Phase-driven manipulation of a superconducting nanowire

A twist on the Cooper pair condensate

Alberto Ronzani

Saclay – April 1st, 2016

C.N.R. – Istituto Nanoscienze and Scuola Normale Superiore, Pisa

motivation

It is known that the superconducting order parameter is strongly affected by breaking of time reversal symmetry.

Examples:

- magnetic impurities
- applied magnetic field
- current bias

The effect of all these sources is depairing, i.e., a suppression in the spatial density of Cooper pairs, corresponding to a weakening of superconductivity.

Kinetic depairing is associated with high values of the Cooper pair velocity, which itself is proportional to the gradient of the gauge-invariant superconducting **phase**.

See e.g., Anthore *et al.*, **P.R.L.** 90, 127001

Is it possible to depair a superconductor only with phase bias techniques?

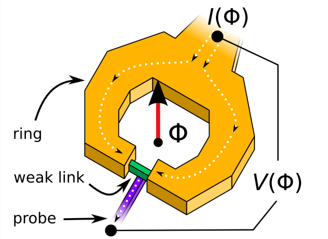
Superconducting QUantum Interference Proximity Transistor

SQUIPT: a sensor for magnetic flux

It is based on a tunnel junction between a probe electrode and a normal metal weak link.

The latter is in clean contact with a superconducting ring threaded by a magnetic flux.

The current–voltage characteristics are modulated by the applied flux with period $\Phi_0 = h/2e$ as a consequence of the phase-dependent proximization of the weak link.

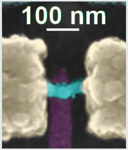


- high responsivity
- micrometric size
- sub-pW power

Inside the interferometer loop:

We switch the `S-N-S` junction with a `S-S'-S` constriction

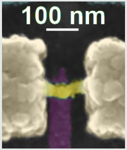
from Al/Cu/Al ...



