SFIS φ Josephson junction as elements of superconducting memory

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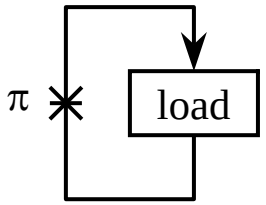
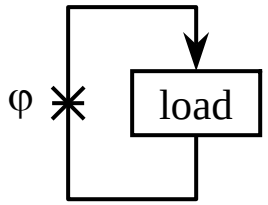
φ Josephson junction



phase battery
(not dischargable)

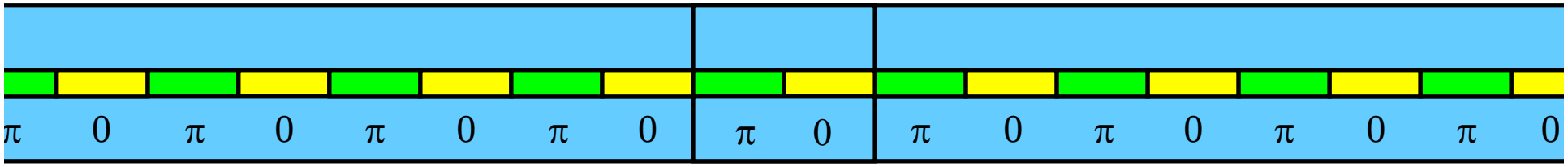


T. Ortlepp et al., Science **312**, 1495 (2006);
A. Feofanov et al., Nat. Phys. **6**, 593 (2010)

R. Mints et al. PRB **57**, R3221 (1998);
A. Buzdin et al. PRB **67**, R220504 (2003).

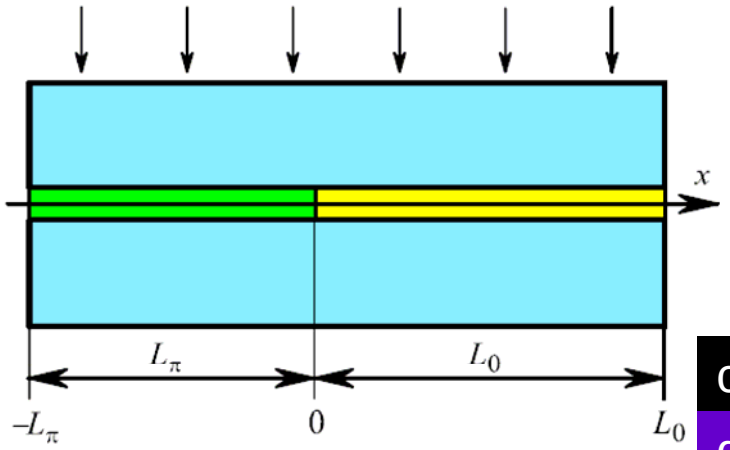
A φ-JJ:
ground states: +φ and –φ
CPR: $I_s = I_{c1}\sin(\phi) + I_{c2}\sin(2\phi)$
$\varphi = \arcsin(-I_{c1}/2I_{c2})$, $I_{c2} < -I_{c1}/2$

A φ_0-JJ:
ground state: $\phi = \varphi_0$
CPR: $I_s \sim I_c \sin(\phi - \varphi_0)$



📖 Proposal: E. Goldobin et al., PRL **107**, 227001 (2011)
📖 Experiment: H. Sickinger et al., PRL **109**, 107002 (2012)
📖 http://www.pro-physik.de/details/news/3790631/Supraleiter_als_Phasenbatterie.htm

The main idea & result



$$\phi''(x) - j_c(x)\sin[\phi(x)] = -\gamma,$$

$$\phi(x) = \psi + \xi(x)\sin\psi, \quad |\xi(x)\sin\psi| \ll 1$$

Taylor:

$$\xi''\sin\psi - \langle j_c\rangle[1 + g(x)][1 + \xi(x)\cos\psi]\sin\psi = -\gamma.$$

const

$$\gamma = \langle j_c\rangle[\sin\psi + \langle g(x)\xi(x)\rangle\sin\psi\cos\psi]. \qquad (11)$$

dev:

$$\xi'' - \text{[redacted]} = \langle j_c\rangle[g(x) - \text{[redacted]}], \qquad (12)$$

$$j_c(x) = \langle j_c\rangle[1 + g(x)],$$

$$g(x) = \begin{cases} g_\pi = \frac{-2L_0}{L_0 - L_\pi}, & \text{for } x < 0; \\ g_0 = \frac{+2L_\pi}{L_0 - L_\pi}, & \text{for } x > 0, \end{cases}$$

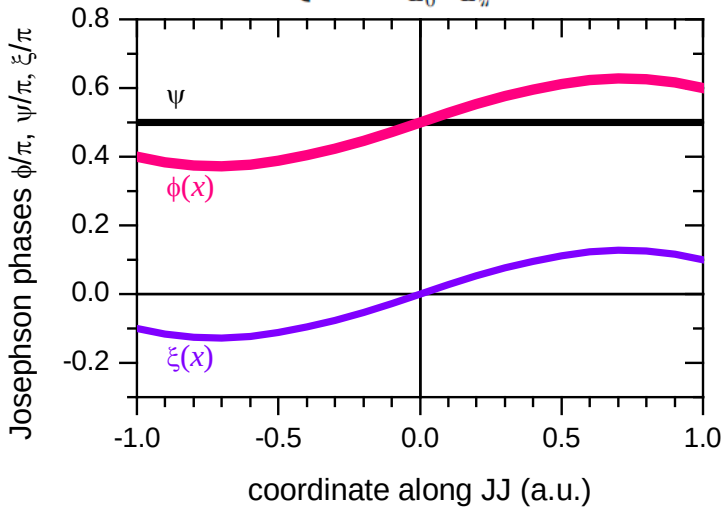
$$\xi'' = \langle j_c\rangle g(x).$$

$$\xi'_\pi(-L_\pi)\sin\psi = h; \qquad \xi'_0(L_0)\sin\psi = h,$$

$$\langle g\xi\rangle = \Gamma_0 + \Gamma_h\frac{h}{\sin\psi},$$

$$\Gamma_0 = -\frac{4}{3}\frac{L_0^2 L_\pi^2}{L_0^2 - L_\pi^2}; \qquad \Gamma_h = \frac{L_0 L_\pi}{L_0 - L_\pi}.$$

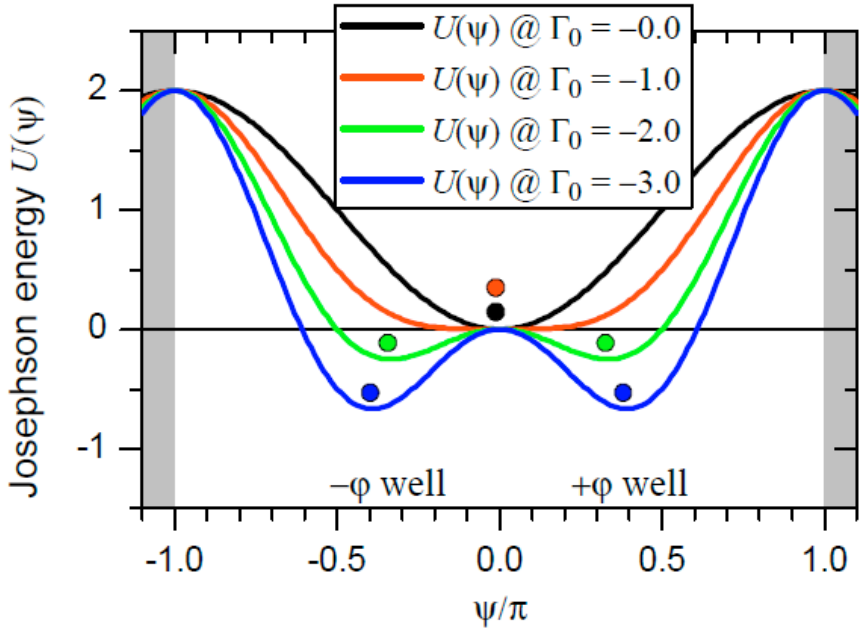
$$\gamma = \langle j_c\rangle\left[\sin\psi + \Gamma_h h\cos\psi + \frac{\Gamma_0}{2}\sin(2\psi)\right].$$



