Storing and manipulating quantum information using atomic ensembles

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Introduction: Rev. Mod. Phys. 75, 457 (2003)

Plan:

- Basic concepts and ideas
  - ✓Application of quantum optics techniques
  - ✓ Some mathematics
  - ✓ Relation of cavity QED & collective enhancement
- Examples of current research:

✓ Quantum state manipulation of atoms and photons
via Raman scattering & photo-detection

✓ Towards enhanced nonlinear optics with stationary pulses
of light in atomic medium

✓ Application in condensed matter:
nuclear spin ensembles in quantum dots

Quantum coherence: linear vs nonlinear systems

- Most non-trivial task in quantum information processing:
  - ✓Coherent manipulation of coupled, interacting, non-linear (unharmonic) systems, e.g. qubits

- Harmonic (linear) systems are often used:
  - ✓to mediate interactions between qubits
  - ✓to store quantum states of qubits

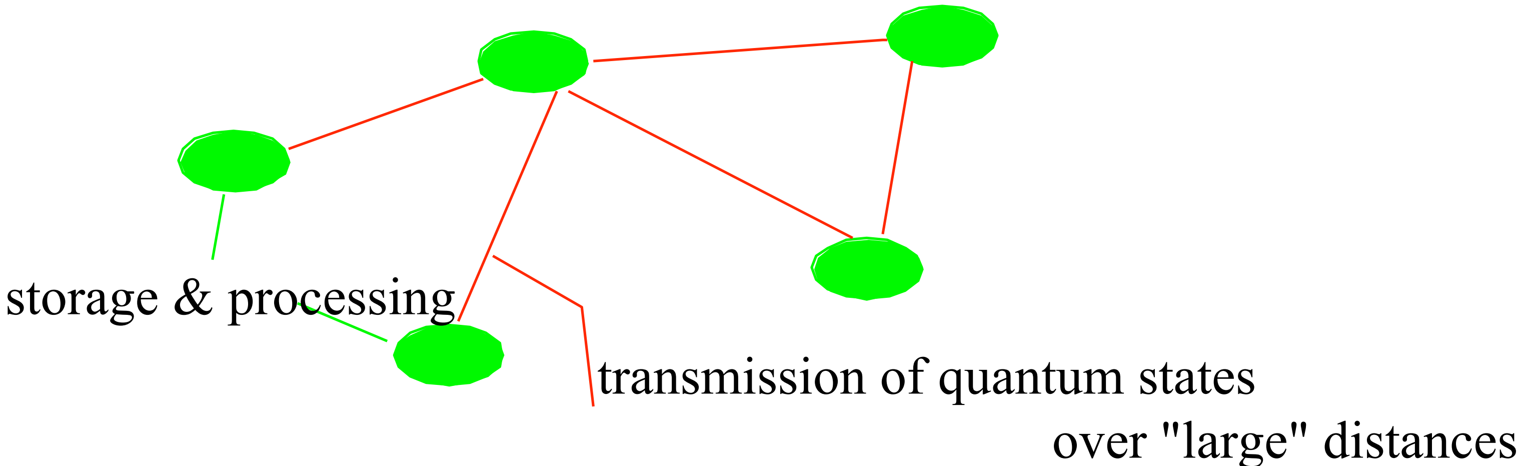
- Examples: cavity QED (two level atom + one mode of radiation)
  ion trap (ion spin + mode of center of mass motion)
  superconductors (Cooper pair box + mode of voltage)

- Note:
  (large) nonlinearity or quantum measurement is required to make the system behave quantum mechanically

This talk

✓ new tools for coherent localization, storage and processing of light signals

- Specifically quantum networks & quantum communication …



storage & processing

transmission of quantum states over "large" distances

… need new tools:

✓photons for communication, matter for storage
✓interface for reversible quantum state exchange between light and matter
✓compatible methods to produce, manipulate …non-classical states

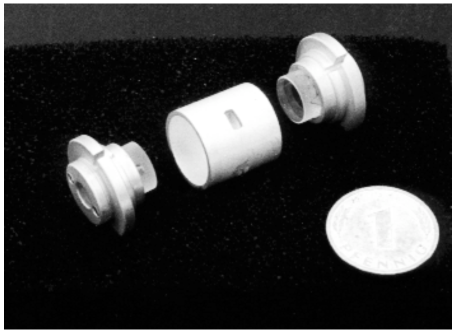
Ongoing efforts

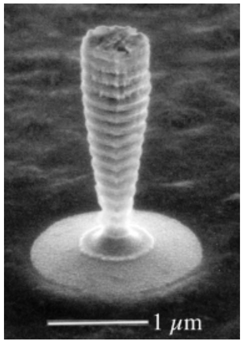
- Use single atoms for memory and absorb or emit a photon in a controlled way

Cirac, Zoller, Mabuchi,Kimble, PRL 78, 3221 (1997)

- ✓ Problem: single atom absorption cross-section is tiny (~ λ^2)
- ✓ Cavity QED: fascinating (but also very difficult) experiments

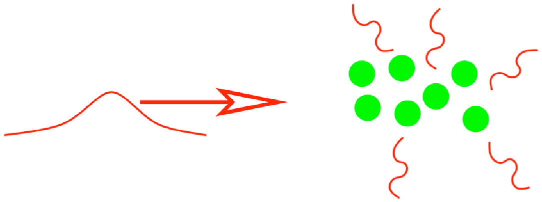
S.Haroche (ENS)
H.Walther (MPQ)
J.Kimble (Caltech)
G.Rempe (MPQ)
Y.Yamamoto (Stanford)





+ new ideas: cavity QED on a chip

- Photons interact strongly with large ensembles of atoms

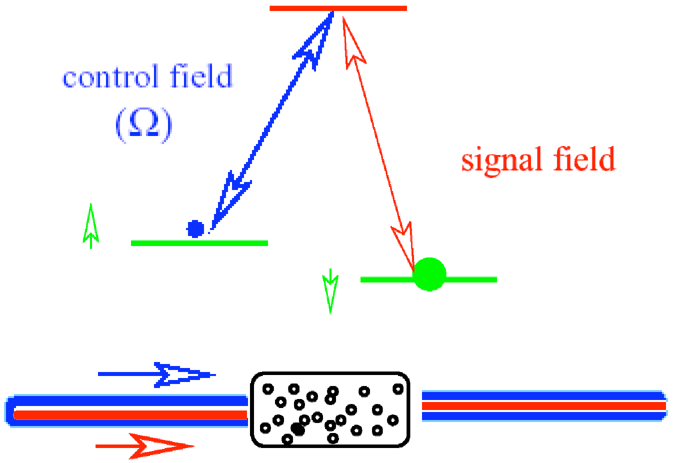


… but usual absorption does not preserve coherence

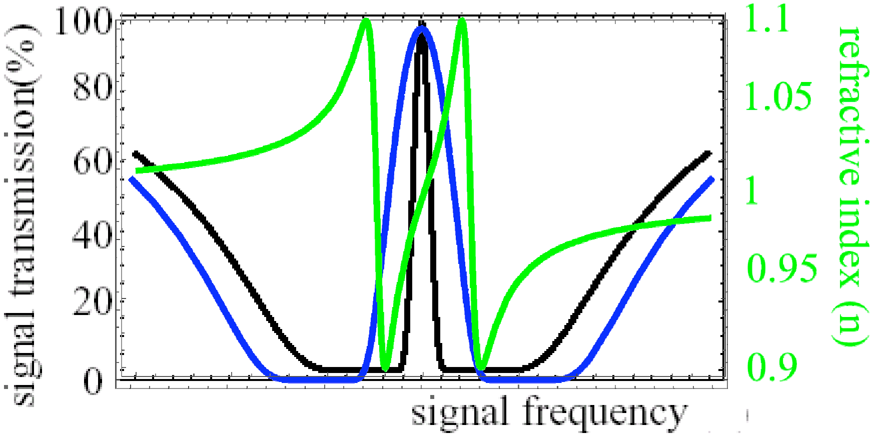
- ✓ Main challenge: coherent control of resonant optical properties
  - "force" the atoms behave the way we want!

