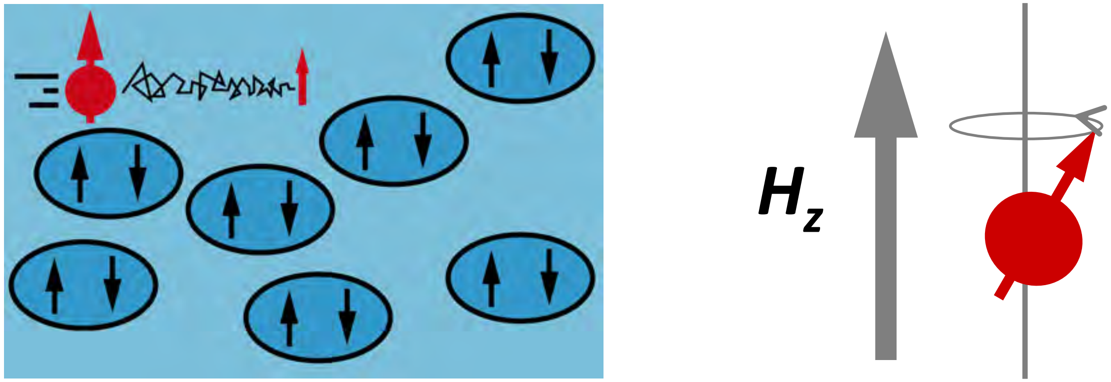
Spin dymanics in out-of-equilibrium superconductors



Charis Quay Huei Li

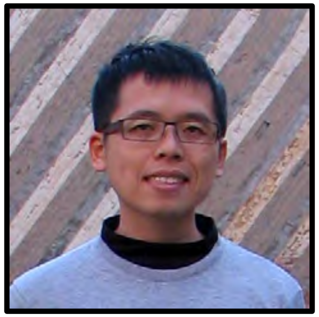
Laboratoire de Physique des Solides

Université Paris-Sud

SPICE – Mainz – 25-28 September 2017

Collaborators


Marko
Kuzmanović
presenting poster


Bi-Yi Wu
(National Taiwan)


Maximilian
Weideneder


Marco Aprili

Denis Chevallier, Mircea Trif, Clément Dutre ou,
Yann Chiffaudel, Baptiste Jost, Cristina Bena
Christoph Strunk (Regensburg)…


Freek Massee
presenting poster on STM noise measurements

Funding

Agence Nationale de la Recherche
ANR

cnrs
dépasser les frontières

erc
European Research Council

NanoSciences
ILE-DE-FRANCE

Spin physics in out-of-equilibrium superconductors

- Spinful excitations in superconductors

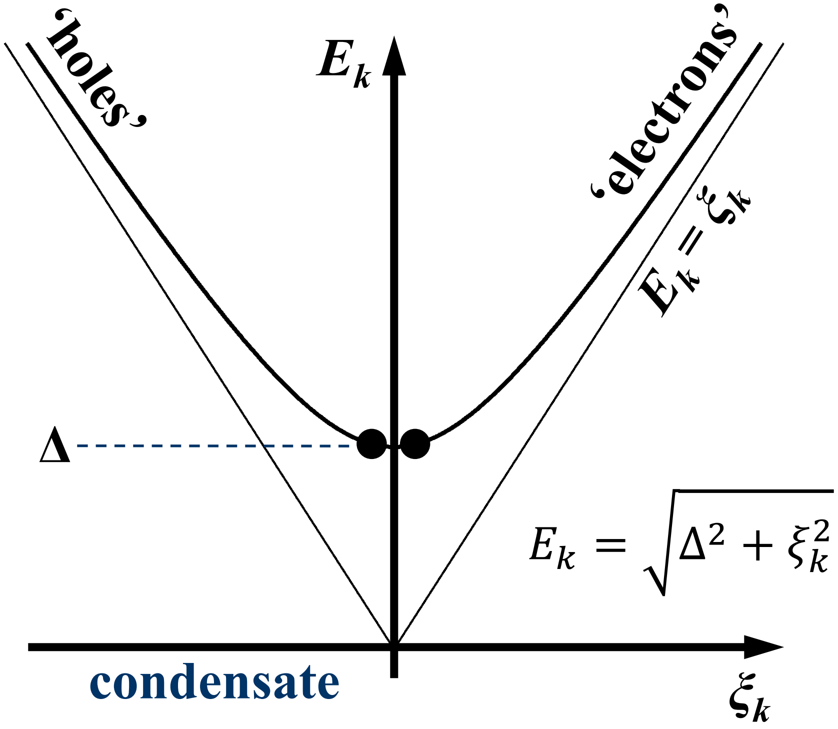
‘STATICS’ (intro)

- Quasiparticle spin resonance
- Spin-dependent recombination dynamics (ongoing work)

DYNAMICS

Excitations in Superconductors

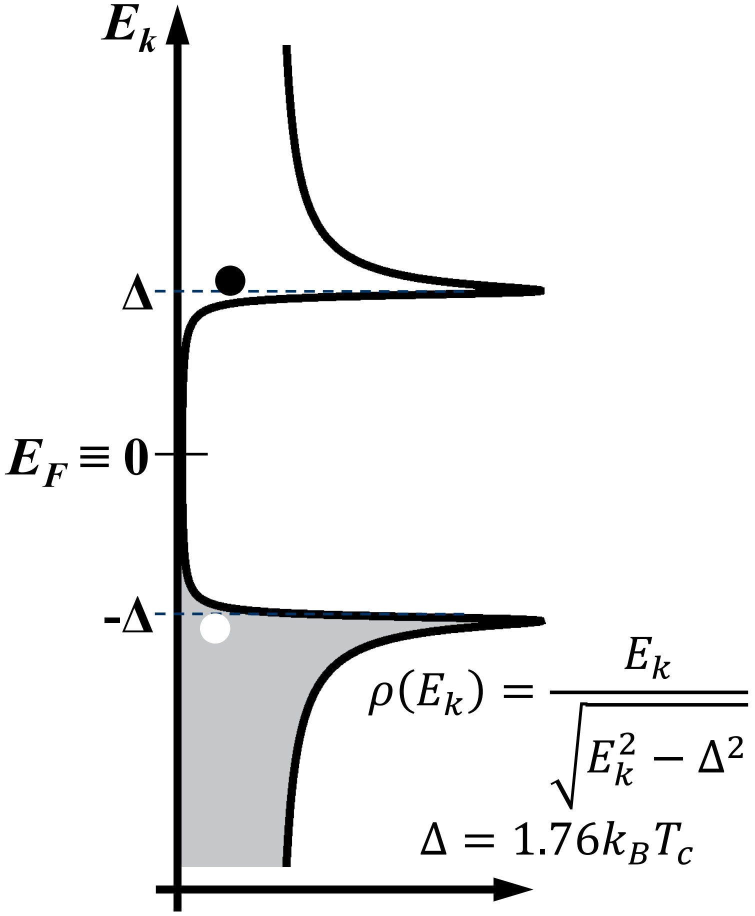
excitation (quasiparticle) spectrum in superconductors



$$E_k = \sqrt{\Delta^2 + \xi_k^2}$$

ξ_k – normal state energy

E_k – superconducting state energy



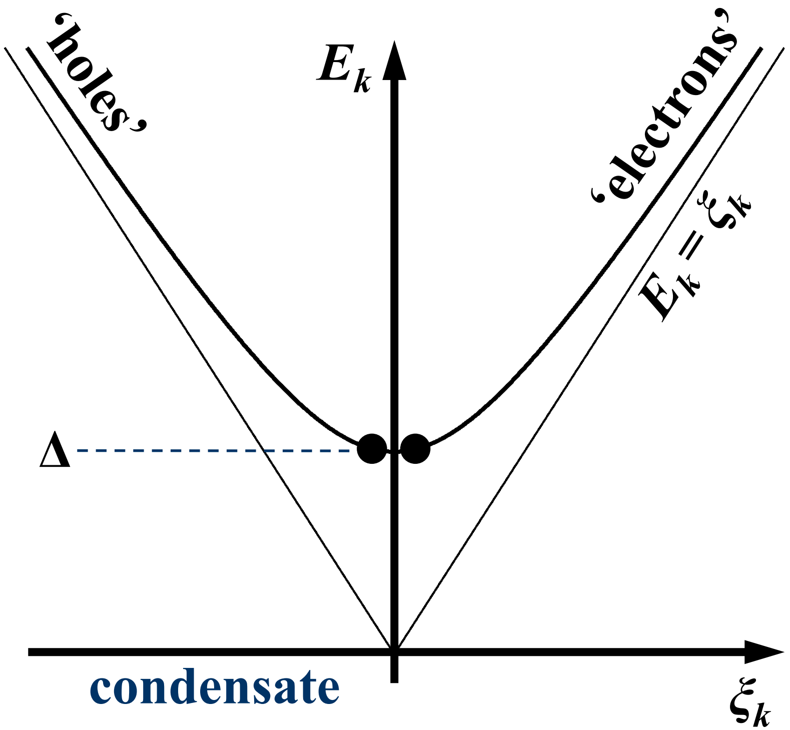
$$\rho(E_k) = \frac{E_k}{\sqrt{E_k^2 - \Delta^2}}$$

$$\Delta = 1.76 k_B T_c$$

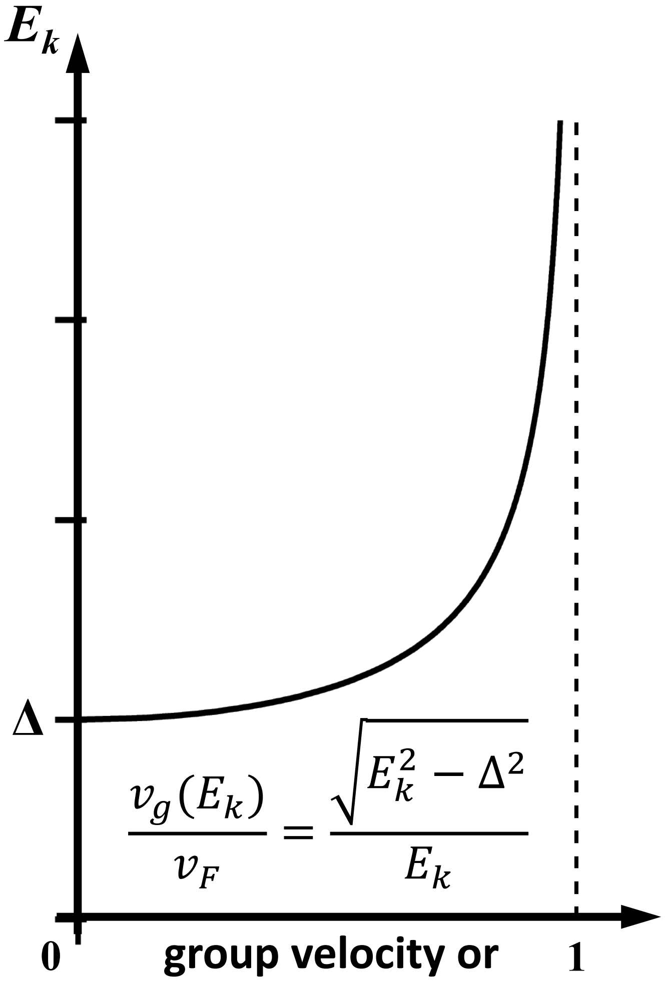
density of states for quasiparticles (= excitations)

Quasiparticle Diffusion

excitation (quasiparticle) spectrum in superconductors



ξ_k – normal state energy
E_k – superconducting state energy



$$\frac{v_g(E_k)}{v_F} = \frac{\sqrt{E_k^2 - \Delta^2}}{E_k}$$

Quasiparticles ↔ Condensate

spinful qp distribution function

$$\frac{2}{V} = \sum_k \frac{1 - f_{k\uparrow} - f_{k\downarrow}}{E_k} = \sum_k \frac{1 - f_{k\uparrow} - f_{k\downarrow}}{\sqrt{\Delta^2 + \xi_k^2}}$$

BCS interaction strength

qp energy

gap energy

electron energy

alternative formulation

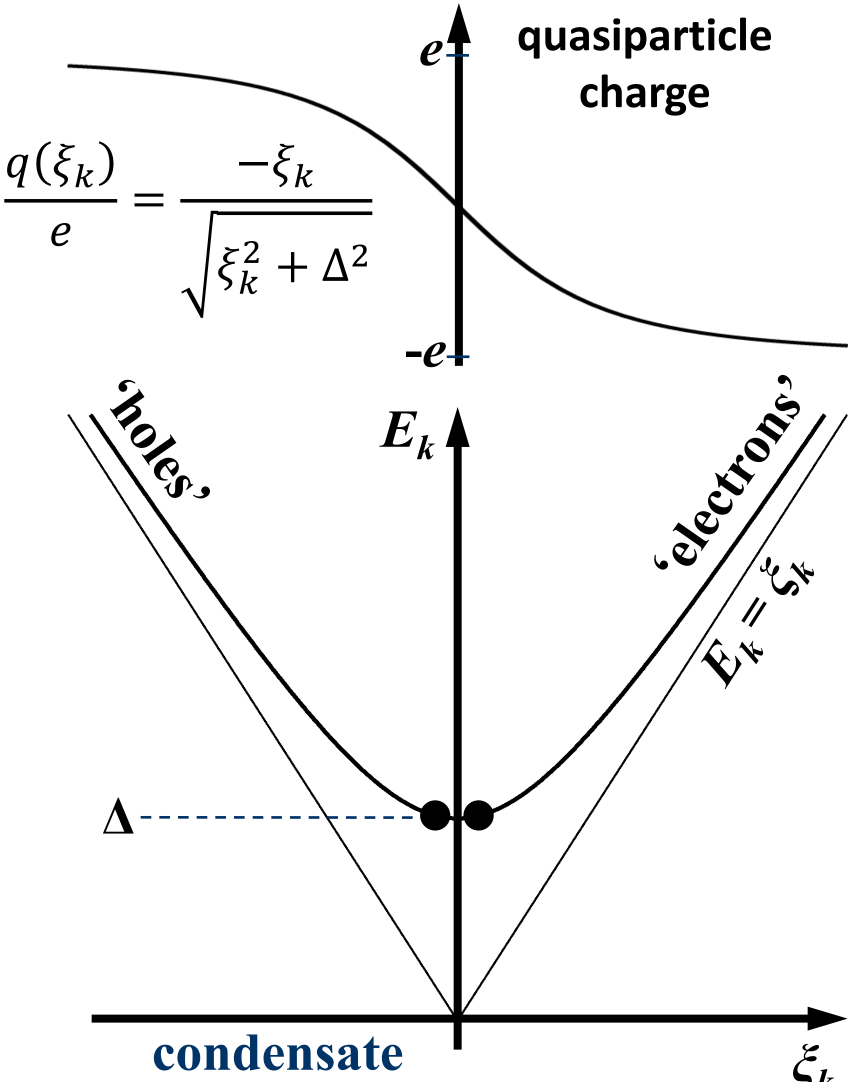
$$\ln\left(\frac{\Delta}{\Delta_0}\right) = \sum_k \frac{f_{k\uparrow} + f_{k\downarrow}}{\sqrt{\Delta^2 + \xi_k^2}}$$

zero temperature, small N_{QP}…

$$\frac{\Delta}{\Delta_0} \sim \left(1 - \frac{2N_{QP}}{N_{CP}}\right)$$

Z. Zheng *et al.*, PRB **62**, 14326 (2000) / C. S. Owen & D. J. Scalapino, PRL **28**, 1559 (1972)

Quasiparticle Charge

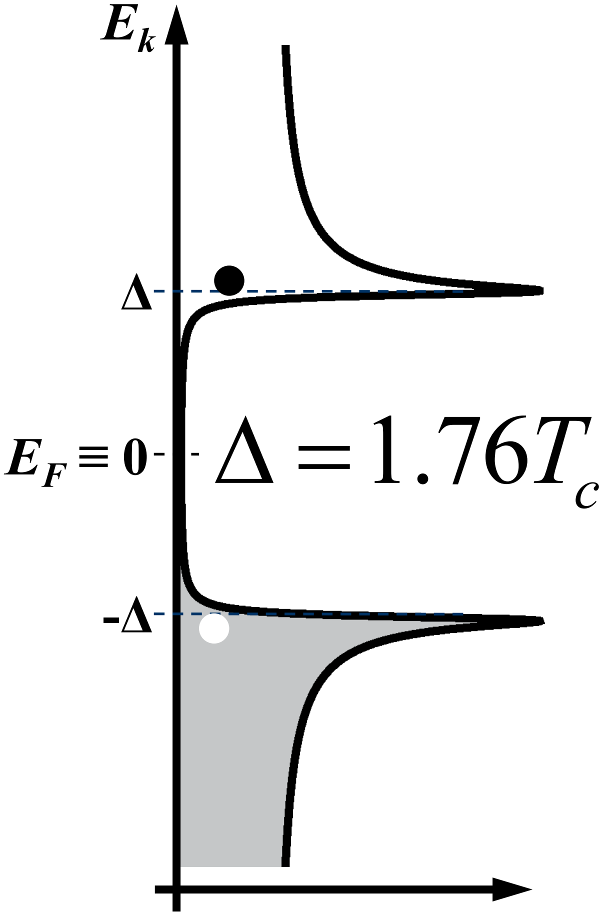


quasiparticle charge

$$\frac{q(\xi_k)}{e} = \frac{-\xi_k}{\sqrt{\xi_k^2 + \Delta^2}}$$

condensate

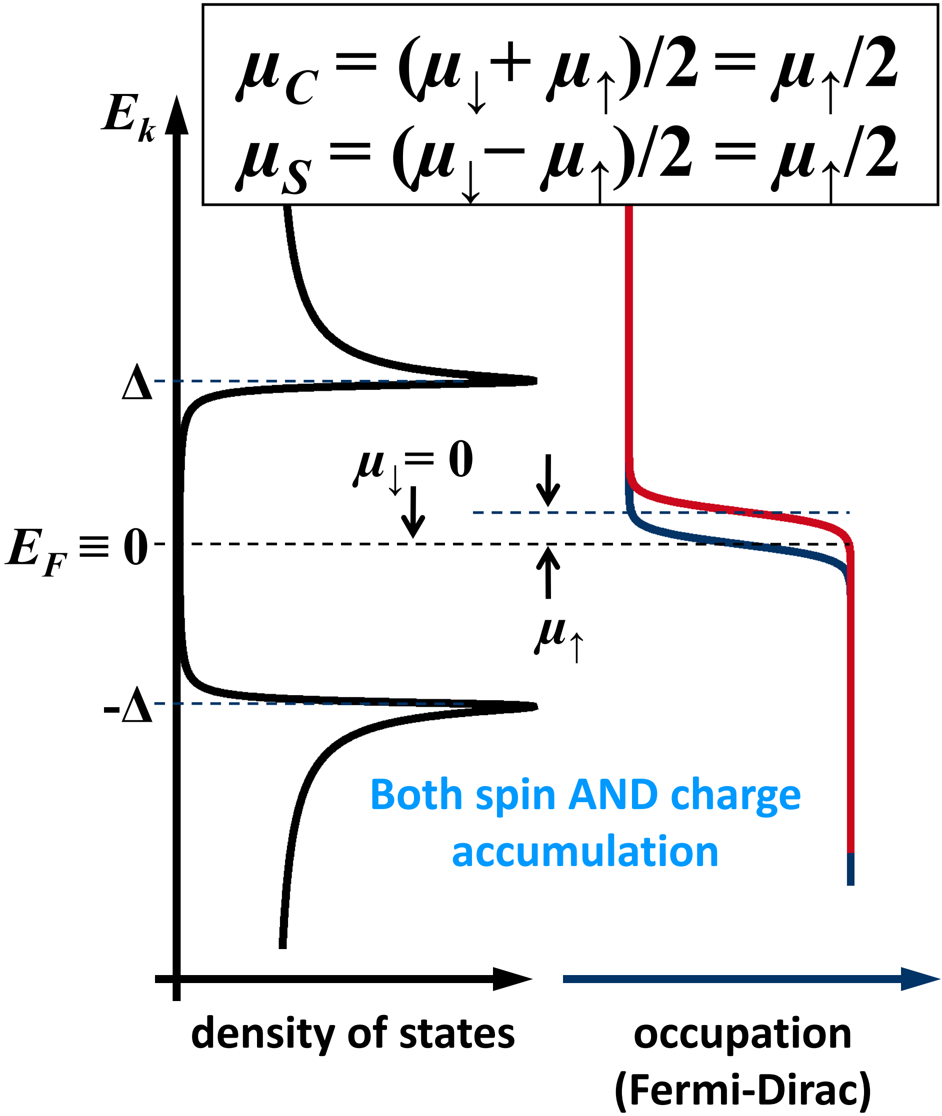
ξ_k – normal state energy
E_k – superconducting state energy



$$\Delta = 1.76 T_c$$

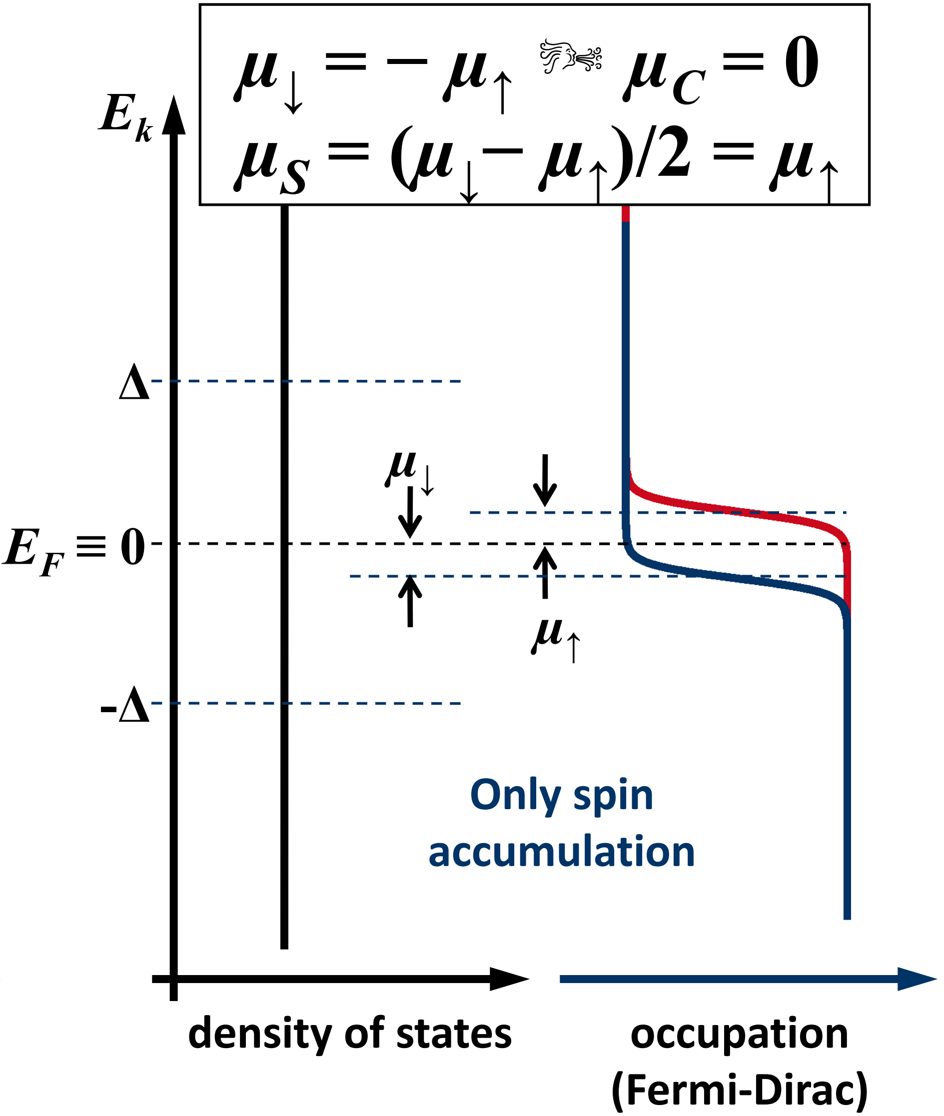
density of states
for quasiparticles
(= excitations)

SCs vs. 'normal' metals



$$\mu_C = (\mu_{\downarrow} + \mu_{\uparrow})/2 = \mu_{\uparrow}/2$$
$$\mu_S = (\mu_{\downarrow} - \mu_{\uparrow})/2 = \mu_{\uparrow}/2$$

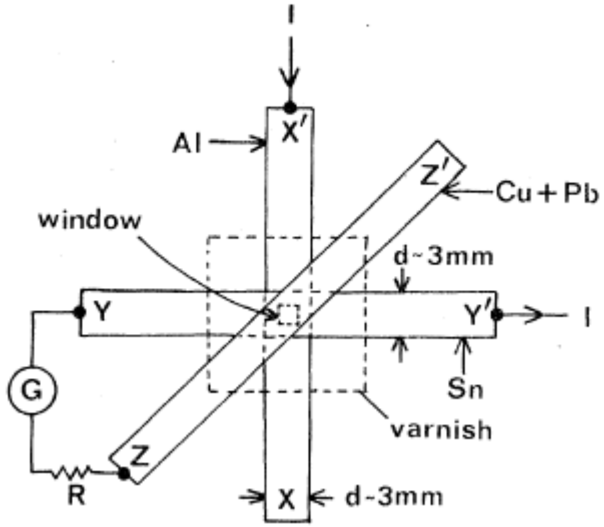
Both spin AND charge accumulation

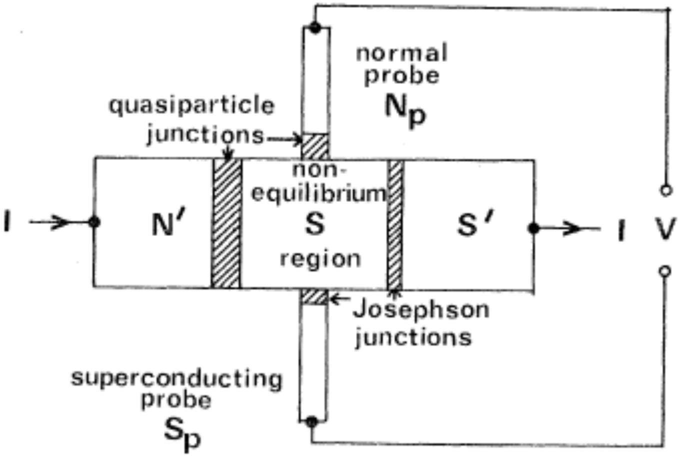


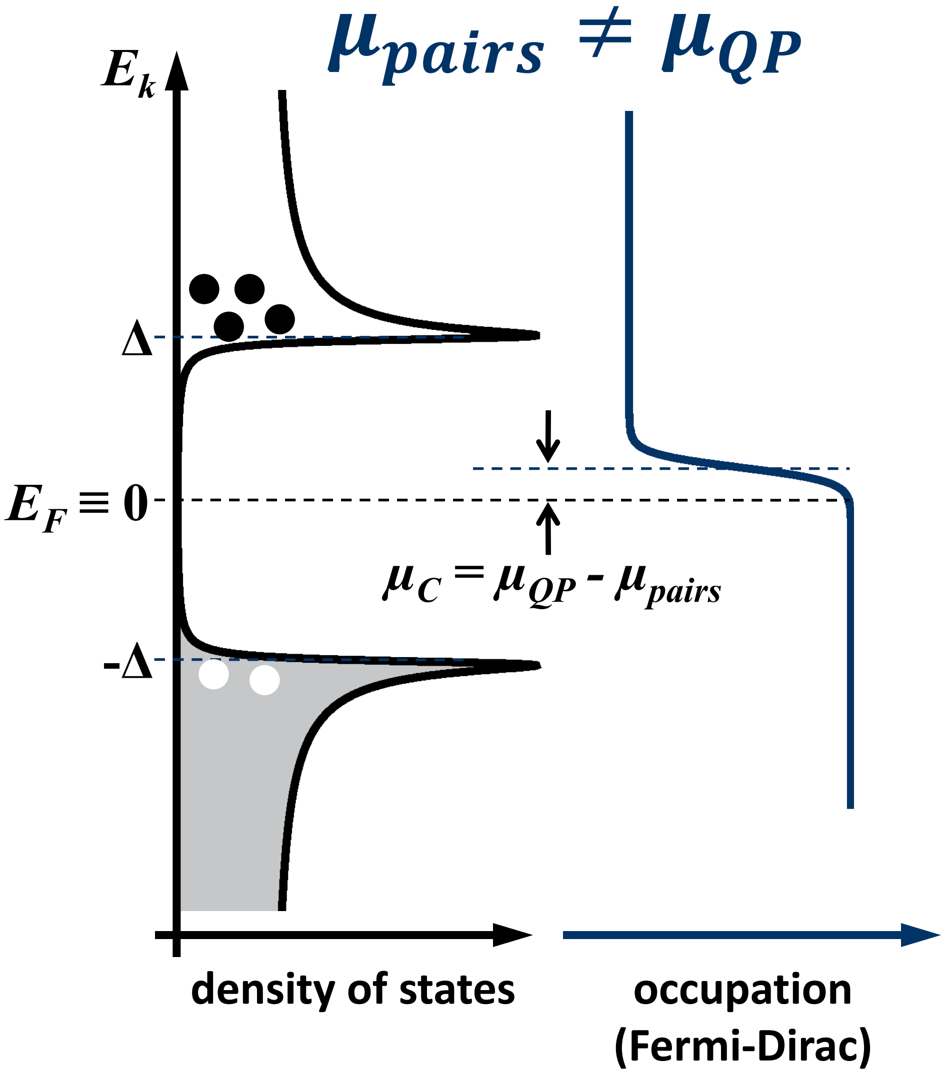
$$\mu_{\downarrow} = -\mu_{\uparrow} \qquad \mu_C = 0$$
$$\mu_S = (\mu_{\downarrow} - \mu_{\uparrow})/2 = \mu_{\uparrow}$$

