Energetics of the driving field during a single qubit gate and a measurement powered engine

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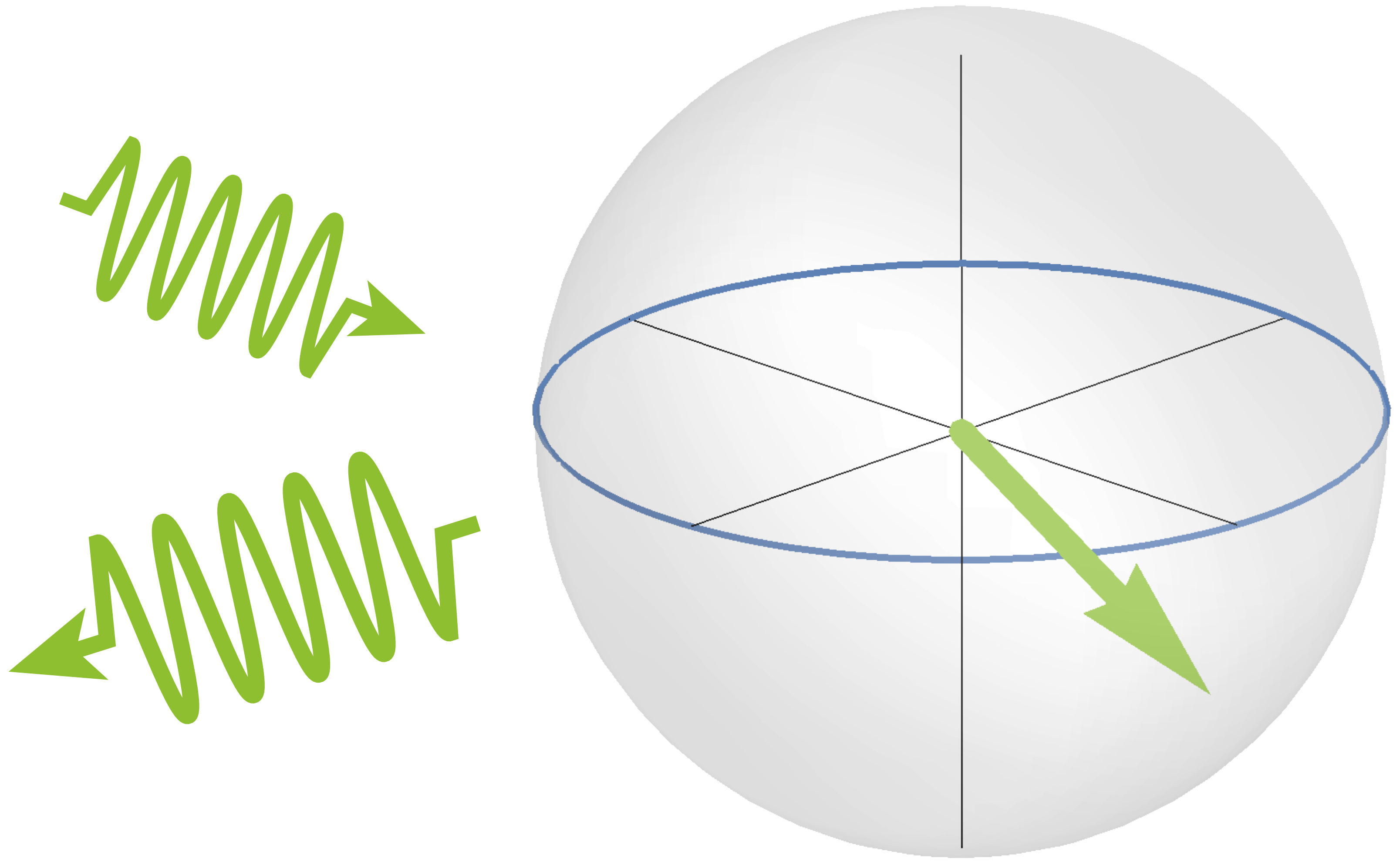
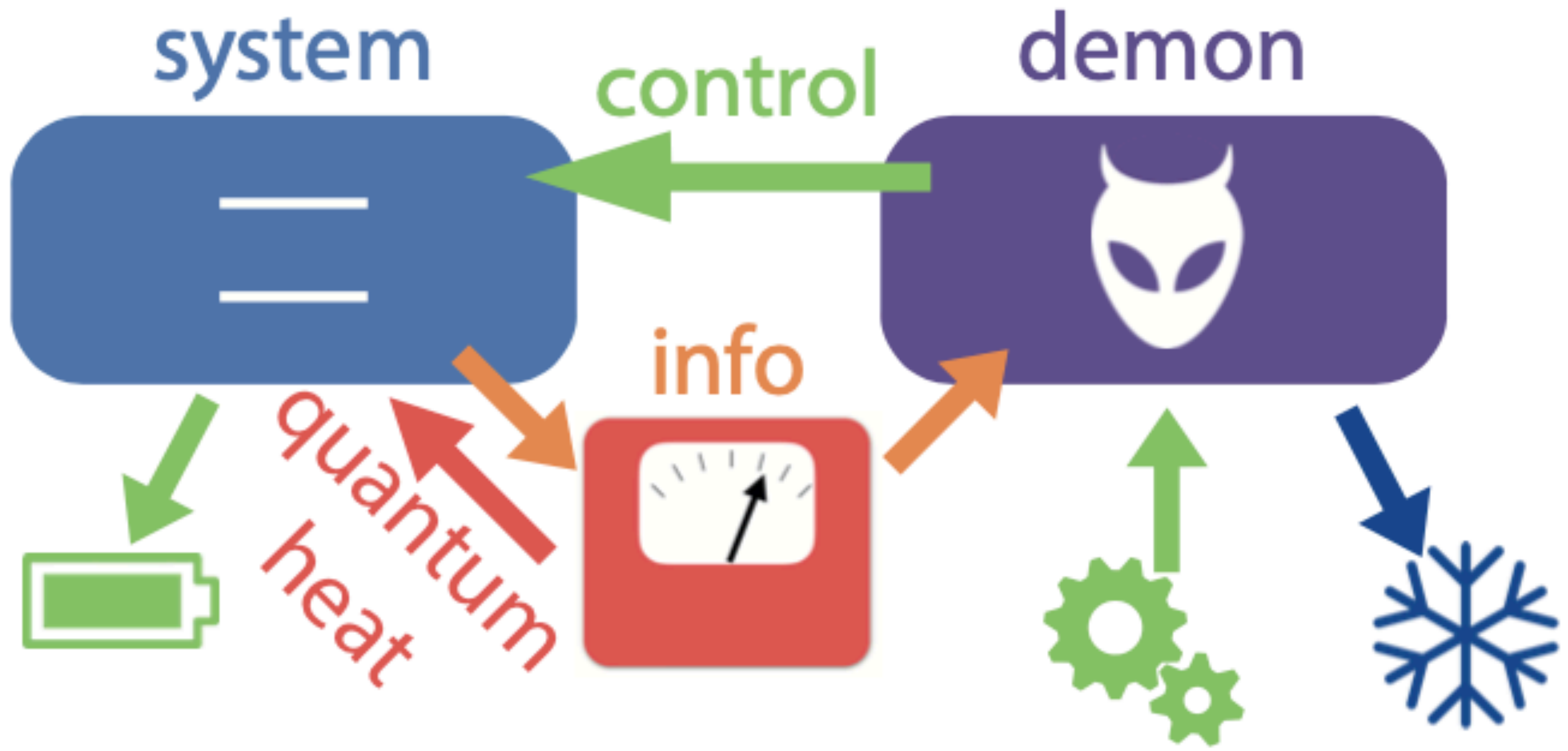
Ecole Normale Supérieure de Lyon, France



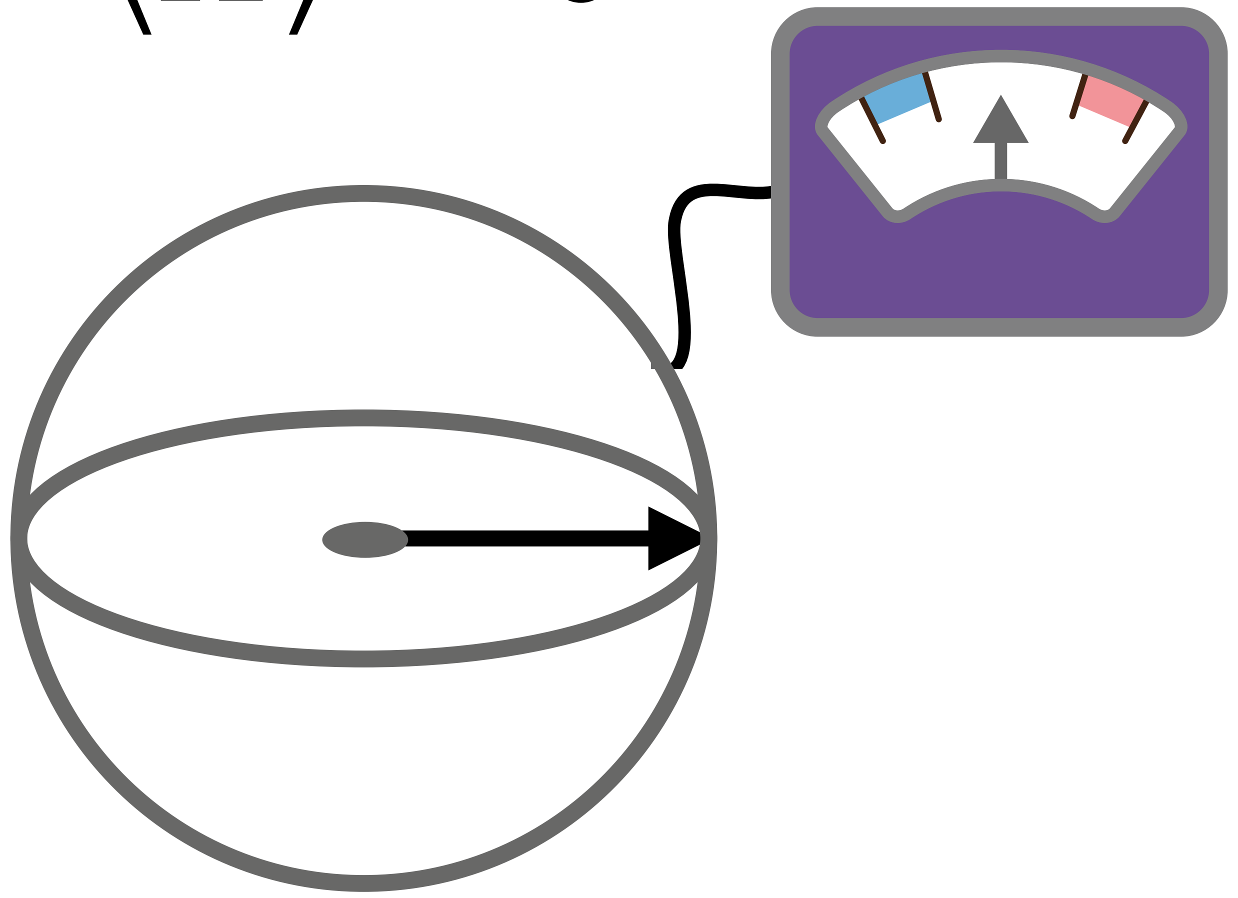


FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

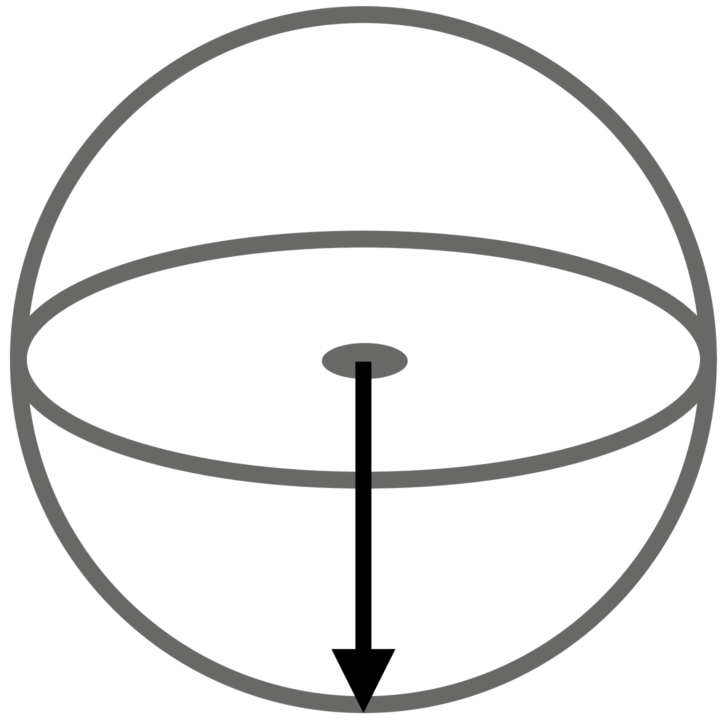
A simple question

$$\hat{H} = \frac{\hbar\omega_Q}{2}\sigma_z$$

$$\langle \hat{H} \rangle = 0$$

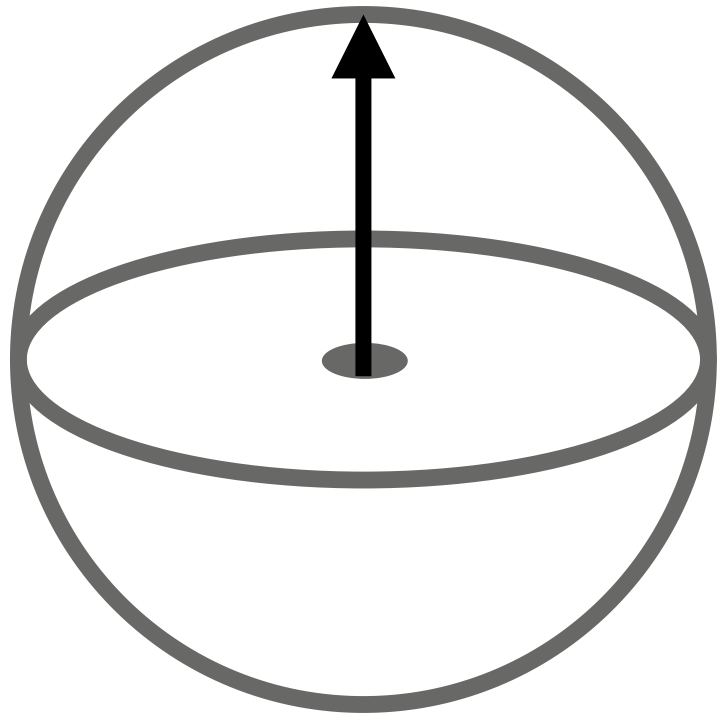


$$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$



$$\langle \hat{H} \rangle = -\frac{\hbar\omega_Q}{2}$$

$$|g\rangle$$

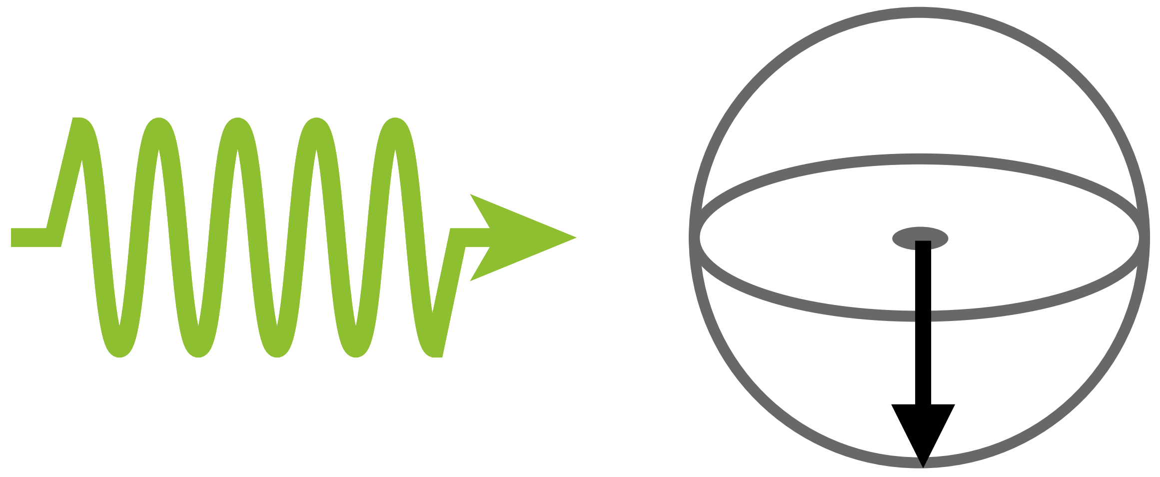


$$\langle \hat{H} \rangle = \frac{\hbar\omega_Q}{2}$$

$$|e\rangle$$

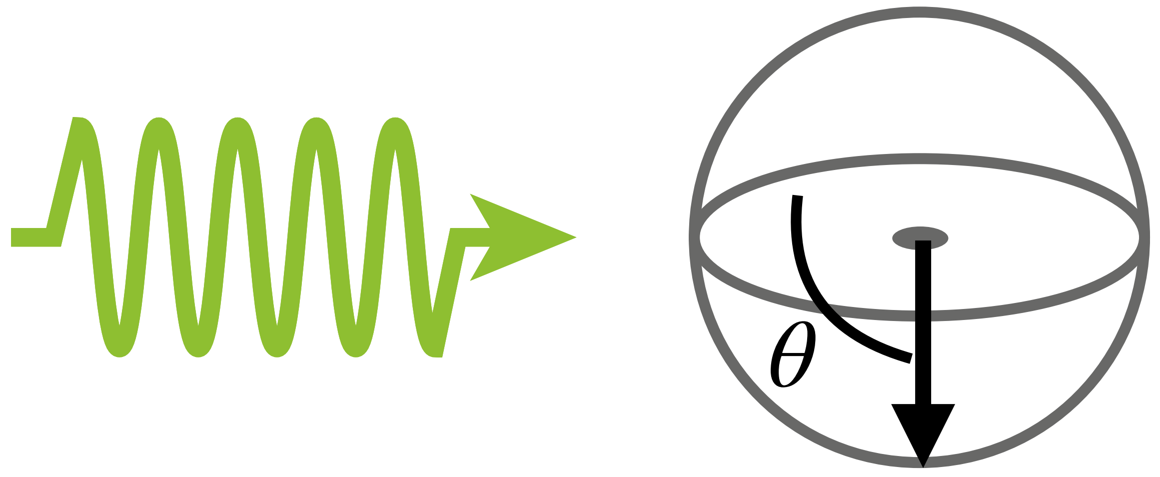
How can we understand this apparent random change in the qubit's internal energy?

Energetics of a Single Qubit Gate



1 photon less

$$|e\rangle$$



? photon less

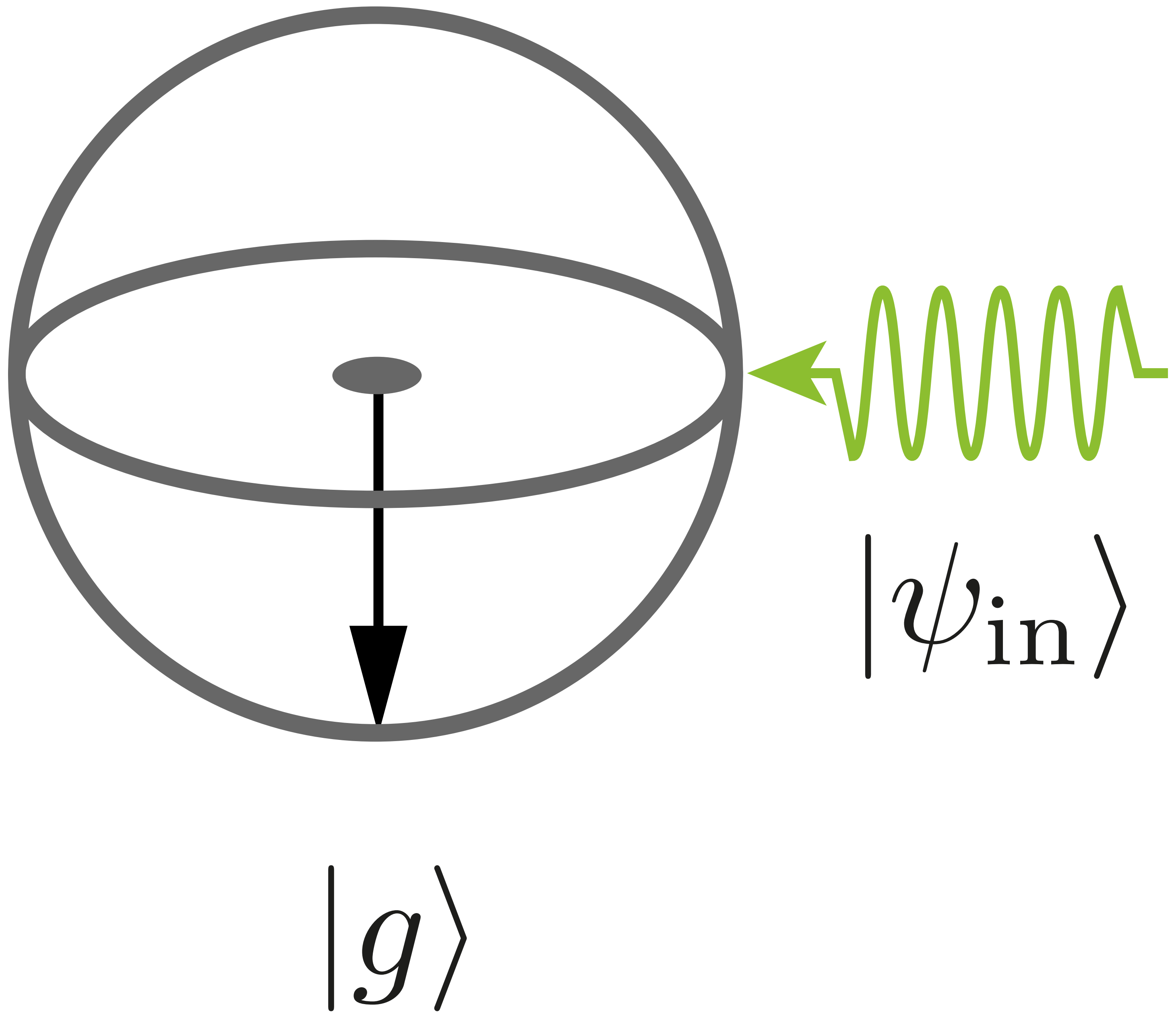
$$\cos\frac{\theta}{2}|g\rangle + \sin\frac{\theta}{2}|e\rangle$$

↓ 0 photon consumed

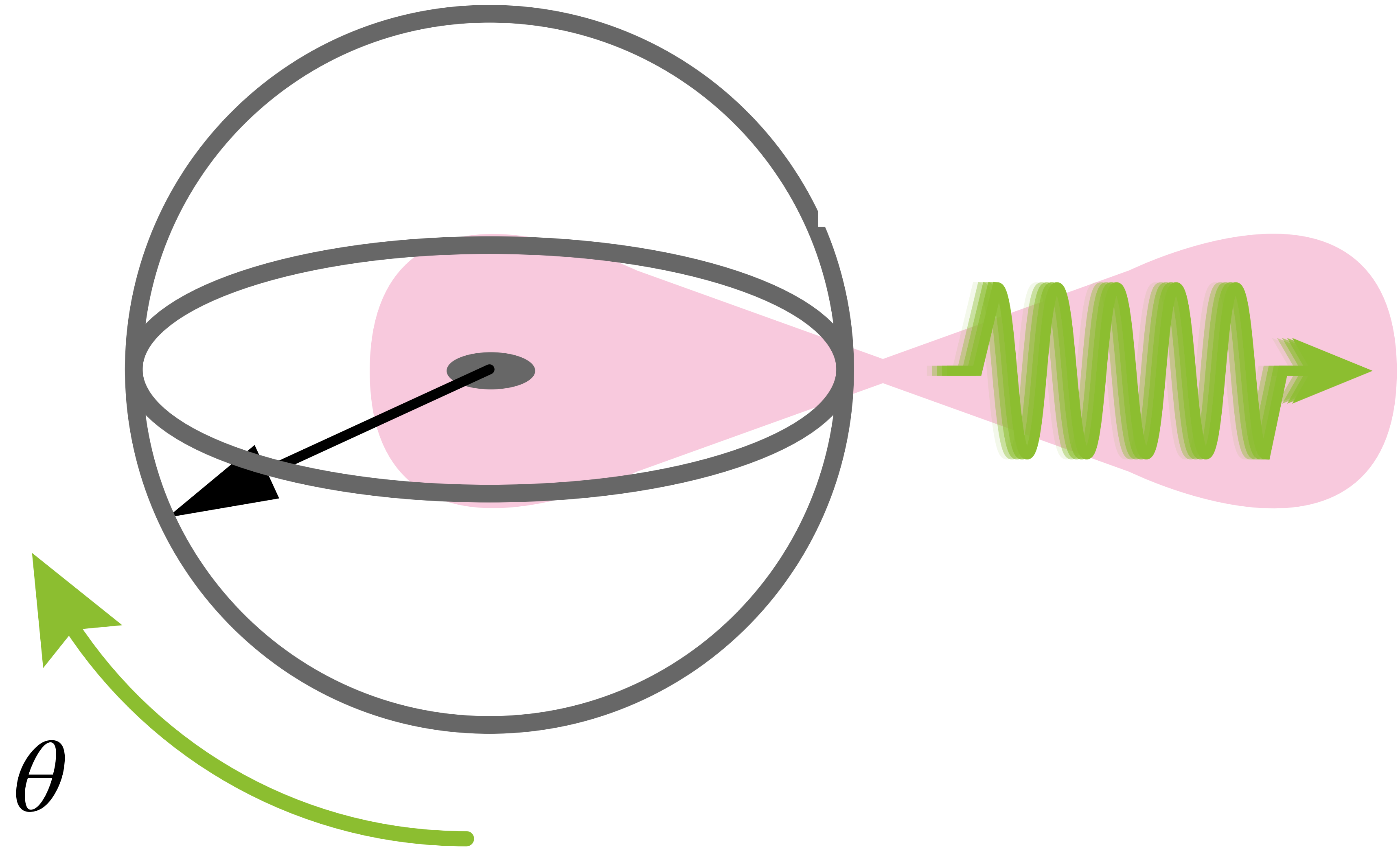
↓ 1 photon consumed

‘Superposition of energy transfers’

Qubit state is prepared by a coherent field



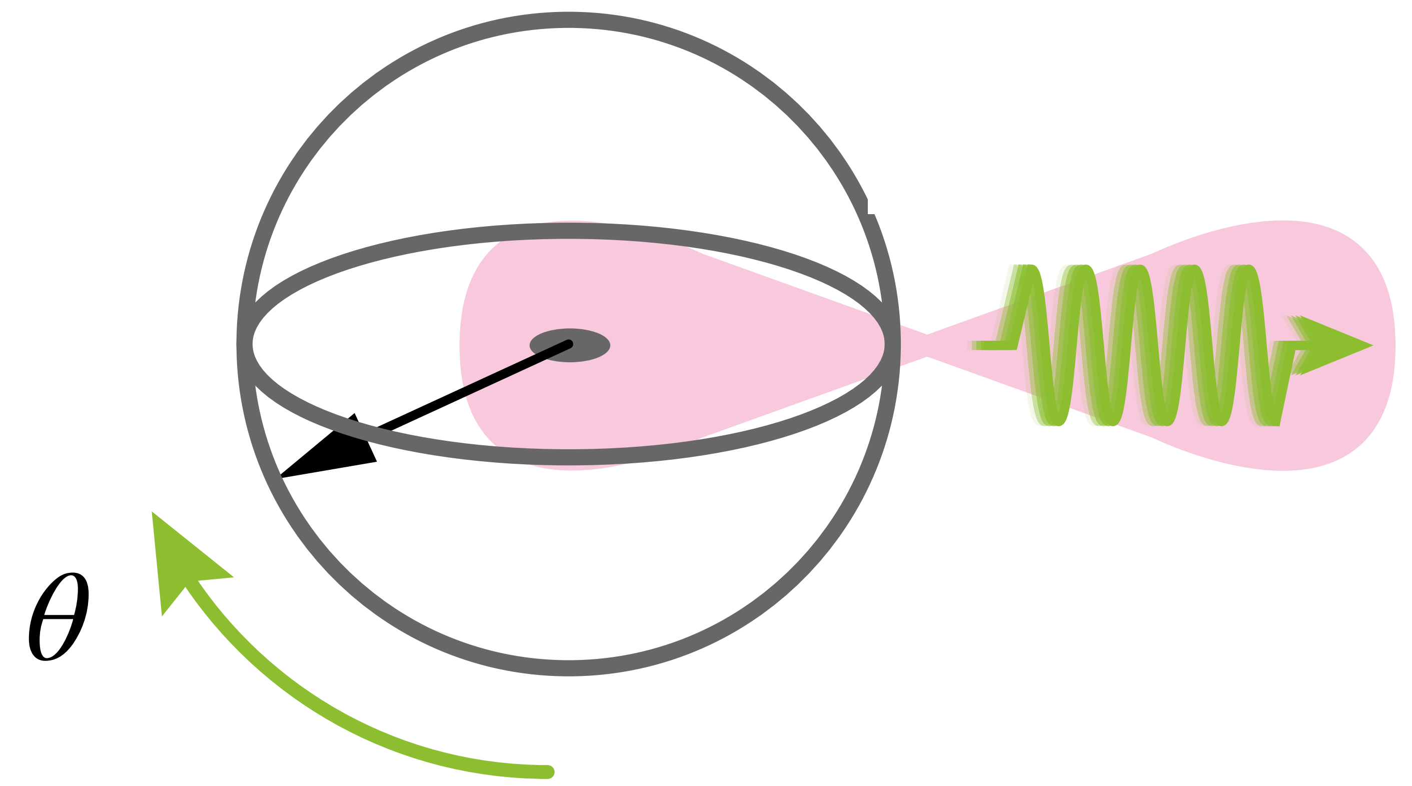
Before interaction



$$\lambda_g|\psi_g\rangle \otimes |g\rangle + \lambda_e|\psi_e\rangle \otimes |e\rangle$$

After interaction

Impacts of entanglement



$$\lambda_g|\psi_g\rangle \otimes |g\rangle + \lambda_e|\psi_e\rangle \otimes |e\rangle$$

Impacts on fidelity Enk 2001, Banacloche 2002, Ozawa 2002, Ikonen 2017

Purity of the qubit's density matrix

$$\mathrm{tr}[\rho^2] = 1 - 2|\lambda_g\lambda_e|^2\left(1 - |\langle\psi_e|\psi_g\rangle|^2\right)$$

pure if $|\langle\psi_e|\psi_g\rangle|^2 \xrightarrow{\alpha_{in}\to\infty} 1$ Bertet, Nature 2001

Suggests fundamental energy cost of operations

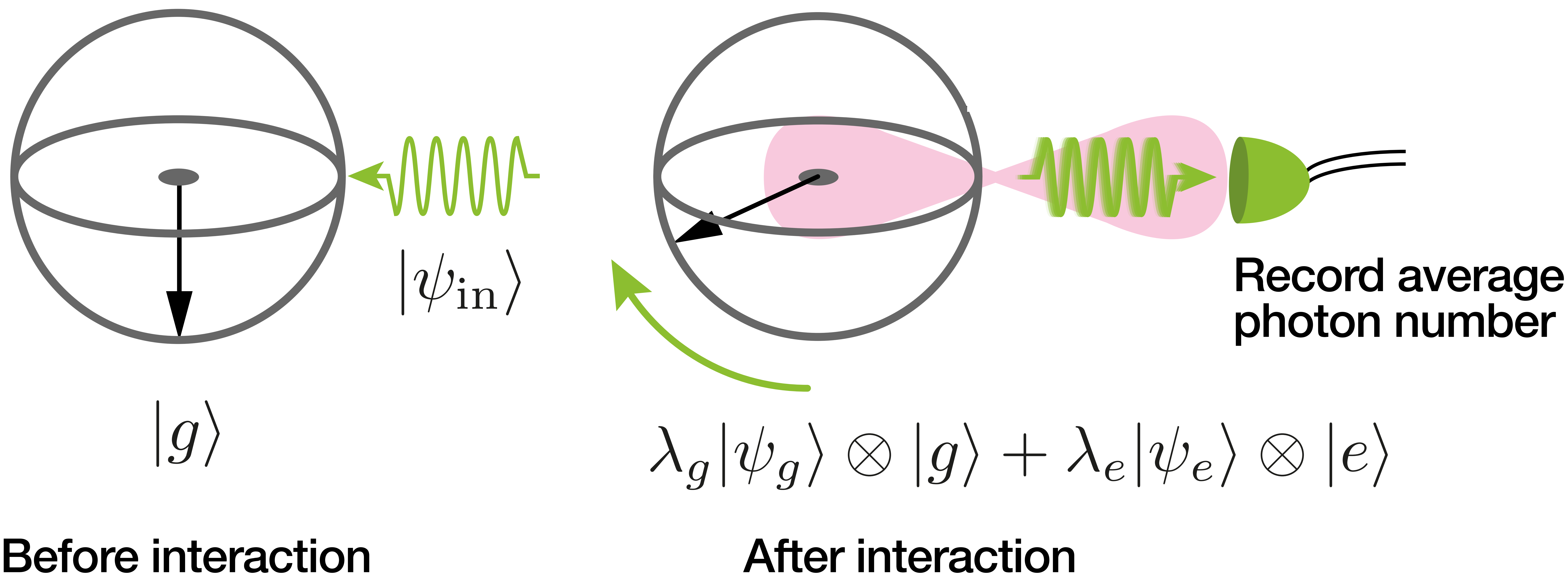
Energy budget of quantum computer?

Auffèves Scipost 2021

Does this not stop us looking at the energy transfers?

No! $|\langle\psi_e|\psi_g\rangle|^2 \xrightarrow{\alpha_{in}\to\infty} 1$ **does not impose** $\langle\psi_e|\hat{n}|\psi_e\rangle - \langle\psi_g|\hat{n}|\psi_g\rangle = 0$

Idea of experiment



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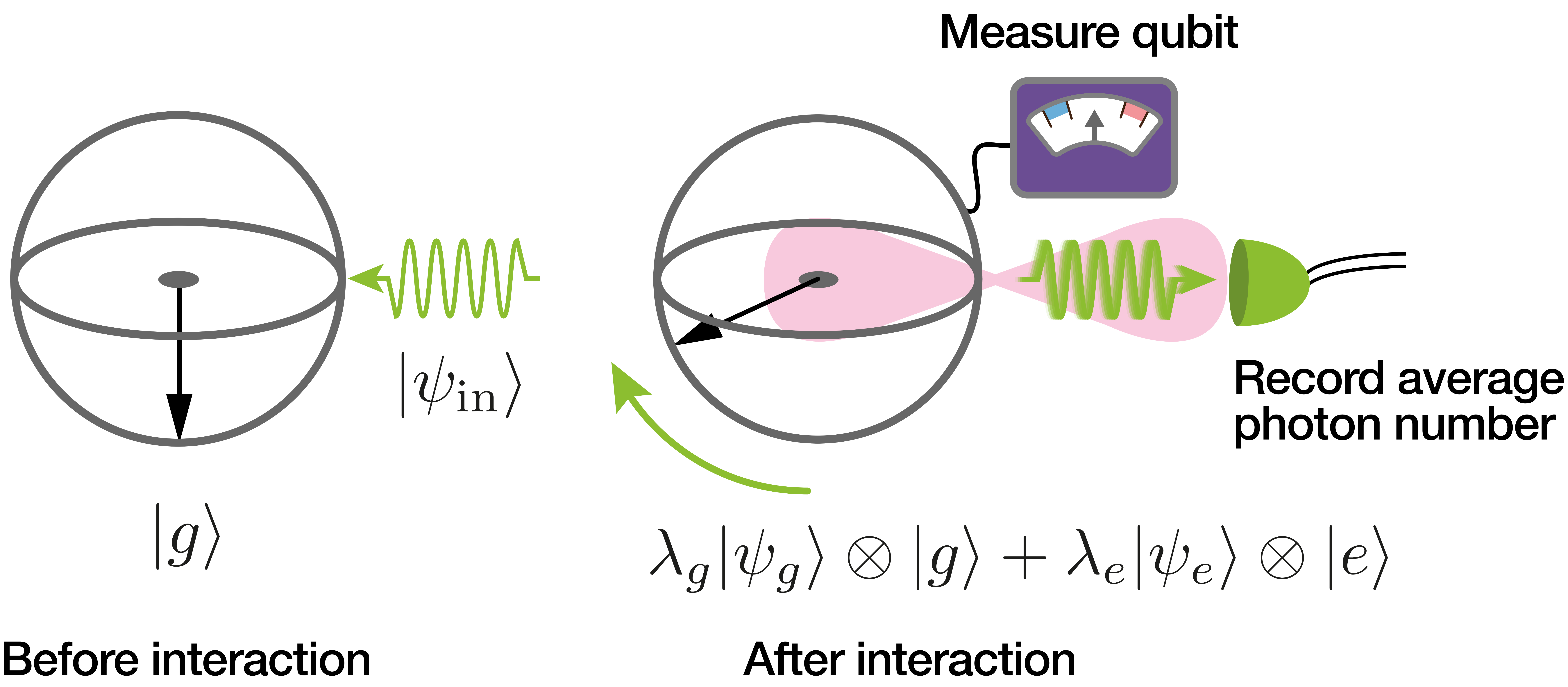
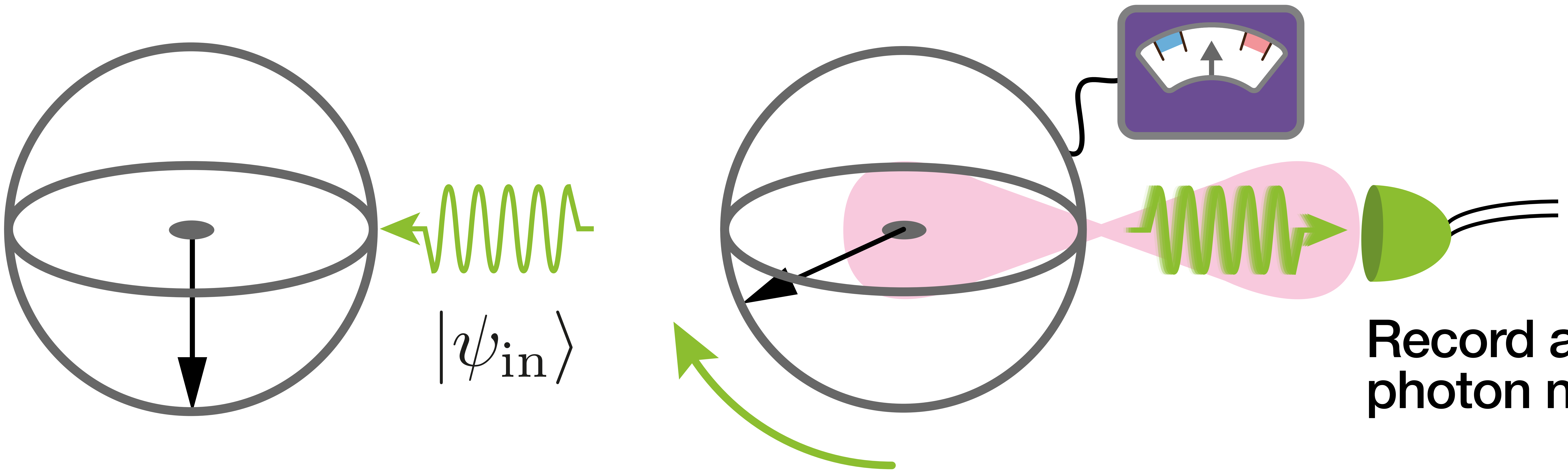


Idea of experiment



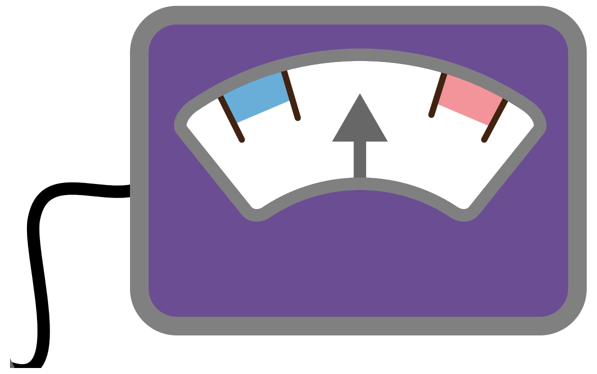
$|g\rangle$

$$\lambda_g|\psi_g\rangle \otimes |g\rangle + \lambda_e|\psi_e\rangle \otimes |e\rangle$$

Before interaction **After interaction**

We expect to measure $\bar{n}_{|e\rangle} - \bar{n}_{|g\rangle} = -1$ quantum heat!

Quantum heat



random energy change
= 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, PRA (2019)]

can it fuel an engine?

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

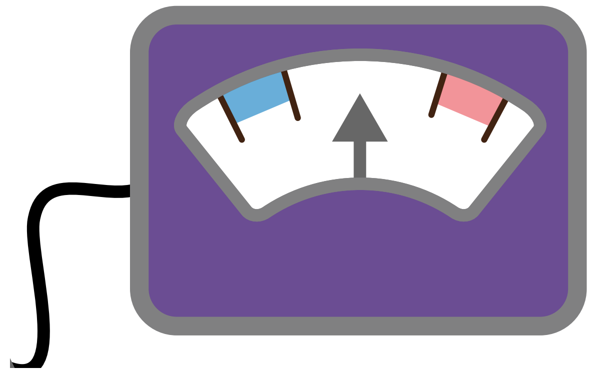
[Yi, Talkner, Kim, PRE (2017)] [Elouard, Herrera-Martí, Huard, Auffèves, PRL (2017)]
[Elouard, Jordan, PRL (2018)] [Ding, Yi, Kim, Talkner, PRE (2018)] [Buffoni et al., PRL (2019)]
[Ronzani et al., Nature Phys. 2018] [Senior et al., Communication Physics 2020] [Bresque et al., PRL (2021)]
[Monsel *et al.*, PRL (2020)] [Manikandan *et al.*, PRE (2022)]

demonstration?

can it be measured directly and not just inferred?

