# Quantum Information Processing with single photons & atomic ensembles

**David Petrosyan**

# Outline

- Motivation: Quantum Information Processing with Single Photons

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- Background: Electromagnetically Induced Transparency

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- Atoms in Microwave Coplanar Waveguide Resonator
- Summary

# Photonic Qubit

Single-photon wavepacket in the polarization state

$$|\psi\rangle = \alpha\,|V\rangle + \beta\,|H\rangle \text{ with } |\alpha|^2 + |\beta|^2 = 1$$

$|V\rangle \equiv |0\rangle$ & $|H\rangle \equiv |1\rangle$ form the computational basis $\{\,|0\rangle, |1\rangle\}$

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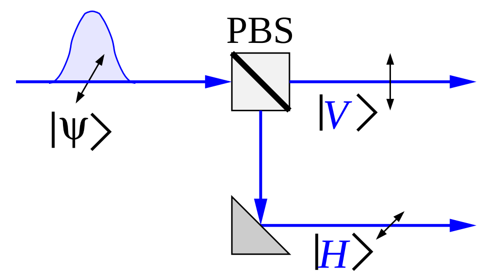
Single-rail $\leftrightarrow$ Dual-rail conversion



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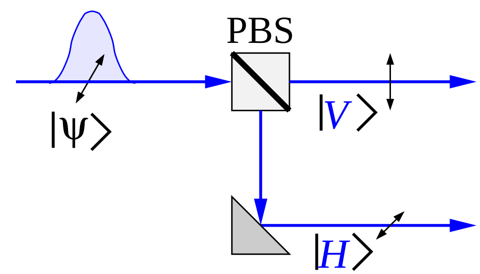
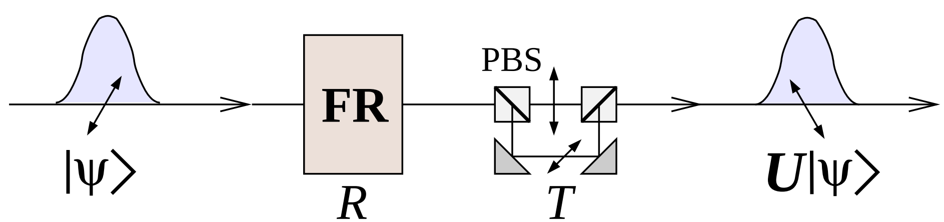



Single-qubit unitary transformations $U \propto R(\vartheta) \otimes T(\phi)$
can be implemented with linear-optics operations



# Universal Two-Qubit Logic Gates

## Controlled-NOT gate

$$W_{\text{CNOT}}\,|a\rangle\,|b\rangle \longrightarrow |a\rangle\,|a\oplus b\rangle$$

$$a, b \in \{0, 1\}$$

## Controlled-Z (PHASE) gate

$$W_{\text{CZ}}\,|a\rangle\,|b\rangle \longrightarrow (-1)^{ab}\,|a\rangle\,|b\rangle$$

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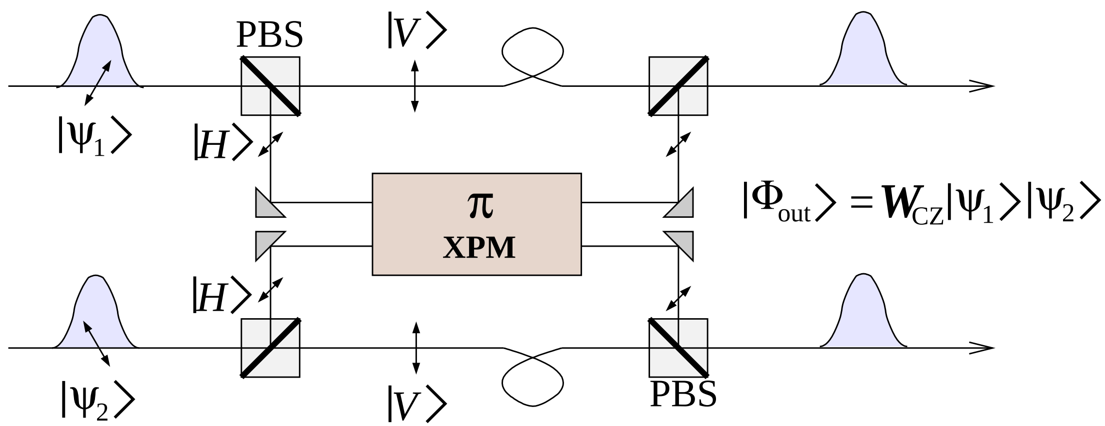
$W_{\text{CZ}}$ requires nonlinear (Kerr) photon-photon interaction – XPM



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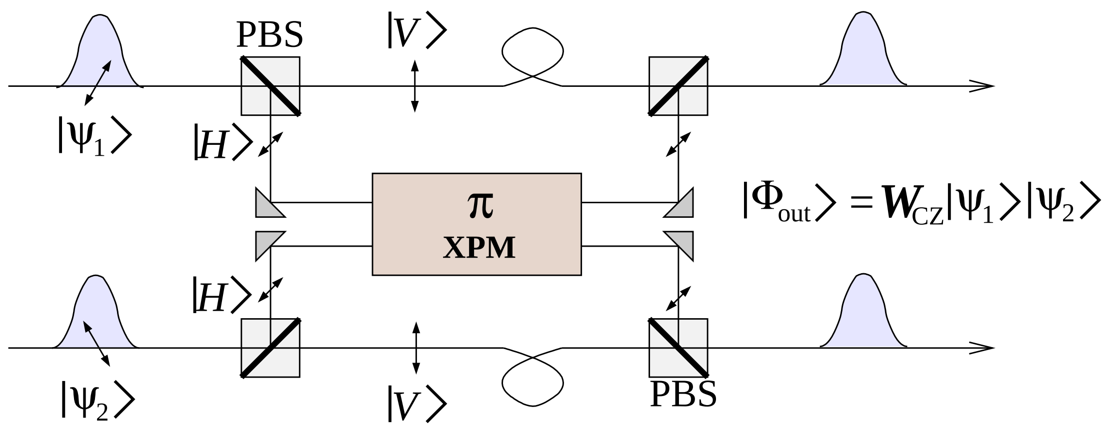
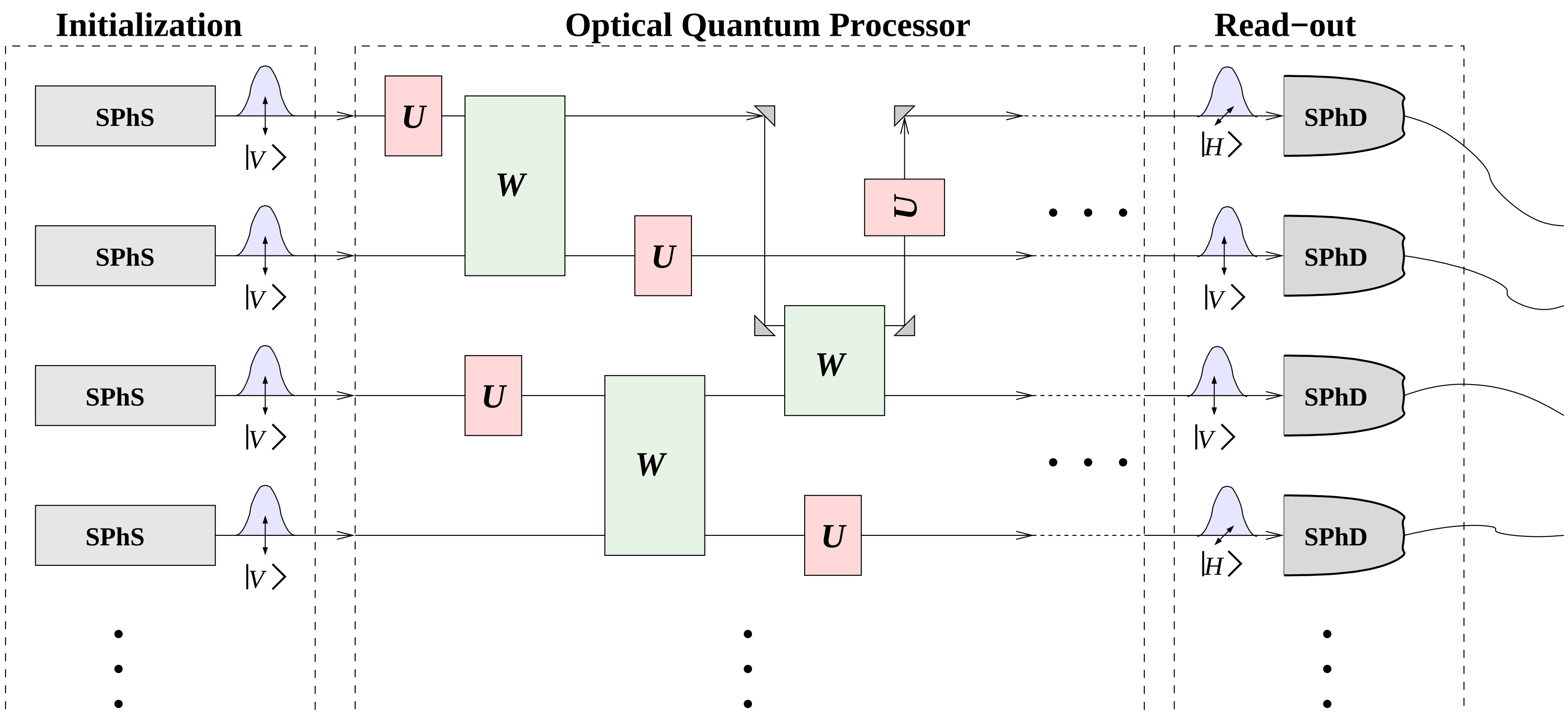



- Any multiqubit transformation can be decomposed into single-qubit $U$ and two-qubit $W_{\text{CNOT}}$ or $W_{\text{CZ}}$ transformations
  $\Longrightarrow$ $U$ and $W$ are Universal

# Optical Quantum Computer



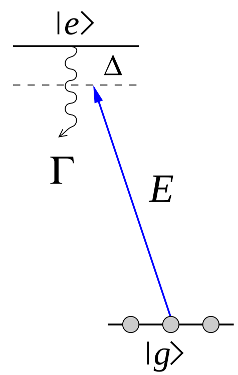

- SPhS: Single Photon Sources
- $W$=XPM: Cross Phase Modulation
- SPhD: Single Photon Detectors

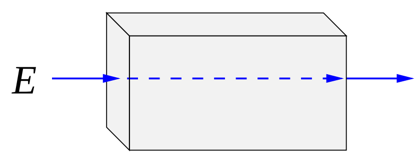
Petrosyan, J. Opt. B. **7**, S141 (2005)

