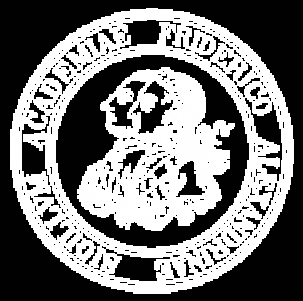
Quantum dynamics of Josephson vortices

A. Wallraff, M.V. Fistul, A. Lukashenko
A. Kemp, J. Lisenfeld, and A. V. Ustinov

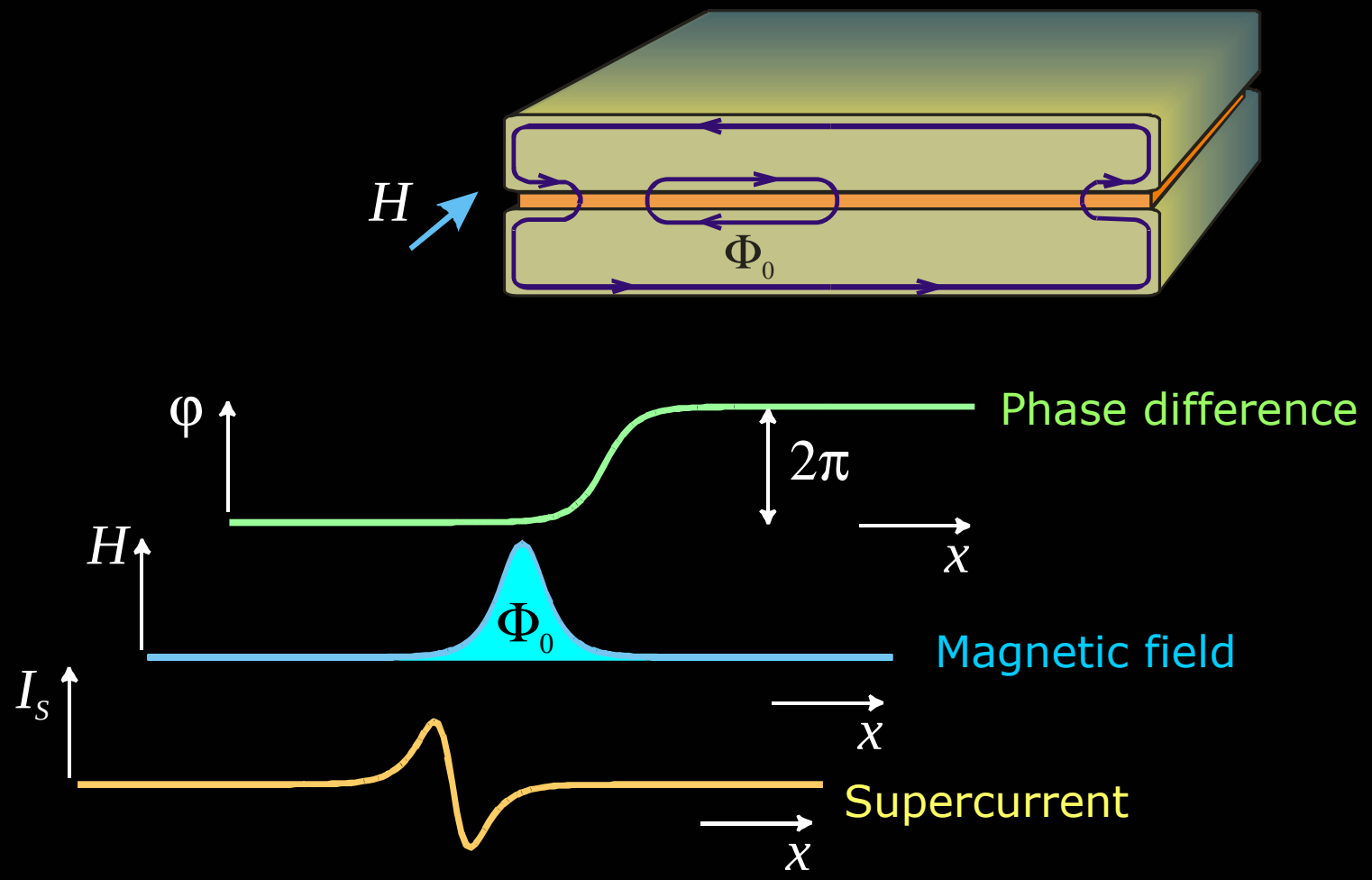


Physikalisches Institut
Universität Erlangen-Nürnberg
Erlangen, Germany

Outline

- A single vortex in the quantum regime
  - Creating a potential well
  - Observation of quantum tunneling
  - Spectroscopy of energy levels
- Quantum dissociation of a vortex-antivortex pair
- Vortex qubit
  - Designing double-well potential
  - Operation and readout scheme
  - Interface to RSFQ
- Summary

Josephson vortex (fluxon)



Perturbed sine-Gordon equation: model for a long Josephson junction

$$\varphi_{xx} - \varphi_{tt} = \sin\varphi + \alpha\varphi_t - \beta\varphi_{xxt} - \gamma$$

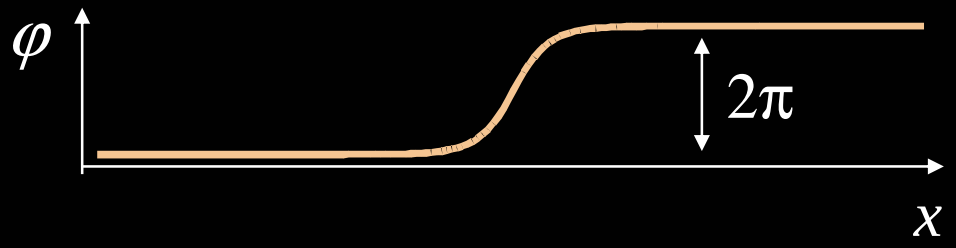
Normalized units:

$$x \to \lambda_J \sim 10\,\mu\text{m}$$

$$t \to \omega_p^{-1} \sim 10\,\text{ps}$$

Vortex is the soliton solution for $\alpha=\beta=\gamma=0$

$$\varphi = 4\arctan\left(\frac{x - vt}{\sqrt{1-v^2}}\right)$$



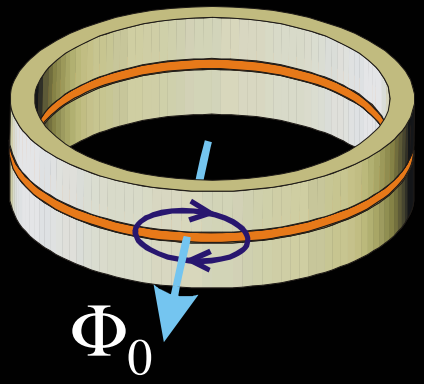
α quasiparticle tunneling

β surface losses

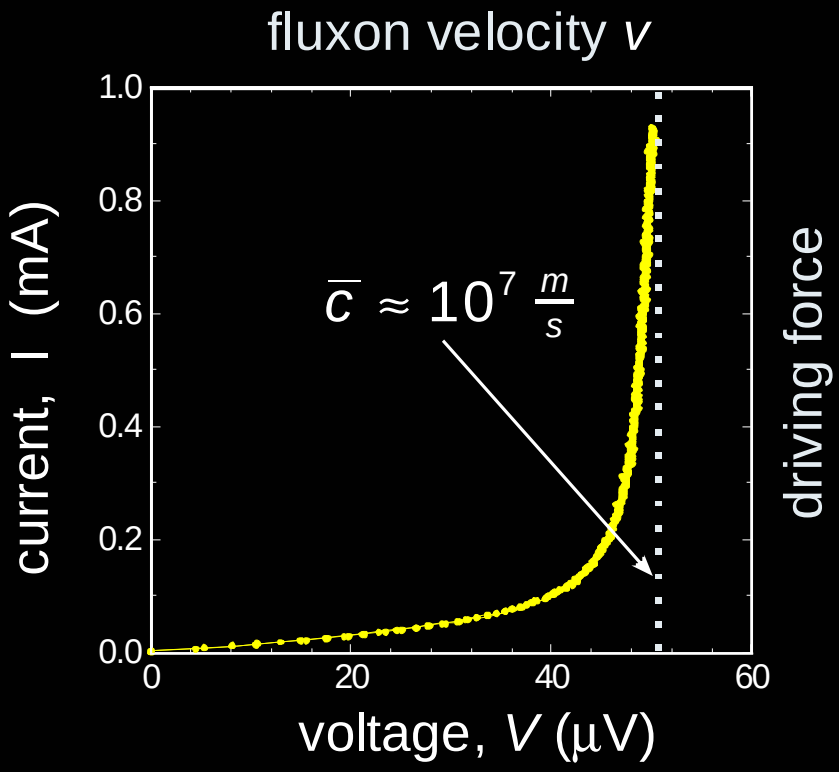
γ bias current

Annular Josephson junction

Vortex driven by bias current moves as a relativistic particle in a ring of 100 μm in diameter

