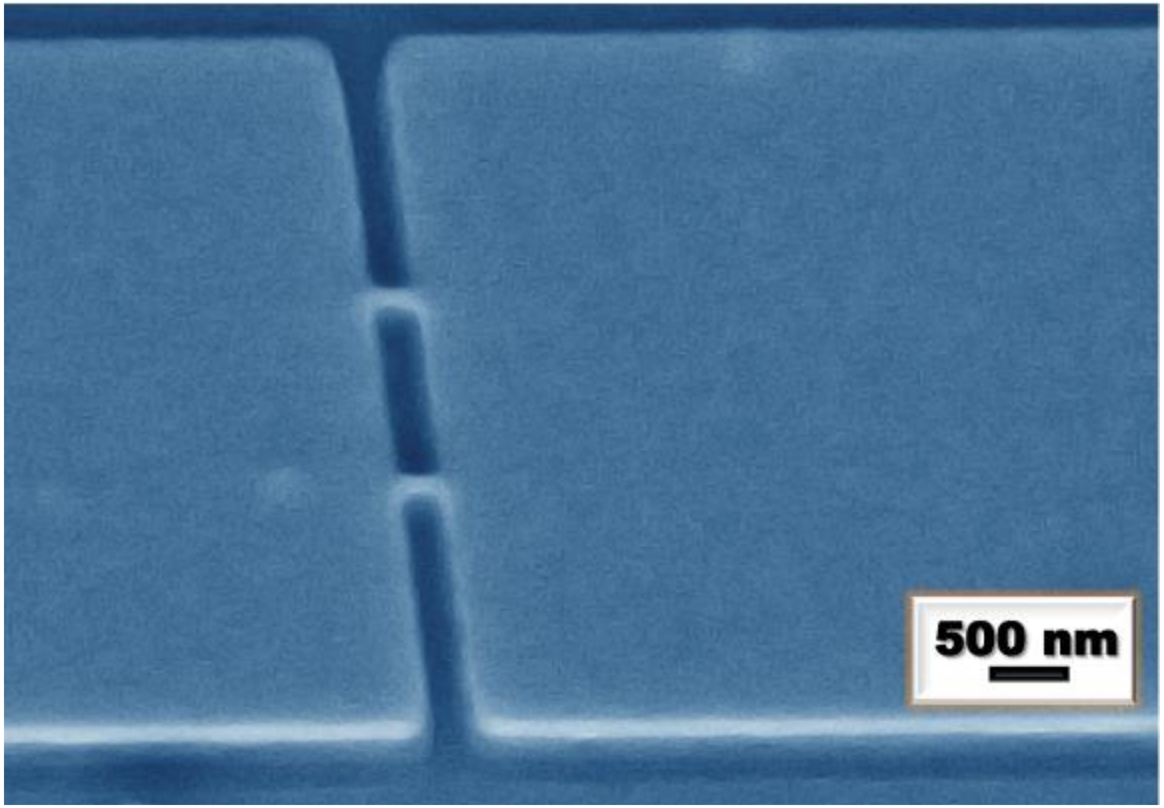
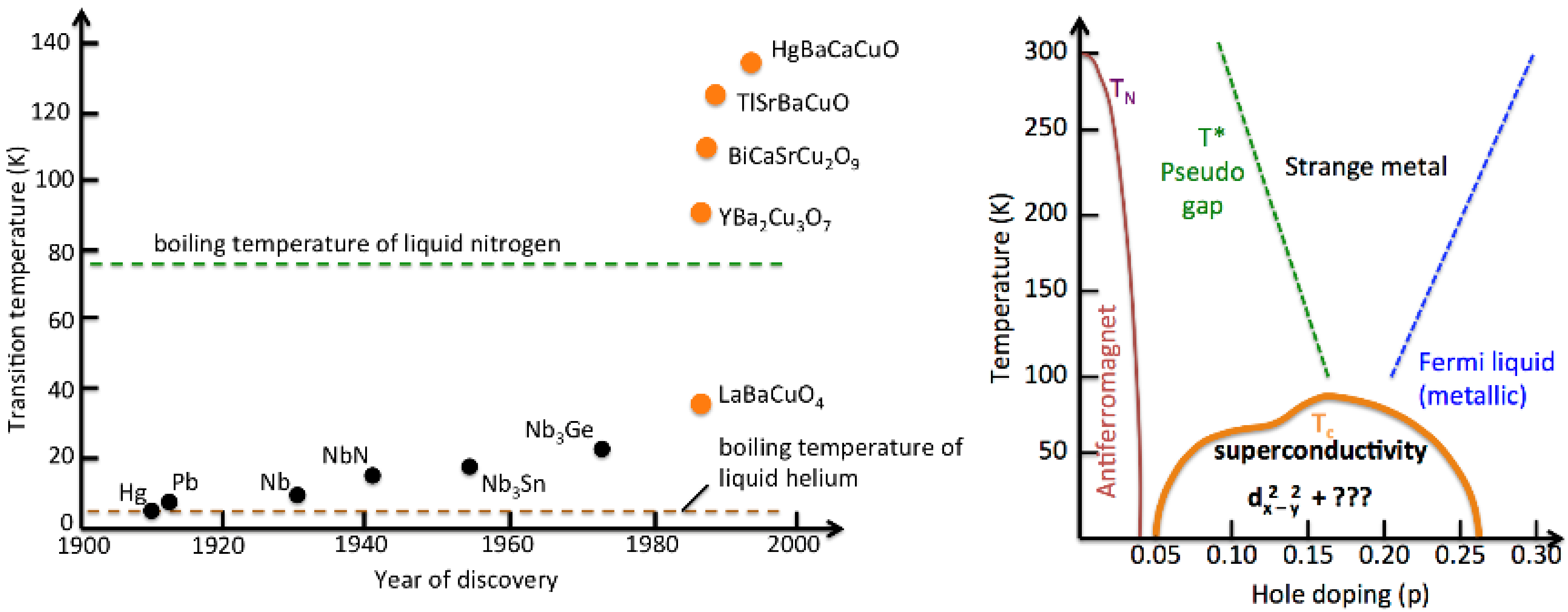
Transport and noise properties of YBCO nanowire based nanoSQUIDs

Thilo Bauch
R. Arpaia, E. Trabaldo, M. Arzeo, R. Baghdadi, E. Andersson, F. Lombardi



Vetenskapsrådet
Knut och Alice Wallenbergs Stiftelse
SEVENTH FRAMEWORK PROGRAMME

Intriguing puzzle in solid state physics: High critical Temperature Superconductors (HTS)



Nature physics 2, 138 (2006)

FEATURE

Towards a complete theory of high T_c

Given the successes of the microscopic theory of conventional superconductors, it seems natural to expect a similar all-encompassing theory for high-temperature superconductivity. But is it the best approach? Where are we heading?

Is high-temperature superconductivity (high-T_c) on the list of the most profound physics problems, or is it a collective illusion rooted in sociological developments in the late 1980s? It is not an illusion — I perceive high-T_c on a par with dark energy, extra dimensions and the secret of life.

High-T_c is a graveyard of theories. However, this has had the beneficial effect of causing a state of mind not dissimilar from the goal of Zen Buddhism: think nothingness, in order to reach enlightenment. Rid the mind from textbook wisdoms, such as the conventional theory of Bardeen, Cooper and Schrieffer (BCS), the Fermi gas and even resonating valence bonds (RVBs), and the essence of high-T_c comes into view. The metallic state at optimal doping embodies the enlightenment. Rather than being complicated, this 'bad' metal shows a sacred simplicity — symbolized, for example, by its linear resistivity as a function of temperature, up to the melting point of the crystal. This reveals principle at work, of a quality of Einstein's principle of equivalence.

I am convinced that this principle cannot be found by merely thinking hard — the reason I stopped designing theories. It requires experiments to give away the clue, and there are reasons to be optimistic. A group of experimentalists are providing further evidence that phonons play an important, albeit quite unusual, microscopic role. Even if this does not lead to the magic bullet, it has at least the effect of discrediting the influential religious dogma that the electronic toy models invented by Anderson and Hubbard will solve all problems.

The experimental characterization of the ordering phenomena competing with the superconductivity at low doping is rapidly improving. A growing body of evidence points at stripe order, though I see stripes as more of a convenience than a cause: the mysterious stuff responsible for the superconductivity and the bad metal comes to a standstill in stripy patterns, enabling experimentalists to have a closer look. The case currently emerging from neutron scattering and scanning tunnelling microscopy (STM) is in this regard highly promising.

There is one candidate for the Great Principle: quantum criticality, which has unlimited resources to make things simple. Unfortunately, the empirical evidence on its behalf is thin at best. I propose two demanding experiments: high-precision measurements of the chemical potential as a function of doping and temperature to catch the elusive quantum criticality, and a high-resolution measurement at small but finite momenta of the electron energy-loss function to look for the dual shear Higgs boson that is the unique signature of strong stripe correlations in the superconductor.

JAN ZAANEN

Physicists are reductionists at heart. Otherwise, our science would be metaphysics. This is not an indictment on emergence, but a perspective that dates back to Newton. Before the BCS theory of conventional superconductivity, would you have thought that a microscopic mechanism of superconductivity existed? Being hardly in existence then, I cannot tell for sure. Yet, the history of science indicates that perhaps there was a wide sense of despair. Do I believe that there is a microscopic theory of high-temperature superconductuctivity? Undoubtedly, yes. Do I believe there is an ultimate microscopic theory, or a final theory of superconductivity? Undoubtedly, no. This is amply clear from the success of the BCS mechanism of conventional superconductors, and, at the same time, from its dramatic failure for high-temperature superconductors.

In certain circles it is fashionable to ignore that the transition temperature itself is the driving force of this field, and to emphasize instead the so-called universal properties of matter. Yet, the dream of room-temperature superconductivity is the secret motivating factor. Think back to the mechanism of

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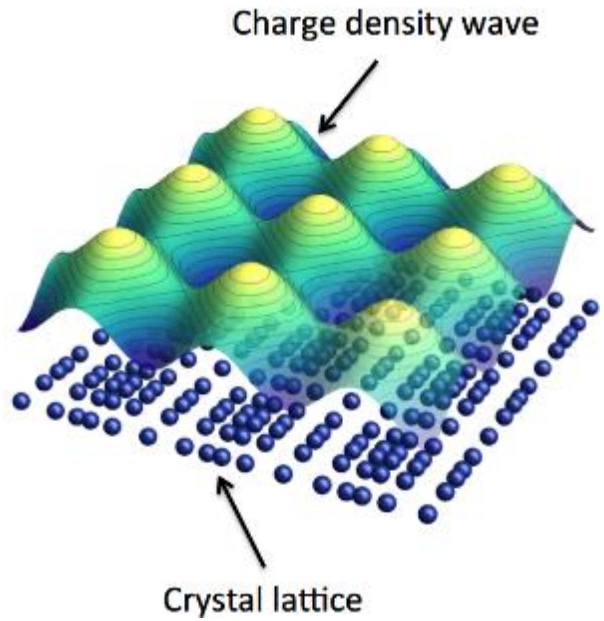
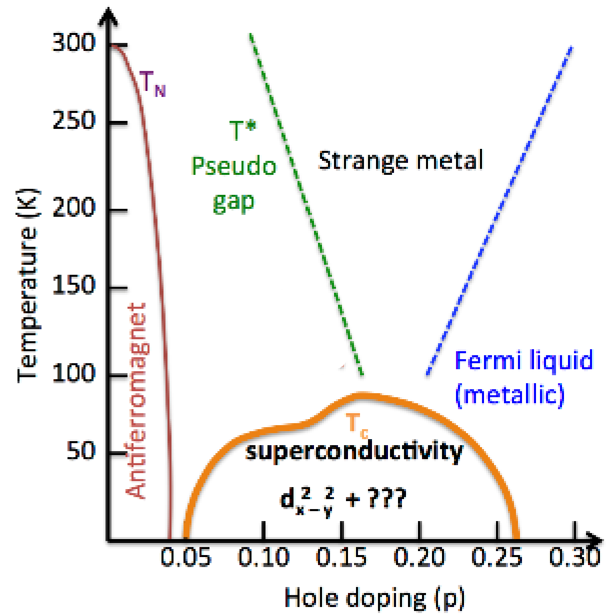
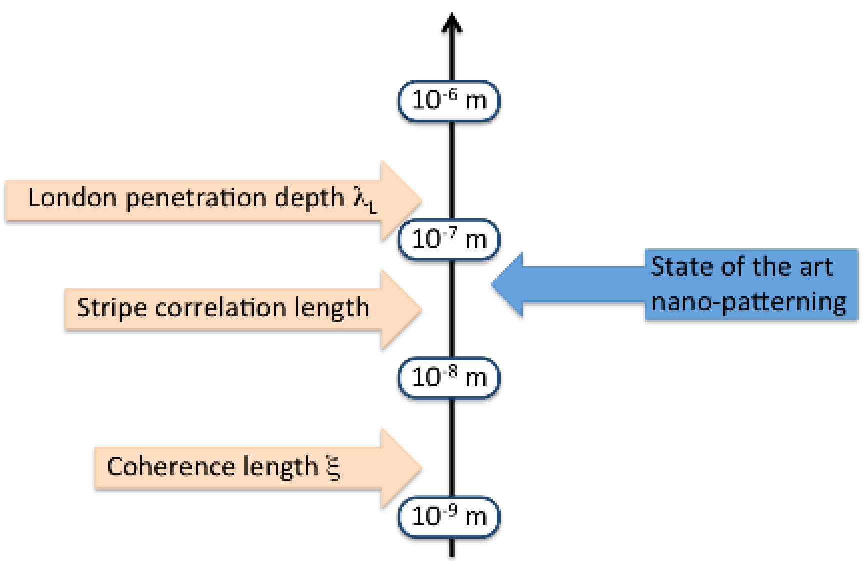
Charge Density Wave (CDW) order



