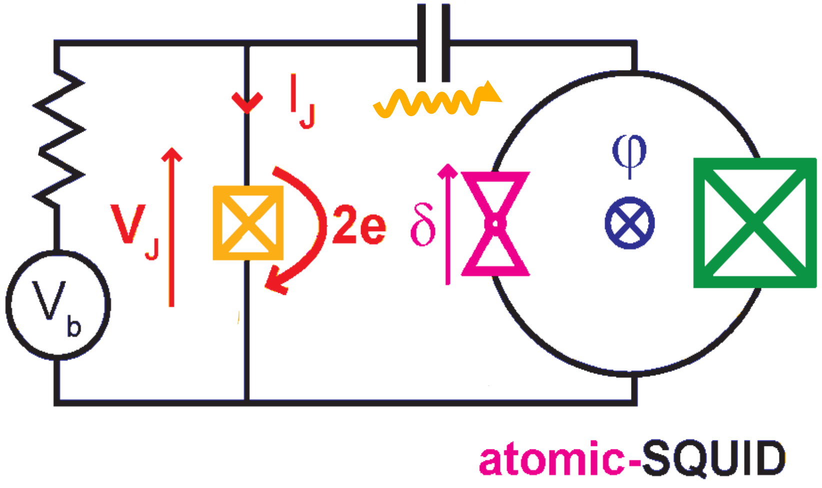
PROBING AND MANIPULATING ANDREEV STATES

1. JOSEPHSON EFFECT
   a) Josephson Junction
   b) Mesoscopic description of Josephson effect
   c) Andreev bound states (ABS)
   d) Andreev Quantum Dot (AQD)

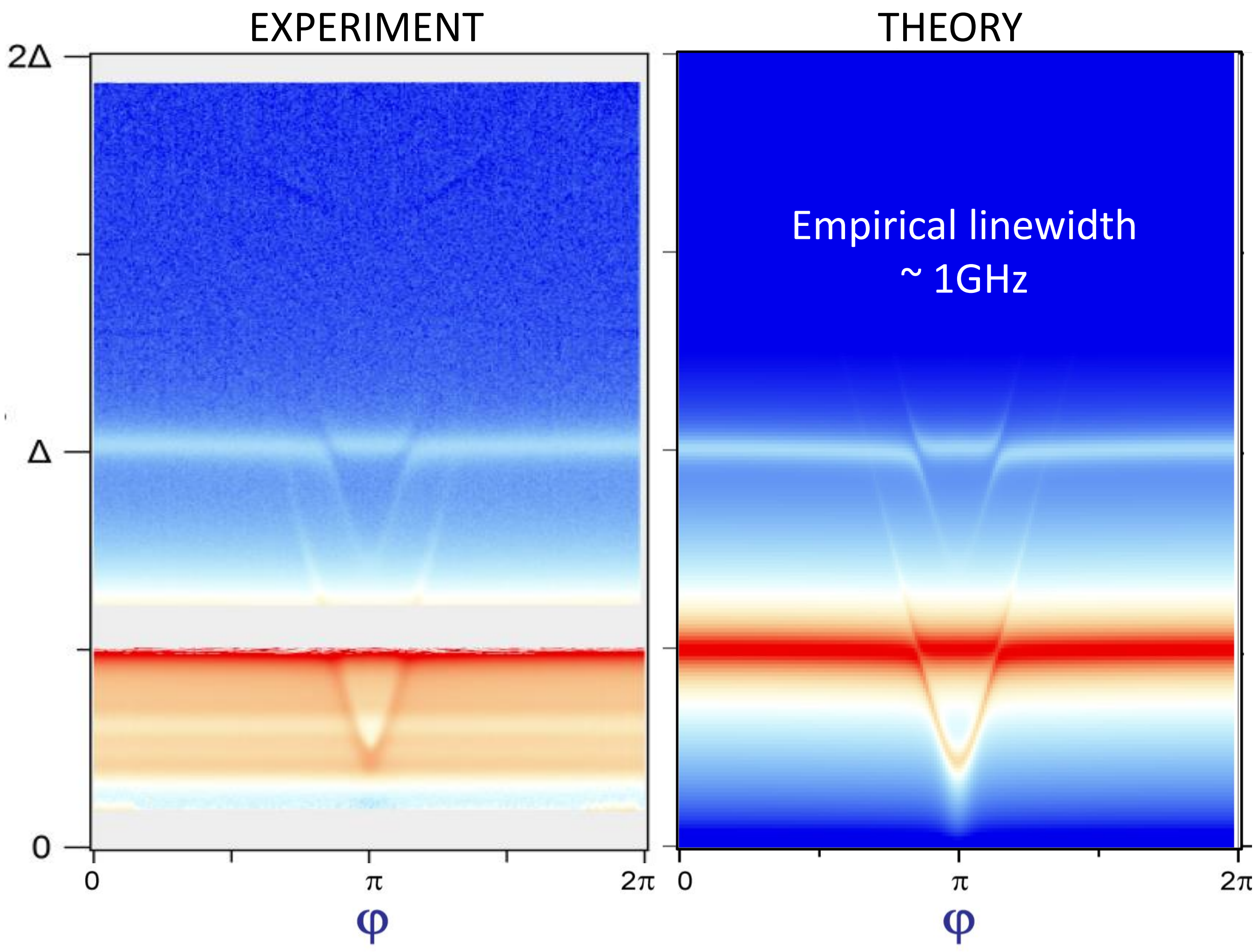
2. dc EXPERIMENTS on ATOMIC CONTACTS
   a. Supercurrent
   b. Current-phase relation
   c. Spectroscopy

3. cQED EXPERIMENTS on ATOMIC CONTACTS
   a. Spectroscopy
   b. Coherent Manipulation of ABS
   c. Continuous monitoring of quantum jumps

