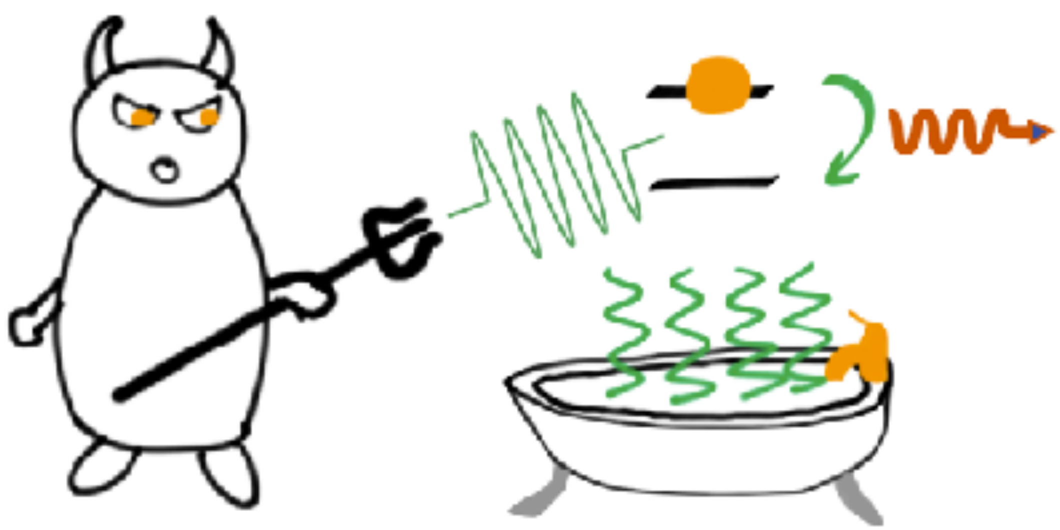
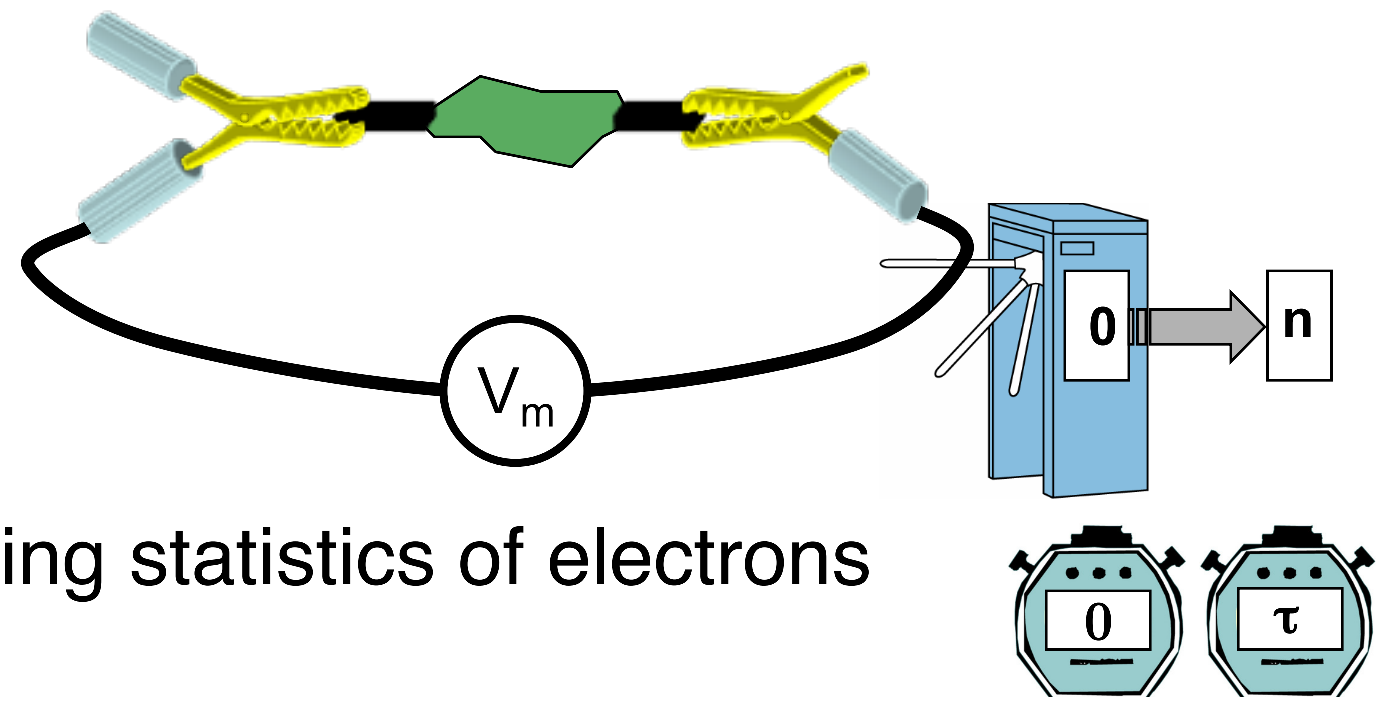
Quantum thermodynamics of fluorescence and « quantum heat »

Benjamin Huard
Ecole Normale Supérieure de Lyon, France



Happy birthday Jukka!

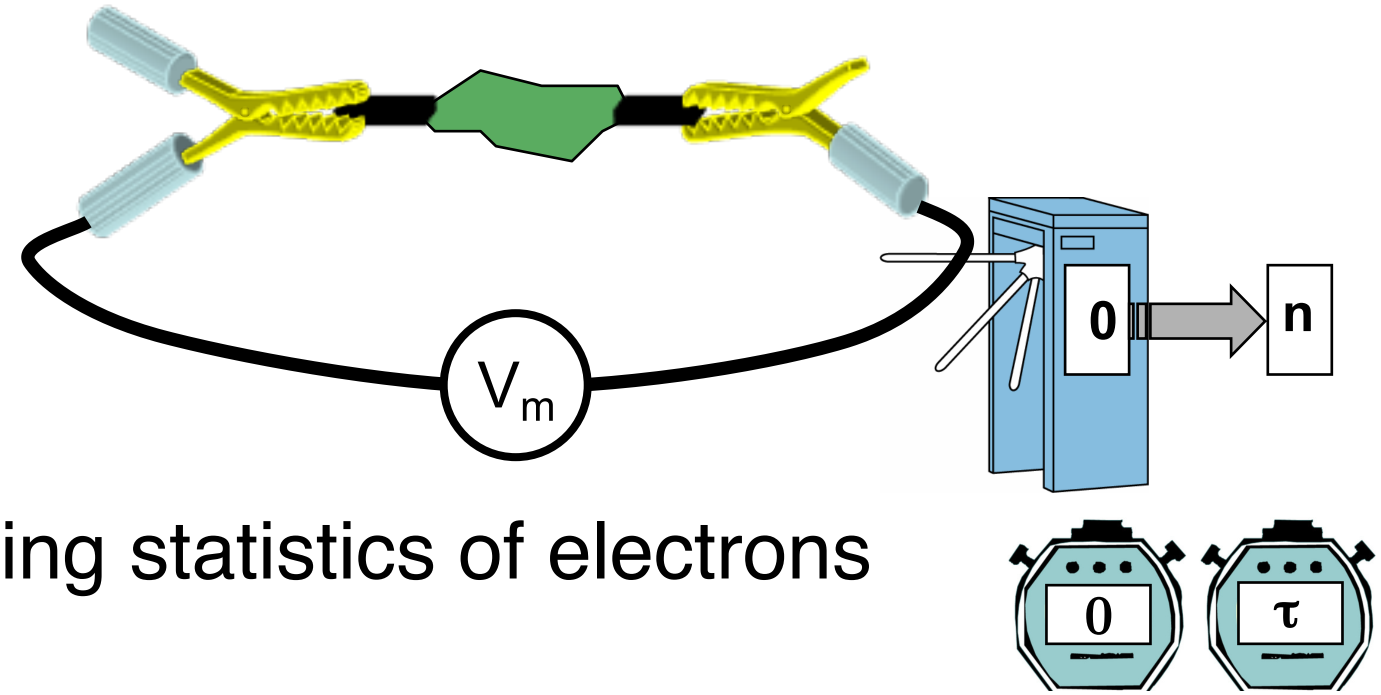
2004-2007



Full counting statistics of electrons

[Levitov, Lesovik, JETP 1993]

2004-2007



Full counting statistics of electrons

PRL 98, 207001 (2007) PHYSICAL REVIEW LETTERS week ending 18 MAY 2007

Wideband Detection of the Third Moment of Shot Noise by a Hysteretic Josephson Junction

A. V. Timofeev,[1,2] M. Meschke,[1] J. T. Peltonen,[1] T. T. Heikkilä,[1] and J. P. Pekola[1]
[1]*Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 3500, 02015 TKK, Finland*
[2]*Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, 142432 Russia*
(Received 4 December 2006; published 16 May 2007)

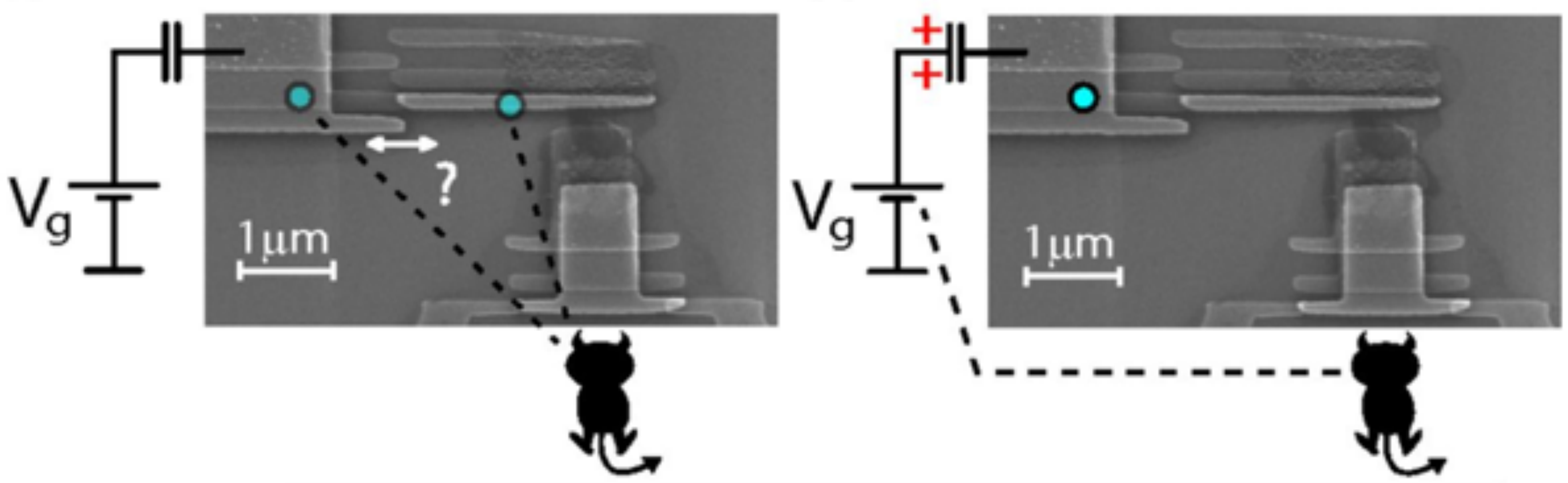
Ann. Phys. (Leipzig) **16**, No. 10–11, 736–750 (2007) / **DOI** 10.1002/andp.200710263

Josephson junctions as detectors for non-Gaussian noise

B. Huard[1,*], **H. Pothier**[1,**], **Norman O. Birge**[1,***], **D. Esteve**[1], **X. Waintal**[2], and **J. Ankerhold**[3]

new common interest

Thermodynamics with mesoscopic circuits



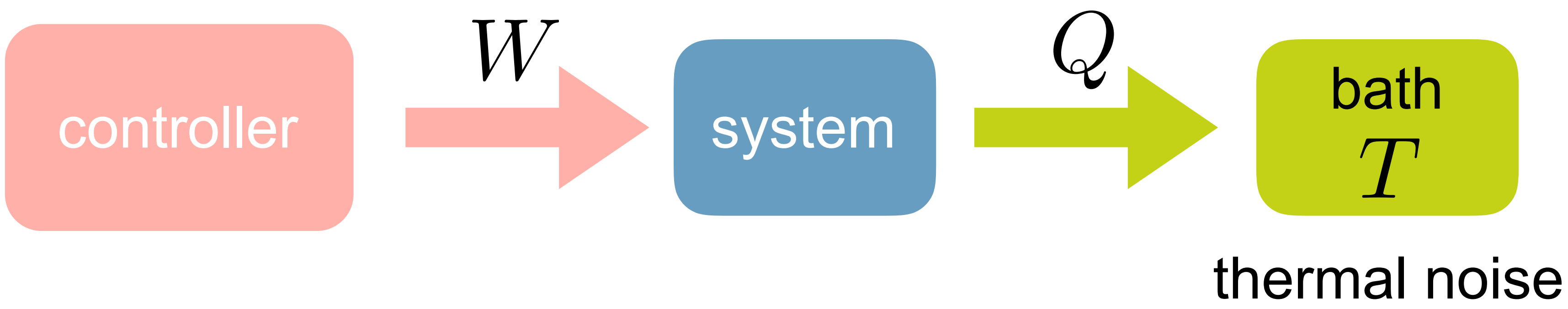
[J. Koski, V. Maisi, J. Pekola, D. Averin, PNAS 2014]

Quantum Thermodynamics Conference QTD2019

Right here next June!

Quantum measurement thermodynamics

Thermodynamics with thermal baths

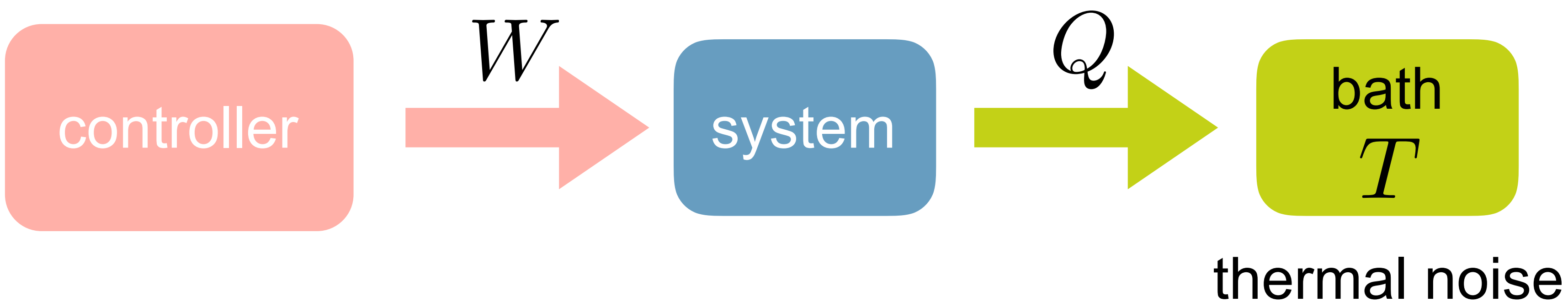


$$U(t) \equiv \langle H_{\mathrm{sys}} \rangle_{\rho(t)}$$

$$U(t) - U(0) = W - Q$$ 1st law

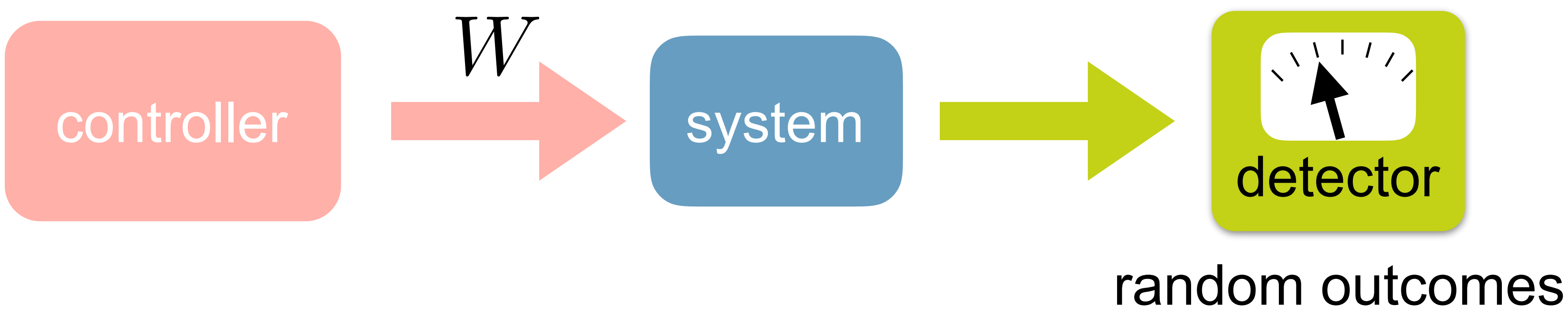
Quantum measurement thermodynamics

Thermodynamics with thermal baths



$U(t) \equiv \langle H_{\mathrm{sys}} \rangle_{\rho(t)}$ $\qquad$ $U(t) - U(0) = W - Q$ 1st law

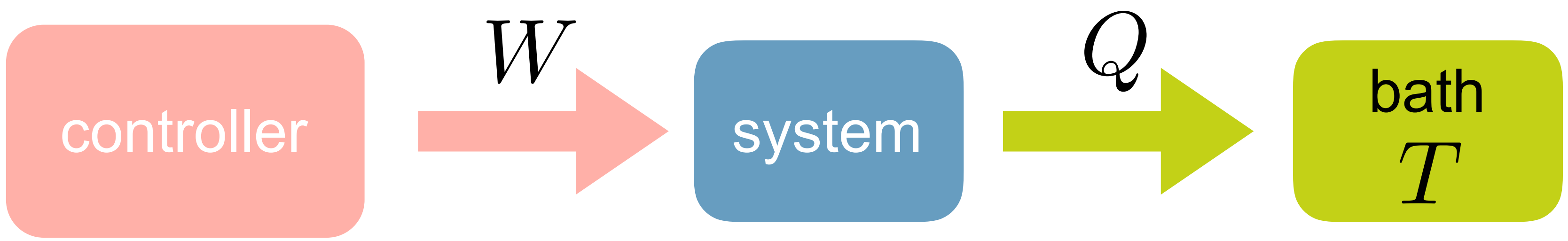
Thermodynamics with quantum measurements
(no thermal bath required)



$U(t) - U(0) \neq W$ the system energy can vary by measurement backaction

Quantum measurement thermodynamics

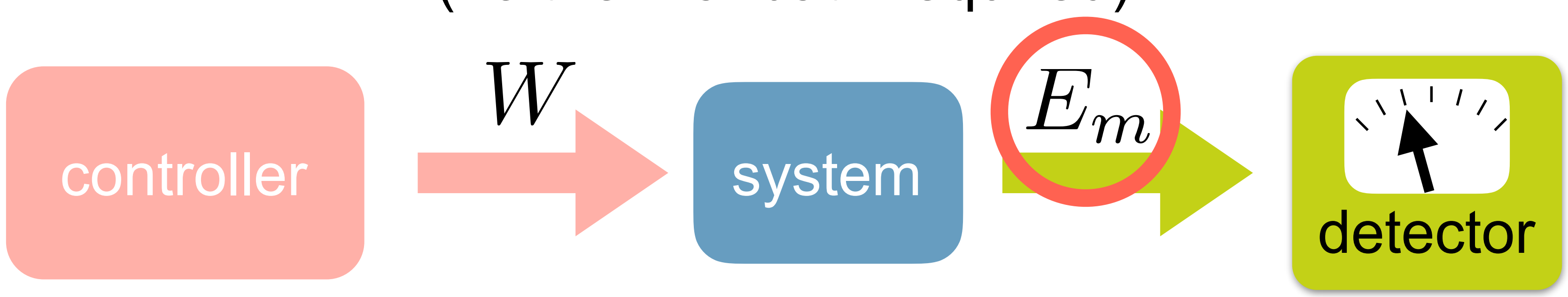
Thermodynamics with thermal baths



thermal noise

$$U(t) \equiv \langle H_{\mathrm{sys}} \rangle_{\rho(t)} \qquad\qquad U(t) - U(0) = W - Q$$ 1st law