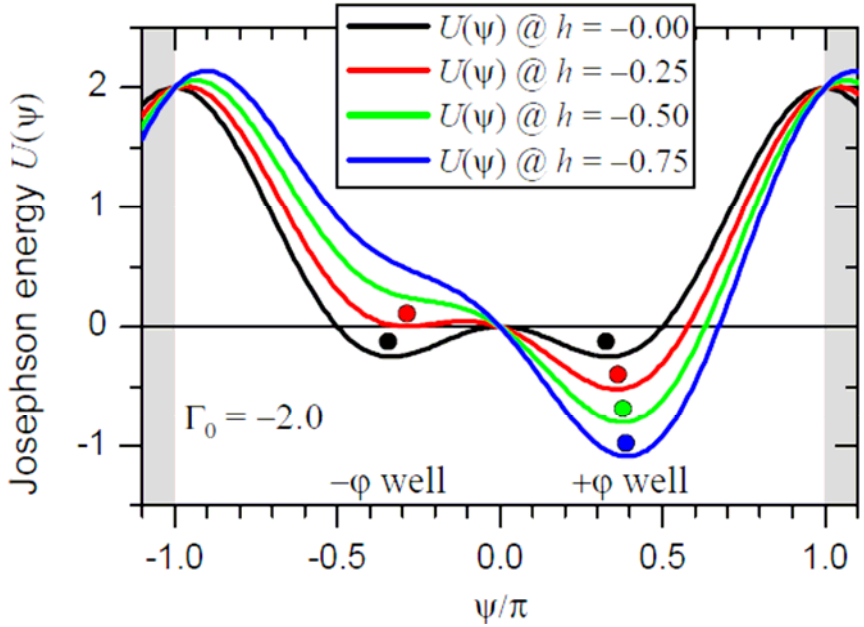
φ Josephson junction

$$U_J(\psi) = 1 - \cos(\psi) + \boxed{\frac{\Gamma_0}{4}[1 - \cos(2\psi)]} + \boxed{\Gamma_h h \sin(\psi)},$$

$$\boxed{\varphi = \arccos(-1/\Gamma_0)}$$



Bistabe/two-level system



Ratchets & co.

🕮 Proposal: E. Goldobin et al., PRL **107**, 227001 (2011)
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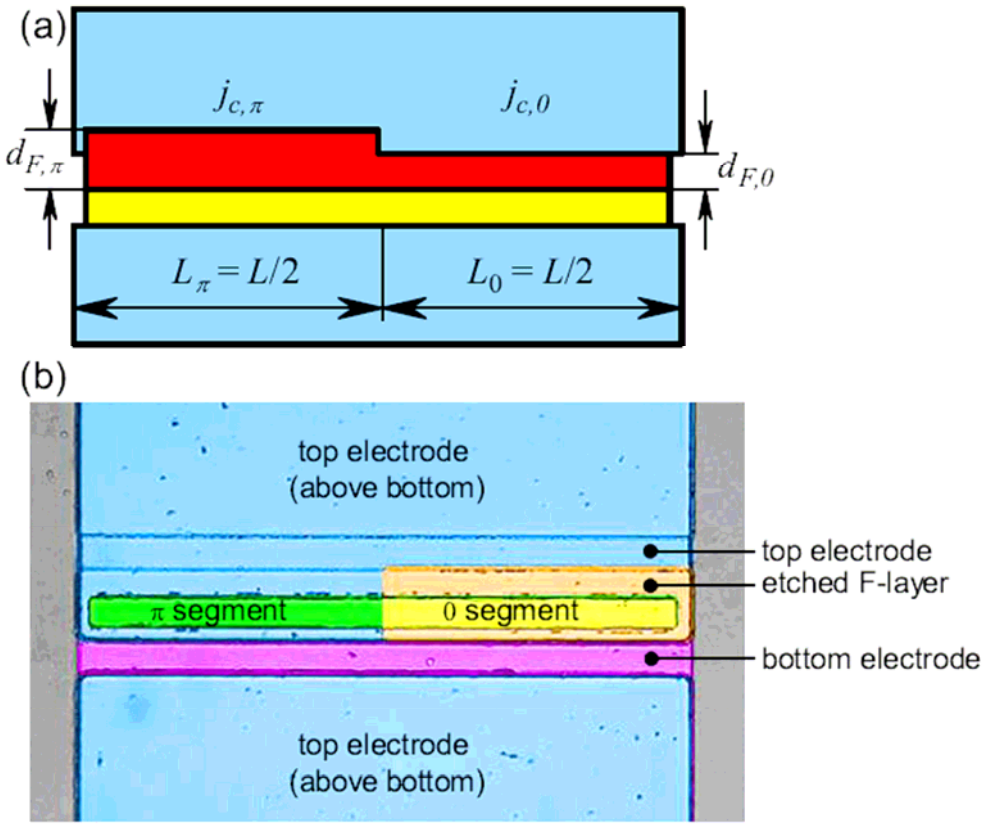
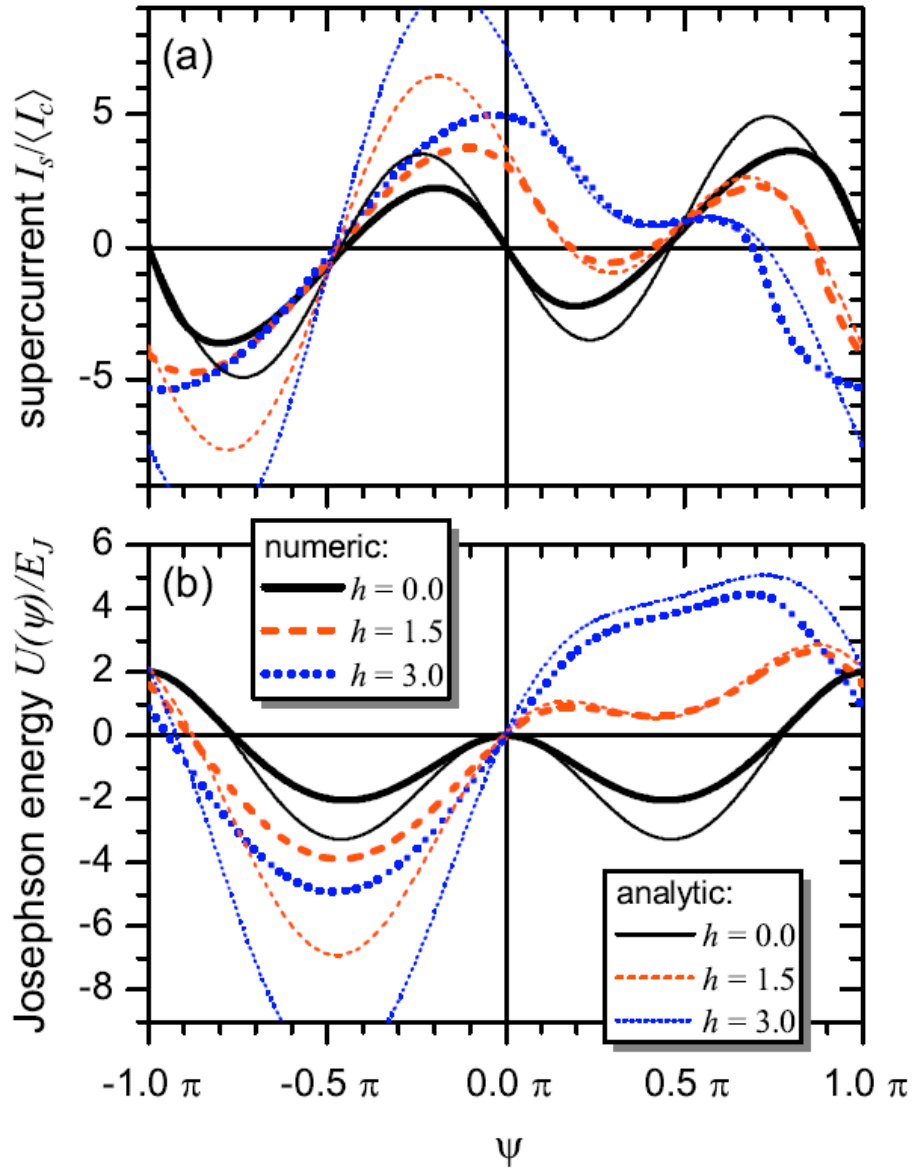
Experiment: samples