typical wire

L	175	nm
W	60	nm
T	25	nm

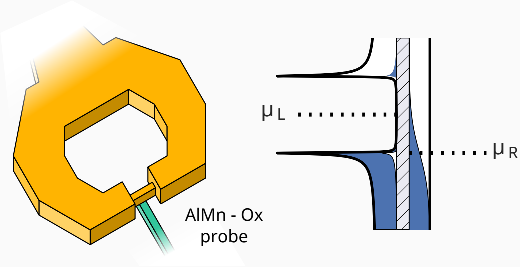
... to Al/Al/Al



Tunnel spectroscopy data

wire geometry

L x W x T = $170 \times 60 \times 25\,\mathrm{nm}$



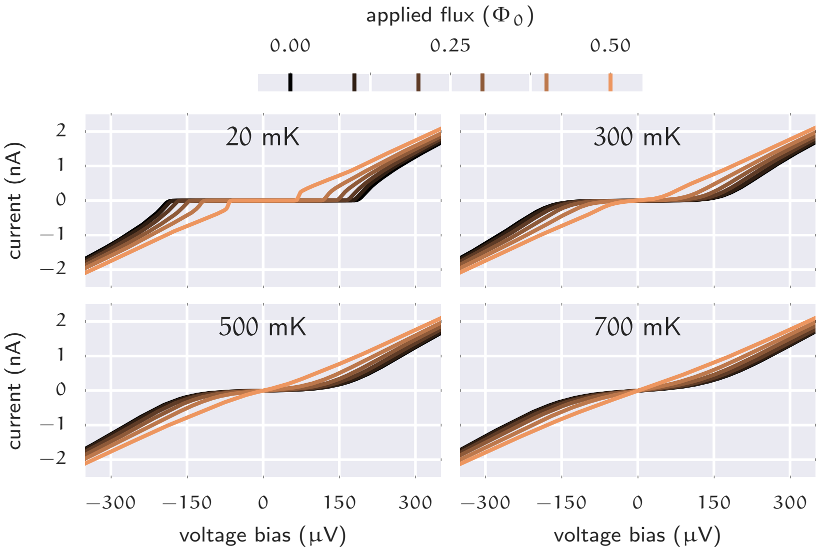
AlMn - Ox probe

2% manganese doping kills superconductivity

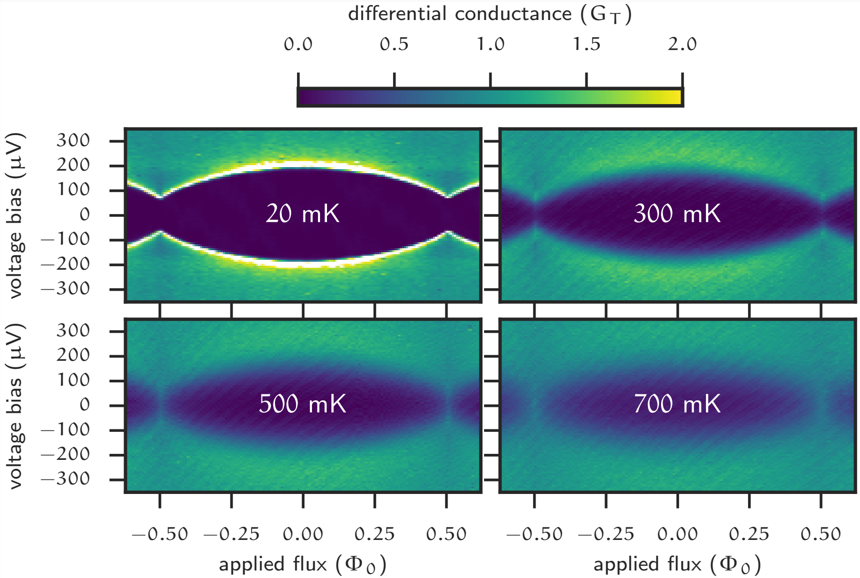
Tunnel barrier

resistance $\simeq 150\,\mathrm{k\Omega}$
surface $\simeq 5400\,\mathrm{nm}^2$

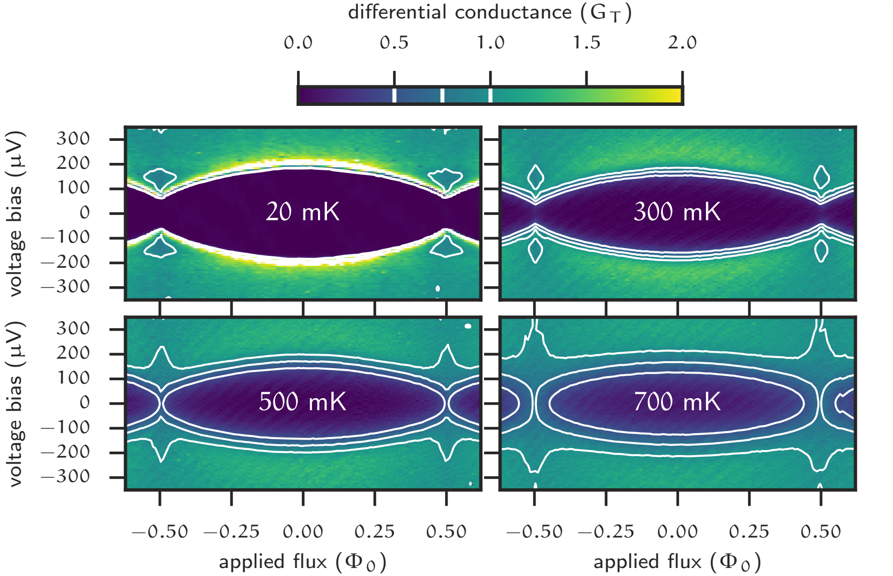
170 nm-long wire — normal-metal probe — $R_T = 150\,\mathrm{k\Omega}$



170 nm-long wire — normal-metal probe — $R_T = 150\,\mathrm{k\Omega}$



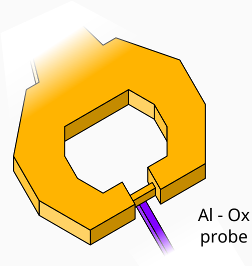
170 nm-long wire — normal-metal probe — $R_T = 150\,\mathrm{k\Omega}$

