FORTH
INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

Single photon sources using a coherently driven Rydberg atom gas

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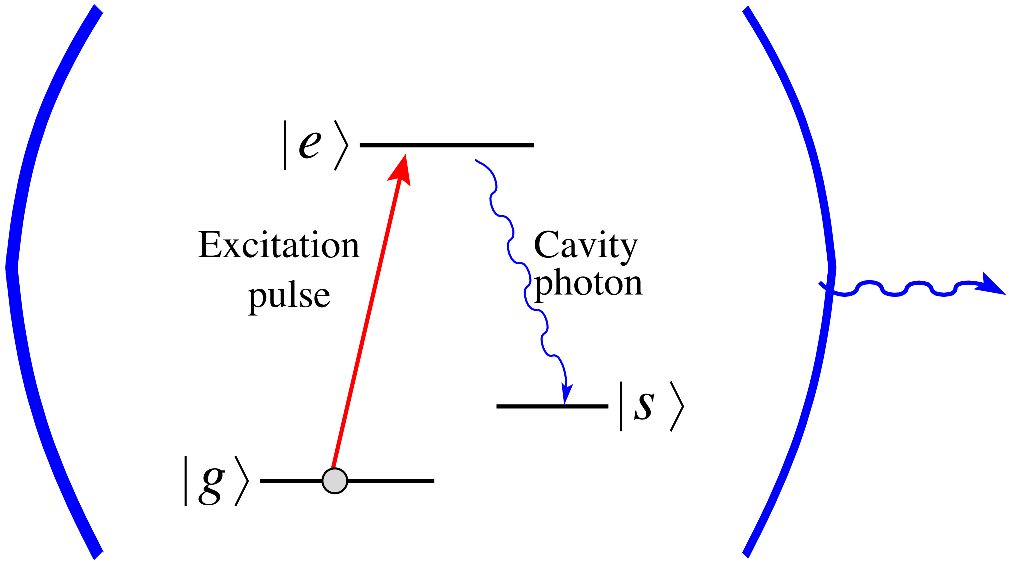
Stiftung / Foundation

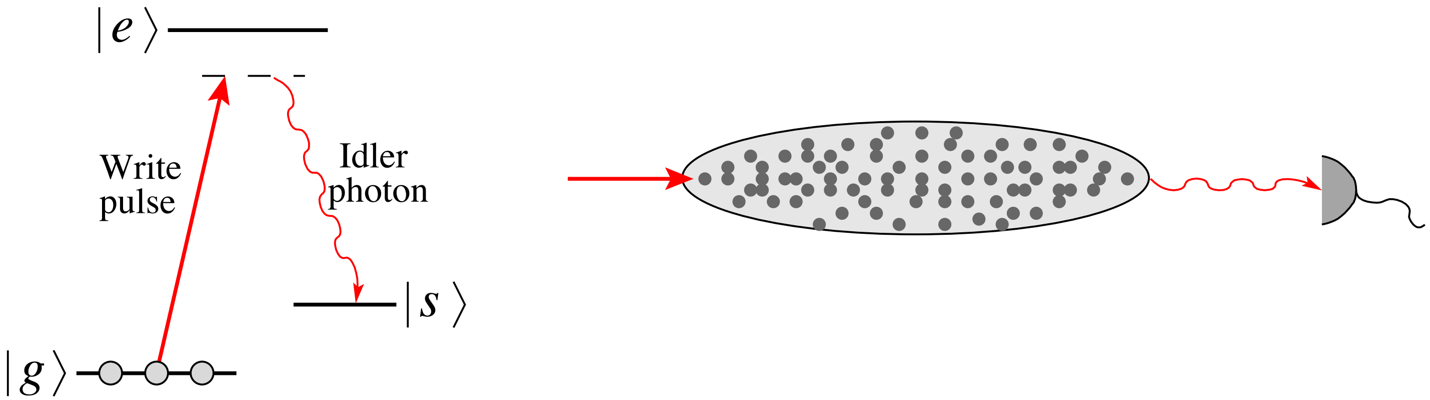
How to produce single photons?

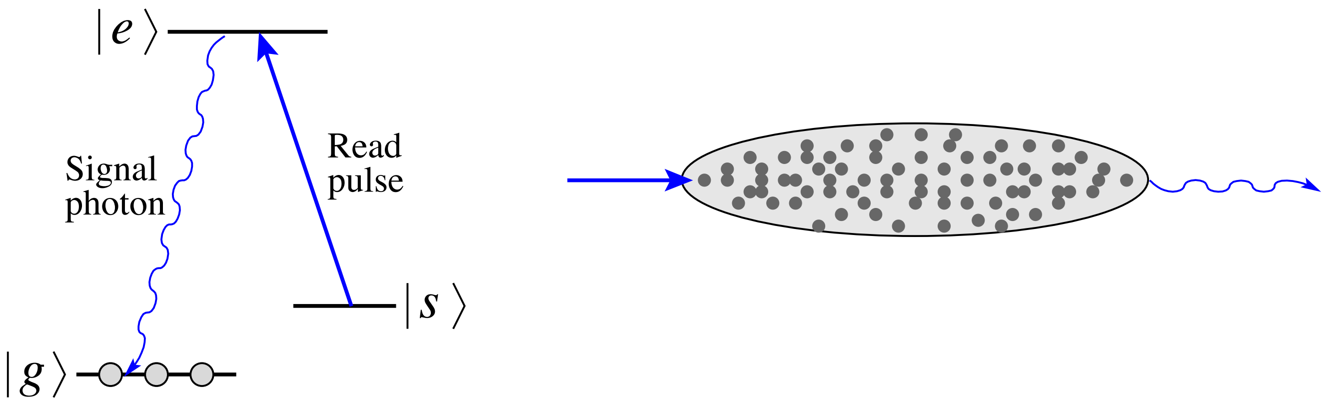
Using single emitter strongly coupled to a resonant cavity (*Γ*<*g*)



