Title: TBA

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Abstract:

Could third order interference be observed in superconducting circuits?

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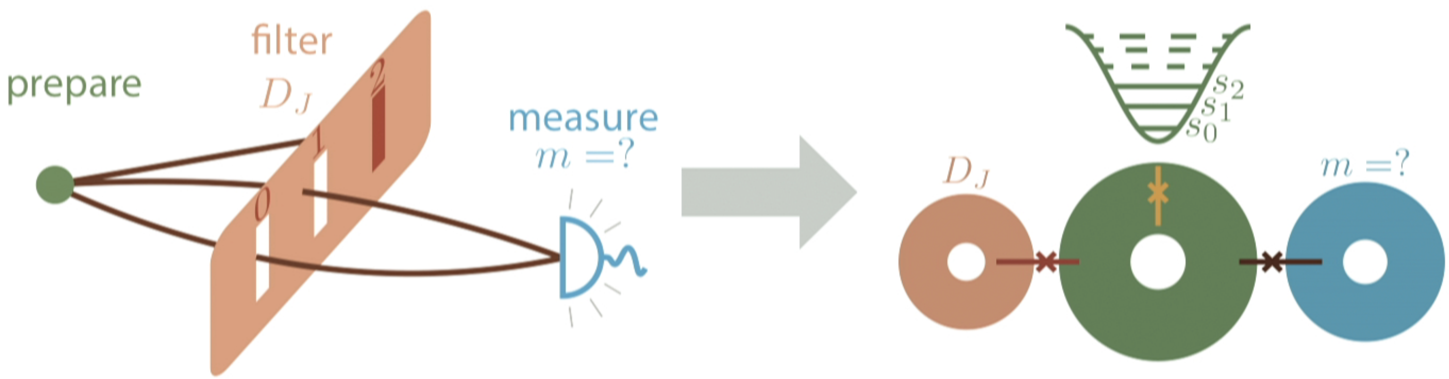

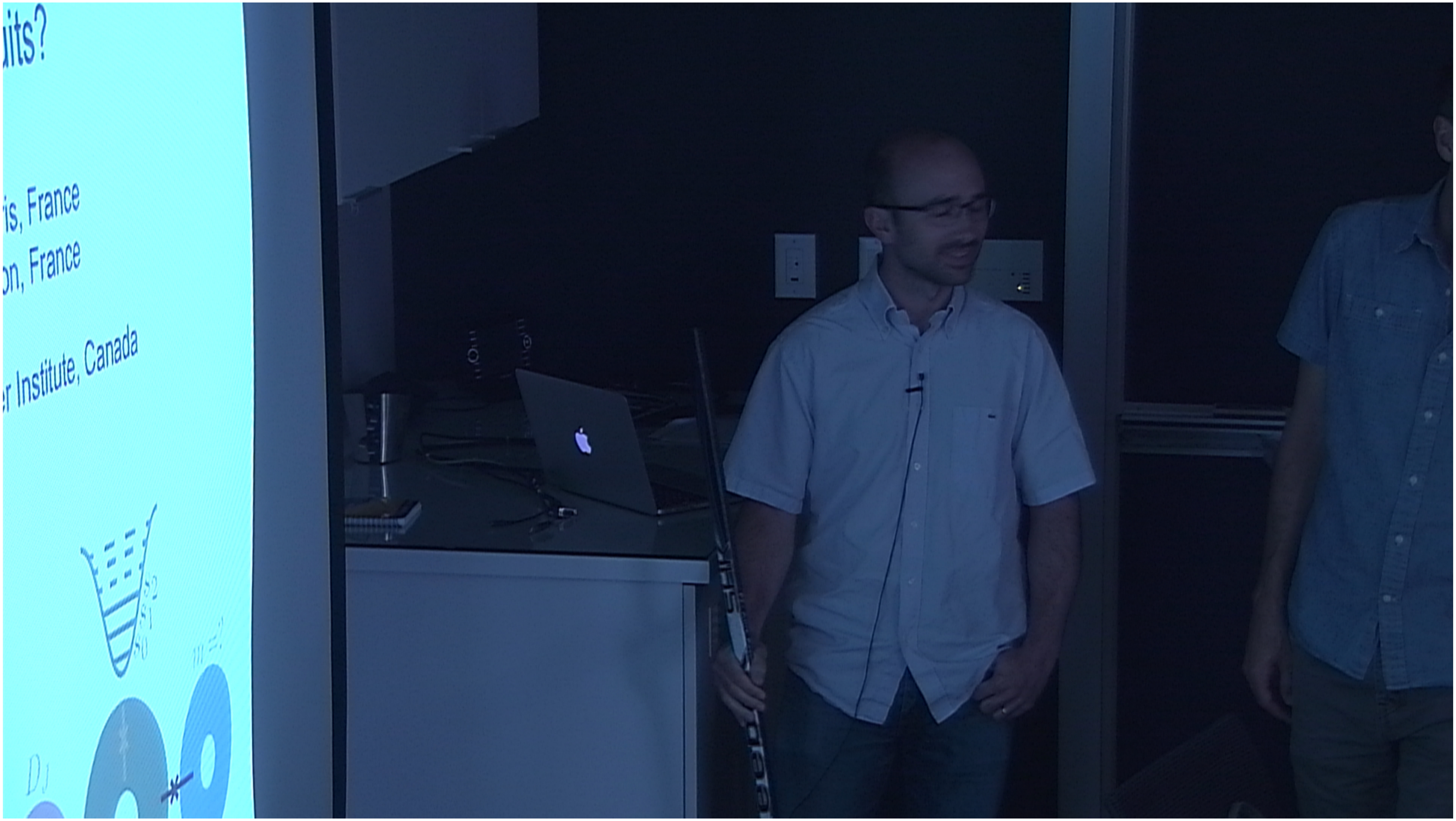
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is, France
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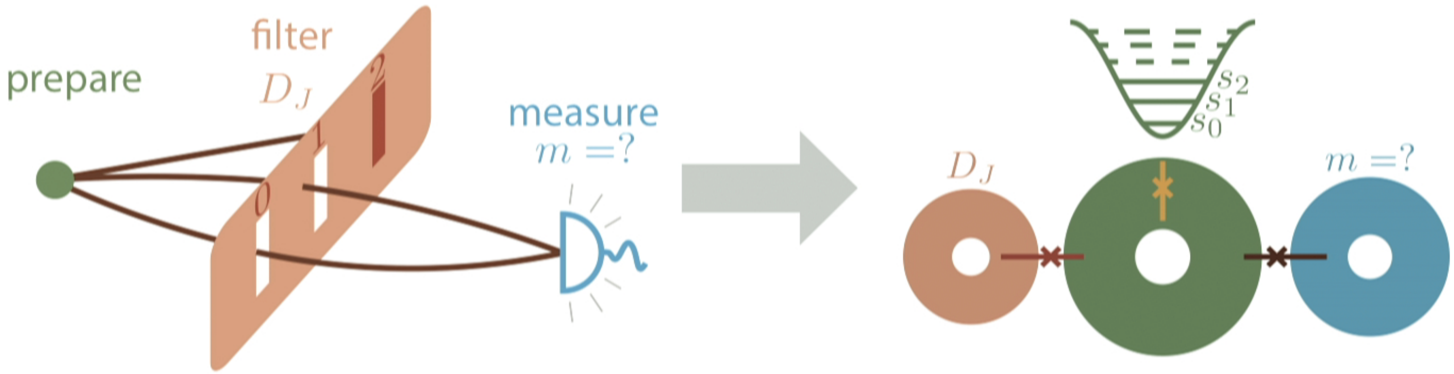
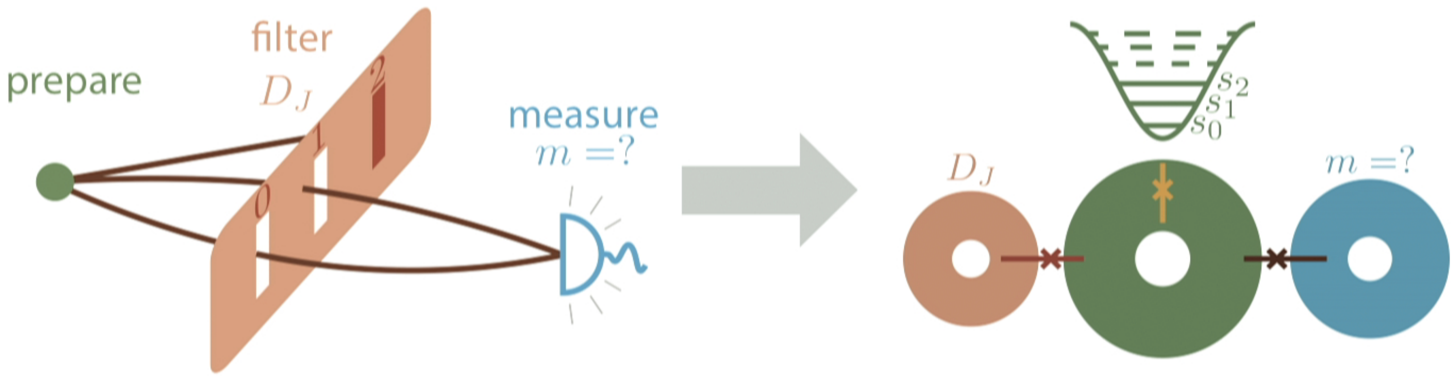
r Institute, Canada

How to describe the three-slit experiment?



① prepare the system in a non classical statistical mixture of states s_0, s_1, s_2

How to describe the three-slit experiment?



① prepare the system in a non classical statistical mixture of states s_0, s_1, s_2

⟷ single particle with x_{ZPF} larger than slit spacing

② filter the experiments by a projective detector D_J where $J \subseteq \{0,1,2\}$

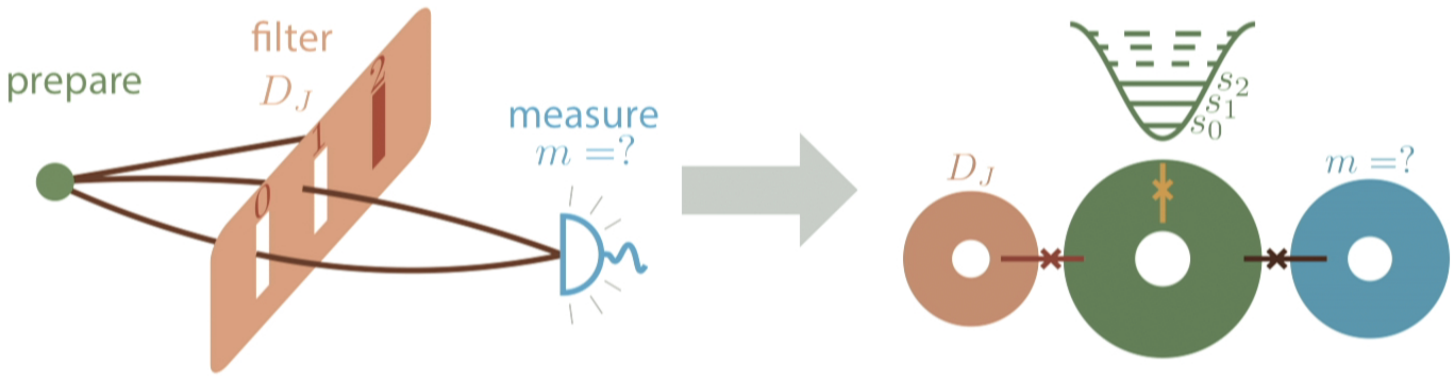
$\forall j \in J$ clicks if sys in s_j ⟷ j is an open slit

$\forall j \in \{0,1,2\} - J$ does not click if sys in s_j ⟷ j is a closed slit

identical stats of outcome for a following measurement if D_J is used once ore twice

not necessarily true for slits, but needed here

How to describe the three-slit experiment?



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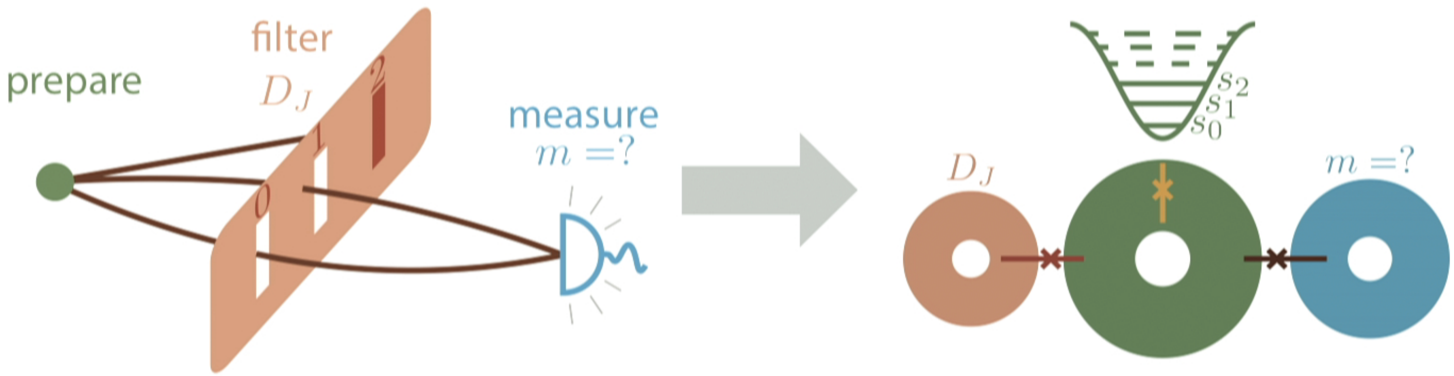
identical stats of outcome for a following measurement if D_J is used once ore twice

③ measure the system by an apparatus which differs from any D_J
(i.e. leads to at least 2nd order interferences)

$$p_J = p(D_J \text{ clicks}, m = +1)$$

What would superconducting circuits hopefully bring?



Single system manipulation and measurement so that
D_J corresponds to a **projective transformation**

→ work directly with event probabilities as in GPTs
and avoid parasitic effects in the modeling of actual slits
[see Urbasi and Thomas talks]

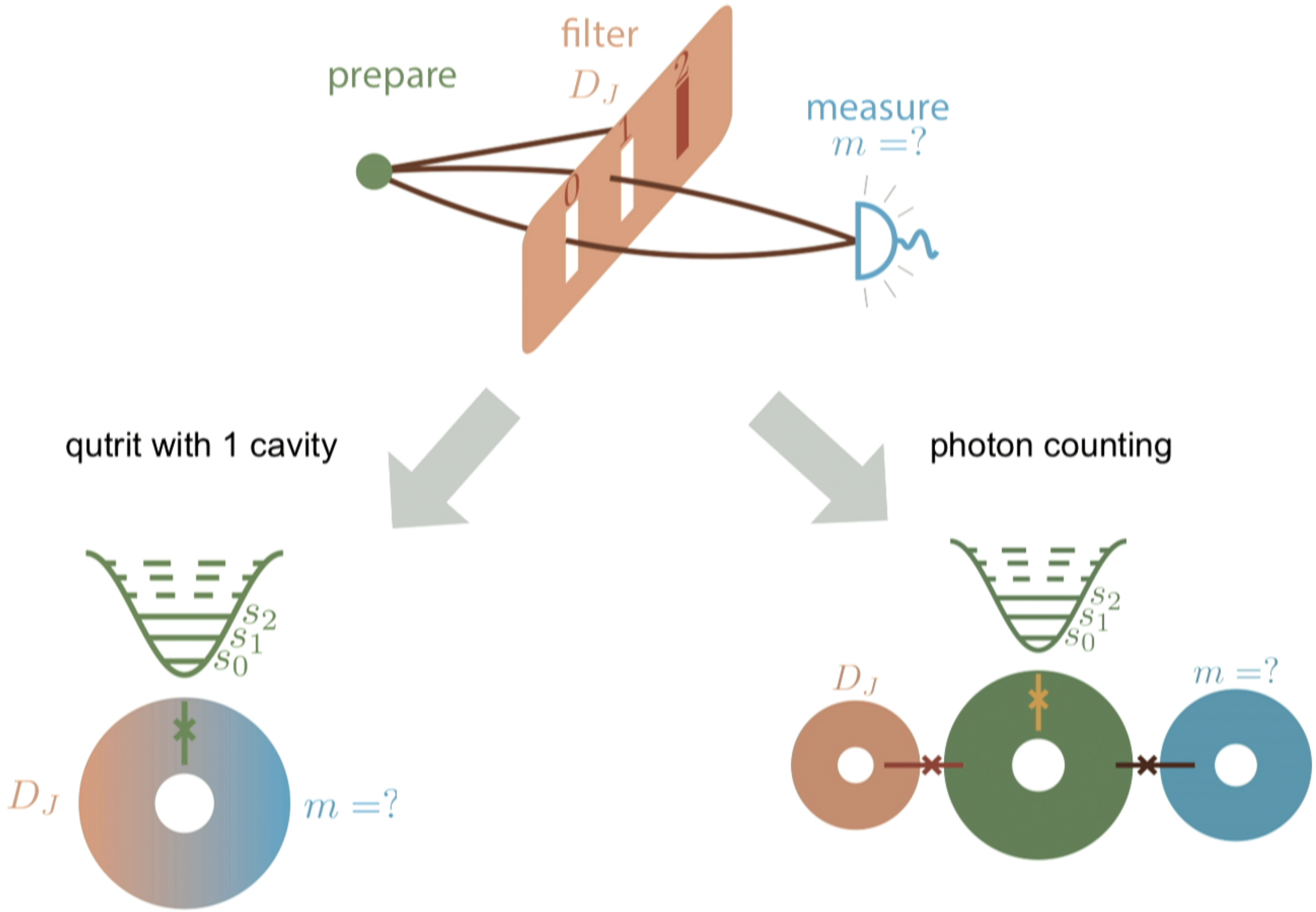
Spatial (+ energy OR phase) degeneracy between alternatives

→ avoid possible interference suppression due to relativistic
structure of space-time [Garner, Müller and Dahlsten arxiv:1412.7112]