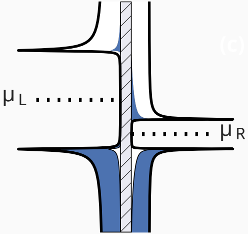


tunnel spectroscopy — superconducting electrode

wire geometry

L x W x T = $215 \times 40 \times 25\,\mathrm{nm}$





Al - Ox probe

thickness $\approx 15\,\mathrm{nm}$

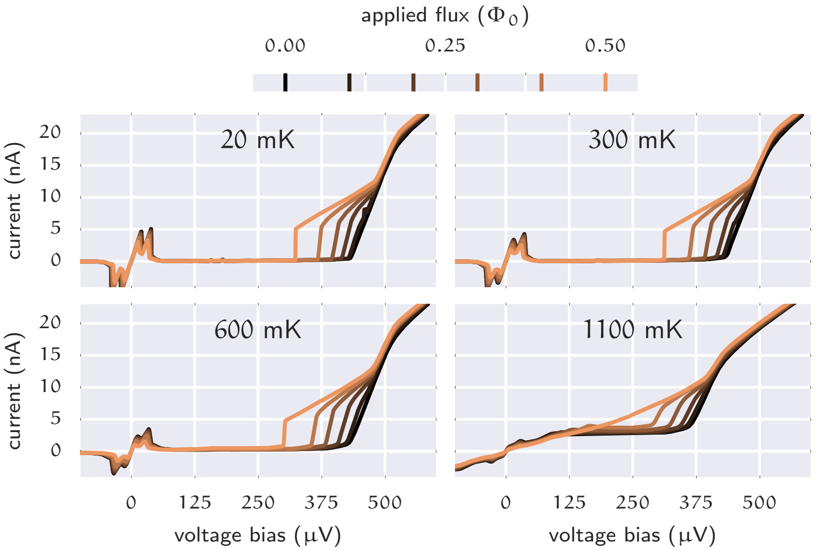
gap $\Delta_{pr} \simeq 230\,\mu\mathrm{eV}$

Tunnel barrier

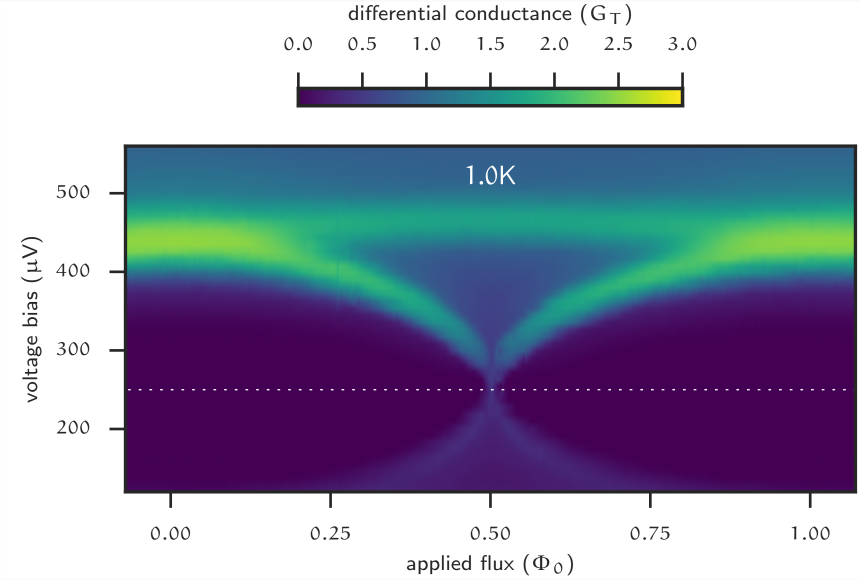
resistance $\simeq 15\,\mathrm{k}\Omega$

