DTU

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Center for Nanoteknologi på DTU

# Spontaneous fluxoid trapping in quenched superconducting rings; Big Bang in the laboratory?


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# Outline

- Big Bang, phase transitions and causality
- Kibble-Zurek experiments with annular JTJ
- Statistical models and comparisons
- K-Z experiments with a single ring in AFM type setup
- K-Z experiments with ring and 2 gap'ed JTJs
- K-Z experiments with ring and SQUID
- Outlook

# Edwin Hubble

1929 discovered a rough proportionality of the objects' distances *D* with their redshifts (relative velocity).

$$V = H_0 D$$

Hubble's constant:

$H_0$ = (500 km/s/Mpc)

70.4±1.5 (km/s)/Mpc for measurements up to 2006 (WMAP data)

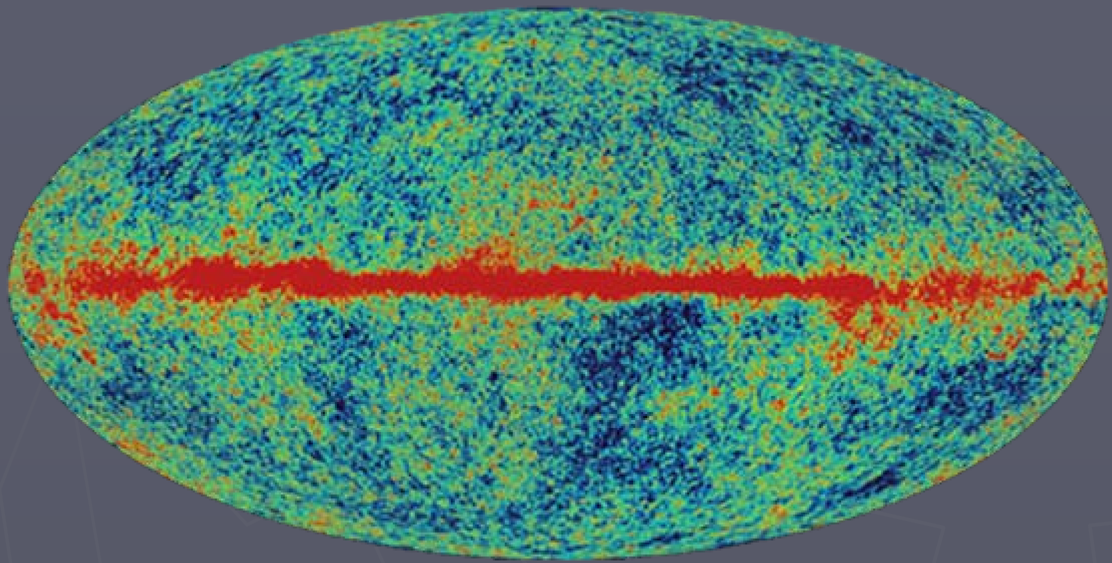
1 AU = $4.85 \times 10^{-6}$ pc
1 pc = 3.25 ly

**Born** November 20, 1889
**Died** September 28, 1953 (aged 63)
American astronomer

Big Bang proof?:
Hubble expansion
CMB
General relativity

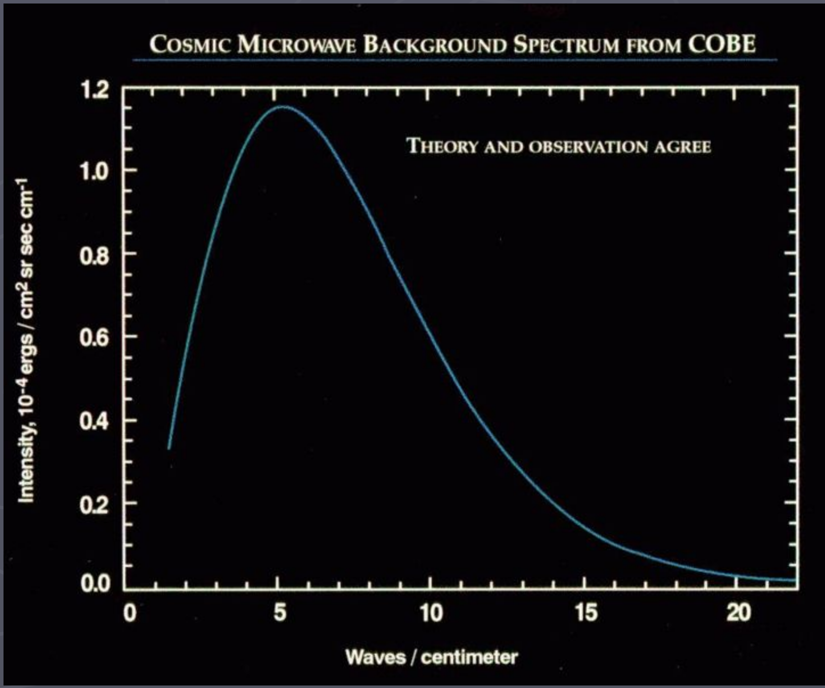
The 100 inch Hooker telescope at Mount Wilson Observatory that Hubble used to measure galaxy redshifts and a value for the rate of expansion of the Universe.

# Cosmic microwave background radiation (CMB)



In 1964 A. Penzias and R. Wilson discovered the CMB radiation. The radiation was found to be isotropic (1:$10^4$) and fitted perfectly a blackbody spectrum of T=2.725K.

WMAP (Wilkinson Microwave Anisotropy satellite) image of the cosmic microwave background radiation temperature anisotropy (2003-2006). Dipole anisotropy from the motion of the sun is subtracted.




The CMB pitched the balance of opinion in favor of the Big Bang hypothesis. In 1978 P&W were awarded the Nobel Price for their discovery

CMB gives a snapshot of the University ≈380.000ys after BB at "time of last scattering" where T≈3000K. CMB received from a spherical surface with R≈13.7 $10^9$ ly.

# Kibble-Zurek phase transitions

- Phase transitions in the early universe, causality, Kibble (1980) [1]
  - Phase transitions involve transmitting information
  - Information has a maximum velocity of transmission
  - Domain structure determined by causality
- Zurek(1996) [2] proposed condensed matter systems for testing the theory
  - Superfluids
  - Superconductors
  - Defect density related to nature of domain structure
- Kavoussanaki *et al.* (2000) [3] proposed testing in
  - Annular Josephson Tunneling Junctions – AJTJs
- Monaco *et al.* [4, 5, 6]
  - Experimental confirmation of scaling properties in ATJs and SC rings

**References:**


[1] T. W. B. Kibble, Phys. Rep. **67**, 183 (1980).
[2] W. H. Zurek, Phys. Rep. **276**, 177 (1996).
[3] E. Kavoussanaki, R. Monaco, and R. J. Rivers, Phys. Rev. Lett. **85**, 3452 (2000)
[4] R. Monaco, J. Mygind, M. Aaroe, R. J. Rivers, and V. P. Koshelets, Phys. Rev. Lett. **96**, 180604 (2006)
[5] R. Monaco, M. Aaroe, J. Mygind, R. Rivers, and V. P. Koshelets, Phys. Rev. B, **77**, 054509 (2008).
[6] R. Monaco, J. Mygind, R. Rivers, and V. P. Koshelets, Phys. Rev. B, **80**,180501 (2009).

# The K-Z scenario

K-Z scenario for continuous (2nd order) phase transitions proposes that transitions take effect as fast as possible
ie. the domain structure initially matches causal horizons

Causality leads to a 'domain' structure because the 'field' cannot order itself instantaneously.

Causality we trust! ie. the K-Z proposition, if true, would apply both to the early Universe and laboratory based condensed matter systems.

First order phase transition analogy; freezing water

# K-Z domains and defects

2'd order transitions:

- no latent heat (eg. heat of fusion, etc.) involved in the change of order
- the adiabatic correlation length $\xi_{ad}(T)$ diverges at the transition temperature $T_C$
- in reality correlation lengths cannot become infinite because there is a maximum speed at which the field can order itself
- maximum physical value of the correlation length is $\xi = \xi ad(T(t))$ where t is the time at which the rate of change of the correlation length is as fast as causality permits
- if the symmetry breaking permits domains (and thus defects) their separation is $\xi$ at the time of their production

For systems with dimension C larger than $\xi$ the trapping rate is given by the allometric formula

$$f_1 \sim C/\xi \sim \tau_Q^{-\sigma}$$

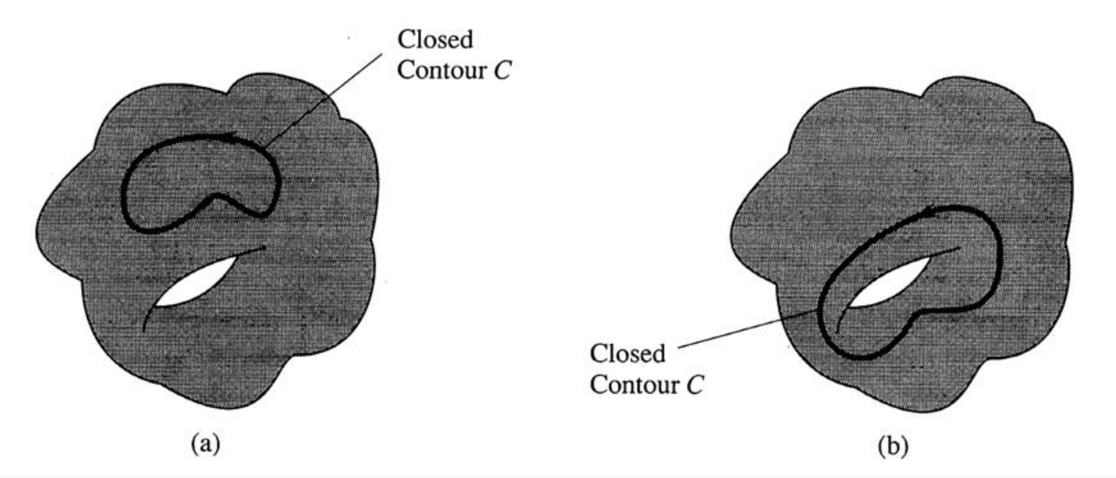
where C is eg. the circumference of a ring, $\xi$ the defect separation, and $\tau_Q$ the quench time

# Superconductivity

Cooper pairing and macroscopic pair wave function

→

**Flux quantization**




Integration of the gradient of the phase of the Bose condensate wavefunction in a multiply connected superconducting body

$$\oint_C (\Lambda \mathbf{J}_s) \cdot d\mathbf{l} + \int_S \mathbf{B} \cdot d\mathbf{s} = n\Phi_o,$$

