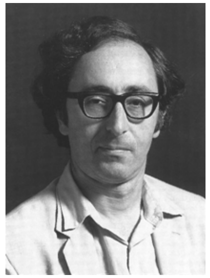
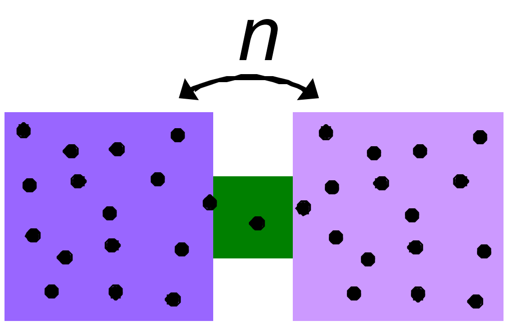
THE JOSEPHSON EFFECT

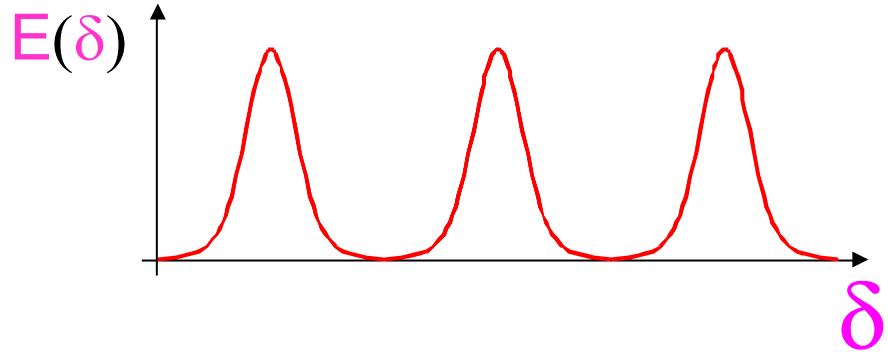


[1962]



$|\Delta| e^{i\phi_L}$ $\quad$ $|\Delta| e^{i\phi_R}$

$$\delta = \phi_L - \phi_R$$



$$\left[\hat{\delta}, \hat{n}\right] = i$$

DISSIPATIONLESS CURRENT

$$\dot{n}(\delta) = \frac{1}{\hbar}\frac{\partial E(\delta)}{\partial \delta}$$

SUPERCONDUCTORS

Smith *et al*,1960

Anderson & Rowell 1963

SUPERFLUIDS

- ^{3}He: Avenel & Varoquaux 1987
- ^{4}He: Sukhatme *et al*, 2001

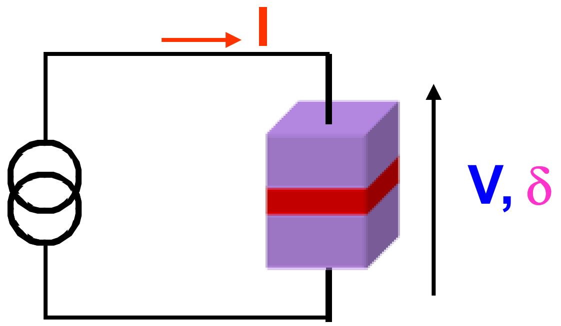
B.E.C.