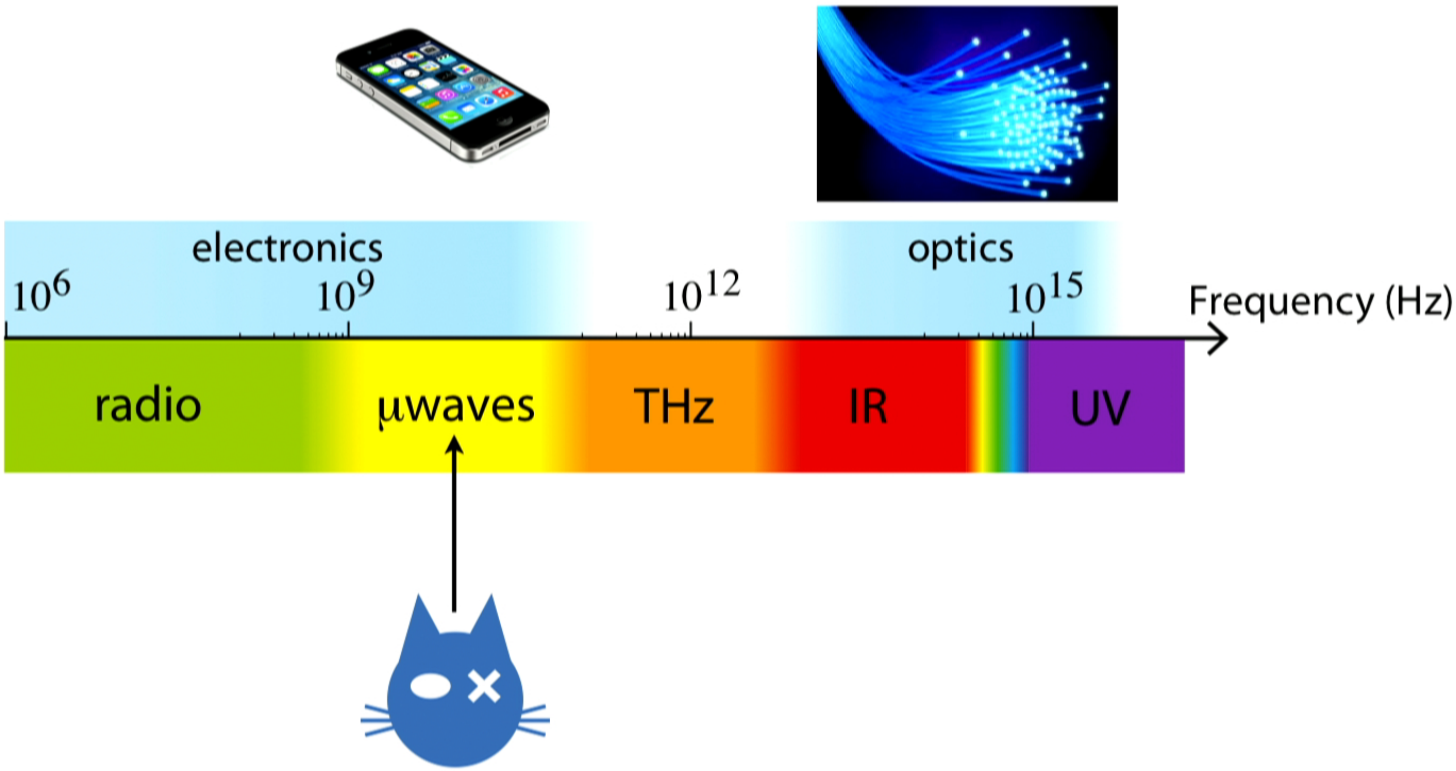
Any input state and **any** final measurement can be realized

Predicted **precision** similar or better than single photons or spin liquids $I_3 \lesssim 10^{-3} I_2$

Two possible ways



Microwave quantum optics



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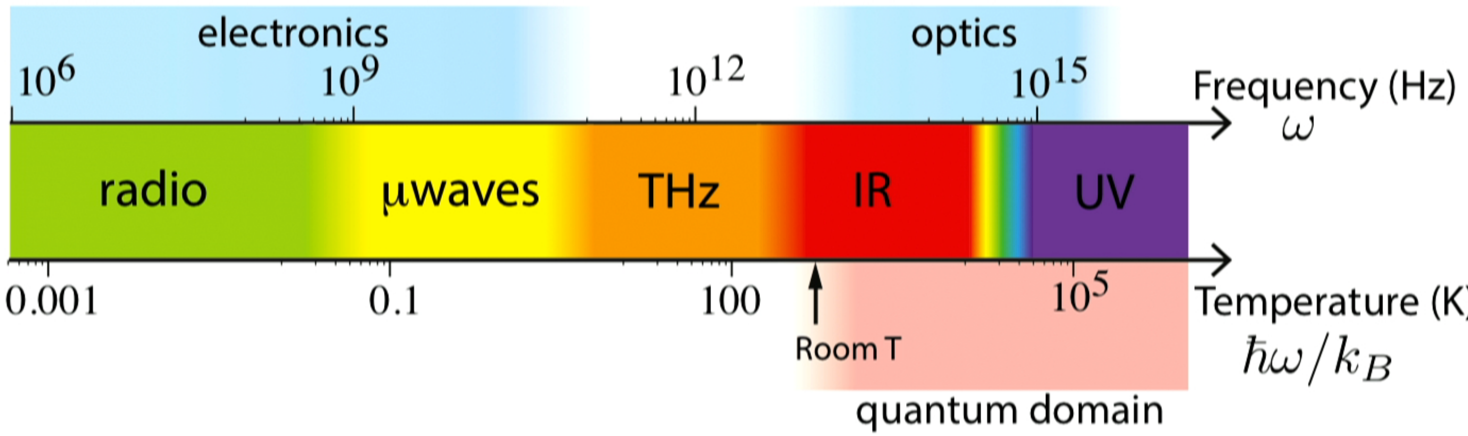
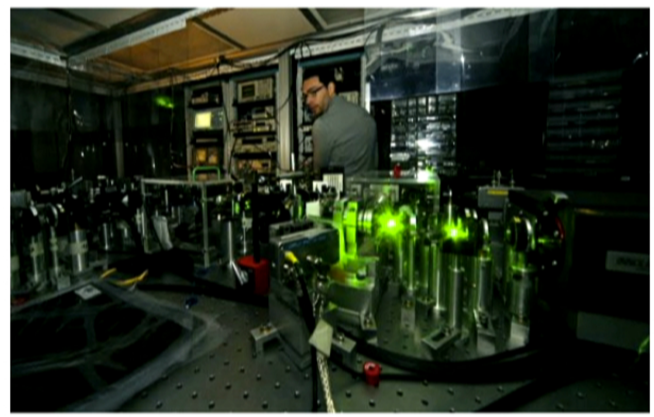


$$k_B T \ll \hbar\omega$$



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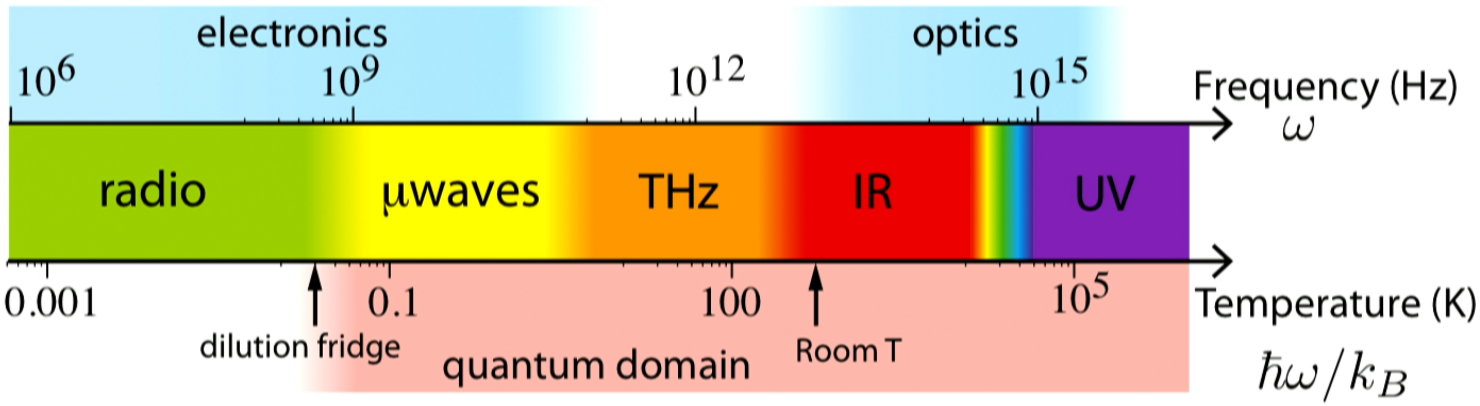
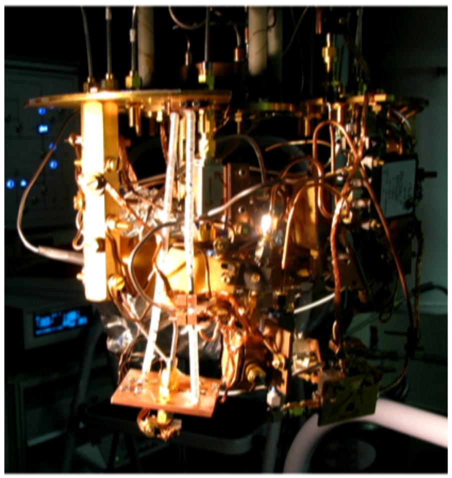
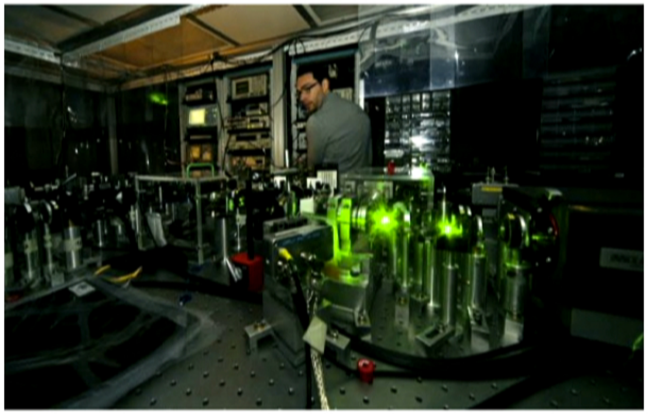
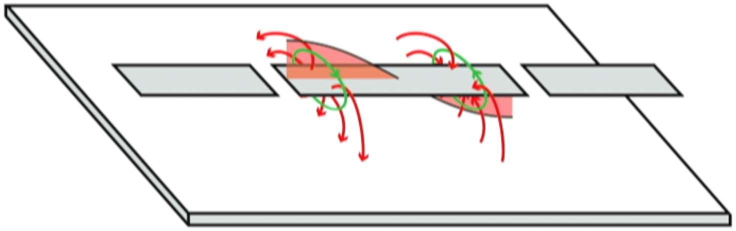
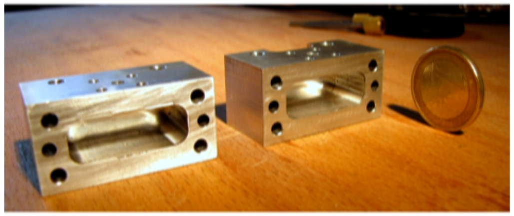




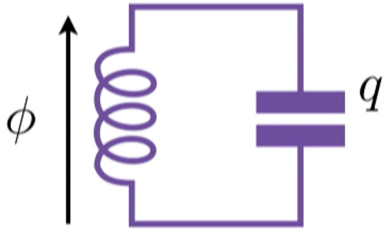


superconducting circuits





dissipationless LC circuit



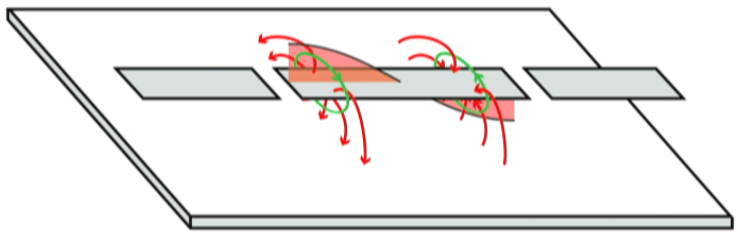
$$\hat{H} = \frac{\hat{q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

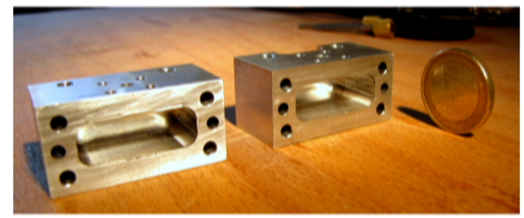
$$[\hat{\phi}, \hat{q}] = i\hbar$$

$$\hat{H} = \frac{k\hat{X}^2}{2} + \frac{\hat{P}^2}{2m}$$

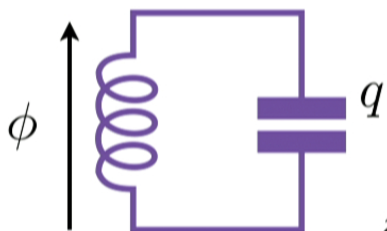
$$[\hat{X}, \hat{P}] = i\hbar$$

superconducting circuits





dissipationless LC circuit...

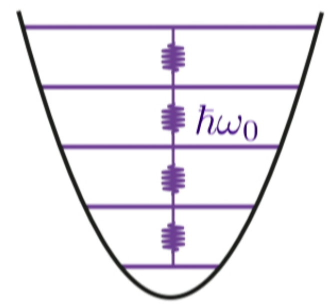


$$\hat{a} = \frac{\hat{\phi}/\phi_{ZPF} + i\hat{q}/q_{ZPF}}{2}$$

$$\hat{H} = \frac{\hat{q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

$$[\hat{\phi}, \hat{q}] = i\hbar$$

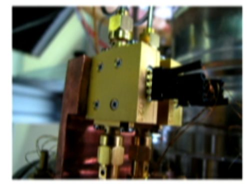
....canonically quantized



$$\hat{H} = \hbar\omega_0(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$

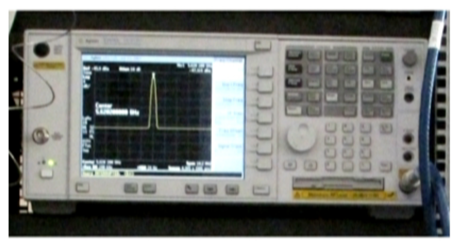
Commercial toolbox for microwave optics

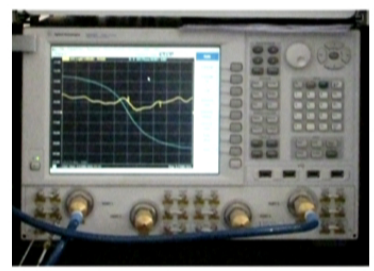
Microwave components



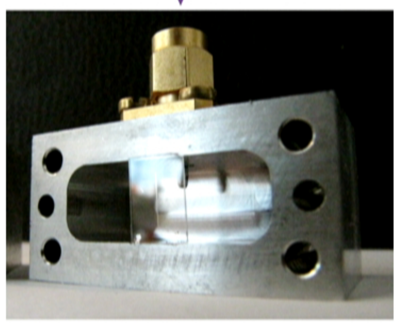
microwave sources

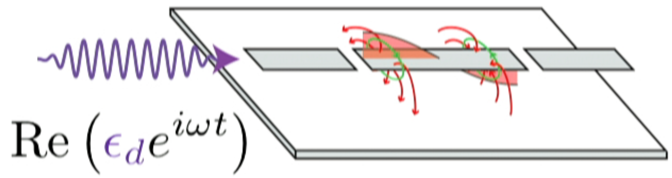
microwave detectors





Manipulating a microwave mode



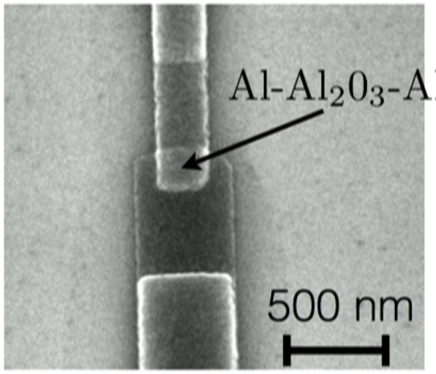


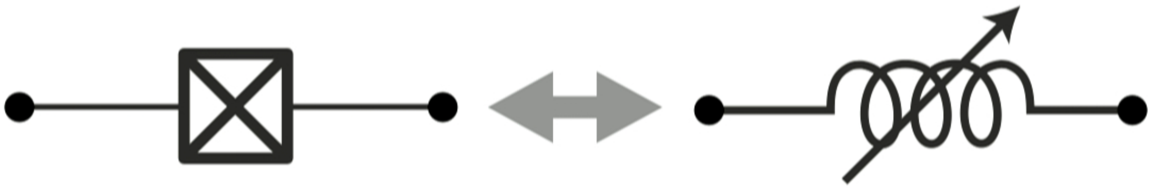
$$H = H_0 + \epsilon_d a^\dagger + \epsilon_d^* a$$