[Stevens et al., PRL 2022]

Quantum heat



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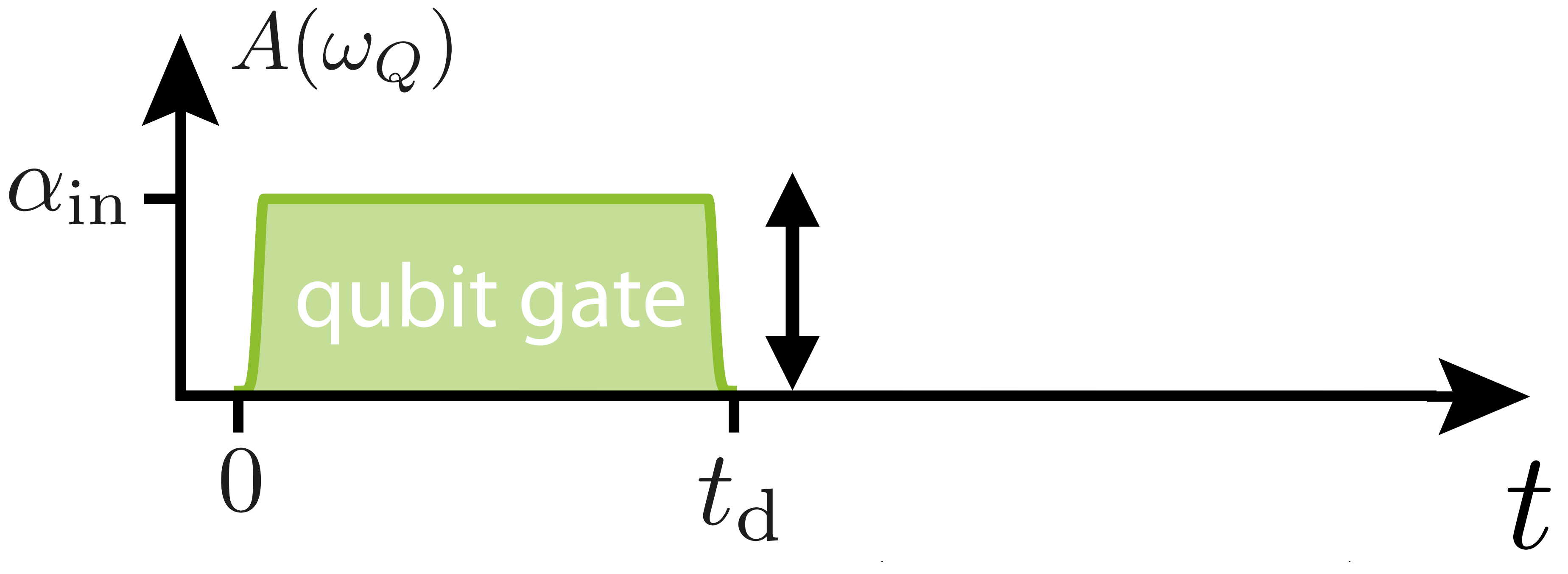
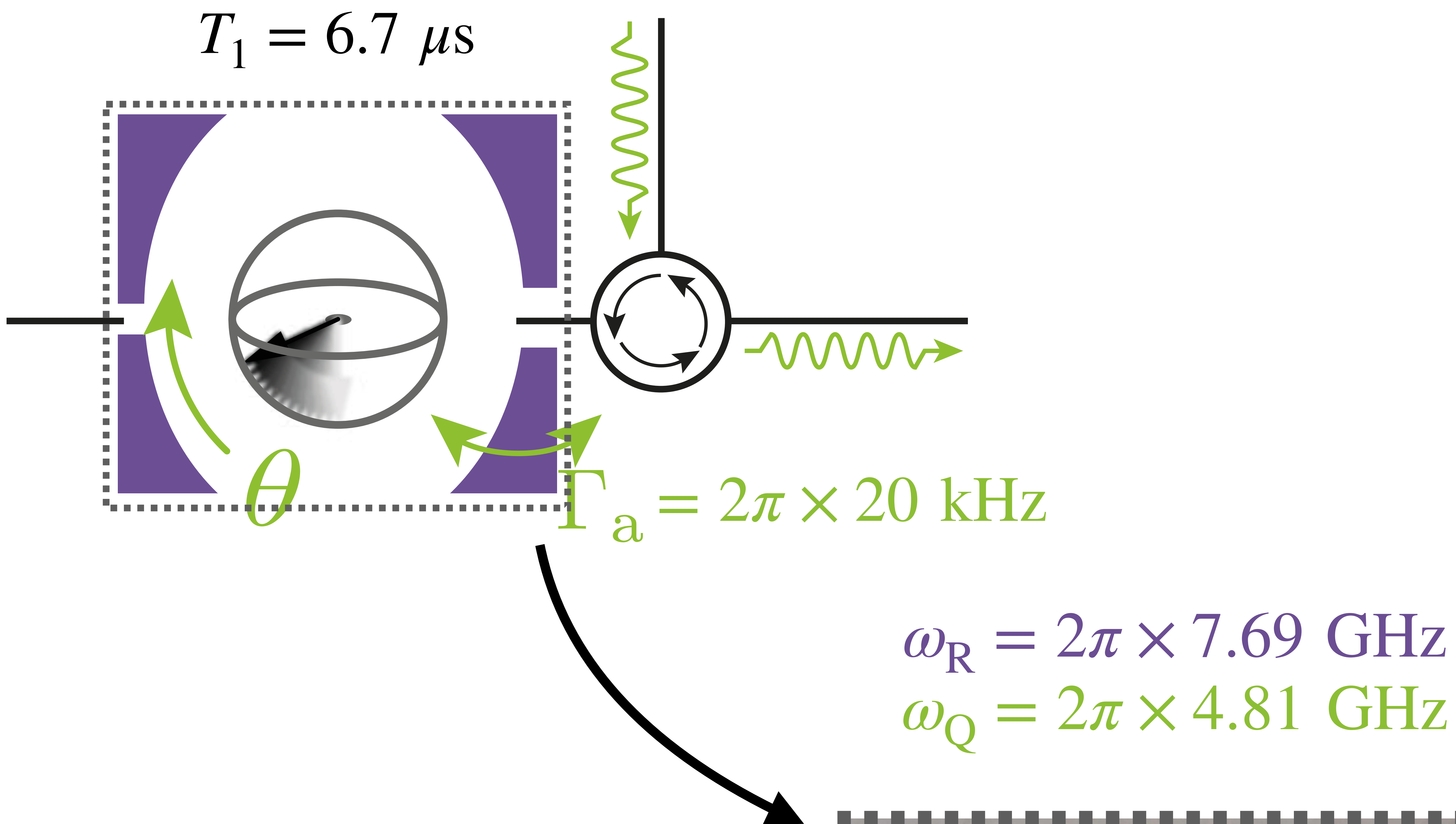
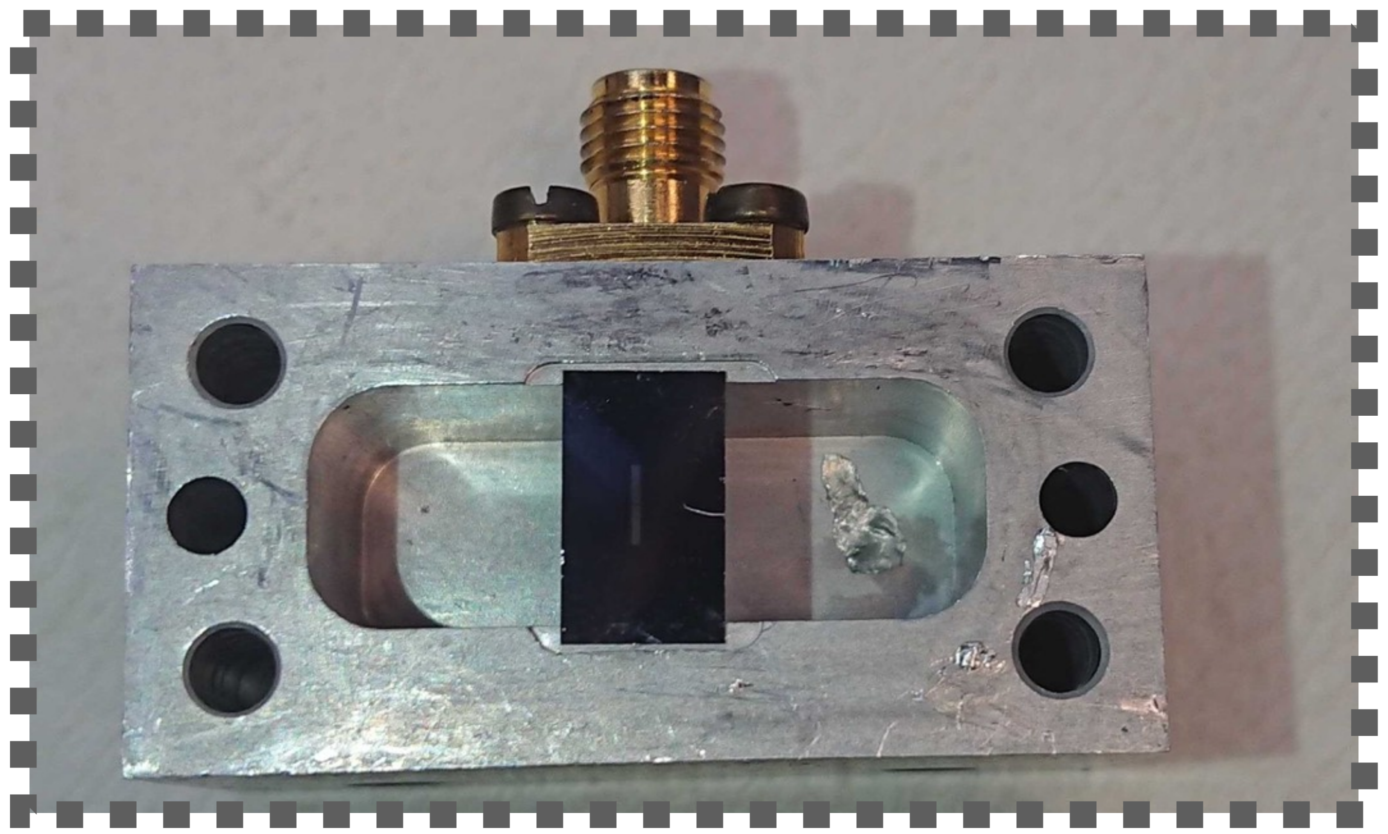
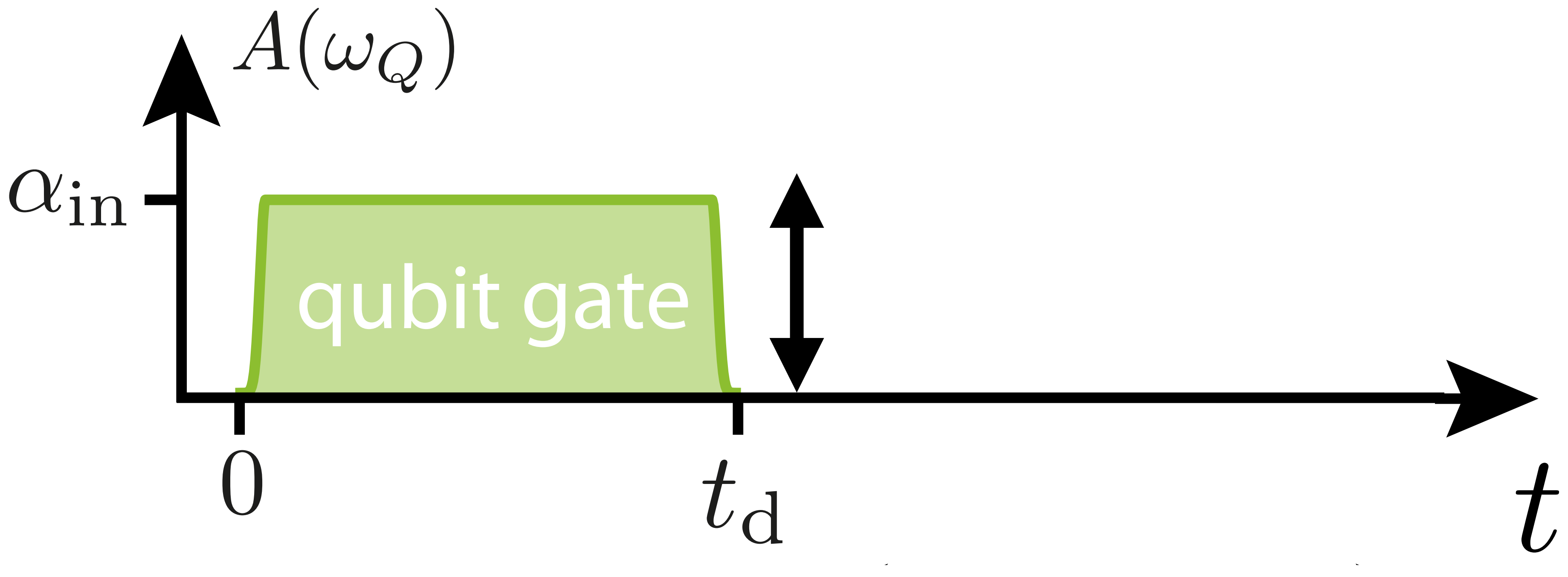
Experimental setup

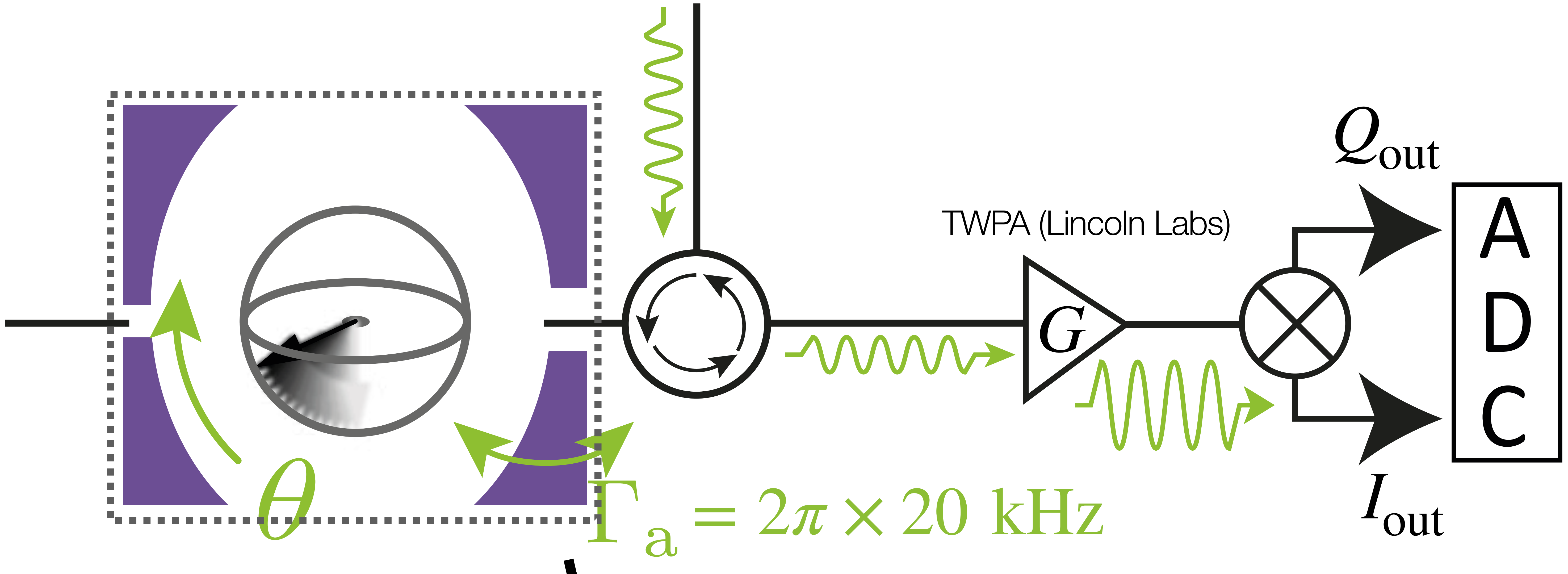






How to measure the average photon number?

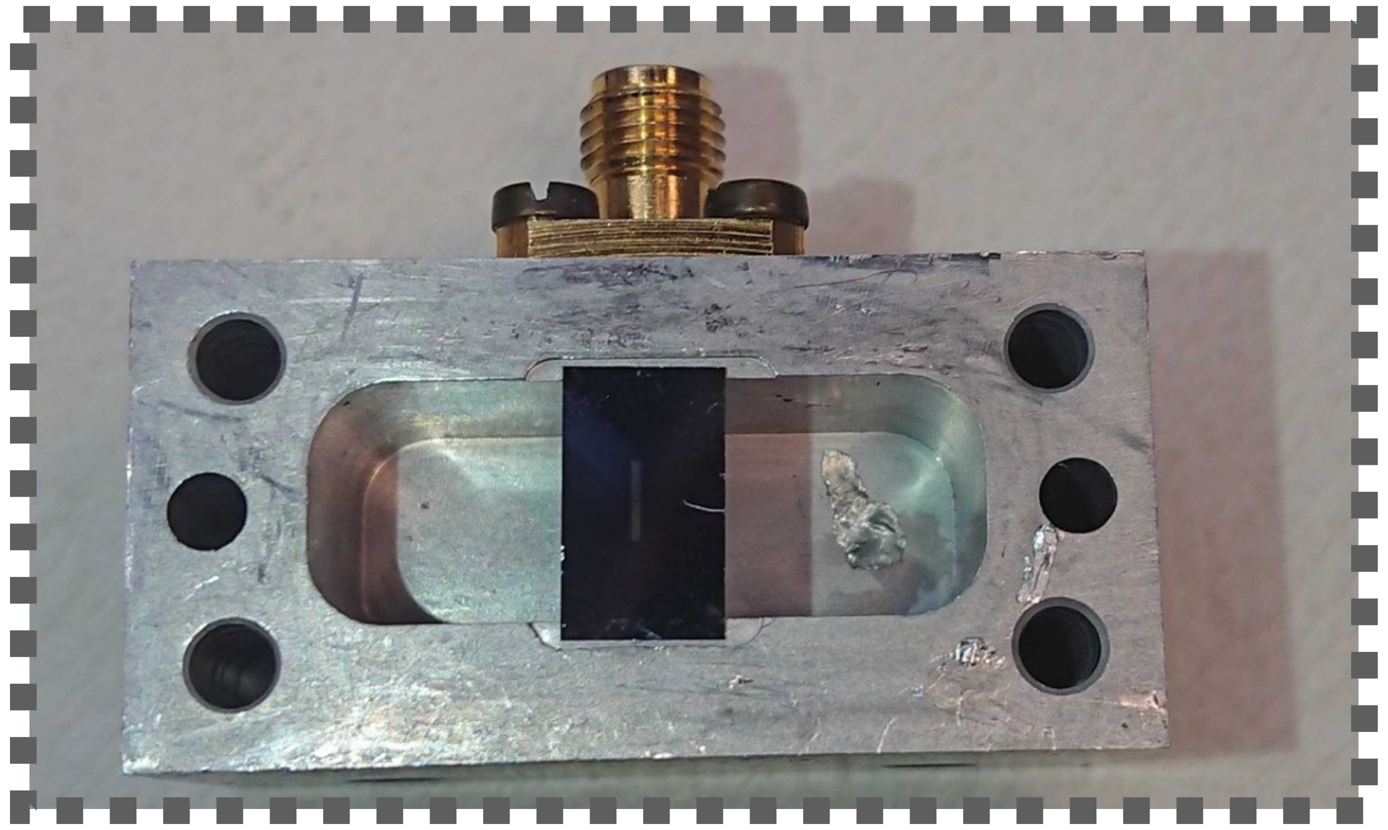




$\omega_{\mathrm{R}} = 2\pi \times 7.69\ \mathrm{GHz}$
$\omega_{\mathrm{Q}} = 2\pi \times 4.81\ \mathrm{GHz}$

measure quadratures

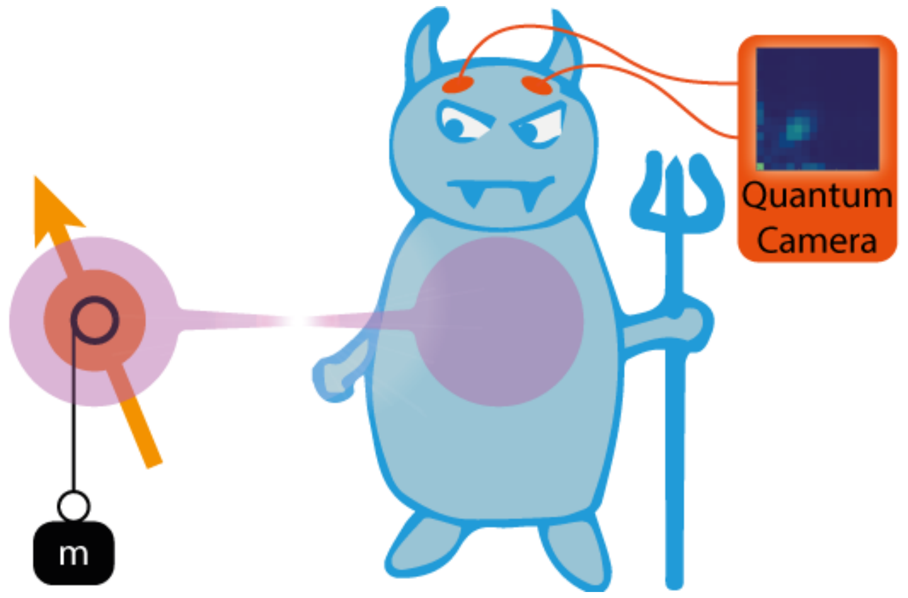
$$\bar{\dot{n}} = G\left(\langle I_{\mathrm{out}}^2(t)\rangle + \langle Q_{\mathrm{out}}^2(t)\rangle\right) + N$$



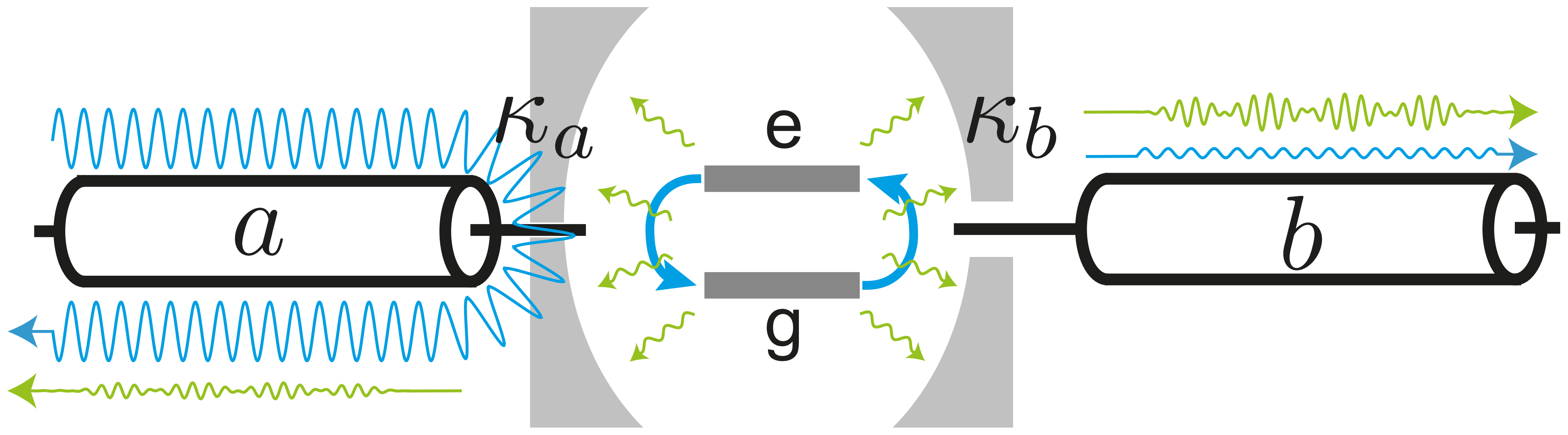
resolution: few aW

see quantum Maxwell demon at work

[Cottet et al., PNAS, 2017]



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

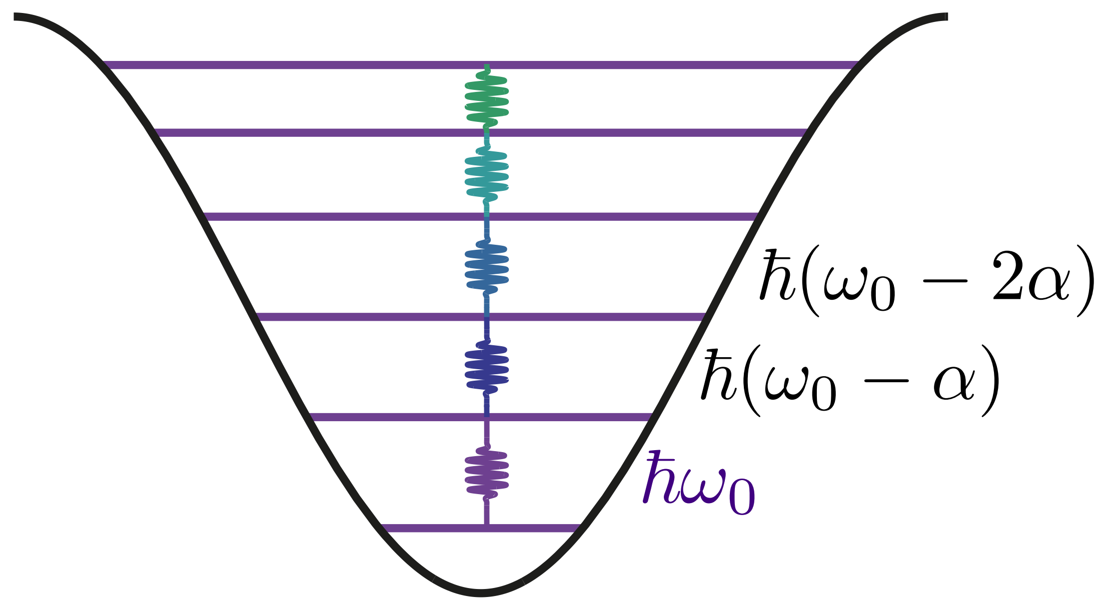
$$\frac{\gamma_a}{\gamma_b} = \frac{\kappa_a}{\kappa_b} \ll 1$$

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

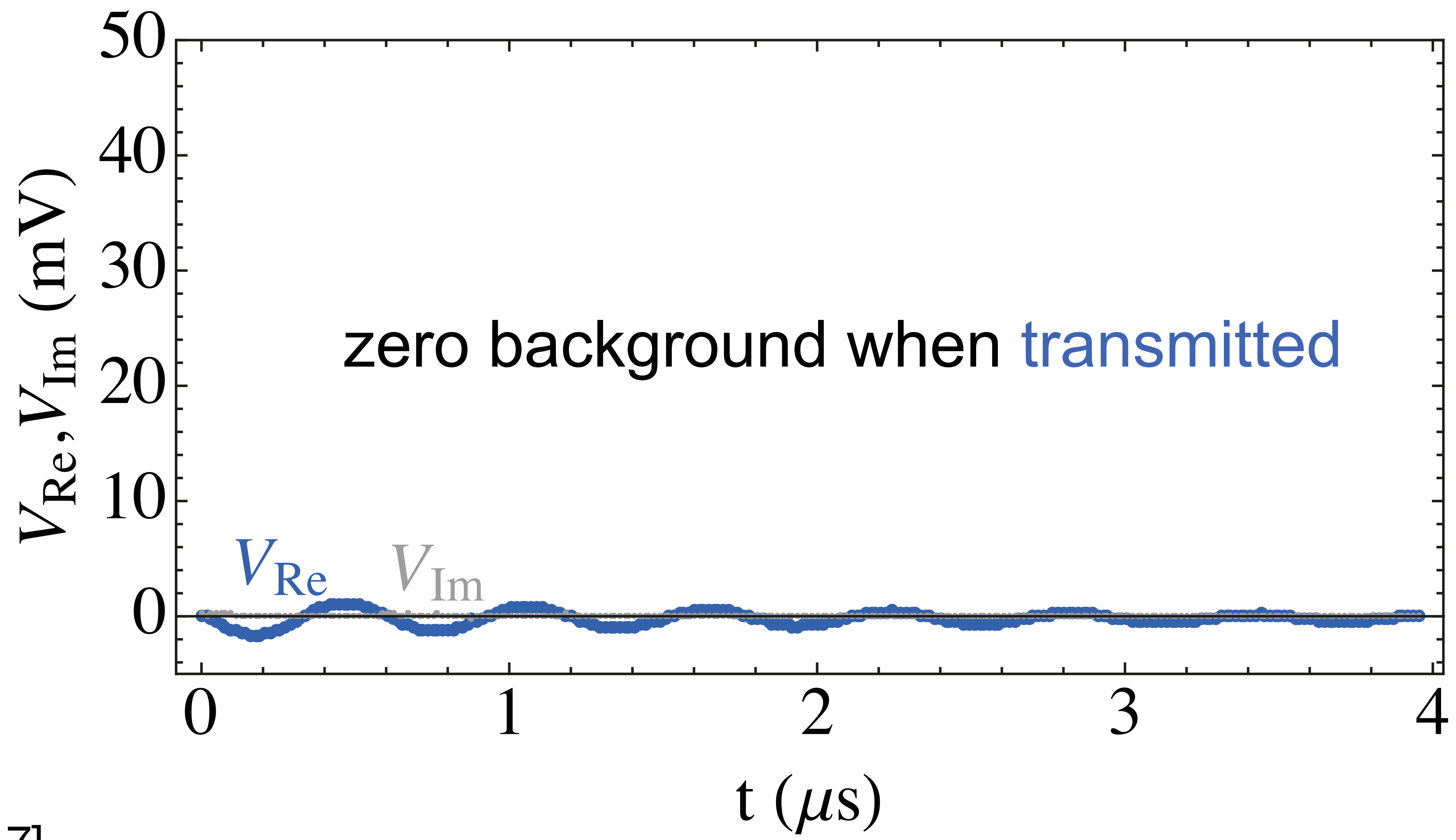
$$H_{\mathrm{coupl}} = -\hbar\chi a^\dagger a|e\rangle\langle e|$$

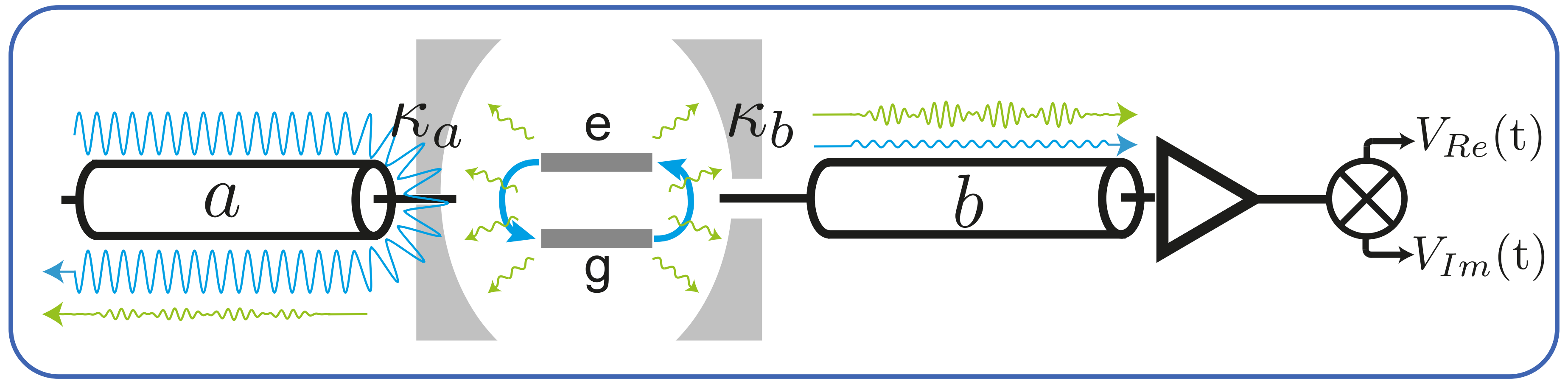
$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\langle\sigma_-\rangle_{\rho(t)}$$

transmitted
driving field



Amplitude of fluorescence



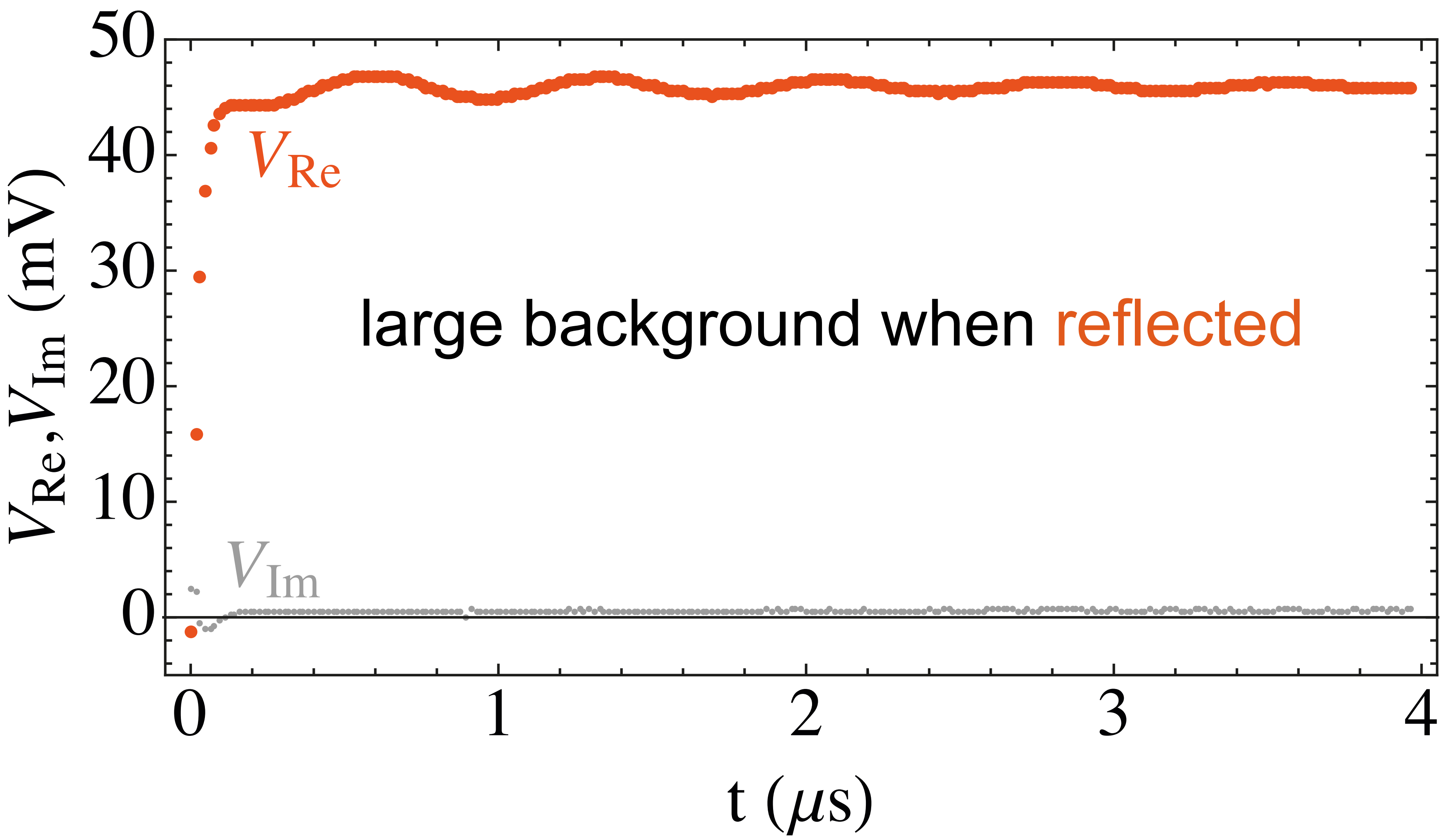


[Cottet et al., PNAS, 2017]

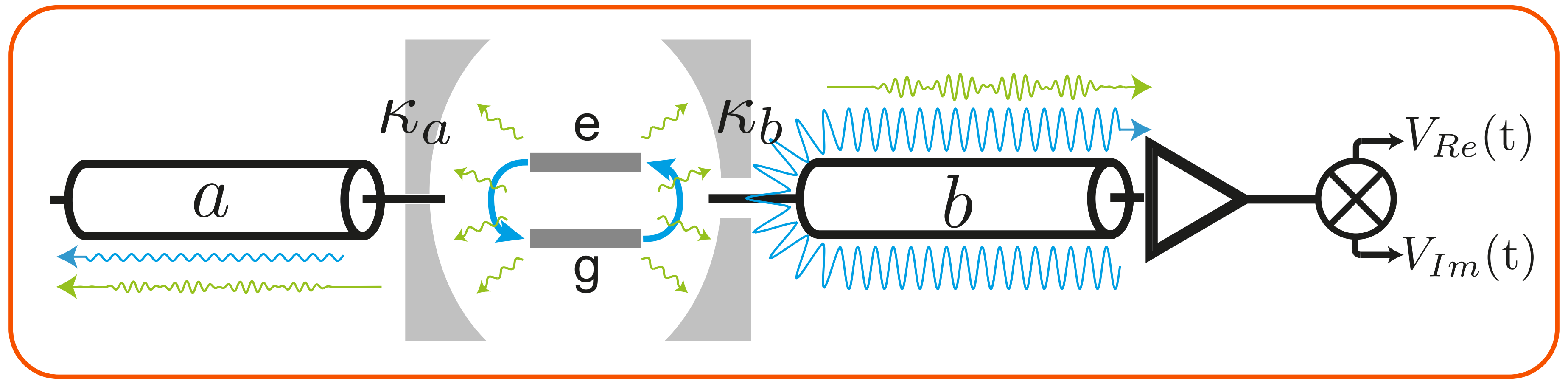
$$\sigma_- = (\sigma_x - i\sigma_y)/2$$

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

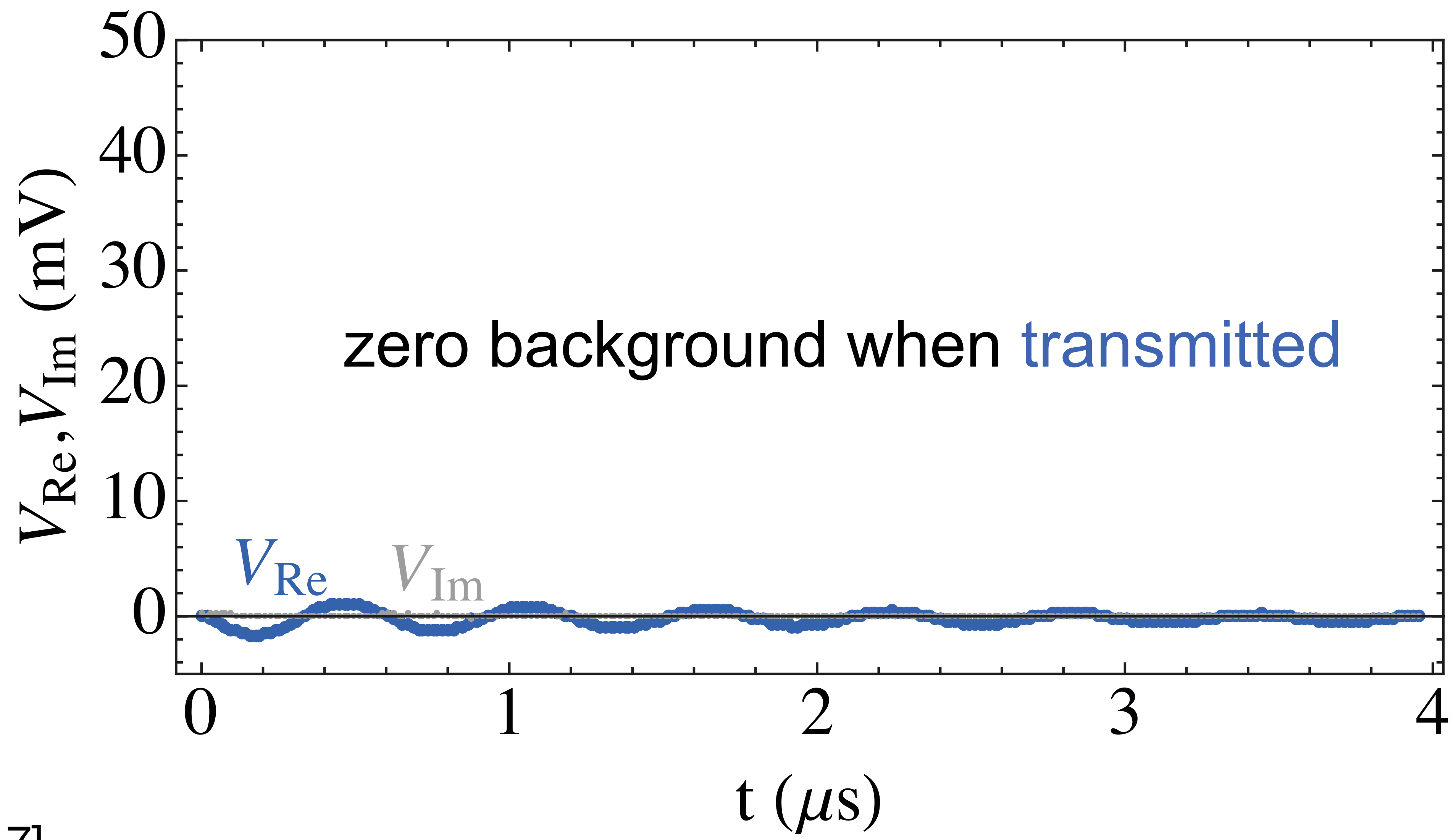
$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\langle\sigma_-\rangle_{\rho(t)}$$



