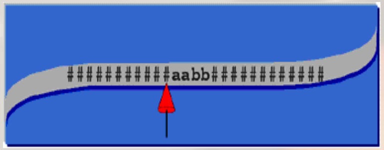
quantum machines… for computing

Alan Turing

the universal Turing machine

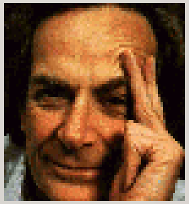


Church-Turing thesis

John von Neumann

sequential computing

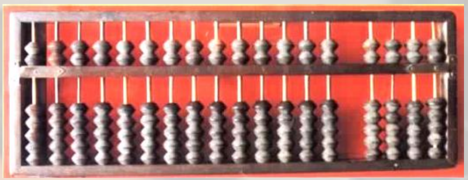
Richard Feynman

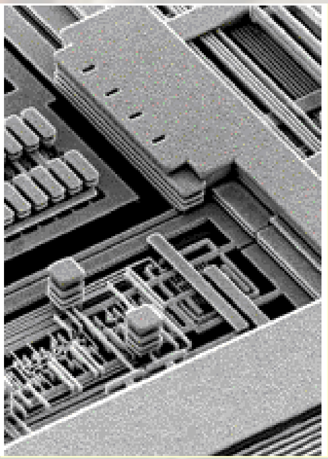


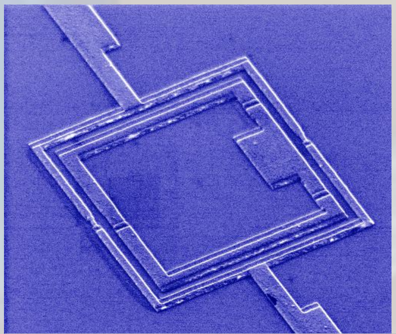
quantum aspects relevant?

David Deutsch

Richard Jozsa





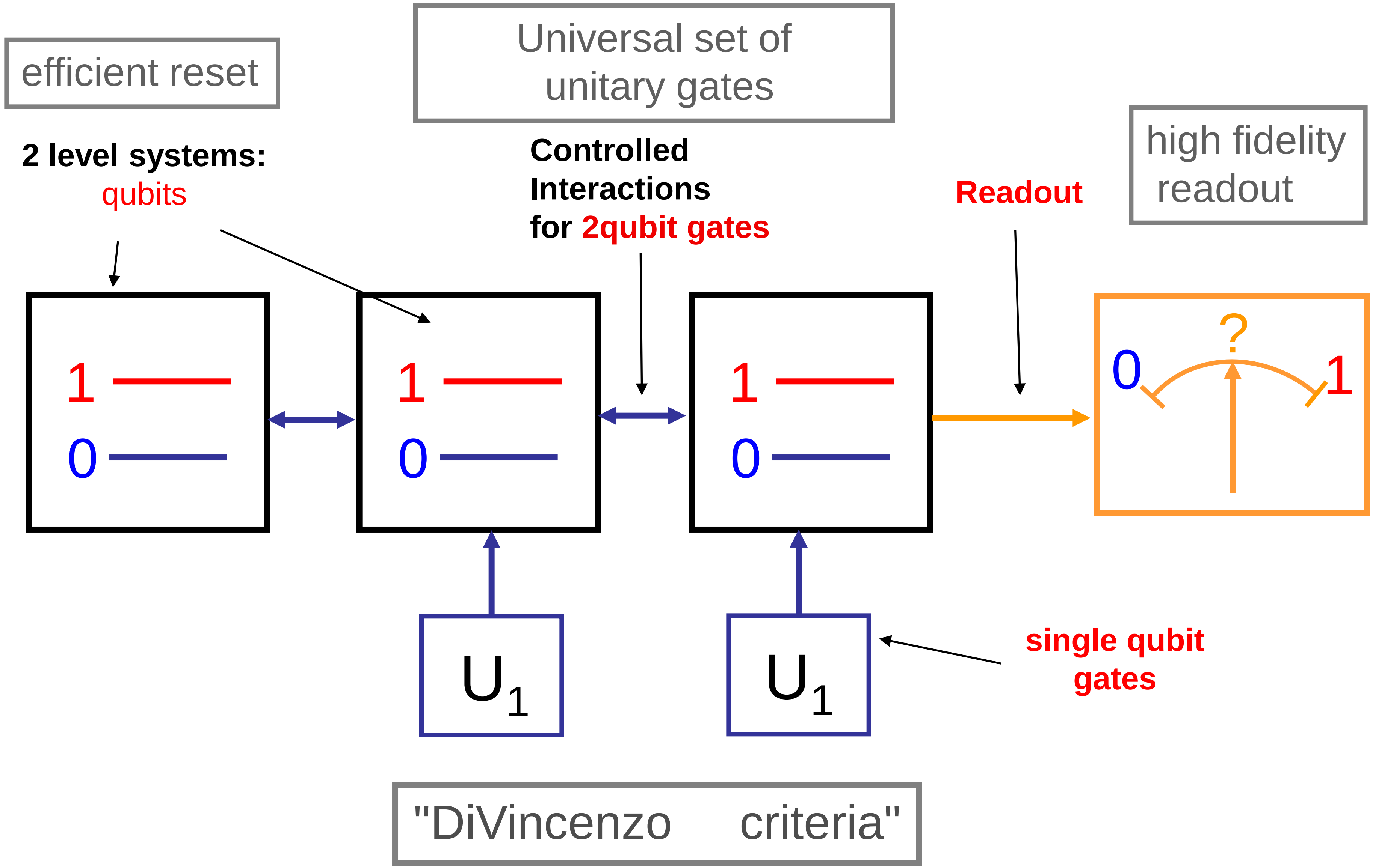


?

1982:
algorithmic complexity
Is not only maths !

quantum computing
more powerful than sequential computing

Schematic blueprint of a quantum processor



Ideal qubit readout :

Projective measurement of $\left|\Psi\right\rangle = \alpha\left|0_1\right\rangle \otimes \left|\Psi_{2...N}\right\rangle + \beta\left|1_1\right\rangle \otimes \left|\Psi'_{2...N}\right\rangle$

yields {

readout 0 and state $\left|0_1\right\rangle \otimes \left|\Psi_{2...N}\right\rangle$ with prob $\left|\alpha\right|^2$

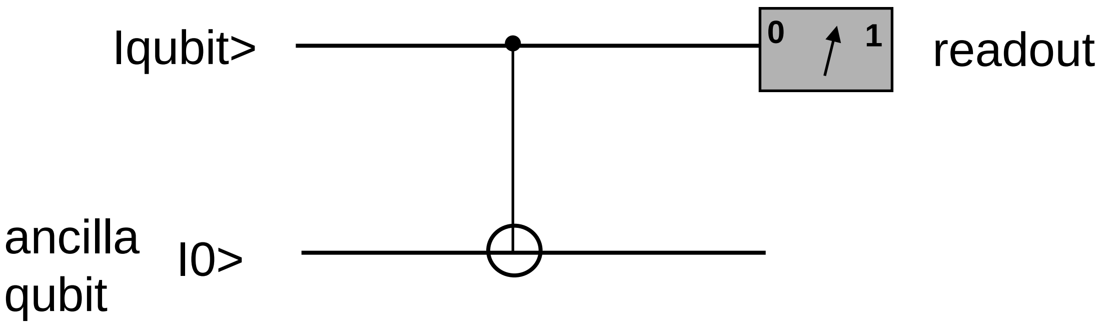
or

readout 1 and state $\left|1_1\right\rangle \otimes \left|\Psi'_{2...N}\right\rangle$ with prob $\left|\beta\right|^2$

Readout fidelity (for answer)

if non destructive: **Projection fidelity** for state after readout (QND ?)

Note: A high fidelity destructive readout can be made QND :



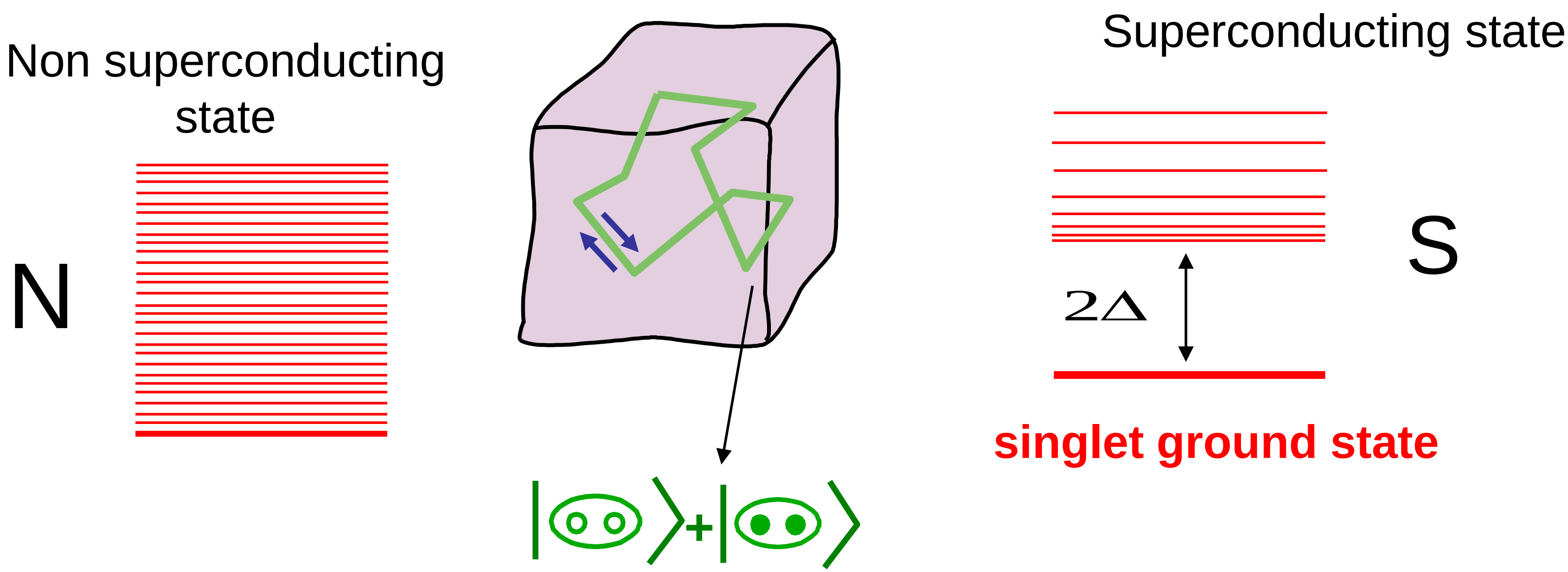
Lecture fidèle non-destructive d'un qubit supraconducteur

QUANTRONICS GROUP
(SPEC, CEA-Saclay branch)

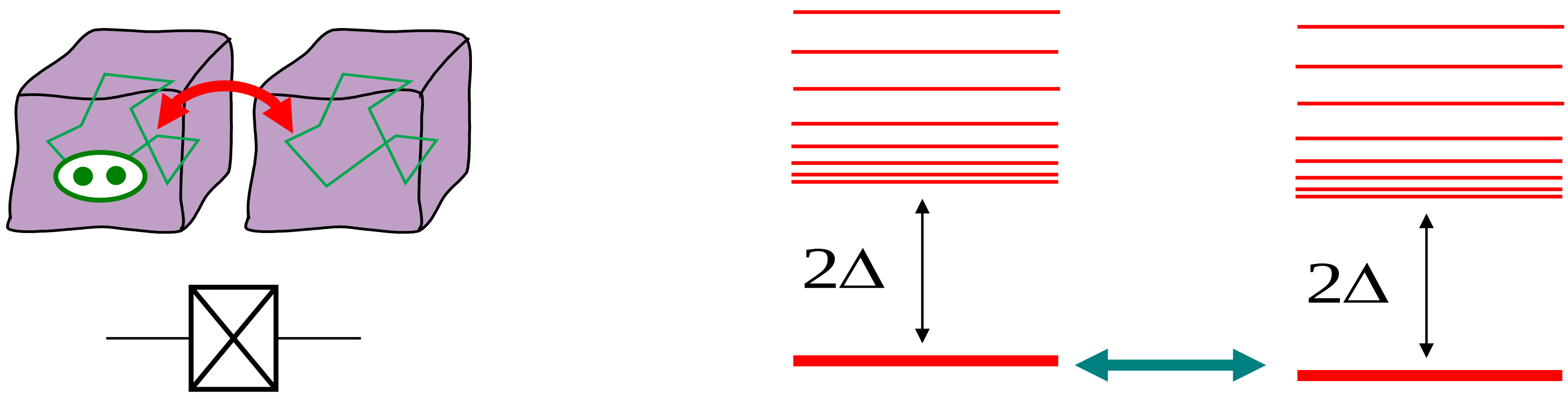
F. Mallet, F. Ong, A. Palacios-Laloy, F. Nguyen,
P. Sénat, P. Orfila P. Bertet, D. Vion, D. Estève
with the help of Quantronics

Superconductivity helps making qubits

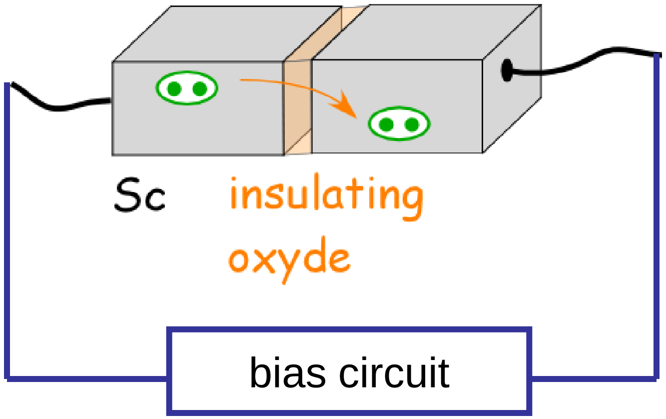
Energy spectrum of an isolated electrode

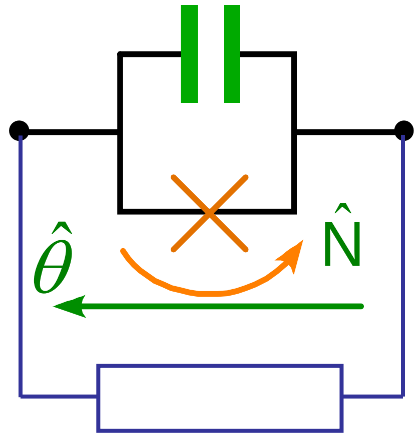


The Josephson junction

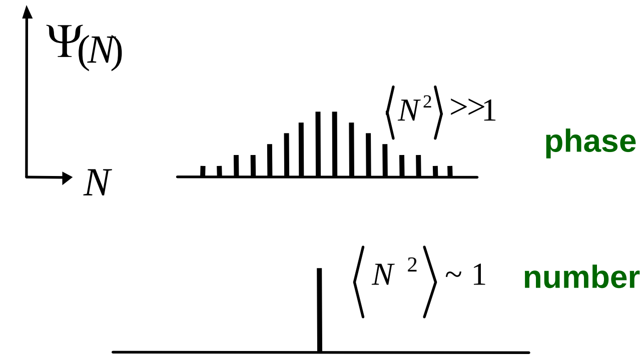


The single Josephson junction circuit





θ and N conjugated variables

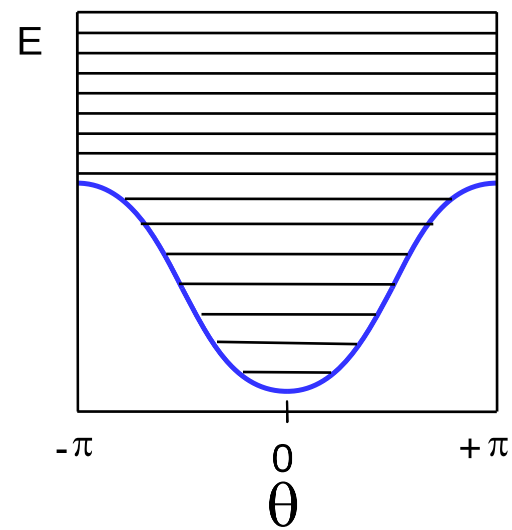


Hamiltonian:

$$H = H_J + H_{elm}$$

Josephson Hamiltonian:

$$H_J = -E_J \cos\hat{\theta}$$

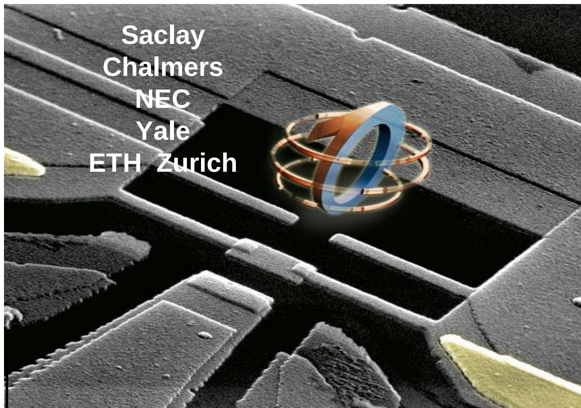


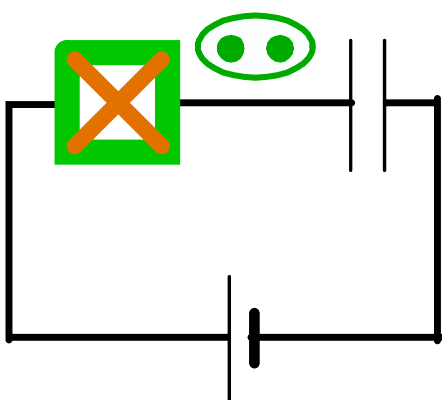
superconducting qubits come in different flavors