Electromagnetically Induced Transparency

- coherently controlled, optically dense medium



- spin coherence causes destructive interference in absorption

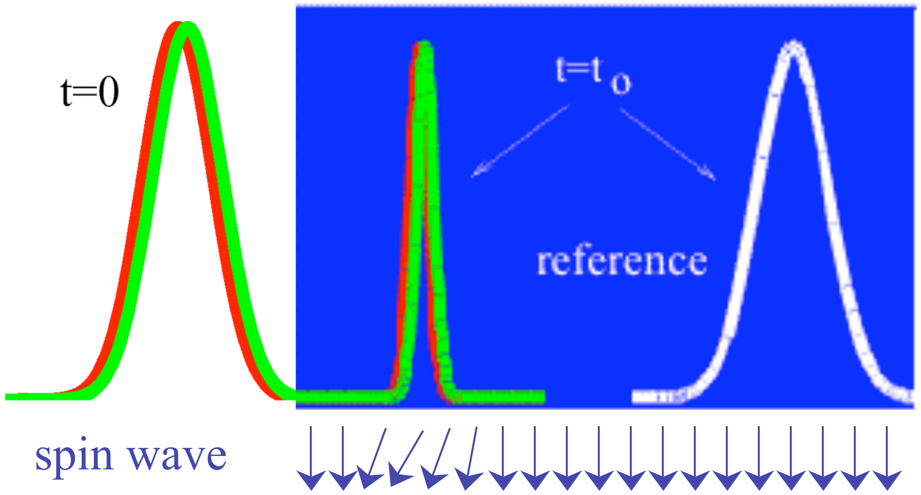


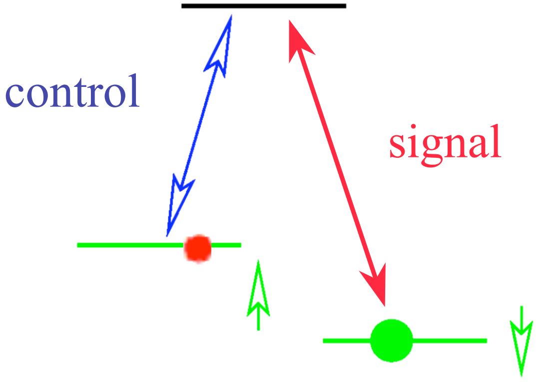
- very small the stronger the
  group velocity v_g is

Boller,Imamoglu, Harri

Early work: Alzetta, Arimondo, Eberly, Bergman, Harris, Kocharovskaya, Mandel, Scully, Imamoglu
“slow light” experiments: L.Hau et al (1999)

Essence of EIT: strong, coherent coupling of photons and atoms





Coupled propagation of photonic and spin wave: “dark state polaritons”

$$\hat{\Psi} = \cos\theta\,\hat{a} - \sin\theta\,\hat{S}_-$$

photons spins

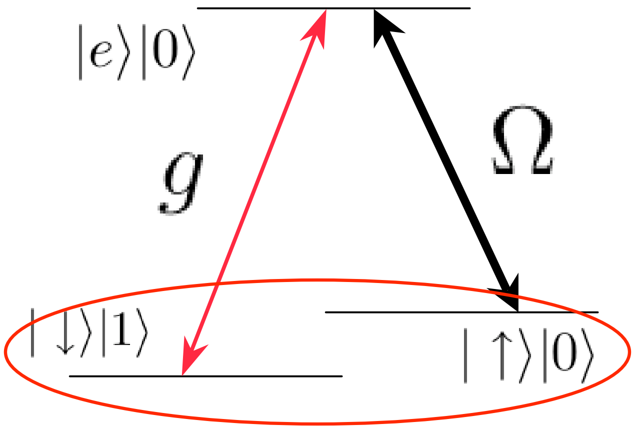
$$\cos^2\theta = \frac{v_g}{c} = \frac{\Omega^2}{\Omega^2 + g^2 N}$$

✓Strongly coupled excitations of light and spin wave slowly propagate together

… and can be manipulated

Dark states for quantum fields: a toy model

✓ One atom interacting with one mode of quantum field + one classical field



$$H = ga|\downarrow\rangle\langle e| + |\uparrow\rangle\langle e|\Omega + h.c.$$

✓ $|\mathbf{g}\rangle = |\downarrow\rangle|n=0\rangle$ not affected: $H|\downarrow\rangle|0\rangle = 0$

✓Consider $\Psi = \cos\theta\; a - \sin\theta|\downarrow\rangle\langle\uparrow|$

$$[H,\Psi] = 0,\ \text{if}\ \tan\theta = \frac{\Omega}{g}$$

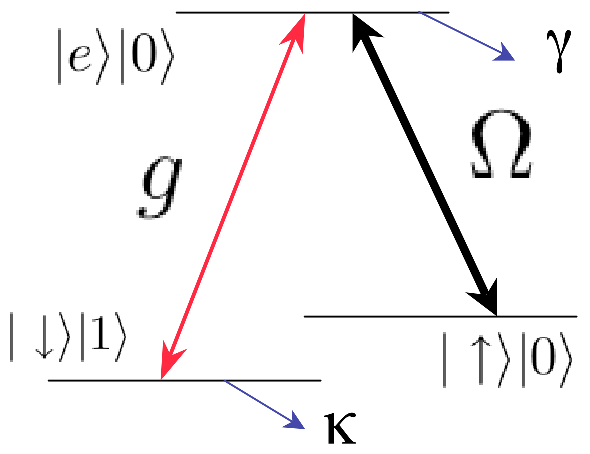
✓ Ψ^+creates dark state : $H\Psi^+|\mathbf{g}\rangle = 0$

✓The idea: adiabatic change of Ω allows to reversibly convert photon state into atomic spin state, i.e. map photonic into atomic qubits

(early work P. Zoller et al 93-97)

Conditions for coherent dynamics

✓ Implementation of one atom + one mode system: cavity QED



✓Two decay channels:

$$\begin{aligned} H_{eff} &= ga|\downarrow\rangle\langle e| + |\uparrow\rangle\langle e|\Omega + h.c. \\ &+ i\frac{\gamma}{2}|e\rangle\langle e| + i\frac{\kappa}{2}a^{+}a \end{aligned}$$

✓Jump probability:

$$p \sim \int_0^T [\gamma\rho_{ee}(\tau) + \kappa\rho_{11}(\tau)]d\tau$$

✓Depend on passage time T: $p \sim \frac{\gamma}{g^2T} + \kappa T \to \sqrt{\frac{\gamma\kappa}{g^2}}$