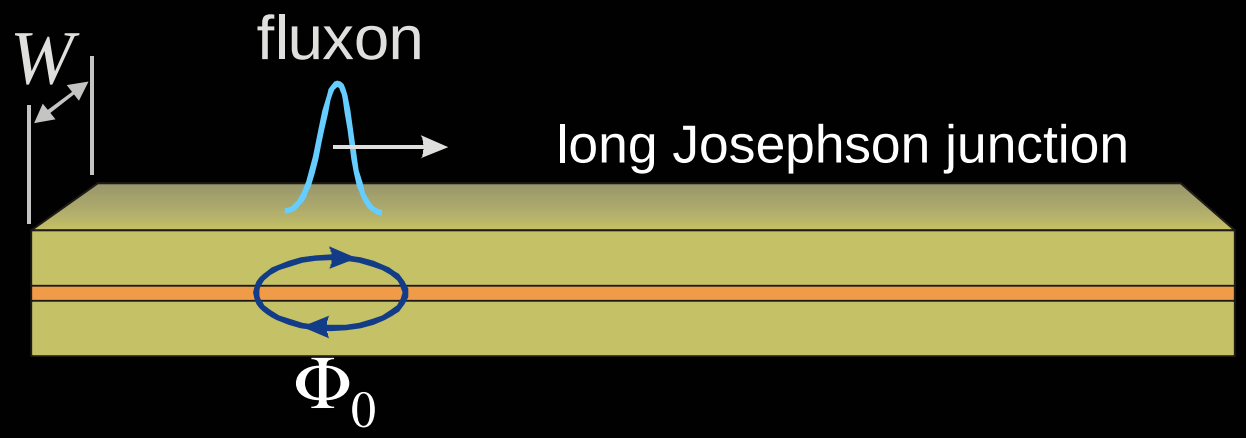


vortex velocity $$v = 2\pi R \frac{V}{\Phi_0}$$



Measurement of a single vortex trapped in annular junction at 4.2K

Vortex as a quantum particle



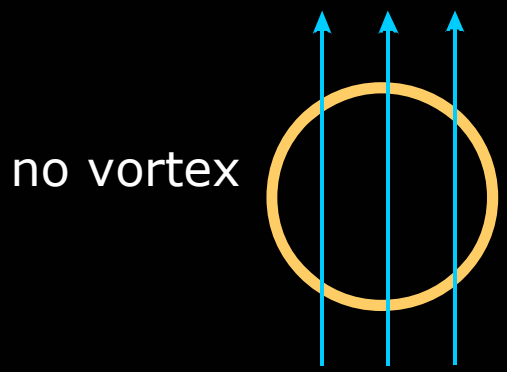
Vortex mass $m_f \sim W$ ➡ for W=1 μm, $m_f \sim 10^{-3}\, m_e$

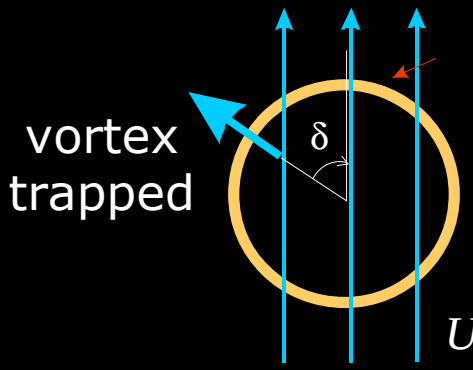
quantum effects are expected at $T < 100$ mK

Major decoherence factor - dephasing by Josephson plasmons $\frac{\hbar\omega_p}{k_B} \approx 3K$

- T.Kato and M. Imada, J. Phys. Soc. Japan **65**, 2963 (1996)
- A. Shnirman, E. Ben-Jacob, and B. Malomed, Phys. Rev. B **56**, 14677 (1997)