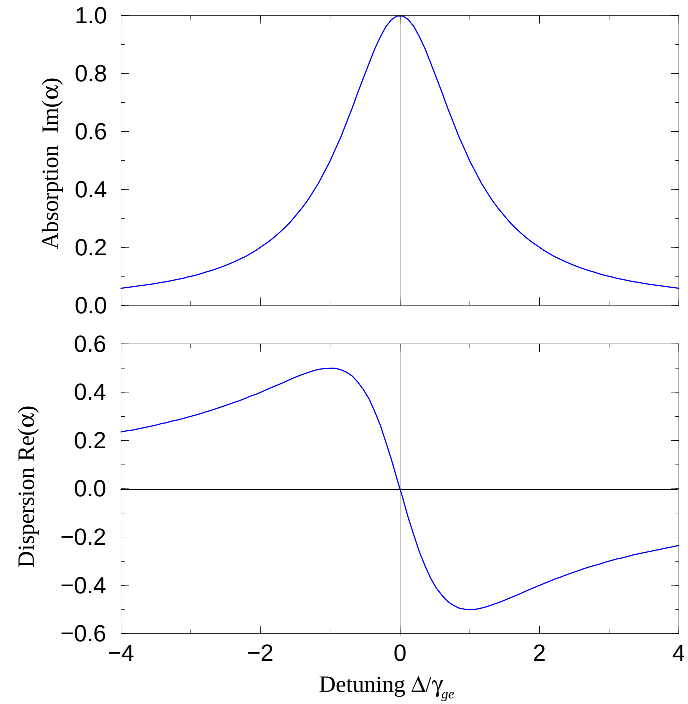
# Electromagnetically Induced Transparency

Fleischhauer, Imamoglu, Marangos, RMP **77**, 633 (2005)

# Spectral Properties



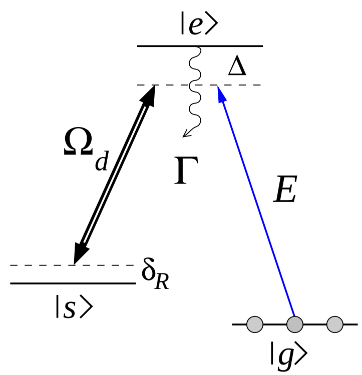



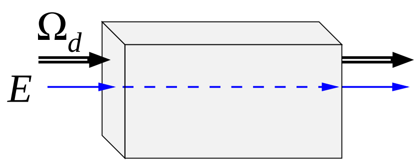

$$E(z,t) = E\left(0, t - \tfrac{z}{c}\right) e^{\mathrm{i}\alpha z}$$

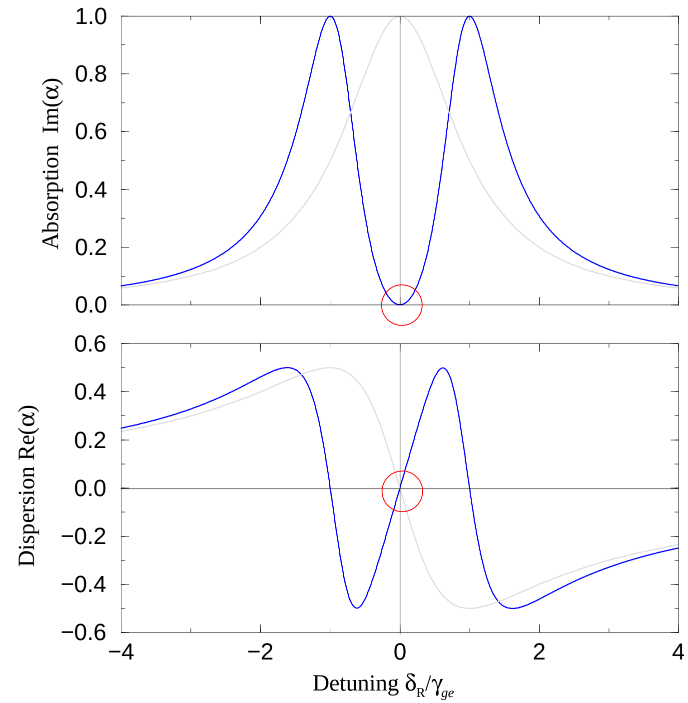
Medium Polarizability $\alpha(\Delta) = \kappa_0 \frac{\mathrm{i}\gamma_{ge}}{\gamma_{ge} - \mathrm{i}\Delta}$ $\Rightarrow$

Absorption $\mathrm{Im}(\alpha) \simeq \kappa_0 \quad (\Delta \ll \gamma_{ge})$

# Spectral Properties



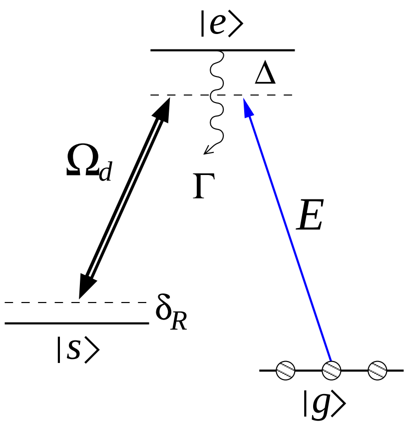

$$E(z,t) = E\left(0, t - \frac{z}{v_g}\right) e^{i\alpha z}$$

Medium Polarizability $\alpha(\Delta) = \kappa_0 \frac{i\gamma_{ge}}{\gamma_{ge} - i\Delta + \frac{|\Omega_d|^2}{\gamma_R - i\delta_R}}$ $\Rightarrow$

Absorption $\mathrm{Im}(\alpha) = \frac{1}{v_g}\left[\gamma_R + \frac{\delta_R^2}{|\Omega_d|^2}\right] \ll \kappa_0$ $\qquad v_g = \frac{c}{1 + c\frac{\partial}{\partial\omega}\mathrm{Re}(\alpha)} \simeq \frac{|\Omega_d|^2}{\kappa_0\gamma_{ge}} \ll c$

EIT conditions: $|\Omega_d|^2 \gg (\gamma_{ge} + |\Delta|)(\gamma_R + \delta_R)$

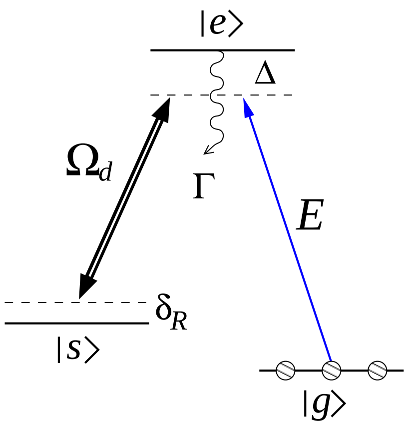
# Hamiltonian




$$H = \hbar \sum_{j=1}^{N} \begin{bmatrix} 0 & g\hat{\mathcal{E}}^\dagger(z_j)e^{-ikz_j} & 0 \\ g\hat{\mathcal{E}}(z_j)e^{ikz_j} & \Delta & \Omega_d(t)e^{ik_d z_j} \\ 0 & \Omega_d^*(t)e^{-ik_d z_j} & \delta_R \end{bmatrix}_j$$

with $\hat{\mathcal{E}}(z,t) = \sum_q a^q(t)e^{iqz}$ and $g = \frac{\wp_{ge}}{\hbar}\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}$

# Hamiltonian

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$\delta_R = 0 \Rightarrow$ **Dark states** ($H\,|D_1^q\rangle = 0\,|D_1^q\rangle$) for single-photons $|1^q\rangle = a^{q\dagger}\,|0\rangle$

$$\boxed{|D_1^q\rangle = \cos\theta\,|1^q, s^{(0)}\rangle - \sin\theta\,|0^q, s^{(1)}\rangle} \qquad \tan^2\theta(t) = \frac{g^2 N}{|\Omega_d(t)|^2}$$

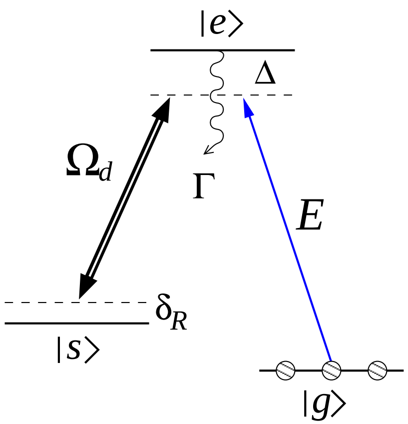
with collective atomic states

$$|s^{(0)}\rangle \equiv |g_1, g_2, \ldots, g_N\rangle$$

$$|s^{(1)}\rangle \equiv \frac{1}{\sqrt{N}}\sum_{j=1}^{N} e^{i(k+q-k_d)z_j}\,|g_1, \ldots, s_j, \ldots, g_N\rangle$$

Fleischhauer, Lukin, PRL **84**, 5094 (2000); PRA **65**, 022314 (2002)

# Hamiltonian

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- $\theta = 0 \quad (|\Omega_d|^2 \gg g^2 N) \Rightarrow |D_1^q\rangle = |1^q\rangle\,|s^{(0)}\rangle$ purely photonic excitation
- $\theta = \pi/2\ (|\Omega_d|^2 \ll g^2 N) \Rightarrow |D_1^q\rangle = |0^q\rangle\,|s^{(1)}\rangle$ purely atomic excitation

Fleischhauer, Lukin, PRL **84**, 5094 (2000); PRA **65**, 022314 (2002)

# Dark-State Polariton

Define operator $$\boxed{\hat{\Psi}(z,t) = \cos\theta(t)\hat{\mathcal{E}}(z,t) - \sin\theta(t)\sqrt{N}\hat{\sigma}_{gs}(z,t)}$$

with $\hat{\sigma}_{gs}(z,t) = \frac{1}{N_z}\sum_{j=1}^{N_z} |g_j\rangle\langle s_j|\,, \quad N_z = \frac{N}{L}dz \gg 1$

- $\hat{\Psi}(z,t) = \sum_q \hat{\psi}^q(t)e^{iqz}$ $\Rightarrow$ $|D_1^q\rangle = \hat{\psi}^{q\dagger}\,|0^q\rangle\,|s^{(0)}\rangle$

