Dissipation as a source of entanglement and fermionized photons

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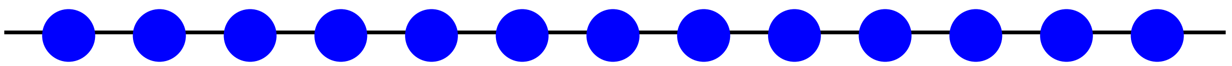
Is it possible to study the physics of strongly correlated systems with photons?

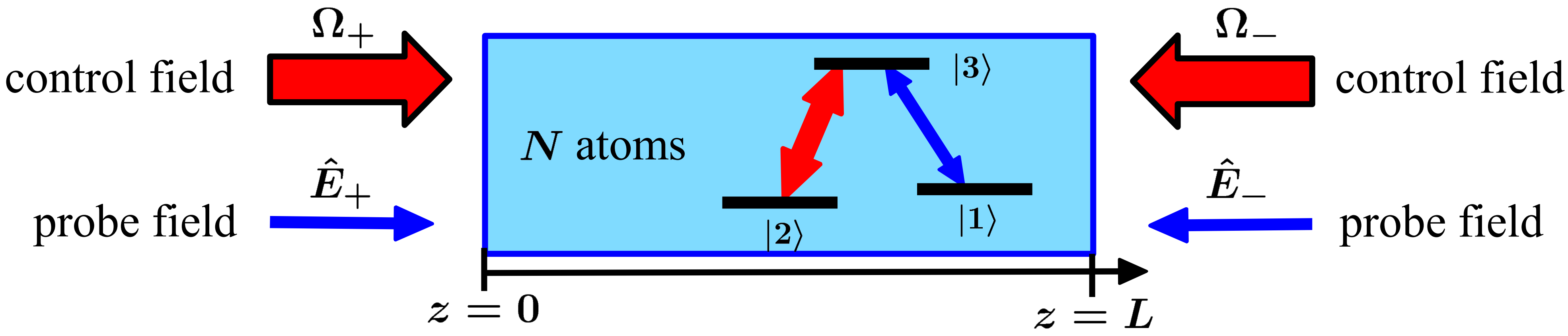
Photons in a highly entangled, fermionized state:

“  ”

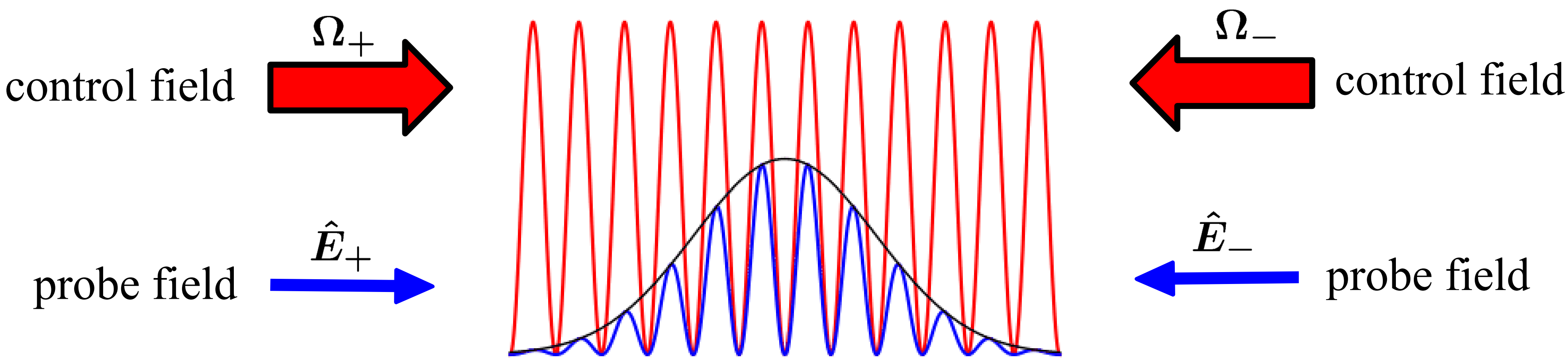
Requirement: strong photon-photon interaction