How to produce single photons?

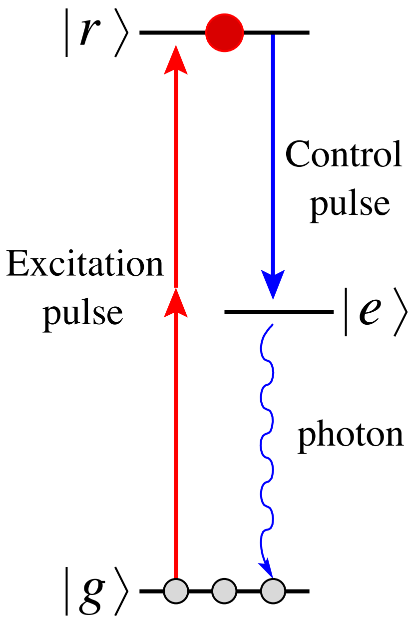
Using the DLCZ scheme (probabilistically)

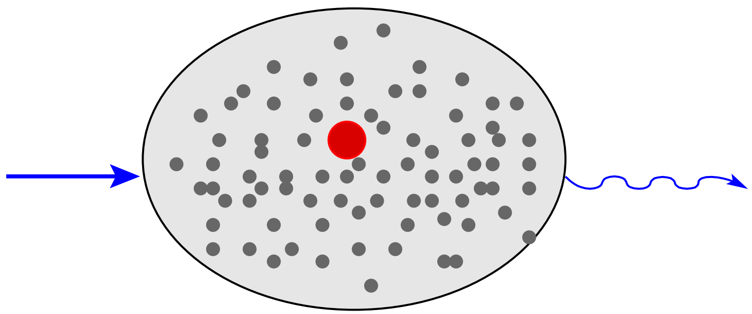




How to produce single photons?

Using massive Rydberg superatom (full blockade)





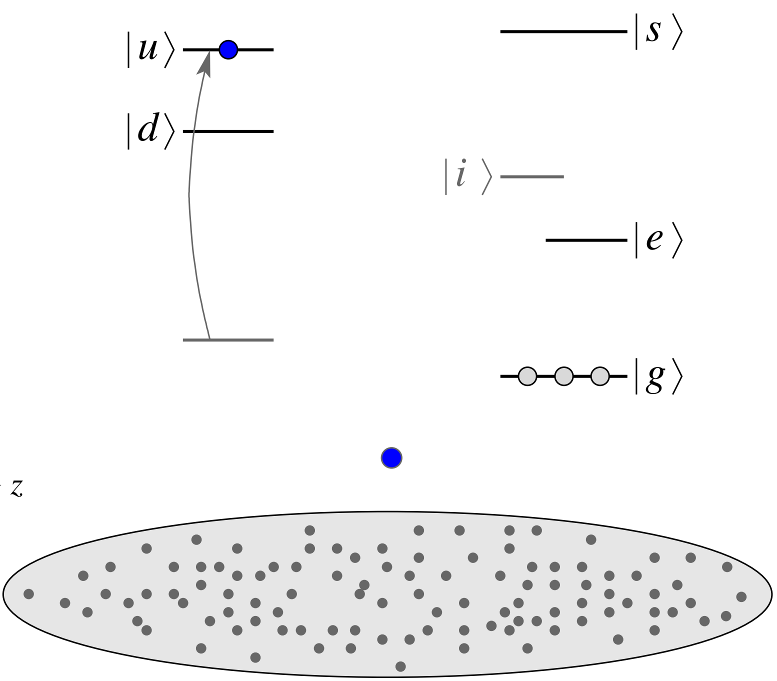
Nearly-deterministic, free-space source of single photons

Combine the best properties of the CQED, Rydberg SA & DLCZ schemes

- Prepare a single atom in an excited state (using a laser)
- Transfer the single excitation to a large atomic ensemble to create a spin-wave with proper spatial phase (using long-range dipole-dipole interactions between the atomic Rydberg states)
- Convert the spin wave to photon wave-packet emitted in the phase-matched direction (using a control laser)