Various types of superconducting qubits

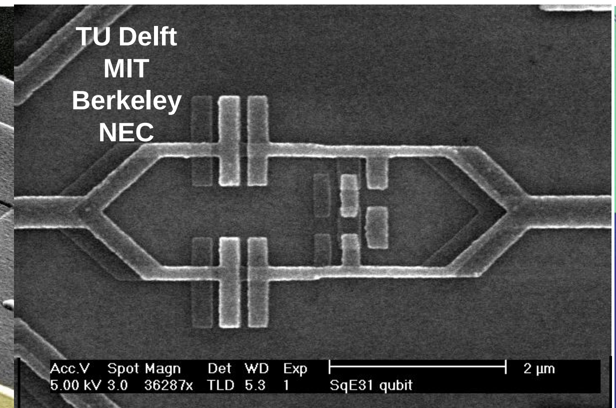
Cooper-pair boxes

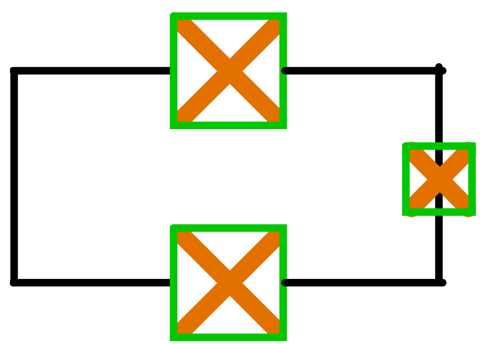
Charge qubit/Quantronium/Transmon



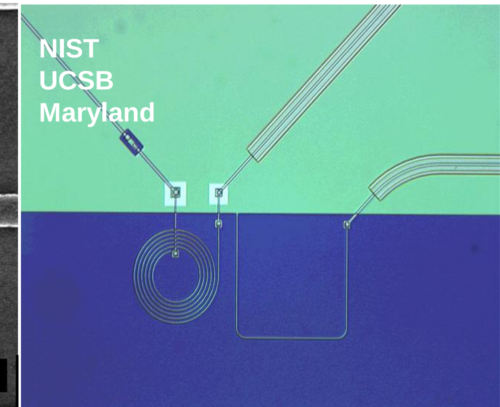


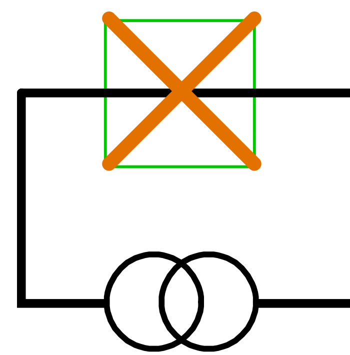
Flux qubits

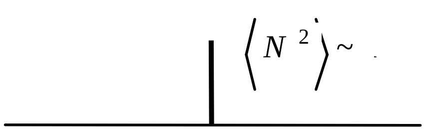




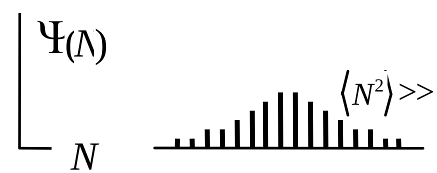
Phase qubits







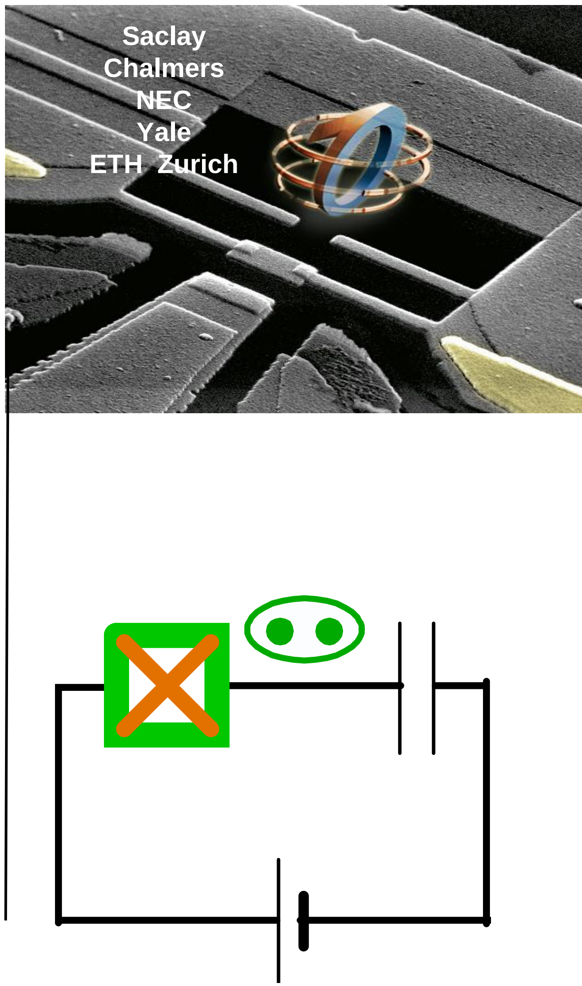
naively: from number to phase states



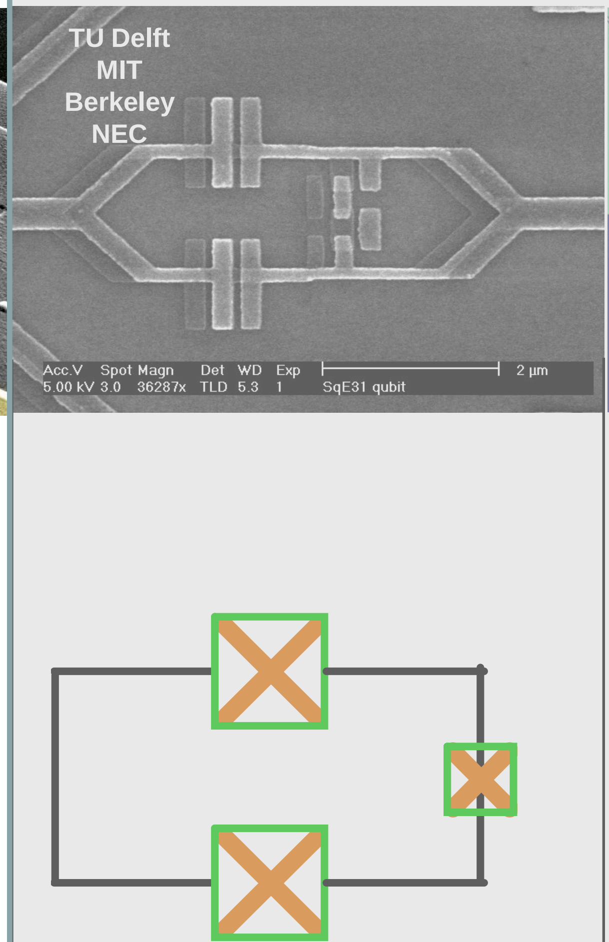
Various types of superconducting qubits

Cooper-pair boxes

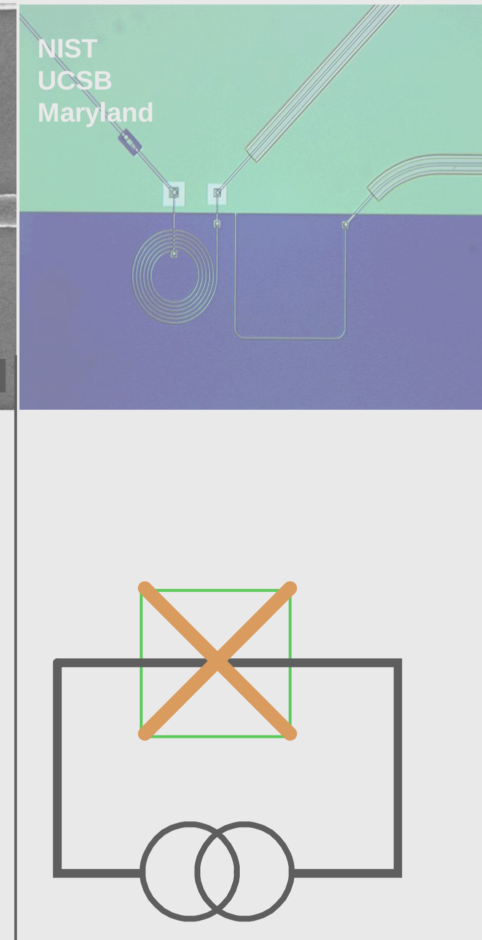
Charge qubit/Quantronium/**Transmon**

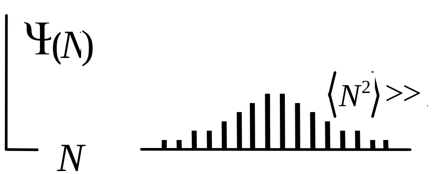


Flux qubits

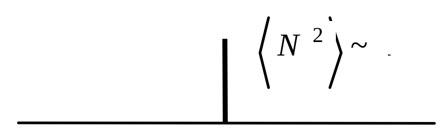


Phase qubits



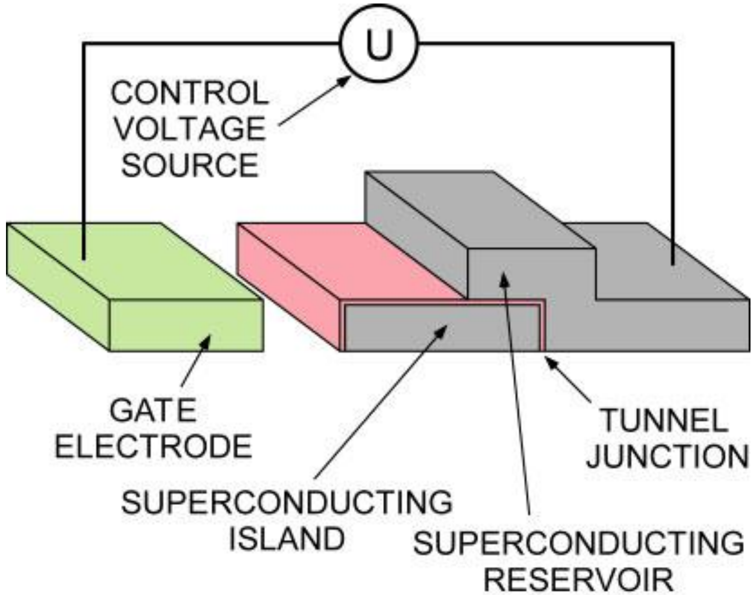


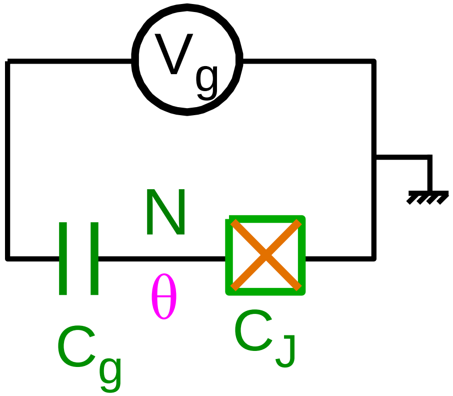
CPBs cover the whole range



simplest superconducting artificial atom: the Cooper pair box

Quantronics 1996
NEC1999





1 degree of freedom: $\left[\hat{\theta},\hat{N}\right]=i$

1 knob: V_g or $N_g = C_g V_g/(2e)$

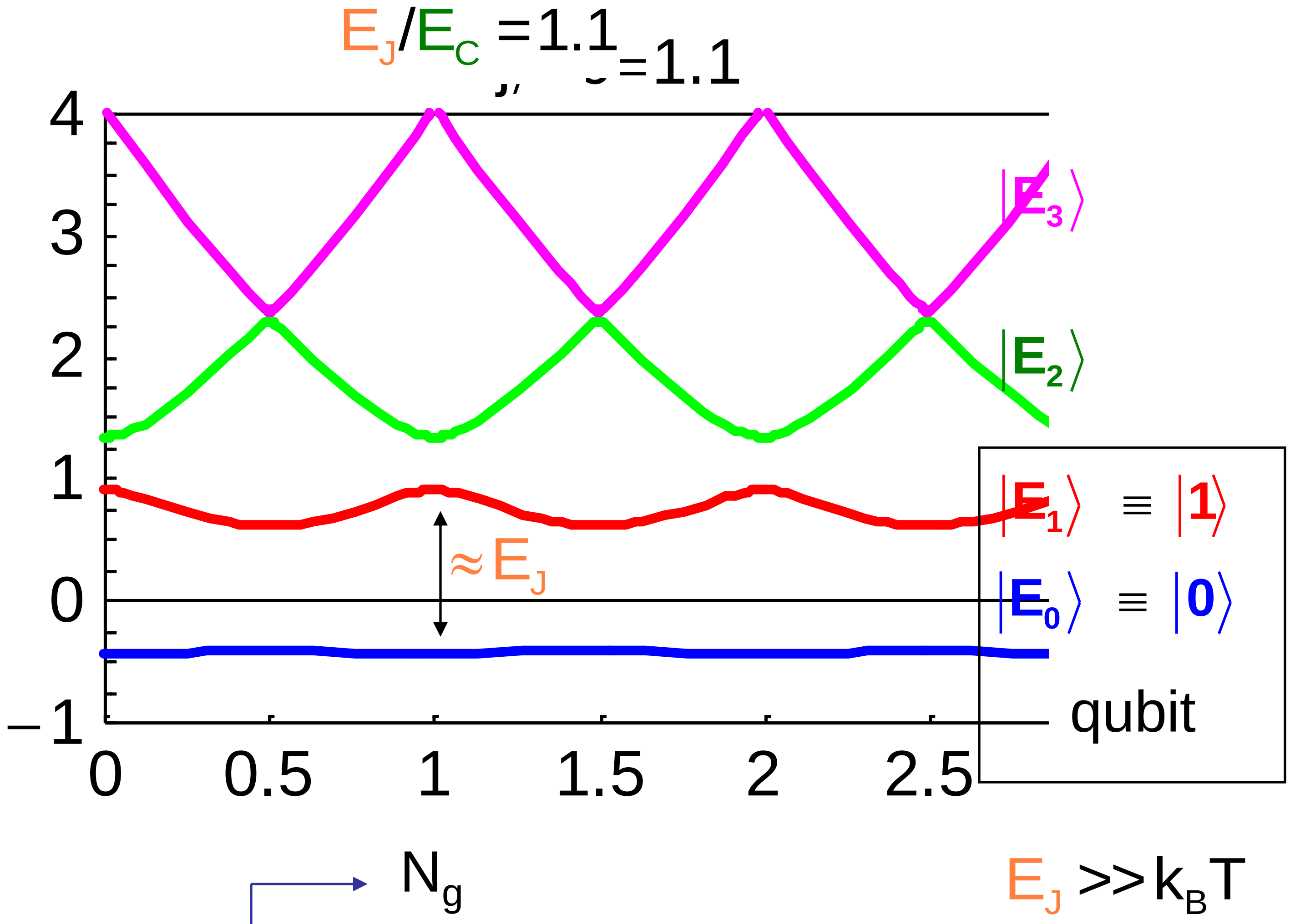
2 characteristic energies: $E_J = \frac{h\Delta}{8e^2 R_t}$ $E_C = \frac{(2e)^2}{2(C_g + C_J)}$

Hamiltonian: $\hat{H} = E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\theta}$

Electrostatic

Phase difference cost

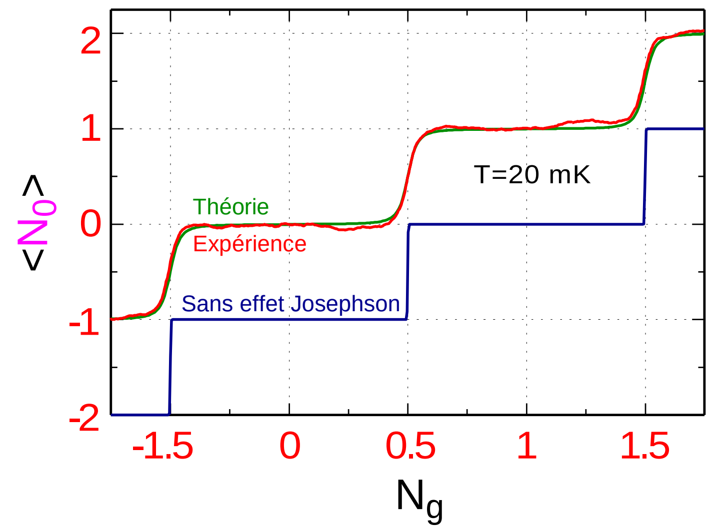
Hamiltonian and energy spectrum



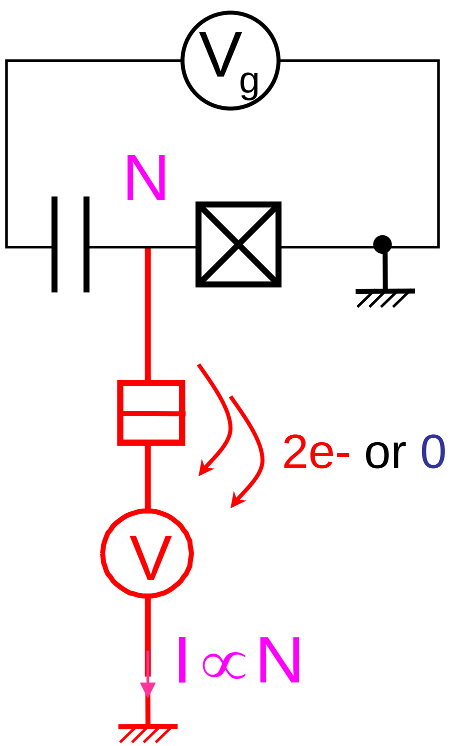
tunable artificial atom

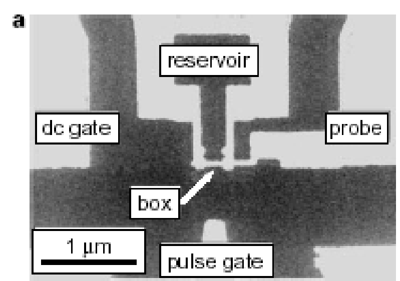
Cooper Pair box coherence : ten years after (I)

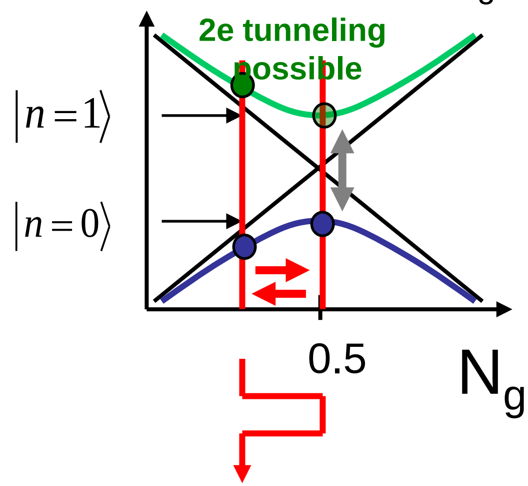
Prehistory: ground state charge (Quantronics 1996)

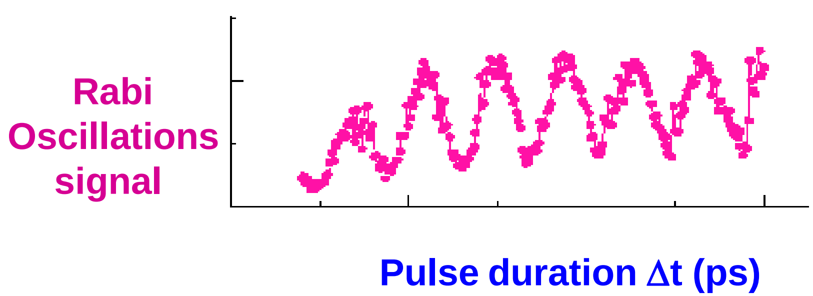


Quantum coherence (NEC, 1999)



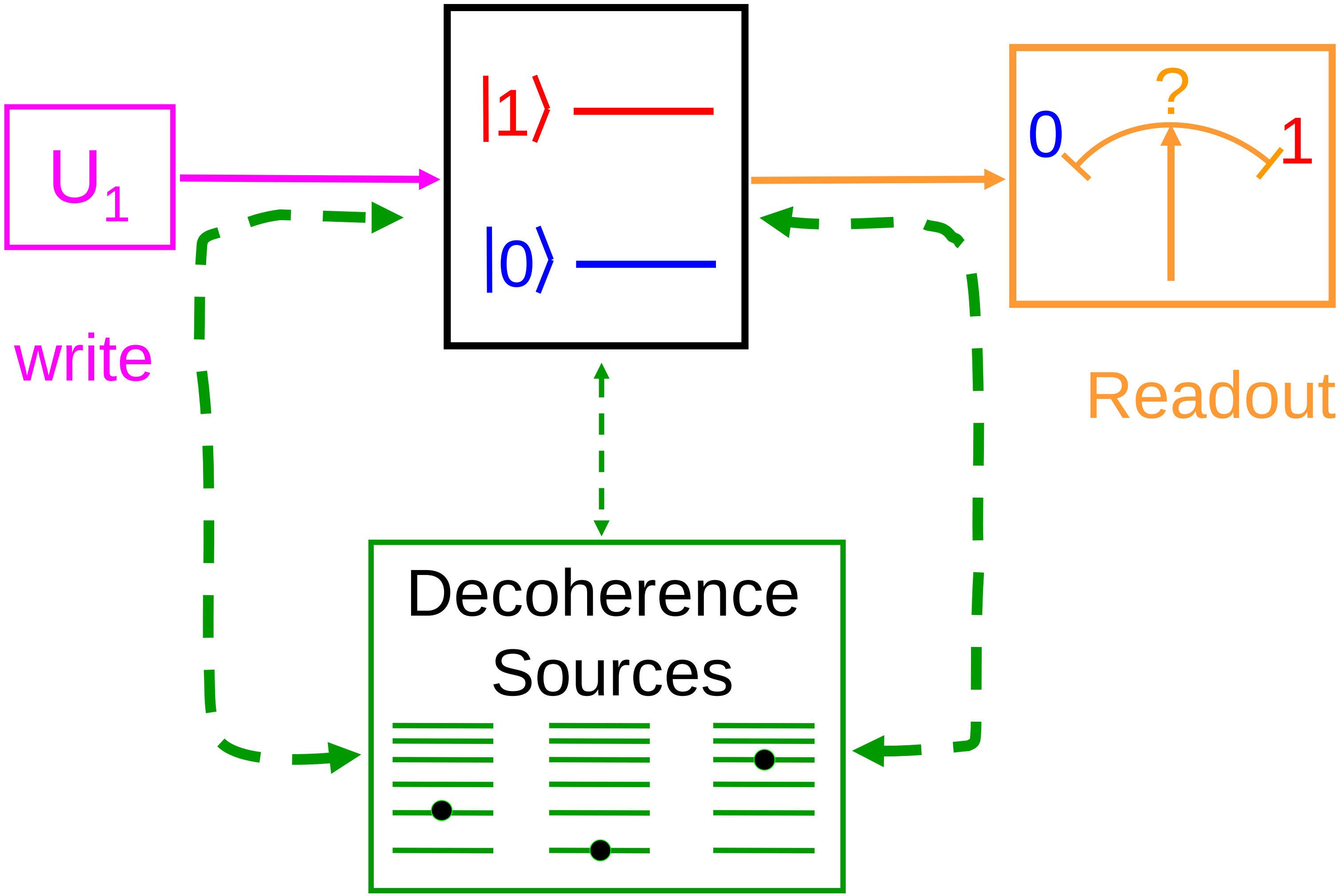






Coherence time: 5-10 ns

The main (?) difficulty

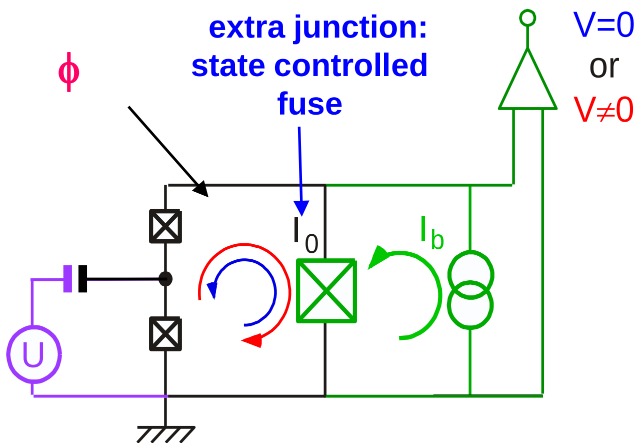


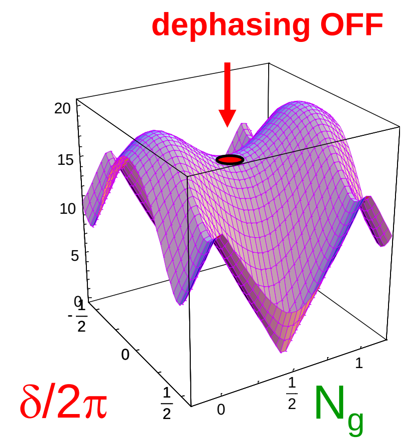
Open ports → Decoherence **relaxation dephasing**

Cooper Pair box coherence : ten years after (II)

a CPB with single shot readout and a strategy against dephasing**: the quantronium**
(Quantronics 2001)

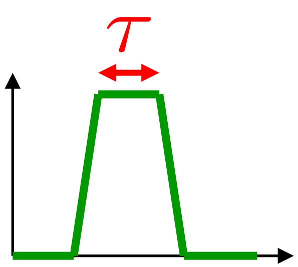
Vion et al., Science 296 (2002)

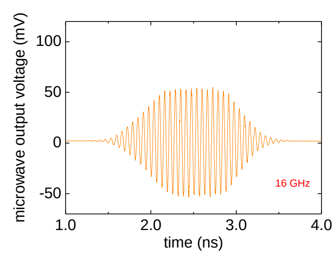


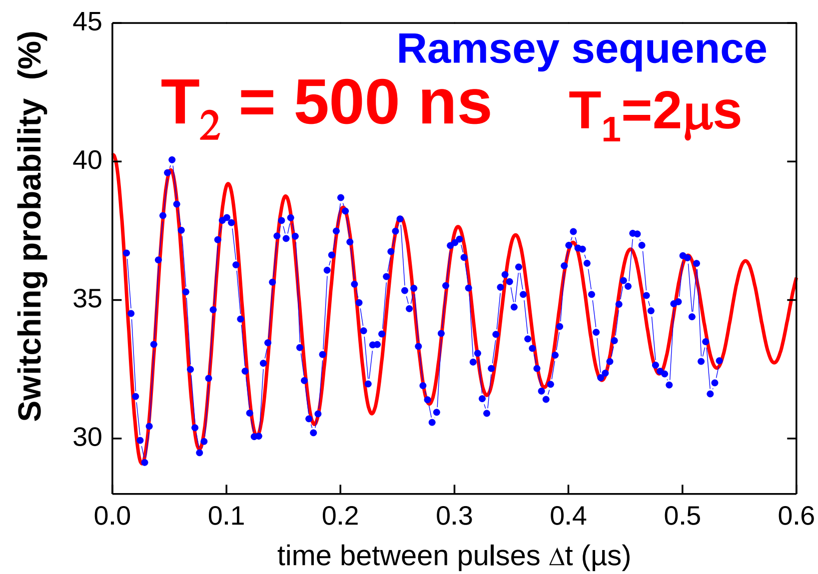


Resonant drive

switching readout



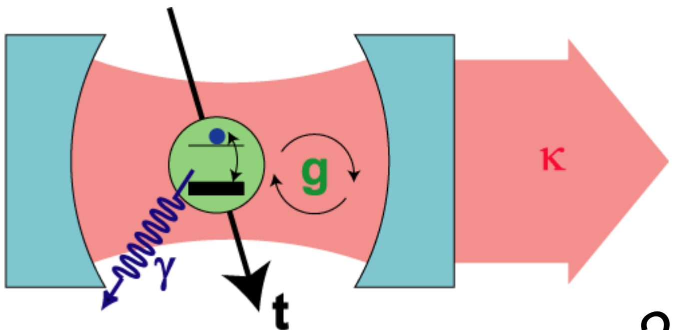




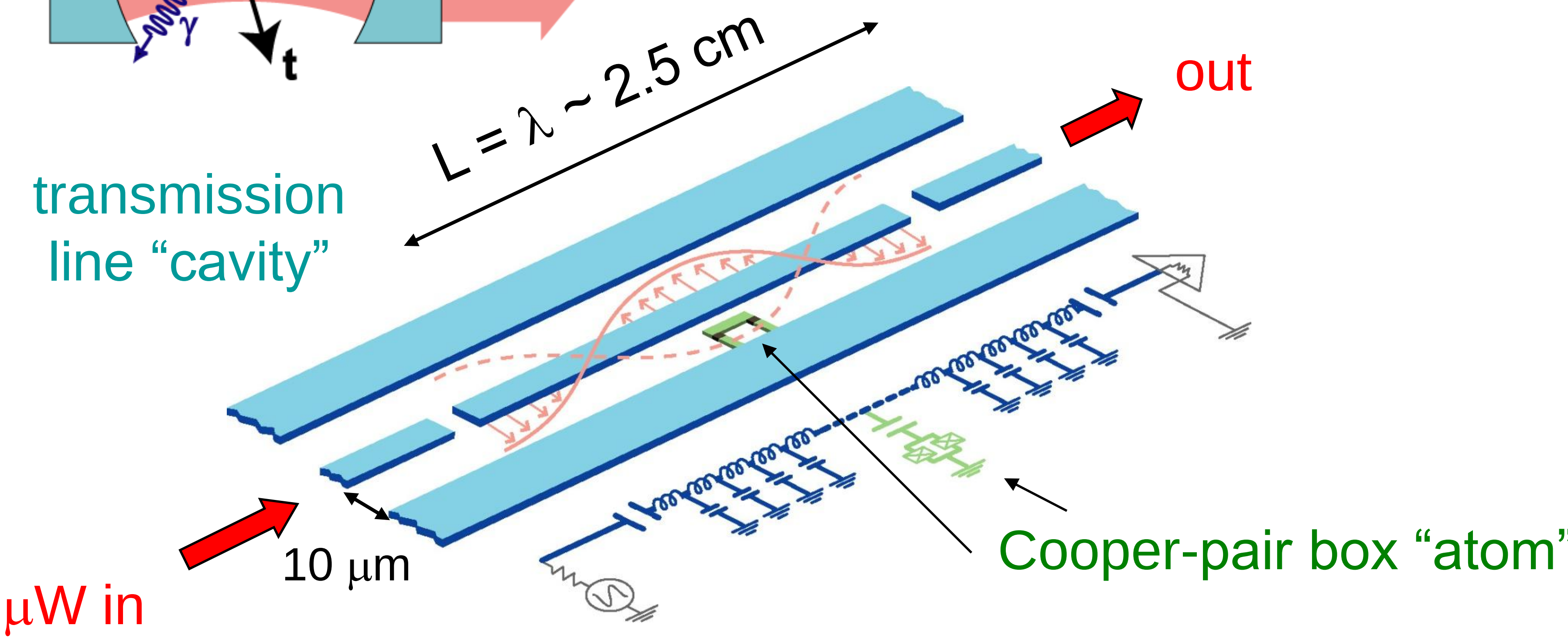
x100 gain
Coherence and readout fidelity still limited
more complex circuits do not work well