In our scheme: **dissipation** is most effective for the creation of strong photon-photon interactions

Stationary pulses of light



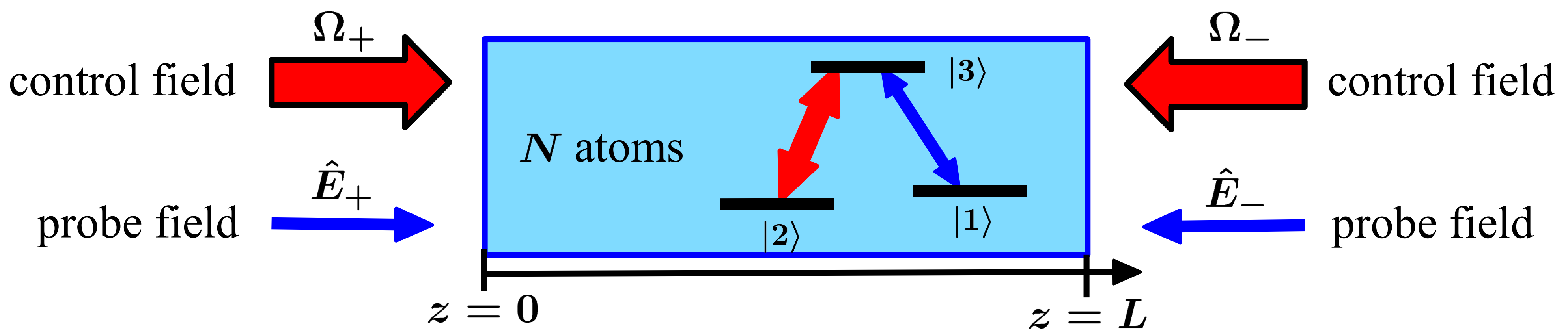
- Intensity profile:



probe field: $|\hat{E}_+ + \hat{E}_-|^2$ forms quasi-stationary standing wave pattern

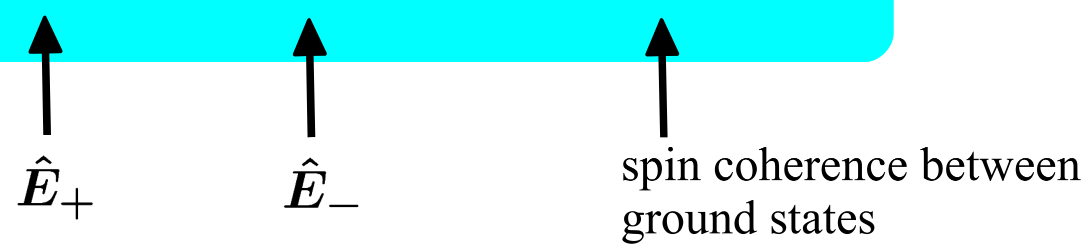
M. Bajcsy, A. S. Zibrov and M. D. Lukin, Nature **426**, 638 (2003).

dark-state polaritons



• Polaritons: collective excitations of photons and atoms $(\Omega_+ = \Omega_-)$

$$\psi_k = \frac{1}{\sqrt{2}}\left(a_{k_c+k} + a_{-k_c+k}\right)\cos\theta - X_{12}^{k}\sin\theta$$

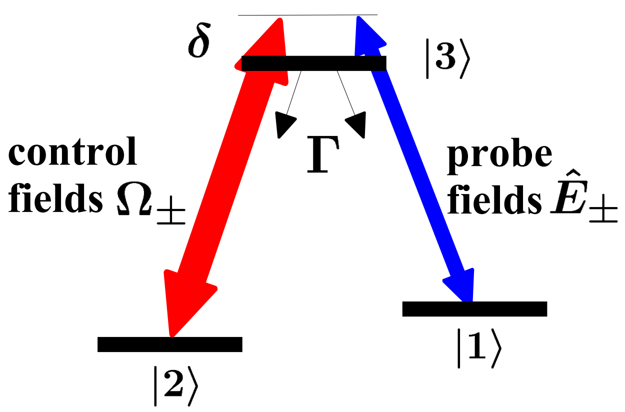


• Dark state polaritons obey **bosonic commutation relations** $\left[\psi_k, \psi_p^\dagger\right] = \delta_{k,p}$

condition: number of photons $\ll$ number of atoms

master equation for dark-state polaritons

$$\dot{\varrho}(t) = \boxed{\textbf{kinetic energy}} + \boxed{\textbf{single-particle losses}}$$