Only spin accumulation

Charge imbalance experiments

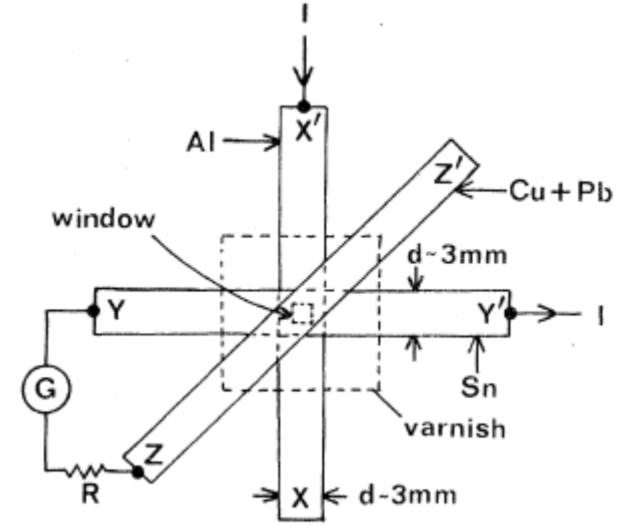


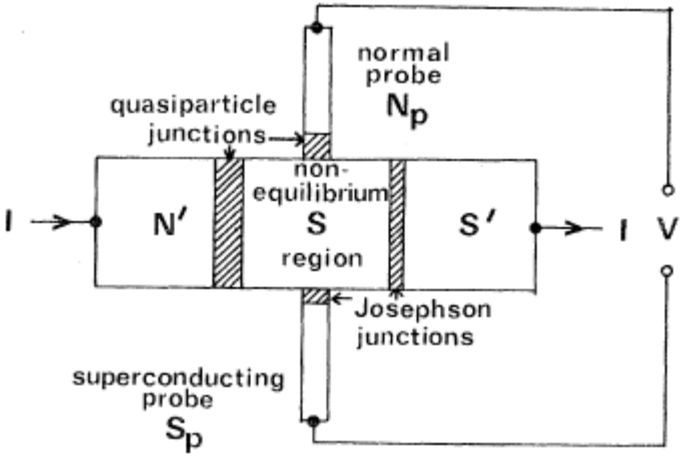


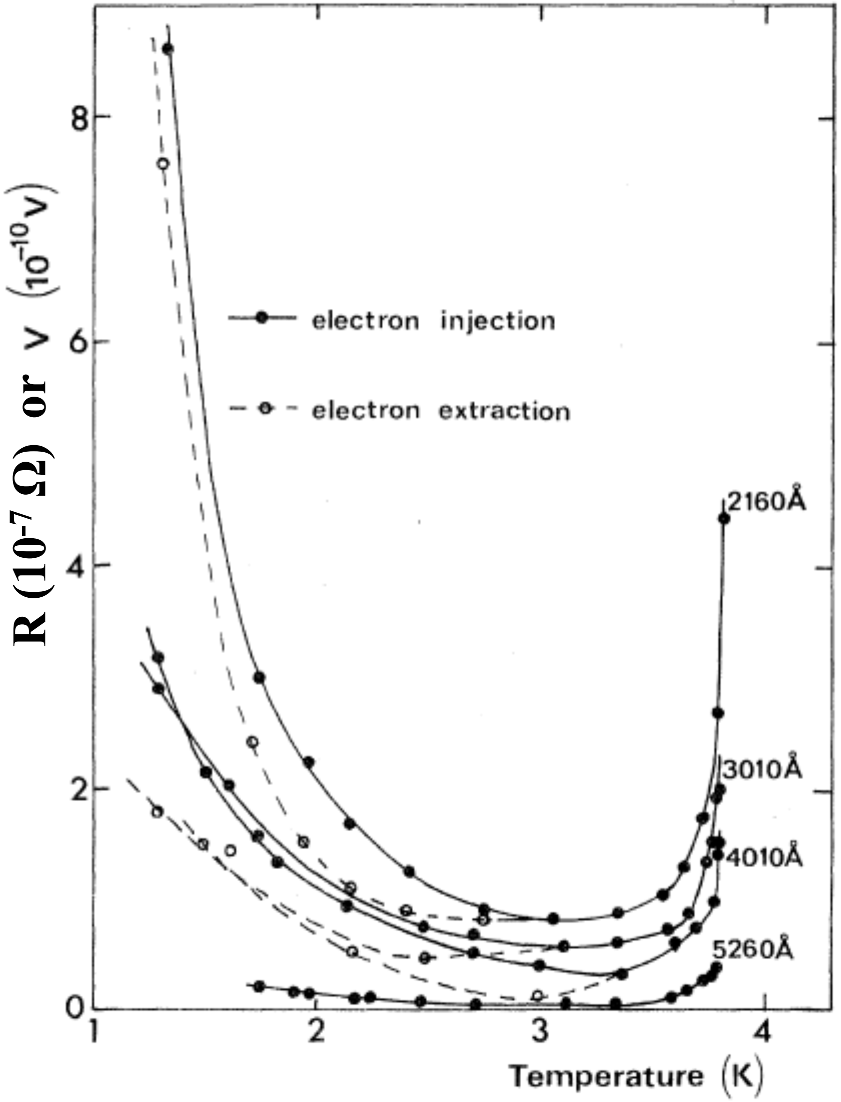


J Clarke, PRL **28**, 1363 (1972) / M Tinkham and J Clarke, *op. cit.* 1366.

Charge imbalance experiments

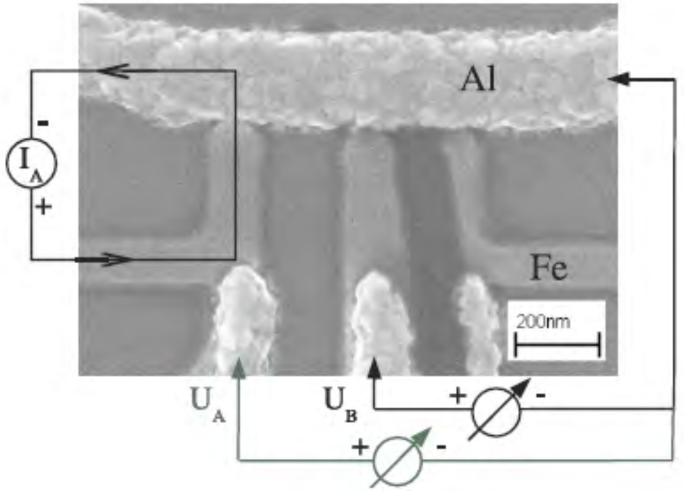


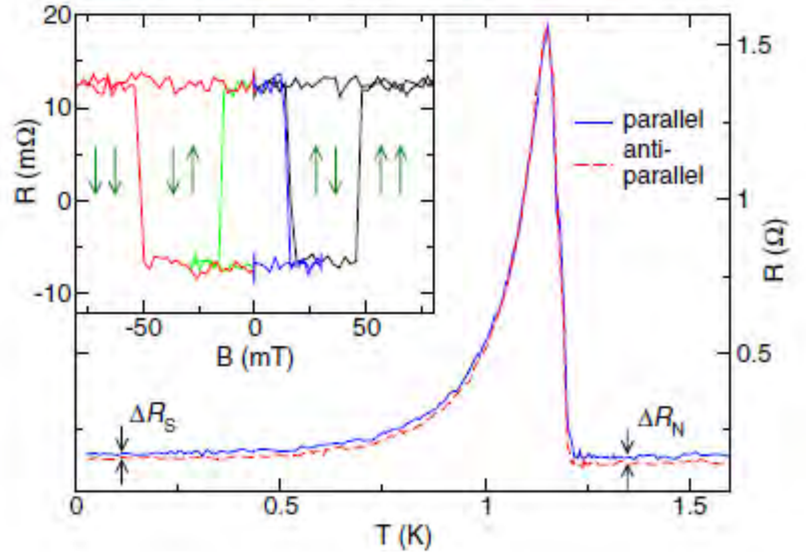


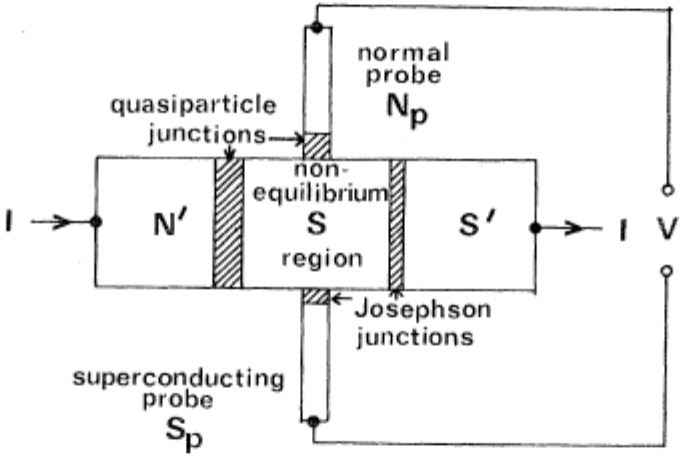


J Clarke, PRL **28**, 1363 (1972) / M Tinkham and J Clarke, *op. cit.* 1366.

Mesoscopic samples



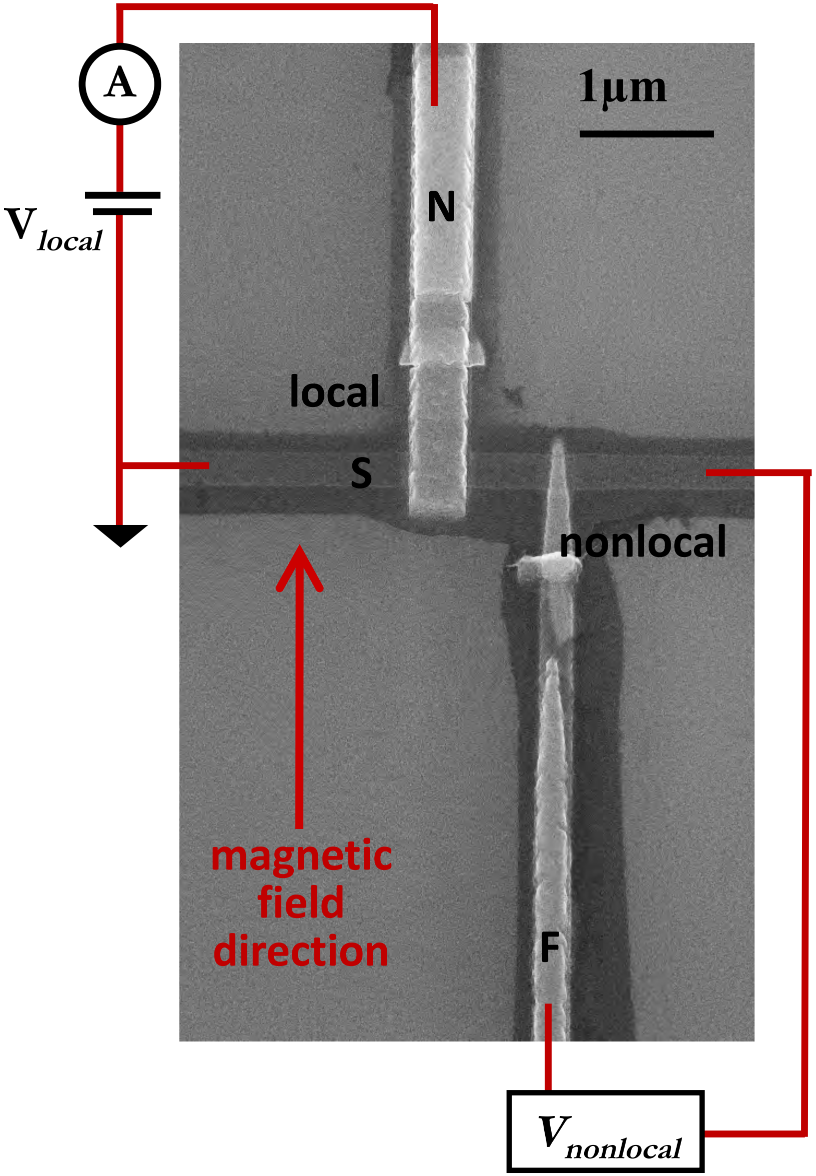




D Beckmann *et al.*, PRL **93**, 19 (2004)
P Cadden-Zimansky *et al.*, NJP **9**, 116 (2007)

J Clarke, PRL **28**, 1363 (1972)

Spin imbalance device

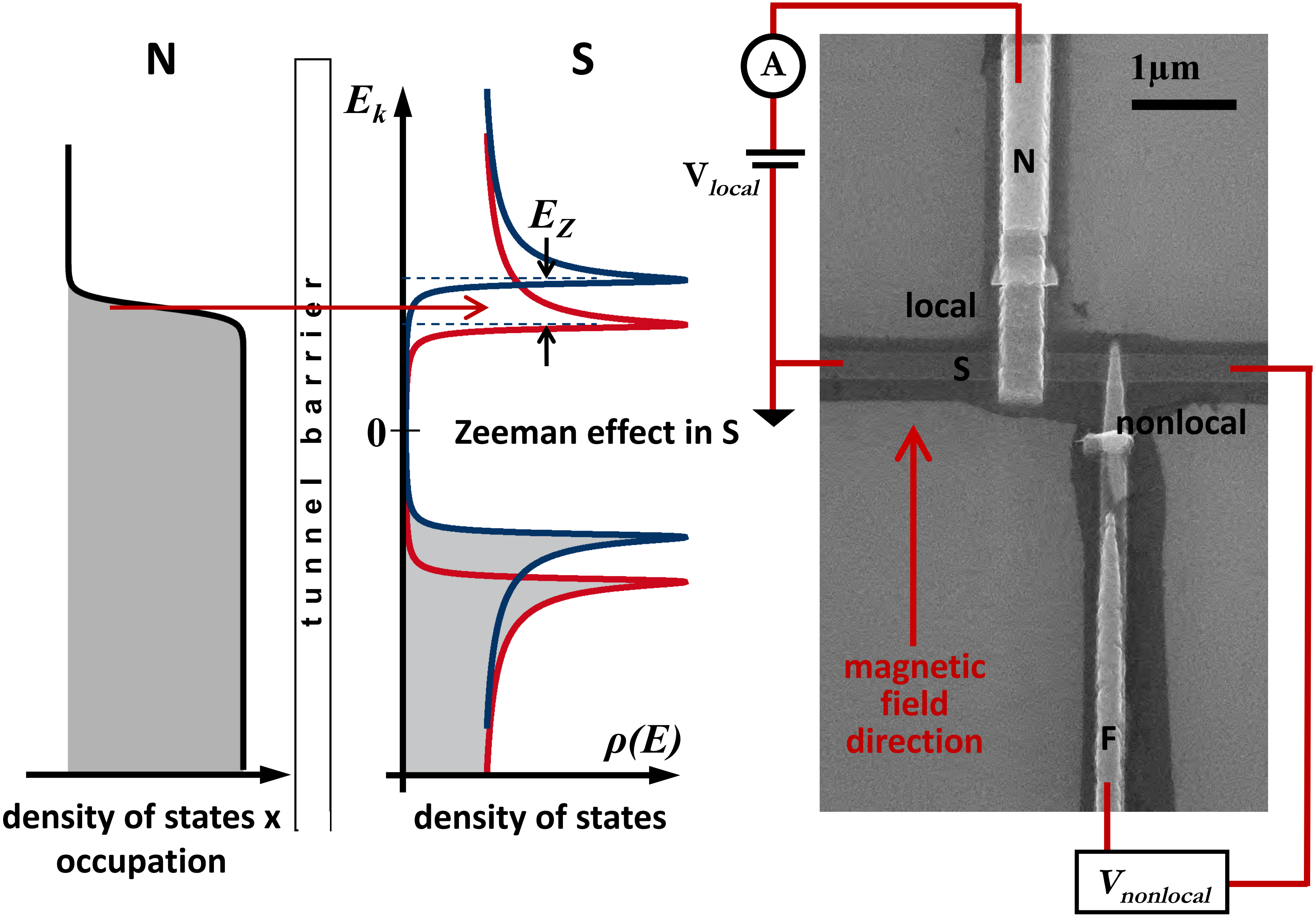


Materials/fabrication details

S = superconductor (6-10nm Al + oxide)
F = ferromagnet (50nm Co/5nm Al)
N = normal (100nm Al, H_C ~400G)

Typical junction restances:
5kΩ for both junctions

Zeeman effect gives spin imbalance



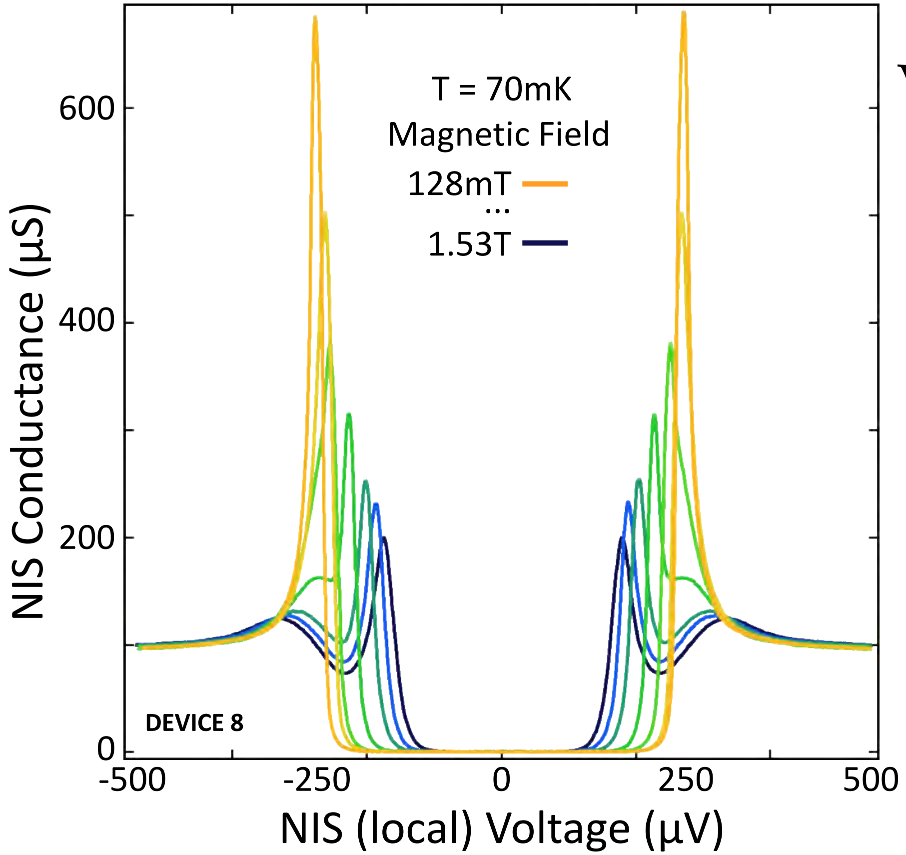
Zeeman effect in S

magnetic field direction

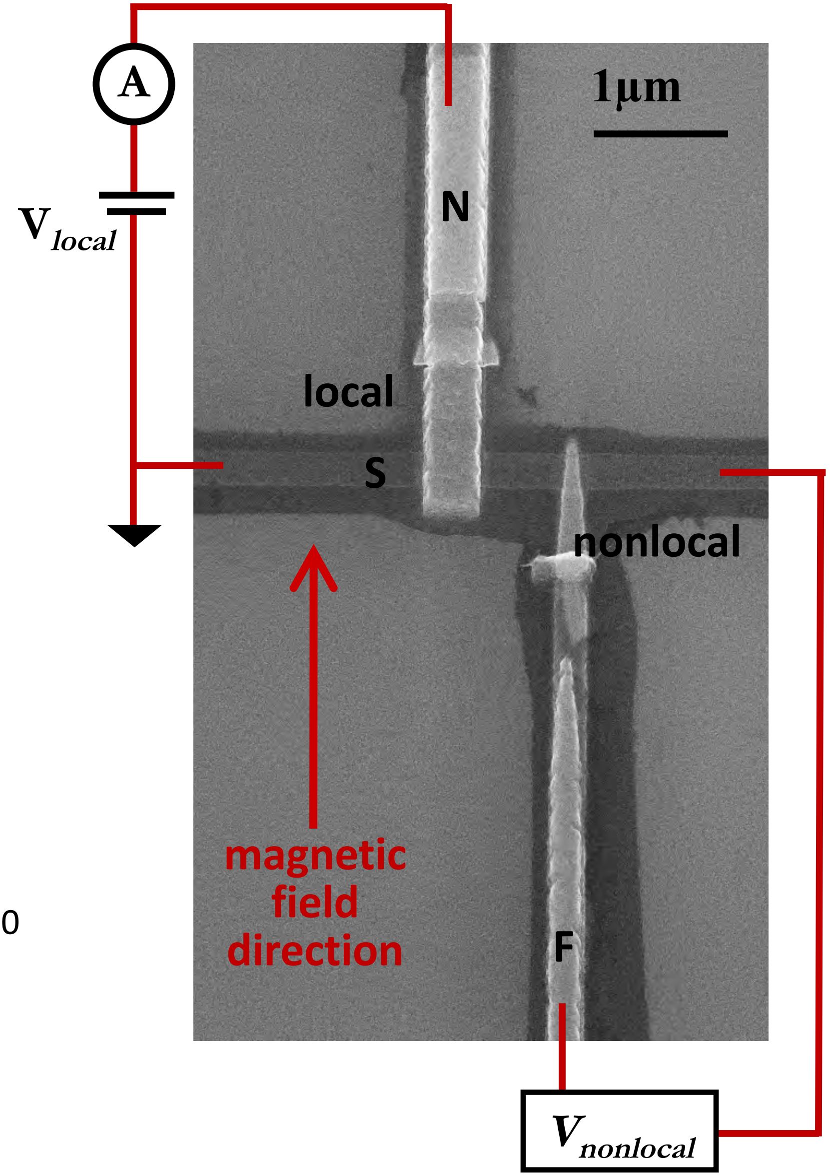
density of states x occupation

density of states

Zeeman splitting @ injector

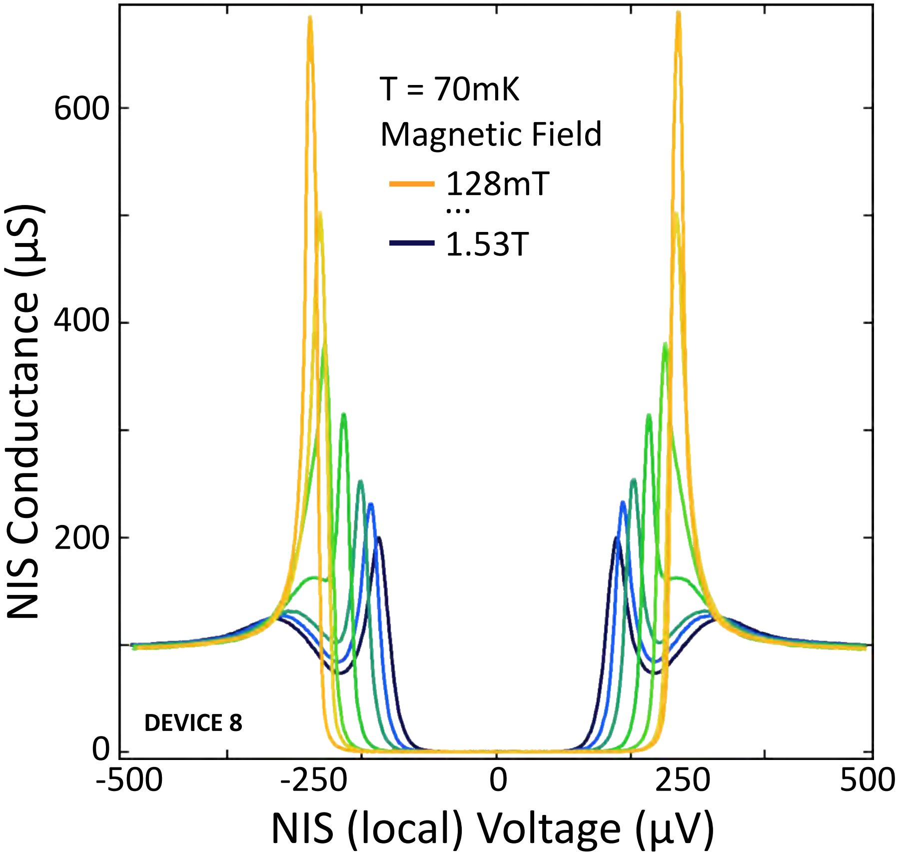


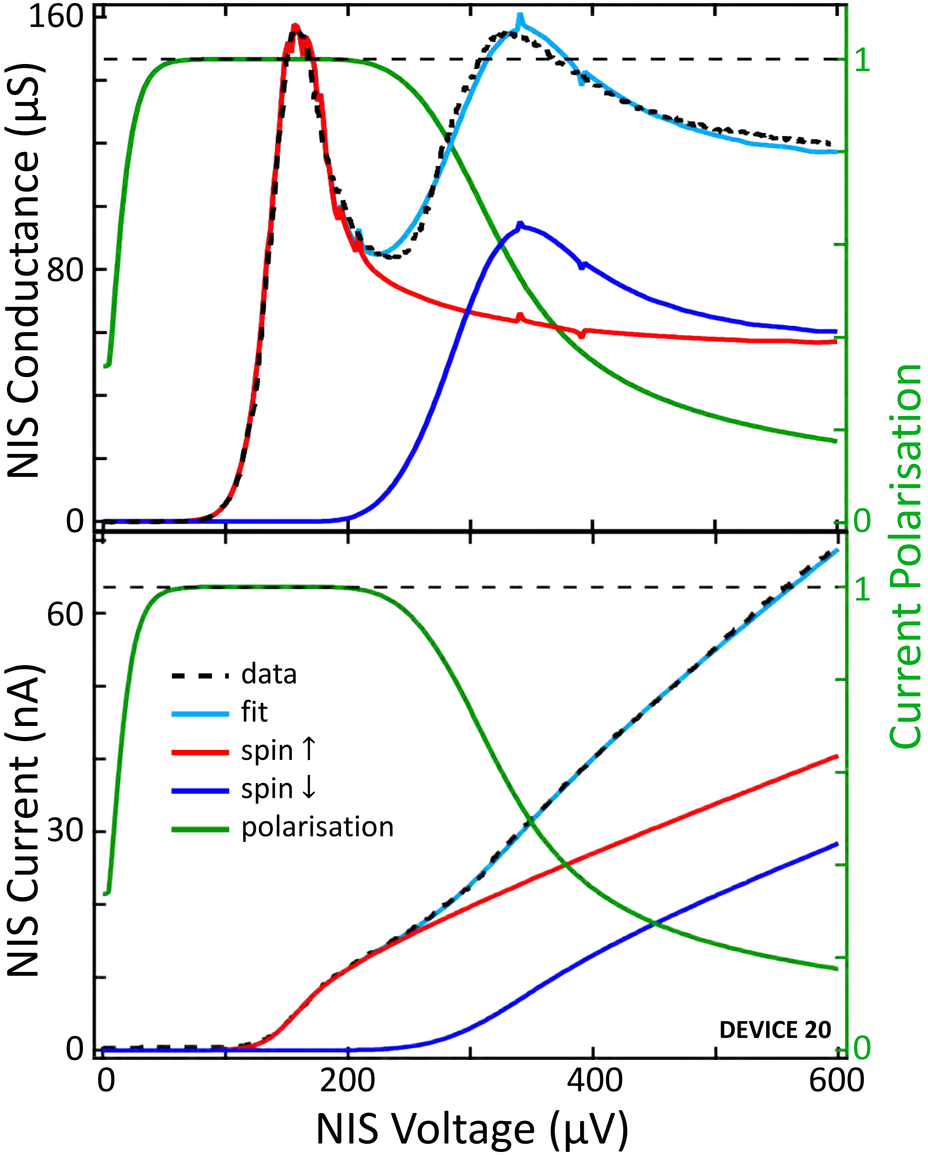
Carefully compensating out-of-plane field is very important!



