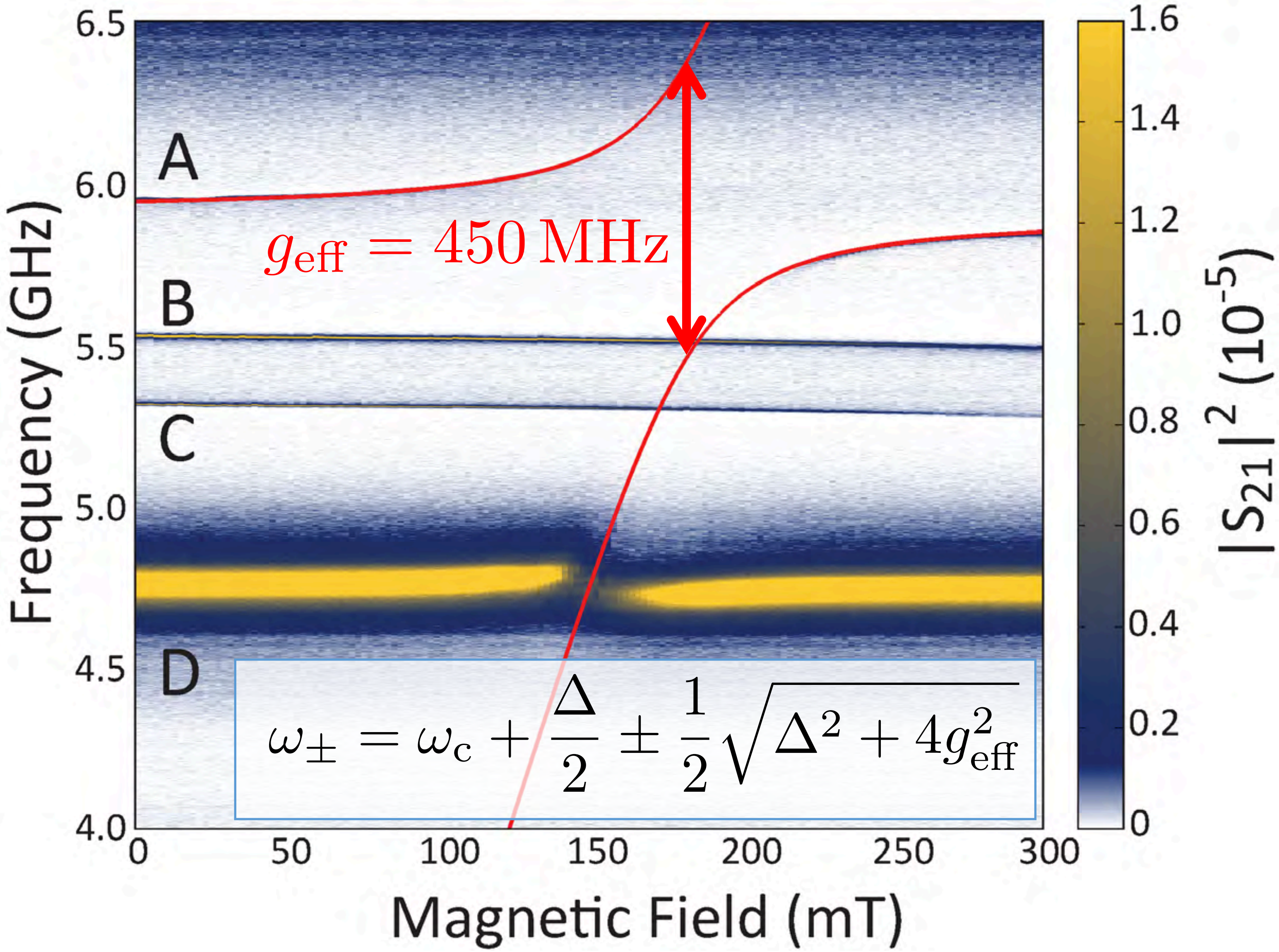
electrical/optical properties:

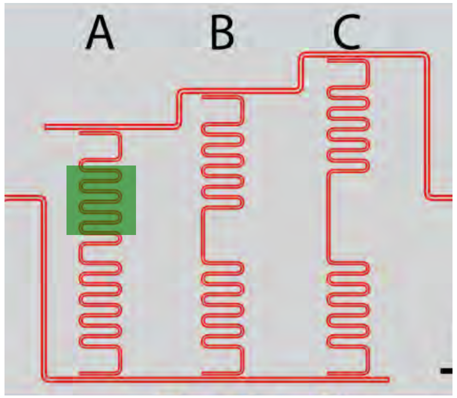
$\sigma = 10^{-11}\ \Omega cm^{-1}$ (at RT)

Bandgap 2.8 eV

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

Transmission spectrum





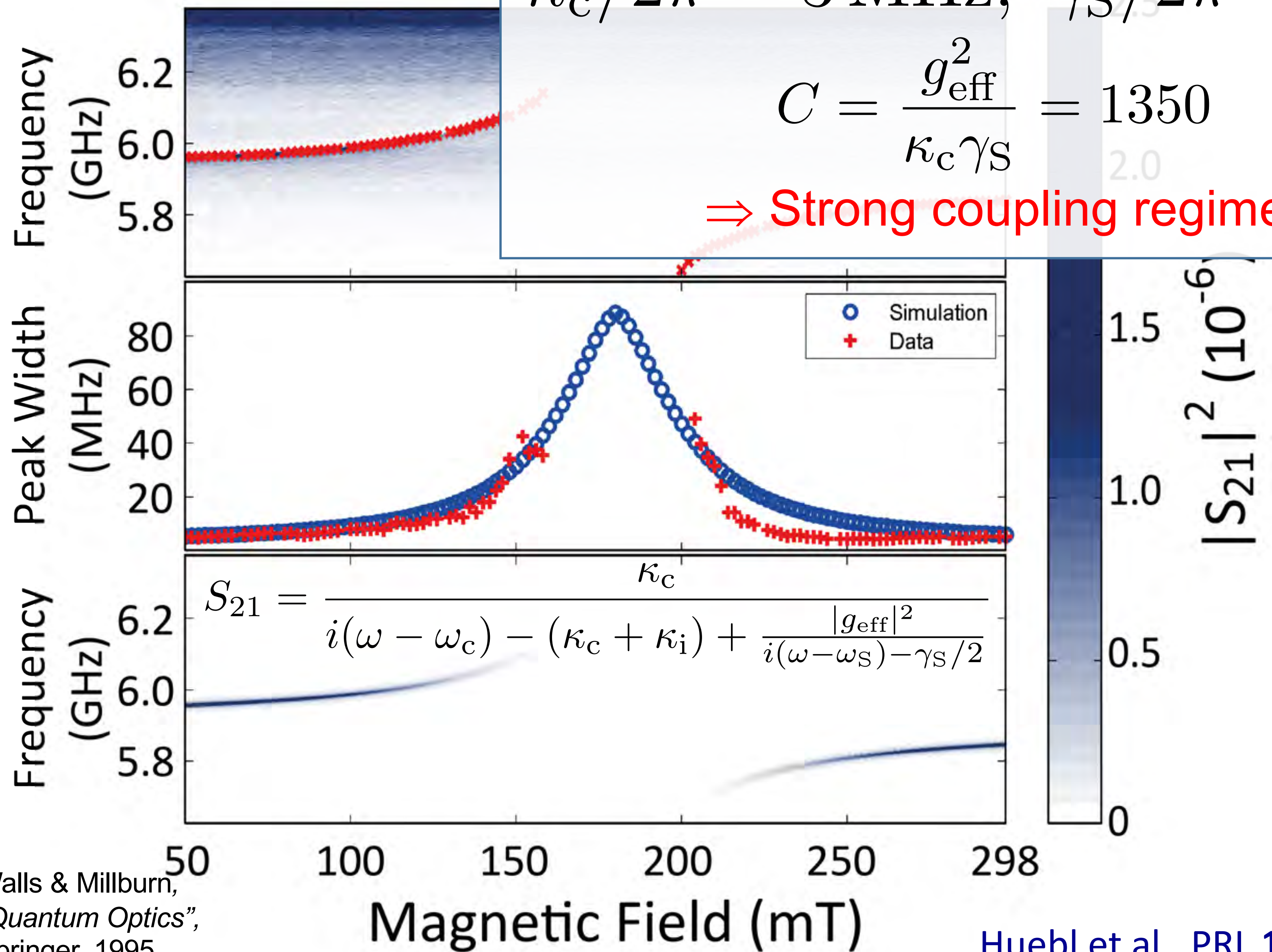
Huebl et al., Phys. Rev. Lett. **111**, 127003 (2013)