Physics (Purcell condition): $\boxed{\frac{g^2}{\kappa\gamma} \sim \frac{\lambda^2}{A} \times F \gg 1}$

beam area

cavity finess

Dark states for quantum fields: system of N atoms

✓ N atoms interacting with one mode of quantum field + one classical field

$$H = ga\sum_{i=1}^{N} |\downarrow\rangle_i\langle e| + \sum_{i=1}^{N} |\uparrow\rangle_i\langle e|\Omega + h.c.$$

$$|\mathbf{g}\rangle = |\downarrow_1 \ldots \downarrow_N\rangle|n=0\rangle$$

$$\Psi = \cos\theta\ a - \sin\theta\ S,\ \text{where } S = \frac{1}{\sqrt{N}}\sum |\downarrow\rangle_i\langle\uparrow|$$

$$[H,\Psi] = 0,\ \text{if}\ \tan\theta = \frac{\Omega}{g\sqrt{N}}$$

- Create family of dark states $H(\Psi^+)^n|\mathbf{g}\rangle = 0$

  ✓couple to collective spin states $(S^+)^n|\mathbf{g}\rangle$

  ✓coupling strength enhanced $g \to g\sqrt{N}$

  ✓for low n<<N, correspond to bosonic excitations $[S, S^+] \approx 1$

Bottom line: photons interacting with N-atom system

✓ Coherent rate of interactions enhanced (collective enhancement):

$$\frac{g^2 N}{\gamma\kappa} \sim L/L_{abs} \gg 1$$

✓Light now couples to collective excitations which have harmonic spectrum

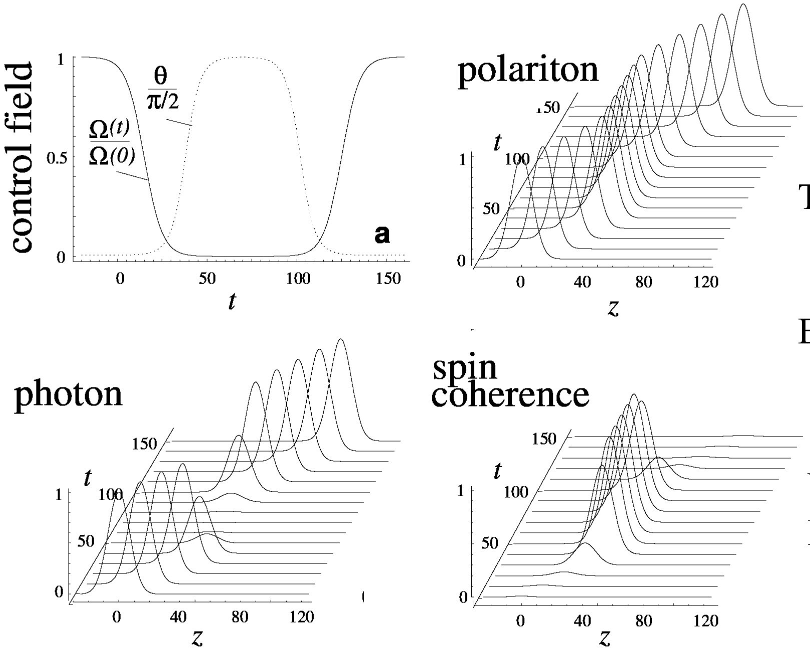
✓N.B. Extension to multimode case straightforward

$$S_k = \sum_i |\downarrow\rangle_i\langle\uparrow| \exp(ikz_i), \ \ \Psi_k = cos\theta a_k - sin\theta S_k$$

$$[cos^2\theta \frac{\partial}{\partial z} + \frac{\partial}{\partial t}]\Psi = 0$$

“Photon trap”: coherent quantum state transfer between light and atoms

- Adiabatic passage in coupled excitations (“dark-state polaritons”)



Theory: Fleischhauer, Yelin, Lukin
PRL, 84, 4232 (2000),
PRL, 84, 5094 (2000)

Expts (weak classical pulses):
Liu et al, Nature 409, 490 (2001)
Phillips et al, PRL 86 783 (2001)

undergrad physics lab:
PHYS 191 @ http://physics.harvard.edu

- Light wave is coherently converted into a spin wave i.e. absorbed in a coherent way!
- Storage time is limited by spin coherence lifetime
- Retrieval by turning on control field

- Linear optical technique: no change in quantum statistics (ideally)
- No light is present after the pulse is stopped

Quantum control of light and atomic ensembles

- Need: techniques for creating & manipulating quantum states of photons or spin waves at a level of single quanta

Two approaches

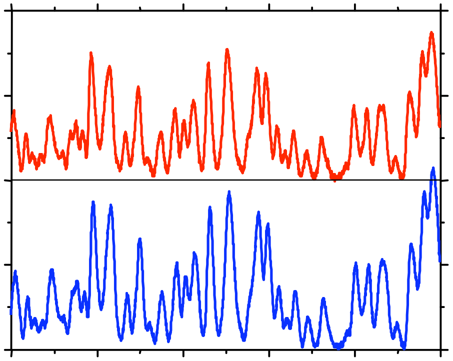
✓ Use weak nonlinearity and quantum measurement

- Atomic and photonic state preparation via Raman scattering
  (weak nonlinearity and quantum measurement)

✓ [illegible]

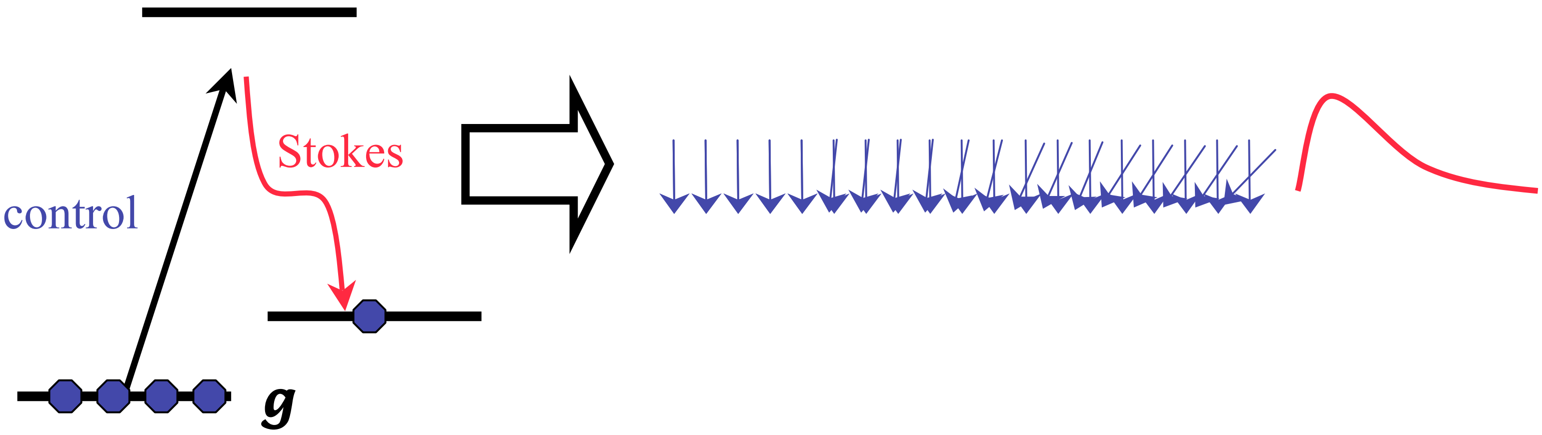
- [illegible]
- [illegible]
  [illegible]

Manipulating quantum states via Raman scattering & quantum measurements



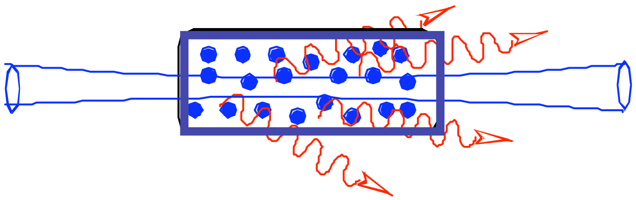
Atom-photon correlations in Raman scattering