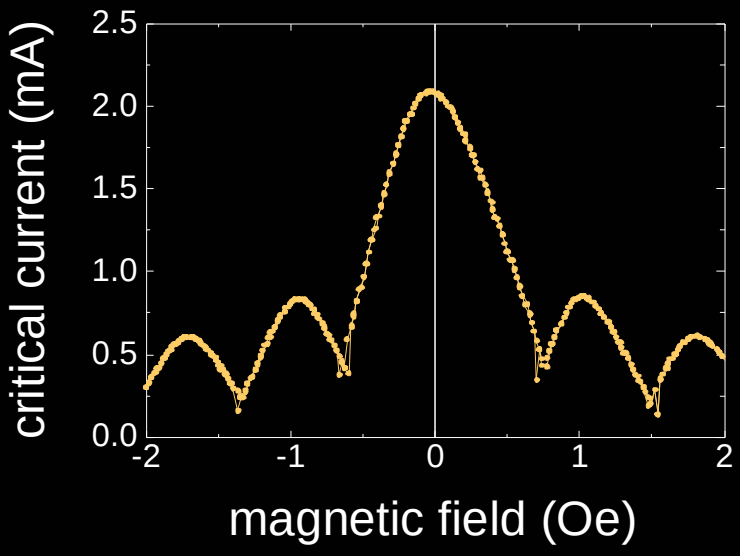
„Fingerprint“ of a trapped vortex

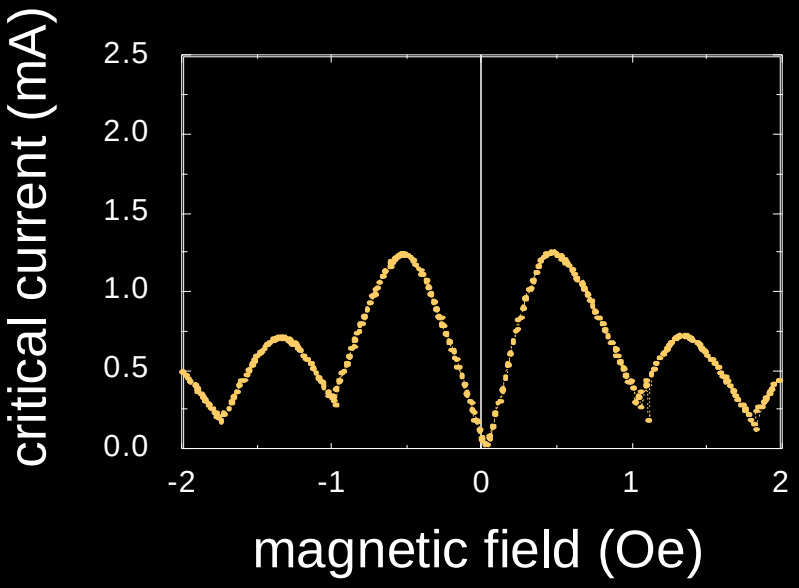




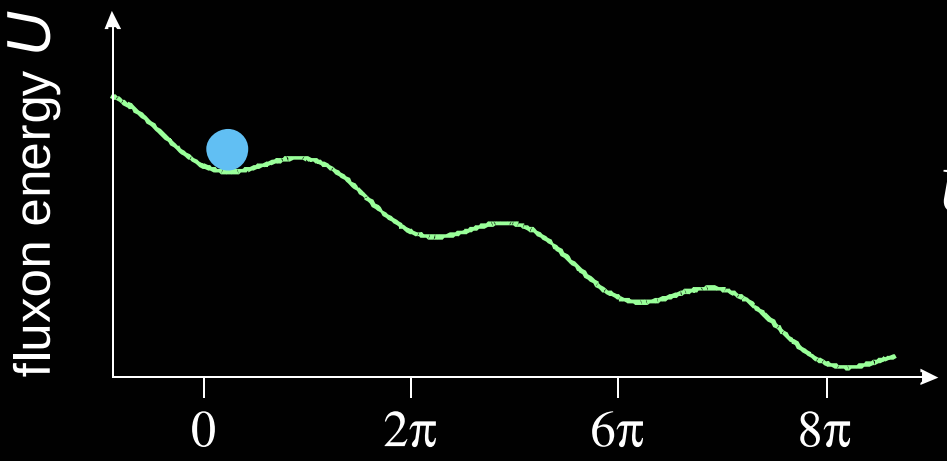
energy

$U(\delta) \sim -H \cos\delta$



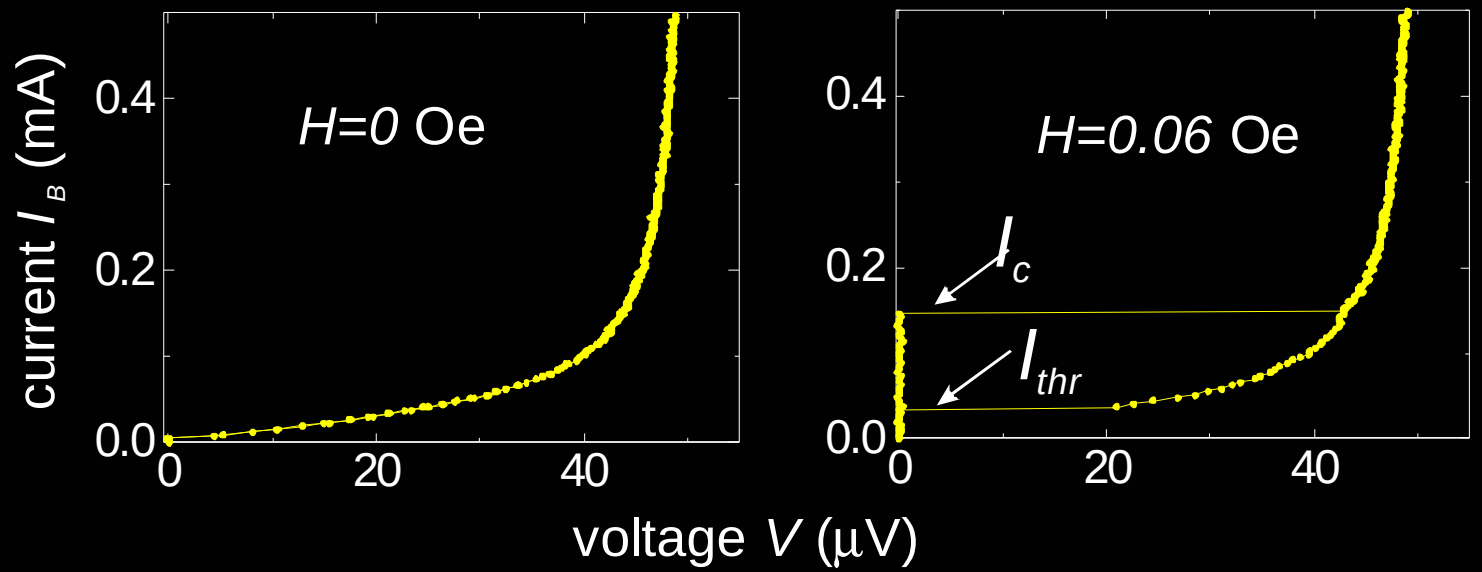


Vortex in the washboard potential

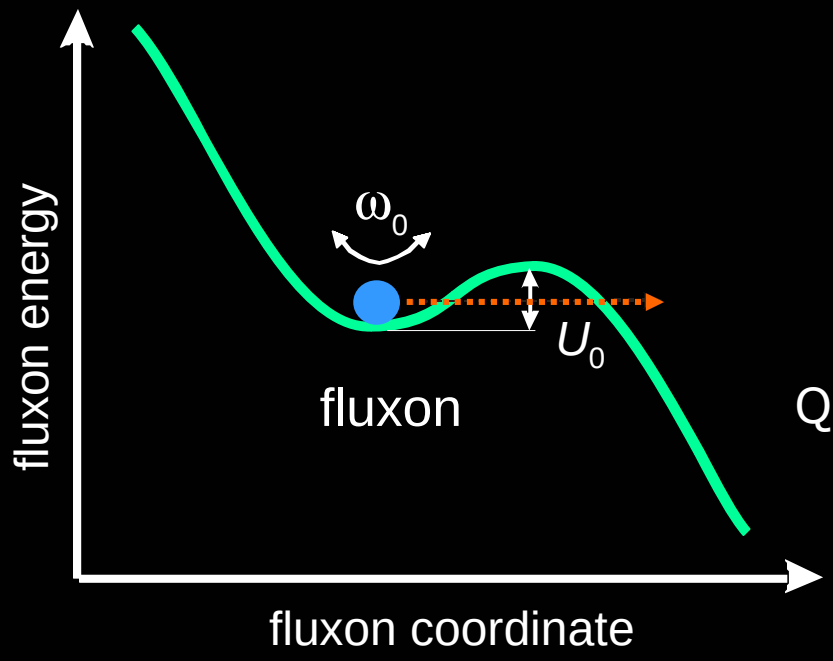


vortex energy

$$U = -mH\cos\delta - \kappa I_B \delta$$



Vortex escape from a potential well



Thermal escape $\Gamma_{ther} = \frac{\omega_0}{2\pi} \exp\left(-\frac{U_0}{k_B T}\right)$