M. Weideneder et al., *in preparation.*

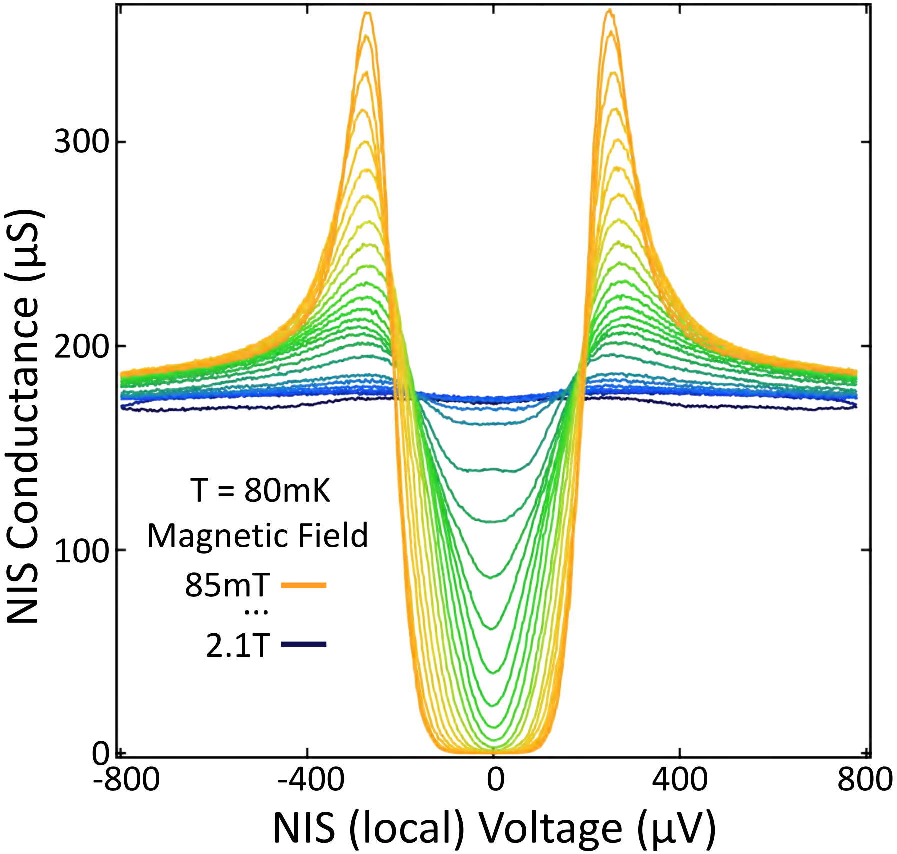
Polarisation can reach 100%

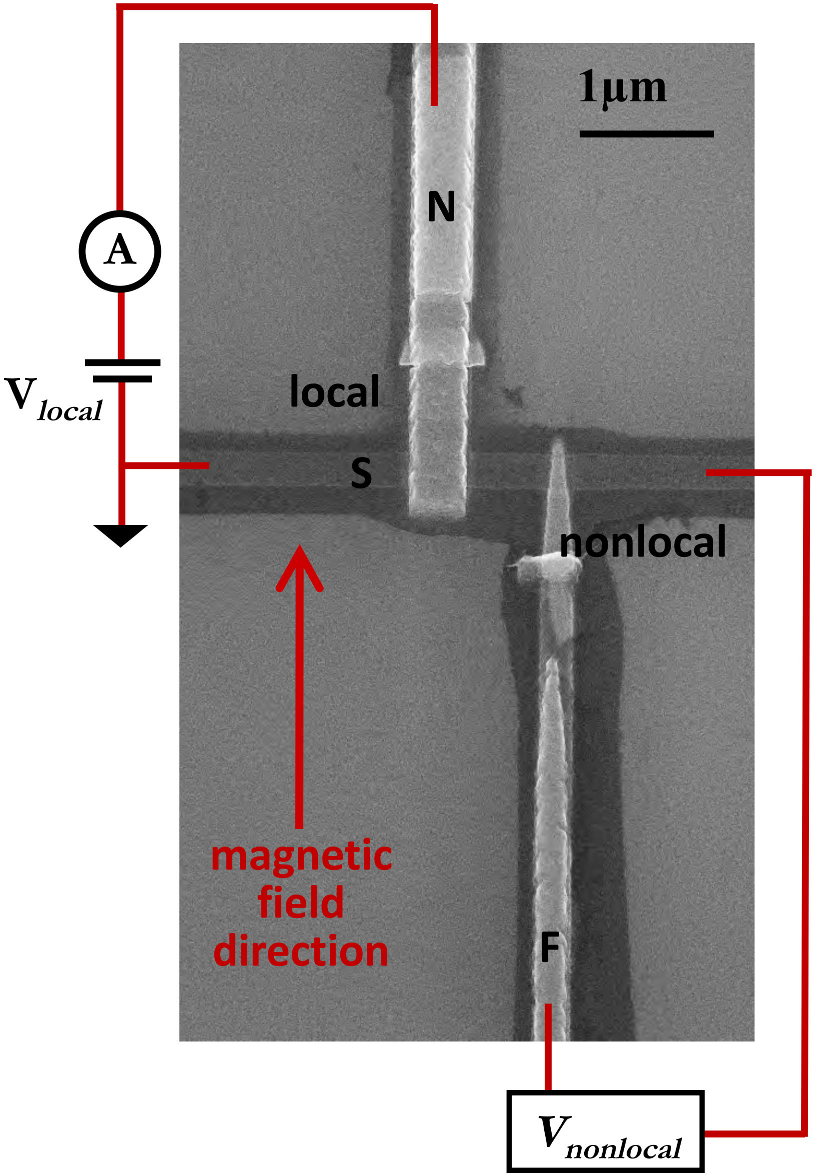




M. Weideneder et al., *in preparation.*

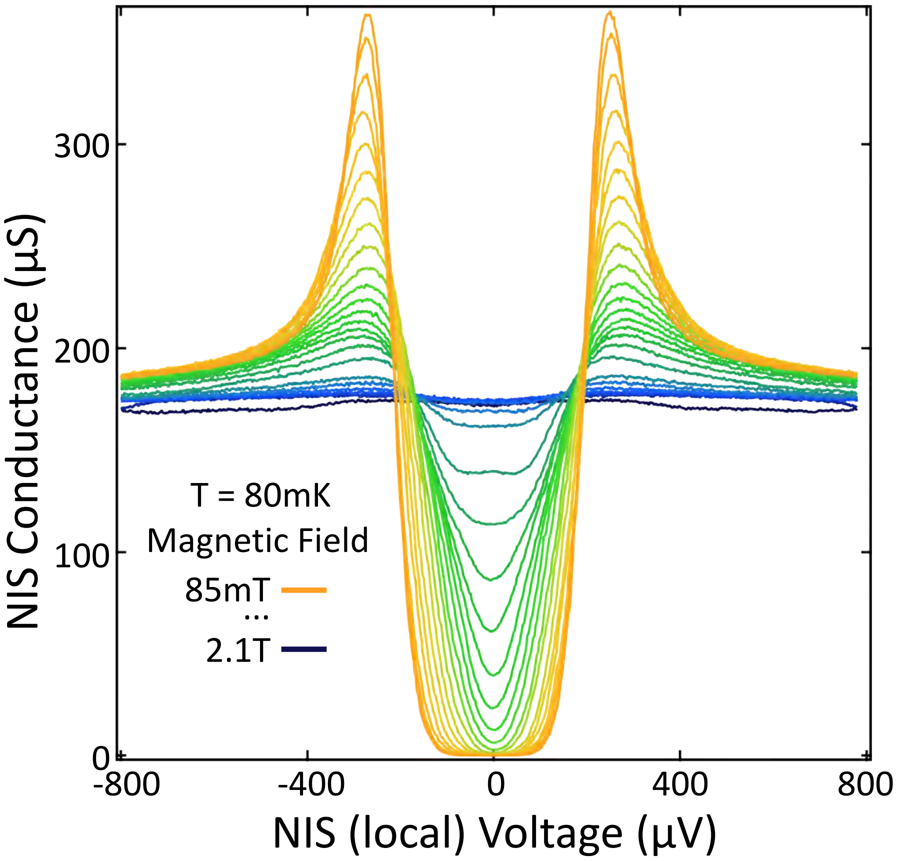
Spin imbalance observation

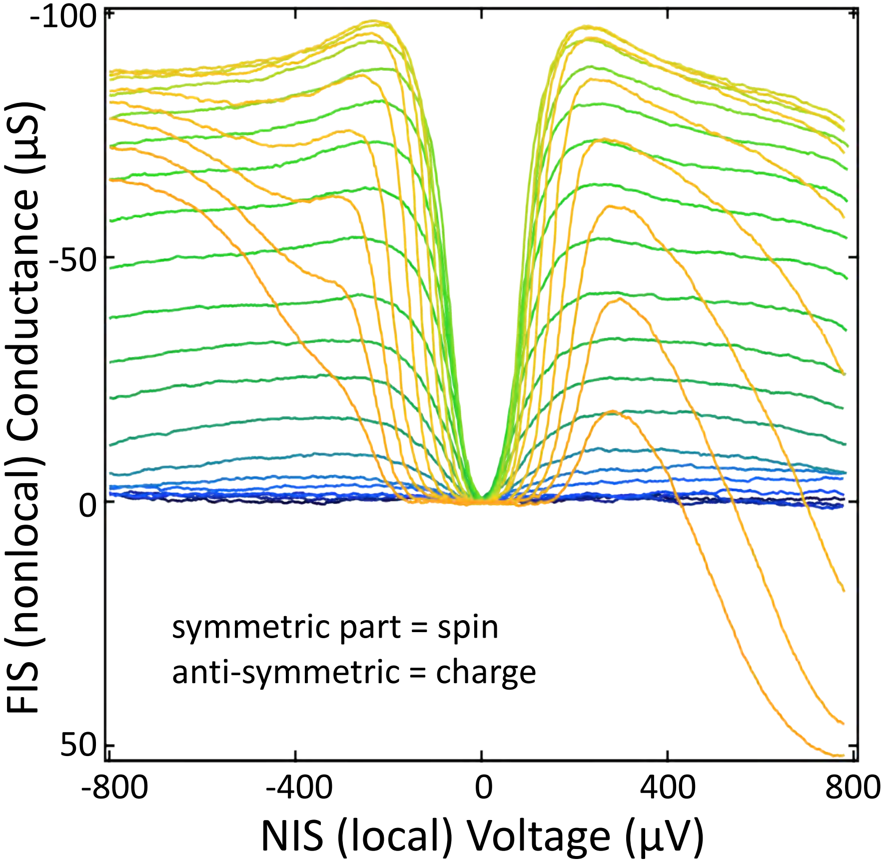




C. H. L. Quay *et al.*, PRB **93**, 220501(R) (2016).

Spin imbalance observation

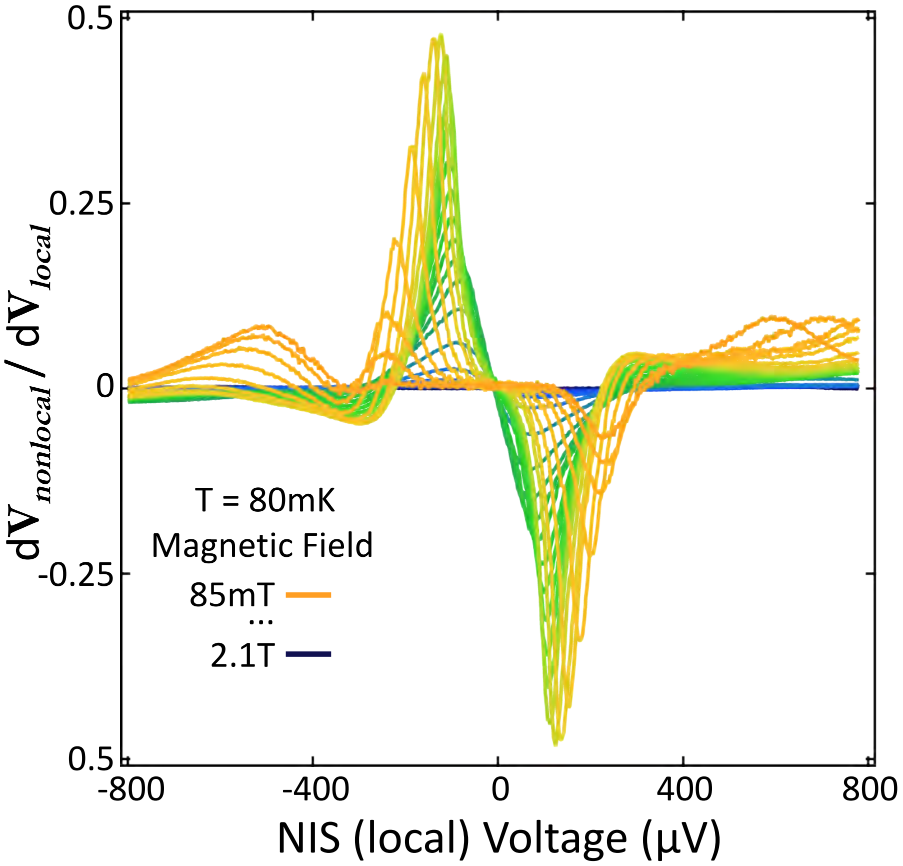


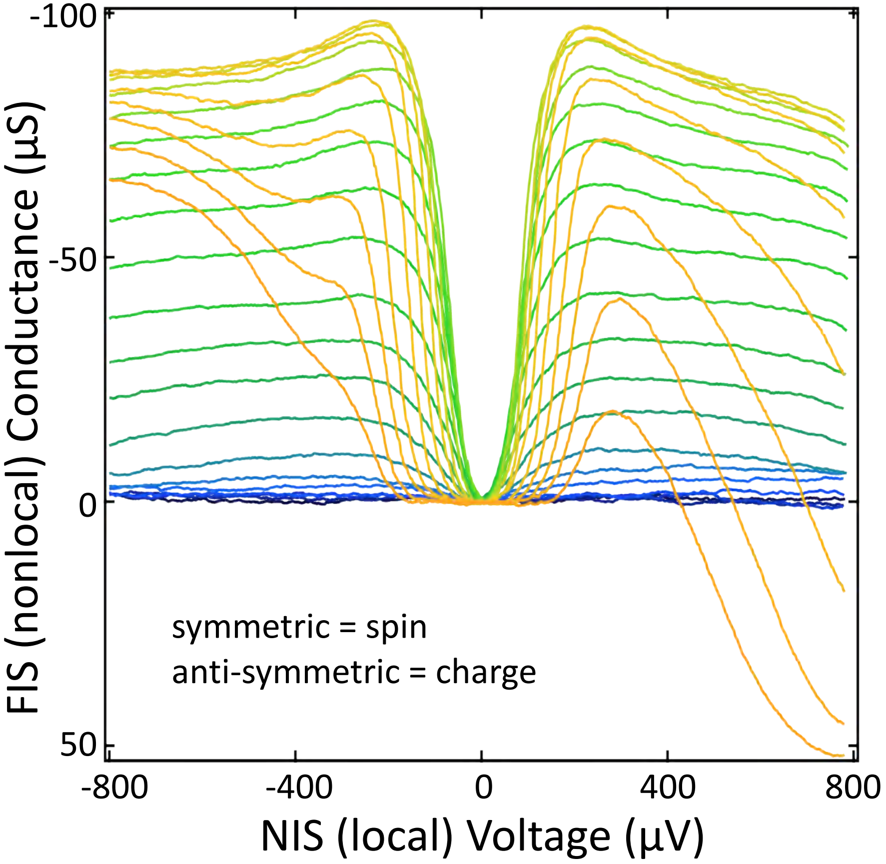


symmetric part = spin
anti-symmetric = charge

C. H. L. Quay *et al.*, Nature Physics, **9**, 84–88 (2013) / PRB **93**, 220501(R) (2016).

Spin imbalance observation

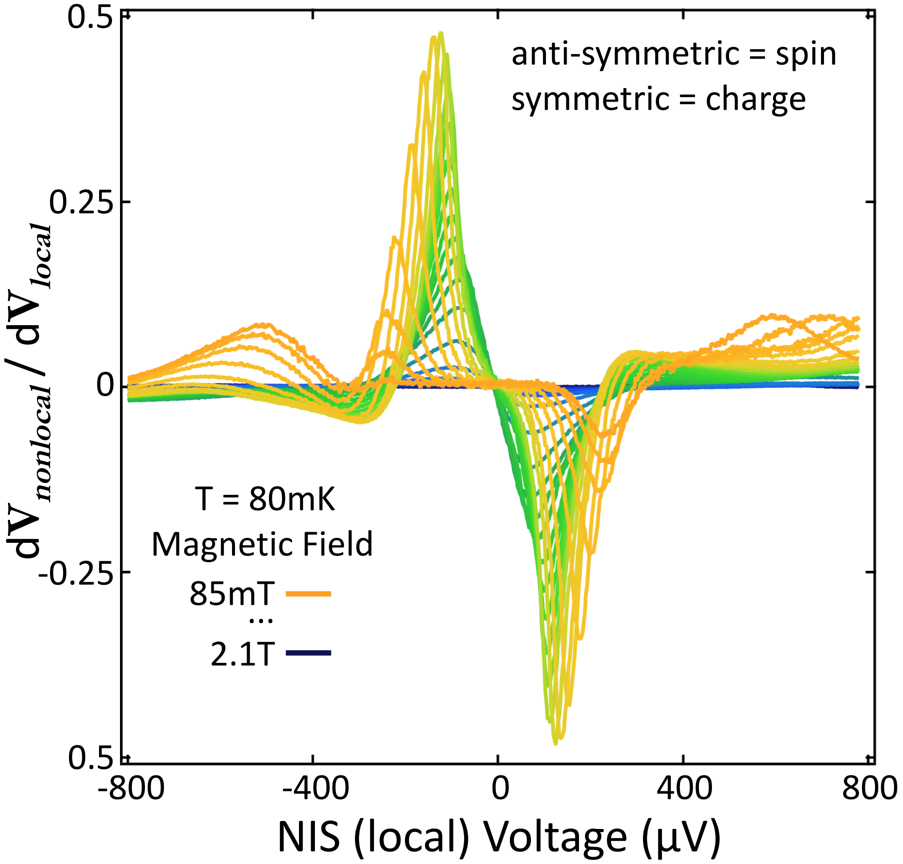


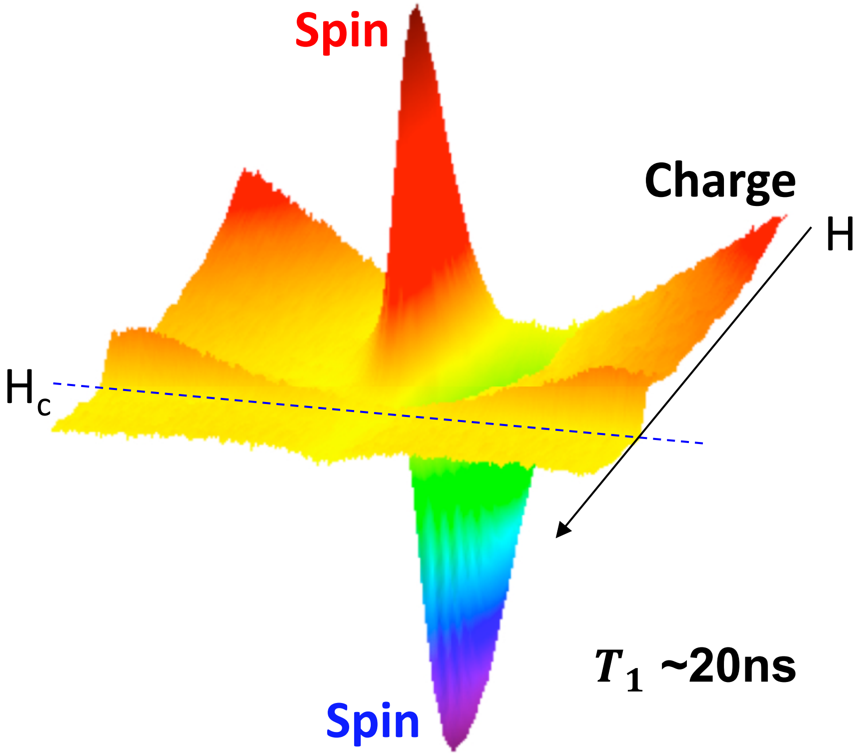


symmetric = spin
anti-symmetric = charge

C. H. L. Quay *et al.*, Nature Physics, **9**, 84–88 (2013) / PRB **93**, 220501(R) (2016).

Spin imbalance observation



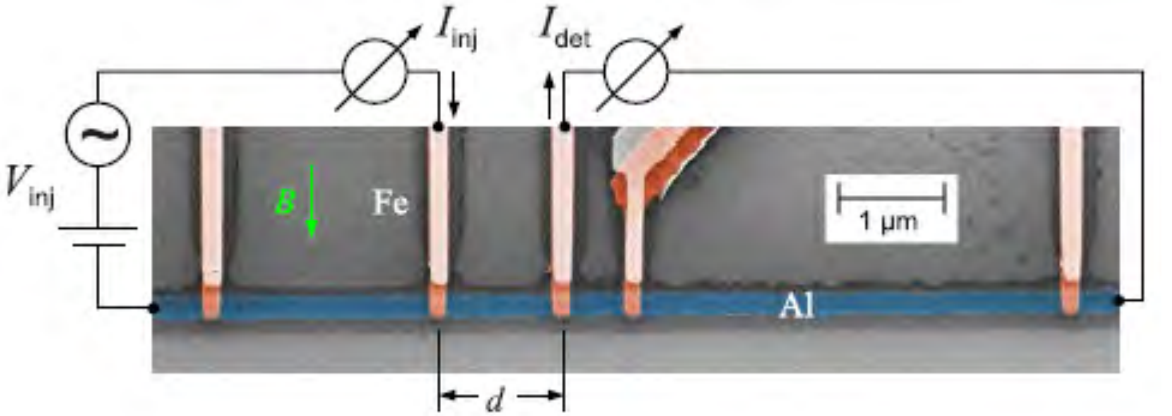


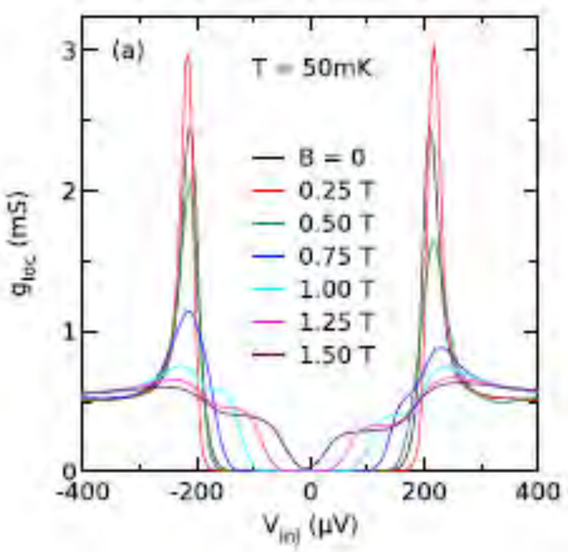
spin imbalance lifetime T_1 ~ 10ns
(confirmed by frequency domain measurements)
$\gg$ charge imbalance lifetime ~ 10ps

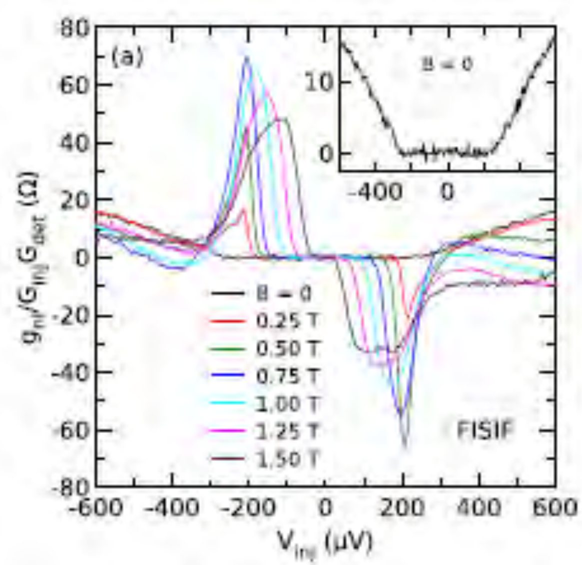
C. H. L. Quay *et al.*, Nature Physics, **9**, 84–88 (2013) / PRB **93**, 220501(R) (2016).

