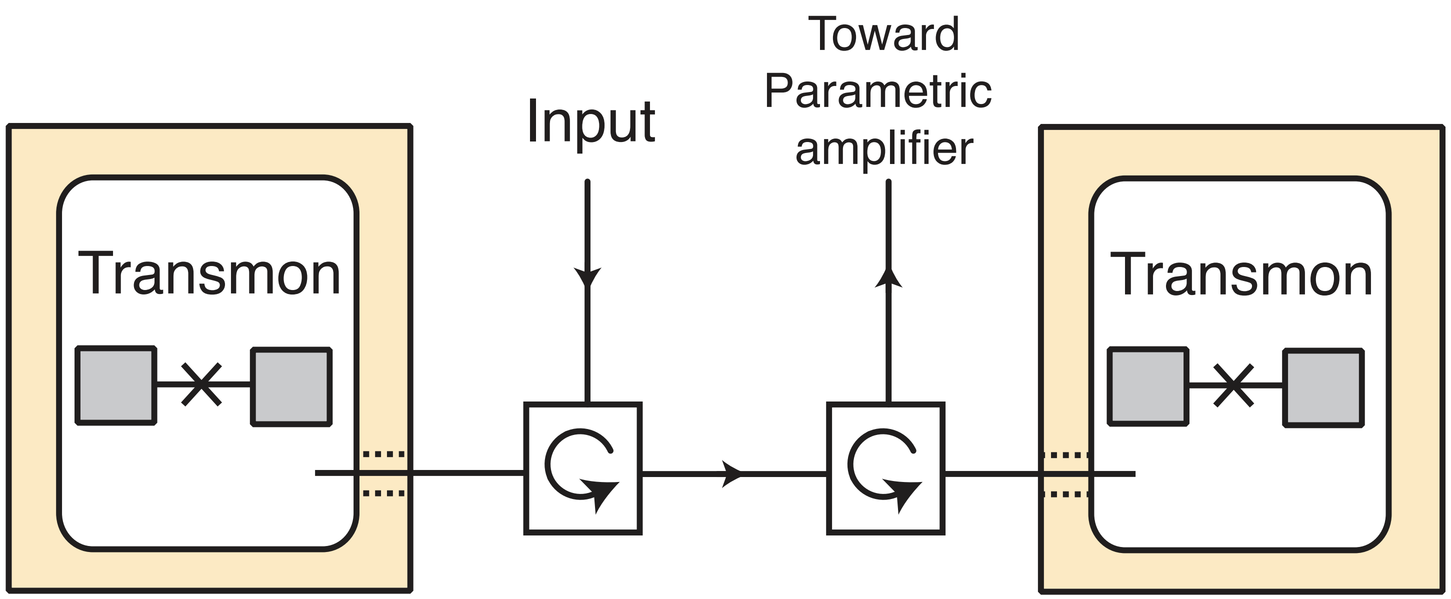
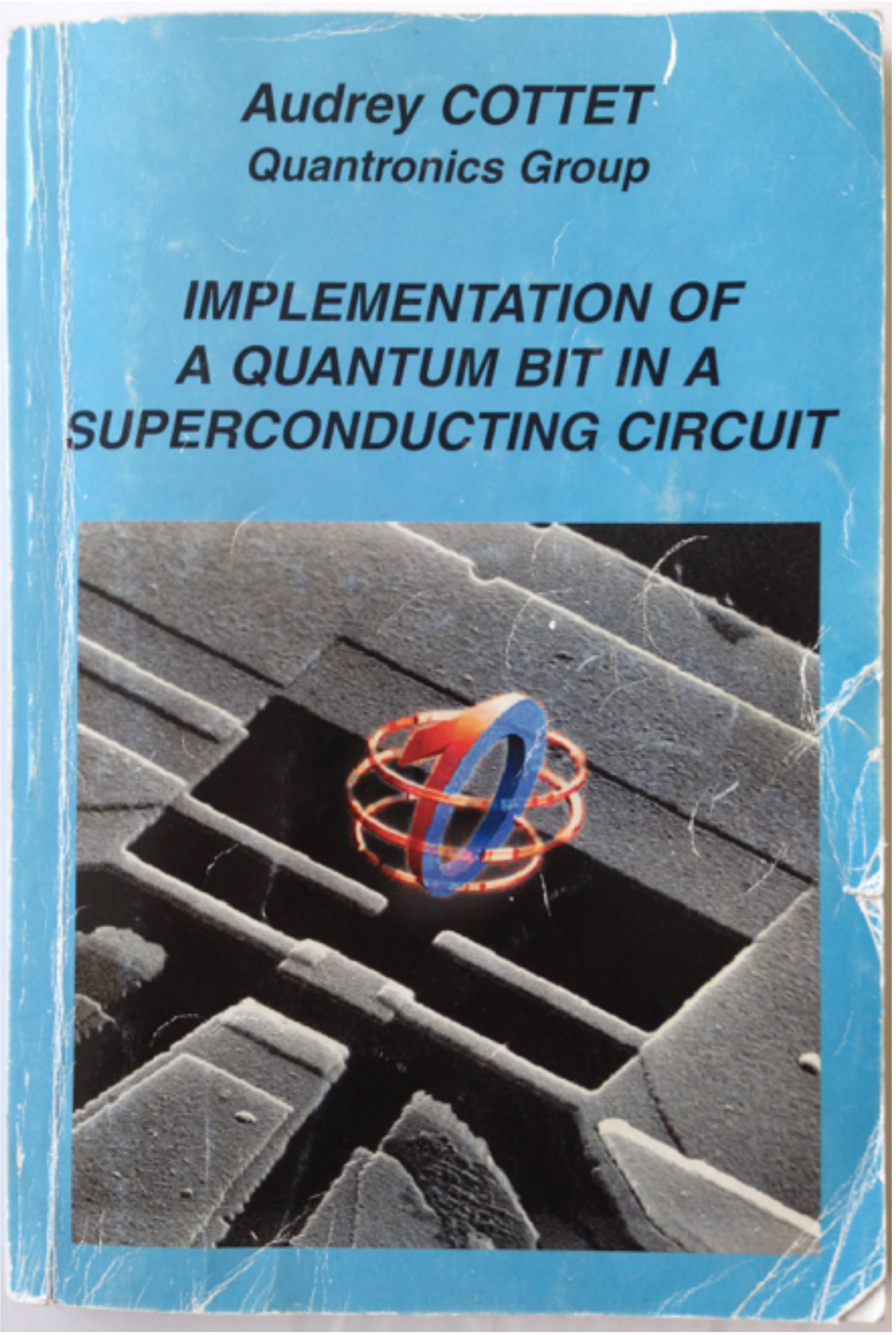
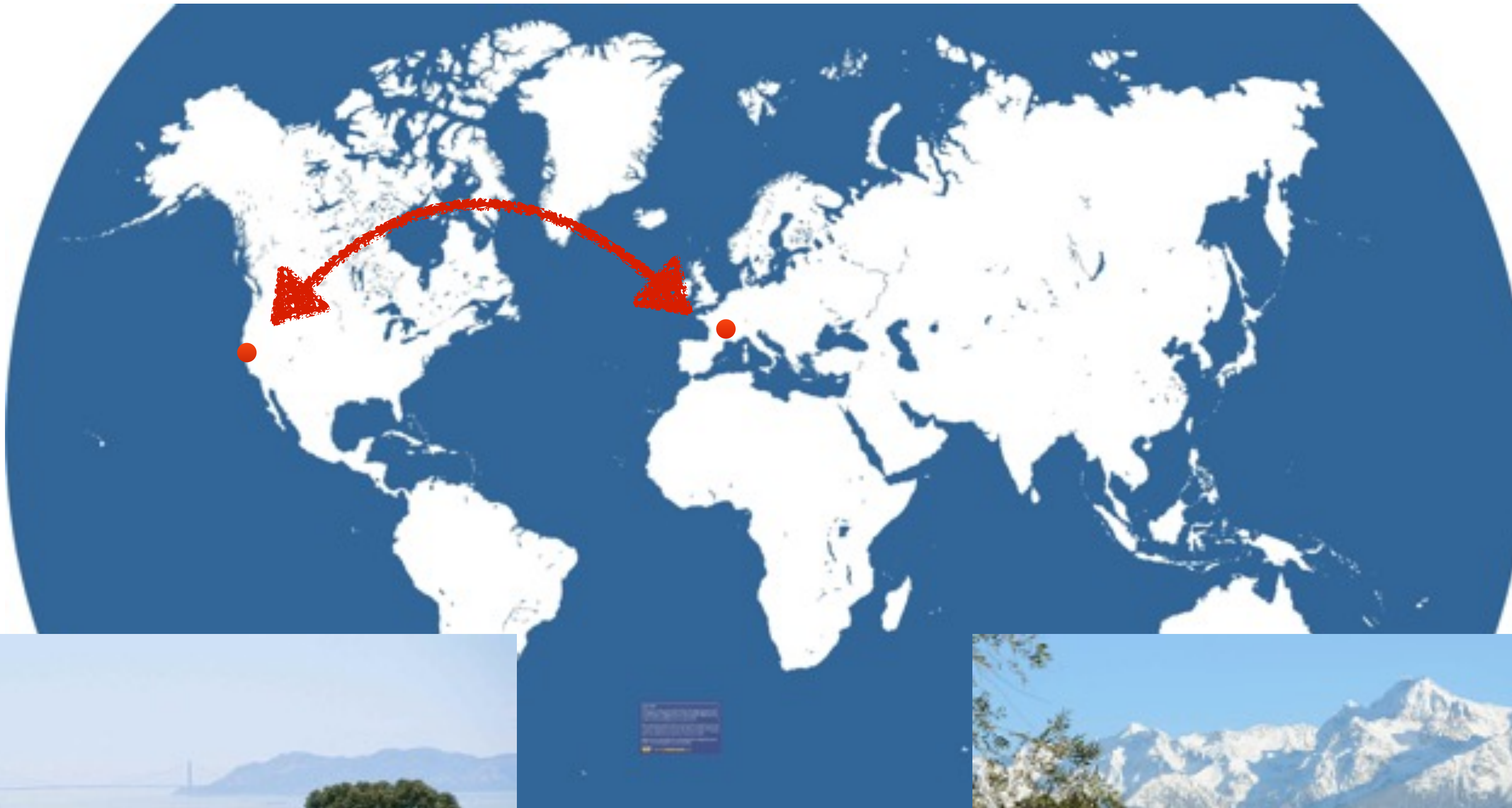
Continuous measurement of remote superconducting qubits:
quantum trajectories and statistics



N. Roch
Neel Institute, Grenoble, France

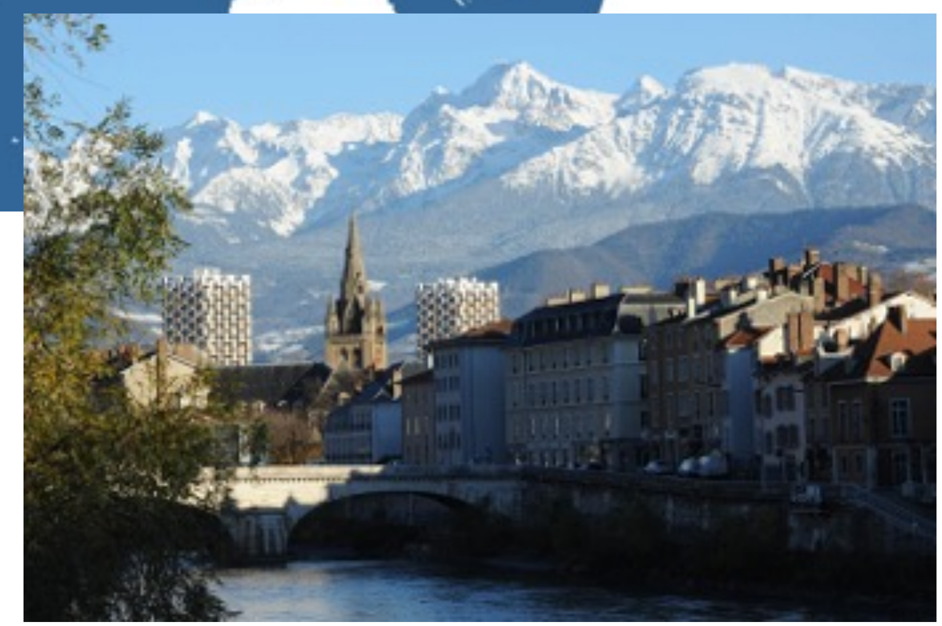
Happy Birthday “Quantro”





Berkeley

Grenoble



Thank you !

Quantum Nanoelectronics Laboratory, Department of Physics, UC – Berkeley
M.E. Schwartz, C. Macklin, A. Eddins I. Siddiqi

Tata Institute of Fundamental Research, Mumbai, India
R. Vijay

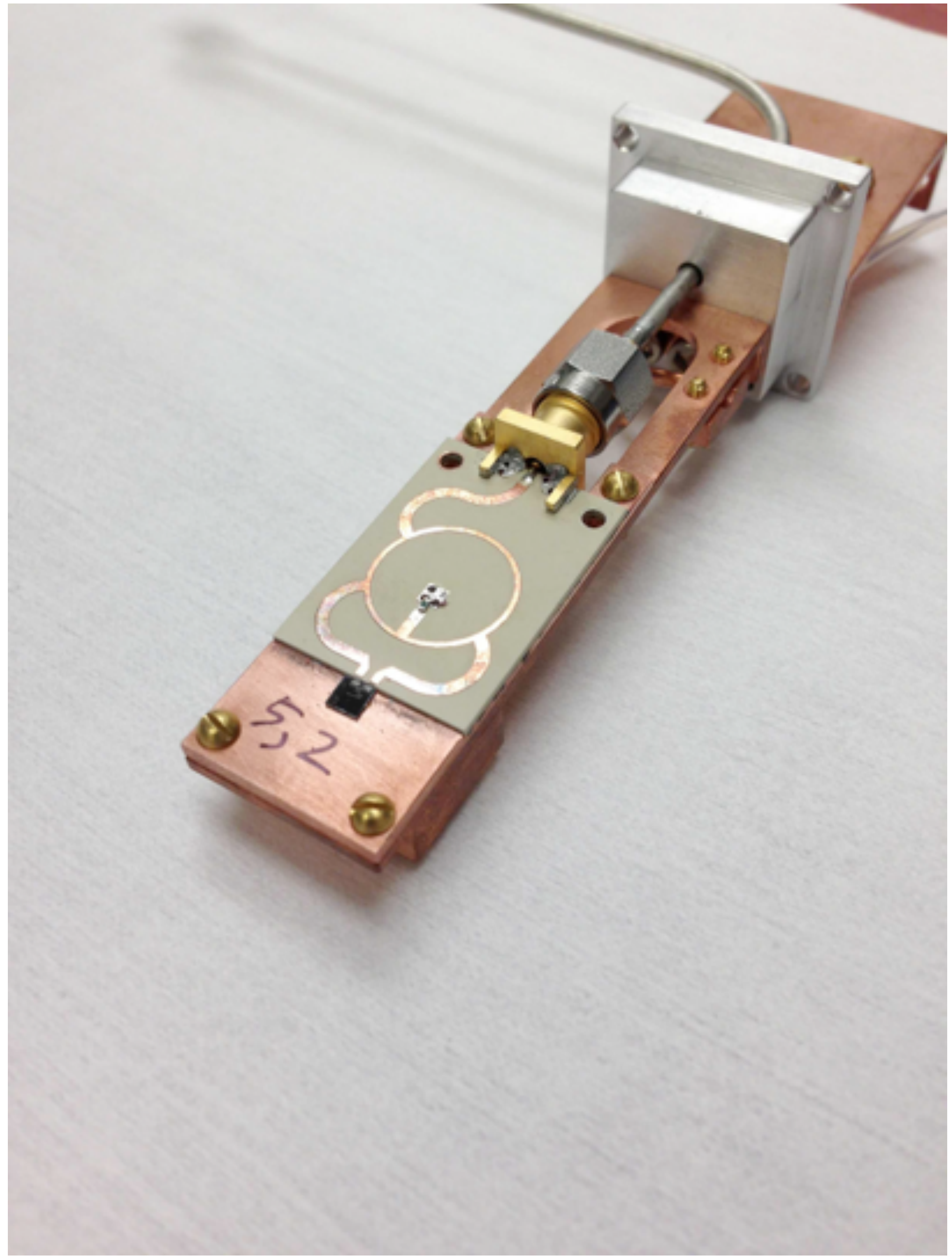
Theory Collaborators:

UC-Berkeley: F. Motzoi, K. B. Whaley

UC-Riverside: A. Korotkov

Sandia National Laboratories : M. Sarovar

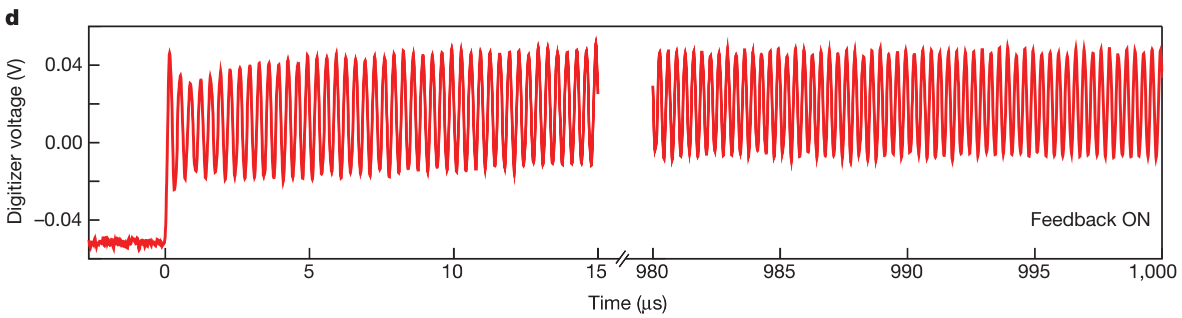
Continuous measurement in cQED



Parametric Amplifier

Continuous measurement in cQED

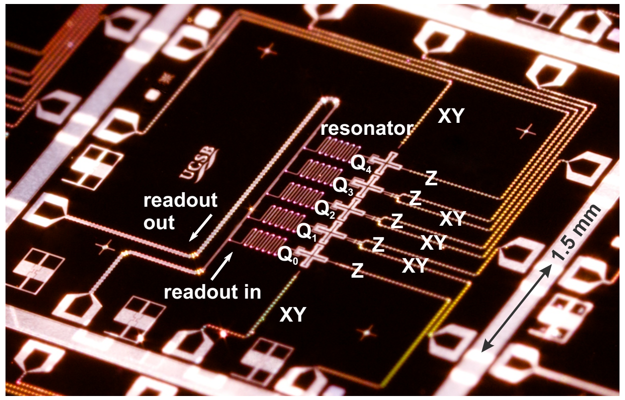
Q Feedback



Vijay et al., **Nature** (2012)

Berkeley, Yale, Delft, ENS-Paris, ETHZ…

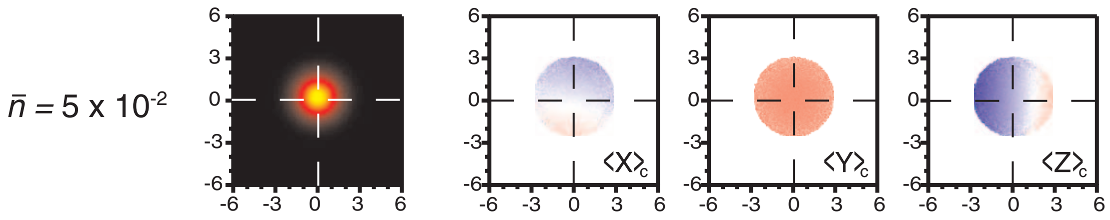
High-fidelity readout and Multiplexing



Barends et al., **Nature** (2014)

Santa Barbara, Berkeley, Yale,
Delft, ENS-Paris, ETHZ, Wisconsin, Princeton, IBM…

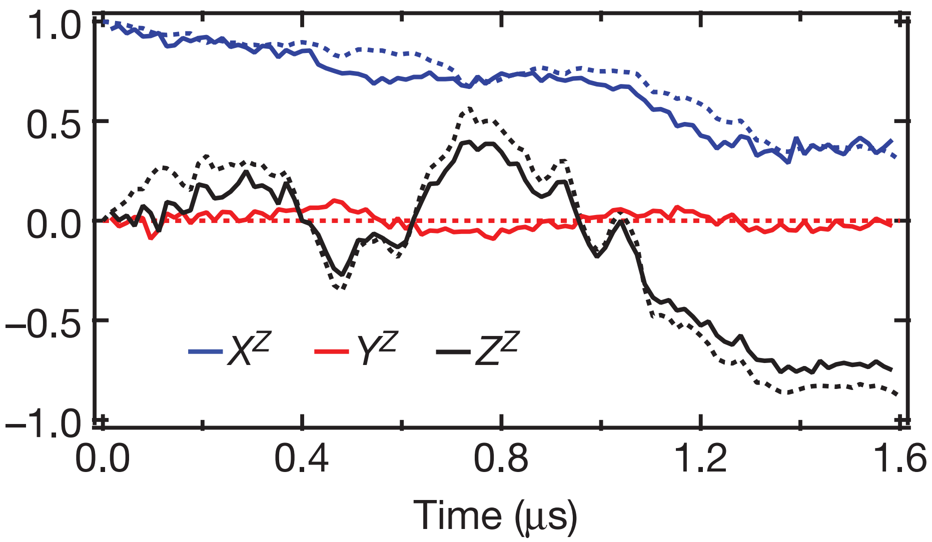
Weak measurements



Hatridge et al., **Science** (2013)

Yale, Santa Barbara, ENS-Paris, Delft…

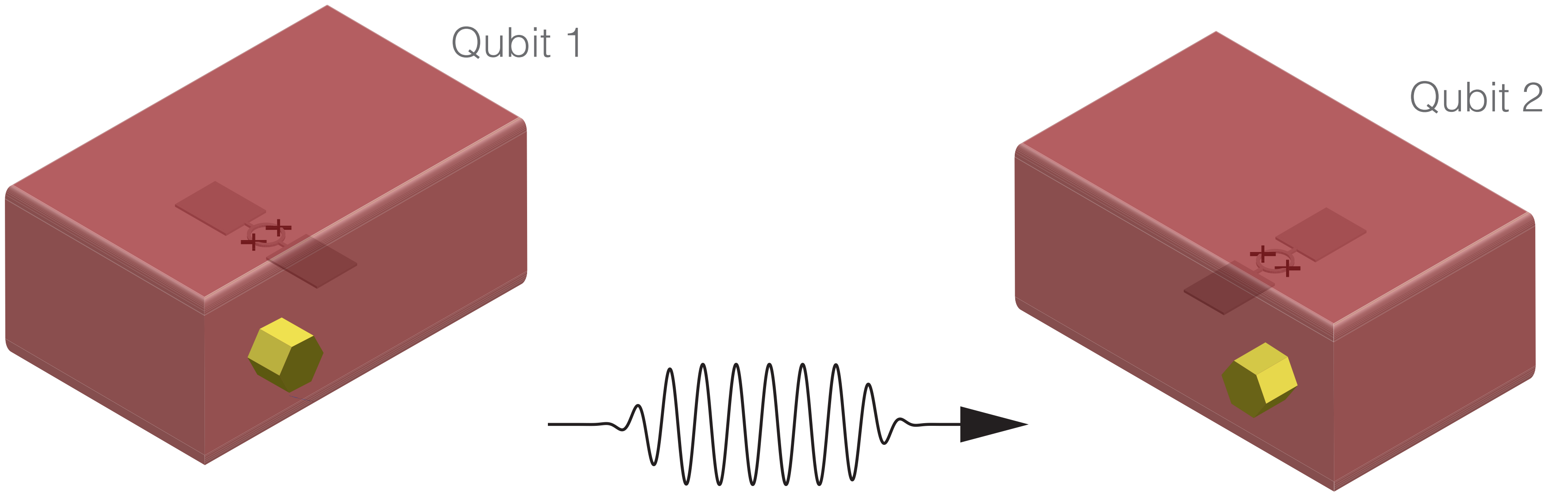
Quantum trajectories



Murch et al., **Nature** (2014)

