Generation of non-classical states for measurements below the standard quantum limit

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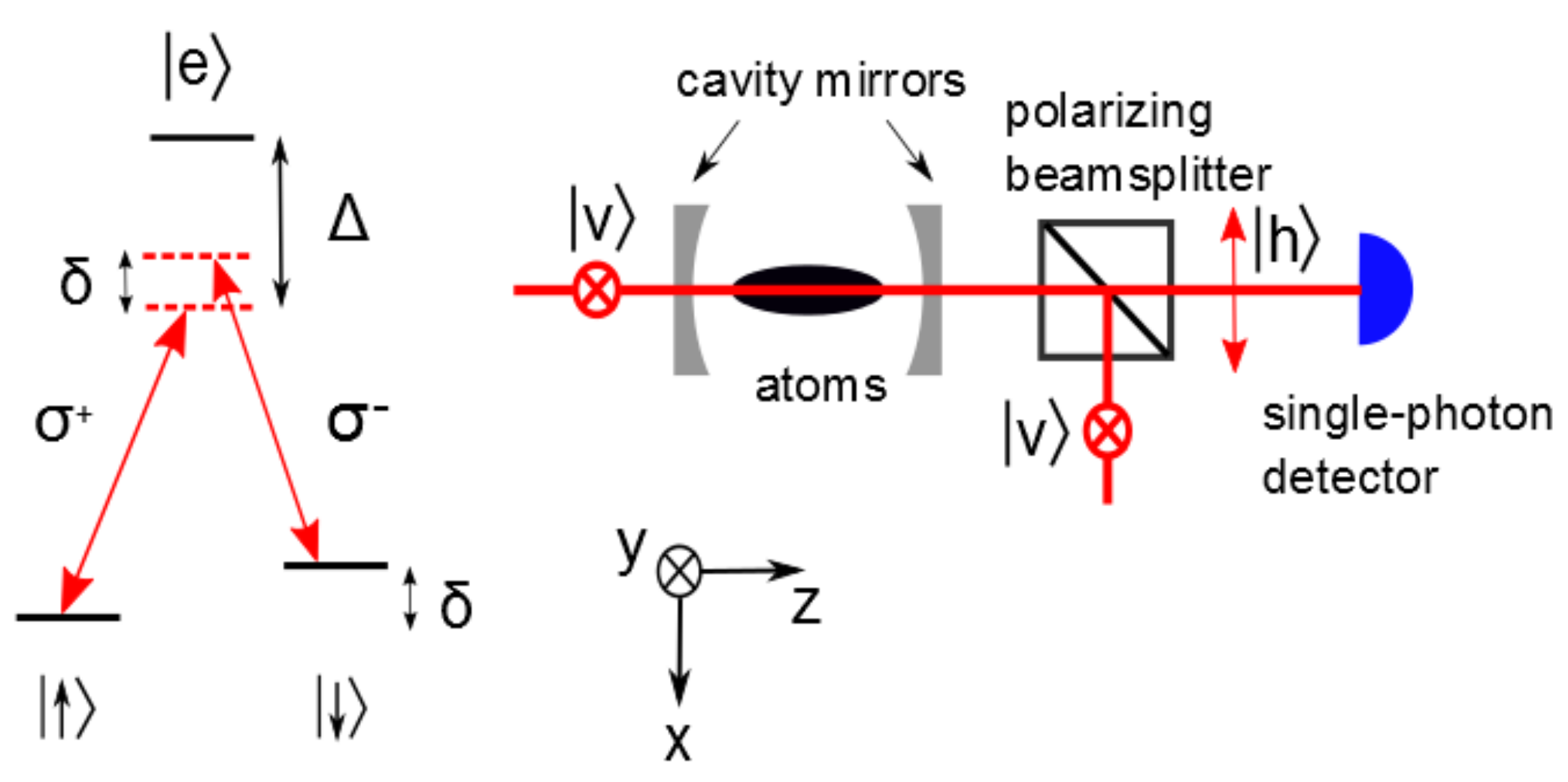
Introduction

