Using spontaneous emission of a qubit as a resource for feedback control

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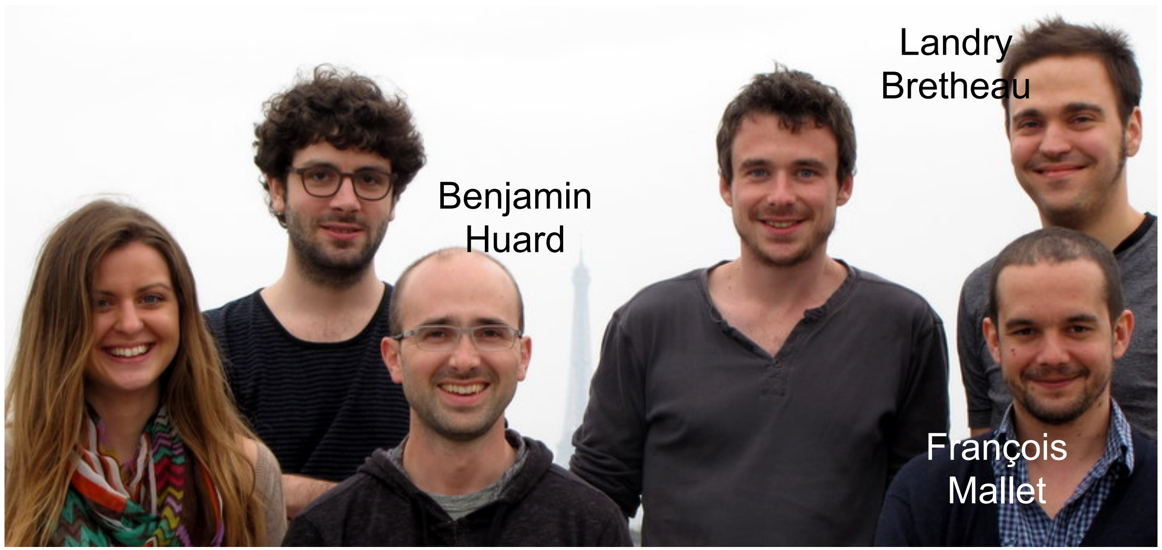
Quantum Electronics group - Quantic team
ENS Paris - Mines ParisTech - INRIA



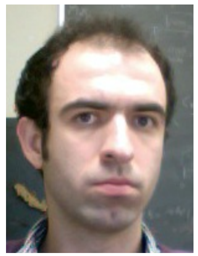
Sébastien Jezouin

Nathanaël Cottet

Pierre Rouchon (Mines)

Pierre Six (Mines)

Alain Sarlette (INRIA)

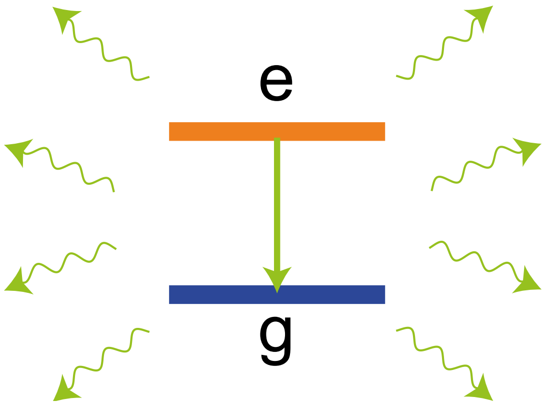


Mazyar Mirrahimi (INRIA)

*now in Quantronics group, CEA Saclay

Information in fluorescence

If we monitor the main relaxation channel for a qubit,



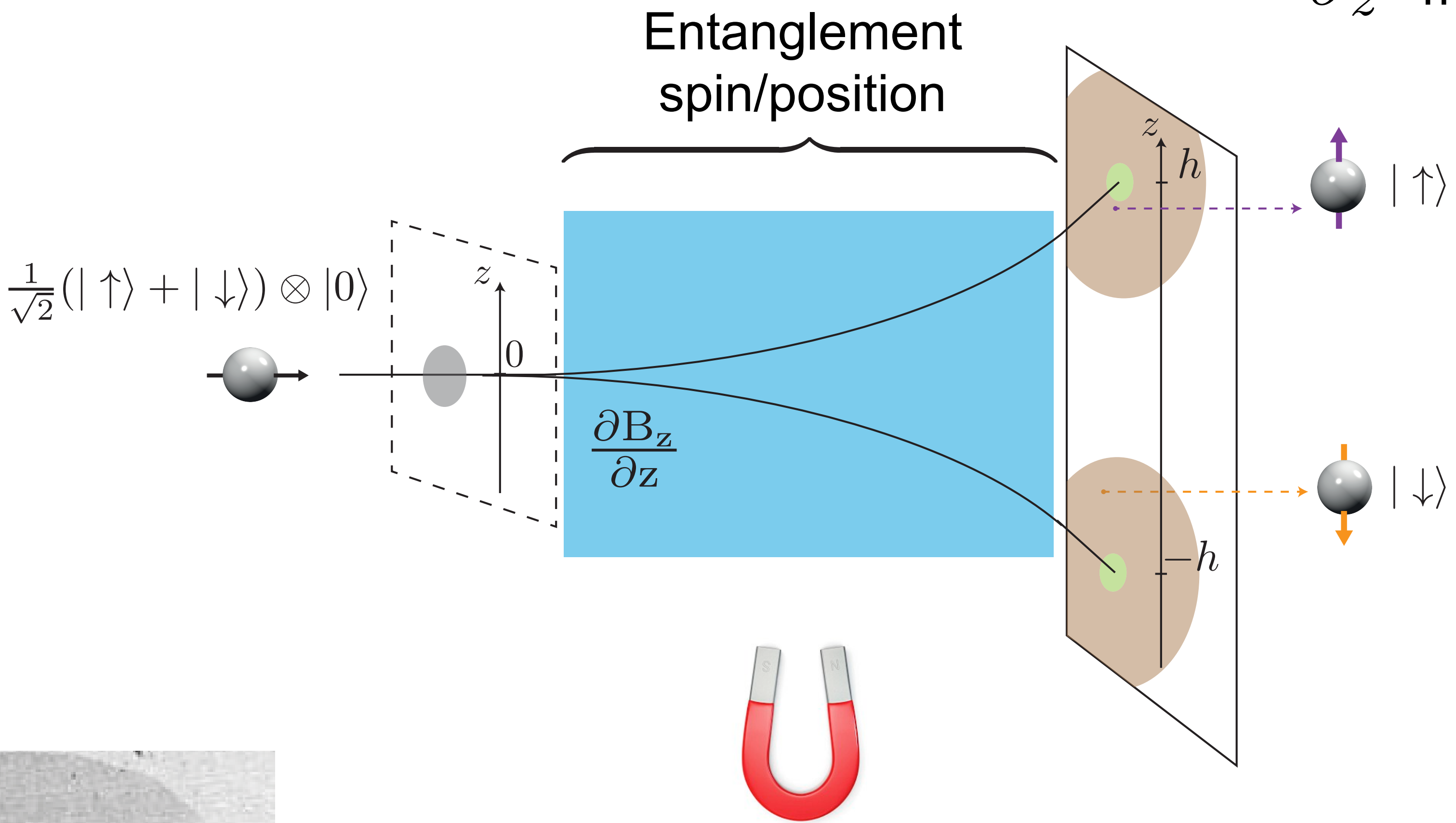
What is the path followed by its state during relaxation?

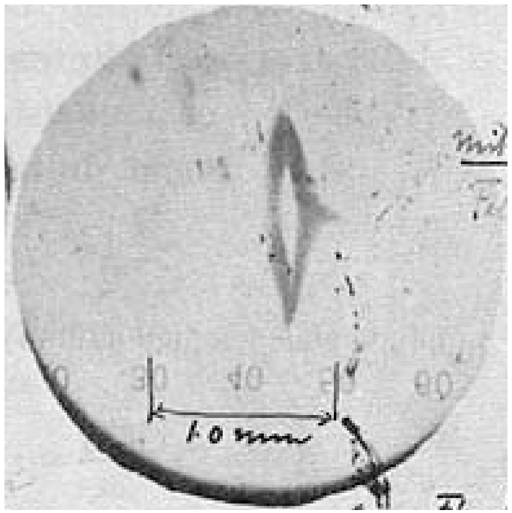
…depends on the detector ⟶ quantum trajectory

How can we use the information?

Projective measurement

σ_z measurement





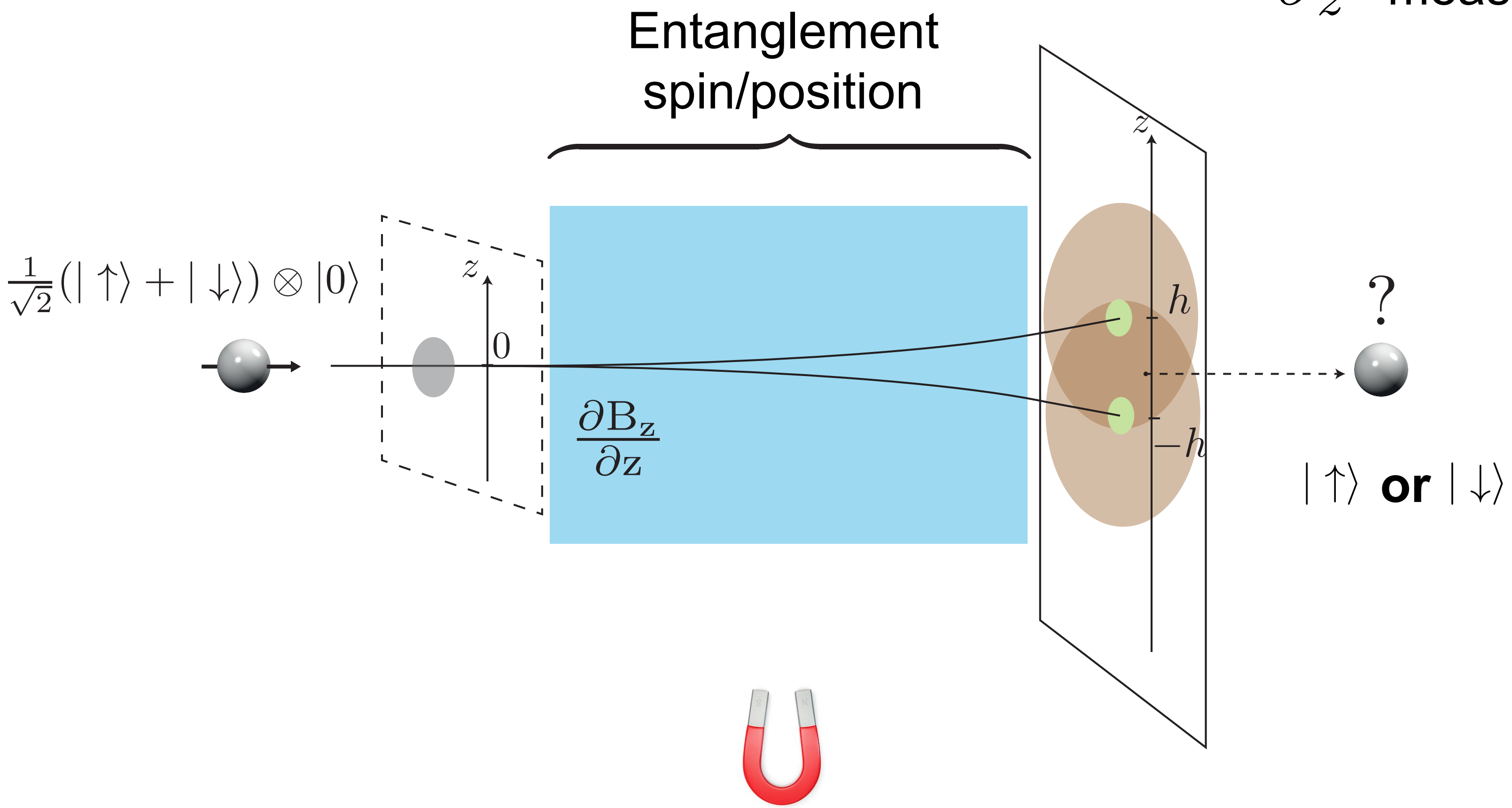
[Gerlach and Stern, 1922]

