Retrieving the information lost during relaxation

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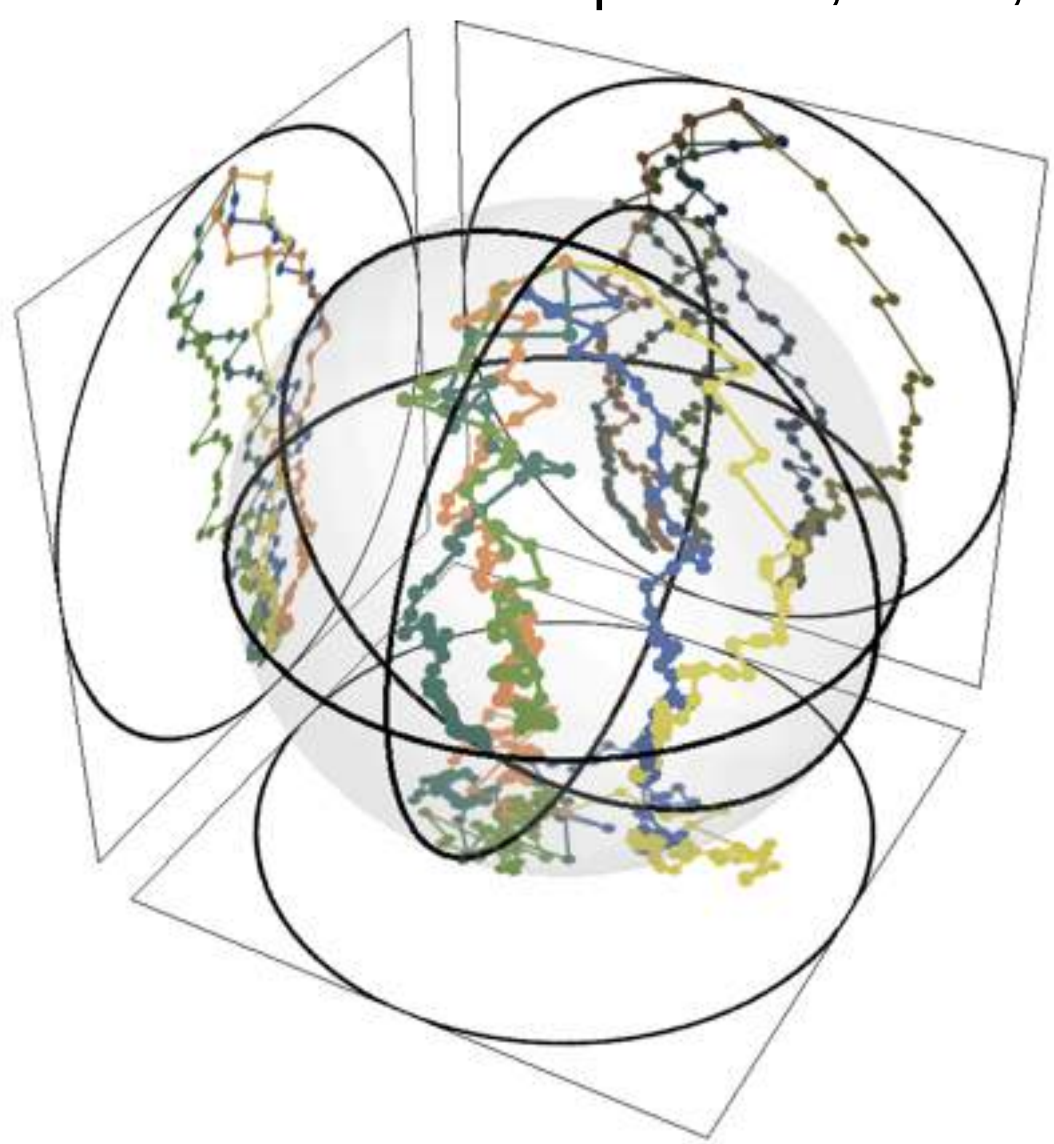
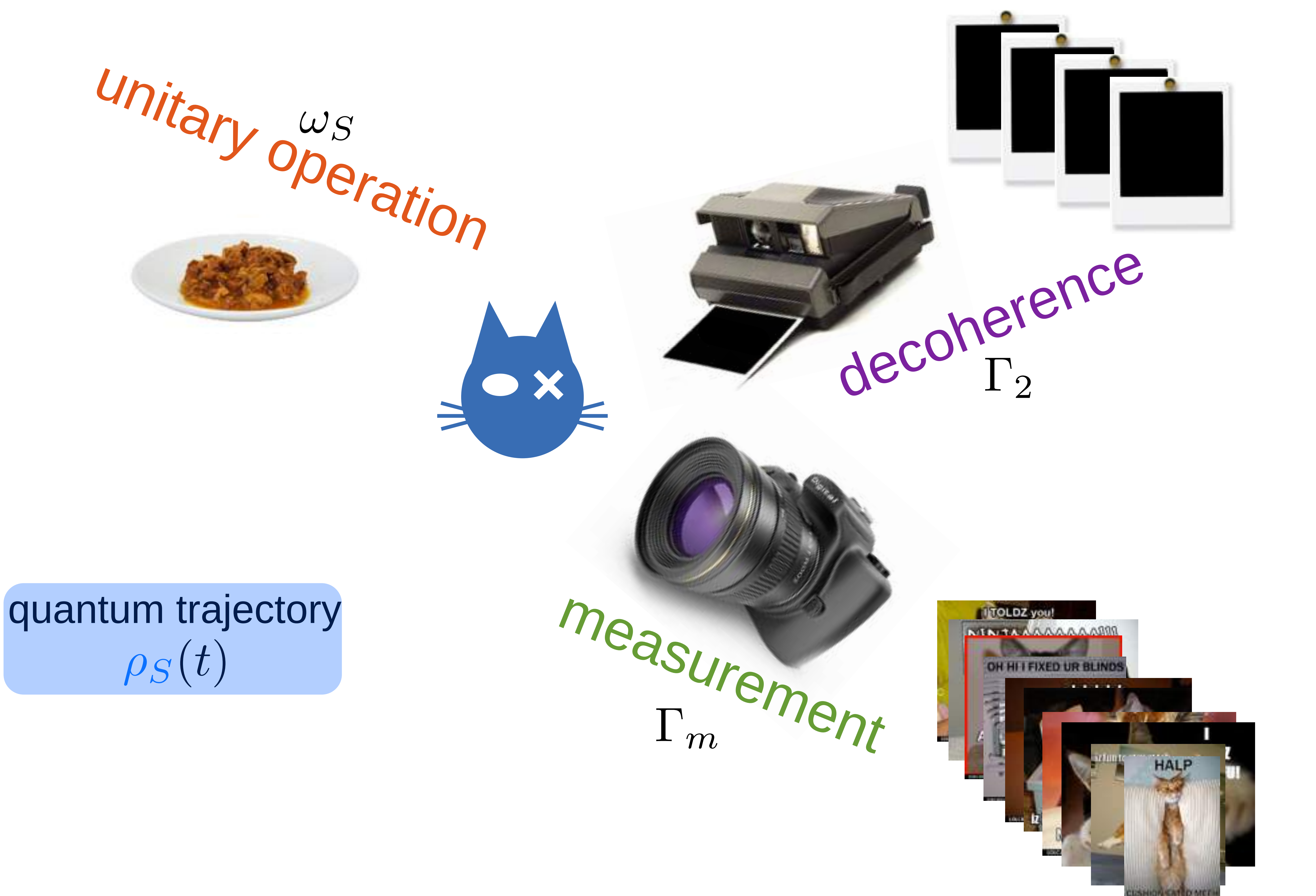
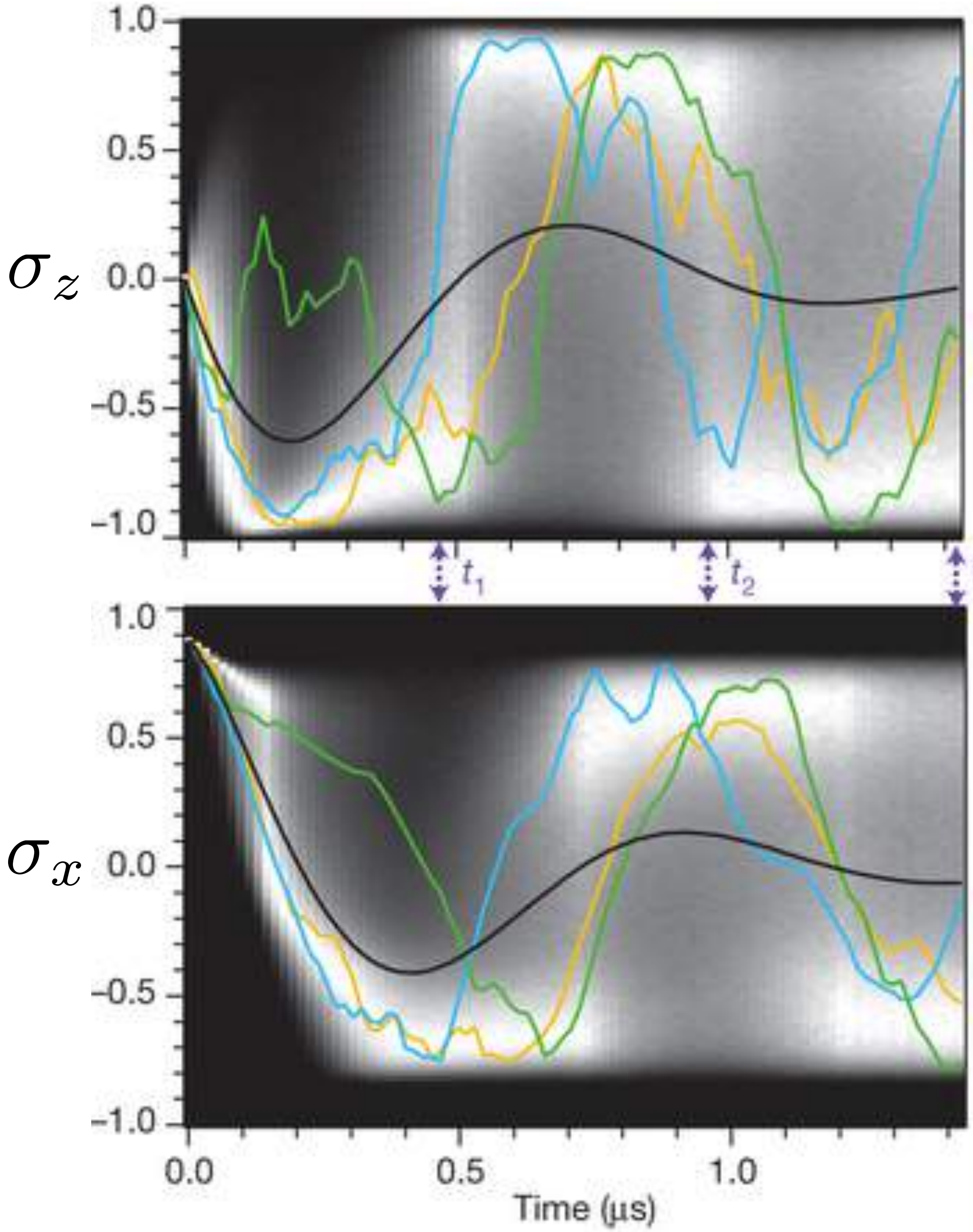


Quantum trajectories



Quantum trajectories

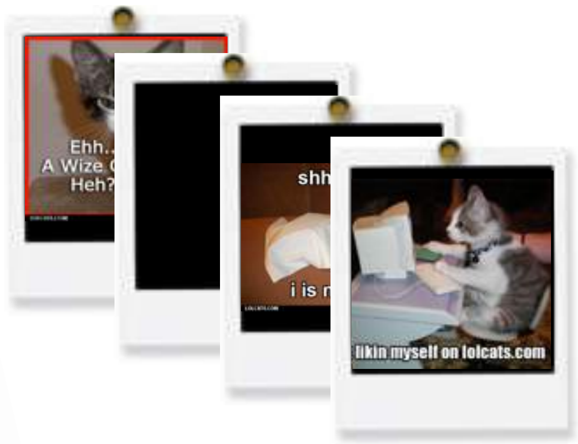


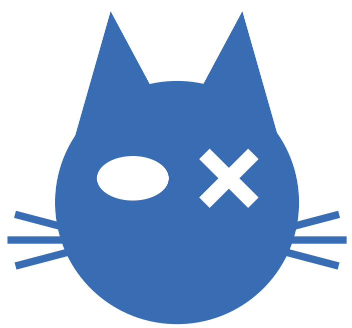
[Murch *et al.*, Nature 2013 (Berkeley)]
[Weber *et al.*, Nature 2014 (Berkeley)]

Retrieving the information lost during decoherence

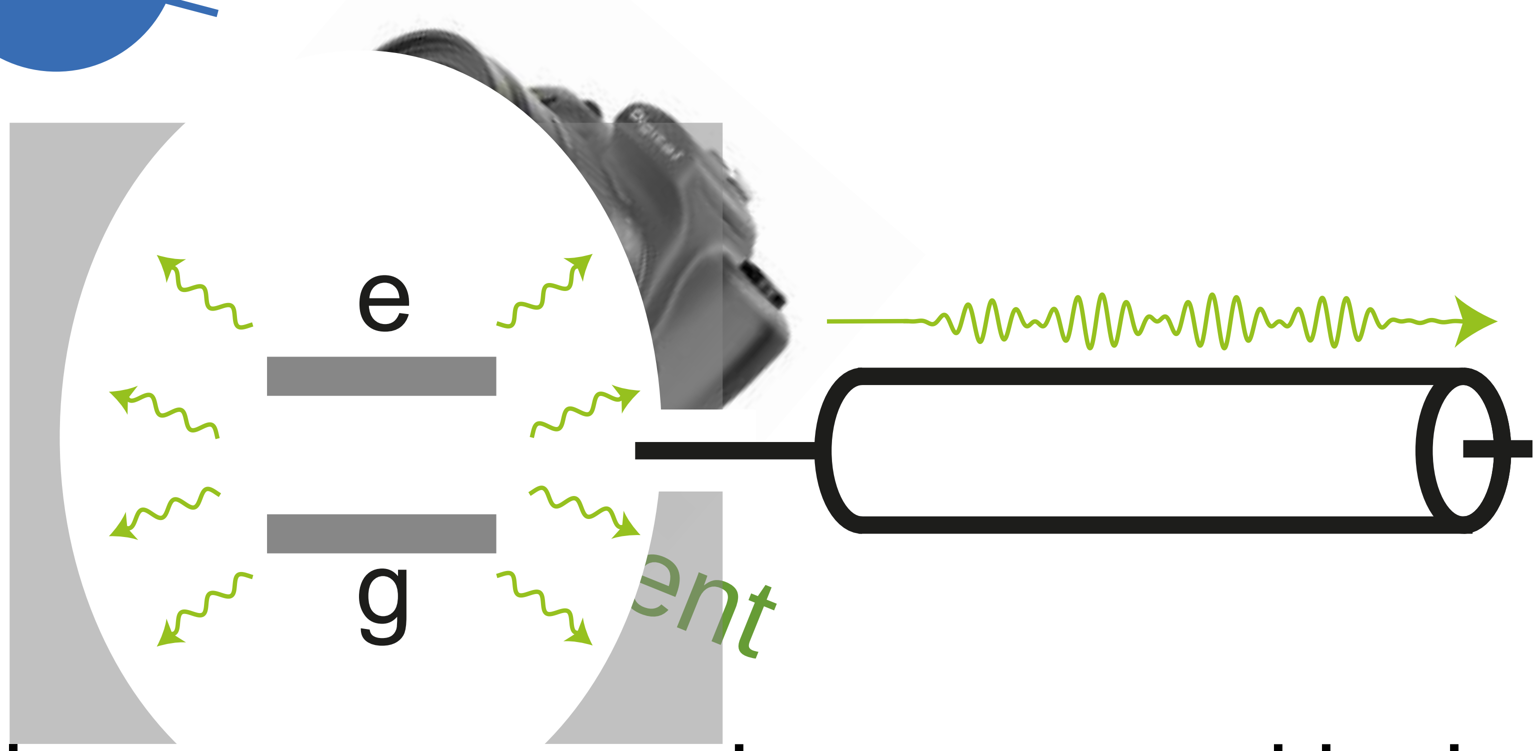
unitary operation

decoherence





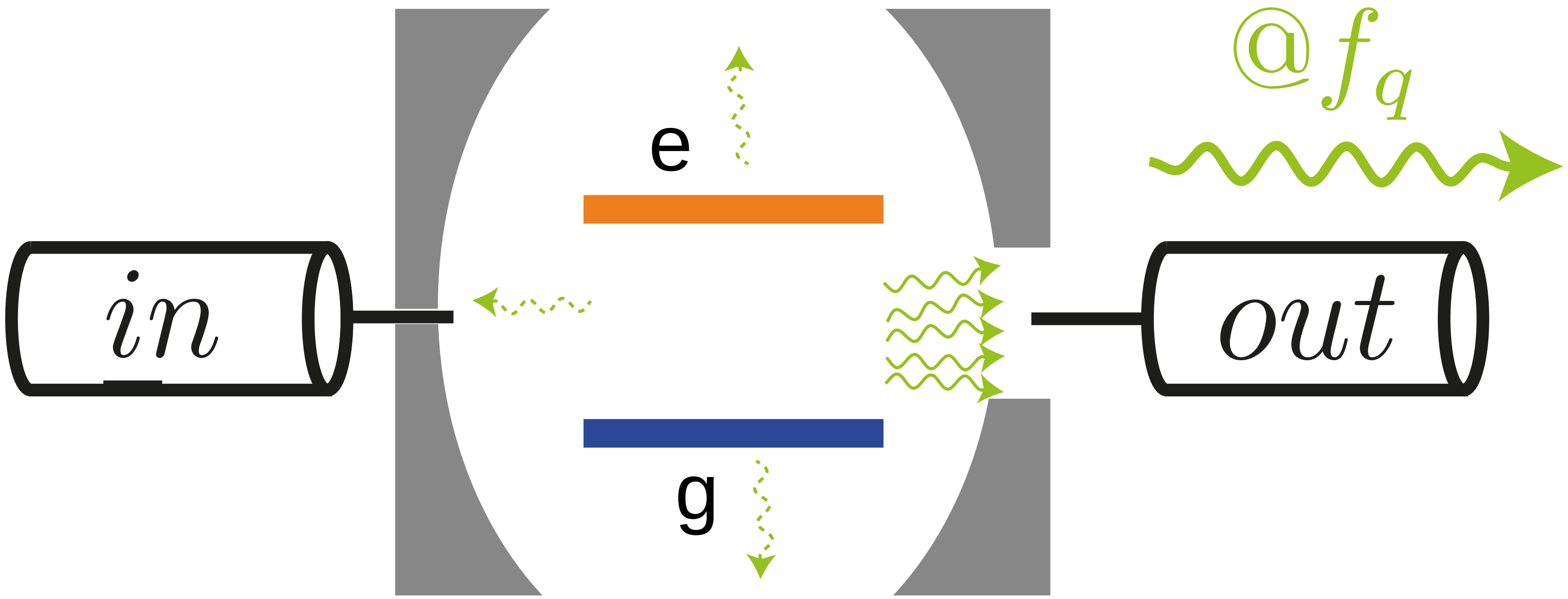
quantum trajectory
$\rho_S(t)$



Fluorescence can be measured in time

Relaxation

measurement efficiency $\eta = \eta_{\text{extract}} \times \eta_{\text{detec}}$



Monitor main relaxation channel itself

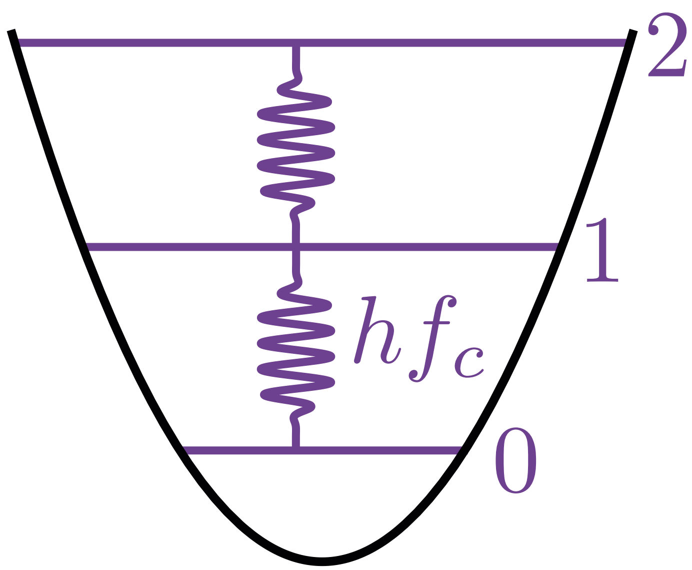
Purcell relaxation ↗

Collect fluorescence field on out

$T_1 = 4\ \mu\text{s}$

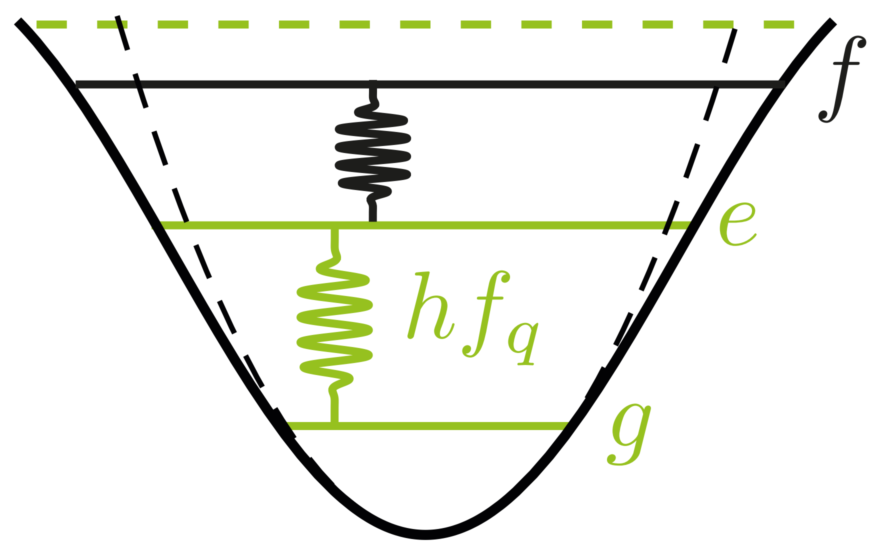
$T_\phi \simeq 25\ \mu\text{s}$

3D transmon



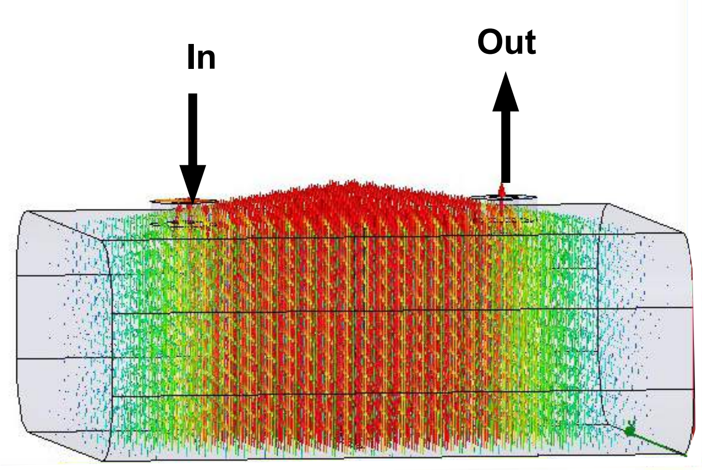
$$H_{\mathrm{disp}} = h\chi \frac{\sigma_z}{2} a^\dagger a$$