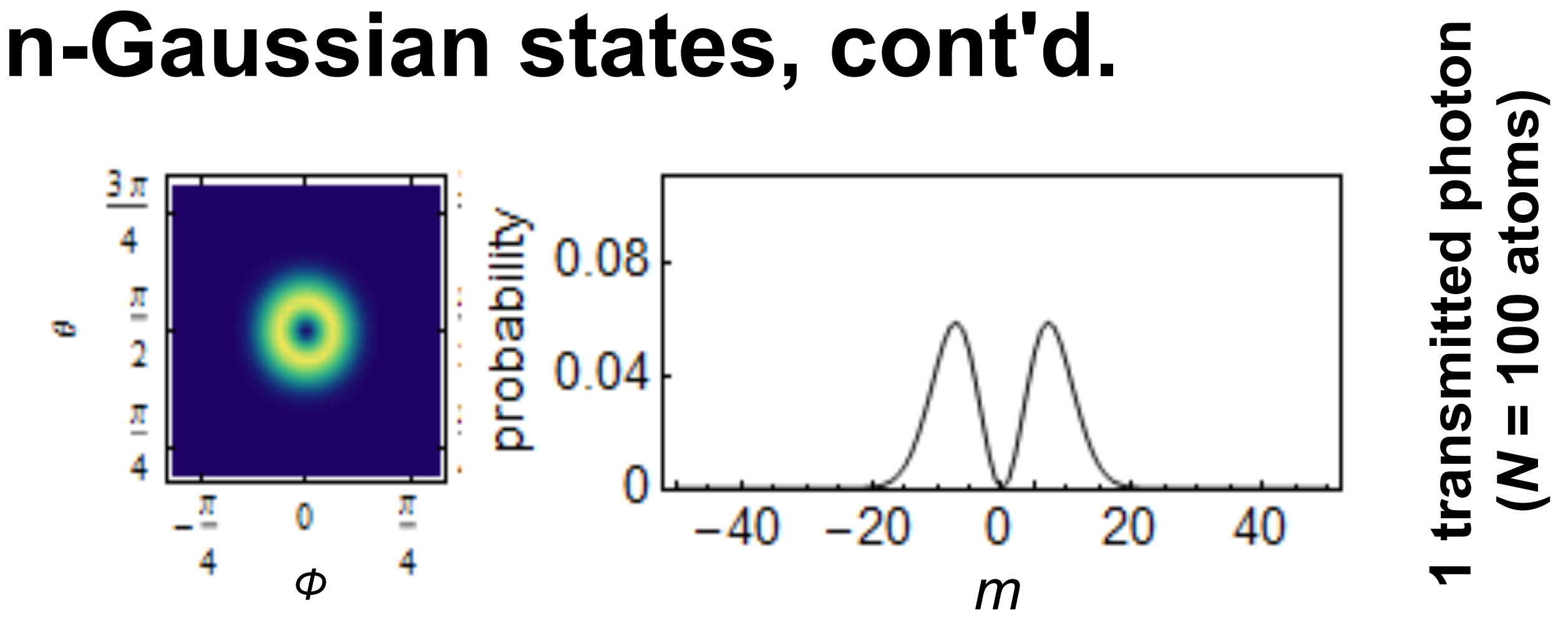
- The standard quantum limit (SQL) for measurements based on atomic coherent states leads to uncertainties scaling with atom number N as $1/\sqrt{N}$, due to atomic projection noise
- Entangled states of atomic ensembles can be used to reduce projection noise, potentially reaching the Heisenberg limit with uncertainties scaling as $1/N$ [1]
- So far, measurements below the SQL have been achieved via squeezed spin states, produced by nonlinear interactions or via measurement by a probe beam strongly coupled to the ensemble [2]
- Here, we propose a novel scheme to produce entangled, non-Gaussian states by detection of a single photon
- These non-Gaussian states allow measurements beyond the SQL and are produced in a probabilistic but heralded manner
- If multiple photons are detected, the method produces “Schrodinger's cat” states, which are of fundamental interest