surface $\simeq 1600\,\mathrm{nm}^2$

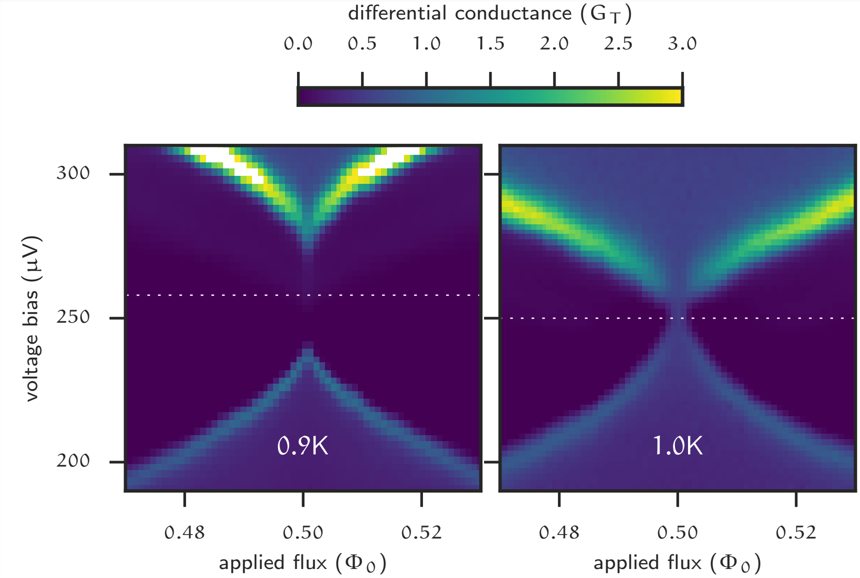
215 nm-long wire — superconducting probe — $R_T = 15\,\mathrm{k\Omega}$



215 nm-long wire — superconducting probe — $R_T = 15\,\mathrm{k\Omega}$



215 nm-long wire — superconducting probe — $R_T = 15\,\mathrm{k}\Omega$



summary so far

- 170 nm wires (normal probe) show evidence of full gap suppression between 500 mK and 700 mK

summary so far

- 170 nm wires (normal probe) show evidence of full gap suppression between 500 mK and 700 mK
- 215 nm wires (superconducting probe) show evidence of full gap suppression between 900 mK and 1K

summary so far

- 170 nm wires (normal probe) show evidence of full gap suppression between 500 mK and 700 mK
- 215 nm wires (superconducting probe) show evidence of full gap suppression between 900 mK and 1K
- In both cases the suppression is extremely sharp; e.g., the last 10% of the gap closes within $\Phi_0/100$.

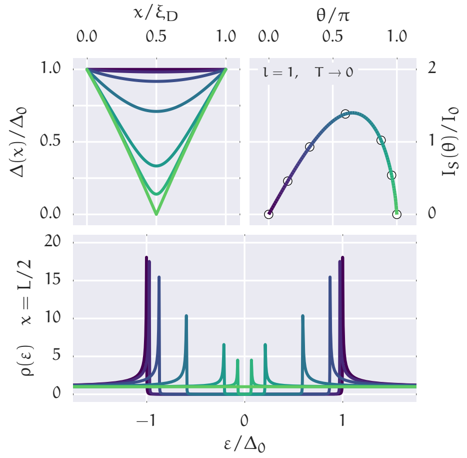
The physical picture inside the wire

self-consistent Usadel: a short superconducting wire

At $T \to 0$:

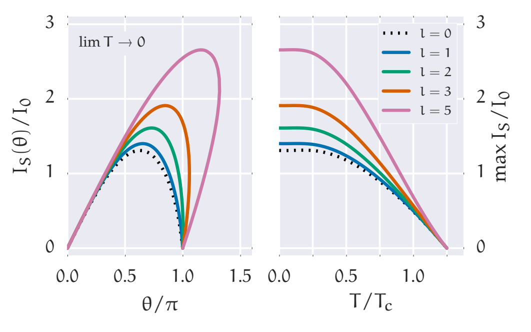
- Josephson regime
- $\rho(\varepsilon)$ is BCS-like

The superconducting gap is suppressed by the presence of a strong phase gradient.



self-consistent Usadel: increasing the length

With increasing length the CPR function $I_S(\theta)$ becomes a multivalued (I_S, θ) locus.