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

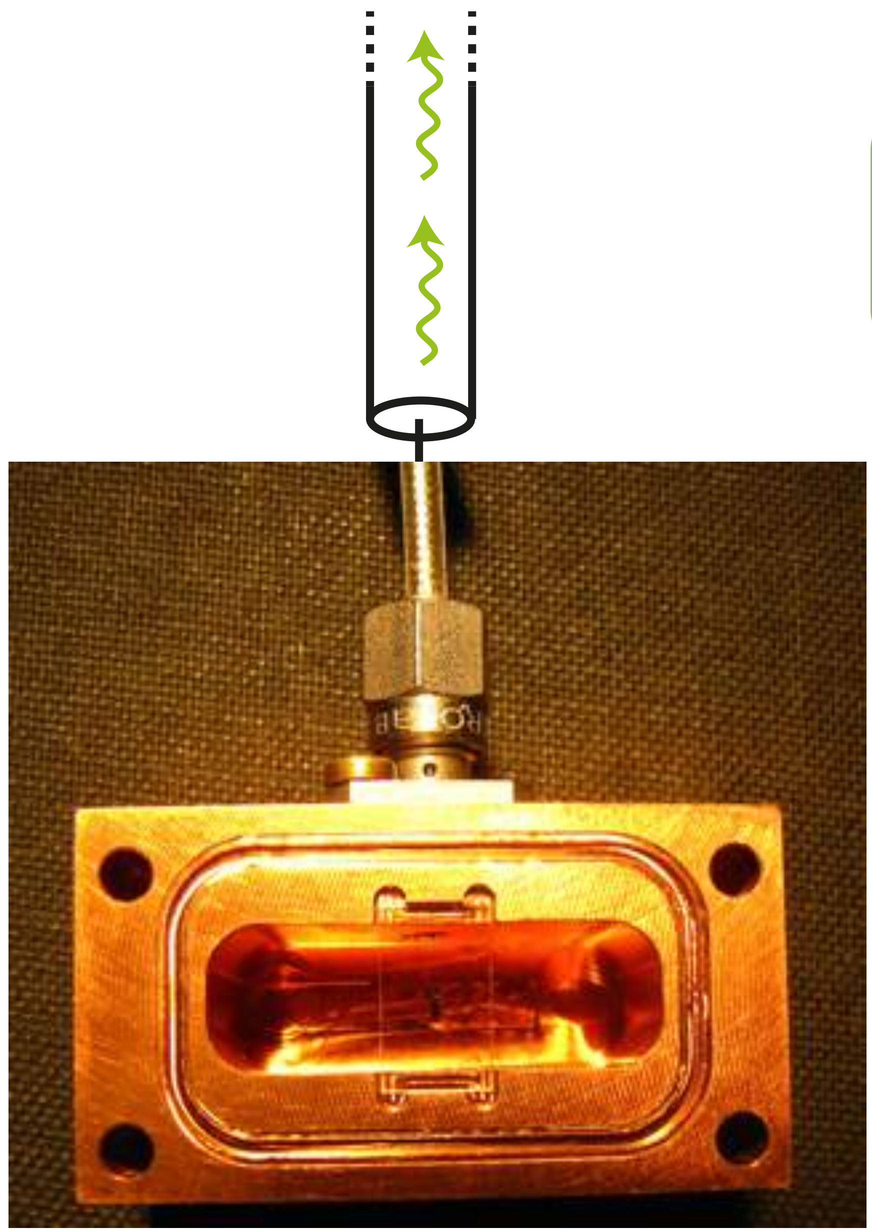


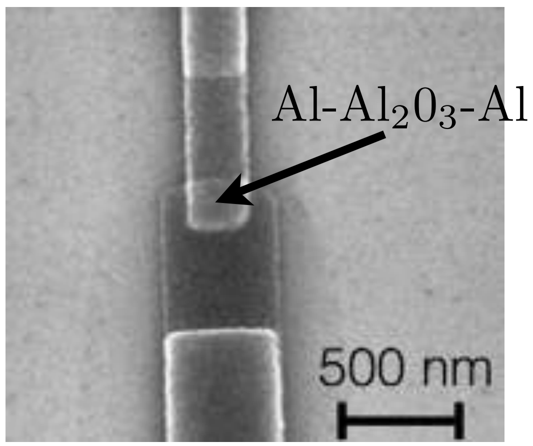
$$H_c = hf_c(a^\dagger a + \frac{1}{2})$$

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



$f_c = 7.5\ \mathrm{GHz}$





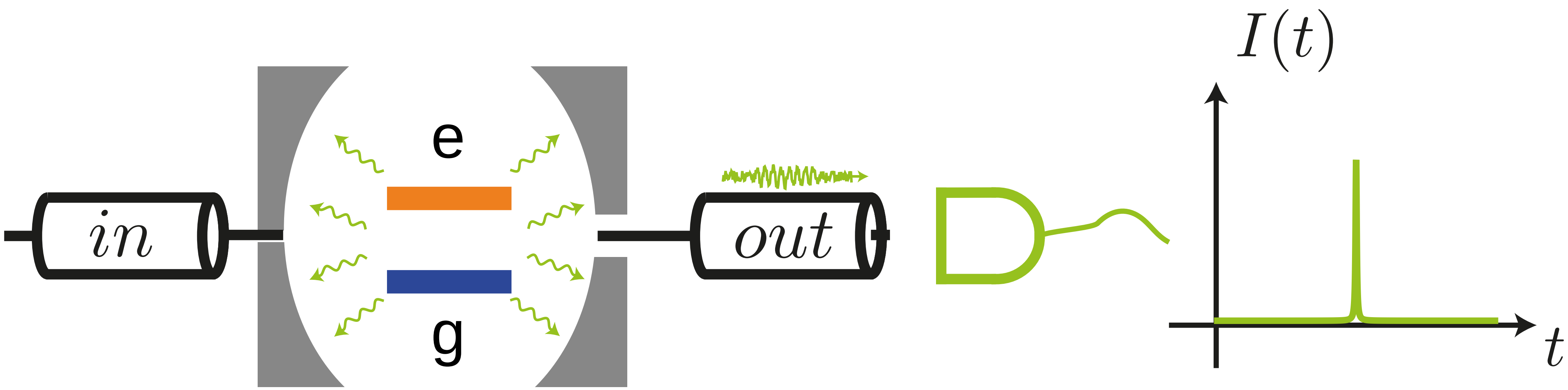
In cavity, $f_q = 6.3\ \mathrm{GHz}$

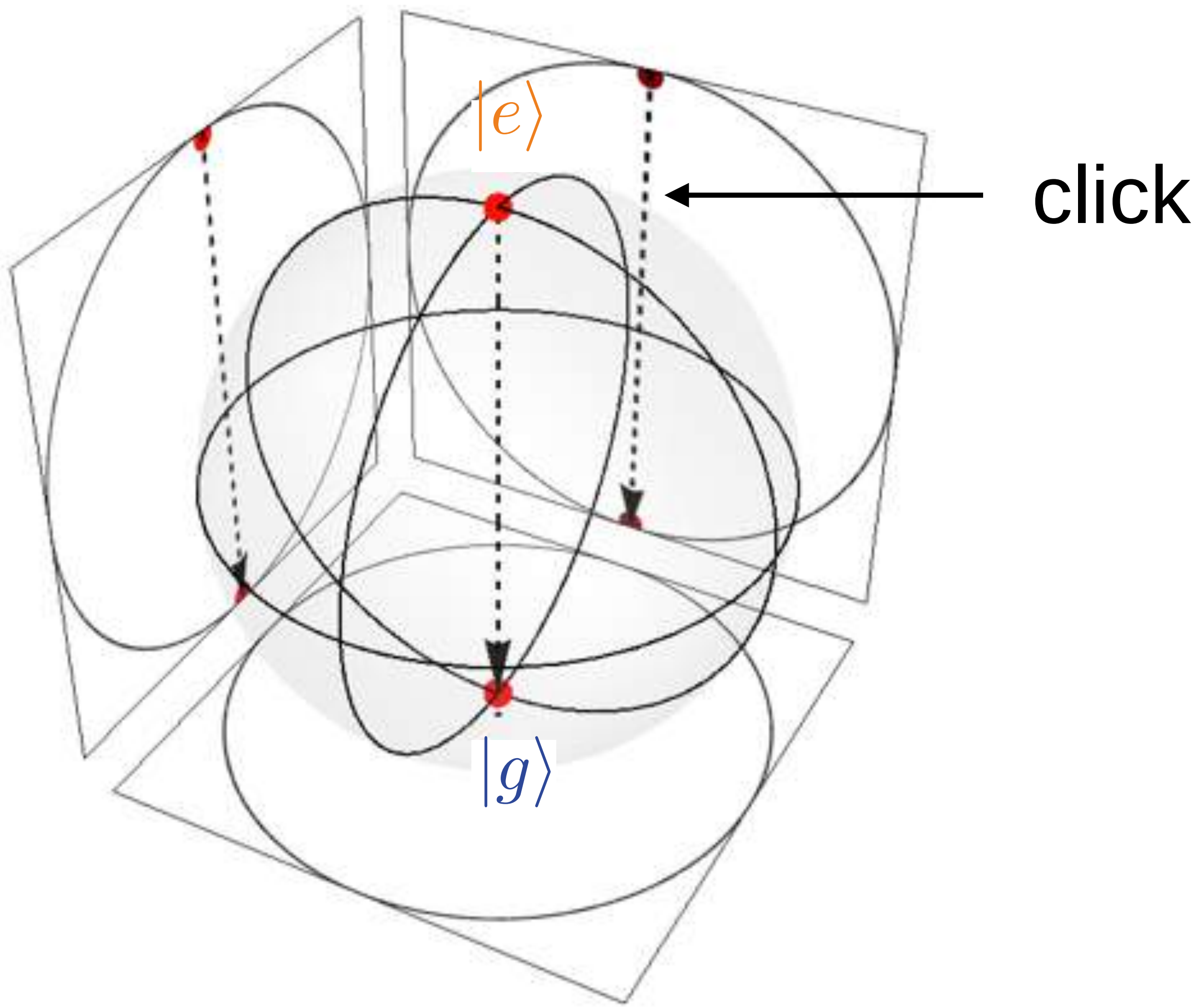
$kT \ll hf$

$T = 20\ \mathrm{mK}$

[Paik et al., Yale Group, PRL 2011]

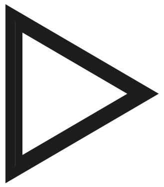
Fluorescence with a photodiode

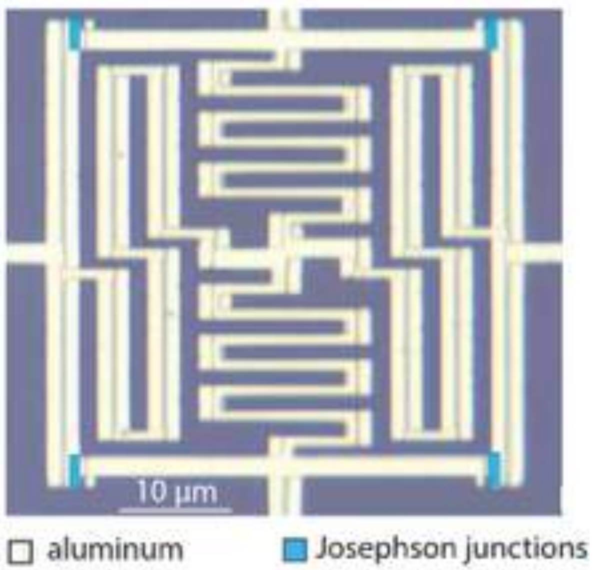




Fluorescence heterodyne measurement

Josephson Mixer
Phase preserving amplifier

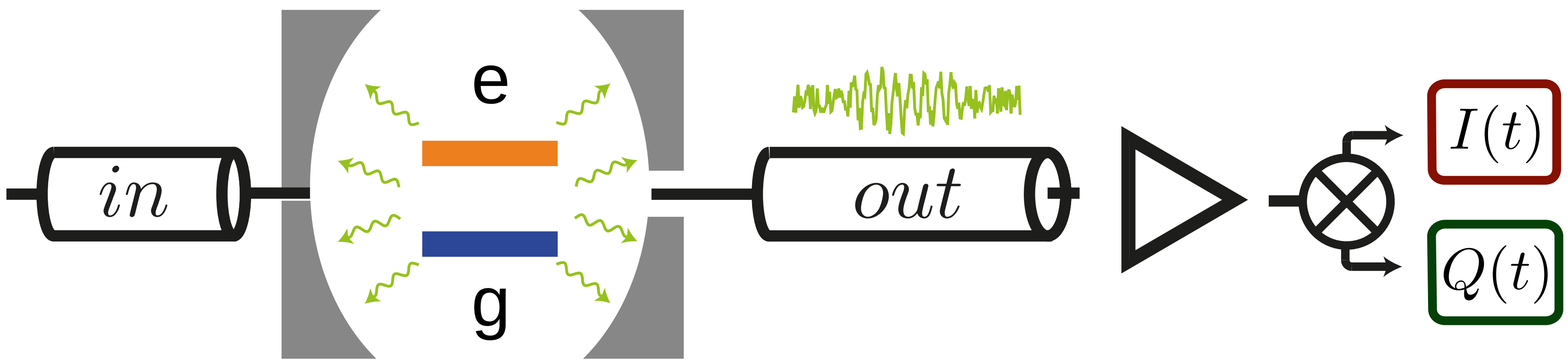




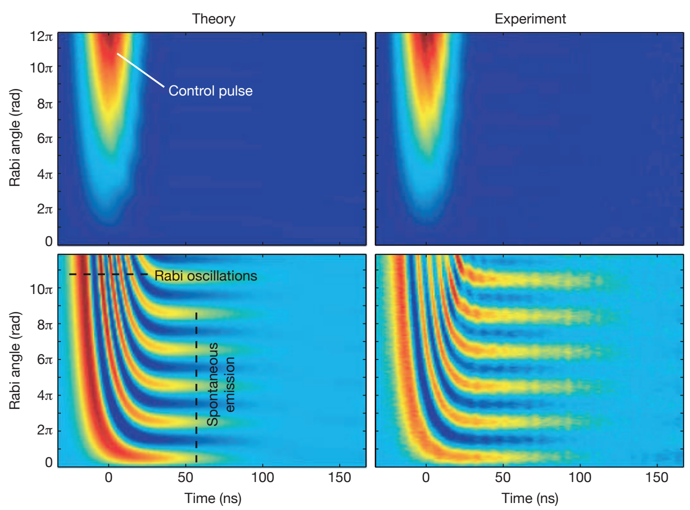
(Yale, 2010)

(ENS Paris, 2012)

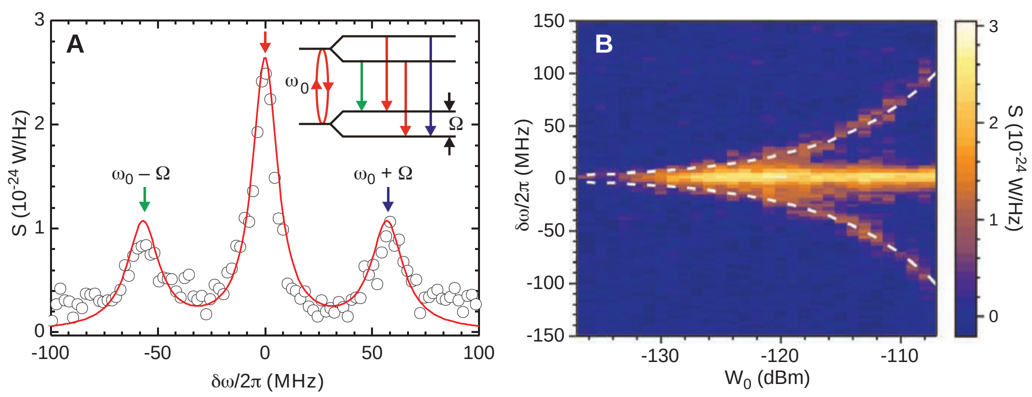
Heterodyne $\longleftrightarrow$ $\begin{cases} 1/2 \rightarrow \text{Homodyne } \theta = 0 \\ 1/2 \rightarrow \text{Homodyne } \theta = \frac{\pi}{2} \end{cases}$



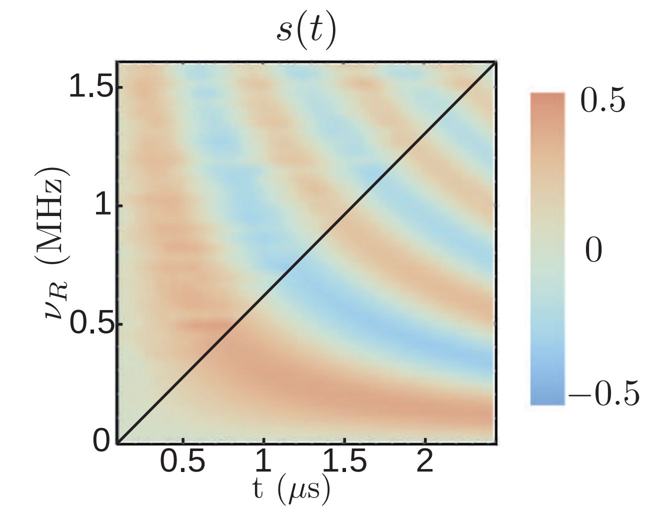
Mean fluorescence signal



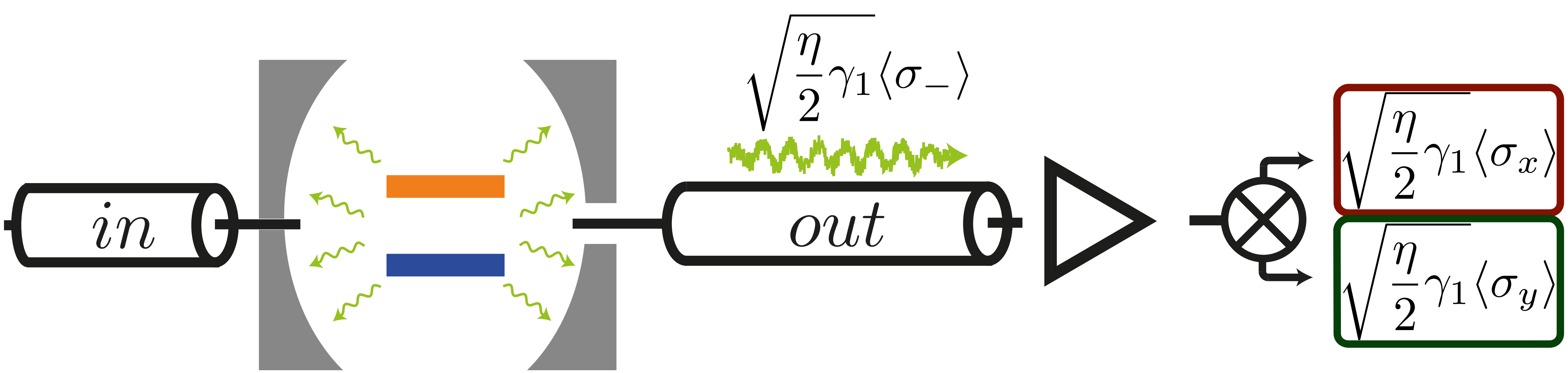
[Houck et al., Yale Nature 2007]



[Astafiev et al., RIKEN & NEC, Science 2010 and PRL 2011]