$$\eta \sim \frac{\delta z_Q^2}{\delta z_Q^2 + \delta z_C^2}$$

$$\eta \ll 1$$

Noisy measurement

σ_z measurement



$$\eta \sim \frac{\delta z_Q^2}{\delta z_Q^2 + \delta z_C^2}$$

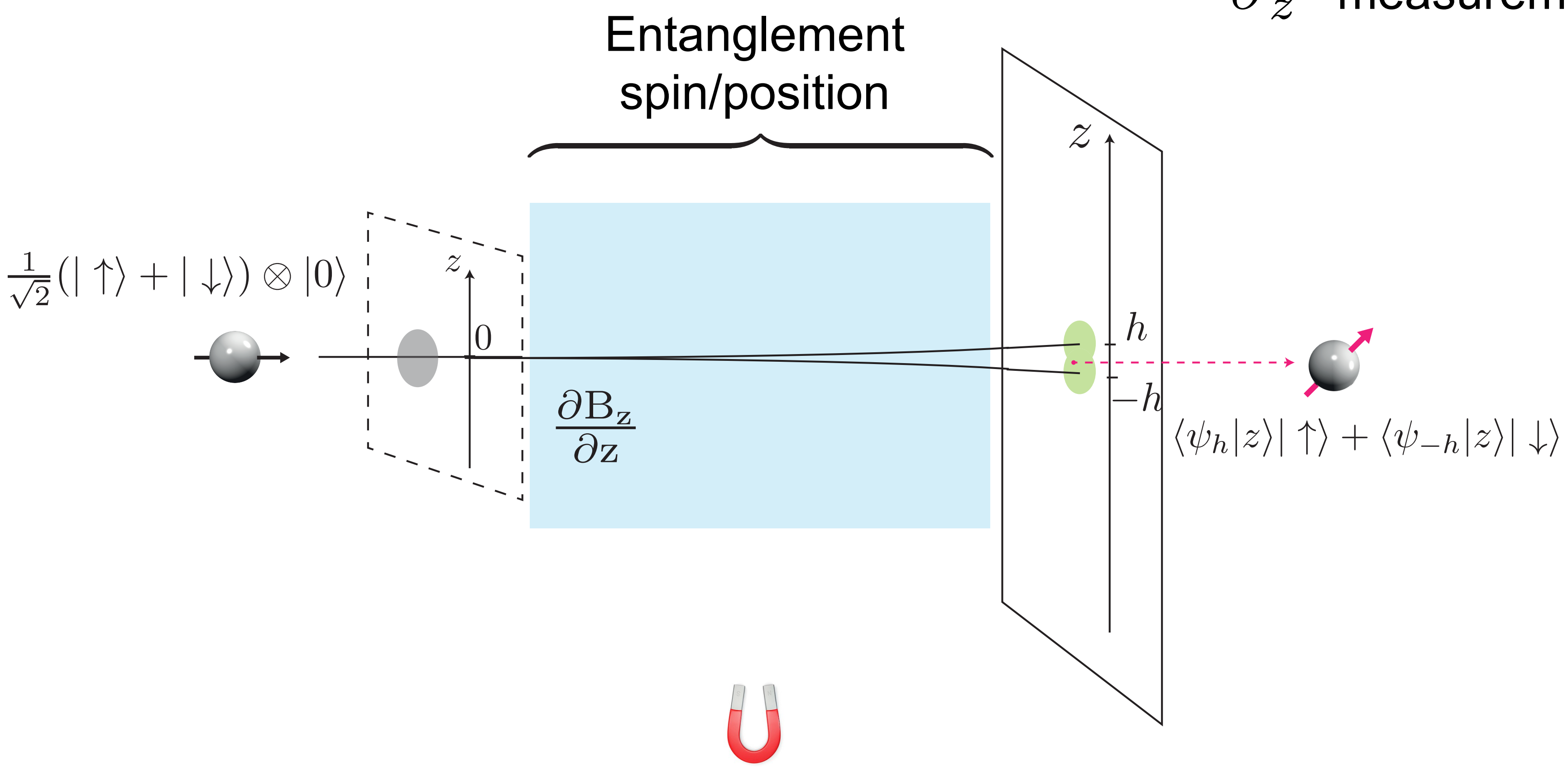
$$\eta \ll 1$$

unknown stochastic evolution

→ **decoherence**

Stochastic backaction

σ_z measurement



$$\eta \sim \frac{\delta z_Q^2}{\delta z_Q^2 + \delta z_C^2}$$

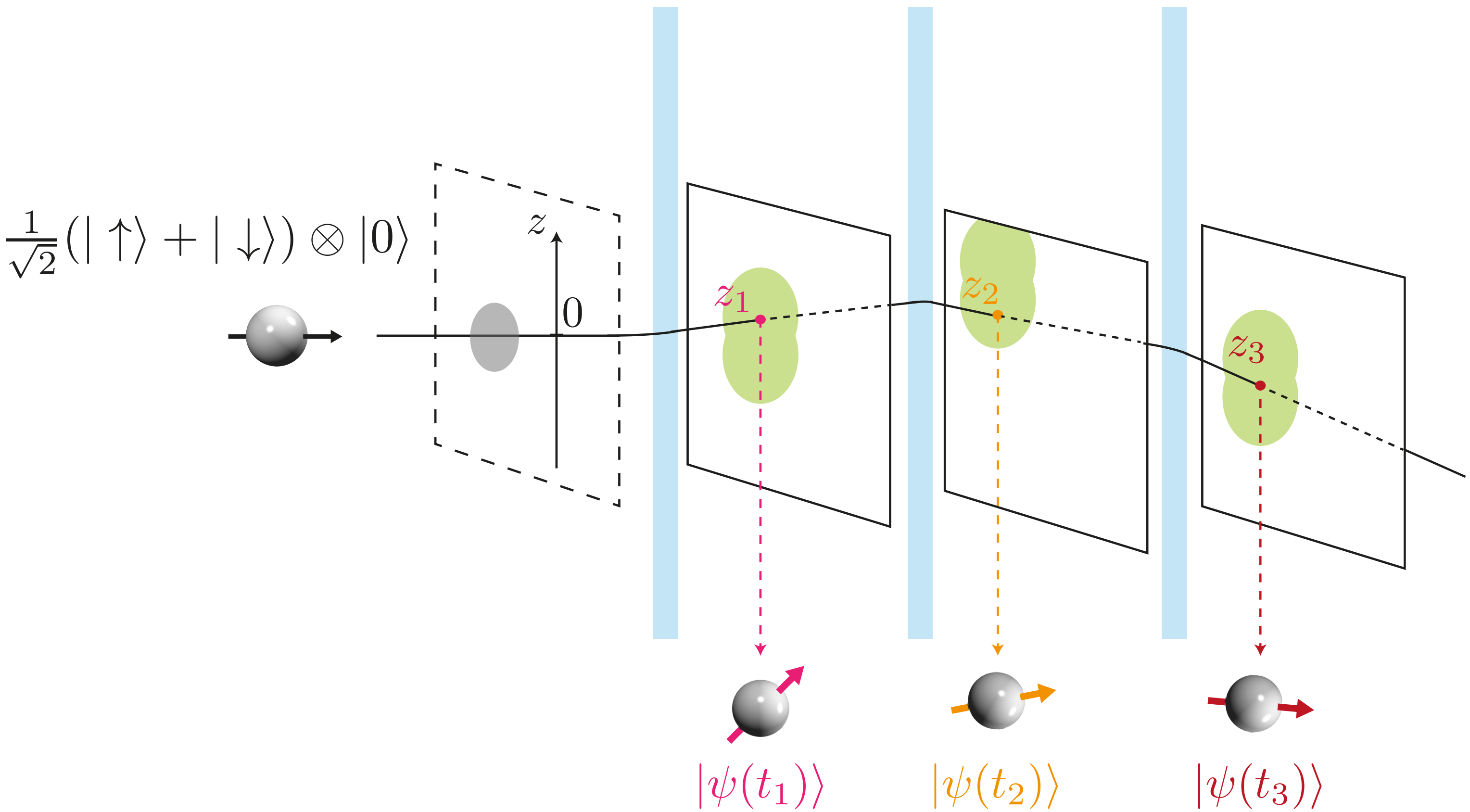
$$\eta \simeq 1$$

known stochastic evolution

→ **backaction**

Quantum trajectories

σ_z measurement

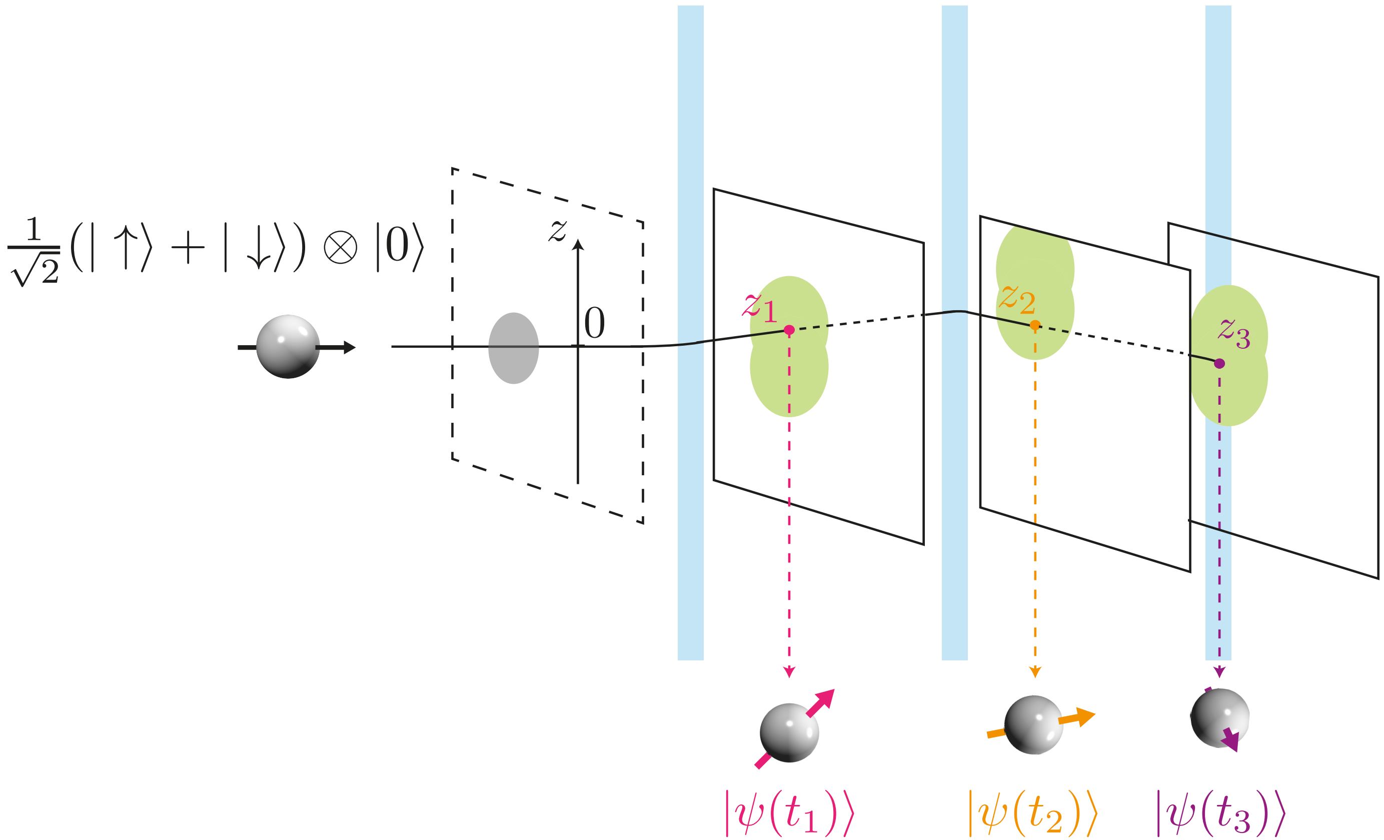


$|\psi\rangle_{[0,T]}$ quantum trajectory

depends on $\longrightarrow$ measurement record $\{z_1, z_2, z_3, \ldots, z_T\}$

Quantum trajectories

σ_z measurement



$|\psi\rangle_{[0,T]}$ quantum trajectory

depends on ⟶ measurement record $\{z_1, z_2, z_3, \ldots, z_T\}$

⟶ detection type

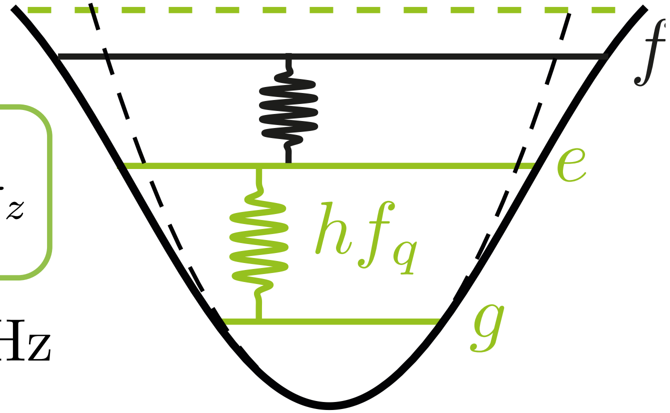
[Murch et al., Berkeley Group, Nature 2013]
[Hatridge et al., Yale Group, Science 2013]

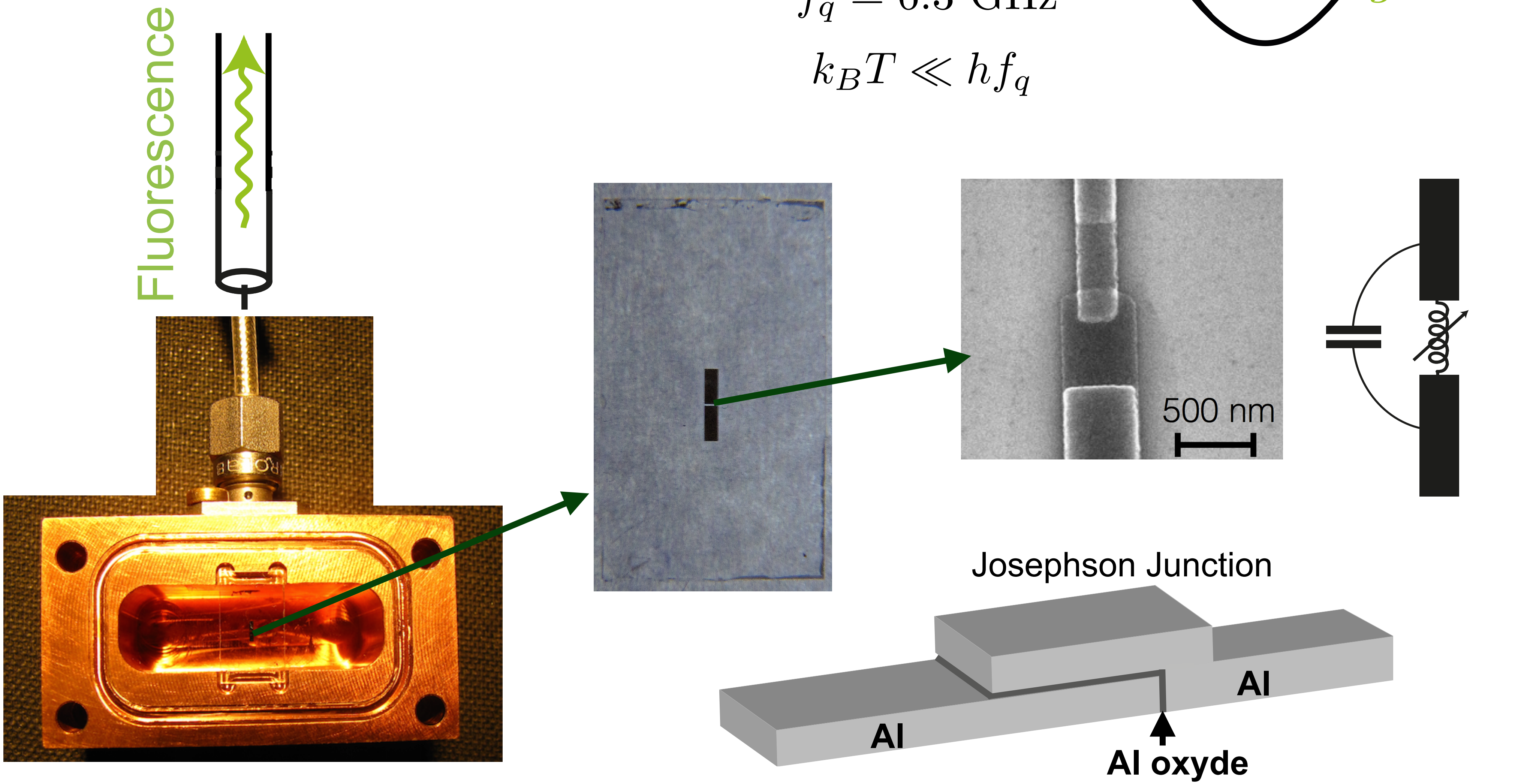
Transmon qubit

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

$$f_q = 6.3 \text{ GHz}$$

$$k_B T \ll hf_q$$





Trajectory of fluorescence

$\rho(t)$?

m_1 , m_2 , m_3 ...