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

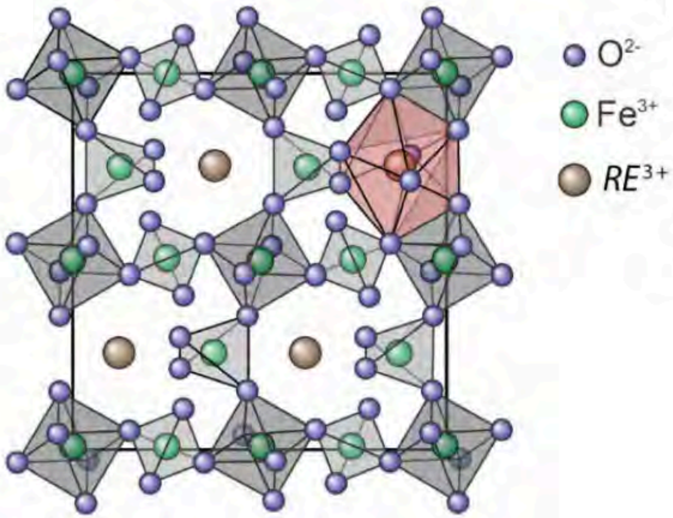


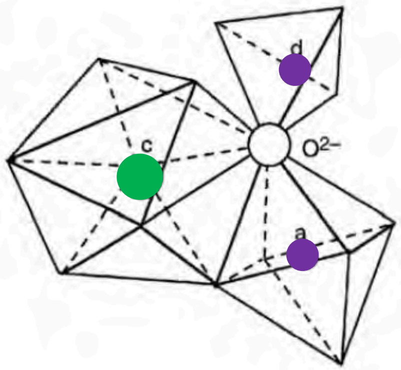
$$S_{21} = \frac{\kappa_c}{i(\omega - \omega_c) - (\kappa_c + \kappa_i) + \frac{|g_{\mathrm{eff}}|^2}{i(\omega - \omega_S) - \gamma_S/2}}$$

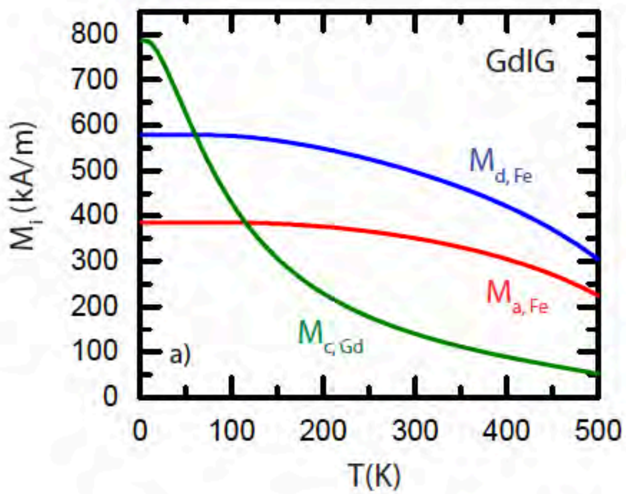
Walls & Millburn, *"Quantum Optics"*, Springer, 1995

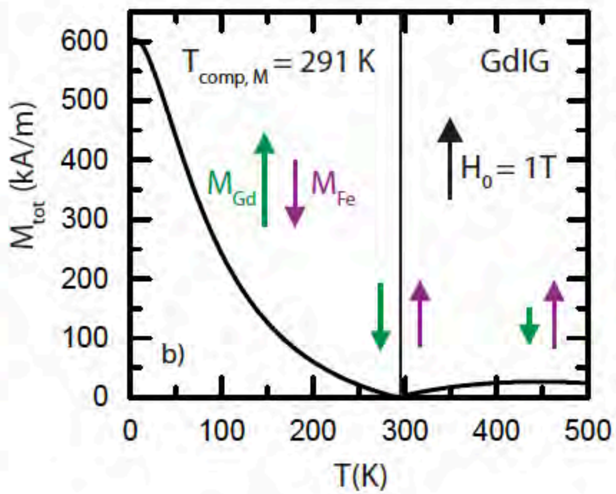
Huebl et al., PRL **111**, 127003 (2013)

