SAND2018-2941C

Fundamental Limits to Single-Photon Detection Determined by Quantum Coherence and Backaction

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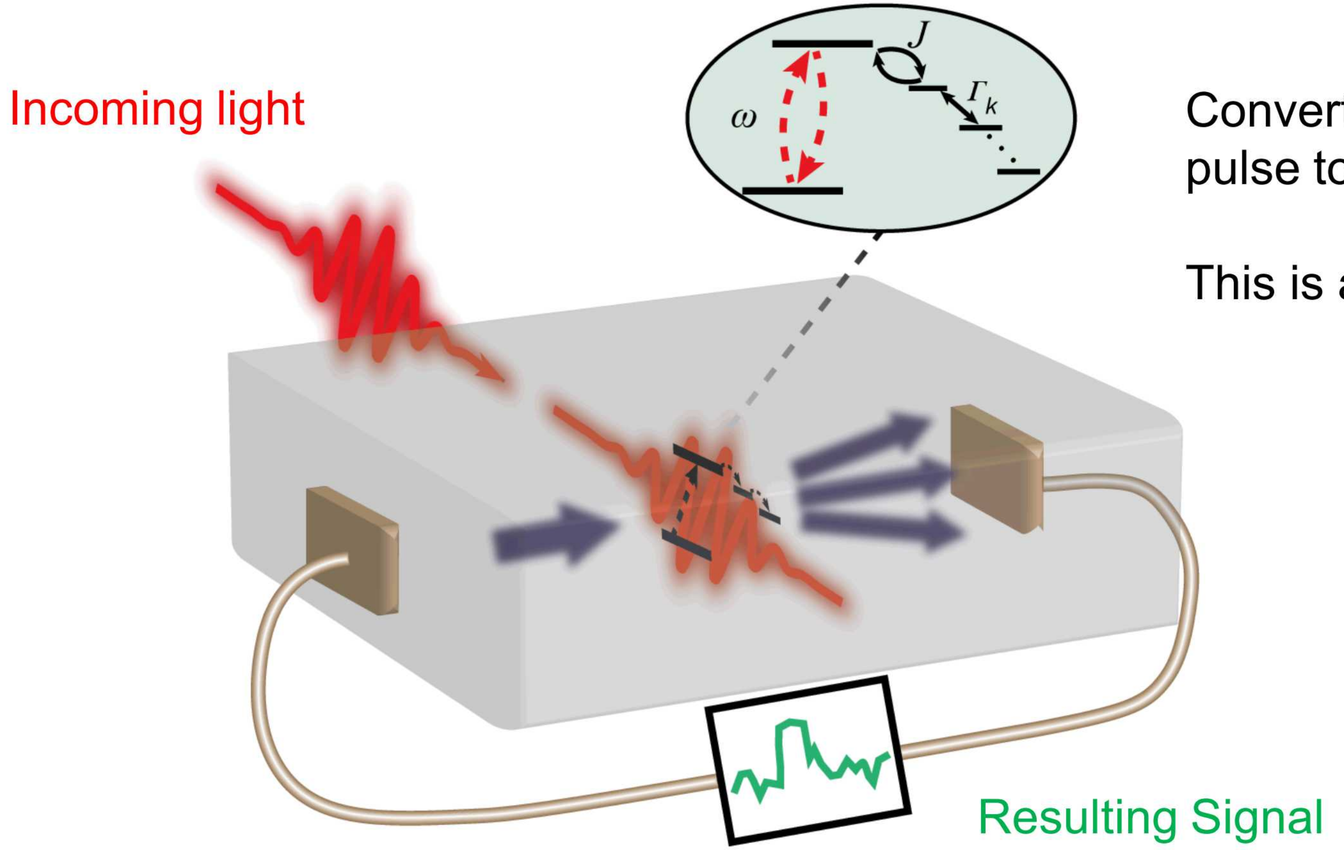
A General Photodector

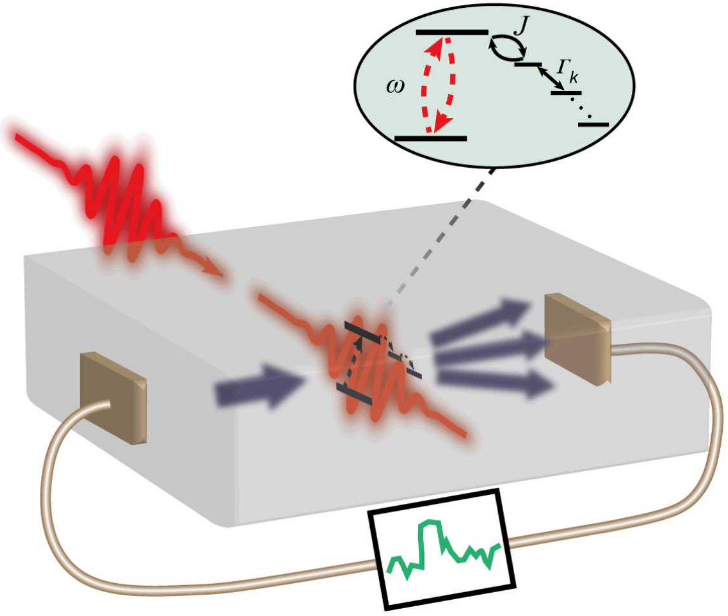


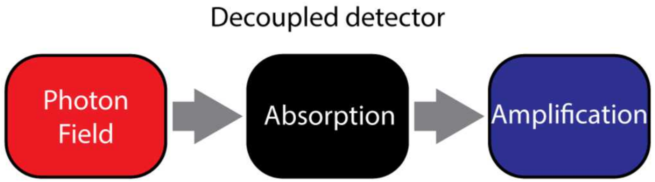
Converts an incident light pulse to an observed signal

This is a very complex device!

