Obergurgl, June 2010

High fidelity latching readout in the photon blockade regime of circuit QED

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arxiv:1004.4385

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Outline

- Quasi-coherent states in the driven-damped Jaynes-Cummings model
- Quantum-semiclassical bistability in the photon-blockade regime
- Coherent control for high fidelity readout

Motivation: the readout fidelity problem in cQED

Dispersive readout:

Employs Jaynes-Cummings interaction

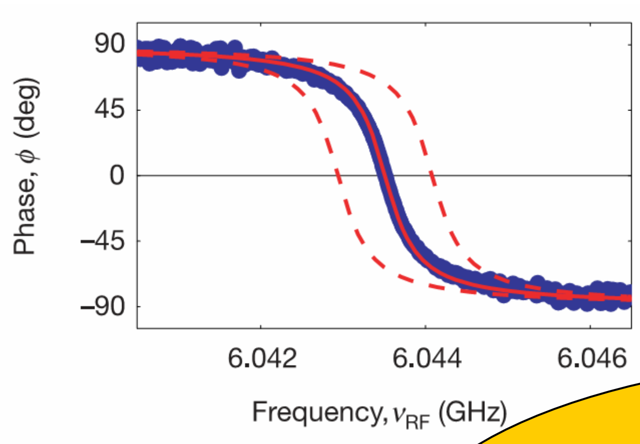
Achieves ~70% single shot fidelity

Latching readout:

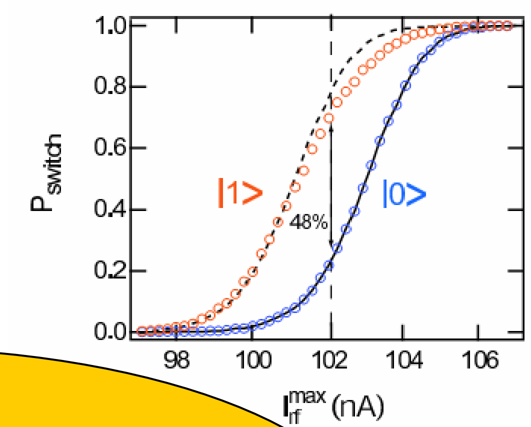
Employs additional nonlinearity

Classical bistability

Achieved ~90% single shot fidelity



A. Wallraff et al.,
Nature 431



510 (2006)

Propose a different physical regime

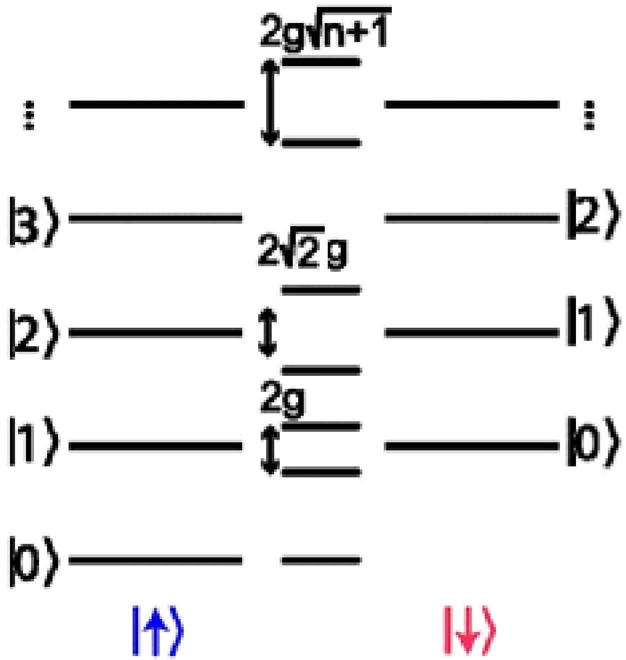
- Photon blockade
- Optimized coherent control

Highly excited Jaynes-Cummings States

Cavity-qubit interaction leads to anharmonic ladder

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma$$

- Photon blockade: with $g \gg \kappa$
- Transition frequencies change by many linewidths with each added photon.
- Anharmonicity diminishes with N: different physics at high excitations.