Tunable Coupling GdIG







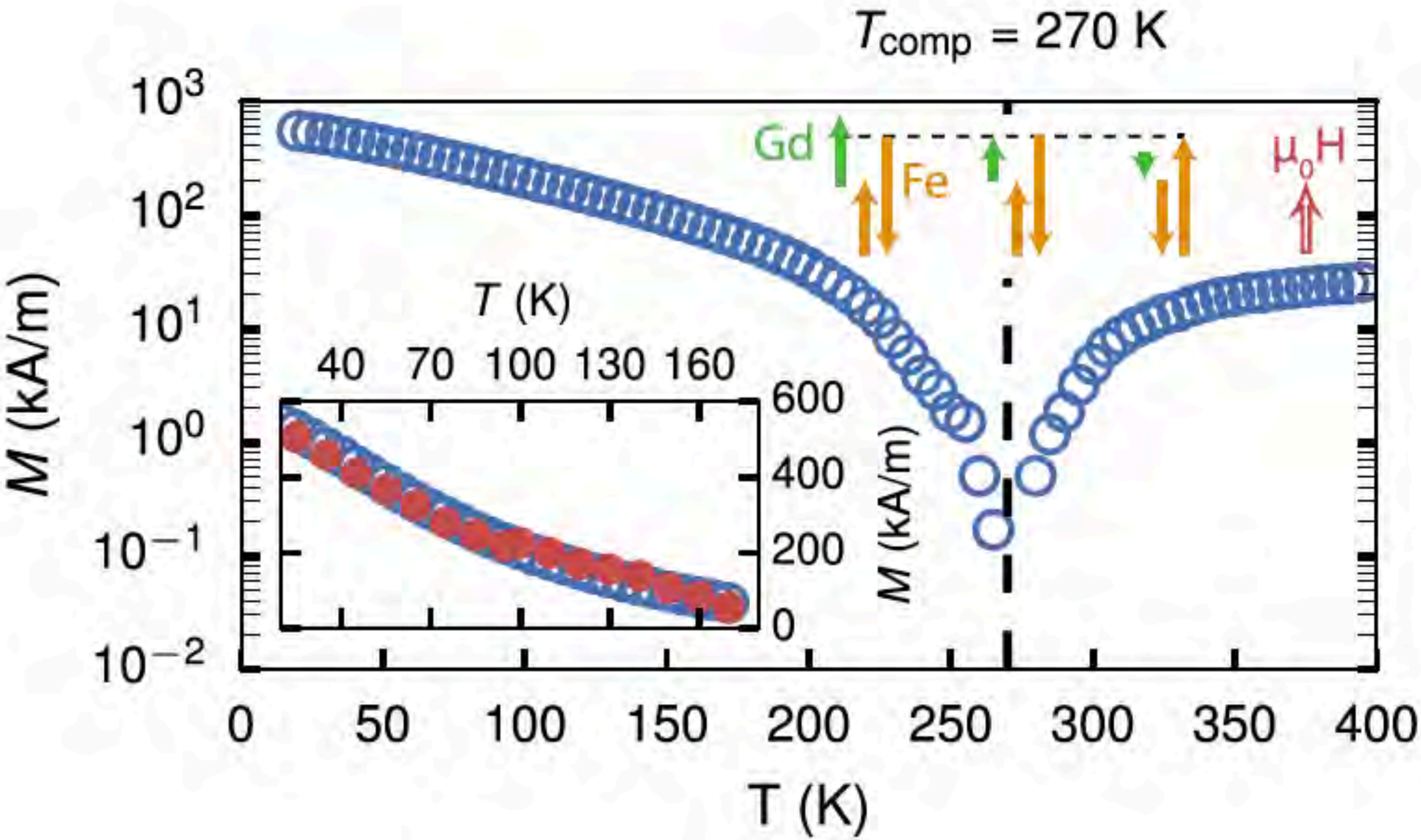


K. Ganzhorn, Masterthesis, TUM 2014

Dionne, *Magnetic Oxides* (Springer, 2009)