We will treat the simplest representative cases to understand the core tradeoffs

A General Photodector



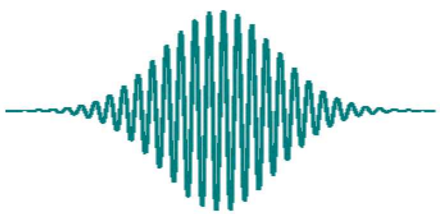


Conventional treatments assume timescale separation of detection stages

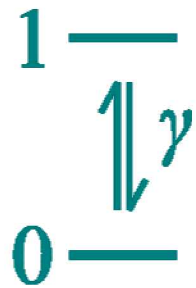
We want to treat as much as possible quantum mechanically, including the impact of amplification; ie, backaction from the measurement process

We will use an open quantum systems formalism that includes a quantized EM field

Isolated System



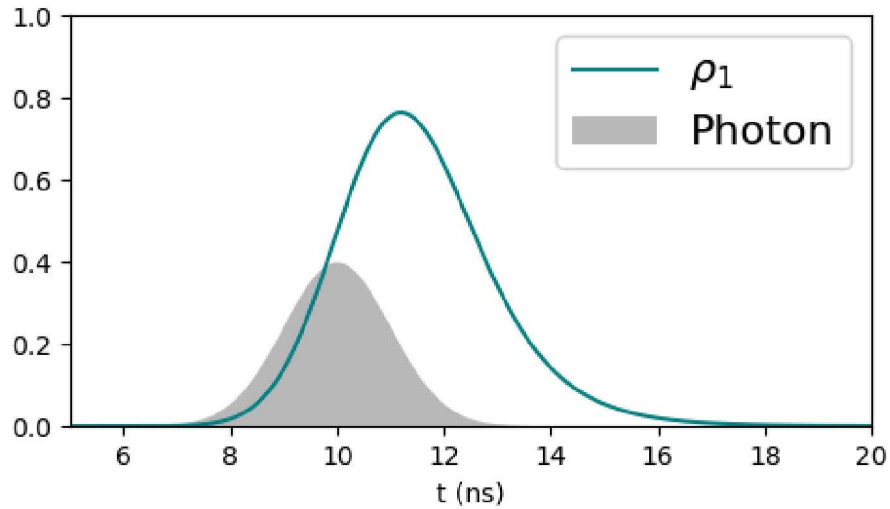
1 Photon



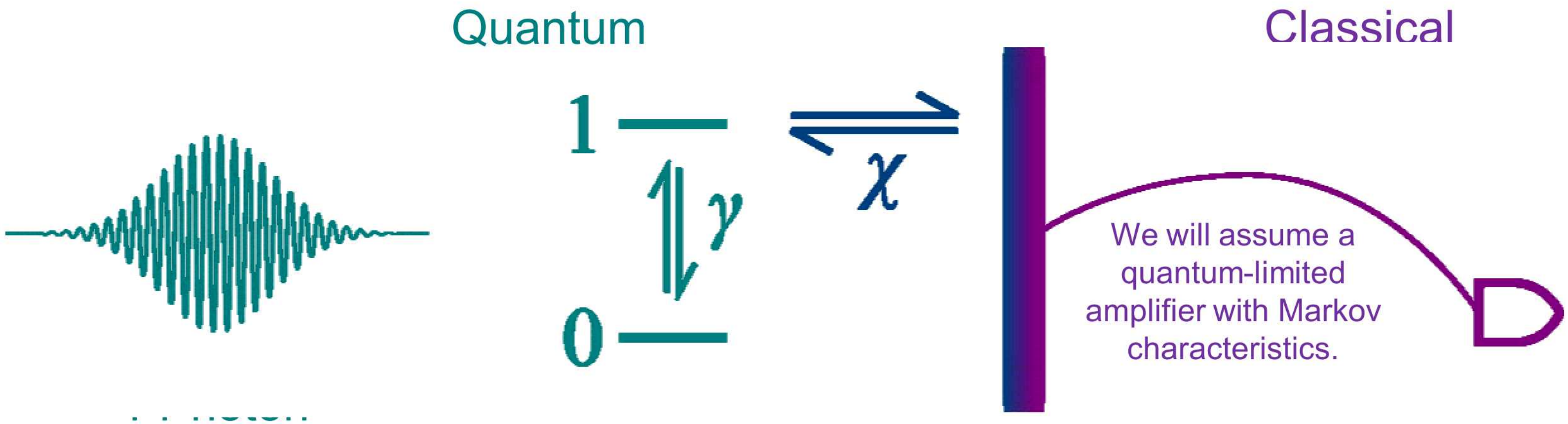
- Single photon, 1ns width Gaussian wavepacket
- Two optically coupled states

How does *measuring* this excitation affect performance?

