Quantum non-destructive detection of photons AND demonstration of multi-partite entanglement in solid-state atomic ensembles

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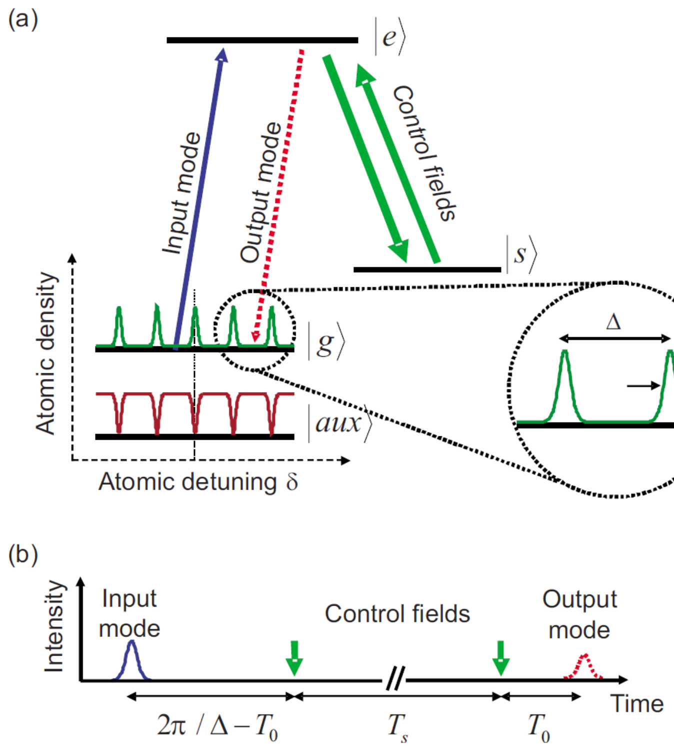
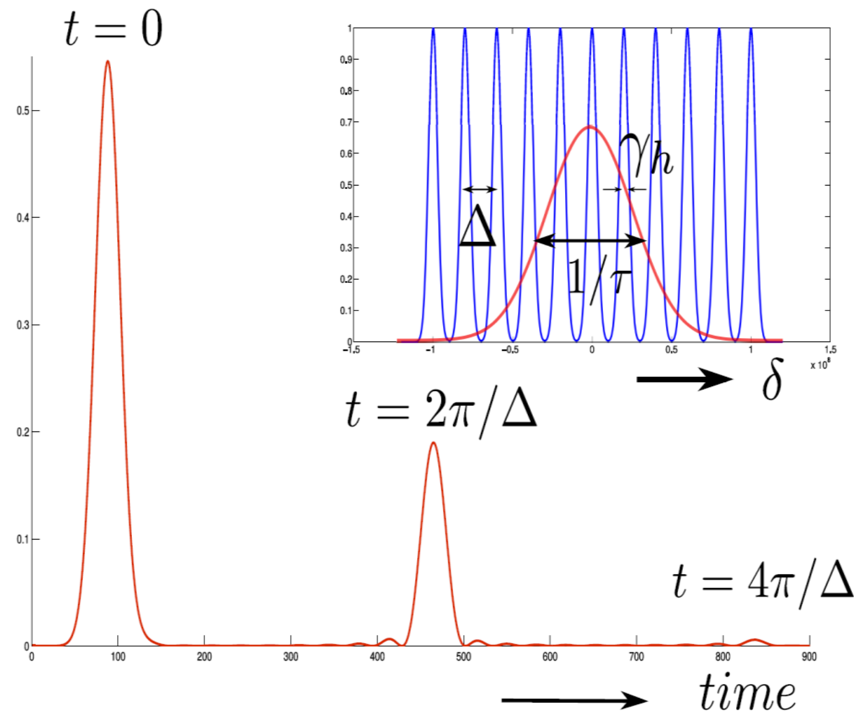
Outline

- Quantum storage in atomic frequency combs
- QND of time-bin qubits based on storage
- Entanglement of many atomic ensembles in a solid

Quantum memory schemes: Atomic Frequency Comb (AFC)

- Storing optical pulses in a periodic distribution of atomic resonances

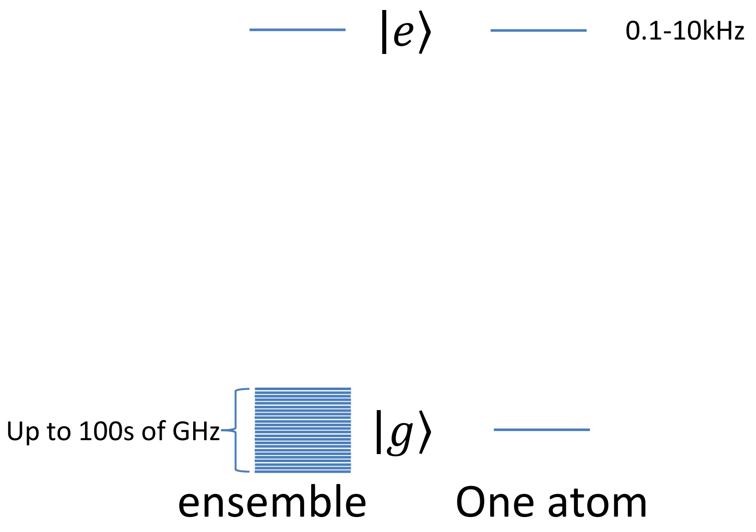




M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin, Phys. Rev. A 79, 052329 (2009)