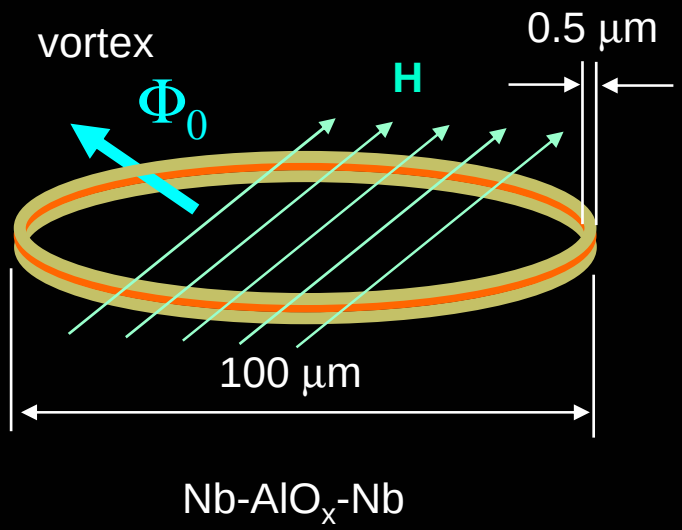
Quantum tunneling $\Gamma = A\exp(-B)$

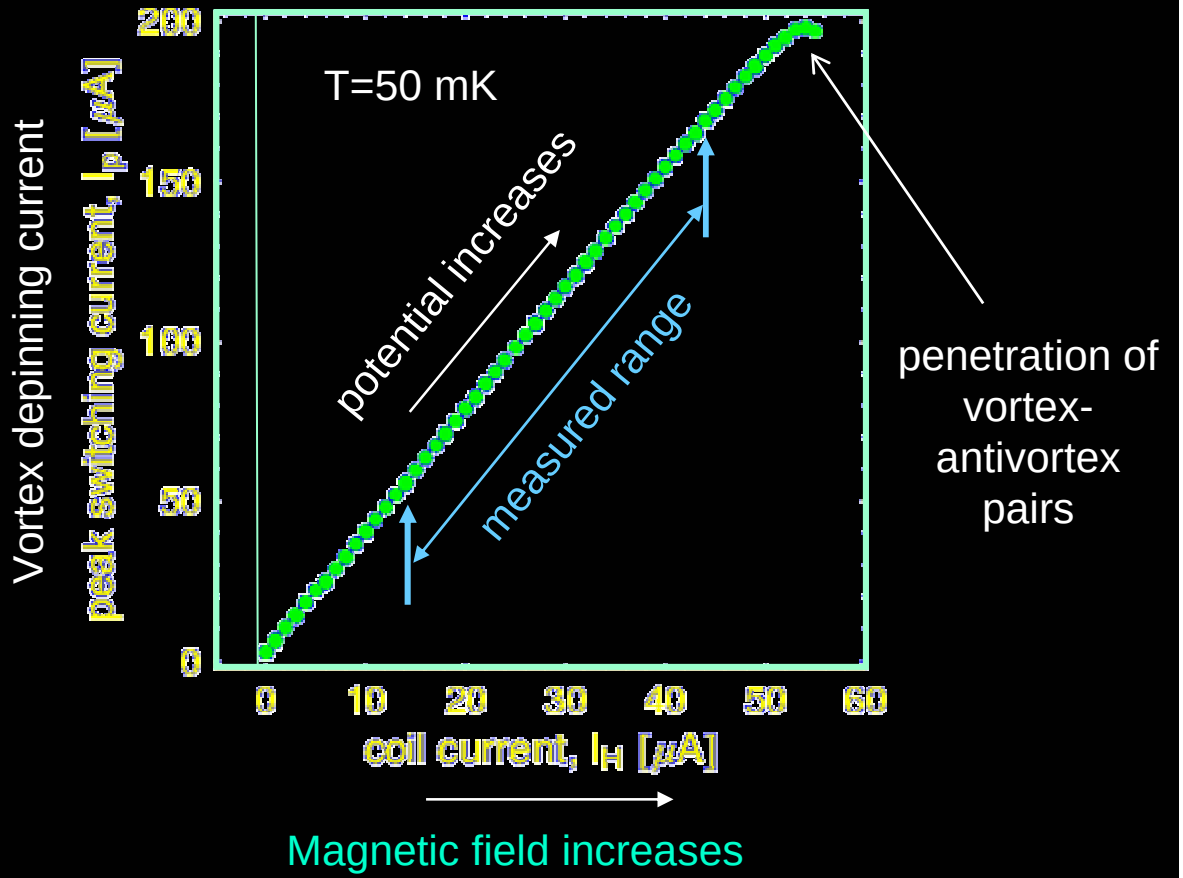
$A \propto \omega_0 \omega_p \sqrt{B}$

$B \propto \frac{U_0 E_0}{\omega_0 \omega_p}$

Josephson energy $E_0 \propto W \omega_p$

Experiments with ultra-narrow long annular Josephson junctions

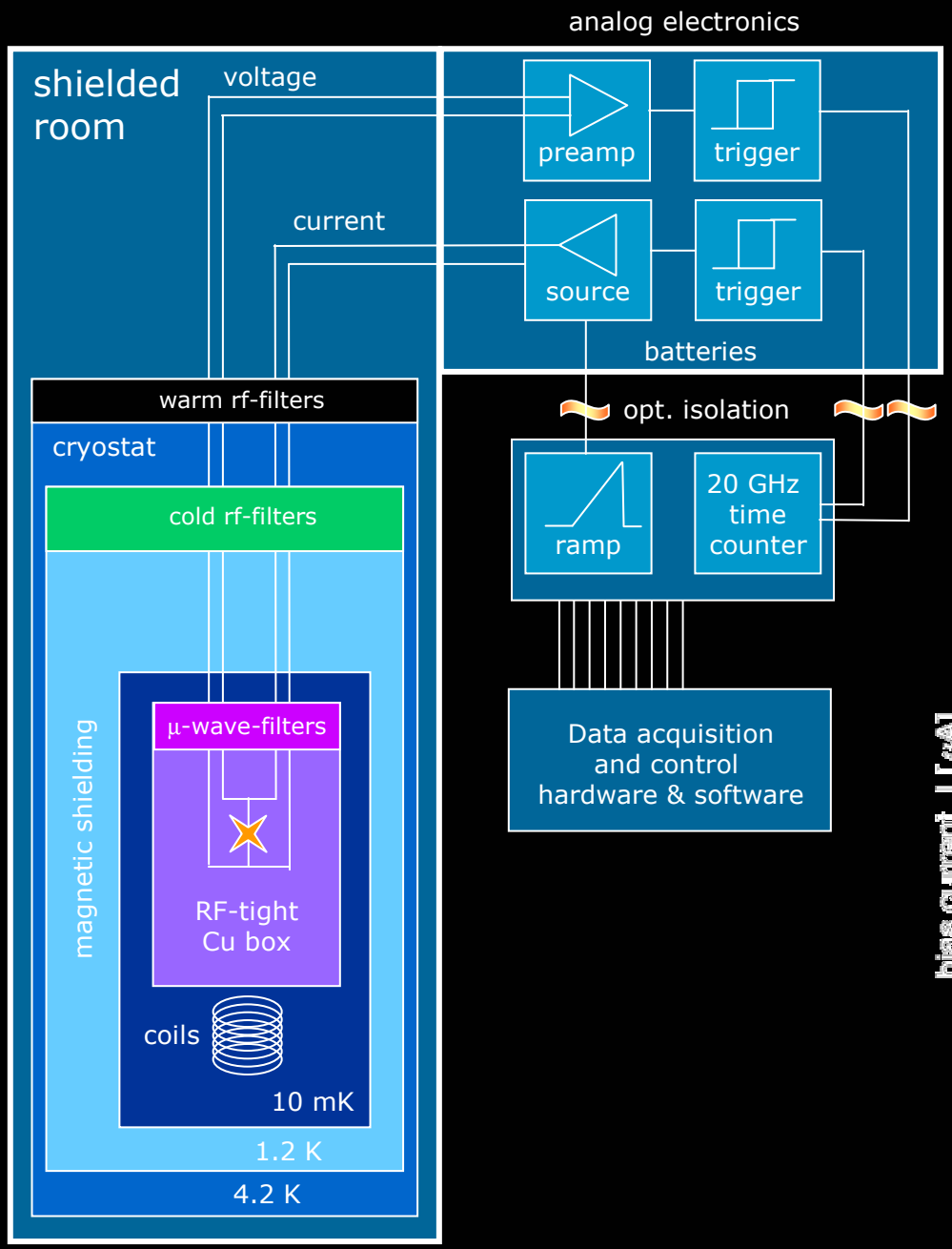


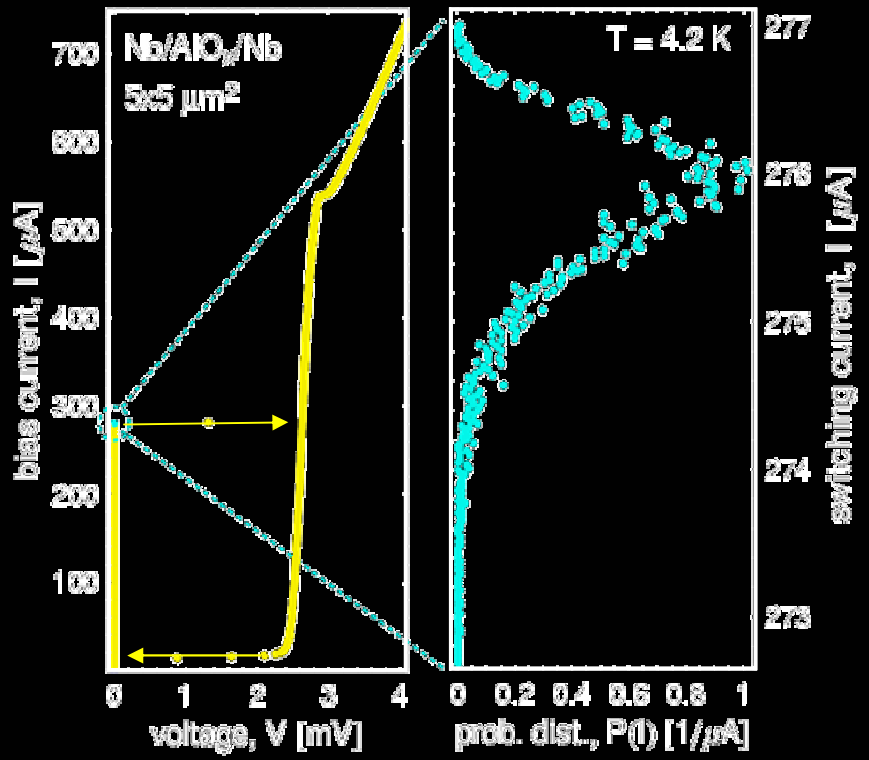


The depth of the potential well of the vortex is proportional to the external magnetic field **H** ~ I_H

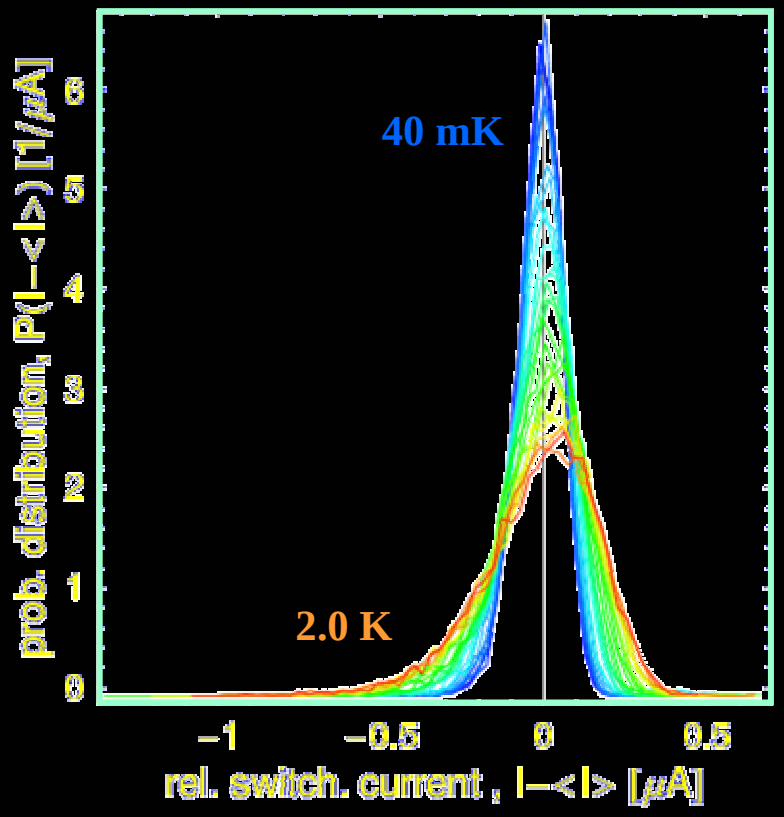
Measurement technique

- A. Wallraff, A. Lukashenko, C. Coqui, T. Duty, and A. V. Ustinov cond-mat/0204527 (2002)