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Equation of motion

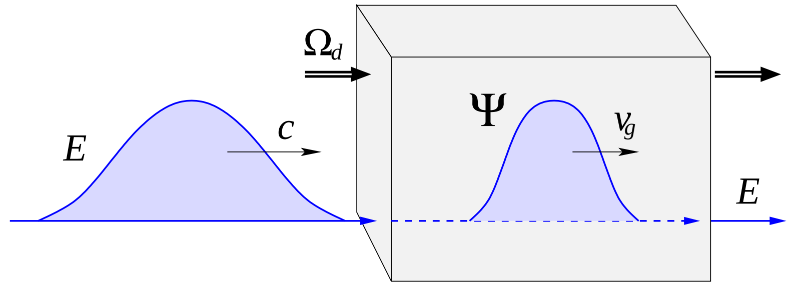
$$\left(\frac{\partial}{\partial t} + v_g(t)\frac{\partial}{\partial z}\right)\hat{\Psi}(z,t) = 0 \qquad \Rightarrow \qquad \hat{\Psi}(z,t) = \hat{\Psi}\left(z - \int_0^t v_g(t')dt', 0\right)$$

$v_g(t) = c\cos^2\theta(t) = c\,\frac{|\Omega_d(t)|^2}{g^2N+|\Omega_d(t)|^2}$ group velocity (time-dependent)

$\Rightarrow$ One can decelerate/accelerate the propagation of $\hat{\Psi}(z,t)$

Fleischhauer, Lukin, PRL **84**, 5094 (2000); PRA **65**, 022314 (2002)

# Stopping of Light




Single-photon WP: $|1\rangle = \sum_q \xi^q \, |1^q\rangle = \frac{1}{L} \int dz f(z) \hat{\mathcal{E}}^\dagger(z) \, |0\rangle$

*i*) At the entrance $0 < \theta(0) \lesssim \pi/2$ $\quad$ ($0 < \Omega_d(t) \ll g^2 N$)

$\Rightarrow$ Pulse is spatially compressed by $\frac{v_g(0)}{c} = \cos^2 \theta(0) \ll 1$

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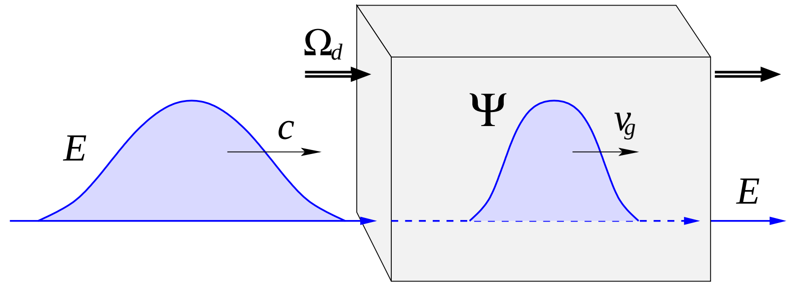


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*ii*) Rotate $\theta(t) \to \pi/2$ ($\Omega_d(t) \to 0$)
$\Rightarrow$ Pulse is stopped $v_g(t) = 0$
and stored as atomic excitation $|D_1^q\rangle = |0^q\rangle |s^{(1)}\rangle$

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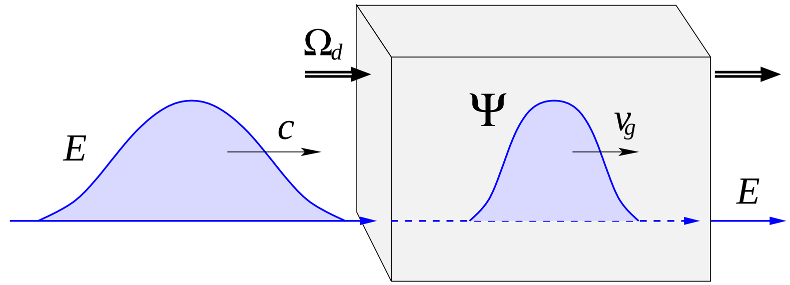


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*iii*) Rotate $\theta(t') < \pi/2$ $\quad$ ($\Omega_d(t') > 0$)

$\Rightarrow$ Pulse is released $v_g(t') > 0$

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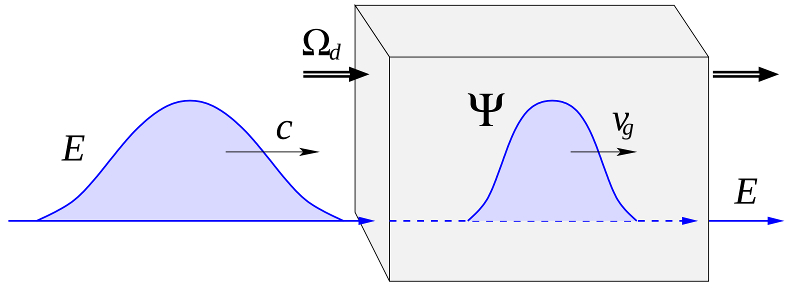


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*iii*) Rotate $\theta(t') < \pi/2$ $(\Omega_d(t') > 0)$

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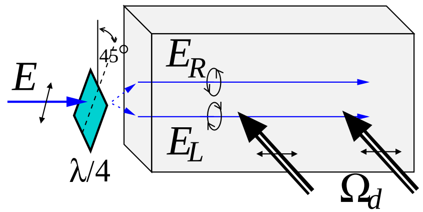
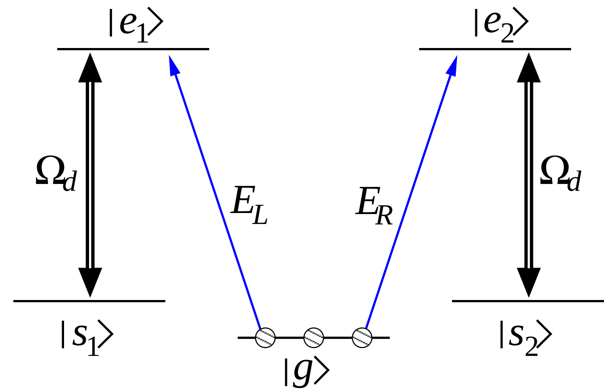
Requires $T v_g(0) < L$ & $T^{-1} < \delta\omega_{\rm tw}$ $\Rightarrow$ large optical depth $2\kappa_0 L \gg 1$

# Photonic Memory




- $\lambda/4$ plate oriented at $45°$

  $|V\rangle \to |R\rangle = \frac{1}{\sqrt{2}}(|V\rangle + i\,|H\rangle) \quad |H\rangle \to |L\rangle = \frac{1}{\sqrt{2}}(|V\rangle - i\,|H\rangle)$

  $\Rightarrow\ |\psi(0)\rangle \to \alpha\,|R\rangle + \beta\,|L\rangle$

Fleischhauer, Mewes (2002); Mewes, Fleischhauer, PRA **72**, 022327 (2005)

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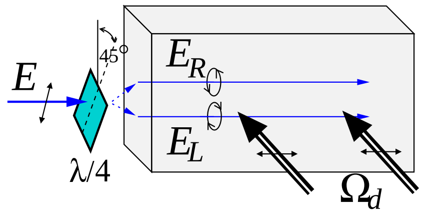


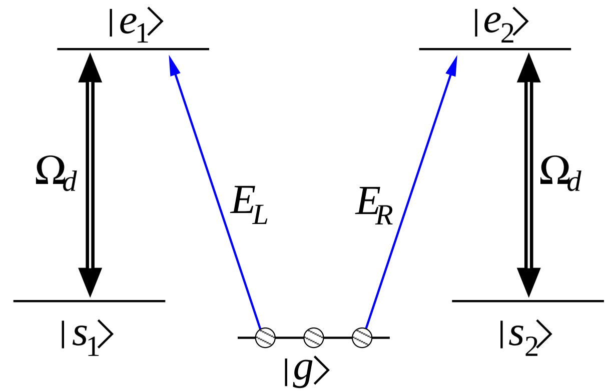


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- Rotate $\theta(t) \to \pi/2 \quad (\Omega_d(t) \to 0)$

  $\Rightarrow$ Photon is stopped and stored as superposition of $|s_1^{(1)}\rangle$ & $|s_2^{(1)}\rangle$

  $$|\psi(t)\rangle = \alpha\,|s_1^{(1)}\rangle + \beta\,|s_2^{(1)}\rangle$$ With low decoherence!

Fleischhauer, Mewes (2002); Mewes, Fleischhauer, PRA **72**, 022327 (2005)

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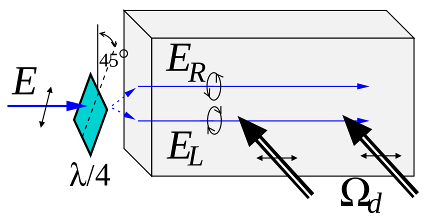


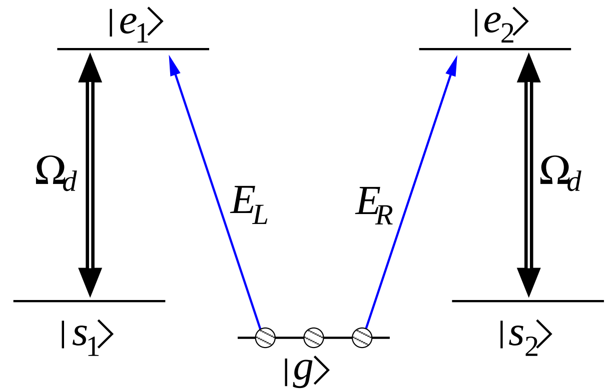


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  $\Rightarrow \; |\psi(0)\rangle \longrightarrow \alpha\,|R\rangle + \beta\,|L\rangle$

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  $$\boxed{|\psi(t)\rangle = \alpha\,|s_1^{(1)}\rangle + \beta\,|s_2^{(1)}\rangle}$$ With low decoherence!