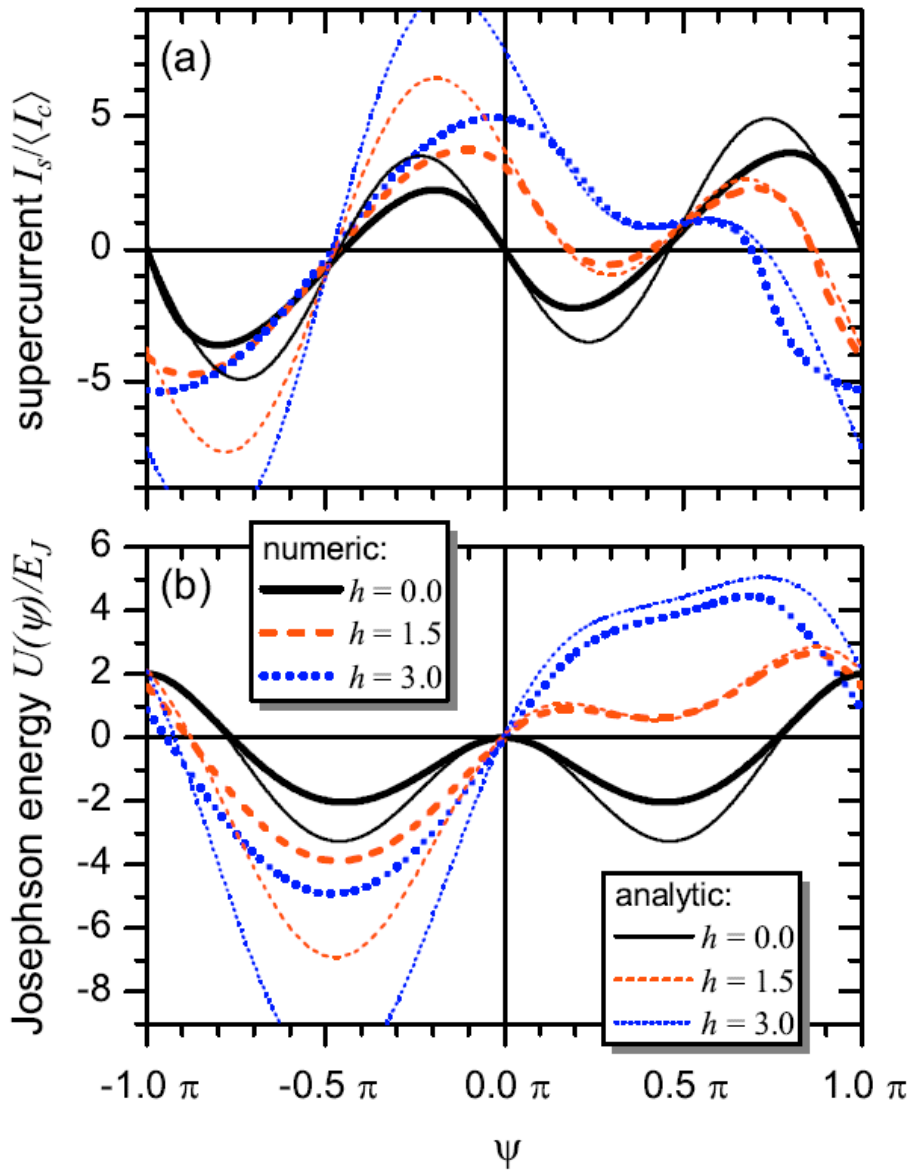
SIFS 0-π Josephson junction:
L = 100+100 μm,
j_{c0}=67.8μA/cm², $j_{c\pi}$=47.4A/cm²,
$L_0 \sim 1.73\ \lambda_{J,0}$, $L_\pi \sim 1.45\ \lambda_{J,\pi}$, @300mK

