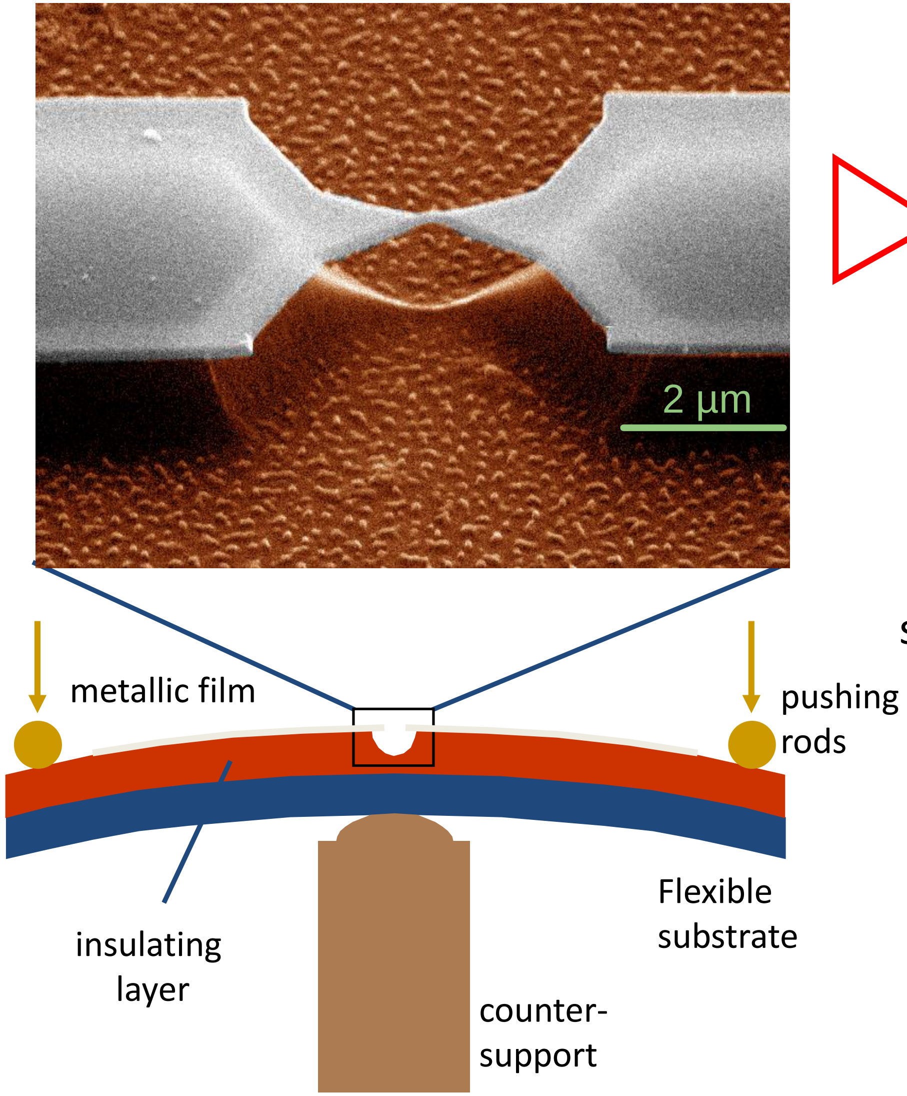
PROBING AND MANIPULATING ANDREEV STATES

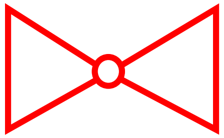
1. JOSEPHSON EFFECT
   a) Josephson Junction
   b) Mesoscopic description of Josephson effect
   c) Andreev bound states (ABS)
   d) Andreev Quantum Dot (AQD)

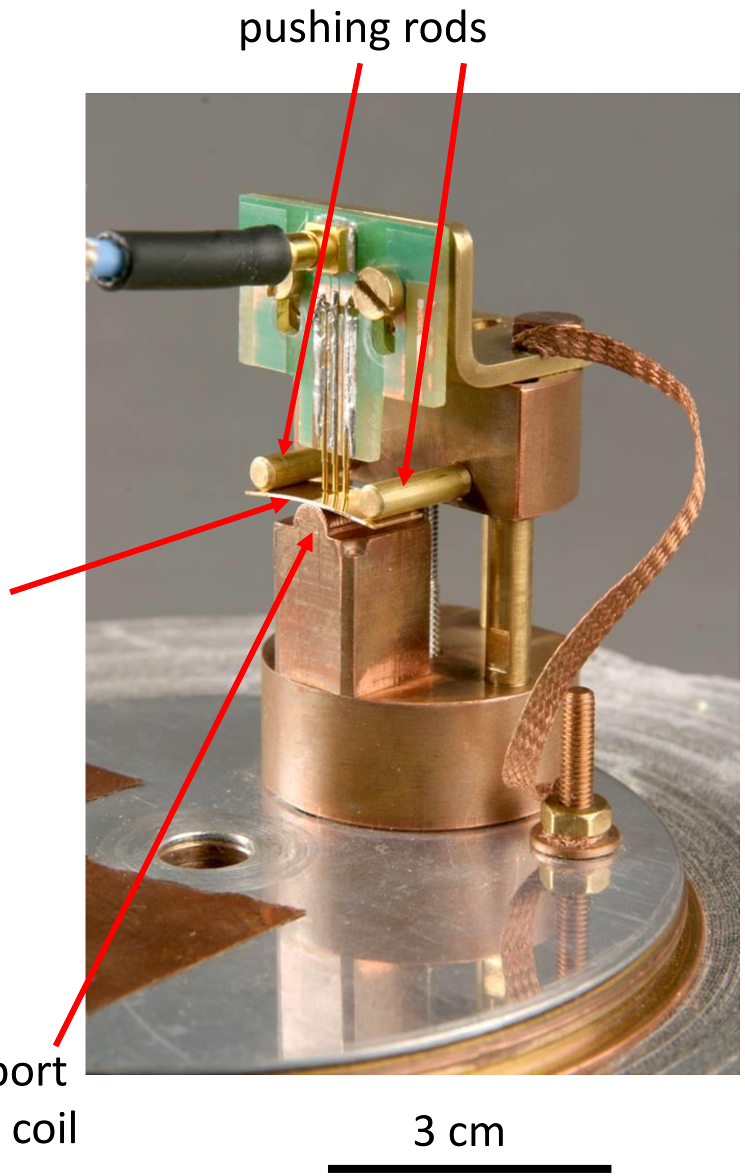
2. dc EXPERIMENTS on ATOMIC CONTACTS
   a. Supercurrent
   b. Current-phase relation
   c. Spectroscopy of ABS

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

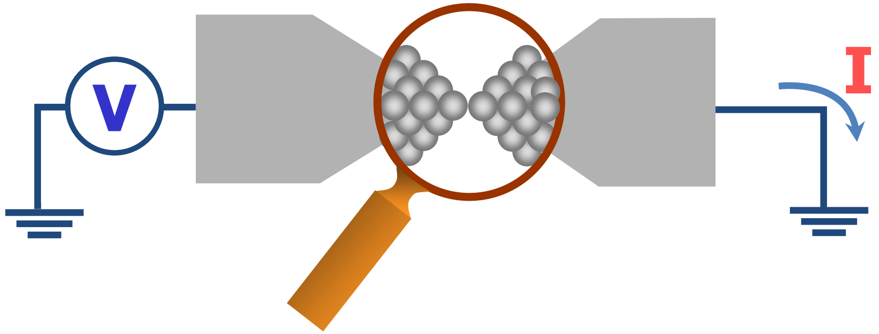
ATOMIC CONTACTS



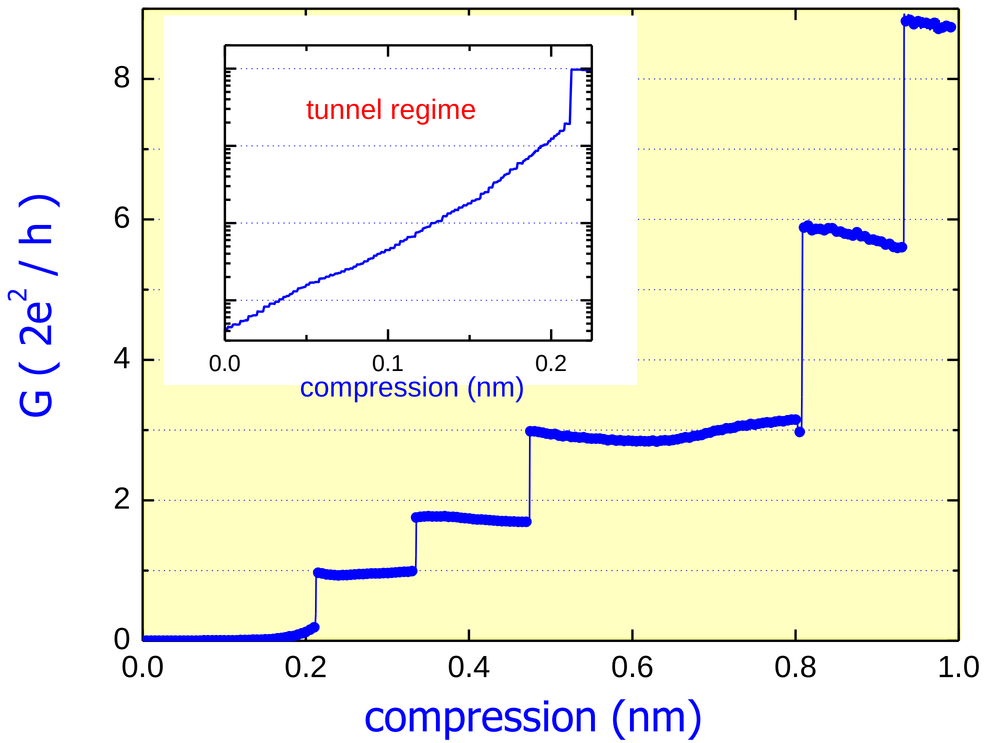




CONDUCTANCE OF ATOMIC CONTACTS IN THE NORMAL STATE

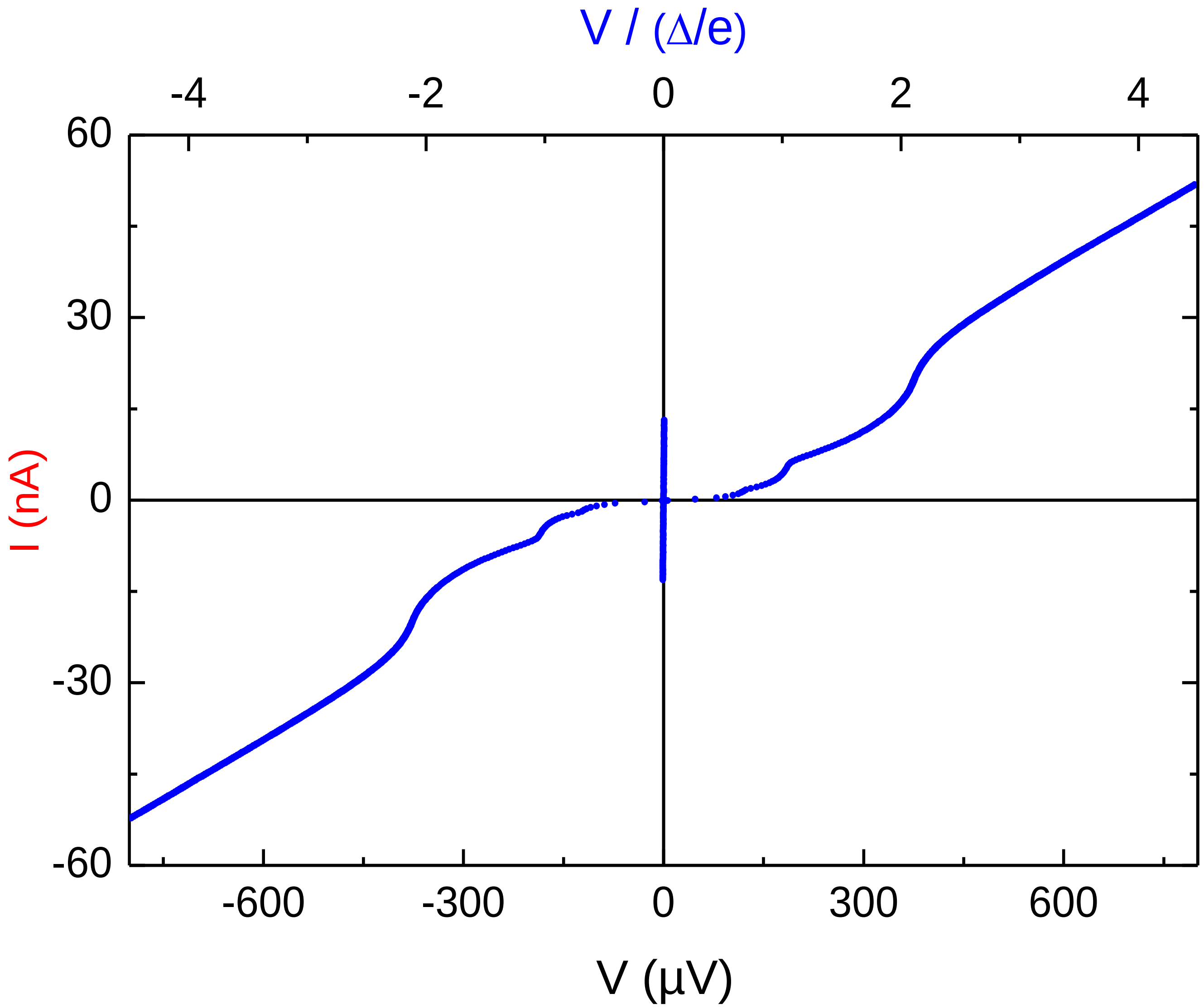


Aluminum
H = 200mT, T = 50 mK

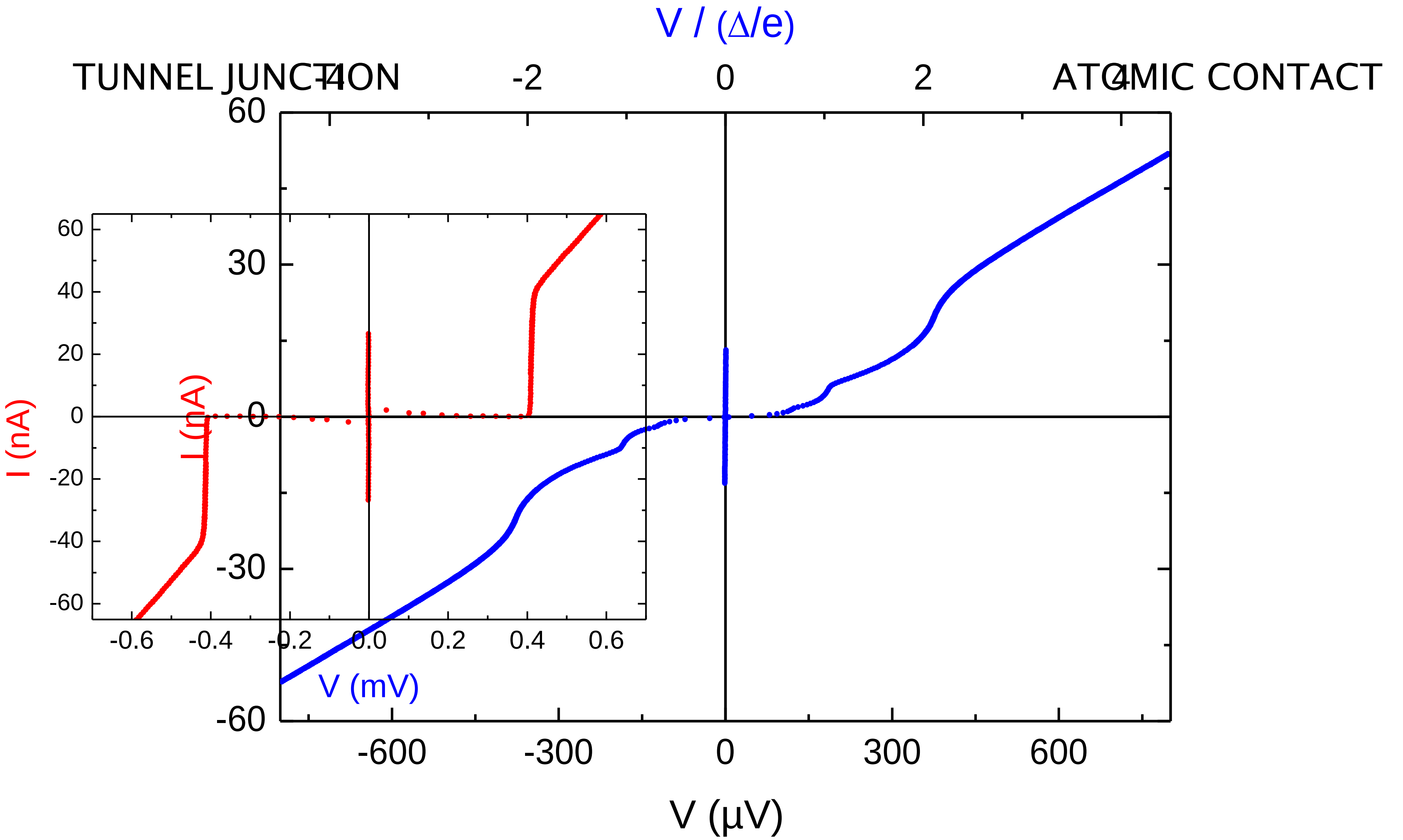


Agraït, Levy-Yeyati, Ruitenbeek
Physics Reports 2003

I-V OF A SUPERCONDUCTING ONE-ATOM CONTACT

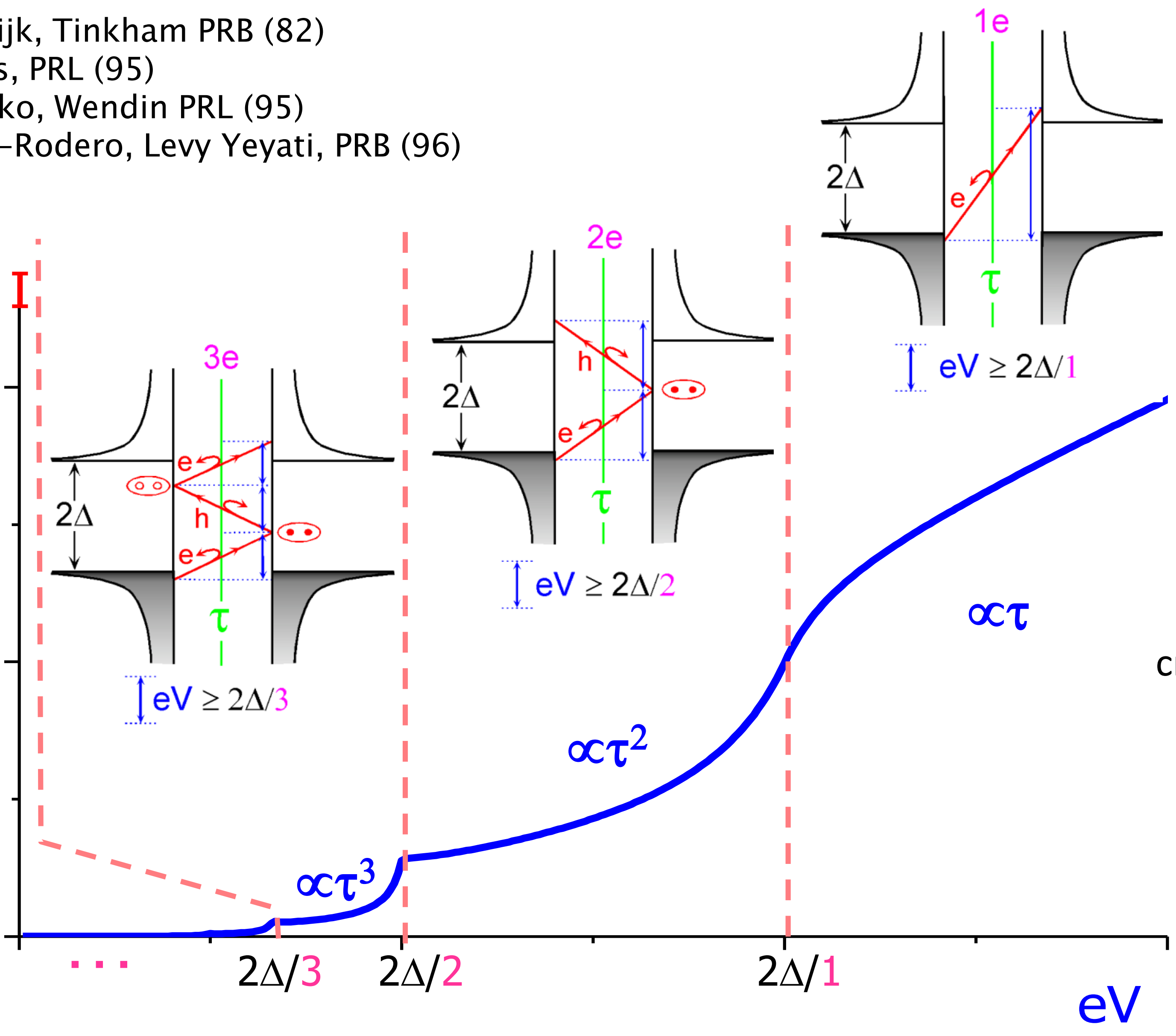


I-V OF A SUPERCONDUCTING ONE-ATOM CONTACT



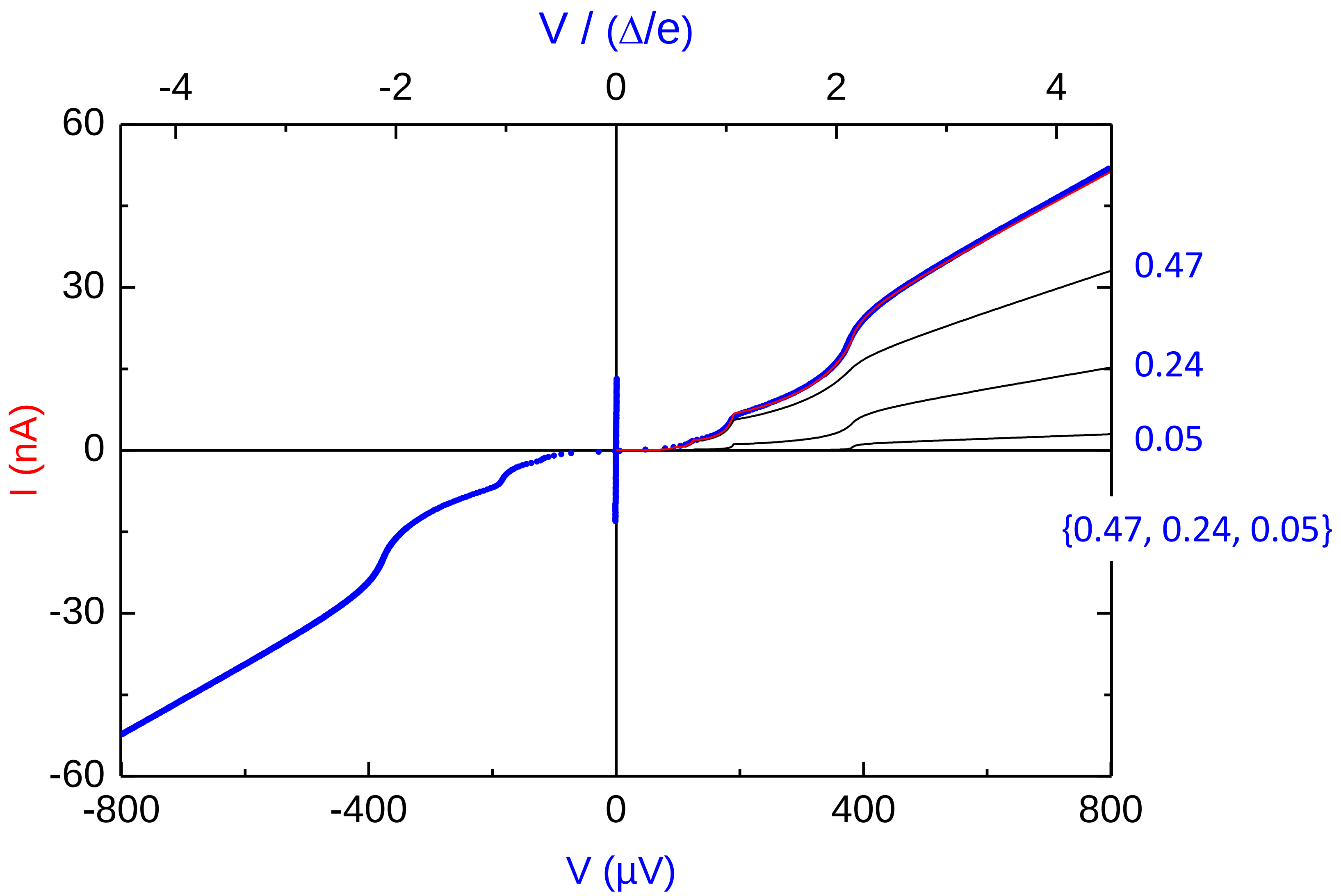
MULTIPLE ANDREEV REFLECTIONS

Blonder, Klapwijk, Tinkham PRB (82)
Averin & Bardas, PRL (95)
Bratus ,Shumeiko, Wendin PRL (95)
Cuevas, Martin-Rodero, Levy Yeyati, PRB (96)



