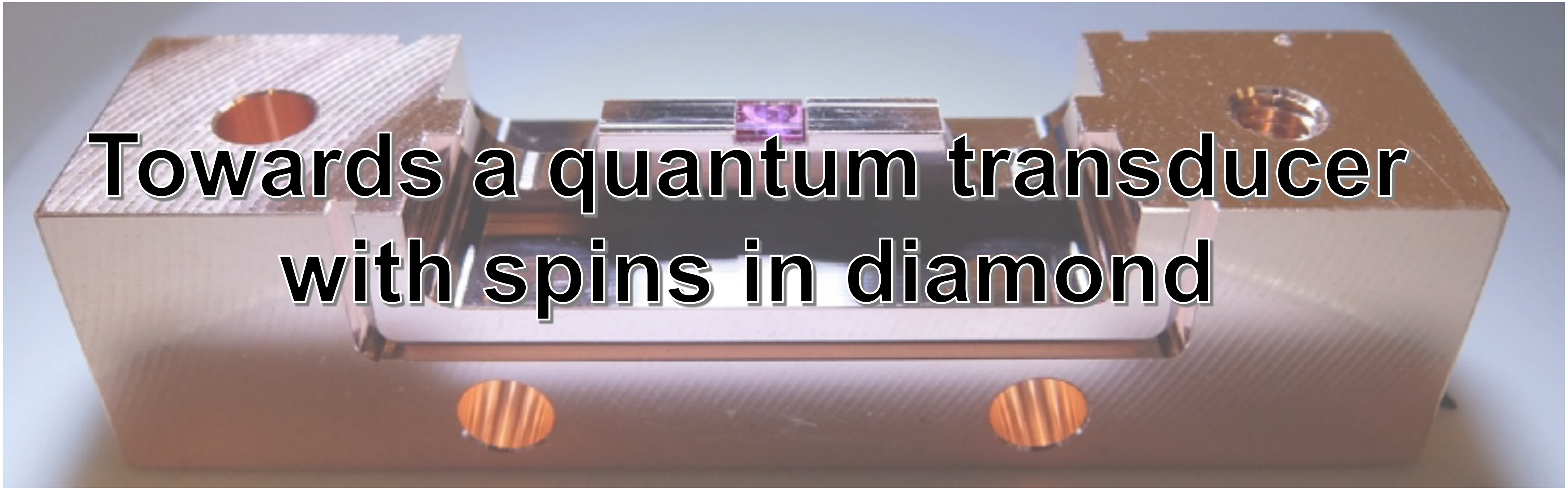
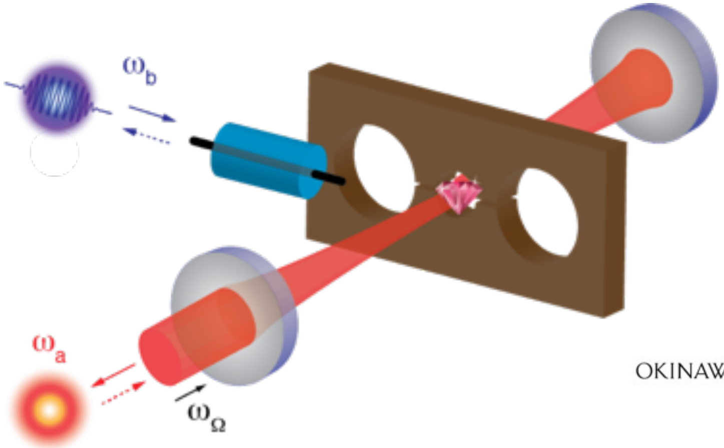


Towards a quantum transducer with spins in diamond

Jason Ball[1], Yu Yamashiro[1,2], Jun-ichi Isoya[3], Shinobu Onoda[4], Takeshi Ohshima[4], Denis Konstantinov[1], Yuimaru Kubo[1,5]

[1]OIST Quantum Dynamics Unit, [2]University of the Ryukyus, [3]University of Tsukuba, [4]QST Takasaki, [5]JST-PRESTO

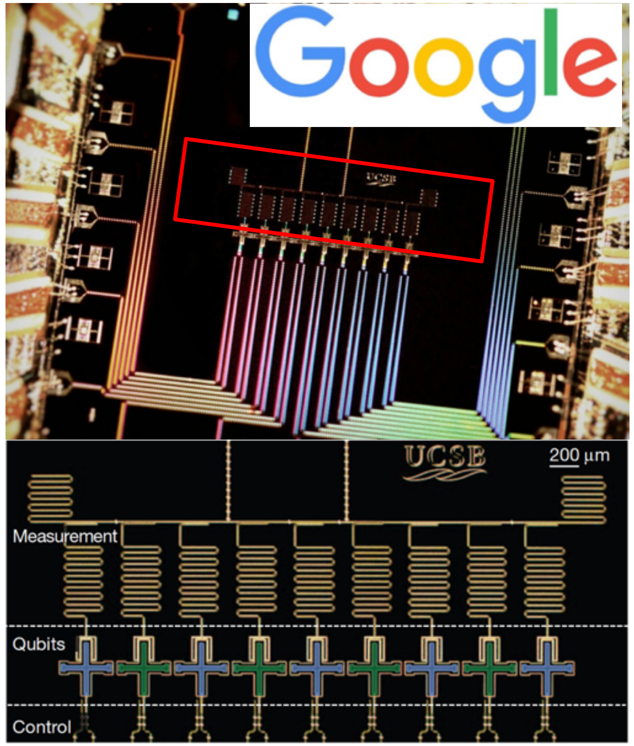


Superconducting quantum circuits

5 GHz (=250 mK) >> 10 mK

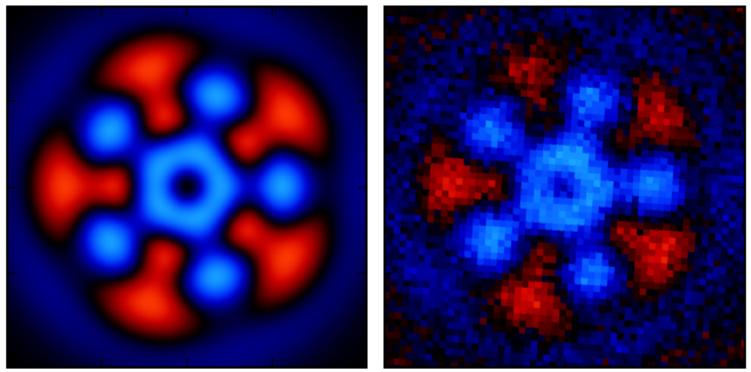
Quantum microwave (**microwave photon**)

- Versatile
- Designable
- Scalable [up to 22 (72?) qubits in 2018]
- Relatively short coherence
- Impossible to send quantum information out of a dilution fridge to elsewhere



Kelly et al., Nature 519,

Wigner function of $|0\rangle + |5\rangle$

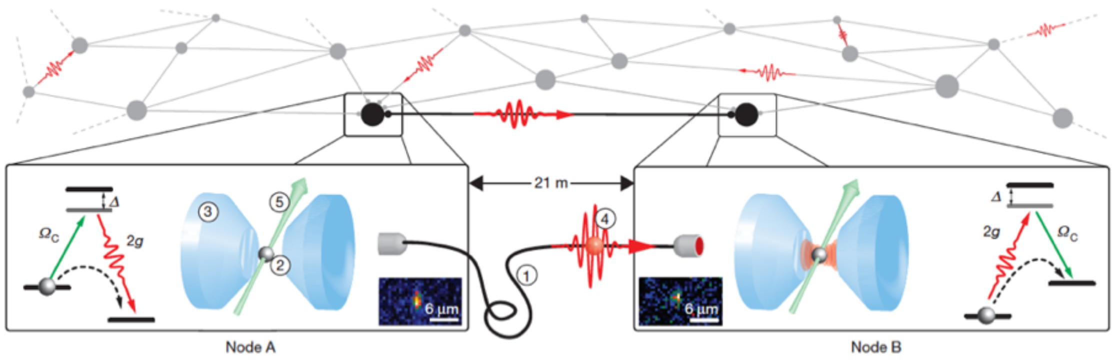


M. Hofheinz *et al.* Nature **459**, 546 (2009)

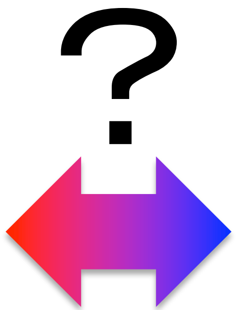
Towards quantum communication network

Optical photons (~eV)

Fiber-based quantum network

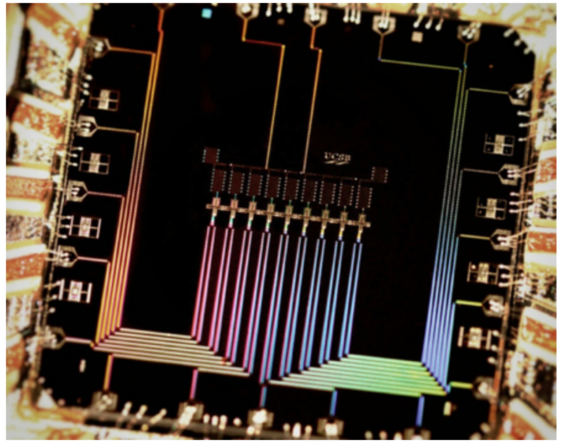


Ritter *et al*., Nature 484 **195** (2012)