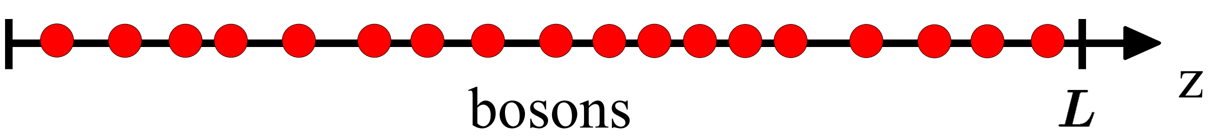


- kinetic energy:

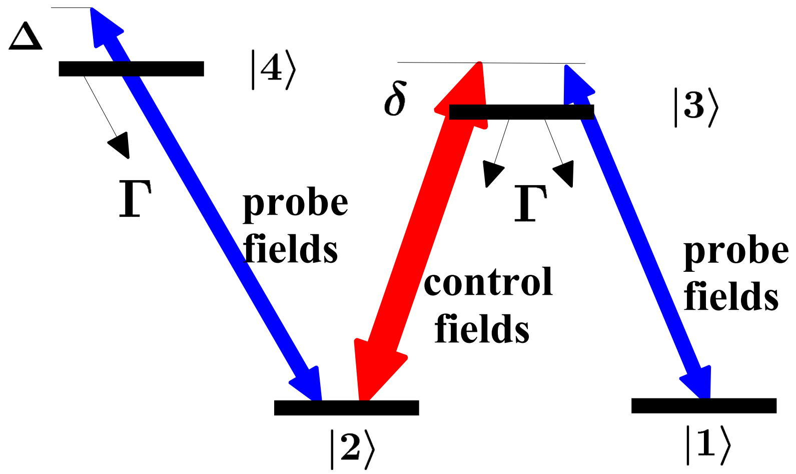
$$H_{\rm kin} = \frac{\hbar^2}{2m_{\rm eff}} \int_0^L {\rm d}z \partial_z \psi^\dagger \partial_z \psi \,, \qquad \text{effective mass } m_{\rm eff}$$

$$\left[\psi_k, \psi_p^\dagger\right] = \delta_{k,p} \;\Rightarrow\; \boxed{\left[\psi(z), \psi^\dagger(z')\right] = \delta(z - z')}\,, \quad \psi(z) = \frac{1}{\sqrt{L}} \sum_k \psi_k e^{ikz}$$

⇒ Polaritons form a system of non-interacting bosons with mass $m_{\rm eff}$ in 1D:

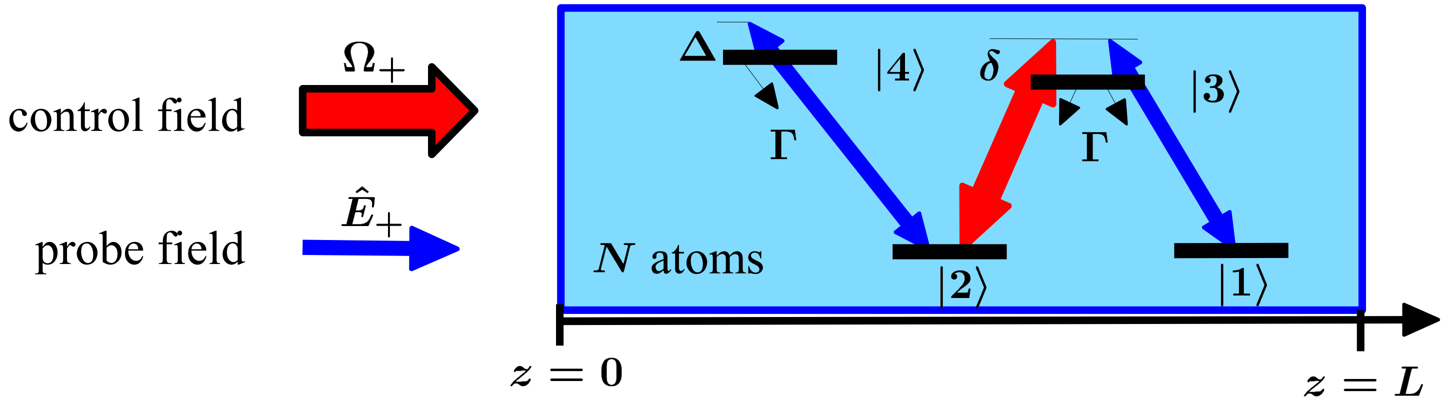


Enable photon-photon interactions



- almost all atoms are in state $|1\rangle$
- single-photon absorption via level $|3\rangle$ is cancelled by EIT
- leading order: two-photon processes $|1\rangle \rightarrow |4\rangle$

⇨ strong photon-photon (polariton/polariton) interaction



- Polaritons are described by the **dissipative Lieb-Liniger model***:

$\partial_t \varrho =$ **kinetic energy** $+$ **elastic 2-particle interactions** ($\mathrm{Re}(\tilde{g})$) $+$ **2-particle losses** ($\mathrm{Im}(\tilde{g})$)

- complex coupling constant: $\tilde{g} \propto \dfrac{1}{\Delta + i\Gamma/2}$

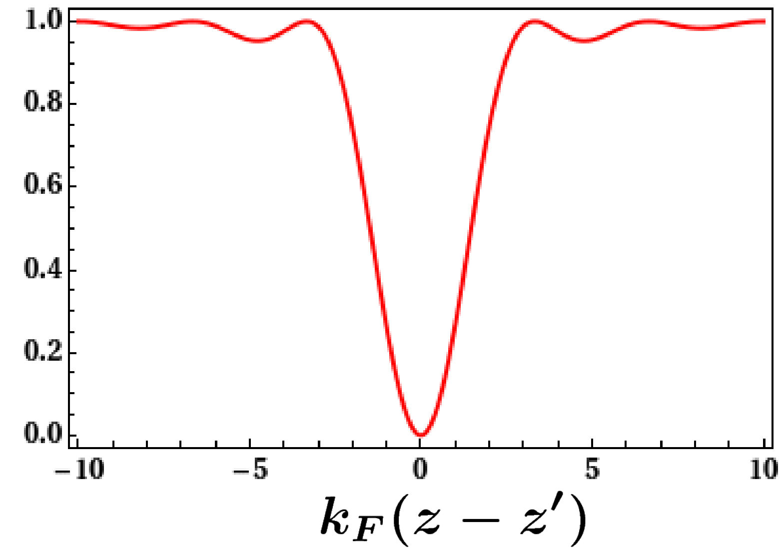
- Interaction strength: $G_{\mathrm{LL}} = \dfrac{\tilde{g} m_{\mathrm{eff}}}{\hbar^2 n_z}$, n_z: number density of polaritons

* S. Dürr et al., PRA **79**, 023614 (2009).

- Interaction strength: $G_{\rm LL} = \dfrac{\tilde{g} m_{\rm eff}}{\hbar^2 n_z}$,

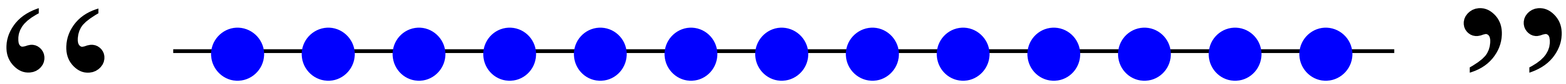
$$|G_{\rm LL}| \gg 1: \qquad g^{(2)}(z,z) \propto \frac{1}{|G_{\rm LL}|^2}$$