leads to quantization of the magnetic flux in units of the flux quantum

$$\Phi_o = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ T-m}^2$$

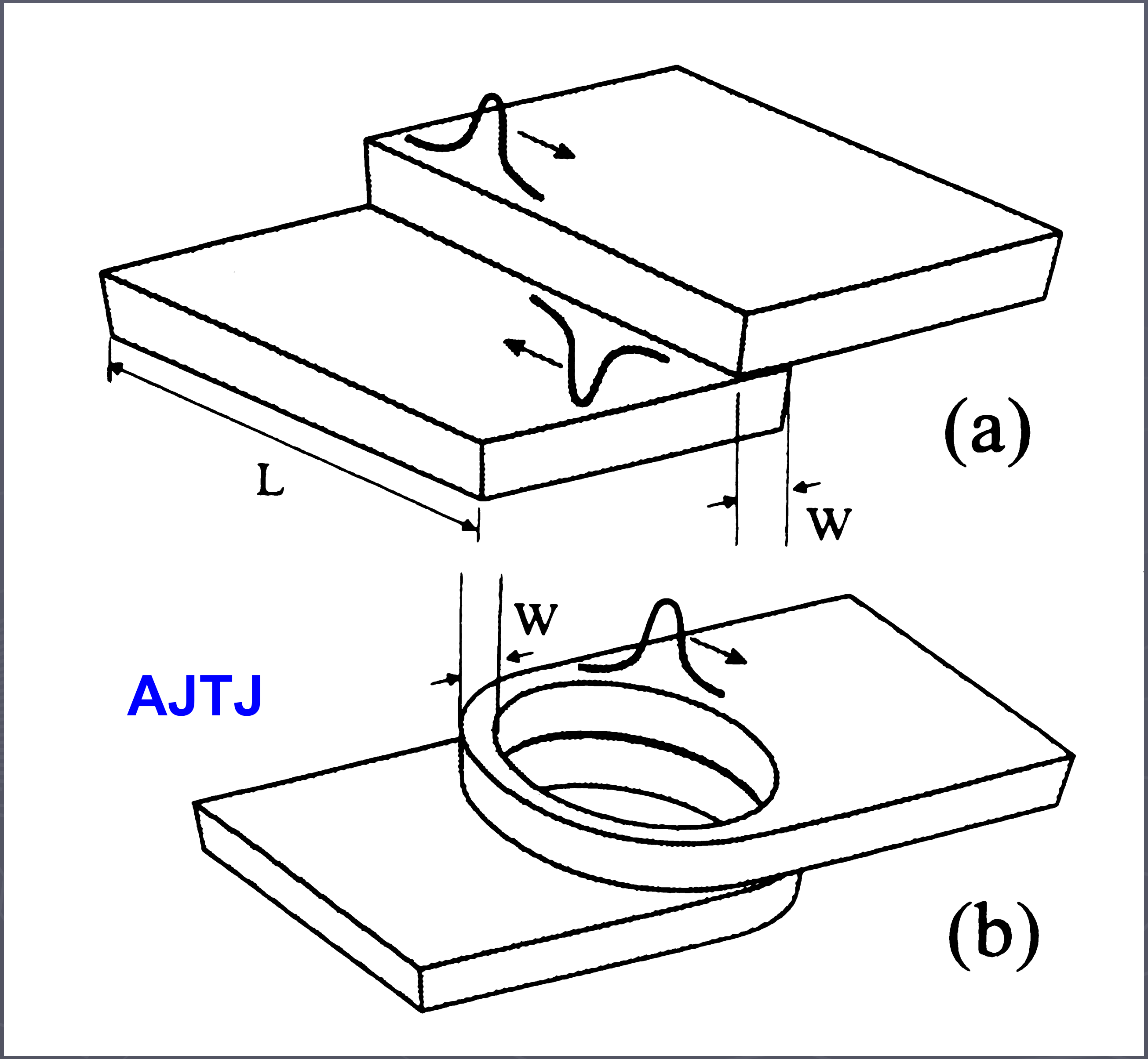
# Long Josephson tunnel junctions

$L \gg \lambda_J$
$W \ll \lambda_J$

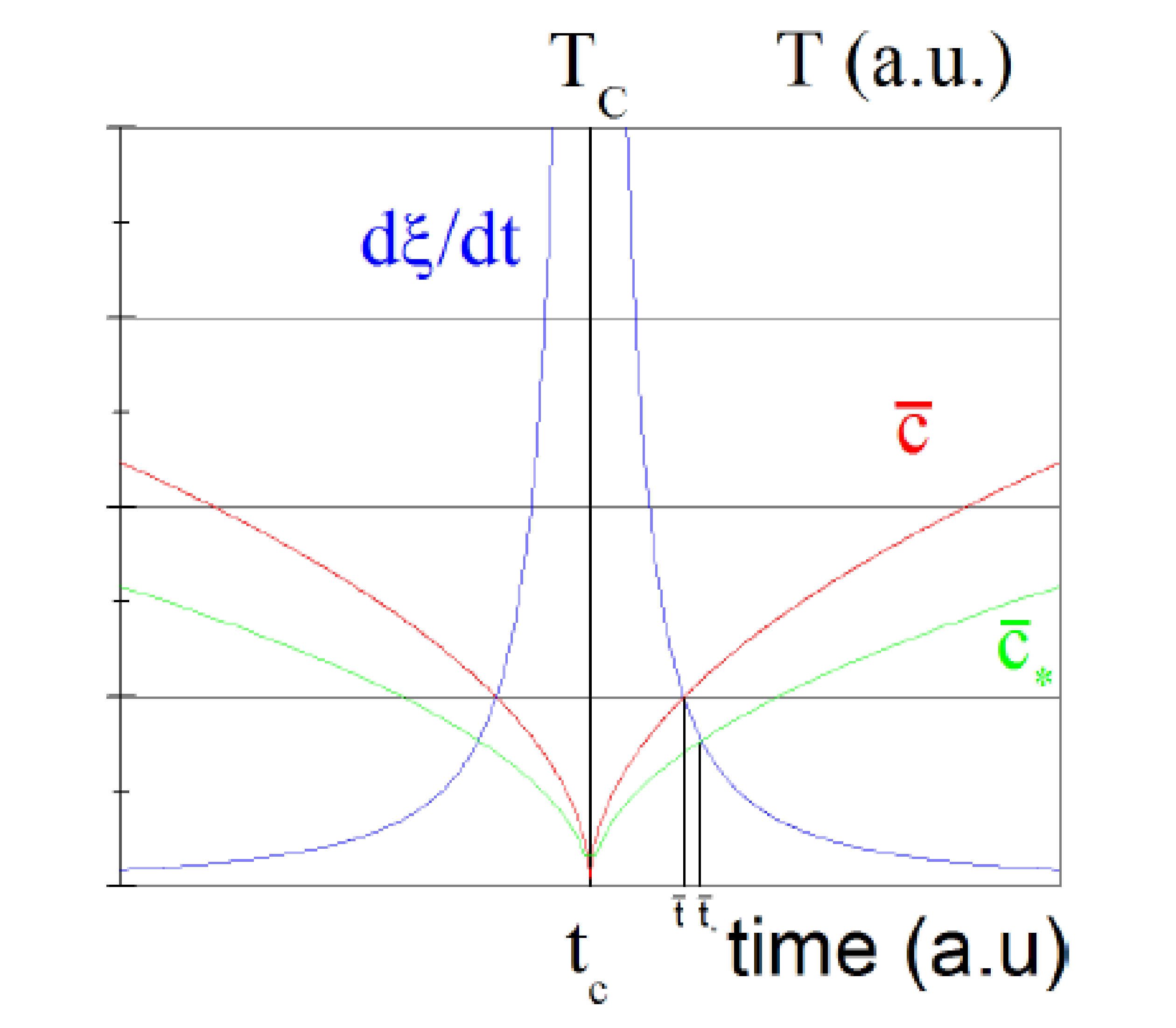
Linear overlap geometry

Annular (Lyngby) geometry

AJTJ



# The causal horizon



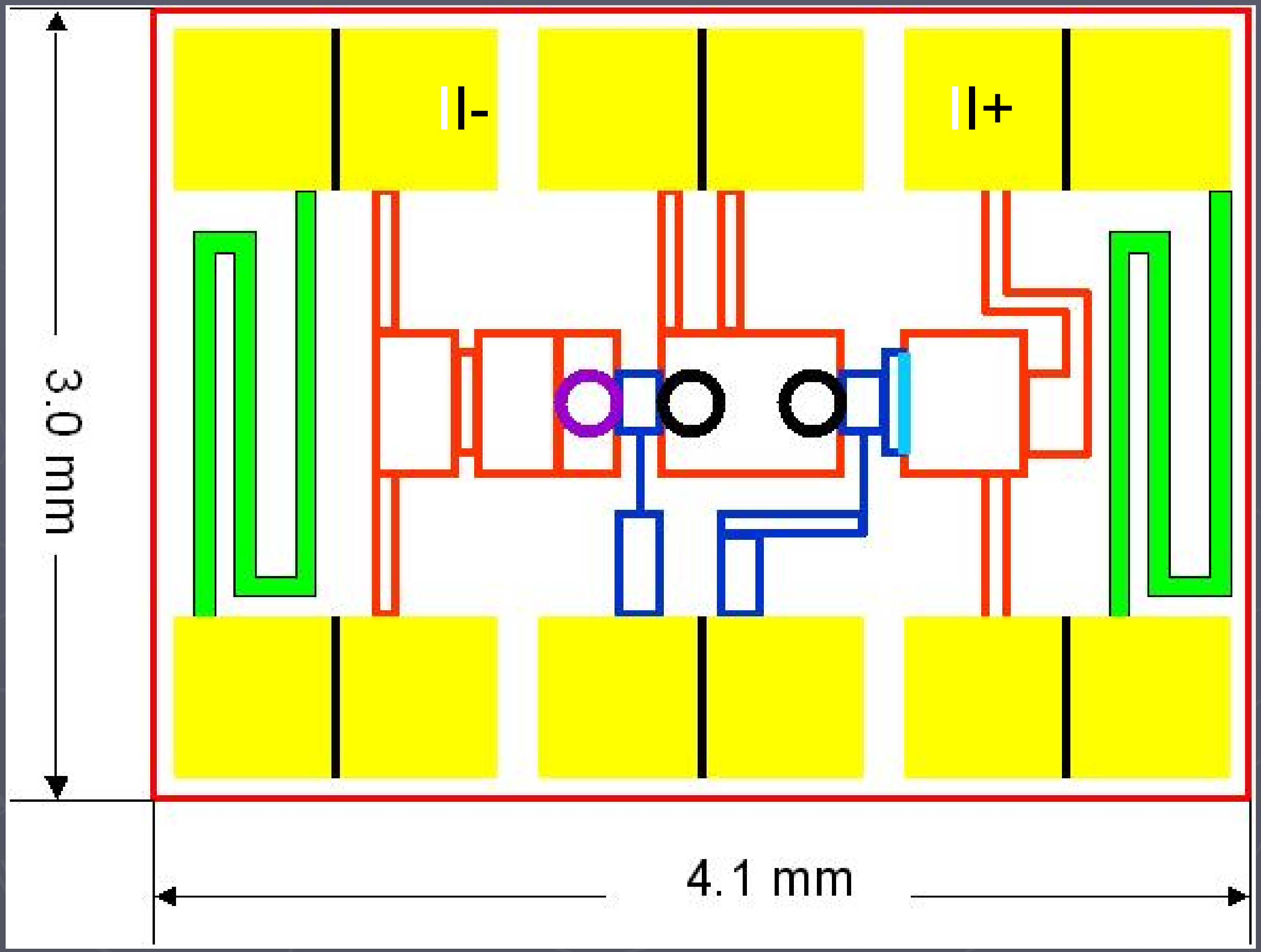

In the AJTJ the maximum propagation velocity is the Swihart velocity, curve **c**. Curve **$c_*$** is shown as a slower version for illustration only.

# Experiments with AJTJ

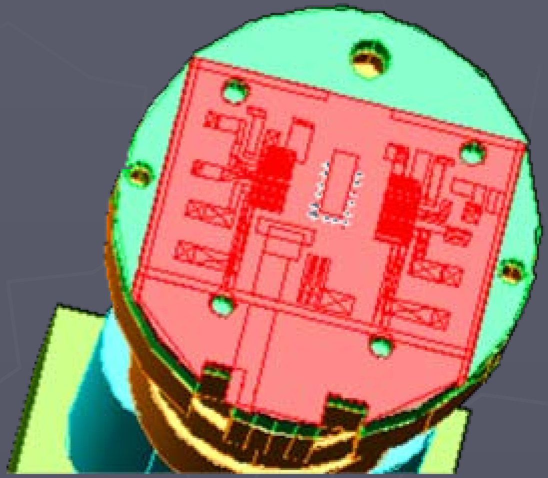
- Samples, geometry
- Cryogenic sampleholder
- Detection of defects (Zero-Field Steps)
- Quench rate
- Main results

# Sample geometry
(3 AJTJs, 1 LJTJ, 2 heaters)

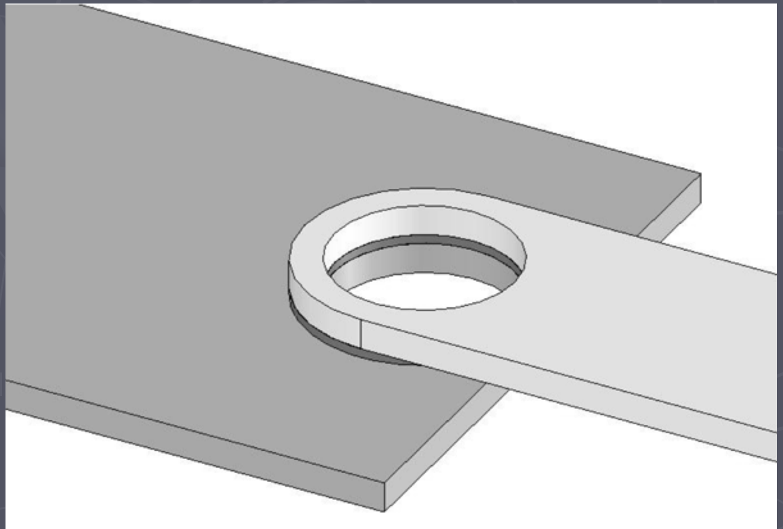
I-



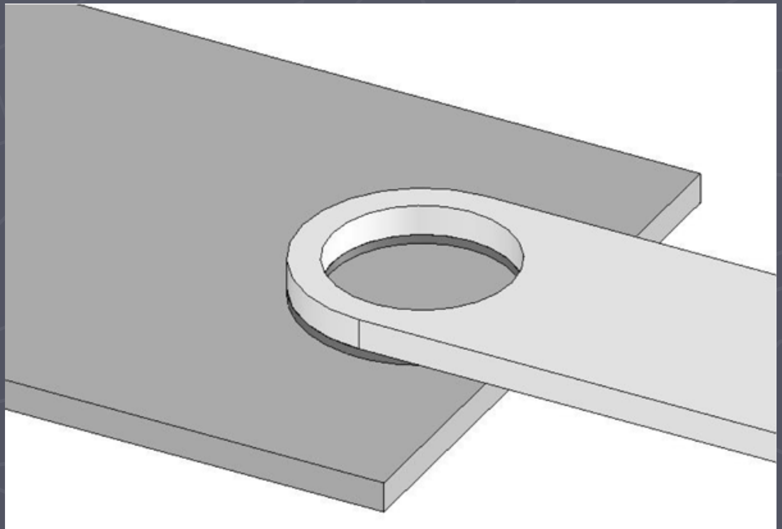
# Sample holder and layout
## (modified Lyngby geometry)