Quasi-harmonic long lived states

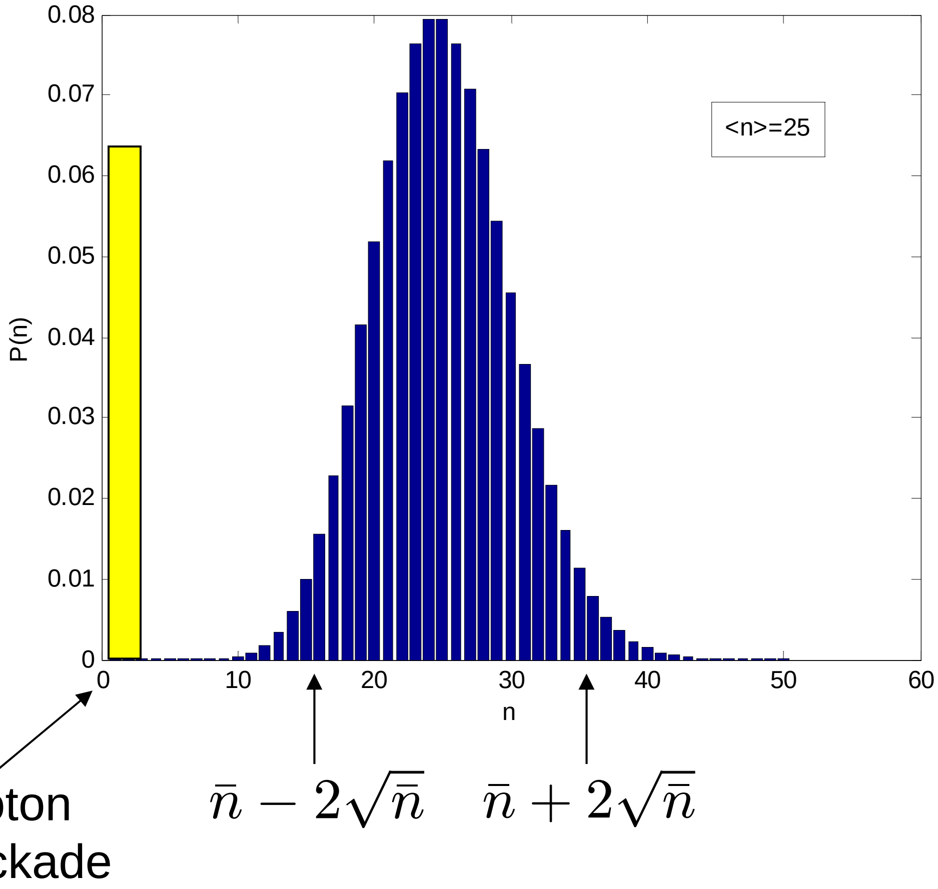
Coherent state with average occupation <n> obeying approximately