- Absorption of pump photon produces a pair of flipped spin and Stokes photon



- Flipped spins and Stokes photons are strongly correlated:
  when *n* Stokes photons emitted *n* spins are flipped

- Spontaneous Stokes photons have arbitrary direction



- ...but each emitted photon is uniquely correlated with a well defined spin-wave mode due to momentum conservation

$$\hbar k_{Pump} = \hbar k_{Stokes} + \hbar k_{Spin}$$

Blombergen,Raymer

Raman preparation of atomic ensemble

- Raman process produces pairs of spins flips and photons:

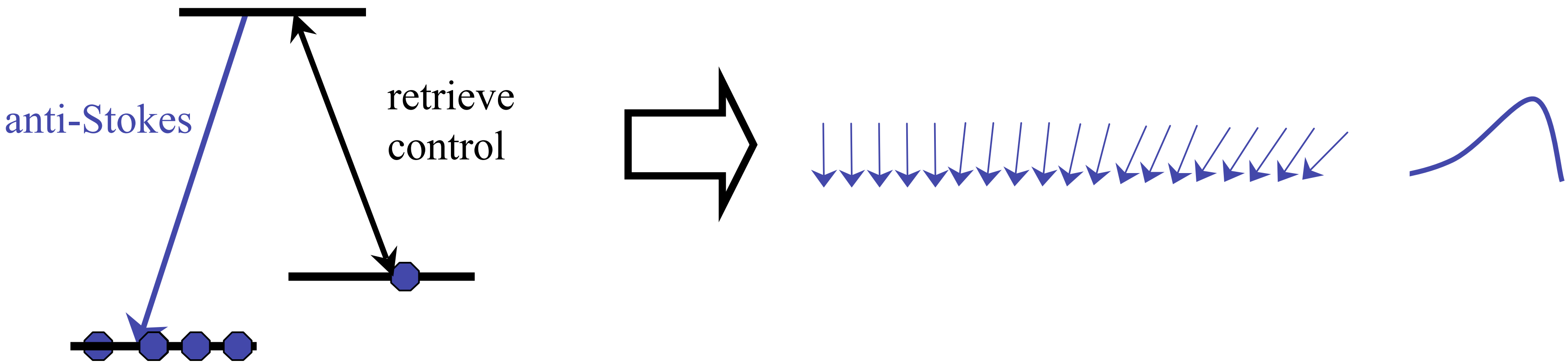
$$H = \frac{g\sqrt{N}\Omega_w}{\Delta} a_k^+ S_k^+ + h.c.$$

- Stokes field and spin wave undergo mutual growth and become entangled:

$$|\mathrm{state}\rangle \sim |g\rangle + \lambda|\uparrow^1\rangle|n_s = 1\rangle + \lambda^2|\uparrow^2\rangle|n_s = 2\rangle + \ldots$$

- Quantum measurement can be used to prepares the state of atomic ensemble: detecting *n* Stokes photons in certain mode "projects" atomic state with exactly *n* excitations in a well-defined mode

Retrieving the state of spin wave



- Stored state can be converted to polariton and then to anti-Stokes photon by applying resonant retrieve control beam
- Retrieval beam prevents re-absorption due to EIT

controls propagation properties of the retrieved (anti-Stokes) pulse

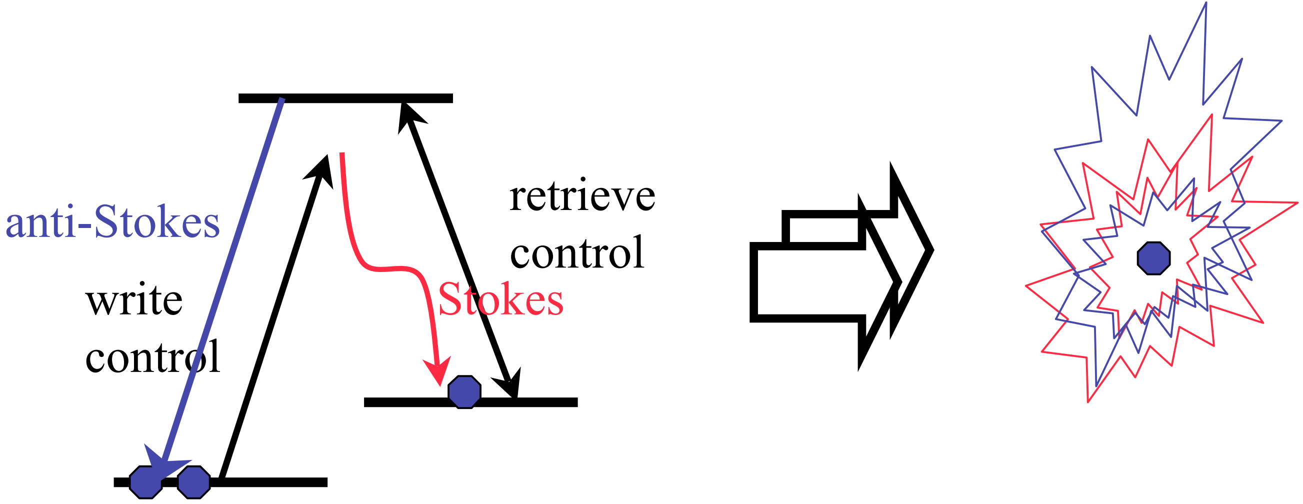
✓ Source of quantum-mechanically Stokes and anti-Stokes photons analogous to “twin beams” in parametric downconverters

but with build-in atomic memory!

Duan et al , Nature 414, 413 (2001)
Andre, Duan, MDL, PRL 88 243602 (2002)
early work: MDL, Matsko, Fleischhauer, Scully PRL (1999)

Single atoms vs atomic ensembles

- Single atom case



- In atomic ensemble:

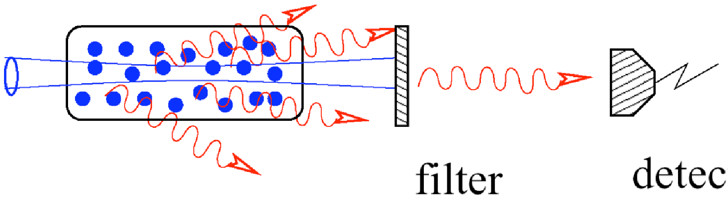
✓ we don't know which particular spin flips: collective states are excited

✓ collective states store all quantum correlations, allow for readout via polaritons, directionality, pulse shaping as long as spin coherence is preserved!

Applications of Raman quantum state manipulation

- Shaped single photon and number-squeezed light source:

  detecting ***n*** photons in a certain mode of Stokes light selects a spin-wave mode and "projects" its state to a Fock state.