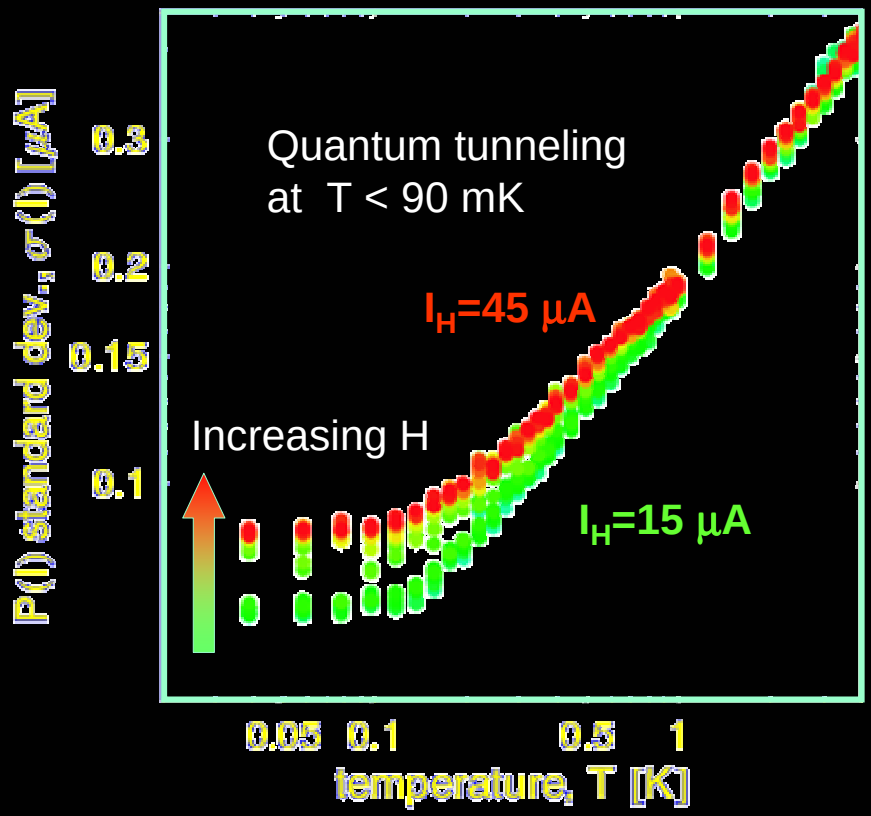




Observation of quantum tunneling of a Josephson vortex

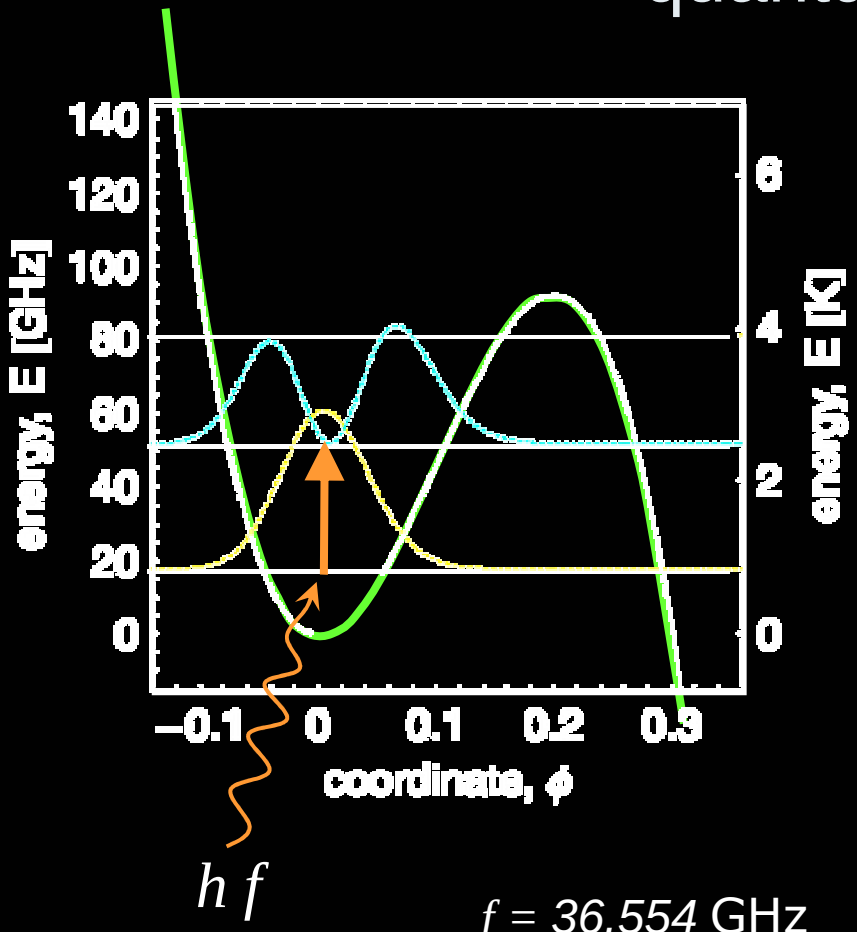


Histograms of the vortex depinning current



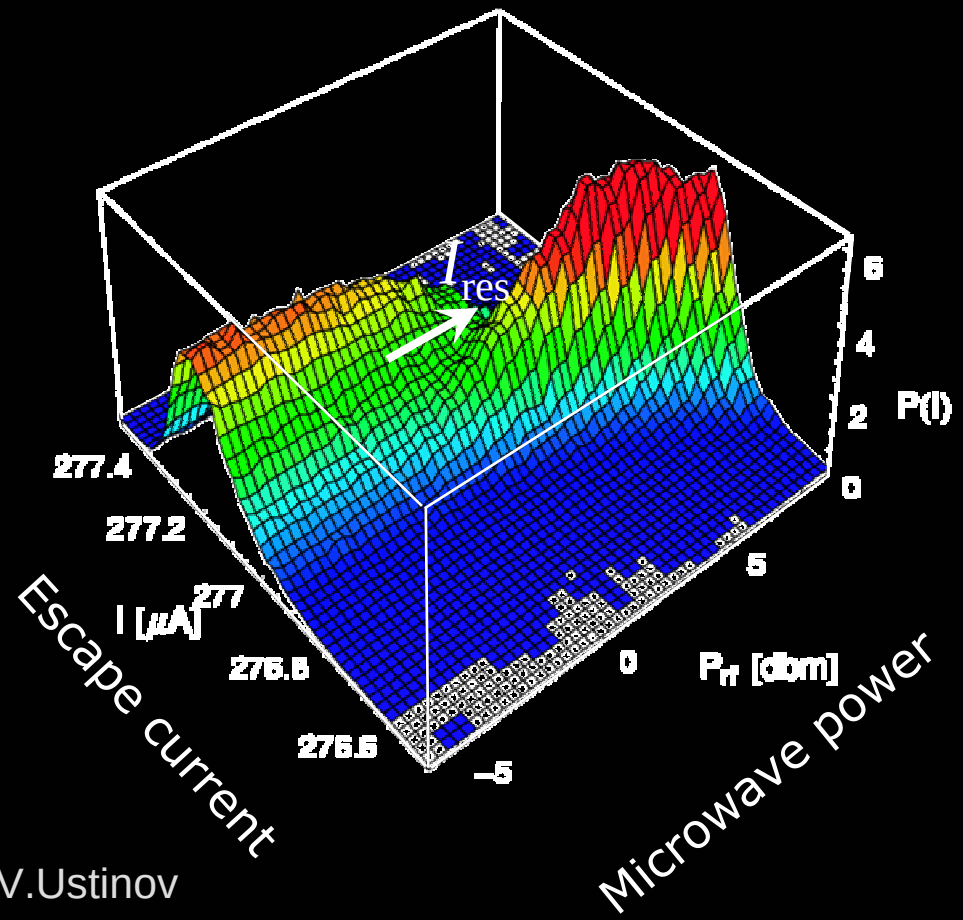
Histogram width versus temperature

Microwave-induced transitions between quantum levels



f = *36.554* GHz
100 mK

Experiments in the frequency range *10 – 40* GHz

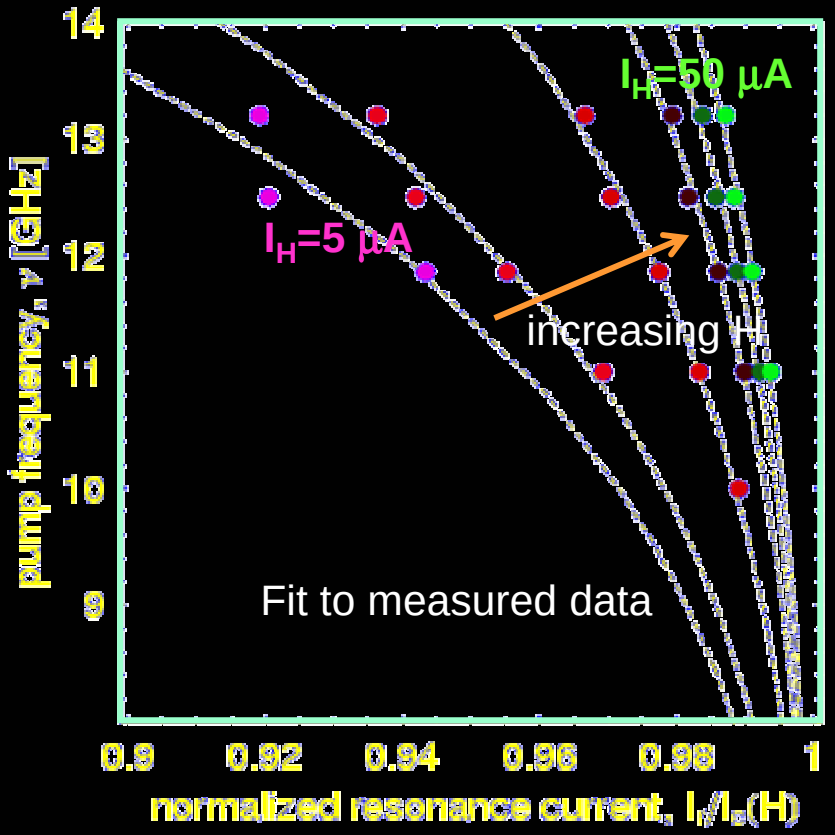


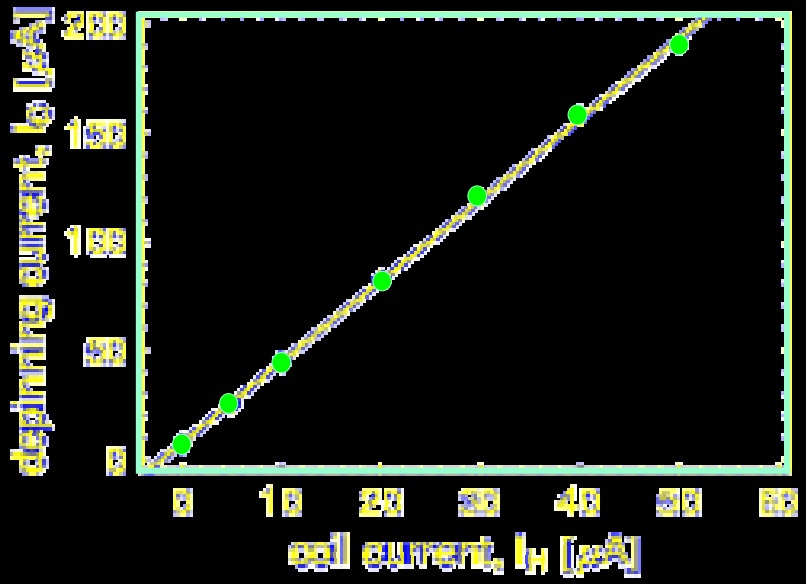
- A. Wallraff, T. Duty, A. Lukashenko, and A.V.Ustinov Phys. Rev. Lett. **90**, 037003 (2003)