Without ground plane

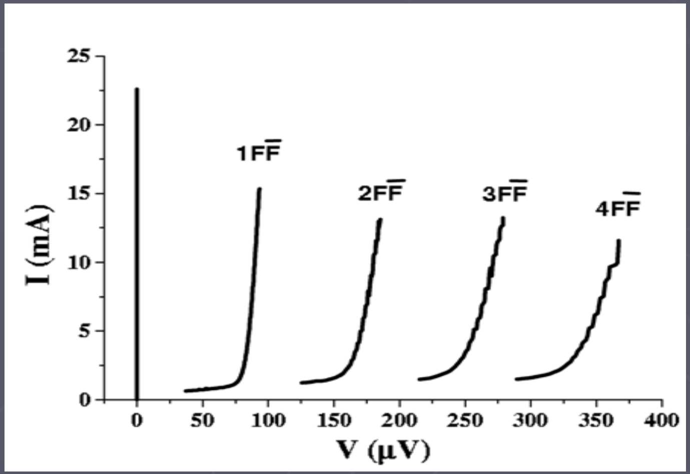


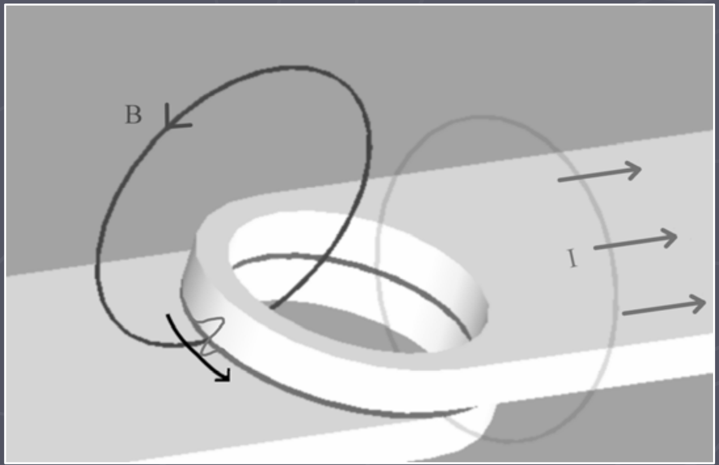
With ground plane



# AJTJ Zero-Field Steps

- Flux quantisation
  - Phase of superconducting wave function is required to be $2\pi-$periodic in a superconducting ring.
  - In the long AJTJ the magnetic flux exists as flux quanta (fluxons), $\Phi_0 = h/(2e)$.
  - The flux is trapped between the two films as fluxons, but the fluxoid is conserved in which ring?
  - Also an integer number (N= 0, ±1, ±2, etc.) of fluxons (defects) in the AJTJ.



# Yes/no experiment

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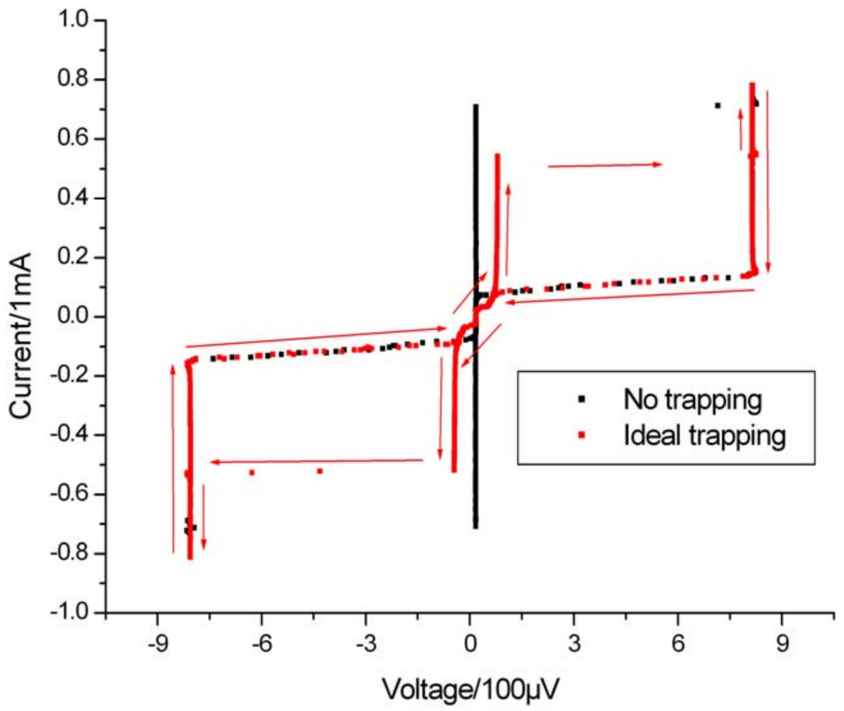
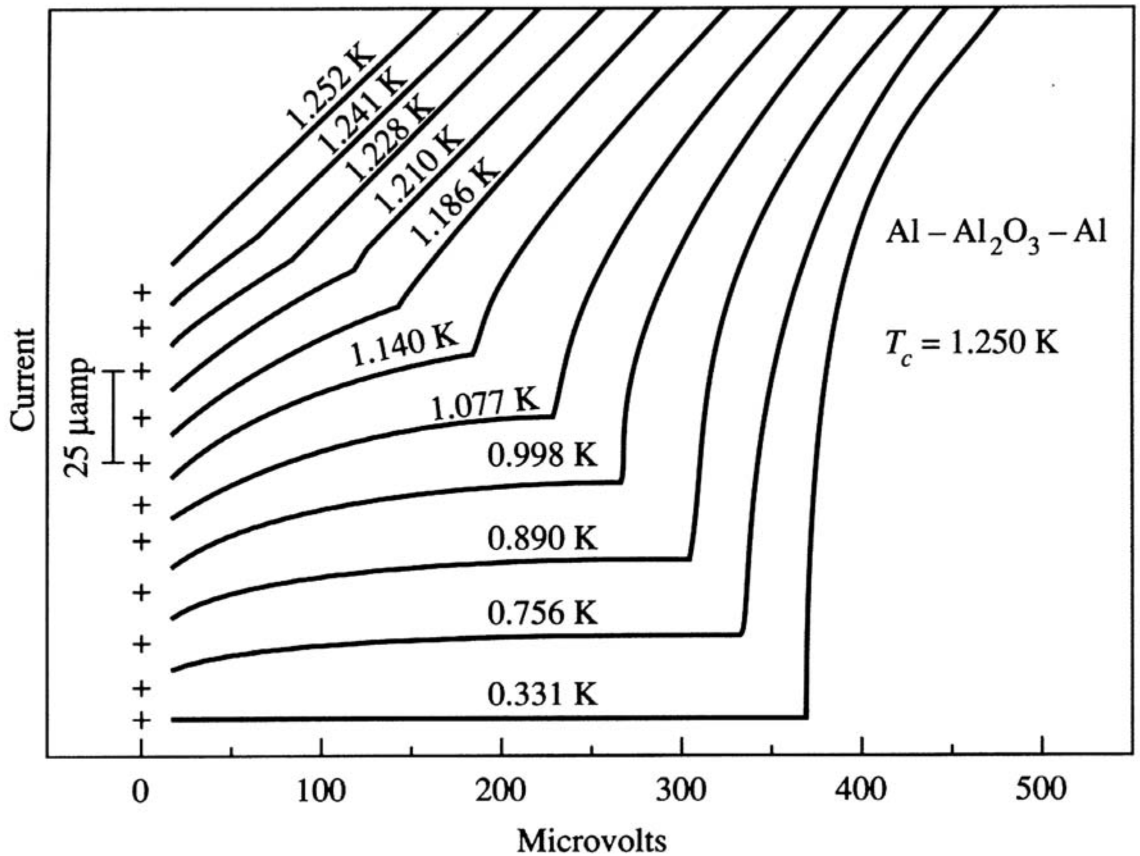
- Josephson Junction
  - DC I-V curve without trapped flux.
- Fluxon detection
  - IV-characteristic




Conclusion: We can unabigiously detect trapping or no trapping of a fluxon.
NOTE: long time after quenching




A sequence of current-voltage characteristics at various temperatures for a constant voltage source driving the junction. The curves are offset from zero for clarity. *Source: B. L. Blackford and R. H. March, "Temperature Dependence of the Energy Gap in Superconductivity A1-A1$_2$O$_3$-A1 Tunnel Junctions,"* Canadian Journal of Physics, *Vol. 46 (1968).*

# DC I-V curve for **SIS junction**

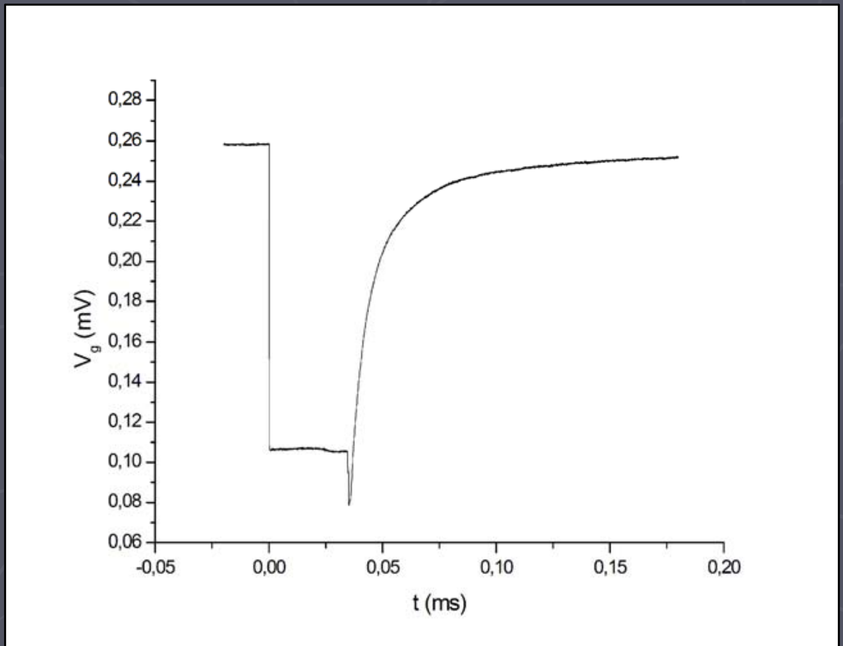
Quasi-particle current vs. temperature shows also **Δ**(T)

Used in the SIS mixer and in many bolometric detectors

# Thermal setup

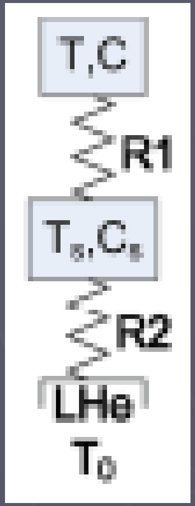
- Challenges
  - Measuring cooling rate at $T=T_C$
  - Reproducible cycles within several decades of cooling rates
  - No electrical connections during transition time
- Quench time:

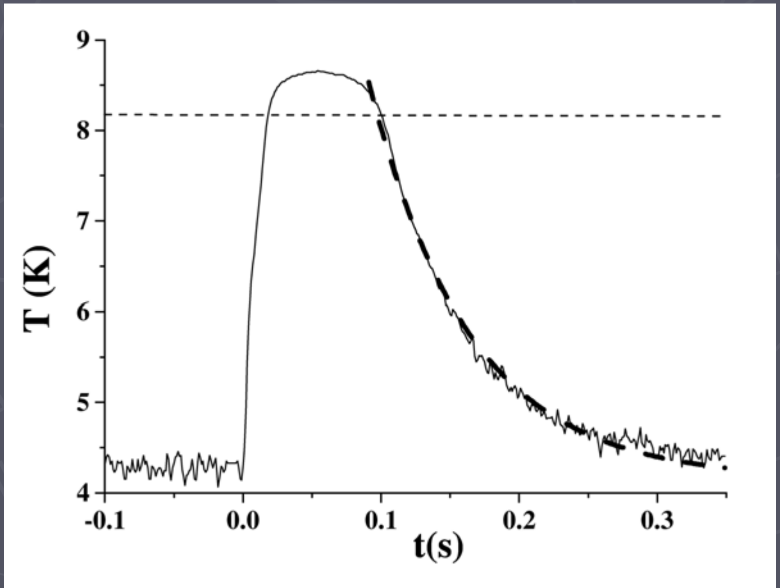
$$\tau_Q = -T_C \left(dT/dt|_{T=T_C}\right)^{-1}$$