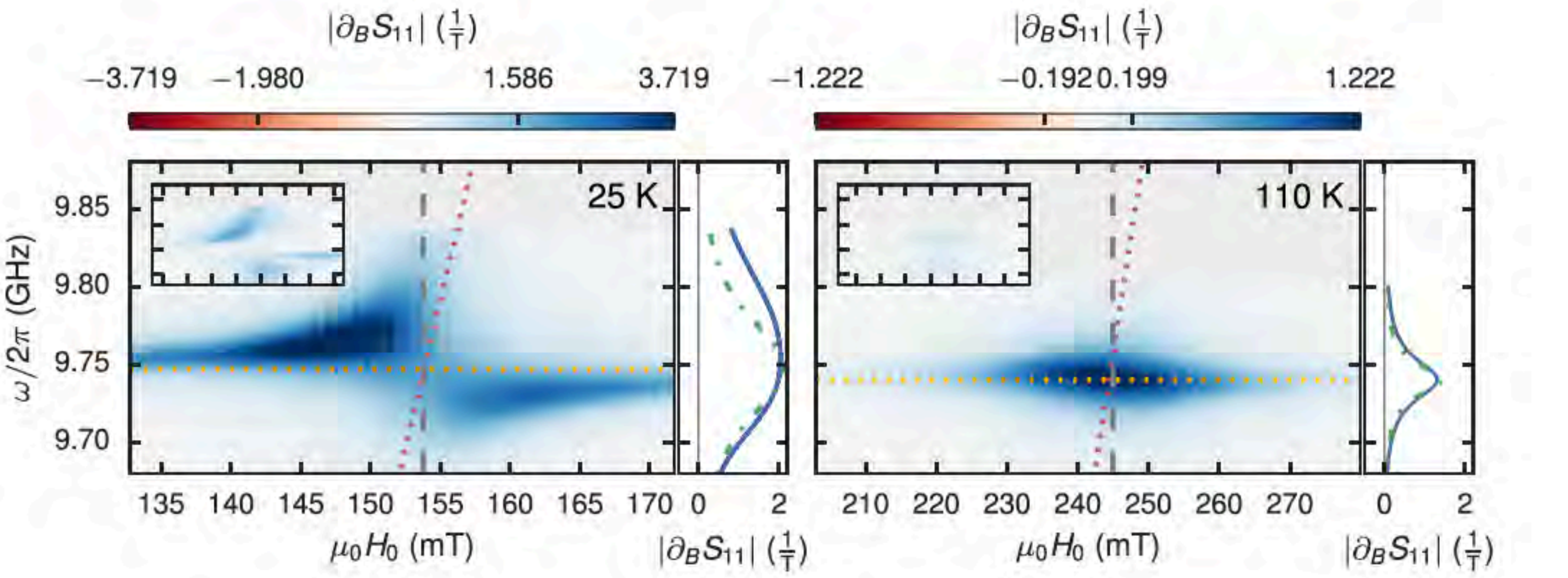
Janiak, *Riedel Moderne Organische Chemie* (De Gruyter, 2012)

