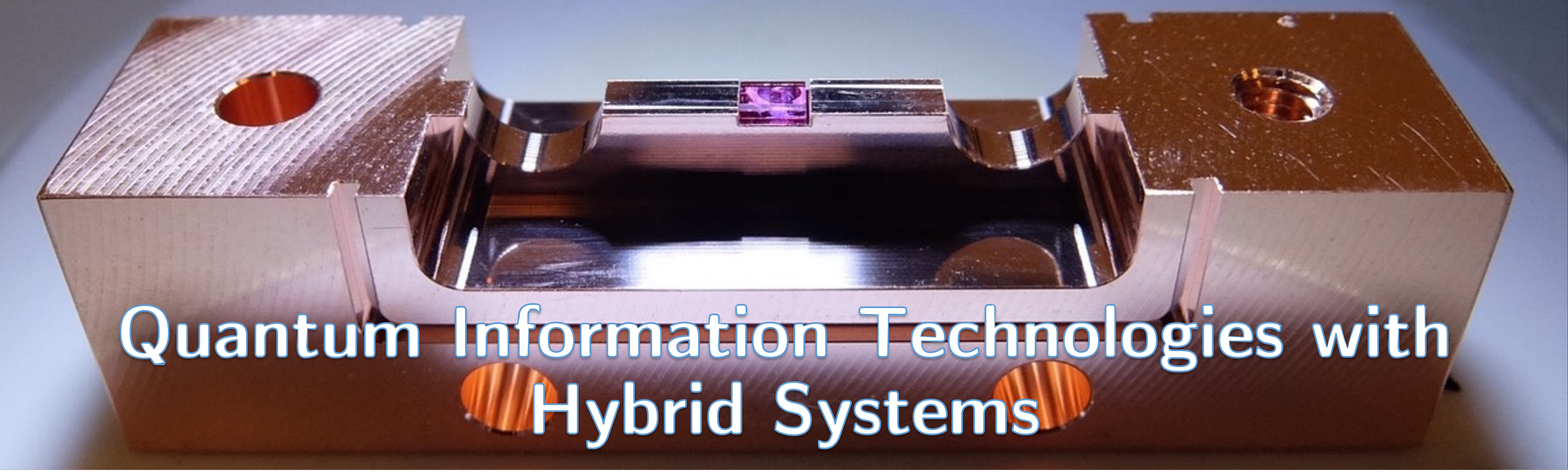


Quantum Information Technologies with Hybrid Systems

Yuimaru Kubo

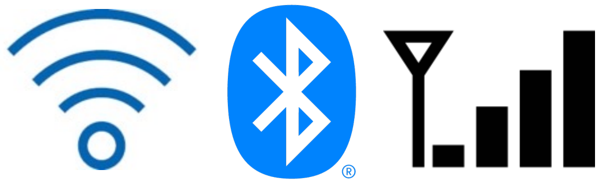
OIST

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY

POC program

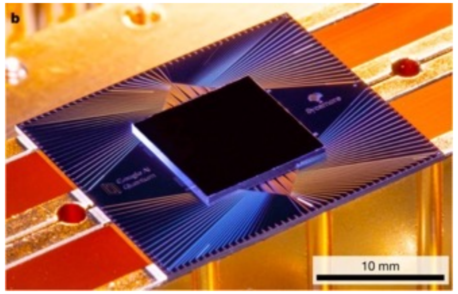
Proof-of-Concept Program

Advantages of microwave



- Well established (4G, 5G) -> operable
  - easy to stabilize phase
  - economically reasonable below ~ 10 GHz

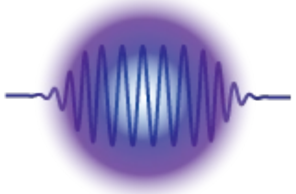
- Easy mode matching (impedance matching) -> handy!



- Solid devices -> integrable

Quantum microwave at millikelvin

$5\ \text{GHz} \times h\ (= 250\ \text{mK} \times k_B) \gg 10\ \text{mK} \times k_B$

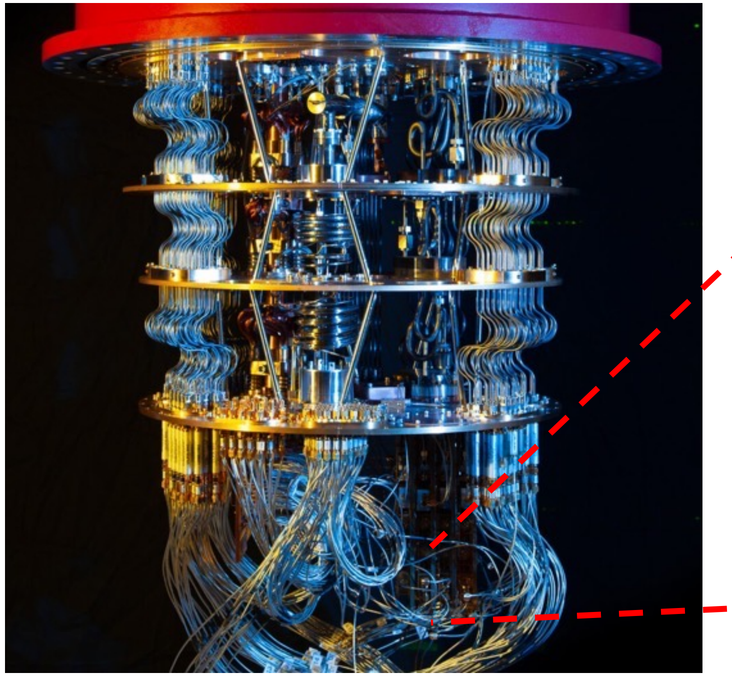


Quantum microwave
(**microwave photon**)

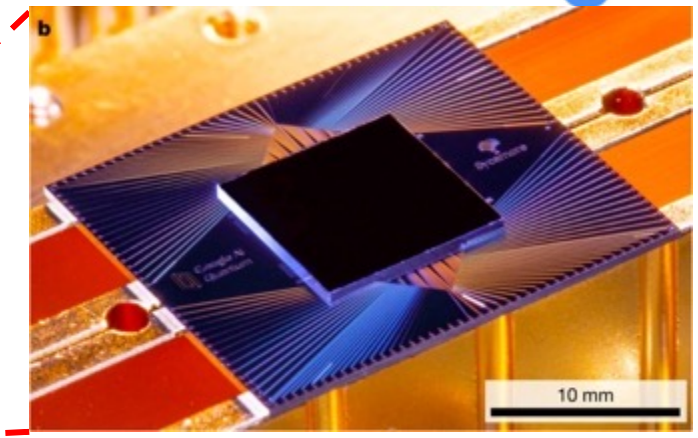
$400\ \text{THz}\ (= 10^4\ \text{K}) \gg 300\ \text{K}$

Optical photon

Dilution refrigerator

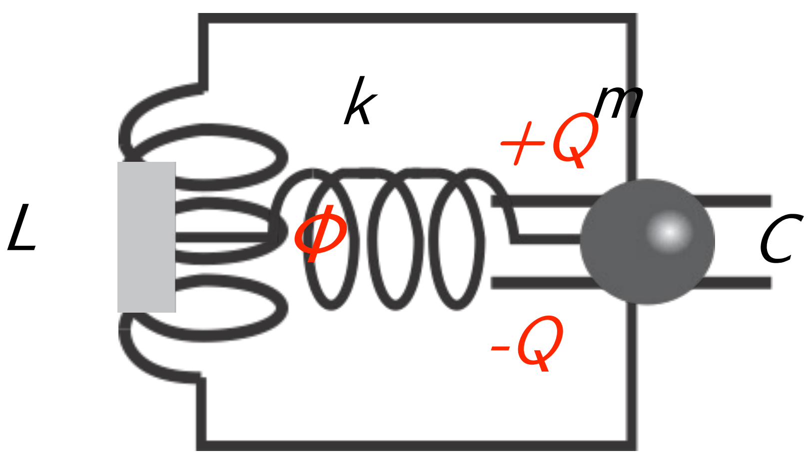


Google



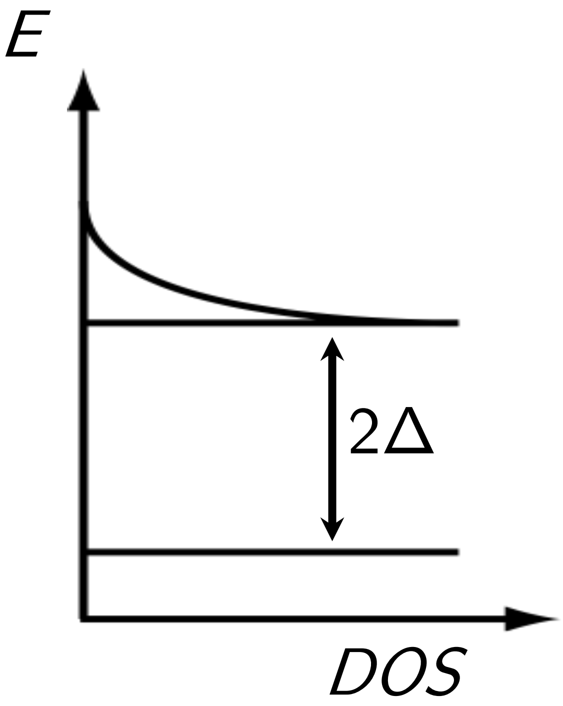
Quantum integrated circuit

LC resonator



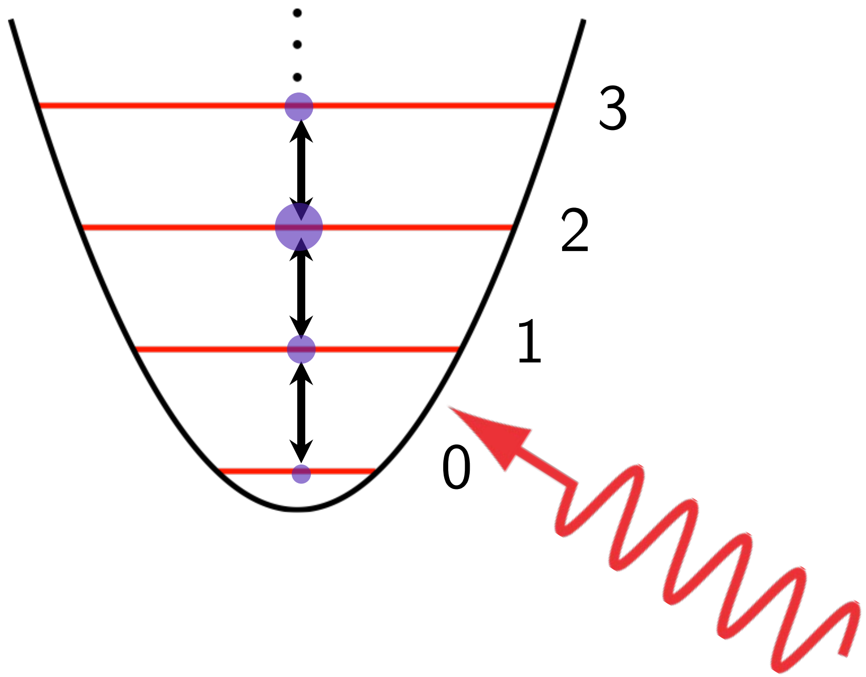
$$\omega = \frac{1}{\sqrt{LC}} \qquad [\Phi, Q] = i\hbar$$

For details, see e.g., Devoret and Martinis, Quantum Inform. Processing **3**, 163 (2004)



- Low loss -> high Q
- Macroscopic phase coherence
- Superconducting gap (>~ 100 GHz)

Harmonic oscillator



Photon number

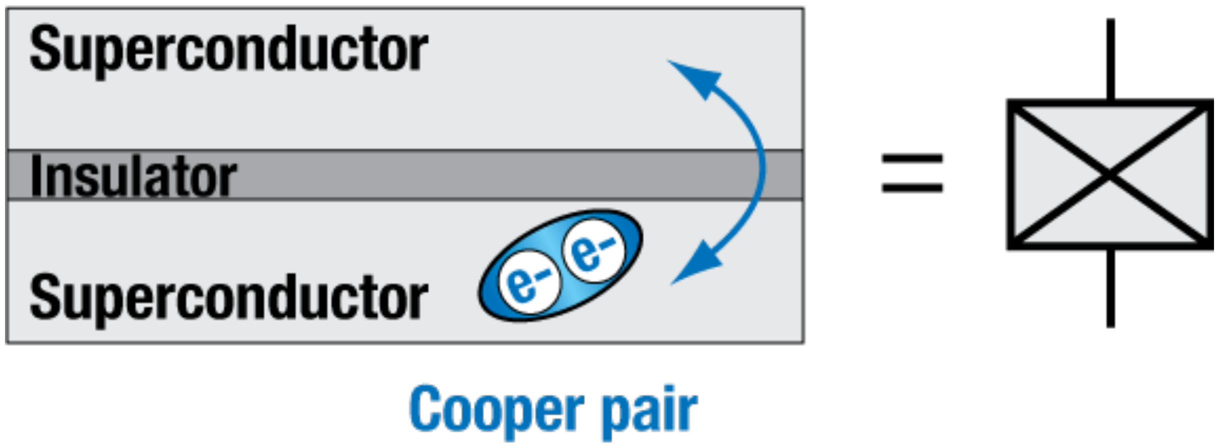
Phase

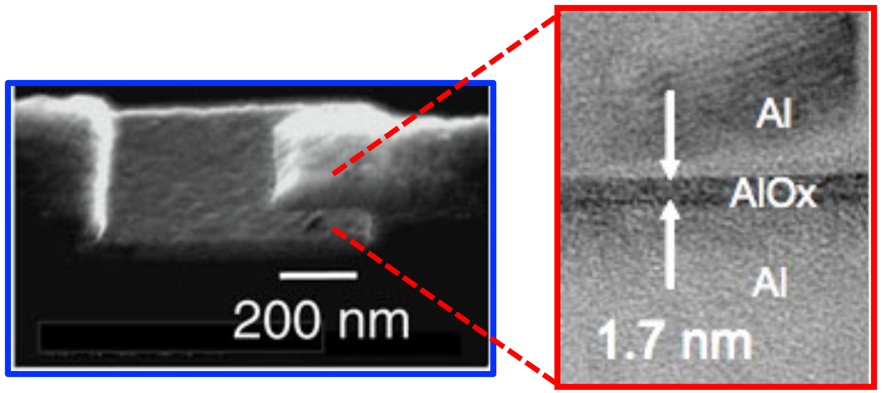
$$[n, \varphi] = i\hbar$$

Only “coherent state” can be prepared when driven by phase-coherent (classical) light

No quantum “bit" possible

Superconducting qubit: Josephson junction



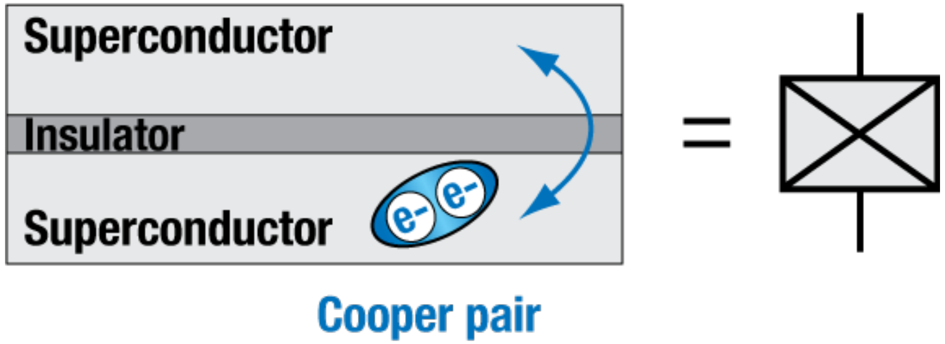


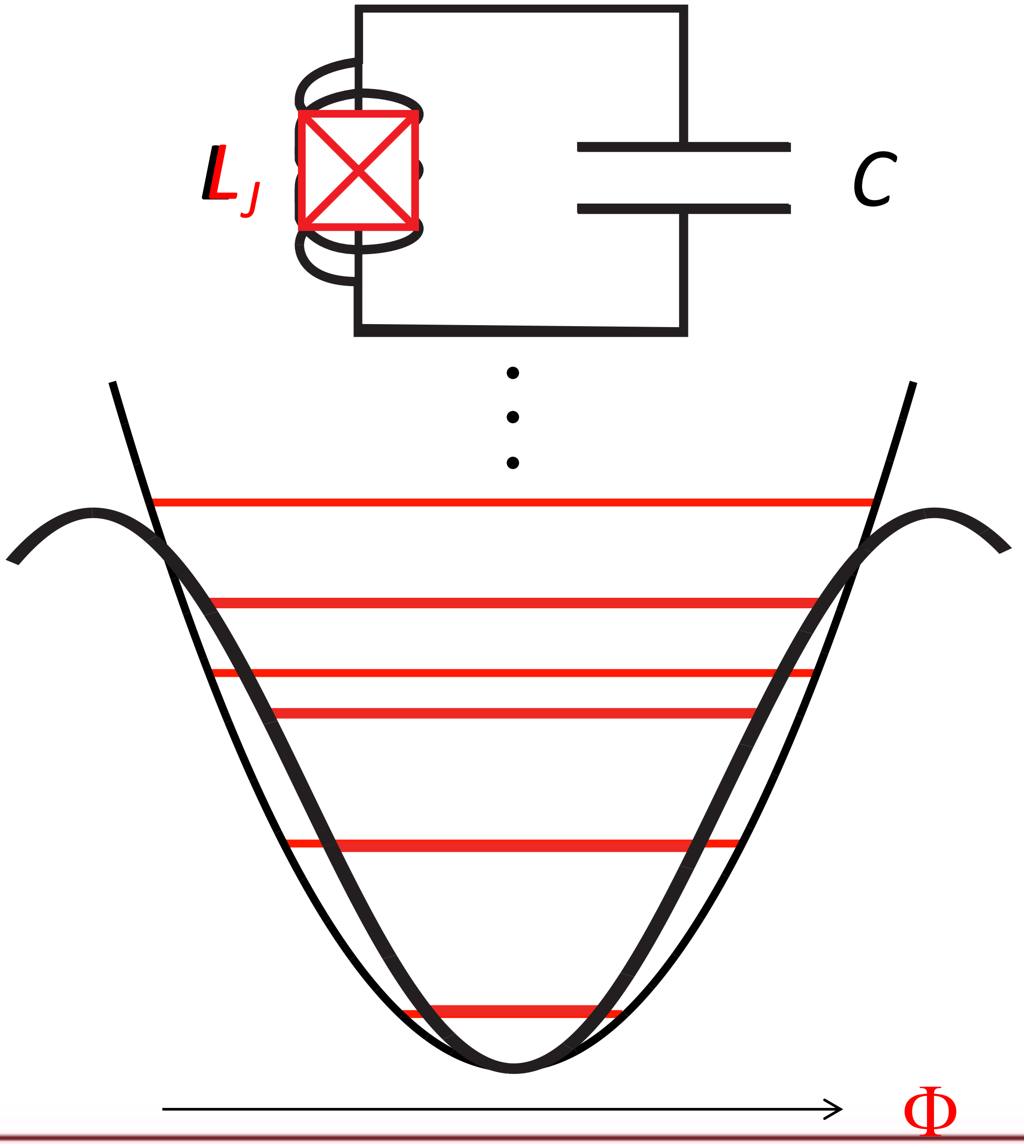
$$H_q = \frac{Q^2}{2C} - \underline{\frac{\hbar I_0}{2e}\cos\left(2\pi\frac{\Phi}{\Phi_0}\right)}$$

I_0: critical current of Junction
$\Phi_0 = h/2e$: Flux quantum

- Point-like lumped element inductance
- Non-liner & **Non dissipative inductance** at a **single quantum of energy (single "microwave photon")**

Superconducting qubit: Josephson junction





- Point-like lumped element inductance
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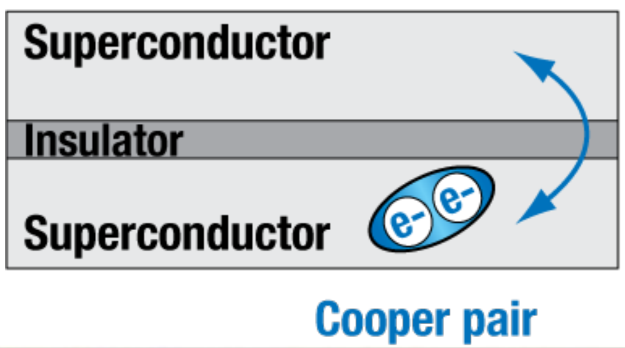
Superconducting qubit: Josephson junction



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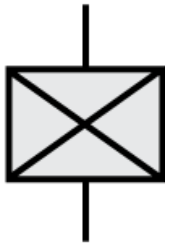
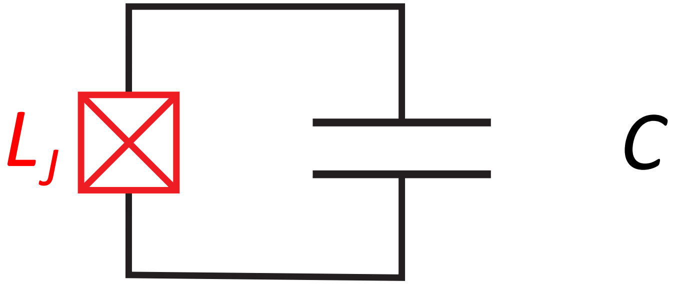
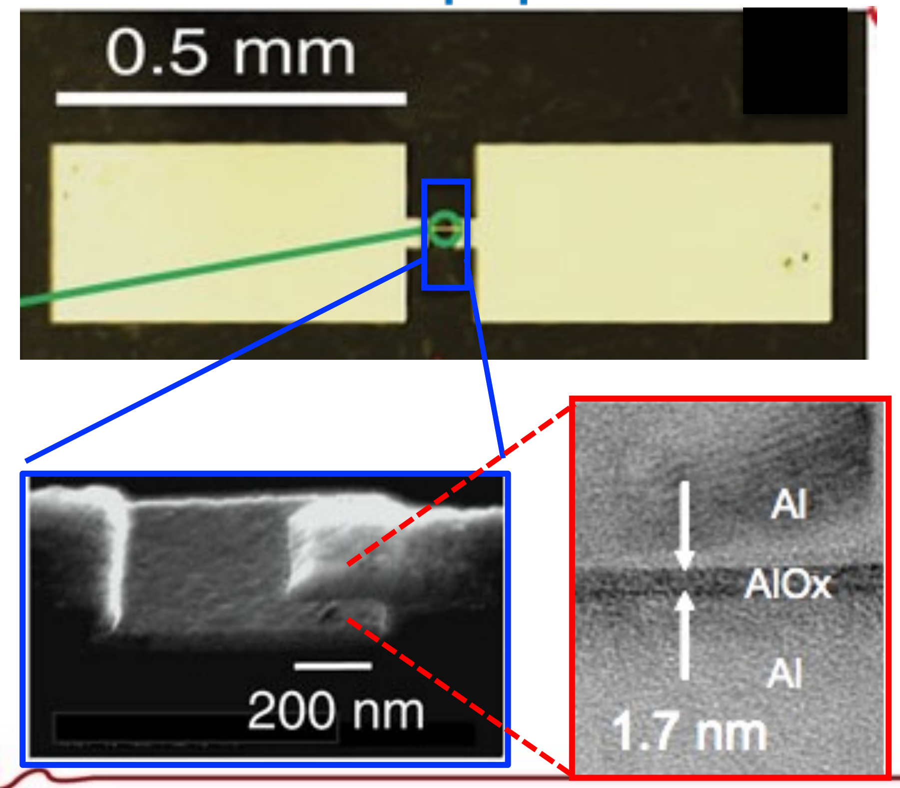
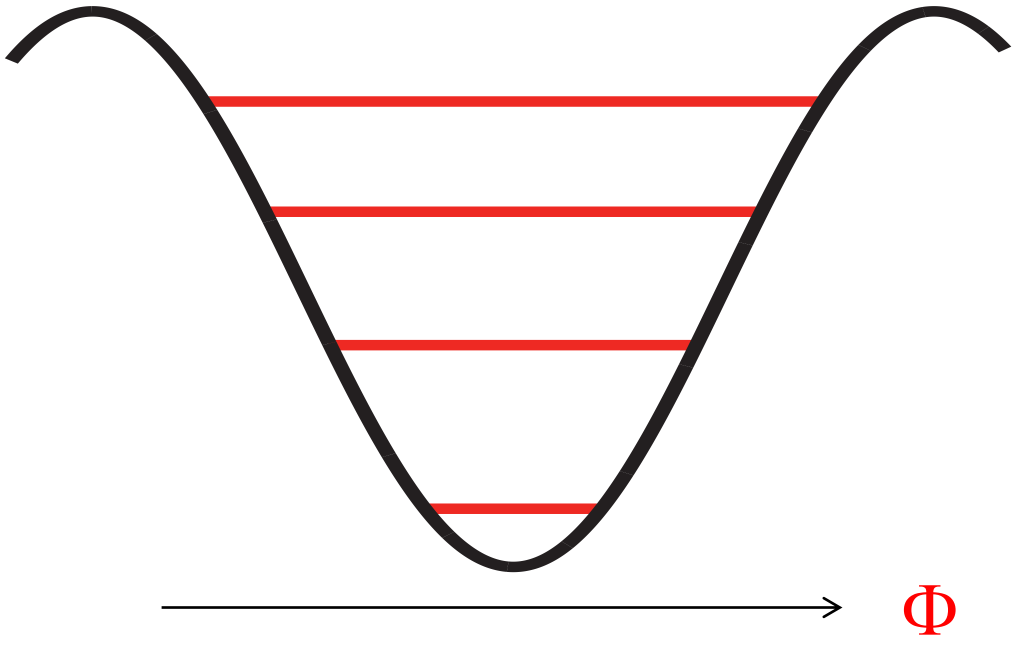
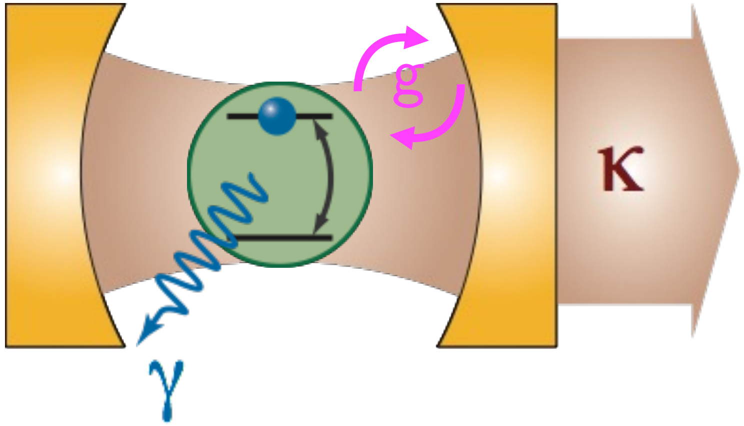