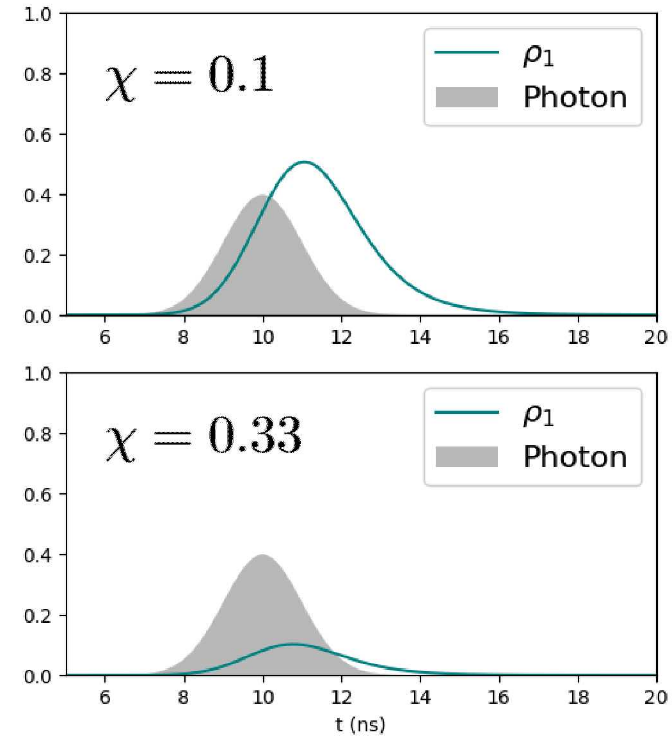
~80% excitation probability



Directly Measured System

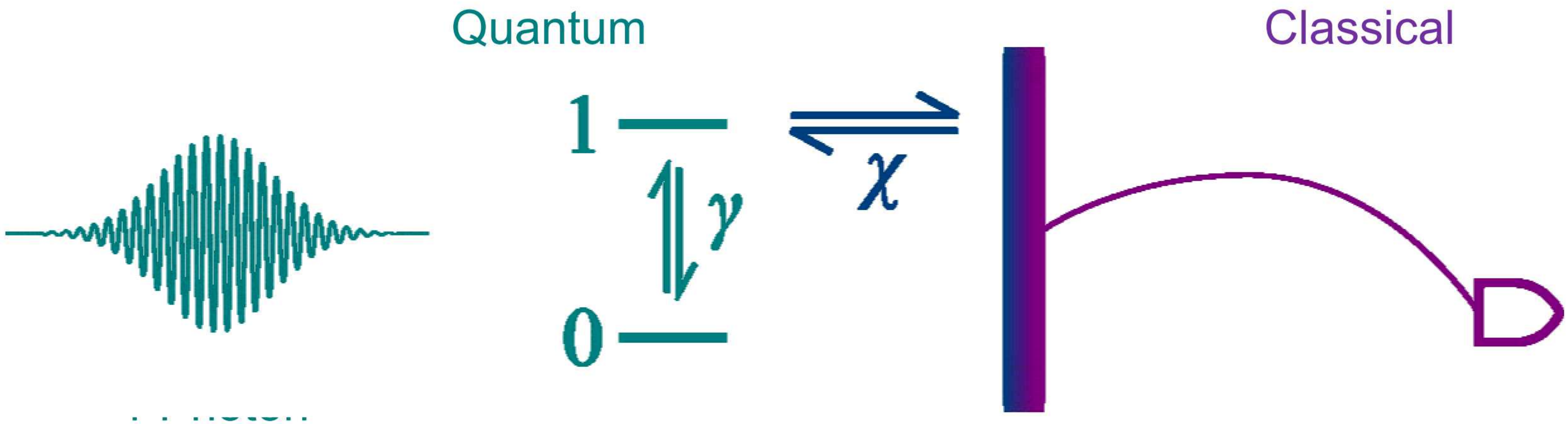


- Excited state coupled to bath whose classical state is monitored
- Excitation changes output reading
- Introduces **decoherence**
- Average excitation probability is reduced according to strength of coupling and signal amplification