$g^{(2)}(z-z')$ for $|G_{\rm LL}| \to \infty$



- $g^{(2)}(z,z) \ll 1$: two particles never occupy the same position → dissipation of particles is avoided

- "fermionized" ground state, Friedel oscillations



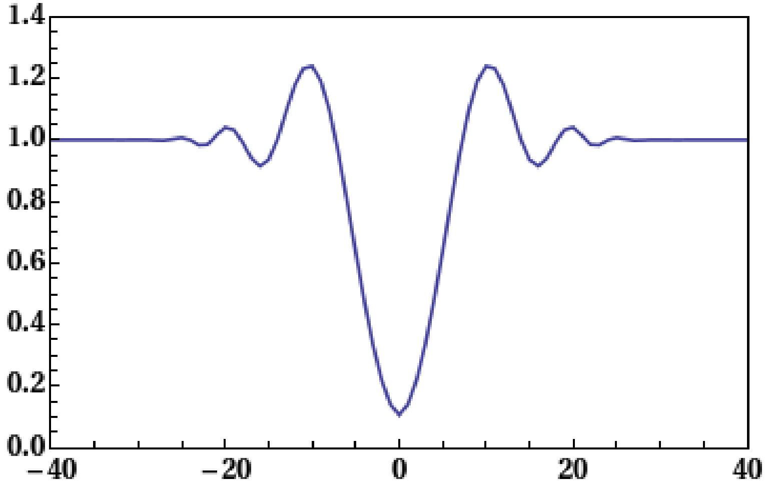
crystal of impenetrable hard-core photons

• Numerical integration of the master equation with the time-evolving block-decimation (TEBD) algorithm and realistic initial conditions:

$|G_{\mathrm{LL}}| = 100$, 500 sites

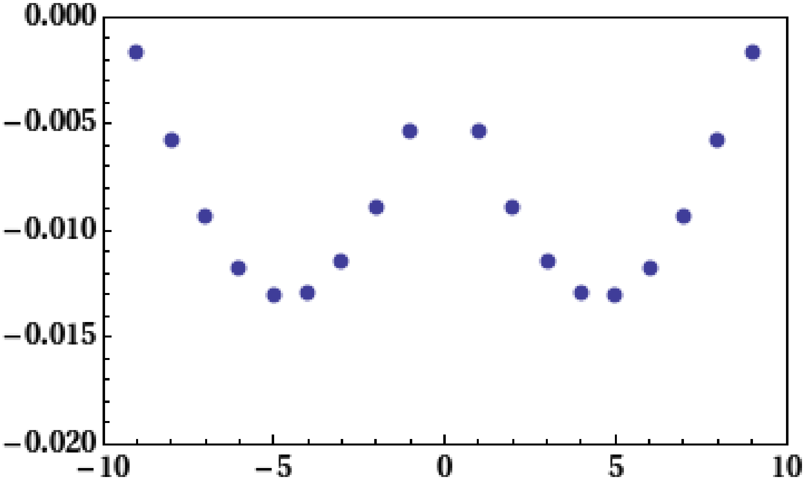
$T_{\mathrm{max}} = 0.012 \times \Gamma^{-1}_{\text{2-particle}}$

$g^{(2)}(z - z')$



Position

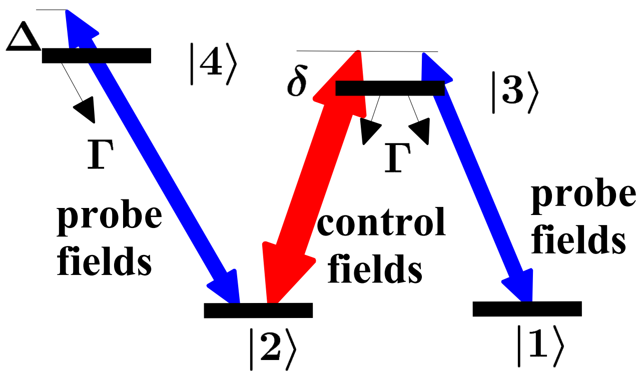
Measure of entanglement



Position

$$|G_{\mathrm{LL}}| = \frac{\Gamma^2\,\mathrm{OD}^2}{16|\delta|\sqrt{\Delta^2+\Gamma^2/4}N_{\mathrm{atom}}N_{\mathrm{ph}}}$$