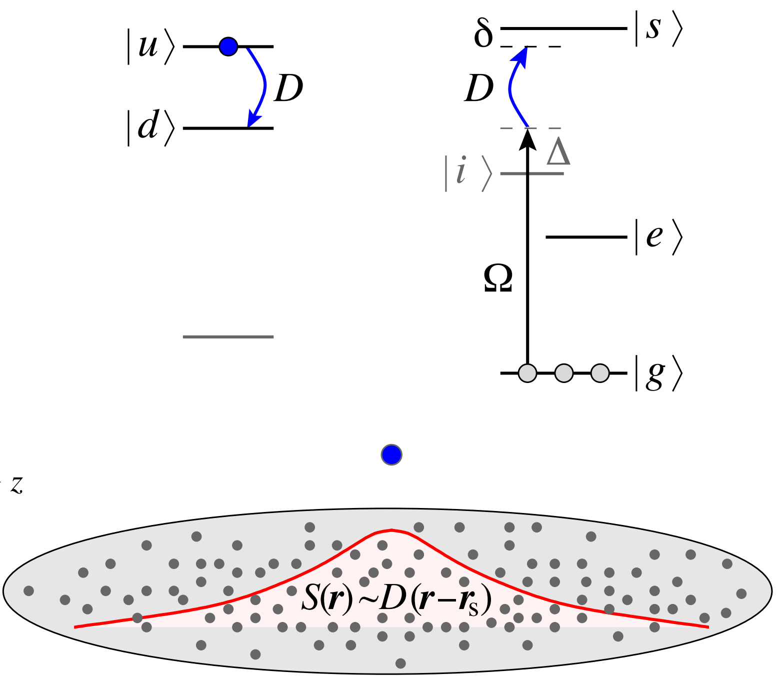
D. Petrosyan, K. Mølmer, [arXiv:1806.07094 [quant-ph]]

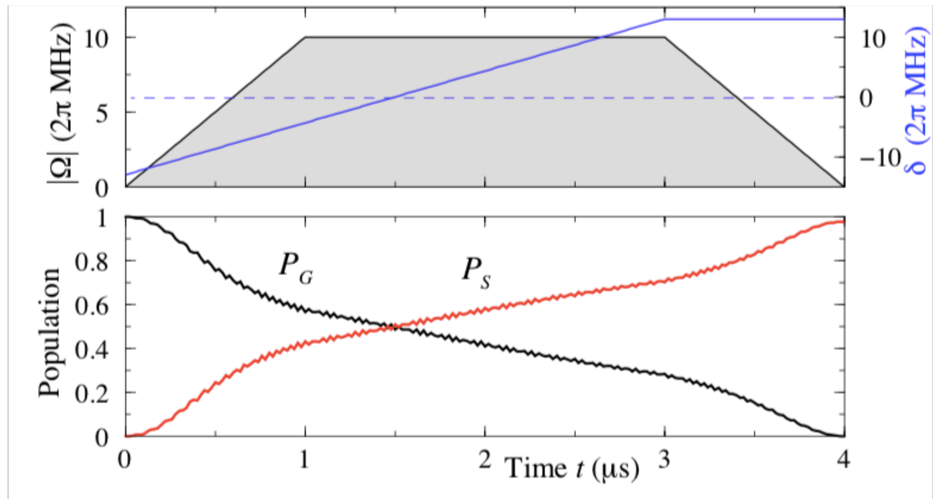
Step 1: Single atomic excitation

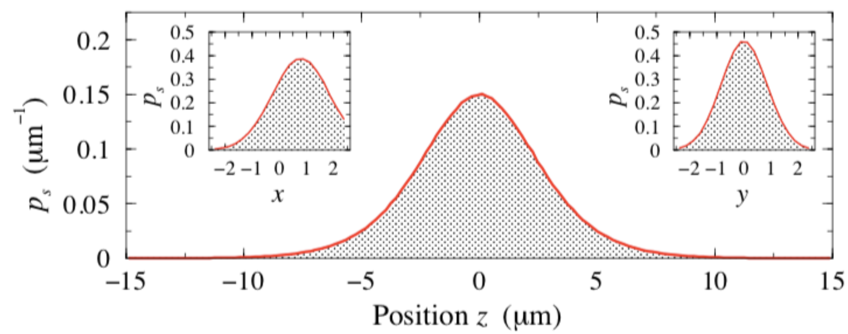


$$|\Psi_1\rangle = |u\rangle \otimes |G\rangle \qquad |G\rangle \equiv |g_1, g_2, \ldots, g_N\rangle$$

