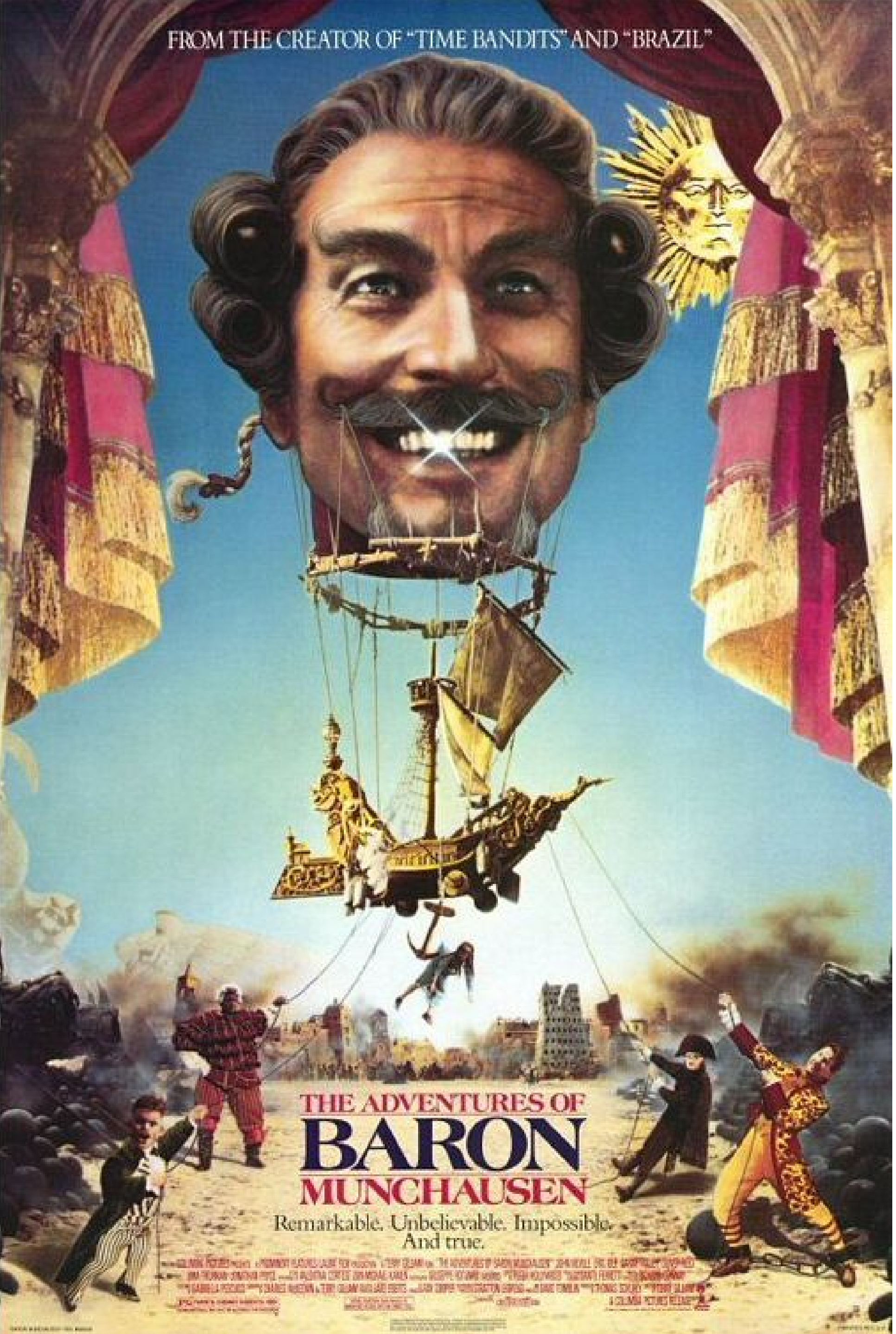
Münchhausen effect, tunneling *in an asymmetric* SQUID



Quantum instability in a dynamically asymmetric dc-SQUID

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with

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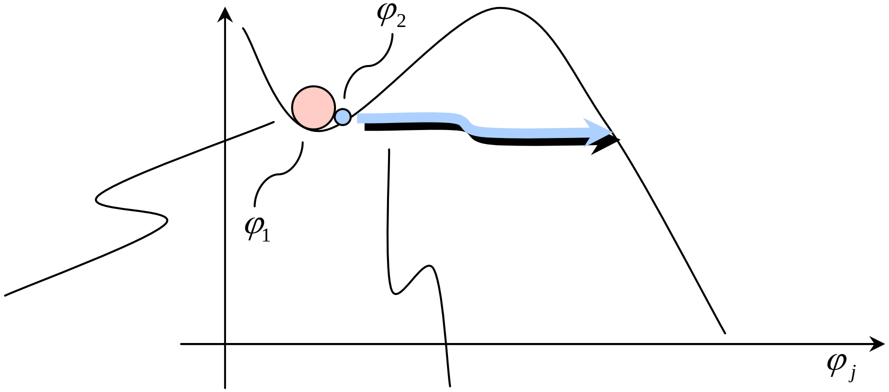
Why can't you understand that
Baron Münchhausen is famous
not because he flew
or did not fly to the moon,
but because he doesn't lie

General idea: Münchhausen

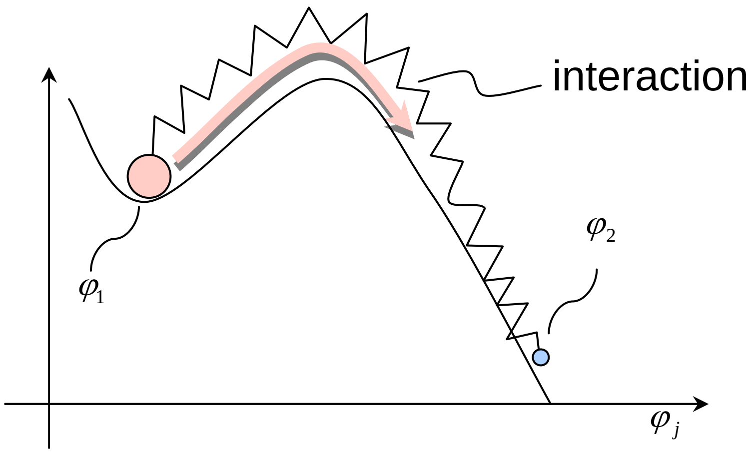
Can a heavy particle tunnel?

Zero temperature: No thermal excitation.



Yes - if it has a light part which drags the heavy part!

Light part tunnels out of metastable minimum.