Spectroscopy of ABS using JJ spectrometer



2eV



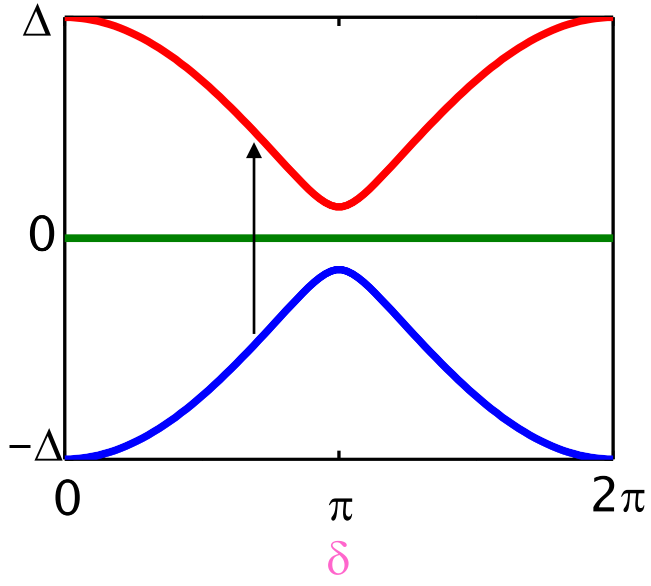
Bretheau *et al.*, PRB 2014

DETECT TRANSITIONS: 3. c-QED SETUP

1 — detect energy absorption

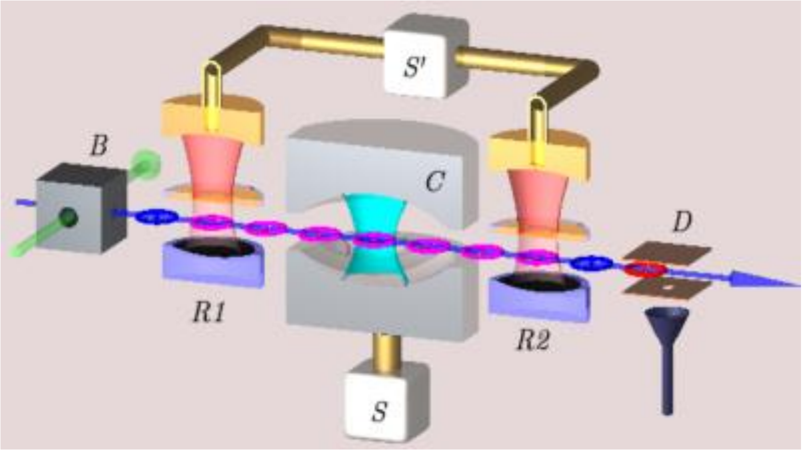
2 — detect change in supercurrent

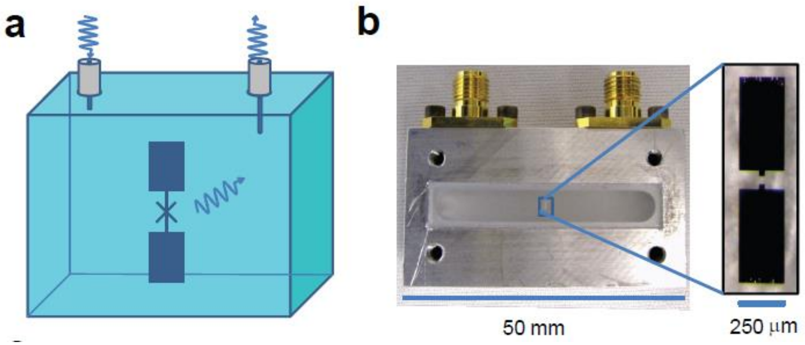
3 — cQED setup



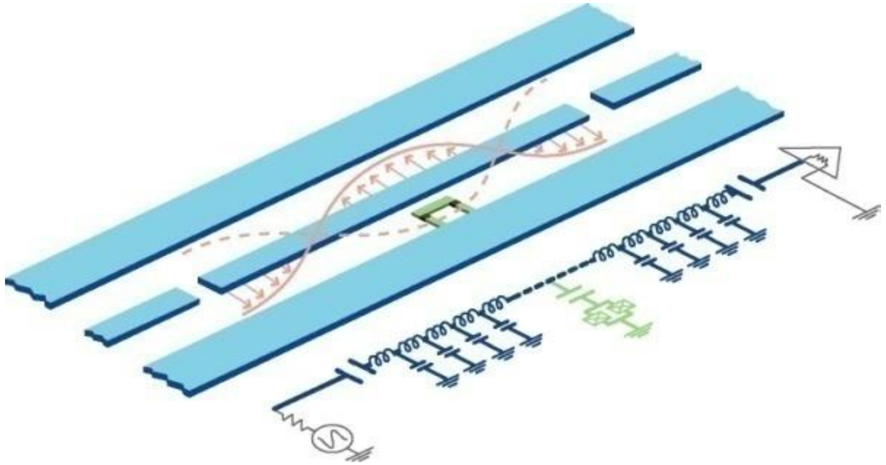
DRIVE AND MONITOR STATE

Cavity/circuit Quantum Electrodynamics setup



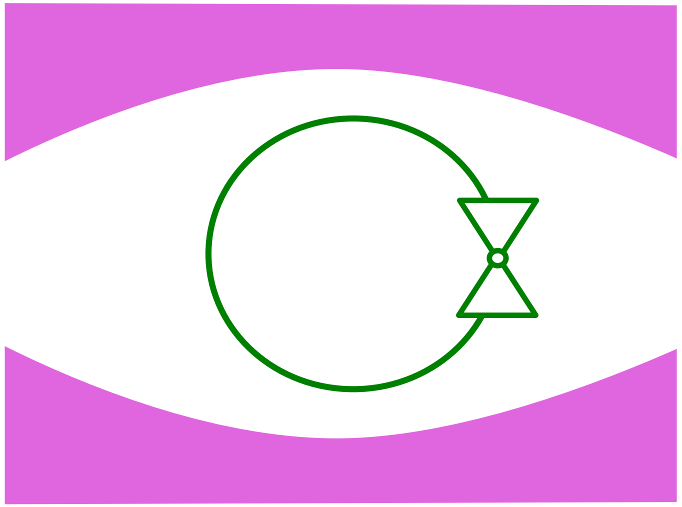


H. Paik *et al.*, PRL (2012)



A. Blais *et al.*, Phys. Rev. A (2004)
A. Walraff *et al.*, Nature (2004)
I. Chiorescu *et al.*, Nature (2004)

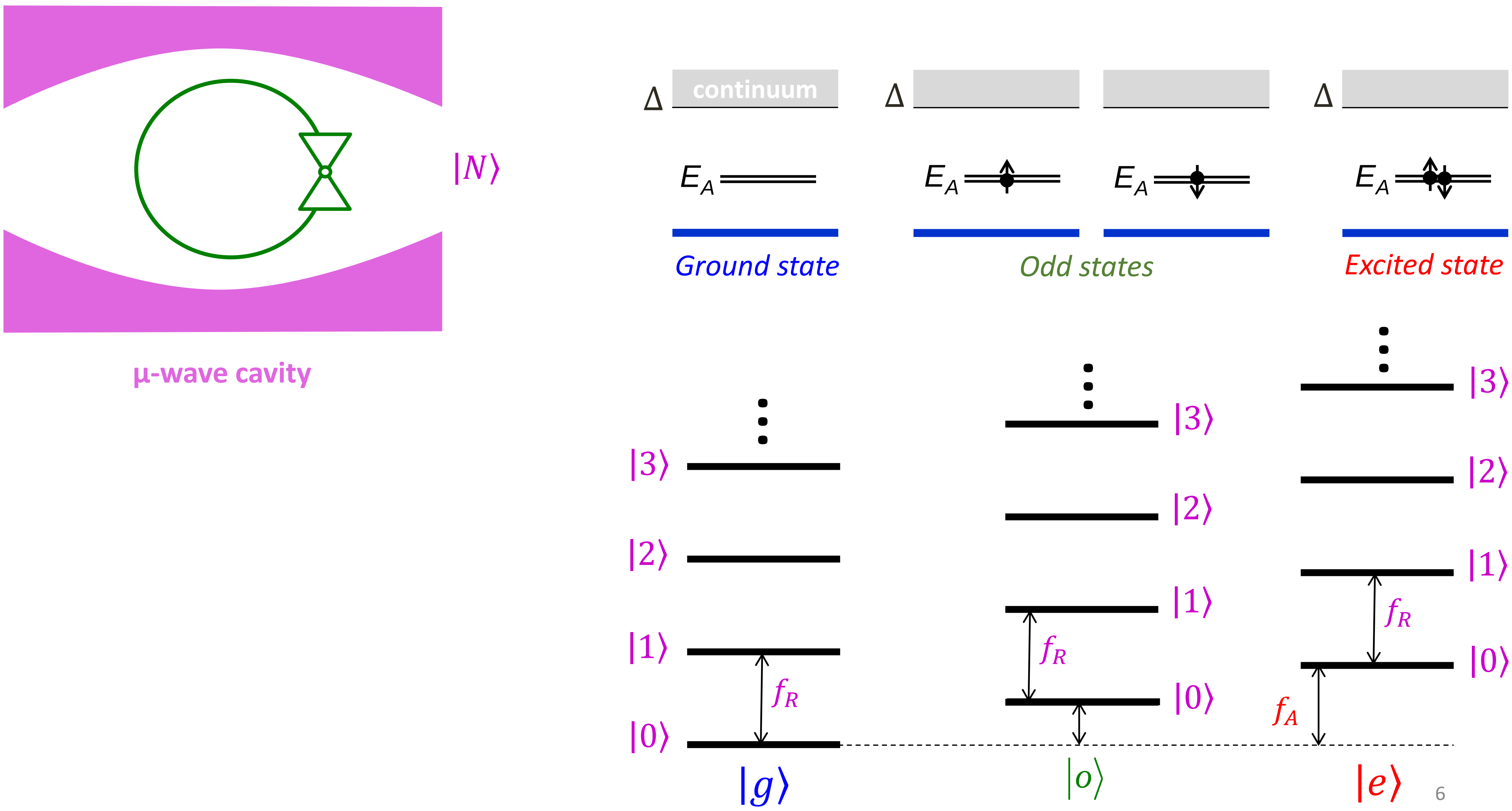
ANDREEV QUANTUM DOT IN CAVITY



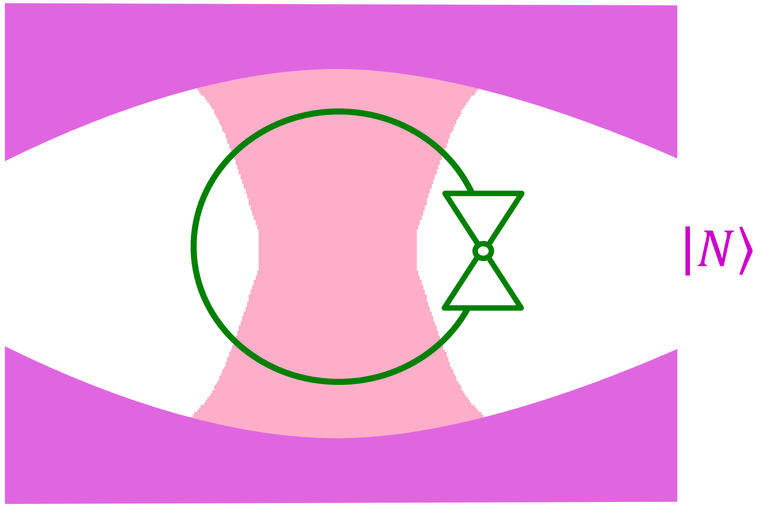
µ-wave cavity

NO CONNECTION WIRES

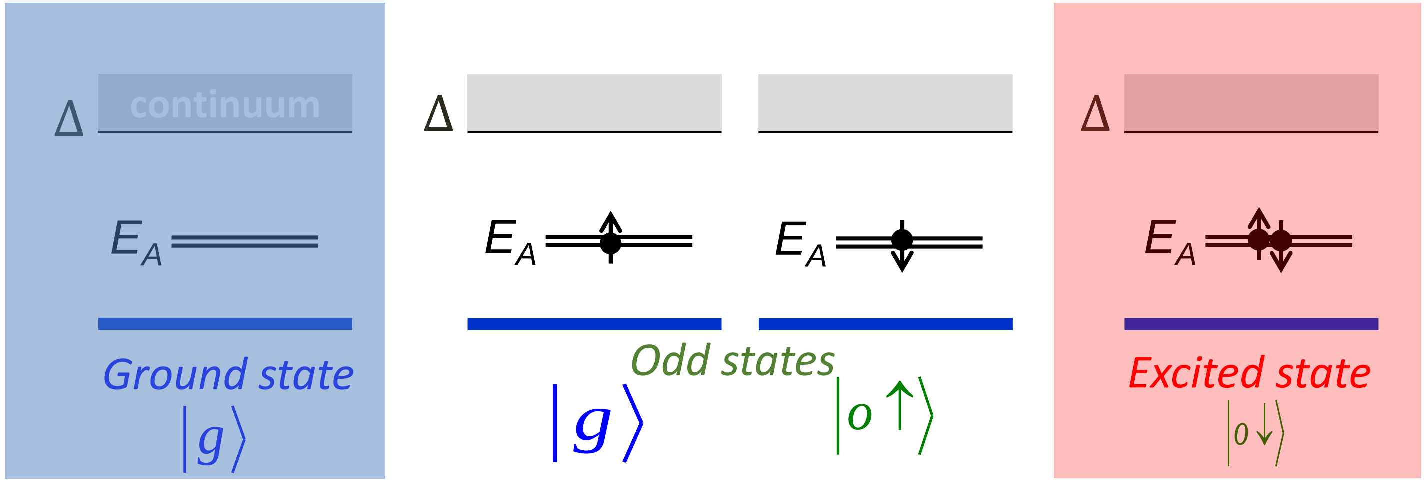
QUANTUM STATE BASIS



TWO COUPLED SYSTEMS



μ-wave cavity



ONLY EVEN STATES COUPLE TO CAVITY

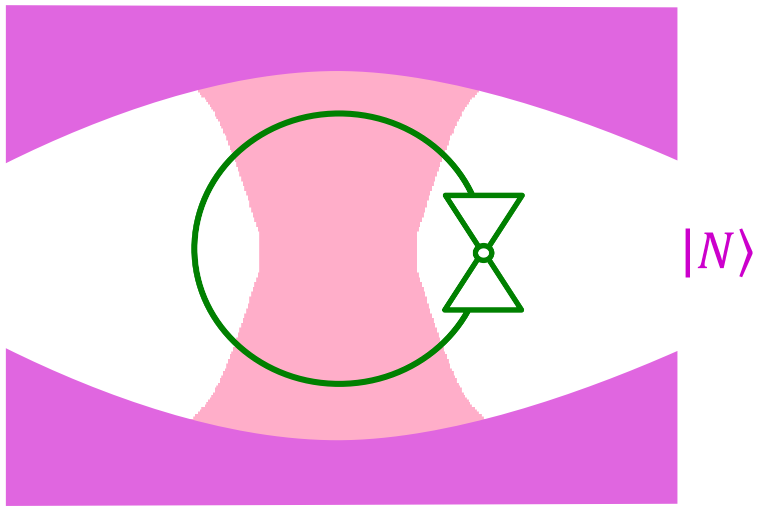
Jaynes-Cummings hamiltonian

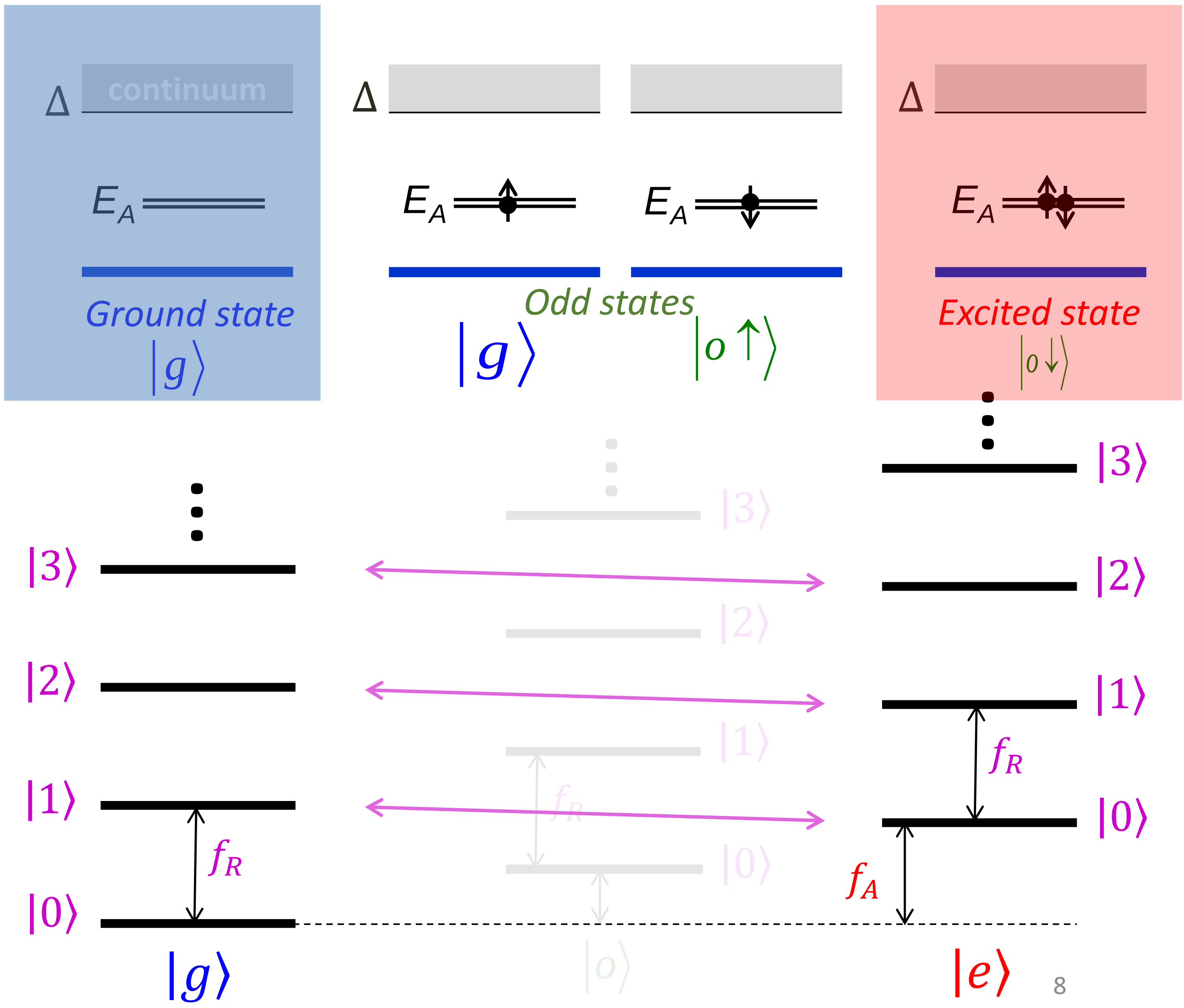
$$H = h\left\{ f_R\left(a^\dagger a + \frac{1}{2}\right) - \frac{f_A}{2}\sigma_z + g(\tau,\delta)\left(a^\dagger\sigma_- + a\sigma_+\right)\right\}$$

$$f_A, f_R \gg g \propto M$$

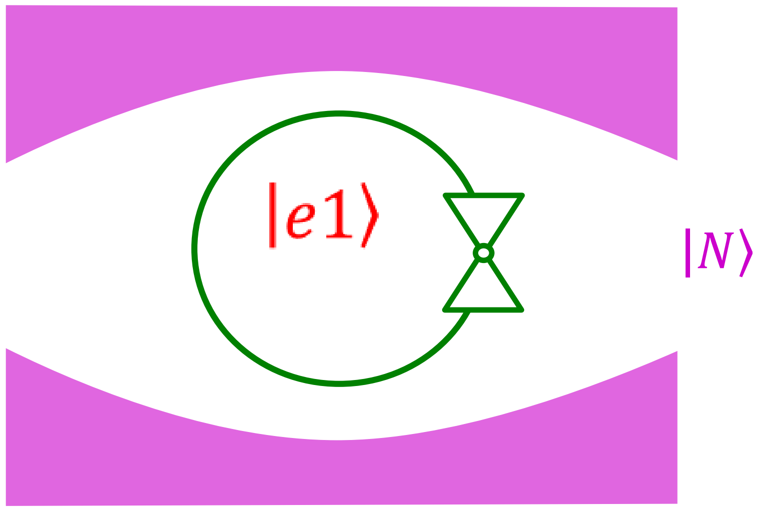
$$M \cdot \widehat{I}_r \cdot \widehat{I}_A$$