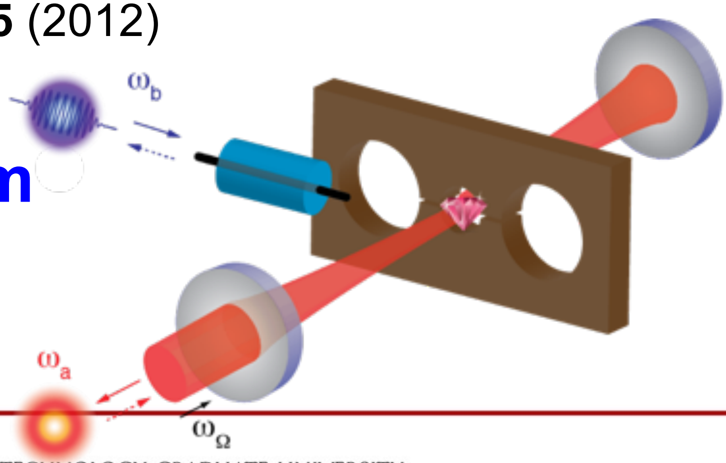
Microwave photons

Q-Processor

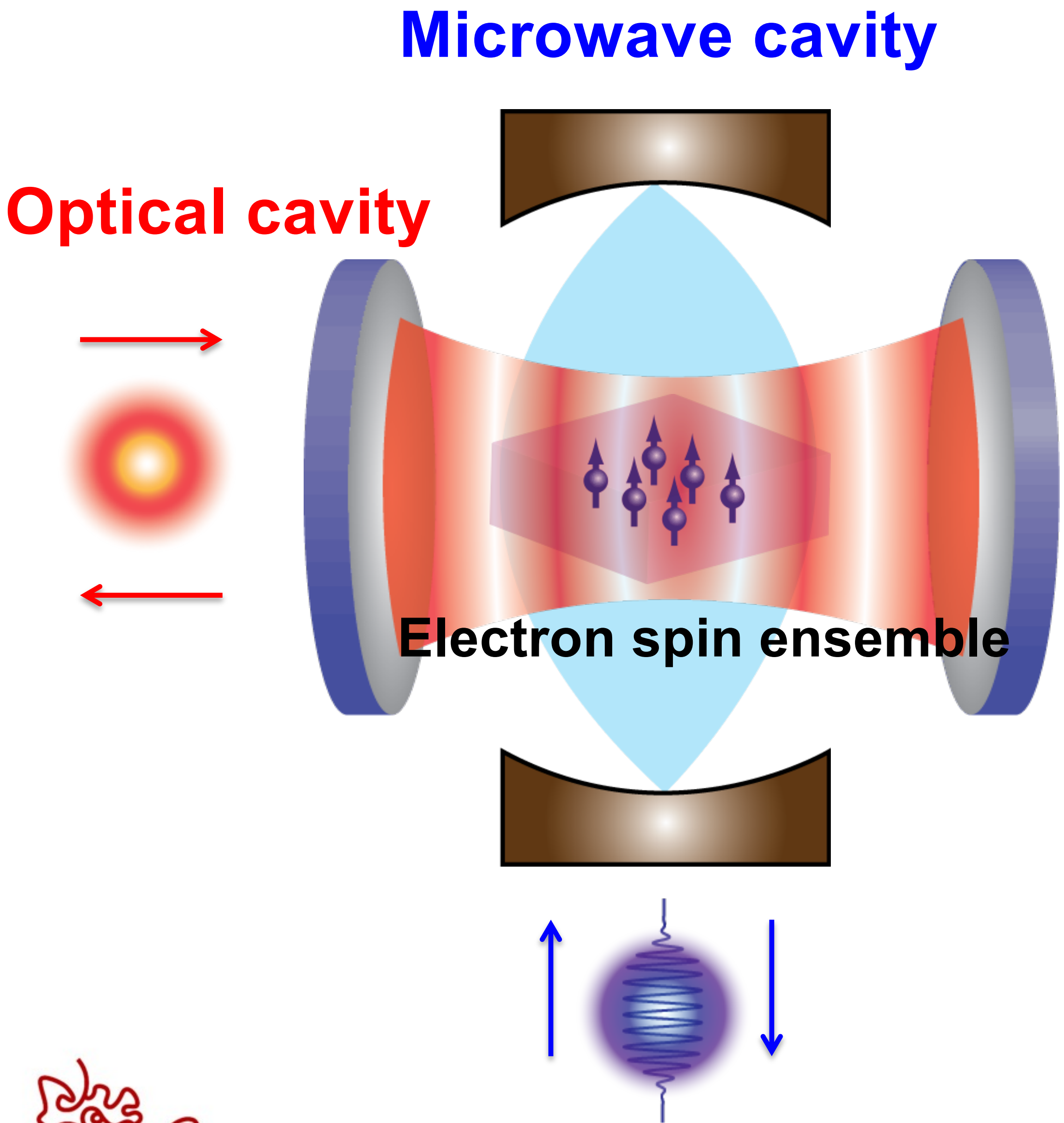


Kelly *et al*., Nature (2015)

Need for a **quantum microwave-optical transducer**

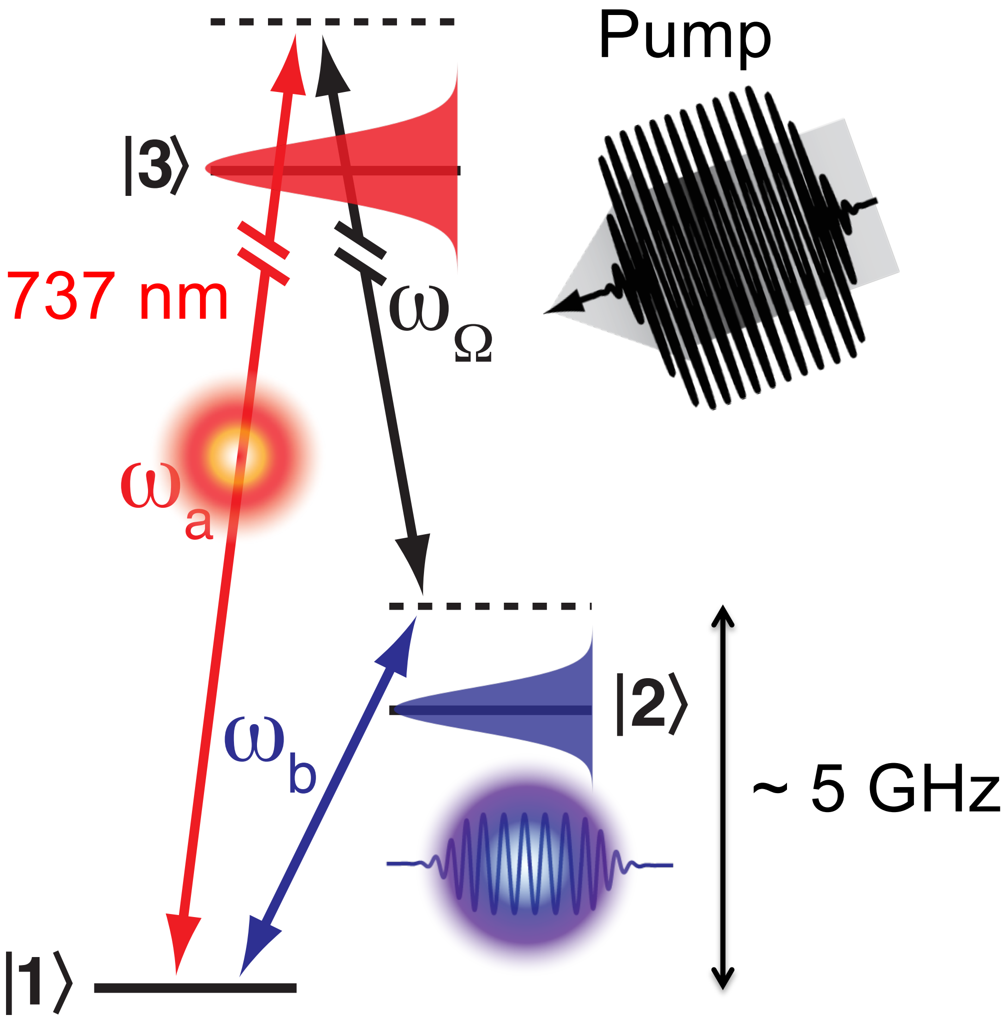


This project: transducer with spins in solids



- Broadband transduction possible (~1-10 MHz)
- Quiet @10 mK ->No active cooling
- Frequency tunable (microwave regime)