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



Amplitude of fluorescence and Rabi oscillations



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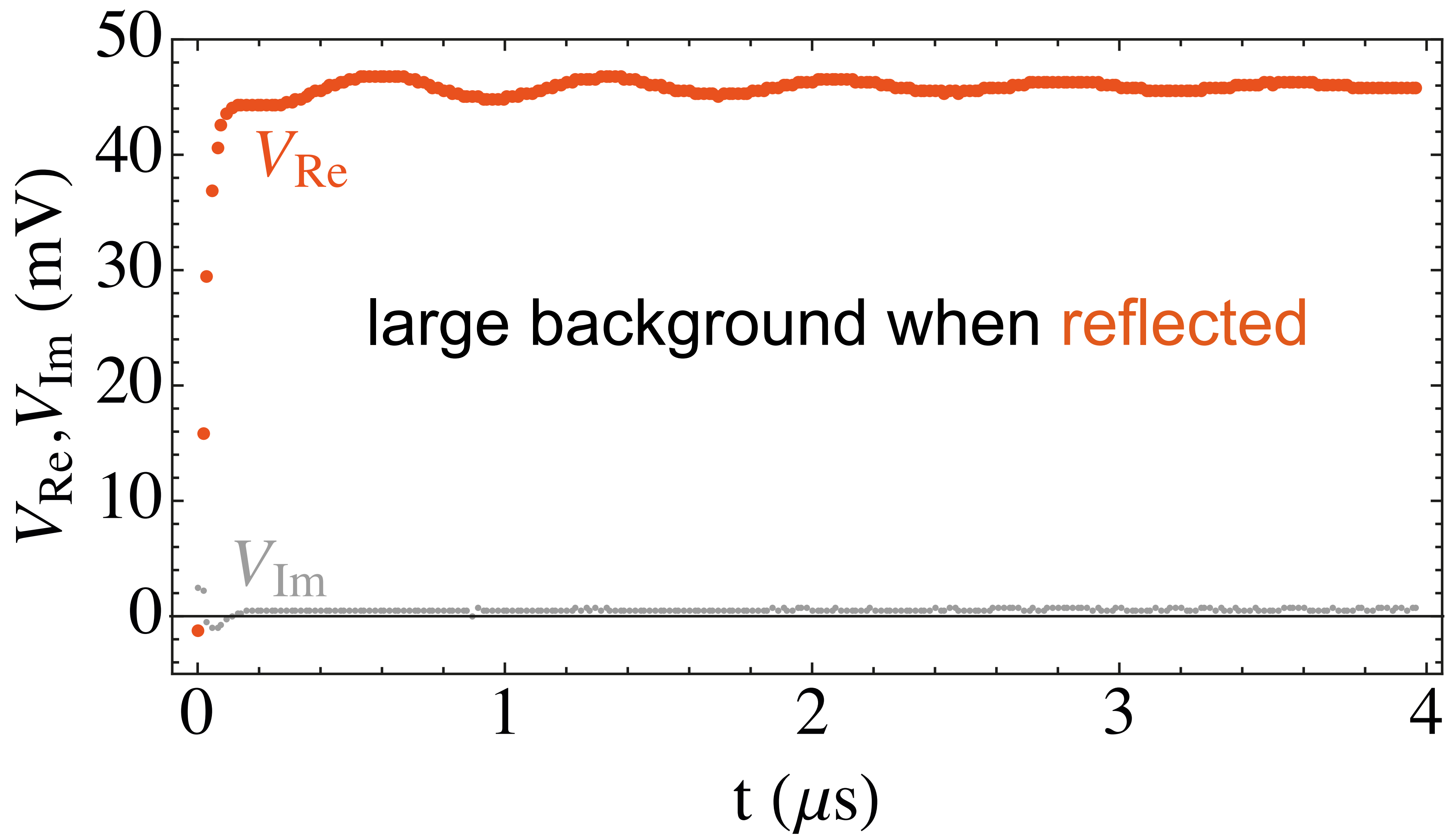
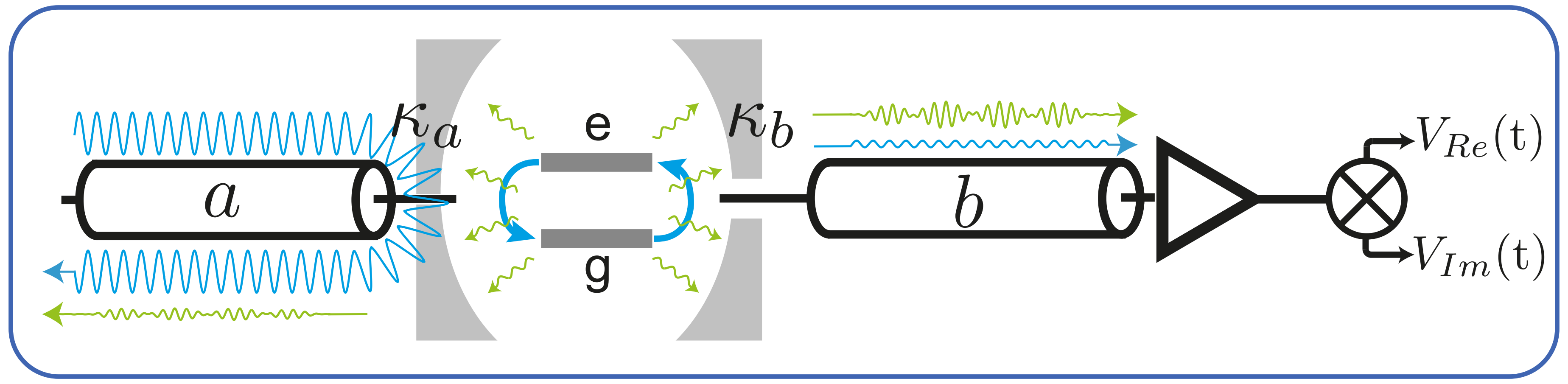
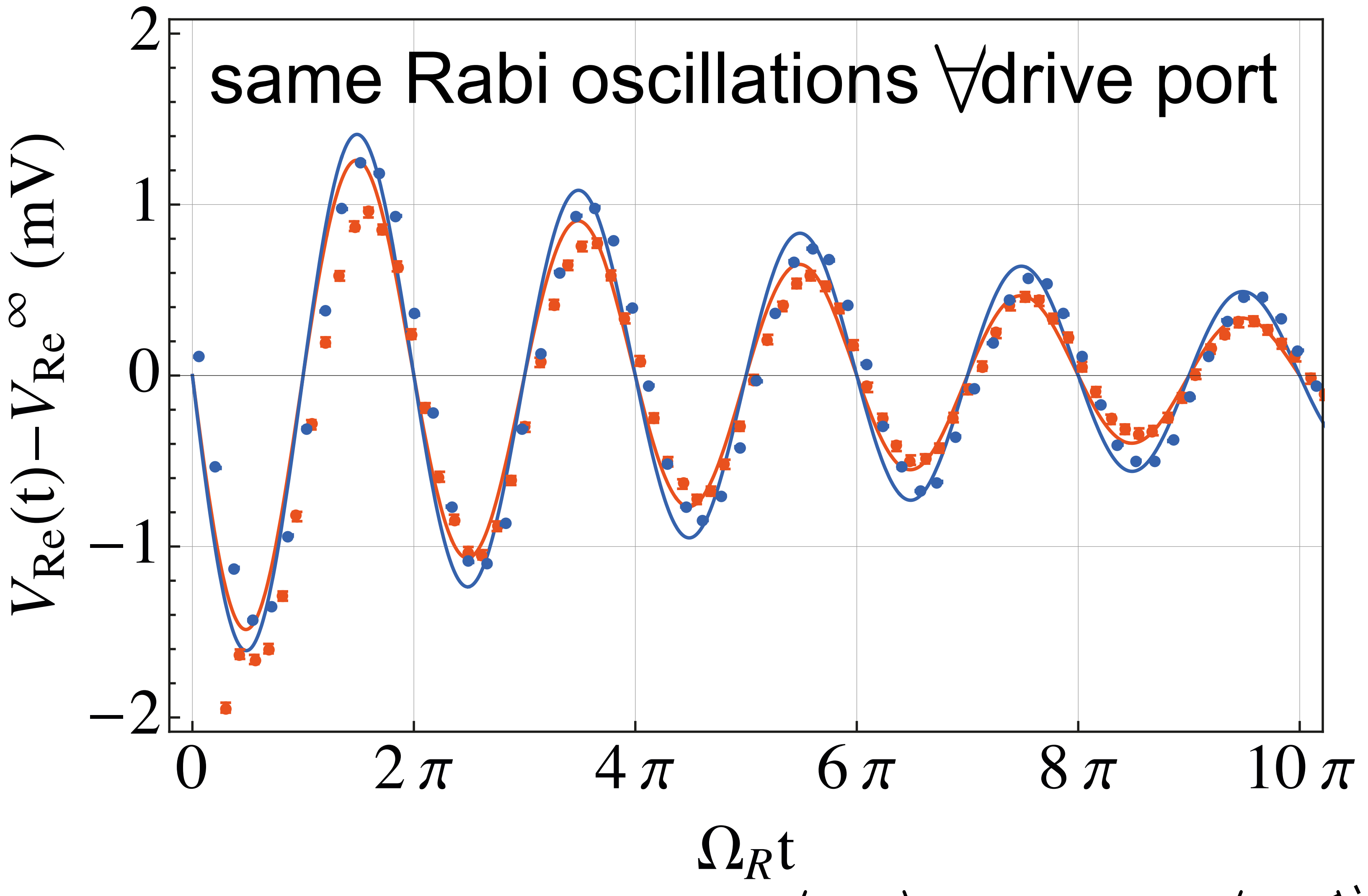
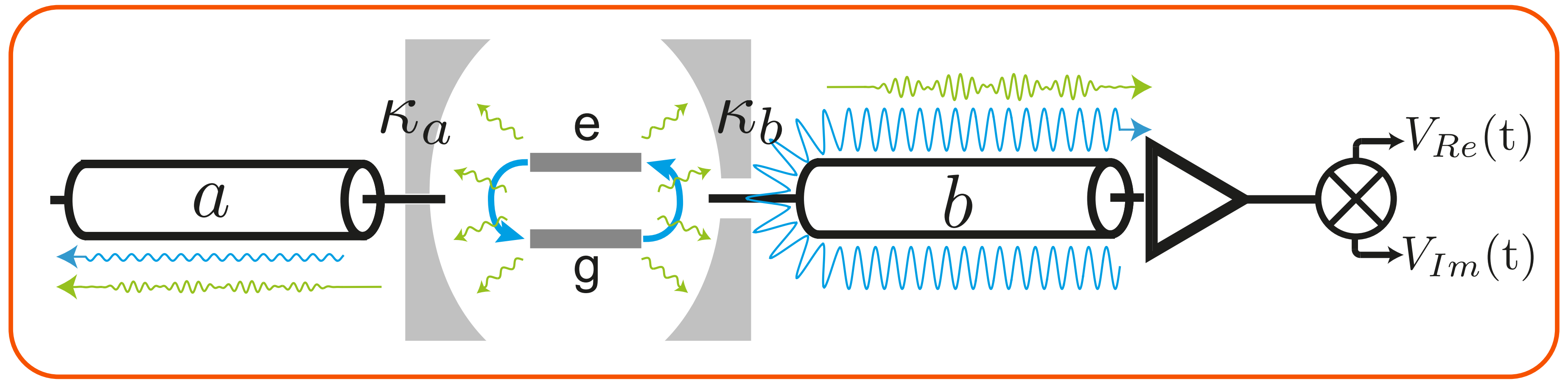


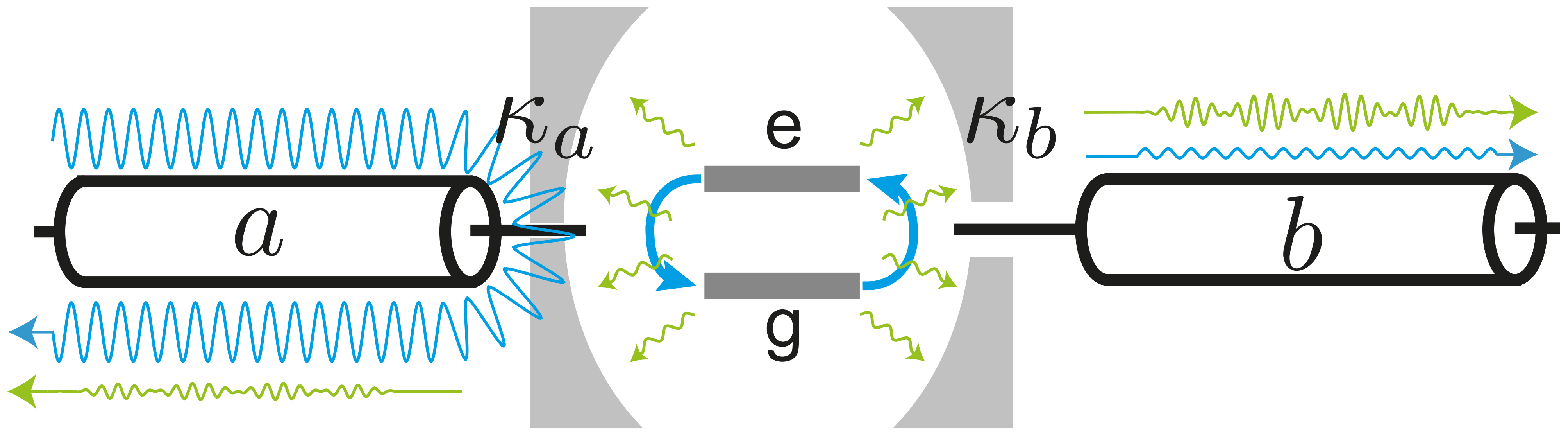




$$\langle b_{out}\rangle = \langle b_{out}\rangle_0 - \sqrt{\gamma_b}\frac{\langle\sigma_x\rangle}{2} - i\sqrt{\gamma_b}\frac{\langle\sigma_y\rangle}{2}$$



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

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

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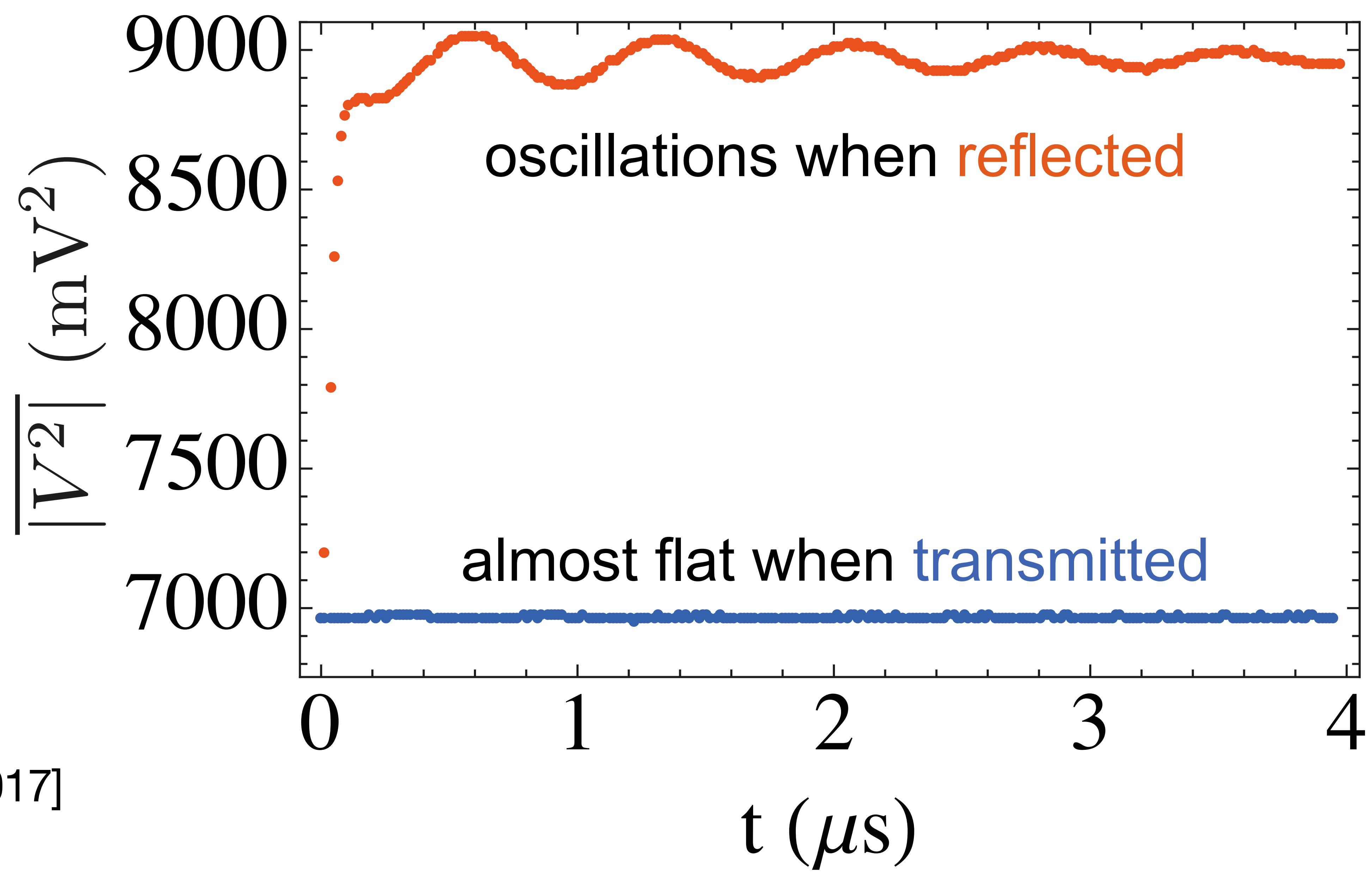
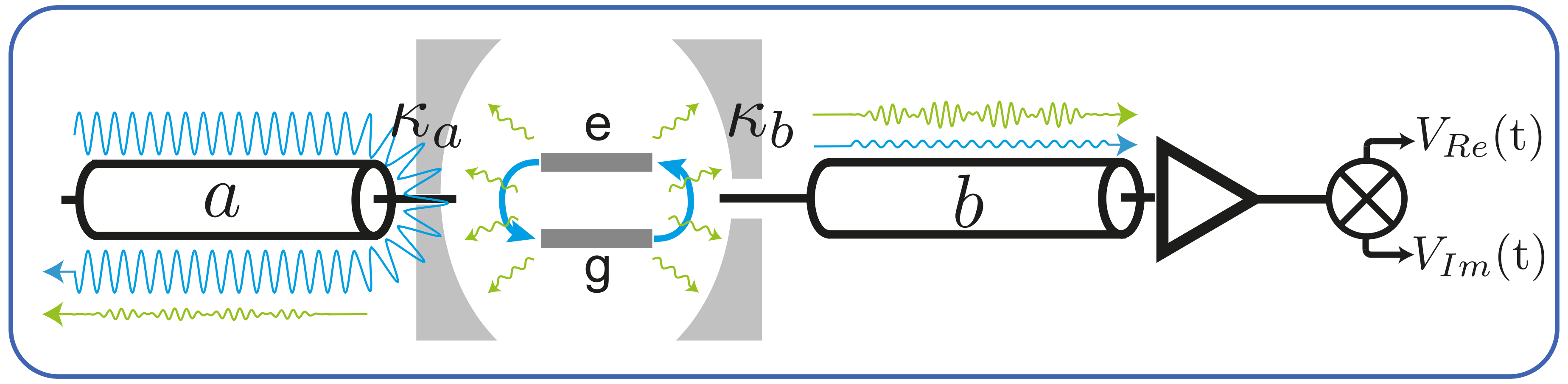


[Cottet et al., PNAS, 2017]



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

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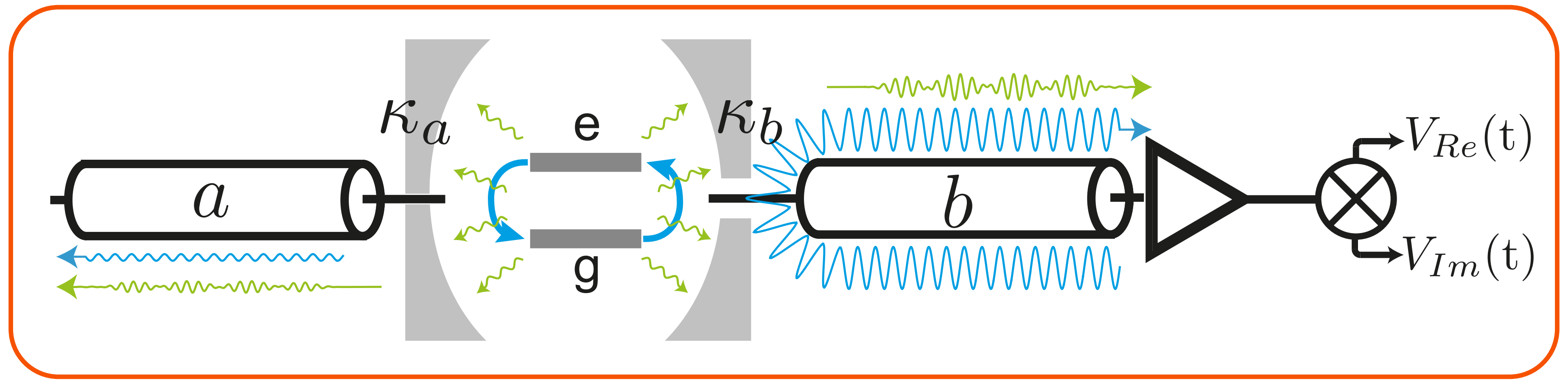
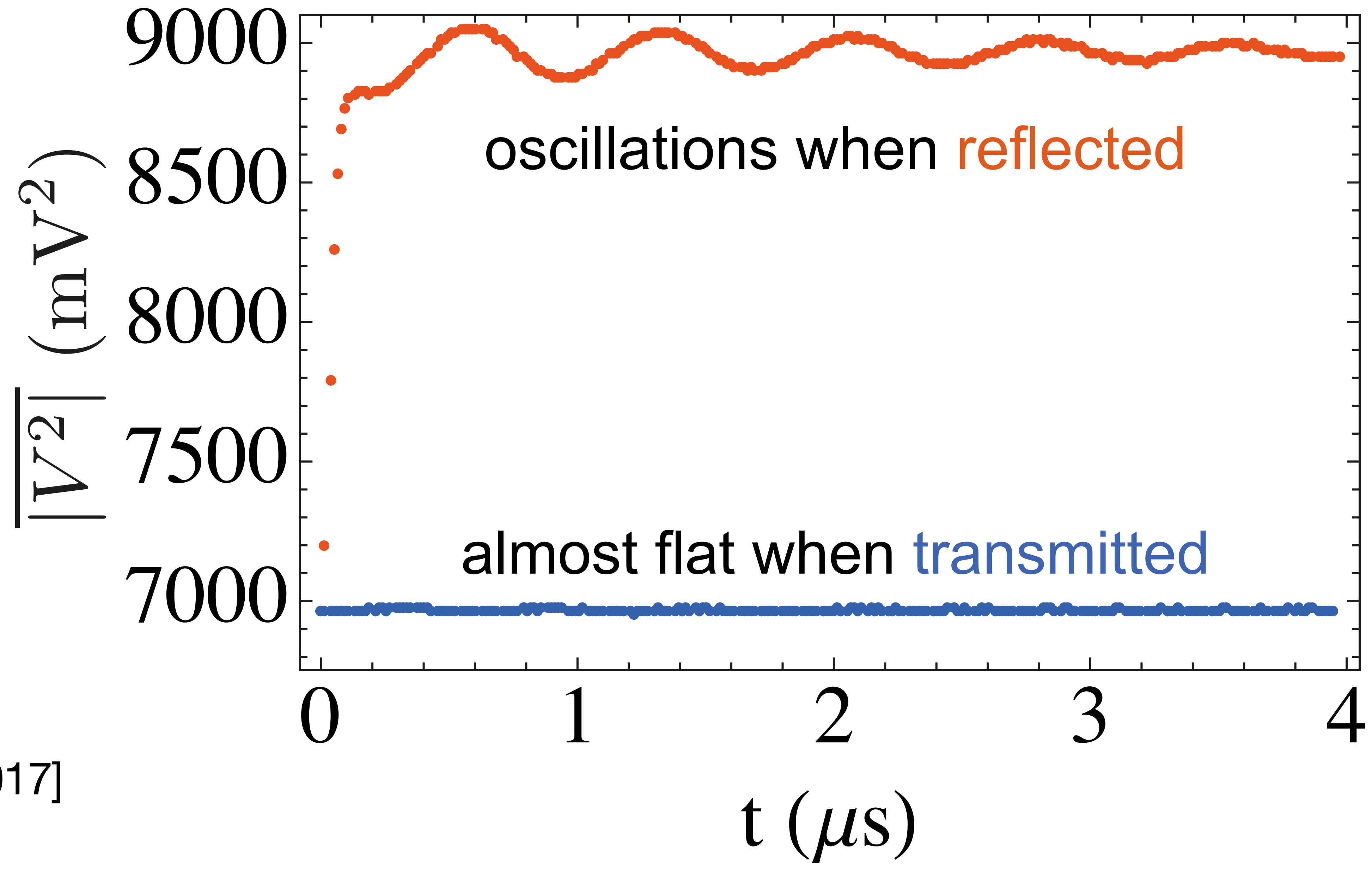
$$\langle b^\dagger_{out} b_{out}\rangle = \langle b^\dagger_{out} b_{out}\rangle_0 + \gamma_b \frac{1+\langle\sigma_z\rangle_{\rho(t)}}{2} + \frac{\Omega_R}{2}\langle\sigma_x\rangle_{\rho(t)}$$

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



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

How many photons exit into the output lines?



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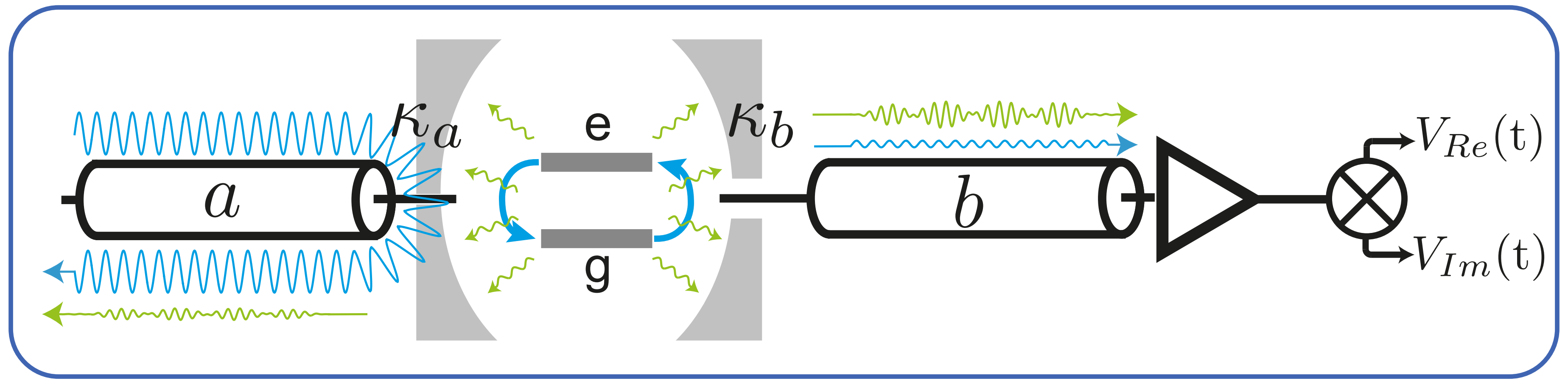

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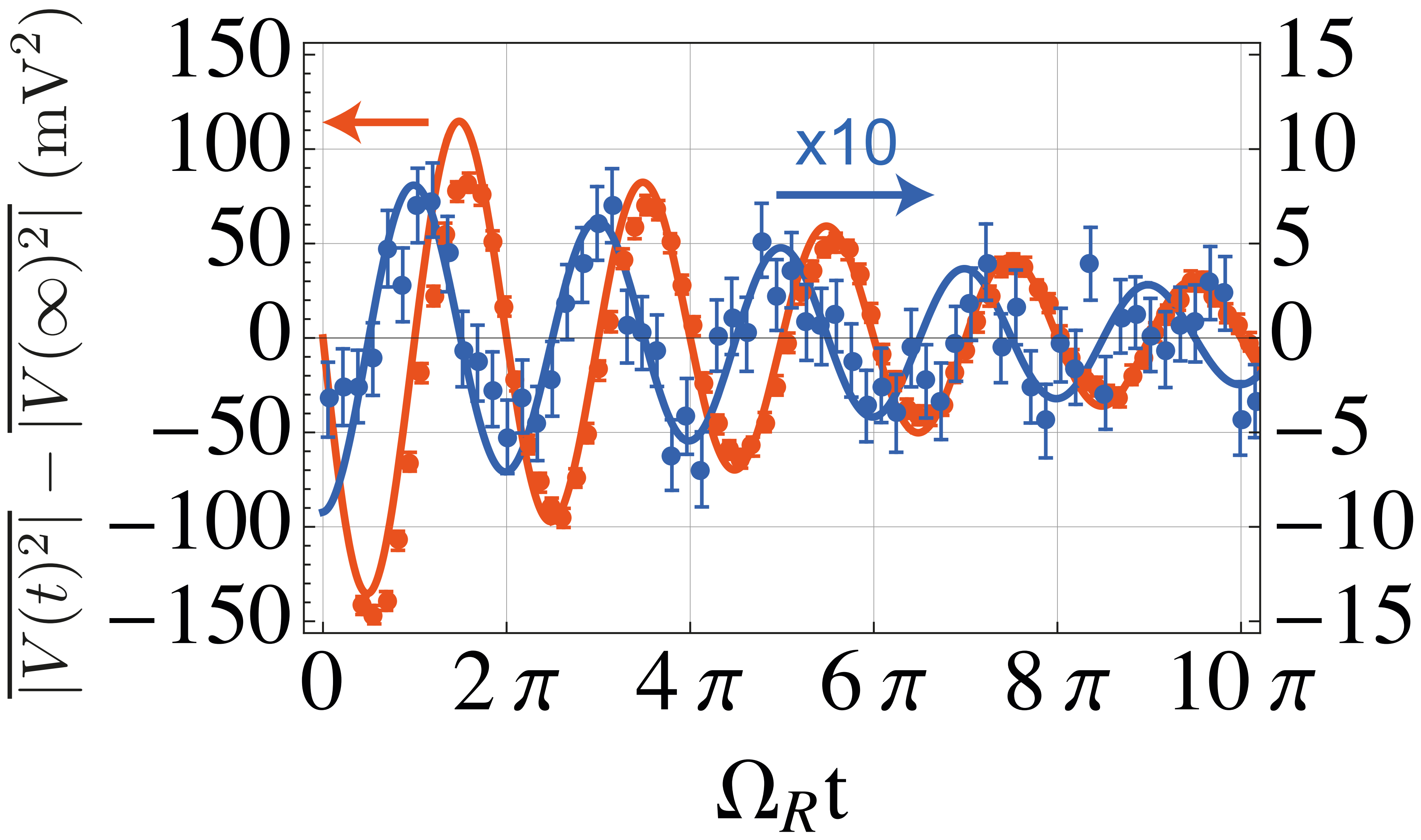
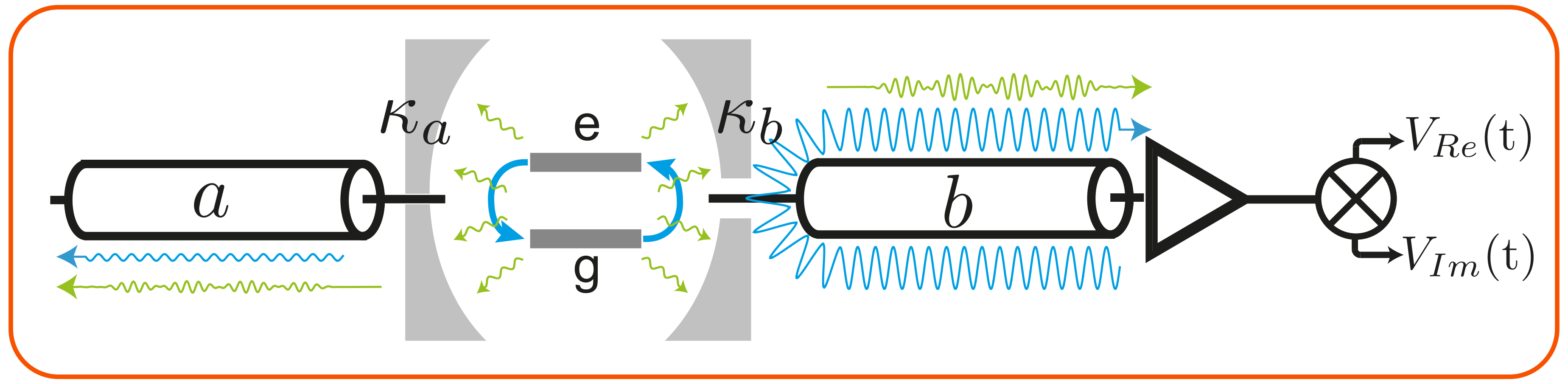


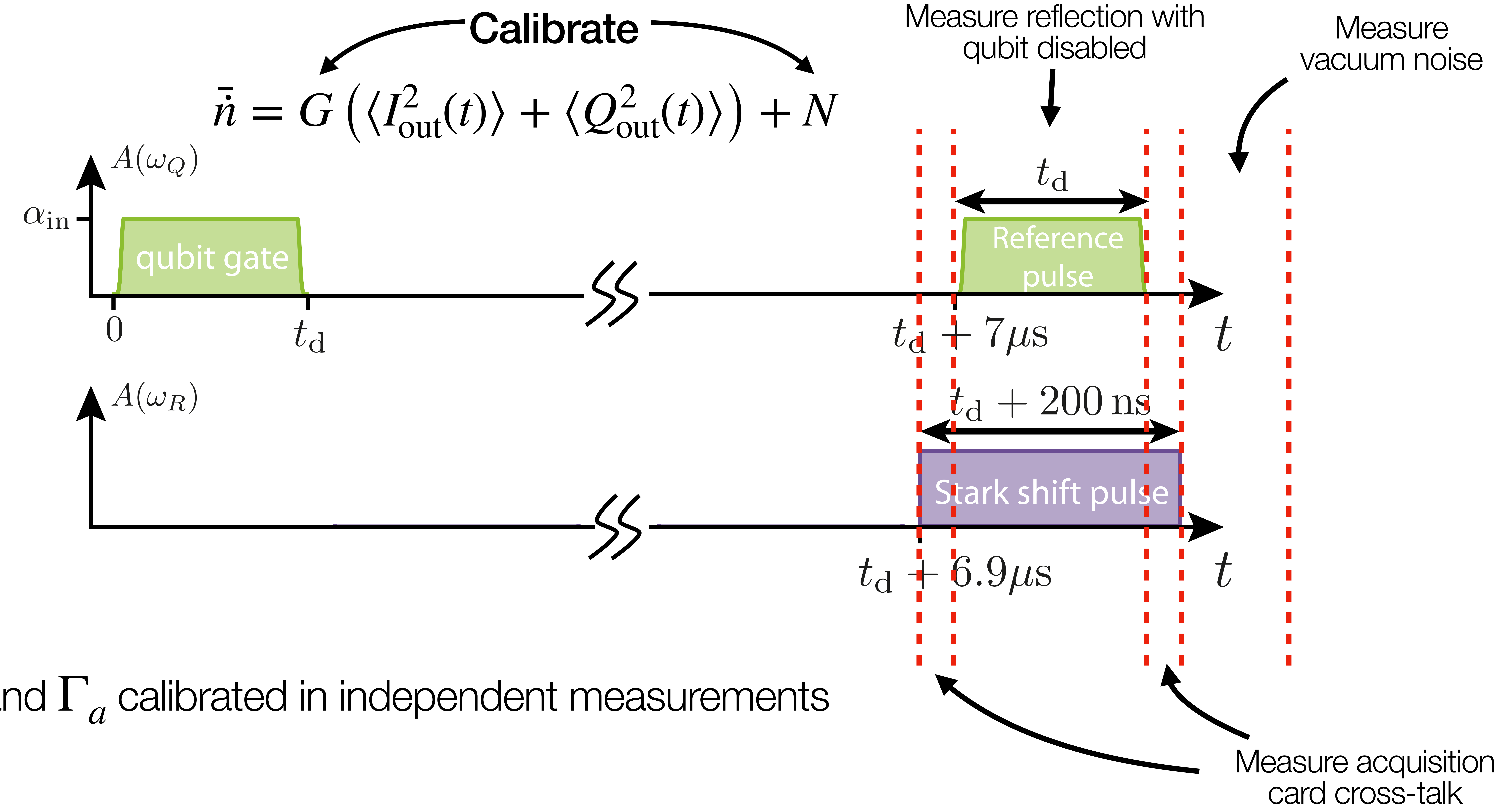


Rabi oscillations of $\langle\sigma_z\rangle$ when transmitted

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

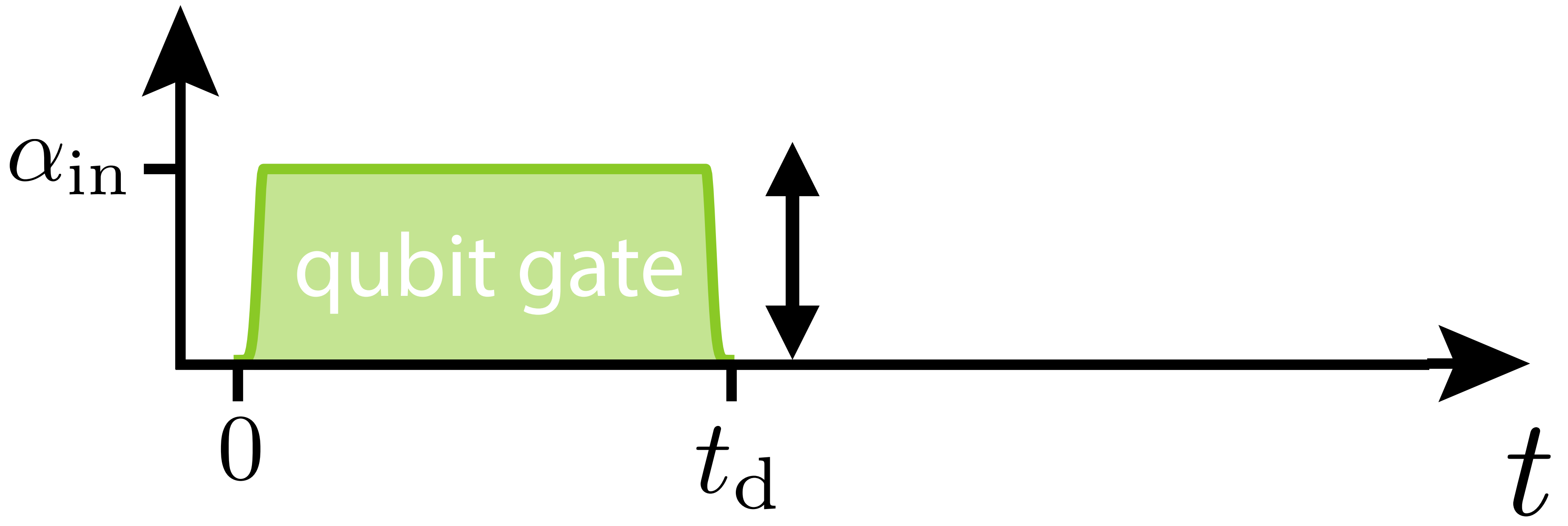
Calibrating the amplification chain

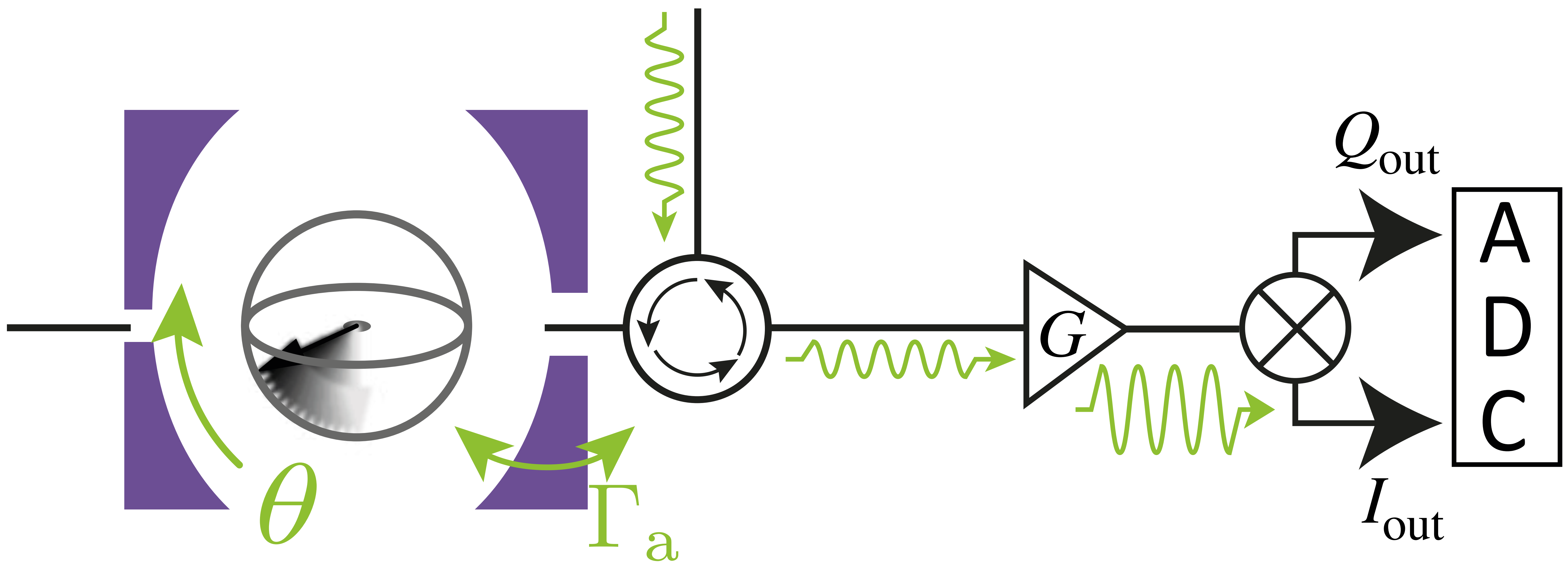
$$\bar{n} = G\left(\langle I_{\mathrm{out}}^2(t)\rangle + \langle Q_{\mathrm{out}}^2(t)\rangle\right) + N$$



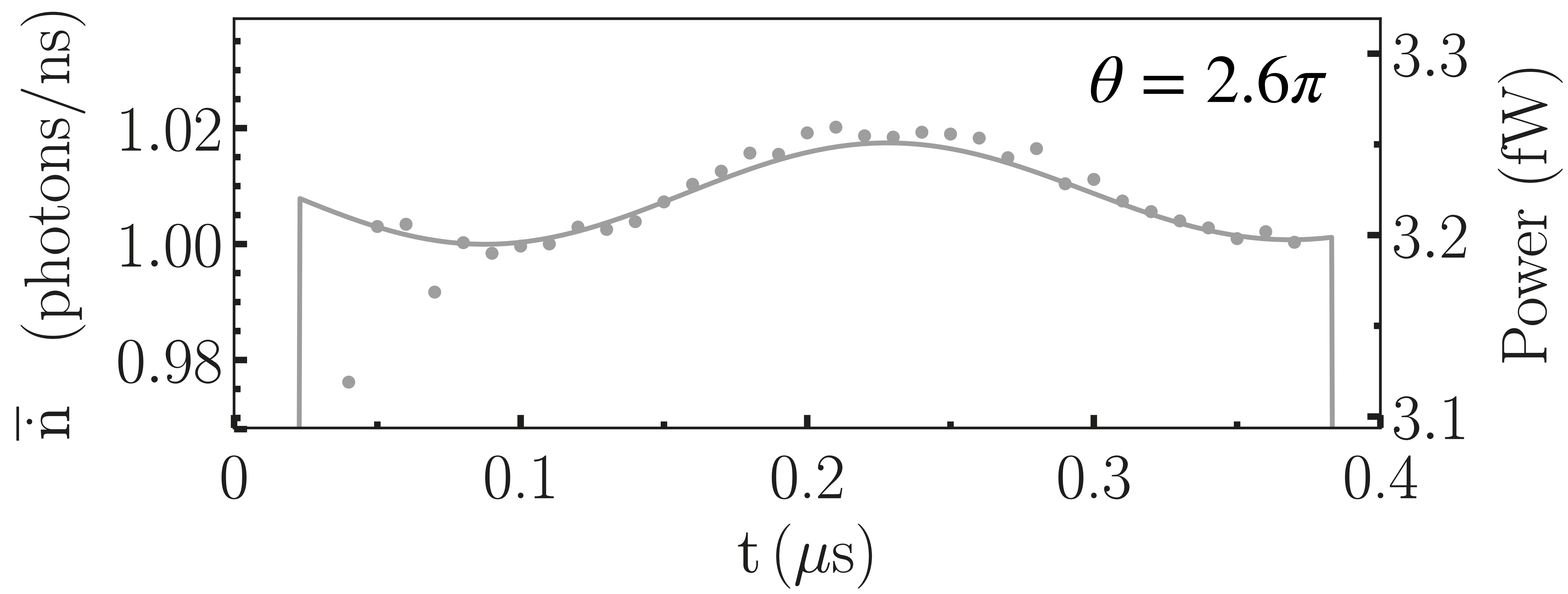
Ω_a and Γ_a calibrated in independent measurements

How to measure the average photon number?





$$\dot{\bar{n}} = G\left(\langle I_{\rm out}^2(t)\rangle + \langle Q_{\rm out}^2(t)\rangle\right) + N$$



Reflected field

Stimulated emission

Spontaneous emission

$$\dot{\bar{n}}^{\rho} = |\alpha_{\rm in}|^2 + \Gamma_a \frac{1 + \langle\hat{\sigma}_z\rangle_\rho}{2} - \frac{\Omega_a}{2}\langle\hat{\sigma}_x\rangle_\rho$$

$$\Omega_a \gg \Gamma_a$$

[Cottet Thesis 2018]