LEVEL REPULSION





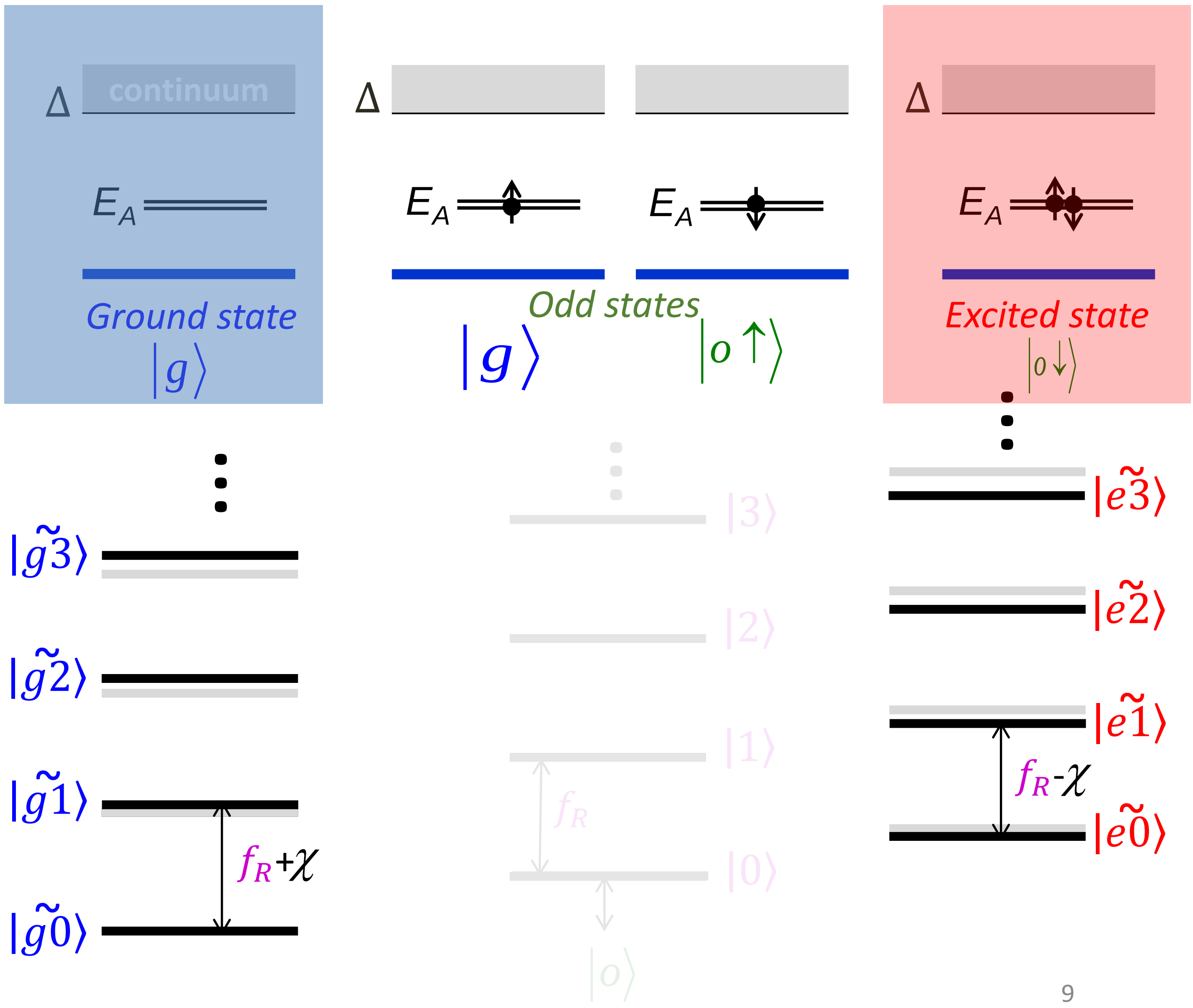
DRESSED STATES



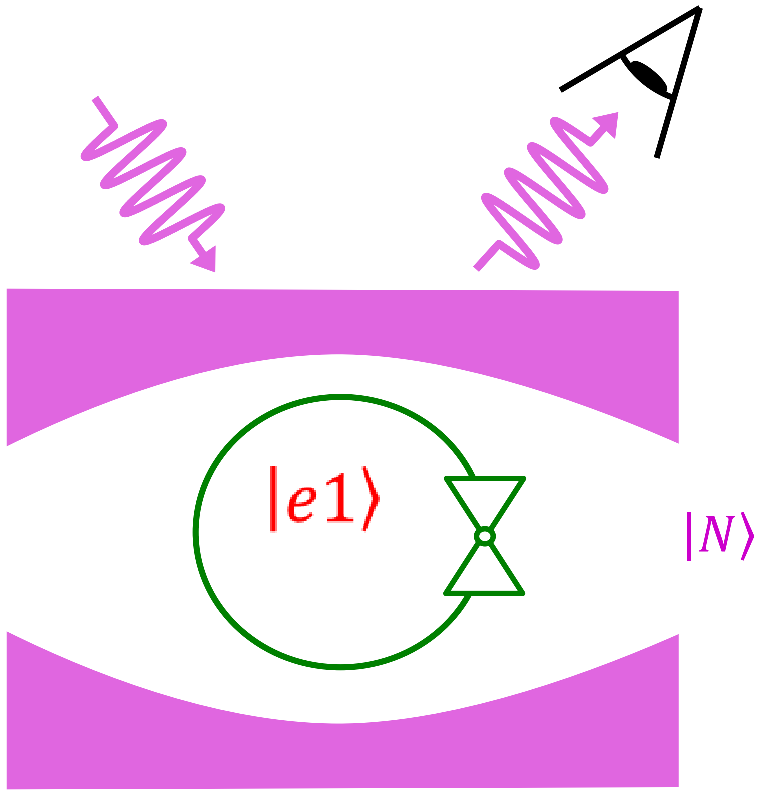
μ-wave cavity

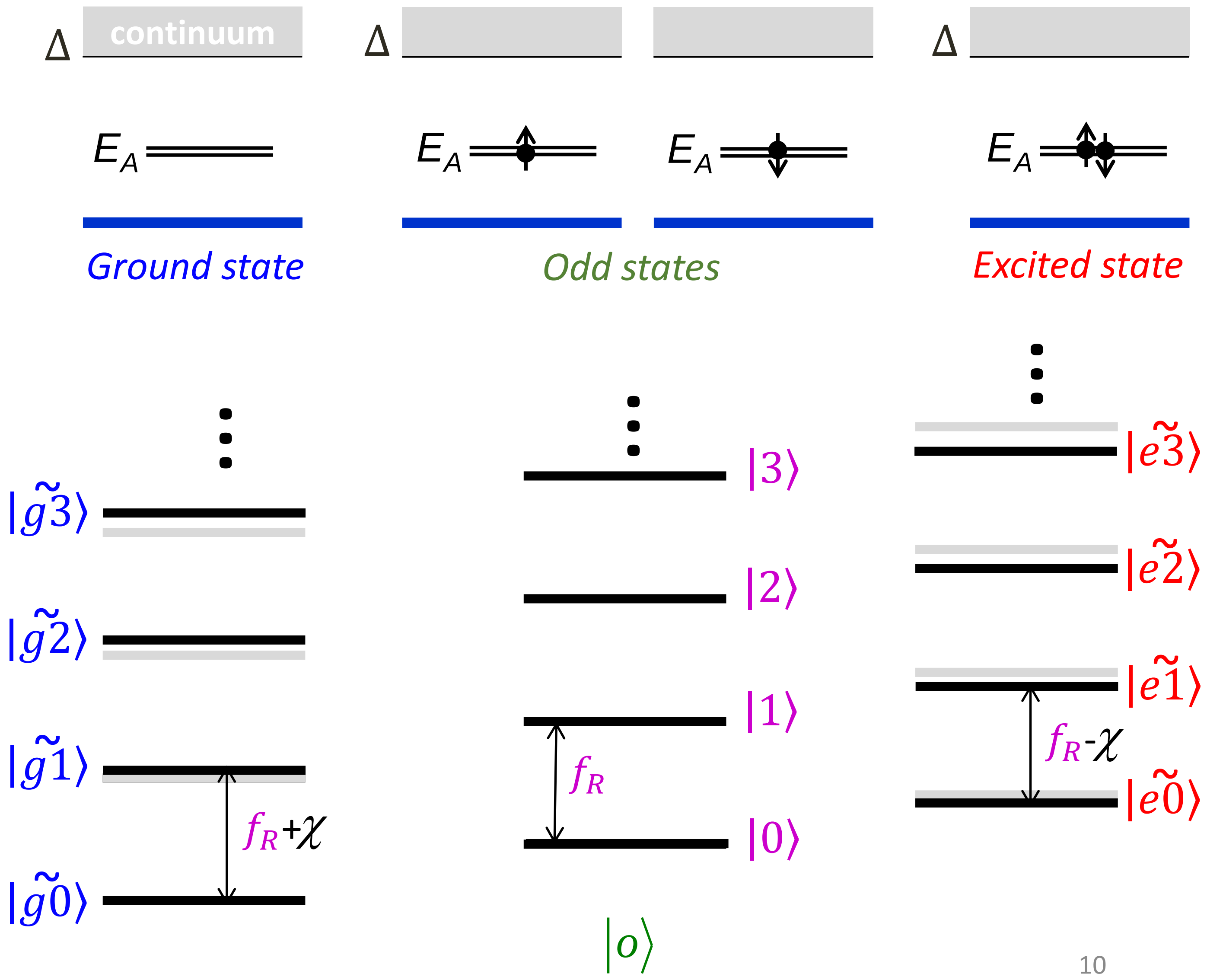
DISPERSIVE SHIFT

$$\chi = \frac{g^2}{f_A - f_R}$$

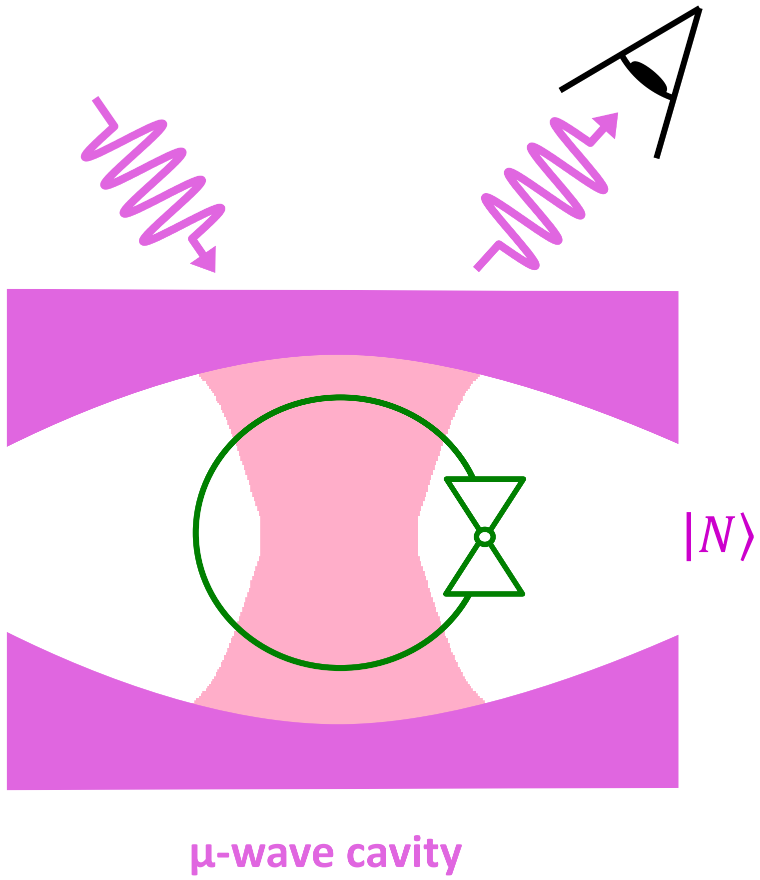


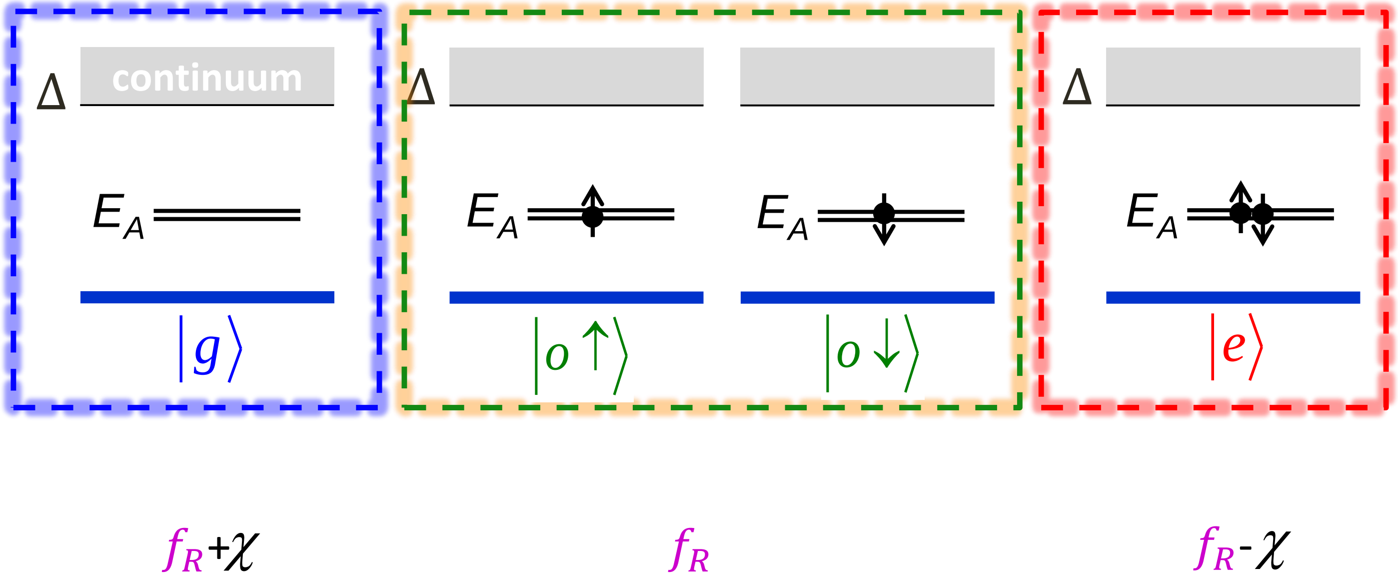
CAVITY DISPERSIVE SHIFTS





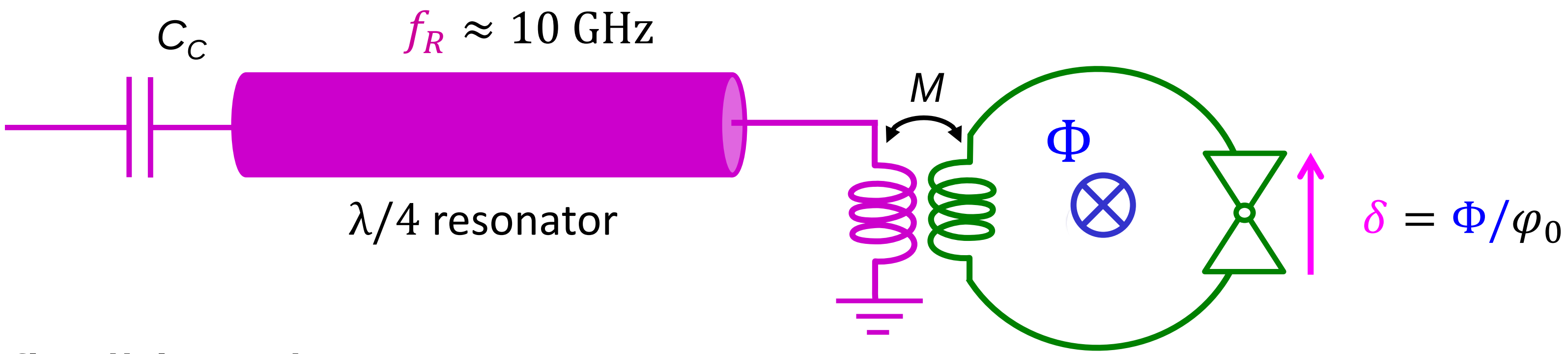
AQD IN CAVITY: STATE READ-OUT



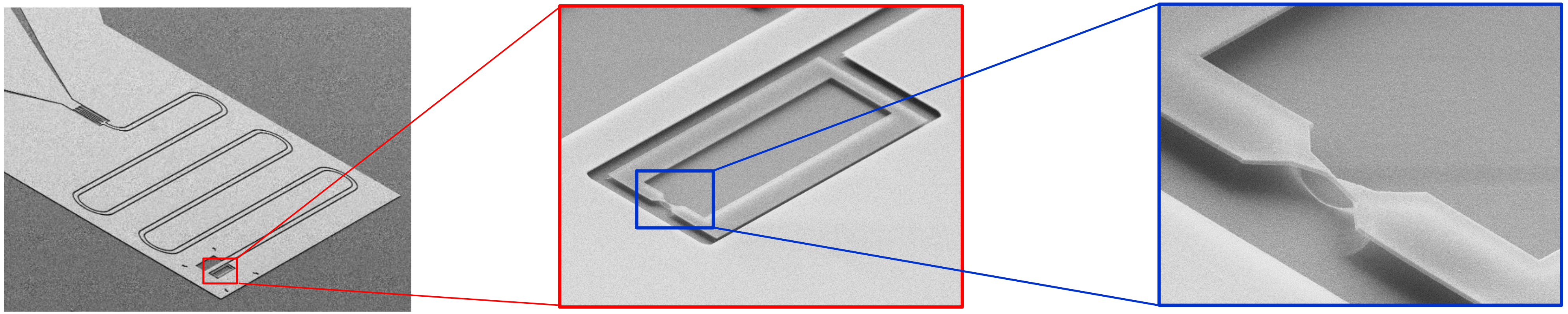


AQD STATE ENCODED IN RESONATOR FREQUENCY

AQD COUPLED TO COPLANAR MICROWAVE RESONATOR

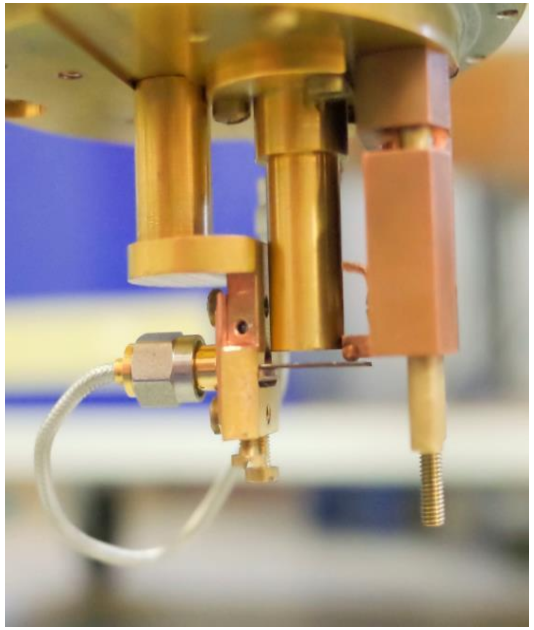


Implementation in a flexible substrate

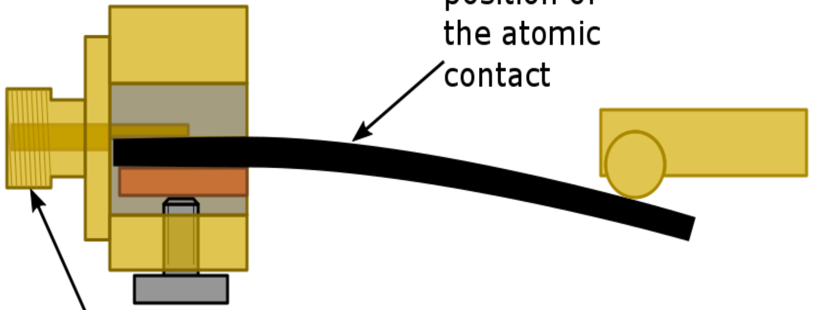


Janvier *et al.*, Science **349**, 1199 (2015)

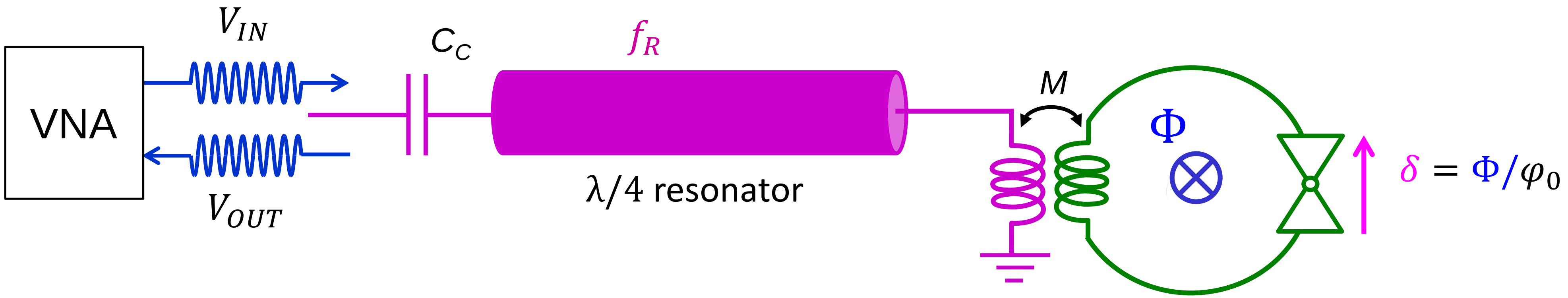
MICROWAVE COMPATIBLE SETUP



Break junction setup

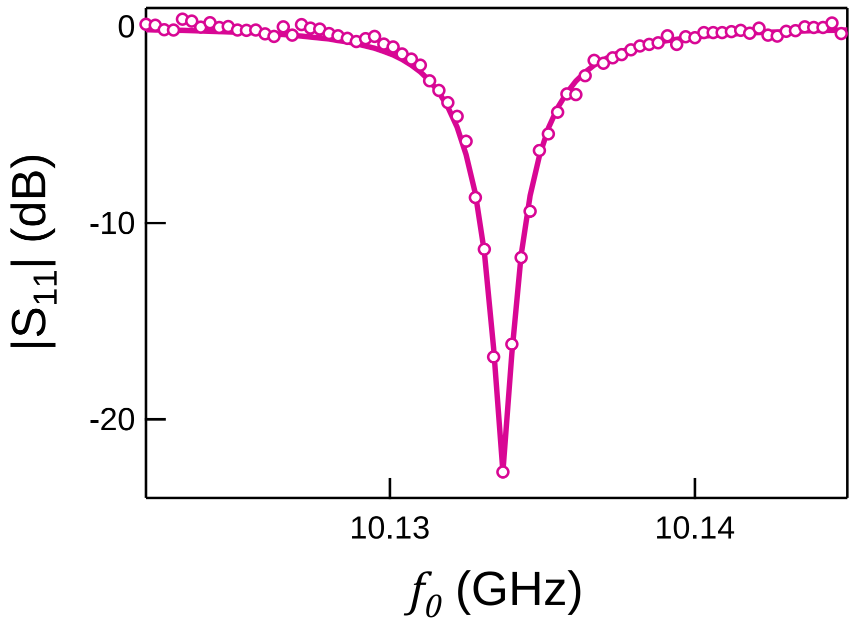


cw RESONATOR CHARACTERIZATION



Reflection coefficient

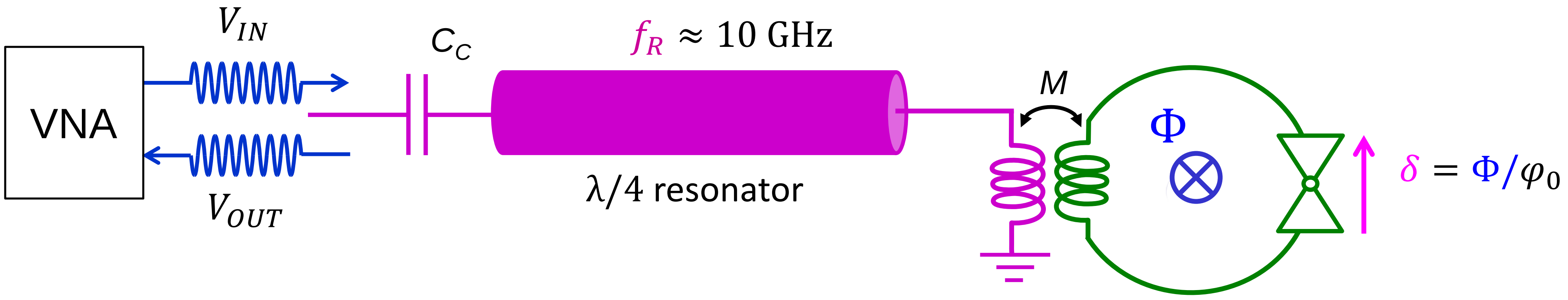
$$\boxed{S_{11}(f_0) \equiv \frac{V_{OUT}}{V_{IN}}}$$