Cataliotti *et al,* 2001

Albiez *et al,* 2005

Levy *et al,* 2007

THE JOSEPHSON JUNCTION



SIS Tunnel Junction

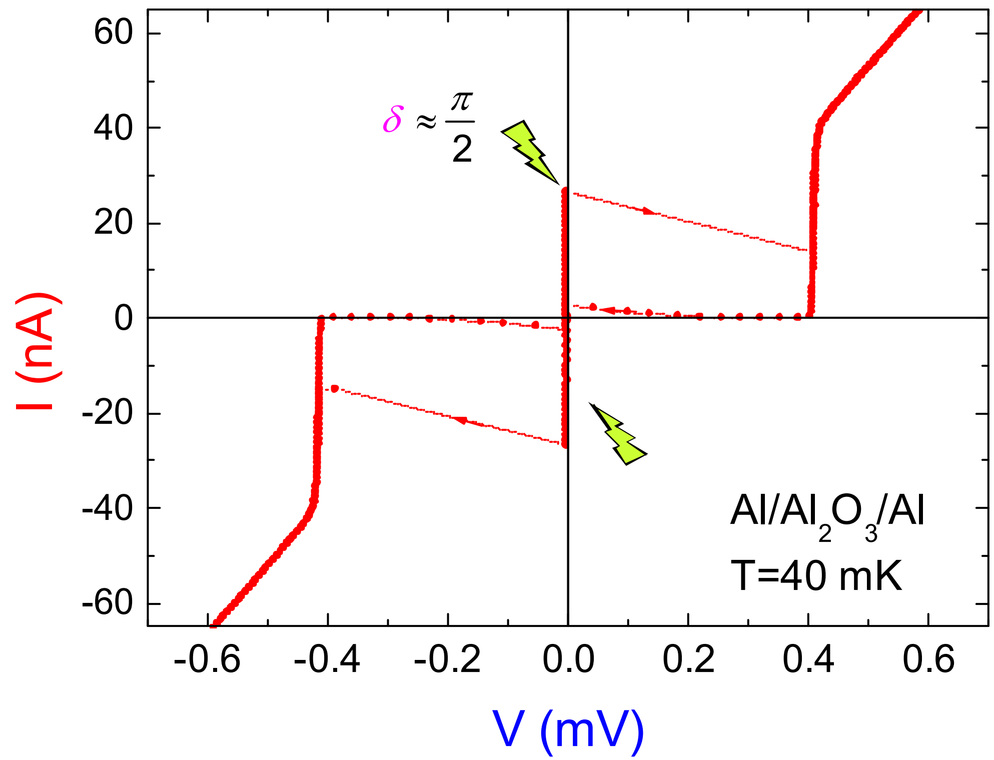
Cooper pair tunneling

$$E(\delta) = -E_J \cos\delta \qquad E_J \propto \frac{1}{R_N}$$

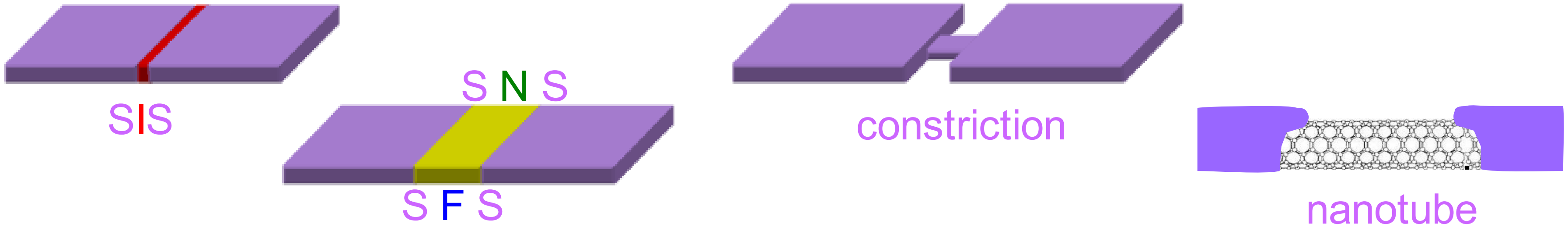
A non-linear inductor

$$V = \varphi_0 \frac{d\delta}{dt}$$

$$I = \frac{1}{\varphi_0}\frac{\partial E}{\partial \delta} = I_0 \sin\delta$$



SUPERCONDUCTING WEAK LINKS

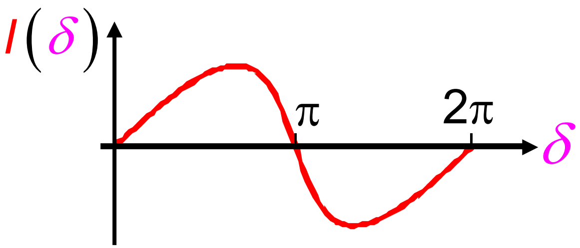


PHASE BIAS	VOLTAGE BIAS
Phase-driven supercurrent	Oscillating supercurrents

PHASE BIAS

Phase-driven supercurrent

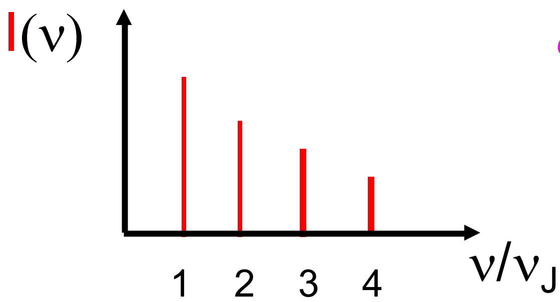
$$V = 0$$



VOLTAGE BIAS

Oscillating supercurrents

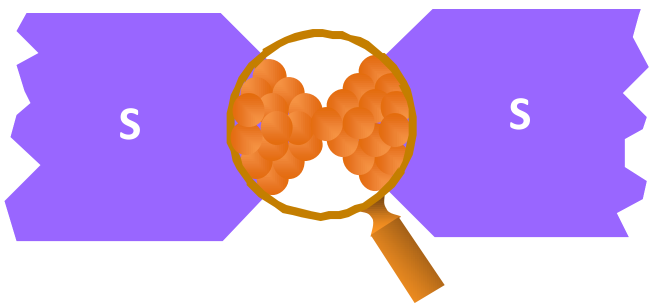
$$\dot{\delta} = V / \varphi_0$$

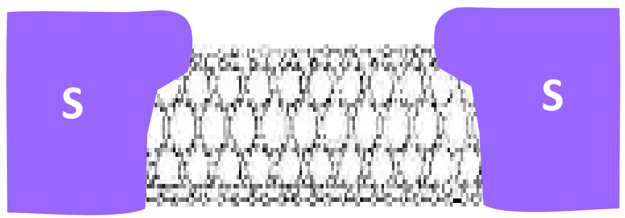


0.4835978982 GHz/μV

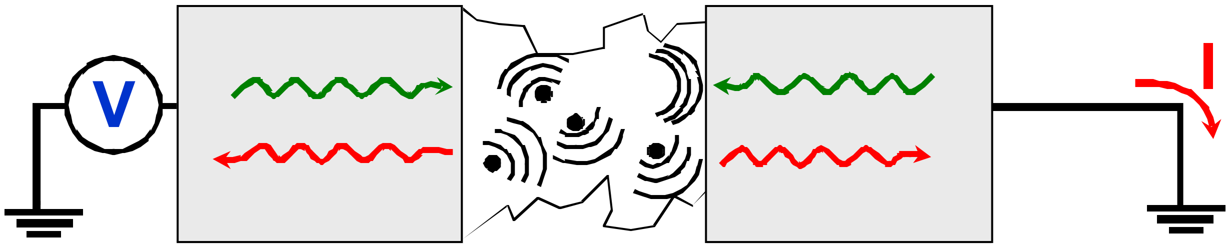
MESOSCOPIC DESCRIPTION OF THE JOSEPHSON EFFECT

Andreev Bound States





CONDUCTION CHANNELS

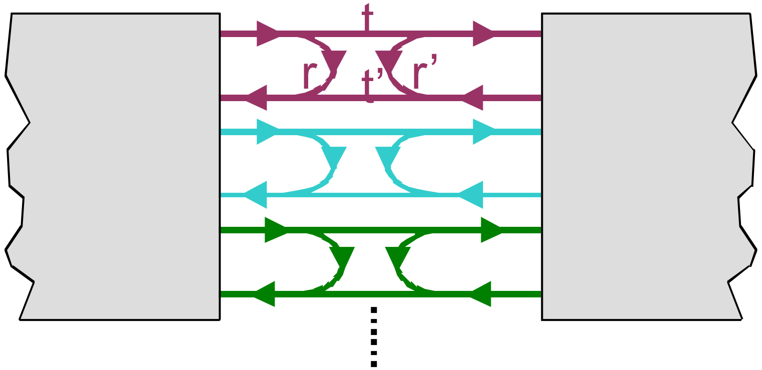


Coherent Conductor

Landauer, Büttiker, Martin

Transport as a scattering problem

Collection of independent channels



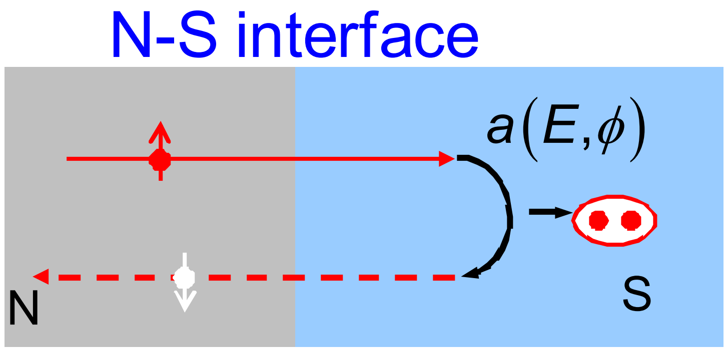
Transmission probabilities

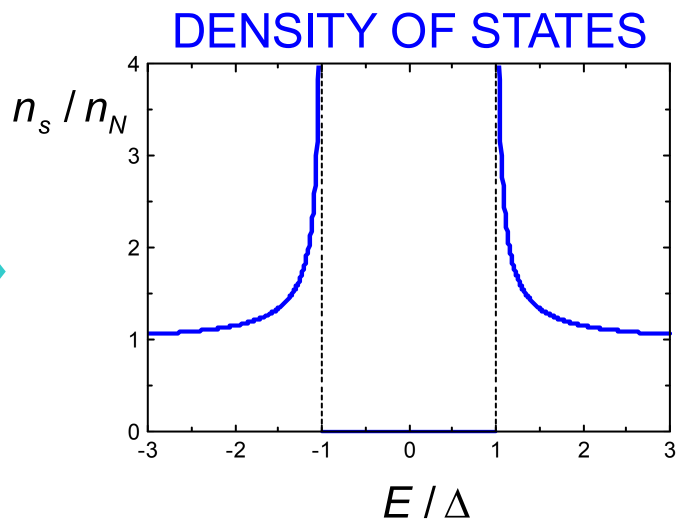
$$\{\tau_n\} = \text{Mesoscopic P.I.N.}$$

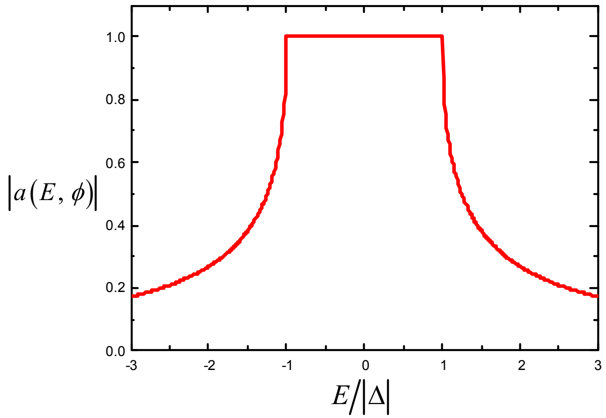
Generic transport property ➡ $F\left(\{\tau_n\},V\right)=\sum_n f_{1ch}\left(\tau_n,V\right)$

ANDREEV REFLECTION

COUPLING OF e↑ AND h↓







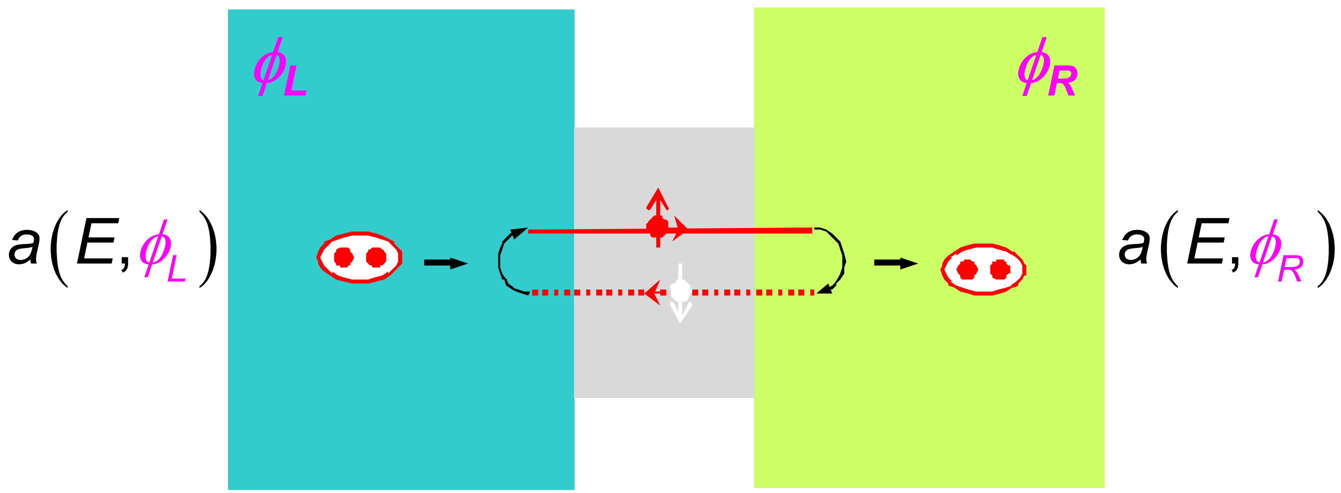
for $|E| < \Delta$ Total Andreev Reflection

$$\arg\left[a(E,\phi)\right] = \phi + \arccos\left(E/\Delta\right)$$

PHASE BIASED SHORT SINGLE CHANNEL

$L < \xi$

$\delta = \phi_L - \phi_R$

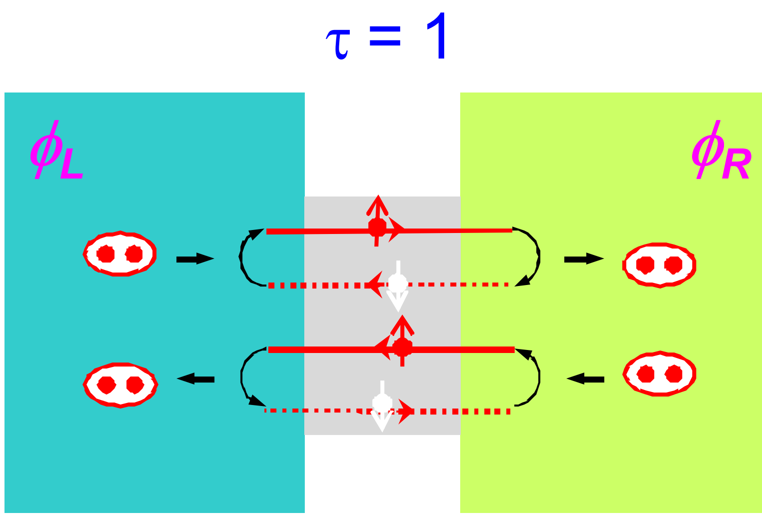


$$\arg\left[a\left(E, \phi_R\right)\right] + \arg\left[a\left(E, -\phi_L\right)\right] \equiv 0 \ [\mathrm{mod}\ 2\pi]$$

Analogous to Fabry-Pérot (with phase-conjugating perfect mirrors!)

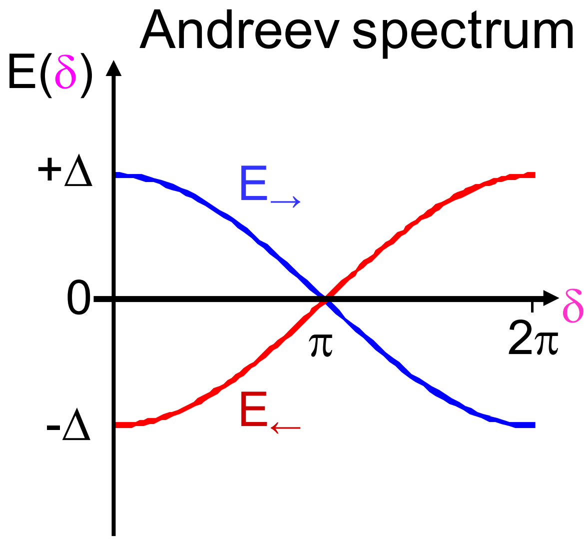
ANDREEV BOUND STATES

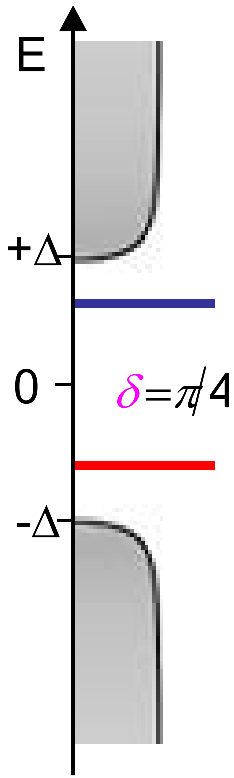
in a short ballistic channel ($\tau = 1$)



2 resonances

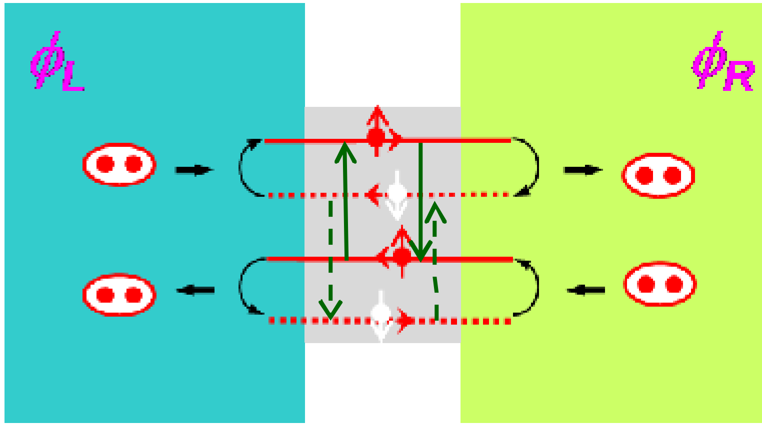
$$E_{\rightleftarrows} = \pm\Delta\cos(\delta/2)$$

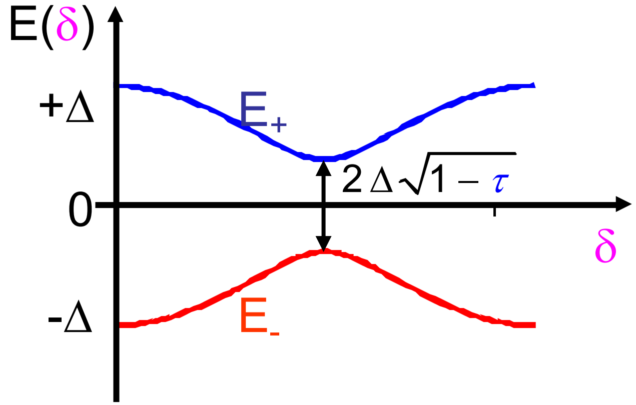




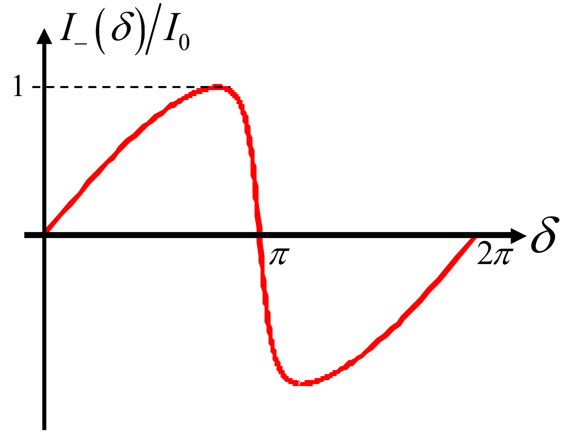
ANDREEV BOUND STATES

in a short reflective channel ($\tau < 1$)