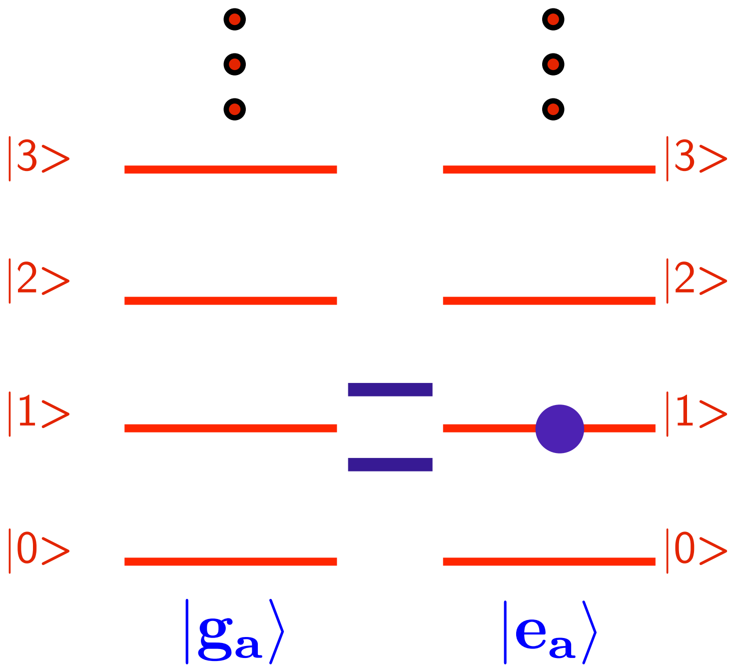






Cavity-QED



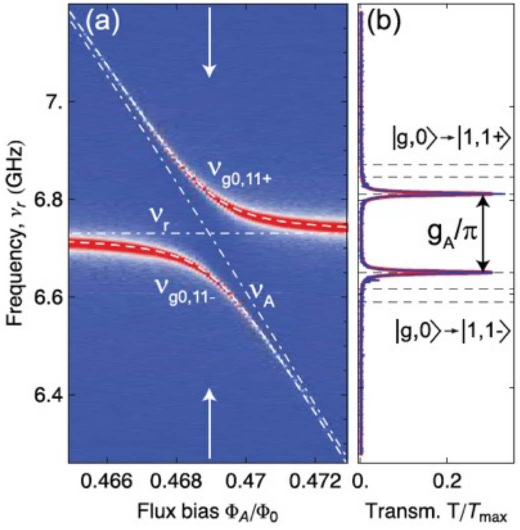


Vacuum Rabi Oscillation

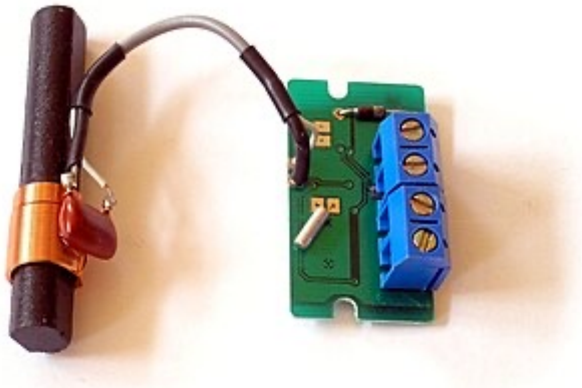
$$H_{\mathrm{JC}}/\hbar = \omega_r a^\dagger a + \frac{1}{2}\omega_a \sigma_z + g(a^\dagger \sigma^- + a\sigma^+)$$

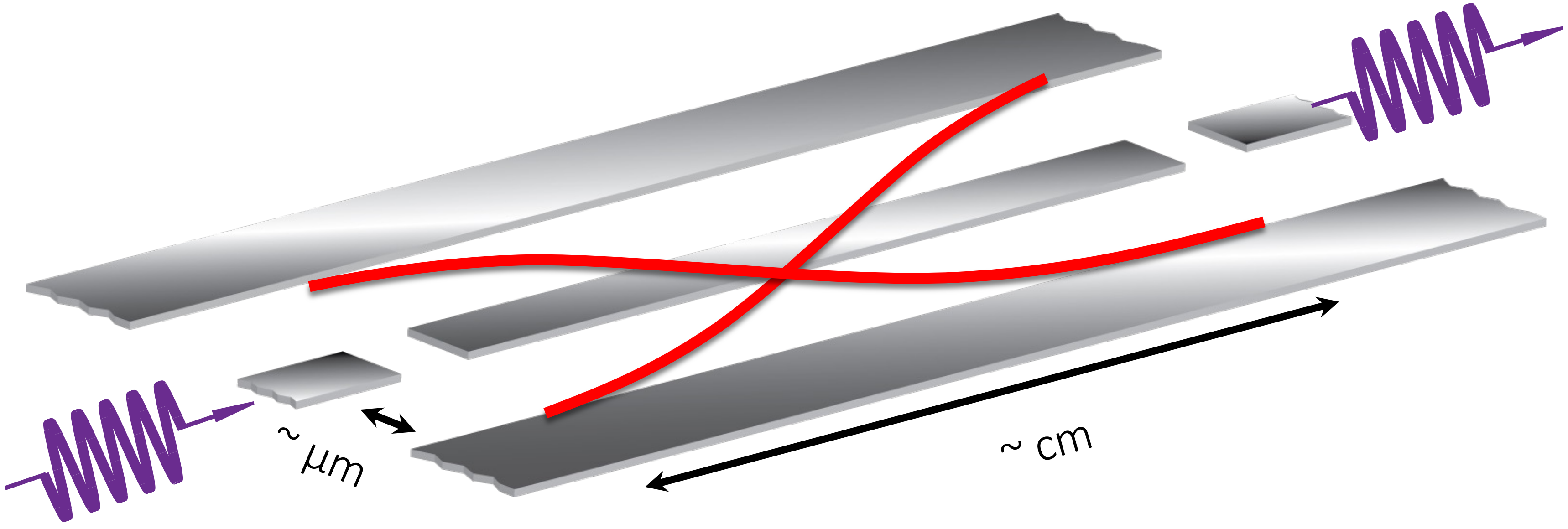
$$g \gg \kappa, \gamma$$

Strong coupling



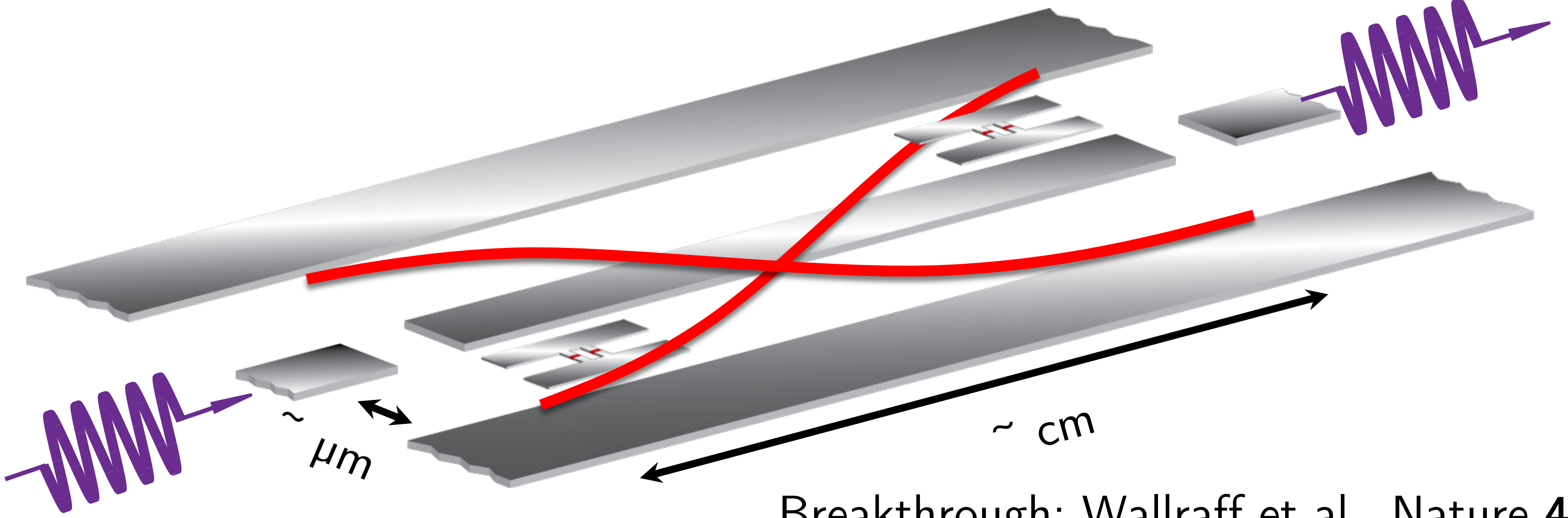
Microwave LC resonator


(from wikipedia)



- Losses and parasitic effect in "bulky lumped element"
- Low-loss and reliable designability using planar superconductor
- 2D version of "coaxial line" (e.g. cable from wall to TV)

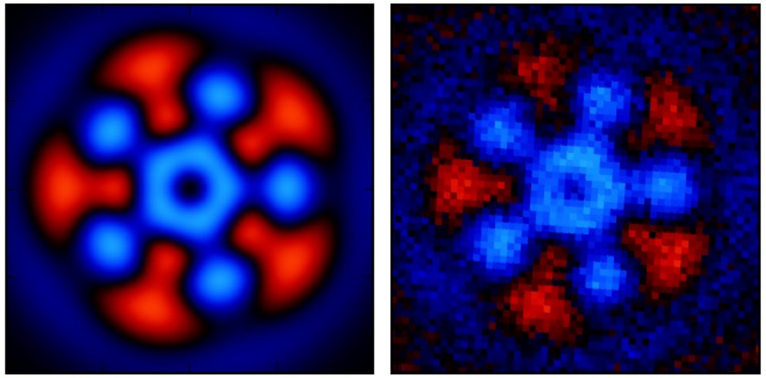
Circuit-QED



Breakthrough: Wallraff et al., Nature **431** 162 (2004)

- Strong coupling of "macroscopic" qubit to microwave photons
- Gigantic dipole -> unprecedented parameter regime
- Manipulating and detecting **single artificial atoms and single microwave photons**

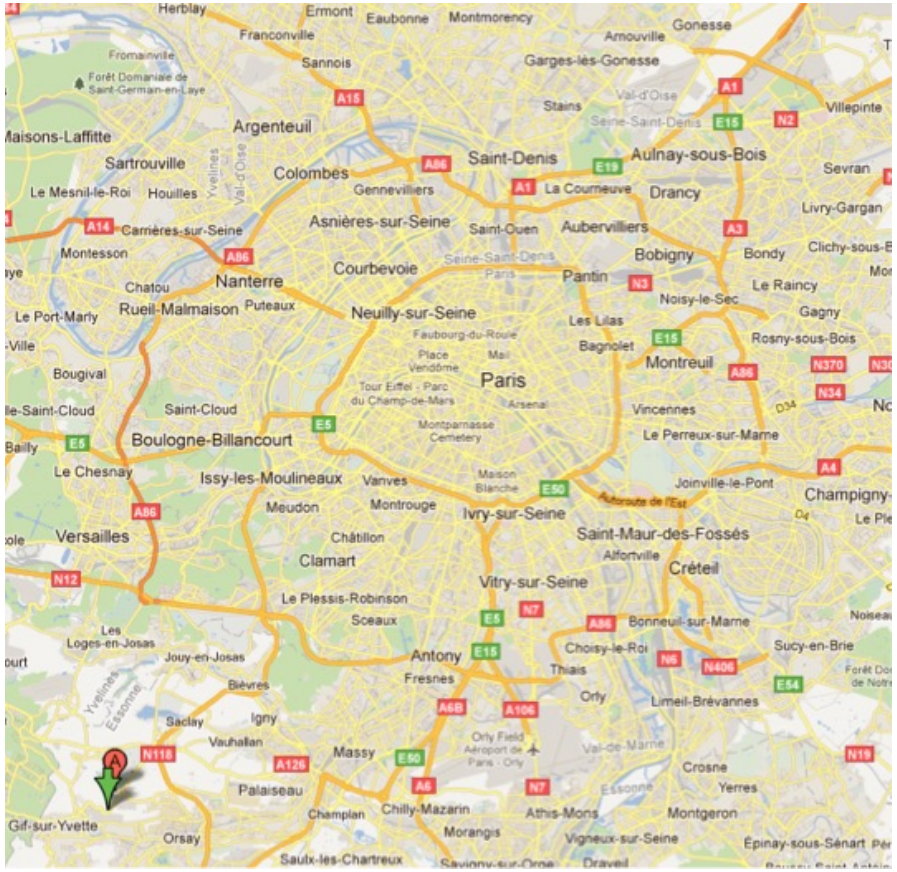
Wigner function of $|0\rangle + |5\rangle$

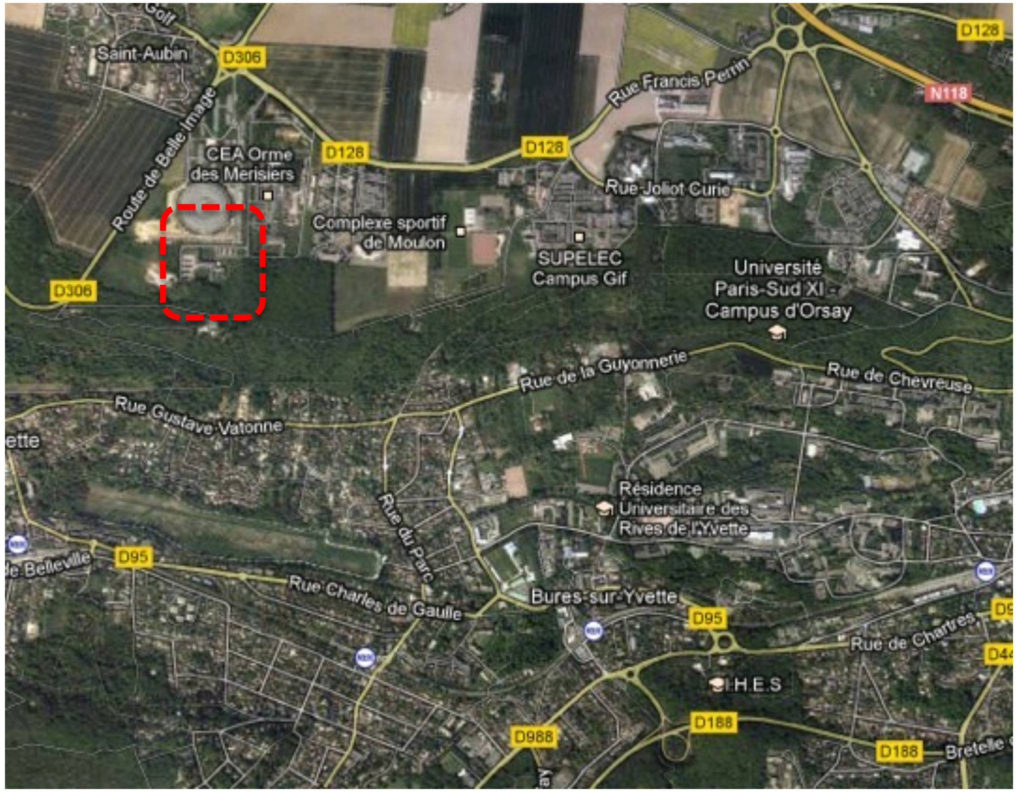


M. Hofheinz *et al.* Nature **459**, 546 (2009)

CEA-Saclay

CEA = Atomic Energy Comission (and Alternative Energy)





20 km from Paris

QUANTum electRONICS Group at CEA-Saclay

Spins in solids

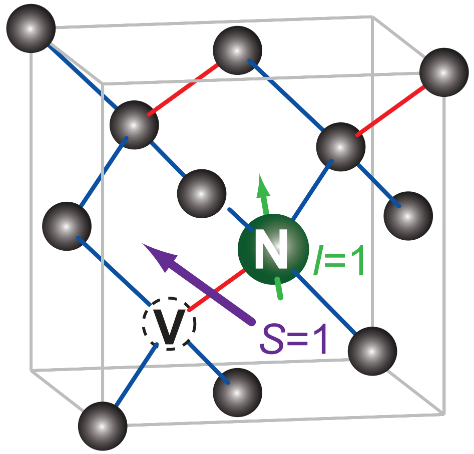
- Very good coherence in “silent” environment (e.g., ^{12}C, ^{28}Si)
- Both microwave (spin) and optical (orbital) transitions
- Scalability, designability ?
- Control on demand ?

Complementary for superconducting circuits

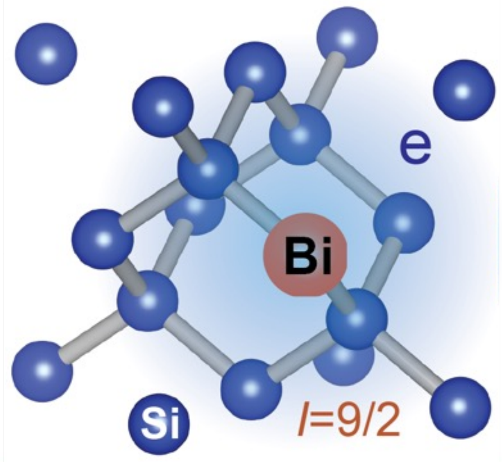
↓

Hybrid quantum systems

NV centers in diamond



P (Bi) donors in Silicon

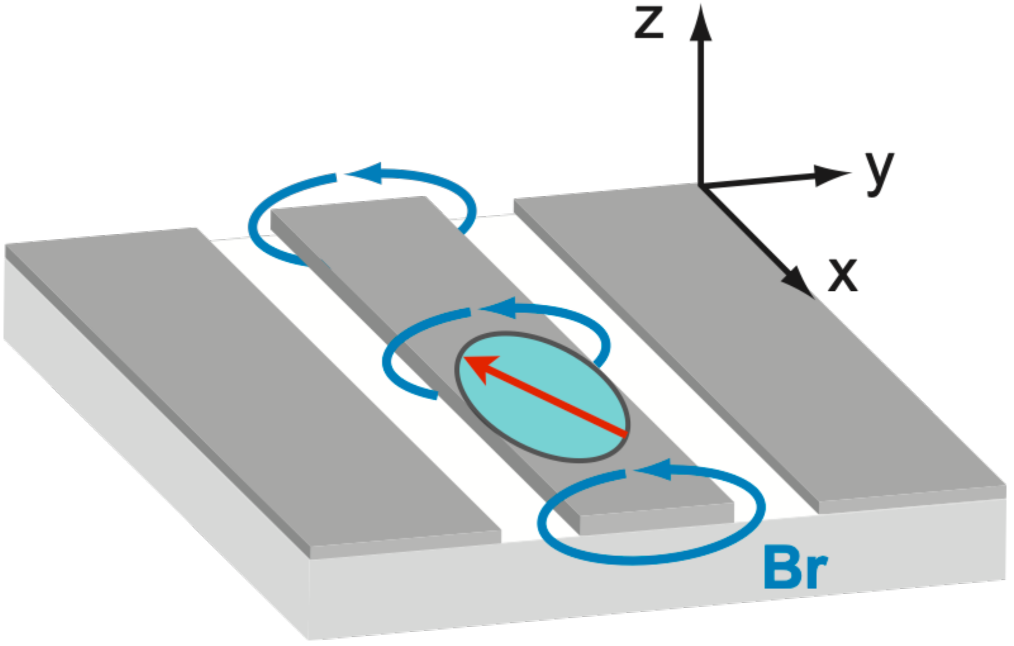


Coupling a single spin to a resonator

- magnetic dipole coupling constant:

$$g/2\pi = \frac{g_{NV}\mu_B\delta B_0}{h}$$

- Assuming 'conventional' coplanar waveguide geometry,
- Single spin coupling: $\sim 1 - 10$ Hz



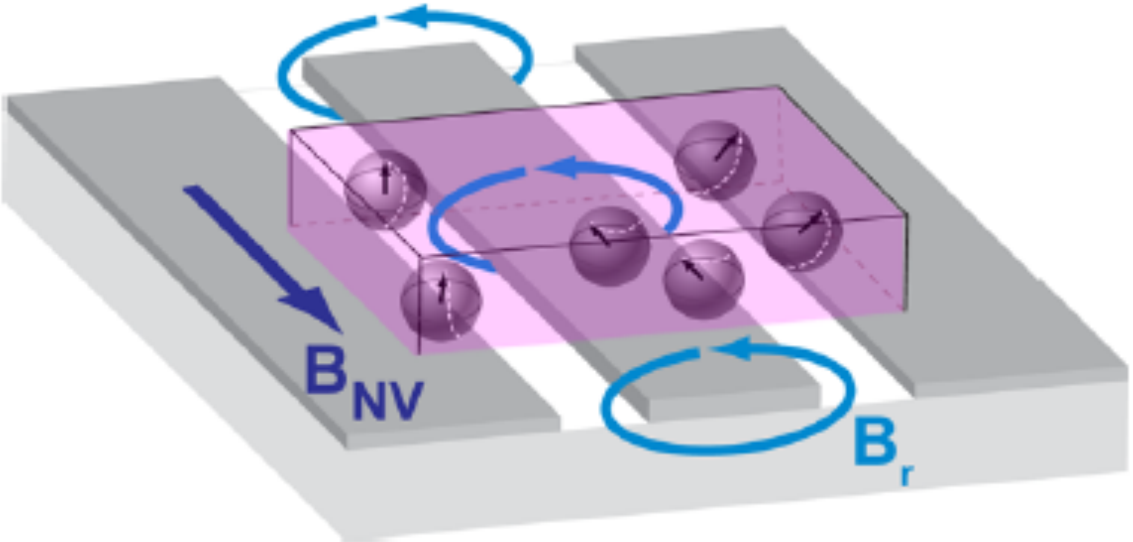
Quantum memory proposal : B. Julsgaard , C. Grezes, P. Bertet and Klaus MØlmer, PRL 110, 250503 (2013)

Coupling many spins to a resonator

- Coupling with N spins:

$$g_{ens} \sim \sqrt{N} g$$

- Coupling N = 10^{12} ($\sim 10^{18}$ cm^{-3}) spins
- Collective coupling of **~ 1 – 10 MHz**



$$H = \sum g_k \left(a\sigma_{k,+} + a^+\sigma_{k,-} \right)$$

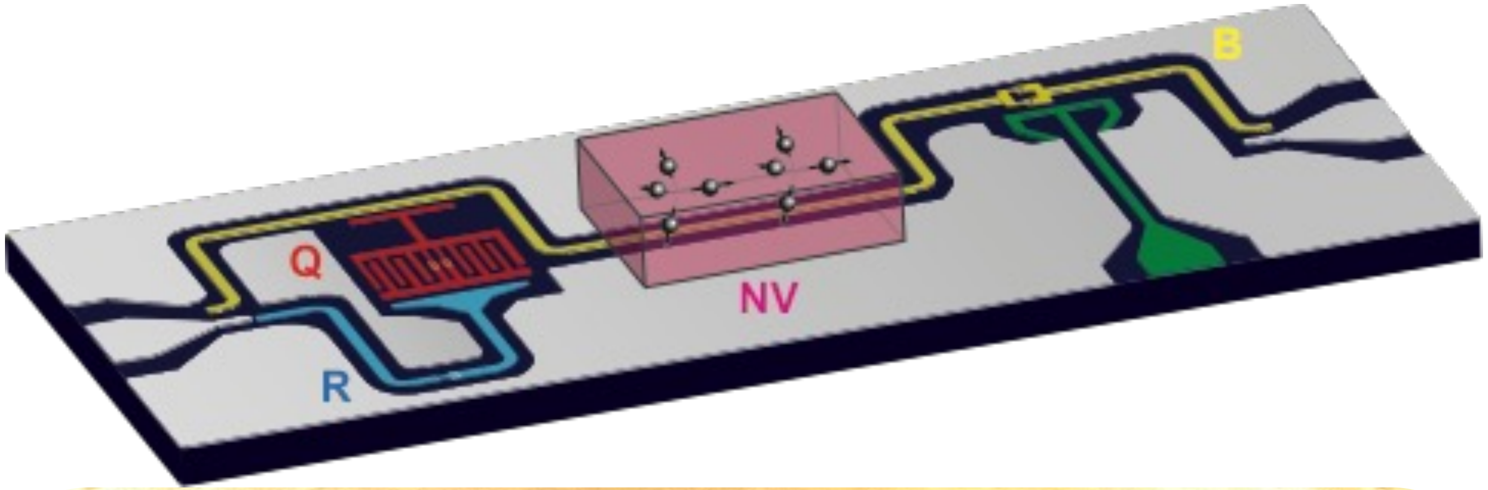
$$\Rightarrow \quad H = g_{ens} \left(aS^+ + a^+S^- \right)$$

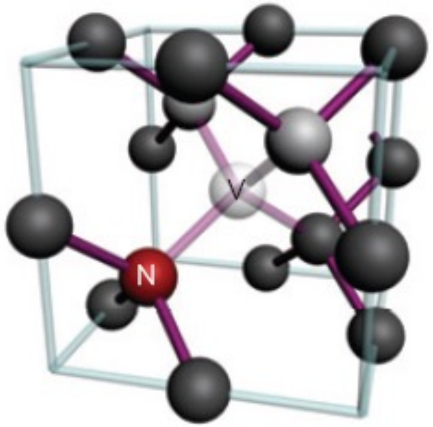
with $\quad S = \sum \left(g_k(r_k) / g_{ens} \right) \sigma_{k,-}$