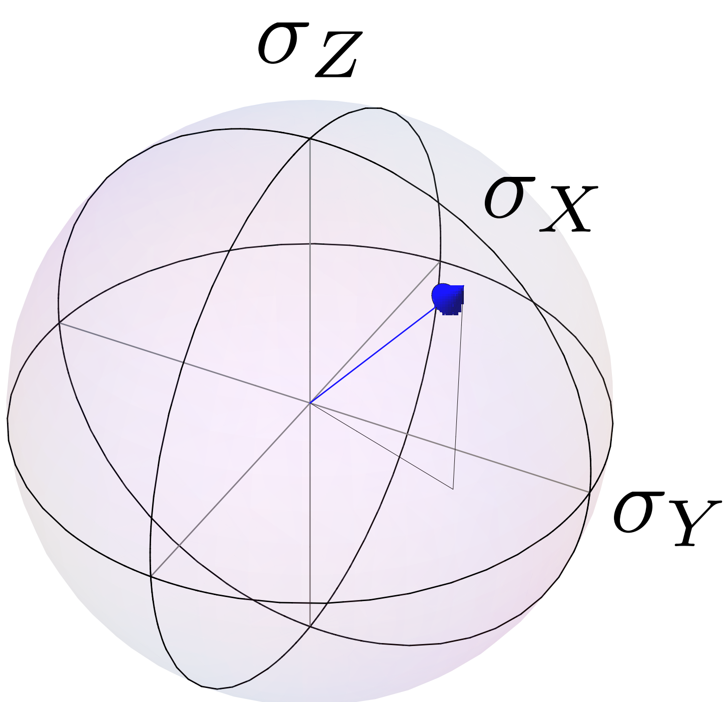
[Campagne-Ibarcq et al., ENS Paris, PRL 2014]

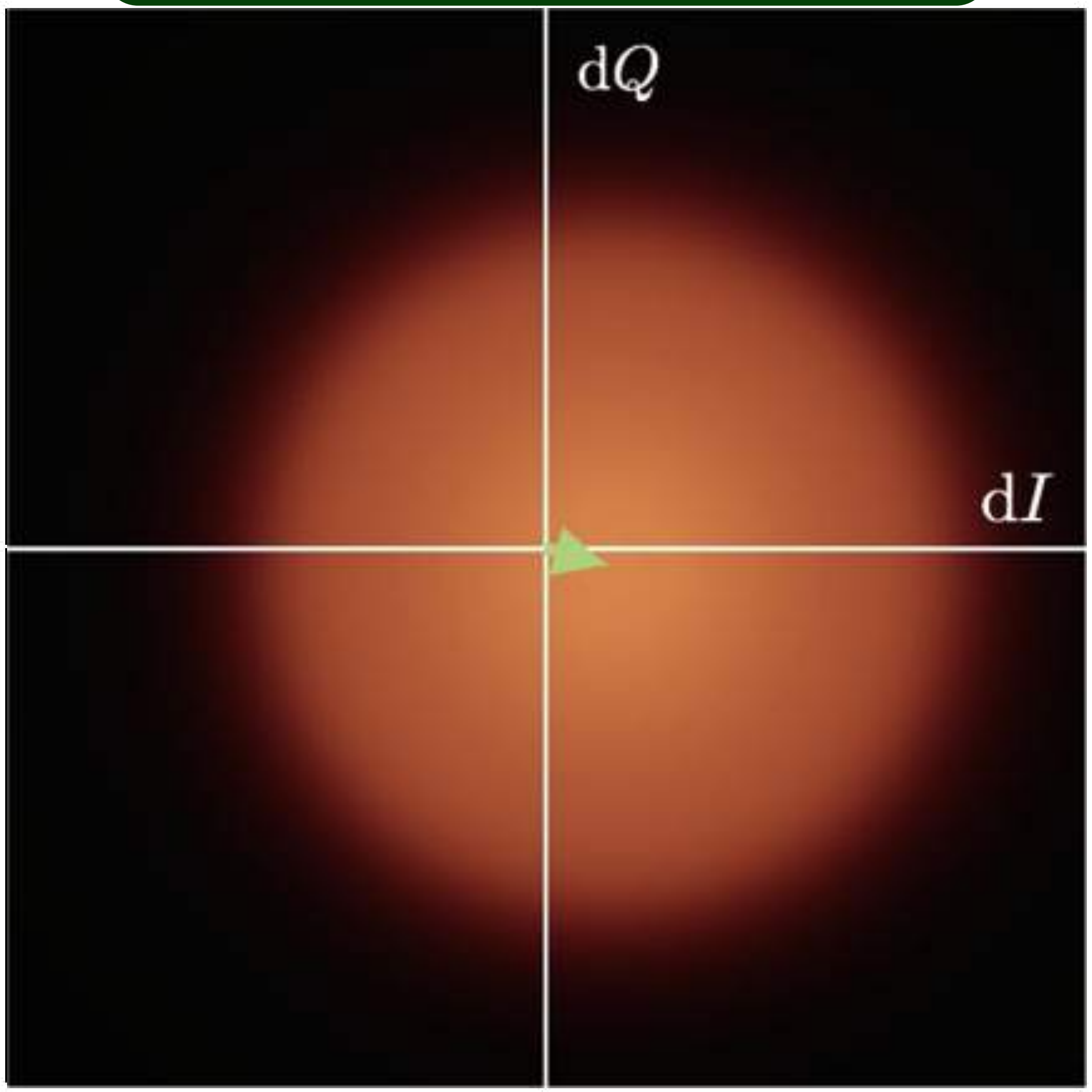


Signal to Noise Ratio

$$\mathrm{d}I = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_x\rangle\mathrm{d}t + \mathrm{d}W_I$$

$$\mathrm{d}Q = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_y\rangle\mathrm{d}t + \mathrm{d}W_Q$$





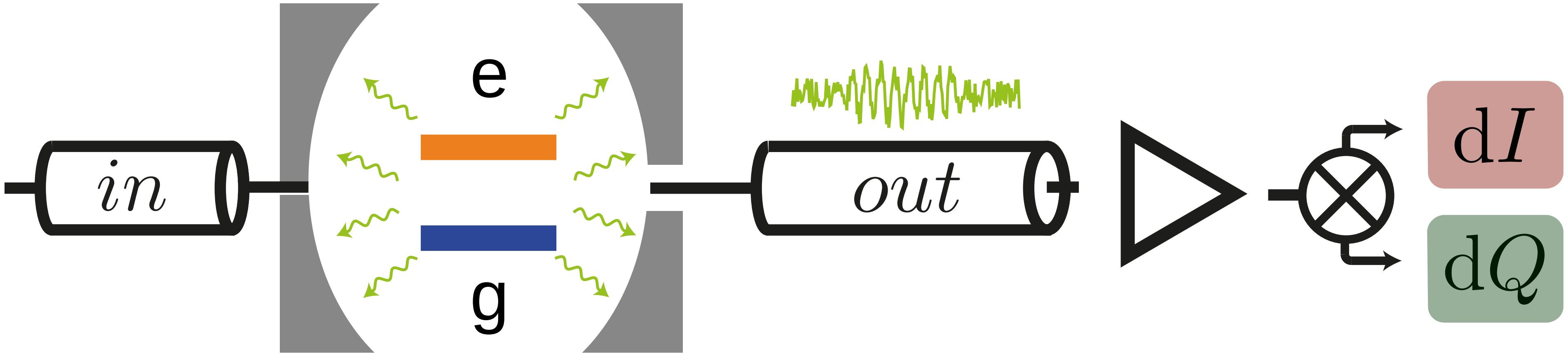
$$T_1 = 4\ \mu\mathrm{s} \quad \mathrm{d}t = 200\ \mathrm{ns}$$

Strong measurement if integrated on $T_{\mathrm{strong}} \simeq \frac{1}{\eta\gamma_1} > T_1$

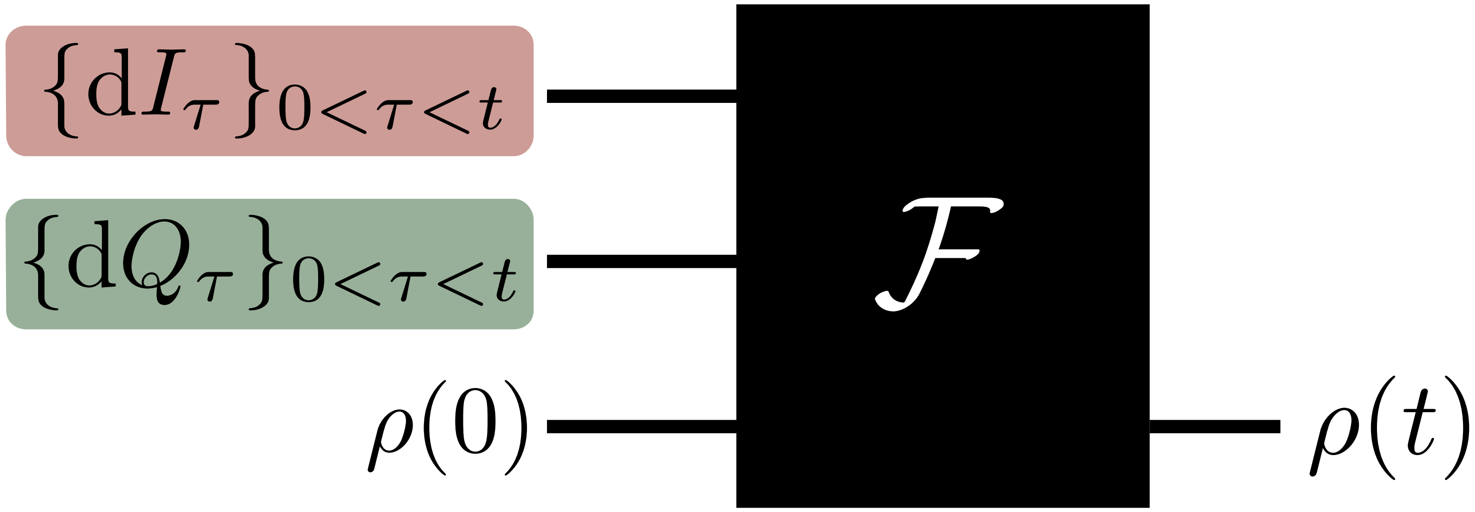
$\longrightarrow$ weak continuous and destructive

$$\eta = 24\%$$

Fluorescence of a single quantum jump

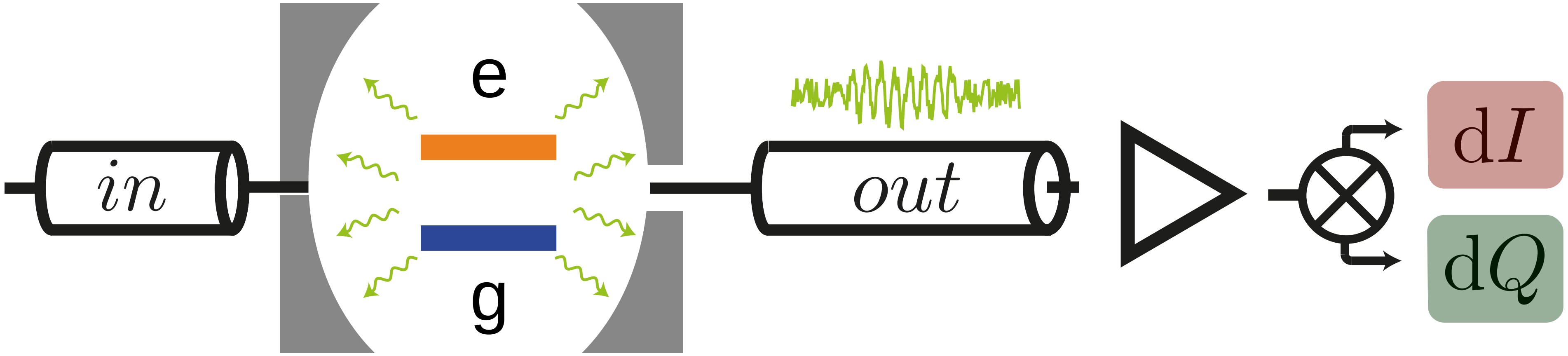


quantum filter $\mathcal{F}$



Stochastic Master Equation

if $\rho(t)$ is known



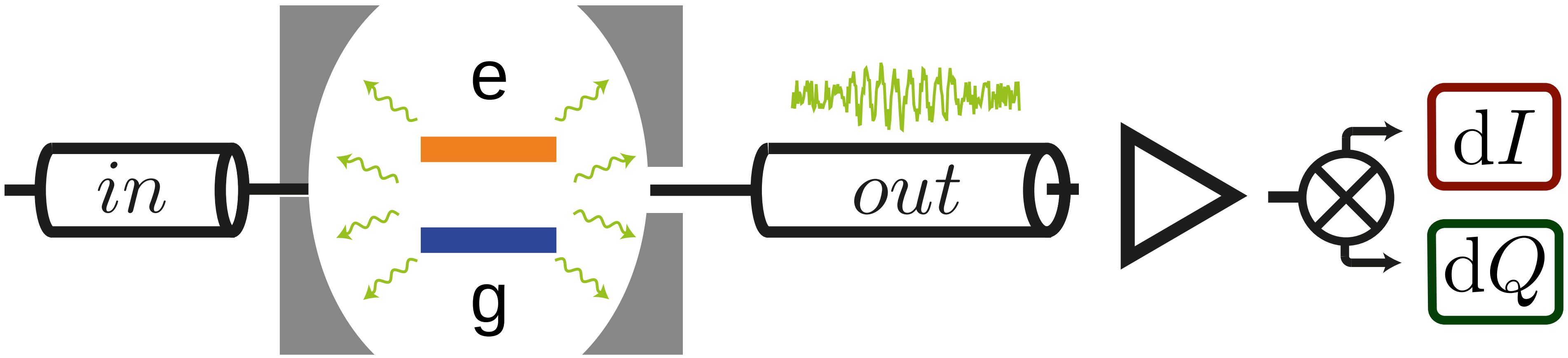
$$\mathrm{d}\rho = \mathrm{d}t\ \mathcal{D}[\sqrt{\gamma_1}\sigma_-]\rho$$

unconditional evolution (Lindblad)

$$\mathcal{D}[L]\rho = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L)$$

Stochastic Master Equation

if $\rho(t)$ is known



$$\boxed{\mathrm{d}I} = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_x\rangle\mathrm{d}t + \mathrm{d}W_I \qquad \boxed{\mathrm{d}Q} = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_y\rangle\mathrm{d}t + \mathrm{d}W_Q$$

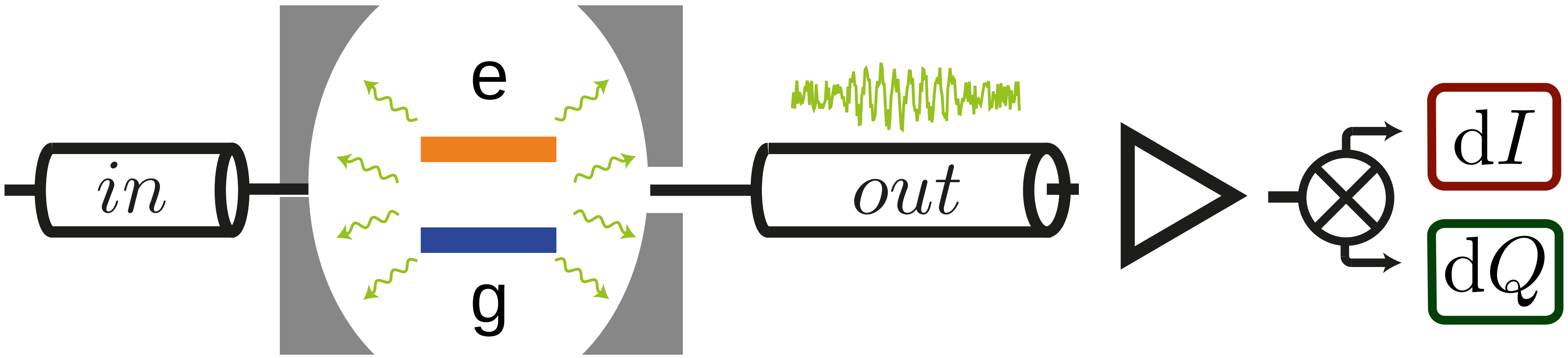
$$\mathrm{d}\rho = \mathrm{d}t\ \mathcal{D}[\sqrt{\gamma_1}\sigma_-]\rho$$

unconditional evolution (Lindblad)

$$\mathcal{D}[L]\rho = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L)$$

Stochastic Master Equation

if $\rho(t)$ is known



$$\mathrm{d}I = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_x\rangle \mathrm{d}t + \mathrm{d}W_I \qquad \mathrm{d}Q = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_y\rangle \mathrm{d}t + \mathrm{d}W_Q$$

$$\mathrm{d}\rho = \mathrm{d}t\ \mathcal{D}[\sqrt{\gamma_1}\sigma_-]\rho$$

unconditional evolution (Lindblad)