✓Stored state can be converted to anti-Stokes photons with defined timing, direction

first experimental results: see L.Childress poster

- Instead of detection Stokes photon can be converted into flipped spins:

  controlled atom interactions

  Andre, Duan, Lukin, PRL 88 243602 (2002)

  Sorensen & Molmer, Phys.Rev.A (2003)

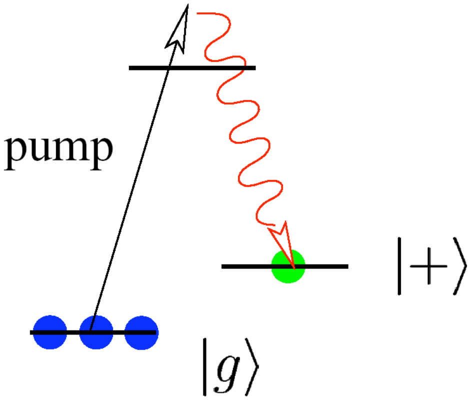
- Long distance quantum communication in lossy channels:

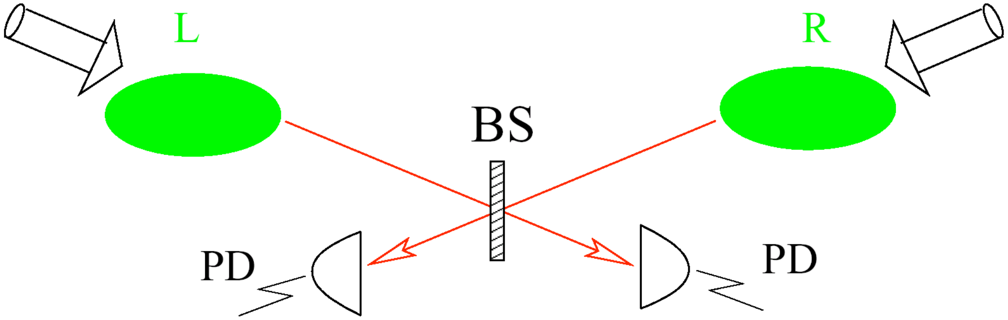
  "quantum repeater" techniques

  Duan, Lukin, Cirac and Zoller, Nature 414, 413 (2001)

Entanglement generation between atomic ensembles via Raman scattering and photodetection

- Simultanoues Raman scattering from two ensembles





- After interference at BS it is impossible to determine where Stokes photon came from: results in an entangled state of two ensembles

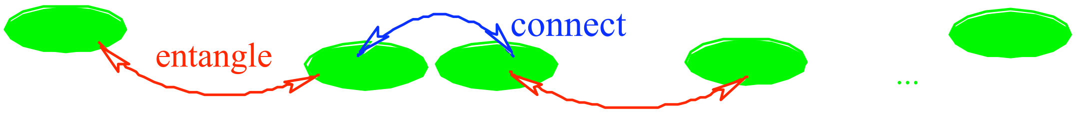
$$|\Psi\rangle_{LR} \sim e^{-L/L_{abs}}|g\rangle_L|1_+\rangle_R + e^{-L/L_{abs}}|1_+\rangle_L|g\rangle_R$$

(an example of "probabilistic" entanglement)

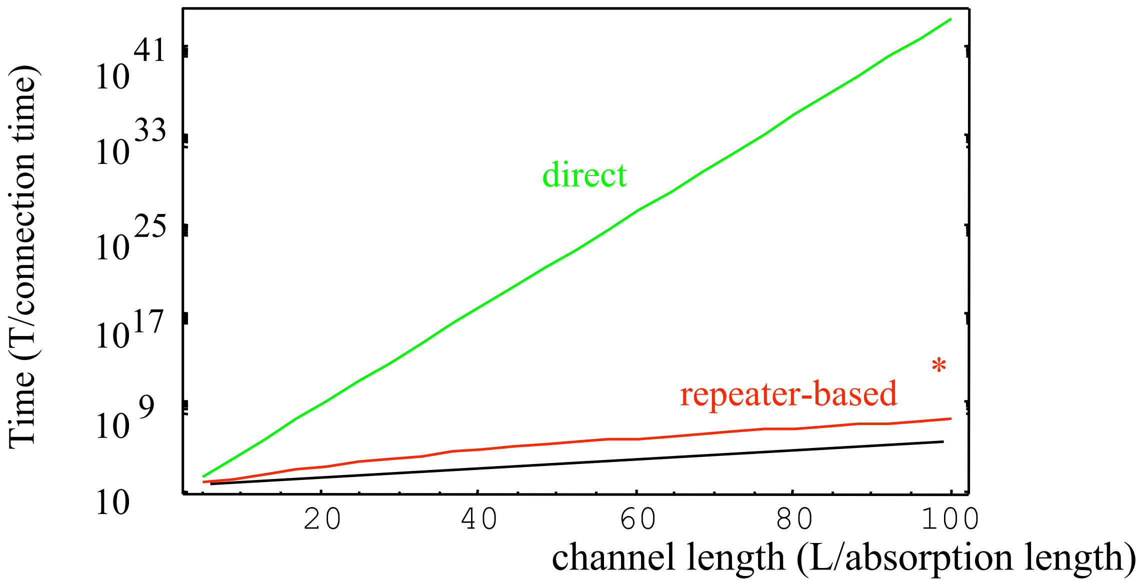
- Remarkably the same state will be created even in the presence of photon losses, provided those are equal in different arms

Application: quantum communication over long distances

- Technique can be cascaded over multiple nodes to correct common errors with only Raman scattering, storage & retrieval and linear optics



- Bottom line: "quantum repeater" for long-distance entanglement generation



* efficiency of storage + detection ~ 50 % is assumed

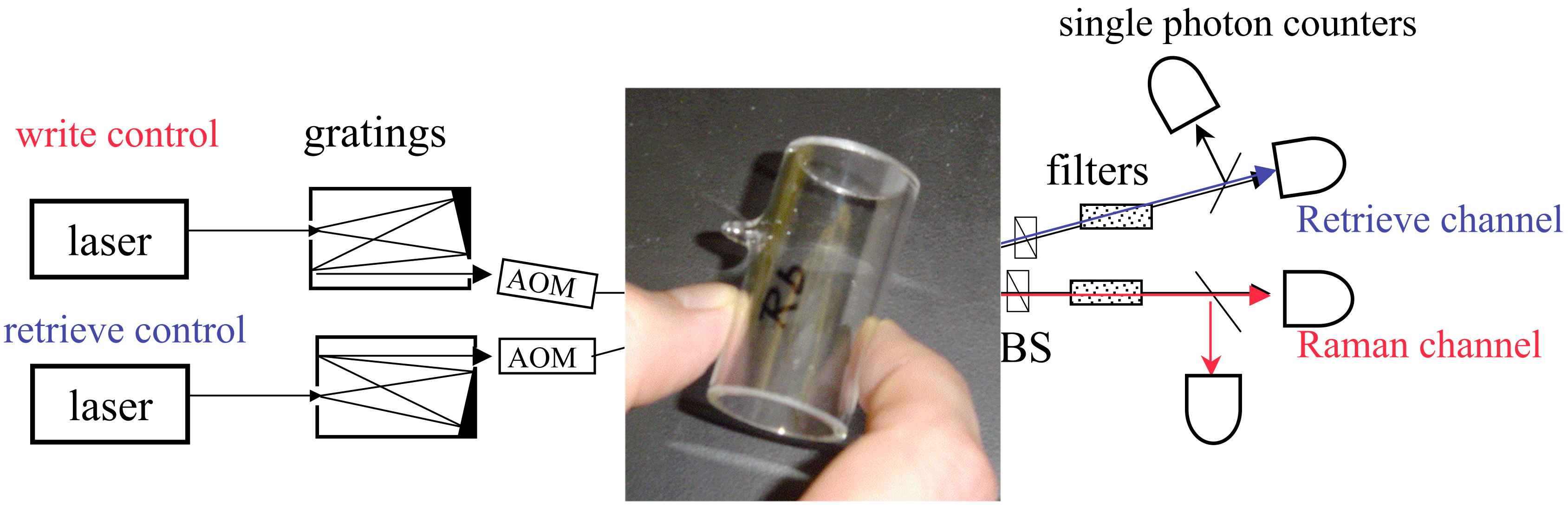
Duan, Lukin, Cirac and Zoller, Nature 414, 413 (2001)