A CPBox embedded in a **1D microwave cavity** (Yale 2003)

Cavity QED
(LKB Haroche Raimond, …)

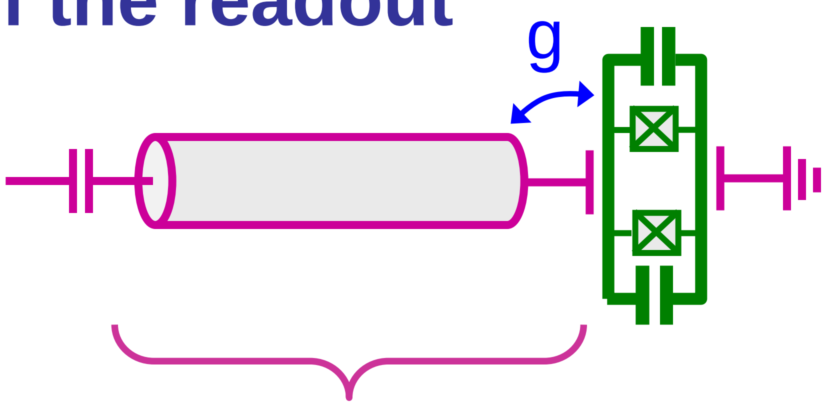


A. Blais *et al*., Phys. Rev. A 69,(2004)
A. Walraff *et al*., Nature 431, (2004)



courtesy of R. Schoelkopf

Principle of the readout

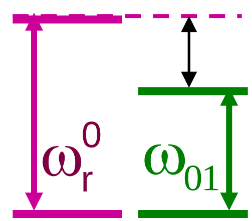


$\lambda/2$ resonator

bare resonance frequency = ν_r^0

Dispersive regime

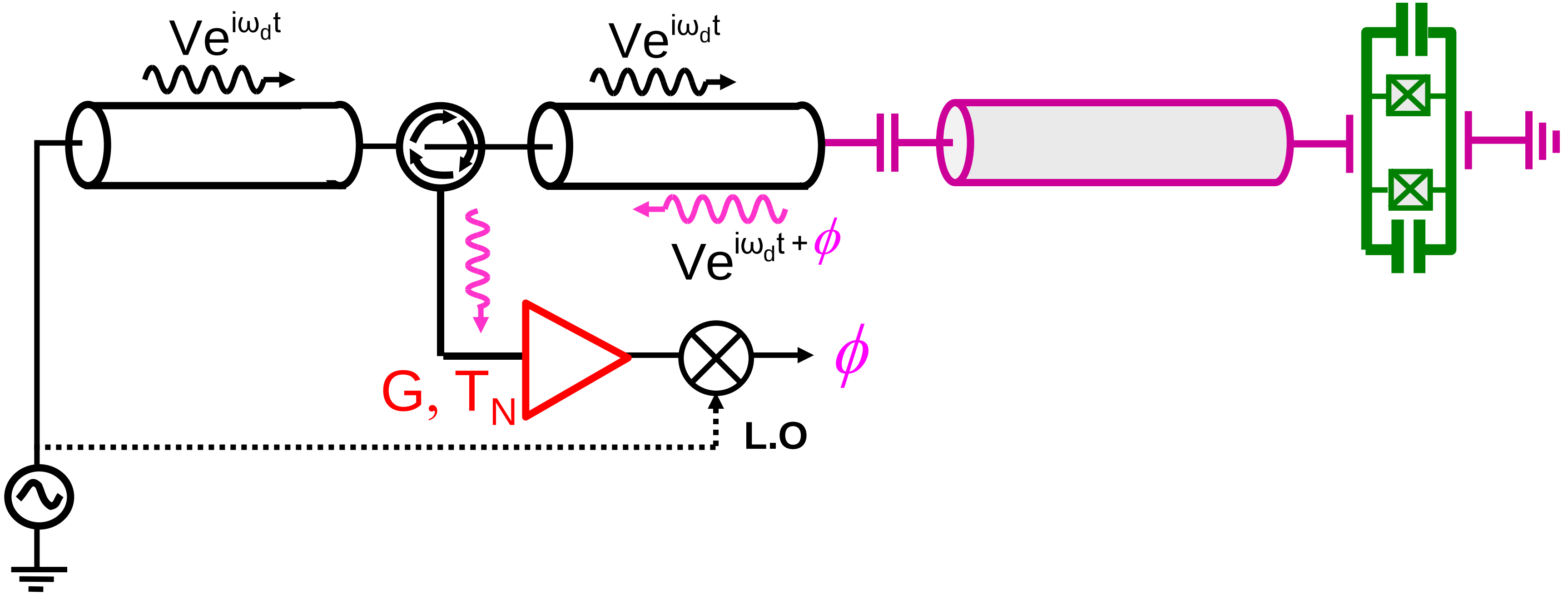
$$|\Delta| = |\omega_{01} - \omega_r^0| >> g$$

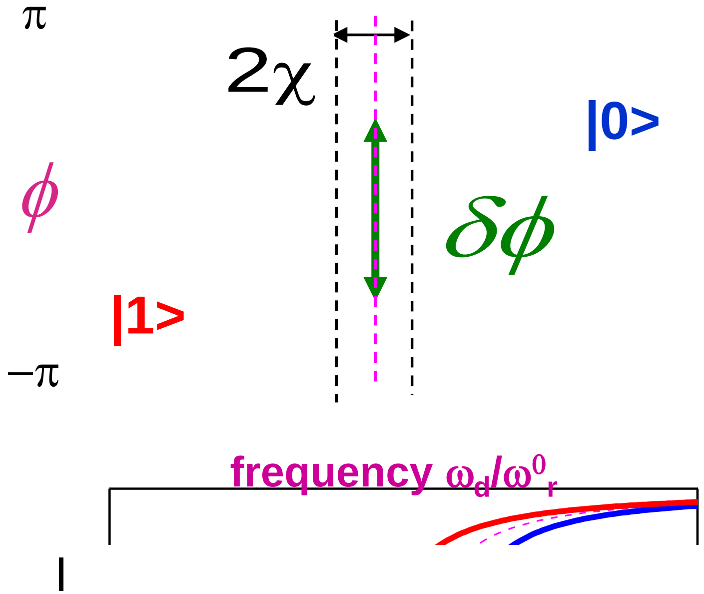


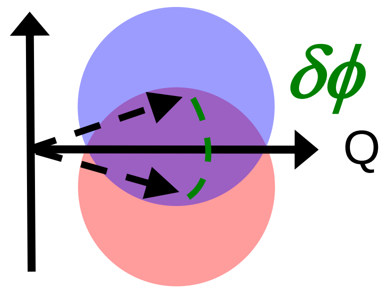
$$\hat{H}_{eff} = -\frac{\hbar}{2}(\omega_{01} + \chi)\hat{\sigma}_Z + \hbar(\omega_r^0 - \chi\hat{\sigma}_Z)\hat{a}^+\hat{a}$$

Qubit controlled Cavity pull

Dispersive readout implementation

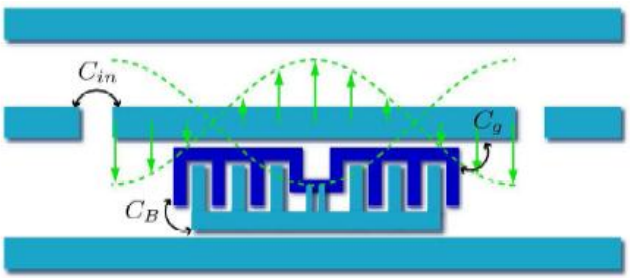




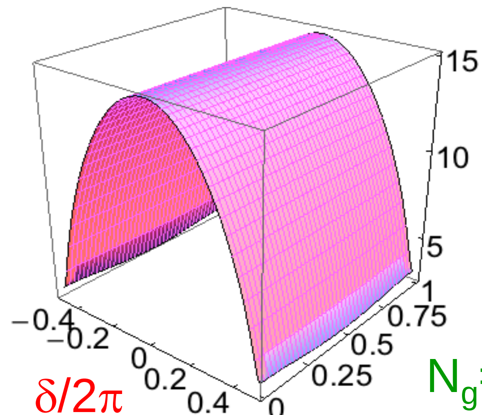


t_{meas}<<T1 → S/N limitation

A CP Box **Ej>>Ec** insensitive to charge noise: **the transmon** (Yale 2007)



added interdigitated C



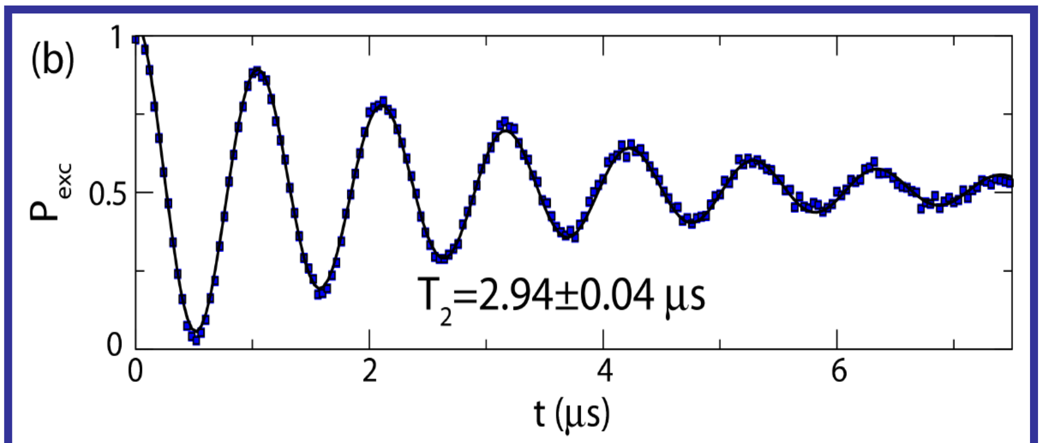
$\delta/2\pi$
$=\Phi/\Phi_0$

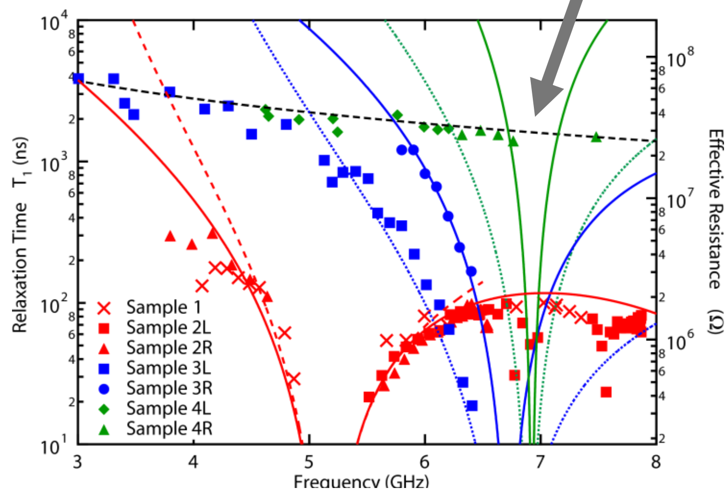
$N_g=$
$C_gV_g/2e$

Koch et al., PRA 76 (2007)
Schreier et al., PR B 77, (2008)

flat CPB bands

saturation origin ?



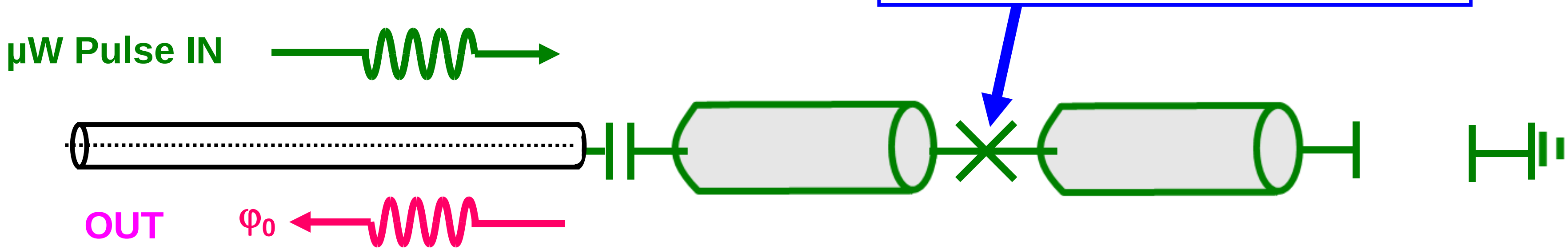


progress on coherence, **but**
high fidelity readout still missing !

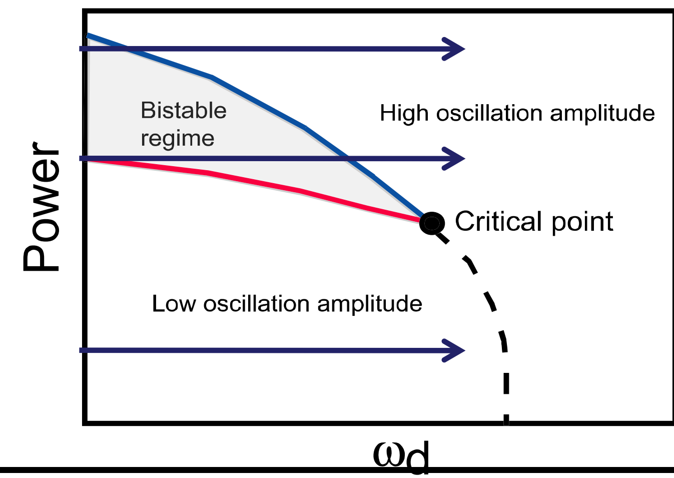
‘our’ Solution: the Josephson Bifurcation Amplifier (JBA)

M. Devoret Qulab (Yale)
JBA: I. Siddiqi et al., PRL 93 (2004)
cavity JBA: M. Metcalfe et al. PRB 76 (2007)

Josephson non linear inductor softens the resonance



Dynamical bifurcation transition
to high oscillation amplitude
in a non-linear oscillator



Readout: the bifurcation transition threshold depends on qubit state

Note: other transitions possible: i.e. onset of parametric oscillations , …

Josephson Bifurcation Amplifier realizations:

lumped element version on Quantronium:

Qulab, Yale

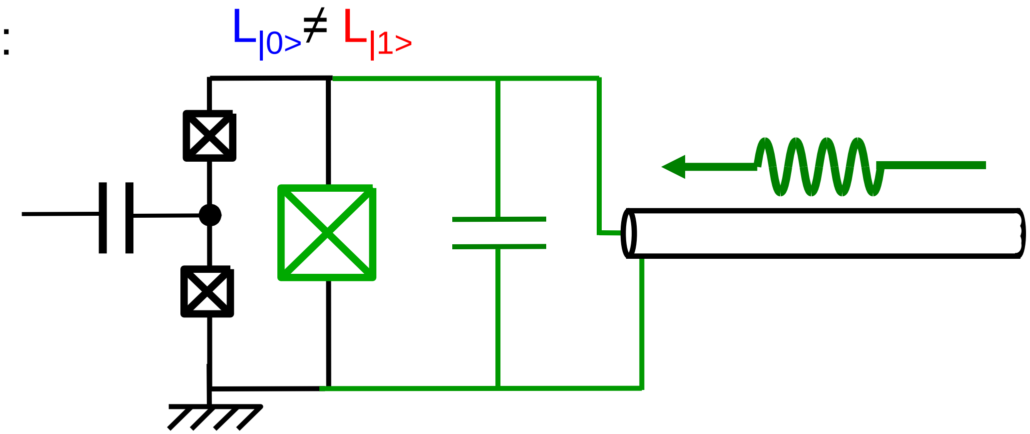
contrast=48%

T_2 ~ 300ns (≠2T_1)

Quantronics

contrast=51%

T_2 ~ 120ns (≠2T_1)

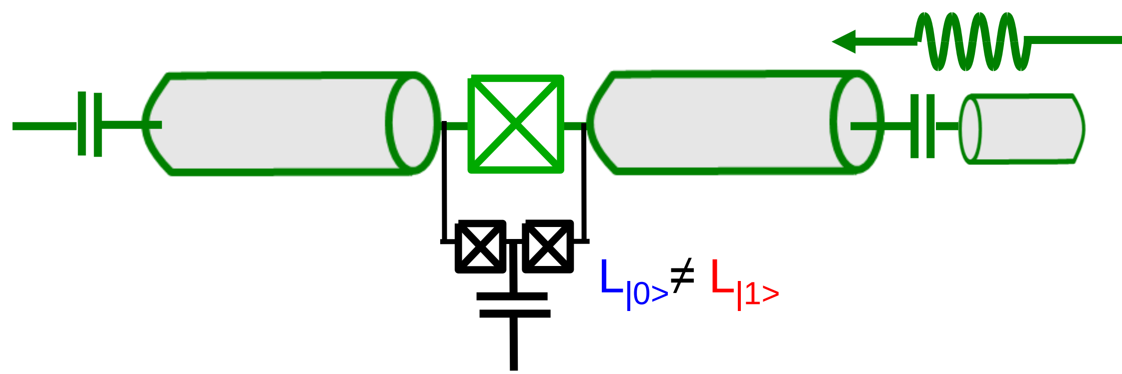


distributed version on Quantronium:

Qulab, Yale

contrast=60%

T_2 ~ 500ns (≠2T_1)



lumped version on flux qubit:

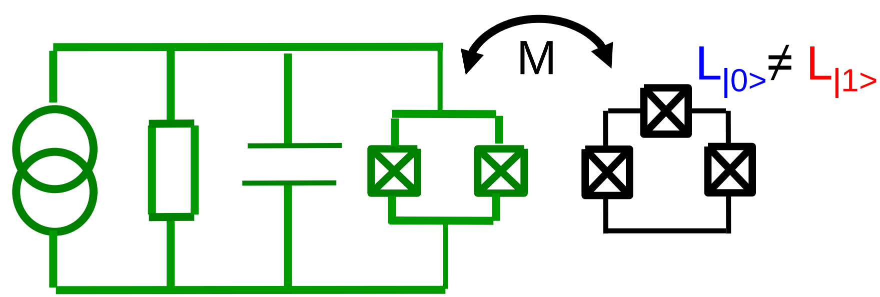
J.E. Mooij Group, T U Delft

Lupascu et al.,
Nature Physics 3
(2007)

contrast=87%

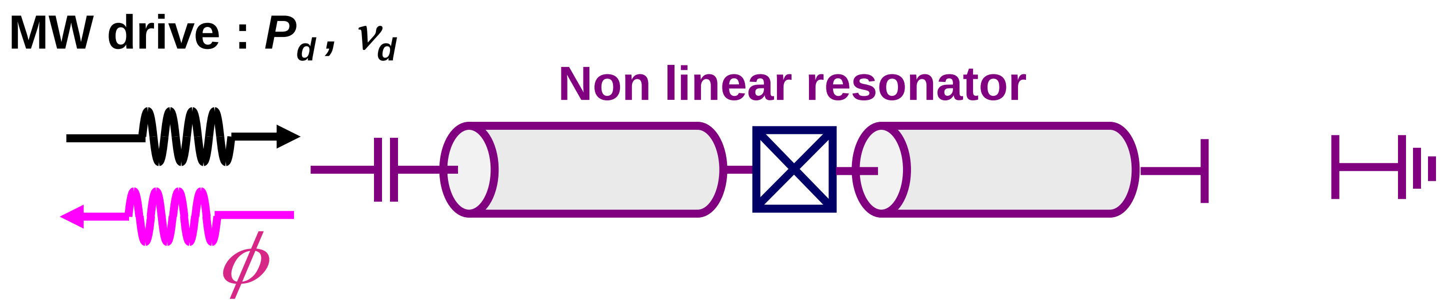
T_2~100ns (≠2T_1)

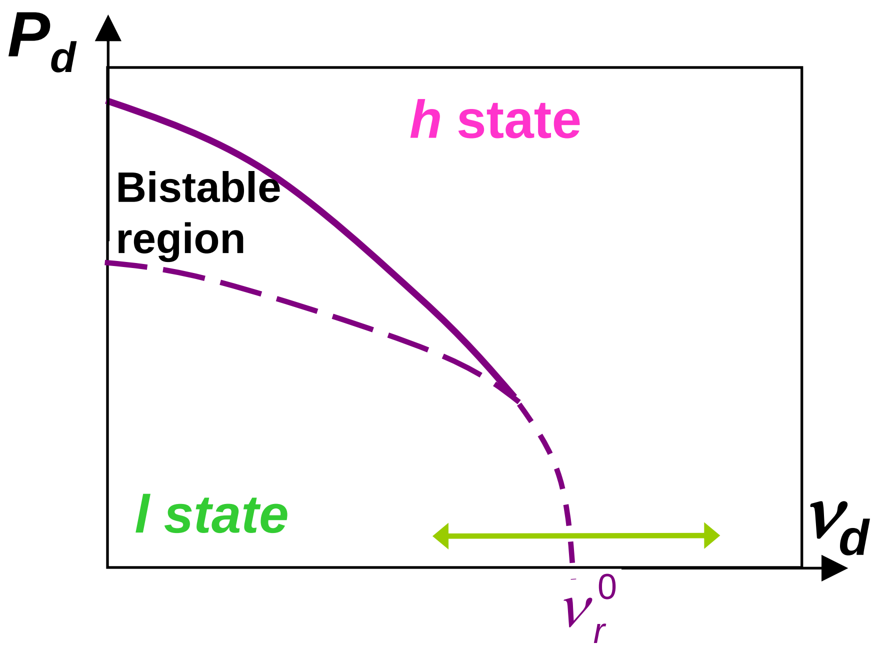
QND

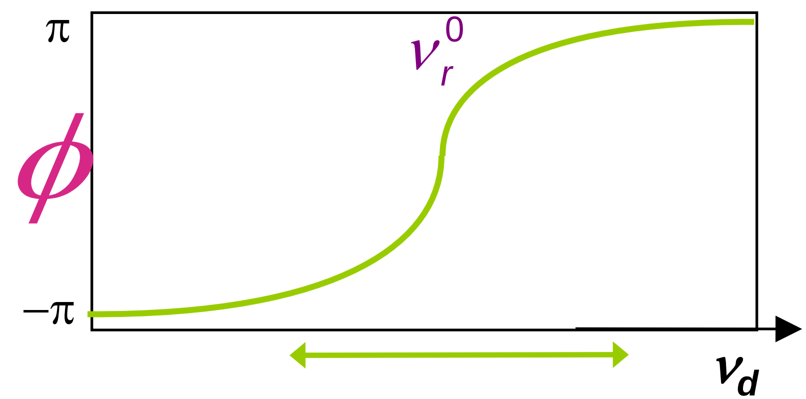


The Cavity Josephson Bifurcation Amplifier

JBA: I. Siddiqi et al., PRL 93, 207002 (2004)
CJBA: M. Metcalfe et al., Phys. Rev. B 76, 174516 (2007)