Amplification (measurement) *backaction* limits performance

Directly Amplified System

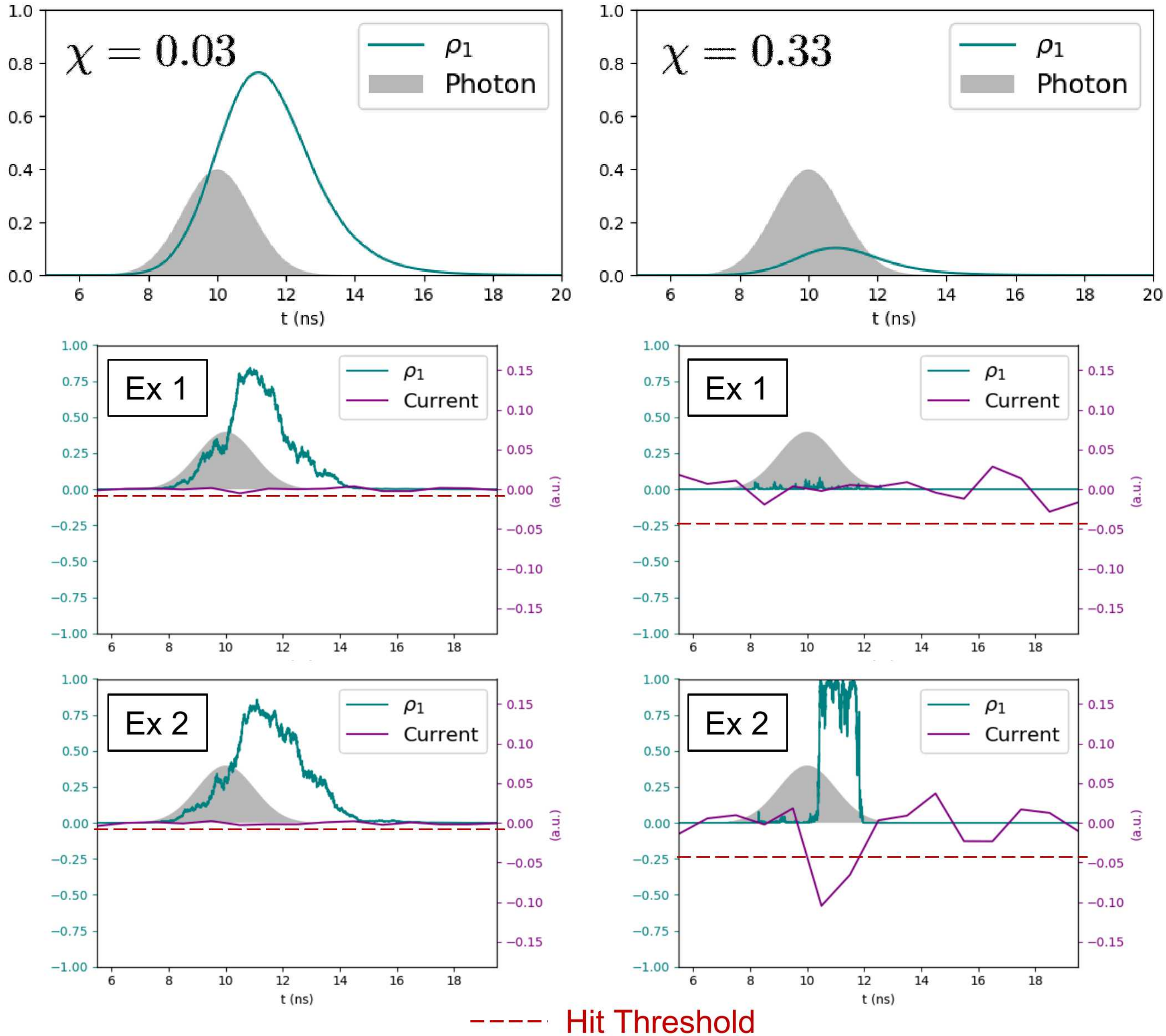


What about modeling *actual measurements*, not just averages?

- Simulate individual events
- Dynamics are conditioned on the measured current
- Obtain measured current as well as excitation population
- Amplification introduces intrinsic noise

$$I_t = \int_t^{t+t_m} \chi^2 \rho_1(t')dt' + \frac{\chi}{2} dW_t$$

Directly Amplified System



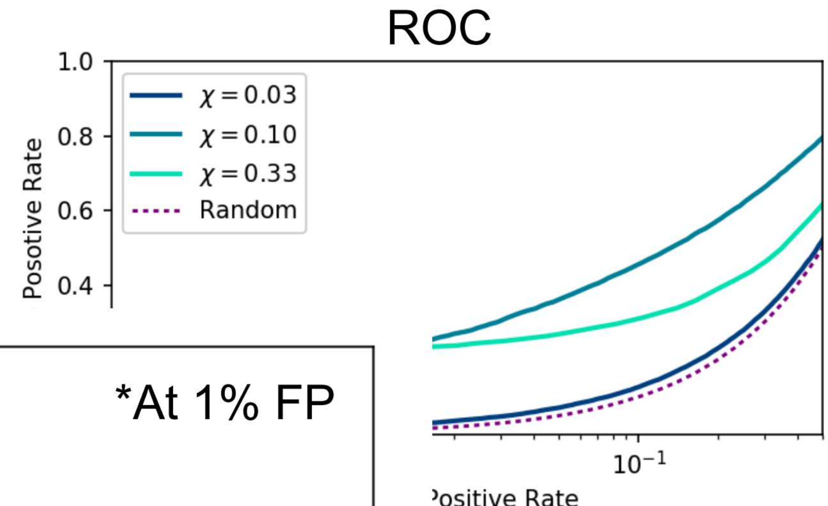
Weaker amplification gives better average signal, but with a lot of noise

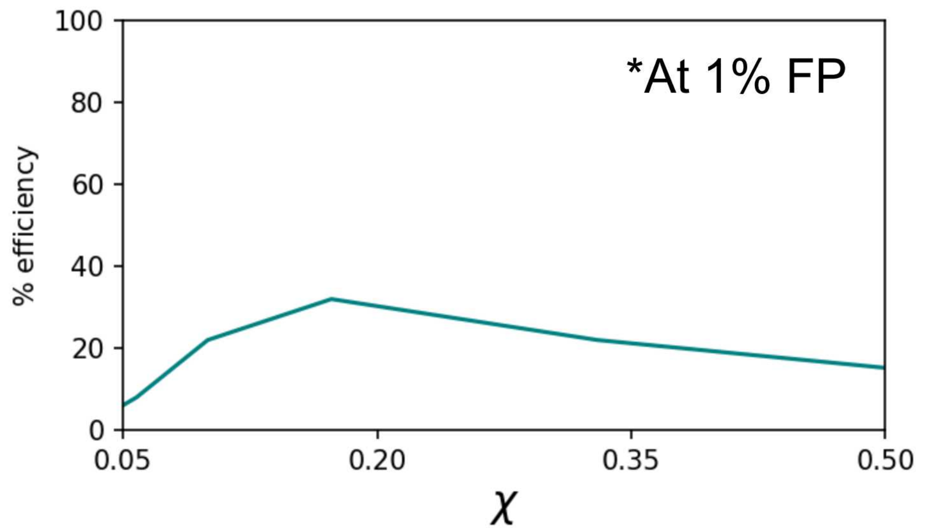
Stronger amplification yields a few recognizable hits