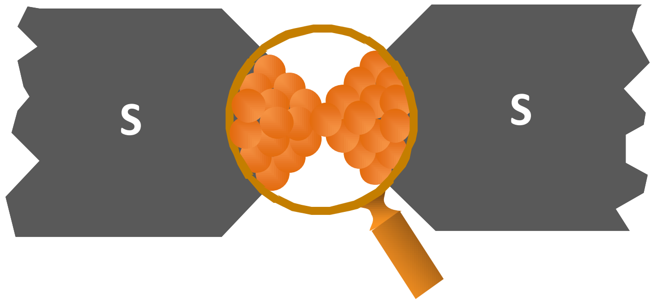
$$E_\pm = \pm\Delta\sqrt{1-\tau\sin^2(\delta/2)}$$



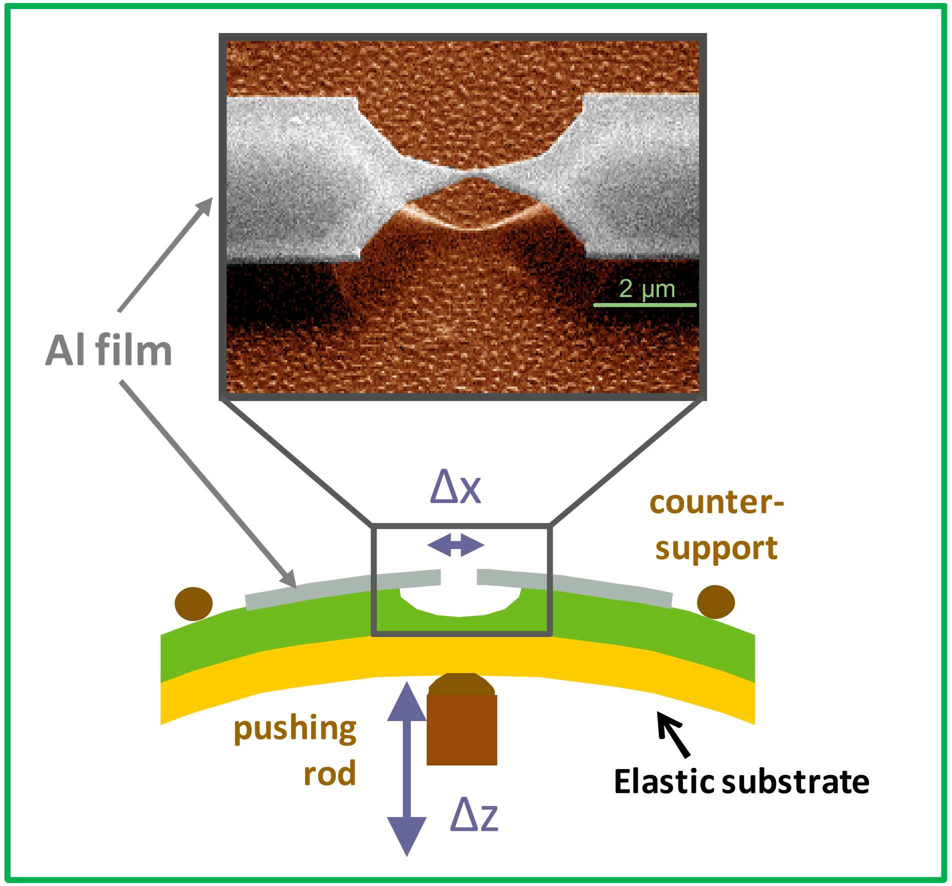
current carrying bound states

Furusaki, Tsukada (1991)
C.W.J. Beenakker

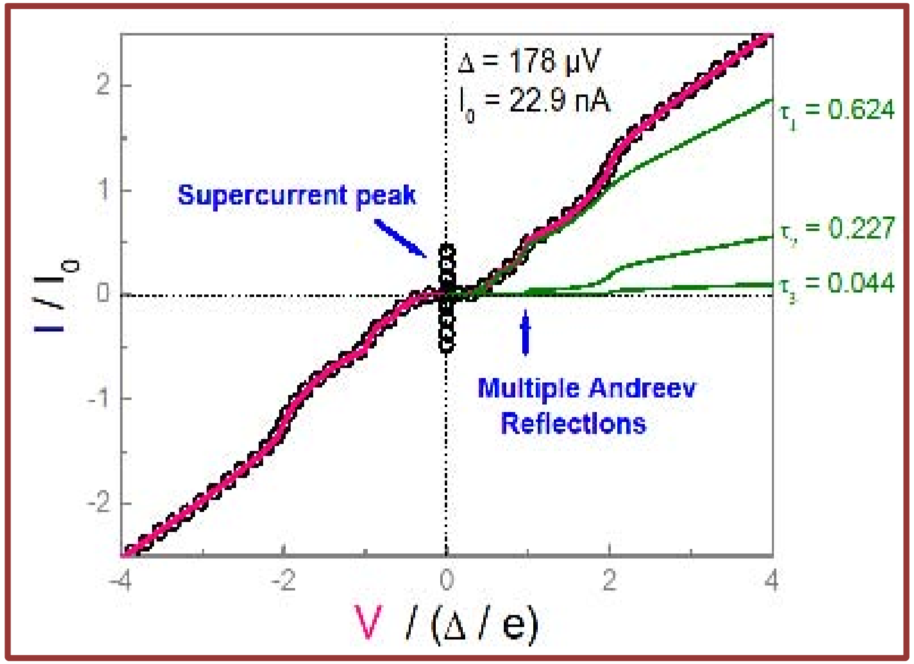
The atomic contact : a model system



System with a few tunable and measurable channels

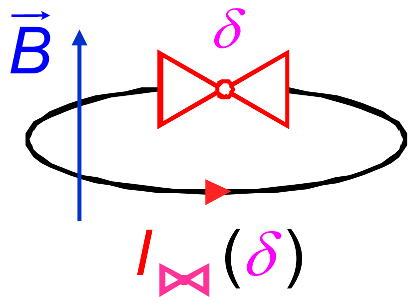


$\{\tau_i\}$ measurement



… requires voltage bias

PHASE BIASING A CONTACT

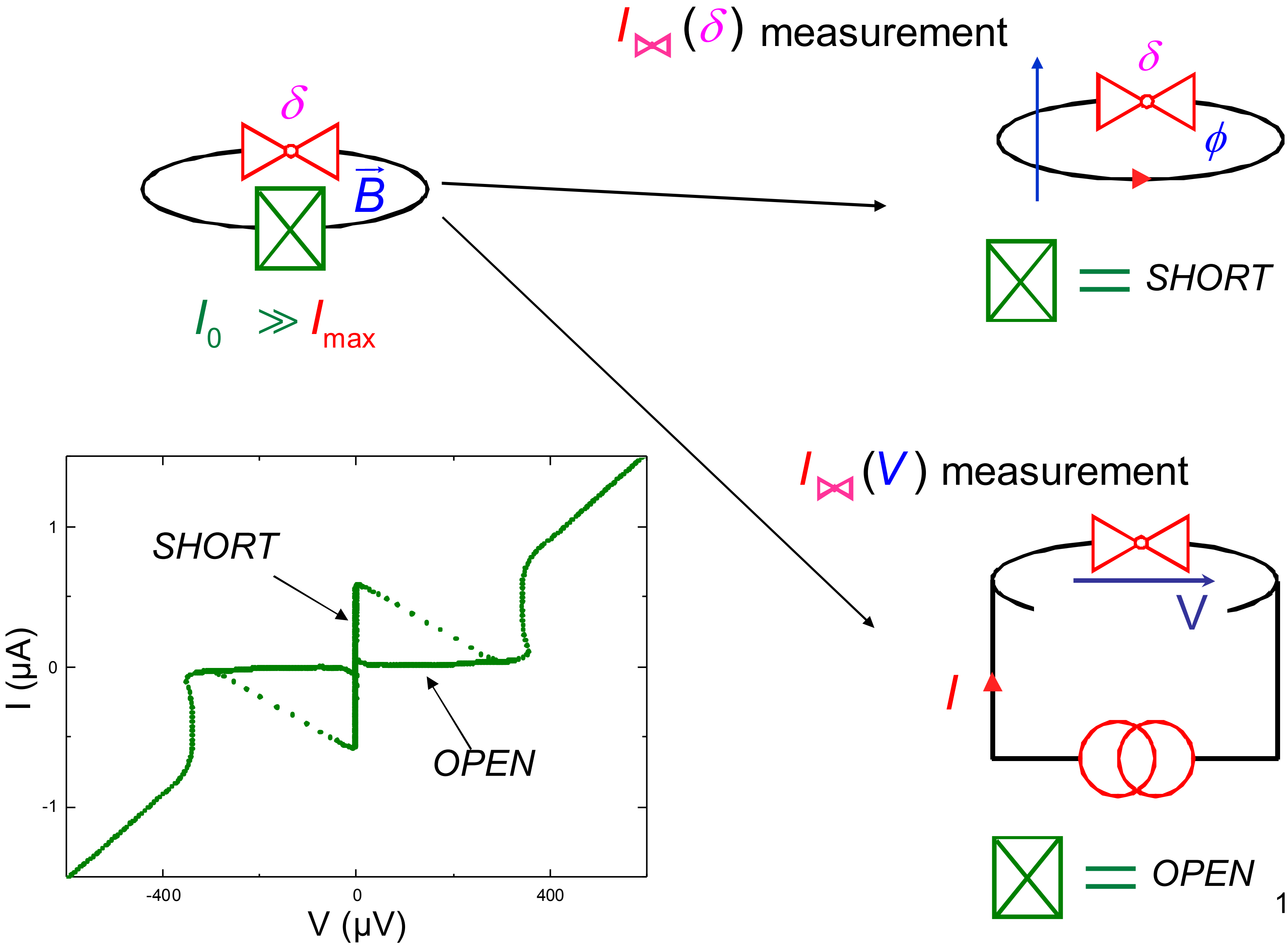


Small superconducting loop

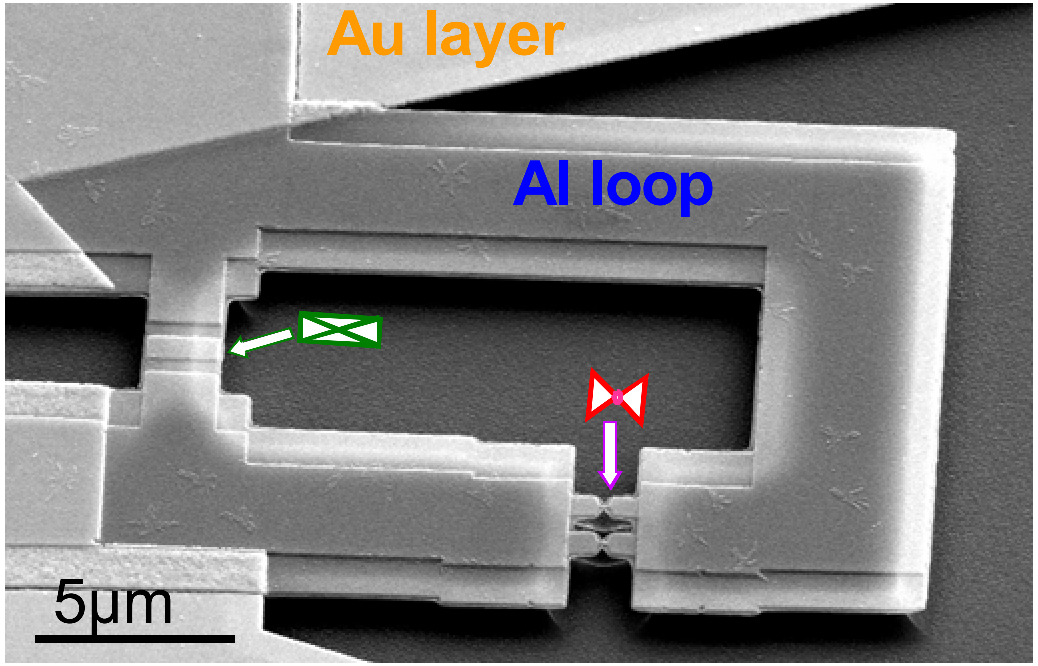
$$\delta \cong 2\pi \phi / \phi_0 = \varphi$$