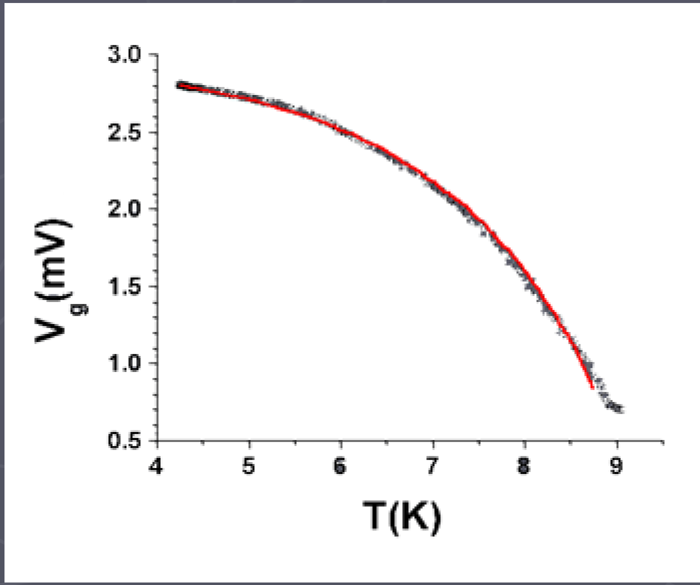


# Measurement of $\tau_Q$

- Simplified model of cooling system
- 5 parameter fit of measured gap voltage data to thermal model
- Gap voltage $V_g(T)$ measured for fixed bias current at ¼ of maximum gap current
- BCS fit with $T_C = (9.12\pm0.04)$K, $V_g(T=0) = (2.89 \pm0.02)$mV



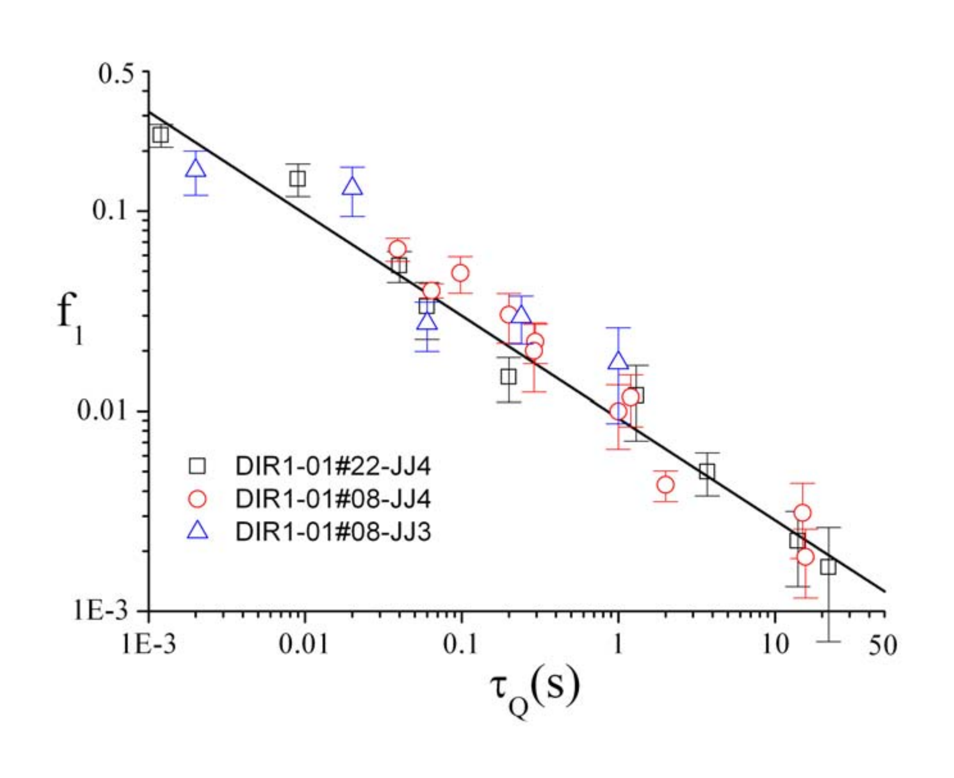
# Results AJTJ

- Trapping probability vs quench rate
- Effect of a (symmetry breaking) magnetic field applied perpendicular to the AJTJ

# Main results in long AJTJ

- Allometric scaling found for trapping probability vs quench time
  - Critical exponent ~ **0.50**
  - Reproduced with **3** samples
  - Variation of cooling rate $\tau_Q$ ±10% over **$10^4$** cycles
  - Reproduced over **4** decades of cooling rates
  - Uncertainty: $f_1/(n_1)^{1/2}$ with 100<N<5000

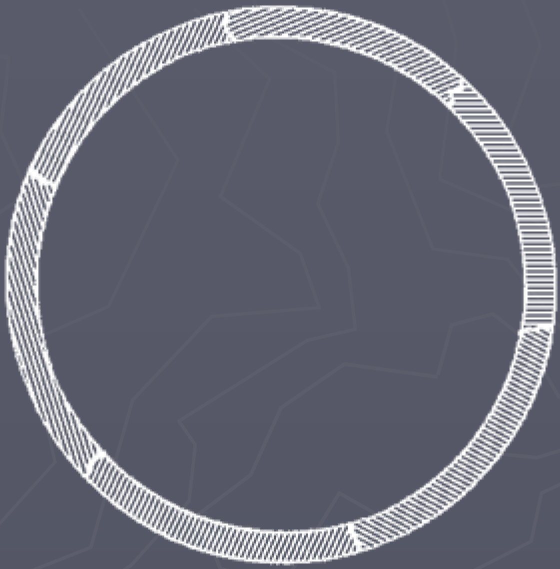
$$f_1 = n_1/N \sim C/\xi \sim \tau_Q^{-\sigma}$$




Zurek theory for single ring: σ = 0.25!

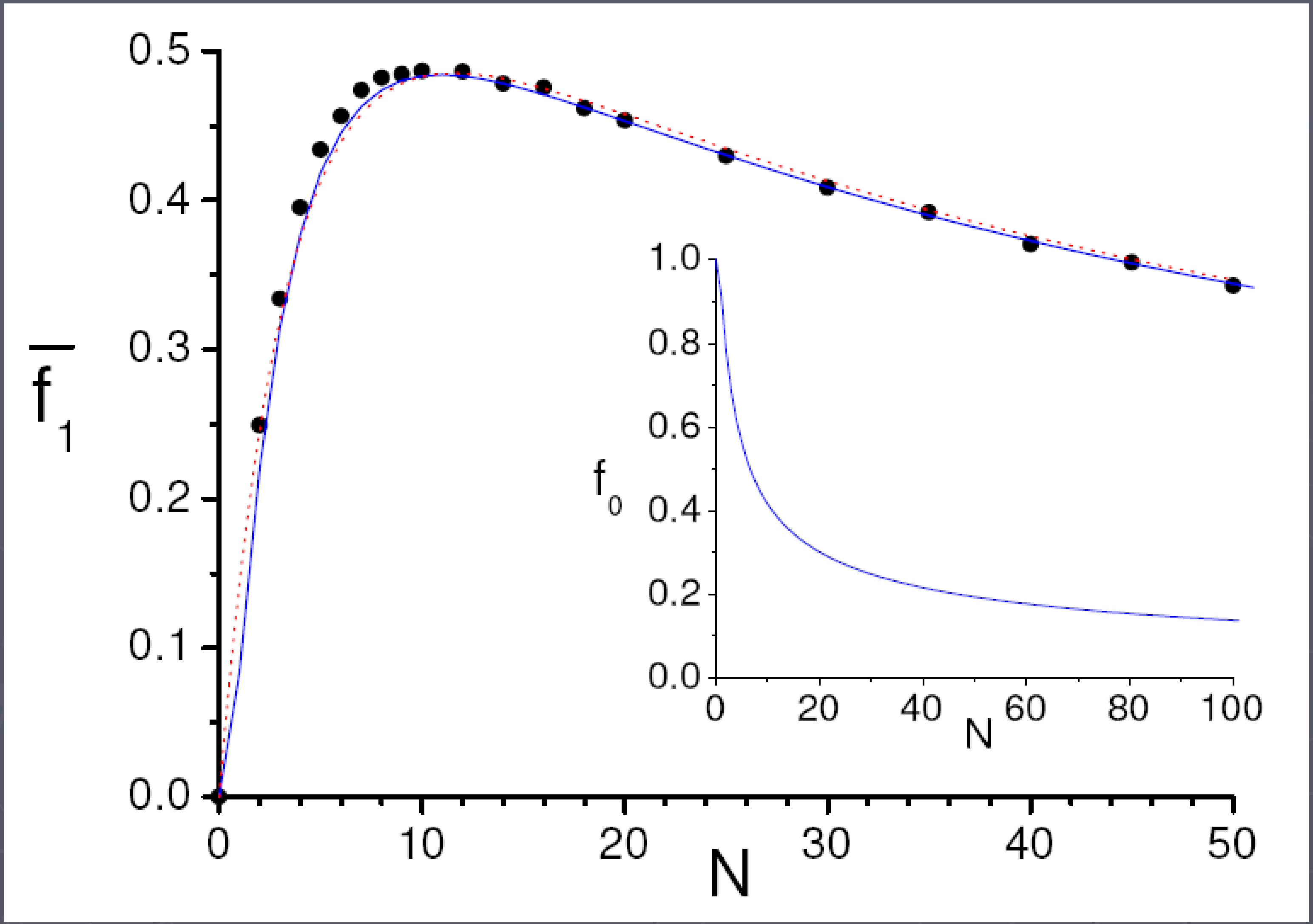
# Model for AJTJ + ring??

- Domains
  - Uncorrelated by causality
  - One macroscopic wave function in the domain
  - Constant phase gradient
  - Size determined by causality
- Magnetic field
  - Generates phase gradient
  - Proportional to external B-field, ie. gradient of phase shift is proportional to vector potential



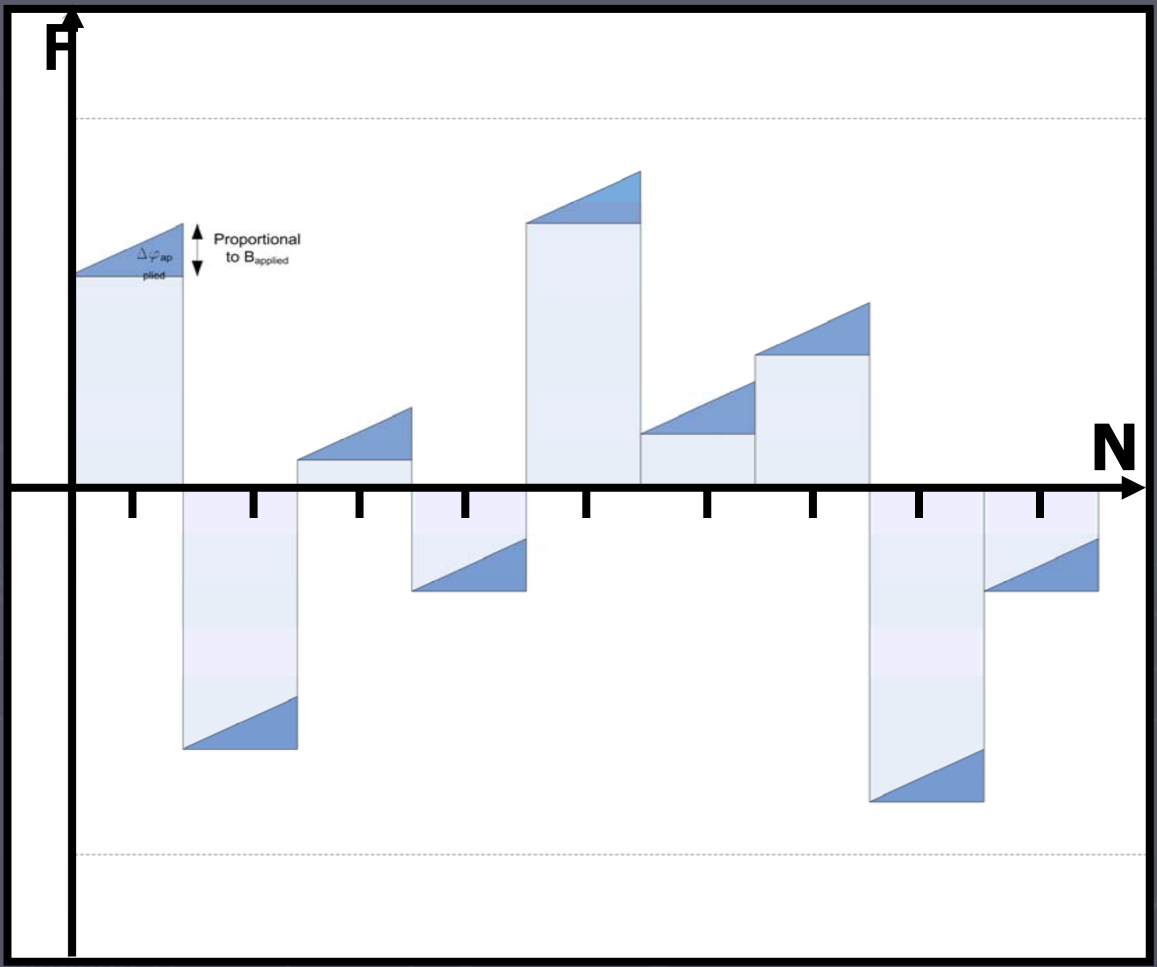
$$\hbar \oint \nabla \theta \cdot dl = e^* \oint (\Lambda \mathbf{J}_s + \mathbf{A}) \cdot dl$$