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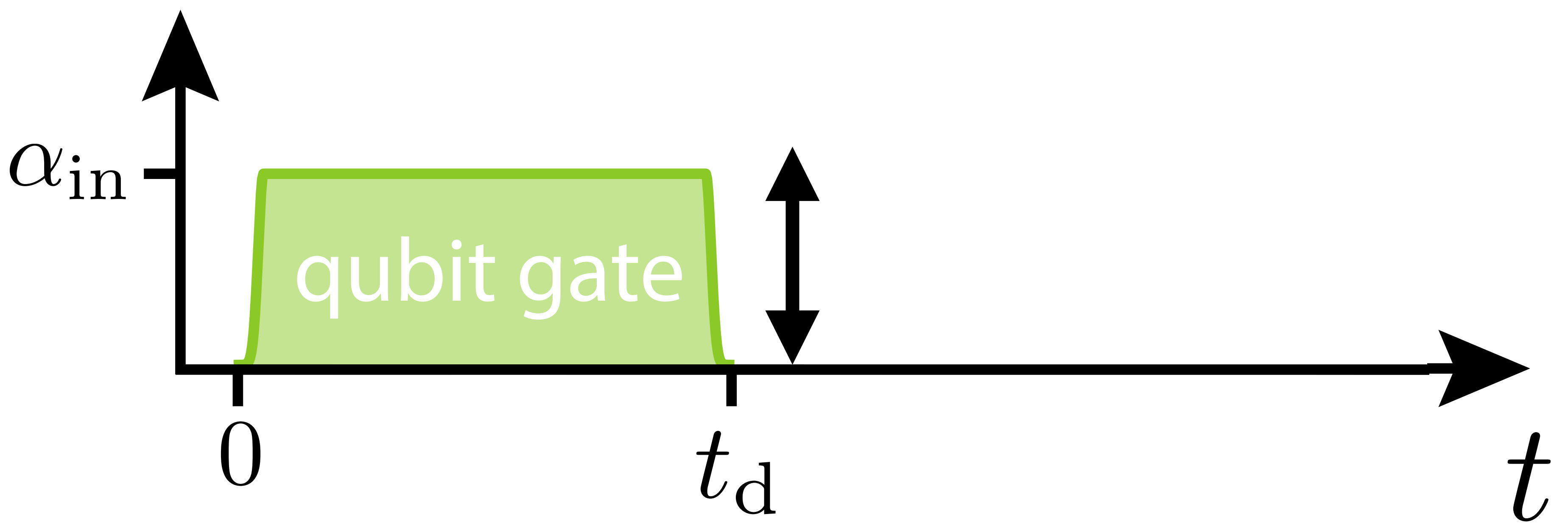
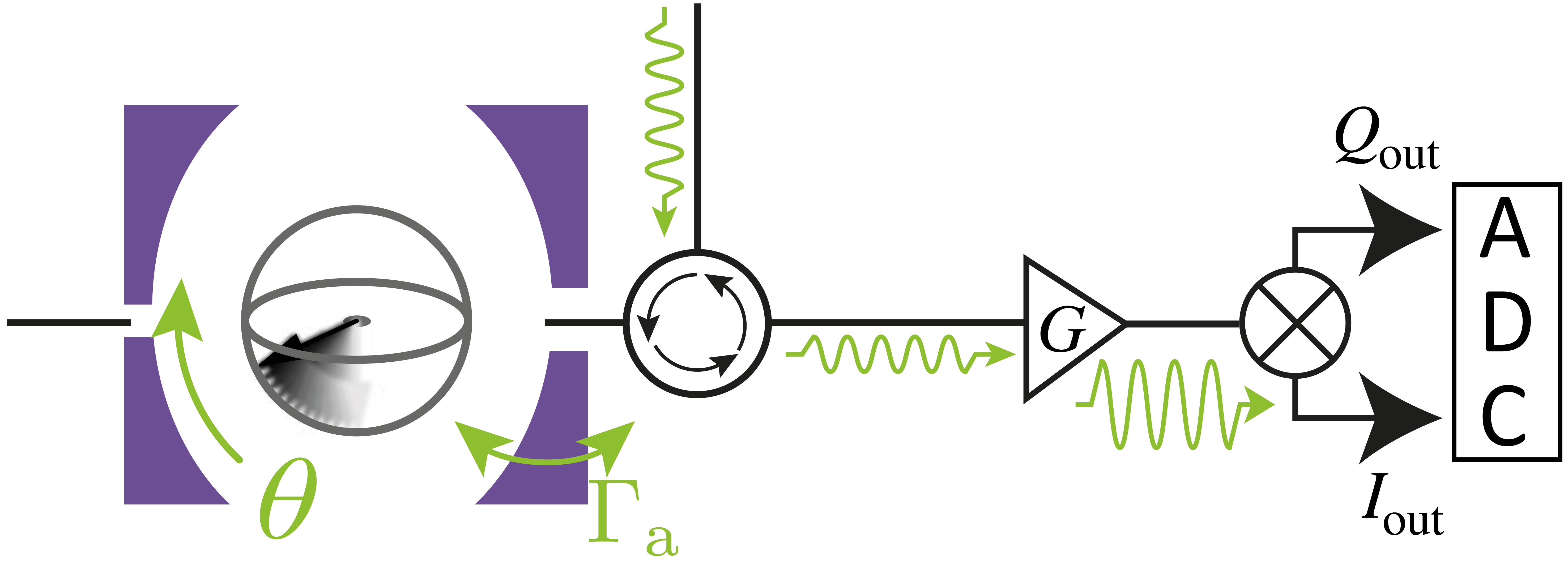
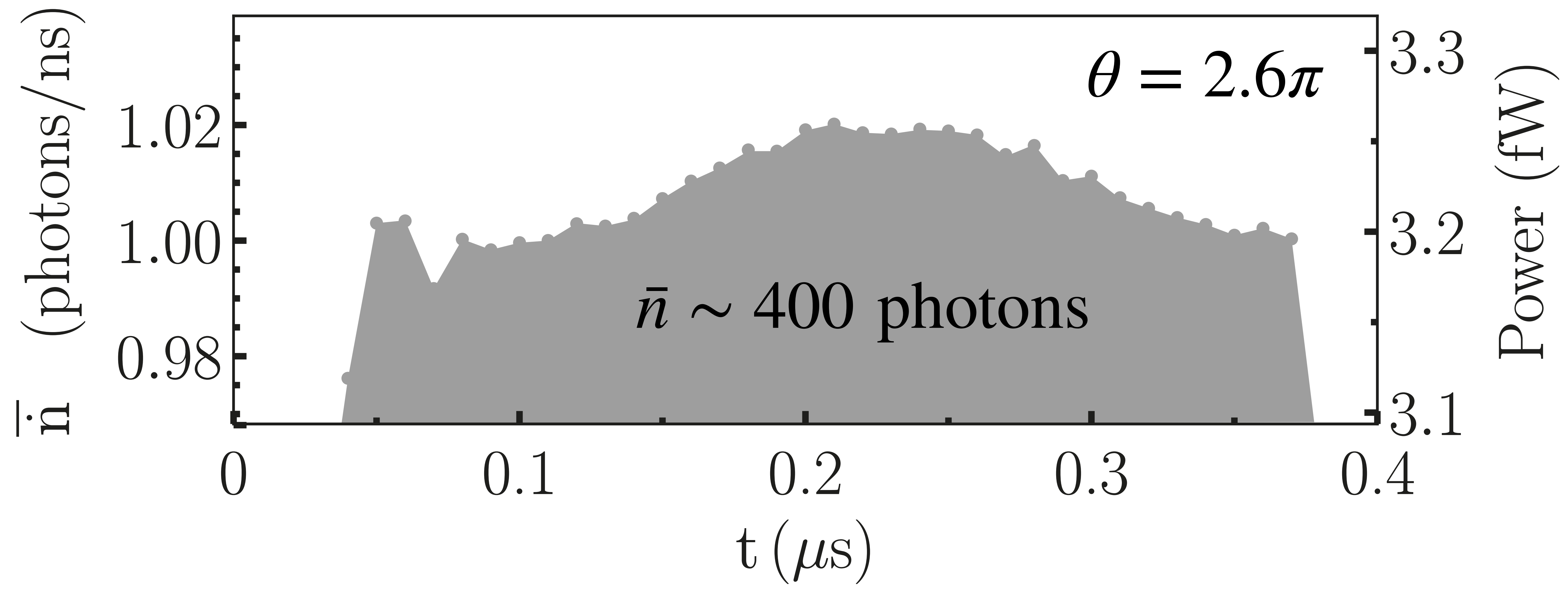




$$\dot{\bar{n}} = G\left(\langle I^2_{out}(t)\rangle + \langle Q^2_{out}(t)\rangle\right) + N$$



Reflected field

Spontaneous emission

Stimulated emission

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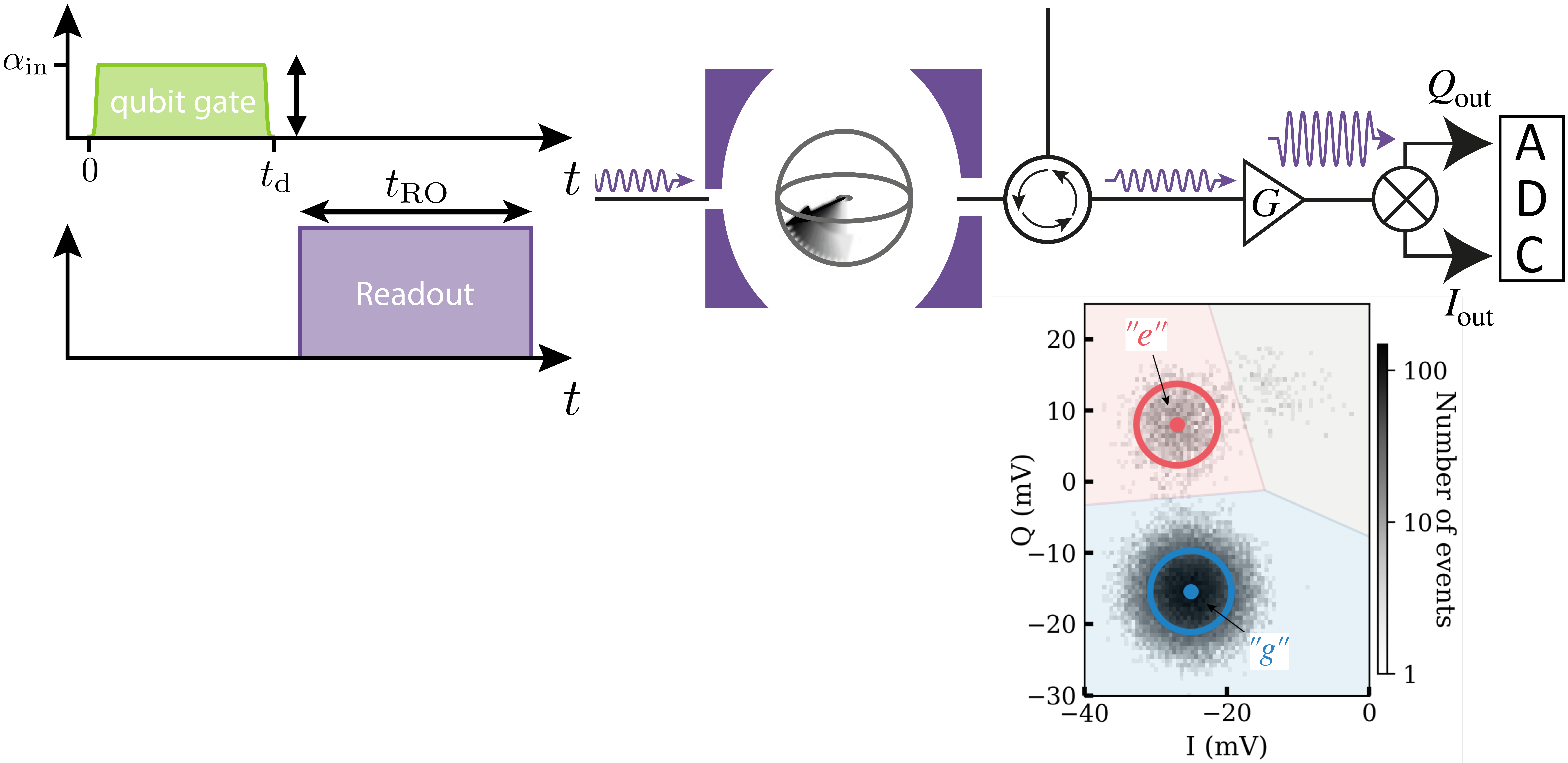
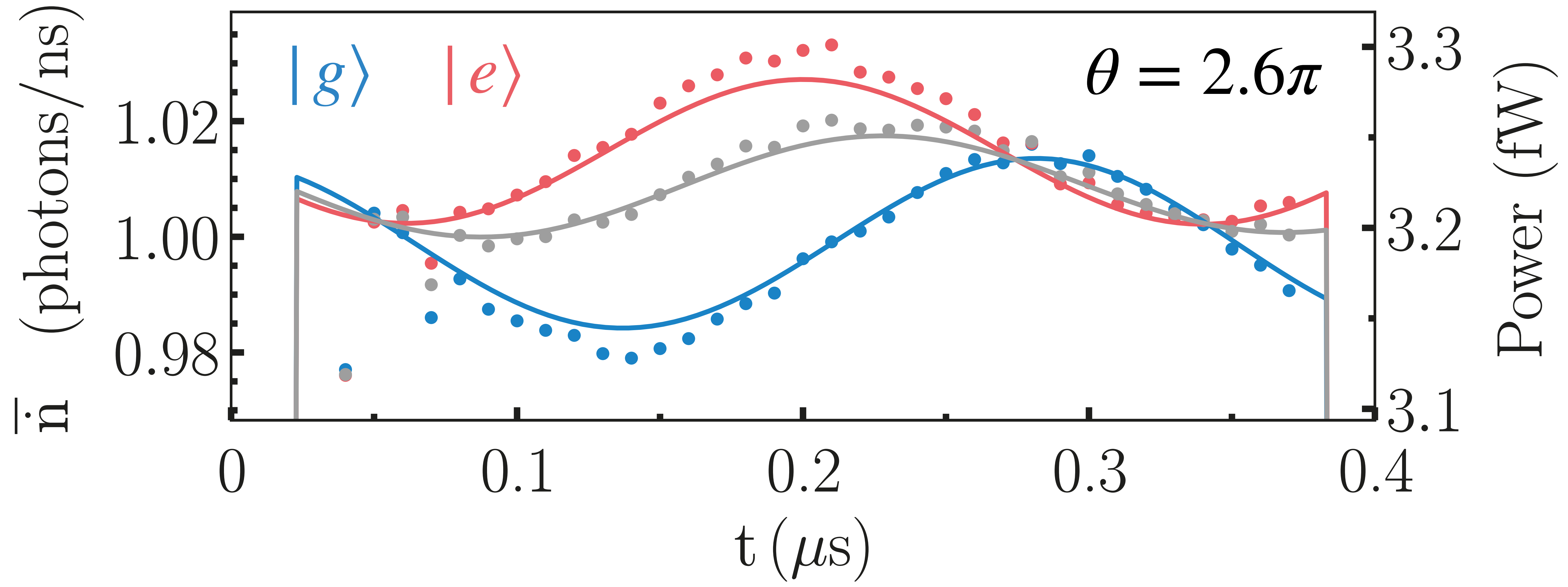
$$\Omega_a \gg \Gamma_a$$

Strong qubit readout



Post-selected fluorescence

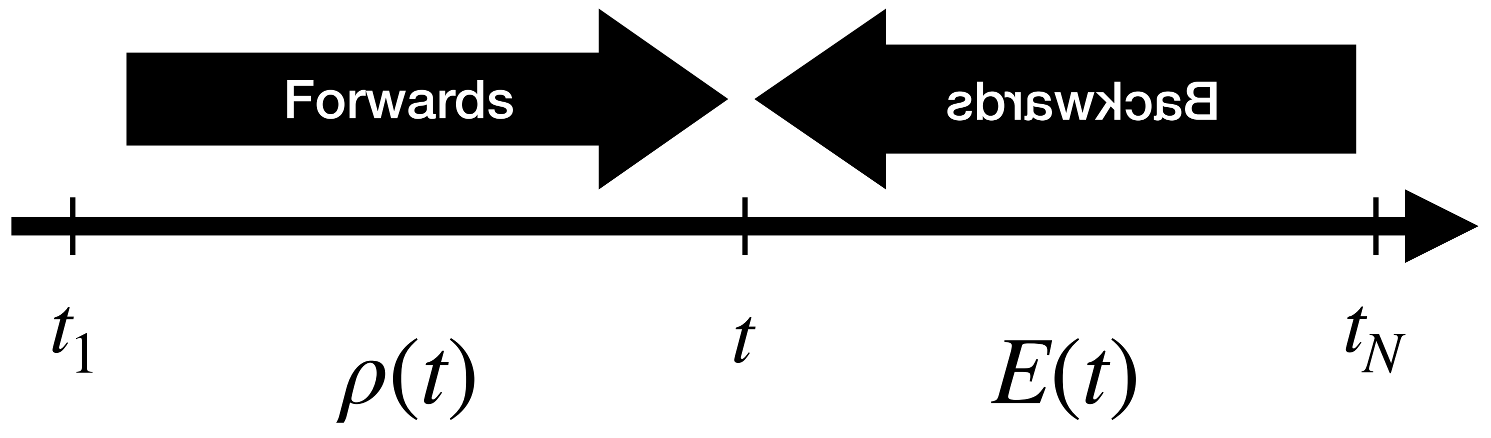


Reflected field **Spontaneous emission** **Stimulated emission**

$$\bar{\dot{n}}^{E,\rho} = |\alpha_{\text{in}}|^2 + \Gamma_a \mathcal{I}(E,\rho) - \Omega_a \text{Re}_E \langle \hat{\sigma}_- \rangle_\rho$$

$$\mathcal{I}(E,\rho) = \frac{\text{tr}\left[E\sigma_-\rho\sigma_+\right]}{\text{tr}\left[E\rho\right]}$$

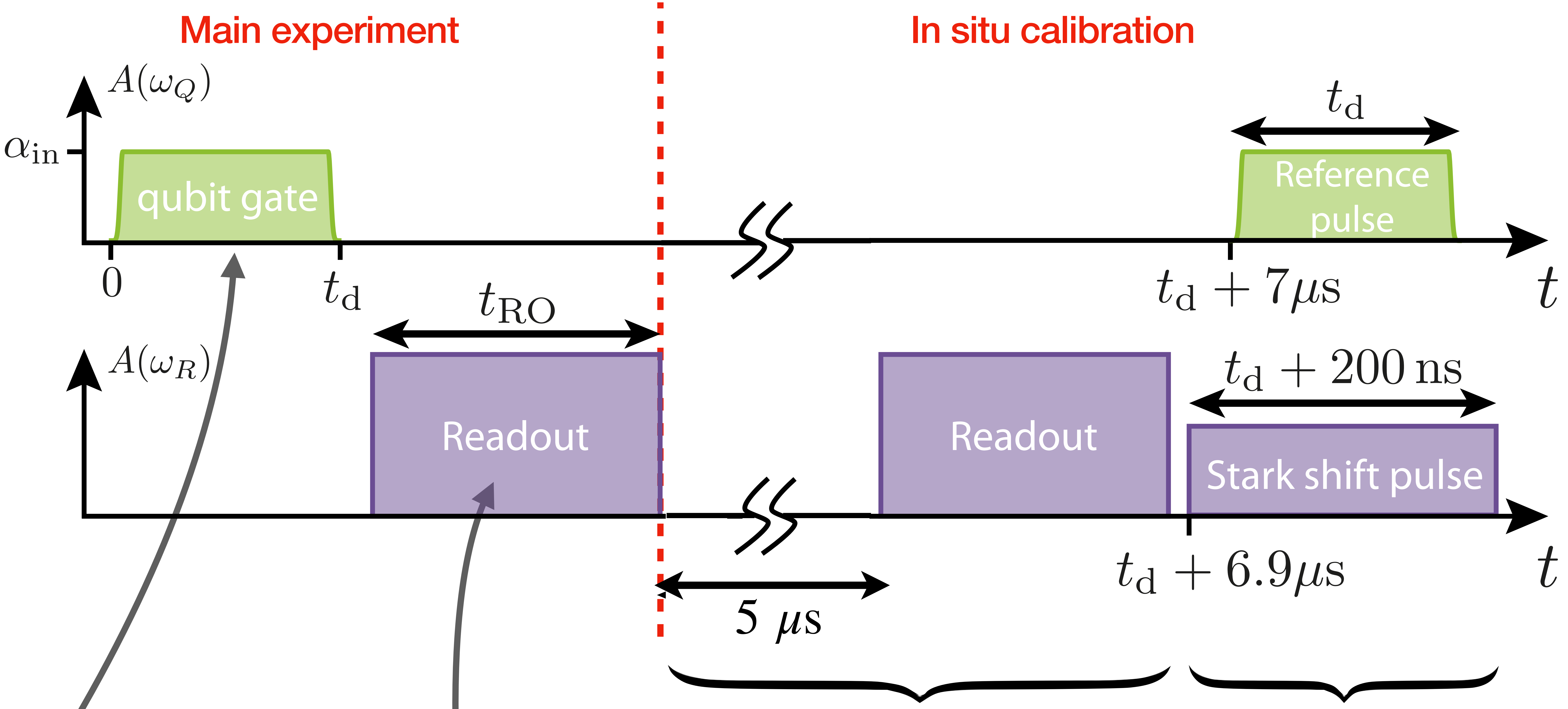
[Mafei et al., PRA 2022]



[Wiseman, PRA 2002; Tsang PRA 2009; Gammelmark et al., PRL 2013]

for amplitudes: [Campagne-Ibarcq *et al.*, PRL 2014]

Total pulse sequence



Qubit drive

Average photon number measurement

Qubit readout

Allows post-selection of photon numbers

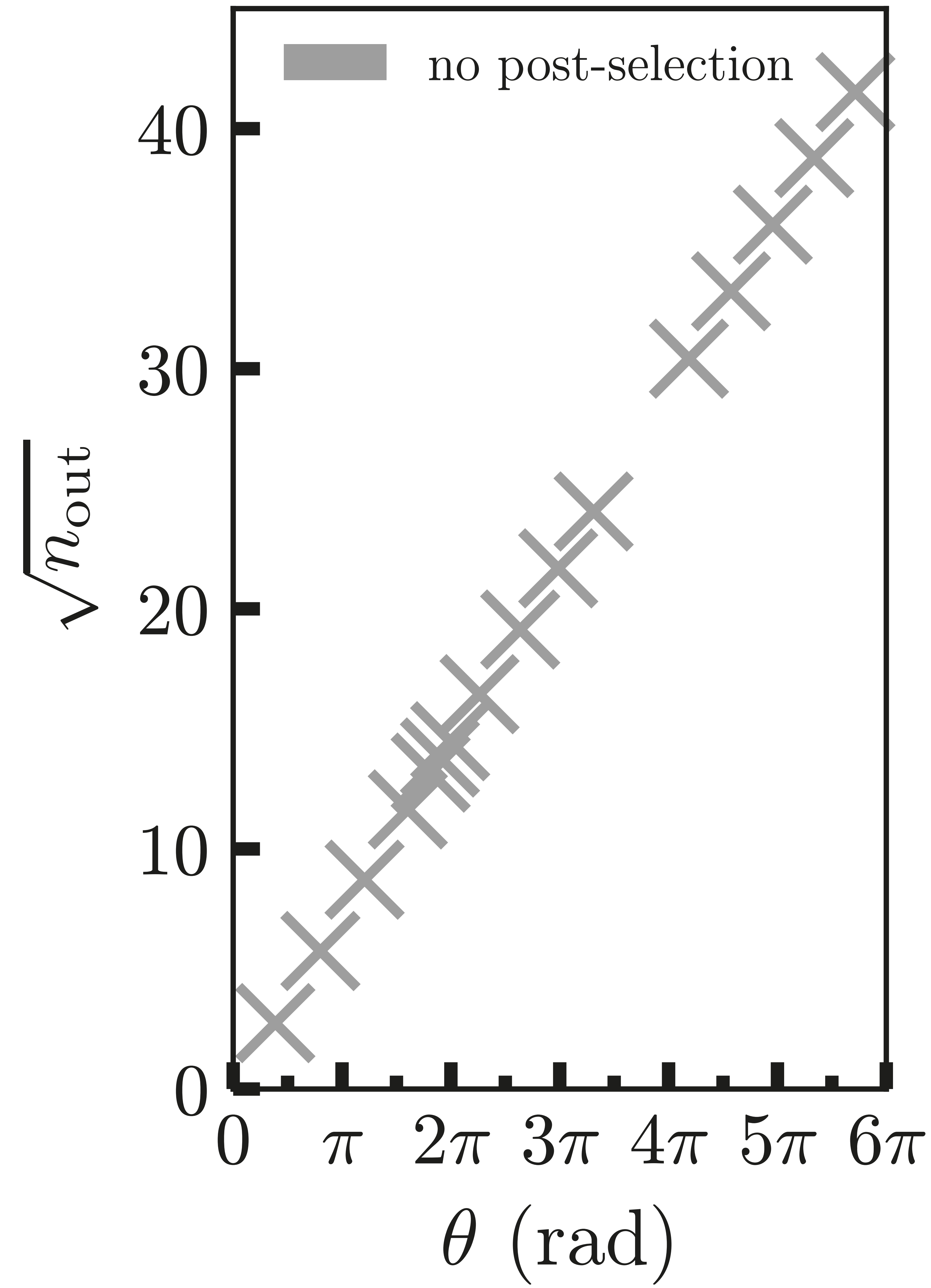
In situ T_1 measurement

Corrects for fast drifts in Γ_1

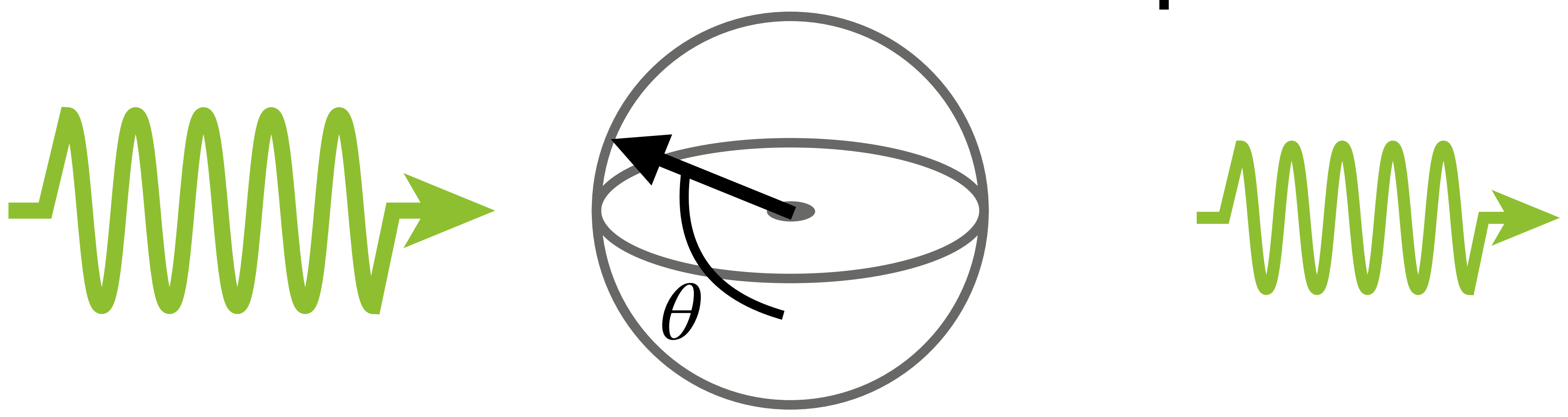
Noise & amplification calibration

Corrects for fast drifts in gain of amplification chain

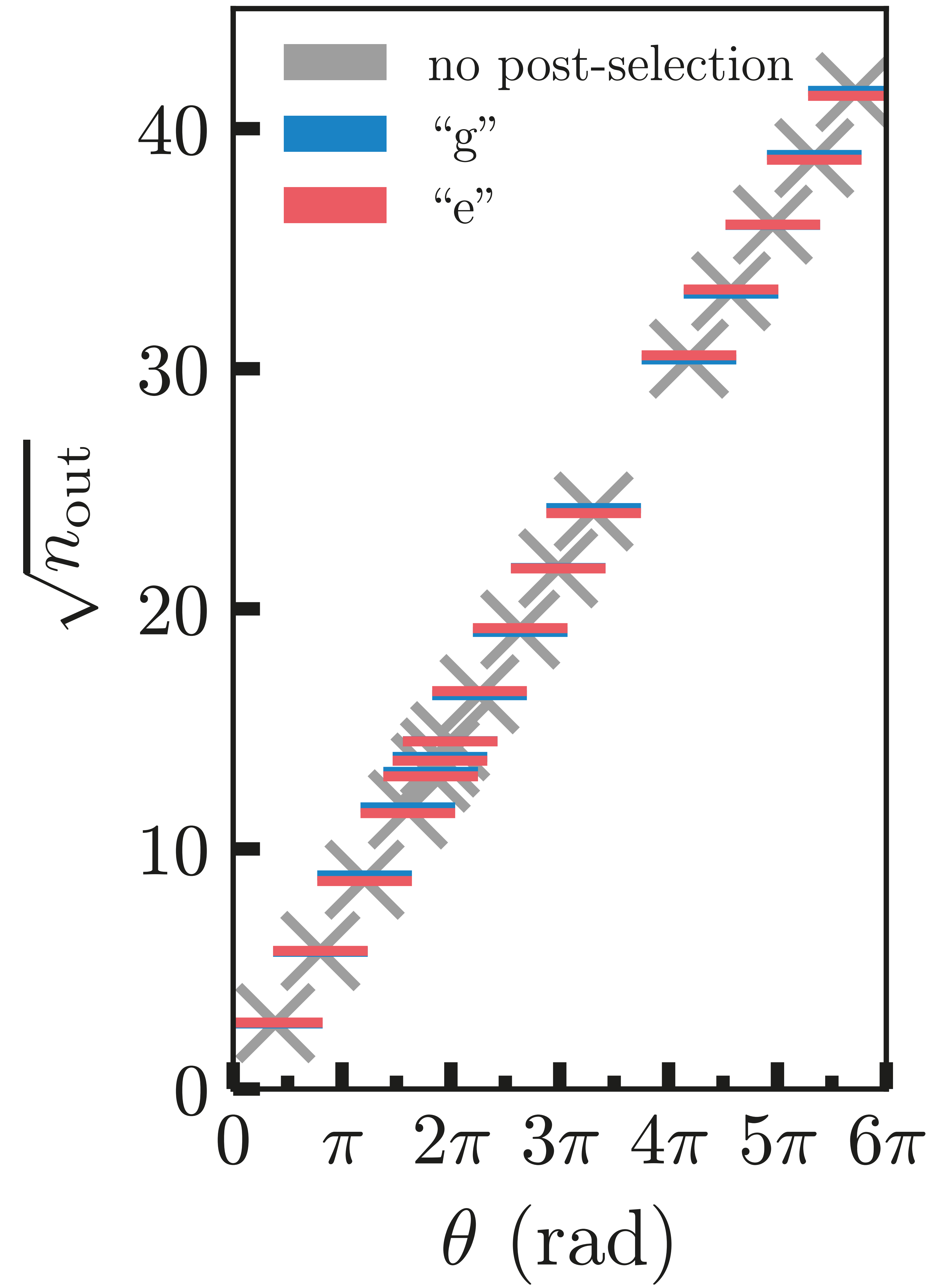
Post-selection of outgoing photon number

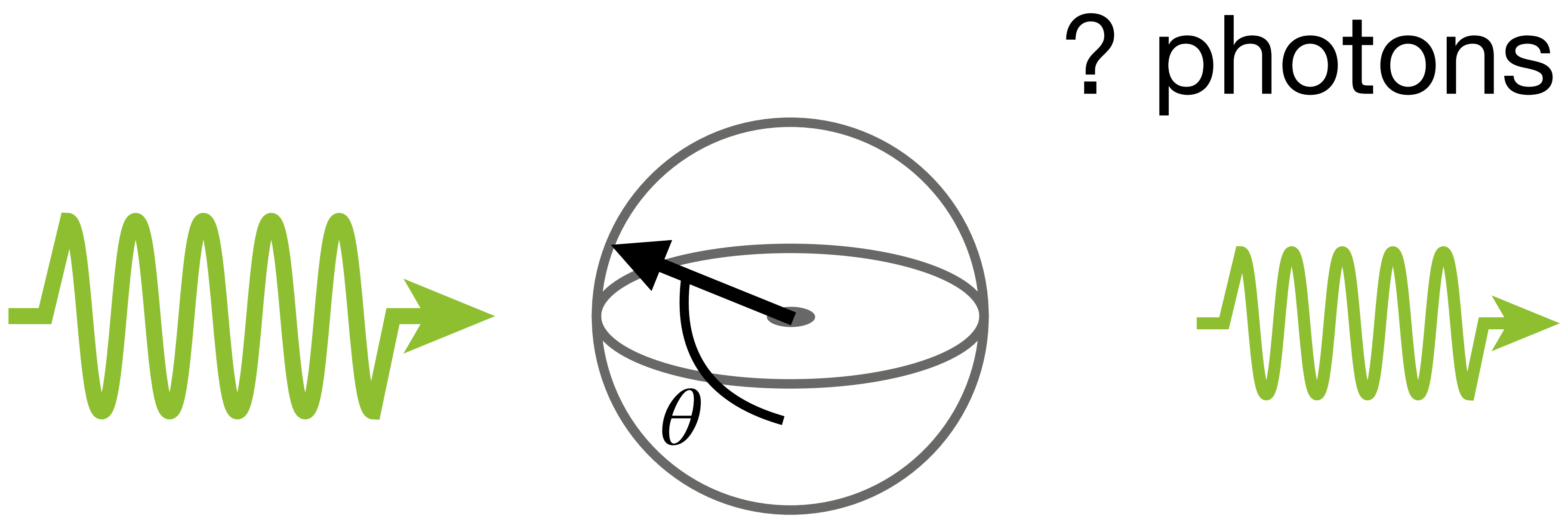


? photons



Post-selection of outgoing photon number





Post-selection of outgoing photon number

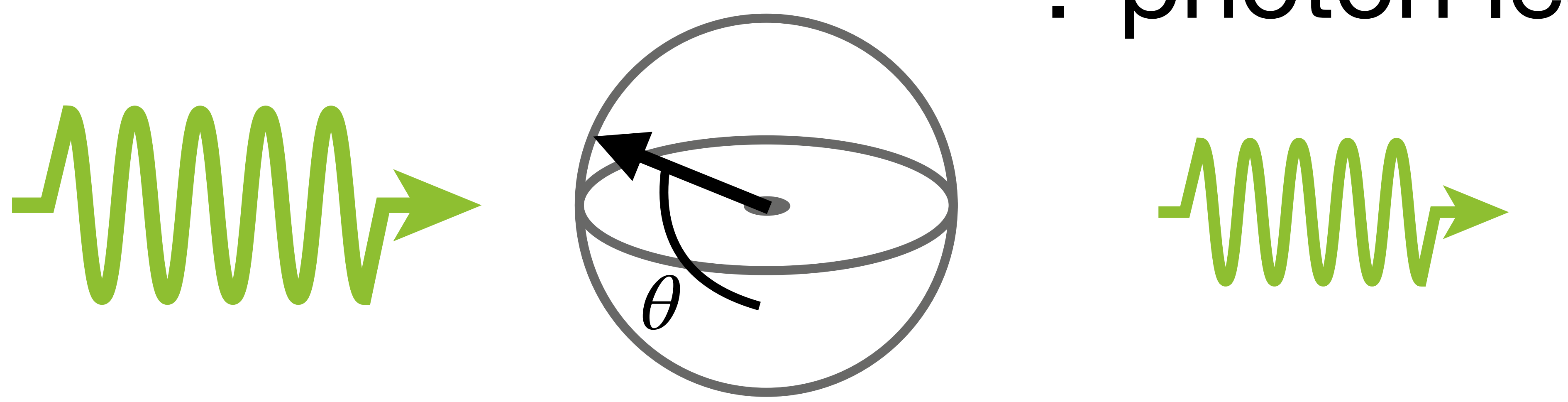
Measured outgoing photon number

Average incoming photon number

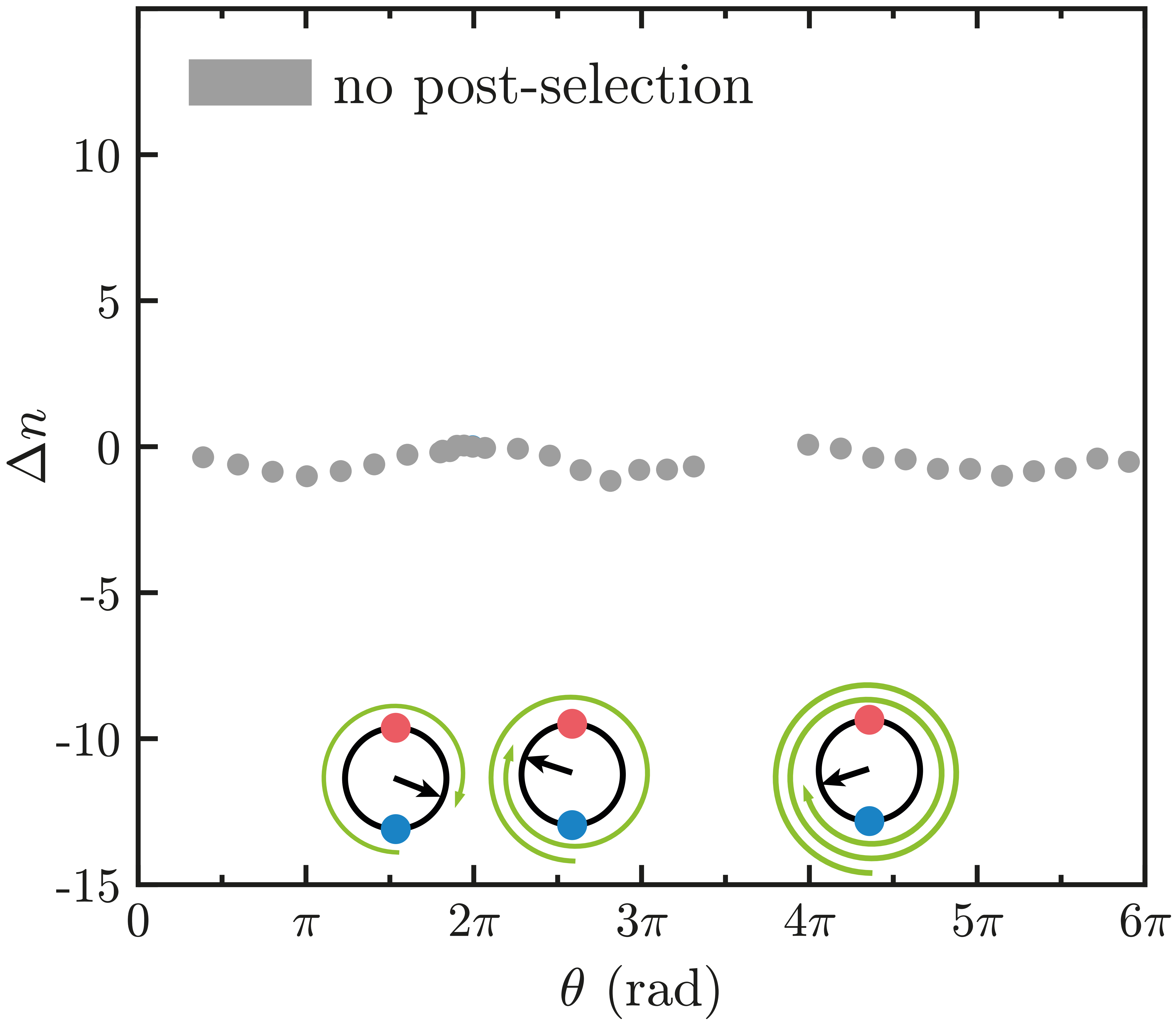
$$\Delta n = n - n_{\text{in}}$$

$$n_{\text{in}} = \int_0^{t_{\text{d}}} |\alpha_{\text{in}}(t)|^2 \, \mathrm{d}t$$

? photon less



Post-selection of outgoing photon number



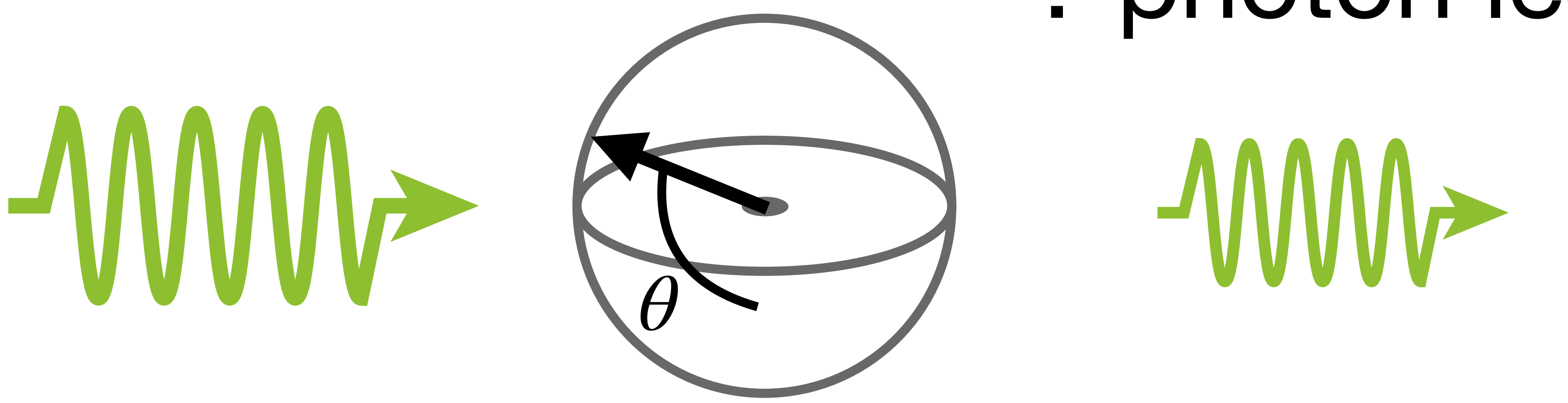
Measured outgoing photon number

Average incoming photon number

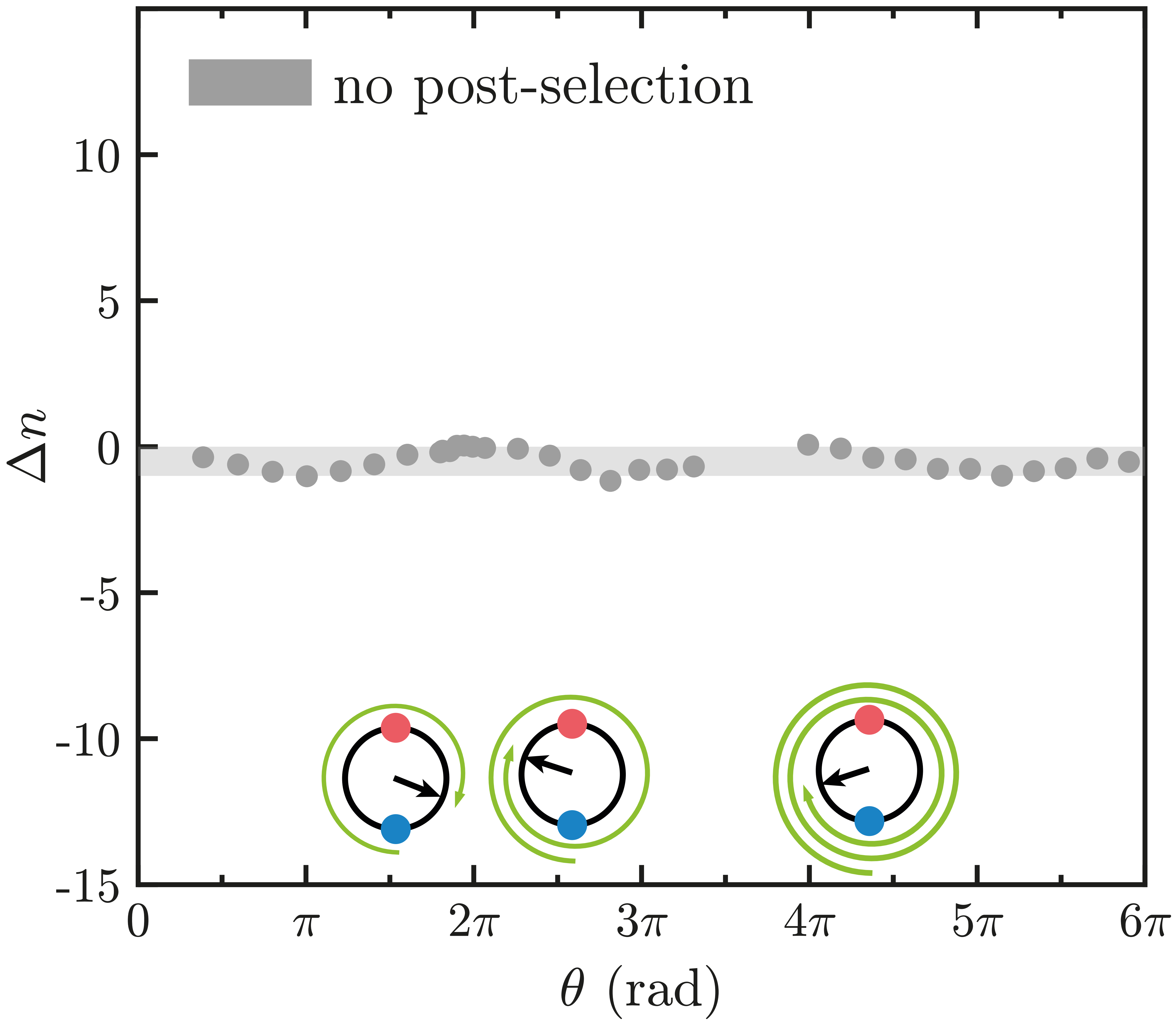
$$\Delta n = n - n_{\text{in}}$$

$$n_{\text{in}} = \int_0^{t_d} |\alpha_{\text{in}}(t)|^2 \mathrm{d}t$$

? photon less



Post-selection of outgoing photon number



Measured outgoing photon number

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$$\Delta n = n - n_{\mathrm{in}}$$