$$\omega_{\bar{n}+2\sigma} - \omega_{\bar{n}-2\sigma} \approx \kappa$$

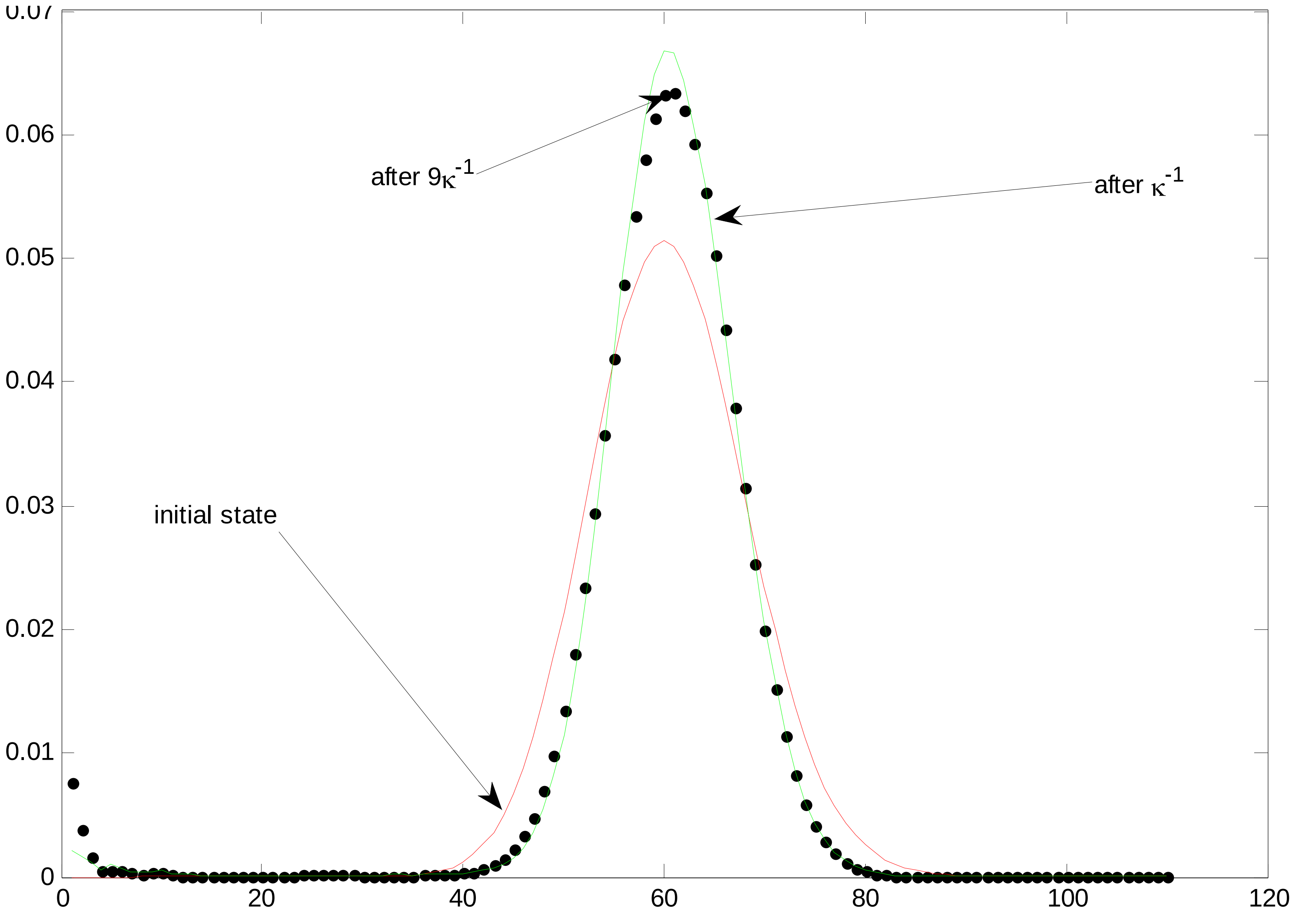
Total frequency shift from "end-to-end" due to anharmonicity should be smaller than the linewidth.

find quasi-coherent states, co-existing with photon-blockaded states (for same parameters and drive).