http://www.mpg.de/6000540/supraconductivity-electron-phonon-coupling



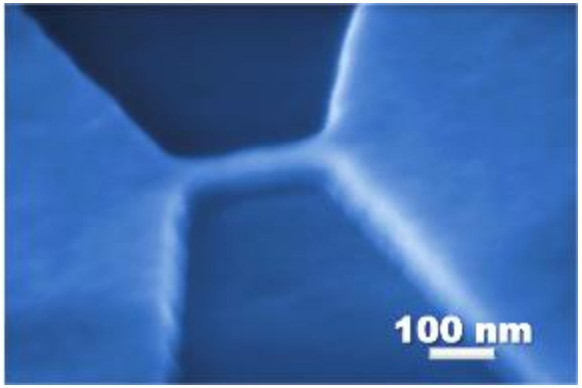


Static CDW:
Competing order to superconductivity, well established in 214 compounds

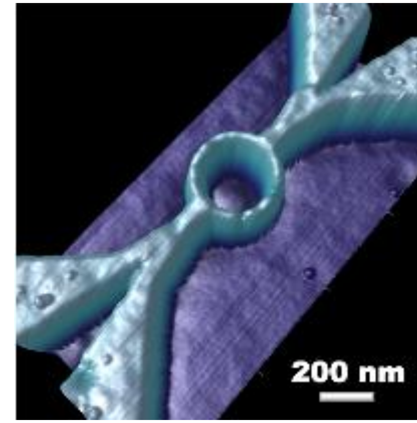
Dynamic/fluctuating CDWs:
Possible mechanism for HTS??

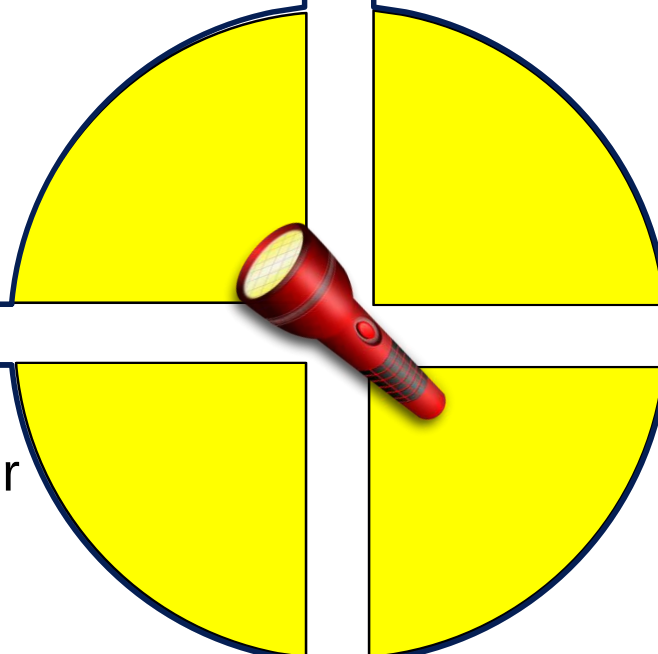
Looking into the superconducting dome from different perspectives

Nano scale ordering
Transport Anisotropy in nanowires

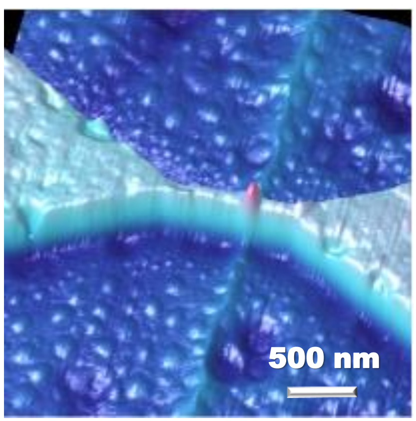


2e or not 2e
Little-Parks ring, nanoSQUID

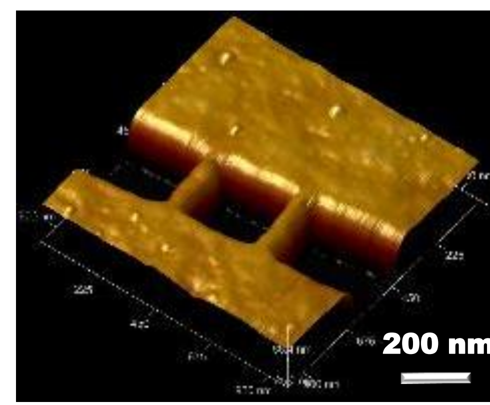




Excitation spectrum
Single Electron Transistor

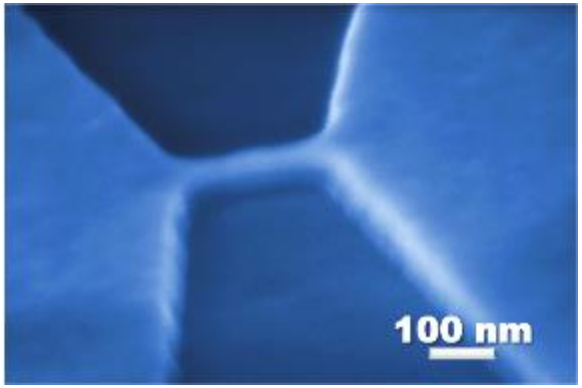


Noise properties
nanoSQUID

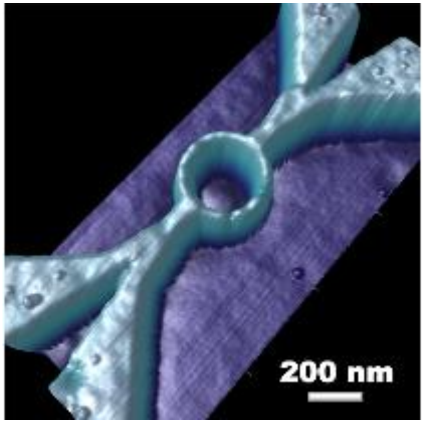


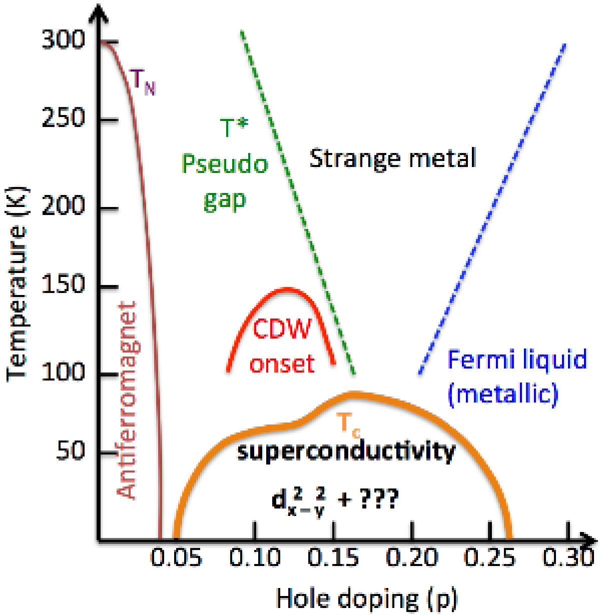
Doping and temperature dependence: new insights about HTS

Nano scale ordering
Transport Anisotropy in nanowires



2e or not 2e
Little-Parks ring, nanoSQUID





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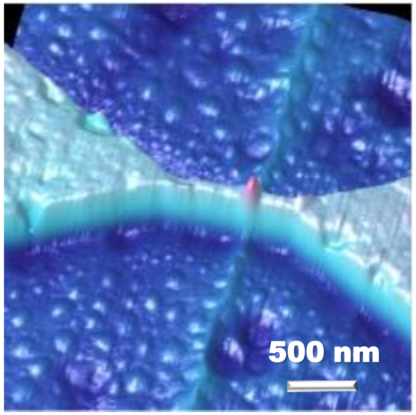

Noise properties
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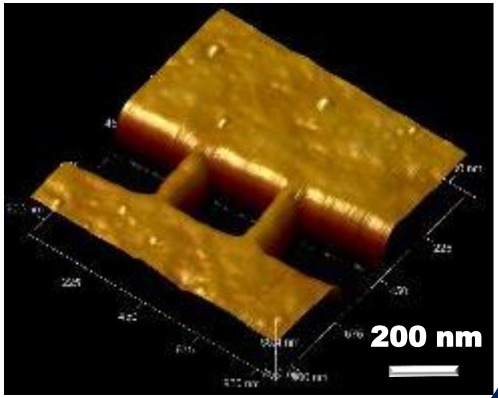
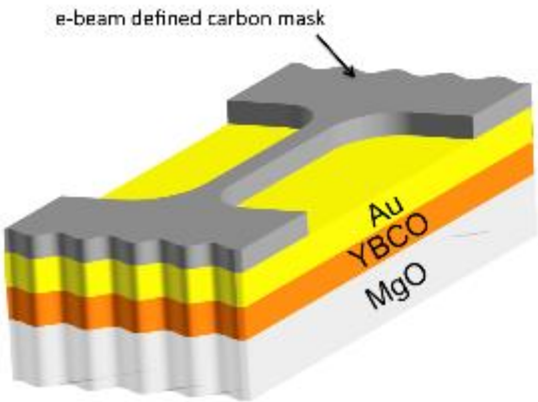
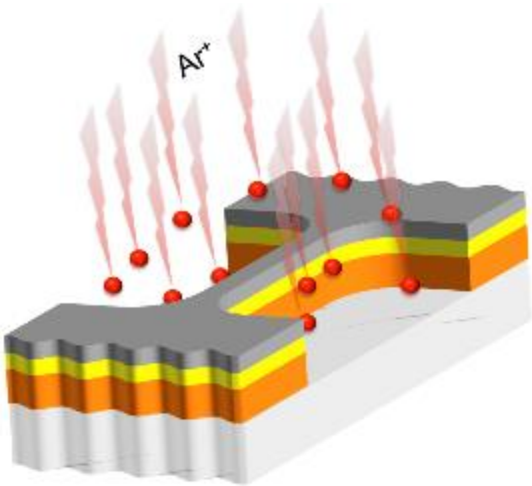


Correlation between properties: Invaluable for microscopic modeling of HTS

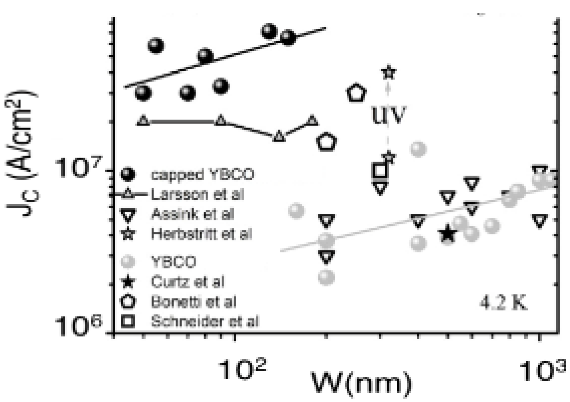
Nano-patterning of HTS films: wires, nano-rings, nanoSQUIDs, SET …