✓ Can allow quantum cryptography, teleportation … over long distances

See also B.Blinov et al, Nature, in press

Experimental progress: shaping quantum pulses of light via atomic memory

- ✓ Goal: generate (anti-Stokes) pulses of light with well-defined number of photons, timing, shapes, direction



single photon counters

write control

gratings

laser

AOM

retrieve control

laser

AOM

filters

Retrieve channel

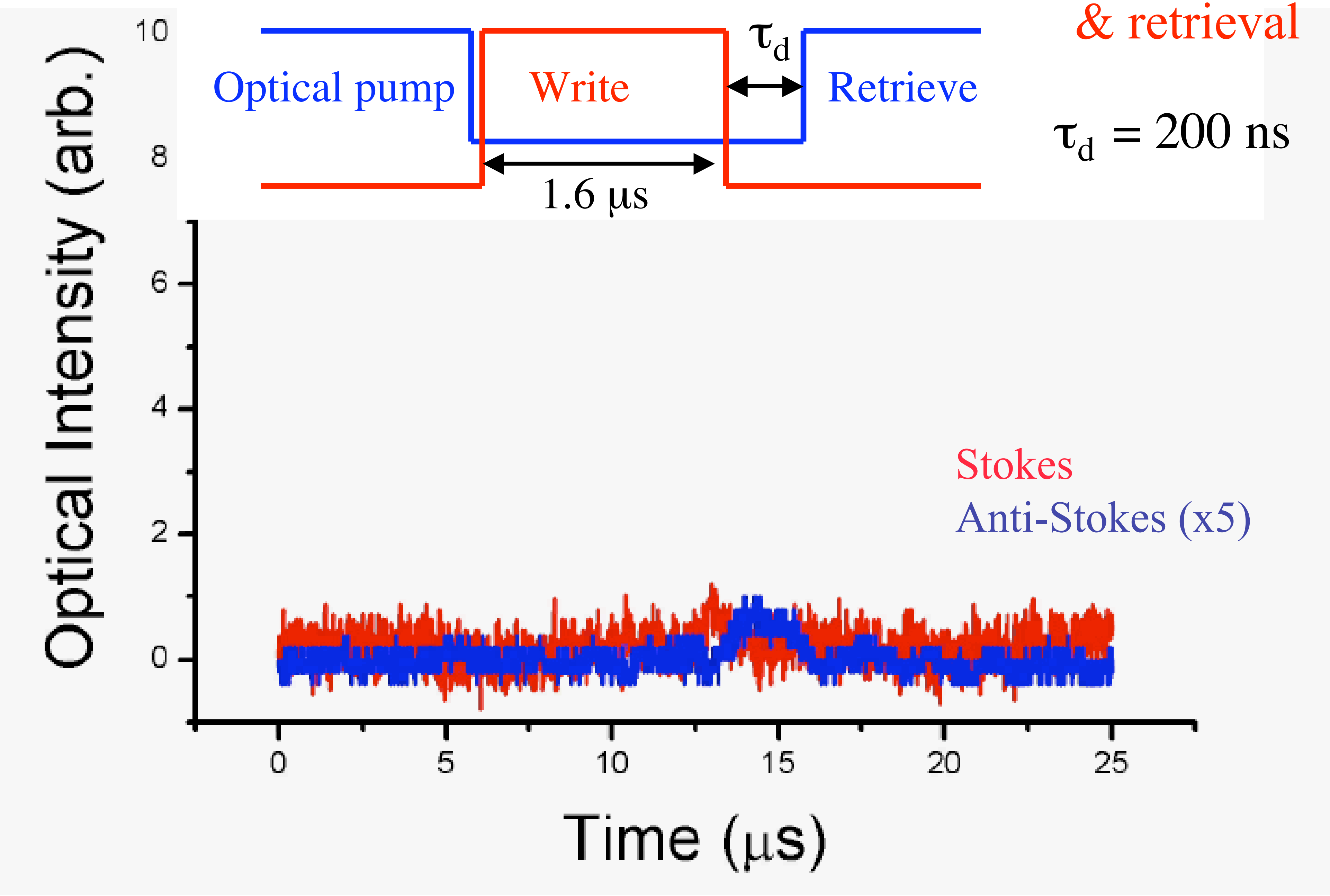
BS

Raman channel

- ✓ medium: $N\sim10^{10}$ Rb atoms + buffer gas, hyperfine states for storage, Raman frequency difference 6.8 GHz
- ✓ implementation: long-lived memory allows to make pulses long compared to time resolution of single photon counters

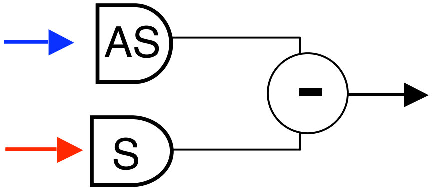
Early work: C.van der Wal et al., Science, 301, 196 (2003)
A.Kuzmich et al., Nature, 423, 731 (2003)

Example: (classical) correlations in Raman preparation & retrieval

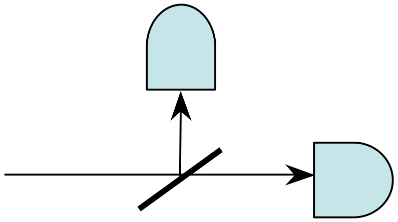


τ_d = 200 ns

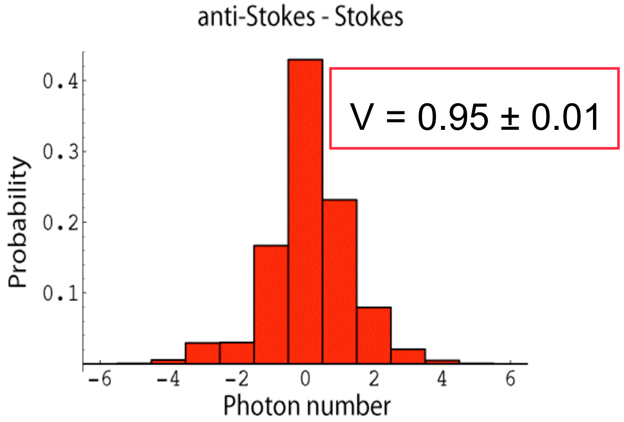
Non-classical correlations in preparation and retrieval



compare with



50-50 beamspliter



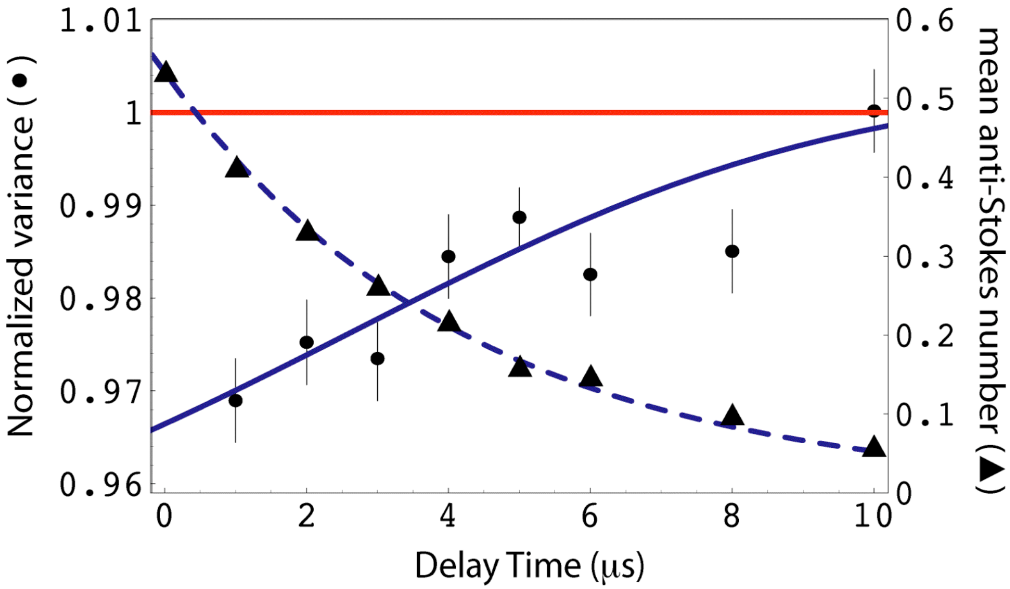
$$V = \frac{\text{variance of difference}}{\text{photon shot noise}}$$

