# Thermodynamics with superconducting circuits

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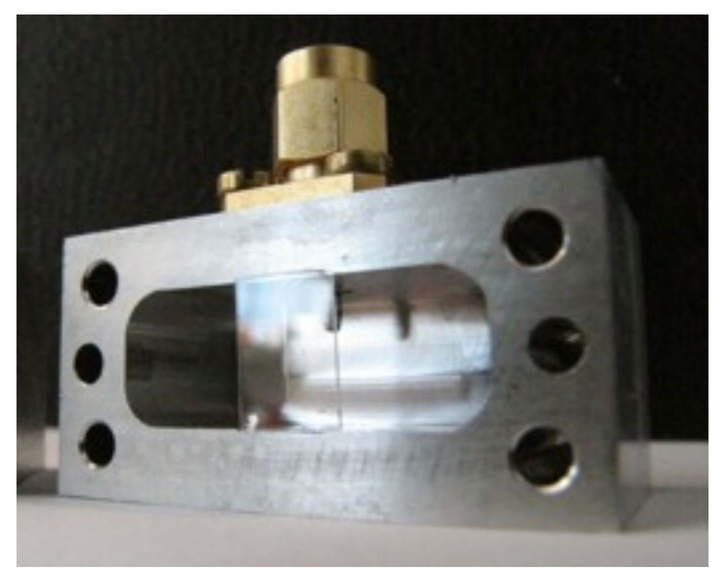
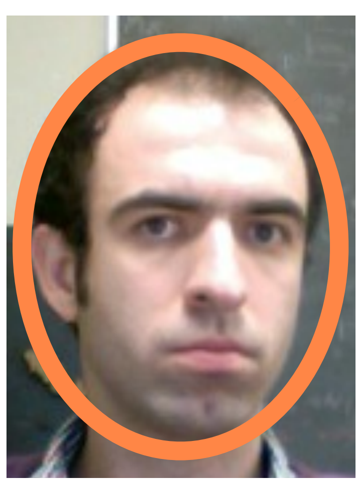


# Team

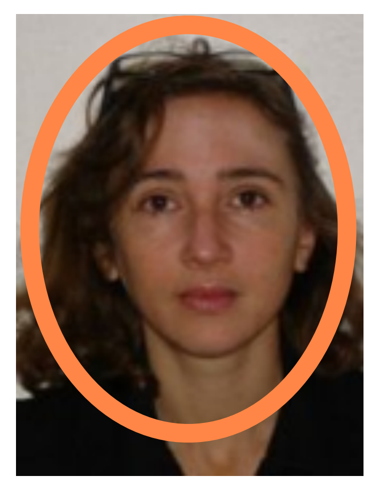

Vlad Manucharyan (JQI Maryland)



Mazyar Mirrahimi (INRIA)

Pierre Six (Mines)

Pierre Rouchon (Mines)



Alexia Auffèves (Grenoble)

MAIRIE DE PARIS

Agence Nationale de la Recherche ANR GIP

DGA

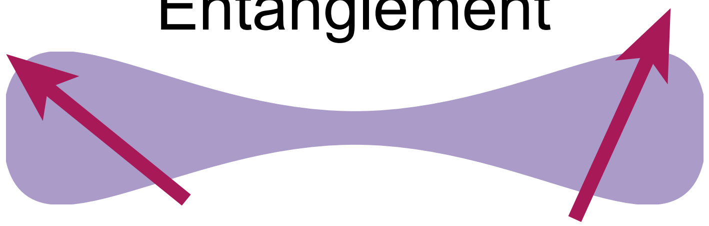
PSL RESEARCH UNIVERSITY

# Thermodynamics of quantum information

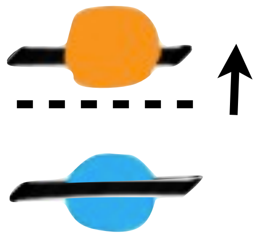
Information ⟷ Energy

Quantum regime

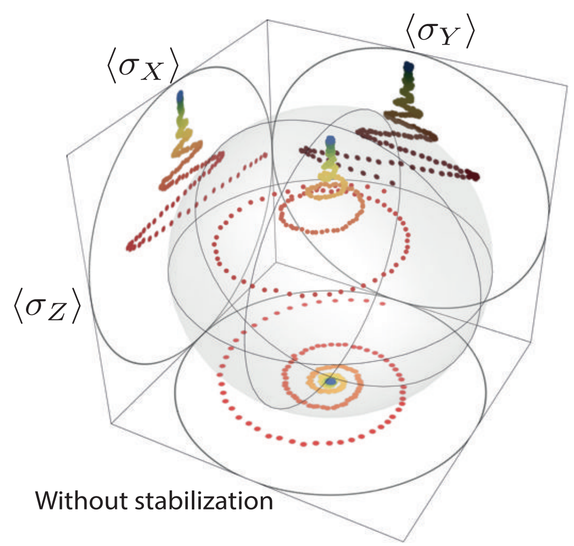
Measurement backaction
Entanglement



Measure heat and work
in quantum systems



Quantum trajectories
and thermodynamics




→ $P(W)$
$S(t)$

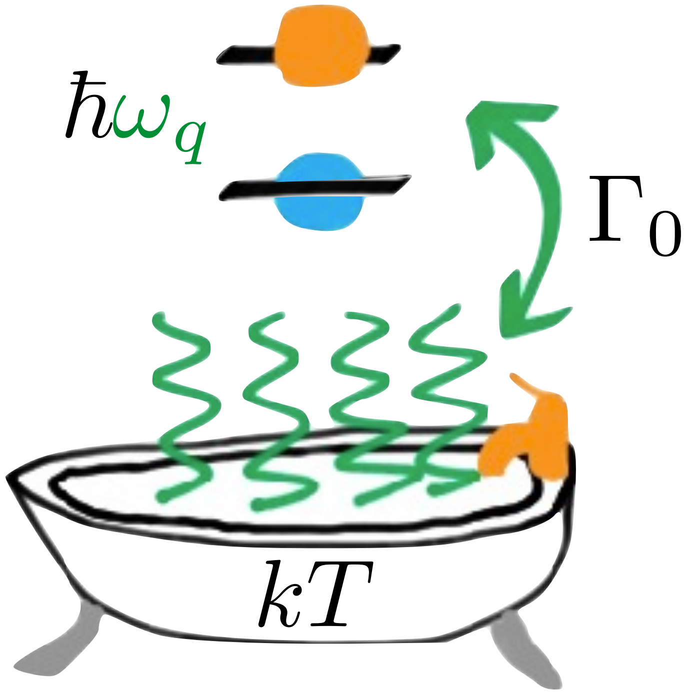
This talk → how to cool down a qubit?
how to measure quantum trajectories?

# Cooling down a qubit

$$\Gamma_\downarrow = \Gamma_0(1 + n_B)$$

$$\Gamma_\uparrow = \Gamma_0 n_B$$

$$n_B = \frac{1}{e^{\hbar\omega_q/kT} - 1}$$



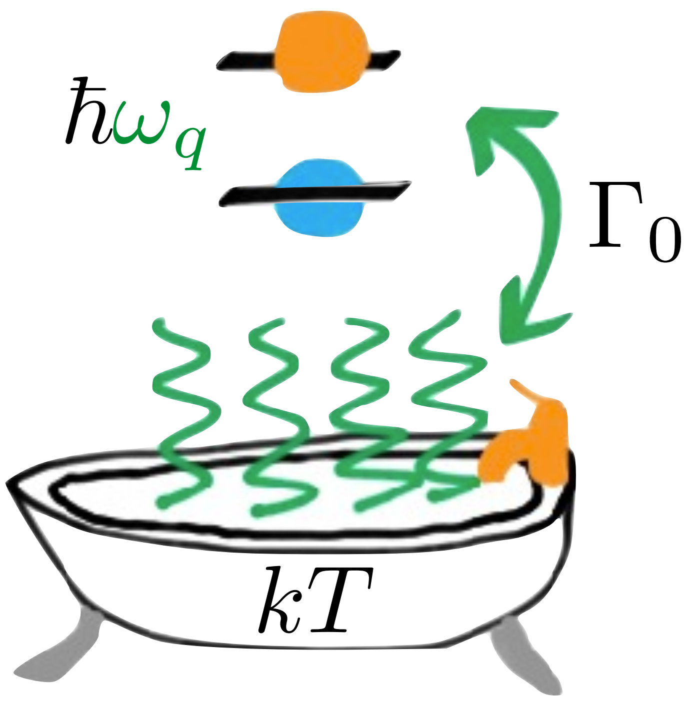
# Cooling down a qubit

$$p_e = \frac{1}{1 + e^{\hbar\omega_q/kT}}$$

$$p_g = \frac{1}{1 + e^{-\hbar\omega_q/kT}}$$

$$\Gamma_\downarrow = \Gamma_0(1 + n_B)$$
$$\Gamma_\uparrow = \Gamma_0 n_B$$

$$n_B = \frac{1}{e^{\hbar\omega_q/kT} - 1}$$

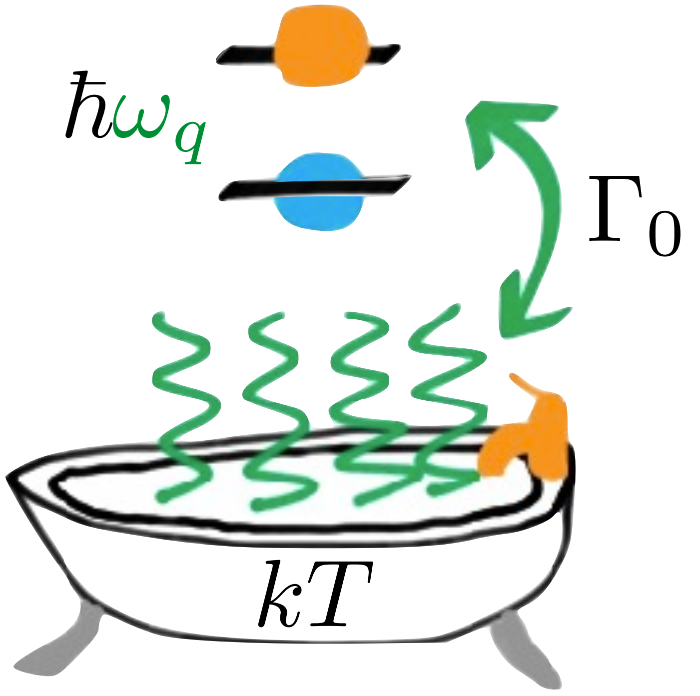


# Cooling down a qubit

$$p_e = \frac{1}{1 + e^{\hbar\omega_q/kT}}$$

$$p_g = \frac{1}{1 + e^{-\hbar\omega_q/kT}}$$

How to get the qubit in its ground state?




Needed to evacuate entropy of errors in quantum codes

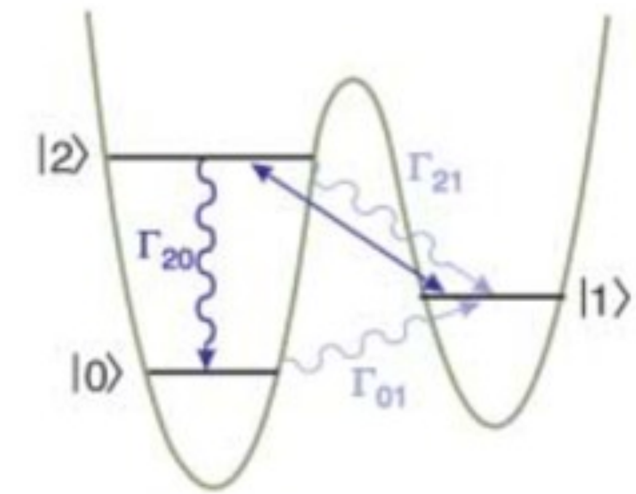
# Various strategies in superconducting circuits

**Sideband cooling**

Additional drive so that

$$\Gamma_\downarrow = \Gamma_0(1 + n_B)$$
$$\Gamma_\uparrow = \Gamma_0 n_B$$

$$\frac{\Gamma_\downarrow}{\Gamma_\uparrow} \nearrow$$




[Valenzuela *et al.*, MIT group, Science 2006;
Grajcar *et al.*, Jena group, Nature Phys. 2008;
Murch *et al.*, Berkeley group, PRL 2012]

**Measure and post-select**

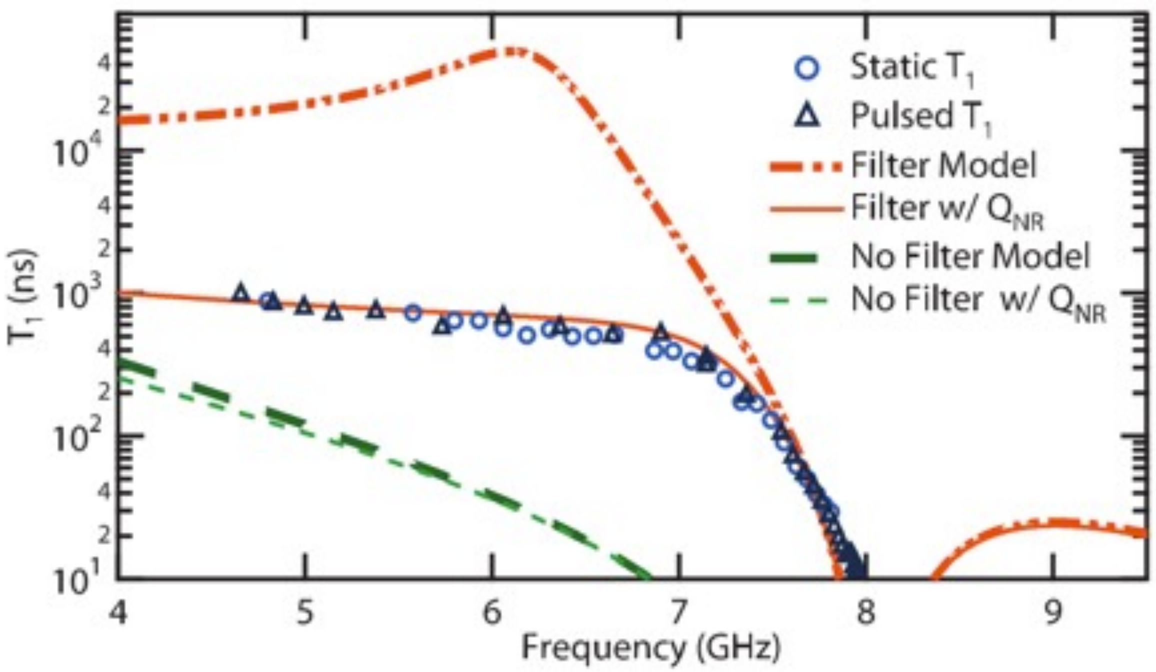
Single shot and QND measurement → consider only the cases where the qubit is in the ground state

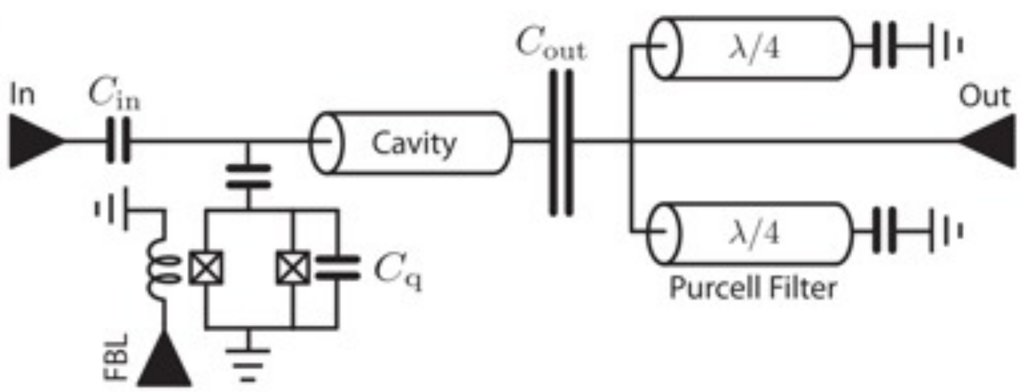
[Johnson *et al.*, Berkeley group, PRL 2012;
Ristè *et al.*, Delft group, PRL 2012]

# Various strategies in superconducting circuits

**Fast qubit tuning**

Coupling to a cold environment with $\Gamma_0(\omega)$



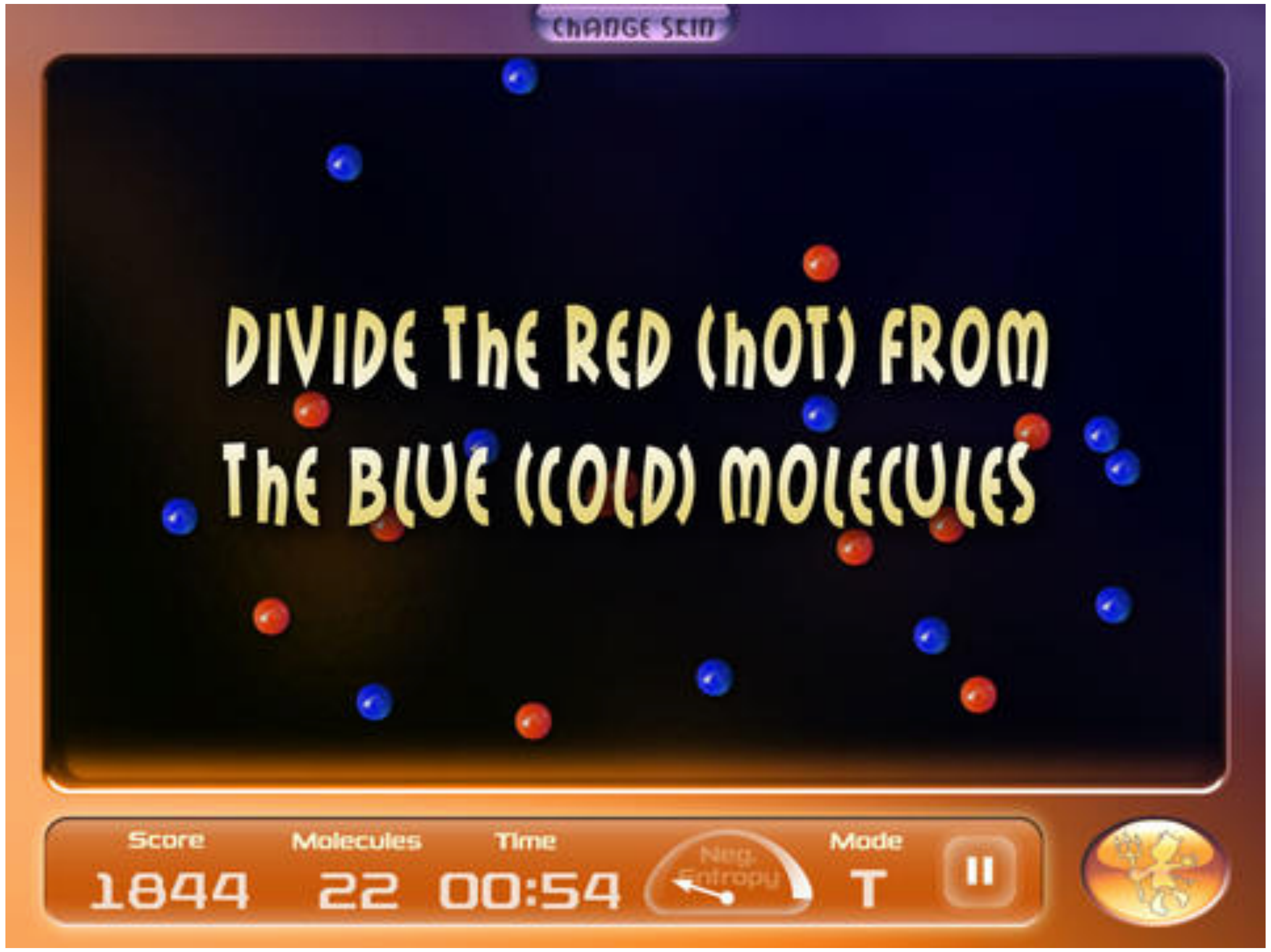




Cooling by varying $\omega_q$

$\Gamma_\downarrow \nearrow$

[Reed *et al.*, Yale group, APL 2010;
Mariantoni *et al.*, UCSB group, Science 2011]

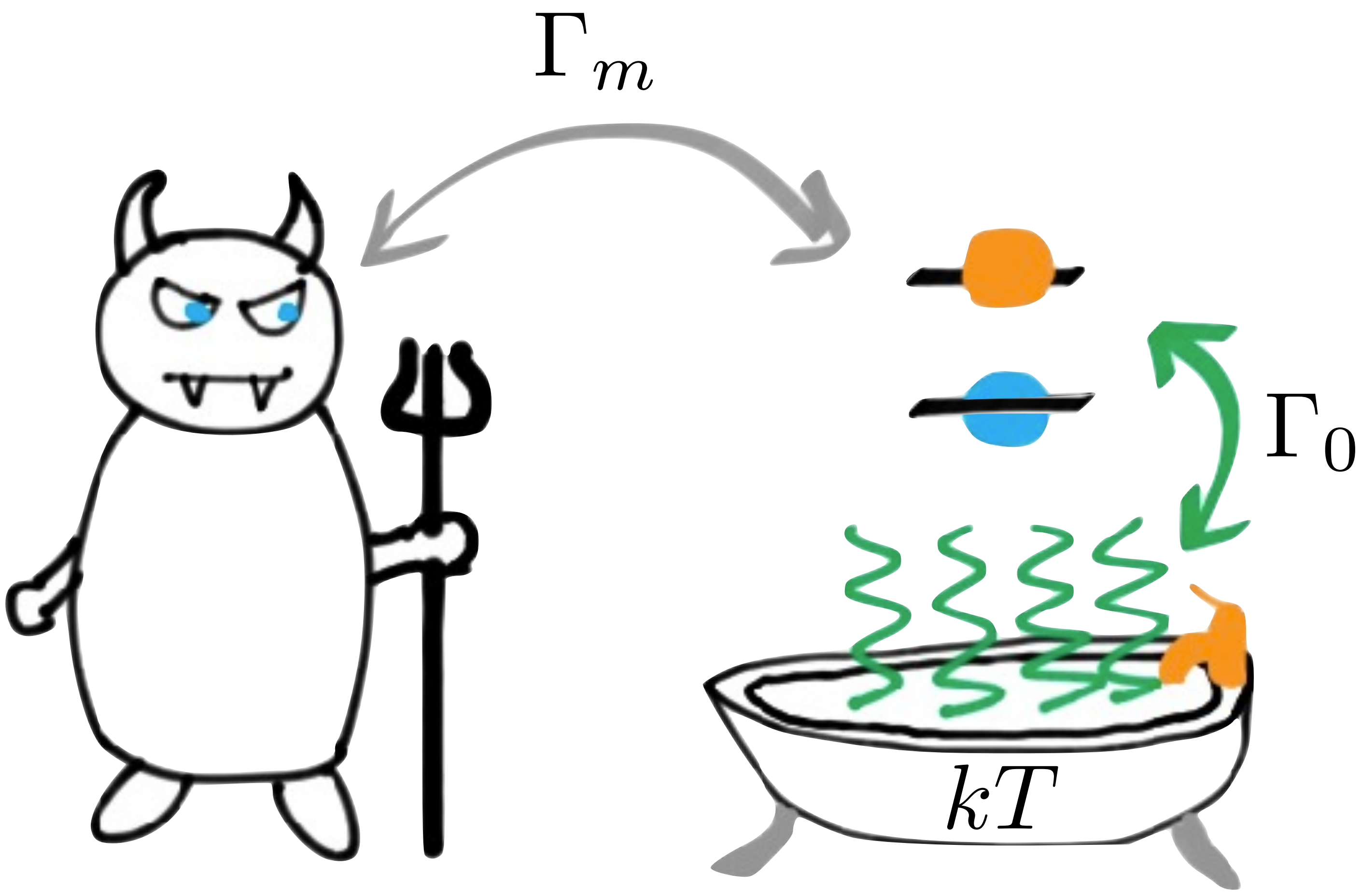
# Cooling with a Maxwell demon

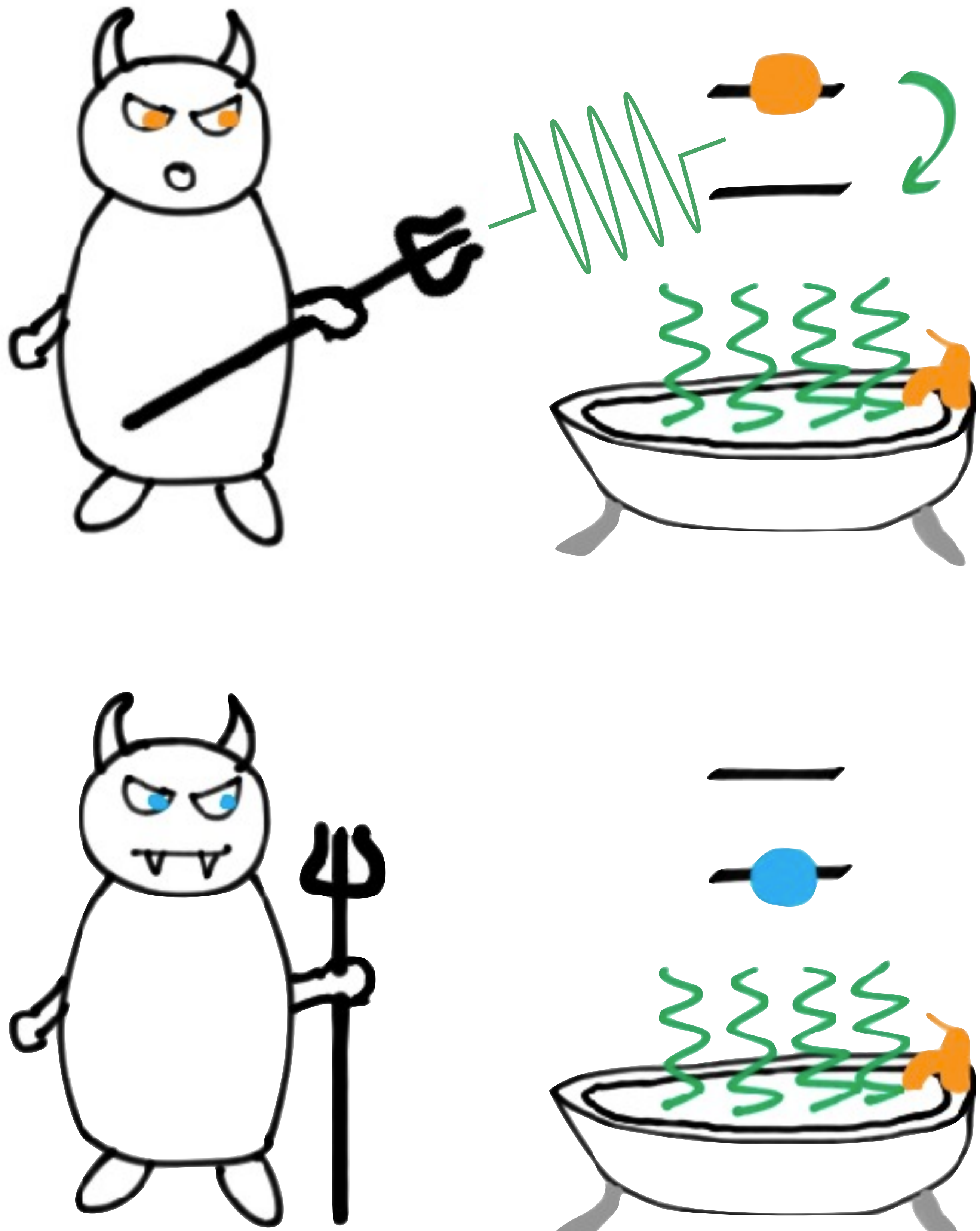

Experiments in classical regime
S. Toyabe et al. (Tokyo) Nature Physics 2010
A. Bérut et al. (Lyon) Nature 2012 & EPL 2013
J. V. Koski et al. (Helsinki) arxiv 2014

Quantum version [Lloyd, PRA 1997]

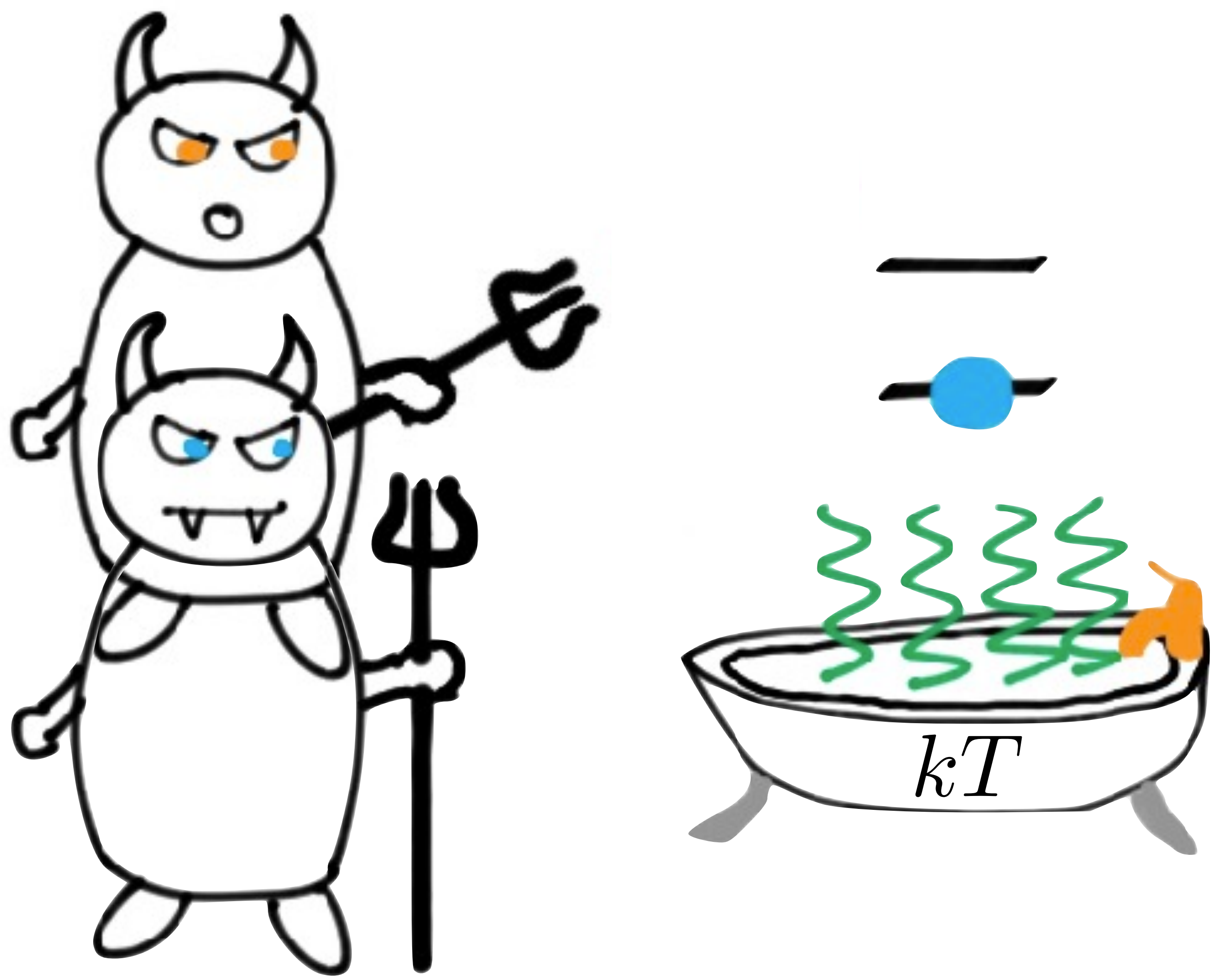
# Maxwell demon



# Maxwell demon



# Maxwell demon



# Maxwell demon

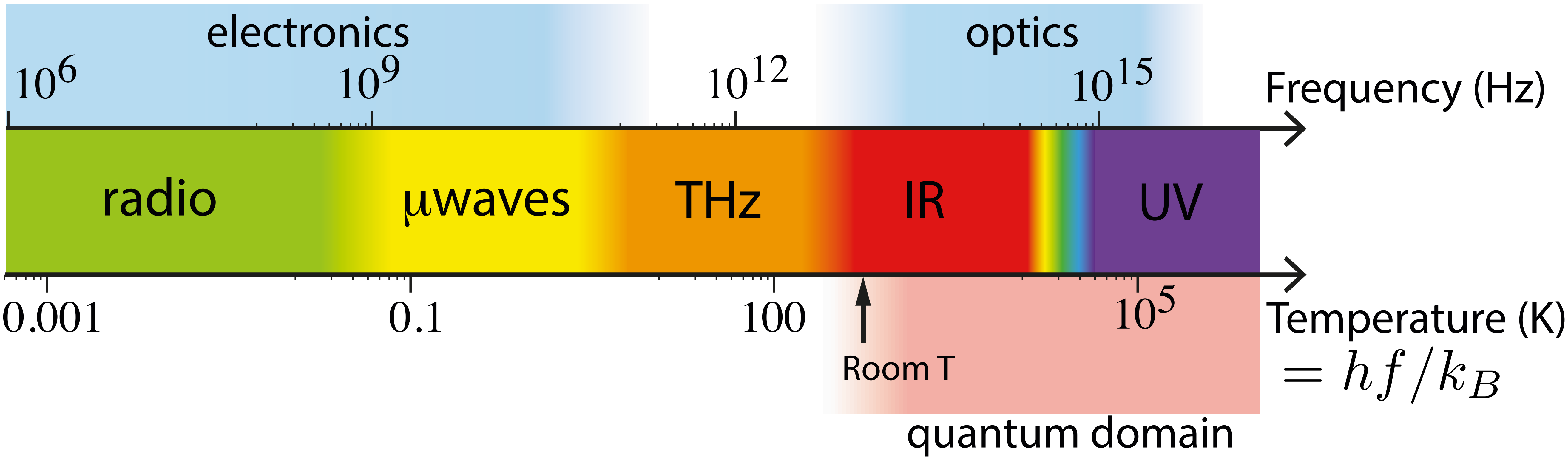
# Maxwell demon

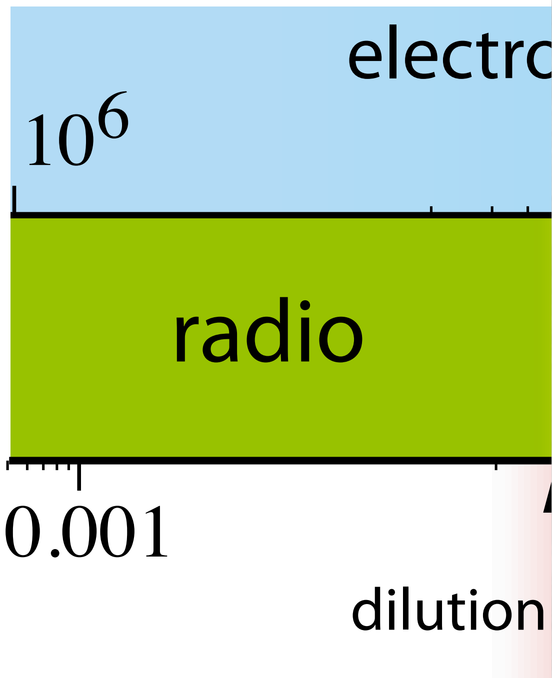

2 examples with superconducting circuits

**Classical demon**
Measurement feedback

**Quantum demon**
Autonomous feedback

# Microwave quantum optics





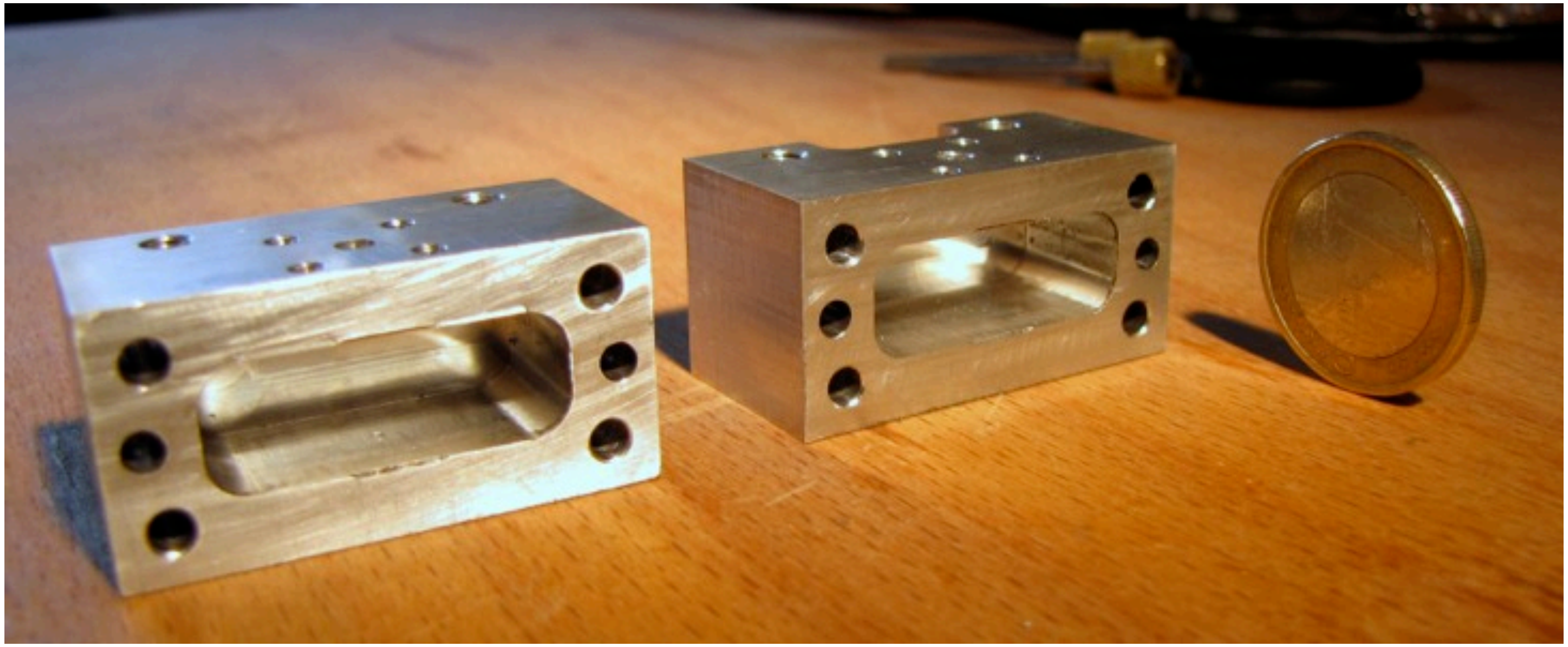


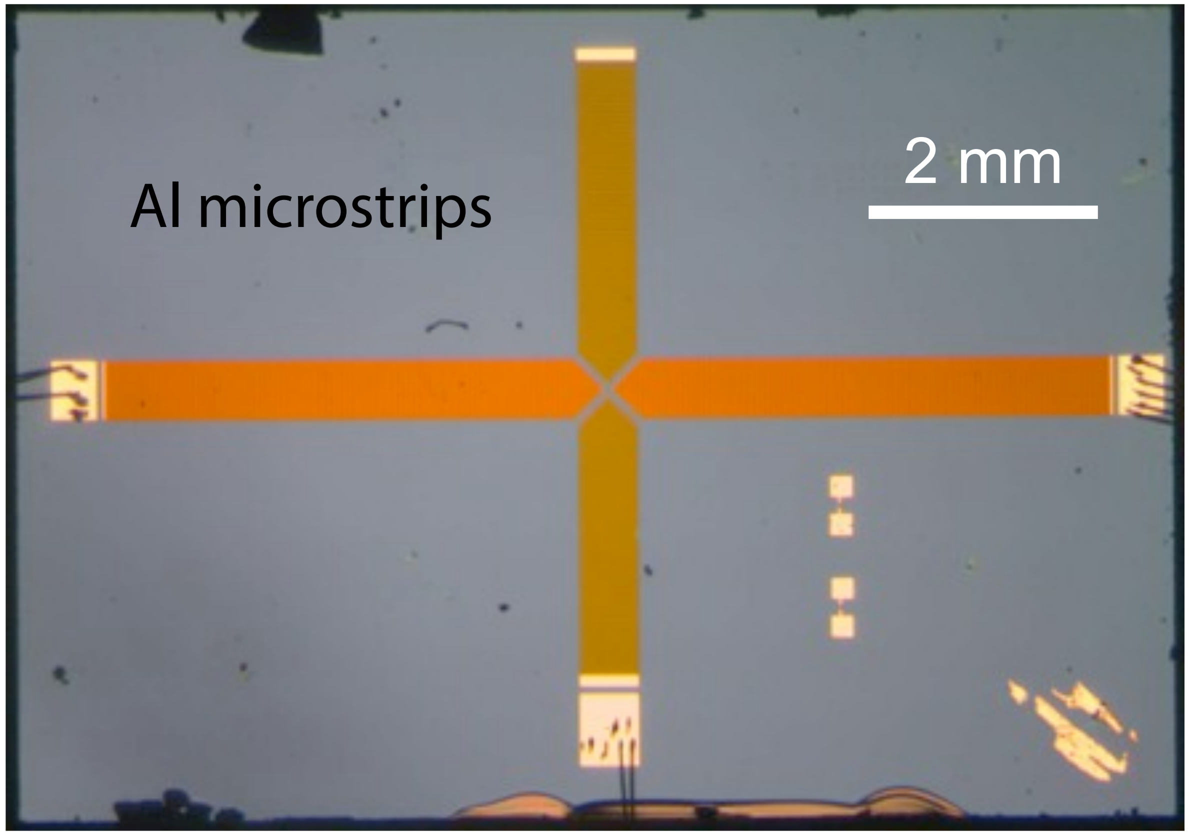
Frequency (Hz) →

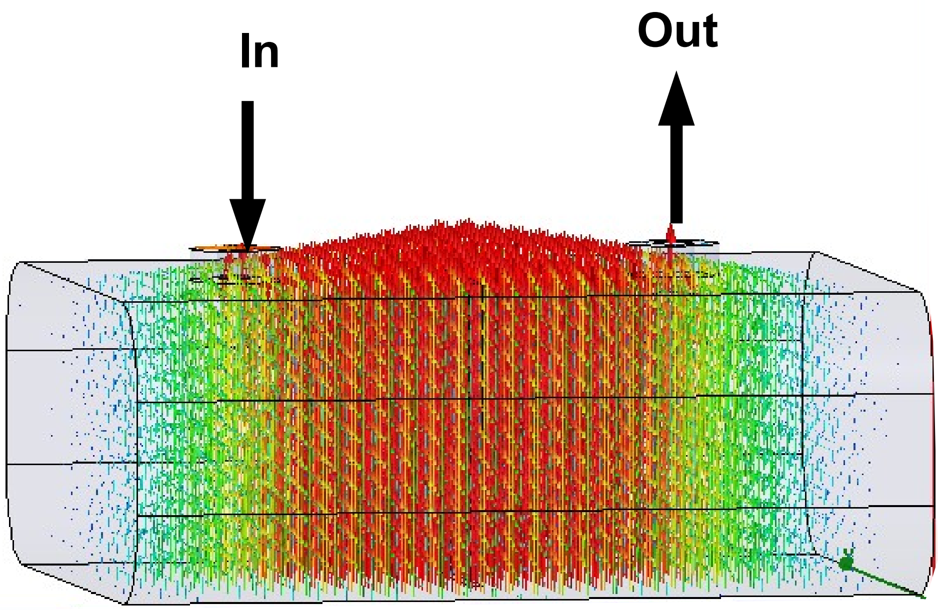
→ Temperature (K)

$= hf/k_B$

# Superconducting circuits





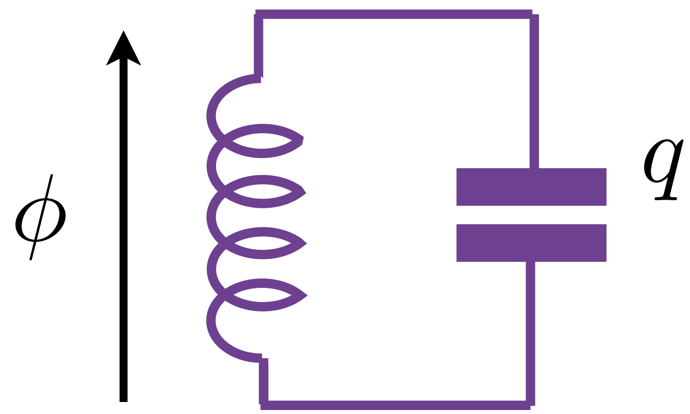




1st mode : 7.63 GHz

$Q \approx 10^6$

# Superconducting circuits

dissipationless LC circuit...