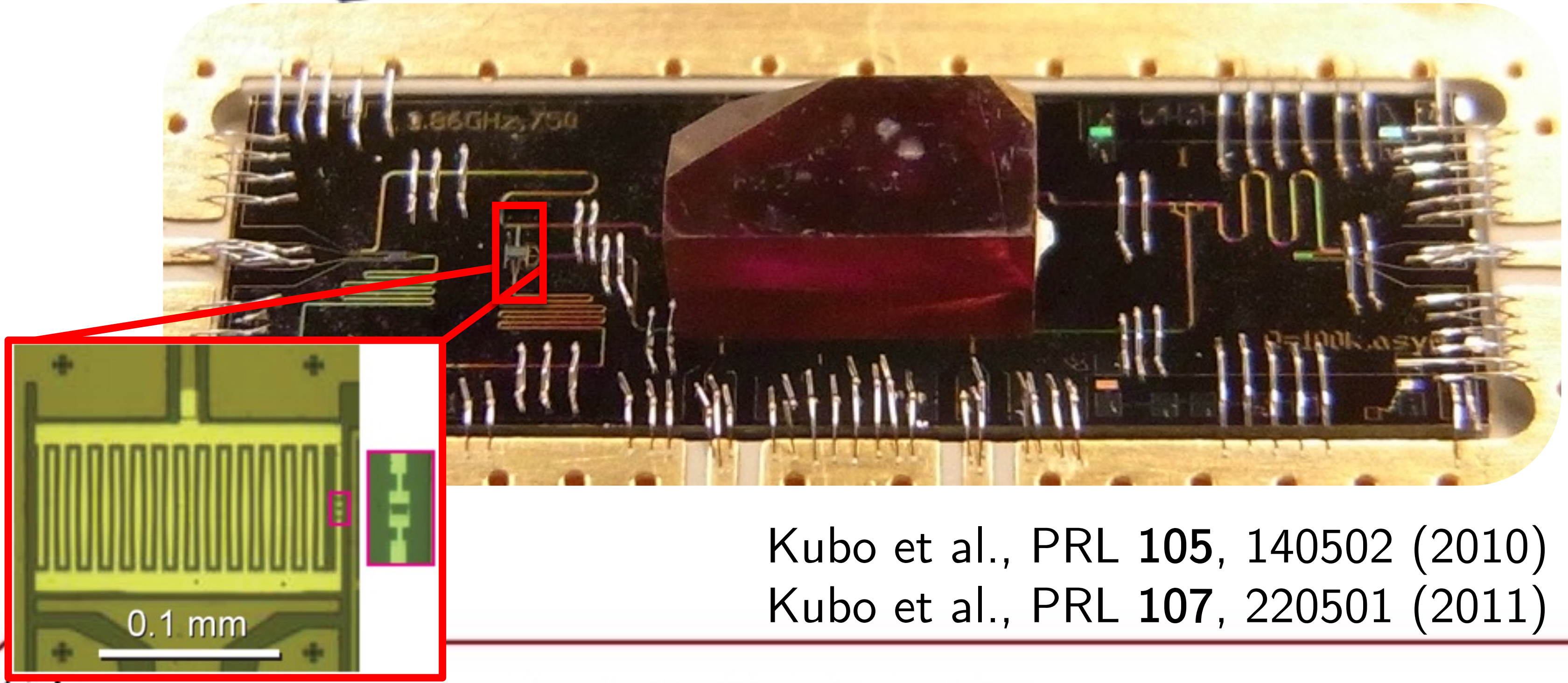
$$|1\rangle \otimes |0_1 0_2 \ldots 0_n\rangle \quad \rightarrow \quad |0\rangle \otimes (g_1|1_1 0_2 \ldots 0_n\rangle + \ldots + g_n|0_1 0_2 \ldots 1_n\rangle)/g_{ens}$$

Quantum memory proposal : B. Julsgaard , C. Grezes, P. Bertet and Klaus MØlmer, PRL 110, 250503 (2013)

The hybrid quantum circuit

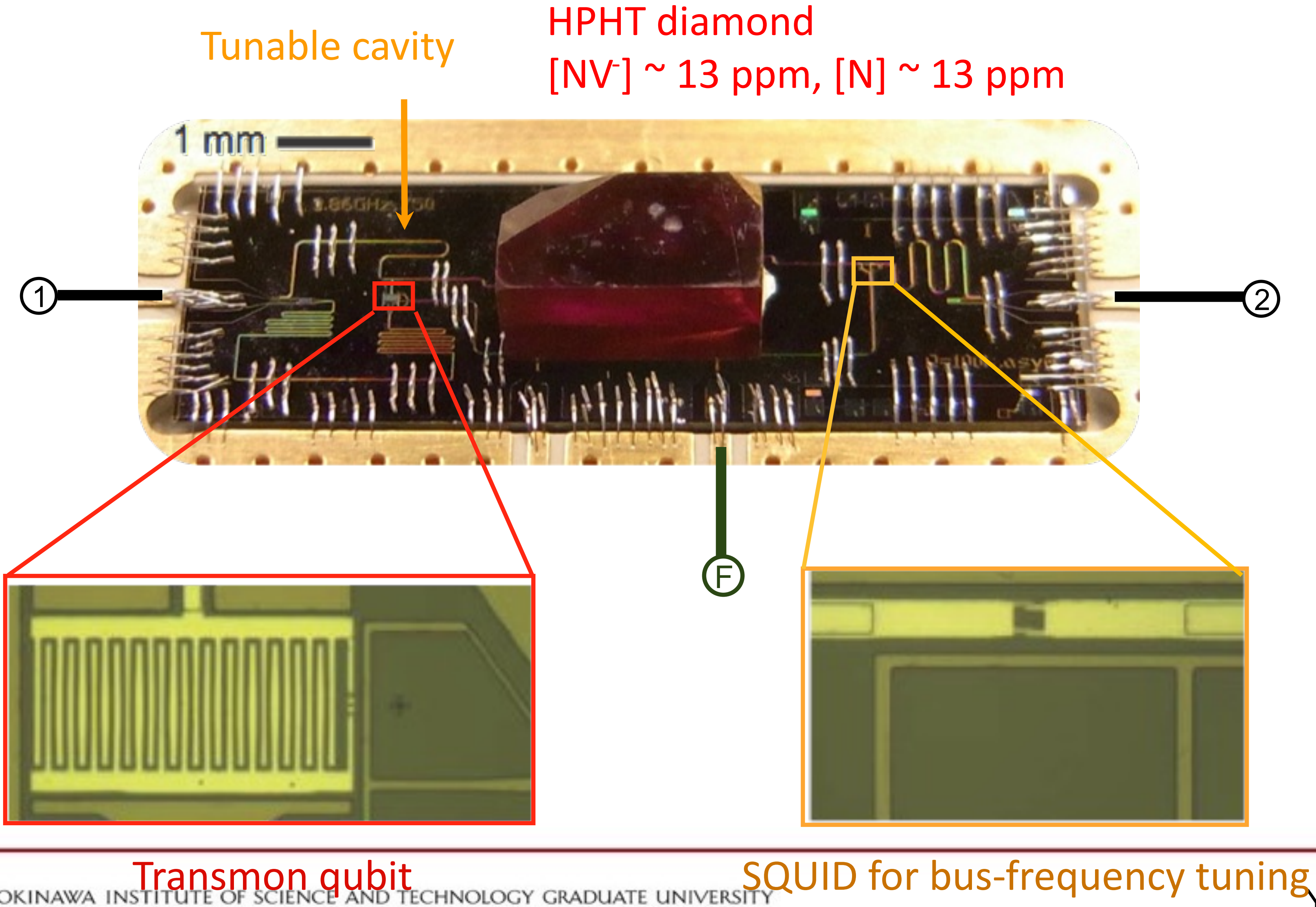






Kubo et al., PRL **105**, 140502 (2010) (photon & spins)
Kubo et al., PRL **107**, 220501 (2011) (qubit, photon, spins)

The hybrid quantum circuit

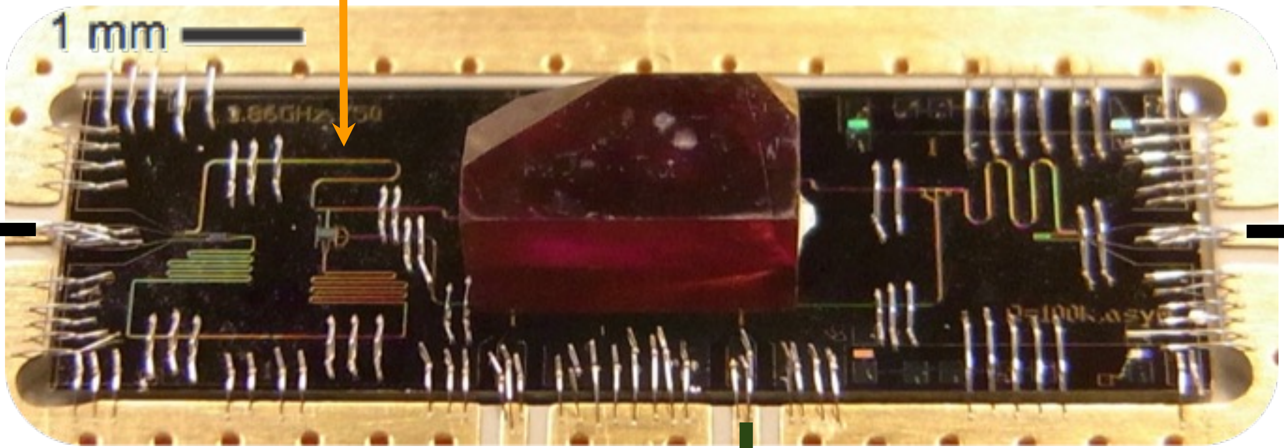


STEP 1 (WRITE): the device

Tunable cavity

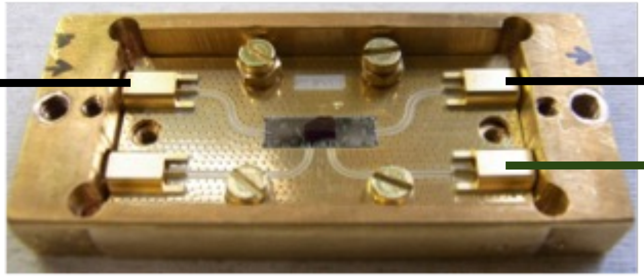
HPHT diamond

[NV-] ~ 13 ppm, [N] ~ 13 ppm



① ② Ⓕ

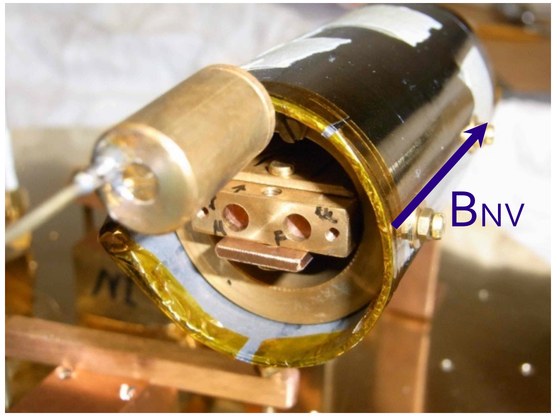
Printed circuit board



① ② Ⓕ

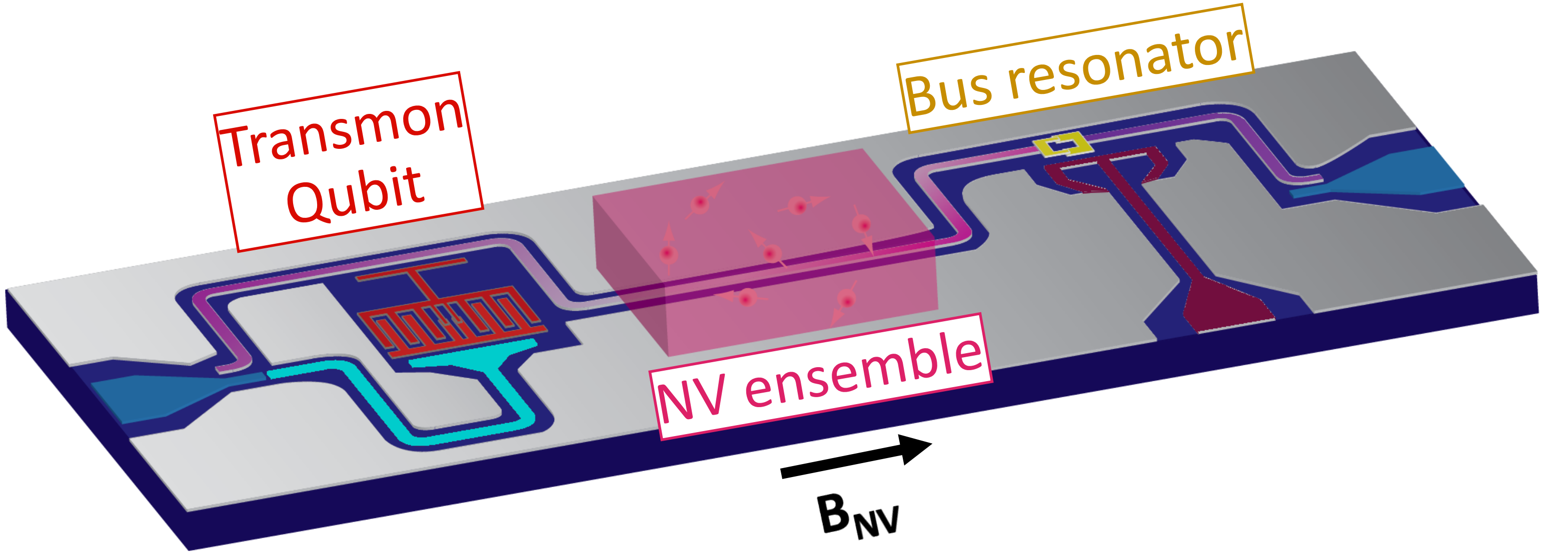
B_{NV} // [111]