Dissipation through creation of quasiparticle excitations

DETERMINATION OF TRANSMISSIONS

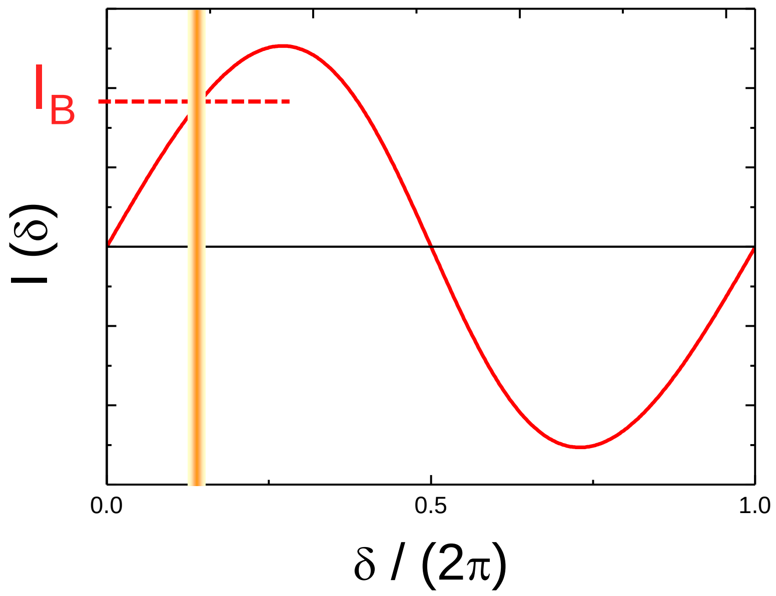


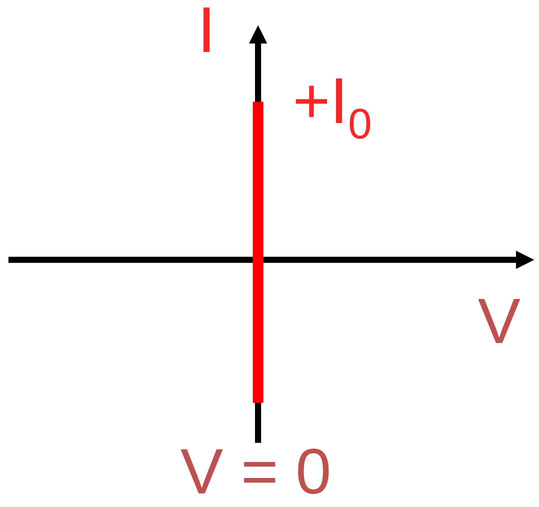
I-V characteristic $\Longrightarrow \{\tau_1, \ldots, \tau_N\}$

Scheer *et al.* PRL 1997

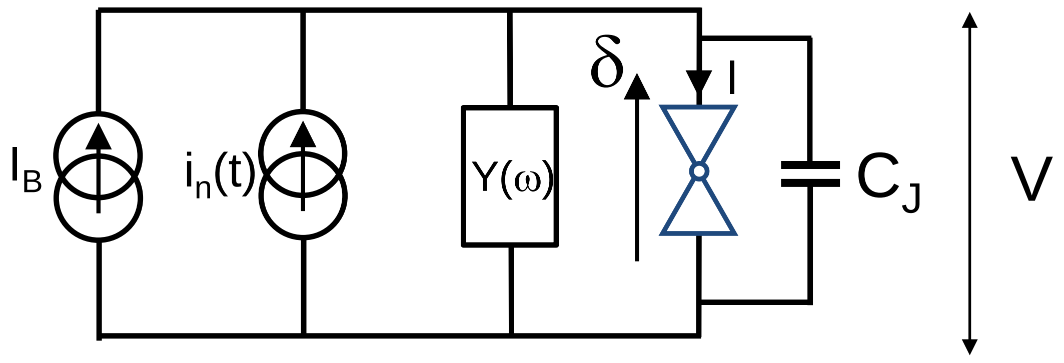
MEASURING THE SUPERCURRENT

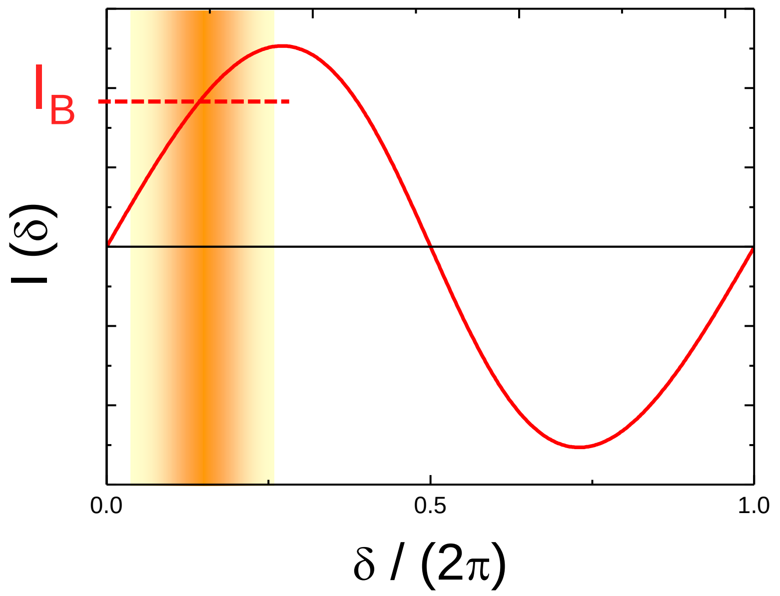
PERFECT CURRENT BIAS





ELECTROMAGNETIC ENVIRONMENT



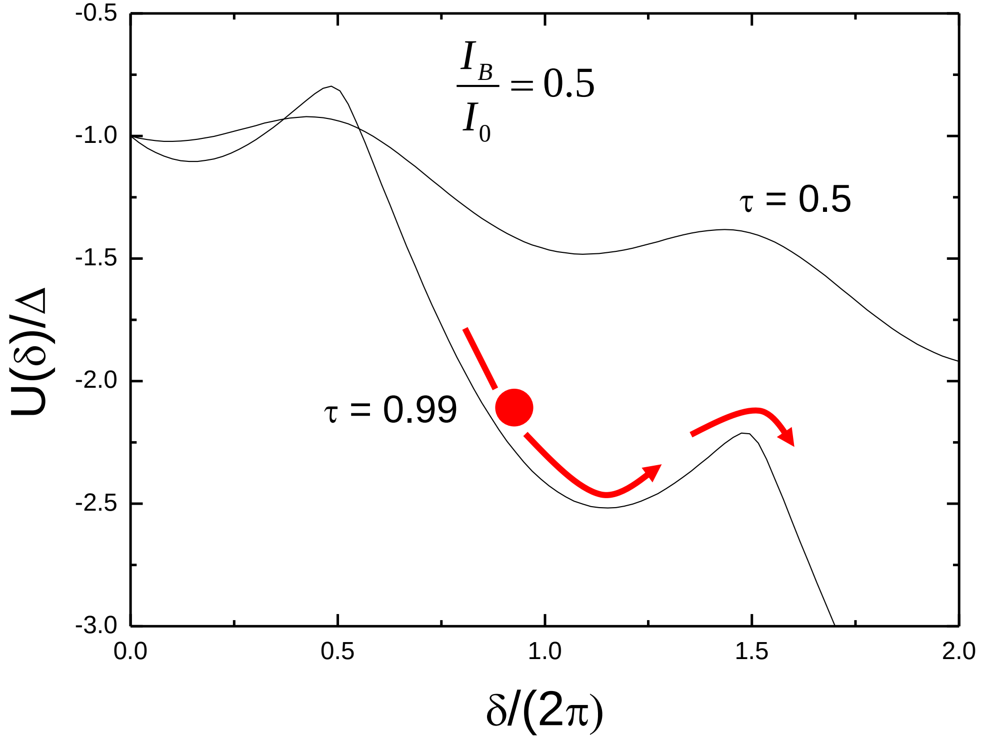


$$E_J \approx \varphi_0 I_0 \sim \frac{\Delta}{2}\left(1-\sqrt{1-\tau}\right) \quad \leftrightarrow \quad k_B T$$

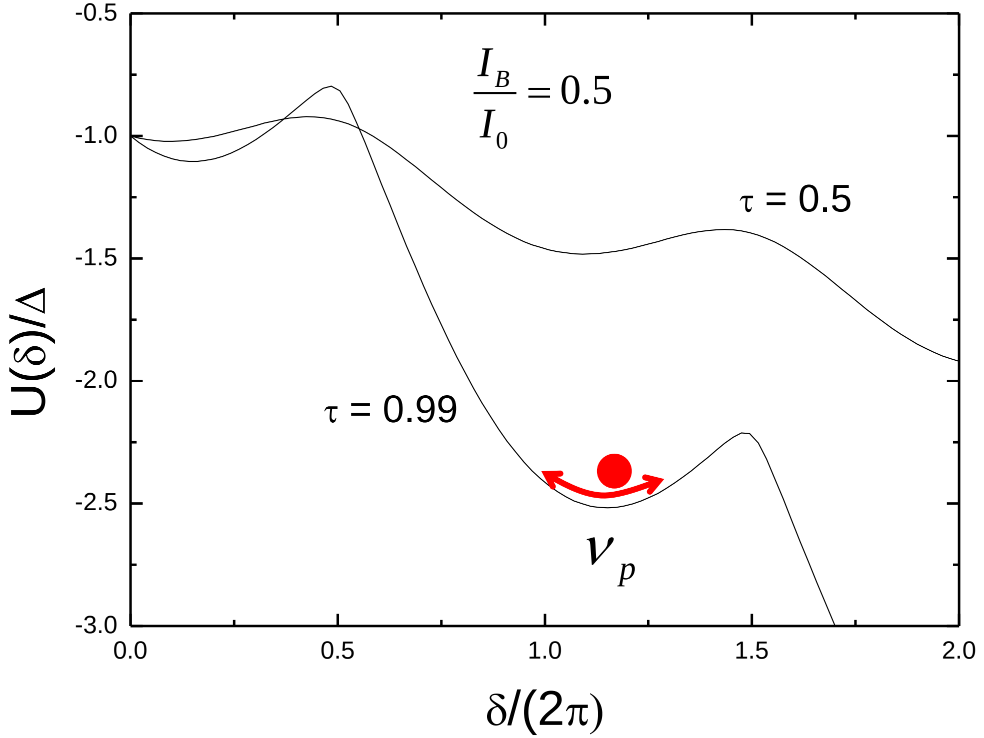
For Aluminum $\quad E_J \leq \frac{\Delta}{2} \sim 1\mathrm{K}$

Yu. M. Ivanchenko L. A. Zil'Berman (1968)
V. Ambegaokar, B. I. Halperin (1968)

PARTICLE IN TILTED WASHBOARD POTENTIAL



PLASMA OSCILLATIONS



$$\nu_p\left(s=0\right) = \frac{1}{2\pi\sqrt{L_J C_J}}$$

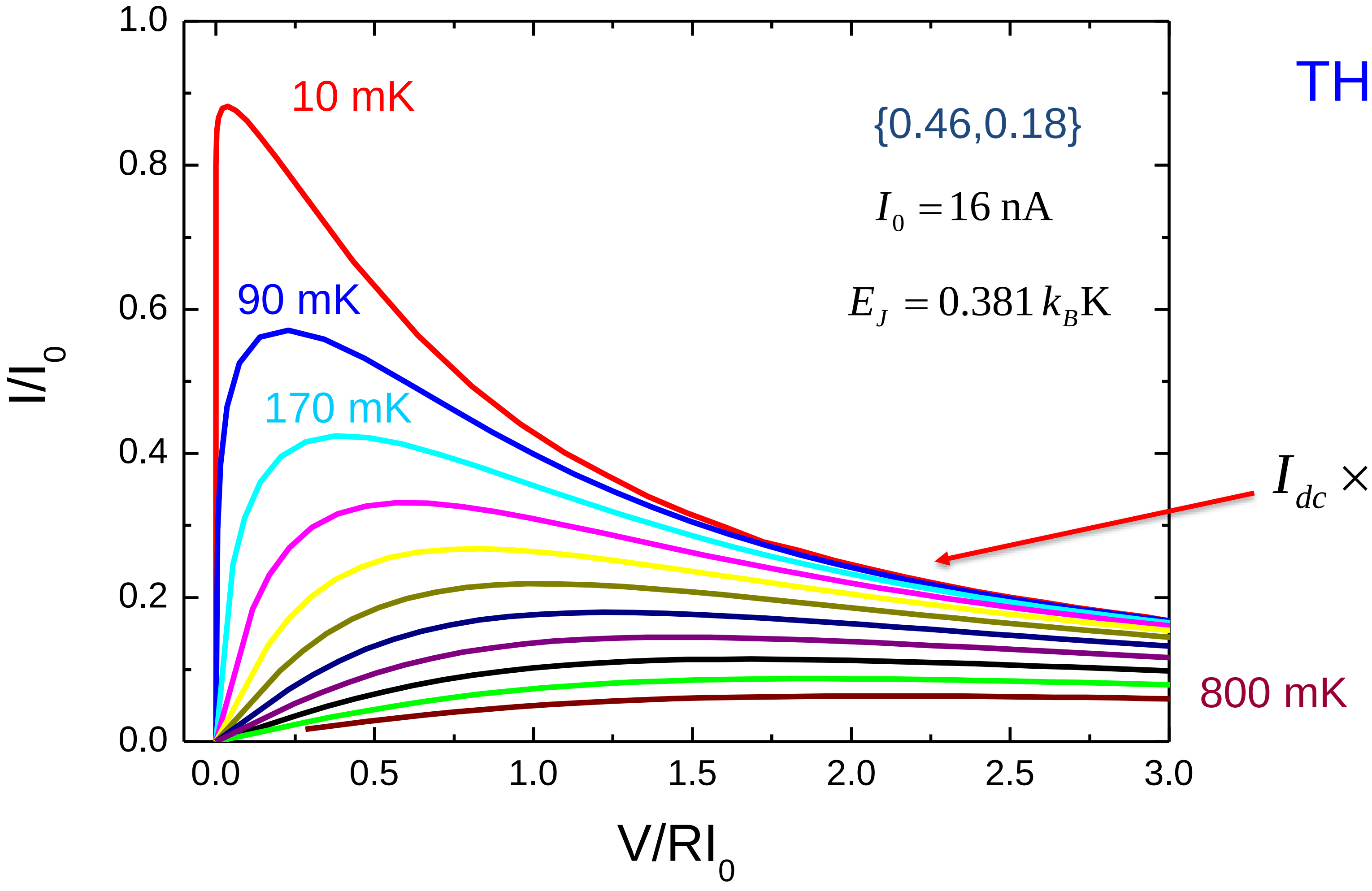
~ 12 GHz for $\tau \sim 0.7$ and $C \sim 10$ fF

FOR A WELL-DEVELOPED JOSEPHSON CURRENT
NEED TO **OVERDAMP** PLASMA OSCILLATIONS

$$Q < 1 \quad \Leftrightarrow \quad r < \sqrt{\frac{L_J}{C_J}} \sim 1\mathrm{k}\Omega$$

➡ Slow phase-diffusion leading to supercurrent peak at low voltages

FINITE TEMPERATURE SUPERCURRENT PEAK



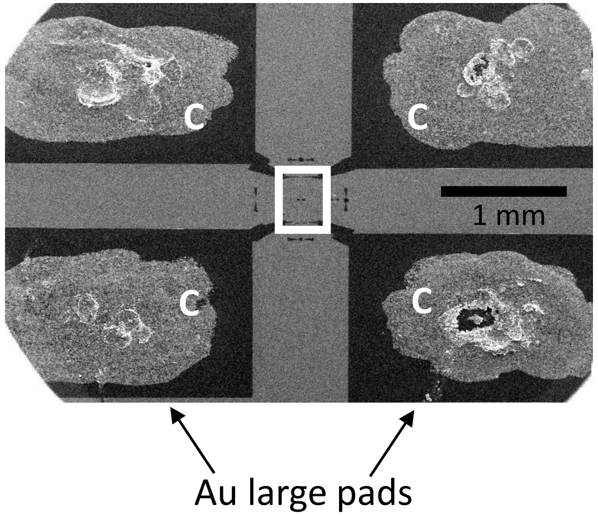
THE BEST ONE CAN DO!

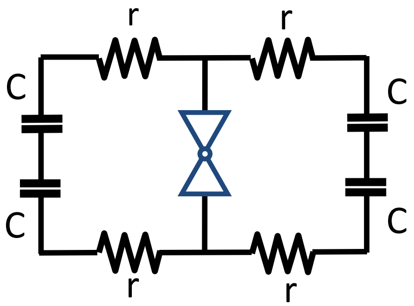
$$I_{dc} \times V_{dc} = \frac{1}{2} R I_0^2$$

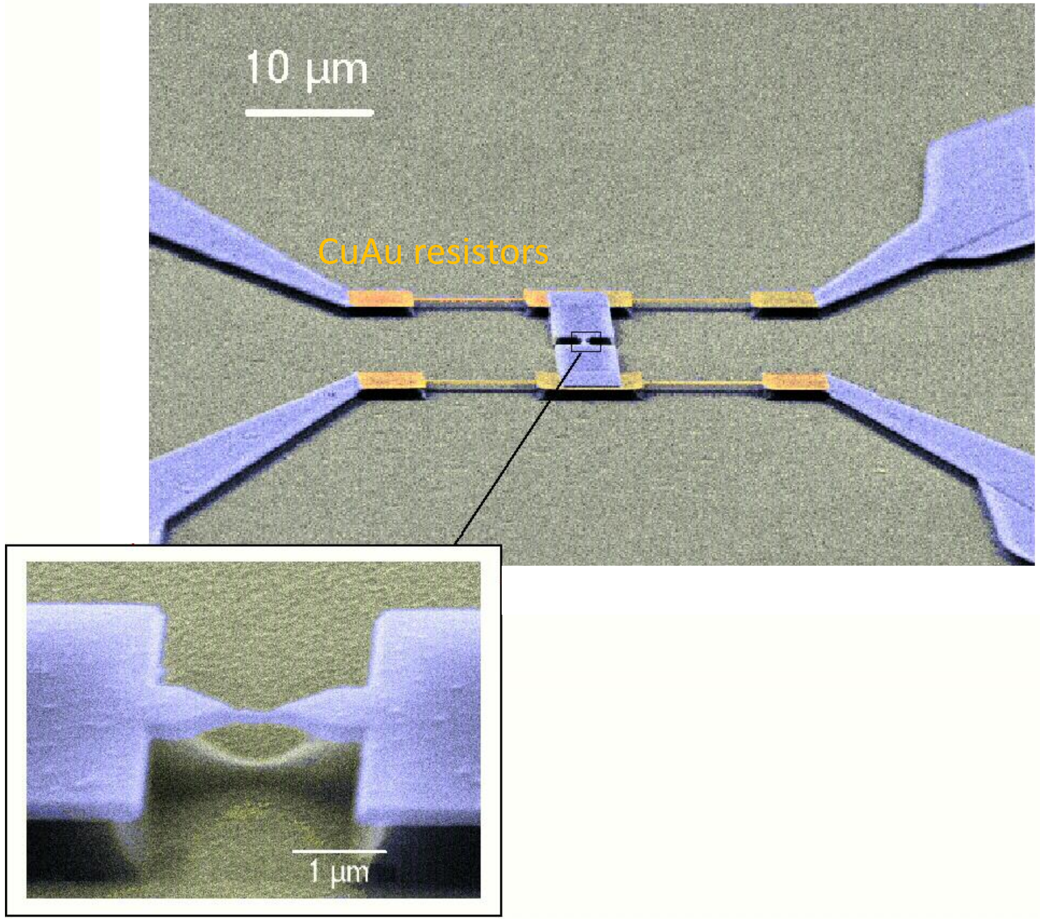
Dissipation through electromagnetic excitations in the environment

Goffman *et al.* (2000)