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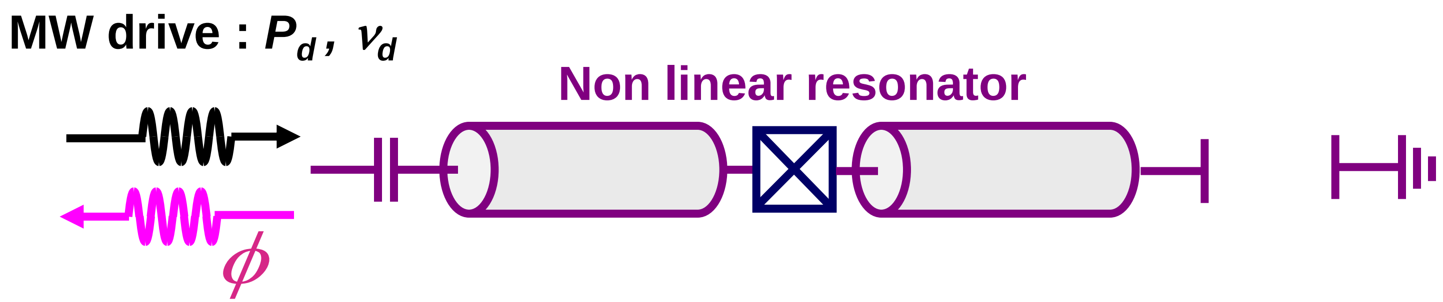

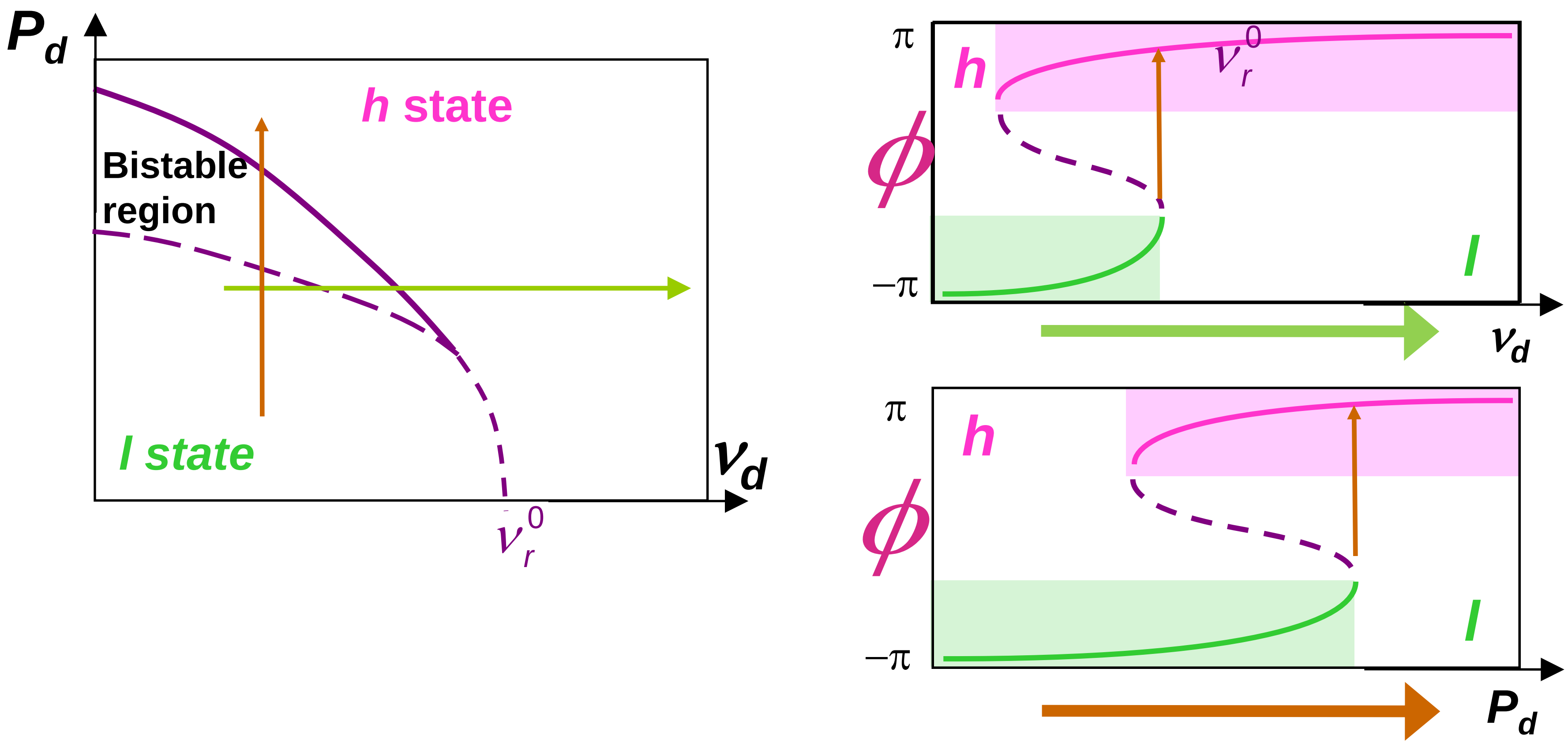

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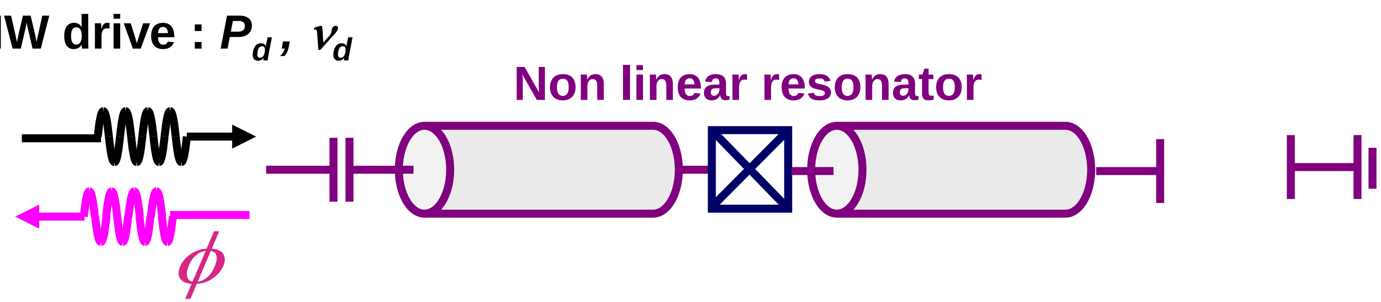
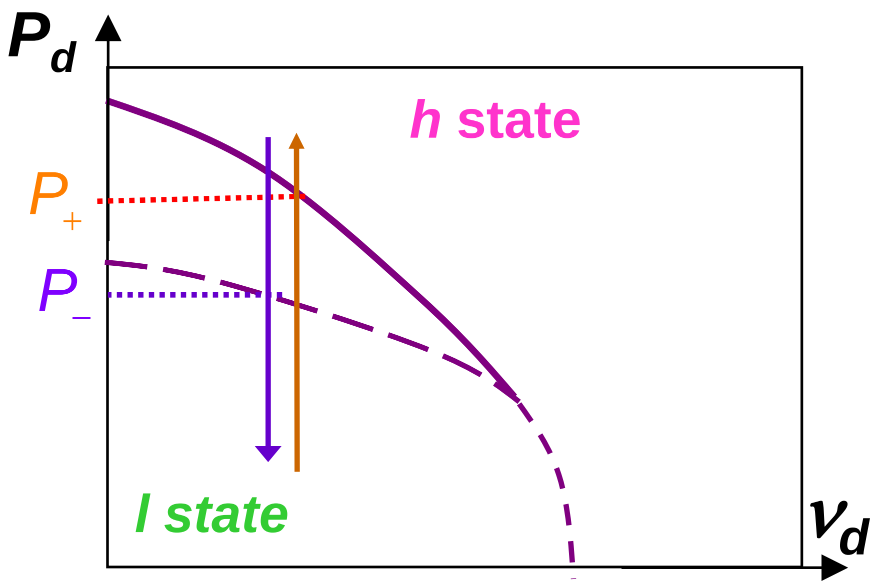
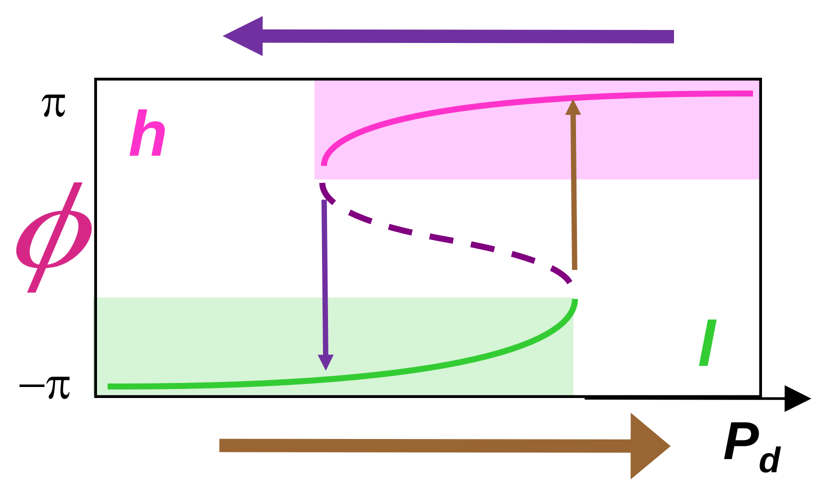
JBA: I. Siddiqi et al., PRL 93, 207002 (2004)
CJBA: M. Metcalfe et al., Phys. Rev. B 76, 174516 (2007)



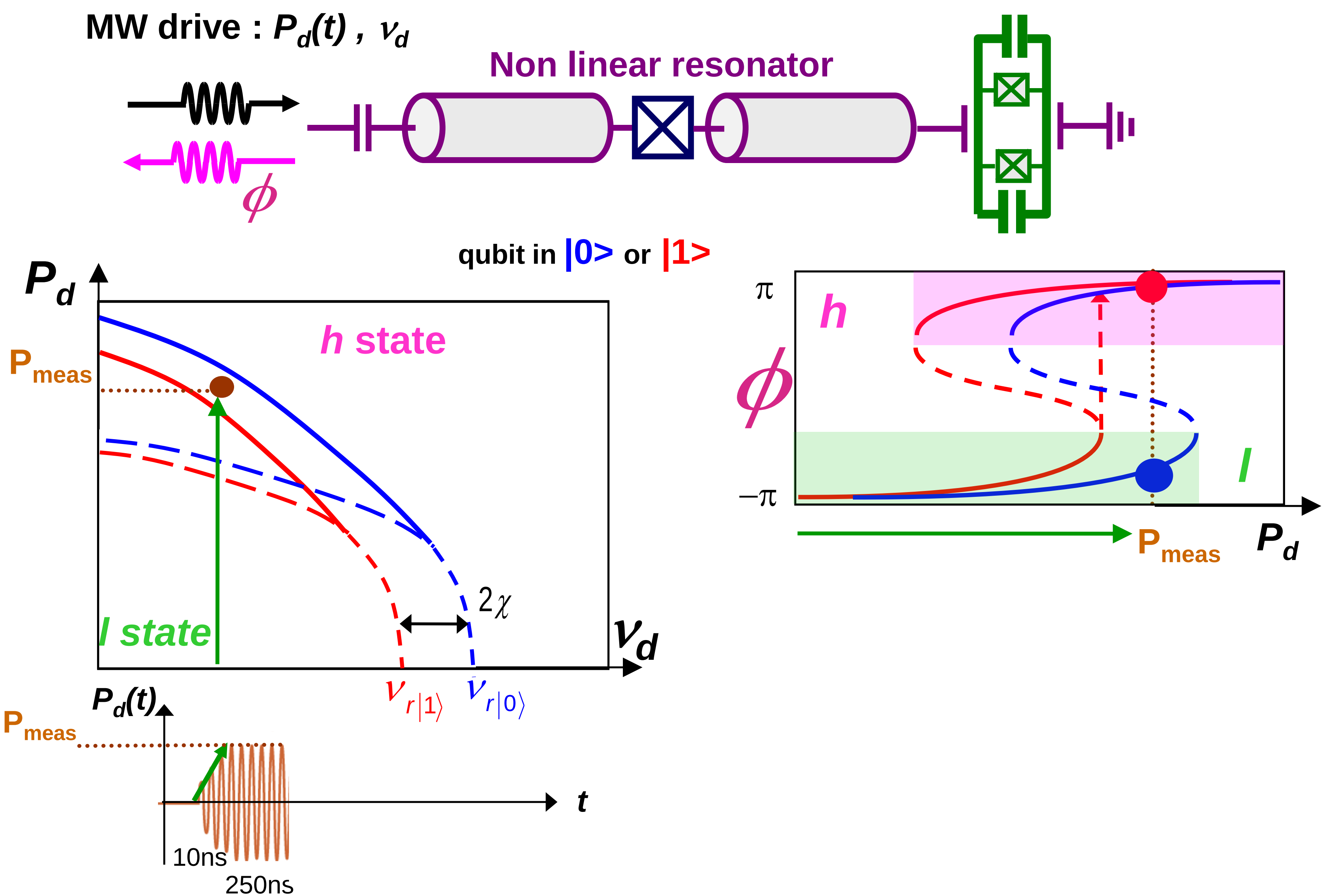


Large drive power :

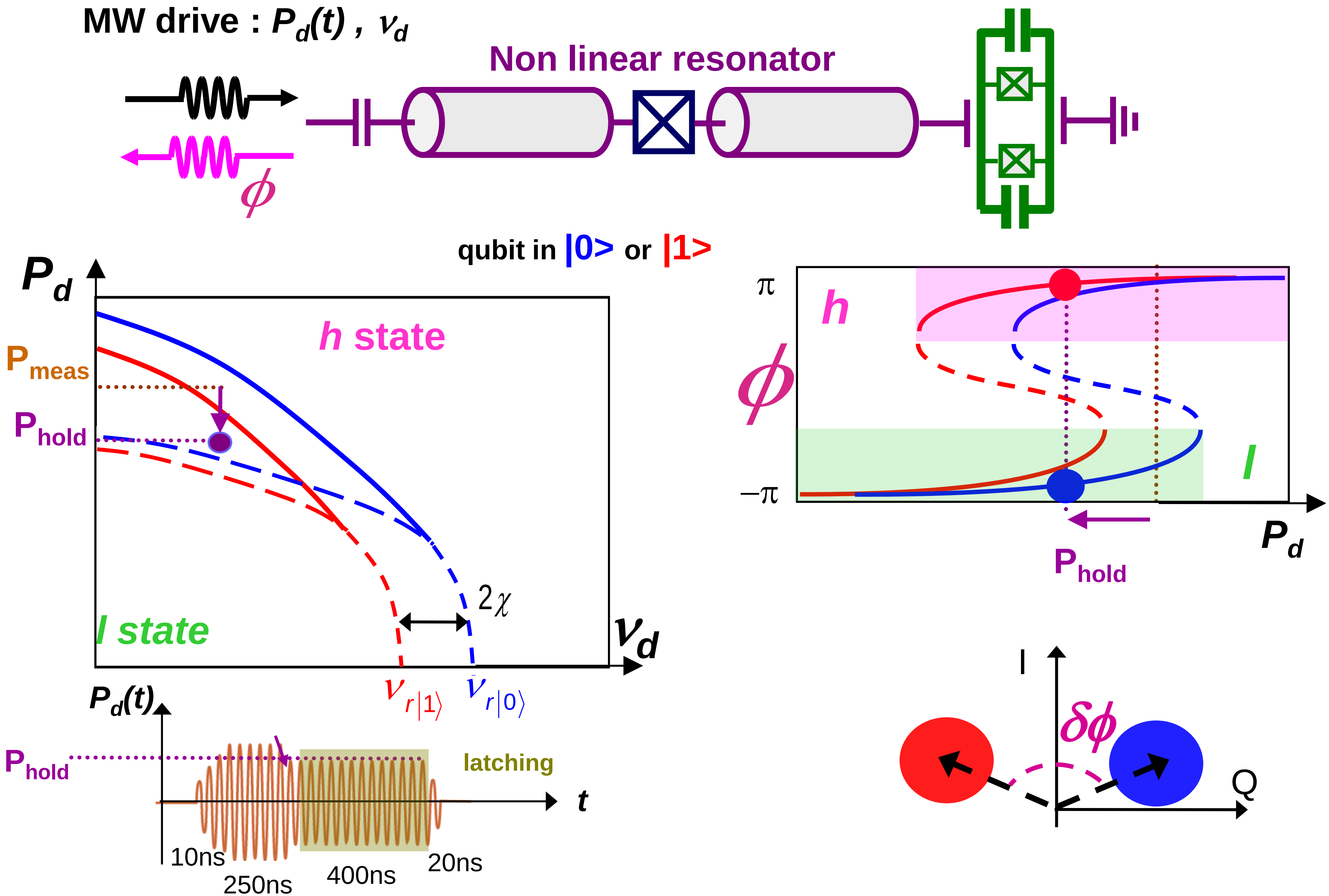
BIFURCATION + HYSTERESIS



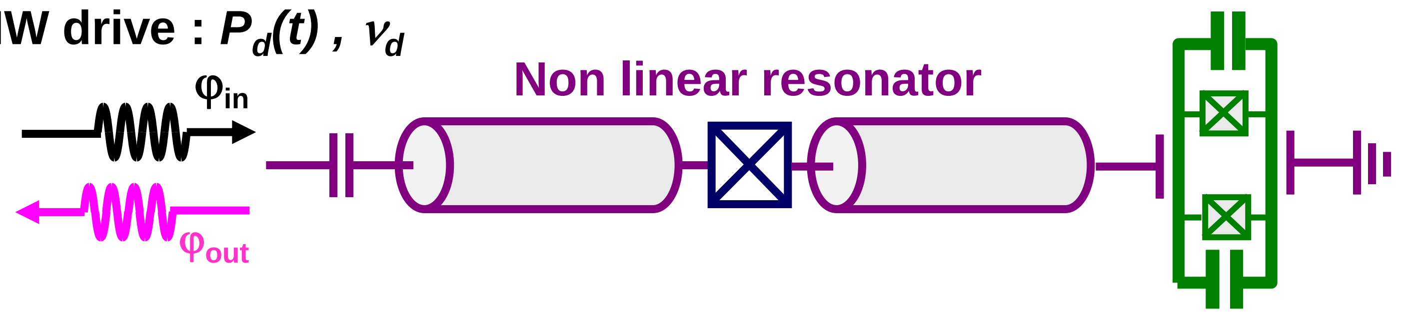
Readout of transmon with CJBA



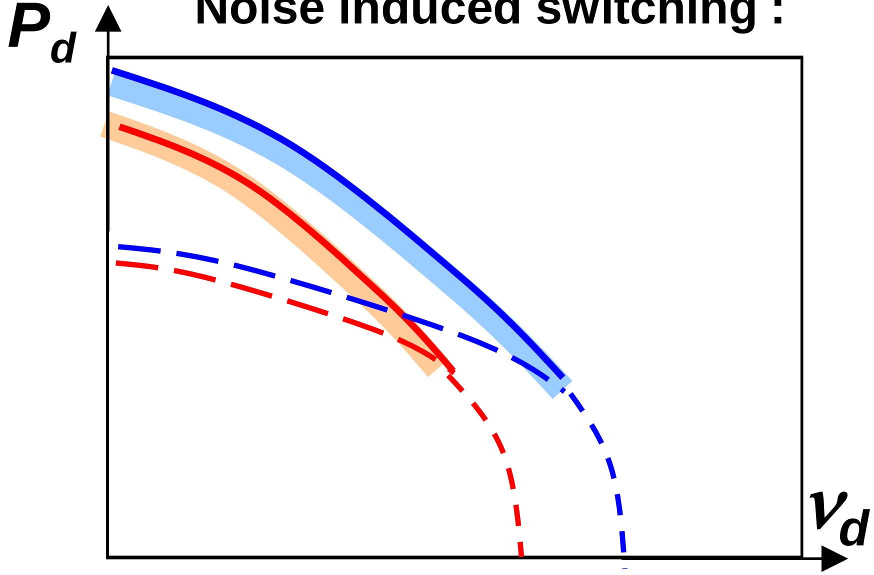
Readout of transmon with CJBA

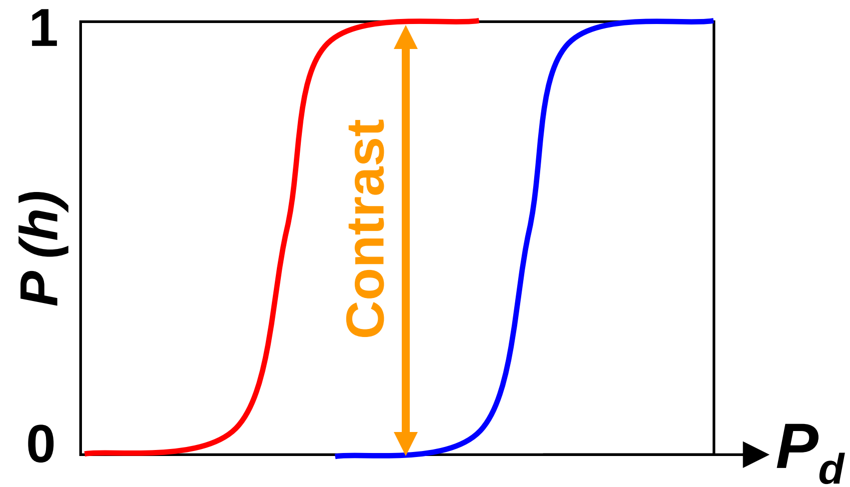


Readout of transmon with CJBA



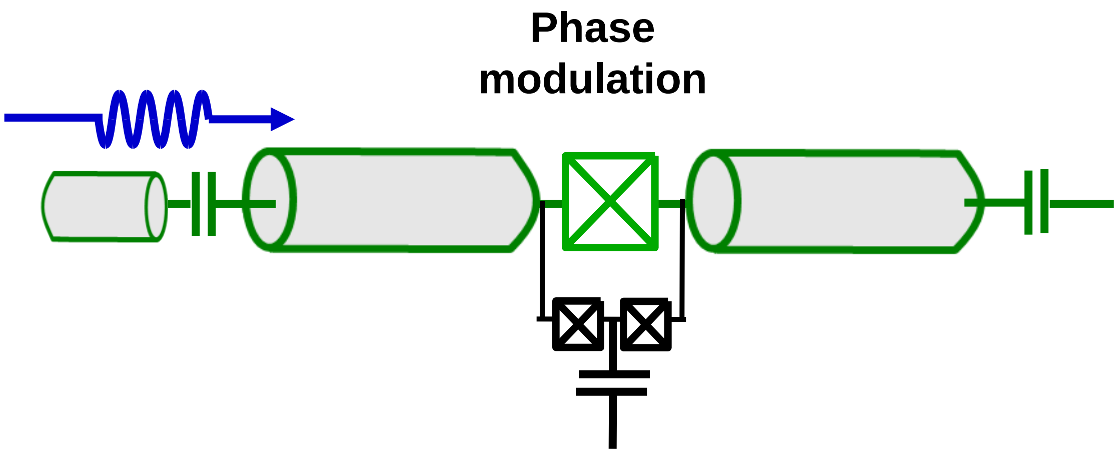
Noise induced switching :