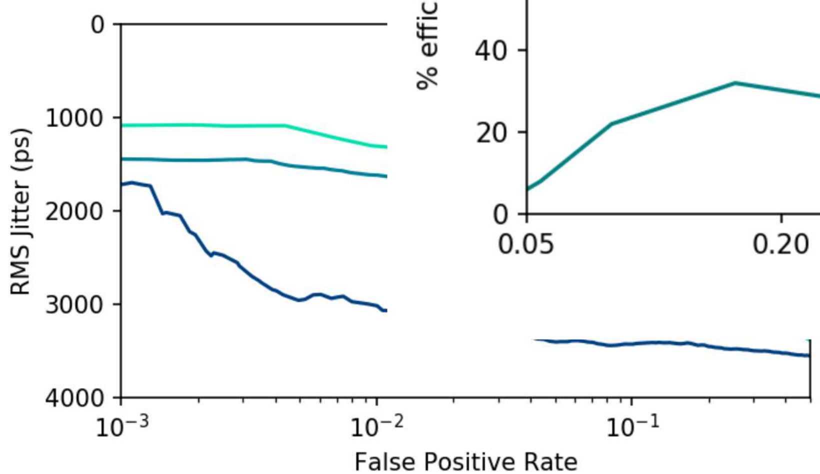
Directly Amplified System

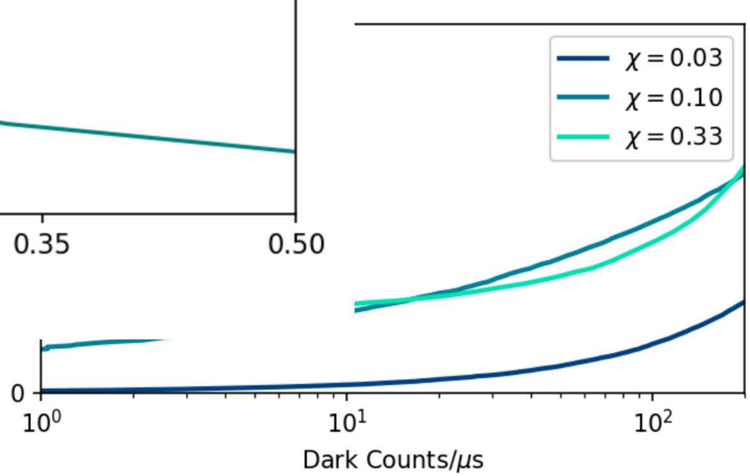
Metrics

- Perform many runs
- Vary threshold for counting a hit
  - True Positive Rate (Efficiency)
  - False Positive Rate (Dark counts)
  - Hit time (Jitt
- For single photor



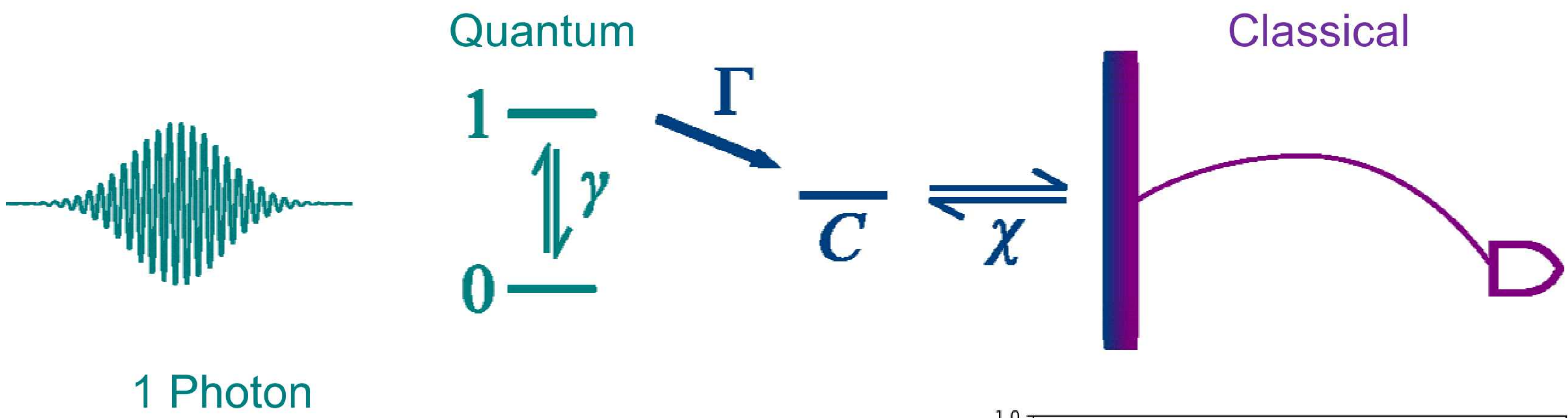






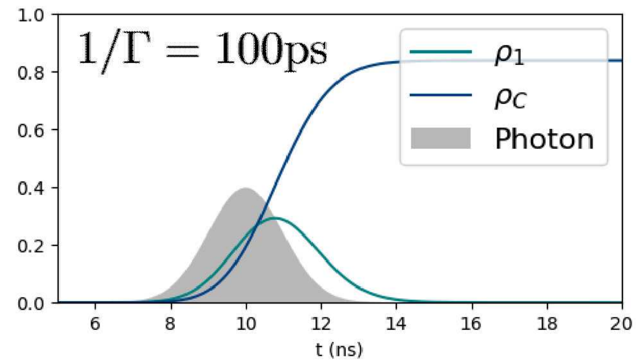
Direct amplification dramatically reduces performance