ON-CHIP DISSIPATIVE ENVIRONMENT

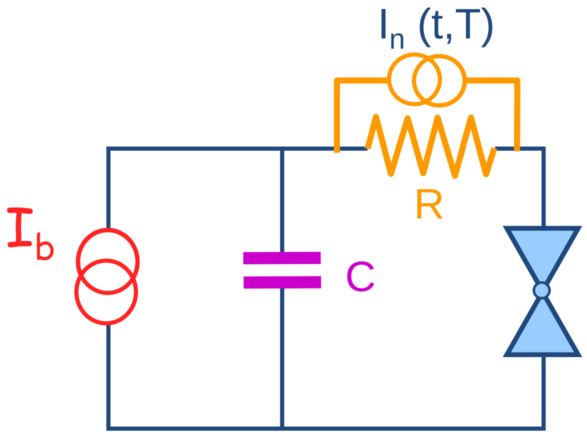


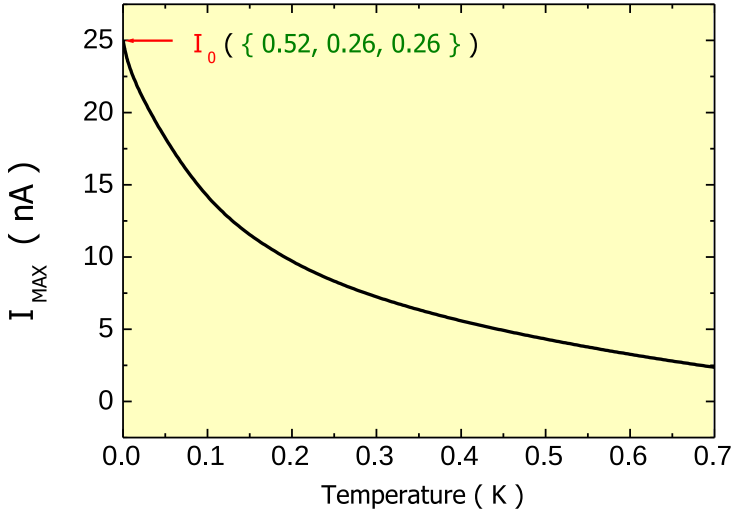


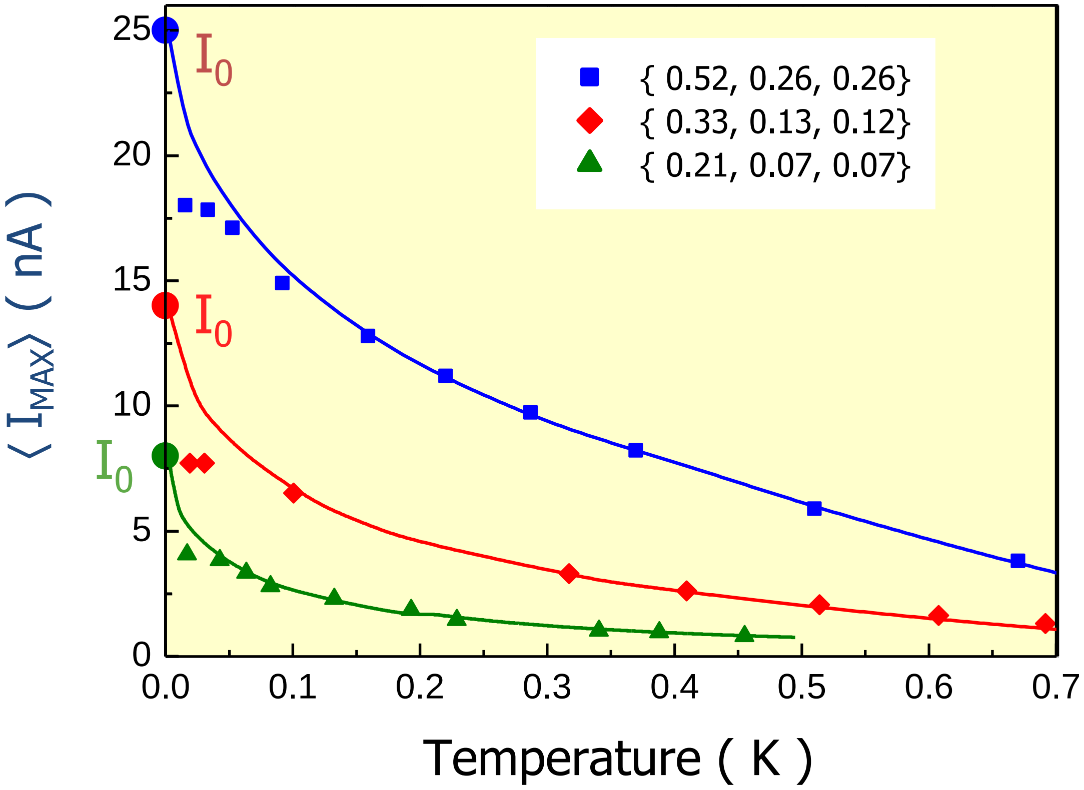


Goffman *et al.* (2000)

MAXIMUM SWITCHING CURRENT

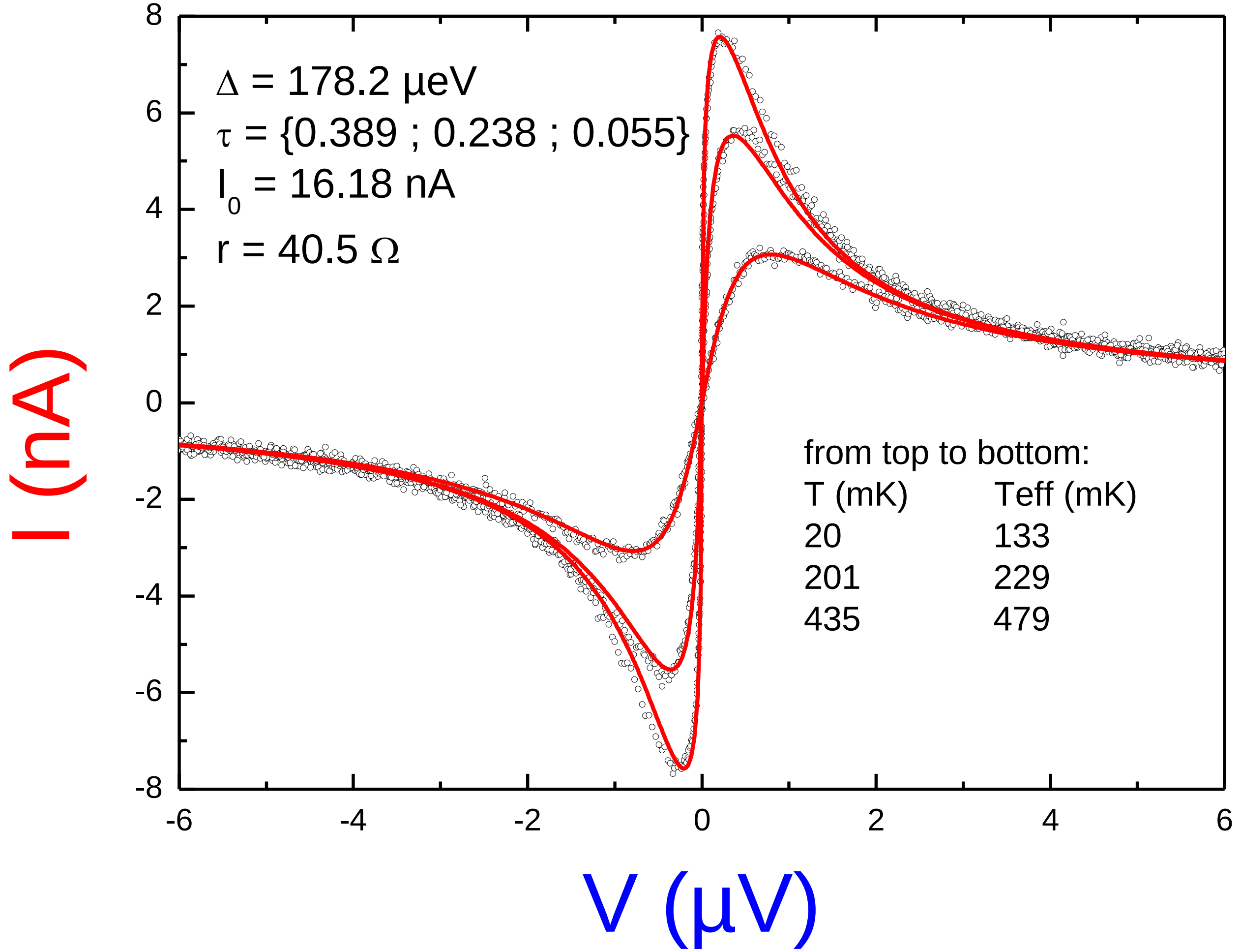






Goffman *et al.* (2000)

SUPERCURRENT PEAK



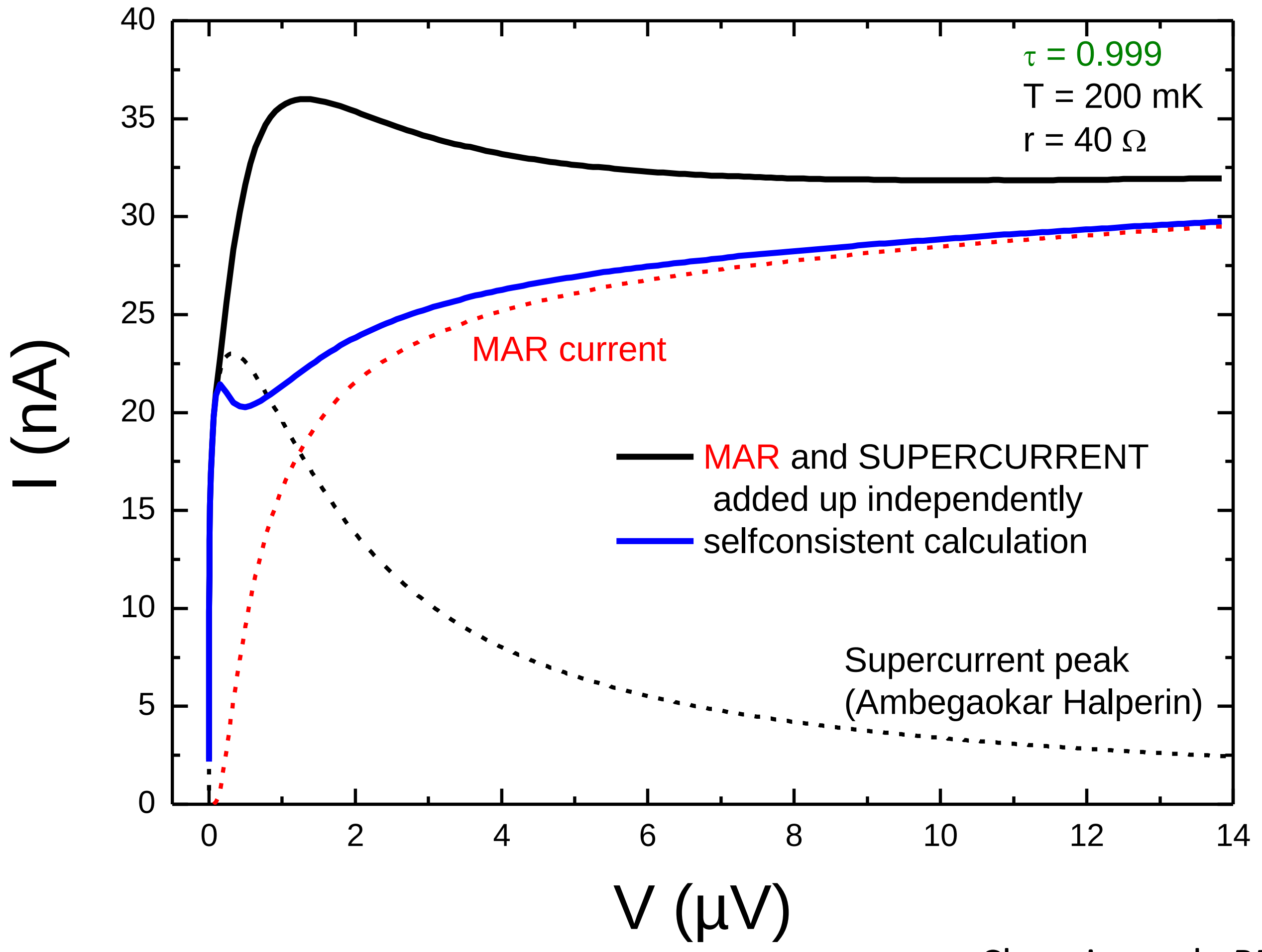
Chauvin *et al.*
PRL 2006, 2007

CROSSOVER FROM SUPERCURRENT PEAK TO MAR

Two different mechanisms
for inelastic
transfer of Cooper pairs

MAR: create quasiparticle excitations

Phase diffusion: create electromagnetic
excitations in environment

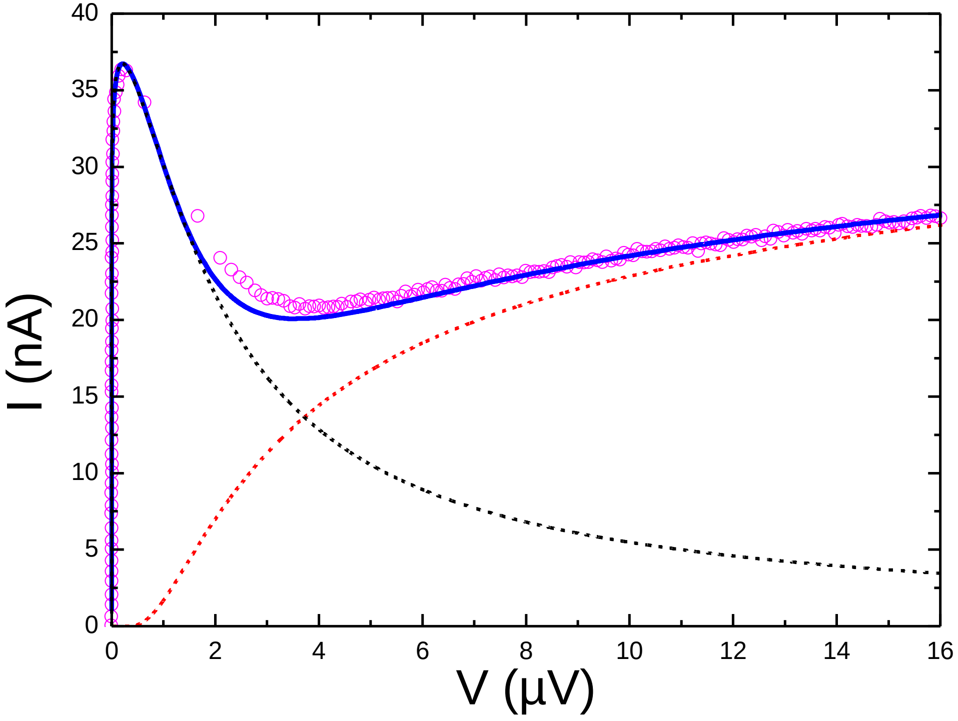


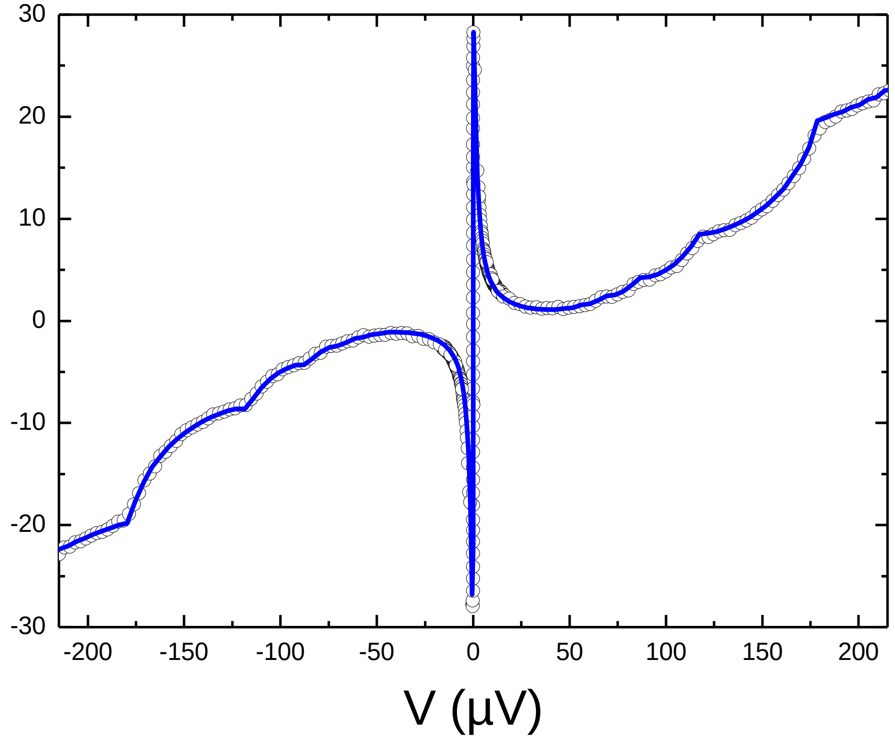
Chauvin et al., PRL 2007

EXP-THEO COMPARISON

$\tau = \{0.995, 0.372, 0.174, 0.022\}$
$I_0 = 50$ nA

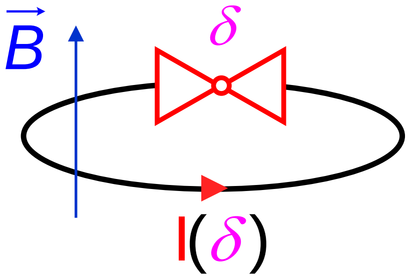
$\tau = \{0.677, 0.391, 0.201, 0.2, 0.2\}$
$I_0 = 42$ nA





r = 40 Ω   T = 125 mK

PHASE BIASING A CONTACT

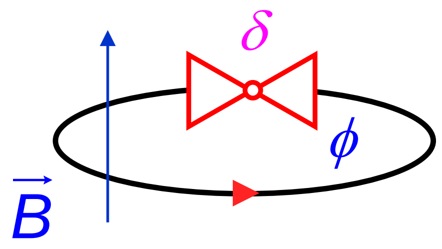


Small superconducting loop

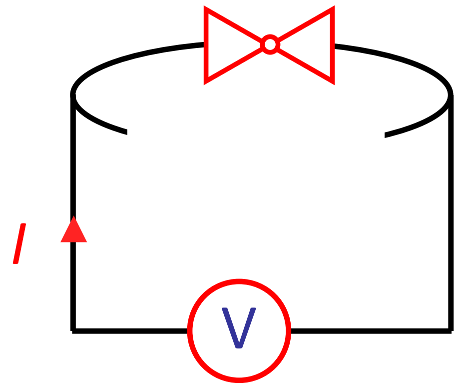
$$\delta \cong 2\pi\,\phi/\phi_0 = \varphi$$

PHASE AND VOLTAGE BIASING A CONTACT

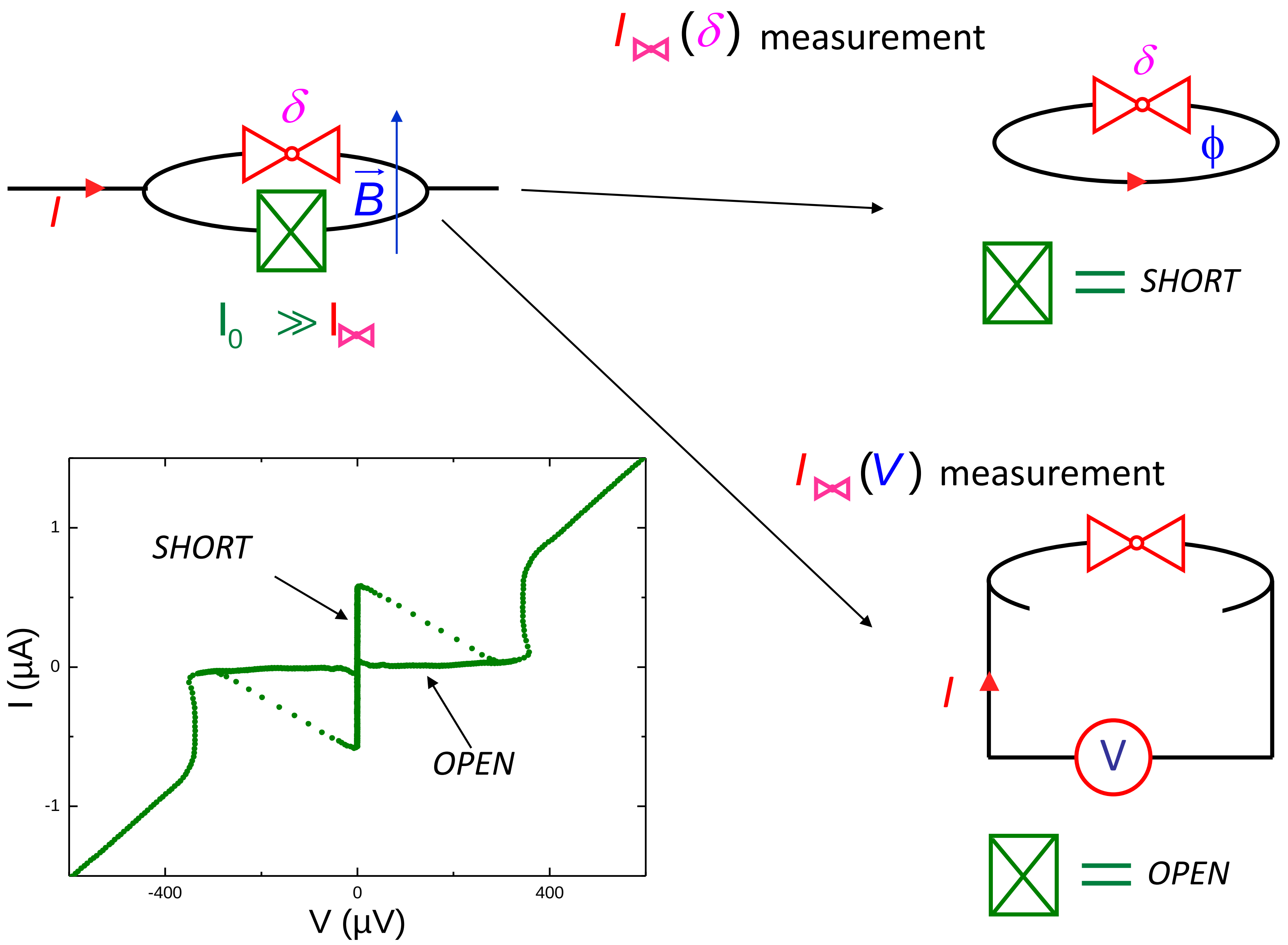
PHASE BIAS TO MEASURE $I_{\bowtie}(\delta)$