Heralded production of non-Gaussian states

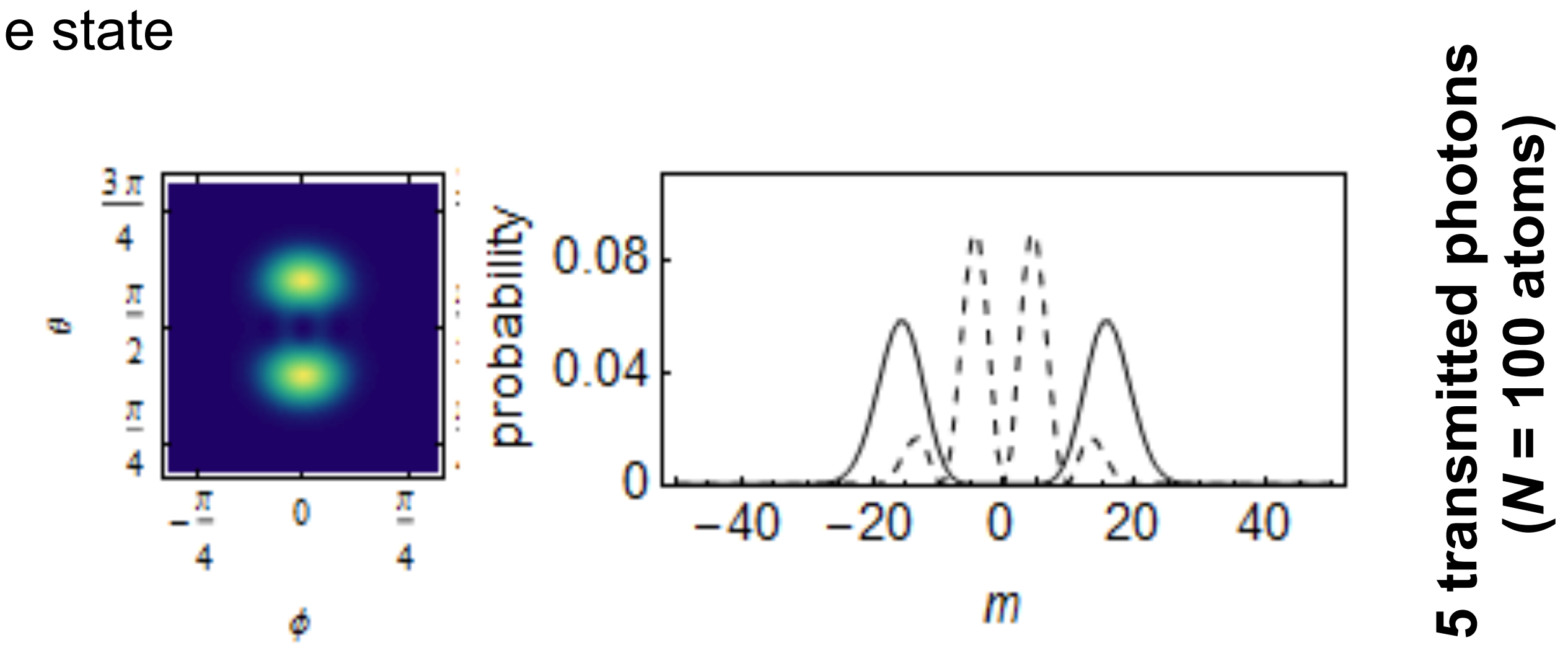


- An ensemble of spin-1/2 atoms with total spin S is confined in an optical cavity and prepared in a coherent state along **x**, with quantization axis **z** determined by a magnetic field along the cavity axis
- A probe laser is coupled into the cavity with single-atom cooperativity $\eta < 1$
- A single vertically-polarized probe photon with detuning Δ from the atomic resonance (of width Γ) passes through the cavity
- A small Faraday rotation of the photon, $\Phi = S_z\eta\Gamma/2\Delta$, occurs as it passes through the cavity. Upon exiting the cavity, if the photon is detected with horizontal polarization (with probability ~ Φ^2), the atomic ensemble is projected into an entangled state
- When initialization time is small compared to measurement (or atom loading) time, entangled-state preparation efforts can be repeatedly and quickly made until success

Non-Gaussian states, cont'd.