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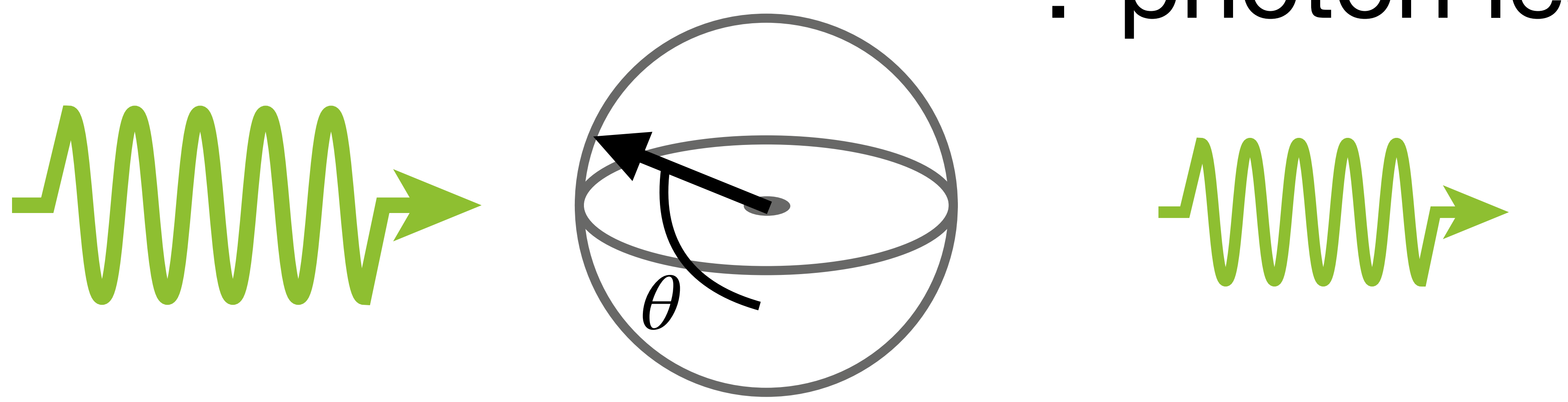
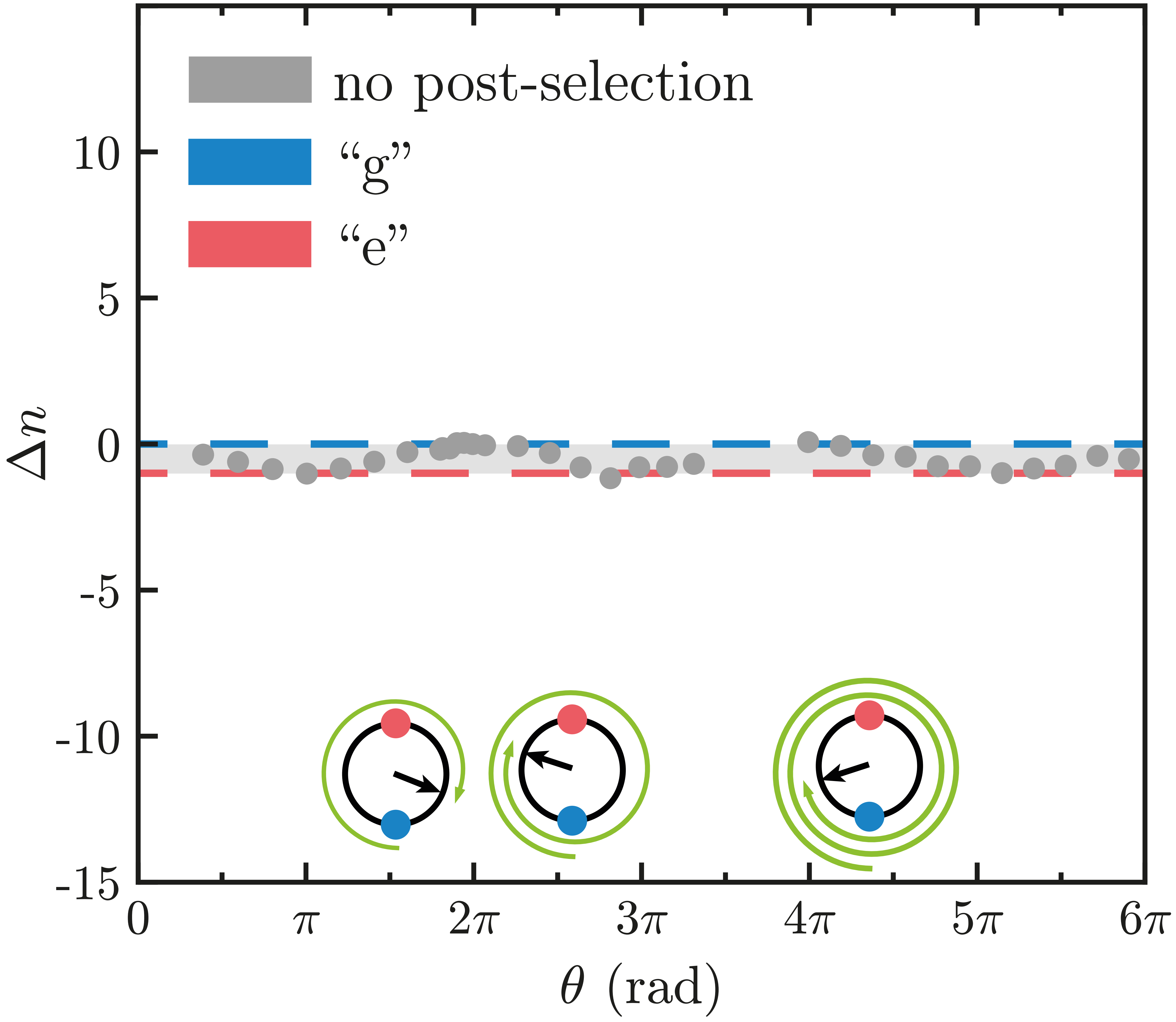
? photon less



Post-selection of outgoing photon number



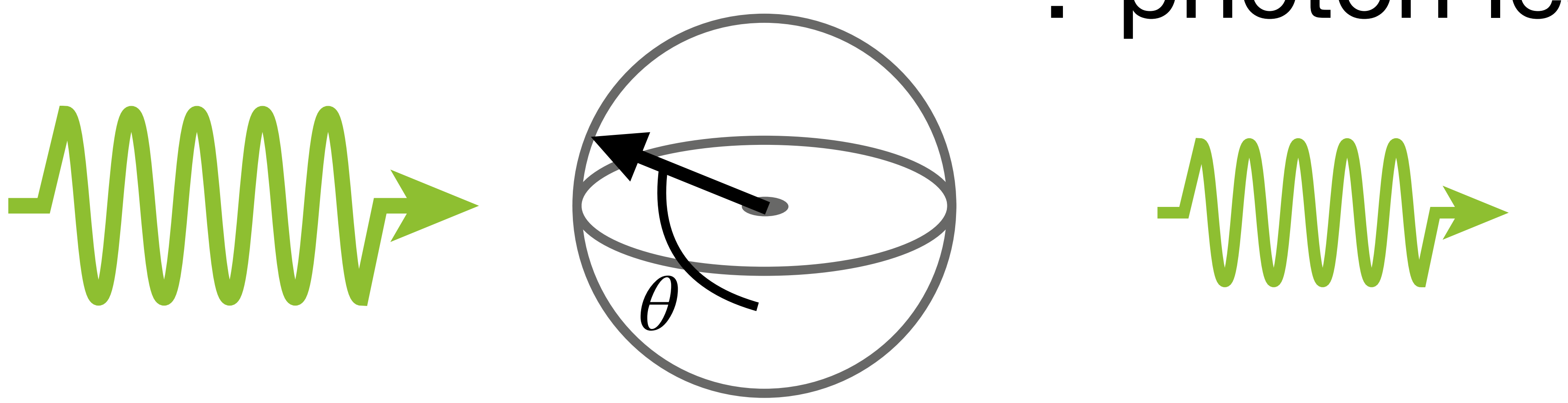
Measured outgoing photon number

Average incoming photon number

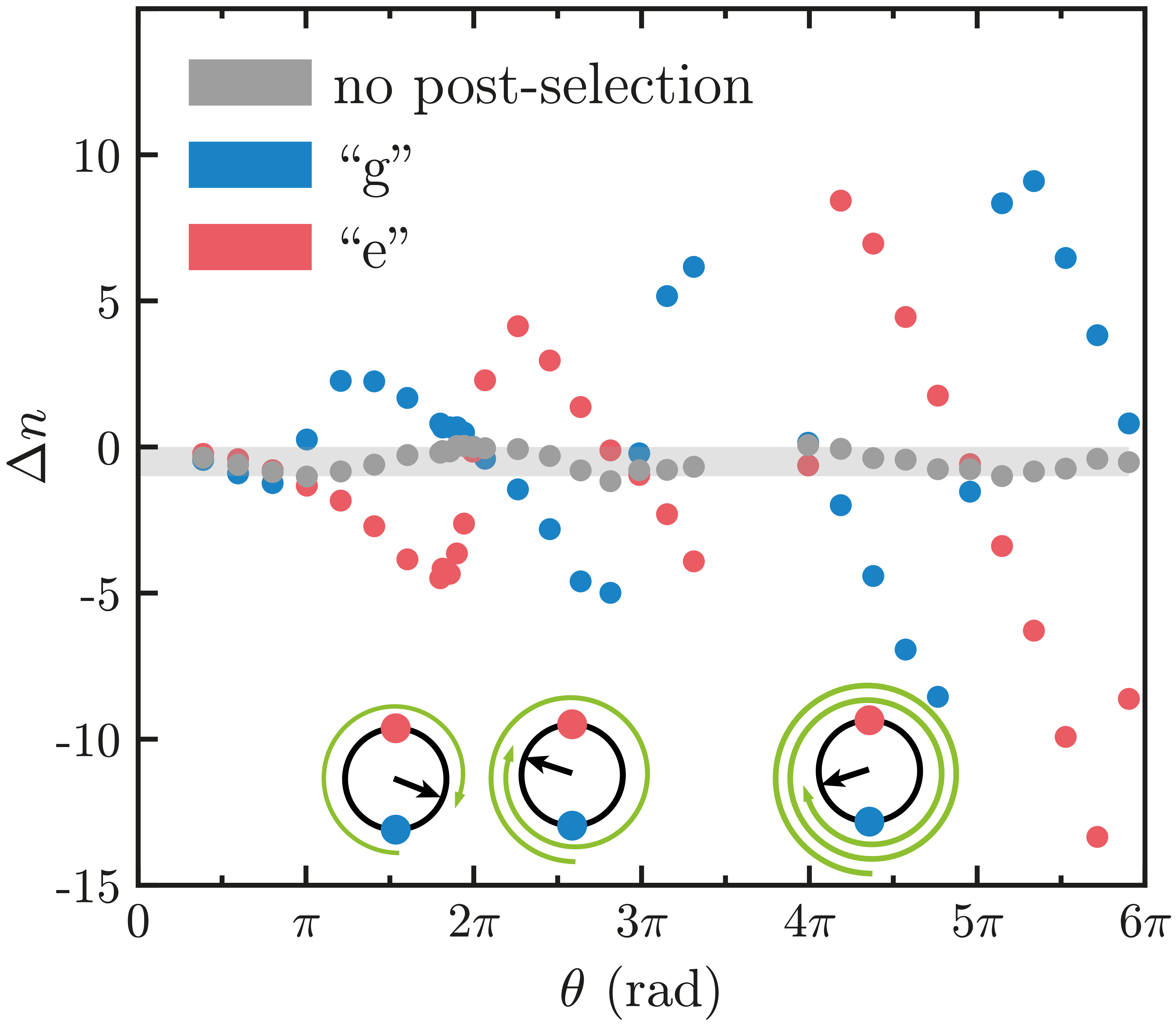
$$\Delta n = n - n_{\text{in}}$$

$$n_{\text{in}} = \int_0^{t_\text{d}} |\alpha_{\text{in}}(t)|^2 \, \mathrm{d}t$$

? photon less



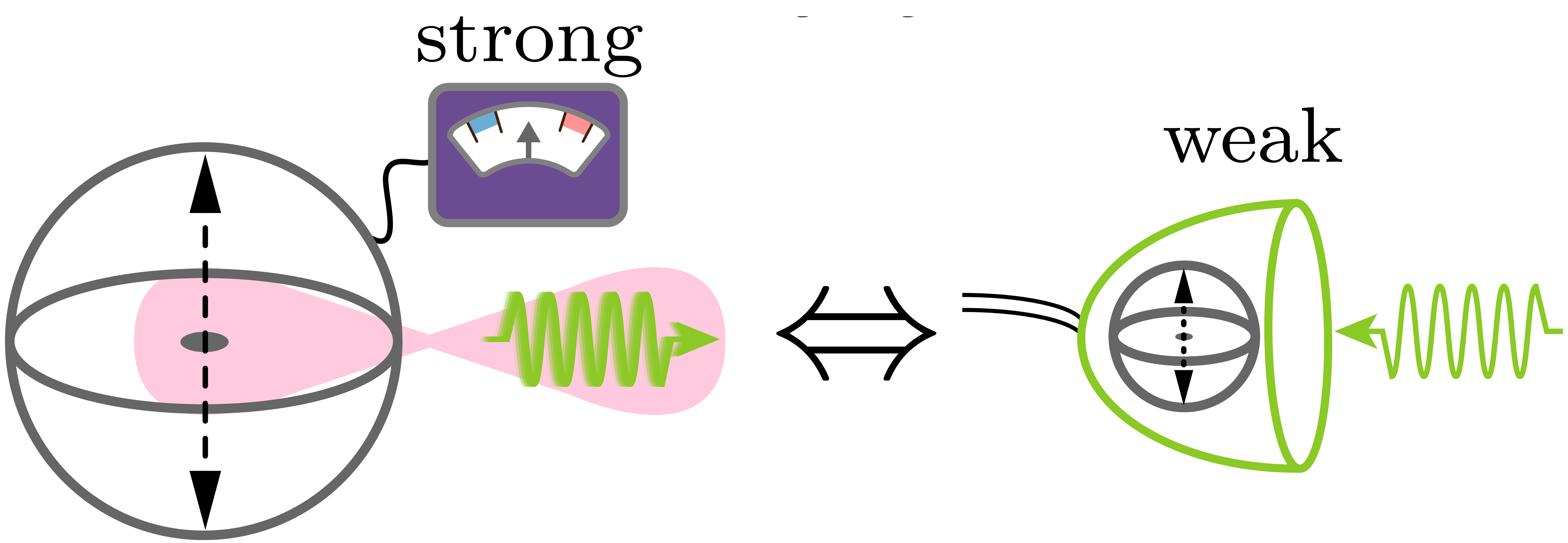
Exchange of more than a single photon?

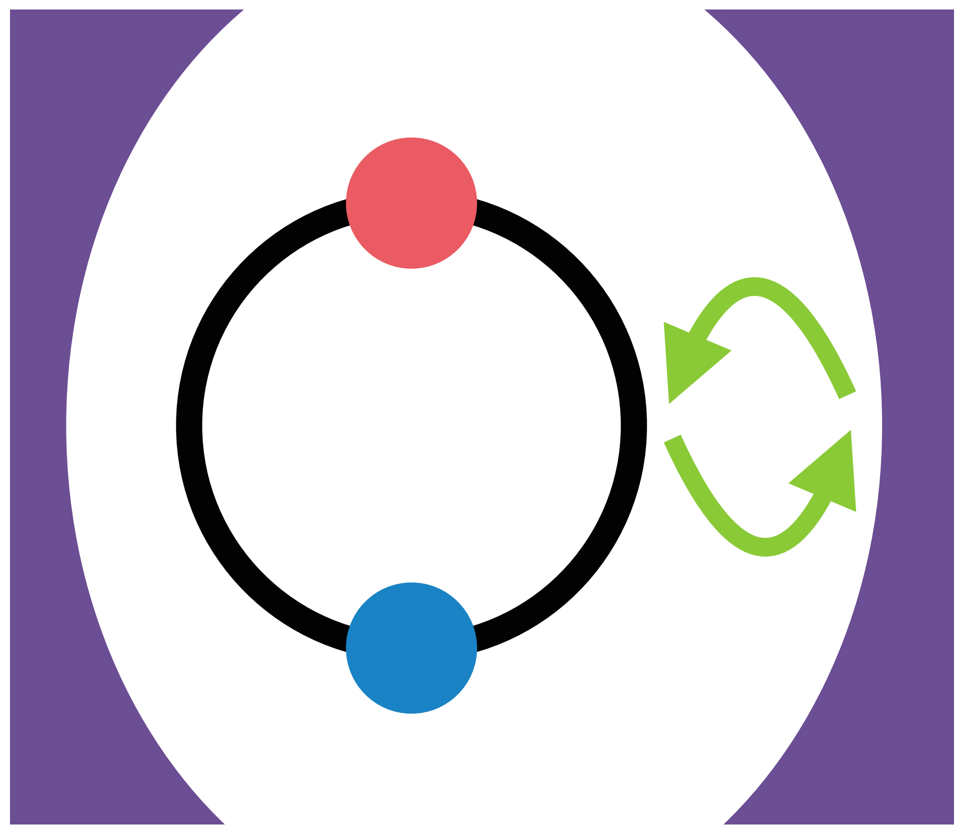


→ **Not so fast…**

Initial energy undetermined

Interpretation as backaction of weak measurement





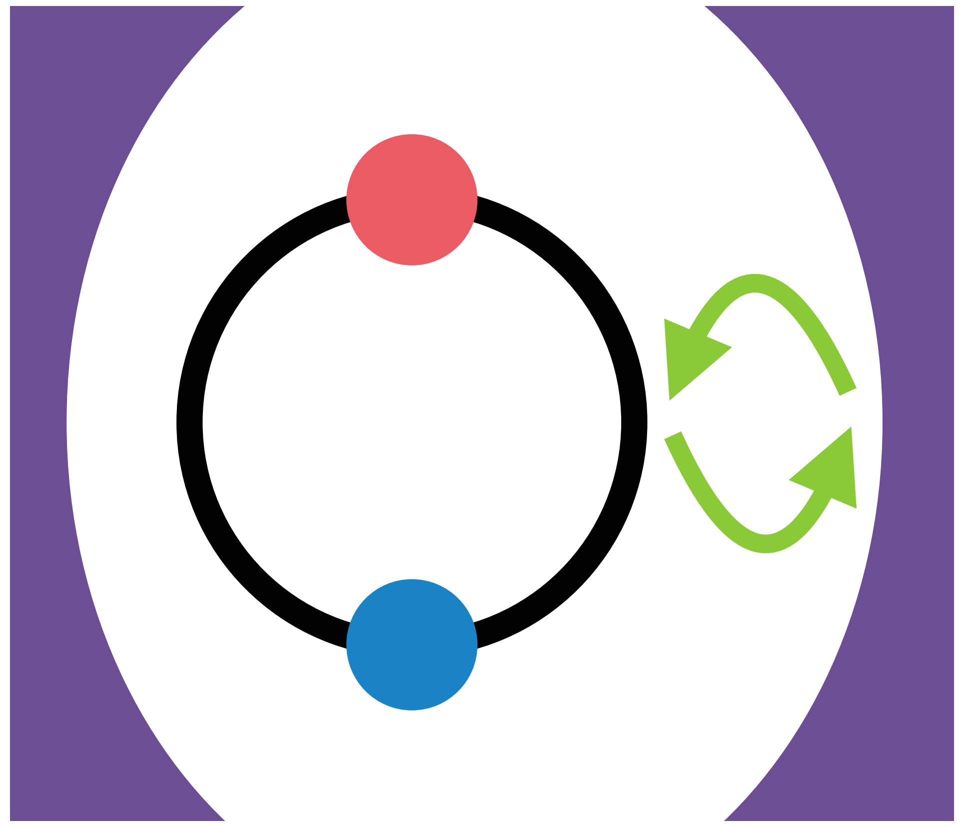
$$g = \sqrt{\frac{\Gamma_a}{t_\mathrm{d}}}$$

$$\hat{M}_g = \cos\left(\sqrt{\Gamma_a t_d \hat{a}^\dagger \hat{a}}\right)$$

$$\hat{M}_e = \left(\sum_n |n\rangle\langle n+1|\right)\sin\left(\sqrt{\Gamma_a t_d \hat{a}^\dagger \hat{a}}\right)$$

$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

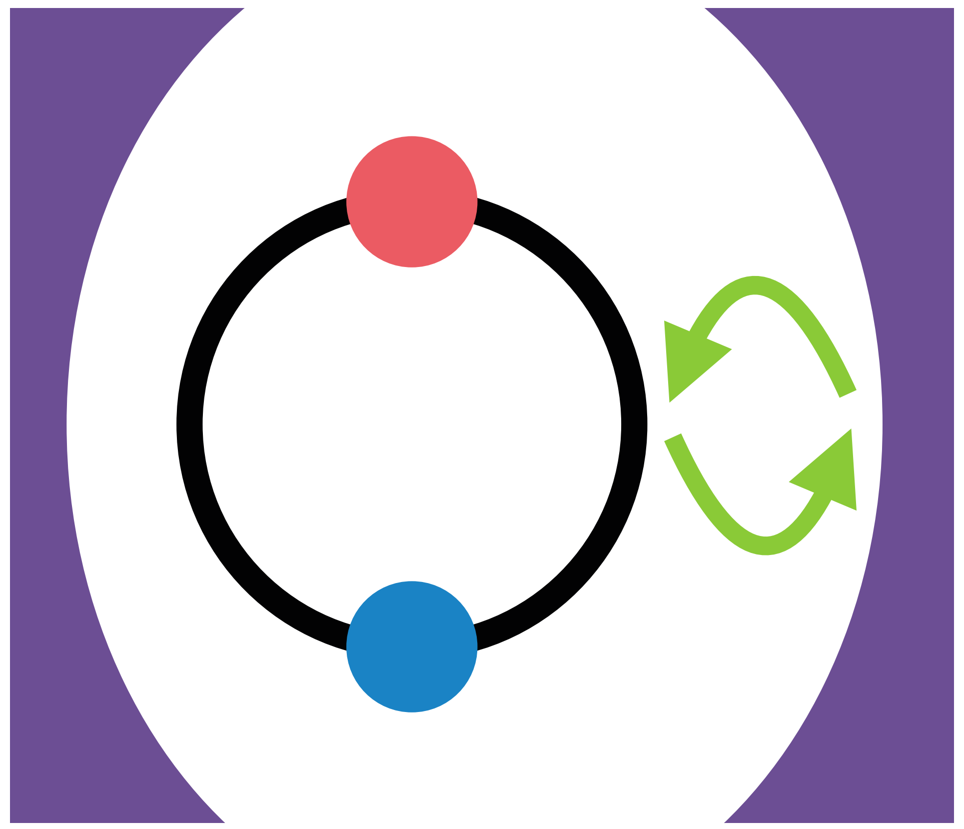
Pedagogical model



$g = \sqrt{\frac{\Gamma_a}{t_\mathrm{d}}}$

$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

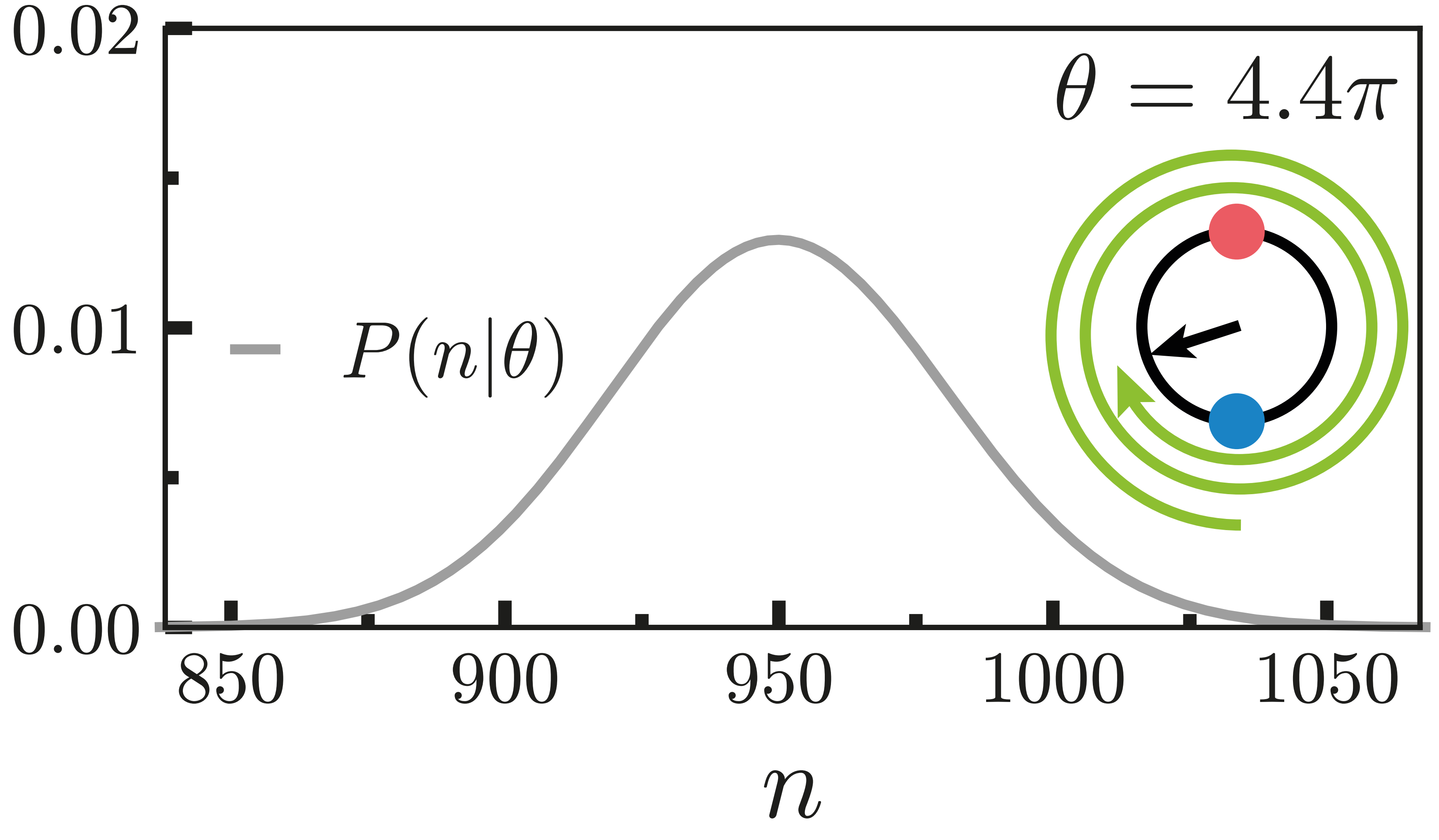
Pedagogical model



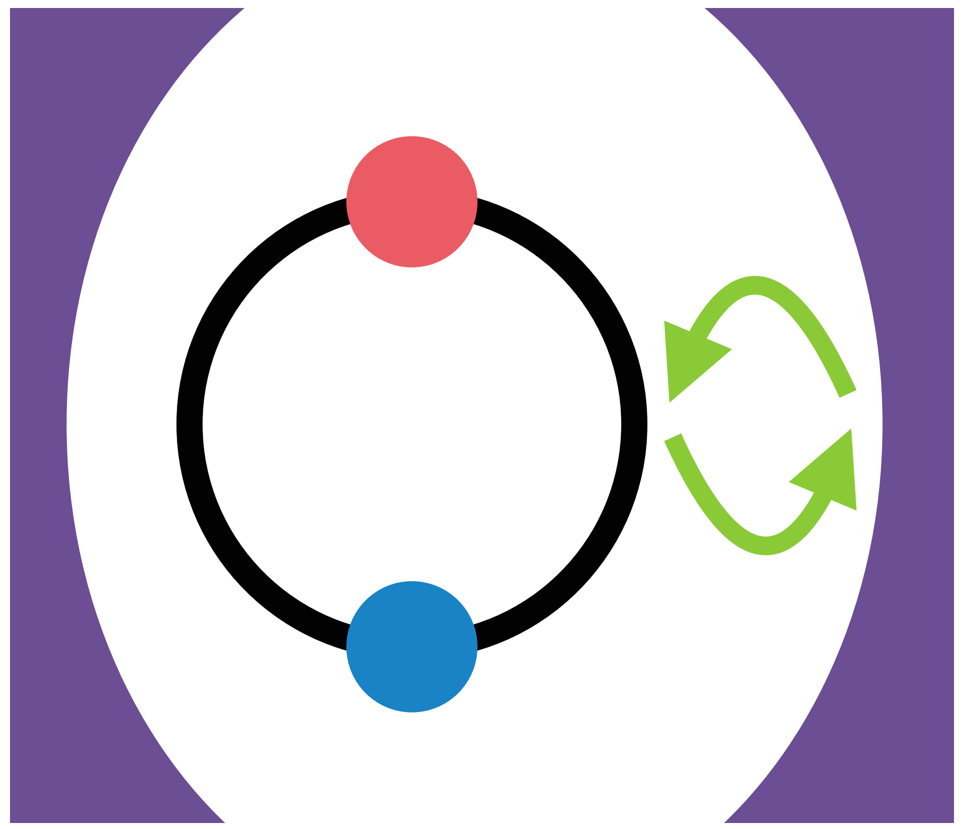
$g = \sqrt{\frac{\Gamma_a}{t_\mathrm{d}}}$

$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_\mathrm{d}} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$



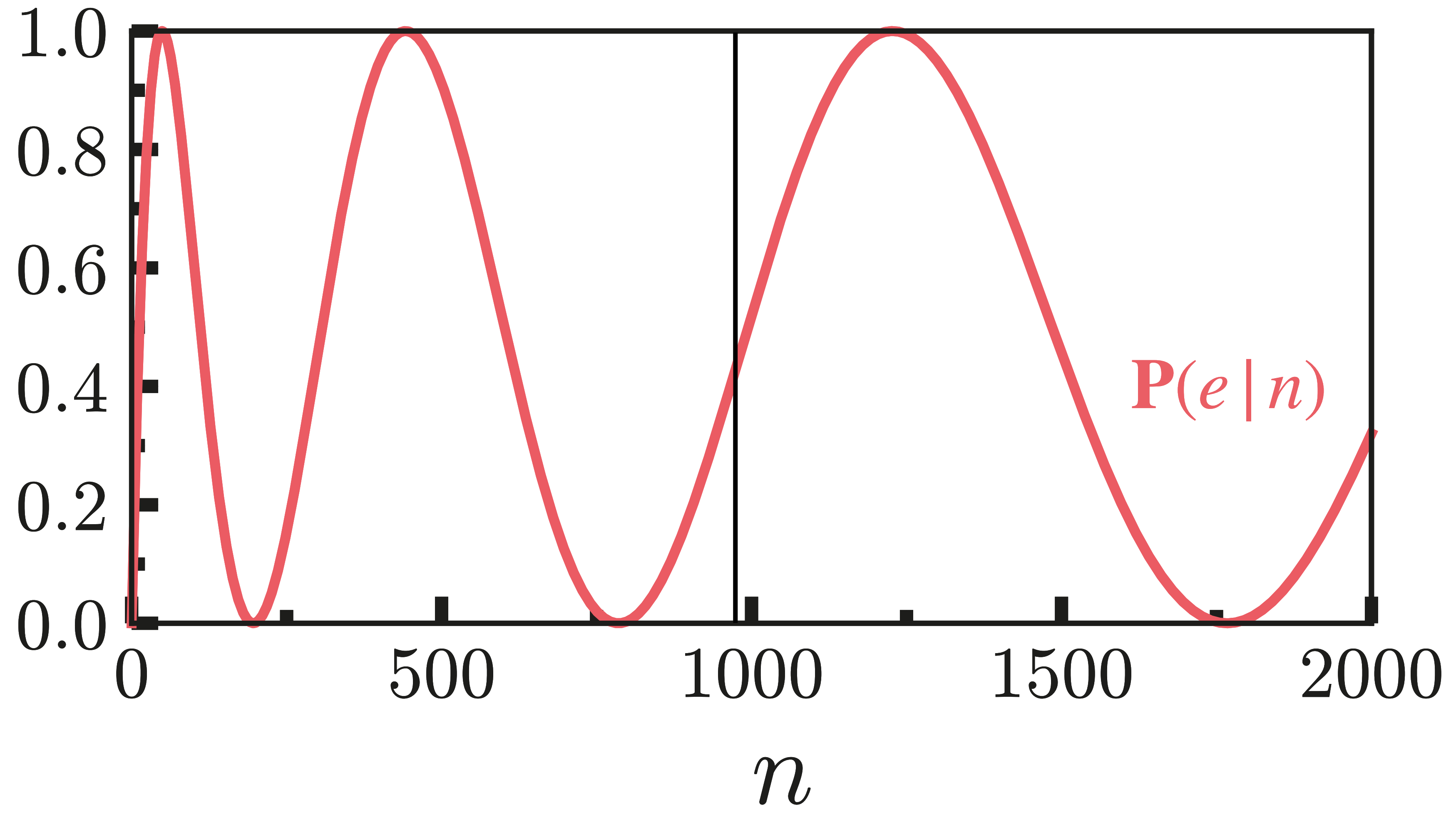
Pedagogical model



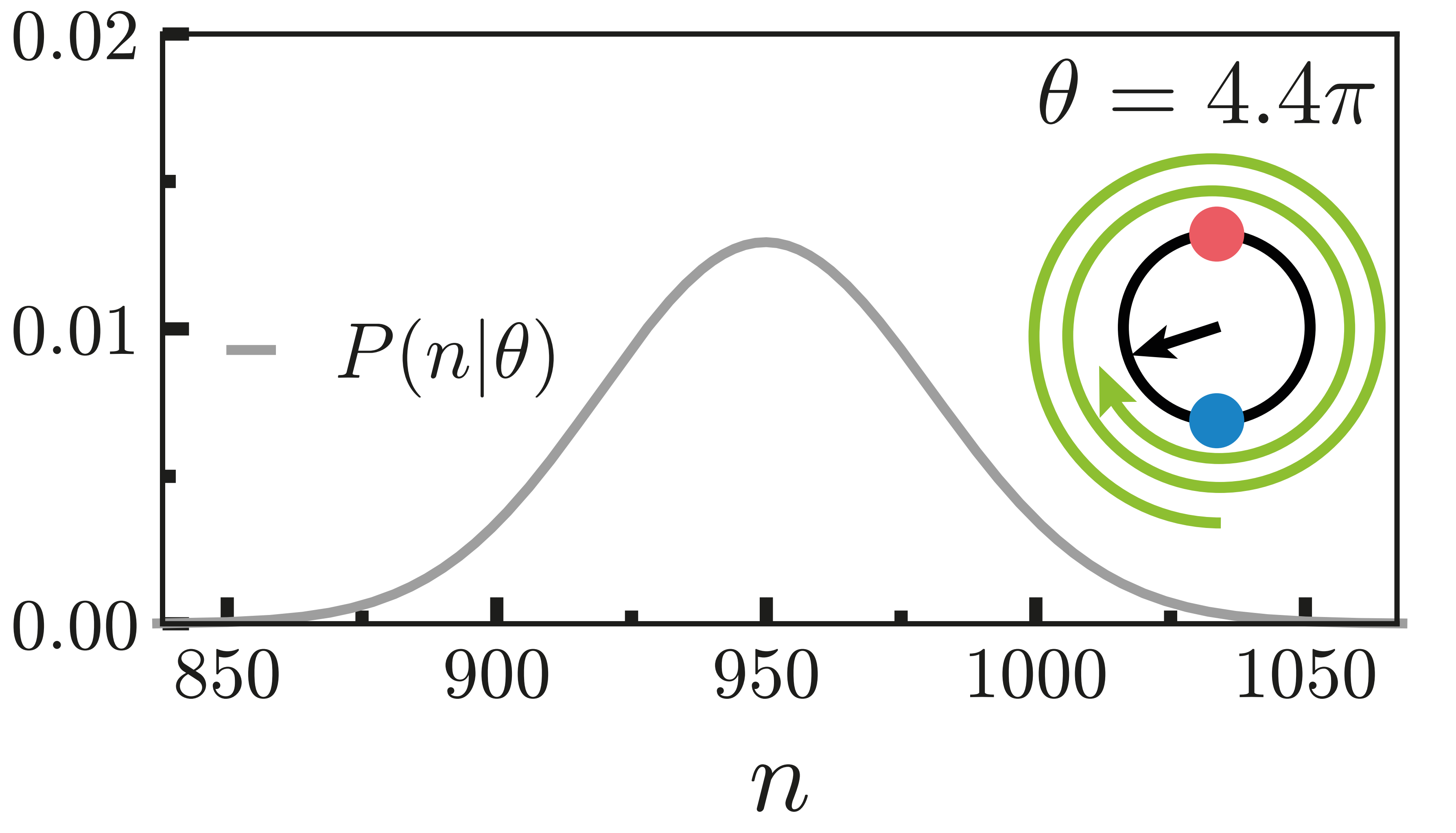
$$g = \sqrt{\frac{\Gamma_a}{t_d}}$$

$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

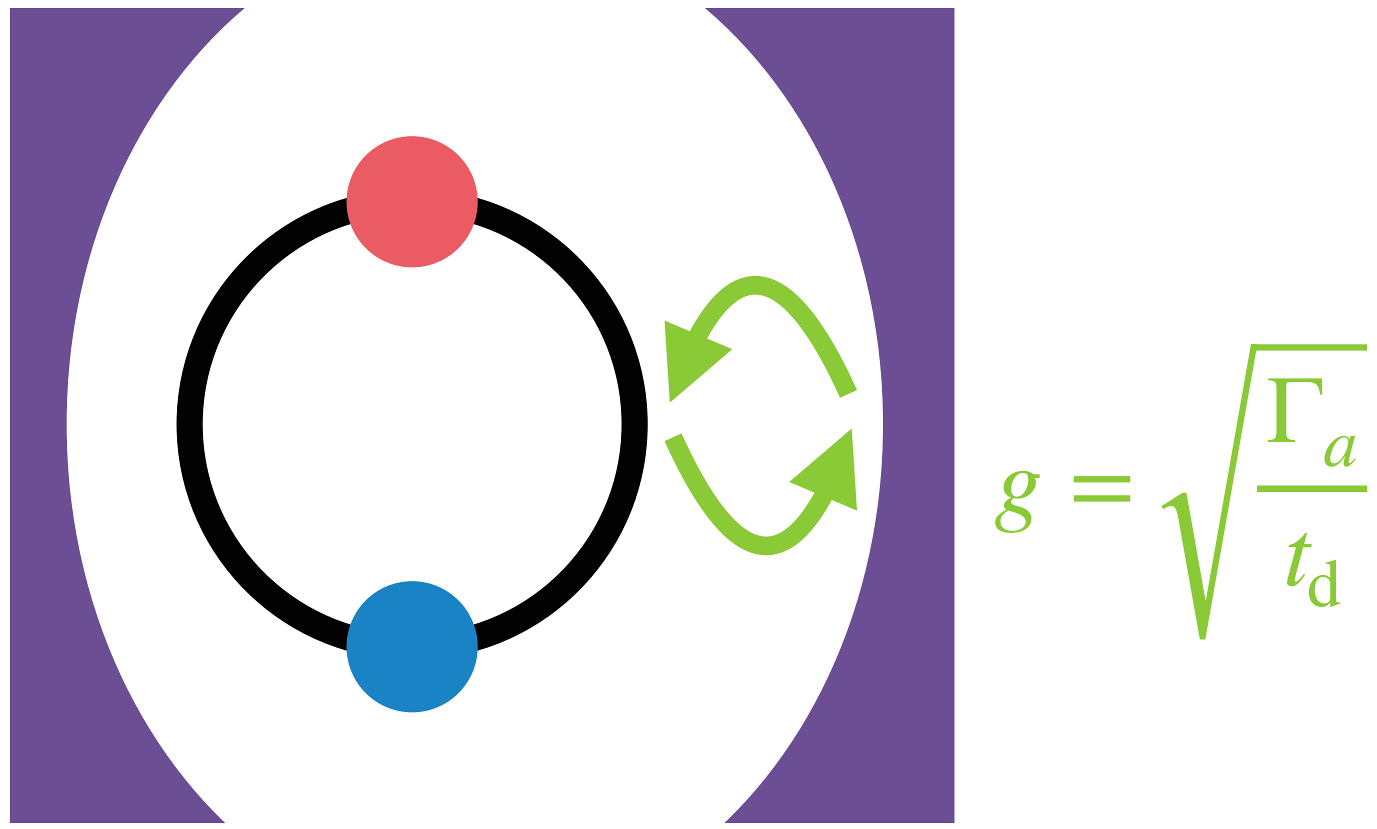
$$\mathbf{P}(e\,|\,n) = \sin^2\left(g\sqrt{n}t_d\right)$$



$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_d} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

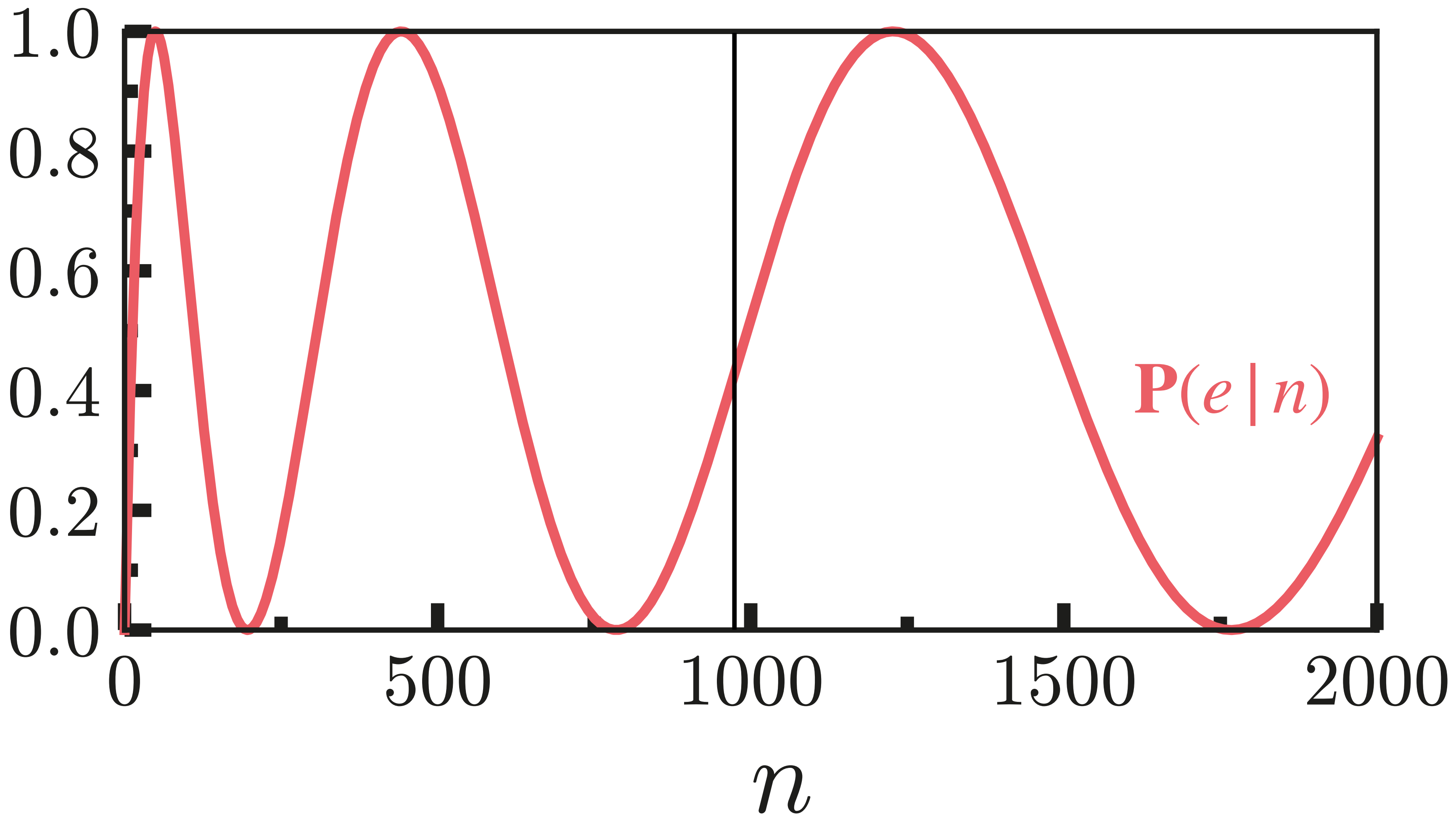


Pedagogical model



$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

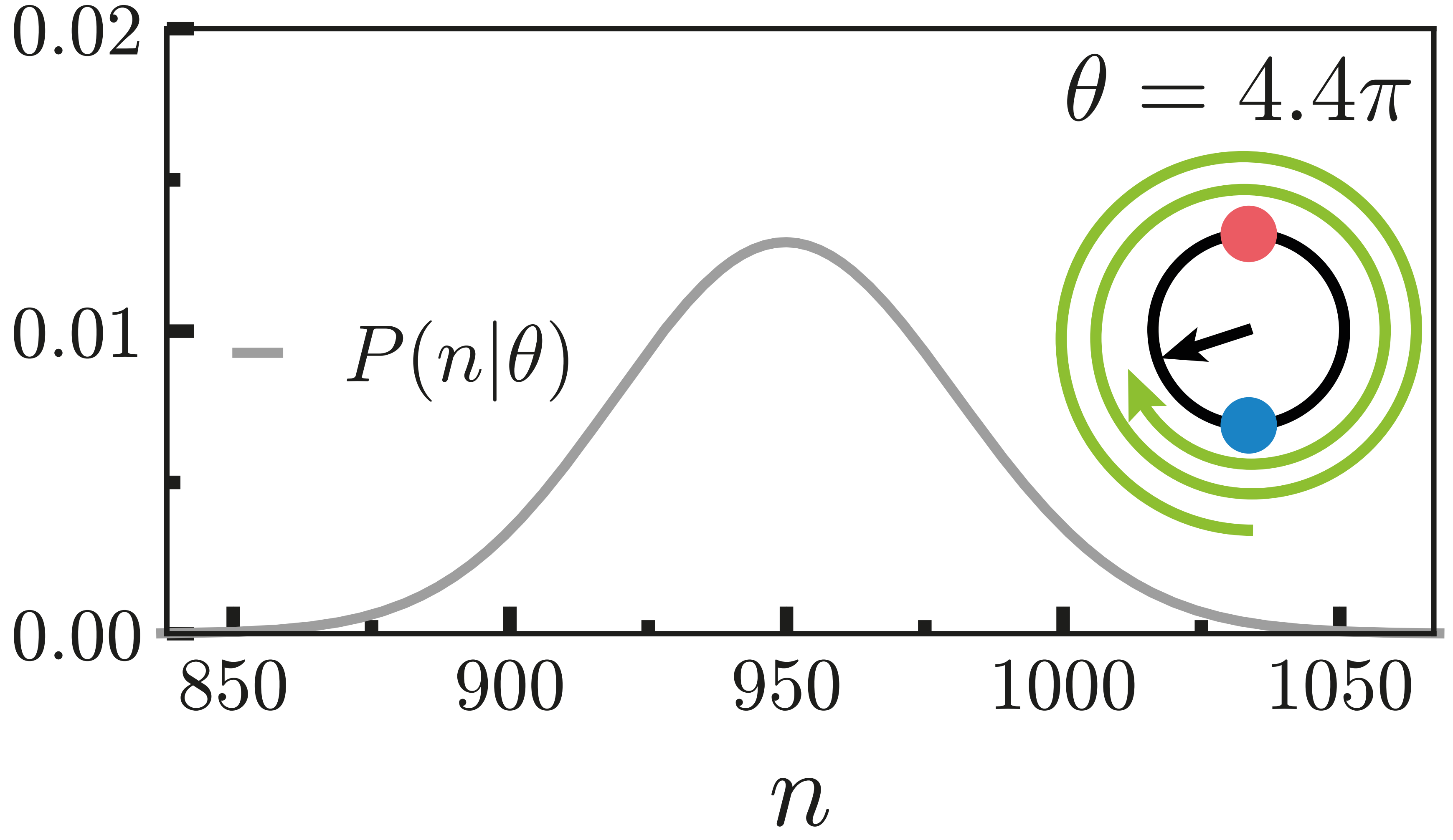
$$\mathbf{P}(e\,|\,n) = \sin^2\left(g\sqrt{n}t_d\right)$$