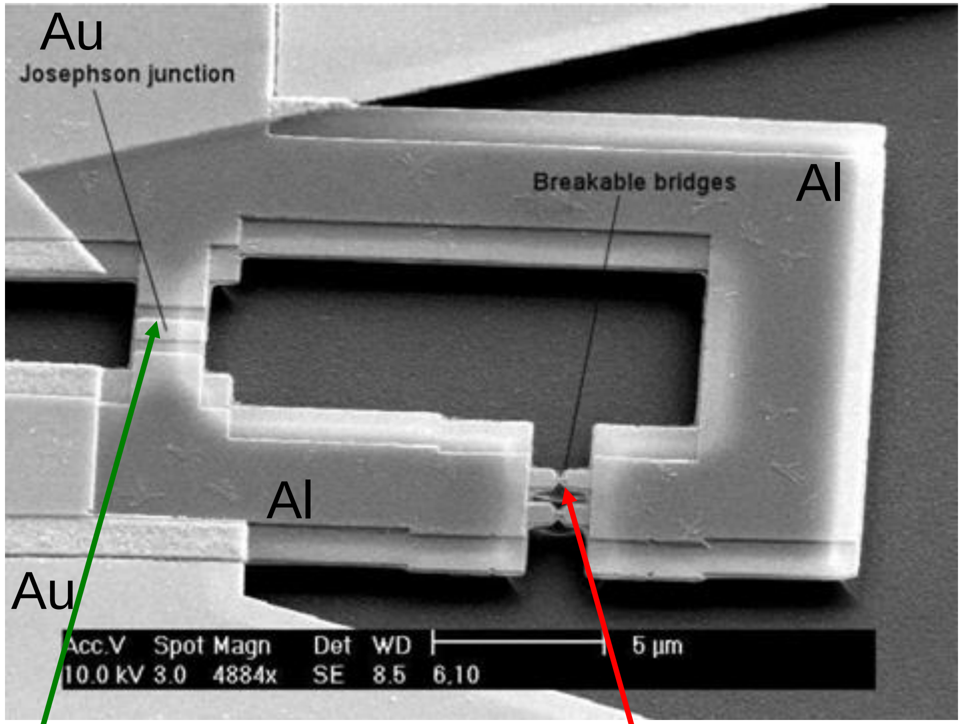
VOLTAGE BIASING TO MEASURE $I_{\bowtie}(V)$
and
TO DETERMINE TRANSMISSIONS



A SUPERCONDUCTING REVERSIBLE SWITCH

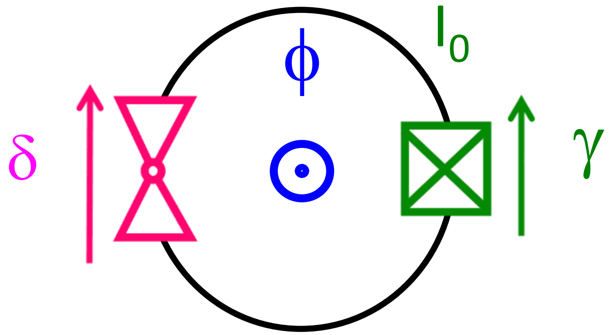


"ATOMIC SQUID"



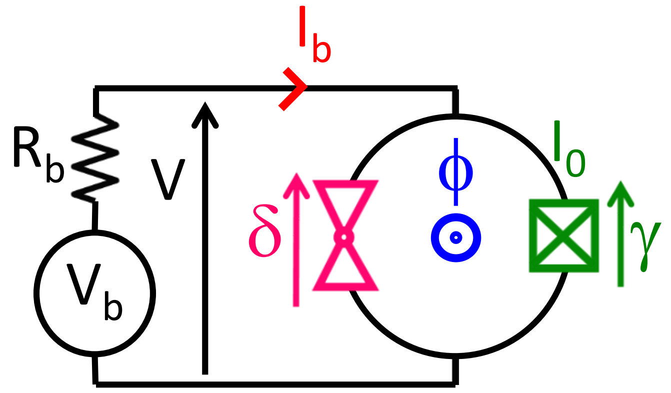
Josephson junction

Metallic bridge (atomic contact)



$$\delta - \gamma = \varphi = 2\pi \frac{\phi}{\phi_0}$$

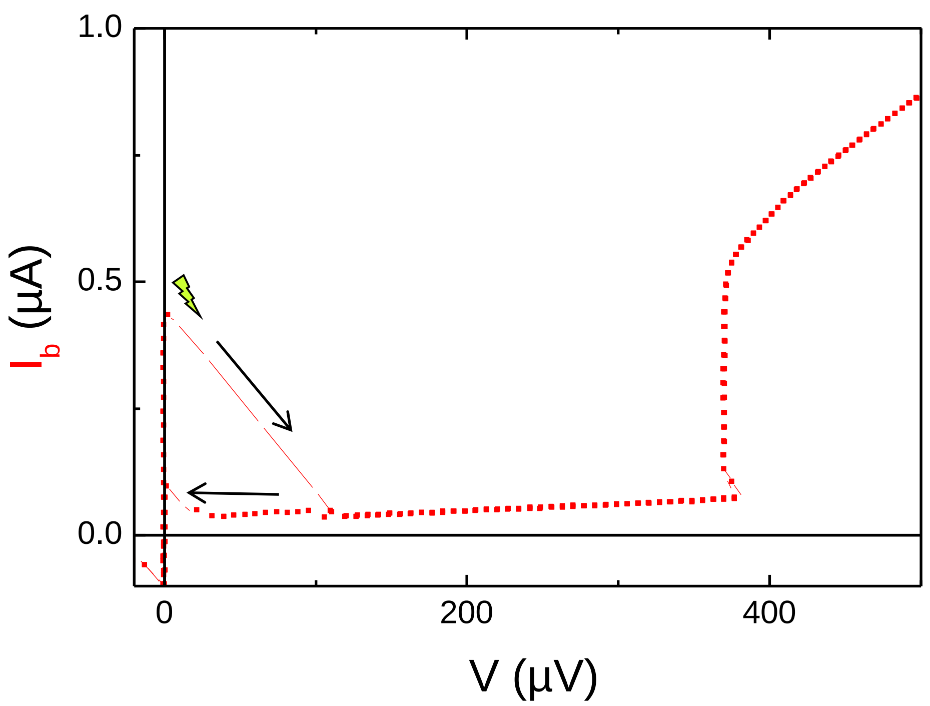
MEASURING CURRENT-PHASE RELATION



$$I_b = I_{\bowtie}(\gamma + \varphi) + I_0 \sin\gamma$$

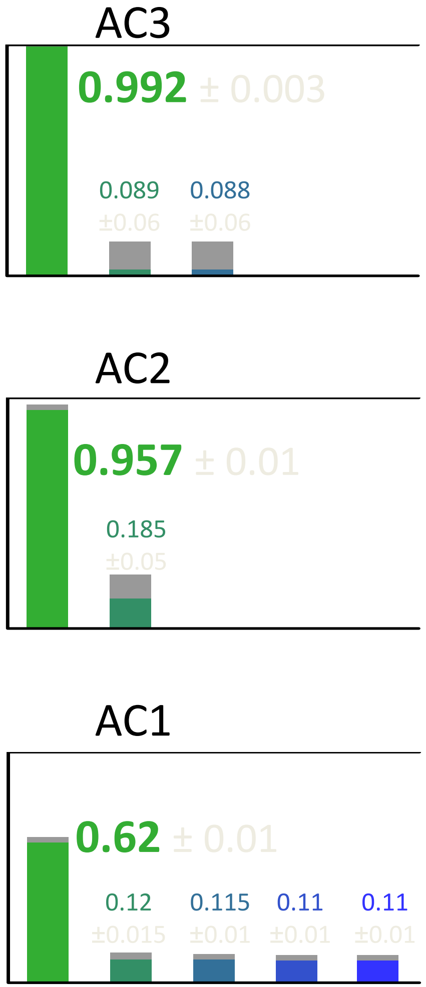
$$I_b(\varphi) \approx I_{\bowtie}\left(\frac{\pi}{2} + \varphi\right) + I_0$$

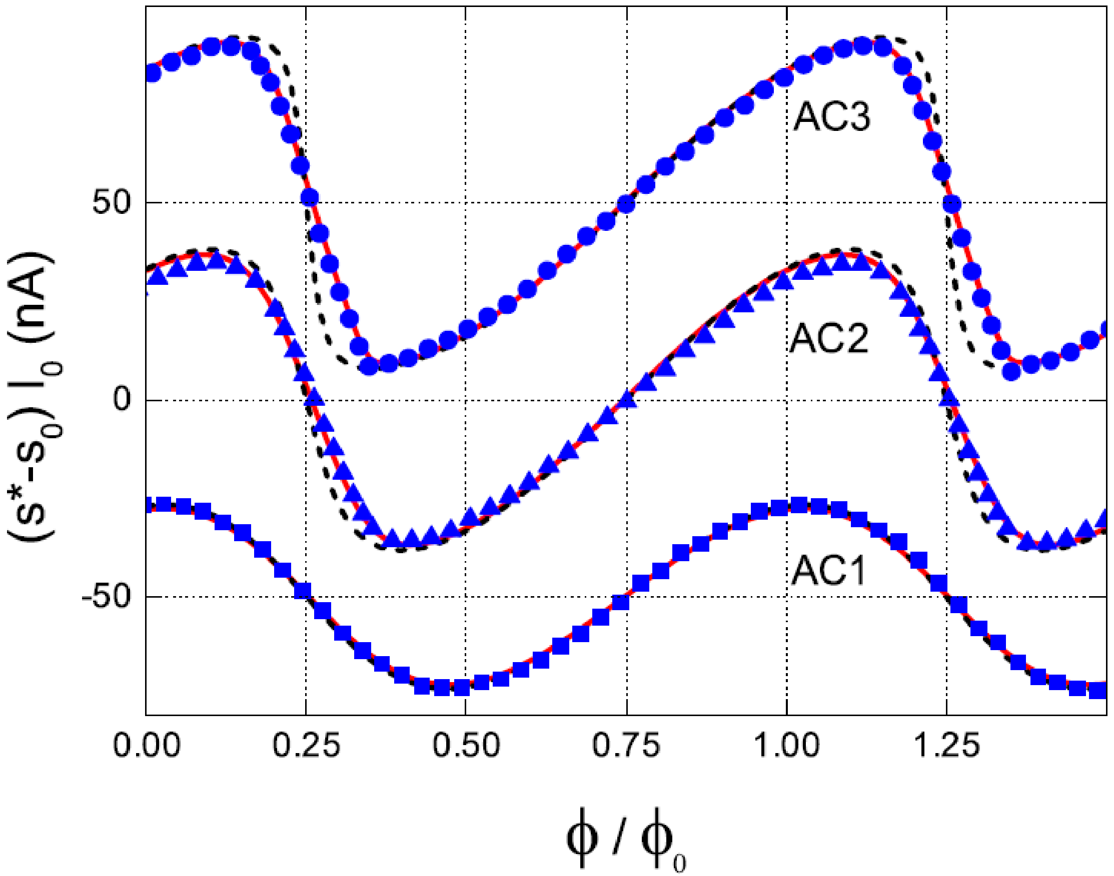
$$\gamma_{sw} \sim \frac{\pi}{2}$$



DIRECT ACCESS TO $I_{\bowtie}(\delta)$

MEASURING CURRENT-PHASE RELATION





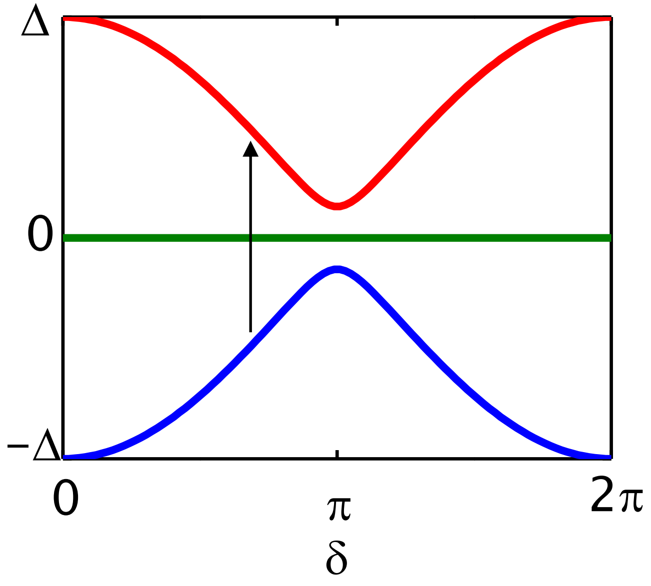
Della Rocca *et al.*, PRL 2007

SPECTROSCOPY OF ABS

1 → detect energy absorption

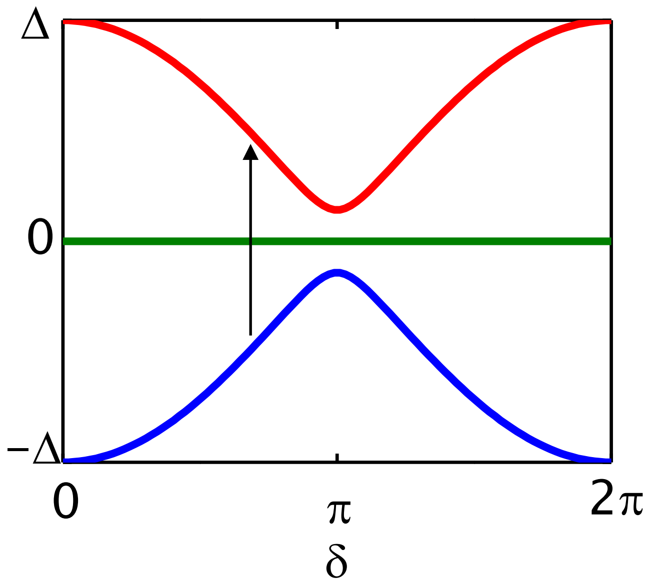
2 → detect supercurrent change

3 → cQED setup



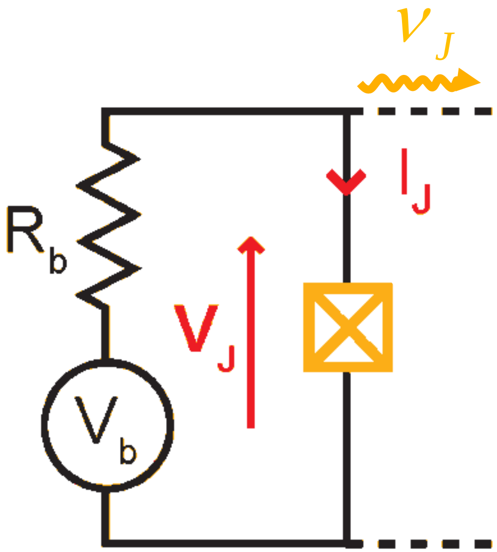
1. USE JOSEPHSON SPECTROMETER

1. detect energy absorption
2. detect supercurrent change
3. cQED setup



JOSEPHSON JUNCTION EMITTER

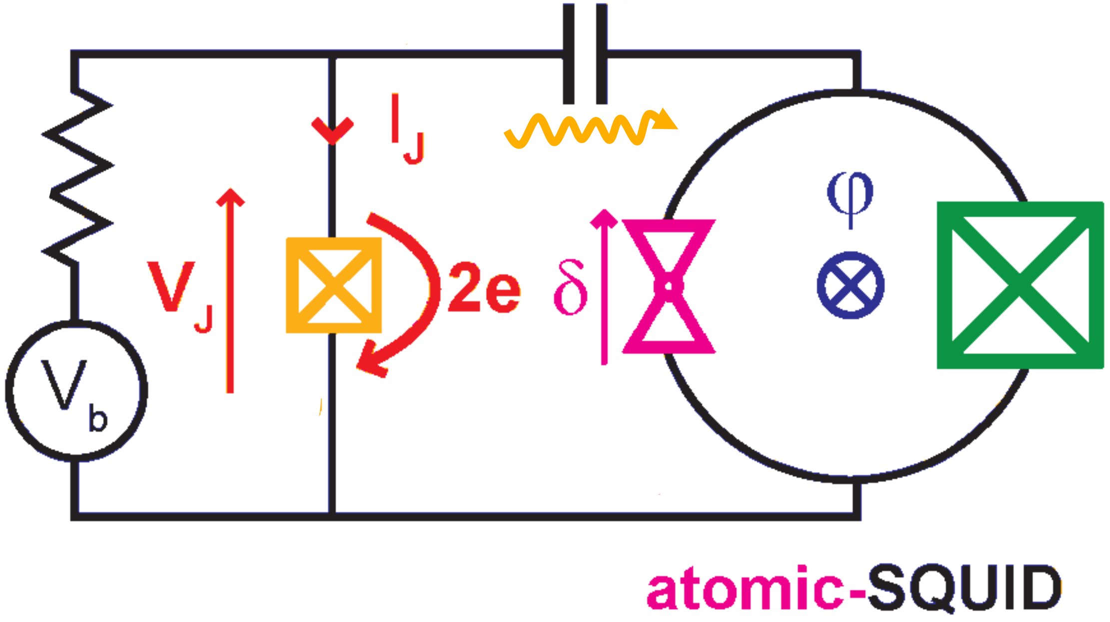
VOLTAGE-BIASED JOSEPHSON JUNCTION

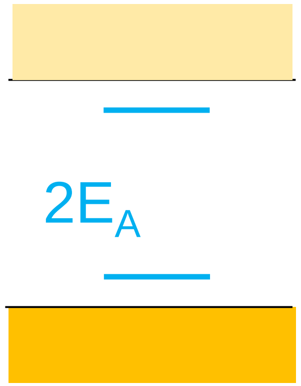


➔ SOURCE OF PHOTONS OF ENERGY $2eV_J$

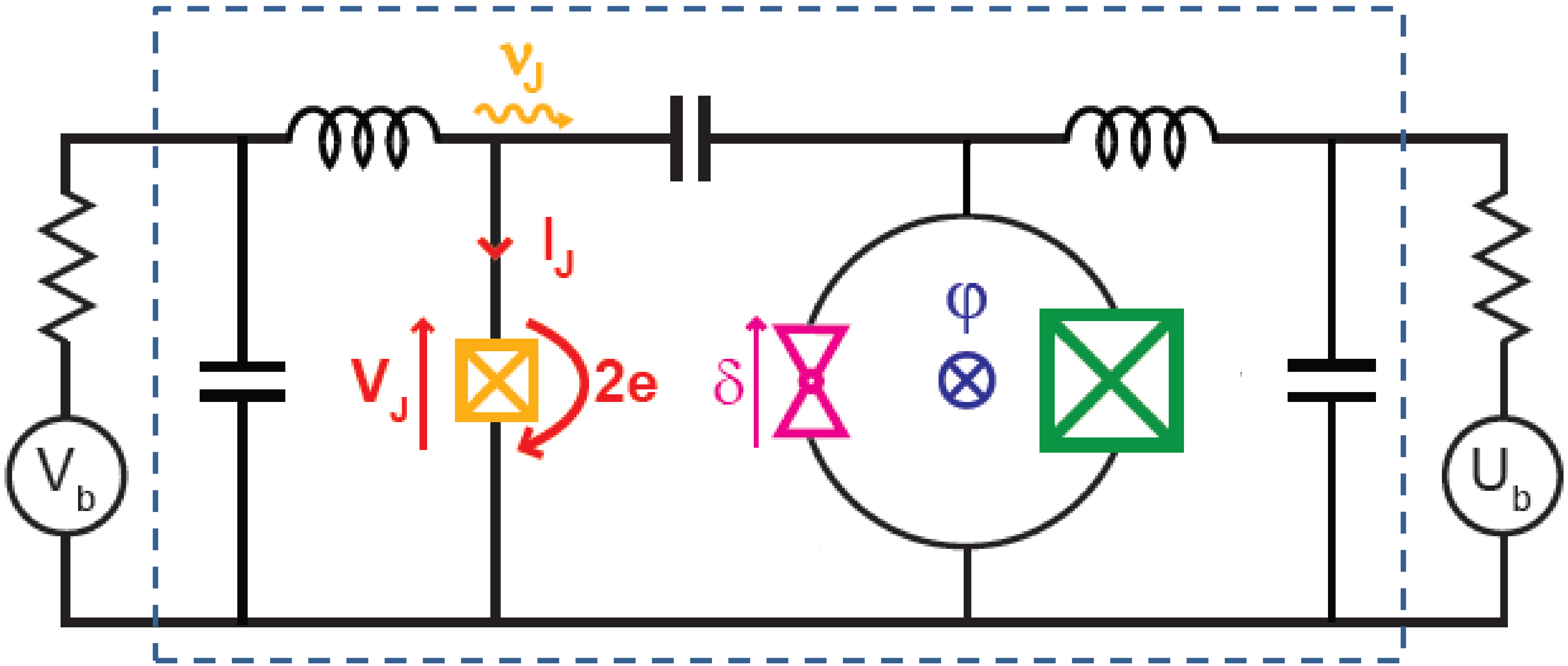
Dayem& Grimes, APL 1966
Lindell *et al.*, PRB 2003
Billangeon *et al.*, PRL 2003