Josephson junction

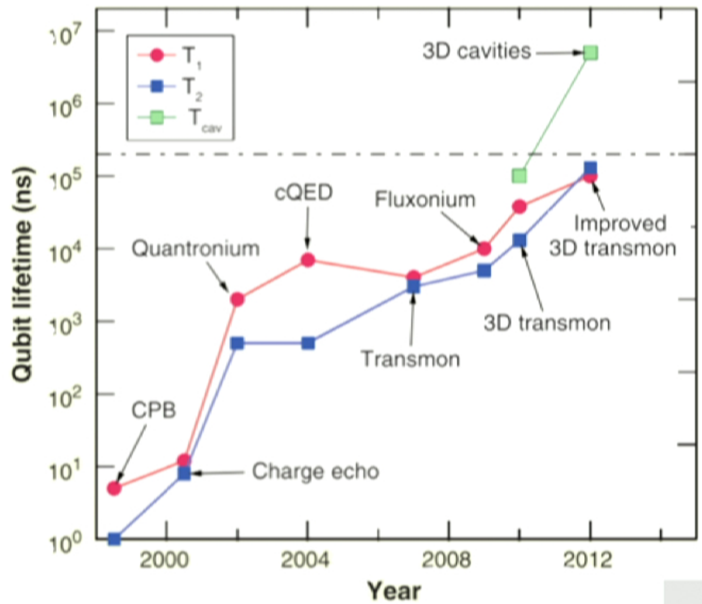
Josephson junction

dissipationless non-linear inductor





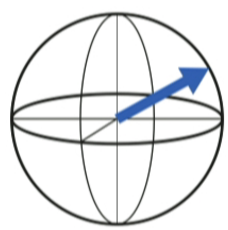
Superconducting qubits

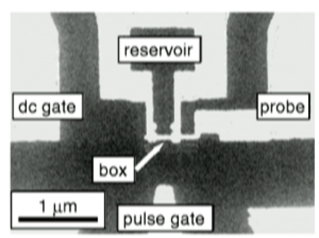


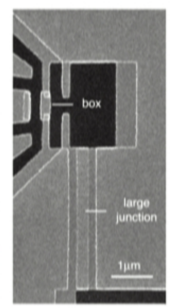
[Devoret & Schoelkopf, Science 2013 (Yale)]

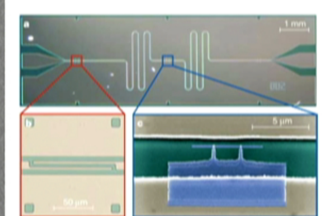
$$\hat{H} = \frac{\hat{q}^2}{2C} - E_J \cos \frac{\hat{\phi}}{\hbar/2e}$$

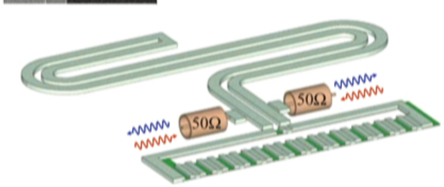
$$+H_{\mathrm{Purcell}} \to 0.02 - 2 \text{ ppm}$$
$$+H_{\mathrm{qp}} \to 0.5 - 10 \text{ ppm}$$
$$+H_{?} \to < 0.04 \text{ ppm}$$









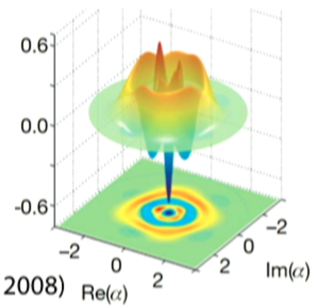


First Rabi oscillations in 1999 [Nakamura et al., Tsukuba]
Quantronium in 2002 [Vion et al., Saclay]
Charge qubit, phase qubit, flux qubit,
transmon, fluxonium, Xmon...

Non classical states in microwave quantum optics

Fock state

$|3\rangle$

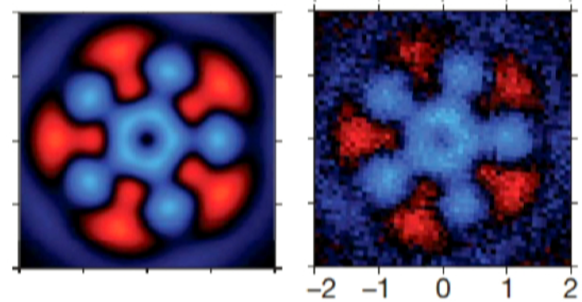


(CQED, Paris 2008)

arbitrary superposition of Fock states

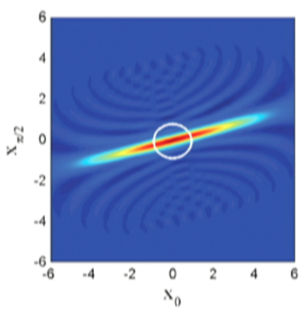
$|0\rangle + |5\rangle$

(Santa Barbara 2010)



itinerant squeezed vacuum state

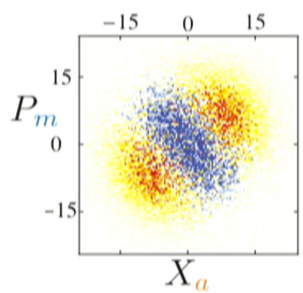
1-mode



(Boulder 2011)

$e^{ra^{\dagger 2} - r^* a^2}|0\rangle$

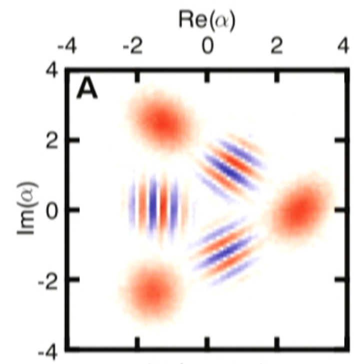
EPR state



(Paris 2013)

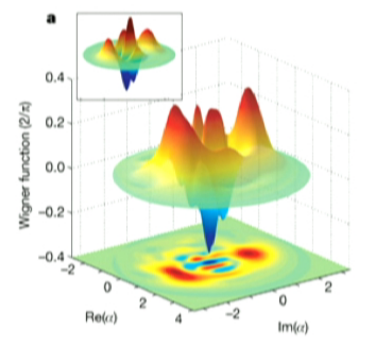
$e^{ra^\dagger b^\dagger - r^* ab}|0,0\rangle$

Schrödinger cats



(Yale 2012)

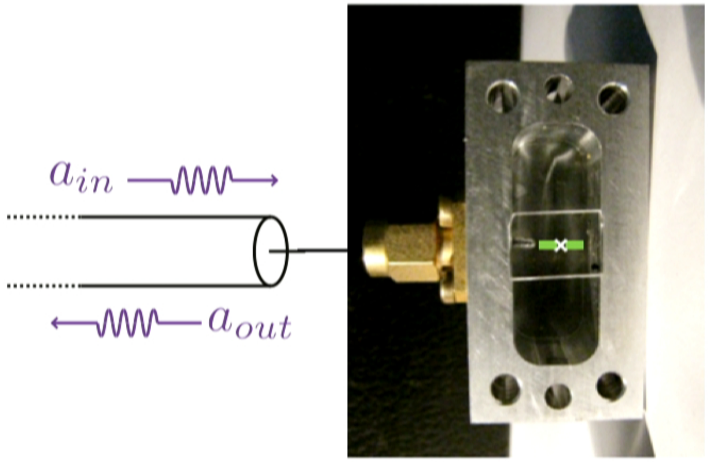
$|\alpha\rangle + |e^{i\frac{2\pi}{3}}\alpha\rangle + |e^{i\frac{4\pi}{3}}\alpha\rangle$

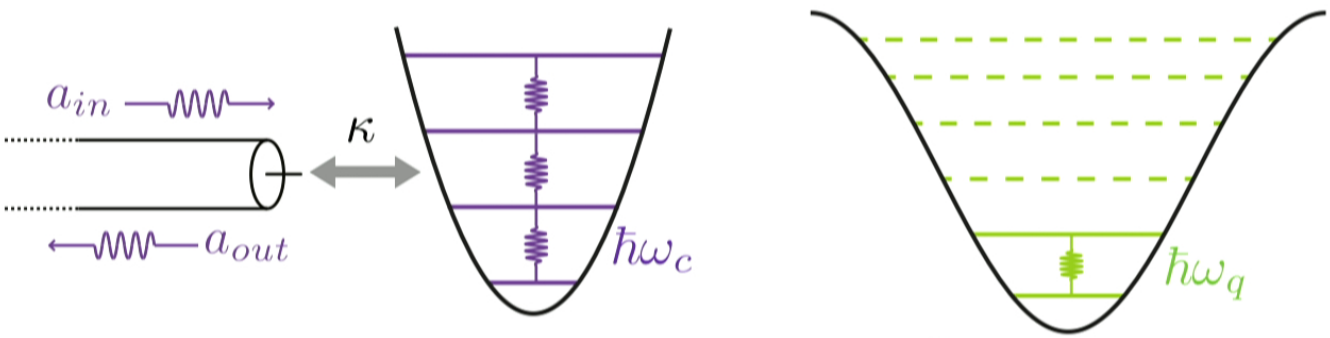


(CQED, Paris 2008)

$|\alpha\rangle + |-\alpha\rangle$

circuit-QED





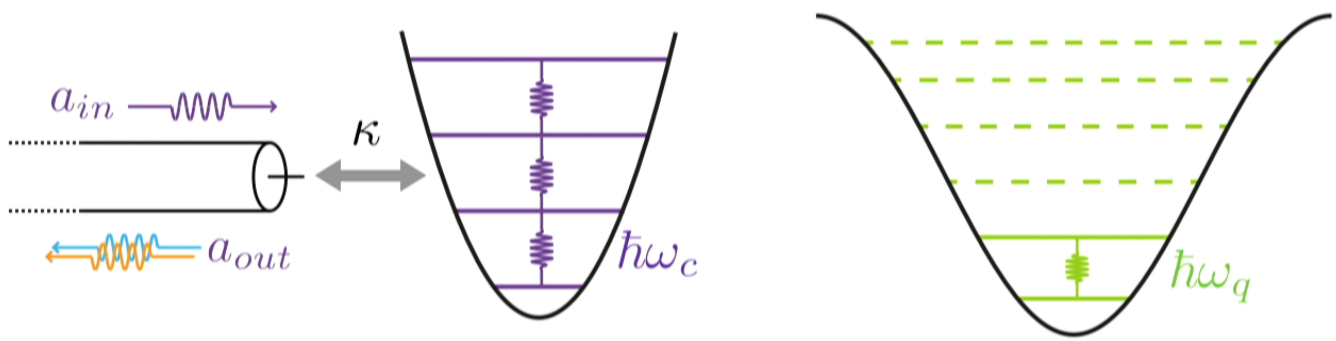
$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_Z}{2}$$

Dispersive measurement

$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_Z}{2}$$

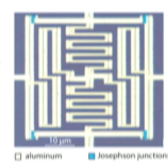
$$\omega_r = \omega_c - \chi/2$$

$$\omega_r = \omega_c + \chi/2$$



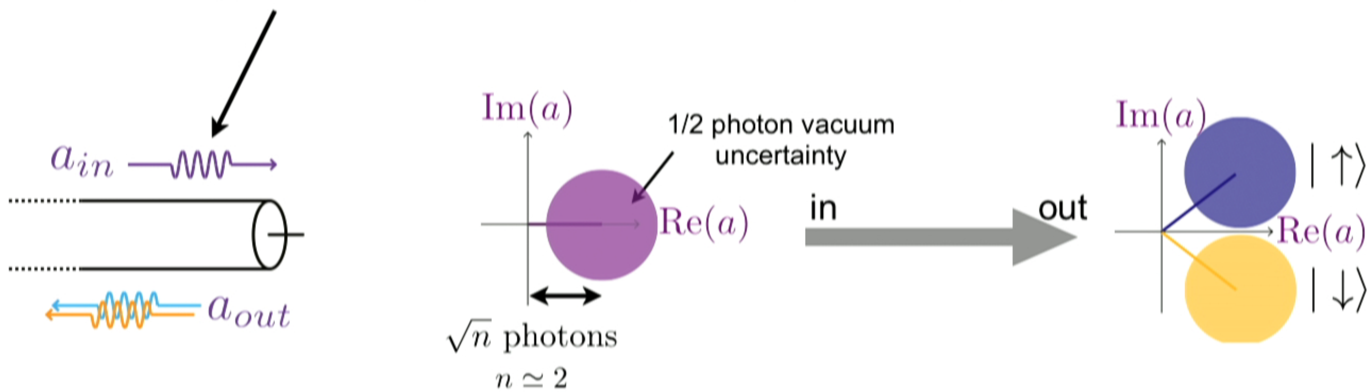
Phase encodes qubit state

measurement uses a non-degenerate quantum limited amplifier
[Roch et al., PRL 2012]



Dispersive measurement

$$\mathrm{Re}\left(\langle a\rangle e^{-i\omega t}\right) = \mathrm{Re}\langle a\rangle\cos(\omega t) + \mathrm{Im}\langle a\rangle\sin(\omega t)$$



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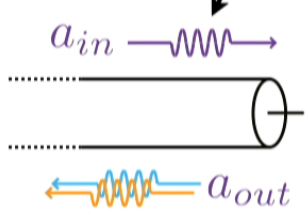

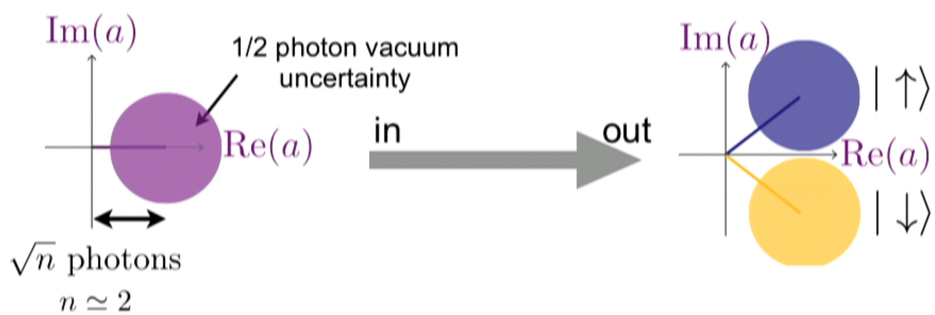

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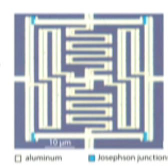
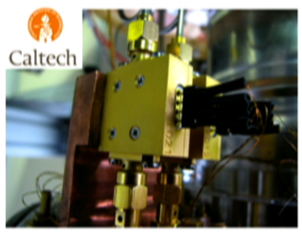
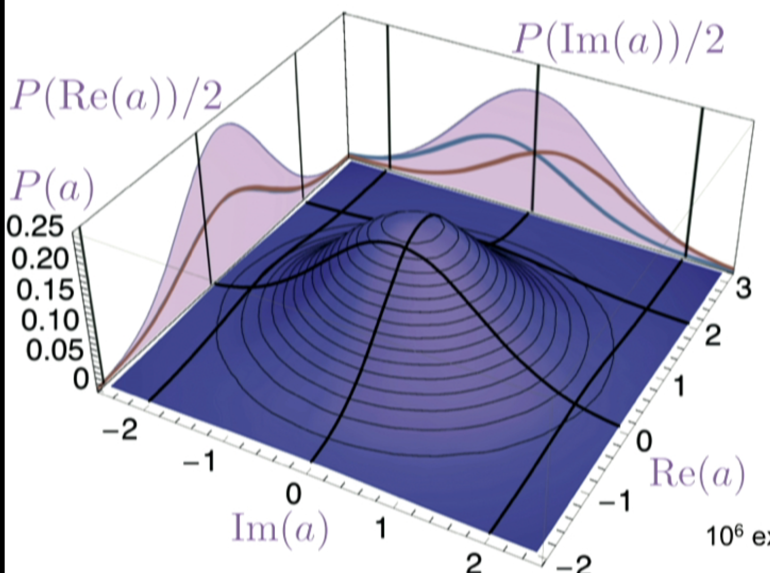


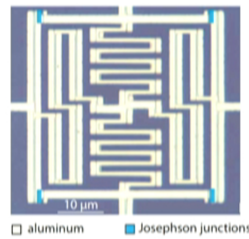
Single shot qubit state readout

Low noise cryogenic amplifier only





Josephson amplifier



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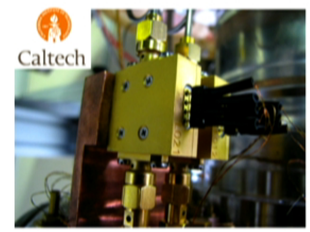
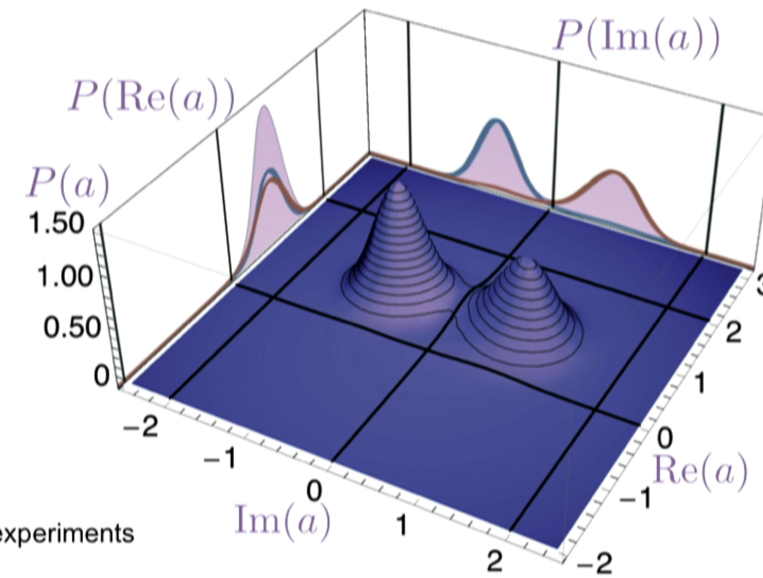


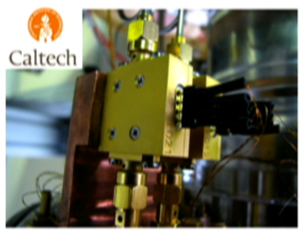


10^6 experiments

[Campagne-Ibarcq et al., PRX 2013 (ENS Paris)]

Single shot qubit state readout

Low noise cryogenic amplifier only



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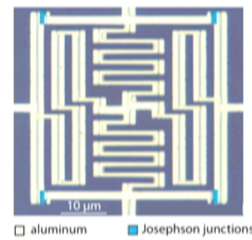

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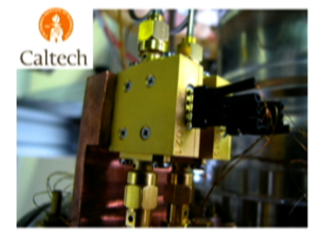