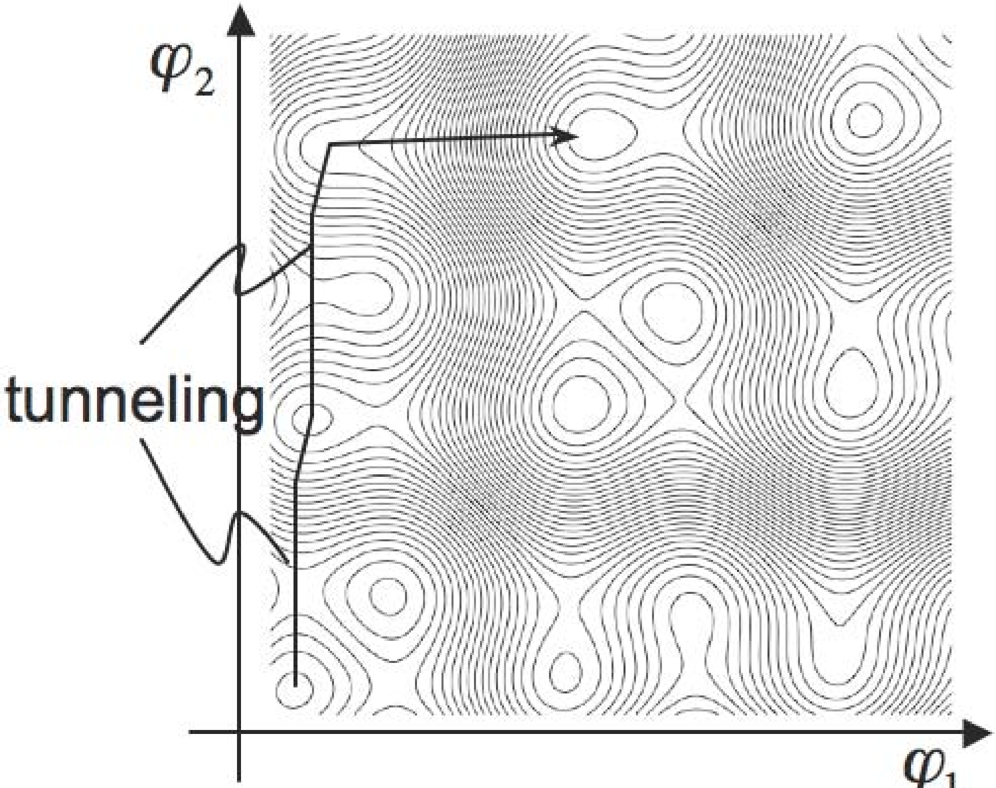
System is unstable w.r.t. macroscopic quantum tunneling of the light degree of freedom φ_2

After tunneling the trapping potential for heavy object is distorted and the state may become unstable.

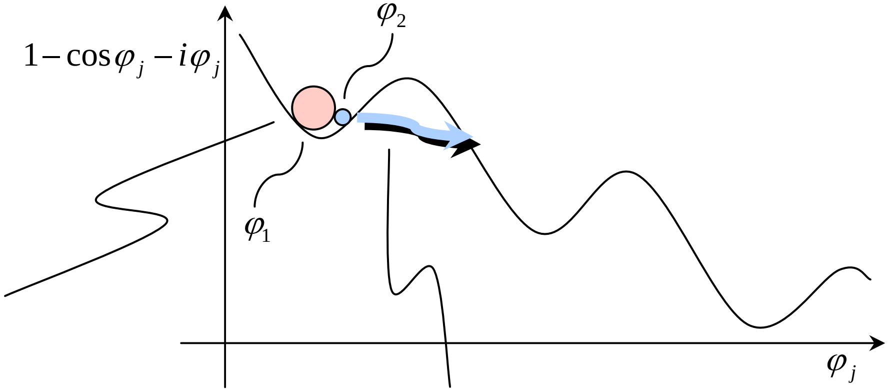
And drags the heavy part!

2d potential

If φ_1 and φ_2 are coordinate of the heavy and light parts we have effectively tunneling of a single particle in a 2d potential with strongly anisotropic mass.



How to realize it ?

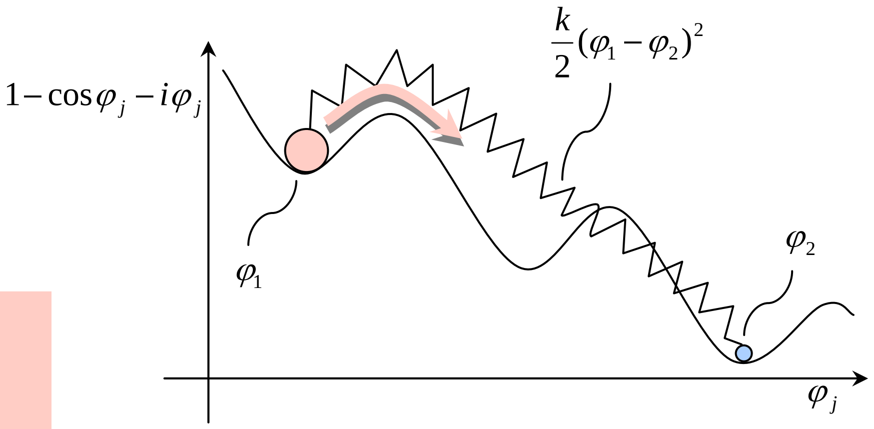


SQUID prepared in a symmetric state with no external magnetic flux: $\varphi_1 = \varphi_2$

Zero temperature: No thermal excitation.

Small junction tunnels out of metastable minimum.

System is unstable w.r.t. macroscopic quantum tunneling of the phase of the small junction φ_2.



For what bias I does the system exhibit a state of finite voltage over the heavy junction at given coupling (inductance L^{-1})?

Is large junction delocalized?

Setup: Capacitance-asymmetry

dc-SQUID: Two Josephson-junctions in a biased (current I) superconducting ring with total inductance L.

Junctions described by RCSJ-model with inductive coupling, (φ_j=phase difference across junction j)

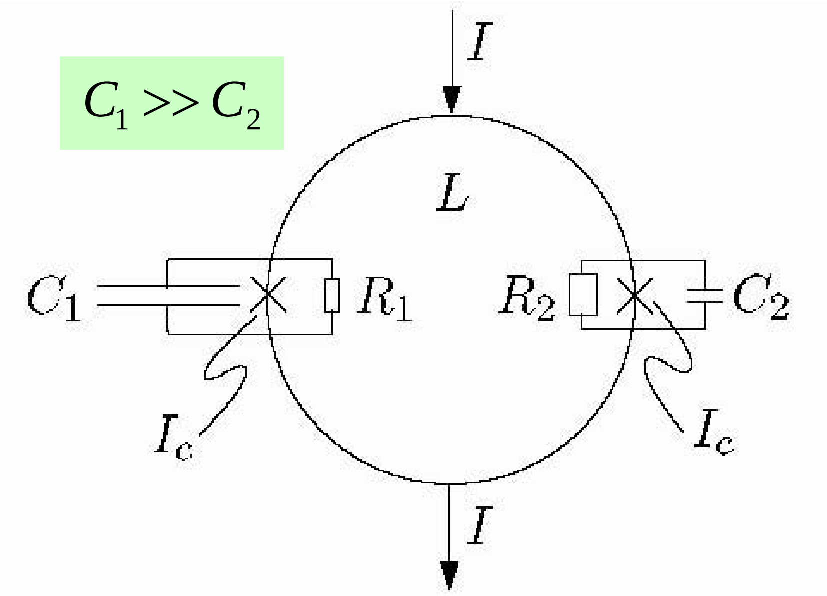
$$m_j \ddot{\varphi}_j + \eta_j \dot{\varphi}_j = -\partial_{\varphi_j} v(\varphi_1, \varphi_2),$$

$$m_j = \frac{\Phi_0}{2\pi I_c} C_j, \qquad \eta_j = \frac{\Phi_0}{2\pi I_c}\frac{1}{R_j}.$$

and the interferometer potential

$$v(\varphi_1,\varphi_2) =$$
$$1 - \cos\varphi_1 + 1 - \cos\varphi_2 - i(\varphi_1 + \varphi_2) + \frac{k}{2}(\varphi_1 - \varphi_2)^2.$$