External coil

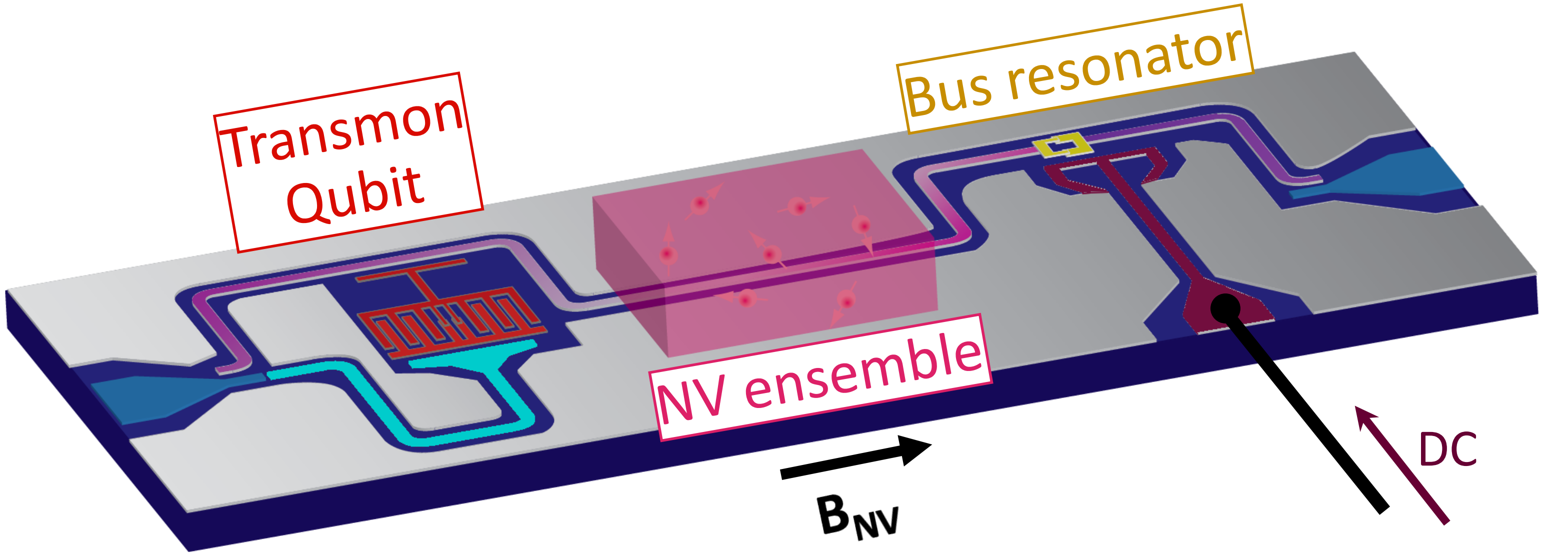


B_{NV}

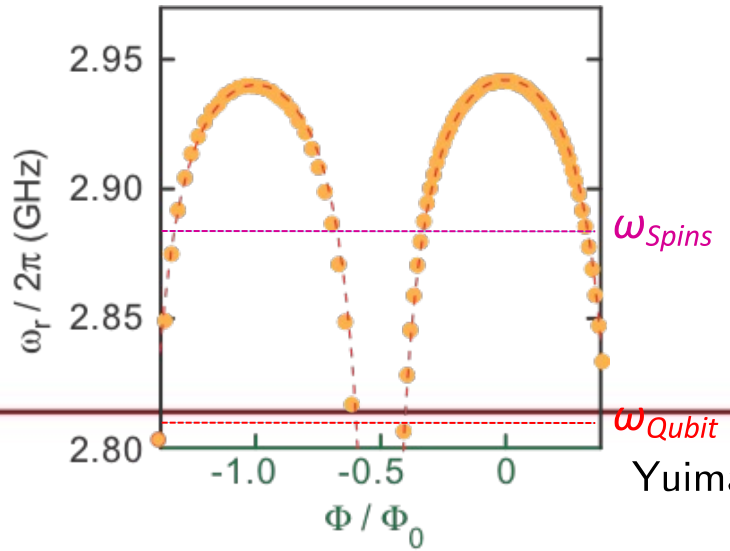
The hybrid quantum circuit



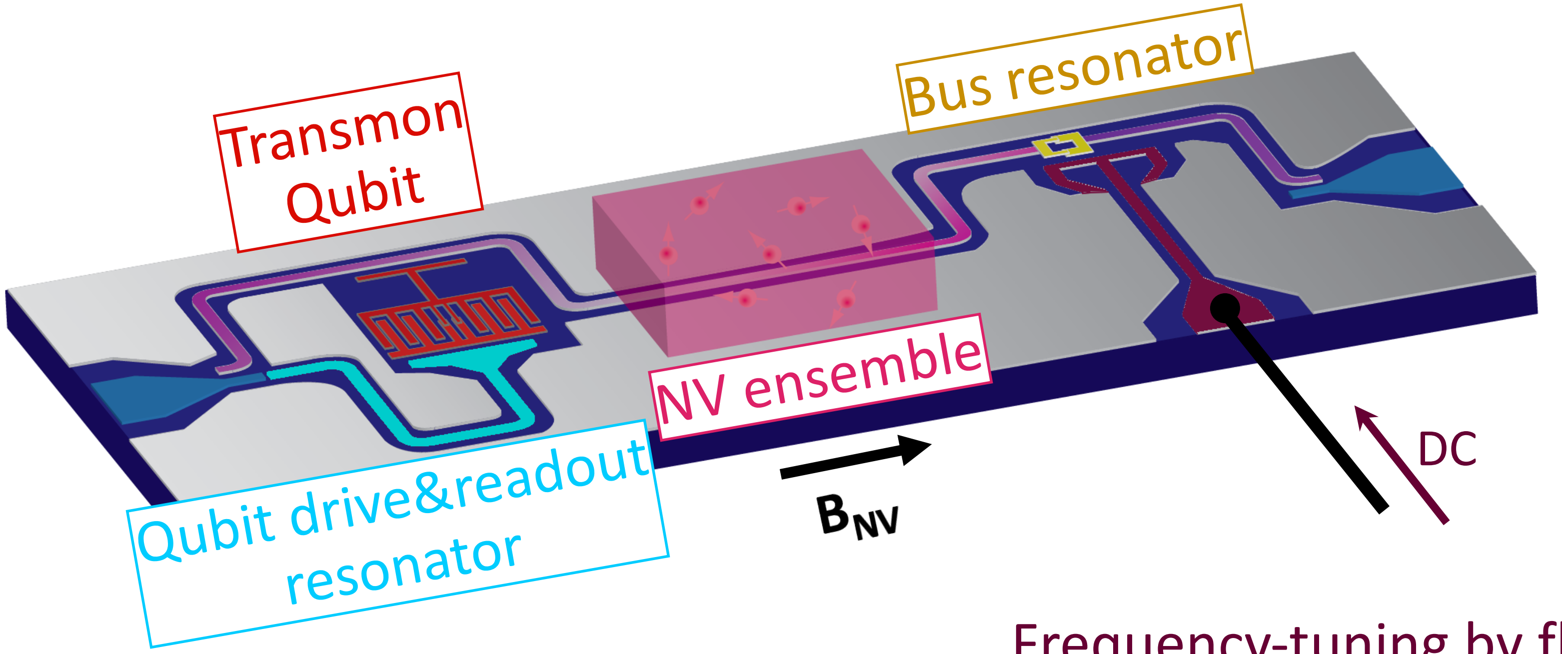
The hybrid quantum circuit



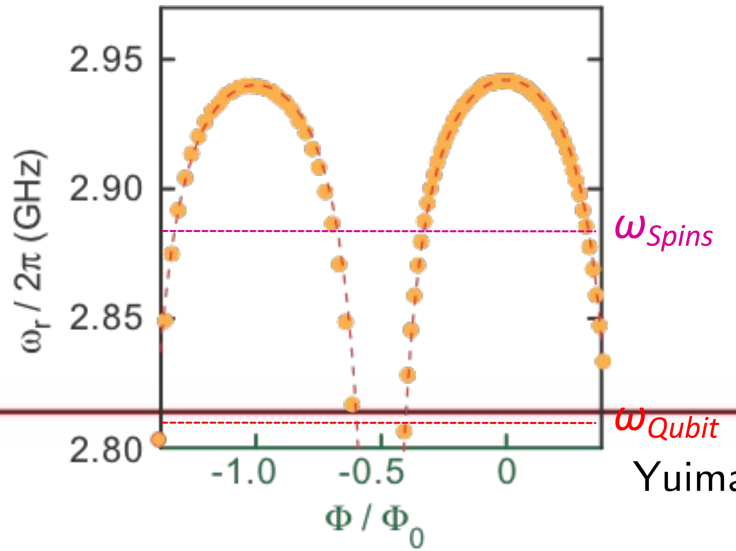
Frequency-tuning by flux



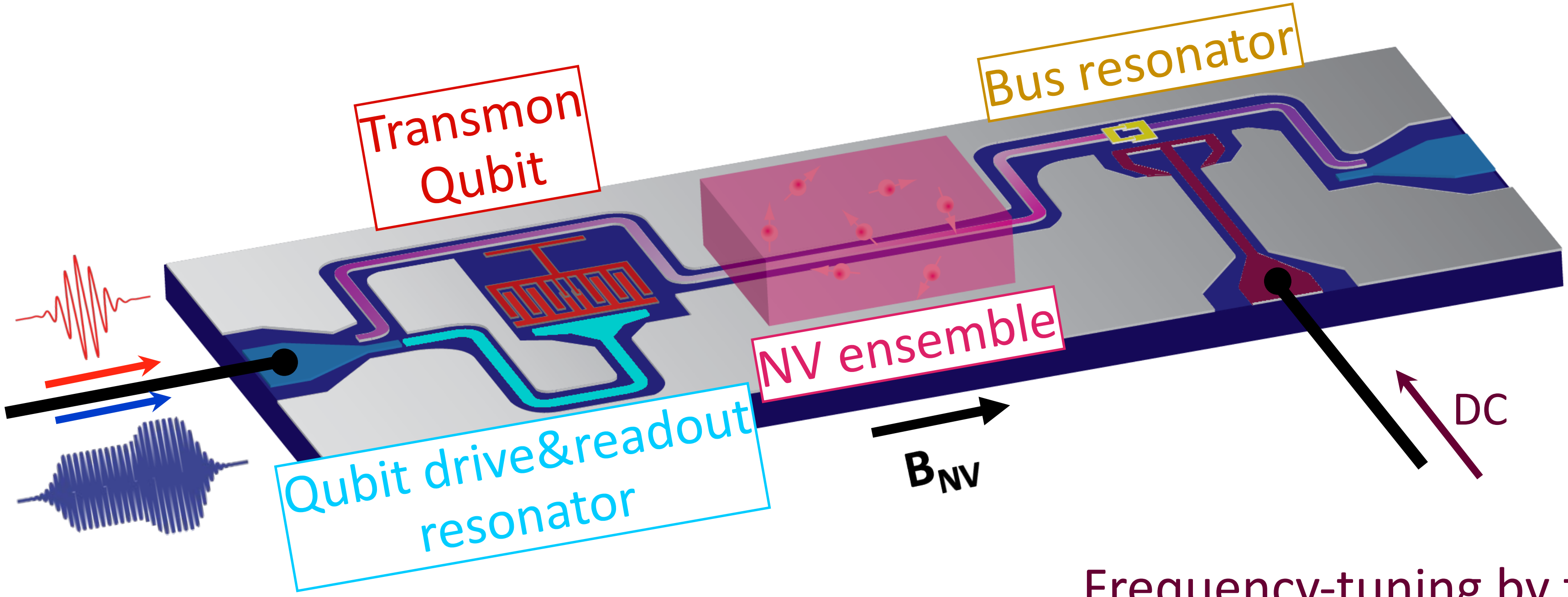
The hybrid quantum circuit



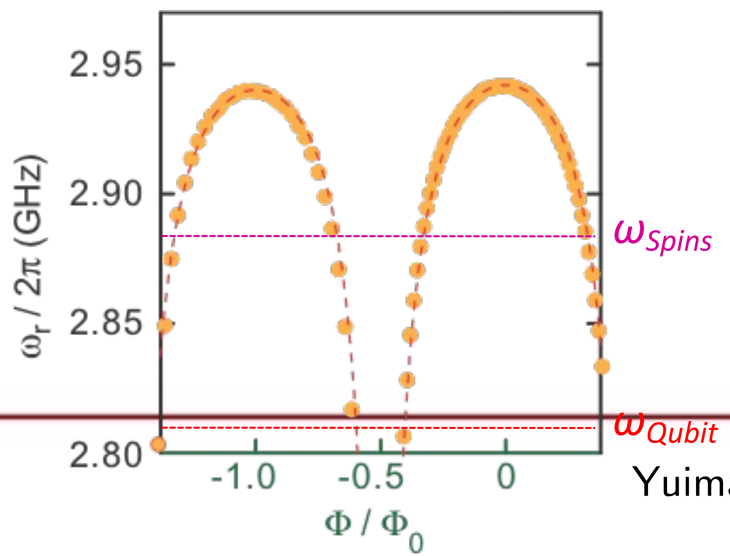
Frequency-tuning by flux



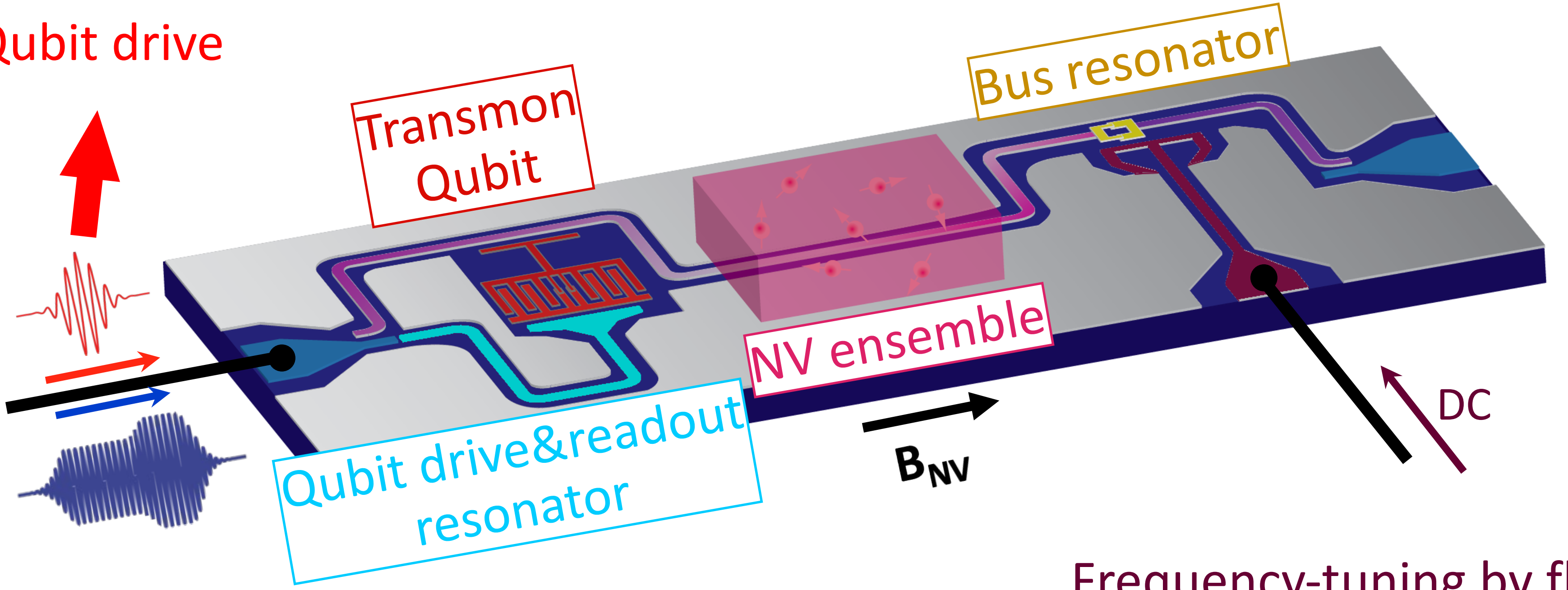
The hybrid quantum circuit



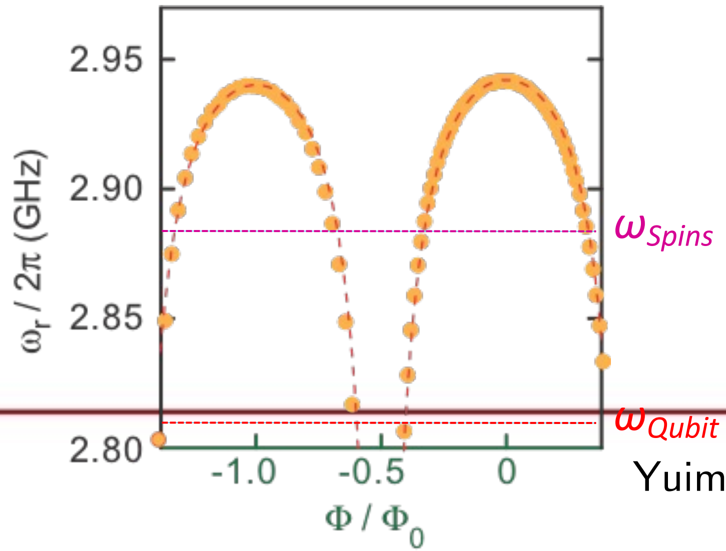
Frequency-tuning by flux



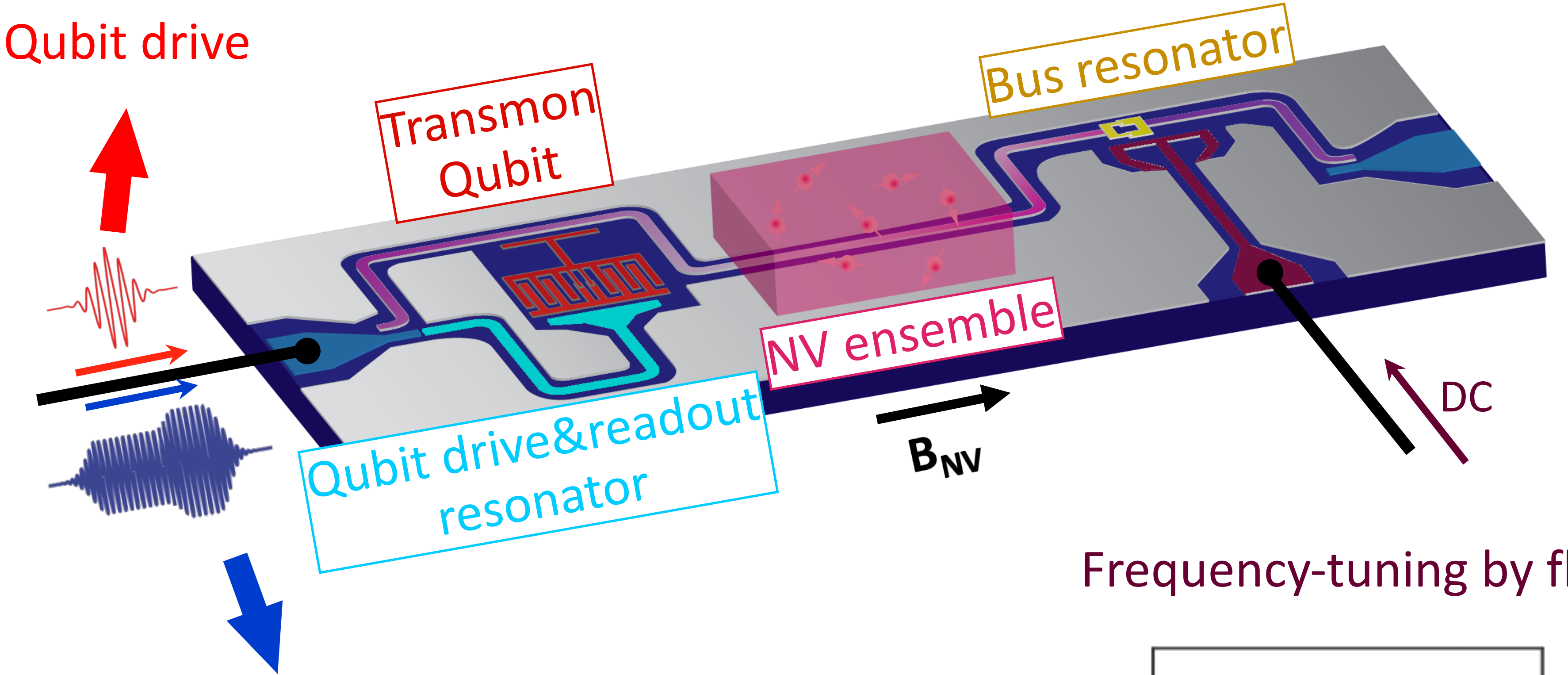
The hybrid quantum circuit



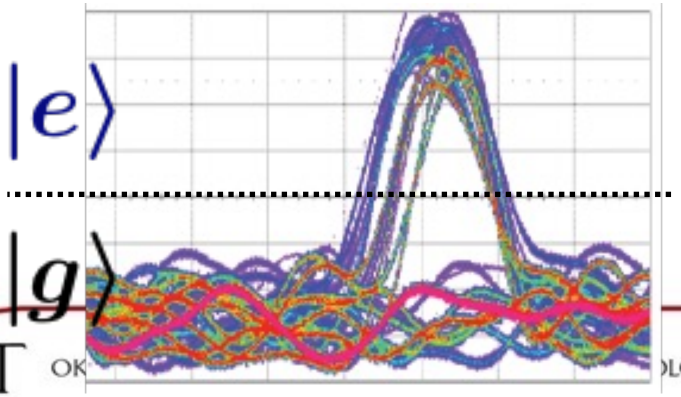
Frequency-tuning by flux



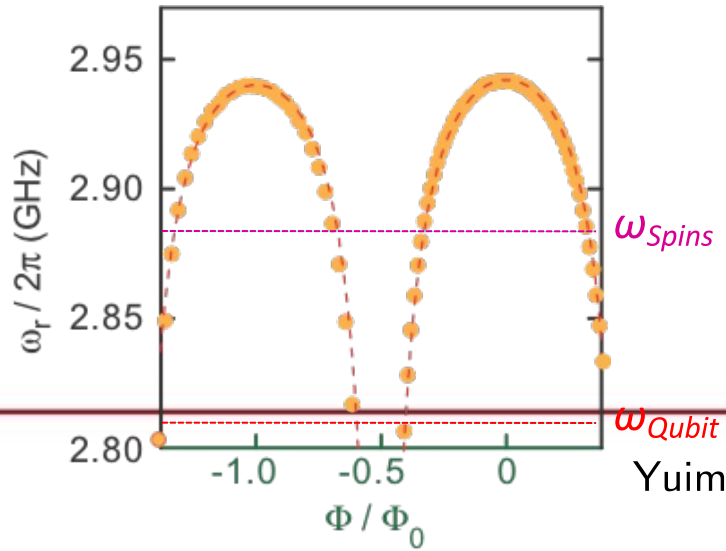
The hybrid quantum circuit



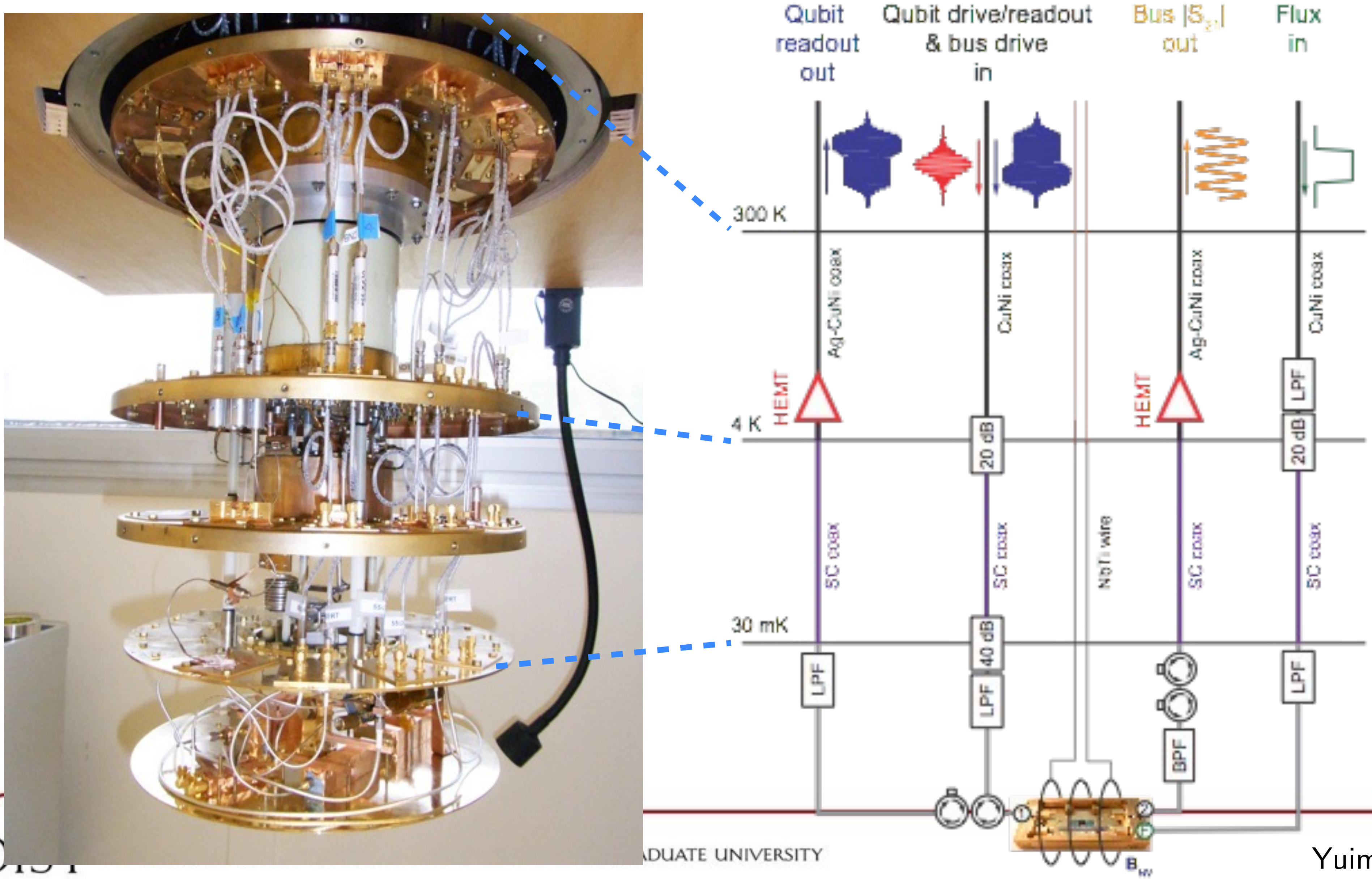
Single-shot Qubit readout



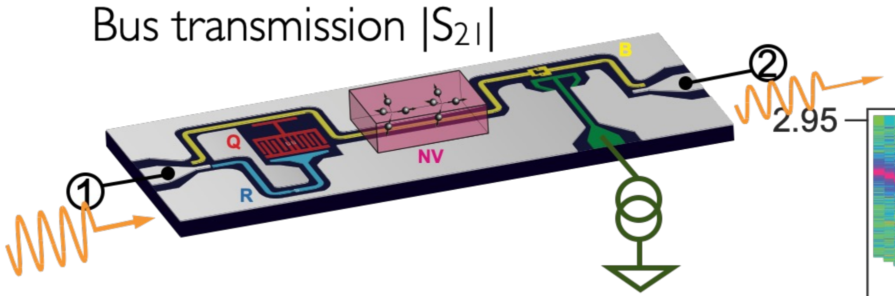
Frequency-tuning by flux

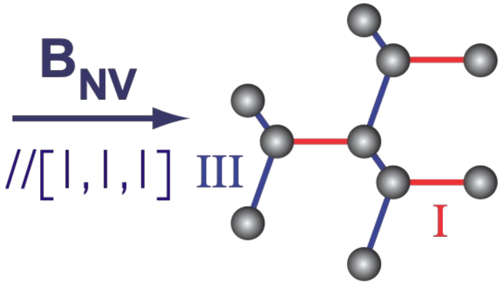


Setup in a dilution fridge

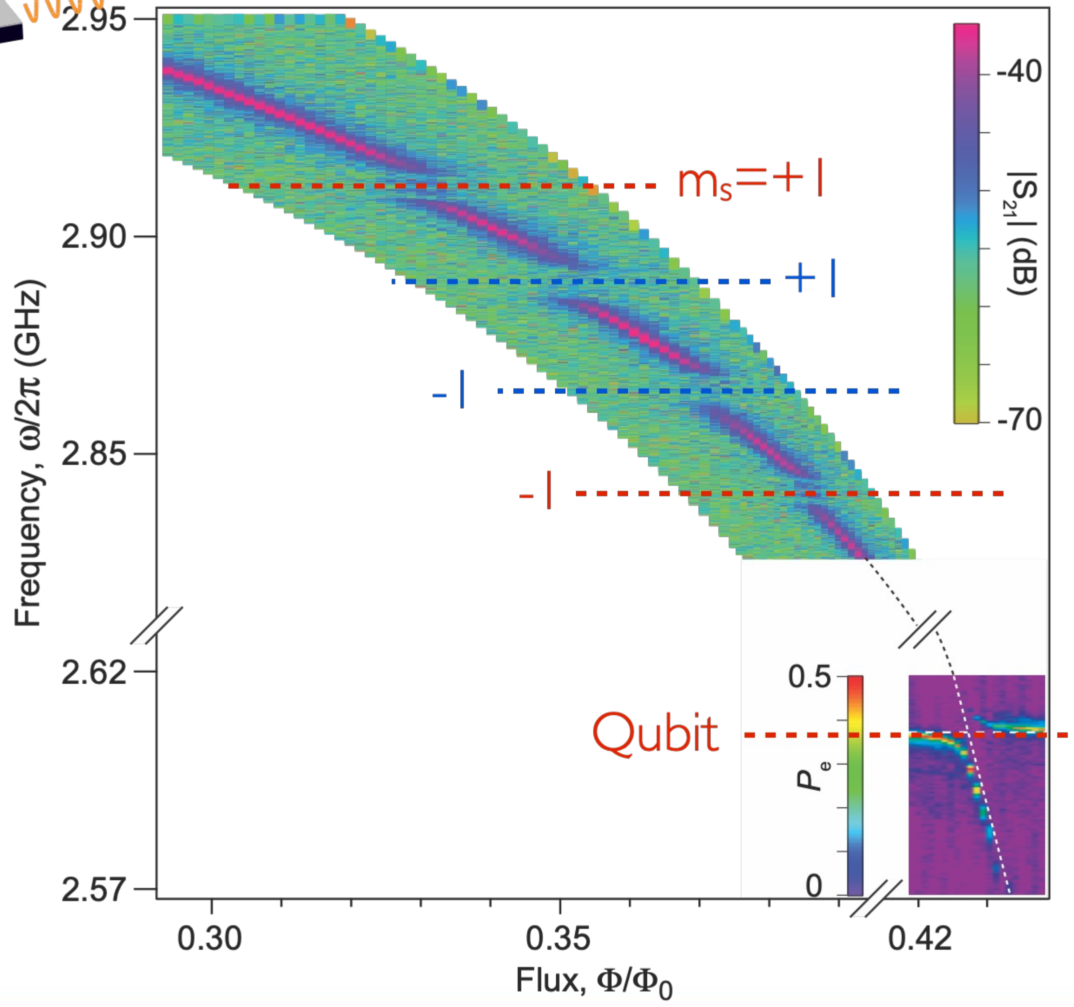


Device characterization: spectroscopy



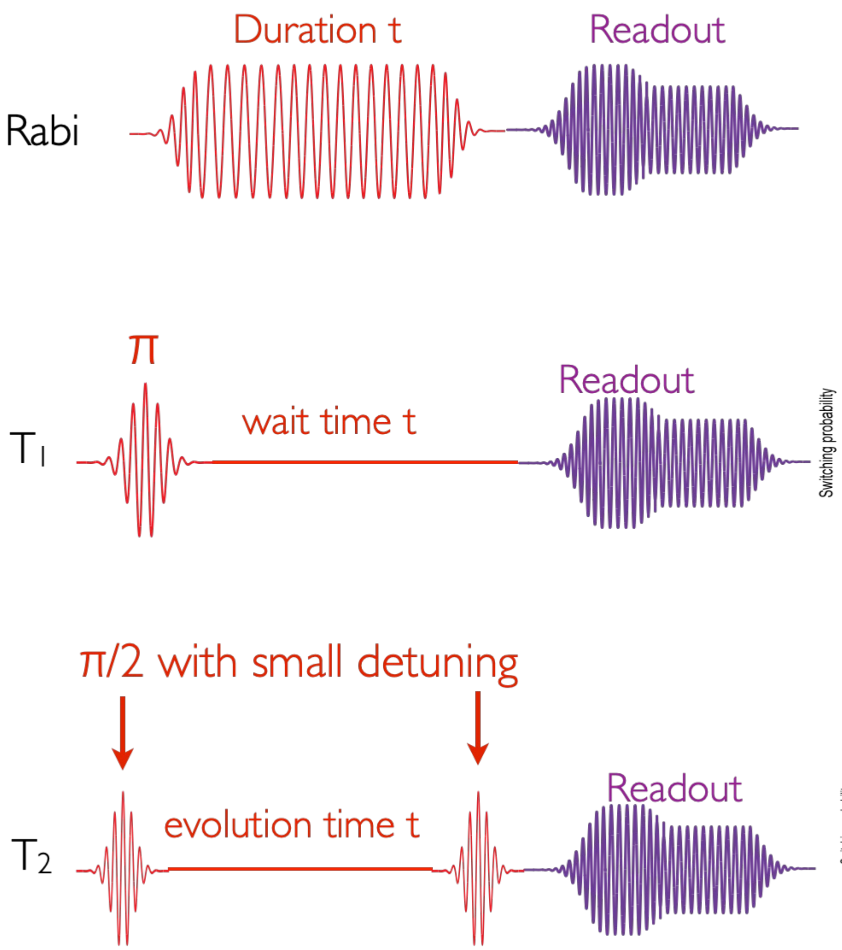


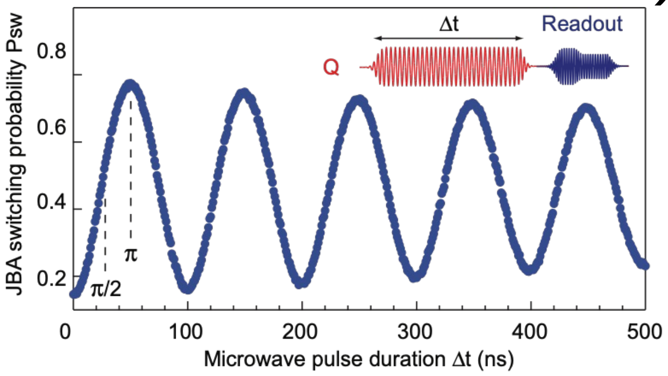
1 isolated bond &
3 degenerated bonds

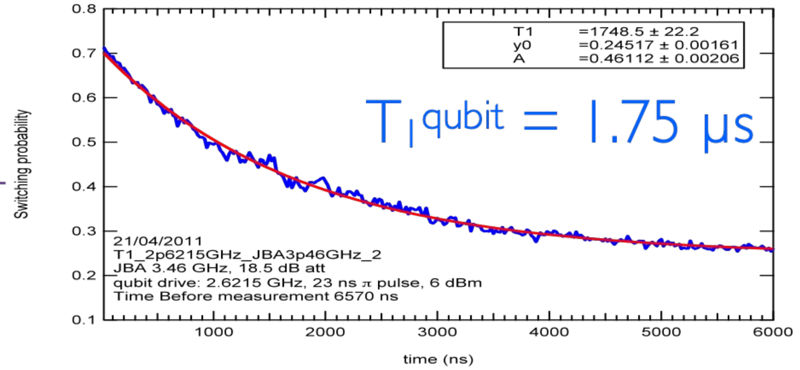


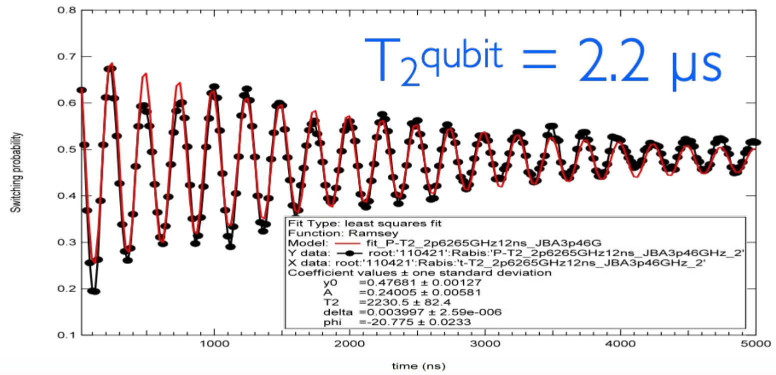
The ‘bad’ qubit (so-so at the time...)