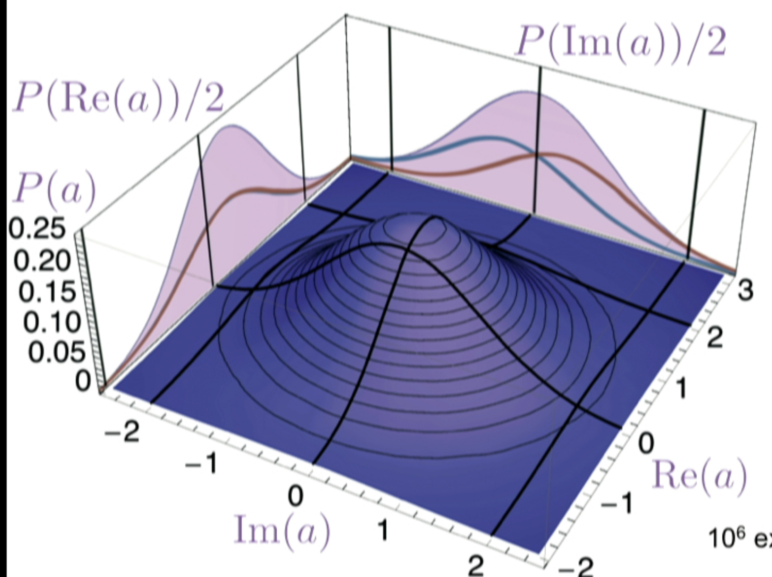

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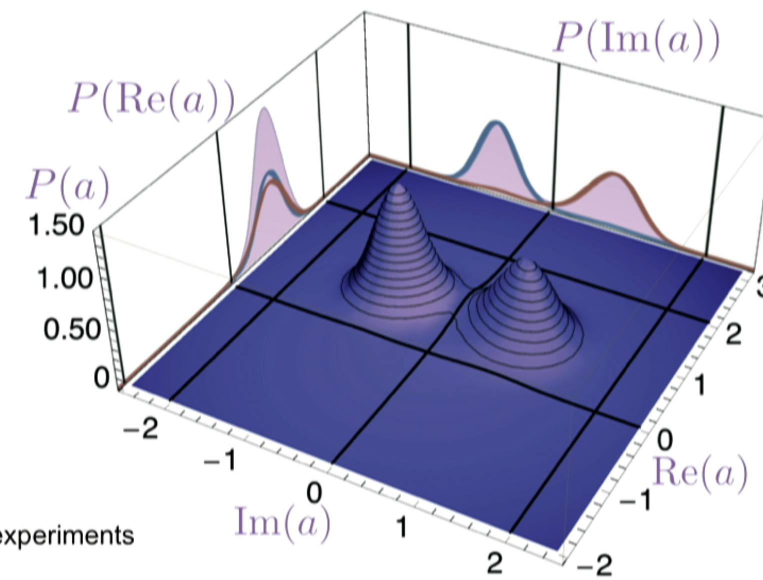
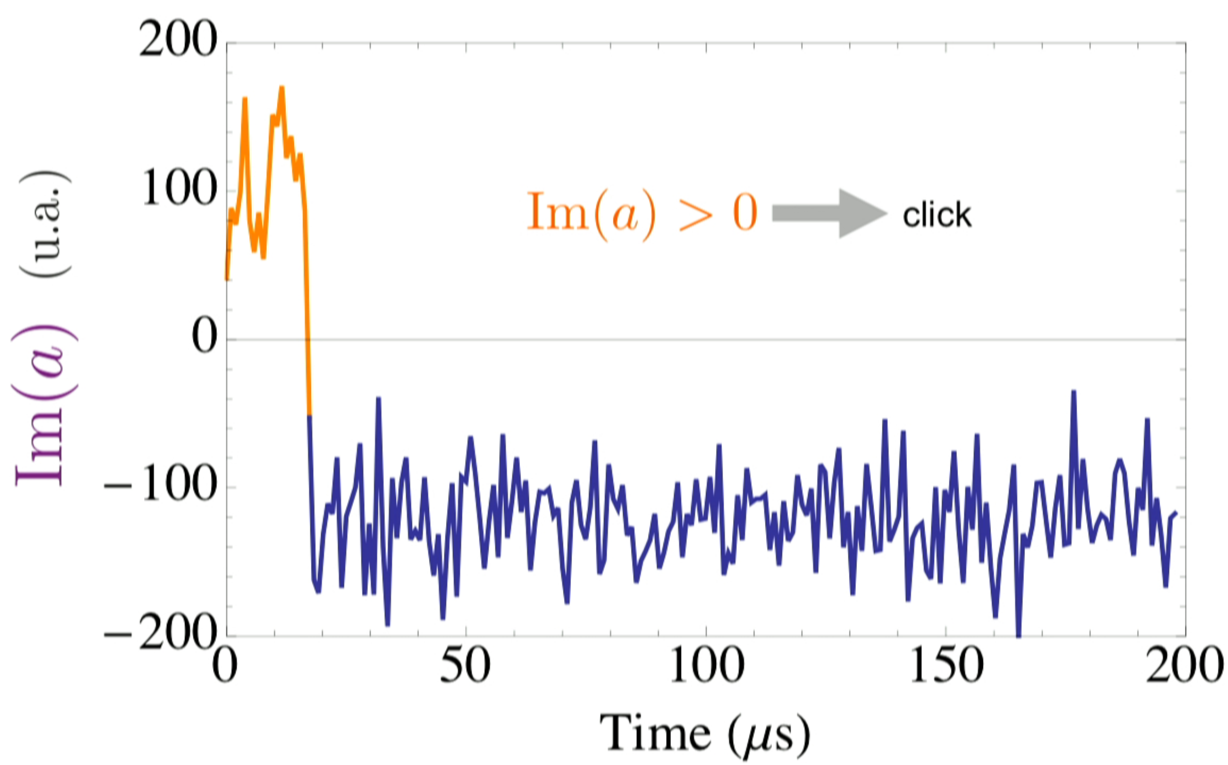


[Campagne-Ibarcq et al., PRX 2013 (ENS Paris)]

Quantum jumps

prepare $|1\rangle$ and continuous measurement at 1.8 photons



similar to [Vijay et al., PRL 2011 (Berkeley)]

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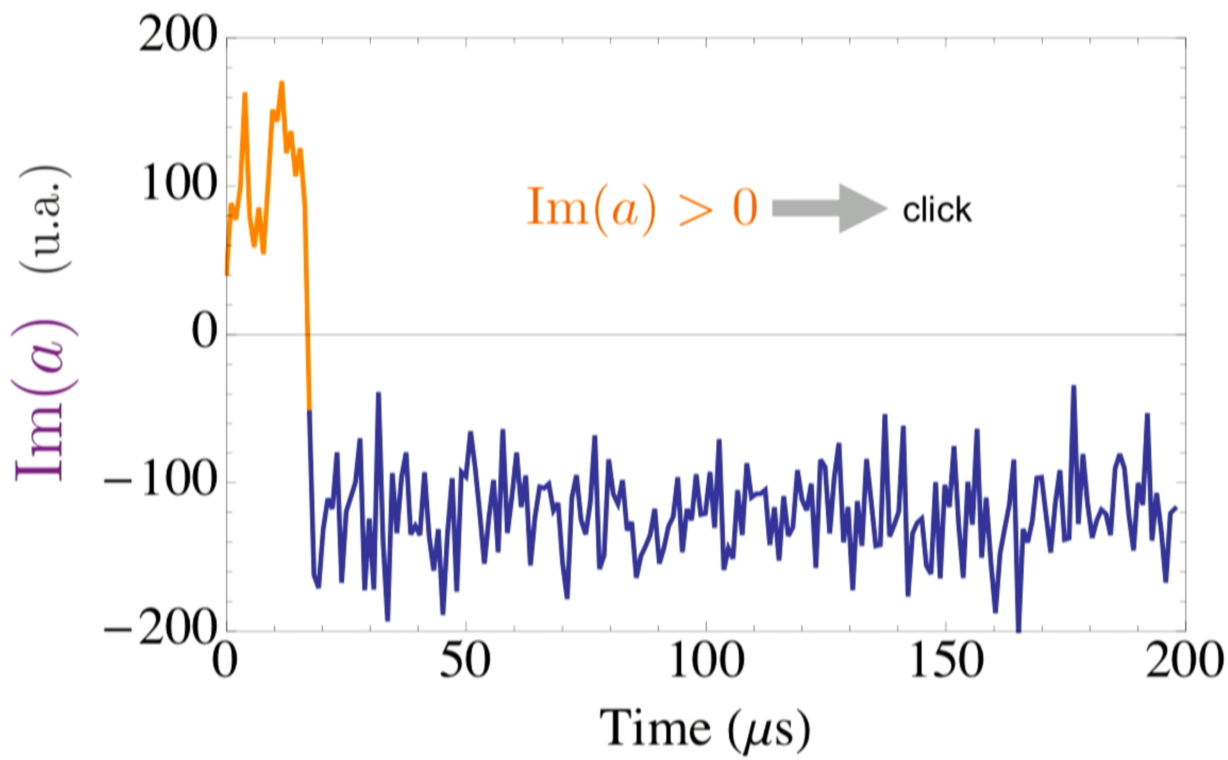

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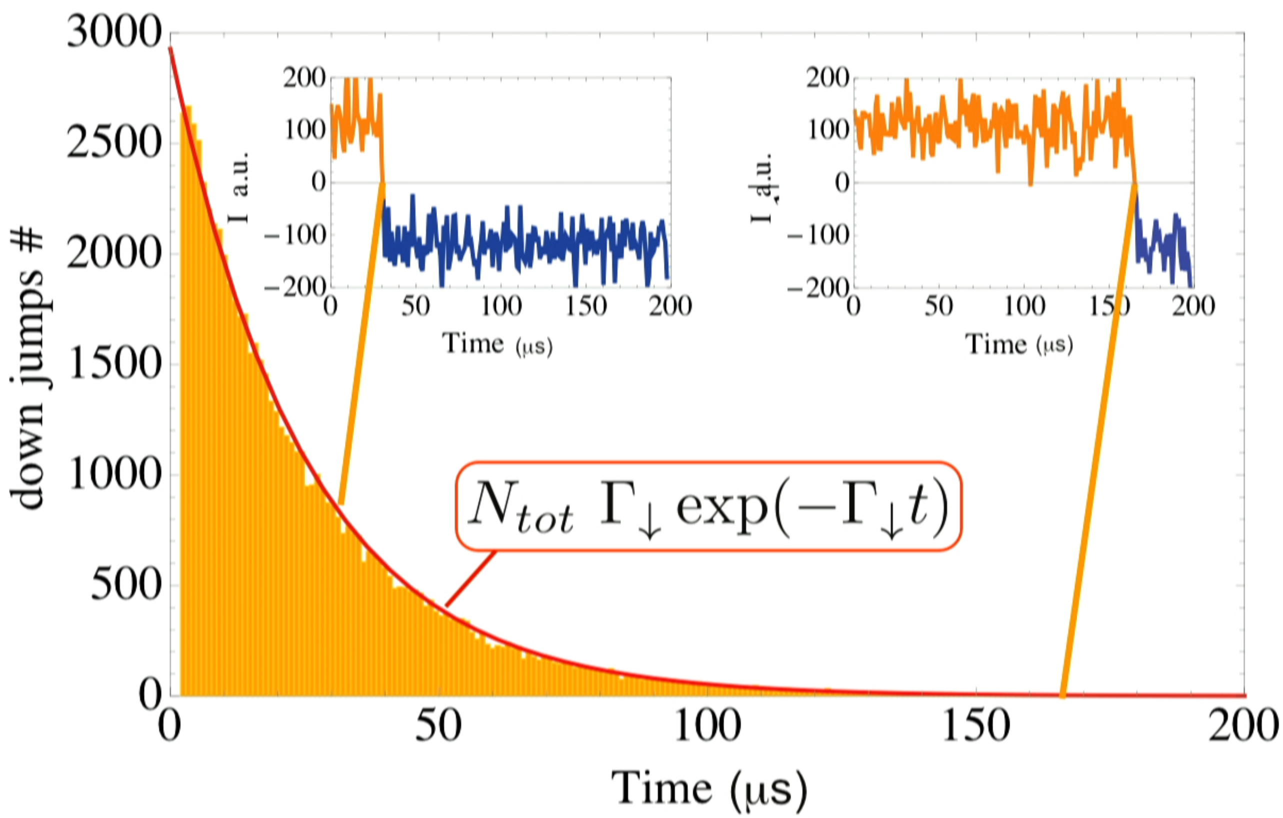
continuous measurement at 1.8 photons

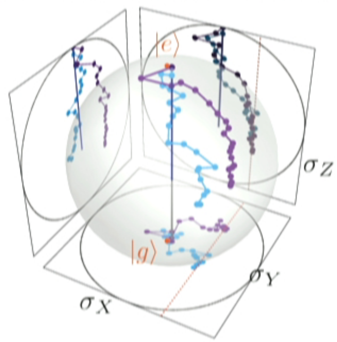


$$\frac{1}{\Gamma\downarrow} \simeq T_1 = 26\ \mu s$$

[Campagne-Ibarcq et al., PRX 2013 (ENS Paris)]

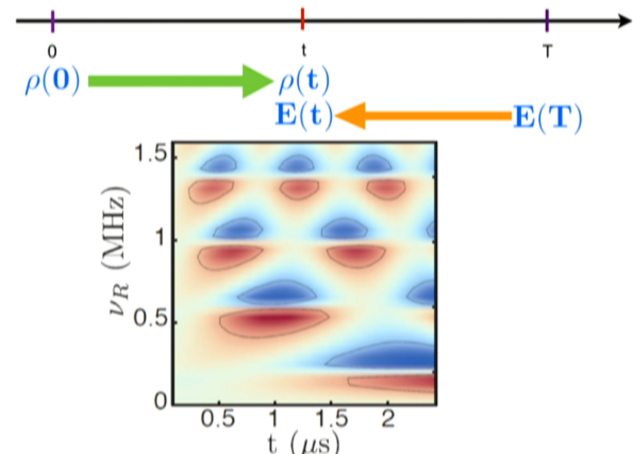
Quantum measurement backaction

quantum trajectories



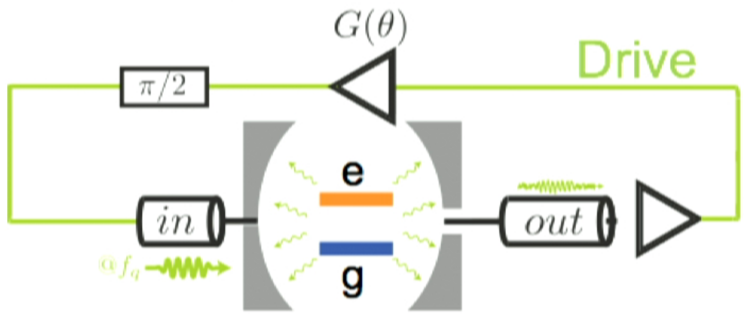
[Campagne-Ibarcq et al., PRX 2016]
[Jordan et al., Quantum Studies: Math and Foundations 2016]

post-selection



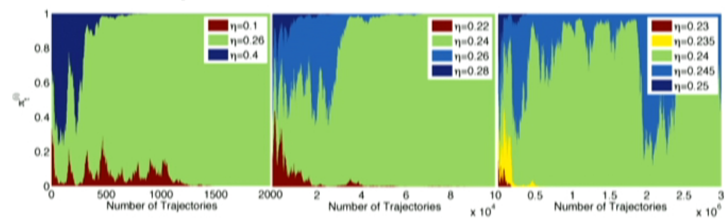
[Campagne-Ibarcq et al., PRL 2014]
[Ficheux et al., in prep.]

quantum feedback



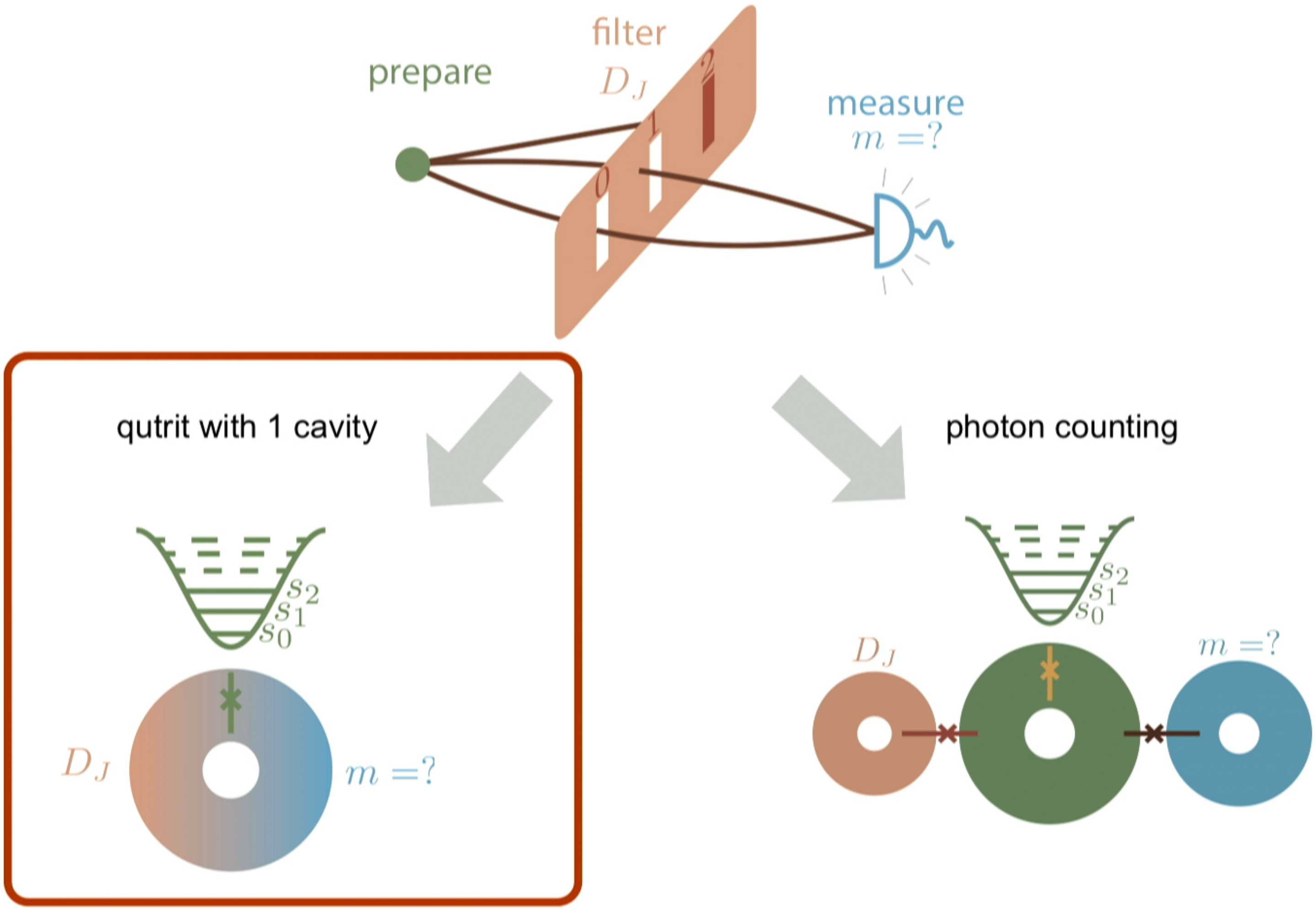
[Campagne-Ibarcq et al., PRX 2013]
[Campagne-Ibarcq et al., PRL 2016]

parameter estimation

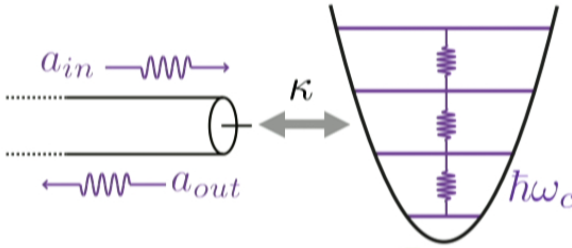


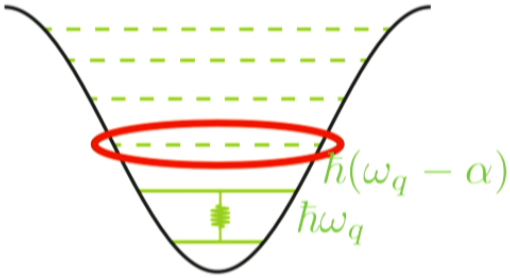
[Six et al., PRA 2016]
[Six et al., CDC IEEE 2015]

Two possible ways



Direct readout of a qutrit?