Related work on spin imbalance

Spin imbalance length of almost 10μm at 1.7T.







F. Hübler *et al.*, PRL **109** (20), 207001 (2012) / M. J. Wolf *et al.*, PRB **87** (2), 024517 (2013)

Spin physics in out-of-equilibrium superconductors

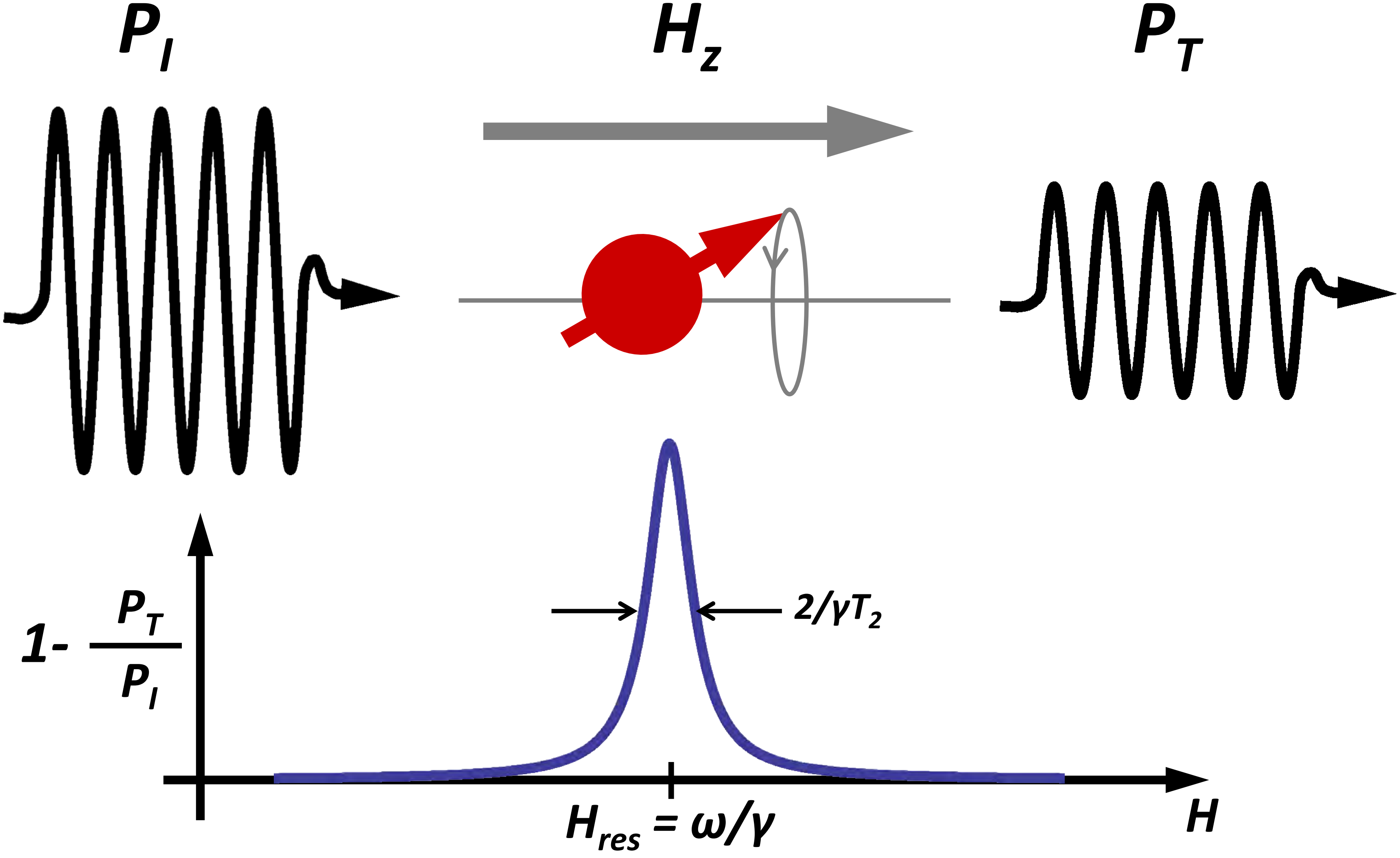
- Spinful excitations in superconductors

‘STATICS’ (intro)

- Quasiparticle spin resonance
- Spin-dependent recombination dynamics (ongoing work)

DYNAMICS

Quasiparticle spin resonance



QSR in superconductors: challenges

Inhomogeneous magnetic field

$$\lambda = \sqrt{\frac{\hbar}{\mu_0 \pi \sigma \Delta}}$$

λ	penetration depth
σ	conductivity
Δ	superconducting gap

In 6-8.5nm aluminium films

→ field homogeneous to $\lesssim$ 1.5%

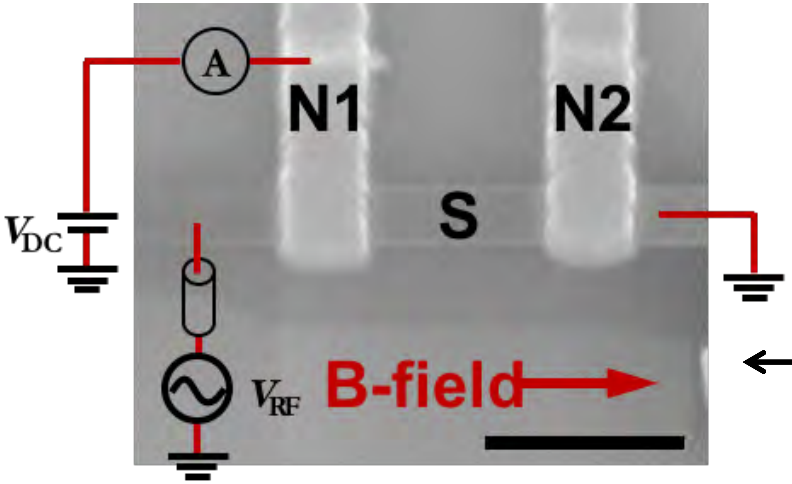
Sensitive powermetres required

→ on-chip power detection

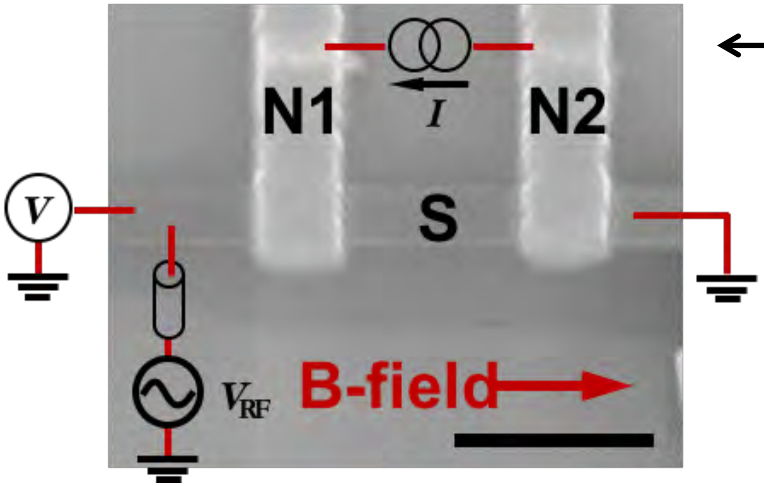
Student putting a macroscopic sample
Into a macroscopic ESR cavity

QSR measurement

TWO ON-CHIP POWER DETECTION SCHEMES



conductance across tunnel barrier



supercurrent

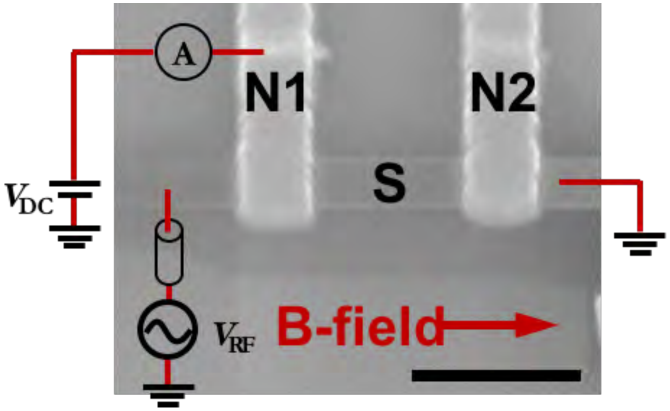
Scale bar 1µm

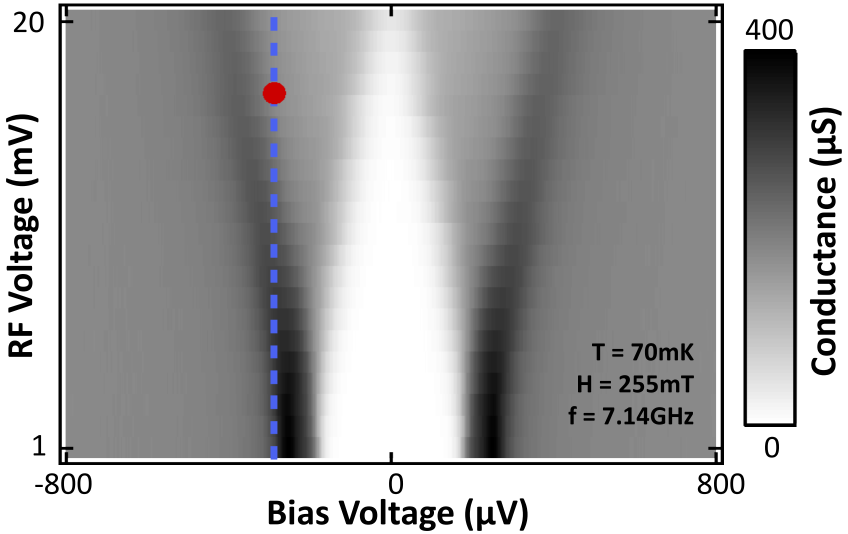
S = superconductor (6 or 8.5nm Al + oxide)
N = normal (100nm Al)
F = ferromagnet (40nm Co/3.5nm Al)
Typical junction resistances: 5kΩ

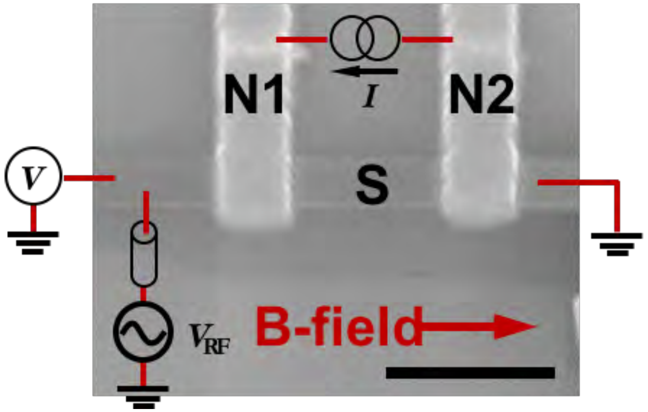
C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

On-chip detection

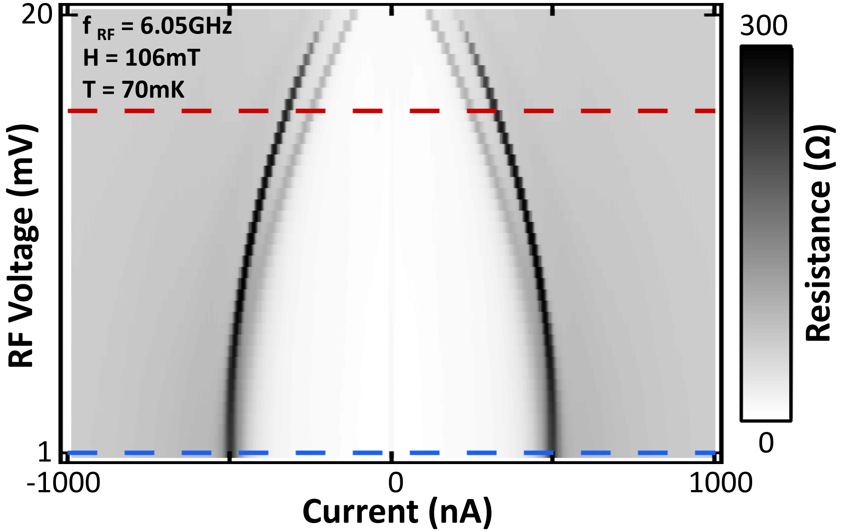
conductance across tunnel barrier





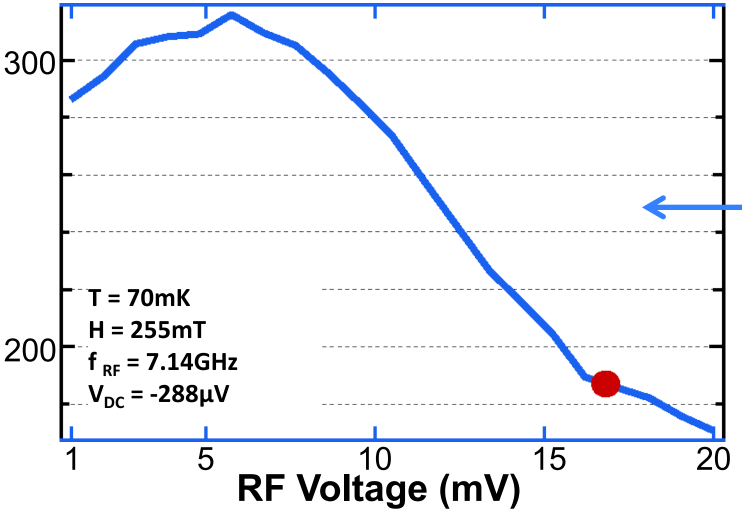


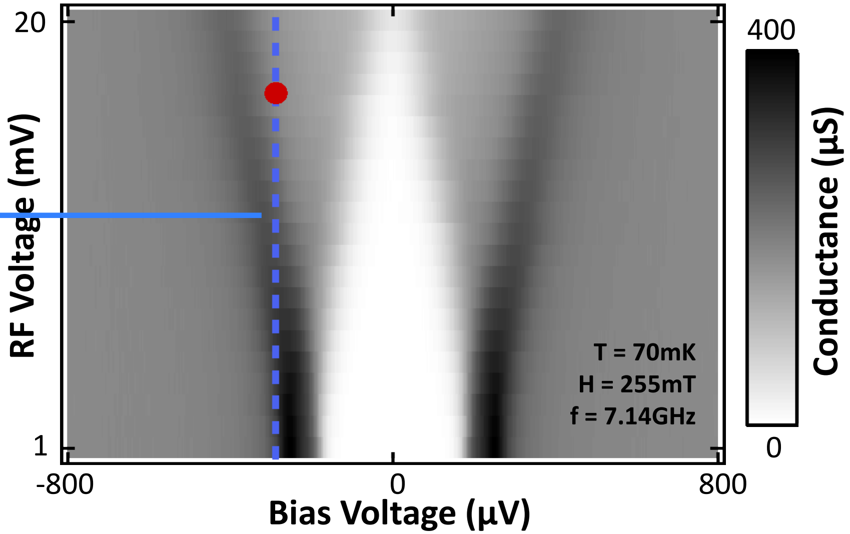
supercurrent

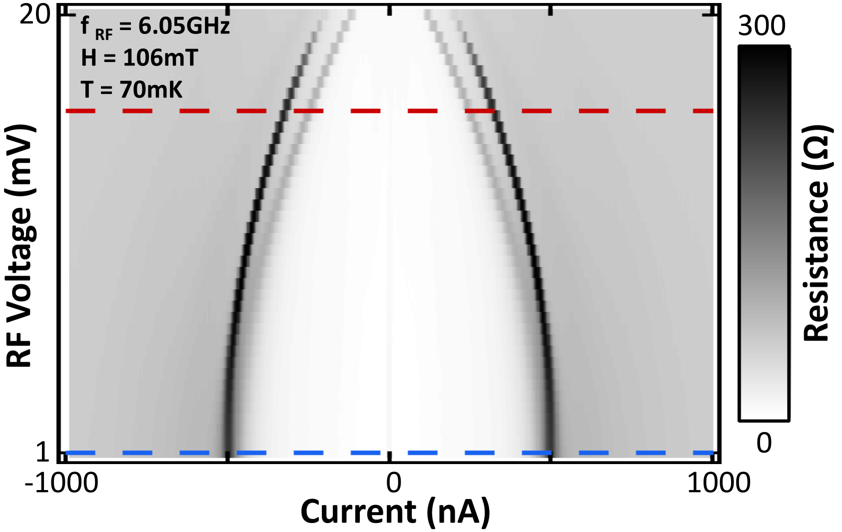


C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

On-chip detection

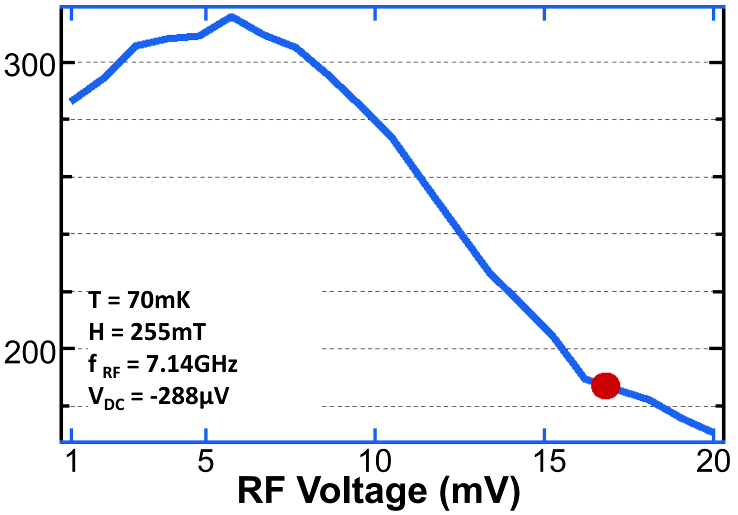


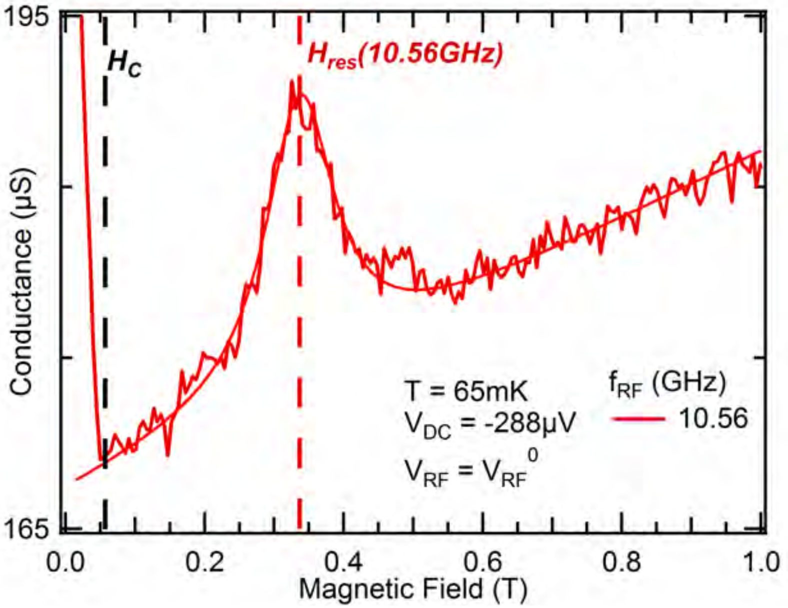


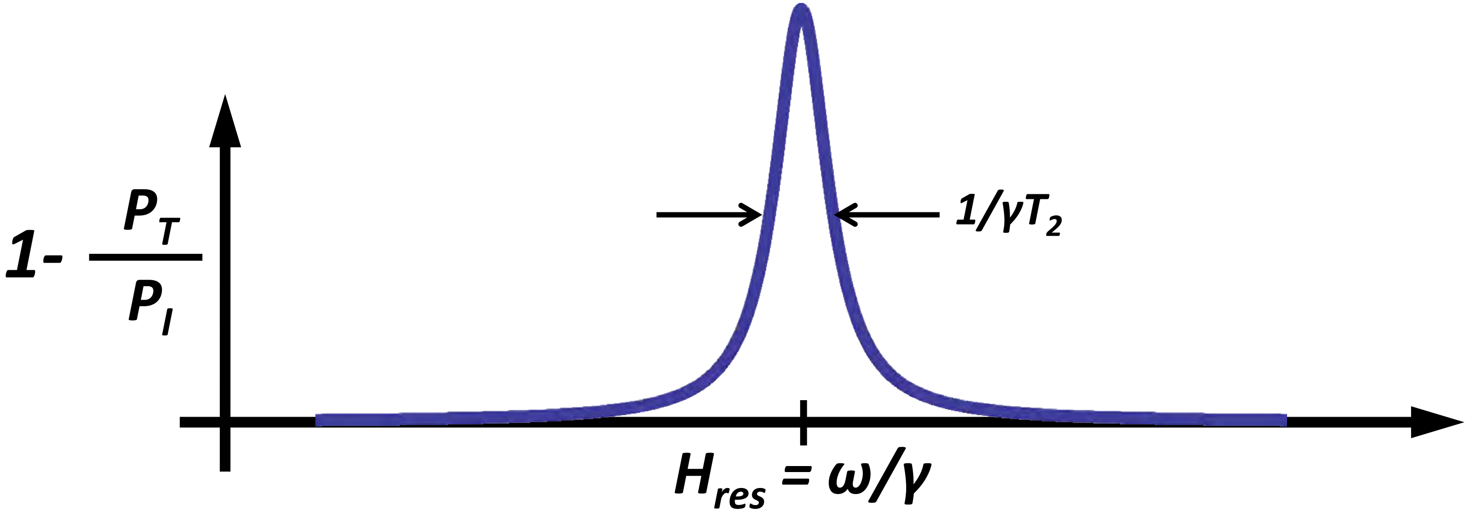


C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

Resonance in conduction







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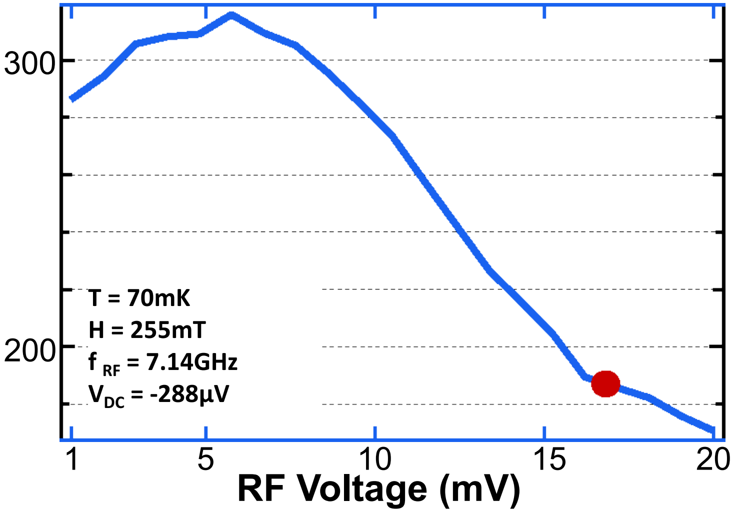
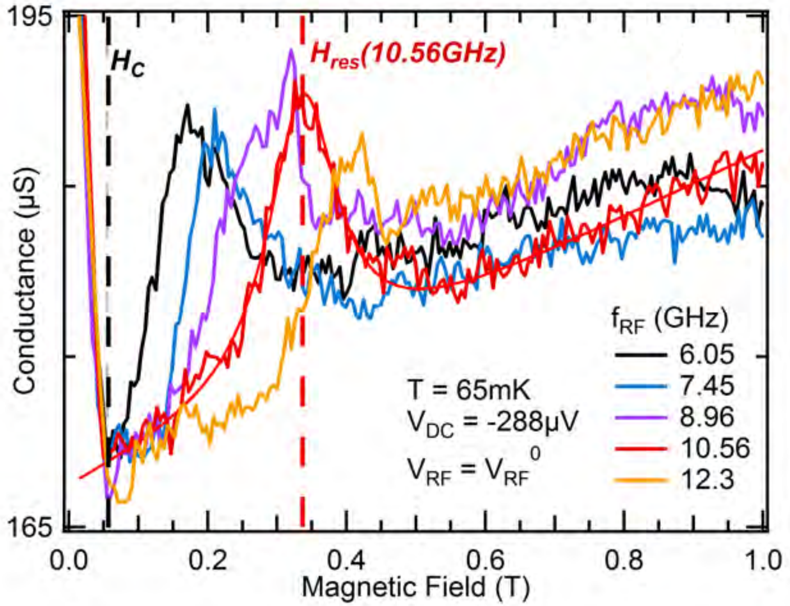
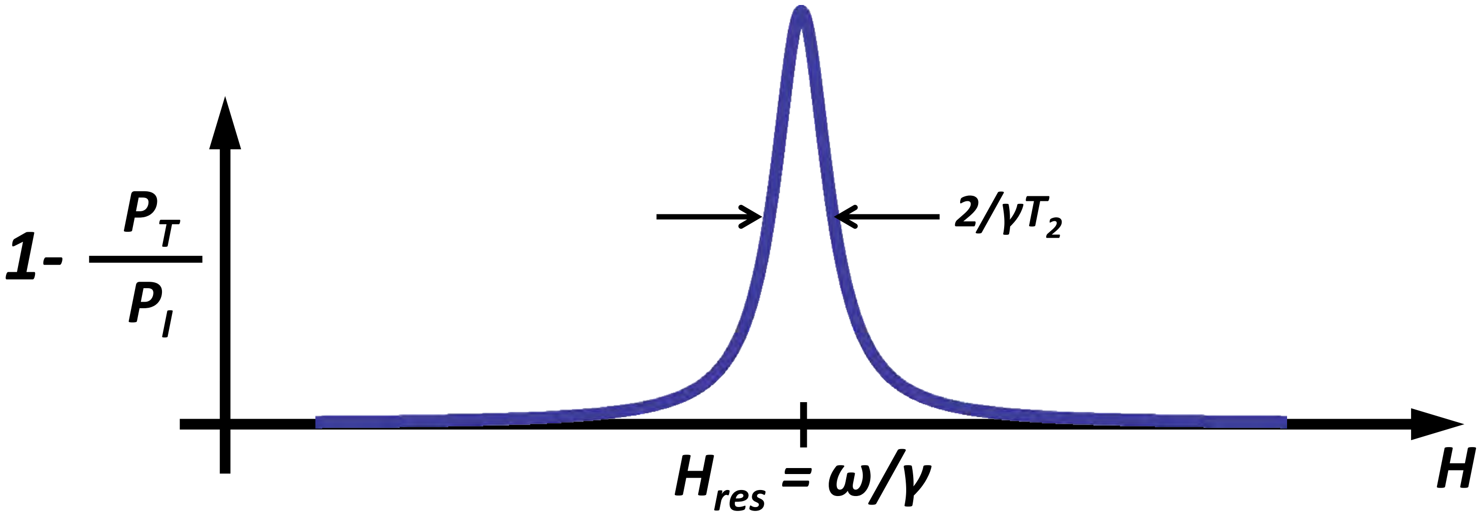
Frequency dependence