http://www.people.nnov.ru/fractal/perc/ising.htm



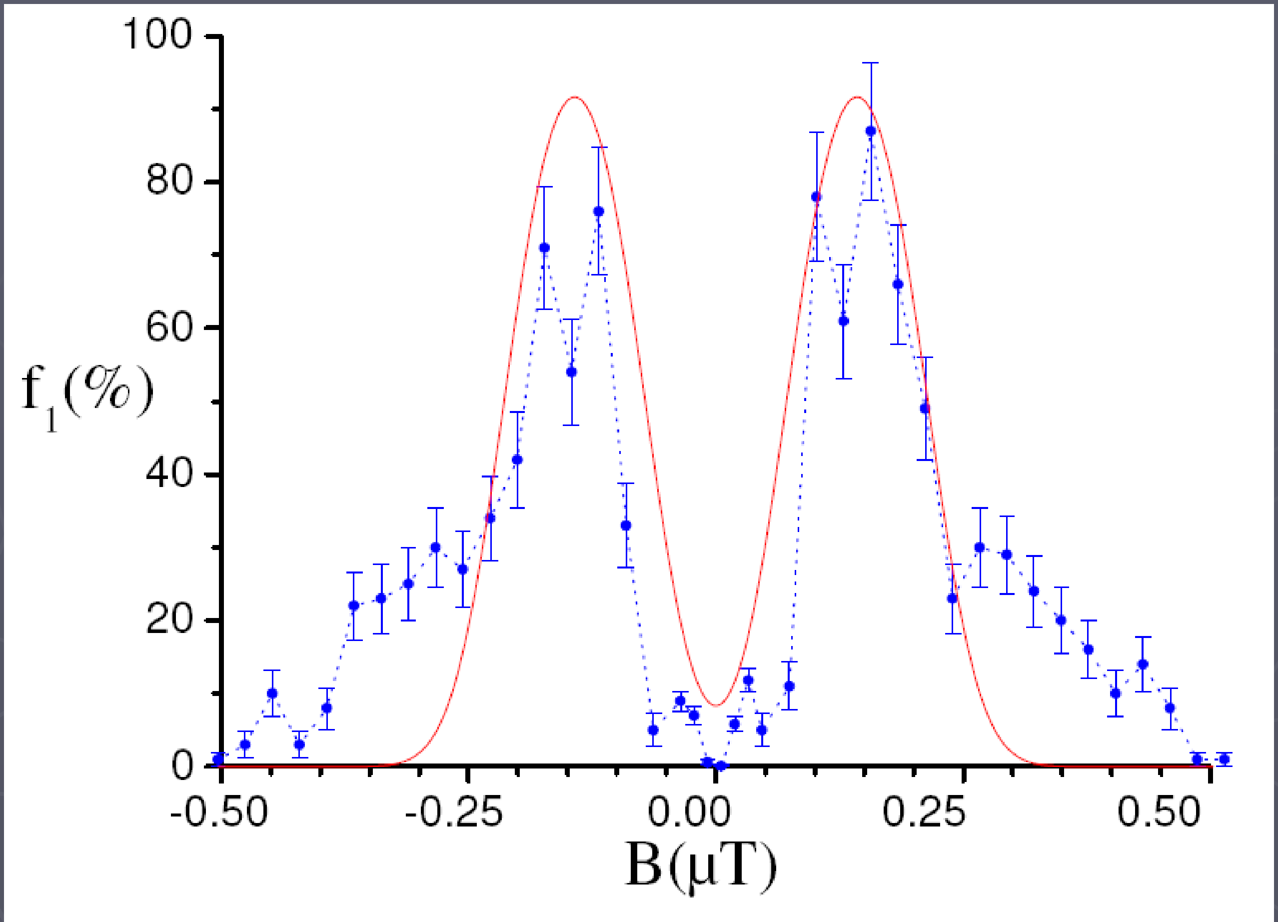

Probability $f_1$ for trapping of a single fluxon versus number N of domains. Note maximum for N ≈ 10.5 with $f_1$ ≈ 49%. Inset shows probability for zero trapping.

# Self-convolution



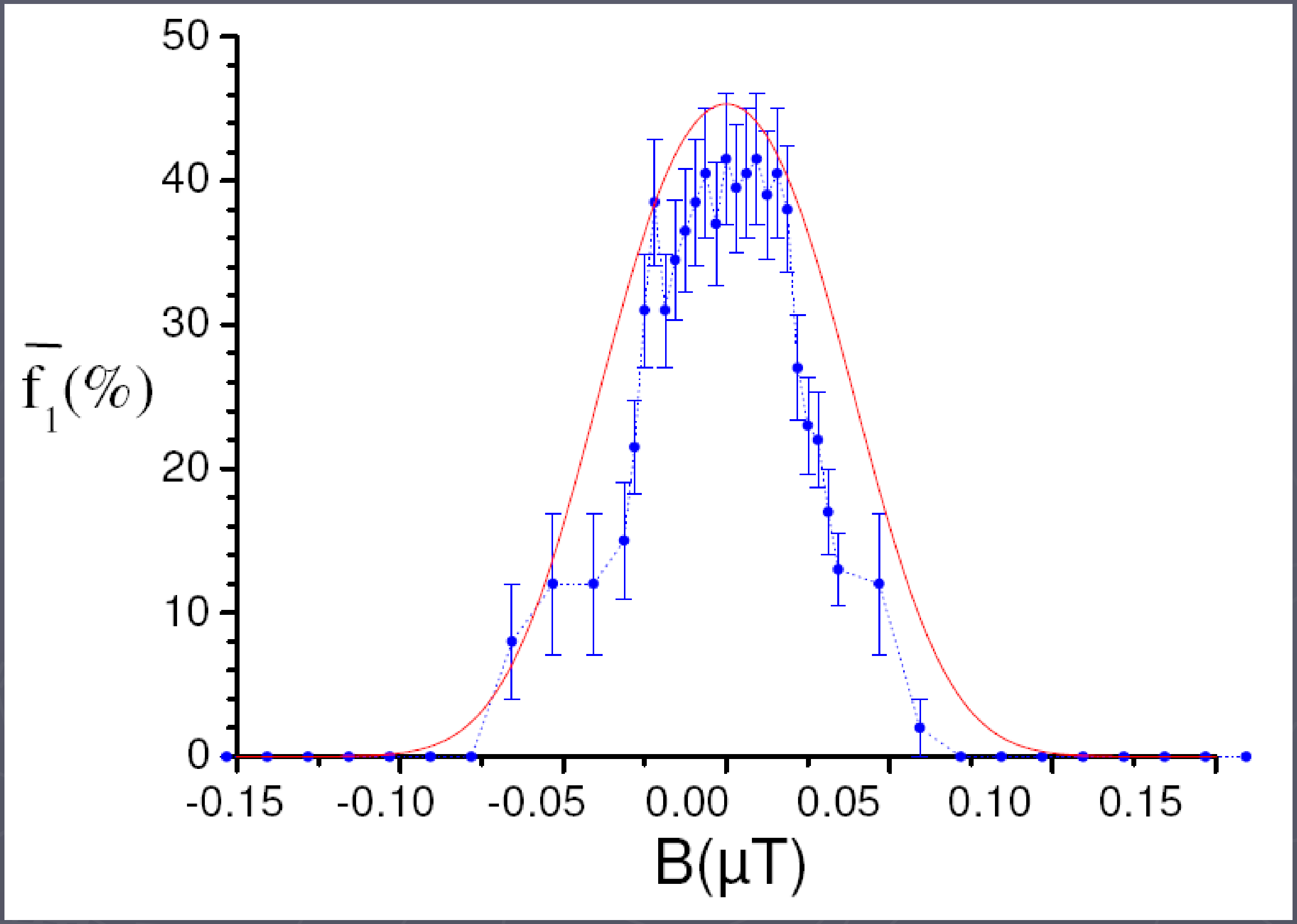

*N = C/ξ_*
number of domains
(or defects)
after cooling below the
transition temperature

# The effect on the trapping rate of a symmetry breaking magnetic field applied perpendicular to the AJTJ




Single flux trapping frequency $f_1$ for fixed quench time $\tau_Q$ = 5 s for AJTJ with C = 0.5 mm. The solid line is our theory with N=1 in $f_1(N)$.

# B-field perpendicular to AJTJplane, large perimeter




Single flux trapping frequency $f_1$ for fixed quench time $\tau_Q$ = 5 s for AJTJ with C = 2.0 mm. The solid line is our theory with N=16 in $f_1(N,n)$

# KZ-experiments with single superconducting rings

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**AFM type mechanical detection**

- Detection of defects, both + and - fluxoids
- Samples, geometry
- Heating and Quench rate
- Cryogenic sampleholder
- Optical lever or interferometer

**Nb ring with gap'ed JTJ (non-mechanical)**

- Detection of fluxoids, both + and - fluxoids
- Model of JTJ: δ-biased LJTJ, linear and circular

**Nb ring + SQUID (Anna Gordeeva, next talk)**

- Setup
- Proof of principle
- both + and - fluxoids

# Chip with superconducting ring on cantilever

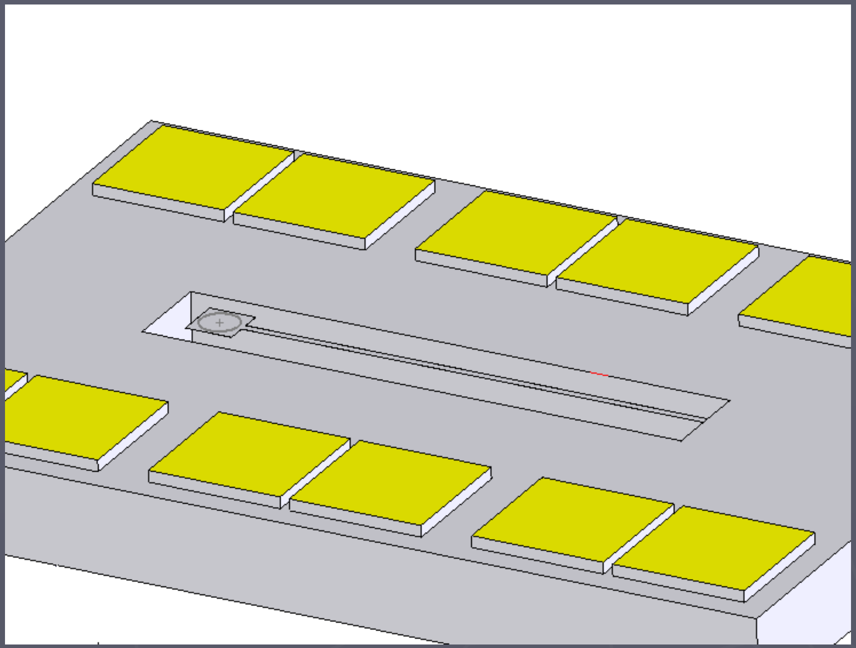
The B-field is applied parallel to the cantilever yielding a tortional moment bending it in or out of the chip plane if a flux quantum is trapped in the ring.