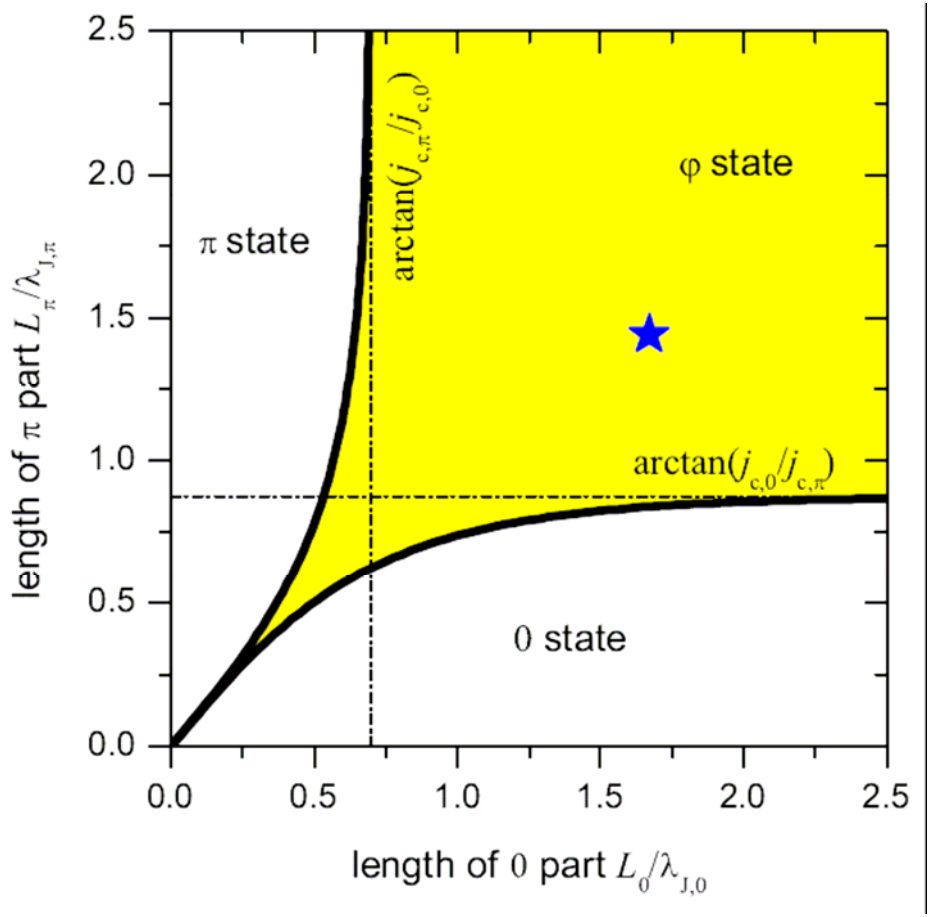




H. Sickinger et al., PRL **109**, 107002 (2012)

CPR: Analytics vs. numerics





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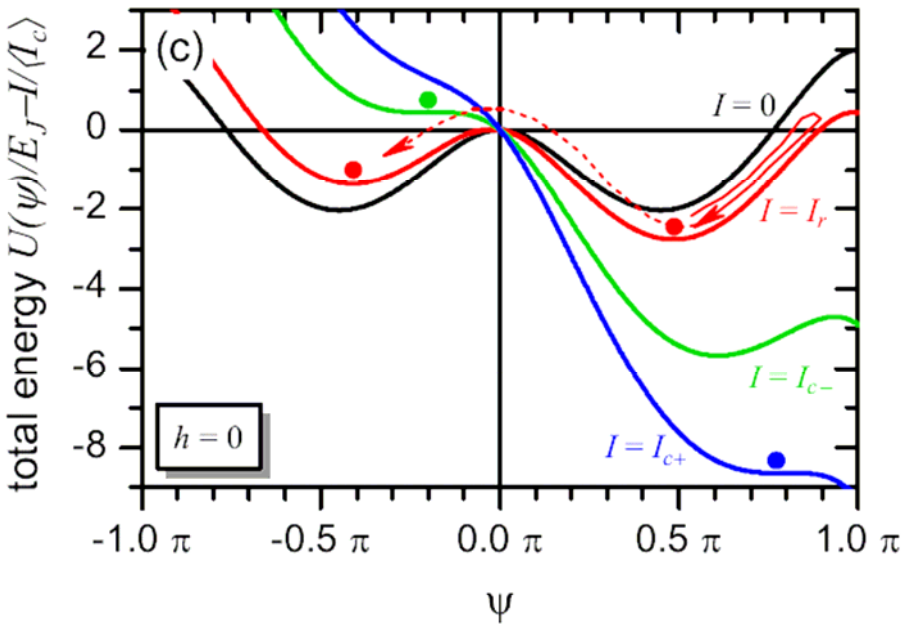
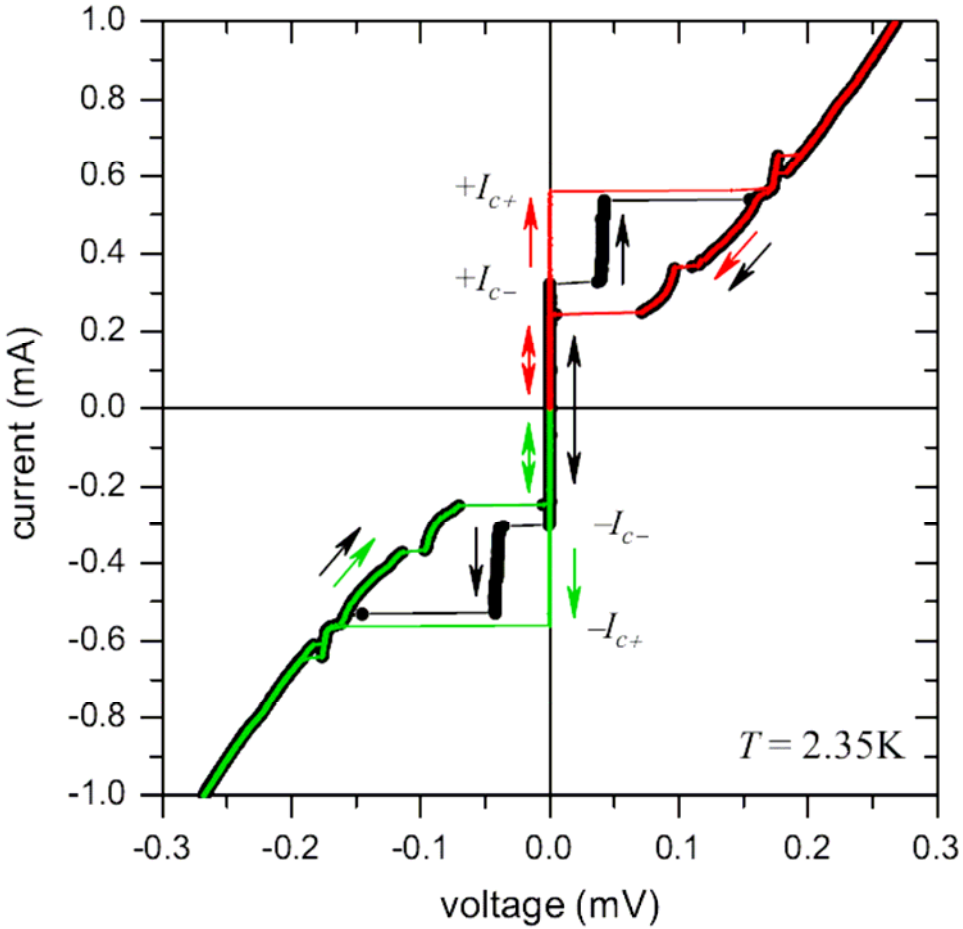
IVC: two critical currents

Observation of I_{c+} and I_{c-}

- I_{c+} is always observed
- I_{c-} only @ 0.3 K < T < 3.5 K (low α)
- immediate retrapping (high α)





state detector!

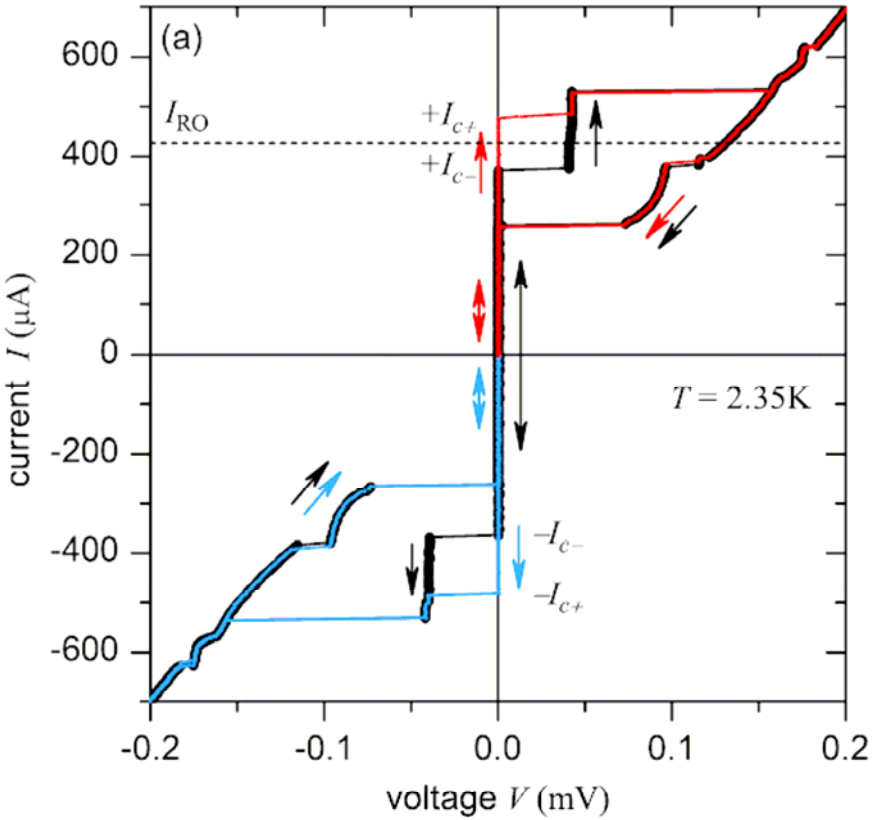
$I_c(H)$

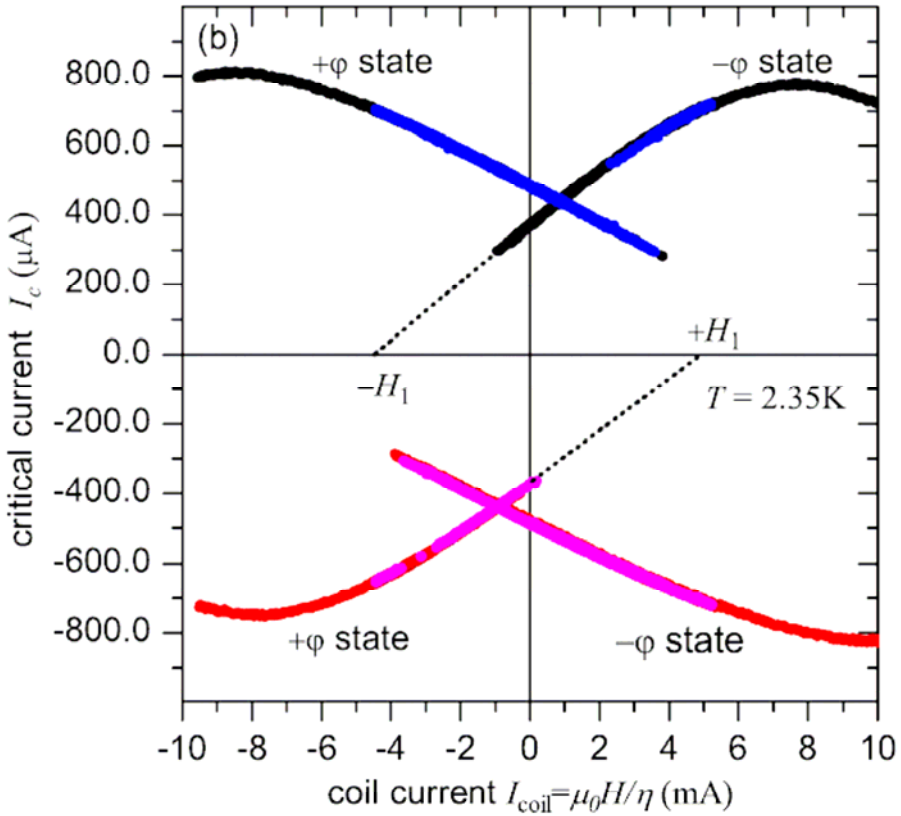
Shifted main minimum

- @ *300*mK < *T* < *4.2*K
- @ *T* = 2.35 K, φ = 0.45π

Two branches crossing

- @ *T* < *3.5* K (low α)
- L-branch = escape from +φ
- R-branch = escape from −φ