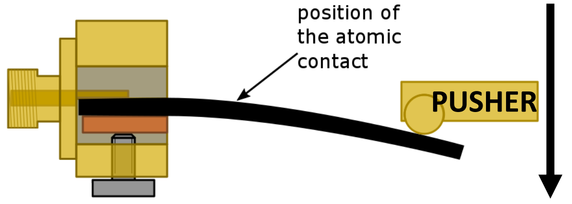


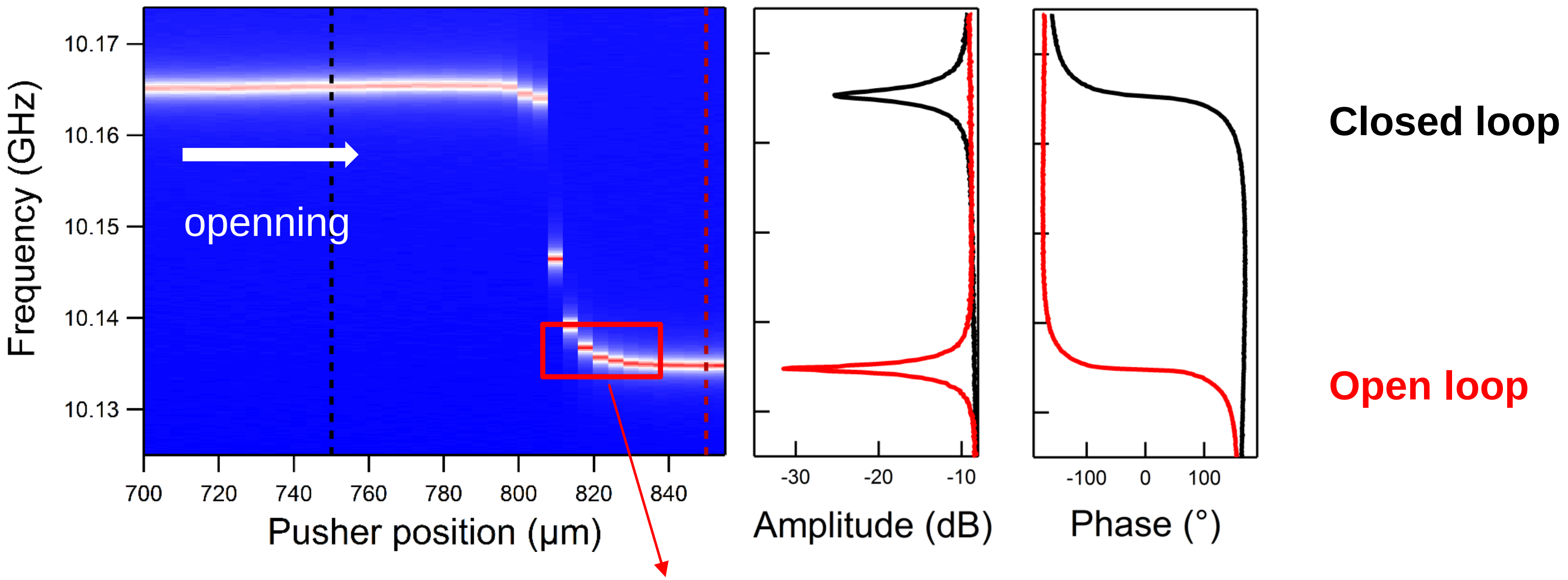
$Q_i = 4100$

$Q_T = 2200$

GETTING ONE-ATOM CONTACTS

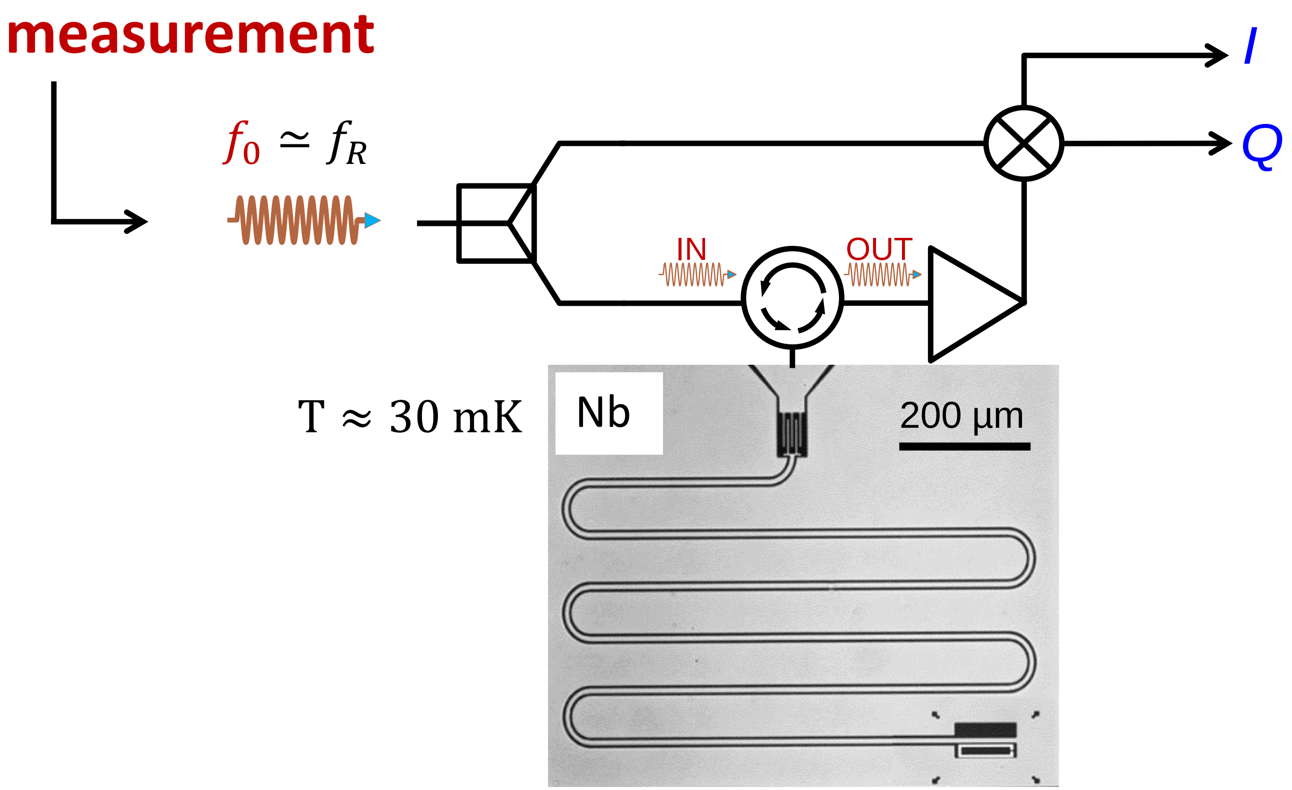




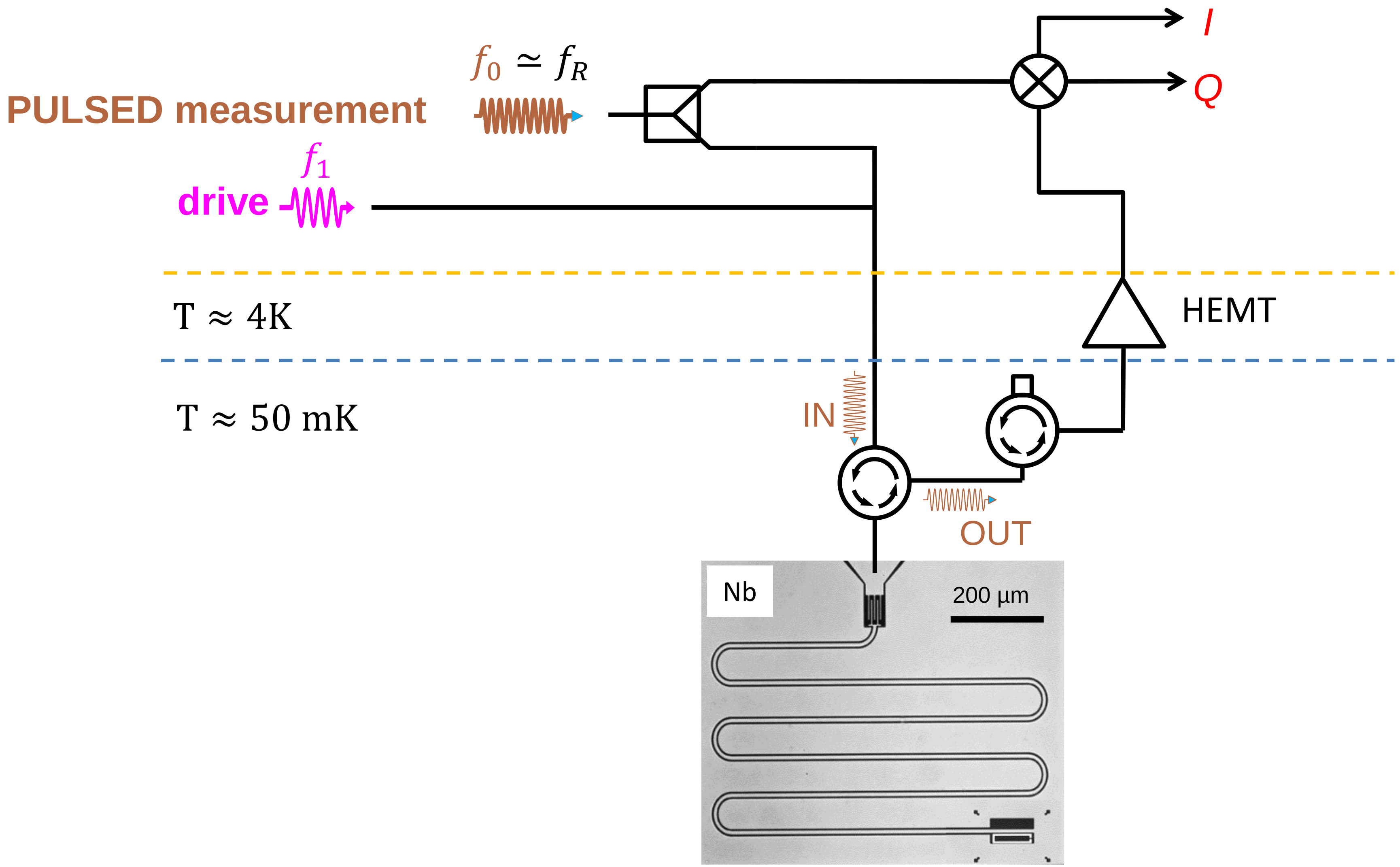


CONTACTS WITH SMALL NUMBER OF CHANNELS

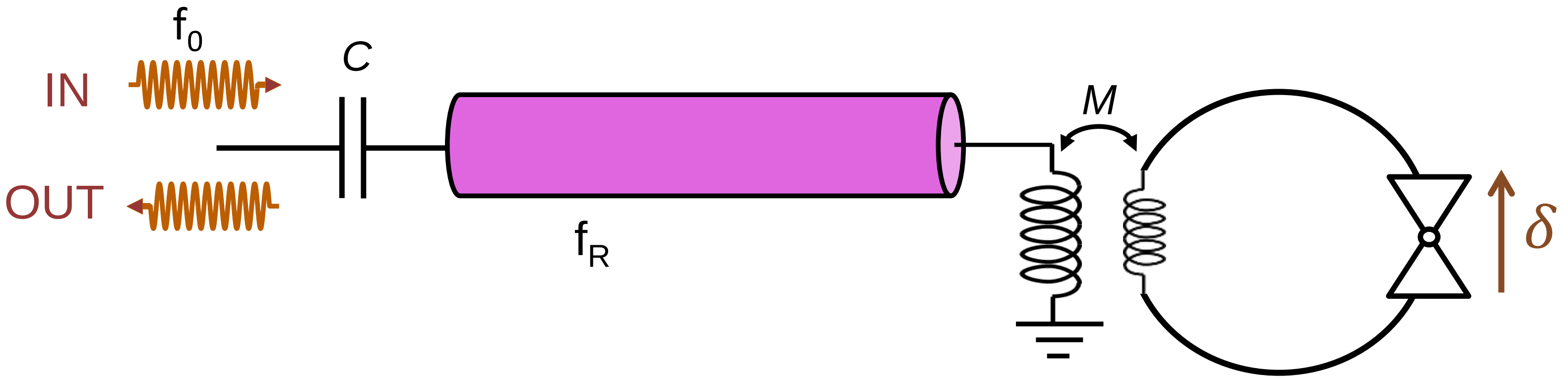
HOMODYNE MEASUREMENTS

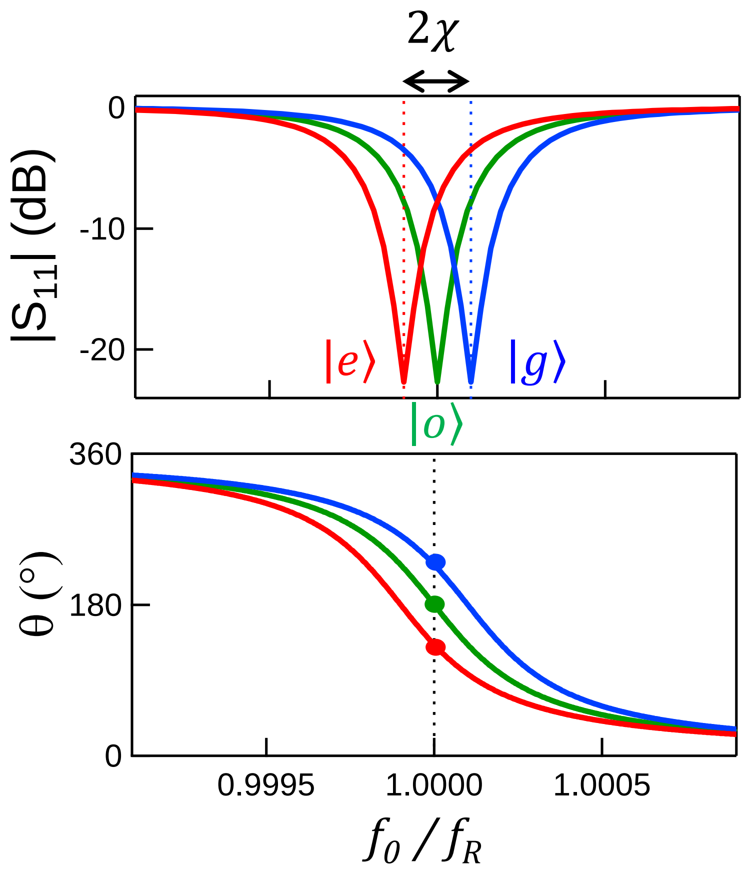


HOMODYNE MEASUREMENTS

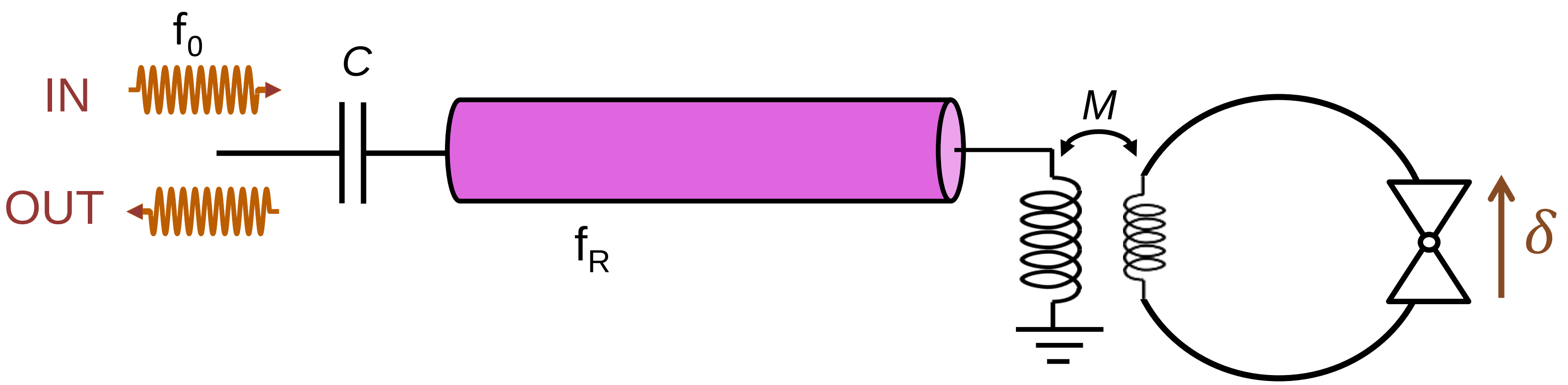


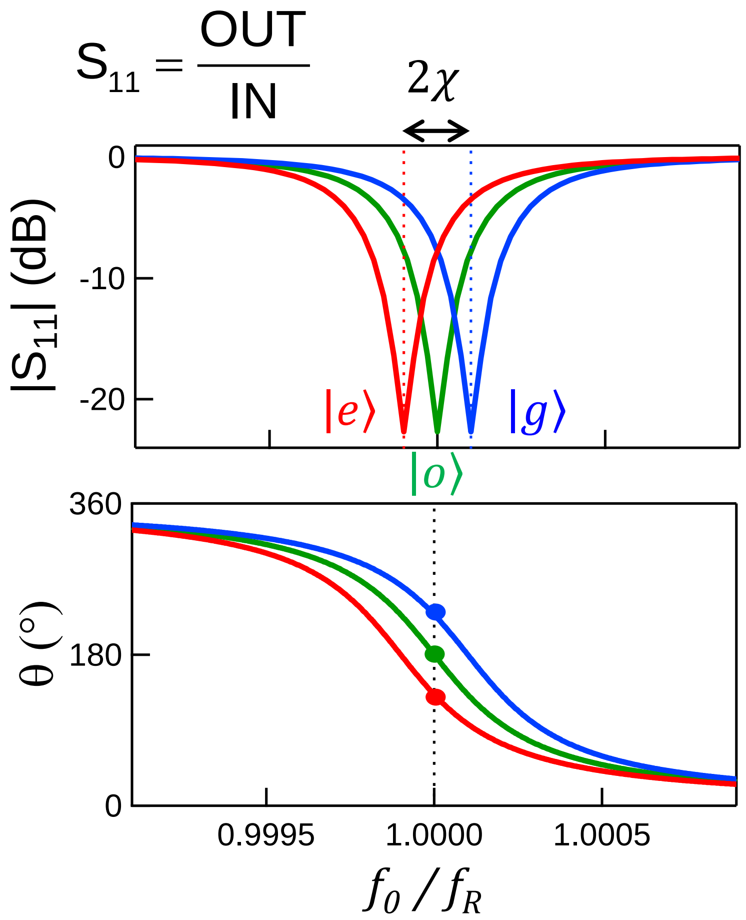
DISPERSIVE READ-OUT



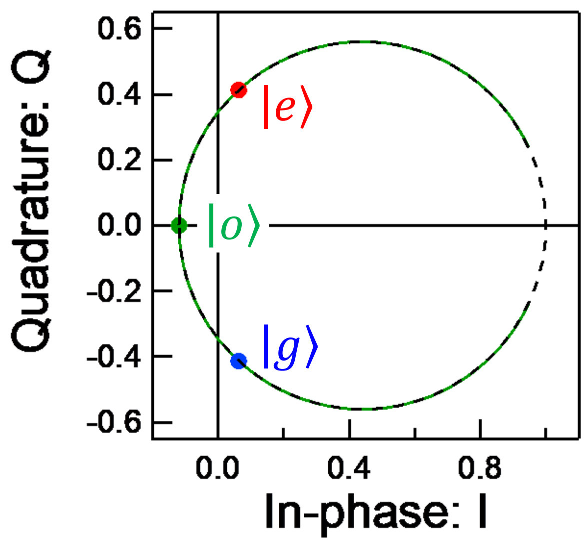


DISPERSIVE READ-OUT



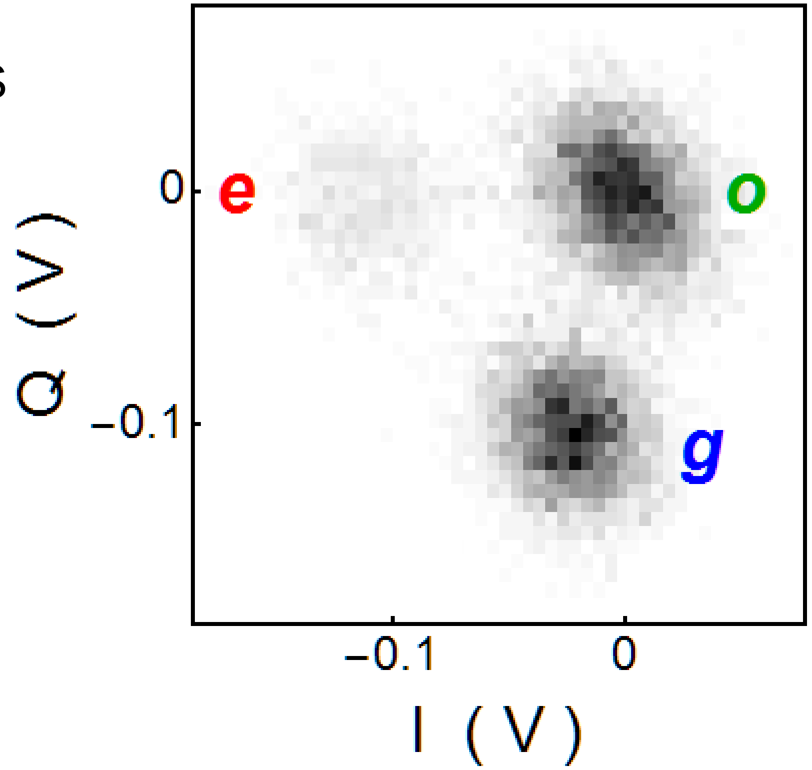


IQ-PLANE REPRESENTATION



MEASUREMENTS AT $\delta=\pi$ WITH NO DRIVE

DENSITY PLOT
FOR ~10^4 PULSES

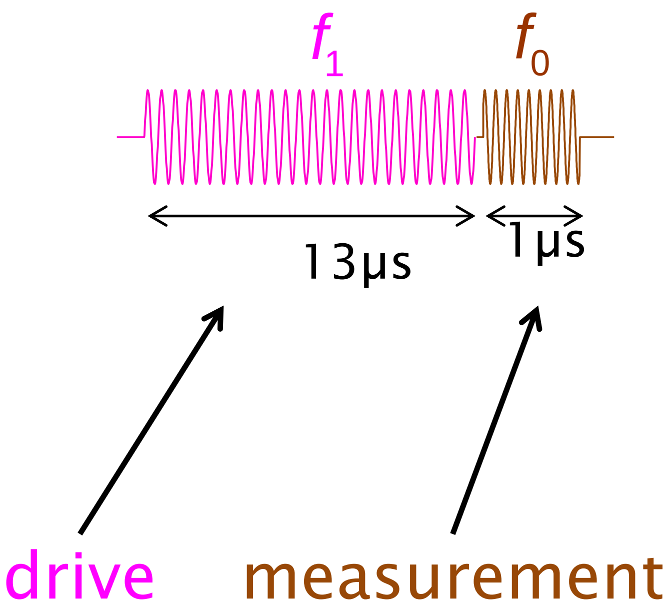


$\bar{n}_{photons} \simeq 30$

SINGLE-SHOT DETERMINATION OF STATE

NUMBER OF POINTS IN EACH CLOUD
GIVES POPULATION OF EACH STATE

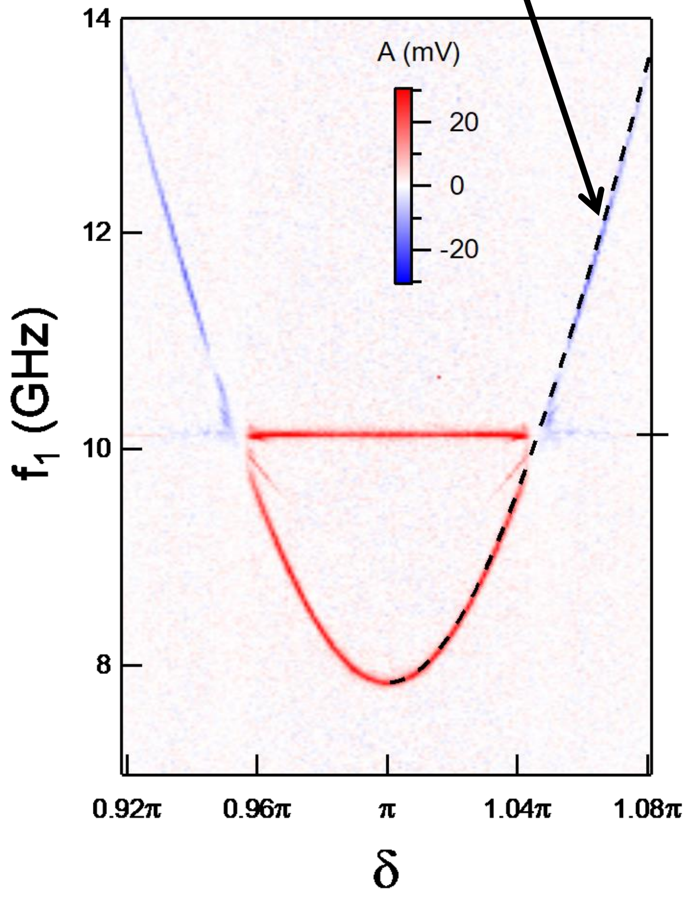
TWO-TONE SPECTROSCOPY



$$hf_A = 2\Delta\sqrt{1-\tau\sin^2(\delta/2)}$$

$$\tau = 0.99217$$

$$\Delta = 44.3\,\text{GHz}$$



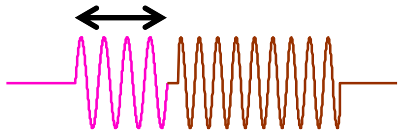
Linewidth
~ 50 Mhz

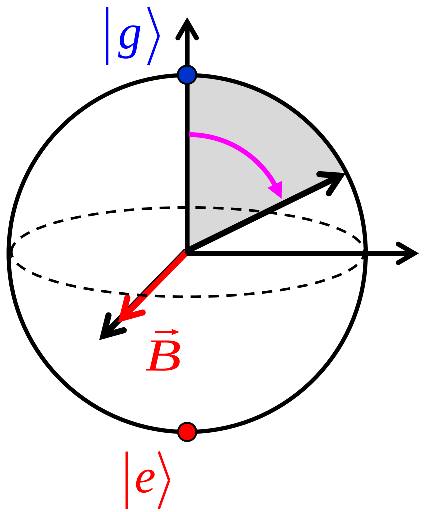
C. Janvier *et al.*, Science **349**, 1199 (2015)