$$i = \frac{I}{2I_c}, \qquad k = \frac{\hbar}{2\pi I_c}\frac{1}{L},$$

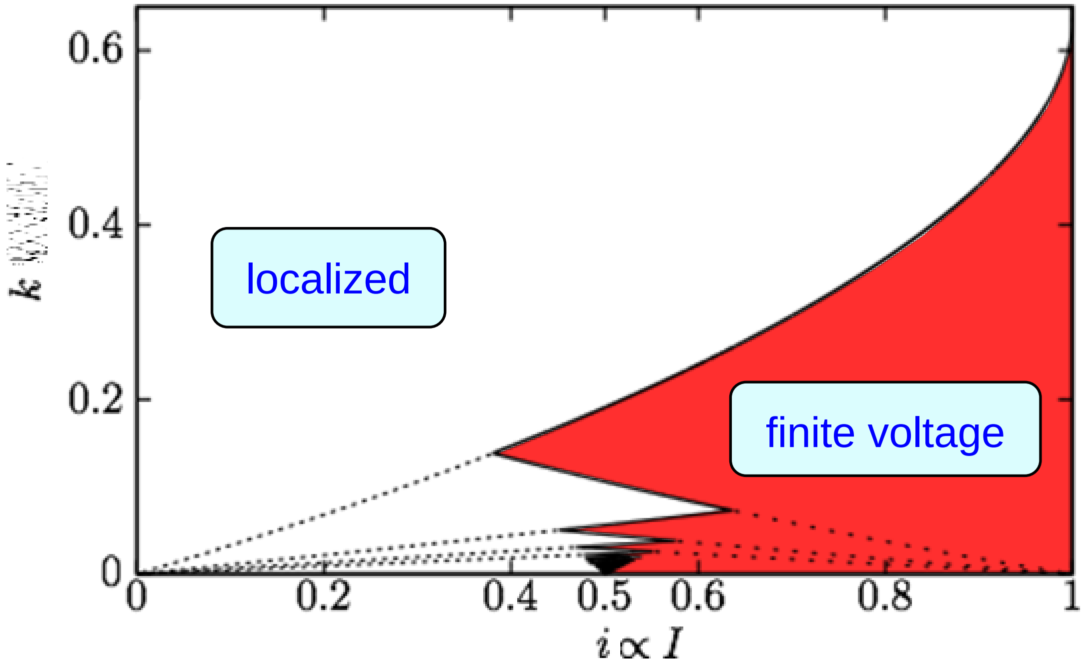


Two junctions in different regimes:

$$\frac{\hbar}{2e} I_c = E_J >> E_{c1} = \frac{e^2}{2C_1}$$ → classical regime

$$E_J \gtrsim E_{c2}$$ → quasi-classical regime

Phase diagram overdamped

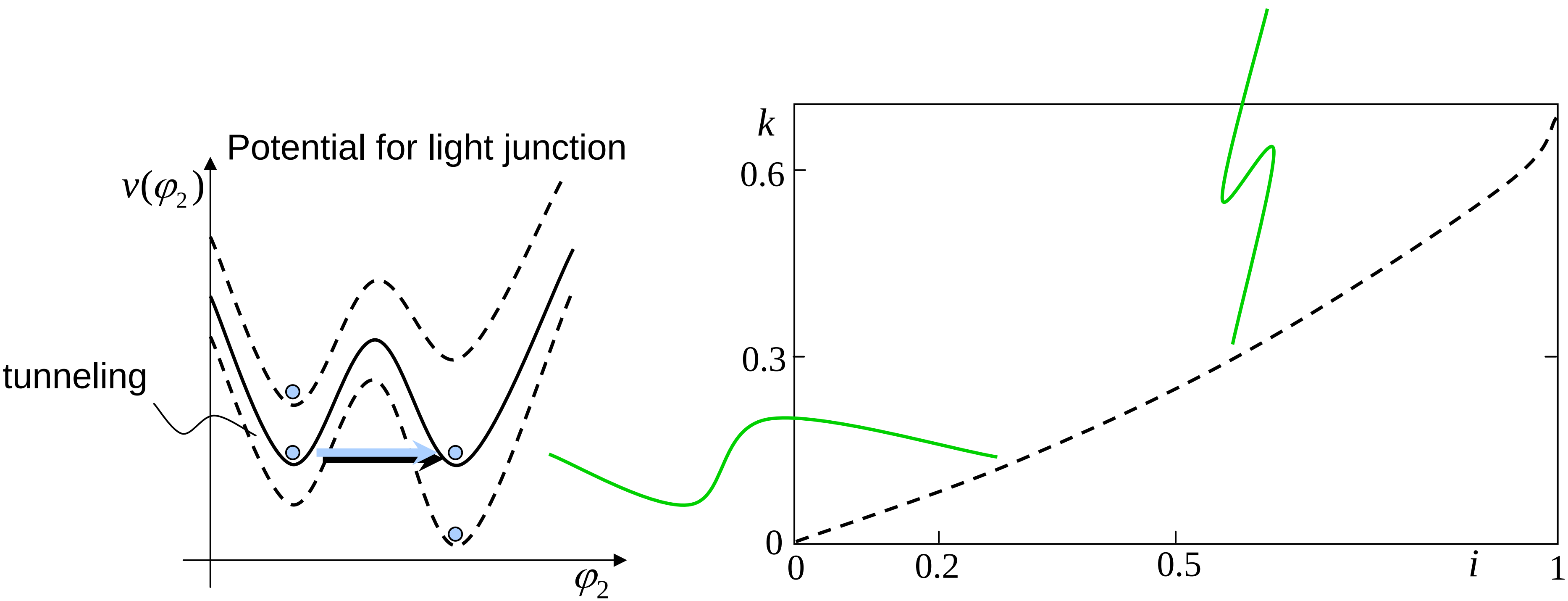


Phase diagram: Strong dissipation

$\alpha_2 = \eta_2 2\pi E_J / \hbar > 1.$ Strong dissipation for small junction.

- Total system is in given local minimum of 2d-SQUID potential.
- With increase of current i the next minimum for quantum junction is lowered below the original minimum.