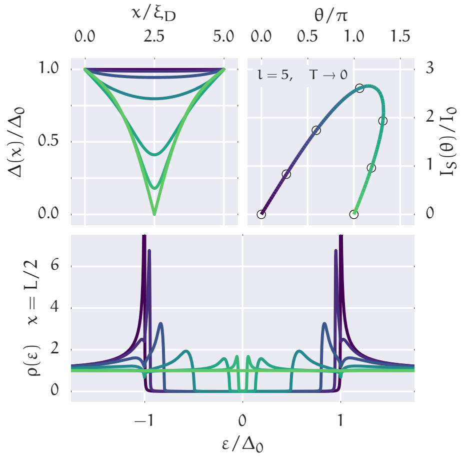


The variable θ is no longer a good mathematical constraint for the PDE problem.

At $T \to 0$:

The rightmost part of the CPR (green colors) is energetically unstable and cannot be reached in practice.

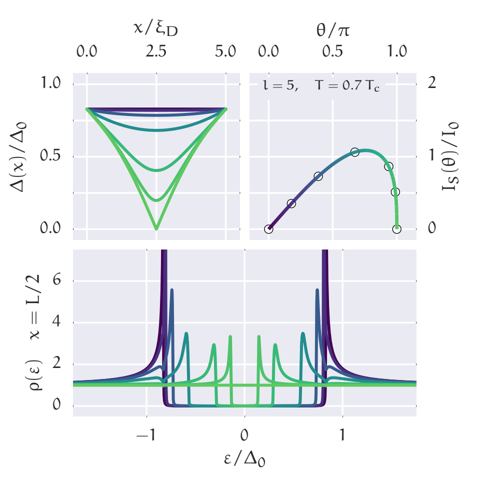
- intrinsic regime
- $\rho(\varepsilon)$ shows the effects of depairing



At higher T:

The effective length changes with $\xi(T)$. The whole CPR locus is available for biasing.

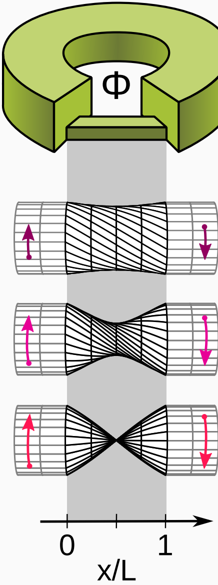
- Josephson regime
- the gap in $\rho(\varepsilon)$ can be completely suppressed



a twist on the Cooper pair condensate

to summarize:

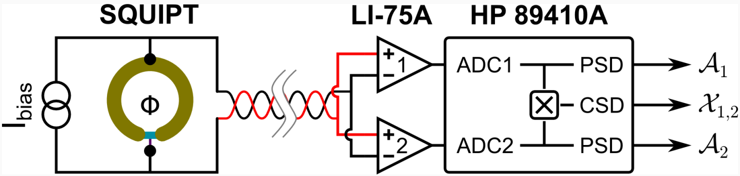
- the rigid boundaries act like reservoirs for the value of the **complex** Δ
- the actual $\Delta(x)$ must be self-consistent with the state of the Cooper pair condensate
- when $\theta \to \pi$ the order parameter is progressively “twisted” along the wire
- $\Delta(L/2) = 0$ with $\theta = \pi$ and $L \approx \xi(T)$.