Step 2: Single collective excitation





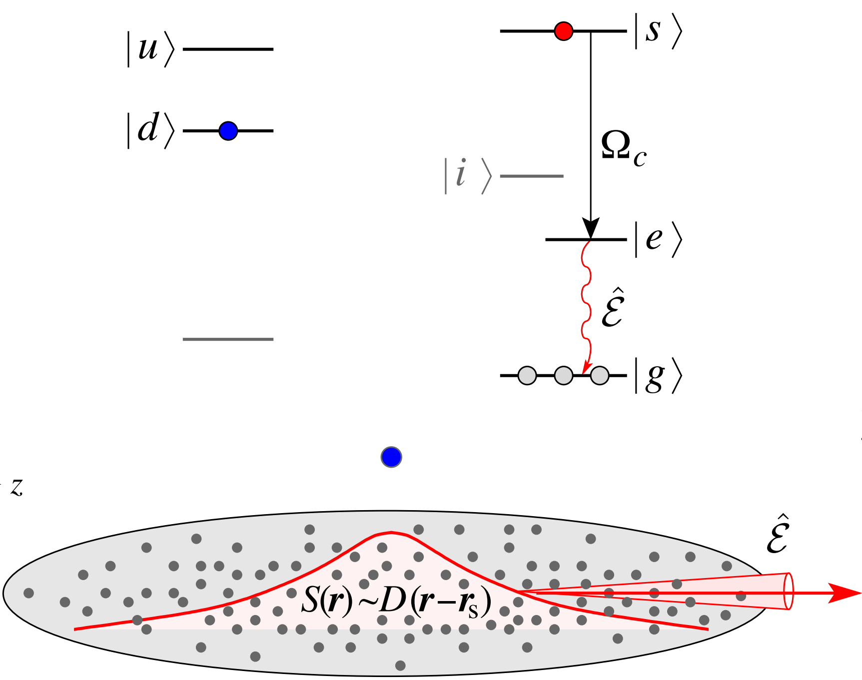


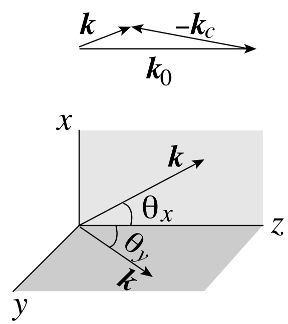
$$|\Psi_2\rangle = |d\rangle \otimes |S\rangle \qquad |S\rangle \equiv \frac{1}{\bar{D}} \sum_{j=1}^{N} \tilde{D}_j e^{i\boldsymbol{k}_0 \cdot \boldsymbol{r}_j} |g_1, g_2, \ldots, s_j, \ldots, g_N\rangle$$

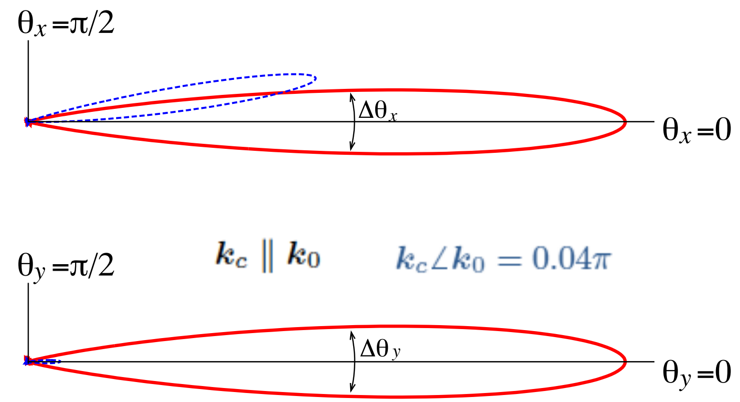
$$\tilde{D}_j \equiv -\frac{D(\boldsymbol{r}-\boldsymbol{r}_{\rm s})\Omega}{\Delta} \qquad \bar{D} \equiv \left(\sum_j^N |\tilde{D}_j|^2 \right)^{1/2}$$

$$D(\boldsymbol{r}-\boldsymbol{r}_{\rm s}) = \frac{C_3}{|\boldsymbol{r}-\boldsymbol{r}_{\rm s}|^3}(1 - 3\cos^2\vartheta) \qquad C_3 = \frac{\wp_{si}\wp_{du}}{4\pi\epsilon_0\hbar}, \quad \wp \approx n^2 e a_0$$

Step 3: Single photon emission







$$P_{\Delta\Omega} \simeq \eta N \Delta\Omega/4\pi \gtrsim 0.7$$

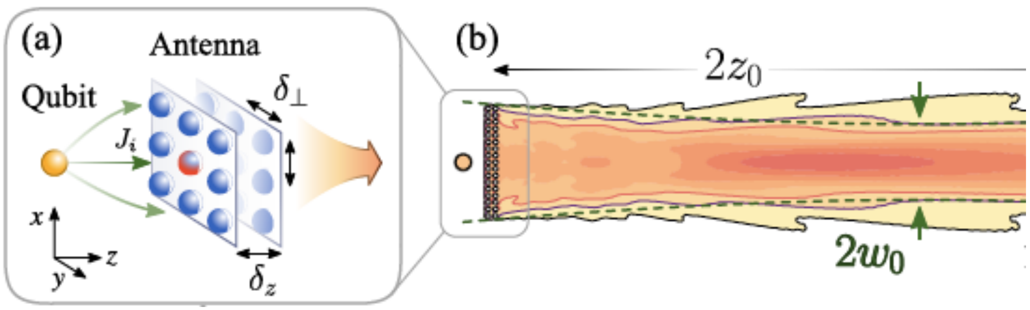
$$\Delta\Omega = 2\pi(1-\cos\Delta\theta)$$

$$|\Psi_3\rangle = |d\rangle \otimes |S\rangle \otimes |1_{\text{phot}}\rangle \qquad |1_{\text{phot}}\rangle \equiv \sum_{\boldsymbol{k}} a_{\boldsymbol{k}} |1_{\boldsymbol{k}}\rangle$$