Thermodynamics with quantum measurements
(no thermal bath required)



random outcomes

$U(t) - U(0) \neq W$ the system energy can vary by measurement backaction

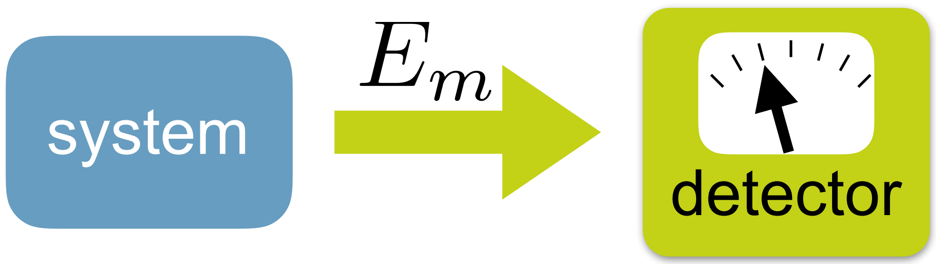
$$\delta W = \mathrm{Tr}(\rho \mathrm{d} H) \qquad \delta E_m = \mathrm{Tr}(H \mathrm{d}\rho)$$

random energy change E_m because outcomes are stochastic → « quantum heat »

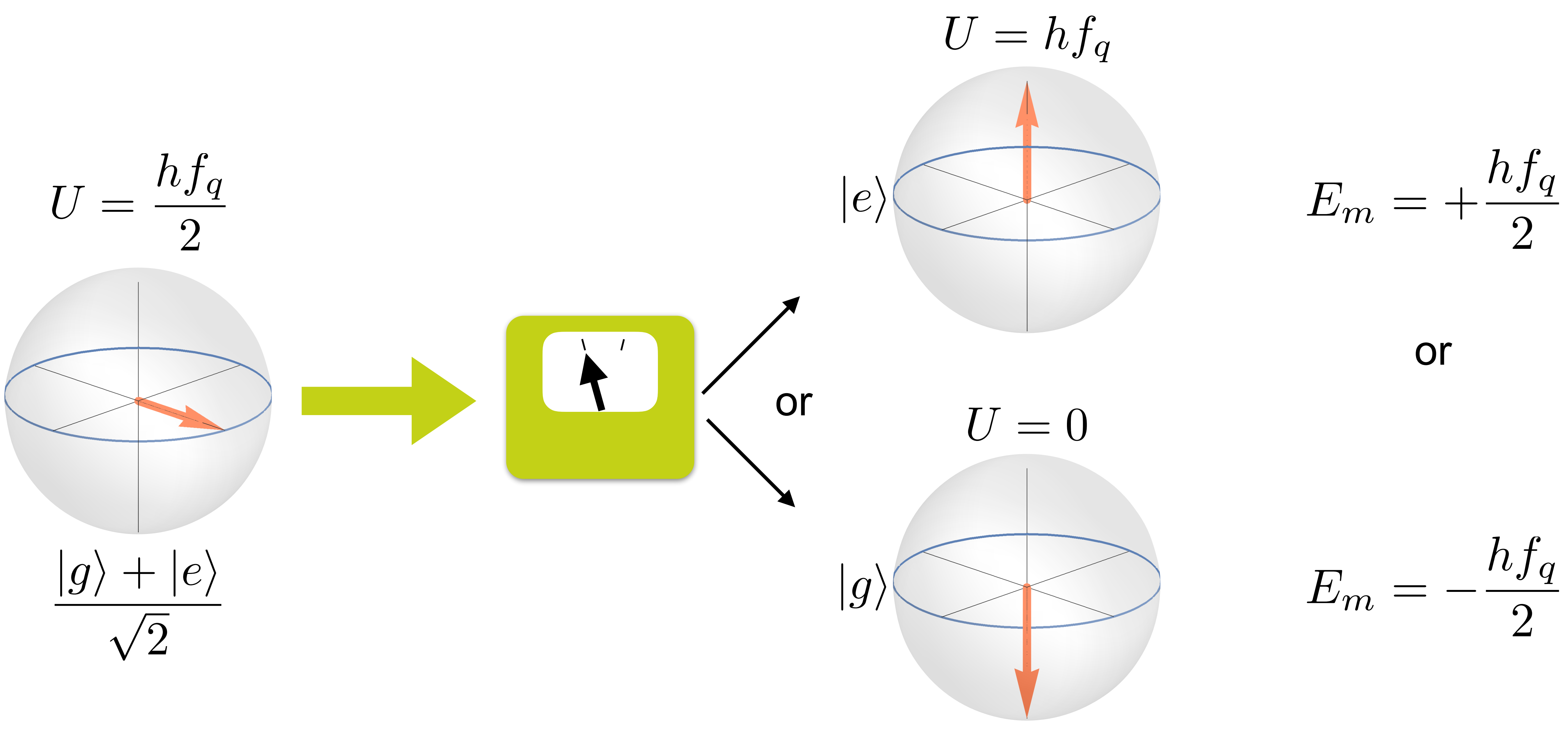
[Alonso, Lutz and Romito, PRL (2016); Elouard, Clusel and Auffèves, npj QI (2017)]

« quantum heat »

« quantum heat »

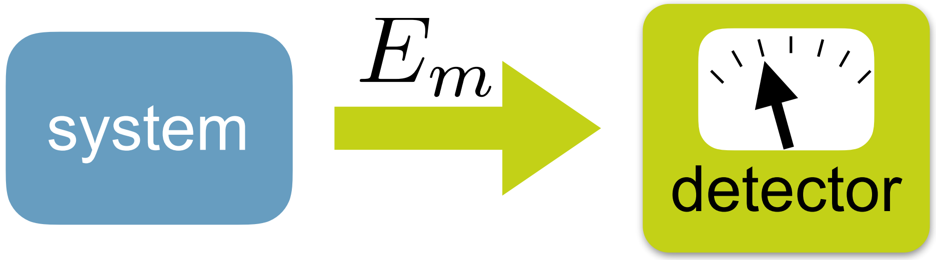


simple example on a qubit



« quantum heat »

« quantum heat »



does it obey a second law?

yes, fluctuation theorems can be extended with this work and « heat »

[Manzano, Horowitz and Parrondo, PRE 2015] [Alonso, Lutz and Romito, PRL (2016)]
[Elouard, Auffèves and Clusel, npj QI (2017)] [Naghiloo et al., PRL (2018)] [Manikandan, Elouard, Jordan, arxiv 2018]

can it fuel an engine?

yes, repeatedly measuring σ_x on a qubit can provide work on a cycle

[Yi, Talkner, Kim, PRE 2017] [Elouard, Herrera-Martí, Huard, Auffèves, PRL (2017)]
[Elouard, Jordan, PRL (2018)] [Ding, Yi, Kim, Talkner, arxiv 2018] [Buffoni et al., arxiv 2018]

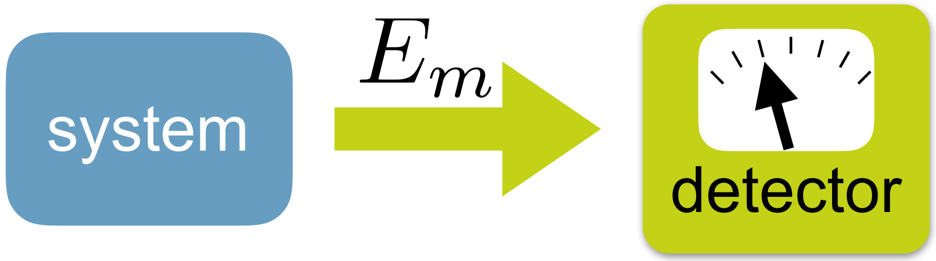
Michele's talk

what provides this energy?

can it be measured directly and not just inferred?

« quantum heat »

« quantum heat »



does it obey a second law?

yes, fluctuation theorems can be extended with this work and « heat »

[Manzano, Horowitz and Parrondo, PRE 2015] [Alonso, Lutz and Romito, PRL (2016)]
[Elouard, Auffèves and Clusel, npj QI (2017)] [Naghiloo et al., PRL (2018)] [Manikandan, Elouard, Jordan, arxiv 2018]

can it fuel an engine?

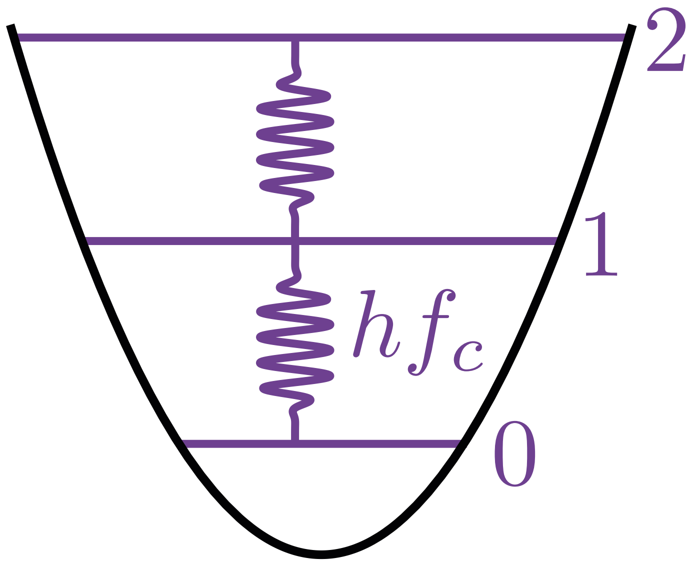
yes, repeatedly measuring σ_x on a qubit can provide work on a cycle

[Yi, Talkner, Kim, PRE 2017] [Elouard, Herrera-Martí, Huard, Auffèves, PRL (2017)]
[Elouard, Jordan, PRL (2018)] [Buffoni et al., arxiv 2018] [Ding, Yi, Kim, Talkner, arxiv 2018]

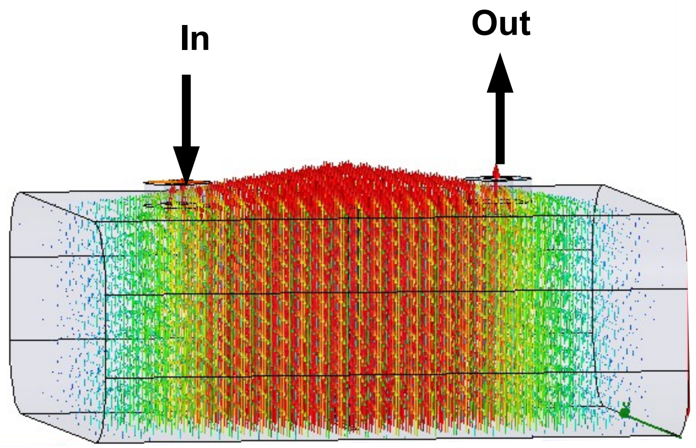
what provides this energy?

can it be measured directly and not just inferred?

3D transmon



$$H_c = hf_c(a^\dagger a + \frac{1}{2})$$

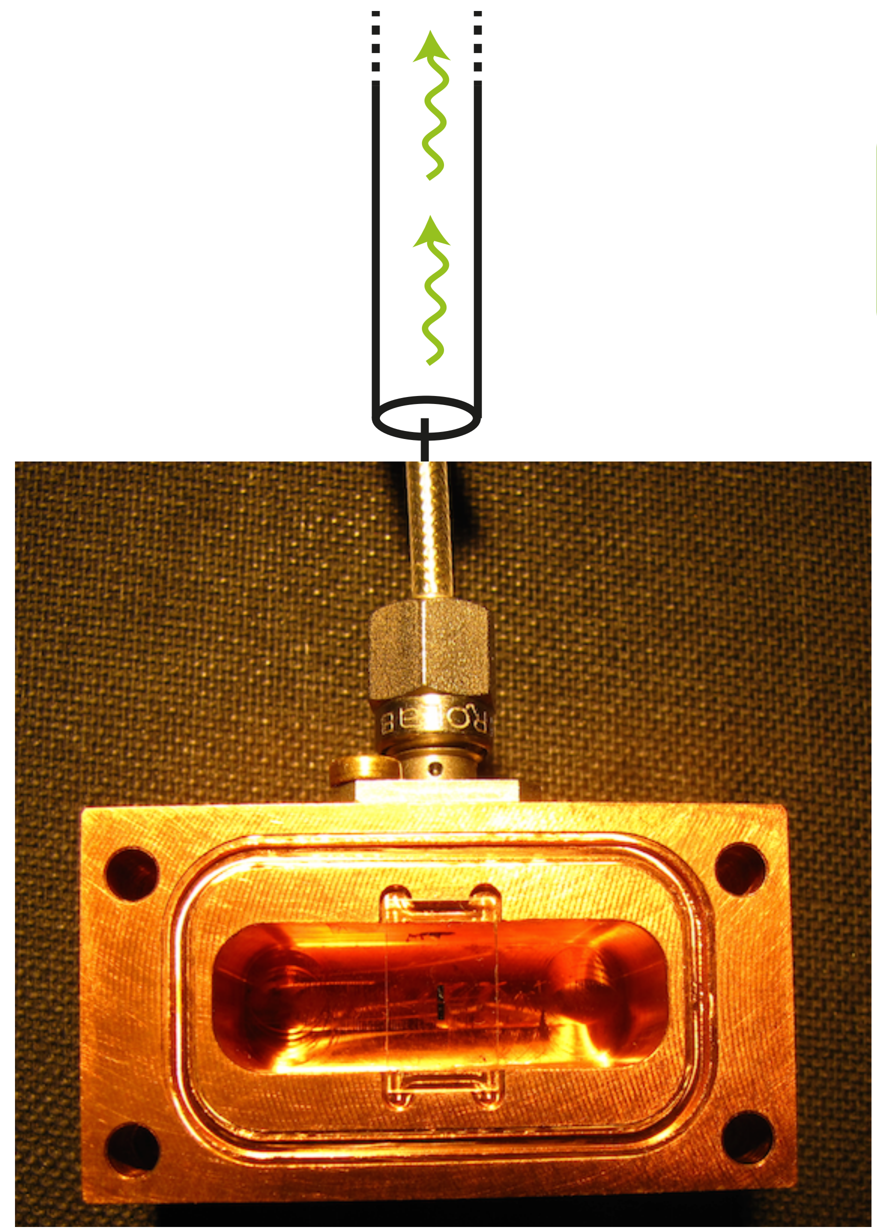


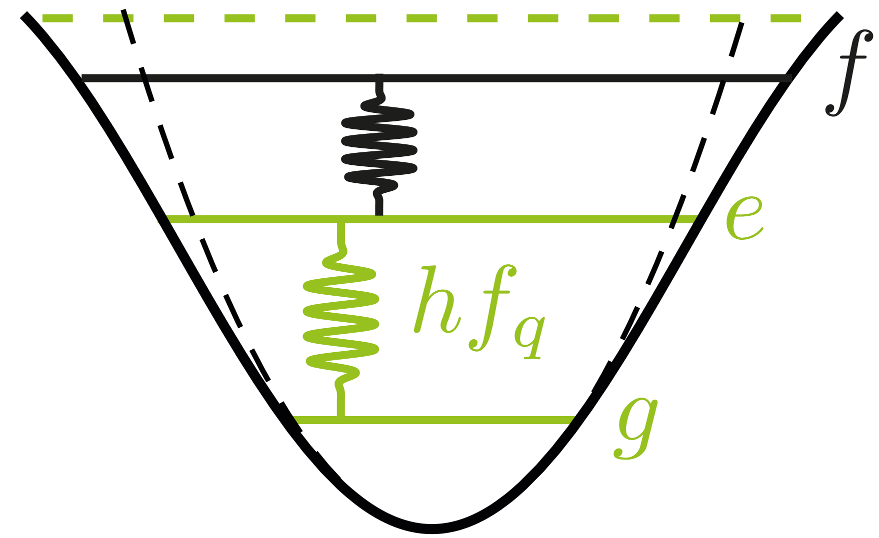
$$f_c = 7.5 \text{ GHz}$$

$$kT \ll hf$$
$$T = 20 \text{ mK}$$

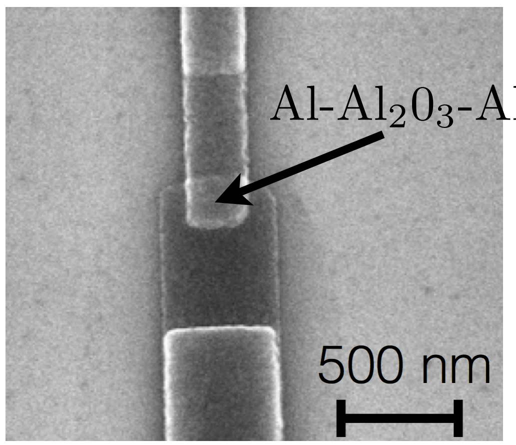
$$H_{\text{disp}} = h\chi \frac{\sigma_z}{2} a^\dagger a$$

