Quantum dynamics in nano Josephson junctions

Permanent:

Wiebke Guichard
Olivier Buisson
Frank Hekking
Laurent Lévy
Bernard Pannetier

CNRS – Université Joseph Fourier
Institut Néel- LP2MC
GRENOBLE

PhD:

Thomas Weissl
Etienne Dumur
Ioan Pop
Florent Lecocq
Aurélien Fay
Rapaël Léone
Nicolas Didier
Julien Claudon
Franck Balestro

Post-doc:

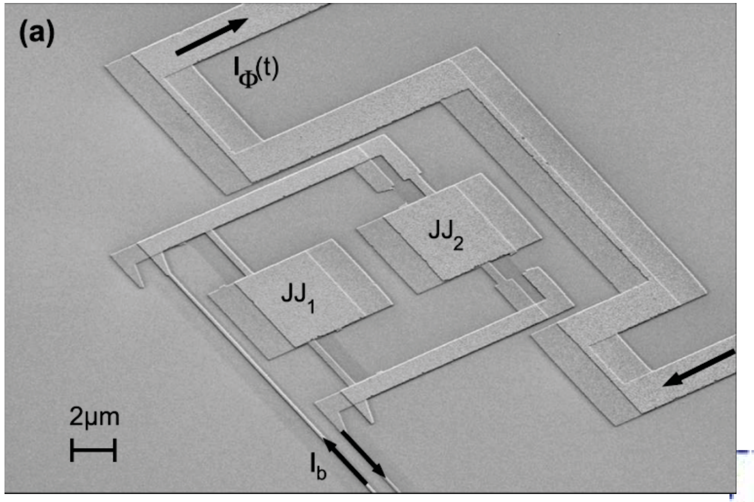
Alexey Feofanov
Iulian Matei
Zhihui Peng
Emile Hoskinson
Alex Zazunov

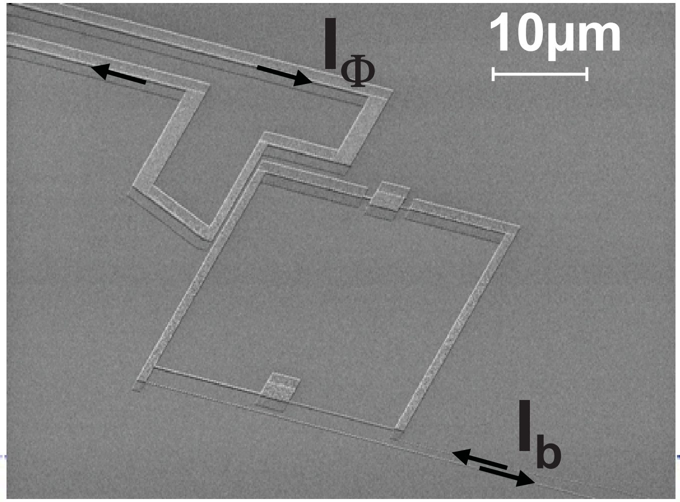
Scientific collaborations: PTB Braunschweig (Germany)
LTL Helsinki (Finland)
Rutgers (USA)

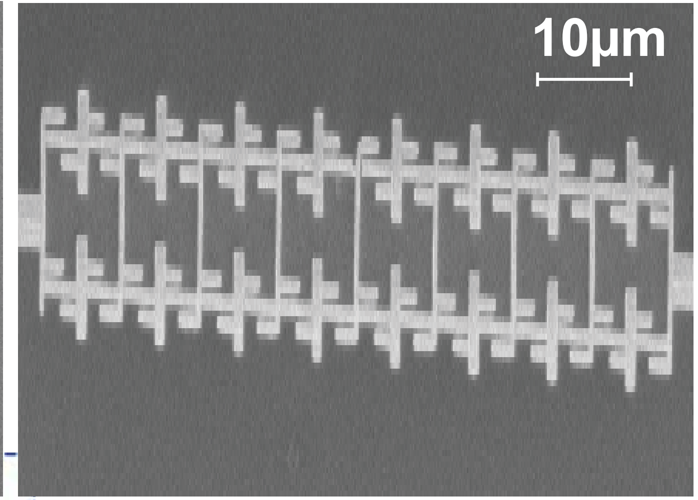
Projects: ANR QUNATJO

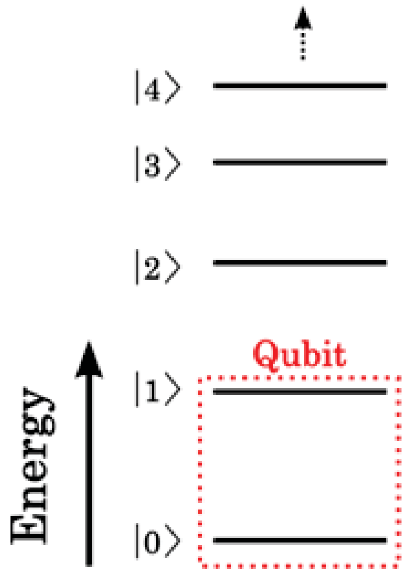
Introduction

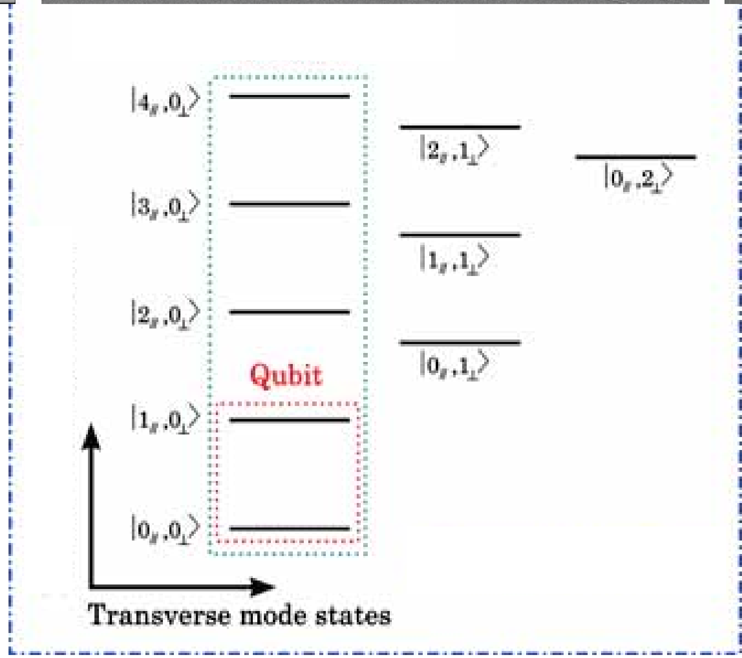
Multi-level quantum system	Two-degrees of freedom	Multi-degrees of freedom











New physics…

Outline

Two-degrees of freedom artificial atom

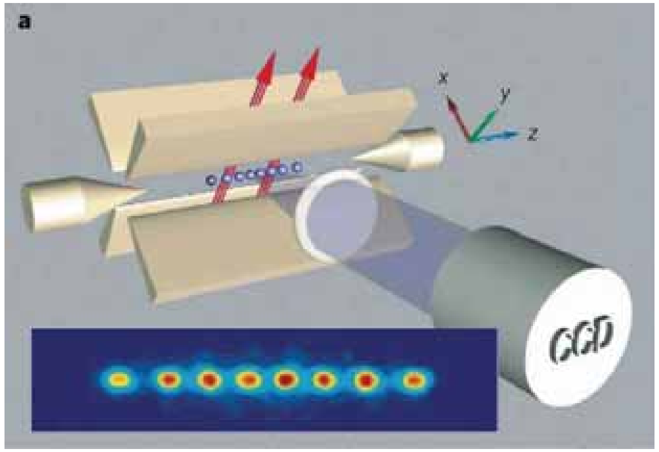
- inductive dc SQUID
- spectroscopy measurements
- strong non-linear coupling
- coherent oscillations

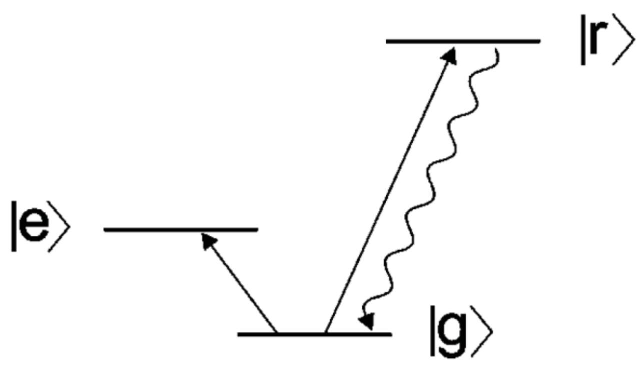
Multi-degrees of freedom system

- Josephson junction chains
- quantum phase slip
- charging effects

Motivations : two degrees of freedom

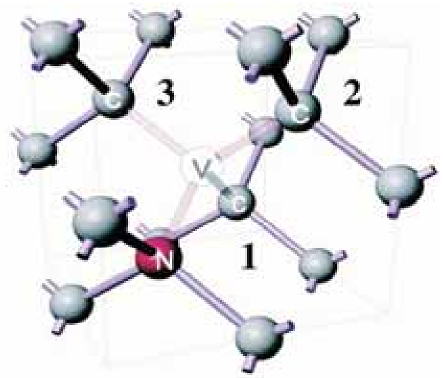
Trapped ion

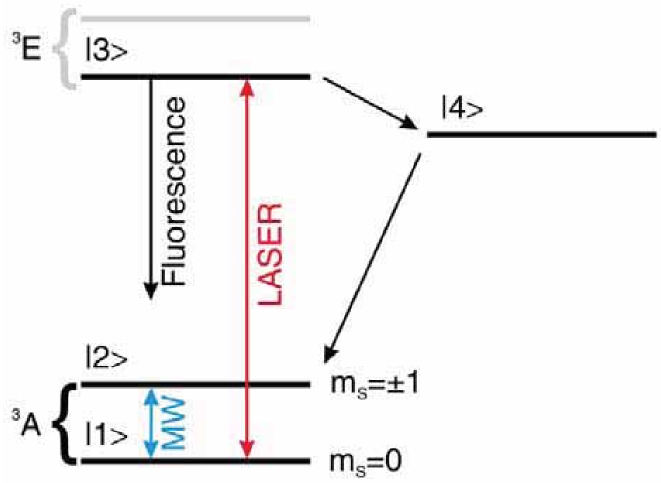




Leibfried, Rev.Mod.Phys (2003)
Blatt and Wineland, Nature (2008)

NV centers in diamond



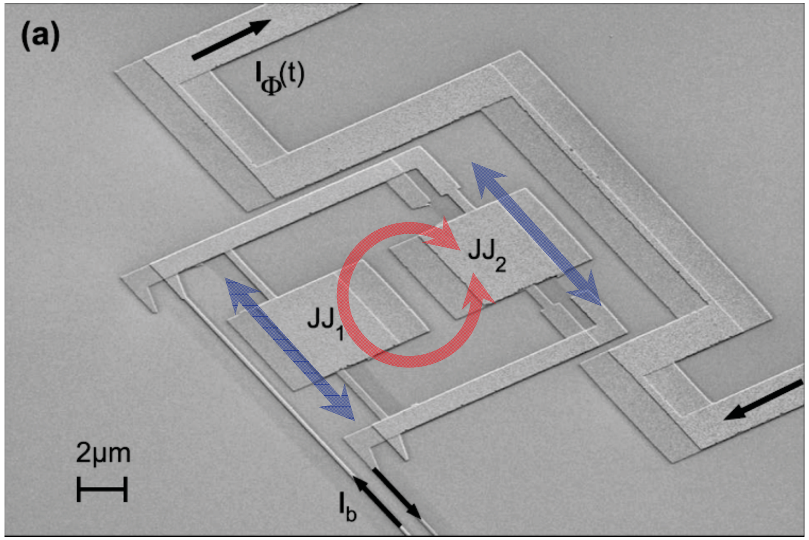


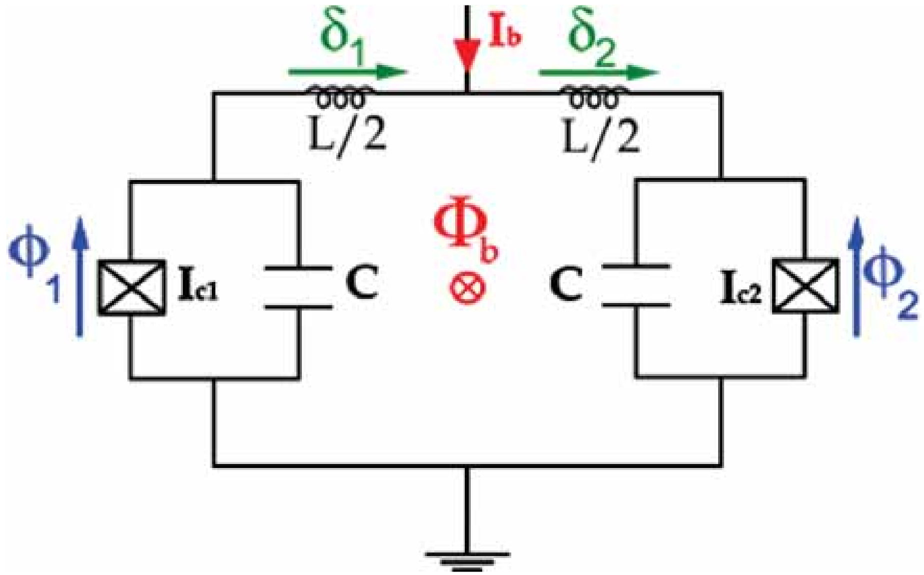
Jelezko et al, PRL (2004)

High fidelity readout & Electromagnetically Induced Transparency

Superconducting artificial atom with multiple degrees of freedom ?

Modes of oscillations



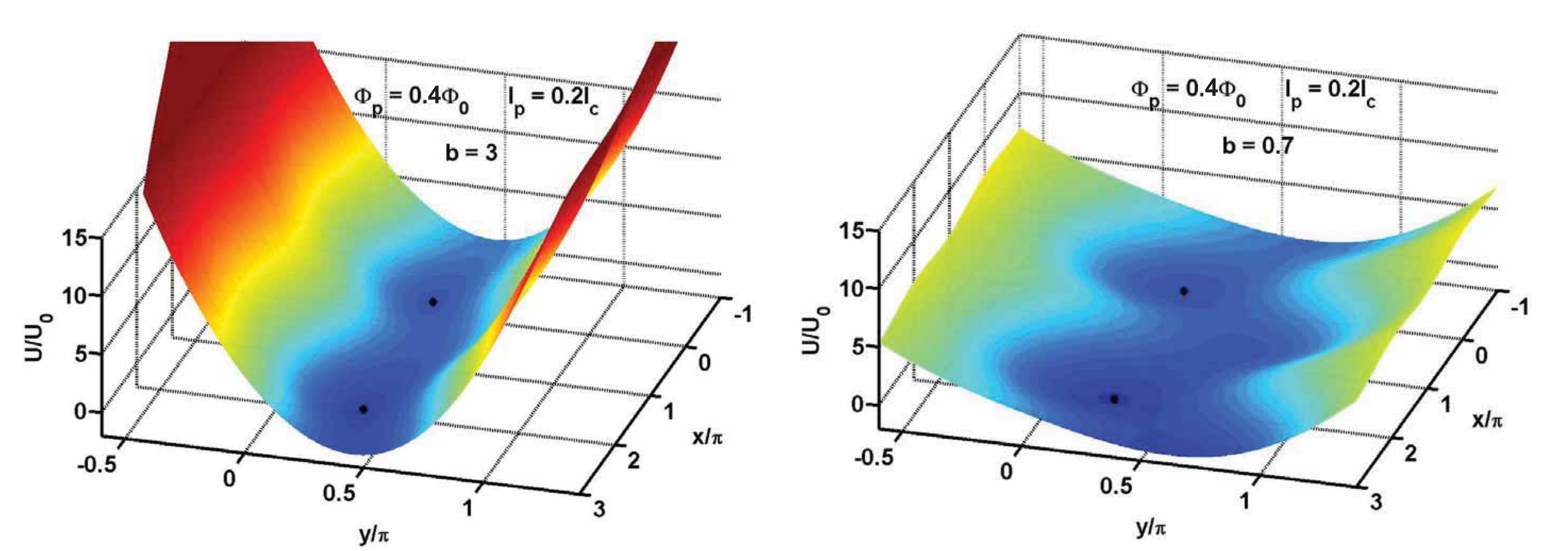


$$\mathbf{U(x,y) = U_0\left[-\cos x \cos y + b(y - \pi\frac{\Phi_b}{\Phi_0})^2\right]}$$ where $$\left\{ x = \frac{\phi_1+\phi_2}{2} \right.$$

$$\mathbf{b = \frac{L_J}{L} = \frac{\Phi_0}{2\pi L I_c}}$$

Parameter of dimensionality

$$\mathbf{U(x,y)} = \mathbf{U_0}\left[-\cos \mathbf{x} \cos \mathbf{y} + \mathbf{b}\left(\mathbf{y} - \pi\frac{\mathbf{\Phi_b}}{\mathbf{\Phi_0}}\right)^2 - \frac{\mathbf{I_b}}{\mathbf{2I_c}}\mathbf{x}\right] \quad \text{where} \quad \begin{cases} x = \frac{\phi_1+\phi_2}{2} \\ y = \frac{\phi_1-\phi_2}{2} \end{cases}$$

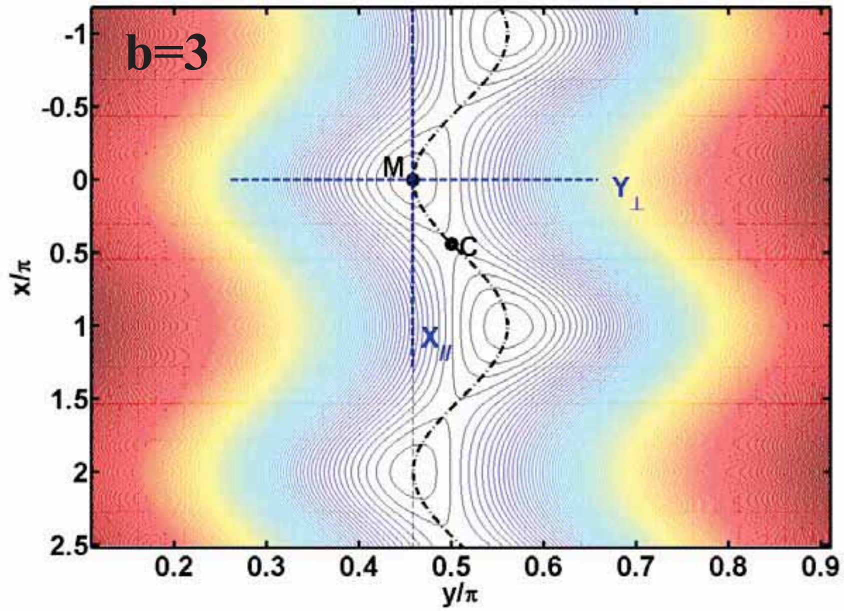


$L < L_{\text{josephson}}$ $(b > 1)$

$L > L_{\text{josephson}}$ $(b < 1)$

$$\mathbf{b} = \frac{\mathbf{L_J}}{\mathbf{L}} = \frac{\mathbf{\Phi_0}}{\mathbf{2\pi L I_c}}$$