Quantum Memory schemes: Inhomogeneous broadening in RE ion doped crystals

- RE atoms: Er, Pr, Nd, Tm …
- Host crystals: YAG, YSO, lithium niobate …



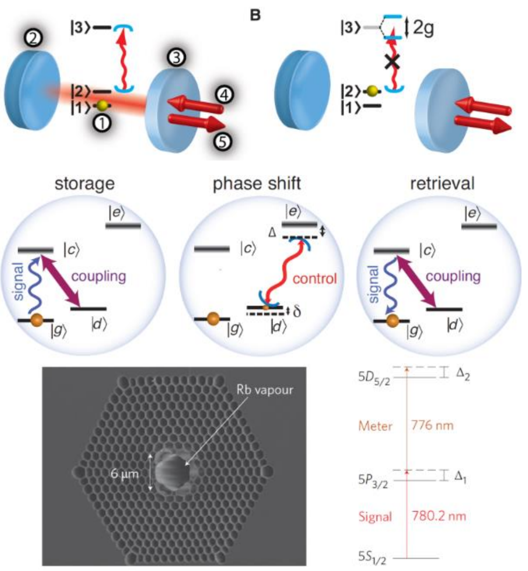
Why non-demolition detection of photons?

- All-optical quantum computation
  - O'Brien et al., Nature **426**, 264 (2003)
  - Nemoto, Munro, PRL **93**, 250502 (2004); Munro et al., New J. Phys. **7**, 137 (2005)
- Quantum Networks
  - Boone et al., PRA **91**, 052325 (2015)
- Improving PDC pair sources
  - Higher photon number contribution can cause infidelity in certain photonic QIP tasks (Entanglement swapping, Bell-state measurement)
  - Guha et al., PRA **92,** 022357 (2015); Wein et al., Phys. Rev. A **94**, 032332 (2016)
- Enhancing conventional (destructive) detectors

Requirement: Non-linear interaction

Chang et al., Nat. Photonics 8, 685–694 (2014)

- Rydberg-Rydberg interaction
  - Rydberg blockade: Tiarks et al., Sci. Advances **2**, No.4, e1600036 (2016); Gorshkov et al., PRL **107**, 1333602 (2011) …
  - Rydberg-interaction-induced cross-phase shift: Khazali et al., PRA **91**, 030301 (2015), …
- Atom-cavity systems
  - Reiserer, Ritter, Rempe, Science **342**, 1349 (2013)
- AC Stark shift
  - N-Scheme (Schmidt & Imamoglu, *Optics letters* 21.23, 1936 (1996)): Feizpour et al., Nat. Phys. **11**, 905 (2015) Hosseini et al., PRL **116**, 033602 (2016); Beck et al., arXiv:1512.02166;
  - Cross-Kerr interaction: Venkataraman, Saha, Gaeta, Nat. Photonics **7**, 138 (2012)