Measurements of vortex energy levels

Energy level separation

$$\Delta E \propto \left[1 - \frac{I_{res}^{\ 2}}{I_c^{\ 2}}\right]^{1/4}$$

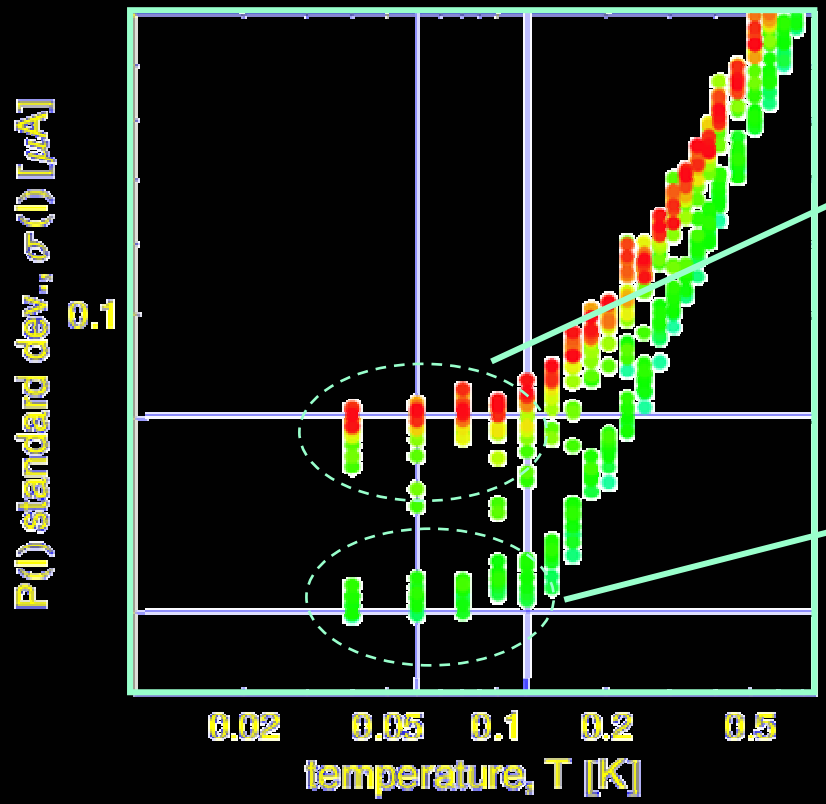




Reconstructed potential

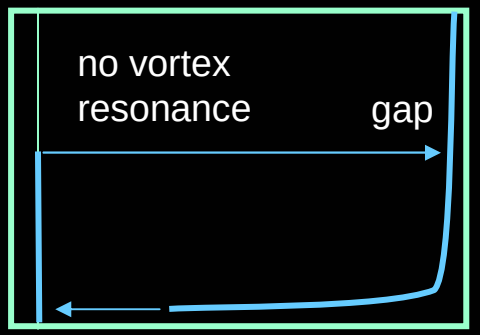
Excellent agreement !

Two different escape processes?

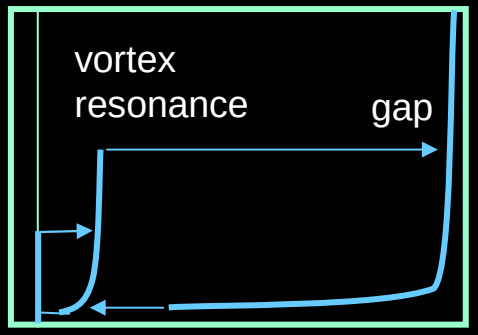


large pinning

small pinning



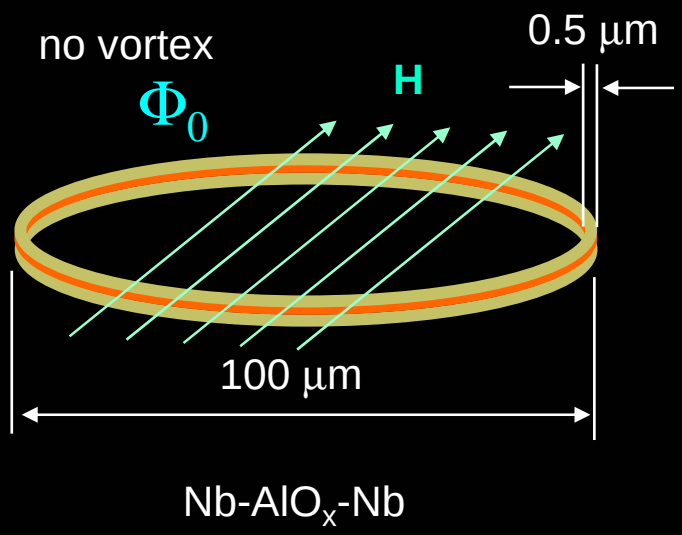
2.

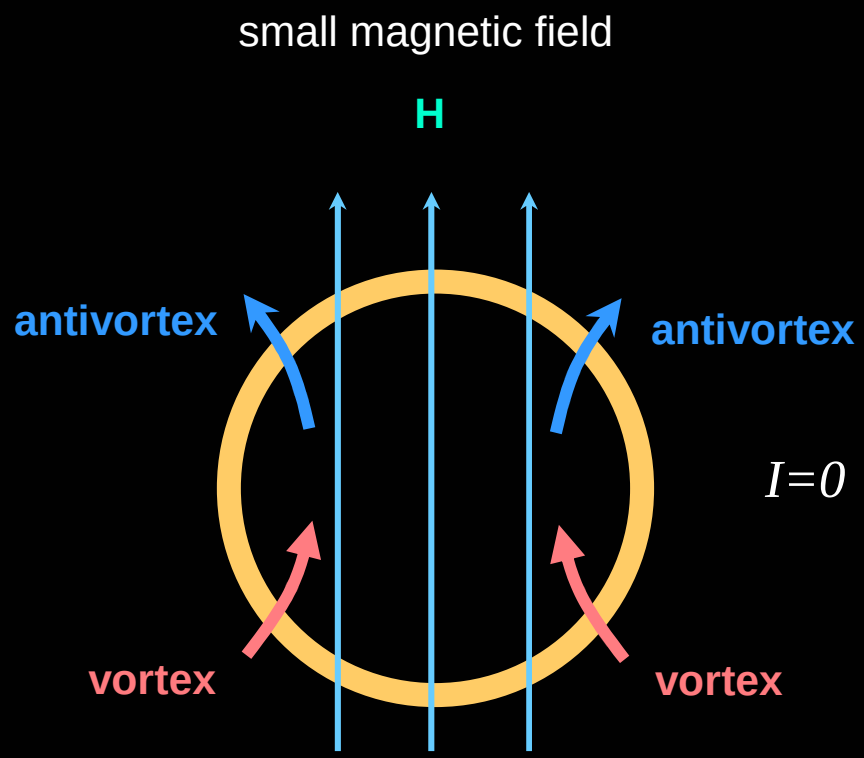


1.

1. Vortex depinning
2. Depinning of an extended phase profile

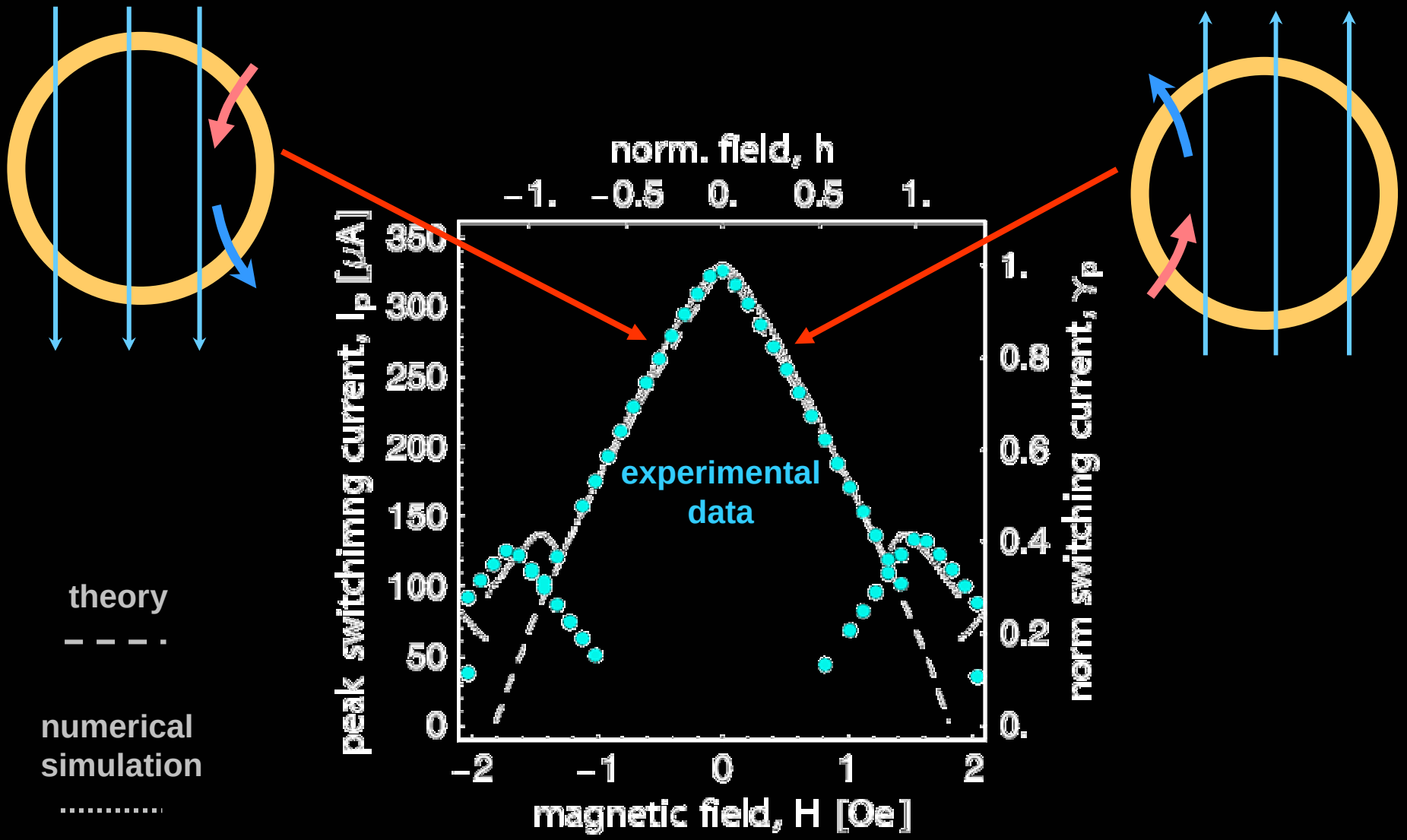
Annular junction **without trapped vortex**