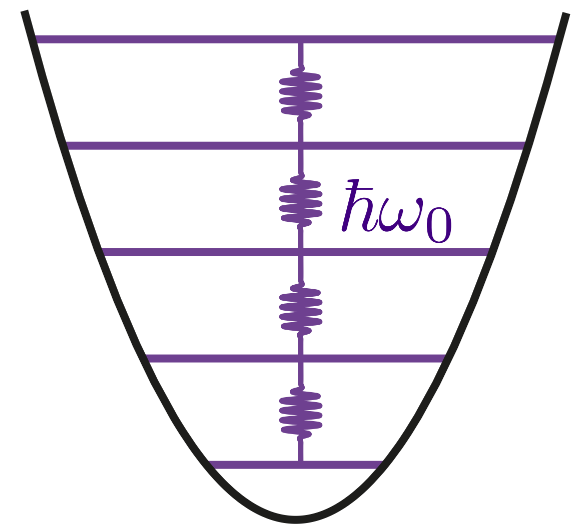



$\omega_0 = 1/\sqrt{LC}$

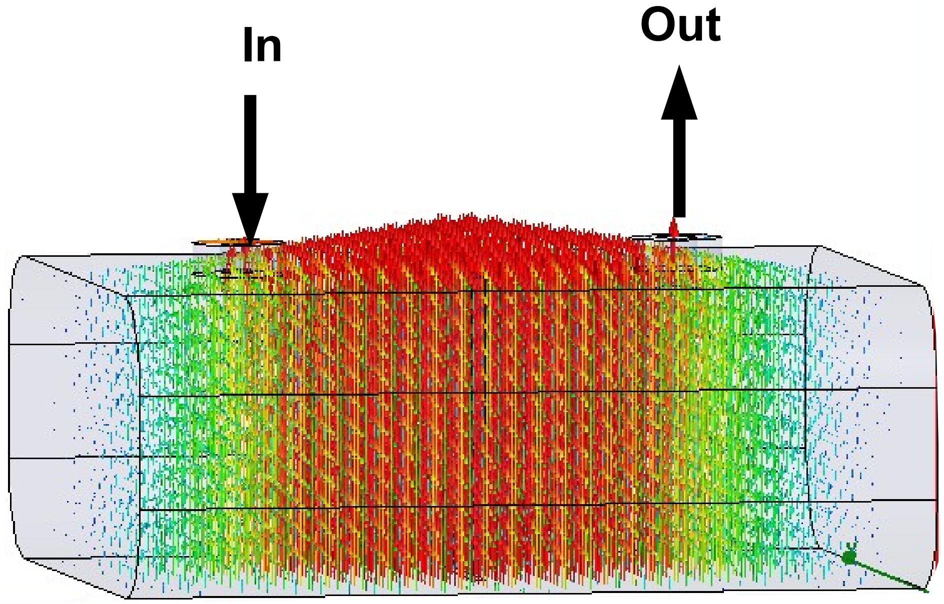
$$\hat{H} = \frac{\hat{q}^2}{2C} + \frac{\hat{\phi}^2}{2L}$$

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

....canonically quantized




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

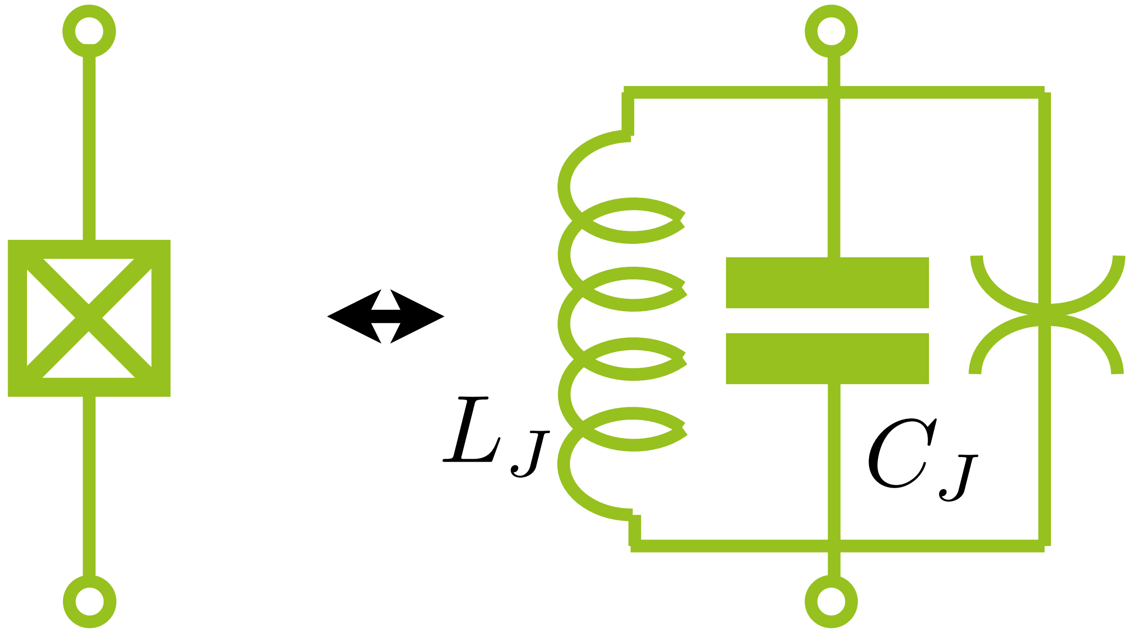



1st mode : 7.63 GHz

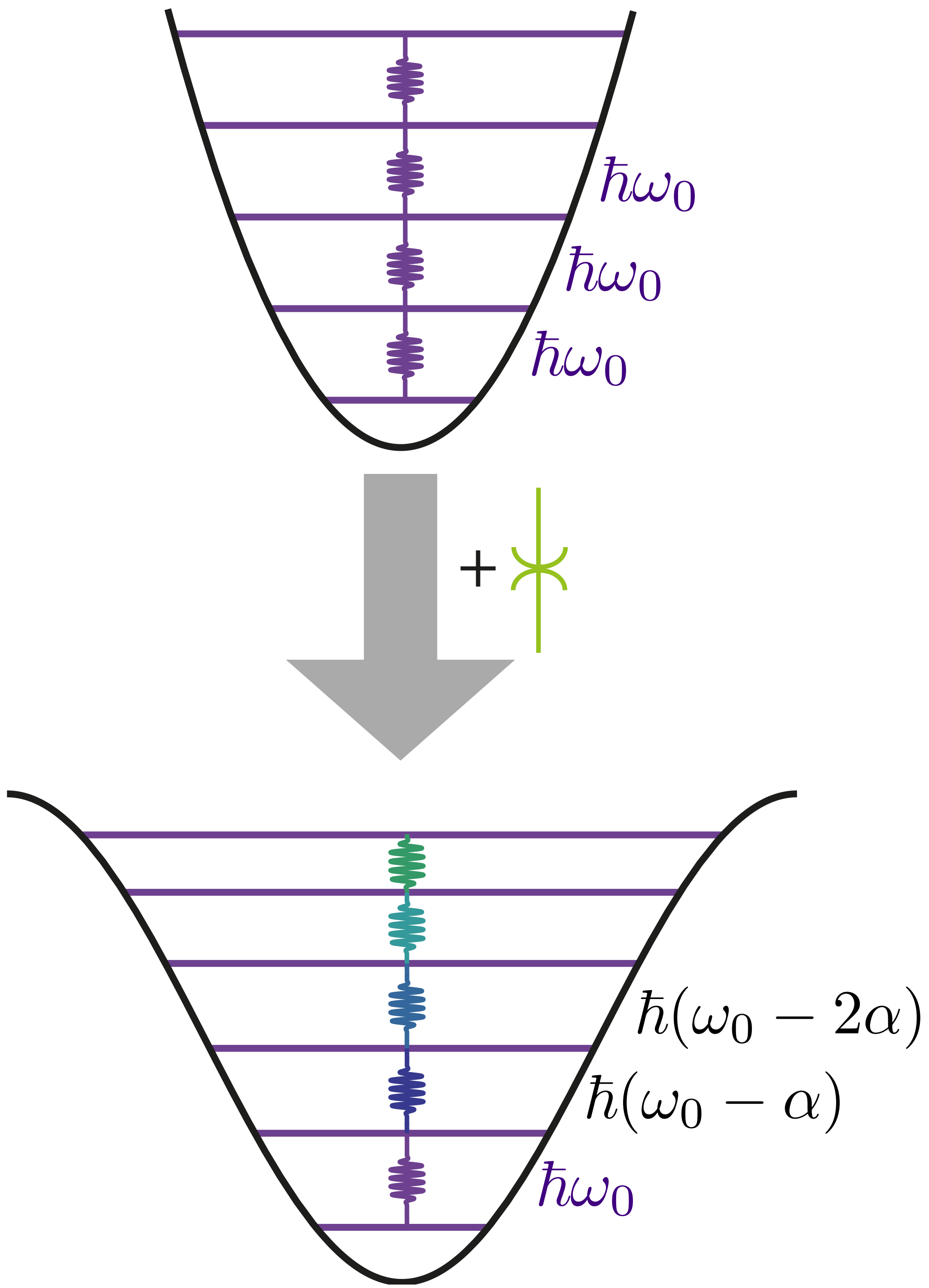
$Q \approx 10^6$

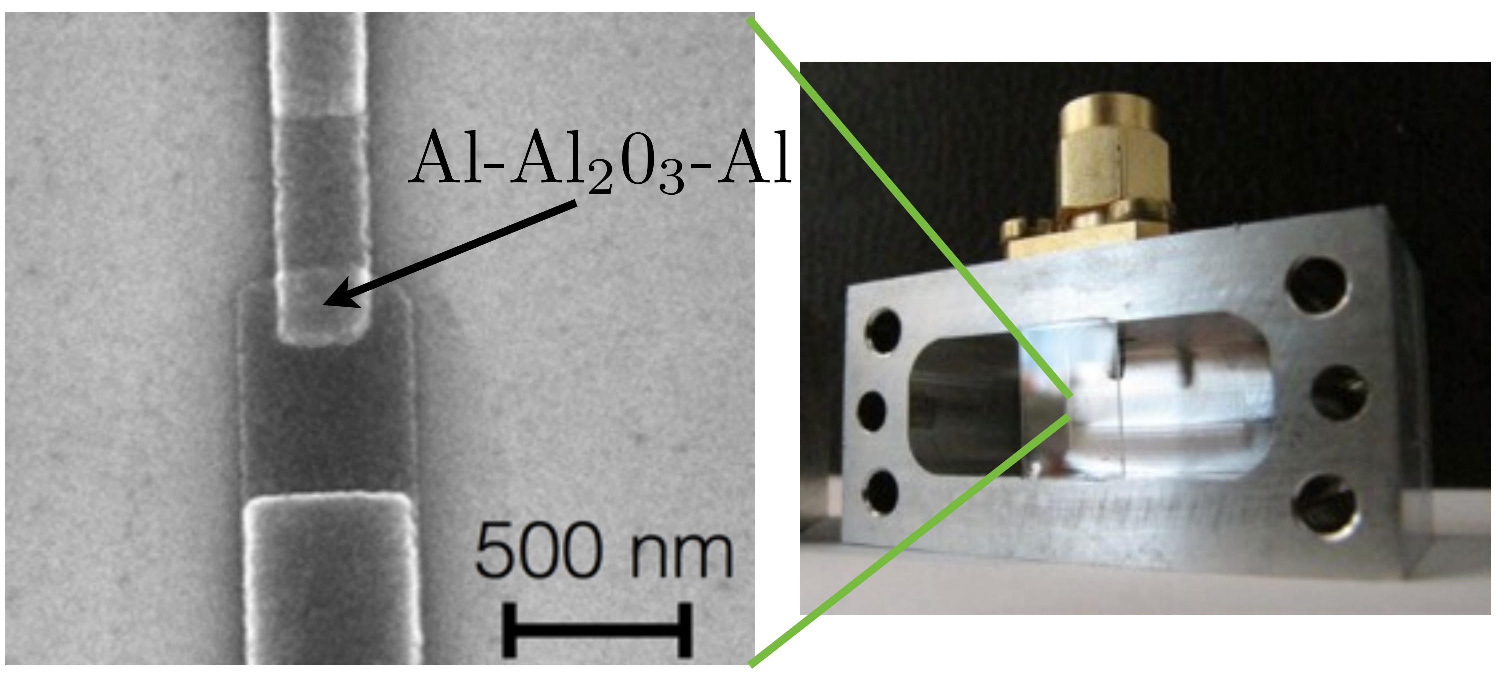
# Superconducting circuits with Josephson junctions

dissipation-less non linear LC circuit



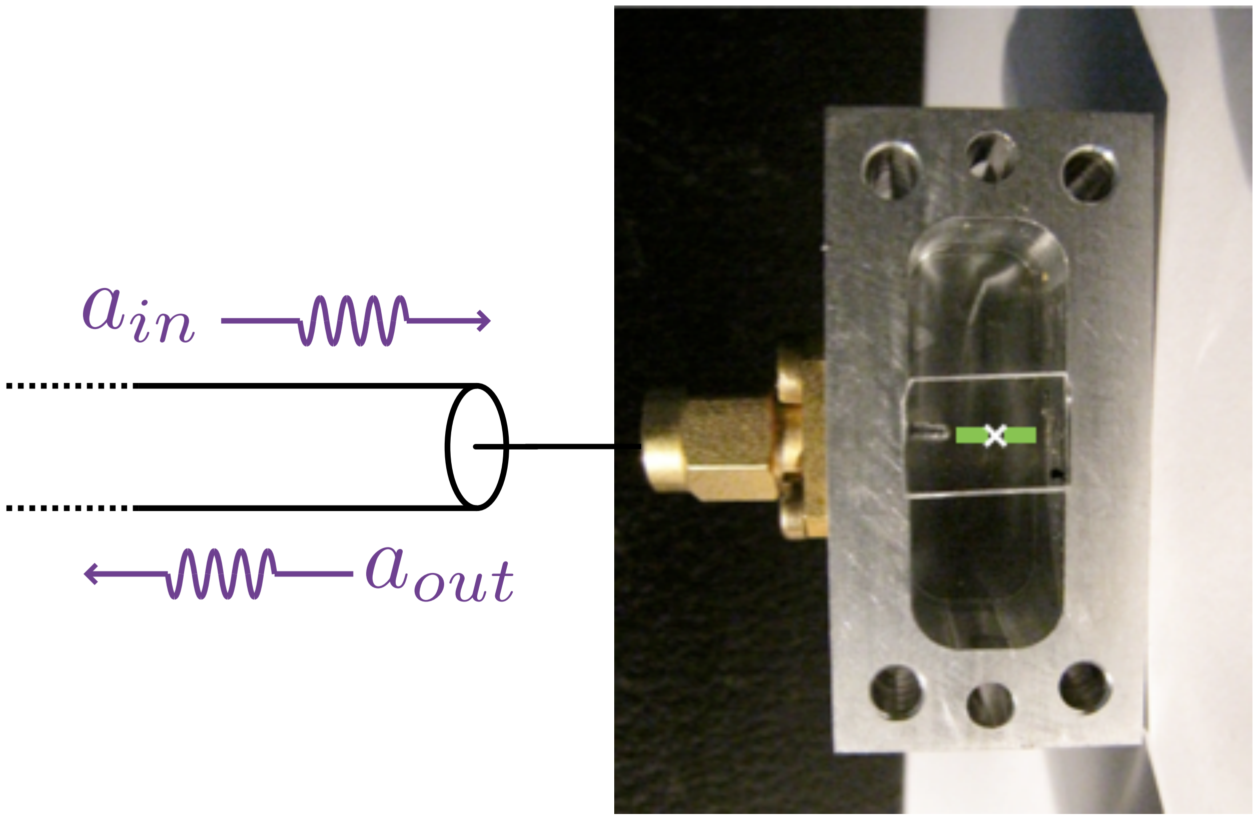

$$\hat{H} = \frac{\hat{q}^2}{2C_J} - E_J \cos\frac{\hat{\phi}}{\hbar/2e} = \frac{\hat{q}^2}{2C_J} + \frac{\hat{\phi}^2}{2L_J} + H_{\mathrm{non-lin}}(\hat{\phi})$$

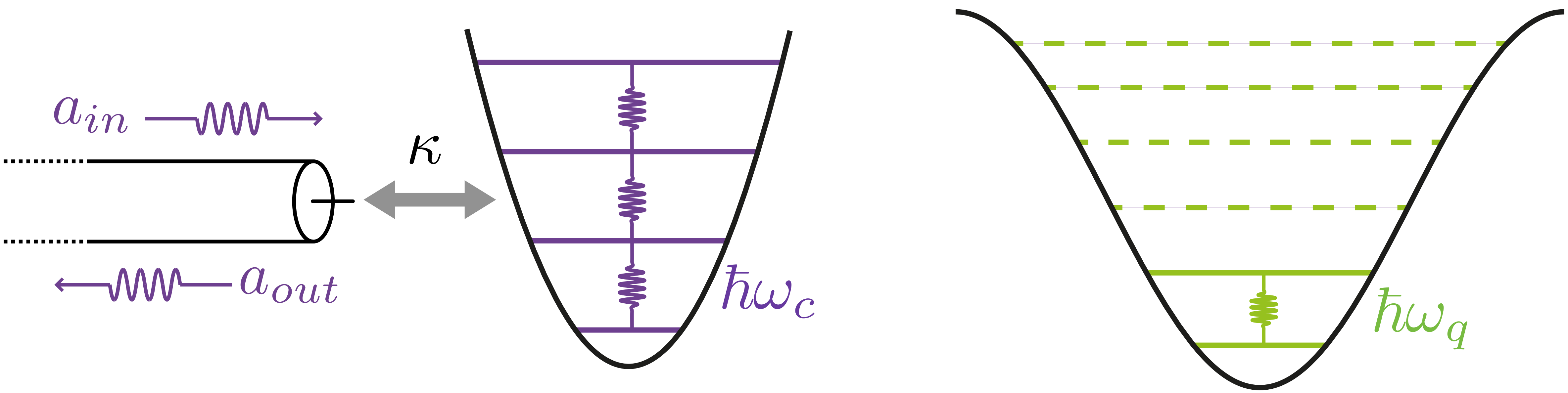



transitions observed in 1980's [Berkeley & Saclay]
strong coupling regime of CQED in 2004 [Yale]

# Circuit-QED




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

# Maxwell demon


2 examples with superconducting circuits

**Classical demon**
Measurement feedback

**Quantum demon**
Autonomous feedback

[Ristè *et al.*, Delft group, PRL 2012;
Campagne-Ibarcq *et al.*, Paris group, PRX 2013]

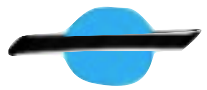
[Geerlings *et al.*, Yale group, PRL 2013]

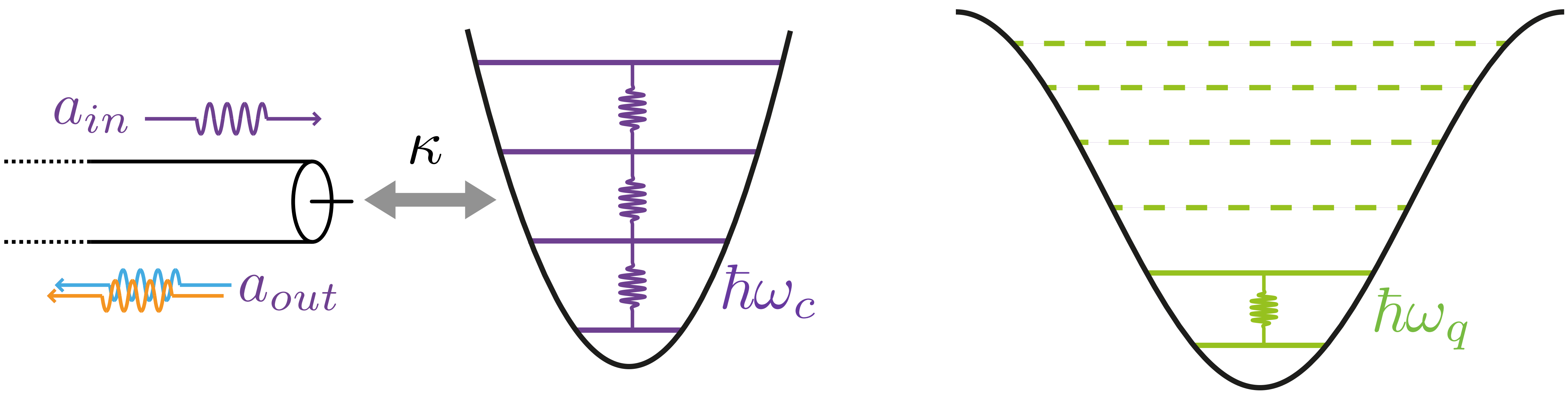
# Maxwell demon

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

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

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



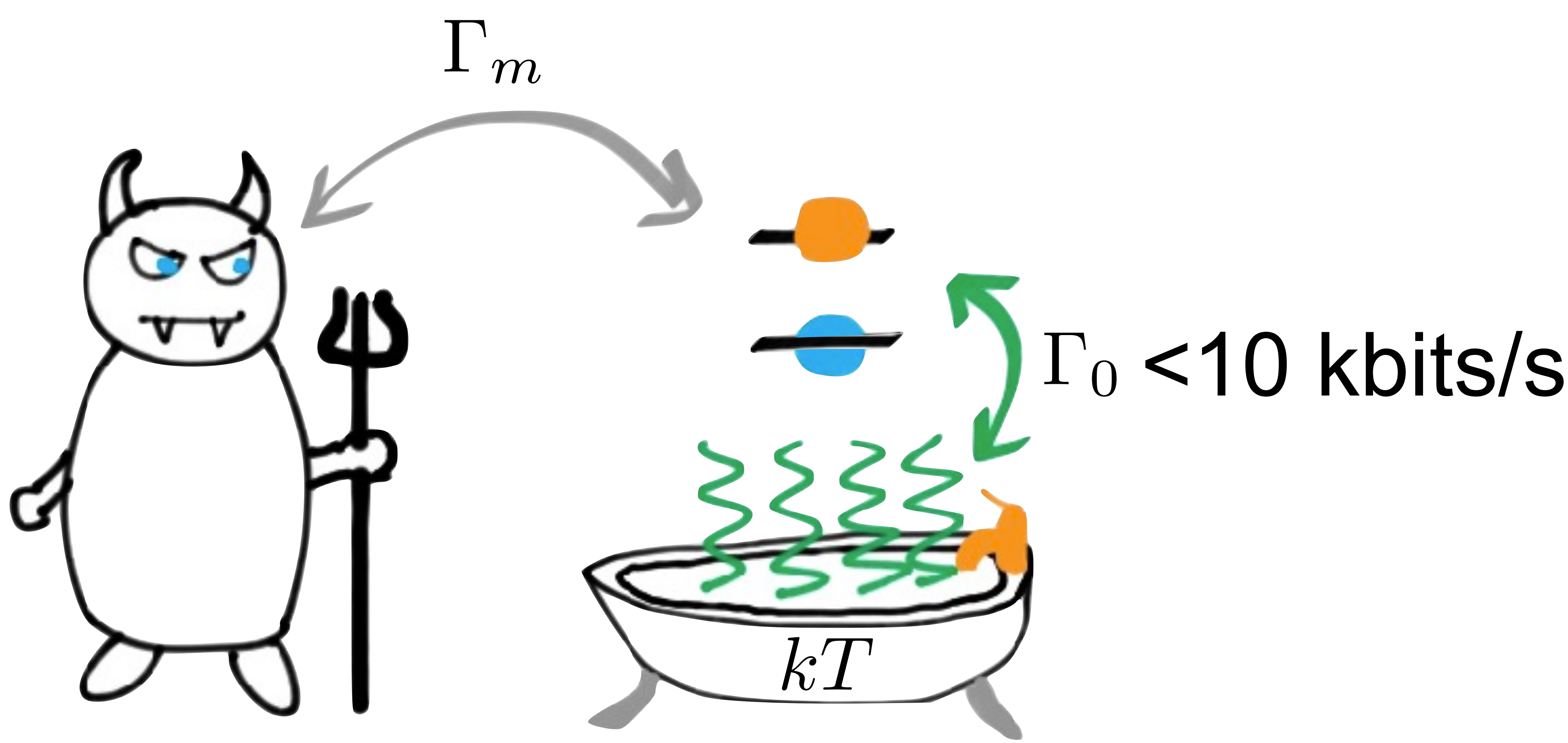



Phase encodes qubit state

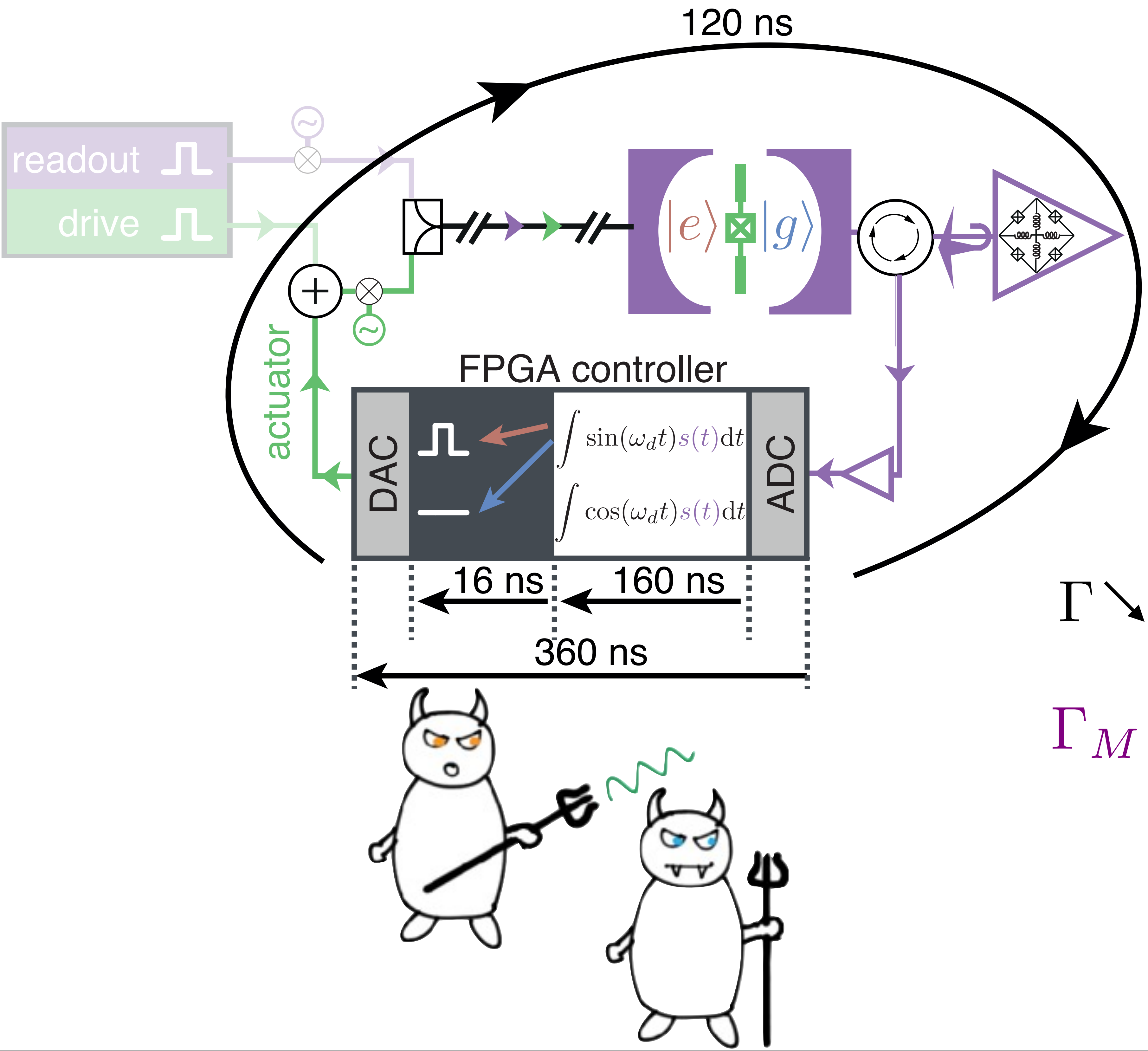
# Maxwell demon

2Mbits/s

Non degenerate quantum limited amplifiers
[Yale, Nature 2010; Paris, PRL 2012]



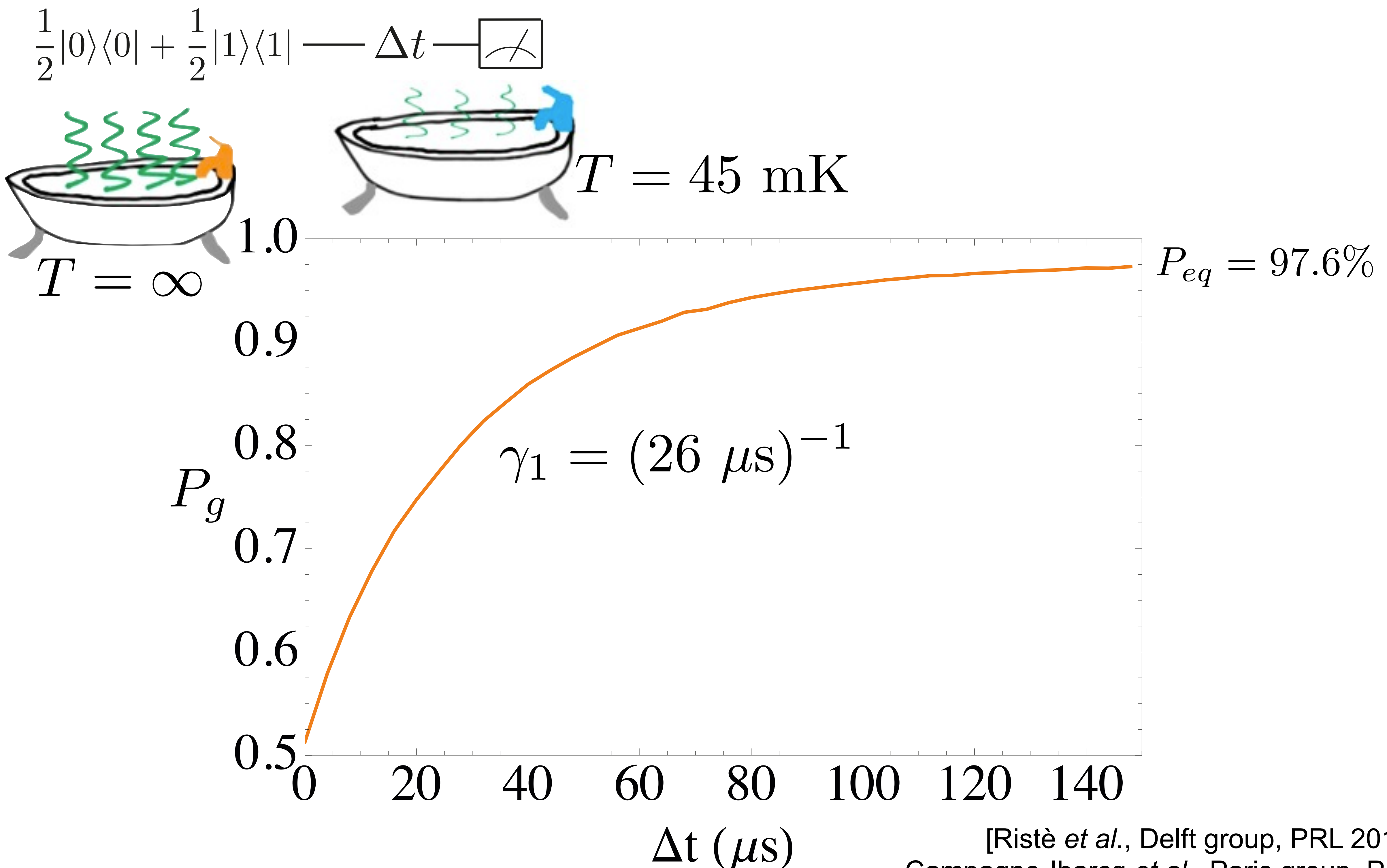
# closing the feedback loop: FPGA board




$\Gamma \searrow$ best < 10 kbit/s

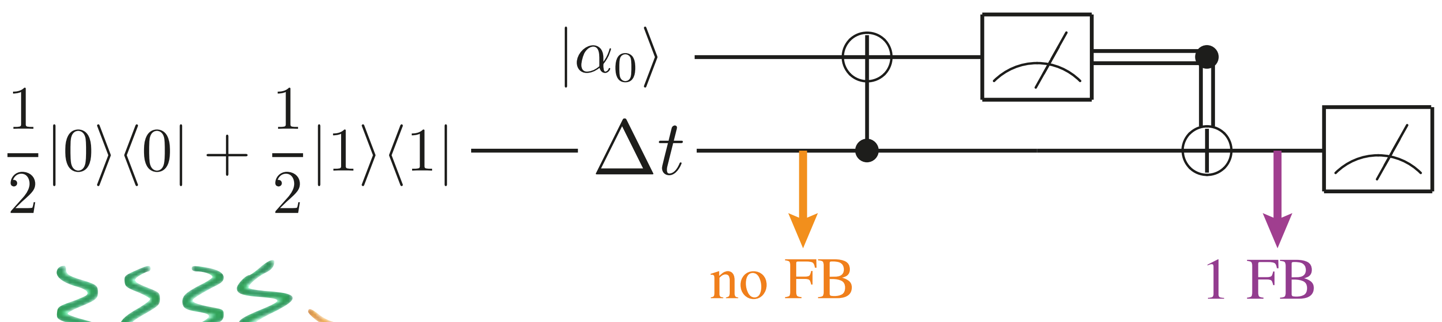
$\Gamma_M \nearrow$ 2 Mbit/s

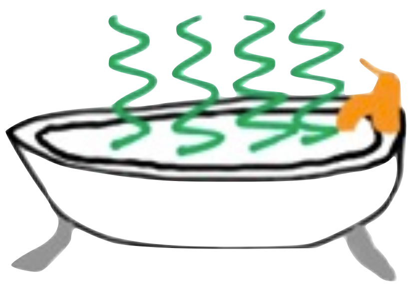
# Cooling down a qubit by measurement feedback