< 1 nonclassical

$= 0$ ideal correlations

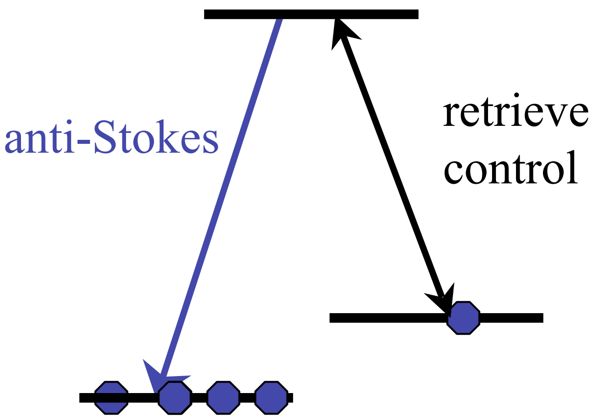
- Vary the delay time between preparation and retrieval

✓ $V > 0$ due to imperfections (loss and background)



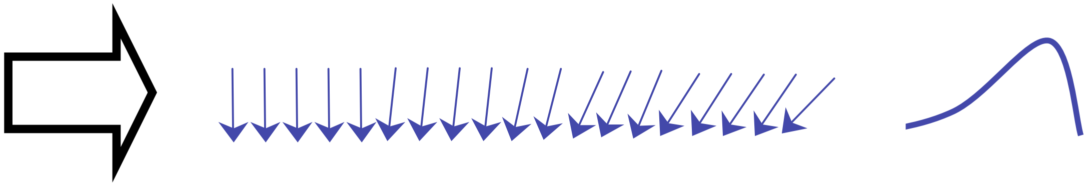
✓Nonclassical correlations exist within spin coherence time

Example of quantum control: shaping few-photon pulses

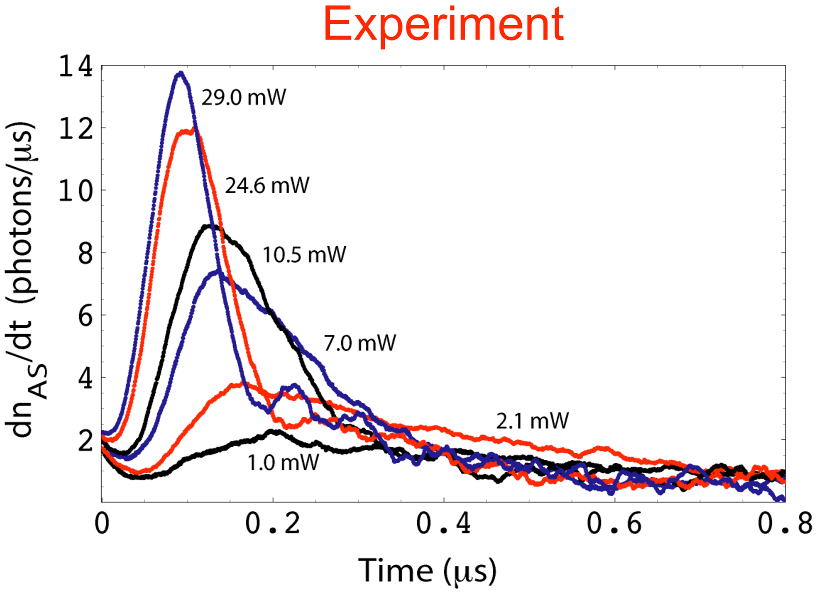


anti-Stokes

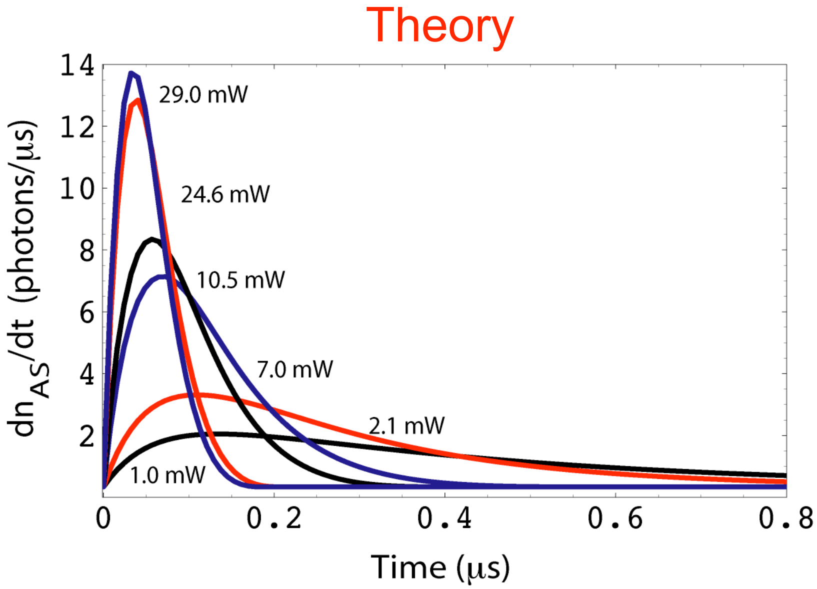
retrieve
control



- Idea: rate of retrieval (polariton velocity)
  is proportional to control intensity