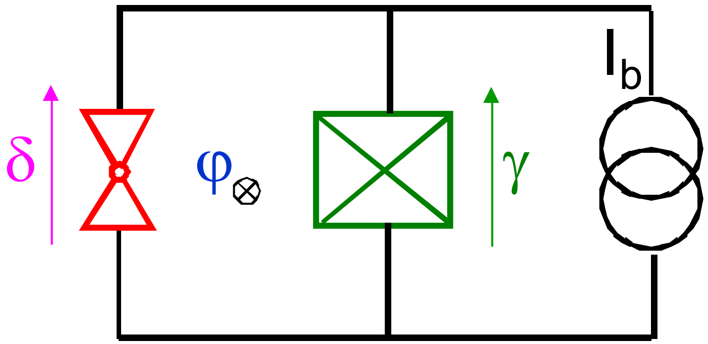
Small? $L \sim \mu_0 d \ll L_J \sim 6\text{ nH}$ ⇒ $d \leq 10\,\mu\text{m}$

A SUPERCONDUCTING REVERSIBLE SWITCH



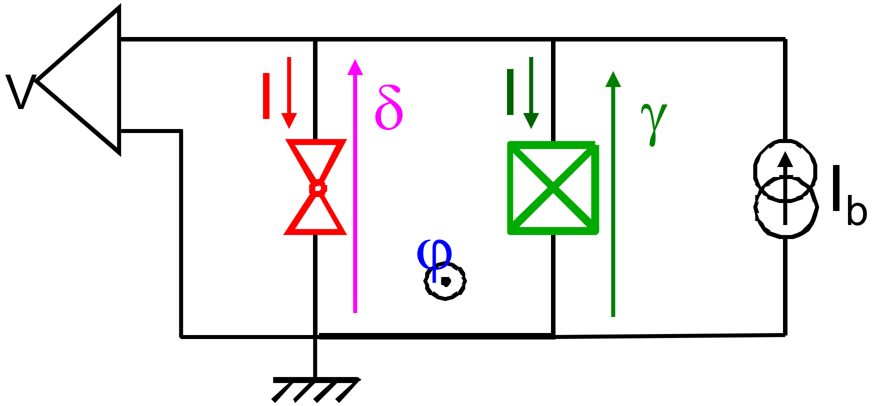
"ATOMIC SQUID"