~~$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma z}{2}$~~

$$H_{\text{pert}} = \hbar\chi a^\dagger a b^\dagger b - \hbar\alpha(b^\dagger b)^2$$

$\Rightarrow \omega_r = \omega_c$

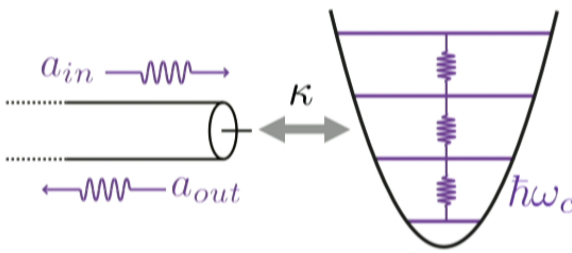
$|0\rangle \Rightarrow \omega_r = \omega_c - \chi$

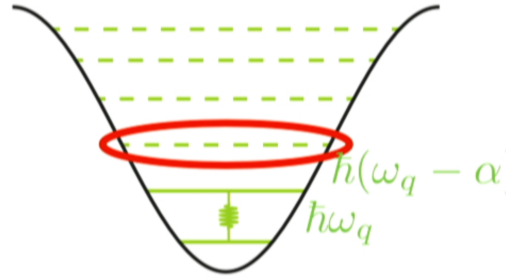
$|1\rangle \Rightarrow \omega_r = \omega_c - 2\chi$

$|2\rangle$

probe at $\omega_p \approx \omega_c - \chi$

Direct readout of a qutrit?





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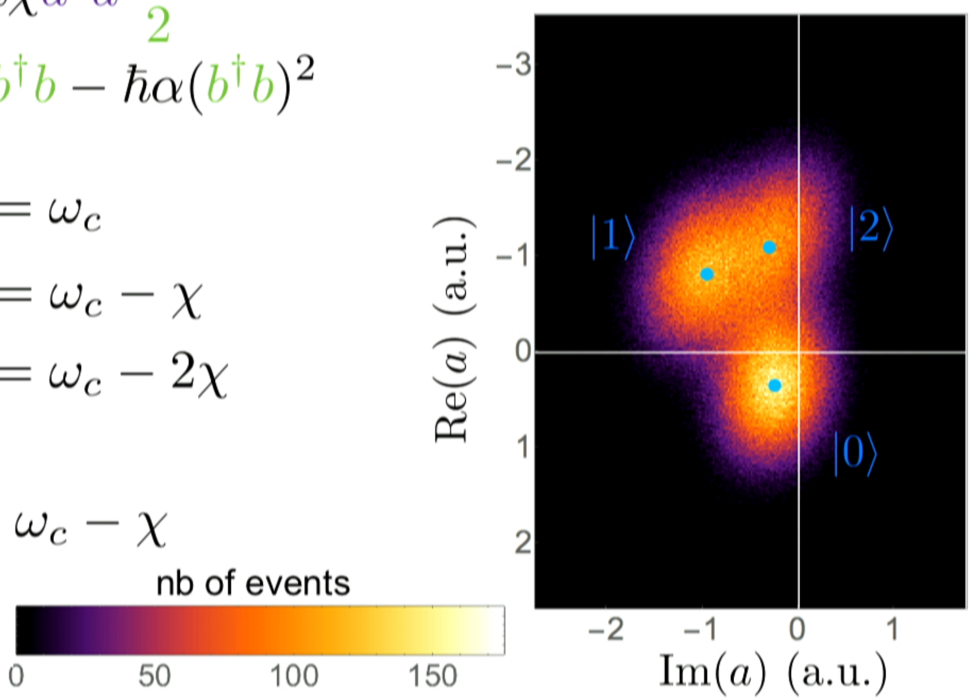
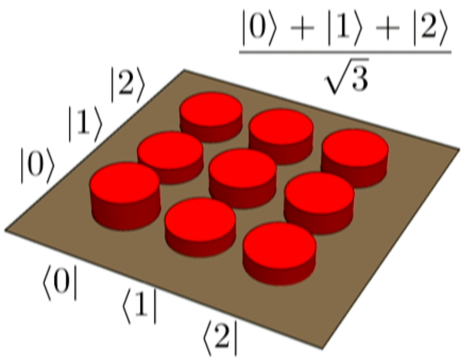
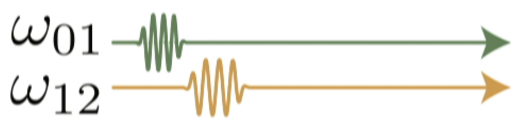


Third order superpositions in a qutrit: experiment



preparation

$$Y^{(12)}_{\frac{\pi}{2}} Y^{(01)}_{2\arccos(3^{-1/2})} |0\rangle$$



tomography

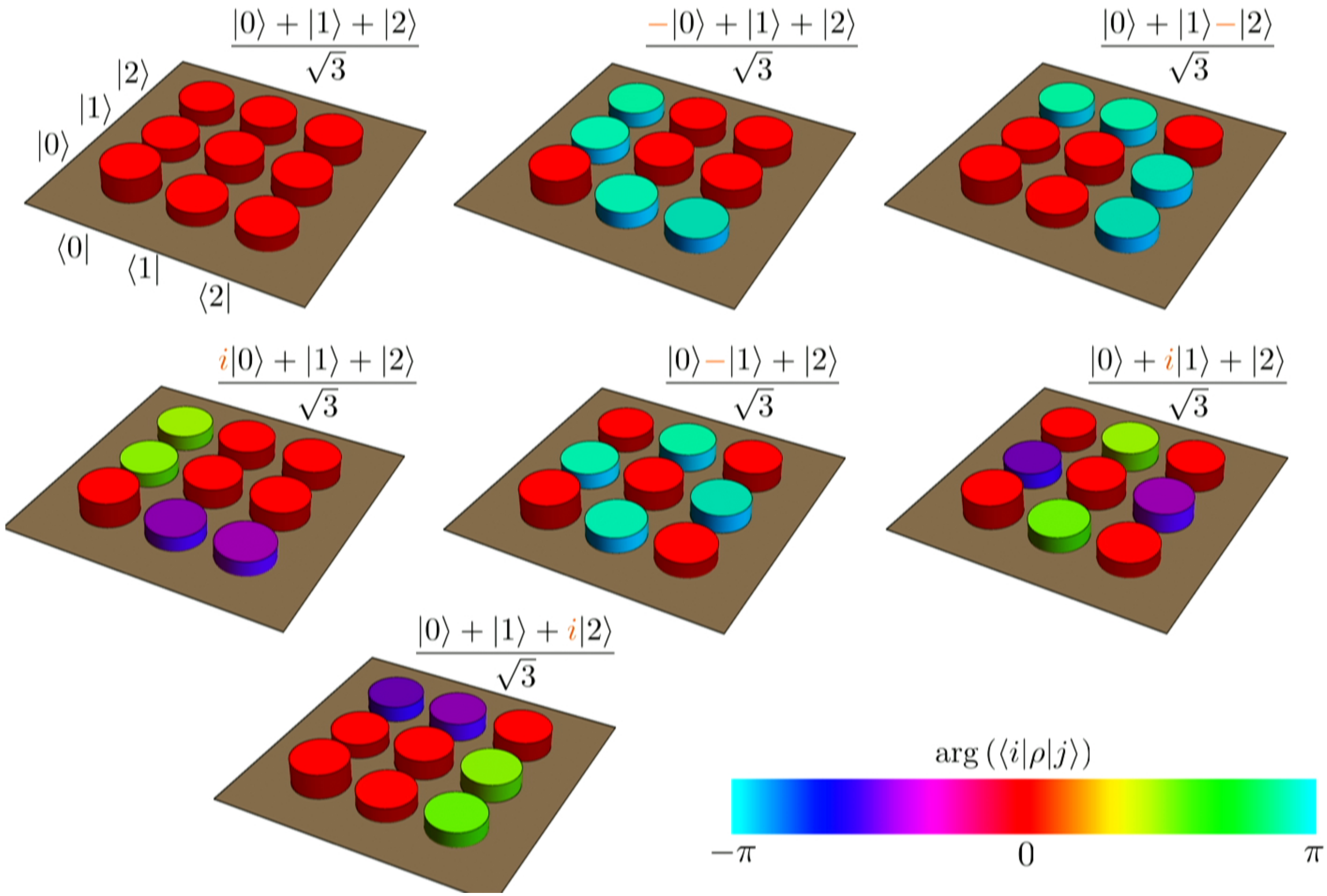
$$\mathbf{1}, X^{(01)}_{\frac{\pi}{2}}, Y^{(01)}_{\frac{\pi}{2}}, X^{(12)}_{\frac{\pi}{2}}, Y^{(12)}_{\frac{\pi}{2}}, X^{(12)}_{\frac{\pi}{2}} X^{(01)}_{\frac{\pi}{2}}, Y^{(12)}_{\frac{\pi}{2}} X^{(01)}_{\frac{\pi}{2}}$$

then measure p_0, p_1, p_2 using heterodyne dispersive measurement

$\arg\left(\langle i|\rho|j\rangle\right)$

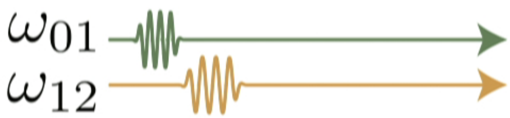
$-\pi$ 0 π

Third order superpositions in a qutrit: experiment



Testing third order interference

① prepare the system in a non classical statistical mixture of states s_0, s_1, s_2



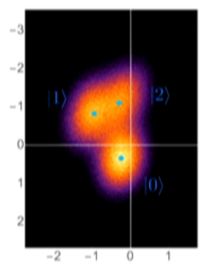
② filter the experiments by a projective detector D_J where $J \subseteq \{0,1,2\}$

$\forall j \in J$ clicks if sys in s_j $\forall j \in \{0,1,2\} - J$ does not click if sys in s_j

identical stats of outcome for a following measurement if D_J is used once ore twice

$D_{\{0\}}, D_{\{1\}}, D_{\{2\}}$

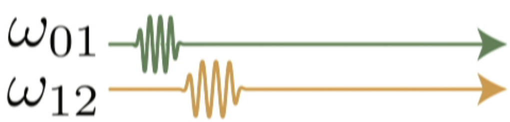
probe at $\omega_p \approx \omega_c - \chi$



$D_{\{01\}}, D_{\{12\}}, D_{\{02\}}$

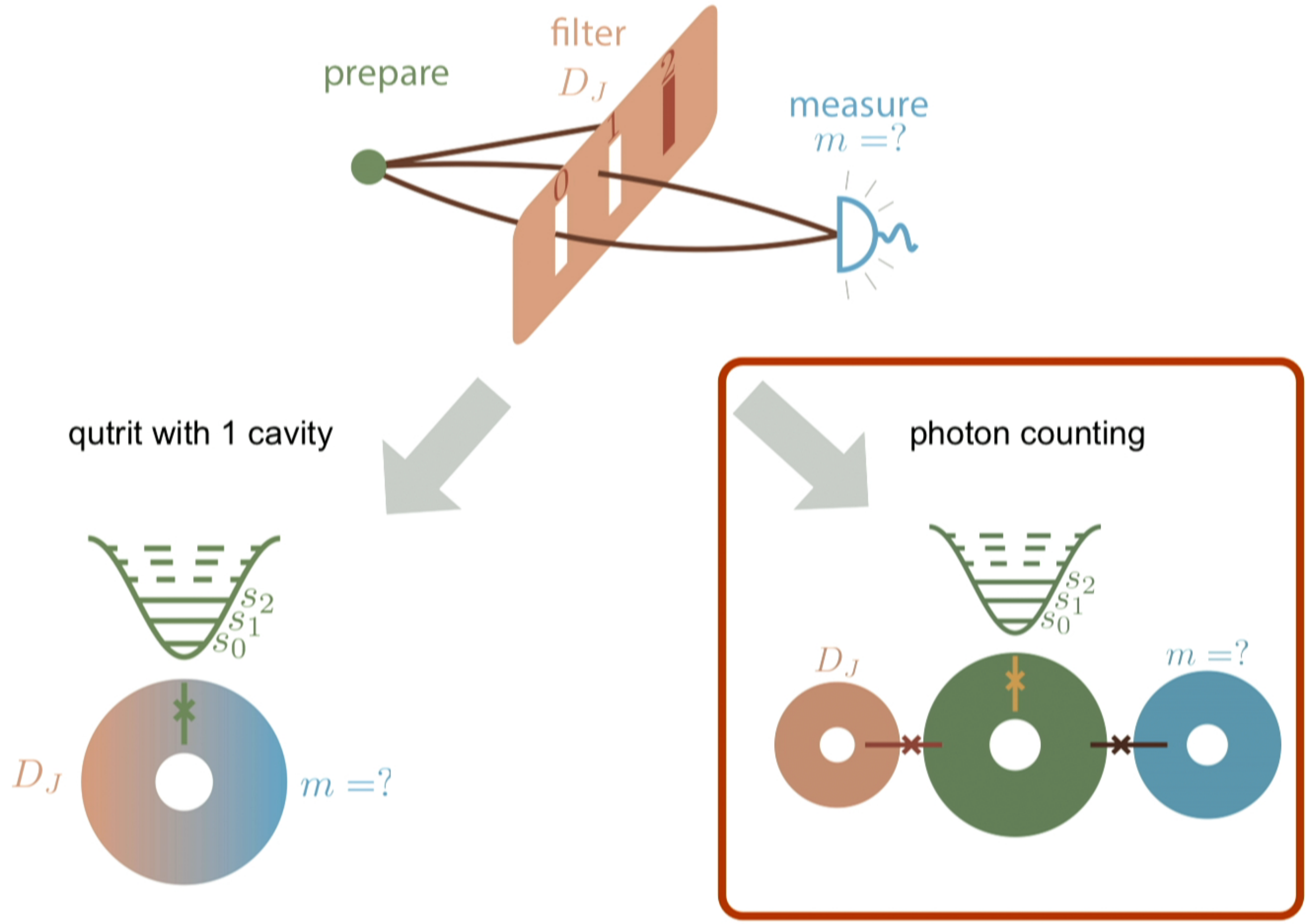
need same outcome for two j's
possible by tuning probe
but **prone to errors**