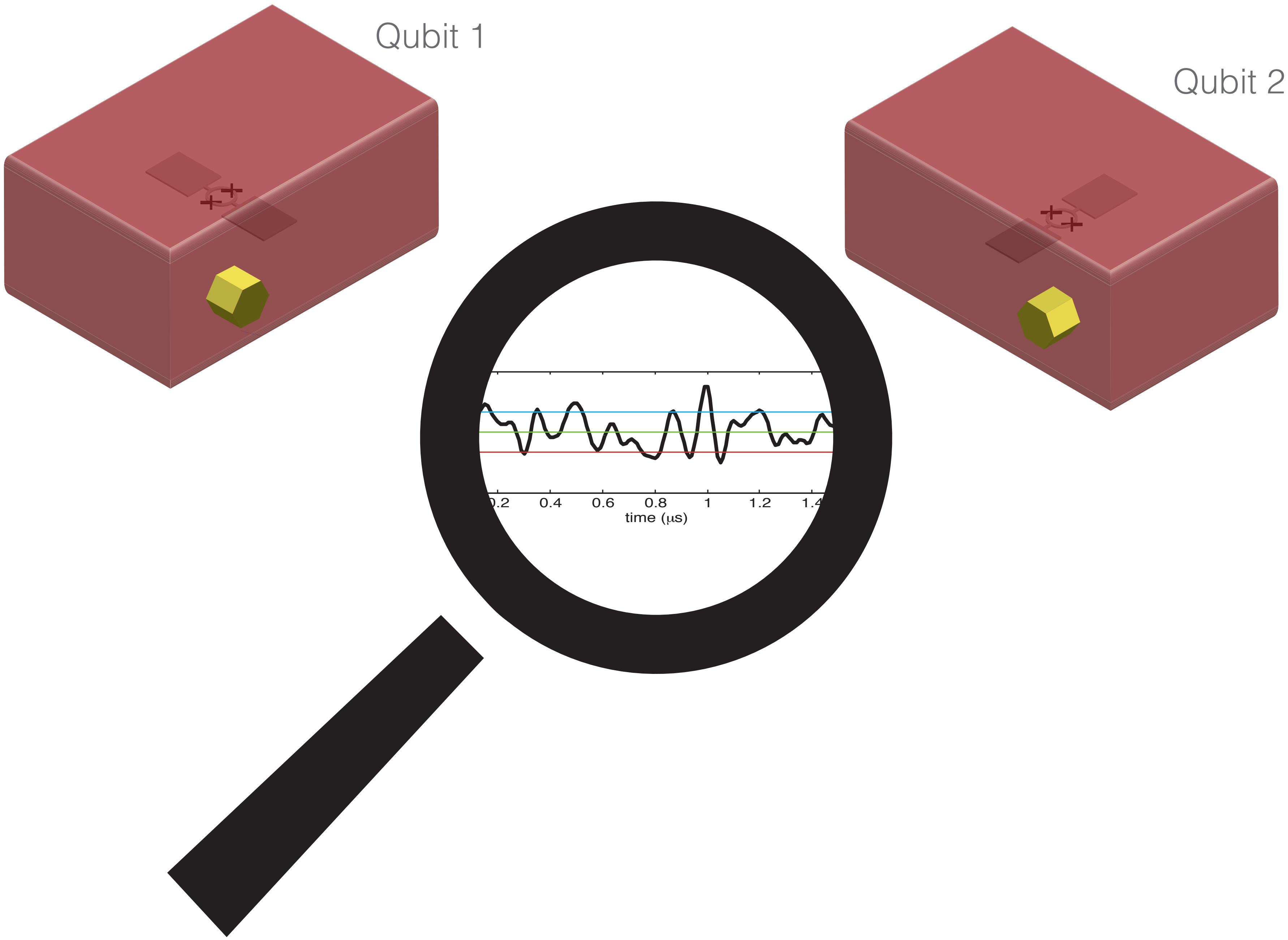
Berkeley, Delft, Yale, ENS-Paris…

Continuous measurement in cQED



Remote entanglement and measurement

Continuous measurement in cQED



Remote entanglement and measurement

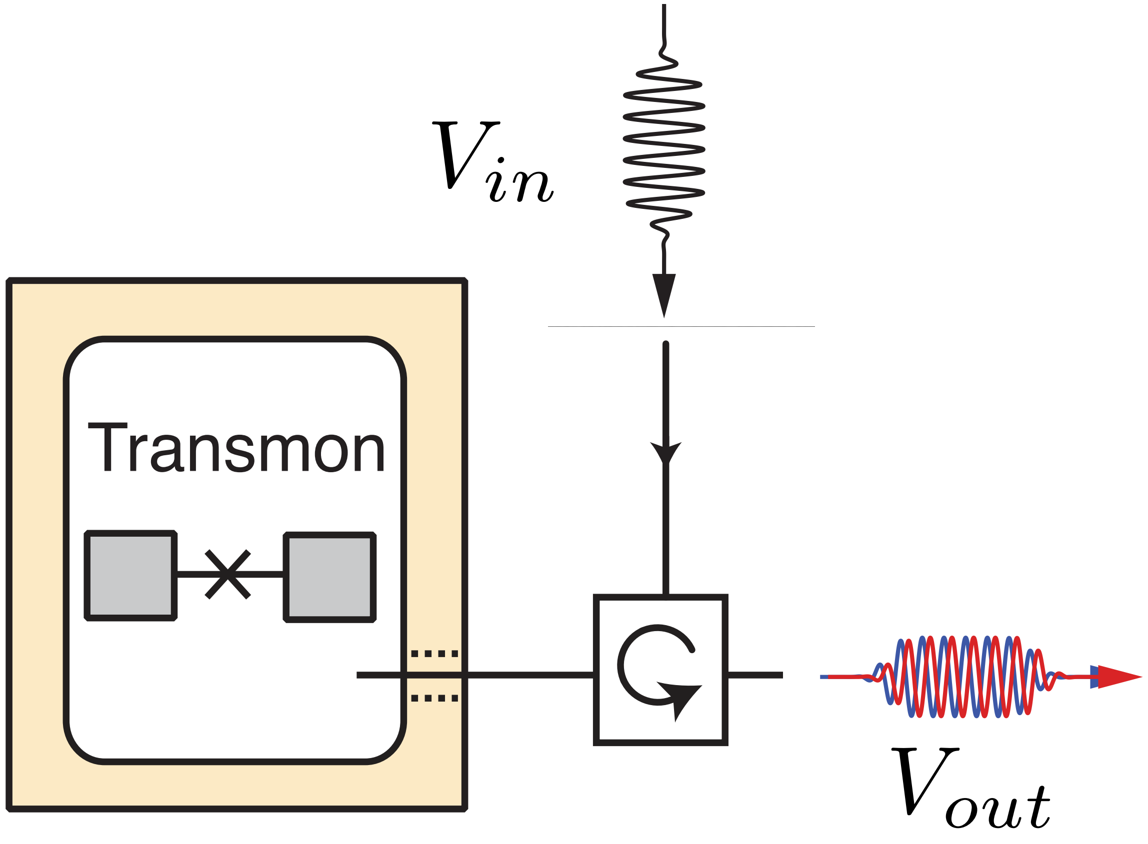
Outline

I. Useful definitions

II . Diffusive measurements to generate entanglement

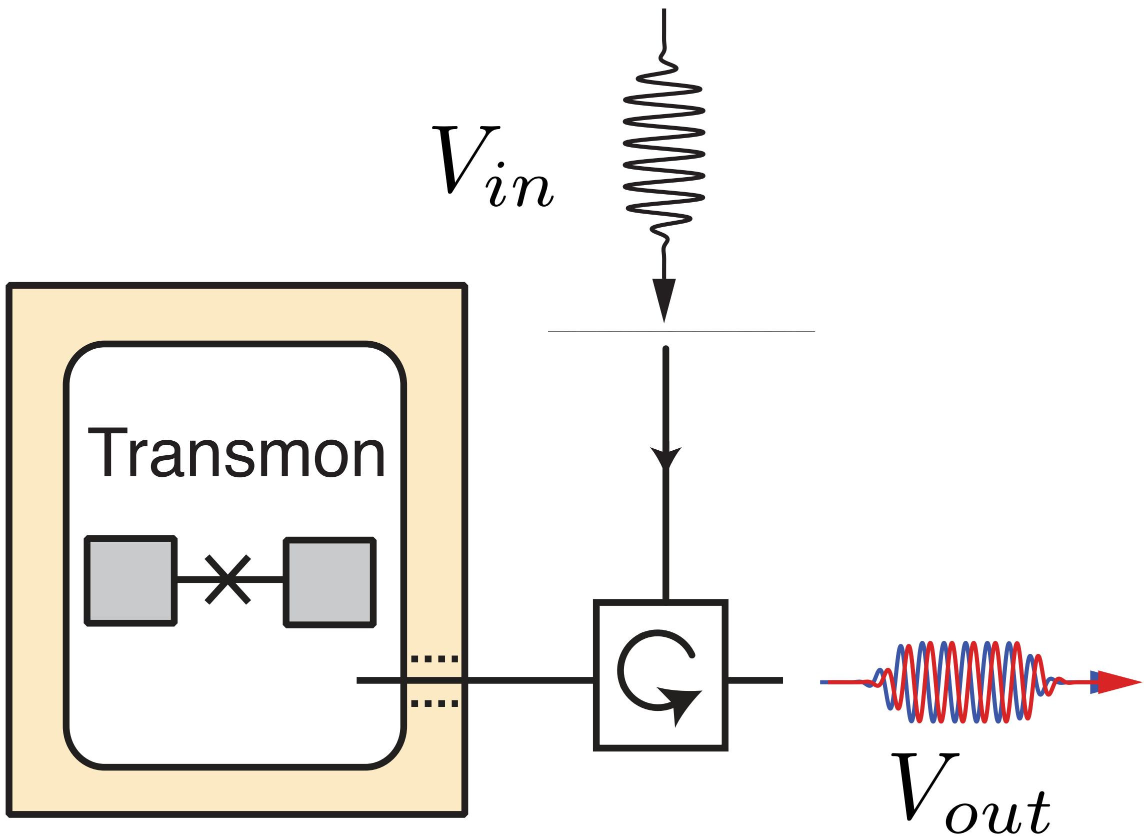
III. Quantum trajectories and entanglement

Quantum measurement: cQED



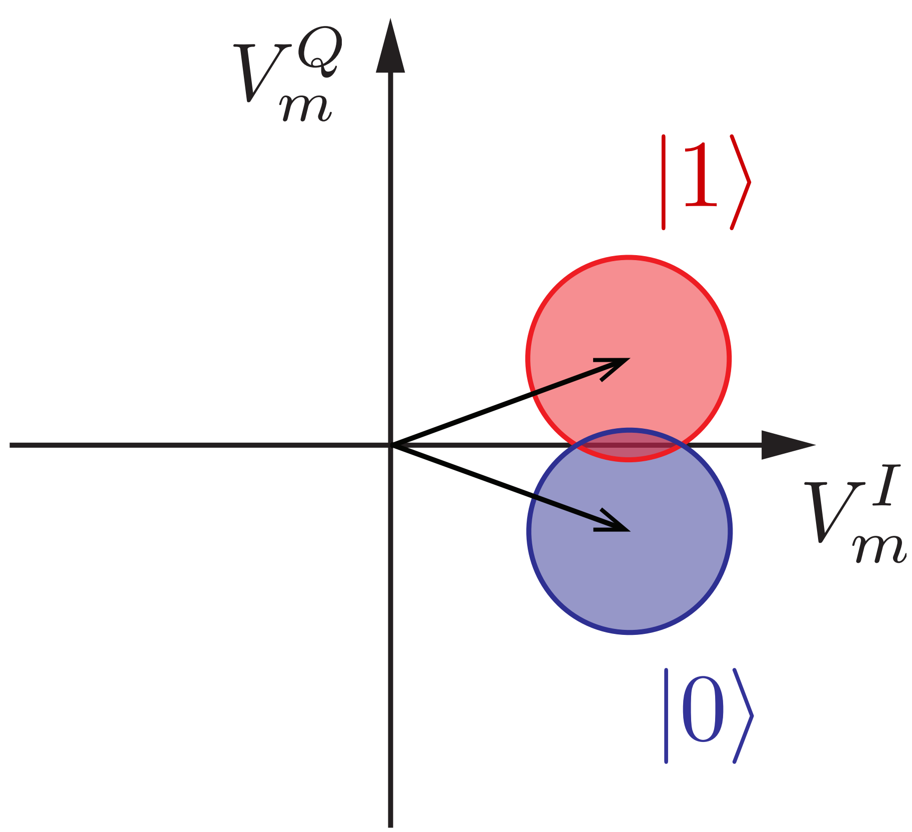
$$V_m = \frac{1}{\Delta t}\int_0^{\Delta t} V_{out}(t)dt$$

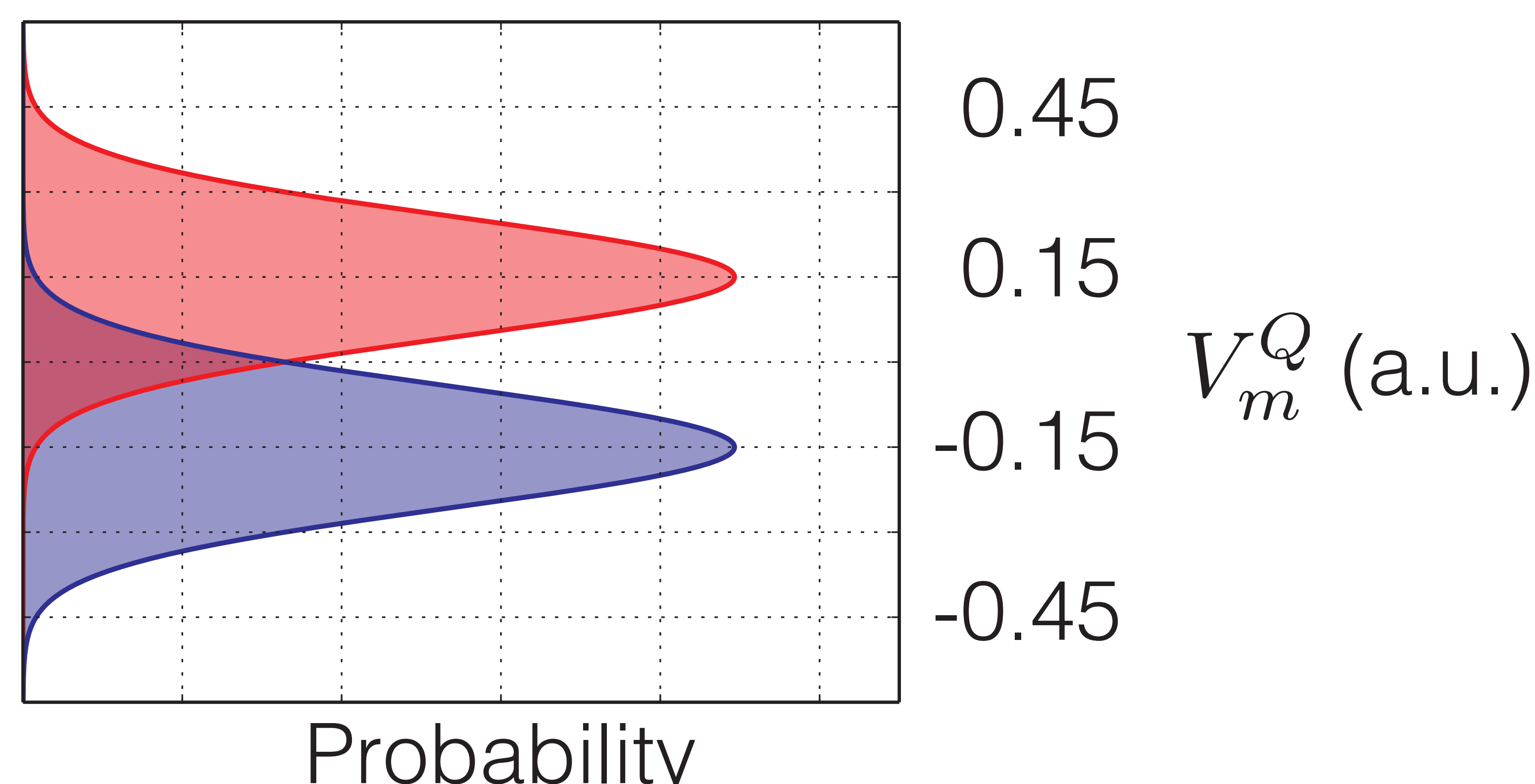
Quantum measurement: cQED



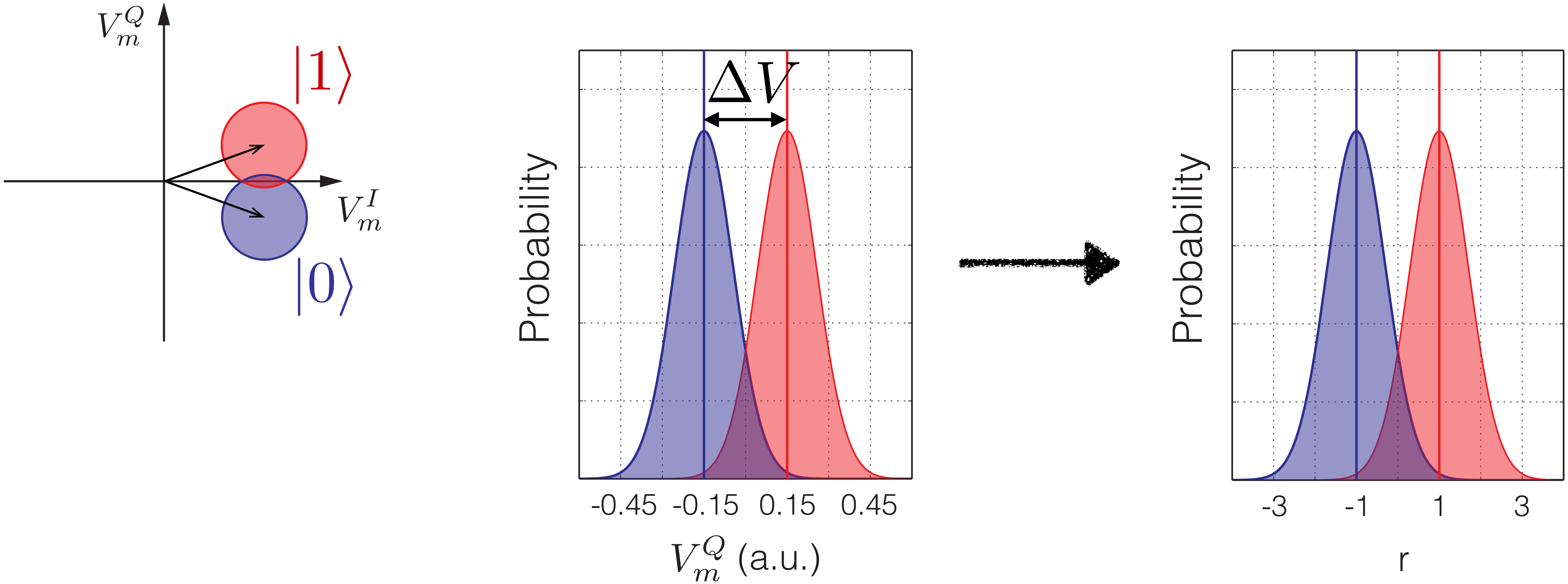
$$V_m = \frac{1}{\Delta t}\int_0^{\Delta t} V_{out}(t)\,dt$$

Histograms of V_m





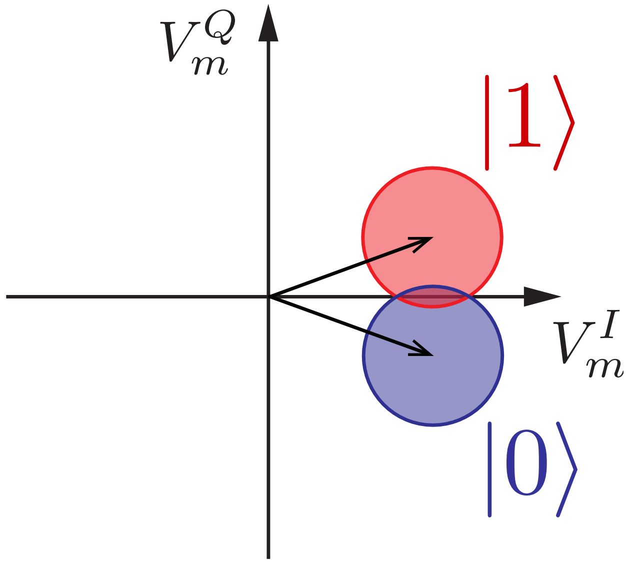
Quantum measurement: cQED

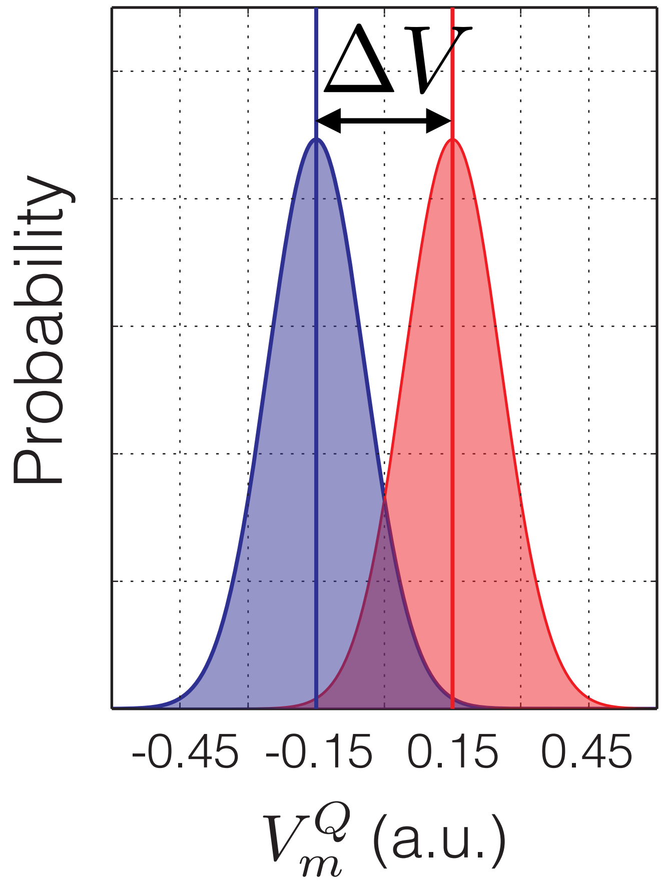


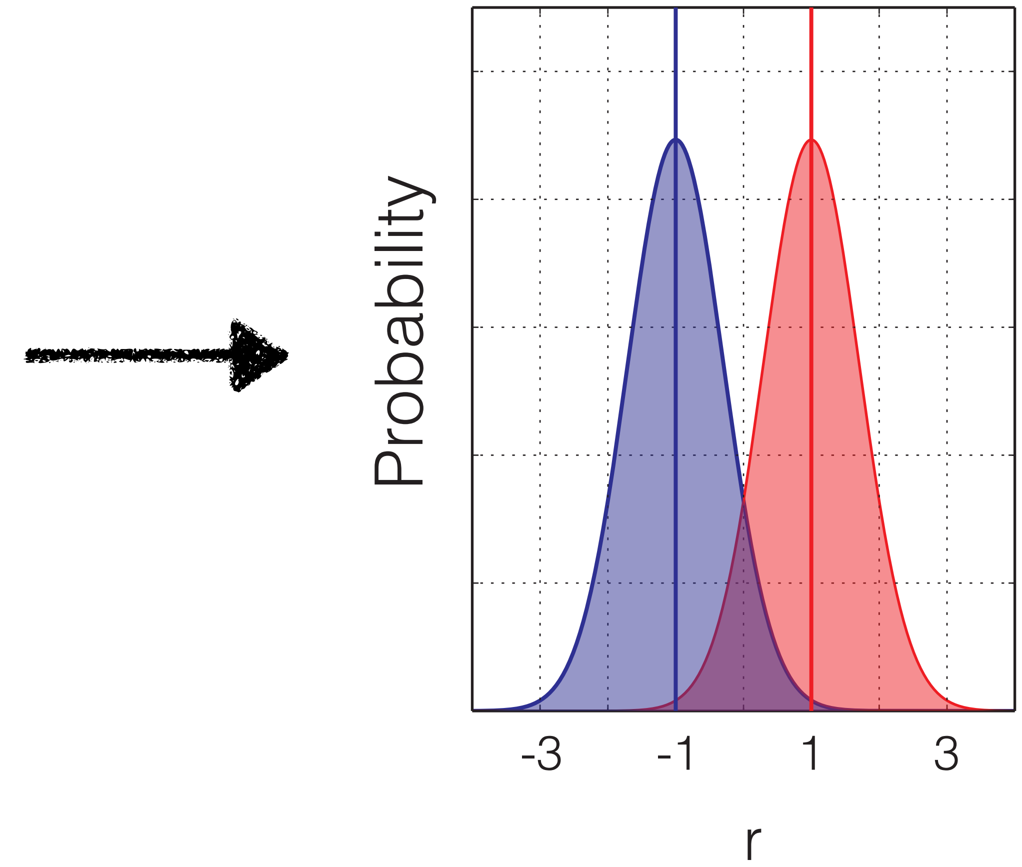
Two useful quantities:

Dimensionless measurement: $r = 2V_m^Q/\Delta V$

Quantum measurement: cQED







Two useful quantities:

Dimensionless measurement: $r = 2V_m^Q/\Delta V$

Characteristic measurement rate: $\Gamma_m = 64\eta_m \frac{\chi^2 \bar{n}}{\kappa}$

Gambetta et al., **Phys. Rev. A** (2008)

$$\Gamma_m \times \Delta t = (2/\sigma)^2$$

σ : standard deviation of the gaussian

Quantum measurement: cQED

Characteristic measurement rate: $$\Gamma_m \times \Delta t = (2/\sigma)^2$$

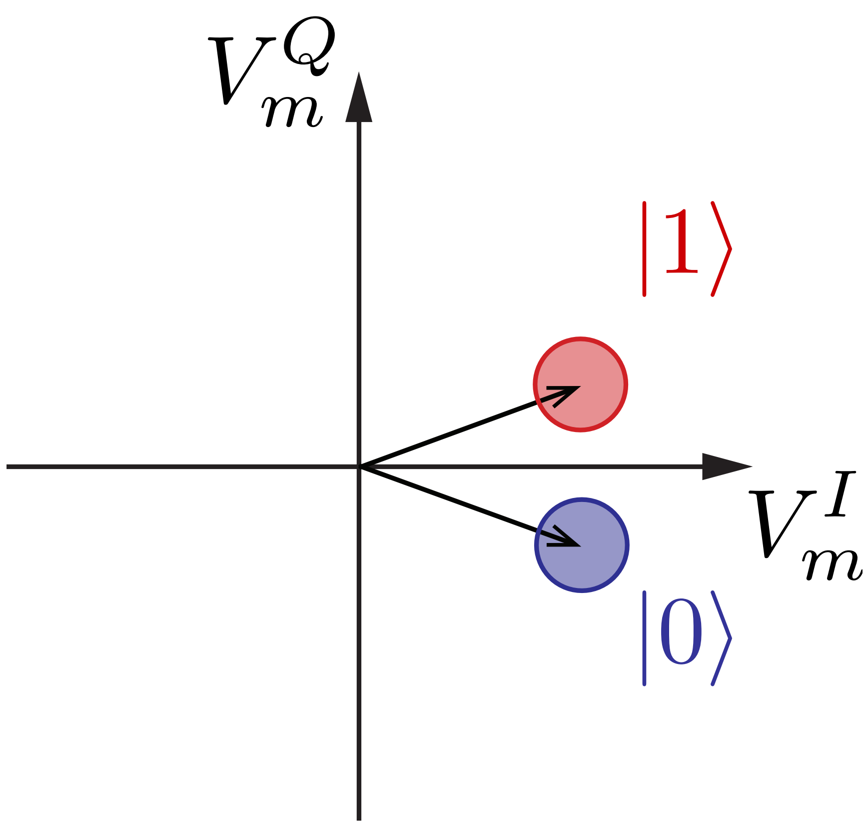
σ : standard deviation of the gaussian

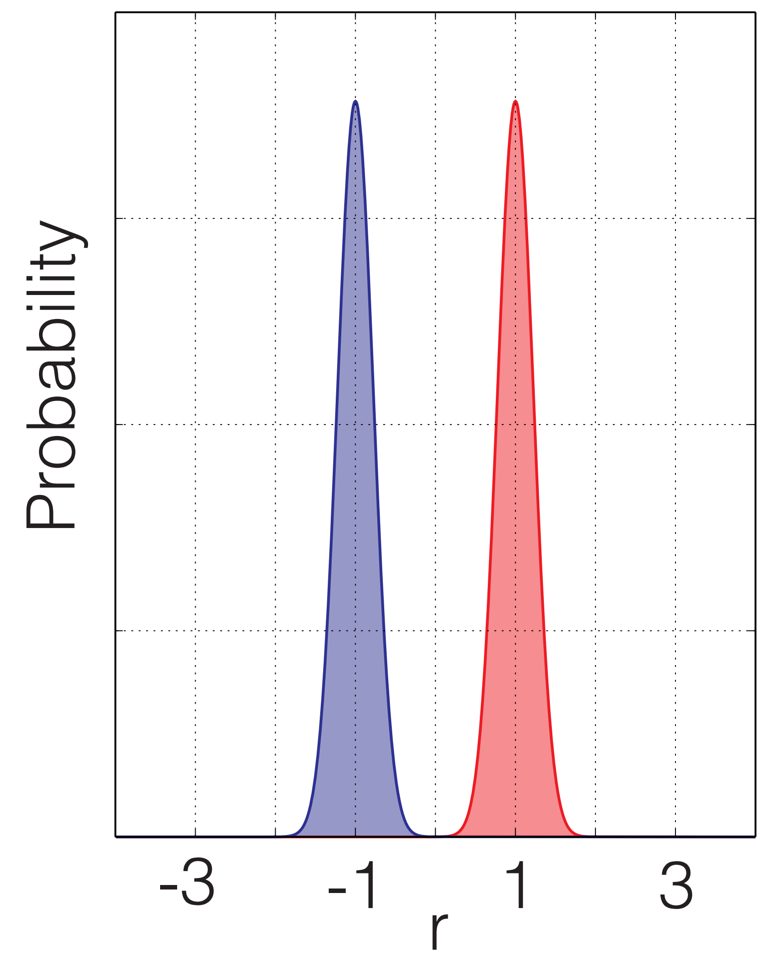
Quantum measurement: cQED

Characteristic measurement rate: $\Gamma_m \times \Delta t = (2/\sigma)^2$

σ : standard deviation of the gaussian

Strong measurement: $\Gamma_m \times \Delta t \gg 1$



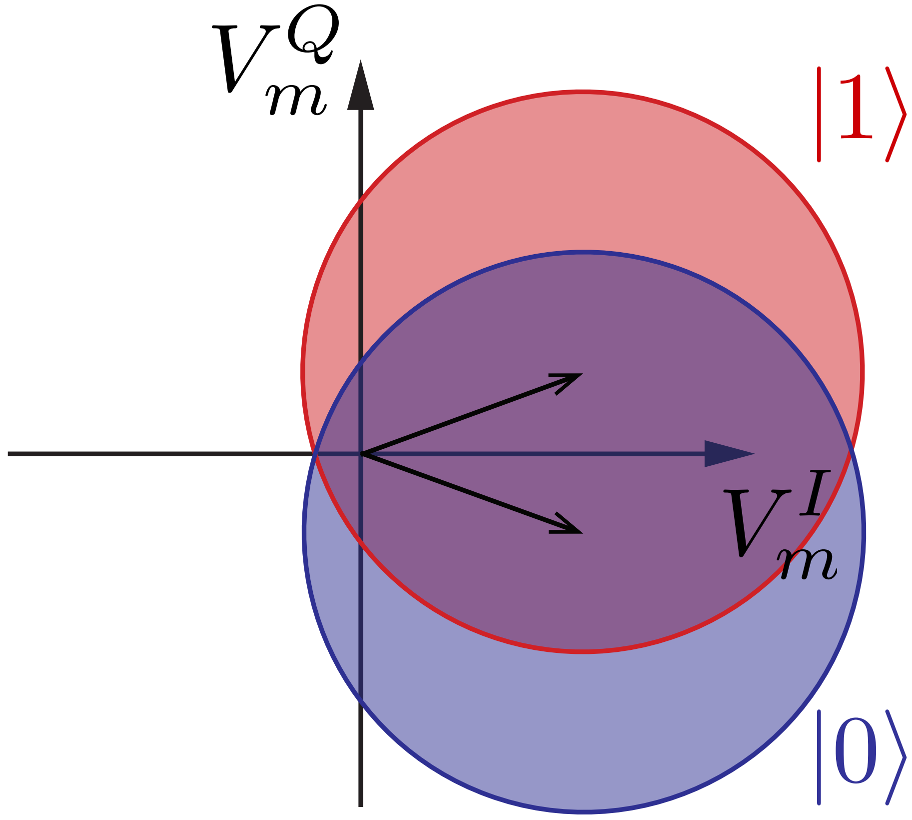


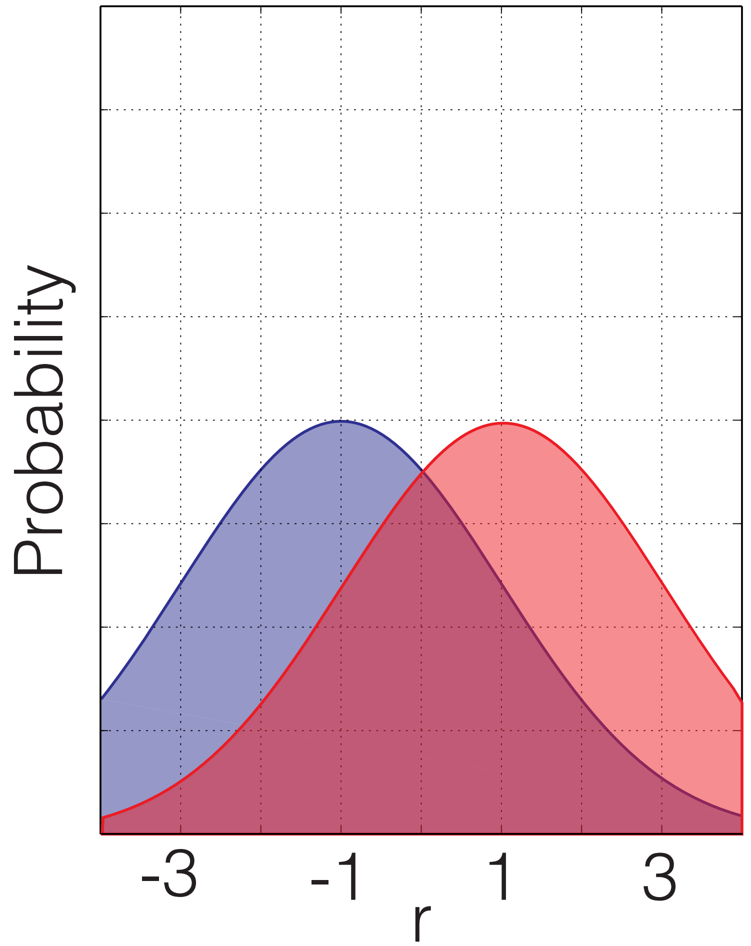
Quantum measurement: cQED

Characteristic measurement rate: $$\Gamma_m \times \Delta t = (2/\sigma)^2$$

σ : standard deviation of the gaussian

Weak measurement: $$\Gamma_m \times \Delta t \ll 1$$

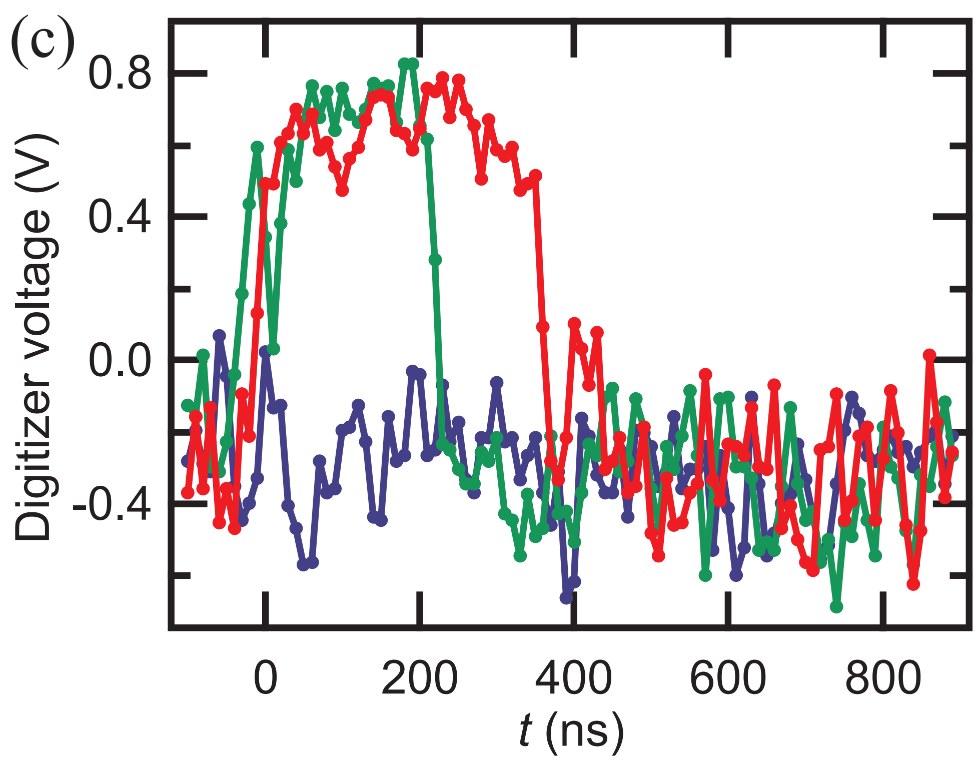




Quantum measurement: cQED

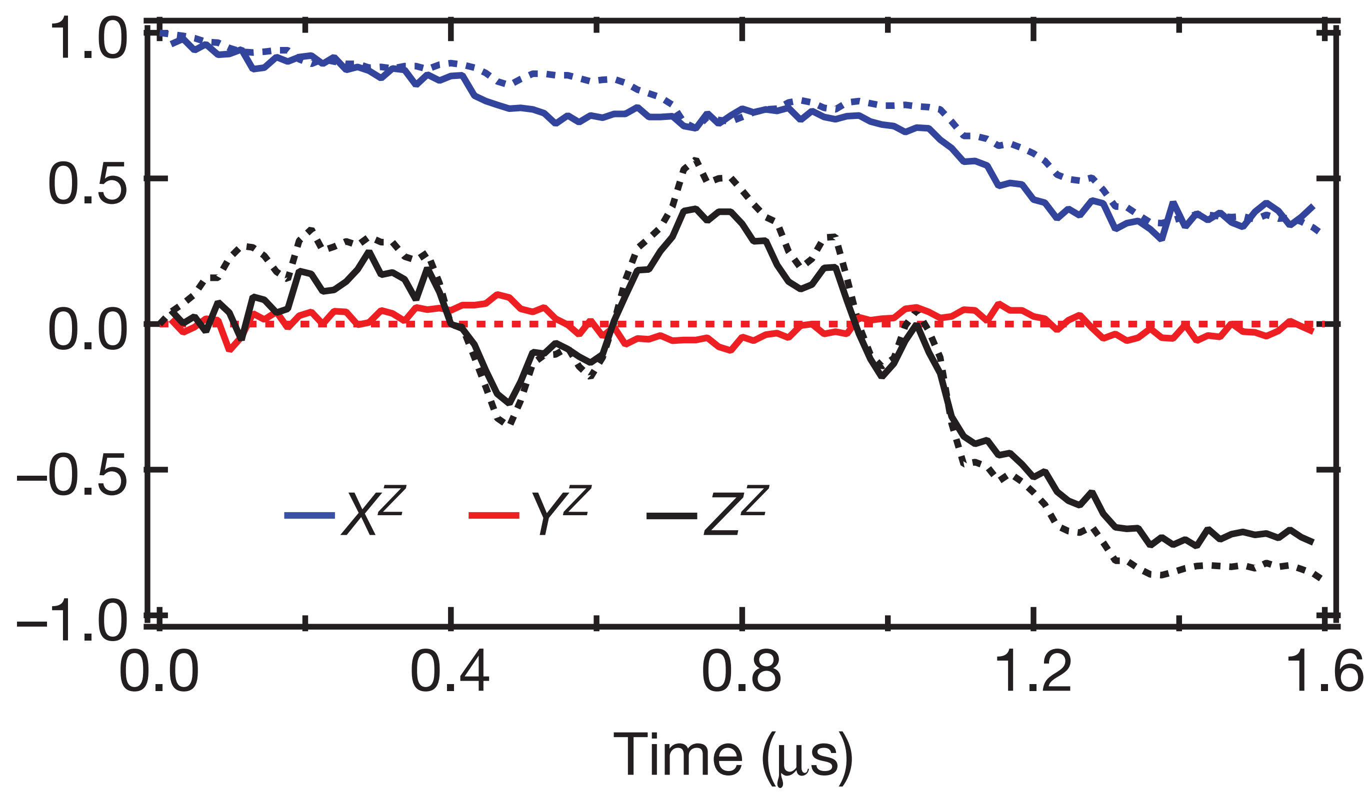
Two limits (single qubit case)

Quantum Jumps



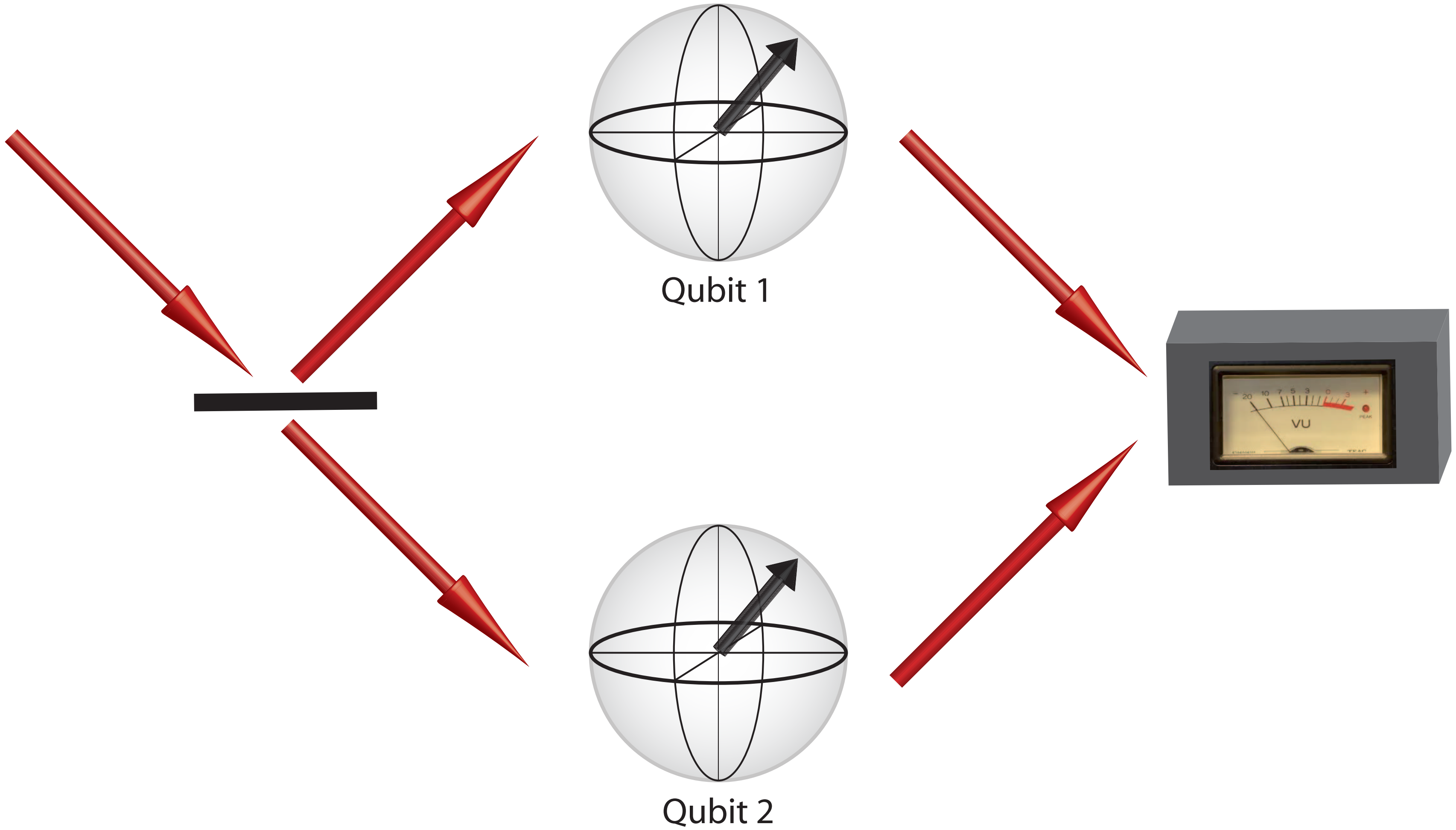
Vijay et al., **Phys. Rev. Lett.** (2011)

Diffusive measurement



Murch et al., **Nature** (2014)