The challenge





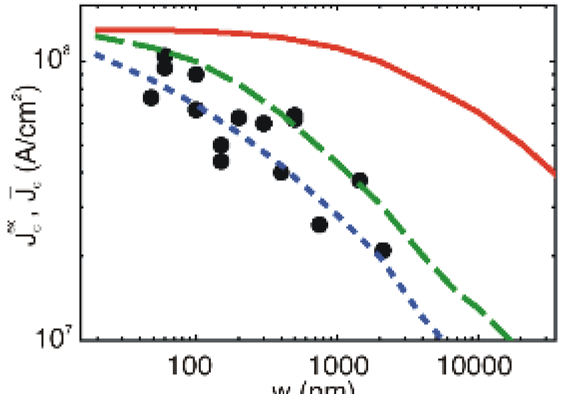
From literature



(Papari et al. **SuST 25**, 035011 (2012))

- Evidence of damage during Ar^+-ion etching

Our achievement:

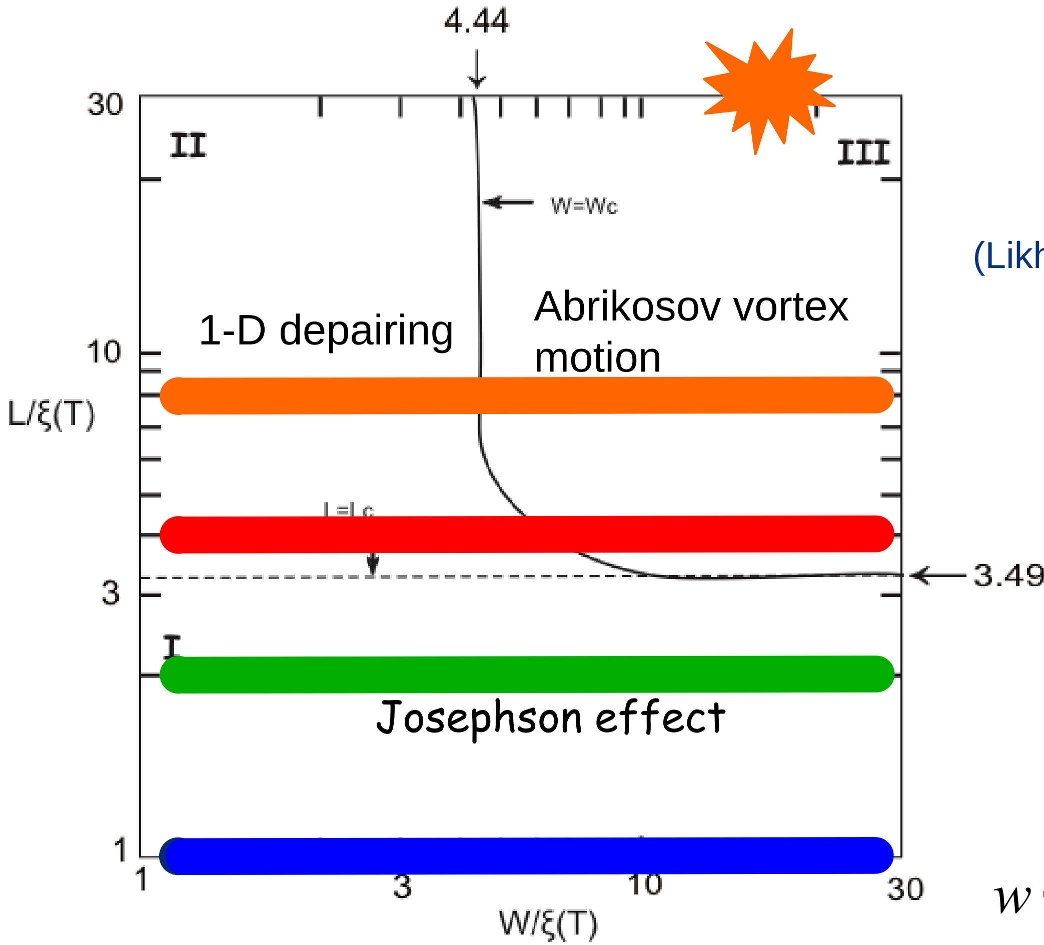


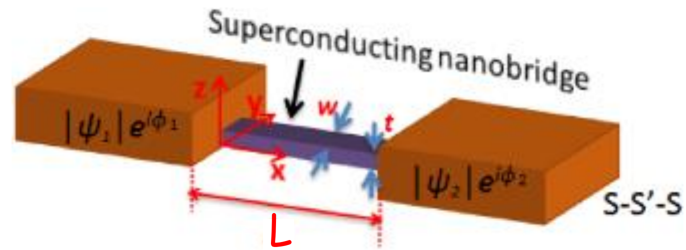
- Depairing critical current measured in YBCO nanowires with cross section 50x50 nm^2

Nawaz, Arpaia, Lombardi, Bauch, **PRL 110**, 167004 (2013);
Nawaz, Arpaia, Bauch, Lombardi, **Physica C 495**, 33, (2013)

Origin of Current Phase Relation

(Likharev, RMP 51, 101 (1971))

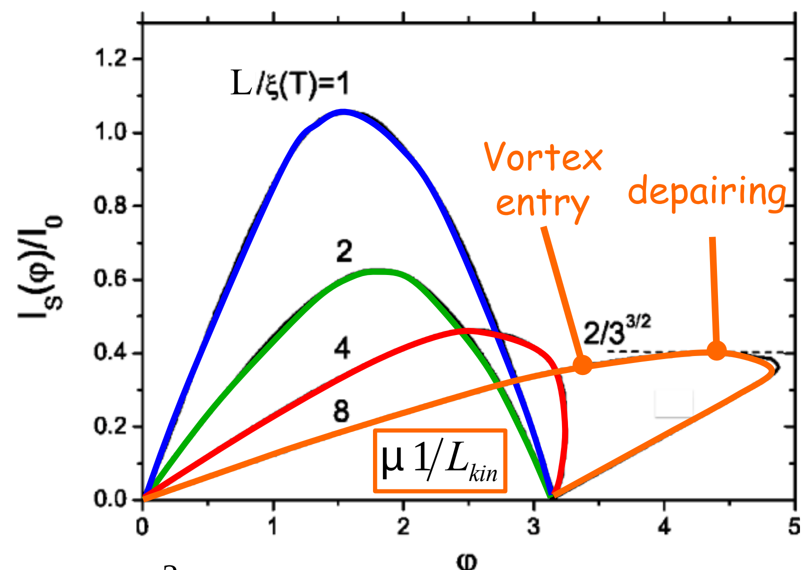




$$\varphi = \phi_2 - \phi_1$$

Current Phase Relation

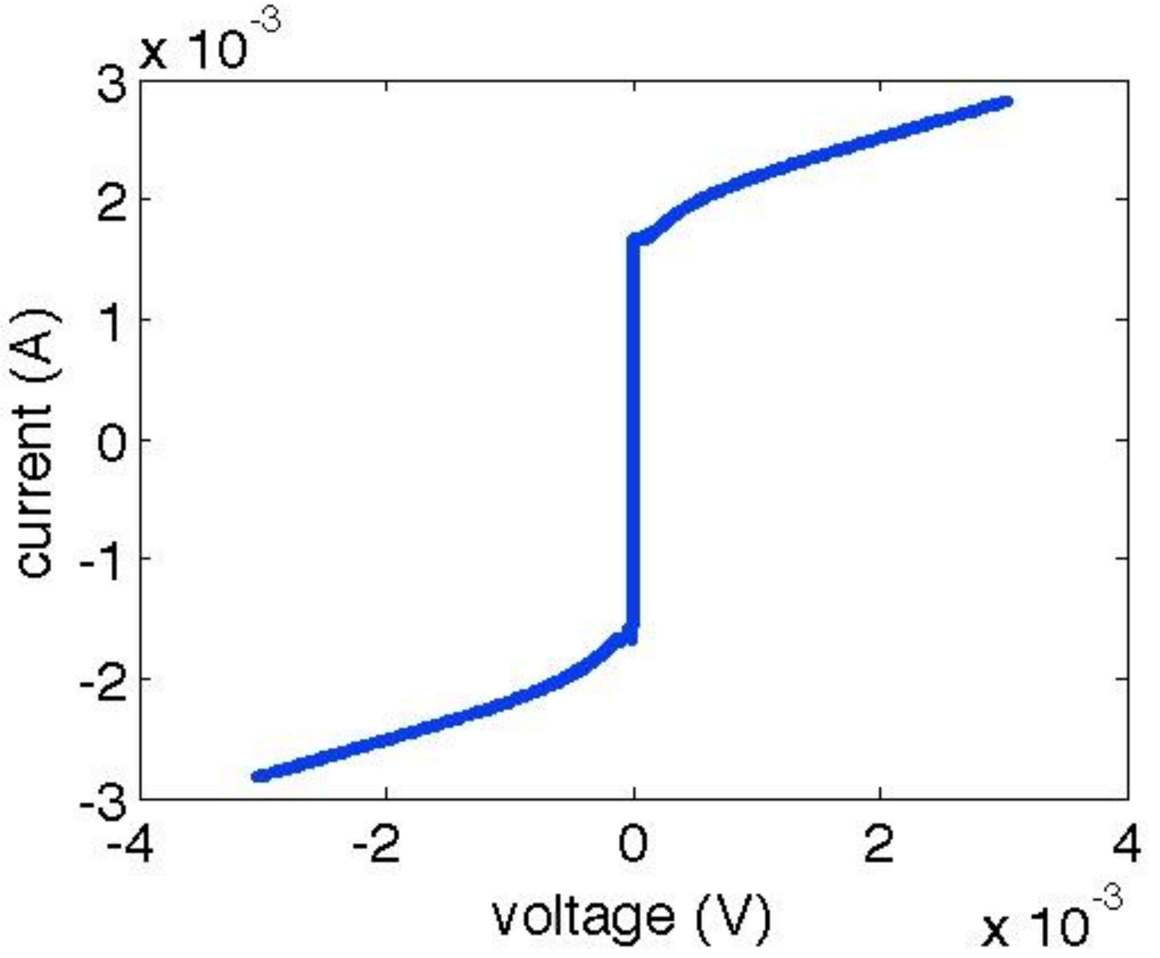
(Likharev, Yakobson, Zh. Tekhn. Fiz. 45, 1503 (1975))



$$w < \lambda_P = \lambda_L^2 / t$$

(Kupriyanov et al., LT14 T027, 104 (1975))

Current Voltage Characteristic



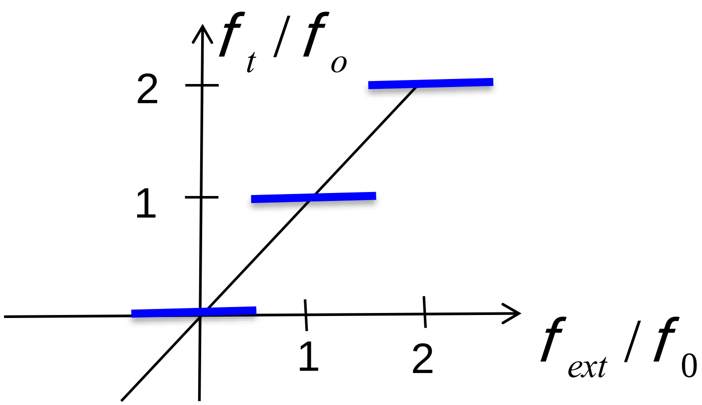
See talk by Riccardo Arpaia
3EO2-02 @ 16:20 on Wednesday