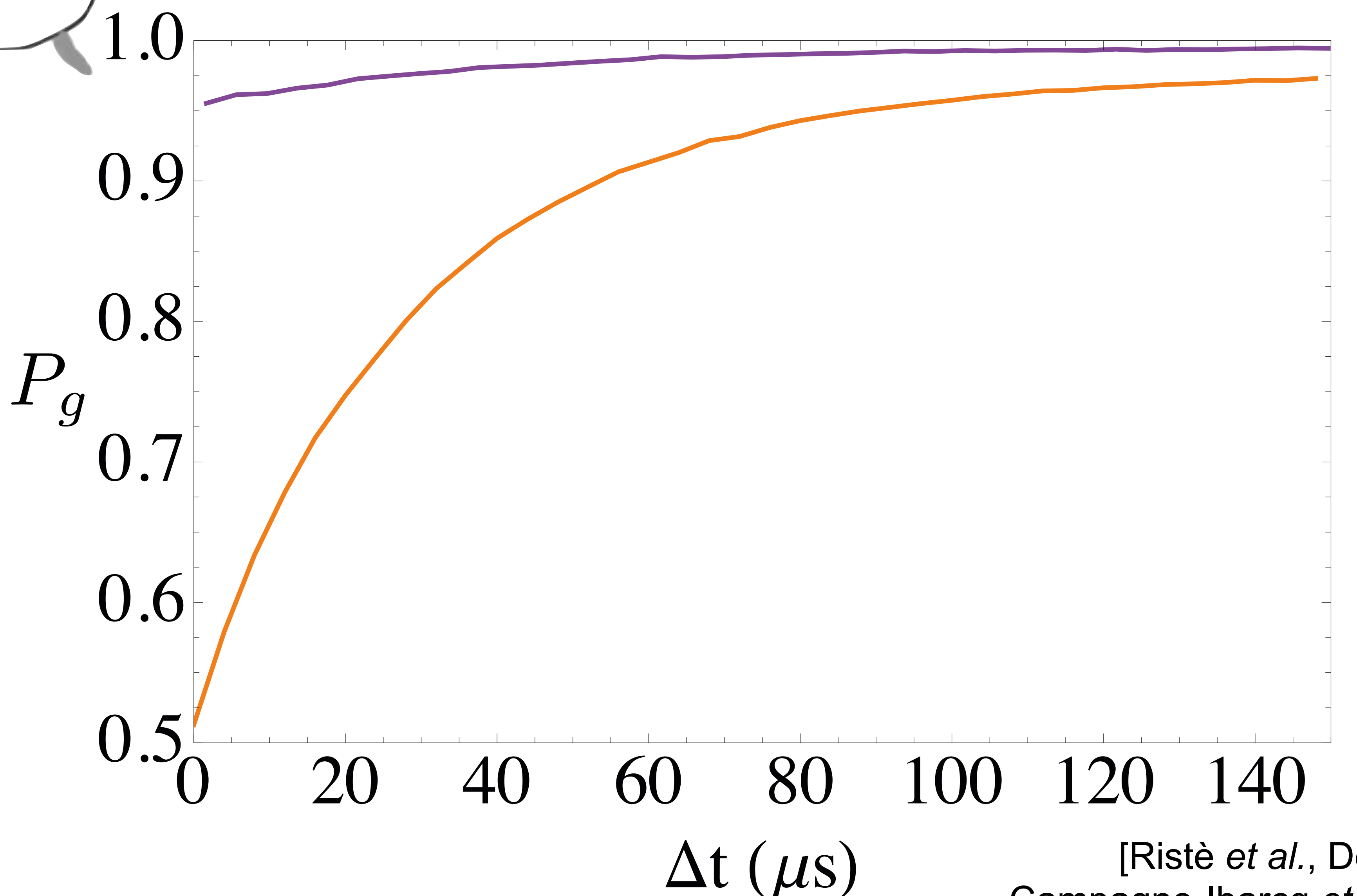



[Ristè *et al.*, Delft group, PRL 2012;
Campagne-Ibarcq *et al.*, Paris group, PRX 2013]

# Cooling down a qubit by measurement feedback



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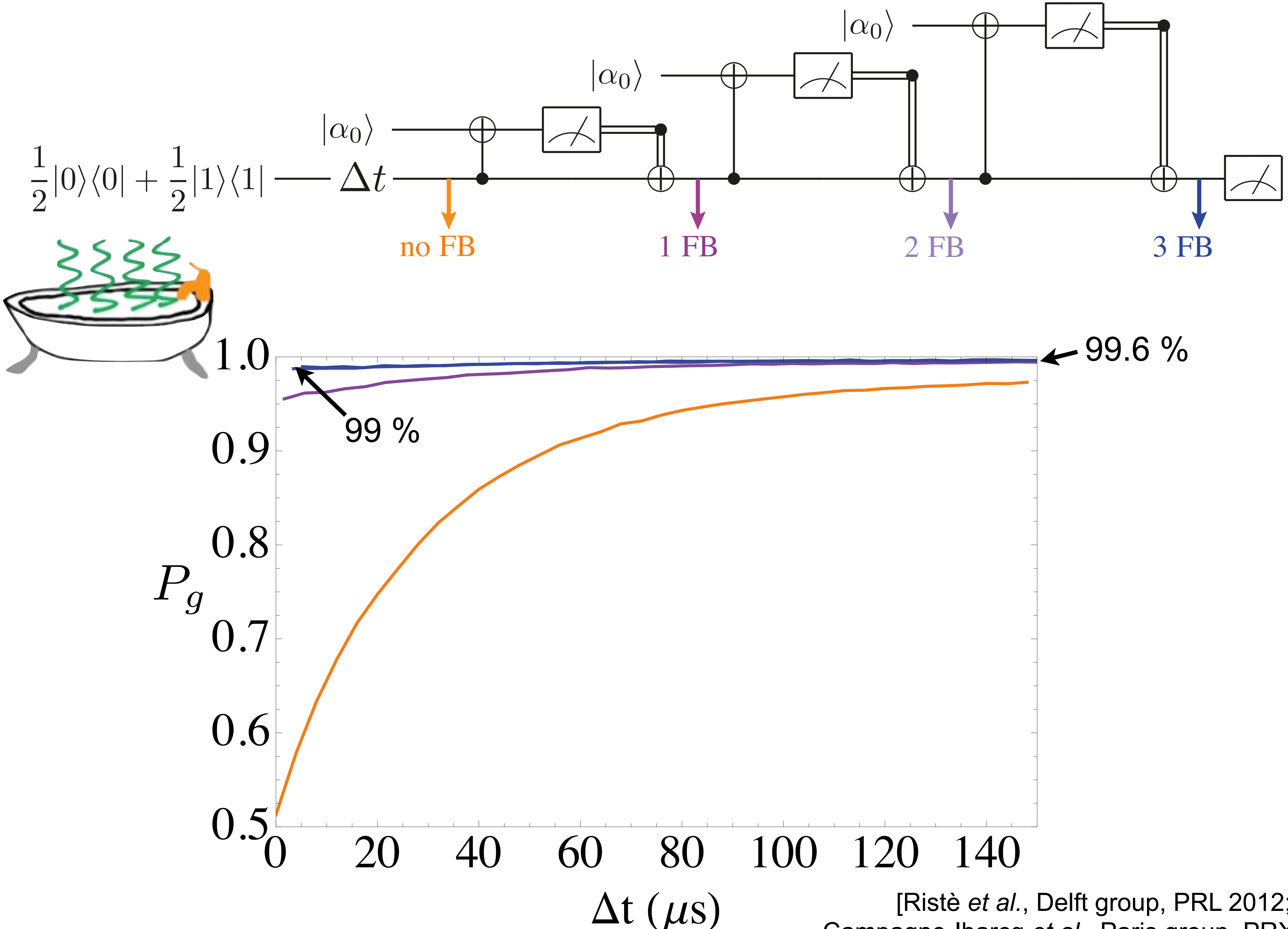
# Cooling down a qubit by measurement feedback




[Ristè *et al.*, Delft group, PRL 2012;
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# Maxwell demon

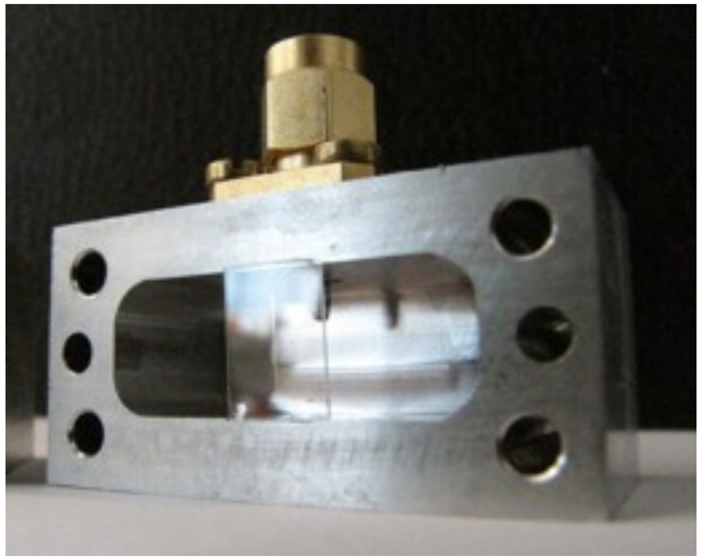

2 examples with superconducting circuits

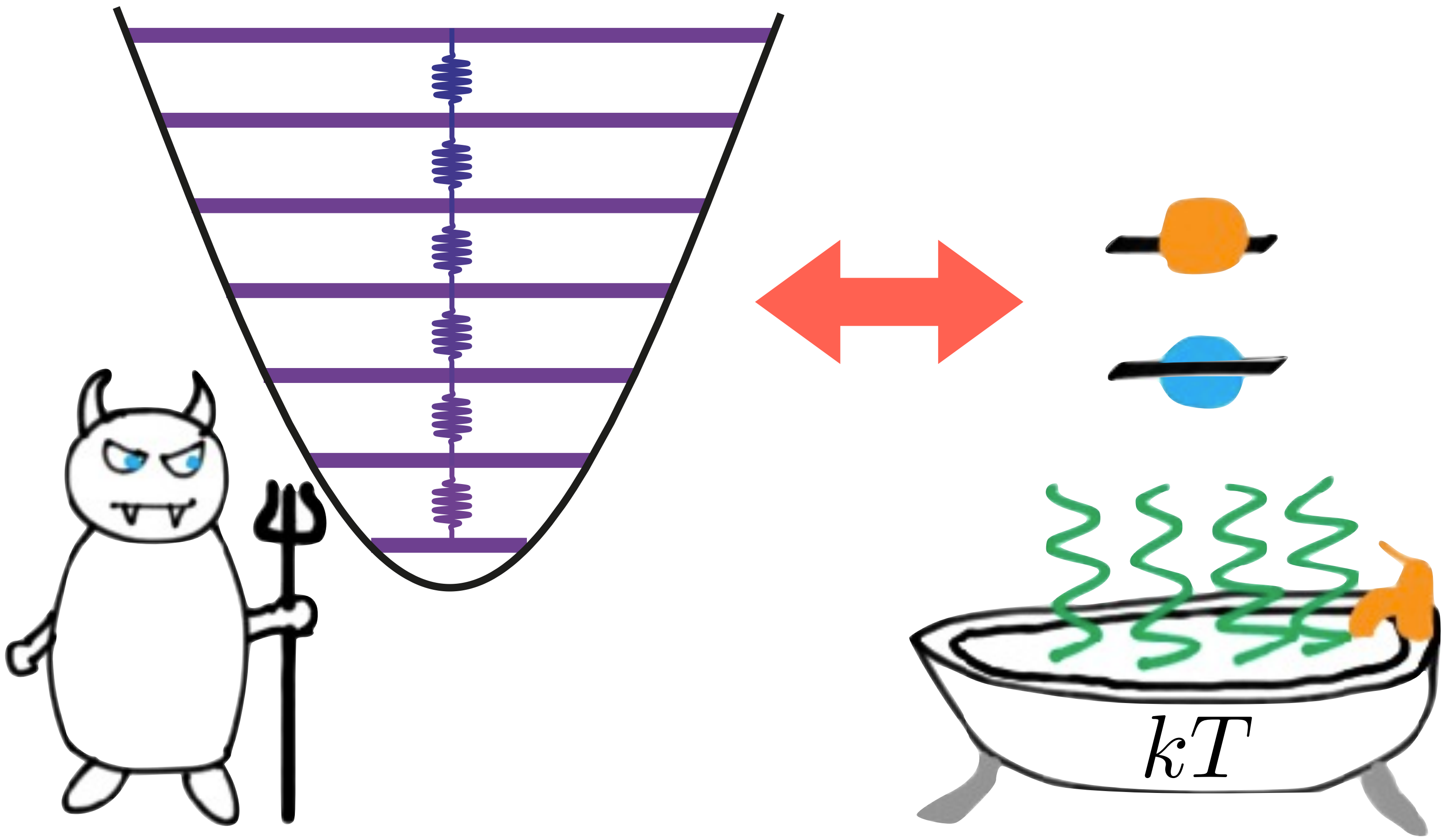
**Classical demon**
Measurement feedback

**Quantum demon**
Autonomous feedback

[Ristè *et al.*, Delft group, PRL 2012;
Campagne-Ibarcq *et al.*, Paris group, PRX 2013]

# Photon resolved regime






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

7.8 GHz 5.6 GHz 4.6 MHz

$f_q \mapsto f_q - \chi N$ Qubit frequency depends on photon number

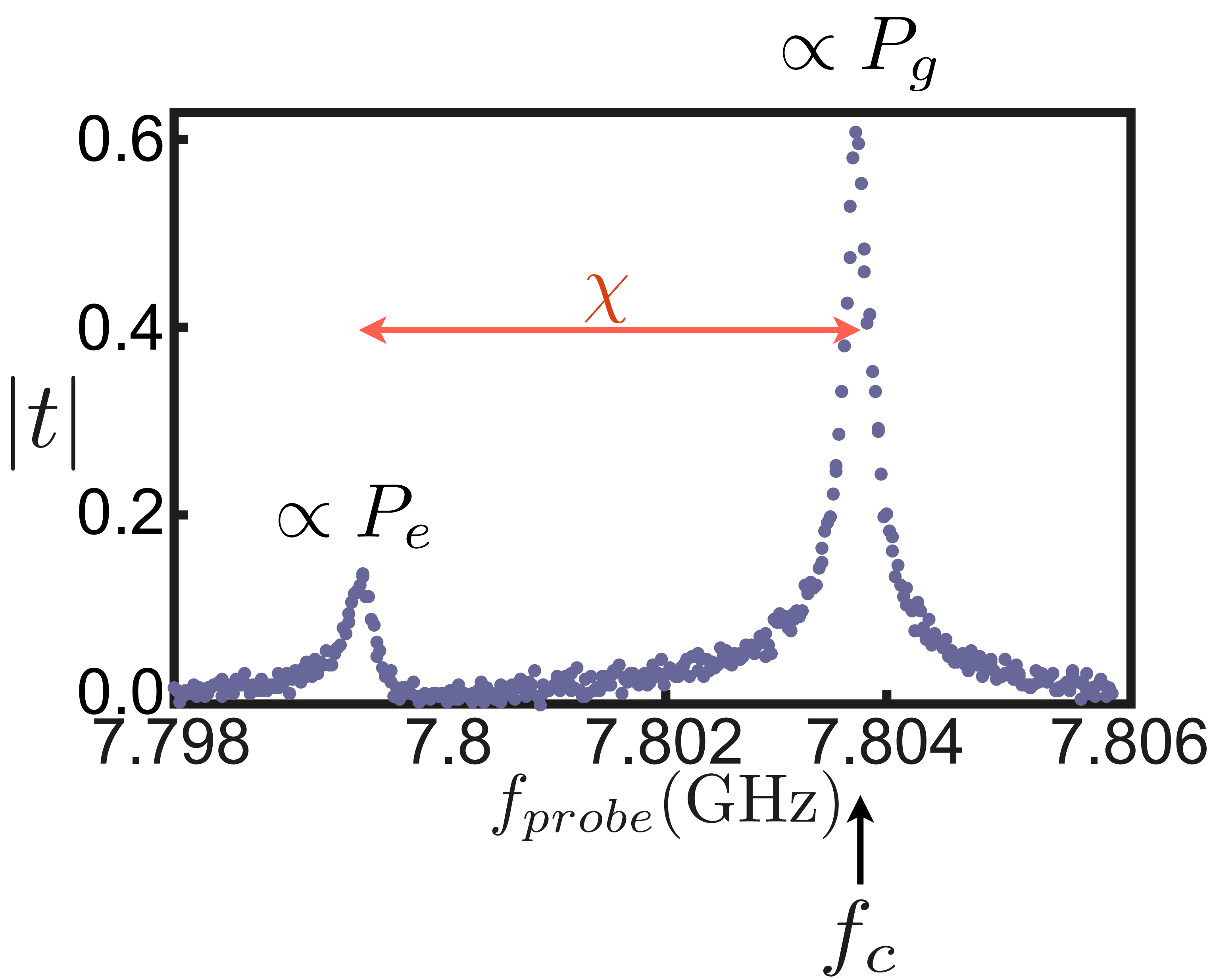
$f_c \mapsto f_c - \chi |e\rangle\langle e|$ Cavity frequency indicates qubit excitation

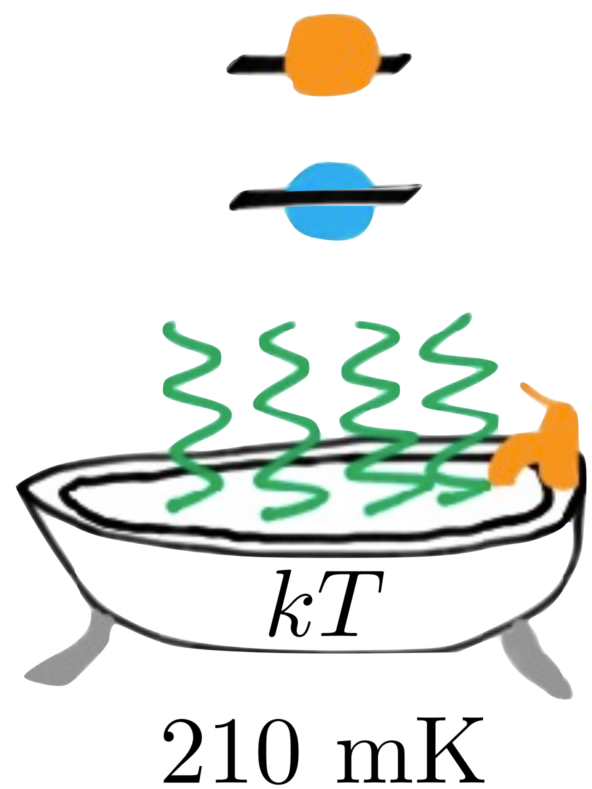
$T_c$=1.3 μs $T_1$=12 μs $T_2$=9 μs $\chi \gg \frac{1}{2\pi T_c} \gg \frac{1}{2\pi T_2}$

# Cavity as a qubit measurement apparatus

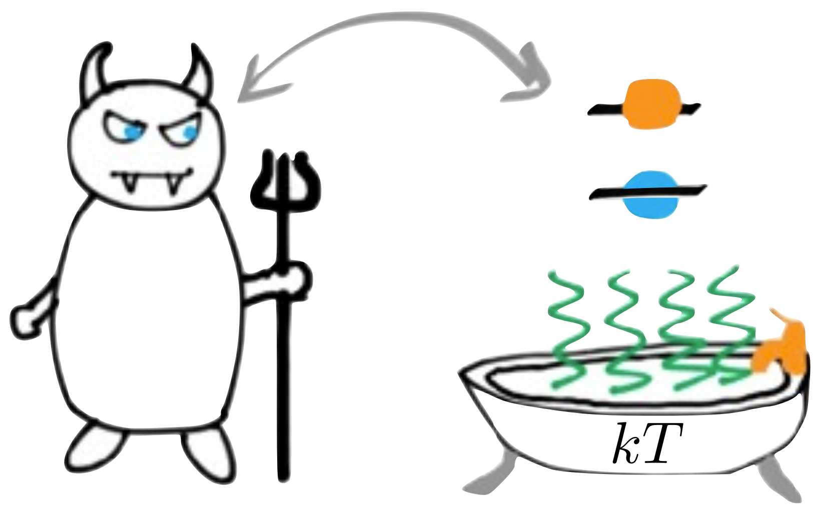
$$f_c \mapsto f_c - \chi|e\rangle\langle e|$$

Cavity frequency indicates qubit excitation
(here 22% at eq.)



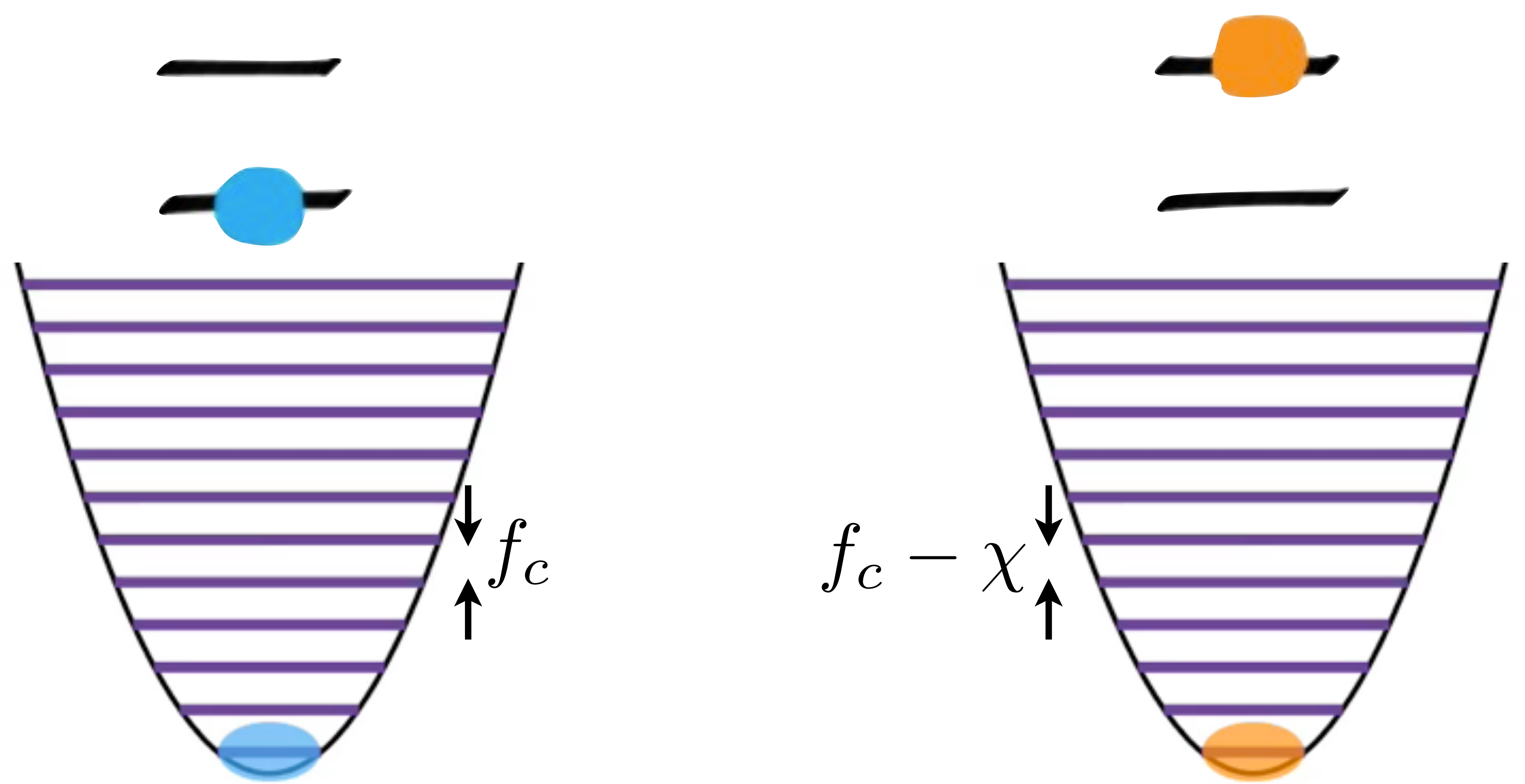



# Cooling down a qubit using a Maxwell demon




Demon measures qubit ⟷ Field displacement ($@f_c$)

DRAG technique
with 240 ns pulse

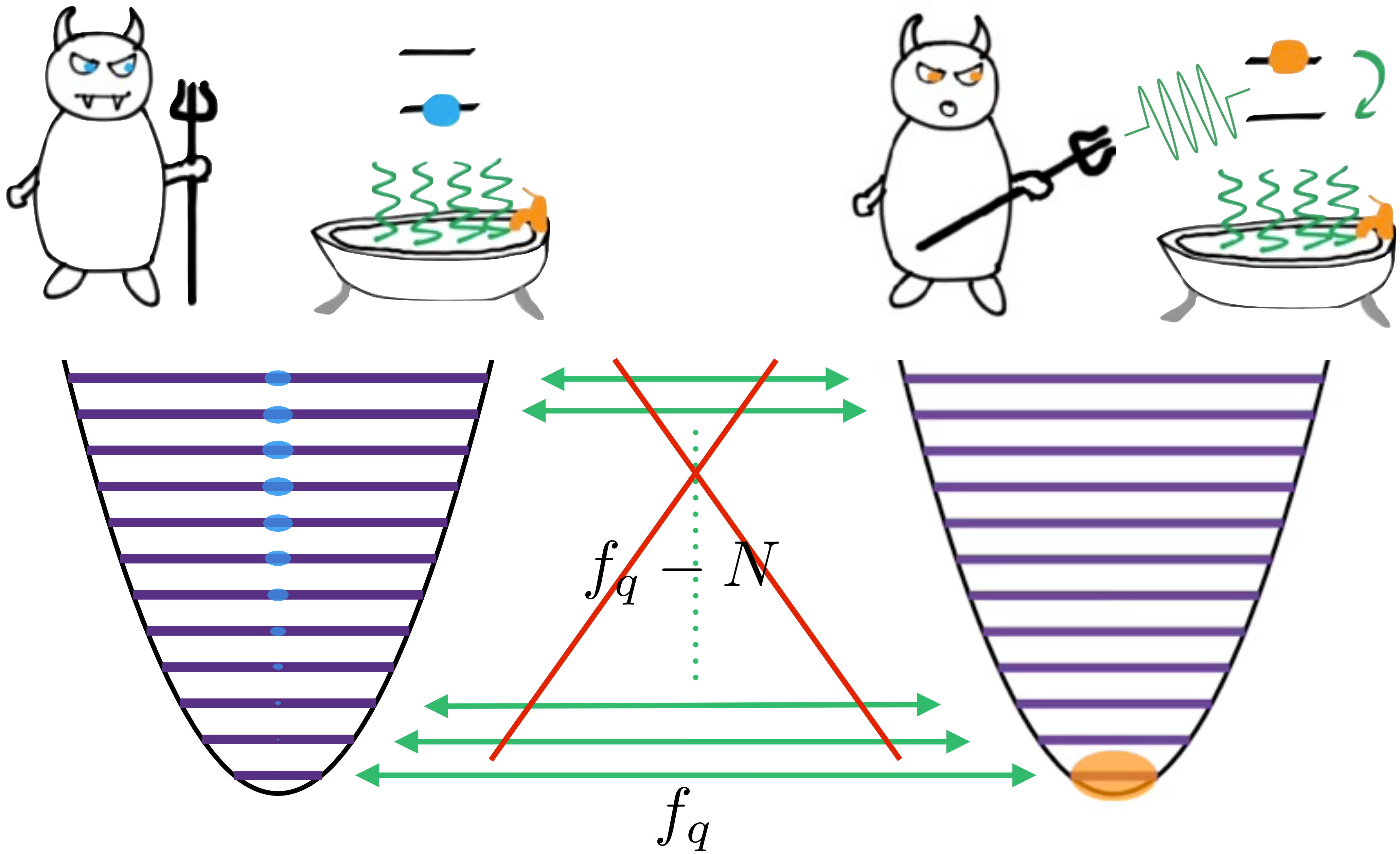


# Cooling down a qubit using a Maxwell demon

Demon measures qubit ⟷ Field displacement (@$f_c$)

Demon make the qubit release 1 ph ⟷ π-pulse @ $f_q$

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

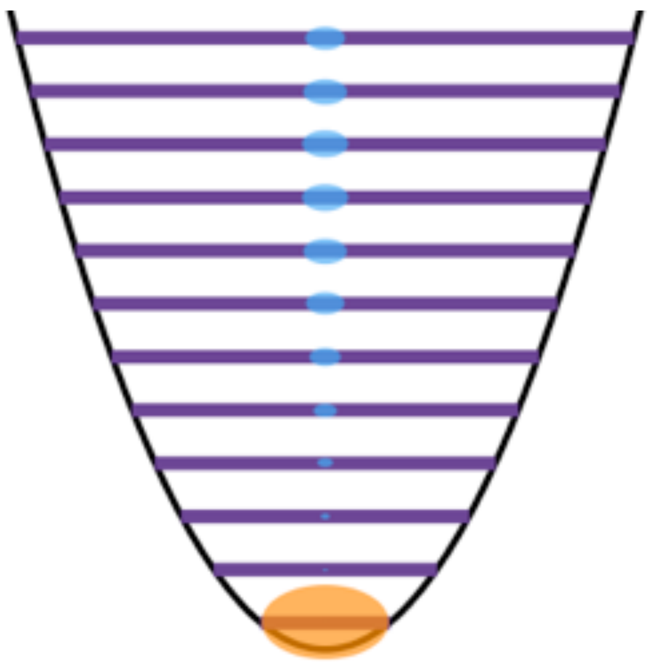


# Cooling down a qubit using a Maxwell demon

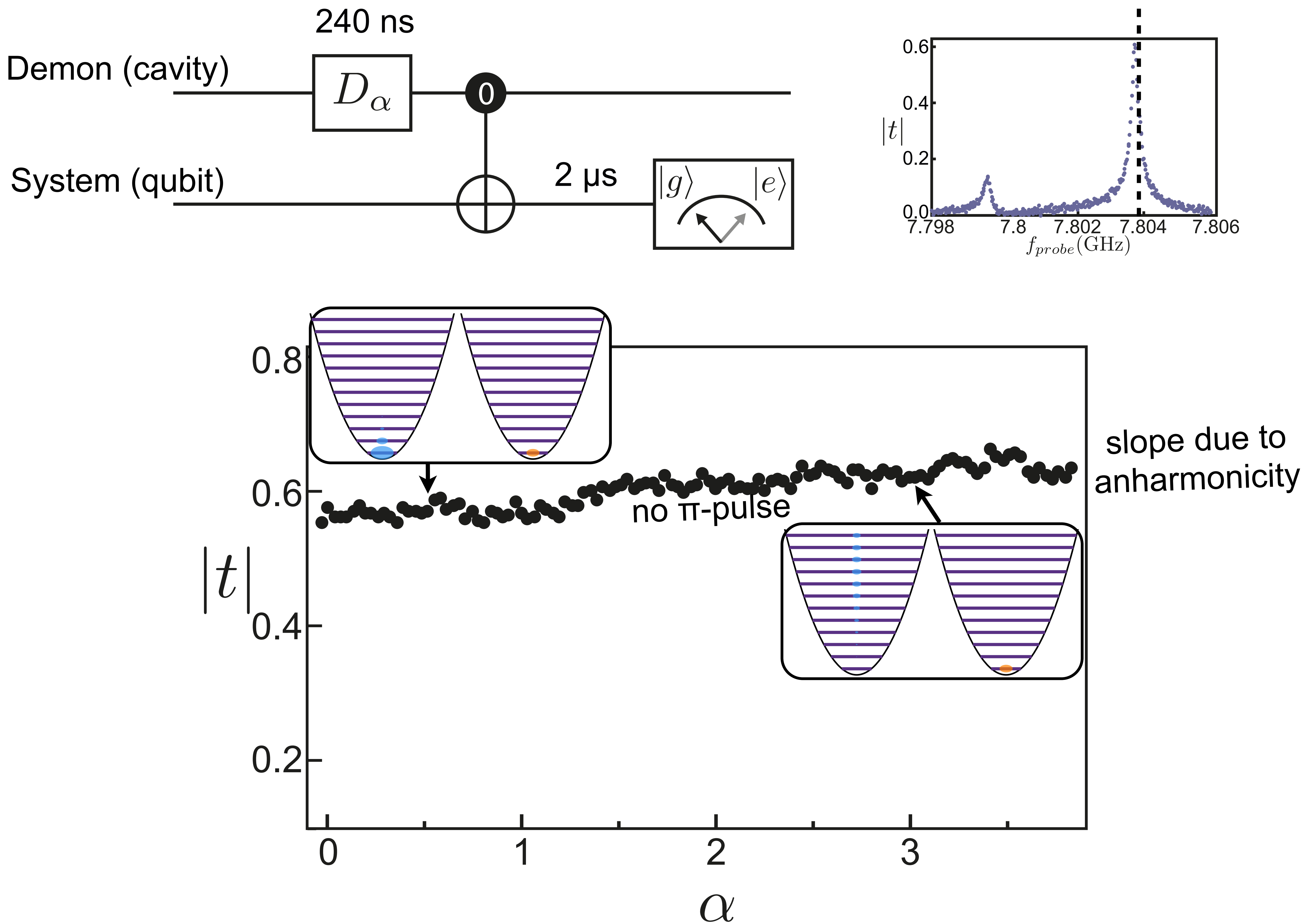
Demon measures qubit ⟷ Field displacement (@$f_c$)

Demon make the qubit release 1 ph ⟷ π-pulse @ $f_q$

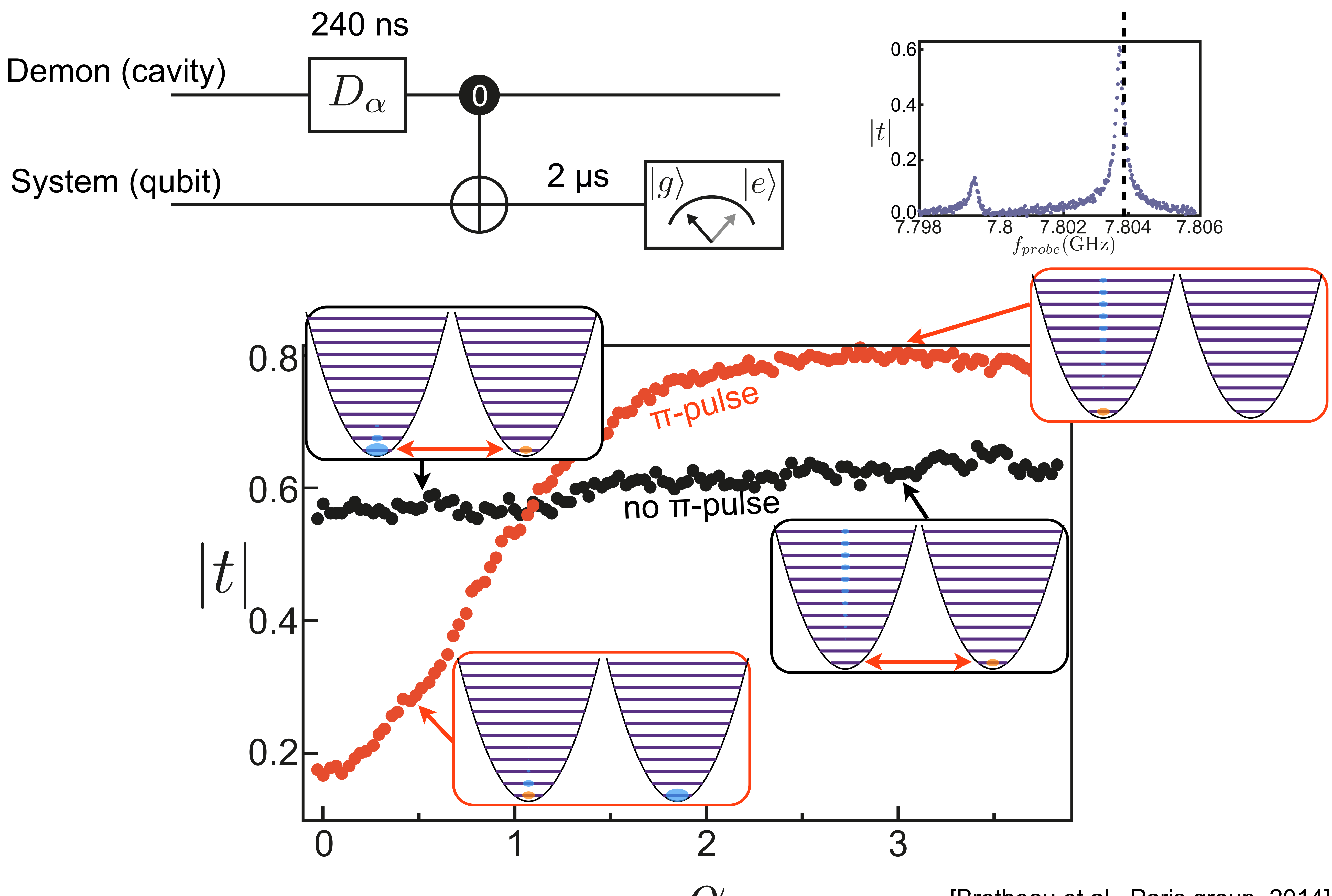
Demon evacuates heat ⟷ wait 2 μs (few Tc)



# Cooling down a qubit using a Maxwell demon

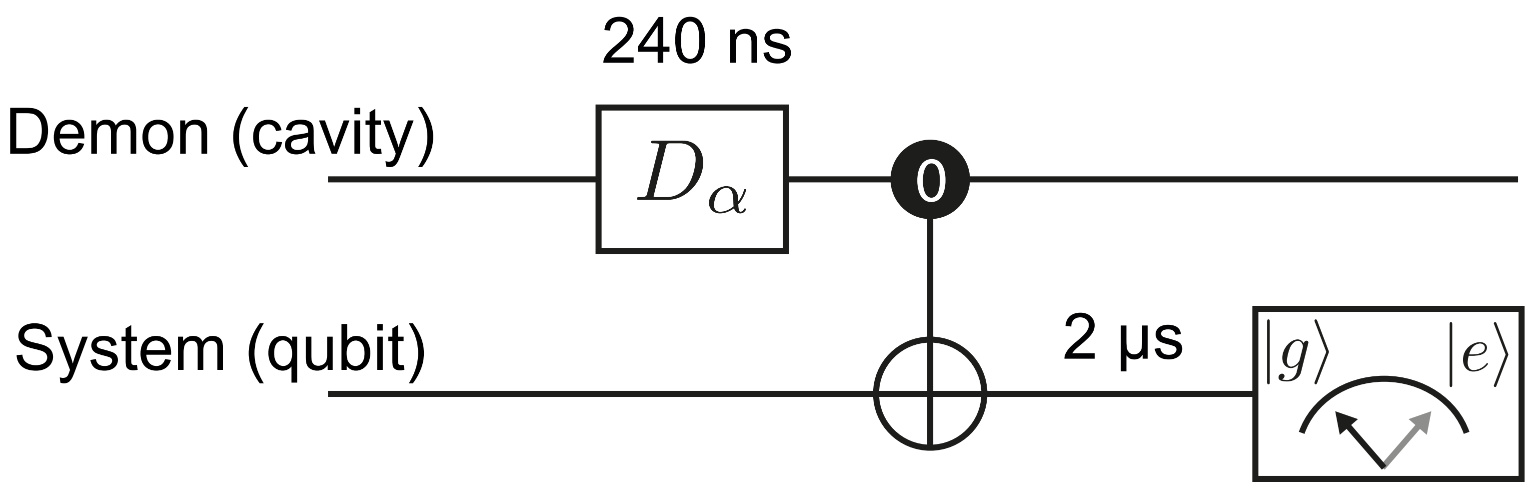


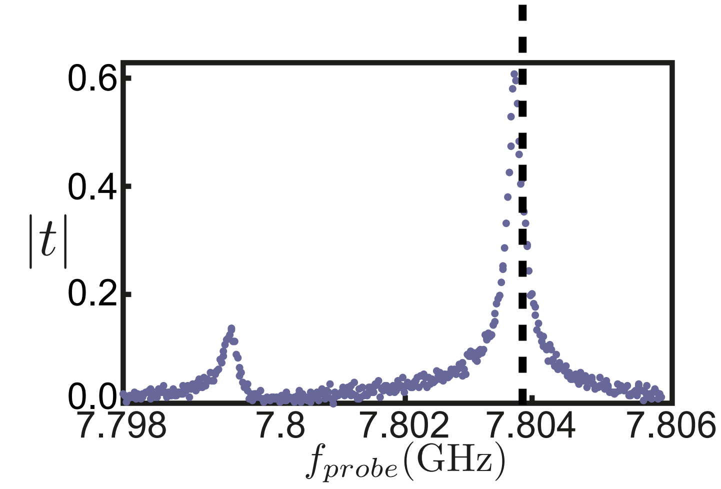
# Cooling down a qubit using a Maxwell demon