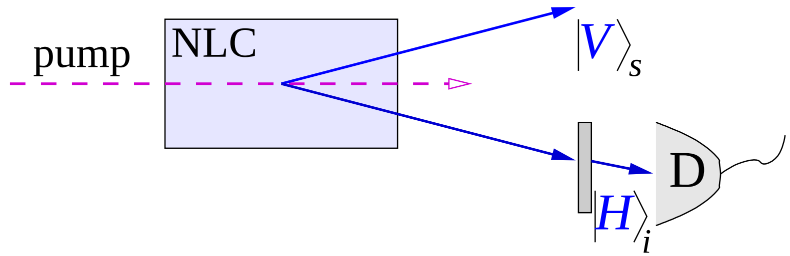
- Rotate $\theta(t') < \pi/2 \quad (\Omega_d(t') > 0)$

  $\Rightarrow$ Photon is released $|\psi(t')\rangle \longrightarrow \alpha\,|R\rangle + \beta\,|L\rangle$

Fleischhauer, Mewes (2002); Mewes, Fleischhauer, PRA **72**, 022327 (2005)

# Single-Photon Sources

# Parametric Down-Conversion

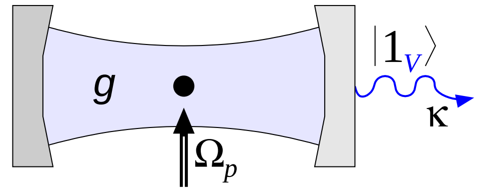


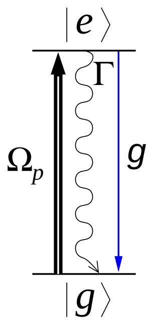

Pairs of P&M entangled photons

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left( |V\rangle_s |H\rangle_i + |H\rangle_s |V\rangle_i \right)$$

Detect *idler* in $|H\rangle_i \Rightarrow$ project *signal* onto $|V\rangle_s$

# Cavity QED



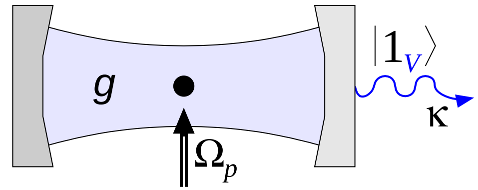



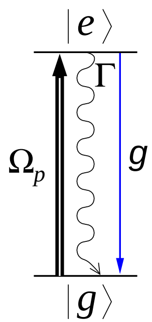

Two-Level System (atom, QD ...) with $\Gamma < g < \kappa$

Apply $\Omega_p T = \pi$ pulse $\Rightarrow$ single photon is emitted (Purcell effect)

Khitrova et al, Nature Physics **2**, 81 (2006)

# Cavity QED

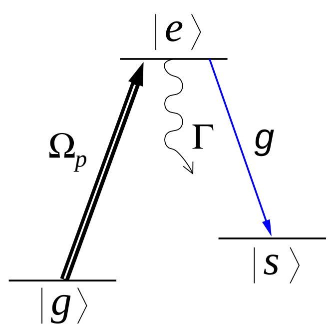



Two-Level System (atom, QD ...) with $\Gamma < g < \kappa$

Apply $\Omega_p T = \pi$ pulse $\Rightarrow$ single photon is emitted
(Purcell effect)

Khitrova et al, Nature Physics **2**, 81 (2006)




Three-Level System with $g > \kappa, \Gamma$

$$|D\rangle = \cos\theta\,|g,0\rangle - \sin\theta\,|s,1\rangle \quad \tan\theta = \frac{\Omega_p}{g}$$

Apply $\Omega_p$ adiabatic pulse $\Rightarrow$ single photon is emitted
(intracavity STIRAP)

Kuhn, Hennrich, Rempe, PRL **89**, 067901 (2002); McKeever et al, Science **303**, 1992 (2004)

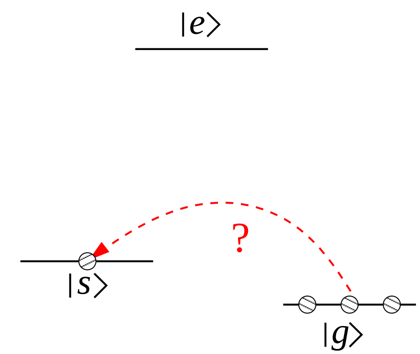
Requires high-$Q$ optical cavities

# EIT Based Single-Photon Sources

*i*) Create symmetric spin (Raman) excitation state

$$|s^{(1)}\rangle = \frac{1}{\sqrt{N}}\sum_{j=1}^{N} e^{i\delta k z_j}\,|g_1,\ldots,s_j,\ldots,g_N\rangle$$

$\Rightarrow\ |D_1(0)\rangle = |0\rangle\,|s^{(1)}\rangle$



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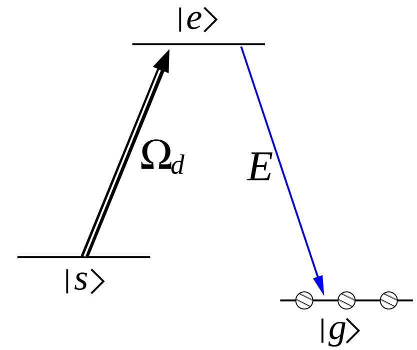


*ii*) Apply $\Omega_d \neq 0$ ($\theta < \pi/2$) & Release SPh WP

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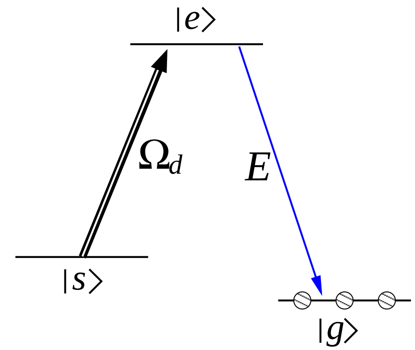


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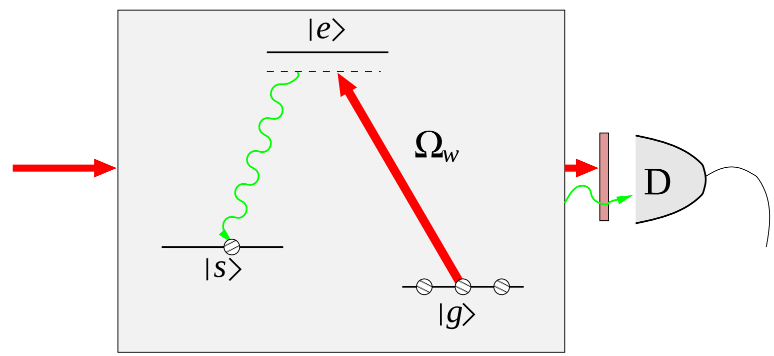
**Spontaneous Raman Scattering**

*i*) Apply *write* pulse $\Omega_w$ & detect forward scattered Stokes photon

$\Rightarrow$ Click of **D** corresponds to $|s^{(1)}\rangle$
(with $\delta k = k_w - k_s$)




Go to *ii*)

Duan et al, Nature **414**, 413 (2001); Kuzmich et al, Nature **423**, 731 (2003);
van der Wal et al, Science **301**, 196 (2003); Chou et al, PRL **92**, 213601 (2004);
Eisaman et al, PRL **93**, 233602 (2004); Eisaman et al, Nature **438**, 837 (2005)

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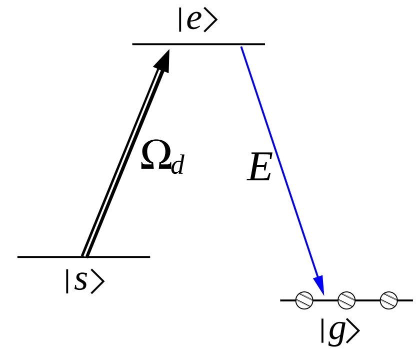



*ii*) Apply $\Omega_d \neq 0$ ($\theta < \pi/2$) & Release SPh WP

$\Rightarrow \left|D_1(t)\right\rangle \to \left|1\right\rangle \left|s^{(0)}\right\rangle$

## Dipole Blockade

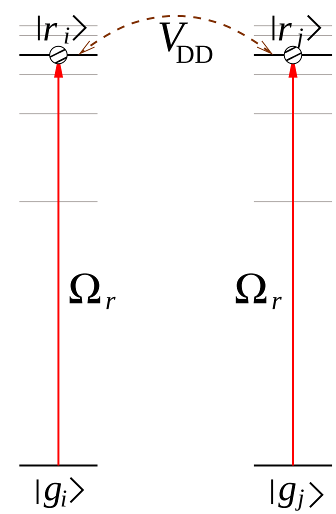
Pair of atoms $i, j$ in Rydberg states $\left|r\right\rangle$

$\Rightarrow$ Dipole-Dipole Interaction (anisotropic)

$$V_{\rm DD} = \hbar D(\mathbf{r}_i - \mathbf{r}_j) \left|r_i\, r_j\right\rangle\left\langle r_i\, r_j\right|$$

Resonant DDI (Förster process) + Static DDI (in dc E-field)

$$D(\mathbf{r}_i - \mathbf{r}_j) \approx -\frac{n^4 e^2 a_0^2}{\pi\hbar\epsilon_0 |\mathbf{r}_i - \mathbf{r}_j|^3}$$




Double-excitation is nonresonant

$P_{\rm double} \sim \frac{|\Omega_r|^2}{D^2} \ll 1$ if $\Omega_r < D$

# EIT Based Single-Photon Sources

*i*) Create symmetric spin (Raman) excitation state

$$|s^{(1)}\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i\delta k z_j} |g_1, \ldots, s_j, \ldots, g_N\rangle$$

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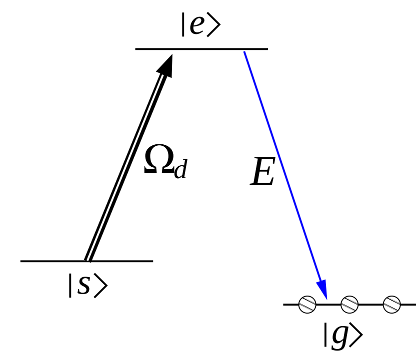


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$\Rightarrow\ |D_1(t)\rangle \to |1\rangle\, |s^{(0)}\rangle$

**Dipole Blockade**

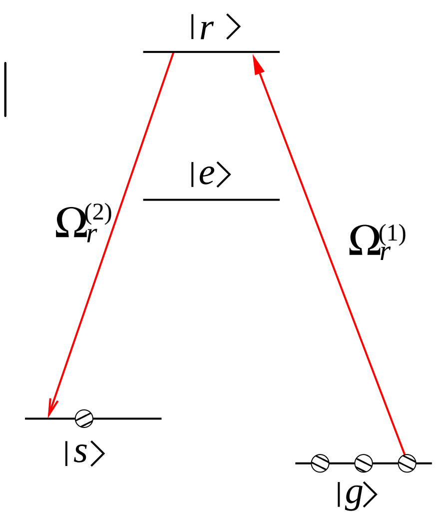
Atomic ensemble $V_{\rm DD} = \hbar \sum_{ij}^{N} D(\mathbf{r}_i - \mathbf{r}_j)\, |r_i\, r_j\rangle\langle r_i\, r_j|$

*i*) Apply $\Omega_r^{(1)}$ for $\sqrt{N}\Omega_r^{(1)} T_1 = \pi$ (collective $\pi$ pulse)

$\Rightarrow\ |s^{(0)}\rangle \equiv |g_1, g_2, \ldots, g_N\rangle \to$

$\to \frac{1}{\sqrt{N}} \sum_j e^{i k_r^{(1)} z_j} |g_1, \ldots, r_j, \ldots, g_N\rangle \equiv |r^{(1)}\rangle$