Tunable Coupling GdIG



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

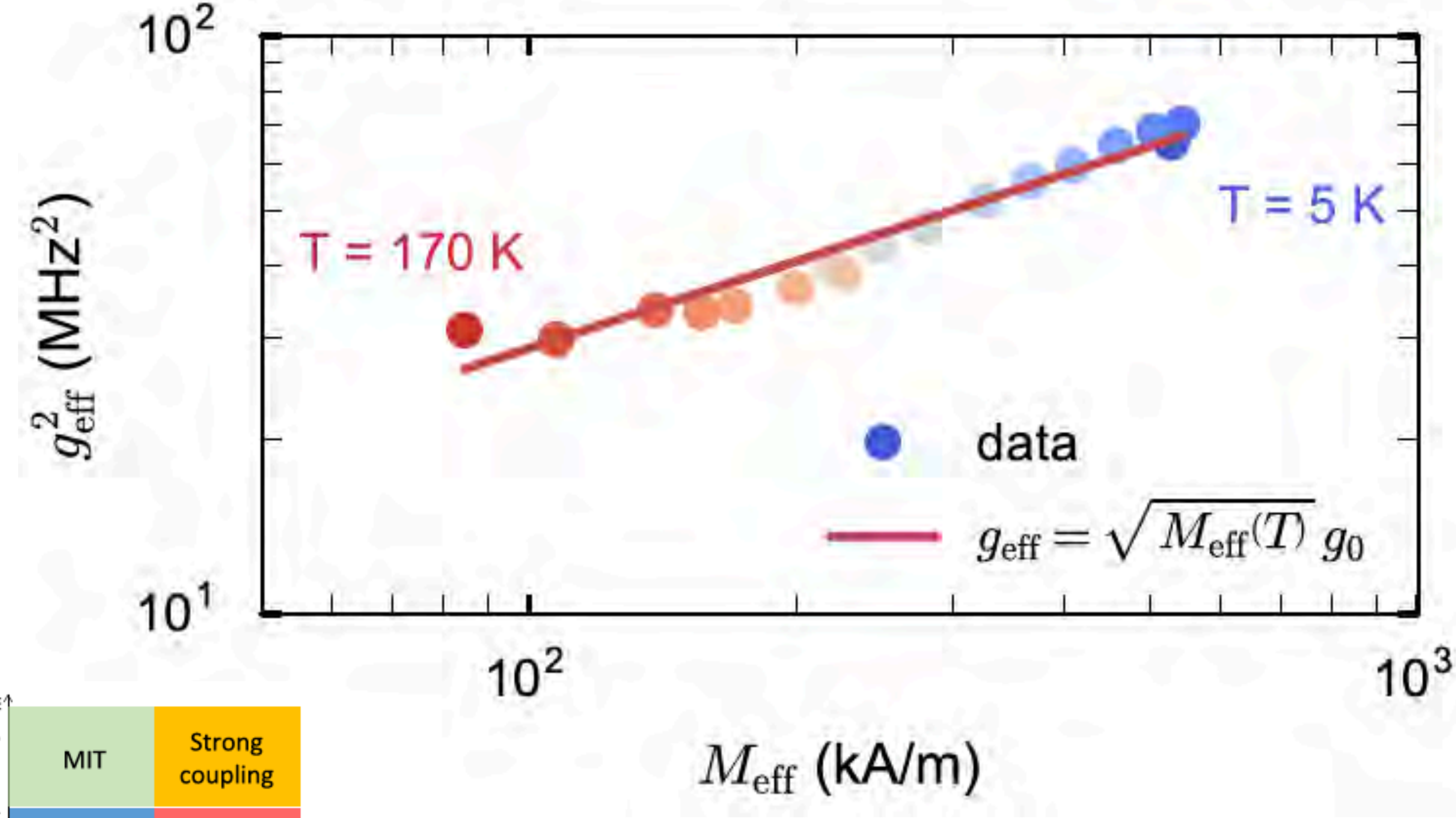
Tunable Coupling GdIG

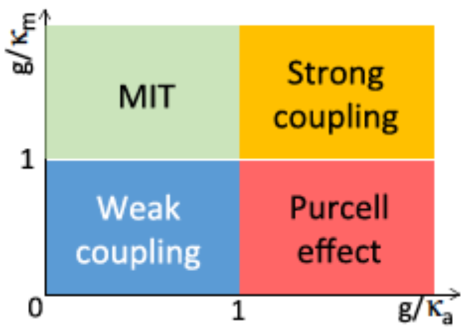


$$S_{11} = \frac{A(1-\kappa_c)}{i(\omega-\omega_c)-\kappa_c-ig_{\text{eff}}^2(\omega-\omega_{\text{FMR}}+i\gamma_s)^{-1}}$$