Superconducting Loop

Key feature of superconductivity: Fluxoid quantization

Total flux through the loop = INTEGER * FLUX QUANTUM

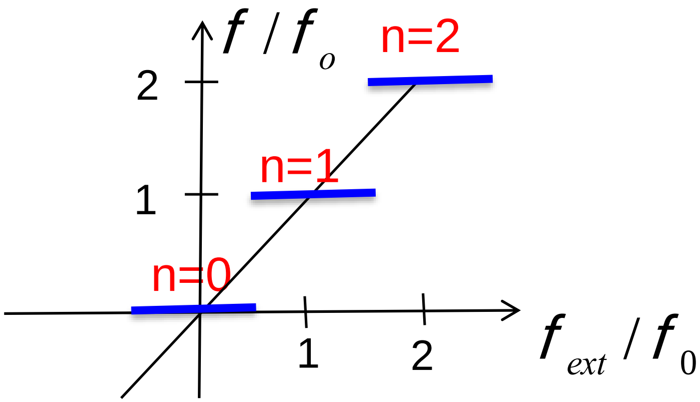
$$\underbrace{\varphi + \mu_0 \oint \lambda_L^2 \overrightarrow{j_S} \cdot d\vec{r}}_{f_t} = n \cdot \frac{h}{2e}$$

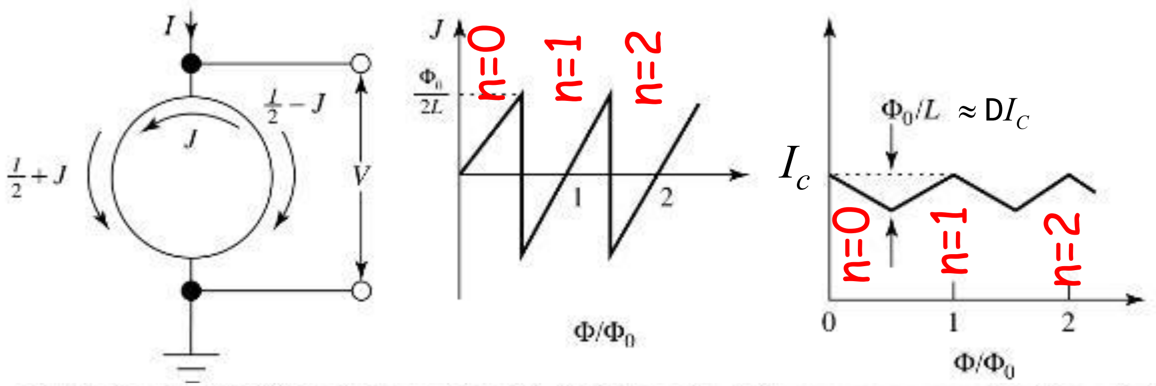


Superconducting loop keeps total flux always at an integer multiple of h/2e

Superconducting QUantum Interference Device (SQUID)

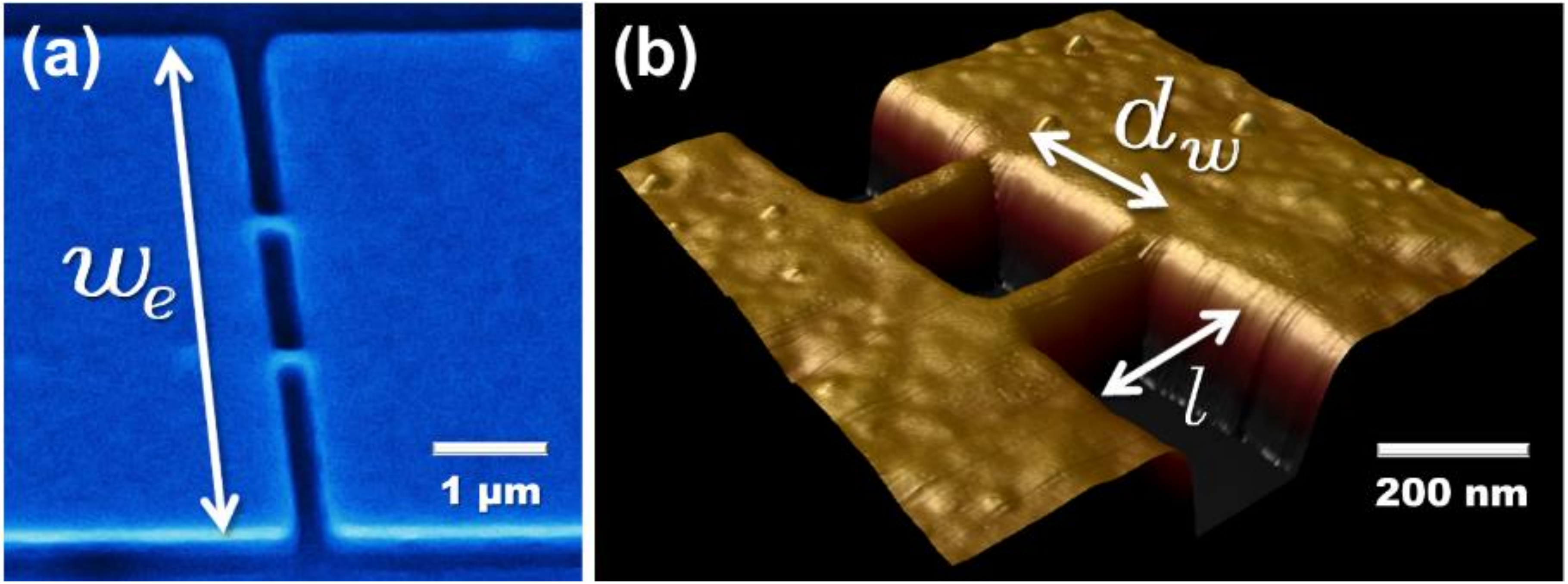
Superconducting loop keeps total flux always at an integer multiple of h/2e





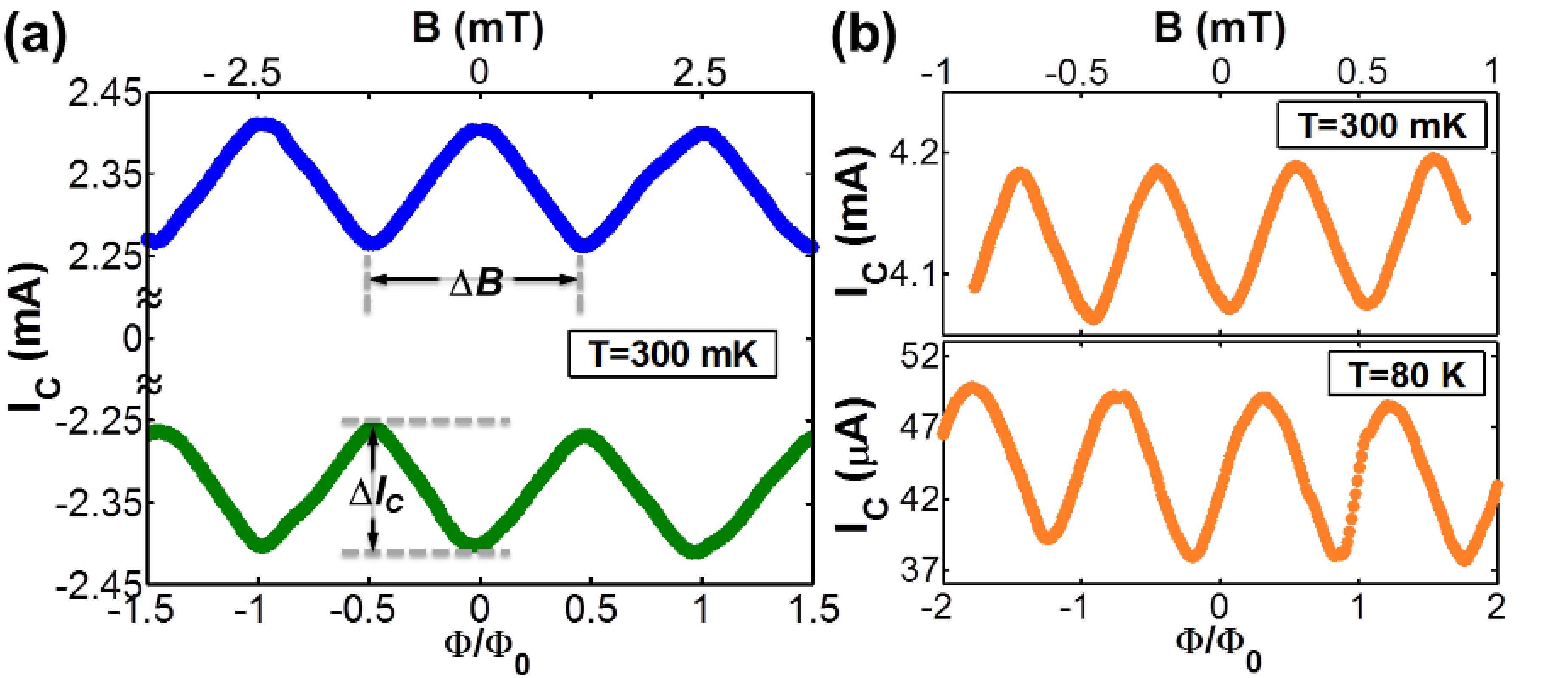
J. Clarke. in H. Weinstock and R. W. Ralston eds. *The new superconducting electronics*, pages 123–180. Kluwer publishers, The Netherlands, 1993.

YBCO nanoSQUID implementing nanowires



Arpaia, Arzeo, Nawaz, Charpentier, Lombardi, TB, ***APL 104,*** *072603* (2014)