Operating principle



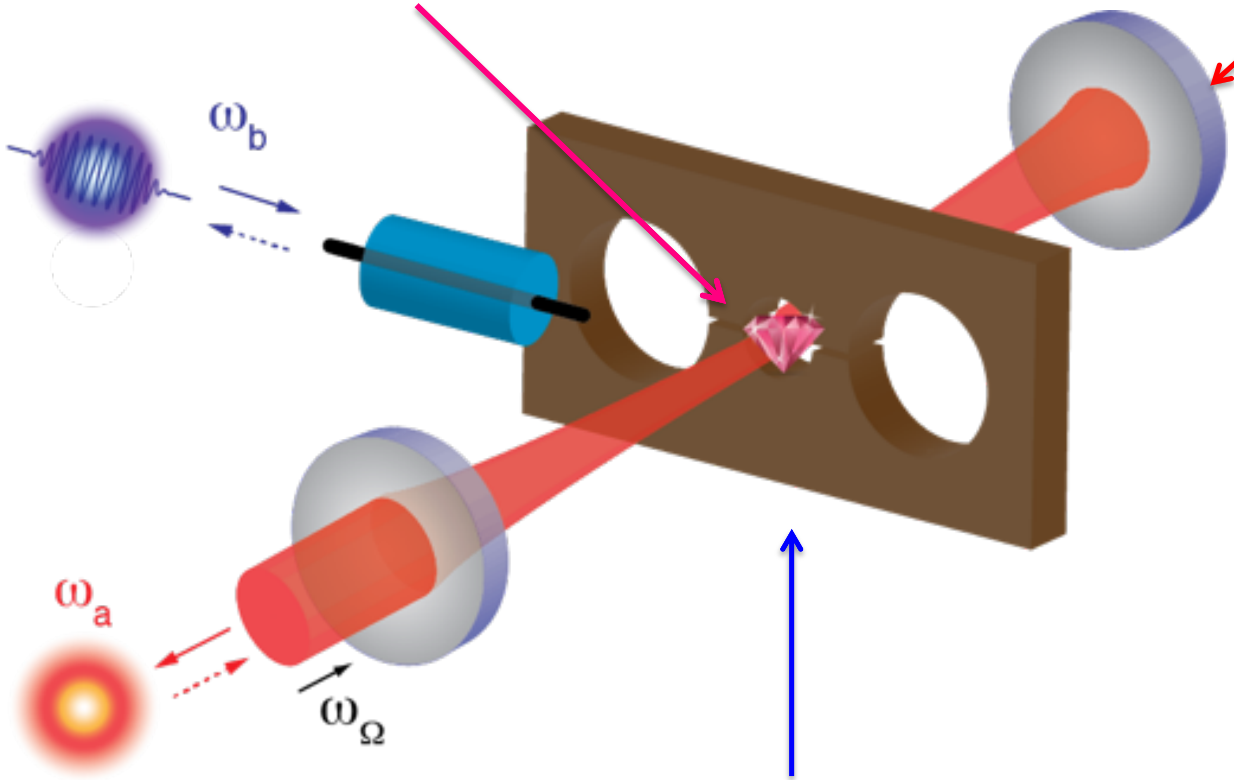
- Detunings >> inhomogeneous broadenings
- Pump power ?

Proposal ($Er:Y_2SiO_5$):
Williamson et al, Phys. Rev. Lett. **113**, 203601 (2014).
Experiment: Fernandez-Gonzalvo et al., arXiv:1501.02014 (**10^{-9} %**)

Proposed Quantum Transducer

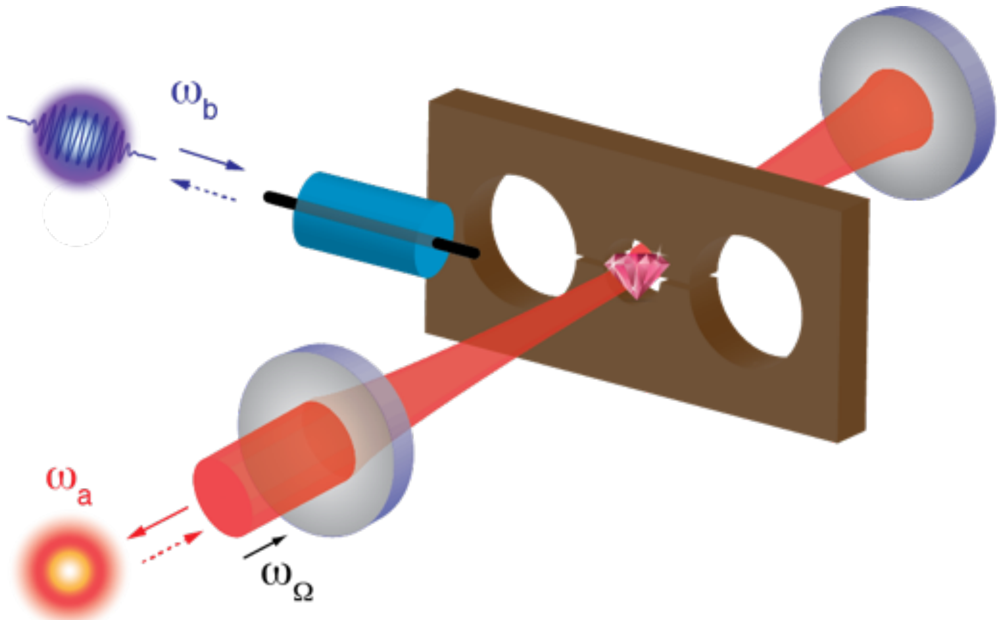
Diamond crystal
with spins

Optical cavity（Fabry-Perot）



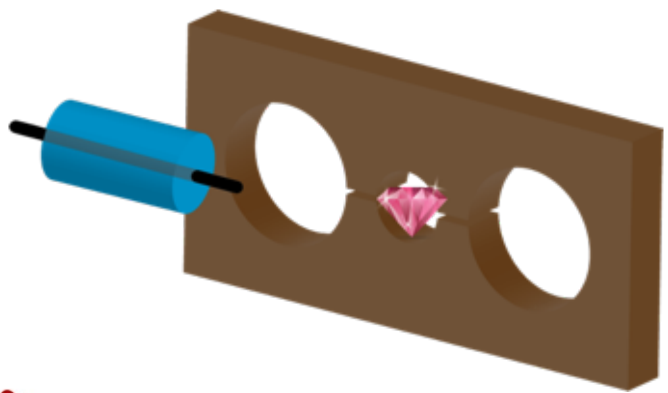
Microwave cavity

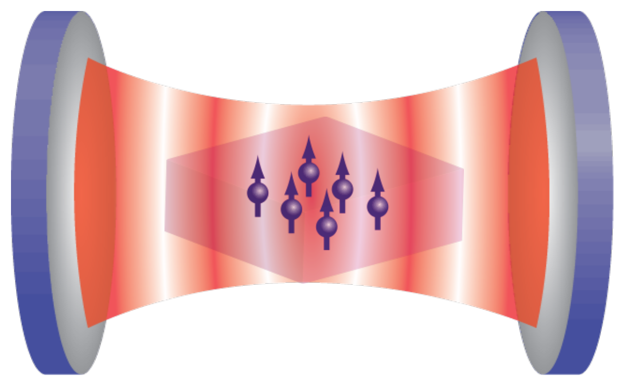
Plan



1. Microwave part

2. Optics part





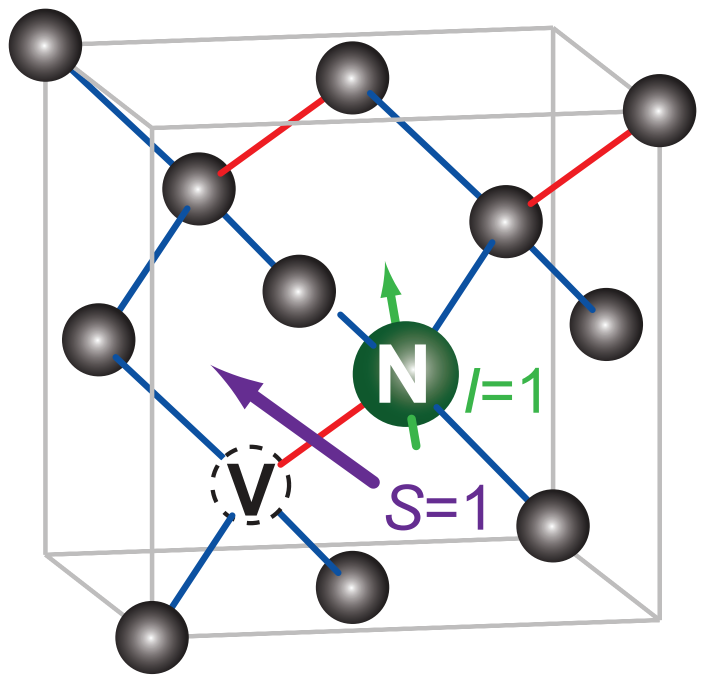
Spins in diamond

- Very good coherence in "silent" environment (e.g., ^{12}C)
- Both microwave (spin) and optical (orbital) transitions inside
- Scalability?
- Designability?