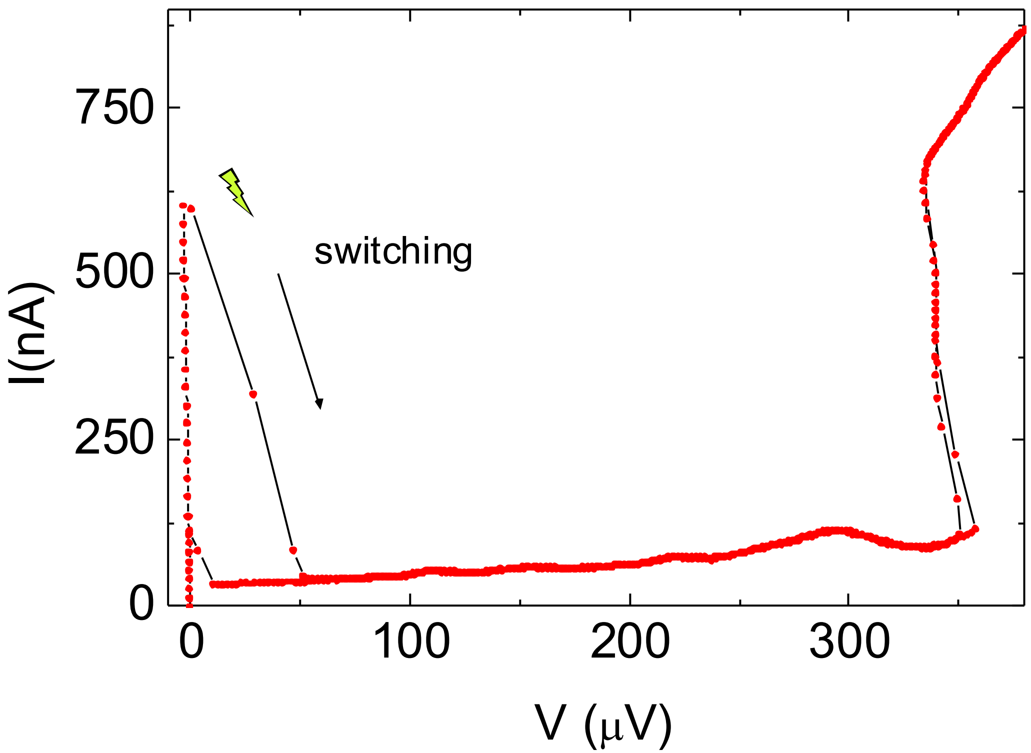


$$\delta - \gamma = \varphi$$

SWITCHING CURRENT OF SQUID



$$I_b = I(\gamma + \varphi) + I_0 \sin\gamma$$



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

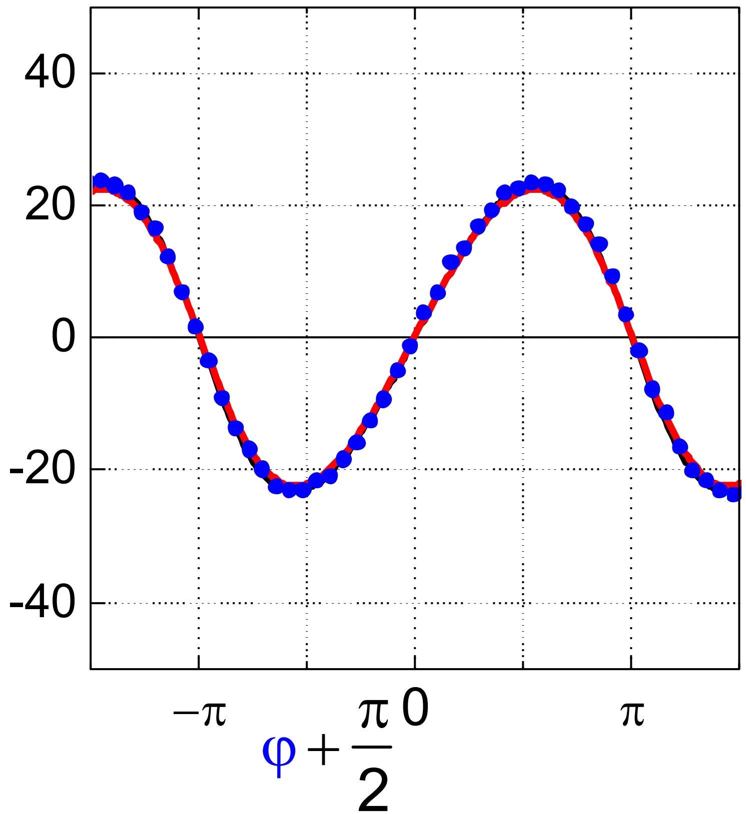
DIRECT ACCESS TO

$$I_{\bowtie}(\delta)$$

I(δ) OF ATOMIC CONTACTS

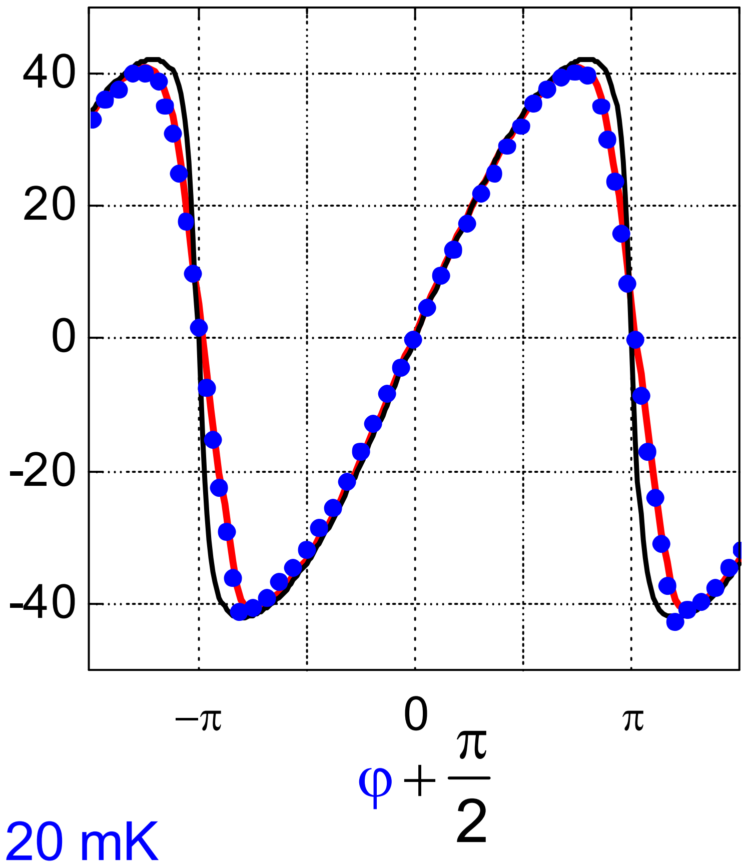
LOW TRANSMISSION

$$\{\tau_i\} = \{0.62, 0.22, 0.07\}$$



HIGH TRANSMISSION

$$\{\tau_i\} = \{0.993, 0.14\}$$



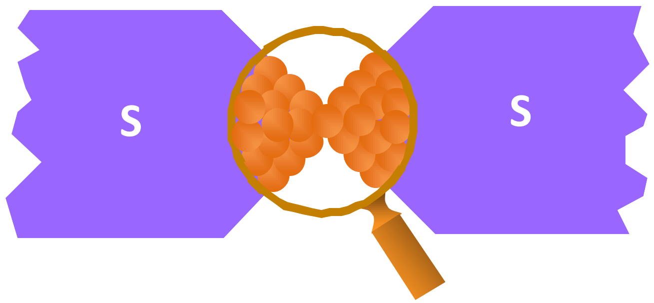
● Data @ 20 mK

— $I_{\bowtie}\left(\{\tau_i\}, \varphi + \frac{\pi}{2}\right)$

— Theory of switching

T_{eff} = 126mK

Della Rocca *et al* PRL 2007



• SUPERCURRENT THROUGH AN ATOM

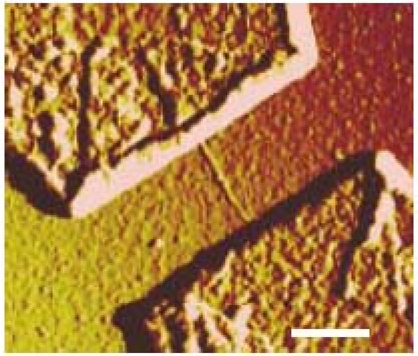
• WELL DESCRIBED BY ABS PICTURE

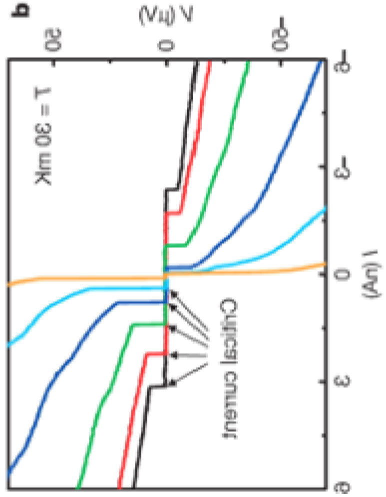
• EXPERIMENT PROBES ONLY THE GROUND STATE

• ONLY INDIRECT EVIDENCE FOR UPPER STATE, NO SPECTROSCOPY YET

SUPERCURRENTS IN CNT

S-FET

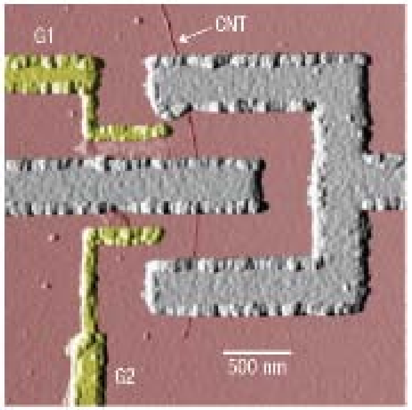


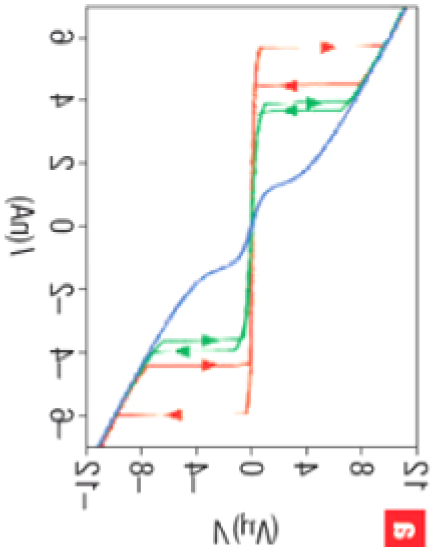


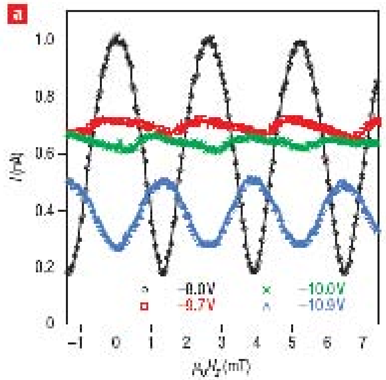
Kazumov et al. *Science (1999)*

Jarillo-Herrero et al. *Nature (2006)*

SQUID

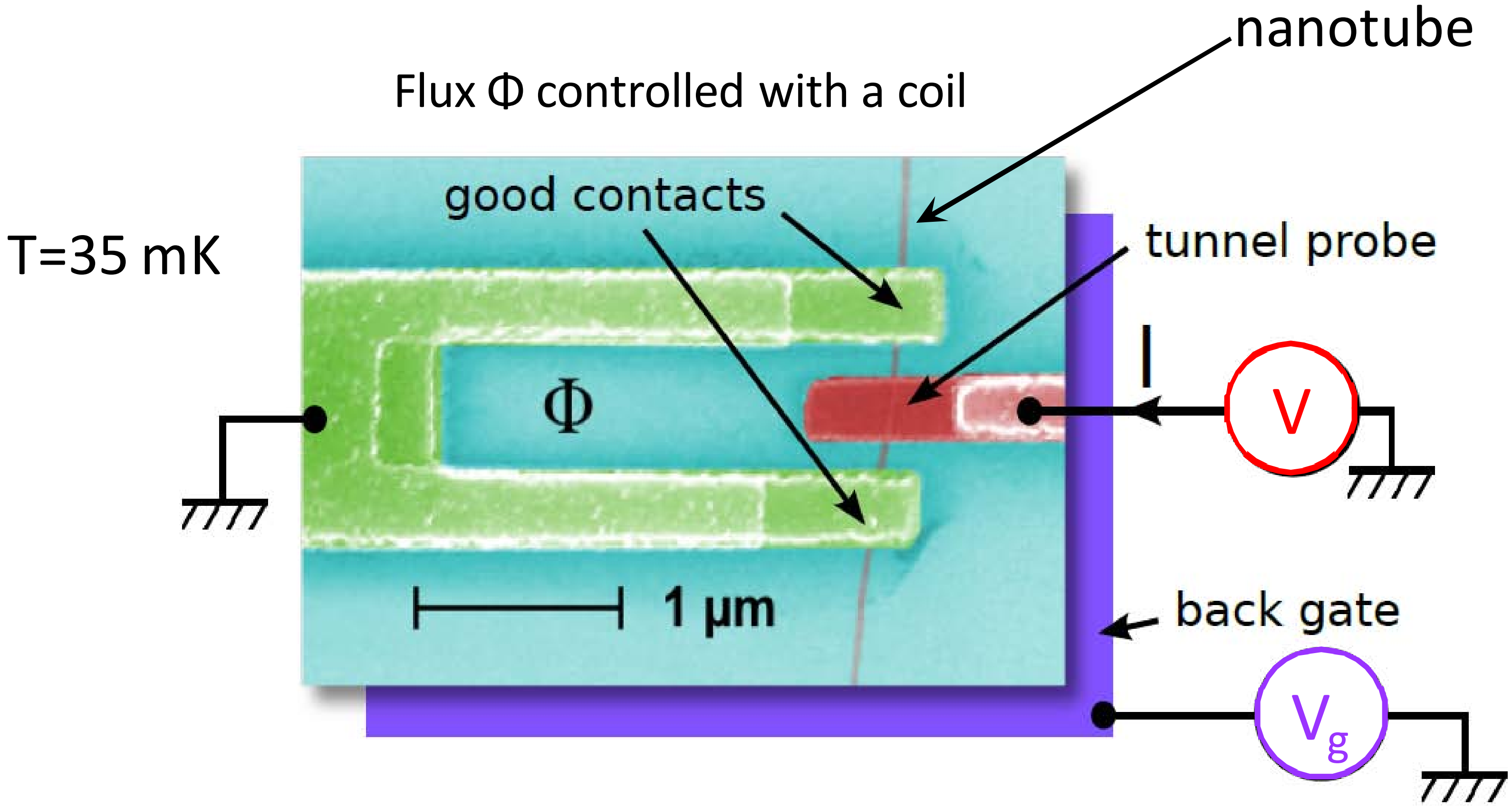






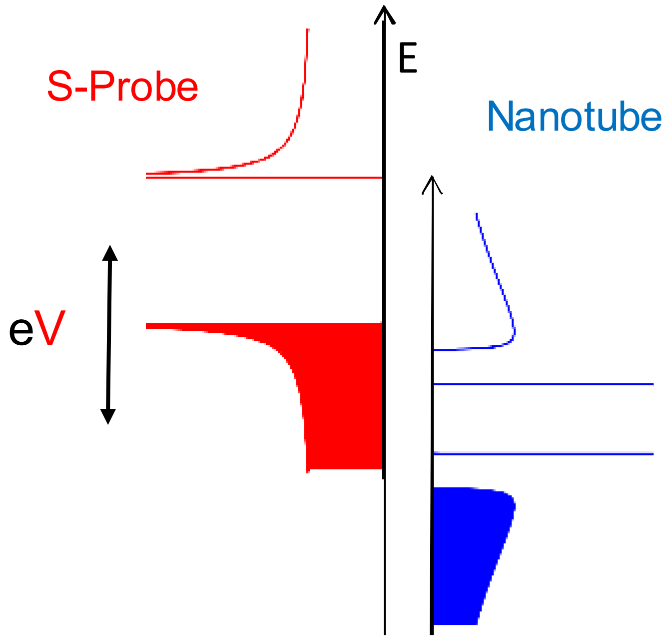
Cleuziou et al. *Nature Nano. (2006)*

SETUP FOR TUNNELING SPECTROSCOPY IN CNT



TUNNEL CURRENT

$$I(V) \propto \int \left(f_P(\varepsilon - eV) - f_{NT}(\varepsilon) \right) \rho_{NT}(\varepsilon)\, \rho_P(\varepsilon - eV)\, d\varepsilon$$

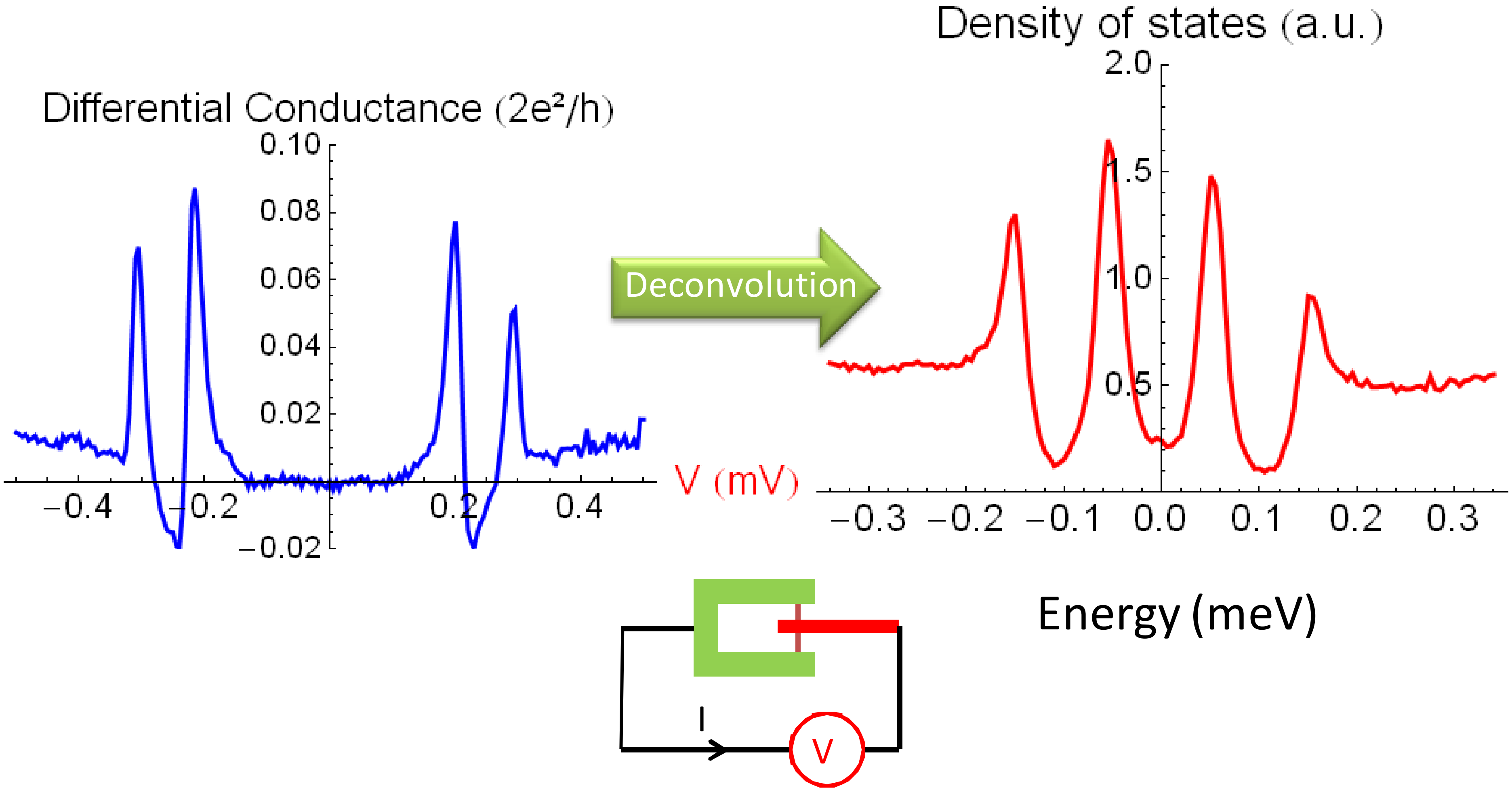


Differential conductance

$$\boxed{\frac{\partial I}{\partial V}(V) \propto g(\varepsilon, V) \otimes \rho_{NT}(\varepsilon)}$$