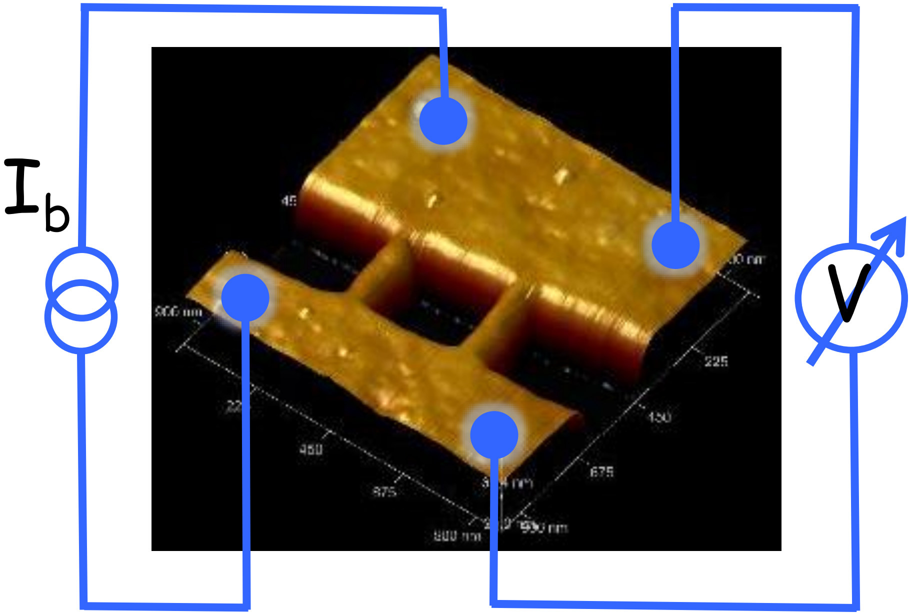
YBCO nanoSQUID implementing nanowires

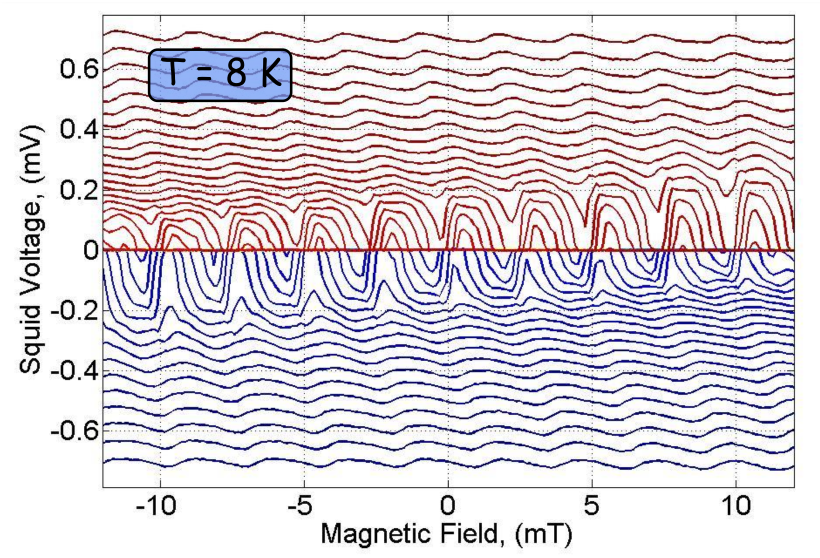


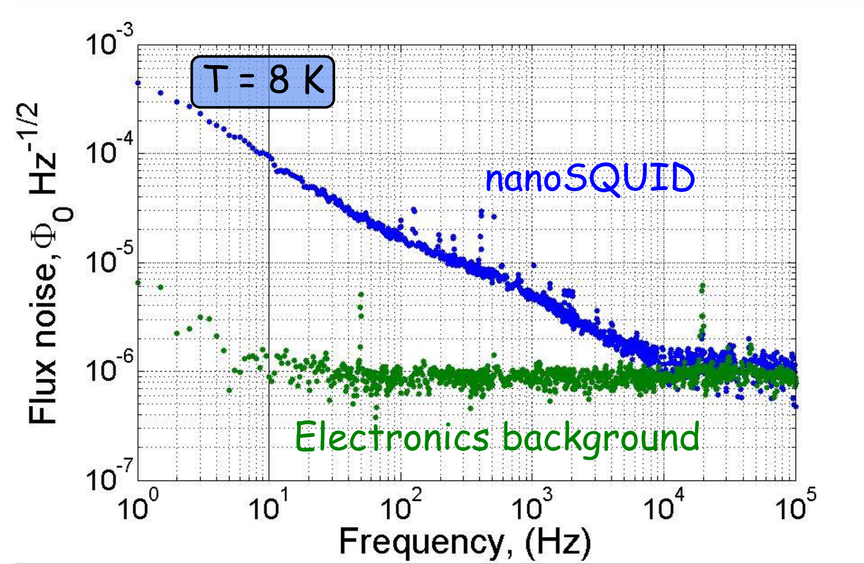
Demonstration of critical current modulations in the full temperature range below the transition temperature Tc.

Arpaia, Arzeo, Nawaz, Charpentier, Lombardi, TB, ***APL 104,*** *072603* (2014)

YBCO nanoSQUID: sub-$\mu\Phi_0/Hz^{1/2}$ sensitivity







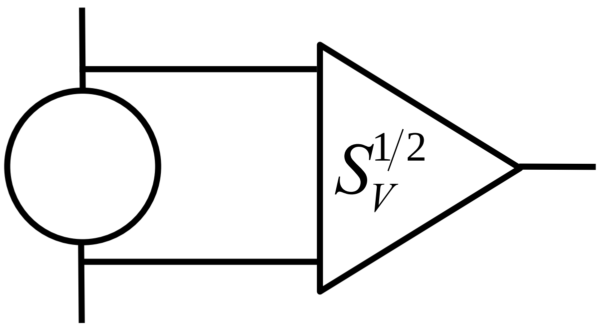
- White noise level **better than 1 $\mu\Phi_0/Hz^{1/2}$** at 8K !

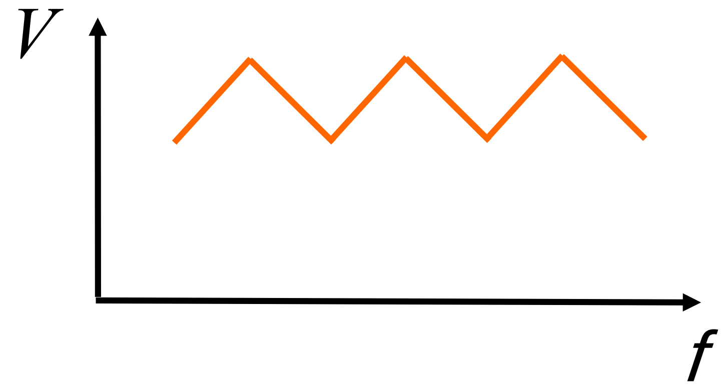
White Flux Noise $S_\Phi(f) \sim 4k_BTL^2/R$ (?)

- Detection of magnetic nanoparticles in high magnetic fields and wide temperature range.
- Single spin detection?

Arpaia, Arzeo, Nawaz, Charpentier, Lombardi, TB, ***APL 104,*** *072603* (2014)

Flux noise limited by amplifier input noise





$$S_f^{1/2} = S_V^{1/2}\left(\frac{\partial V}{\partial f}\right)^{-1}$$

- Large voltage modulation depth is needed.
- One possibility is to increase normal state resistance of the wire.

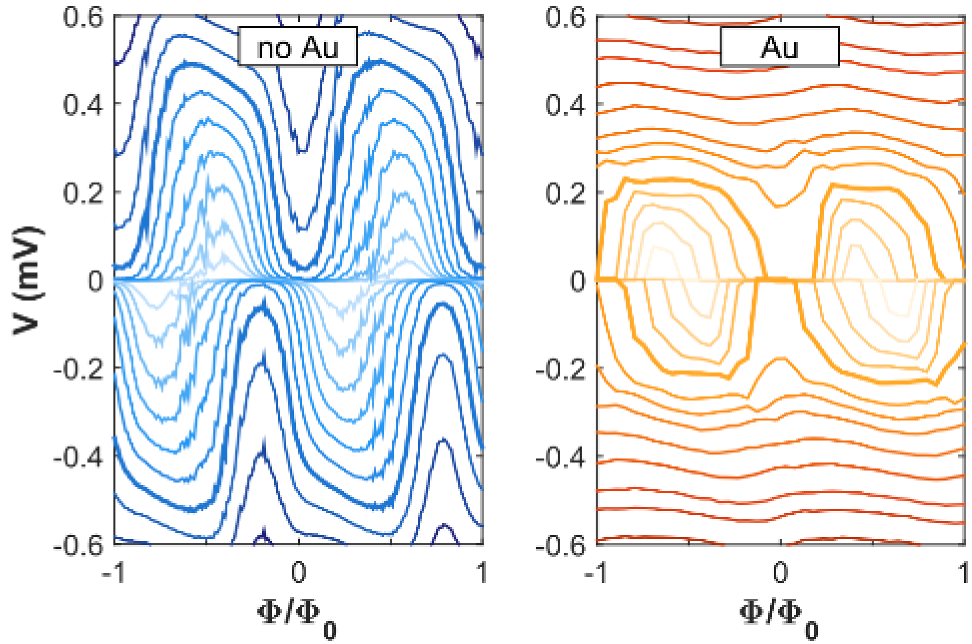
Arpaia, Arzeo, Baghdadi, Trabaldo Lombardi, Bauch, SuST 30, 014008 (2017)

Improving white flux noise

White flux noise limited by amplifier input noise

Increasing normal state resistance by:

- Removing gold capping — $1\ \mu\Phi_0/Hz^{1/2}$ ➔ $0.6\ \mu\Phi_0/Hz^{1/2}$
- Using thinner YBCO films — $0.6\ \mu\Phi_0/Hz^{1/2}$ ➔ $0.45\ \mu\Phi_0/Hz^{1/2}$



@ 18 K

Device	Au	t (nm)	w (nm)	l (nm)	I_C (μA)	J_C ($A\ cm^{-2}$)	β_L	δR (Ω)	$R_\square$ (Ω)	ΔV_{max} (mV)	V_Φ (mV/Φ_0)	$S^{1/2}_{\Phi,w}$ ($\mu\Phi_0\ Hz^{-1/2}$)
NSQ10	No	10	75	100	130	1.0×10^7	23	110	130	0.65	3.6	<0.45
NSQ20	No	20	65	100	580	2.2×10^7	24	19	33	0.45	2.7	–
NSQ50	No	50	65	100	1000	1.5×10^7	20	13	12	0.42	2.2	<0.6
NSQR	Yes	50	65	100	2220	3.4×10^7	18	1.5	4	0.2	1.5	<1

Arpaia, Arzeo, Baghdadi, Trabaldo Lombardi, Bauch, SuST 30, 014008 (2017)

Towards field sensitivity

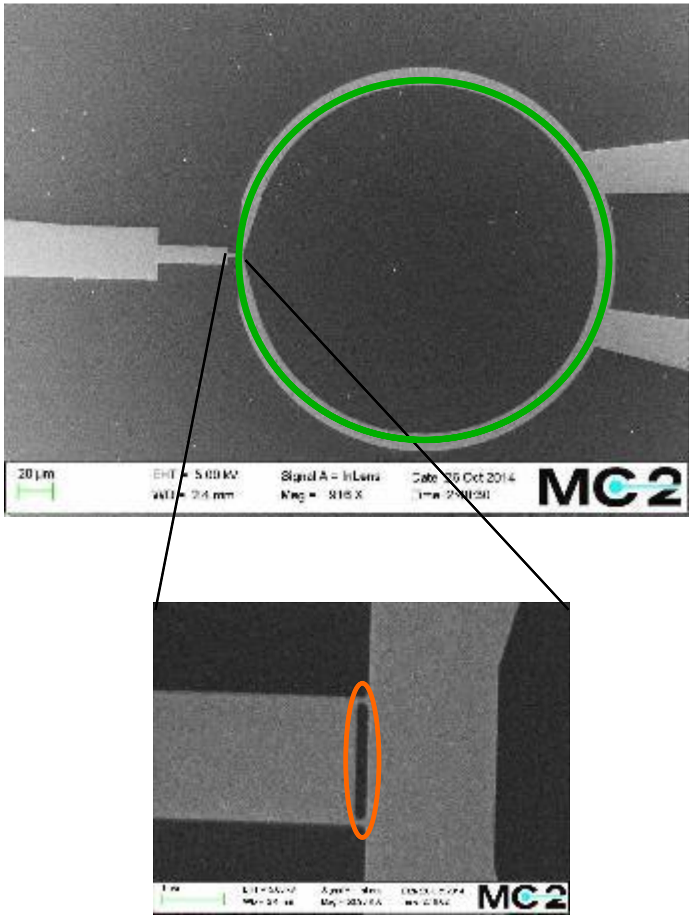
Improving white flux noise

Flux noise $\propto$ loop area

Implications on:

- Single spin detection.
- Detection of magnetic nanoparticles in high magnetic fields.

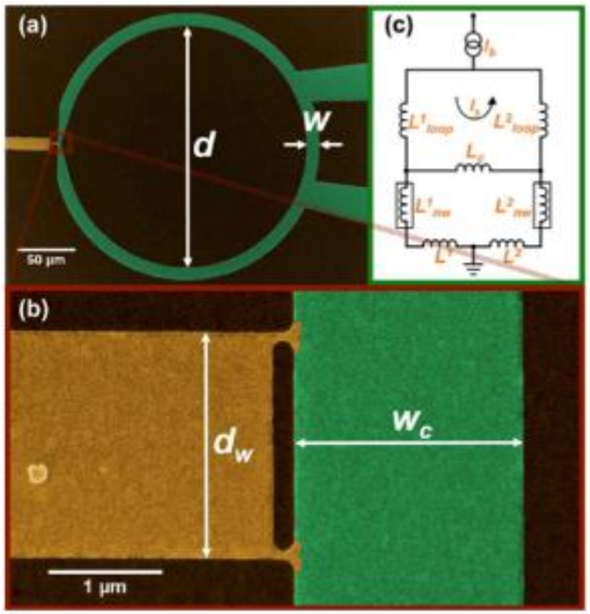
Magnetic Field noise =
Flux noise / magnetic pickup area



Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)