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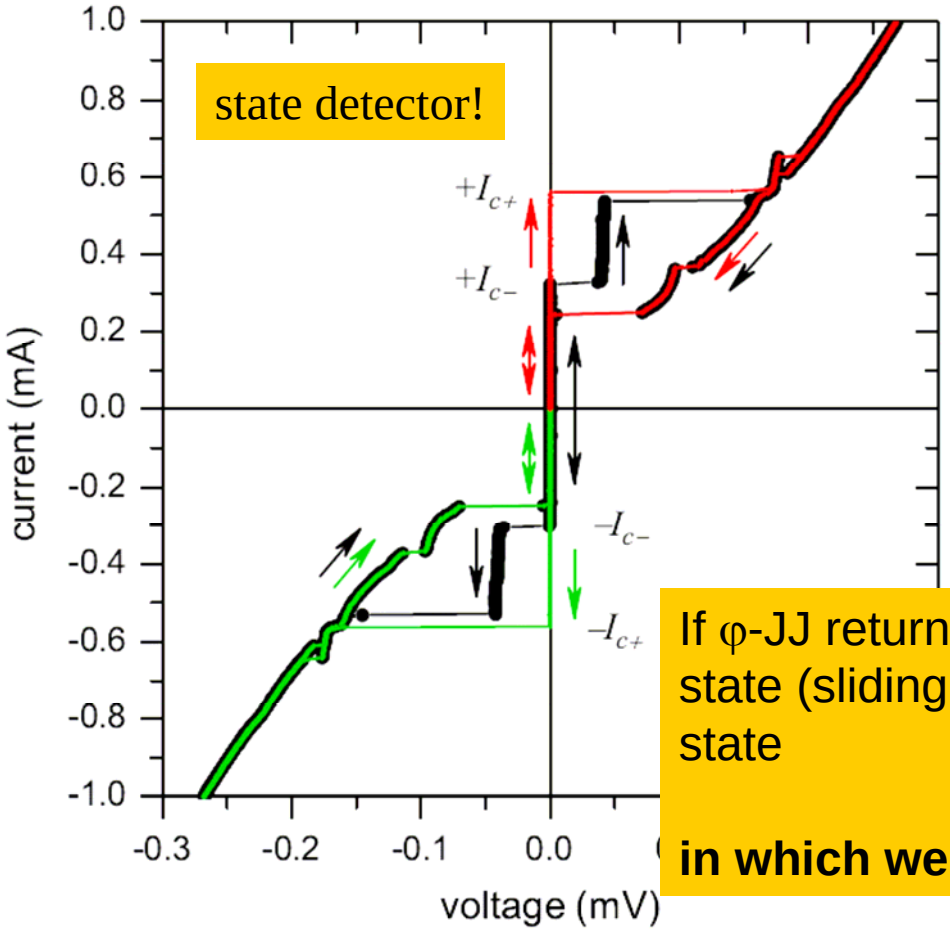
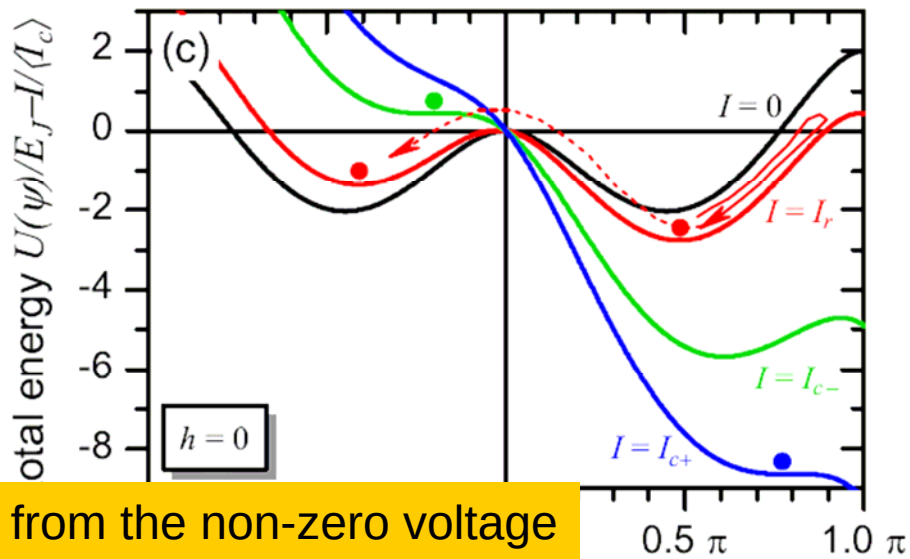
IVC and phase retrapping