Pulse sequences

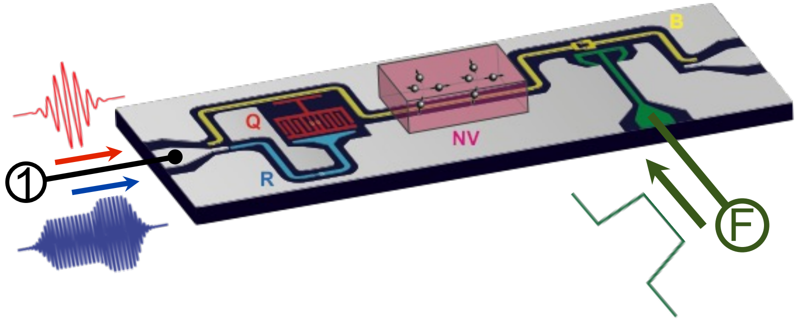


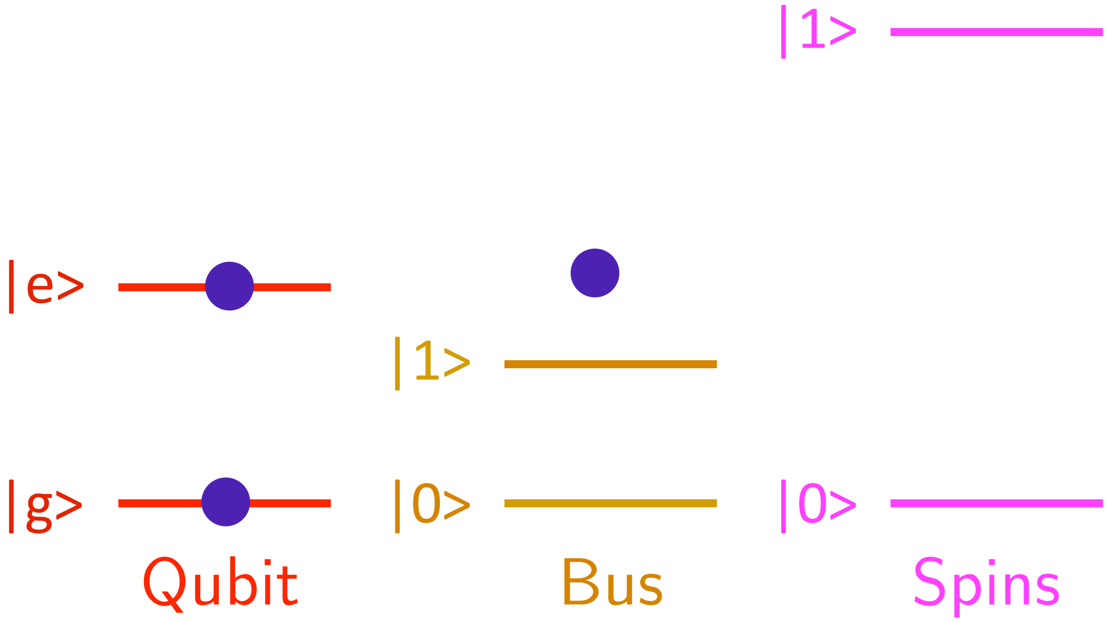


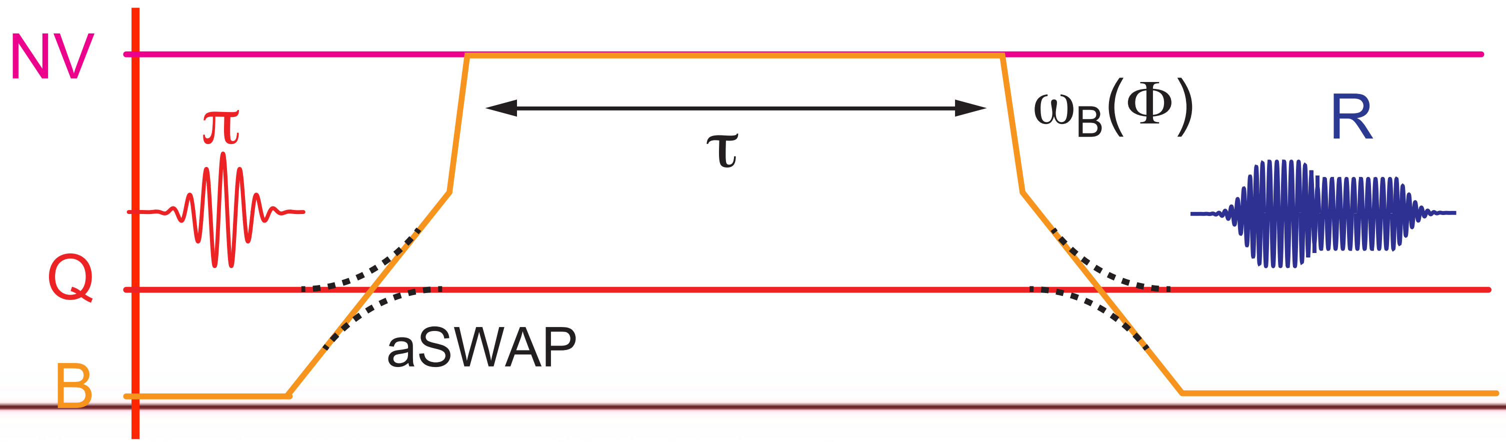




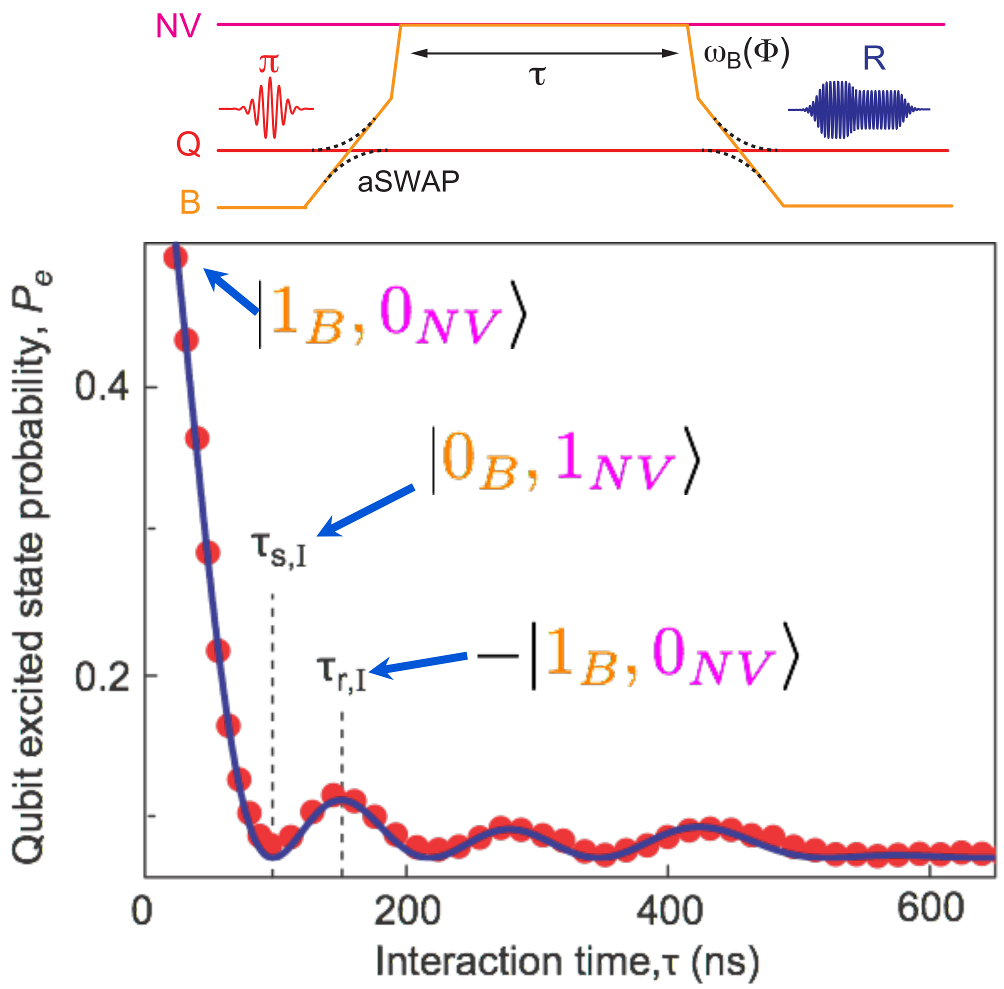
Quantum memory: single μ-wave photon swap







Coupling qubit to spin ensemble: single photon swap



Kubo et al., PRL **107**, 220501 (2011)

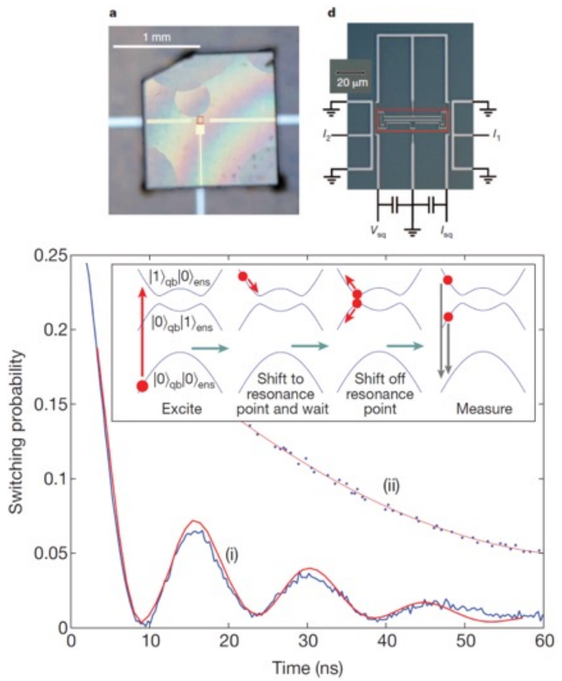
See also: Zhu et al. Nature **478** 221 (2011)

Storage/retrieval of a **SINGLE microwave photon** into/from a spin ensemble

Related works

Storage of $|1\rangle$

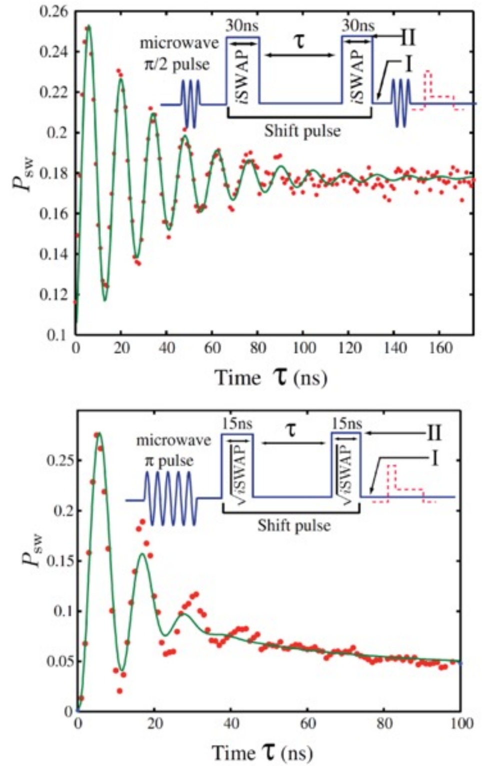
NTT, NV centers



Zhu et al.,
Nature, **478**, 7368 (2011)

Storage of $|0\rangle + |1\rangle$

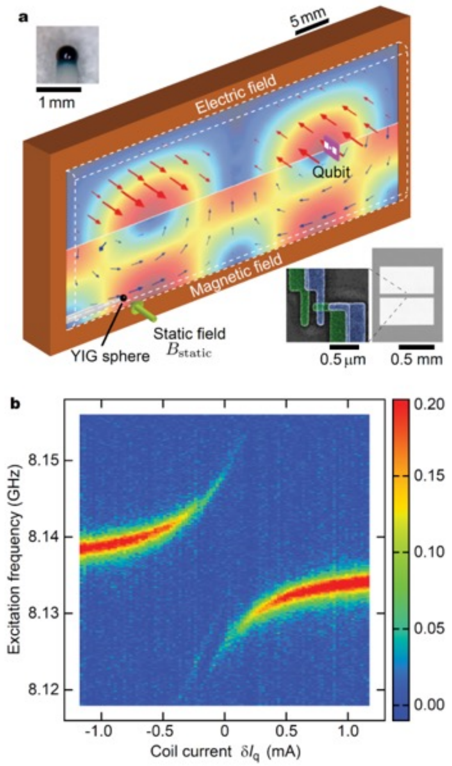
NTT, NV centers



Saito et al.,
PRL, **111** 107008 (2013)

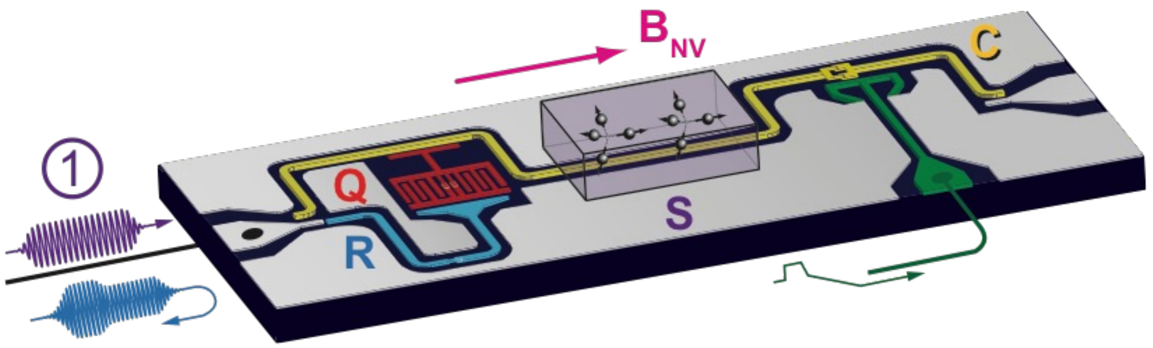
Coherent coupling with a qubit

Tokyo University, YIG

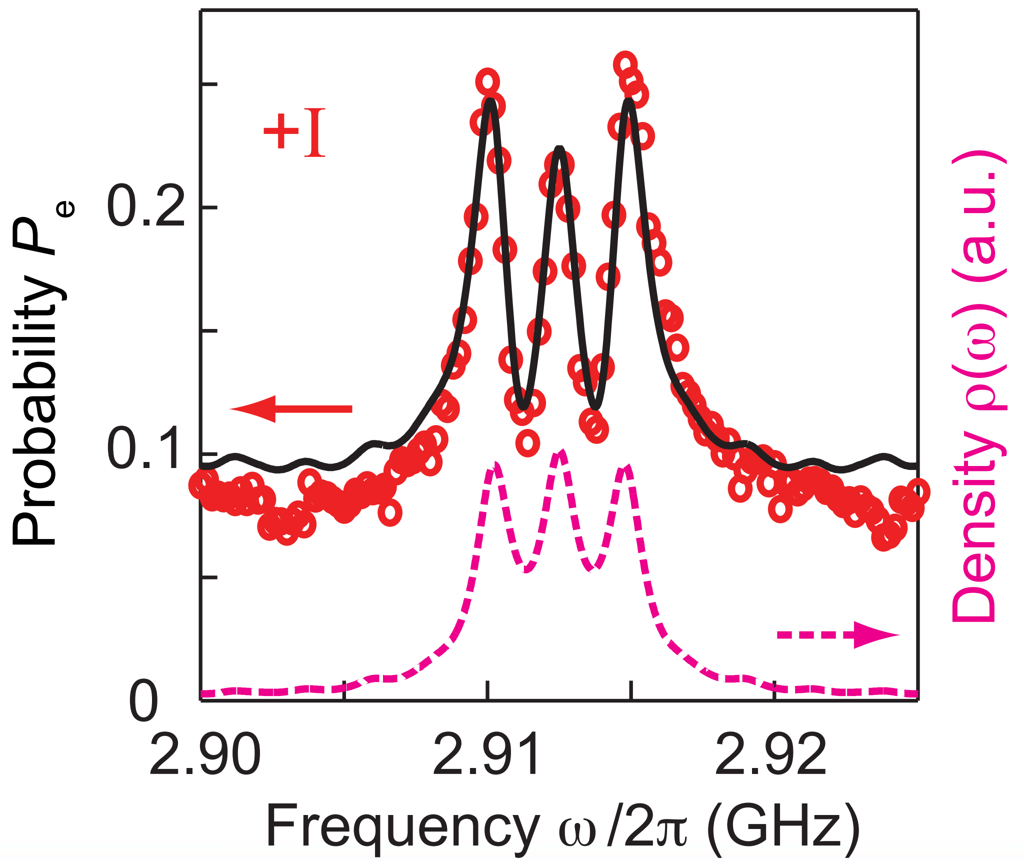


Tabuchi et al.,
Science **349** 405 (2015)

Qubit detected ESR

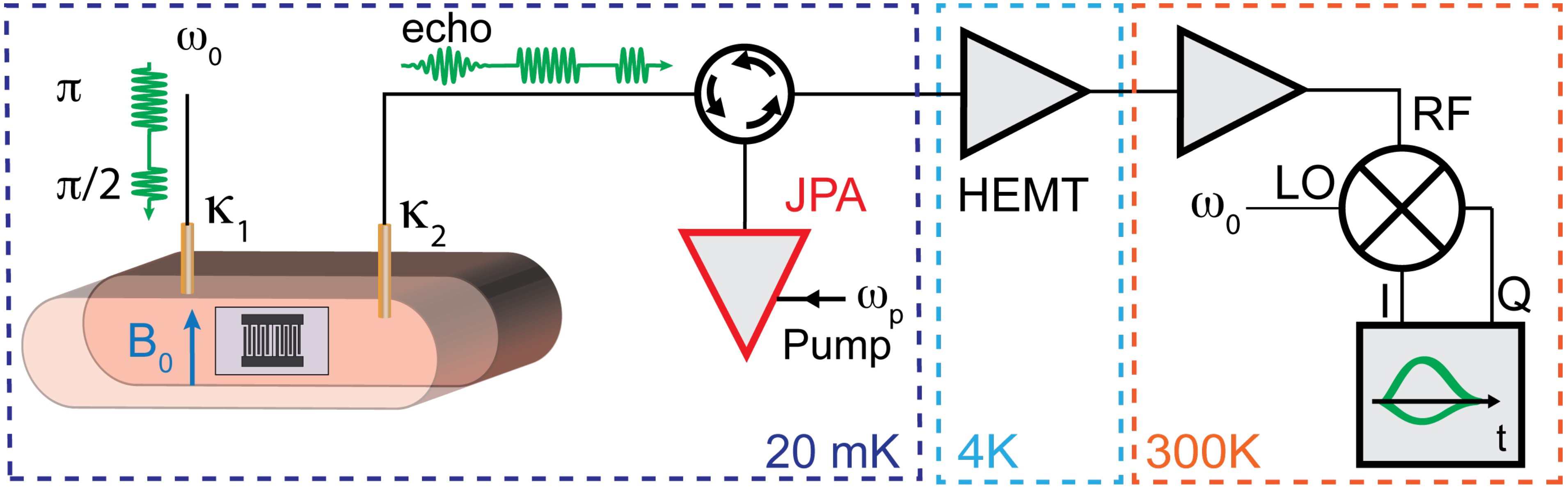


Kubo et al., PRB 86, 064514 (2012)



- Clear ^{14}N hyperfine
- Ultra-low excitation (≈15 spins) was detected -> 10^5 spins $Hz^{-1/2}$

Quantum-limited ESR Spectrometer

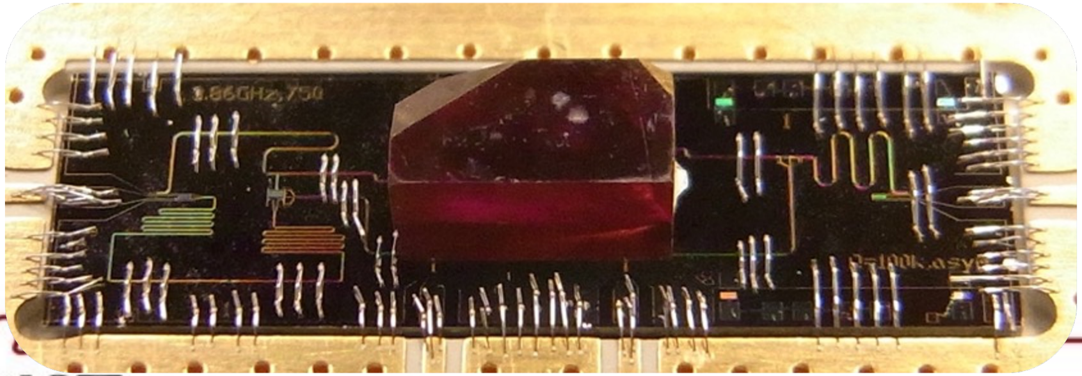


- Full spin polarization @ 20 mK
- High Q ($3\ 10^5$) resonator and large coupling (~ 50 Hz)
- Quantum-limited Josephson parametric Amplifier (T_N ~< 200 mK)

Bienfait et al., Nature Nanotech 11, 253 (2016)

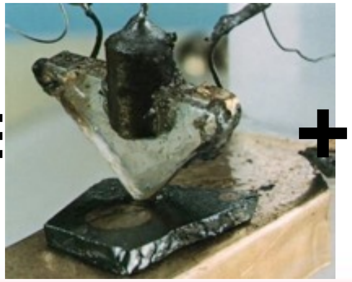
Summary & Perspective

- Hybrid quantum circuit with a spin ensemble and superconducting circuit
  - PoC for a superconducting quantum CPU + spin ensemble quantum RAM
  - Quantum RAM operation
- Hybrid circuit as a sensitive magnetization detector
  - Single-spin microwave detection [Wang et al., Nature (2023)]



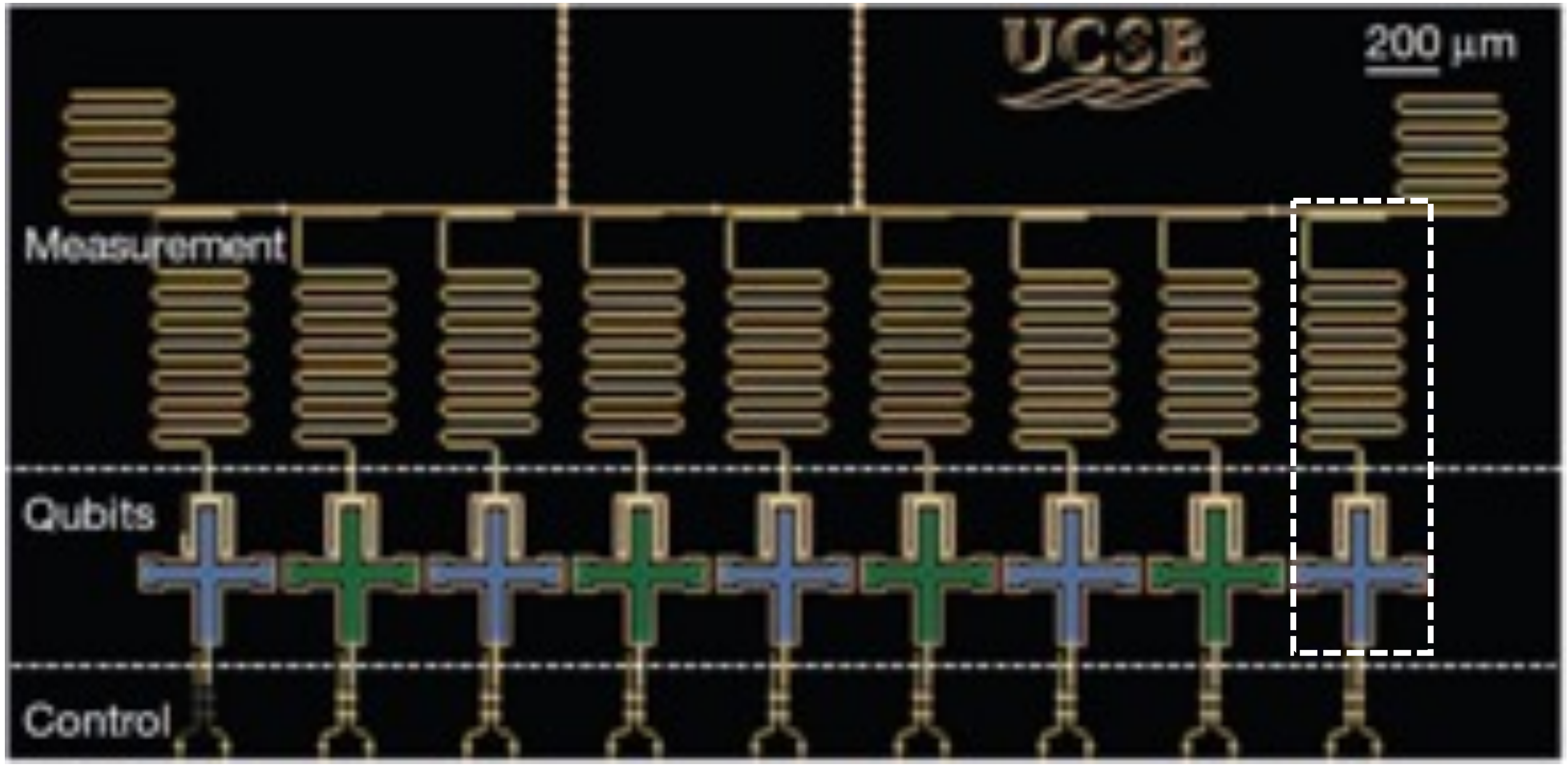
≡

Quantum version of...

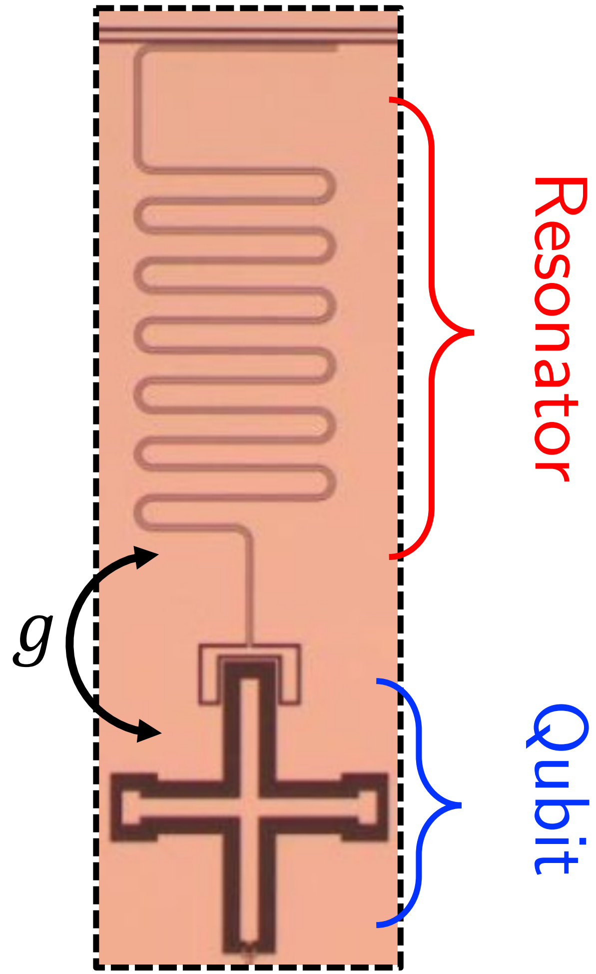


+

Measuring qubit states with a resonator



Kelly et al., Nature 519, 66 (2015)



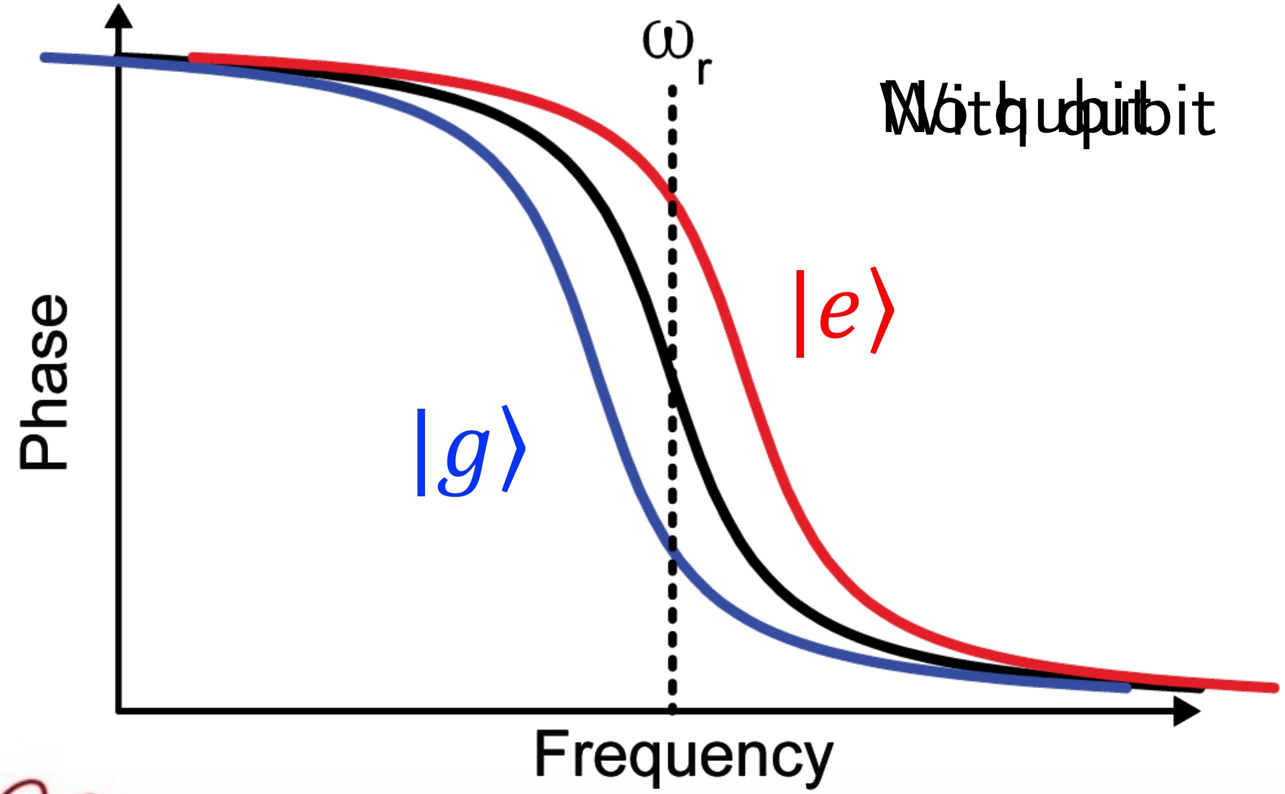
$$\mathcal{H}_{JC}/\hbar = \left(\omega_r + \frac{g^2}{\omega_r - \omega_q}\sigma_z\right)\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \frac{\omega_q\sigma_z}{2}$$