Towards field sensitivity

Magnetic Field noise =
Flux noise / magnetic pickup area



$$A_{eff}^{an} = A_{nS} + A_{eff}^{pl} \frac{L_c}{L_{loop}},$$

Relevant inductances (per unit length)

$$L'_{loop} = \frac{\mu_0 \lambda_L}{w} \coth\left(\frac{t}{\lambda_L}\right) + \frac{\mu_0}{2\pi}\left[\ln\left(\frac{16r}{w}\right) - 2\right]$$

$$L'_c = \frac{\mu_0 \lambda_L}{w_c} \coth\left(\frac{t}{\lambda_L}\right) + k/2$$

$$k \simeq 0.3\ \mathrm{pH}/\mu\mathrm{m}$$

Kinetic inductance

Superconducting strip of width w, thickness t

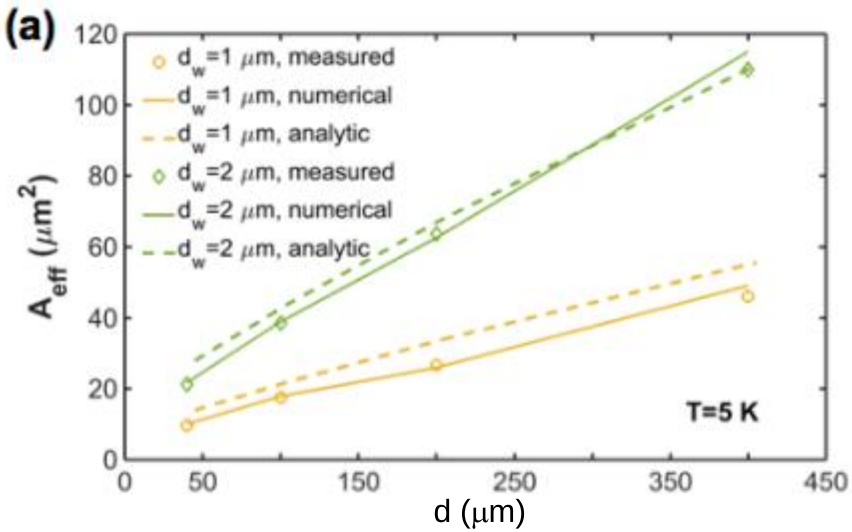
$$L_k = \mu_0 \frac{\lambda^2}{wt}$$

$\lambda(T)$: London penetration depth

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)

Towards field sensitivity

Effective area vs. pick up loop diameter



$/\,(T)$ » $150\,\mathrm{nm}$

70% of flux coupling occurs via kinetic inductance

$/\,(T)$ » $400\,\mathrm{nm}$

94% of flux coupling occurs via kinetic inductance

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)

Towards field sensitivity

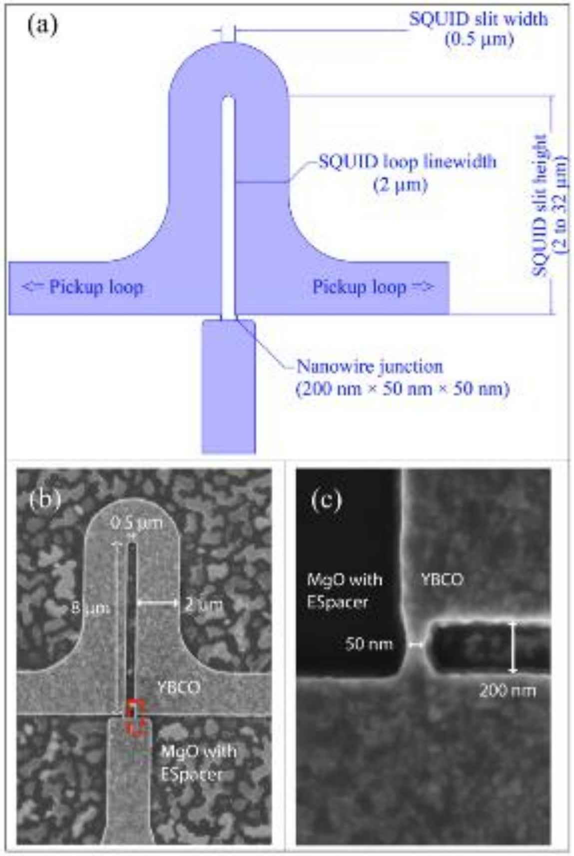
Summary of nanoSQUIDs w/ pickup loop

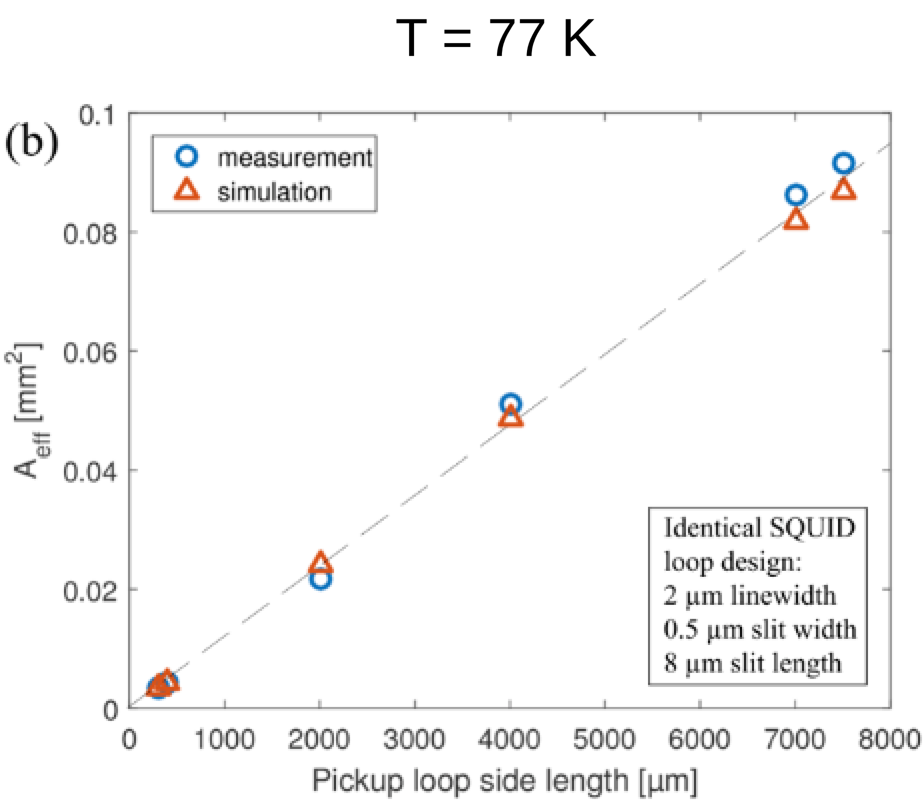
Device	$\mathbf{d_w}(\mu m)$	$\mathbf{l}$ (nm)	$\mathbf{w}$ (nm)	$\mathbf{d}(\mu m)$	$\mathbf{A_{eff}}(\mu m^2)$	$\mathbf{I_C}(mA)$	$\delta\mathbf{R}(\Omega)$	$\mathbf{V_\Phi}(mV/\Phi_0)$	$\mathbf{S^{1/2}_{\Phi,w}}(\mu\Phi_0/\sqrt{Hz})$
NSQ1	1	200	65	100	24	1.7	0.8	2.4	<1
NSQ2	1	200	65	400	62	2.4	2.4	0.75	<2
NSQR	1	100	65	-	2.8	1.75	0.2	1.5	<1

- Flux noise independent of pick up loop.
- Magnetic field noise properties improve with pick up loop size.
- Coupling mainly via kinetic inductance.

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)

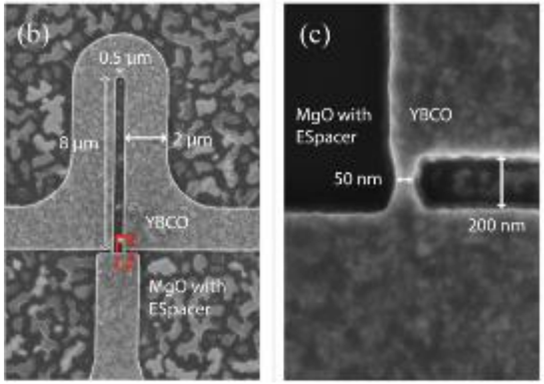
Increasing further effective area

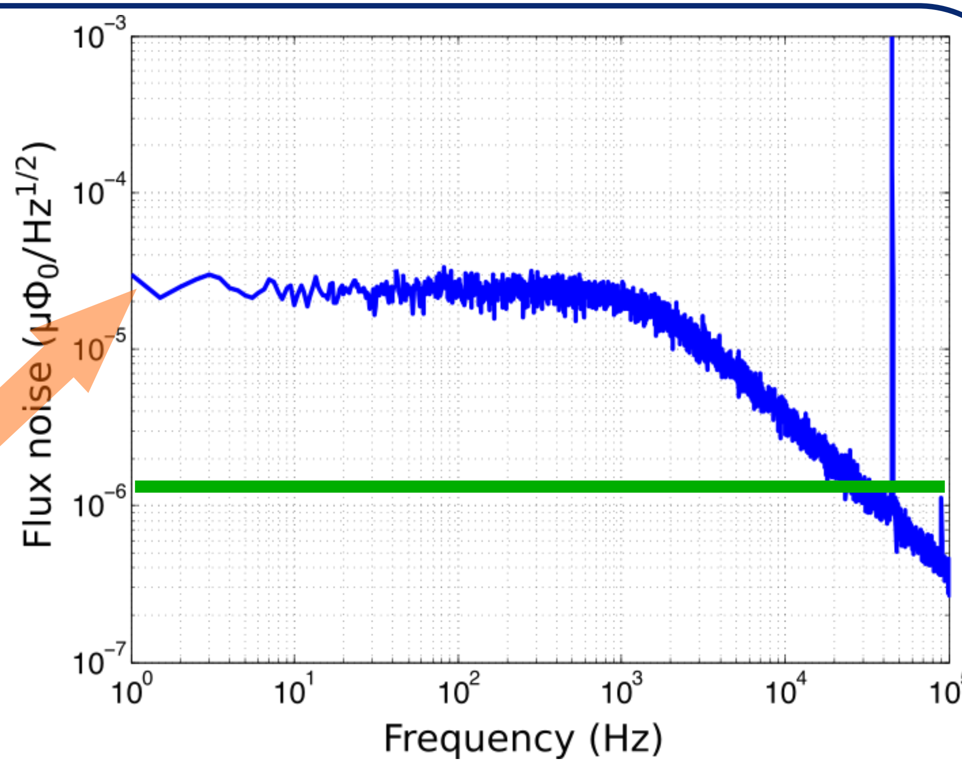




Xie, Chukharkin, Ruffieux, Schneiderman, Kalabukhov, Arzeo, TB, Lombardi, Winkler, submitted to SuST

Noise at 77 K





50 nm YBCO:

- no Au capping
- no pick up loop
- $V_\phi \sim 15\ \mu V/\phi_0$
- Amp: $S_V^{1/2} \sim 0.4\ nV/Hz^{1/2}$

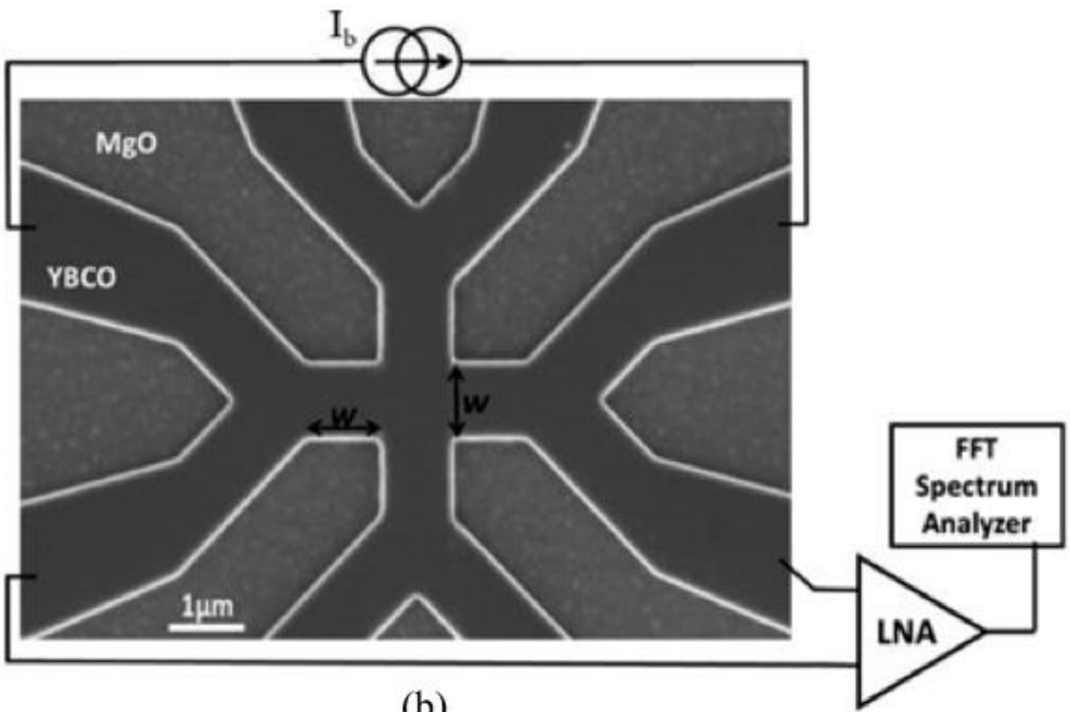
Expected field noise taking achieved effective area $A_{eff} \sim 0.1\ mm^2$:

$$S_\phi^{1/2} \sim 500\ fT/Hz^{1/2}$$

For HTS MEG applications: $S_\phi^{1/2} < 50\ fT/Hz^{1/2}$ needed

➔SQUID electronics with lower input noise (Cryoton)