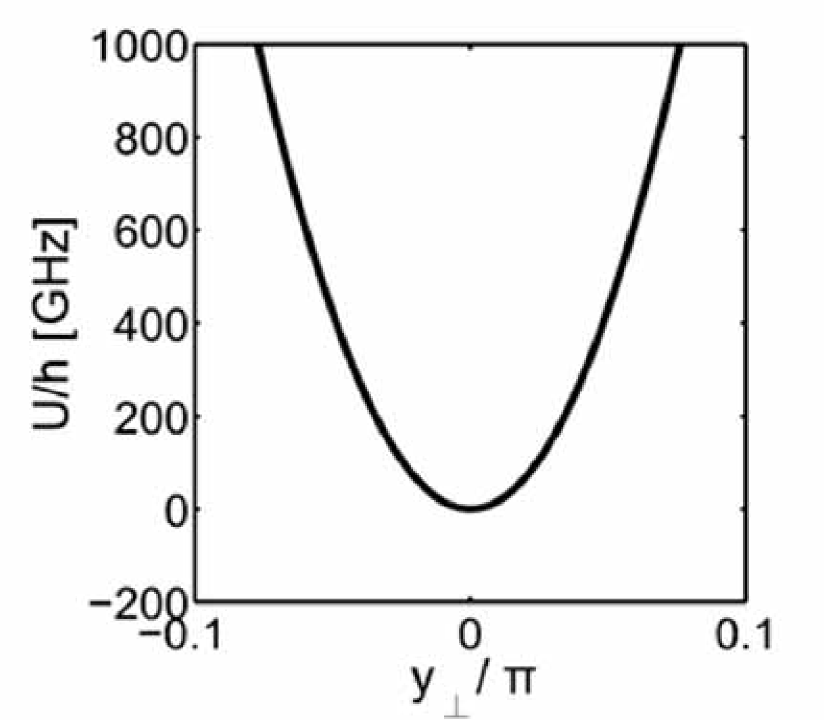
Dynamics close to a minimum

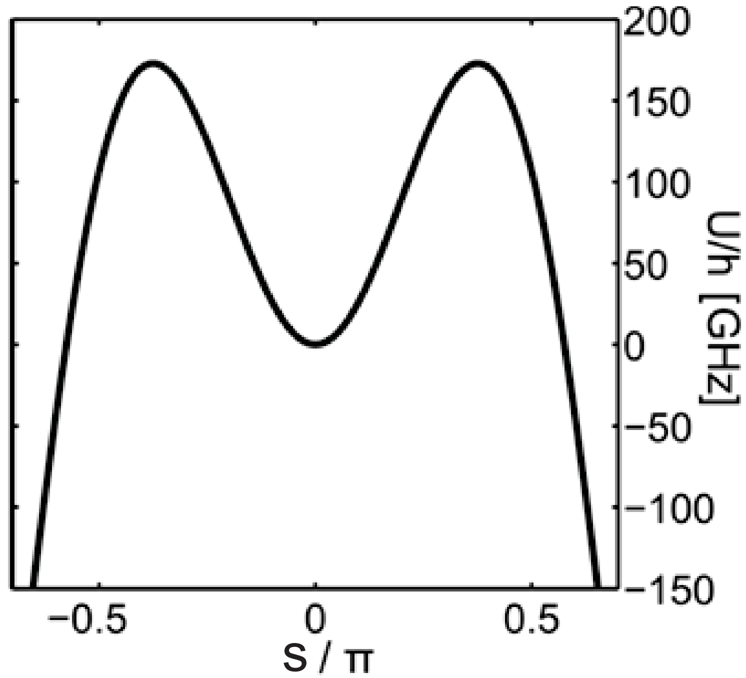


Expansion in X and Y directions :

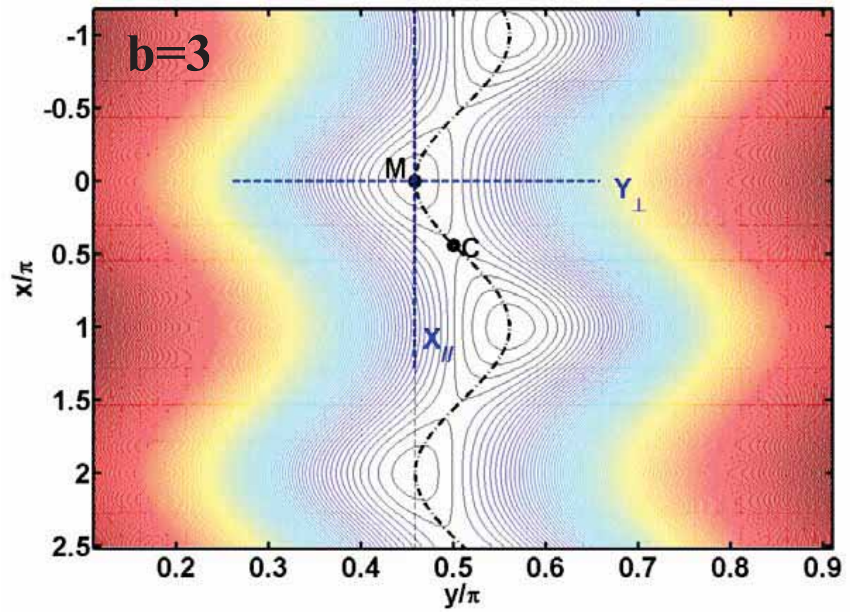
$$\hat{H}^0_{2D} = \hat{H}_{\parallel} + \hat{C}_{\parallel\perp} + \hat{H}_{\perp}$$

$$\begin{cases} \hat{H}_{\parallel} = \frac{1}{2}h\nu_{\parallel}\left(\hat{P}^2_{\parallel} + \hat{X}^2_{\parallel}\right) - h\nu_{\parallel}\sigma_{\parallel}\hat{X}^3_{\parallel} - h\nu_{\parallel}\delta_{\parallel}\hat{X}^4_{\parallel} \\ \hat{H}_{\perp} = \frac{1}{2}h\nu_{\perp}\left(\hat{P}^2_{\perp} + \hat{Y}^2_{\perp}\right) - h\nu_{\perp}\sigma_{\perp}\hat{Y}^3_{\perp} - h\nu_{\perp}\delta_{\perp}\hat{Y}^4_{\perp} \\ \hat{C}_{\parallel\perp} = h\nu^c_{21}\hat{X}^2_{\parallel}\hat{Y}_{\perp} + h\nu^c_{12}\hat{X}_{\parallel}\hat{Y}^2_{\perp} + h\nu^c_{22}\hat{X}^2_{\parallel}\hat{Y}^2_{\perp} \\ \qquad + h\nu^c_{31}\hat{X}^3_{\parallel}\hat{Y}_{\perp} + h\nu^c_{13}\hat{X}_{\parallel}\hat{Y}^3_{\perp} \end{cases}$$





Dynamics close to a minimum



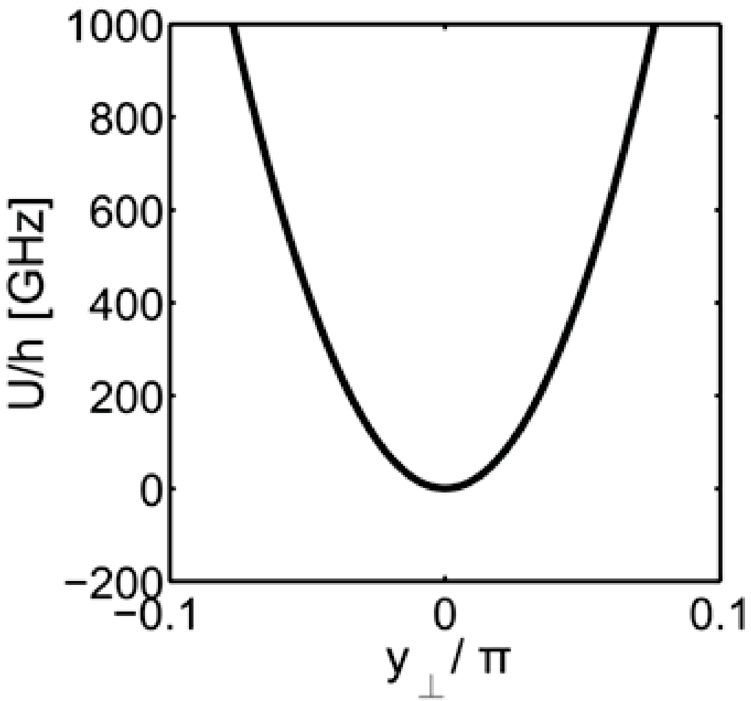
Expansion in X and Y directions :

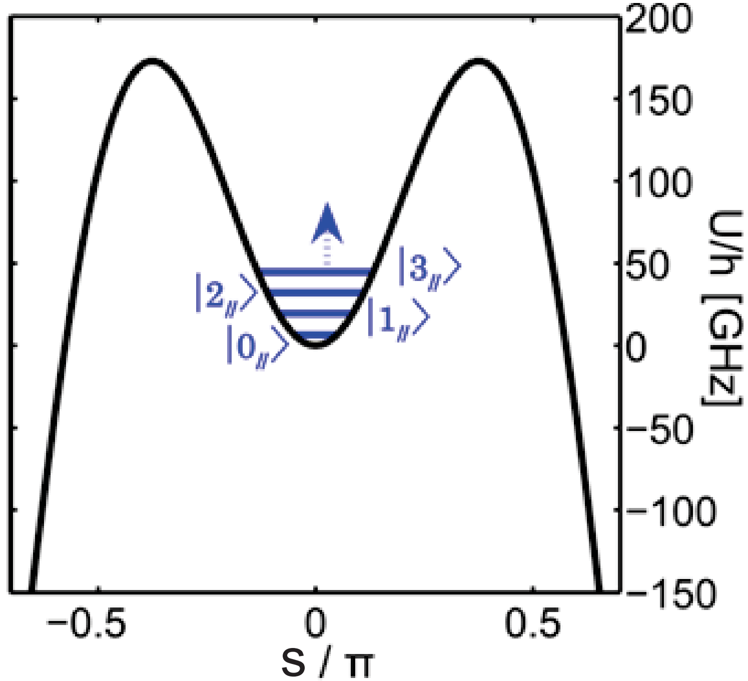
$$\hat{H}^0_{2D} = \hat{H}_{\parallel} + \hat{C}_{\parallel\perp} + \hat{H}_{\perp}$$

$$\hat{H}_{\parallel} = \frac{1}{2}h\nu_{\parallel}\left(\hat{P}^2_{\parallel} + \hat{X}^2_{\parallel}\right) - h\nu_{\parallel}\sigma_{\parallel}\hat{X}^3_{\parallel} - h\nu_{\parallel}\delta_{\parallel}\hat{X}^4_{\parallel}$$

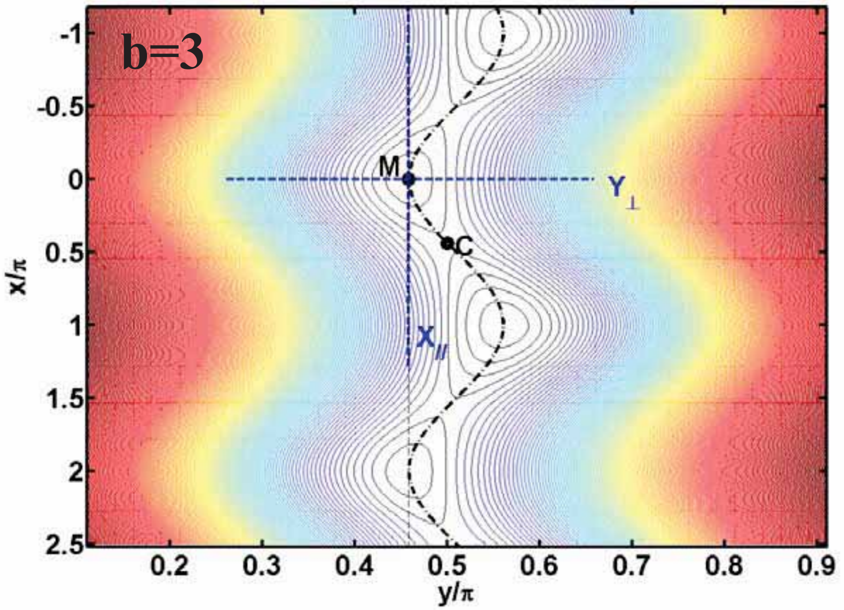
$$\hat{H}_{\perp} = \frac{1}{2}h\nu_{\perp}\left(\hat{P}^2_{\perp} + \hat{Y}^2_{\perp}\right) - h\nu_{\perp}\sigma_{\perp}\hat{Y}^3_{\perp} - h\nu_{\perp}\delta_{\perp}\hat{Y}^4_{\perp}$$

$$\hat{C}_{\parallel\perp} = h\nu^c_{21}\hat{X}^2_{\parallel}\hat{Y}_{\perp} + h\nu^c_{12}\hat{X}_{\parallel}\hat{Y}^2_{\perp} + h\nu^c_{22}\hat{X}^2_{\parallel}\hat{Y}^2_{\perp} + h\nu^c_{31}\hat{X}^3_{\parallel}\hat{Y}_{\perp} + h\nu^c_{13}\hat{X}_{\parallel}\hat{Y}^3_{\perp}$$





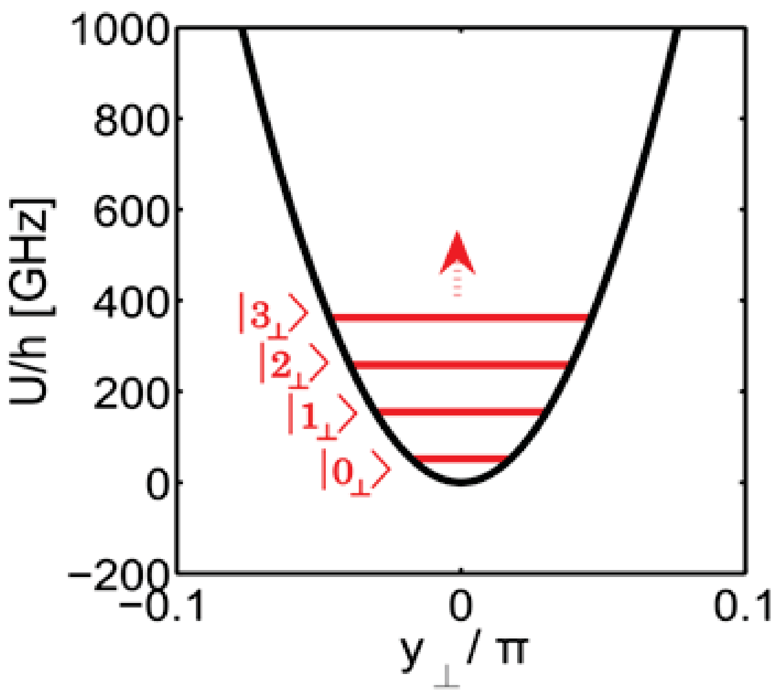
Dynamics close to a minimum

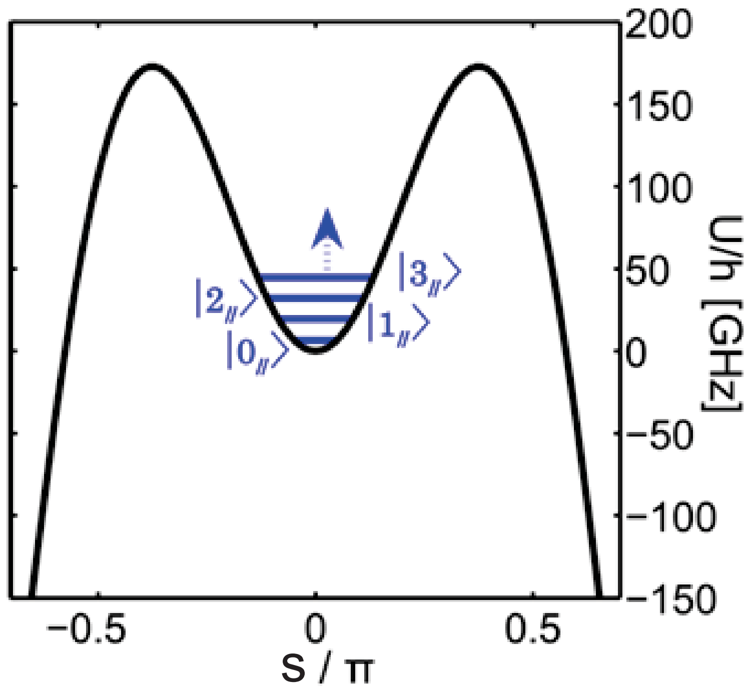


Expansion in X and Y directions :

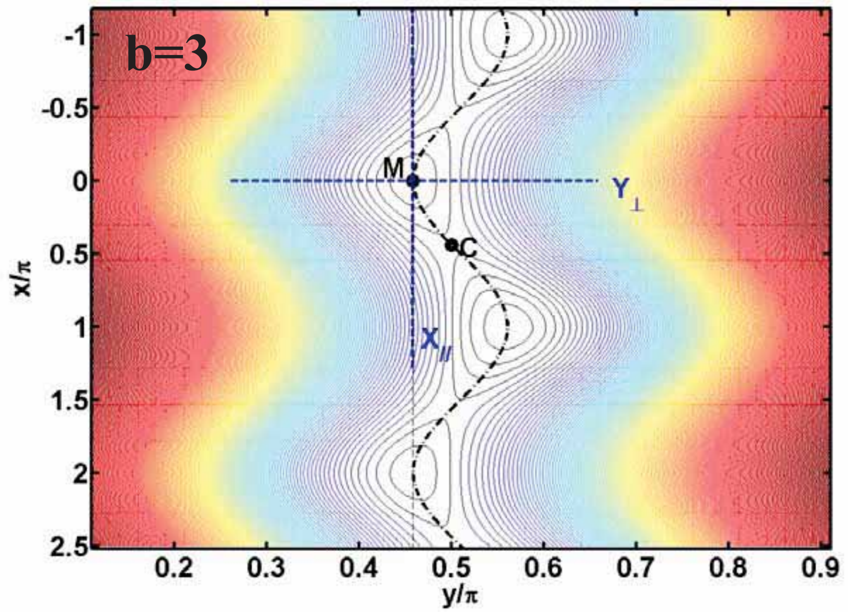
$$\hat{H}^0_{2D} = \hat{H}_\parallel + \hat{C}_{\parallel\perp} + \hat{H}_\perp$$

$$\begin{cases} \hat{H}_\parallel = \frac{1}{2}h\nu_\parallel \left(\hat{P}^2_\parallel + \hat{X}^2_\parallel\right) - h\nu_\parallel\sigma_\parallel\hat{X}^3_\parallel - h\nu_\parallel\delta_\parallel\hat{X}^4_\parallel \\ \hat{H}_\perp = \frac{1}{2}h\nu_\perp \left(\hat{P}^2_\perp + \hat{Y}^2_\perp\right) - h\nu_\perp\sigma_\perp\hat{Y}^3_\perp - h\nu_\perp\delta_\perp\hat{Y}^4_\perp \\ \hat{C}_{\parallel\perp} = h\nu^c_{21}\hat{X}^2_\parallel\hat{Y}_\perp + h\nu^c_{12}\hat{X}_\parallel\hat{Y}^2_\perp + h\nu^c_{22}\hat{X}^2_\parallel\hat{Y}^2_\perp \\ \qquad + h\nu^c_{31}\hat{X}^3_\parallel\hat{Y}_\perp + h\nu^c_{13}\hat{X}_\parallel\hat{Y}^3_\perp \end{cases}$$