$$+\mathrm{d}W_I\ \mathcal{M}[\sqrt{\frac{\eta}{2}\gamma_1}\sigma_-]\rho$$

$$+\mathrm{d}W_Q\ \mathcal{M}[\sqrt{\frac{\eta}{2}\gamma_1}i\sigma_-]\rho$$

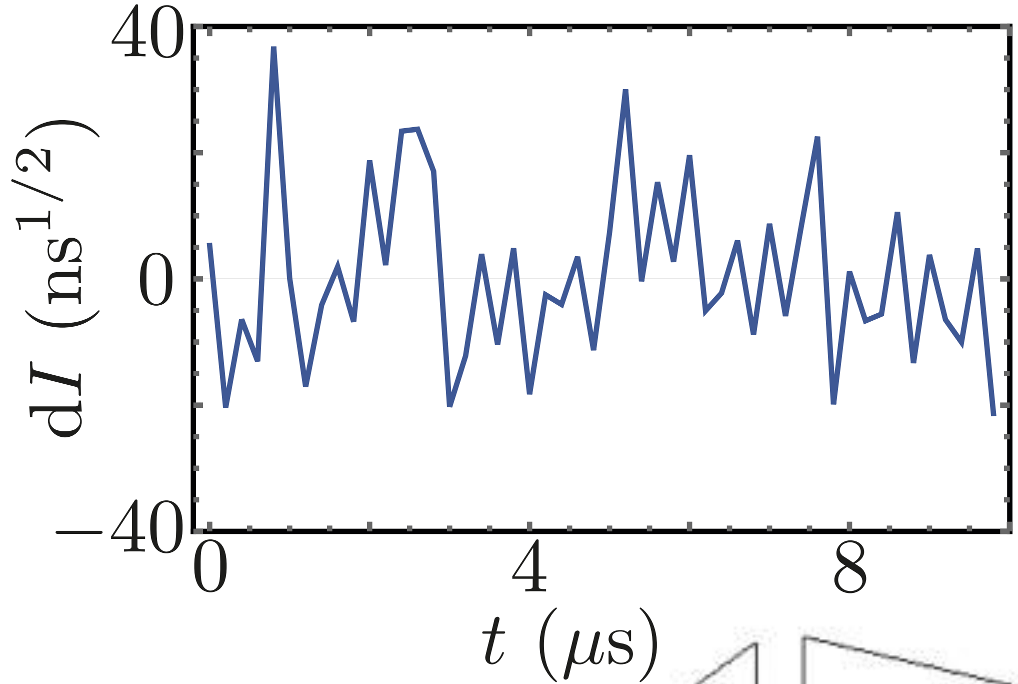
stochastic kicks

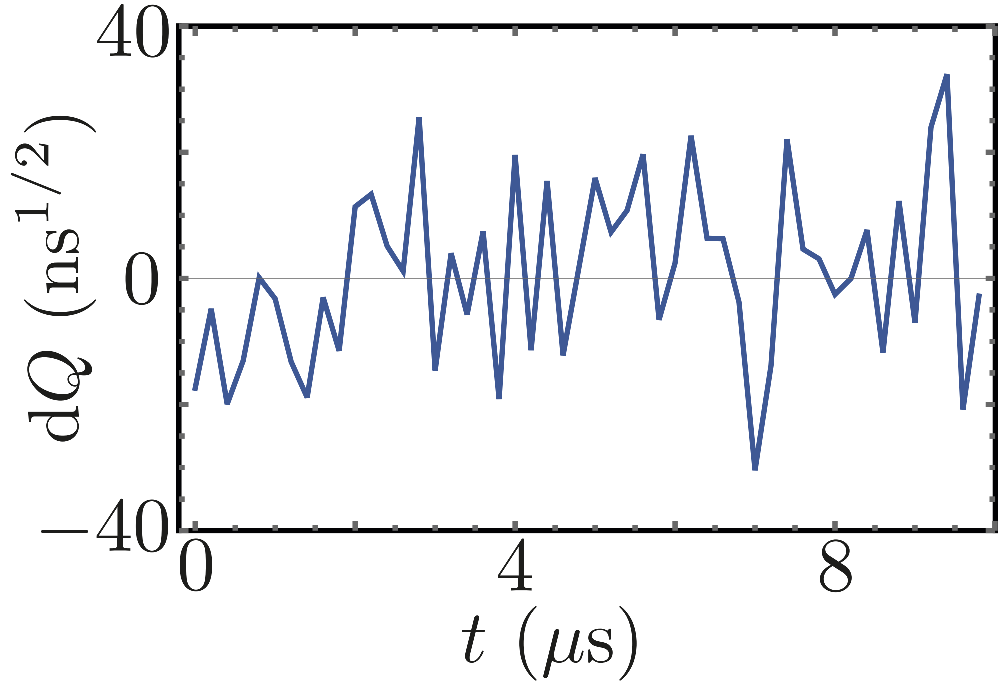
$$\eta = 24\%$$

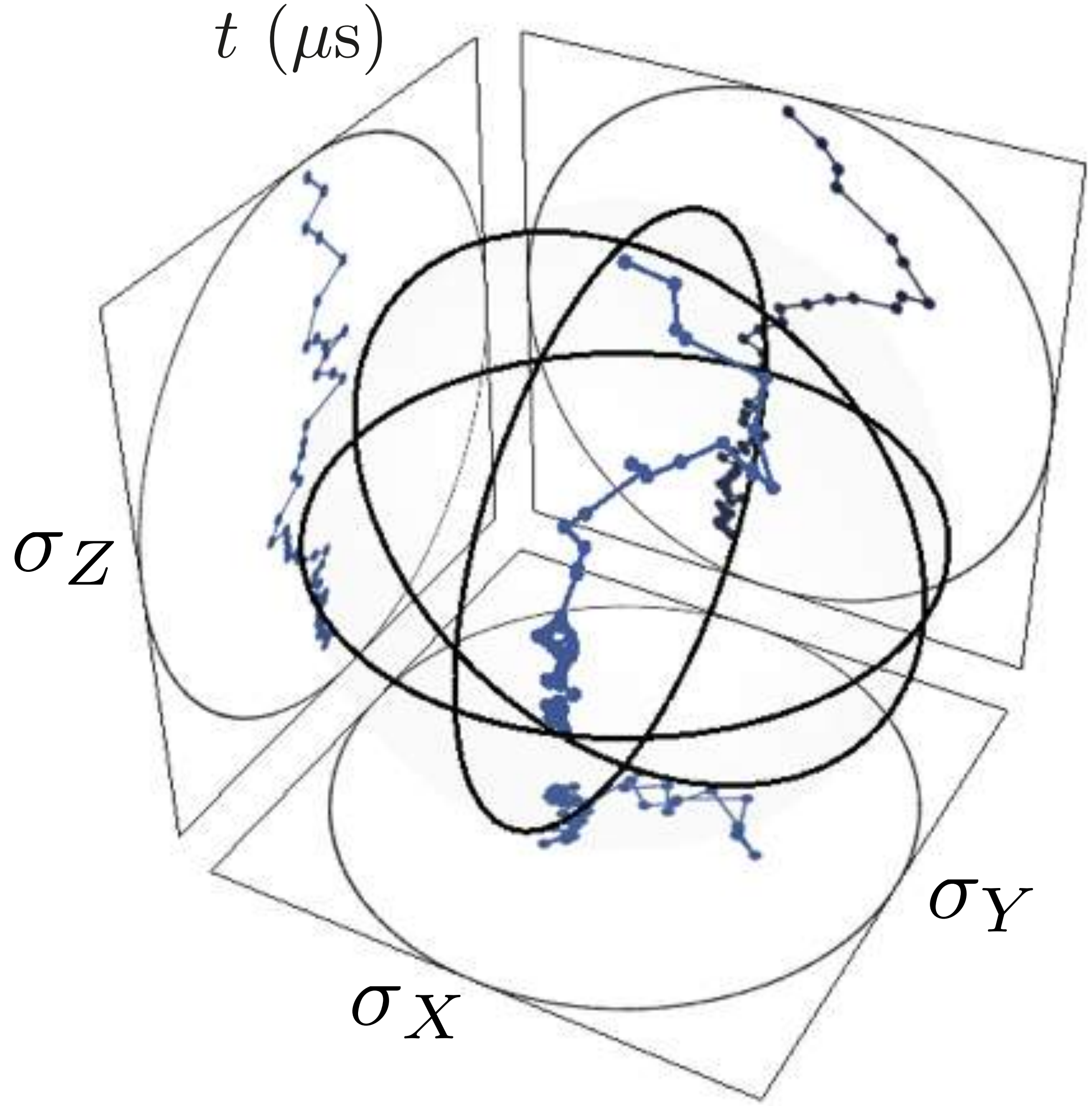
$$\mathcal{D}[L]\rho = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L) \qquad \mathcal{M}[L]\rho = (L - \langle L\rangle)\rho + \rho(L^\dagger - \langle L^\dagger\rangle)$$