Single collective Rydberg excitation ($\sqrt{N}\Omega_r^{(1)} < \bar{D}$)

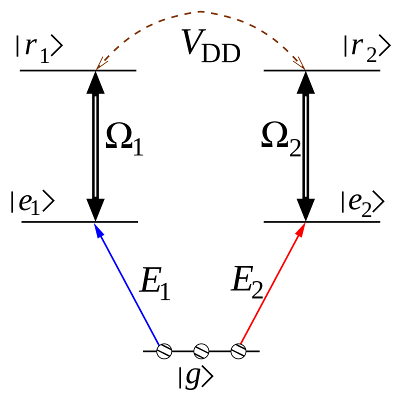


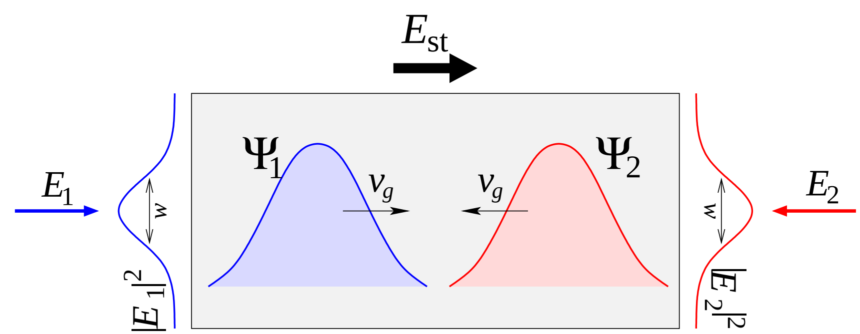

*i'*) Apply $\Omega_r^{(2)} T_2 = \pi \Rightarrow |r^{(1)}\rangle \to |s^{(1)}\rangle$ (with $\delta k = k_r^{(1)} - k_r^{(2)}$)

Go to *ii*)

Lukin et al, PRL **87**, 037901 (2001)

# Cross-Phase Modulation via Static DDI




Static $E_{\rm st}\mathbf{e}_z \Rightarrow$ Rydberg states $|r_i\rangle$ have large permanent dipole moments

$\wp_r \mathbf{e}_z = \frac{3}{2} n q e a_0 \mathbf{e}_z$ (Stark eigenstates)

$E_i \to \hat{\Psi}_i = \cos\theta \hat{\mathcal{E}}_i - \sin\theta\sqrt{N}\hat{\sigma}_{gr_i}$ $(i = 1, 2)$ propagate with $\pm v_g = c\cos^2\theta$

Atomic components of $\hat{\Psi}_i$ interact via Static DDI $\Rightarrow$ induces XPM

$$V_{\rm DD} = \hbar\rho^2 \iint {\rm d}^3 r\, {\rm d}^3 r' \hat{\sigma}_{rr}(\mathbf{r}) D(\mathbf{r} - \mathbf{r}') \hat{\sigma}_{rr}(\mathbf{r}')$$

$$D(\mathbf{r} - \mathbf{r}') = C\, \frac{1 - 3\cos^2\vartheta}{|\mathbf{r} - \mathbf{r}'|^3} \quad \text{with} \quad C = \frac{\wp_{r_l}\wp_{r_{l'}}}{4\pi\epsilon_0\hbar}$$

Resonant DDI (state mixing) is suppressed for $q = n - 1$, $m = 0$

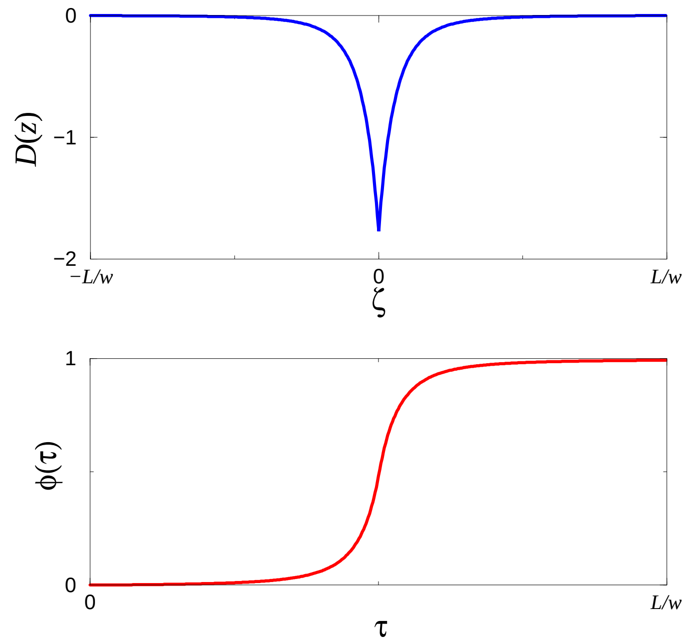
# Cross-Phase Modulation via Static DDI

- DD level shift [vs. $\zeta = (z - z')/w$]

$$D(z - z') = \frac{1}{\pi w^2} \int_0^{2\pi} \mathrm{d}\varphi' \int_0^{\infty} \mathrm{d}r'_\perp \, r'_\perp \, e^{-r'^2_\perp / w^2} D(z\mathbf{e}_z - \mathbf{r}')$$

- Phase shift [vs. $\tau = v_g t / w$]

$$\phi(z_1, z_2, t) = -\sin^4\theta \int_0^t \mathrm{d}t' D(z_1 - z_2 - 2v_g(t - t'))$$



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FORTH IESL

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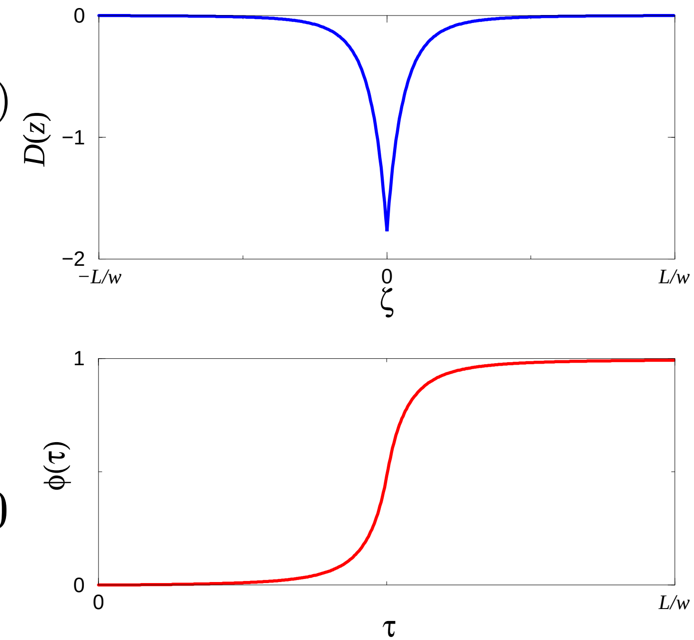


Initially $t=0$, $z_1 = 0$ & $z_2 = L \Rightarrow \phi(0, L, 0) = 0$

After the interaction $t = L/v_g$, $z_1 = L$ & $z_2 = 0$

$$\phi(L, 0, L/v) = -\frac{\sin^4\theta}{v_g} \int_0^L dz' D(2z' - L) = \frac{2C}{v_g w^2}$$

- Phase shift $\phi = \pi$

$\Rightarrow$ Universal CPHASE gate between SPh pulses $\hat{\mathcal{E}}_1$ & $\hat{\mathcal{E}}_2$

$$|x\rangle_1 |y\rangle_2 \to (-1)^{xy} |x\rangle_1 |y\rangle_2 \qquad (x, y \in [0,1])$$

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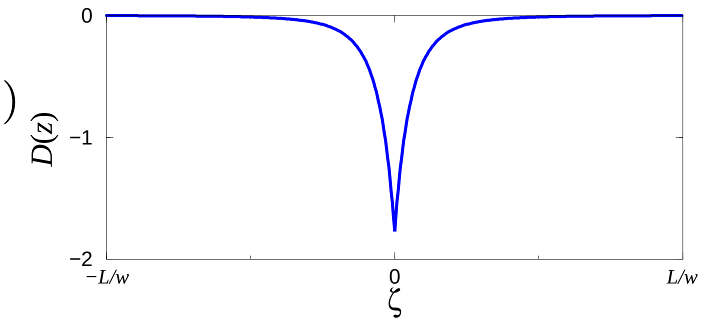


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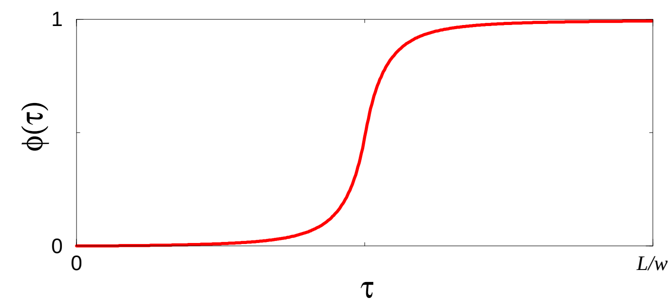


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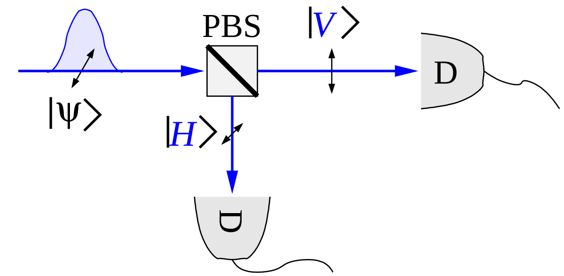
Advantages: Weak focusing ($w \sim 30\mu$m) & Uniform phase-shift

Friedler, Petrosyan, Fleischhauer, Kurizki, PRA **72**, 043803 (2005)

# Single Photon Detection

Single photon WP $|\psi\rangle = \alpha\,|V\rangle + \beta\,|H\rangle$ passes through PBS

$\Rightarrow$ $|V\rangle$ and $|H\rangle$ polarization components are directed into Photodetectors D




$\Downarrow$

Qubit Measurement Requires High-Efficiency Photodetectors

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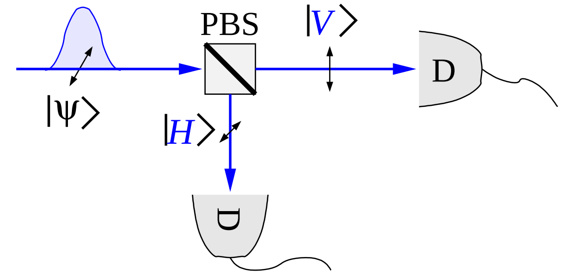