OD : optical depth of the medium



- $\Delta \gg \Gamma$ **:** elastic two-particle interaction

  D. E. Chang et al., Nature Physics **4**, 884 (2008).

- $\Delta = 0$ **:** inelastic two-particle interaction

$|G_{\mathrm{LL}}|$ **is maximal for purely dissipative interaction** $(\Delta = 0)$

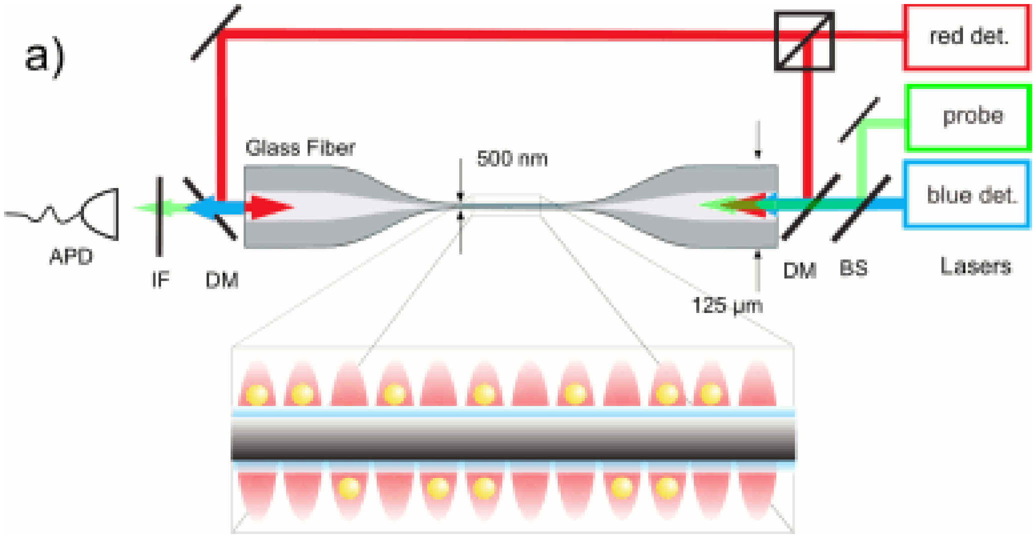
M. Kiffner and M. J. Hartmann, Phys. Rev. A **81**, 021806(R) (2010).

M. Kiffner and M. J. Hartmann, arXiv:10054865.

Experiments

1. Atoms outside an optical nanofiber

E. Vetsch et al., e-print arXiv:0912.1179.



2. Atoms inside a hollow core fiber

M. Bajcsy et al., Phys. Rev. Lett. **102**, 203902 (2009).

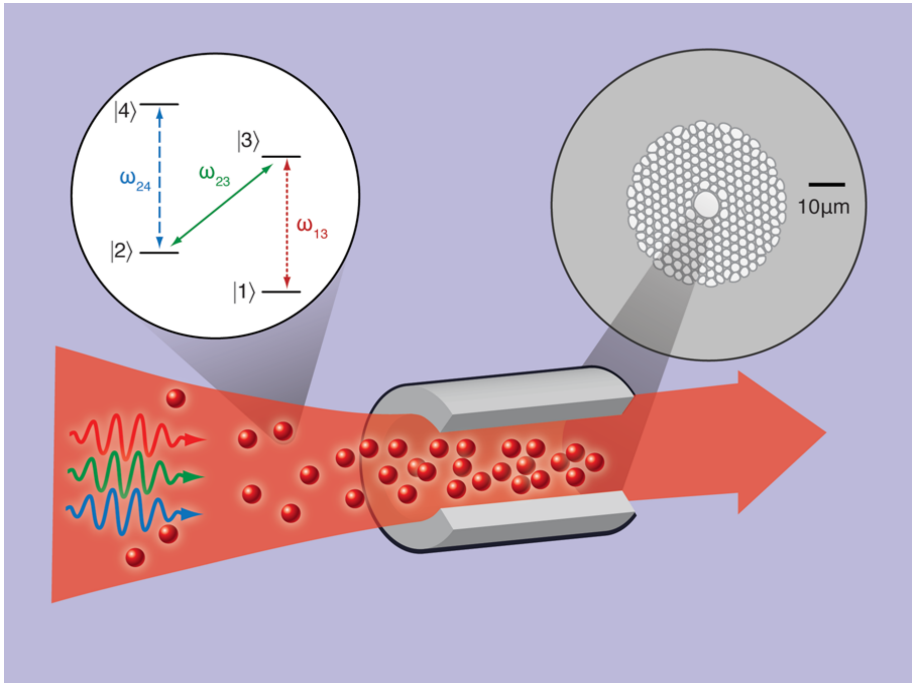
- for 2 photons, $G_{\mathrm{LL}} > 1$ requires