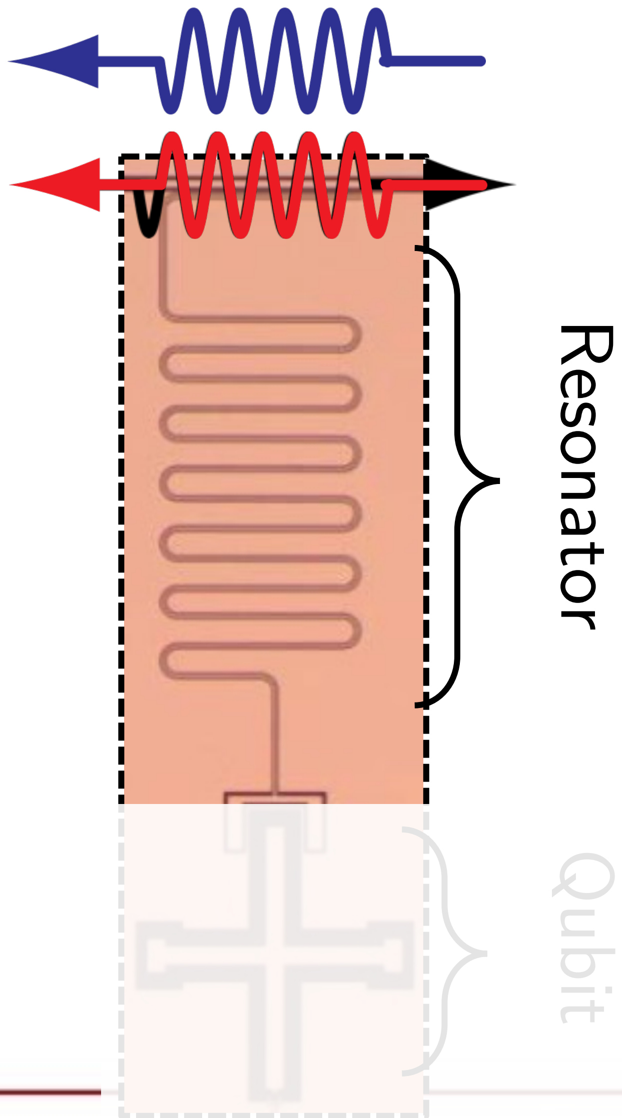
(Dispersive regime: $|\omega_r - \omega_q| \gg g$)

Measuring qubit states with a resonator

$$\mathcal{H}_{JC}/\hbar = \left(\omega_r + \boxed{\frac{g^2}{\omega_r - \omega_q}}\sigma_z\right)\left(\hat{a}^\dagger \hat{a} + 1/2\right) + \frac{\omega_q \sigma_z}{2}$$

"Dispersive" shift depending on qubit state



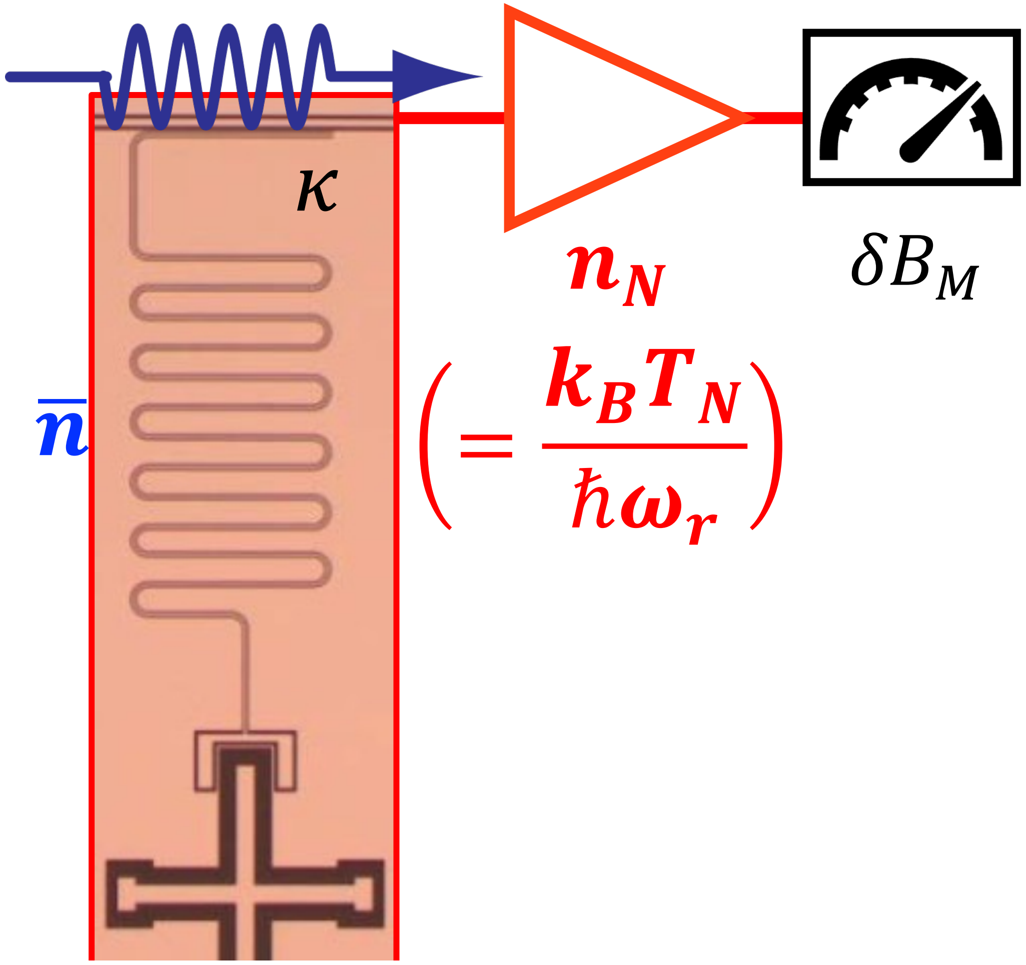


Haroche and Raimond, "Exploring the Quantum"; Blais et al., PRA **69**, 062320 (2004)

Requirements for single-shot readout

$$\text{SNR} \sim \sqrt{\frac{\bar{n}\kappa}{n_N \delta B_M}}$$

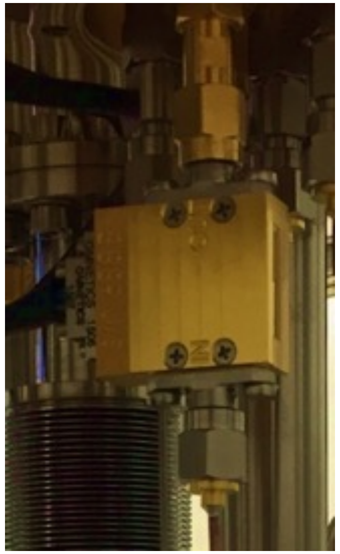
- Measurement bandwidth $\delta B_M \gtrsim 10$ MHz
- Resonator leak: $\kappa \lesssim 10$ MHz
- **Low power of the readout pulse**:
  $\bar{n} \sim \mathbf{10}$ photons $\equiv \lesssim$ **fW**
- **Small noise from the amplifier**:
  $n_N \sim \mathbf{1}$ ($\equiv \lesssim$ **250 mK**)



Noiseless (quantum-limited) microwave amplifier needed!!

Commercial cryogenic amplifier

Low Noise Factory
(http://www.lownoisefactory.com)



- Cryogenic HEMT (high electron mobility transistor) amplifier

- $T_N \approx 3$ K $\gg \hbar\omega/k_B = 250$ mK
- 1-10 mW dissipation $\gg \sim 100\ \mu$W
- How to implement a **quantum-limited amplifier** at microwave frequency **at millikelvin**? (hopefully without much dissipation)

State-of-the-art: Josephson parametric amplifier

- **Josephson junction: Non-linear & non-dissipative inductance**
- **Quantum limited noise**
- **Wideband** ($\tilde{<}$ 1 GHz)
- Versatile **superconducting quantum technology**

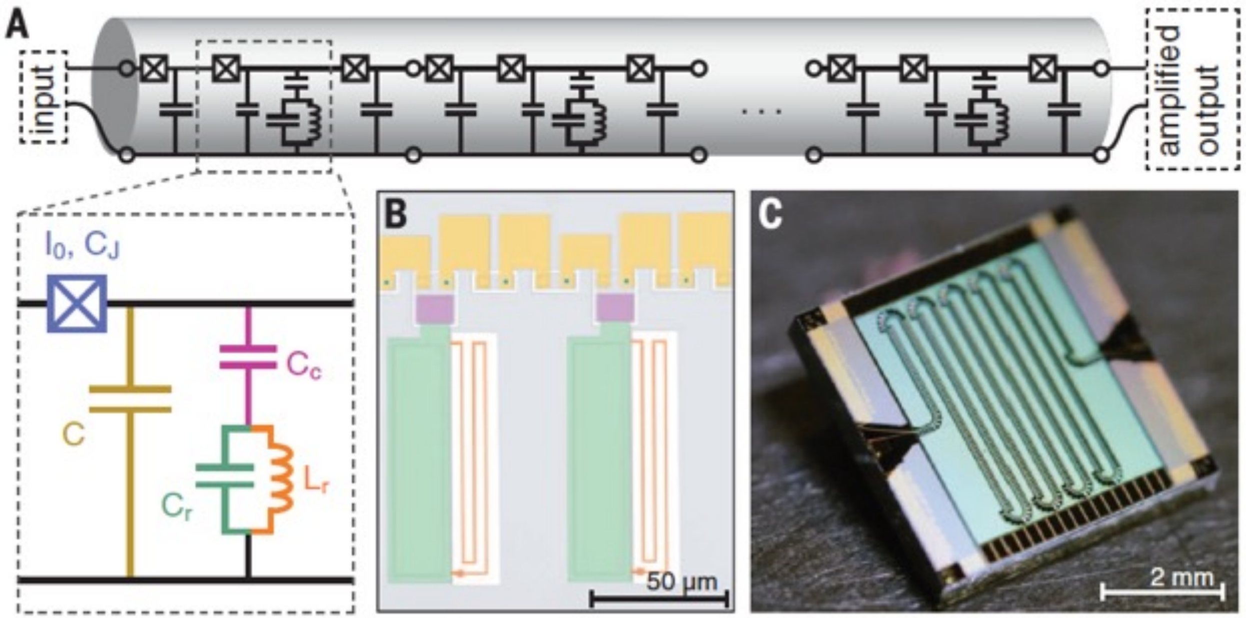
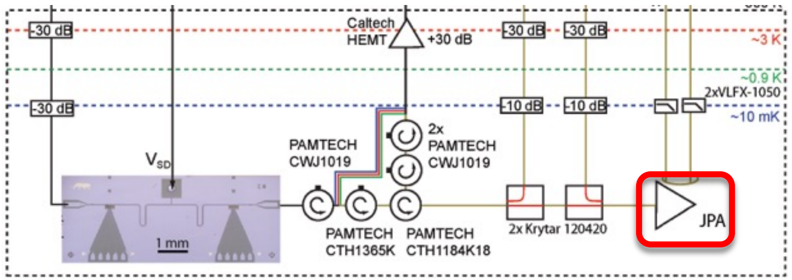


Fig. 1. Josephson traveling-wave parametric amplifier. (**A**) Circuit diagram. The JTWPA is implemented as a nonlinear lumped-element transmission line; one unit cell consists of a Josephson junction with critical current $I_0 = 4.6$ µA and intrinsic capacitance $C_J = 55$ fF with a capacitive shunt to ground $C = 45$ fF. Every third unit cell includes a lumped-element resonator designed with capacitance $C_r = 6$ pF and inductance $L_r = 120$ pH, with coupling strength set by a capacitor $C_c = 20$ fF. The value of C in the resonator-loaded cell is reduced to compensate for the addition of C_c. (**B**) False-color optical micrograph. The coloring corresponds to the inset in (A), with the lower metal layer shown in gray. (**C**) Photograph of a 2037 junction JTWPA. The line is meandered several times on the 5 mm by 5 mm chip to achieve the desired amplifier gain.

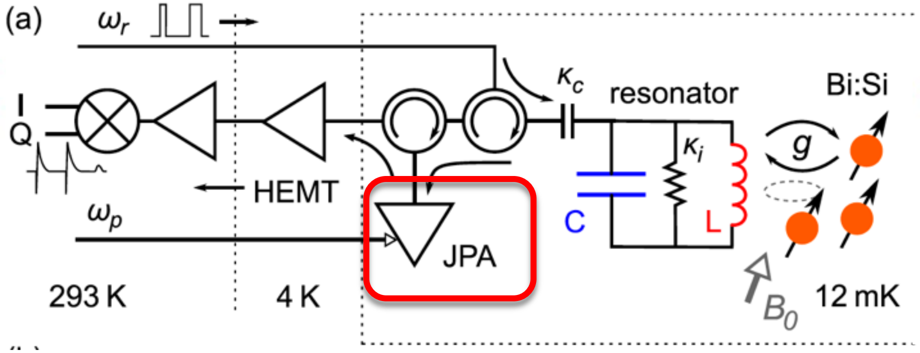
Macklin et al., Science **350**, 307 (2015).

Paramp as microwave quantum technology

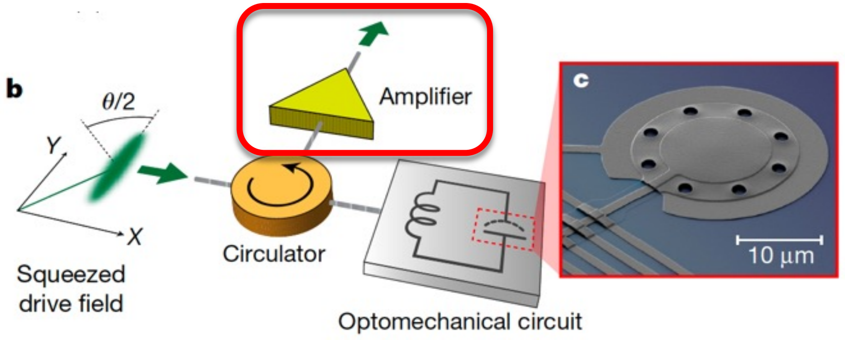
Quantum-dot qubits



Spin resonance



Mechanical motion



Liu et al., Science **347**, 285 (2015)
Mi et al., Nature **555**, 599 (2018)

Eichler et al., PRL **118**, 037701 (2017)
Bienfait et al., Nature Nano **11**, 253 (2016)
Probst et al., APL **111**, 202604 (2017)

Clark et al., Nature **541**, 191 (2017)
Satzinger et al., Nature **563**, 661 (2018)
Noguchi et al., PRL **119**, 180505 (2017)

Drawbacks of Josephson parametric amplifier

- Limited dynamic range (currently reported: -100 dBm = 0.1 pW) -> readout ONLY 20 qubits simultaneously (5 qubits so far)
- Inoperable under (moderate) magnetic fields

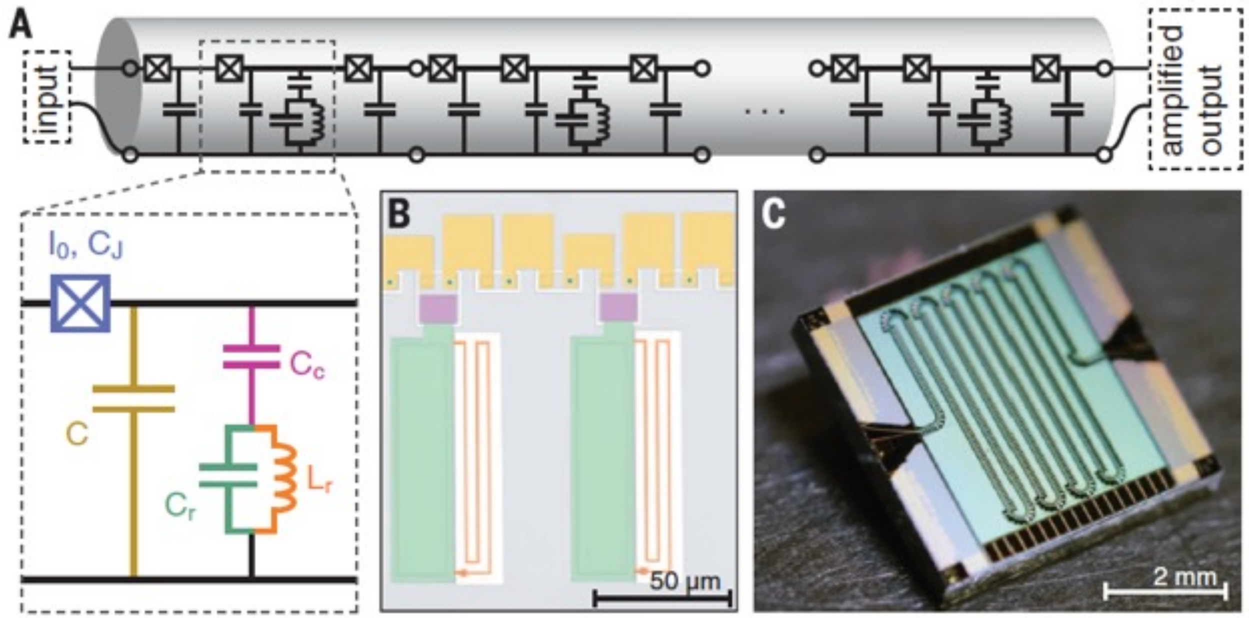


Fig. 1. Josephson traveling-wave parametric amplifier. (**A**) Circuit diagram. The JTWPA is implemented as a nonlinear lumped-element transmission line; one unit cell consists of a Josephson junction with critical current $I_0 = 4.6\ \mu A$ and intrinsic capacitance $C_J = 55$ fF with a capacitive shunt to ground $C = 45$ fF. Every third unit cell includes a lumped-element resonator designed with capacitance $C_r = 6$ pF and inductance $L_r = 120$ pH, with coupling strength set by a capacitor $C_c = 20$ fF. The value of C in the resonator-loaded cell is reduced to compensate for the addition of C_c. (**B**) False-color optical micrograph. The coloring corresponds to the inset in (A), with the lower metal layer shown in gray. (**C**) Photograph of a 2037 junction JTWPA. The line is meandered several times on the 5 mm by 5 mm chip to achieve the desired amplifier gain.

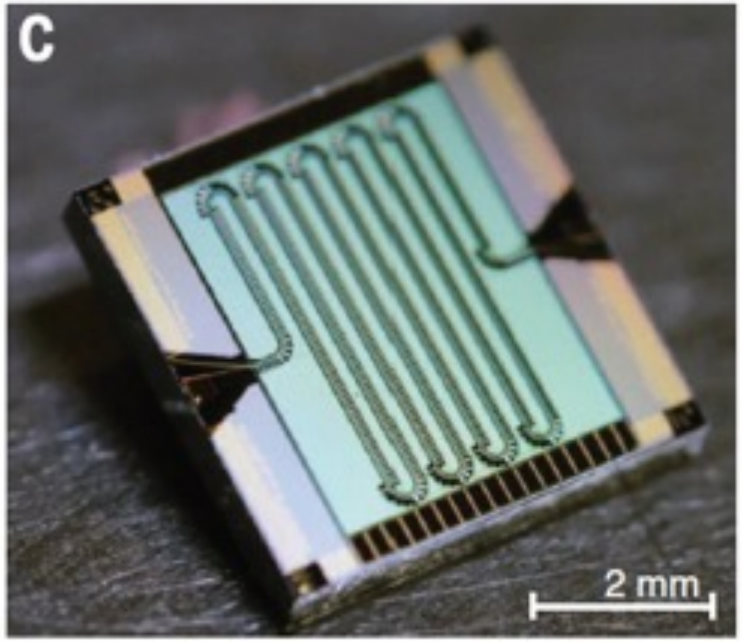
Macklin et al., Science **350**, 307 (2015).

Summary of microwave amplifier for qu-technologies

- Necessary to operate at millikelvin without adding noise without dissipating too much power for the fridge

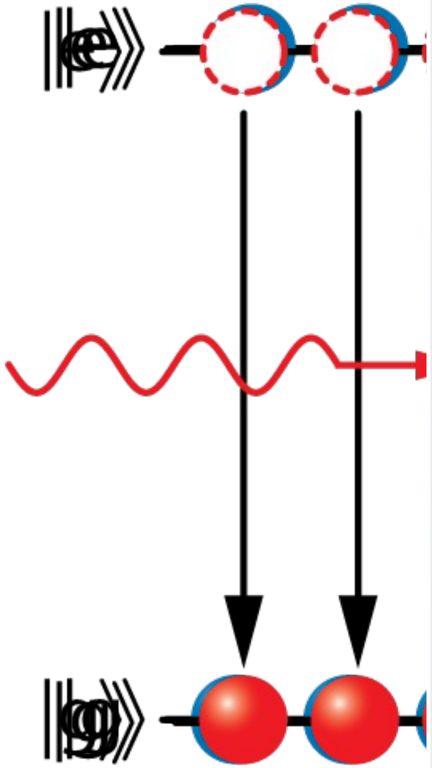
- **The only solution (to date)**:
  Josephson parametric amplifer (JPA)

Is it really true?

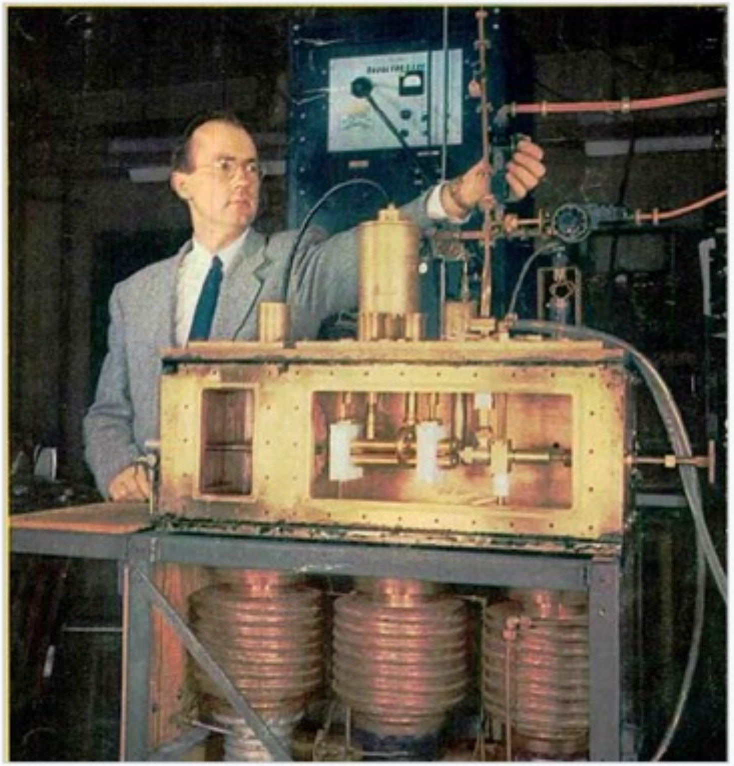


Stimulated emission

- Maser (Microwave amplification by stimulated emission of radiation)
- Population inversion (negative temperature)
- Intensively studied in 1950's - 60's but **left behind** due to
- birth of laser
- low temperature operation (useless for **CLASSICAL** information technologies)



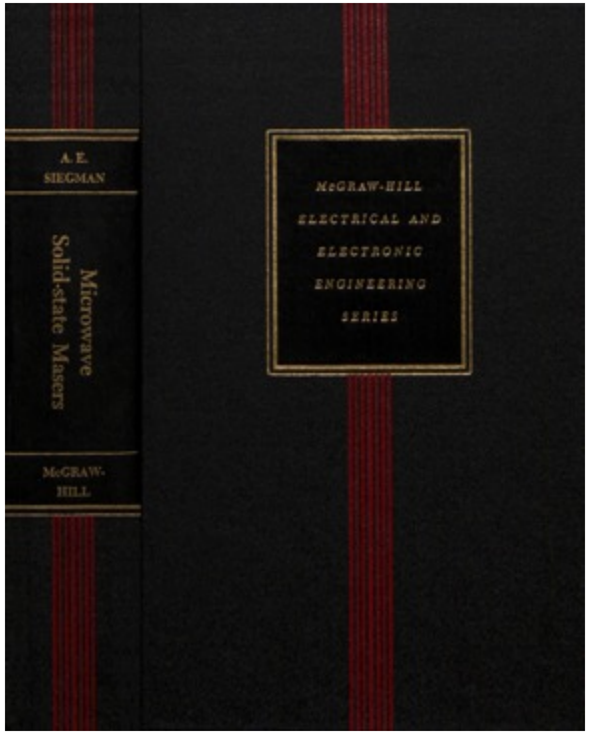
Charles Townes (Nobel prize in 1964)



First prototype ammonia maser and inventor Charles H. Townes. The ammonia nozzle is at left in the box, the four brass rods at center is the quadrupole state selector, and the resonant cavity is at right. The 24 GHz microwaves exit through the vertical waveguide Townes is adjusting. At bottom are the vacuum pumps.

(From Wikipedia)

How maser can be good ?