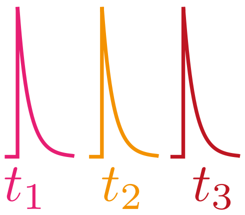
$\rho(0) \rightarrow \rho(t_1) \rightarrow \rho(t_2) \rightarrow \rho(t_3)$

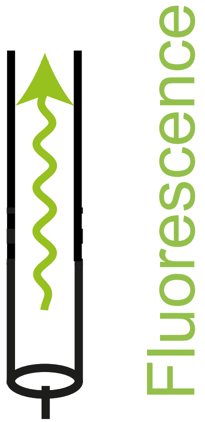
Rotating frame @ f_q

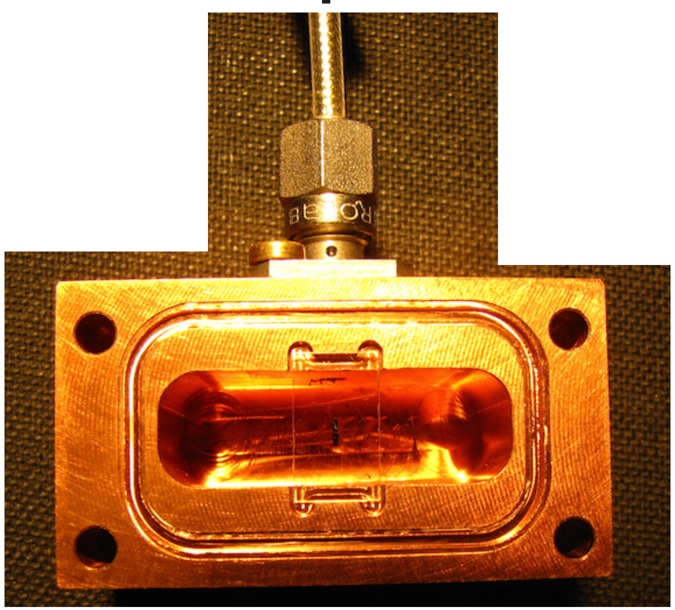
$$H = 0$$

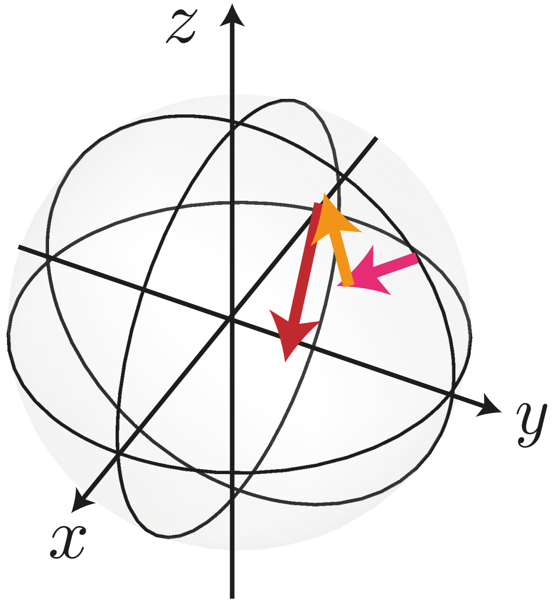
$$\rho = \frac{1}{2}(x\sigma_x + y\sigma_y + z\sigma_z)$$

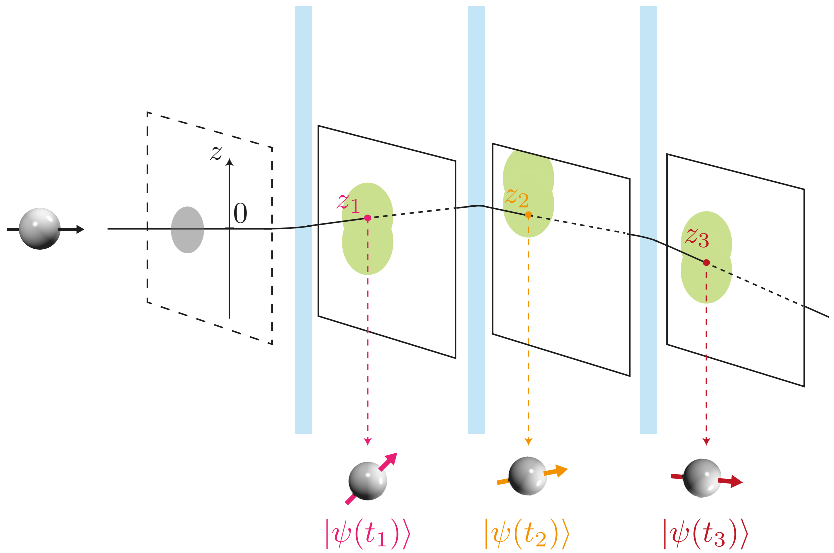
line modes



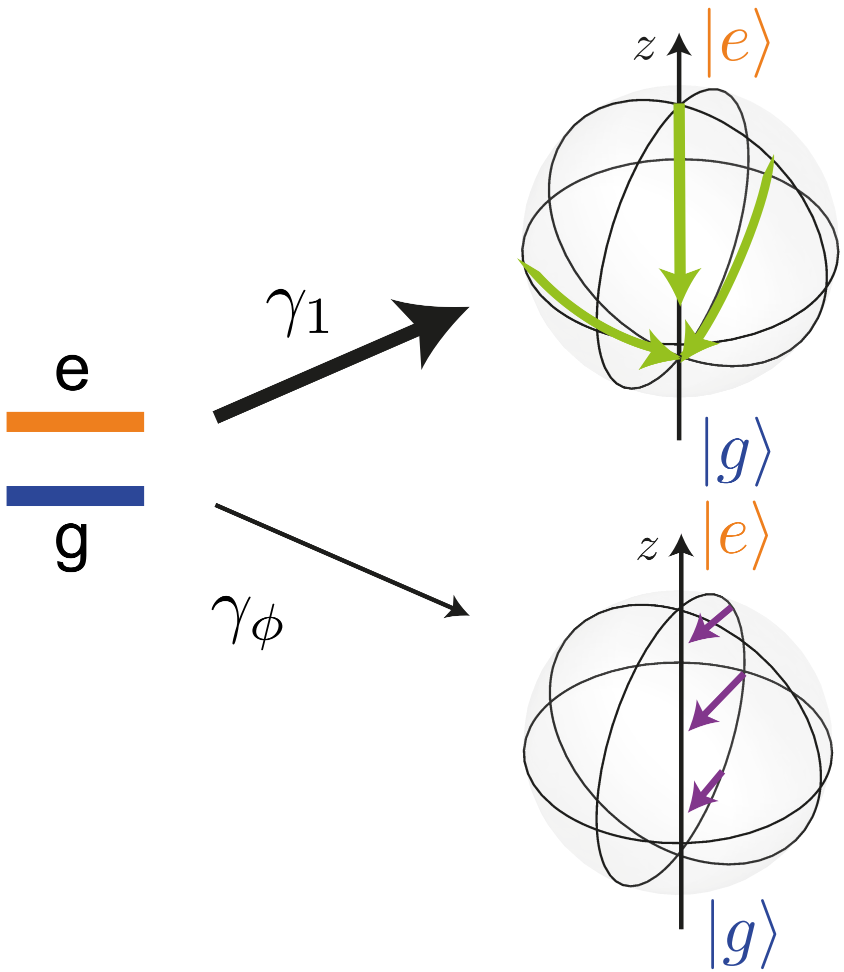








No detector ($\eta = 0$)



Relaxation

$$\gamma_1 = (4.15\ \mu\text{s})^{-1}$$

Dephasing (σ_z measurement)

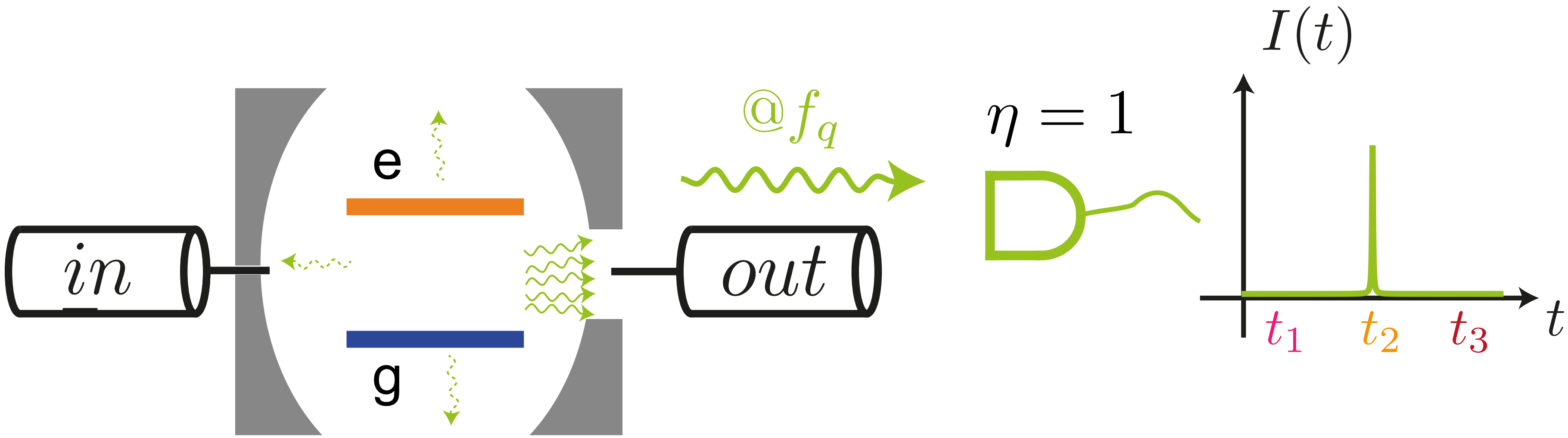
$$\gamma_\phi = (35\ \mu\text{s})^{-1}$$

$$\gamma_2 = \gamma_1/2 + \gamma_\phi$$

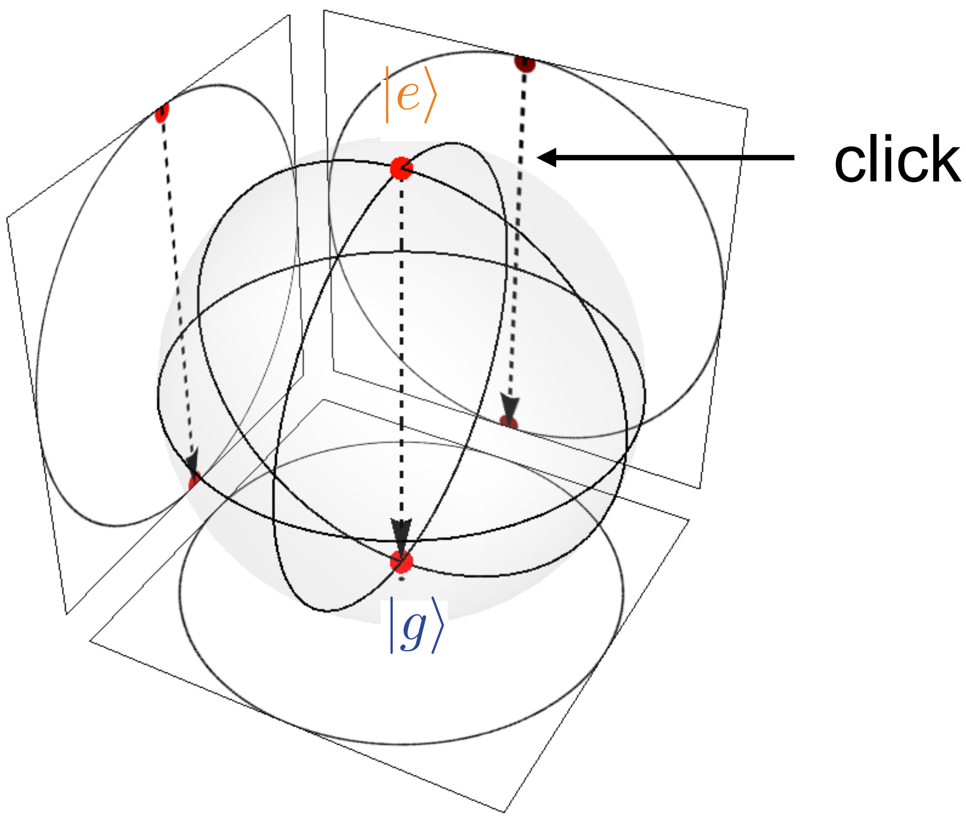
Lindblad $$\mathrm{d}\rho = \gamma_1 \mathcal{D}[\sigma_-]\rho(t) + \gamma_\phi/2\mathcal{D}[\sigma_z]\rho(t)$$