Resistance and critical current 1/f noise



(b)

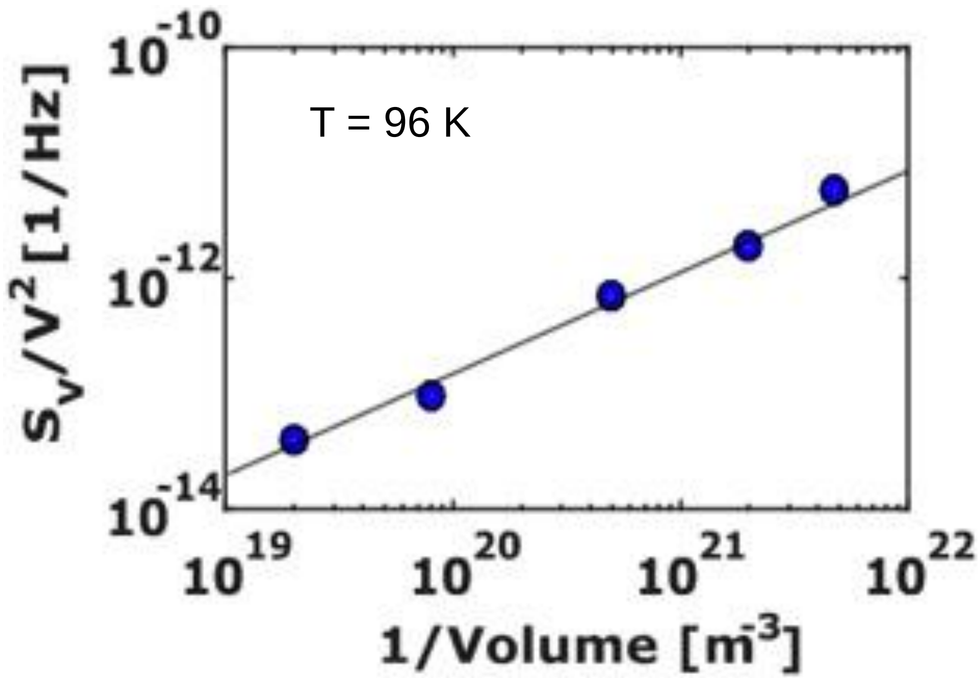
$$\delta V = (\partial V/\partial R)\,\delta R + (\partial V/\partial Ic)\,\delta Ic$$

Trabaldo, Arzeo, Arpaia, Baghdadi, Andersson, Lombardi, Bauch, IEEE TAS 27, 7500904 (2017)

Resistance and critical current 1/f noise

Hooge's law for 1/f noise

$$S_V = \gamma \frac{V^2}{f \cdot n \cdot Vol}$$



Vol = $3w^2t$
t = 50 nm,
w=65 nm, …, 1μm

$$\gamma \approx 3.4 \times 10^{-4}$$ (Hooge's parameter)

Critical current 1/f noise is roughly 10 times larger

Trabaldo, Arzeo, Arpaia, Baghdadi, Andersson, Lombardi, Bauch, IEEE TAS 27, 7500904 (2017)

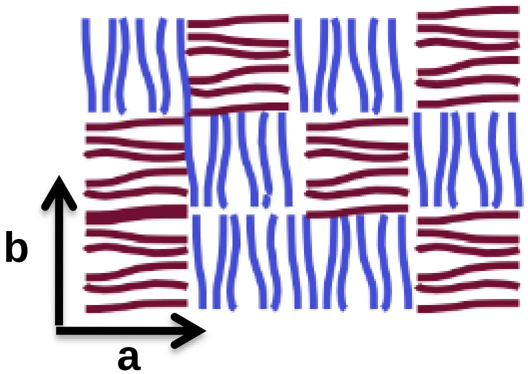
Summary

High critical temperature superconductor nanodevices

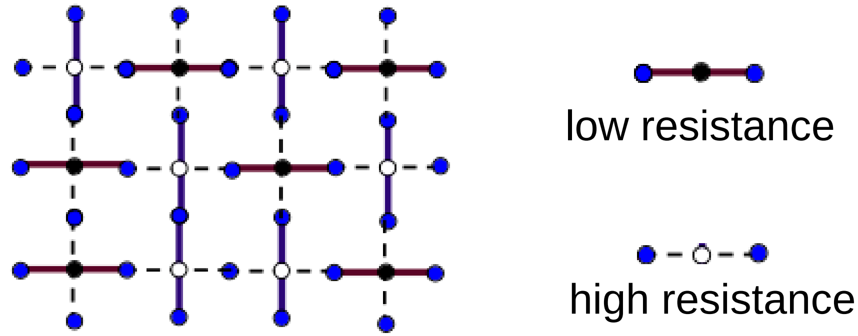
- Nanoscale devices beyond state-of-the-art
- Vision: obtain groundbreaking information about the microscopic mechanism of HTS
- quantum limited detectors
  - Nanomagnetism
  - HTS MEG systems

Transport anisotropy and noise

Finite correlation length of charge density waves (CDW): 10-40 nm

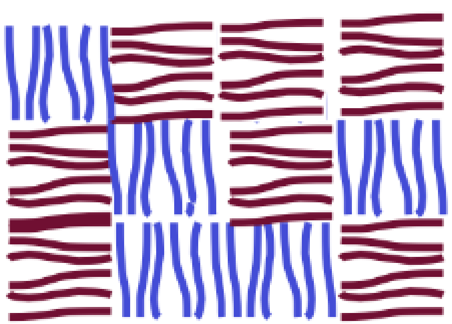


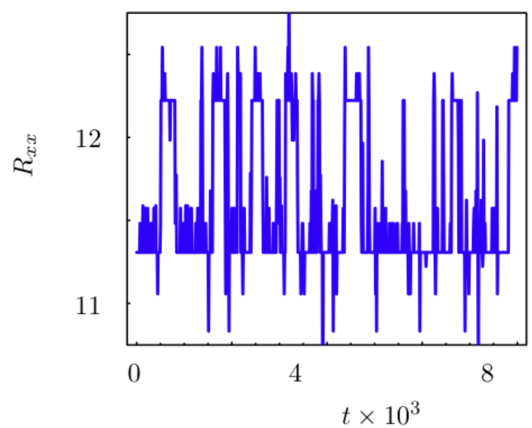
Alignment of CDW along a- or b-direction in CuO_2 planes



Equivalent resistor network

Fluctuating CDW:





Resistance fluctuations as a function of:

Doping
Temperature
Substrate
Magnetic field

Similar effects expected for superfluid density: critical current fluctuations

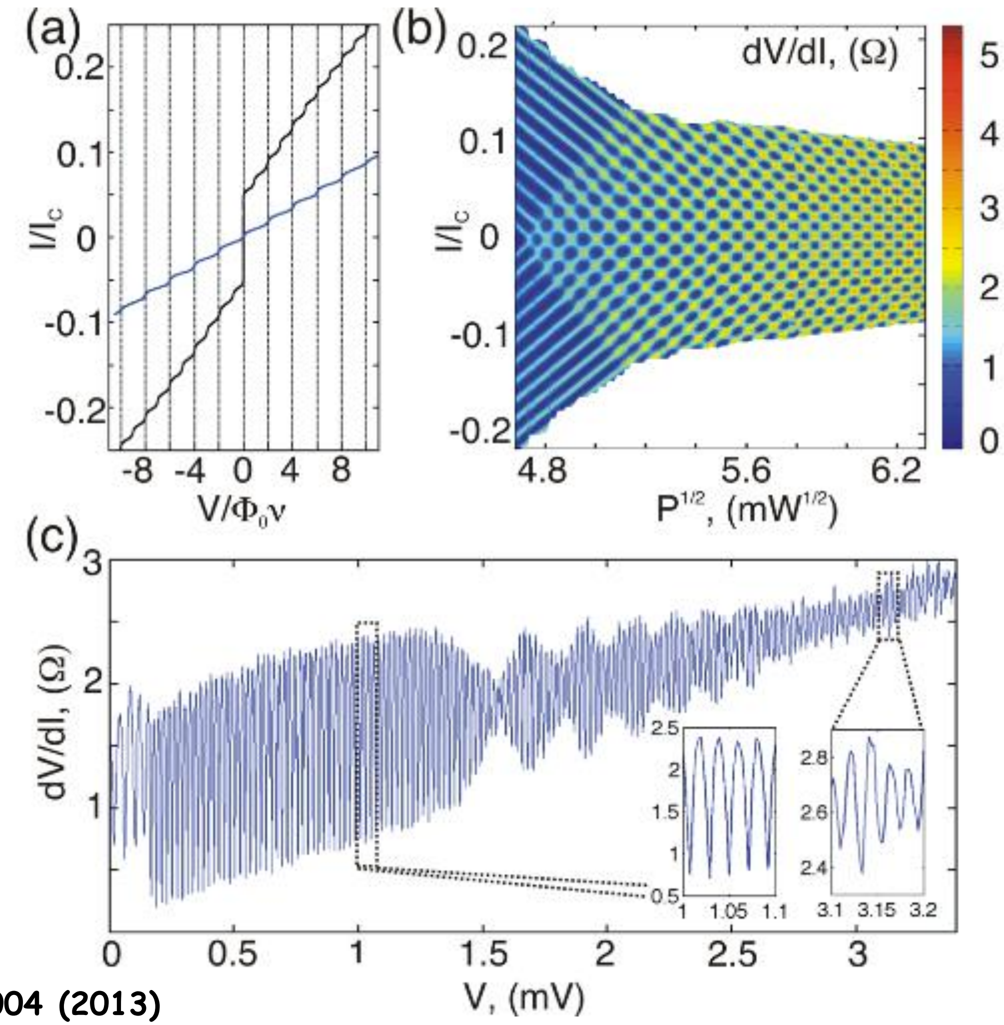
Carlson et al., Phys. Rev. Lett. 96, 097003 (2006)

Probing the AC-Josephson-like behavior:
Detection of Shapiro-like steps under microwave irradiation

- Phase locking of driving microwave field at frequency ω_d and Abrikosov vortex motion across the wire.

$$V_n = n \times \frac{W_d}{2p} f_0$$

- Shapiro steps observable to the 160^{th} order



Nawaz, Arpaia, Lombardi, Bauch, **PRL 110,167004 (2013)**

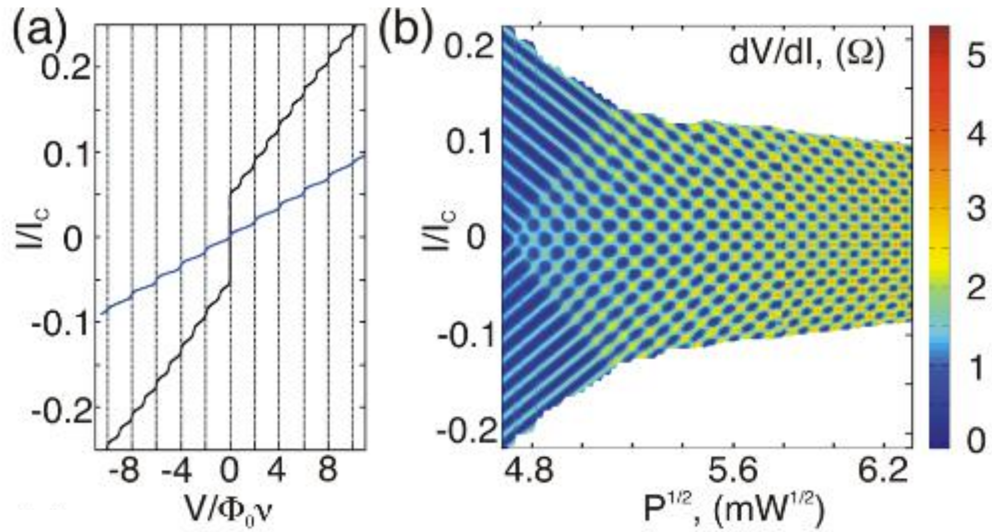
Probing the AC-Josephson-like behavior: Detection of Shapiro-like steps under microwave irradiation