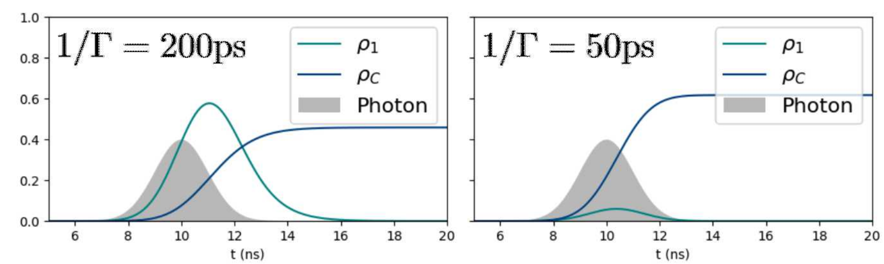
3-State System



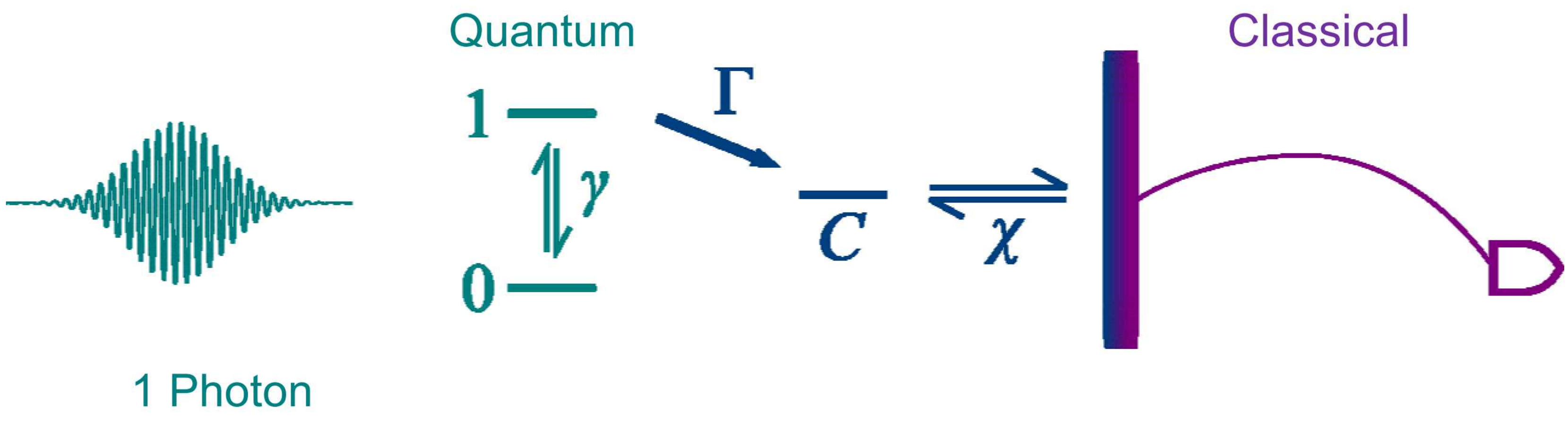
- Excited state relaxes to dark state coupled to bath whose classical state is monitored
- Average excitation is insensitive to amplification!
- Relaxation “protects” excitation but introduces **decoherence**
- Average excitation probability is reduced according to relaxation rate