A.E. Siegman,
"Microwave Solid-state Masers"
McGraw-Hill (1964)

Maser noise figures

The low-temperature operation of the maser is in part a virtue in that it is at least partly responsible for the major virtue of the maser amplifier—its extraordinarily low noise figure. In discussing ultralow noise figures, it is most convenient to discuss not the noise figure F as conventionally defined, but rather the equivalent excess input noise temperature T_a of the amplifier. This noise temperature is related to the conventional noise figure F by the equation

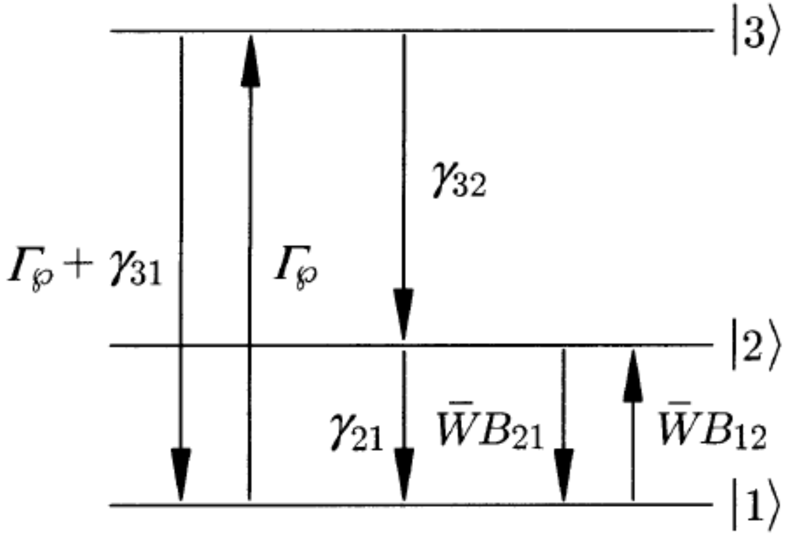
$$F = 1 + T_a/290°\text{K} \qquad (1\text{-}2\text{-}1)$$

Using this notation, typical masers have noise temperatures of the same order as their operating temperature, or about 4°K. The noise figure is then $F \sim 1.01$, or a few one-hundredths of a decibel.

Two reasons can be given for this extremely low noise figure. In the first place, the maser contains none of the usual noise-generating elements found in conventional amplifiers—no d-c currents, hot cathodes, or shot noise. The only noise source in the maser is thermal noise. Secondly,

Quantum-limited microwave amplifier possible by maser!?

Laser (Maser) principle



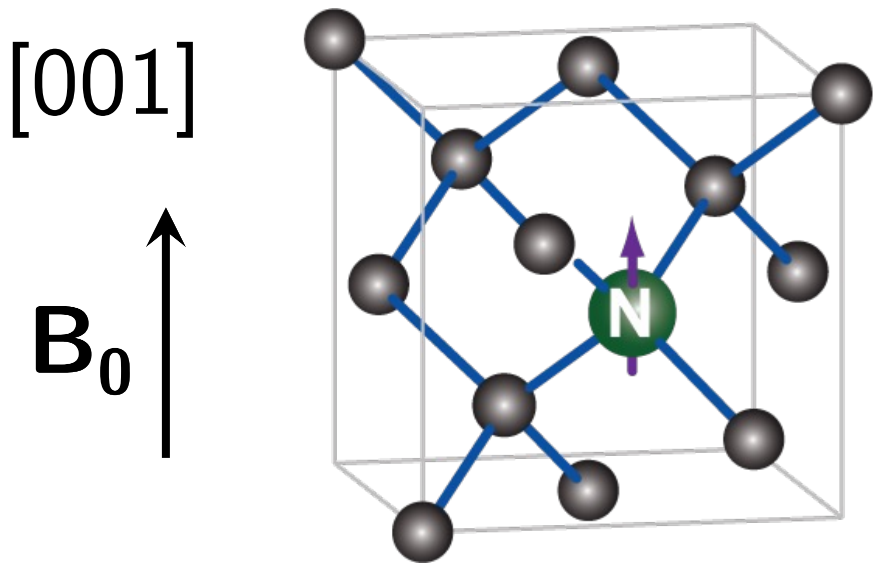
$$\dot{N}_1 = -\Gamma_\wp N_1 + \gamma_{21} N_2 + (\Gamma_\wp + \gamma_{31}) N_3 + \overline{W} B_{21}(N_2 - N_1),$$
$$\dot{N}_2 = -\gamma_{21} N_2 + \gamma_{32} N_3 - \overline{W} B_{21}(N_2 - N_1),$$
$$\dot{N}_3 = -(\Gamma_\wp + \gamma_{31} + \gamma_{32}) N_3 + \Gamma_\wp N_1.$$

[Carmichael, "Statistical methods in quantum optics 1" (1999)]

- N_i: atom (spin) population on level $|i\rangle$
- $\Gamma_\wp$: pump rate
- γ_{ij}: decay rate from $|i\rangle$ to $|j\rangle$
- $\bar{W}B_{21}$: stimulated emission (absorption) rate ($\bar{W}$: mode energy density, B_{21}: Einstein's coefficient)
- n: photons in the cavity, κ: cavity leak rate

The spins: defect in diamond

Nitrogen impurity (**P1 center**)

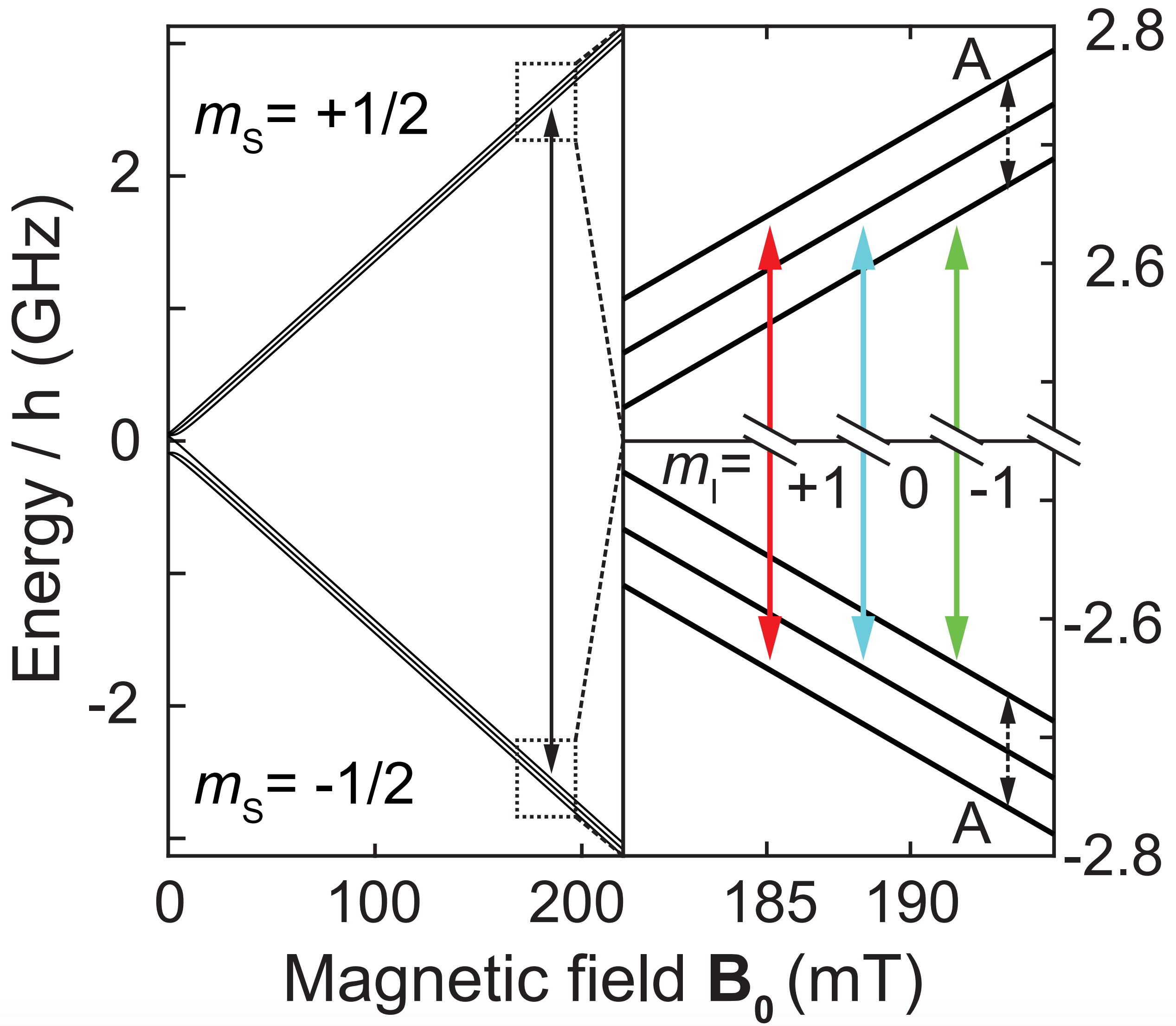


$$\mathbf{H}_{P1} = \gamma \vec{B}\cdot\vec{S} + \vec{S}\cdot\mathbf{A}\cdot\vec{I}$$

$S = 1/2 \quad I = 1$

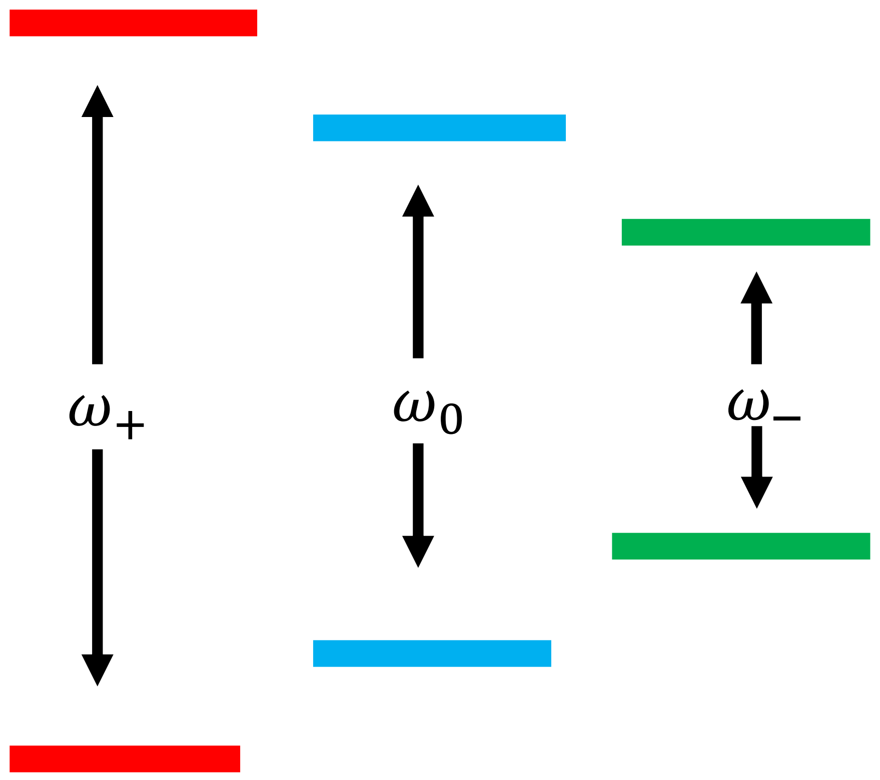
$A_{\perp}$ = 114 MHz

$A_{||}$ = 81 MHz

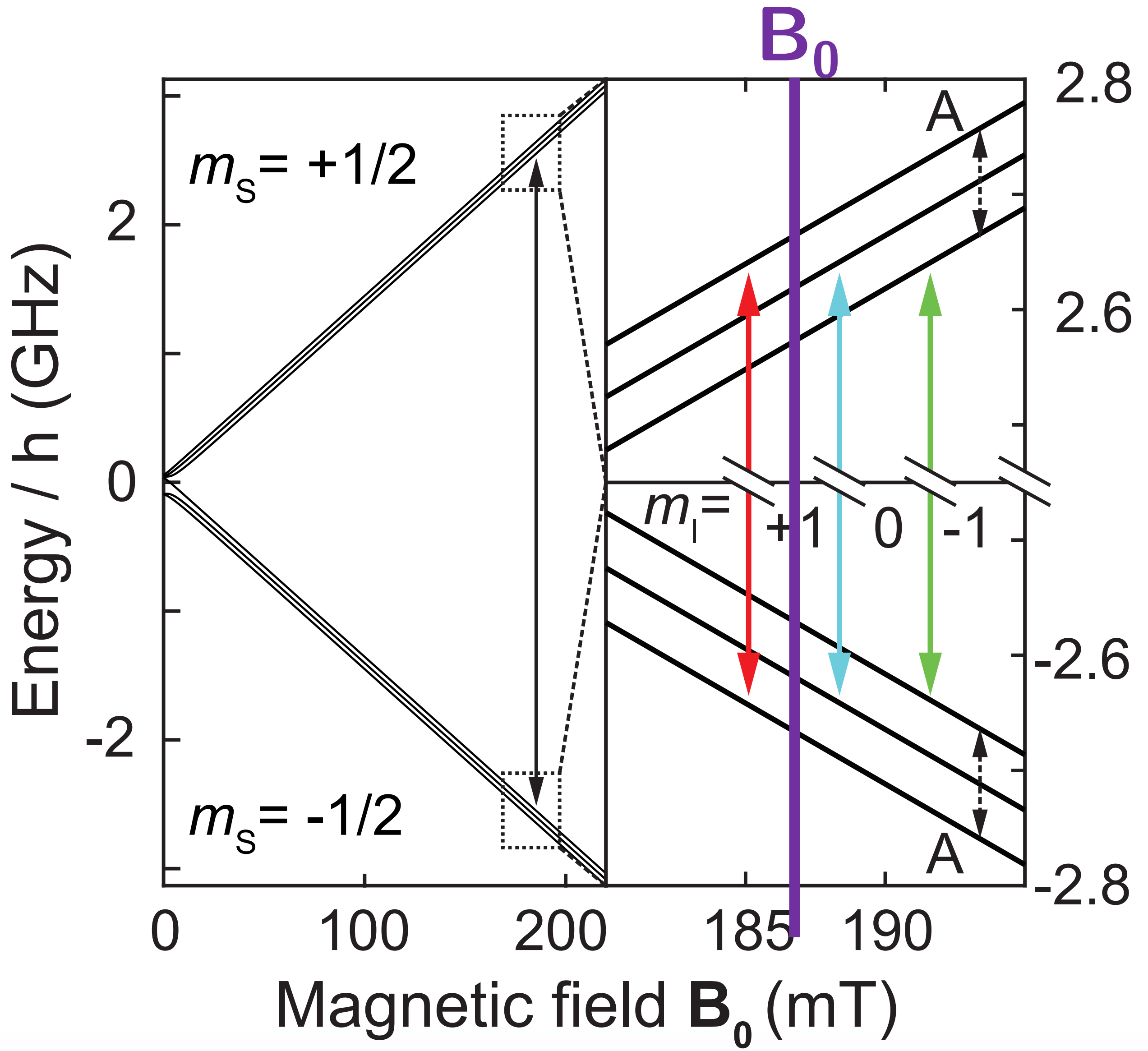


Three "evenly-spaced" 2-levels in P1 center

Nitrogen impurity (**P1 center**)



$$2\omega_0 = \omega_+ + \omega_-$$



Four-spin flip-flop process in nitrogen centers

- Four-spin flip-flop process (cross-relaxation): two central spins' flips "up (down)"
  = one spin on each satellite flips "down (up)"
- Measured to be ~10 ms
- Claimed could be used to generate inversion by **pumping central line** (reported, but data not shown)

Cross Relaxation Studies in Diamond*

P. P. Sorokin, G. J. Lasher, and I. L. Gelles
Research Laboratory, International Business Machines Corporation, Poughkeepsie, New York
(Received December 18, 1959)

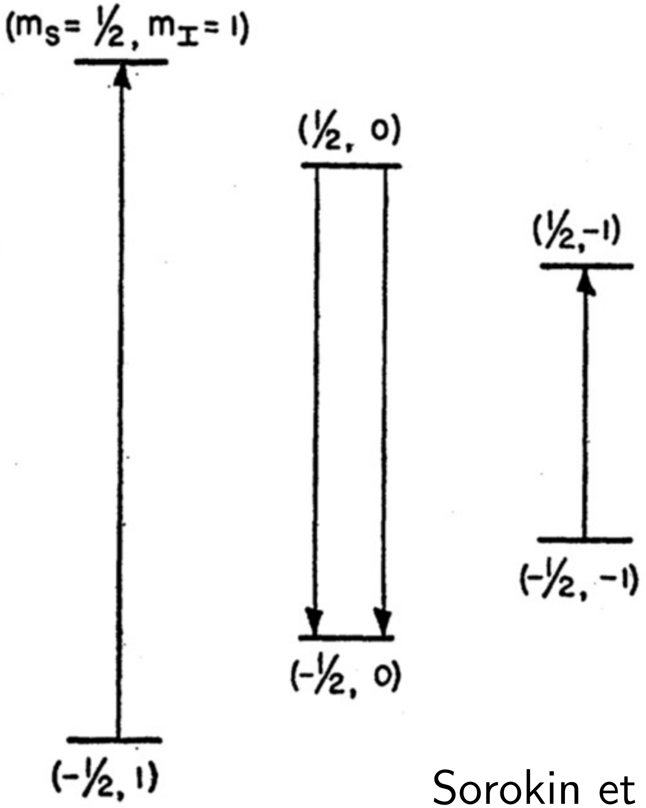
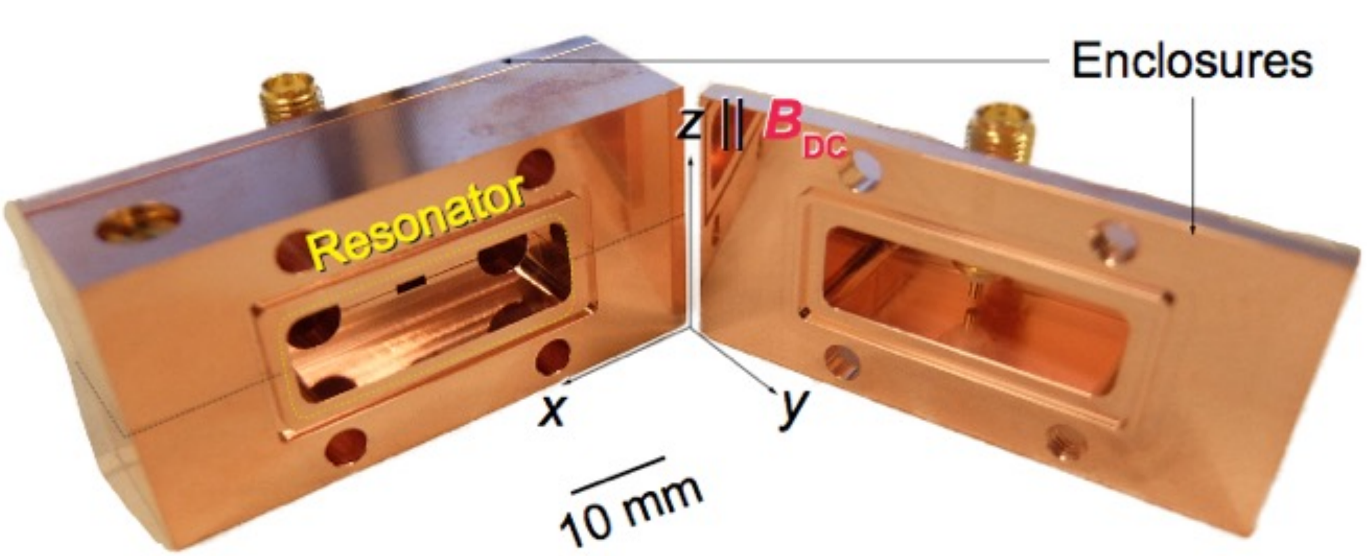
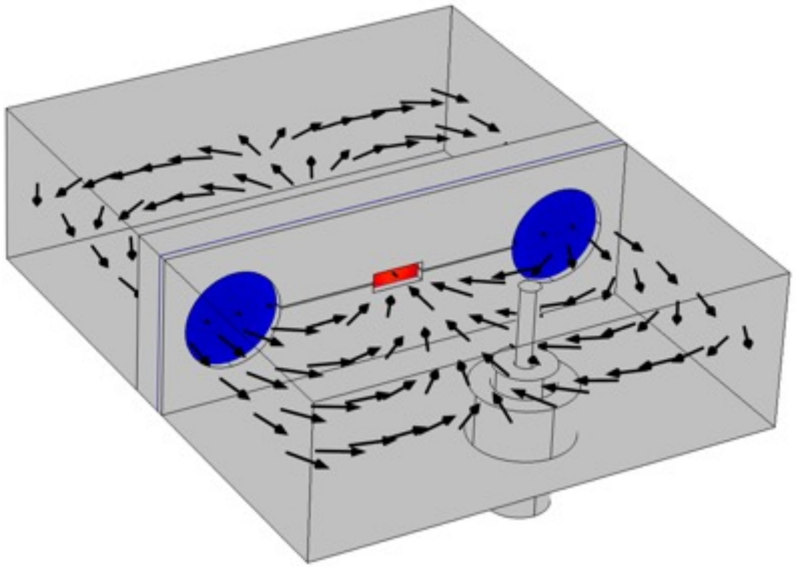


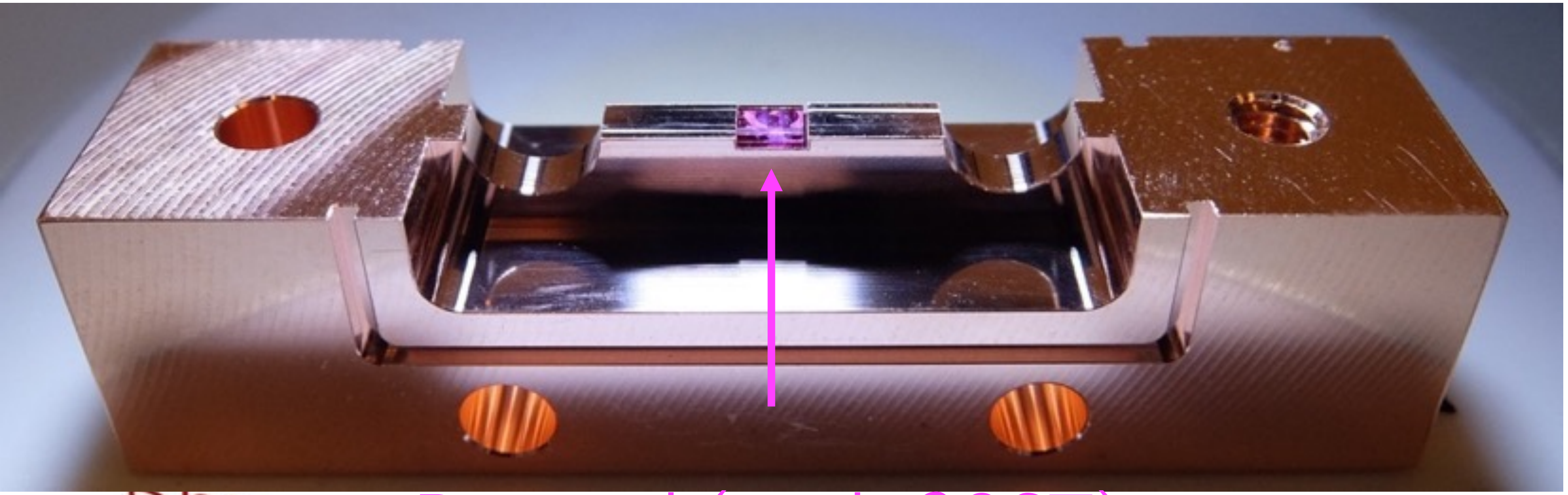
Fig. 1. Electron spin resonance energy level diagram for nitrogen centers in diamond (H_0||[100]) showing the four spin flip mechanism through which cross-relaxation proceeds. The hyperfine splitting is 94.2 Mc/sec.

Sorokin et al., Phys. Rev. **118** (1960).