$$\chi = 9.6 \text{ MHz}$$





$$H_q = \frac{hf_q}{2}\sigma_z$$

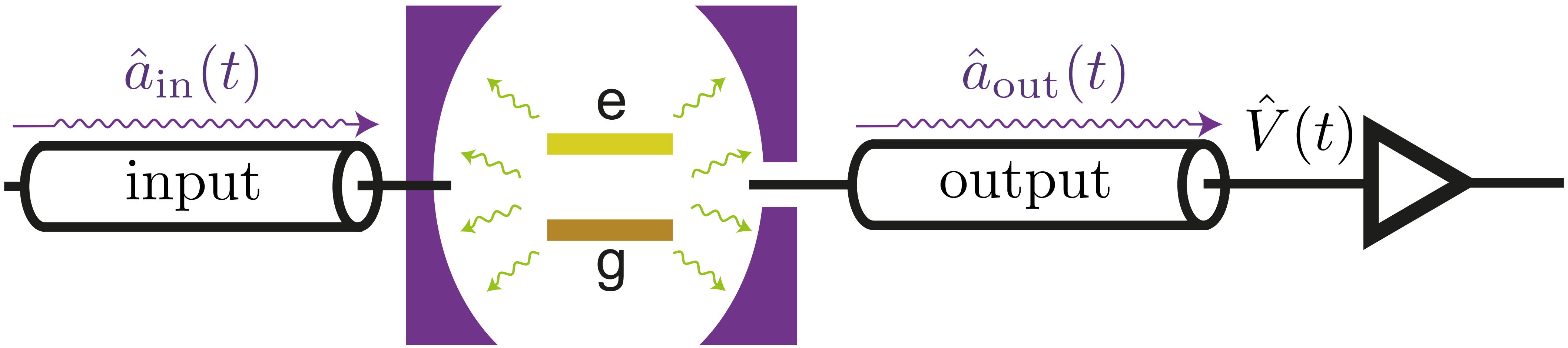


In cavity, $f_q = 6.3 \text{ GHz}$

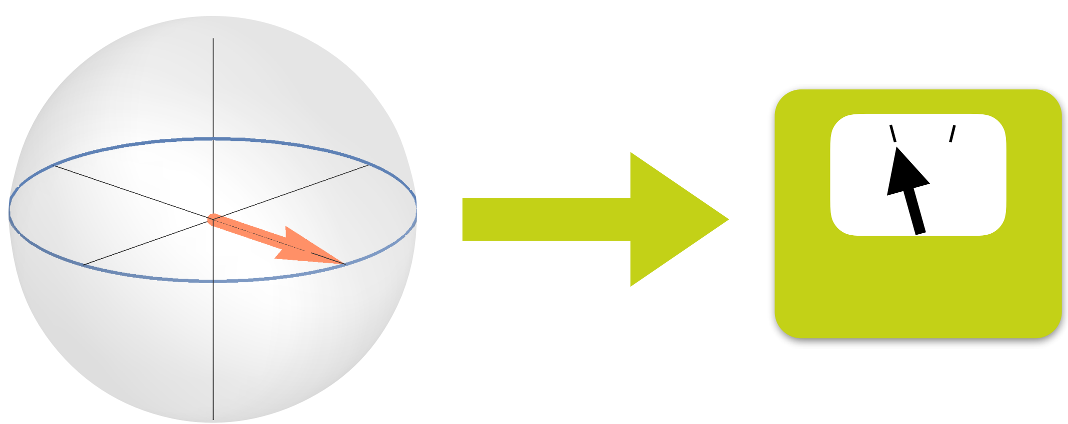
$$\gamma_1 = (4.2\ \mu\text{s})^{-1}$$

Dispersive Measurement

$$H = hf_q\frac{\sigma_Z}{2} + h(f_c - \frac{\chi}{2}\sigma_z)a^\dagger a$$



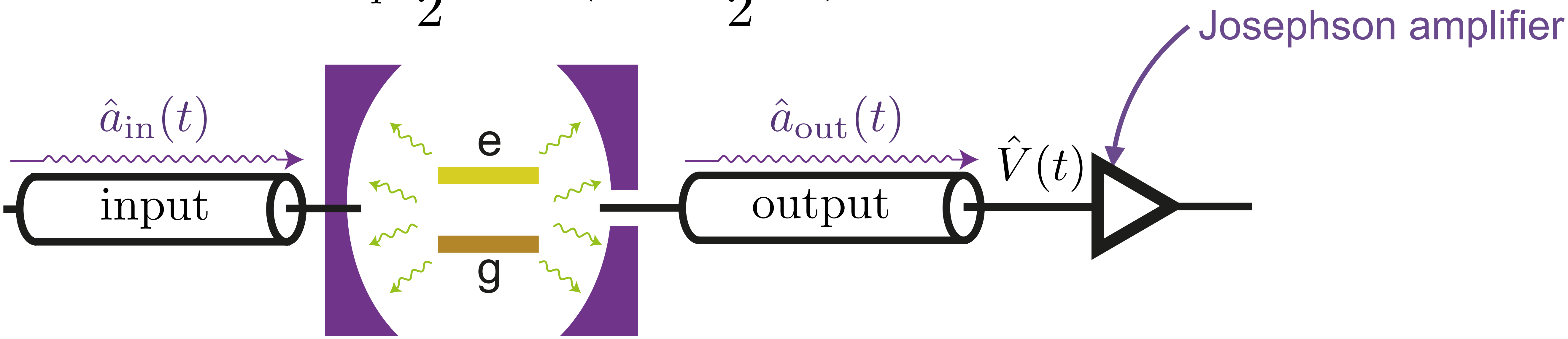
$$U = \frac{hf_q}{2}$$



$$\frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

Dispersive Measurement

$$H = hf_q\frac{\sigma_Z}{2} + h(f_c - \frac{\chi}{2}\sigma_z)a^\dagger a$$



Classically $V(t) = I(t)\cos(2\pi f_c t) + Q(t)\sin(2\pi f_c t)$

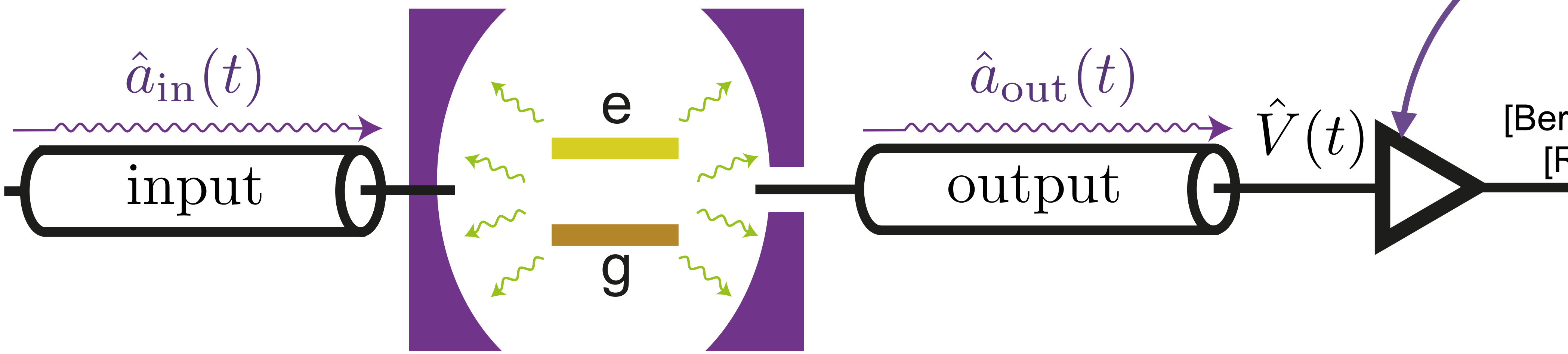
$$I_t \to \hat{I}_t \propto \frac{\hat{a}_{\text{out}} + \hat{a}^\dagger_{\text{out}}}{2} = \text{Re}(\hat{a}_{\text{out}})$$

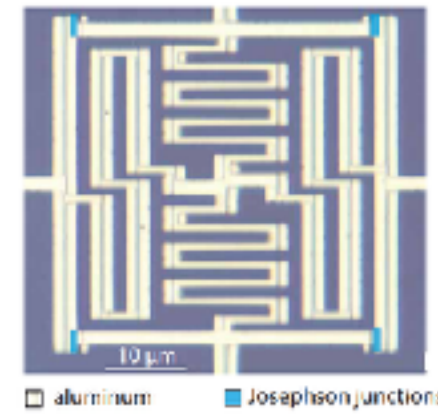
$$Q_t \to \hat{Q}_t \propto \frac{\hat{a}_{\text{out}} - \hat{a}^\dagger_{\text{out}}}{2i} = \text{Im}(\hat{a}_{\text{out}})$$

Dispersive Measurement

$$H = hf_q\frac{\sigma_Z}{2} + h(f_c - \frac{\chi}{2}\sigma_z)a^\dagger a$$

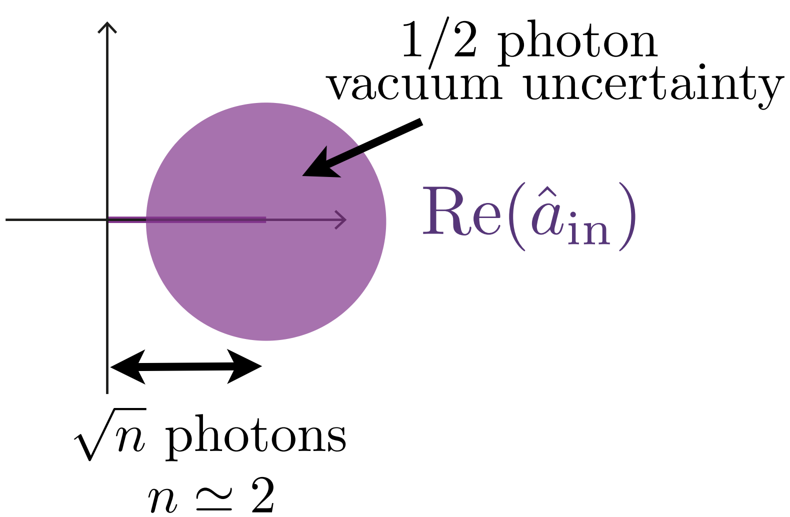
Josephson amplifier



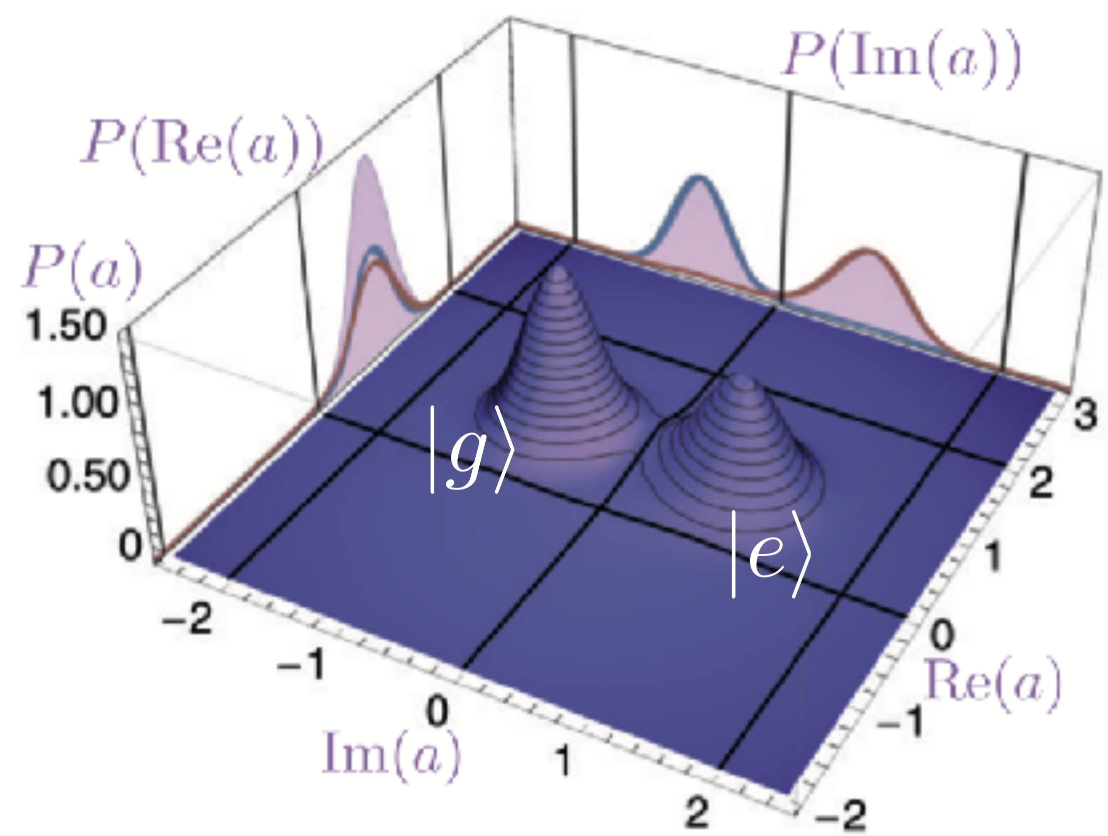


[Bergeal *et al.*, Nature 2010]
[Roch *et al.*, PRL 2012]

field going in ...



... field coming out

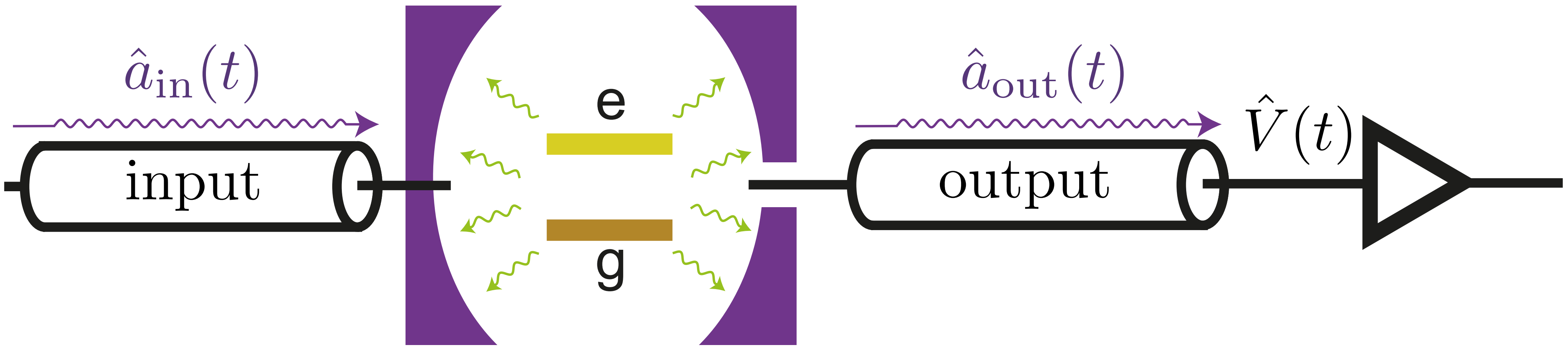


the phase changes depending on qubit state

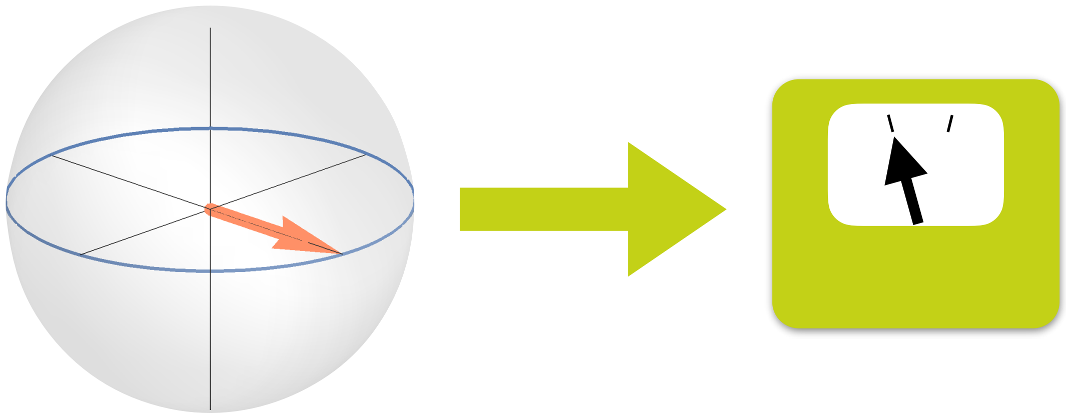
[Campagne-Ibarcq *et al.*, PRX 2013]

Dispersive Measurement

$$H = hf_q\frac{\sigma_Z}{2} + h(f_c - \frac{\chi}{2}\sigma_z)a^\dagger a$$



$$U = \frac{hf_q}{2}$$



$$\frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

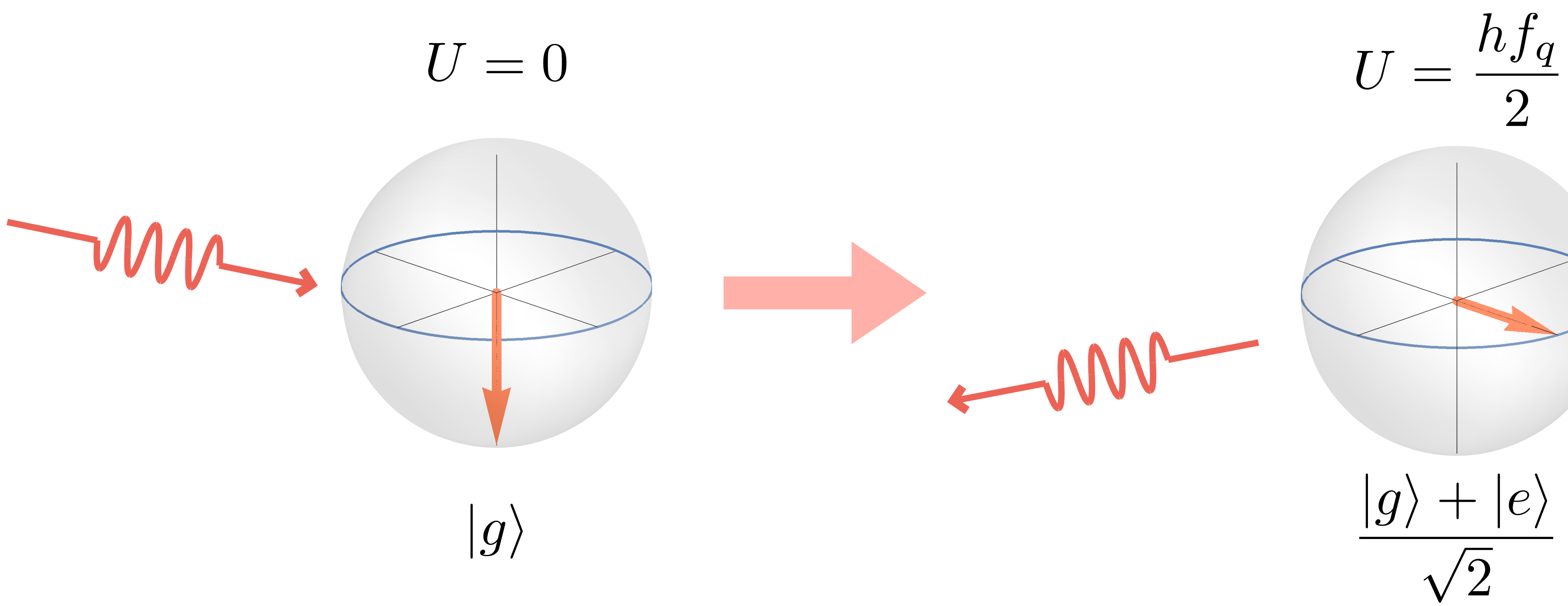
only the phase changes
not the field **amplitude**

no matter what the qubit state is,

$$P_{in} = P_{out}$$

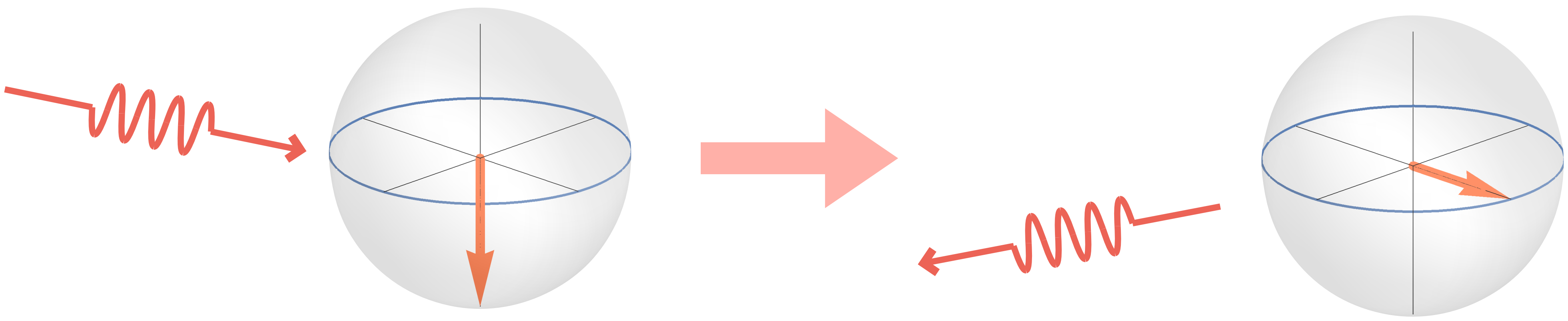
so, where does the « quantum heat » comes from?