Magnetic flux sensing performance

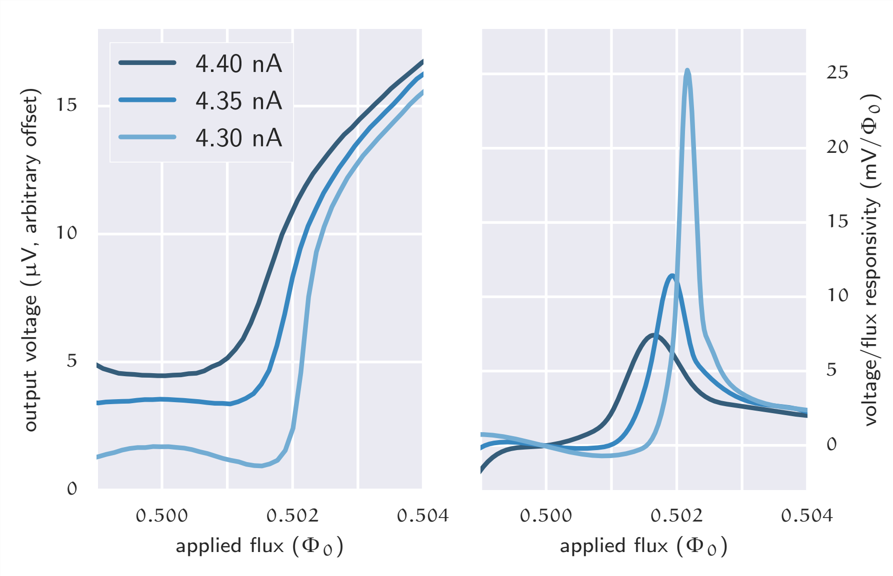
fixed current bias — the setup

We exploit the sharp response of the 215 nm-long wire device.



- Battery-powered DC current bias
- Battery-powered voltage amplification
- Cross-spectrum analysis for uncorrelated noise rejection

voltage traces



minimal catalogue of noise sources

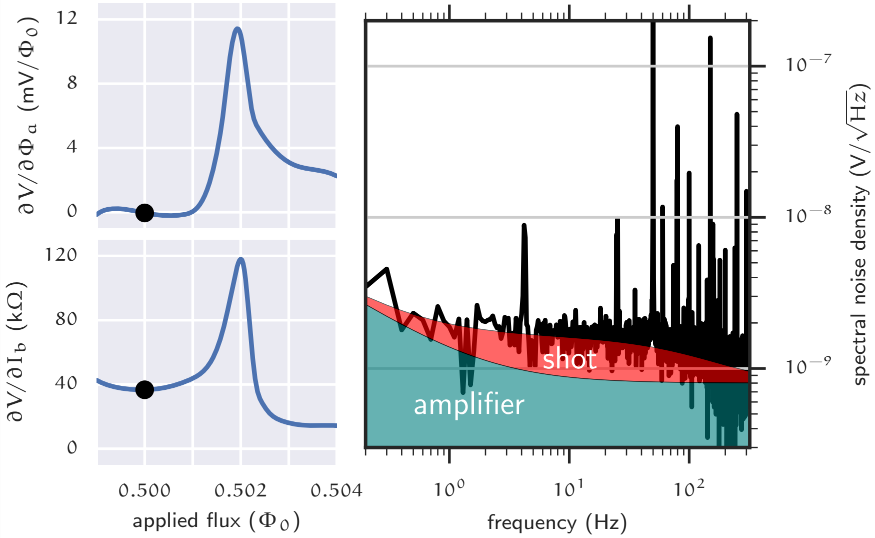
voltage amplifier

NF Corporation `LI-75A`
white noise level $2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
1/f noise below $1\,\mathrm{Hz}$

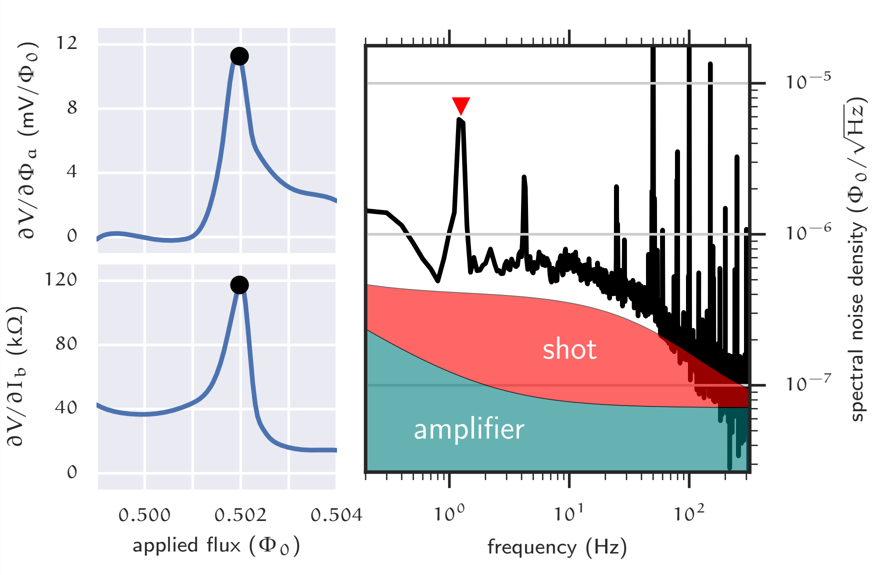
tunnel shot noise

dependent on current bias I_b
$\sqrt{2qI_b} \approx 40\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ with $I_b = 5\,\mathrm{nA}$