I--*V* characteristic



$$U(\psi) = U_J(\psi) - \gamma\psi,$$

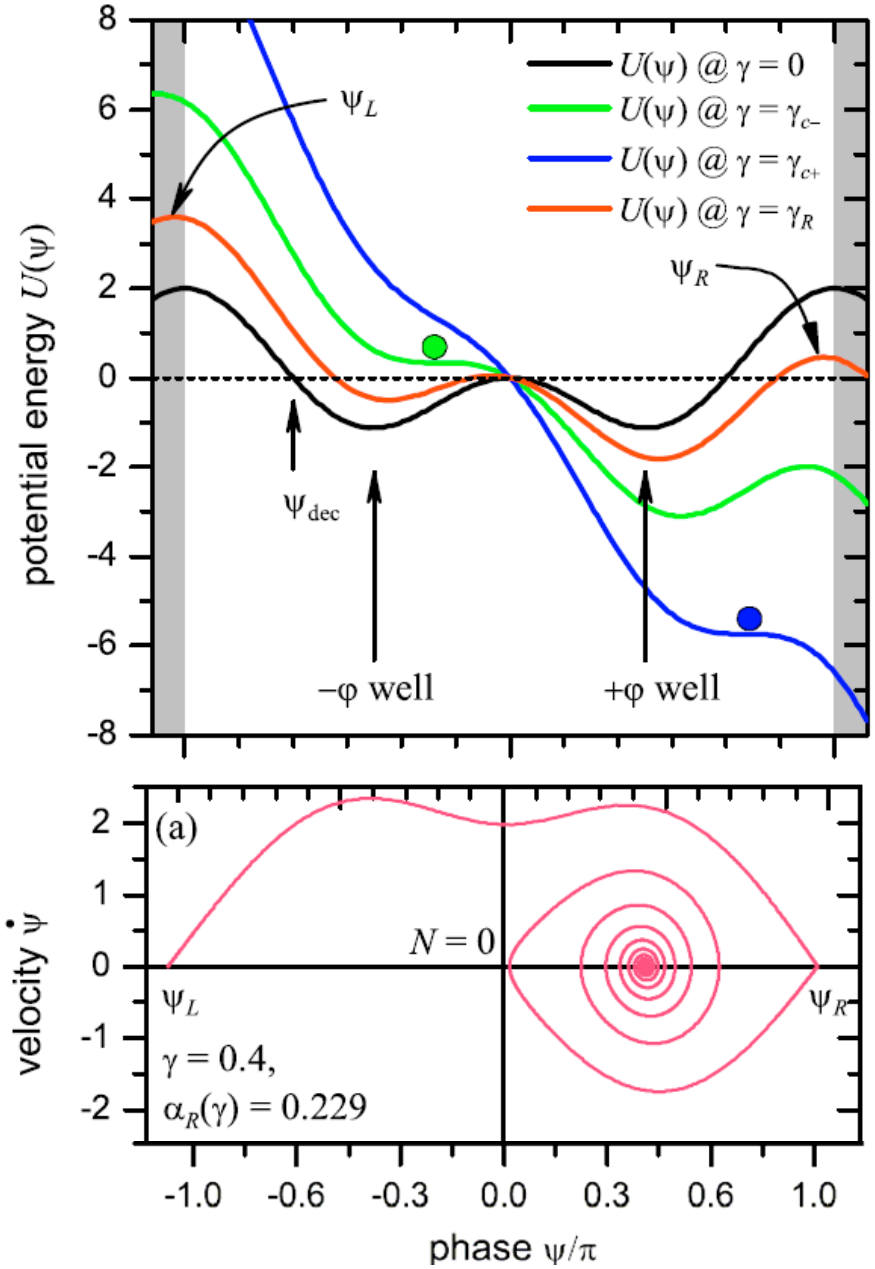


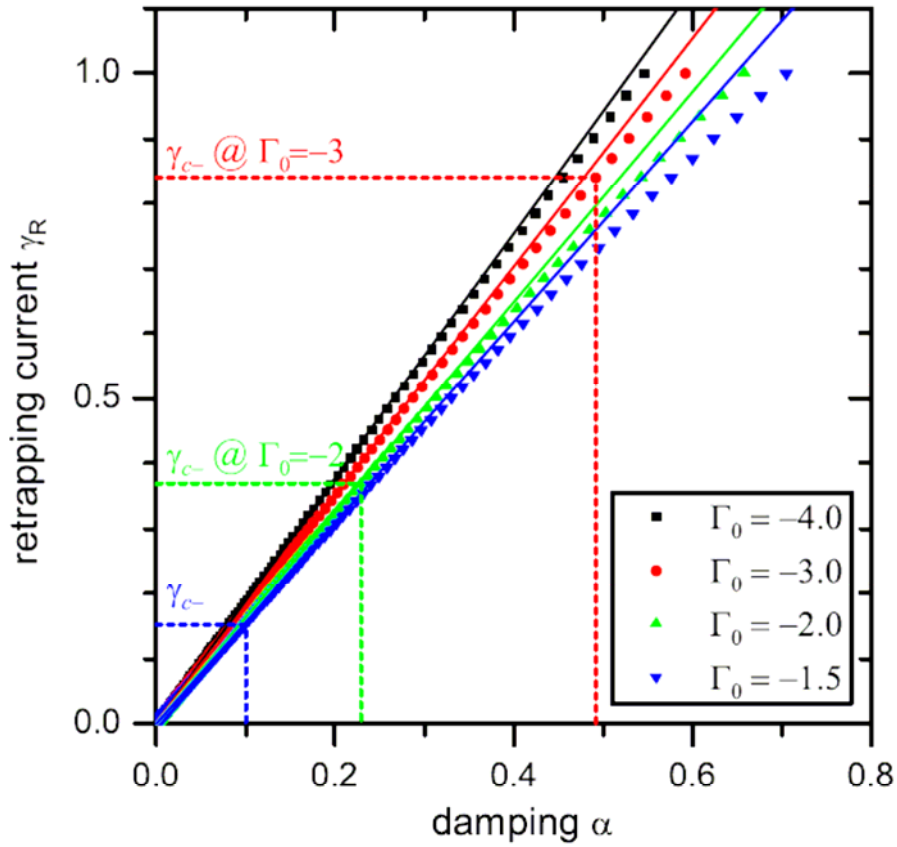
If φ-JJ returns from the non-zero voltage state (sliding phase) to zero voltage state

in which well the phase is trapped?

$$\ddot{\psi} + \frac{\partial U_J}{\partial \psi} = \gamma - \alpha\dot{\psi},$$