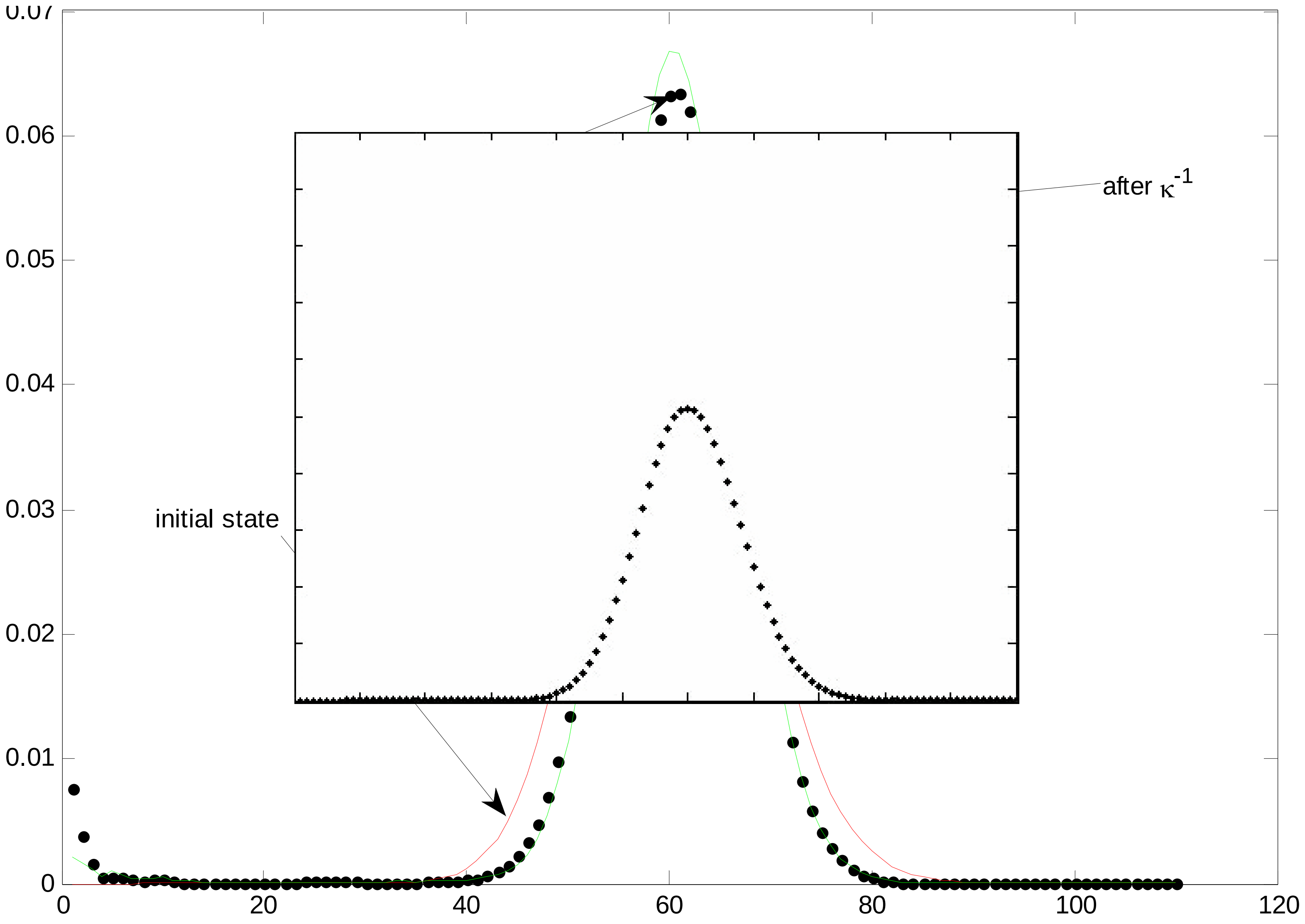
➔ Quantum states coexisting with semiclassical states (bistability)