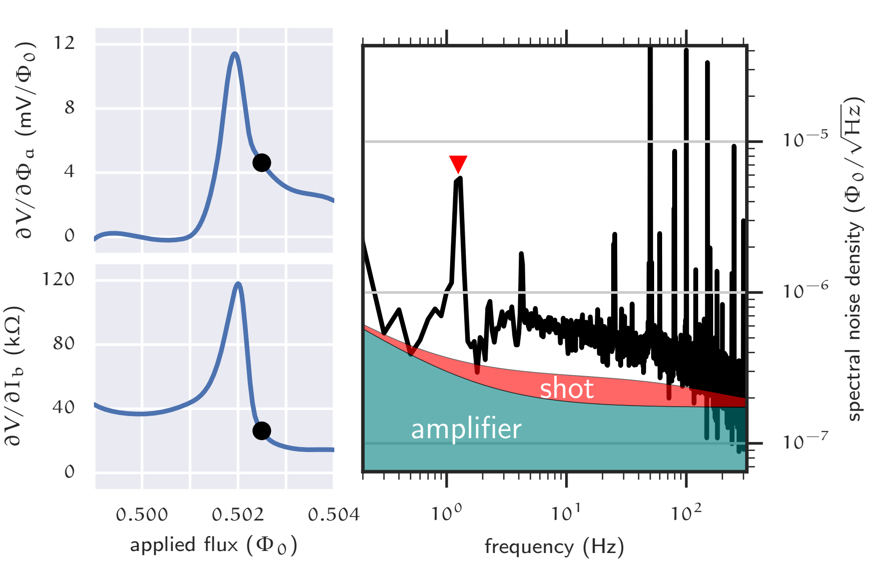
noise characterization — current bias: 4.35 nA — bath 1K



noise characterization — current bias: 4.35 nA — bath 1K



noise characterization — current bias: 4.35 nA — bath 1K



In conclusion...

final messages (1/2)

Two supercurrent transport regimes

Tunnel spectroscopy allows the observation of the transition between the Josephson and intrinsic transport regimes in S/S'/S weak links

Effect on the LDOS of the superconductor

The transition is accompanied by the sudden collapse of the gap of the "proximized" superconductor with $\theta = \pi$

Effect on magnetic bias

Coincidentally the dynamic weak link inductance at $\theta = \pi$ vanishes, boosting the flux-to-phase responsivity

Limits in magnetic flux resolution

Near the transition the flux responsivity figures are so high that the limiting factor for noise performance is likely the shot noise of the tunneling quasiparticles

Actual performance (T=1K) — optimal working point

$\partial V/\partial\Phi$	Φ_{ns} @ $10\,\mathrm{Hz}$	R_{dyn}	bandwidth	power
mV/Φ_0	$\mathrm{n}\Phi_0/\sqrt{\mathrm{Hz}}$	$\mathrm{k}\Omega$	Hz	pW
5	250*	20	150	1

* amplifier + shot noise-equivalent level

acknowledgements

very few of this would have been possible without

- **Dr. Carles Altimiras**: fabrication, measurements and discussions
- **Dr. Sophie D'Ambrosio**: fabrication and analysis
- **Dr. Pauli Virtanen**: theory, numerics and discussions
- **Mr. Martin Meissner**: measurements and analysis
- **Dr. Francesco Giazotto**: scientific direction

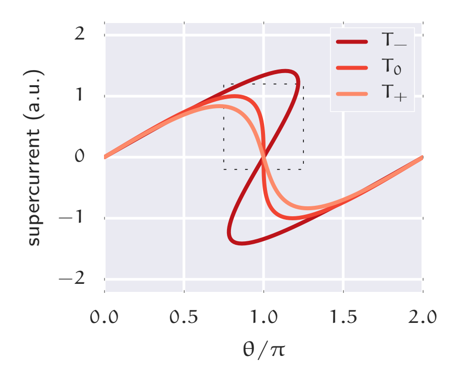
… and the constant support of all past and present members of the mesoscopic superconductivity group in Pisa.