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

Fluorescence with a (perfect) photocounter

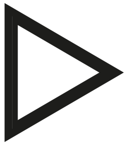


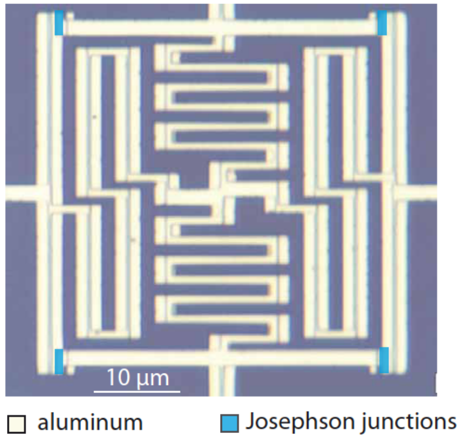
start from $|e\rangle$



Fluorescence heterodyne measurement

Josephson Parametric Converter
Phase preserving amplifier

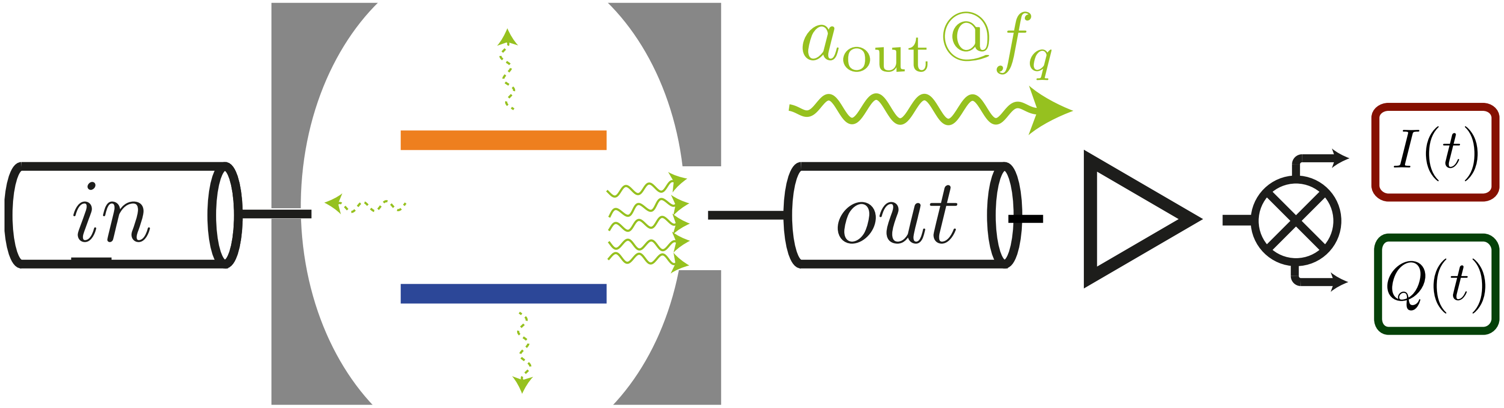




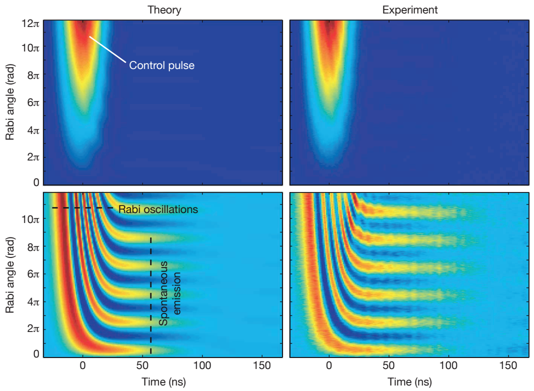
(Yale, 2010)

(ENS Paris, 2012)

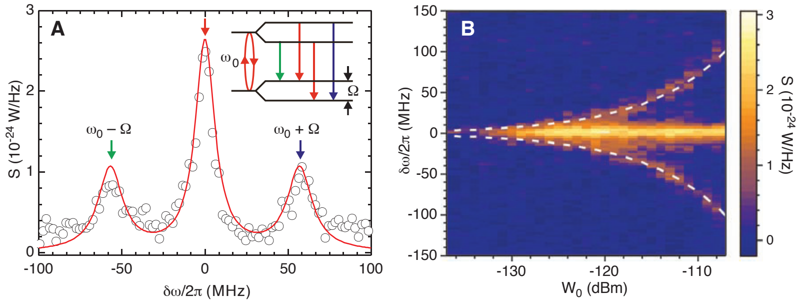
detect $\mathrm{Re}[a_{\mathrm{out}}]$ **and** $\mathrm{Im}[a_{\mathrm{out}}]$ **simultaneously**



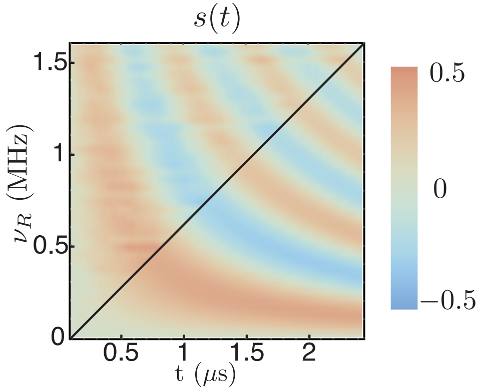
Mean fluorescence signal



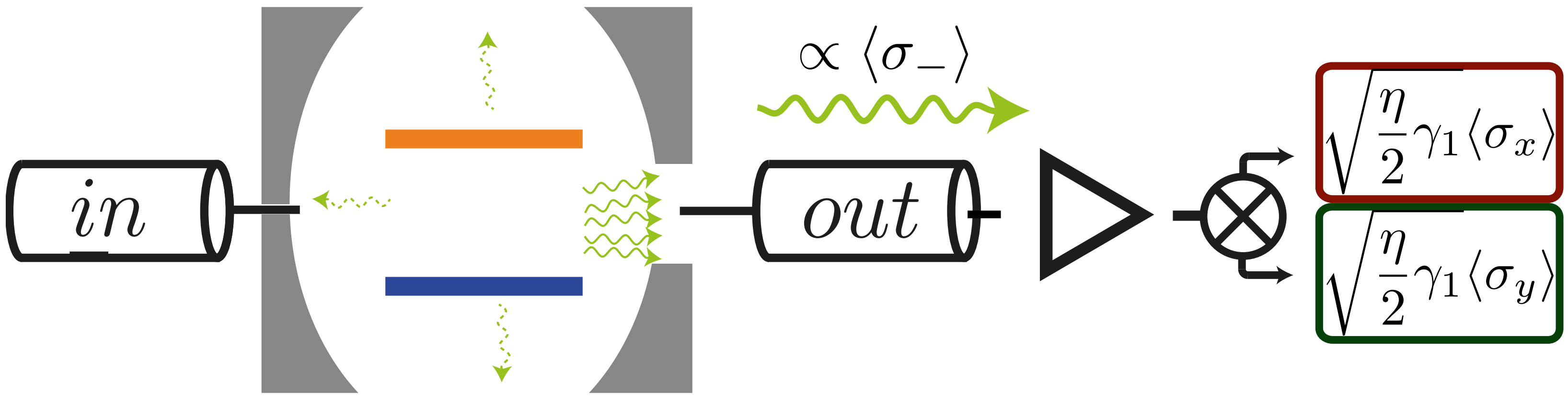
[Yale, Nature 2007]



[RIKEN & NEC, Science 2010 and PRL 2011]



[Paris, PRL 2014]



$$\sigma_- = |e\rangle\langle g| = \sigma_x - i\sigma_y$$

Single measurement record

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

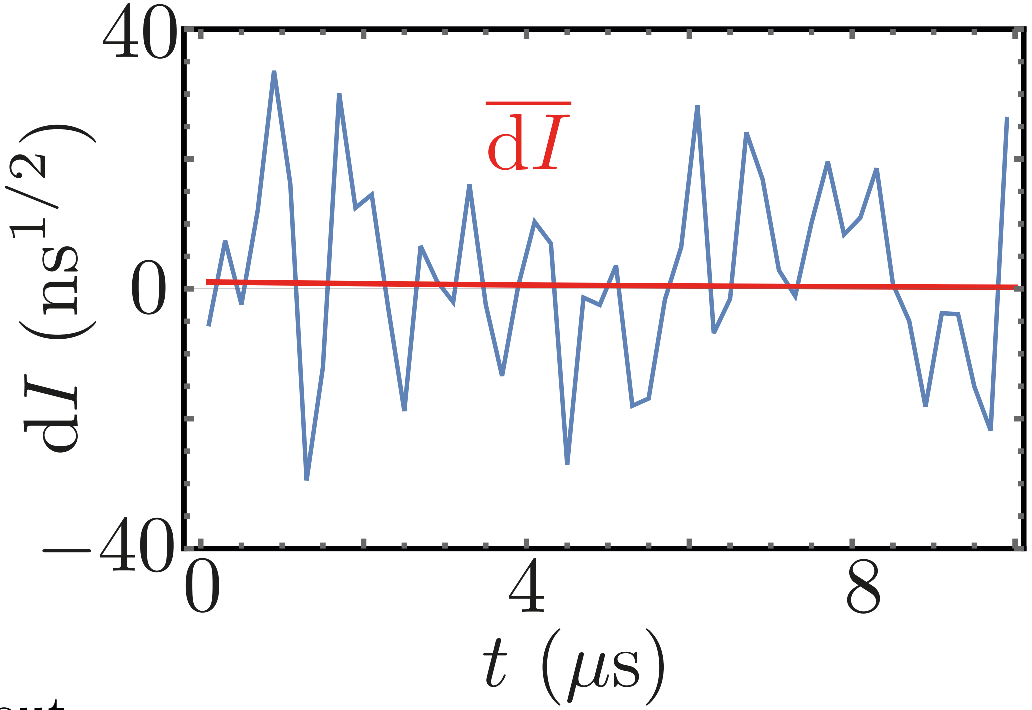
$$\mathrm{d}Q = \sqrt{\frac{\eta}{2}\gamma_1}\langle\sigma_y\rangle\mathrm{d}t + \mathrm{d}W_Q$$

start from $(|e\rangle + |g\rangle)/\sqrt{2}$

Wiener $\overline{\mathrm{d}W} = 0$

$$|\mathrm{d}W| \sim \sqrt{\mathrm{d}t}$$

$$\mathrm{d}t = 200 \text{ ns} \ll T_1$$



$$\eta = 24\ \%$$

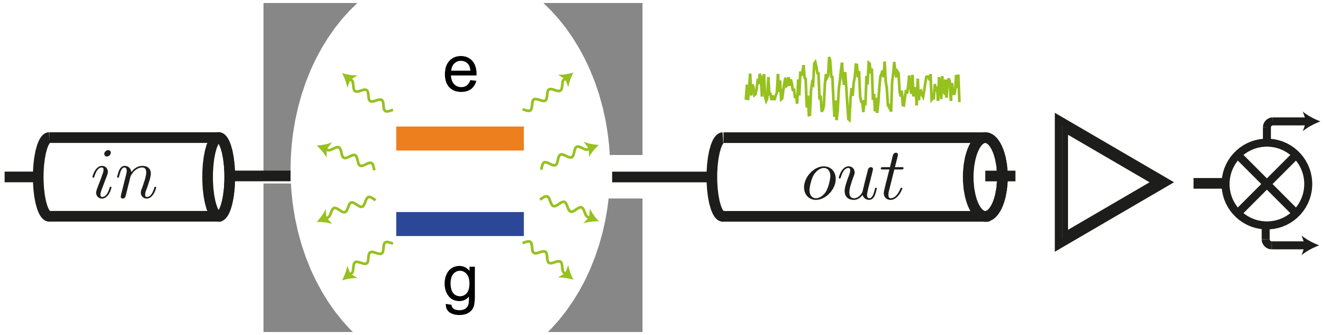
$$\eta_{\text{coll}} = \frac{\gamma_{\text{Purcell,out}}}{\gamma_1}$$

$$\eta = \eta_{\text{coll}} \times \eta_{\text{detec}}$$

Stochastic Master Equation

if $\rho(t)$ is known

$\eta = 24\ \%$



$\mathrm{d}I = \overline{\mathrm{d}I} + \mathrm{d}W_I$

$\mathrm{d}Q = \overline{\mathrm{d}Q} + \mathrm{d}W_Q$

$$\mathrm{d}\rho = \mathrm{d}t\ \mathcal{D}[\sqrt{\gamma_1}\sigma_-]\rho + \mathrm{d}t\ \mathcal{D}[\sqrt{\gamma_\phi/2}\sigma_z]\rho$$

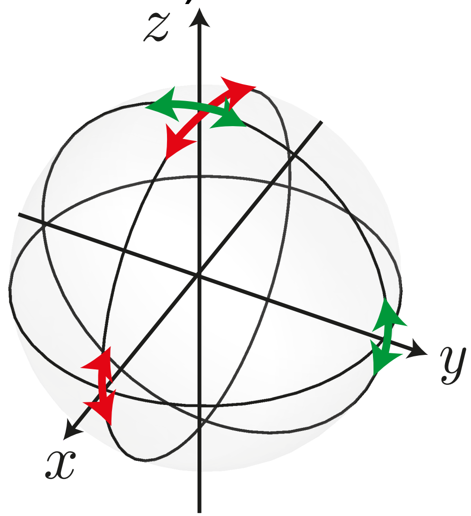
unconditional evolution (Lindblad)

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

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

stochastic kicks

… whose amplitude depends on position

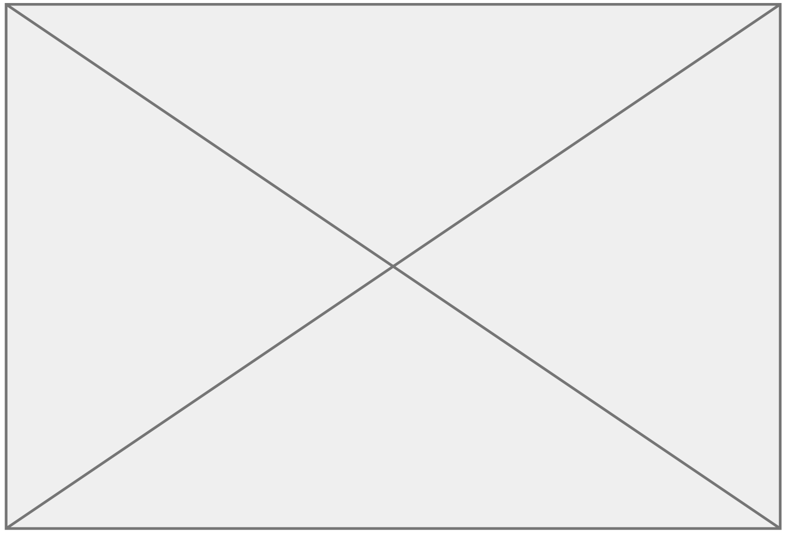


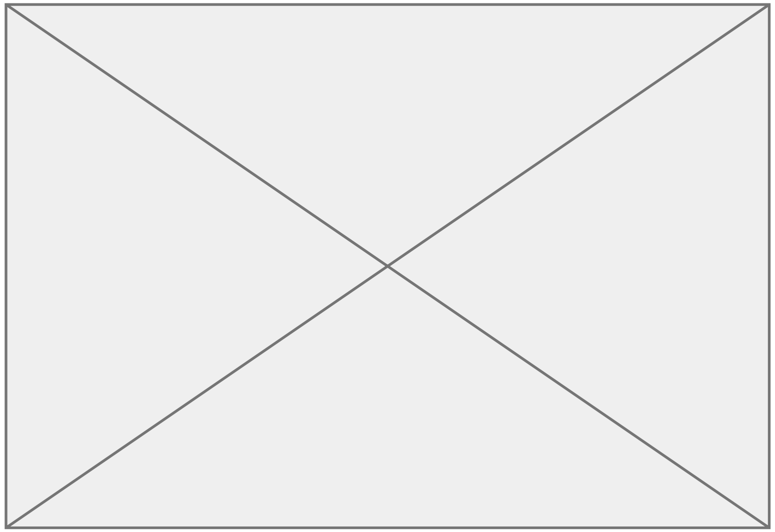
$$\mathcal{D}[L]\rho = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L)$$

$$\mathcal{M}[L]\rho = (L - \langle L\rangle)\rho + \rho(L^\dagger - \langle L^\dagger\rangle)$$