③ measure the system by an apparatus which differs from any D_J

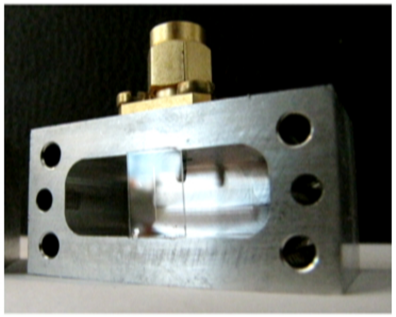


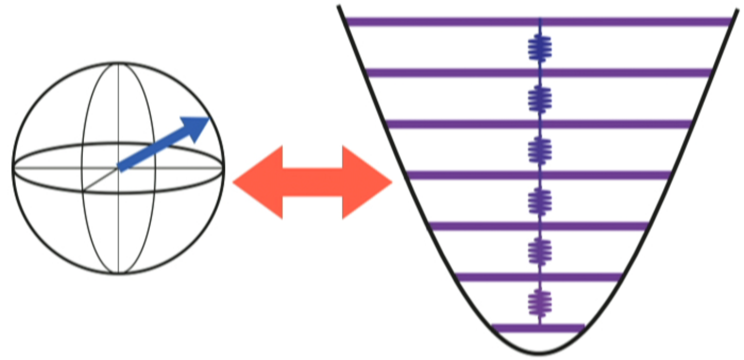
then $D_{\{0\}}$

Two possible ways



Qubit as a photocounter





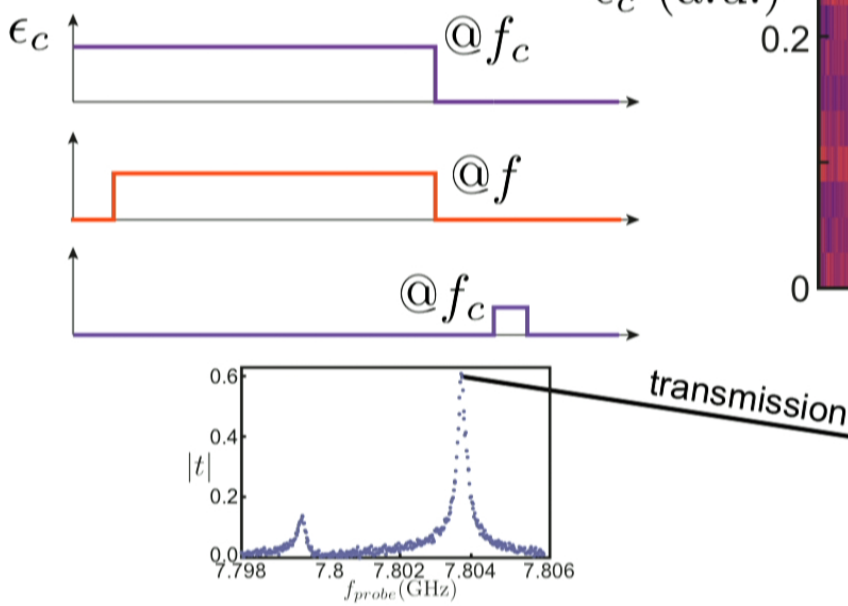
$$H = hf_c a^\dagger a + hf_q |e\rangle\langle e| - h\chi a^\dagger a |e\rangle\langle e|$$

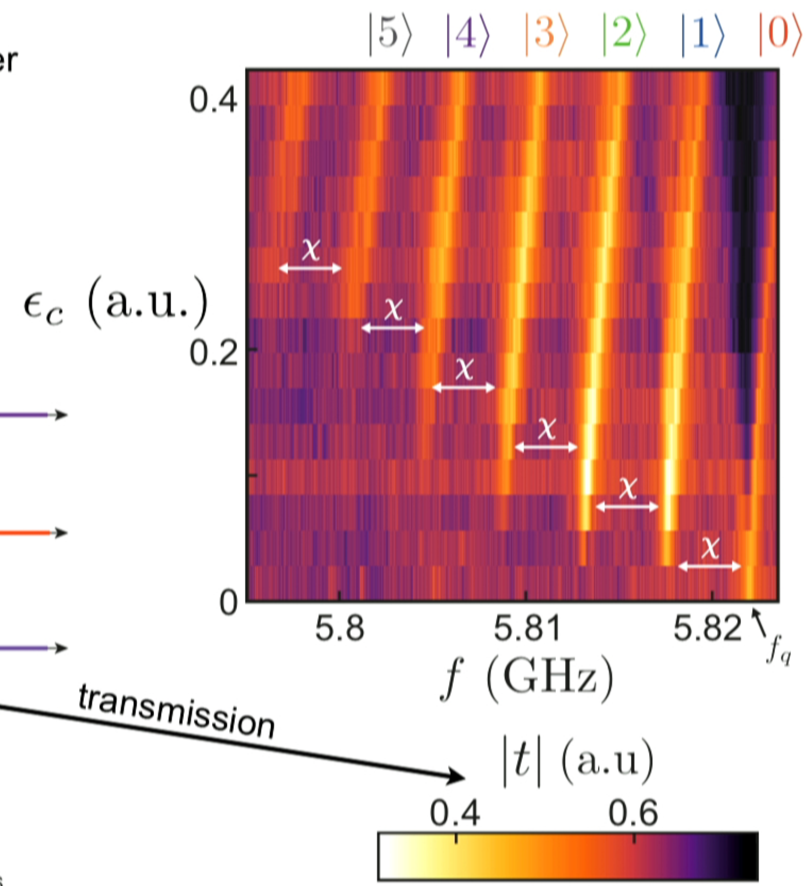
7.8 GHz 5.6 GHz 4.6 MHz

Qubit as a photocounter

$$f_q \mapsto f_q - \chi N$$

Qubit frequency indicates photon number





[Schuster et al., Yale group, 2007]

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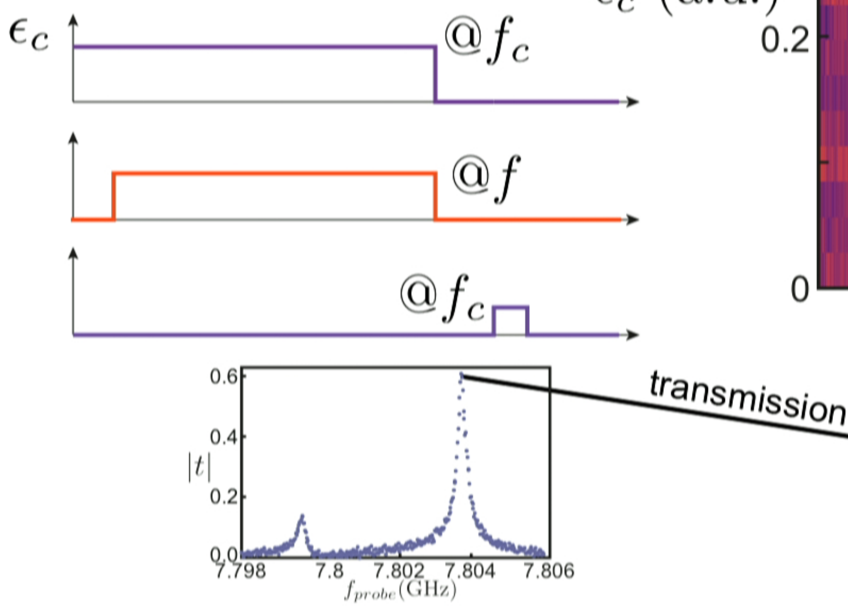
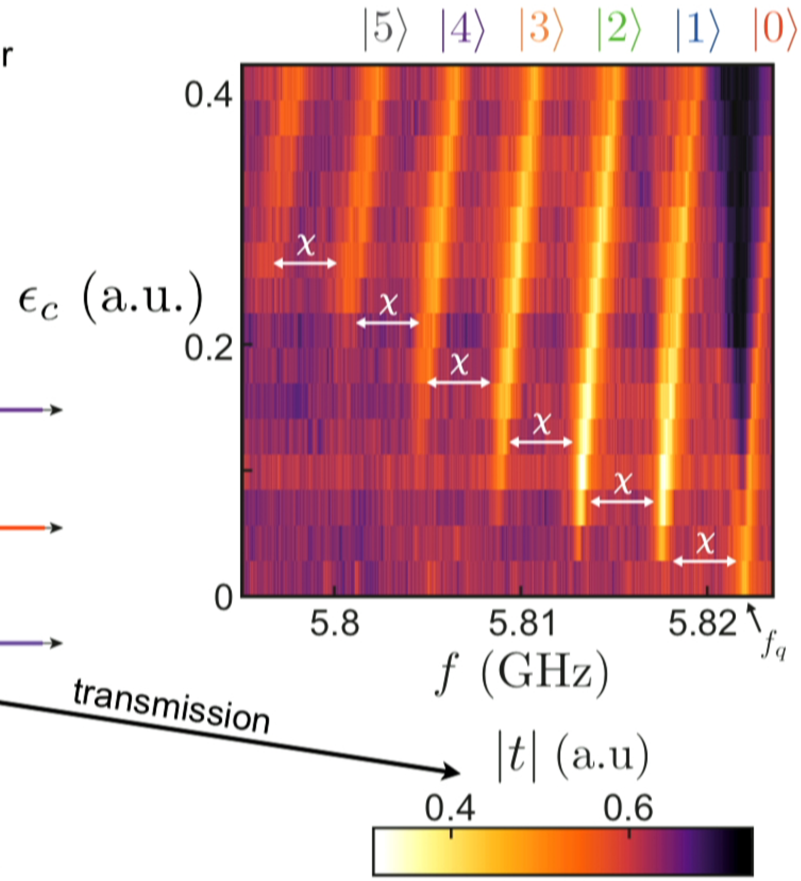
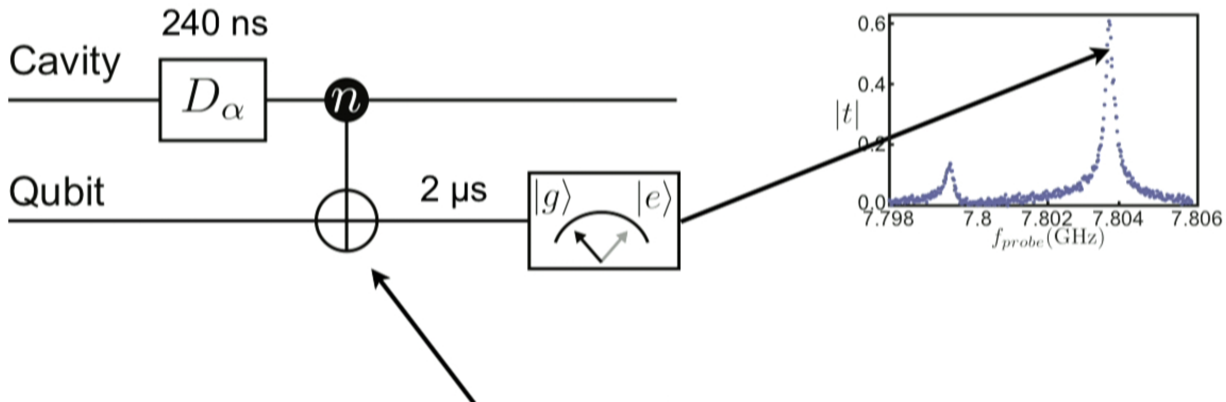




[Schuster et al., Yale group, 2007]

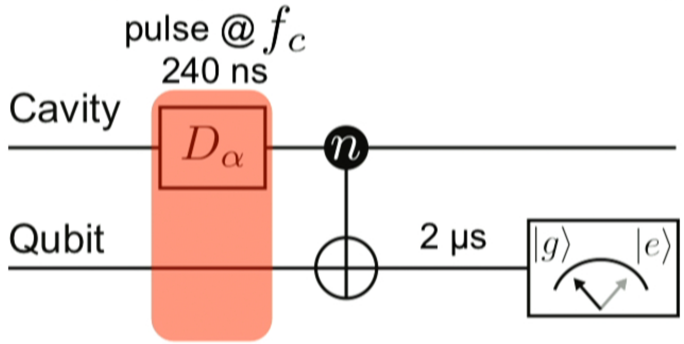
Photocounting a coherent state

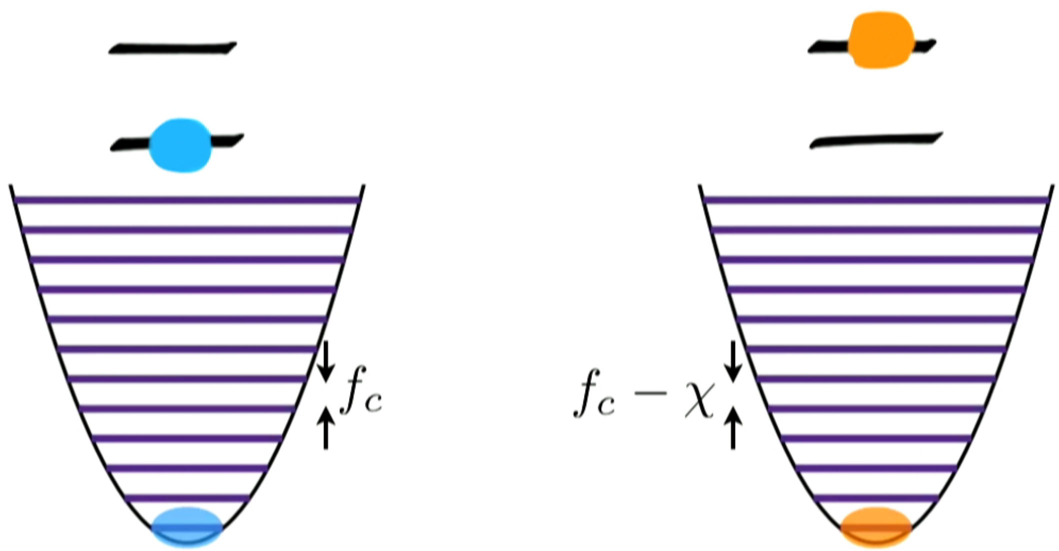


$$\pi - \text{pulse at } f_q - \chi n$$

$$\frac{1}{2\pi\chi} \ll 400 \text{ ns} \ll T_c$$

Photocounting a coherent state





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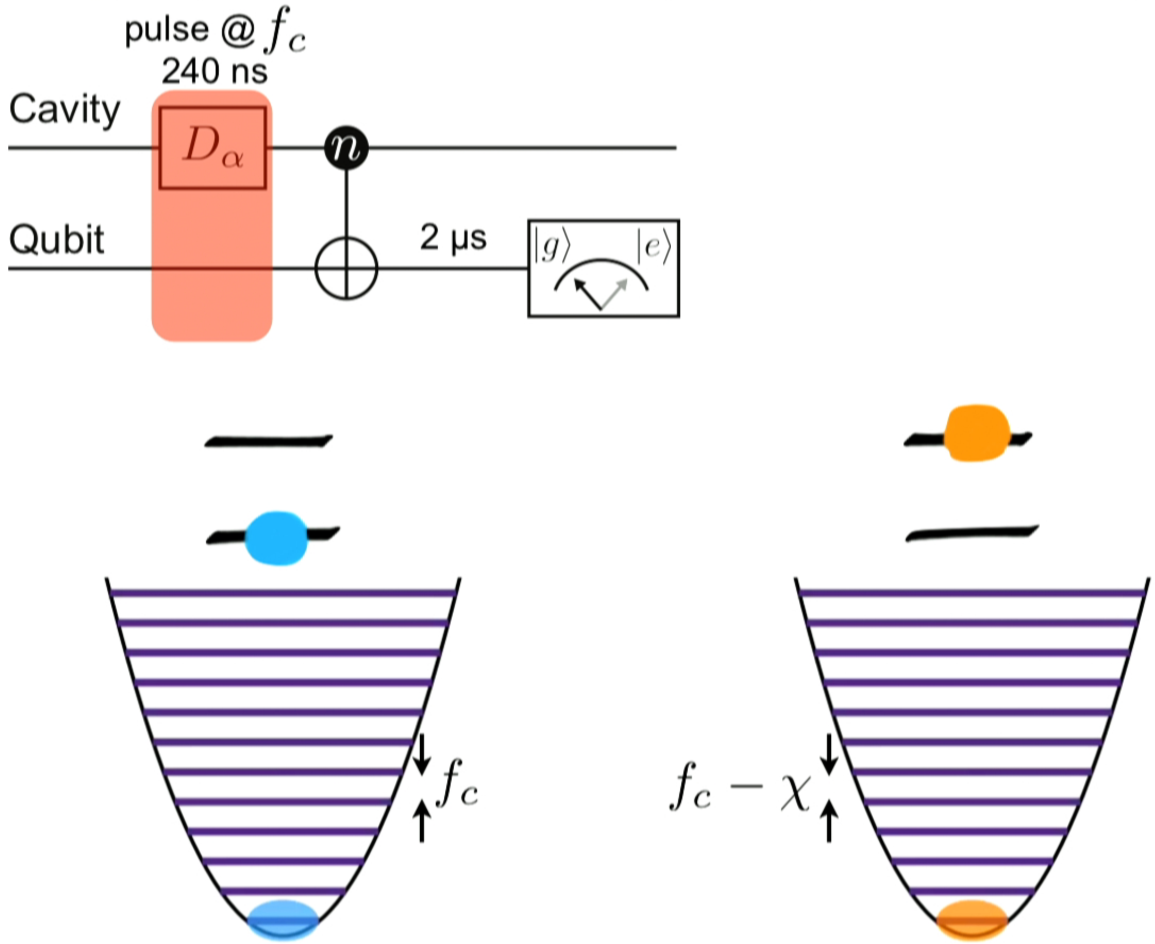

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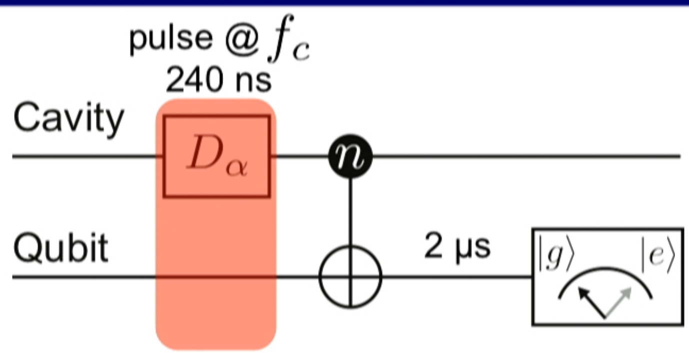