COHERENT MANIPULATION AT δ=π

RABI OSCILLATIONS

$f_1 = f_A$

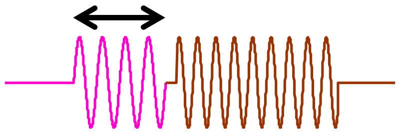


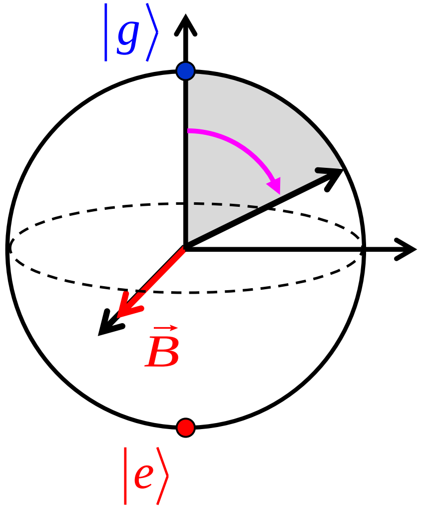


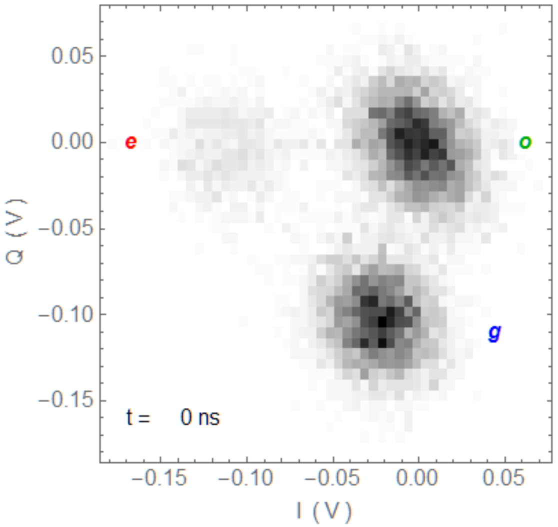
COHERENT MANIPULATION AT δ=π

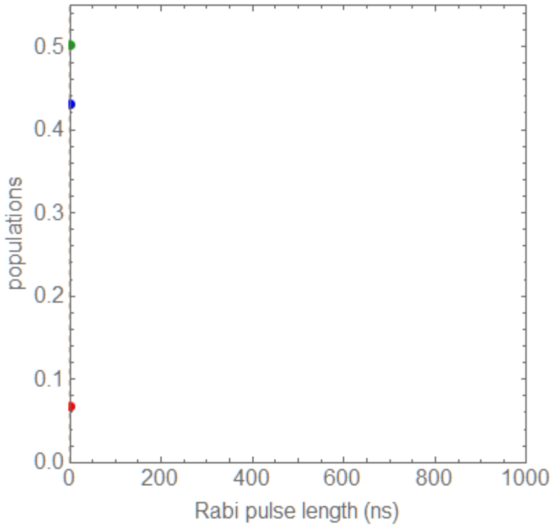
RABI OSCILLATIONS

$f_1 = f_A$





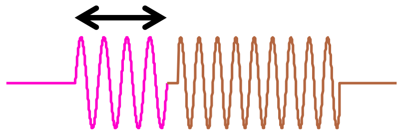


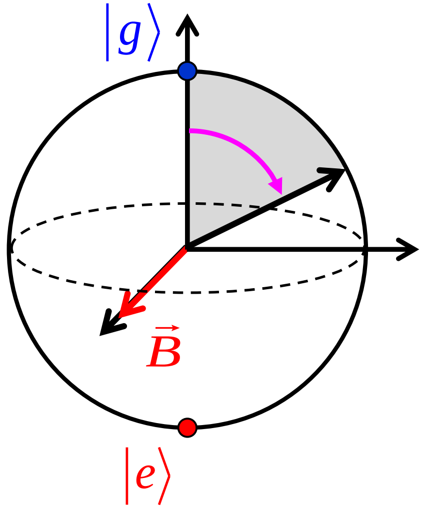


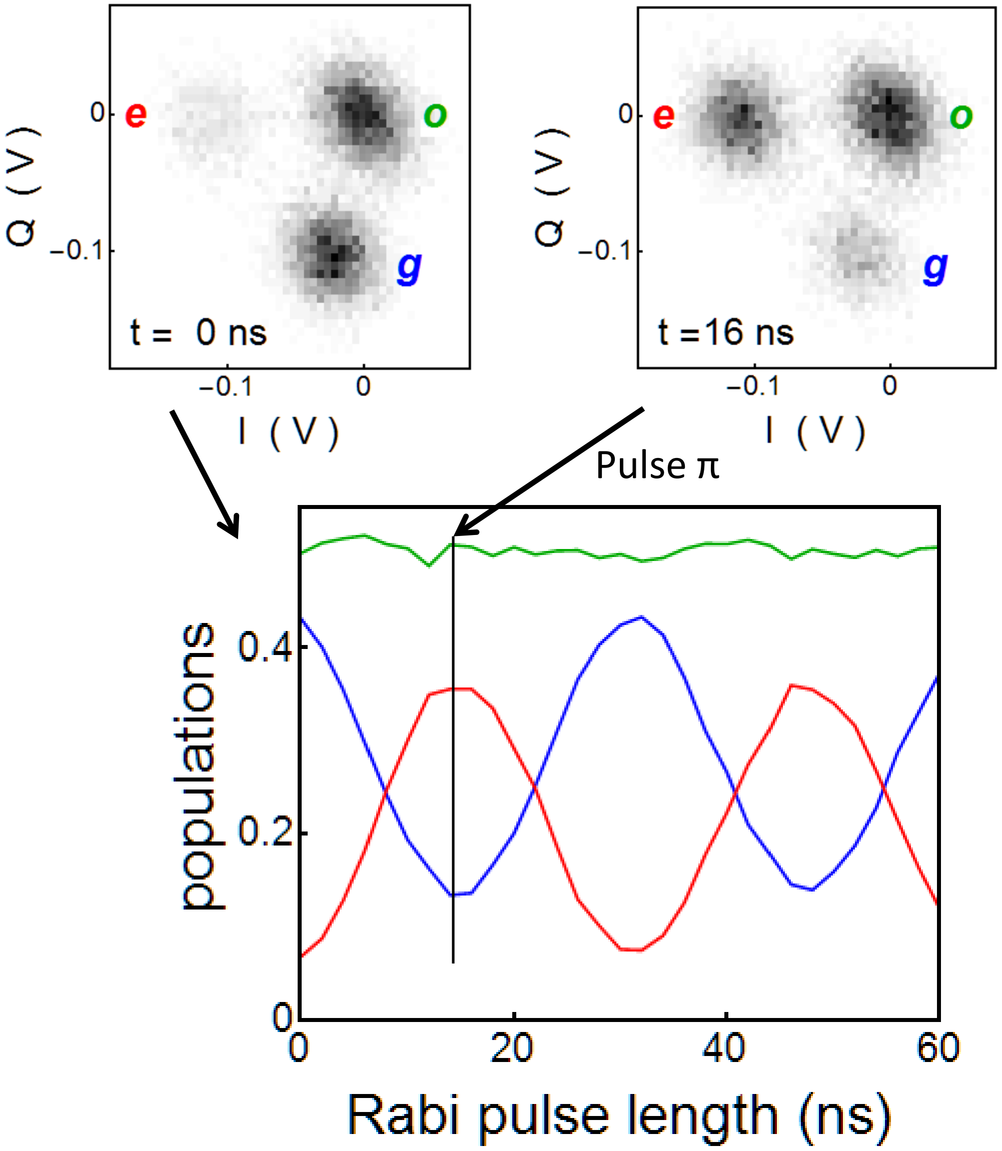
COHERENT MANIPULATION AT δ=π

RABI OSCILLATIONS

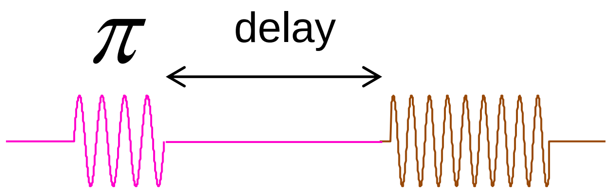
$f_1 = f_A$

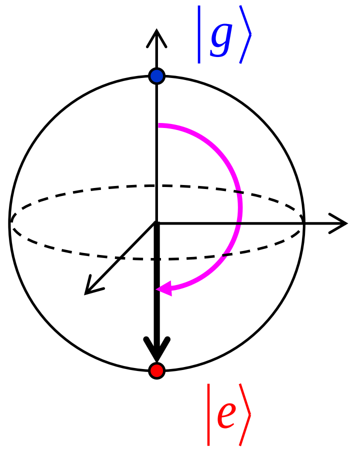


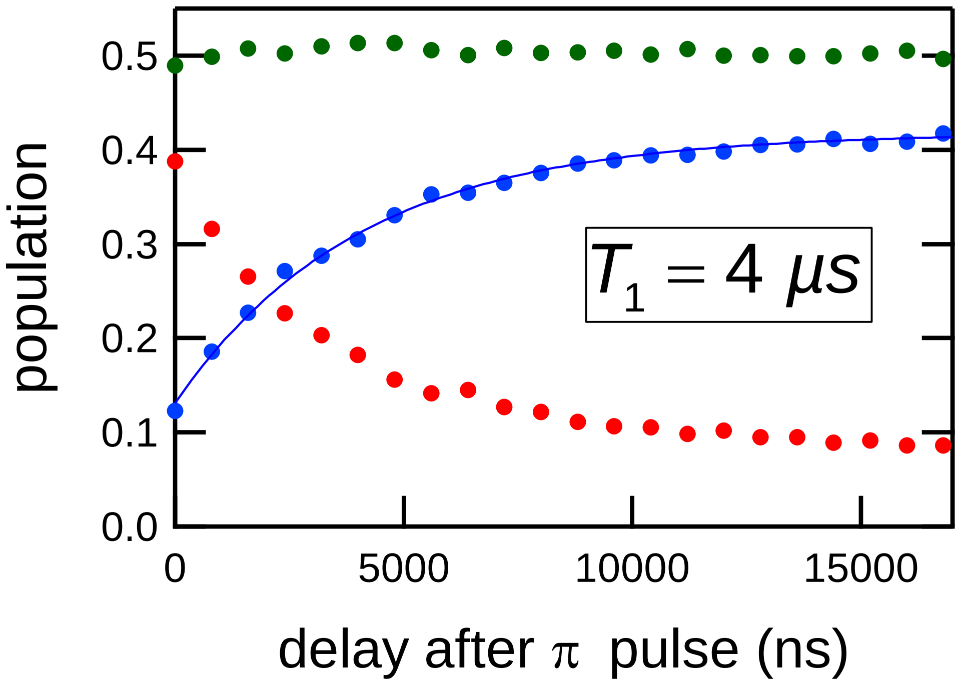