Thermodynamics of preparing a quantum superposition



Thermodynamics of preparing a quantum superposition

$U = 0$ $\qquad$ $U = \frac{hf_q}{2}$



more accurate description

$$|\alpha\rangle \otimes |g\rangle$$

$$\frac{|\psi_g\rangle \otimes |g\rangle + |\psi_e\rangle \otimes |e\rangle}{\sqrt{2}}$$

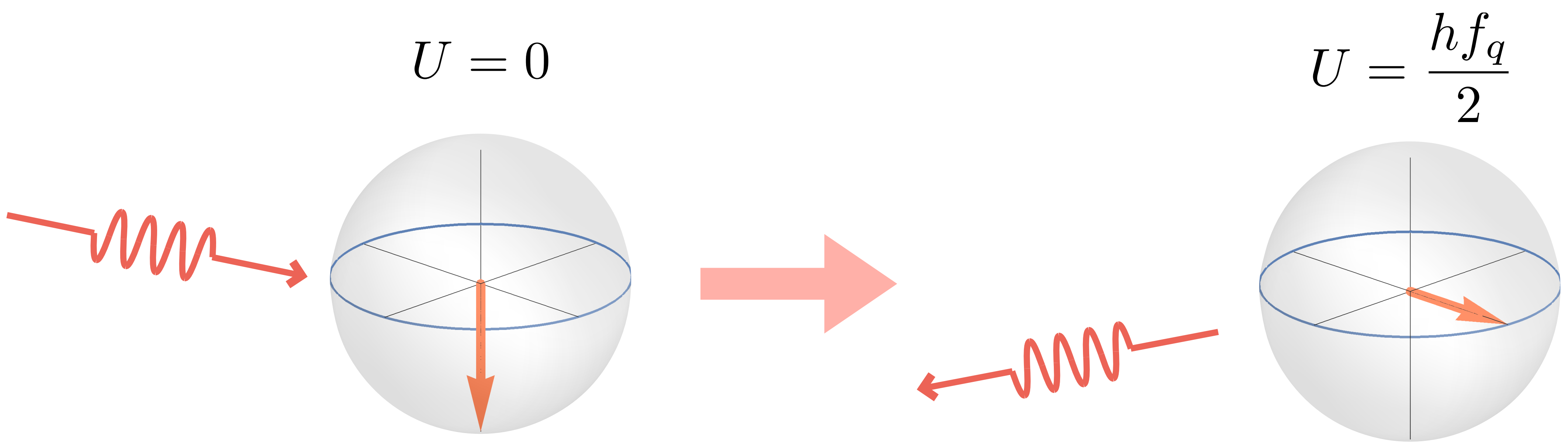
where $\langle a^\dagger a\rangle_{|\psi_g\rangle} = 1 + \langle a^\dagger a\rangle_{|\psi_e\rangle}$

superposition of two cases

field did not give a quantum of work to system + it did

$$\frac{|\psi_g\rangle \otimes |g\rangle + |\psi_e\rangle \otimes |e\rangle}{\sqrt{2}}$$

Thermodynamics of preparing a quantum superposition



more accurate description

$$|\alpha\rangle \otimes |g\rangle$$

$$\frac{|\psi_g\rangle \otimes |g\rangle + |\psi_e\rangle \otimes |e\rangle}{\sqrt{2}}$$

where $\langle a^\dagger a\rangle_{|\psi_g\rangle} = 1 + \langle a^\dagger a\rangle_{|\psi_e\rangle}$

note that the qubit-field interaction barely modifies the field state if $\alpha \gg 1$

$\langle\psi_g|\psi_e\rangle \to 1$ does not prevent $\langle\psi_g|a^\dagger a|\psi_g\rangle - \langle\psi_e|a^\dagger a|\psi_e\rangle = 1$

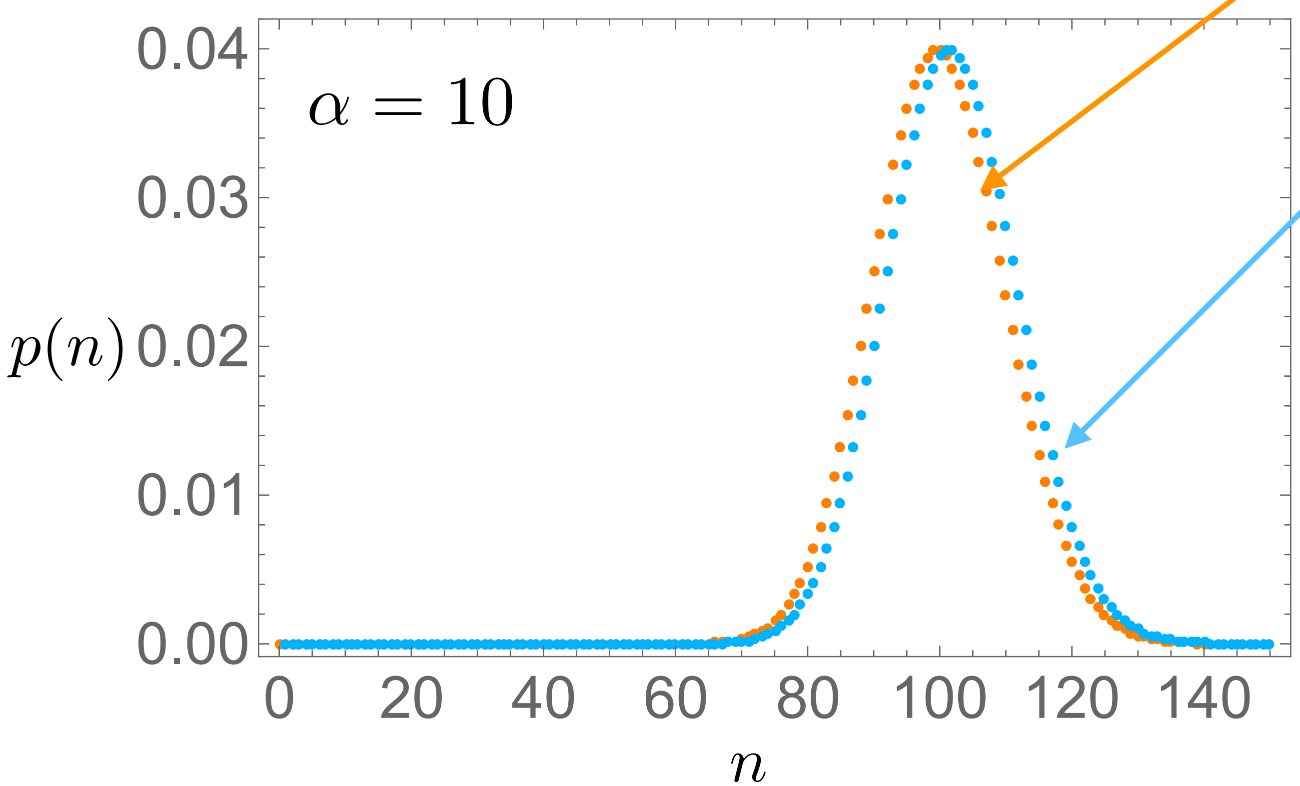
$$\alpha \gg 1 \Rightarrow \frac{|\psi_g\rangle \otimes |g\rangle + |\psi_e\rangle \otimes |e\rangle}{\sqrt{2}} \approx |\alpha\rangle \otimes \frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

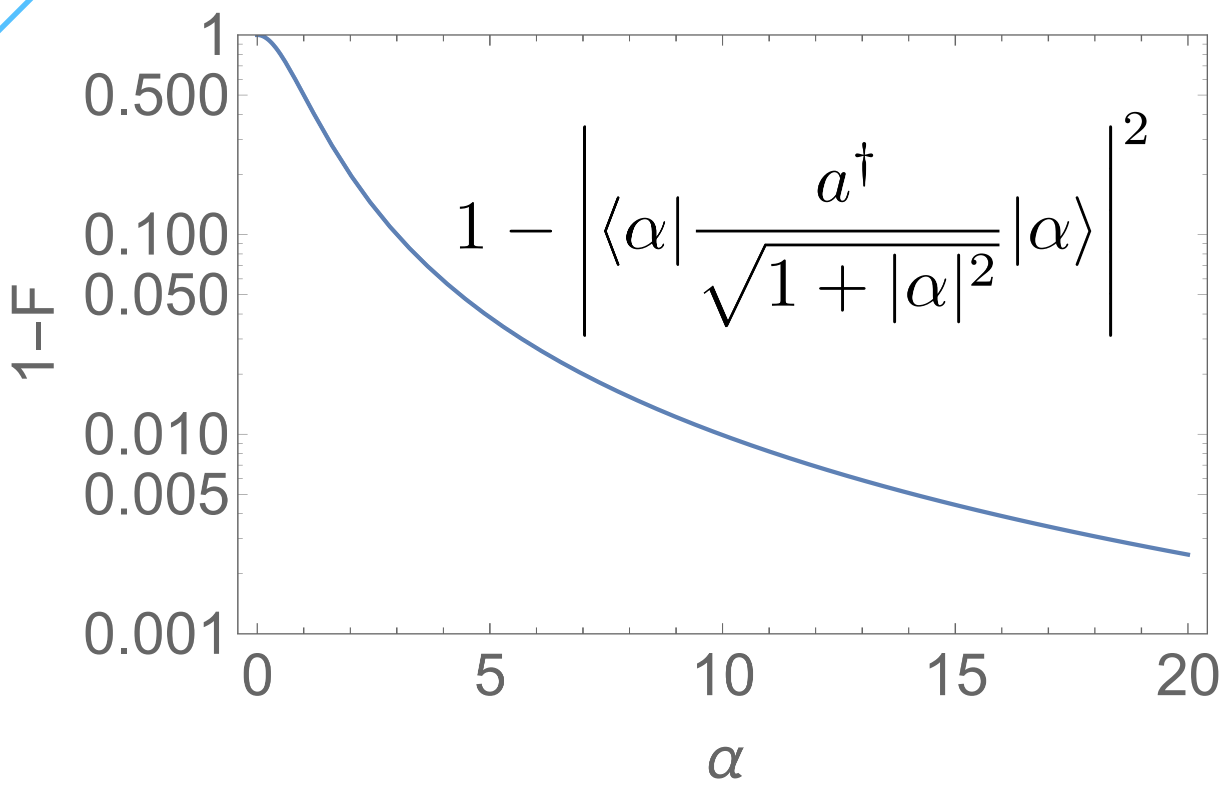
almost zero correlations

yet, a measurable energy difference!

can one measure it in single shot?

simple example: $|\alpha\rangle$ and $\frac{a^\dagger|\alpha\rangle}{\sqrt{1+|\alpha|^2}}$

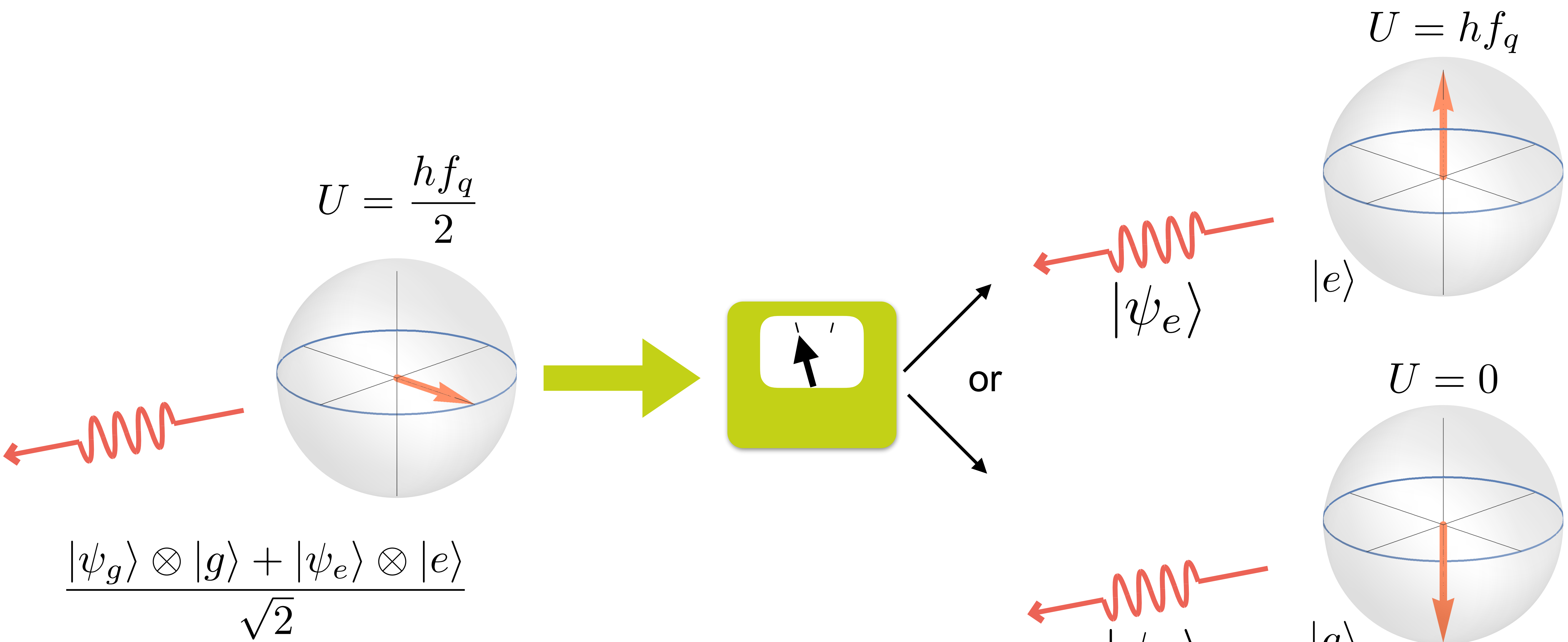




in one shot, no measurement can tell with high fidelity whether one state of the other

energy difference can be measured on average only

where does the « quantum heat » comes from?



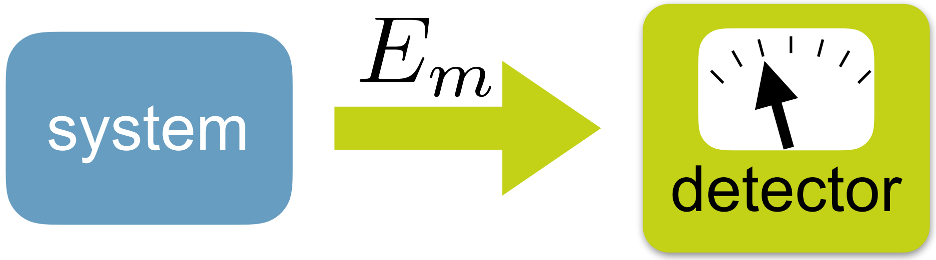
where $\langle a^\dagger a\rangle_{|\psi_g\rangle} = 1 + \langle a^\dagger a\rangle_{|\psi_e\rangle}$

measurement **reveals** what amount of **work** has been transferred from the drive to the qubit

can we measure this energy difference in the drive?

« quantum heat »

« quantum heat »



does it obey a second law?

yes, fluctuation theorems can be extended with this work and « heat »

can it fuel an engine?

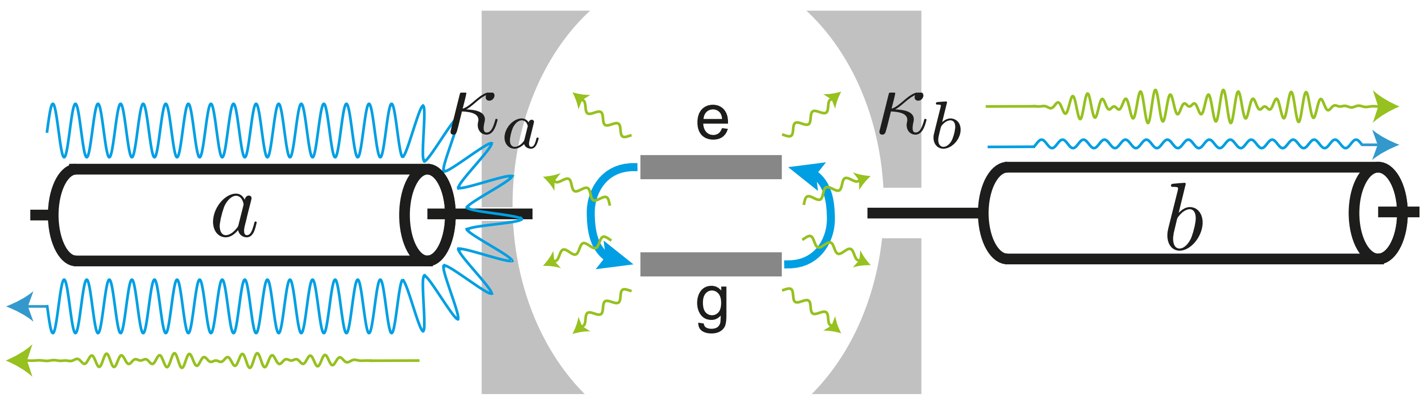
yes, repeatedly measuring σ_x on a qubit can provide work on a cycle

what provides this energy?

the **work** used to prepare the system state

can it be measured directly and not just inferred?

What do the output lines contain?



input-output theory
+
adiabatic elimination of the cavity

$$\langle a_{out}\rangle = \langle a_{out}\rangle_0 - \sqrt{\gamma_a}\langle\sigma_-\rangle_{\rho(t)}$$

reflected
driving field

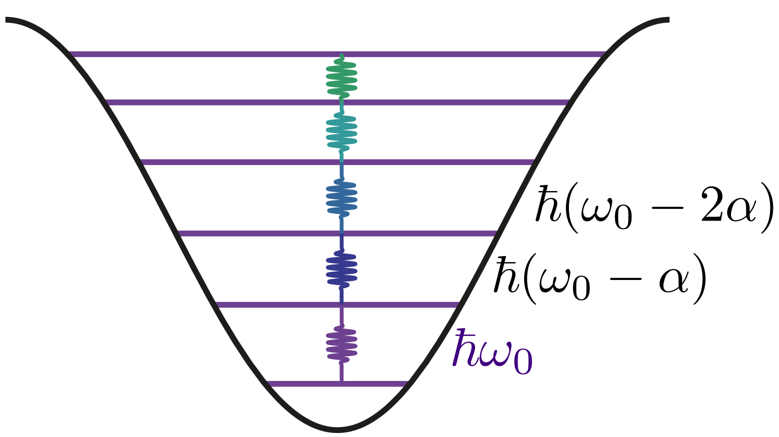
$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\langle\sigma_-\rangle_{\rho(t)}$$

transmitted
driving field

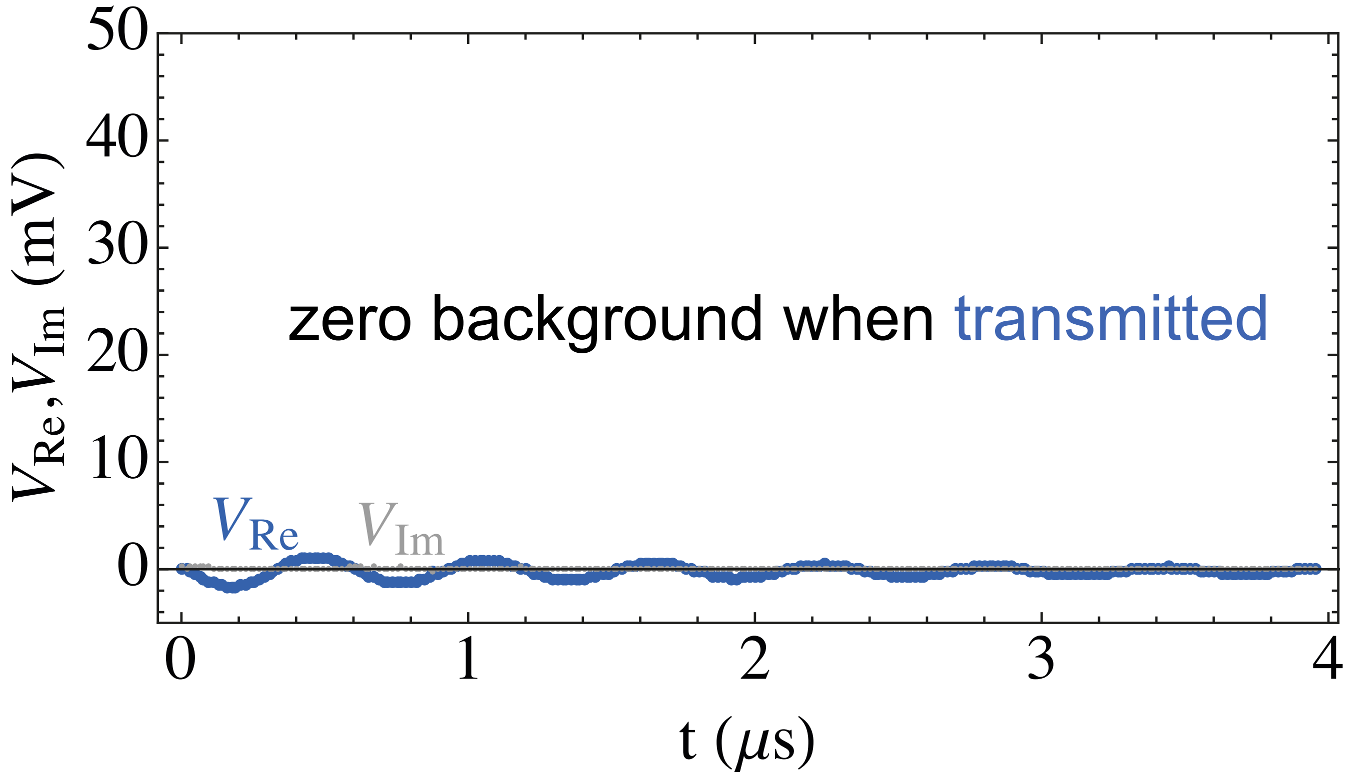
$$\frac{\gamma_a}{\gamma_b} = \frac{\kappa_a}{\kappa_b} \ll 1$$