$\Downarrow$

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- Avalanche Photodetectors — quantum efficiency $\eta \lesssim 70\%$

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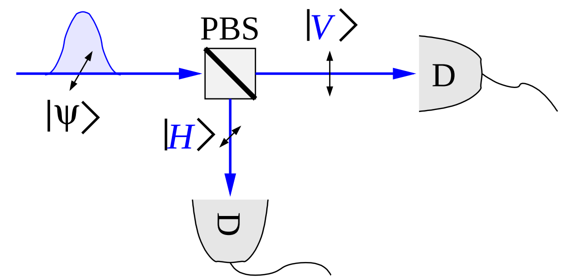
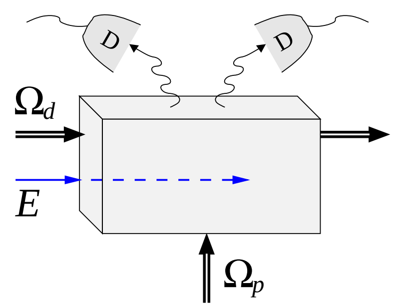


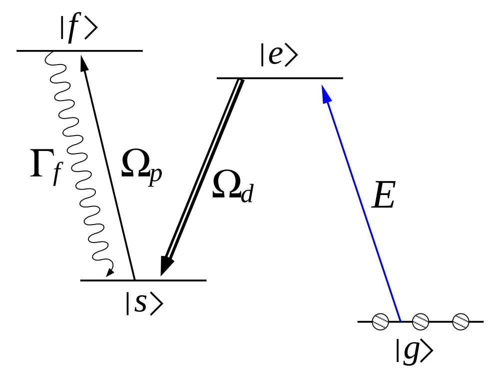

$\Downarrow$

Qubit Measurement Requires High-Efficiency Photodetectors

- Avalanche Photodetectors — quantum efficiency $\eta \lesssim 70\%$
- EIT based Photodetection — quantum efficiency $\eta \to 100\%$

*i*) Rotate $\theta(t) \to \pi/2$ ($\Omega_d(t) \to 0$)
$\Rightarrow$ Pulse is stopped
$|1^q\rangle\,|s^{(0)}\rangle \;\to\; |0^q\rangle\,|s^{(1)}\rangle$




*ii*) Apply pump $\Omega_p$ to
cycling transition $|s\rangle \to |f\rangle \Rightarrow R_f \simeq \frac{1}{2}\Gamma_f$

$\Rightarrow$ Collect fluor. with **D** ($\eta < 1$) for time $T$: $\boxed{S_f \simeq \frac{1}{2}\eta\Gamma_f T \gg 1}$

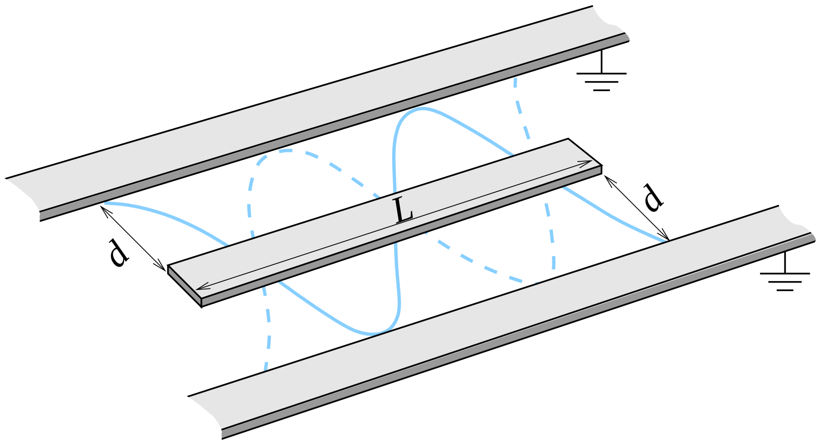
Imamoğlu, PRL **89**, 163602 (2002); James, Kwiat, PRL **89**, 183601 (2002)

# Atoms in Microwave CPW Resonator

Petrosyan, Fleischhauer, PRL **100**, 170501 (2008)

# The System

## Superconducting CPW resonator




Strip-line length $L \simeq 1$ cm and electrode distance $d \sim 15$ $\mu$m
$u(\mathbf{r}) = \cos(m\pi z/L)$ or $\sin(m\pi z/L)$ cavity mode function (1D)
with $m$ even or odd integer and $z \in [-L/2, L/2]$.

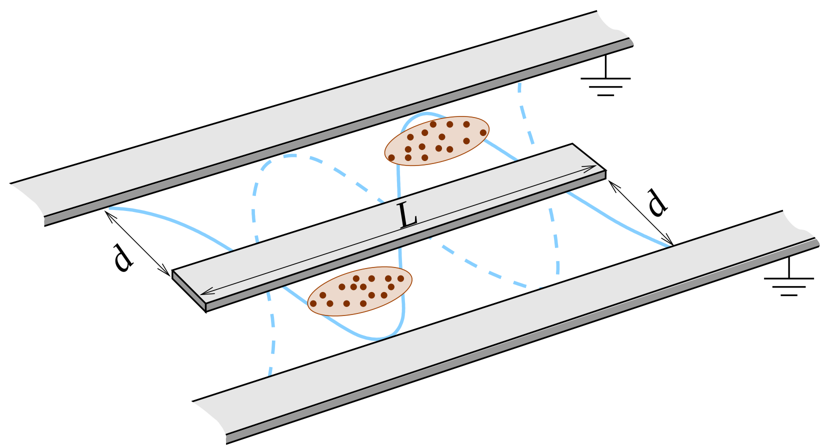
$m = 5$ ($m + 1$ field antinodes)
$\lambda_c = \frac{2L}{m} \simeq 4$ mm and $\omega_c = \frac{2\pi c}{\lambda_c \sqrt{\epsilon_r}} \simeq 2\pi \times 30$ GHz

$Q \simeq 10^6 \Rightarrow$ photon decay rate $\kappa = \frac{\omega_c}{Q} \simeq 200$ KHz

Blais et al., PRA **69**, 062320 (2004); Majer et al., Nature **449**, 443 (2007)

# The System

## Ensembles of cold ground-state atoms trapped near field antinodes

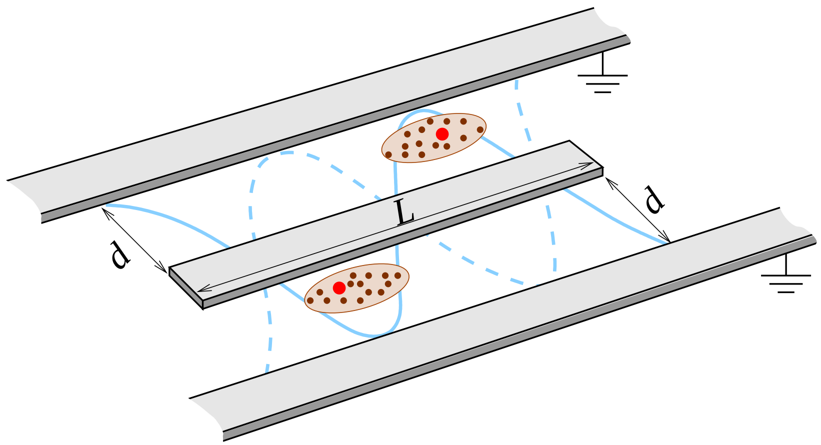


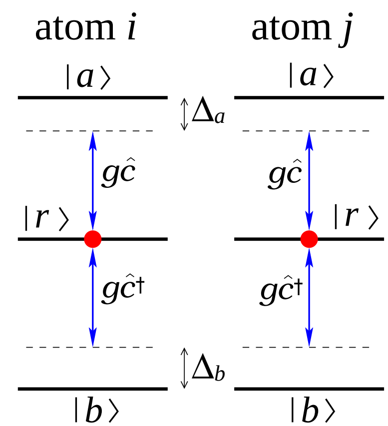

Atom density $\rho_a \sim 2 \times 10^{13}$ cm$^{-3}$ trap volume $V_a \sim d \times d \times \lambda_c/20$

$N = \rho_a V_a \sim 10^6$ atoms in each ensemble

# The System

## Excited Rydberg atoms $i$ & $j$ interact via common cavity mode




Hamiltonian for atom $i$ + atom $j$ + cavity field:

$$H = \hbar \sum_{l=i,j} [(\Delta_a \hat{\sigma}^l_{aa} - \Delta_b \hat{\sigma}^l_{bb}) + (g^l_{br} \hat{c}^\dagger \hat{\sigma}^l_{br} + g^l_{ar} \hat{c}\, \hat{\sigma}^l_{ar} + \text{H.c.})]$$

$\Delta_a = \omega_{ar} - \omega_c$ and $\Delta_b = \omega_{rb} - \omega_c$ detunings

$\hat{\sigma}^l_{\mu\nu} = |\mu_l\rangle\langle\nu_l|$ atomic transition operator $\quad \hat{c}$, $\hat{c}^\dagger$ cavity field operators

$g^l_{\mu\nu} = -\frac{\wp_{\mu\nu}}{\hbar} \varepsilon_c u(\mathbf{r}_l)$ atom-field coupling ($g^l_{br} \approx g^l_{ar} \equiv g_r$)

$\varepsilon_c = \sqrt{\frac{\hbar\omega_c}{\epsilon_0 2\pi d^2 L}}$ field per photon in the cavity

Atomic dipole matrix elements $\wp \propto n^2 a_0 e \Rightarrow g_r \sim 2\pi \times 10$ MHz (for $n \sim 50$)

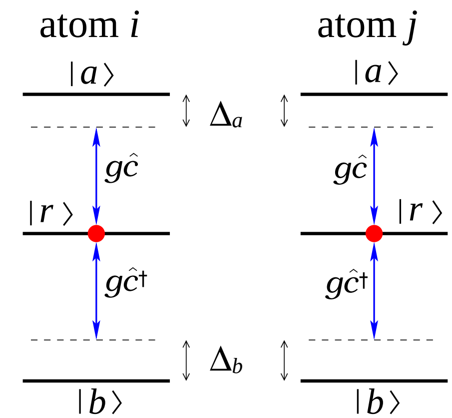
# Resonant Dipole-Dipole Interaction

$$\Delta_{a,b} \simeq g_r f \gg g_r \quad (f \gg 1)$$

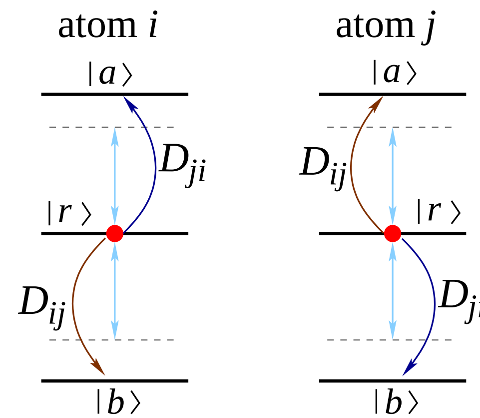
- $|r_i\rangle\,|r_j\rangle\,|0_c\rangle \to |r_{i,j}\rangle\,|b_{j,i}\rangle\,|1_c\rangle$ (1Ph) nonresonant
- $|r_i\rangle\,|r_j\rangle\,|0_c\rangle \to |a_{i,j}\rangle\,|b_{j,i}\rangle\,|0_c\rangle$ (2Ph) resonant