RELAXATION TIME

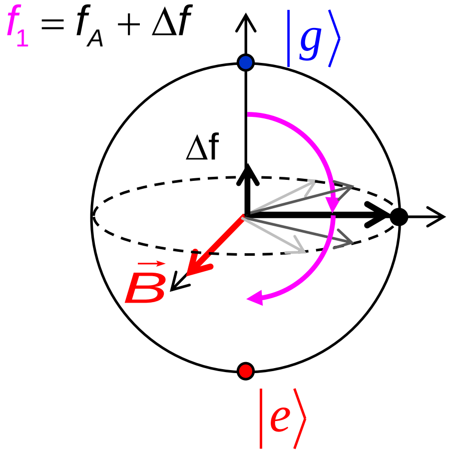


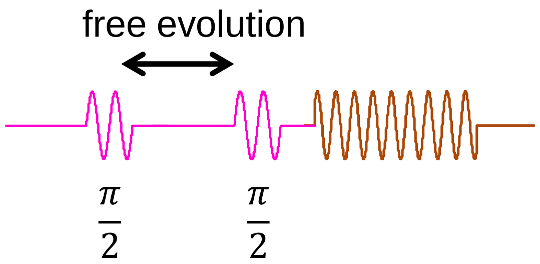


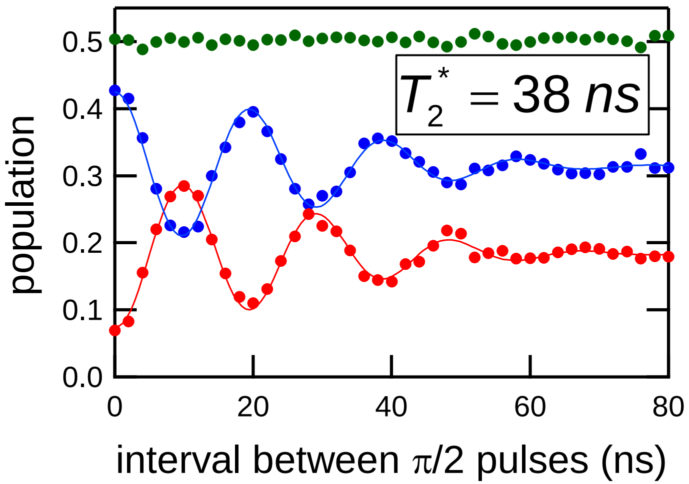


COHERENCE TIMES

RAMSEY FRINGES

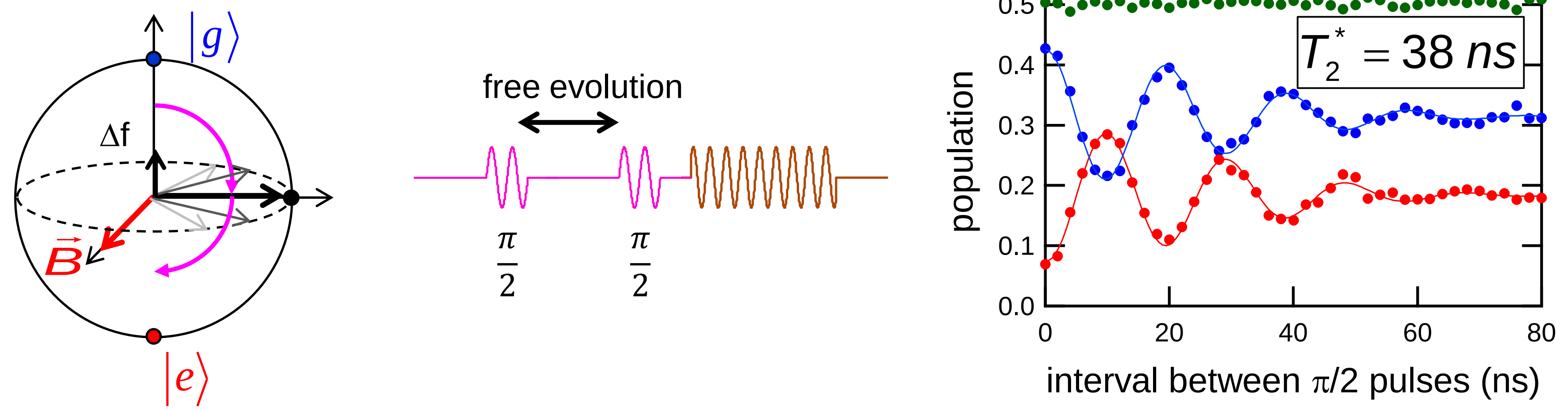




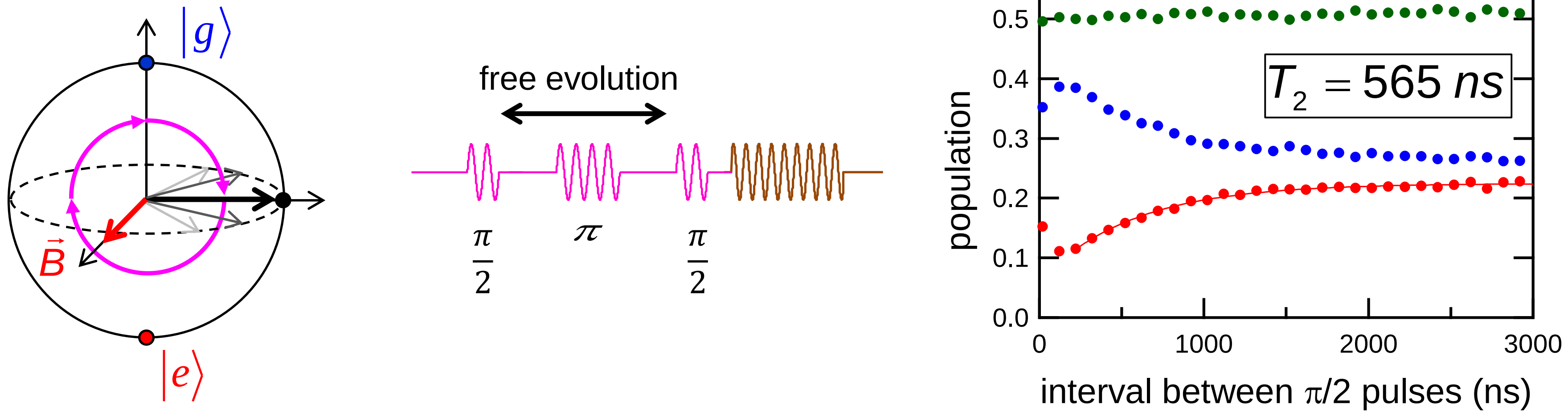


COHERENCE TIMES

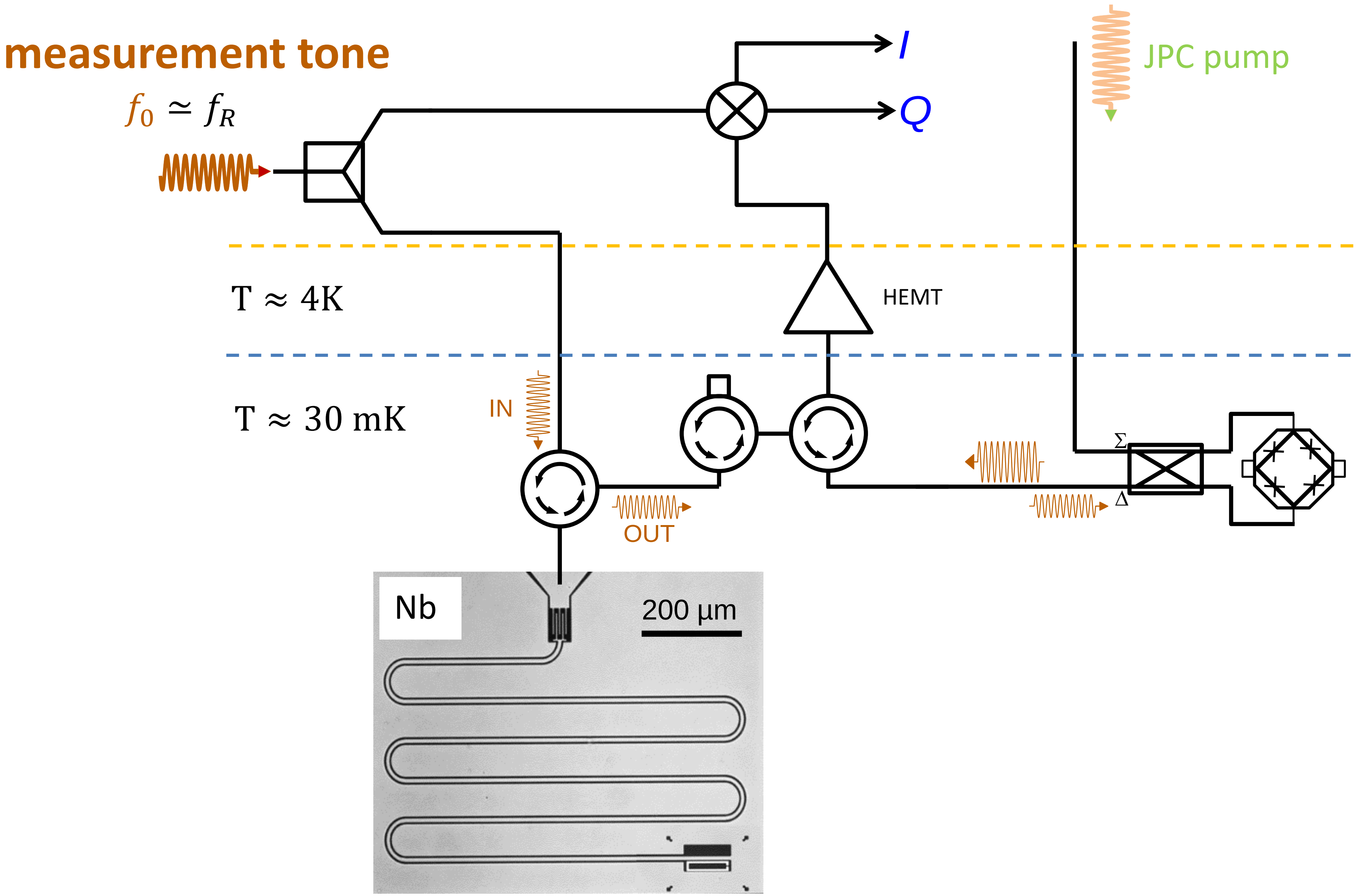
RAMSEY FRINGES



HAHN ECHO



MONITORING WITH QUANTUM LIMITED AMPLIFIER

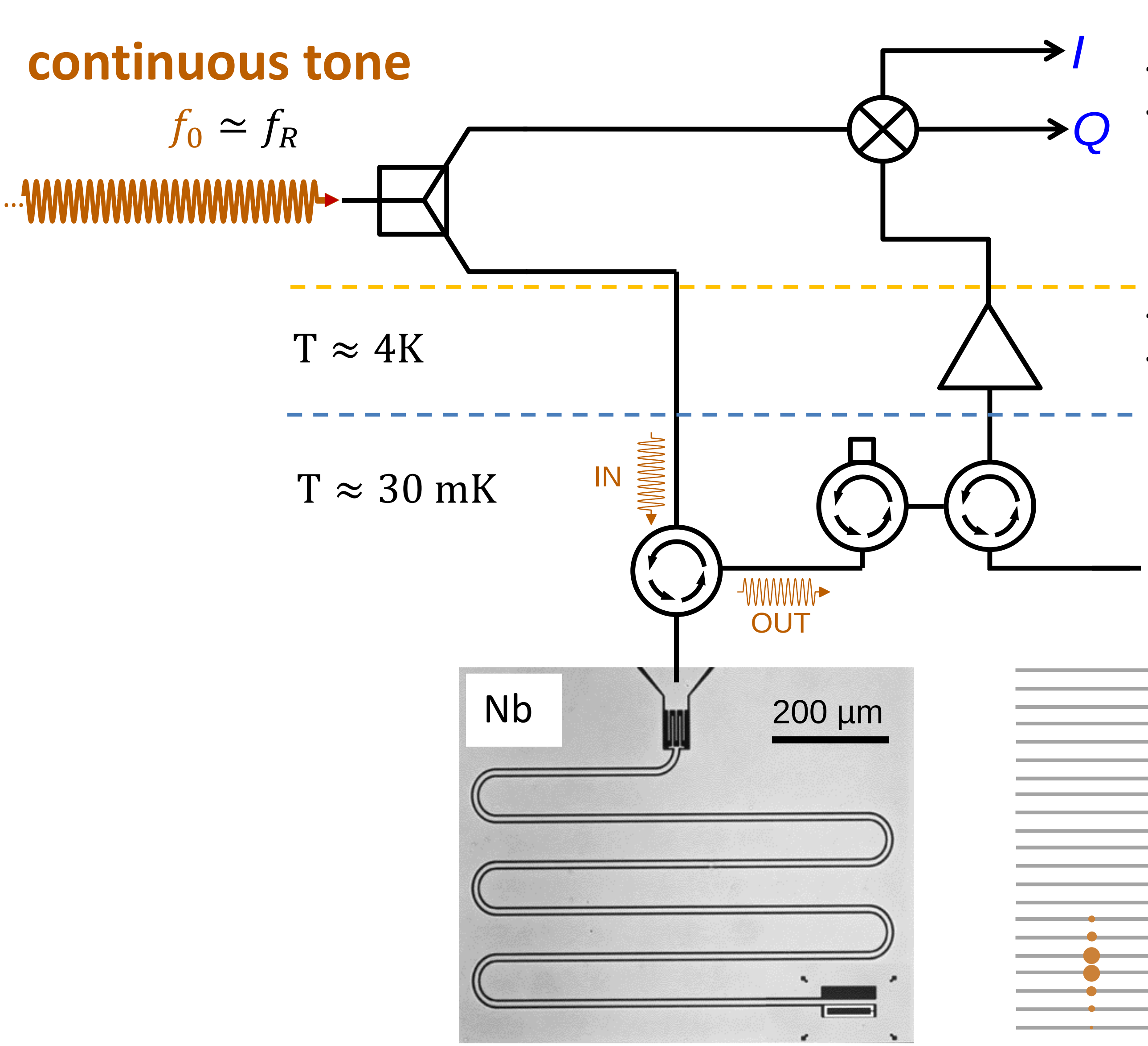


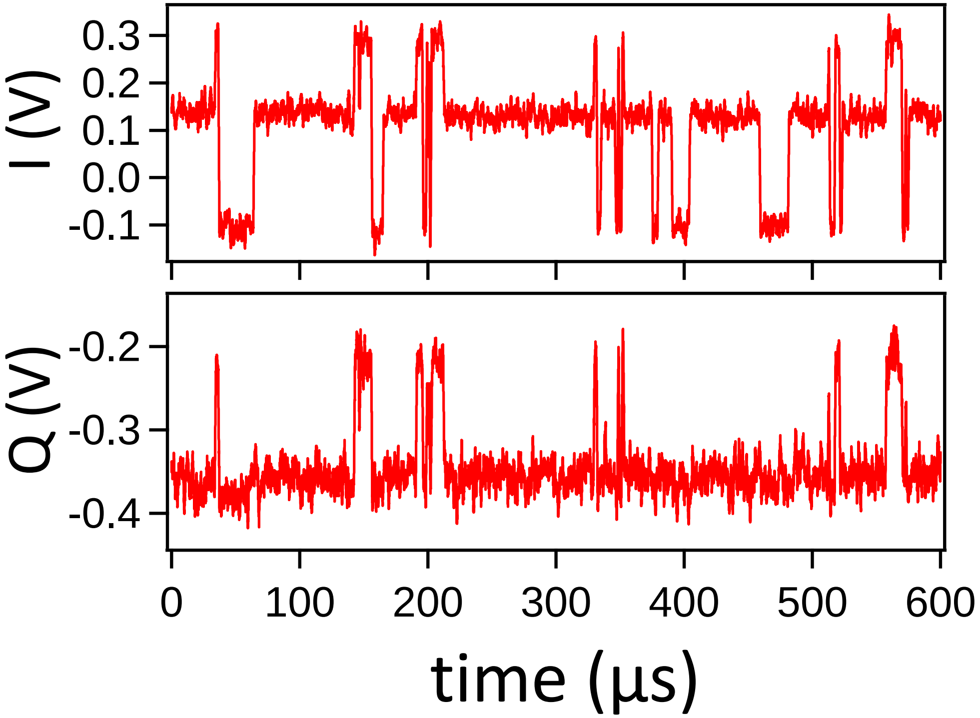
JOSEPHSON
PARAMETRIC CONVERTER*

*B. Huard, ENS, Paris

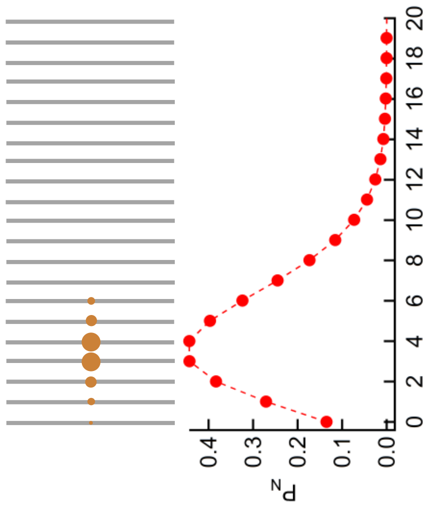
N. Bergeal et al., Nature **465**, 64 2010