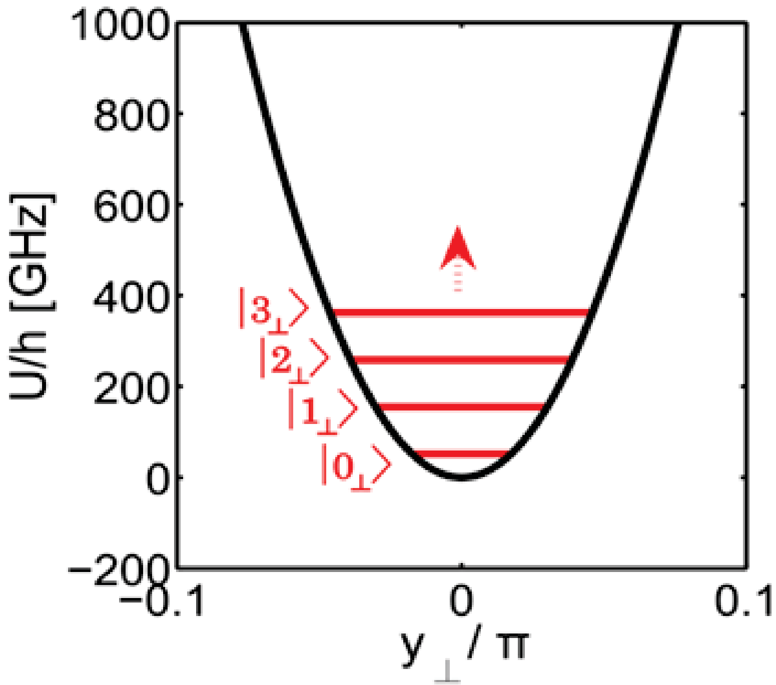
Dynamics close to a minimum



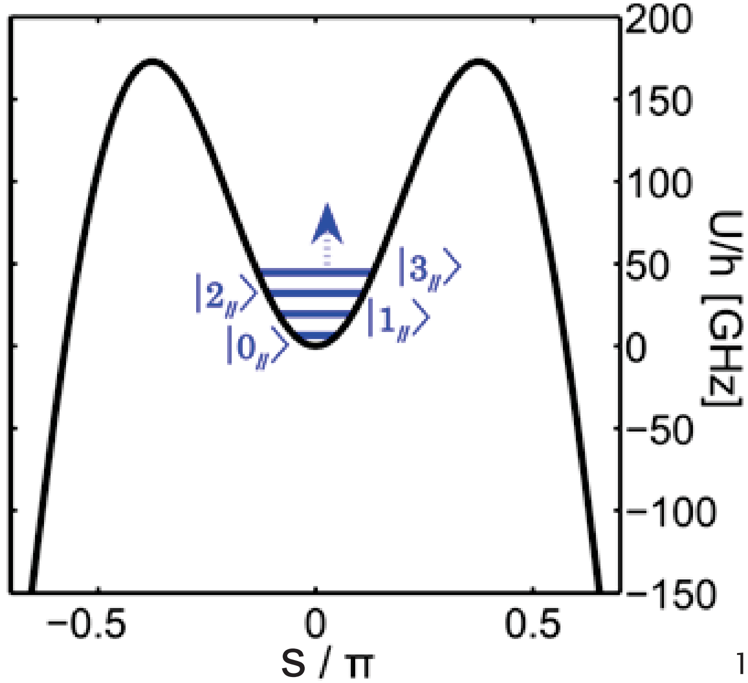
Expansion in X and Y directions :

$$\hat{H}^0_{2D} = \hat{H}_{\parallel} + \hat{C}_{\parallel\perp} + \hat{H}_{\perp}$$

$$\left\{\begin{aligned}
\hat{H}_{\parallel} &= \tfrac{1}{2}h\nu_{\parallel}\left(\hat{P}^2_{\parallel} + \hat{X}^2_{\parallel}\right) - h\nu_{\parallel}\sigma_{\parallel}\hat{X}^3_{\parallel} - h\nu_{\parallel}\delta_{\parallel}\hat{X}^4_{\parallel} \\
\hat{H}_{\perp} &= \tfrac{1}{2}h\nu_{\perp}\left(\hat{P}^2_{\perp} + \hat{Y}^2_{\perp}\right) - h\nu_{\perp}\sigma_{\perp}\hat{Y}^3_{\perp} - h\nu_{\perp}\delta_{\perp}\hat{Y}^4_{\perp} \\
\hat{C}_{\parallel\perp} &= h\nu^c_{21}\hat{X}^2_{\parallel}\hat{Y}_{\perp} + h\nu^c_{12}\hat{X}_{\parallel}\hat{Y}^2_{\perp} + h\nu^c_{22}\hat{X}^2_{\parallel}\hat{Y}^2_{\perp} \\
&\quad + h\nu^c_{31}\hat{X}^3_{\parallel}\hat{Y}_{\perp} + h\nu^c_{13}\hat{X}_{\parallel}\hat{Y}^3_{\perp}
\end{aligned}\right.$$



$\otimes$

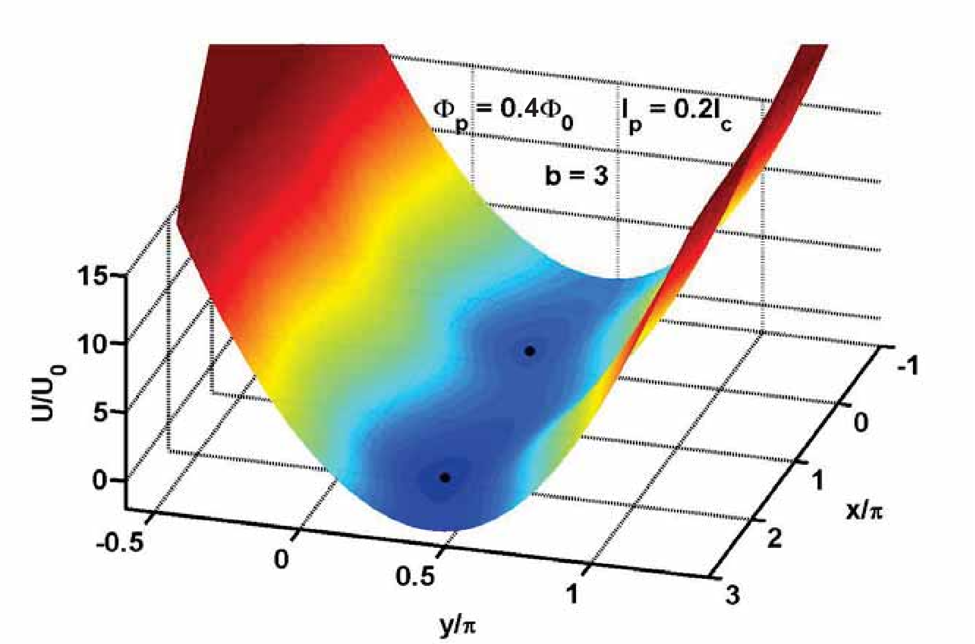


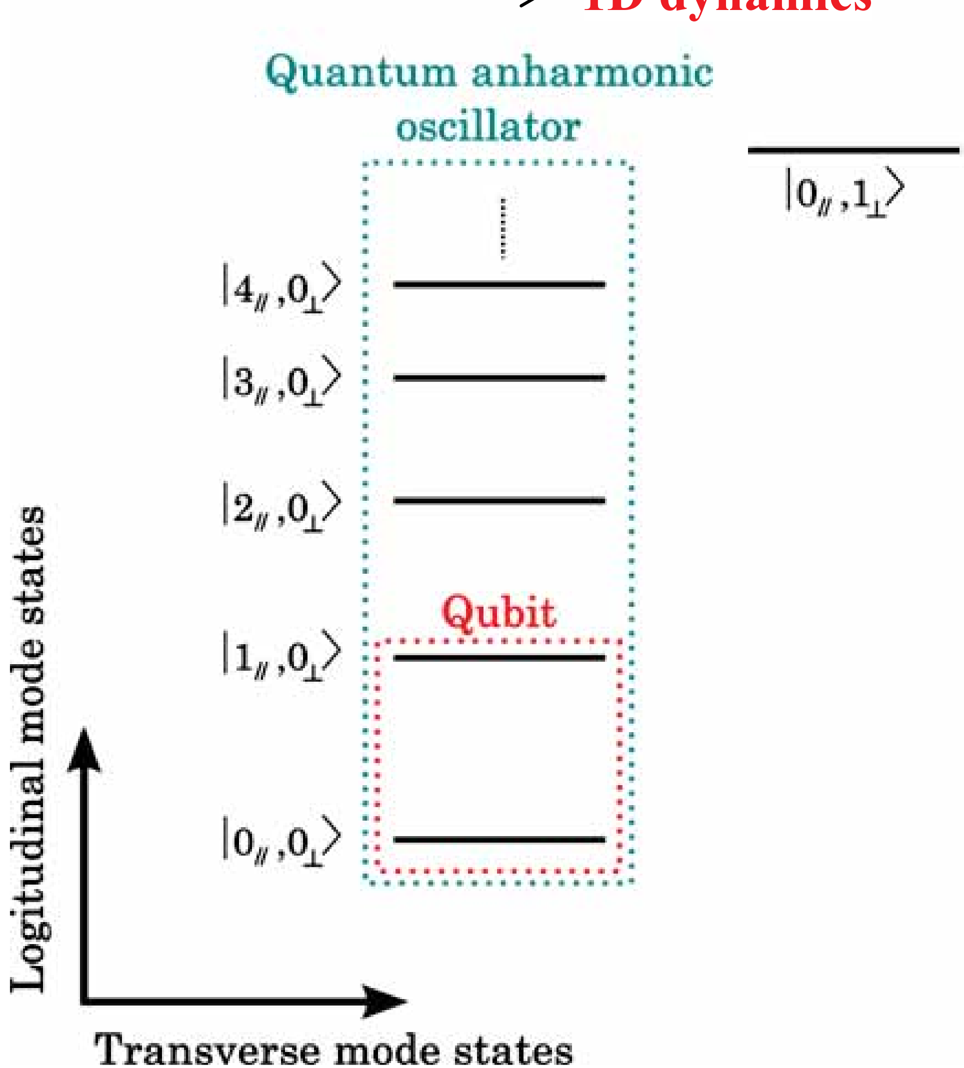
From a phase qubit …

L < L josephson → Transverse mode high in energy

→ Considered in the ground state

→ **1D dynamics**





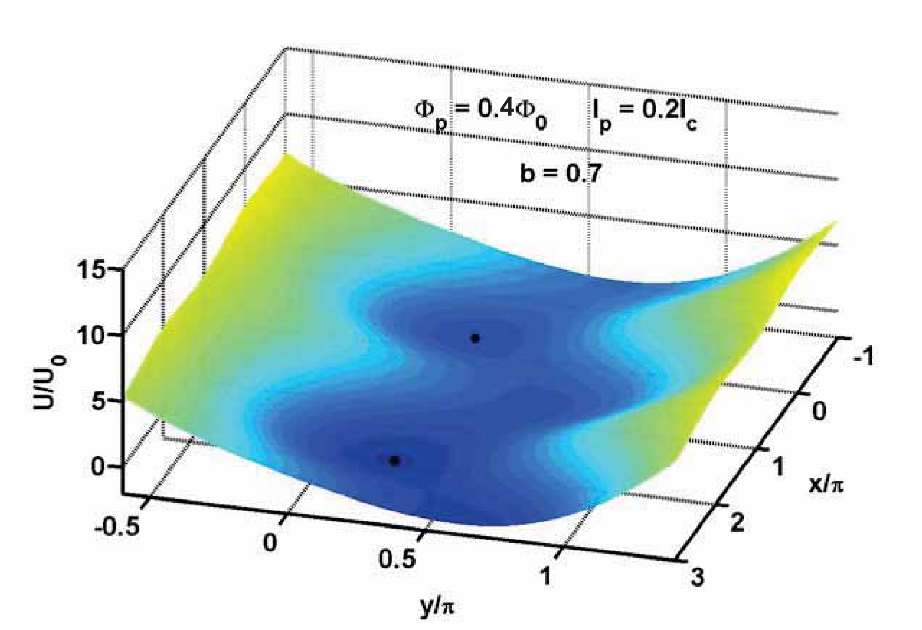
Claudon, et al , PRL, 2004

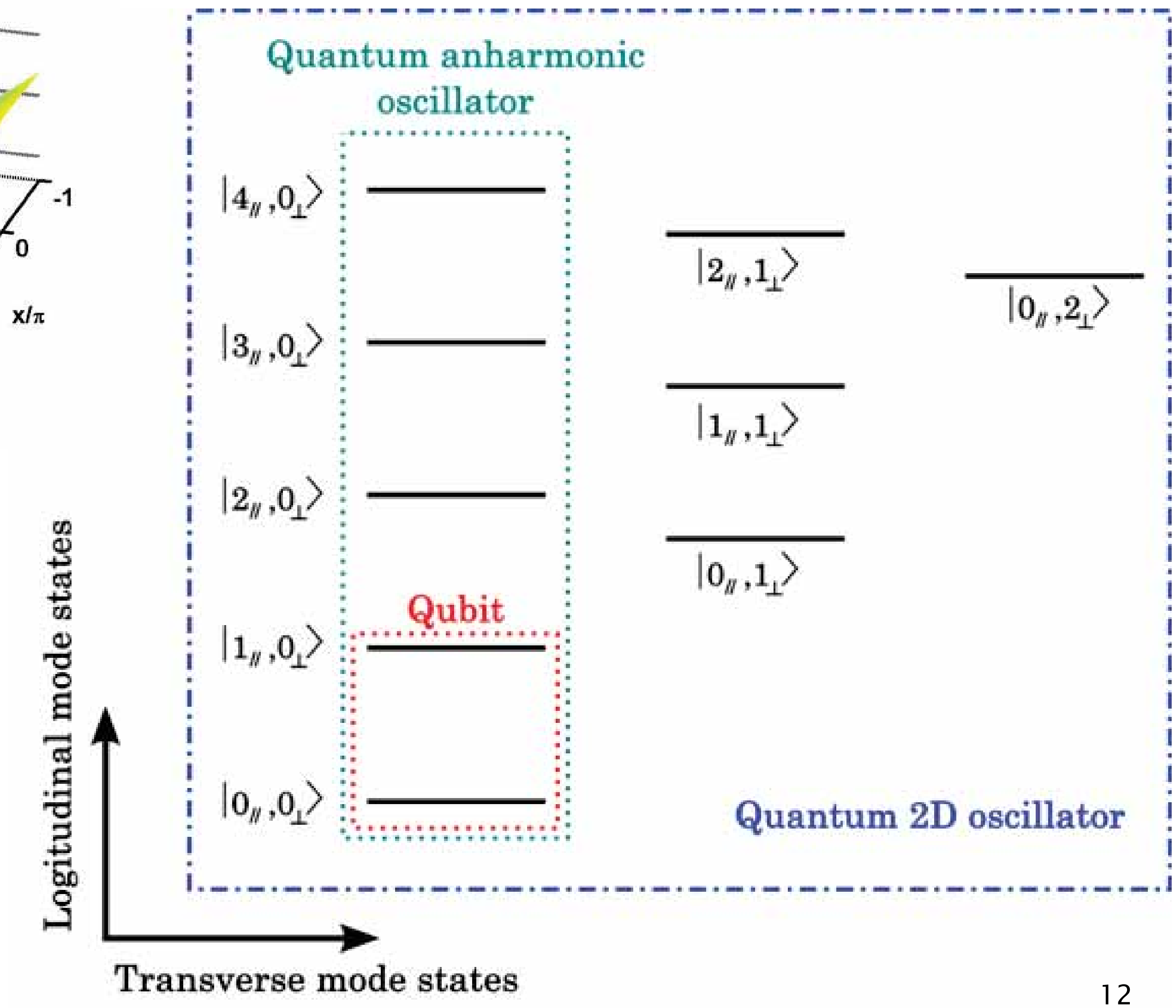
Hoskinson and Lecocq , et al , PRL, 2009

Palomaki, et al , PRB, 2010

…to a 2D oscillator

$L > L_{josephson}$ ⟶ Transverse mode energy decreased





Outline

1 Introduction :

1D and 2D dynamics in a dcSQUID

2 Spectroscopic evidence of the transverse mode

and coherent manipulation

3 Using the non linear coupling :

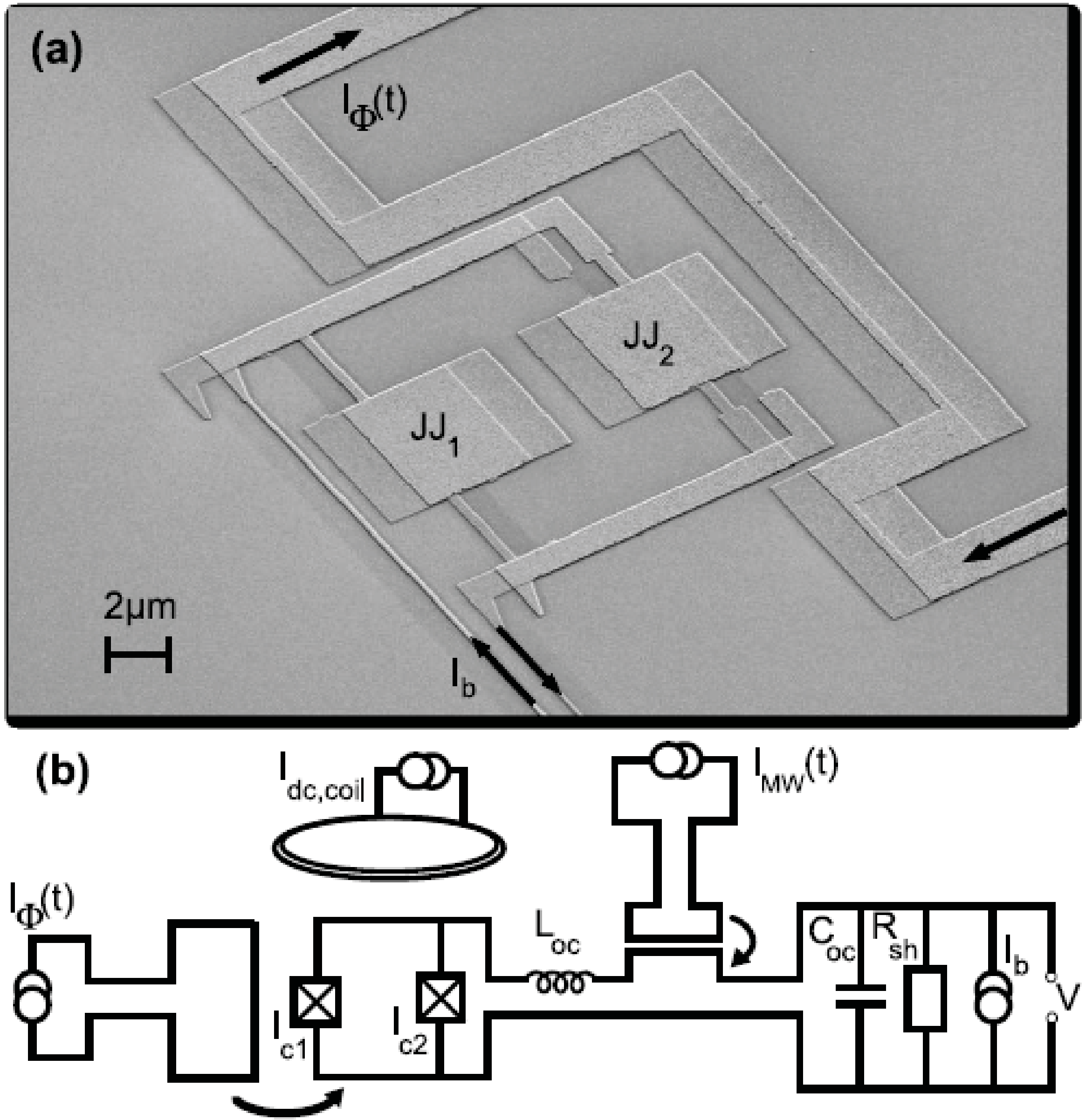
coherent oscillations between internal modes