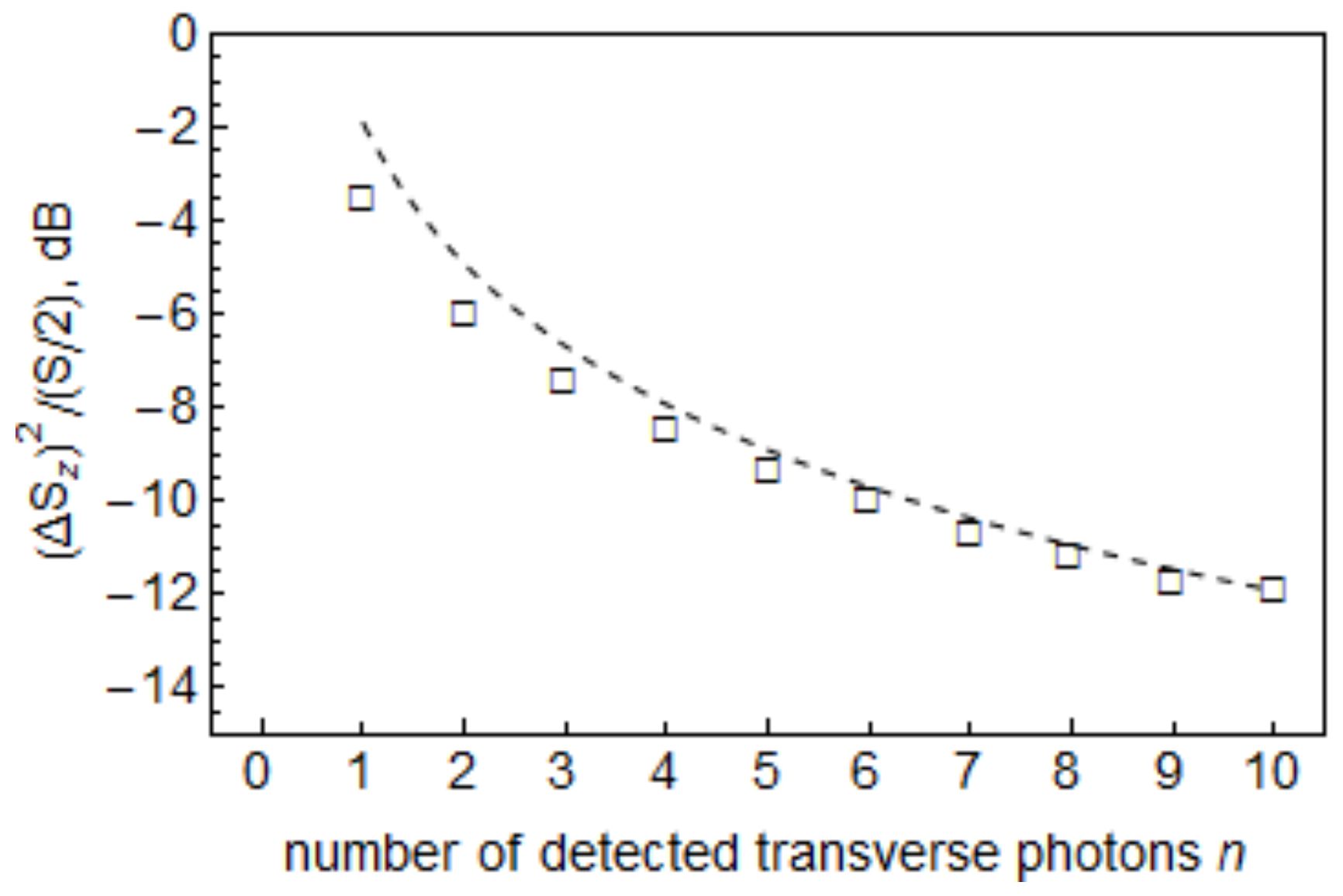


- The entangled state thus produced is the first excited Dicke state along **x** (see above)
- This entangled state displays a negative Wigner function, which can be demonstrated via tomographic reconstruction
- If multiple photons are sent through the cavity, the conditional detection of n vertically-polarized photons produces further entangled states, which become Schrodinger's cat states for n of more than a few (see below)
- As long as $Nn_H\Phi^2 \ll 1$, a number n_H of additional probe photons exiting with horizontal polarization have minimal impact on the state