$$\mathbf{OD}^2/N_{\mathbf{atom}} > 160$$

- status: $\mathbf{OD}^2/N_{\mathbf{atom}} \approx 0.3$

but $\mathbf{OD}^2/N_{\mathbf{atom}} \propto N_{\mathbf{atom}}$

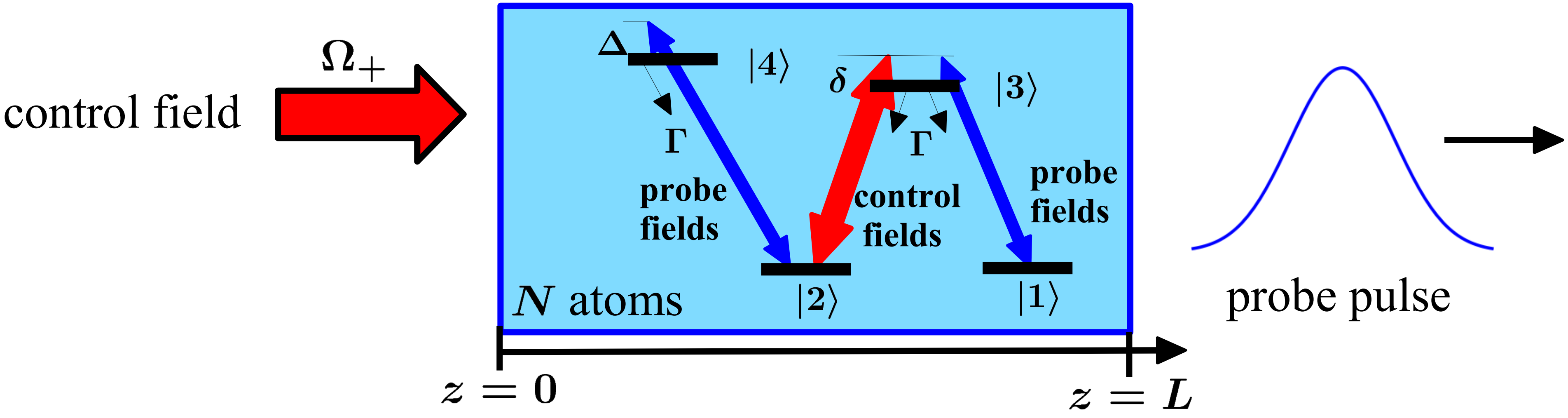
OD : optical depth of the medium



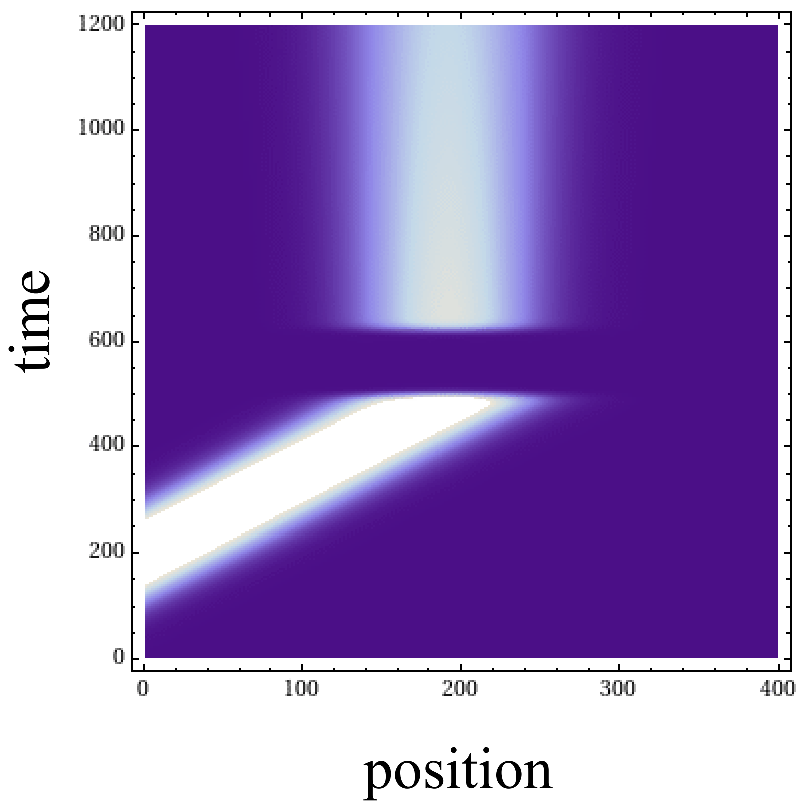
A. M. C. Dawes, Physics **2**, 41 (2009)

Measurements

- Advantage of a Tonks-Girardeau gas of polaritons (rather than atoms):