- M. Fistul, A. Wallraff, Y. Koval, A. Lukashenko, and A.V.Ustinov, unpublished (2003)

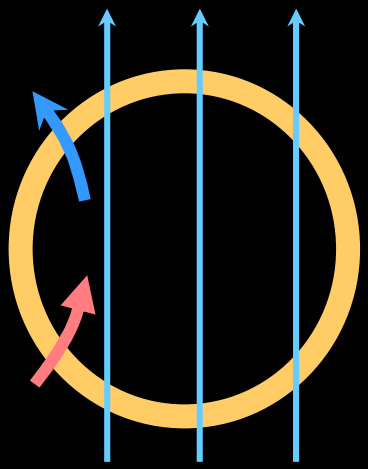
$I_P(H)$: no trapped vortex

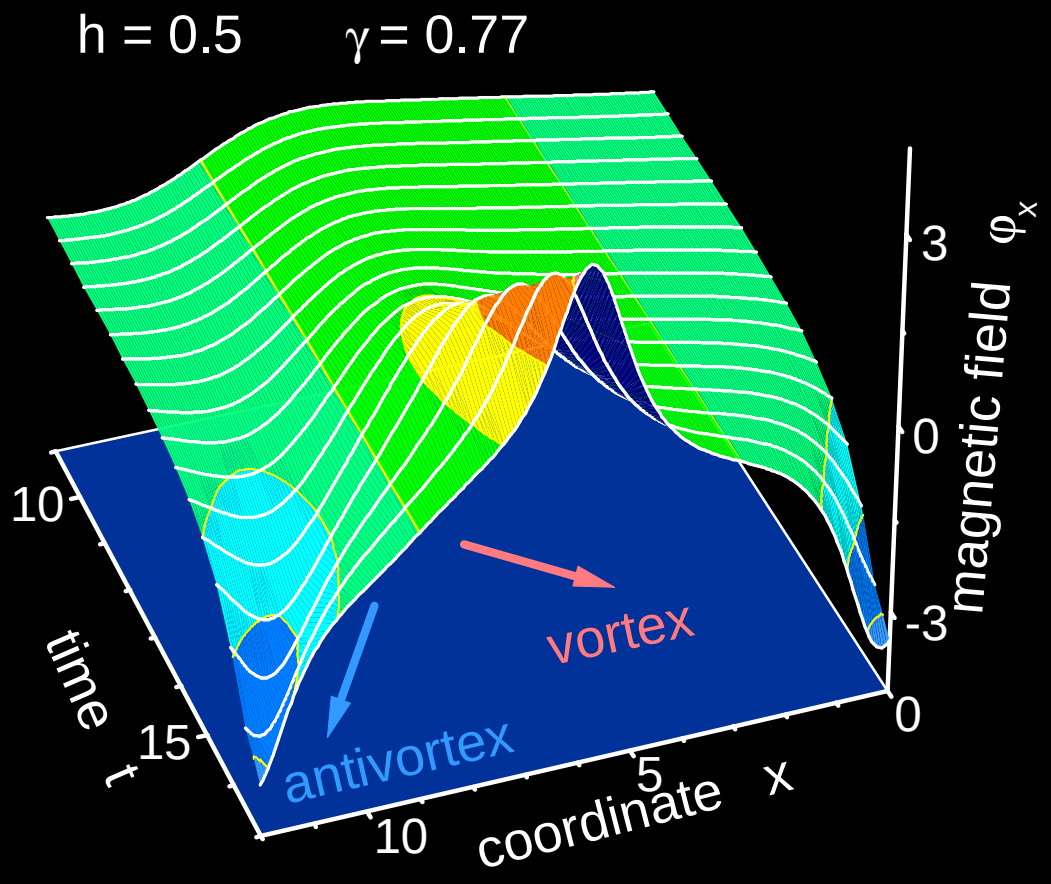


Dissociation of a vortex-antivortex pair at $I=I_C$

Numerical simulation:

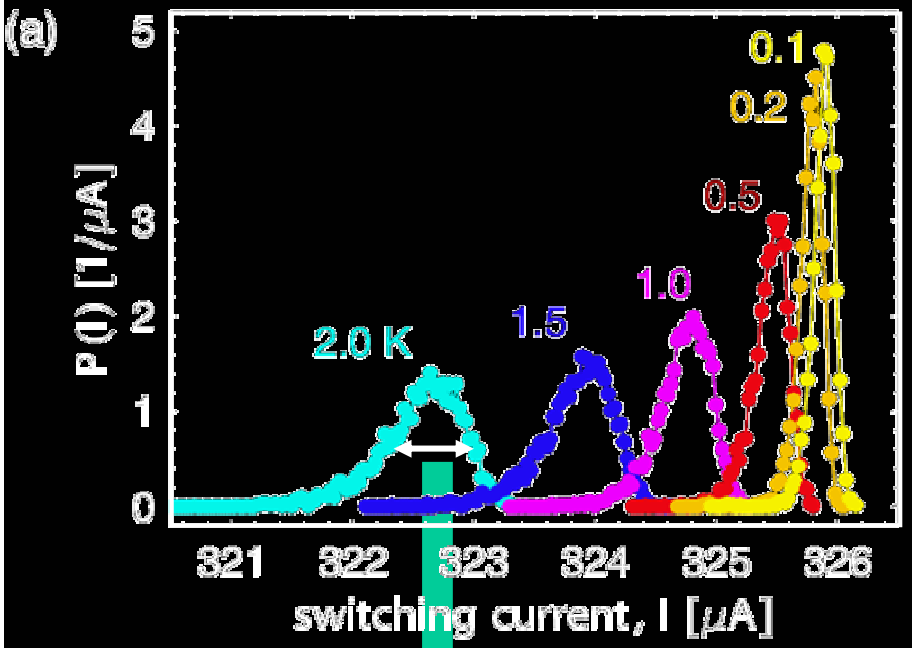
magnetic field $\varphi_x(x,t)$



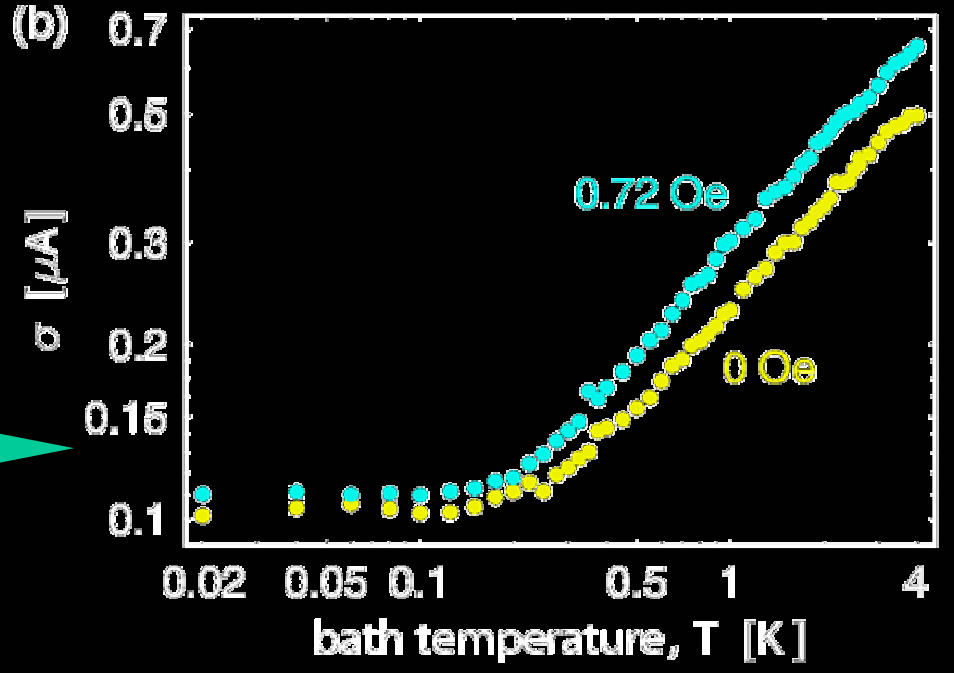


Switching current measurements

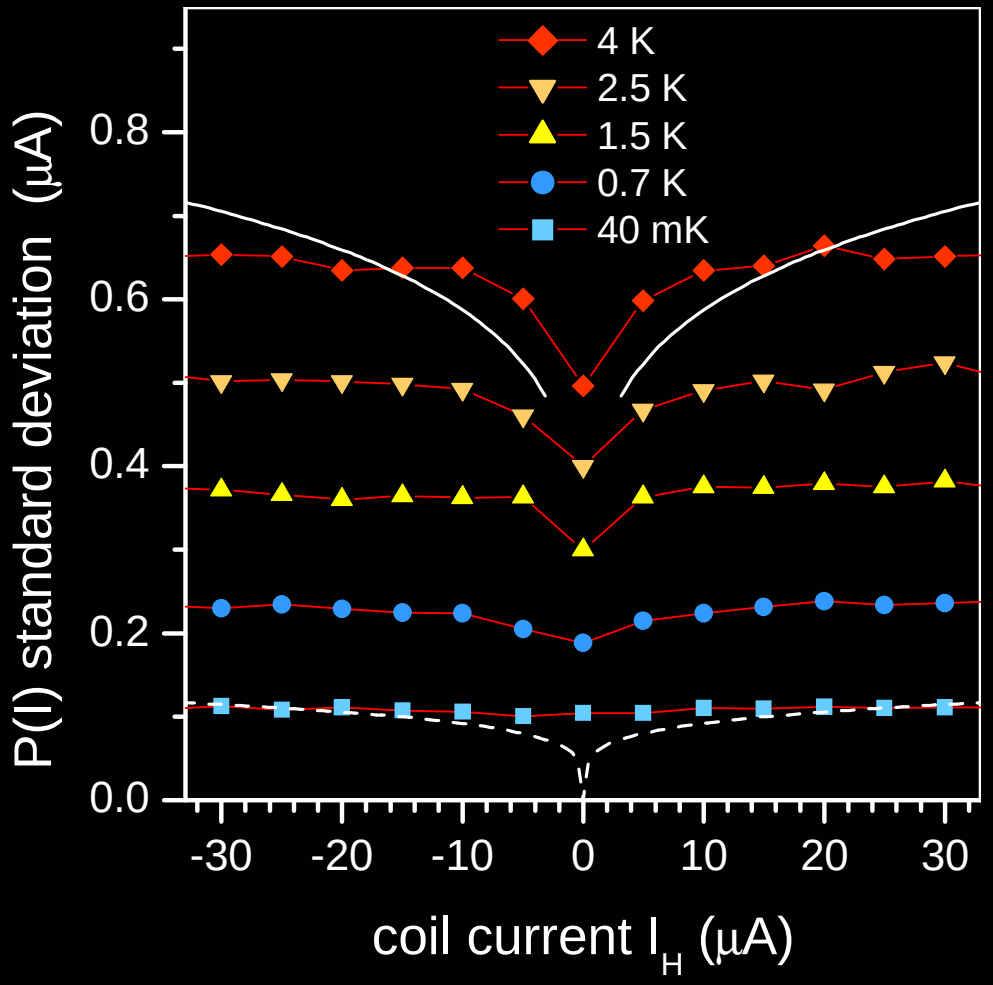
P(I) distributions versus bath temperature



Annular junction without trapped vortices



Experimental data: standard deviation of P(I) distributions *vs* T and H



theory: M. Fistul

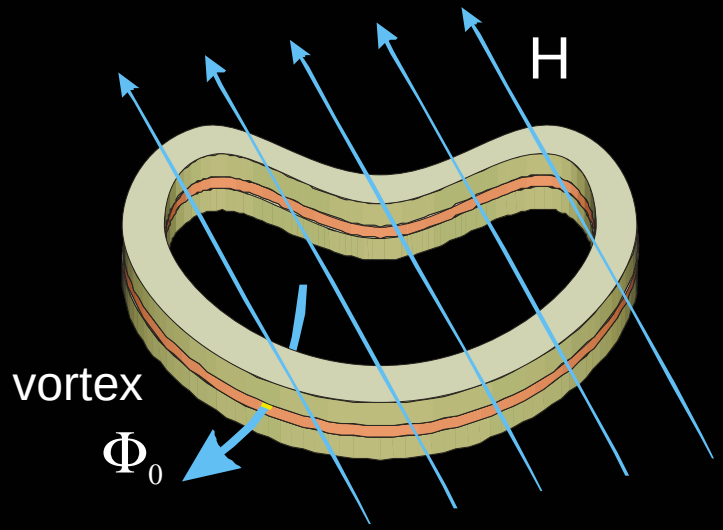
- dissociation of a vortex-antivortex pair
- decay of a “stretched breather” state

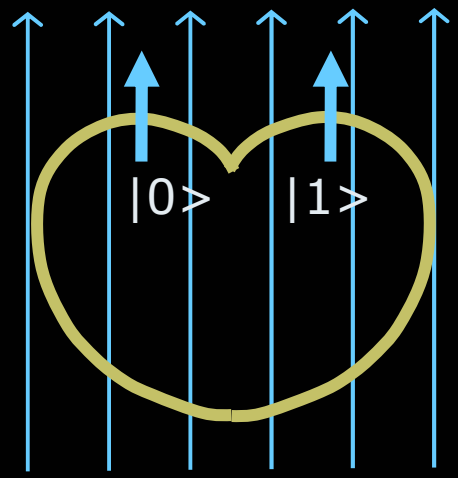
thermal decay ——

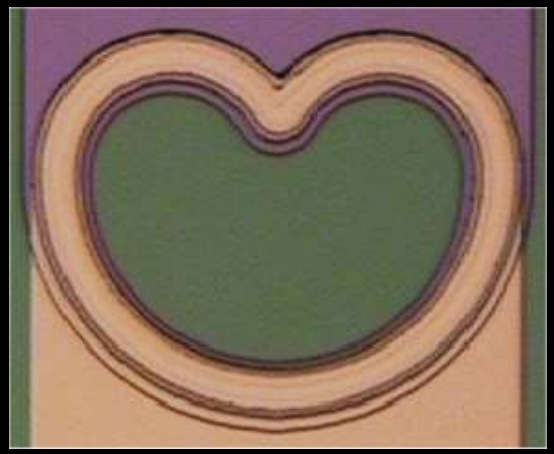
quantum decay - - - - - - -

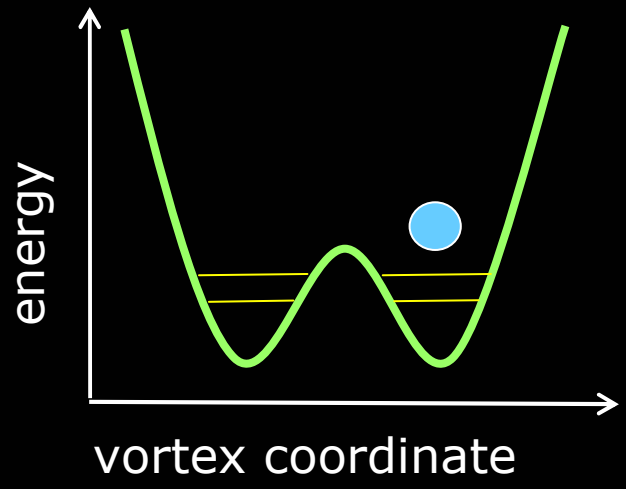
Vortex qubit

Shaped long Josephson junction









Summary

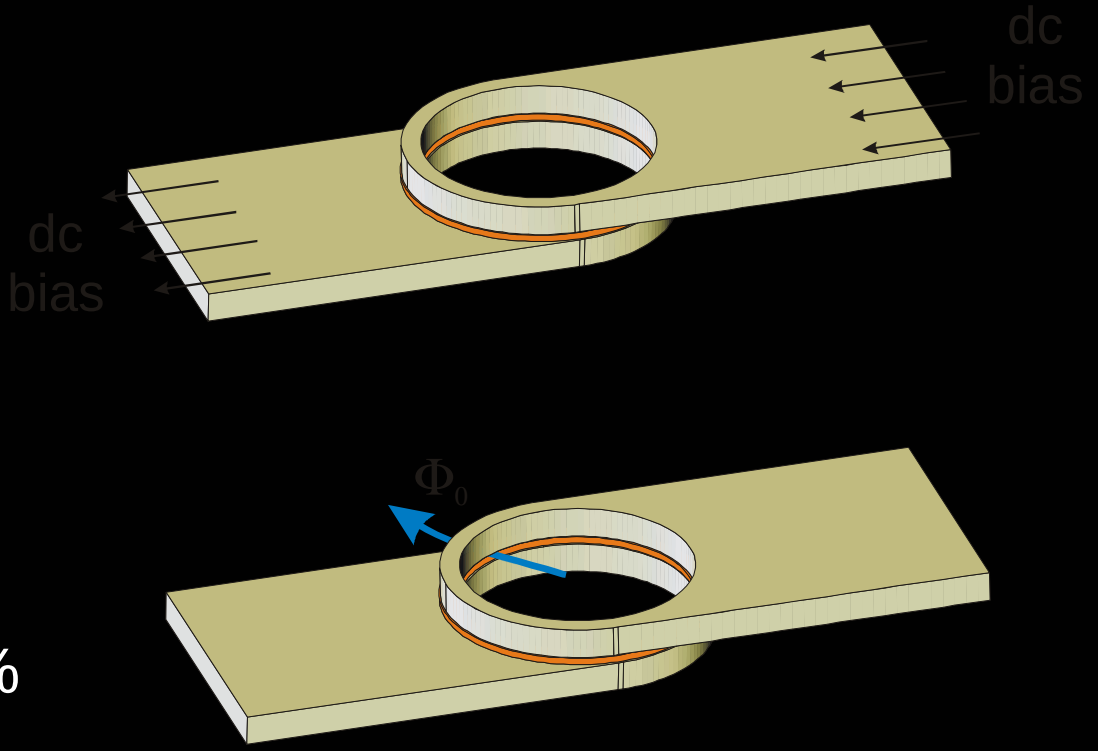
- Quantum tunneling of a single Josephson vortex is observed for the first time
- Vortex energy levels in a potential well are measured by microwave spectroscopy
- Quantum dissociation of vortex-antivortex pairs is observed in annular junctions with no trapped vortices
- Vortex qubit state can be designed by tailoring the junction shape

Catching a vortex

- Trick 1:

1. Heat above T_c
2. (Apply current)
3. Cool below T_c
4. Pray

Success rate: < 5-10%



- A. Davidson, B. Dueholm, B. Kryger, and N. F. Pedersen, *Phys. Rev. Lett.* **55**, 2059 (1985)