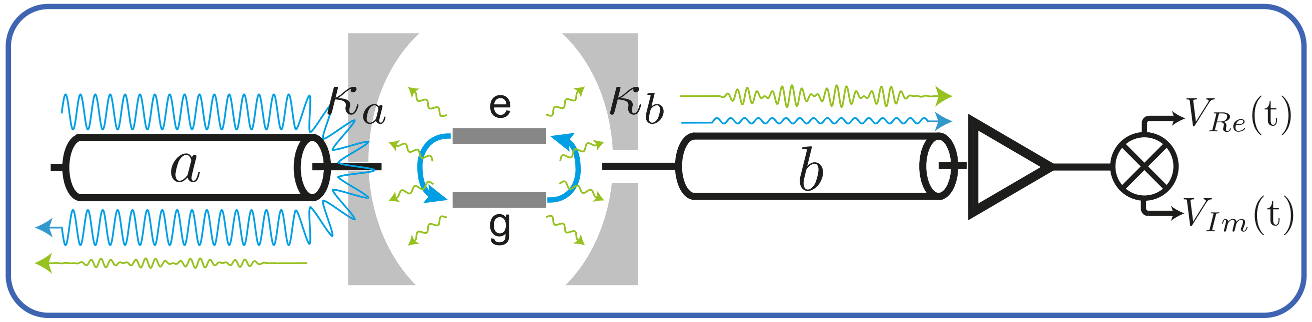
$$\gamma_i = \kappa_i \frac{\chi}{2\alpha}$$

$$H_{\text{coupl}} = -\hbar\chi a^\dagger a|e\rangle\langle e|$$



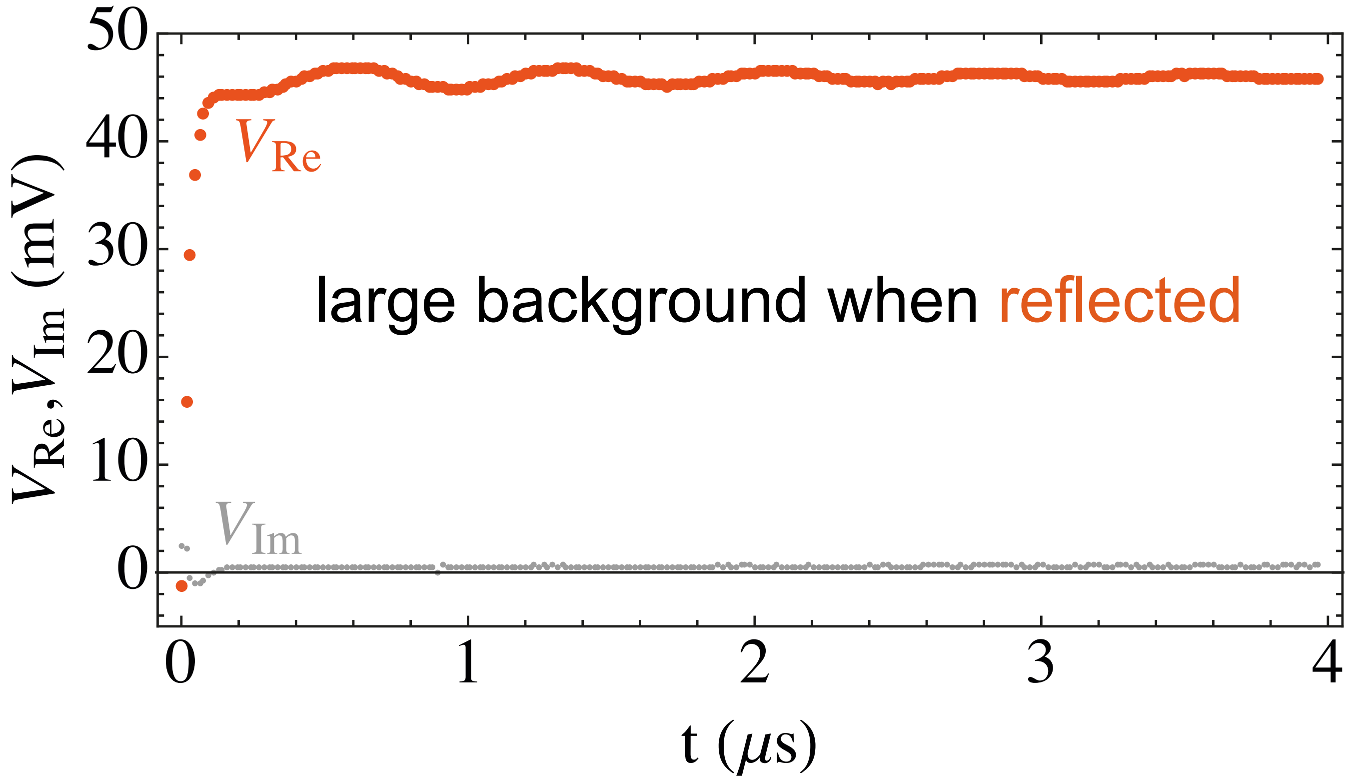
Amplitude of fluorescence



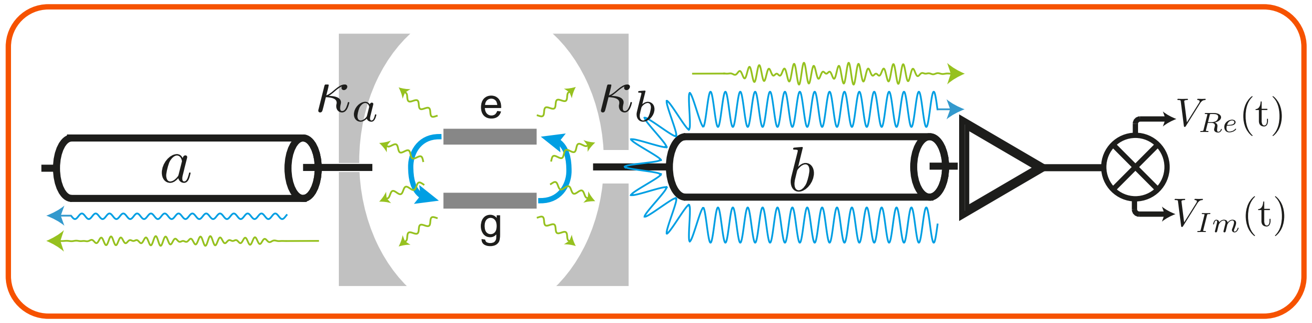


$$\langle b_{out}\rangle \propto \overline{V_{Re}} + i\overline{V_{Im}}$$

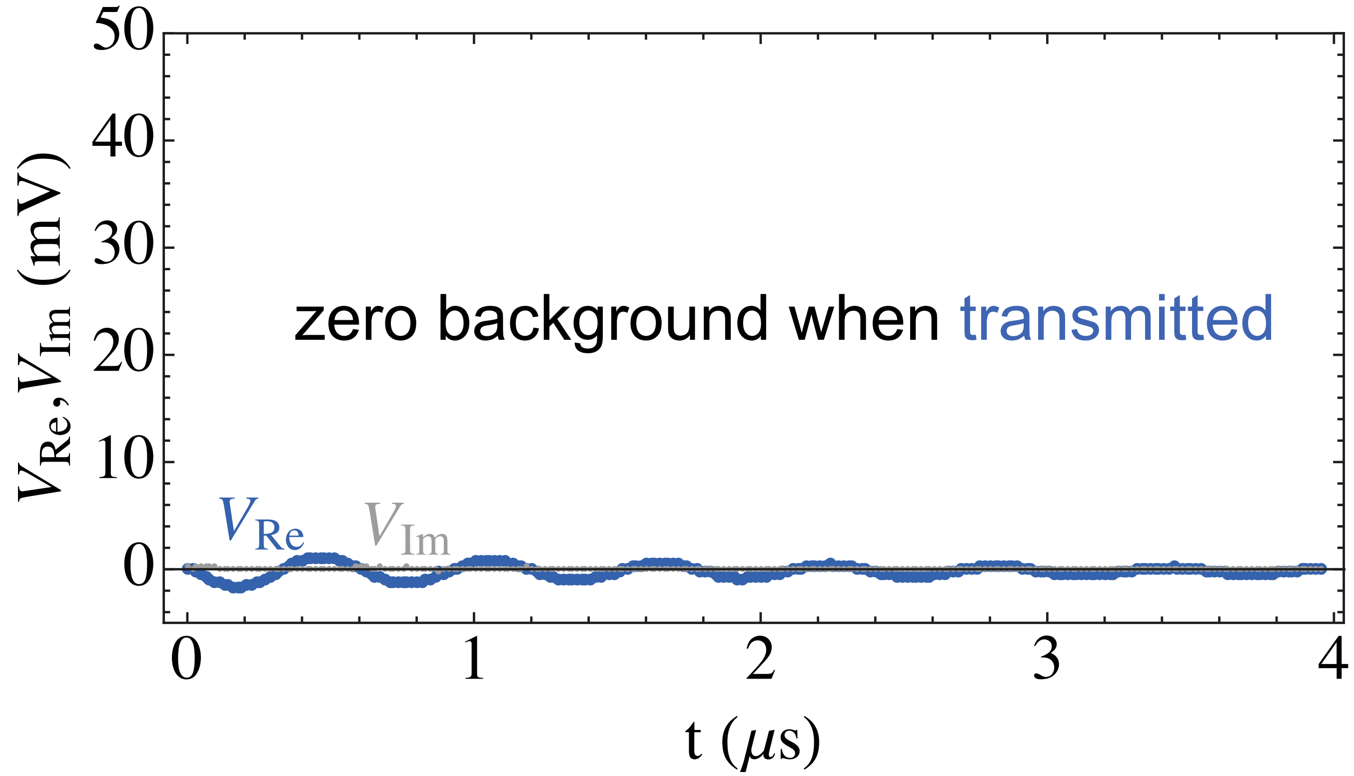
$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\langle\sigma_-\rangle_{\rho(t)}$$

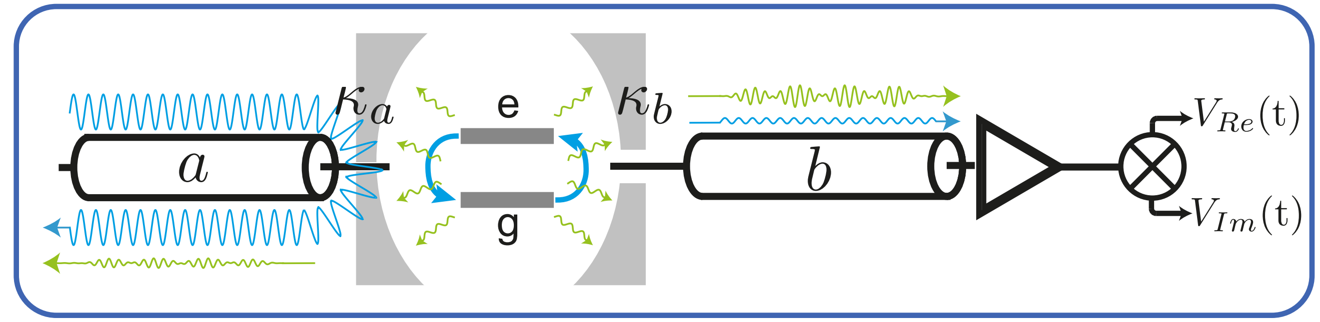


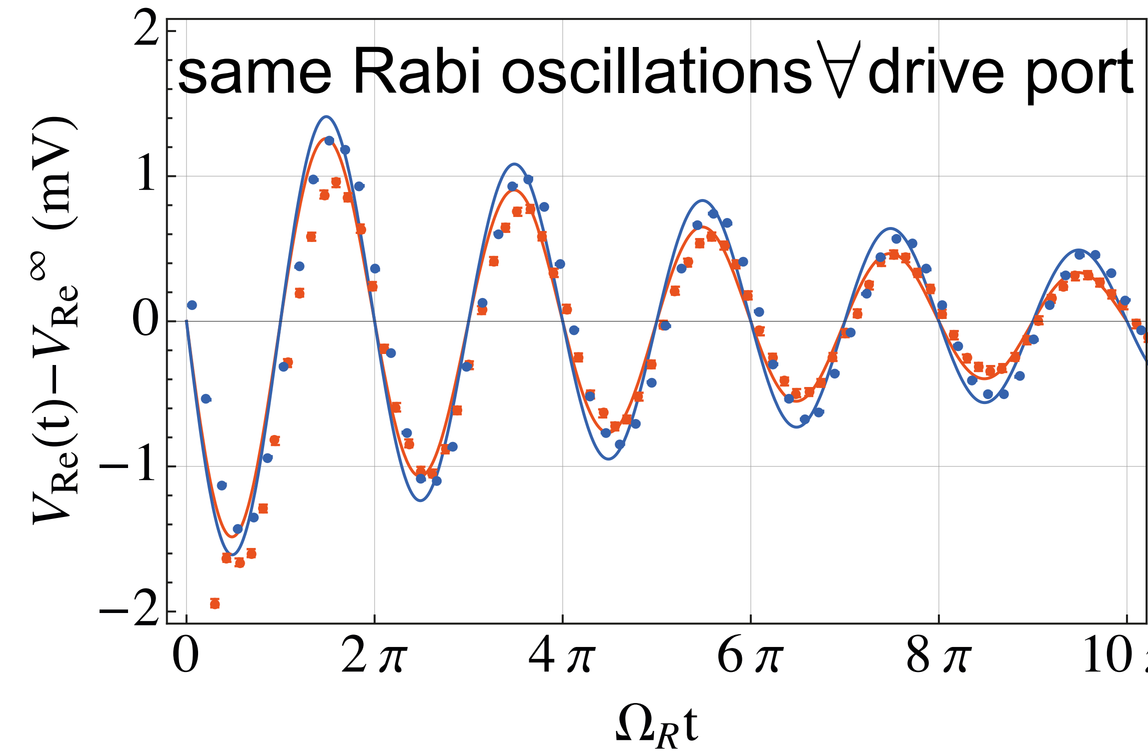
$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\frac{\langle\sigma_x\rangle}{2} - i\sqrt{\gamma_b}\frac{\langle\sigma_y\rangle}{2}$$



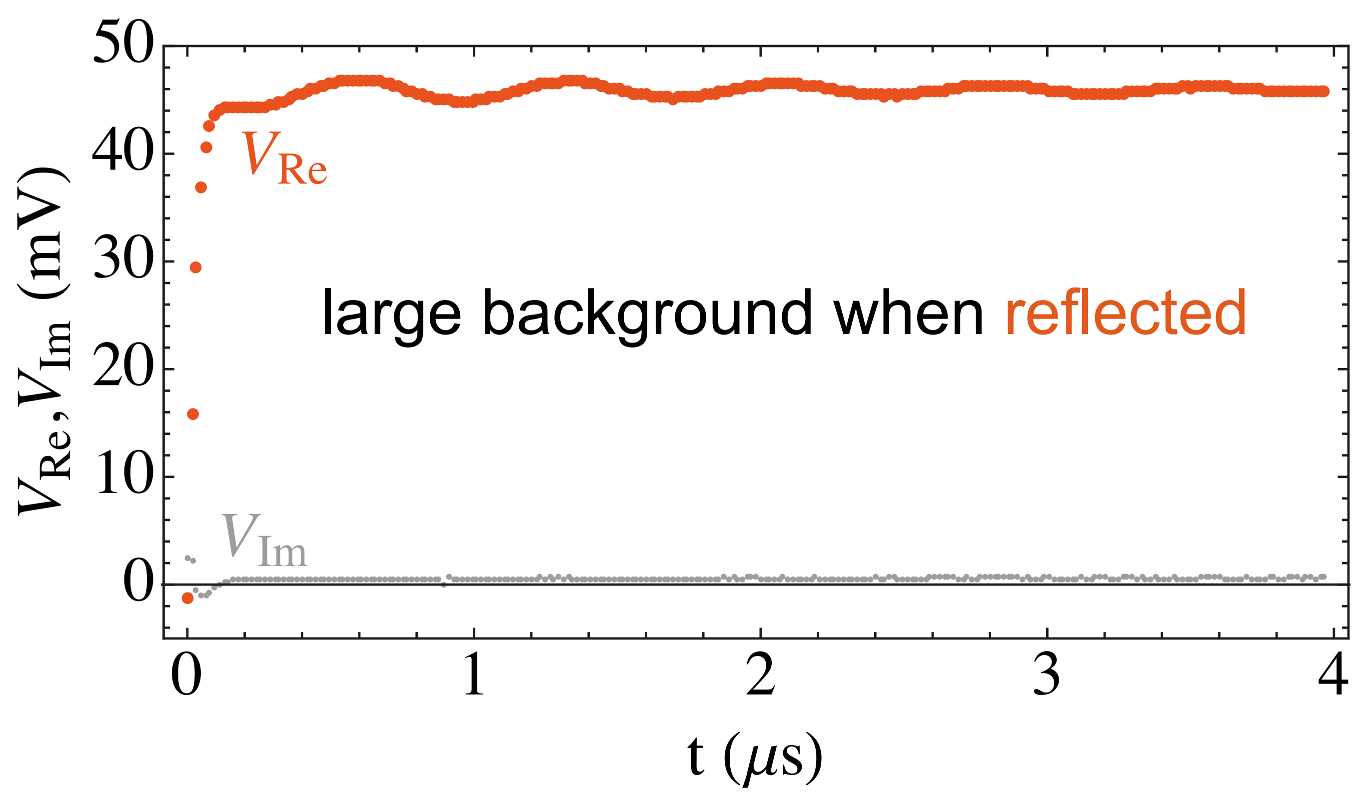
Amplitude of fluorescence and Rabi oscillations

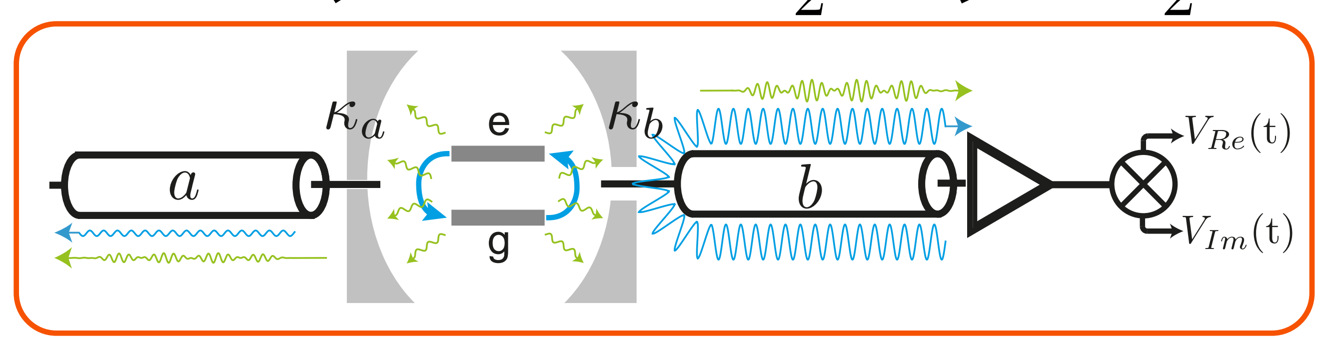




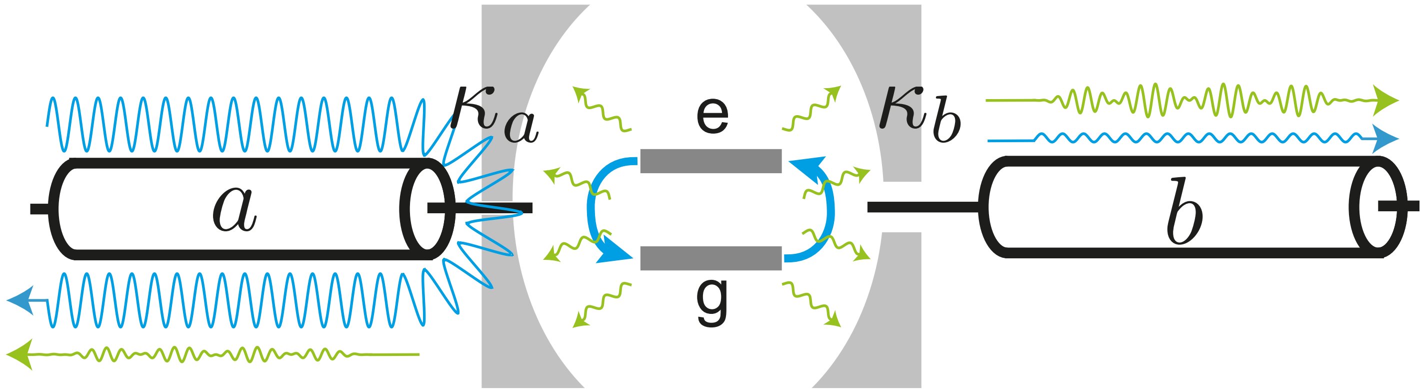


$$\langle b_{out} \rangle = \langle b_{out} \rangle_0 - \sqrt{\gamma_b} \frac{\langle \sigma_x \rangle}{2} - i \sqrt{\gamma_b} \frac{\langle \sigma_y \rangle}{2}$$