Experimental Setup

dcSQUID in aluminum

Fabricated by shadow evaporation
without suspended bridges

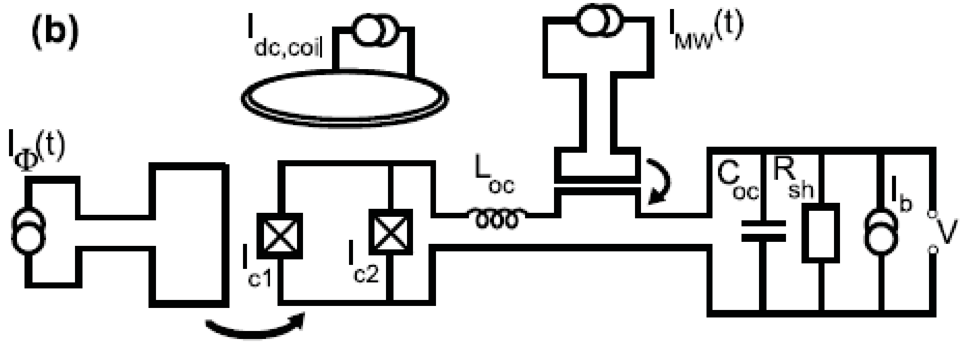
(Controlled Undercut Technique) *F. Lecocq, et al , ArXiv 1101.4576v2*

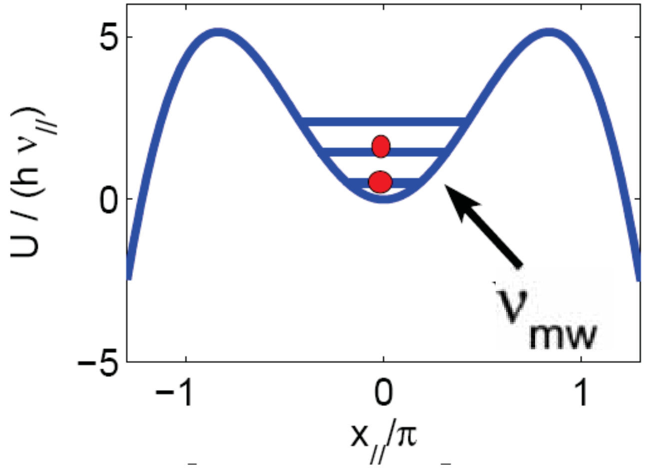


Experimental Setup

Measurement technique :

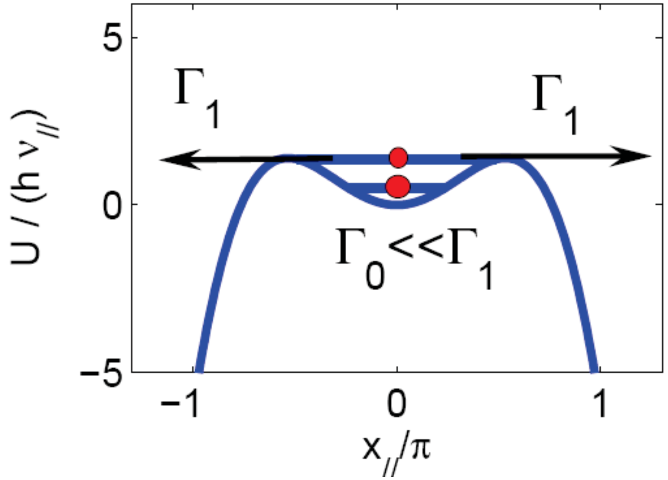
Switching to the voltage state



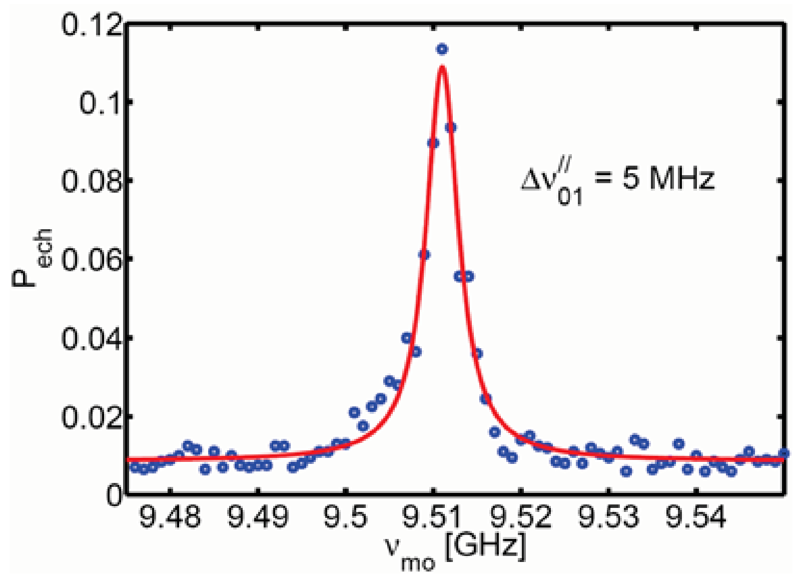


Nanosecond

flux pulse

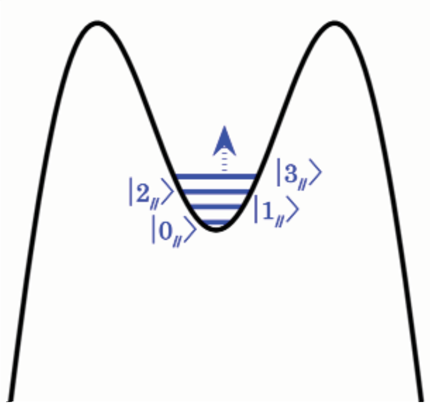


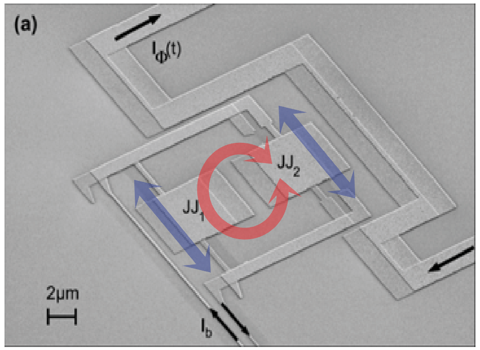
Escape = voltage = detection

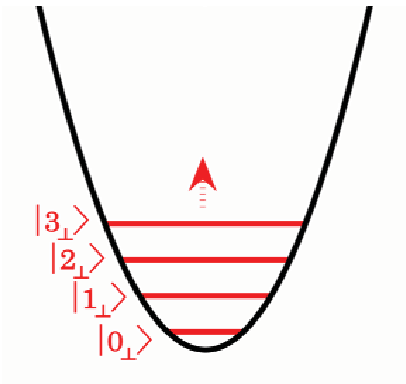


Spectroscopy

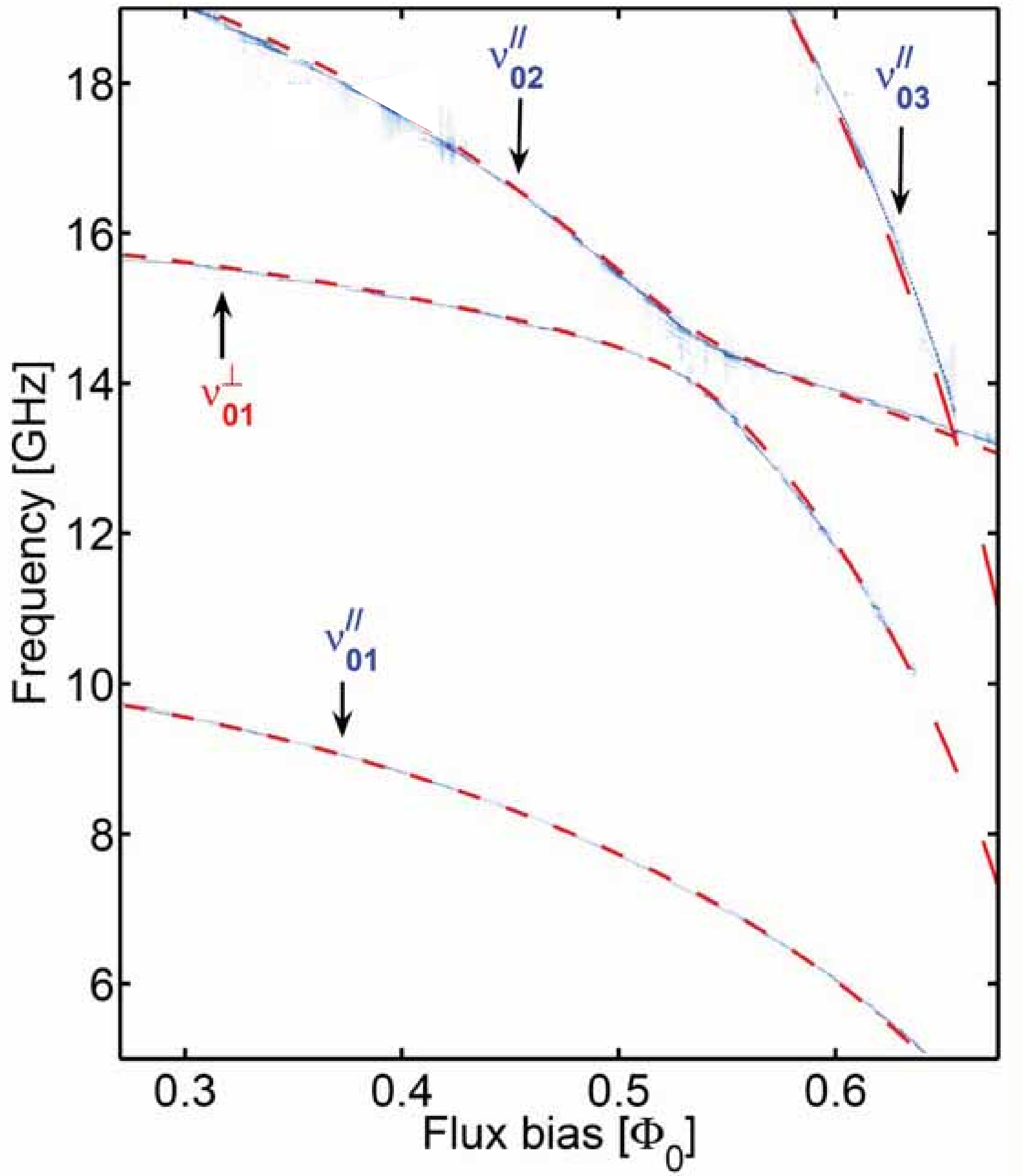
Longitudinal mode







Transverse mode



Spectroscopy

Large anti-crossing at the resonance between $\nu_{02}^{\|}$ and $\nu_{01}^{\perp}$

Non linear coupling

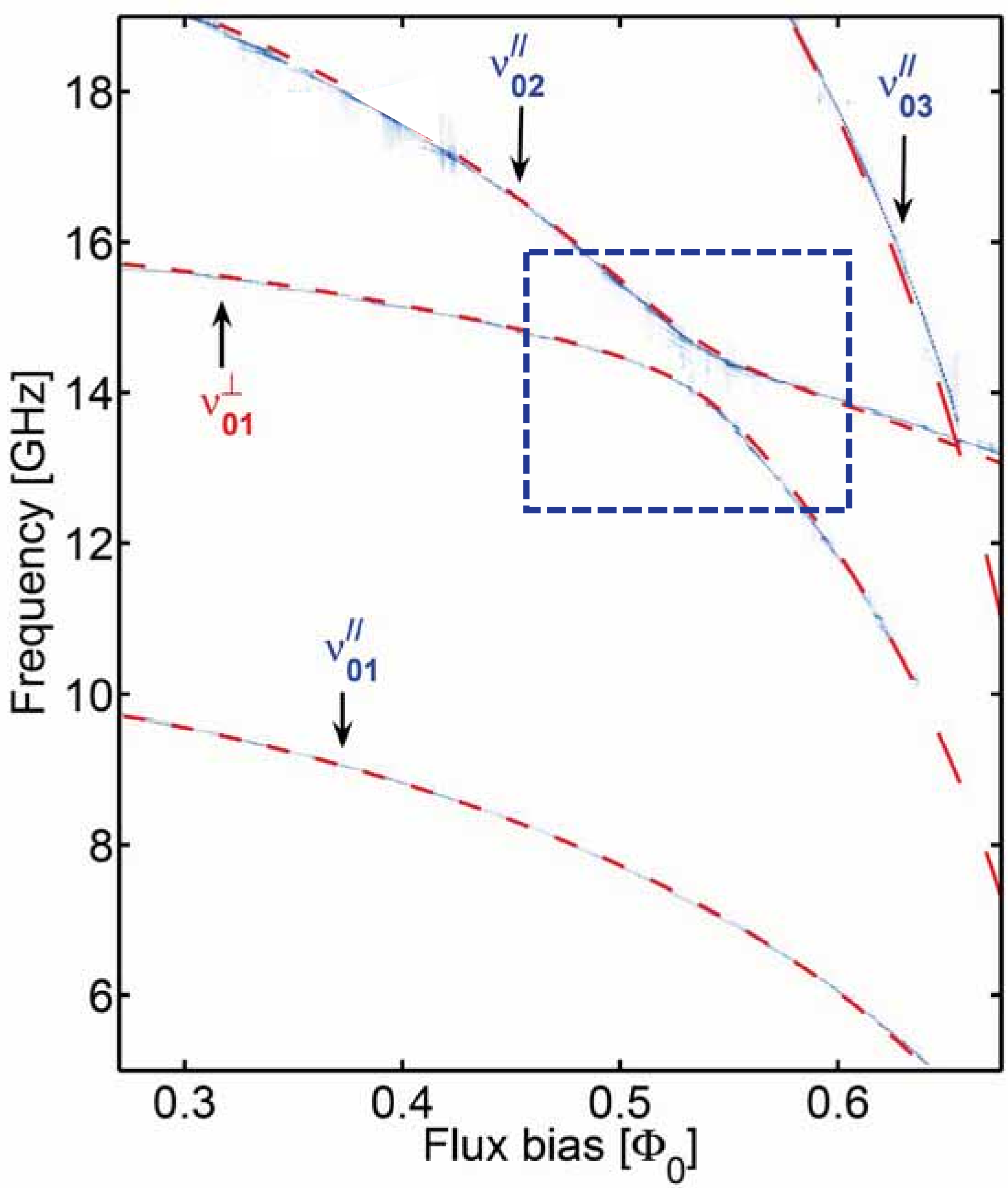
$$\hat{C}_{\|\perp} = h\nu_{21}^{c}\hat{X}_{\|}^{2}\hat{Y}_{\perp}$$

Also discussed in quantum optics and ion traps

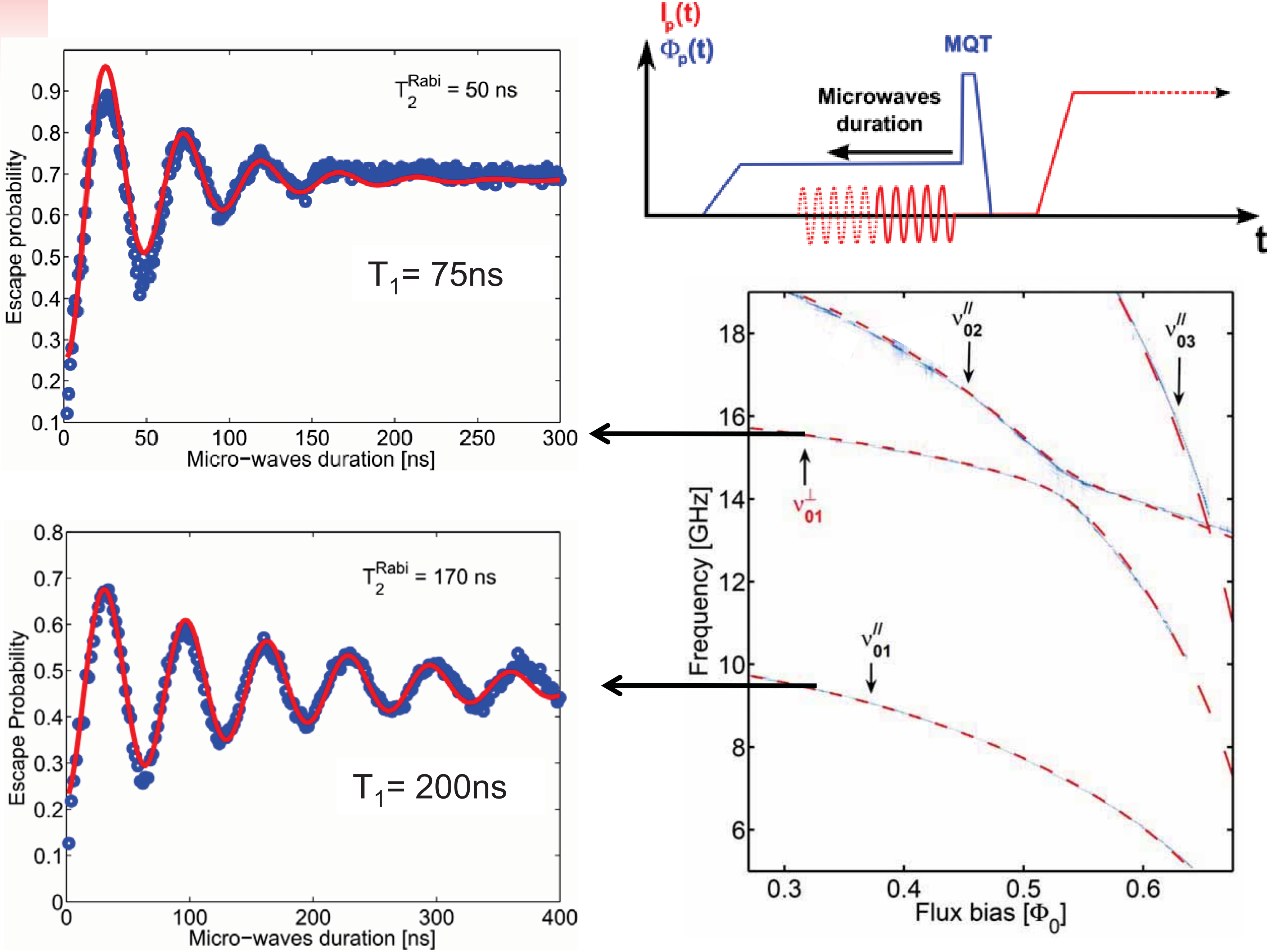
Bertet et al, PRL (2002)
Vogel and Dematos, PRA (1995)

Strong coupling regime

$$\nu_{21}^{\mathbf{c}} = \mathbf{700MHz}$$



Coherent oscillations of the two modes



Outline

1 Introduction :

1D and 2D dynamics in a dcSQUID

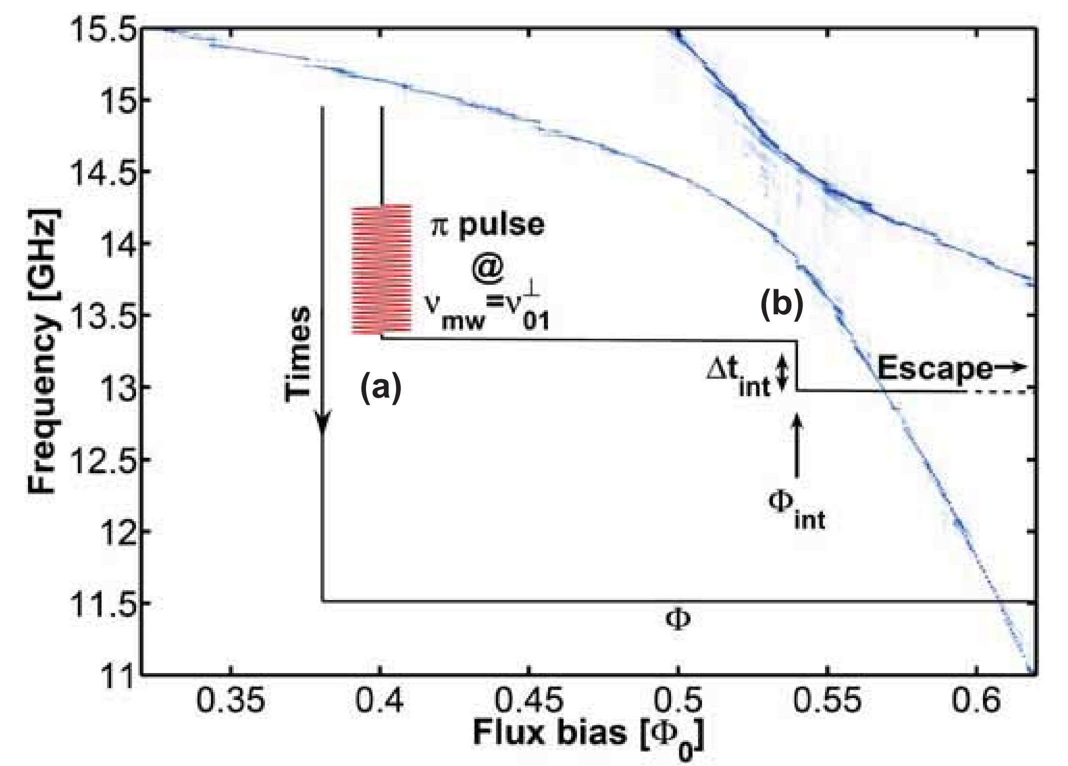
2 Spectroscopic evidence of the transverse mode