↓

Complementing superconducting circuits

NV centers in diamond

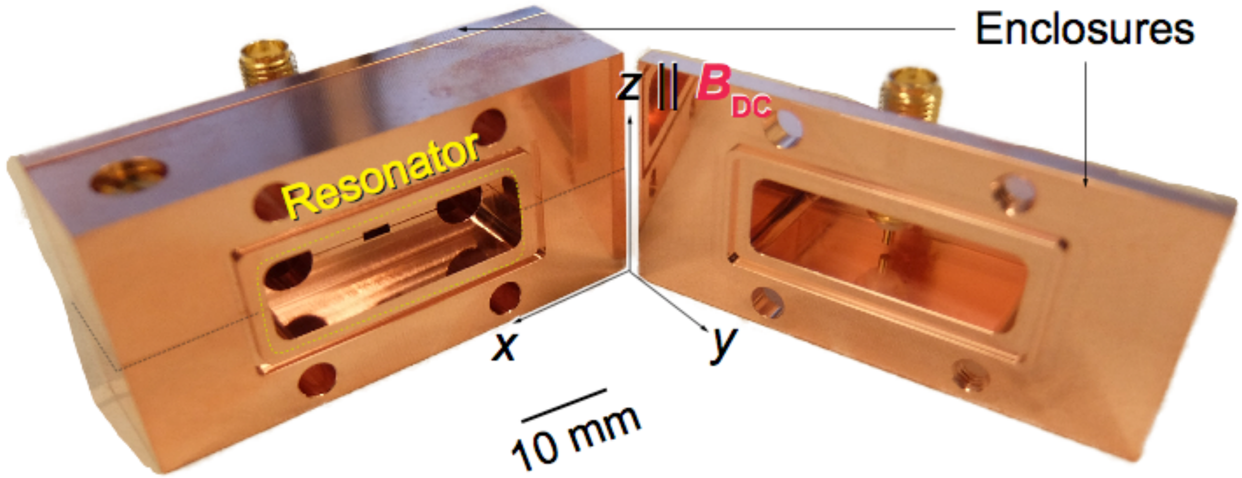


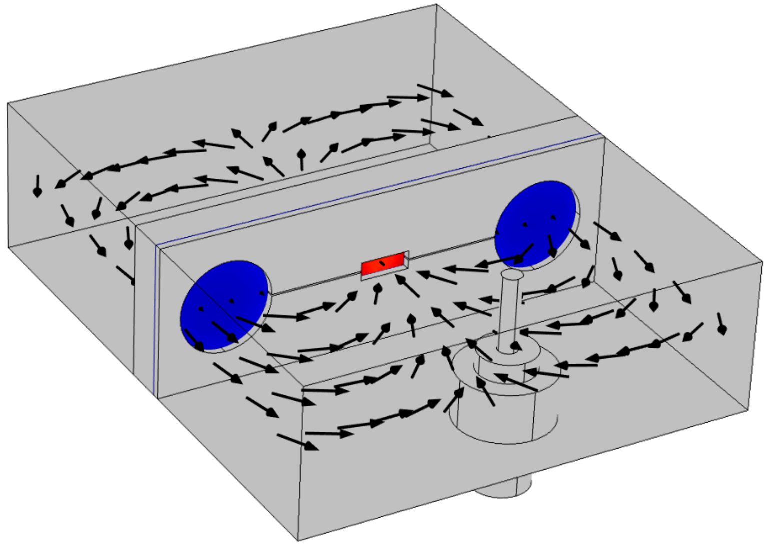
Loop-Gap Microwave Resonator

- Highly homogenous B-field:

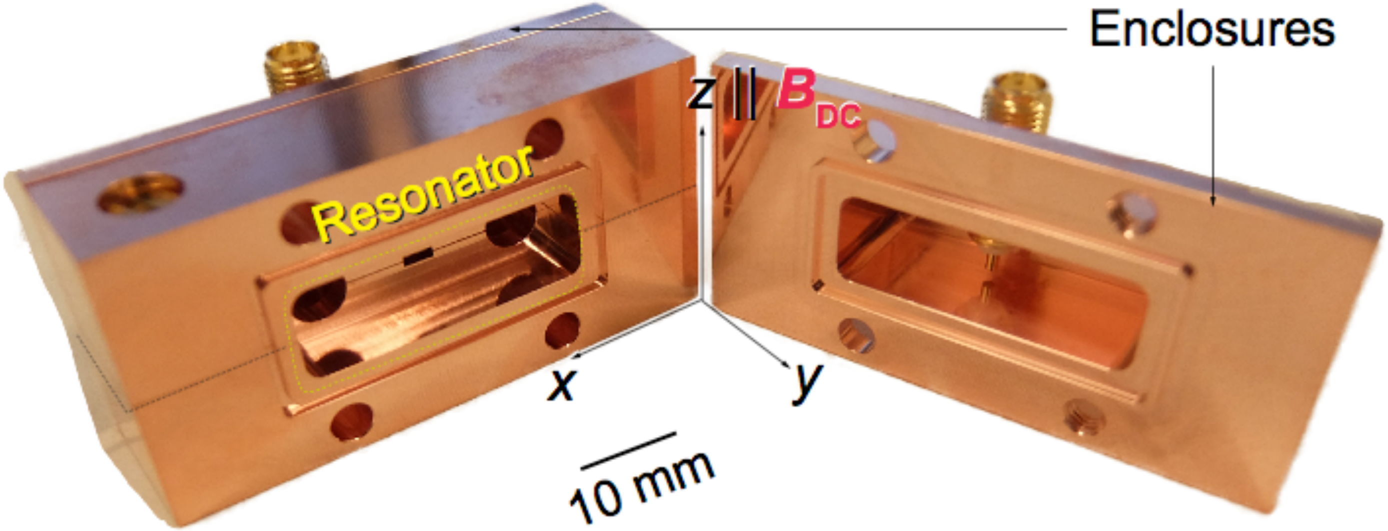
  $$\delta B_0 \approx 14\ \mathrm{pT}$$

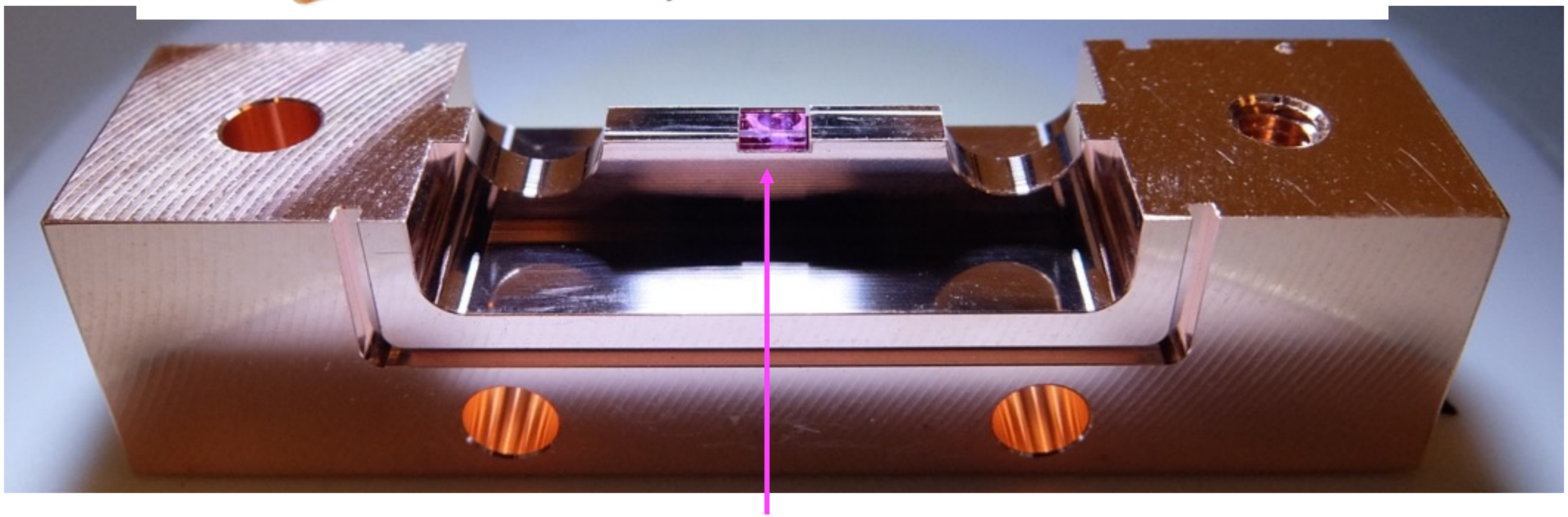
- Filling factors of up to 0.5
- $\omega_R/2\pi \approx$ 5.3 GHz
- Qint ~ 600 at RT, 1500 at 10 mK