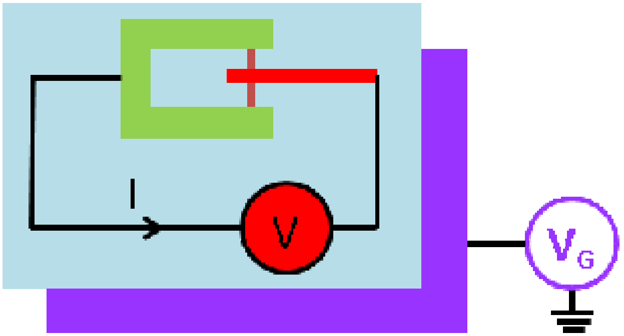
$$g(\varepsilon, V) = \left(f_{NT}(\varepsilon + eV) - f_P(\varepsilon) \right) \rho'_P(\varepsilon) - f'_P(\varepsilon)\, \rho_P(\varepsilon)$$

TUNNELING DENSITY OF STATES (TDOS)

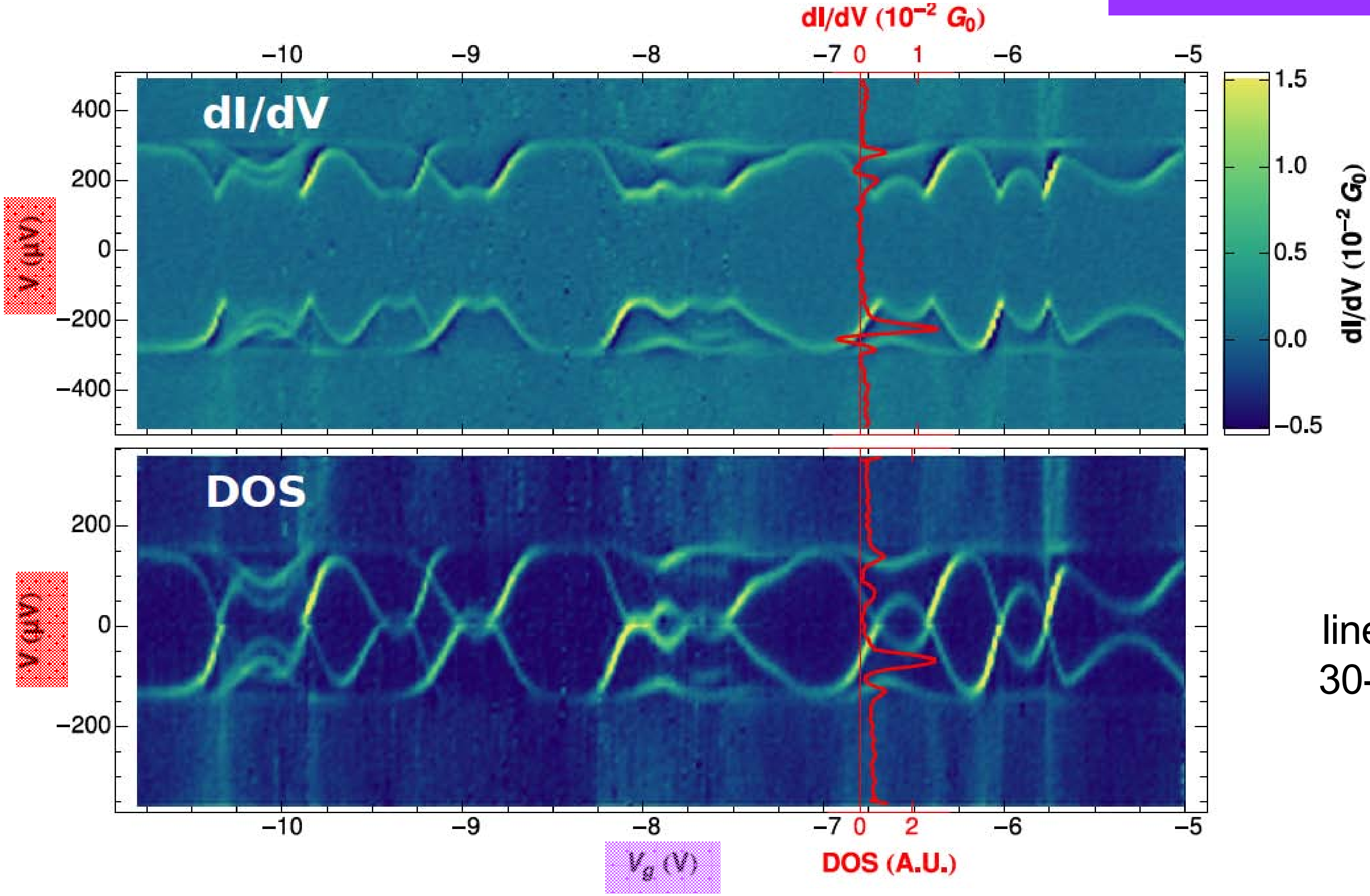


Probe DOS: BCS + small depairing ~ $\Delta/100$

TDOS GATE DEPENDENCE



@ I_{coil}= 0



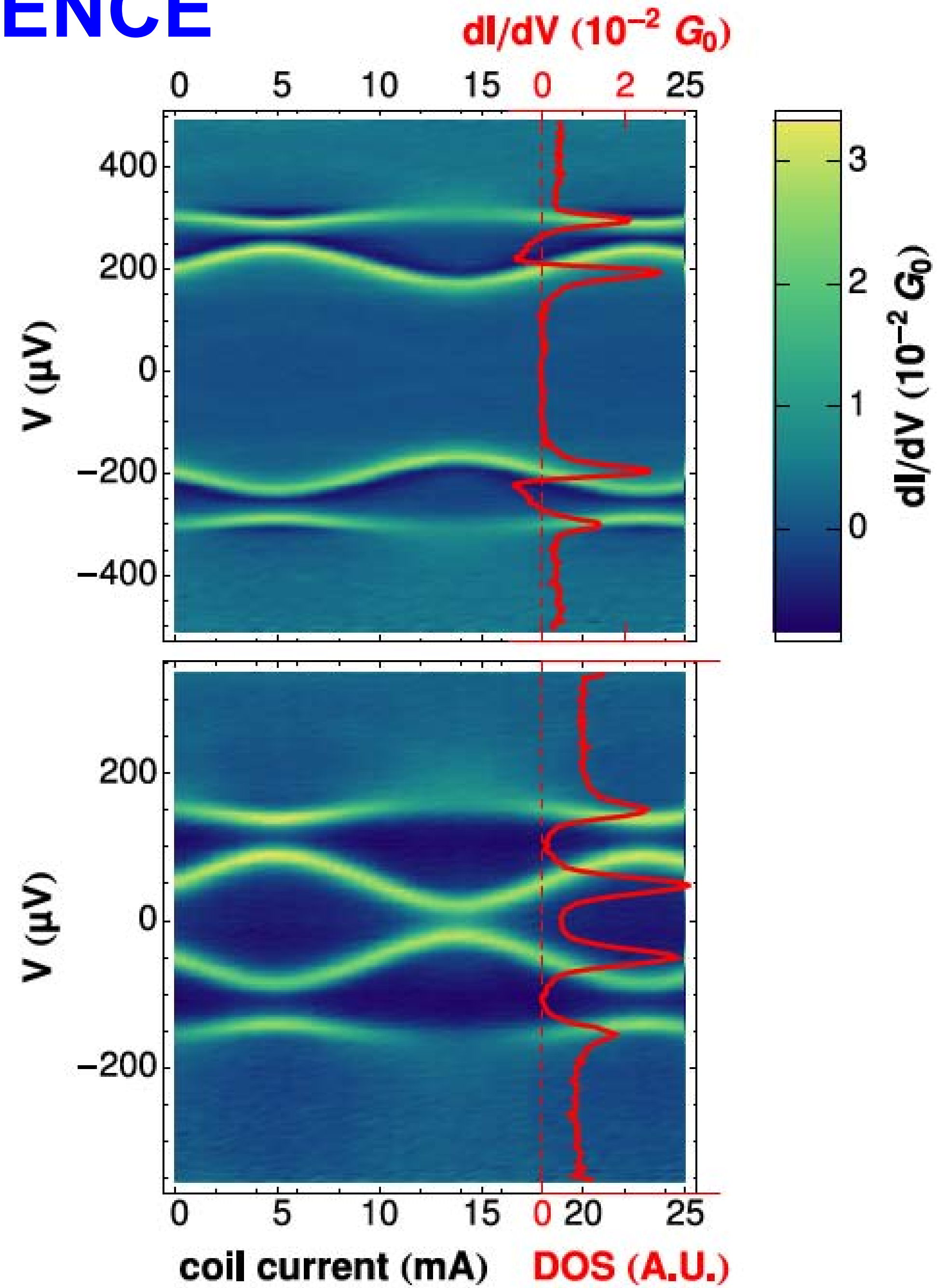
linewidth
30-40 μV

TDOS FLUX DEPENDENCE

Raw dI/dV

Deconvolved DOS

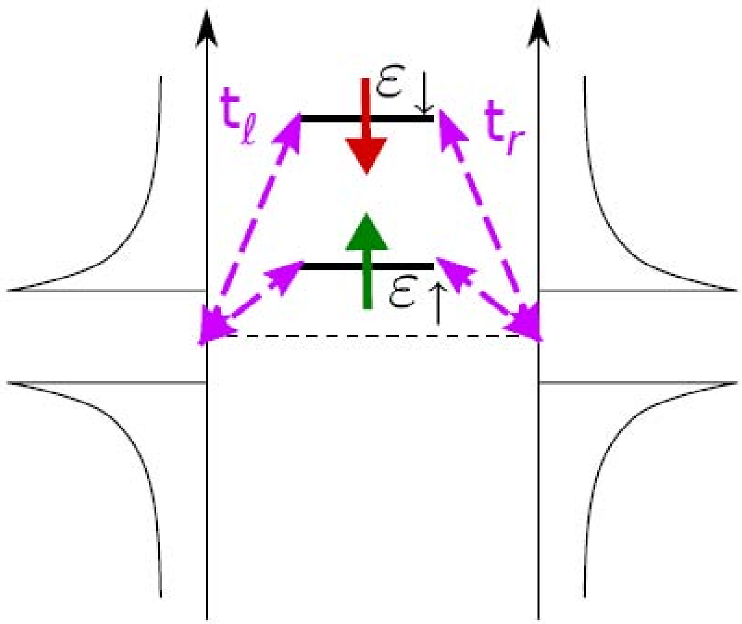
(@ Vg=-0.5V)