Quantum trajectory

corrected for JPC low-pass filter →





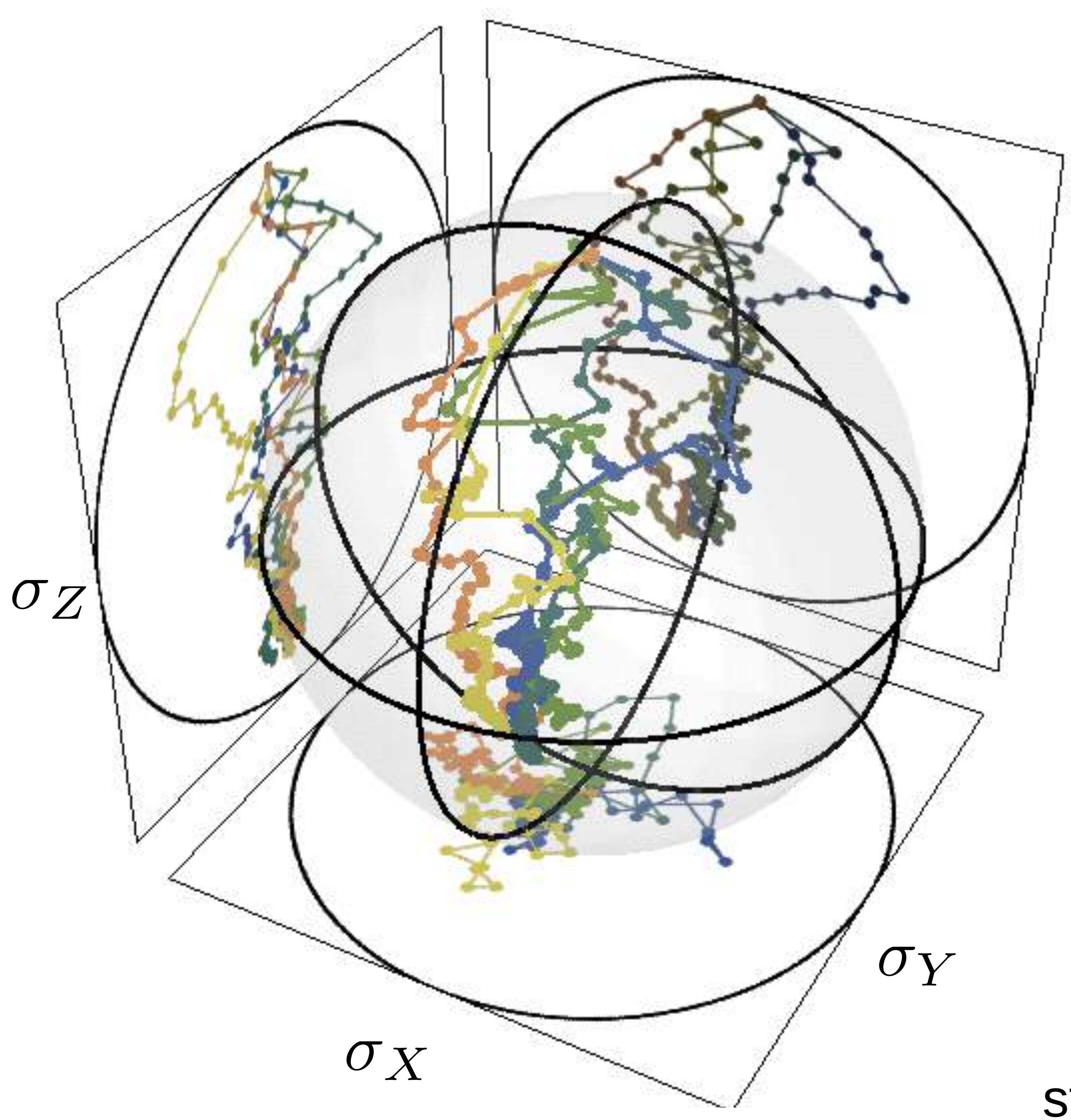


start from $|e\rangle$ at $t = 0$

5 Quantum trajectories

$T_{\mathrm{traj}} = 10\ \mu\mathrm{s}$

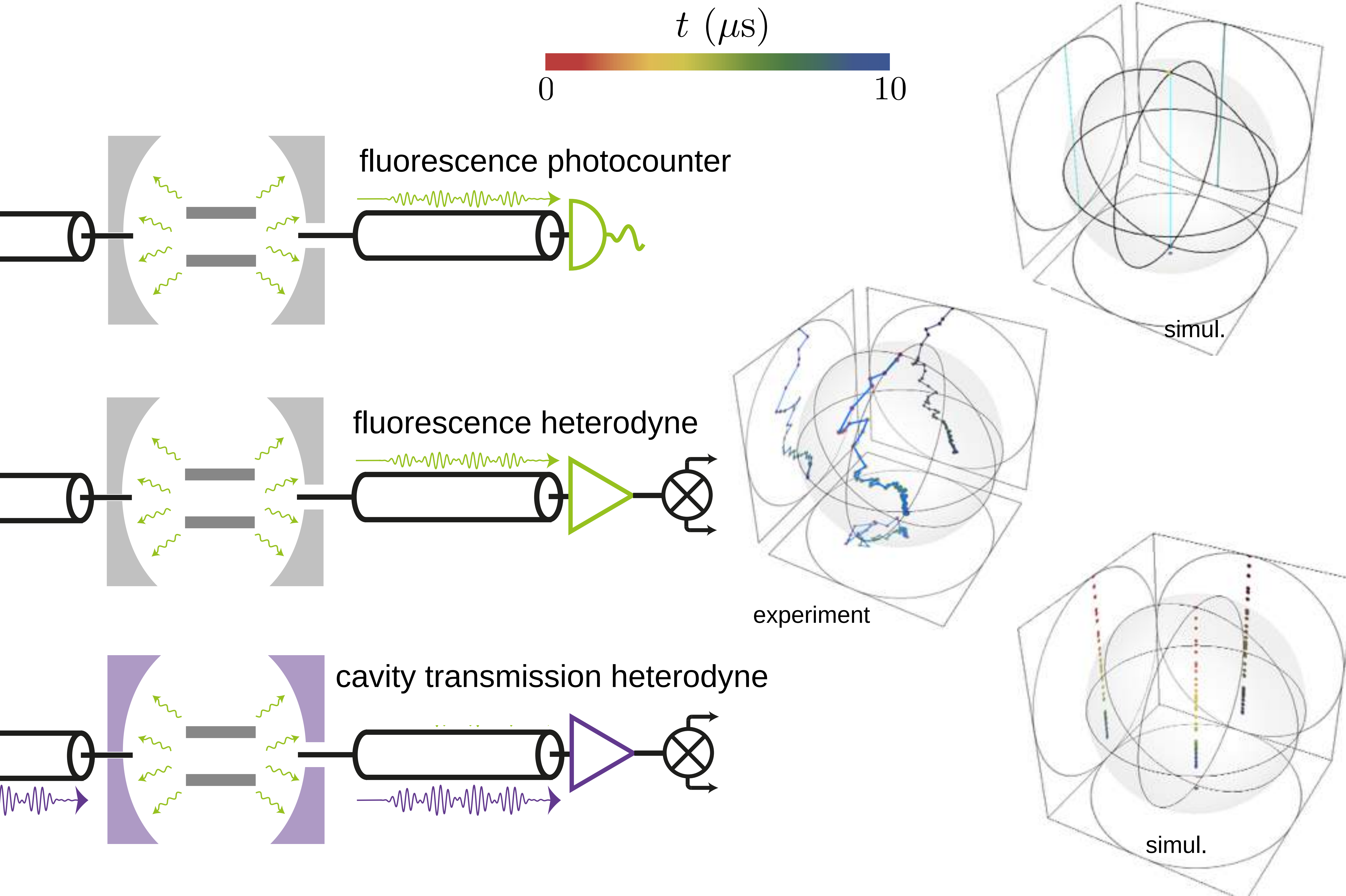
$T_1 = 4\ \mu\mathrm{s}$



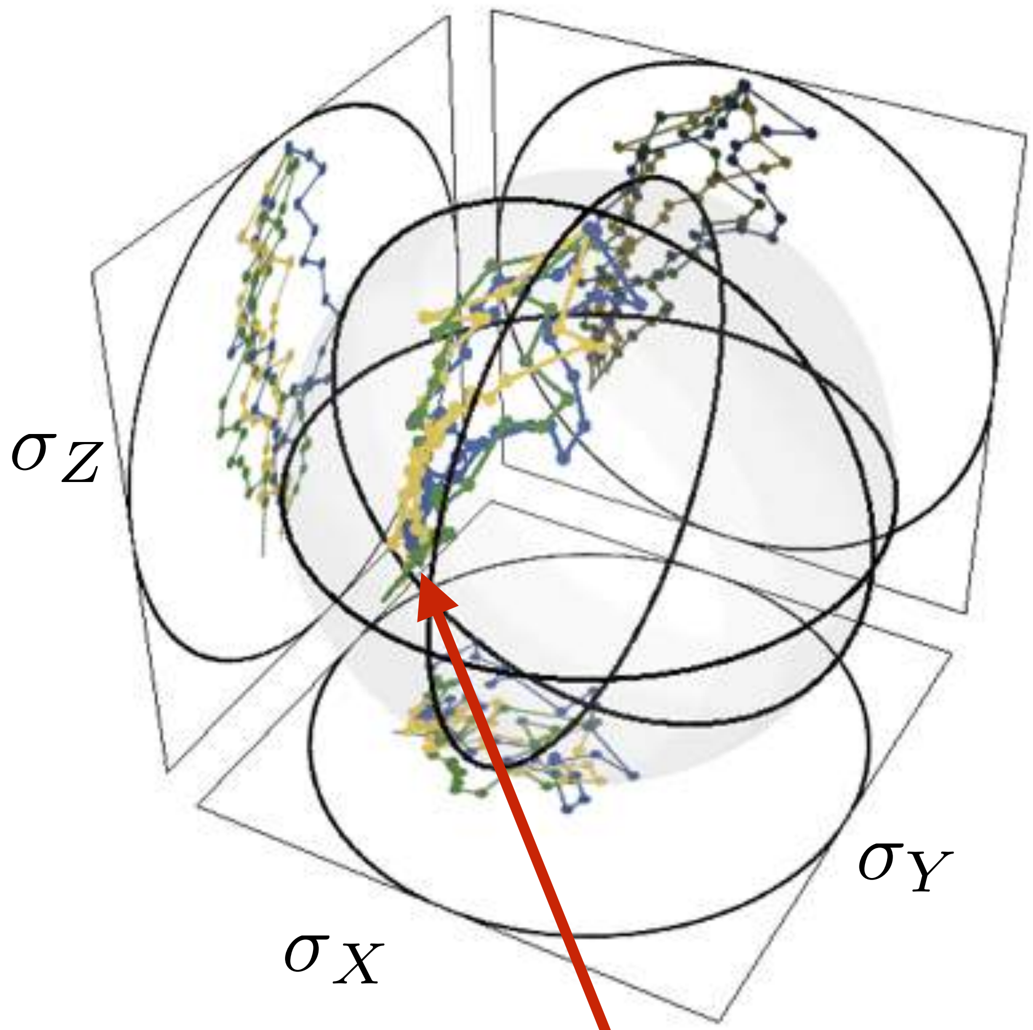
start from $|e\rangle$

at $t = 0$

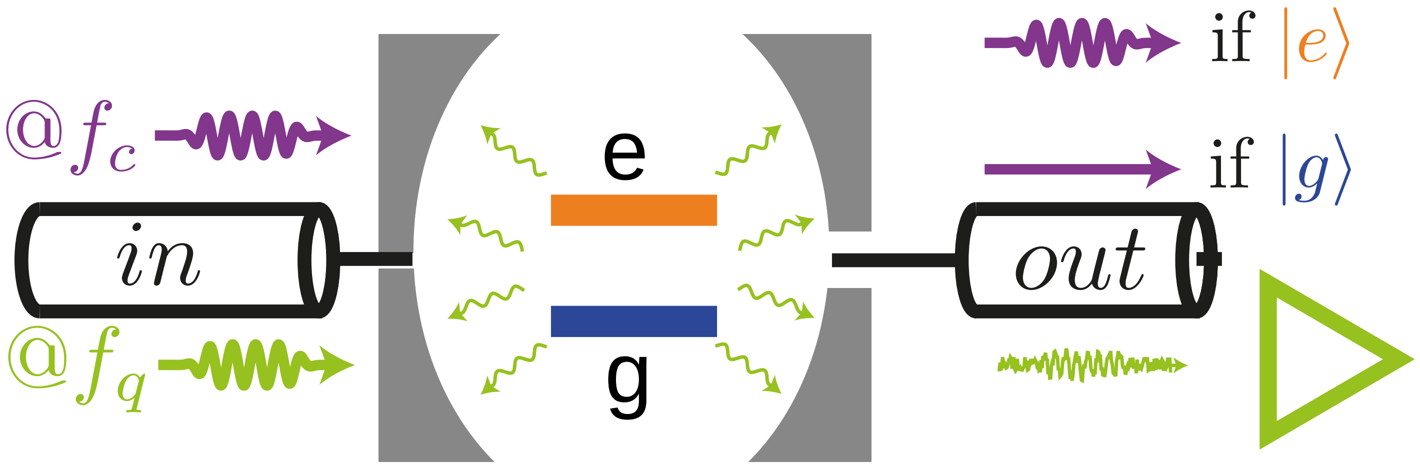
Trajectory as a function of detector

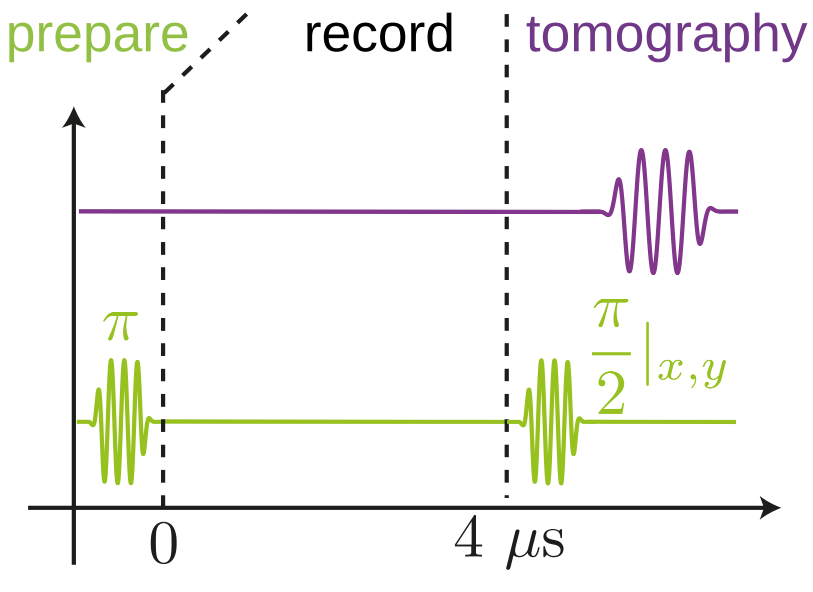


Trajectories vs tomography

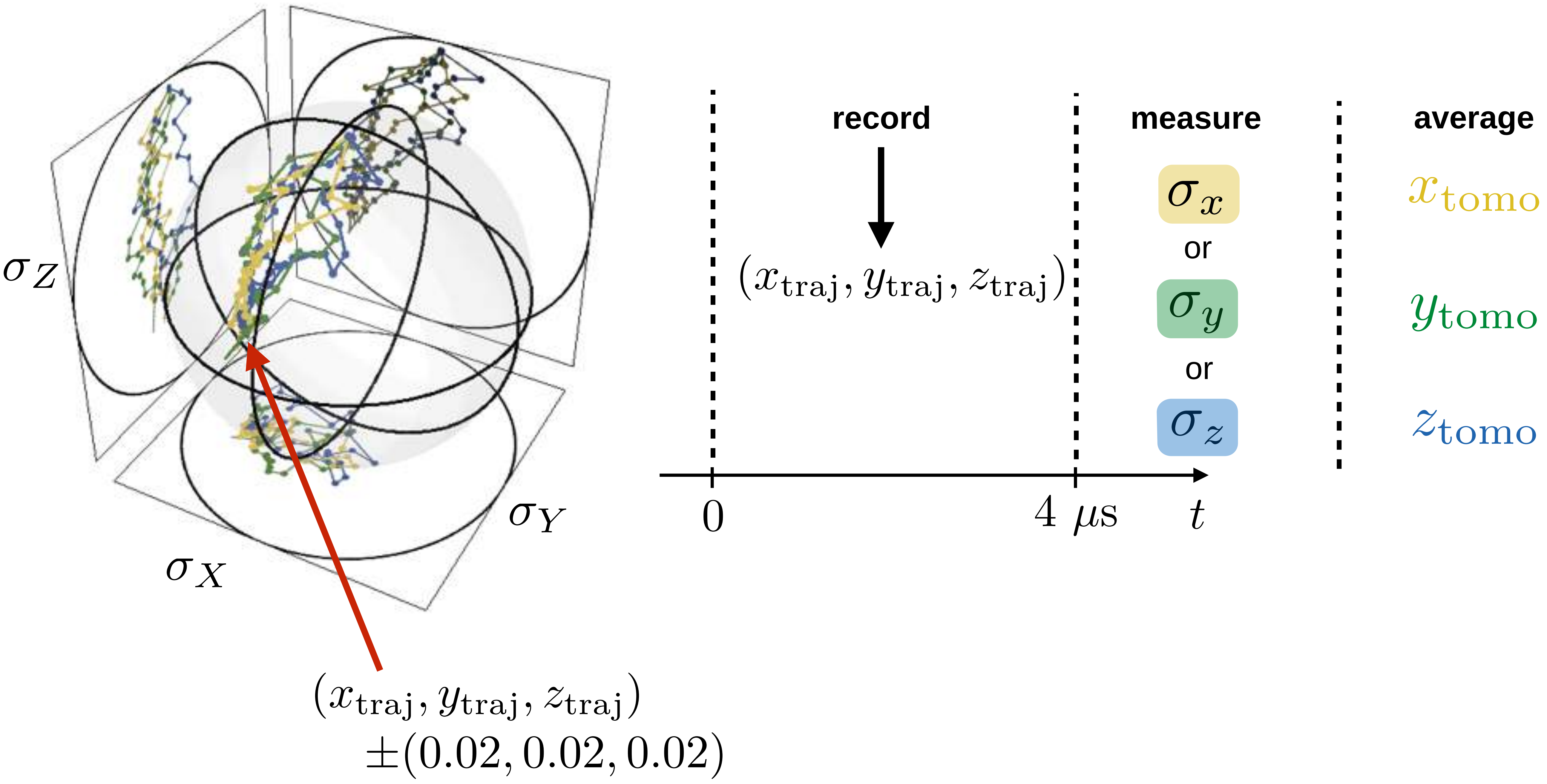


$(x_{\rm traj}, y_{\rm traj}, z_{\rm traj})$
$\pm(0.02, 0.02, 0.02)$



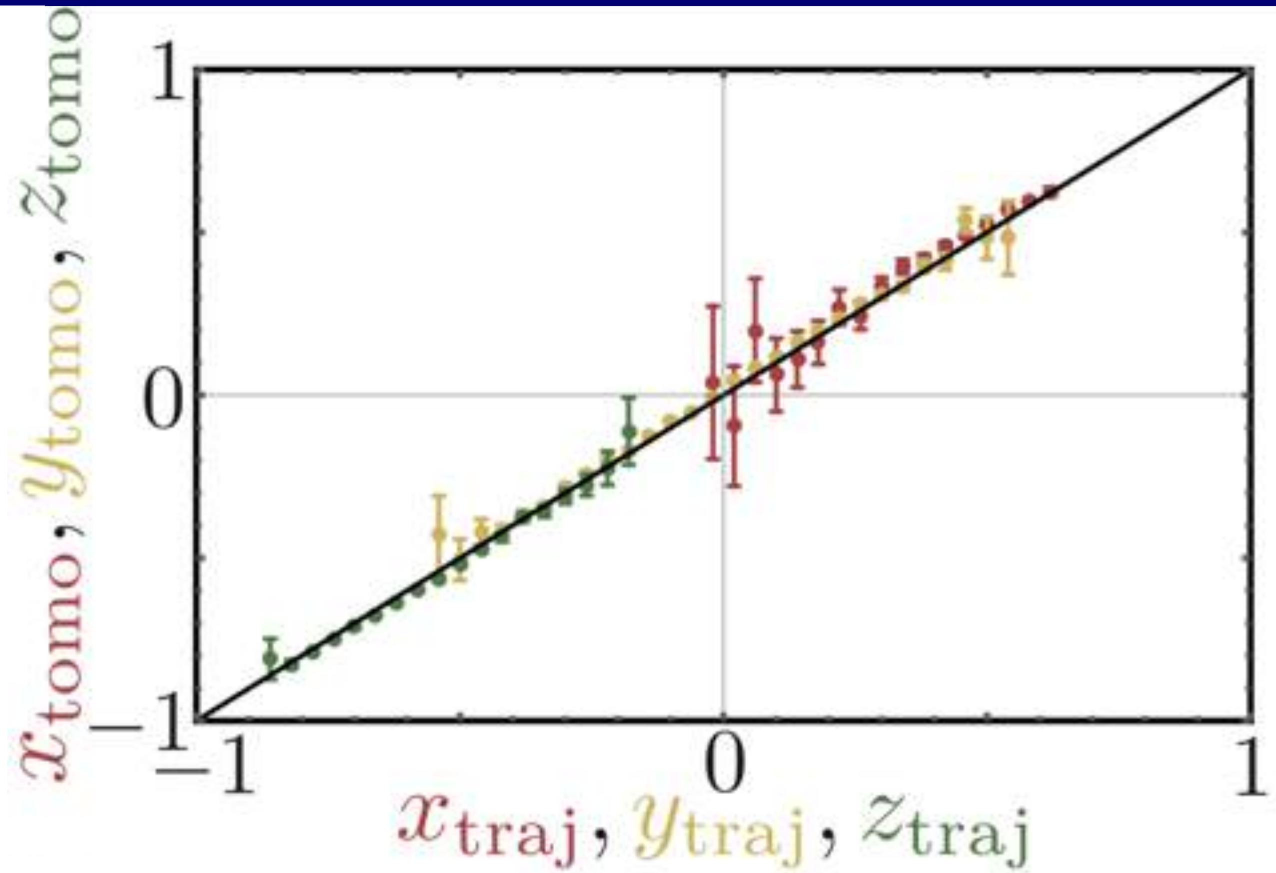


Trajectories vs tomography



Trajectories vs tomography

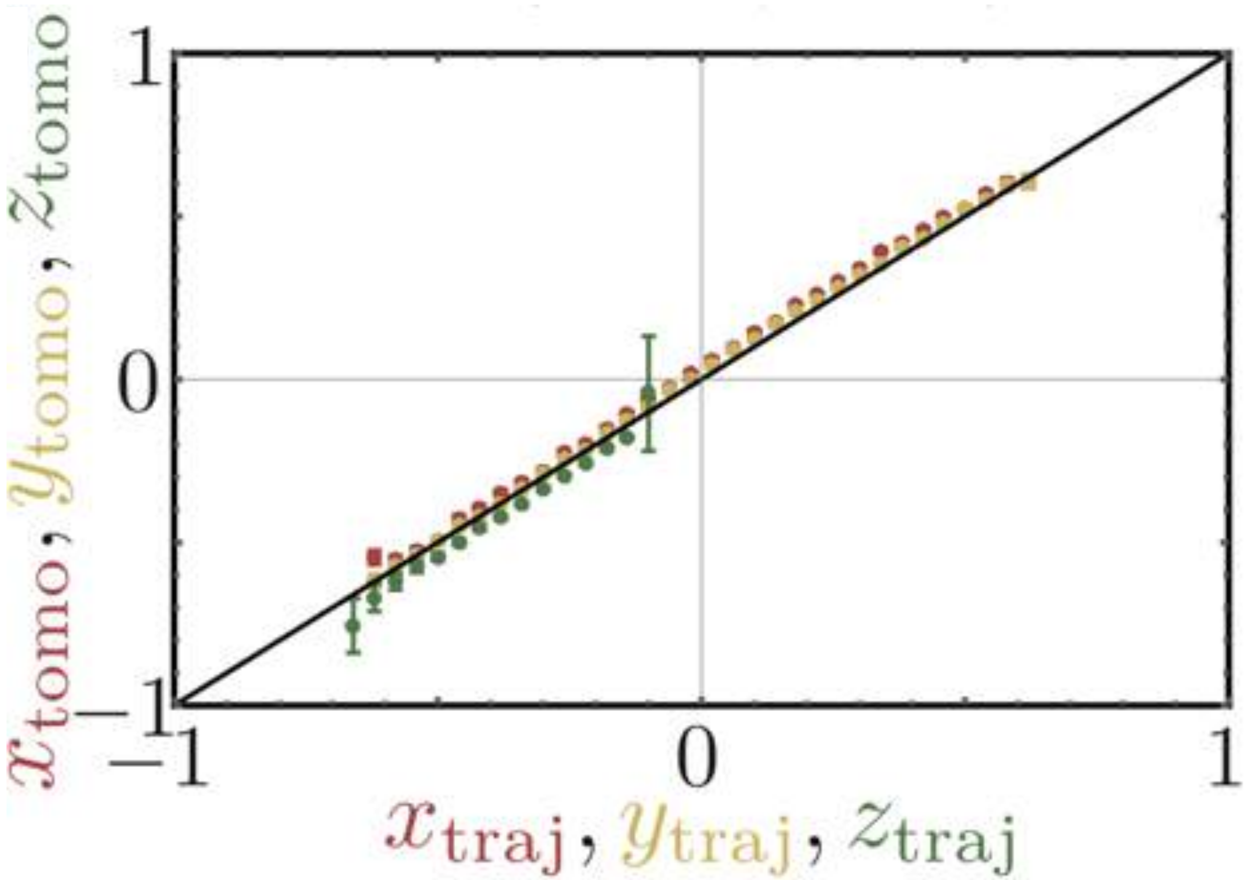
from $\frac{|g\rangle + |e\rangle}{\sqrt{2}}$



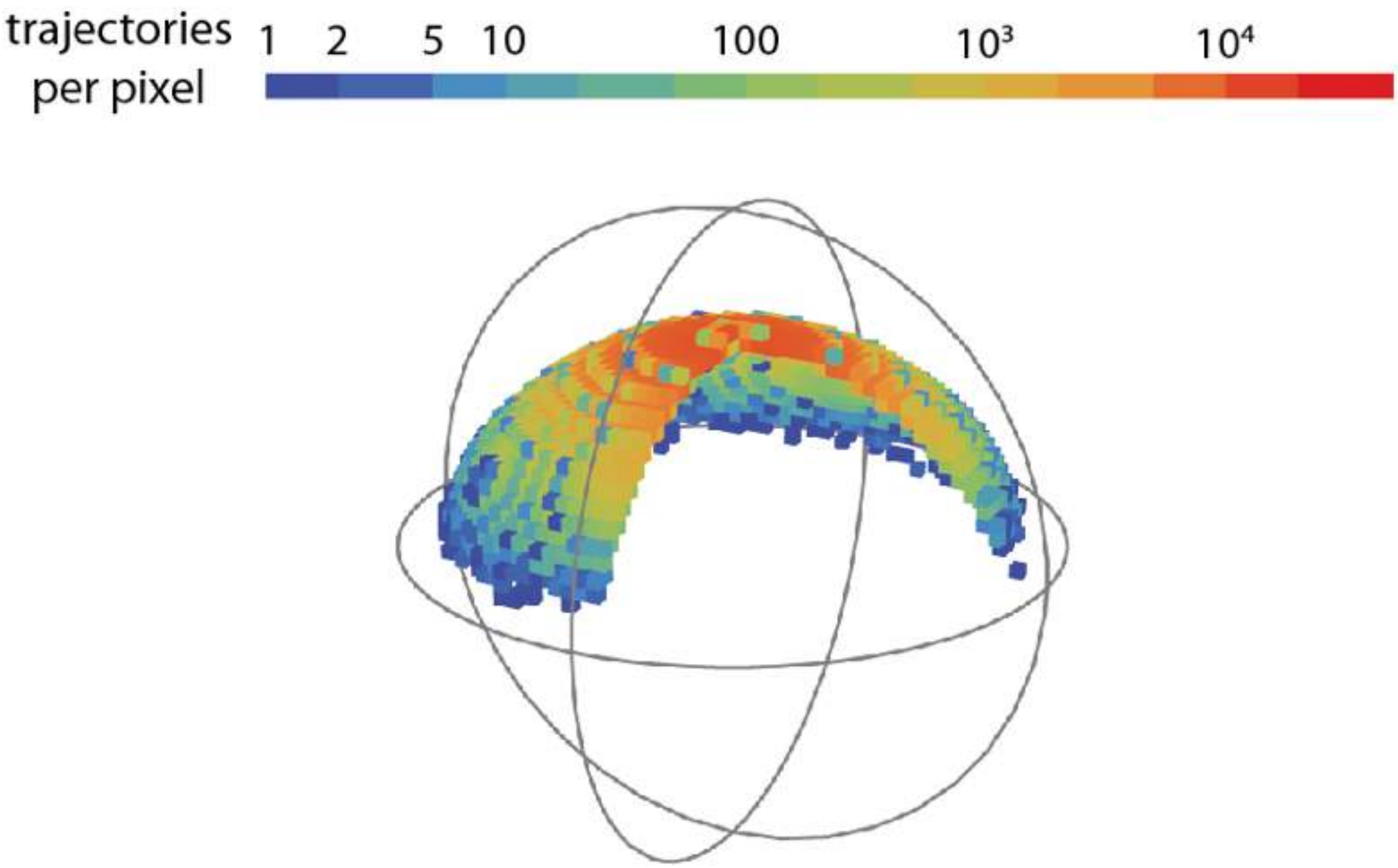
after $4\ \mu\text{s}$

$\eta = 24\%$

from $|e\rangle$

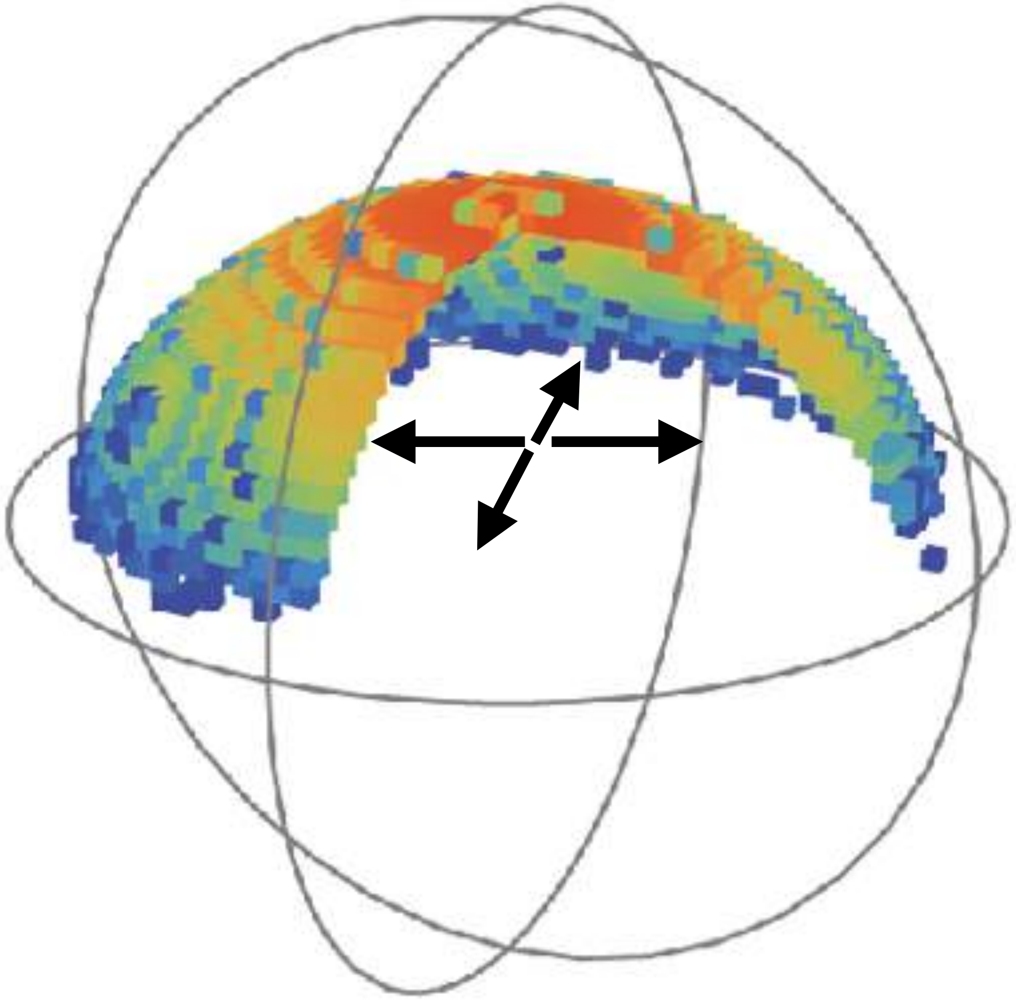


Trajectory distribution



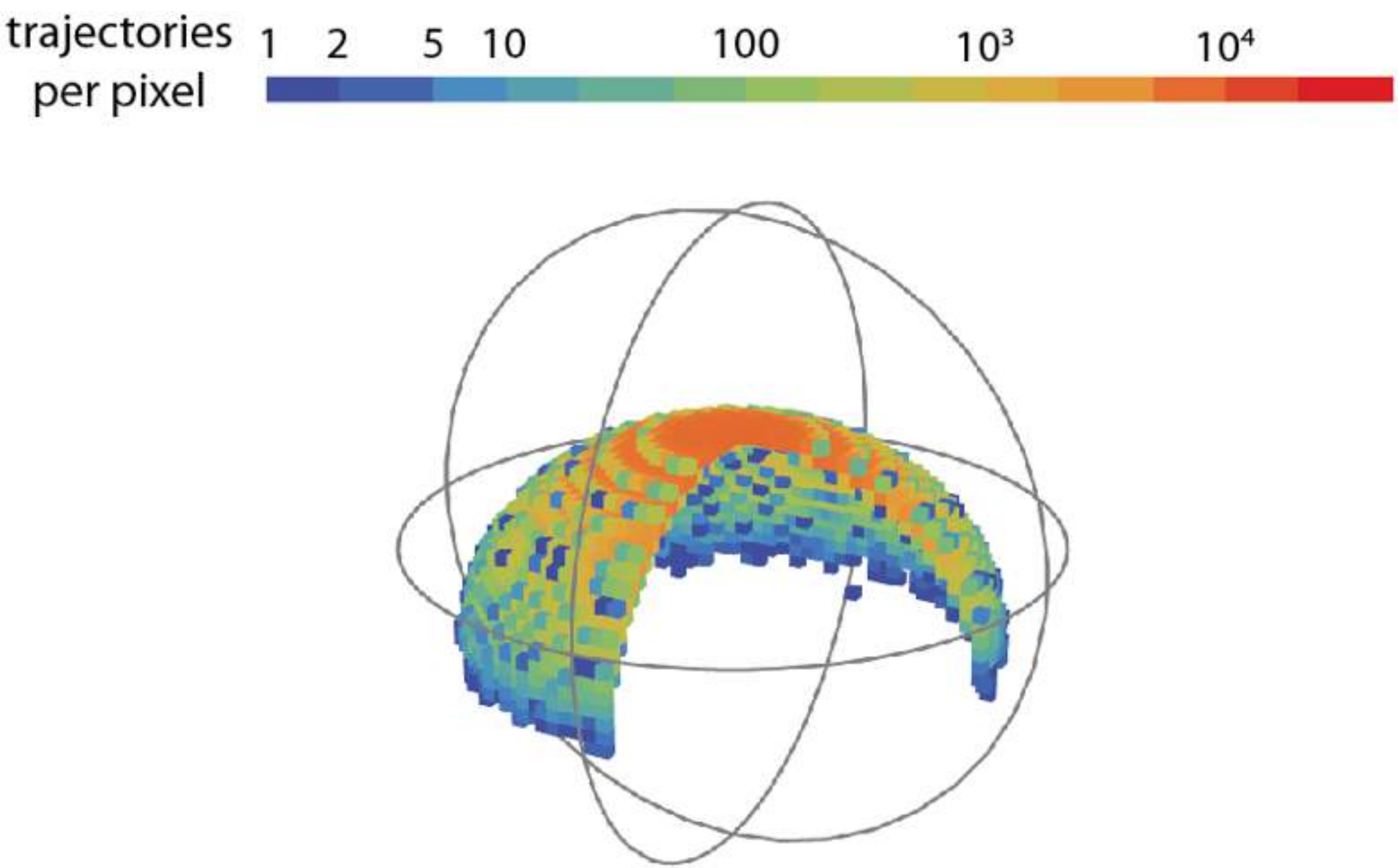
$$t = 1\ \mu\text{s}$$
$$T_1 = 4\ \mu\text{s}$$