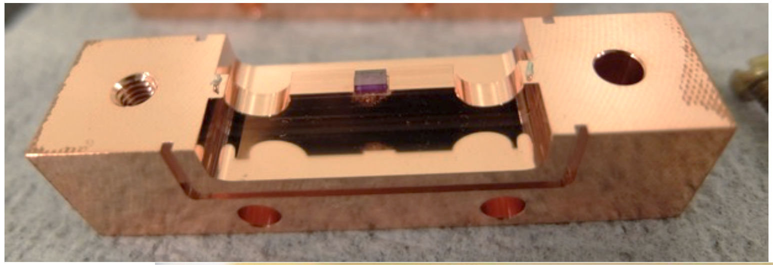


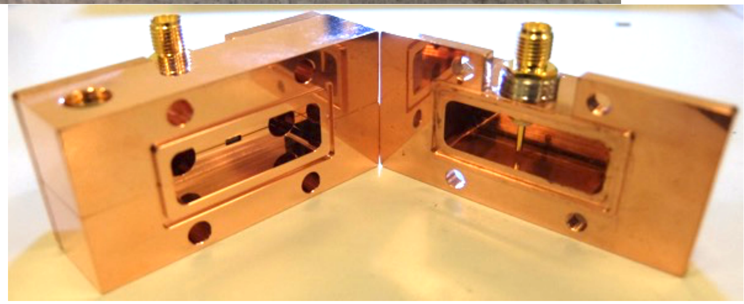
Loop-Gap Microwave Resonator



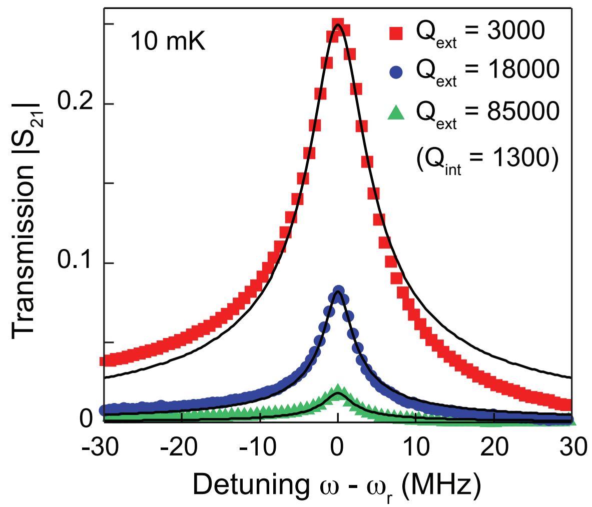


Tunable coupling

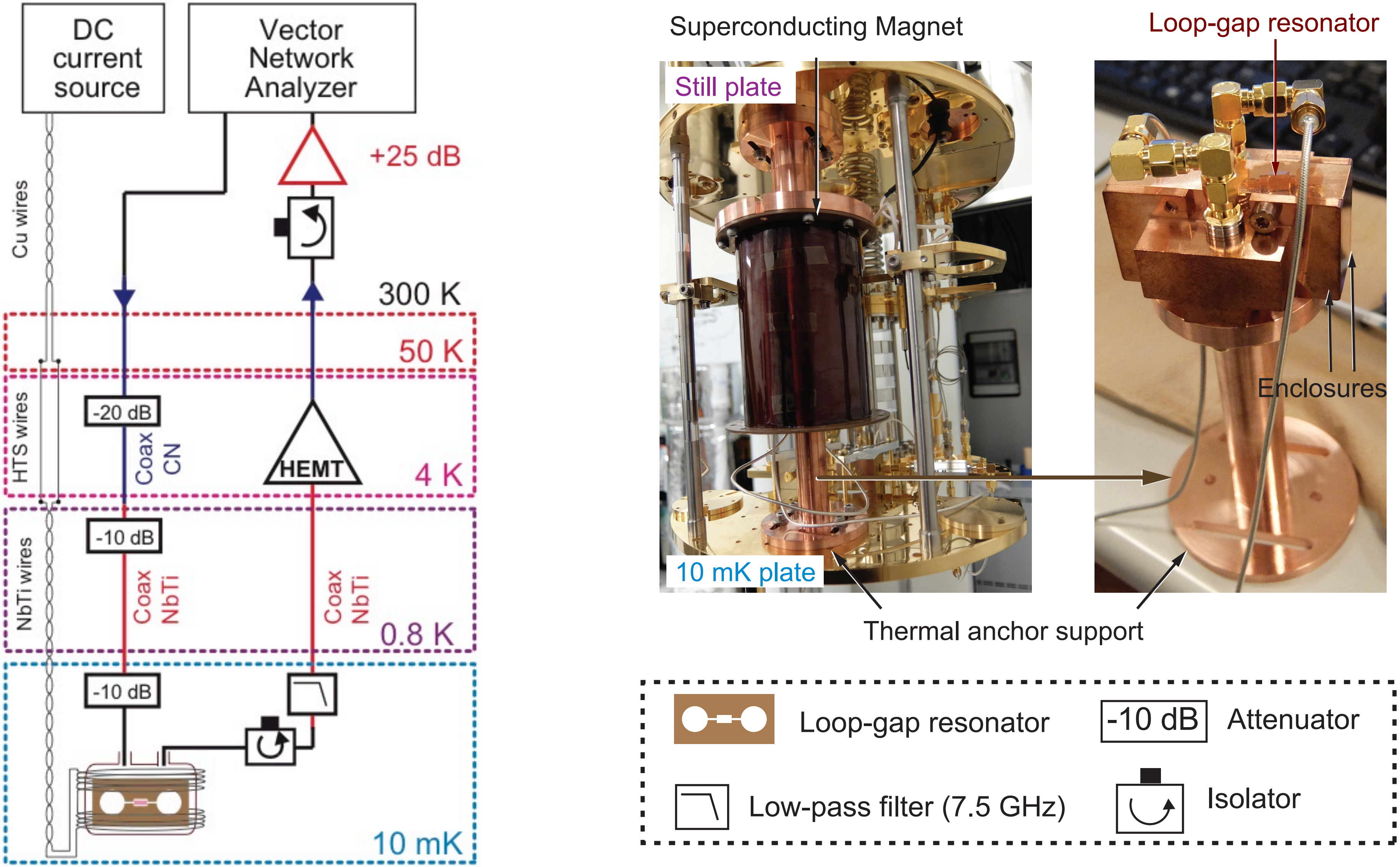




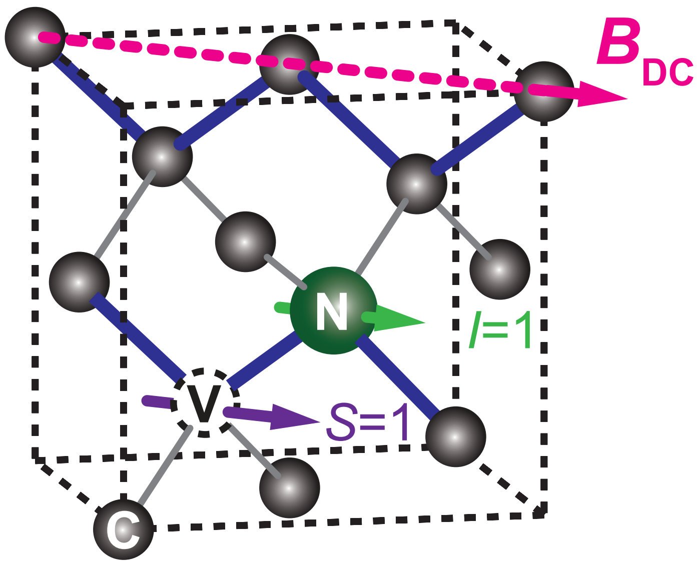
- Change length of SMA pin extending into cavity
- Tuning between critical coupling and undercoupled regimes
- Can be used for CQED and conventional ESR experiments

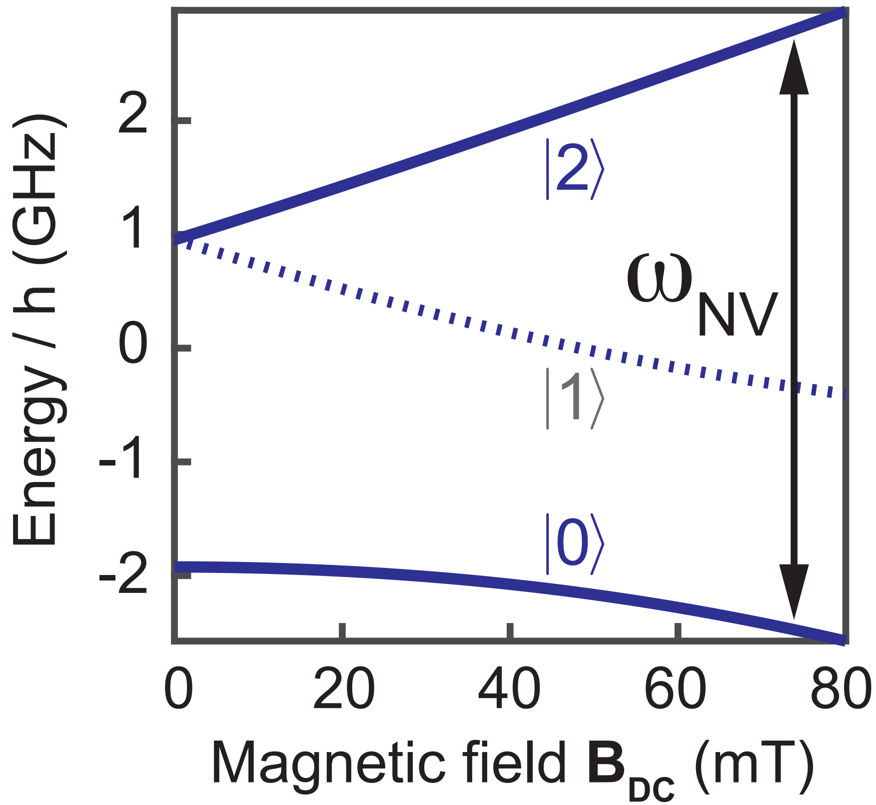


Experimental Setup



Diamond Sample #1 (NV)