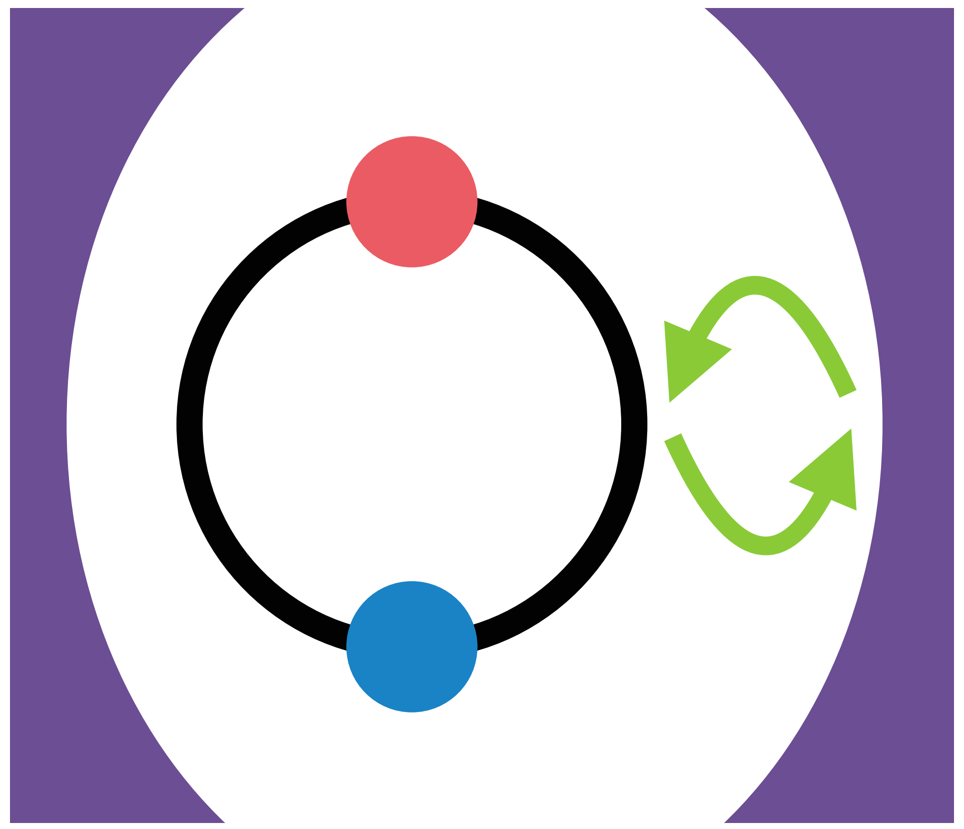
Bayes Rule

$$\mathbf{P}_\theta(n\,|\,e) \propto \mathbf{P}(e\,|\,n) \times \mathbf{P}_\theta(n)$$

$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_\mathrm{d}} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

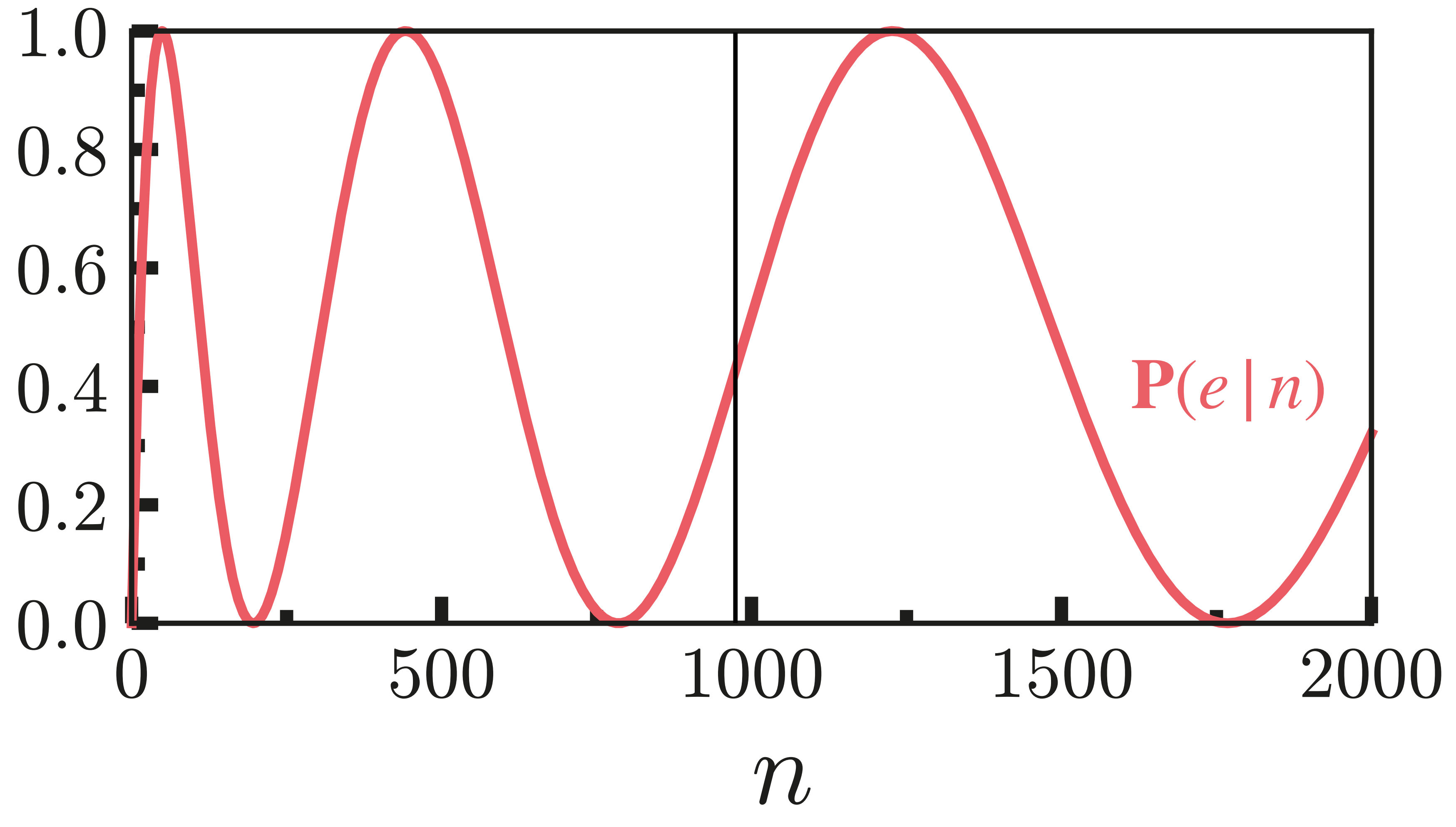


Pedagogical model



$$g = \sqrt{\frac{\Gamma_a}{t_d}}$$

$$\mathbf{P}(e\,|\,n) = \sin^2\left(g\sqrt{n}t_d\right)$$



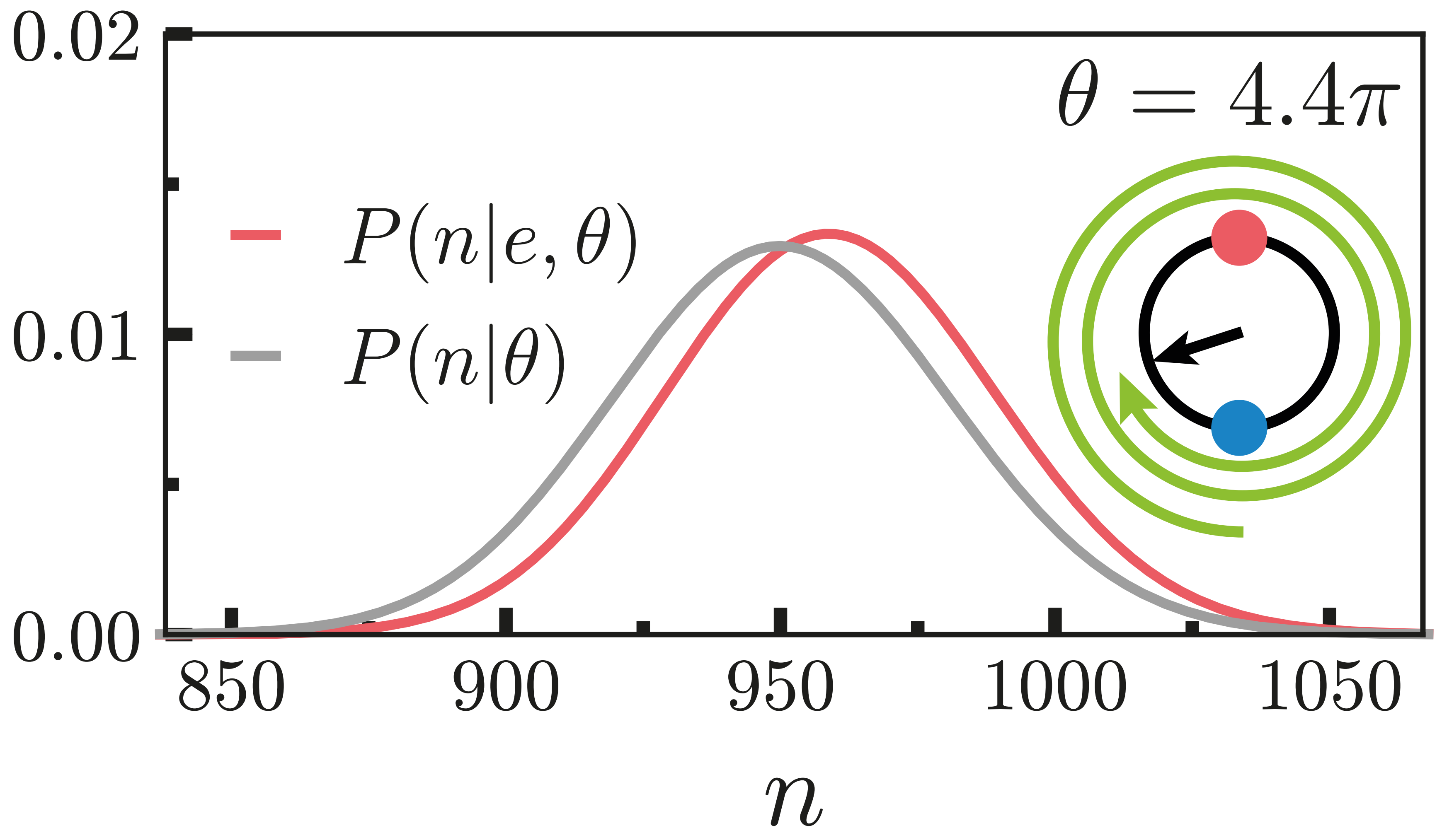
$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

Bayes Rule

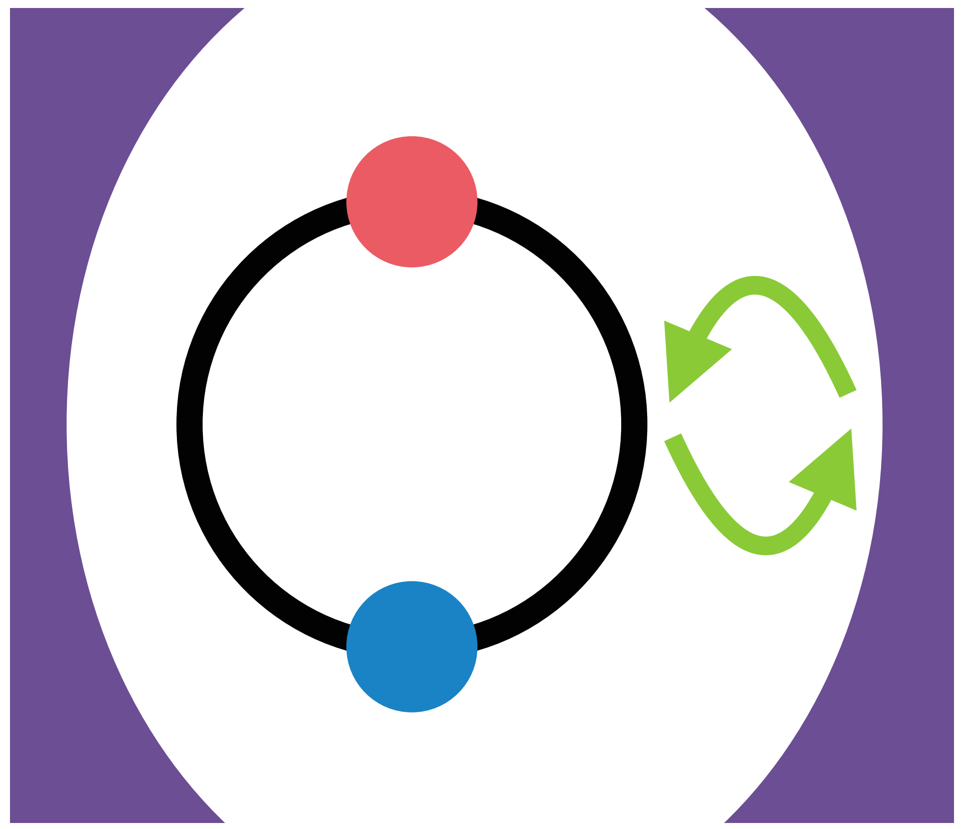
$$\mathbf{P}_\theta(n\,|\,e) \propto \mathbf{P}(e\,|\,n) \times \mathbf{P}_\theta(n)$$

$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_d} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

$$\Rightarrow \quad \mathbf{P}_\theta(n\,|\,e) \propto \frac{\bar{n}^n e^{-\bar{n}}}{n!}\sin^2\left(\sqrt{n\Gamma_a t_d}\right)$$



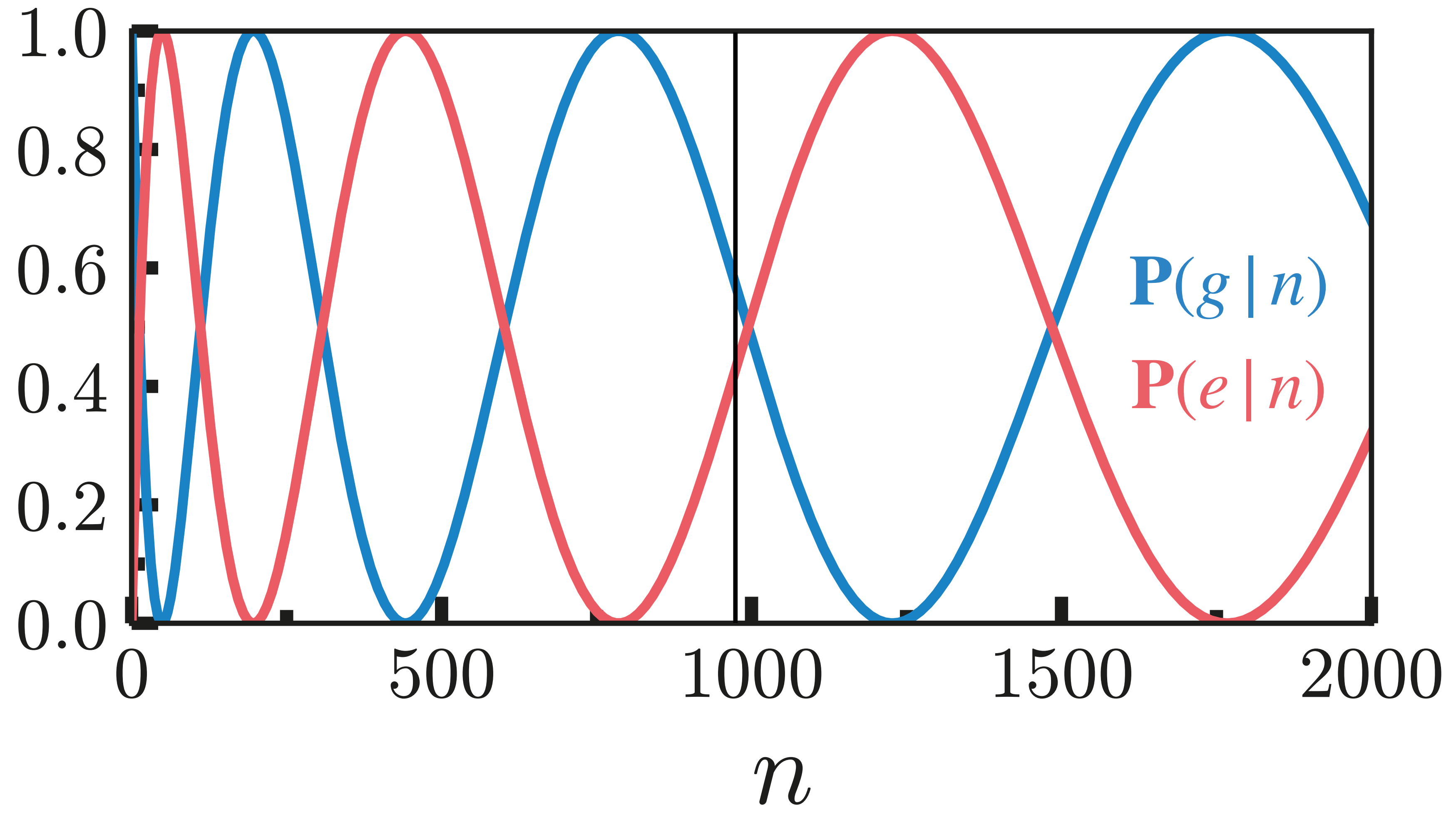
Pedagogical model



$g = \sqrt{\frac{\Gamma_a}{t_d}}$

$$\hat{H} = i\hbar g(\hat{a}\hat{\sigma}_+ - \hat{a}^\dagger\hat{\sigma}_-)$$

$$\mathbf{P}(e\,|\,n) = \sin^2\left(g\sqrt{n}t_d\right)$$



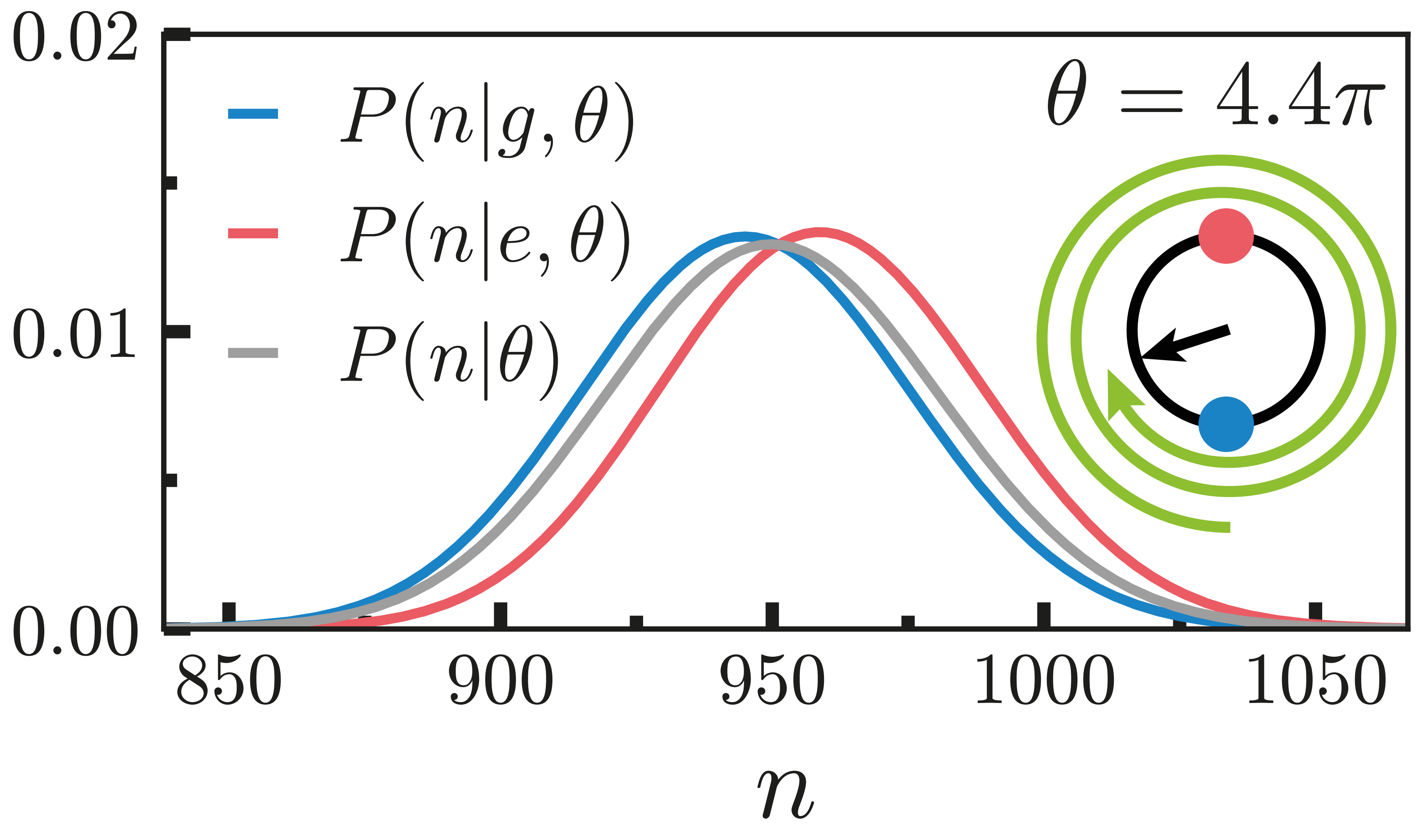
Bayes Rule

$$\mathbf{P}_\theta(n\,|\,e) \propto \mathbf{P}(e\,|\,n) \times \mathbf{P}_\theta(n)$$

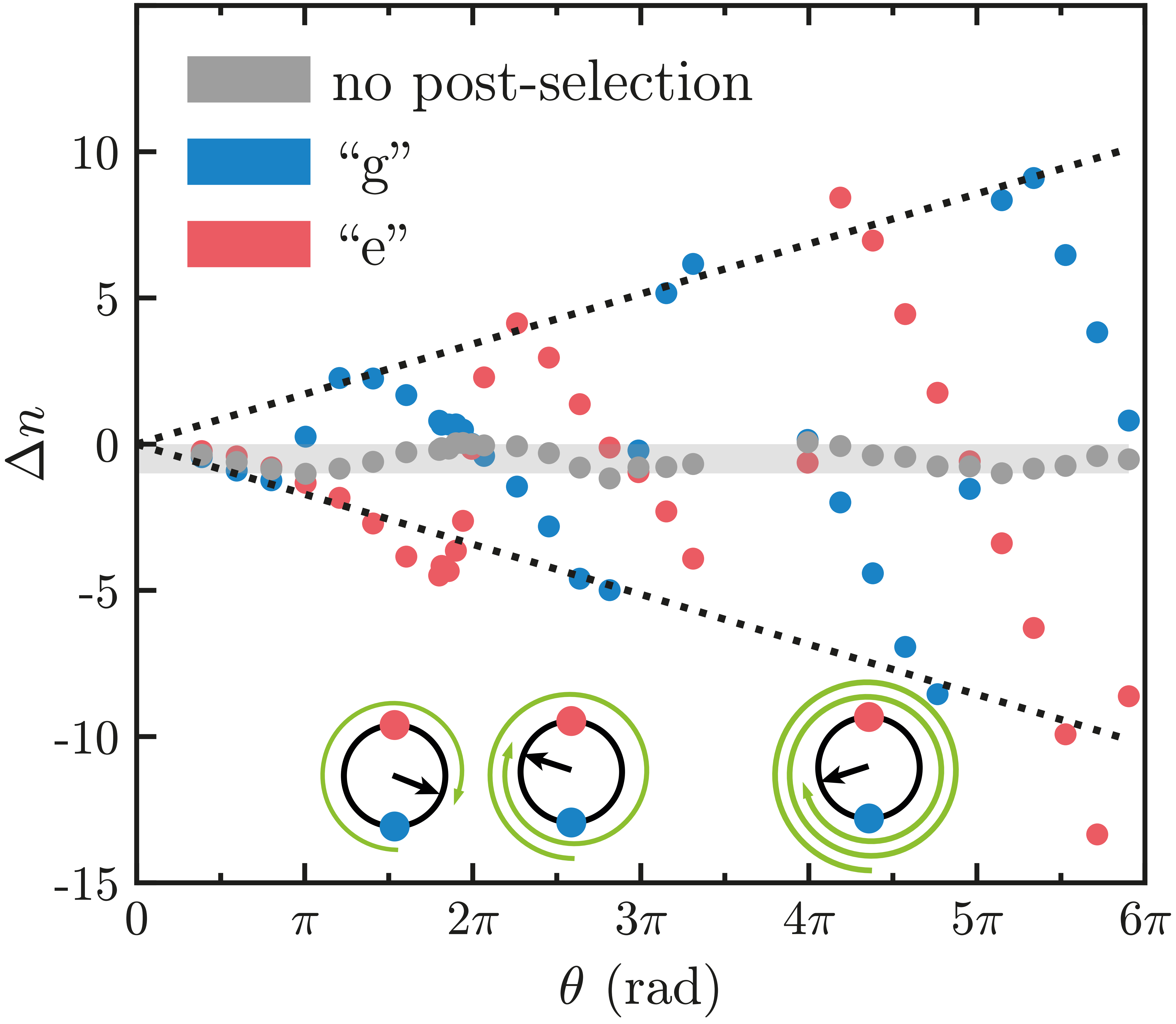
$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_d} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

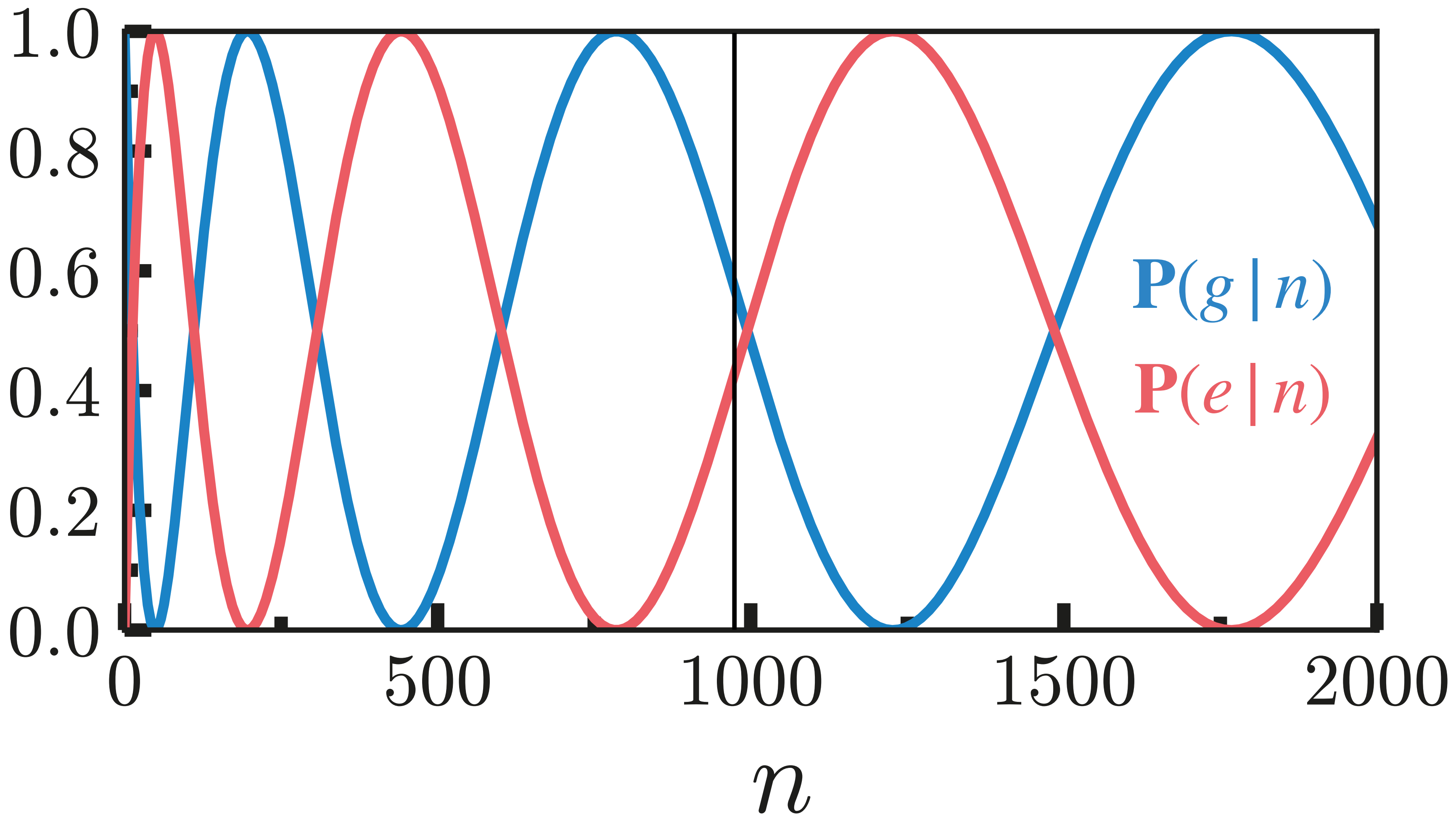
$$\Rightarrow \mathbf{P}_\theta(n\,|\,e) \propto \frac{\bar{n}^n e^{-\bar{n}}}{n!}\sin^2\left(\sqrt{n\Gamma_a t_d}\right)$$

$$\Rightarrow \mathbf{P}_\theta(n\,|\,g) \propto \frac{\bar{n}^n e^{-\bar{n}}}{n!}\cos^2\left(\sqrt{n\Gamma_a t_d}\right)$$

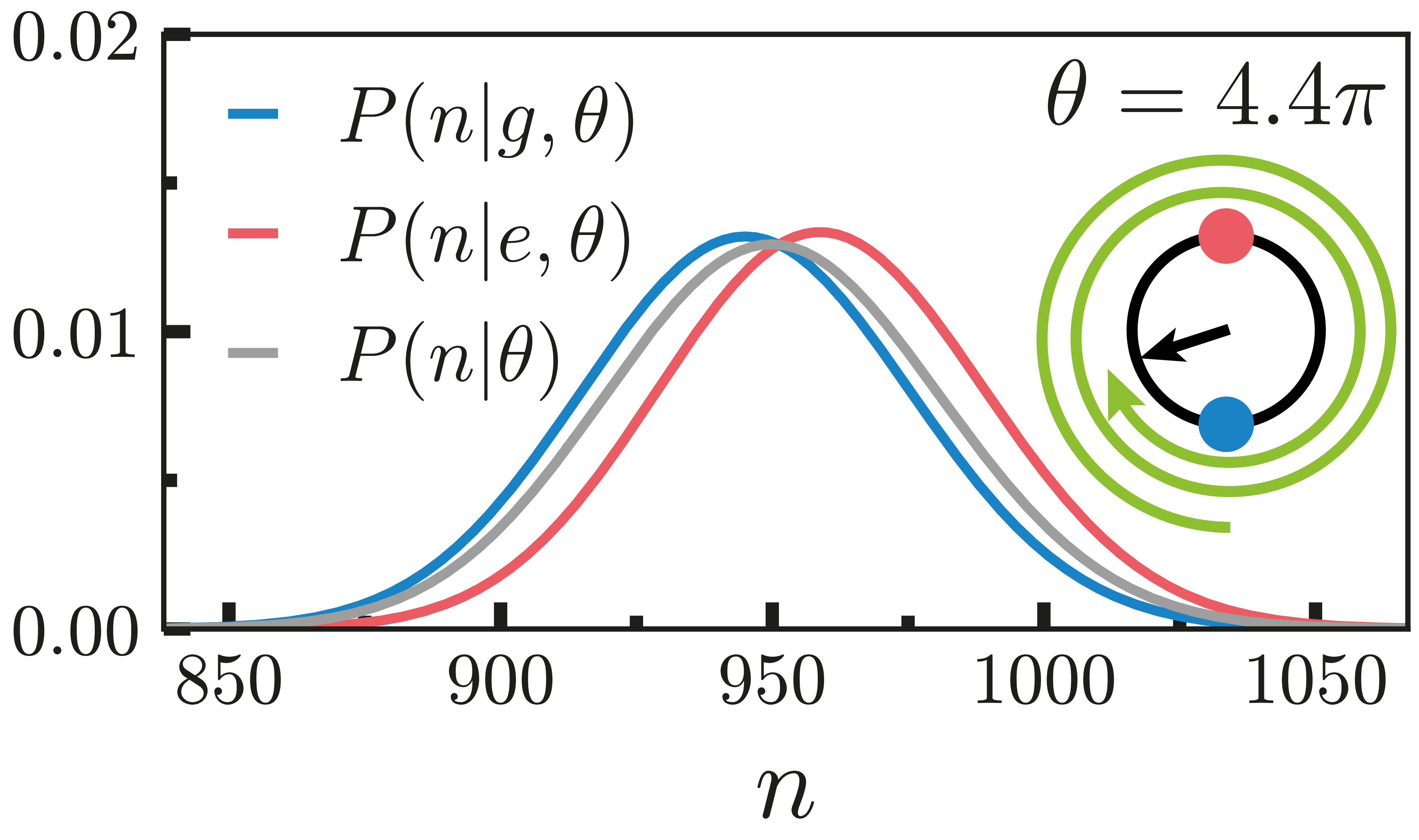


Pedagogical model

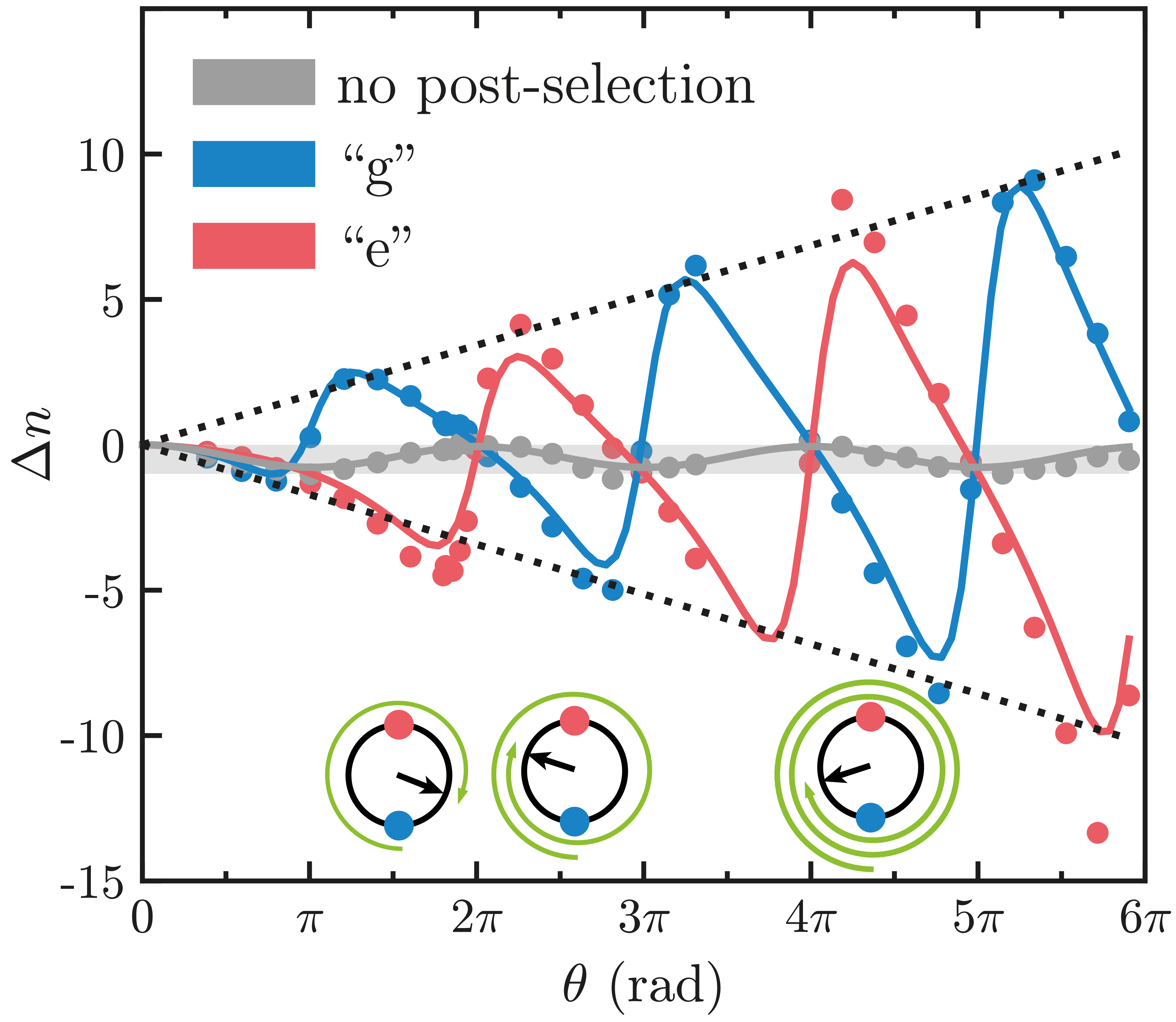




$$\bar{n} = \frac{\theta^2}{4\Gamma_a t_\mathrm{d}} \qquad \mathbf{P}_\theta(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$



Weak value theory



Well explained by weak values

$$\bar{n}^{E,\rho} = \int_0^T |\alpha_{\text{in}}|^2 + \Gamma_a \mathcal{I}(E,\rho) - \Omega_a \text{Re}_E \langle \hat{\sigma}_- \rangle_\rho \text{d}t$$

[Maffei, Elouard *et al.*, PRA 2023]

Energy exchanged with the drive contains two terms:

1) quantum heat
2) information impact on initial energy

measurement backaction on a cavity

information update
about photon number

$$p(n\,|\,\text{click}) = \frac{p(\text{click}\,|\,n)}{p(\text{click})} p_{\text{ini}}(n)$$

a photon came out
so **energy update**

$$p_{\text{fin}}(n) \leftarrow p(n+1\,|\,\text{click})$$

final state

$$\frac{\hat{a}\,|\,\psi\rangle}{\sqrt{\langle \hat{n} \rangle_{|\psi\rangle}}}$$

measurement backaction on a cavity

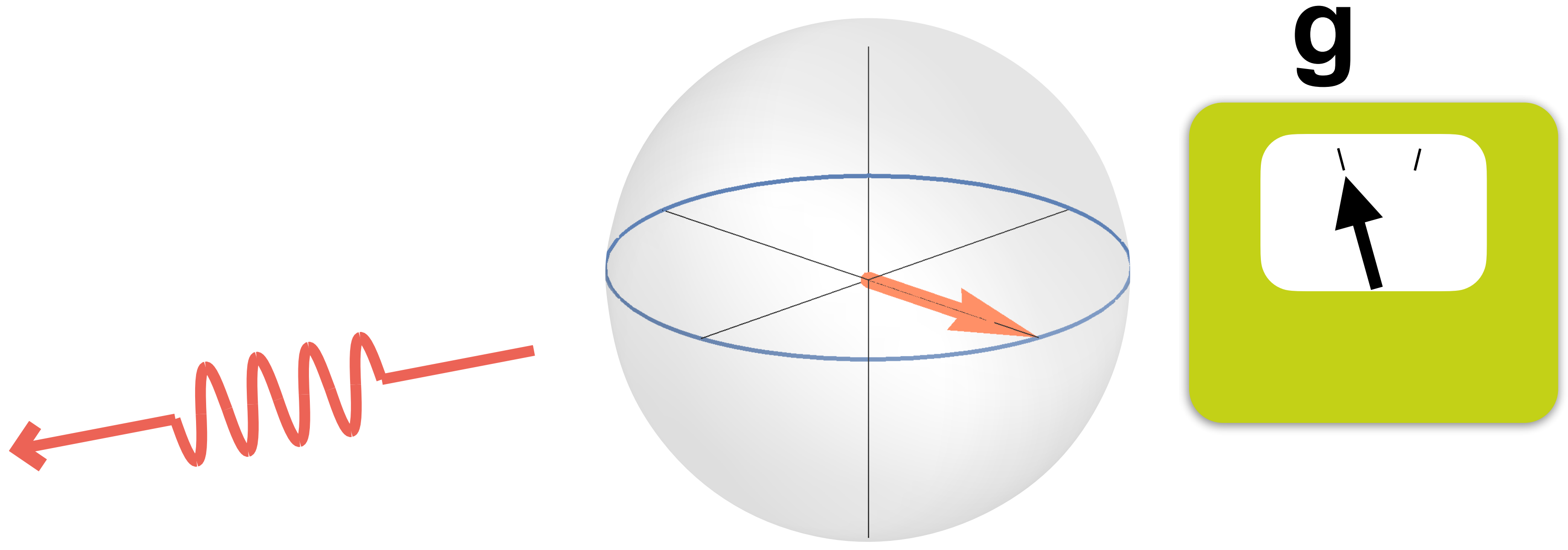
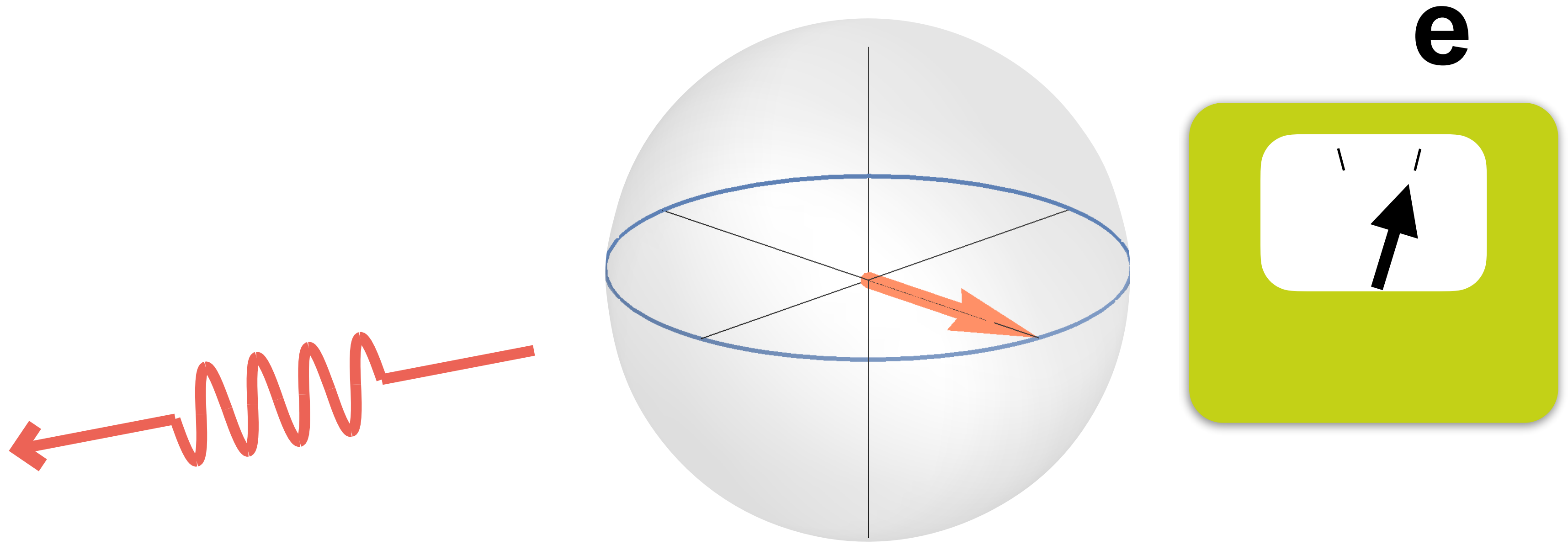
	information update about photon number	a photon came out so **energy update**	final state
	$p(n\,|\,\text{click}) = \dfrac{p(\text{click}\,|\,n)}{p(\text{click})} p_{\text{ini}}(n)$	$p_{\text{fin}}(n) \leftarrow p(n+1\,|\,\text{click})$	$\dfrac{\hat{a}\,|\psi\rangle}{\sqrt{\langle \hat{n} \rangle_{|\psi\rangle}}}$
	$p(n\,|\,\text{click}) = \dfrac{n\kappa\tau}{k\kappa\tau}\delta_{n,k} = \delta_{n,k} = p_{\text{ini}}(n)$	$p_{\text{fin}}(n) = \delta_{n,k-1}$	$|k-1\rangle$

measurement backaction on a cavity

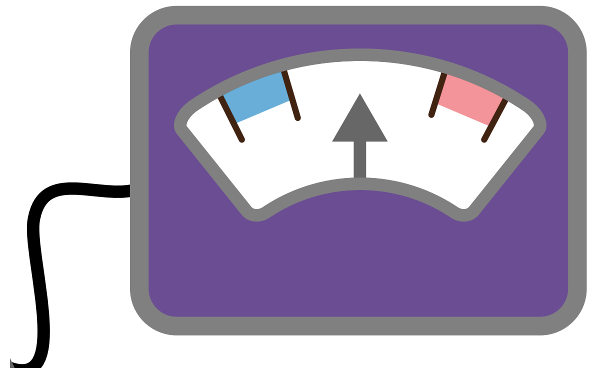
	information update about photon number	a photon came out so **energy update**	final state
	$p(n\,\|\,\text{click}) = \frac{p(\text{click}\,\|\,n)}{p(\text{click})} p_{\text{ini}}(n)$	$p_{\text{fin}}(n) \leftarrow p(n+1\,\|\,\text{click})$	$\frac{\hat{a}\|\psi\rangle}{\sqrt{\langle \hat{n} \rangle_{\|\psi\rangle}}}$
	$p(n\,\|\,\text{click}) = \frac{n\kappa\tau}{k\kappa\tau}\delta_{n,k} = \delta_{n,k} = p_{\text{ini}}(n)$	$p_{\text{fin}}(n) = \delta_{n,k-1}$	$\|k-1\rangle$
	$p(n\,\|\,\text{click}) = \frac{n\kappa\tau}{\bar{n}\kappa\tau}\frac{\bar{n}^n e^{-\bar{n}}}{n!} = p_{\text{ini}}(n-1)$	$p_{\text{fin}}(n) = p_{\text{ini}}(n)$	$\|\alpha\rangle$

measurement backaction on a cavity

the qubit readout is a weak measurement of the pulse that drives it!

	information update about photon number	**energy update**	final state
	$p(n\,\vert\,\mathrm{g}) = ?$	$\bar{n}_{\text{fin}} = \bar{n}\big\vert_g + 0$	$\vert\psi_g\rangle$
		quantum heat!	
	$p(n\,\vert\,\mathrm{e}) = ?$	$\bar{n}_{\text{fin}} = \bar{n}\big\vert_e - 1$	$\vert\psi_e\rangle$
	$p(n\,\vert\,\text{click}) = \frac{n\kappa\tau}{\bar{n}\kappa\tau}\frac{\bar{n}^n e^{-\bar{n}}}{n!} = p_{\text{ini}}(n-1)$	$p_{\text{fin}}(n) = p_{\text{ini}}(n)$	$\vert\alpha\rangle$

Quantum heat



random energy change
= 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, PRA (2019)]

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, PRE (2018)] [Buffoni et al., PRL (2019)]
[Ronzani et al., Nature Phys. 2018] [Senior et al., Communication Physics 2020] [Bresque et al., PRL (2021)]
[Monsel *et al.*, PRL (2020)] [Manikandan *et al.*, PRE (2022)]

demonstration?

can it be measured directly and not just inferred?