BASIC MODEL

Vecino, Martin-Rodero, Levy-Yeyati, PRB 2003

Quantum dot with **single** **spin-split** **level** + superconducting leads



$$H = H_L + H_{T_L} + H_{dot} + H_{T_R} + H_R$$

3 fixed parameters:

t_ℓ, t_r, splitting $(\varepsilon_\downarrow - \varepsilon_\uparrow)$

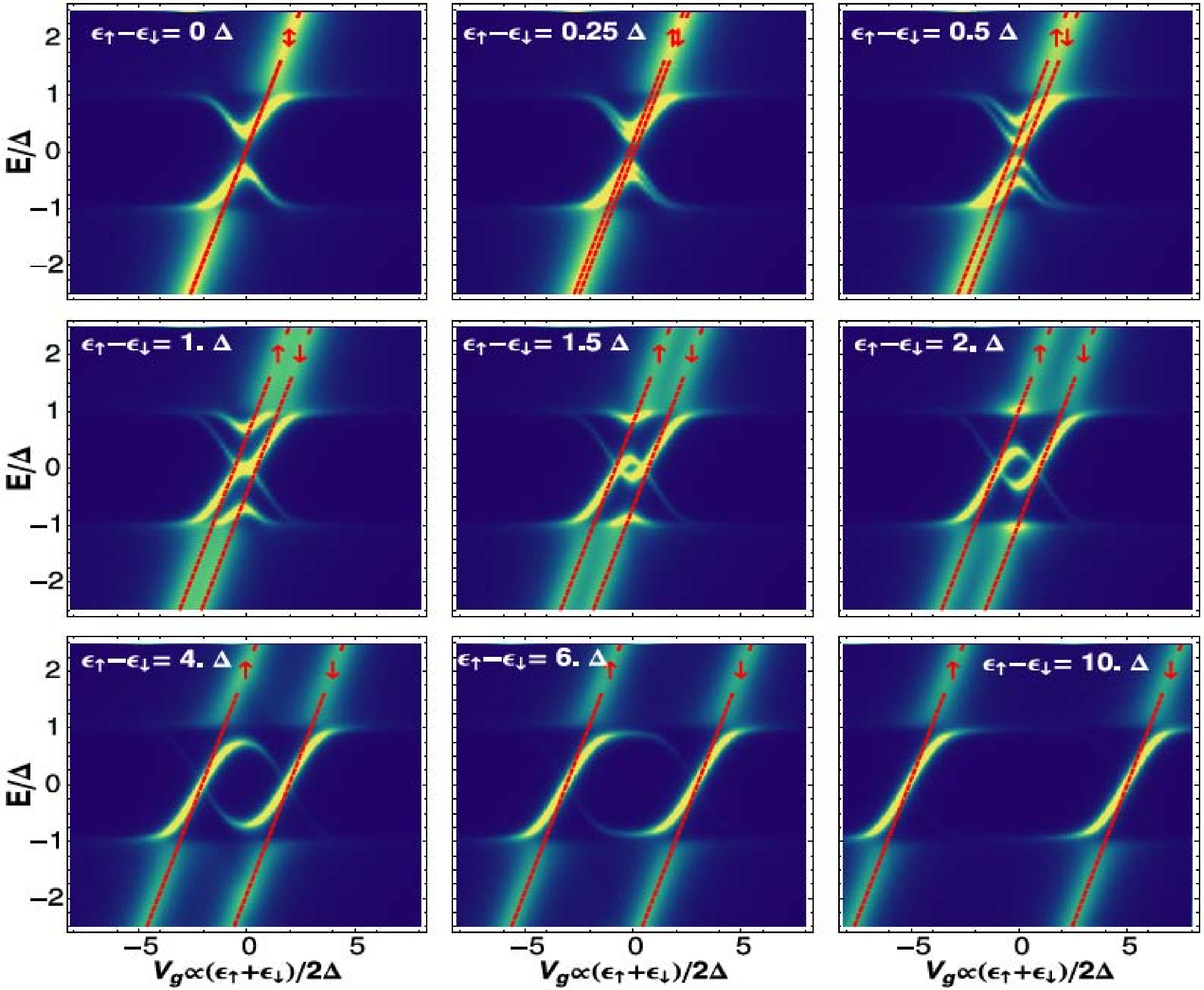
+ 2 adjustable knobs :