Measurement Induced Entanglement



Outcomes

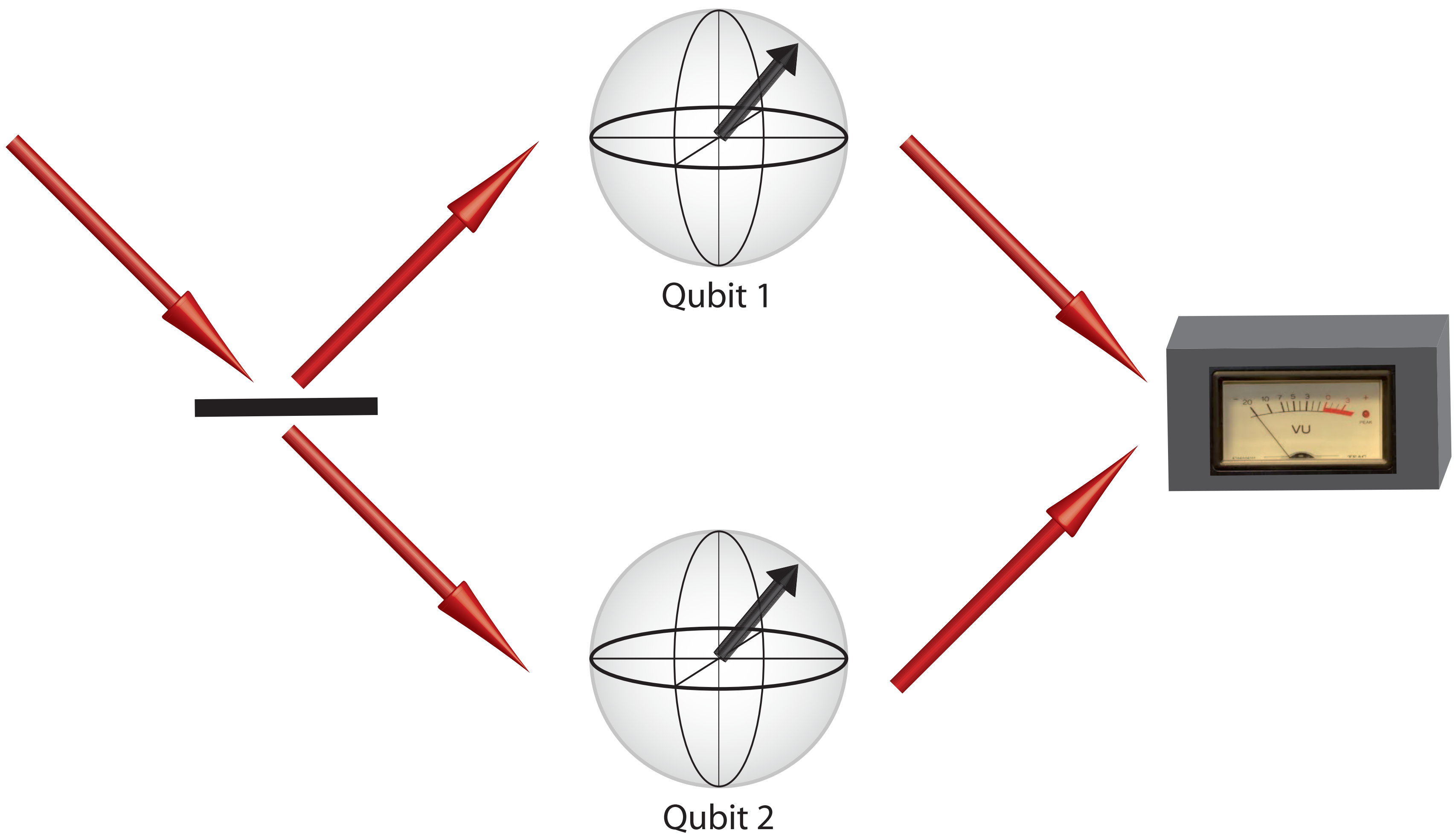
$|00\rangle$

$|01\rangle$

$|10\rangle$

$|11\rangle$

Measurement Induced Entanglement



Outcomes

$|00\rangle$

$|01\rangle$

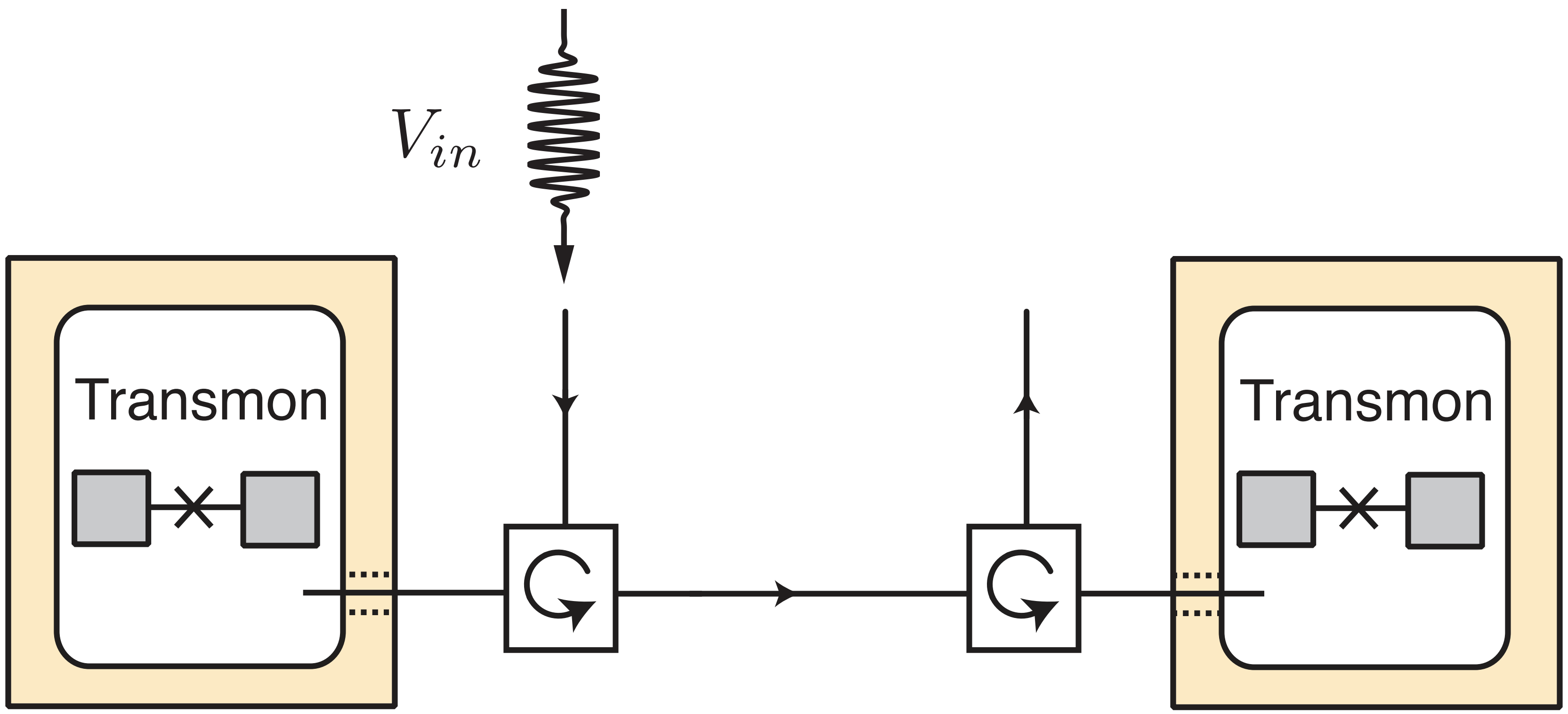
$|10\rangle$

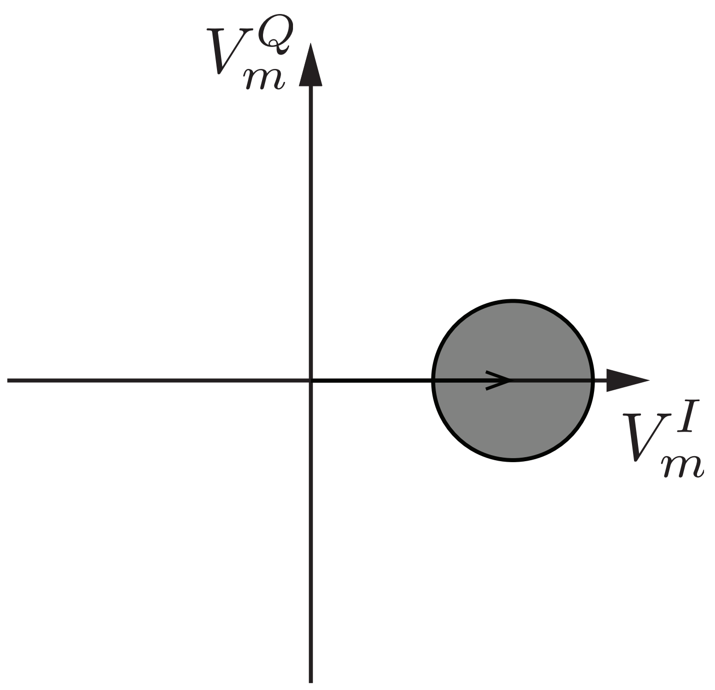
$|11\rangle$

If two outcomes are indistinguishable, measurement projects into an entangled subspace

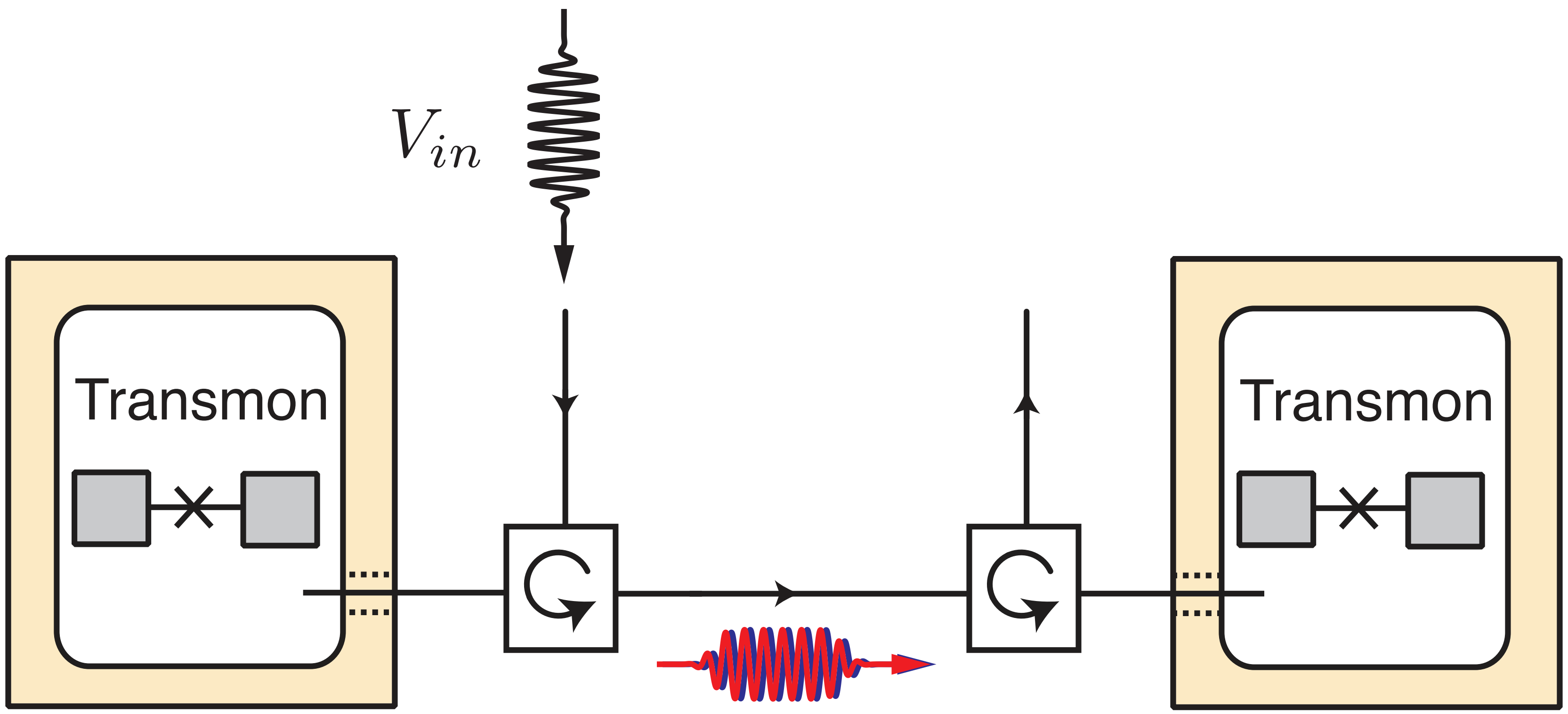
Measurement induced entanglement in the single cavity limit:
Ristè, D., et al., **Nature** (2013)