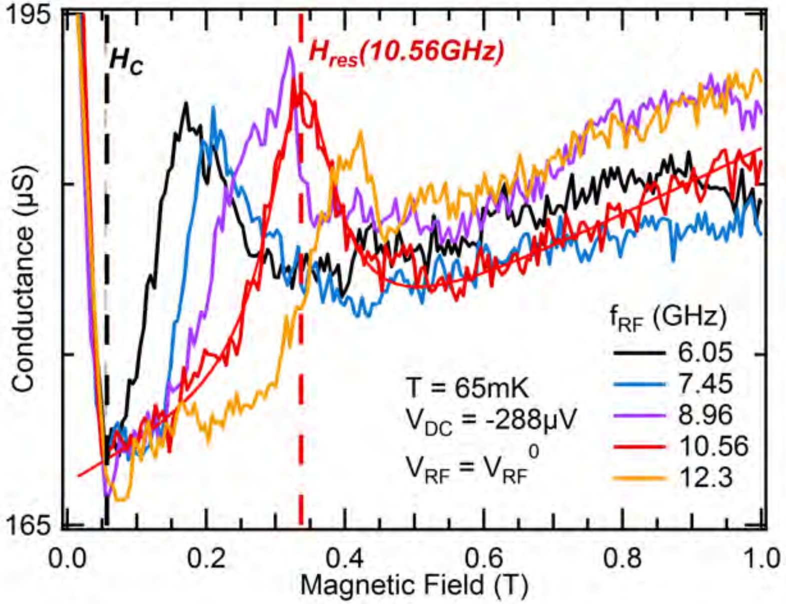


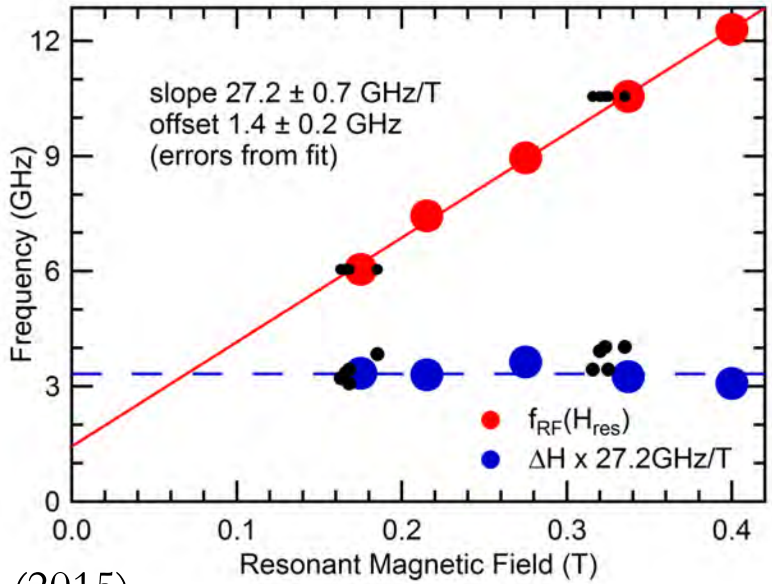


C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

Landé g-factor and T_2

$g = 1.95 \pm 0.2$
$T_2 = 95 \pm 20\text{ps}$

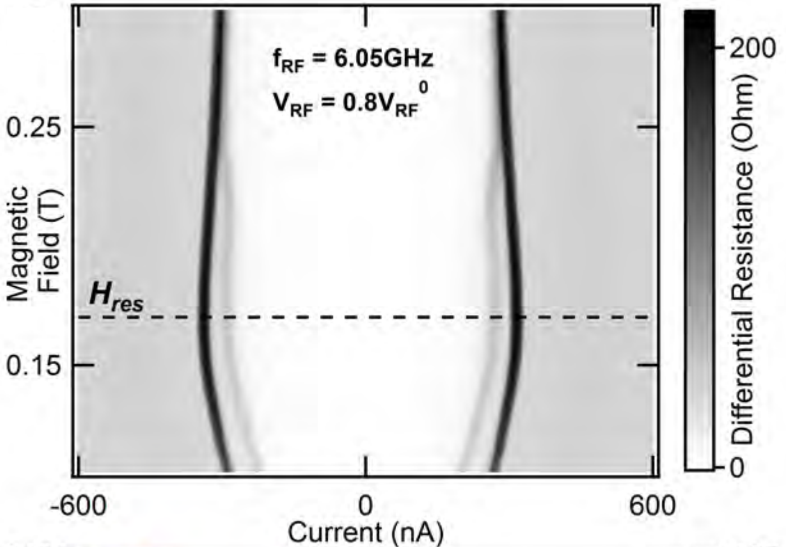




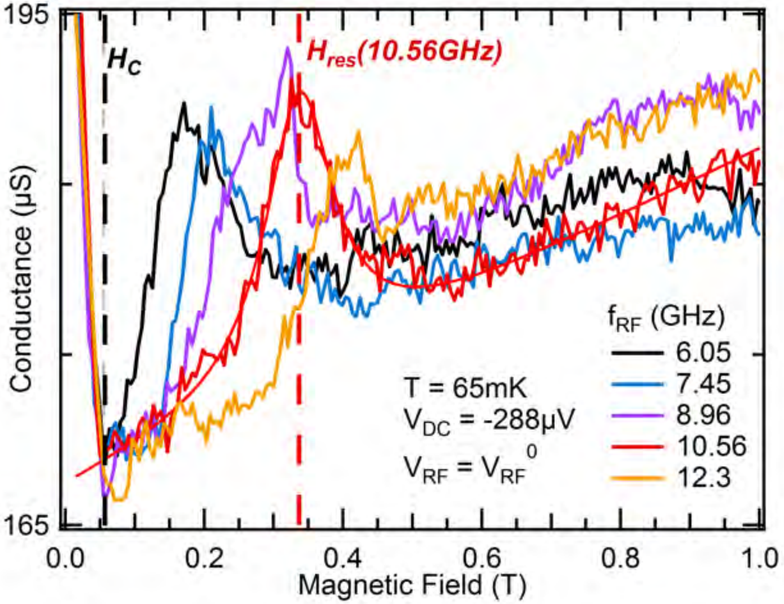
C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

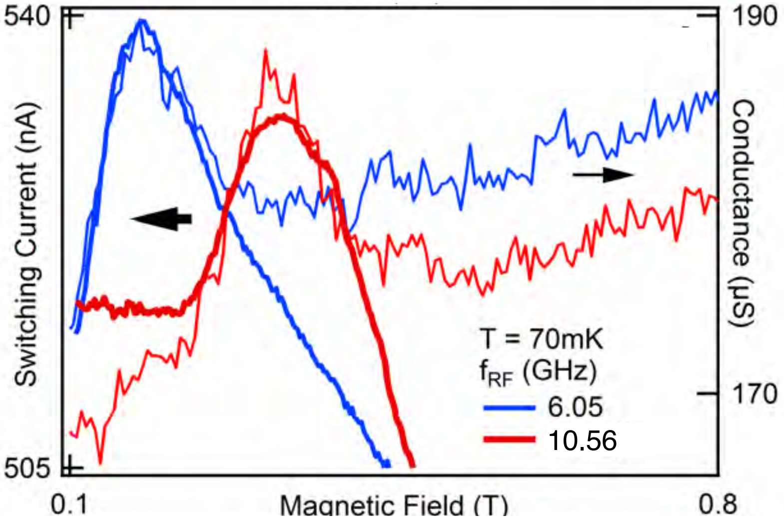
Both methods compared

g = 1.95 ± 0.2
T_2 = 95 ± 20ps



measured T_2 same in both cases



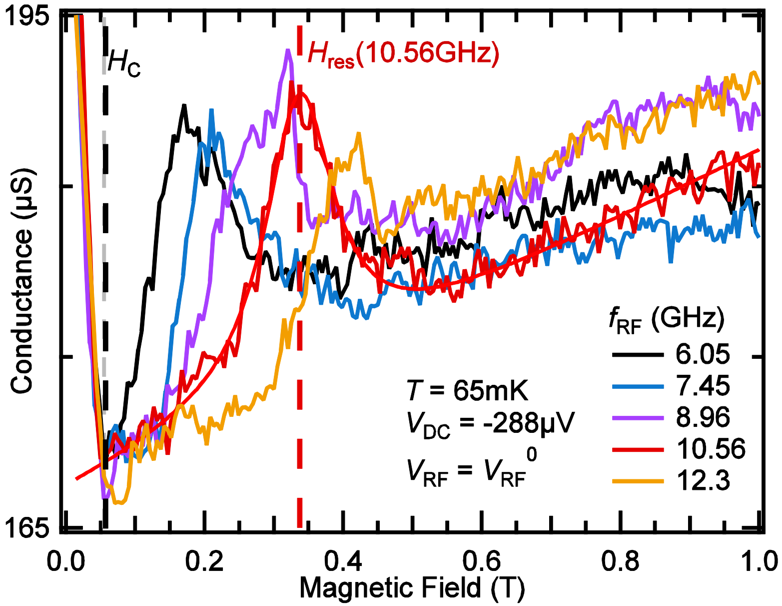


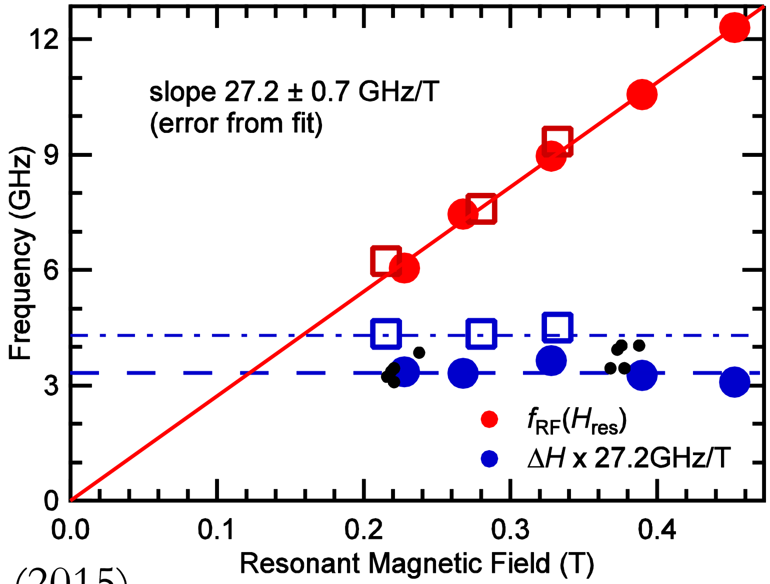
C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

Thickness dependence

g **= 1.95 ± 0.2**
T_2 **= 95 ± 20ps (8.5nm)**
70 ± 15ps (6nm)

T_1 **~ 10ns, limited by**
inelastic e-e scattering
T_2 **~ 100ps, limited by**
Elliott-Yafet spin-orbit scattering





C. H. L. Quay *et al.*, Nature Communications, **6**, 8660 (2015)

Spin physics in out-of-equilibrium superconductors

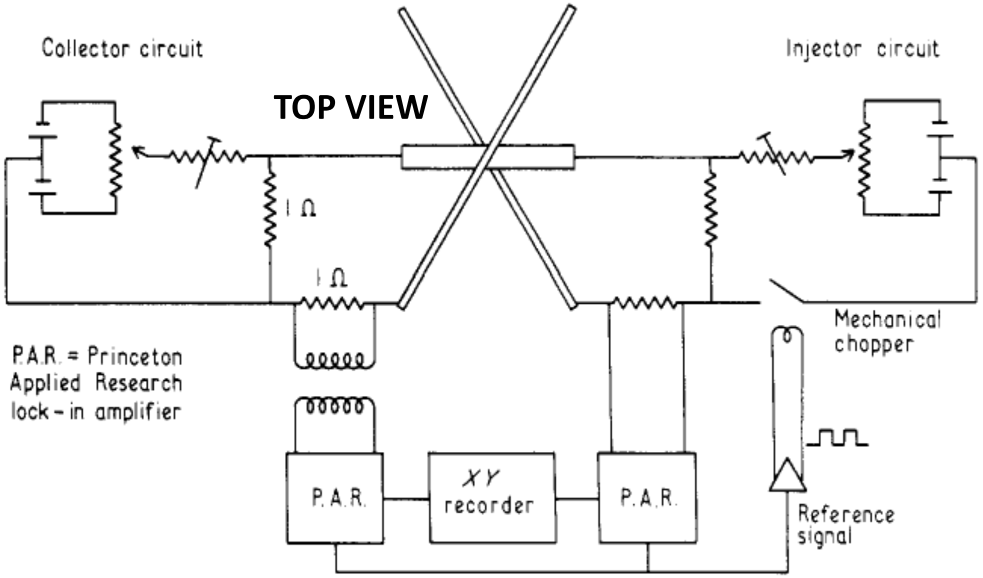
- Spinful excitations in superconductors

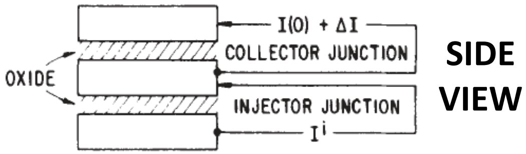
‘STATICS’ (intro)

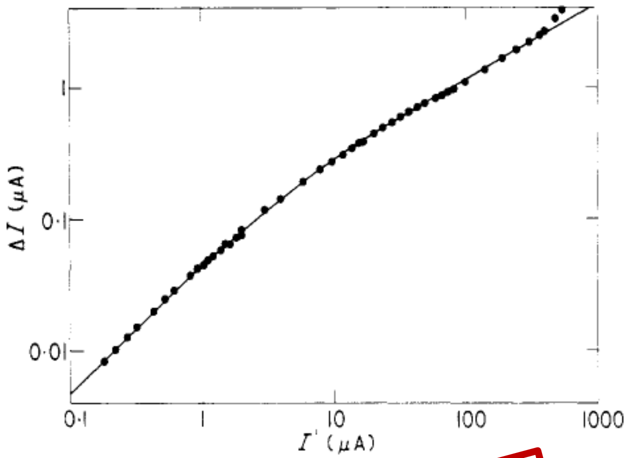
- Quasiparticle spin resonance
- Spin-dependent recombination dynamics (ongoing work)

DYNAMICS

Recombination dynamics (no spin yet)







$\tau_{rc} = 10\text{ns} - 1\mu\text{s}$, depending …

KE Gray, J. Phys. F **1**, 290 (1971) / KE Gray, *Nonequilibrium Superconductivity*

$$\frac{\partial N}{\partial t} = I + 2\Gamma_{PB} N_\omega - R N^2$$

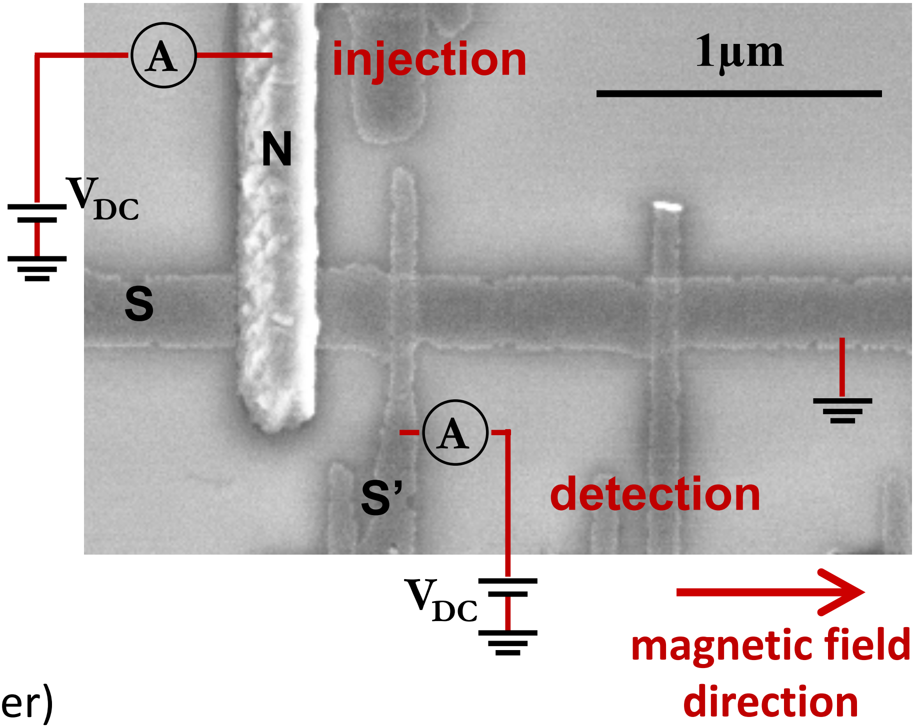
$$\frac{\partial N_\omega}{\partial t} = R N^2 - \Gamma_{PB} N_\omega - \Gamma_E N_\omega$$

onstant

- + spin
- $\Delta(x, I_{inj})$
- $D(x, E, I_{inj})$
- injection density x 1000
- − phonons

A and BN Taylor, PRL **19**, 27 (1967)

Devices for recombination dynamics



Injector-Detector distances

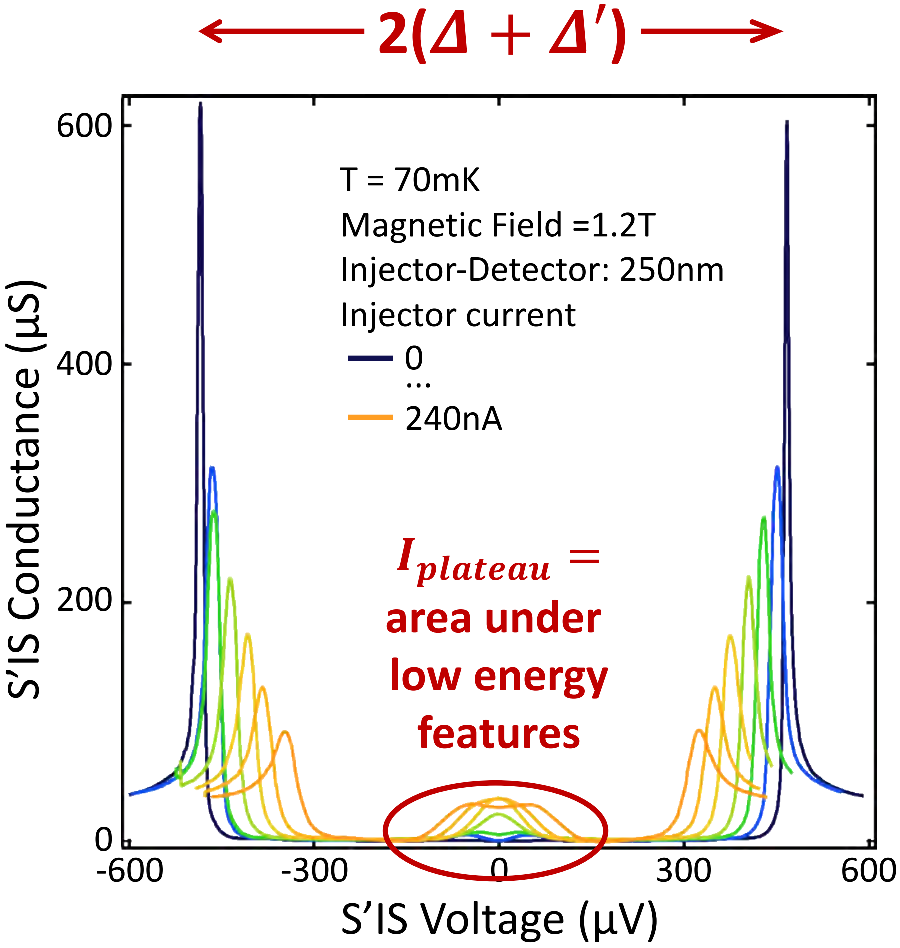
250nm, 350nm, 1400nm,
2250nm, 3250nm

Materials/fabrication details

S = superconductor (6nm Al + oxide layer)
S' = superconductor (8.5nm Al)
N = normal metal (100nm Al, normal at ~50mT)

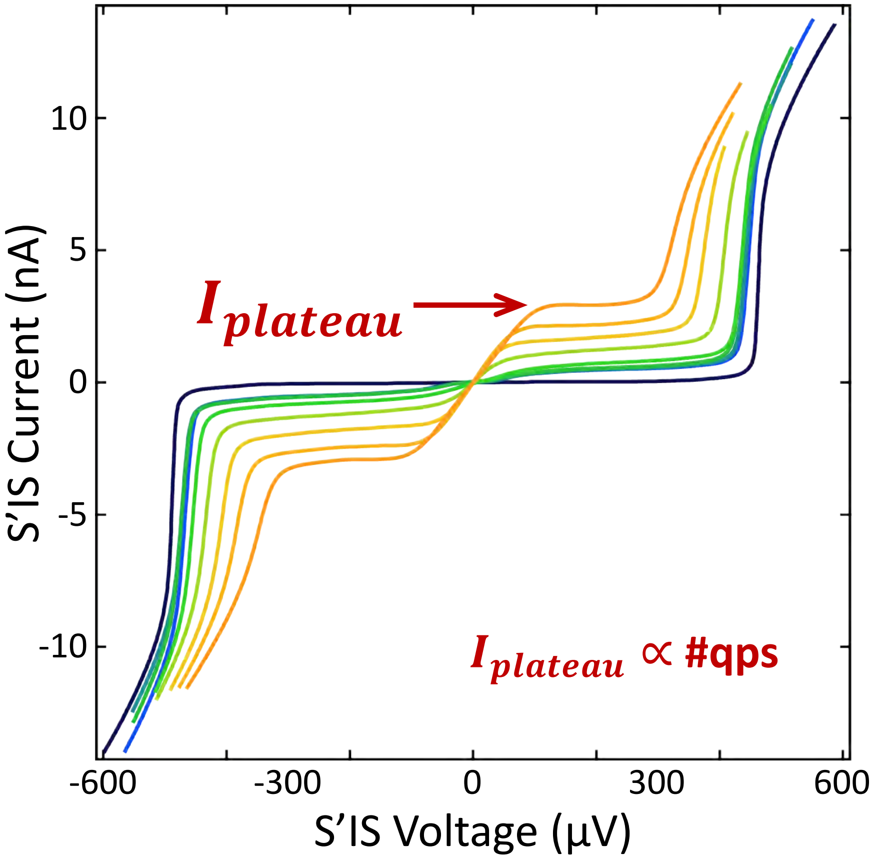
Typical S'IS junction resistance: 30kΩ
Typical NIS junction resistance: 12kΩ

S'IS Detector Signal



$\longleftarrow 2(\Delta + \Delta') \longrightarrow$

$I_{plateau} =$ **area under low energy features**

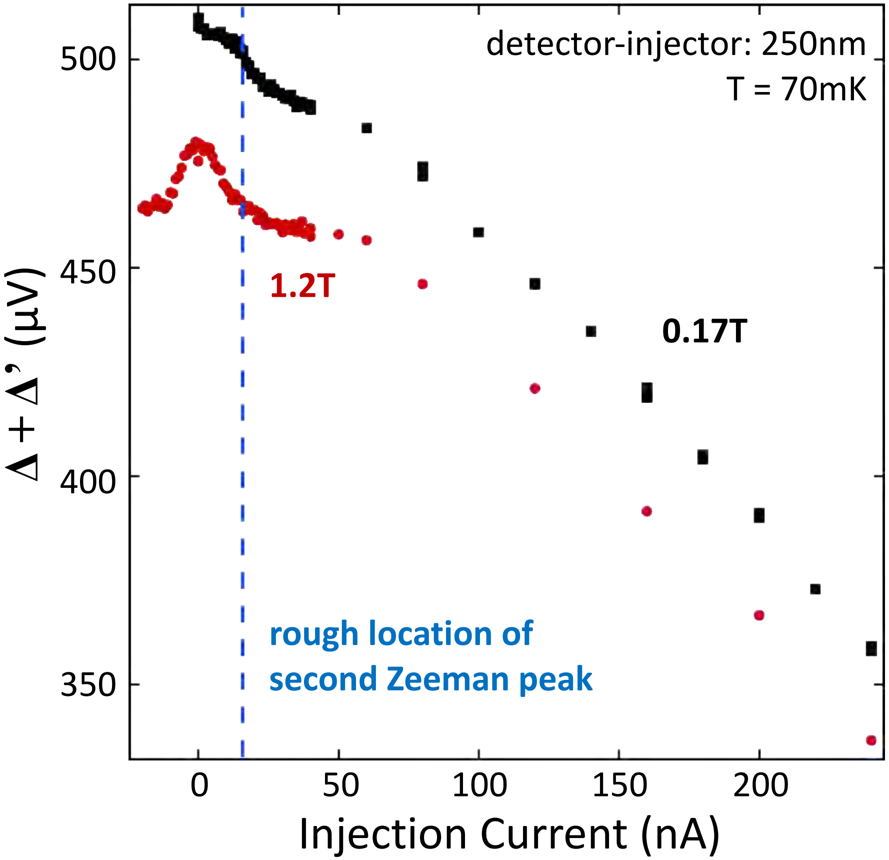


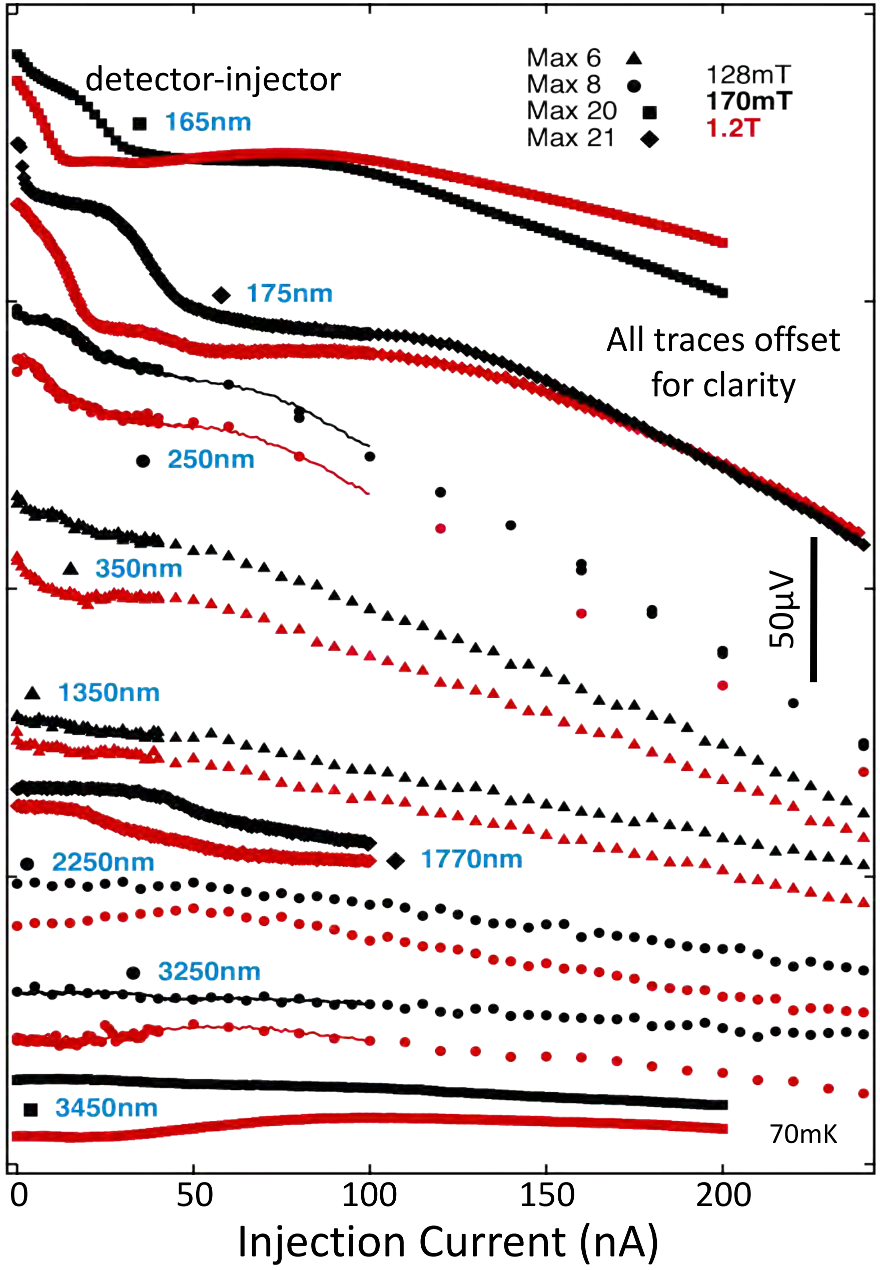
$I_{plateau} \longrightarrow$

$I_{plateau} \propto$ **#qps**

M. Kuzmanović et al., *in preparation*.

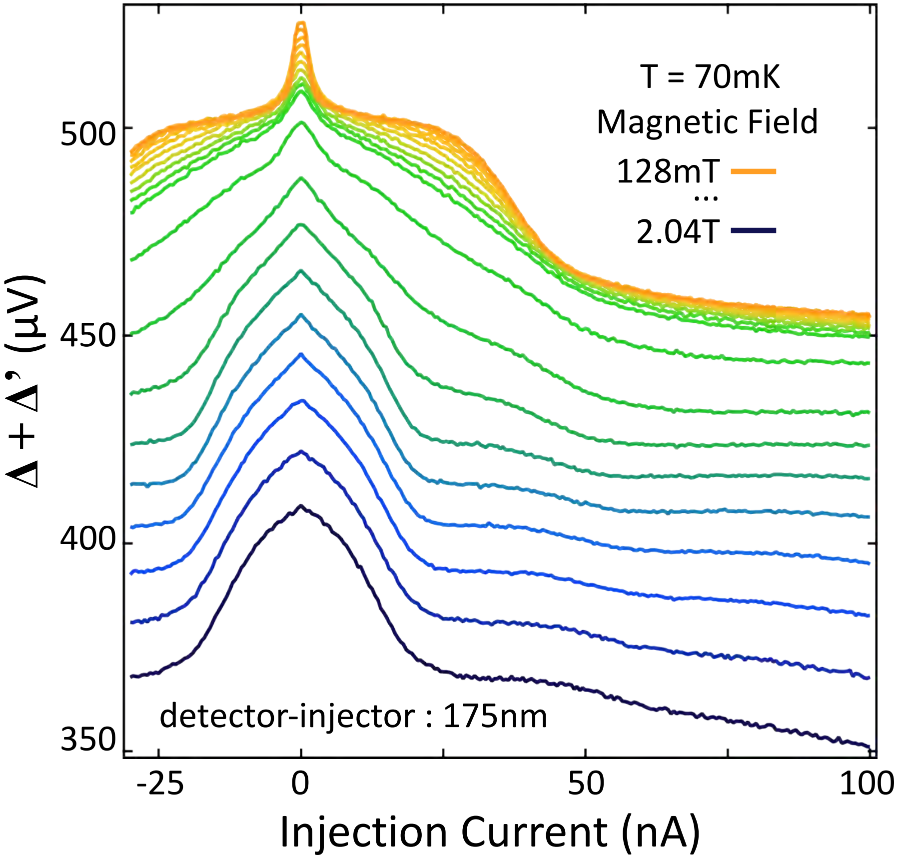
$\Delta + \Delta'$ (field, injection, space)