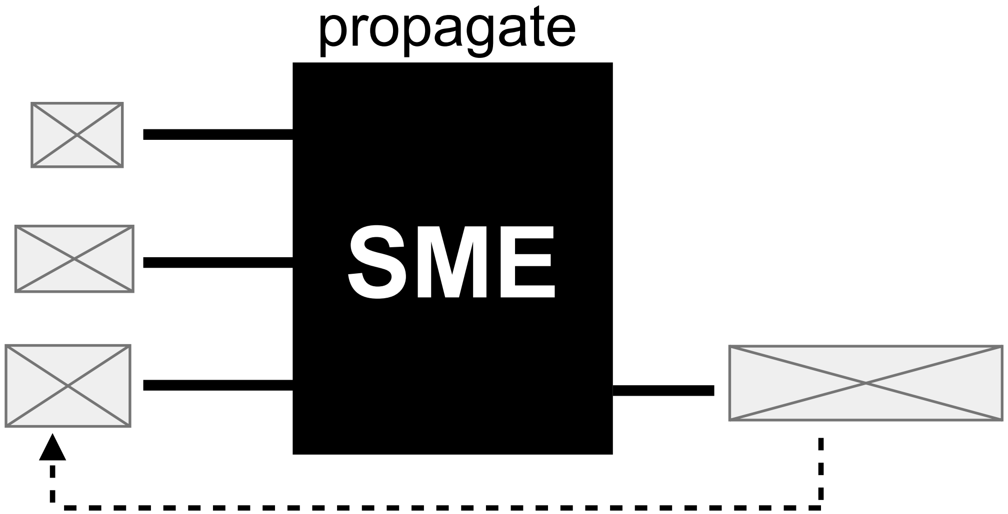
From measurement record to Q trajectory

corrected for JPC low-pass filter →





start from at

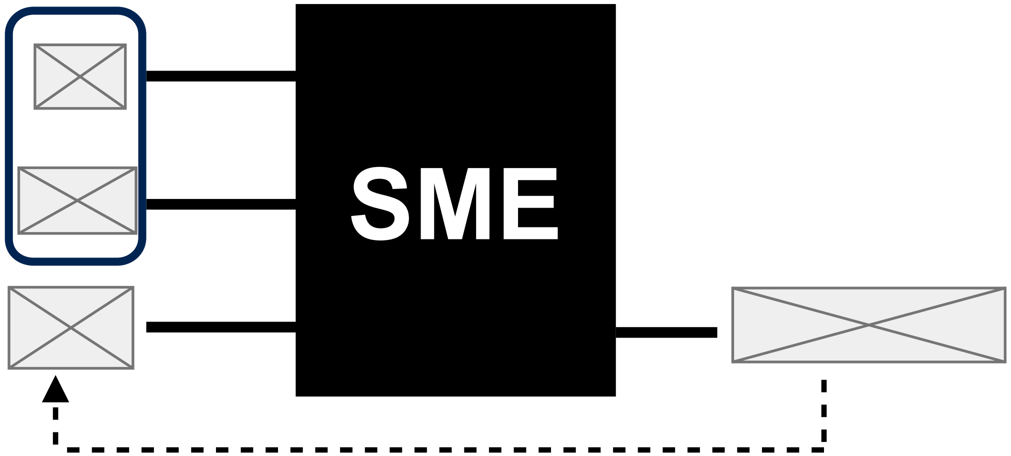


From measurement record to Q trajectory

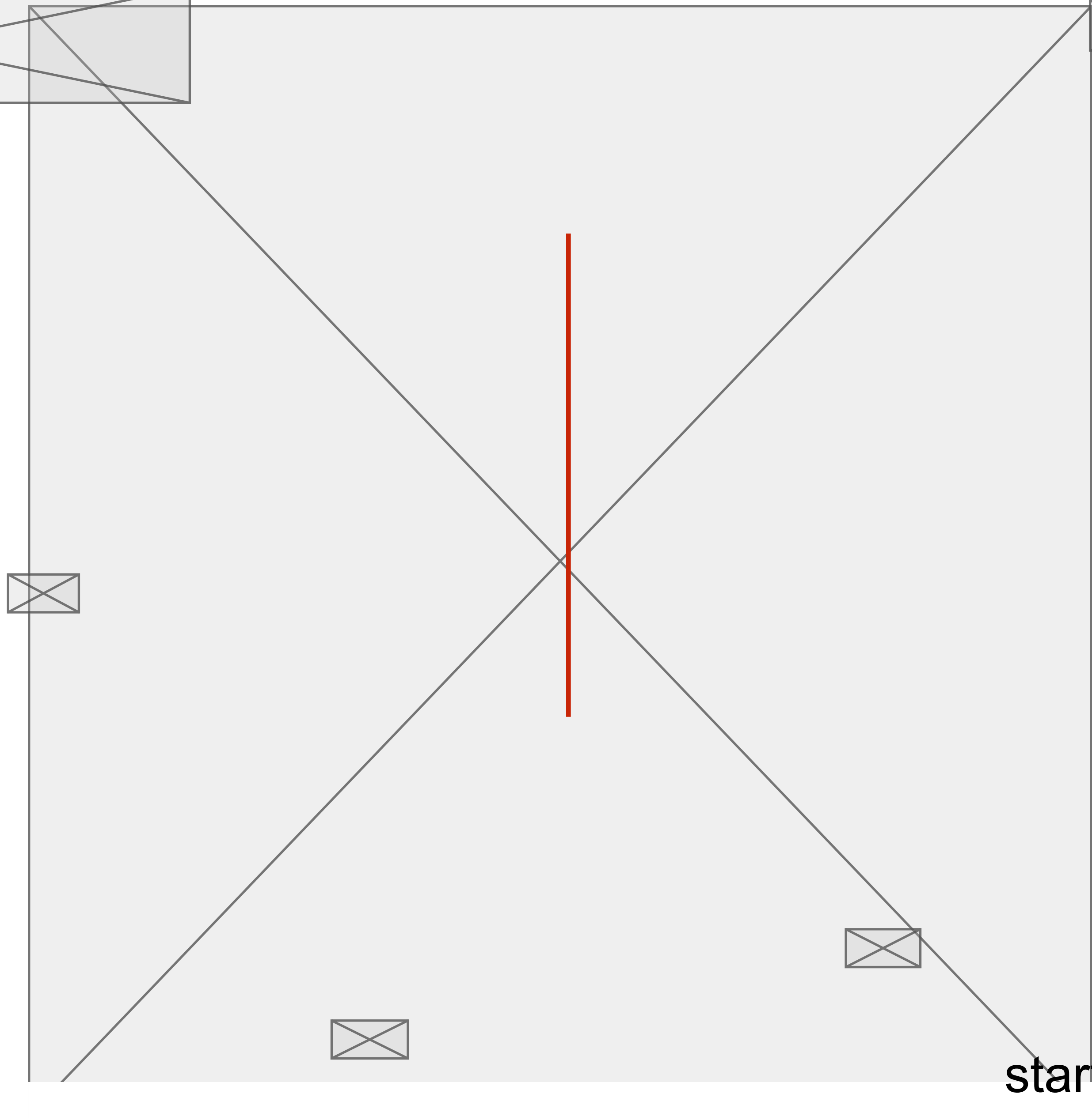
corrected for JPC low-pass filter →

start from at

stochastic



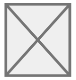
5 Quantum trajectories

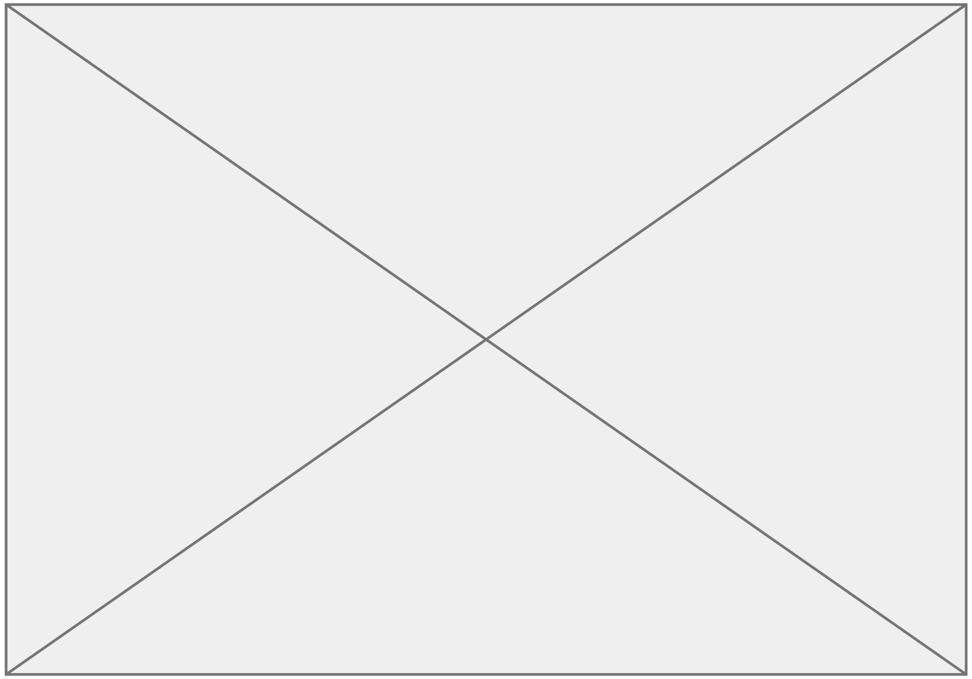


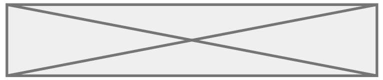
start from

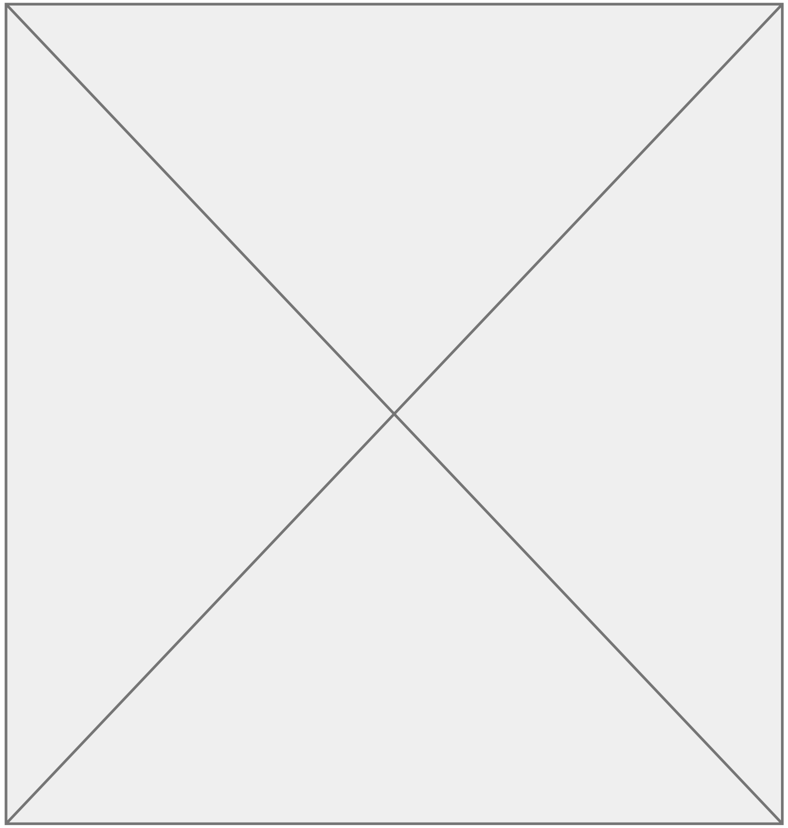
at

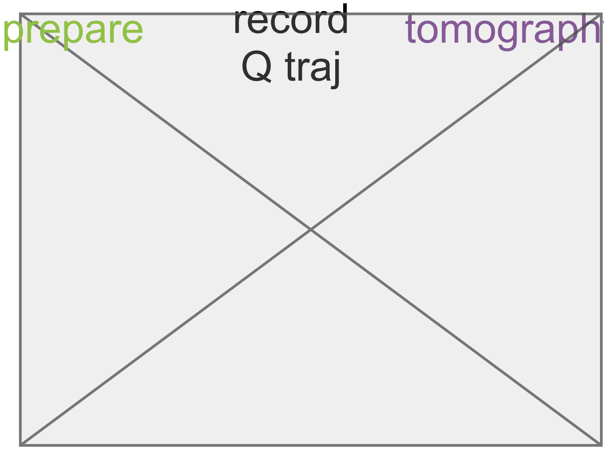
Trajectories vs tomography

from 







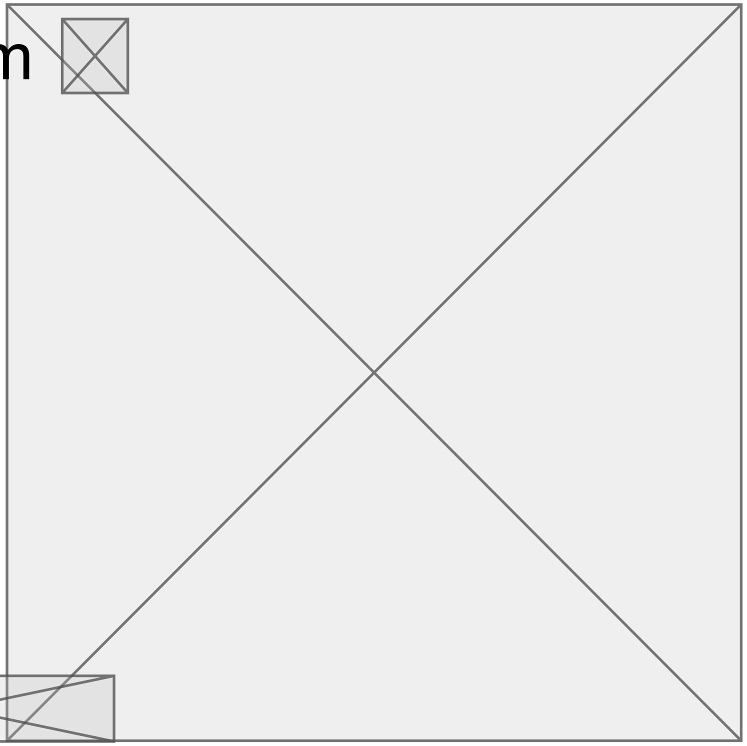


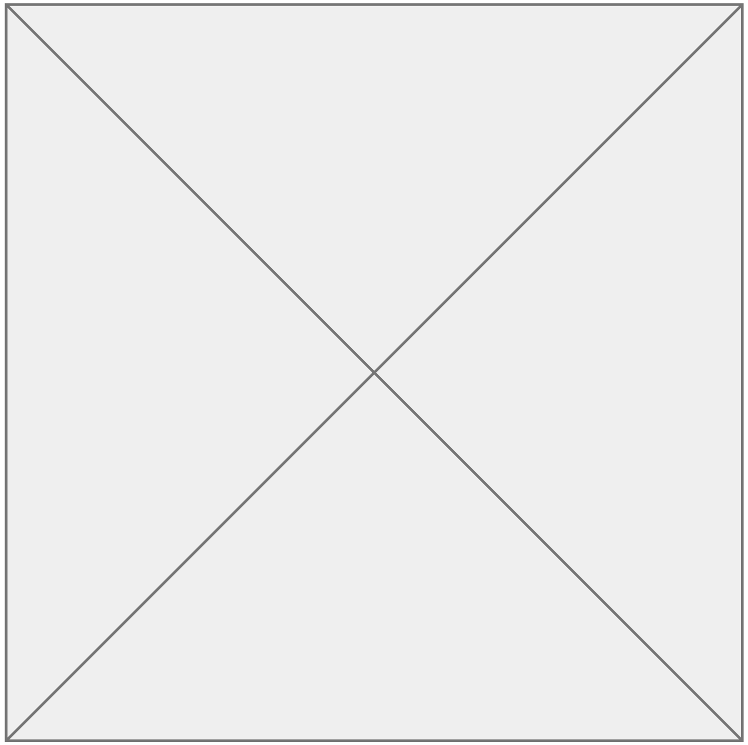
use dispersive shift on cavity

[Campagne-Ibarcq *et al.*, PRX, 2015]