Phase Retrapping

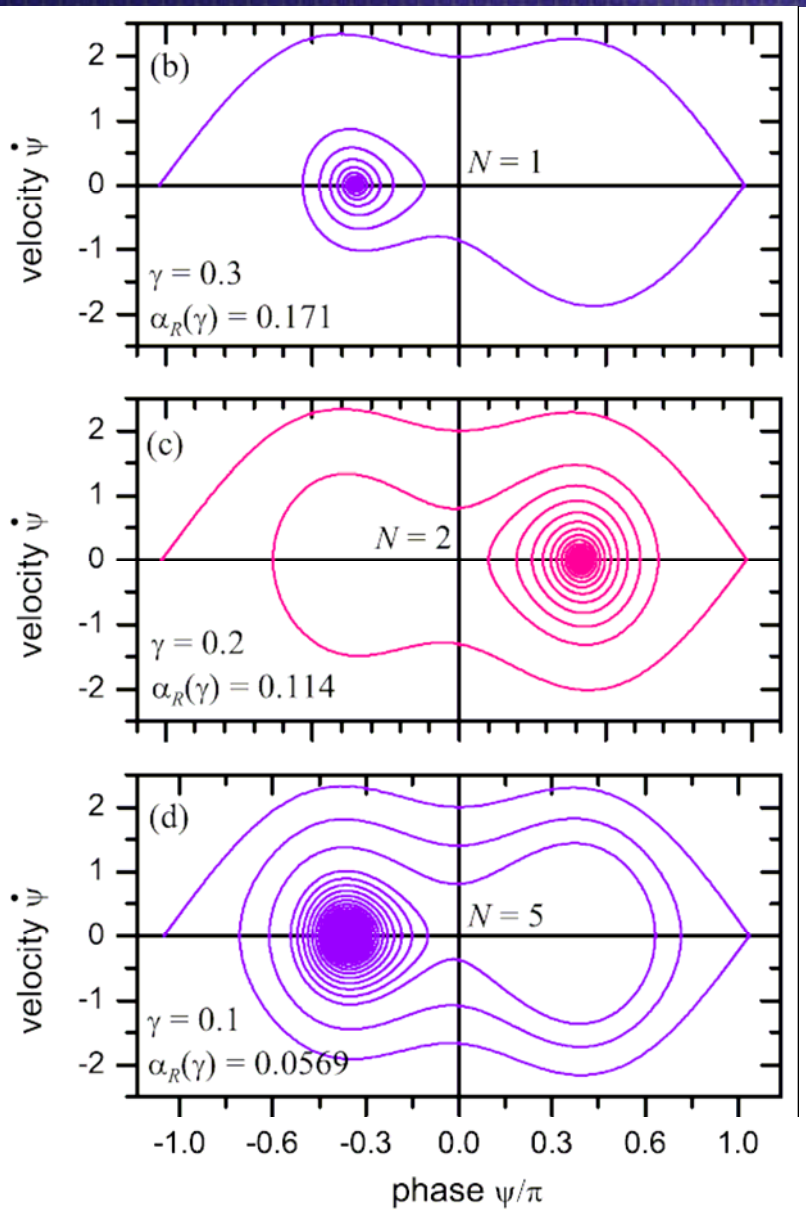


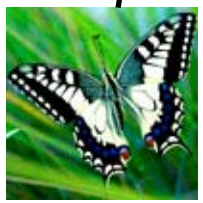


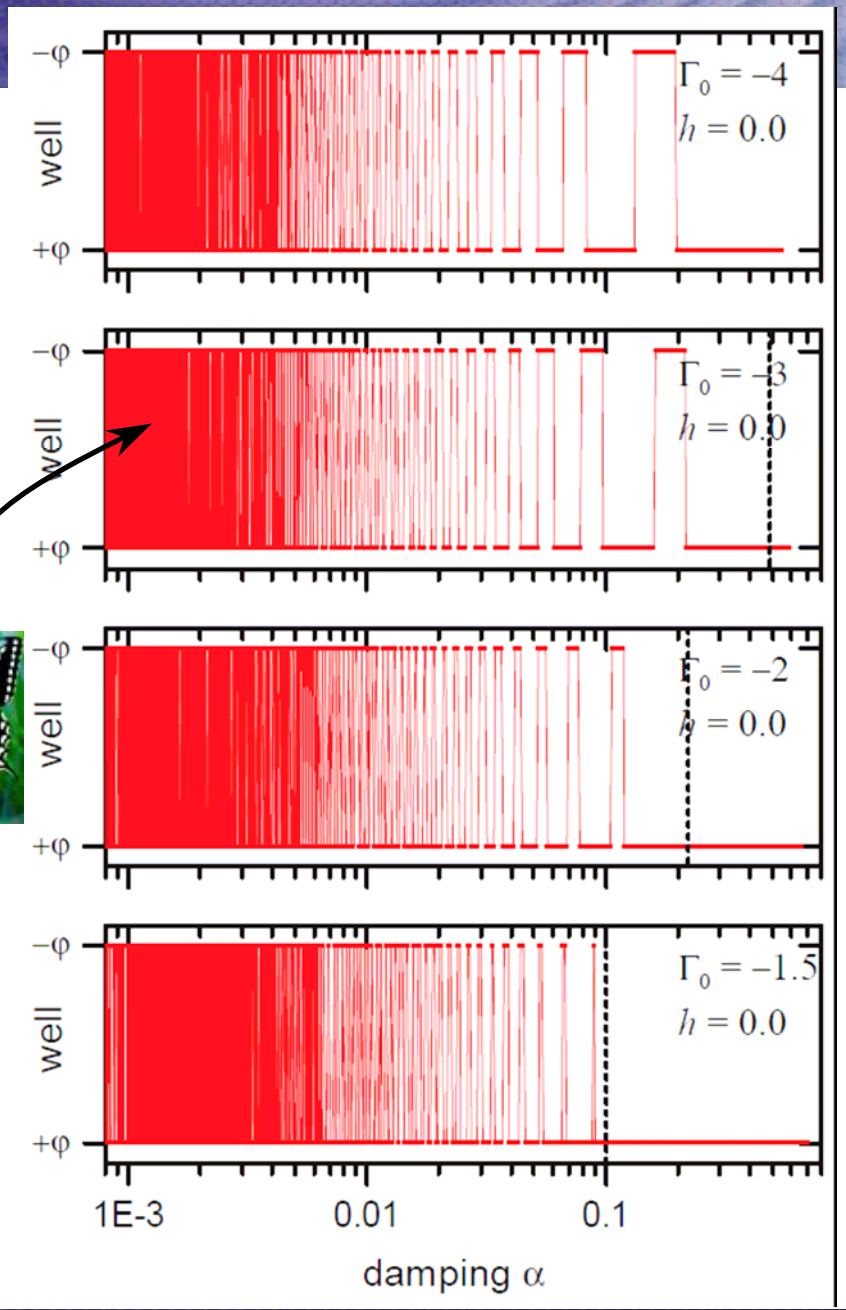
Perturbation theory (α<<1, γ<<1):

$$\gamma_R(\alpha) = \frac{I(\Gamma_0)}{2\pi}\alpha.$$

Butterfly effect

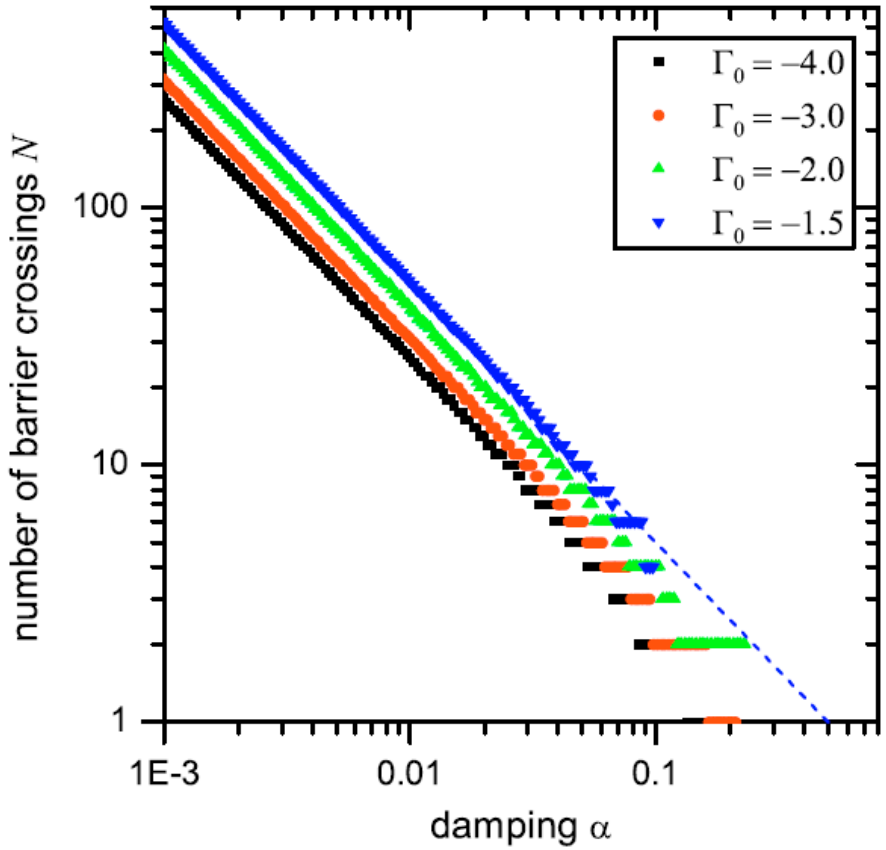






E. Goldobin et al. (unpublished)

How many jumps before decision?



Perturbation theory
(large N, i.e. small α and γ):

$$N = \frac{C_\alpha}{\alpha} = \frac{1}{\alpha}\int_{\psi_{\rm dec}}^{\psi(E_{\rm max})} \frac{\partial U(\psi_{\rm st})}{\partial \psi_{\rm st}} \frac{d\psi_{\rm st}}{W(\psi_{\rm st})}$$