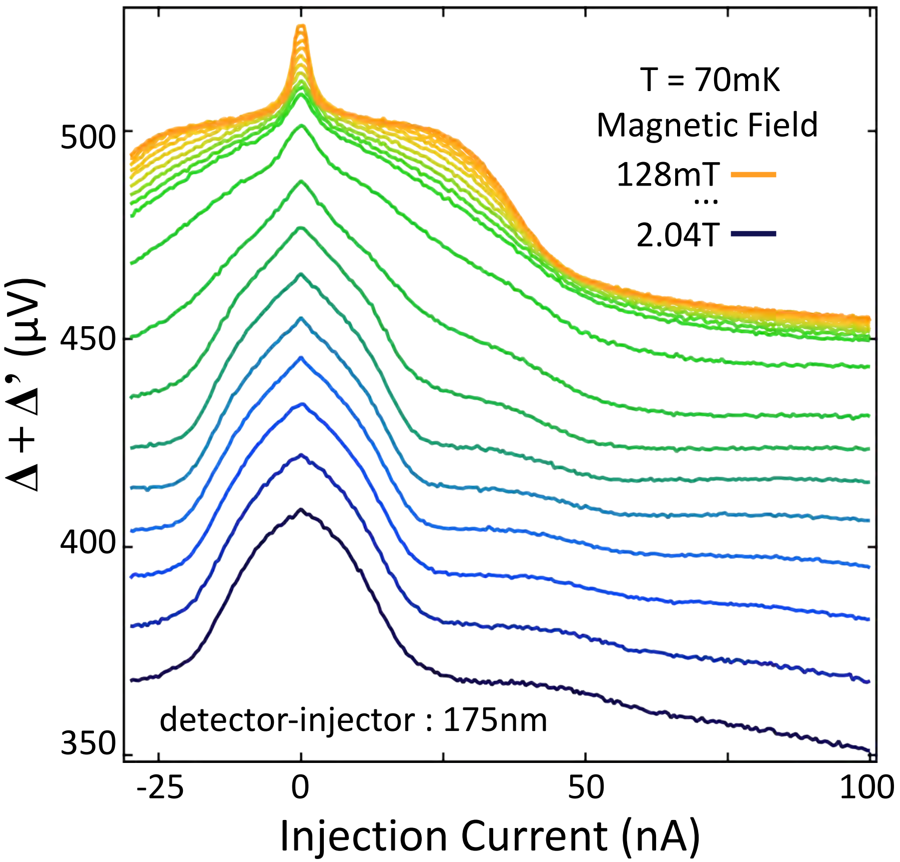


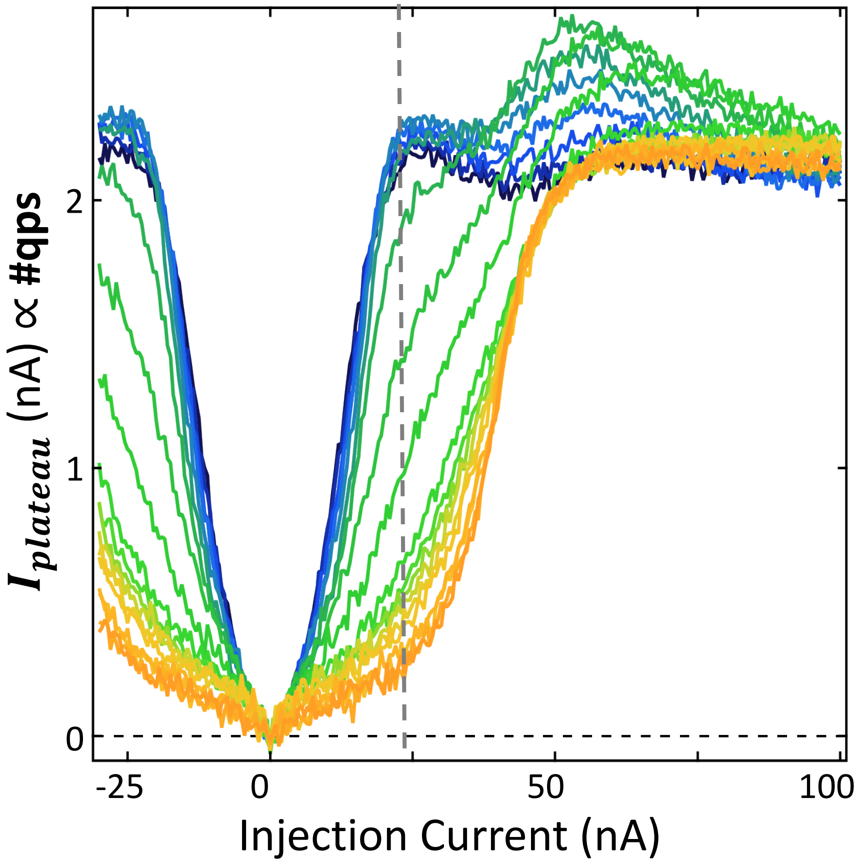
M. Kuzmanović et al., *in preparation.*

$\Delta + \Delta'$: a closer look in field



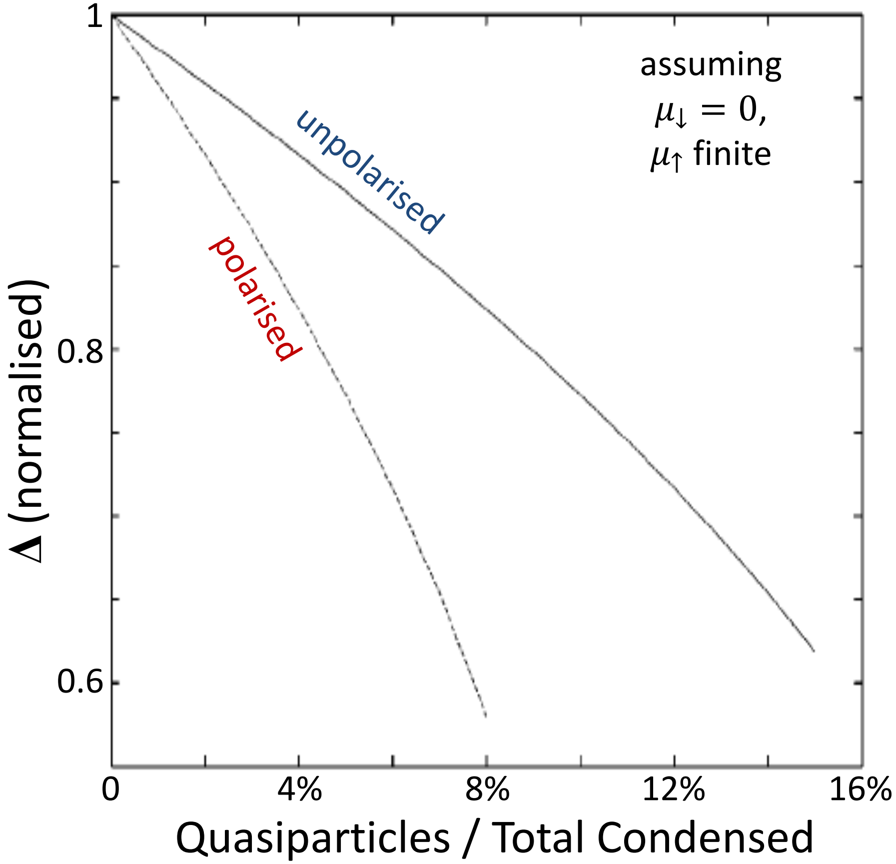
Spin-dependent recombination

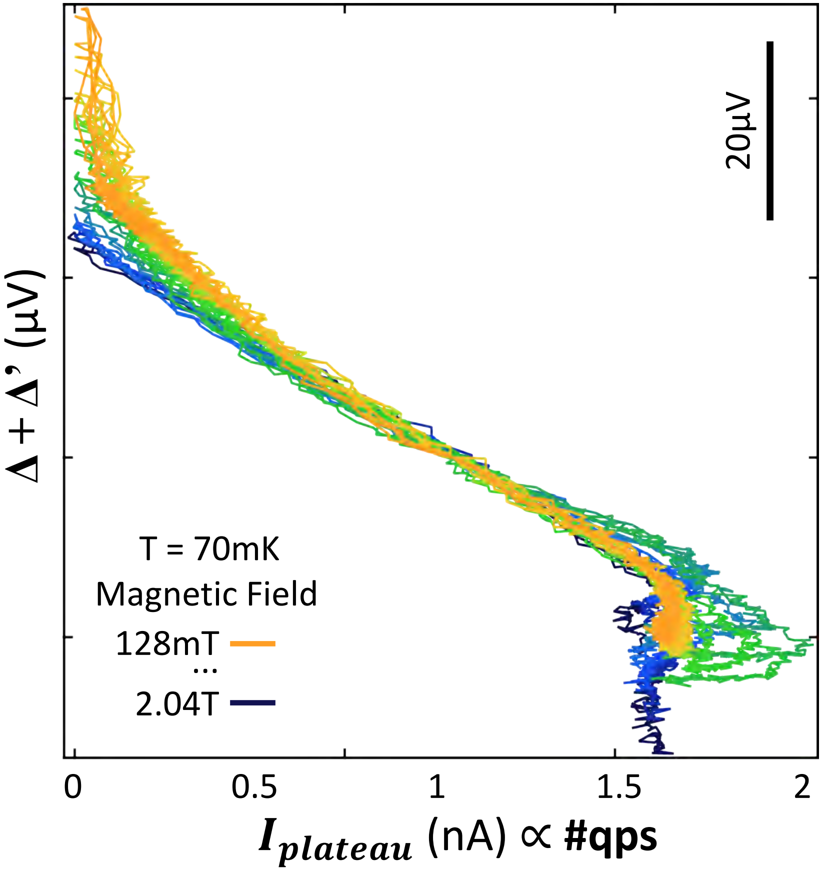




$\frac{\Delta}{\Delta_0} \sim \left(1 - \frac{2N_{QP}}{N_{CP}}\right)$ … or does $\Delta(N_{QP})$ have some spin dependence?

Quasiparticles ↔ Condensate

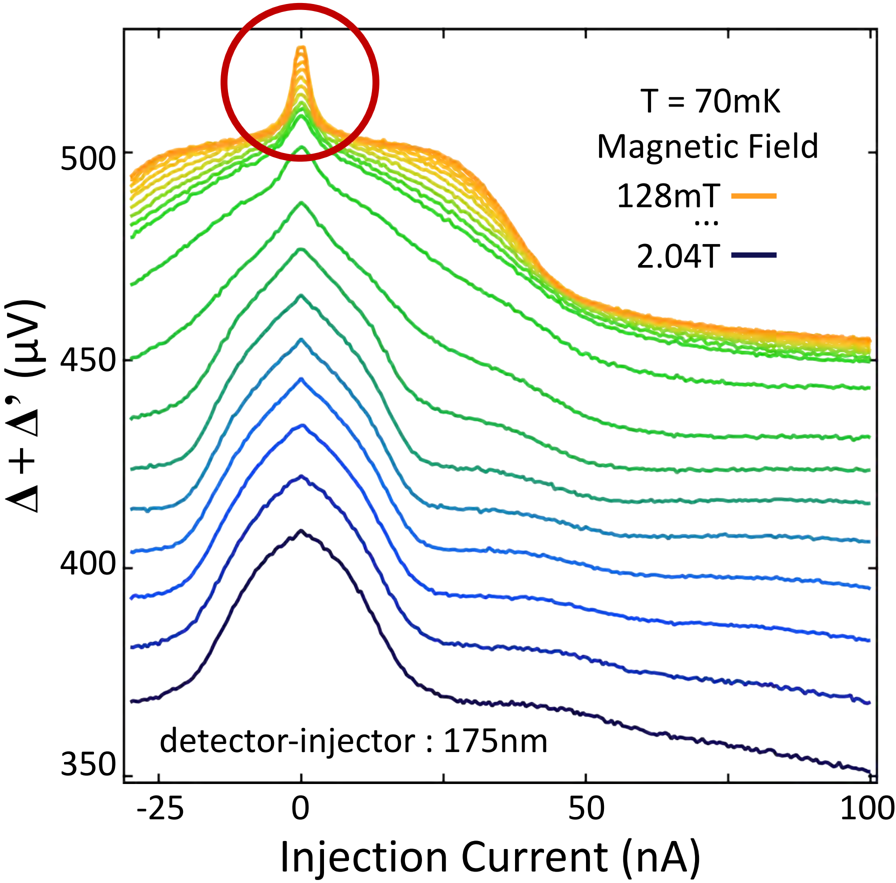


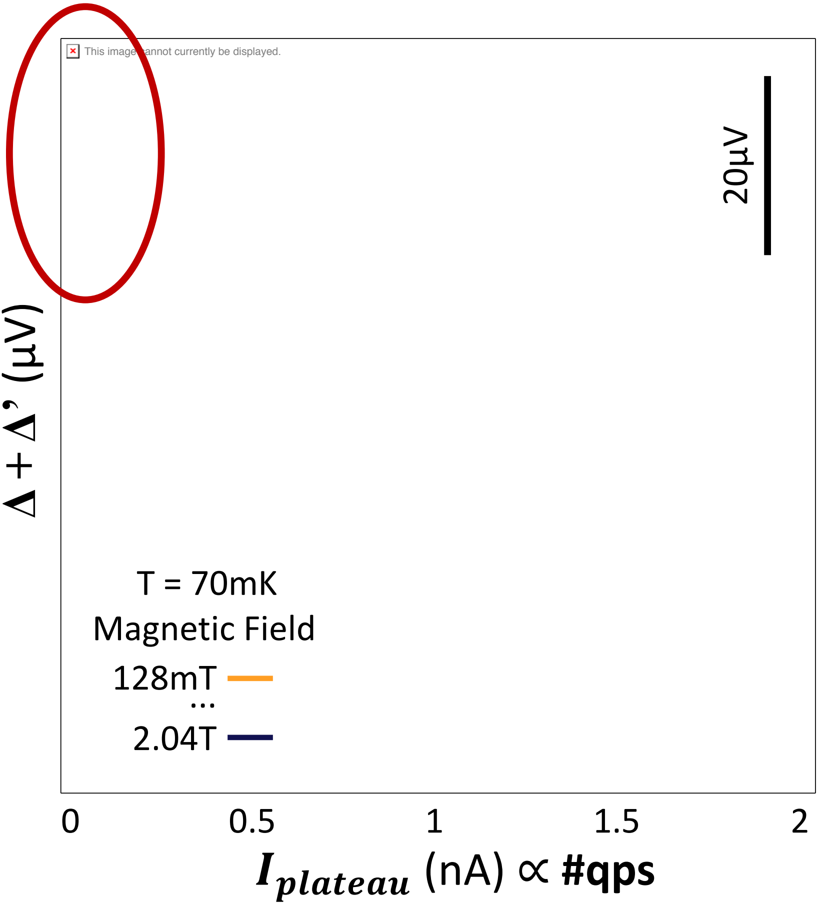


No or minimal *direct* spin effect on the gap Δ

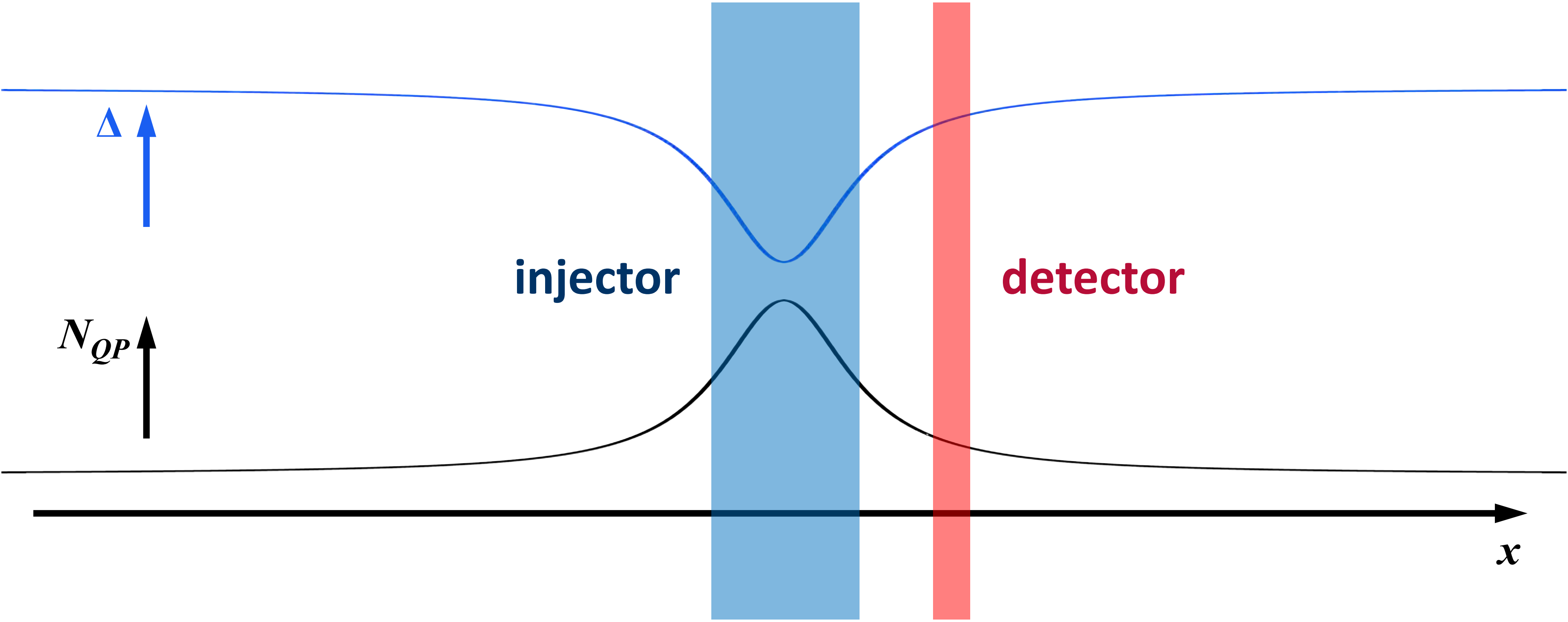
S Bhattacharjee & M Sardar, PRB **62**, R6139 (2000)

Proximity-induced gap change



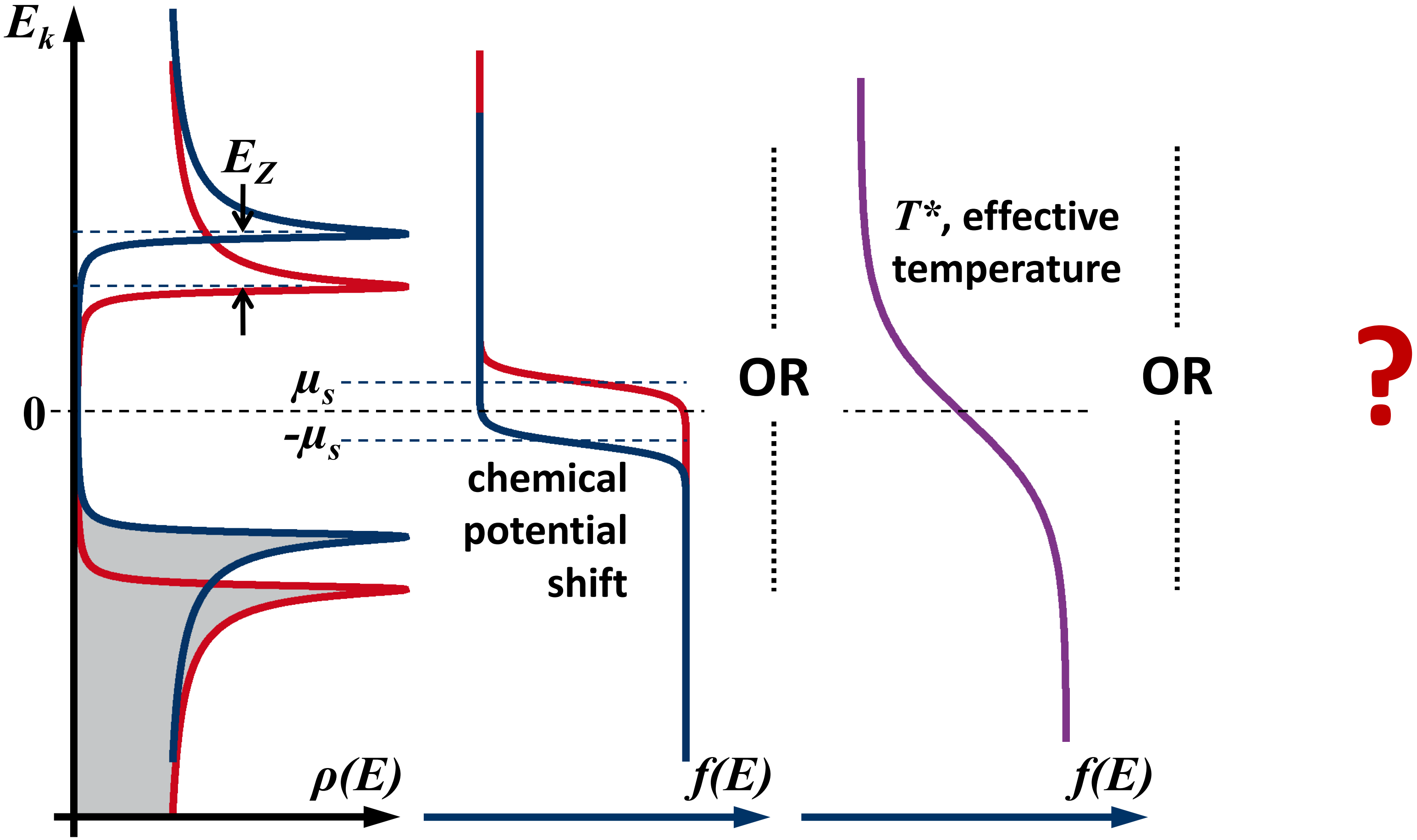


Likely $\Delta(x)$, $N_{QP}(x)$



Andreev processes also have to be taken into account.