Quantum trajectory simulations of quasi-stationary states

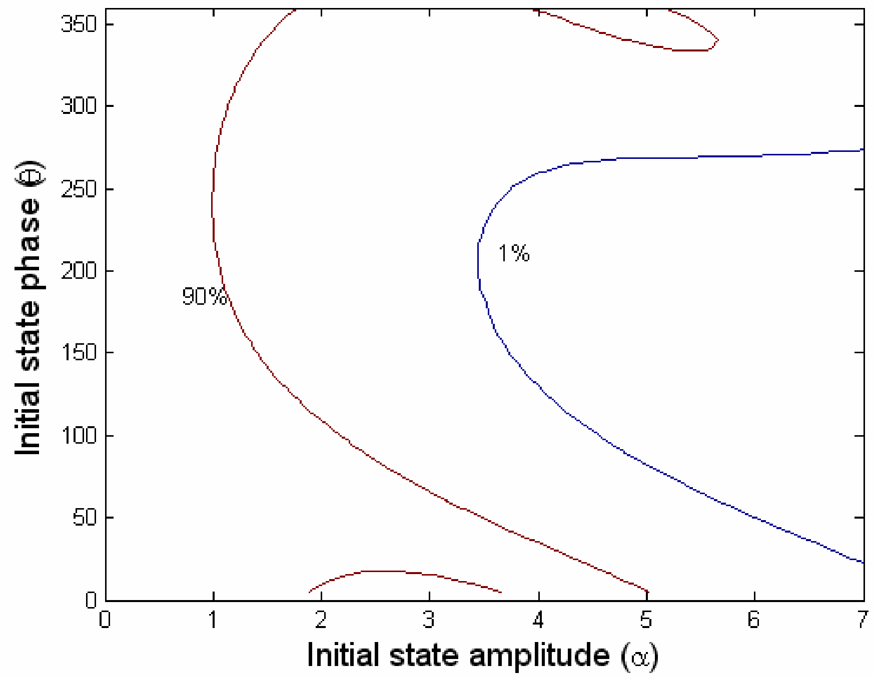


Quantum trajectory simulations of quasi-stationary states

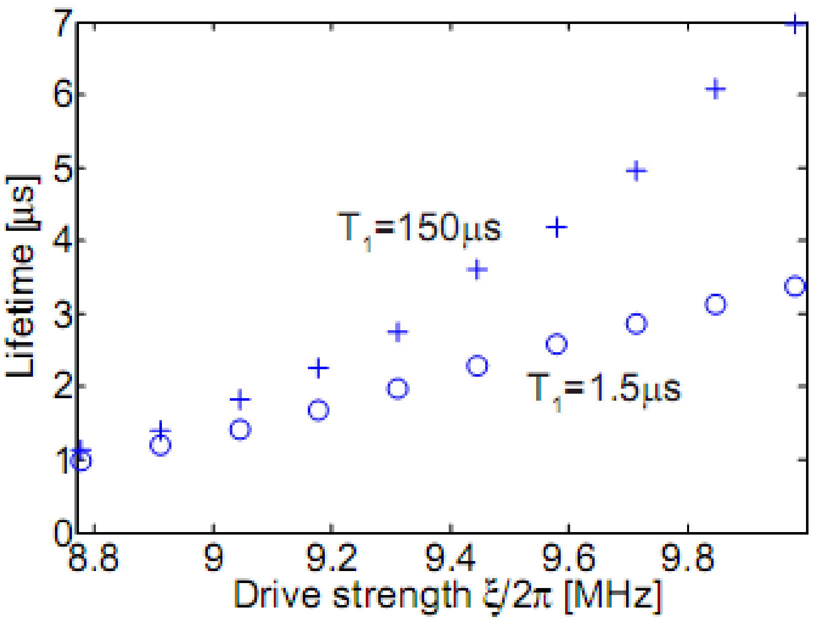


Coexistence of blockaded and long lived quasi-coherent states

Probability for decay after κ^{-1}



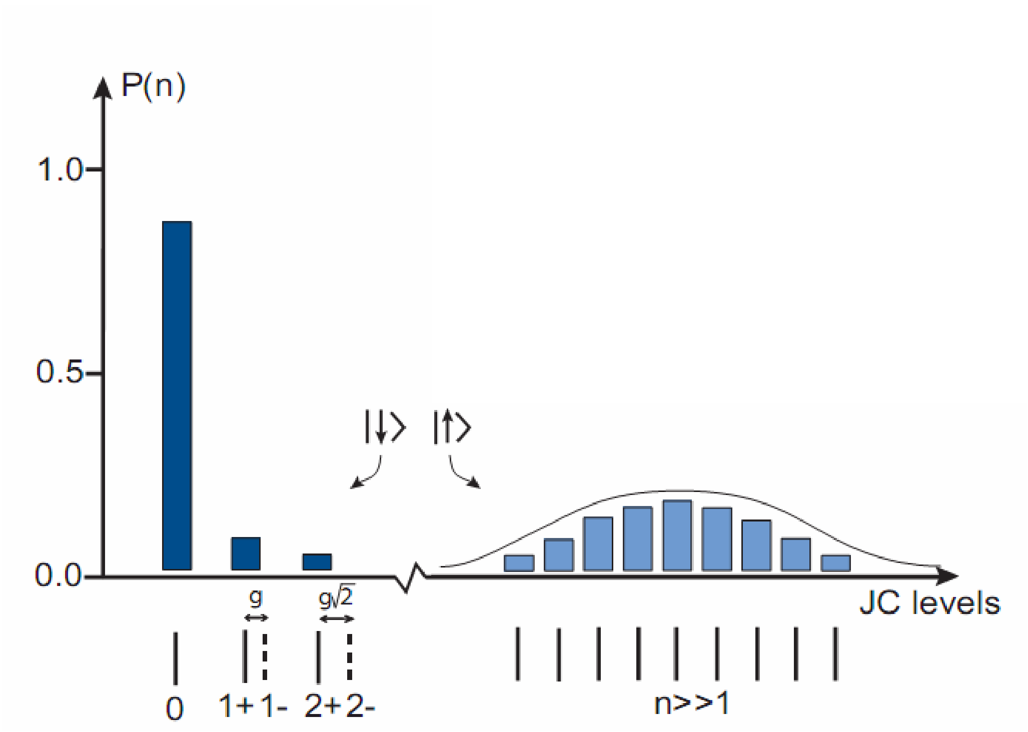
Quasi-coherent states lifetimes



- Lifetime is <u>large</u> on the scale of the cavity lifetime (60ns)
- Experimental – realistic for typical circuit QED parameters