Trajectory distribution



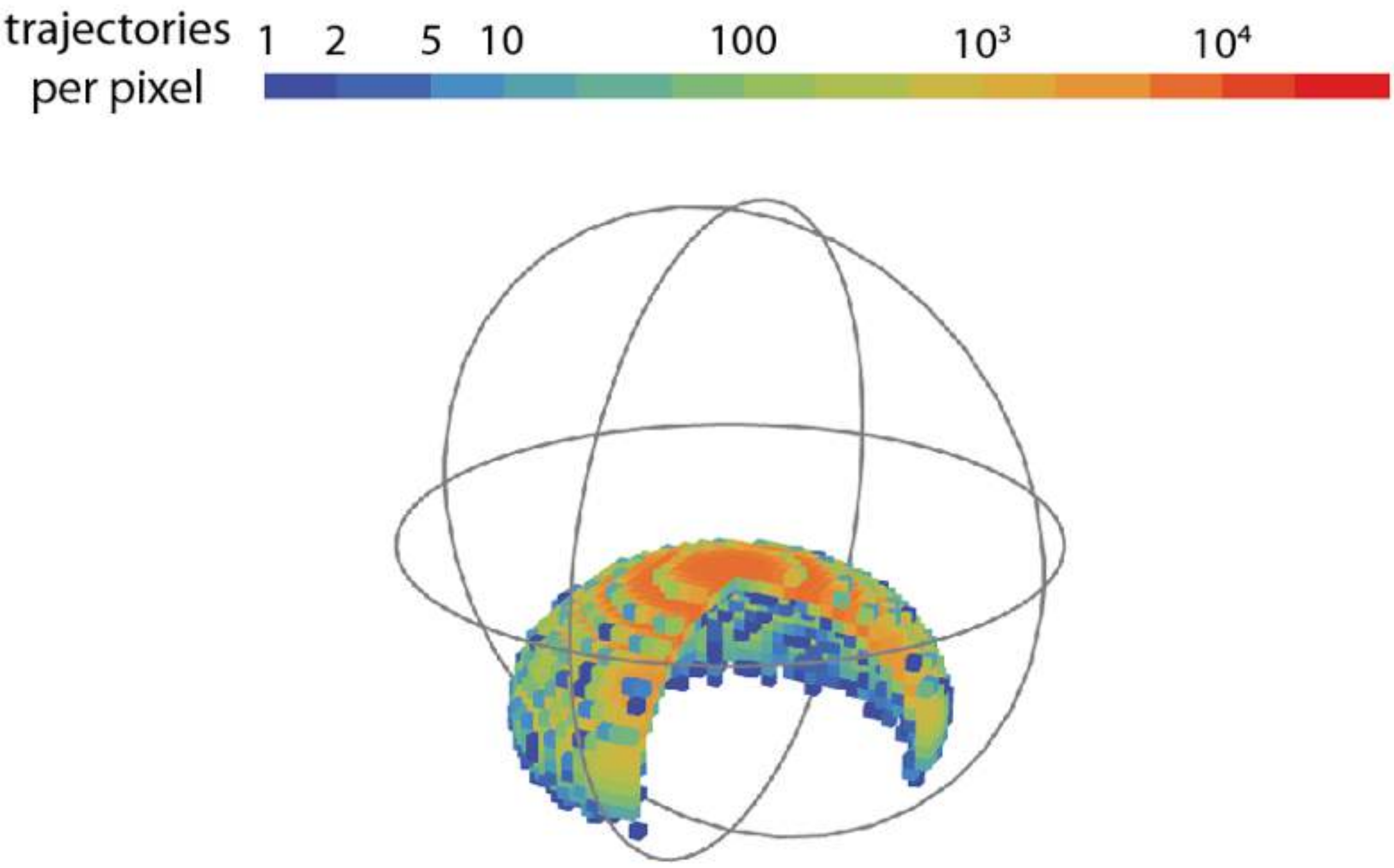
$$t = 1\ \mu s$$
$$T_1 = 4\ \mu s$$

Trajectory distribution



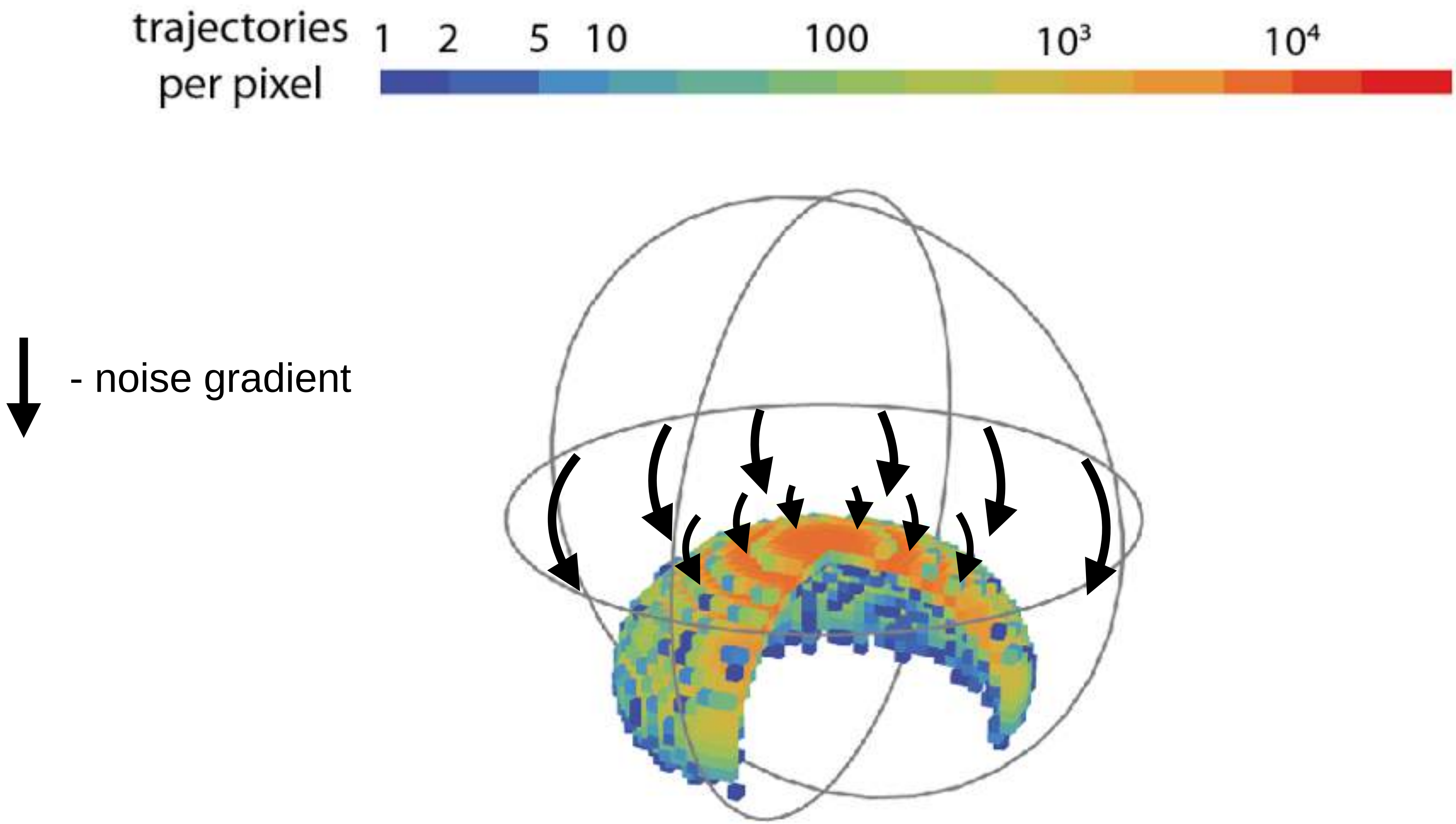
$$t = 2\ \mu\text{s}$$
$$T_1 = 4\ \mu\text{s}$$

Trajectory distribution



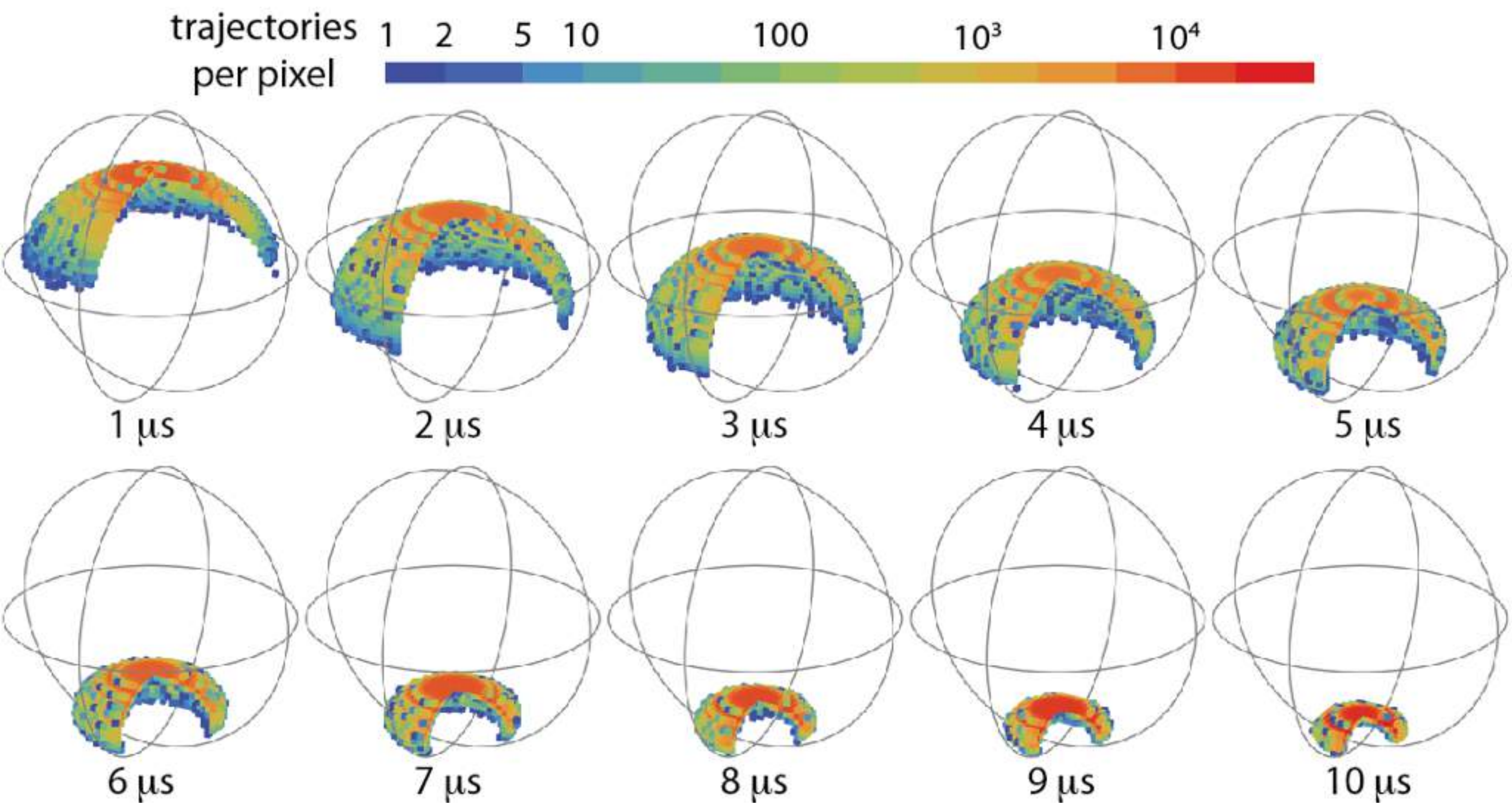
$$t = 4\ \mu s$$
$$T_1 = 4\ \mu s$$

Trajectory distribution

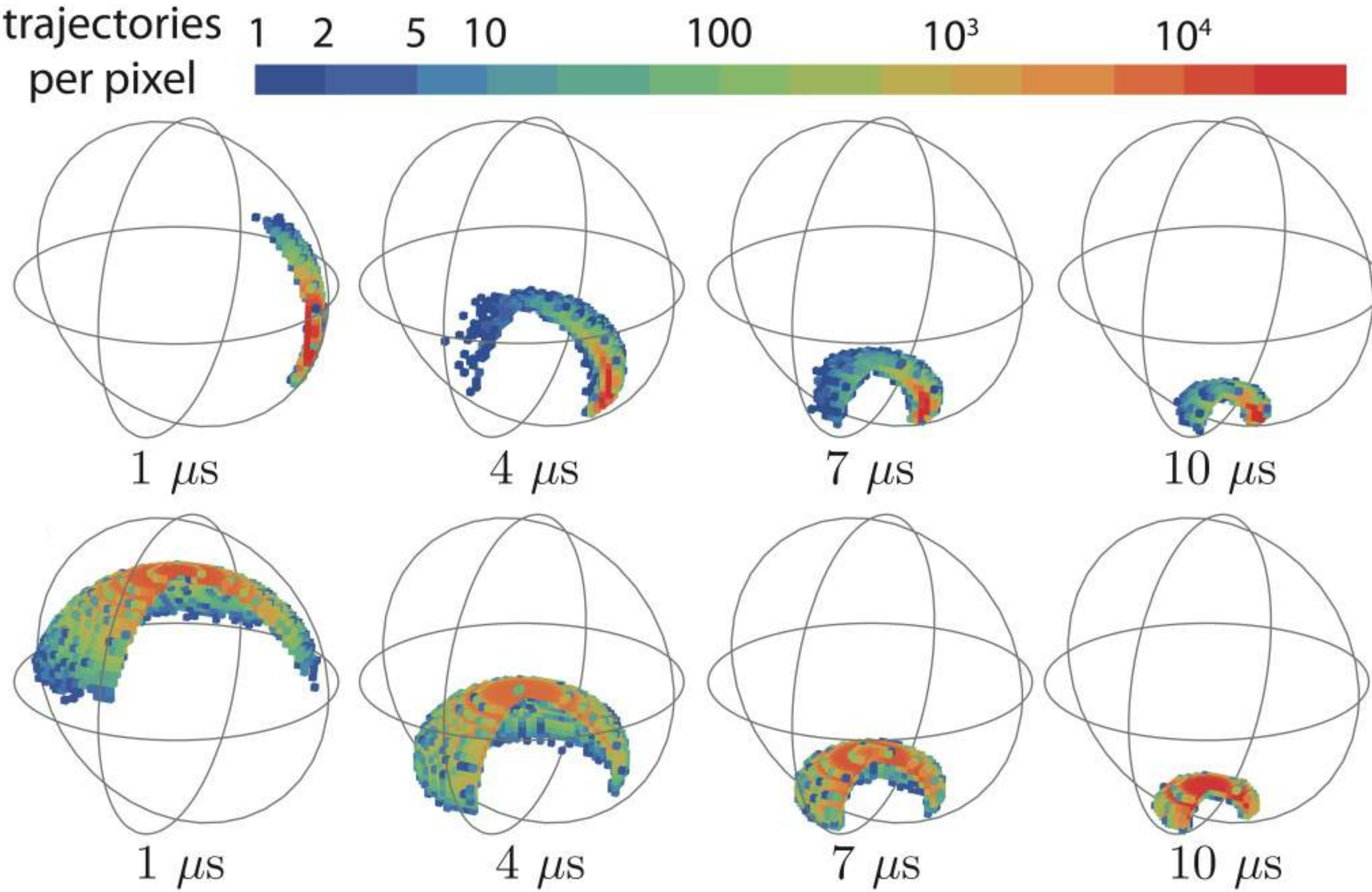


$$t = 4\ \mu s$$
$$T_1 = 4\ \mu s$$

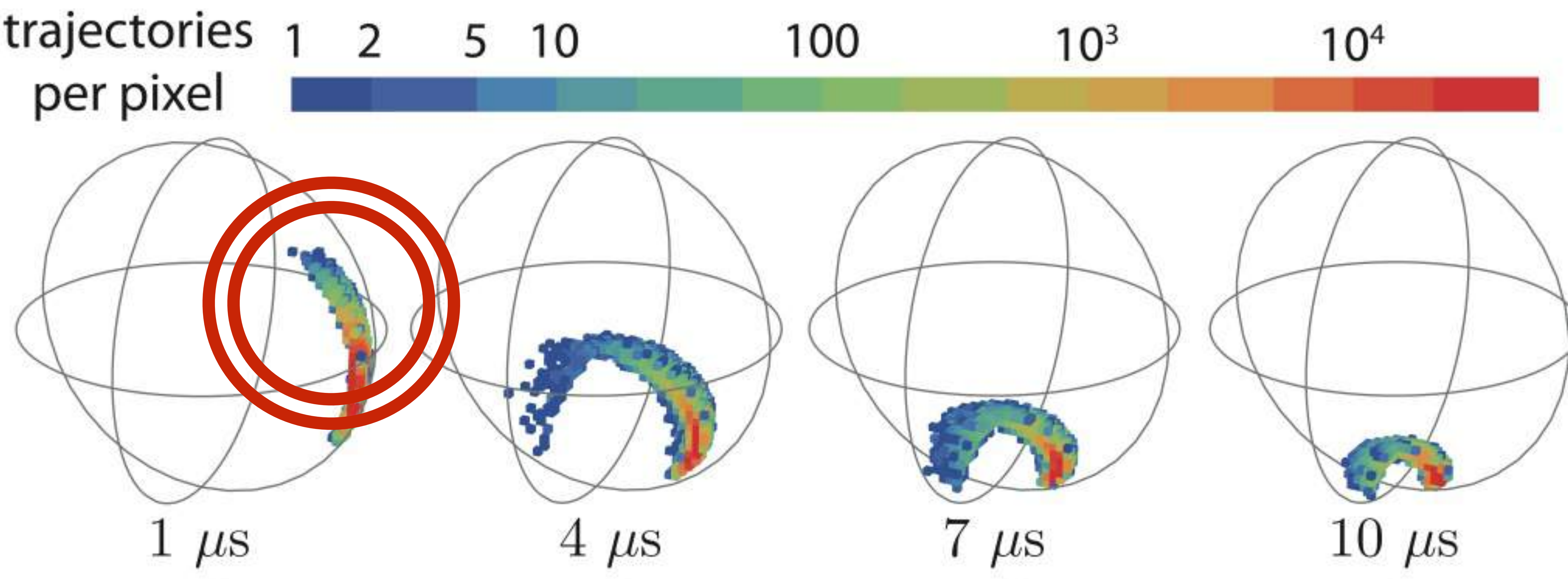
Trajectory distribution



Trajectory distribution starting from equator

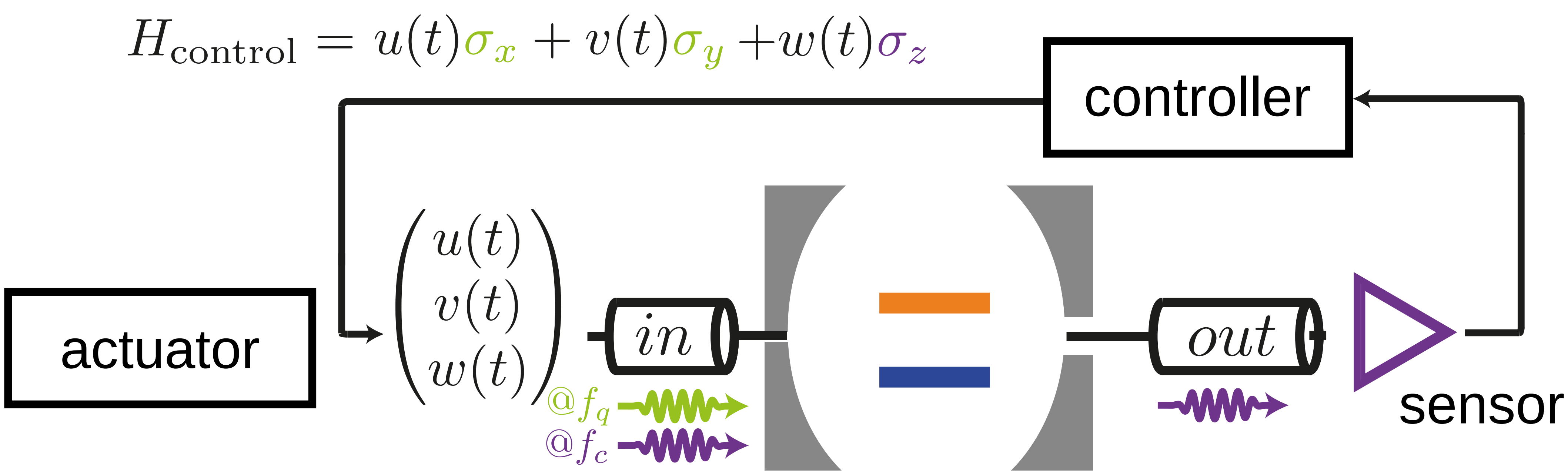


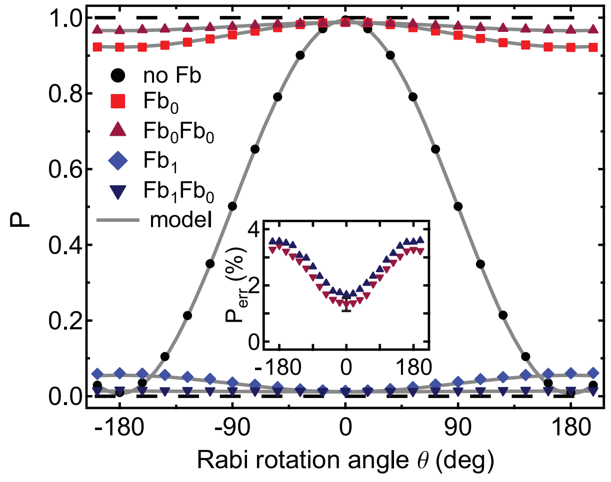
Trajectory distribution starting from equator



Measuring the field emitted during relaxation
can **increase** the proba to be in $|e\rangle$

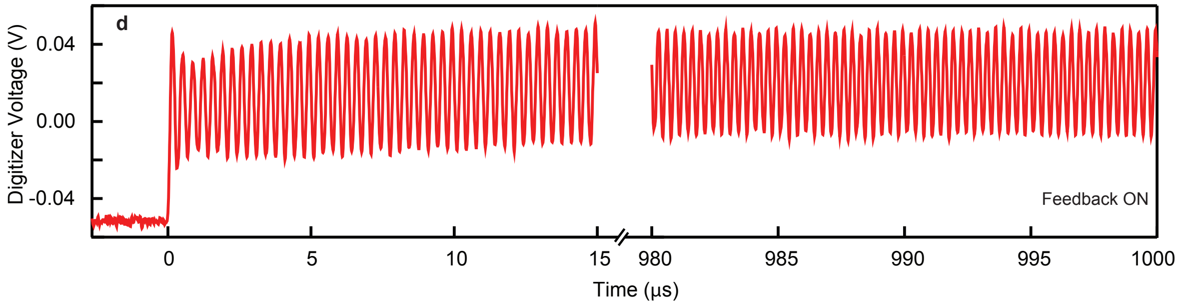
Measurement based feedback



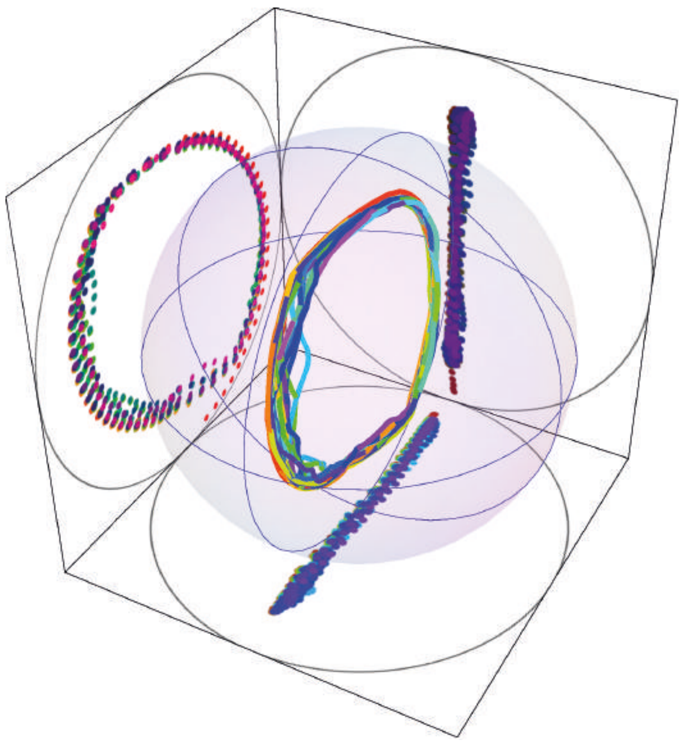


[Ristè et al., Delft, PRL (2012)]