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

Tunable Coupling GdIG

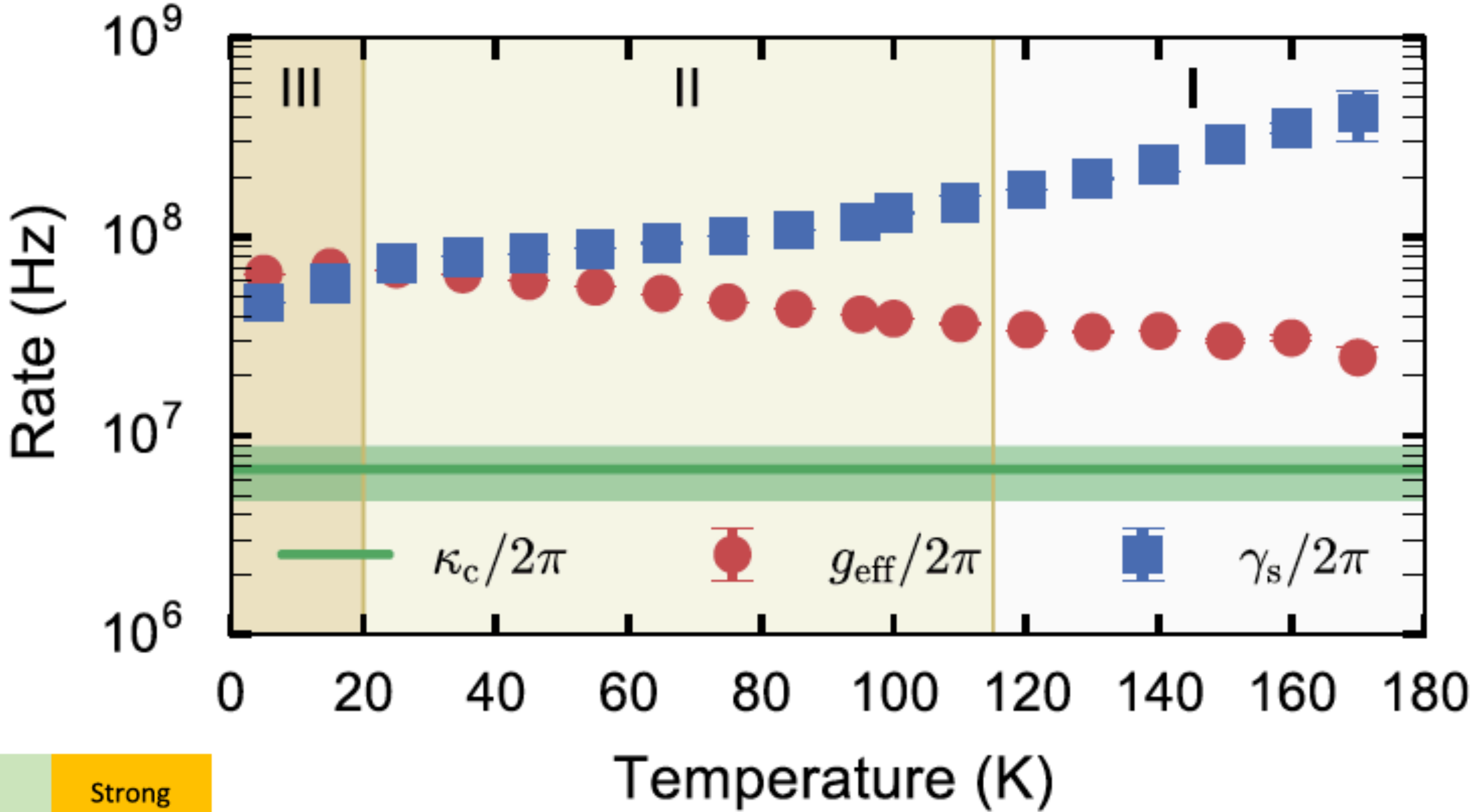


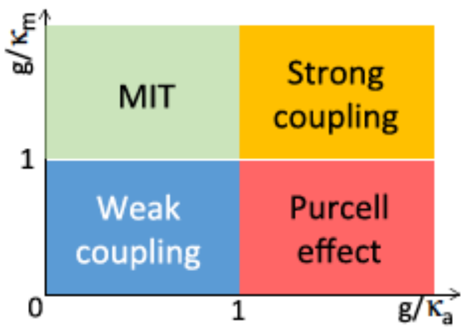


Zhang et al., PRL **113**, 156401 (2015)

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

Franz Haselbeck
Christian Pfleiderer

INNOVENT
Carsten Dubs
O. Surzhenko

Martin Brandt
Felix Hoehne
David Fanke
Lukas Dreher

WMI
Daniel Schwienbacher
Stefan Weichselbaumer
Matthias Pernpeintner
Christoph W. Zollitsch
Mohammad T. Amawi
Petio Natzkin

Natalie Segercrantz
Frank Deppe
Kirill Fedorov
Achim Marx
Rudolf Gross

Jan Goetz
Karl F. Wulschner

Matthias Althammer
Andreas Erb
Stephan Geprägs
Matthias Opel
Mathias Weiler
Nynke Vlietstra
Kathrin Ganzhorn
Tobias Wimmer
Stefan Klingler
Johannes Lotze
Hannes Maier-Flaig