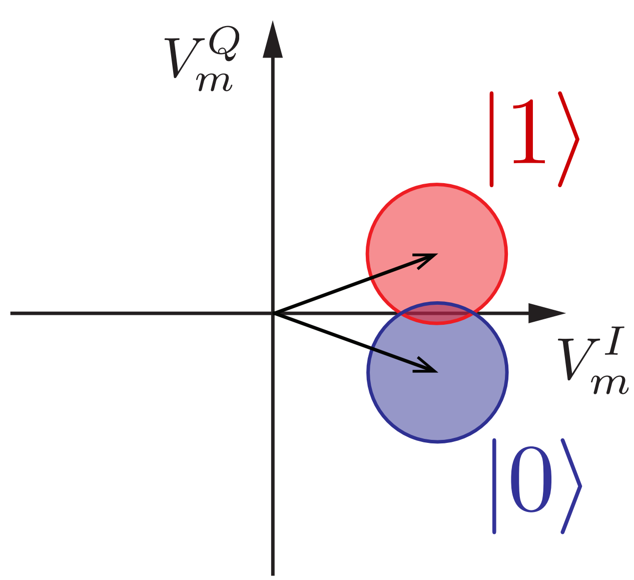
Generating entanglement

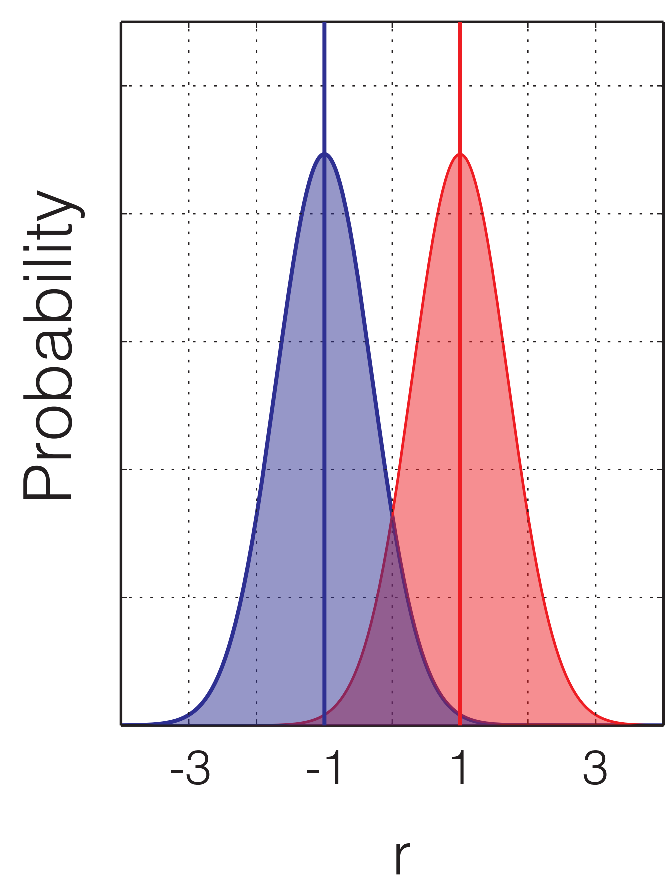




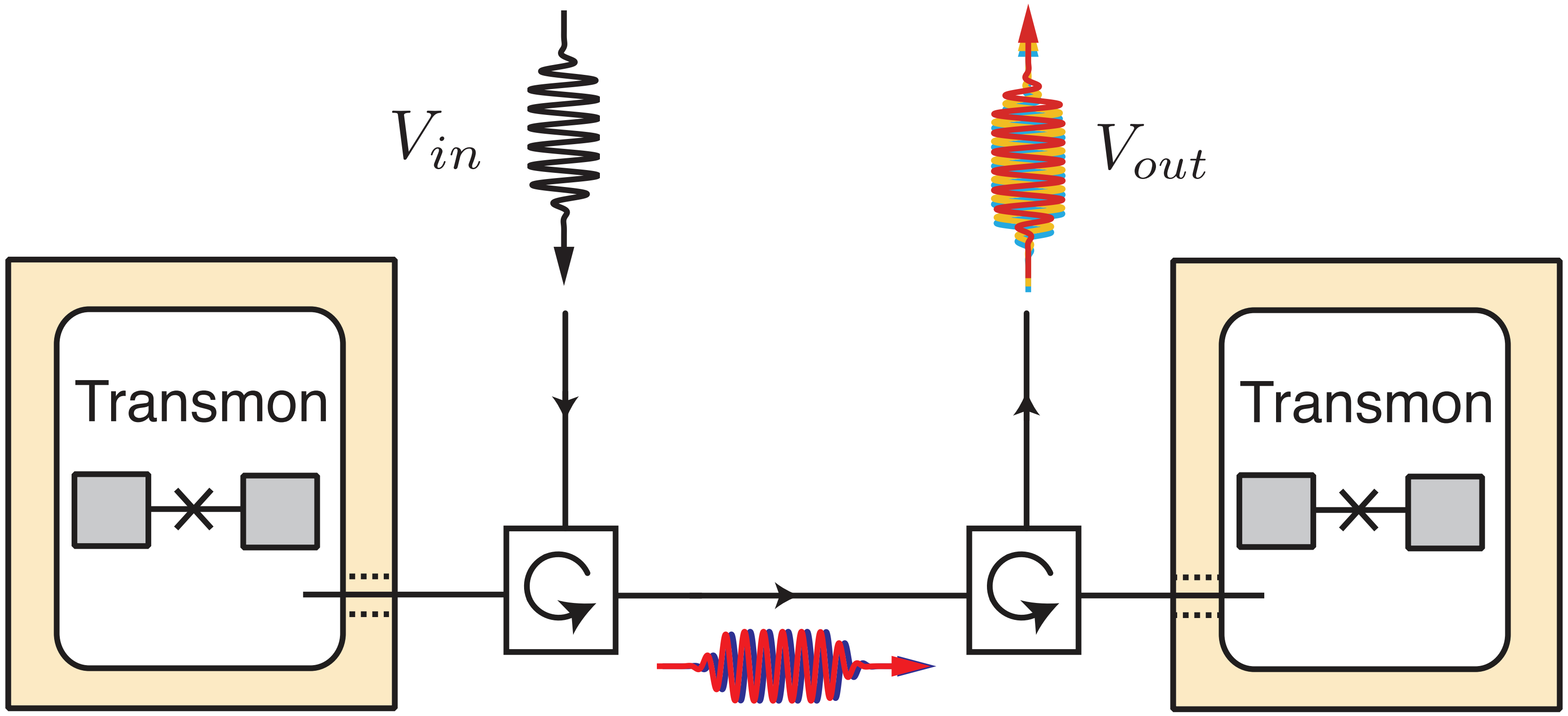
Generating entanglement

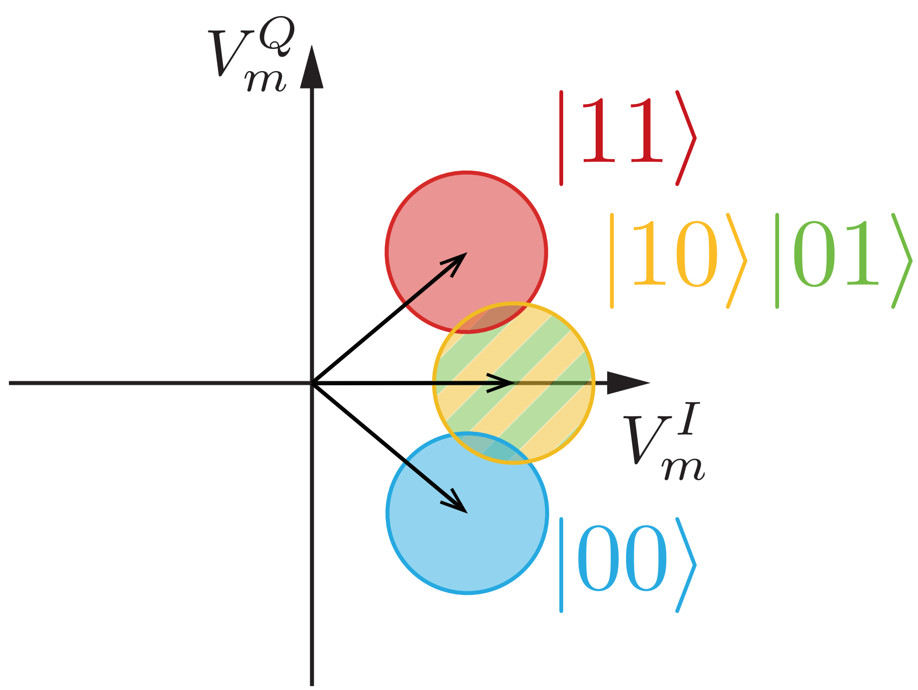


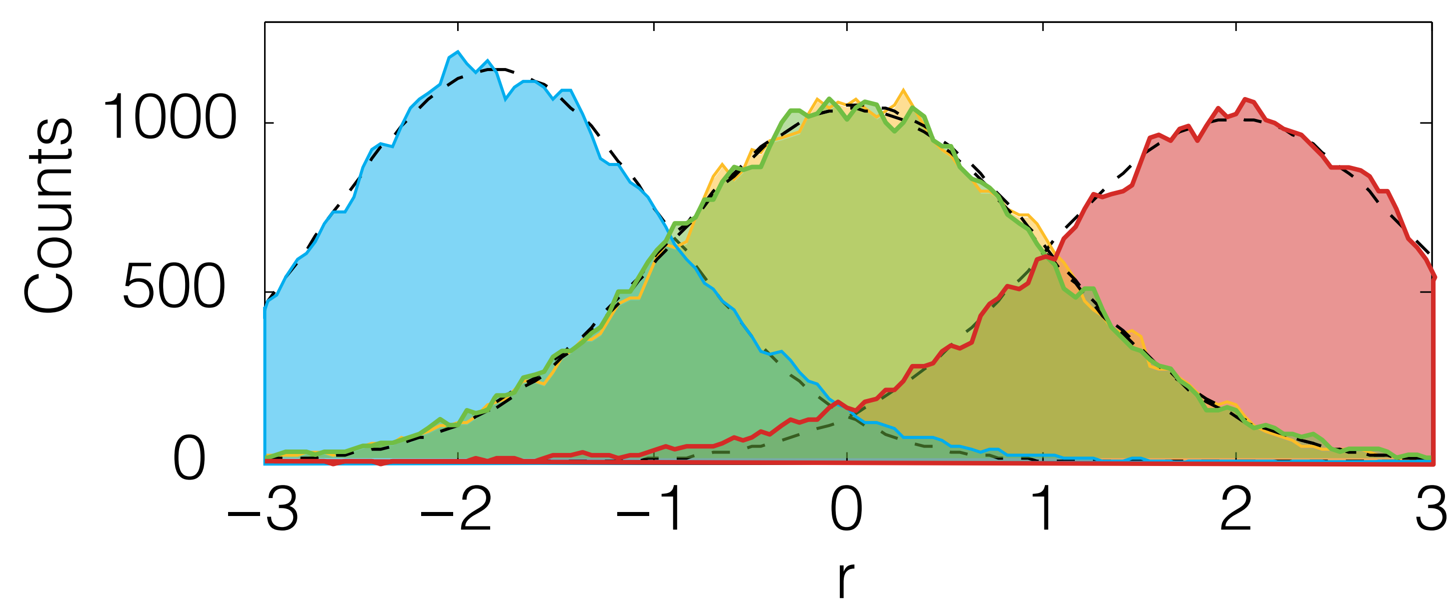




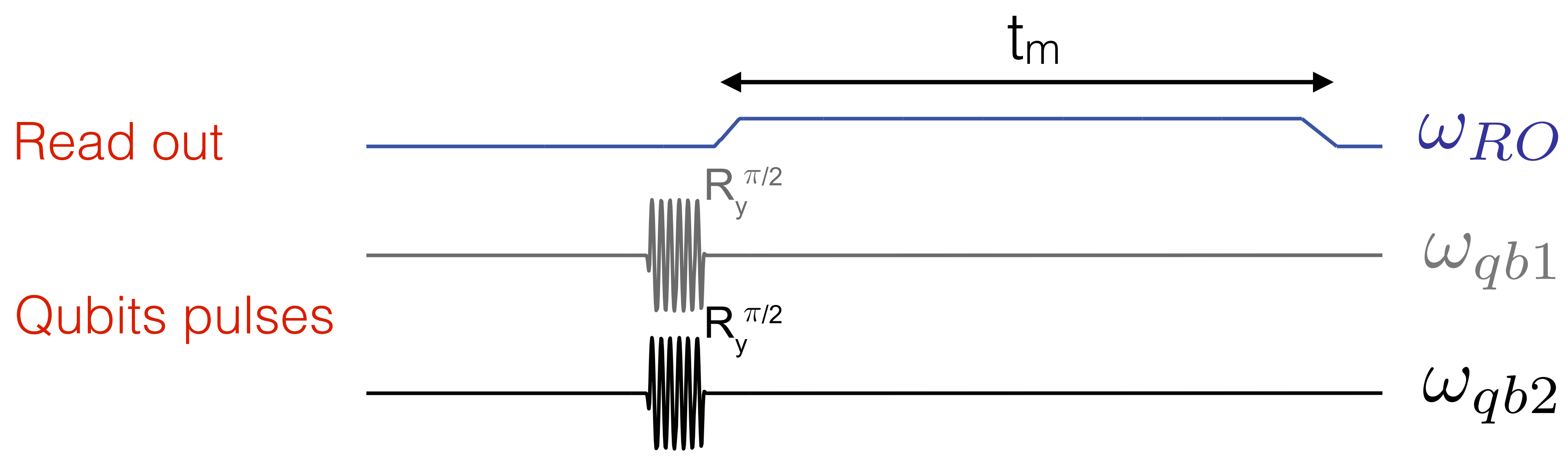
Generating entanglement



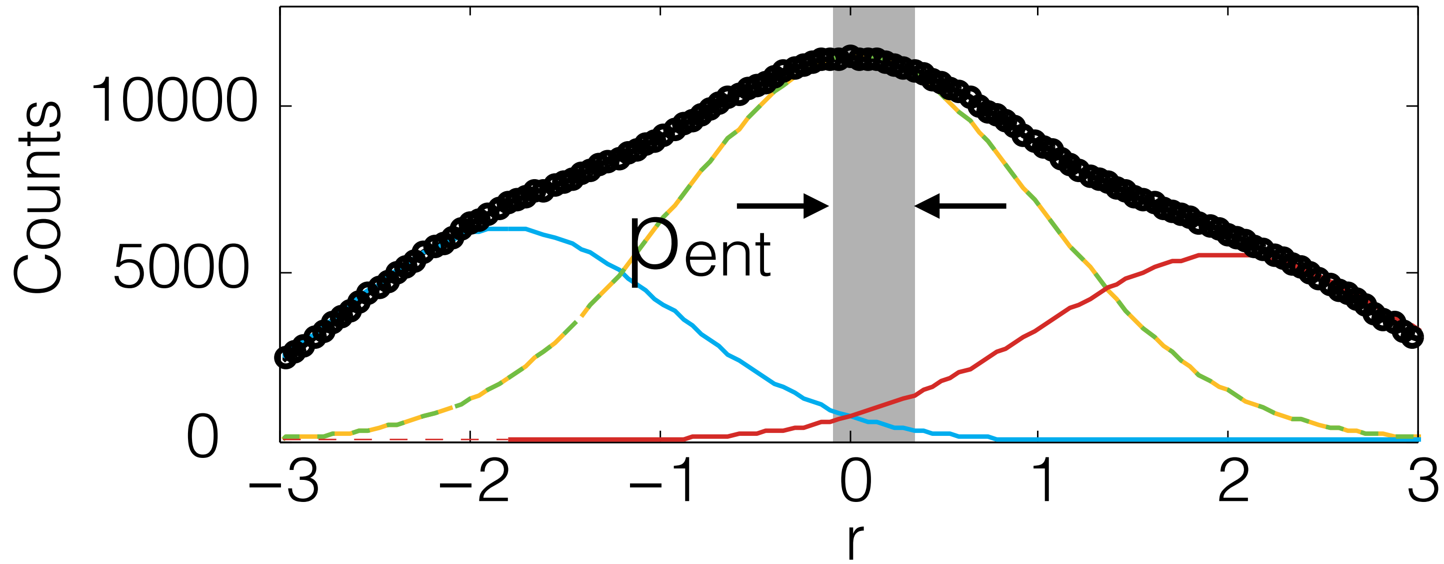




Measurement induced entanglement

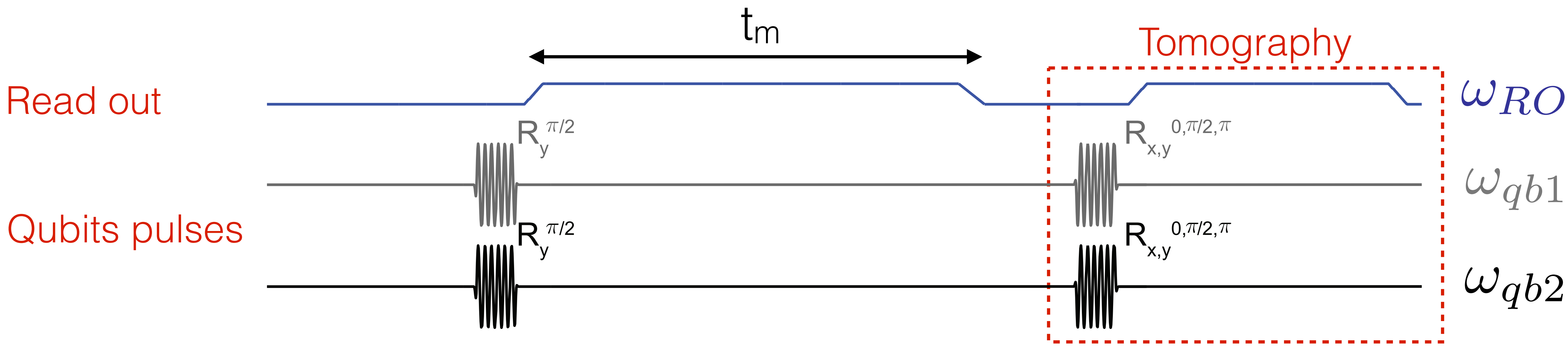


$$|\psi_i\rangle = (|00\rangle + |01\rangle + |10\rangle + |11\rangle)/\,2$$

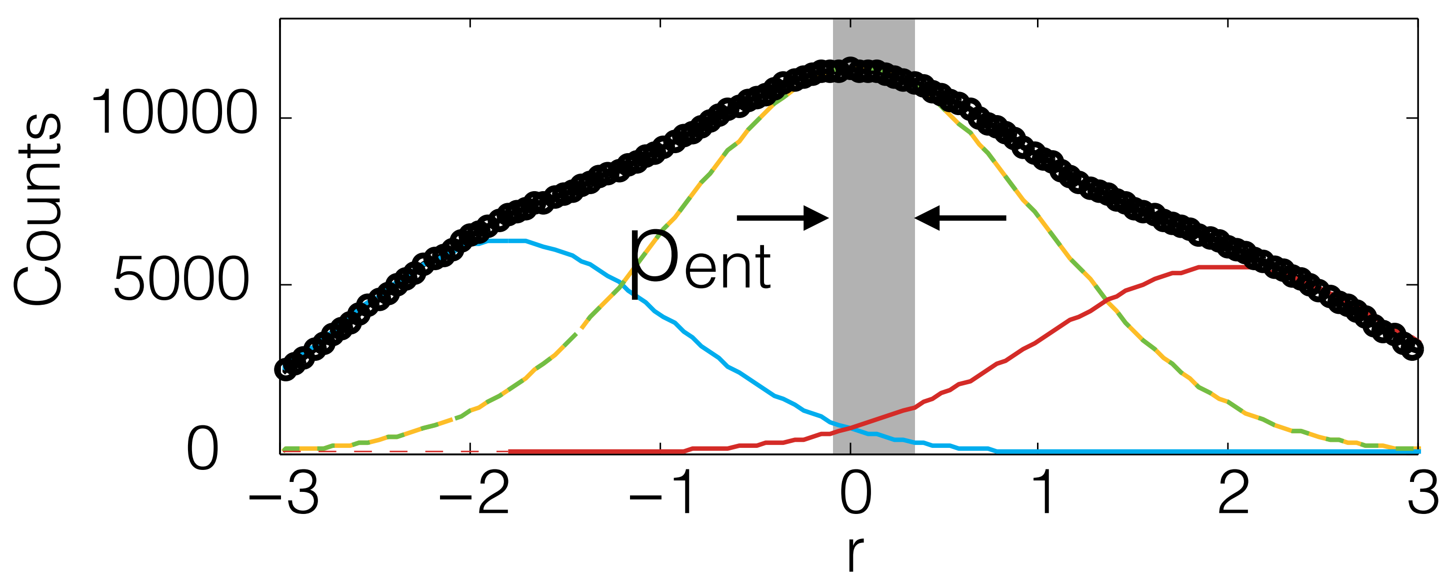


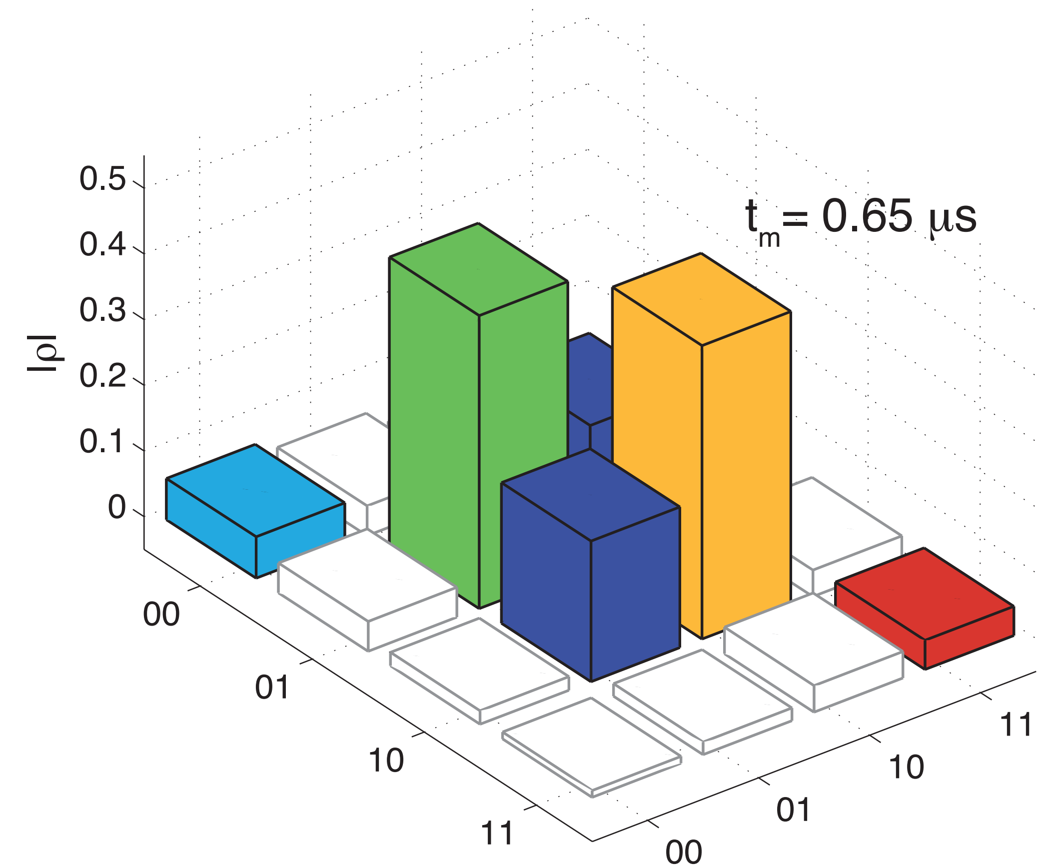
p_{ent}=10%

Measurement induced entanglement



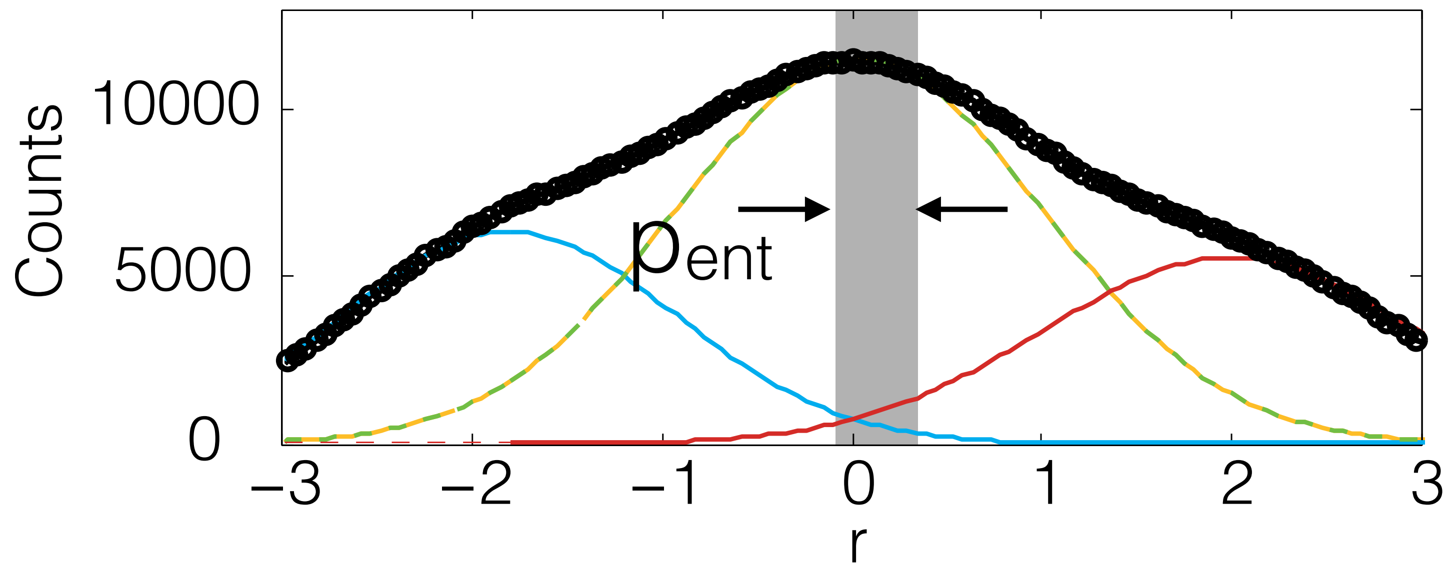
$$|\psi_i\rangle = (|00\rangle + |01\rangle + |10\rangle + |11\rangle)/\,2$$

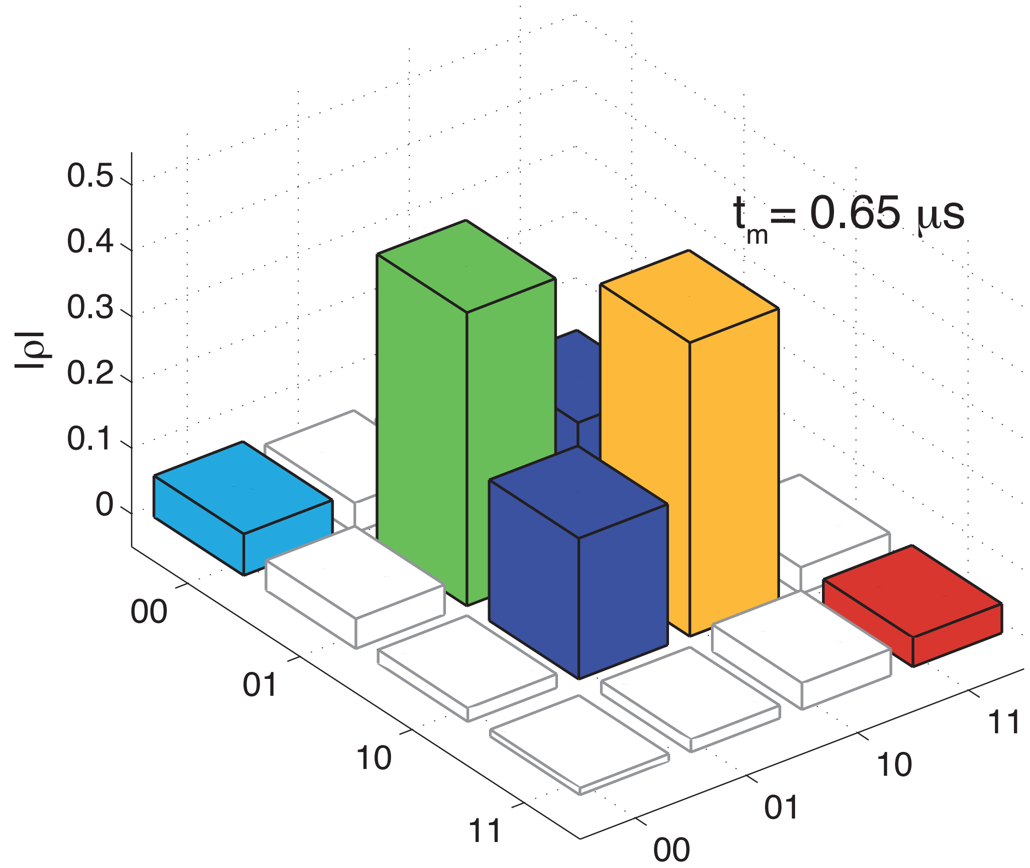




p_{ent}=10%

Measurement induced entanglement





p_{ent}=10%

Quantifying the entanglement:

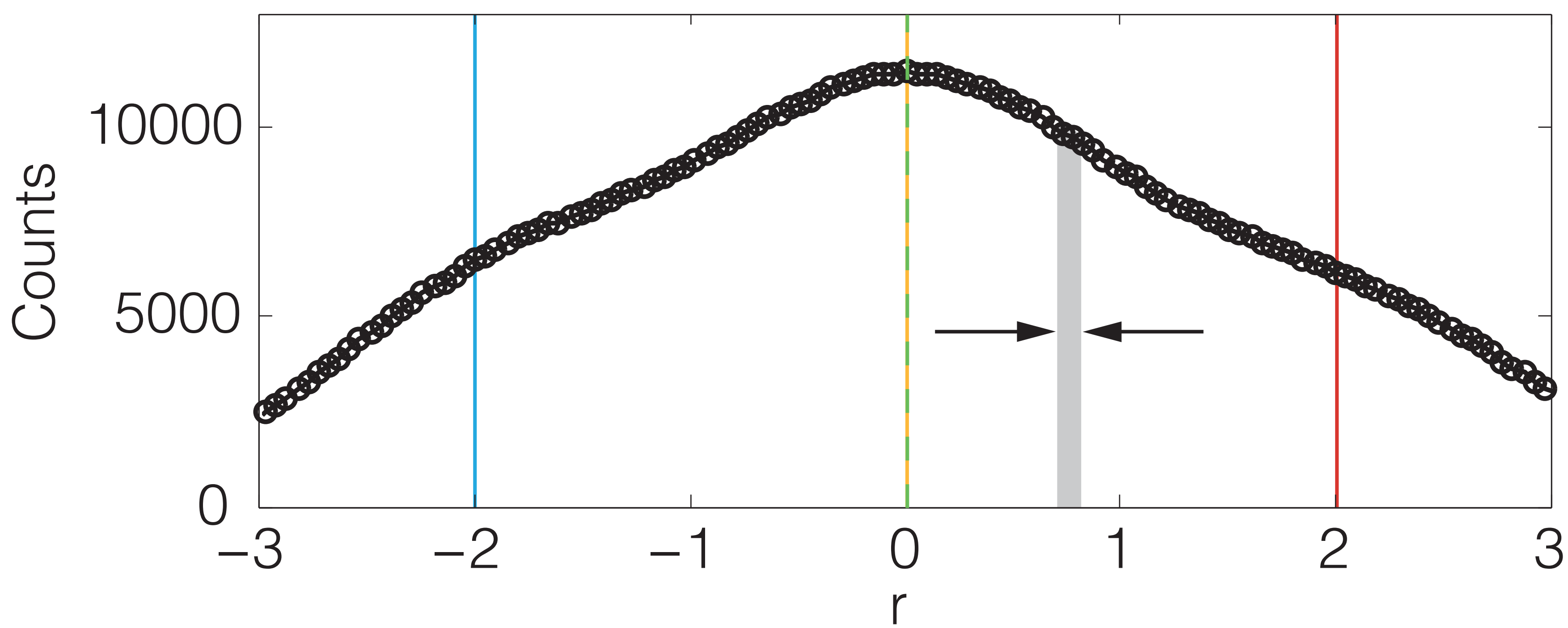
Entanglement of formation or concurrence

$$\mathcal{C} = \max(0, 2(|\rho_{01,10}| - \sqrt{\rho_{00,00}\rho_{11,11}}))$$

$$\mathcal{C} = 0.35$$

Wooters, **Phys. Rev. Lett.** (1998)   Simplified formula: L. Jakóbczyk and A. Jamróz, **Phys. Lett. A** (2005)

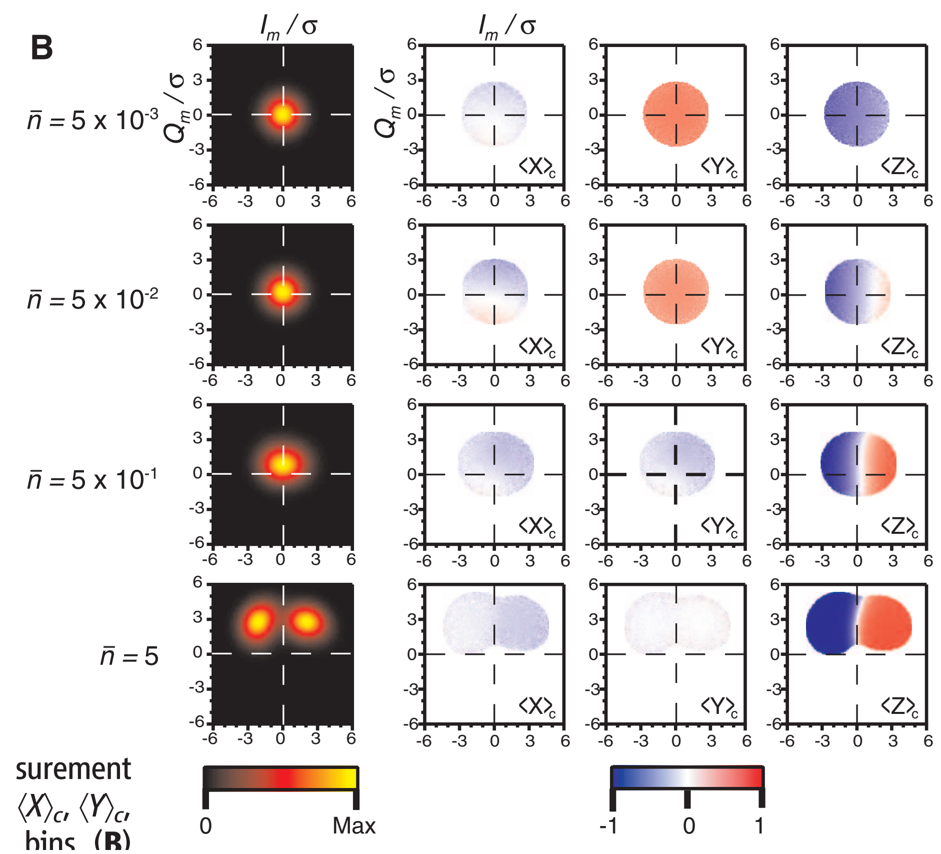
Conditional Tomography



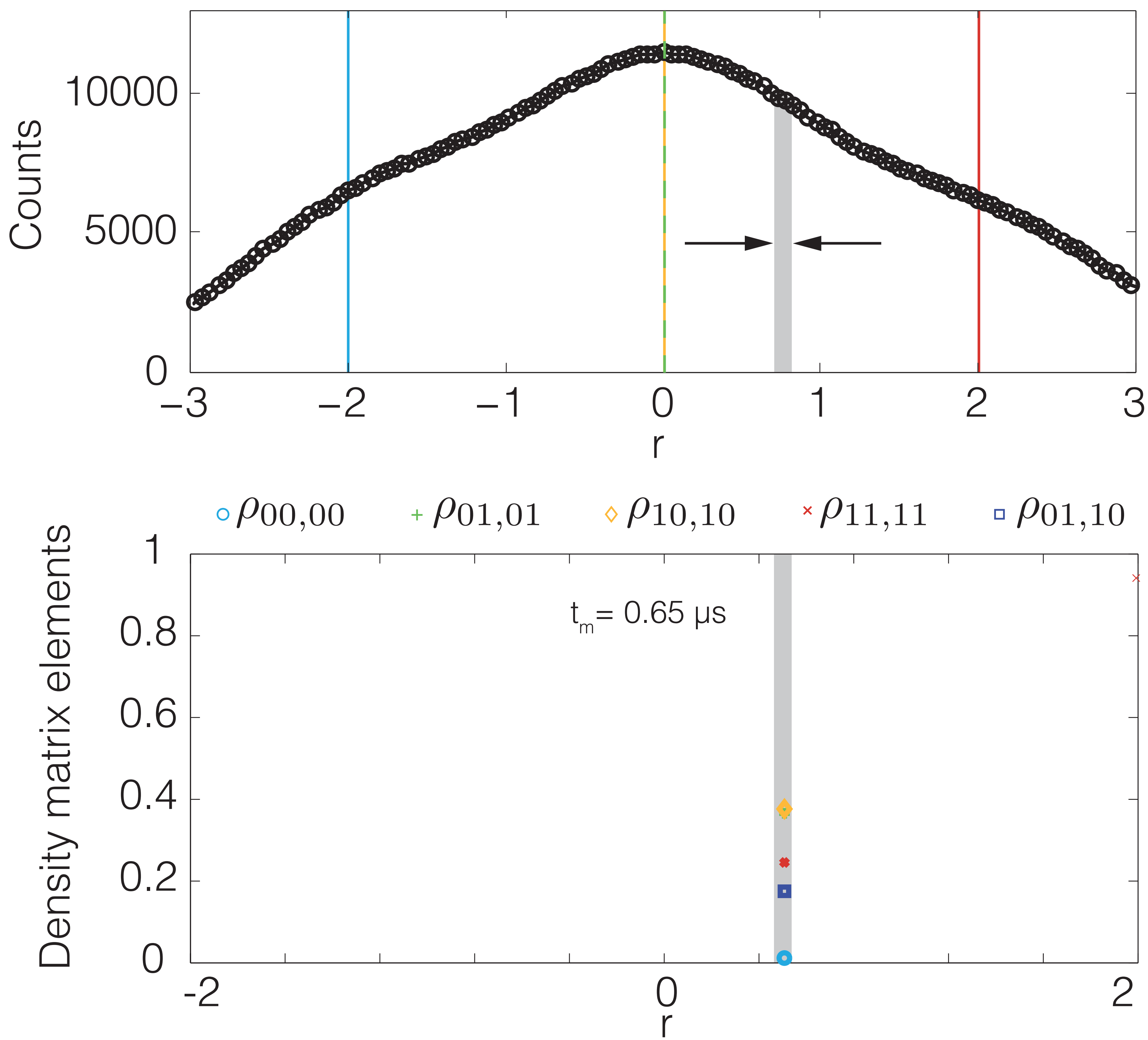
Single qubit case:

Hatridge et al., **Science** (2013)

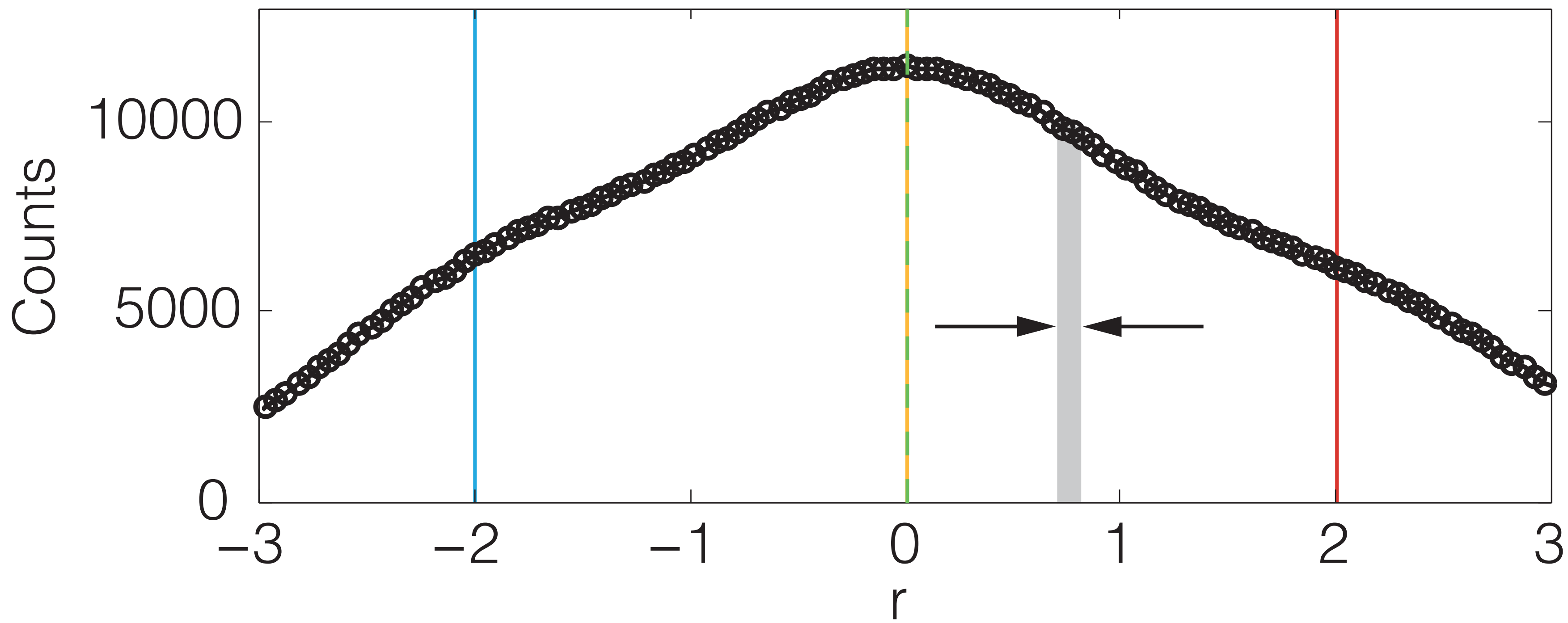
See also:
Murch et al., **Nature** (2014)

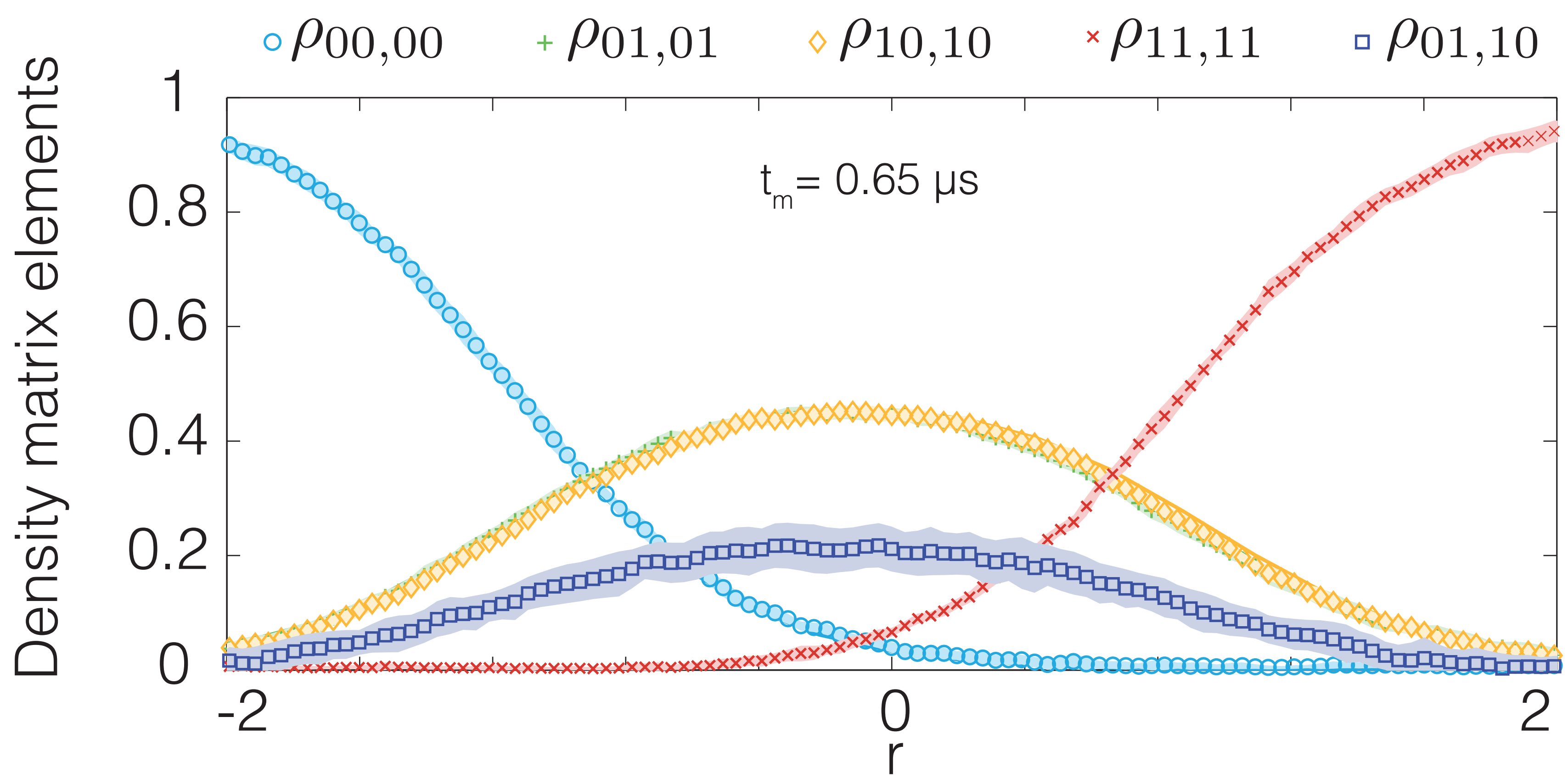


Conditional Tomography

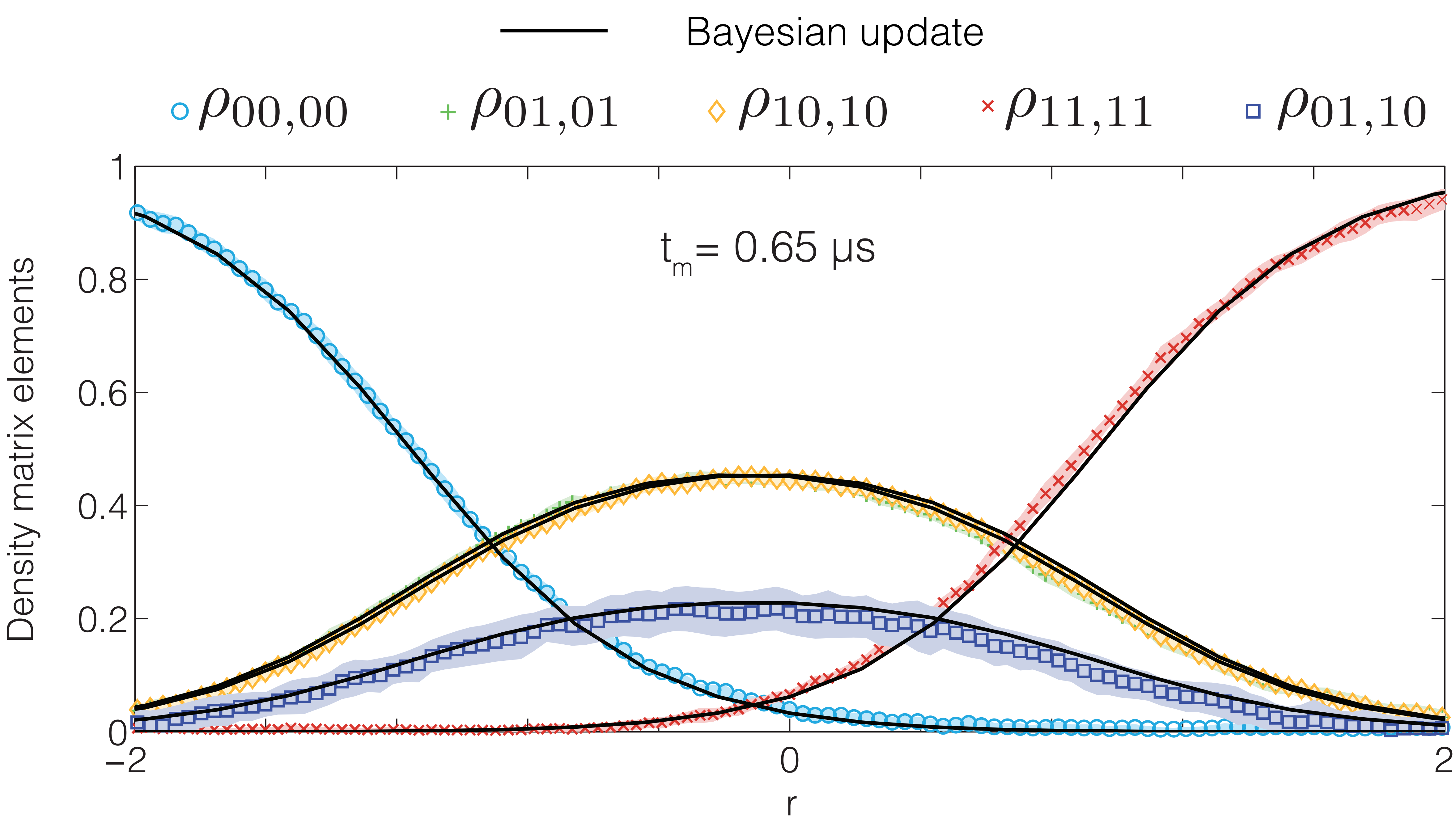


Conditional Tomography





Conditional Tomography



Bayes rule:

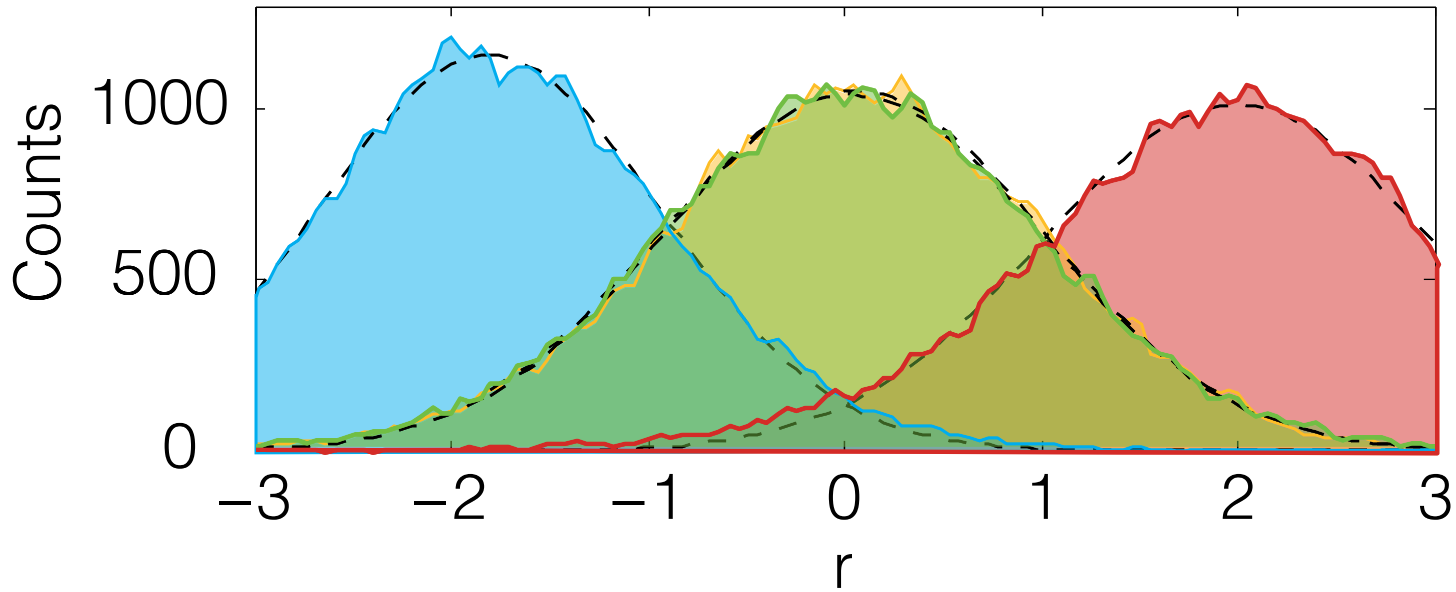
$$p(|ij\rangle|r) = \frac{p(|ij\rangle)p(r||ij\rangle)}{p(r)}$$

→ Mapping of r onto ρ

Conditional Tomography

Reminder:

$$p(r||ij\rangle) =$$



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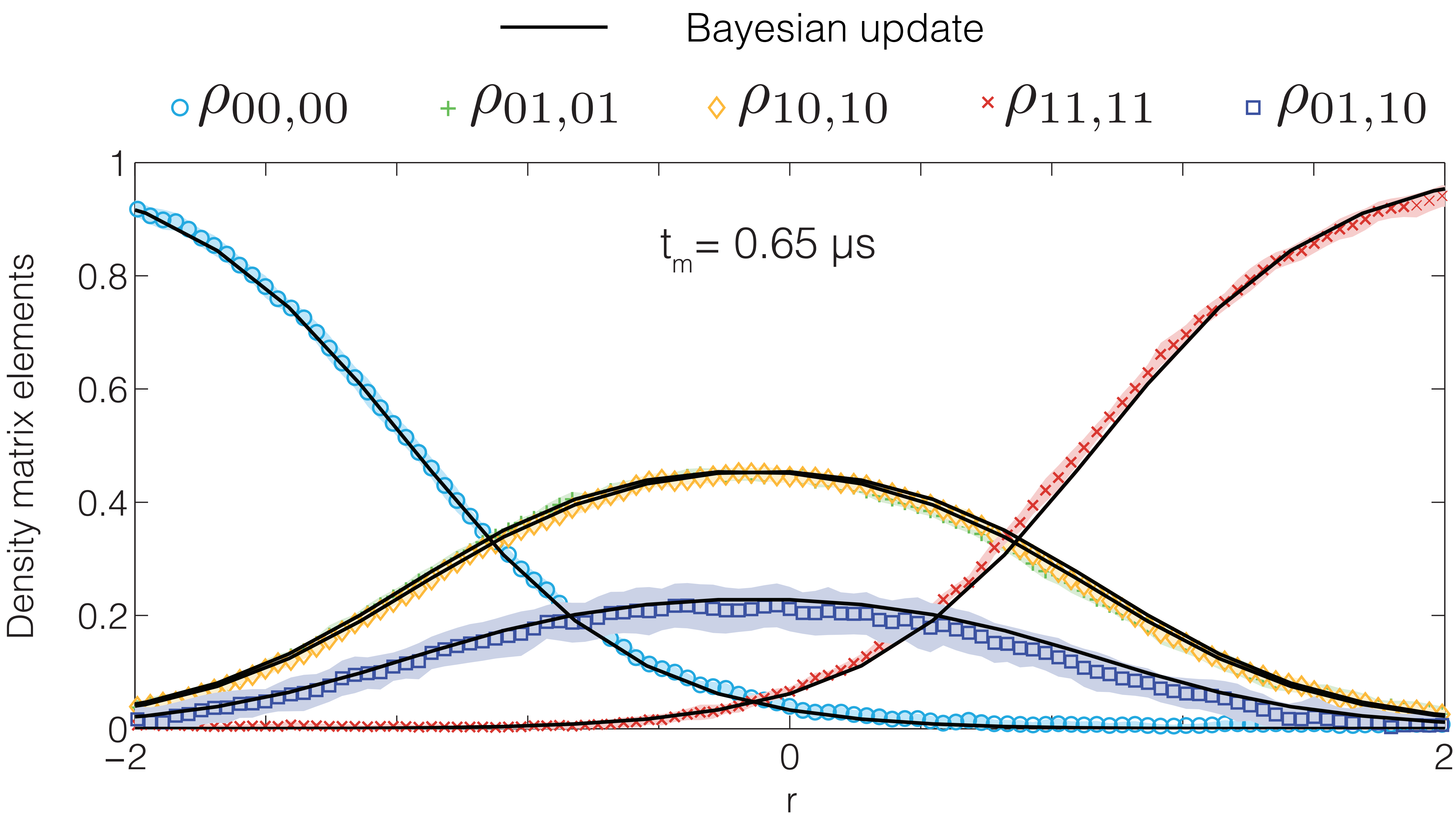
Conditional Tomography



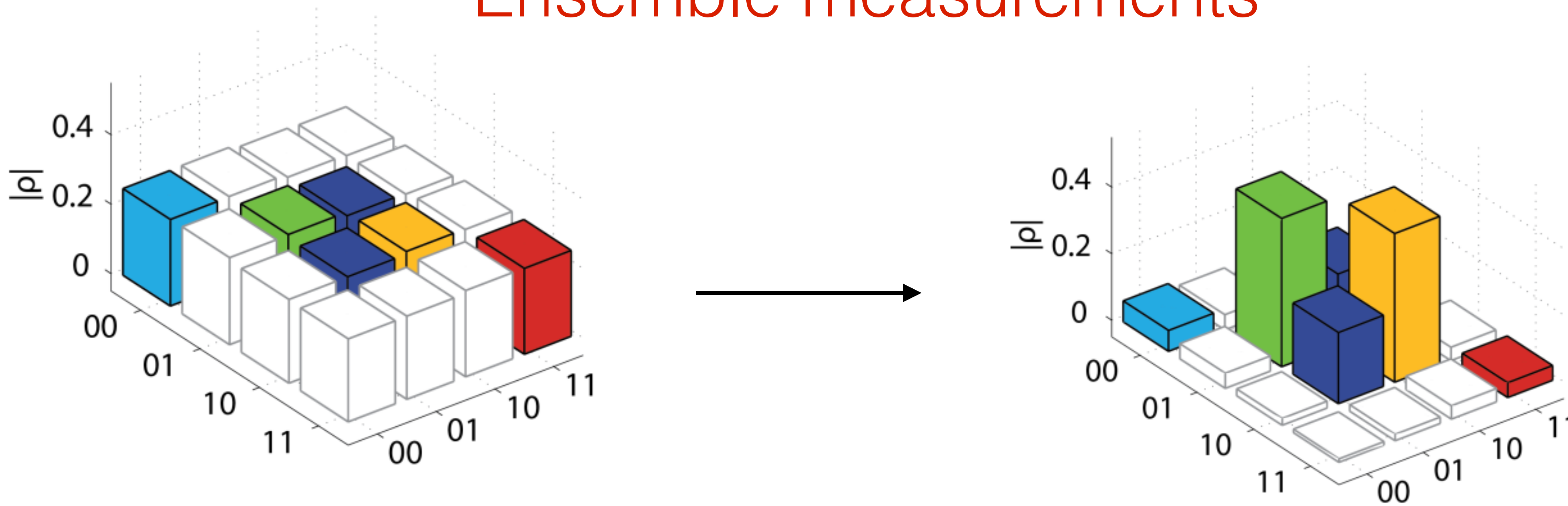
Bayes rule:

$$p(|ij\rangle|r) = \frac{p(|ij\rangle)p(r||ij\rangle)}{p(r)}$$

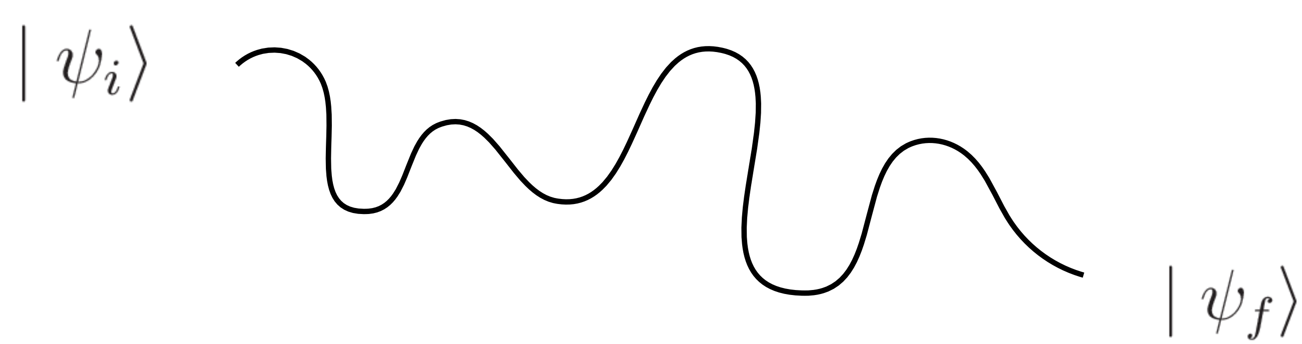
Mapping of r onto ρ

Quantum trajectories and entanglement

Ensemble measurements



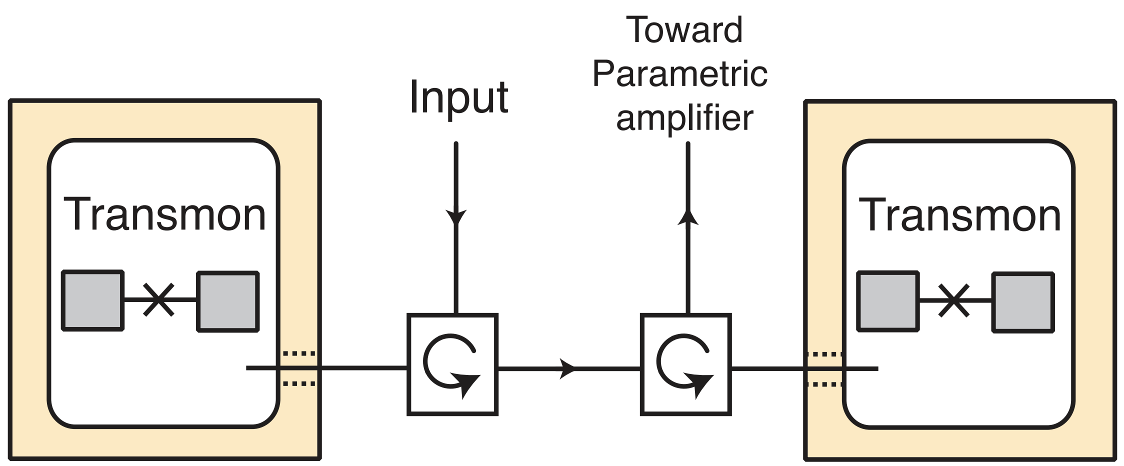
Single experimental realisation

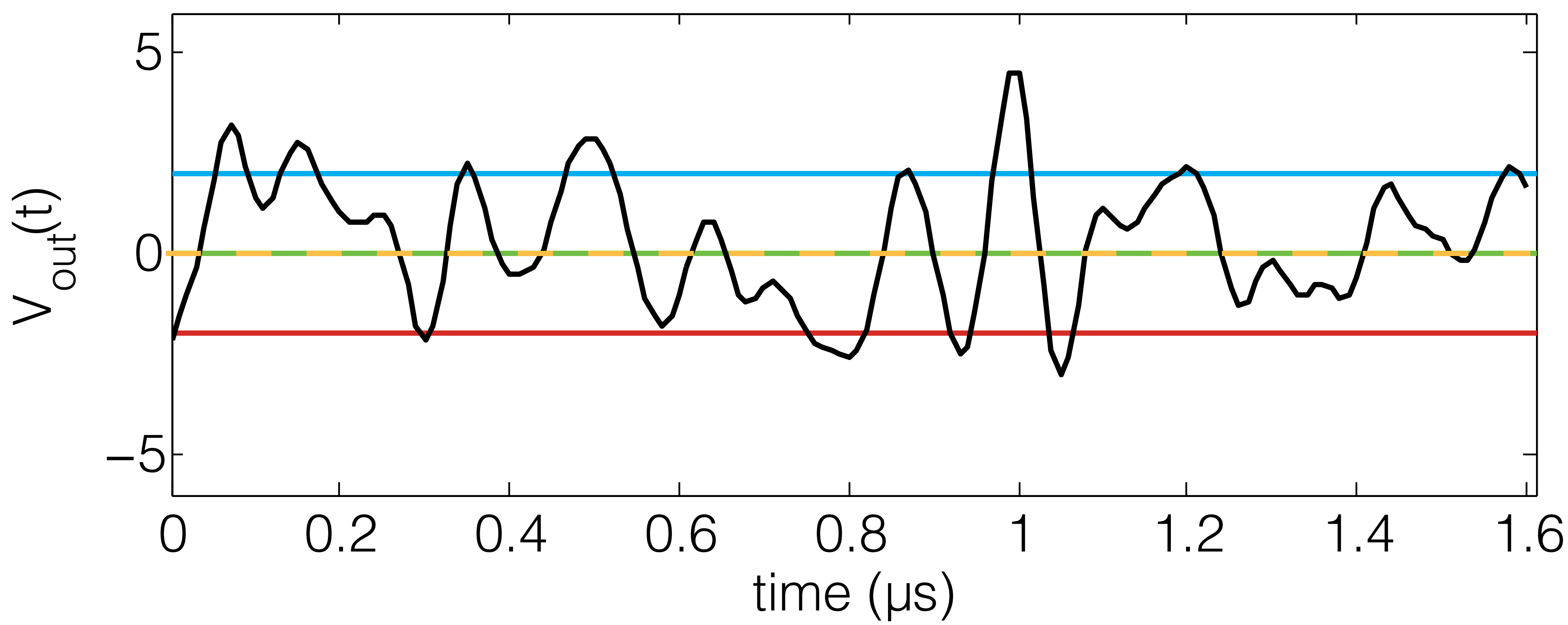


Quantum trajectory reconstruction allows us to directly observe quantum state evolution under measurement