How many photons exit into the output lines?



input-output theory
+
adiabatic elimination of the cavity

$$\langle a_{out} \rangle = \langle a_{out} \rangle_0 - \sqrt{\gamma_a} \langle \sigma_- \rangle_{\rho(t)}$$

$$\langle a^\dagger_{out} a_{out} \rangle = \langle a^\dagger_{out} a_{out} \rangle_0 + \gamma_a \frac{1 + \langle \sigma_z \rangle_{\rho(t)}}{2} + \frac{\Omega_R}{2} \langle \sigma_x \rangle_{\rho(t)}$$

spontaneous emission

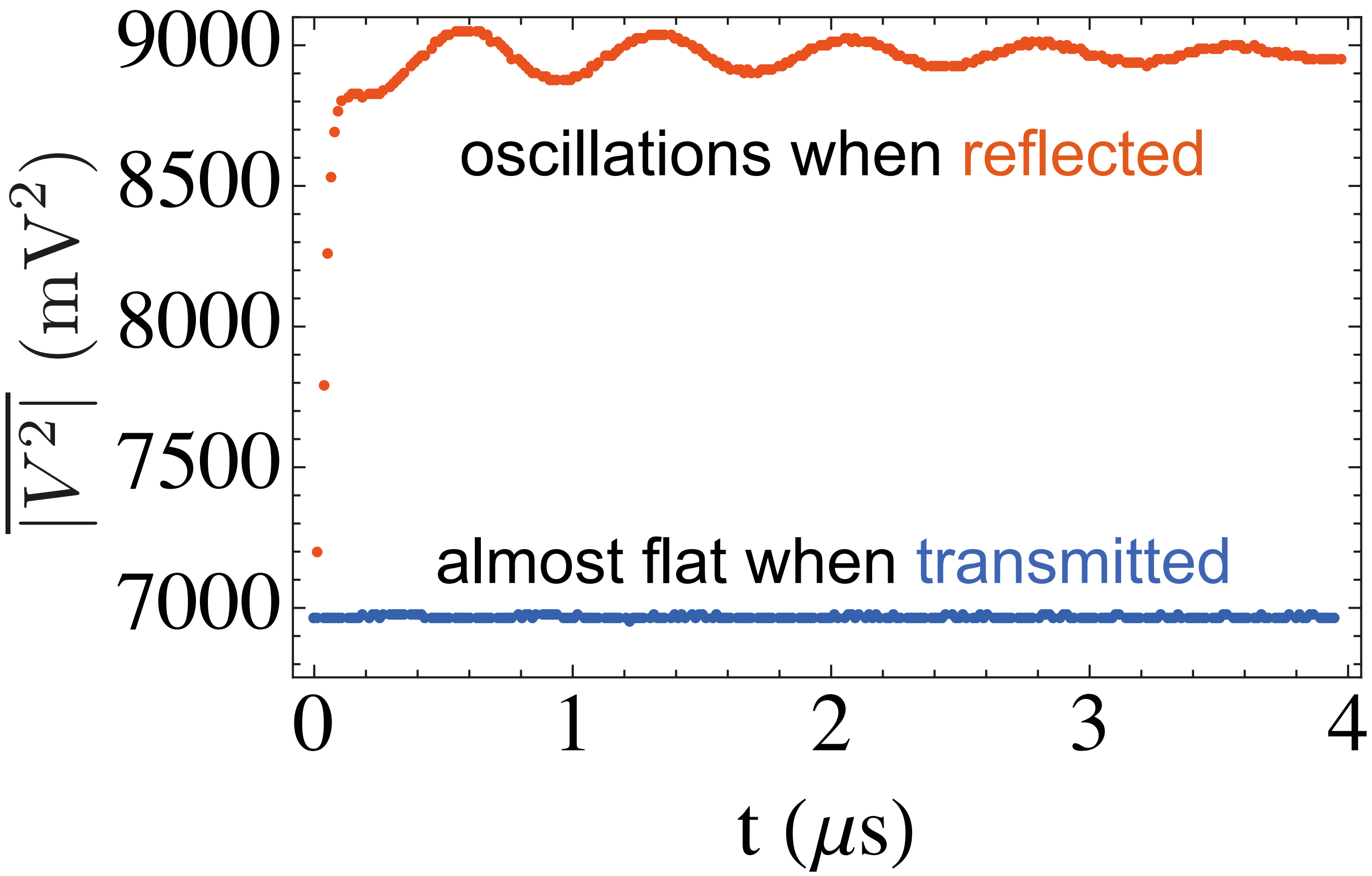
stimulated emission

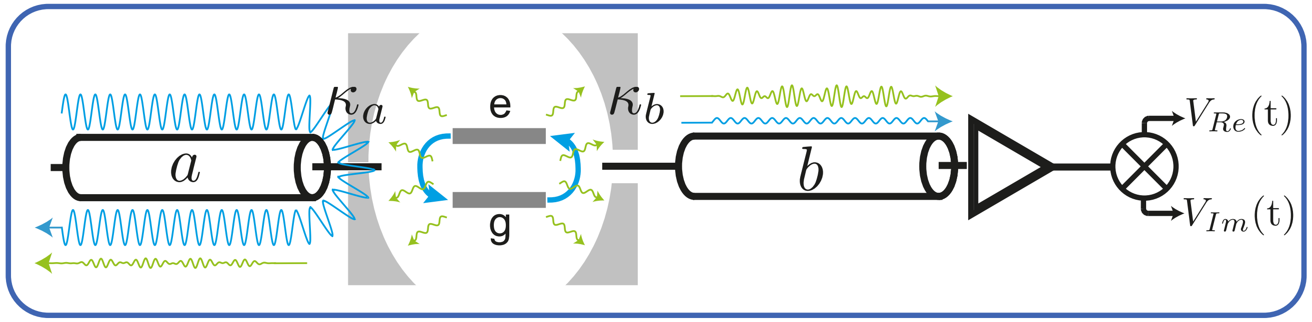
goes back with reflected drive

$$\langle b_{out} \rangle = \langle b_{out} \rangle_0 - \sqrt{\gamma_b} \langle \sigma_- \rangle_{\rho(t)}$$

$$\langle b^\dagger_{out} b_{out} \rangle = \langle b^\dagger_{out} b_{out} \rangle_0 + \gamma_b \frac{1 + \langle \sigma_z \rangle_{\rho(t)}}{2}$$

How many photons exit into the output lines?



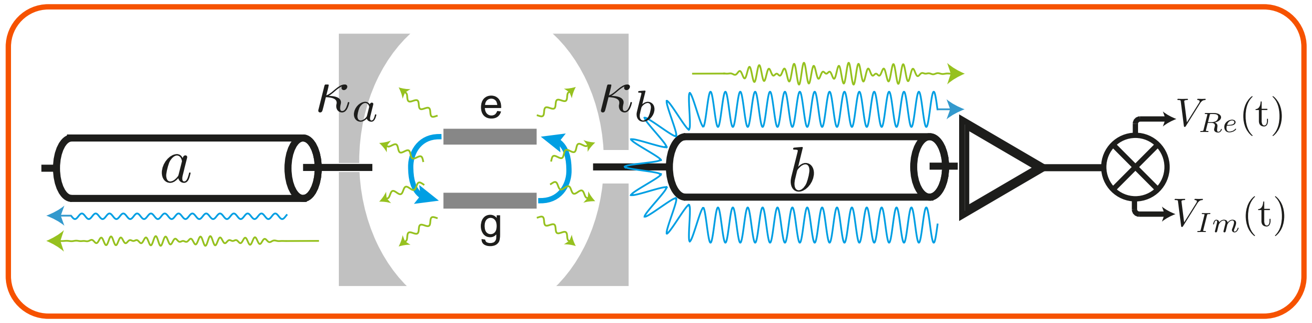


$$\langle b_{out} \rangle \propto \overline{V_{Re}} + i\overline{V_{Im}}$$

$$\langle b^\dagger_{out} b_{out} \rangle \propto \overline{|V|^2} = \overline{V^2_{Re}} + \overline{V^2_{Im}}$$

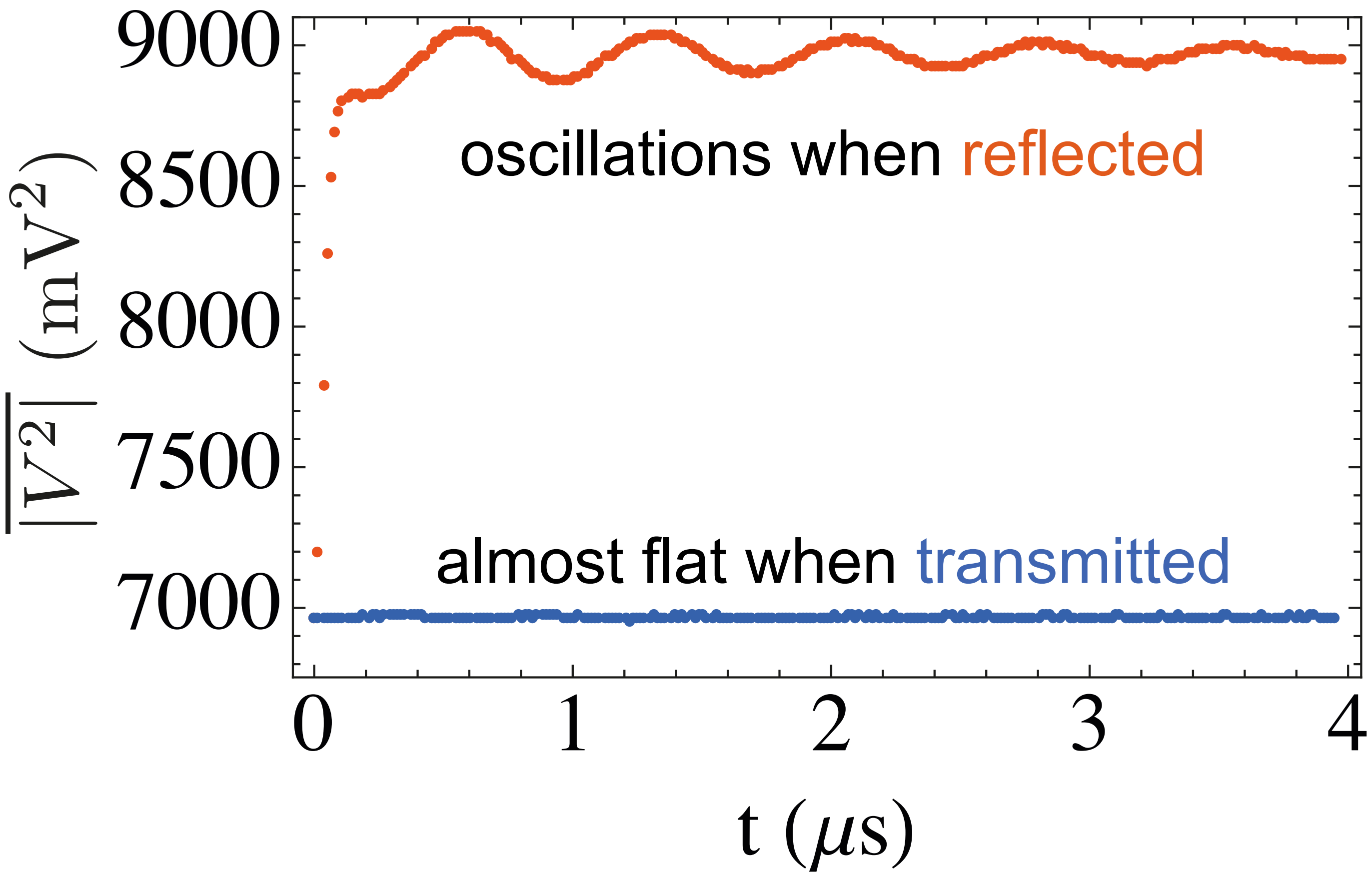
$$\langle b^\dagger_{out} b_{out} \rangle = \langle b^\dagger_{out} b_{out} \rangle_0 + \gamma_b \frac{1 + \langle \sigma_z \rangle_{\rho(t)}}{2} + \frac{\Omega_R}{2} \langle \sigma_x \rangle_{\rho(t)}$$

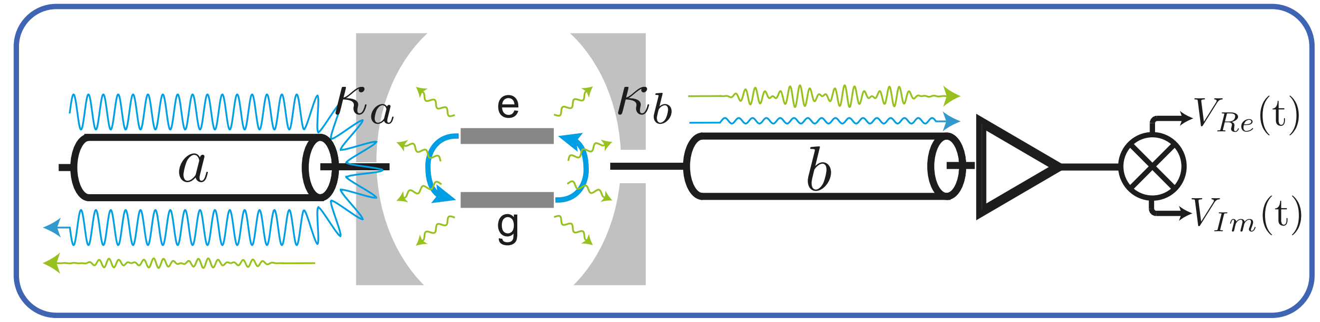
$$\gamma_b \approx (2\ \mu\text{s})^{-1} \ll \frac{\Omega_R}{2} \approx (0.2\ \mu\text{s})^{-1}$$



Power density measured in [Astafiev et al., Science 2010]

How many photons exit into the output lines?

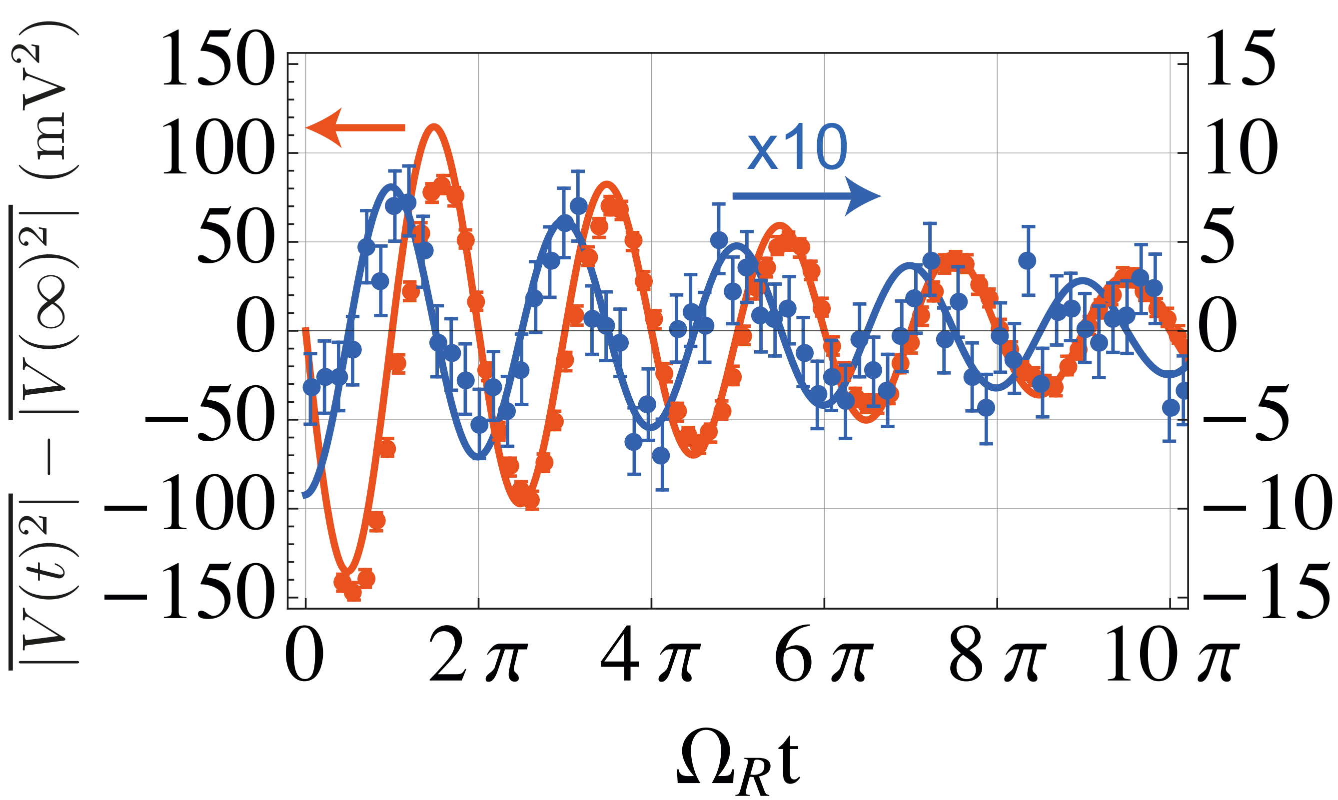




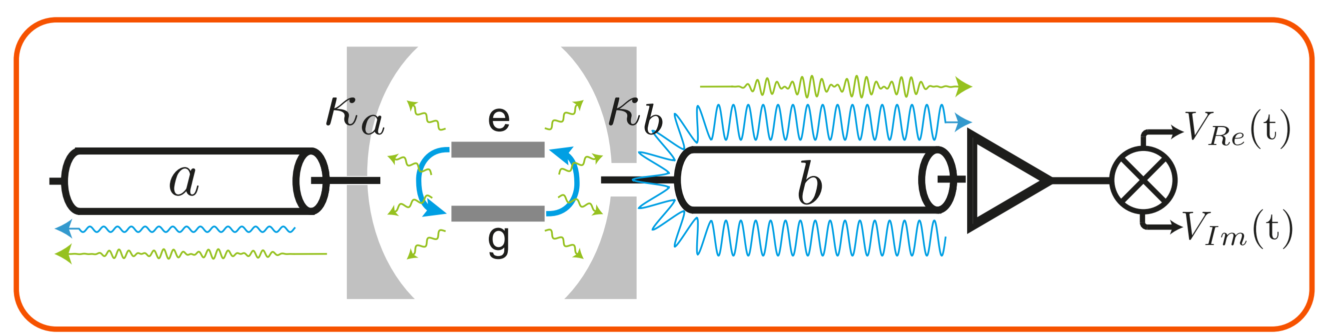
$$\langle b_{out} \rangle \propto \overline{V_{Re}} + i\overline{V_{Im}}$$

$$\langle b^{\dagger}_{out} b_{out} \rangle \propto \overline{|V|^2} = \overline{V^2_{Re}} + \overline{V^2_{Im}}$$

$$\langle b^{\dagger}_{out} b_{out} \rangle = \langle b^{\dagger}_{out} b_{out} \rangle_0 + \gamma_b \frac{1 + \langle \sigma_z \rangle_{\rho(t)}}{2} + \frac{\Omega_R}{2} \langle \sigma_x \rangle_{\rho(t)}$$