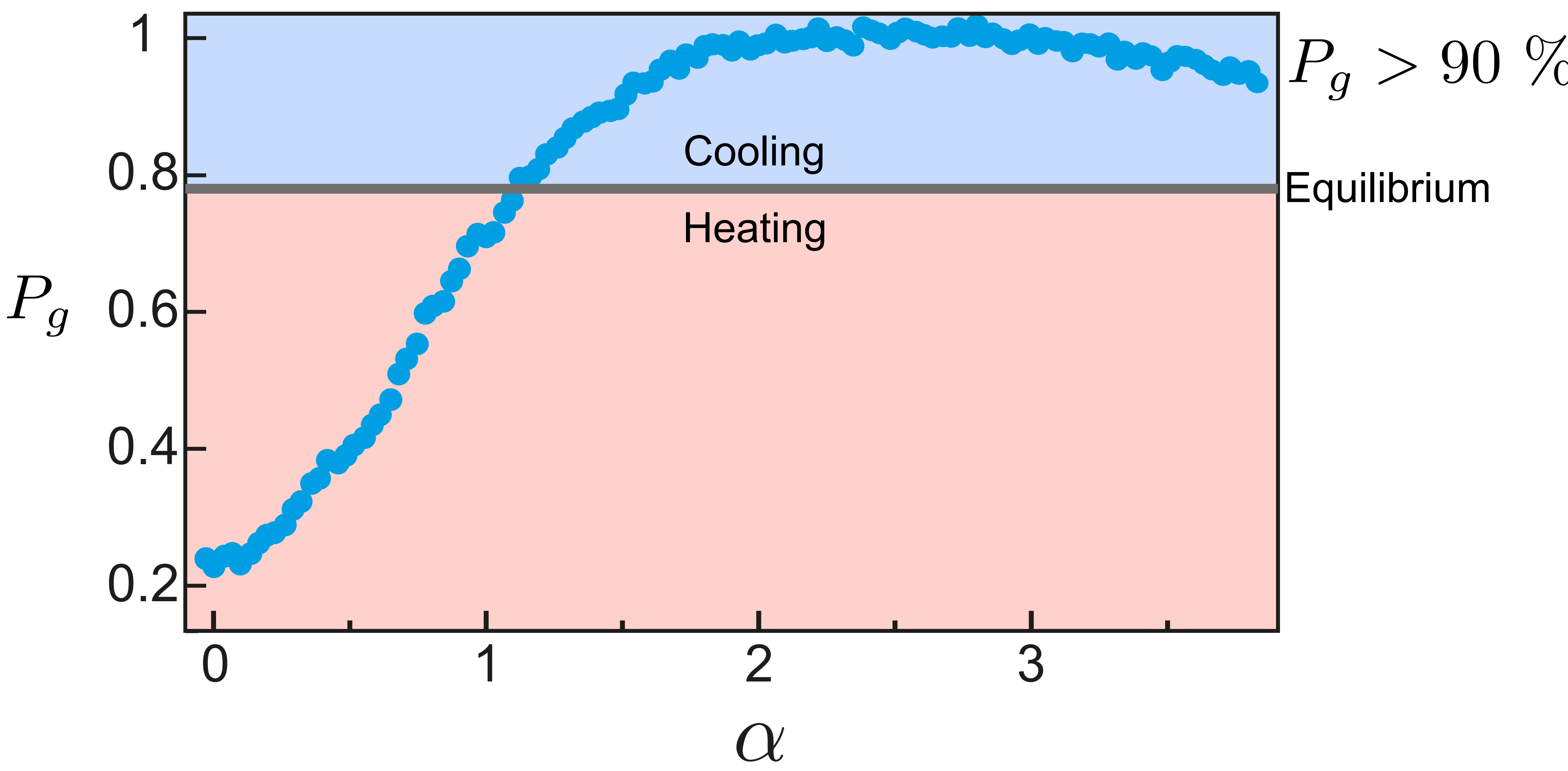



[Bretheau et al., Paris group, 2014]

# Cooling down a qubit using a Maxwell demon



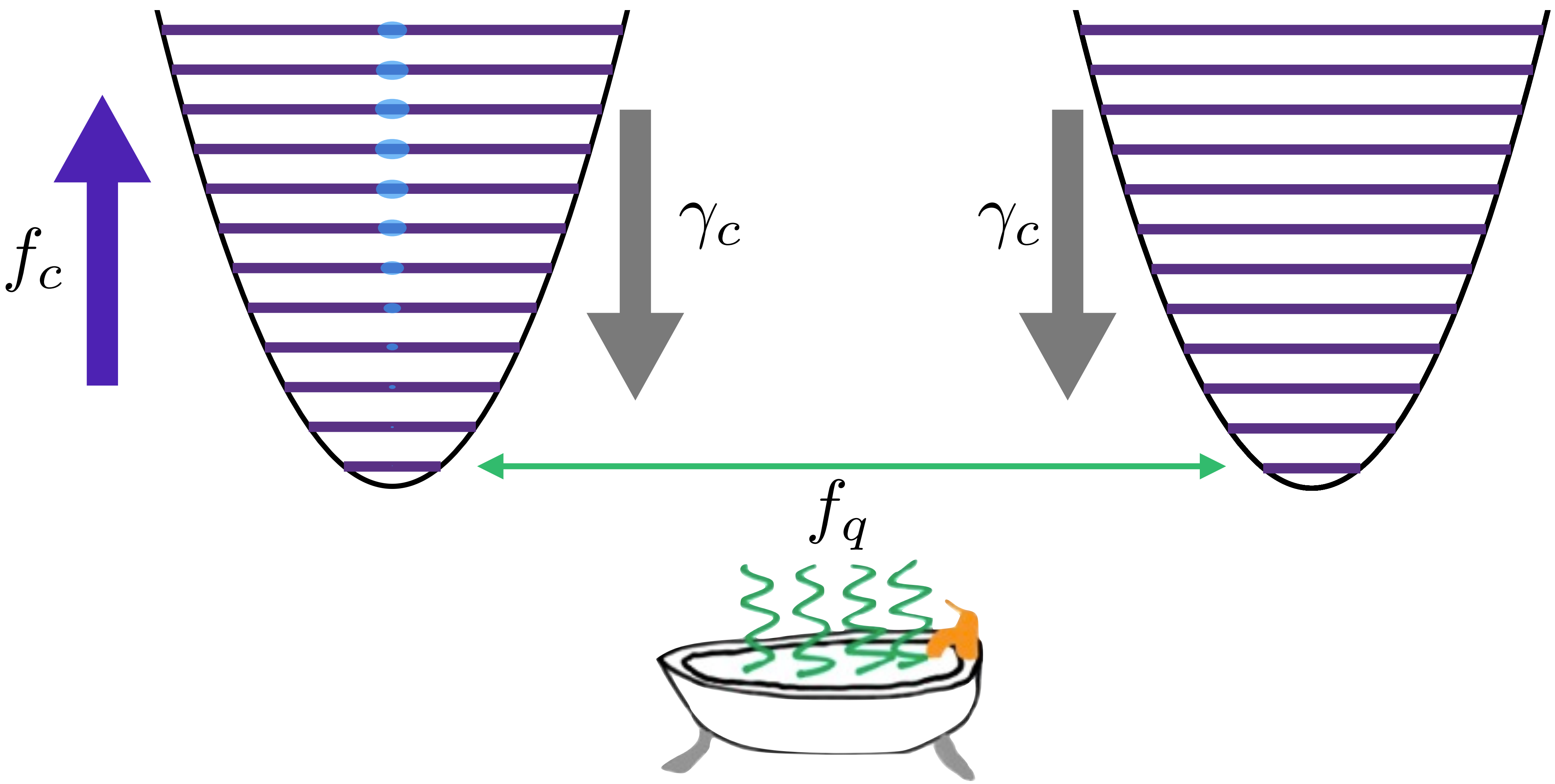



# Continuous version

Demon measures qubit ⟷ drive @ $f_c$

Demon make the qubit release ⟷ drive @ $f_q$



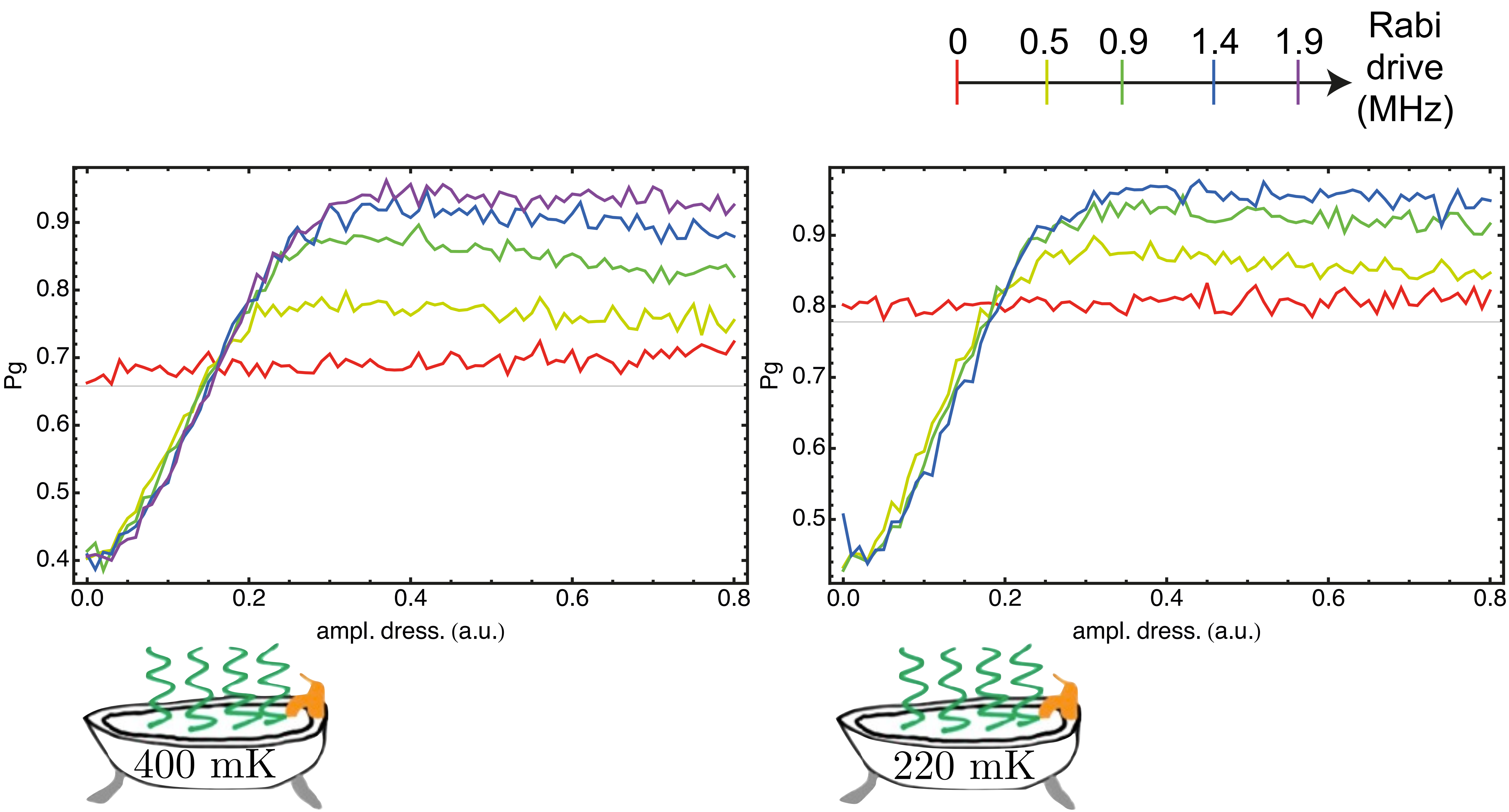

Relaxation towards $|g\rangle \otimes |\alpha\rangle$

DDROP technique
[Geerlings *et al.*, Yale group, PRL 2013]

# Continuous version

Demon measures qubit ⟷ drive @ $f_c$

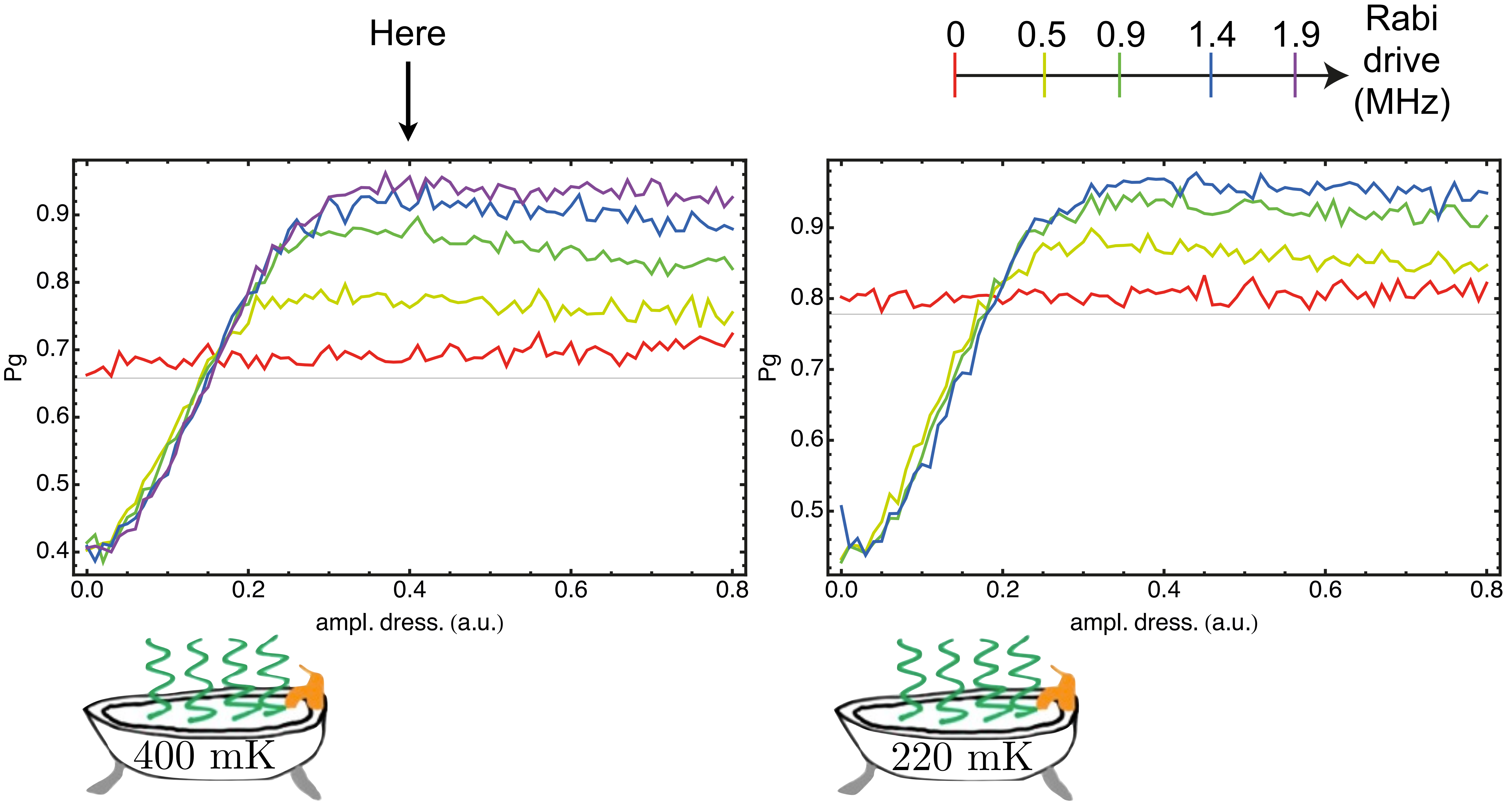
Demon make the qubit release ⟷ drive @ $f_q$



# Continuous version

Demon measures qubit ⟷ drive @ $f_c$

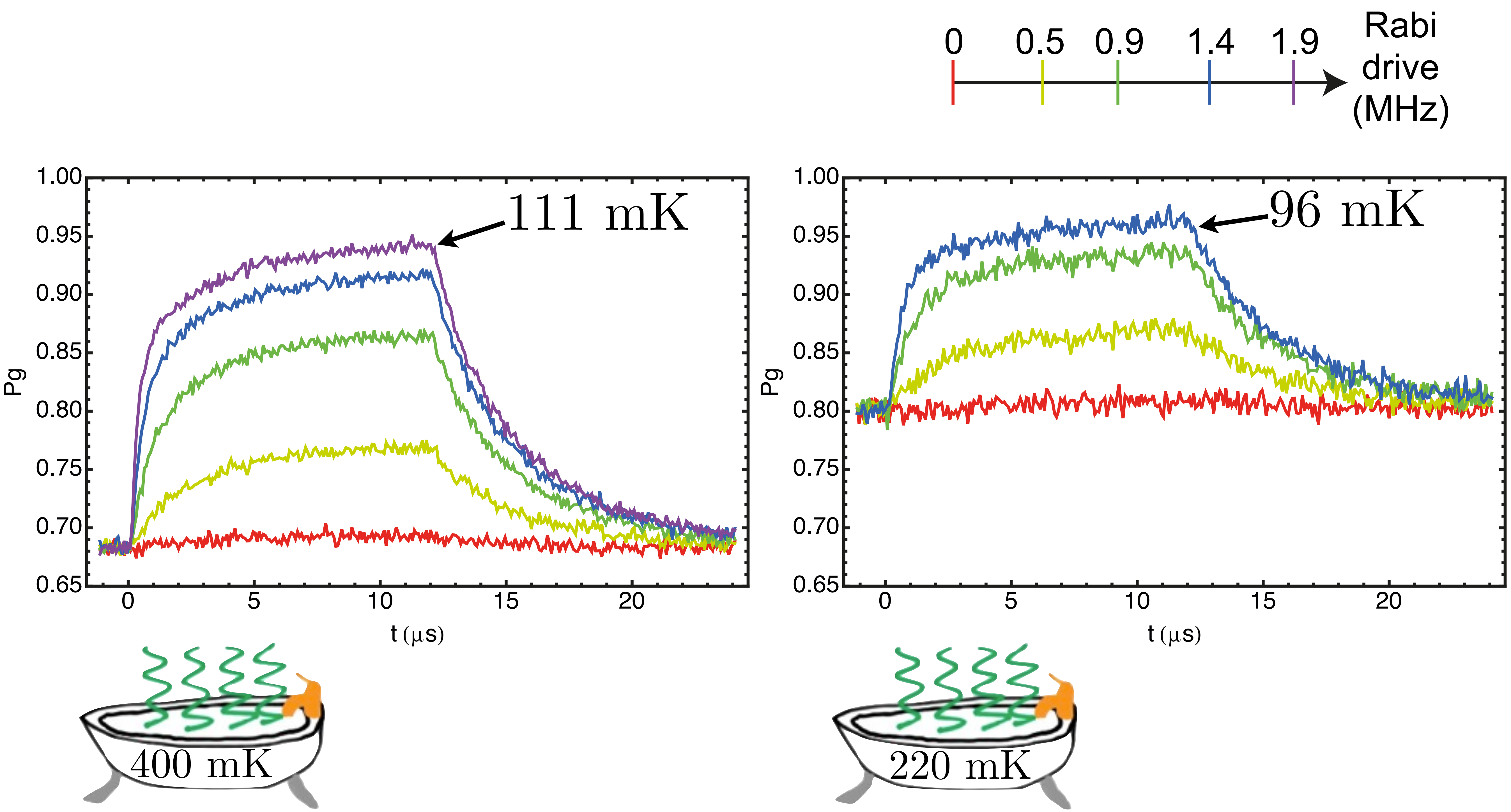
Demon make the qubit release ⟷ drive @ $f_q$



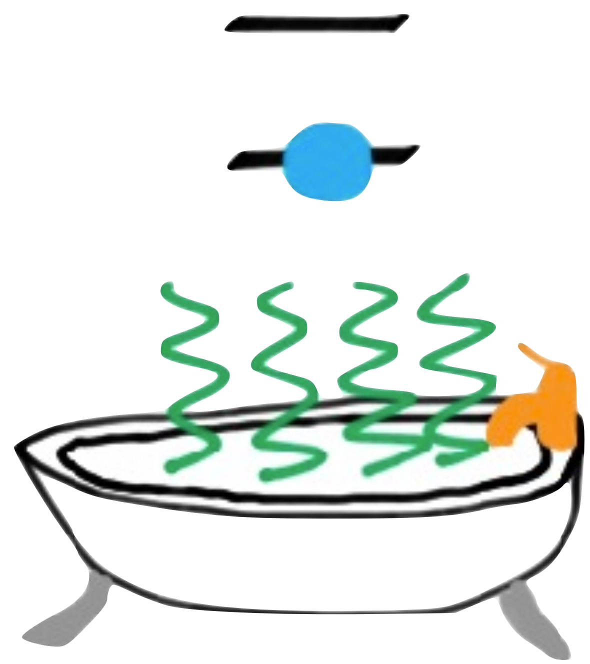
# Continuous version

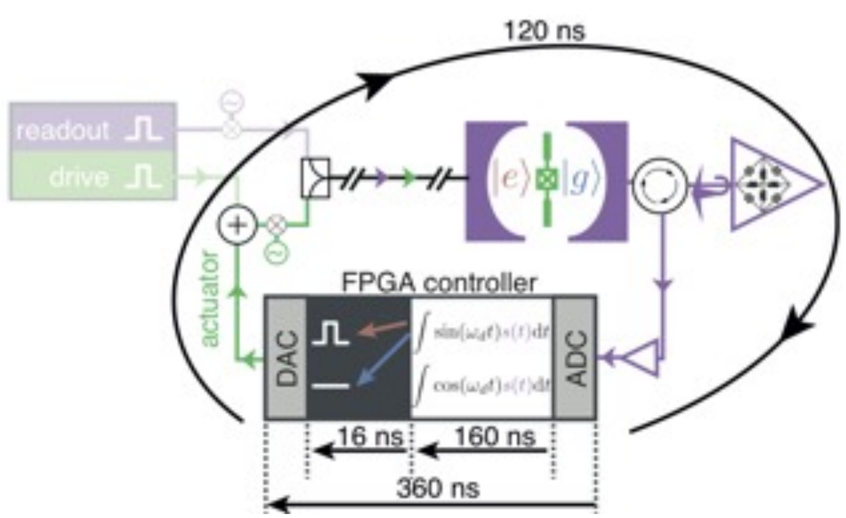
Demon measures qubit ⟷ drive @ $f_c$

Demon make the qubit release ⟷ drive @ $f_q$

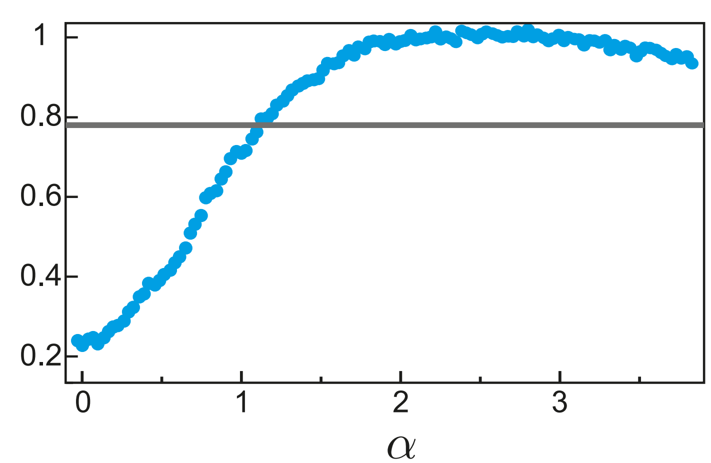


# In a nutshell

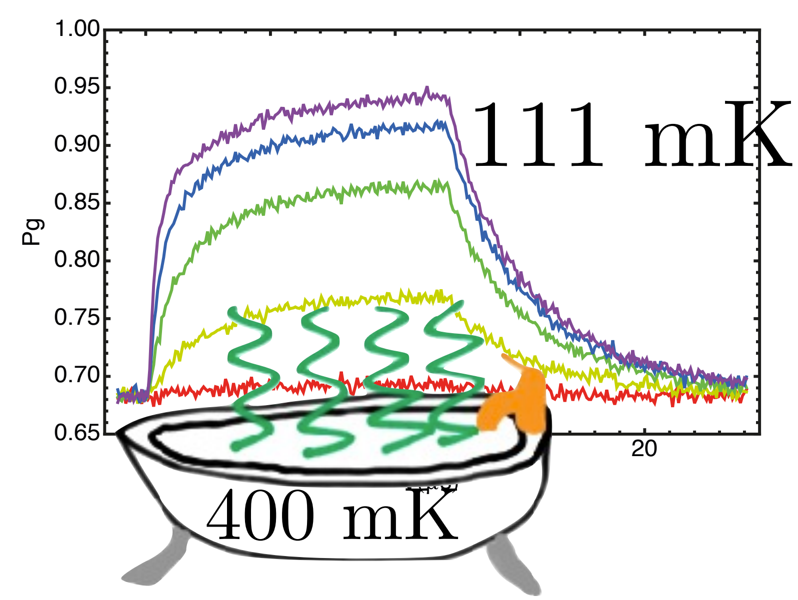





Classical Maxwell demon
Measurement-based feedback

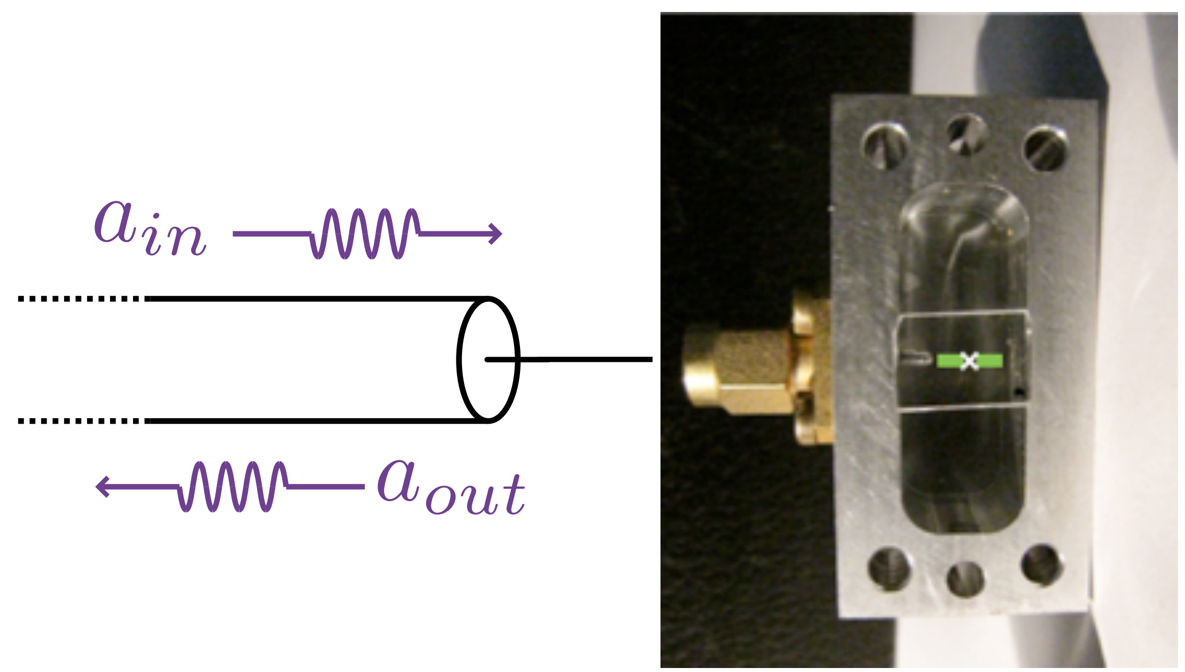


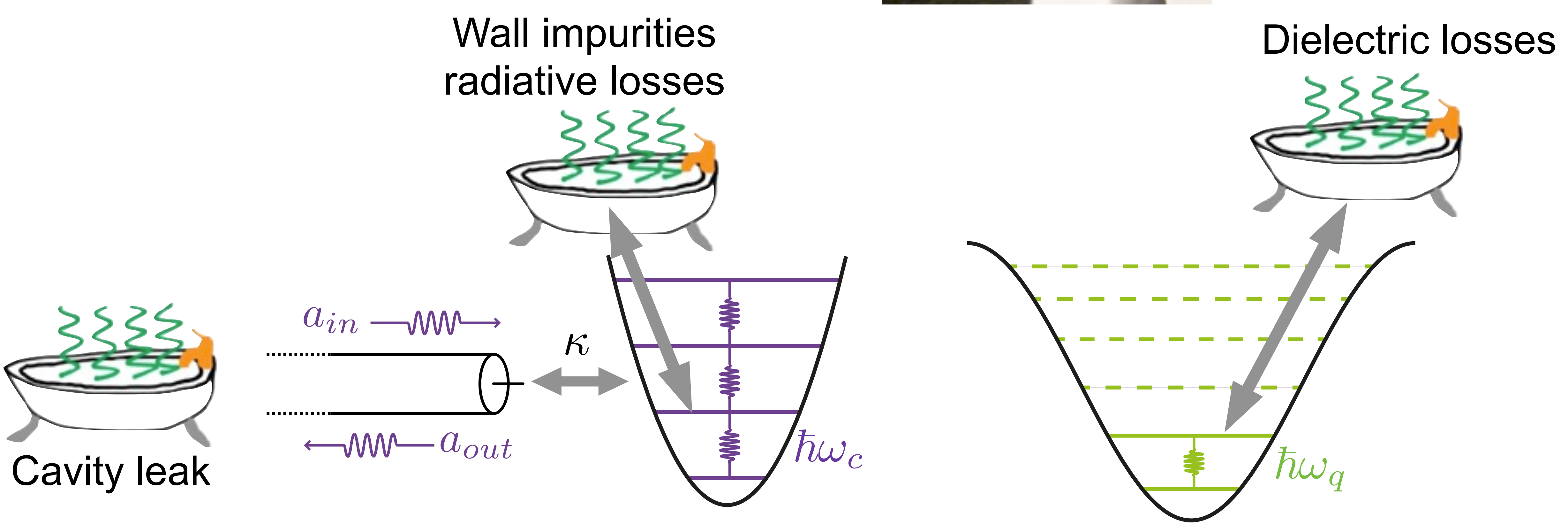

Quantum Maxwell demon
autonomous feedback



# Thermal baths coupled to a 3D transmon

$$\Gamma_1 = \Gamma_{\text{leak}} + \Gamma_{\text{loss}} + \Gamma_{\text{imp}}$$

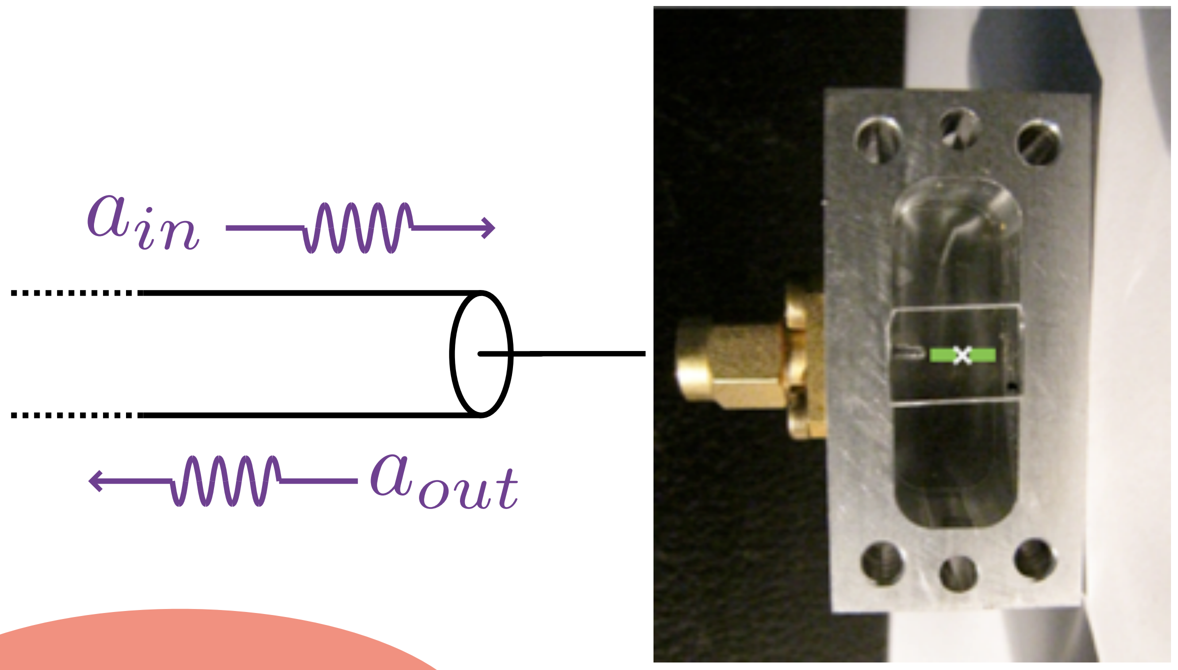


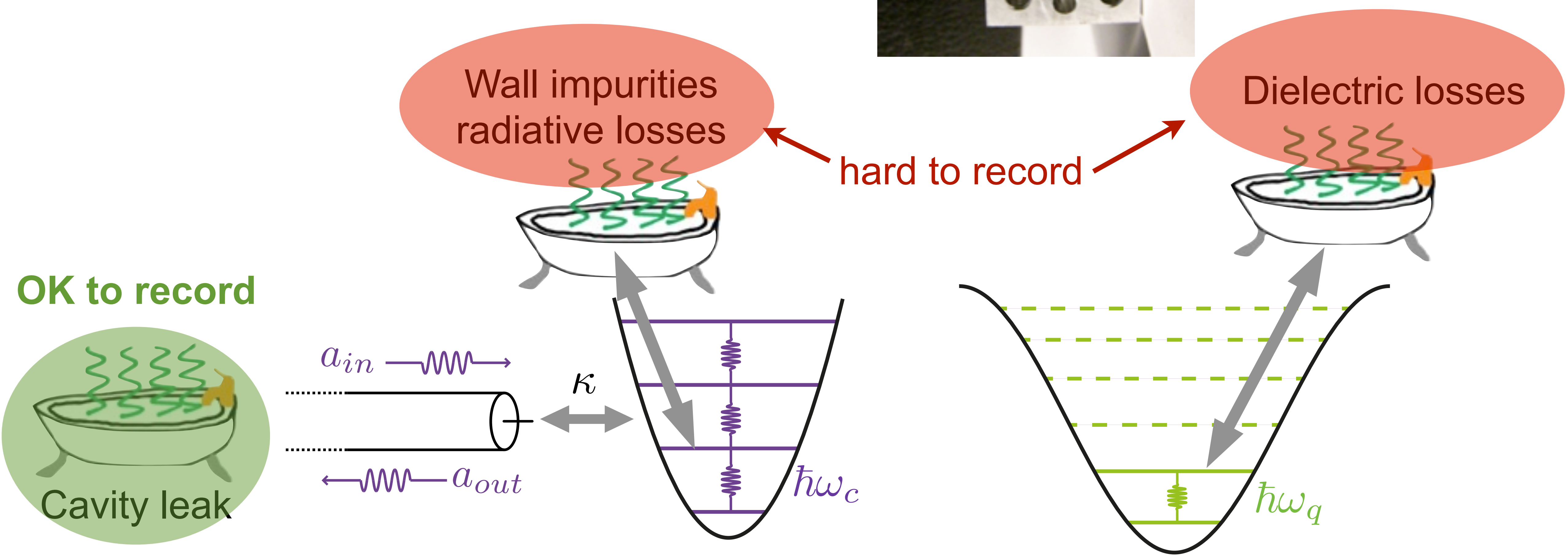




$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_Z}{2}$$

# Thermal baths coupled to a 3D transmon

$$\Gamma_1 = \Gamma_{\text{leak}} + \Gamma_{\text{loss}} + \Gamma_{\text{imp}}$$



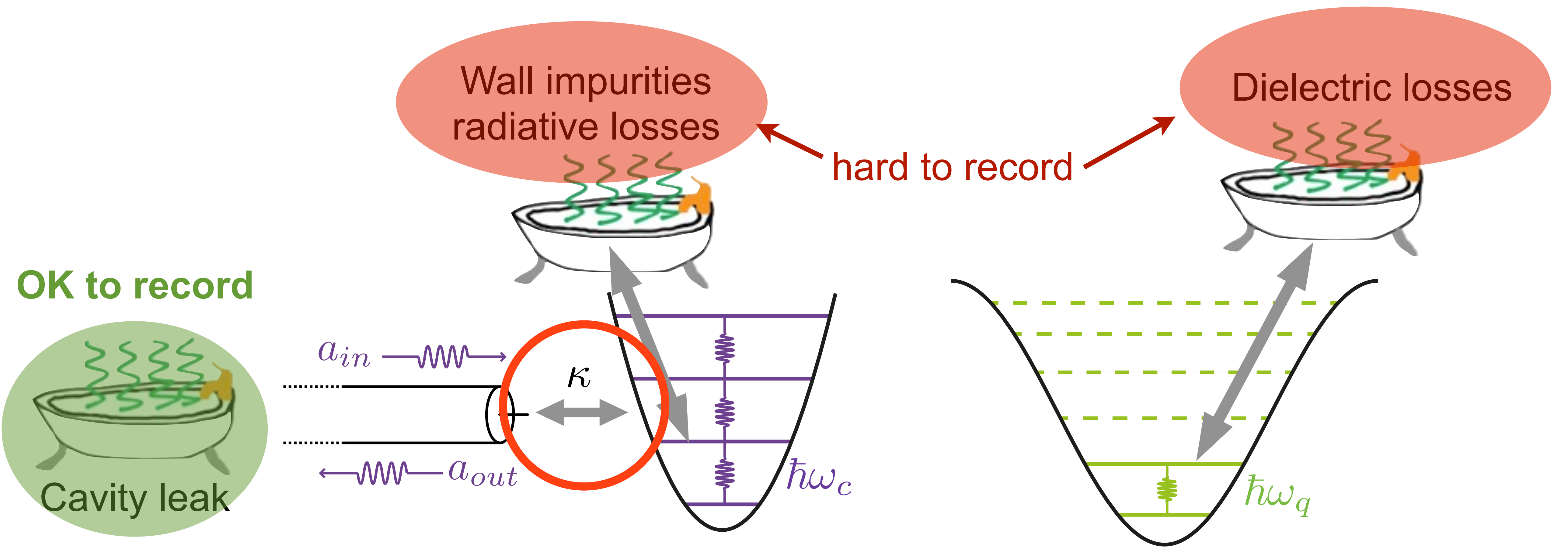




$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_Z}{2}$$

# Purcell effect

$$\Gamma_1 = \Gamma_{\rm leak} + \cancel{\Gamma_{\rm loss} + \Gamma_{\rm imp}}$$

Open cavity so that $\Gamma_{\rm leak} \gg \Gamma_{\rm loss} + \Gamma_{\rm imp}$




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

# Purcell effect from a quantum optics perspective

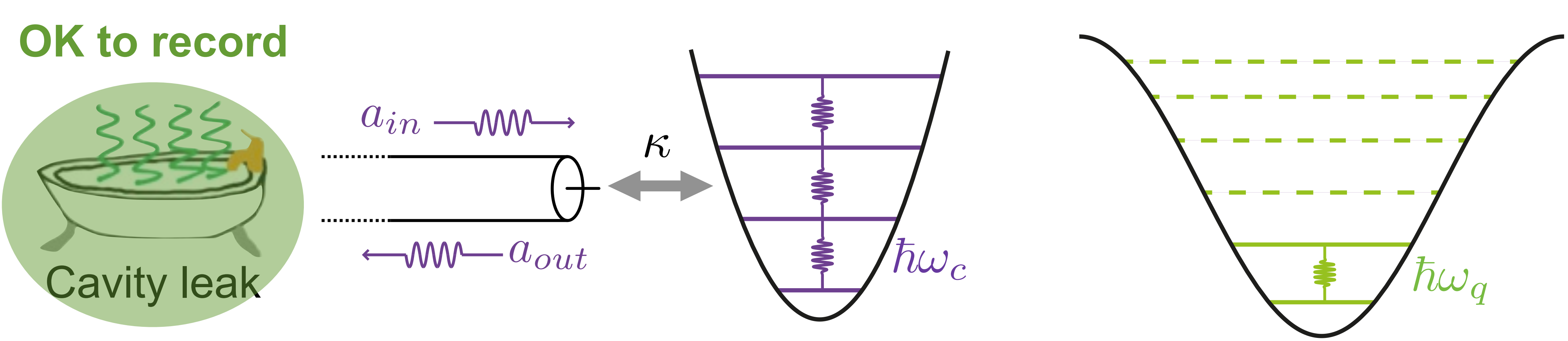
$$H_{JC} = \hbar g(a^\dagger \sigma_- + a\sigma_+)$$

$$g \ll \Delta$$

$$|g\rangle \longrightarrow |-,n\rangle = |g,n\rangle - \frac{g}{\Delta}\sqrt{n}|e,n-1\rangle$$