$$k < i/(\pi - \arcsin i)$$



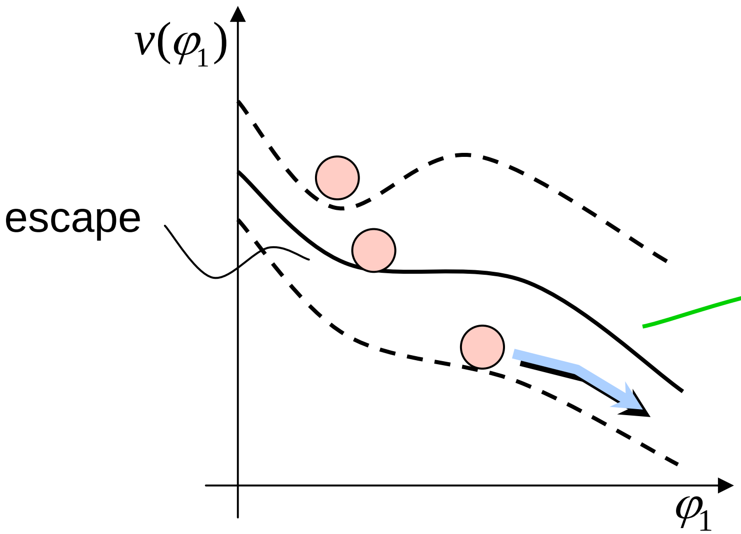
Phase diagram: Strong dissipation

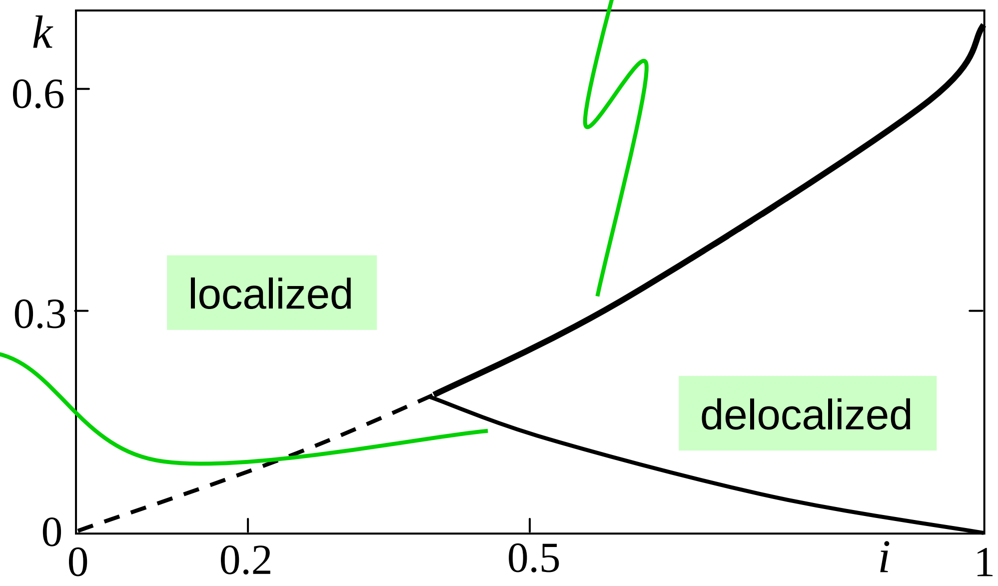
$\alpha_2 = \eta_2 2\pi E_J / \hbar > 1.$ Strong dissipation for small junction.

- Total system is in given local minimum of 2d-SQUID potential.
- Large junction is delocalized if minimum becomes unstable.

$$k < i/(\pi - \arcsin i)$$

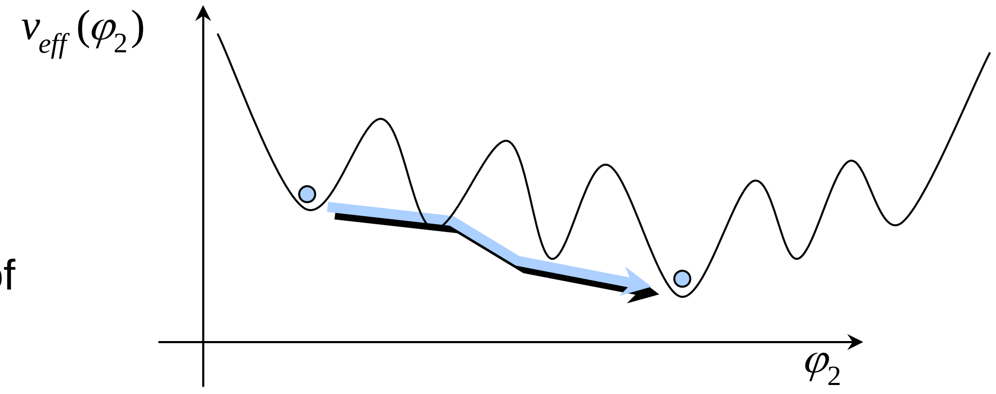
Potential for heavy junction

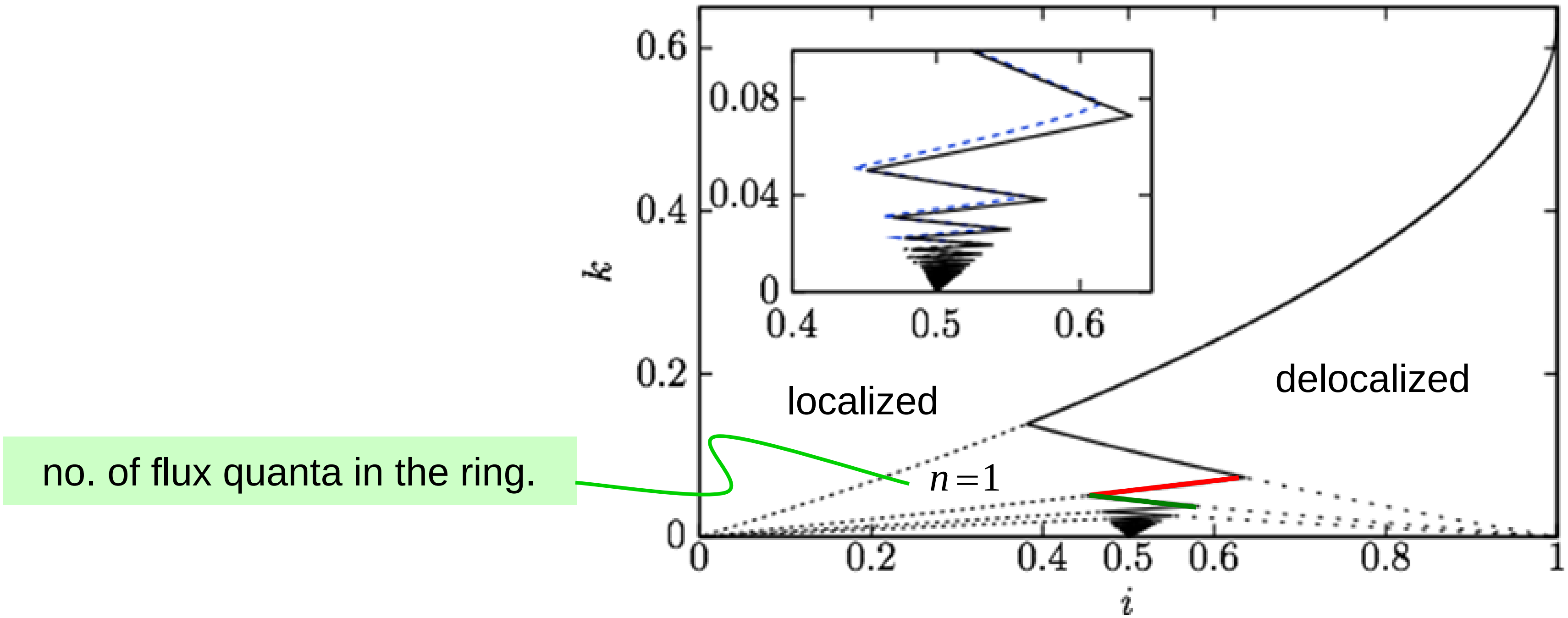




Phase diagram: Strong dissipation

- Every time weak junction tunnels flux enters inside the SQUID loop.
- Small junction will come to rest at global minimum of effective potential.
- Total system is in given local minimum of 2d-SQUID potential.
- Large junction is delocalized if minimum becomes unstable.





Decay process/phase diagram technical

Given i, k

How far can quantum junction tunnel?

Find largest n such that

$$k < \frac{i}{(2n-1)\pi - \arcsin i}$$

Can classical junction decay?

Modifications in numerical solutions.

n-th minimum is stable if

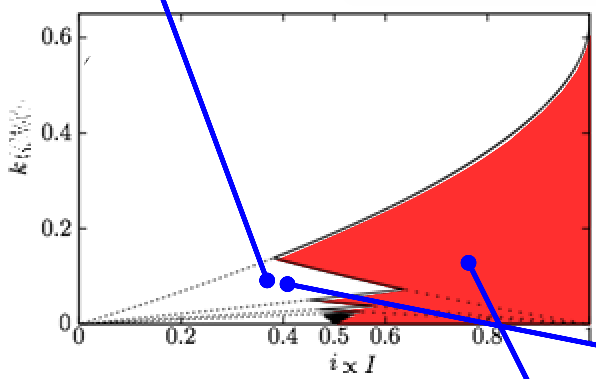
$$k < \frac{1-i}{(2n-1/2)\pi + \arcsin(2i-1)}$$