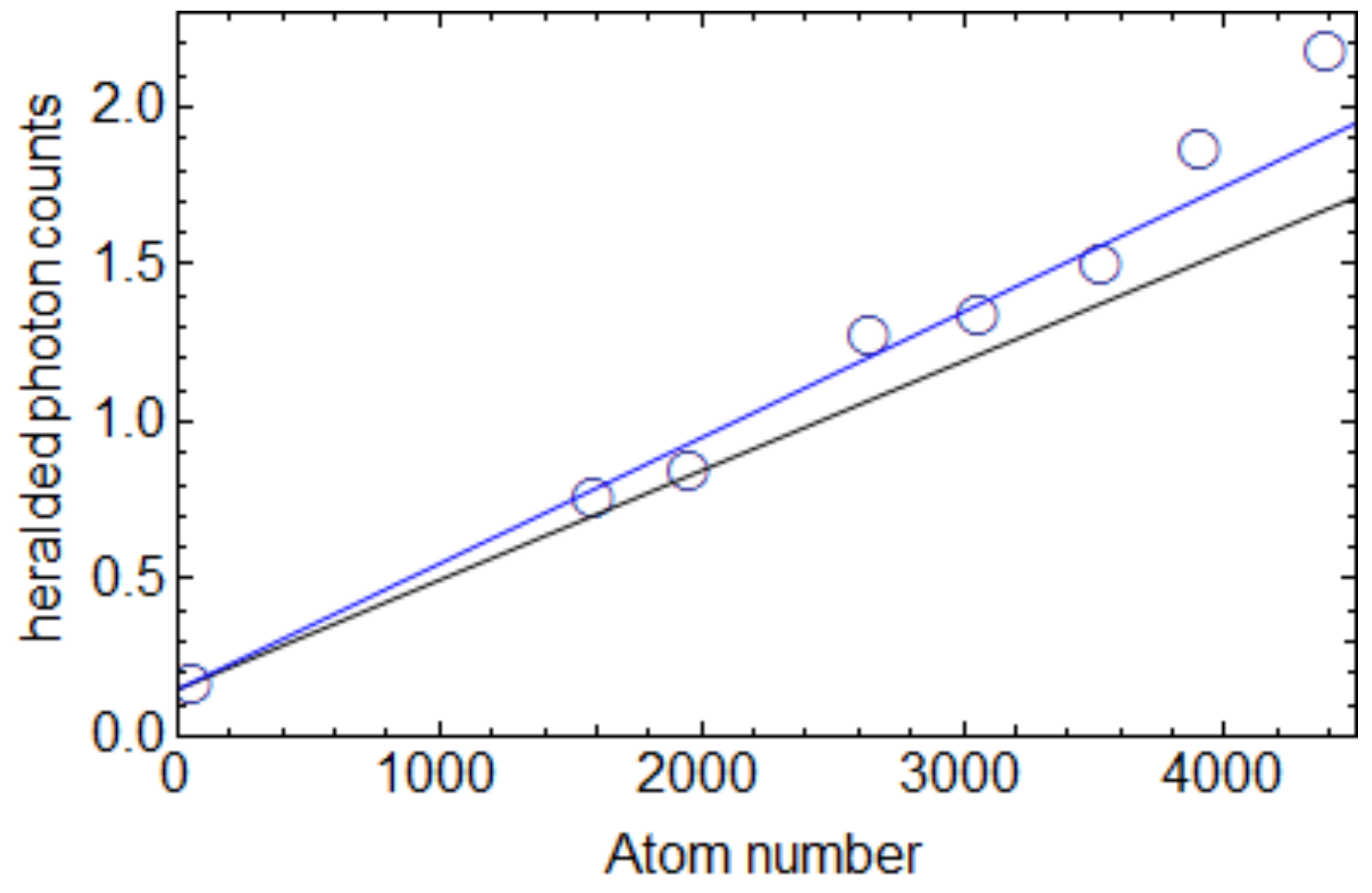
Metrological gain

- After a rotation about **x**, the resulting state distributions contain peaks with width less than the coherent-state width; thus, a weighted average achieves measurement precision greater than that which can be achieved without entanglement
- The resulting noise reduction compared to the SQL, $(\Delta S_z)^2 / (S/2)$, scales with detected photon number n as $1/n$
- Even for a single detected vertical photon, measurement variance is improved by 3 dB relative to the SQL