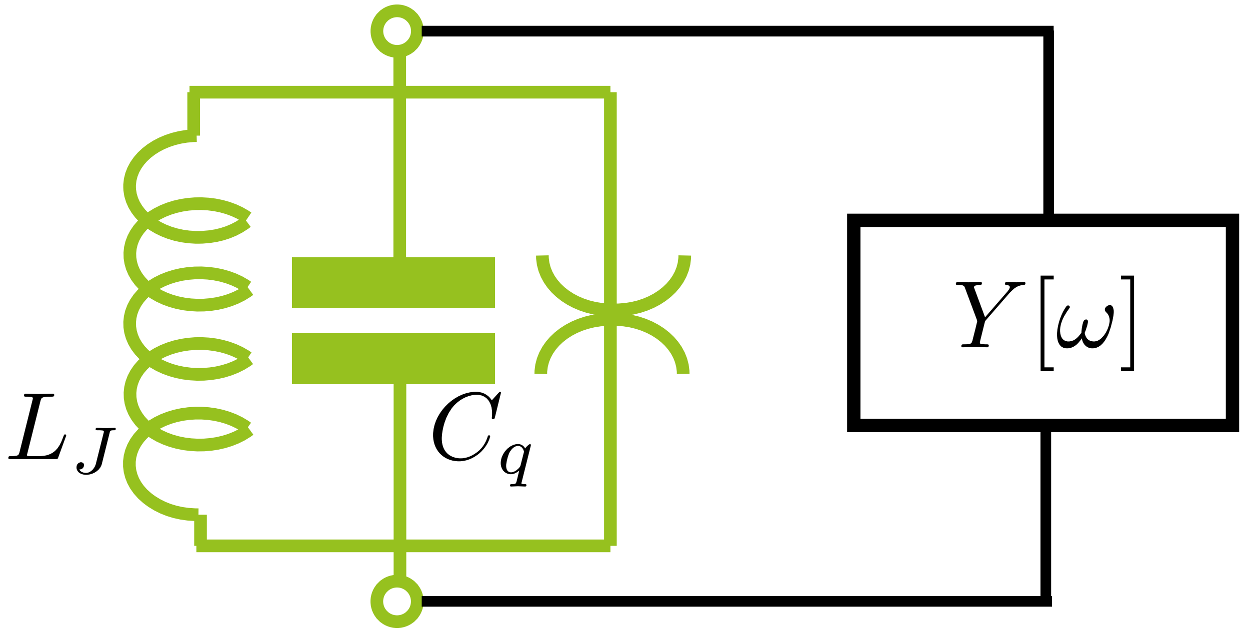
$$|e\rangle \longrightarrow |+,n+1\rangle = |e,n\rangle + \frac{g}{\Delta}\sqrt{n+1}|g,n+1\rangle$$

$$\Gamma_{\text{leak}} = \kappa|\langle -,n|a|+,n+1\rangle|^2 = \left(\frac{g}{\Delta}\right)^2 \kappa$$

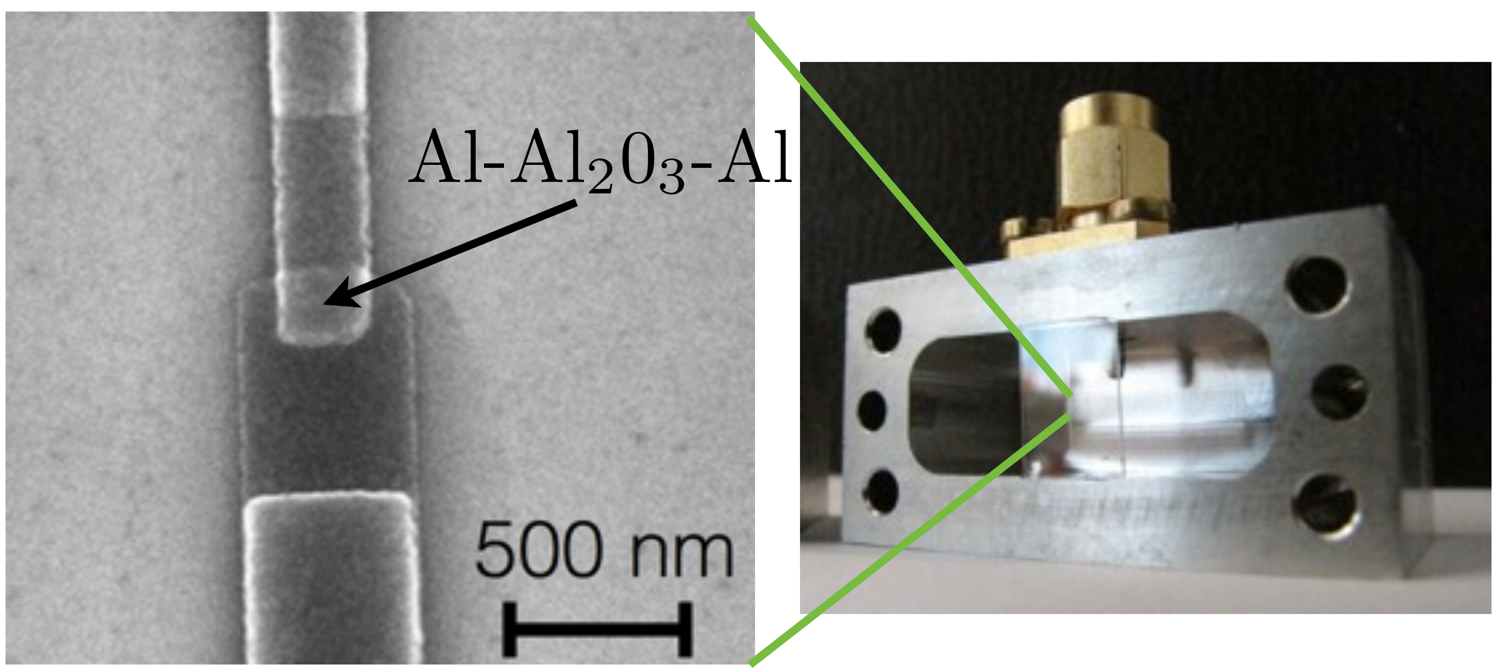


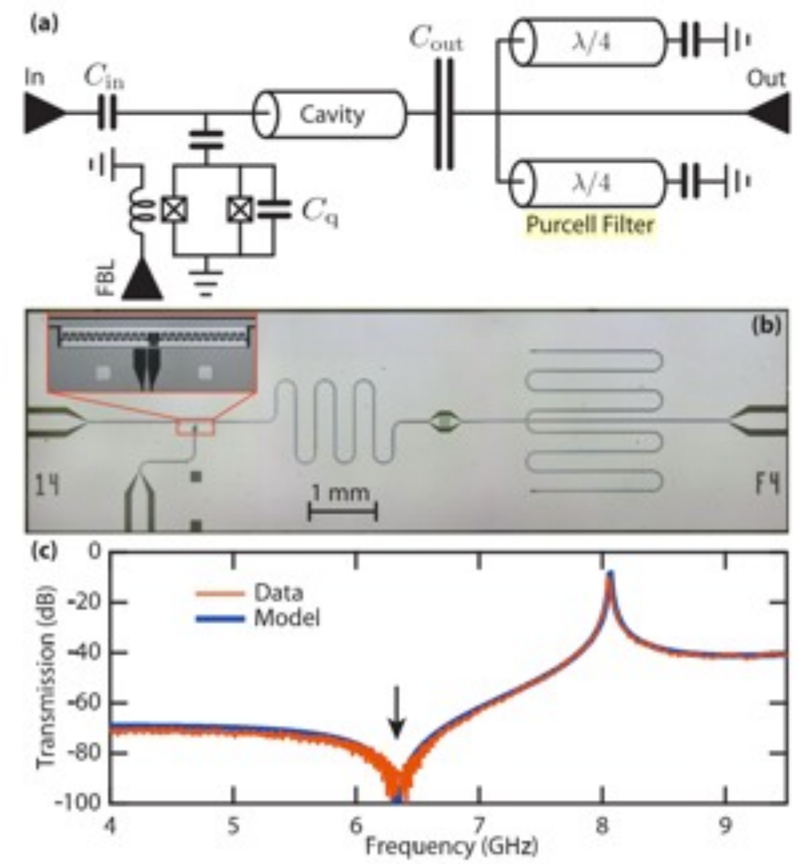

$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_Z}{2}$$

# Purcell effect from a microwave engineer perspective




$$\Gamma_{\text{leak}} = \frac{\text{Re}(Y[\omega_q])}{C_q}$$



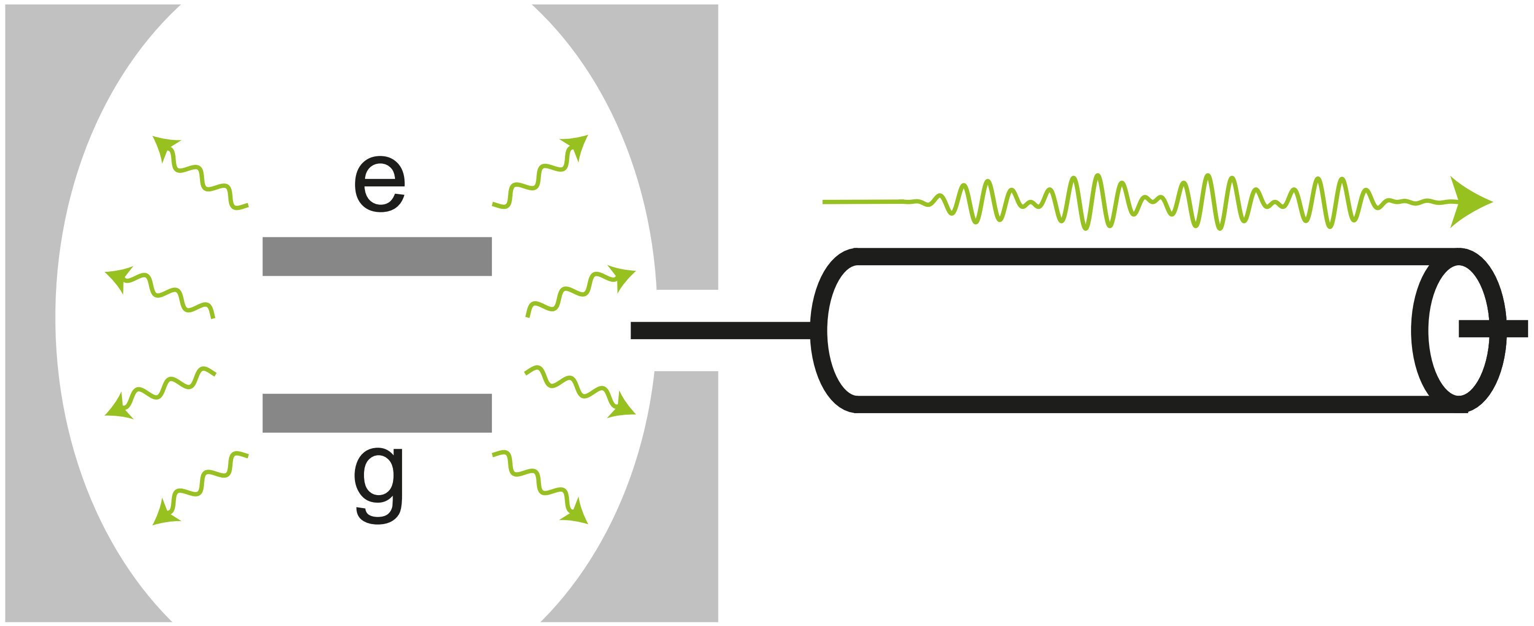

[Reed et al., Yale group, APL (2010)]

# Purcell effect leads to fluorescence

$$\Gamma_{\text{leak}} \gg \Gamma_{\text{loss}} + \Gamma_{\text{imp}}$$

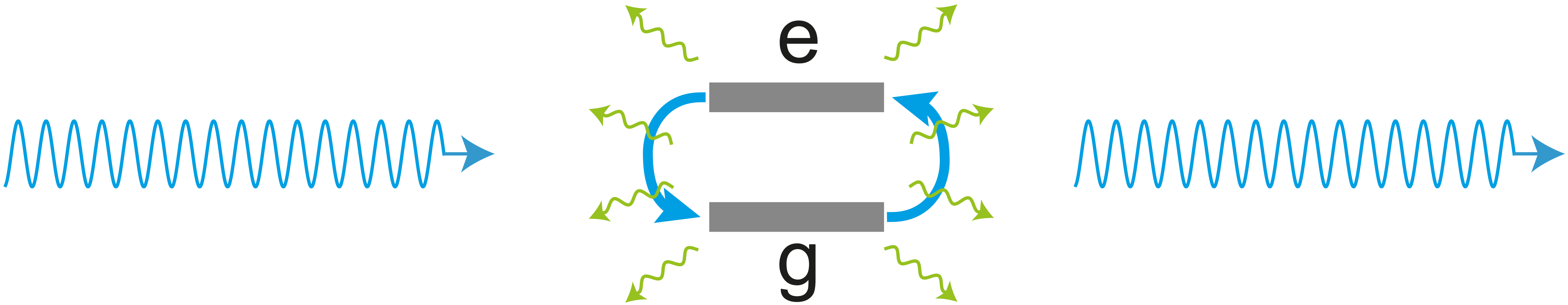
Qubit relaxation
e⟶g

Fluorescence signal
photon emitted at $\omega_q$

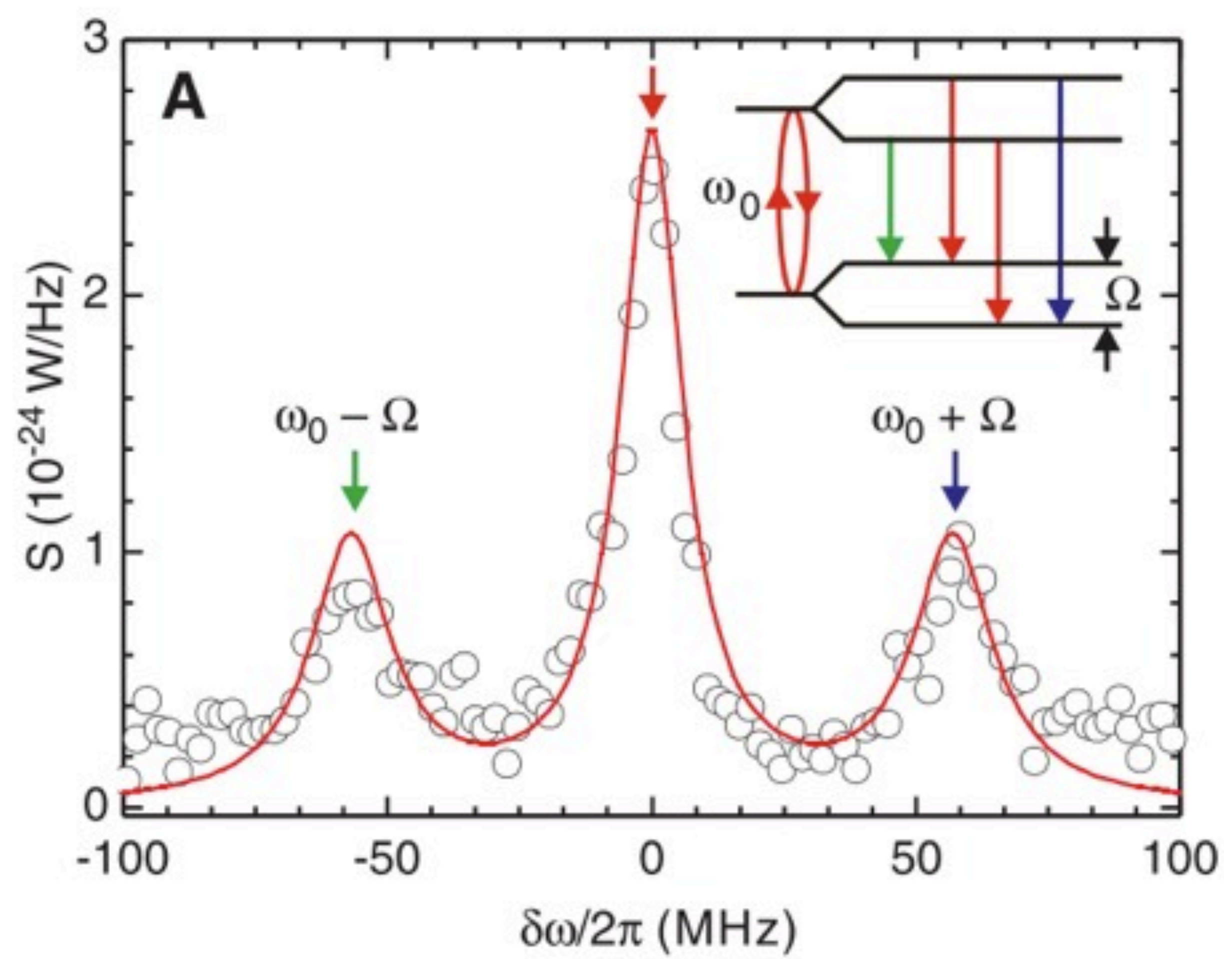



**Energy release can be measured directly**

# Resonance fluorescence in frequency domain




Mollow triplet
in freq. domain
seen in atoms, semiconductors, ...

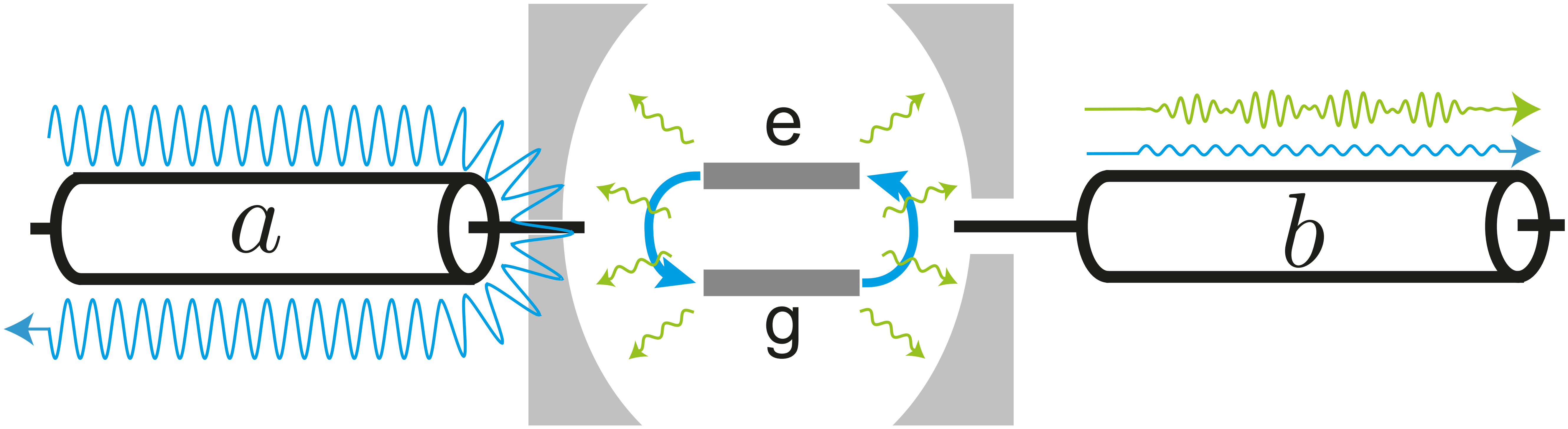



[Astafievev *et al.*, Tsukuba
Science 2010]

**Fluorescence field as a pointer?**

**→ need time domain**

# Resonance fluorescence in time domain




$\nu_{\text{cav}} \approx 8\ \text{GHz}$ $\nu_{\text{q}} \approx 5\ \text{GHz}$ $\Gamma_b \approx 0.25\ \text{MHz}$

$$\langle b_{out} \rangle = \langle b_{out} \rangle_0 - \sqrt{\Gamma_{\text{leak}}} \langle \sigma_- \rangle$$

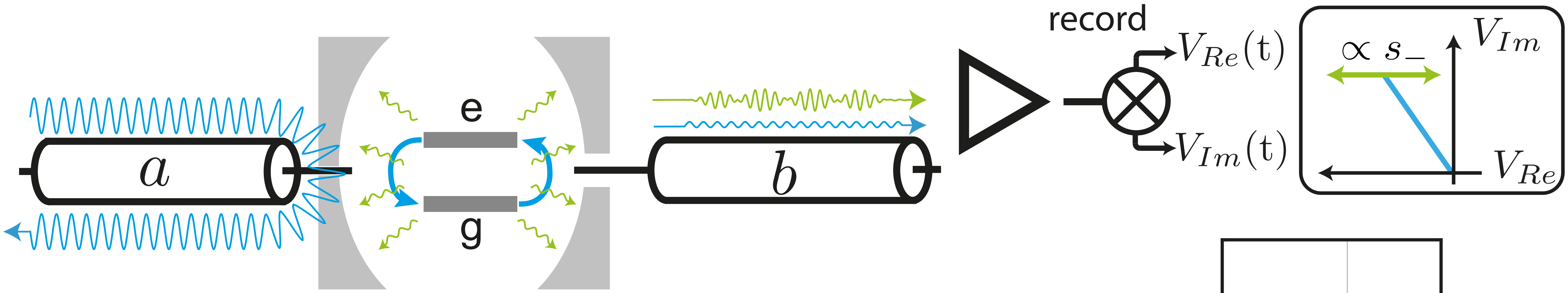
parasitic transmission

spontaneous emission into b line

$$\sigma_- = |g\rangle\langle e| = \frac{\sigma_x - i\sigma_y}{2}$$

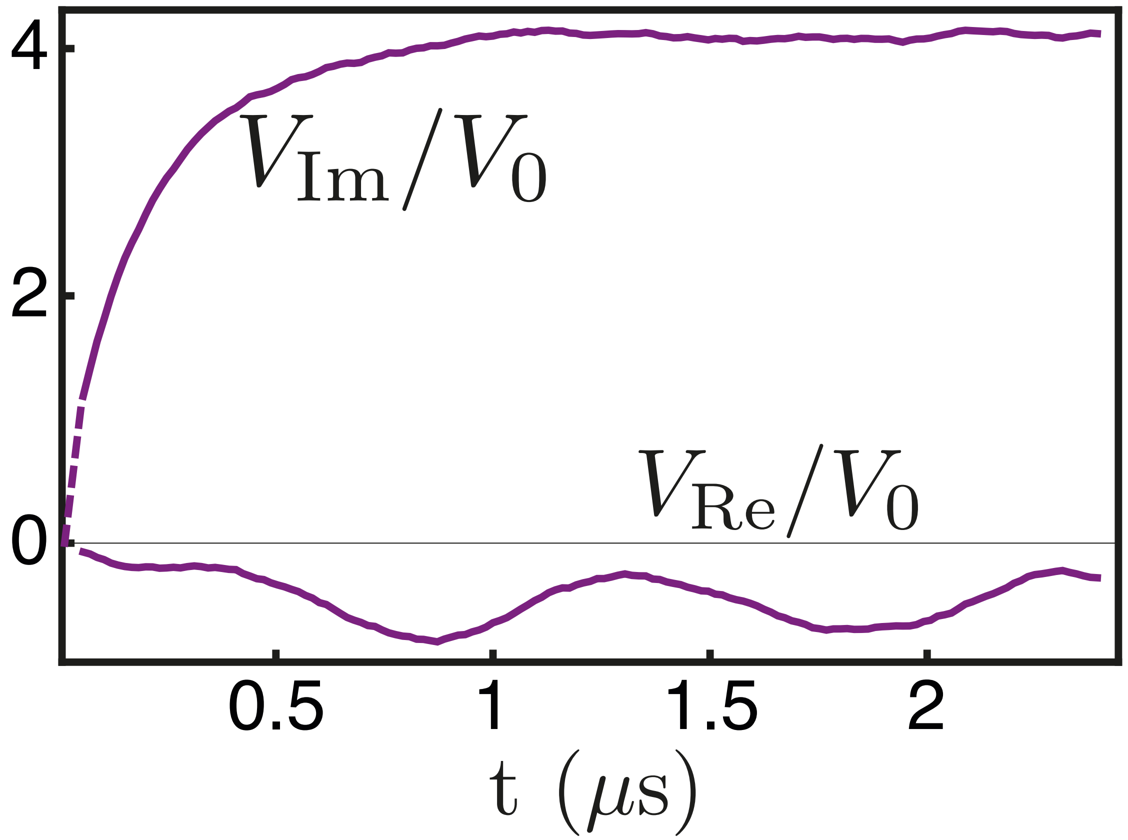
$$\Gamma_{\text{leak}} \approx \frac{1}{50\ \mu\text{s}}$$

# Resonance fluorescence in time domain

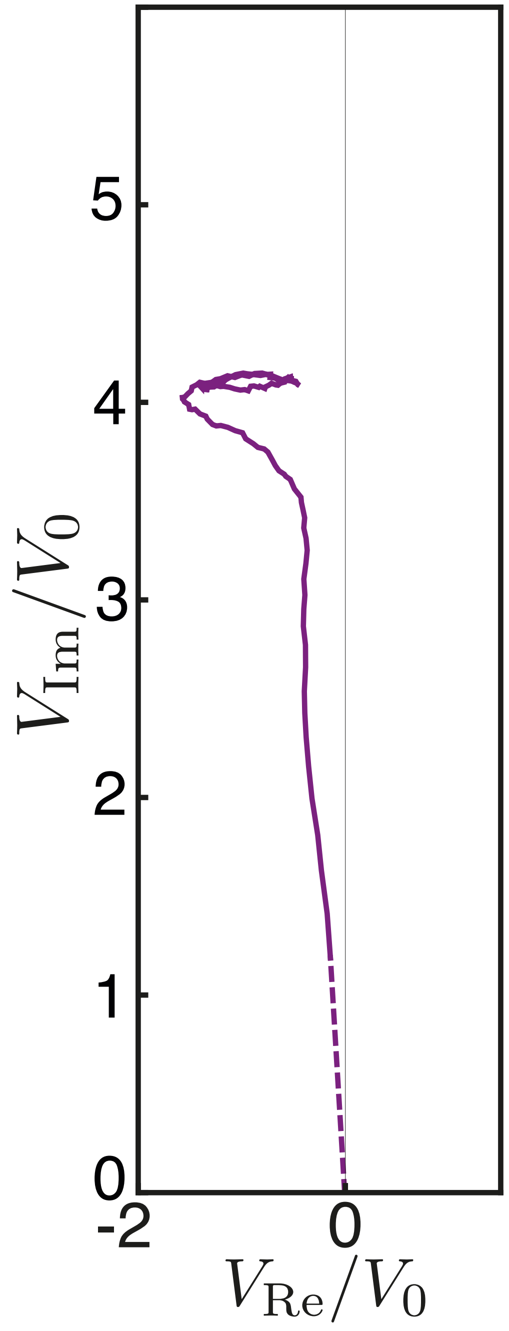



$$\overline{V_{\mathrm{Re}}}(t) = \overline{V_{\mathrm{Re}}^{(0)}}(t) - V_0 \mathrm{Re}\langle \sigma_- \rangle$$

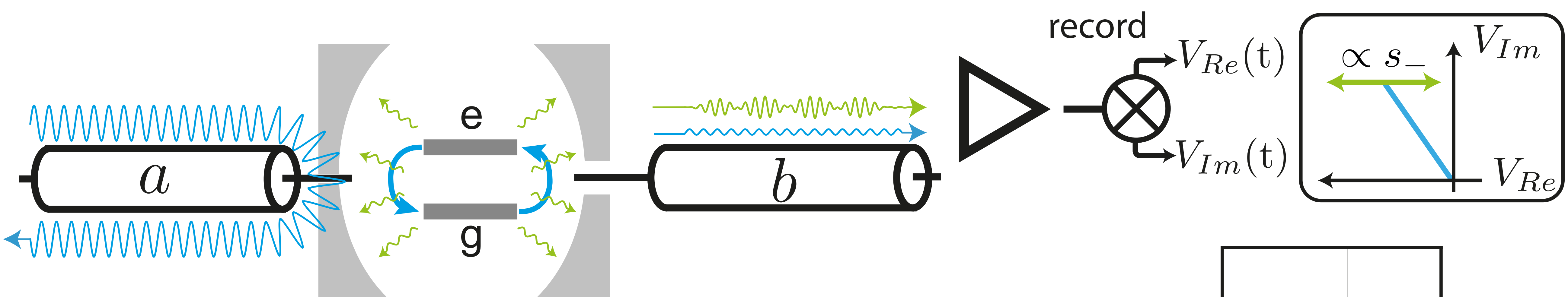
$$\overline{V_{\mathrm{Im}}}(t) = \overline{V_{\mathrm{Im}}^{(0)}}(t) - V_0 \mathrm{Im}\langle \sigma_- \rangle$$




qubit starts in $|g\rangle$

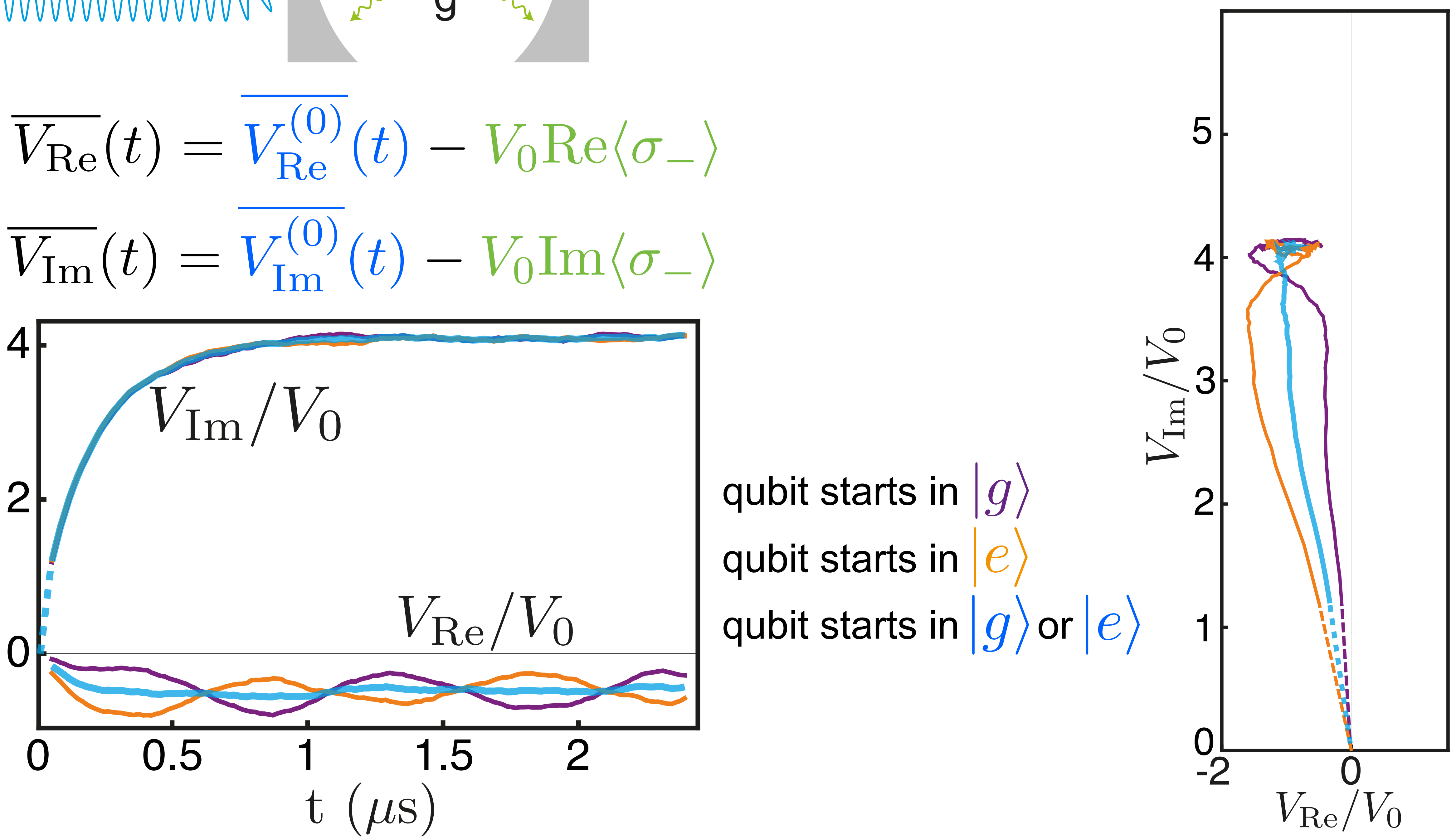


# Resonance fluorescence in time domain

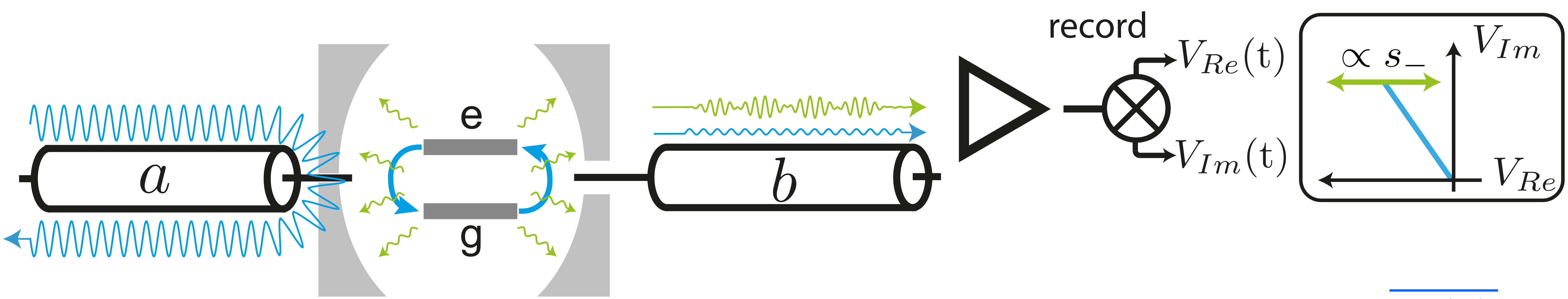



$$\overline{V_{\rm Re}}(t) = \overline{V_{\rm Re}^{(0)}}(t) - V_0 {\rm Re}\langle\sigma_-\rangle$$

$$\overline{V_{\rm Im}}(t) = \overline{V_{\rm Im}^{(0)}}(t) - V_0 {\rm Im}\langle\sigma_-\rangle$$