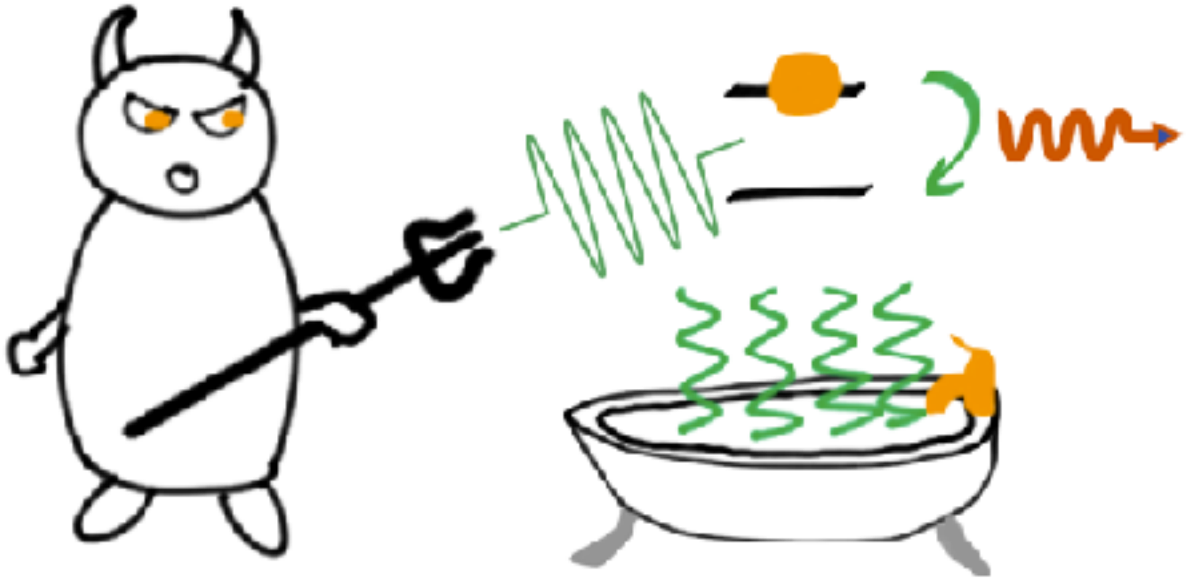
$$\gamma_b \approx (2\ \mu\text{s})^{-1} \ll \frac{\Omega_R}{2} \approx (0.2\ \mu\text{s})^{-1}$$



Rabi oscillations of $\langle \sigma_z \rangle$ when transmitted

Rabi oscillations of $\langle \sigma_x \rangle$ when reflected

Measuring the outgoing energy



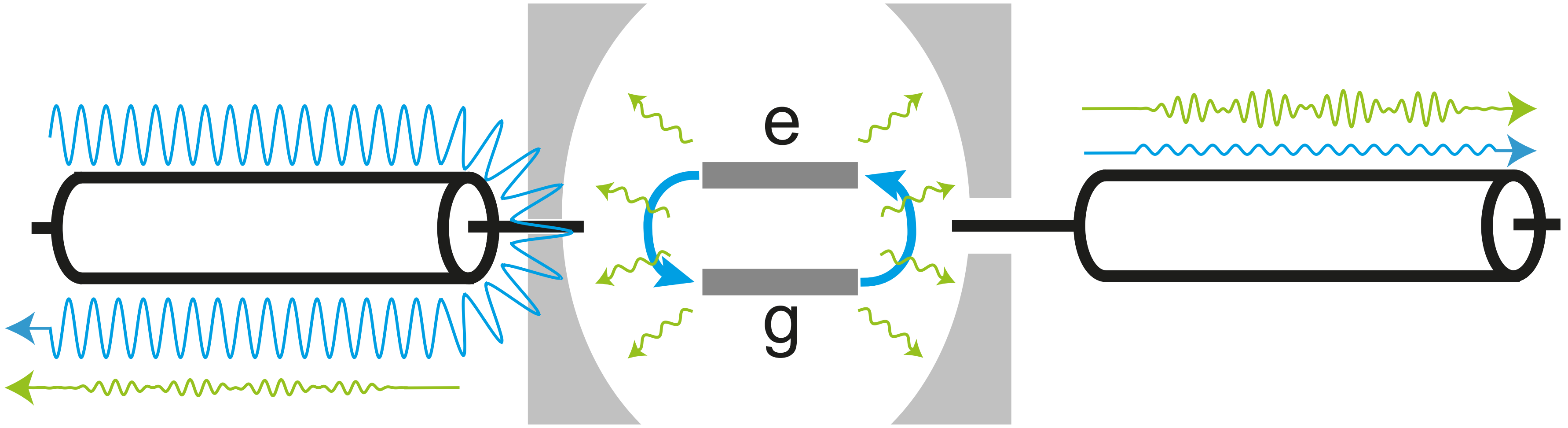
work

extra photon at f_q

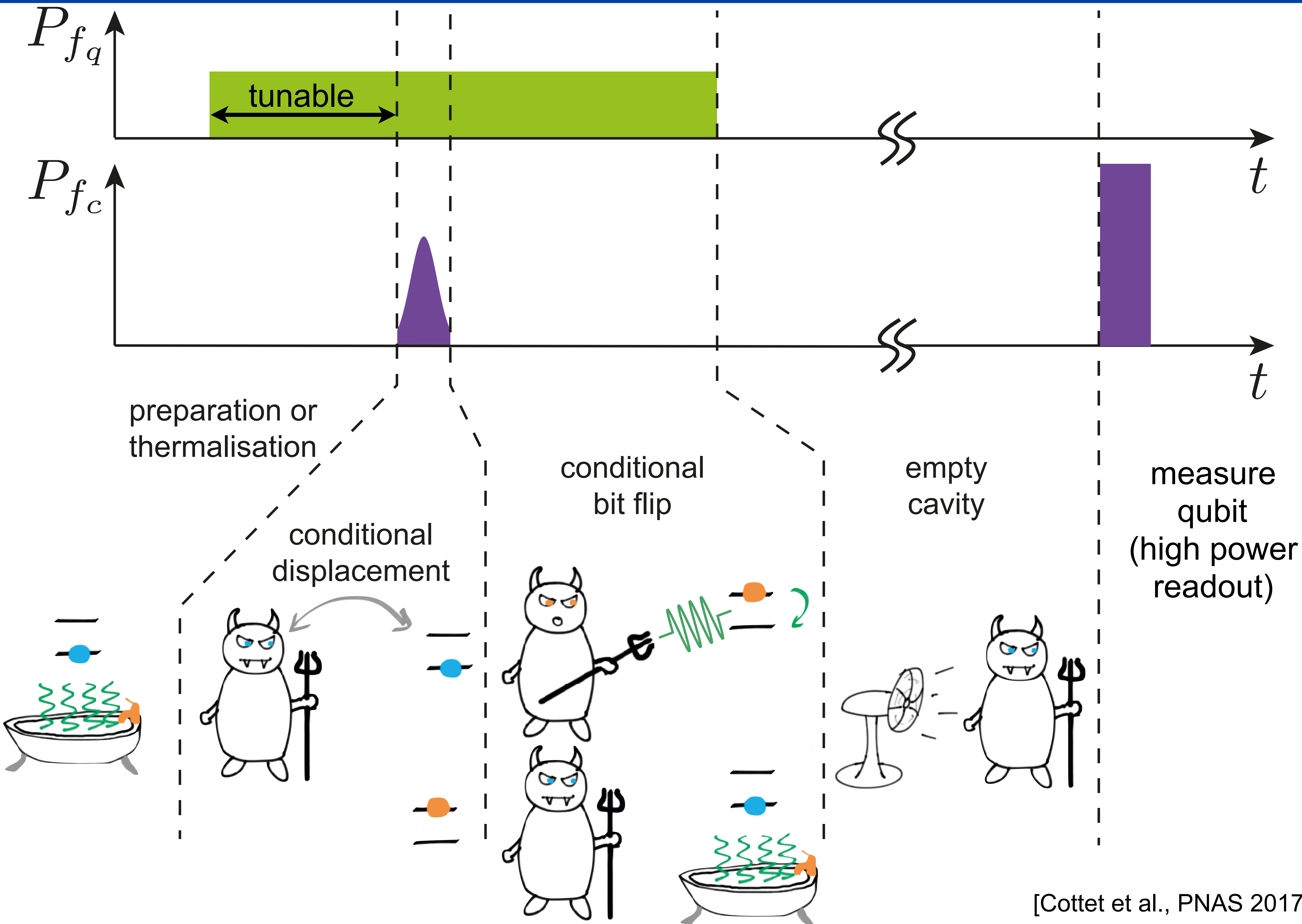
quantum Maxwell demon

[Cottet et al., PNAS 2017]

How to extract and observe a quantum of work out of a qubit?



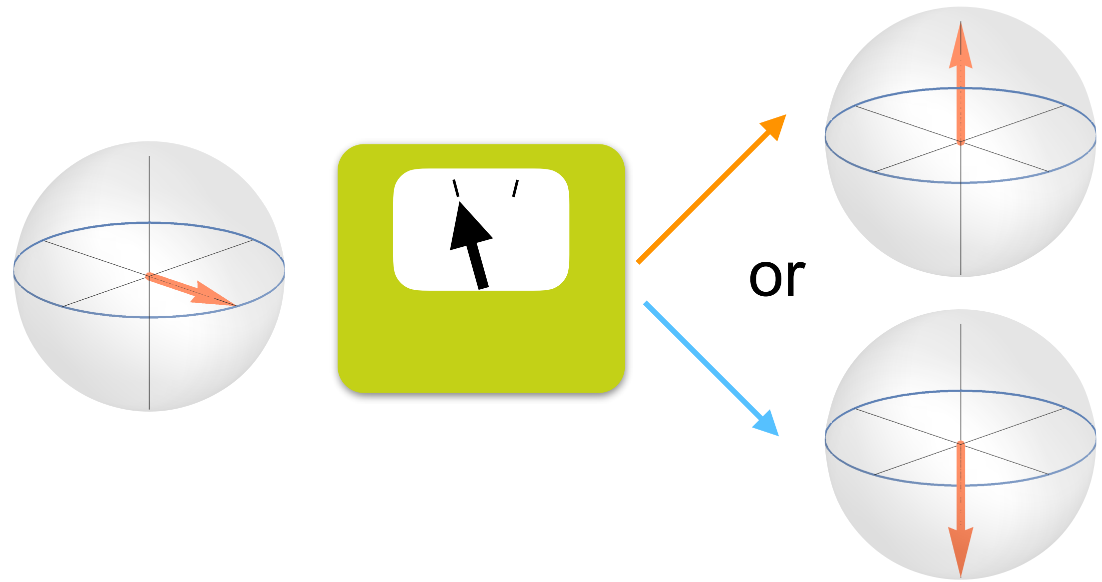
Pulse sequence



[Cottet et al., PNAS 2017]

extracted work post selected on demon's memory

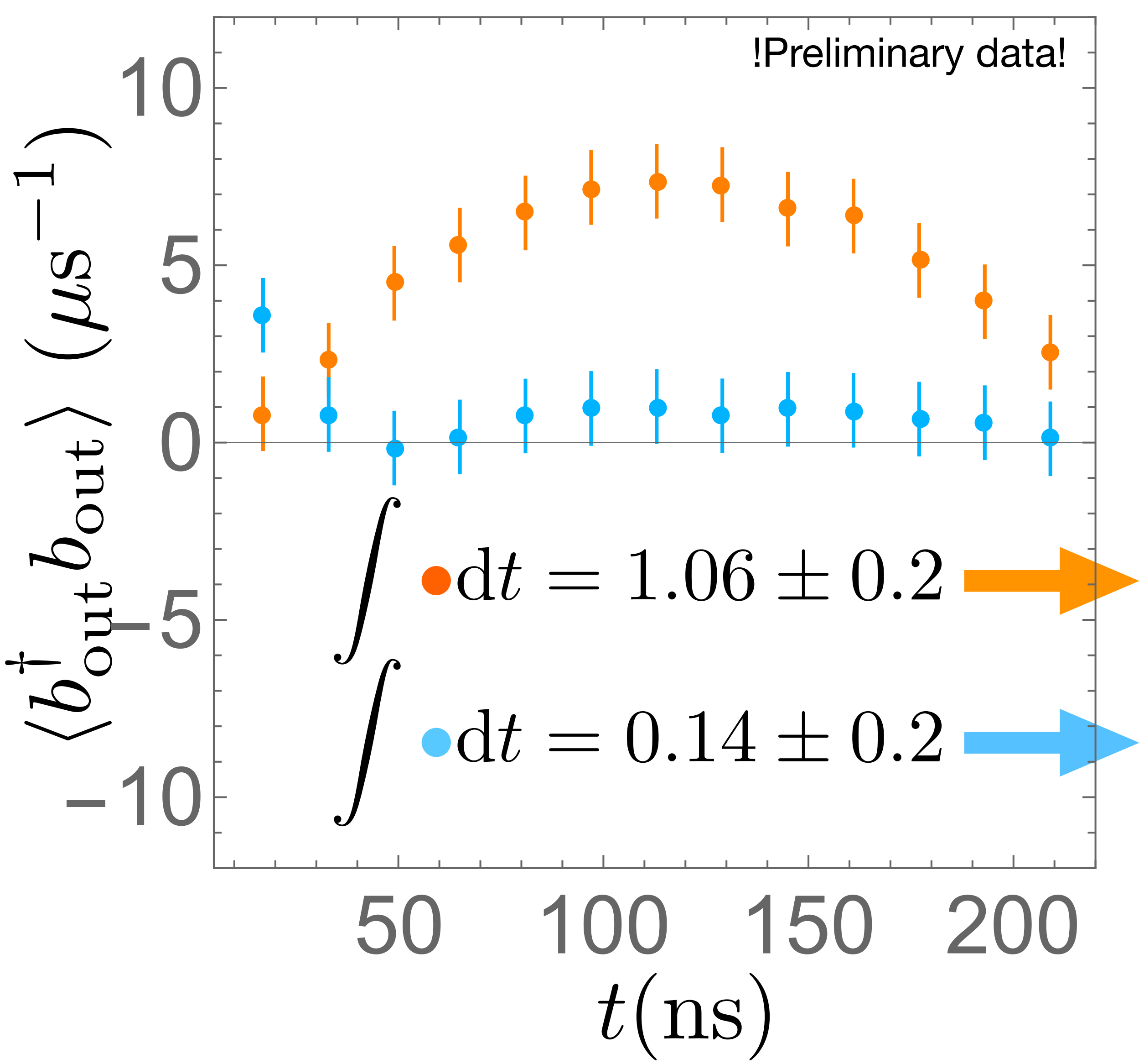
$U = \frac{hf_q}{2}$



$E_m = +\frac{hf_q}{2}$ demon's memory allows work extraction

or

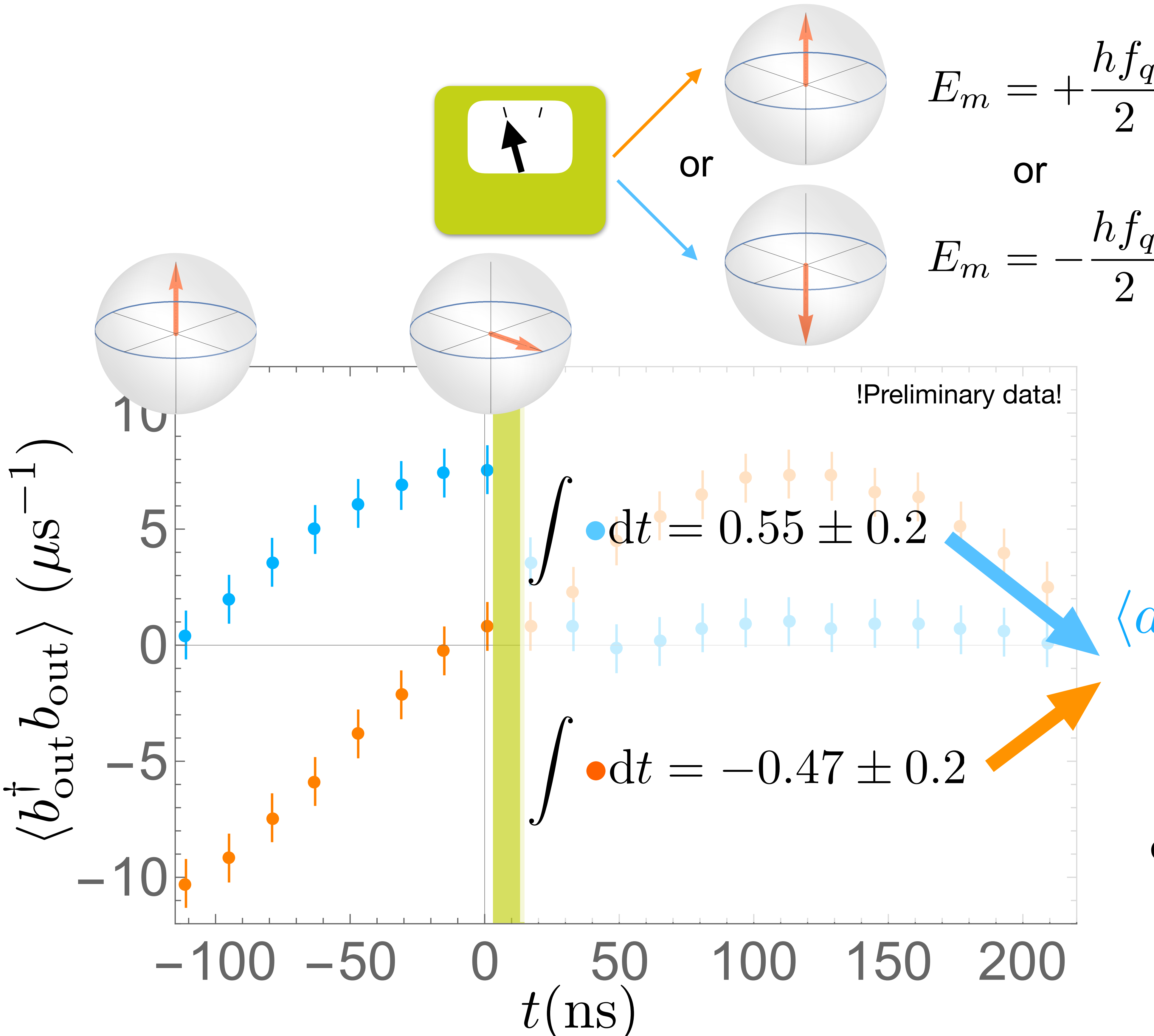
$E_m = -\frac{hf_q}{2}$ demon's memory prevents work exchange



1 extracted quantum

no extraction

measuring the « quantum heat »

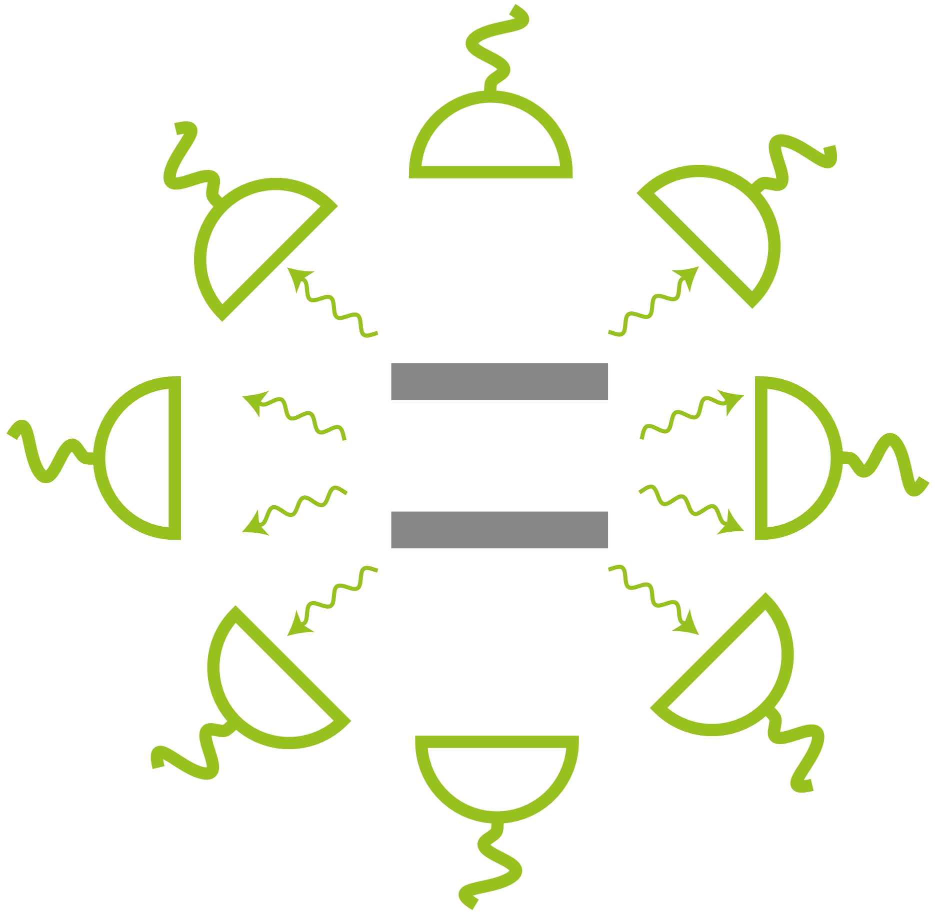


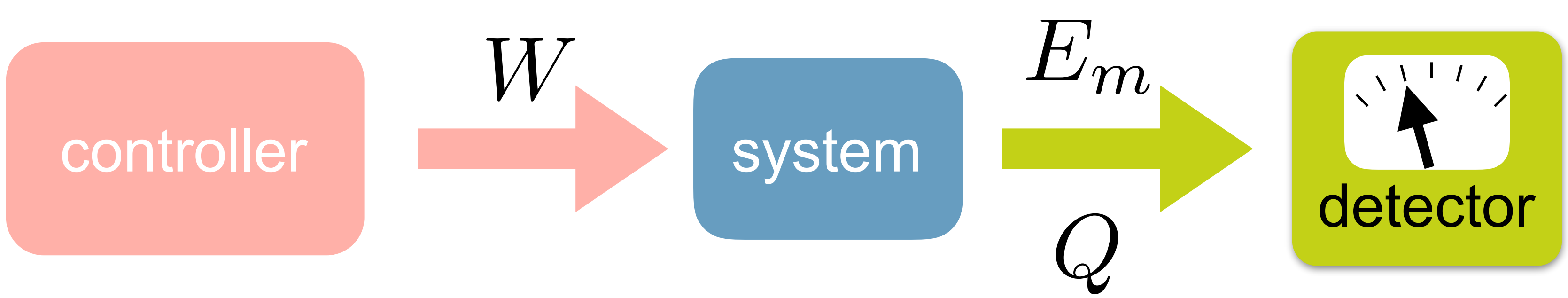
$$\langle a^\dagger a \rangle_{|\psi_g\rangle} - \langle a^\dagger a \rangle_{|\psi_e\rangle} = 1.02 \pm 0.4$$