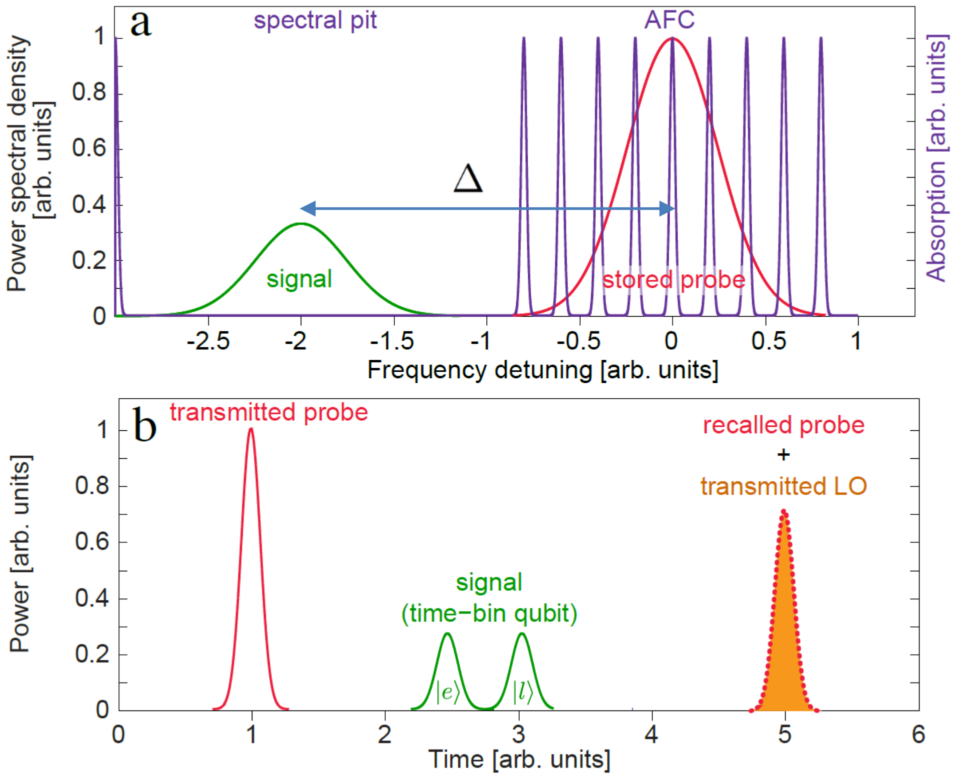


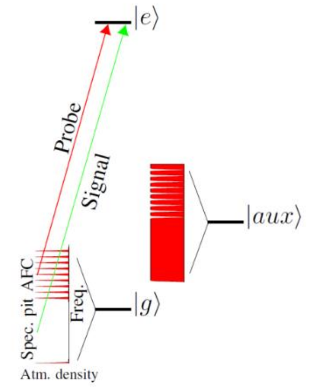
State of the art

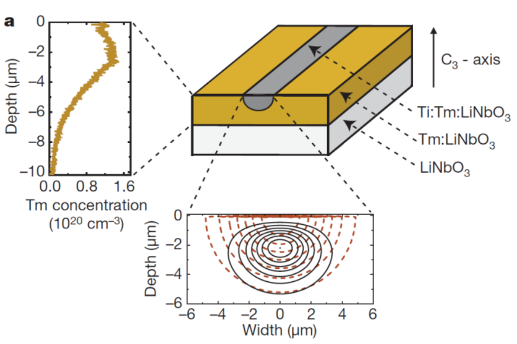
- Most advanced experiments are in atom-cavity systems or trapped (cold) atomic ensembles
    - Hosseini et al., PRL **116**, 033602 (2016); Beck et al., PNAS **113**, 35, 9740-9744 (2016); Feizpour et al., Nat. Phys. **11**, 905-909 (2015); Reiserer et al., Science **342**, 1349-1351 (2013)

- From the practical point of view, we are interested in implementations in solid-state systems or warm atomic ensembles (still relying on AC Stark shift or Rydberg interaction)

Quantum non-demolition detection of time-bin photonic qubits in waveguide quantum memories







Probe storage

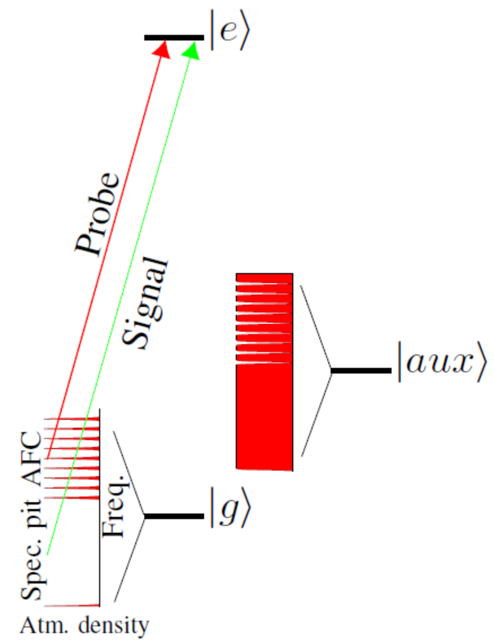
$$\hat{H} = \hat{H}_0 + \hat{H}_{int},$$

$$\hat{H}_0 = \sum_{j=1}^{N} \hbar\omega_{ge}^j \hat{\sigma}_{ee}^j,$$

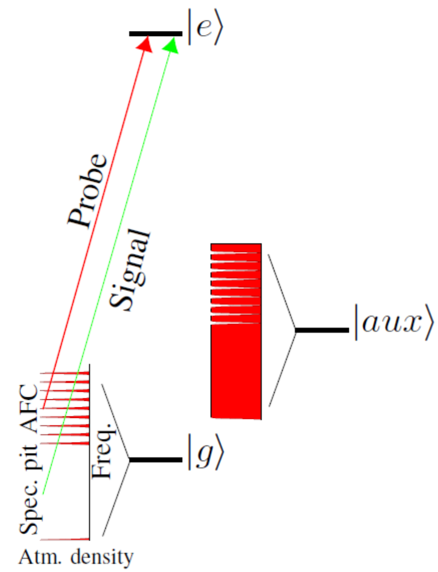
$$\hat{H}_{int} = -\hbar \sum_{j=1}^{N} \left(\Omega(z,t) \hat{\sigma}_{eg}^j e^{-i\omega_p (t - z_j/c)} + H.c. \right)$$