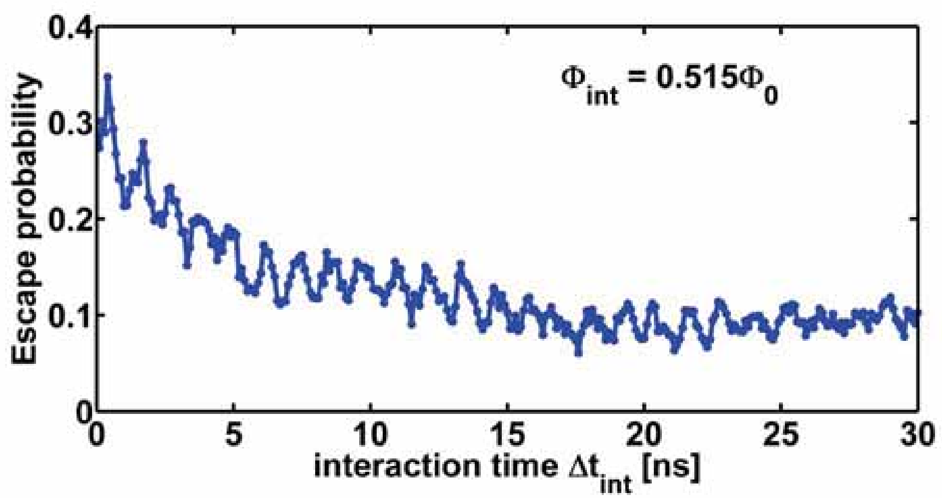
and coherent manipulation

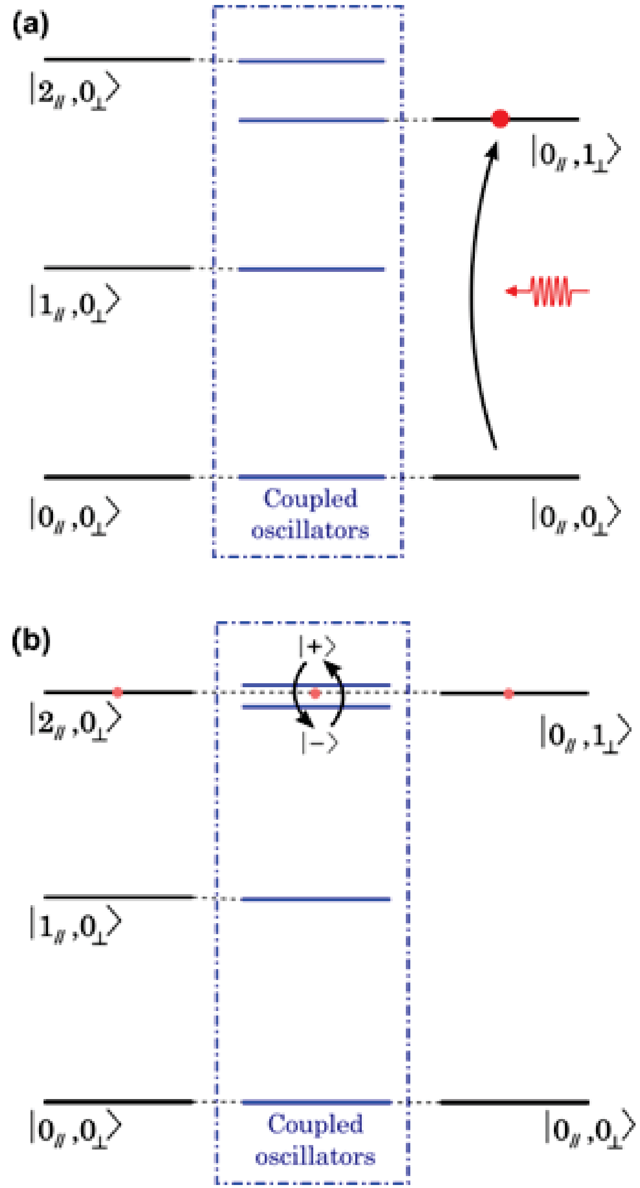
3 Using the non linear coupling :

coherent oscillations between internal modes

Coherent oscillation between modes

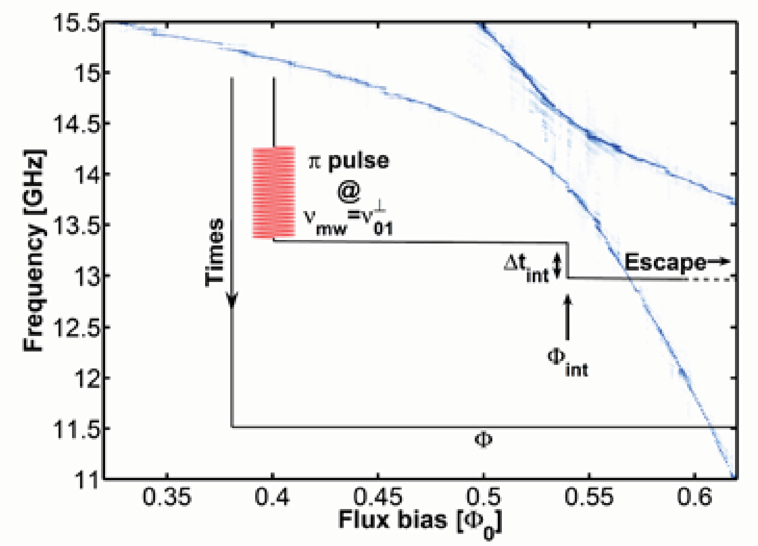




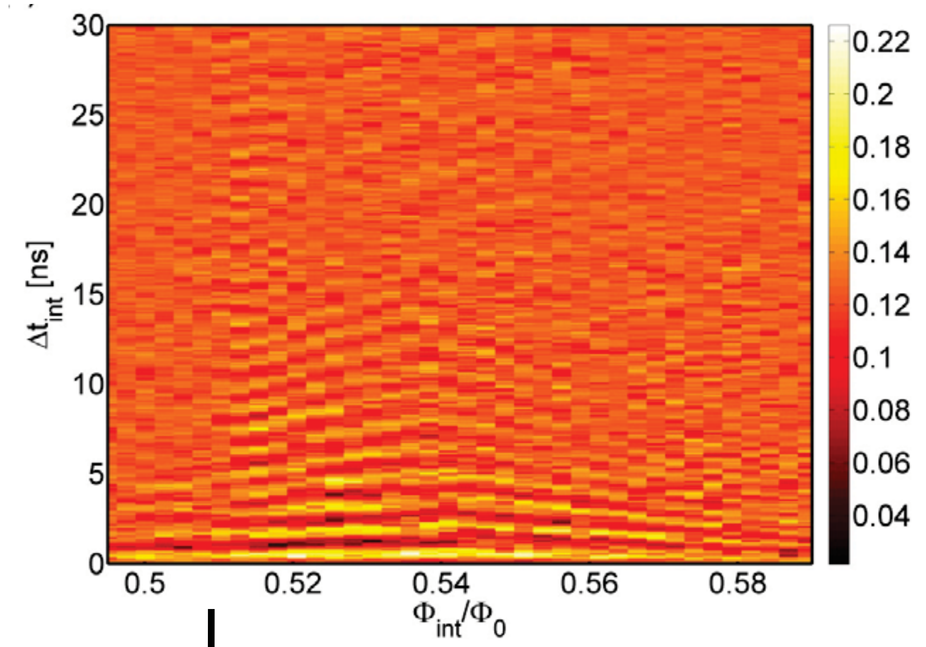


Non linear coupling, strong ~700MHz

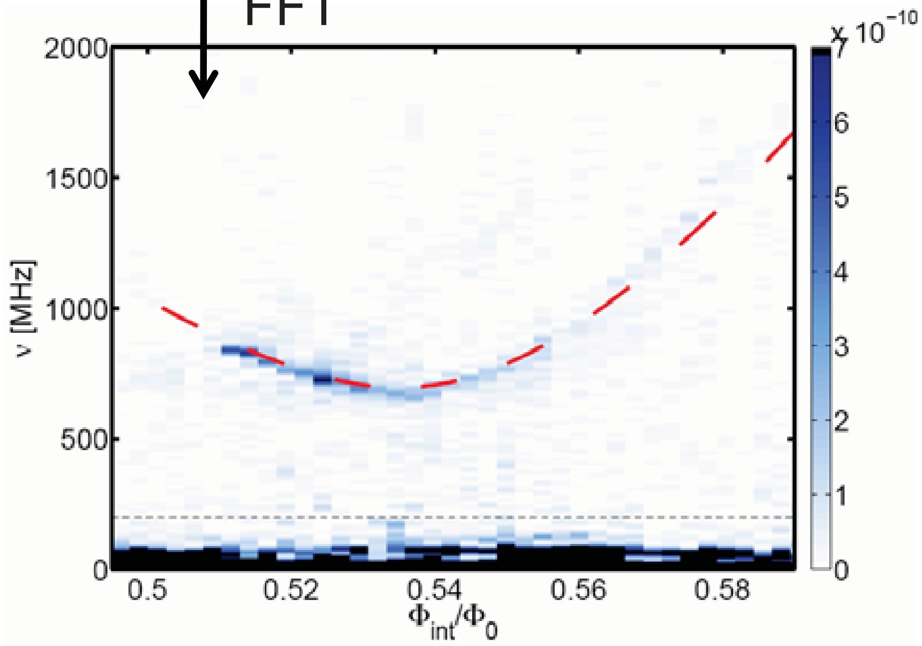
Coherent oscillation between modes



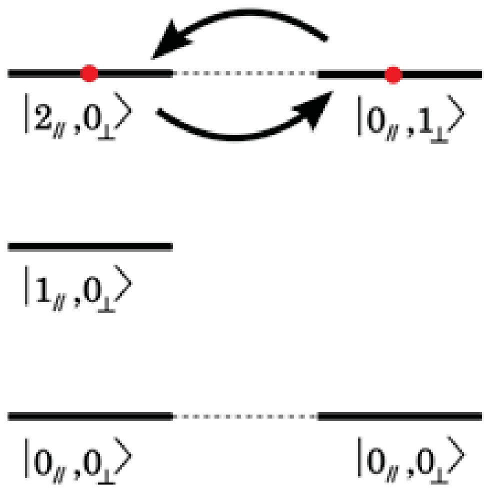
Coherent exchange of quanta between the modes



FFT



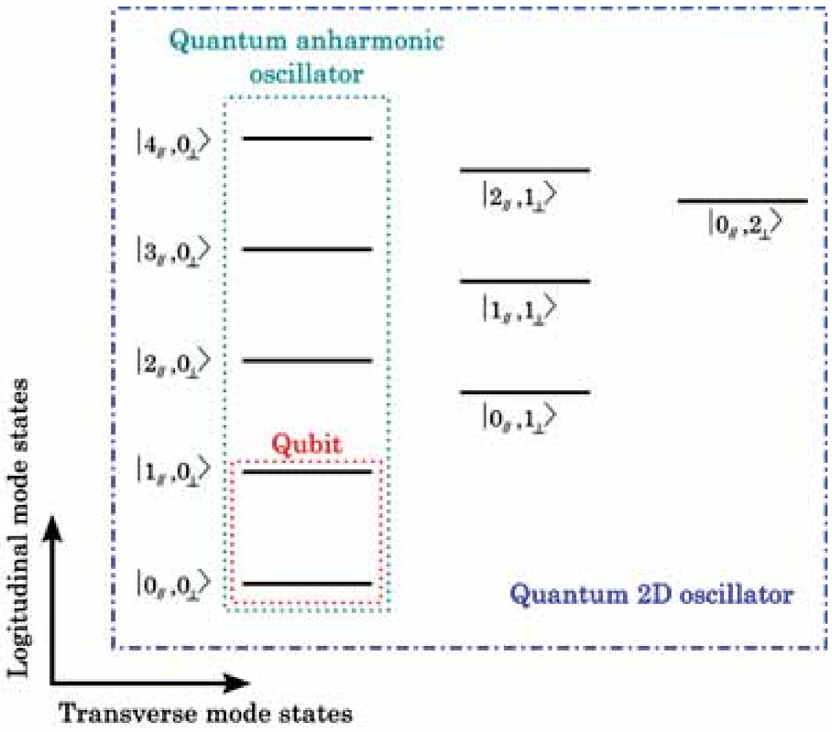
Frequency conversion back and forth

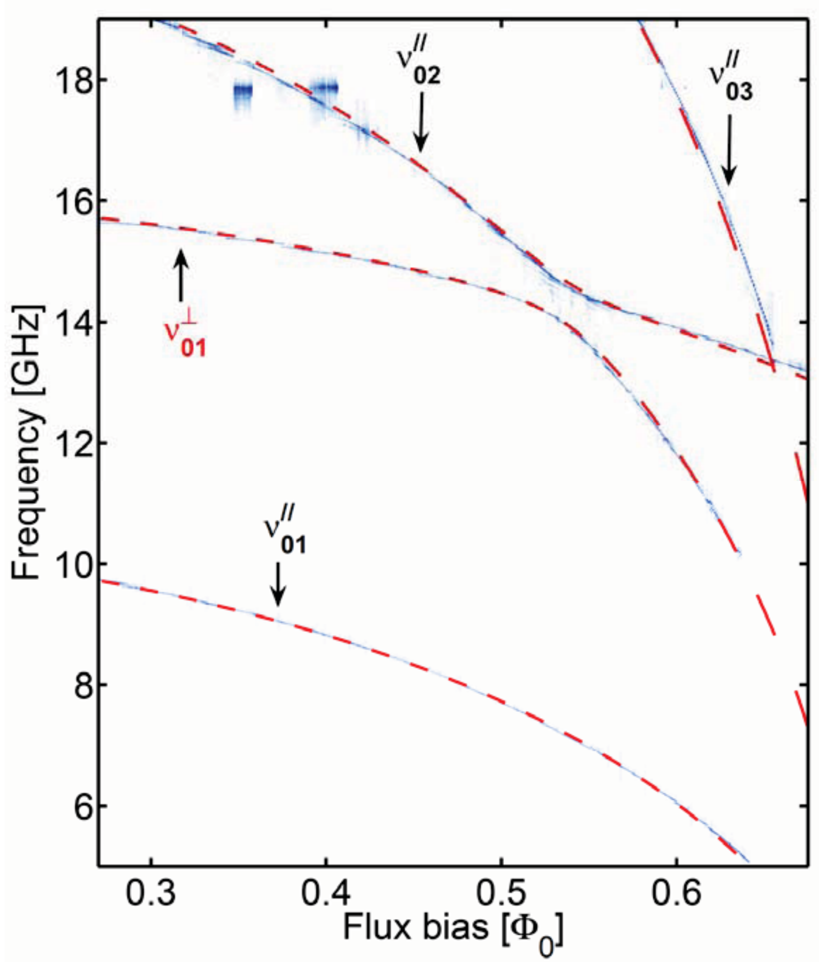


Conclusion

• A dcSQUID with a large loop inductance can be describe as two coupled oscillator

•Non linear coupling
(exchange of 2 quanta in one mode, 1 quantum in the other)



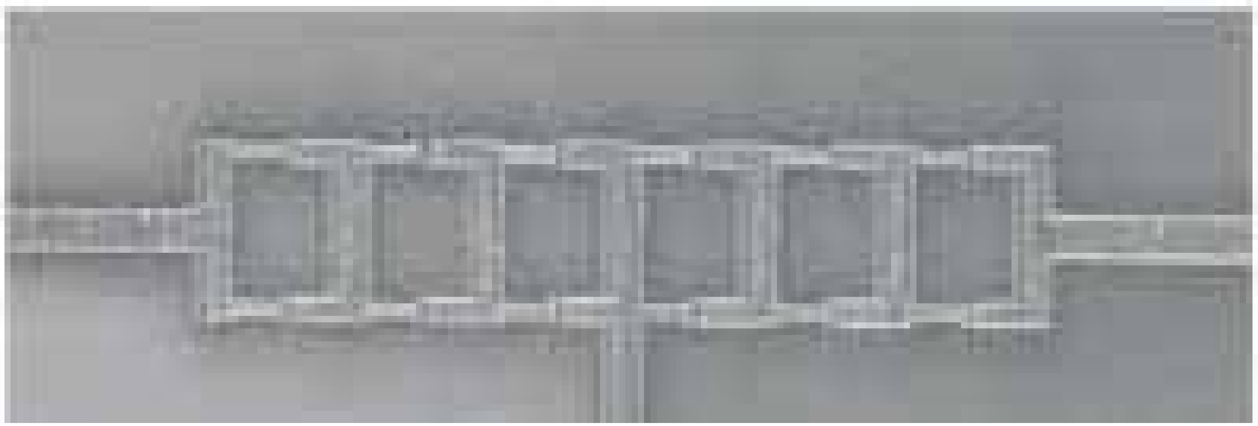


Artificial atom with
two degrees of freedom…

Quantum dynamics in Josephson junction chains

Wiebke Guichard
PhD: I. Pop

Single Josephson (SQUID) junction chains



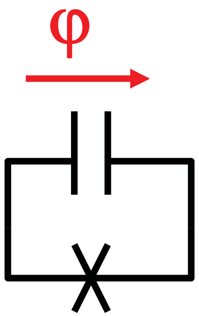
Fundamental research:

- collective behavior in multi-degrees of freedom_system
- Quantum Phase-Slips

(Mateveev, Larkin, Glazman, PRL2002)

Possible applications:
→ Current standard
→ New type of qubits topologically protected