EMITTER CAPACITIVELY COUPLED TO ATOMIC SQUID



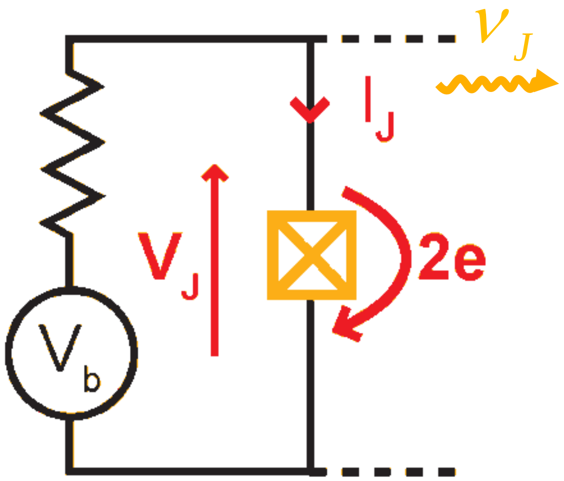


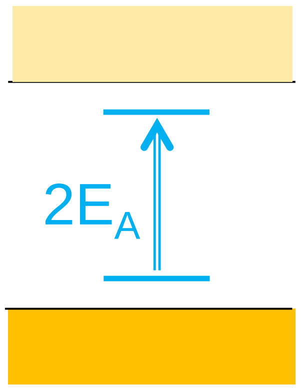
BIASING CIRCUIT



JOSEPHSON JUNCTION DETECTOR

For a photon to be absorbed, a Cooper pair has to tunnel

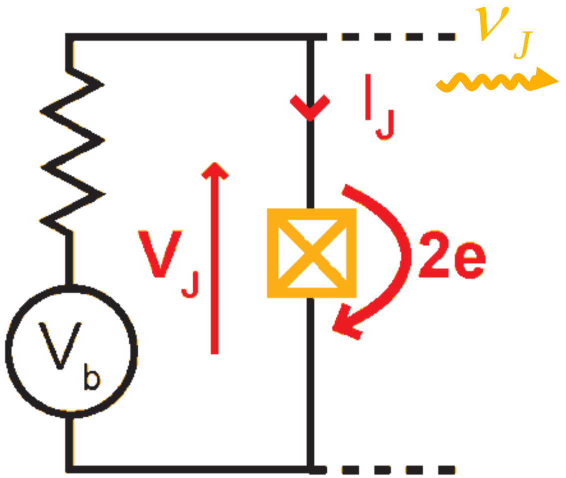


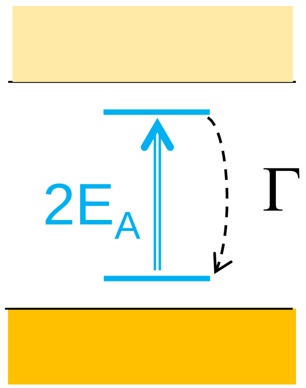


$$2eV_J = 2E_A$$

CURRENT IN JOSEPHSON JUNCTION DETECTOR

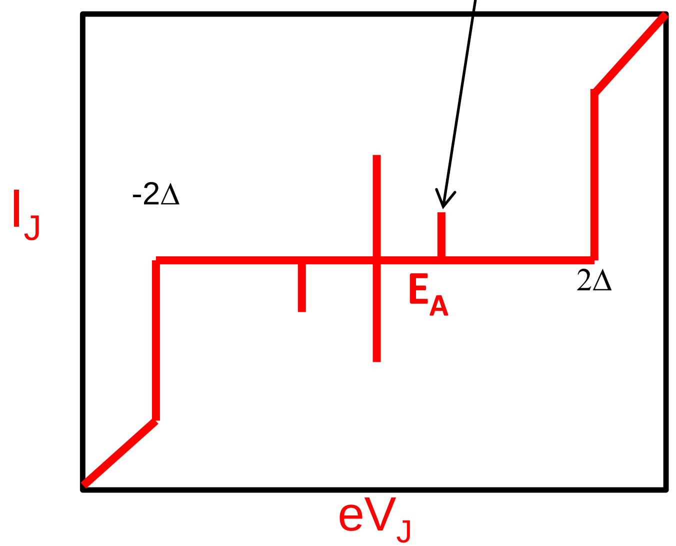
JJ = emitter + detector ➔ spectrometer



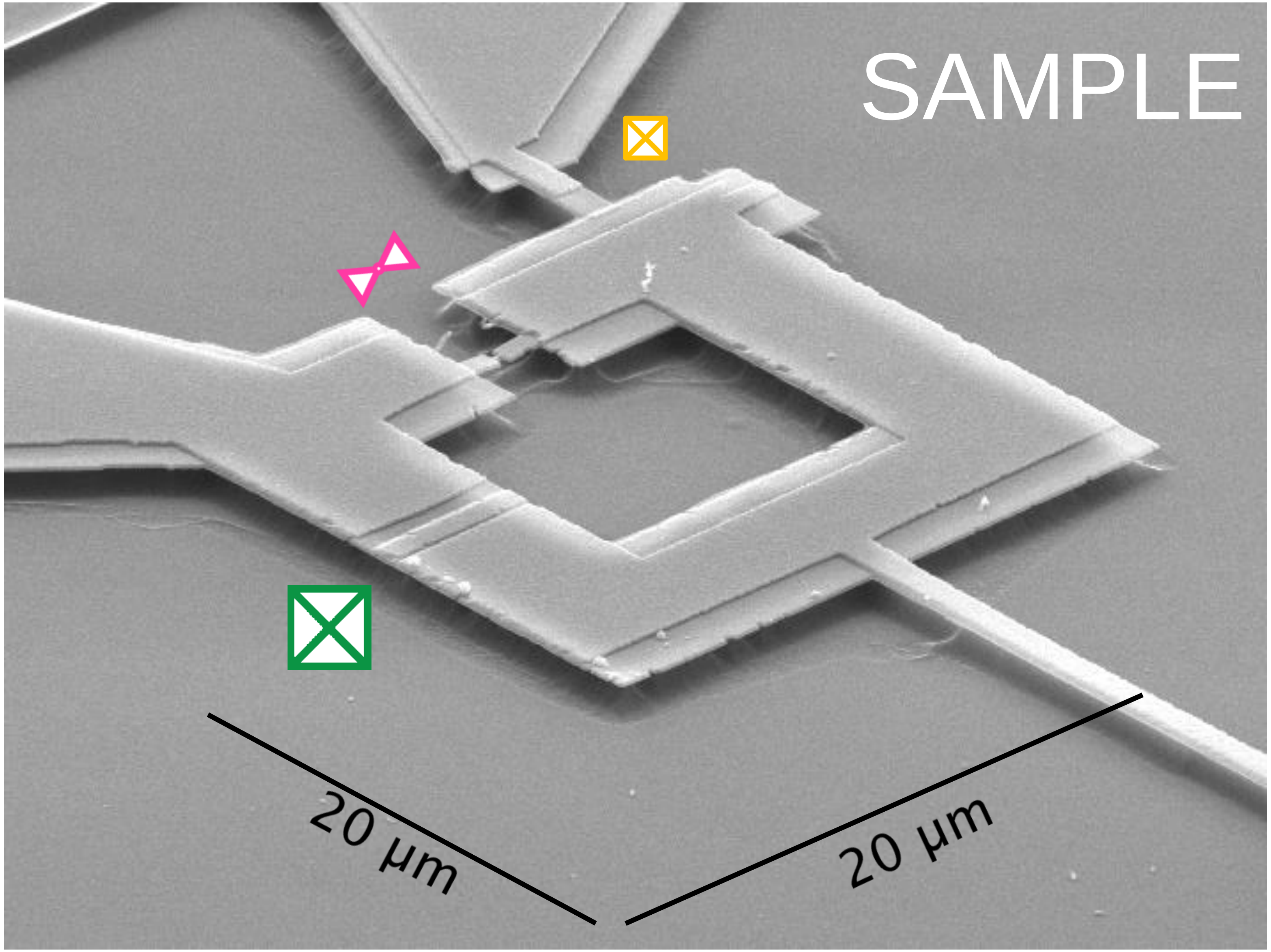


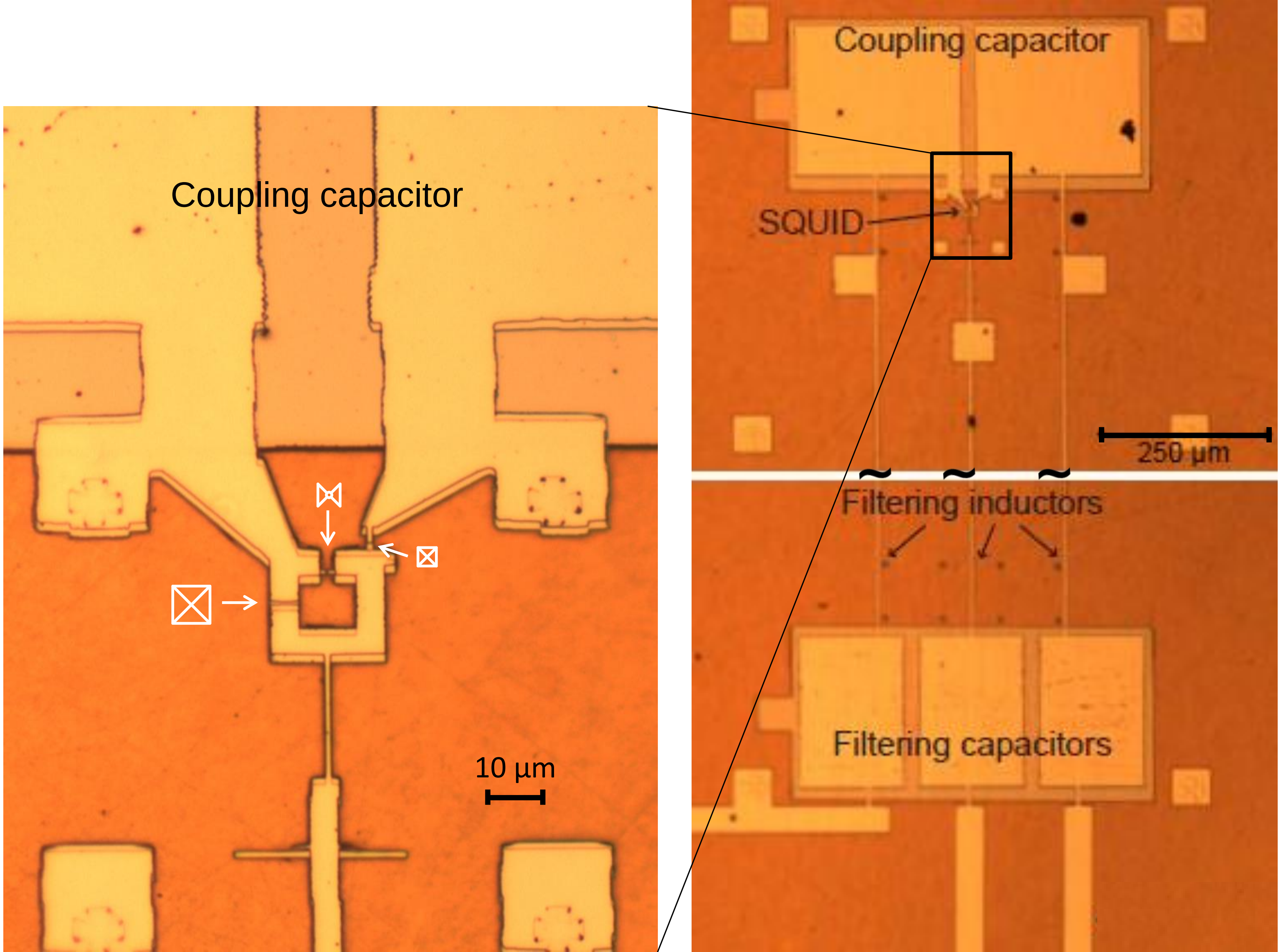
$$2eV_J = 2E_A$$

$$I_J = 2e\Gamma$$

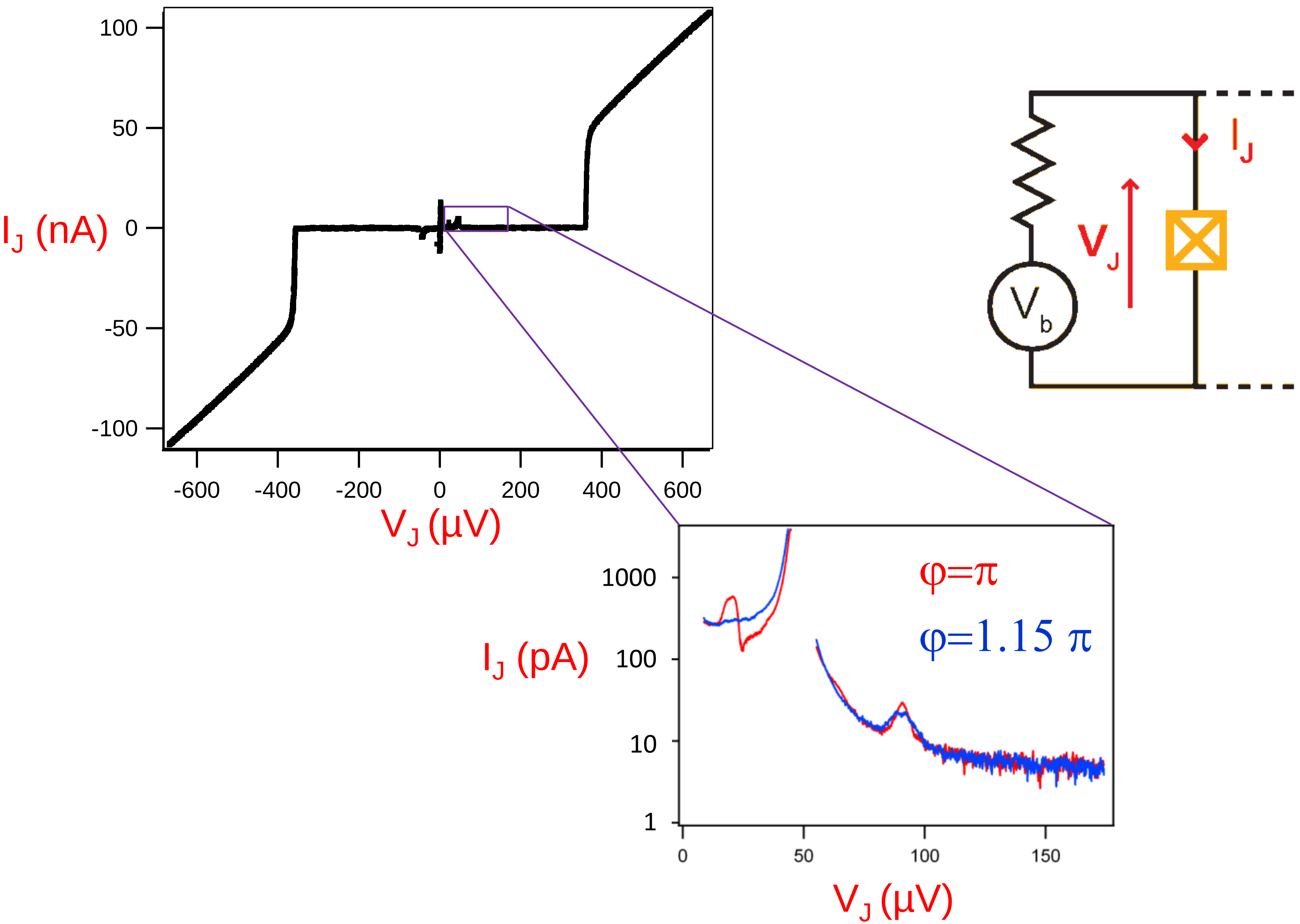


DETECT ENERGY ABSORPTION

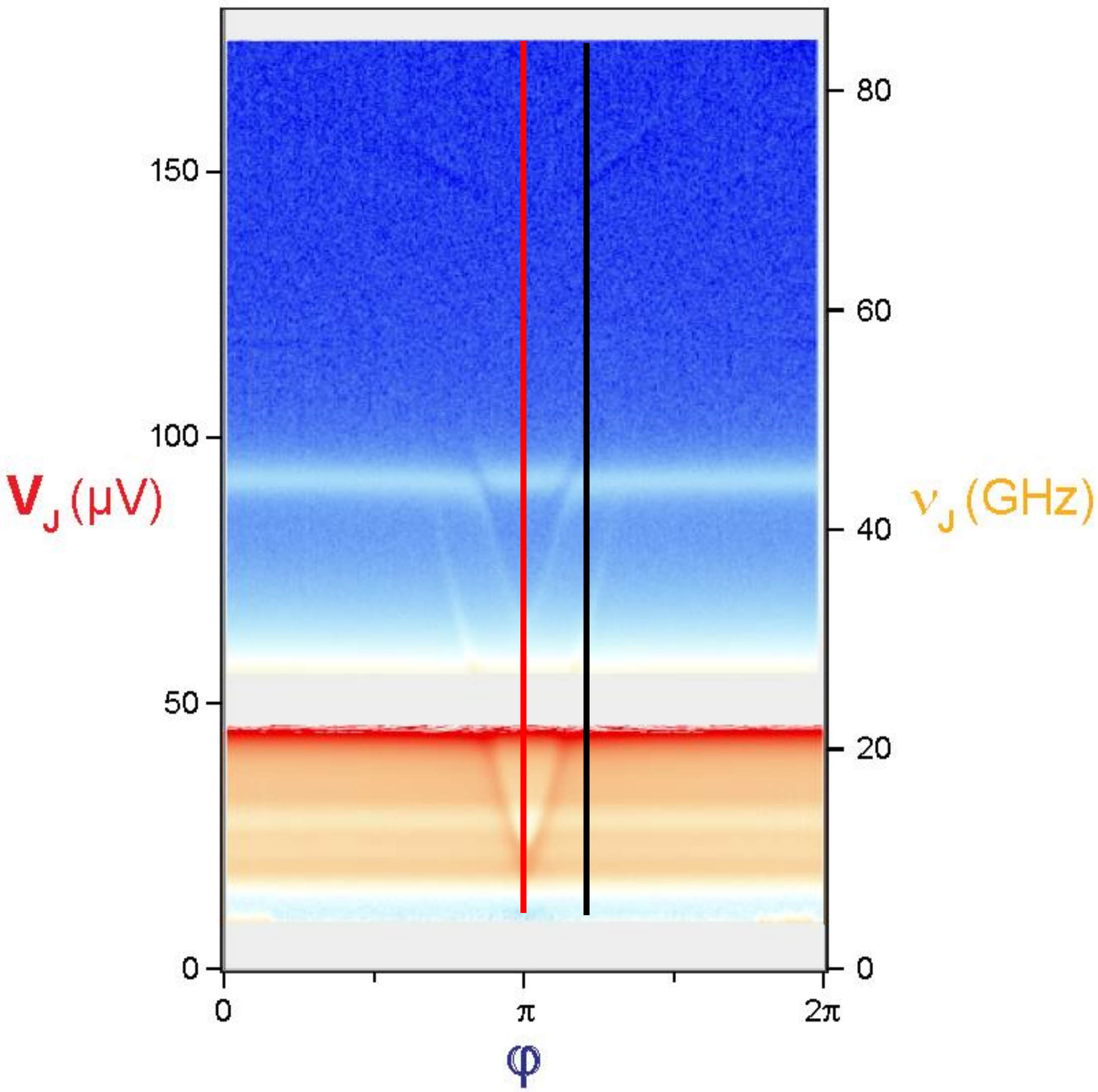

SAMPLE
20 µm
20 µm

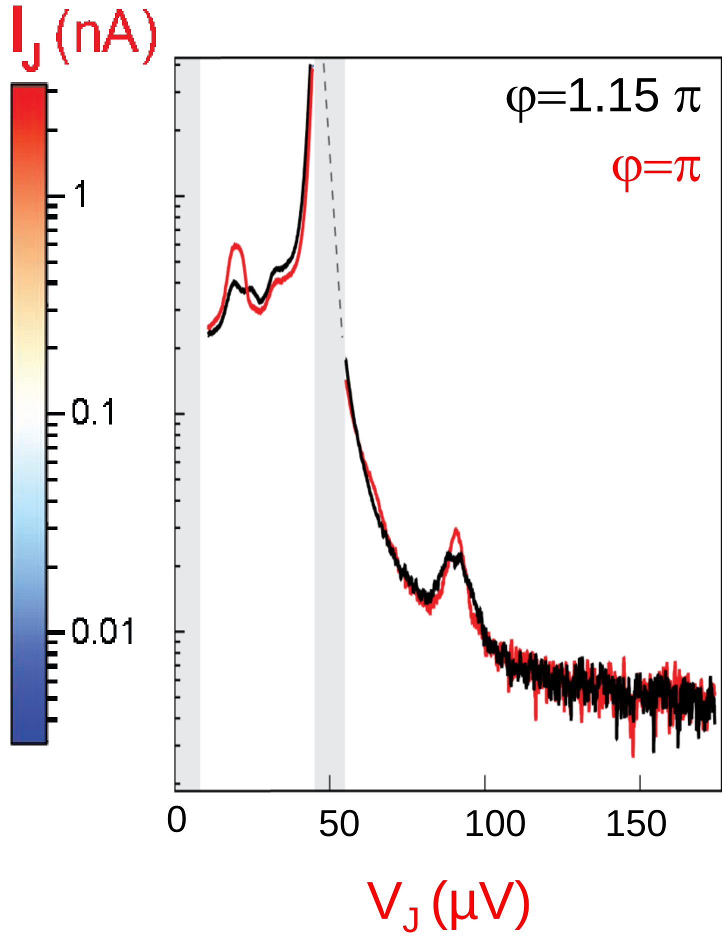

Coupling capacitor
10 µm
Coupling capacitor
SQUID
250 µm
Filtering inductors
Filtering capacitors