# Resonance fluorescence in time domain



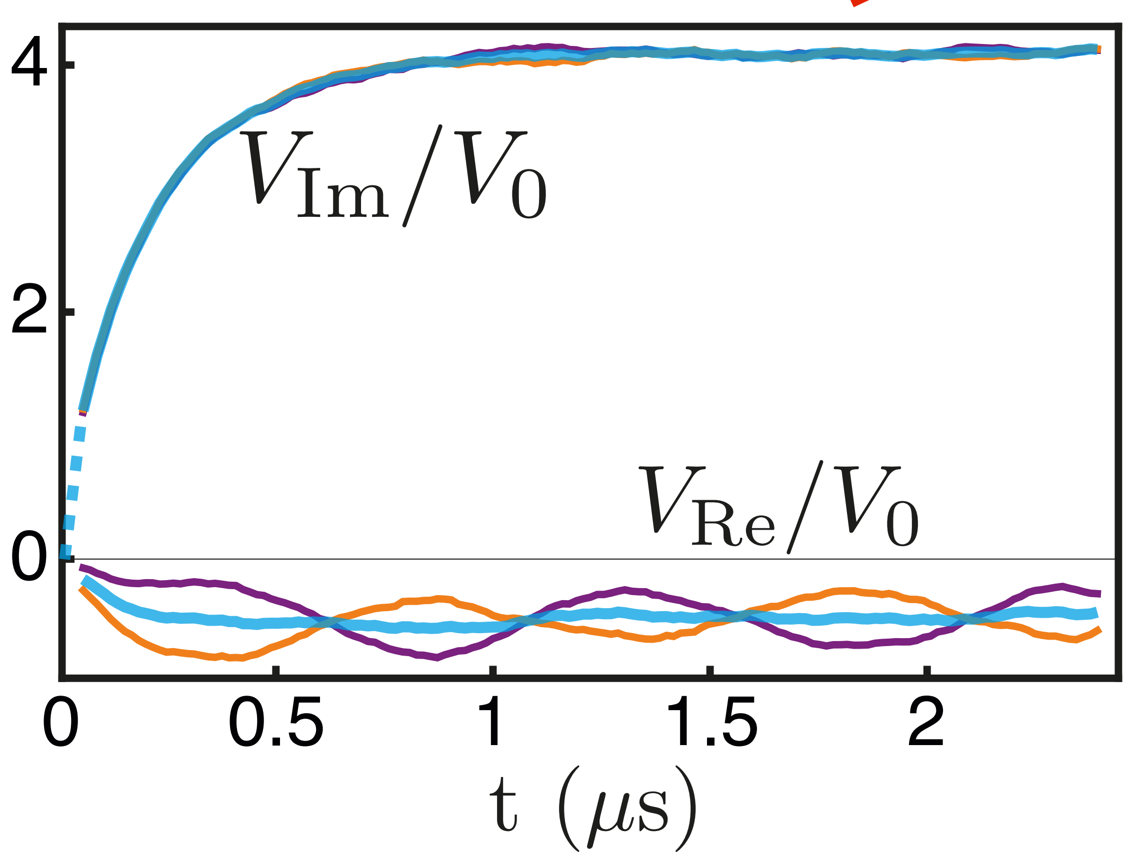

$$\overline{V_{\mathrm{Re}}}(t) = \overline{V_{\mathrm{Re}}^{(0)}}(t) - V_0 \mathrm{Re}\langle \sigma_- \rangle$$

$$\overline{V_{\mathrm{Im}}}(t) = \overline{V_{\mathrm{Im}}^{(0)}}(t) - V_0 \mathrm{Im}\langle \sigma_- \rangle$$

if qubit driven around Y

$$s_-(t) \equiv \frac{V_{\mathrm{Re}}(t) - \overline{V_{\mathrm{Re}}^{(0)}}(t)}{V_0}$$

$$\sigma_- = |g\rangle\langle e| = \frac{\sigma_x - i\sigma_y}{2}$$

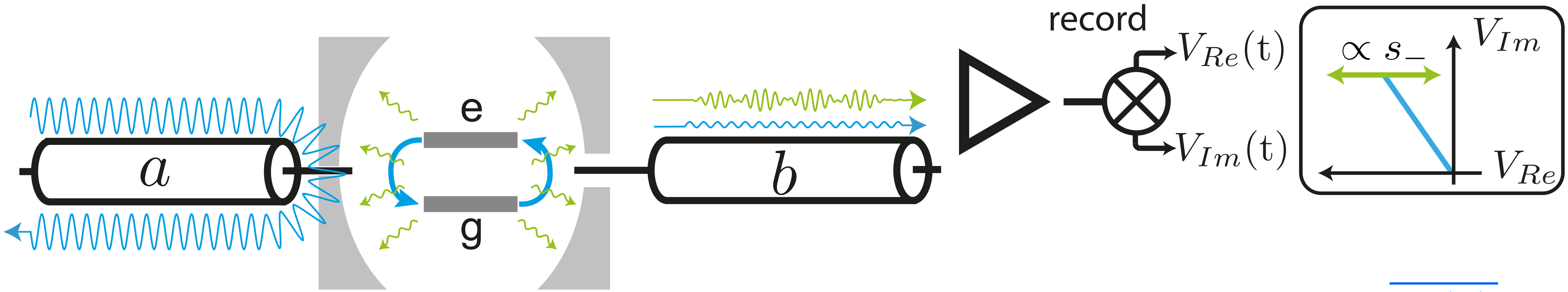



qubit starts in $|g\rangle$

qubit starts in $|e\rangle$

qubit starts in $|g\rangle$ or $|e\rangle$

# Resonance fluorescence in time domain

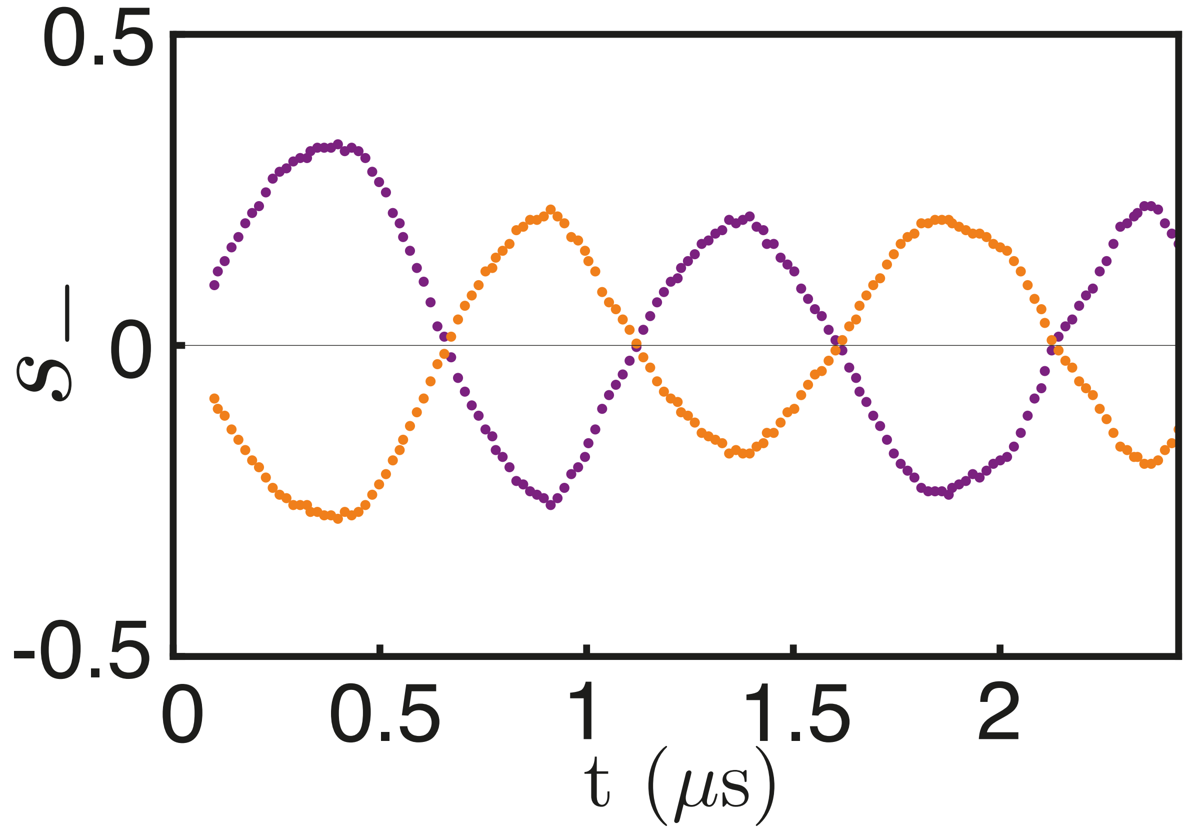



$$\overline{V_{\mathrm{Re}}}(t) = \overline{V_{\mathrm{Re}}^{(0)}}(t) - V_0 \mathrm{Re}\langle\sigma_-\rangle$$

$$s_-(t) \equiv \frac{V_{\mathrm{Re}}(t) - \overline{V_{\mathrm{Re}}^{(0)}}(t)}{V_0}$$

$$\overline{V_{\mathrm{Im}}}(t) = \overline{V_{\mathrm{Im}}^{(0)}}(t) - V_0 \mathrm{Im}\langle\sigma_-\rangle$$

if qubit driven around Y

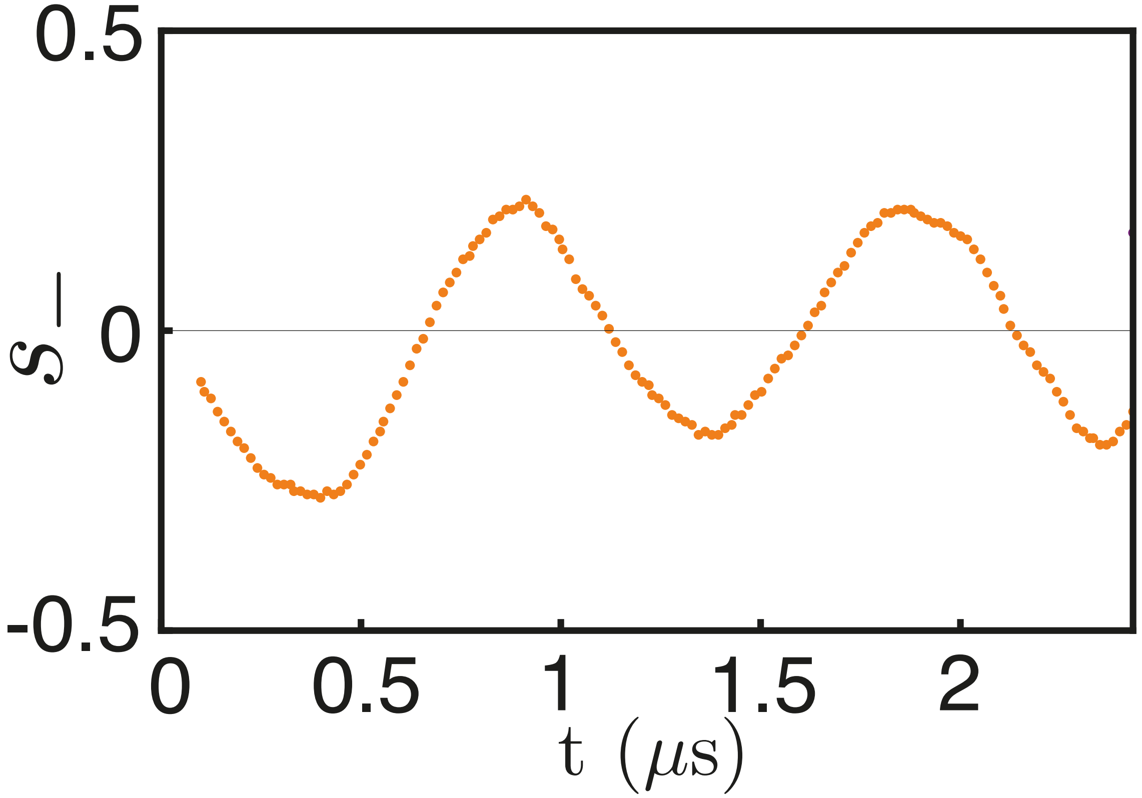


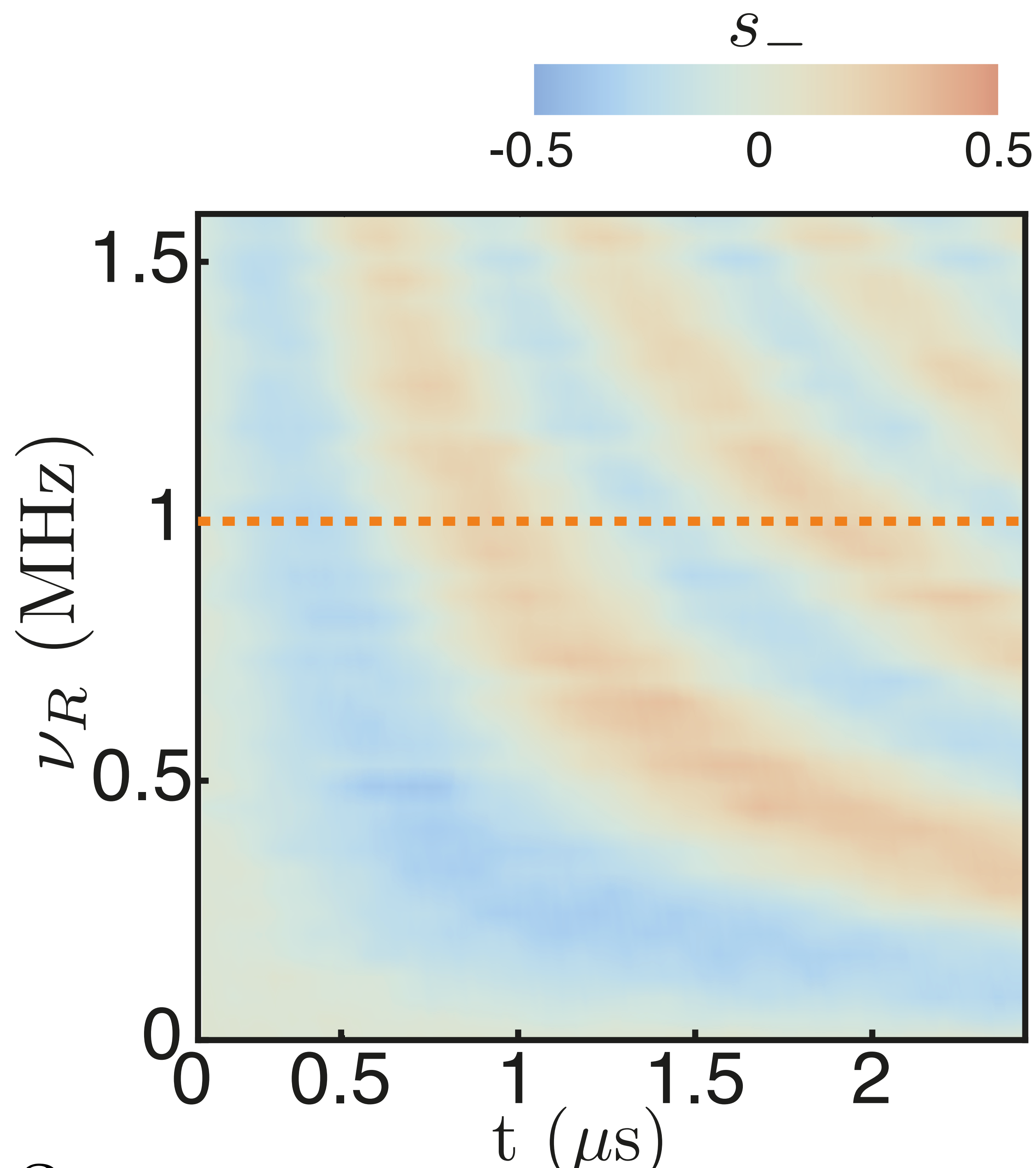

qubit starts in $|g\rangle$

qubit starts in $|e\rangle$

# Resonance fluorescence in time domain

$$s_-(t) \equiv \frac{V_{\mathrm{Re}}(t) - \overline{V_{\mathrm{Re}}^{(0)}(t)}}{V_0}$$

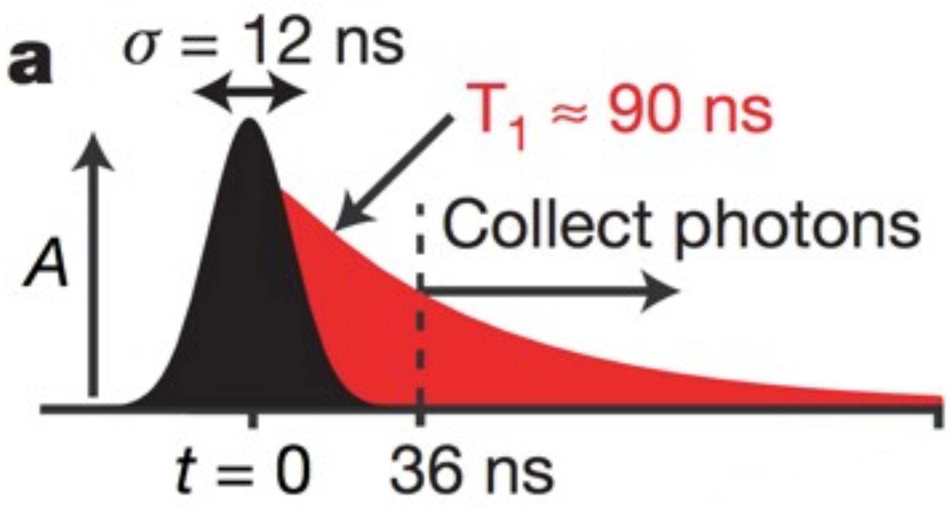


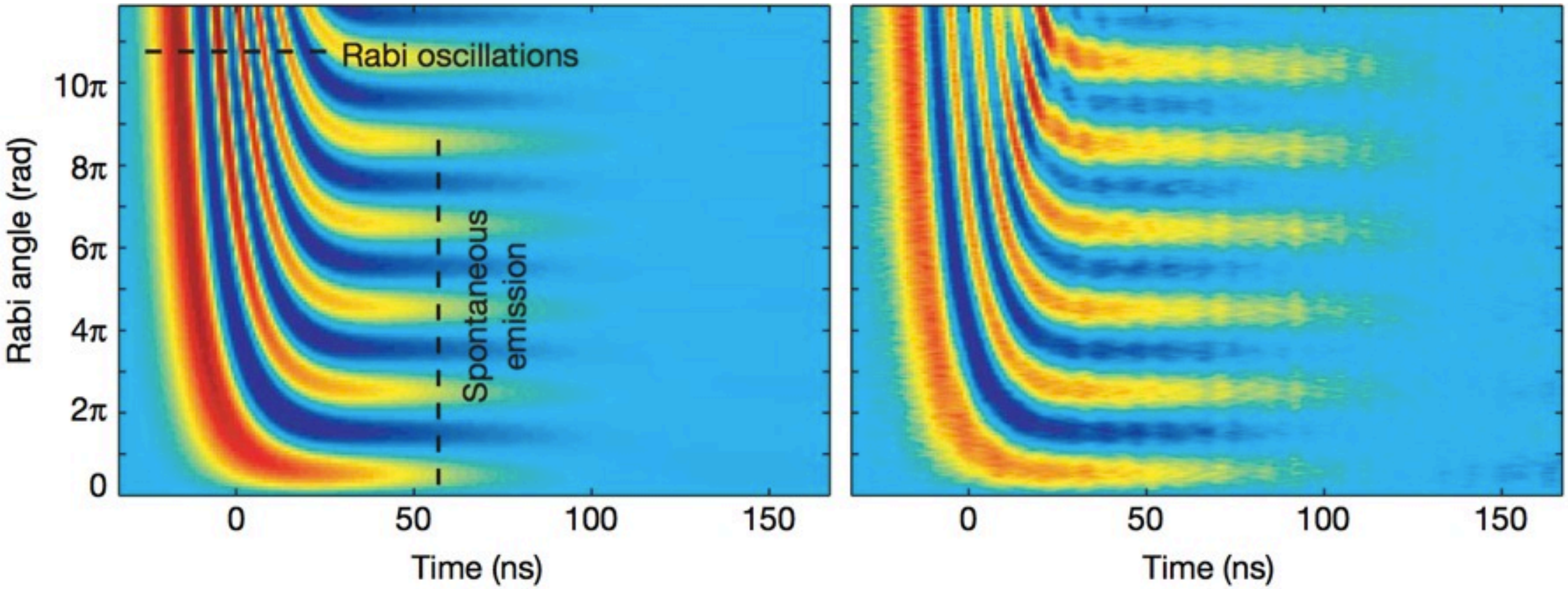

$$\overline{s_-}(t) = \mathrm{Re}\langle\sigma_-(t)\rangle ?$$

# Resonance fluorescence in time domain

Similar oscillations were observed with pulsed driving in 2007




[Houck et al., Yale University, Nature 2007]



# Master equation

$$\mathrm{Re}\langle\sigma_-(t)\rangle = \frac{\langle\sigma_x(t)\rangle}{2} = \frac{\mathrm{Tr}(\sigma_x\rho(\mathbf{t}))}{2}$$


$$\rho(\mathbf{0}) \longrightarrow \rho(\mathbf{t})$$

$$\rho(\mathbf{0}) = 0.85|e\rangle\langle e| + 0.15|g\rangle\langle g|$$

Preparation

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}\left[\tilde{H},\rho\right] + \gamma_1\left(\sigma_-\rho\sigma_+ - \frac{1}{2}\left[\sigma_+\sigma_-\rho + \rho\sigma_+\sigma_-\right]\right)$$

Dynamics

$$\tilde{H} = \frac{1}{2}h\nu_q\sigma_z + \frac{1}{2}h\nu_R\sigma_y$$

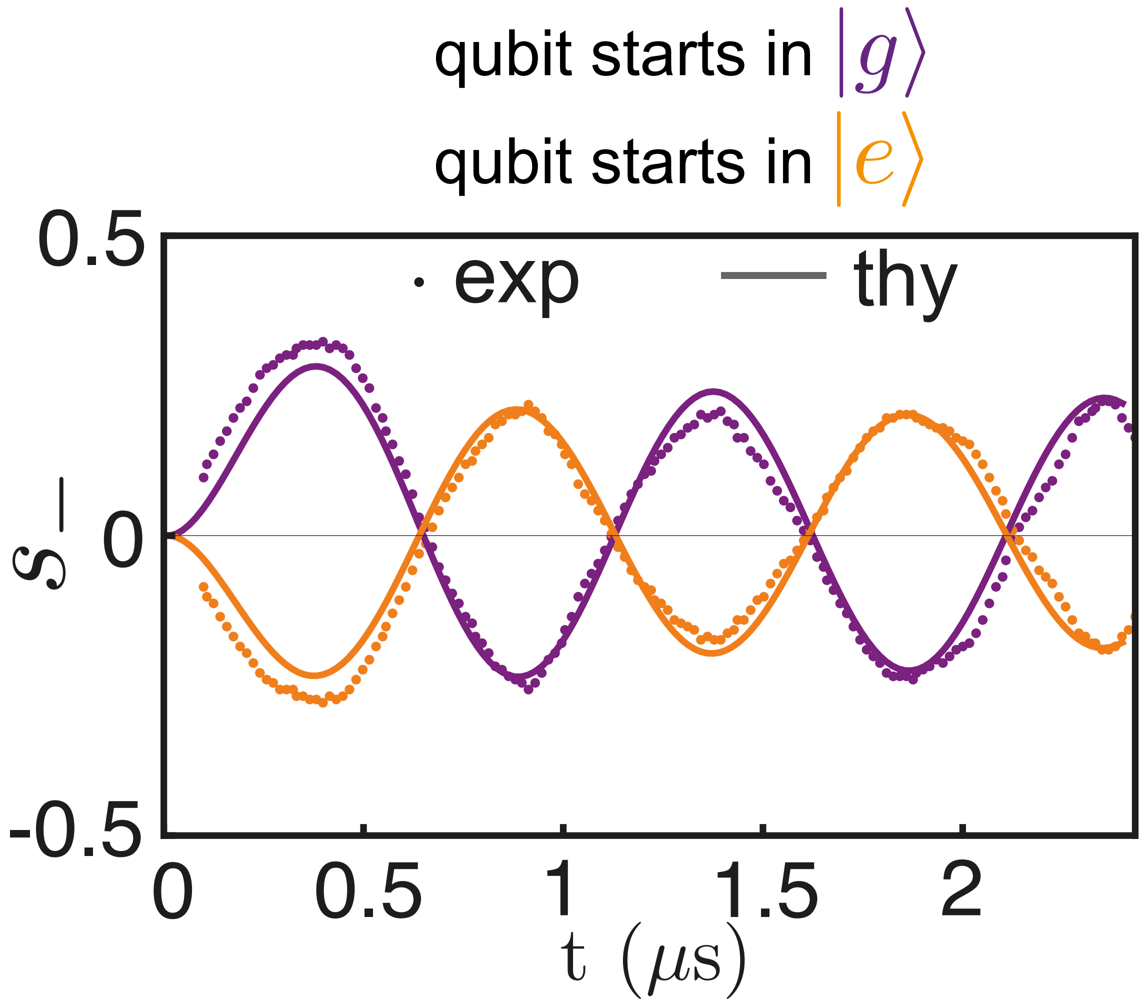
drive

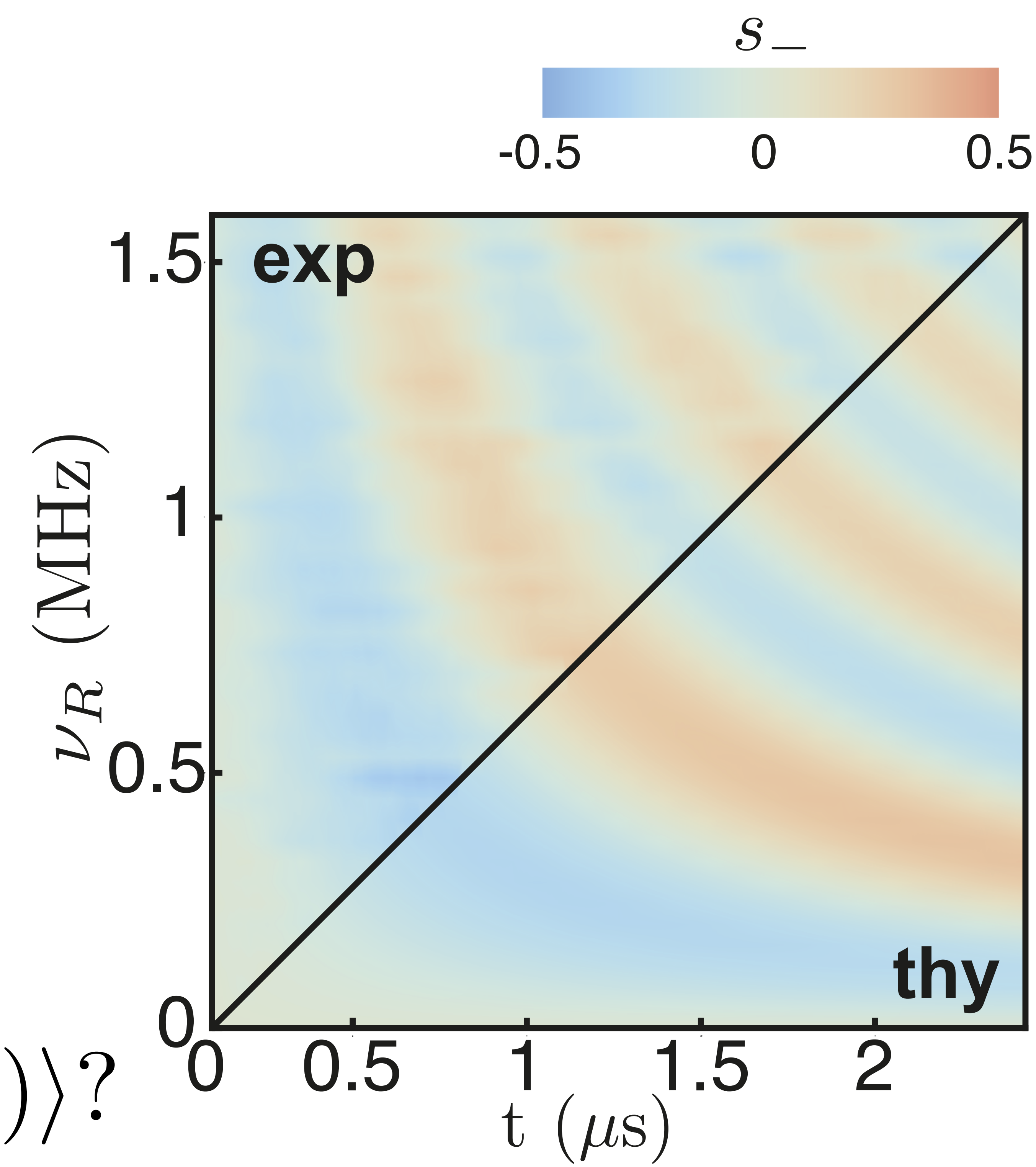
qubit relaxation $\frac{1}{\gamma_1} = 16\ \mu\mathrm{s}$

[Lindblad 1976]

# Resonance fluorescence in time domain

$$s_-(t) \equiv \frac{V_{\mathrm{Re}}(t) - \overline{V_{\mathrm{Re}}^{(0)}}(t)}{V_0}$$



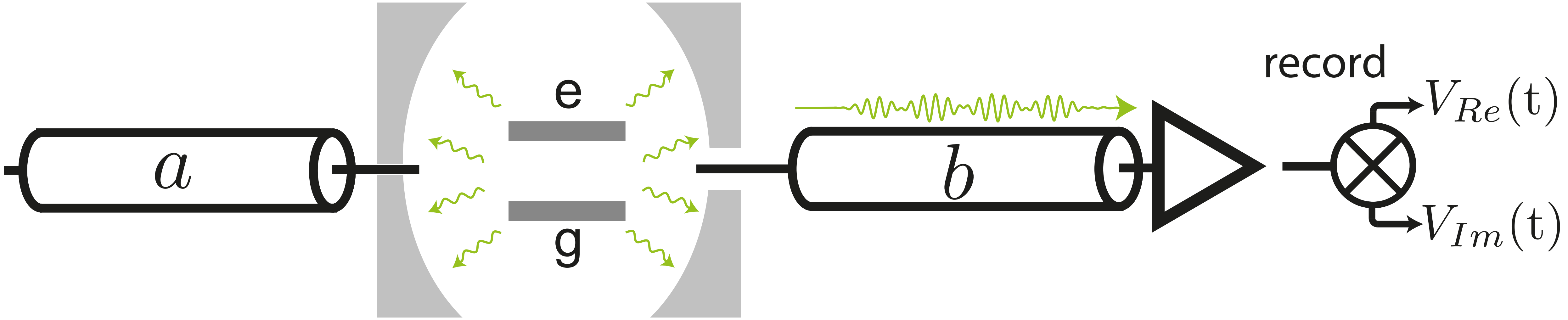



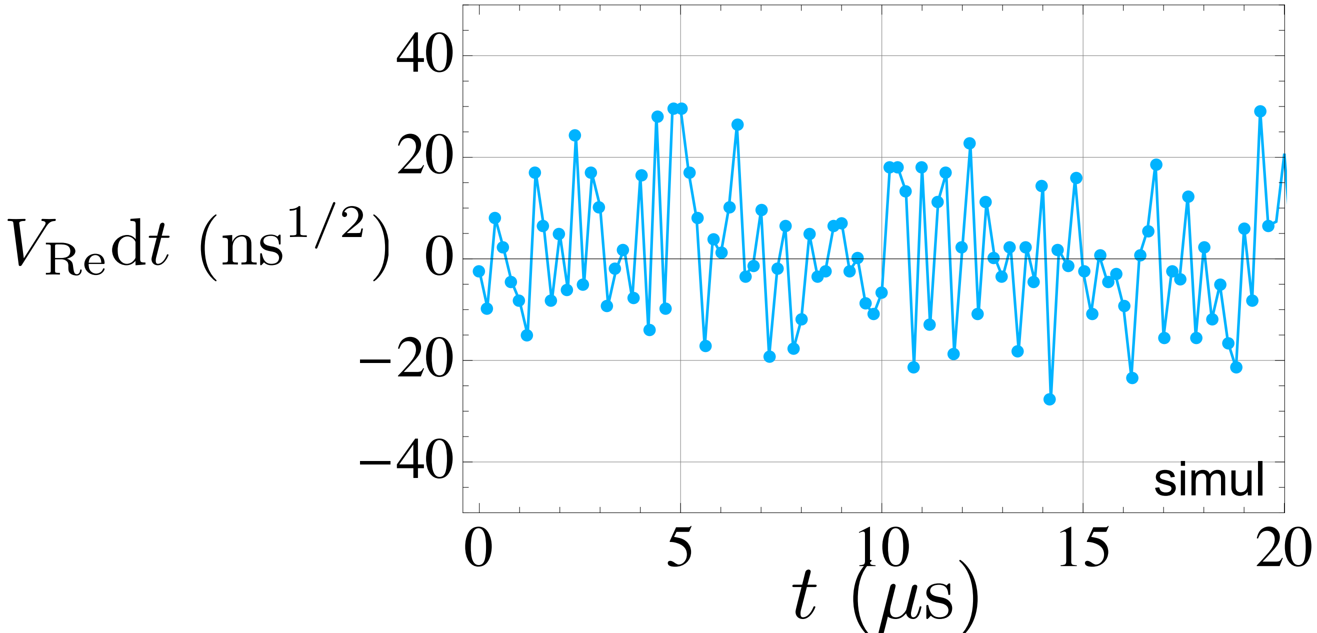

$$\overline{s_-}(t) = \mathrm{Re}\langle \sigma_-(t) \rangle ?$$

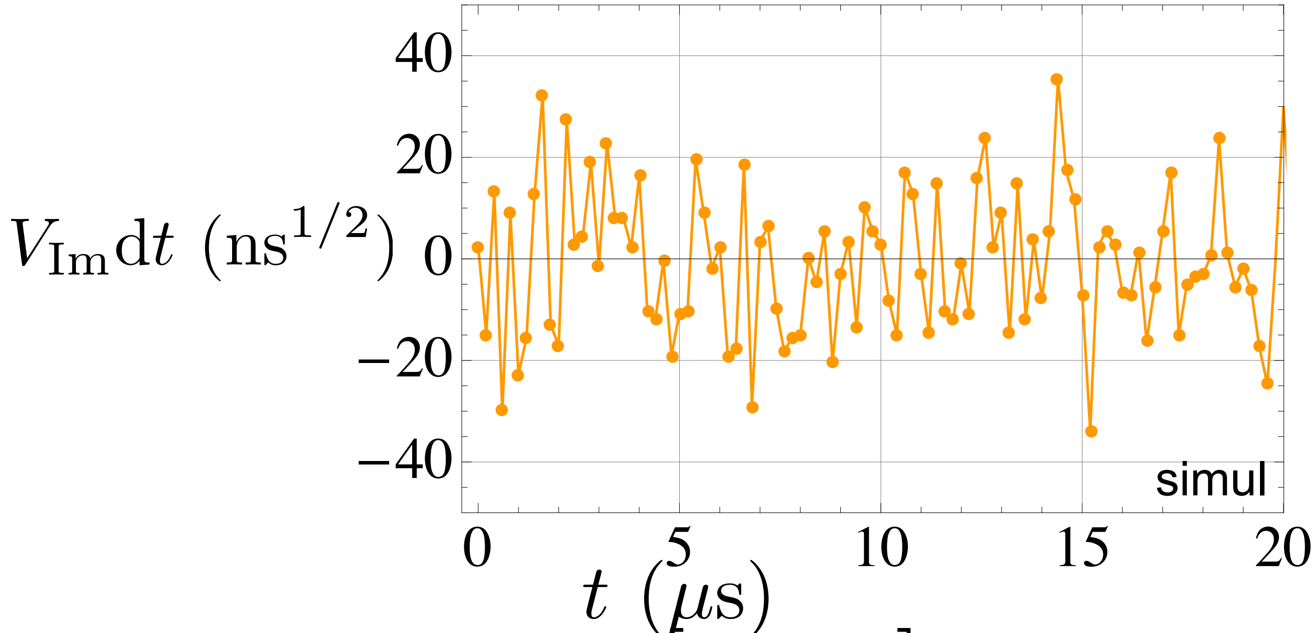
Yes if considering the 1.6 MHz detector bandwidth

# Fluorescence of single realizations

What can be said about single realizations?



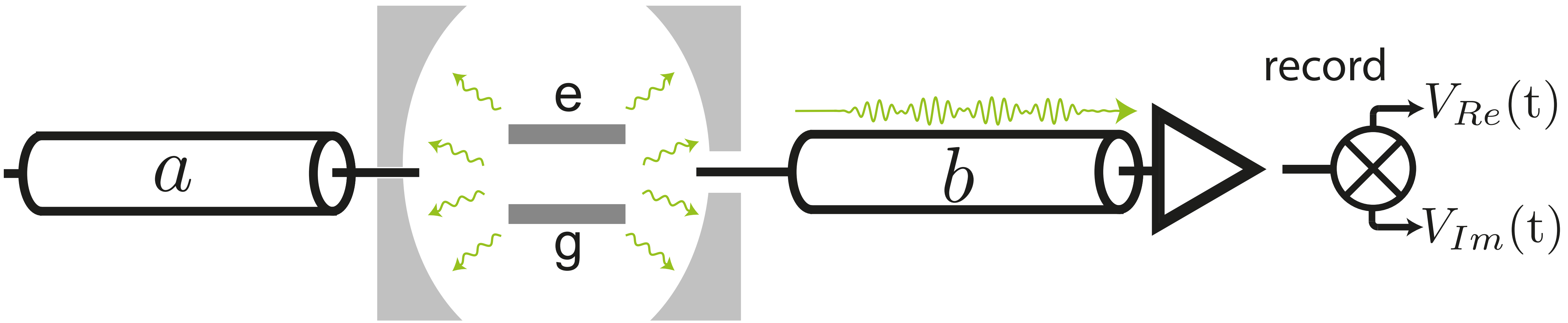




Knowing a given measurement record on $t \in [0, t_M]$
predict the result of a strong measurement that follows

Similar experiment: record weak meas of $\sigma_z$ [Murch et al., Berkeley Group, Nature 2013]

# Fluorescence of single realizations

What can be said about single realizations?




if $\rho(t)$ is known,
$$V_{\mathrm{Re}}(t)\mathrm{d}t = \sqrt{\eta\Gamma_{\mathrm{leak}}/2}\mathrm{Tr}\left(\sigma_X\rho\right)\mathrm{d}t + \mathrm{d}W_{\mathrm{Re}}$$
$$V_{\mathrm{Im}}(t)\mathrm{d}t = \sqrt{\eta\Gamma_{\mathrm{leak}}/2}\mathrm{Tr}\left(\sigma_Y\rho\right)\mathrm{d}t + \mathrm{d}W_{\mathrm{Im}}$$

average outcome

noise (Wiener)

detection efficiency $0 \leq \eta \leq 1$

$$\overline{\mathrm{d}W} = 0$$
$$\mathrm{d}W^2 = \mathrm{d}t$$

# Fluorescence of single realizations

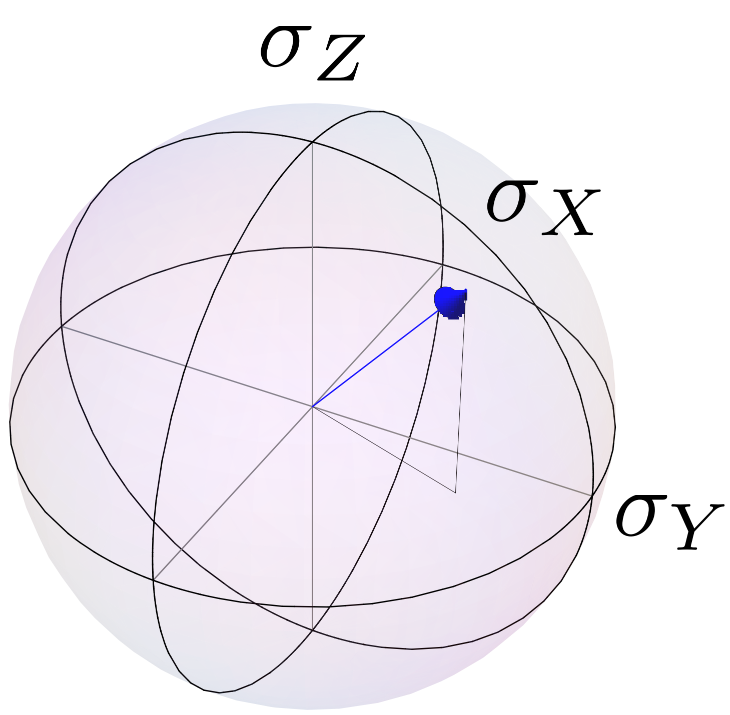
What can be said about single realizations?

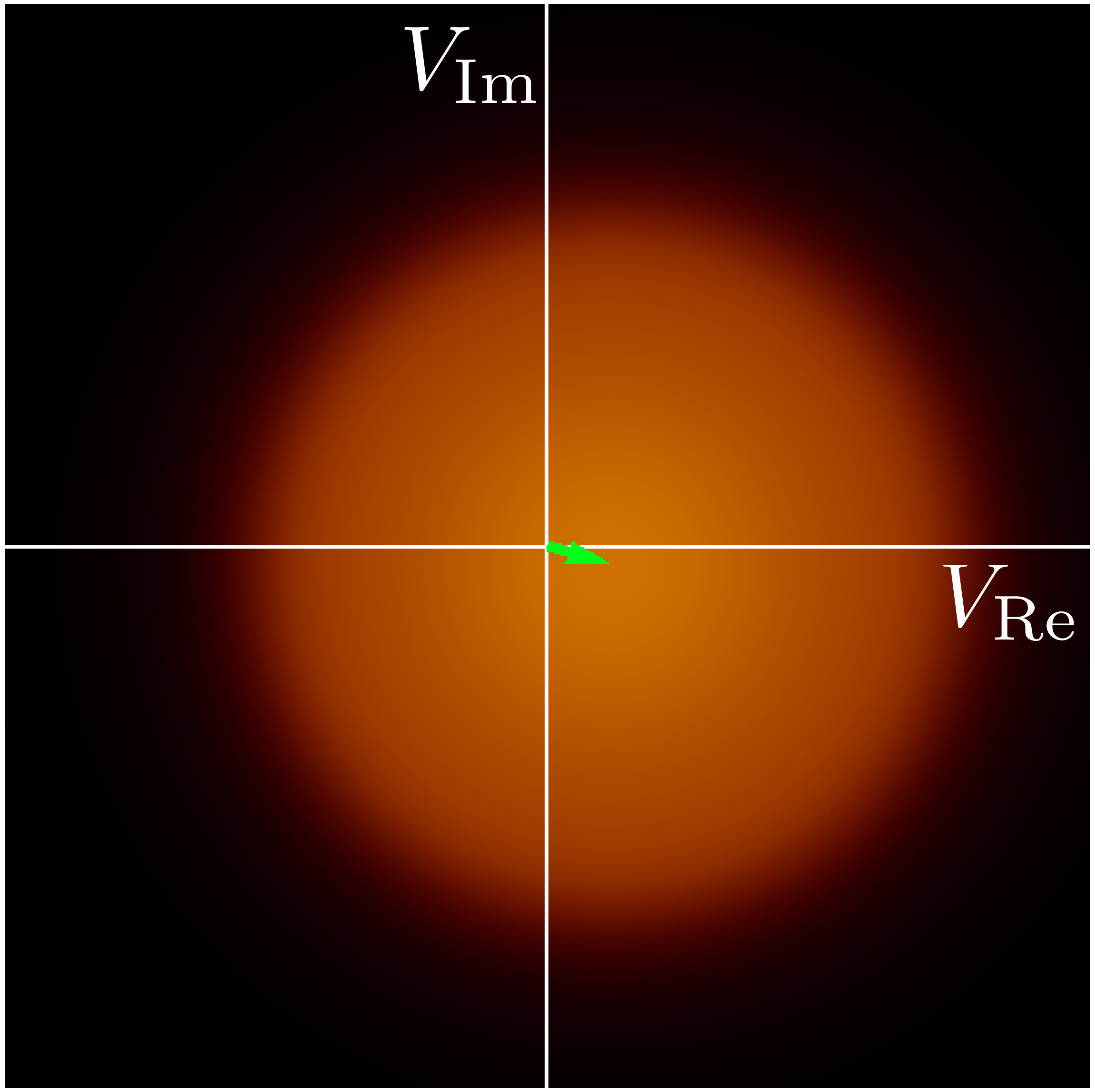
if $\rho(t)$ is known,

$$V_{\mathrm{Re}}(t)\mathrm{d}t = \sqrt{\eta\Gamma_{\mathrm{leak}}/2}\mathrm{Tr}\left(\sigma_X\rho\right)\mathrm{d}t + \mathrm{d}W_{\mathrm{Re}}$$
$$V_{\mathrm{Im}}(t)\mathrm{d}t = \sqrt{\eta\Gamma_{\mathrm{leak}}/2}\mathrm{Tr}\left(\sigma_Y\rho\right)\mathrm{d}t + \mathrm{d}W_{\mathrm{Im}}$$

average outcome

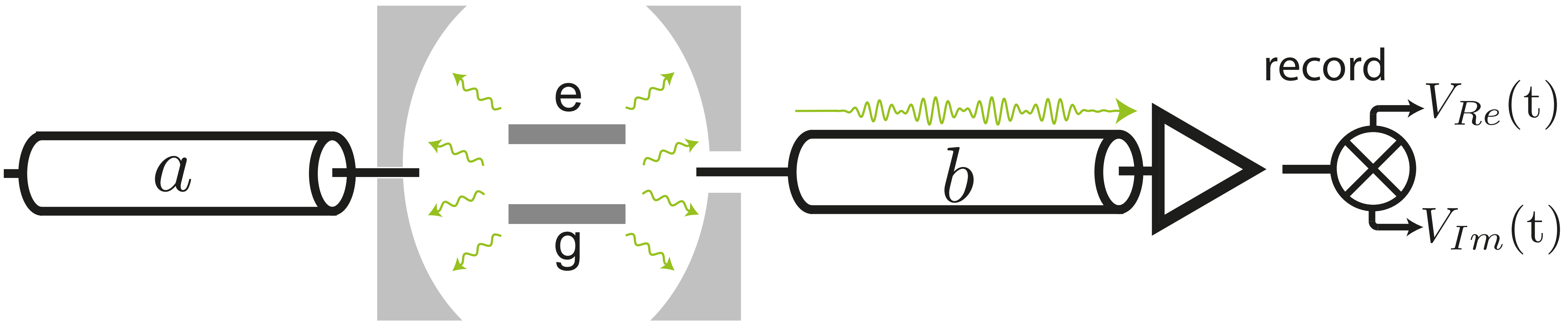
noise (Wiener)



# Fluorescence of single realizations

What can be said about single realizations?