Quantum phase-slip in a single junction



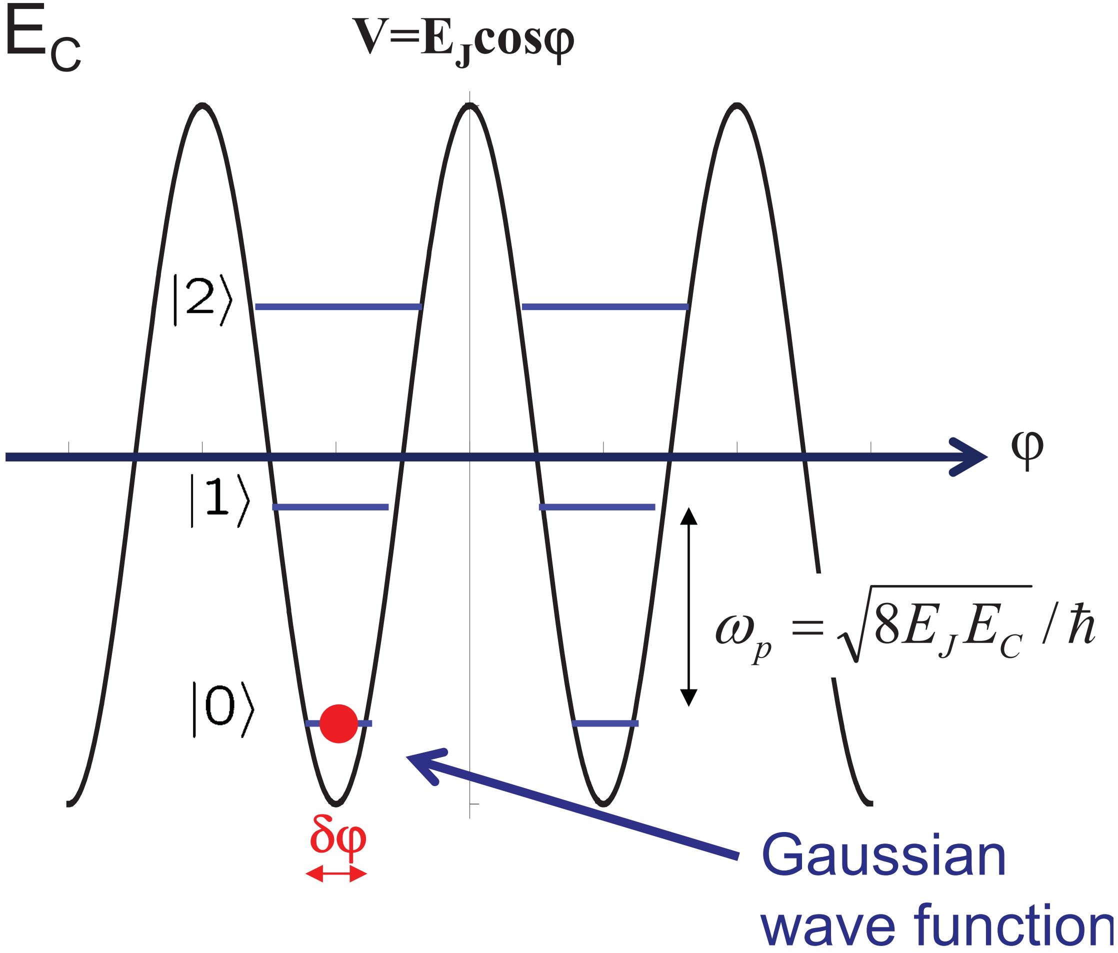
E_J slightly larger than E_C

$$\hat{H} = E_C (\hat{Q}/e)^2 + E_J \cos\hat{\varphi}$$

$$[Q,\varphi] = -2ie$$

Schrödinger equation:

$$\frac{d^2\psi}{d(\varphi/2)^2} + \left(\frac{E}{E_C} + \frac{E_J}{E_C}\cos\varphi\right)\psi = 0$$

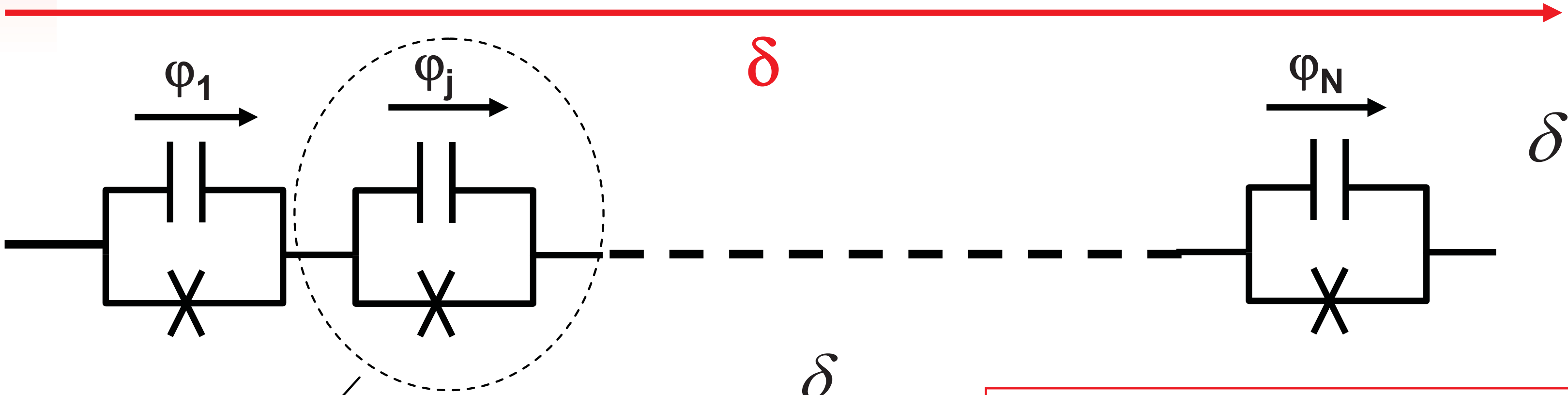


Exponentially small overlap of Gaussian tails

Phase-slip rate $\nu \approx \left(E_J^3 E_C\right)^{1/4} \exp\left(-\sqrt{8E_J/E_C}\right)$

Phase biased Josephson junction chain

N Josephson junctions in series

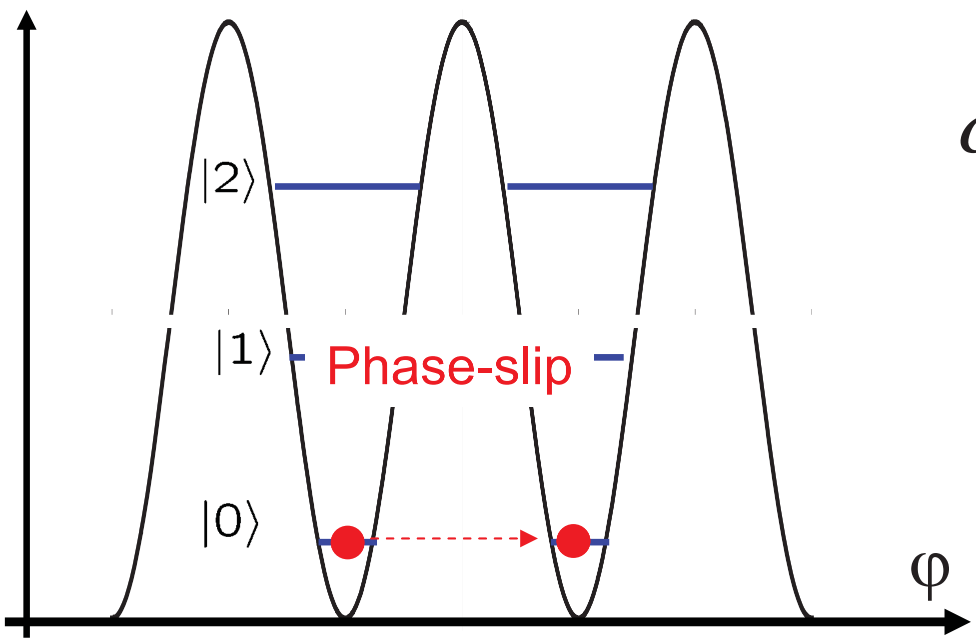


$$\delta = \sum_{i=1}^{N} \varphi_i$$

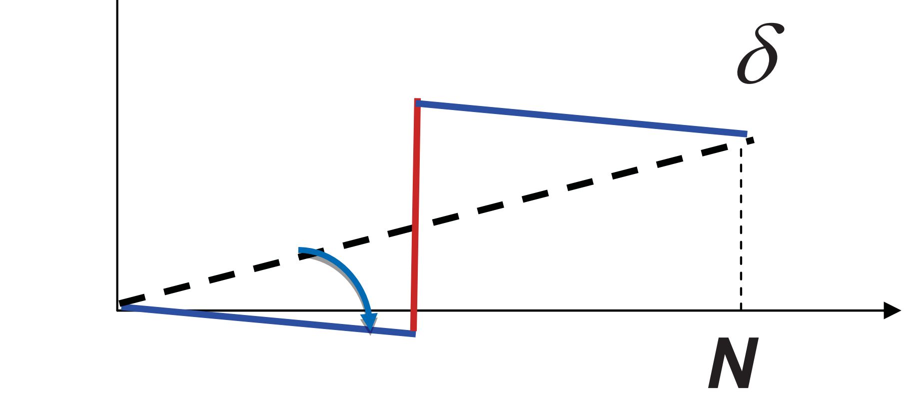
$$\varphi_i = \frac{\delta}{N}$$

Phase slip rate in a chain: $N\nu$

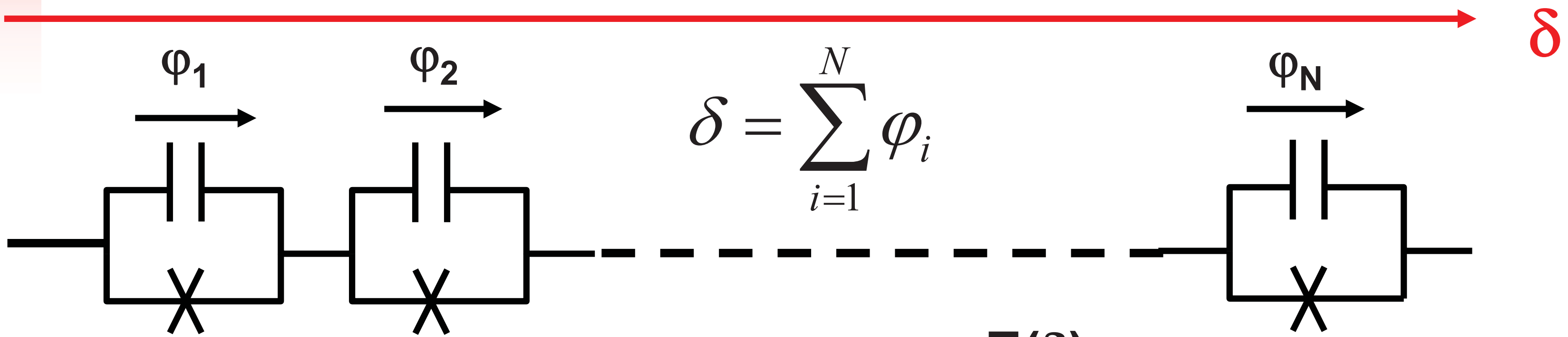
$E_{Pot} = -E_J\cos(\varphi)$



$$\varphi_j = \frac{\delta}{N} \to \frac{\delta - 2\pi}{N}$$



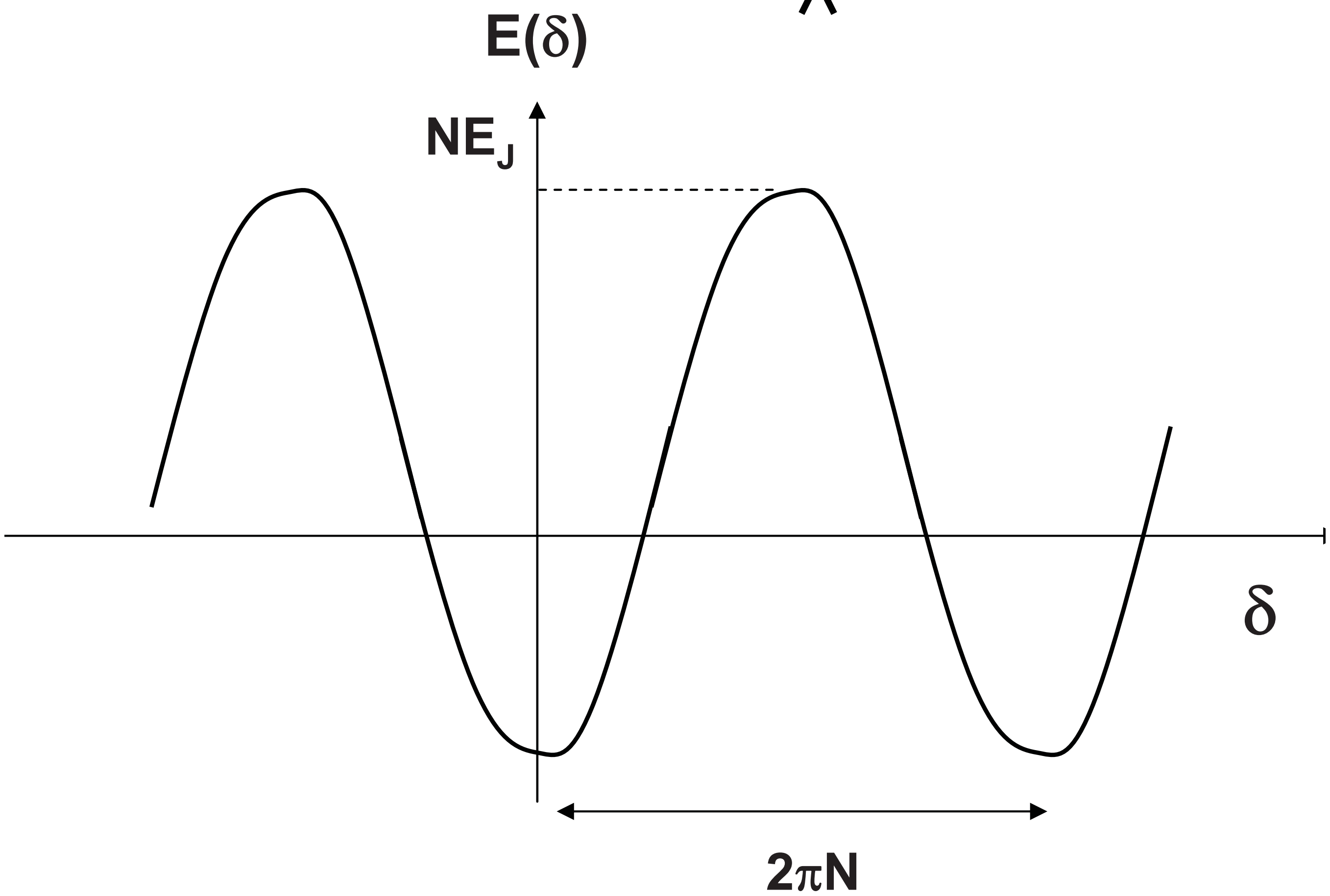
"Classical regime": E_J large and $E_C=0$