$$\left(\partial_z + \frac{n}{c}\partial_t \right) \mathcal{E}_p(z,t) = \frac{i\mu_0\omega_p^2}{2k_p} \langle \hat{\mathcal{P}}_{tot} \rangle$$

$$\hat{\mathcal{P}}_{tot} = \sum_{\delta} \langle g | \hat{d}.\epsilon_p | e \rangle \frac{N(\delta)}{V} \hat{\sigma}_{ge}(z,t;\delta)$$



Off-resonant interaction between the signal and AFC



$$\hat{h}^j_{int} = -\hbar g \sqrt{\frac{L}{2\pi c}} \int d\omega \hat{a}_\omega e^{i\omega z_j/c} \hat{\sigma}^j_{eg} + \text{H.c.}$$

$$\hat{H}_{int} = -\hbar g \int dz n_z(\delta) e^{i\Delta(t-z/c)} \hat{\mathcal{E}}_s(z,t) \hat{\sigma}_{eg}(z,t;\delta) + H.c.$$

$$\hat{H}^{eff}_{int} = -\frac{\hbar g^2}{\Delta} \int dz n_z(\delta) \left(\hat{\mathcal{E}}_s(z,t) \hat{\mathcal{E}}^\dagger_s(z,t) + \hat{\mathcal{E}}^\dagger_s(z,t) \hat{\mathcal{E}}_s(z,t) \right) (\hat{\sigma}_{gg}(z,t;\delta) - \hat{\sigma}_{ee}(z,t;\delta))$$

$$\hat{\sigma}_{eg}(z,t=T_2;\delta) = e^{i\delta t} e^{i\hat{\Phi}} \hat{\sigma}_{eg}(z,t=T_1;\delta),$$

$$\hat{\Phi} = \int_{T_1}^{T_2} dt' \frac{2g^2}{\Delta} \left(\hat{\mathcal{E}}_s(z,t') \hat{\mathcal{E}}^\dagger_s(z,t') + \hat{\mathcal{E}}^\dagger_s(z,t') \hat{\mathcal{E}}_s(z,t') \right)$$

$$\phi = \frac{2g^2}{\Delta} \tau_s = \frac{1}{4\pi} \frac{\lambda_0^2}{n^2 A} \frac{\gamma}{\Delta}$$

Cross-phase modulation, and off-resonant loss

- Induced cross-phase shift

$$\phi = N_s \frac{1}{4\pi} \frac{\lambda^2}{n^2 A} \frac{\gamma}{\Delta}$$

- Loss

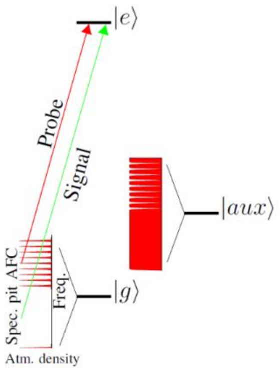
$$\zeta L = \frac{1}{8\pi} \frac{N_g \lambda_0^2}{n^2 A} \frac{\gamma^2}{\Delta^2}$$

- Single-shot measurement sensitivity requirement

$$N_g > \frac{1}{\eta \phi^2} = \frac{1}{\eta} \left(\frac{8\pi n^2 A \Delta}{\lambda_0^2 \gamma} \right)^2$$

- Signal loss due to off-resonant absorption

$$\zeta L = \frac{N_g \lambda_0^2 \gamma^2}{8\pi \eta n^2 A \Delta^2} > \frac{8\pi n^2 A}{\eta \lambda_0^2}$$



Multiple passes or cavity enhancement

- Bound on loss is reduced by number of passes (finesse)

$$\zeta L > \frac{8\pi n^2 A}{m\eta\lambda_0^2}$$

- Number of passes required to keep loss to 10%

$$m > 80\pi/\eta$$

- Optical depth required for single-photon sensitivity

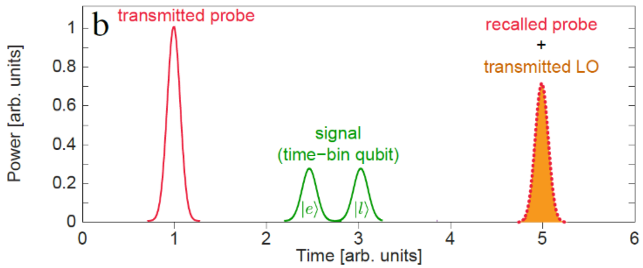
$$d > \frac{128\pi^2\Delta^2}{n_t\gamma^2 m^2\eta}$$