Murch K., et al., **Nature** (2013)

Dynamics of entanglement creation

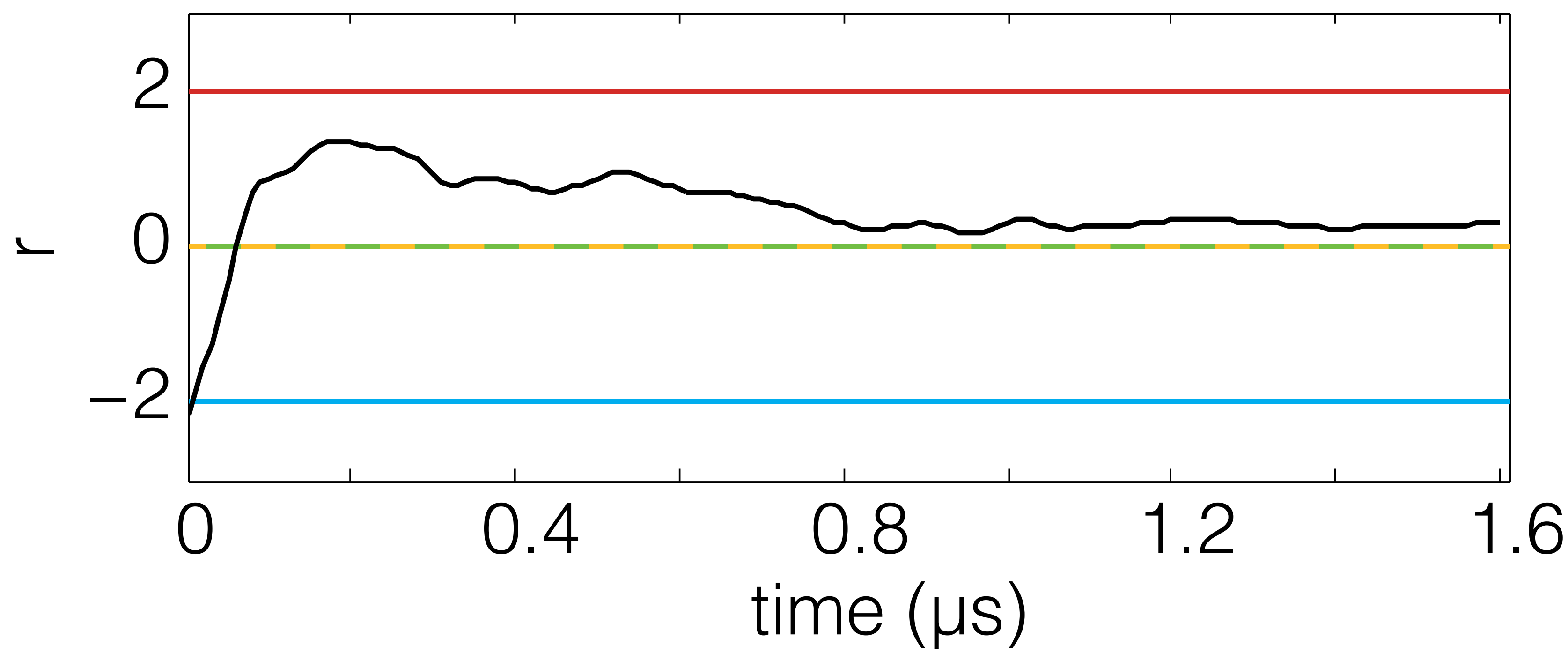




Single time trace

Dynamics of entanglement creation

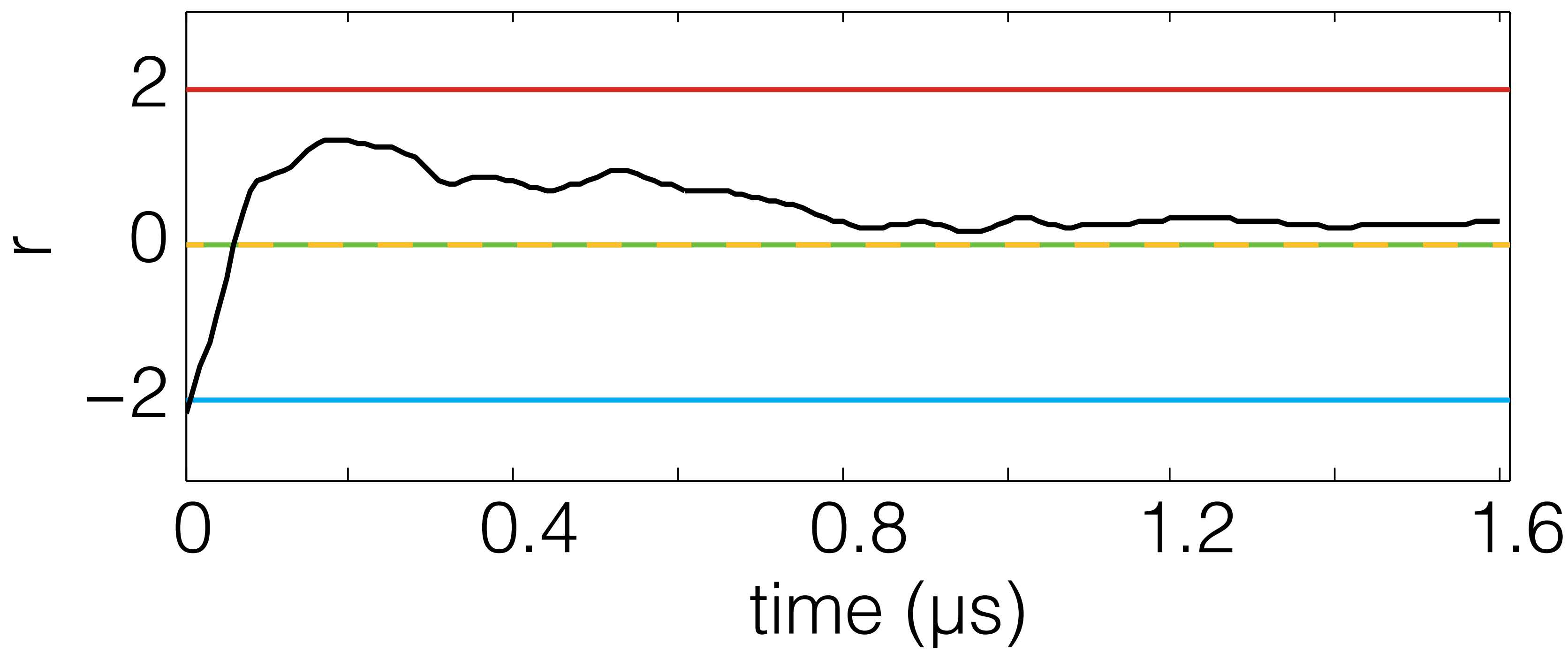
$$V_m = \frac{1}{\Delta t}\int_0^{\Delta t} V_{out}(t)dt \qquad \text{and} \qquad r = 2V_m^Q/\Delta V$$



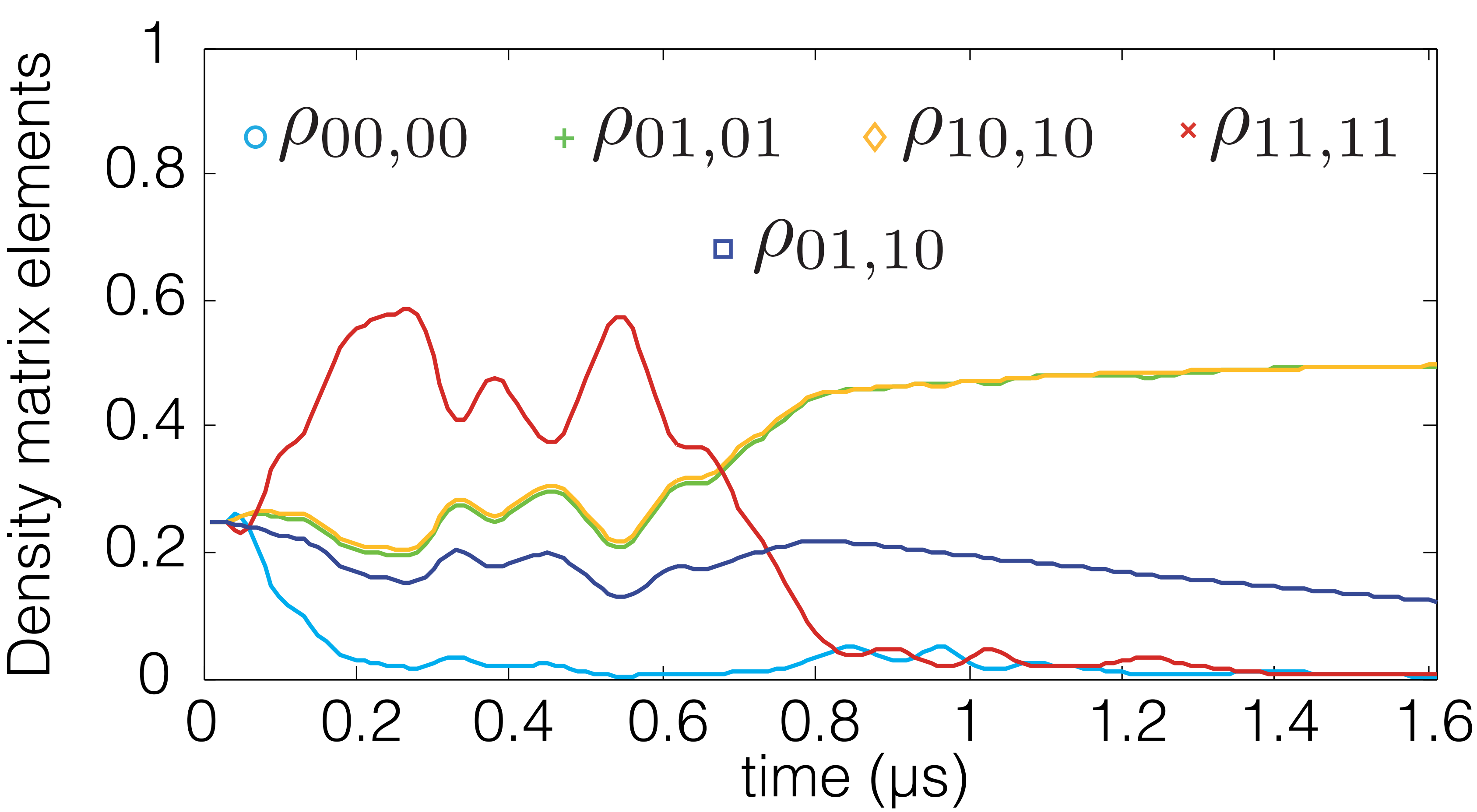
Integrated single time trace

Question: can we infer the evolution of the density matrix ?

Dynamics of entanglement creation

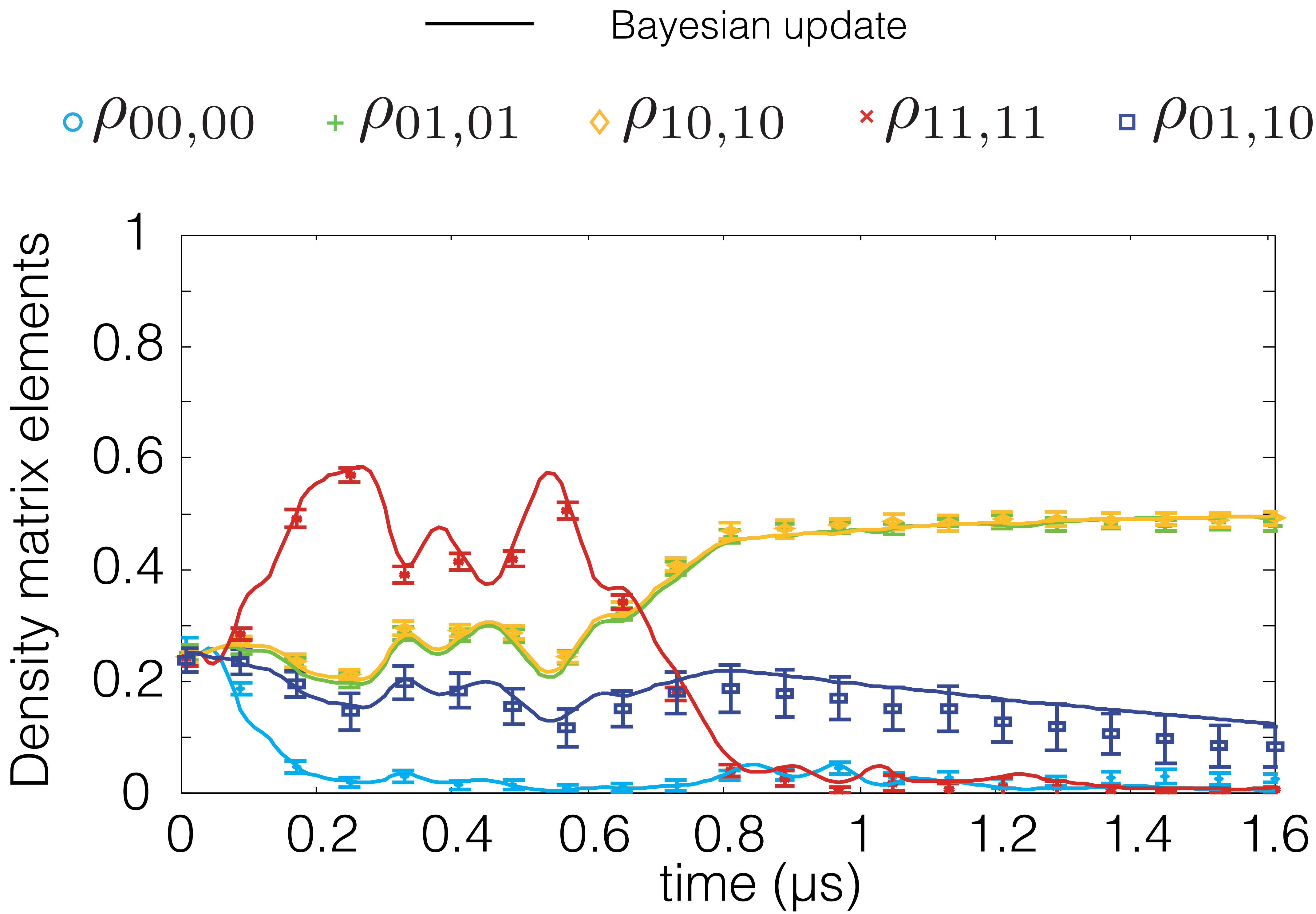


for each point:



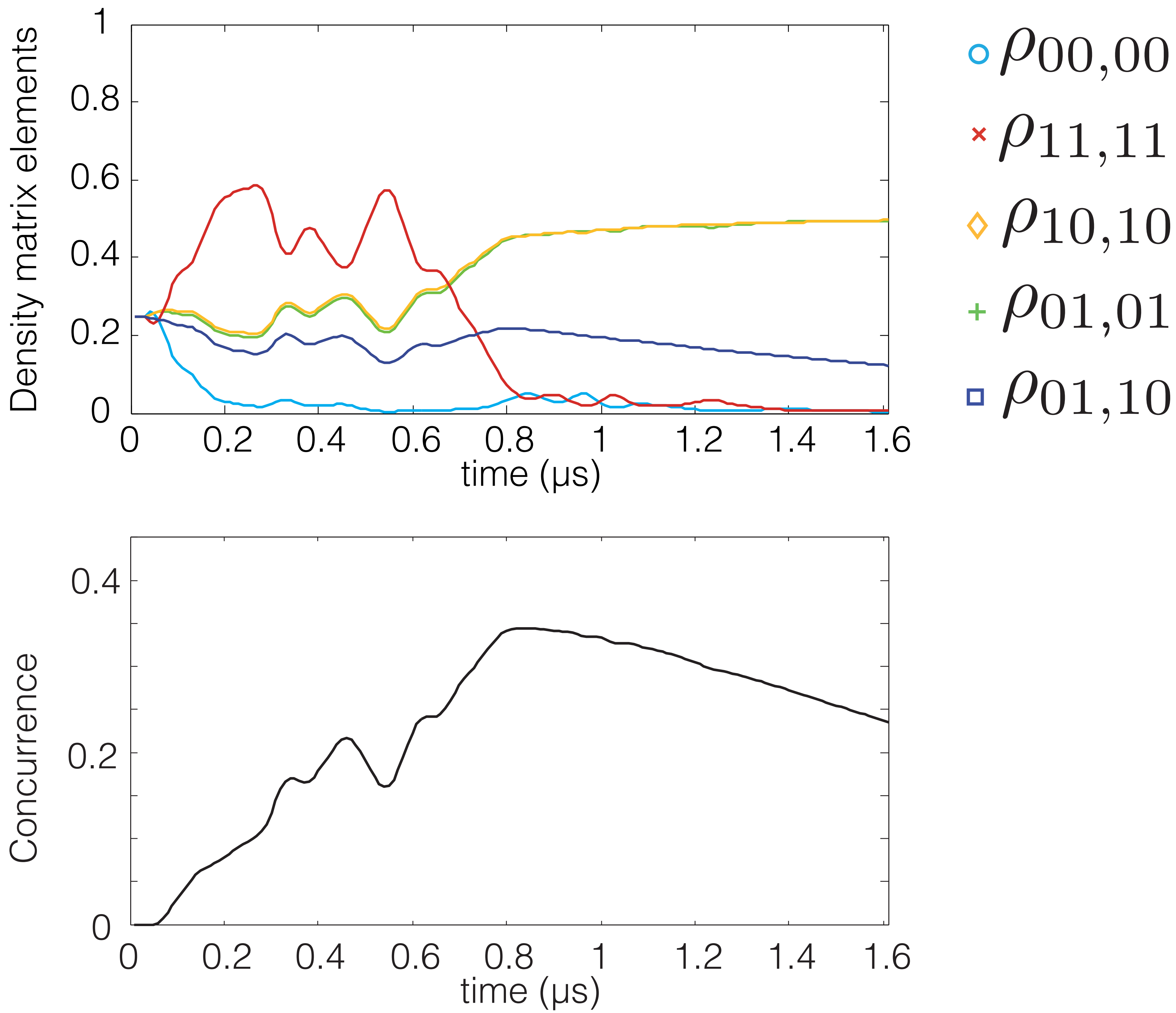
$$p(|ij\rangle|r) = \frac{p(|ij\rangle)p(r||ij\rangle)}{p(r)}$$

Single quantum trajectory



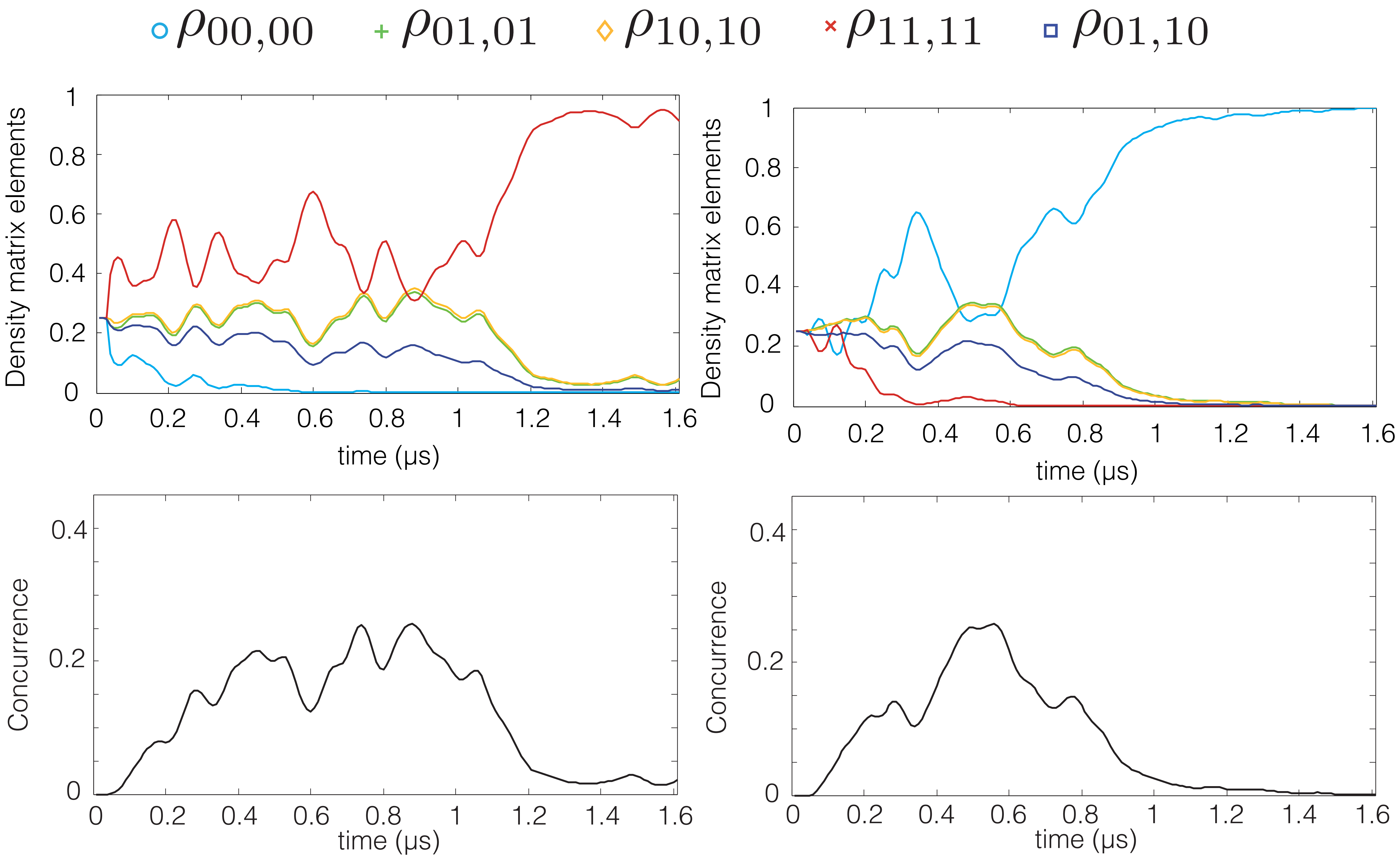
Reconstructing a single quantum trajectory of one cascaded system