  - Measurement of nonlocal observables (e.g., momentum distribution) with standard quantum optical techniques
  - spatial correlations $\langle\psi^\dagger(z)\psi(z')\rangle$, $\langle\psi^\dagger(z)\psi^\dagger(z')\psi(z)\psi(z')\rangle$ translate into temporal correlations after release of the pulse



Thank you for your attention!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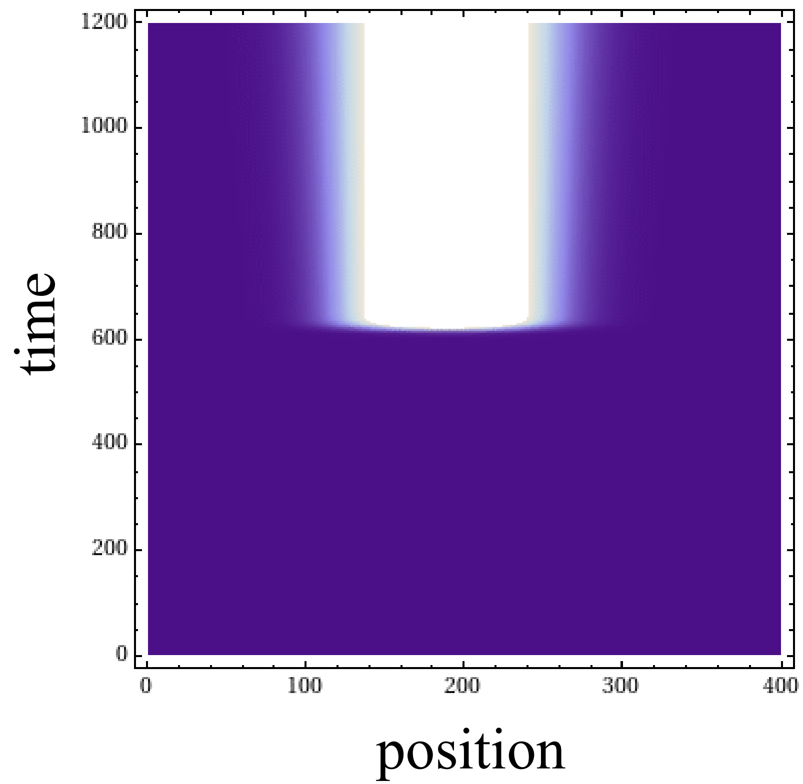
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