- Number of passes required for given bandwidth *B*

$$m > \frac{16\sqrt{2}\pi^2 f B}{\sqrt{n_t\eta d\gamma}}$$

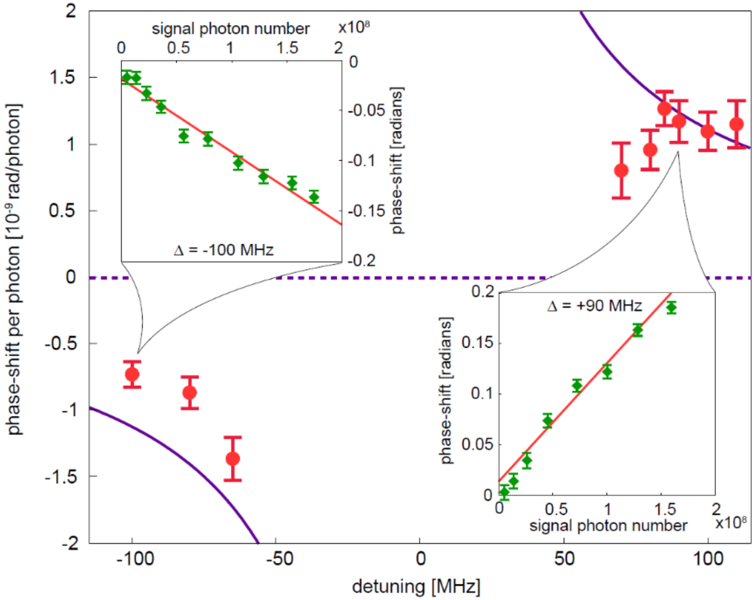
Example: Tm:LiNbO3, Linewidth 9 kHz. Optical depth 30, Bandwidth 500 kHz. 930 passes.

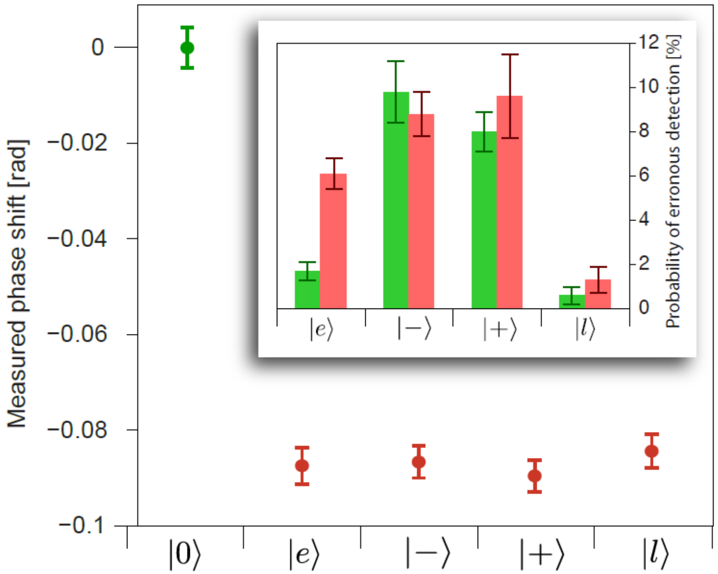
Shorter spontaneous lifetime (e.g. Ce) would allow higher bandwidth.

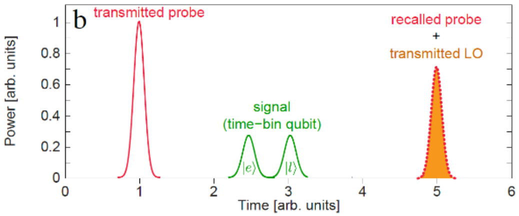


A proof-of-principle experiment

- Highlight the time dependence in phase measurement results







Summary

- Proposal for QND detection of time-bin qubits based RE ion-doped crystals
- Proof-of-principle experiment demonstrating the expected cross-phase shift and time-bin state independence
- Enhancing the cross-phase shift per photon through optical cavities is necessary to reach single-shot, lossless, non-demolition single-photon detection

Neil Sinclair, Khabat Heshami, Chetan Deshmukh, Daniel Oblak, Christoph Simon, Wolfgang Tittel, Nature Communications **7**, 13454 (2016).

Part2:
Entanglement between many macroscopic atomic ensembles in a solid

P. Zarkeshian *et. al.,* Entanglement between more than two hundred macroscopic atomic ensembles in a solid, to appear arXiv:1701.????.