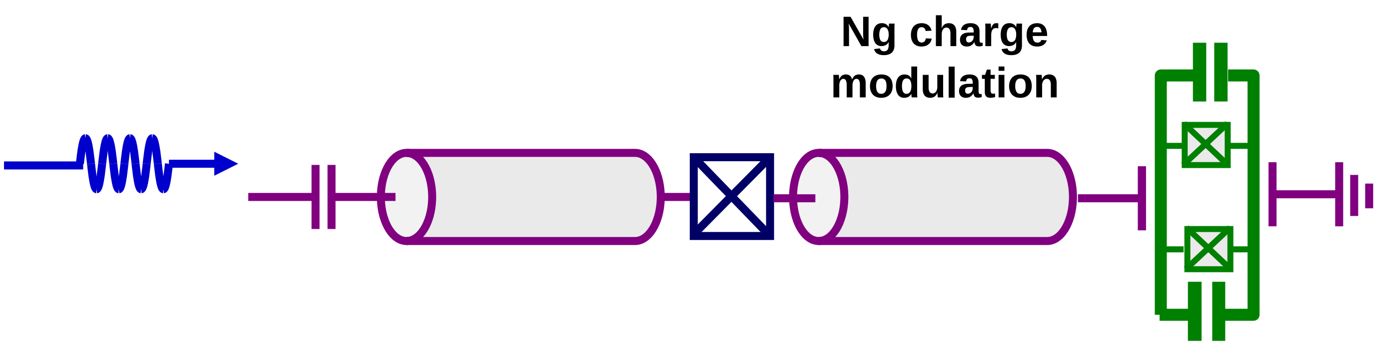


"S-curves" shift > S width ⟶ Single shot readout

The bonus of transmon readout with CJBA



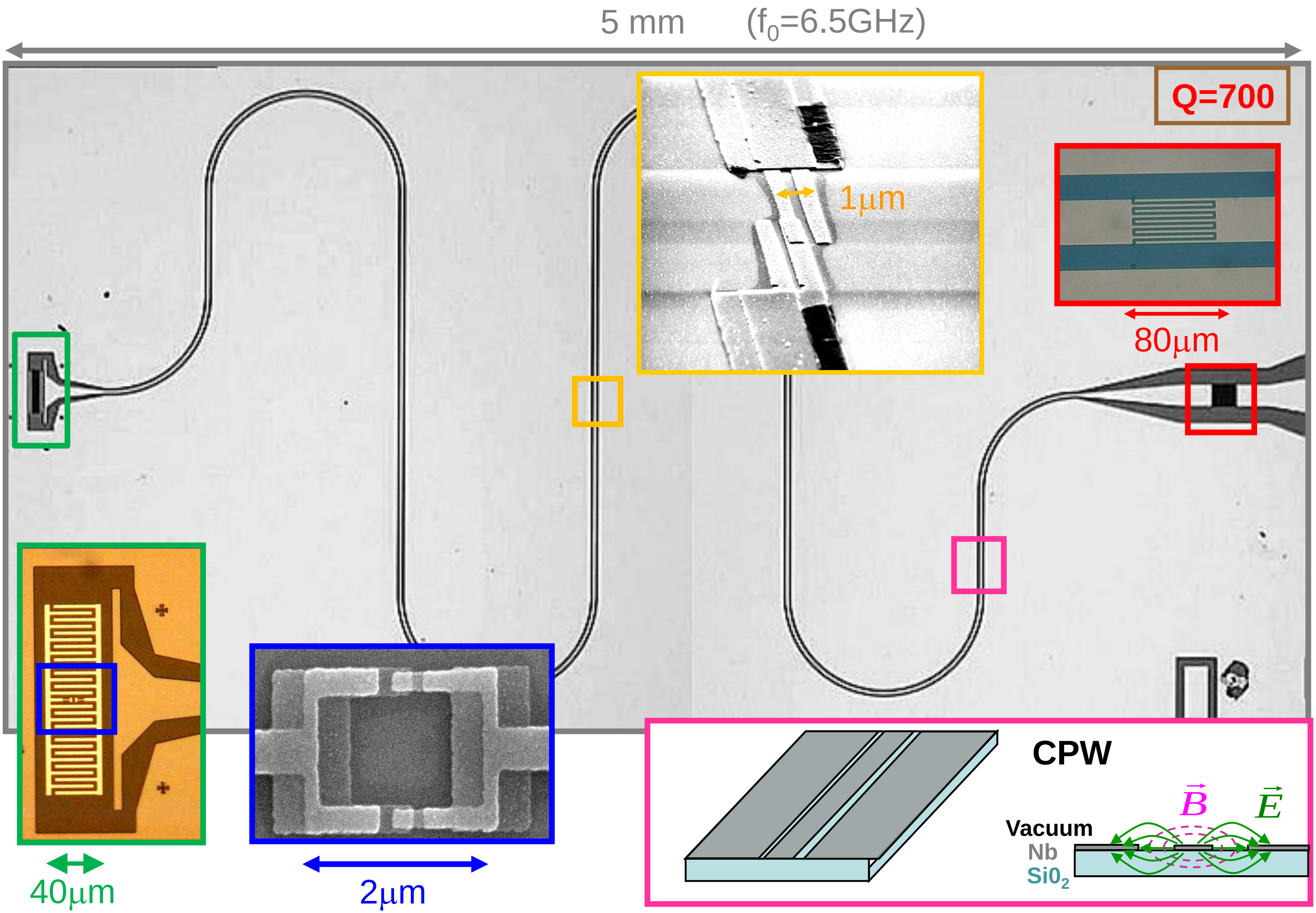
Eigenstates swept
// Starck shifted energy
sweeps a wide
frequency range



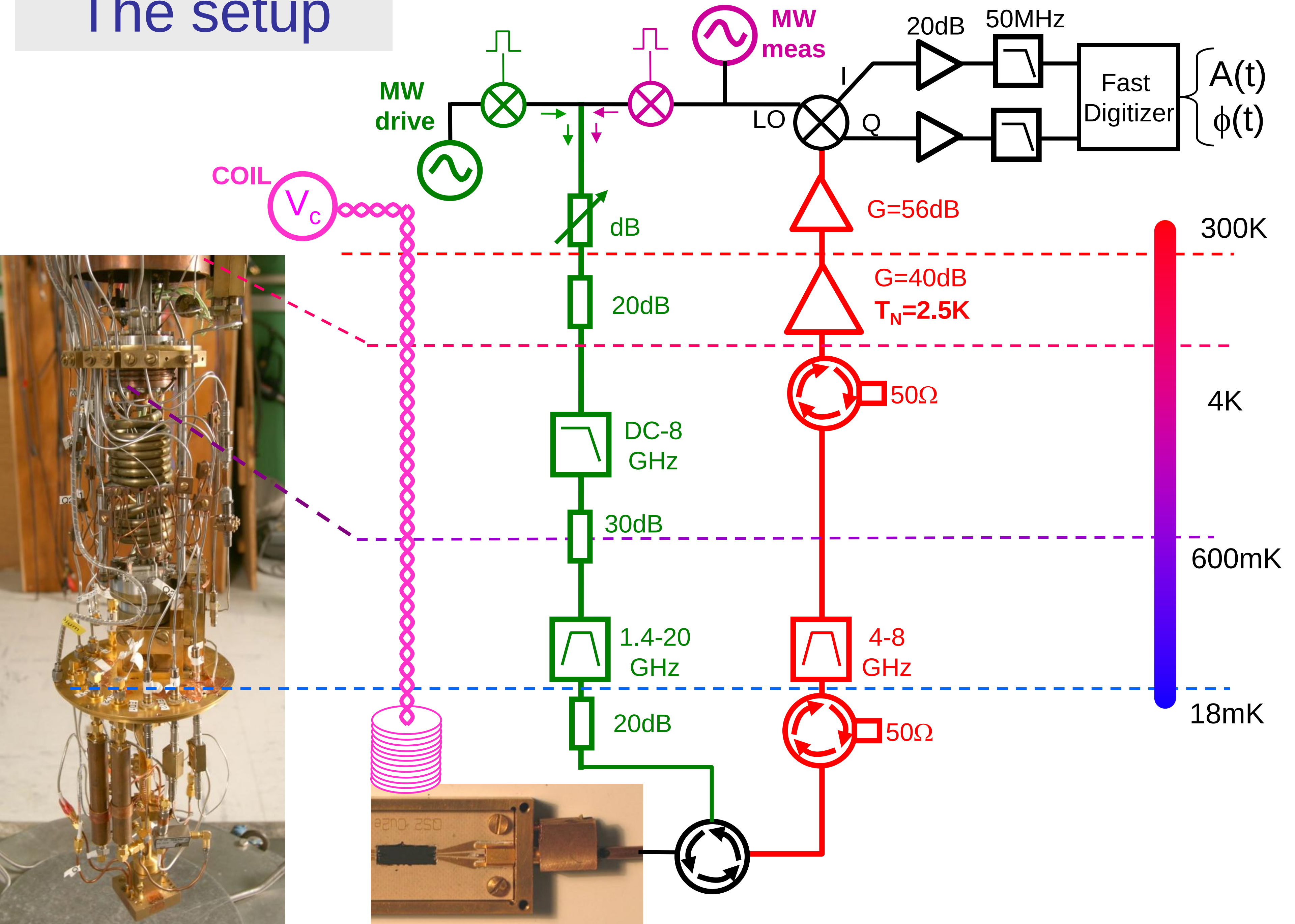
Eigenstates
Insensitive to charge
Changes; small
⊥ Starck shift only

Charge insensitivity combined with bifurcation at low photon number

Physical implementation

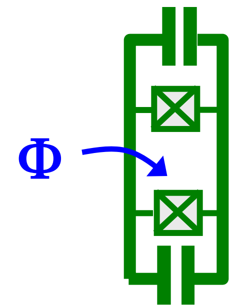


The setup

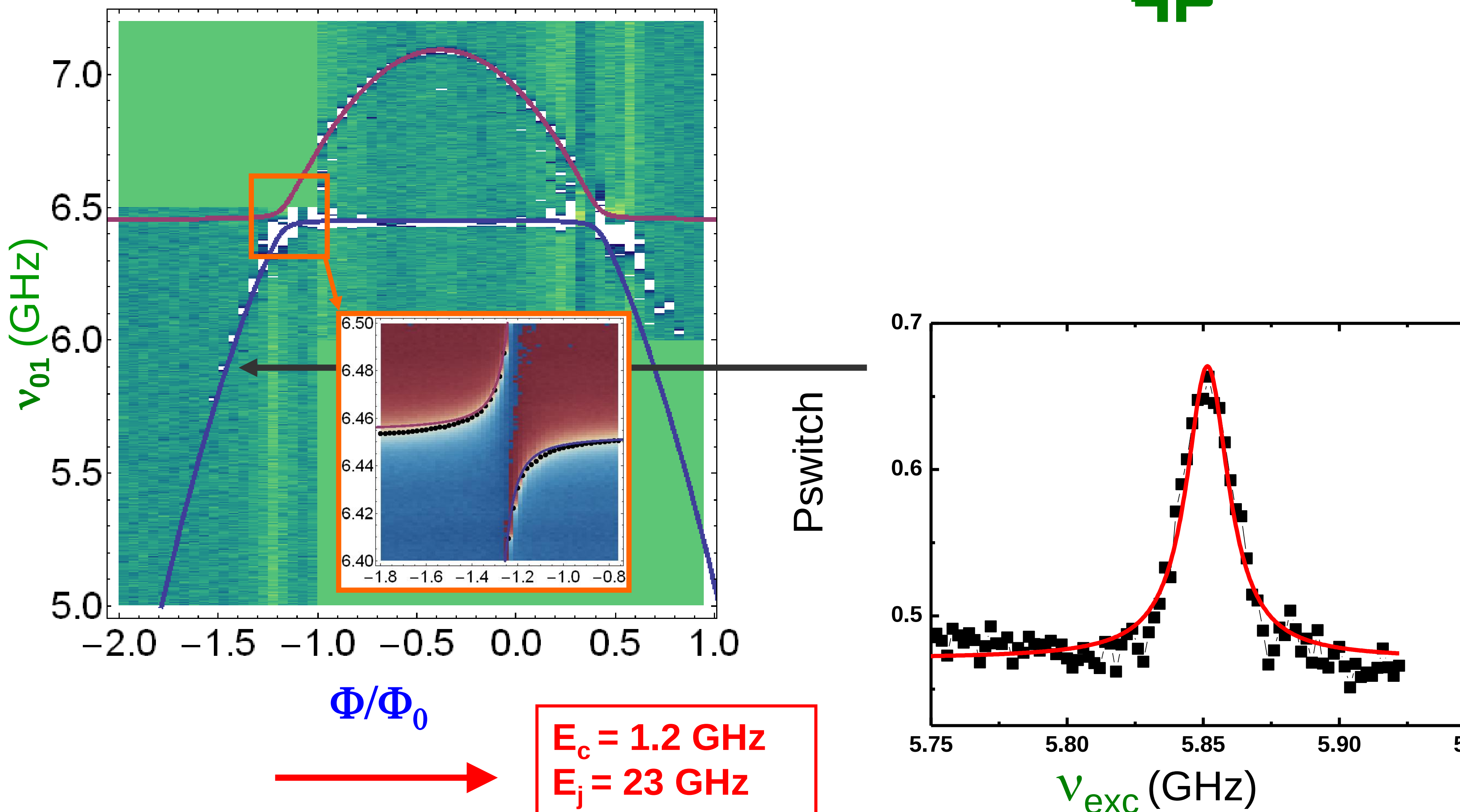


MW
meas
20dB
50MHz
MW
drive
I
LO
Q
Fast
Digitizer
A(t)
ϕ(t)
COIL
V
c
dB
G=56dB
300K
20dB
G=40dB
T
N
=2.5K
50Ω
4K
DC-8
GHz
30dB
600mK
1.4-20
GHz
4-8
GHz
18mK
20dB
50Ω

Qubit and cavity characterization

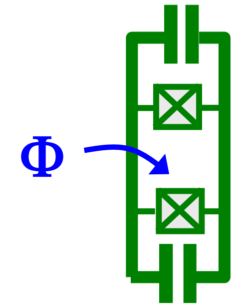


Spectroscopy of the coupled system

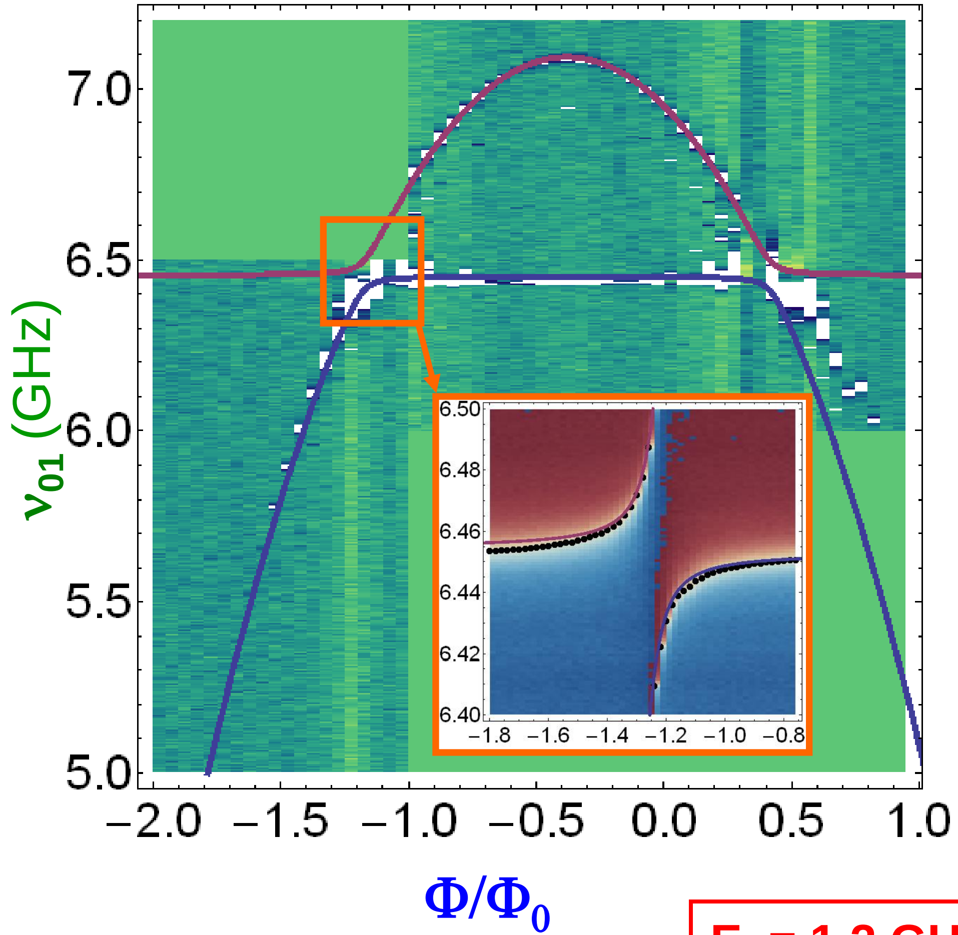


E_c = 1.2 GHz
E_j = 23 GHz
g = 45 MHz

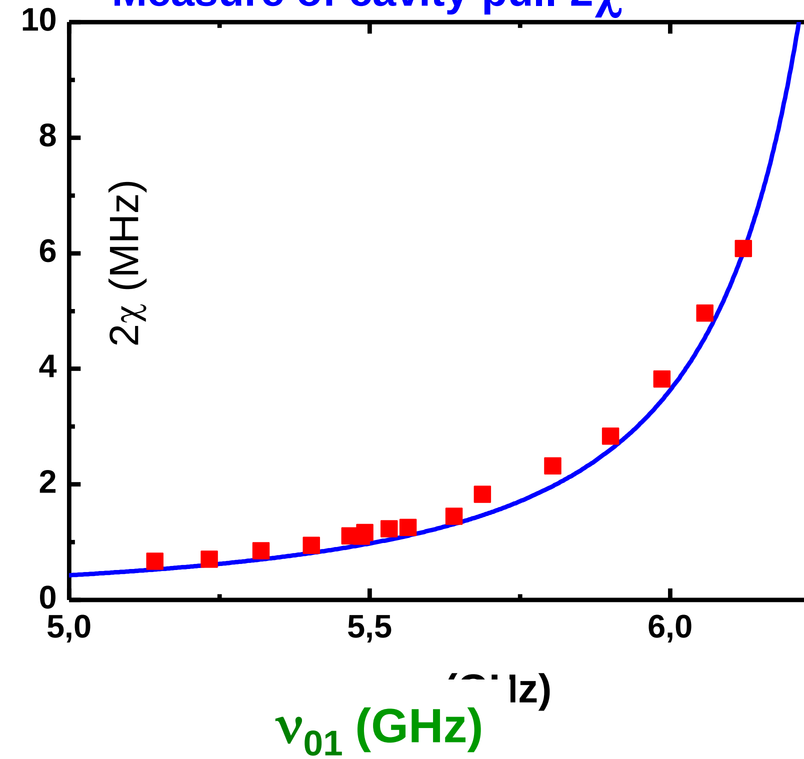
Qubit and cavity characterization



Spectroscopy of the coupled system

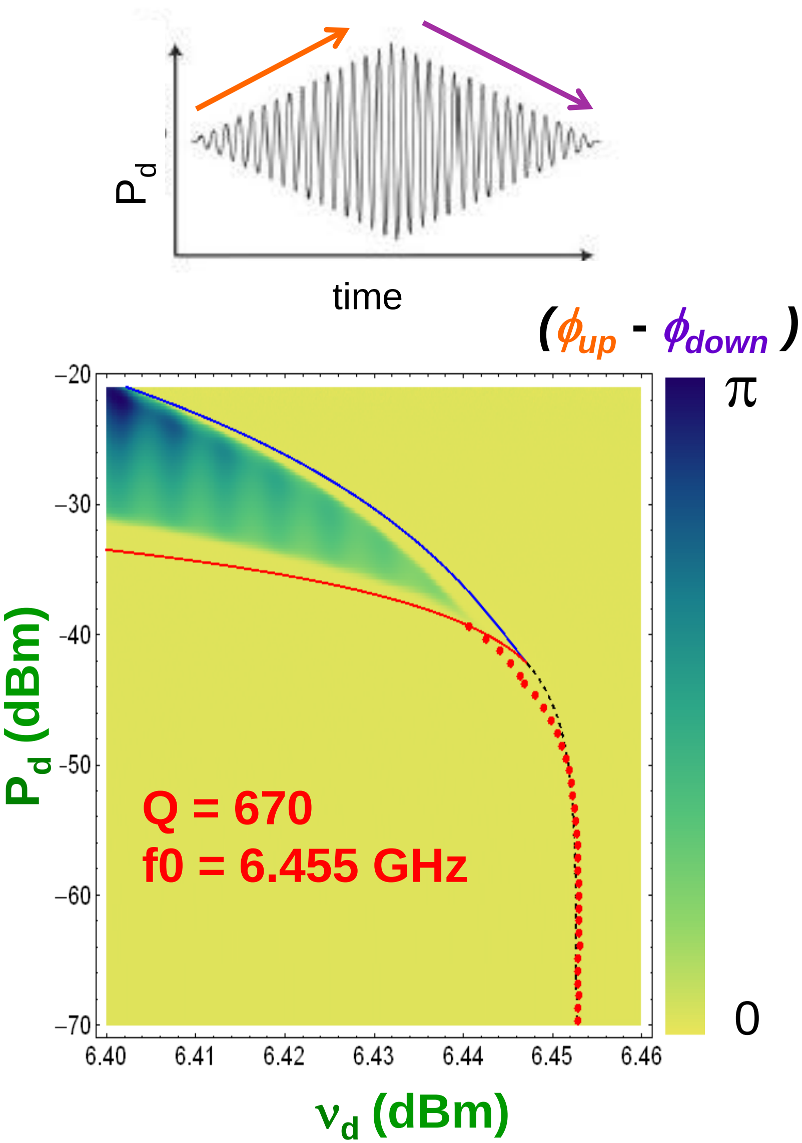


Measure of cavity pull 2χ

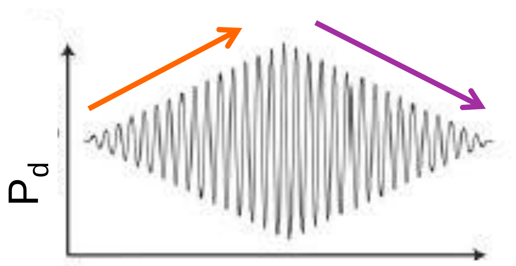


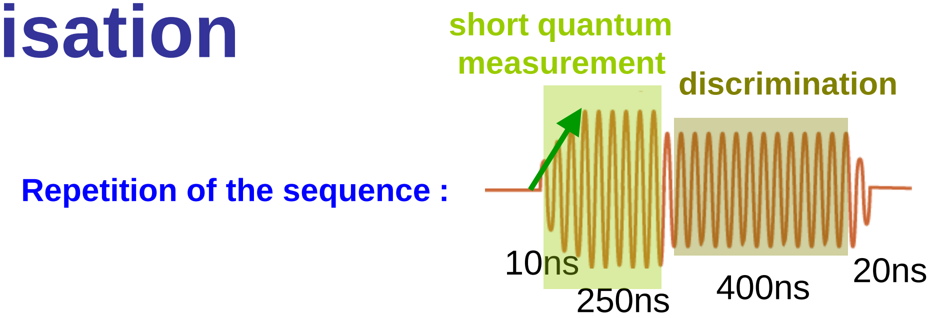
$E_c = 1.2$ GHz
$E_j = 23$ GHz
$g = 45$ MHz