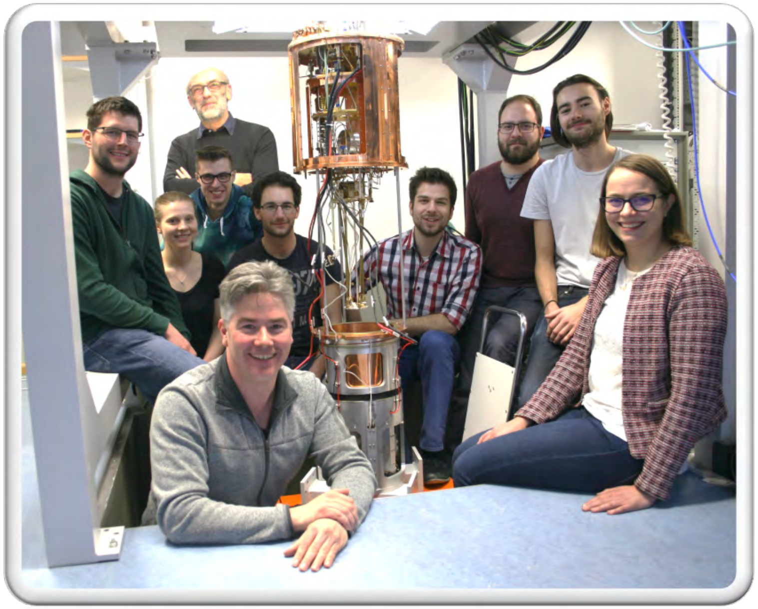
TECHNISCHE UNIVERSITÄT DRESDEN
S.T.B. Goennenwein
Richard Schlitz

TOHOKU
Gerrit Bauer
Yunshan Cao
Joe Barker
Eiji Saitoh
Zhiyong Qiu

Masashi Shiraishi
Ryo Ohshima

rijksuniversiteit groningen
Aisha Aqueel
Thom Palstra
Maxim Mostovoi

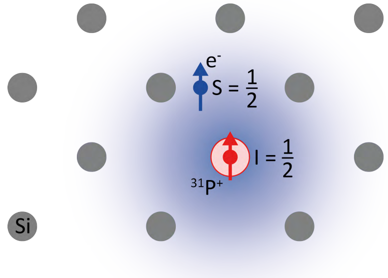
University of Manitoba
Can-Ming Hu
Michael Harder

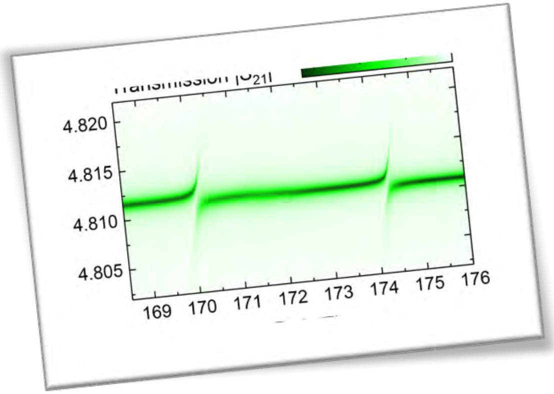


Controlling the Collective Coupling in Spin-Photon Hybrids

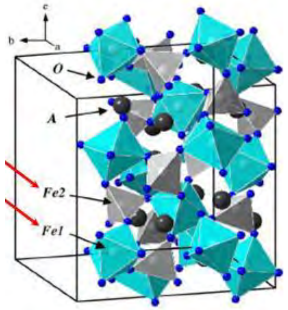
Si:P

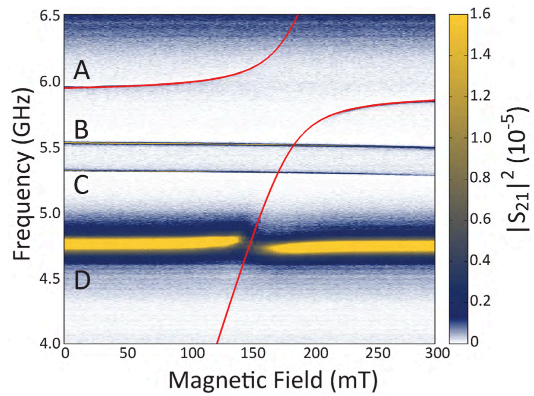
$$g_{\mathrm{eff}} \propto \sqrt{P(T)}$$





YIG





GdIG

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