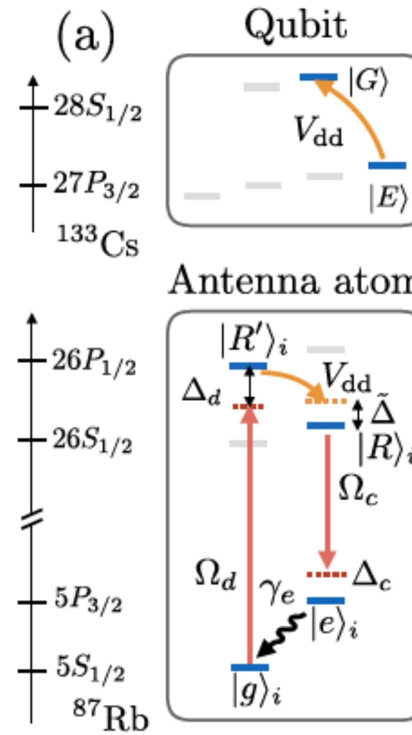
$$a_{\boldsymbol{k}} = -\tilde{g}_k(t) \sum_j \frac{\tilde{D}_j}{\tilde{D}} e^{i(\boldsymbol{k}_0-\boldsymbol{k}_c-\boldsymbol{k})\cdot\boldsymbol{r}_j} \quad \tilde{g}_k \simeq \frac{g_k \Omega_c^*}{\Gamma_e(ck-\omega_{eg})/2+i|\Omega_c|^2} \text{ for } t \gg \frac{\Gamma_e/2}{|\Omega_c|^2}$$

Phased-array optical antenna with atoms in a lattice

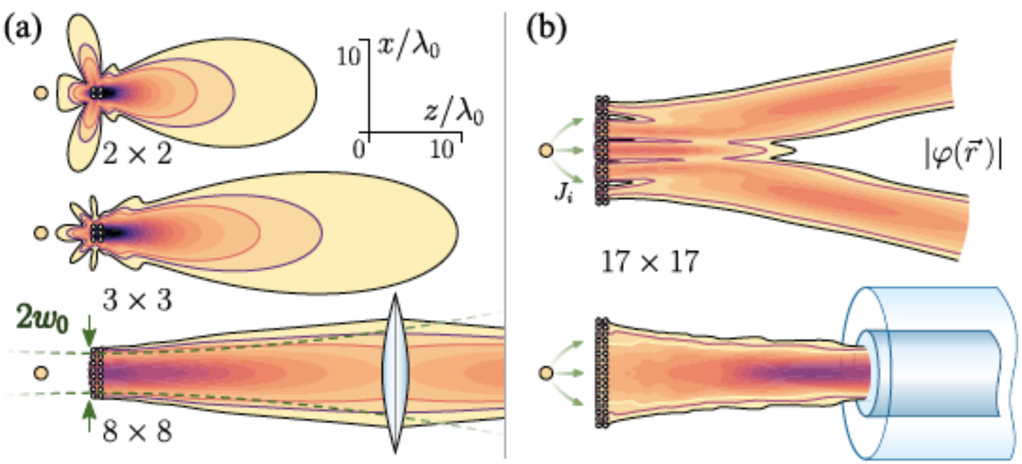
Subwavelength interatomic distances, two or more layers



Rydberg implementation



Shaping the spatial distribution of the emitted radiation by tailoring the phase and amplitudes of the antenna atoms



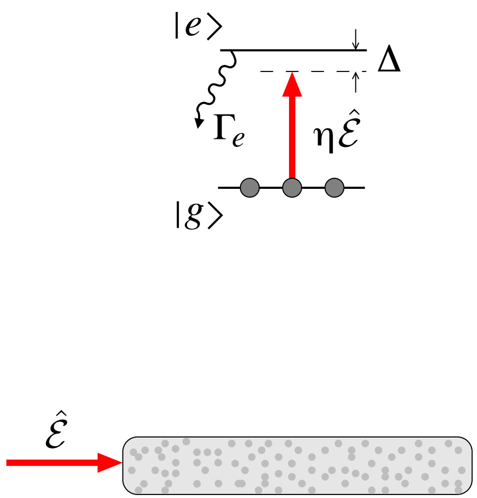
Fixed atomic positions,
Control of spatial phase and amplitude of Ω_d

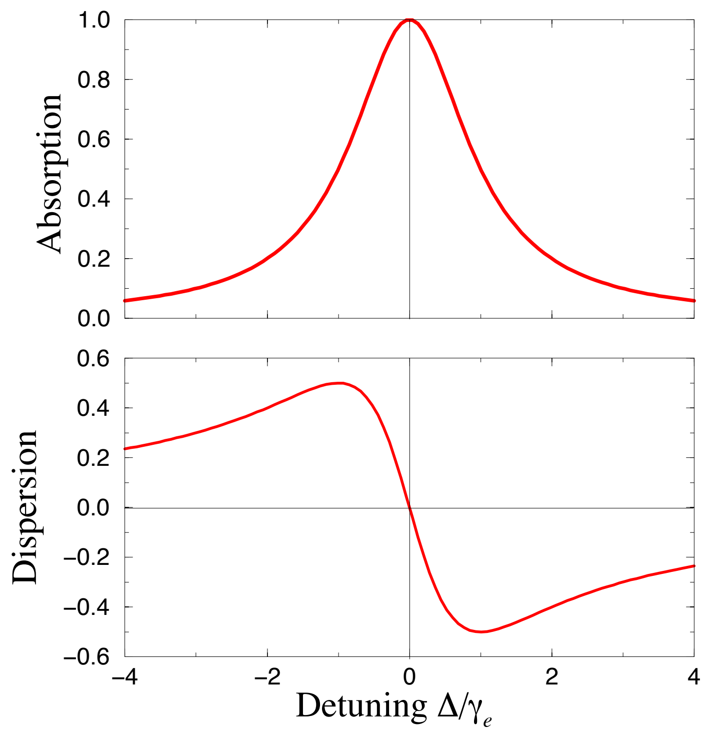
A. Grankin, P. O. Guimond, D. V. Vasilyev, B. Vermersch, P. Zoller, arXiv:1802.05592 [quant-ph]