  (ac Stark compensated: $\Delta_a - \Delta_b + s_a^{i,j} - s_r^i - s_r^j = 0$)

$\Downarrow$



# Resonant Dipole-Dipole Interaction




Effective cavity-mediated RDDI between atoms $i$ and $j$

**Effective Hamiltonian** (2nd-order in $g_r$):

$$V_{ij}^{(2)} = \hbar D_{ij} \left( \hat{\sigma}_{br}^{i} \hat{\sigma}_{ar}^{j} + \hat{\sigma}_{ar}^{i} \hat{\sigma}_{br}^{j} \right) + \mathrm{H.c}$$

$D_{ij} = \frac{g_{br}^{i} g_{ar}^{j}}{\Delta_b} = \frac{g_{ar}^{i} g_{br}^{j}}{\Delta_b} = \frac{g_r}{f} \equiv D$ — RDDI constant

# Resonant Dipole-Dipole Interaction

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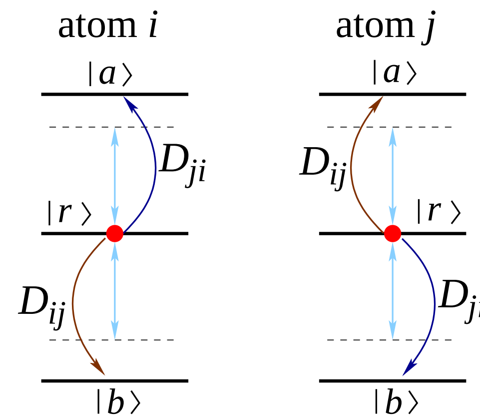


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**Eigenstates of** $V_{ij}^{(2)}$

$$|\psi_{ij}^{0}\rangle = \frac{1}{\sqrt{2}} \left( |b_i\rangle |a_j\rangle - |a_i\rangle |b_j\rangle \right) \qquad \lambda_0 = 0$$

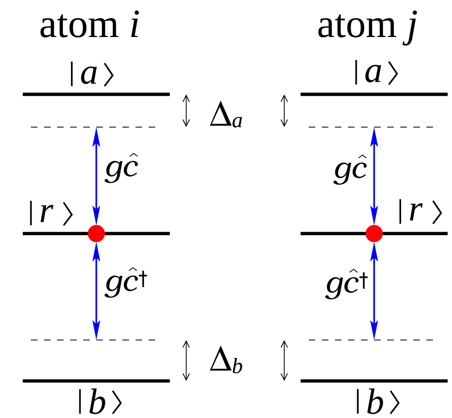
$$|\psi_{ij}^{\pm}\rangle = \frac{1}{\sqrt{2}} |r_i\rangle |r_j\rangle \pm \frac{1}{2} \left( |b_i\rangle |a_j\rangle + |a_i\rangle |b_j\rangle \right) \qquad \lambda_{\pm} = \pm \hbar \sqrt{2} D_{ij}$$

# Van der Waals Interaction

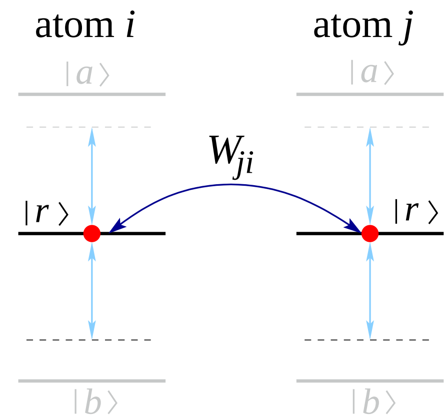
$$\boxed{\Delta_a \simeq g_r(f-1) \quad \& \quad \Delta_b \simeq g_r f \qquad (f \gg 1)}$$

- 1ph and 2ph transitions nonresonant

$\Downarrow$



# Van der Waals Interaction




Effective cavity-mediated VdWI between atoms $i$ and $j$

**Effective Hamiltonian** (4th-order in $g_r$):

$$V_{ij}^{(4)} = \hbar\, \hat{\sigma}_{rr}^{i} W_{ij} \hat{\sigma}_{rr}^{j}$$

$W_{ij} = \frac{2|g_{br}^{i} g_{br}^{j}|^2}{\Delta_b^3} - \frac{2|g_{br}^{i} g_{ar}^{j}|^2}{(\Delta_a - \Delta_b)\Delta_b^2} = \frac{4g_r}{f^3} \equiv W$ — WdVI constant

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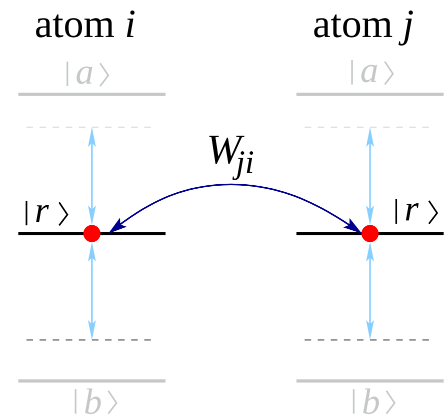


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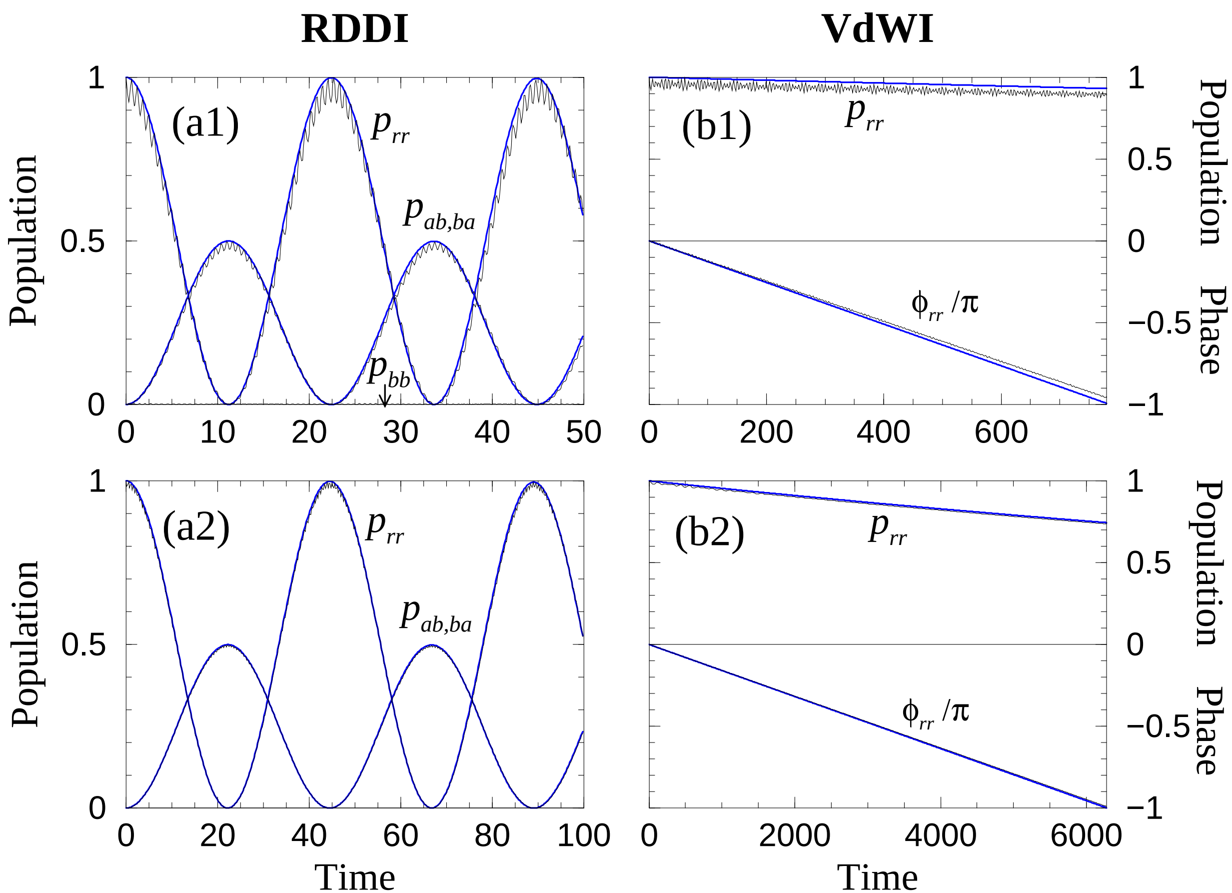
**Evolution due to** $V_{ij}^{(4)}$

$$|r_i\rangle \, |r_j\rangle \rightarrow e^{i\phi_{rr}(t)} \, |r_i\rangle \, |r_j\rangle \quad \phi_{rr}(t) = Wt$$

# Numerical Simulations

**Dynamics of Rydberg atoms $i$ , $j$ in CPW cavity,** $|\Phi(0)\rangle = |r_i\rangle |r_j\rangle |0_c\rangle$




(a1),(b1) $f = 10$

(a2),(b2) $f = 20$

$p_{\mu\nu}$ populations of $|\mu_i\rangle |\nu_j\rangle$  $\phi_{rr}$ phase-shift of $|r_i\rangle |r_j\rangle$

"—": ME simulations for the full system using Hamiltonian $H$

"—": ME simulations for the effective Hamiltonians $V_{ij}^{(2)}$ and $V_{ij}^{(4)}$