IV OF SPECTROMETER JUNCTION



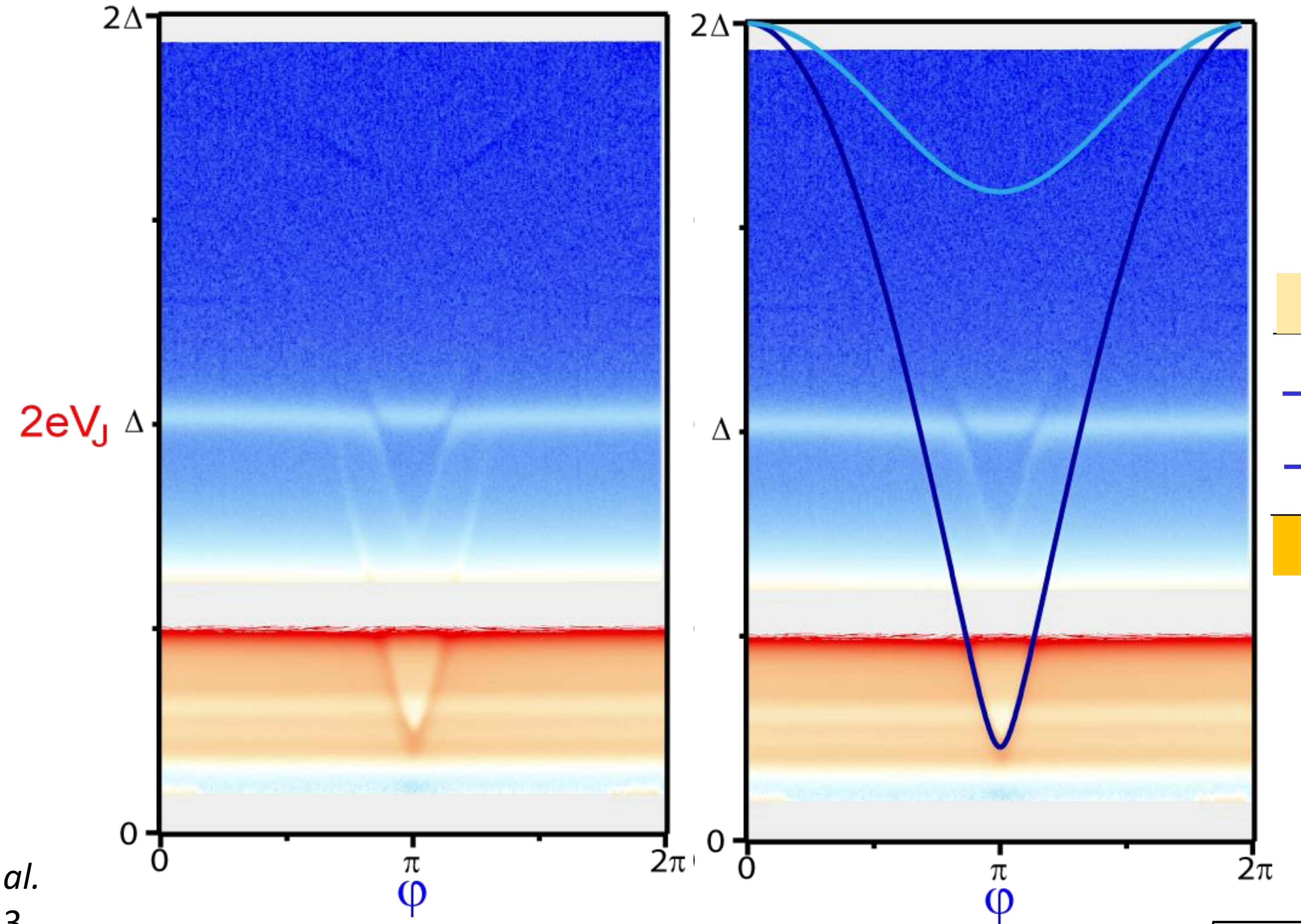
SPECTRUM CONSTRUCTION

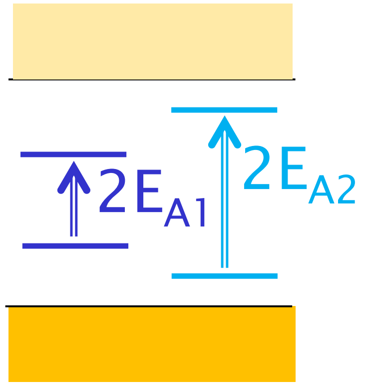




COMPARISON WITH CALCULATED ANDREEV ENERGIES

AC2: {0.985, 0.37}



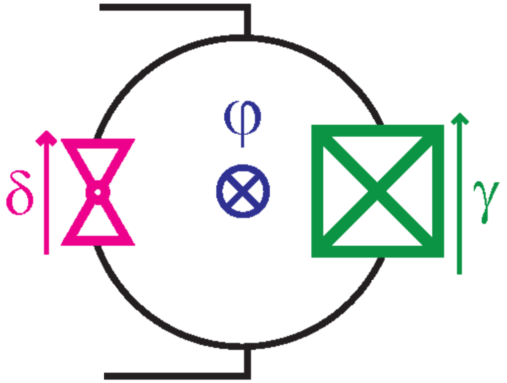


$\tau_1=0.985$
$\tau_2=0.37$

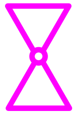
Bretheau *et al.*
Nature 2013

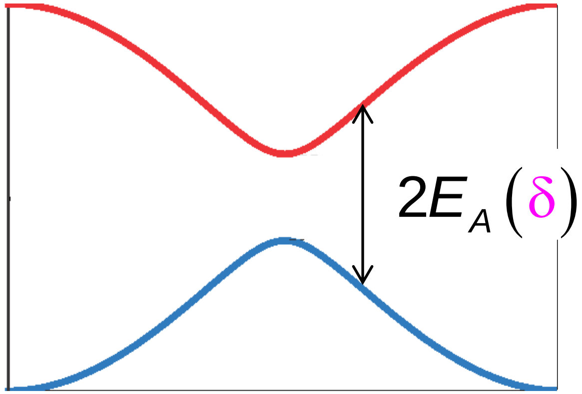
$$E_A = \Delta\sqrt{1-\tau\sin^2(\varphi/2)}$$