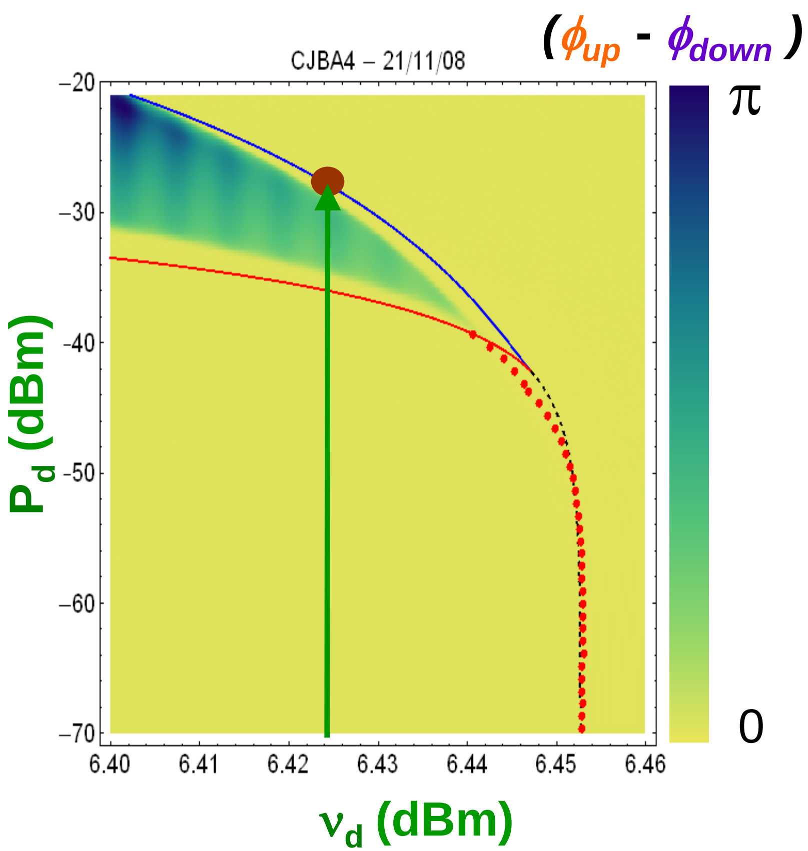
Cavity JBA characterisation

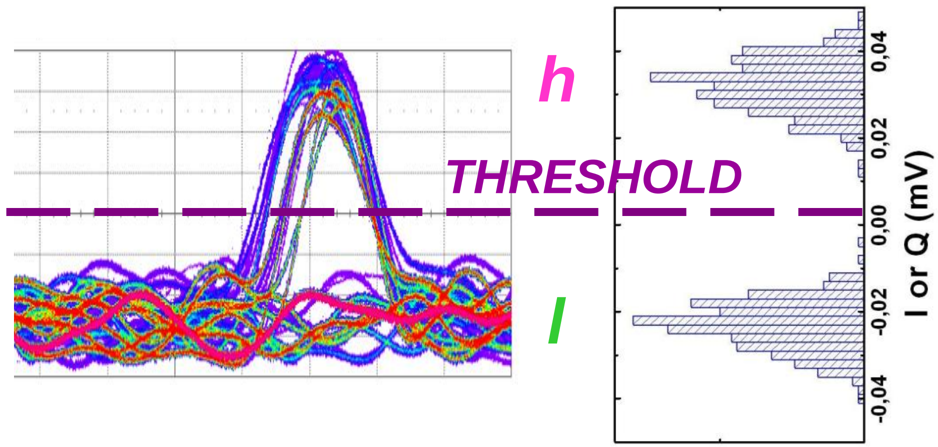


Cavity JBA characterisation



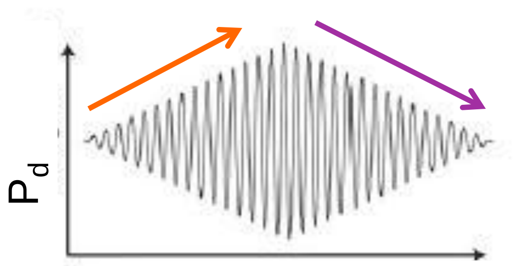




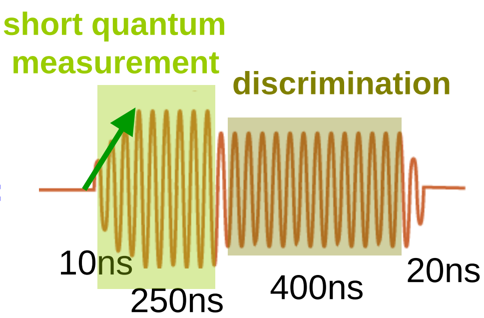


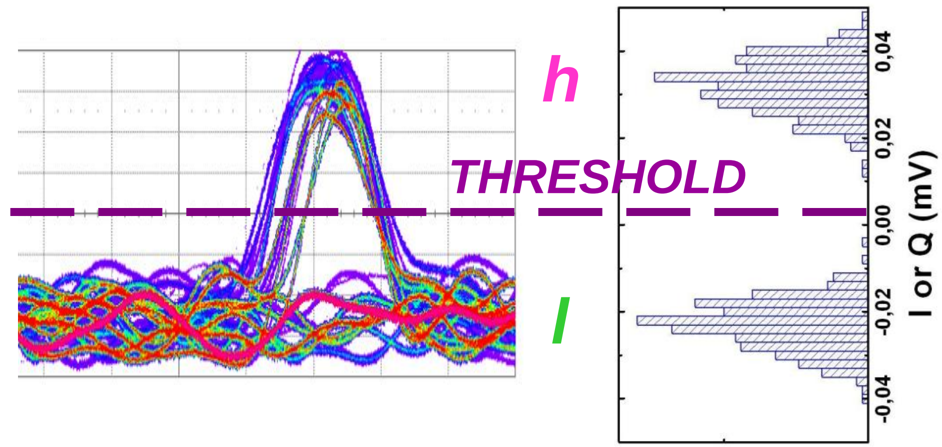
No discrimination errors

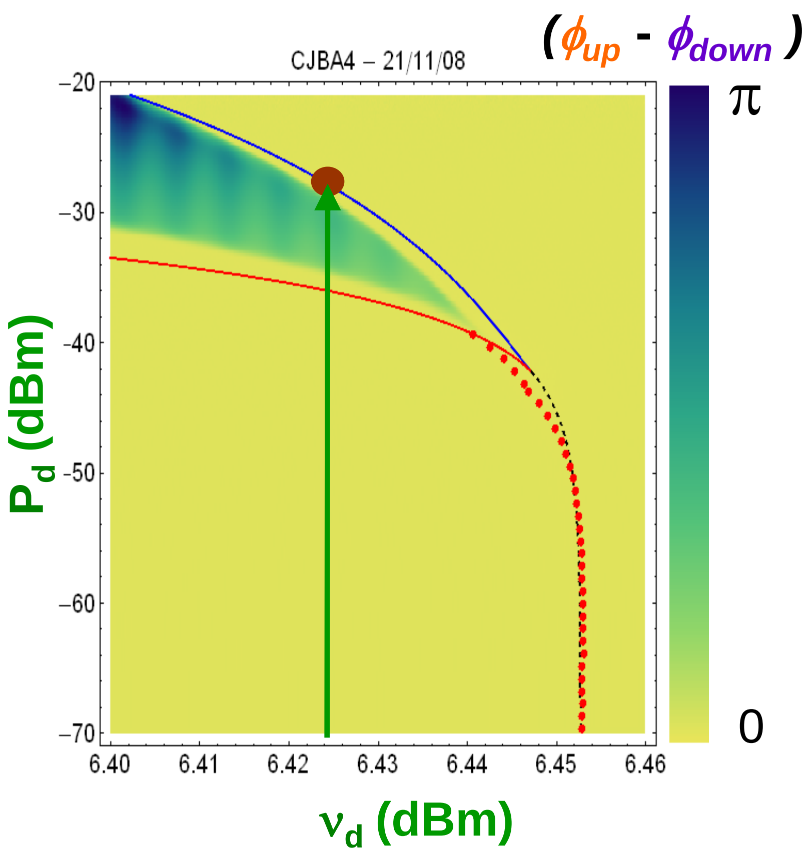
Cavity JBA characterisation

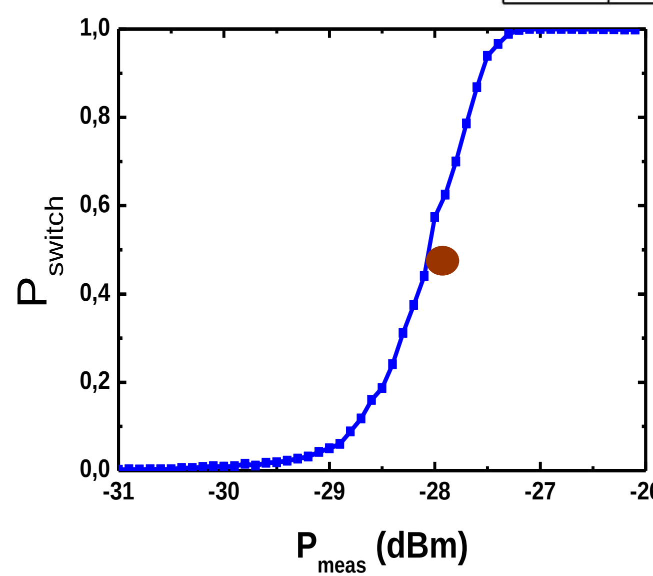


Repetition of the sequence :

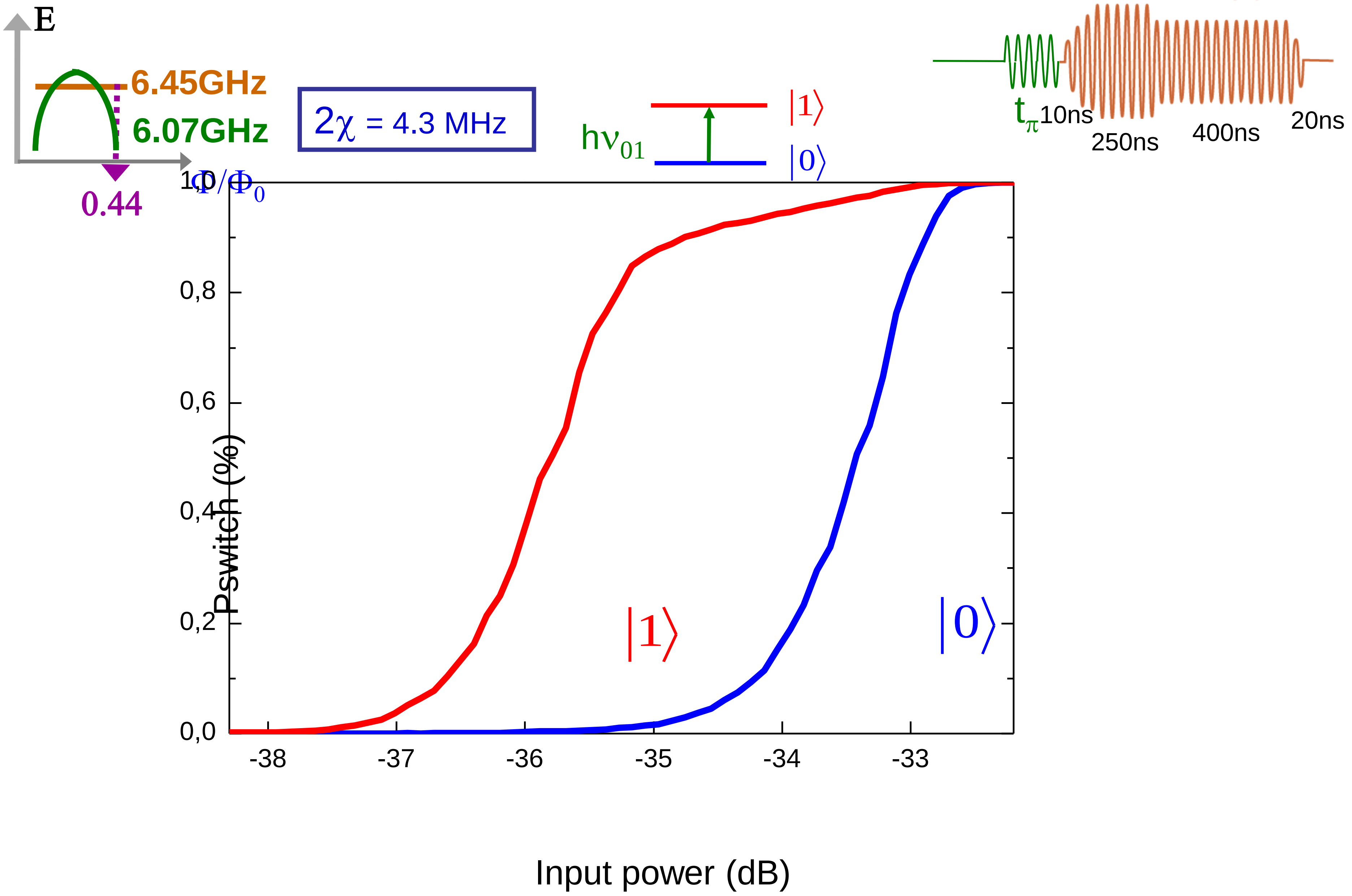




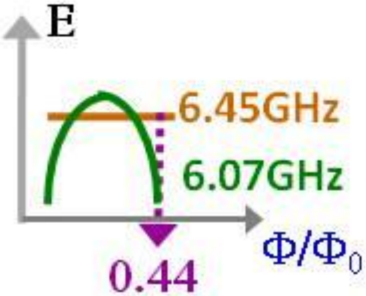




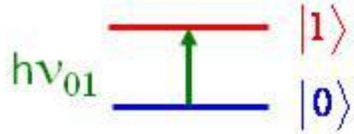
Readout of qubit state 400 MHz below cavity

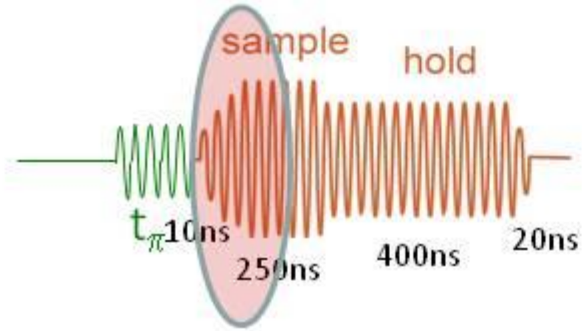


Contrast as good as expected ?

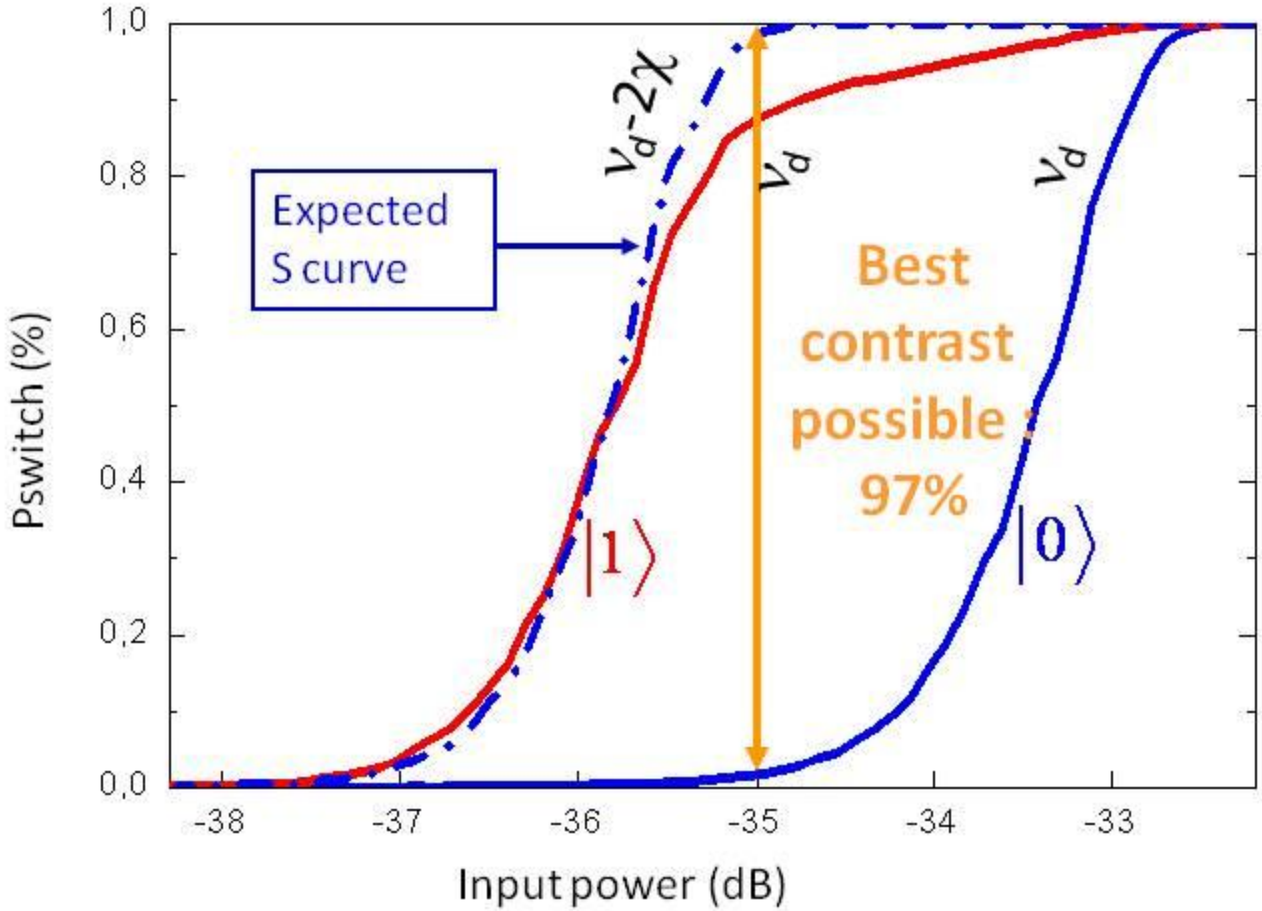


2χ = 4.3 MHz

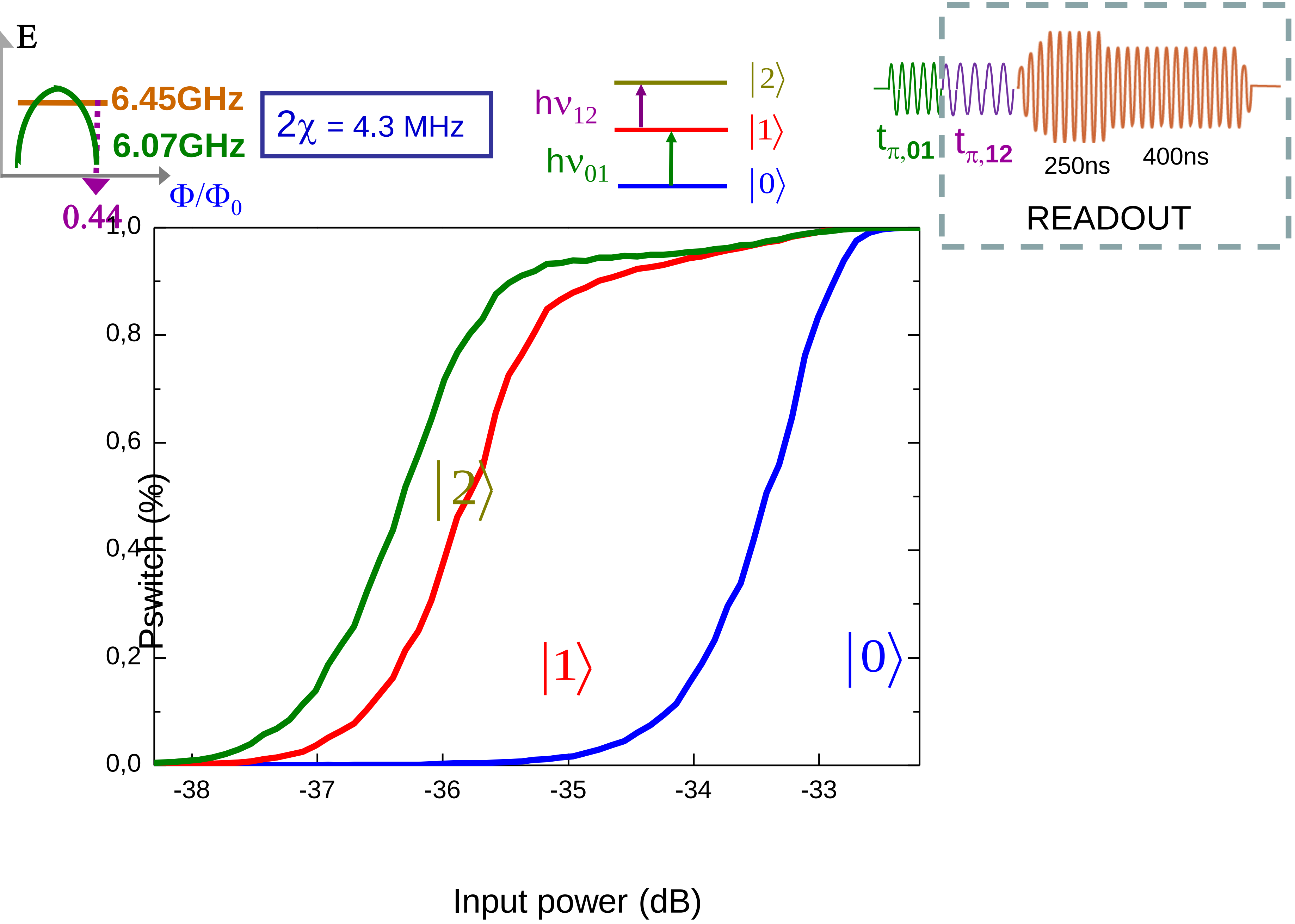




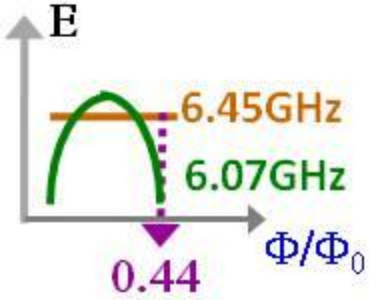
relaxation during readout



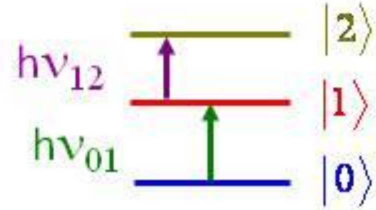
Climbing one extra step yields better fidelity ...