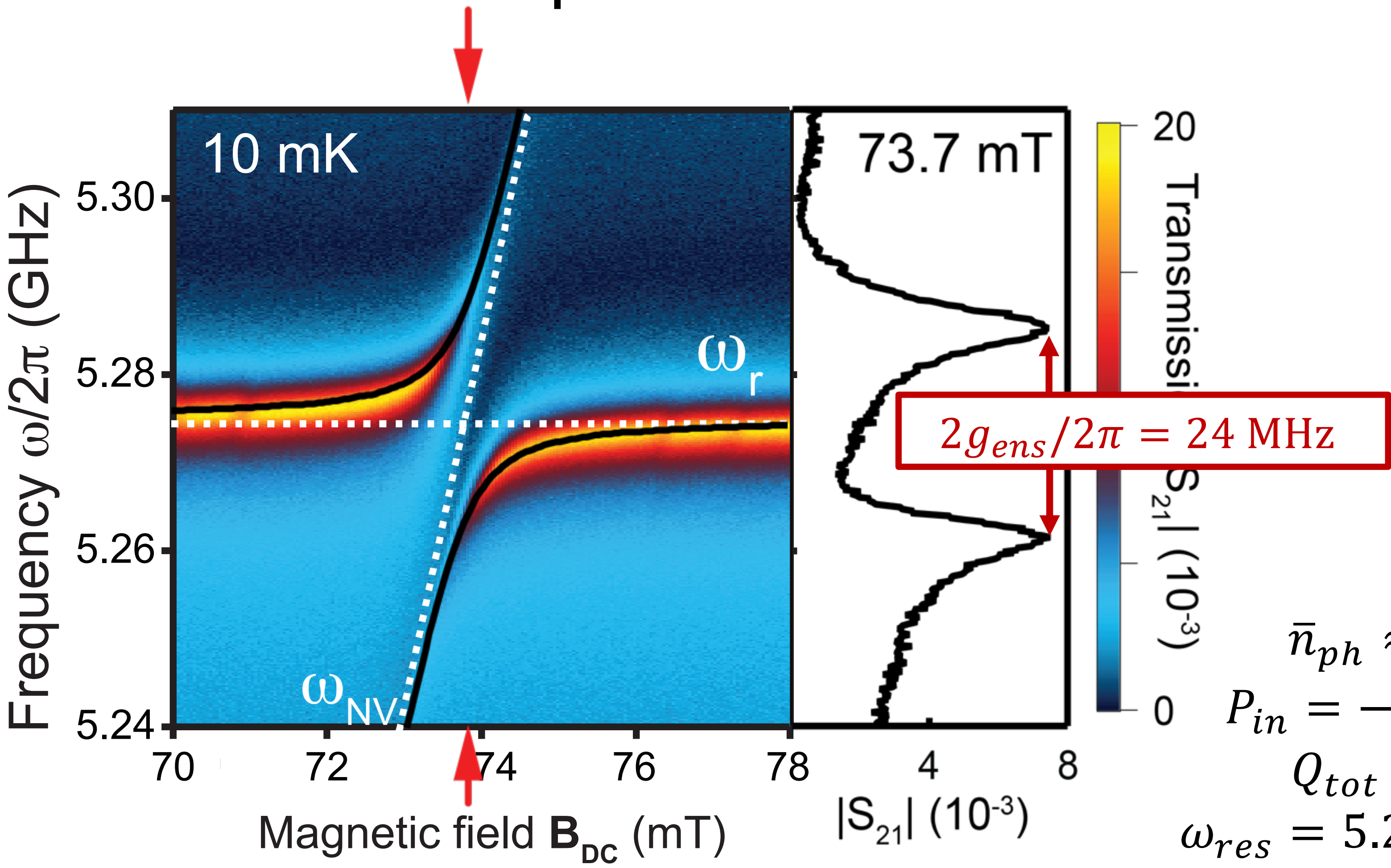




[NV] = 4 ppm
~10^{15} spins
linewidth ~ 1 MHz

$$\hat{H}/\hbar = \underbrace{\boldsymbol{S}\cdot\bar{\boldsymbol{D}}\cdot\boldsymbol{S}}_{\text{ZF}} - \underbrace{\gamma_e \boldsymbol{B}_{DC}\cdot\boldsymbol{S}}_{\text{Zeeman}} + \left(\underbrace{\boldsymbol{S}\cdot\bar{\boldsymbol{A}}\cdot\boldsymbol{I}}_{\text{HF}} + \underbrace{P\hat{I}_Z^2}_{\text{Q}}\right)$$

Transmission Data – Sample 1



$\bar{n}_{ph} \approx 10000$

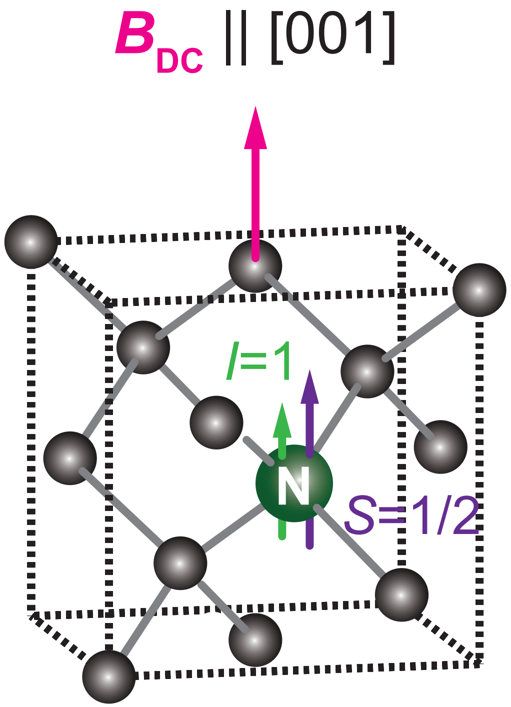
$P_{in} = -106$ dBm

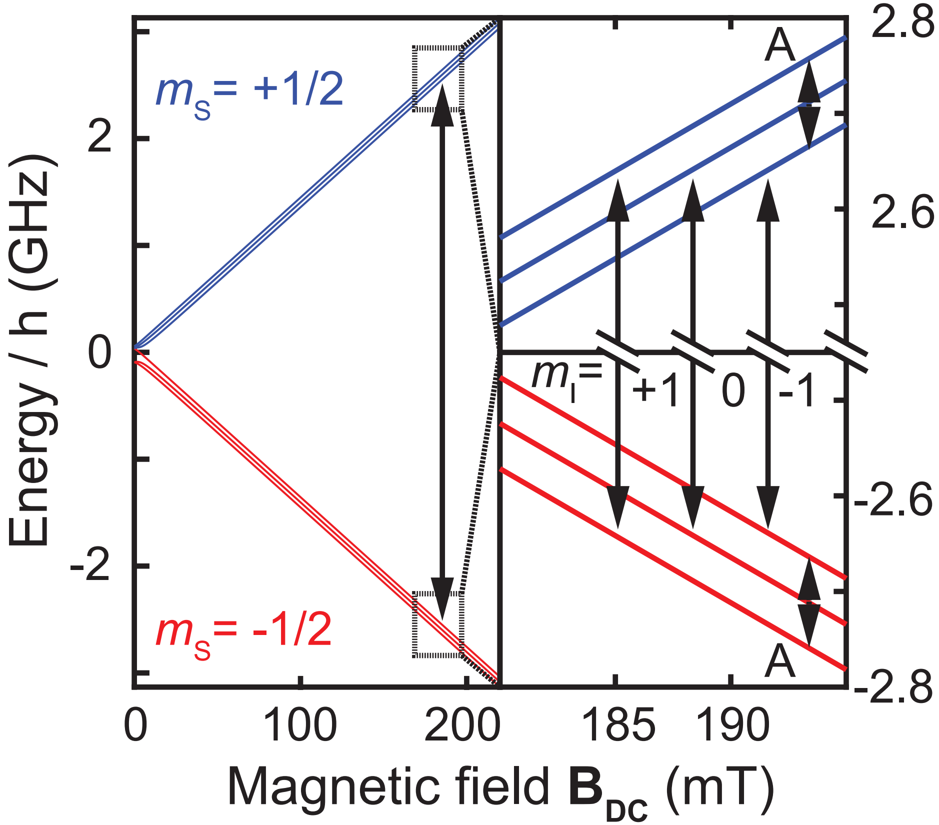
$Q_{tot} = 1550$

$\omega_{res} = 5.275$ GHz

Ball et al., Appl. Phys. Lett. **112** 204102 (2018)

Diamond Sample #2 (P1)

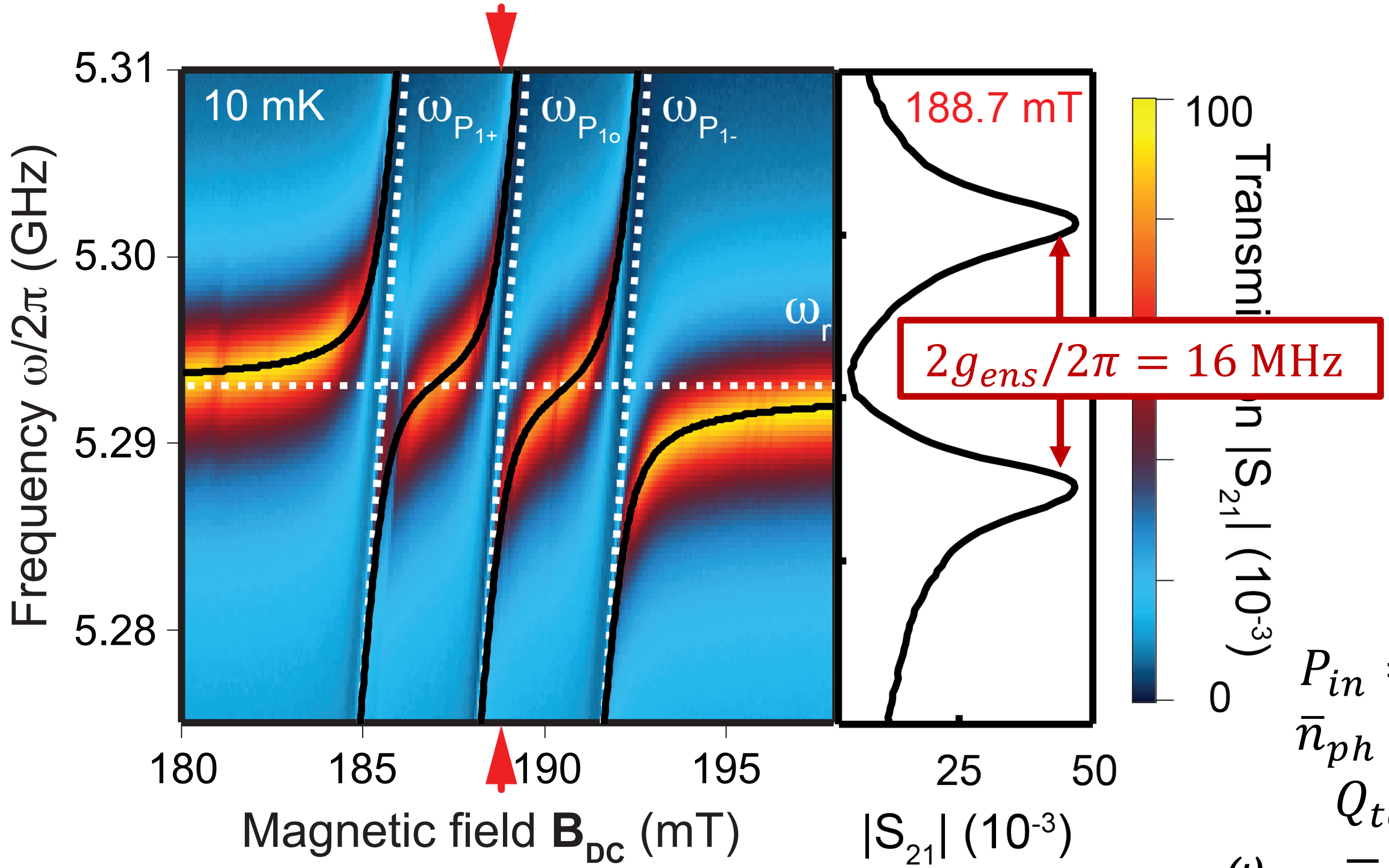




[P1] = 10 ppm
~ 10^{15} spins

$$\hat{H}/\hbar = \underbrace{\gamma_e \boldsymbol{B_{DC}} \cdot \boldsymbol{S}}_{\text{Zeeman}} + \underbrace{\boldsymbol{S} \cdot \bar{\boldsymbol{A}} \cdot \boldsymbol{I}}_{\text{HF}}$$