TWO COUPLED DEGREES OF FREEDOM



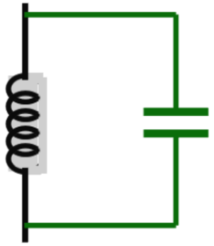
Andreev doublet

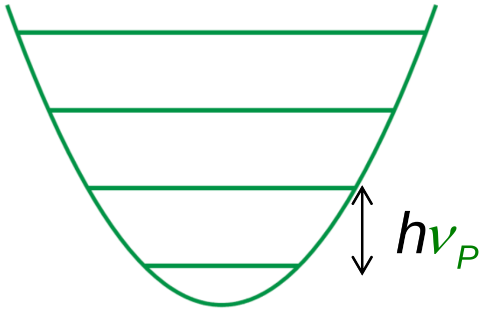




$$0 \leq 2E_A / h \leq 85\,\text{GHz}$$

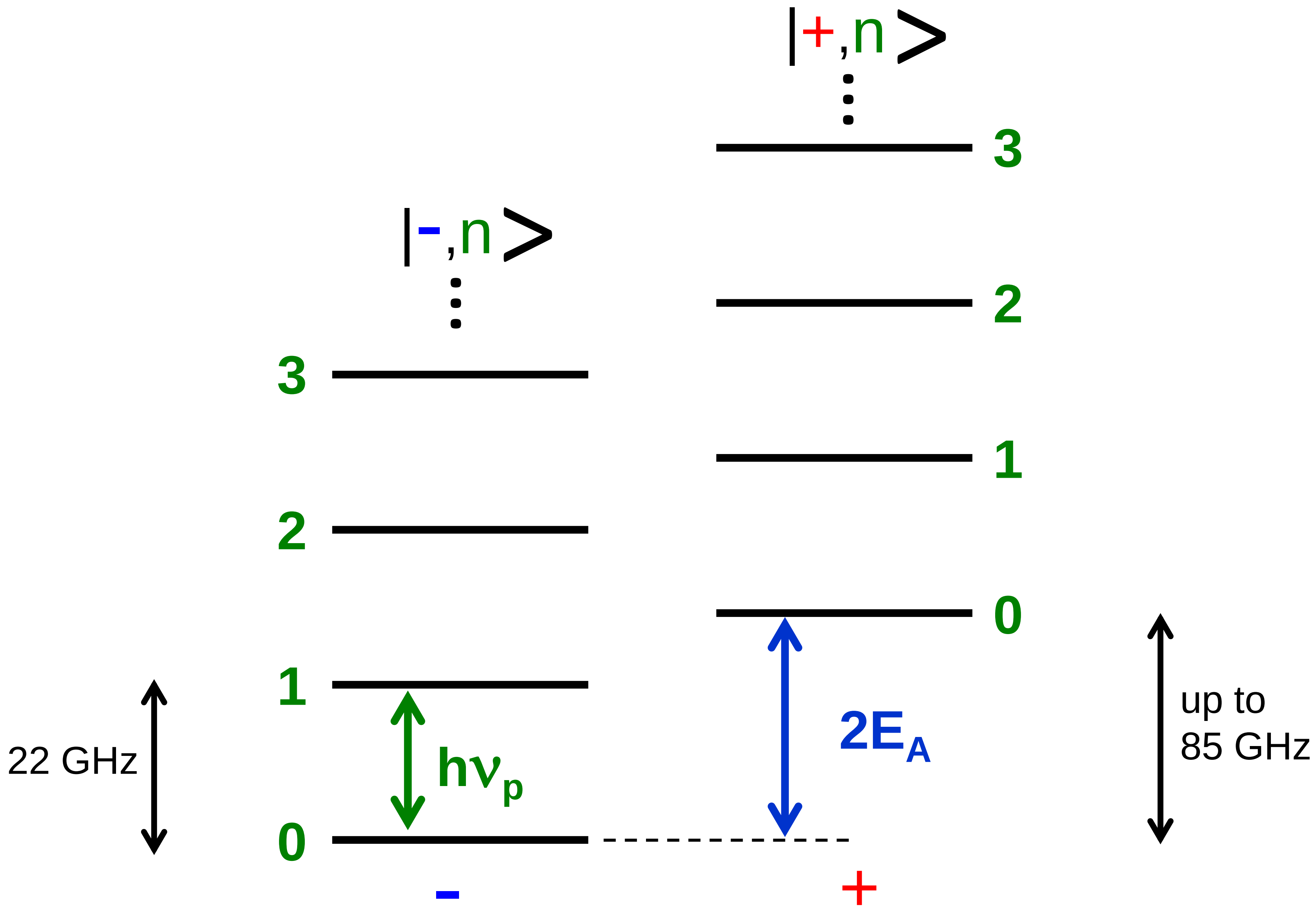
Plasma mode



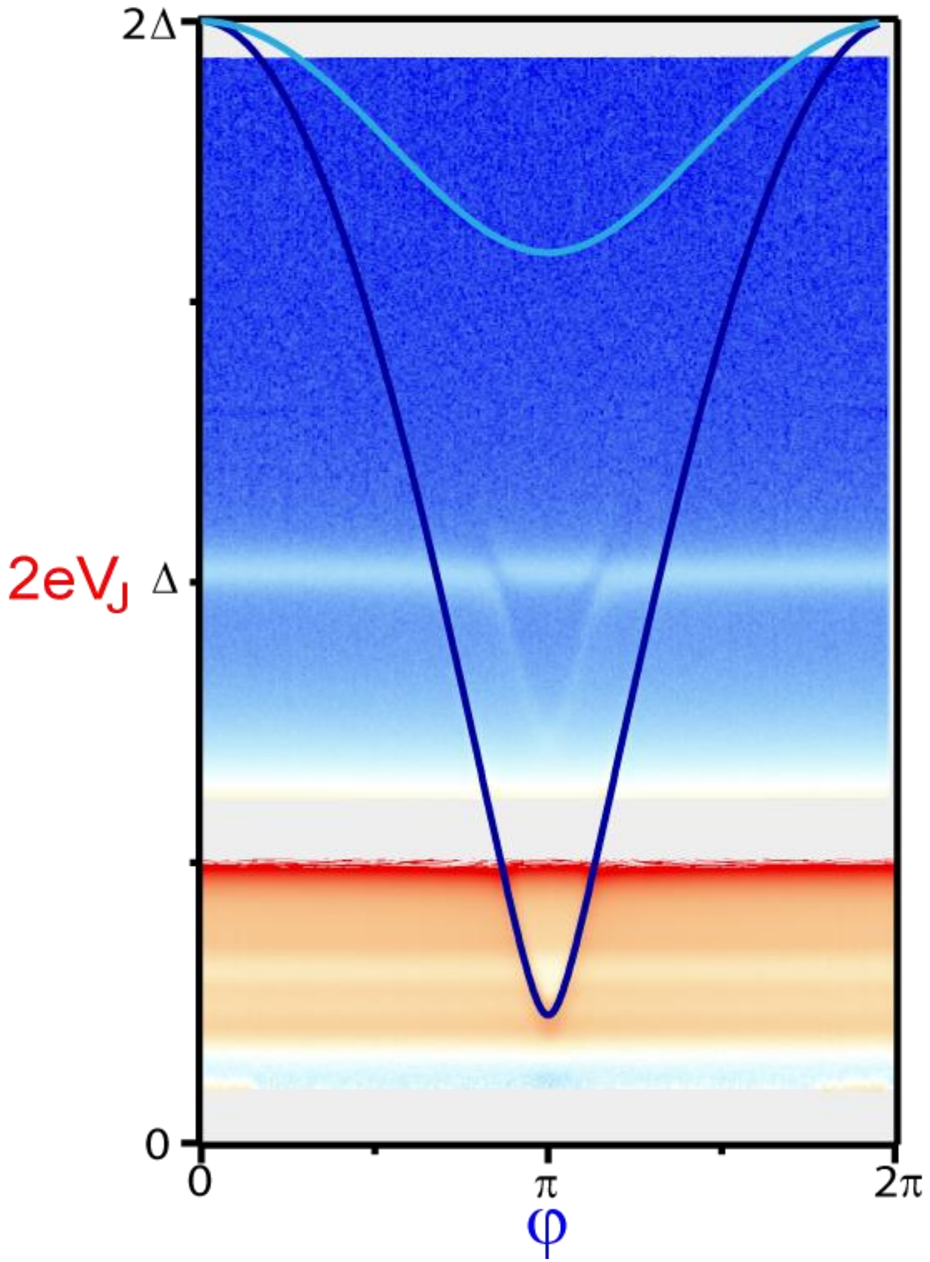


$$\nu_P \simeq 22\,\text{GHz}$$

ENERGY LADDERS

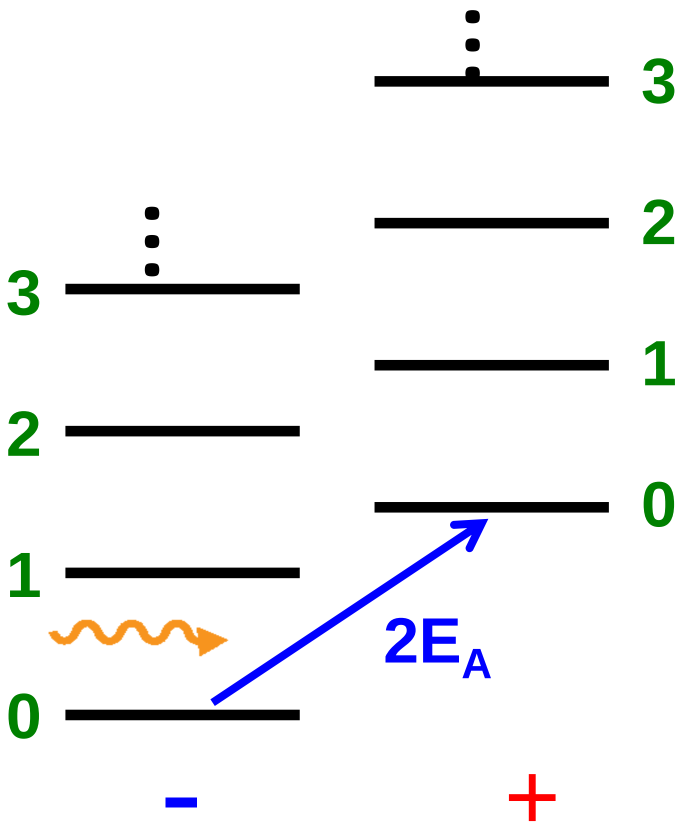


EXPECTED TRANSITIONS: 1-PHOTON PROCESSES

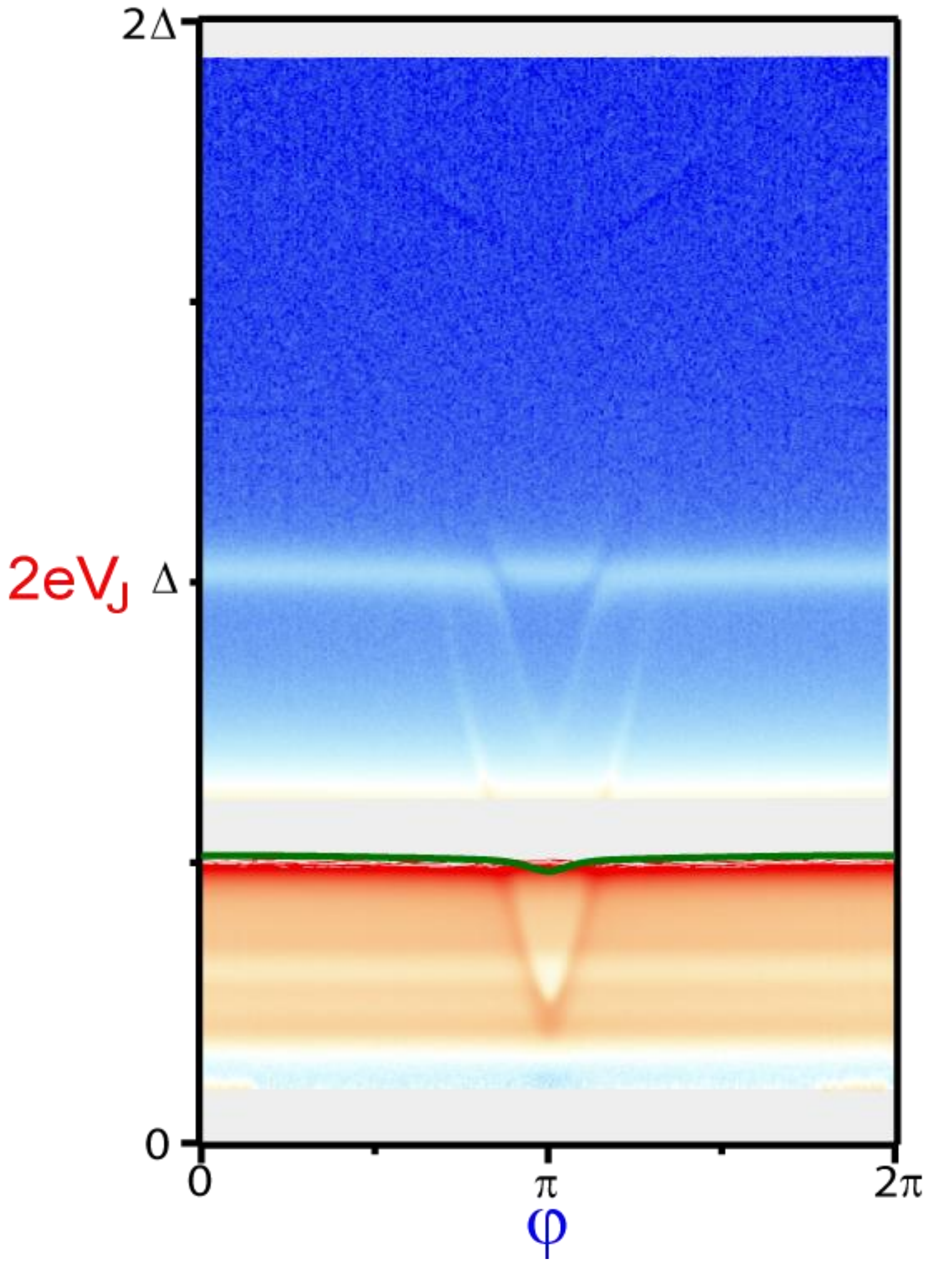


Andreev transitions

$2eV_J = 2E_A$

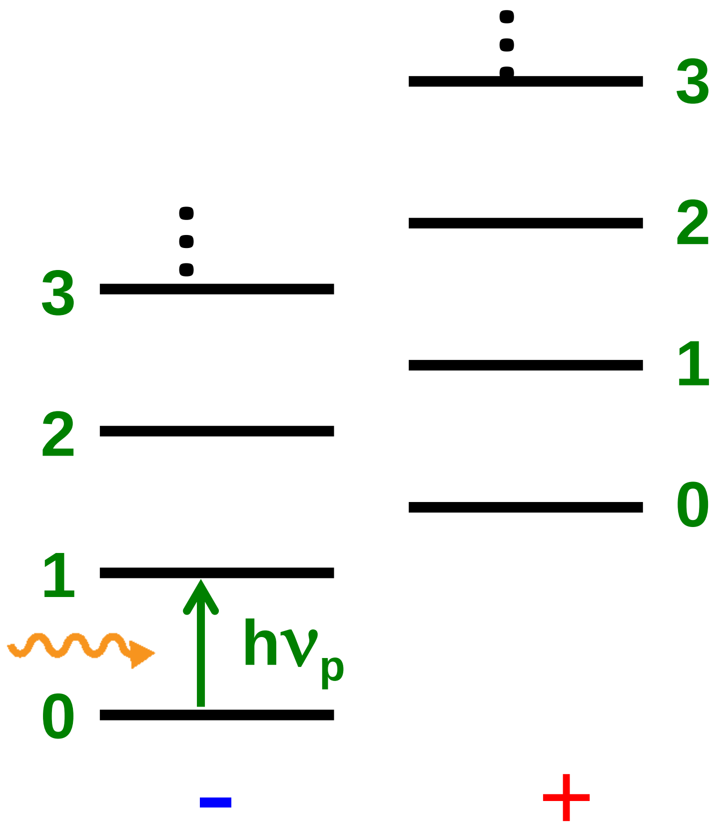


EXPECTED TRANSITIONS: 1-PHOTON PROCESSES

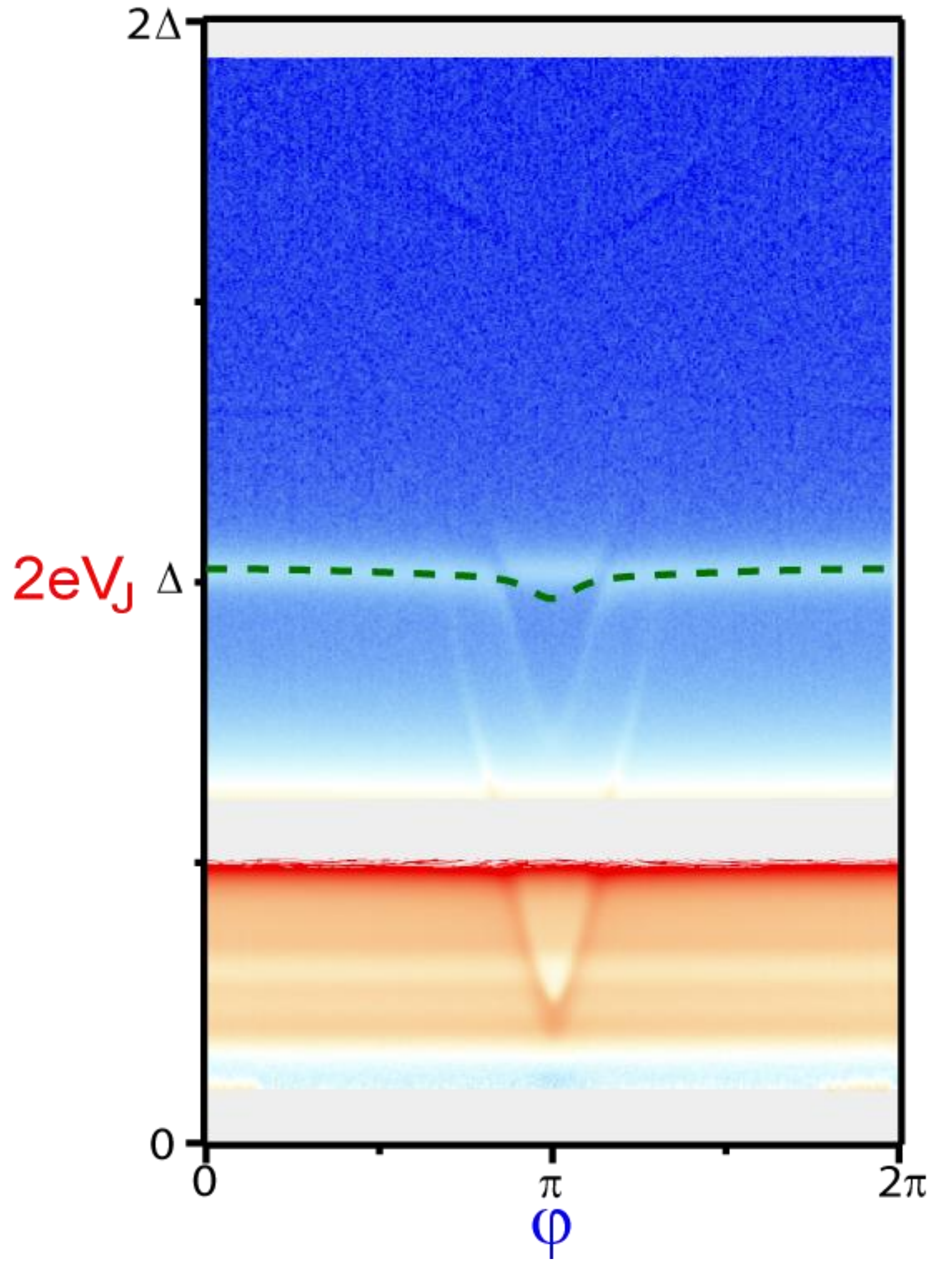


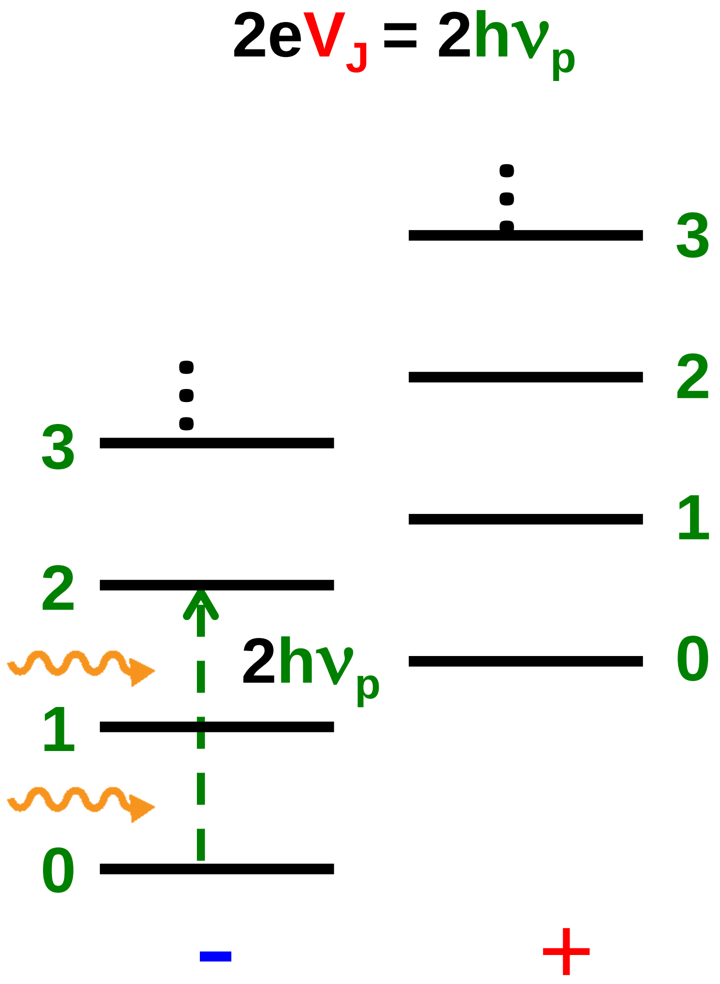
Plasma transition

$2eV_J = h\nu_p$

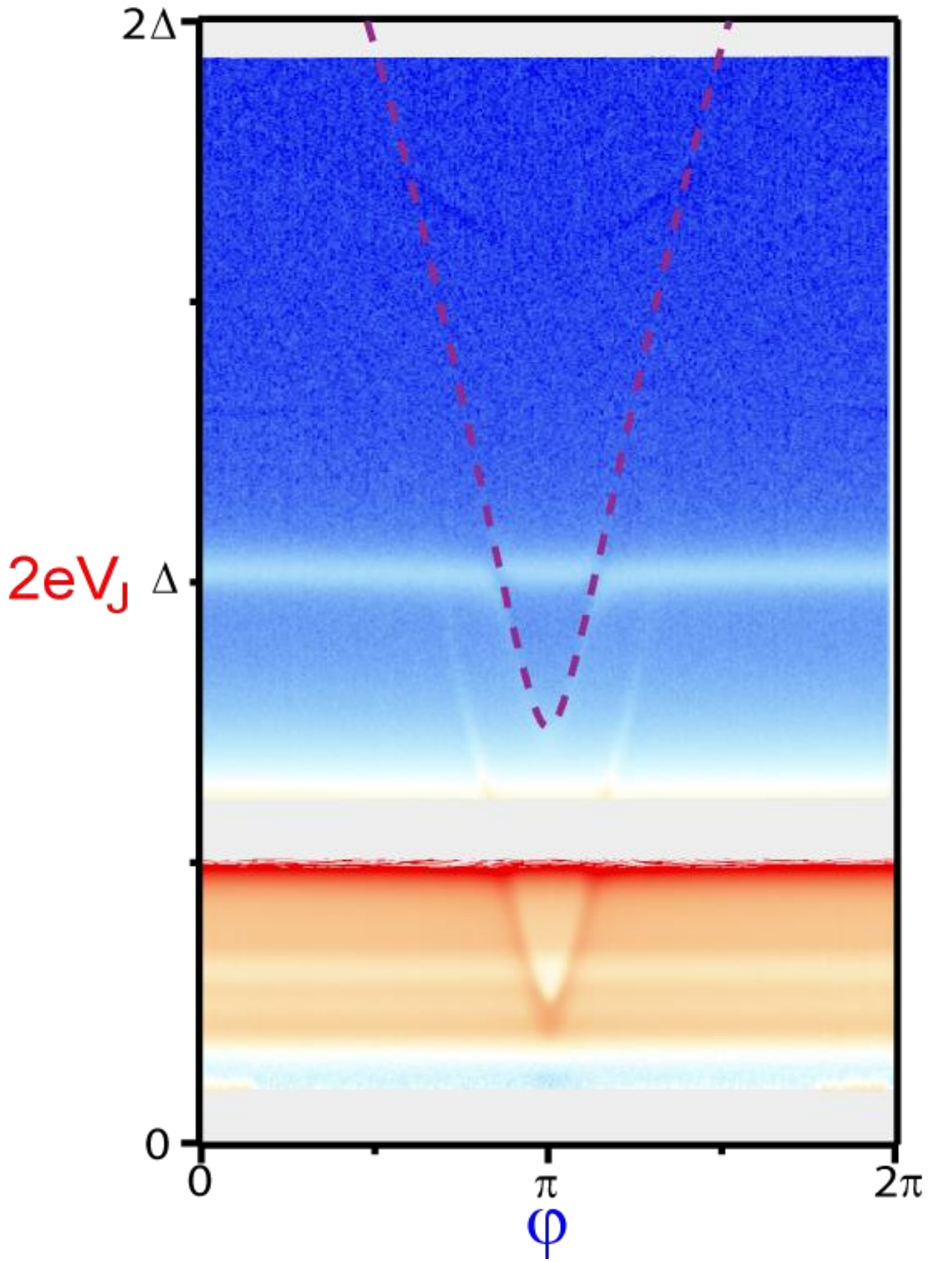


EXPECTED TRANSITIONS: 2-PHOTONS PROCESSES

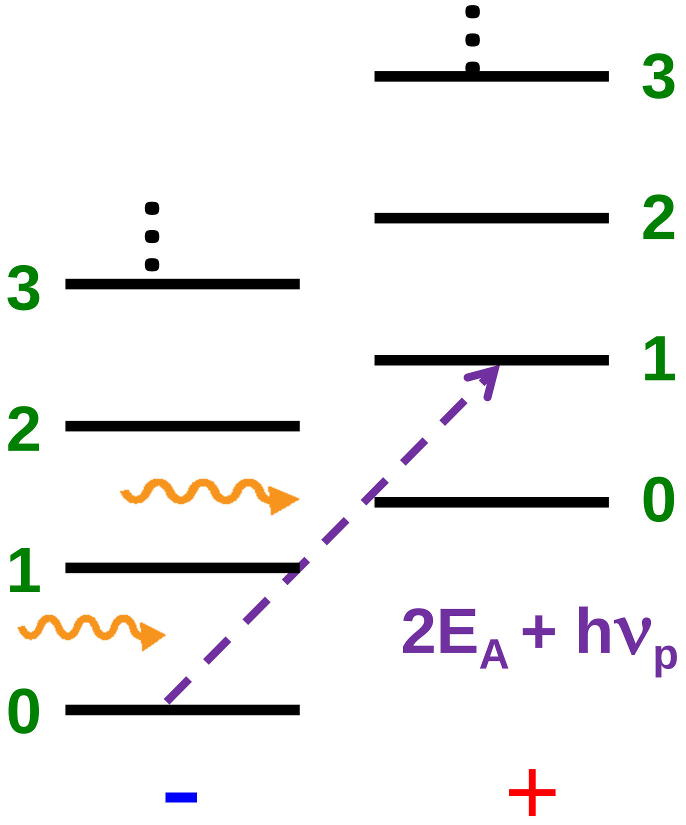




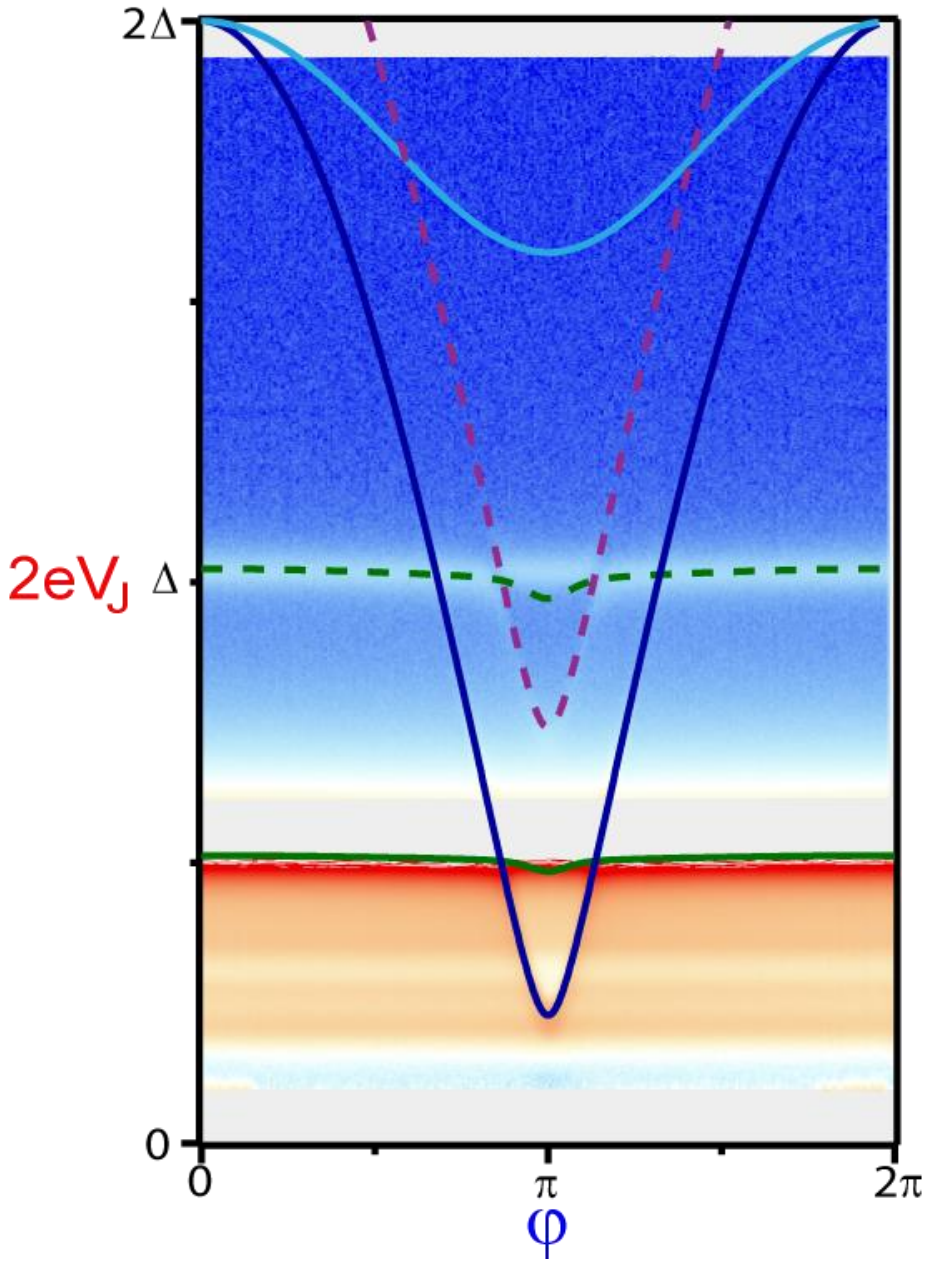
EXPECTED TRANSITIONS: 2-PHOTONS PROCESSES



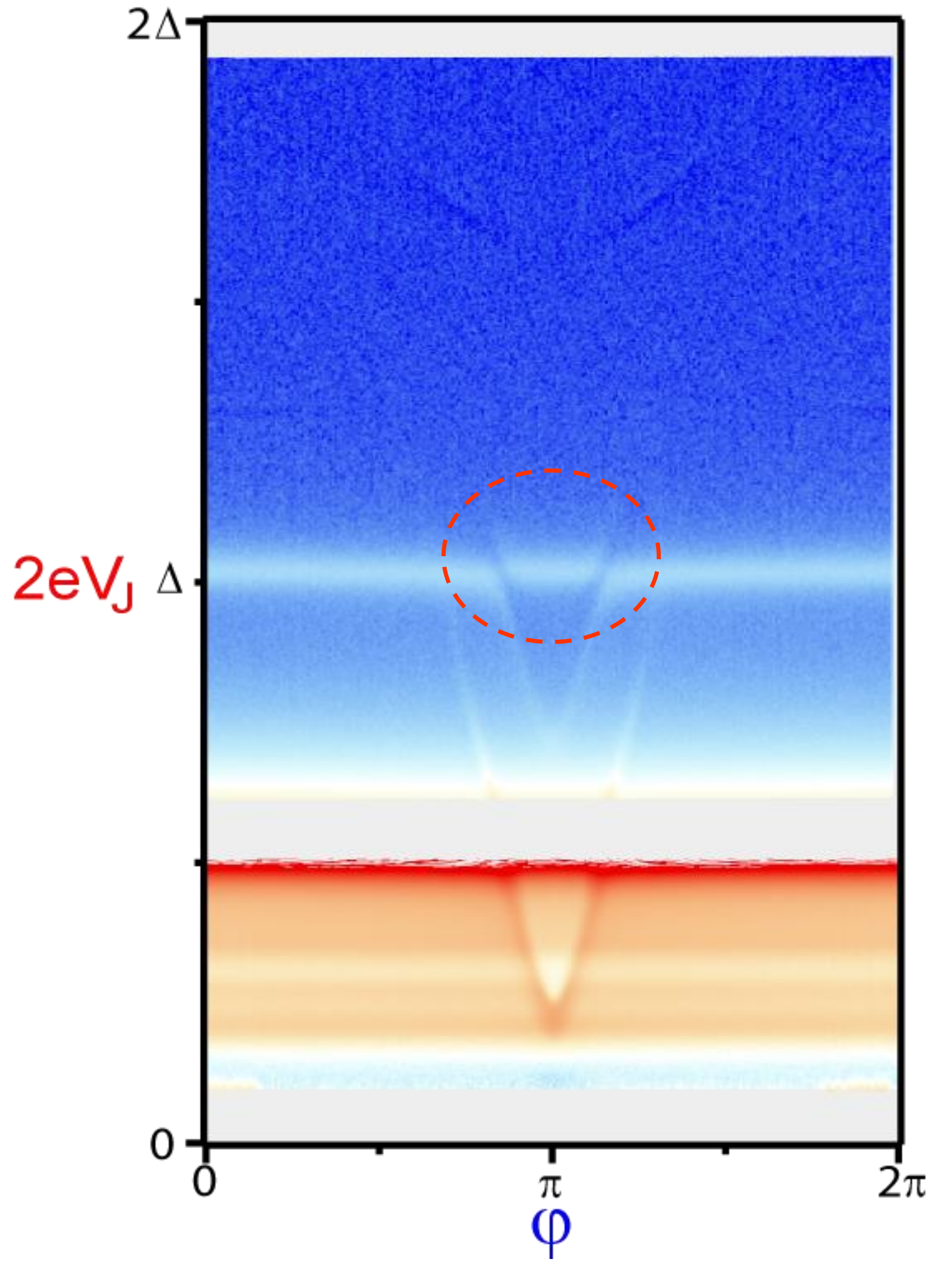
$$2eV_J = 2E_A + h\nu_p$$



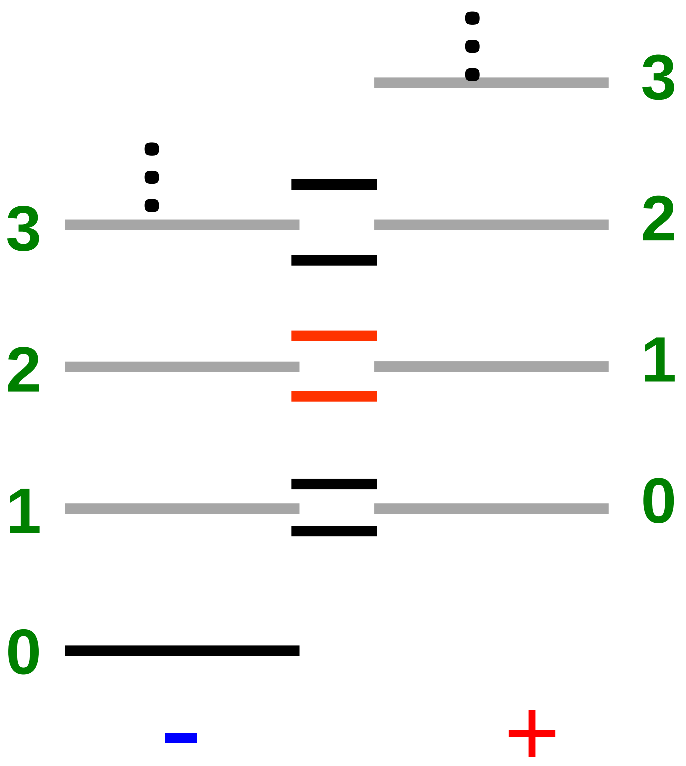
BARE TRANSITIONS



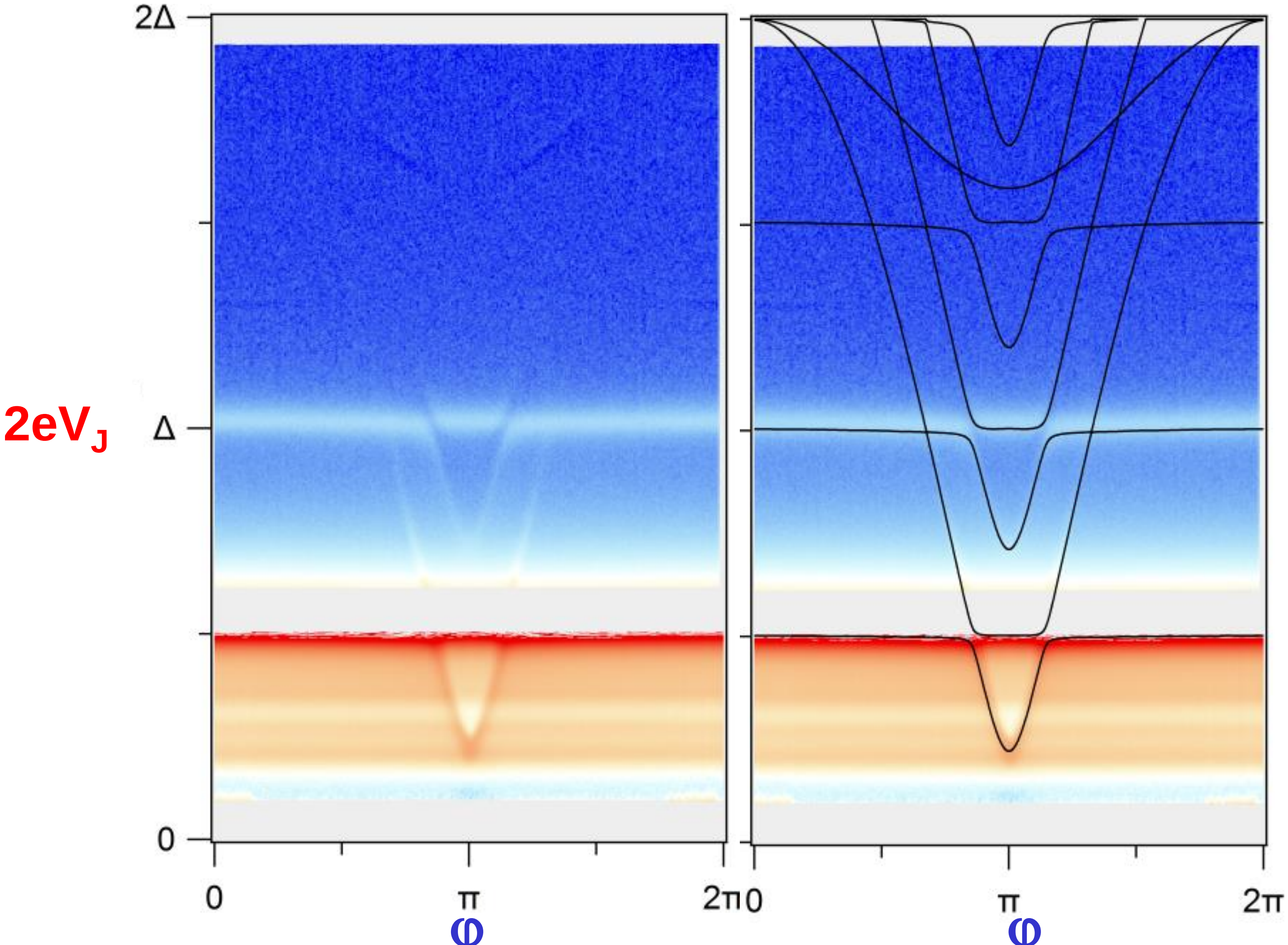