Single photon filter using dipolar exchange induced transparency with Rydberg atoms

D. Petrosyan, NJP **19**, 033001 (2017)

Electromagnetically Induced Transparency





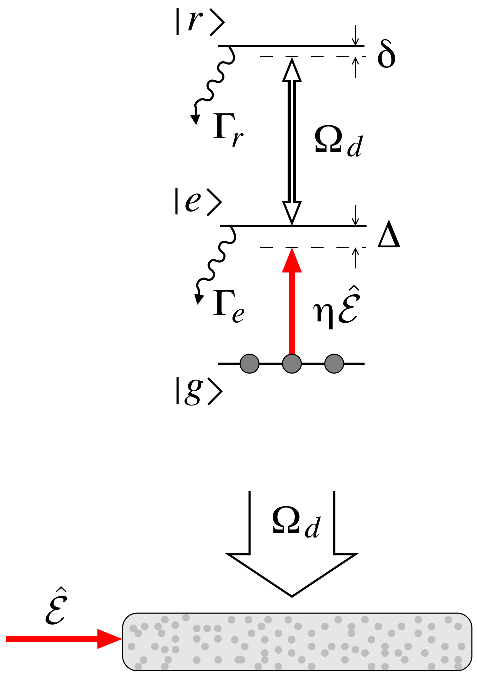
Stationary propagation

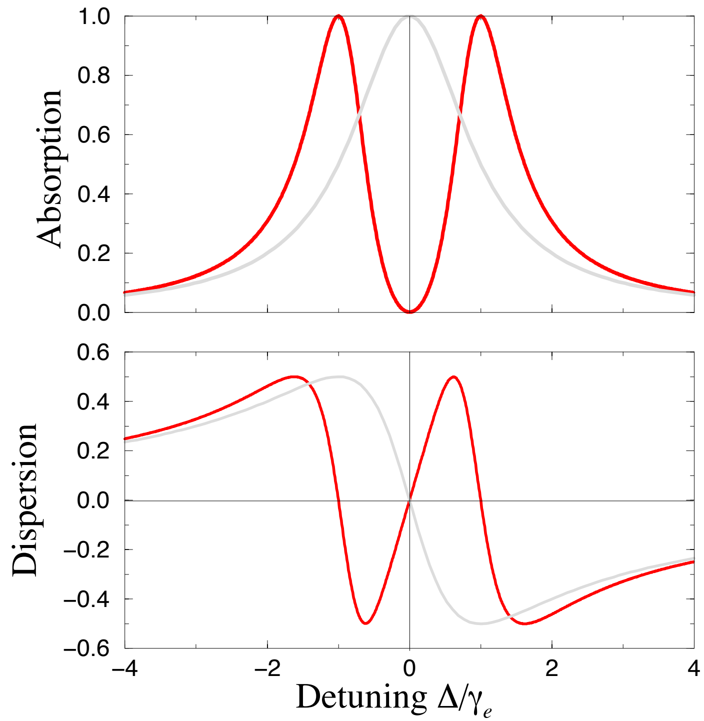
$$\boxed{\partial_z \mathcal{E} = i\frac{\omega}{2c}\chi\mathcal{E}}$$

2LA medium susceptibility

$$\chi = \frac{2}{\omega}\frac{i\eta^2 N}{\gamma_e - i\Delta_p} = \frac{c}{\omega}\frac{\sigma_0\bar{\rho}\Gamma_e}{\gamma_e - i\Delta_p}$$