Transmission Data – Sample 2



$P_{in} = -96$ dBm

$\bar{n}_{ph} \approx 100000$

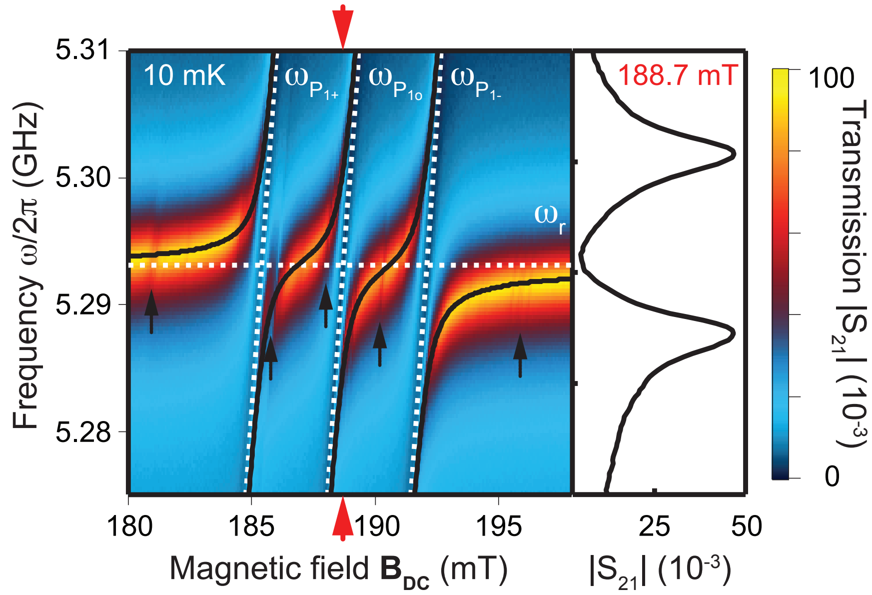
$Q_{tot} = 1510$

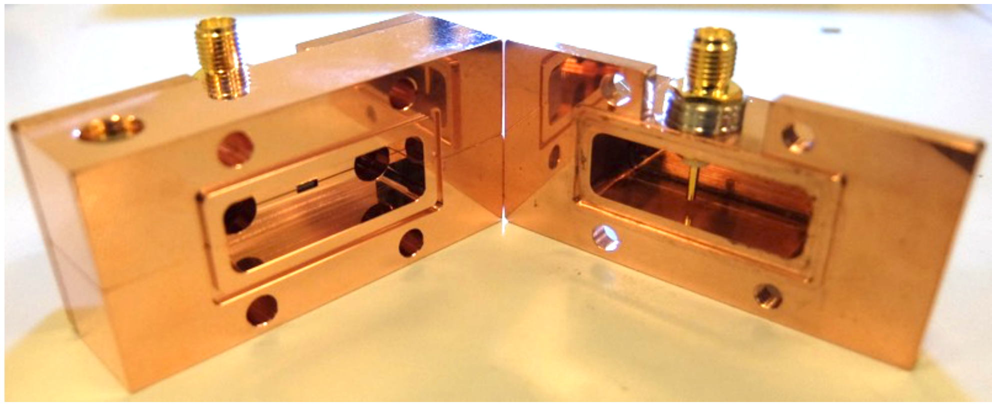
$\omega_{res} = 5.293$ GHz

Ball et al., Appl. Phys. Lett. **112** 204102 (2018)

Summary and perspectives

- Designed and tested loop-gap resonator compatible with optical setup
- Demonstrated strong coupling to ensembles of spin defects in diamond.
- Next step – coupling SiV ensemble to the same 3D microwave cavity



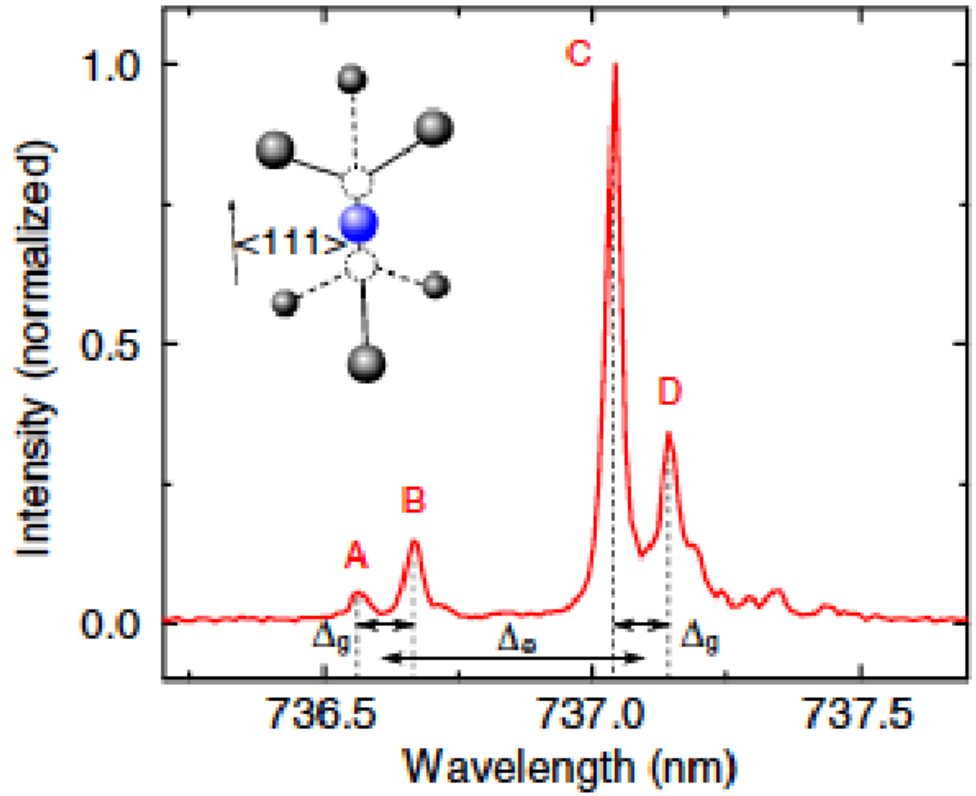


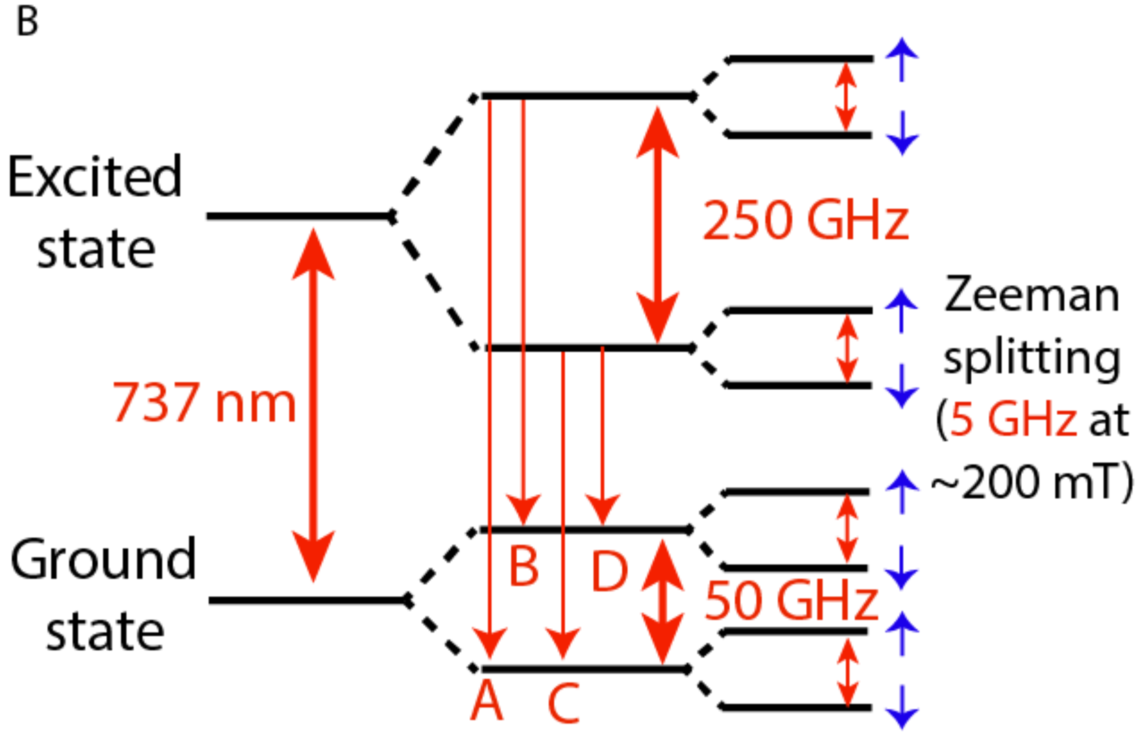
Ball et al., Appl. Phys. Lett. **112** 204102 (2018)