Macroscopic quantum superpositions and entanglement

- Example:

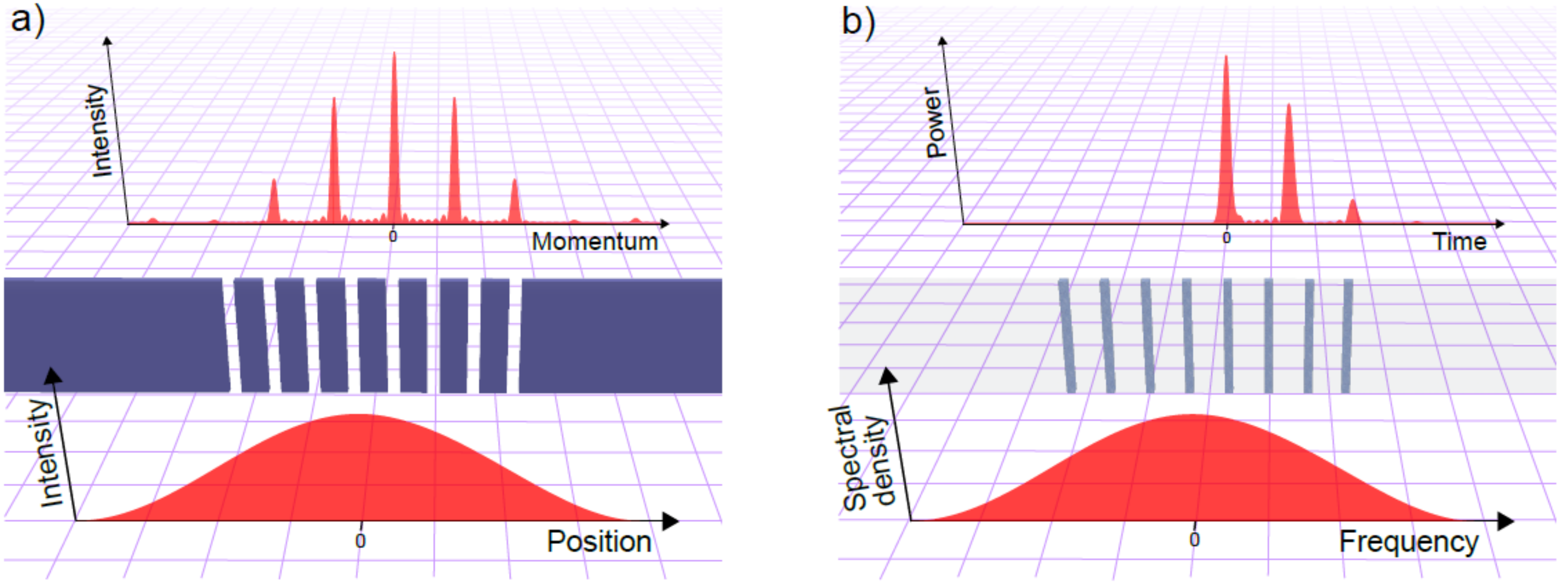
$$(|0\rangle + |1\rangle)^{\otimes N} \quad \text{vs.} \quad |0\rangle^{\otimes N} + |1\rangle^{\otimes N}$$

- Dicke states (symmetric superposition of a single excitation):

$$|W\rangle = \frac{1}{\sqrt{N}}(|100\ldots0\rangle + |010\ldots0\rangle \ldots + |000\ldots1\rangle)$$

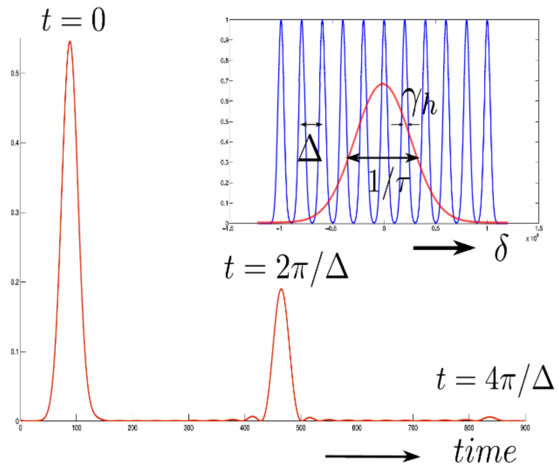
Recent experiments:
-McConnell *et. al.* Entanglement with negative Wigner function of almost 3,000 atoms heralded by one photon. Nature 519, 439–442 (2015).
-Haas *et. al.* Entangled states of more than 40 atoms in an optical fiber cavity. Science 344, 180–183 (2014).

Analogy between multi-slit experiment and AFC



Note: This does not prove entanglement!