Electromagnetically Induced Transparency





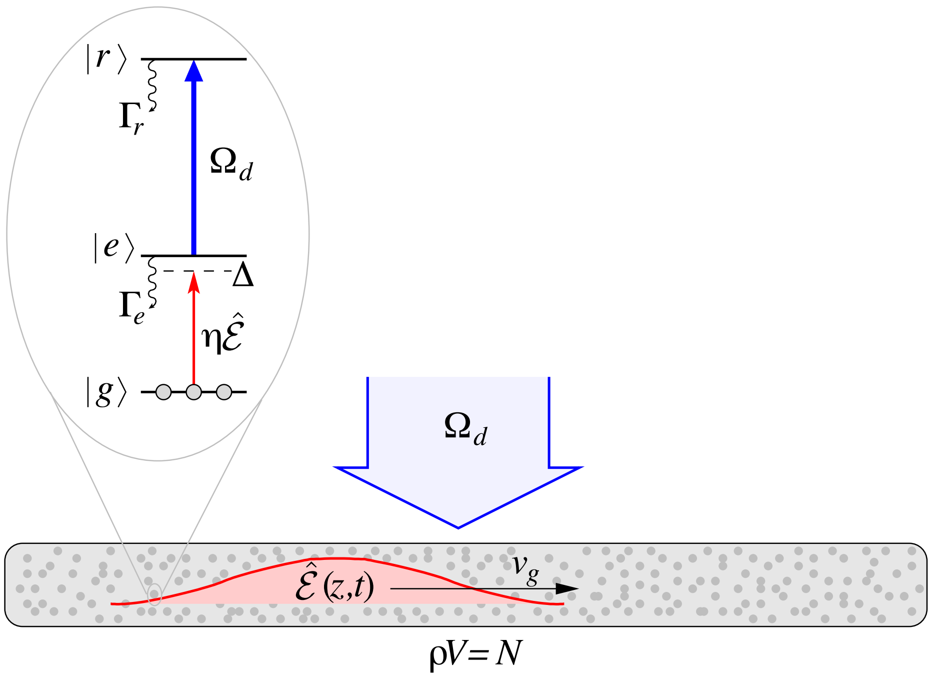
Stationary propagation

$$\boxed{\partial_z \mathcal{E} = i\frac{\omega}{2c}\chi\mathcal{E}}$$

EIT (3LA) susceptibility

$$\chi = \frac{2}{\omega}\frac{i\eta^2 N}{\gamma_e - i\Delta + \frac{|\Omega_d|^2}{\gamma_r - i(\Delta+\delta)}}$$

Pulse propagation in EIT medium



$$(\partial_t + v_g \partial_z)\hat{\mathcal{E}}(z,t) = i\frac{\omega}{2}\chi\,\hat{\mathcal{E}}(z,t)$$

with

$$v_g = \frac{c}{1+\frac{\omega}{2}\frac{\partial}{\partial\Delta}\mathrm{Re}\chi} \simeq c\frac{|\Omega_d|^2}{\eta^2 N} \ll c$$

@ two-photon resonance

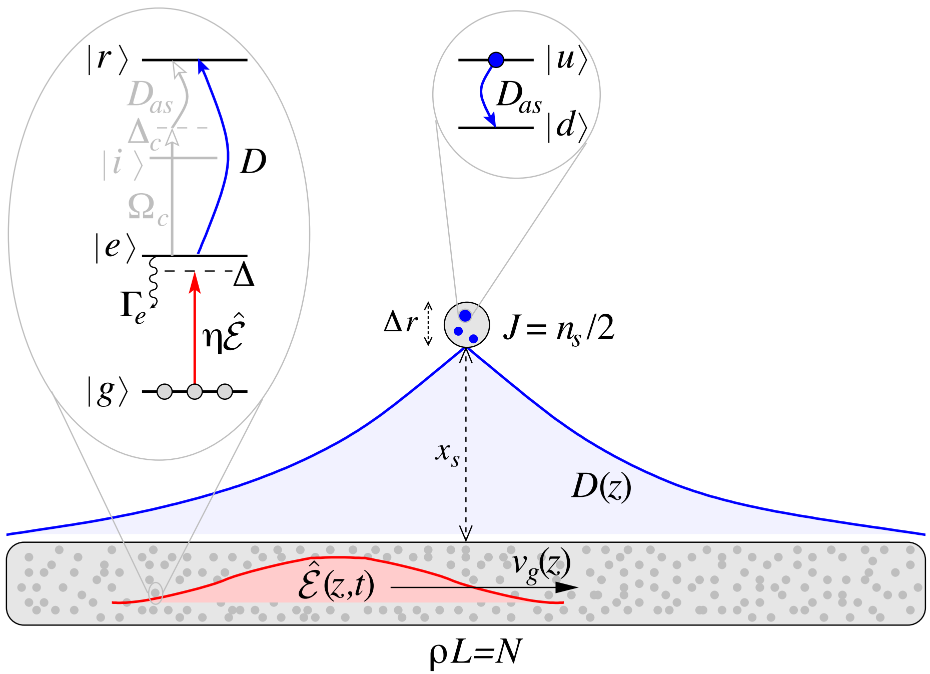
$$\boxed{\Delta = -\delta \;\;\&\;\; |\gamma_e + i\delta|\gamma_r \ll |\Omega_d|^2}$$

Inside the medium ⇒ dark-state polariton

$\hat{\mathcal{E}} \to \hat{\Psi} = \cos\theta\hat{\mathcal{E}} - \sin\theta\sqrt{N}\hat{\sigma}_{gr}$ with $\tan^2\theta = \frac{\eta^2 N}{|\Omega_d|^2} \gg 1$

Photons are converted to atomic $|r\rangle$ excitations $(\cos\theta \ll 1)$ and propagate with slow group velocity $v_g = c\cos^2\theta \ll c$