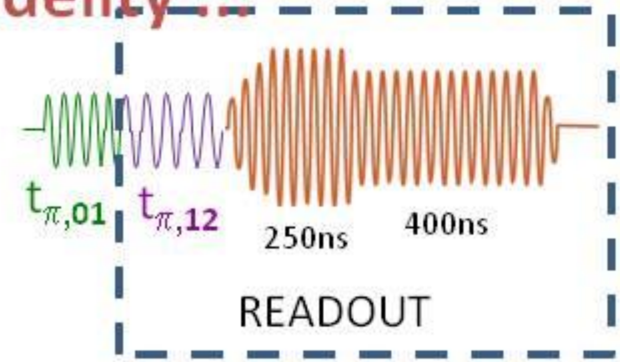


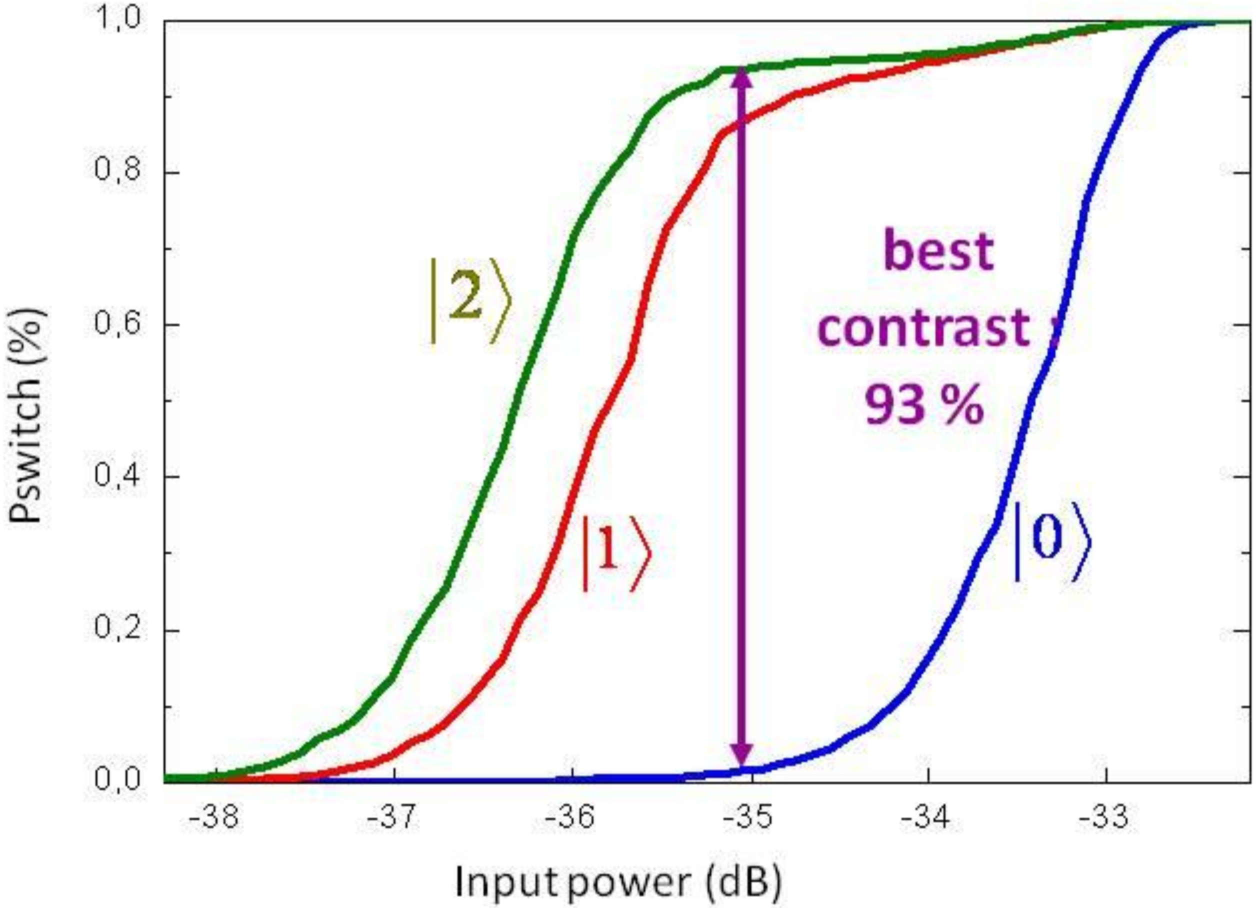
Climbing one extra step yields better fidelity…

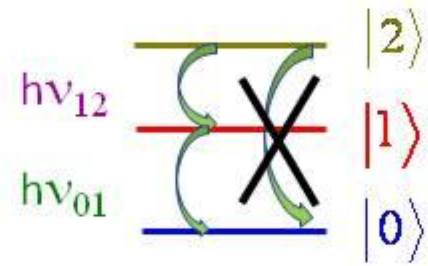


2χ = 4.3 MHz

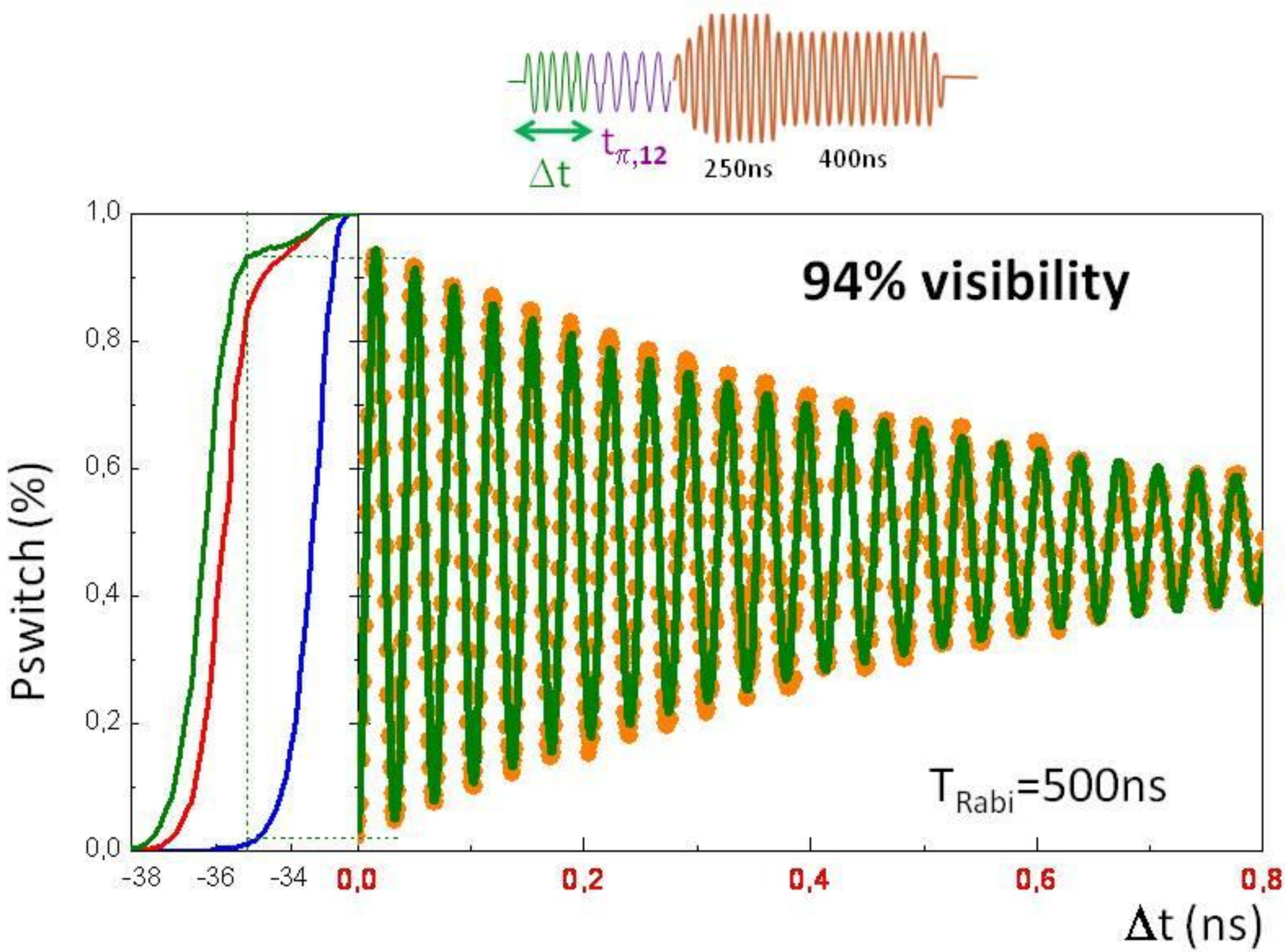




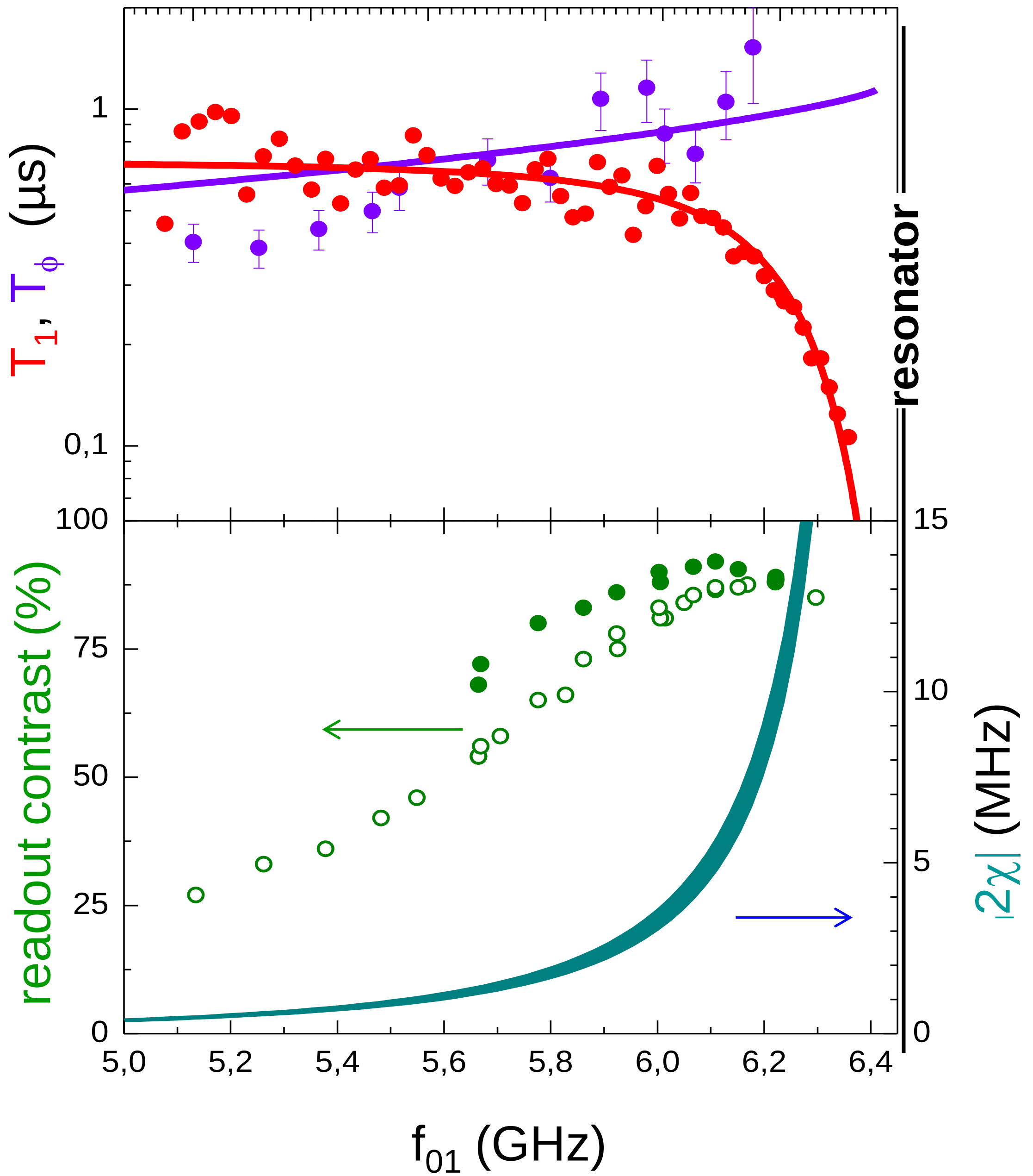




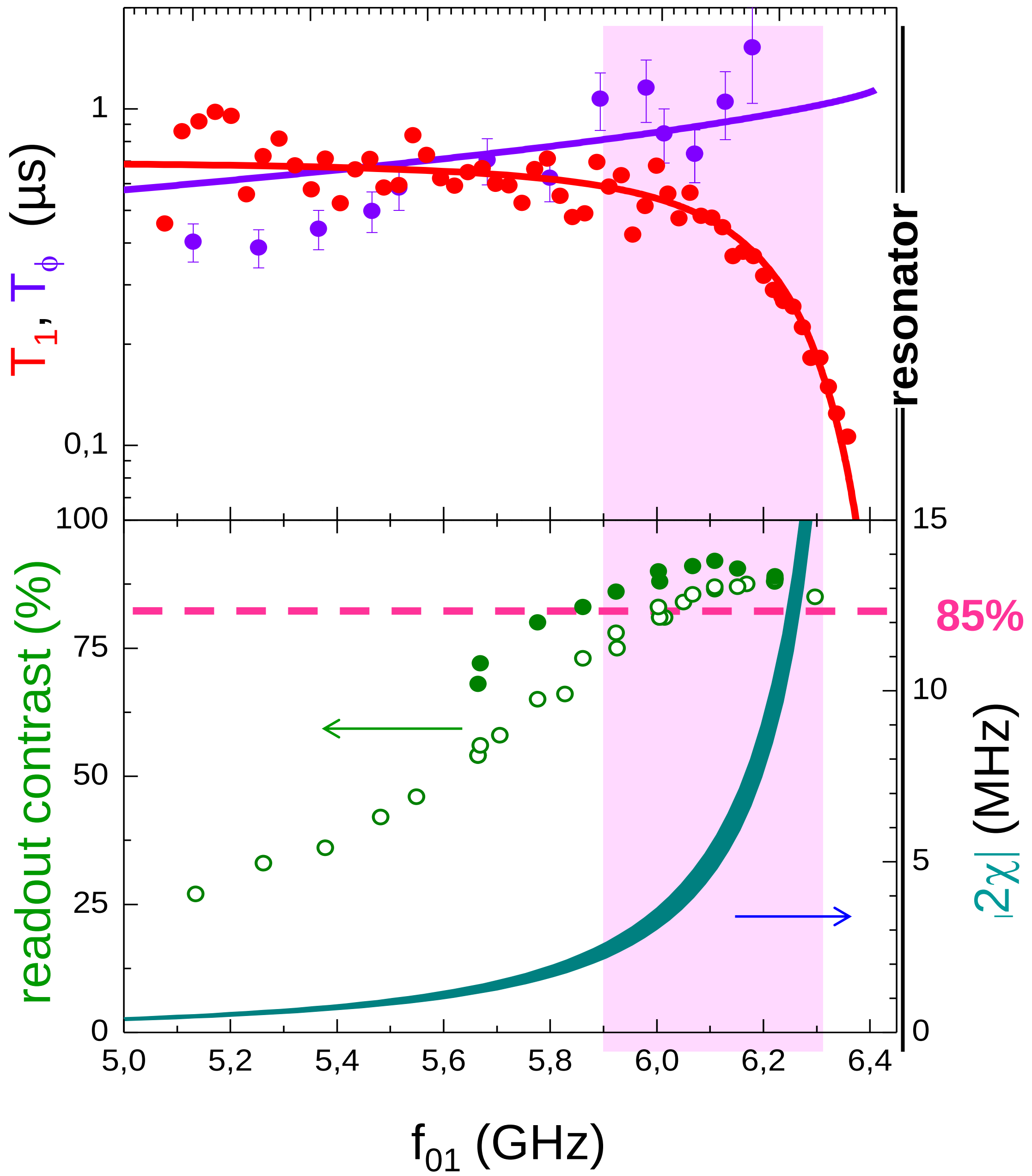
Single-shot high visibility Rabi oscillations



Trade-off readout contrast – coherence ?



readout fidelity compatible with coherence



Projection fidelity ?

Projective measurement of $|\Psi\rangle = \alpha|0_1\rangle \otimes |\Psi_{2...N}\rangle + \beta|1_1\rangle \otimes |\Psi'_{2...N}\rangle$

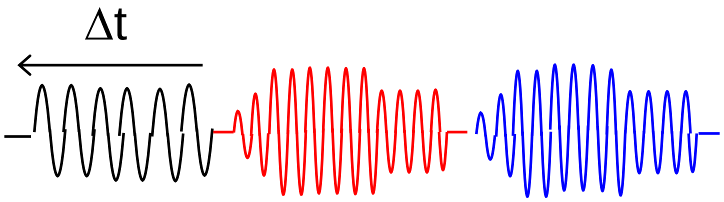
yields
- readout 0 and state $|0_1\rangle \otimes |\Psi_{2...N}\rangle$ with prob $|\alpha|^2$

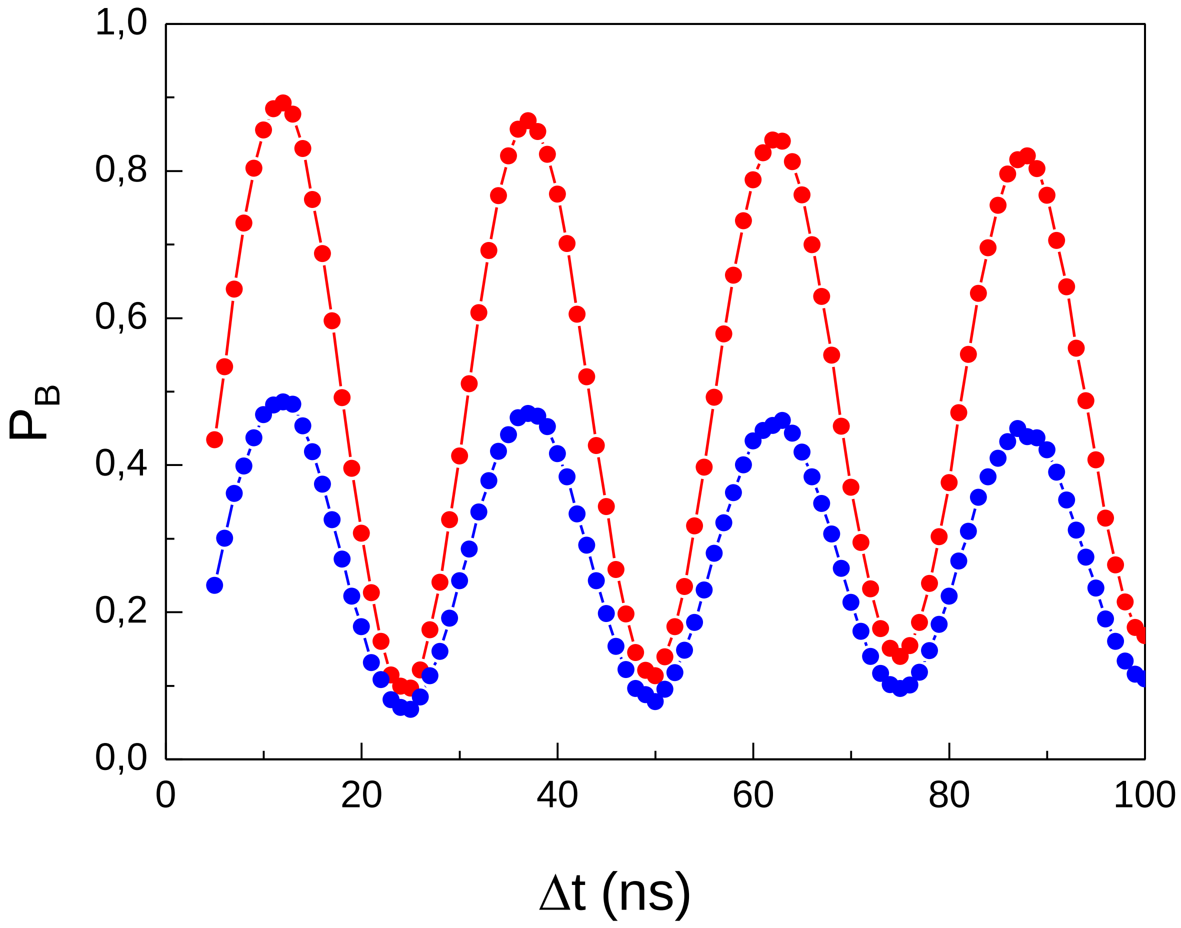
  or

- readout 1 and state $|1_1\rangle \otimes |\Psi'_{2...N}\rangle$ with prob $|\beta|^2$