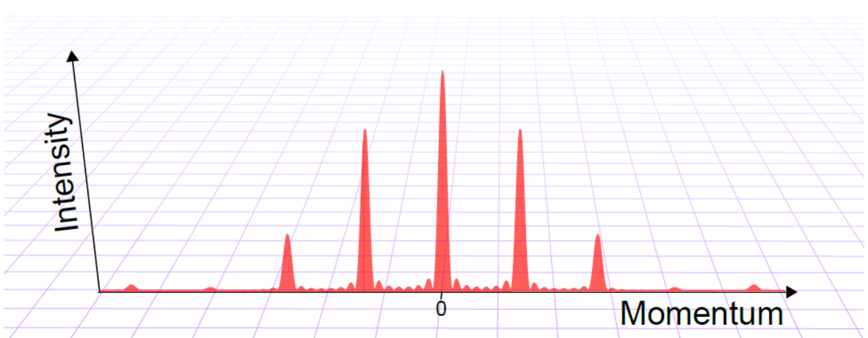
Reminder:

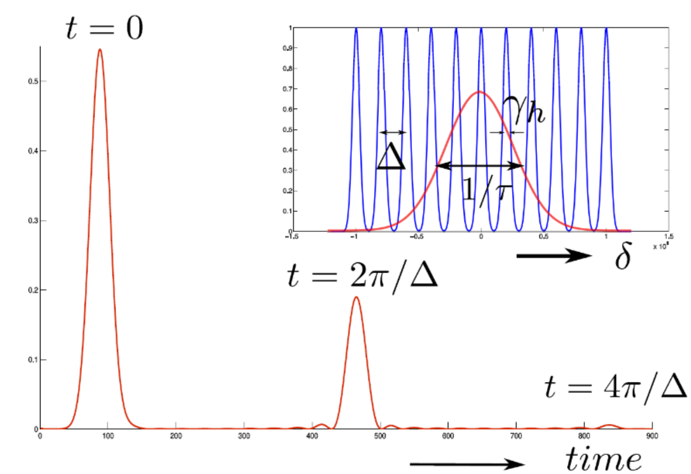


Visibility or coherence depth

- Peak intensity compared to background noise is proportional to the number of modes coherently involved.

$$R = \frac{P(\frac{2\pi}{\Delta})}{\frac{\Delta}{2\pi}\int_{\frac{\pi}{\Delta}}^{\frac{3\pi}{\Delta}} P(t)dt}$$





Echo visibility

- Each mode (path or teeth in AFC) can be modeled as a two-level system (|0> or |1> with or without and excitation)
- One can show

$$P(t) \text{ is proportional to } \langle S_+(t) S_-(t) \rangle$$

$$S_-(t) = \sum_j e^{i\delta_j t} S_-^j \text{ and } S_-^j = |0\rangle^j \langle 1|^j$$

- This leads to

$$R = \frac{P(\frac{2\pi}{\Delta})}{\frac{\Delta}{2\pi}\int_{\frac{\pi}{\Delta}}^{\frac{3\pi}{\Delta}} P(t)dt} = \frac{\langle S_+ S_- \rangle}{\left\langle \sum_j |1\rangle^j \langle 1|^j \right\rangle}$$

Missing step: How *R* is related to entanglement?

- First example, single excitation in N modes:

Suppose *R=M* is experimentally measured, then given the definition of *R*

$$R = \frac{\langle S_+ S_- \rangle}{\left\langle \sum_j |1\rangle^j \langle 1|^j \right\rangle}$$

R=M can be achieved with the state

$$|W\rangle_M \otimes |0\rangle^{\otimes (N-M)}$$

$$|W\rangle_M = \frac{1}{\sqrt{M}}(|100\ldots0\rangle + |010\ldots0\rangle \ldots + |000\ldots1\rangle)$$

Allowing vacuum and non-zero higher order excitations

- Suppose there is a limited probability of creating a single excitation $P_1<1$:

$R=\langle S_+S_-\rangle/P_1=M$ is possible with

$$P_1\,|W\rangle_M \otimes |0\rangle^{\otimes(N-M)} + (1-P_1)|0\rangle^{\otimes N}$$

- Suppose there is a non-zero probability of creating two excitations $P_2\neq 1$
- This would allow contributions from completely separable states such as

$$(\alpha|0\rangle + \beta|1\rangle)^{\otimes N}$$

- A completely separable state such as

$$(\alpha|0\rangle + \beta|1\rangle)^{\otimes N}$$

has a Dicke state component of size N. This leads to *R*=*N* (in the limit of small β) and $P_2 \simeq {P_1}^2/2$.