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$$V_{\mathrm{Im}}(t)\mathrm{d}t = \sqrt{\eta\Gamma_{\mathrm{leak}}/2}\mathrm{Tr}\left(\sigma_Y\rho\right)\mathrm{d}t + \mathrm{d}W_{\mathrm{Im}}$$

average outcome

noise (Wiener)

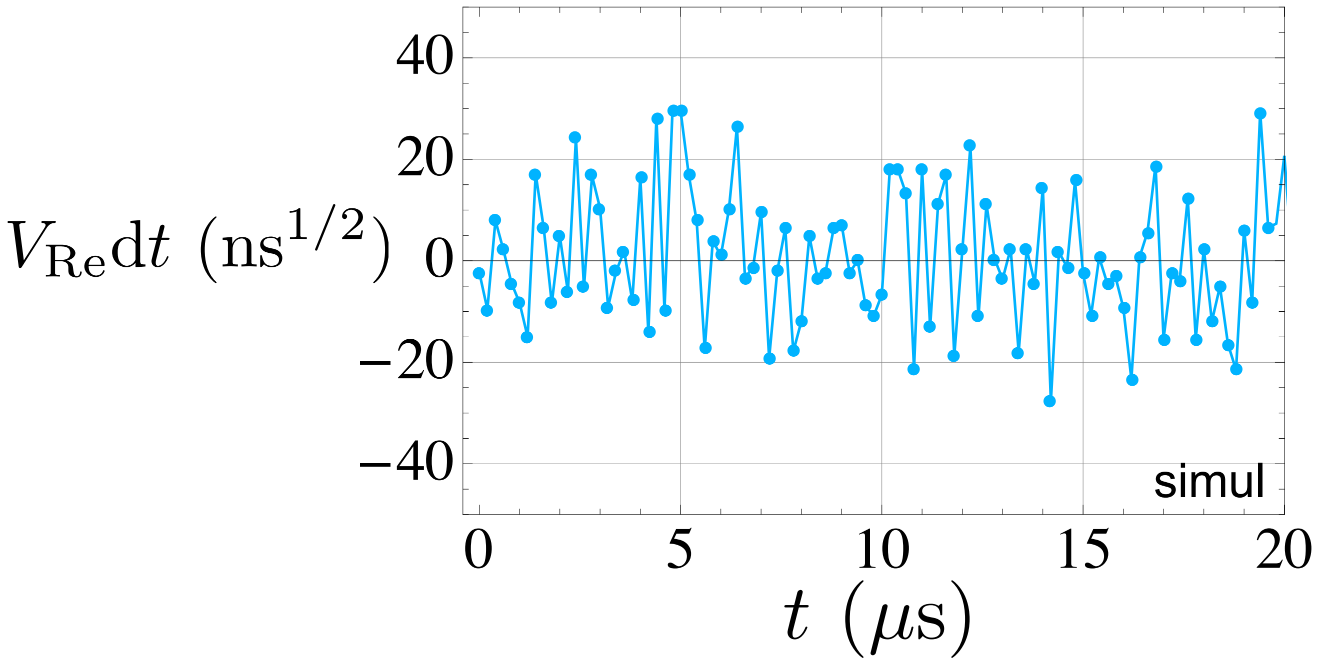
$$\mathrm{d}\rho = -\frac{i}{\hbar}[H,\rho]\mathrm{d}t + \Gamma_{\mathrm{leak}}\left(\sigma_-\rho\sigma_+ - \frac{\sigma_+\sigma_-\rho + \rho\sigma_+\sigma_-}{2}\right)\mathrm{d}t$$

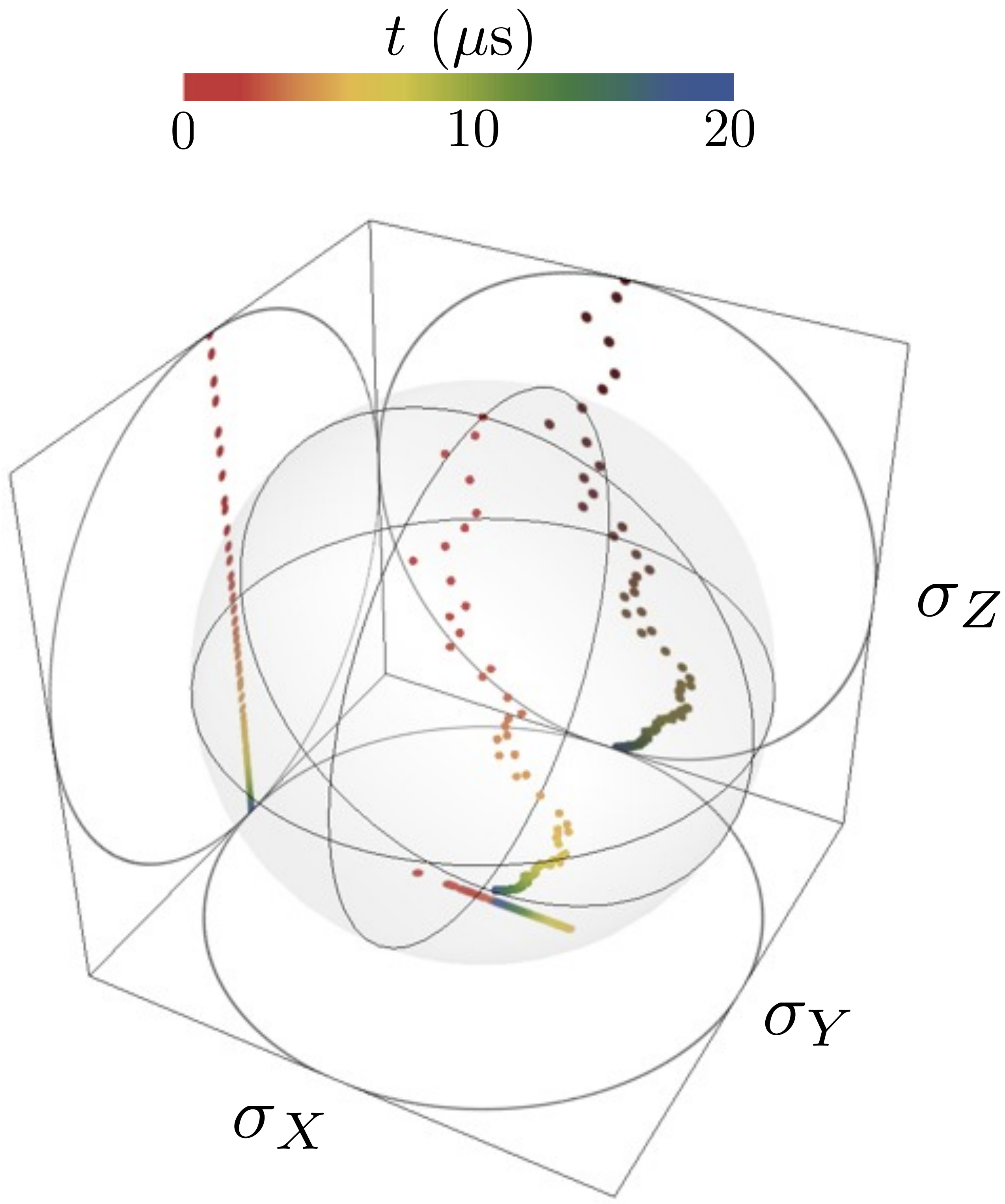
unconditional evolution

$$+\sqrt{\eta\Gamma_{\mathrm{leak}}/2}\left(\sigma_-\rho + \rho\sigma_+ - \mathrm{Tr}\left(\sigma_X\rho\right)\rho\right)\mathrm{d}W_{\mathrm{Re}}$$
$$+\sqrt{\eta\Gamma_{\mathrm{leak}}/2}\left(\sigma_-\rho + \rho\sigma_+ - \mathrm{Tr}\left(\sigma_Y\rho\right)\rho\right)\mathrm{d}W_{\mathrm{Im}}$$

record is plugged here

# Fluorescence of single realizations




Simulation starting in $|e\rangle$

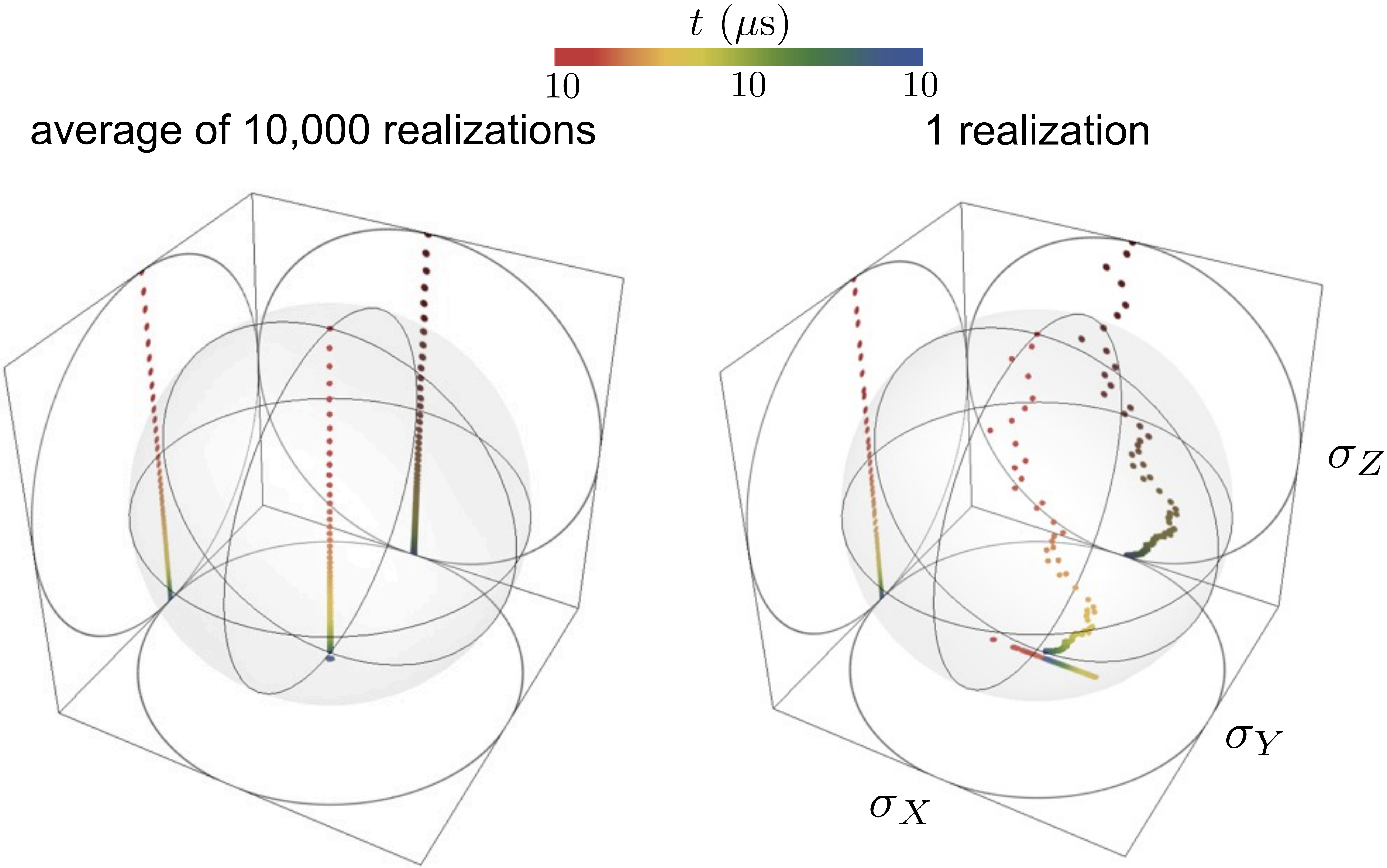
Considering only $V_{\mathrm{Re}}$

$$\eta = 0.3$$

$$\mathrm{d}t = 200\ \mathrm{ns}$$

$\Gamma_{\mathrm{leak}}^{-1} = 3.865\ \mu\mathrm{s}$ $\Gamma_{\varphi}^{-1} = 40.85\ \mu\mathrm{s}$

# Fluorescence of single realizations

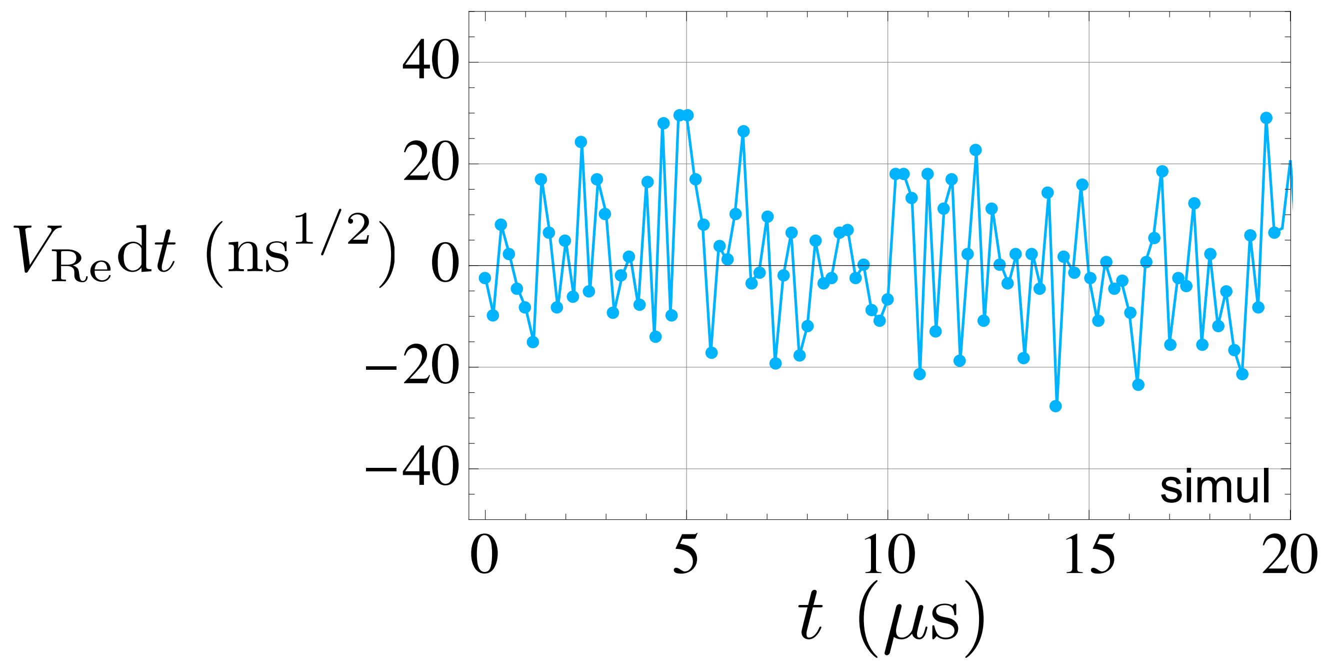


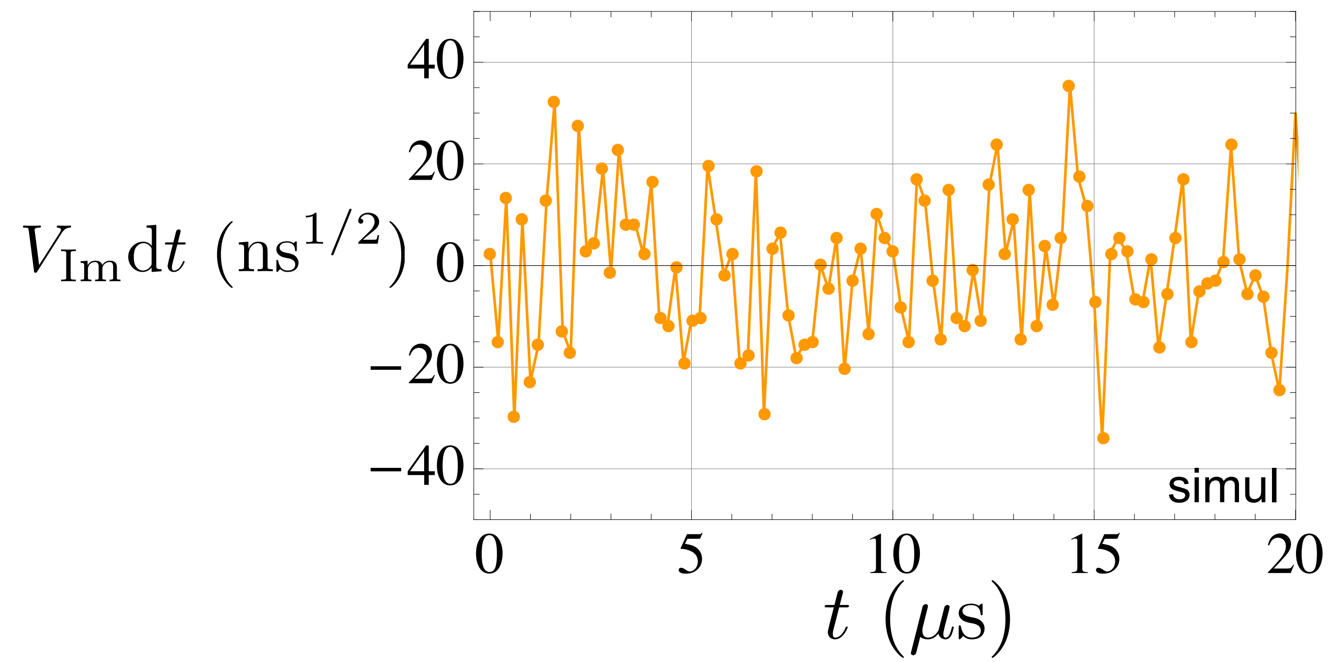
# Experimental verification

How to check that prediction on $\rho(t)$?

Measure $\langle\sigma_X\rangle$, $\langle\sigma_Y\rangle$, $\langle\sigma_Z\rangle$ for a given trace $\{V_{\rm Re}(t), V_{\rm Im}(t)\}$

Problem: ∞ time to get the same traces many times



# Reproducible quantity

How to check that prediction on $\rho(t)$?

Measure $\langle\sigma_X\rangle$, $\langle\sigma_Y\rangle$, $\langle\sigma_Z\rangle$ for a given trace $\{V_{\mathrm{Re}}(t), V_{\mathrm{Im}}(t)\}$

Problem: ∞ time to get the same traces many times

One solution

$$\zeta_X \equiv \frac{\langle\sigma_X\rangle_\rho}{1+\langle\sigma_Z\rangle_\rho} \qquad \zeta_Y \equiv \frac{\langle\sigma_Y\rangle_\rho}{1+\langle\sigma_Z\rangle_\rho}$$

$$e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)t/2}\zeta_X(t) - \zeta_X(0) = \sqrt{\frac{\eta}{2}\Gamma_{\mathrm{leak}}}\int_0^t e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)\tau/2} V_{\mathrm{Re}}\,\mathrm{d}\tau$$

measured traces

$$e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)t/2}\zeta_Y(t) - \zeta_Y(0) = \sqrt{\frac{\eta}{2}\Gamma_{\mathrm{leak}}}\int_0^t e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)\tau/2} V_{\mathrm{Im}}\,\mathrm{d}\tau$$

# Reproducible quantity

How to check that prediction on $\rho(t)$?

Measure $\langle\sigma_X\rangle$, $\langle\sigma_Y\rangle$, $\langle\sigma_Z\rangle$ for a given trace $\{V_{\mathrm{Re}}(t), V_{\mathrm{Im}}(t)\}$

Problem: ∞ time to get the same traces many times

One solution

$$\zeta_X \equiv \frac{\langle\sigma_X\rangle_\rho}{1+\langle\sigma_Z\rangle_\rho} \qquad \zeta_Y \equiv \frac{\langle\sigma_Y\rangle_\rho}{1+\langle\sigma_Z\rangle_\rho}$$

$m_X(t)$

$$e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)t/2}\zeta_X(t) - \zeta_X(0) = \sqrt{\frac{\eta}{2}\Gamma_{\mathrm{leak}}}\int_0^t e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)\tau/2} V_{\mathrm{Re}}\,\mathrm{d}\tau$$

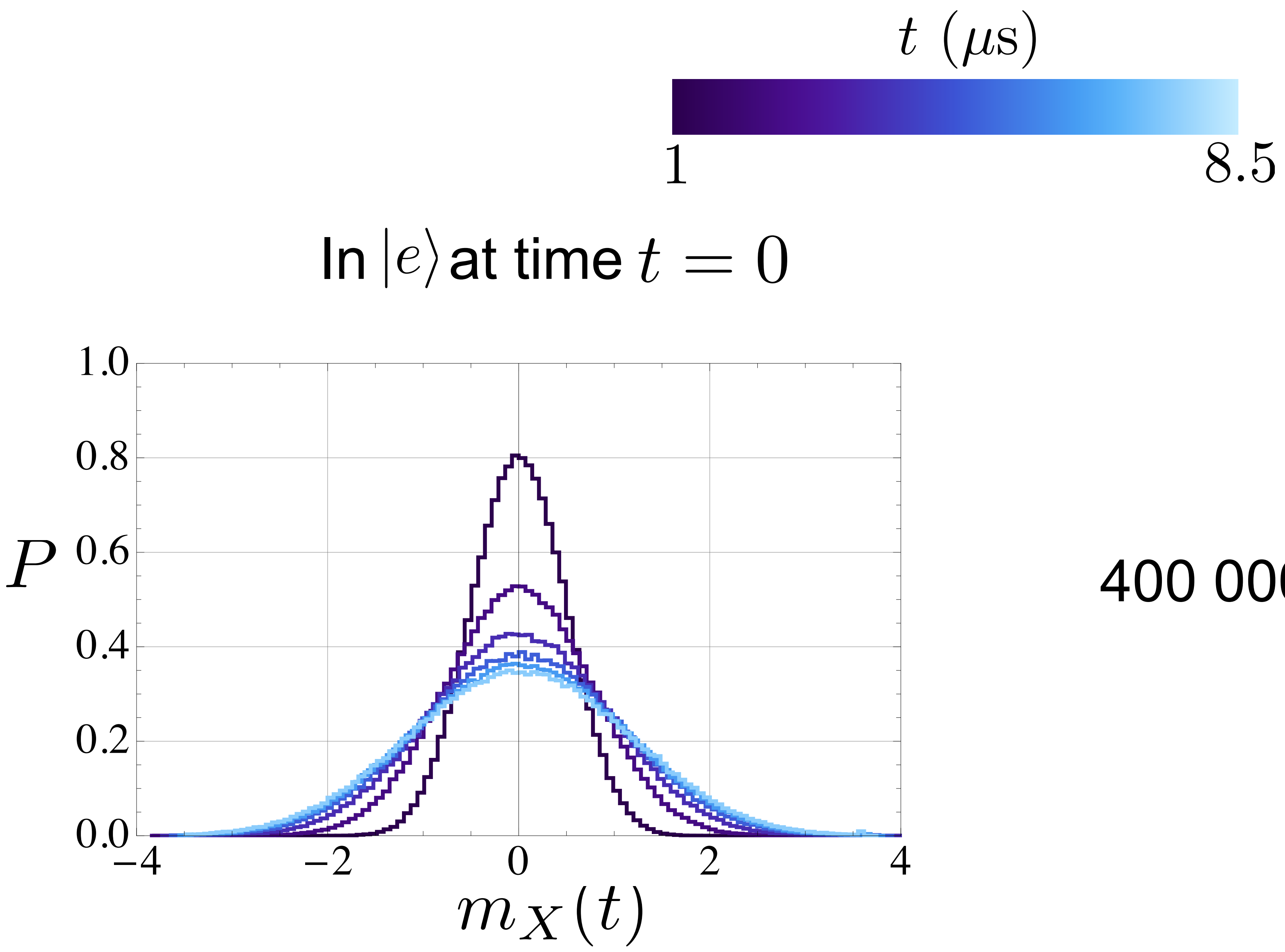
$$e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)t/2}\zeta_Y(t) - \zeta_Y(0) = \sqrt{\frac{\eta}{2}\Gamma_{\mathrm{leak}}}\int_0^t e^{-(\Gamma_{\mathrm{leak}}-2\Gamma_\varphi)\tau/2} V_{\mathrm{Im}}\,\mathrm{d}\tau$$

$m_Y(t)$

# Distribution of m's

$\Gamma_{\text{leak}}^{-1} = 3.865\ \mu\text{s} \qquad \Gamma_{\varphi}^{-1} = 40.85\ \mu\text{s}$

In $|e\rangle$ at time $t = 0$

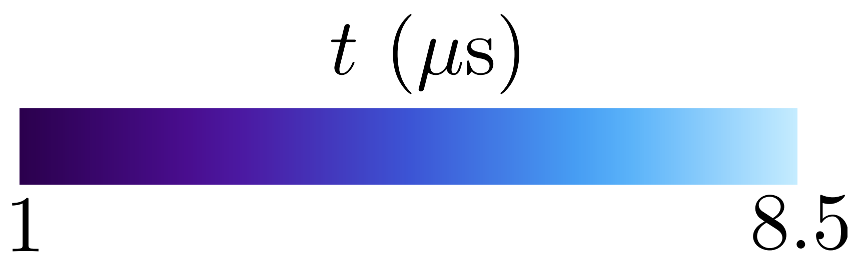



400 000 experiments at each $t$

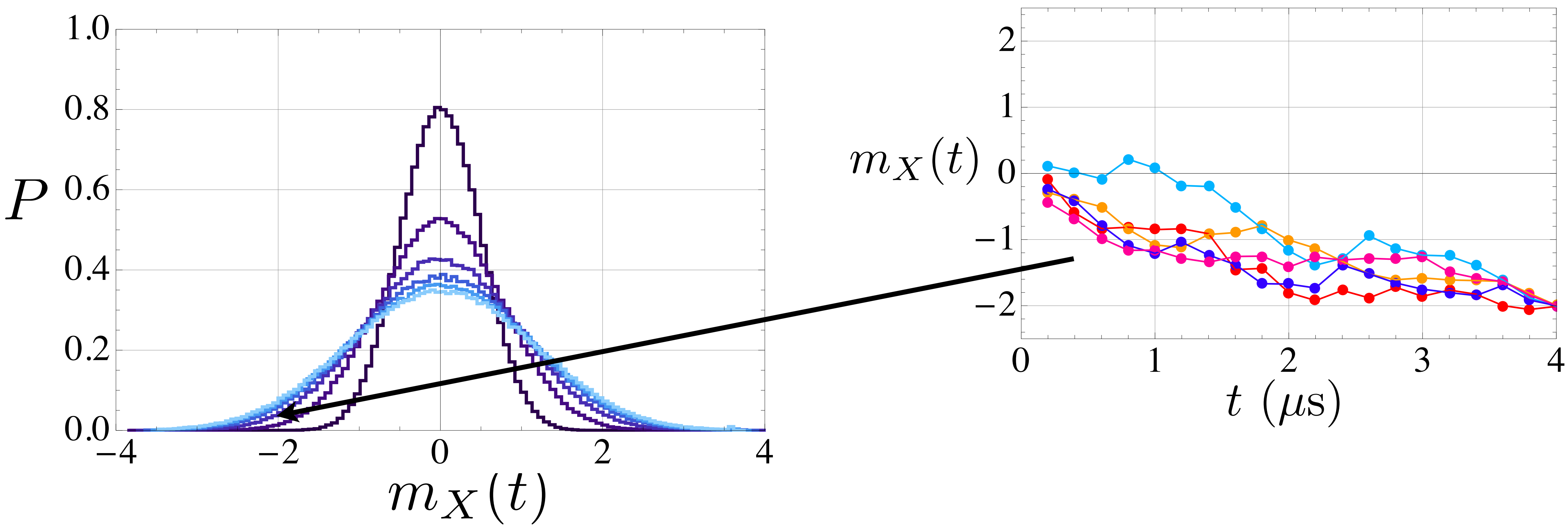
$$m_X(t) = \sqrt{\Gamma_{\text{leak}}} \int_0^t e^{-(\Gamma_{\text{leak}} - 2\Gamma_{\varphi})\tau/2} V_{\text{Re}} \mathrm{d}\tau$$

# Distribution of m's

$\Gamma_{\text{leak}}^{-1} = 3.865\ \mu\text{s} \qquad \Gamma_{\varphi}^{-1} = 40.85\ \mu\text{s}$




In $|e\rangle$ at time $t = 0$




$$m_X(t) = \sqrt{\Gamma_{\text{leak}}} \int_0^t e^{-(\Gamma_{\text{leak}} - 2\Gamma_{\varphi})\tau/2} V_{\text{Re}} \, d\tau$$

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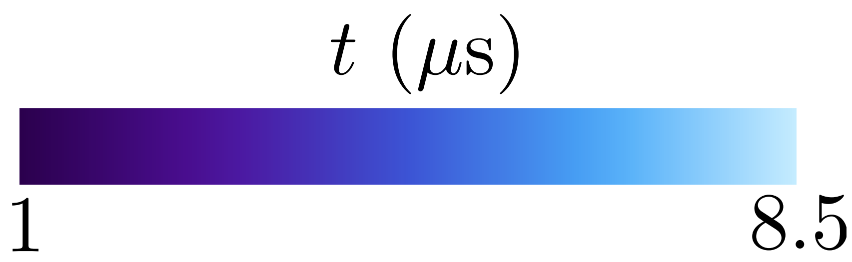
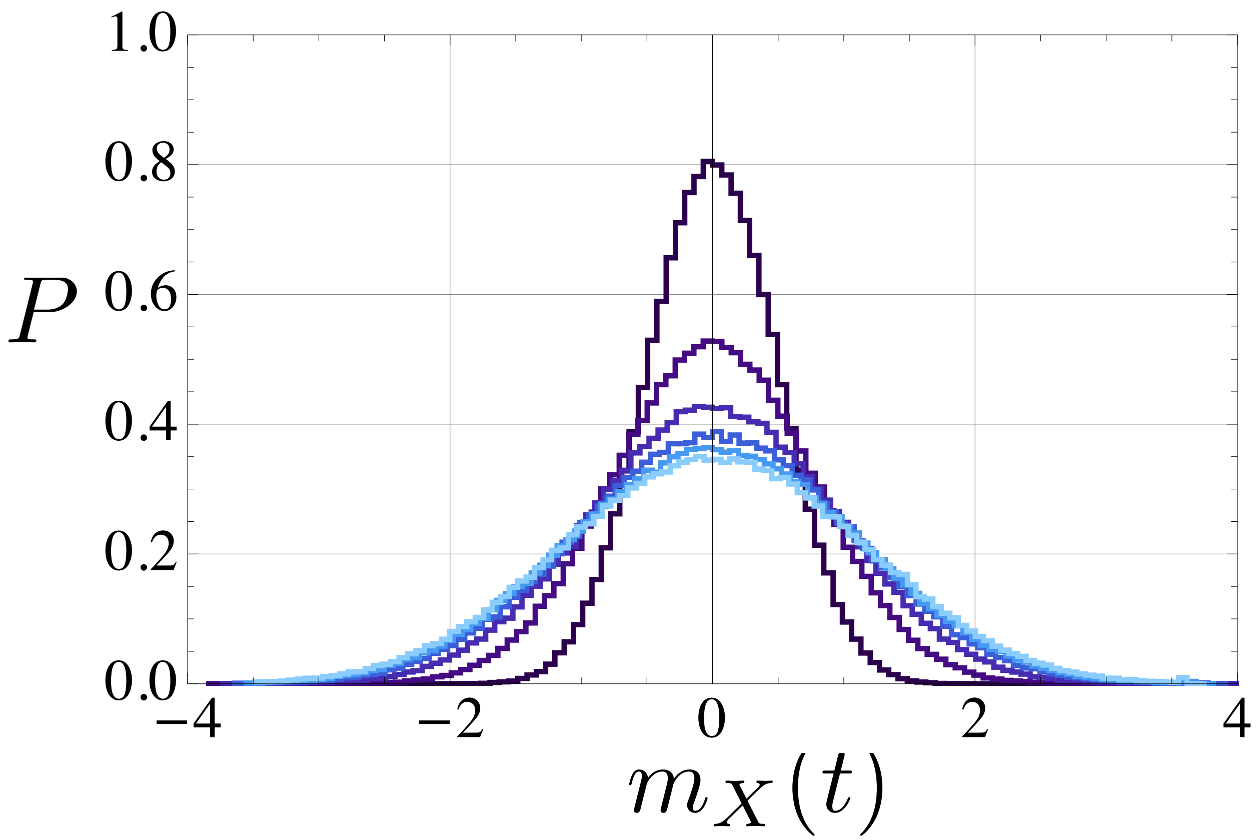
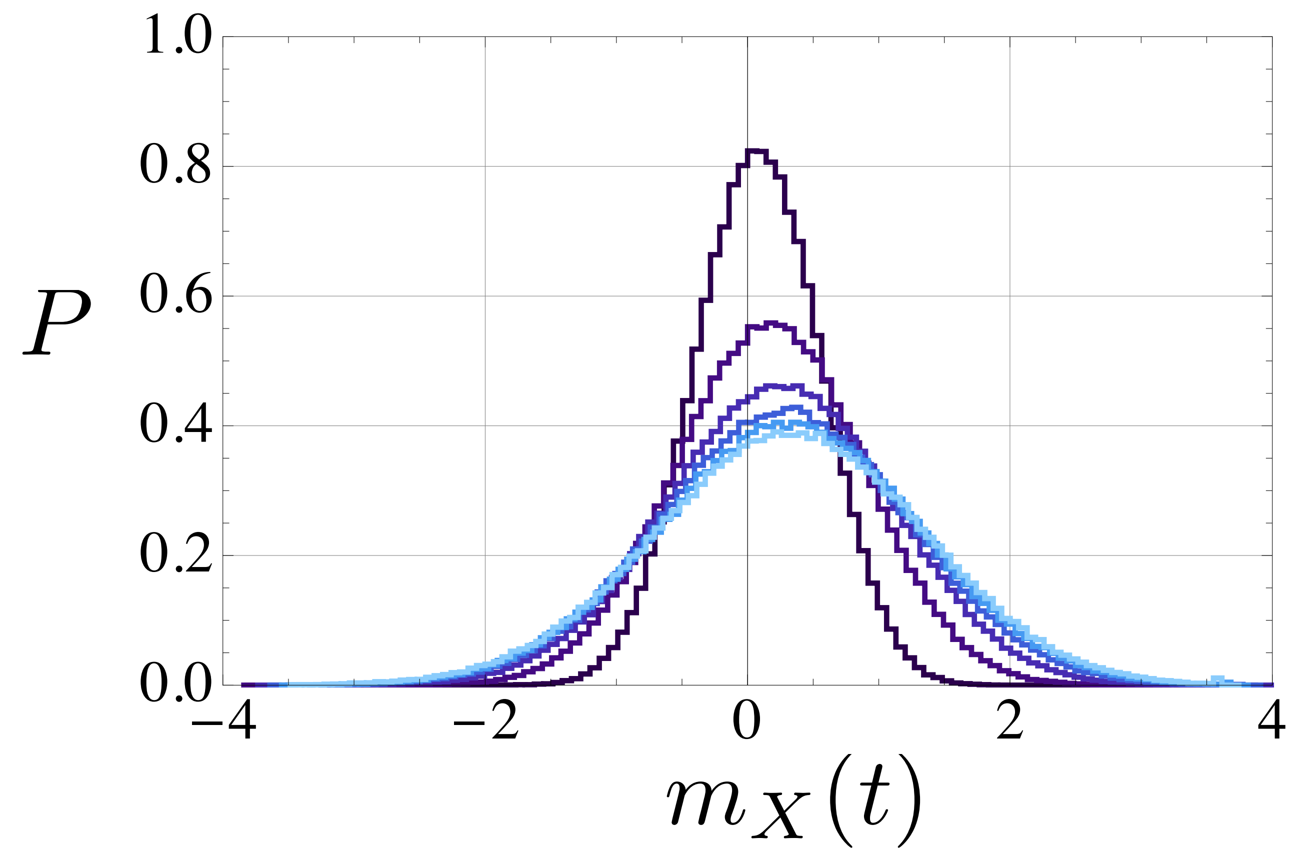



In $|e\rangle$ at time $t = 0$




In $\frac{|g\rangle + |e\rangle}{\sqrt{2}}$ at time $t = 0$




$$m_X(t) = \sqrt{\Gamma_{\text{leak}}} \int_0^t e^{-(\Gamma_{\text{leak}} - 2\Gamma_{\varphi})\tau/2} V_{\text{Re}} \, \mathrm{d}\tau$$