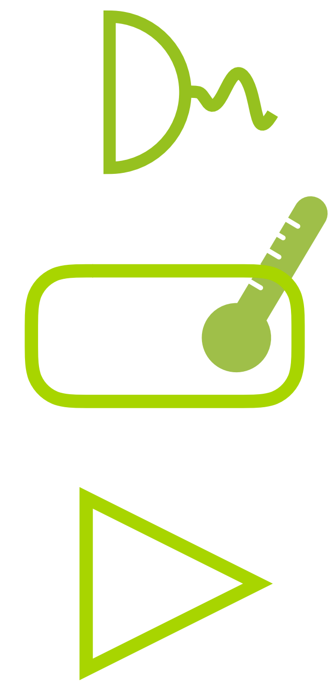
direct measurement of the quantum heat!

but each signal are unexpected => **need to reproduce**

Particular case of fluorescence measurement



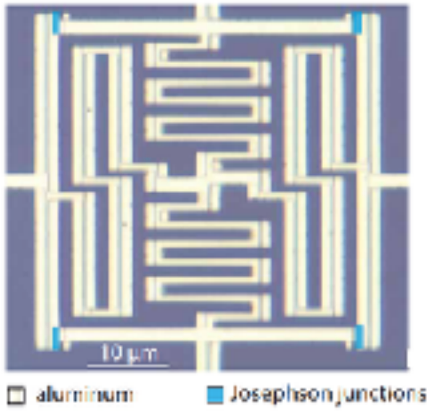




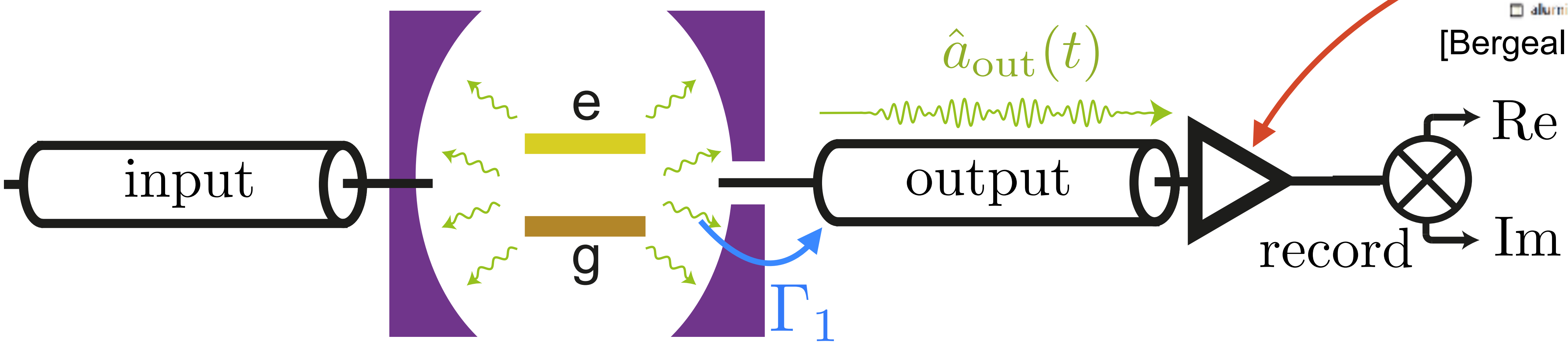
the detector can also get heat from system

[Elouard, Herrera-Marti, Auffèves, Esposito, in prep.]

Fluorescence Measurement



[Bergeal *et al.*, Nature 2010]

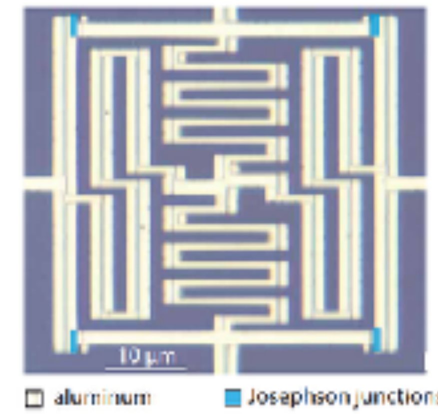


mean signal $\langle \hat{a}_{\text{out}} \rangle \propto \sqrt{\Gamma_1} \langle \sigma_- \rangle$

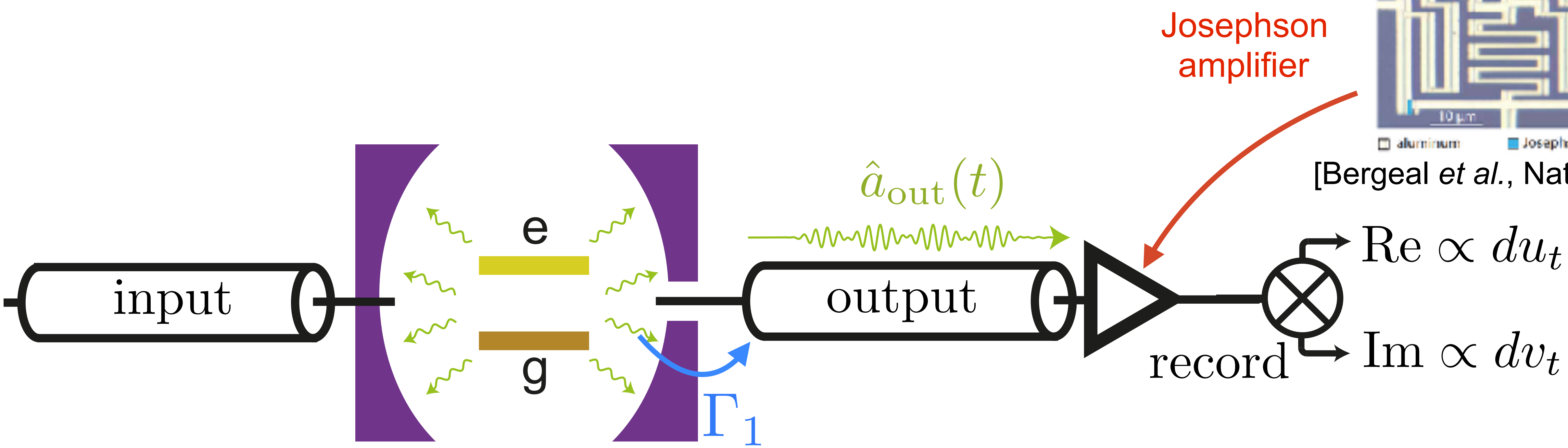
jump operator $\propto \sigma_- = |g\rangle \langle e| = \dfrac{\sigma_x - i\sigma_y}{2}$

$\Gamma_1 = (12.5\ \mu\text{s})^{-1}$

Fluorescence Measurement



[Bergeal *et al.*, Nature 2010]



$$du_t = \sqrt{\frac{\eta\Gamma_1}{2}} \langle \sigma_X \rangle_{\rho_t} dt + dW_{t,1}$$

$$dv_t = \sqrt{\frac{\eta\Gamma_1}{2}} \langle \sigma_Y \rangle_{\rho_t} dt + dW_{t,2}$$

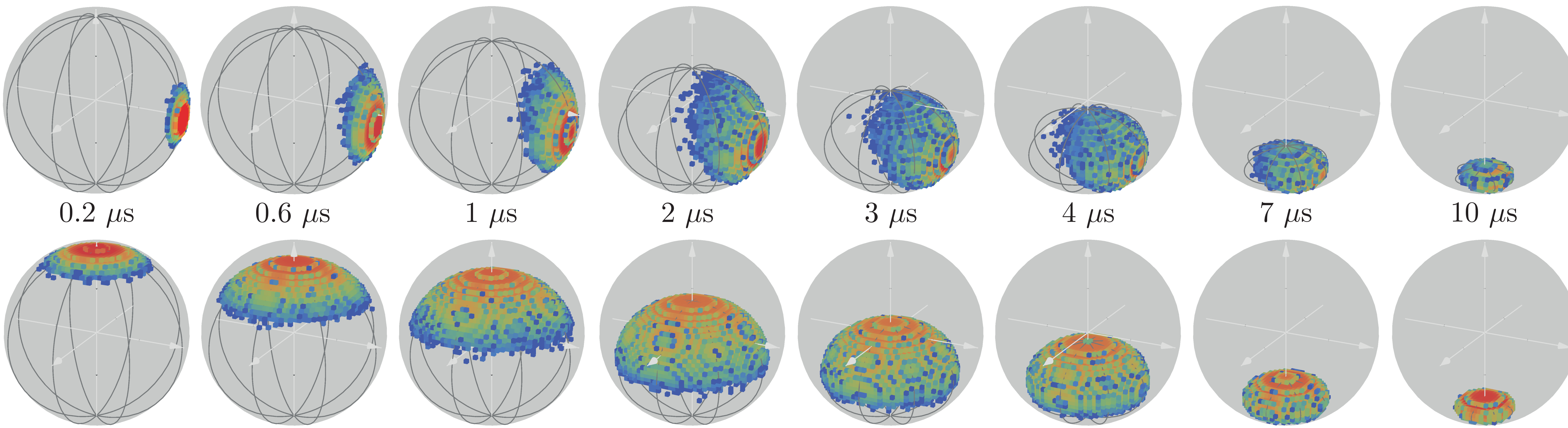
average outcome

noise (Wiener)

$$\{du_t, dv_t\} \xrightarrow{\text{stochastic master equation}} \rho_t^{\mathrm{B}}$$

[Campagne-Ibarcq *et al.*, PRX 2016]
[Naghiloo *et al.*, Nat. Comm. 2016]
[Ficheux *et al.*, Nat. Comm. 2017]

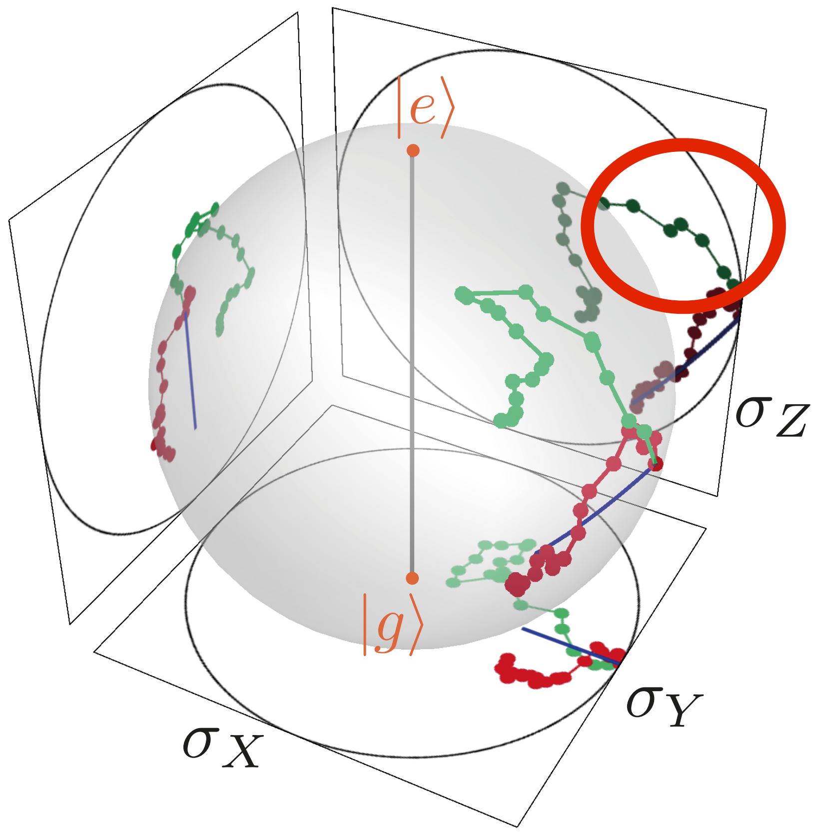
Statistics of trajectories



[Campagne-Ibarcq *et al.*, PRX 2016]

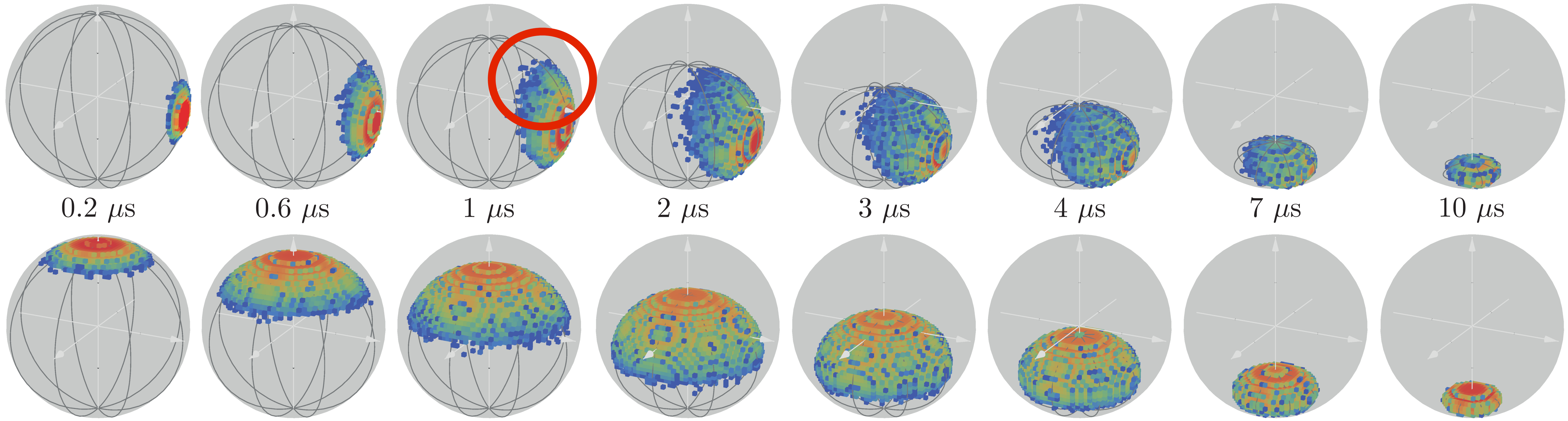
[Jordan, Chantasri, Rouchon, BH., arxiv:1511:06677]

Counterintuitive trajectories



Energy expectation can **increase** due to the backaction of measuring spontaneously emitted photons

[Bolund and Mölmer, PRA 2014]



[Campagne-Ibarcq *et al.*, PRX 2016]

[Jordan, Chantasri, Rouchon, BH., arxiv:1511:06677]

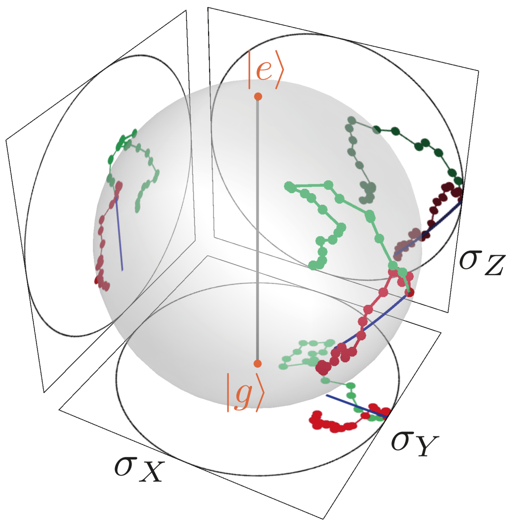
Conclusion

Measurement backaction leads to **changes in expected energy**

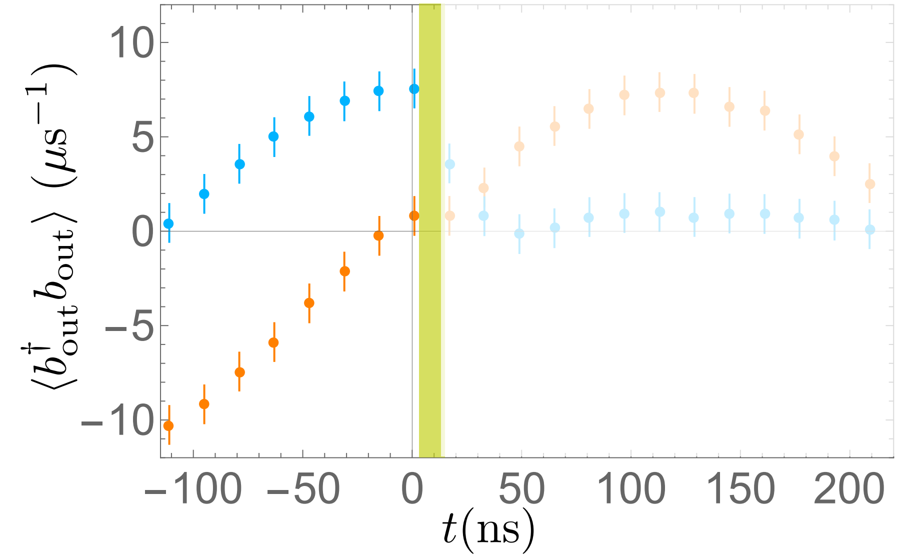
This back action energy variation (« quantum heat ») can be

- inferred from reconstructed quantum trajectory

[Campagne-Ibarcq et al., PRX 2016]
[Ficheux et al., Nat. Comm. 2018]



- measured in the battery that prepared the system **on average only**



It can be used as a fuel to power up measurement based engines

[e.g. Elouard et al., PRL 2017]

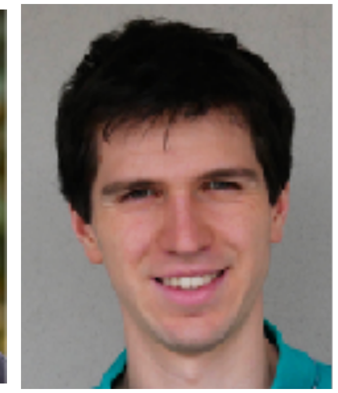
The team

Nathanaël Cottet

Quentin Ficheux

Théau Peronnin

Jeremy Stevens



Antoine Essig

UNIVERSITÉ DE LYON

ENS DE LYON

Sébastien Jezouin (now Sherbrooke)

Philippe Campagne-Ibarcq (now Yale)

Landry Bretheau (now Polytechnique)

Pierre Rouchon

Mazyar Mirrahimi

Alain Sarlette

Alexia Auffèves (Grenoble)

Areeya Chantasri (Griffith)

Andrew Jordan (Rochester)

Cyril Elouard (Rochester)

Agence Nationale de la Recherche GIP ANR

Happy birthday Jukka!