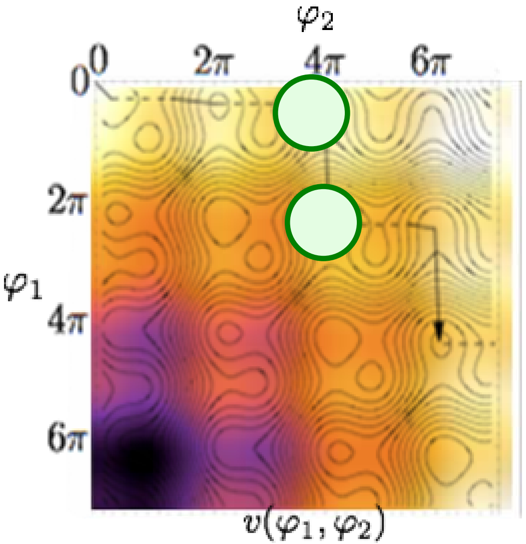
Localized state

n-th minimum is unstable if

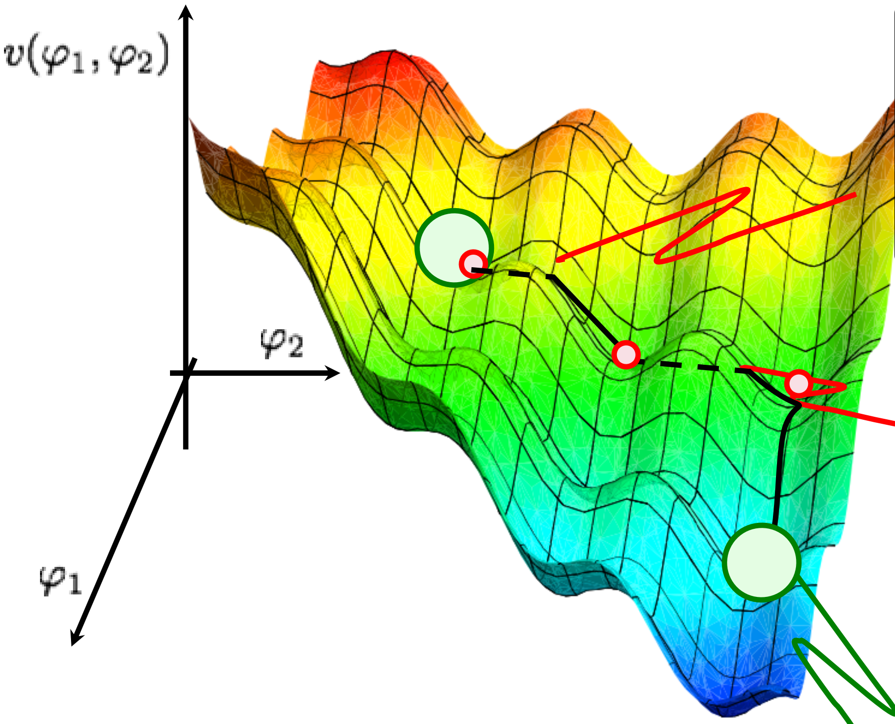
$$k > \frac{1-i}{(2n-1/2)\pi + \arcsin(2i-1)}$$

Finite voltage state

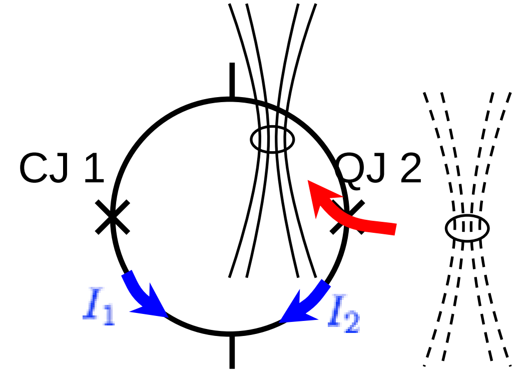




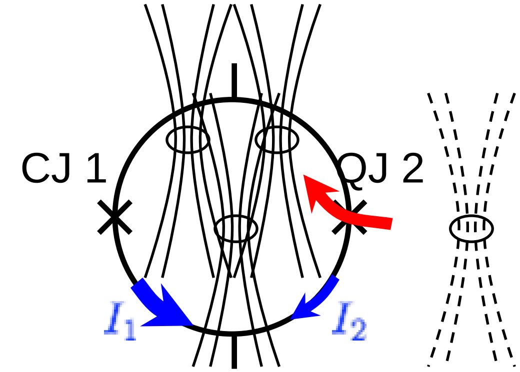
Decay process initial stage



Quantum tunneling of QJ, phase slip: Approximate flux unit enters.



More flux enters until ground state is reached.



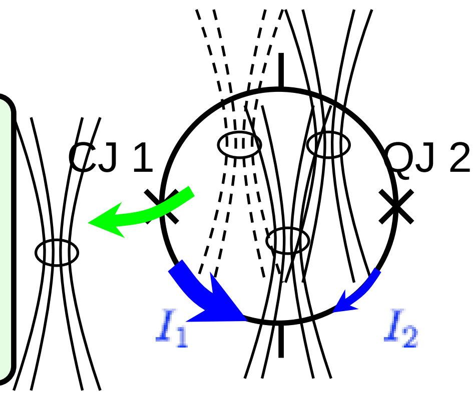
overdamped junctions:

$$\boxed{\alpha_1,\ \alpha_2 > 1}$$

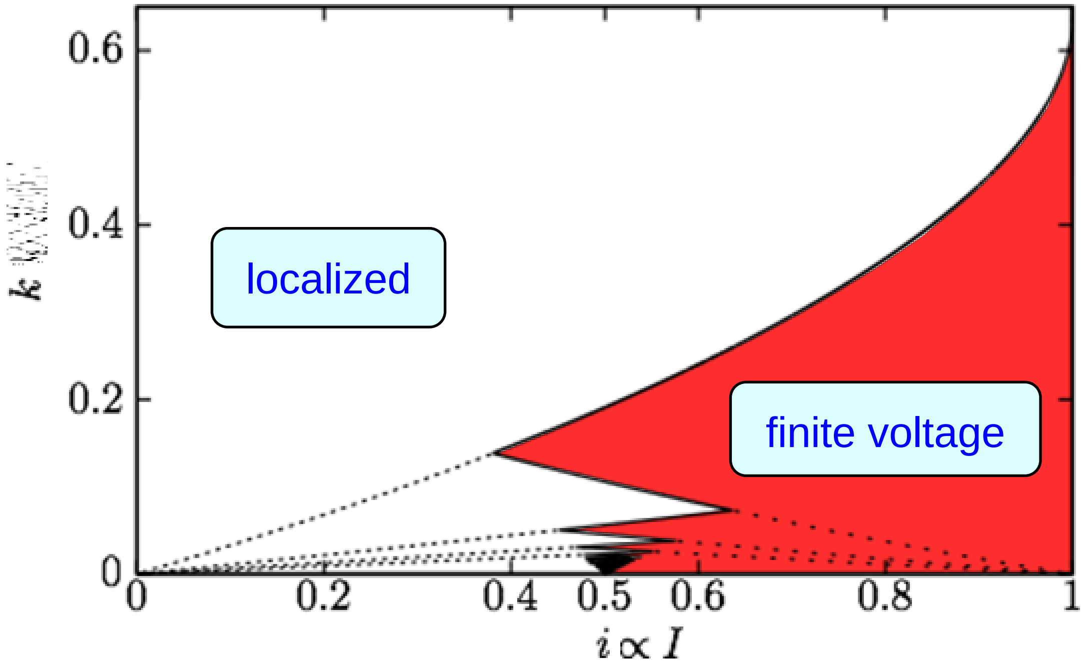
$$\alpha = (2RC\omega_p)^{-1}$$

$$\hbar^2\omega_p^2 = 8E_J E_c$$

CJ overcritical, flux leaves through CJ upon classical relaxation.