Dipolar Exchange Induced Transparency



One or more spin atoms play the role of Ω_d via exchange interaction

$$\boxed{D(z)\,\hat{\sigma}_{re}(z)\otimes\hat{\sigma}_{-}}$$

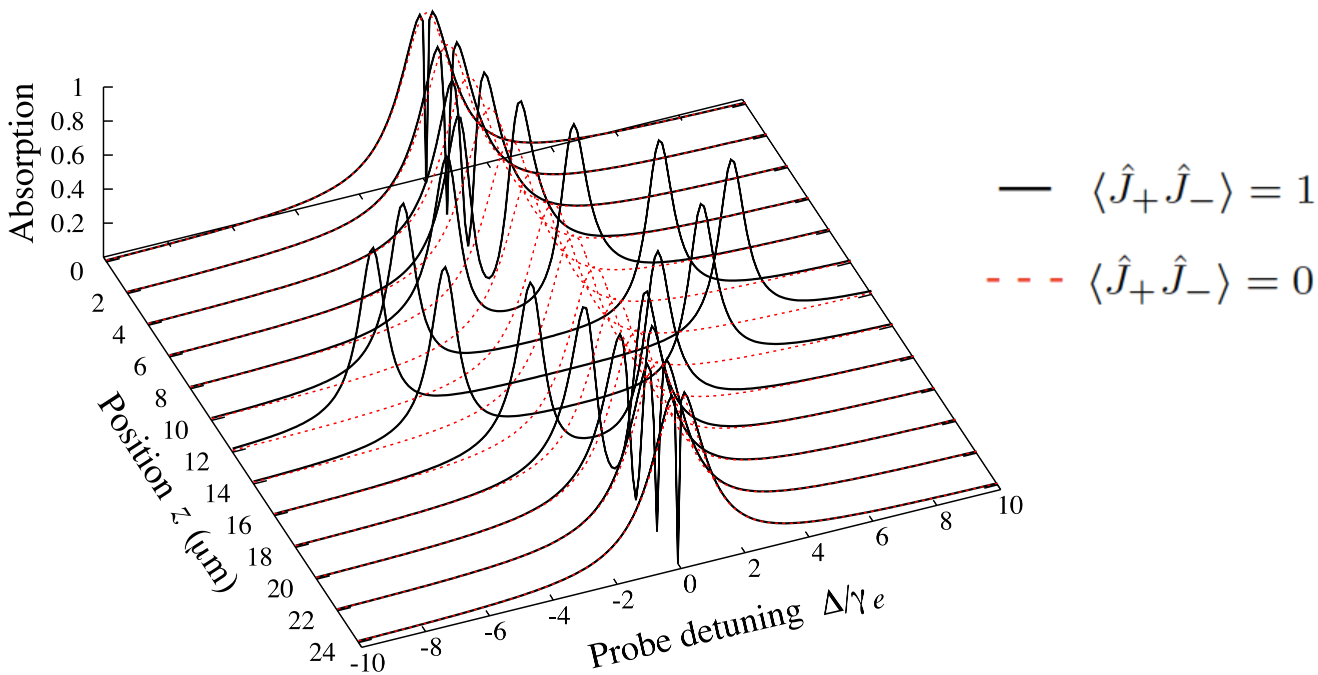
$$D(z) = \frac{C_3\Omega_c/\Delta_c}{|z\boldsymbol{e}_z - \boldsymbol{r}_j|^3}$$

Each probe photon in the medium attempts to create atomic $|r\rangle$ excitation with *simultaneous* flip of one spin atom $|u\rangle \to |d\rangle$ $[\hat{J}_- \equiv \sum_j^{n_s} \hat{\sigma}_-^j \;\; (\Delta r \ll x_s)]$

$\Rightarrow$ DEIT exists for $n_p \leq n_s \equiv 2J$ photons ["spin" state $|J, J-n_p\rangle$]

$\Rightarrow$ $(n_p - n_s)$ photons are absorbed by resonant 2LA medium: OD$= 2\sigma_0\bar{\rho}L > 1$

DEIT medium response



Susceptibility $\hat{\chi}(z,\Delta) = \frac{2}{\omega} \frac{i\eta^2 N}{\gamma_e - i\Delta + \frac{|D(z)|^2 \hat{J}_+ \hat{J}_-}{\gamma_r - i(\Delta+\delta)}}$ $\Rightarrow$ n_p-dependent

group velocity @ $\Delta \simeq -\delta$

$\hat{v}_g(z) \simeq c\frac{|D(z)|^2 \hat{J}_+ \hat{J}_-}{\eta^2 N}$ $\Rightarrow$ $v_g^{(n_p+1)}(z) = c\frac{|D(z)|^2}{\eta^2 N}(n_s - n_p)(n_p+1)$

Summary

Strong, long-range dipole-dipole exchange interactions between Rydberg atoms can be used to couple a singe atom to a large atomic ensemble

Excitation of a single emitter can be converted to a collective medium excitation

Single photons can then be emitted with large probability into the phase-matched spatial direction [arXiv:1806.07094]

State transfer between single atomic qubits coupled to optical phase-array antennas can be achieved [arXiv:1802.05592]

In DEIT n_s "spin" atoms can play the role of the quantized control field Ω_d of the EIT

The system can serve as photon number filter or transistor for $n_p \leq n_s$ photons

Poster: ***Simulating spin-lattice models with cold Rydberg atoms***