Focus on $f(E, x = \text{detector})$



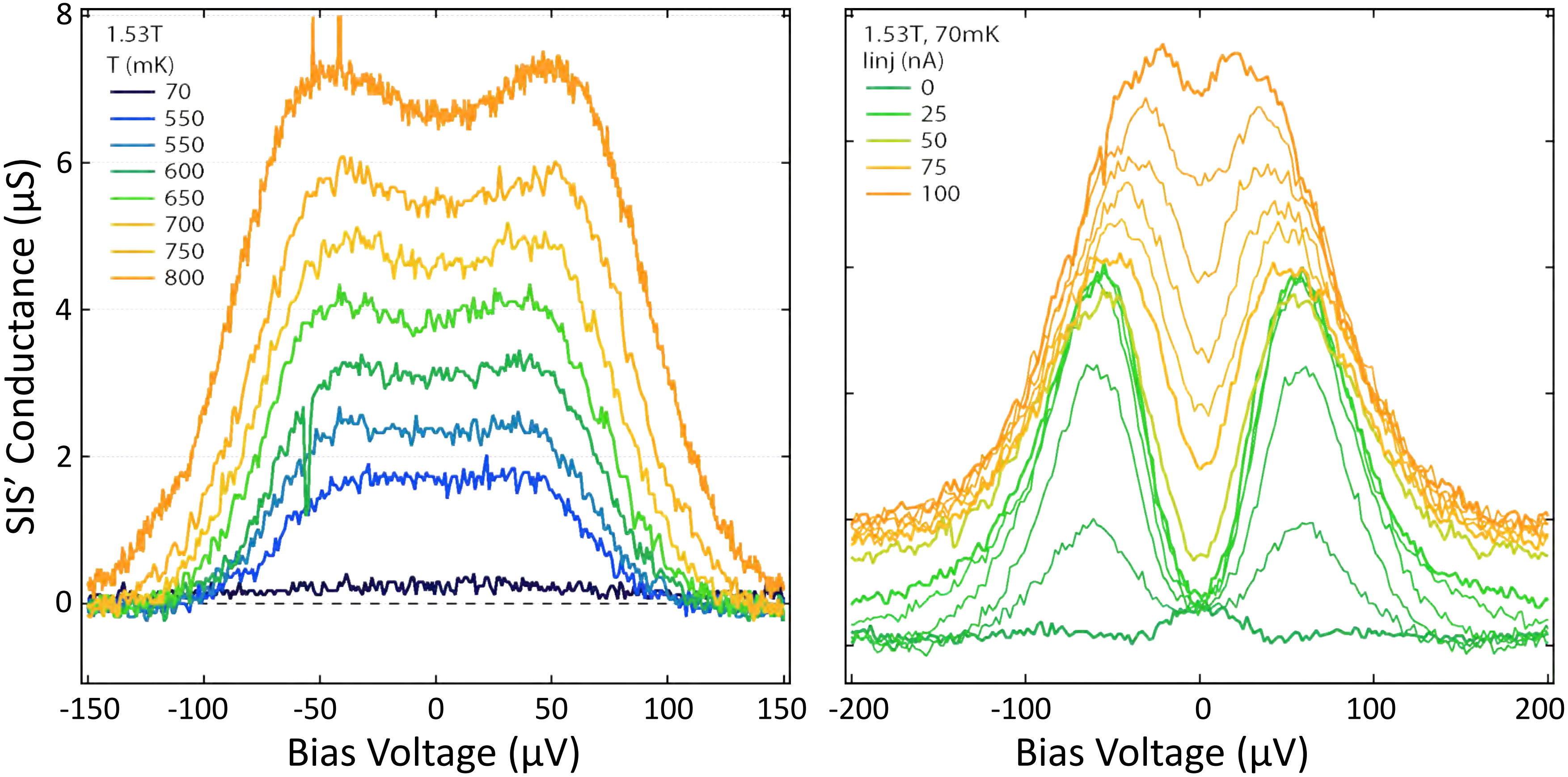
chemical potential shift

T^*, effective temperature

density of states

out-of-equilibrium distribution functions

$f(E)$ is non-Fermi-Dirac…



$f(E)$ from deconvolution & fits

- Deconvolution of detector $G(V)$
- Spinful fit

$$f_\uparrow(E) = a_\uparrow f_{FD}(T_\uparrow, \mu_\uparrow)$$

$$f_\downarrow(E) = a_\downarrow f_{FD}(T_\downarrow, \mu_\downarrow) \qquad E > 0$$

- Spinless fit

$$f(E) = a_1 f_{FD}(T_1, \mu_1) + a_2 f_{FD}(T_2, \mu_2)$$

- Effective temperature fit

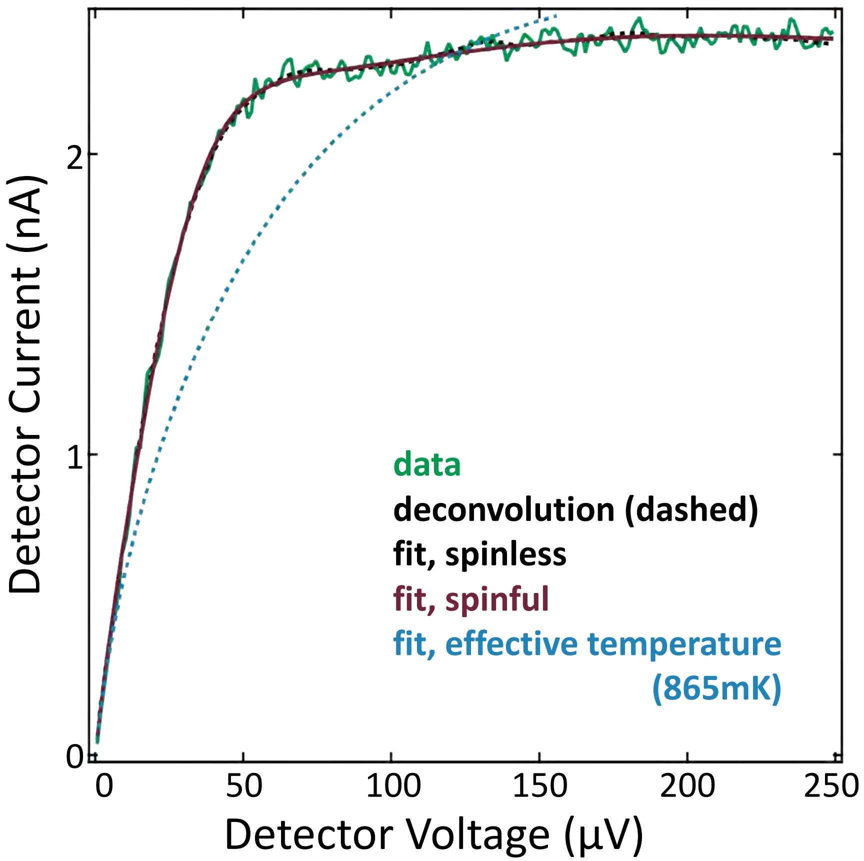
$$f(E) = f_{FD}(T^*, 0)$$

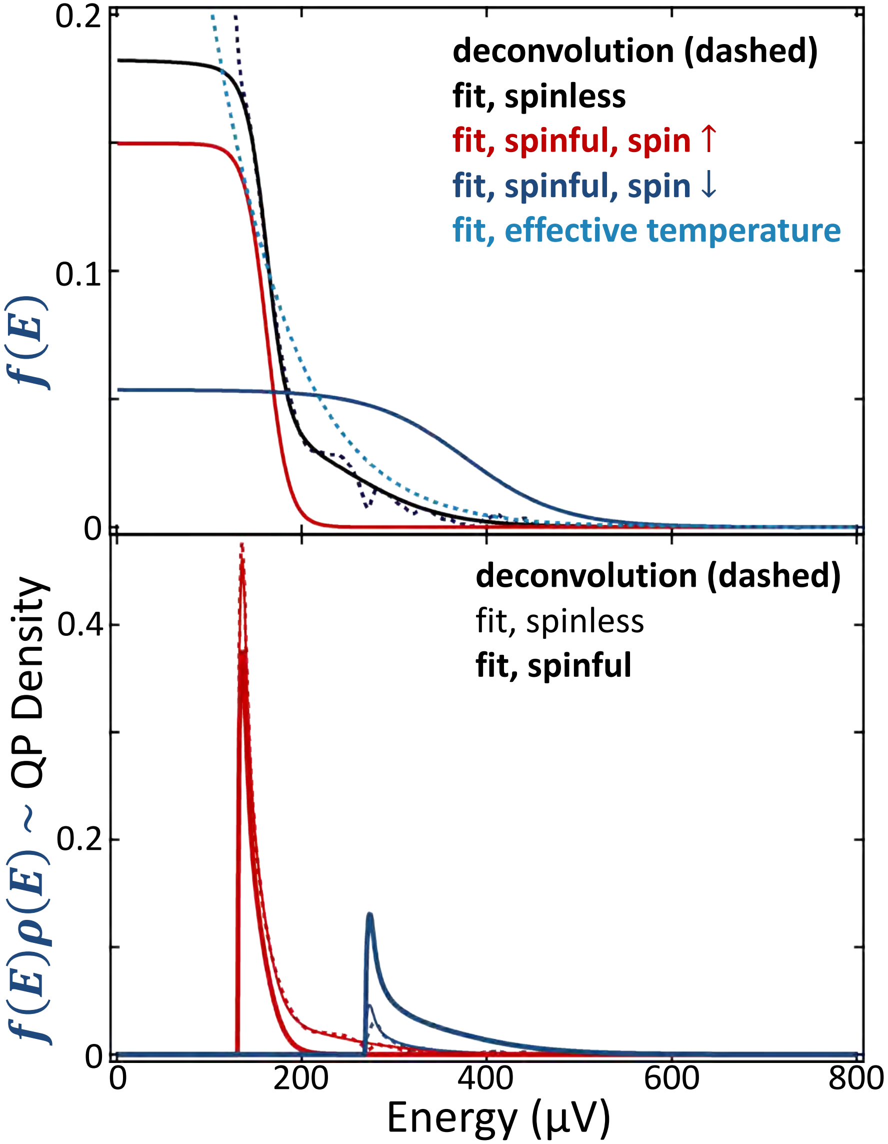
Assumptions: $\Delta_S = \Delta_{det}, f_S(E) = f_{det}(E)$

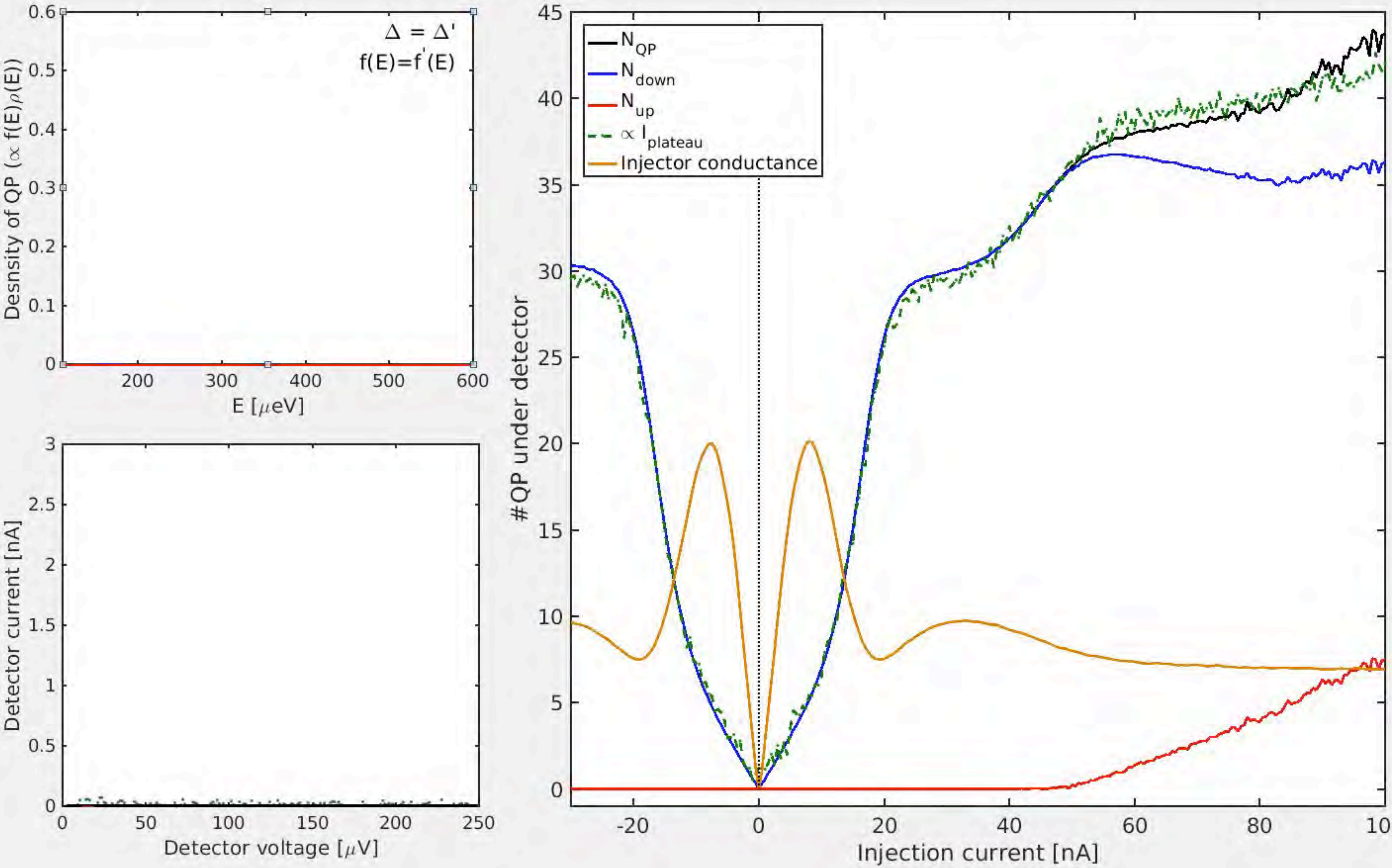
D. R. Heslinga & T. M. Klapwijk, PRB, **47**, 5157 (1993)

$f(E)$ from deconvolution & fits

I_{inj} = 80nA






Δ = Δ'
f(E)=f'(E)
Desnsity of QP (∝ f(E)ρ(E))
0
0.1
0.2
0.3
0.4
0.5
0.6
200
300
400
500
600
E [μeV]
Detector current [nA]
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250
Detector voltage [μV]
#QP under detector
0
5
10
15
20
25
30
35
40
45
-20
0
20
40
60
80
100
Injection current [nA]
N_QP
N_down
N_up
∝ I_plateau
Injector conductance

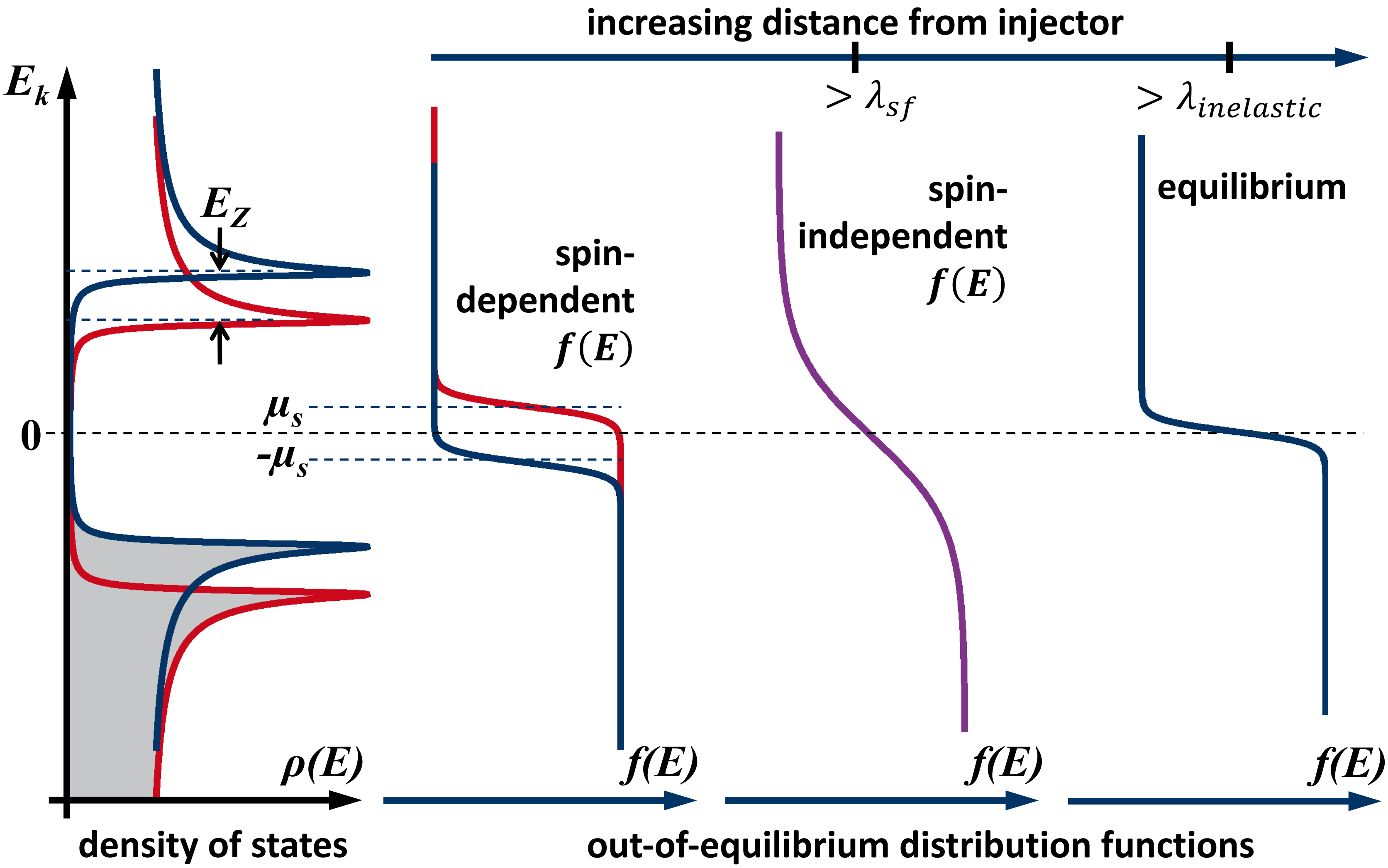
Problems with $f(E)$ determination

- Strong assumptions
- Does not work for all samples

Samples in preparation

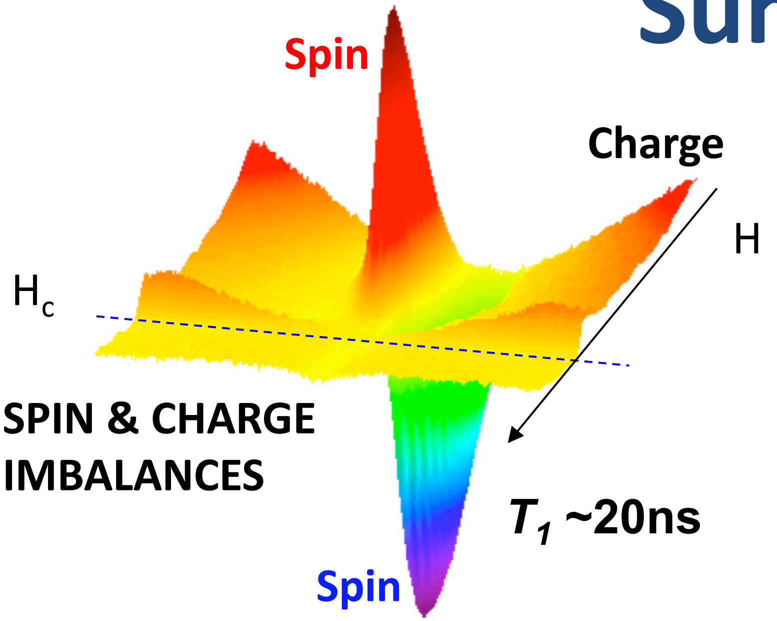
- Thicker injector to keep injector at equilibrium
- Al/Pt/Al detector to remove Zeeman splitting in detector, spinless/spinful fit ambiguity
- More resistive detector barrier