• mean level position ↔ Gate

$$V_G \propto (\varepsilon_\downarrow + \varepsilon_\uparrow)/2$$

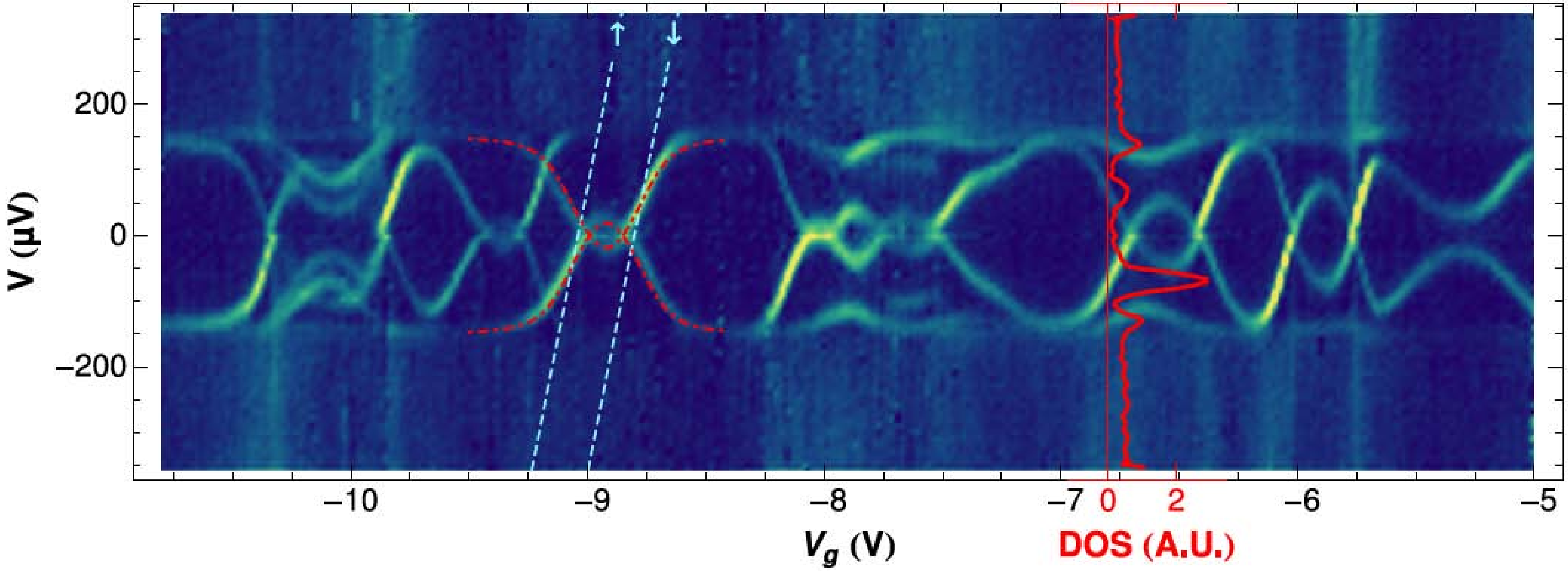
• phase difference ↔ Flux

PREDICTED DOS vs GATE AND SPLITTING



COMPARISON WITH THE DATA

depairing in electrodes ~.1Δ to get linewidth

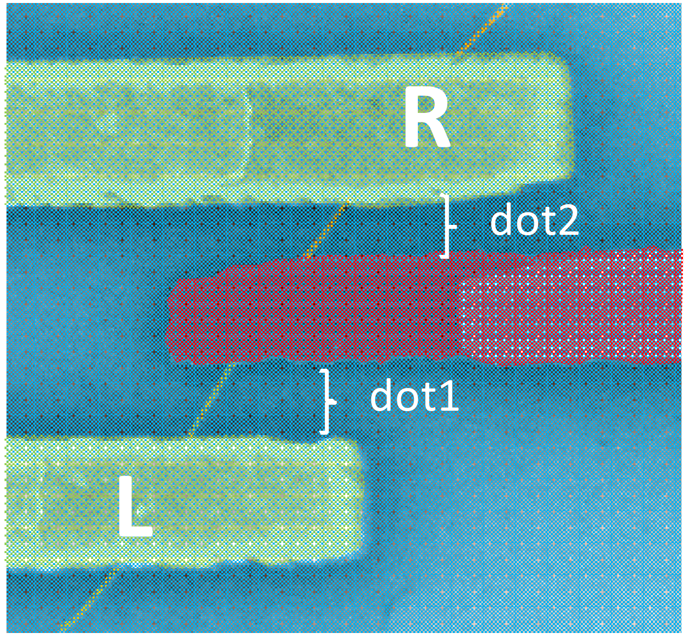


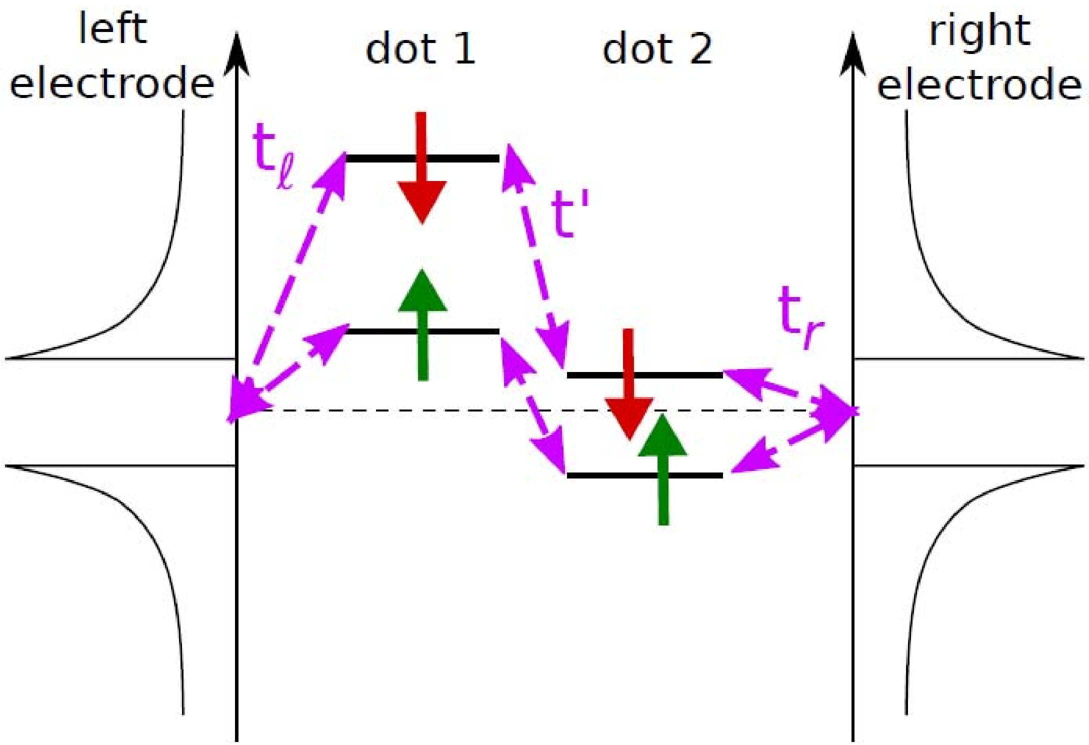
Loops : Spin-split levels

Identify states of opposite spin coupled by AR : New Spectroscopy

Some adjacent pairs coupled : Need need to enlarge model

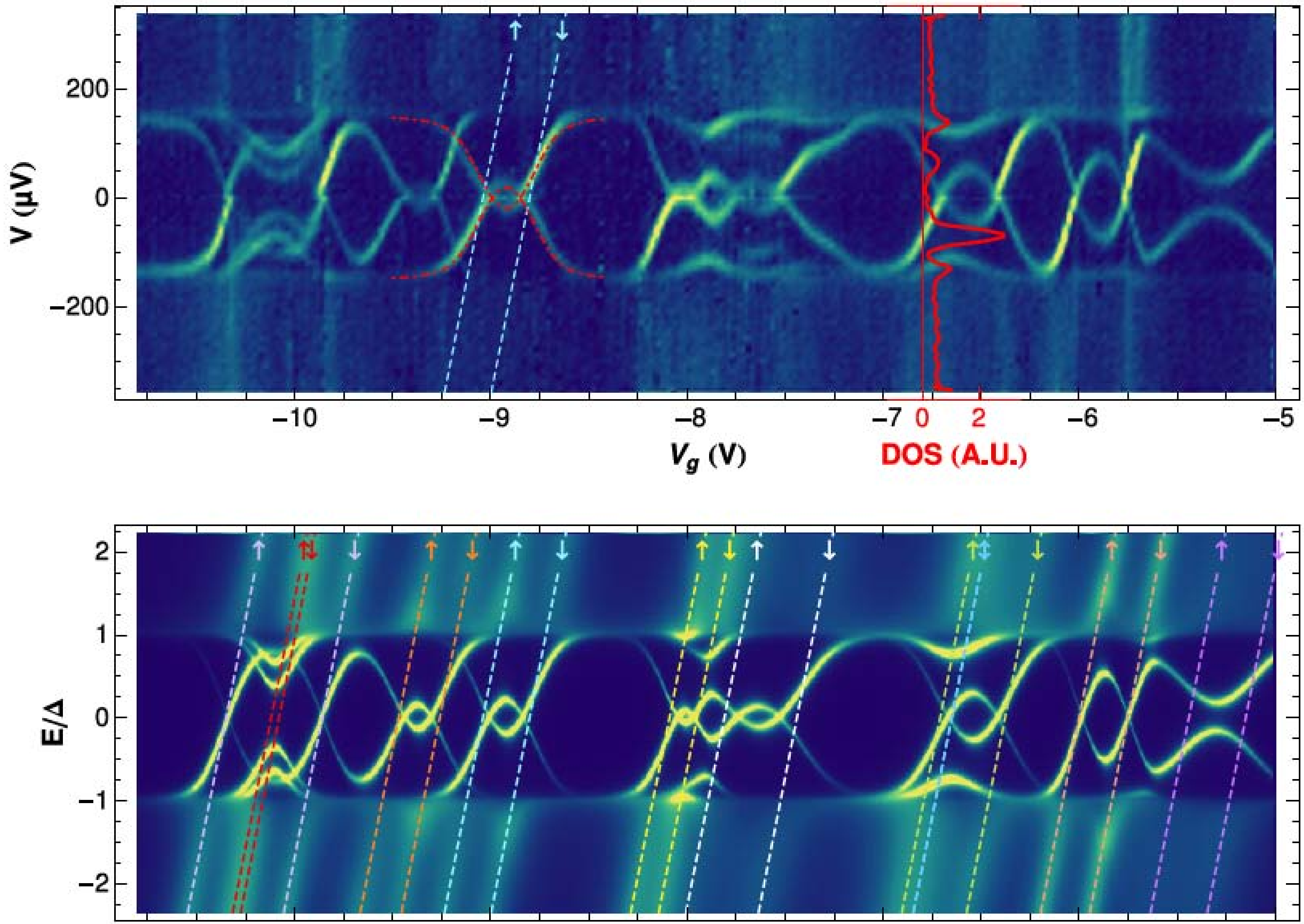
TWO DOTS MODEL



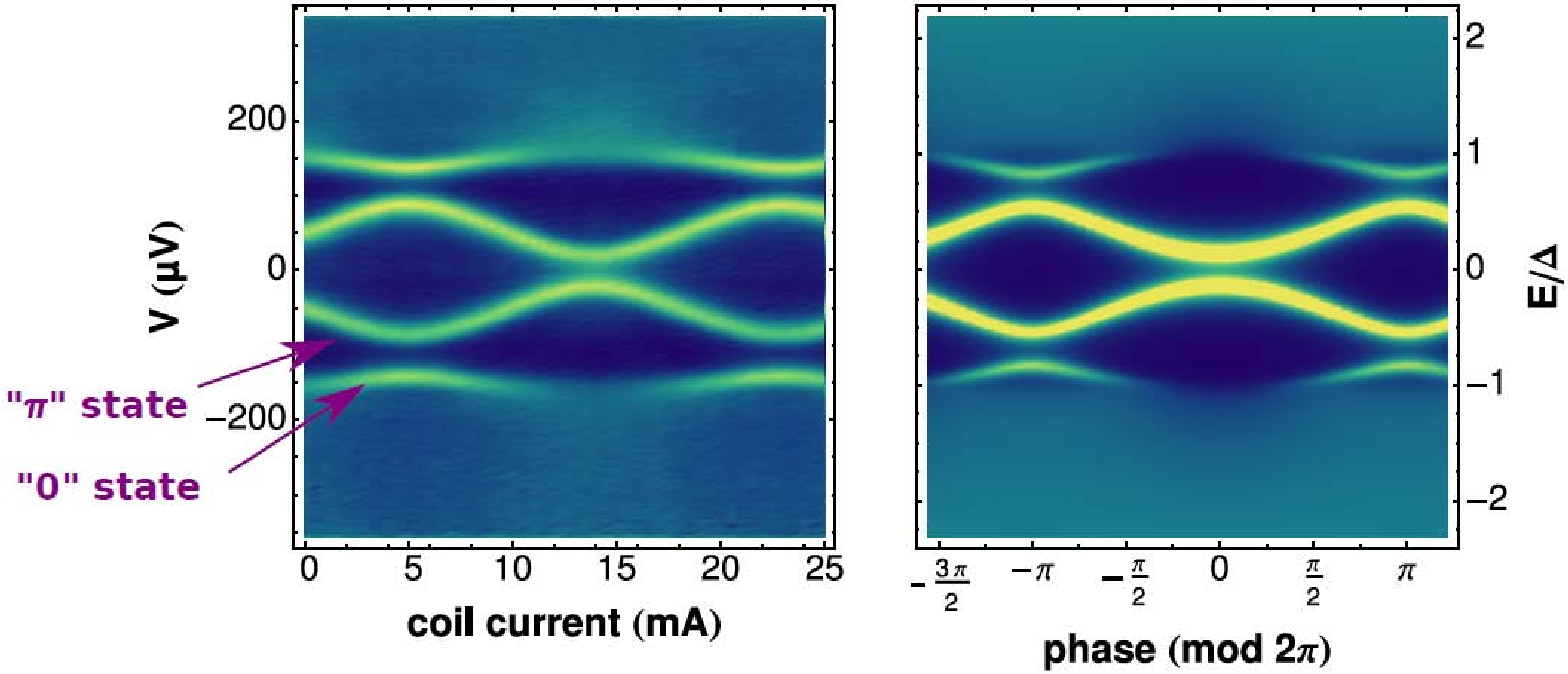


Similar to Hermann et al. PRL 2010
Mason et al. Science 2004

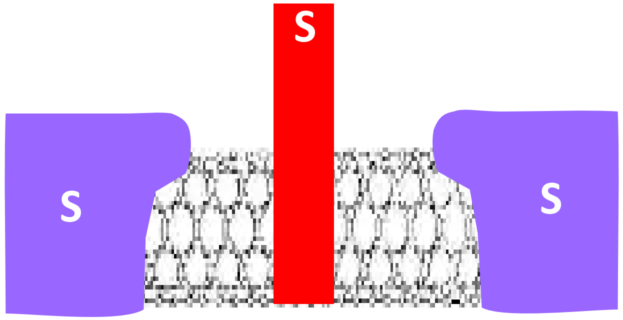
INCLUDING COUPLED PAIRS OF LEVELS



FLUX DEPENDENCE



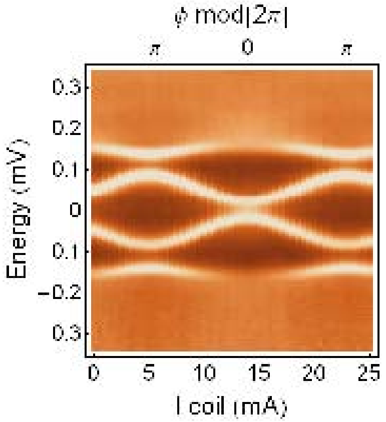
This is a π- junction

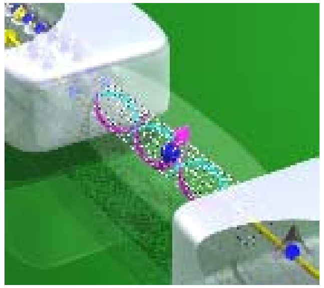


- FIRST OBSERVATION OF INDIVIDUAL ABS
- NEW SPECTROSCOPY OF WELL-COUPLED NANOTUBE:
  - MOLECULAR LEVELS PERSIST (QUANTUM DOT MODEL VALID)
  - SPIN-SPLIT LEVELS
  - SPIN RELATION BETWEEN SUCCESSIVE COUPLED LEVELS
  - ALL PARAMETERS ACCESSIBLE

PERSPECTIVES

POTENTIAL APPLICATIONS
- MAGNETOMETER
- SUPERCONDUCTING FET





T. Delattre *et al*
Nature Physics 2009

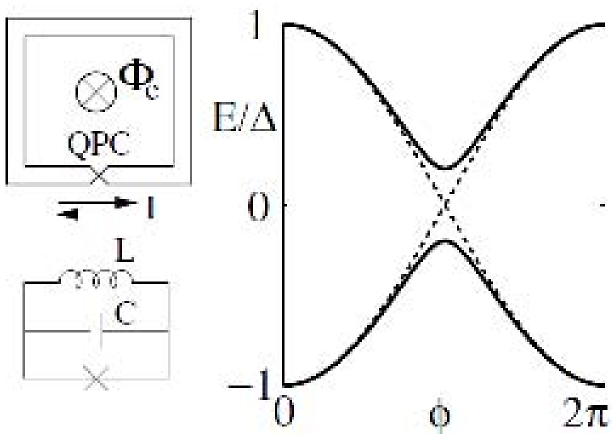
EXPLORE:

- TRANSITION FROM FABRY-PEROT TO COULOMB BLOCKADE REGIMES

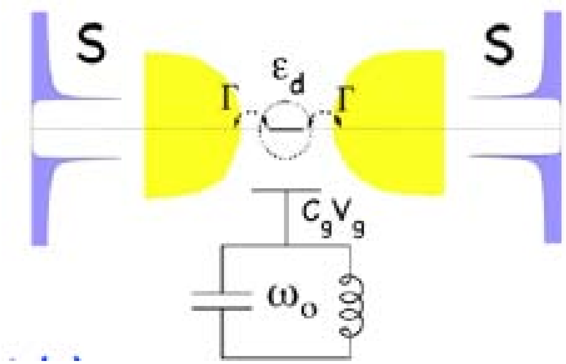
- COMPETITION BETWEEN KONDO EFFECT AND SUPERCONDUCTIVITY

- QUBIT ?

- MICROWAVE SPECTROSCOPY



Zazunov et al, PRL 2003



Sköldberg et al, PRL 2008

Quantronics Group, CEA-Saclay

P. BERTET	**ATOMIC CONTACTS**	
D. ESTEVE		**CNT**
M. GOFFMAN	M. CHAUVIN	
P. JOYEZ	B. HUARD	J.D. PILLET
P. F. ORFILA	Q. LE MASNE	C. H. L. QUAY
H. POTHIER	M. L. DELLA ROCCA	
P. SENAT		
C. URBINA	L. BRETHEAU	
D. VION	M. ZGIRSKI	

Theory collaborators

UAM, Spain

A. LEVY YEYATI

LPS, Orsay & IPhT, Saclay

C. BENA