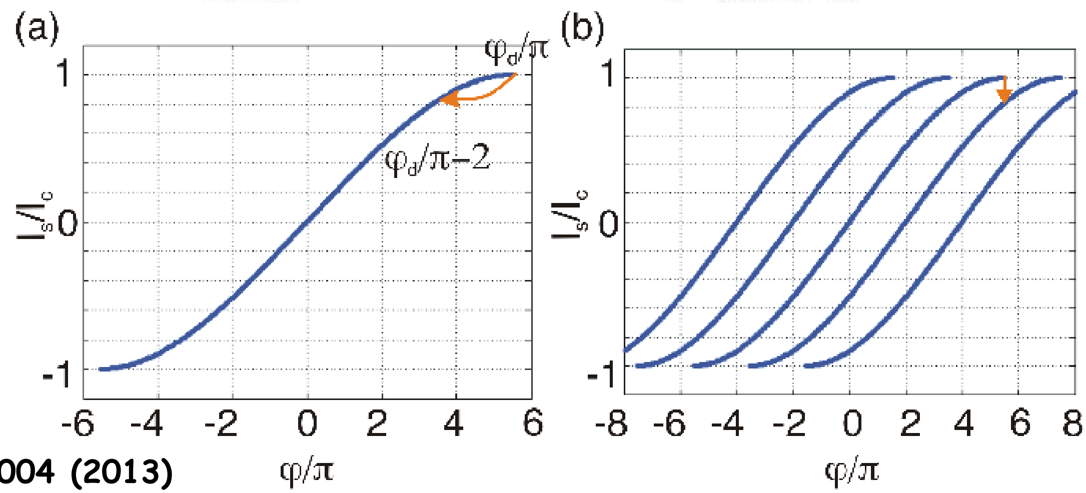
- Phase locking of driving microwave field at frequency ω_d and Abrikosov vortex motion across the wire.

$$V_n = n \times \frac{W_d}{2p} f_0$$

- Shapiro steps observable to the 160^{th} order

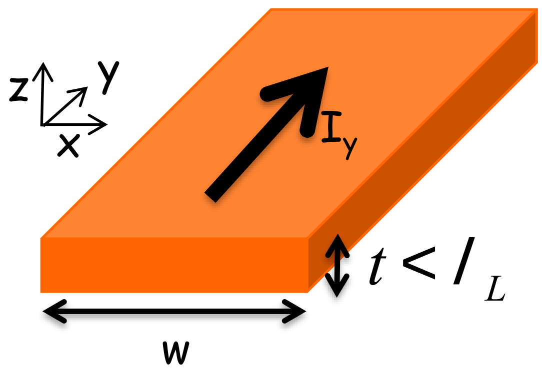
- Modulation of Shapiro-like steps indicates the existence of a periodic Current Phase Relation



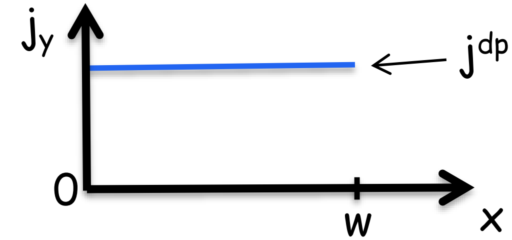


Nawaz, Arpaia, Lombardi, Bauch, **PRL 110,167004 (2013)**

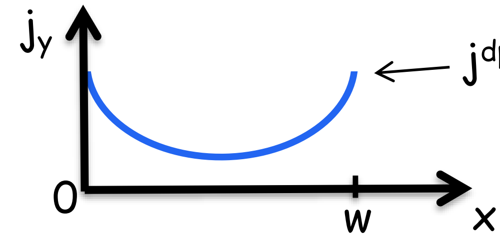
Critical current density J_C vs wire width w: a quality check



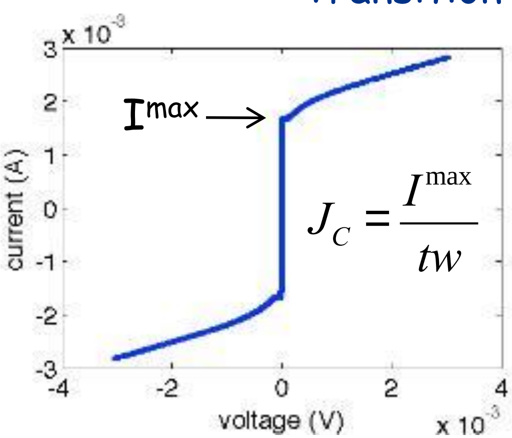
For $w < \lambda_P = \lambda_L^2 / t$



For $w > \lambda_P = \lambda_L^2 / t$



Transition from zero voltage state to finite voltage state of a wire:



Transition from the zero voltage state to the finite voltage state when the **LOCAL** current density j_y (typically at the edge of the wire) is close to the Ginzburg Landau depairing current density $j_y \sim j^{dp}$ (nucleation of vortices)

$$J^{dp} = \frac{\Phi_0}{3\sqrt{3}\pi\mu_0\lambda_L^2\xi} \approx 1.5\times10^8 \ \text{A/cm}^2$$

YBCO nano-wire SQUIDs in literature

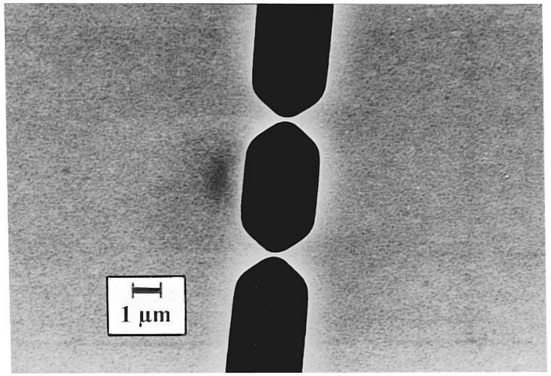
Appl. Phys. Lett. **65** (19), 7 November 1994

dc SQUIDs based upon $YBa_2Cu_3O_7$ nanobridges

J. Schneider, M. Mück, and R. Wördenweber
Institute of Thin Film and Ion Technology (ISI), Research Centre Jülich (KFA), 52425 Jülich, Germany

(Received 6 April 1994; accepted for publication 30 August 1994)

$\times 100\ \mathrm{nm}^3\ (l,w,d)$.[11] Even for a calculated $\beta_L \approx 1$, no significant modulation of the critical current was observed for our HTS SQUIDS, i.e., $\Delta I_c/I_c \ll 1$. The relatively high volt-



Appl. Phys. Lett., Vol. 68, No. 8, 19 February 1996

Superconducting quantum interference devices based on YBaCuO nanobridges

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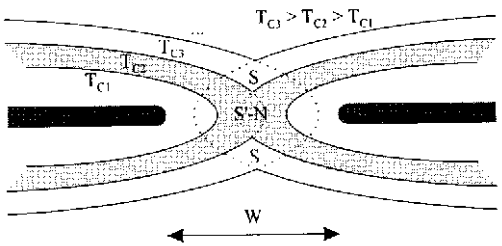
(Received 21 September 1995; accepted for publication 18 December 1995)

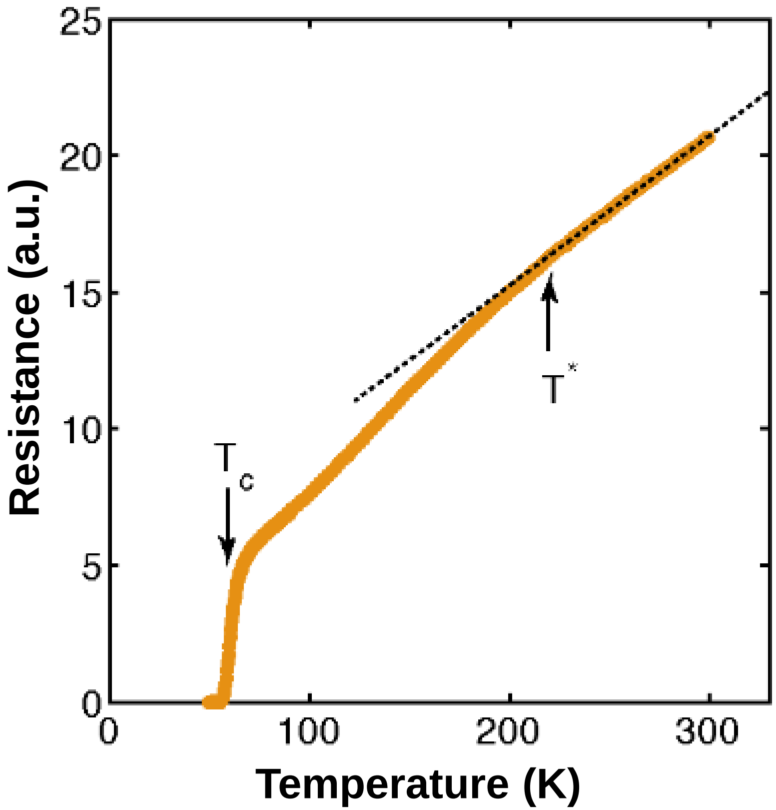
for weak link SQUIDs. To explain this phenomenon, we considered degradation of superconductor in the nanobridge area, which leads to a local suppression of T_c and to a transition from SNS to SS′S-type junctions with decreasing temperature. This approach allows us to explain the experimen-

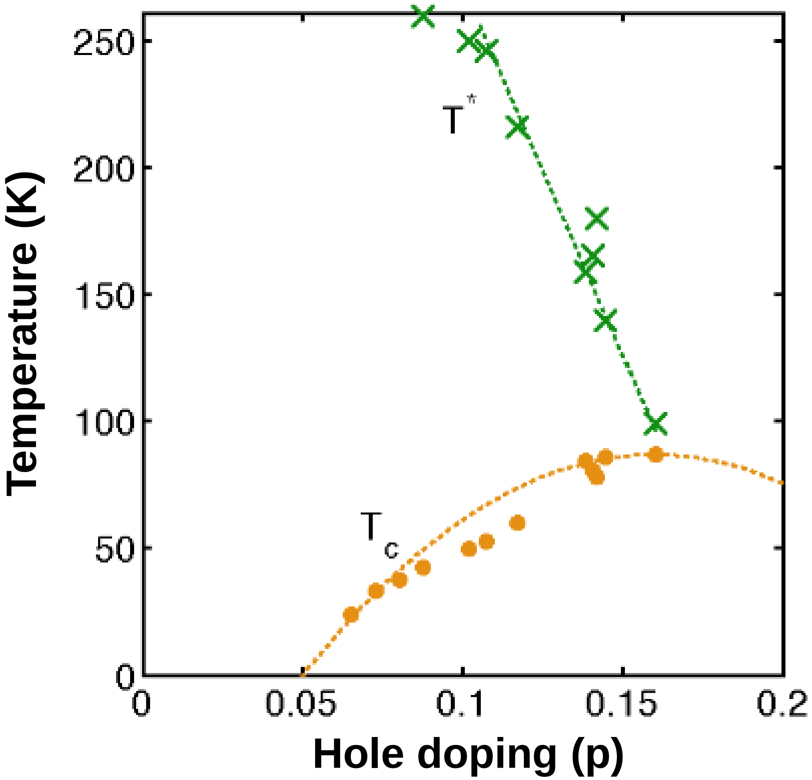


See also Supercond. Sci.Technol. 22 (2009) 064001
“Why NanoSQUIDs are important: an introduction to the focus issue”
by C. P. Foley and H. Hilgenkamp

Doping dependence: thin films

Variation of hole doping through proper annealing





(unpublished)