Single quantum trajectory

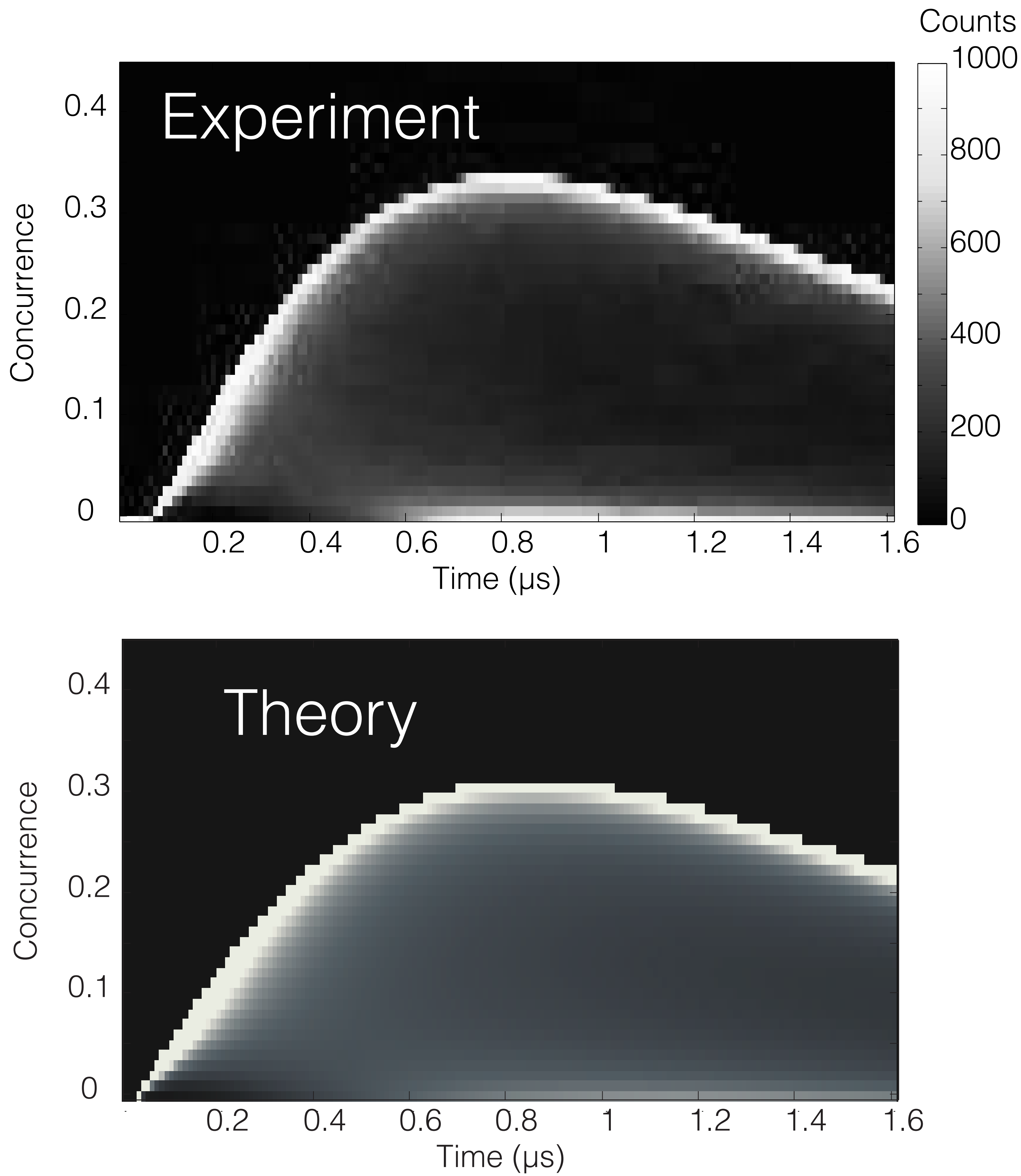


$$\mathcal{C} = \max(0, 2(|\rho_{01,10}| - \sqrt{\rho_{00,00}\rho_{11,11}}))$$

Single quantum trajectory



Perspectives



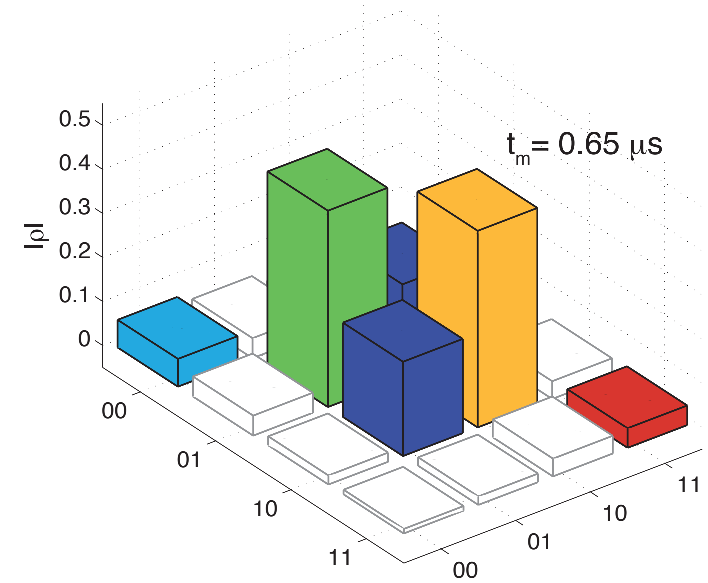
Probability density function of the concurrence

University of Rochester:

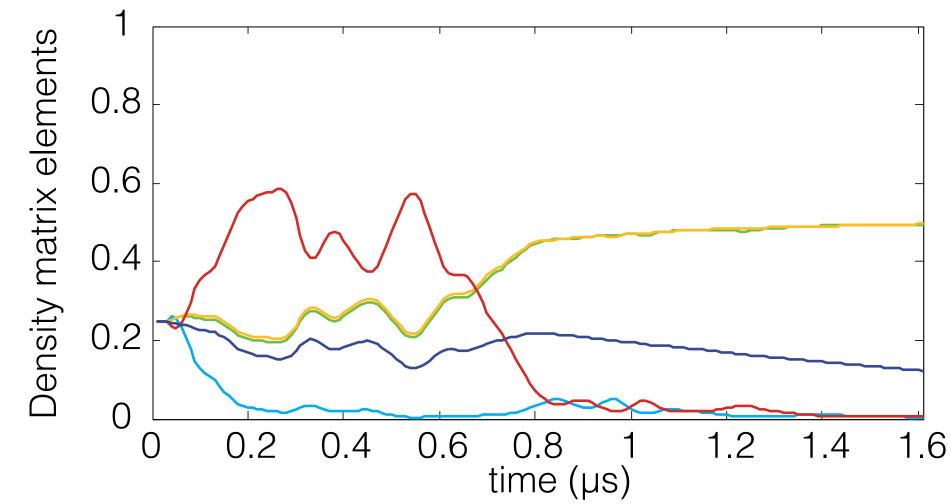
A. Chantasri and A. N. Jordan

Summary

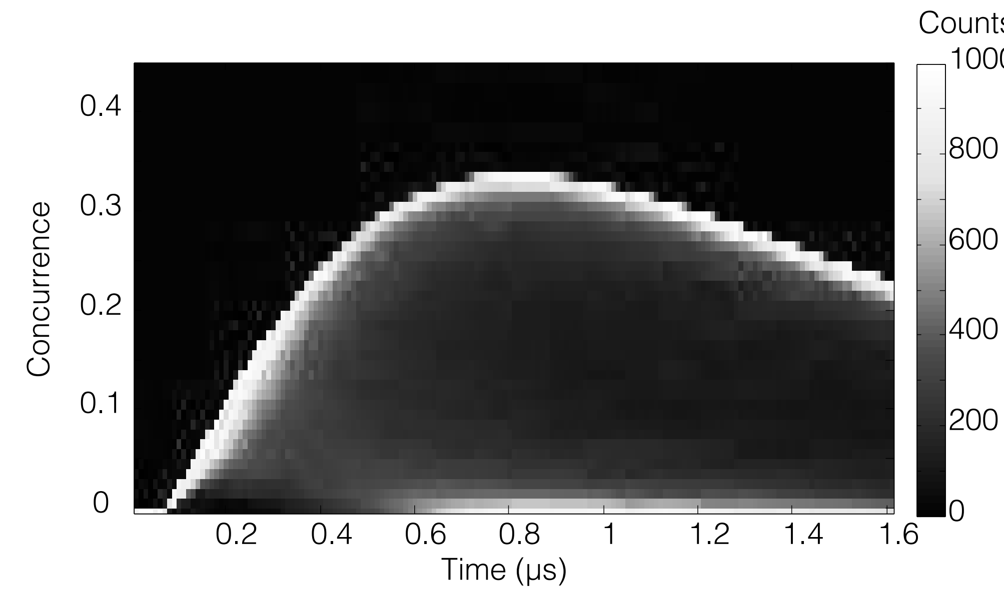
Entangling remote qubits using measurement



Reconstructing single quantum trajectories



Statistics of remote entanglement creation



Roch N., et al. **Phys. Rev. Lett.**, (2014)

Viewpoint in Physics: Remote Controlled Entanglement by K. Lalumière and A. Blais

Thanks !

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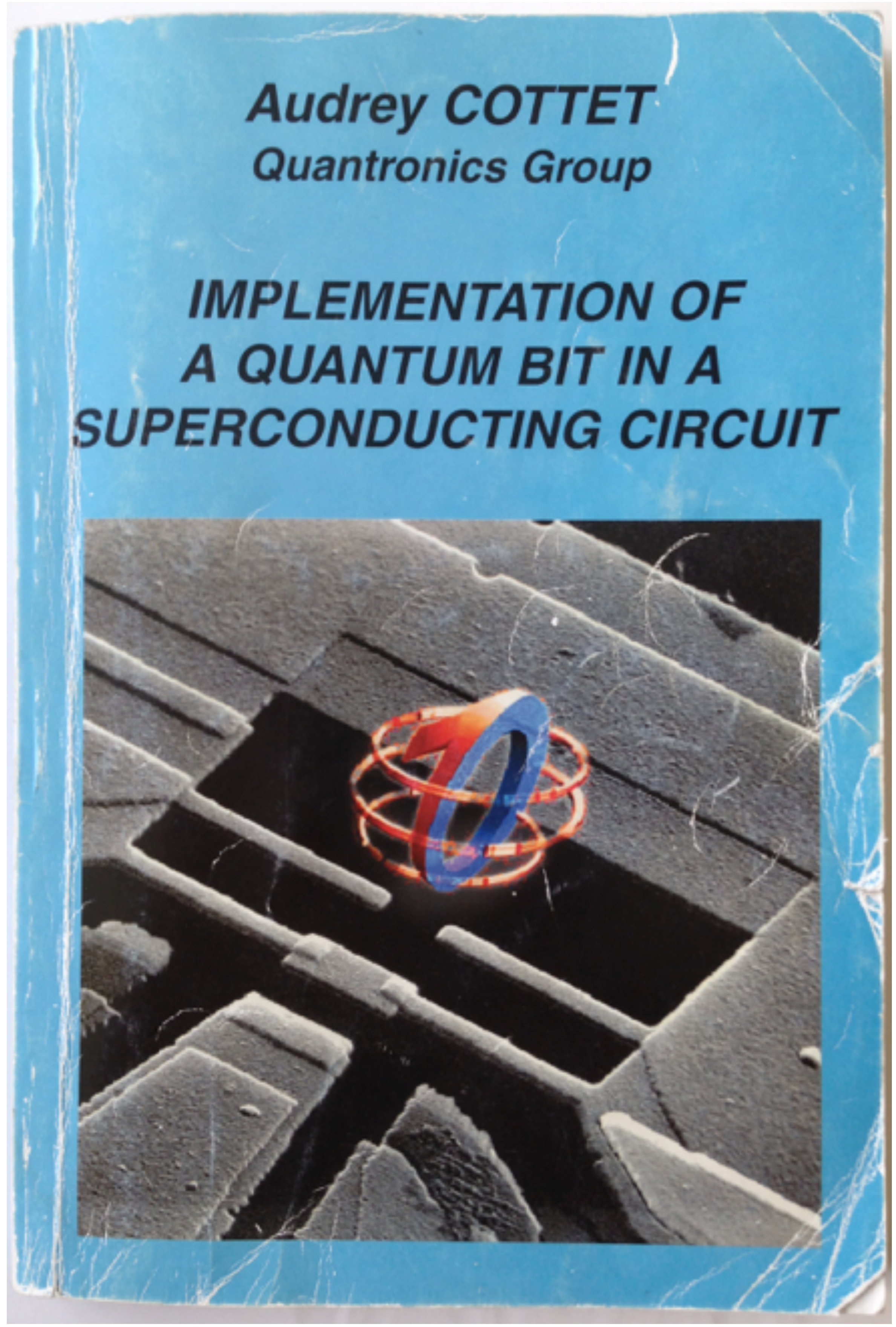
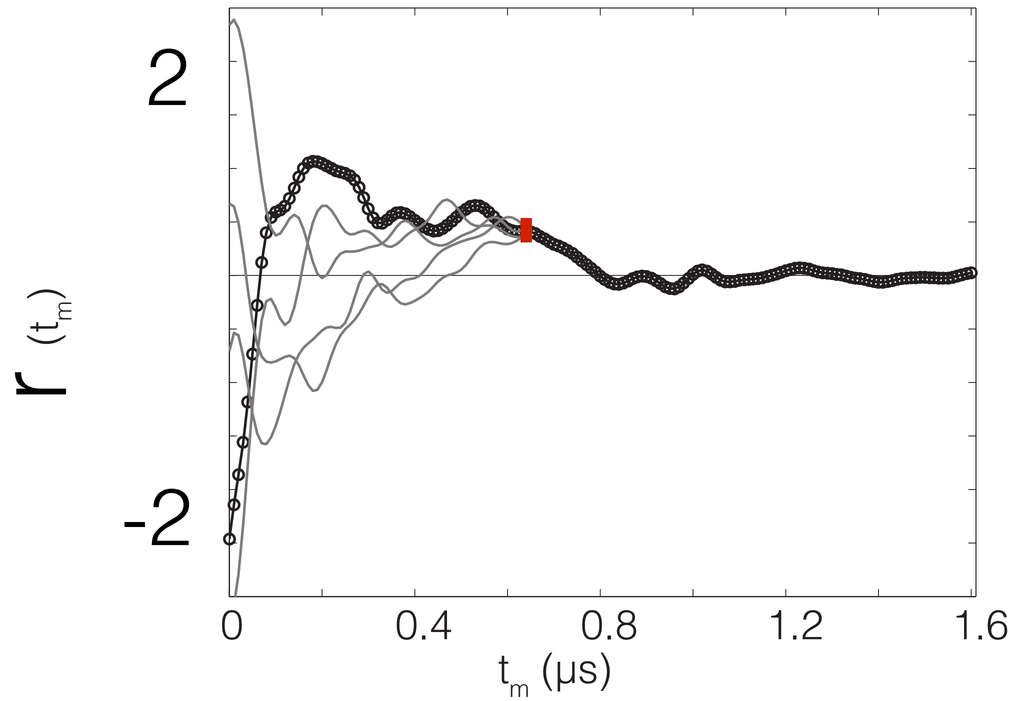
Happy Birthday “Quantro”



Off-diagonal elements

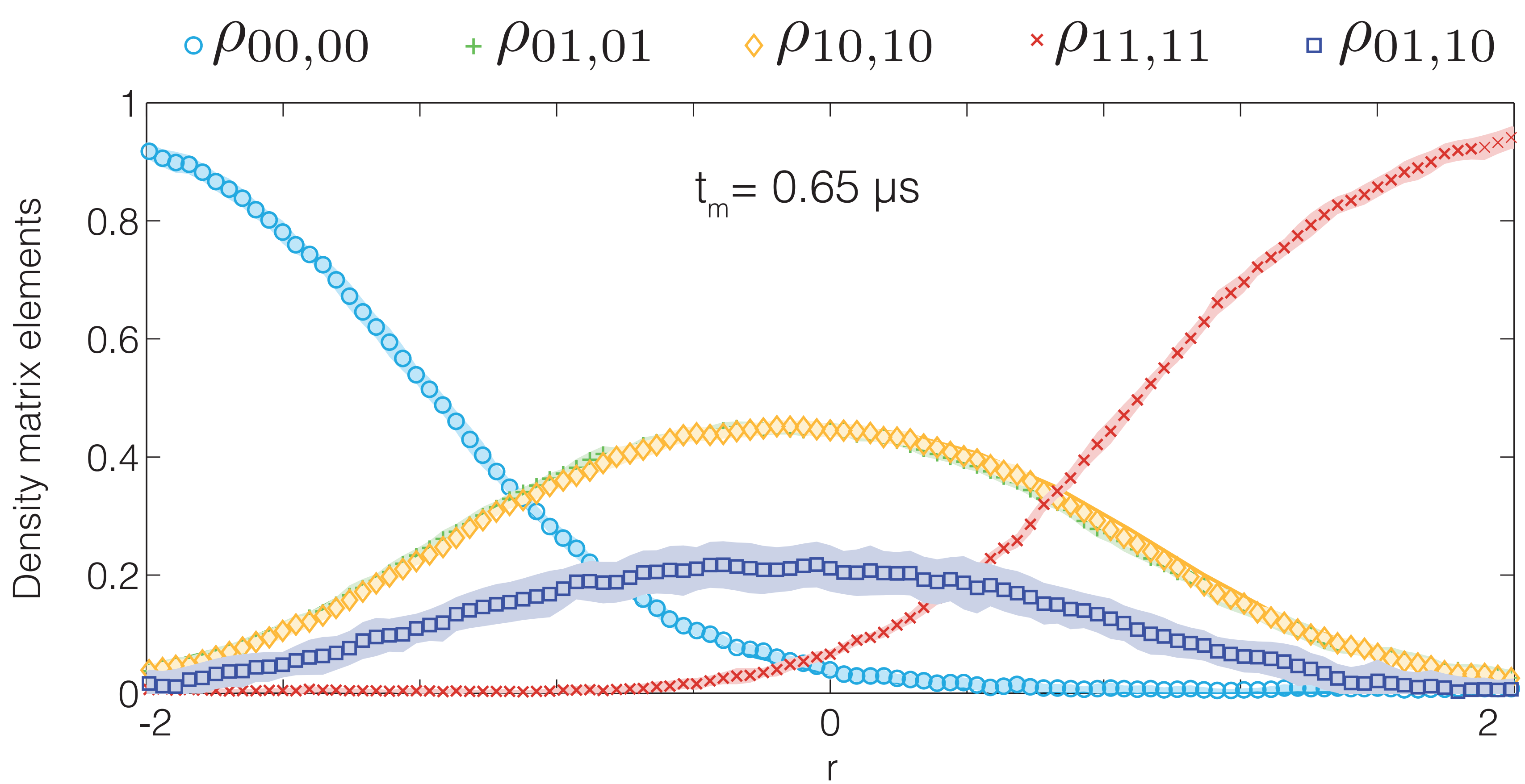
$$
\begin{aligned}
|\rho^{fin}_{01,10}| = |\rho^{in}_{01,10}| \, \frac{\sqrt{\rho^{fin}_{01,01}\rho^{fin}_{10,10}}}{\sqrt{\rho^{in}_{01,01}\rho^{in}_{10,10}}} \\
\times \exp\left[-\frac{1}{2}\int |B^{(01)}_{out}(t) - B^{(10)}_{out}(t)|^2 dt\right] \\
\times \exp\left[-\frac{1}{2}\int \left(\left(1-\eta_{loss}\right)\kappa_{s,1} + \kappa_{w,1} + \kappa_{decay,1}\right)|A^{(01)}(t) - A^{(10)}(t)|^2 dt\right] \\
\times \exp\left[-\frac{1}{2}\int \left(\kappa_{w,2} + \kappa_{decay,2}\right)|B^{(01)} - B^{(10)}|^2 dt\right],
\end{aligned}
$$

Conditional Tomography

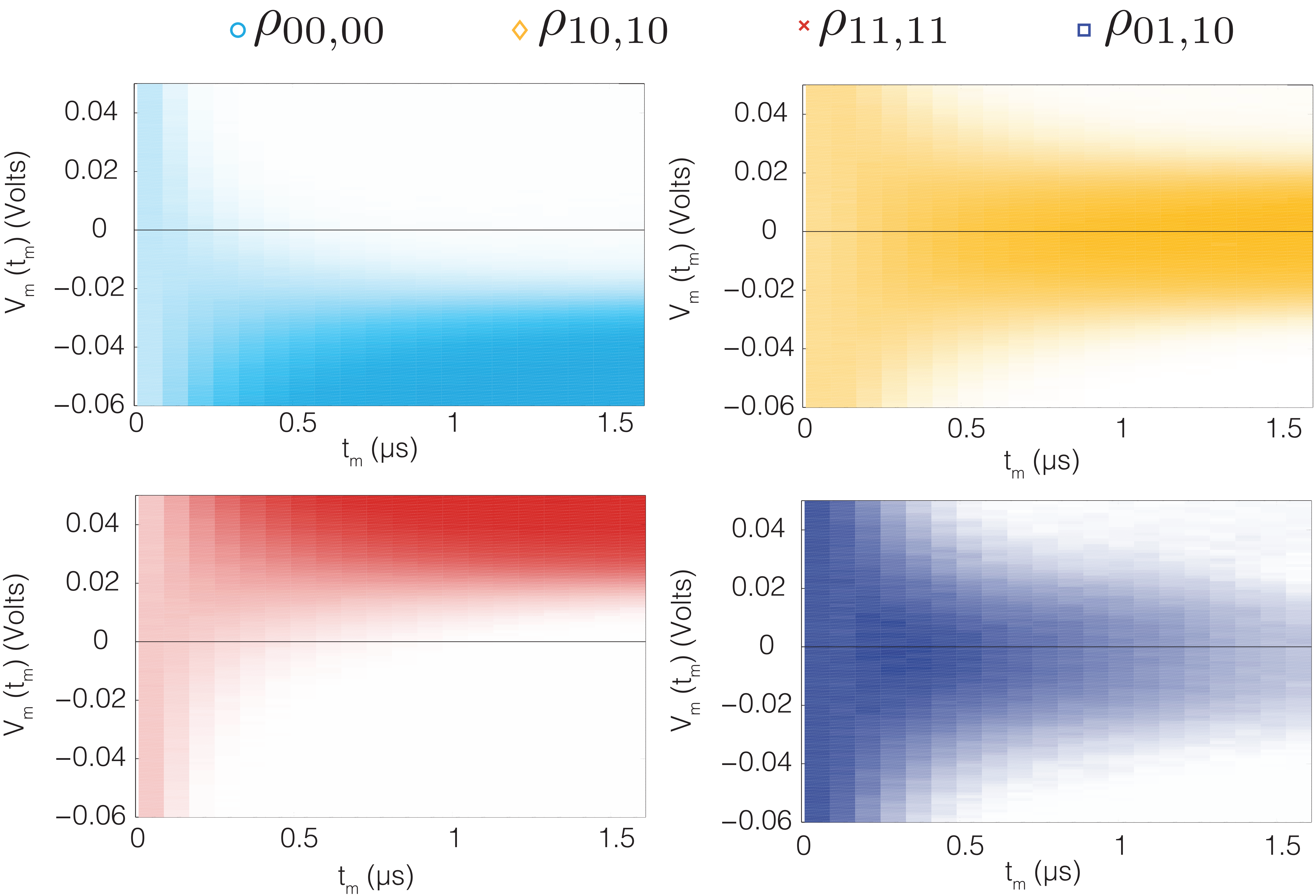


keep only traces in the window r(t_m)
to perform tomography

Exemple: tm=0.65 μs



Conditional Tomography



Conditional Tomography