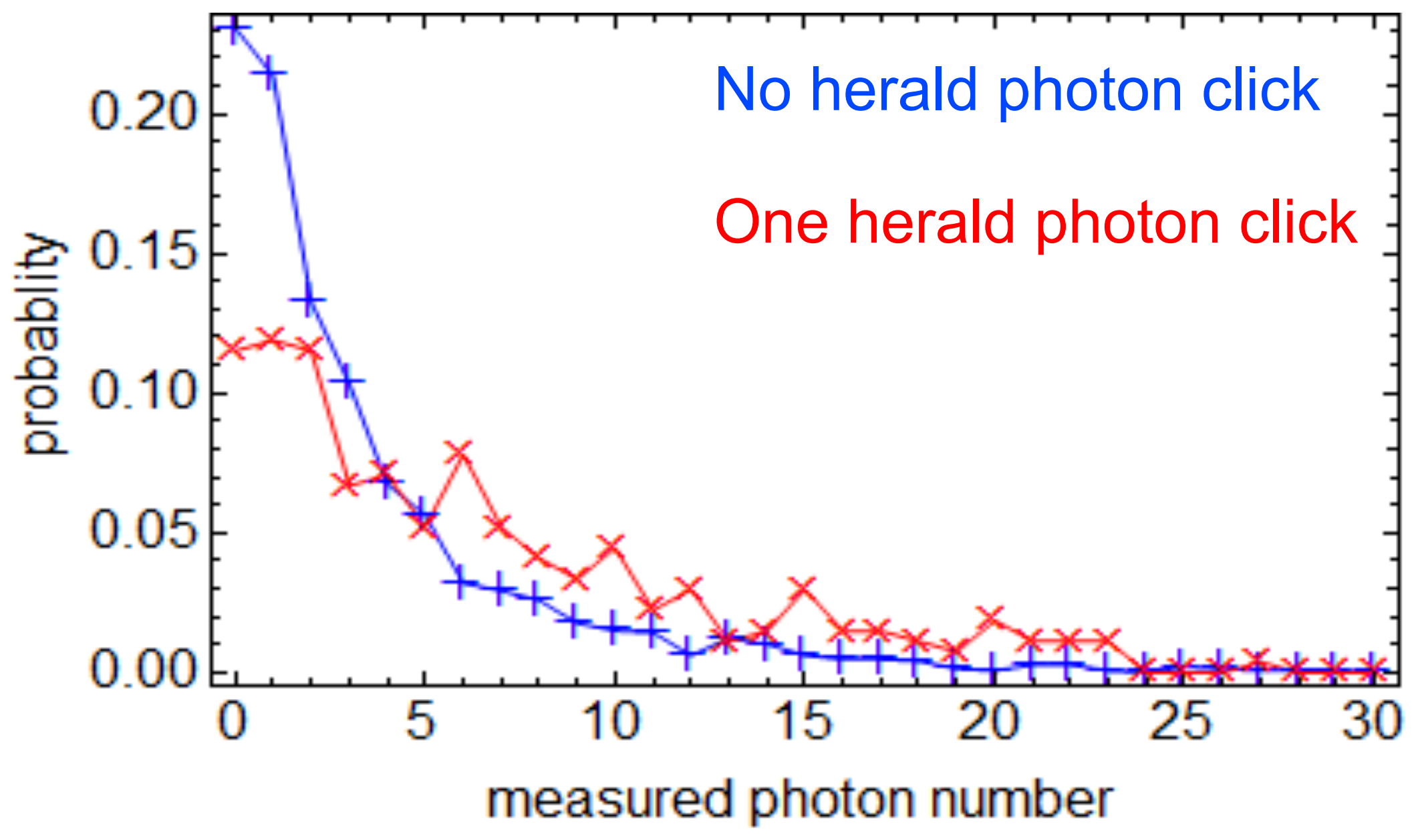


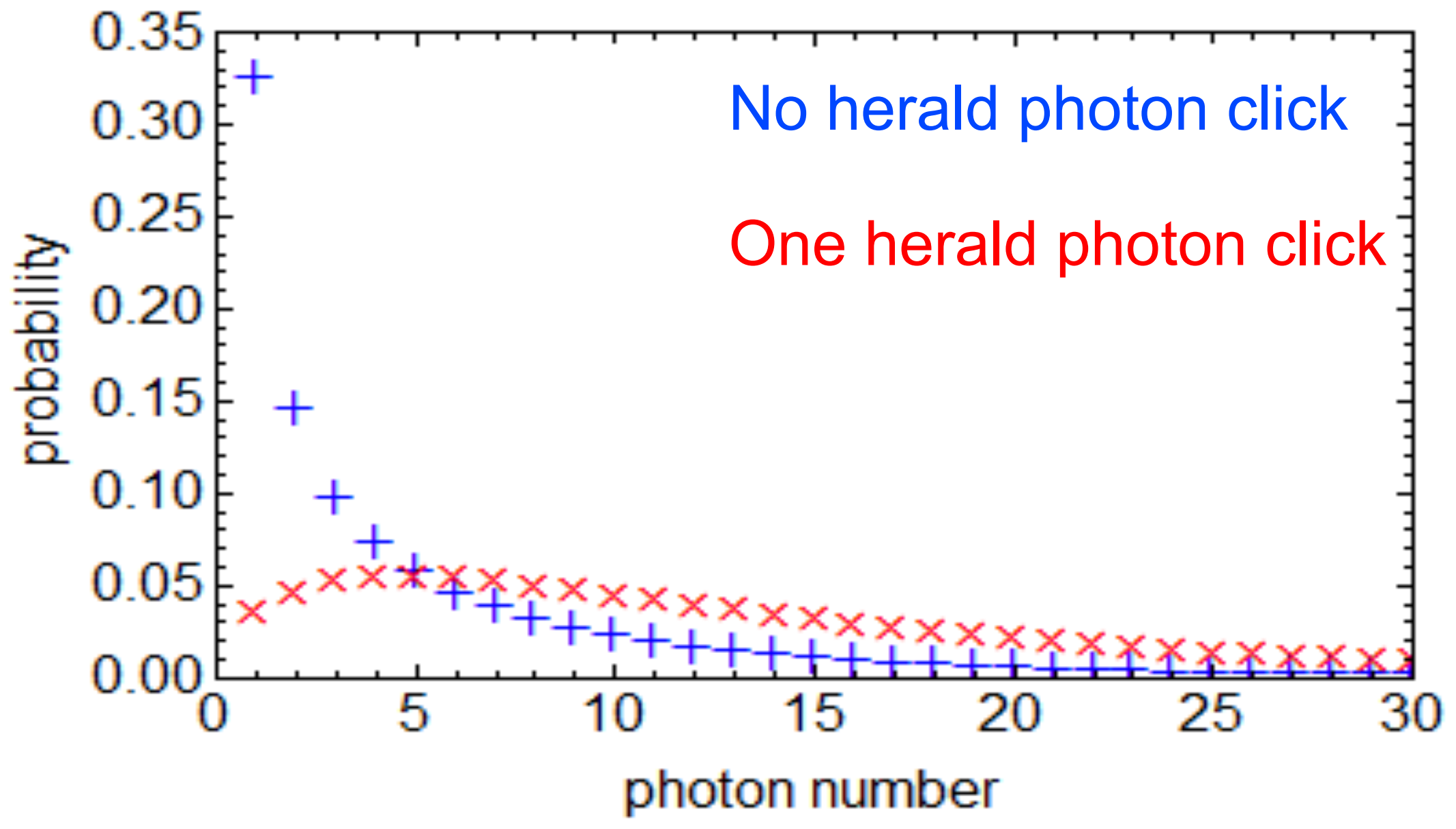
Progress and results

- High-fidelity optical pumping and coherent state preparation via rf pulses



- Measure the distribution functions of the coherent state and the first excited Dicke state





Conclusions and Future Steps

- Single photons in the non-strongly-coupled regime can produce non-Gaussian states of atomic ensembles in a probabilistic but heralded way
- These states can be used to achieve measurements surpassing classical limits and are also of interest for fundamental reasons
- Improve the purity of the heralded Dicke state
- Tomographic reconstruction of the atomic Wigner function

[1]. M. Kitagawa and M. Ueda, Phys. Rev. A, 5138 (1993). D. J. Wineland, *et. al.,* Phys. Rev. Lett., **50**, 67 (1994). A. Andre, *et. al.,* Phys. Rev. Lett., **92**, 230801 (2004). J.J. Bollinger, *et. al.*, Phys. Rev. A **54**, R4649 (1996).

[2]. T. Fernholz, H. Krauter, K. Jensen, J. F. Sherson, A. S. Sorensen, and E. S. Polzik, Phys. Rev. Lett. **101**, 073601, (2008). M. H. S.-S., I. D. Leroux and V. V., Phys. Rev. Lett., **104**, 073602 (2010). C. Gross, T. Zibold, E. Nicklas, J. Est eve, and M. K. Oberthaler, Nature **464**, 1165 (2010). M. F. Riedel, P. Bohi, Y. Li, T. W. Hansch, A. Sinatra, and P. Treutlein, Nature **464**, 1170 (2010). Z. Chen, J. G. Bohnet, S. R. Sankar, J. Dai, and J. K. Thompson, Phys. Rev. Lett. **106**, 133601 (2011).