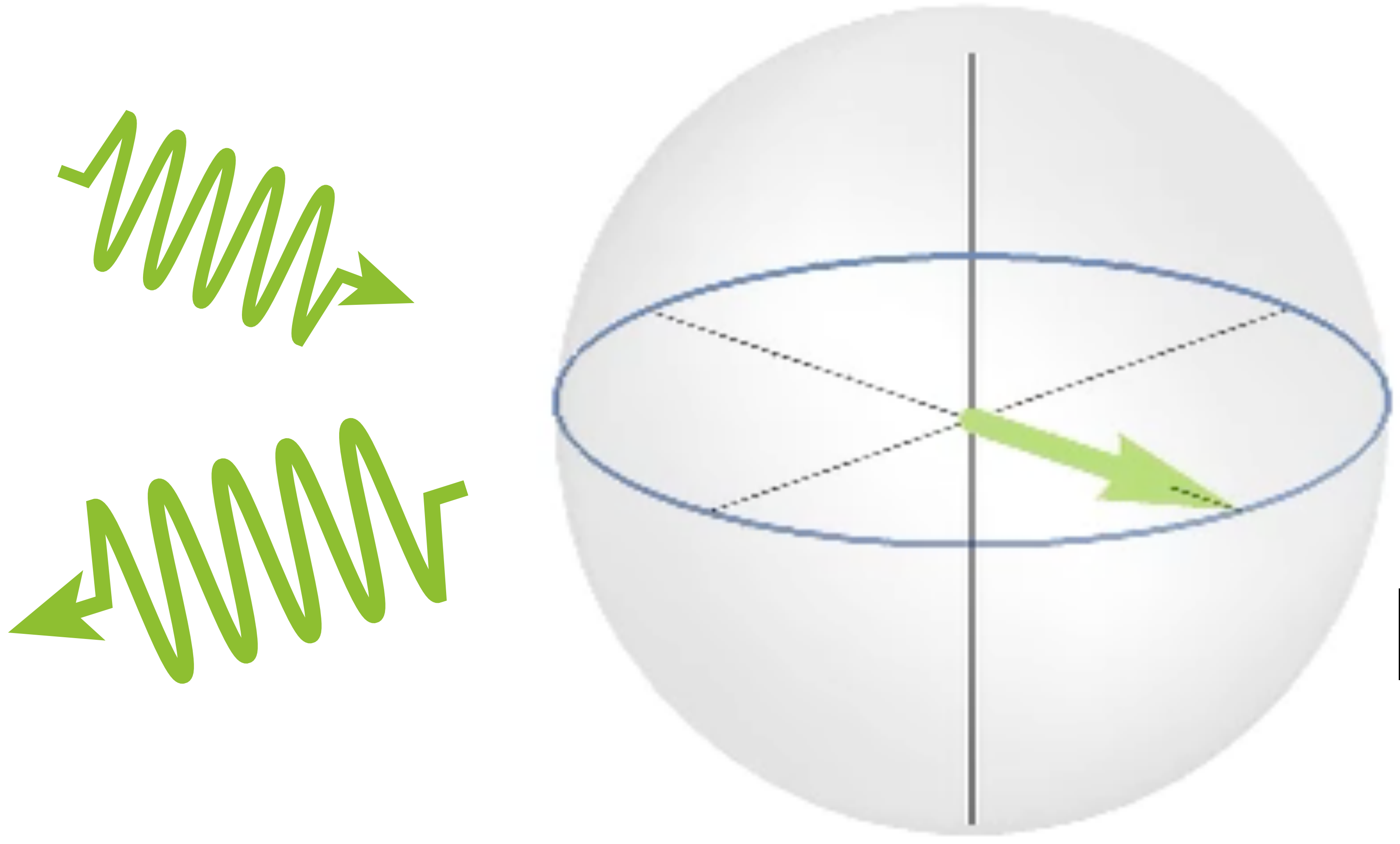
yes, but subtle back action on initial photon number

[Stevens et al., PRL 2022]

Measurement power engine

$$\langle n_{\text{in}} \rangle = \int \mathrm{d}t \langle \hat{a}_{\text{in}}^{\dagger} \hat{a}_{\text{in}} \rangle$$

$$\langle n_{\text{out}} \rangle = \int \mathrm{d}t \langle \hat{a}_{\text{out}}^{\dagger} \hat{a}_{\text{out}} \rangle$$



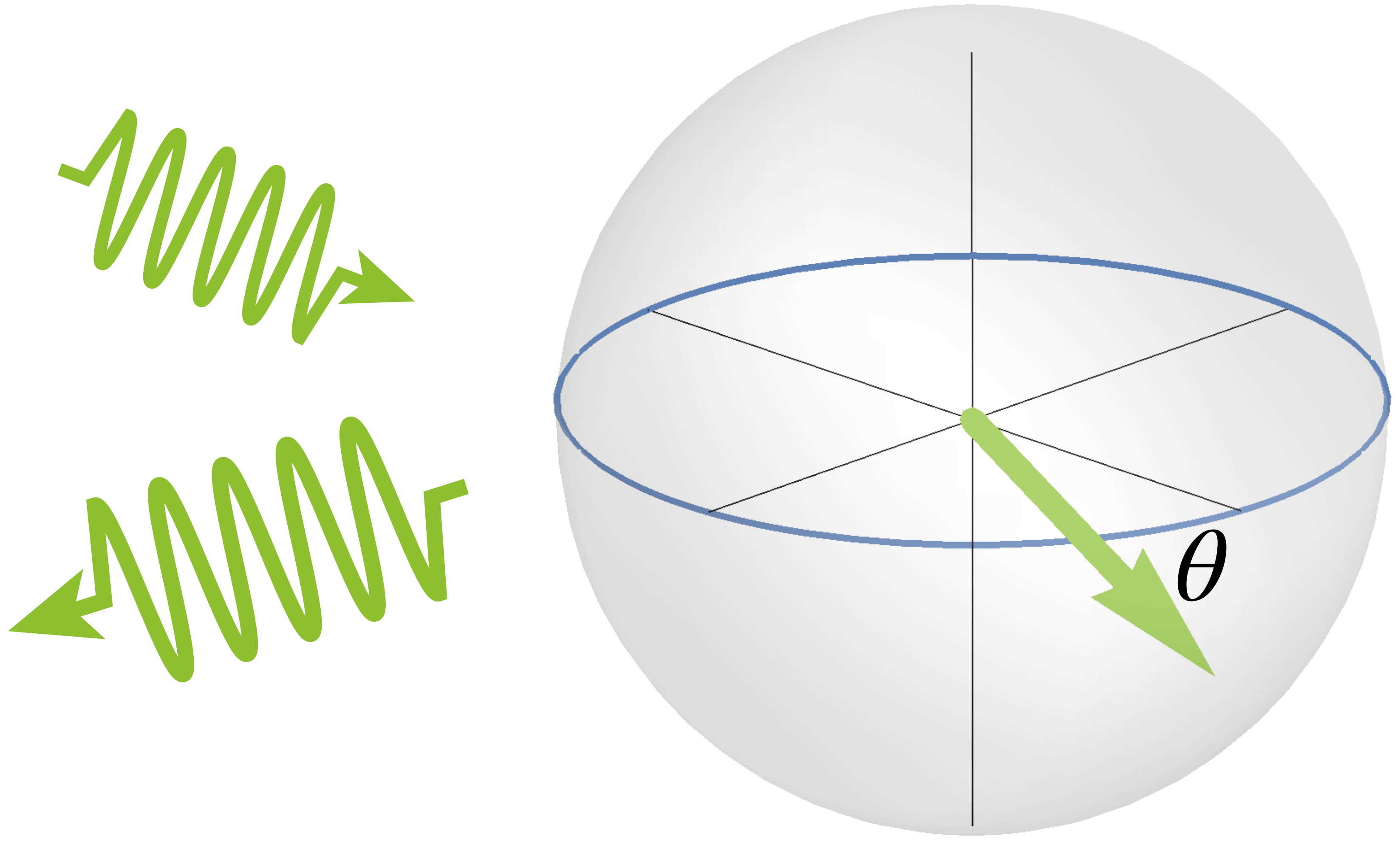
$|+X\rangle$

[Elouard *et al.*, PRL (2017)]

Measurement power engine

$$\langle n_{\text{in}} \rangle = \int \mathrm{d}t \langle \hat{a}_{\text{in}}^{\dagger} \hat{a}_{\text{in}} \rangle$$

$$\langle n_{\text{out}} \rangle = \int \mathrm{d}t \langle \hat{a}_{\text{out}}^{\dagger} \hat{a}_{\text{out}} \rangle$$

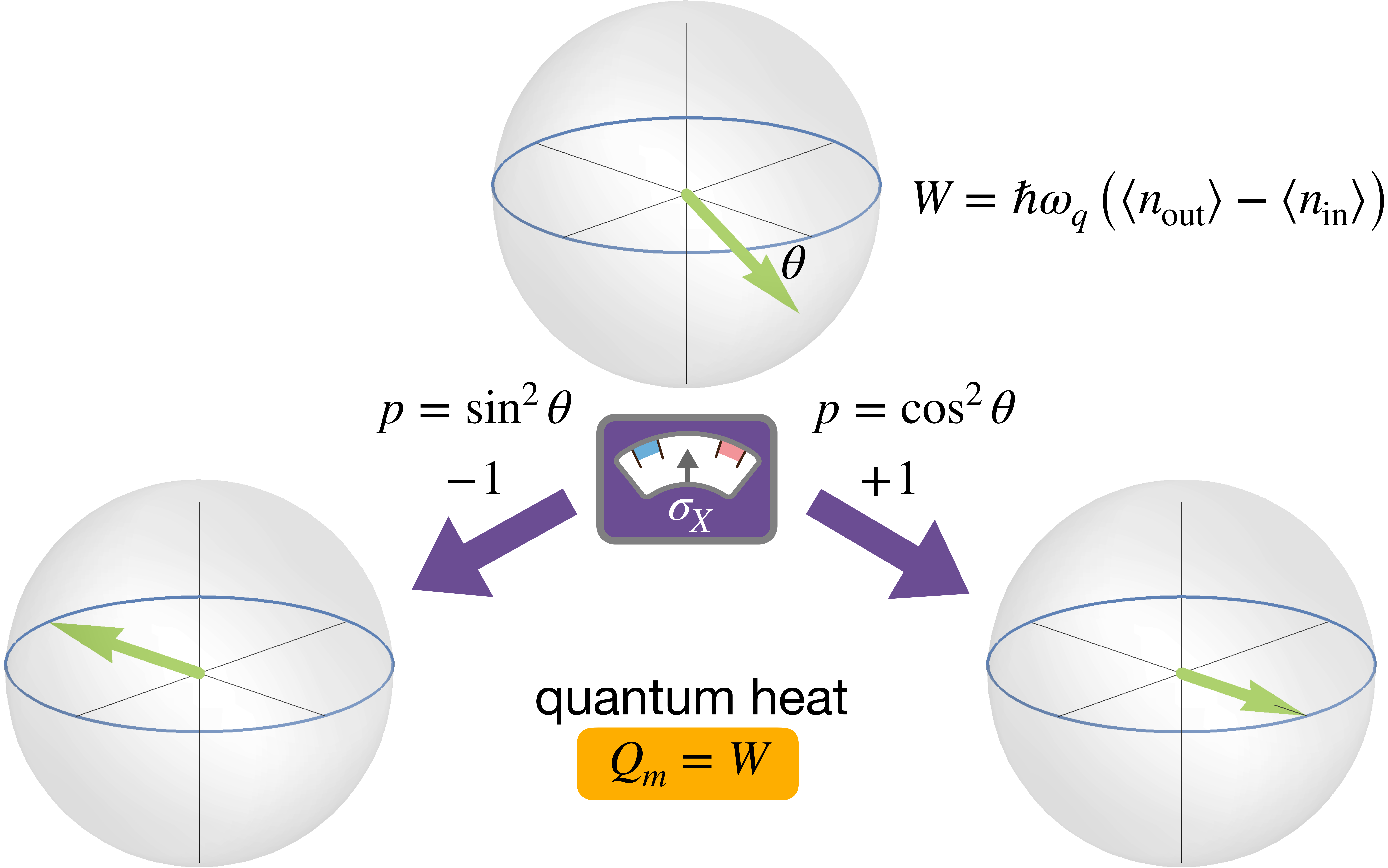


$$W = \hbar\omega_q \left(\langle n_{\text{out}} \rangle - \langle n_{\text{in}} \rangle \right) = \hbar\omega_q \frac{\sin(\theta)}{2}$$

[Elouard *et al.*, PRL (2017)]

Measurement power engine

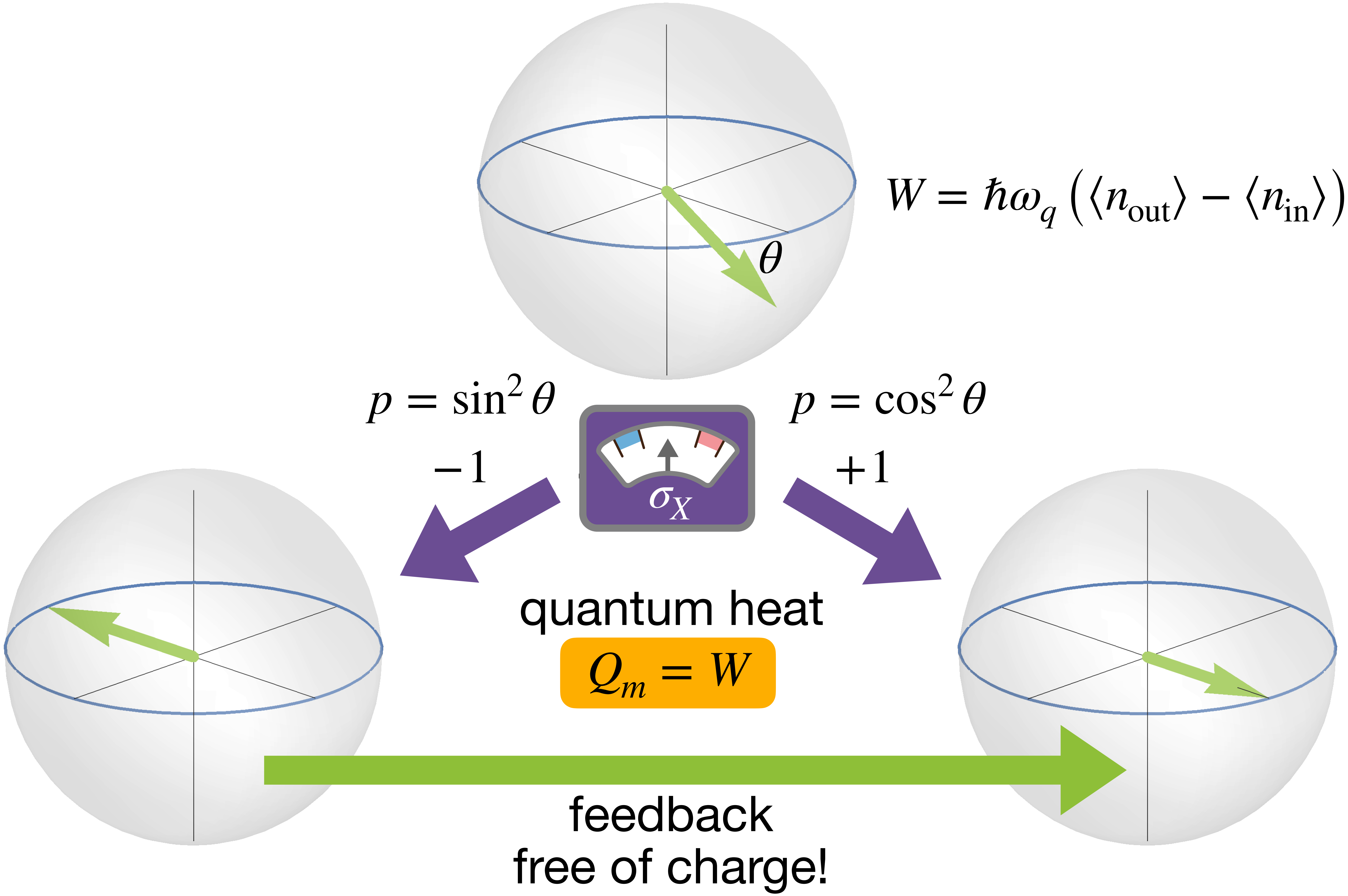
$$W = \hbar\omega_q \left(\langle n_{\text{out}}\rangle - \langle n_{\text{in}}\rangle\right) = \hbar\omega_q \frac{\sin(\theta)}{2}$$



[Elouard *et al.*, PRL (2017)]

Measurement power engine

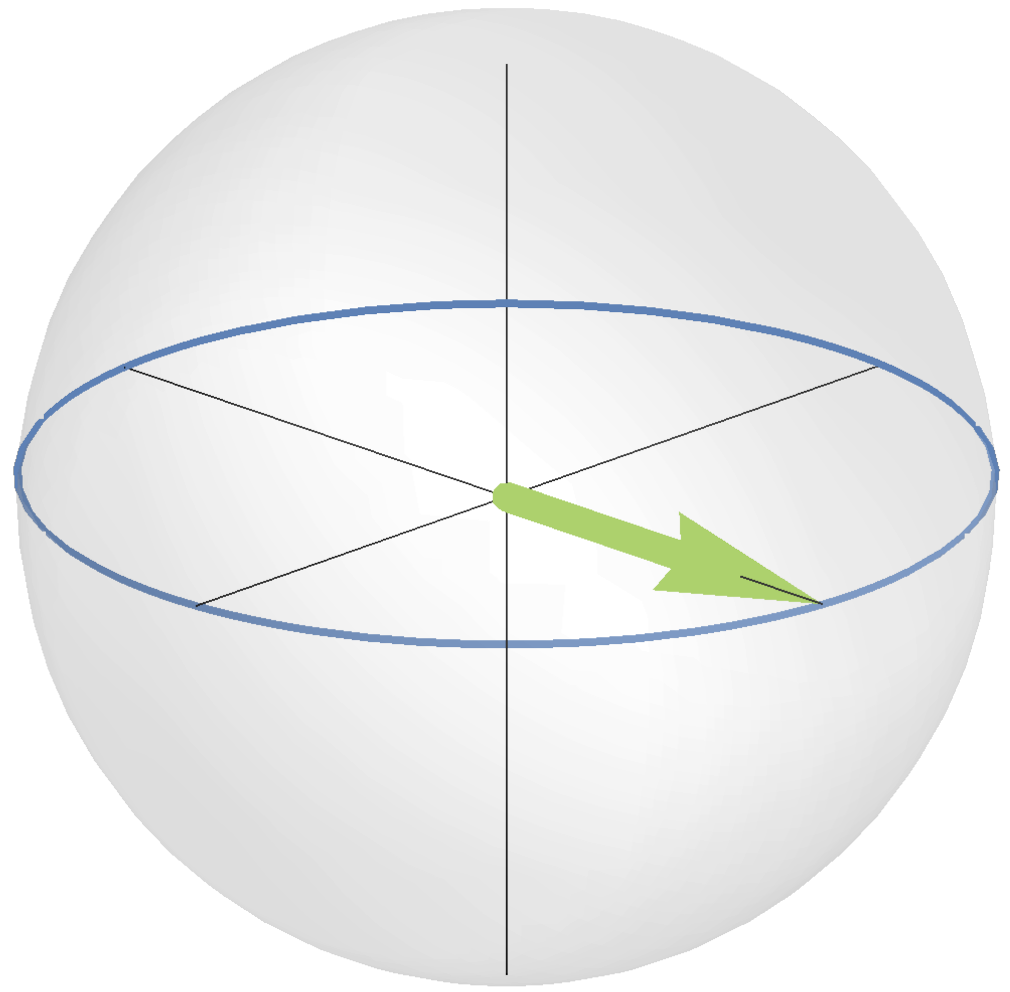
$$W = \hbar\omega_q \left(\langle n_{out}\rangle - \langle n_{in}\rangle\right) = \hbar\omega_q \frac{\sin(\theta)}{2}$$



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

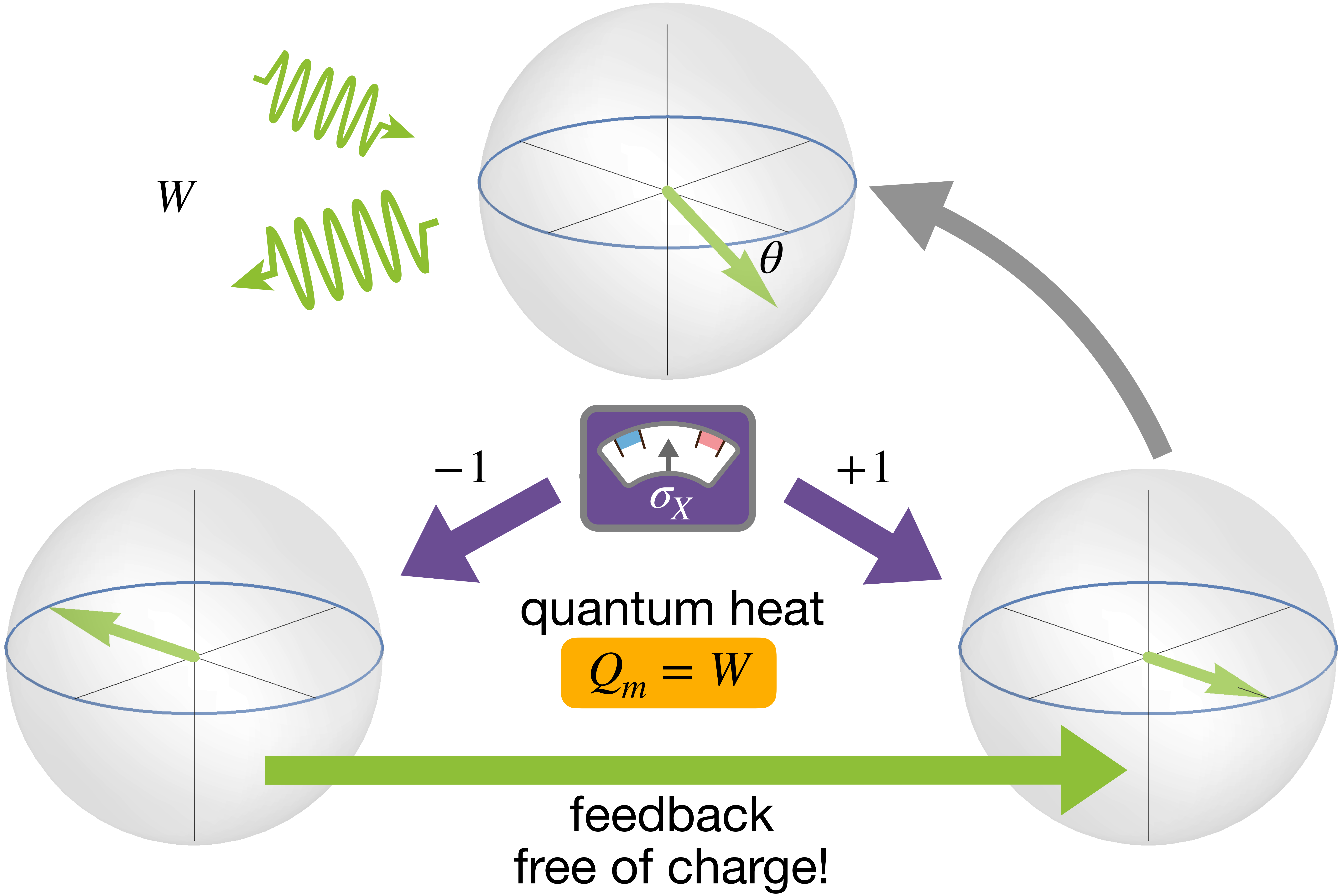
[Elouard *et al.*, PRL (2017)]

Measurement power engine



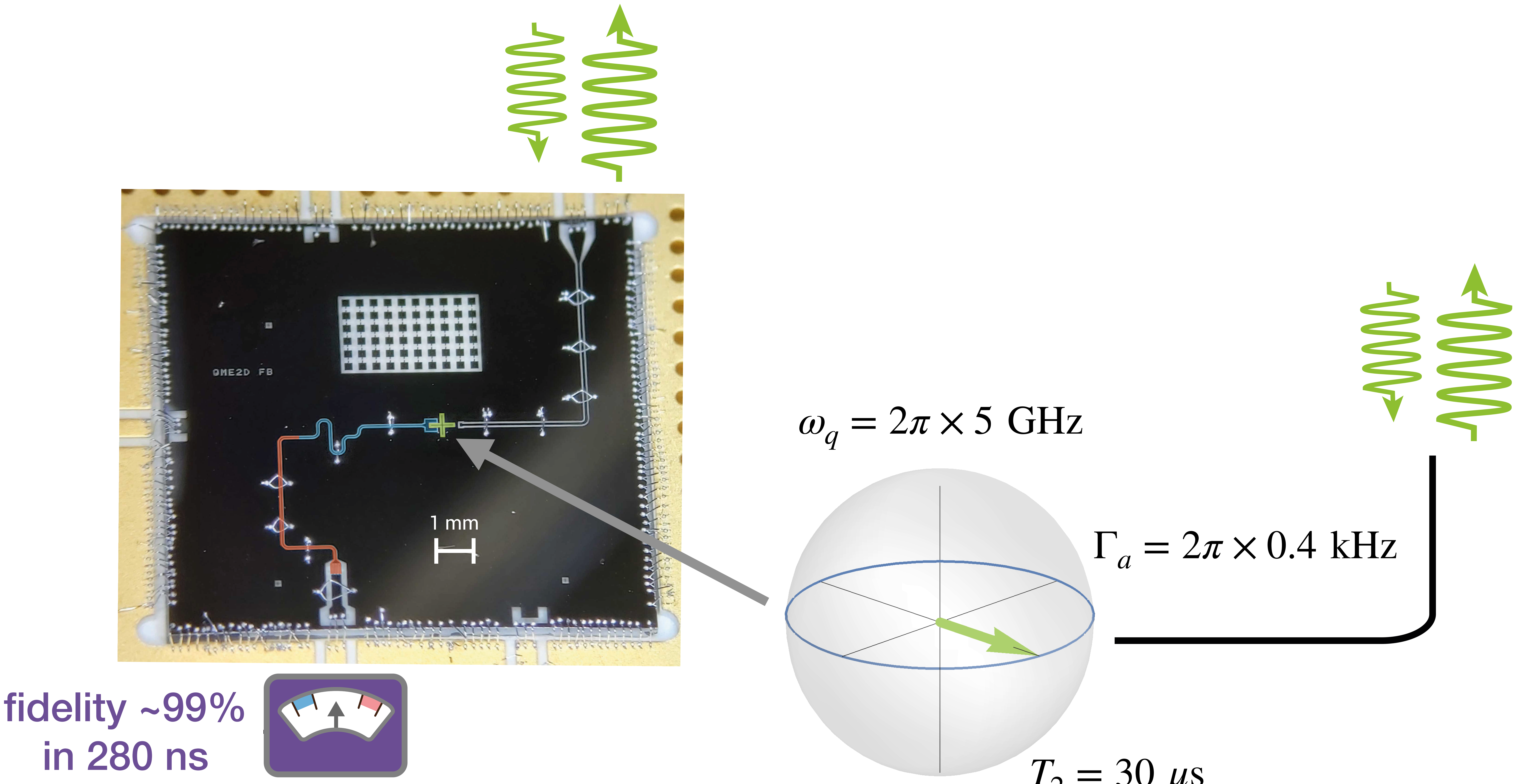
[Elouard *et al.*, PRL (2017)]

Measurement power engine



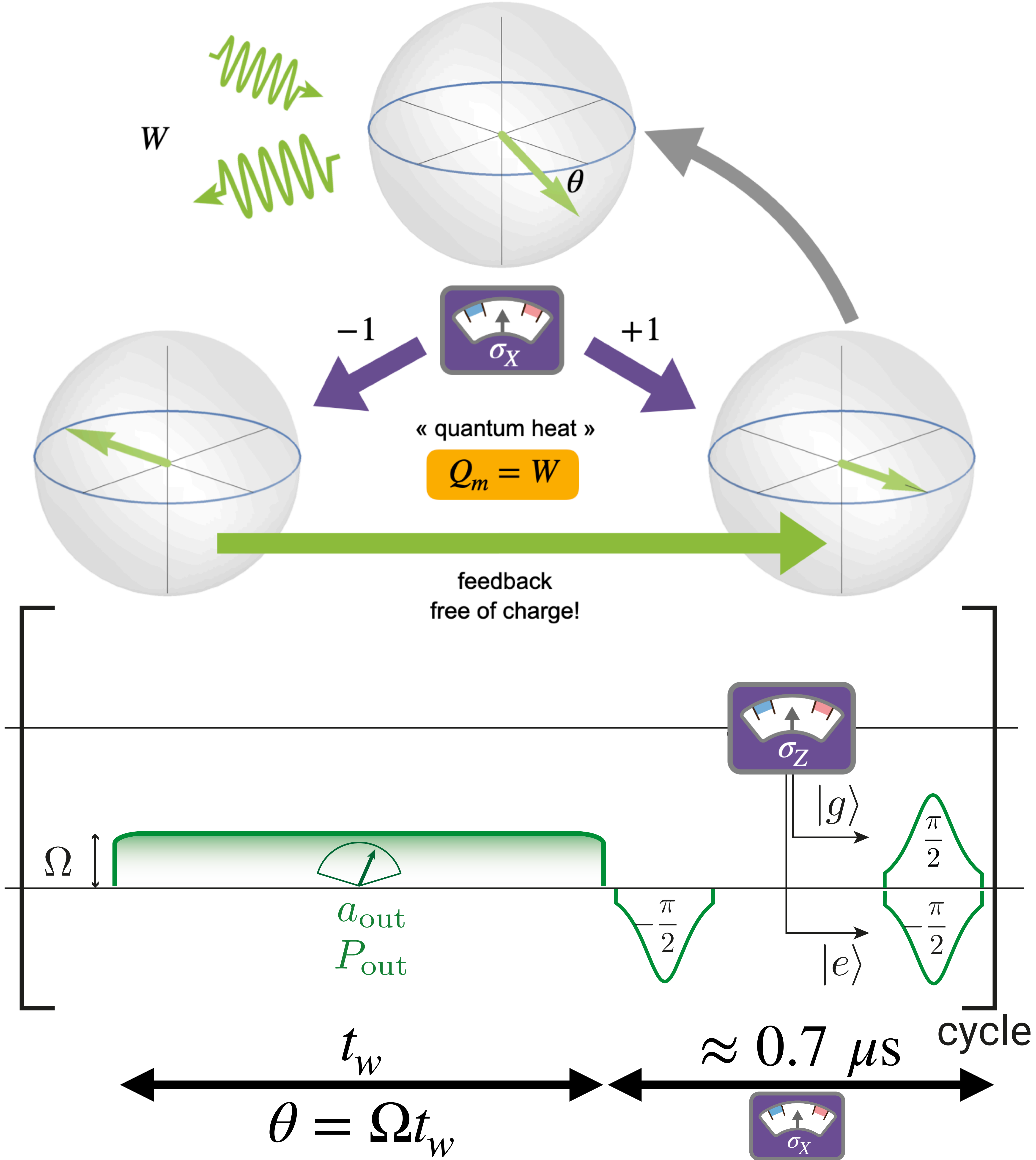
[Elouard *et al.*, PRL (2017)]

Device


QME2D FB
1 mm
$\omega_q = 2\pi \times 5$ GHz
$\Gamma_a = 2\pi \times 0.4$ kHz
$T_2 = 30\ \mu s$
fidelity ~99%
in 280 ns

Measurement sequence

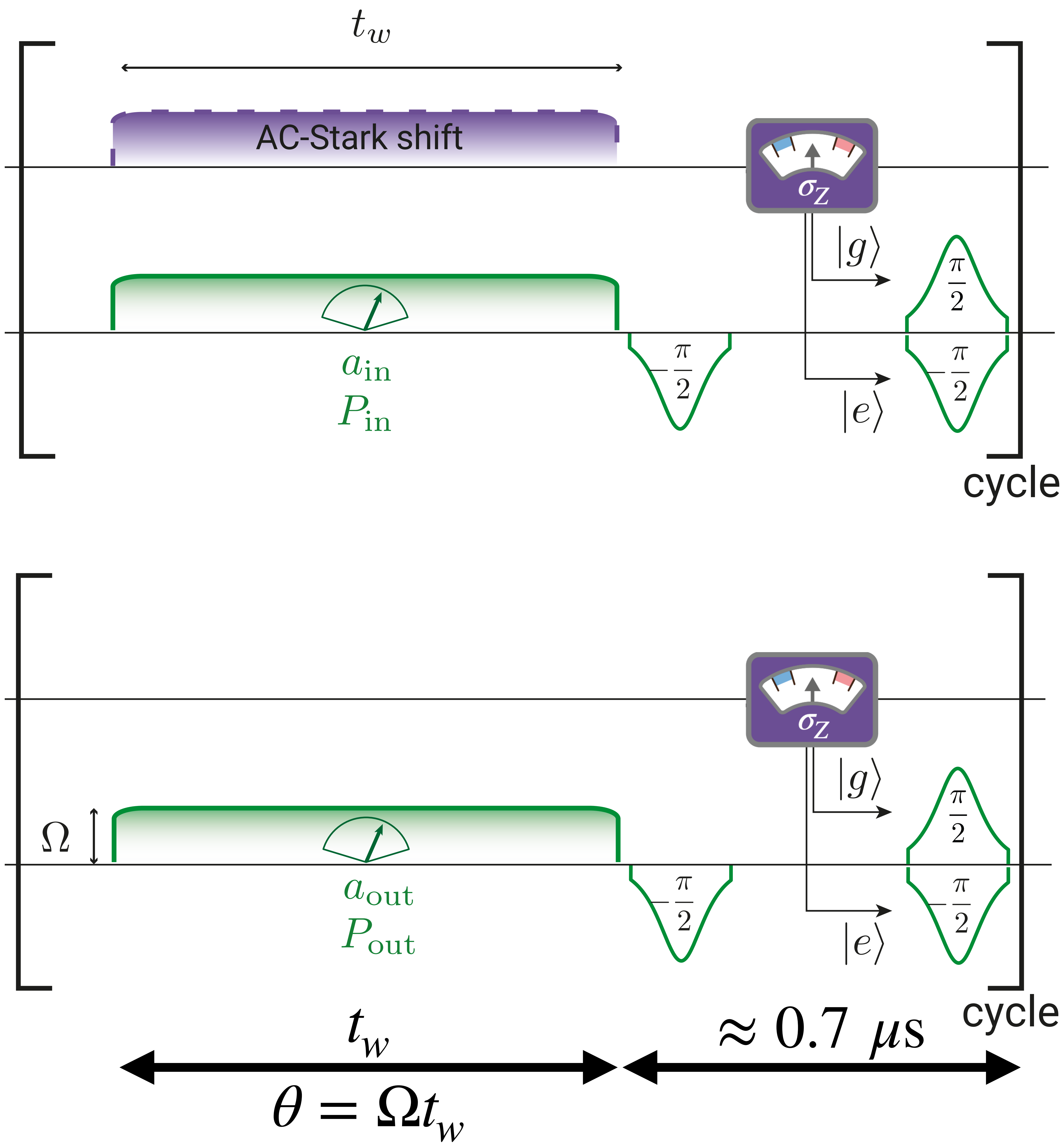
$$P_{out} = \frac{1}{t_w} \int_0^{t_w} |a_{out}(\tau)|^2 \, d\tau$$