The financial support of ERC Grant 615187-COMANCHE and MIUR-FIRB2013–Project CoCa is acknowledged.

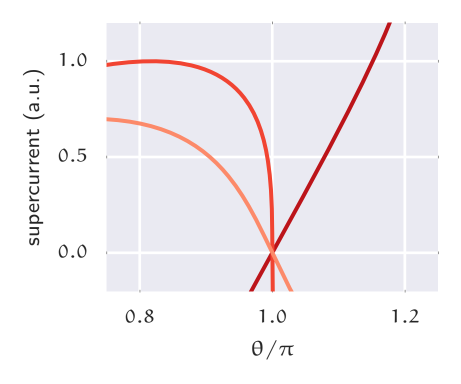
Thank you for your attention

tuning the flux-to-phase responsivity

At the transition temperature (T_0) the CPR curves switch from multi-valued to single-valued.

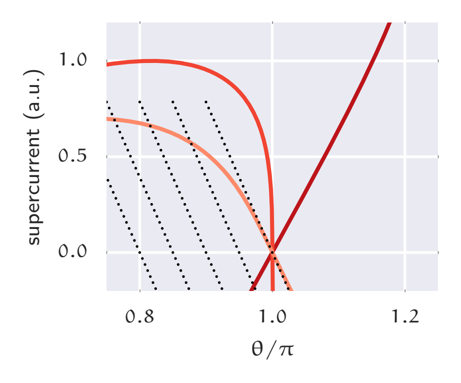


Here is a zoomed view. The dynamic inductance at the $\theta = \pi$ node changes sign at T_0.



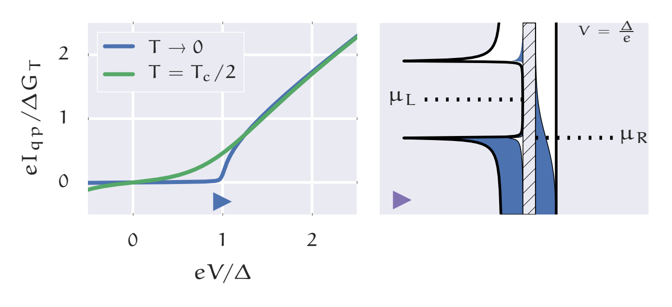
tuning the flux-to-phase responsivity

The orange CPR is matched to the small but finite inductive load represented by the interferometer ring (dots).



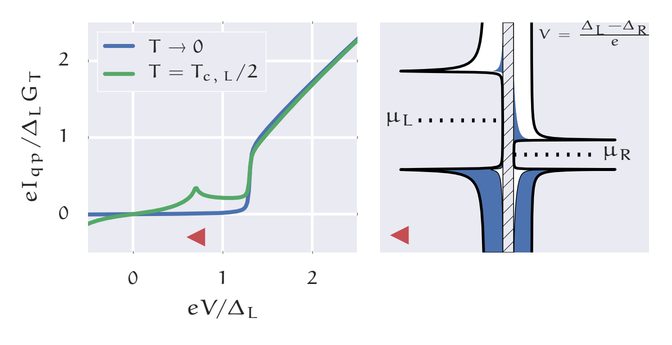
In these conditions one finds a nonlinear boost to the flux-to-phase transduction at $\theta \approx \pi$.

A normal probe is useful to estimate directly the local density of states of the wire. In fact the latter is proportional to the low-temperature differential conductance.



Thermal broadening of the F.D. distribution in the probe **limits the energy resolution** exactly when we need it the most!

In a superconducting probe the gapped form of the density of states protects from thermal broadening effects, increasing the **energy selectivity** at finite temperature.



dynamical Coulomb blockade effects

data recorded at
$T \simeq 25\,\mathrm{mK}$
$B = 0.4\,\mathrm{T}$

Fit parameters:

- $R_T = 158\,\mathrm{k\Omega}$
- $C_j = 2\,\mathrm{nF}$
- $R_{env} = 1.2\,\mathrm{k\Omega}$