CONTINUOUS MONITORING WITH NO DRIVE





1 point every 10ns



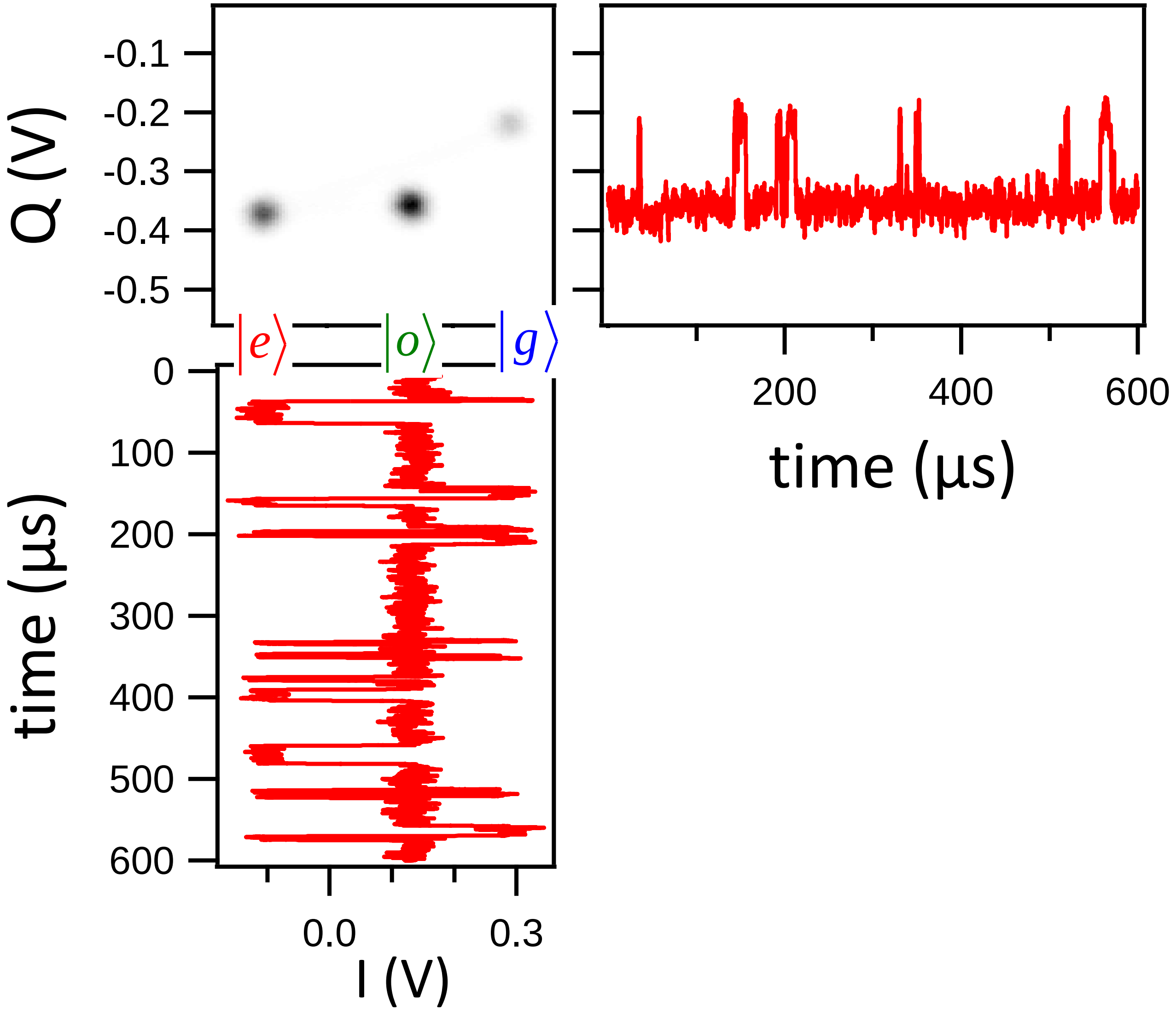
COHERENT STATE

$$\langle n_{g,e} \rangle, \langle n_o \rangle$$

I,Q HISTOGRAMS

$f_A = 6.33$ GHz

$\langle n_{g,e} \rangle = 220$



ANDREEV QD DYNAMICS

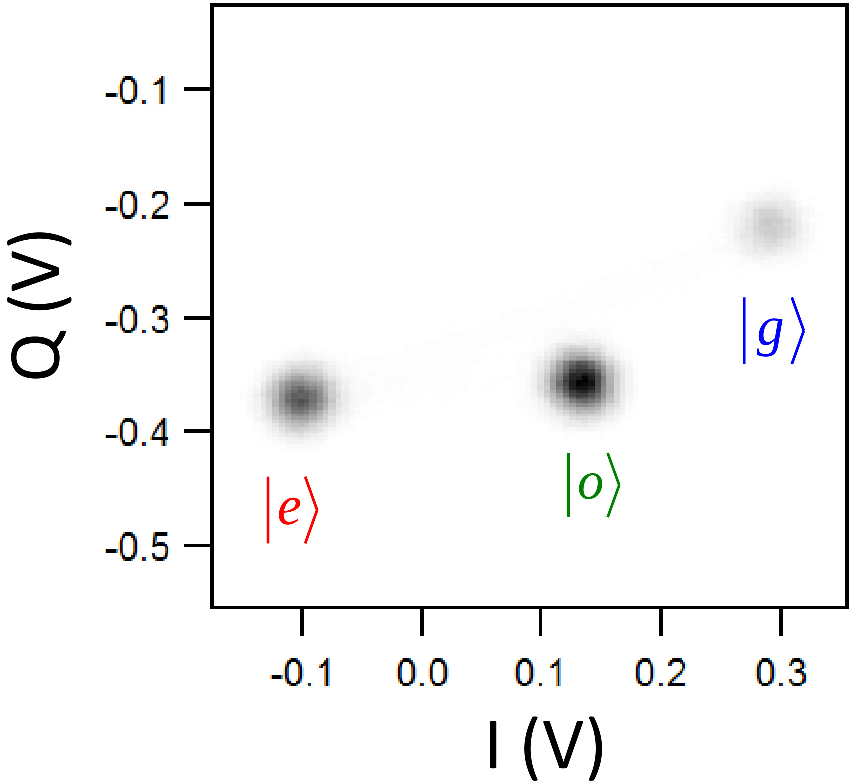
f_A = 6.33 GHz

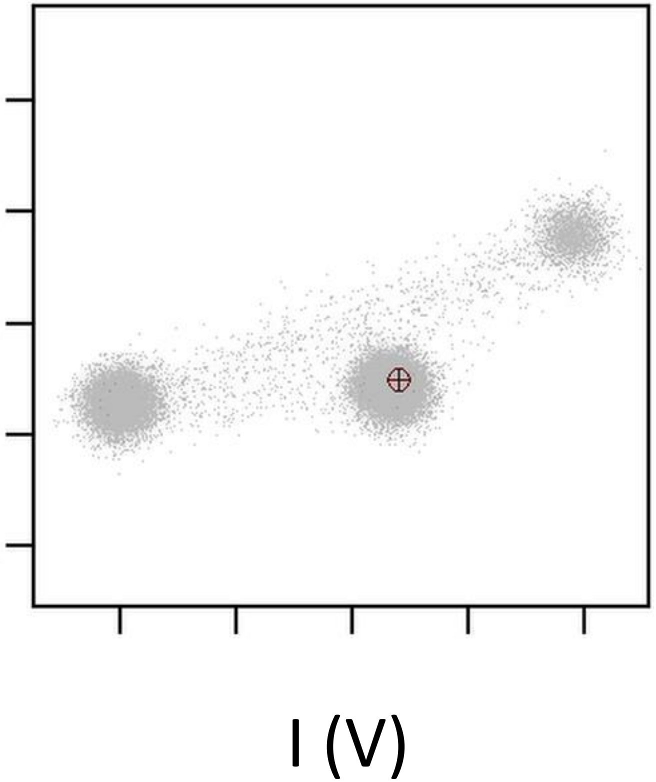
$\langle n_{g,e} \rangle = 220$

Histogram of measurements

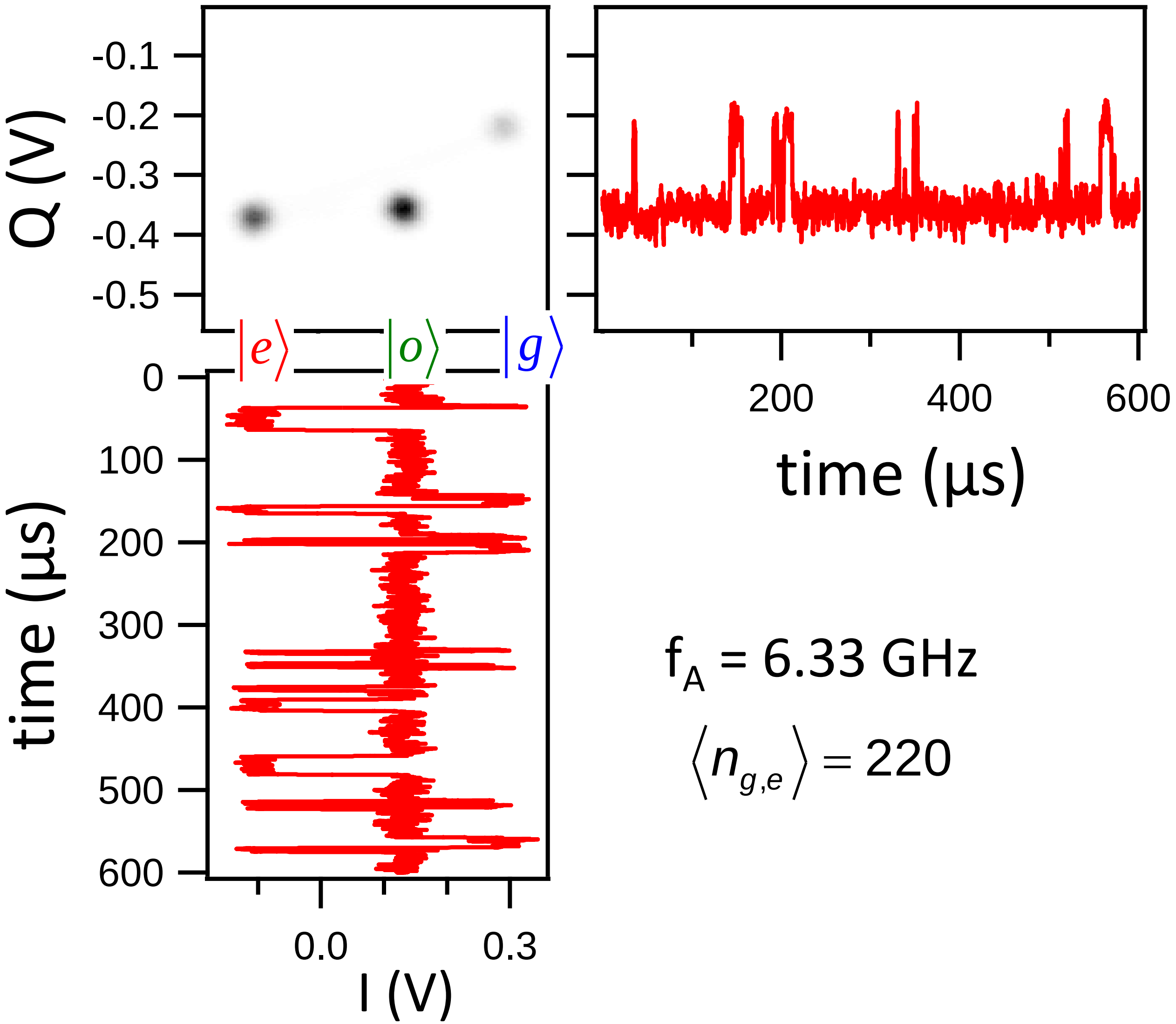
Movie

1s ↔ 30µs



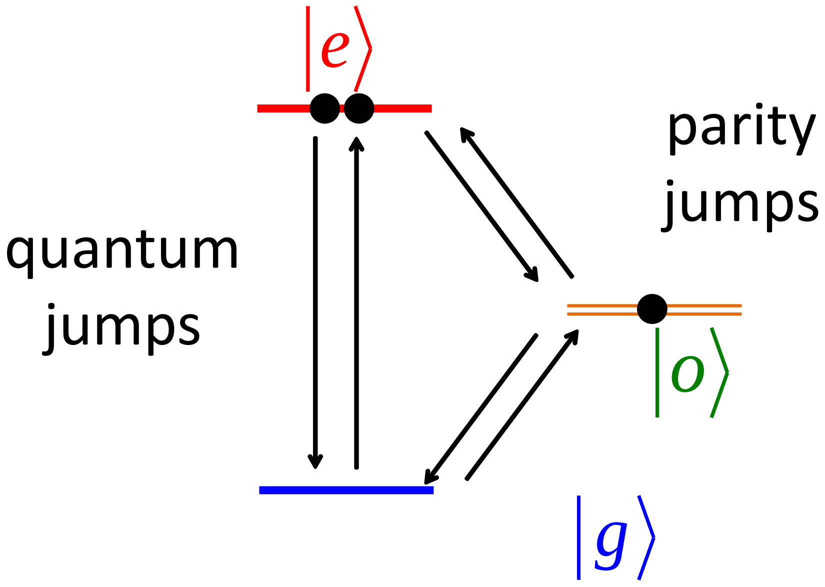


TRANSITION RATES



$f_A = 6.33$ GHz

$\langle n_{g,e} \rangle = 220$



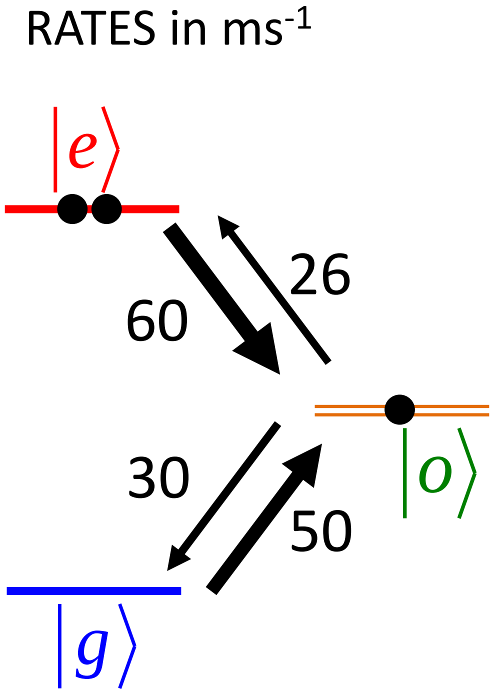
Hidden Markov model toolbox

M. Greenfeld, *et al.*, *PLoS ONE* **7**, e30024 (2012)

PARITY JUMPS

$f_A = 6.33$ GHz

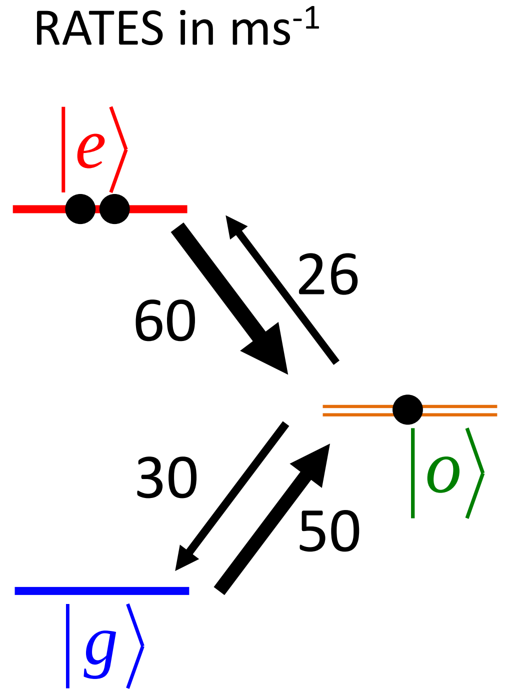
$\langle n_{g,e} \rangle = 220$

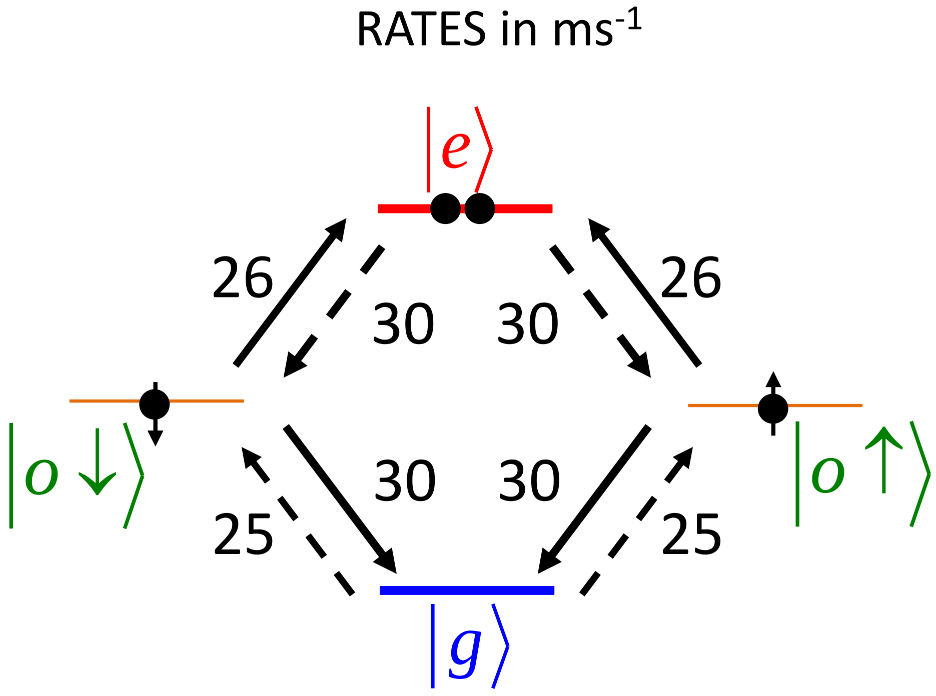


PARITY JUMPS

$f_A = 6.33$ GHz

$\langle n_{g,e} \rangle = 220$

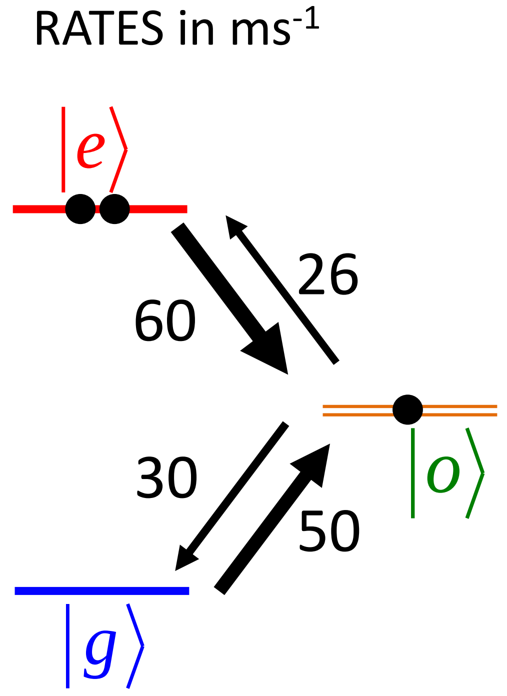


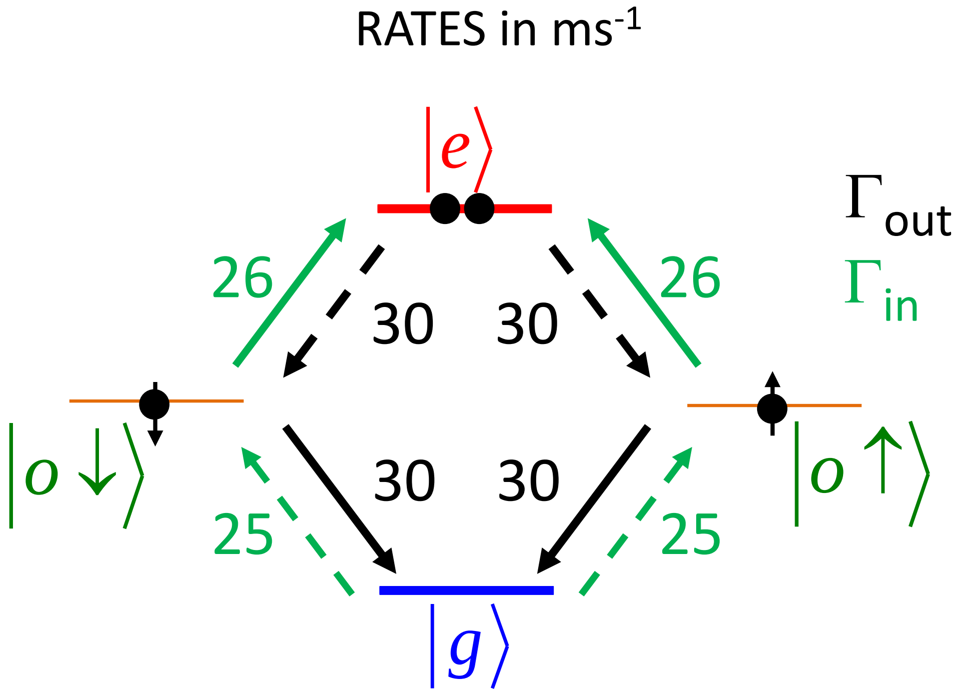


PARITY JUMPS

$f_A = 6.33$ GHz

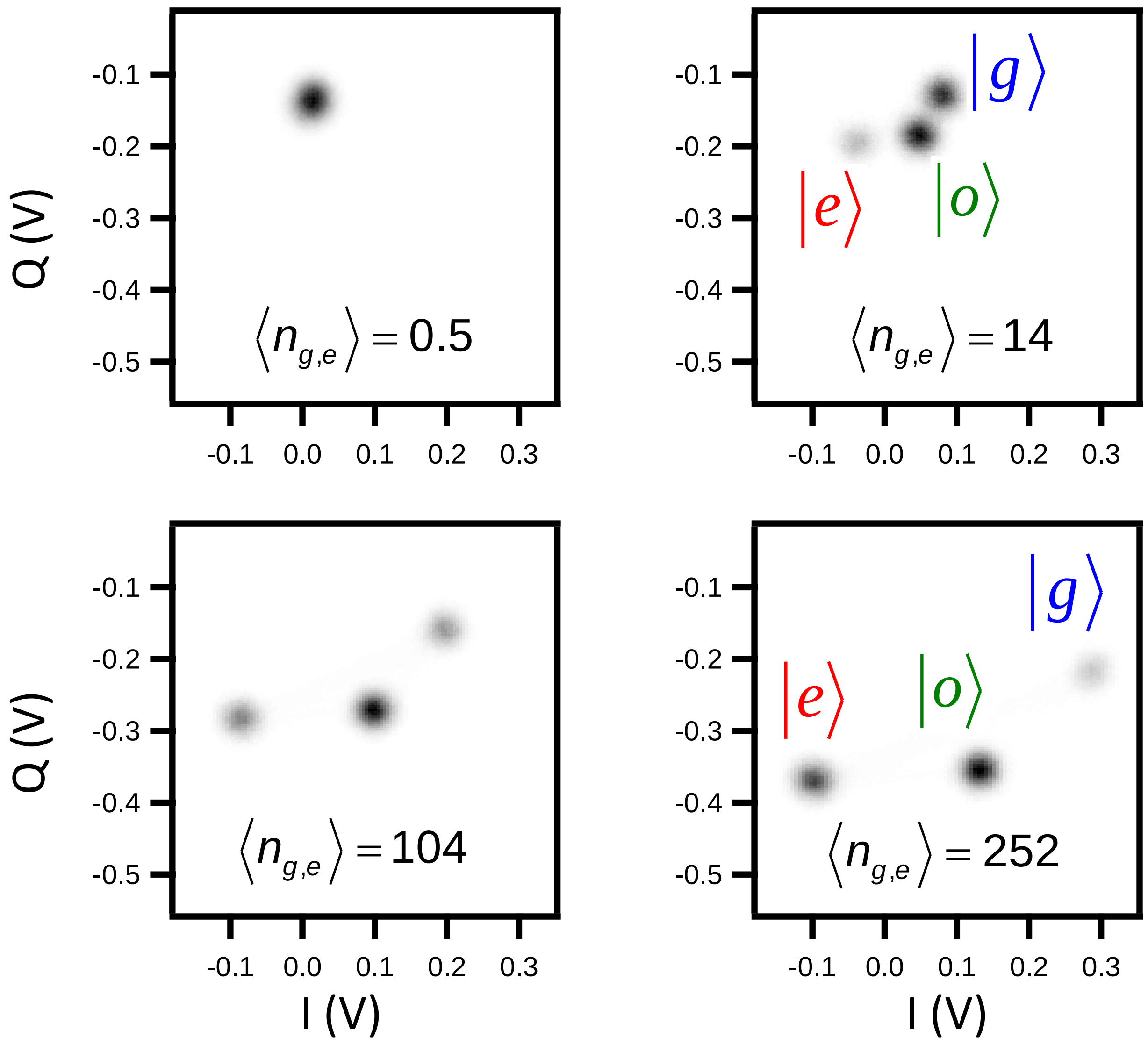
$\langle n_{g,e} \rangle = 220$





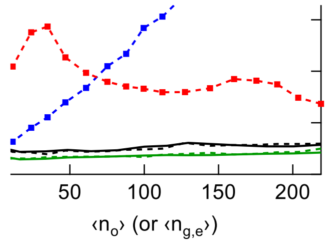
-No interaction effects

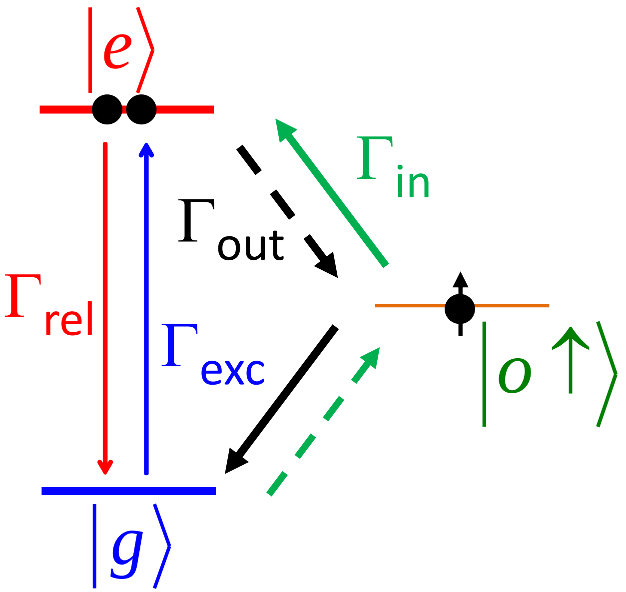
EFFECT OF MEASUREMENT POWER



EFFECT OF MEASUREMENT POWER

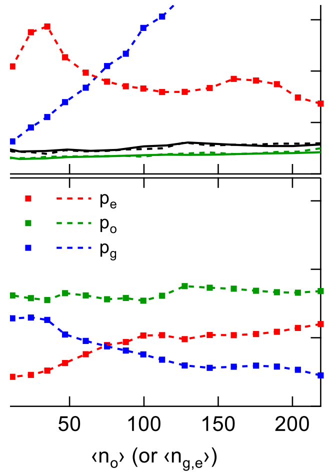
f_A = 6.33 GHz