Relaxation rate must be optimized for performance





3-State System

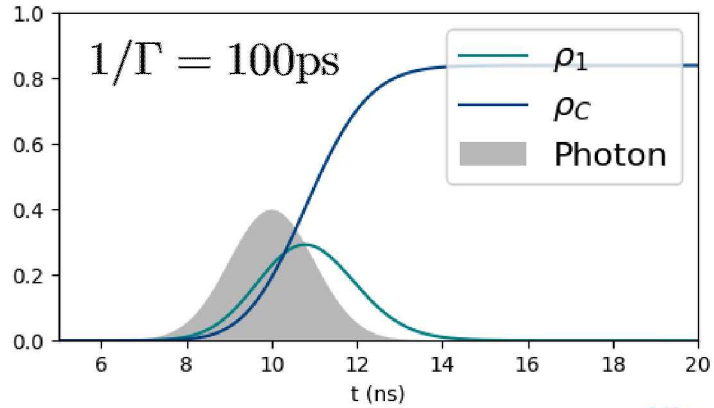


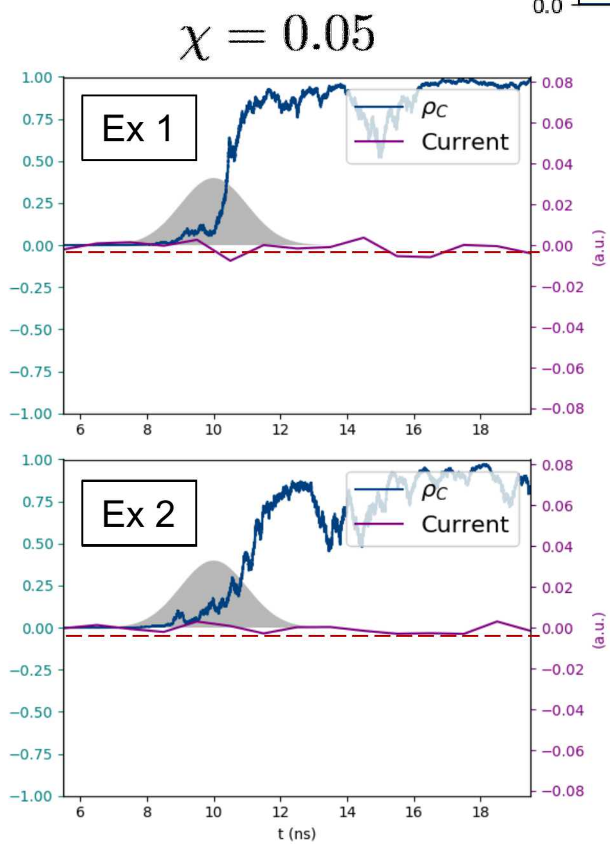
Modeling actual measurements

- Individual event dynamics *do* depend on amplification
- Must also still contend with noise

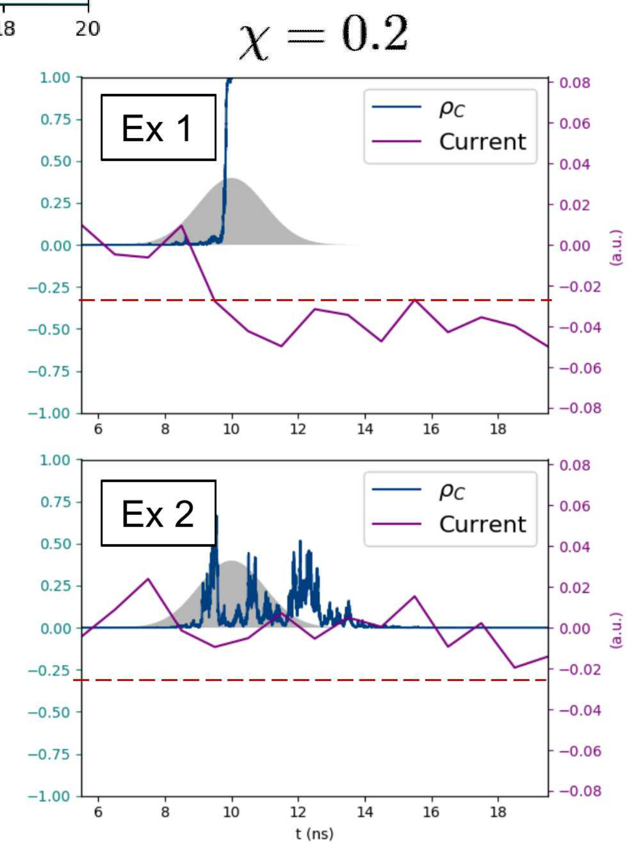
$$I_t = \int_t^{t+t_m} \chi^2 \rho_C(t')dt' + \frac{\chi}{2} dW_t$$

3-State System





Long lifetime in *C* state yields more distinct signal



Hit Threshold

3-State System

Metrics

- Perform many runs
- Vary threshold for counting a hit
  - True Positive Rate (Efficiency)
  - False Positi
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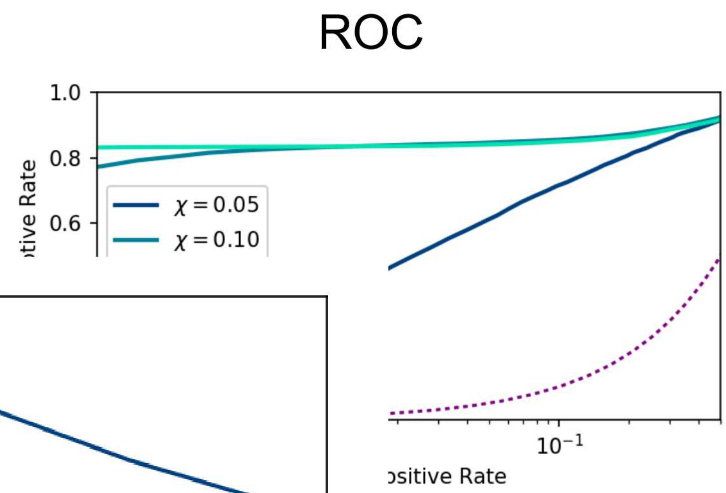
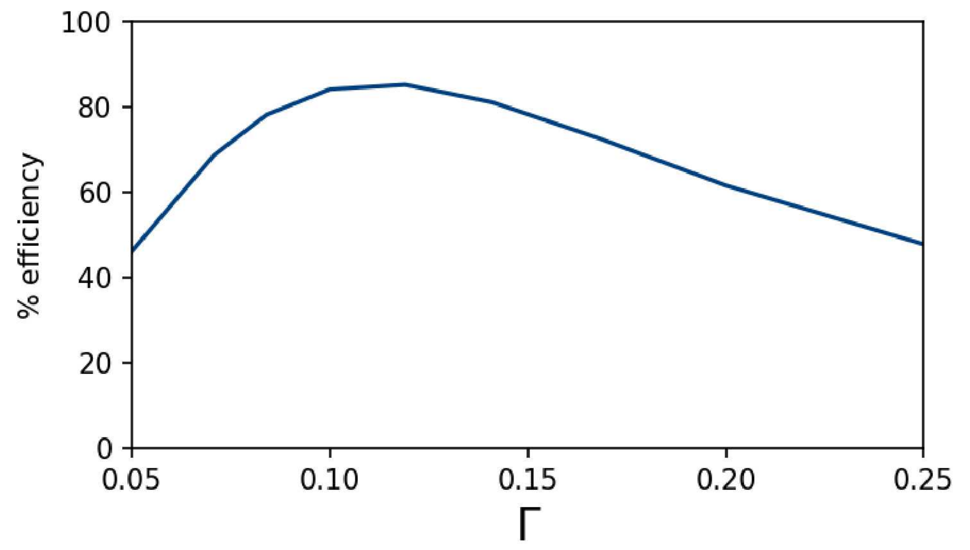
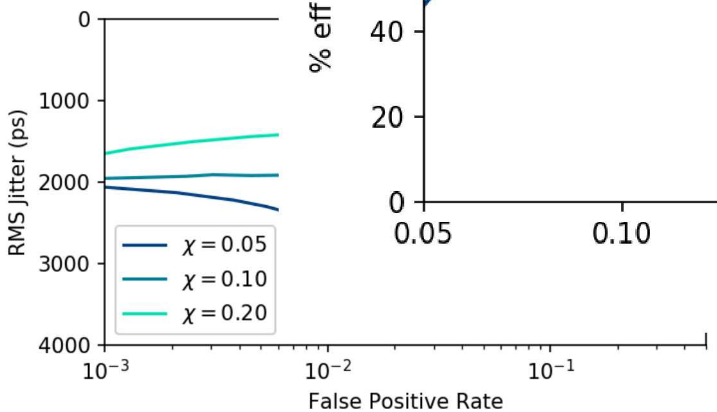
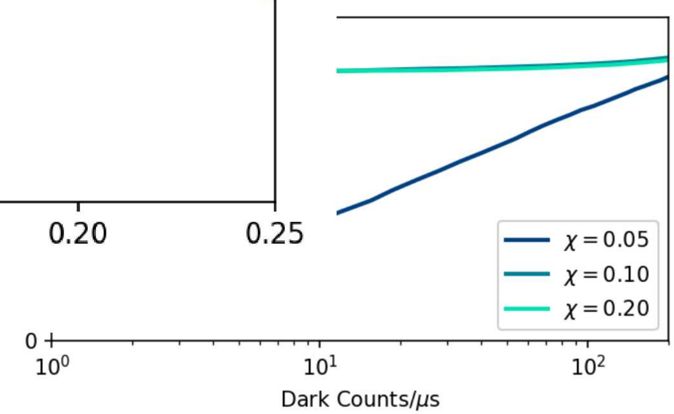
- For single photo