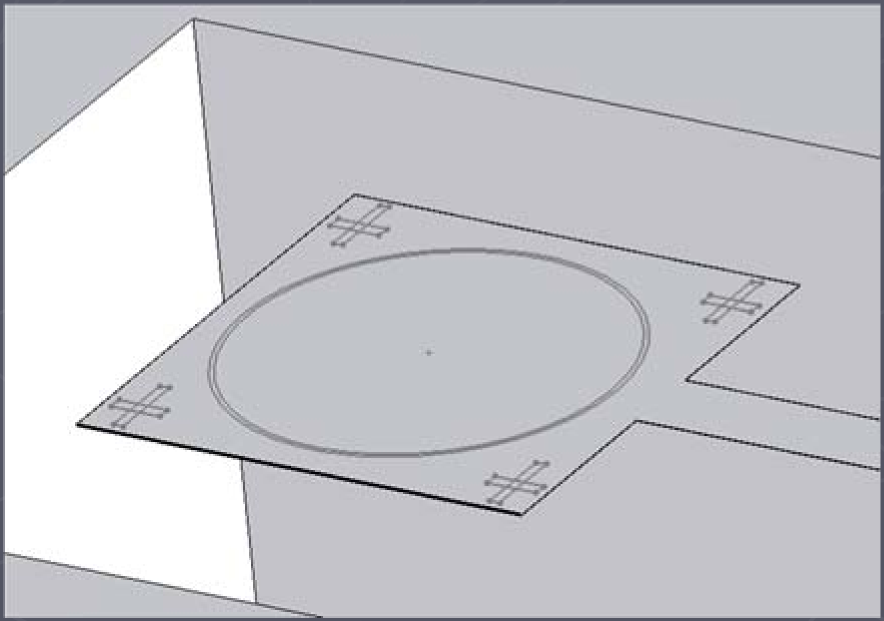
Torsional moment

$$\boldsymbol{\Gamma} = \mathbf{m} \times \mathbf{B}$$

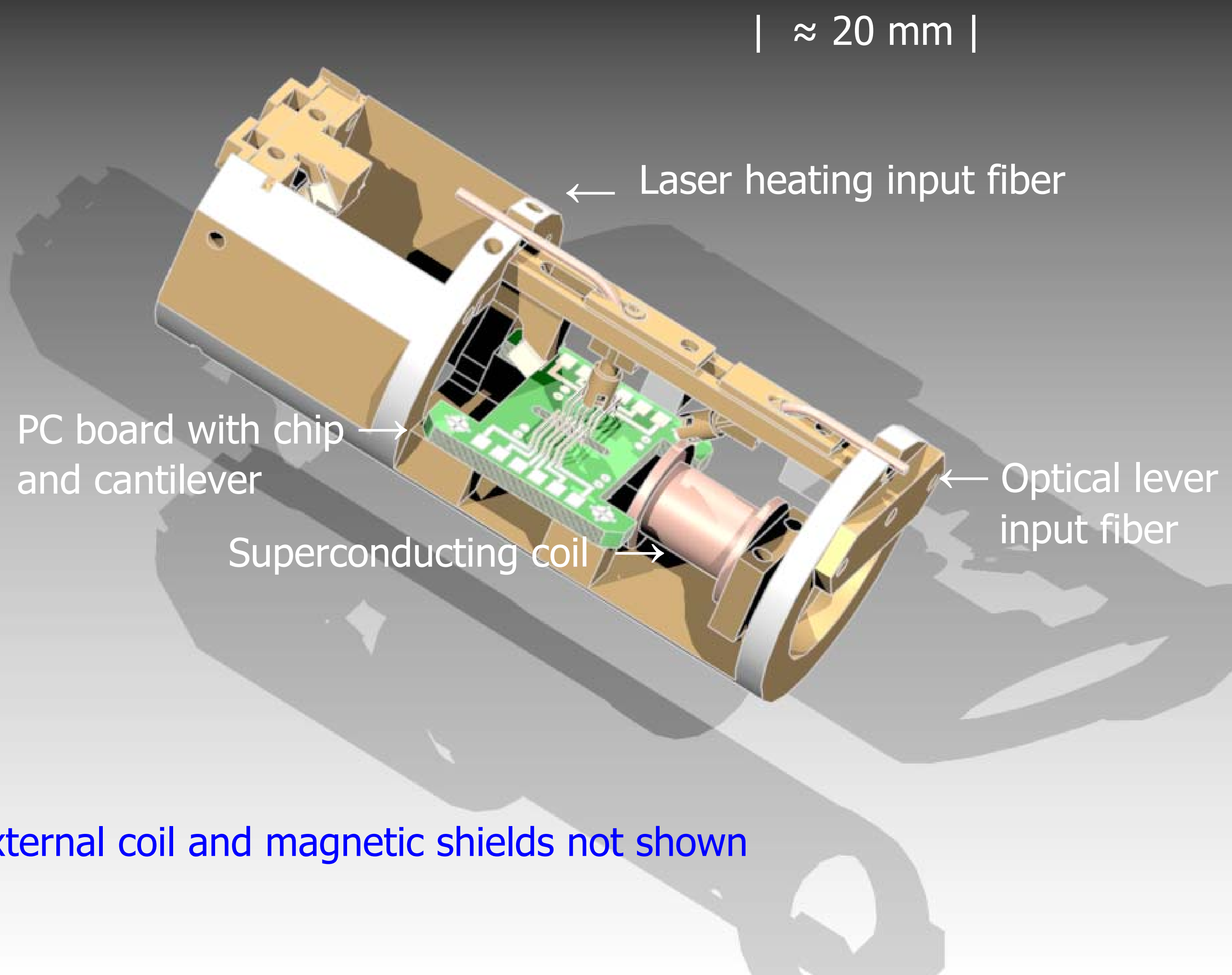
In each corner is placed a small Josephson junction thermometer. used to measure $\tau_Q$ and eventual thermal gradients

Length of cantilever is 3 - 800 μm.
DC determines N = 0, ±1, ….
Vibrational mode of operation only N= 0, 1, 2, ….





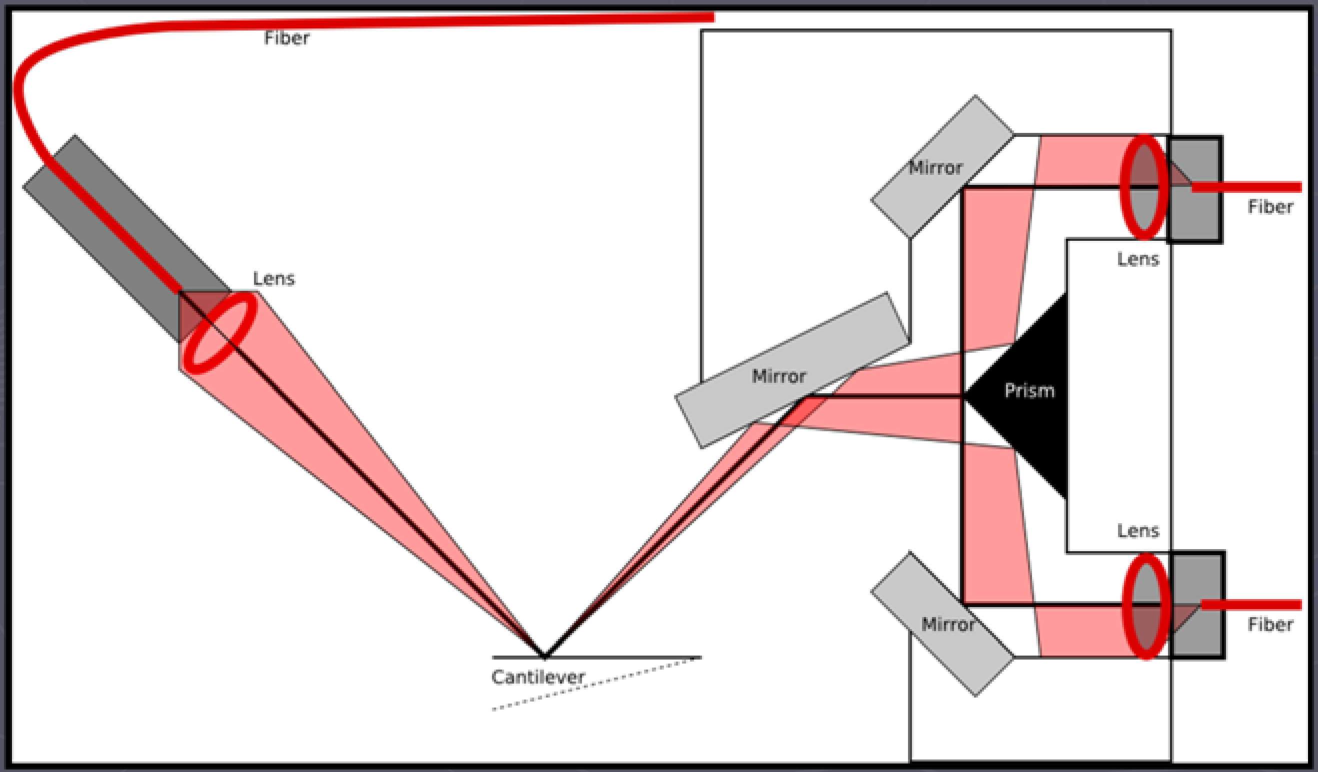
# AFM type cryogenic sample holder




External coil and magnetic shields not shown

# Cryogenic optical AFM type lever detection system

A cryogenic optical lever design is implemented using purely passive components in the cryogenic compartment. The deflection of the cantilever is on the order of 1nm, which is amplified by a factor of ~500 by the optical lever before it hits the sharp edge of the mirror (prism, black). Also a sharp edge (broken front mirror) as well as Near-field standing wave method is being tested.



# Status on the single ring AFM type experiment

Under-etch of cantilever not made yet

The calculated resolution is ≈0.25 $\Phi_0$ using DC measurement of the deflection. Using oscillations at the cantilever eigenfrequency (~1kHz) should increase the resolution by at least an order of magnitude.

A new multiple reflection set-up is being tested. Its sensitivity may be increased by interferometic detection.

The AFM setup will be used, both to verify earlier results in AJTJs [4, 5 and 6]

# ZK, ring with gap'ed JTJ

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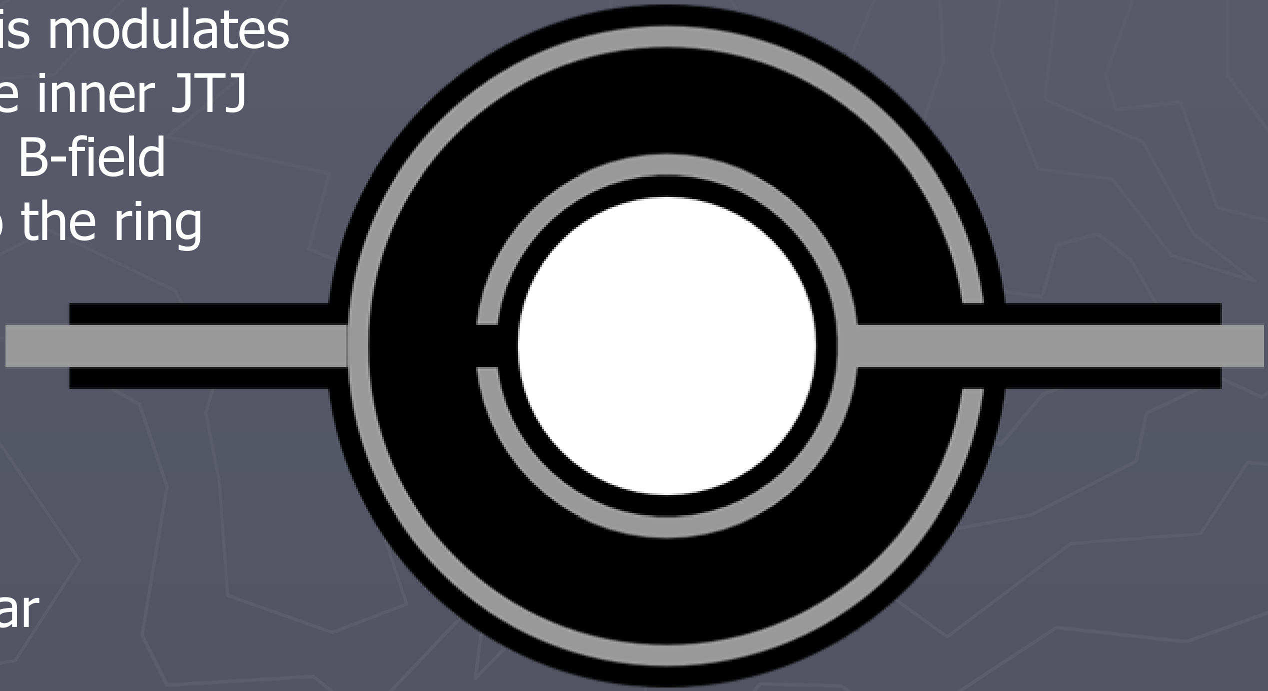
**Kibble-Zurek trapping of flux quanta in rings; detected by gap'ed long JTJ placed along inner and outer circumference of the ring**

# Geometry of single Nb ring with gap'ed Long Josephson Tunnel Junctions

A trapped fluxoid generates in the surface of the ring a shielding current with maximum near the inner circumference. This modulates the critical current of the inner JTJ similar to the effect of a B-field applied perpendicular to the ring (See Monaco et al. APL **104**, 023906 (2008))