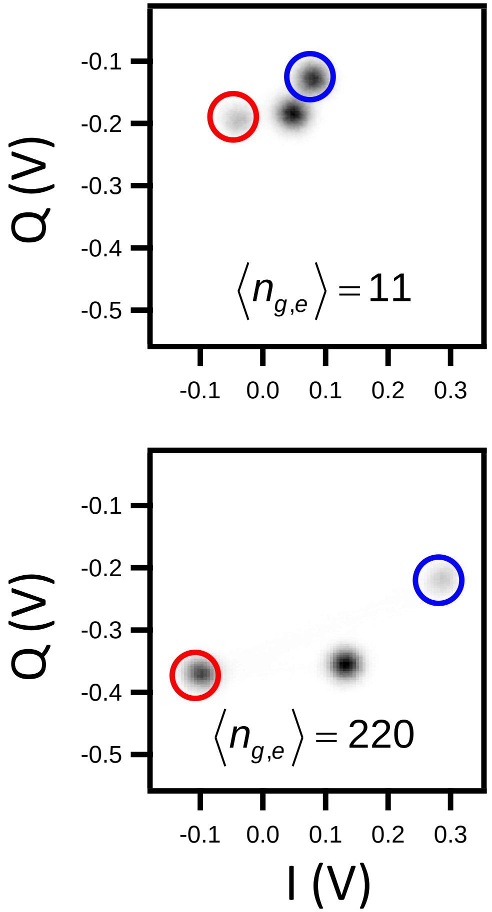




POPULATION INVERSION

f_A = 6.33 GHz





CONCLUSIONS

- SPIN-LIKE DEGREE OF FREEDOM IN JOSEPHSON WEAK LINKS
- CAN COHERENTLY MANIPULATE A LOCALIZED MICROSCOPIC EXCITATION OF THE SUPERCONDUCTING CONDENSATE : ANDREEV QUBIT ?
  - Lifetime of excited state : < 14 μs
  - Coherence time of superpositions: $T_2^* < 180$ ns $T_2 < 1.8$ μs

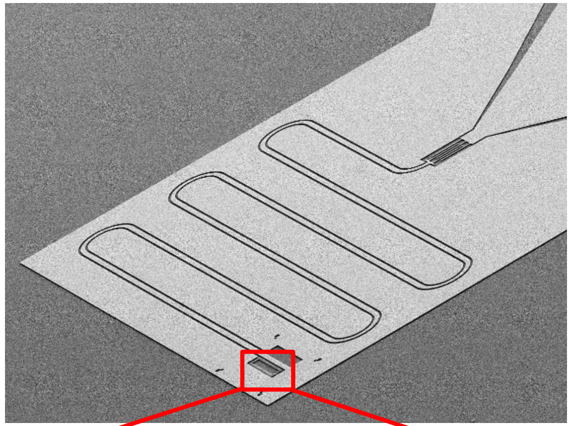
LIMITATION OF LIFETIME ?
- photons
- phonons
- poisoning by single QPs
- …

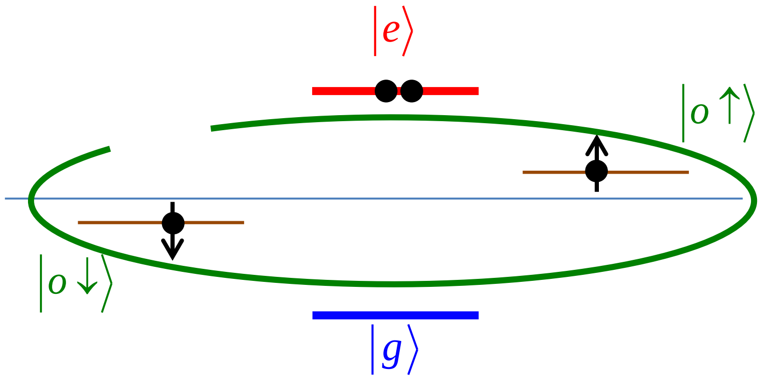
SOURCES OF DECOHERENCE ?
- flux noise
- atomic motion (tunneling)
- poisoning by single QPs
- …

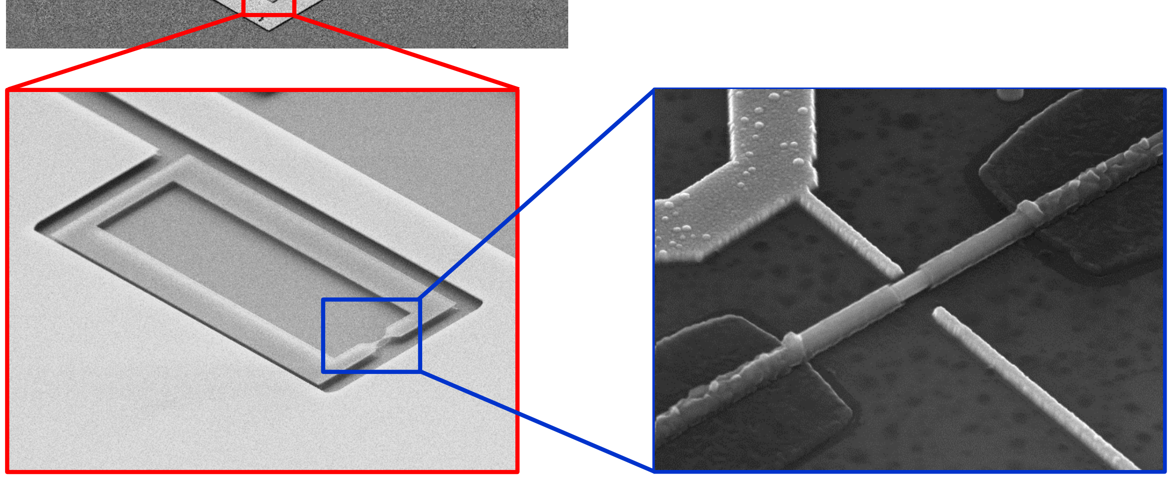
- LONG LIVED TRAPPED QUASIPARTICLES

PERSPECTIVES

MANIPULATE THE SPIN OF A SINGLE TRAPPED QUASIPARTICLE







InAs/Al :core/shell NW

P. Krogstrup, Copengagen

Observation of Andreev bound states in a S-NW-S junction using circuit QED

arXiv:1711.01645

Max Hays
MLS 12/5/16

Yale: experiment

Gijs de Lange
Kyle Serniak
Uri Vool
Michel Devoret

Yale: theory

Jukka Väyrynen
Bernard van Heck
Leonid Glazman

Delft: fab

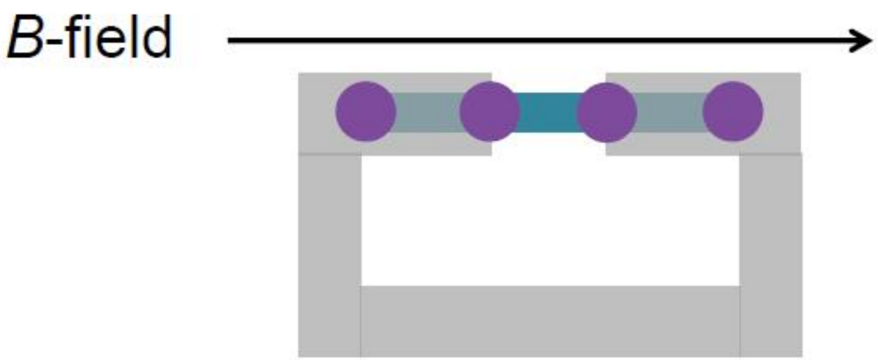
David van Woerkom
Attila Geresdi

Copenhagen: NW growth

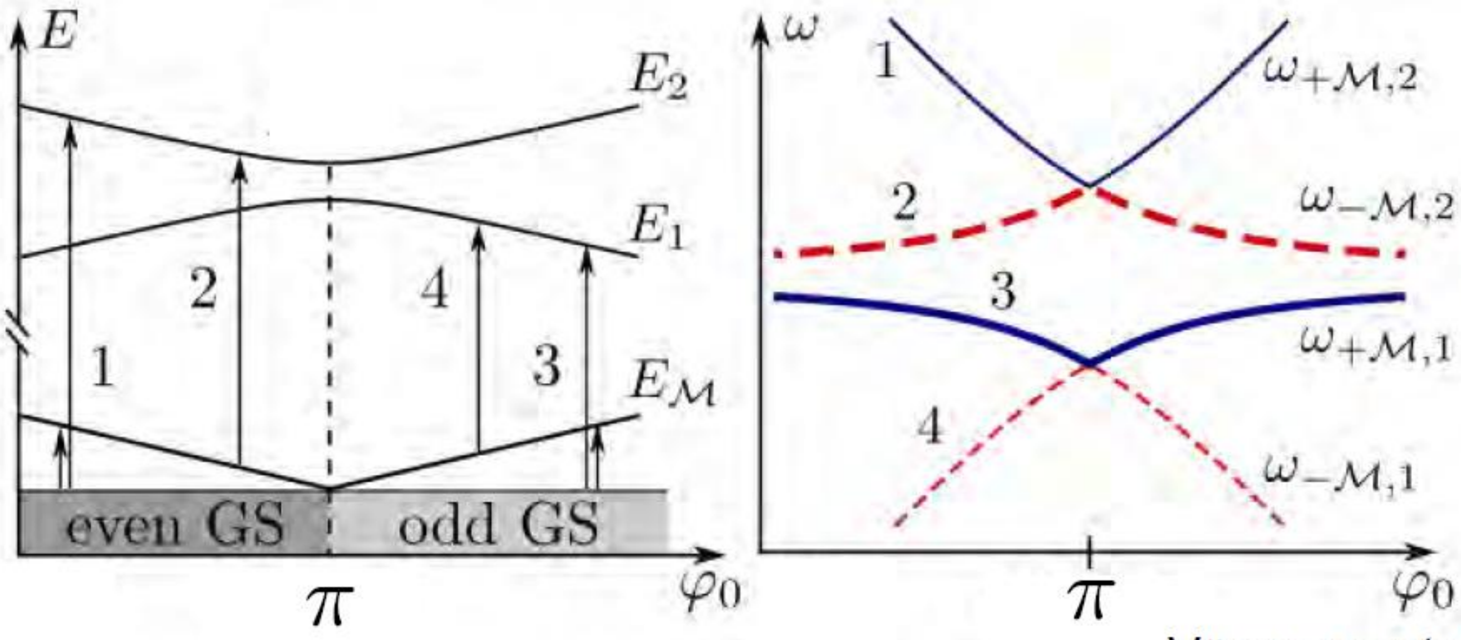
Peter Krogstrup
Jesper Nygård

Thanks to Qulab, RSL, and YINQE

Future direction: apply B-field



Majorana signatures in ABS spectrum



Väyrynen *et al.*, 2015