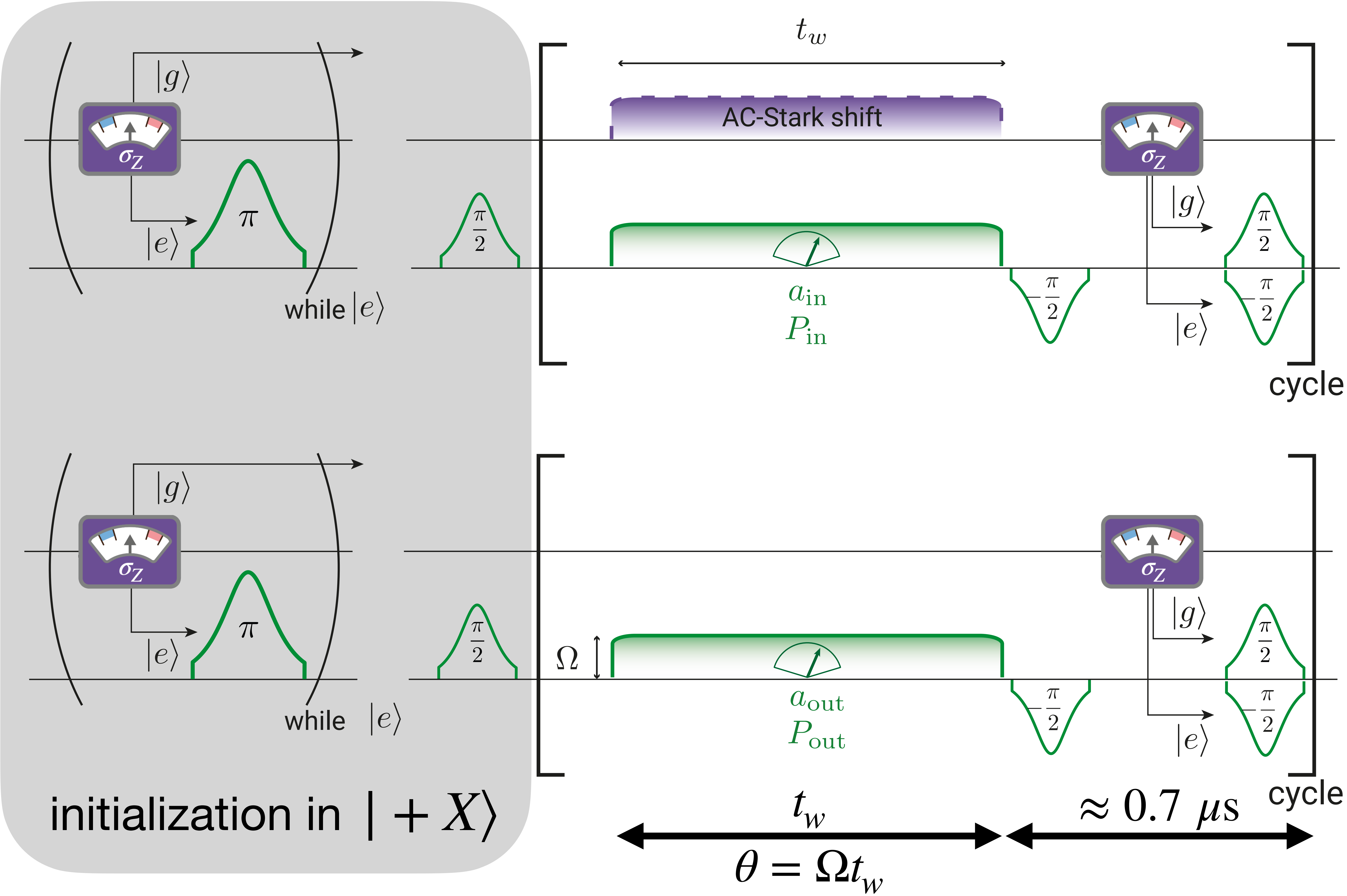
Measurement sequence

$$P_{\text{in}} = \frac{1}{t_w}\int_0^{t_w} |a_{\text{in}}(\tau)|^2 \, d\tau$$

$$P_{\text{out}} = \frac{1}{t_w}\int_0^{t_w} |a_{\text{out}}(\tau)|^2 \, d\tau$$

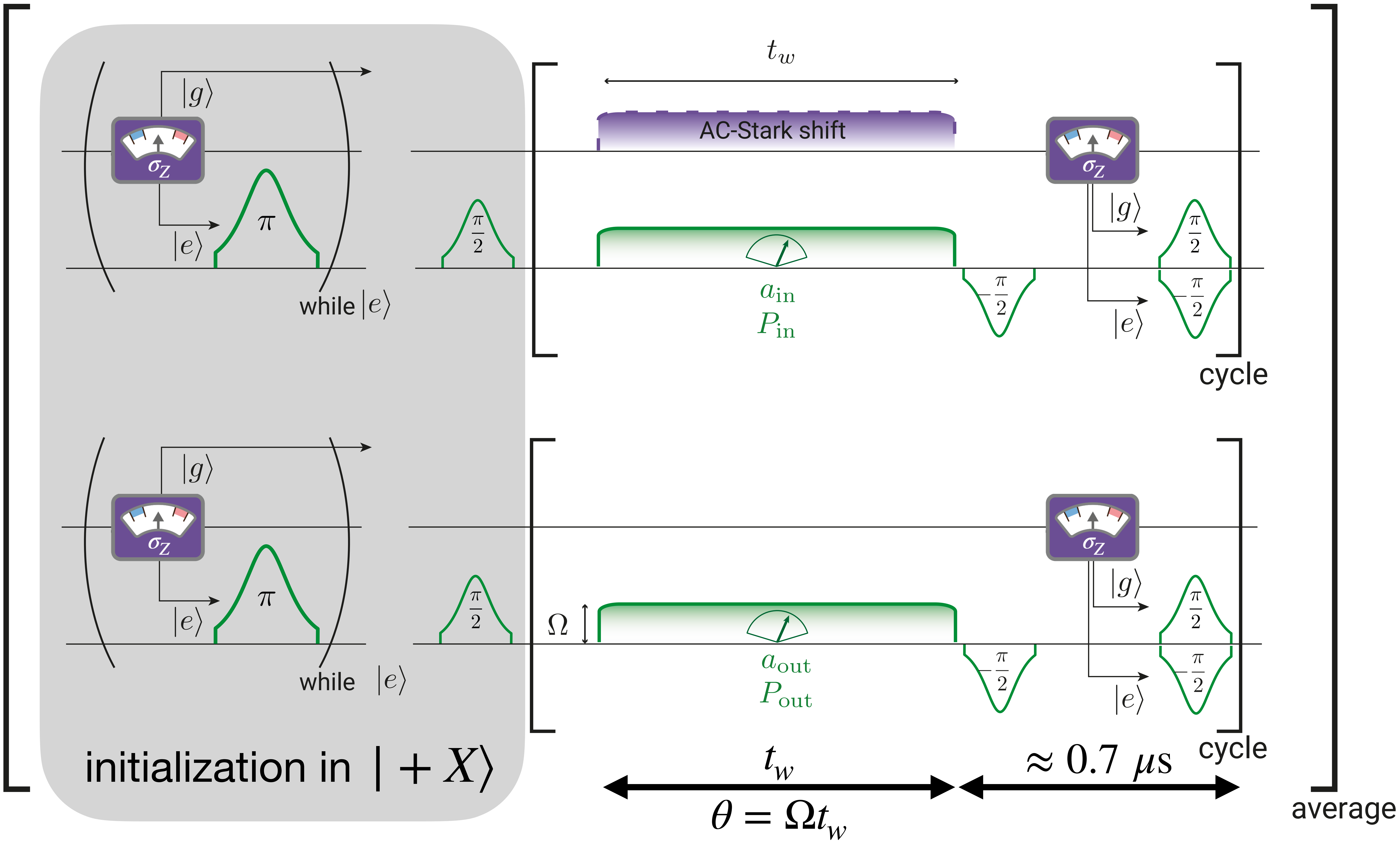


Measurement sequence



Measurement sequence

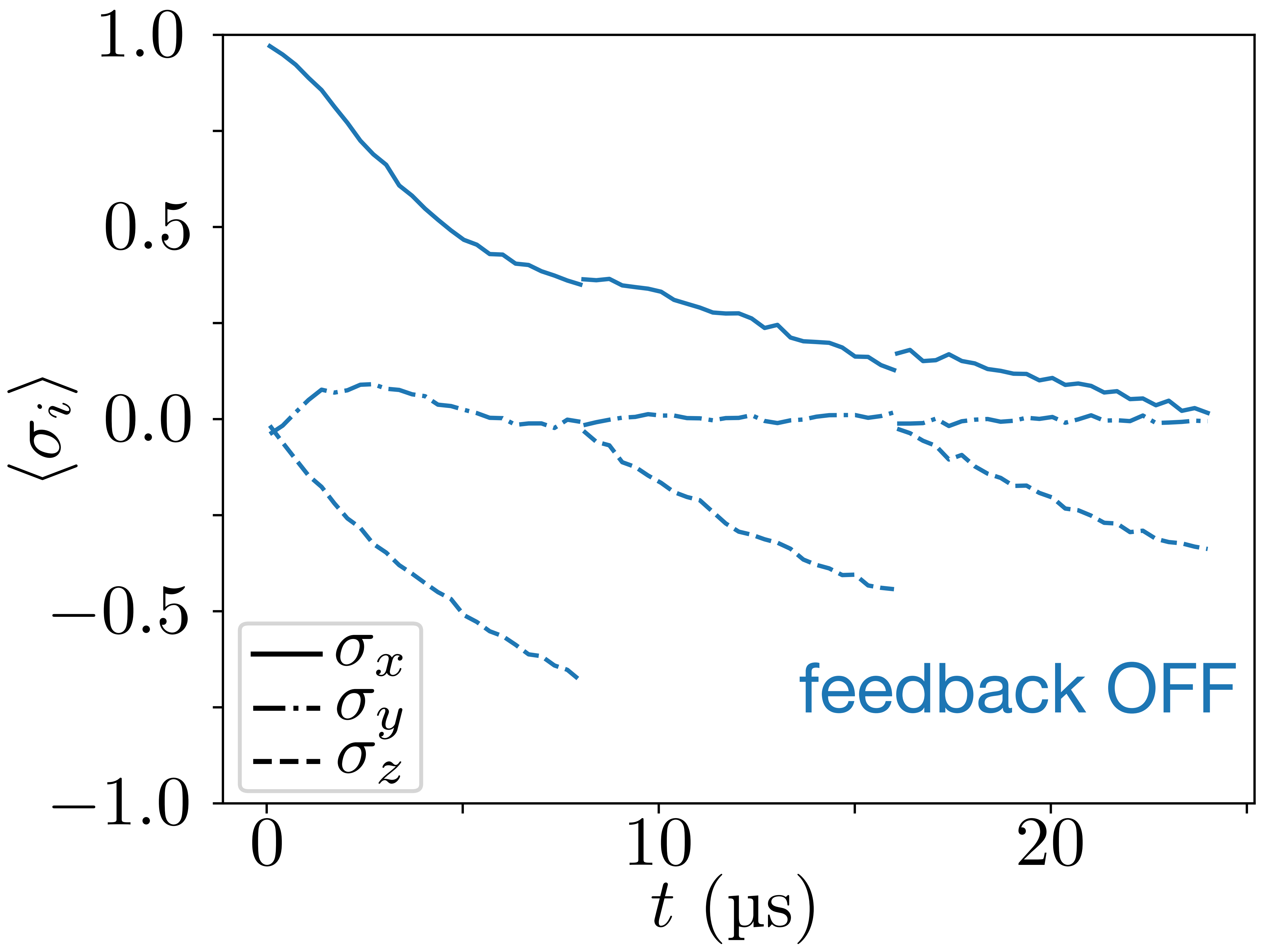
$$\dot{W} = \overline{P_{\mathrm{out}} - P_{\mathrm{in}}}$$



Dynamics of the qubit

$\Omega/2\pi = 14.2$ kHz

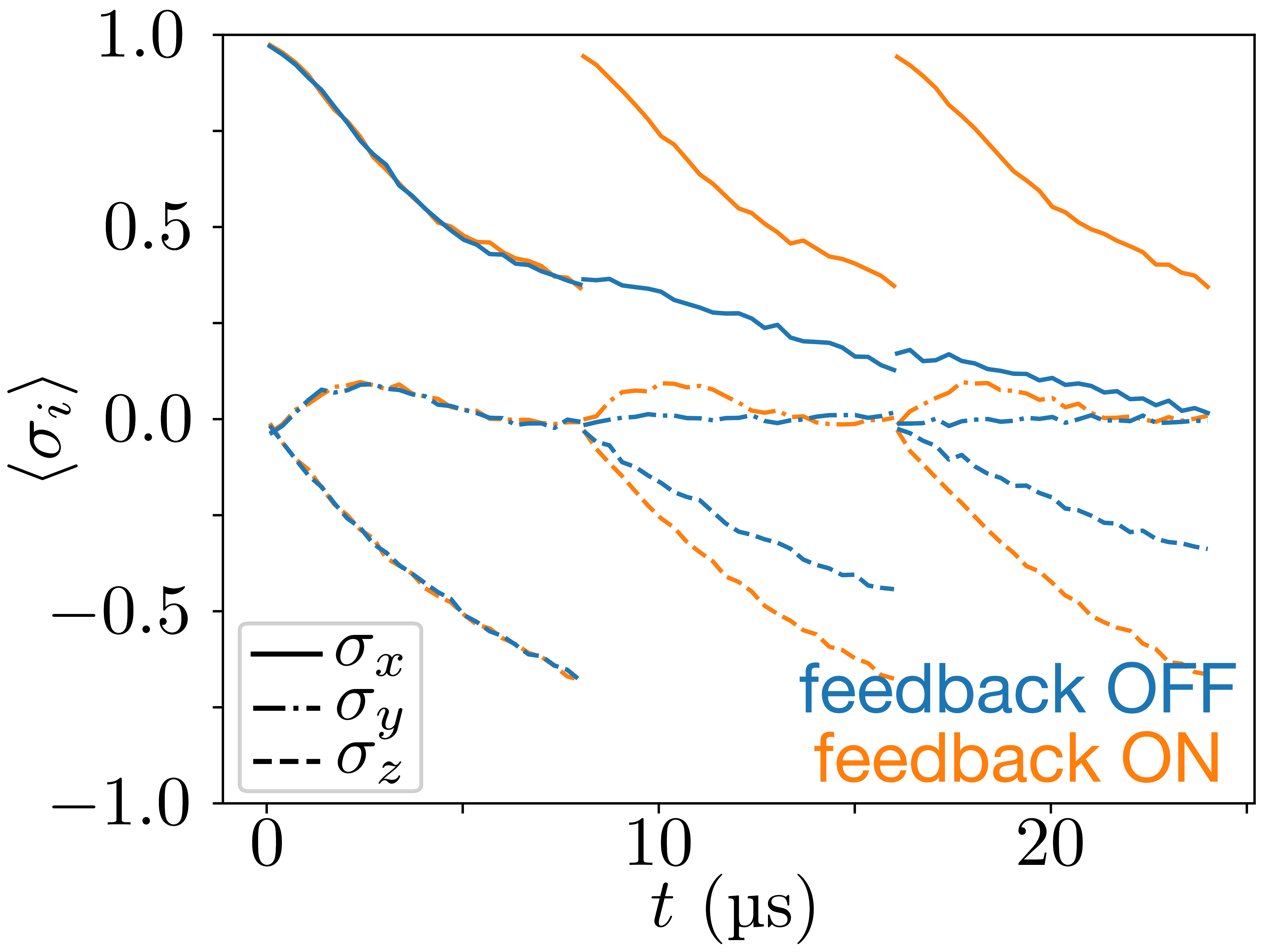
Tomography of the qubit as a function of time



Dynamics of the qubit

$\Omega/2\pi = 14.2\ \mathrm{kHz}$

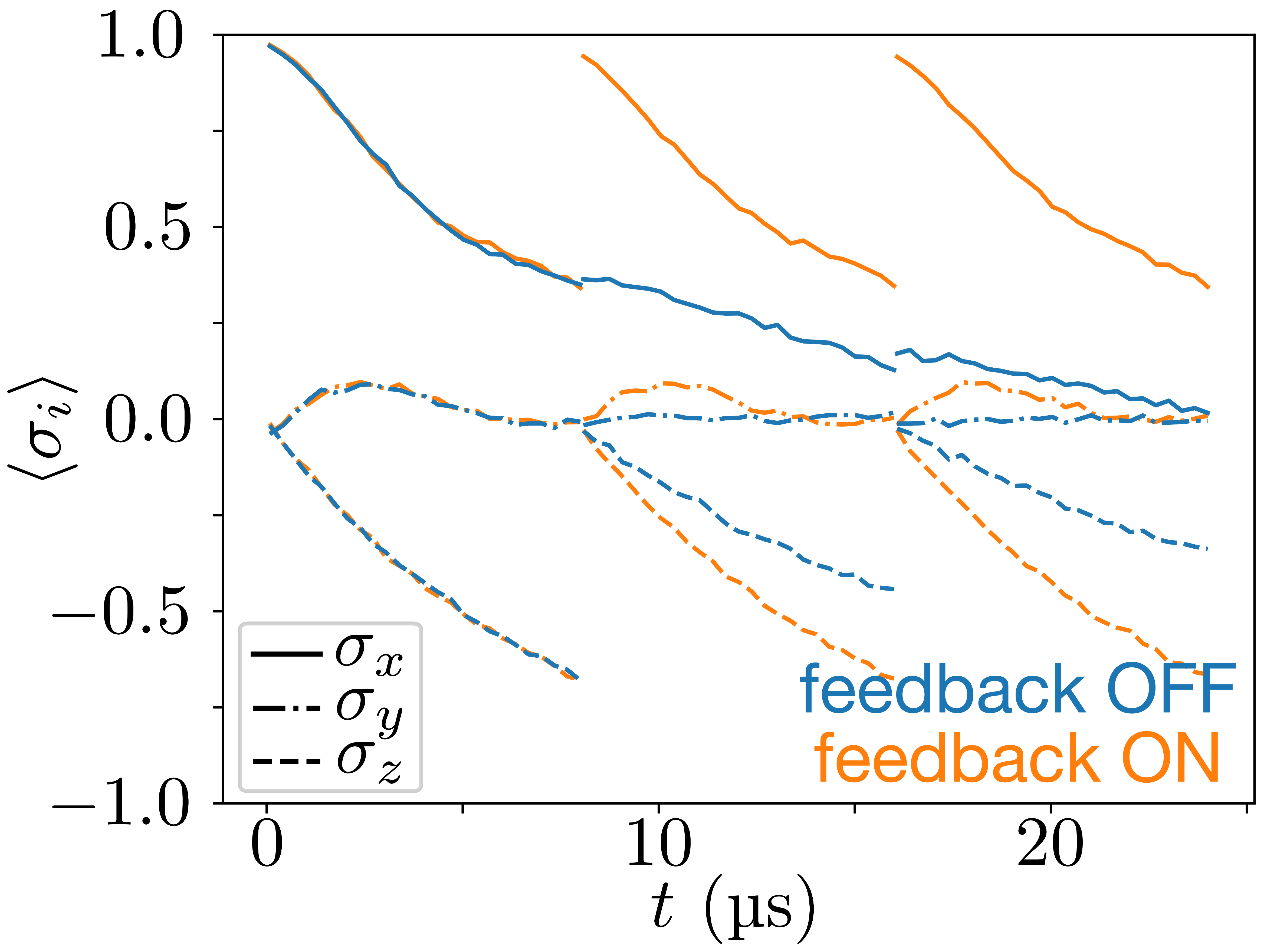
Tomography of the qubit as a function of time

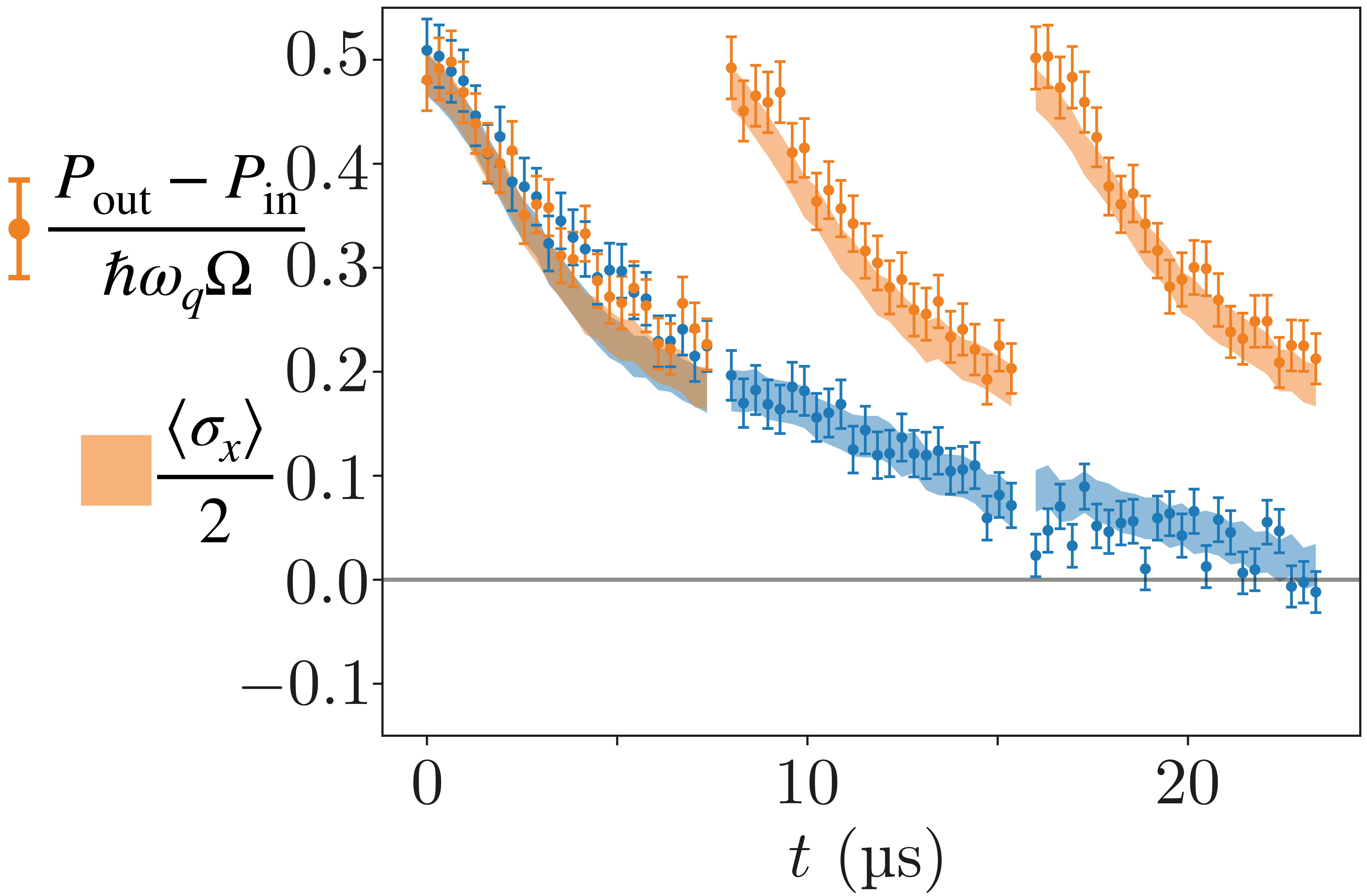


Dynamics of the qubit

$\Omega/2\pi = 14.2$ kHz

Tomography of the qubit as a function of time + Direct measurement of the work power



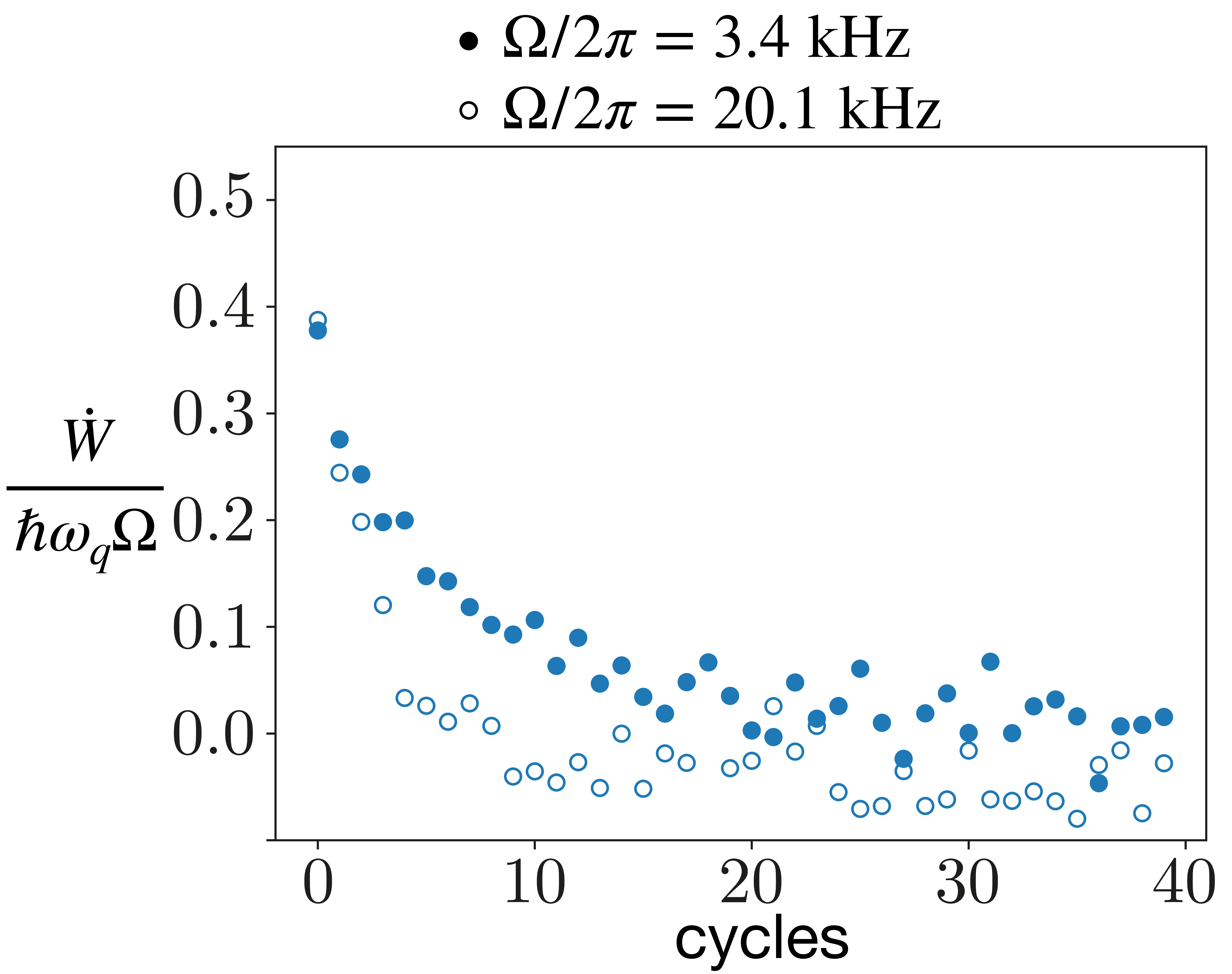


Measurement powered engine at work

$\dot{W} = \overline{P_{\mathrm{out}} - P_{\mathrm{in}}}$

$T_1 = 25\ \mu s$
$T_2 = 30\ \mu s$

$t_w = 4\ \mu s$

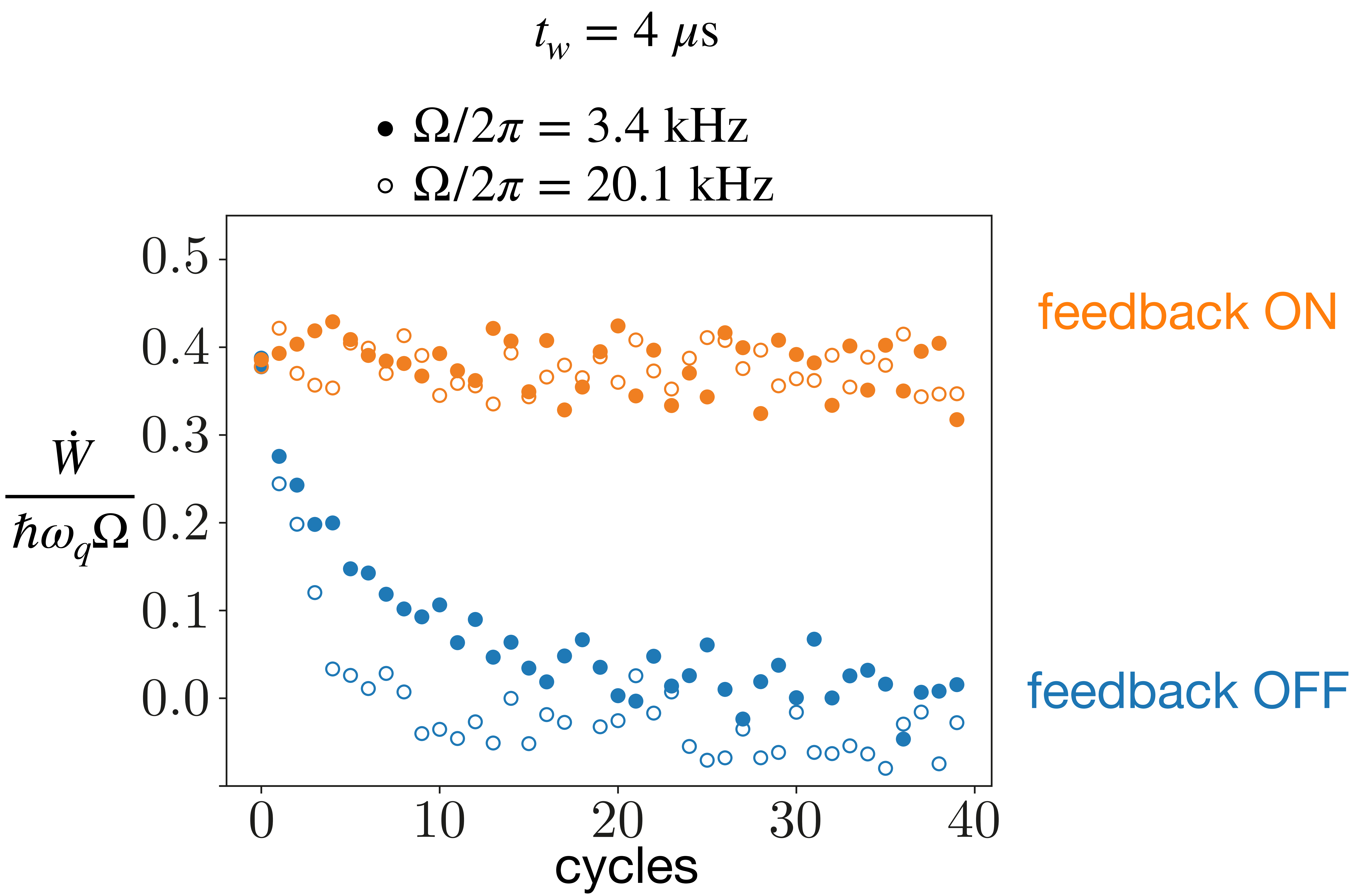


feedback OFF

Measurement powered engine at work

$$\dot{W} = \overline{P_{\text{out}} - P_{\text{in}}}$$

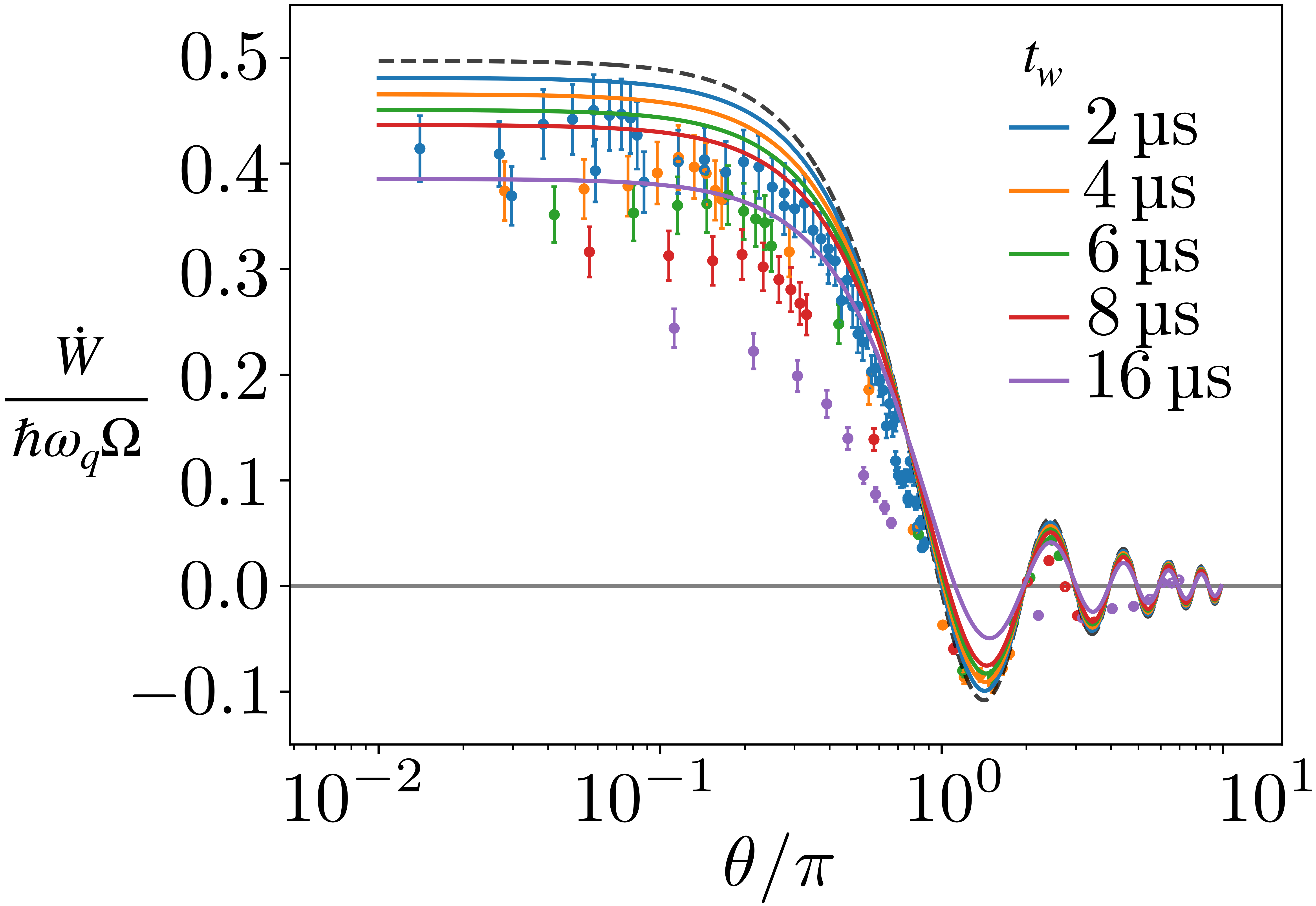
$$T_1 = 25\ \mu s$$
$$T_2 = 30\ \mu s$$



Dependence on rotation angle

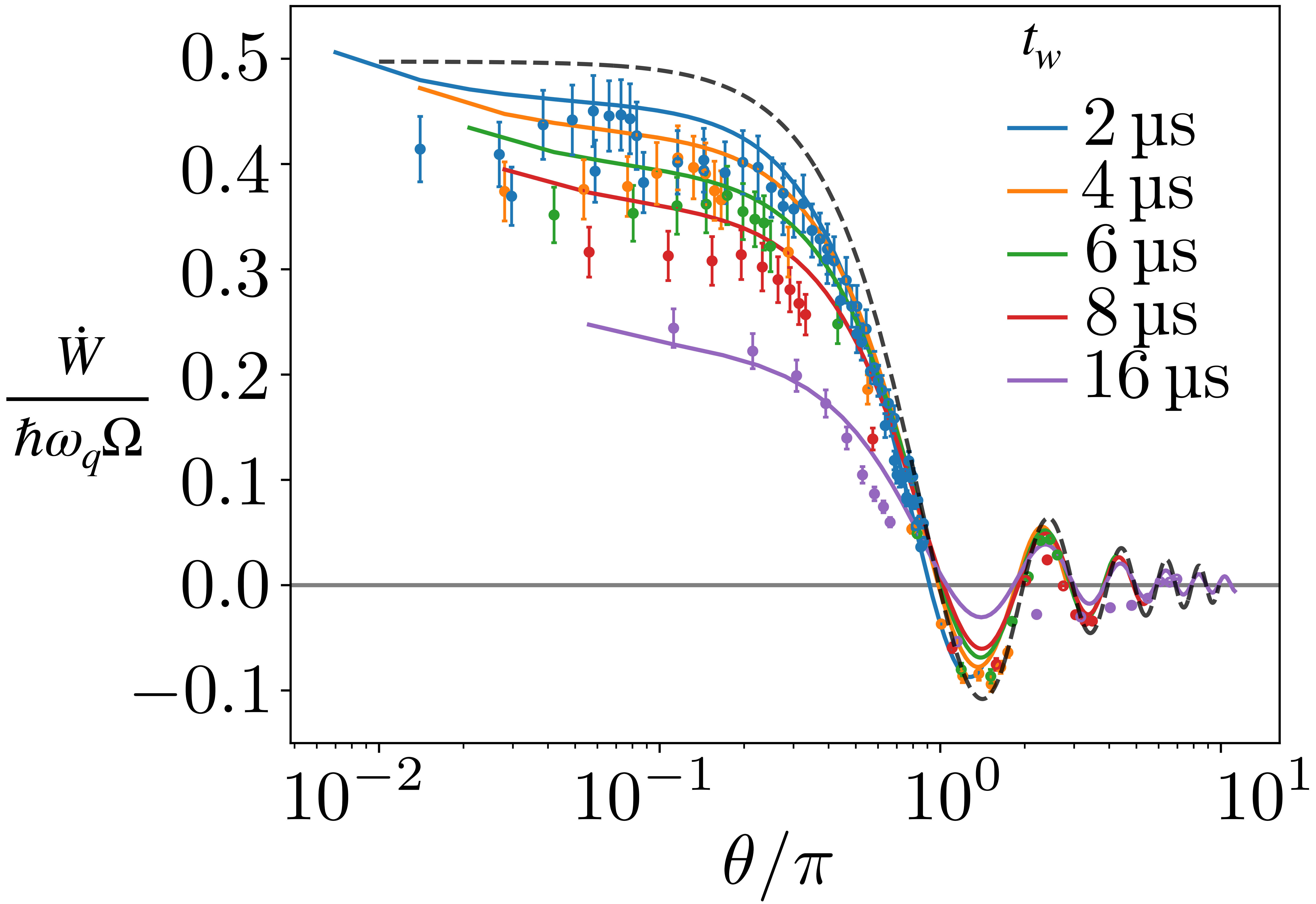
ideally, $$\frac{\dot{W}}{\hbar\omega_q\Omega} = \frac{1}{2t_w}\int_0^{t_w}\cos(\Omega t)e^{-\Gamma_2 t}\mathrm{d}t$$

$$\theta = t_w\Omega$$



Dependence on rotation angle

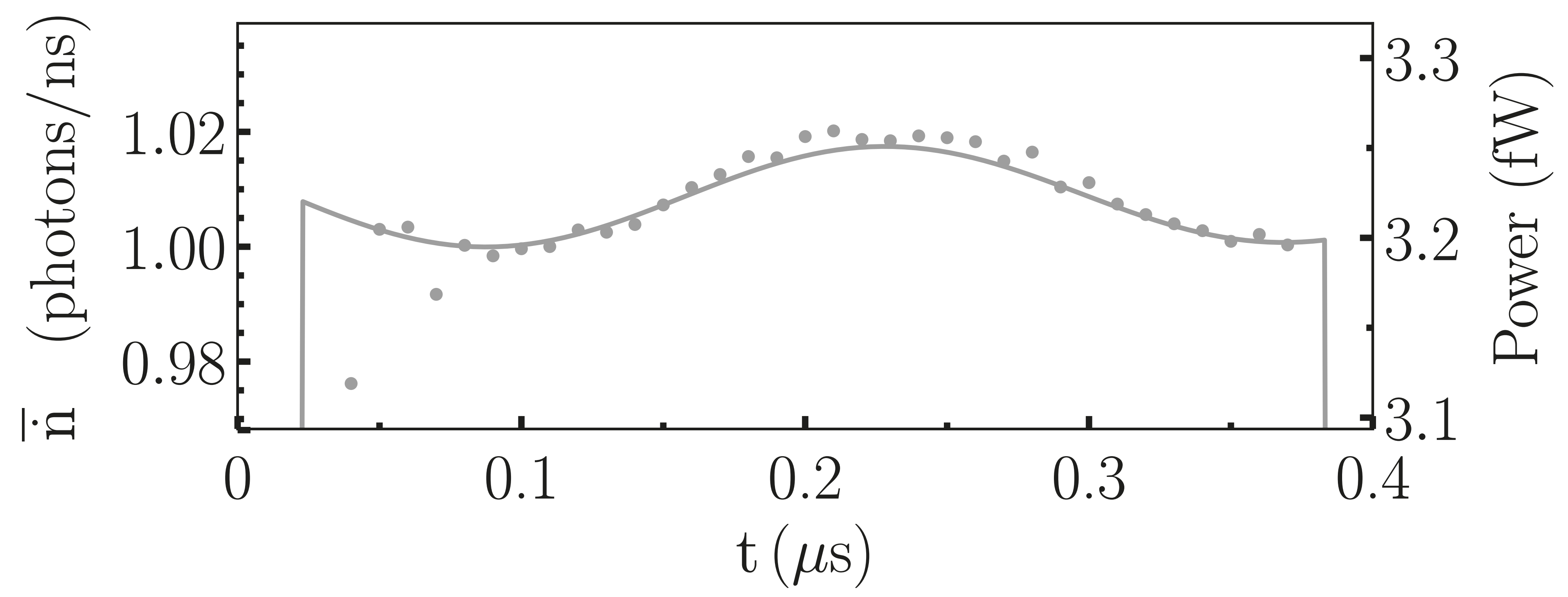
ideally, $$\frac{\dot{W}}{\hbar\omega_q\Omega} = \frac{1}{2t_w}\int_0^{t_w} \cos(\Omega t)e^{-\Gamma_2 t}\mathrm{d}t \qquad \theta = t_w\Omega$$

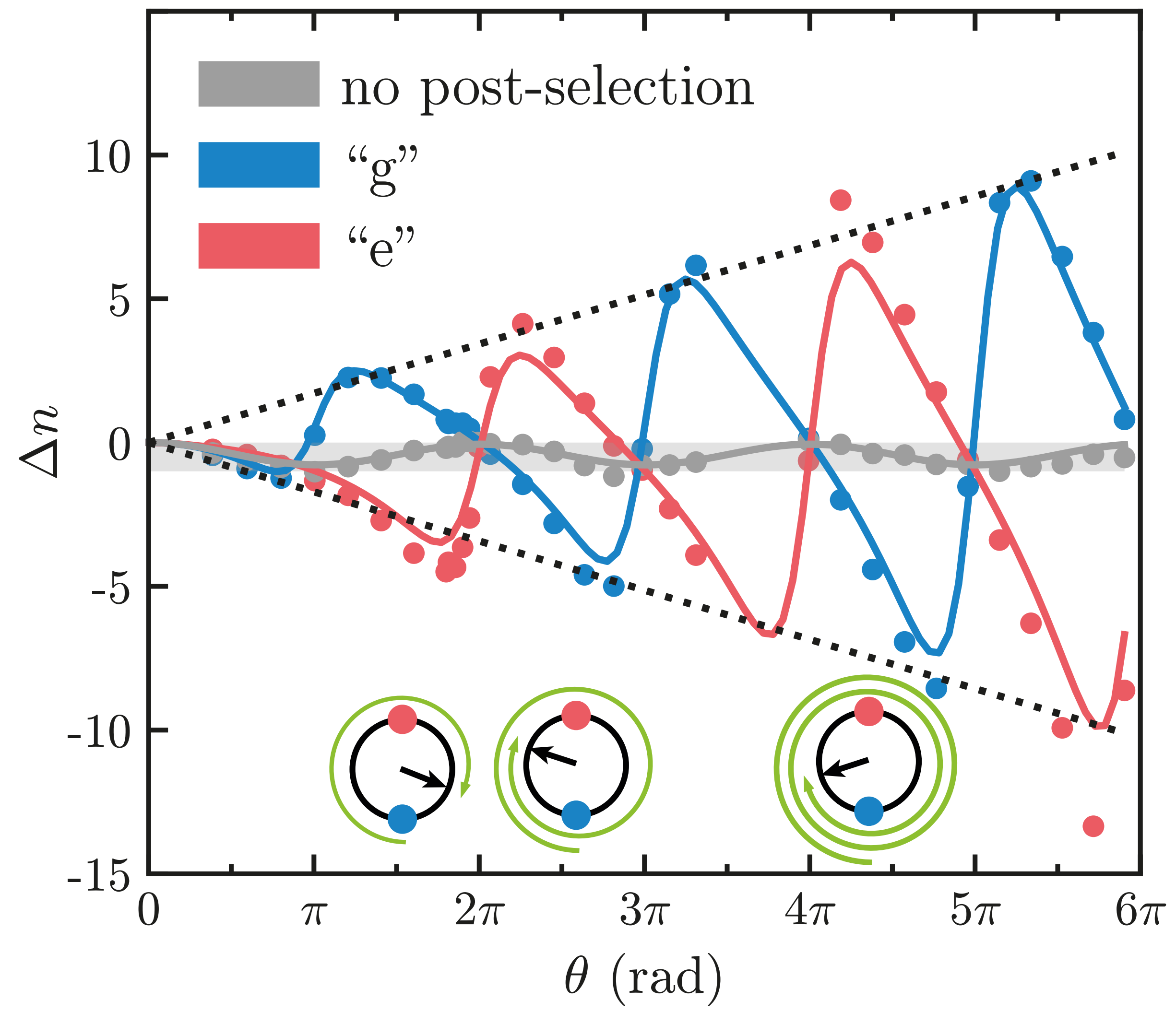


deviations to ideality might come from about 150 kHz qubit frequency jumps

Energetics of a single qubit gate

Measured transfer of single excitation on average

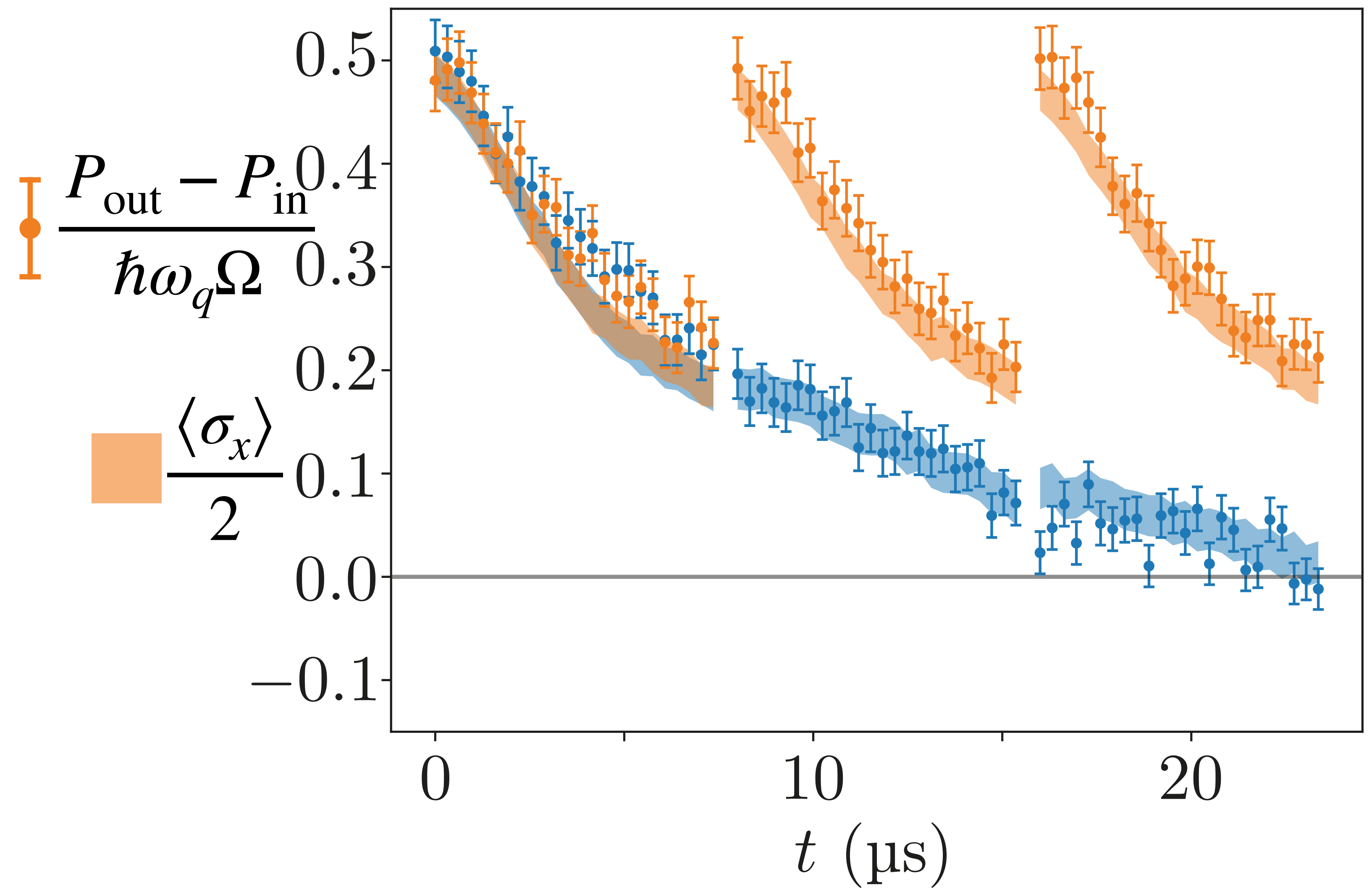




Post-selected energy transfer contains both quantum heat and measurement backaction of the qubit measurement on the drive pulse

[Stevens et al., PRL 2022]
[Mafei et al., PRA 2023]

measurement powered engine works
work directly measured not inferred



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Audrey Bienfait

Rémy Dassonneville

Jeremy Stevens

Daniel Szombati

Réouven Assouly

ENS DE LYON

Alice & Bob

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