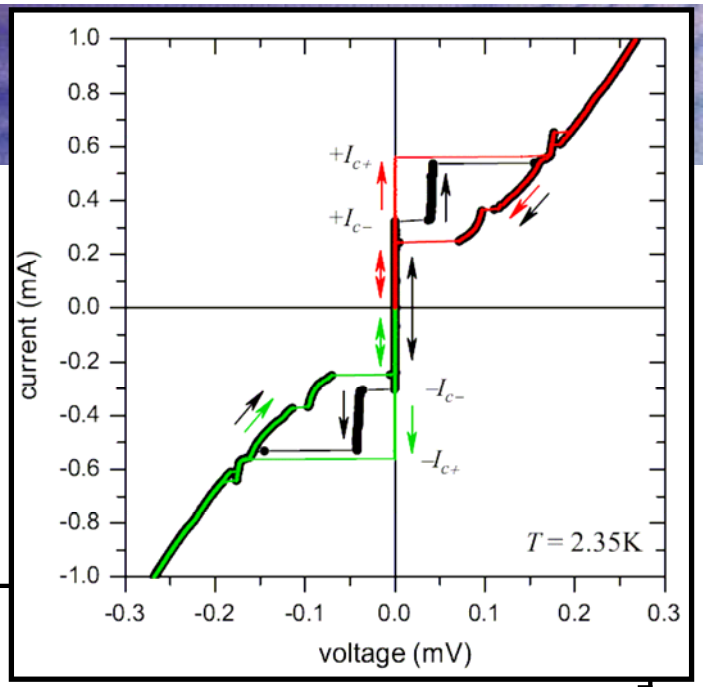
where

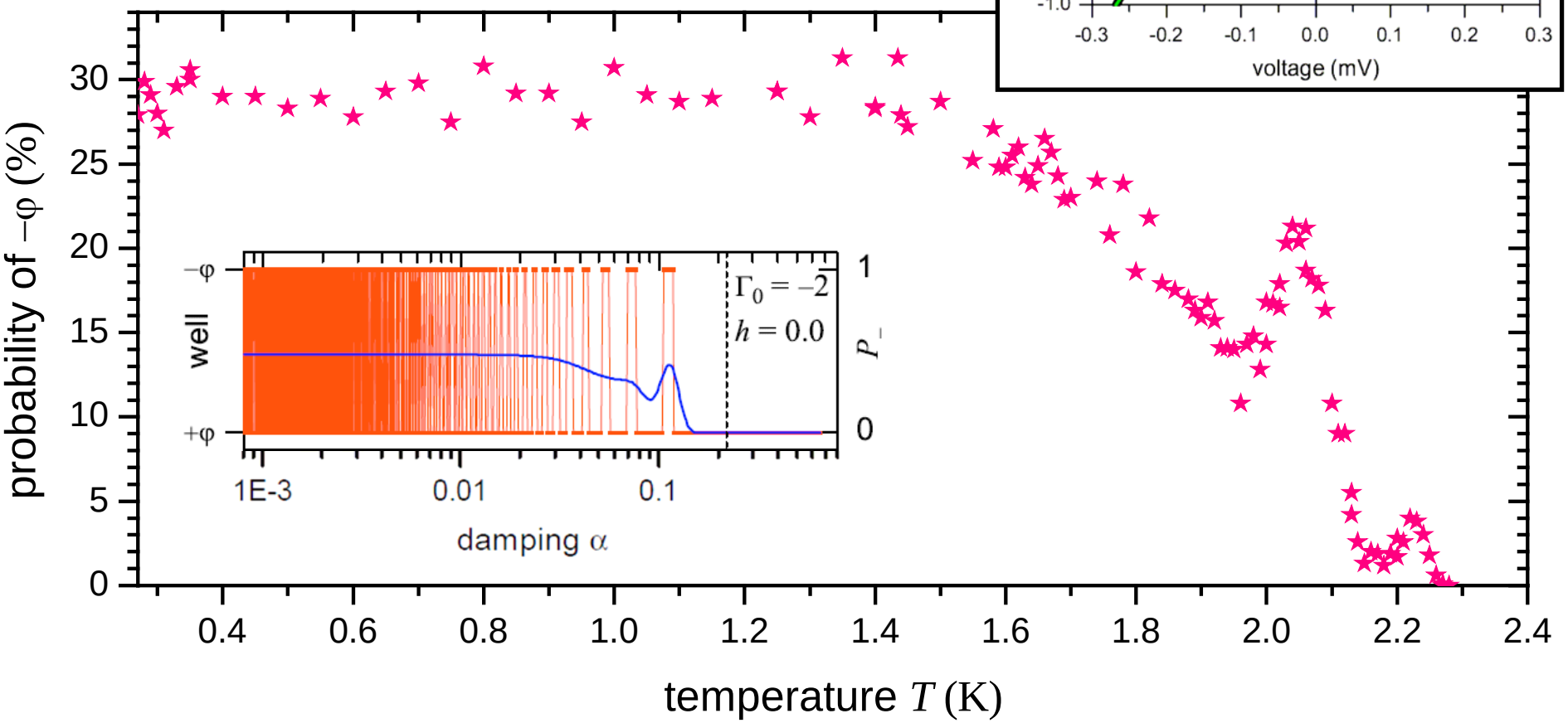
$$W(\psi_{\rm st}) = \int_{-\psi_{\rm st}}^{+\psi_{\rm st}} \sqrt{2[U(\psi_{\rm st}) - U(\psi)]}\, d\psi,$$

for **ANY** double-well potential $U(\psi)$!

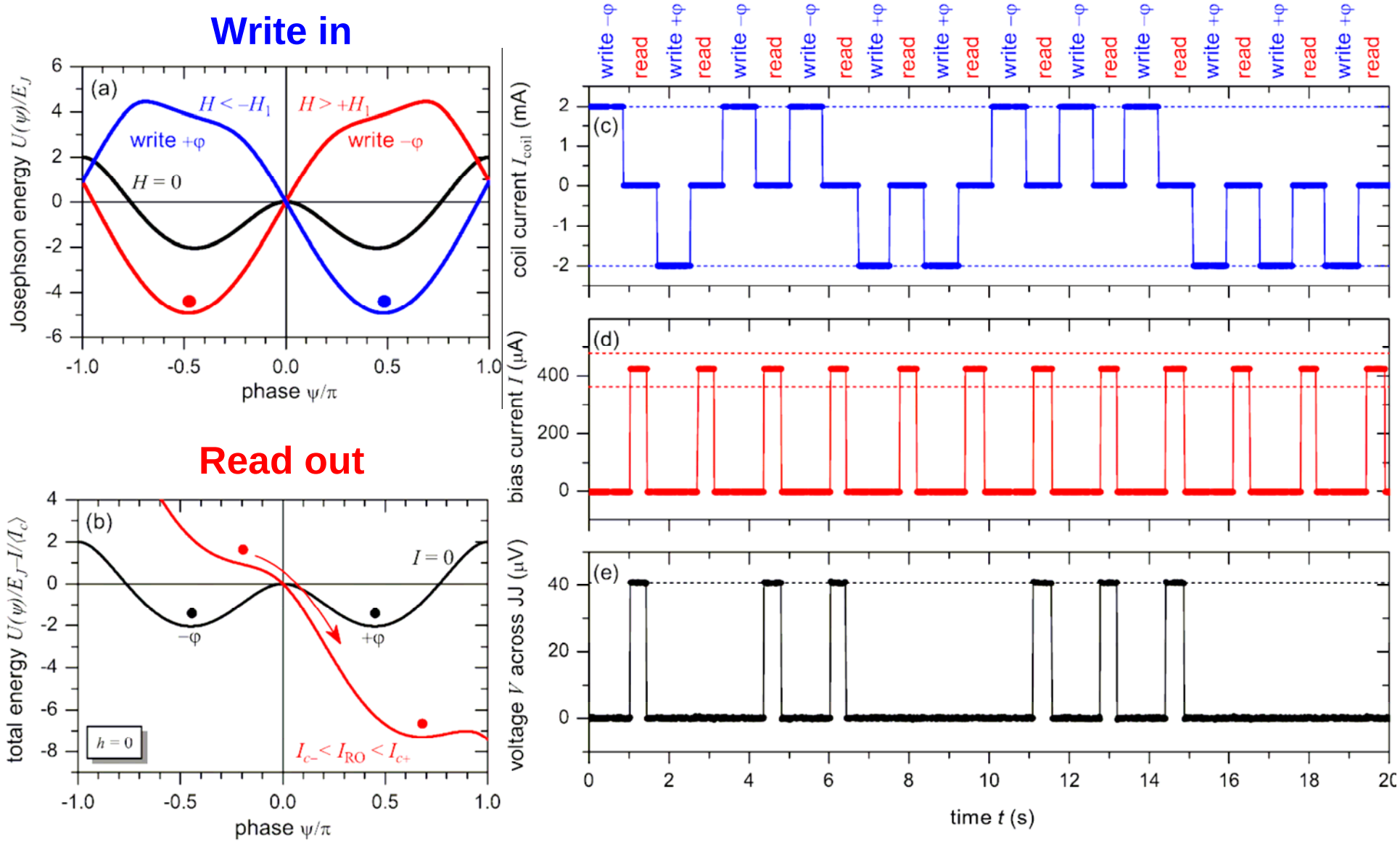
Retrapping statistics

Nb-AlO-CuNi-Nb φ JJ:
L = 100+100 μm,
j_{c0}=67.8μA/cm^2, $j_{c\pi}$=47.4A/cm^2,
$L_0 \sim 1.73\ \lambda_{J,0}$, $L_\pi \sim 1.45\ \lambda_{J,\pi}$, @300mK





Experiment: φ bit (memory cell)



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Summary & Outlook

Summary:

- φ-JJ based on SIFS 0-π JJ:
- Properties of φ-JJ:
  - degenerate ground states
  - magnetic field tunable CPR (write in, ratchet)
  - two critical currents near H=0 (readout)
- Experiment
  - butterfly effect
  - φ-bit (memory cell)

Outlook:

- smaller φ-bit
- RSFQ integration of φ-bit