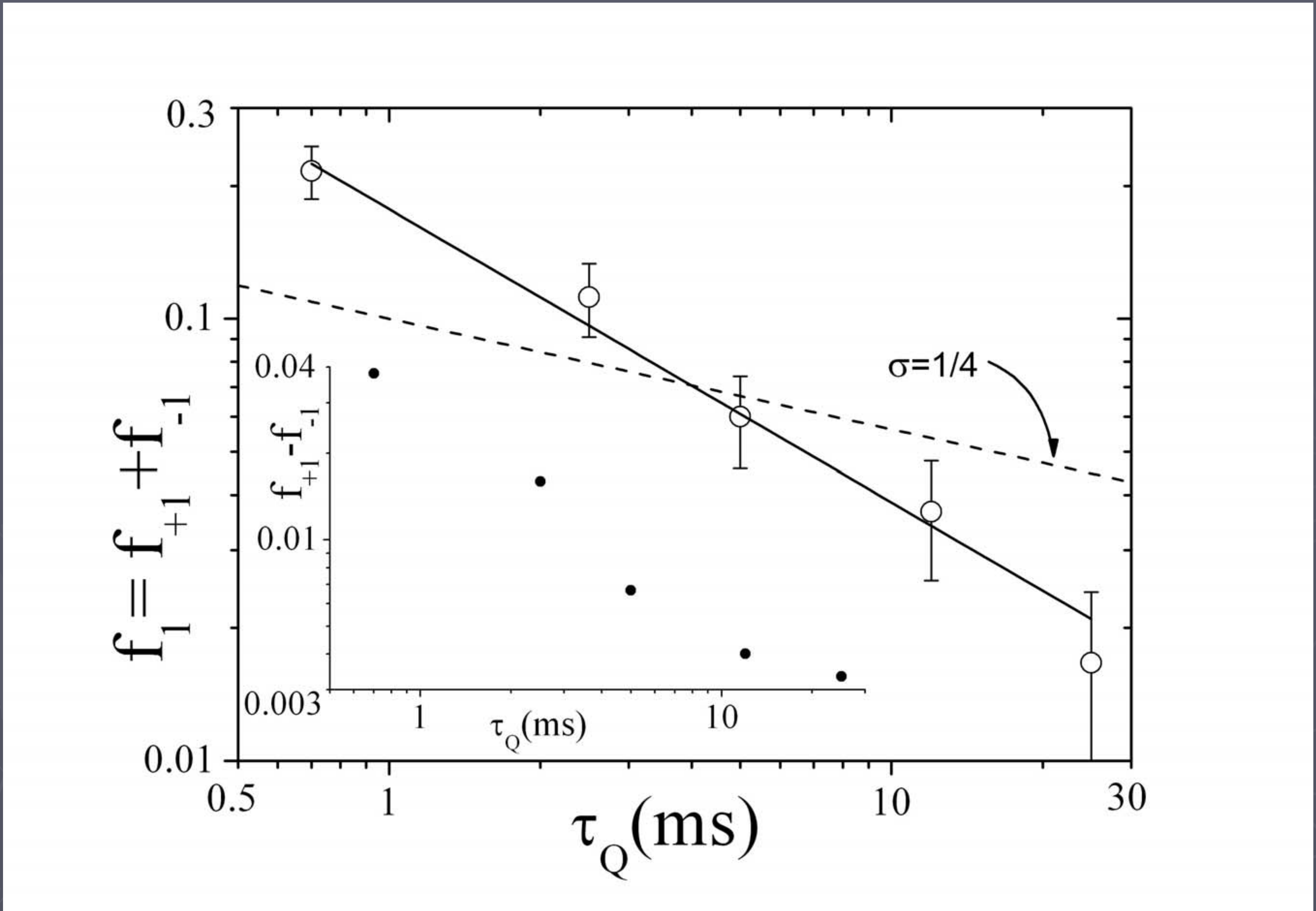
Ring diameters ranging from 20 – 200 µm.
JTJ width: 5µm



An external perpendicular B-field also generates a shielding current!

**Both internal and external B-field can be measured.**
**Note: symmetri of ring is broken.**

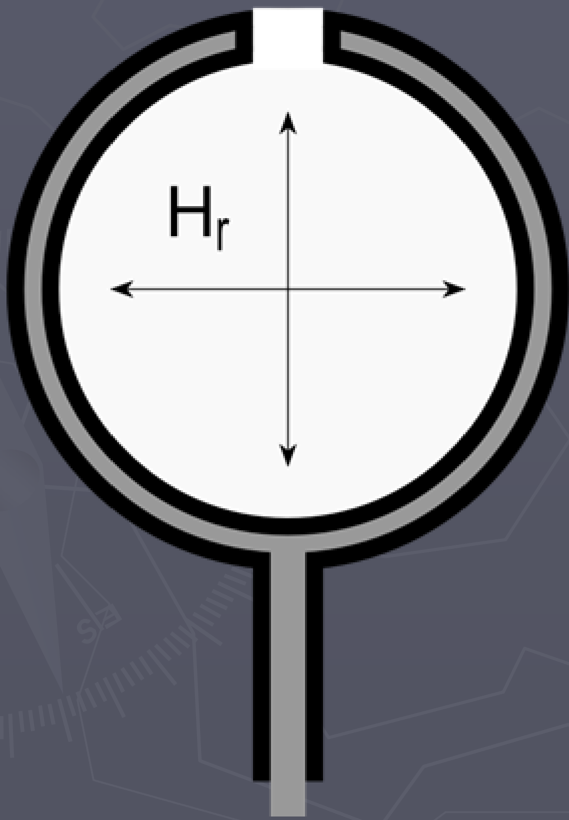
# KZ trapping in single ring using inner JTJ



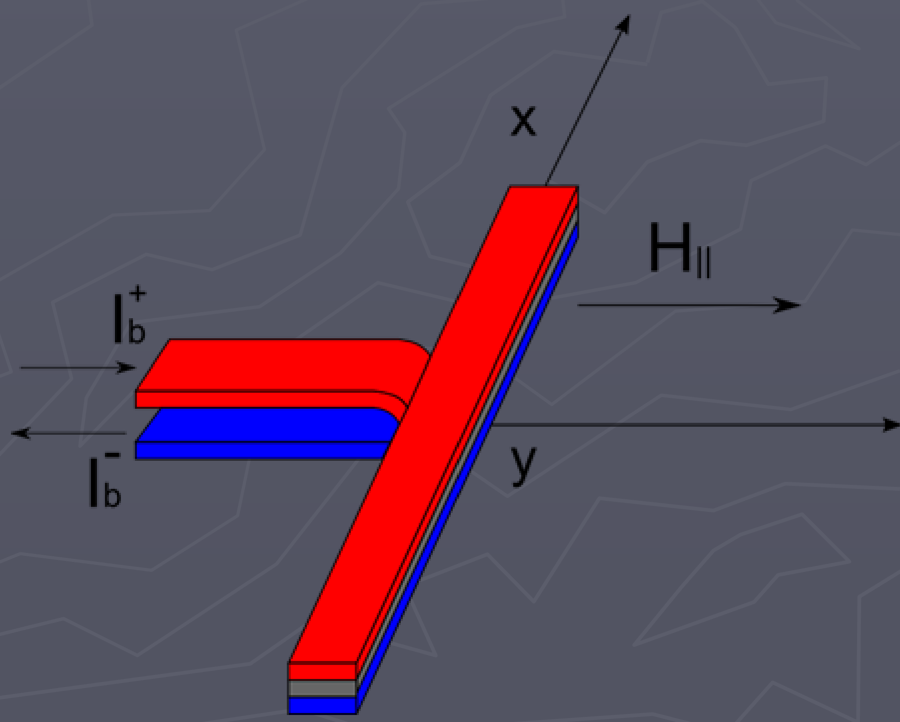

**Note: slope not 0.25 or 0.50. See Ref. [6] Monaco et al. PRB, vol 80, (2009)**

# Geometry of δ-biased LJTJ
# (spin-off: paper in preparation)

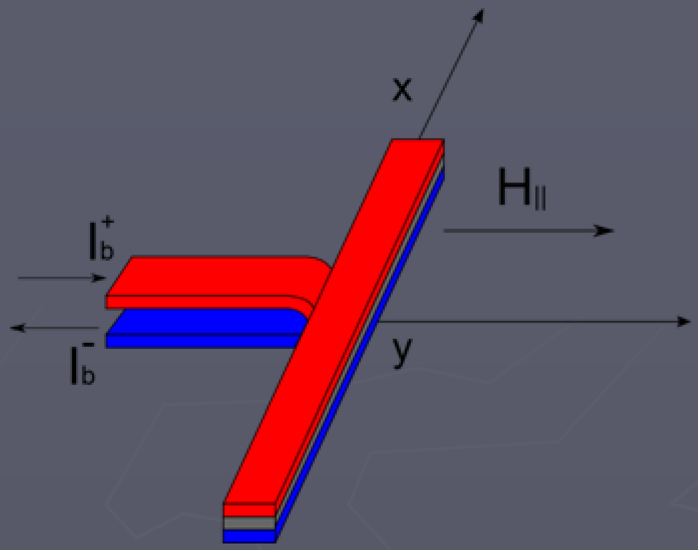
A magnetig field perpendicular to the junction plane gives a radial field due to demagnetization.