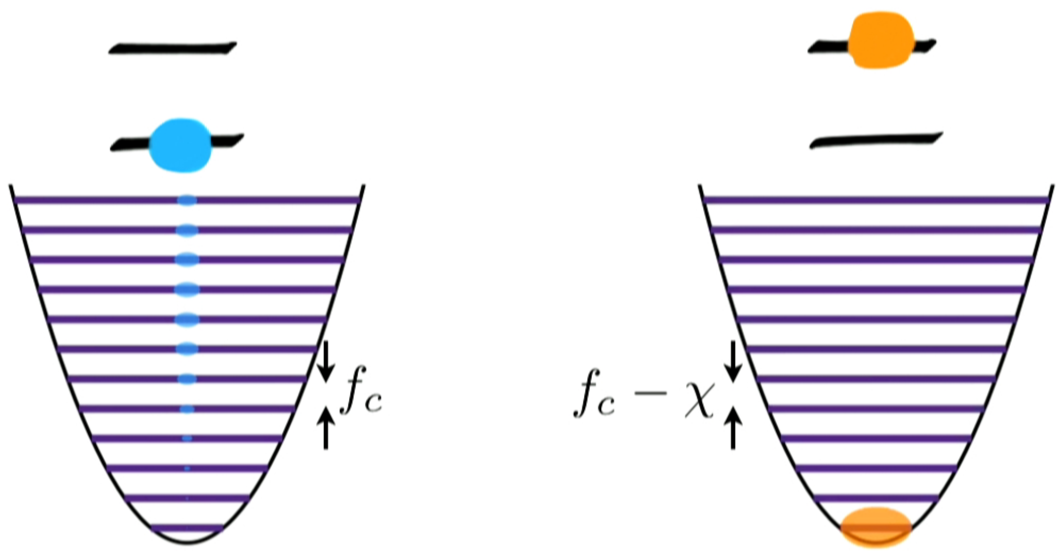

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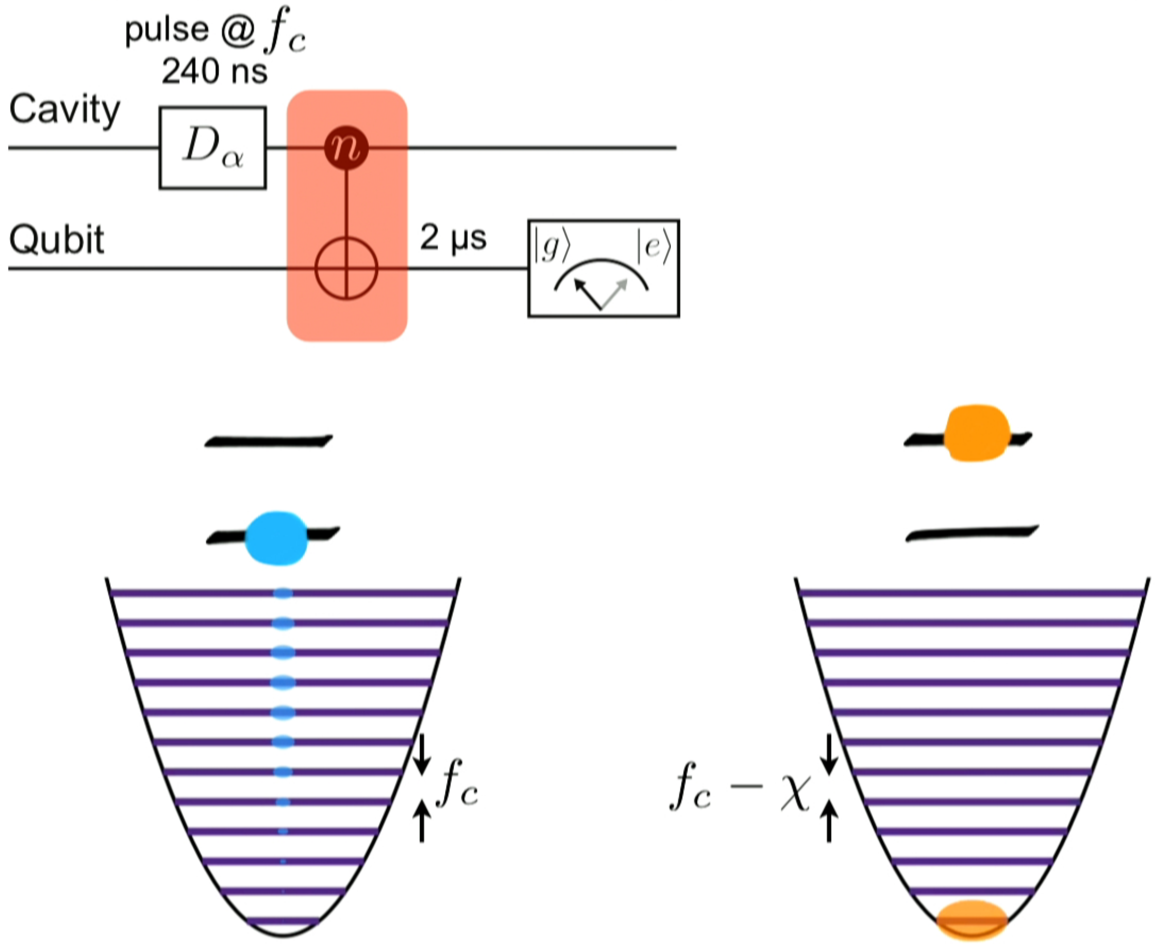

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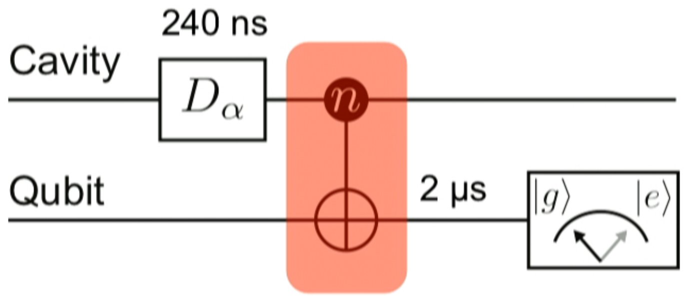
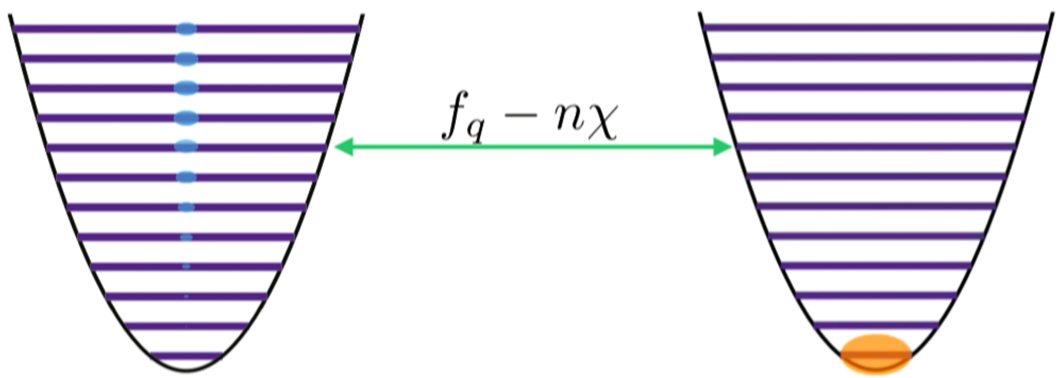


π-pulse @ $f_q - n\chi$

$\frac{1}{2\pi\chi} \ll 400 \text{ ns} \ll T_c$



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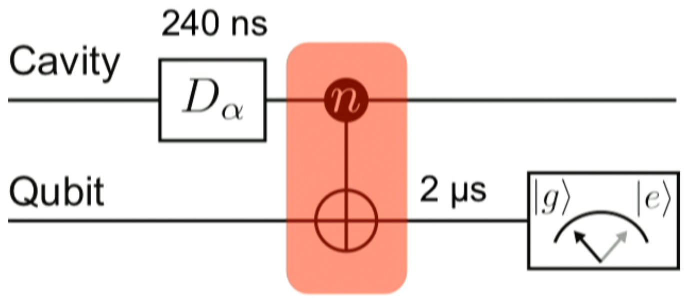

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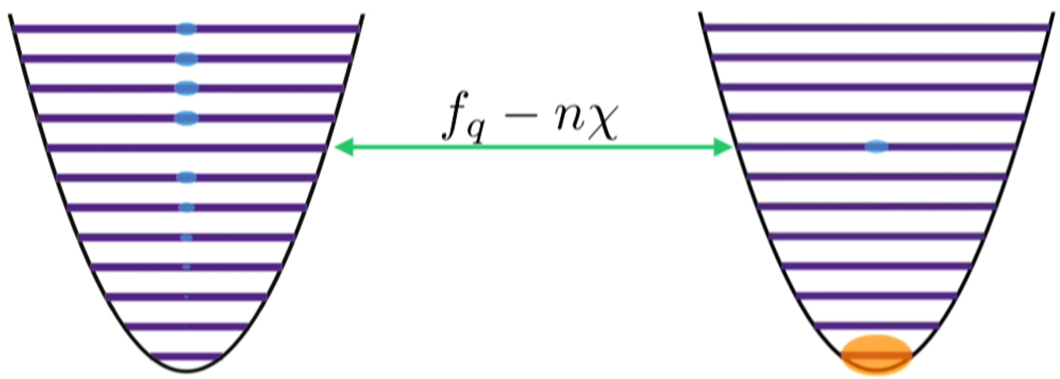

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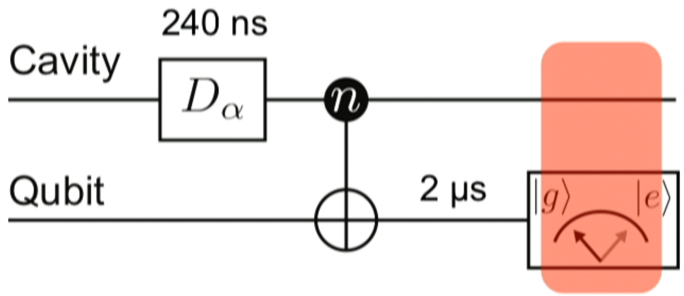

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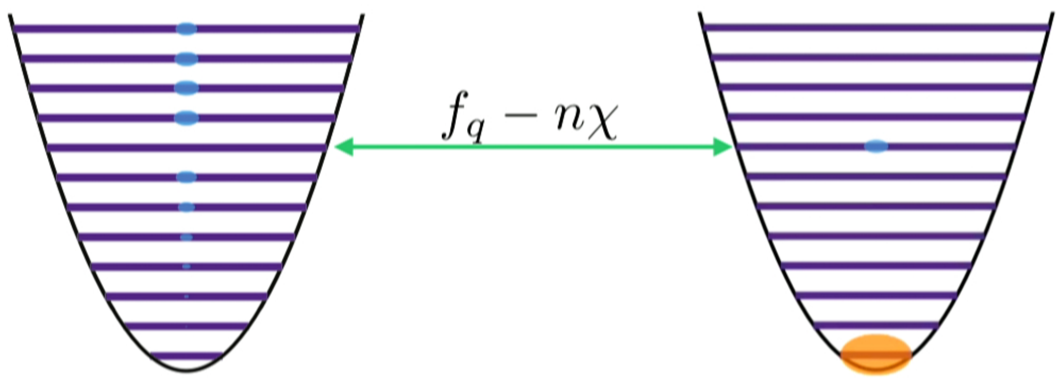
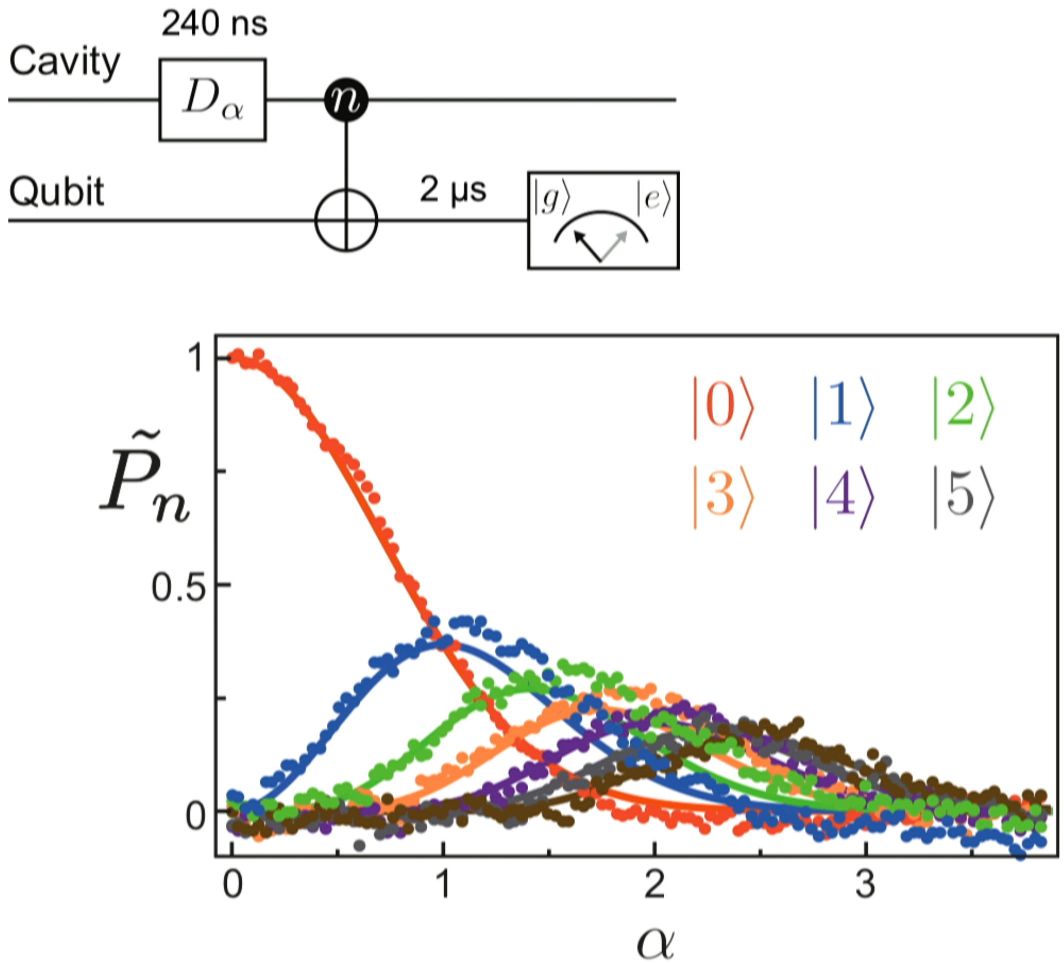
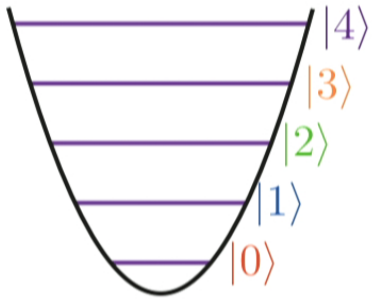


22% thermal qubit excitations → offset for n=0

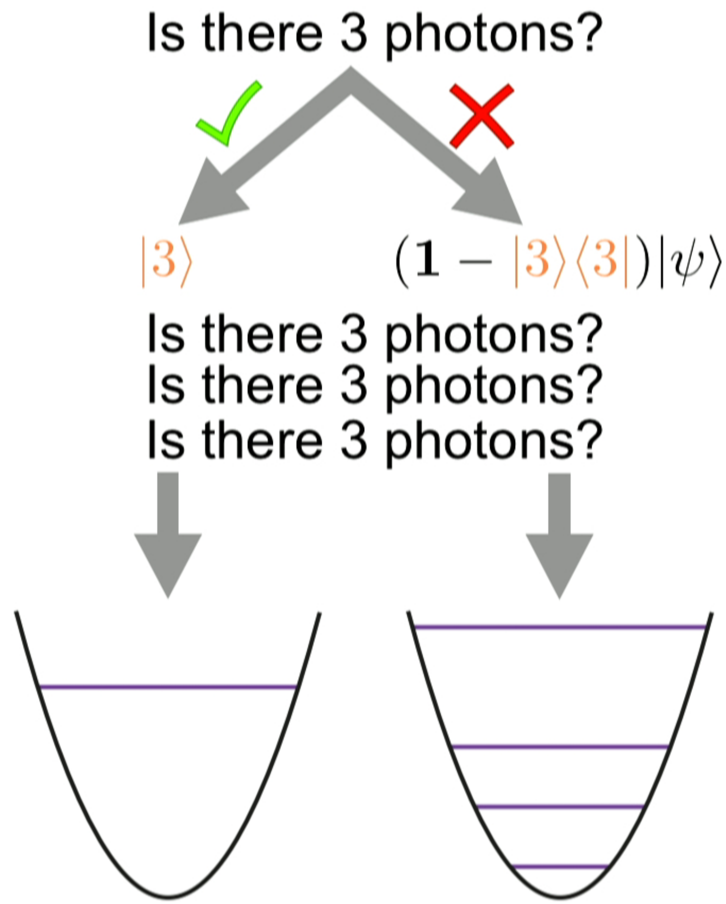
Photocounting a coherent state



Application: quantum Zeno Dynamics of light

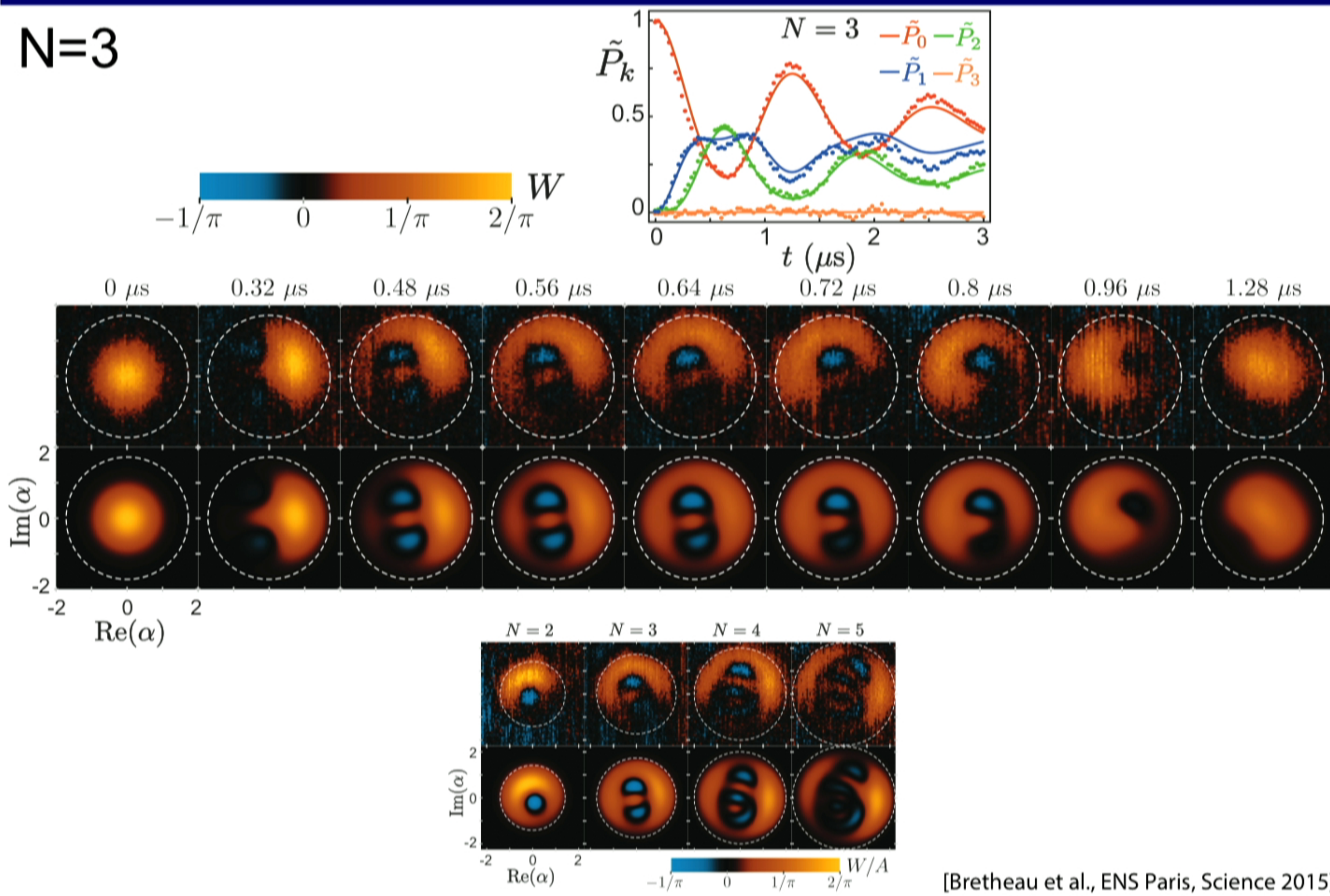


Probe qubit at
$f_q - 3\chi$



Wigner function in time

N=3



[Bretheau et al., ENS Paris, Science 2015]