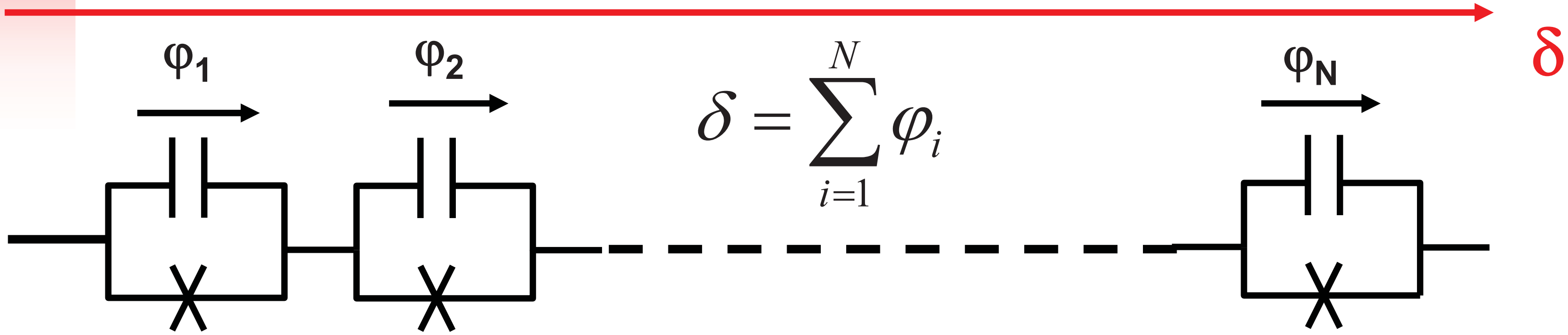
$$\delta = \sum_{i=1}^{N} \varphi_i$$

$$\varphi_i = \frac{\delta}{N}$$

$$E_{pot} = \sum_i E_J[1-\cos(\varphi_i)]$$
$$= NE_J[1-\cos(\delta/N)]$$



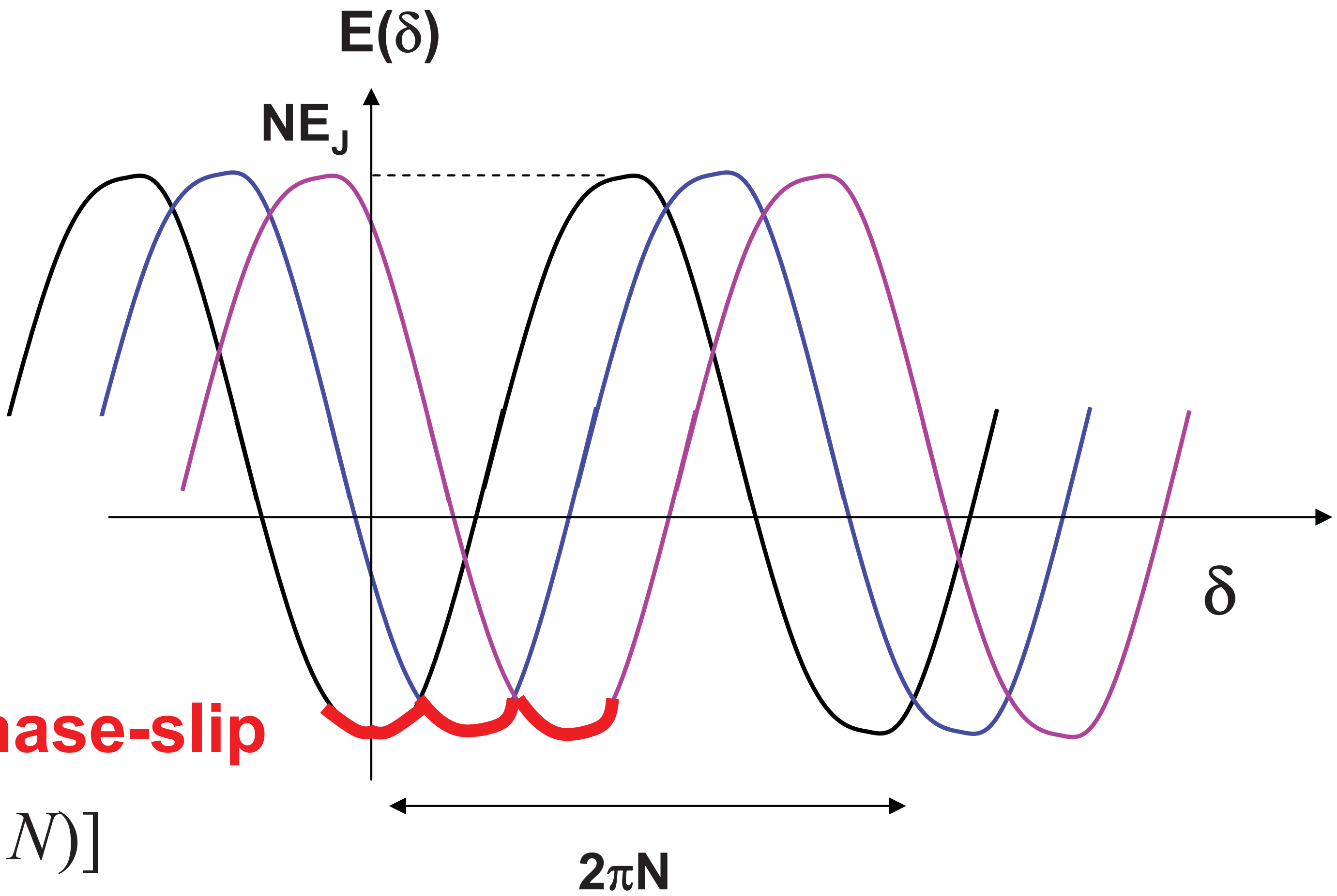
"quasi-classical regime ": $E_J >> E_C$



$$\delta = \sum_{i=1}^{N} \varphi_i$$

$$\varphi_i = \frac{\delta}{N} \rightarrow \frac{\delta - 2\pi}{N} + 2\pi$$

$$\varphi_j = \frac{\delta}{N} \rightarrow \frac{\delta - 2\pi}{N}$$



$$E_{pot} = \sum_i E_J[1 - \cos(\varphi_i)]$$

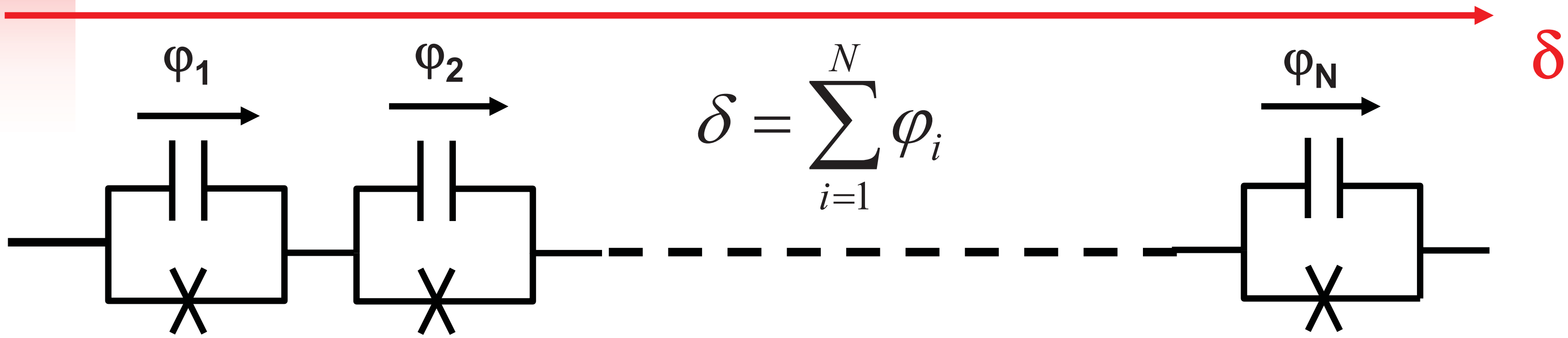
$$= NE_J[1 - \cos(\delta / N)]$$

$$\downarrow$$

Phase-slip

$$= NE_J[1 - \cos((\delta - 2\pi) / N)]$$

"quasi-classical regime ": $E_J >> E_C$



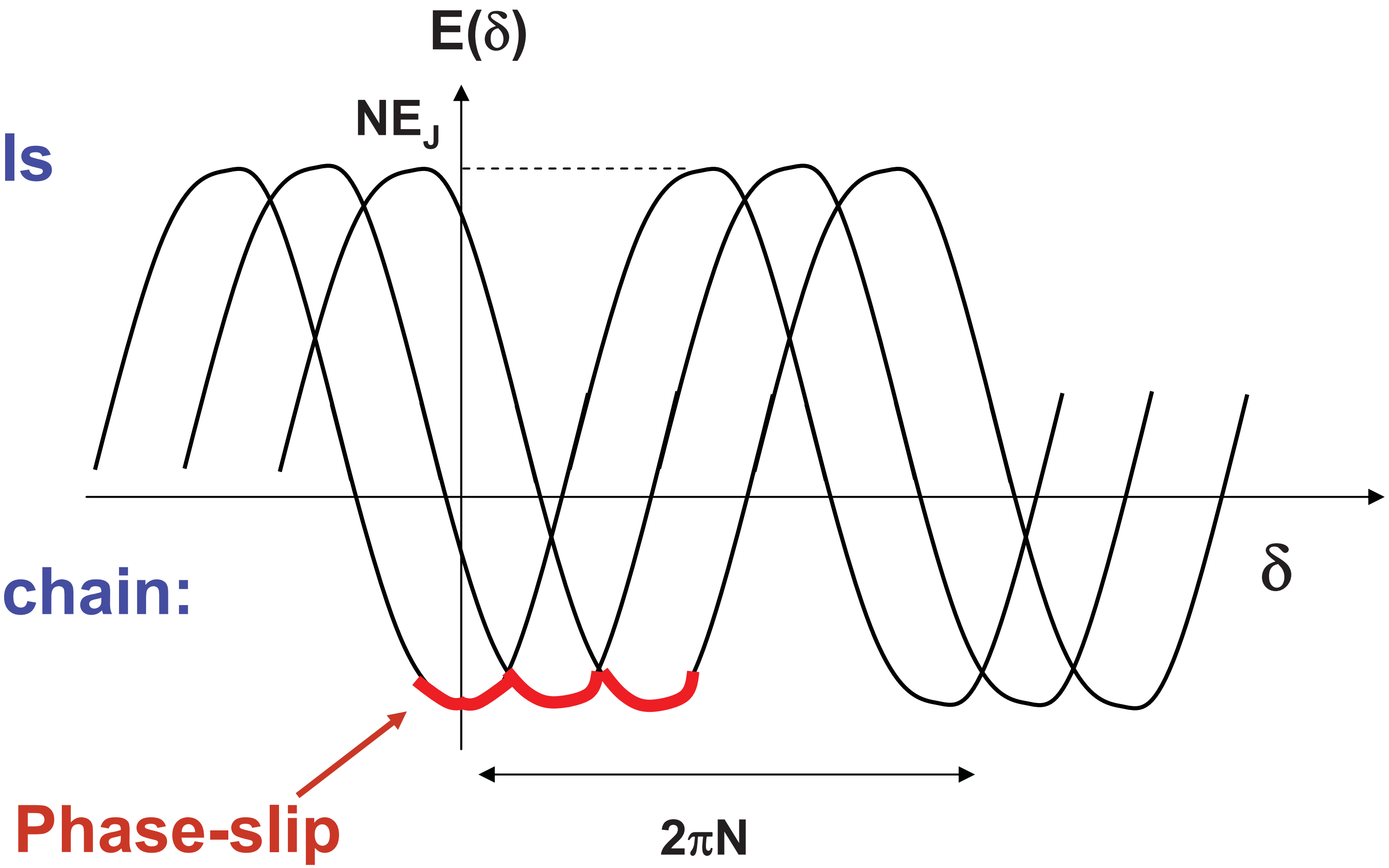
$$\delta = \sum_{i=1}^{N} \varphi_i$$

Low energy levels of the chain:

$$E_m \approx \frac{E_J}{2N}(\delta + 2\pi m)^2$$

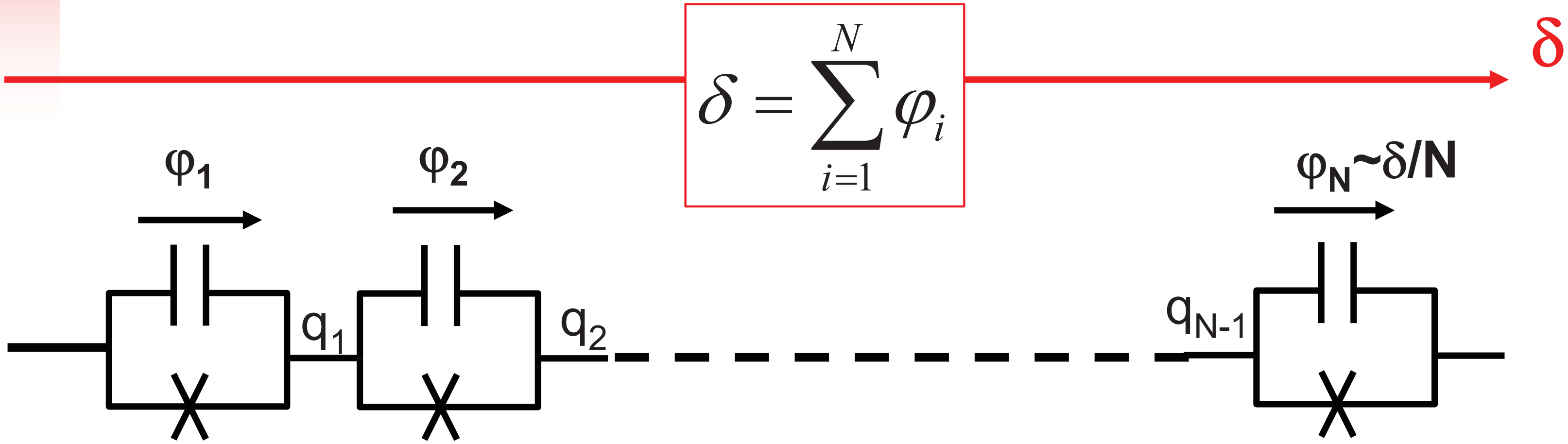
Critical current of chain:

$$I_c^{chain} \approx \frac{\pi I_c}{N}$$

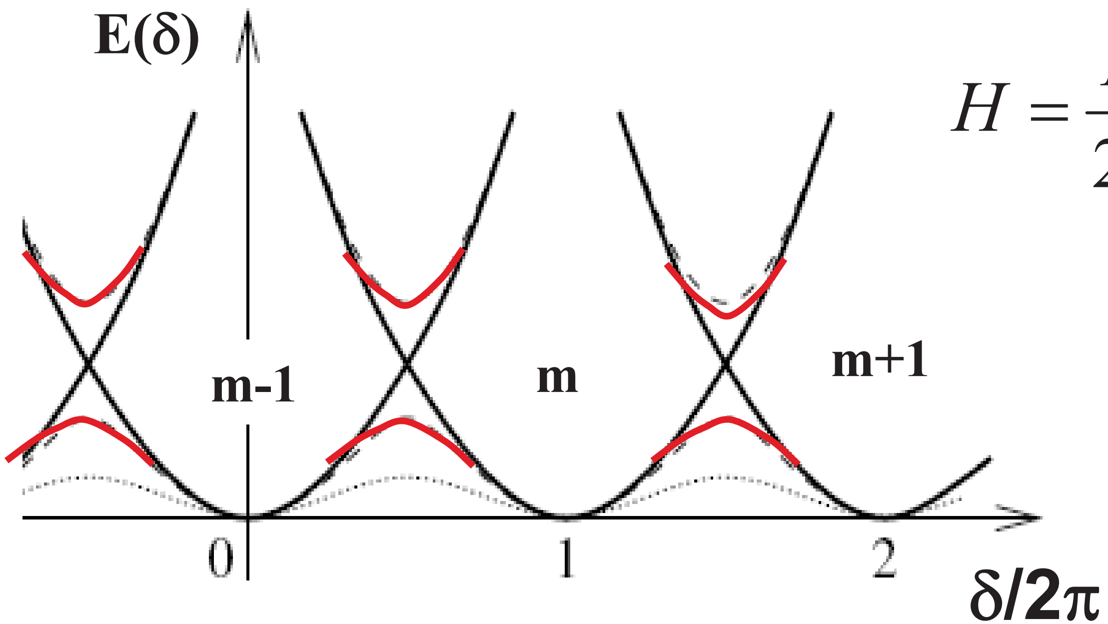


"Quantum regime": $E_J > E_C$

$$\delta = \sum_{i=1}^{N} \varphi_i$$



$$\upsilon^{chain} \approx N\left(E_J^3 E_C\right)^{1/4} \exp\left(-\sqrt{8E_J / E_C}\right)$$



$$H = \frac{E_J}{2N}\left(2\pi\hat{m} - \delta\right)^2 + \sum_m \upsilon^{chain}\left(|m+1\rangle\langle m| + |m\rangle\langle m+1|\right)$$

Matveev et al (2002)

Experimental verification of the quantum-phase slip model in a 6 Josephson junctions chain

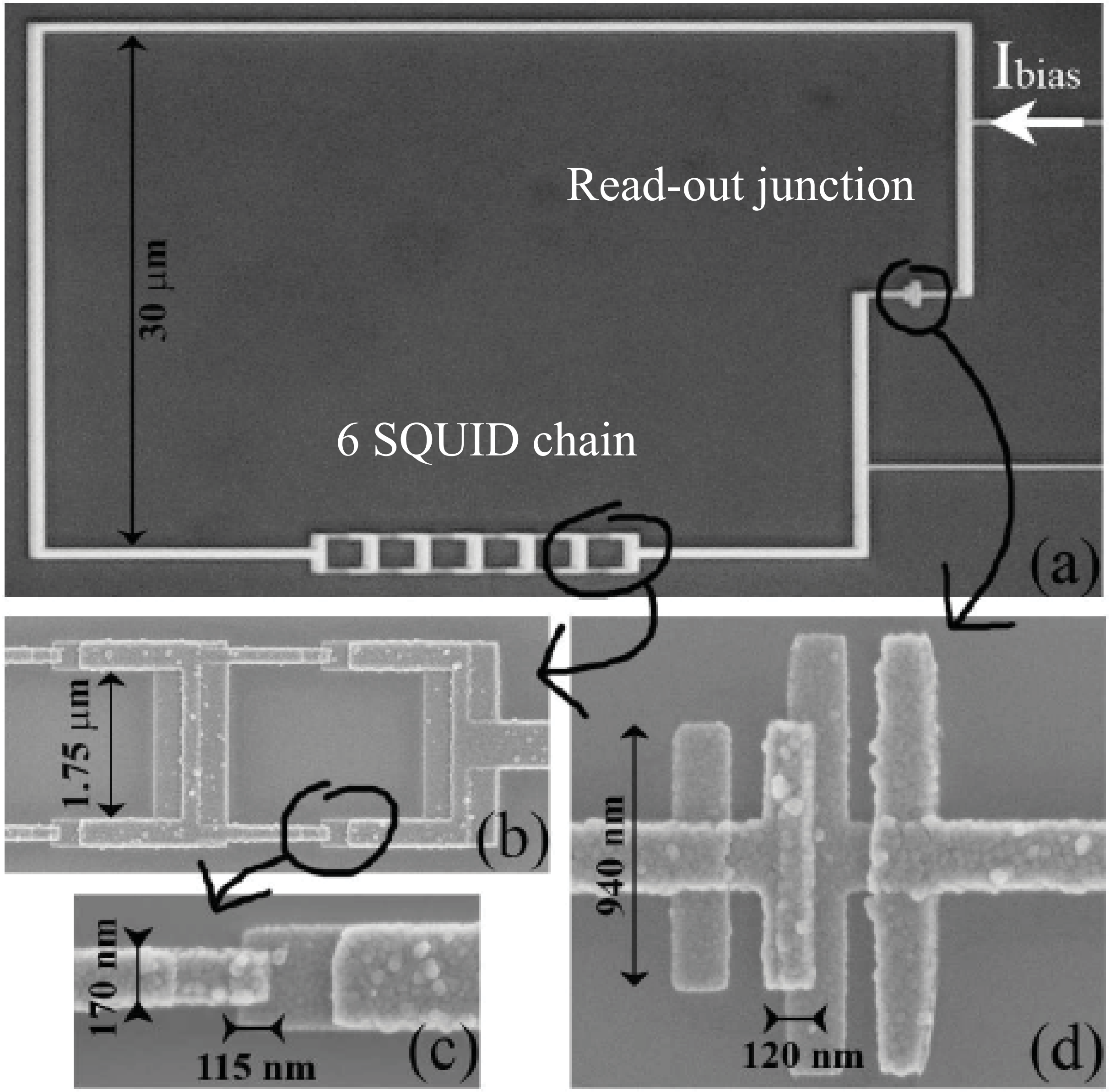
Idea:
tune strength of quantum fluctuations with flux

$$\frac{E_J(f)}{E_C} = \frac{E_J^{SQ}|\cos(f\pi)|}{E_C}$$

$$I_c^{\text{Readout}} = 330nA$$

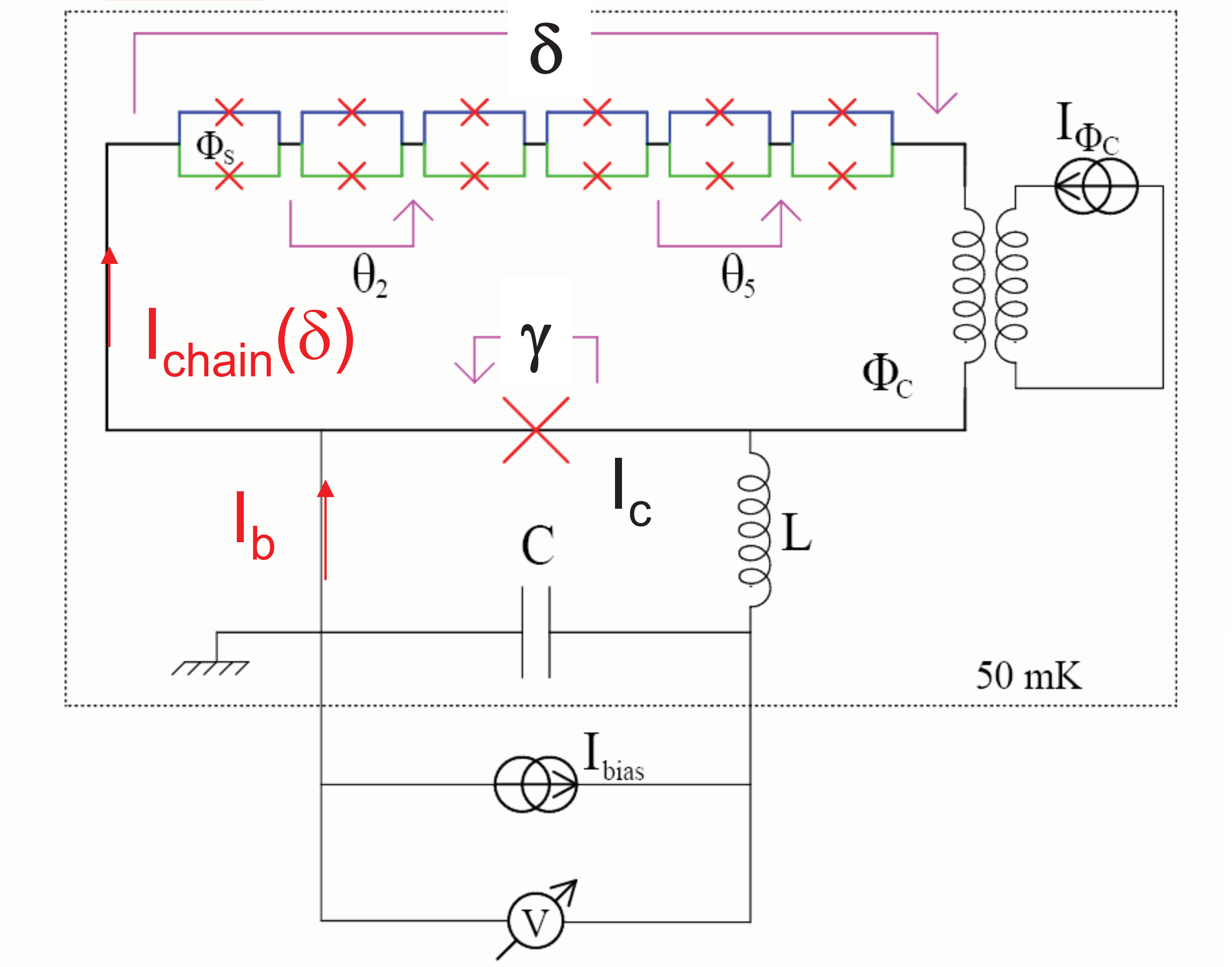
$$I_c^{\text{SQUID}} = 83nA$$

$$\frac{E_J^{\text{SQUID}}}{E_c} \approx 3$$



Nanofab-facility

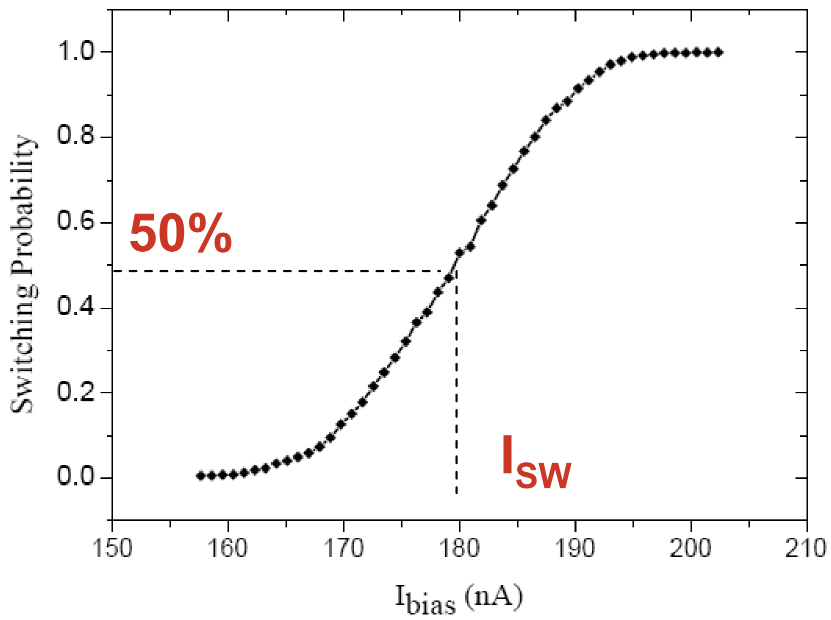
Measurement circuit



Switching event:

$$I_b - I_{chain}(\delta) \approx I_C$$

$$\delta = 2\pi\Phi_C / \Phi_0 - \pi / 2$$



Statistic of N=10 000 events

Measurement of the ground state of the chain as a function of bias phase

I. Pop, et al., Nature Physics (2010)

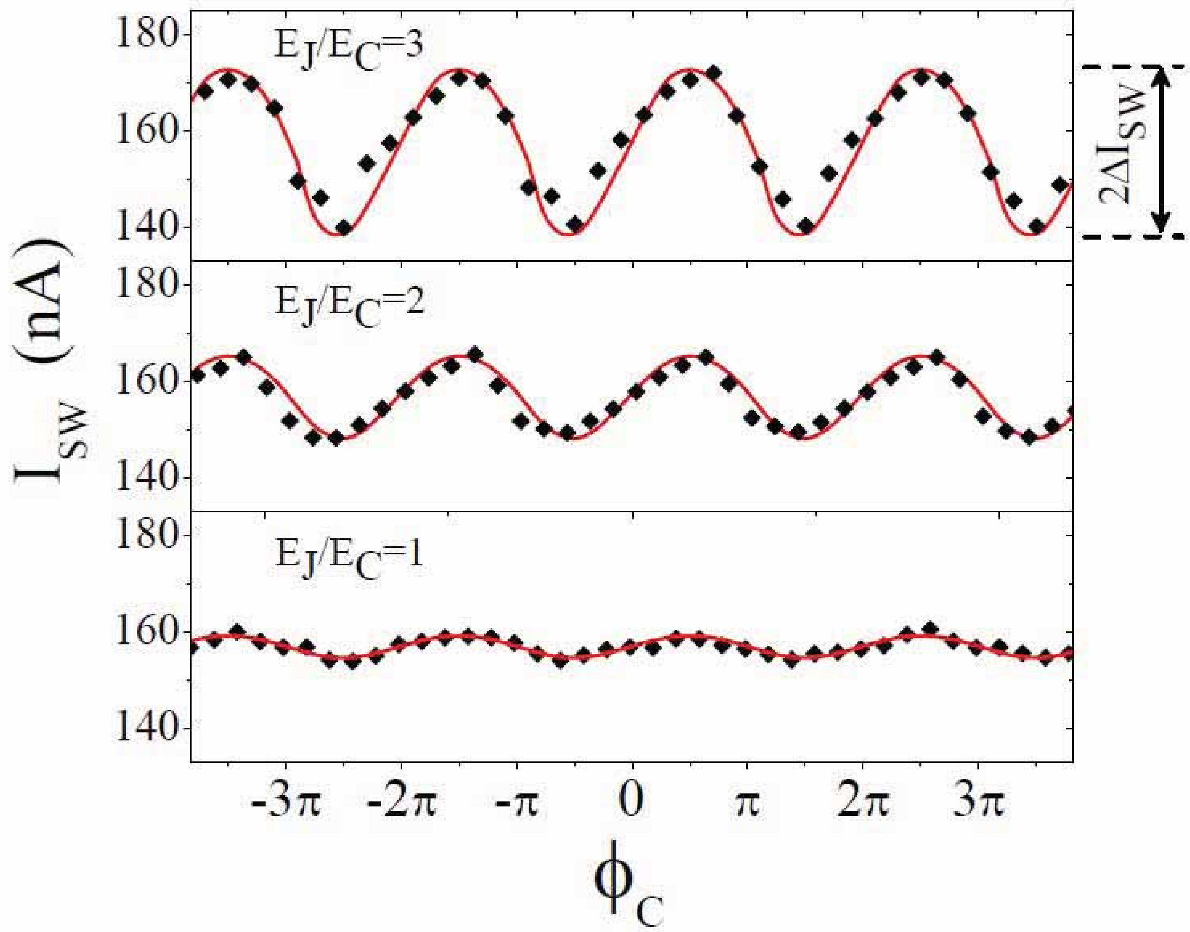
Switching current at 50% escape probability

$$R_{SQUID} = 3.87\ \mathrm{k\Omega}$$

$$R_{Readout} = 968\ \Omega$$

$$E_J = 2\ \mathrm{K}$$

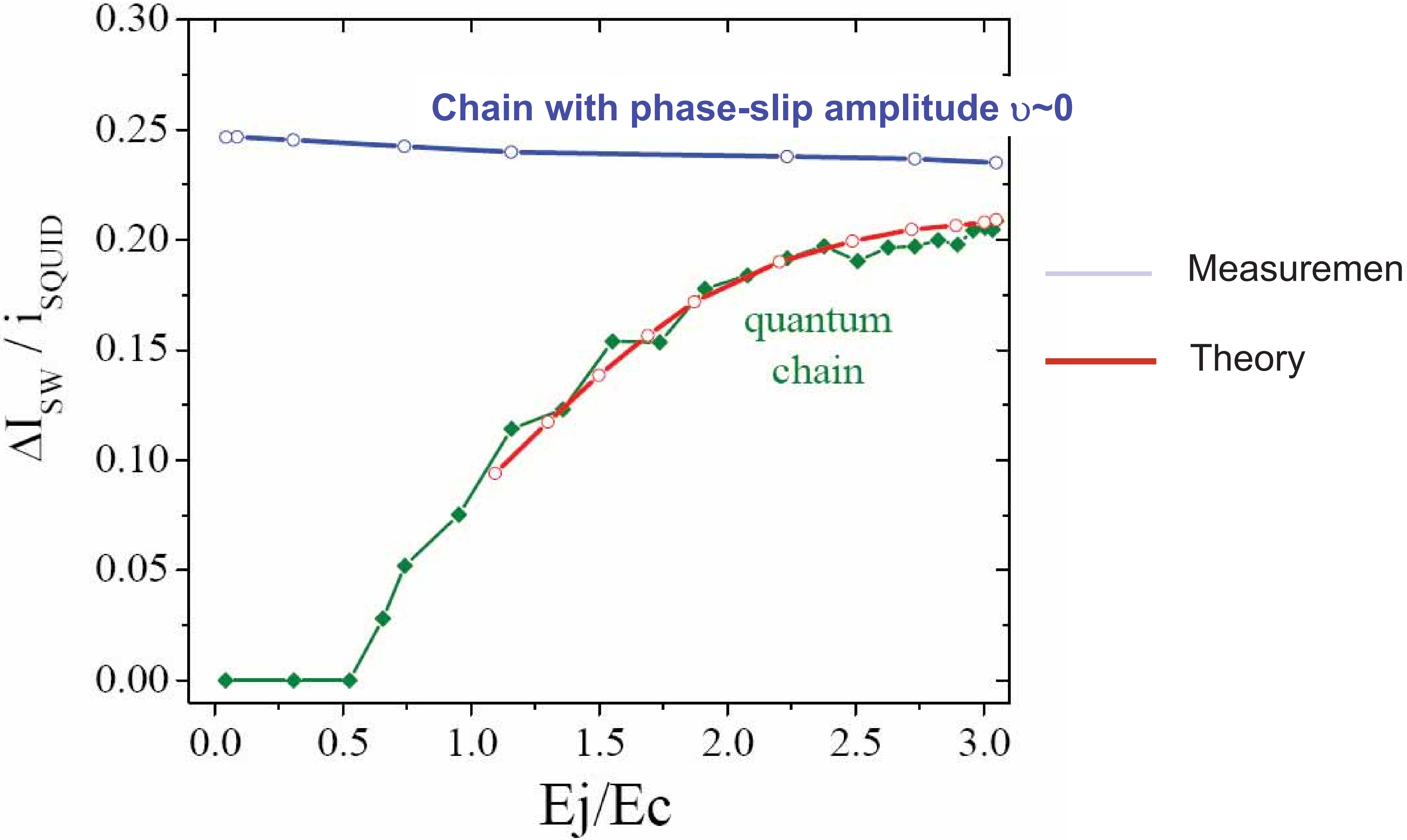
$$E_C = 0.66\ \mathrm{K}$$



Good agreement with quantum phase-slip model

Strong quantum fluctuations

I. Pop, et al., Nature Physics (2010)



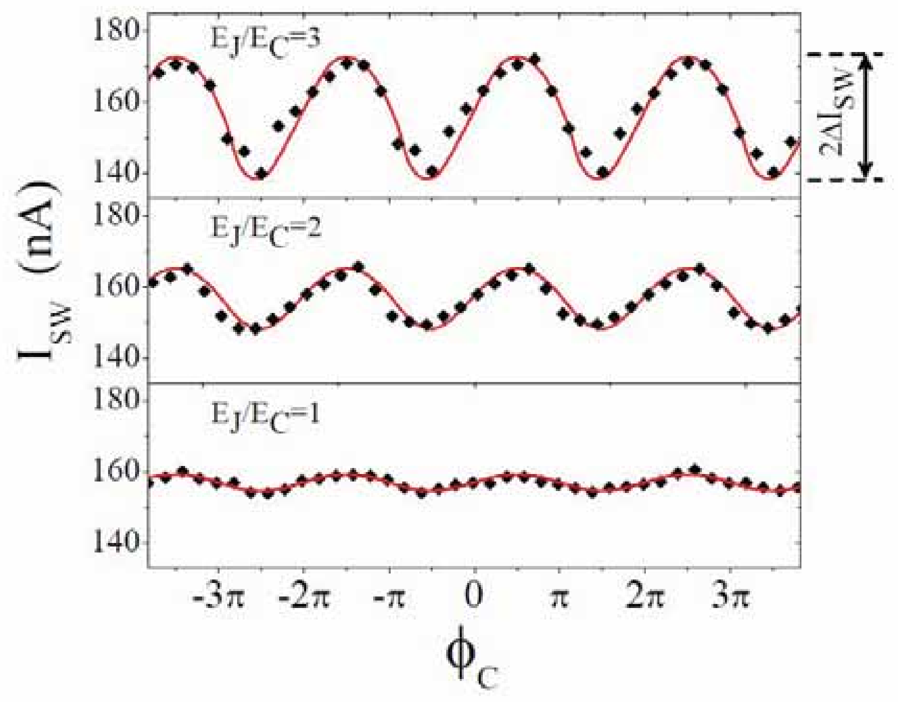
Conclusion

- Evidence of quantum phase slips
  in a short Josephson junction chains

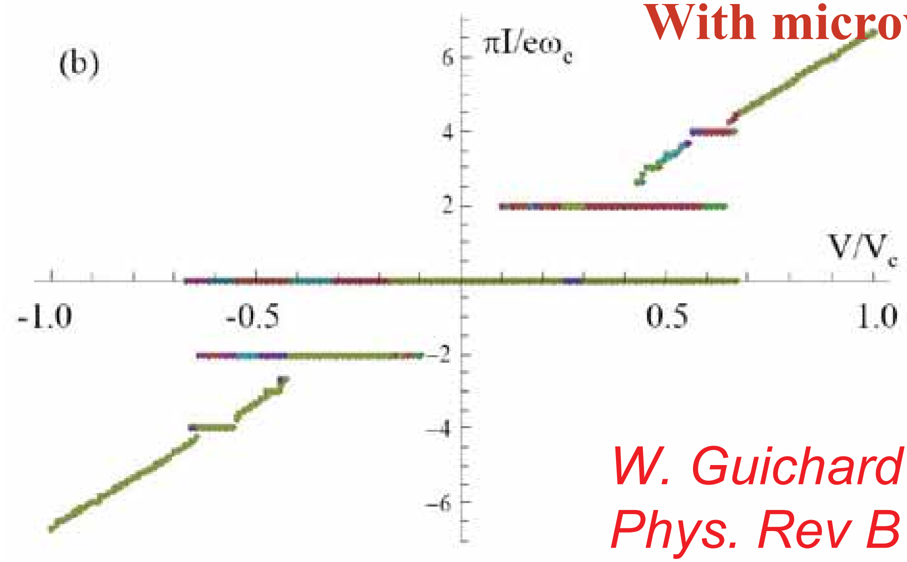
- Current-phase relation: $I=I_c^{chain}\sin(d)$

- Ground state well understood
  What about excited states?

- Current standard in a chain?



With microwave irradiation

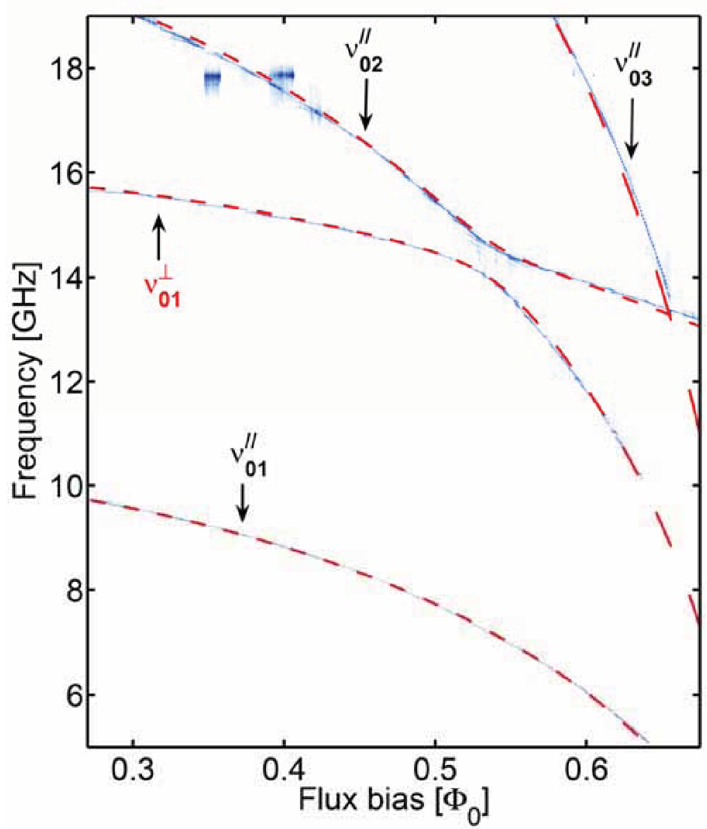


W. Guichard and F. Hekking, Phys. Rev B (2010)

Conclusion

Superconducting quantum circuits:

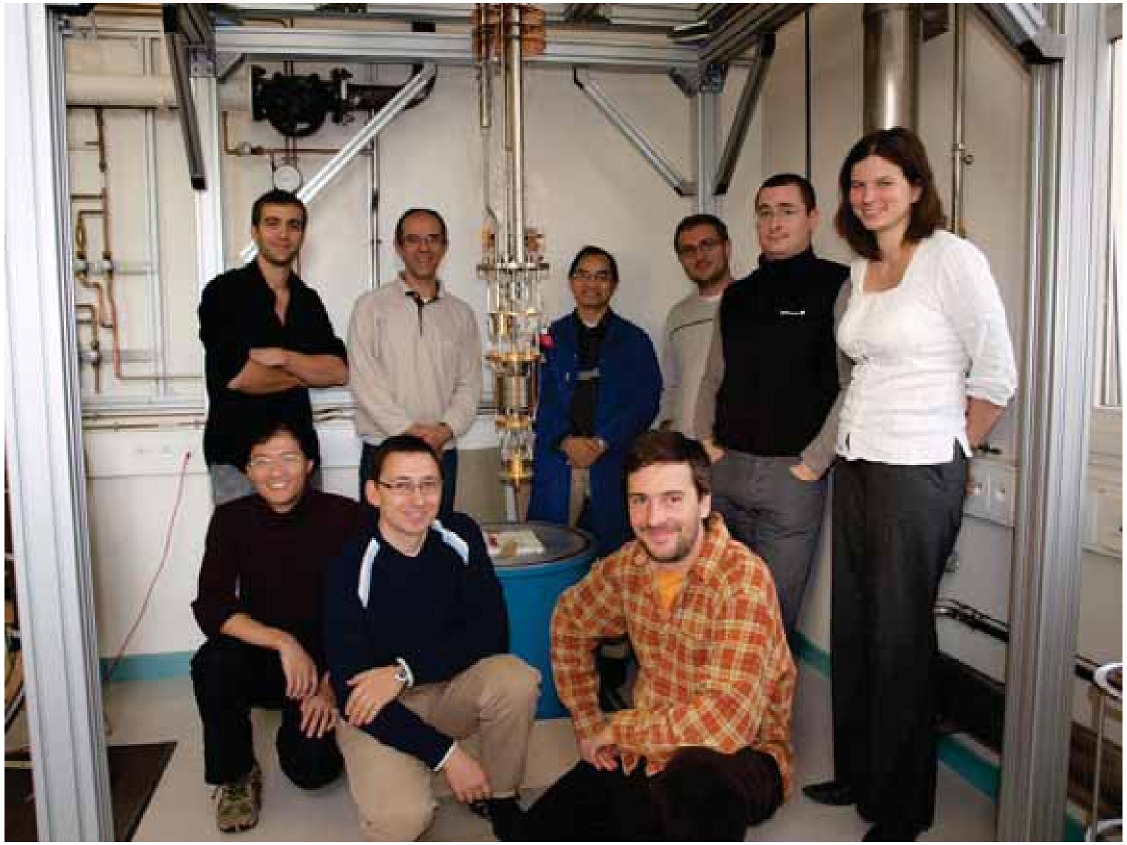
- controllable artificial atoms
- model system for quantum experiments
- adjustable circuits parameters to reach:
    - qubits
    - multilevel system
    - 2D properties
    - multi-degrees of freedom system



In the future:

- reproduction of well known atomic or quantum optics experiments
- realization of new quantum experiments and phenomena

THANK YOU TO!



Projects:
ANR QUNATJO

EURO SQIP

SOLID

Wiebke Guichard, Bernard, Pannetier,
Frank Hekking, Laurent Lévy, Cécile Naud,Ioan Pop,
Iulian Matei, Florent Lecocq, Zihui Peng
and Quantum Coherence group

Cryogénie:
Pierre Chantib, Guillaume Donnier-Valentin,
Christian Gianese, André-Julien Vialle, Anne Gerardin,
Henri Godfrin…

SERAS:
Cyril Bruyère, Olivier Tissot…

Service électronique:
Olivier Exshaw, Maurice Grollier, Jean-Luc Mocellin,
Christophe Gutin, Julien Minet…

Nanofab:
Thierry Fournier, Thierry Crozes, Christophe Lemonias….

Administration:
Nathalie Bourgeat-Lami, Caroline Bartoli, Assya Achour,
Véronique Fauvel, Louise Infuso, Sabine Gadal, Marielle
Lardato, Christine Martinelli,
Martine Lemoine, Jessica Fernandez
and all others I forgot…

Service informatique

Liquefacteur