Loop-gap microwave resonator





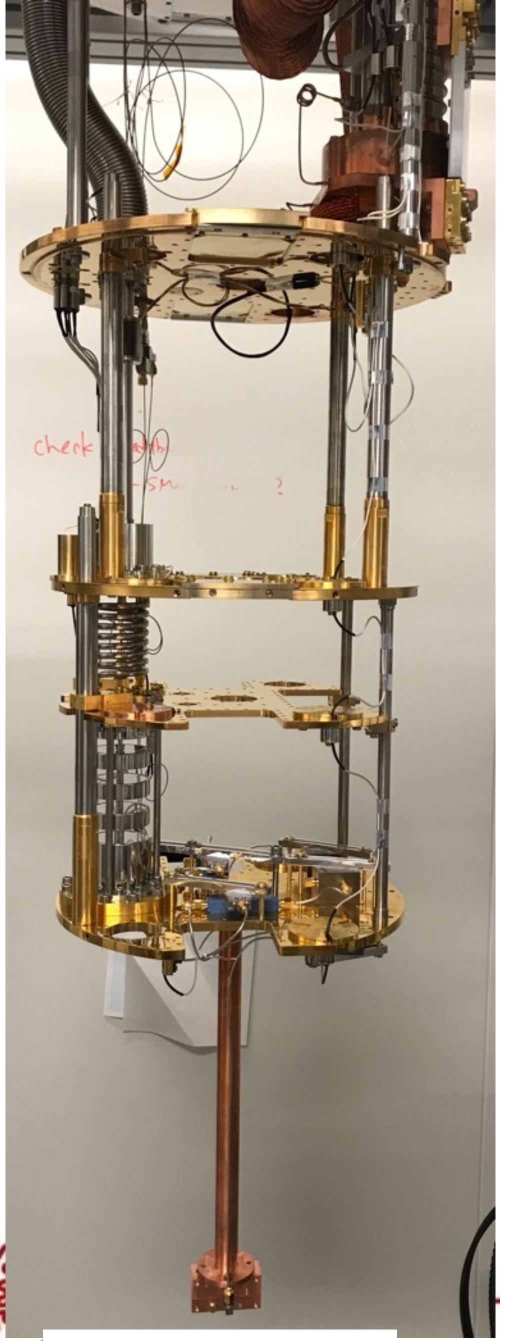


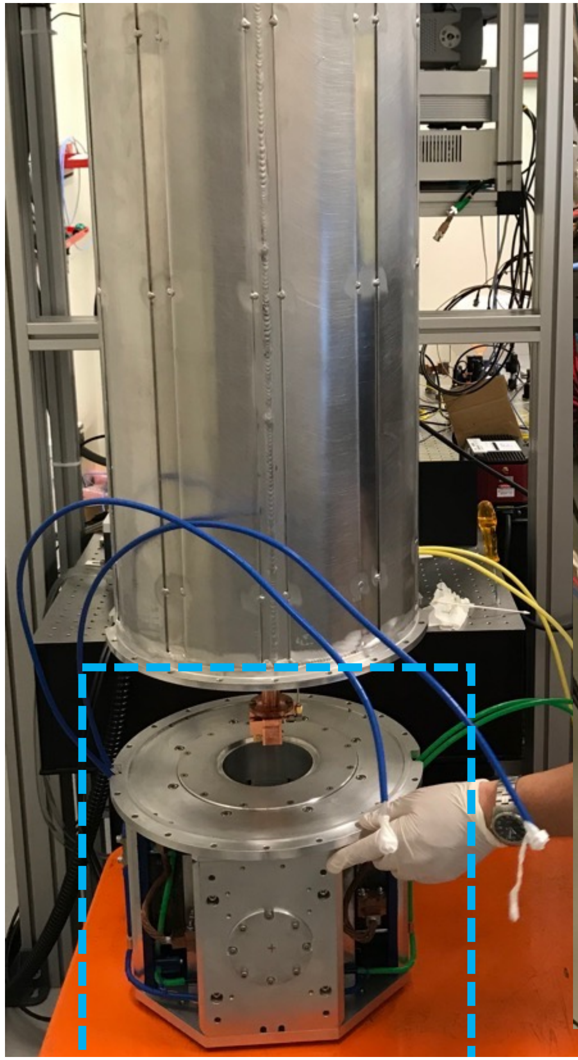
Diamond (irrad. @QST)

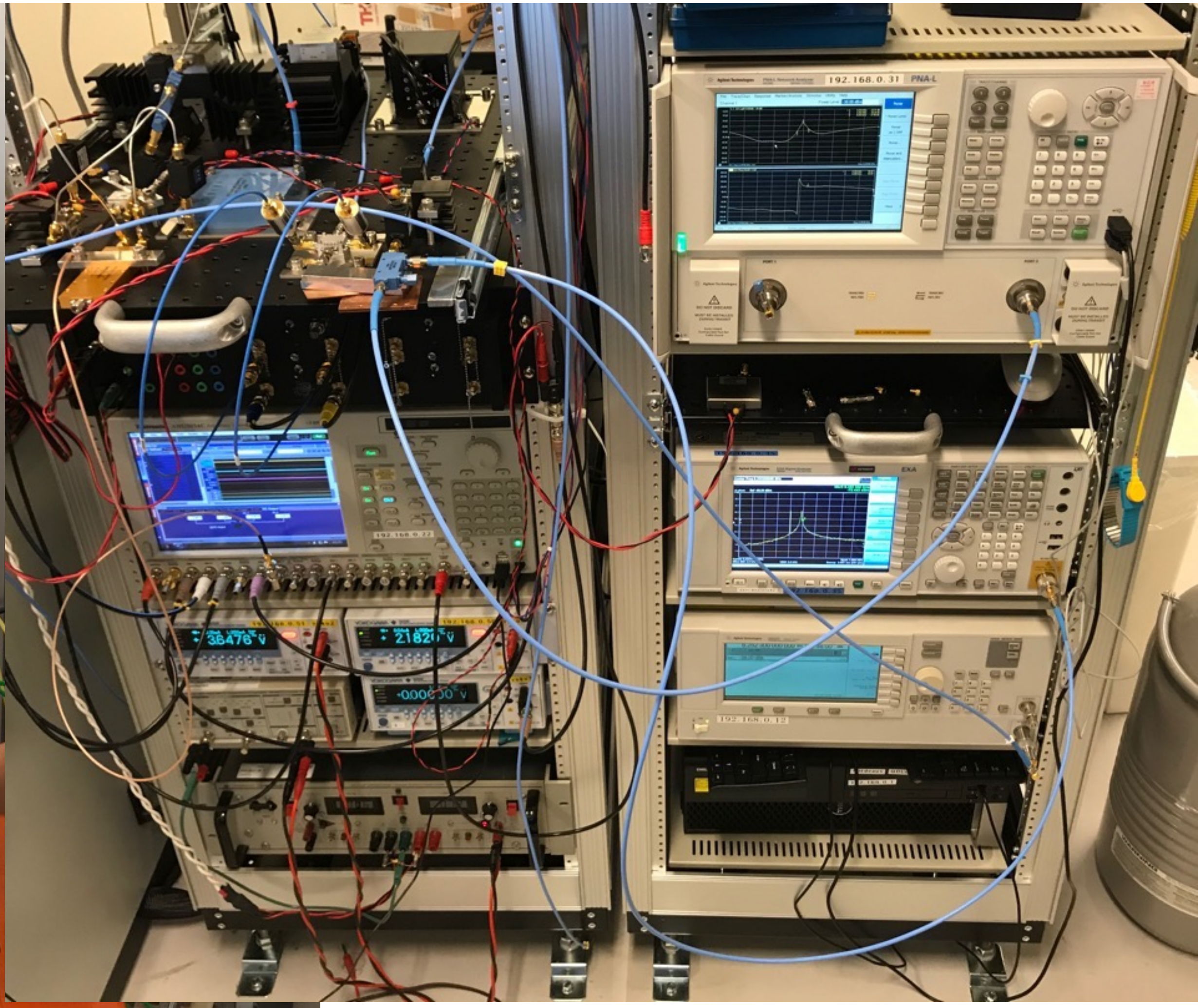
fr = 6.25 GHz
Qext = 750
Qint = 2500

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

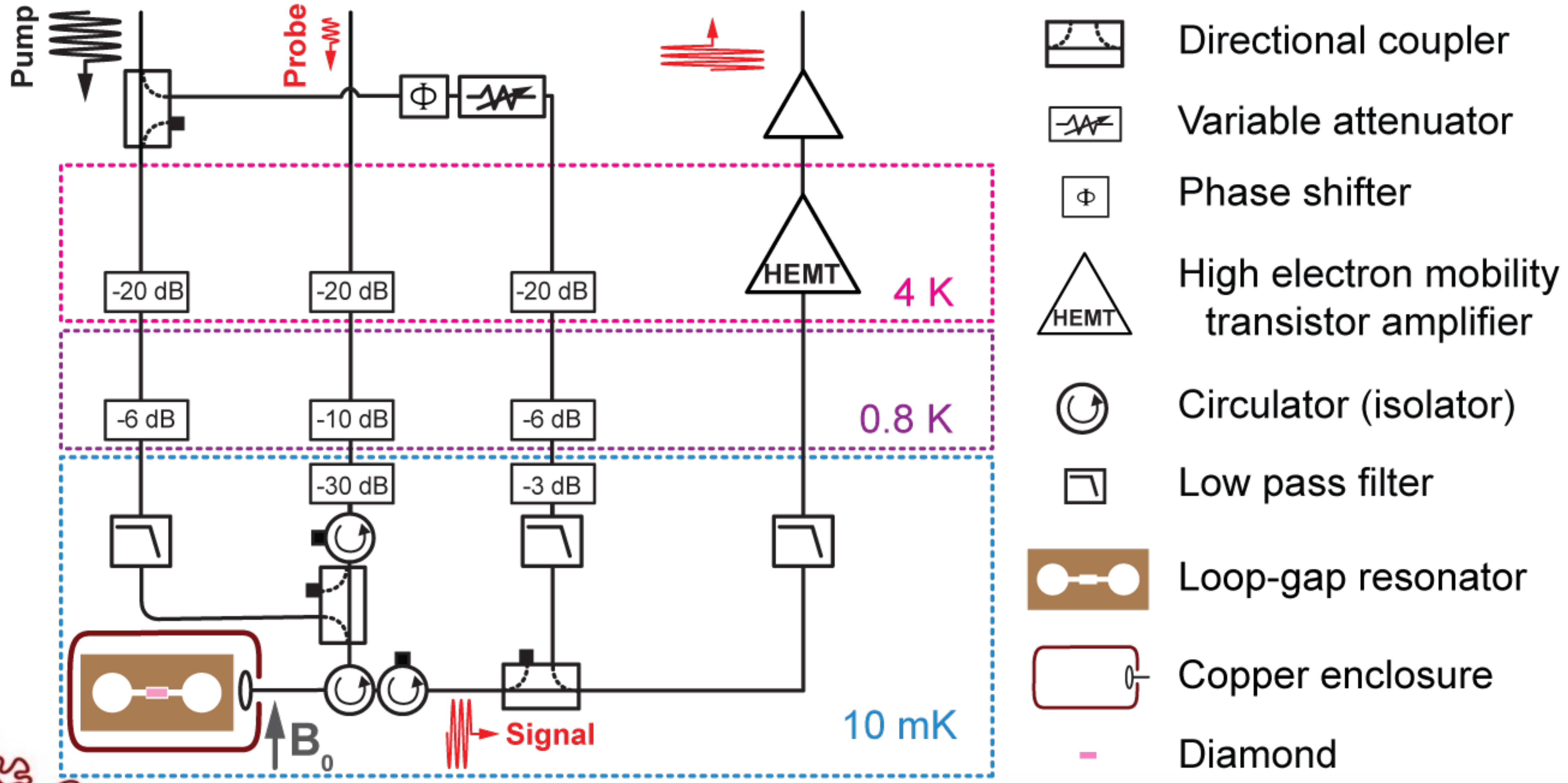
Setup photos



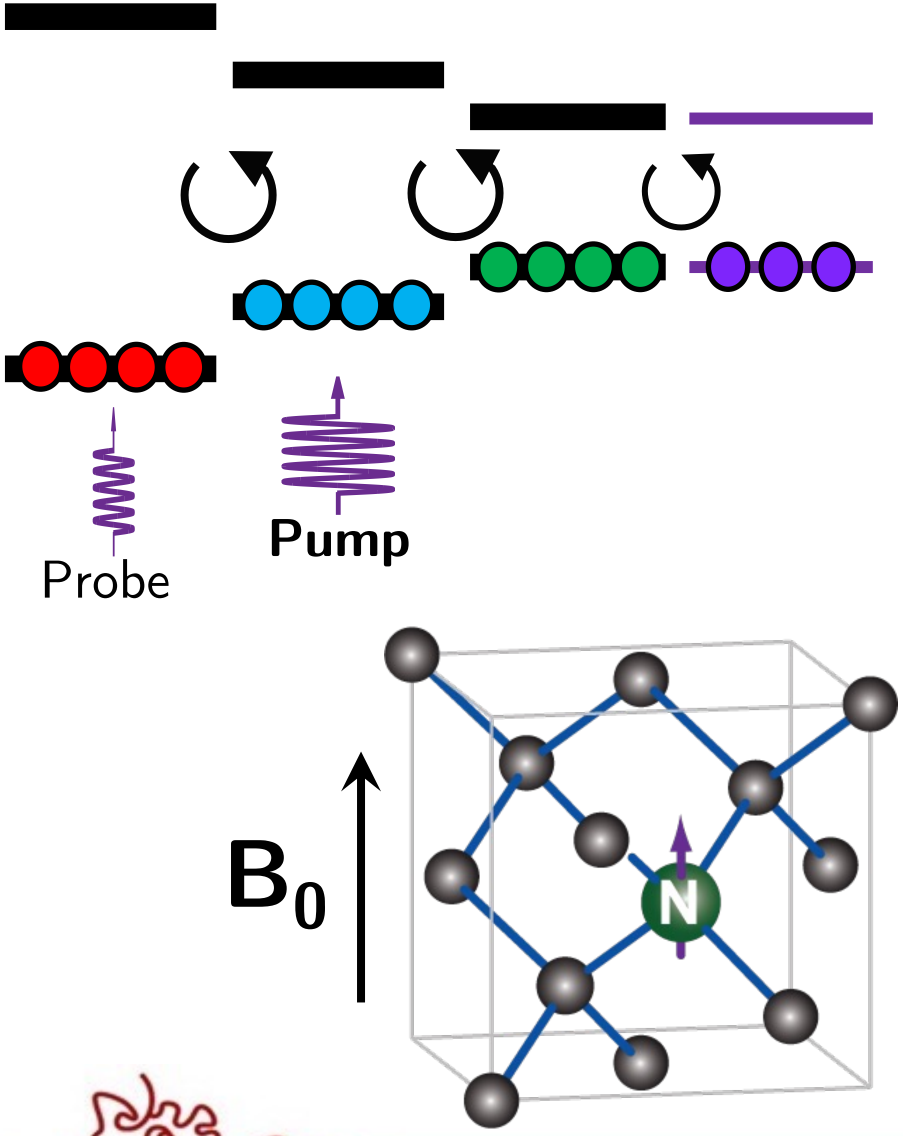


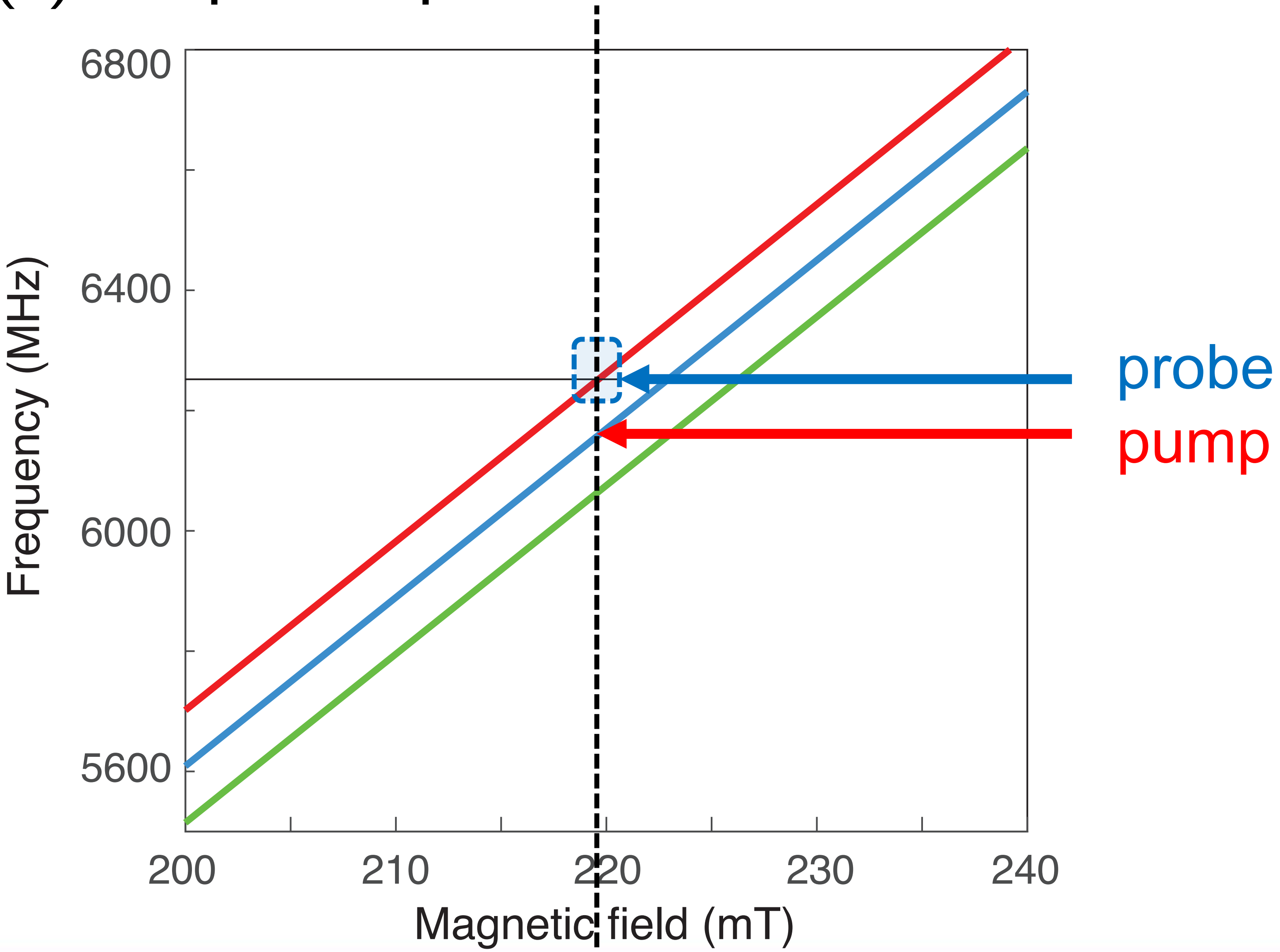


Setup


Pump
Probe
-20 dB
-20 dB
-20 dB
HEMT
4 K
-6 dB
-10 dB
-6 dB
0.8 K
-30 dB
-3 dB
B0
Signal
10 mK
Directional coupler
Variable attenuator
Phase shifter
HEMT
High electron mobility transistor amplifier
Circulator (isolator)
Low pass filter
Loop-gap resonator
Copper enclosure
Diamond

Mase(r) amplifier protocol



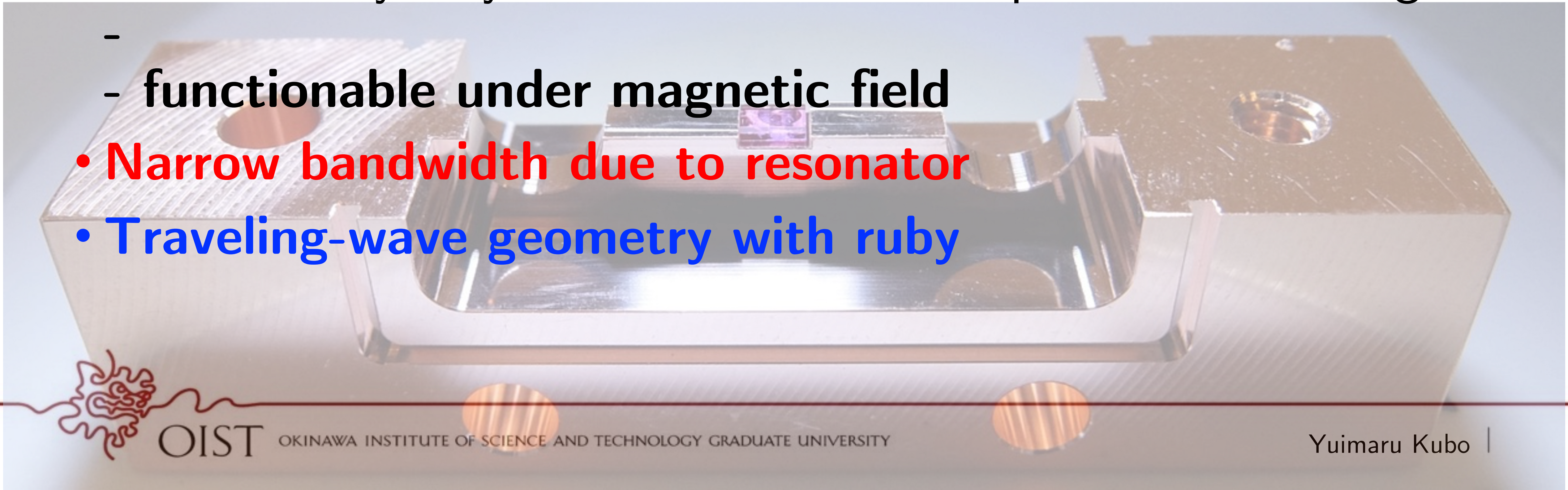


P1 maser amplifier

To be published...

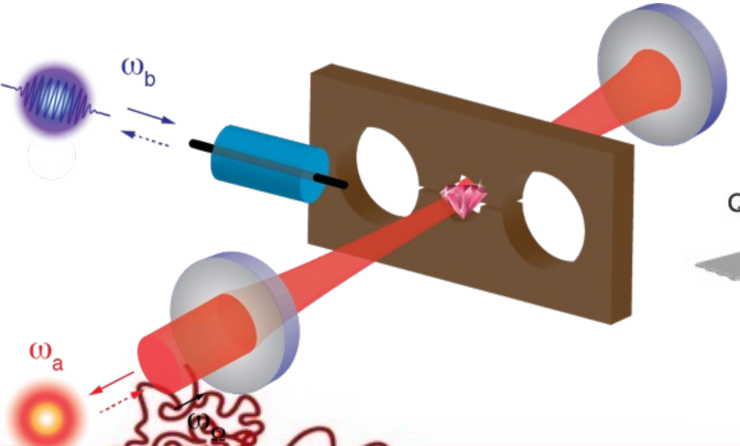
Summary and perspectives

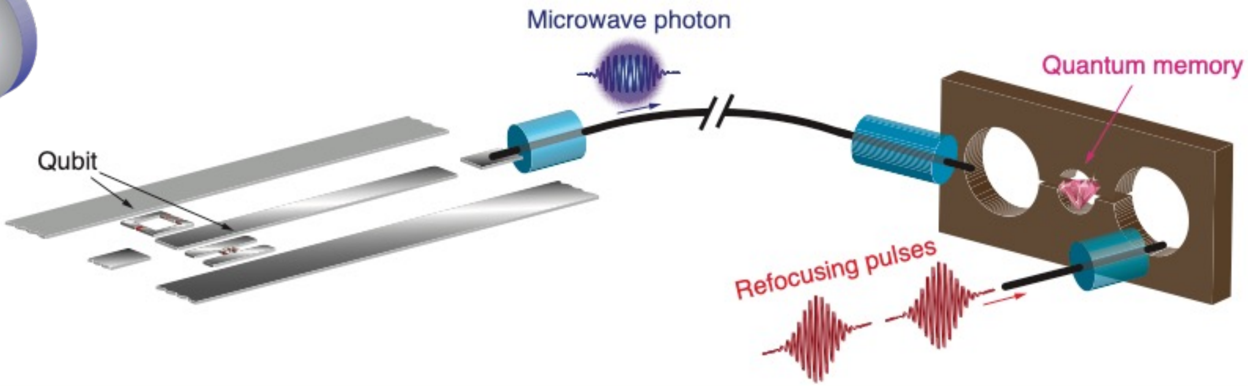
- **Maser amplifier at millikelvin temperature** by means of P1 centers in diamond
- **(Near-)quantum-limited noise and huge dynamic range**
  ->Potentially very useful for microwave quantum technologies:
  -
  - **functionable under magnetic field**
- **Narrow bandwidth due to resonator**
- **Traveling-wave geometry with ruby**

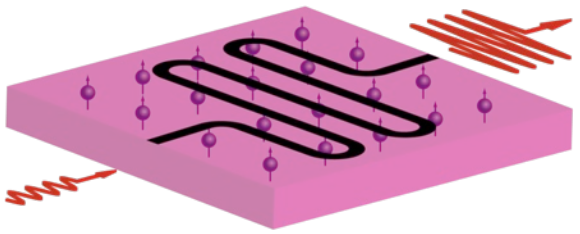


On-going projects at OIST

- **Quantum microwave-optical photon transducer** with spins in diamond
- **Spin ensemble quantum memory** for superconducting qubits
- **Spin-based ultra-low noise microwave amplifier**







Acknowledgements

- Grants:

JST

科研費 KAKENHI

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Science of Hybrid Quantum Systems

公益財団法人 中島記念国際交流財団 THE NAKAJIMA FOUNDATION

公益財団法人 住友財団

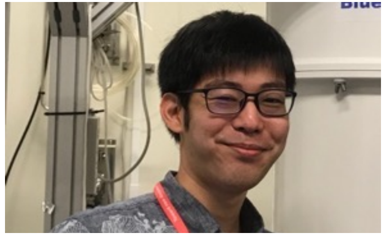
日本私立学校振興・共済事業団 Promotion and Mutual Aid Corporation for Private Schools of Japan

公益財団法人 平和中島財団 +++ HEIWA NAKAJIMA FOUNDATION HOMEPAGE +++

af THE ASAHI GLASS FOUNDATION

POC program Proof-of-Concept Program

Shota Norimoto
(ruby maser,
Now @NPL, UK)



Tatsuki Hamamoto
(transducer)

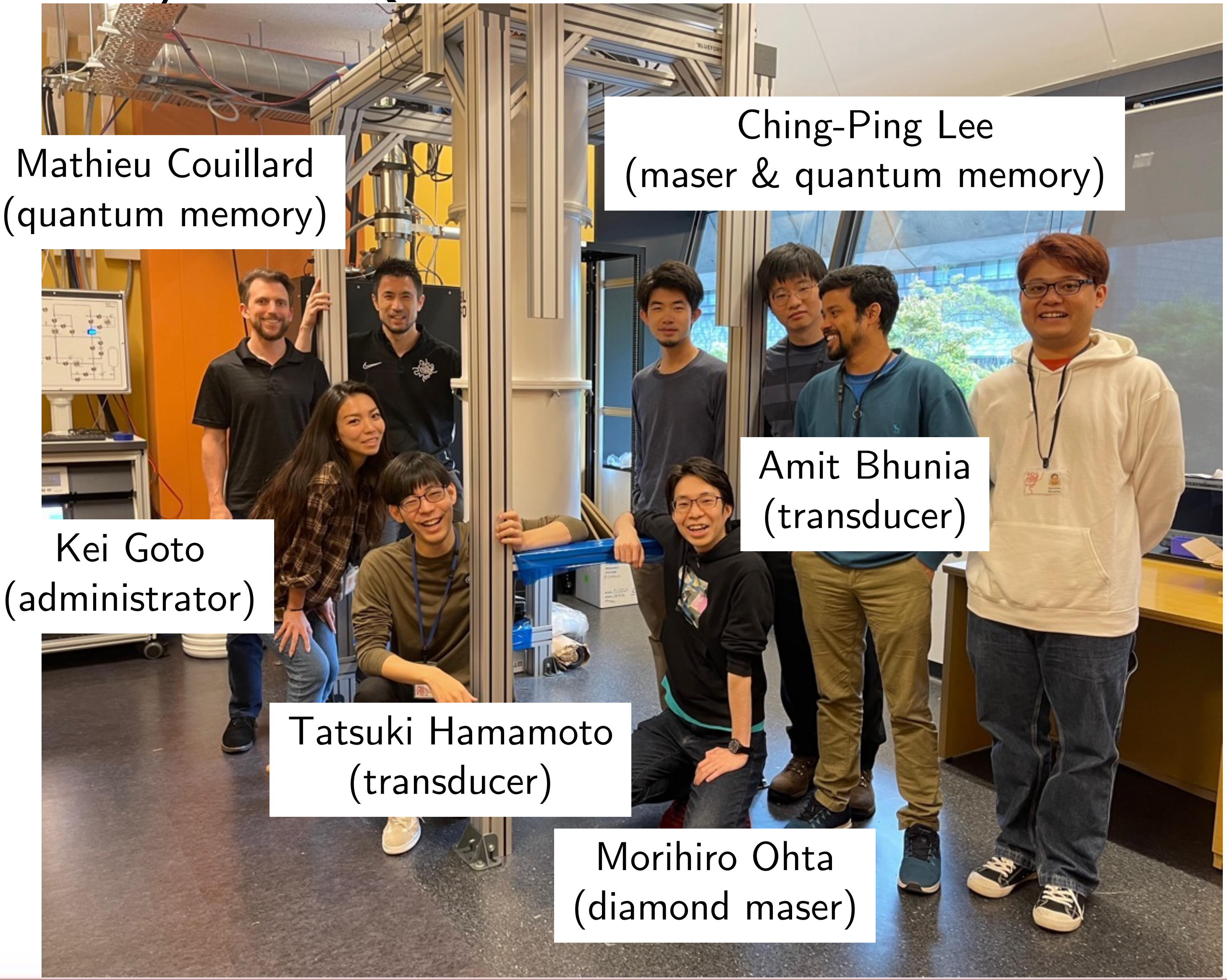
Jason Ball
(diamond maser
Now @Tabor)

Morihiro Ohta
(diamond maser)

oroshkin
Brown)

Denis Konstantinov

Hybrid Quantum Device Team



Thank you!!