σ_z measurement

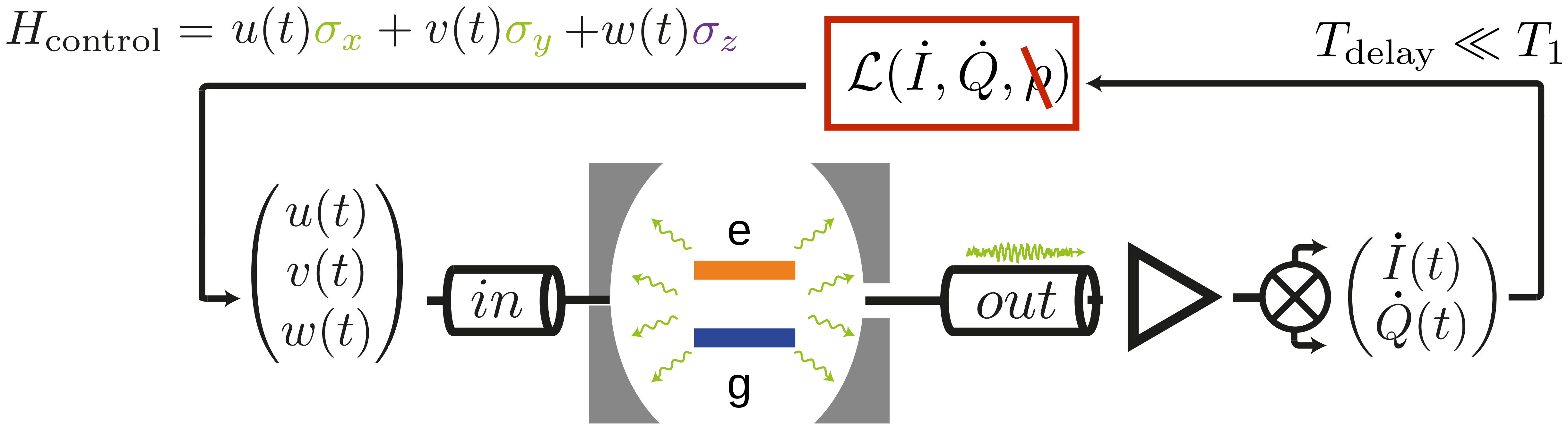


[Vijay et al., Berkeley, Nature (2012)]



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

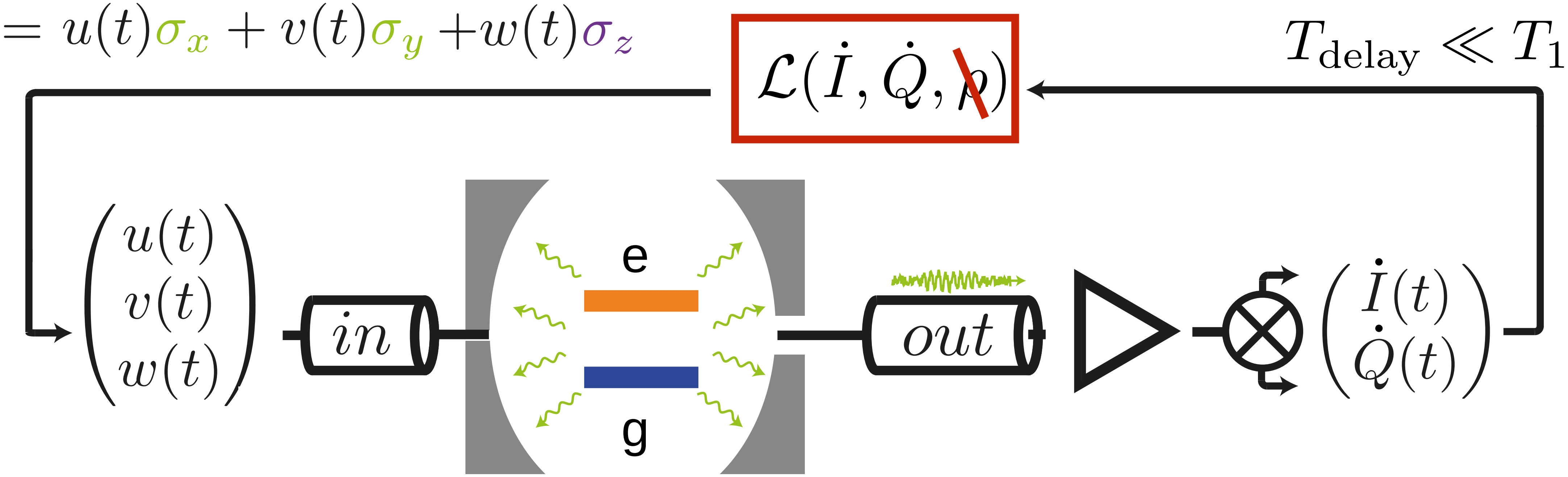
Markovian feedback



[A. Chia and H. M. Wiseman, PRA (2011)]

Markovian feedback

$$H_{\text{control}} = u(t)\sigma_x + v(t)\sigma_y + w(t)\sigma_z$$



if $\eta = 1$

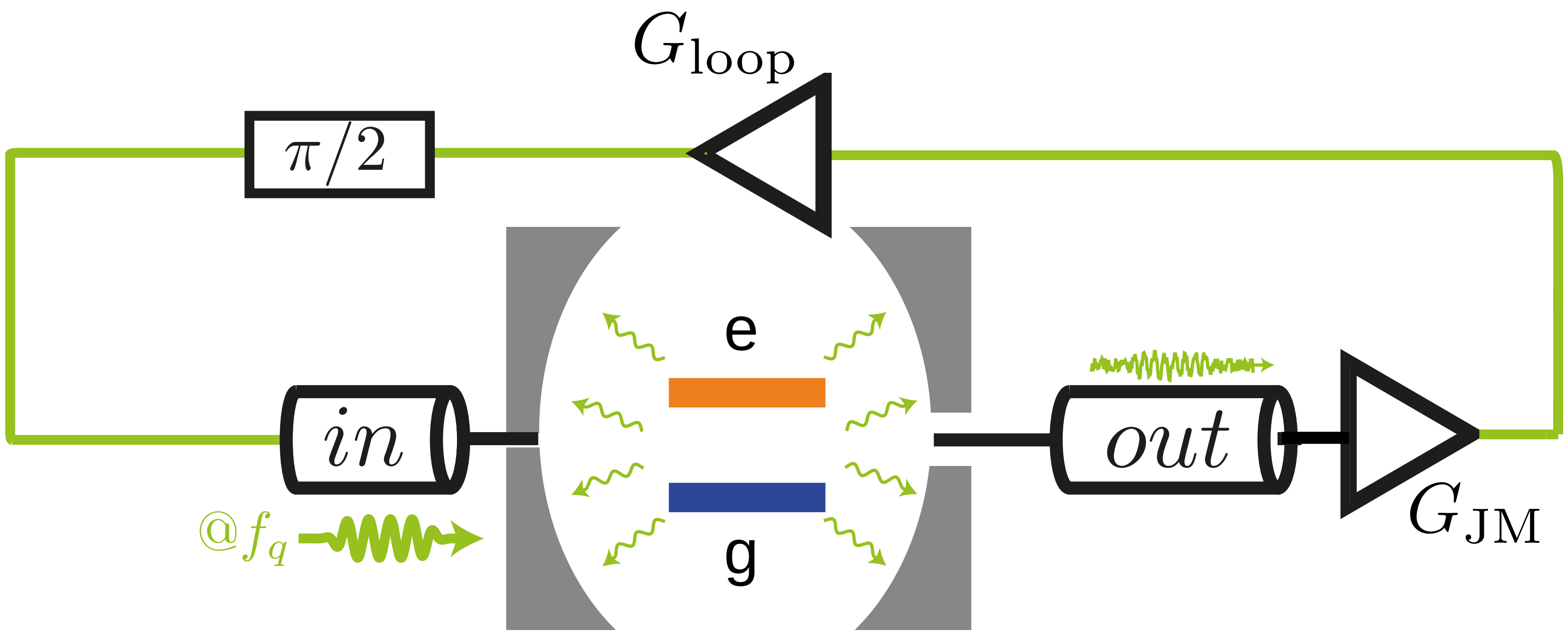
$$\begin{cases} u = \sqrt{\frac{\gamma_1}{2}}\dot{Q} + u_0 \\ v = -\sqrt{\frac{\gamma_1}{2}}\dot{I} \end{cases} \Longrightarrow \mathcal{D}[\sigma_-] \to \mathcal{D}[\sigma_+]$$

Dissipation to $|e\rangle$

[A. Chia and H. M. Wiseman, PRA (2011)]

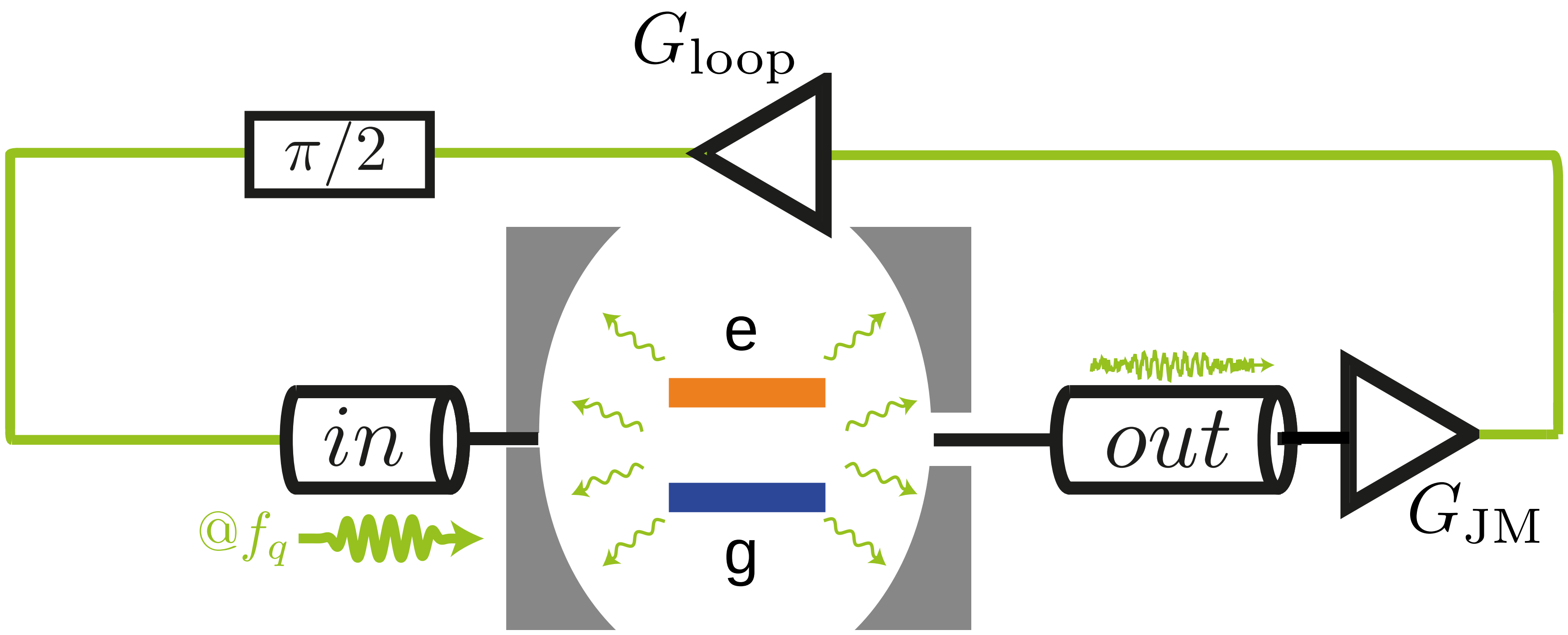
Stabilizing $|e\rangle$

$$\begin{cases} u = \sqrt{\frac{\gamma_1}{2}}\dot{Q} + u_0 \\ v = -\sqrt{\frac{\gamma_1}{2}}\dot{I} \end{cases}$$

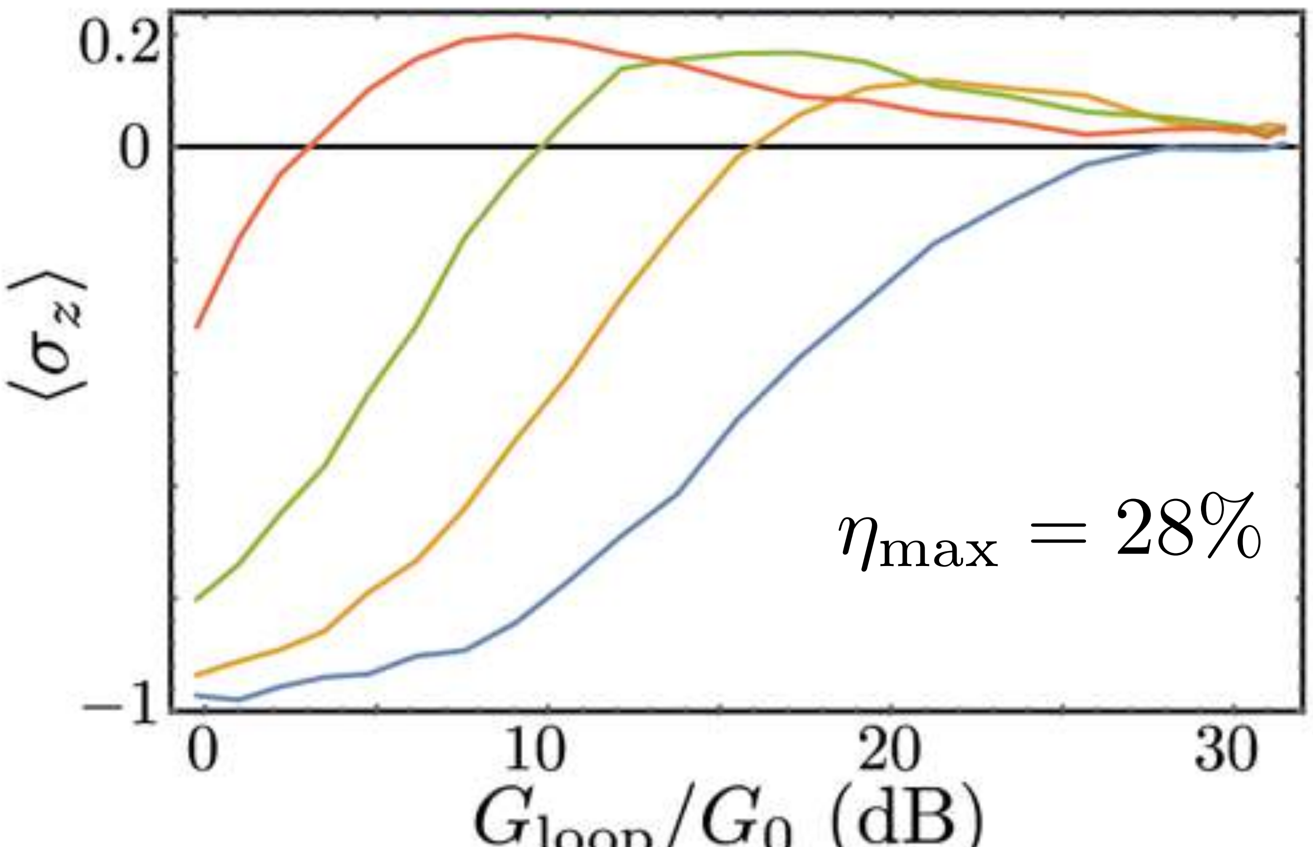


Stabilizing $|e\rangle$

$$\begin{cases} u = \sqrt{\frac{\gamma_1}{2}}\dot{Q} + u_0 \\ v = -\sqrt{\frac{\gamma_1}{2}}\dot{I} \end{cases}$$

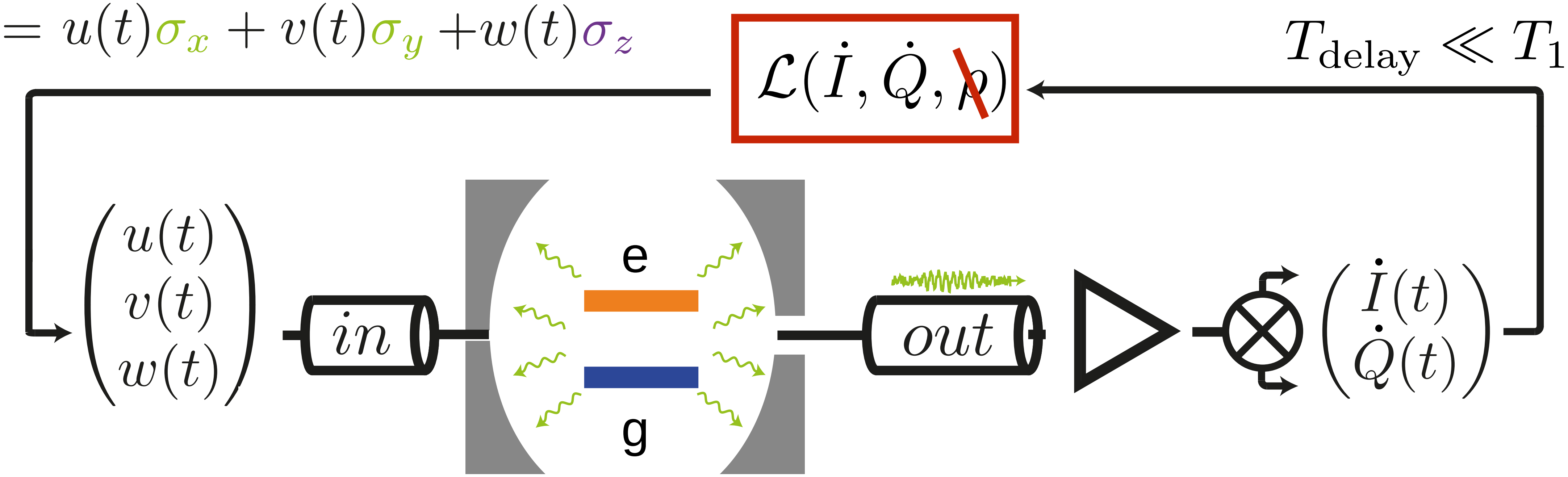


G_{JM}		η
0 dB	blue	0.005
18 dB	orange	0.16
22 dB	green	0.23
27 dB	red	0.28



Generalization

$$H_{\text{control}} = u(t)\sigma_x + v(t)\sigma_y + w(t)\sigma_z$$



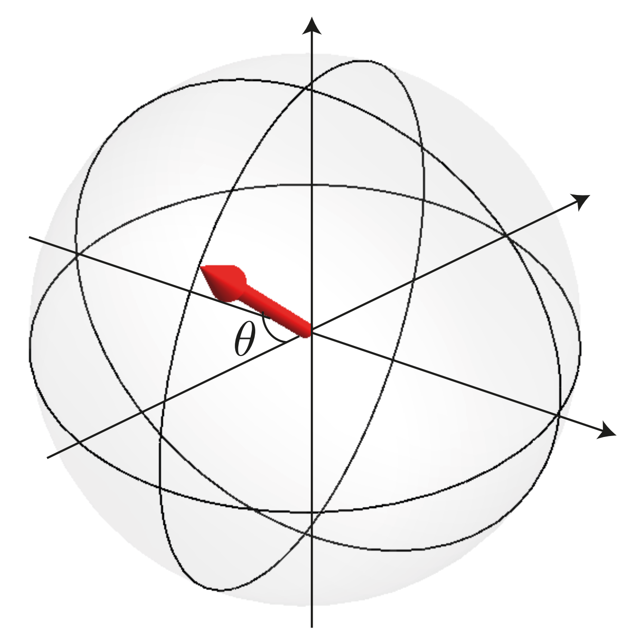
if $\eta = 1$

$$u = \sqrt{\frac{\gamma_1}{8}}(1 + \sin\theta)\dot{Q} + u_0$$

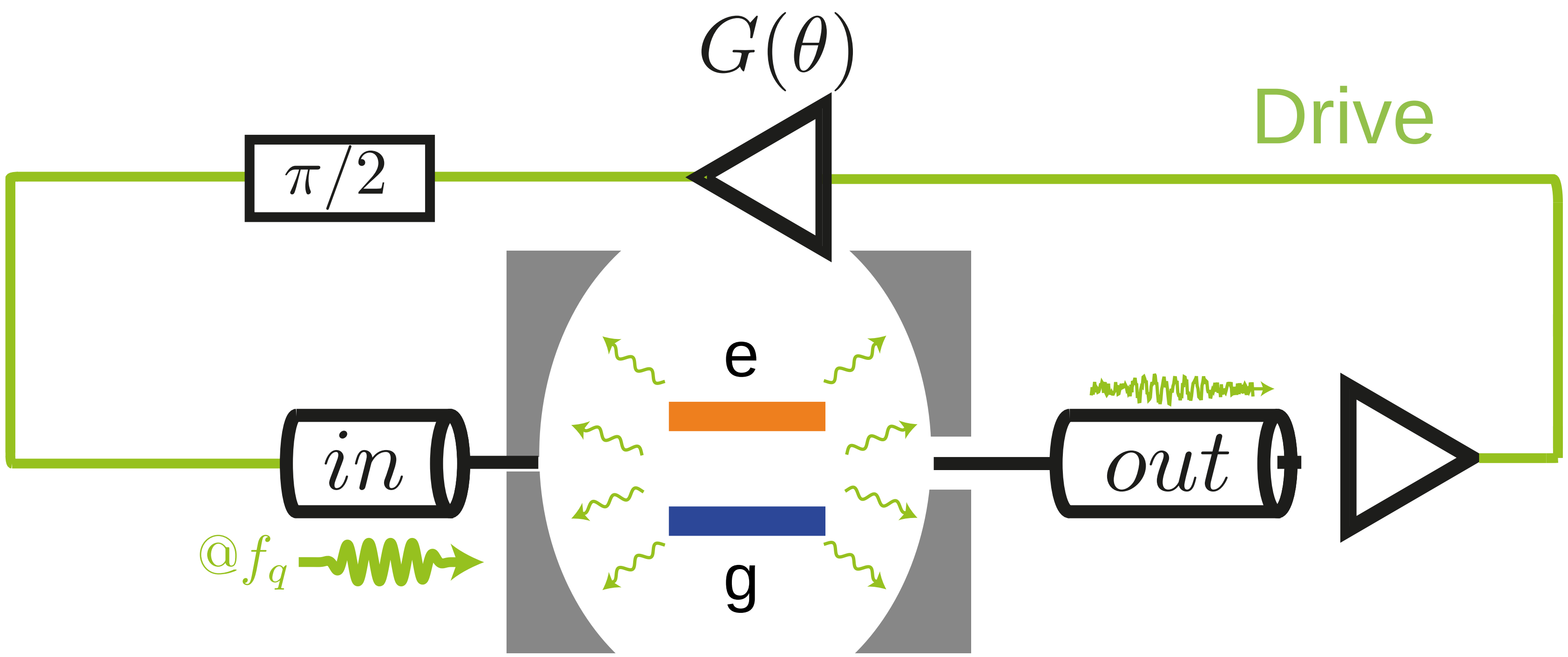
$$v = -\sqrt{\frac{\gamma_1}{8}}(1 + \sin\theta)\dot{I}$$