Testing third order interference

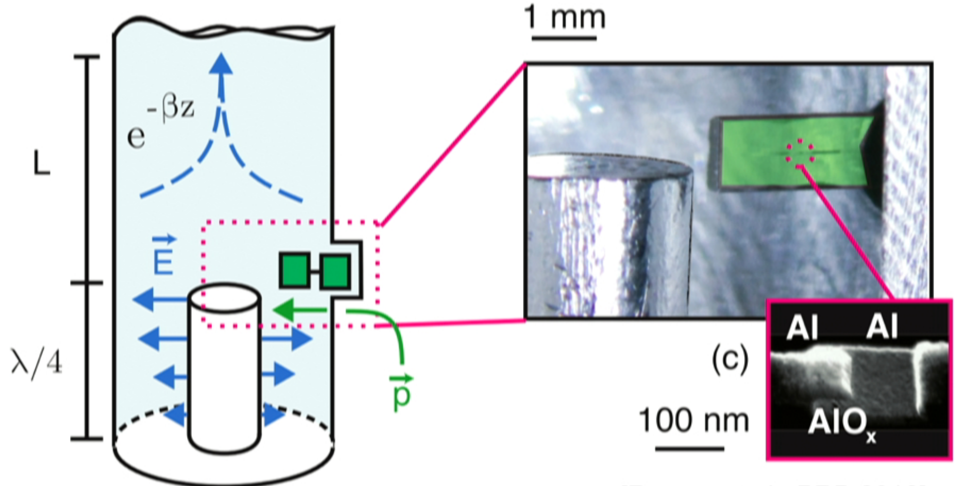
① prepare the system in a non classical statistical mixture of states s_0, s_1, s_2

② filter the experiments by a projective detector D_J where $J \subseteq \{0,1,2\}$

$\forall j \in J$ clicks if sys in s_j $\quad \forall j \in \{0,1,2\} - J$ does not click if sys in s_j

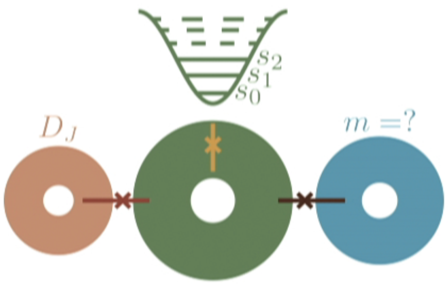
identical stats of outcome for a following measurement if D_J is used once ore twice

③ measure the system by an apparatus which differs from any D_J



[Reagor et al., PRB 2016]

$Q = 7\ 10^7$



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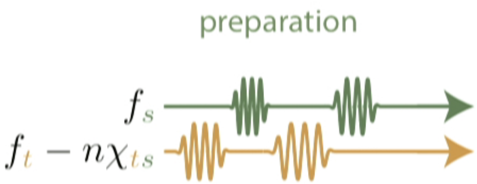
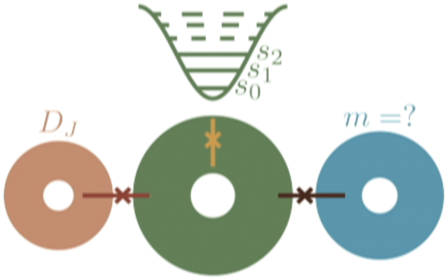


SNAP gate
[Krastanov et al., PRA 2015]



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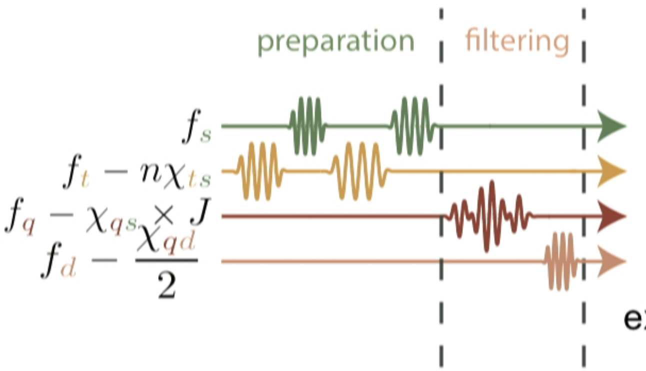
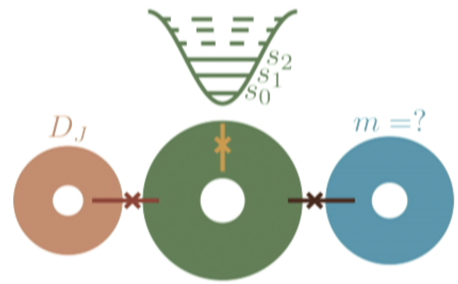
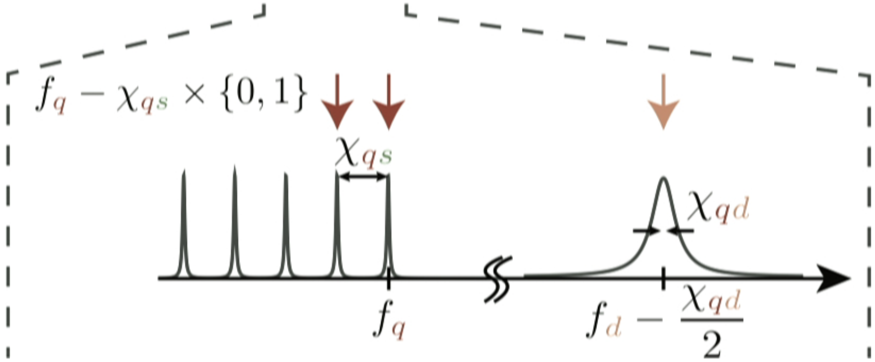
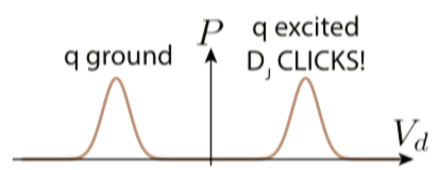


example: $D_{\{0,1\}}$







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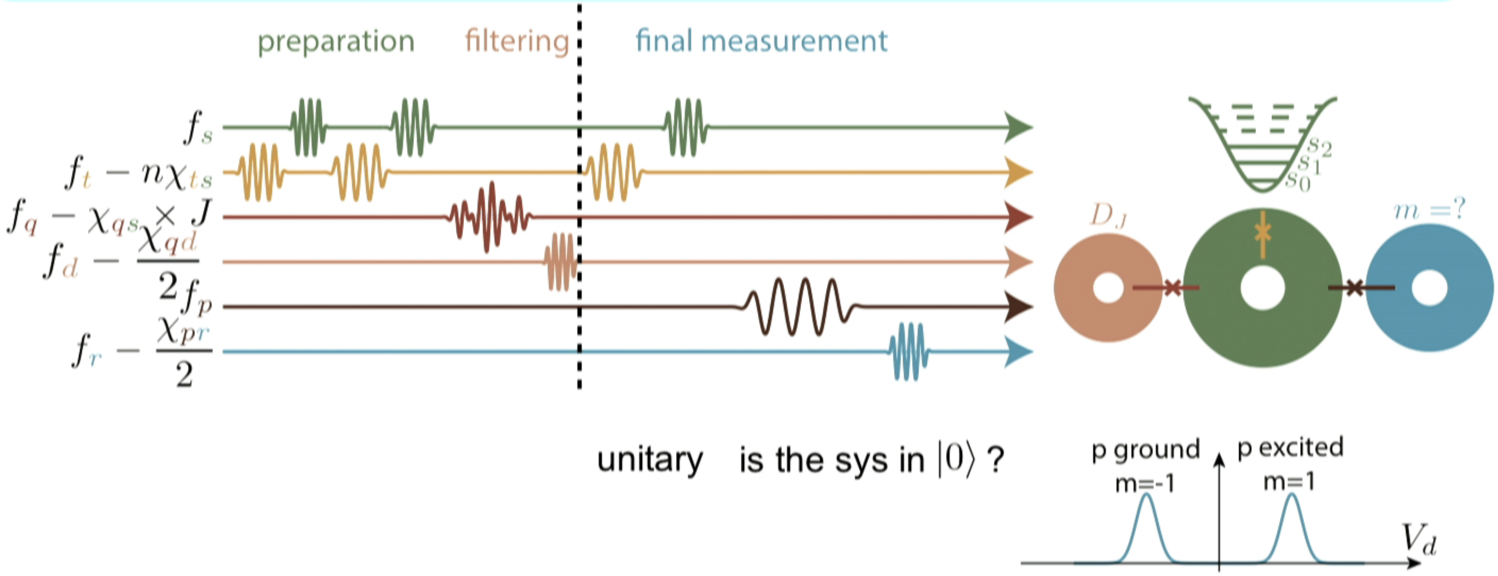

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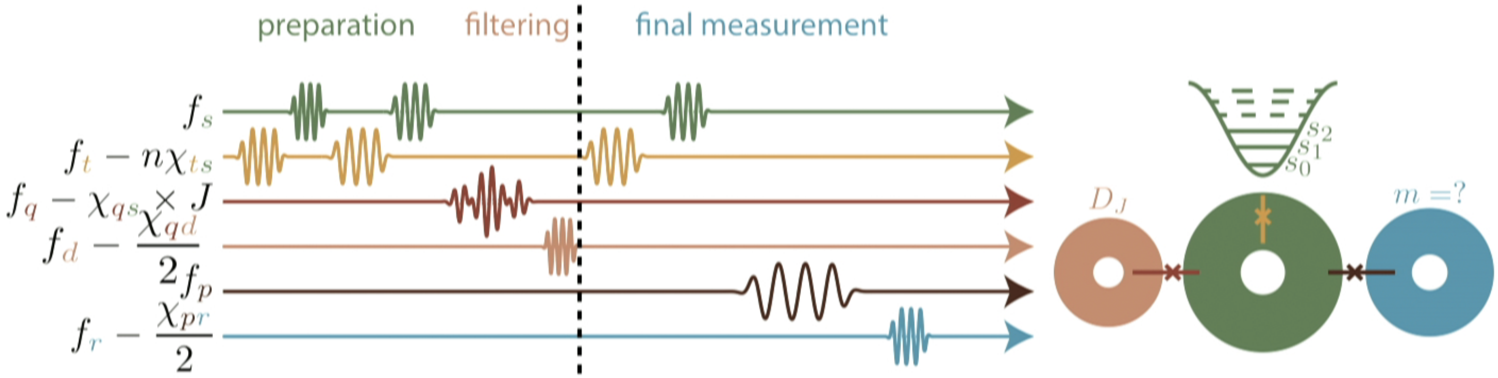
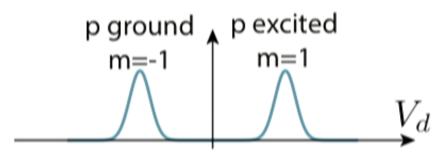


unitary is the sys in $|0\rangle$?



$$p_J = p(D_J \text{ clicks}, m = +1)$$

$$\kappa = \frac{I_3}{\delta}$$

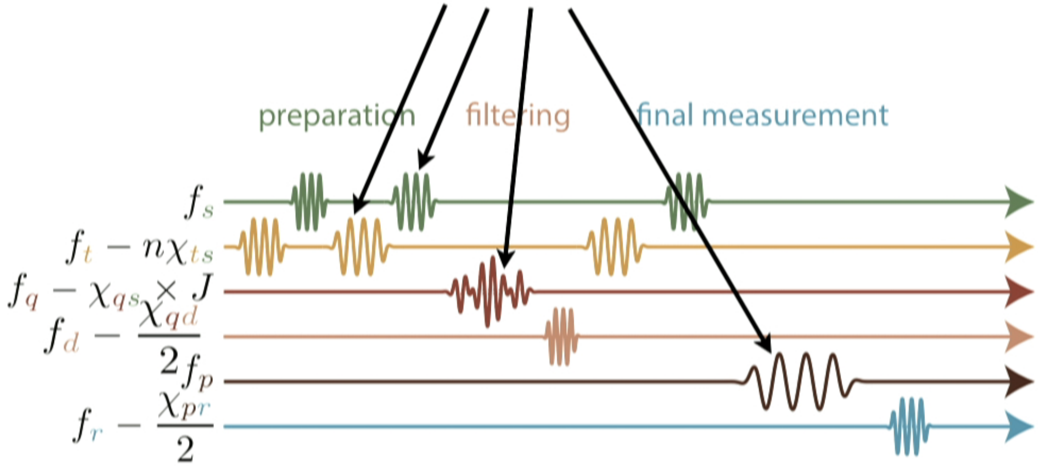
$$I_3 = p_{012} - p_{01} - p_{02} - p_{12} + p_0 + p_1 + p_2 - p_\emptyset$$

$$\delta = |p_{01} - p_0 - p_1 + p_\emptyset| + |p_{12} - p_1 - p_2 + p_\emptyset| + |p_{20} - p_2 - p_0 + p_\emptyset|$$

Expected sources of error

gate error for preparation
and measurements

state of the art is 10^{-3} error
leading to 10^{-4} precision on κ

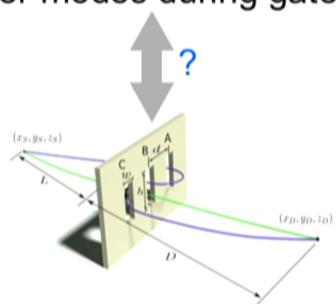


leak of the system into
higher excited states

cancels out since
no D_J will click

entanglement with
other modes during gates

?

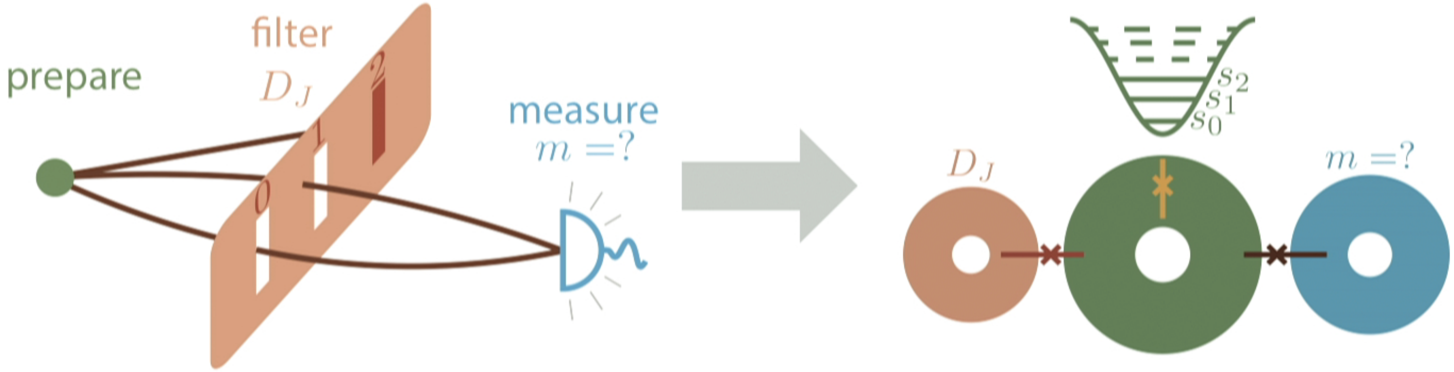


see Urbasi's talk

readout error / decoherence of
the system during measurement

peak discrimination better than 10^{-5}
current limitation: qubit lifetime
leading to 10^{-3} on κ

What would superconducting circuits hopefully bring?



Single system manipulation and measurement so that D_J corresponds to a **projective transformation**

→ work directly with event probabilities as in GPTs and avoid parasitic effects in the modeling of actual slits

Spatial (+ energy OR phase) degeneracy between alternatives

→ avoid possible interference suppression due to relativistic structure of space-time [Garner, Müller and Dahlsten arxiv:1412.7112]

Any input state and **any** final measurement can be realized

Predicted **precision** similar or better than single photons or spin liquids $I_3 \lesssim 10^{-3} I_2$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