Trajectory distribution

start from

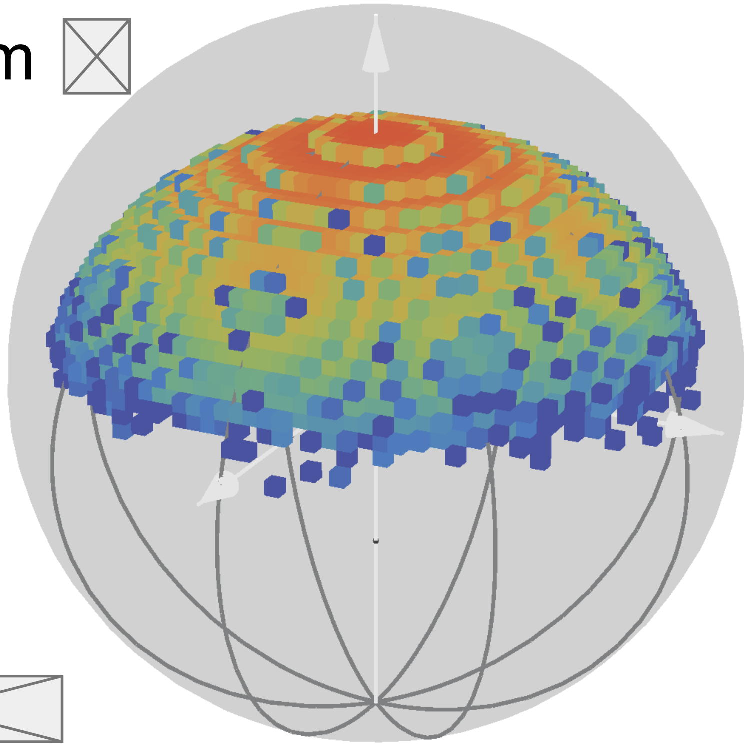




[Campagne-Ibarcq *et al.*, PRX, 2015]