Likely spatial dependence of $f(E)$



+ trapping effects + …

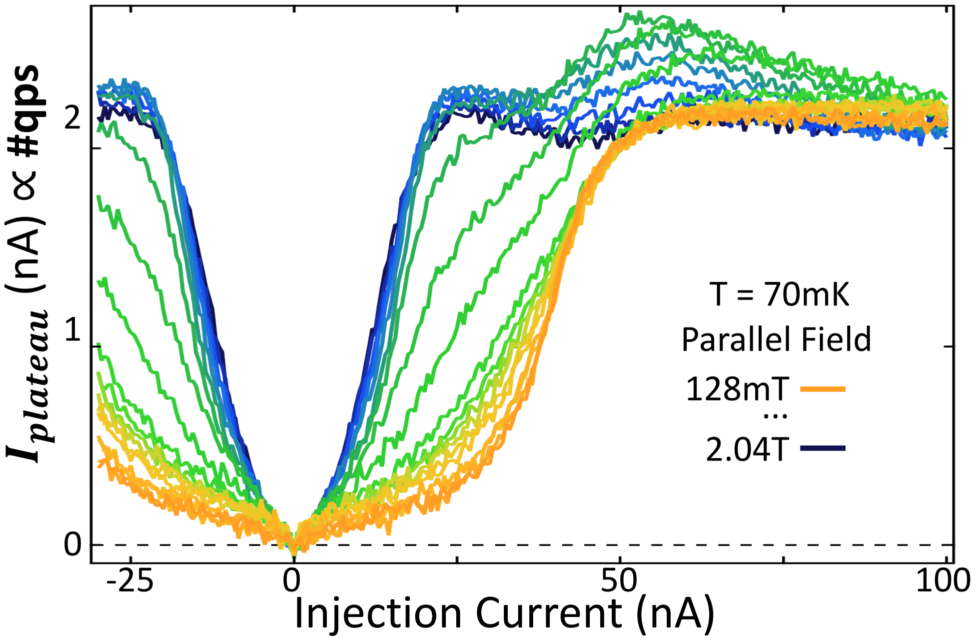
Summary



SPIN & CHARGE IMBALANCES

***T_1* ~20ns**

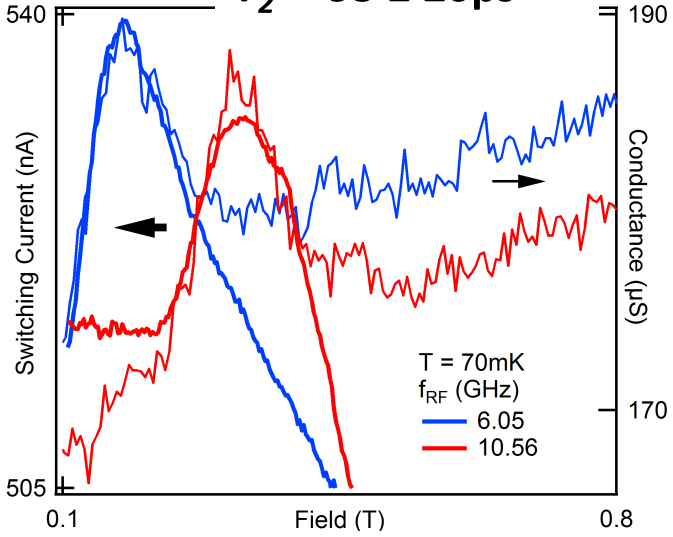
SPIN-DEPENDENT RECOMBINATION

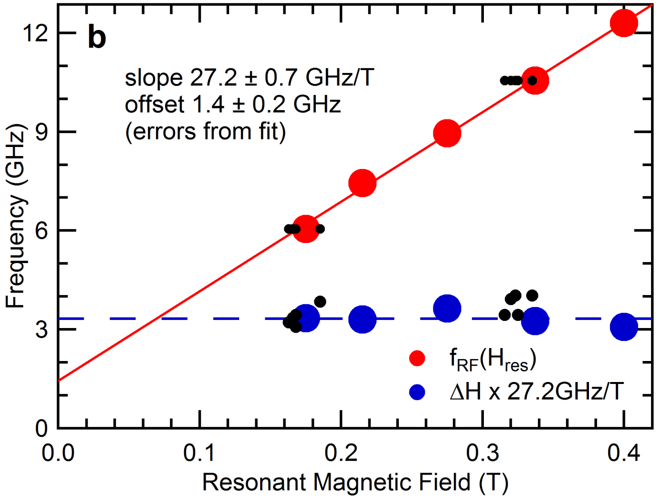


SPIN RESONANCE

***g* = 1.95 ± 0.2**

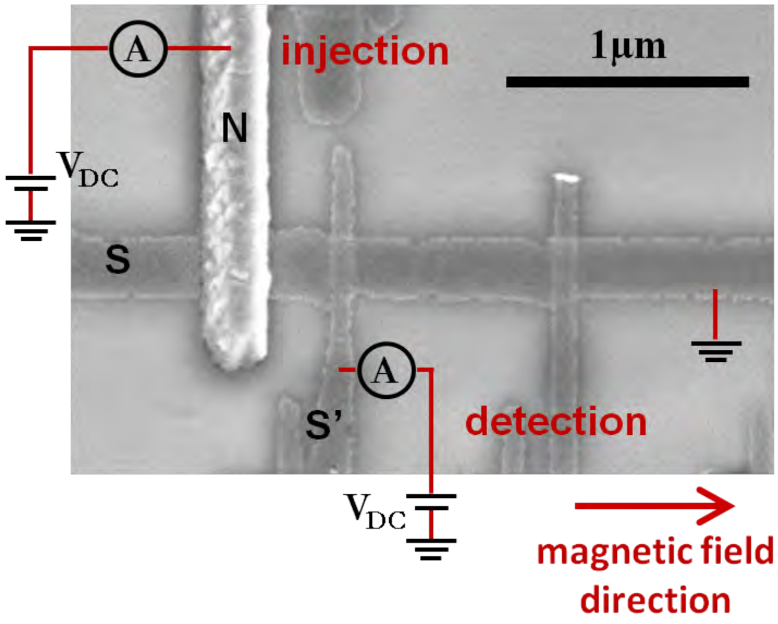
***T_2* = 95 ± 20ps**

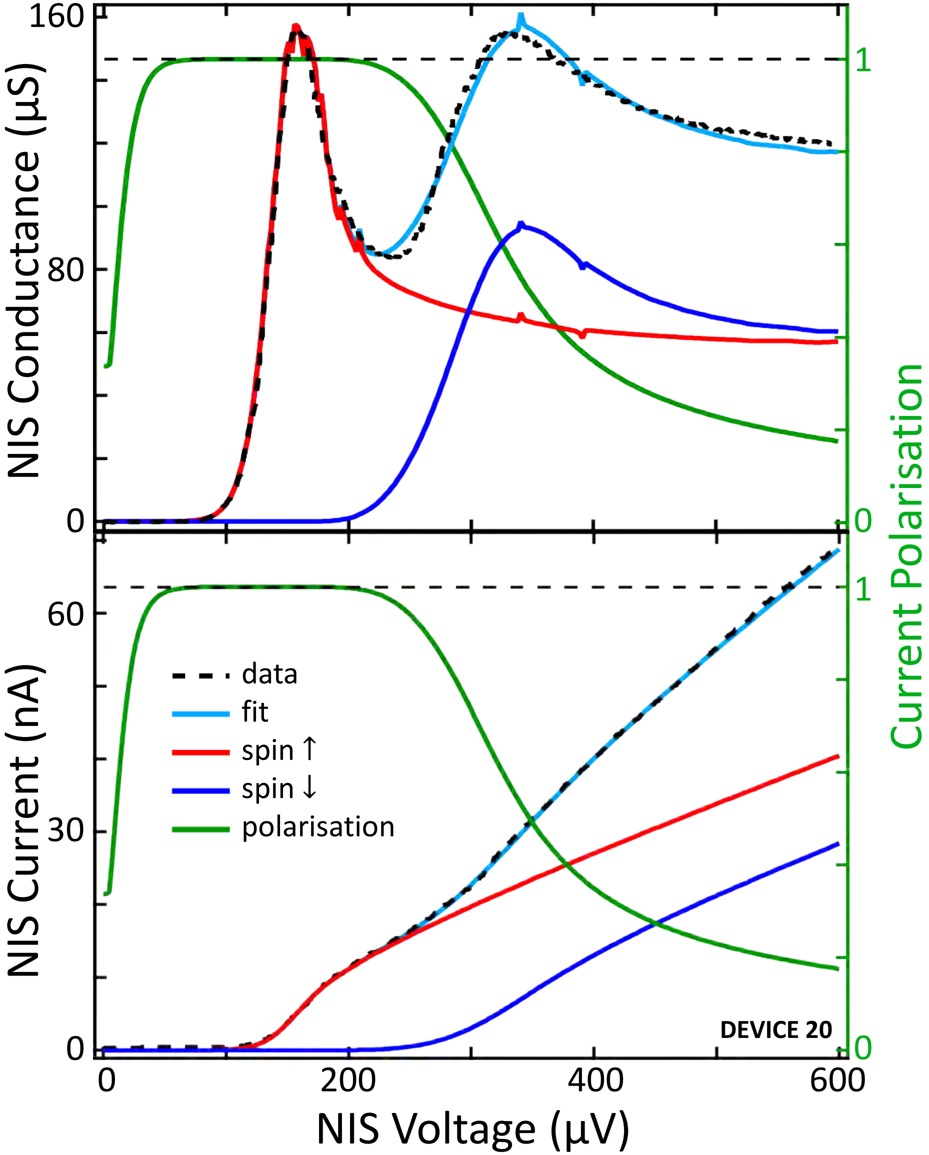




Perspectives

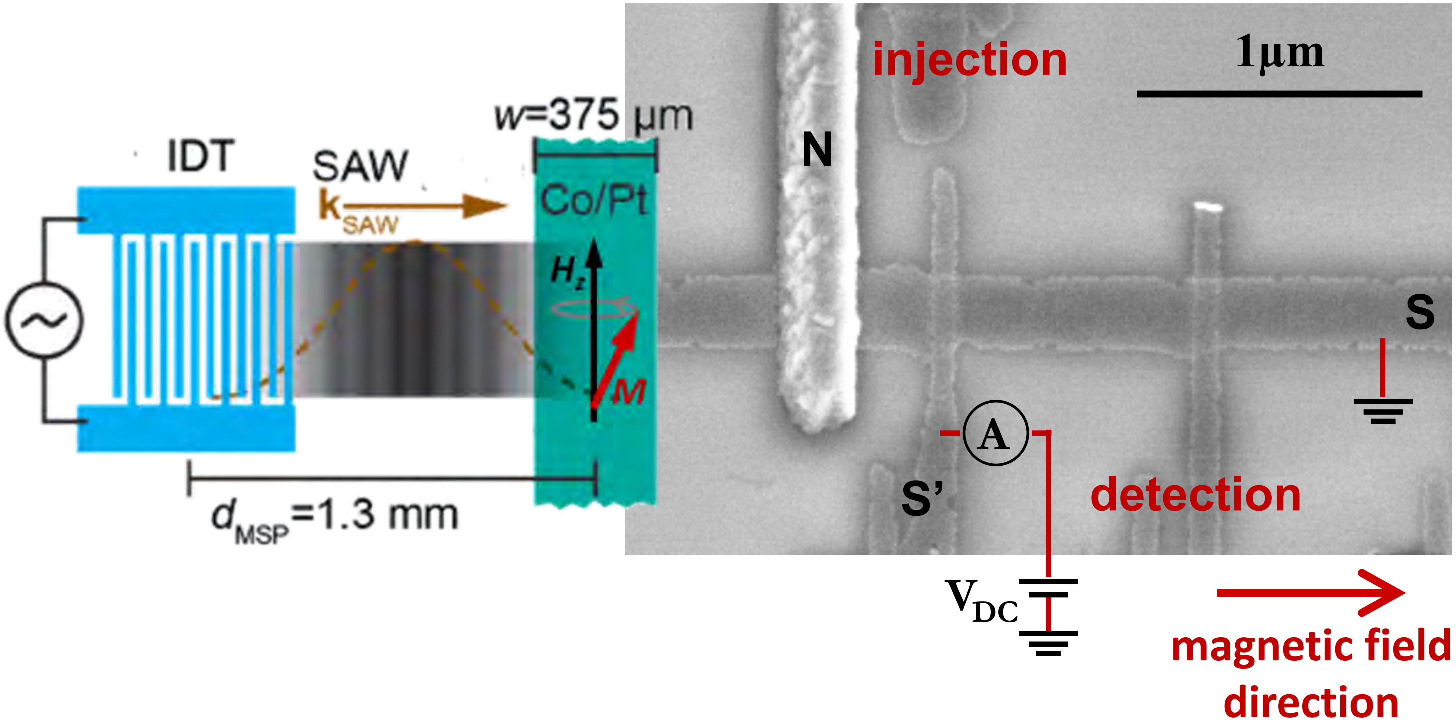
Excitation by injection constrainted by $I(V)$ of junction!





Perspectives

spin injection by acoustically excited ferromagnetic resonances



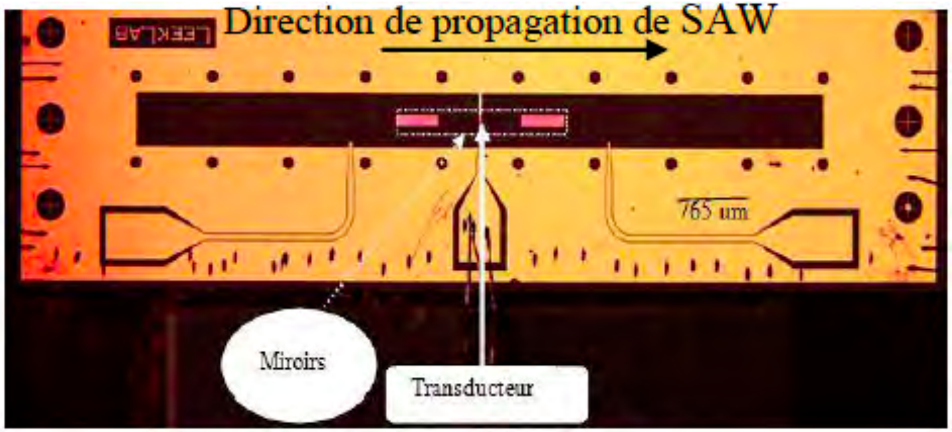
- Low-energy spin injection
- Spin current determined by RF drive power

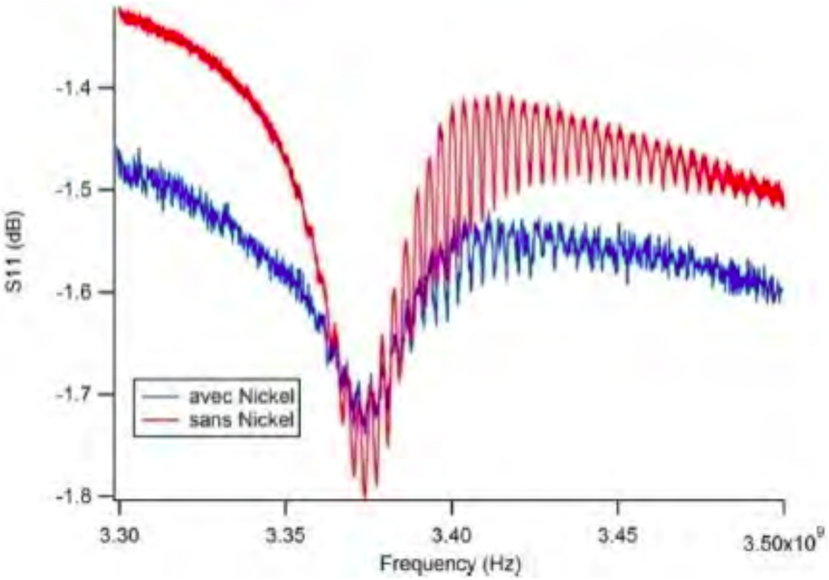
M Weiler et al., PRL **106**, 117601 (2011) / M Weiler et al., PRL **108**, 176601 (2012)

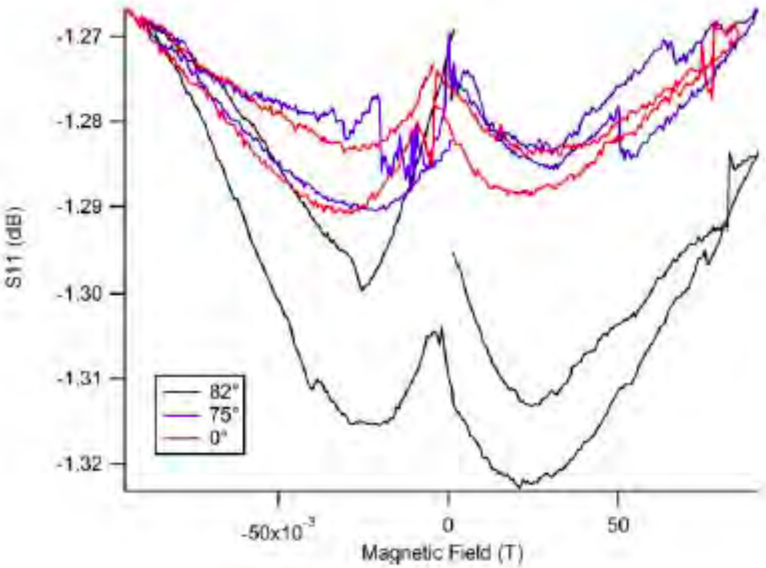
Perspectives

spin injection by acoustically excited ferromagnetic resonances

Collaboration with Peter Leek (Oxford)



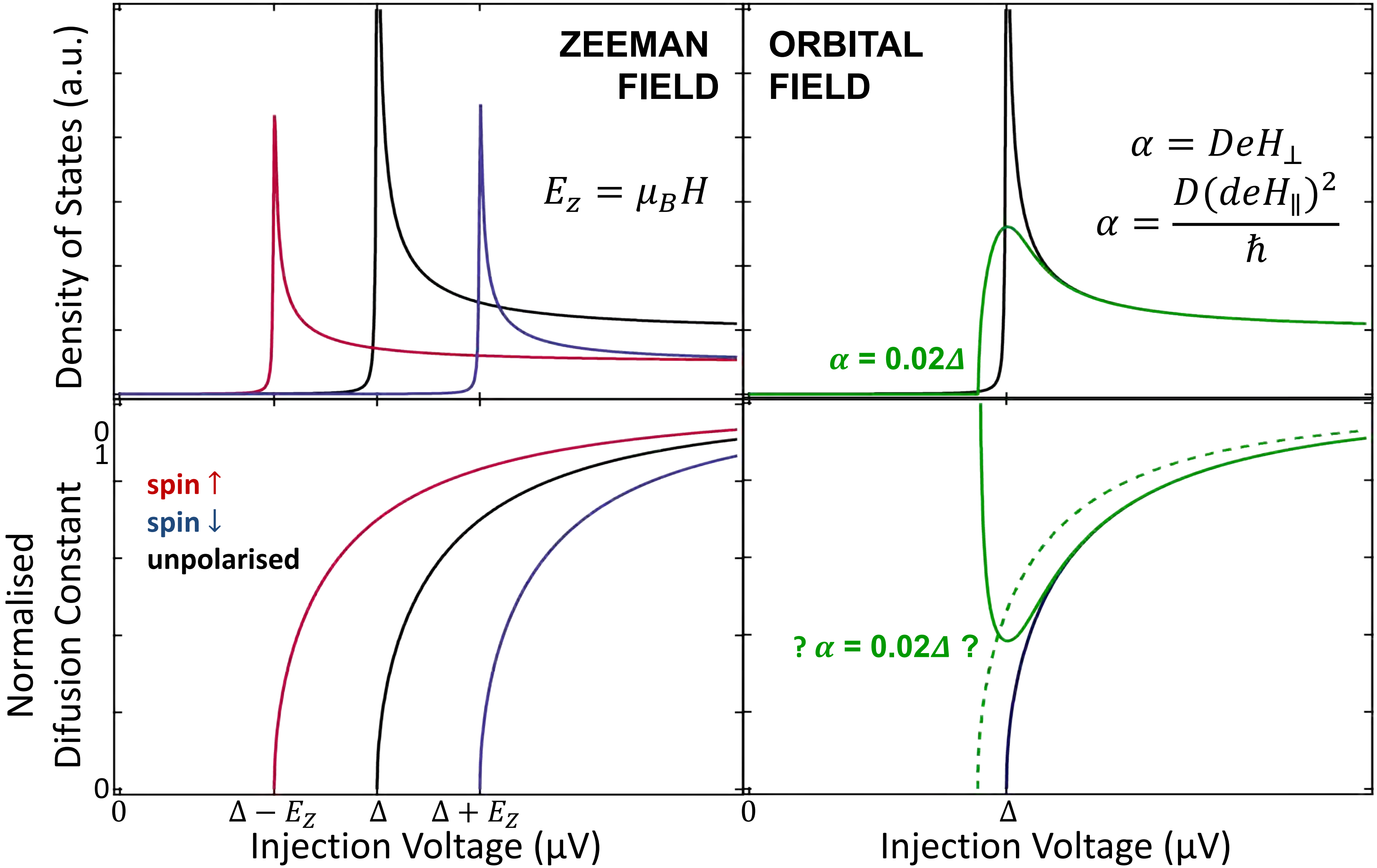




F Ben Chaabane internship report

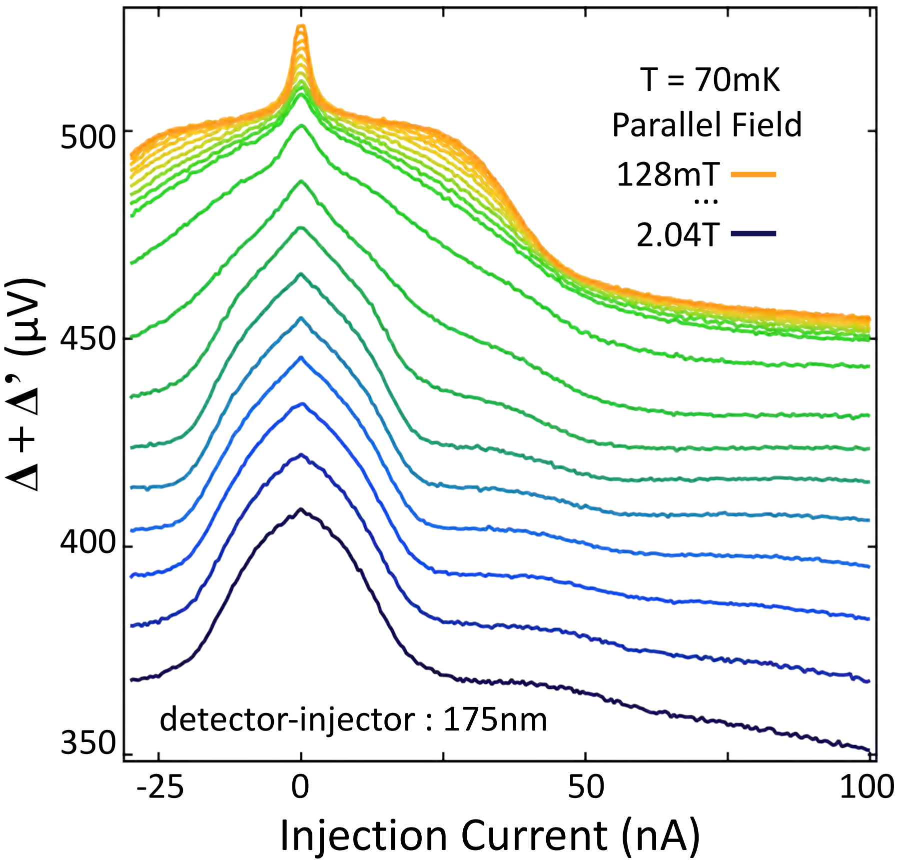
Questions?

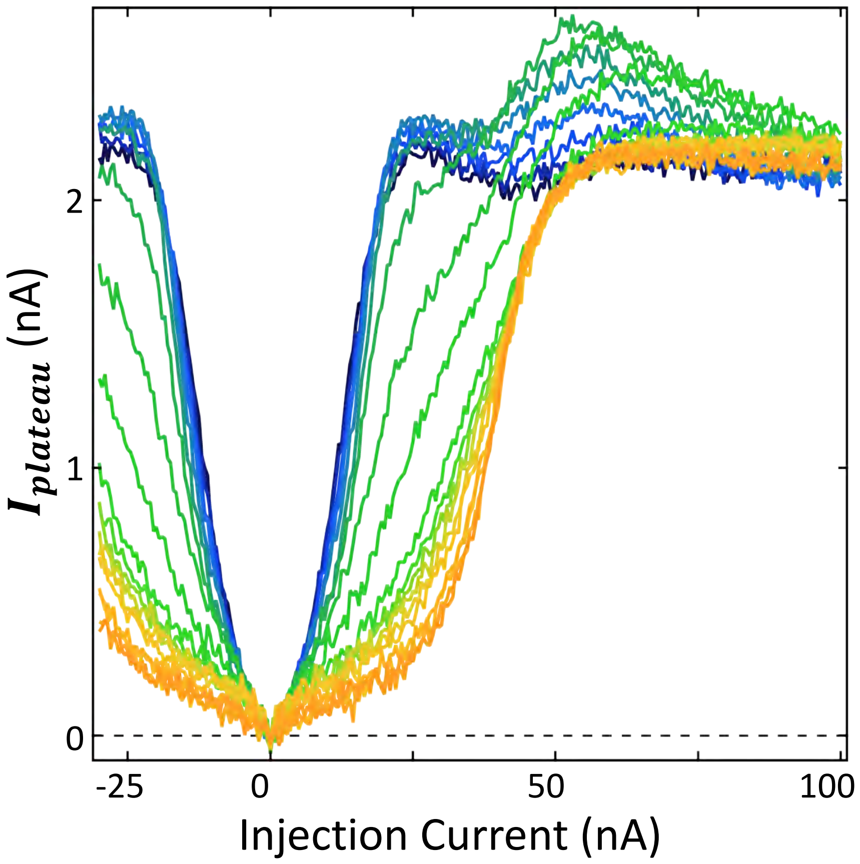
Effects of magnetic field



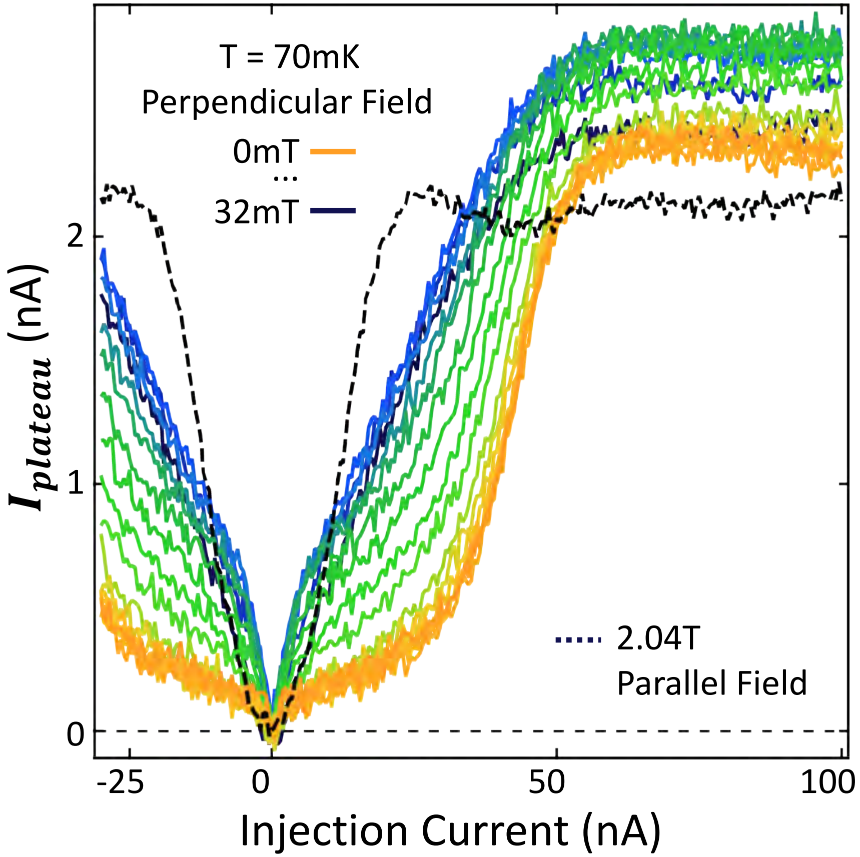
- Both present in parallel field (due to finite sample thickness)
- Diffusion dependence on energy in orbital field unknown
- Perpendicular (purely orbital) field can disentangle effects

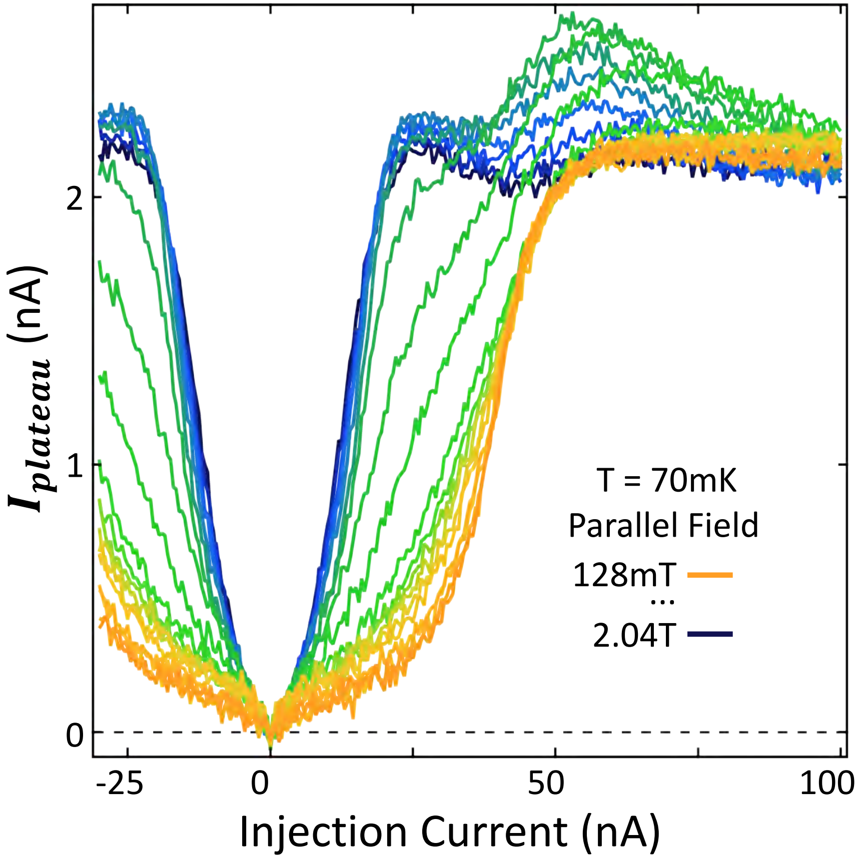
Parallel field



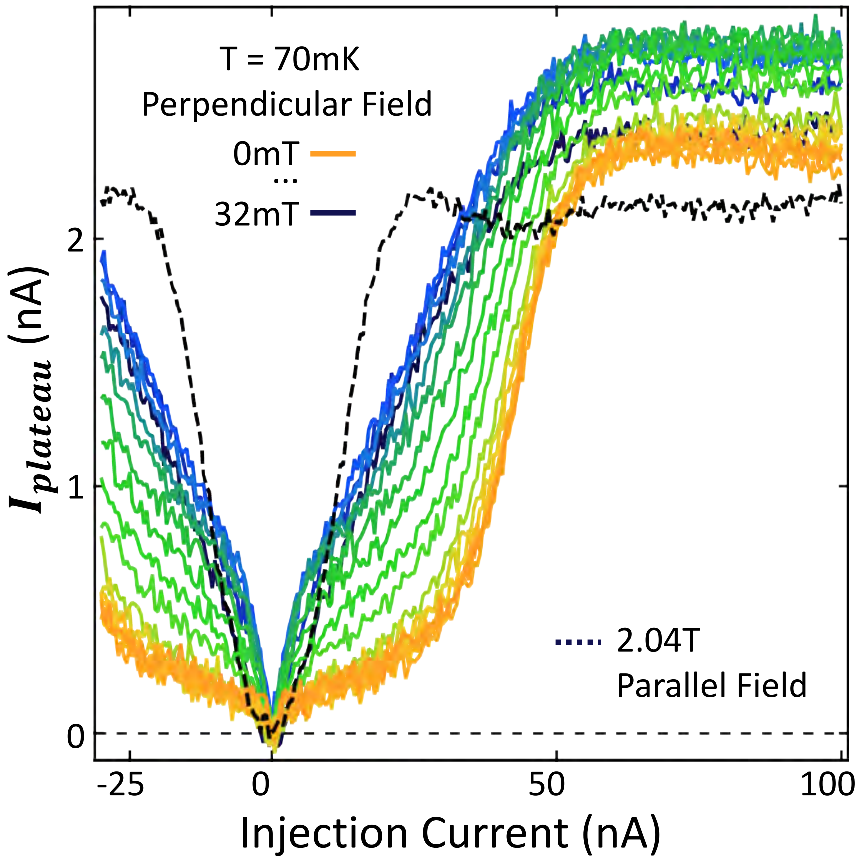


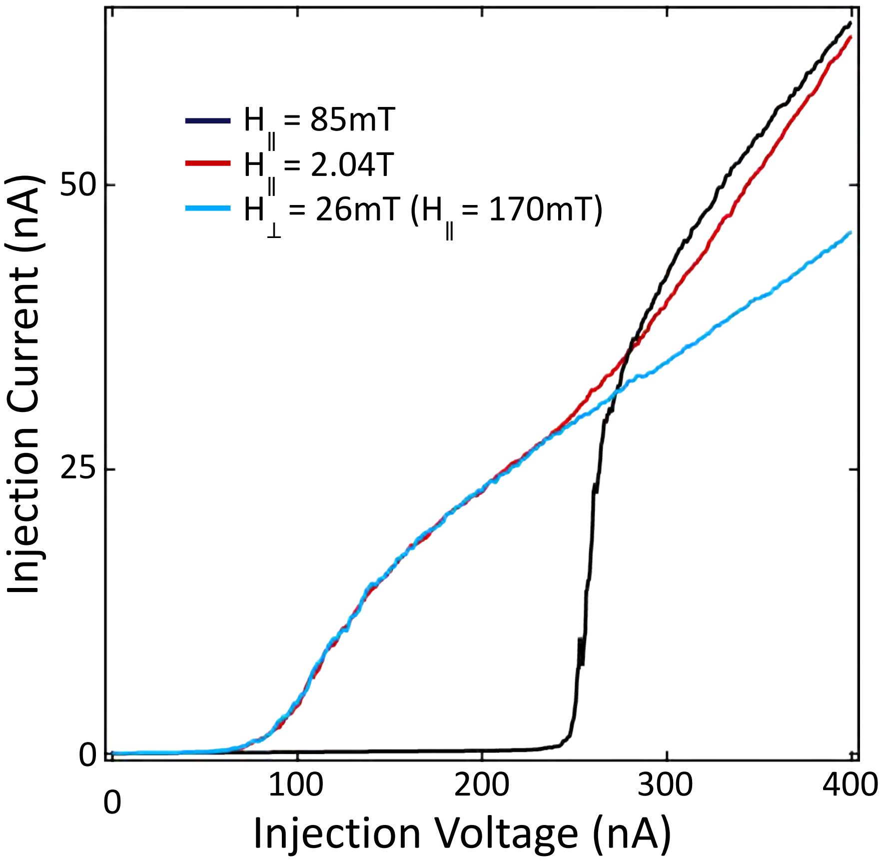
Parallel vs perpendicular field





Parallel vs perpendicular field





Perpendicular field