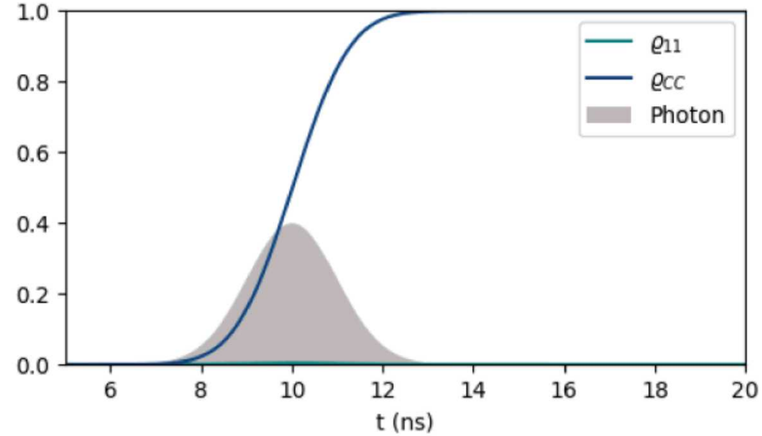


Intermediate state sidesteps negative impact of amplification on performance

Ideal Detection

Simple two state system shows pulse shape and duration dependent performance
What about the monitored case?

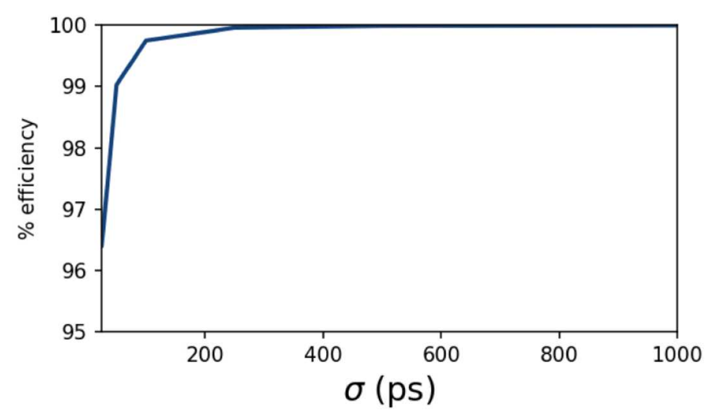
$$\gamma^2 = \Gamma^2 = 0.1\text{ps}^{-1}$$



Suppose $$\gamma^2 = \Gamma^2 \gg \frac{1}{\sigma_{\text{Pulse}}}$$

Average dynamics

When pulse is long compared to excitation and relaxation rates, detection efficiency approaches unity!



Even much shorter pulses can be detected efficiently

Conclusions

- Can simulate fully quantum detection
- Generate detector metrics and quantify tradeoffs and limits
- We learn that:
  - Details of amplification matter
  - Detector can be tuned to minimize negative impact of amplification

- Ongoing work: Extend to more complicated systems, *e.g.*:
  - Multiple photons in pulse
  - Excitations into band

Acknowledgements

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