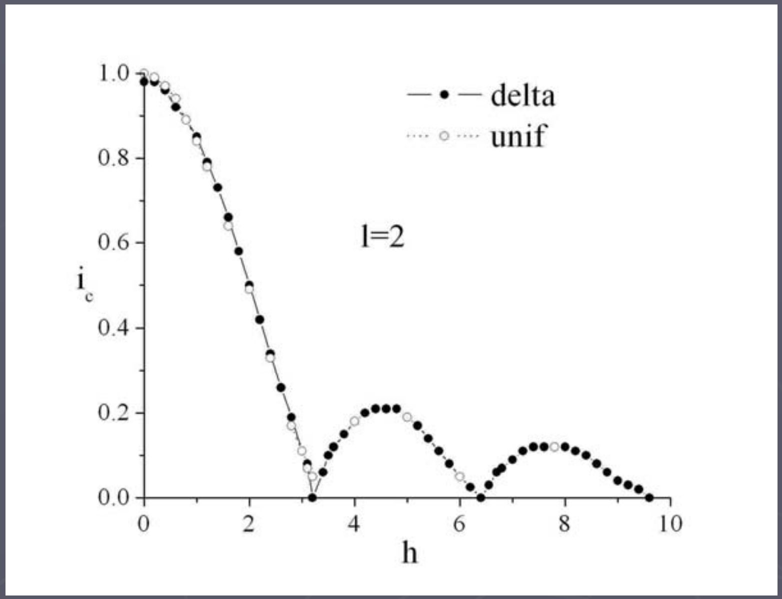


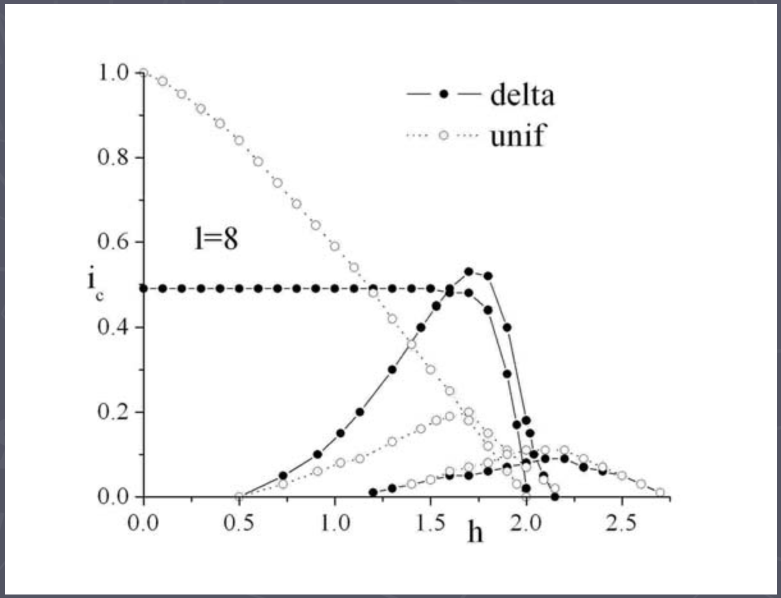

Magnetic field is applied in the junction plane perpendicular to the long side

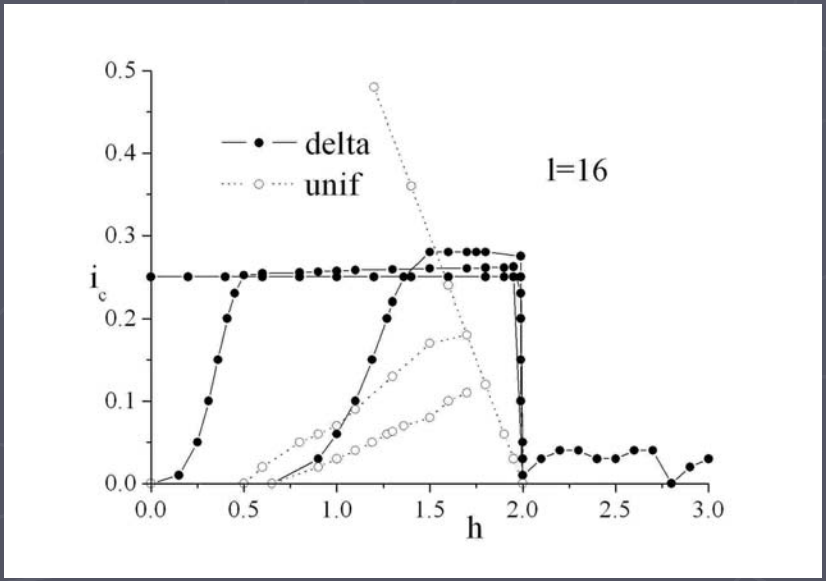


# Critical current vs magnetic field applied in the plan of the gap'ed LJTJ



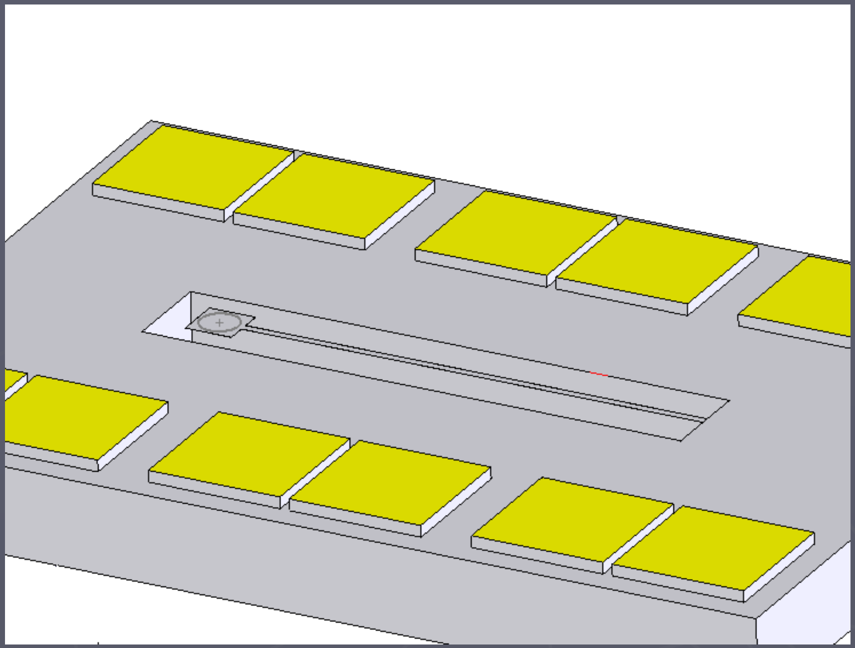



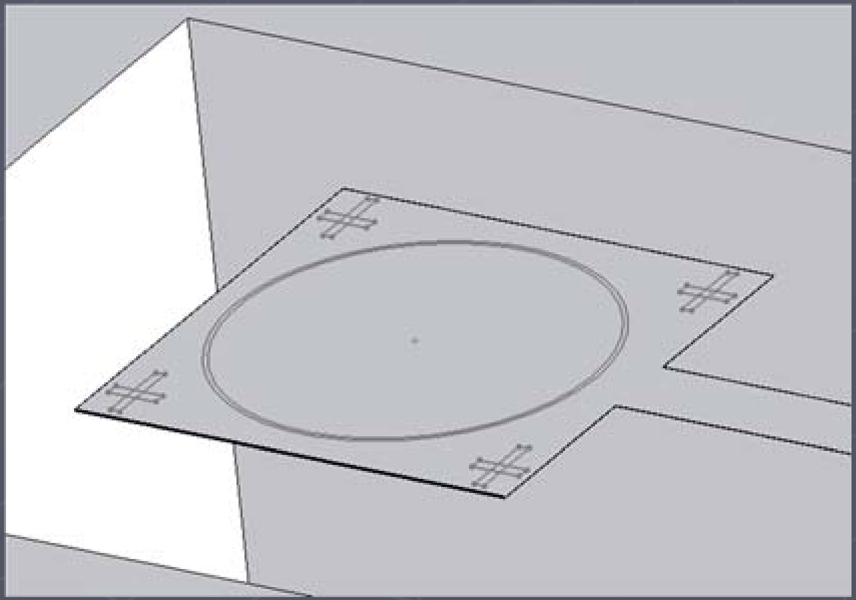
# ZK, ring with SQUID

## Kibble-Zurek spontaneous trapping of flux quanta in rings; detected with SQUID

# Ring - SQUID experiment

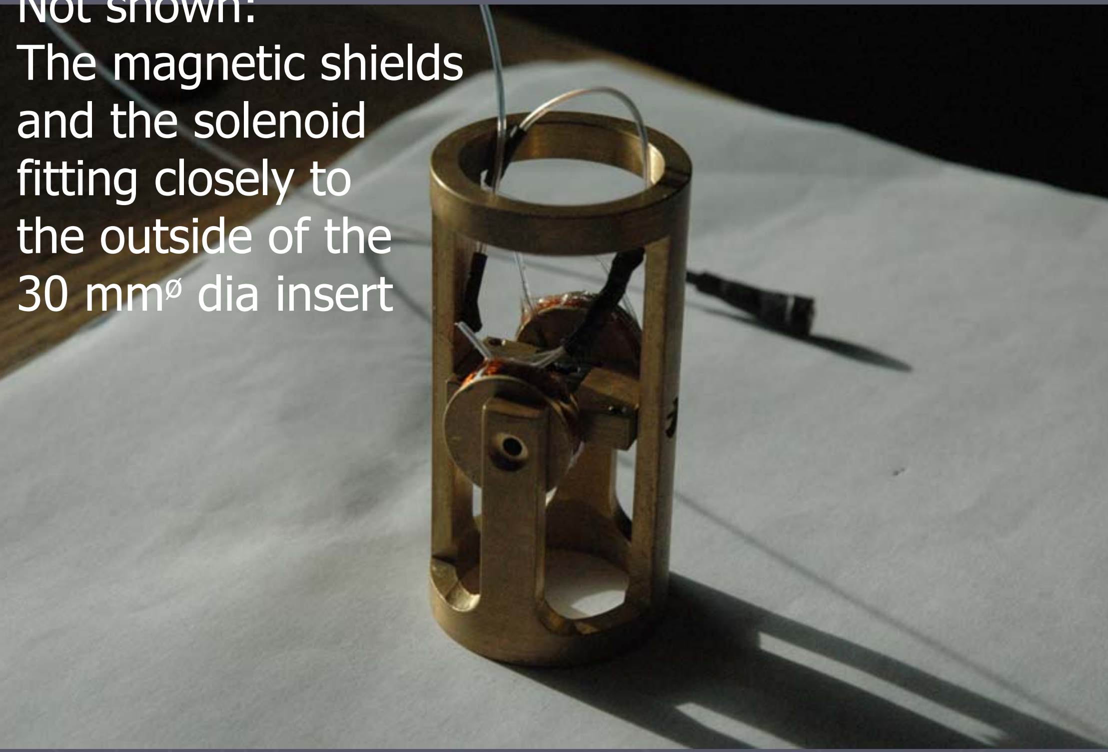
- Samples; same chip as AFM type but no under-etching of cantilever
- 4 small JTJ used as thermometers
- Common current bias lead used as calibration coil
- On-chip resistive heater
- Chip with HTSC SQUID placed back-to-back, co-centric with ring
- SQUID remains superconducting during quench
- Perpendicular B-field applied from solenoid inside magnetic shield
- Heating by laser pulse via fibre



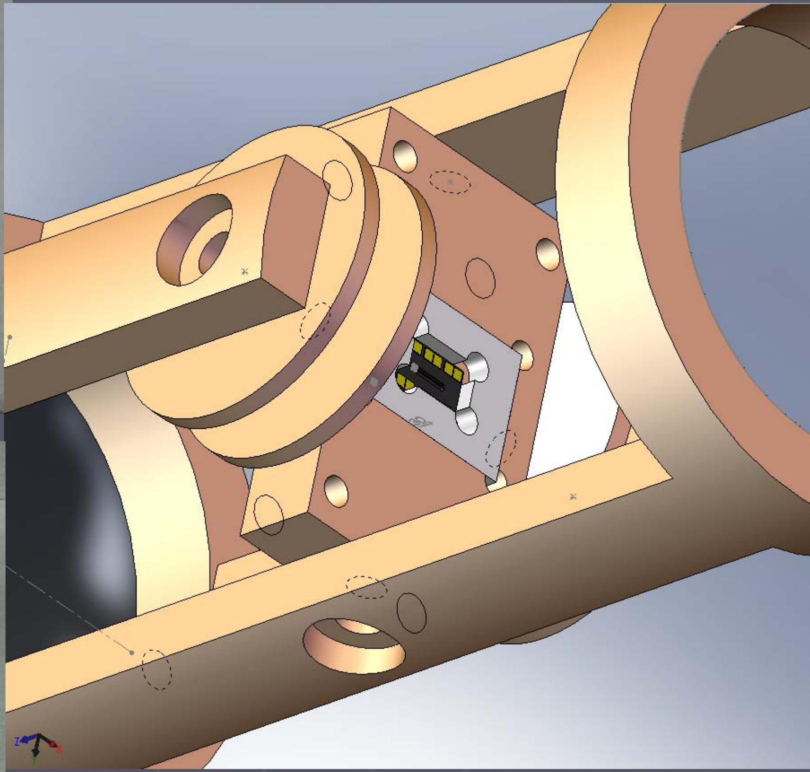


The magnetic coupling between ring and SQUID is critical.

# Experiment



Not shown:
The magnetic shields and the solenoid fitting closely to the outside of the 30 mmø dia insert



Cryogenic insert with holder for both the SQUID chip and the chip with the ring

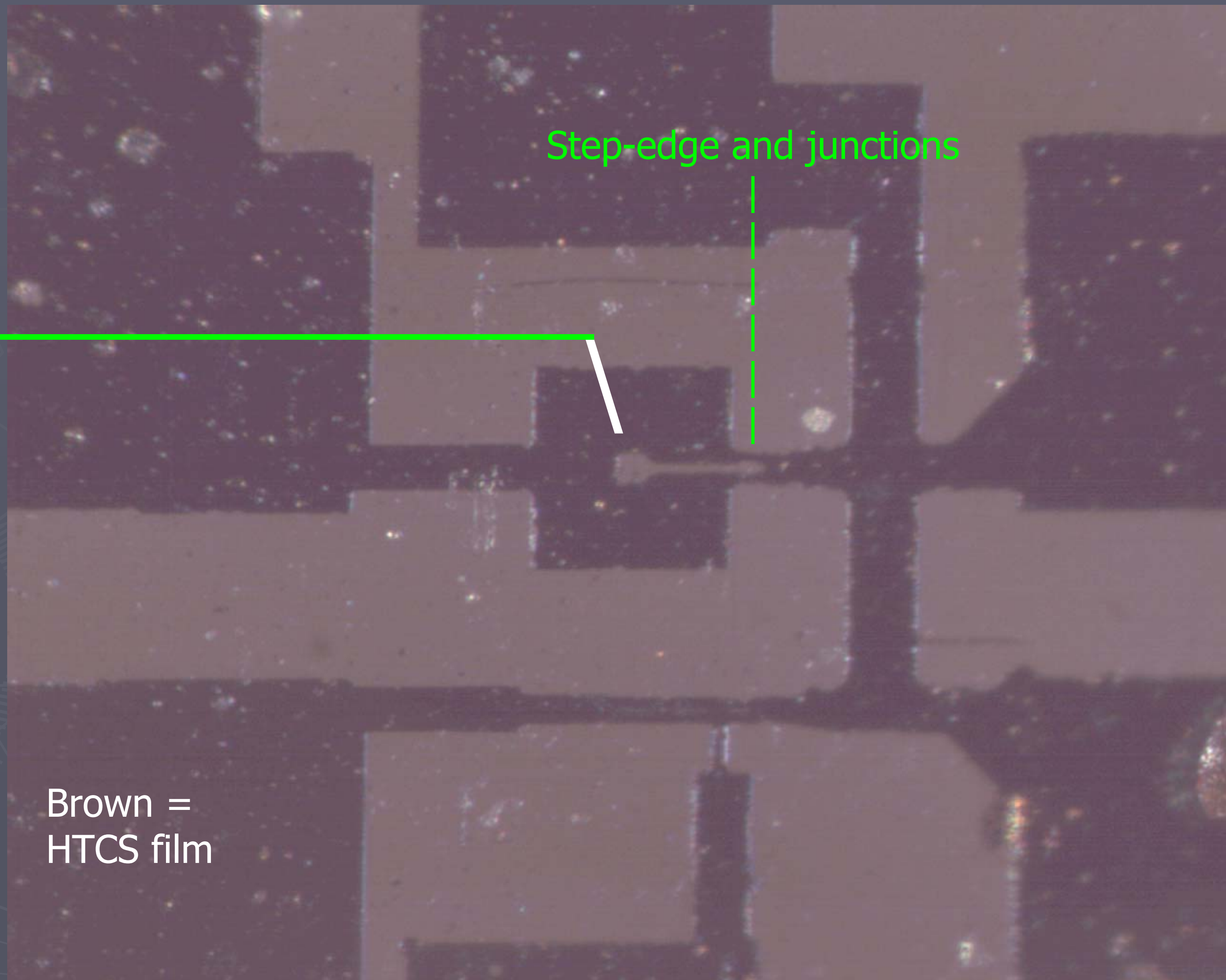
One of the PC boards with spring contact to the chips

# First attempt: HTSC SQUID

Area of
SQUID loop
in washer:

~200 μm²

NKT
step-edge
SQUID
on zirconia
substrate



# Future

- Single ring
  - SQUID/ring experiments
  - AFM cantilever experiments
  - Nano ring with imbedded nano JTJ
- Improved magnetic shielding
  - Presently B < 0.05 $\Phi_0$ in a 150μm dia. ring
  - Investigate influence of AC magnetic noise
  - Helmholtz coils, 3-D DC field compensation
- Simulations (sG + GL) by Anna Gordeeva + Mads Peter Soerensen + Andrey Pankratov

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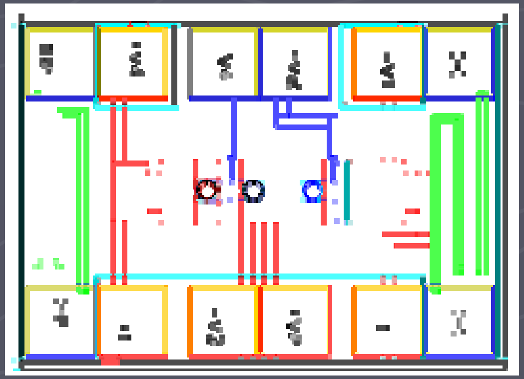

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