Diffusion on a surface

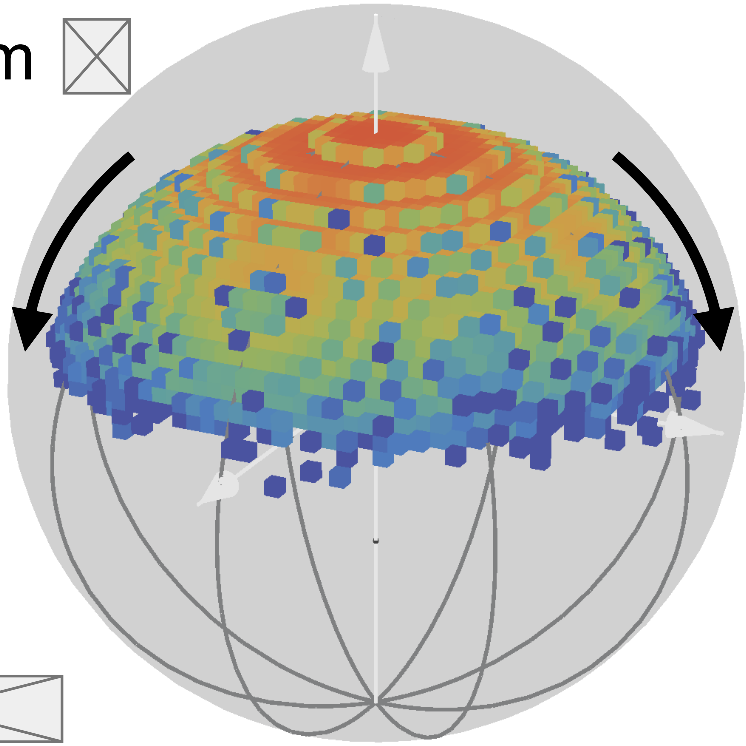
start from

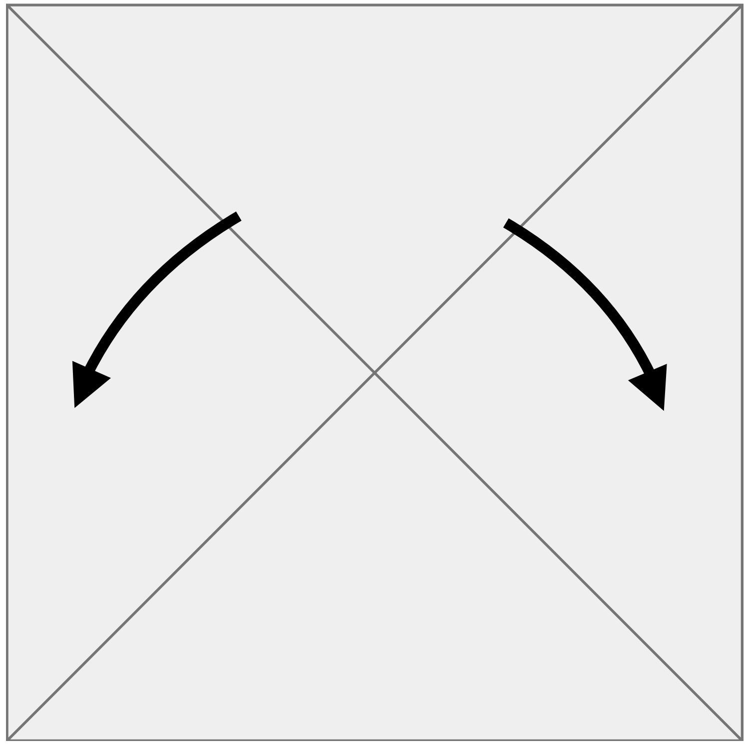


diffusion on a shrinking surface

Diffusion on a surface

start from

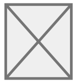




diffusion on a shrinking surface

- noise gradient

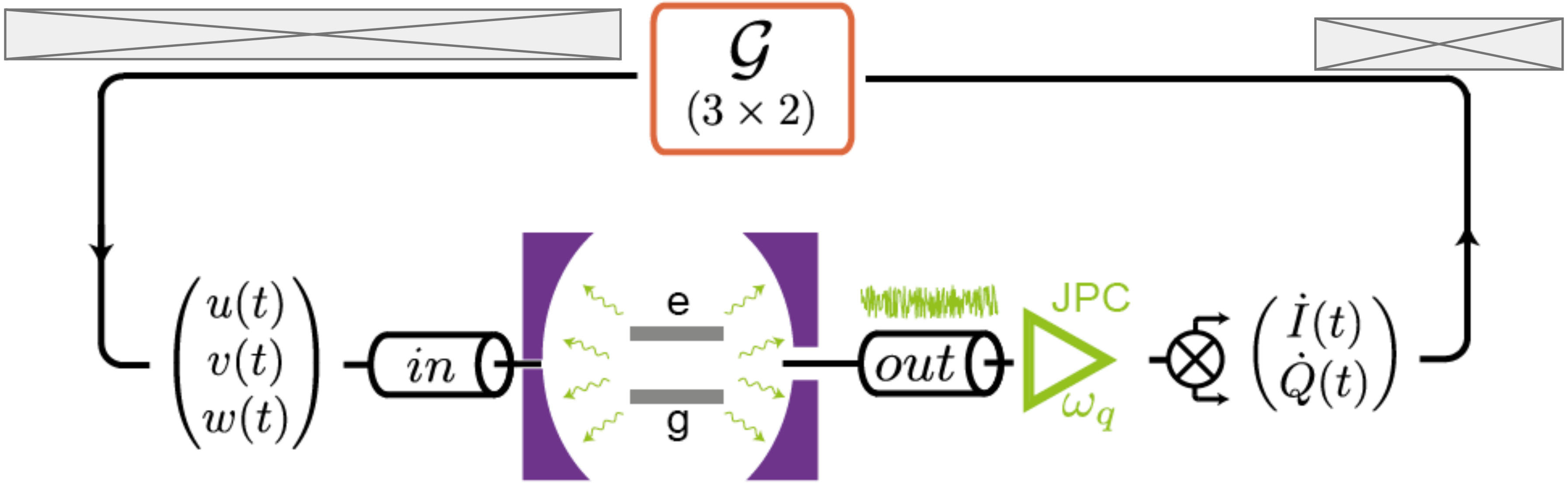
Trajectory distribution

start from 

Trajectory distribution

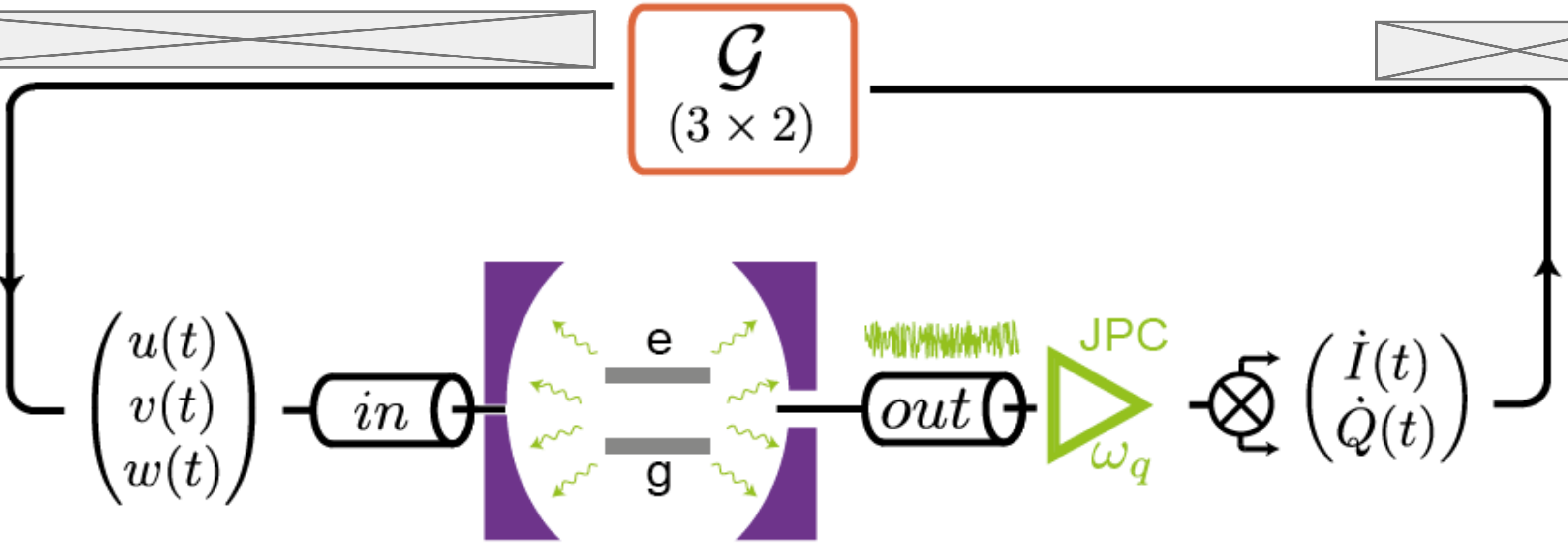
start from

Markovian feedback



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

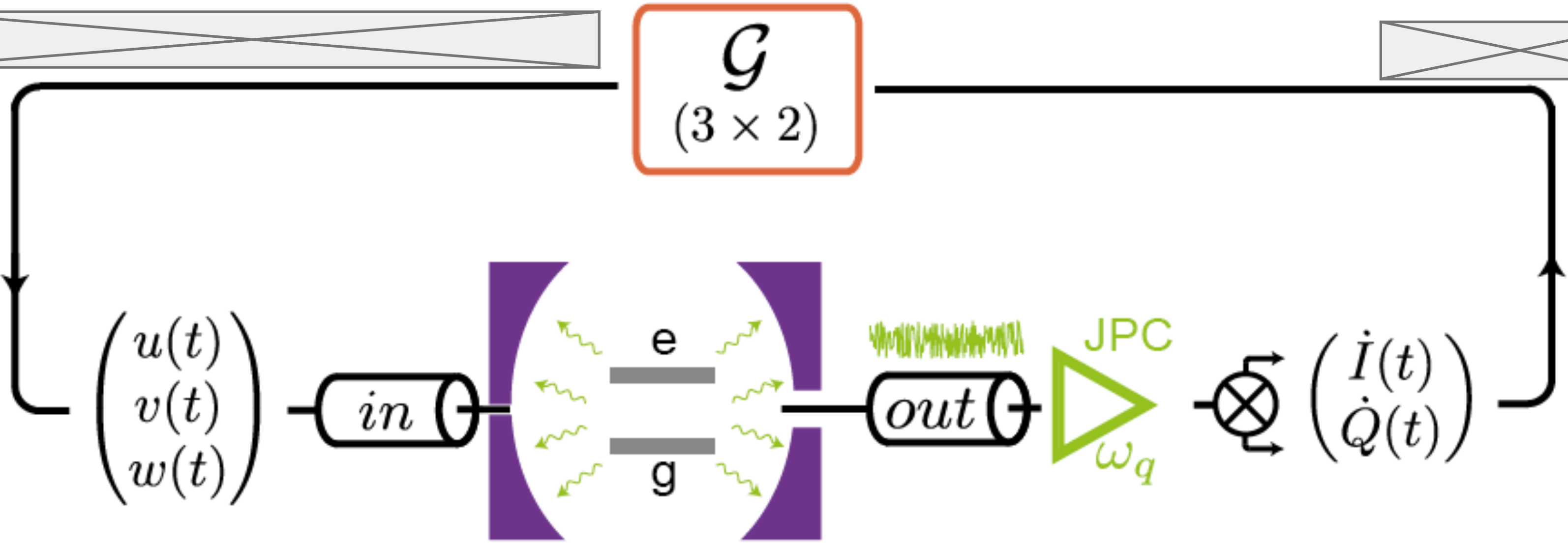
Markovian feedback



open-loop SME

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

Markovian feedback

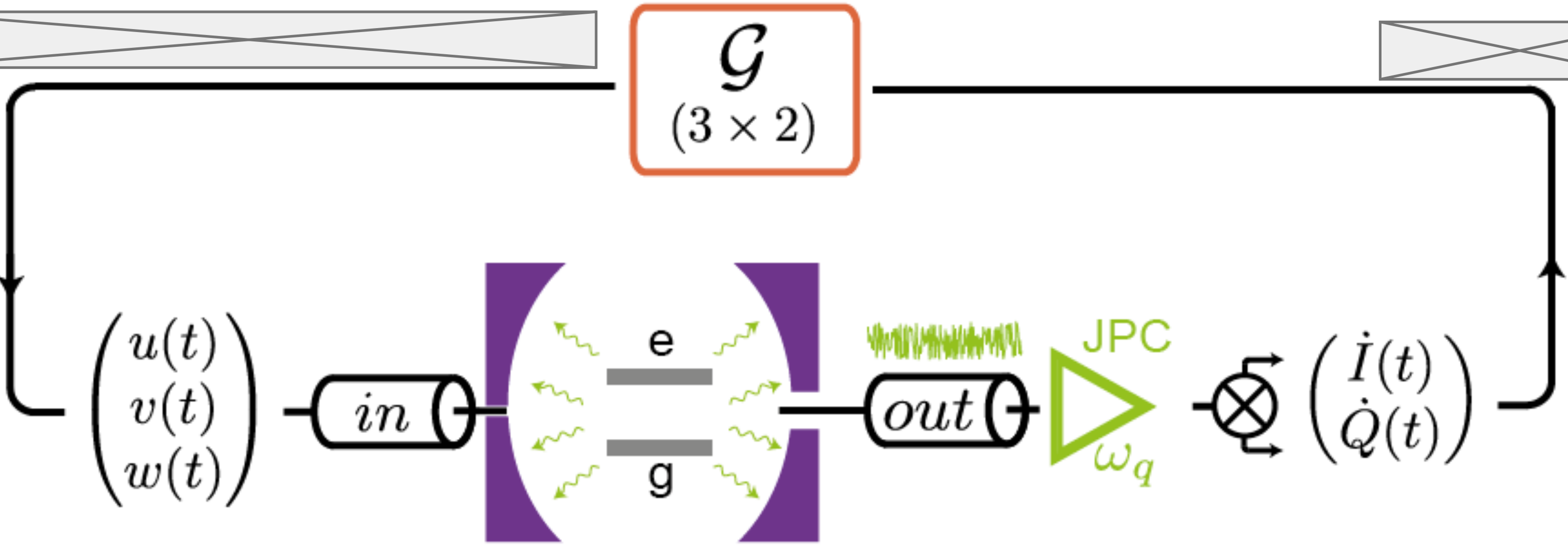


If

effective Lindblad equation

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

Markovian feedback



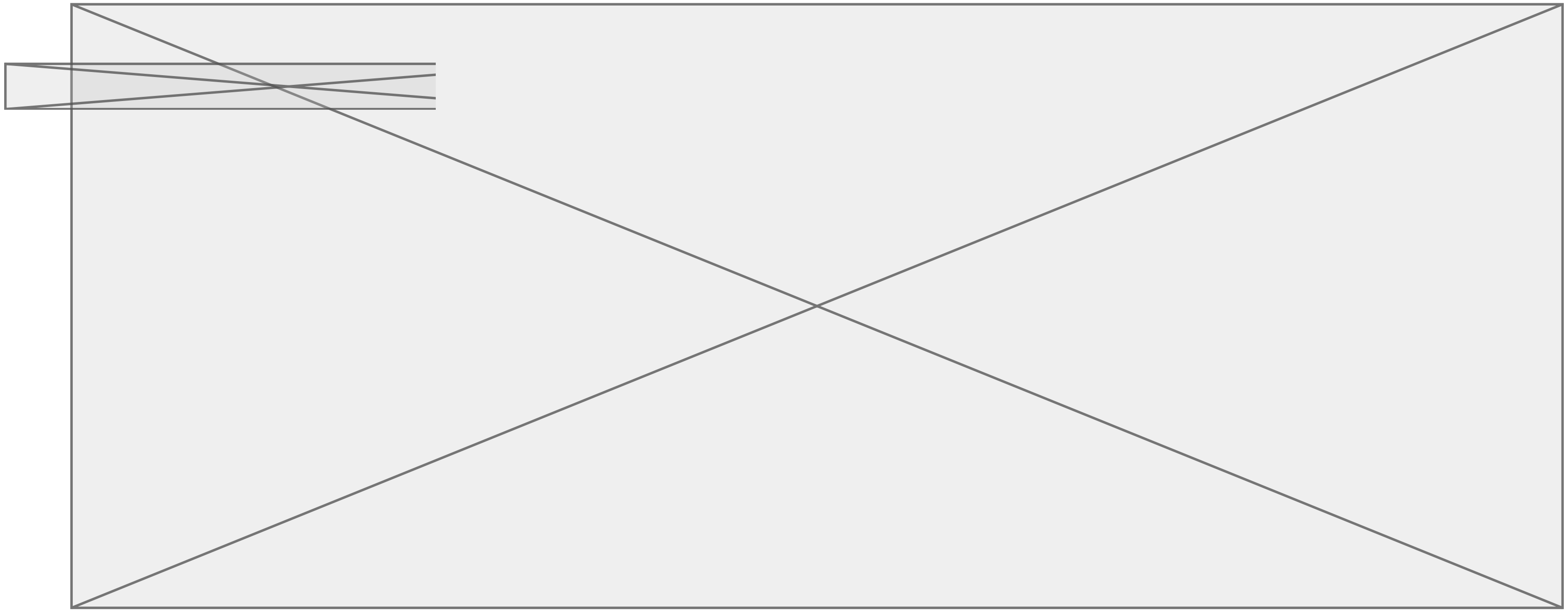
If

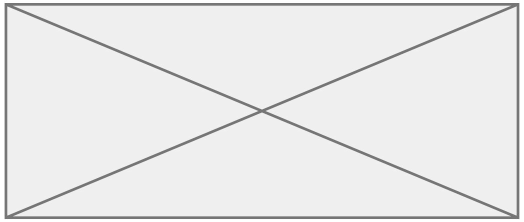
effective Lindblad equation

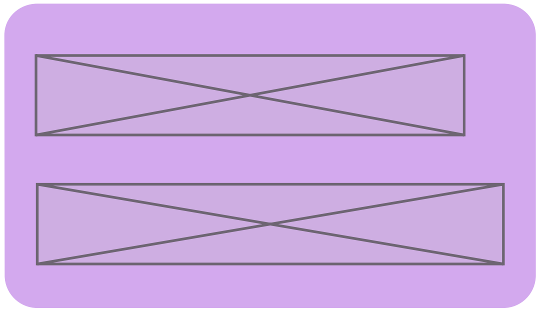
extra decoherence

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

Stabilizing |e>

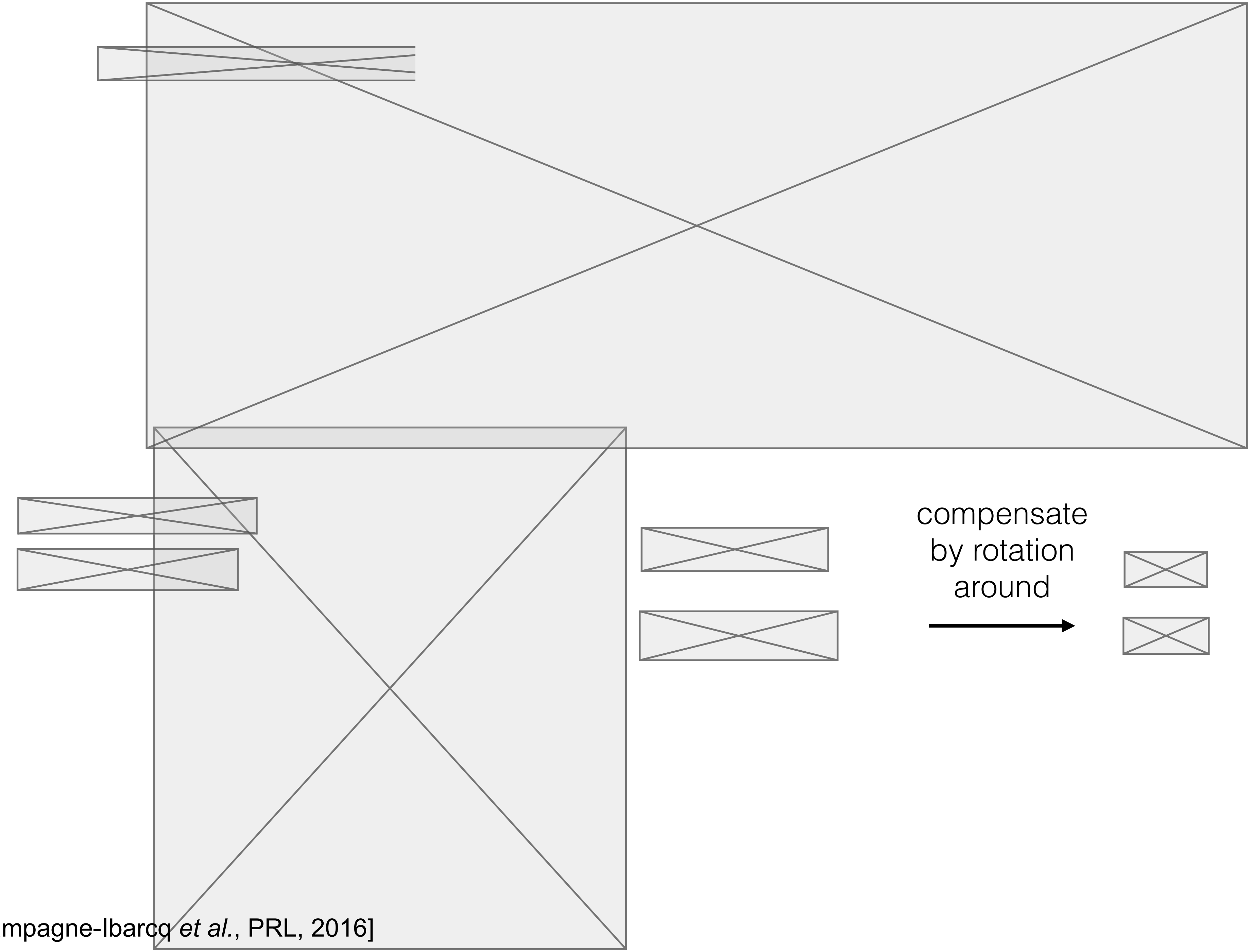






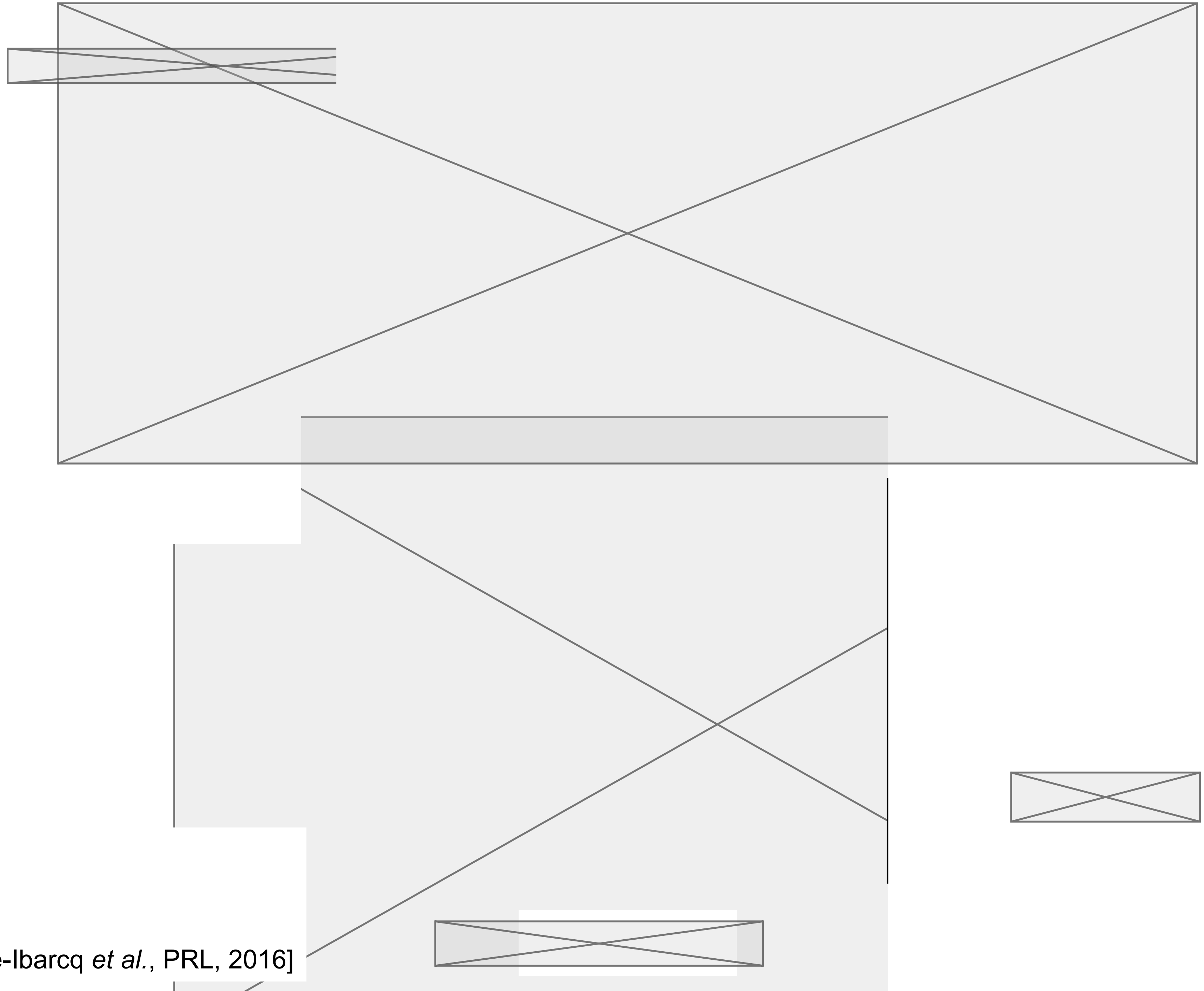
relaxation toward le> !