WANTED

- Both microwave and optical transitions
- **Narrow line widths of both microwave and optical transition**
- **Large optical dipole moment**

SiV centers in diamond

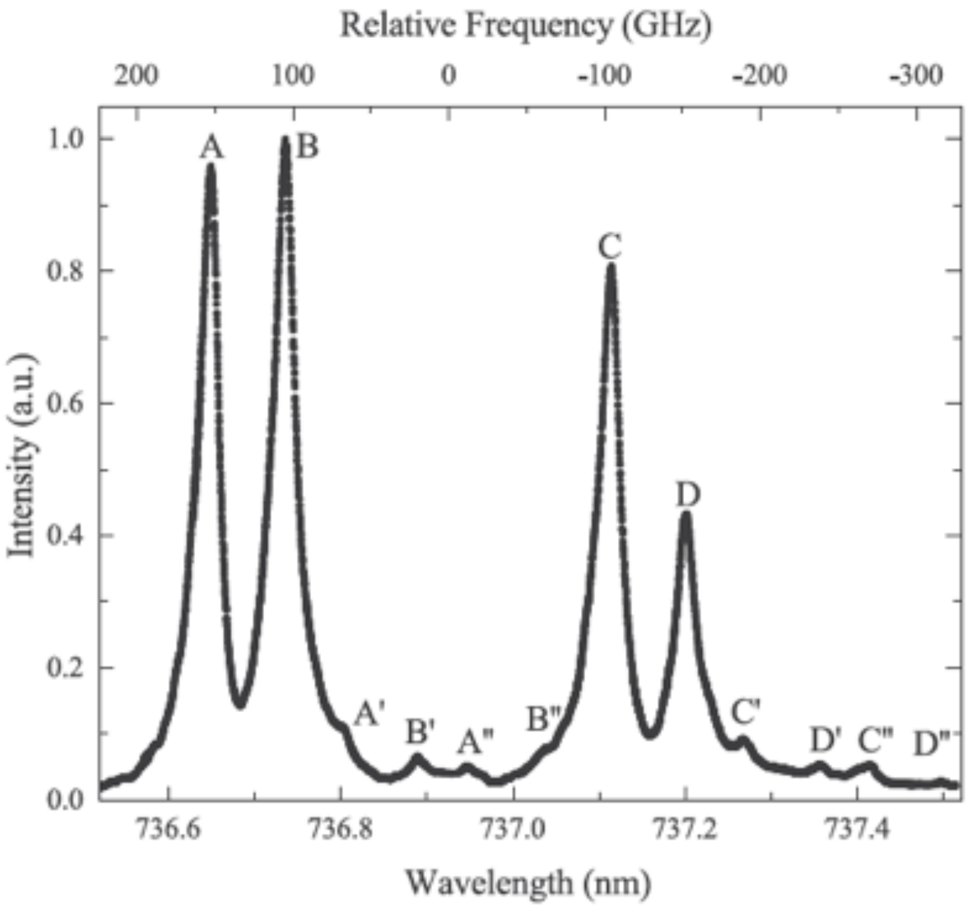




Müller *et al.* Nat. Comm. 2014

- Strong (and stable) zero phonon line
- Large dipole (10^3 bigger than Er)

SiV centers in diamond



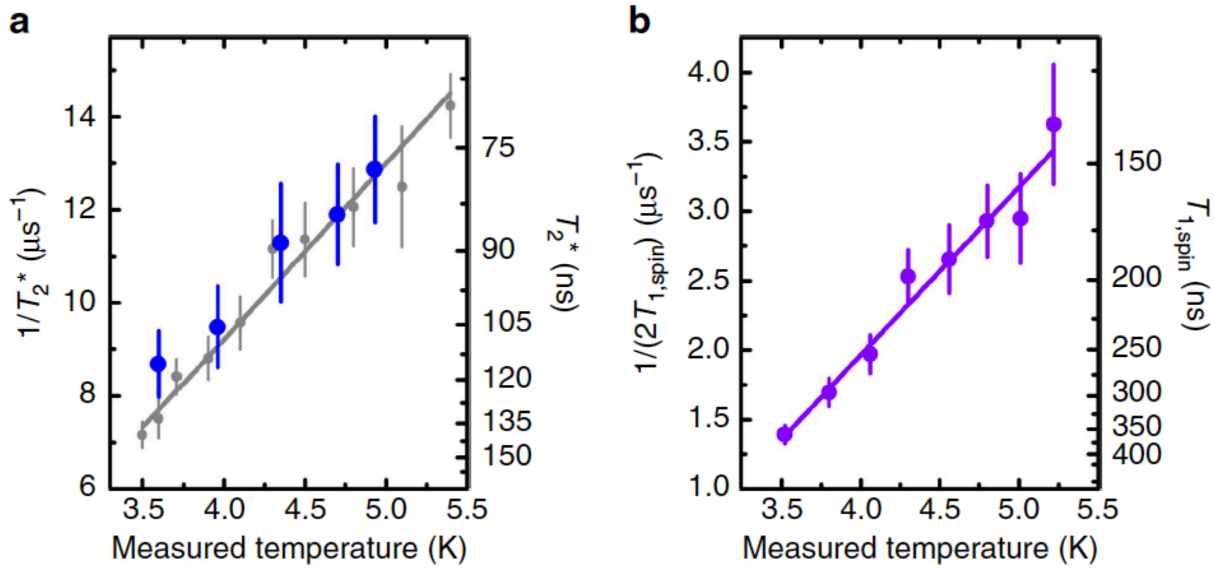
Homogeneous optical transition:

~10 GHz in ensemble
(cf. NV >> 100 GHz)

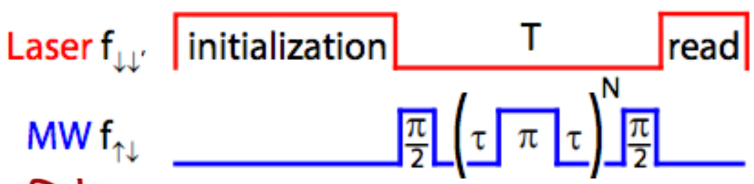
Arend et al. PRB **94**, 045203 (2016)

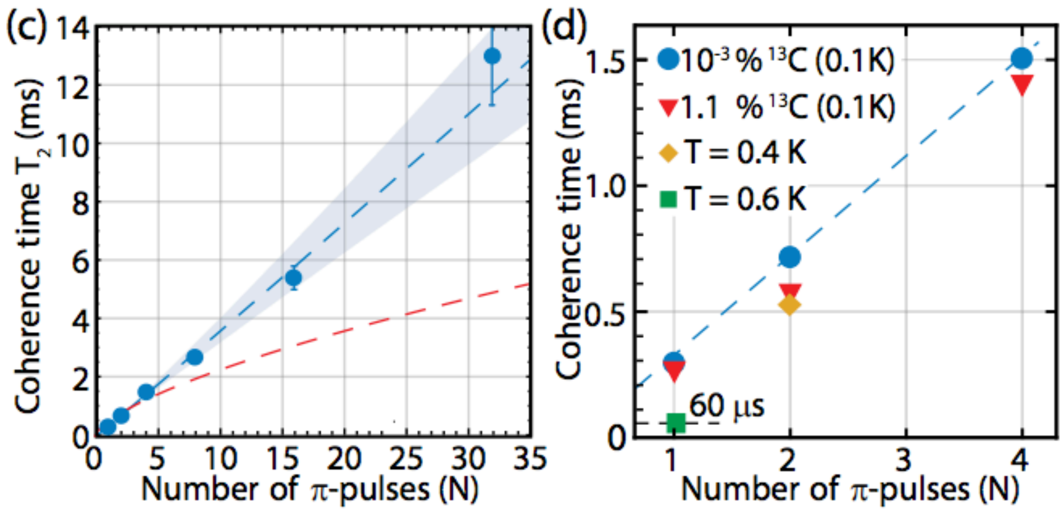
Recent work on SiV

- Coherence time strongly limited by orbit flip-flopping at T ~ 4K
- However, ground state spin transition $|1\rangle \rightarrow |2\rangle$ is not forbidden! (Gali and Maze, PRB 2013)
- Recently, $T_{2,CPMG}$ has been measured to exceed 1 ms at 100 mK.



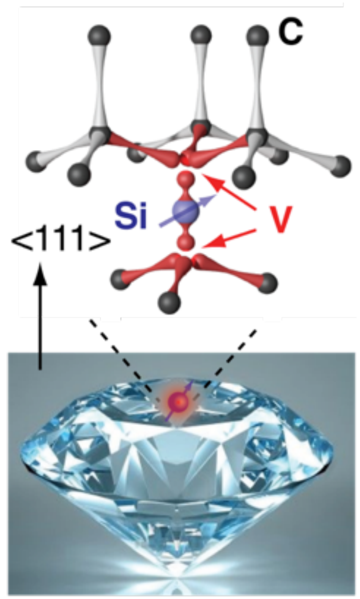
Pingault *et al.*, Nat. Comm. 2017





Sukachev *et al.*, PRL 119 223602 (2017)

Summary and perspectives



- Good optical properties - potential use for SiV as a quantum transducer
- Long coherence time @ mK may be a promising quantum memory as well
- Next step – coupling SiV ensemble to the same 3D microwave cavity