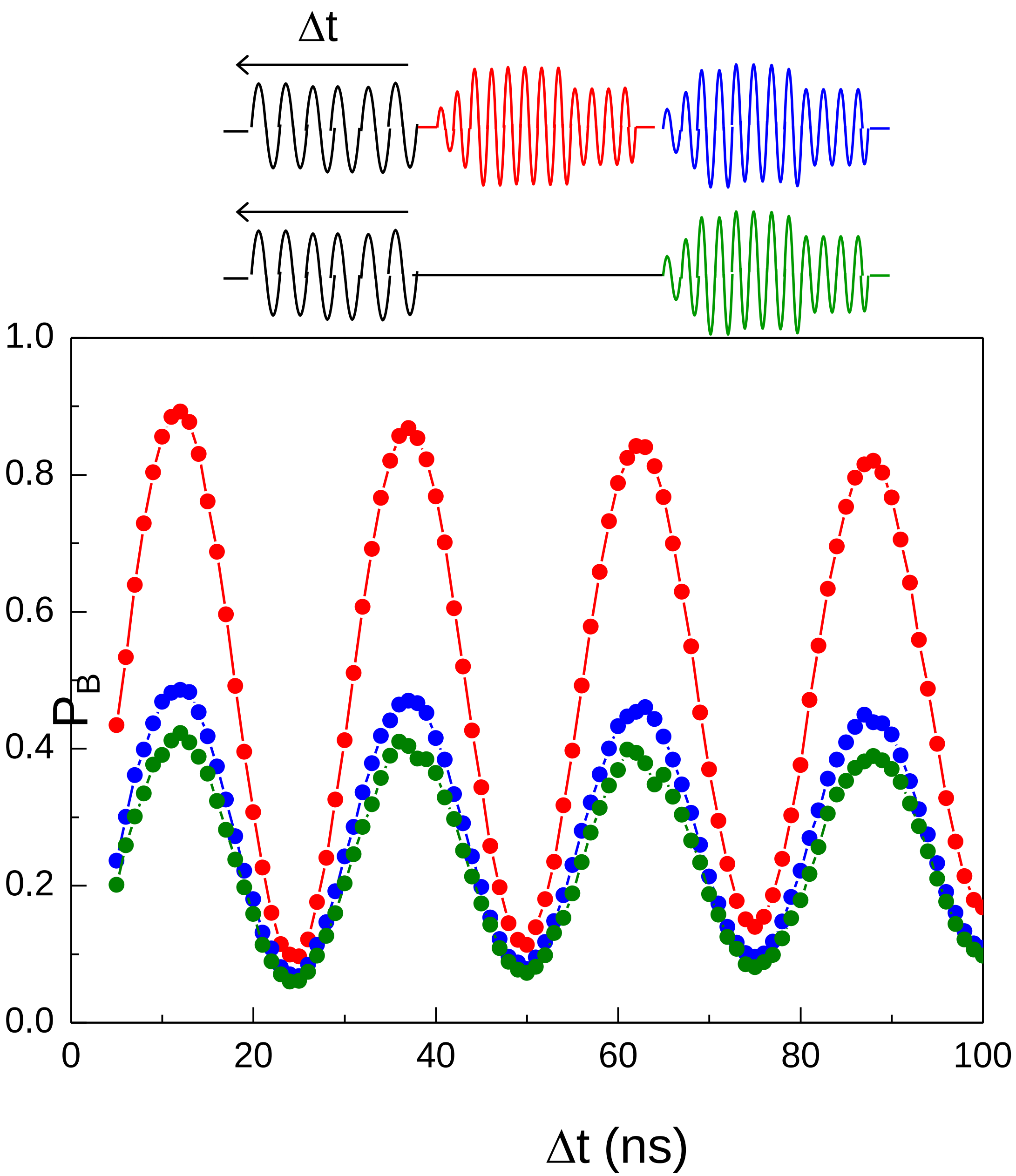
QND character can be tested with repeatedmeasurements

relaxation limited test of projection fidelity





relaxation limited test of projection fidelity



No EXTRA Relaxation during readout

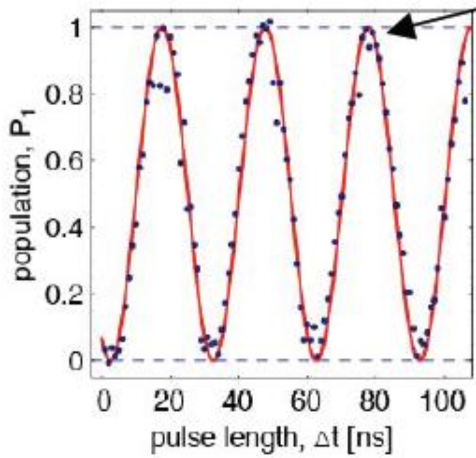
Data compatible with non-demolition

Claims above 90% : a brief (critical) review

High visibility Rabi oscillations (Yale, Wallraff et al. ,PRL 2005)

Rabi oscillations:

visibility 95 ± 5%



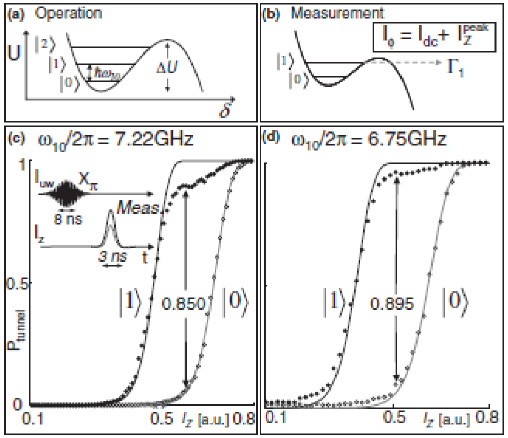
for superconducting qubits:

- high visibility

we have observed high visibility in the oscillations of state population of a superconducting qubit. The tem-

~95% population inversion, but no high fidelity readout

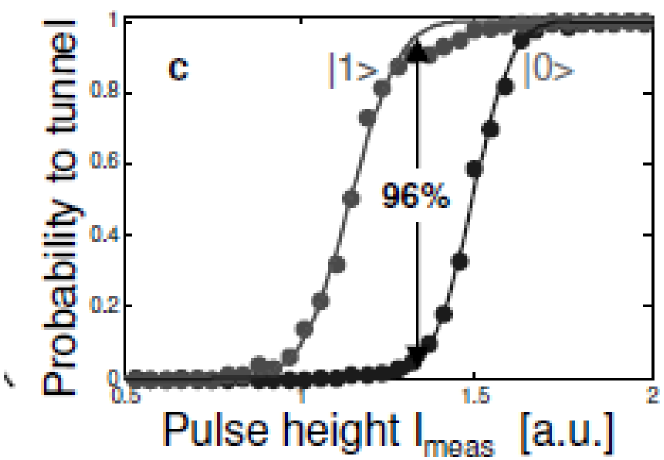
High measurement fidelity (J. Martinis, UCSB)

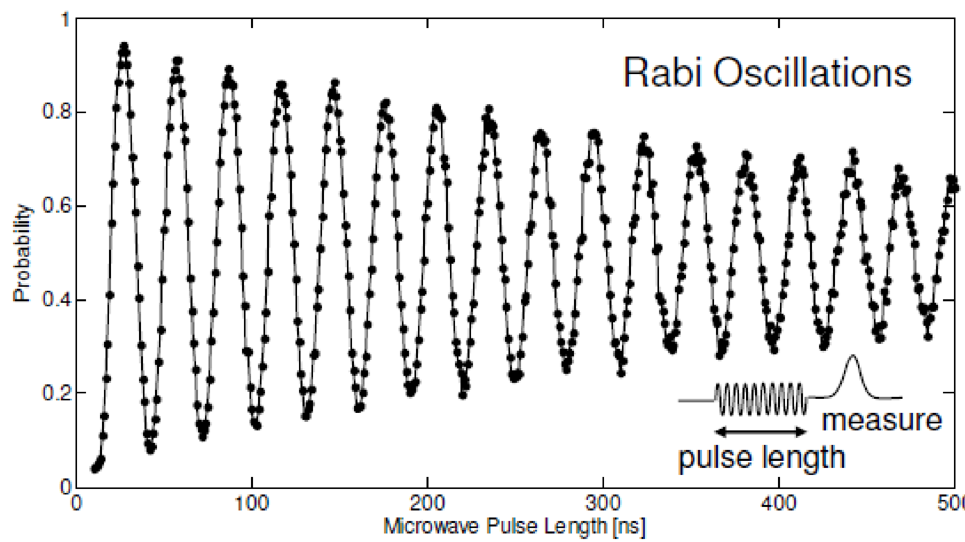


Lucero et al., PRL 100 (2008)

~90% readout contrast
(destructive)

J. Martinis'review ,QIP 8(2009)



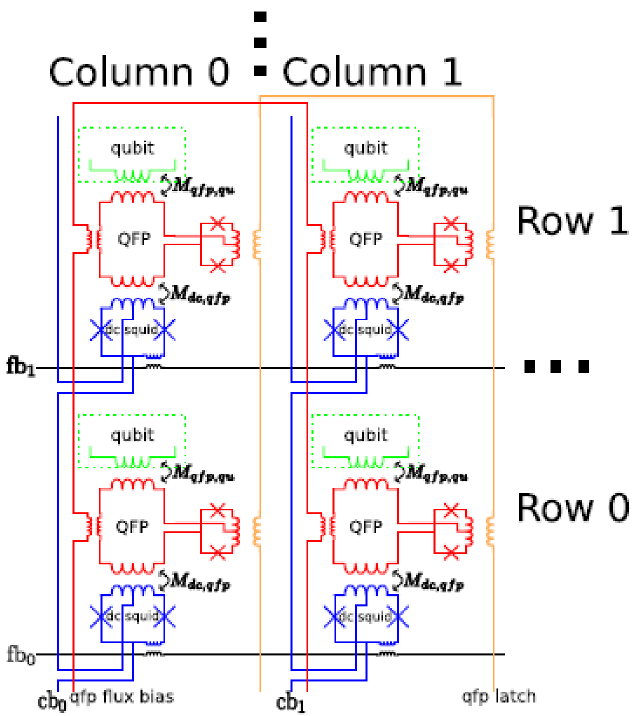


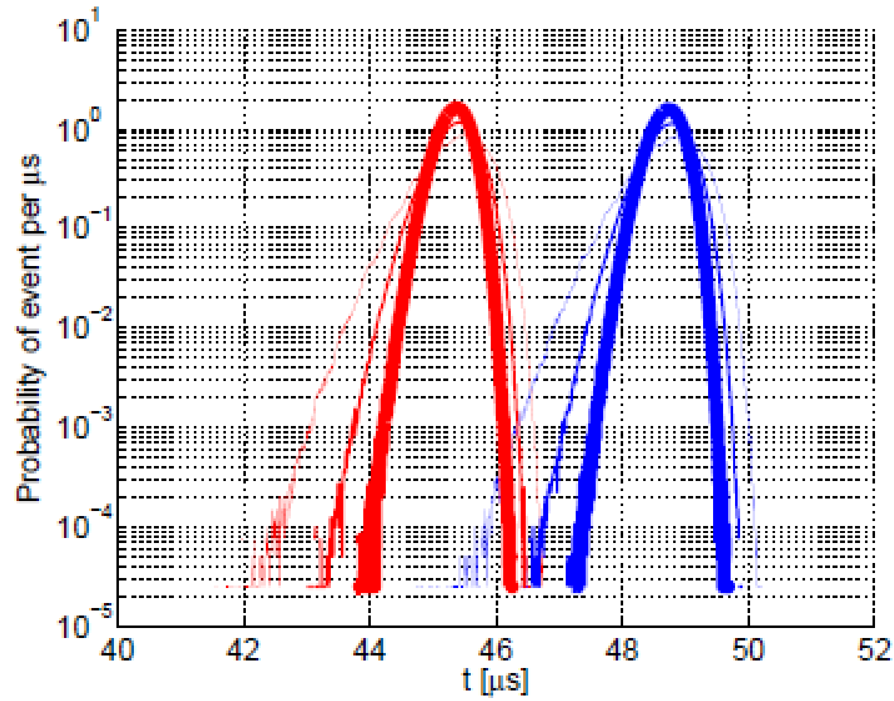
The Rabi oscillations have fidelity of about 90 %, a value reasonably close to the theoretical expectation 96 % [15]. The energy decay time for this qubit is $T_1 = 600$ ns.

Rabi oscillations with about 90% fidelity

A record 99.9999% claim from DWAVE

Berkley et al.,
arXiv 0905.0891





QFP (Quantum Flux Parametron):
tunable barrier device

Fig. 6: Improving readout fidelity with repeated dc SQUID sampling of the QFP state. The dc SQUID has a current ramp applied which lasts approximately 50 μs. The red and blue curves correspond to different initialized flux states of the qubit (which is then adiabatically transferred to the QFP). There are three separate traces showing the probability per time of the dc SQUID switching as the current bias is ramped. The three lines going from thin to thick correspond to 1, 2, and 4 averaged reads of the dc SQUID. Once 4 reads are performed we see no errors in the data set, which was 4 million points. The thick lines on this plot are the fidelity data from which we extract the 99.9999% fidelity quoted in the text.

Not even wrong, but readout fidelity is more than frozen flux state discrimination

Perspectives??

Optimize parameters :

readout fidelity

and

coherence

and

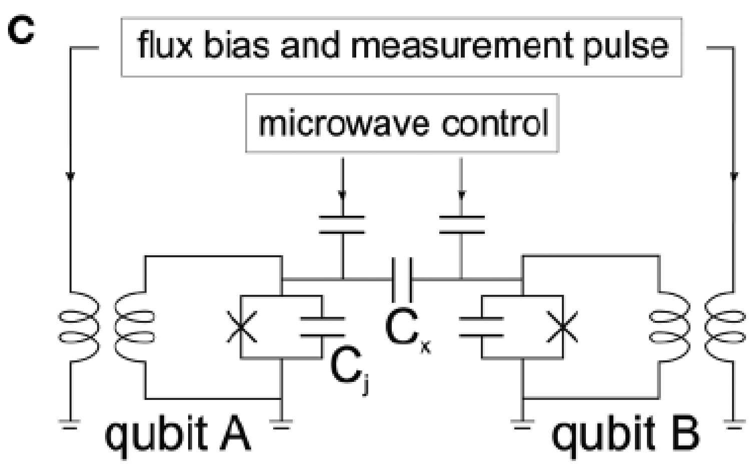
projection fidelity

and

in multiqubit circuits

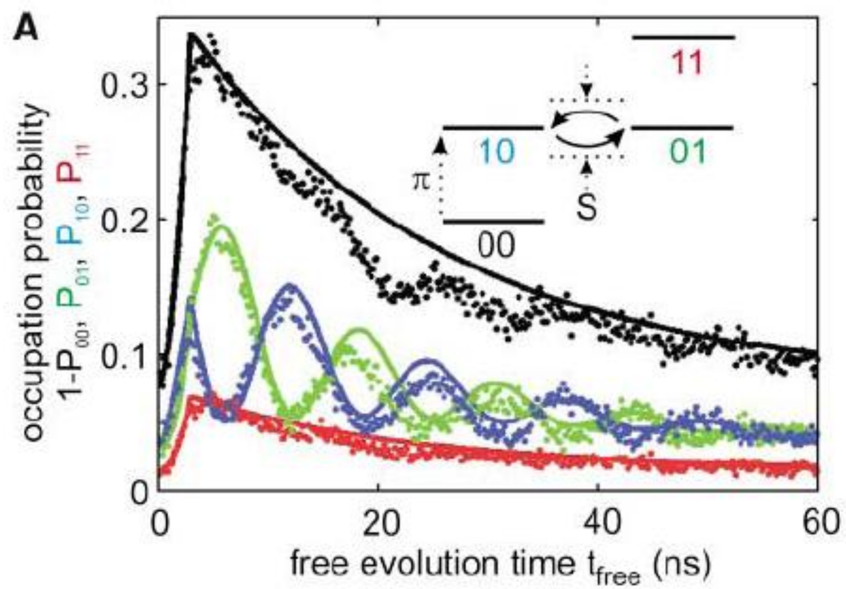
Readout: multiqubit circuits

2 coupled phase qubits



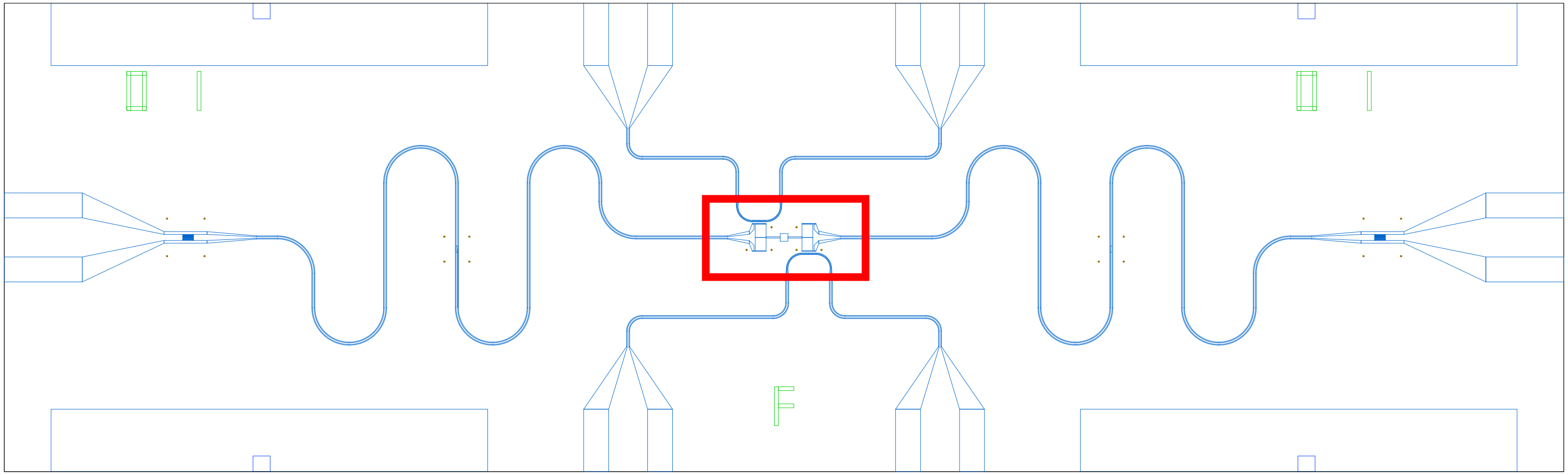
McDermott et al., Science 307 (2005)

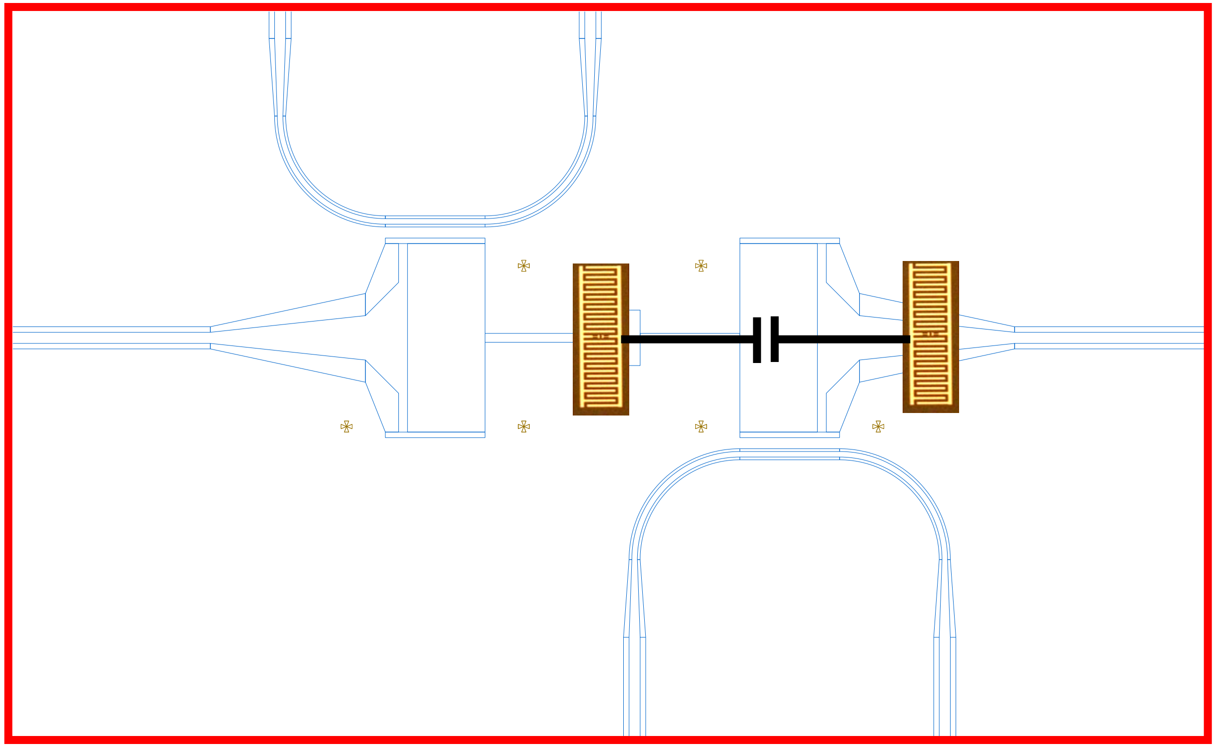
Swapping demonstrated



~simultaneous & destructive readout: fidelity ~70%

Entangling 2 transmons with individual readouts

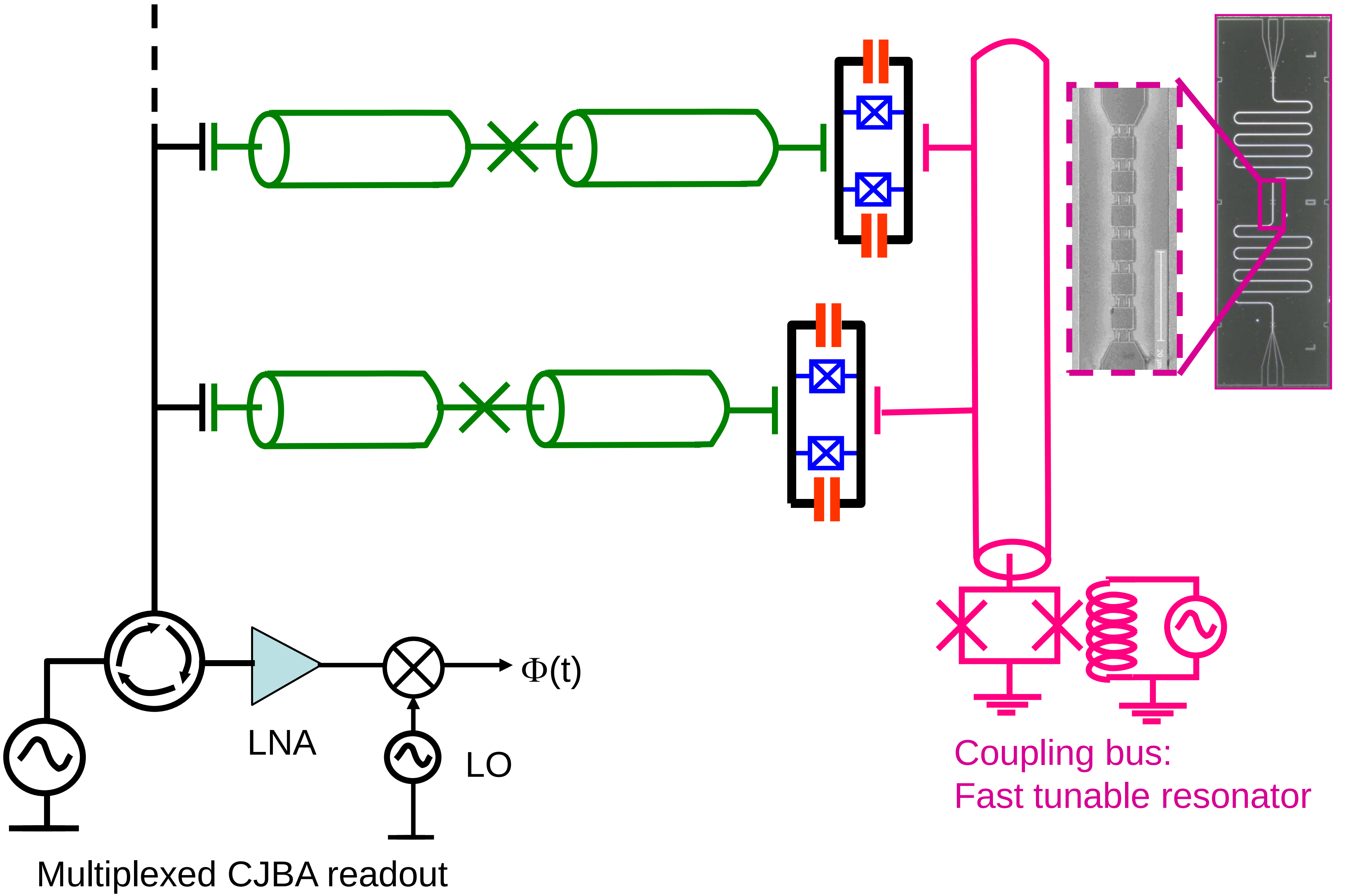




for Bell test

Note: just achieved for phase qubits (UCSB)

Towards a scalable architecture



QUANTUM ELECTRONICS GROUP

SPEC CEA-Saclay

Merci !

« Qubit team » :

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F. Nguyen
F. Mallet
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P. Bertet
D. Vion
D. Esteve
P. Senat
P. Orfila
with the help
of Quantronics
(worldwide)

Qulab Yale

LUX ET VERITAS

Quantum mechanical electronics group, ENS, CdF

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Your questions