Stabilizing |e>



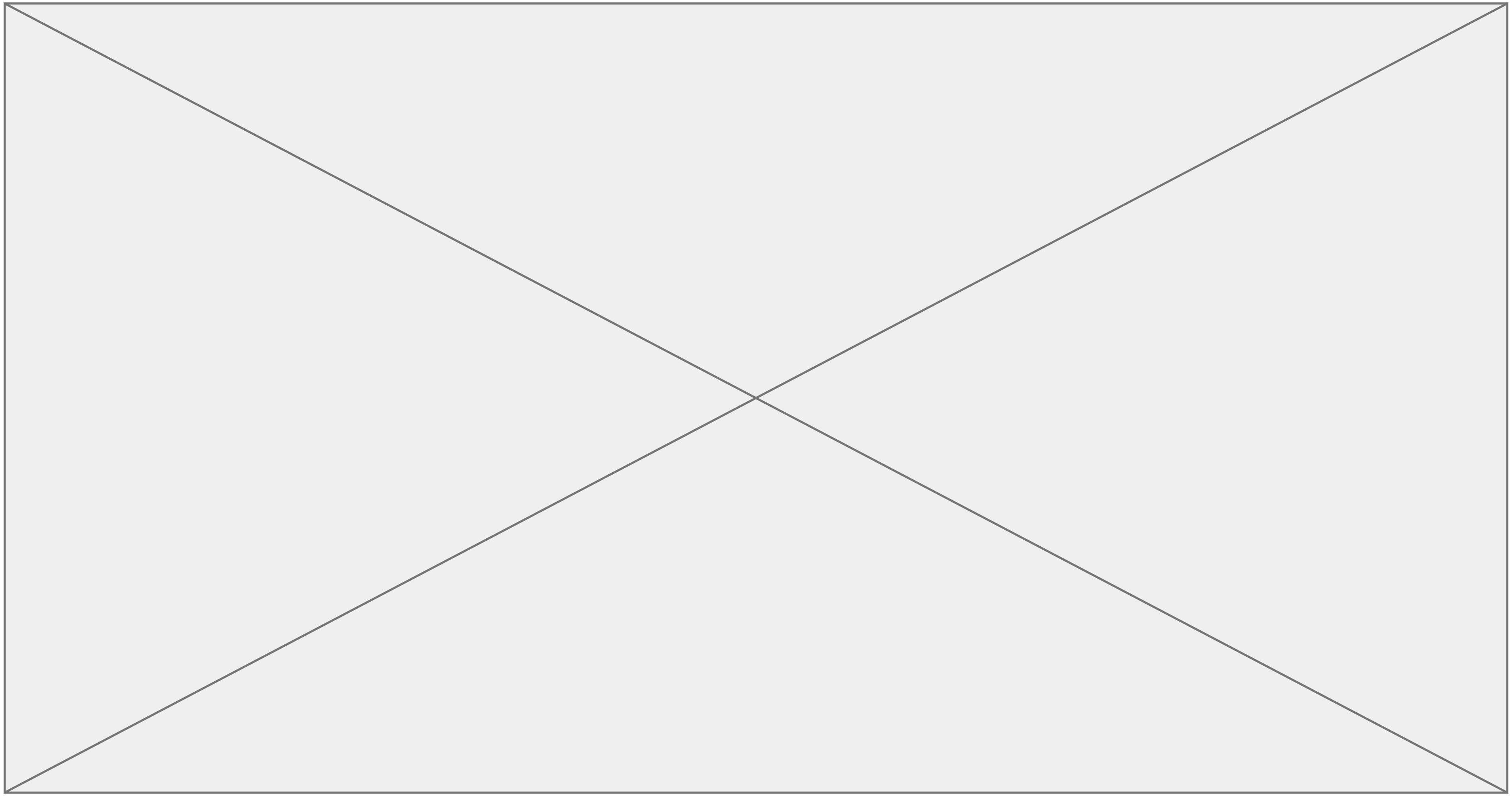
[Campagne-Ibarcq *et al.*, PRL, 2016]

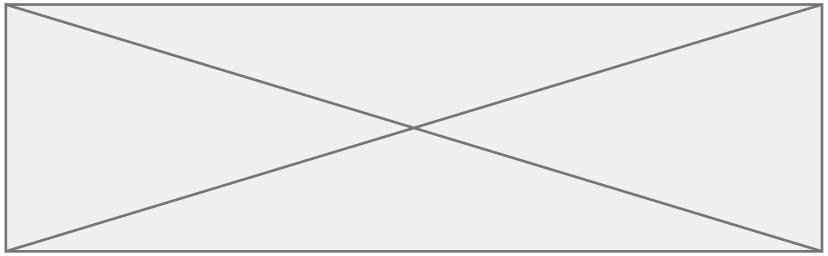
Stabilizing |e>

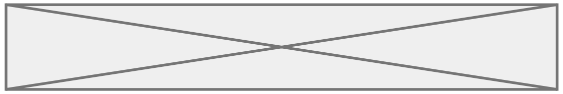


[Campagne-Ibarcq *et al.*, PRL, 2016]

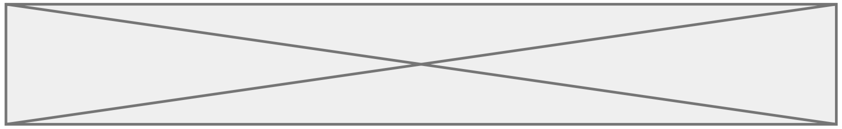
Stabilizing an arbitrary state



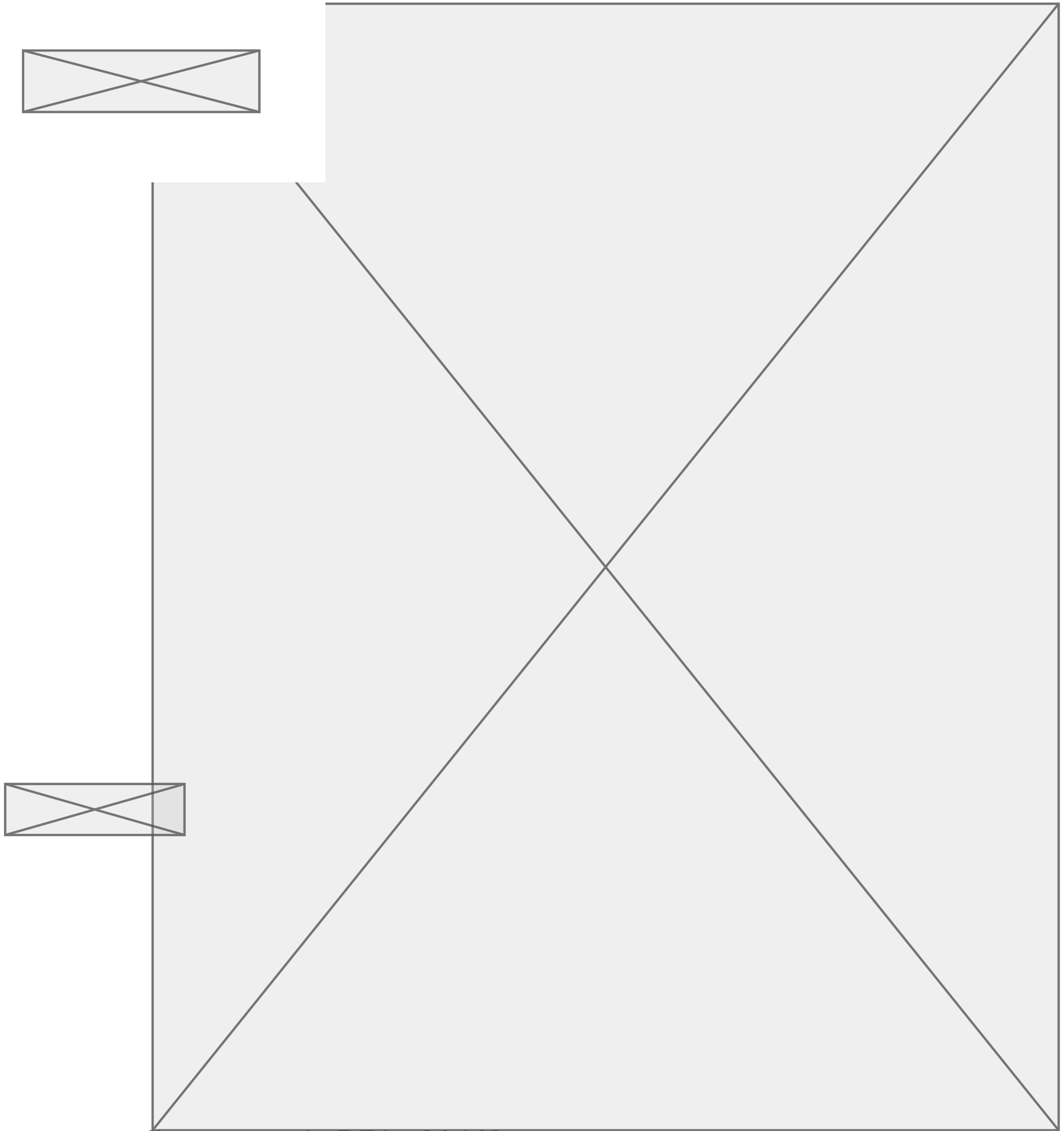




stabilizes



Stabilizing an arbitrary state



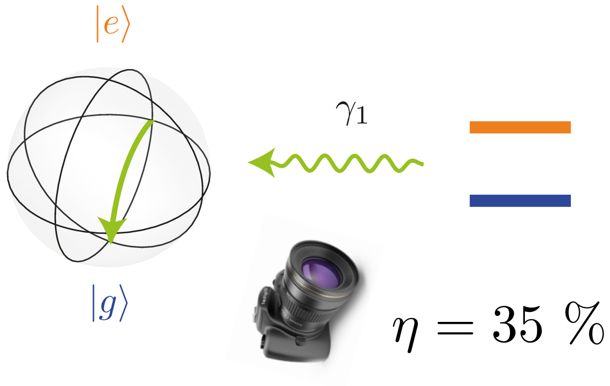
Simulations
inaccurate
for

(include efficiency,
delay, meast
induced dephasing,
detection BW…)

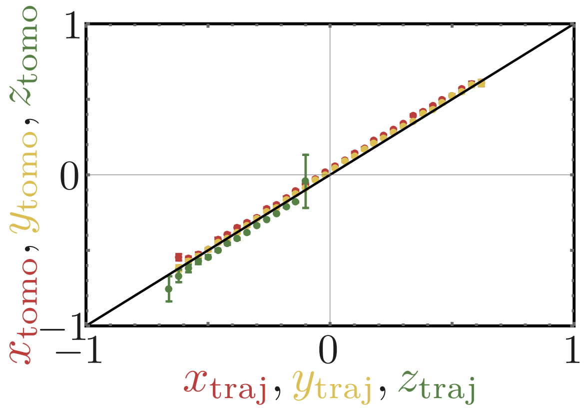
[Campagne-Ibarcq *et al.*, PRL, 2016]

Conclusion

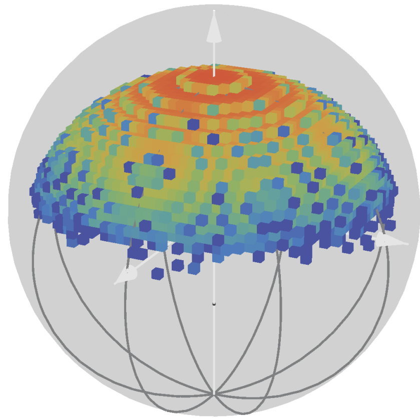
Efficiently monitored relaxation channel



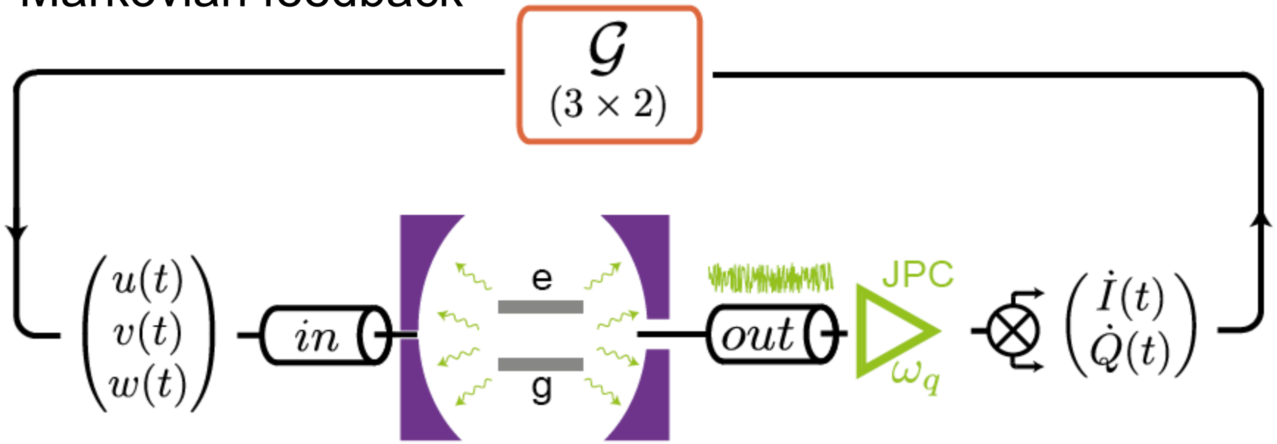
Validated by tomography



Trajectories diffuse on a surface



Markovian feedback



first MIMO implementation in quantum regime

→ arbitrary state stabilization
engineered dissipation
complementary to σ_z based feedback
large variety of systems