ANTI-CROSSING



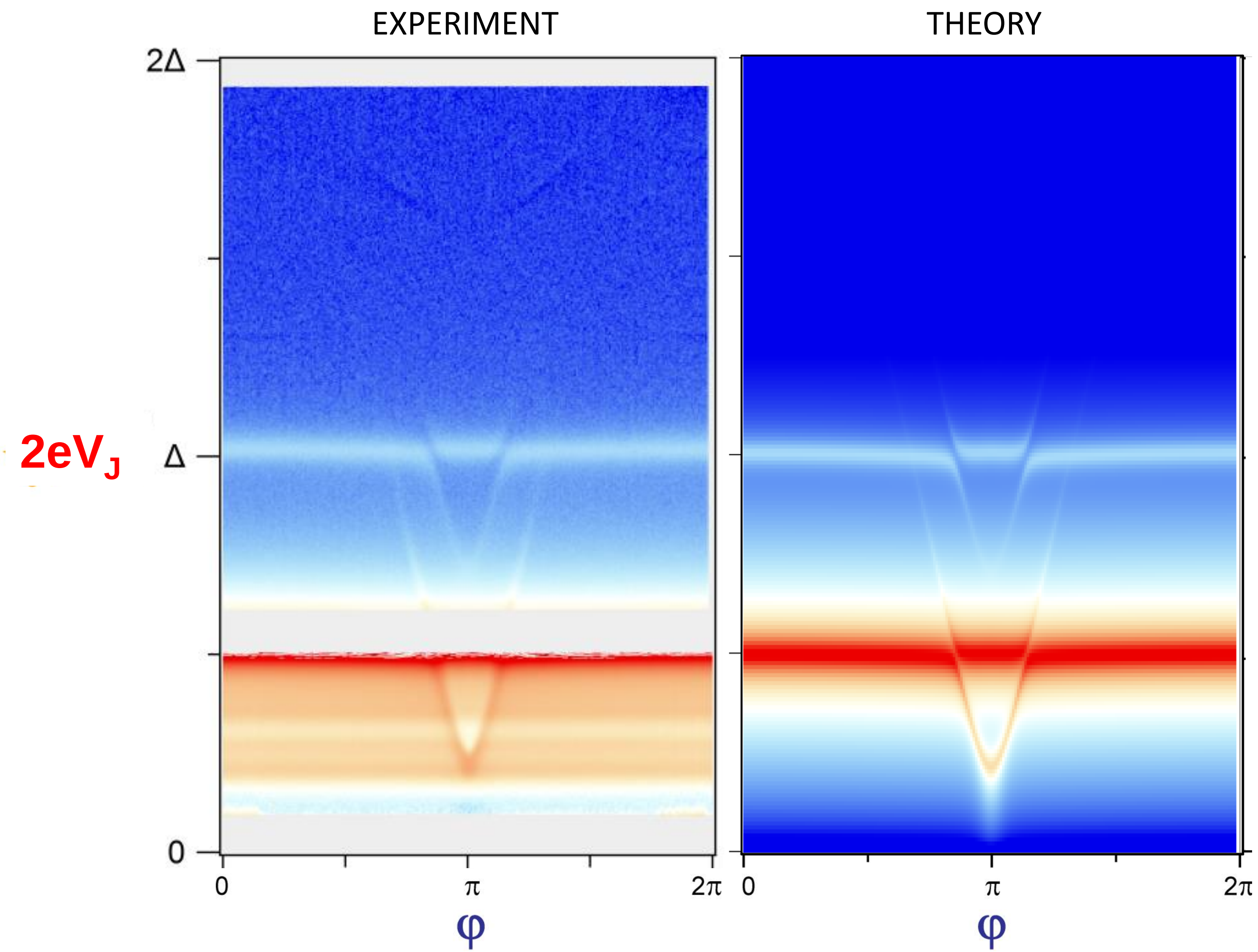
$h\nu_p = 2E_A$



ENERGY SPECTRUM FOR CONTACT {0.985, 0.37,...}



EXPERIMENTAL VS THEORETICAL SPECTRUM



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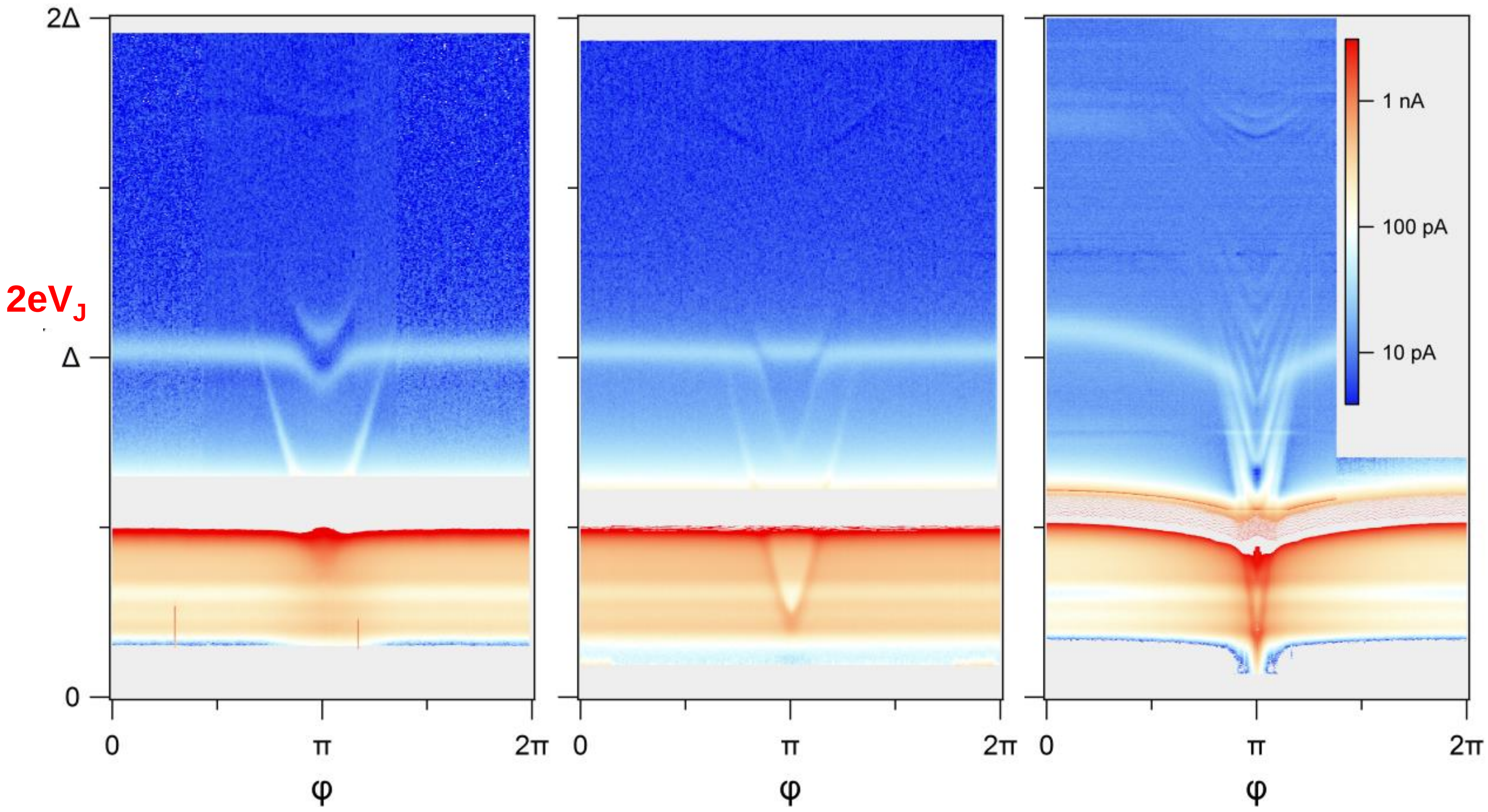
PRB 2014

SPECTRA OF DIFFERENT CONTACTS



{0.942,0.26,...}

{0.985, 0.37,...}

many

DETECT TRANSITIONS: 2. SWITCHING MEASUREMENT

1

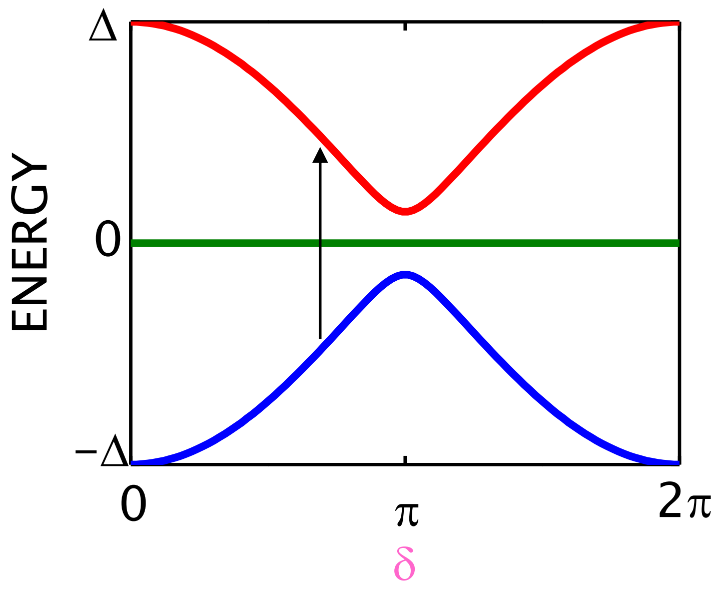
2

3

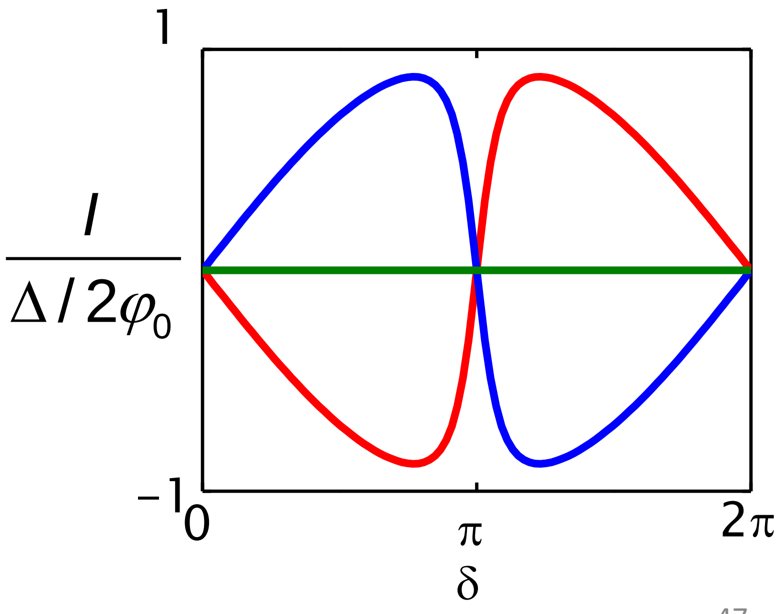
detect energy absorption

detect change in supercurrent

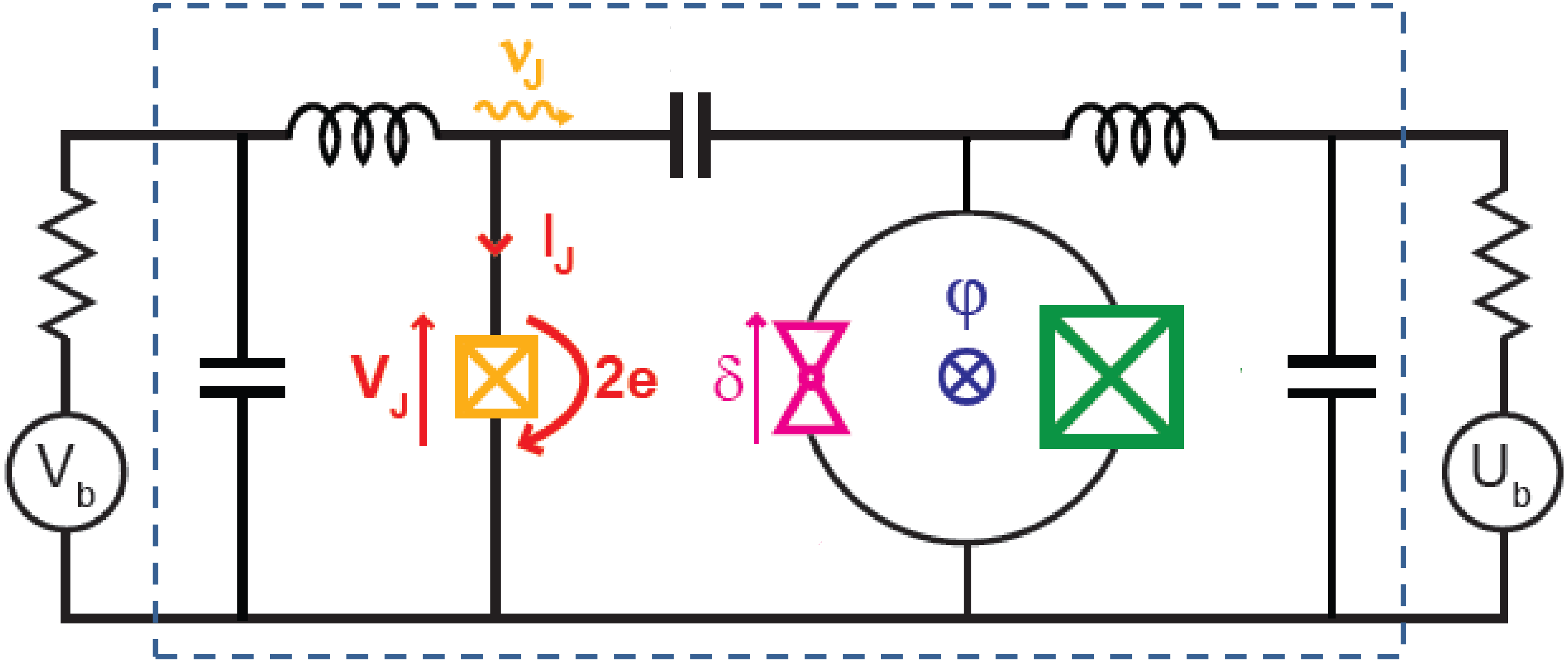
cQED setup



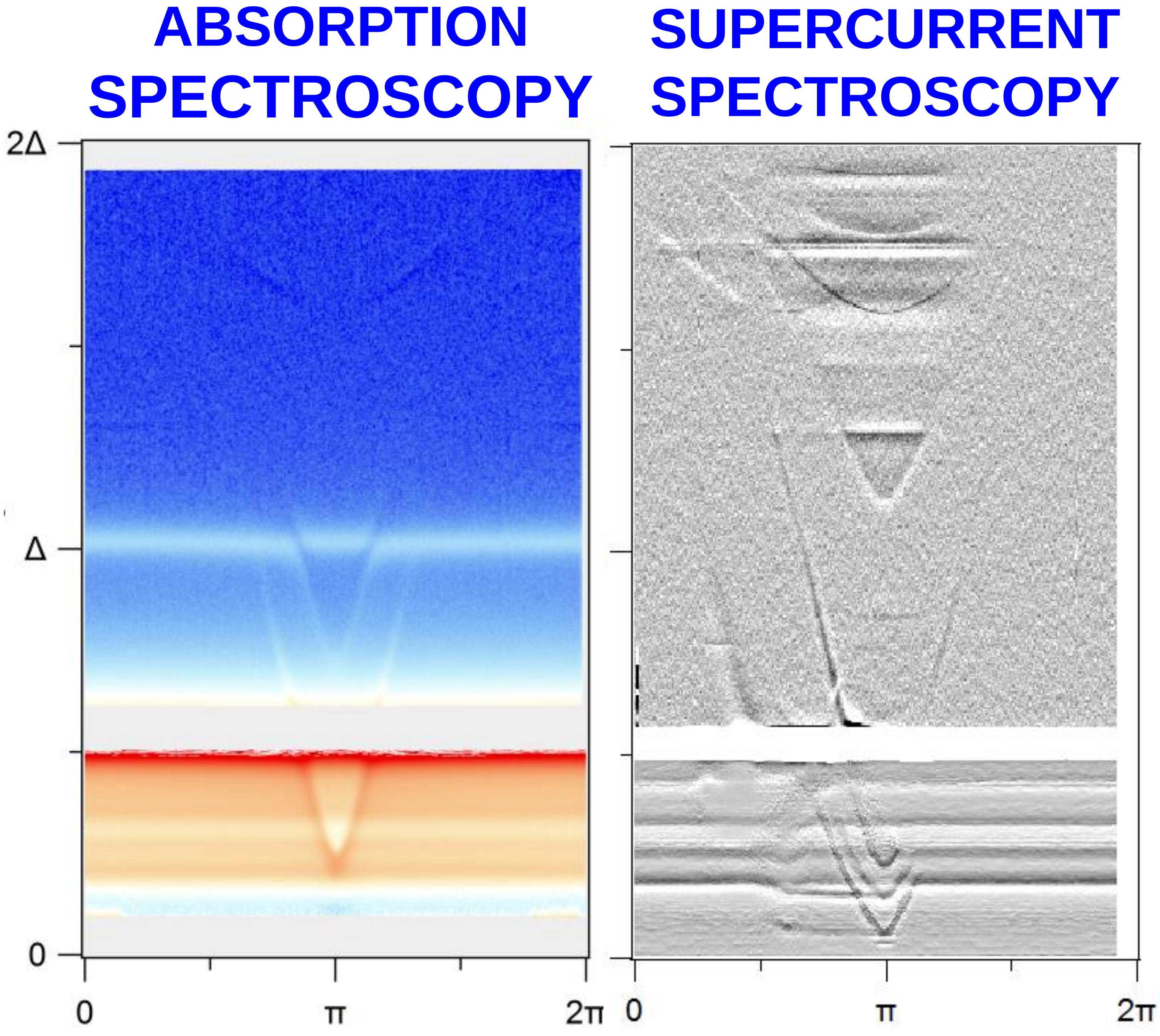
switching measurements
of the atomic SQUID



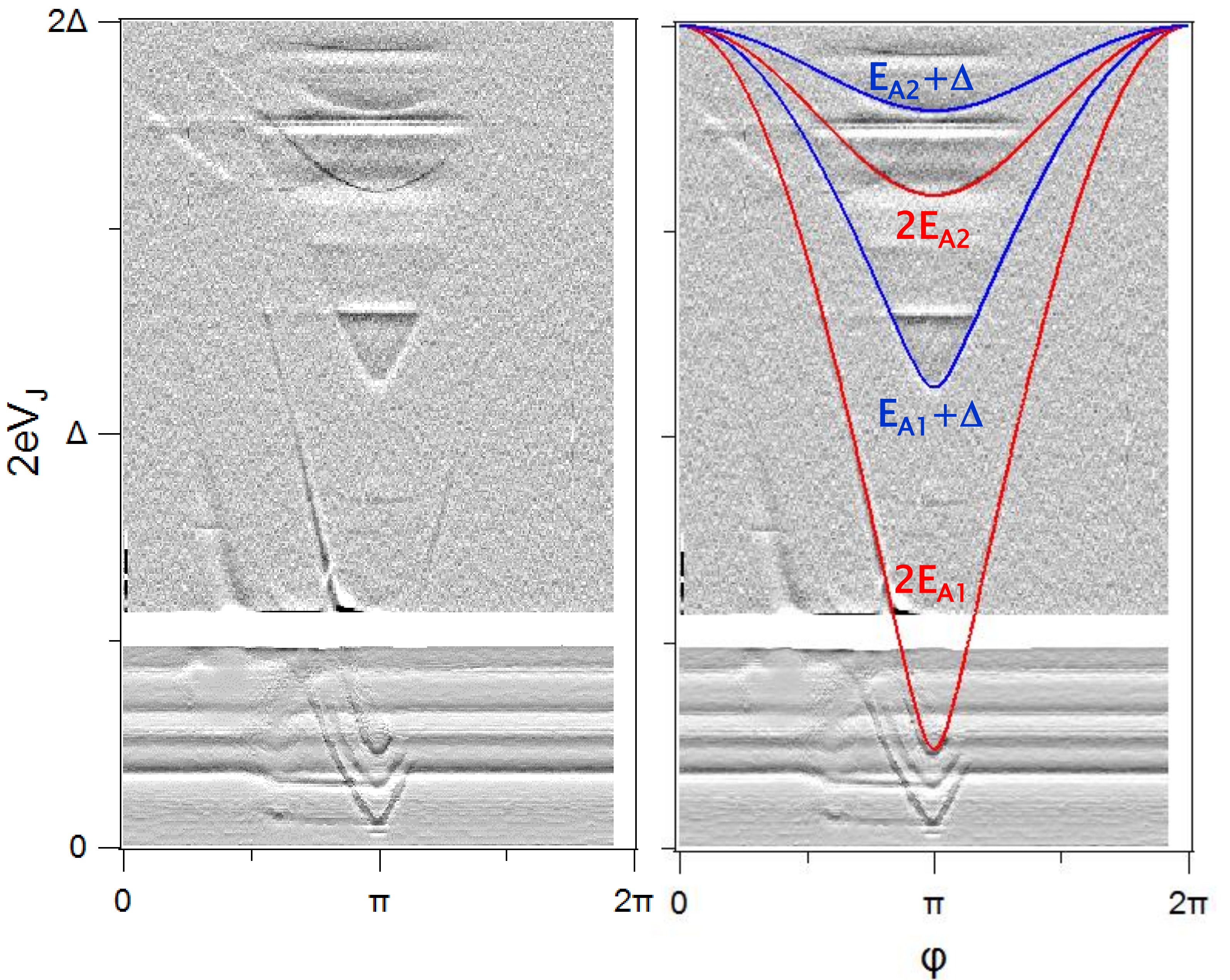
MEASURE SUPERCURRENT CHANGE

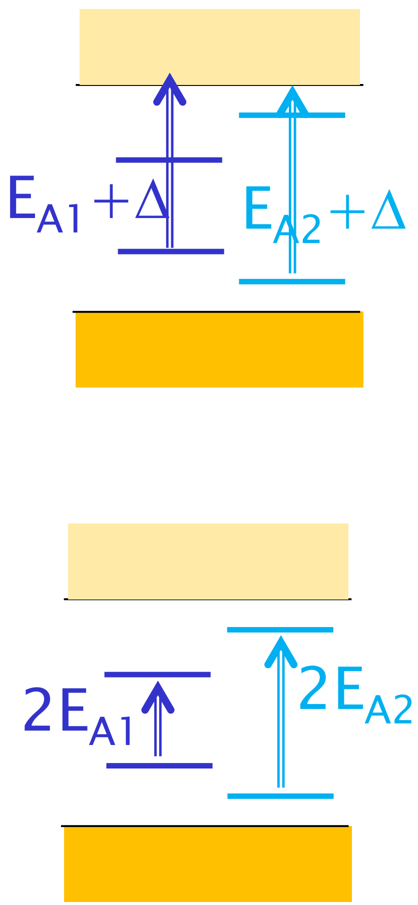


0.985
0.37


ABSORPTION SPECTROSCOPY
SUPERCURRENT SPECTROSCOPY
2Δ
Δ
0
0
π
2π
0
π
2π

SUPERCURRENT SPECTROSCOPY





Bretheau, Girit *et al.*, Phys. Rev. X **3**, 041034 (2013)

DETECT TRANSITIONS: 3. COUPLE TO RESONATOR

1

2

3

Detect
energy absorption

Detect
Supercurrent change

cQED setup