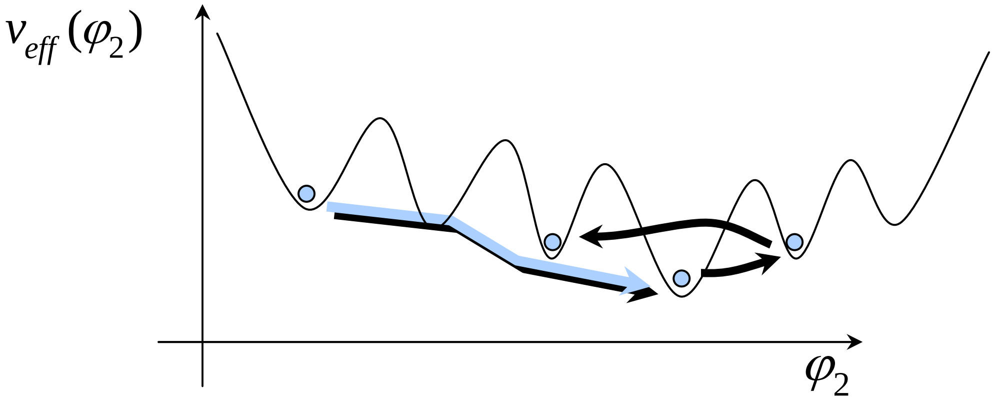
Phase diagram overdamped



Weak dissipation

$\alpha_2 = \eta_2 2\pi E_J / \hbar < 1.$ weak dissipation for small junction.

•Weak junction is delocalized between several wells



Massive dynamics fast ramping

- We consider instantaneous ramping

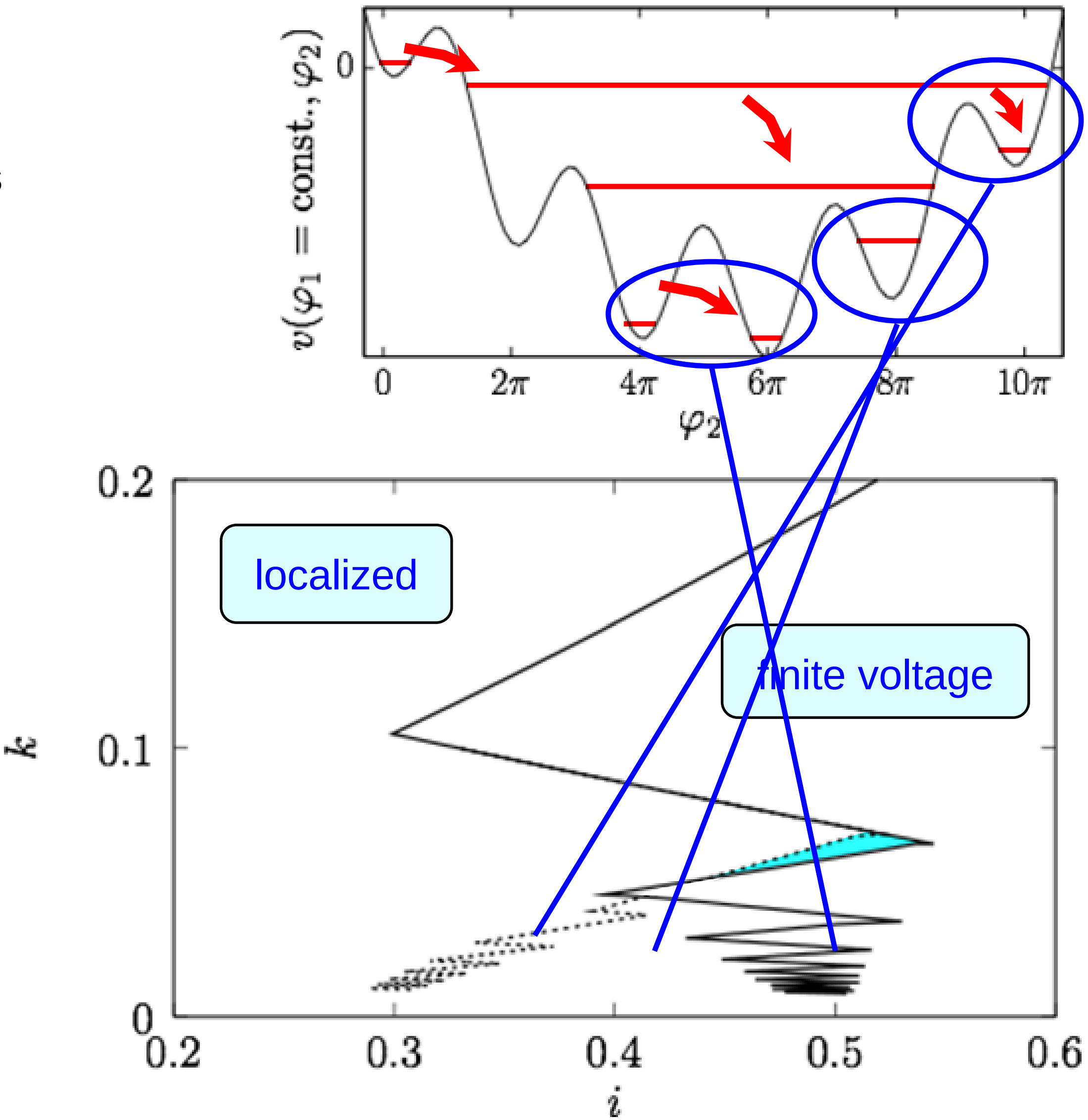
- Relevant residual dissipation: Assume relaxation in initial/side wells before decay of QJ (can be made consistent with experimental parameters).

- relevant time scales:

$$\Delta_2 \lesssim \omega_{p1} \ll \omega_{p2}.$$

➡ QJ may be trapped in any local minimum for a significant amount of time.

➡ smearing of decay line.



Parameters

RCSJ-model: Parameters:

“mass” $$m_j = \frac{\Phi_0 C_j}{2\pi c I_c}$$

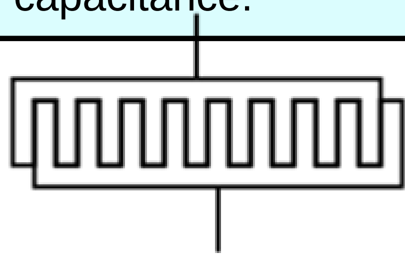
damping parameter $$\eta_j = \frac{\Phi_0}{2\pi c I_c R_j}$$

dimensionless bias current $$i = \frac{I}{2I_c}$$

coupling constant $$k = \frac{\Phi_0 c}{2\pi I_c L}$$

Realistic design:

- Two identical Josephson junctions, one of them shunted with large capacitance:



Realistic parameters:

$C_1 \approx 1\text{pF}$

$C_2 \approx 3\text{fF}$

$I_c \approx 550\text{nA}$

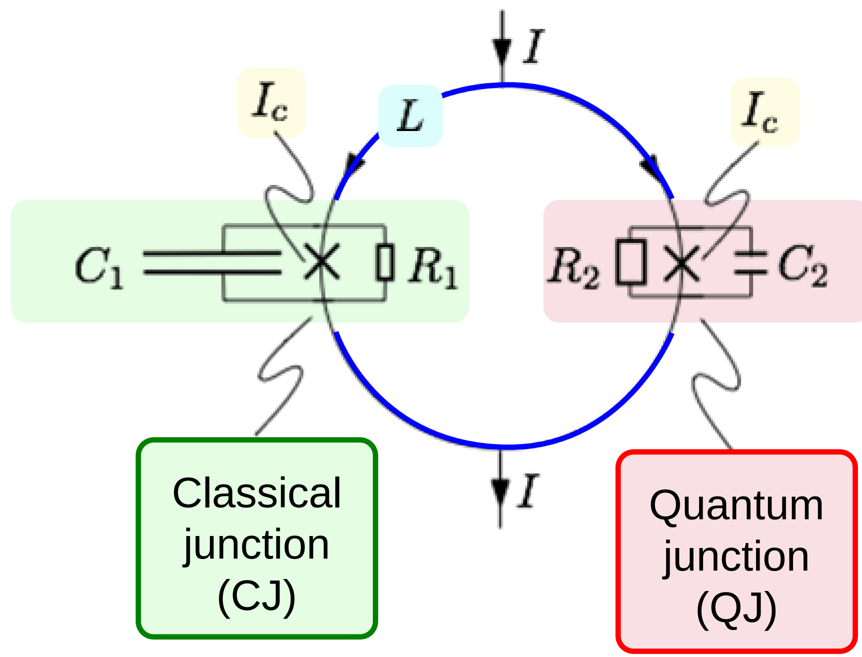
$L \approx 4 - 8\text{nH}$

$\Rightarrow$

$E_J/E_{c2} \approx 40$ (~ 4-5 levels)

$m_1/m_2 \approx 330$

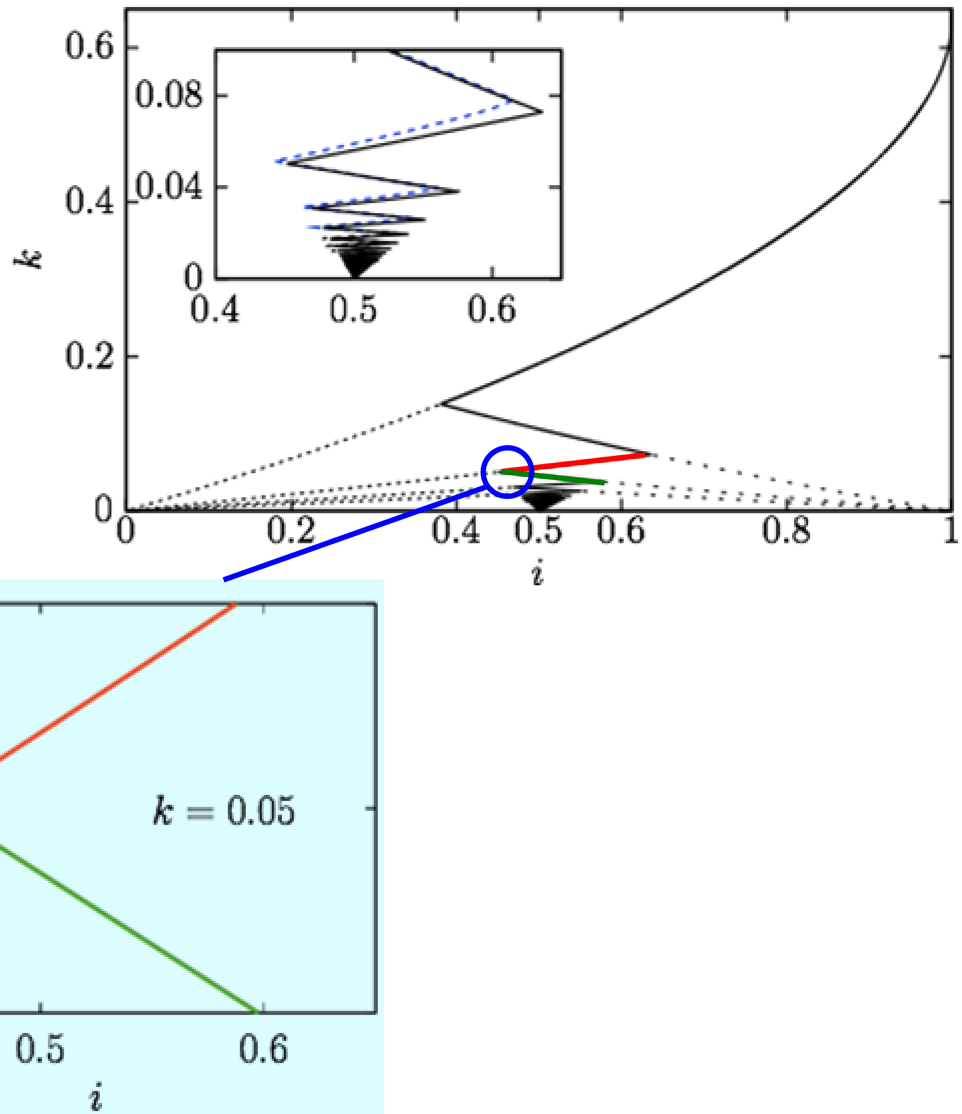
$k \approx 0.07 - 0.15$



Measurements tuning external flux

- Building many SQUIDS with different L is tedious.
- Tuning the externally applied magnetic flux Φ_e is easy.

➡ See one whole "tip" with a single device.

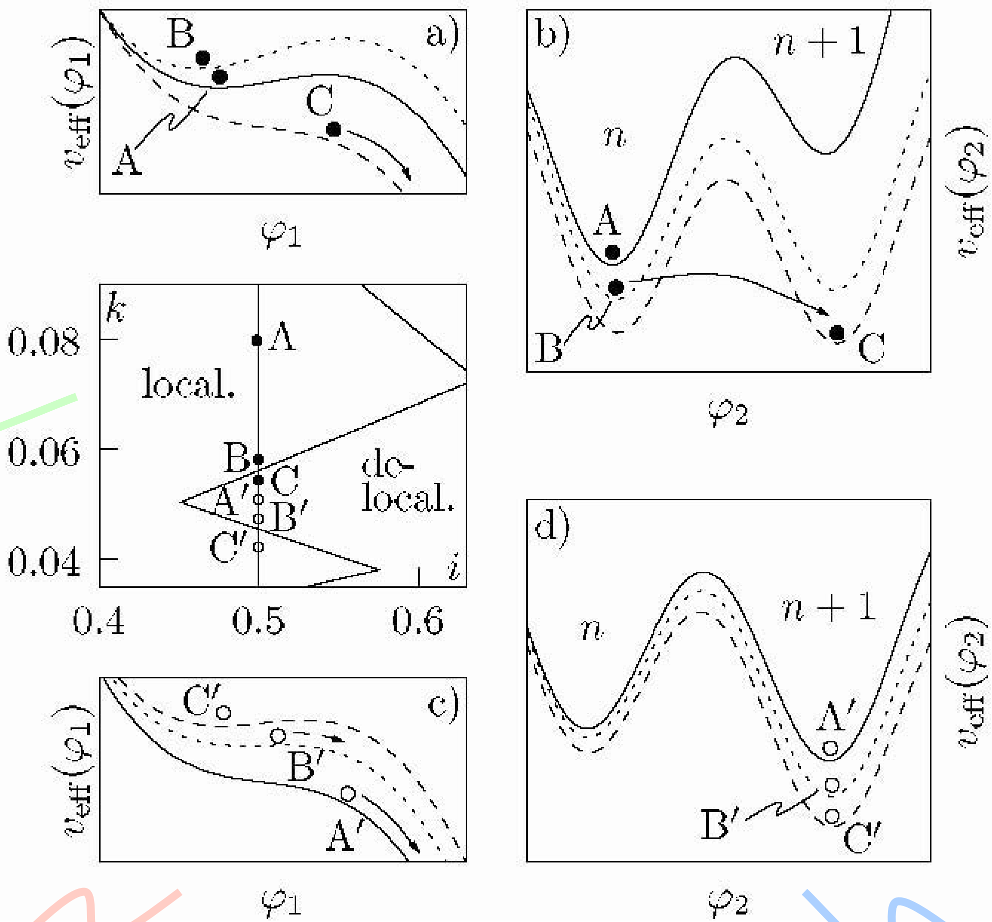


More insight

A Heavy junction localized.
B Barrier higher with lower k.
C Barrier is lowered by force of light junction, heavy junction escapes.