# Applications of RDDI

**Intracavity Dipole Blockade** $[D = 2\pi \times 1$ MHz $(f = 10)]$

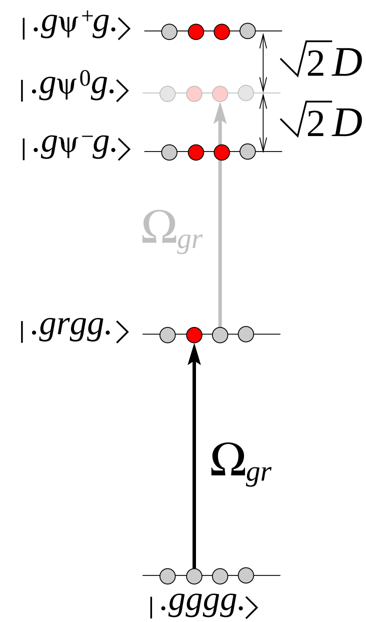
$\langle rg | \, \hat{\sigma}_{gr} \Omega_{gr} \, |\psi^0\rangle = 0$ & $\Omega_{gr} < D \quad \Rightarrow$

Single Rydberg excitation of atomic ensemble by $\Omega_{gr}$

(effective $\pi$-pulse: $\sqrt{N}\Omega_{gr}T_1 = \frac{\pi}{2}$)

$$\boxed{\;|s^{(0)}\rangle \rightarrow \; |r^{(1)}\rangle\;}$$

$$|s^{(0)}\rangle \equiv \; |g_1, g_2, \ldots, g_N\rangle \qquad |r^{(1)}\rangle \equiv \frac{1}{\sqrt{N}} \sum_i e^{i\mathbf{k}_{gr}\cdot\mathbf{r}_i} \; |g_1, \ldots, r_i, \ldots, g_N\rangle$$



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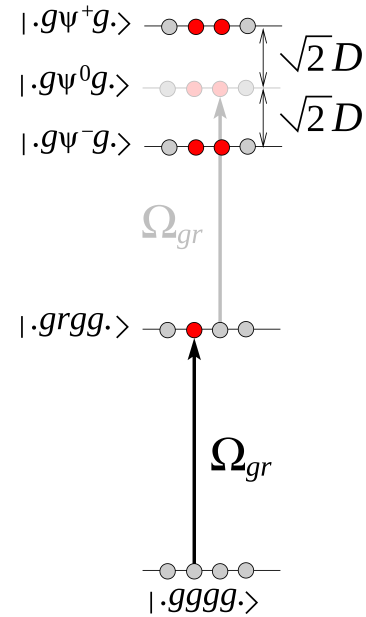


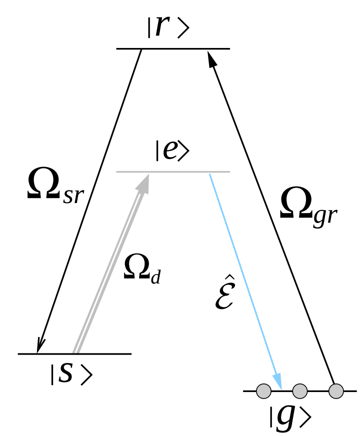

## Single Photon Generation

- Apply $\Omega_{sr}$ ($\pi$-pulse: $\Omega_{sr}T_2 = \frac{\pi}{2}$)

$$\left|r^{(1)}\right\rangle \rightarrow \left|s^{(1)}\right\rangle$$

$|s^{(1)}\rangle \equiv \frac{1}{\sqrt{N}} \sum_i e^{i\delta\mathbf{k}\cdot\mathbf{r}_i} |g_1, \ldots, s_i, \ldots, g_N\rangle$

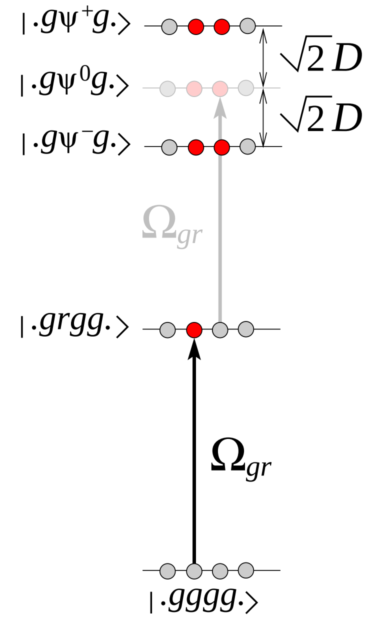
single collective Raman excitation of atomic ensemble (equivalent to EIT stored single photon)




- Turn on $\Omega_d \rightarrow$ release single photon pulse $\hat{\mathcal{E}}$

# Applications of RDDI

**Intracavity Dipole Blockade** $[D = 2\pi \times 1$ MHz $(f = 10)]$

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(effective $\pi$-pulse: $\sqrt{N}\Omega_{gr}T_1 = \frac{\pi}{2}$)

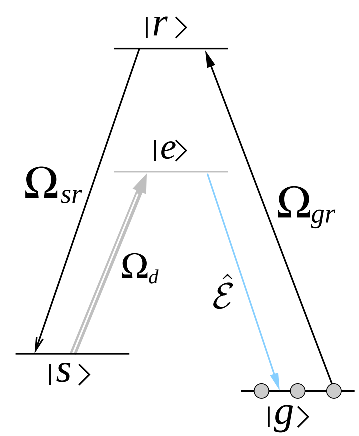
$$\boxed{|s^{(0)}\rangle \rightarrow |r^{(1)}\rangle}$$

$$|s^{(0)}\rangle \equiv |g_1, g_2, \ldots, g_N\rangle \quad |r^{(1)}\rangle \equiv \frac{1}{\sqrt{N}} \sum_i e^{i\mathbf{k}_{gr}\cdot\mathbf{r}_i} |g_1, \ldots, r_i, \ldots, g_N\rangle$$

## Entangling two (or more) ensembles $A$ and $B$

- Apply $\Omega_{gr}$ simultaneously to $A$ and $B$ ($\sqrt{2N}\Omega_{gr}T_1 = \frac{\pi}{2}$)
- Apply $\Omega_{sr}$ ($\pi$-pulse: $\Omega_{sr}T_2 = \frac{\pi}{2}$)

$$\Rightarrow \frac{1}{\sqrt{2}}\left( |s^{(1)}\rangle_A |s^{(0)}\rangle_B + |s^{(0)}\rangle_A |s^{(1)}\rangle_B \right)$$



# Applications of VdWI

**Dispersive phase shift** $[W = 2\pi \times 40$ KHz $(f = 10)]$

$$\boxed{|r\rangle\,|r\rangle \rightarrow e^{i\phi(t)}\,|r\rangle\,|r\rangle \quad \phi(t) = Wt}$$

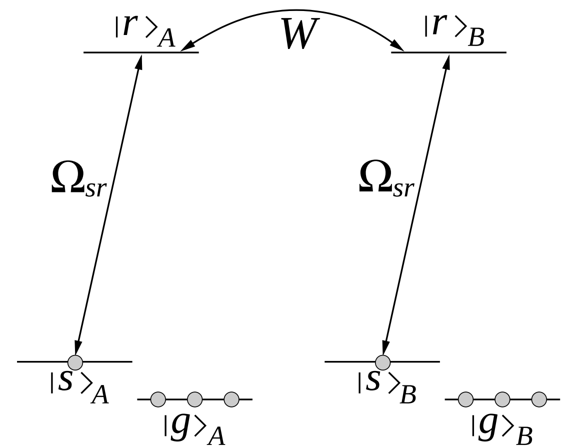
# Applications of VdWI

**Dispersive phase shift** $[W = 2\pi \times 40$ KHz $(f = 10)]$

$$|r\rangle\,|r\rangle \rightarrow e^{i\phi(t)}\,|r\rangle\,|r\rangle \quad \phi(t) = Wt$$

Ensemble qubits $A, B, \ldots$ in states

$|\psi\rangle_q = \alpha_q\,|s^{(0)}\rangle_q + \beta_q\,|s^{(1)}\rangle_q$




- Apply $\Omega_{sr}$ to $A$ & $B$ ($\Omega_{sr}T_1 = \frac{\pi}{2}$):

$$|s^{(1)}\rangle_{A,B} \longrightarrow |r^{(1)}\rangle_{A,B}$$

- Phase-shift $\phi = WT_\pi = \pi$ (during $T_\pi = \pi/W$)

- Apply $\Omega_{sr}$ again ($\Omega_{sr}T_2 = \frac{\pi}{2}$):

$$|r^{(1)}\rangle_{A,B} \longrightarrow |s^{(1)}\rangle_{A,B}$$

$\Rightarrow$ Universal CPHASE gate between ensemble qubits $A$ & $B$

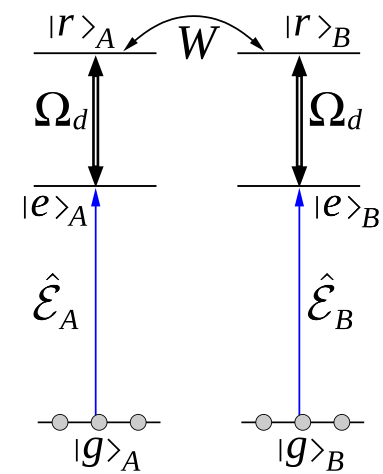
$$|s^{(x)}\rangle_A\,|s^{(y)}\rangle_B \rightarrow (-1)^{xy}\,|s^{(x)}\rangle_A\,|s^{(y)}\rangle_B \qquad (x, y \in [0, 1])$$

# Applications of VdWI

**Dispersive phase shift** $[W = 2\pi \times 40$ KHz $(f = 10)]$

$$|r\rangle|r\rangle \rightarrow e^{i\phi(t)}|r\rangle|r\rangle \quad \phi(t) = Wt$$

Photonic qubits $A, B, \ldots$ in states
$|\psi\rangle_q = \alpha_q|0\rangle_q + \beta_q|1\rangle_q$




- EIT dark-state polaritons in ensembles $A$ & $B$

$$\Psi_{A,B} = \cos\theta\,\hat{\mathcal{E}}_{A,B} - \sin\theta\sqrt{N}\hat{\sigma}_{gr}^{A,B}$$

- Phase shift $\phi = WT_{\text{int}} = \pi \quad (T_{\text{int}} = \frac{L_a}{v_g}$, $v_g = c\cos^2\theta \ll c)$

$\Rightarrow$ Universal CPHASE gate between photonic qubits $A$ & $B$
$|x\rangle_A|y\rangle_B \rightarrow (-1)^{xy}|x\rangle_A|y\rangle_B \qquad (x, y \in [0, 1])$

# Summary

Scalable and efficient quantum computation with photonic qubits requires:

- Deterministic sources of single-photons (qubit initialization)
- Reversible photon storage (static qubits)
- High-fidelity logic gates between flying/static qubits
- Reliable state detection

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Scalable and efficient quantum computation with photonic qubits requires:

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- Reliable state detection

EIT based (or related) techniques can implement these requirements
$\Longrightarrow$ Deterministic all-optical quantum computation & communication may become possible