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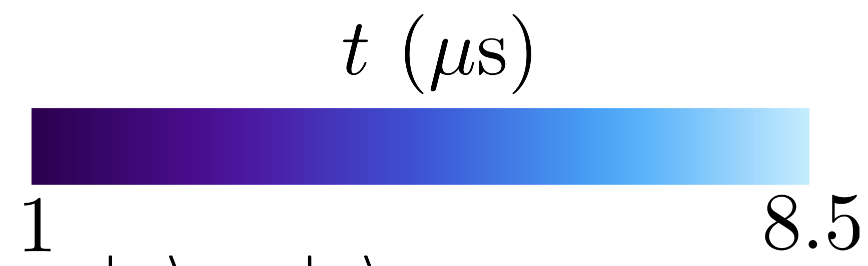
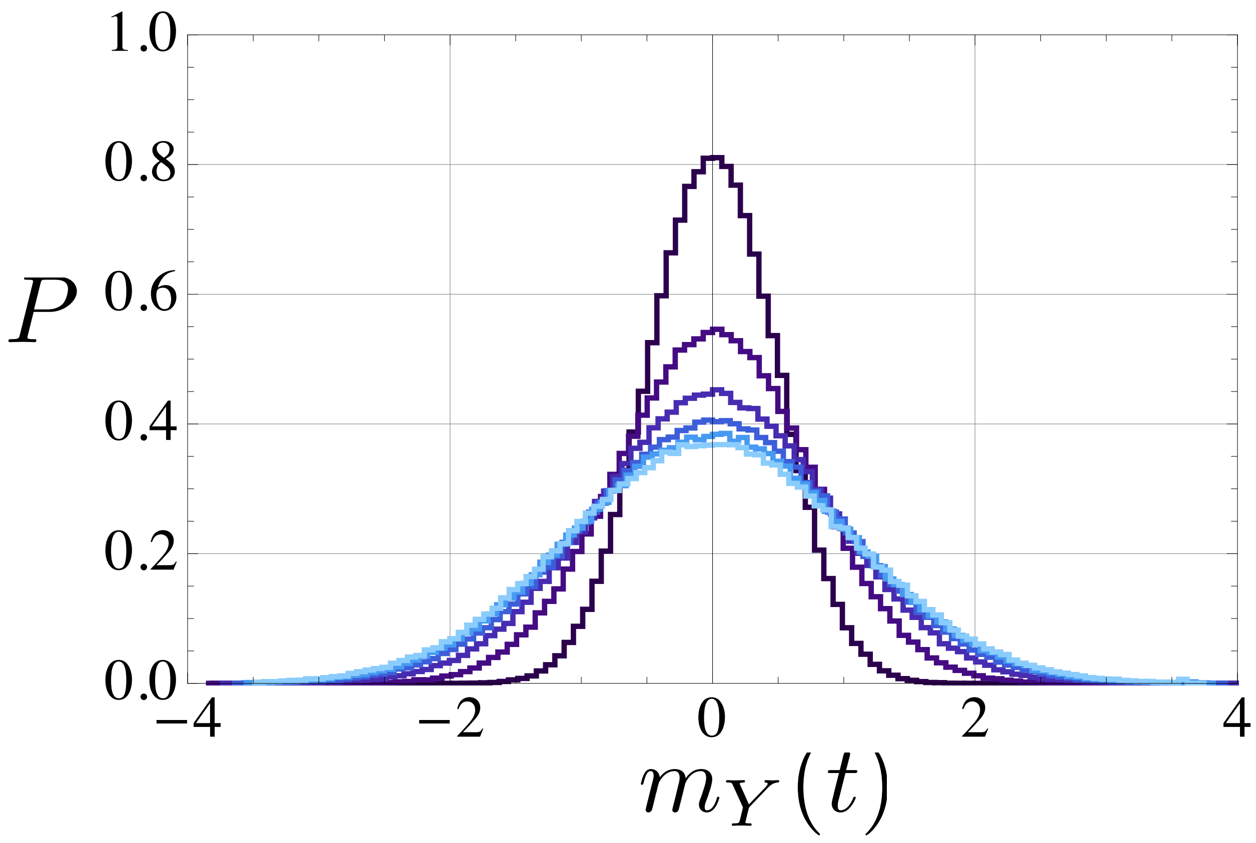
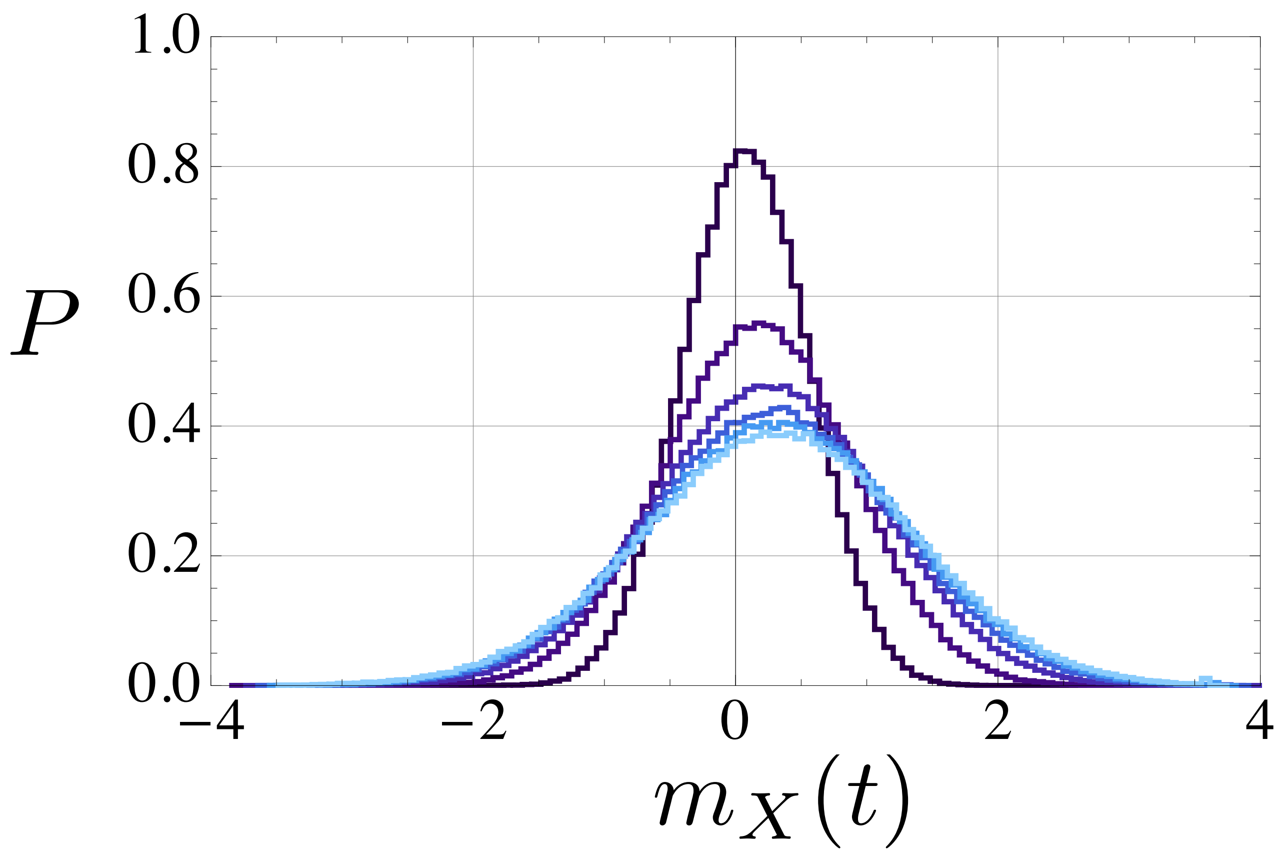



In $\frac{|g\rangle + |e\rangle}{\sqrt{2}}$ at time $t = 0$



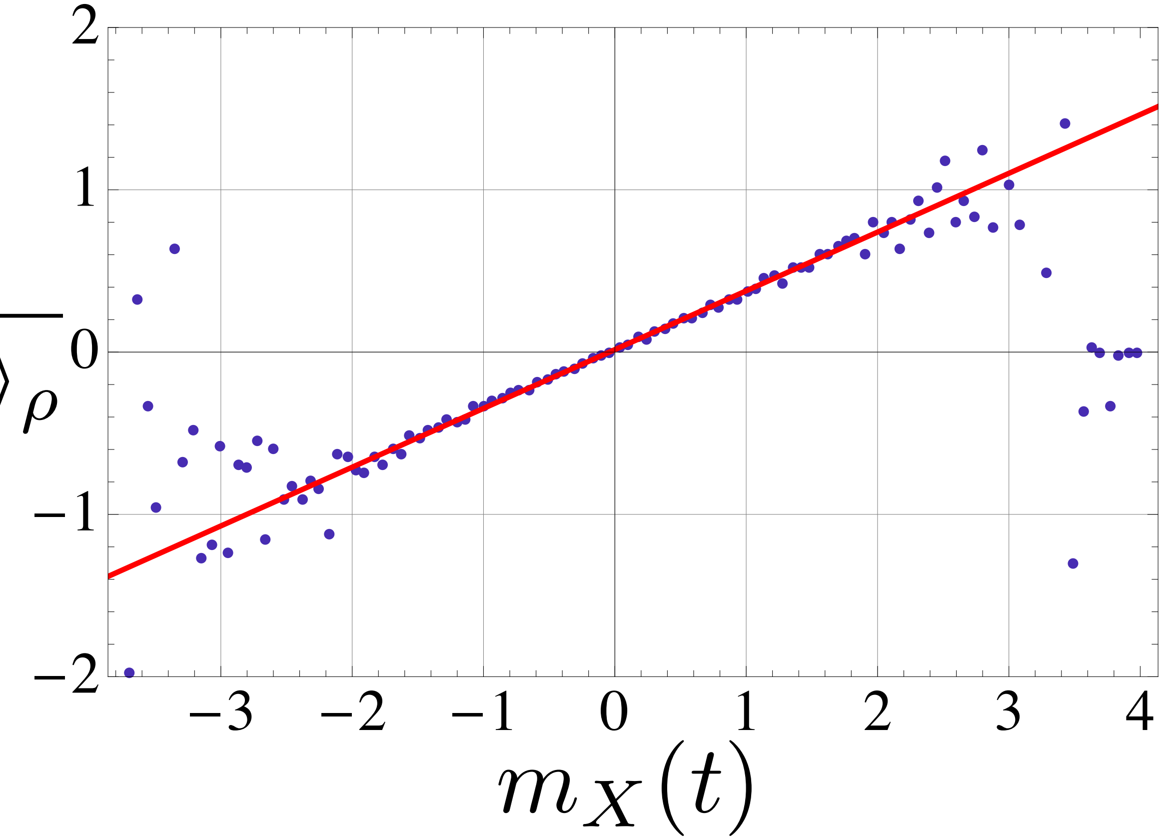




$$m_X(t) = \sqrt{\Gamma_{\text{leak}}} \int_0^t e^{-(\Gamma_{\text{leak}} - 2\Gamma_{\varphi})\tau/2} V_{\text{Re}} \mathrm{d}\tau$$

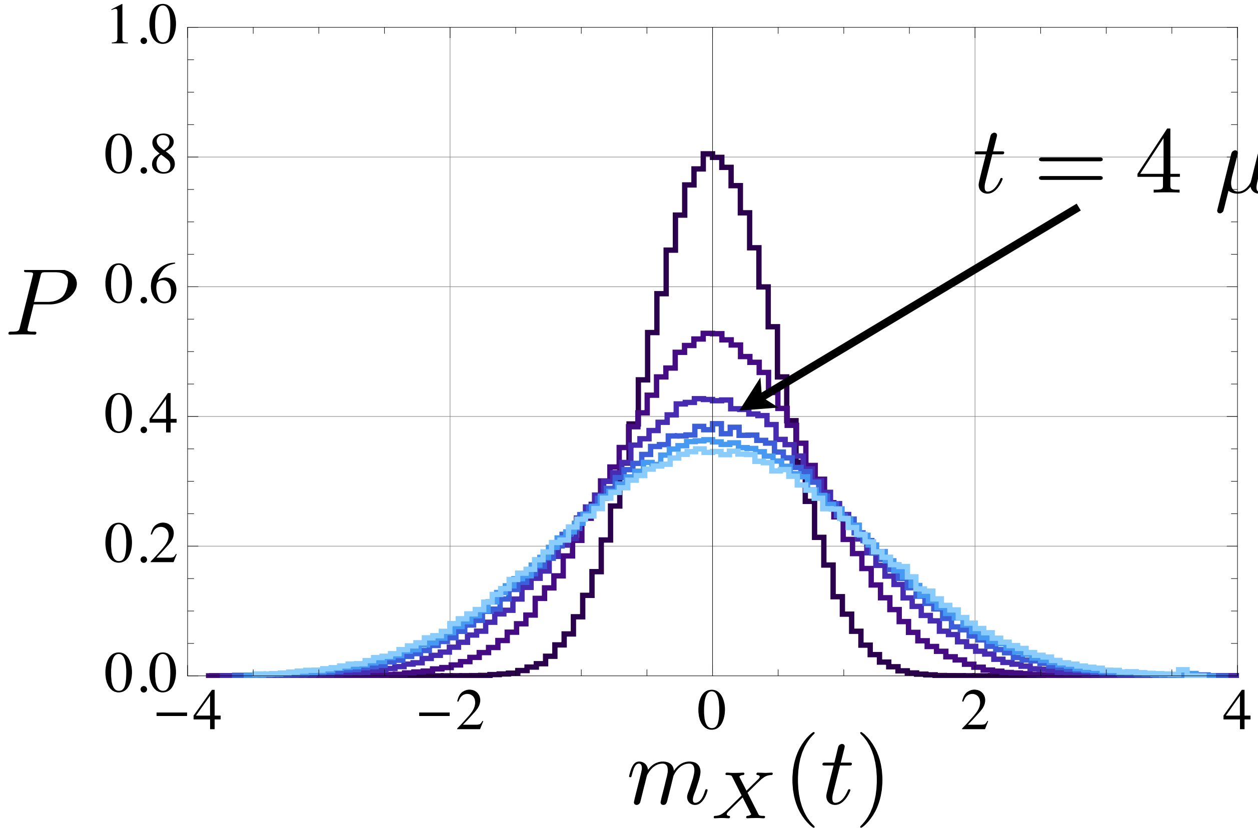
# Correlation between m and tomography

$$\Gamma_{\text{leak}}^{-1} = 3.865\ \mu\text{s} \qquad \Gamma_{\varphi}^{-1} = 40.85\ \mu\text{s}$$

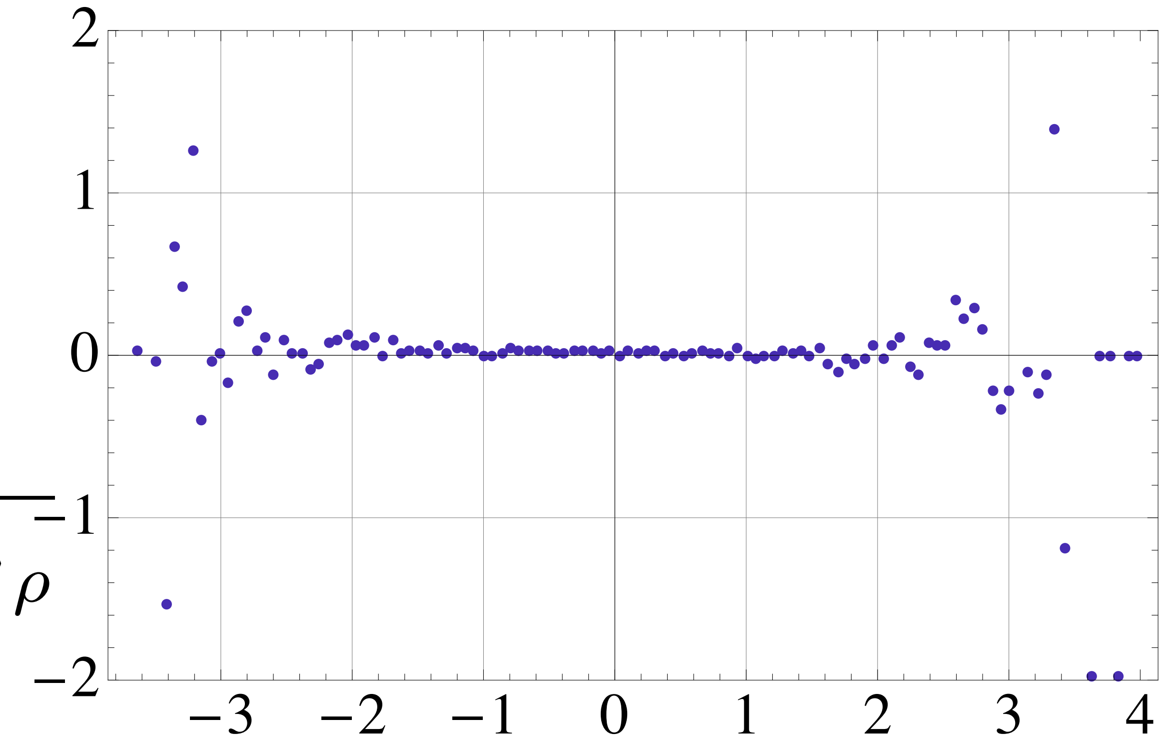
In $|e\rangle$ at time $t = 0$




$$\zeta_X \equiv \frac{\langle \sigma_X \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$




$$\zeta_Y \equiv \frac{\langle \sigma_Y \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$

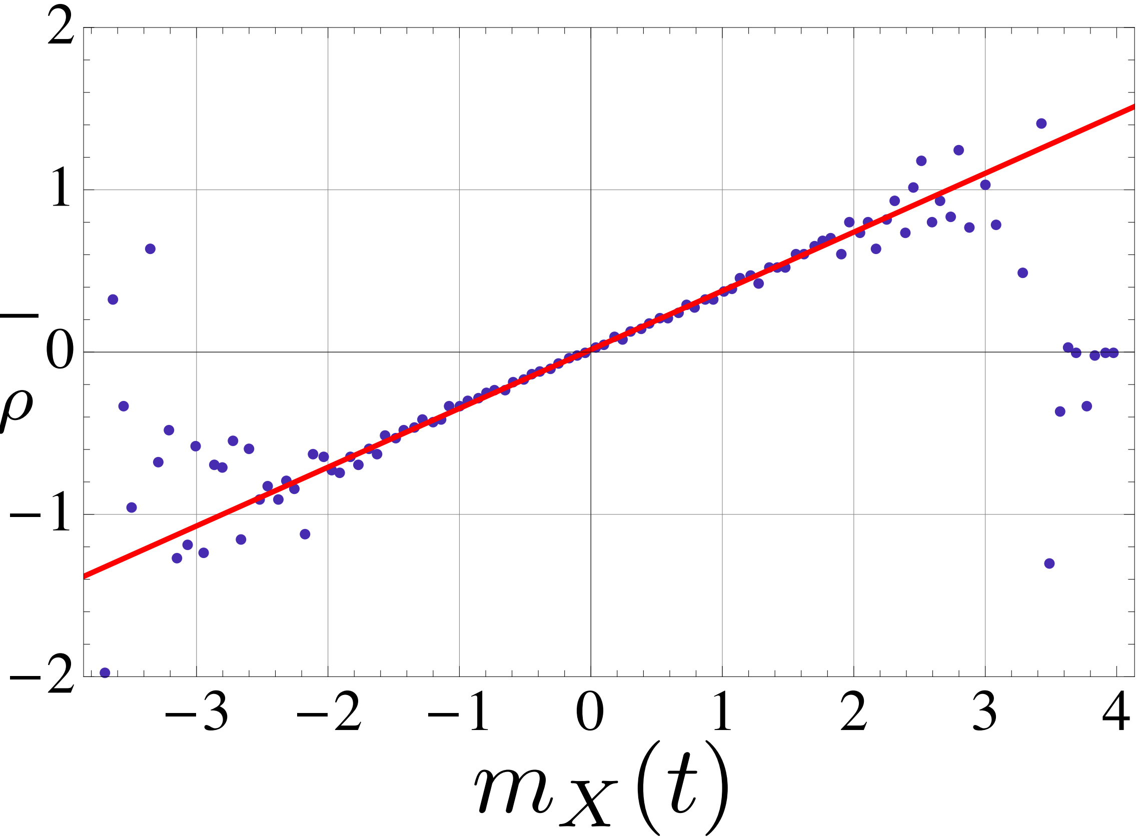


# Correlation between m and tomography

$$\Gamma_{\rm leak}^{-1} = 3.865\ \mu{\rm s} \qquad \Gamma_{\varphi}^{-1} = 40.85\ \mu{\rm s}$$

In $|e\rangle$ at time $t = 0$

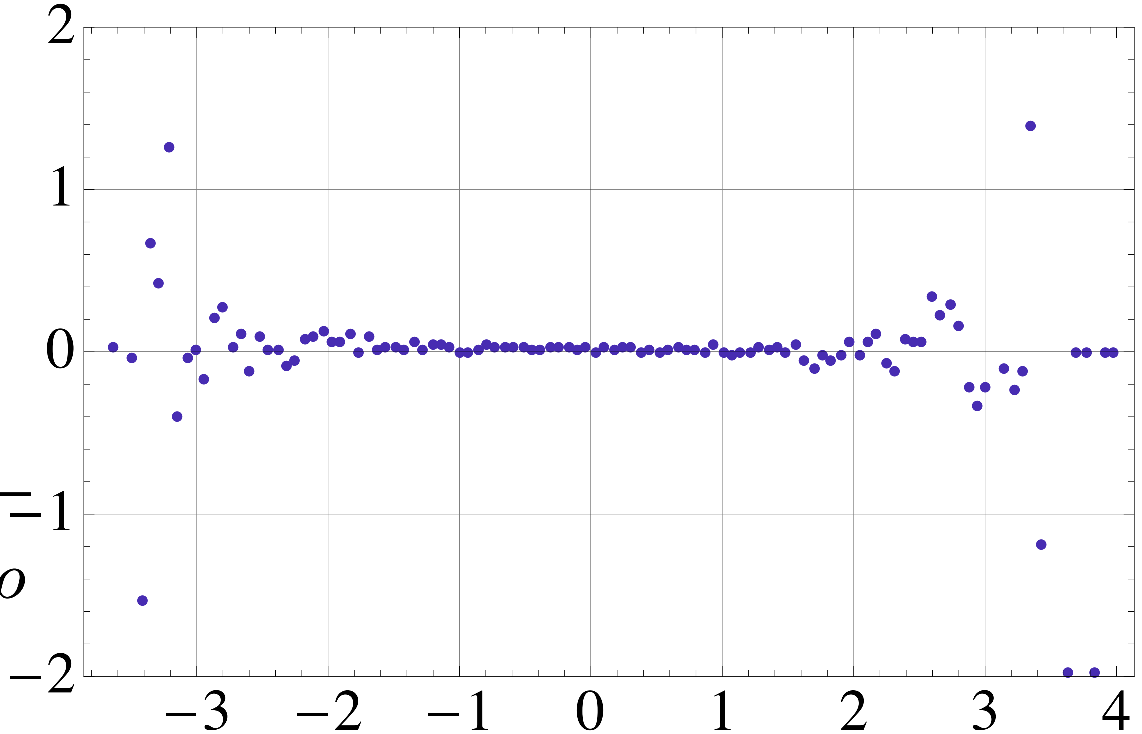
$$\zeta_X \equiv \frac{\langle \sigma_X \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$




Slope gives efficiency

$$\eta = 0.32 \pm 0.05$$

$$\zeta_Y \equiv \frac{\langle \sigma_Y \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$



# Correlation between m and tomography

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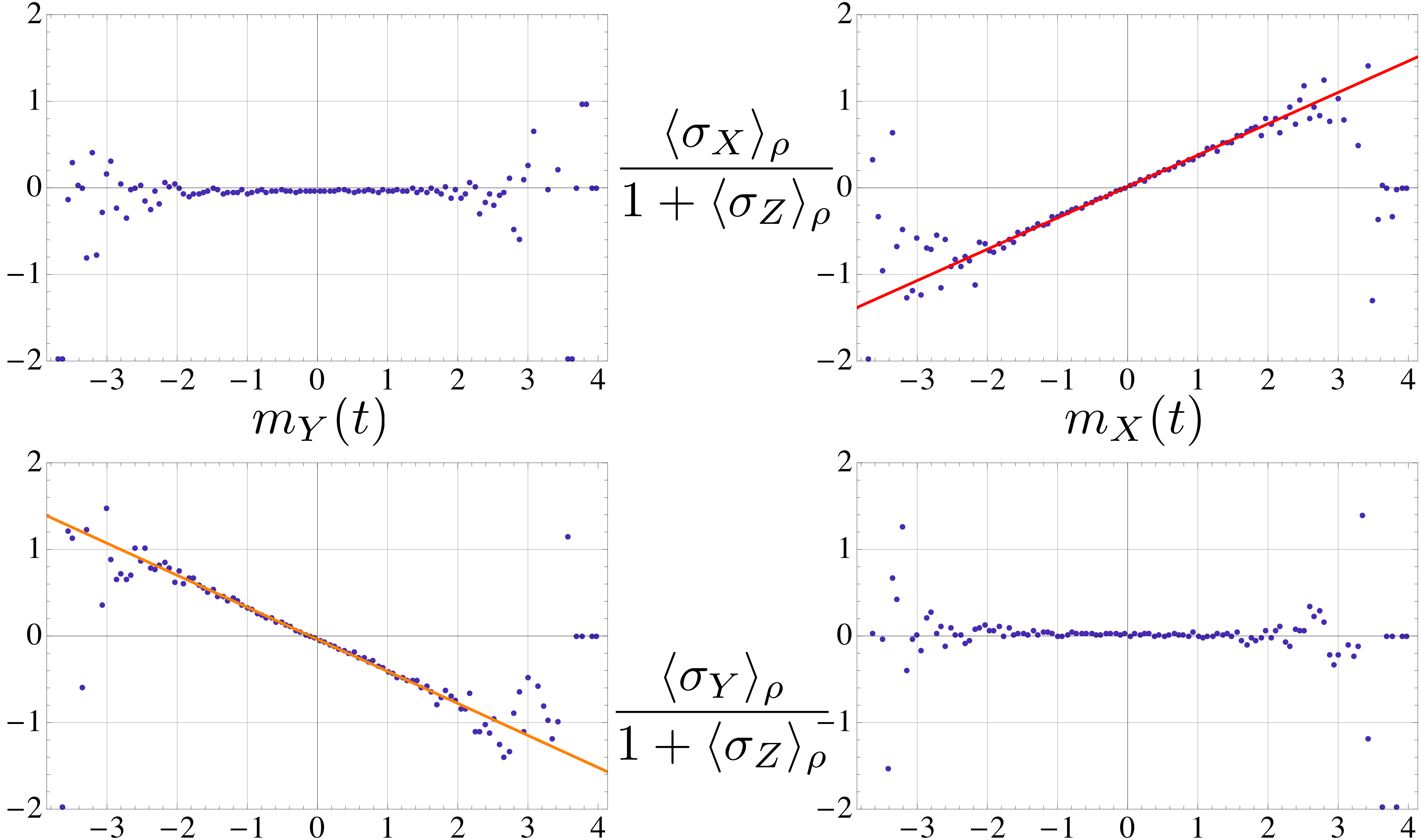
In $|e\rangle$ at time $t = 0$

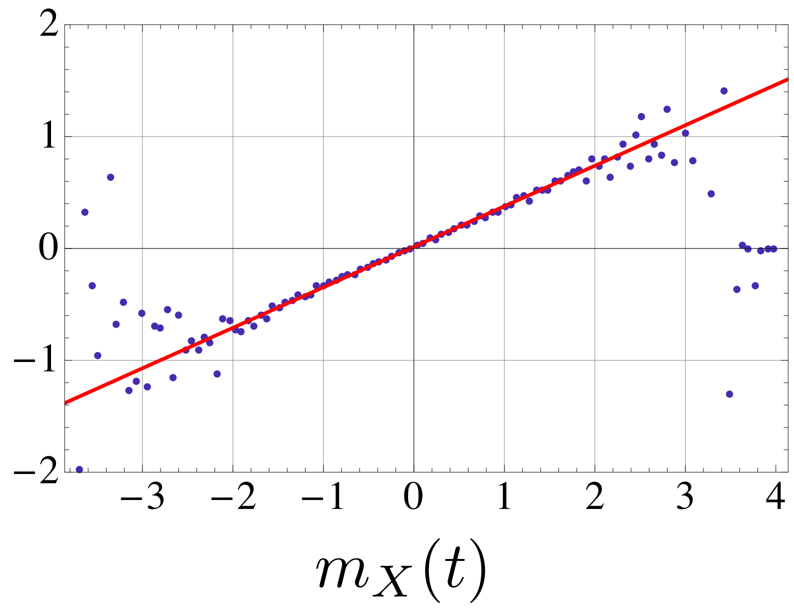


# Quantum efficiency

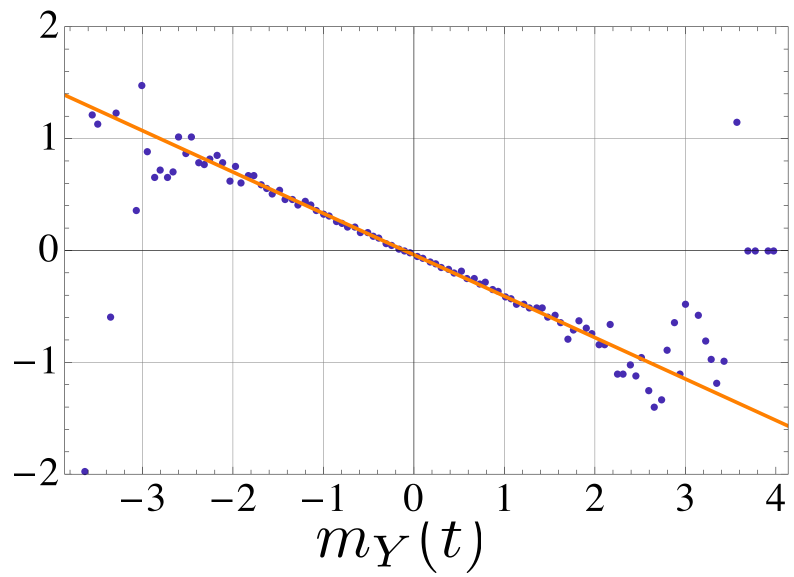
$$\Gamma_{\text{leak}}^{-1} = 3.865\ \mu\text{s} \qquad \Gamma_{\varphi}^{-1} = 40.85\ \mu\text{s}$$

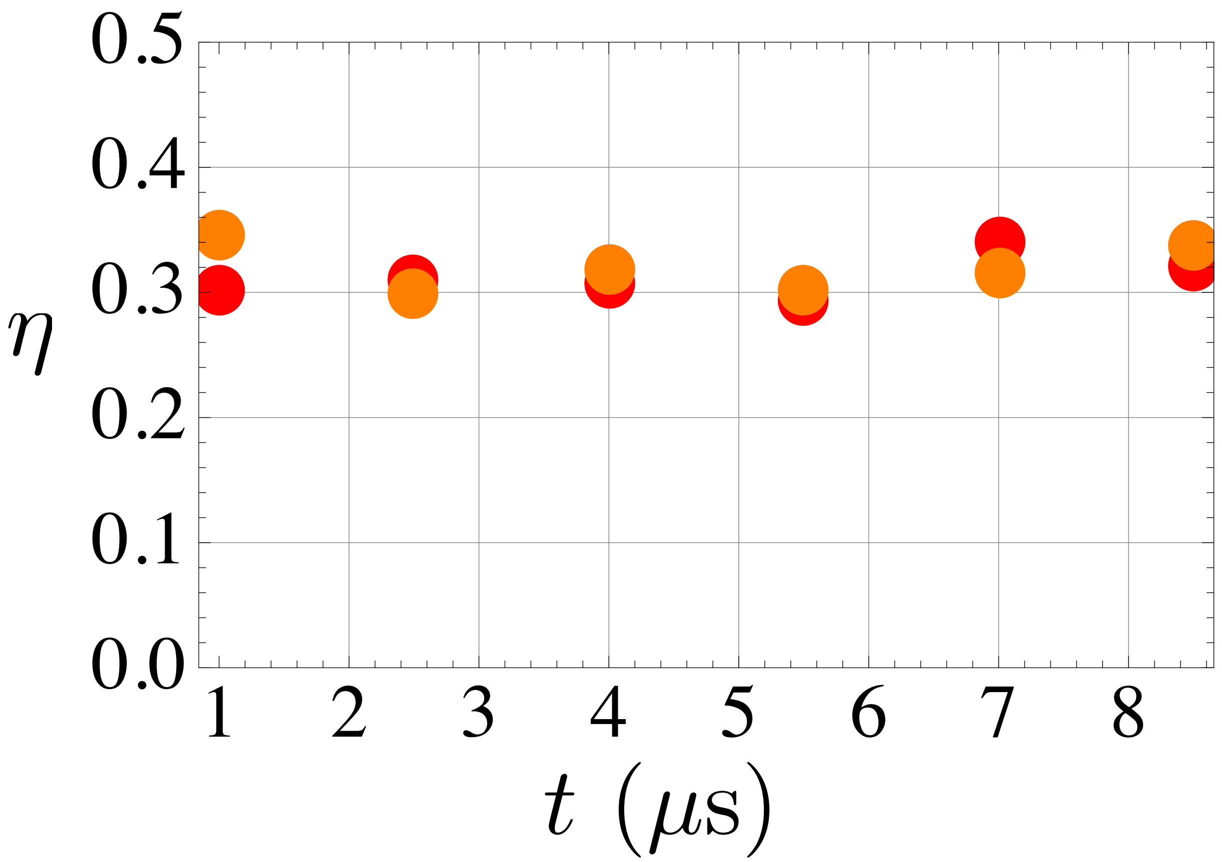
In $|e\rangle$ at time $t = 0$

$$\zeta_X \equiv \frac{\langle \sigma_X \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$




$$\zeta_Y \equiv \frac{\langle \sigma_Y \rangle_\rho}{1 + \langle \sigma_Z \rangle_\rho}$$

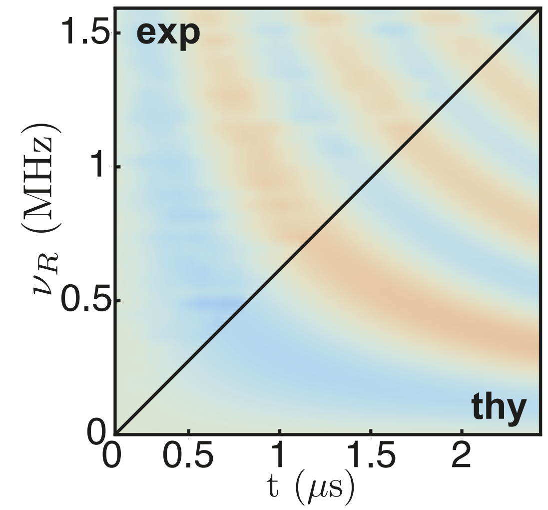


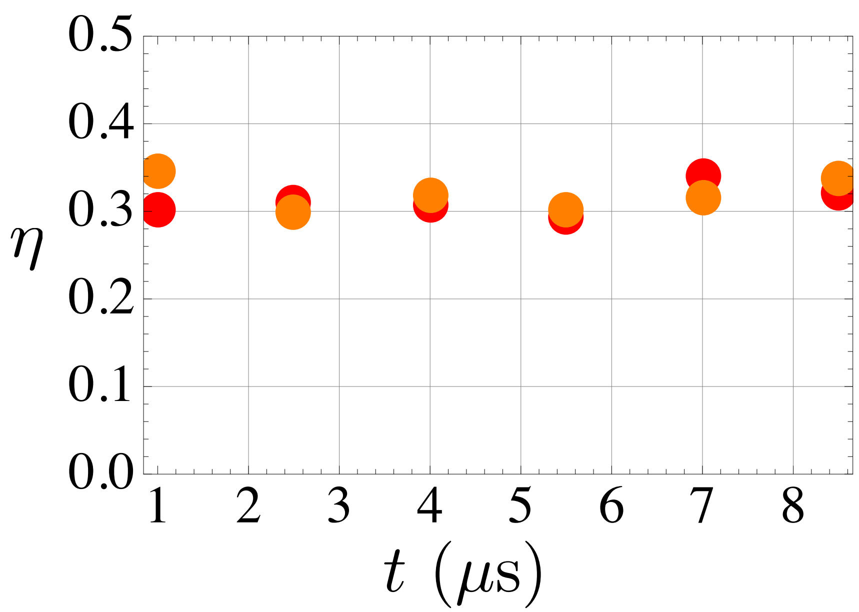

$$e^{-(\Gamma_{\text{leak}} - 2\Gamma_\varphi)t/2} \zeta_{X,Y}(t) - \zeta_{X,Y}(0) = \sqrt{\eta/2}\, m_{X,Y}(t)$$

# Thermodynamics with quantum trajectories

Qubit energy release measured directly




Qubit state can be followed with 30 % efficiency




What can be said about the thermodynamics of all these quantum trajectories? → in progress

Next: tunable qubit frequency → quantum work statistics

# Thanks

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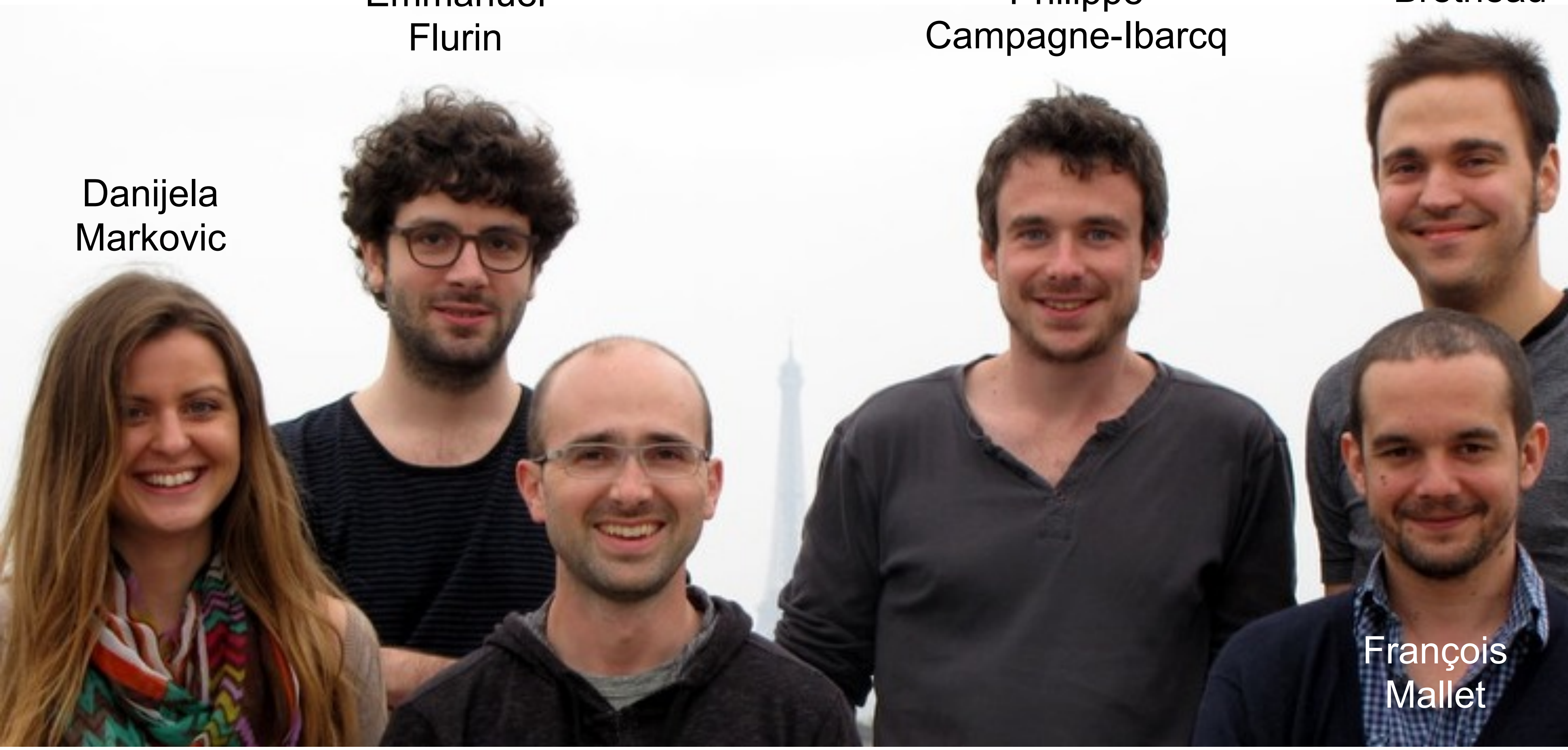
Landry Bretheau



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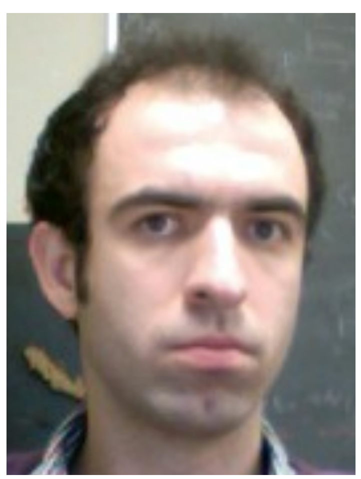
Vlad Manucharyan (JQI Maryland)



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