Extract from phase diagram.

A' Heavy junction delocalized
B' Barrier higher with reduced k.
C' Heavy junction is trapped again.



A Light junction at rest in minimum n.
B No change.
C As minimum n+1 is lowered, it eventually tunnels.

A' Light junction at rest in new global min. n+1.
B' No change.
C' No change.

Different cases

$\alpha_2 = \eta_2 2\pi E_J / \hbar > 1.$ Strong dissipation for small junction.

•Strong damping of heavy junction:

•Total system is in given local minimum of 2d-SQUID potential.

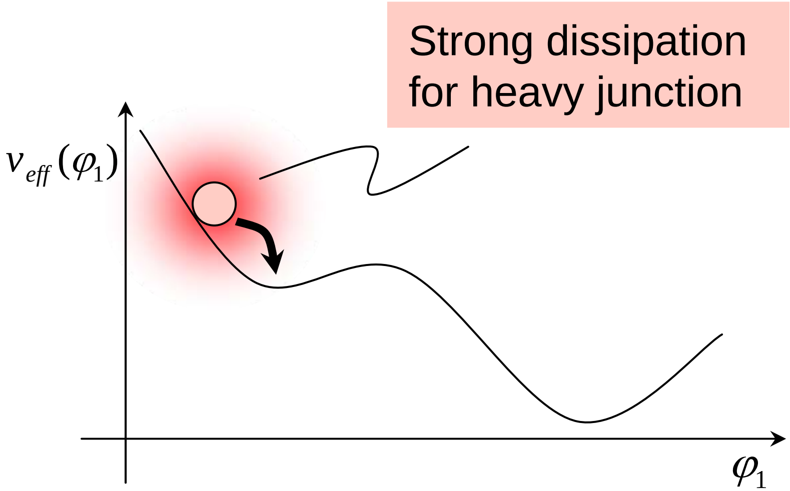
•Large junction is delocalized if minimum becomes unstable.

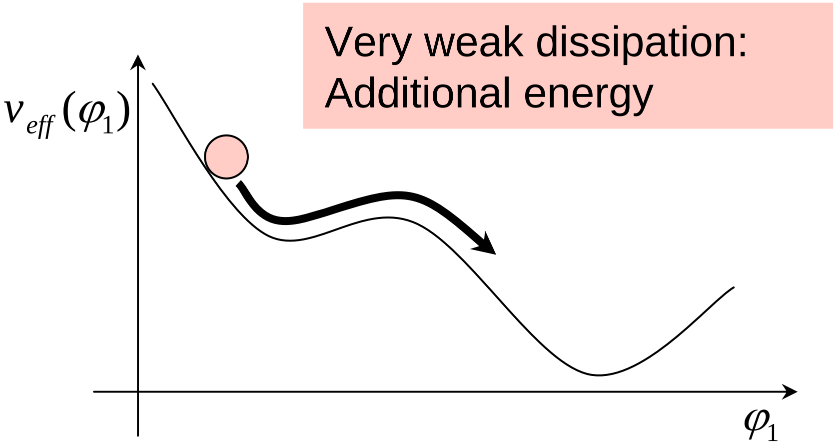
For very weak damping of heavy junction:

•Effective force of small junction lowers barrier for heavy junction,

•and shifts the local minimum.

•Heavy junction has additional initial energy (plasma oscillations), is delocalized at lower bias current.





Strong dissipation for small junction.

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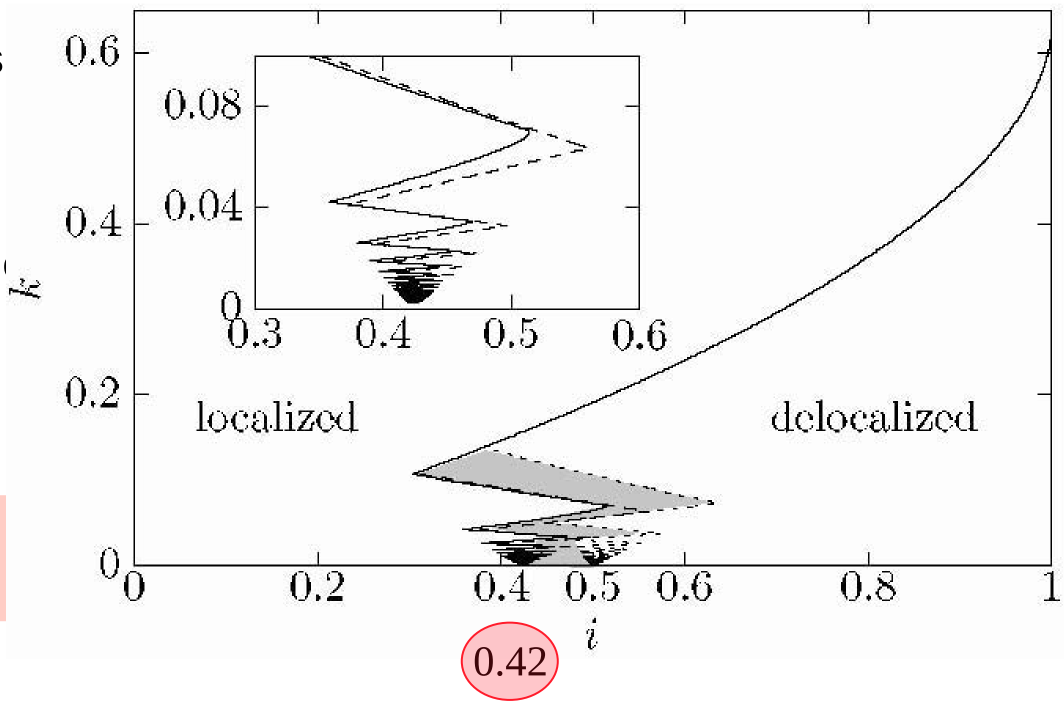
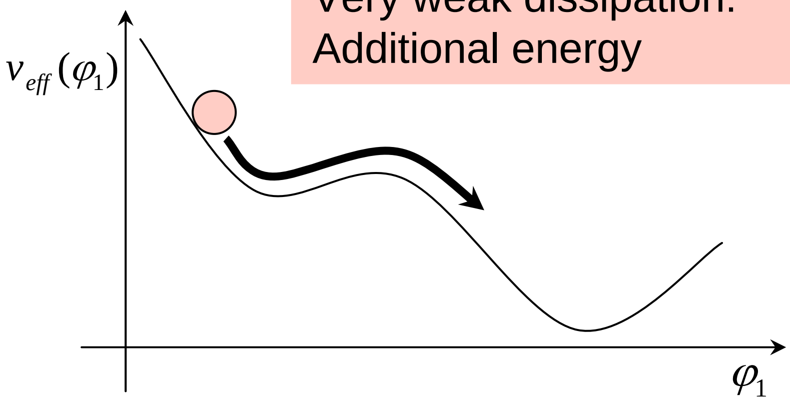


Very weak dissipation:
Additional energy



Summary and Outlook

SQUID with symmetric potential.

Junction 1 heavy/classical: No tunneling.

Junction 2 light/quasi-classical: Tunneling.

Small junction, after tunneling, exerts effective force on heavy junction.

For sufficiently high bias/sufficiently low inductance: Total SQUID in finite voltage state.

More general cases:

- Asymmetric critical currents.
- Geometrically asymmetric SQUIDS (asymmetric inductance).
- Additional external magnetic flux threading the ring (easily tunable parameter).

Other projects include:

- Detailed analysis of the low-dissipation case.