$$w = \sqrt{\frac{\gamma_1}{8}}\cos\theta \; \dot{I}$$

$$\rho_{\text{target}} = \frac{1}{2}(I + \cos\theta \; \sigma_y + \sin\theta \; \sigma_z)$$



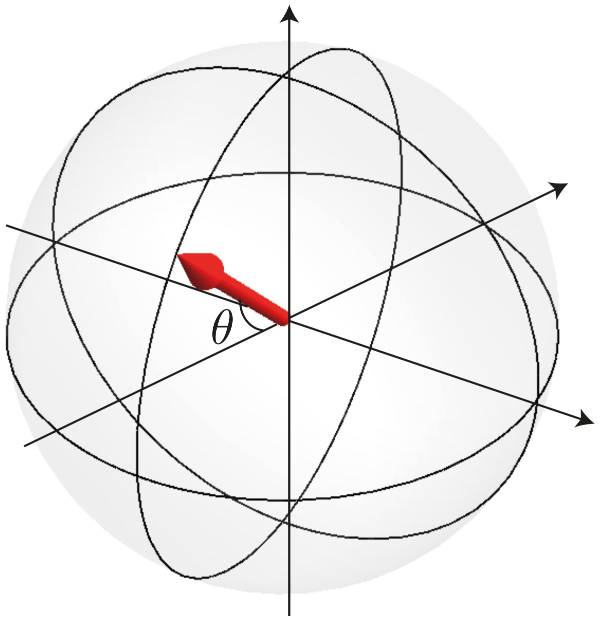
Stabilizing any state



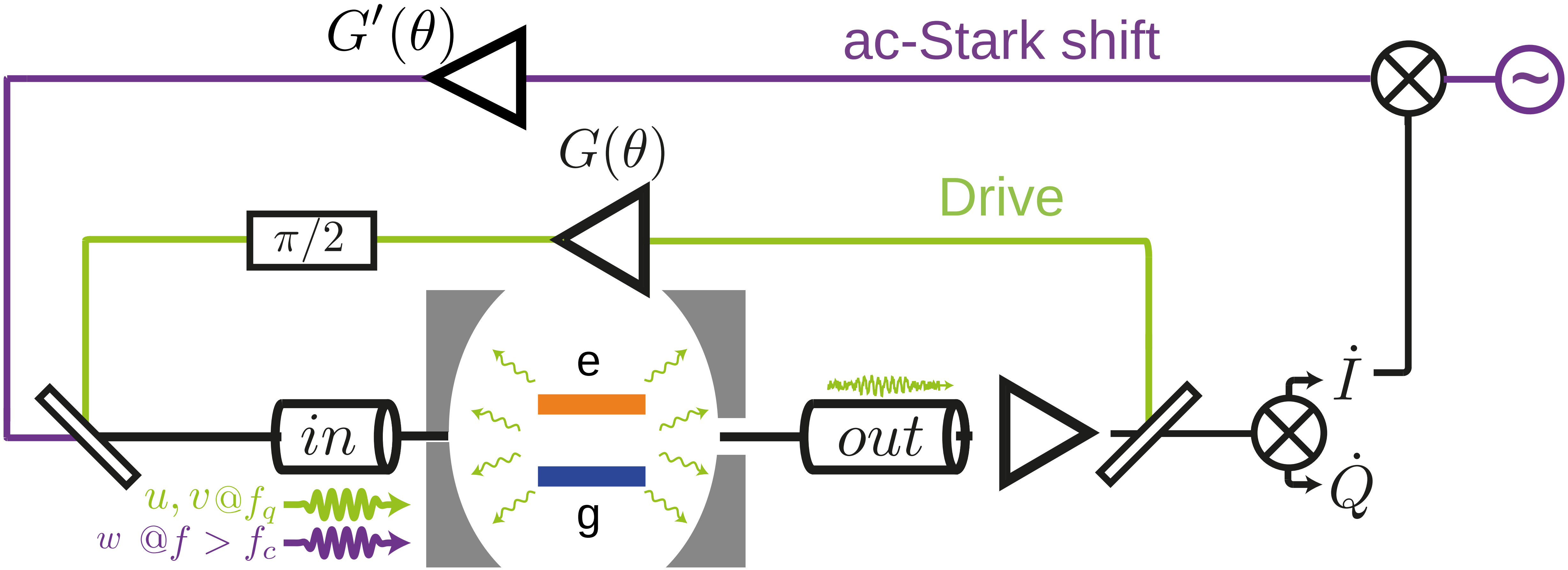
$$u = \sqrt{\frac{\gamma_1}{8}}(1+\sin\theta)\dot{Q} + u_0$$

$$v = -\sqrt{\frac{\gamma_1}{8}}(1+\sin\theta)\dot{I}$$

$$w = \sqrt{\frac{\gamma_1}{8}}\cos\theta \; \dot{I}$$



Stabilizing any state



$$u = \sqrt{\frac{\gamma_1}{8}}(1+\sin\theta)\dot{Q} + u_0$$

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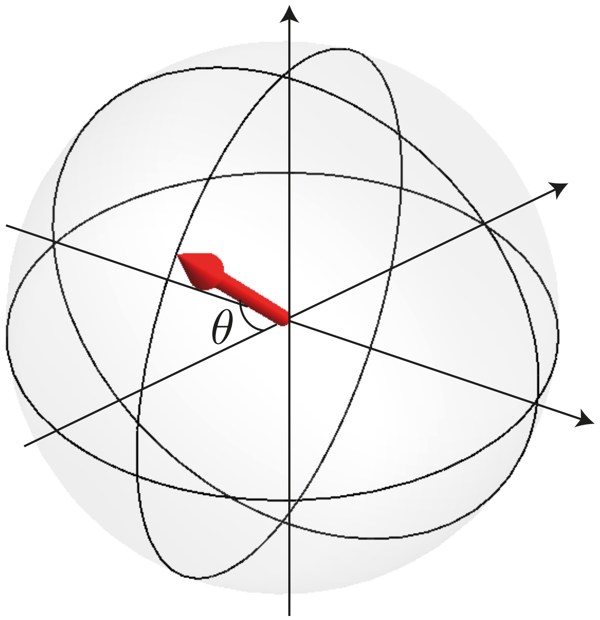
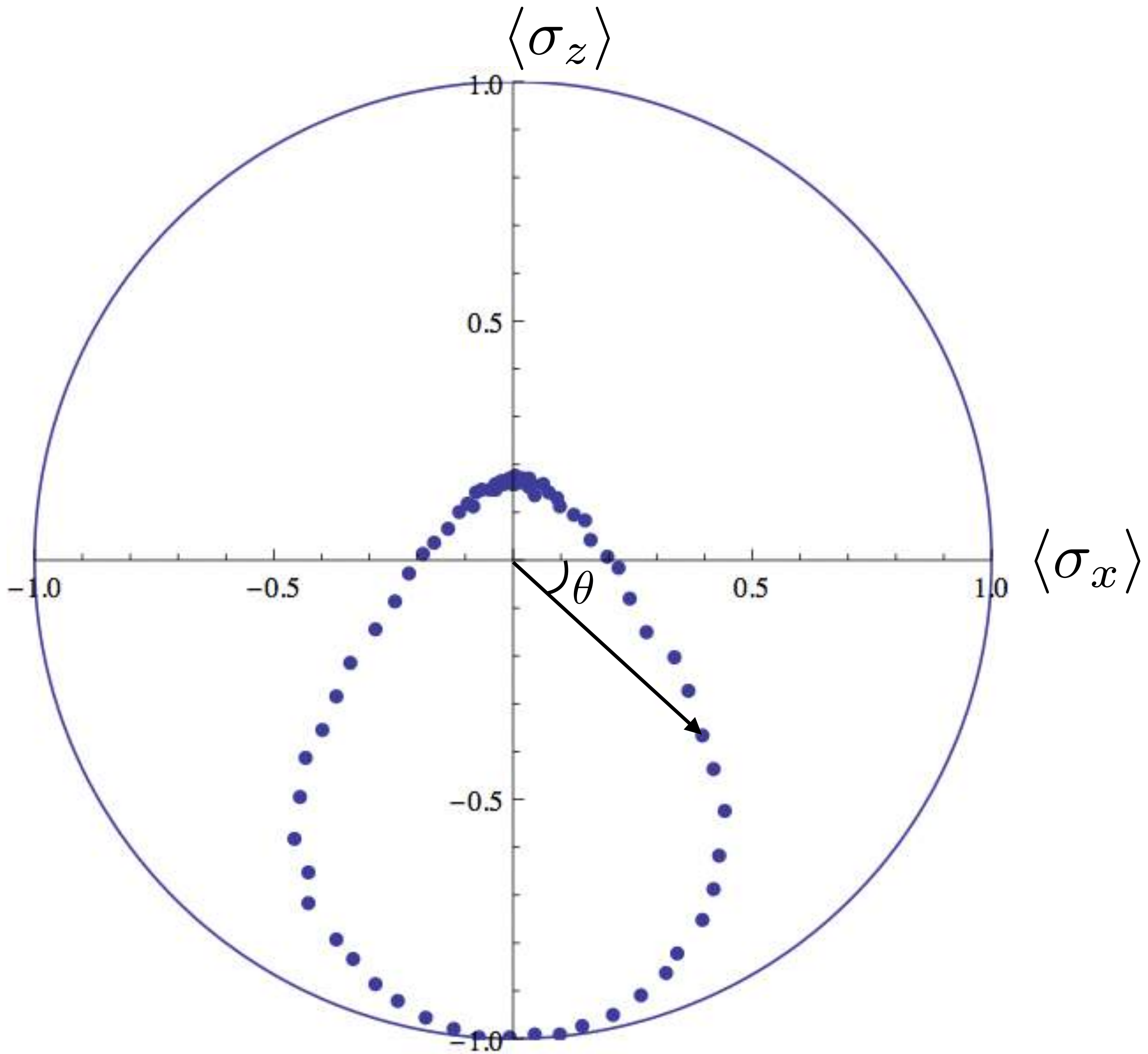


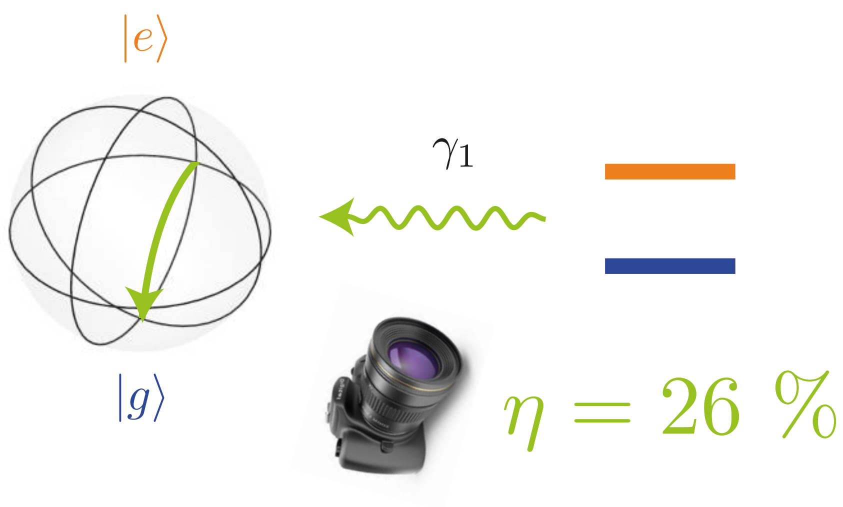
Stabilized states



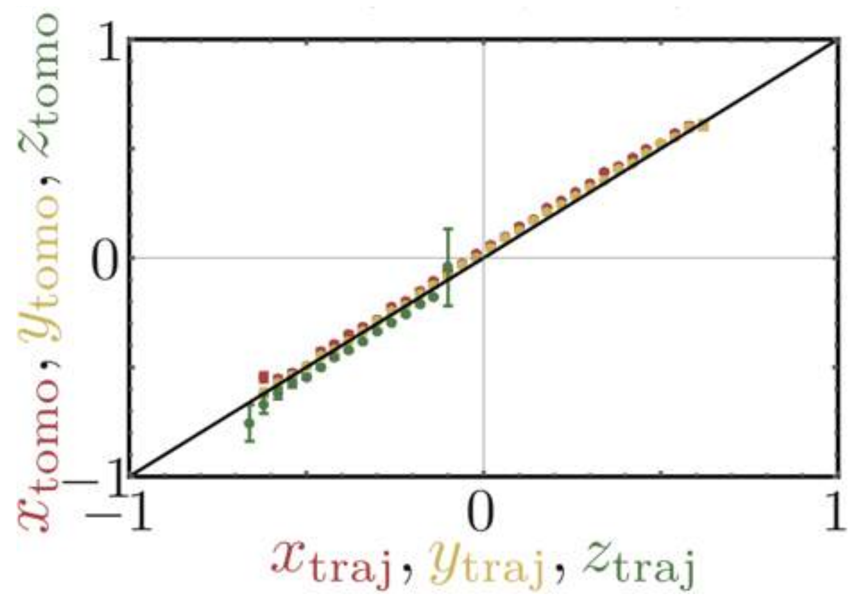
First measurement based feedback with multi inputs and multi outputs

Conclusion

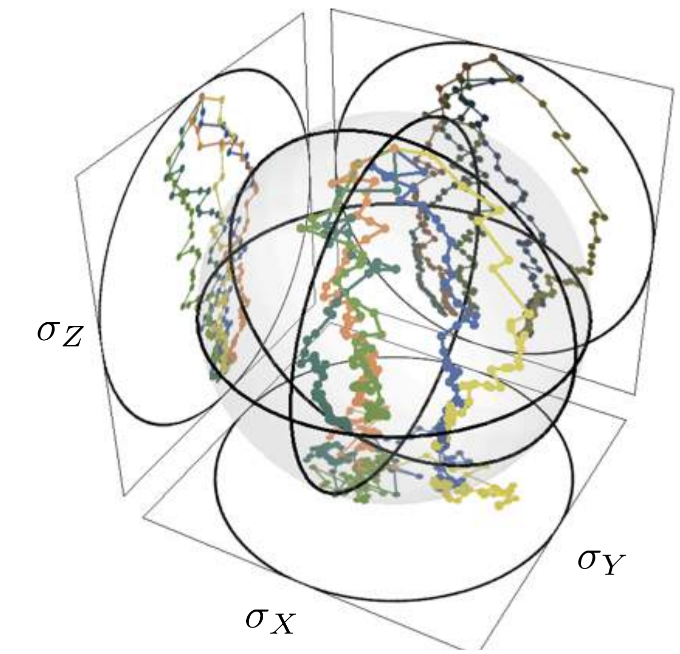
Efficiently monitor relaxation channel



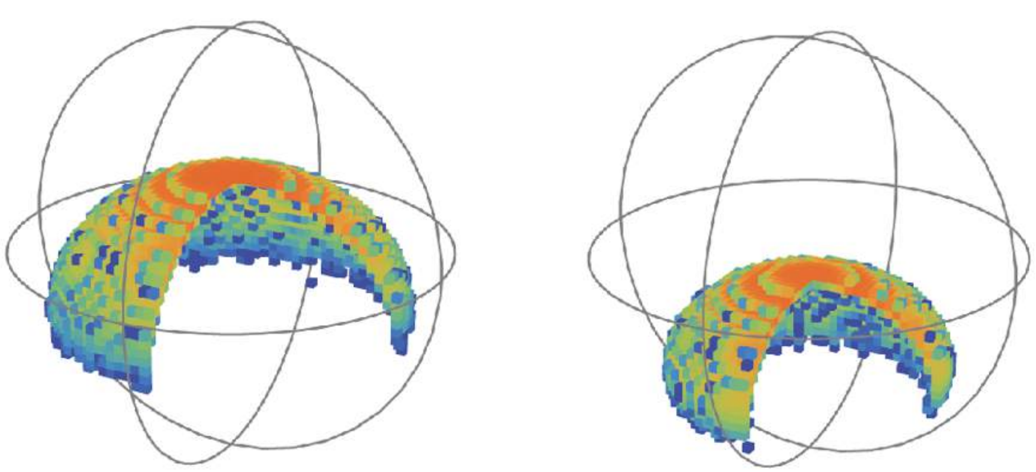
Validated by tomography



Unravel relax events

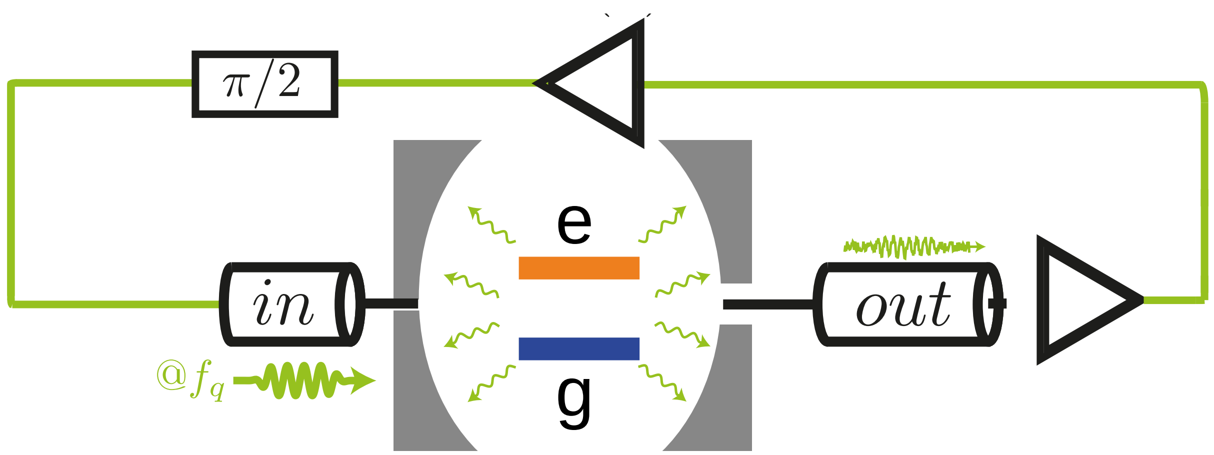


Statistical study



$t = 2\ \mu s$ $t = 4\ \mu s$

Markovian feedback



Quantic - Experiments

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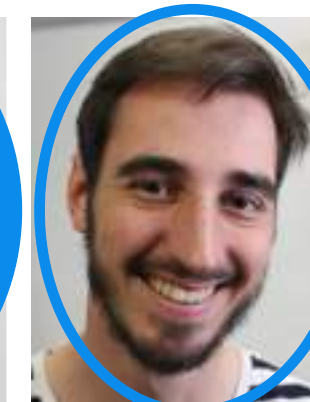

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Quantic - Theory

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