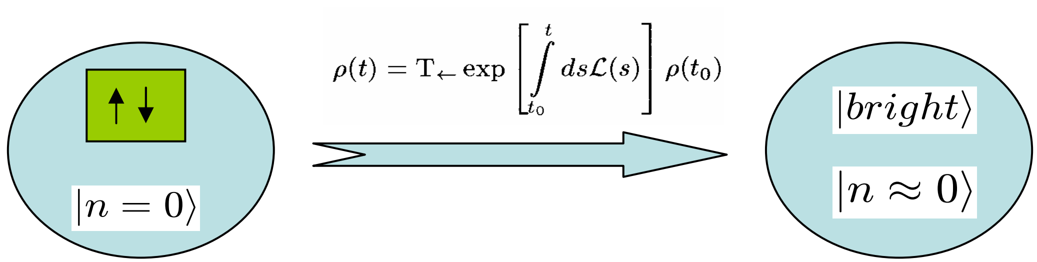
High fidelity readout : a dynamical mapping

Idea: use co-existence of bright and dim states to readout qubit.



High fidelity readout : a dynamical mapping

Selective state transfer problem in coherent control



$$\mathcal{L}\left[\omega_d(t), \xi_d(t), \omega_q(t), \kappa, \gamma\right]$$

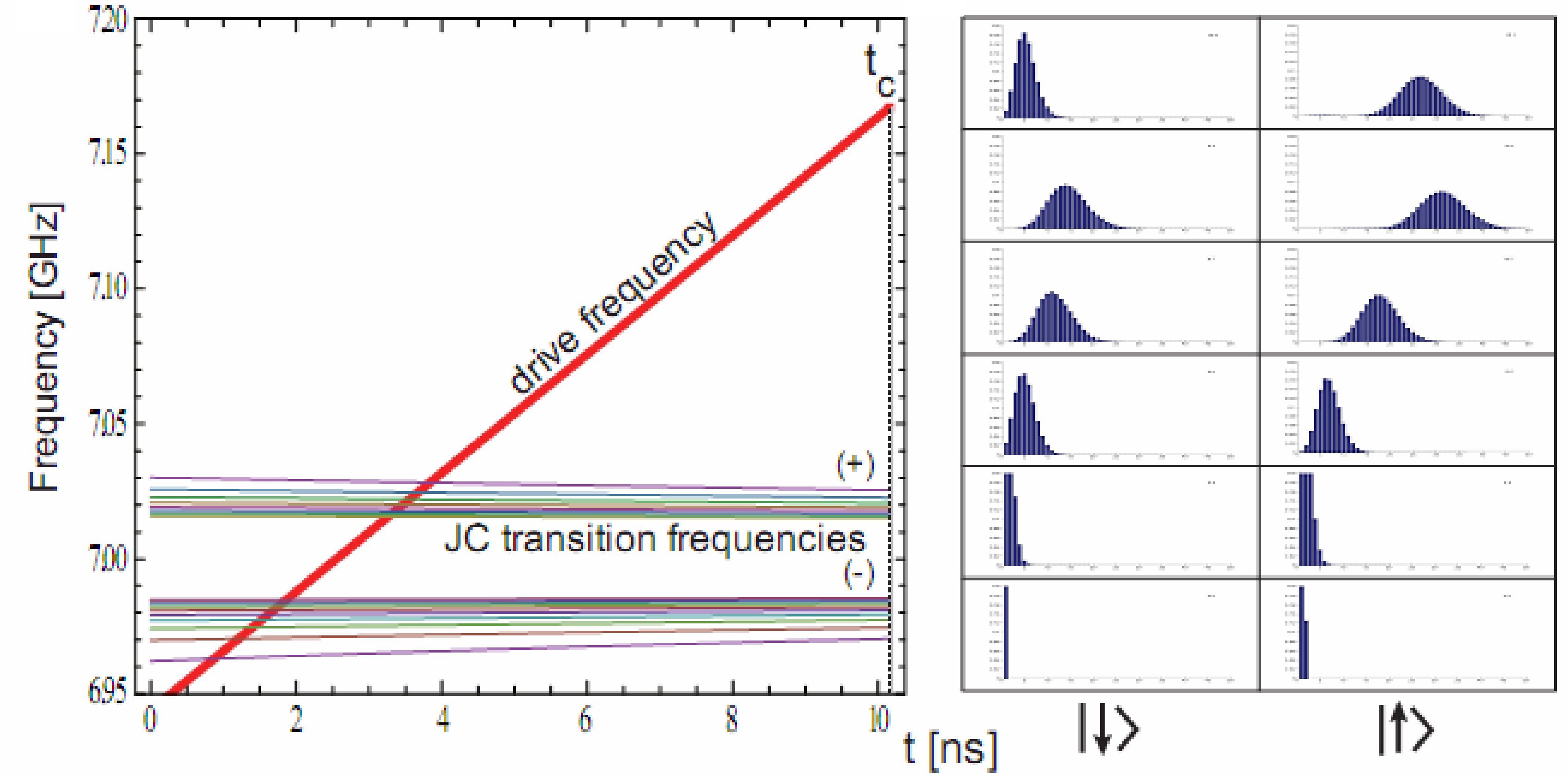
A different coherent control problem:

~~Typically: Given states $|i\rangle$ and $|f\rangle$, maximize P(i $\rightarrow$ f)~~

Given states $|i,i'\rangle$ and $|f,f'\rangle$, maximize P(i $\rightarrow$ f)+P(i' $\rightarrow$ f')

(and make it very close to it's upper bound value of 2)

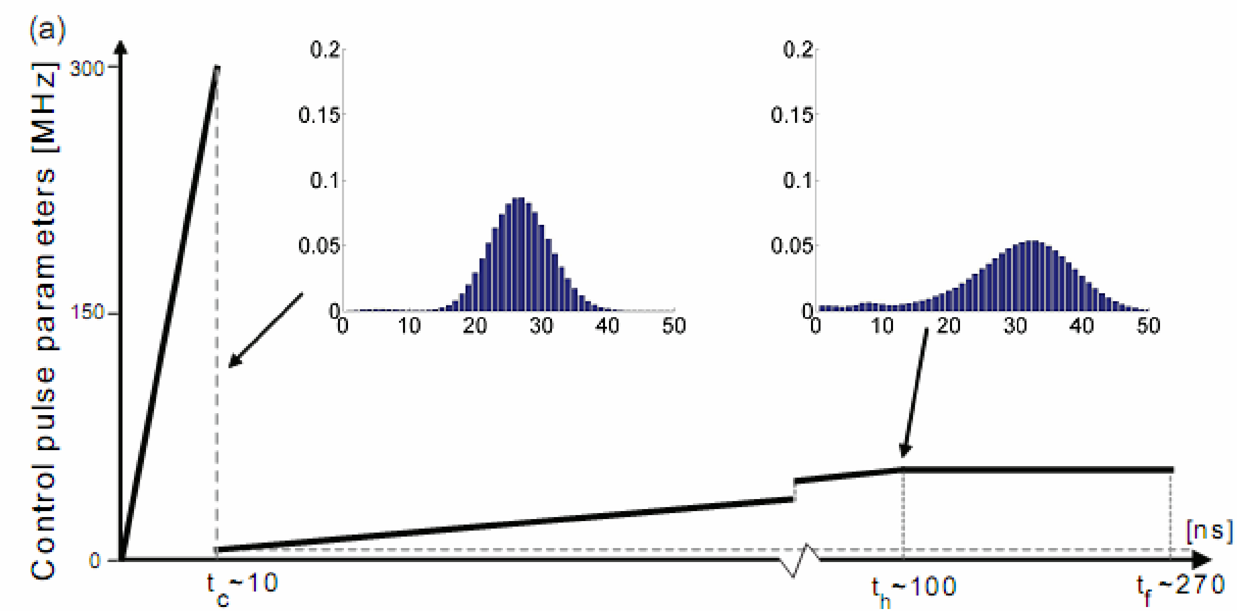
Initial chirp: achieving selectivity via coherent oscillation