- For a general ansatz state of

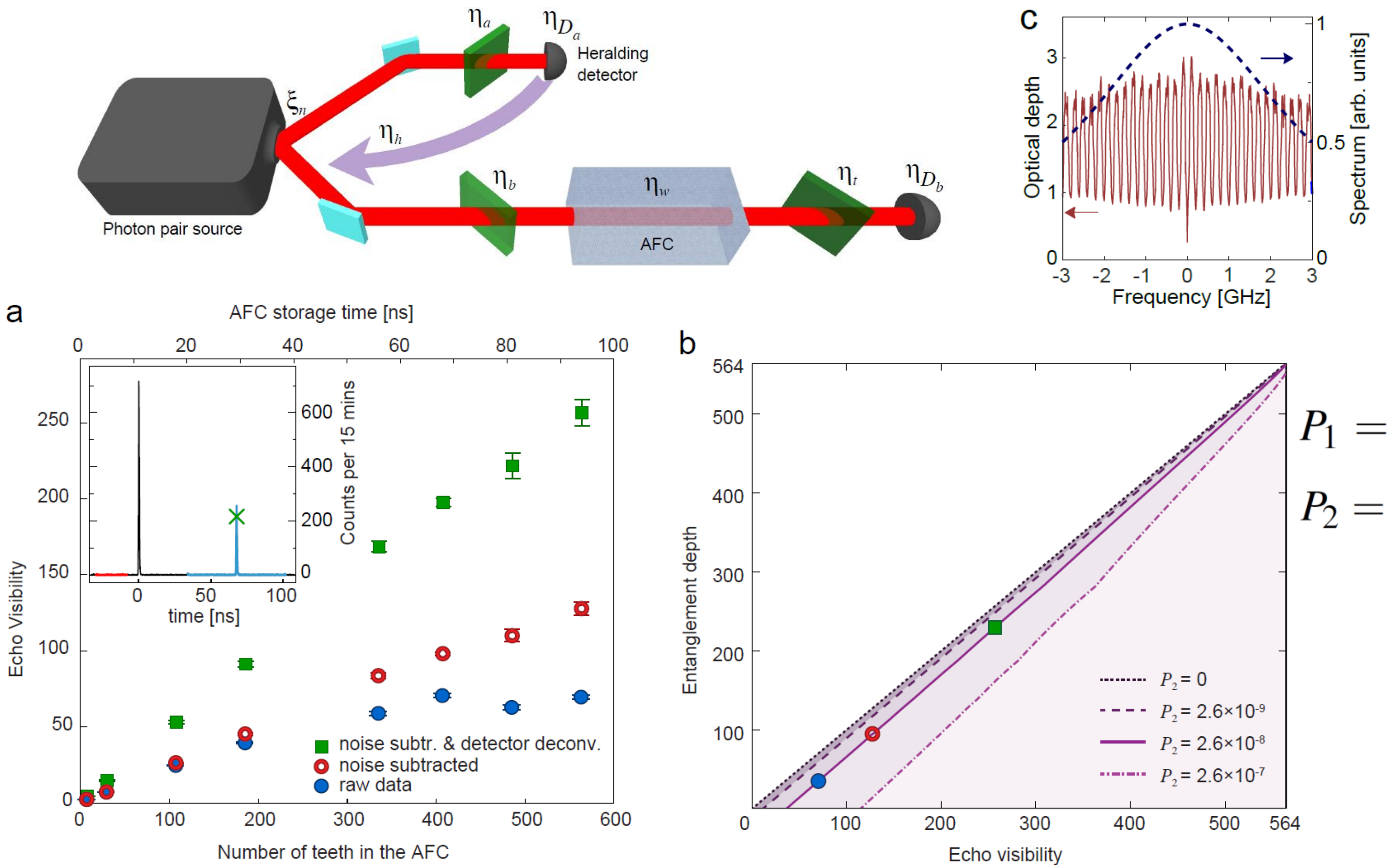
$$\rho = \sum q_i \, |\varphi_i\rangle\langle\varphi_i|$$

consisting optimal components of

$$|\varphi_i\rangle = (\alpha_i|0\rangle + \beta_i|W\rangle_M)^{\otimes^i} \otimes |0\rangle^{\otimes^{N-iM}}$$

$$R_{max} \simeq M + \frac{\sqrt{2P_2}}{P_1}N \quad \text{OR} \quad M > R - \frac{\sqrt{2P_2}}{P_1}N$$

Experimental demonstration of entanglement between many ensembles



$$P_1 = 3.5 \times 10^{-3}$$

$$P_2 = 2.6 \times 10^{-8}$$

Summary

- A proposal and a theoretical treatment to measure and prove multipartite entanglement of Dicke-type states
- Experimental demonstration of entanglement between over 200 ensembles inside a solid

Thanks!

- **Theory:**

Christoph Simon (PI), QND & Ent.

Parisa Zarkeshian, Ent.

Sandeep Goyal, Ent.

- **Experiment**

Wolfgang Tittel (PI), QND & Ent.

Chetan Deshmukh, QND & Ent.

Neil Sinclair, QND & Ent.

Daniel Oblak, QND & Ent.

G. H. Aguilar, Ent.

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V. B. Verma, Ent.

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