• Chirping in the quasi-dispersive regime can be thought of as oscillator ringing

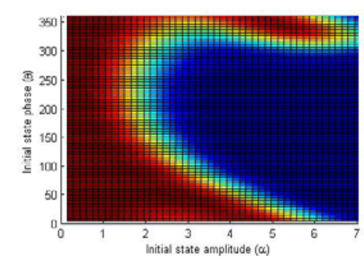
High fidelity readout : Coherent control

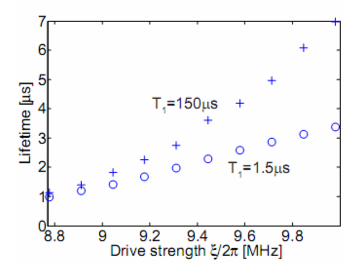
Optimization of a linear chirp readout protocol in the bistable regime



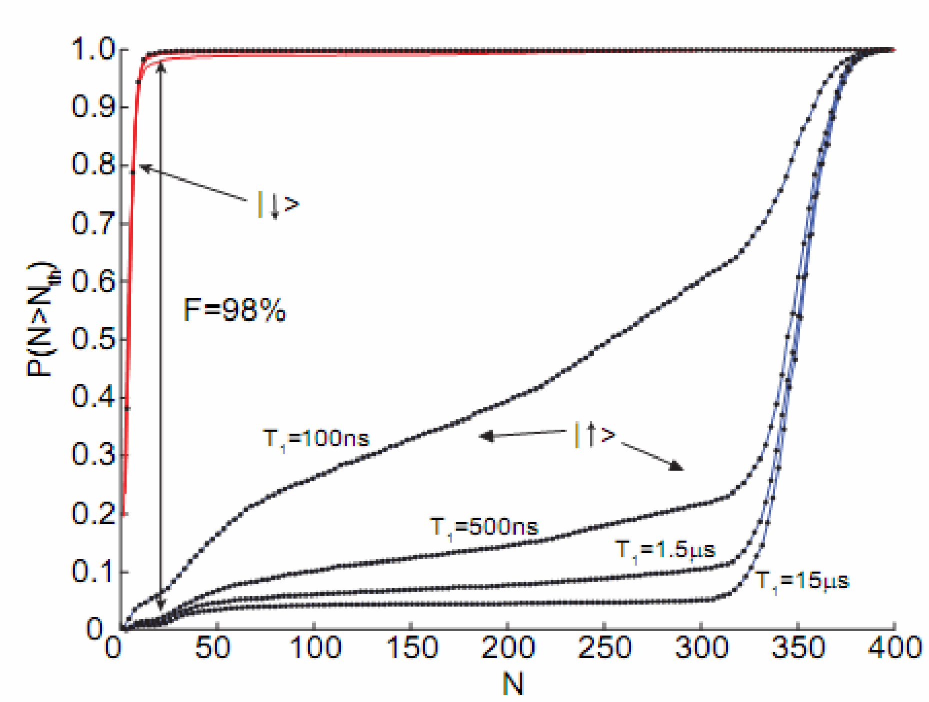
1) An initial strong pulse excites the cavity-qubit system selectively (quasi-dispersive regime)

2) A weak long pulse displaces the quasi-coherent state and does not affect the blockaded state, thus generating the readout contrast.





Cumulative probability distributions (s-curves)



- High fidelities for a low photon threshold, trades off with contrast
- Robust against variations of the system and control parameters

Summary

- Novel type of bistability:
  → photon-blockaded states coexist with quasi-coherent meta-stable states

- Coherent control:
  → high-dimensional open system control problem, not of the usual initial-to-final state type

- Efficient readout protocol of individual qubits
  - high fidelity readout (already >90% for piecewise linear pulse)
  - no additional “moving parts”, only qubit and cavity
  - further optimization naturally fits adaptive feedback control techniques

Outlook

- Theory for the additional slow timescales that emerged in simulation

- What physics ultimately limits the fidelity and contrast?

- Improved optimal control algorithms (e.g. GRAPE)

- Extensions: multi-qubit readout, effect of additional Transmon levels.

Thank you!

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