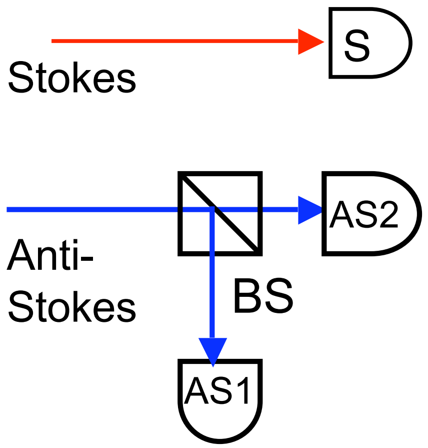
Experiment



Theory

✓ Duration, shape of retrieved pulses controllable

Conditional preparation of non-classical pulses

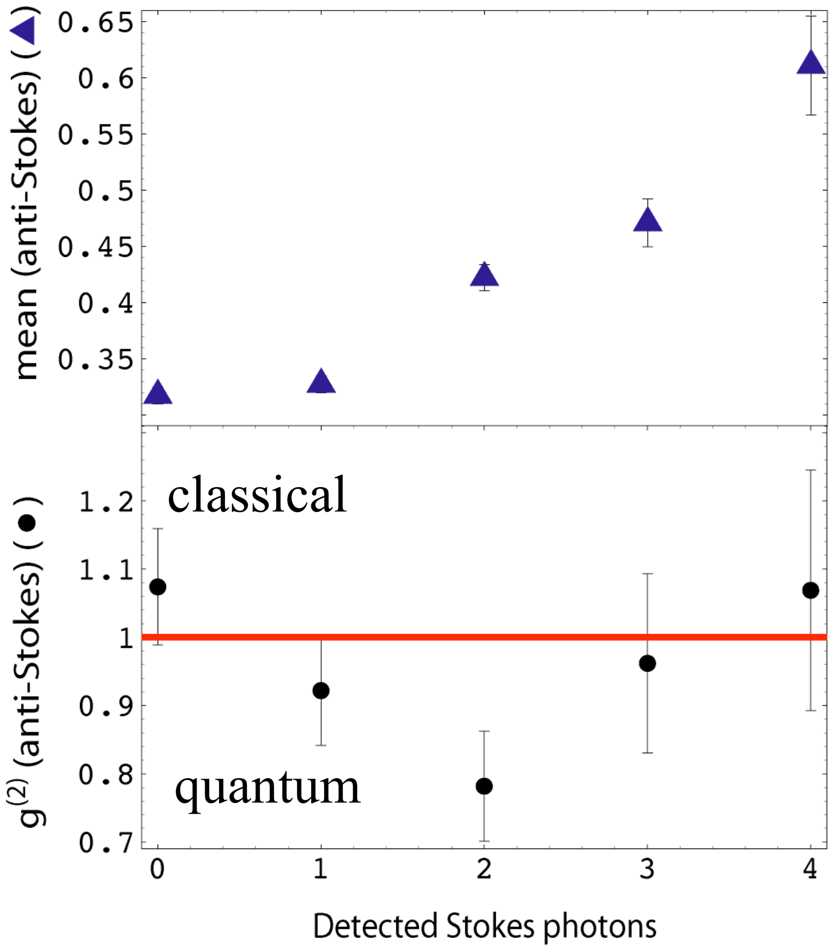


Condition on n_S Stokes photons

Measure fluctuations of the anti-Stokes photons

$g^{(2)}$ (AS) = ‹AS1•AS2›/ ‹AS1›‹AS2›

≥ 1	classical
< 1	quantum
= 1 - 1/n	Fock state



✓Conditional generation of few-photon light pulses with suppressed intensity fluctuations ; current limitations: losses and background

M.Eisaman, L.Childress, F.Massou, A.Andre,A.Zibrov, MDL

Summary of Raman state manipulation

- ✓Probabilistic technique to prepare quantum states of matter & light
- ✓First experimental results
- ✓Can be used for long-distance quantum communication

Quantum control of light and atomic ensembles

- Need: techniques for creating & manipulating quantum states of photons or spin waves at a level of single quanta

Two approaches

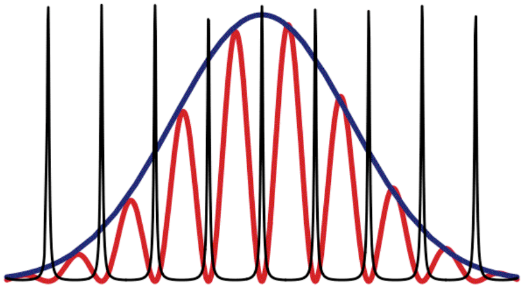
✓ Use weak nonlinearity and quantum measurement

- [illegible]
  weak nonlinearity and quantum measurement [illegible]

✓Create large nonlinearity at a level of single atoms or photons

- Dipole blockade: strong dipole-dipole interaction of (Rydberg) atoms
- Stationary pulses of light in atomic medium:
  towards enhanced nonlinear optics with stored states

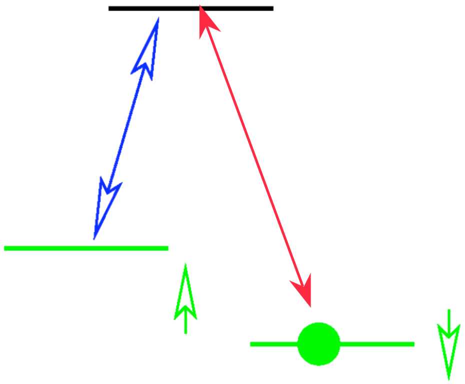
Stationary light pulses in an atomic medium: toward enhanced nonlinear optics

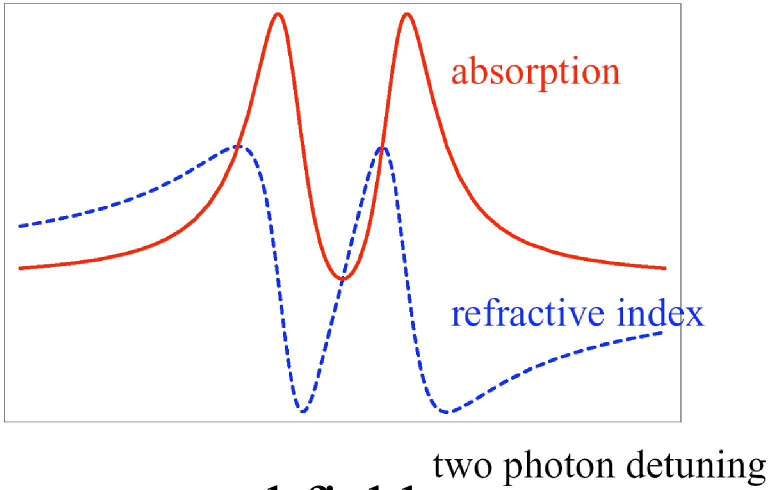


- ✓Key idea: controlled conversion of the propagating pulse into the excitation with localized, stationary electromagnetic energy
- ✓Mechanism: Bragg reflections from controlled, spatial modulation of the atomic absorption
- ✓New possibilities for enhanced nonlinear optical processes, analogous to cavity QED

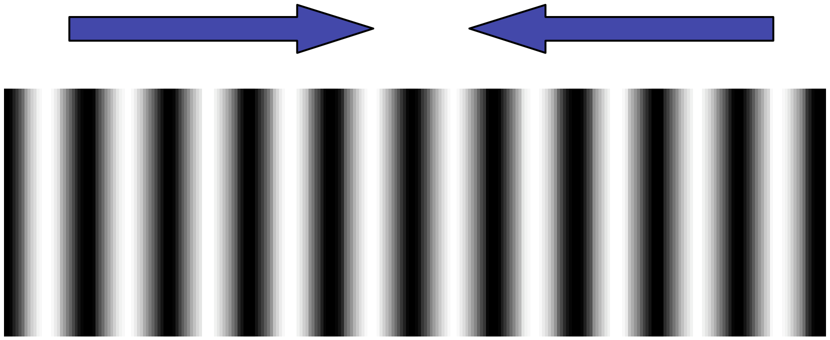
EIT in a standing wave control light

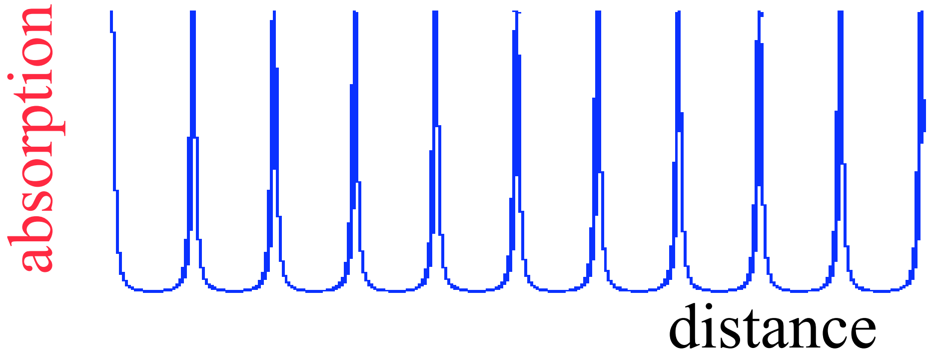
- ✓ Optical properties of EIT medium …





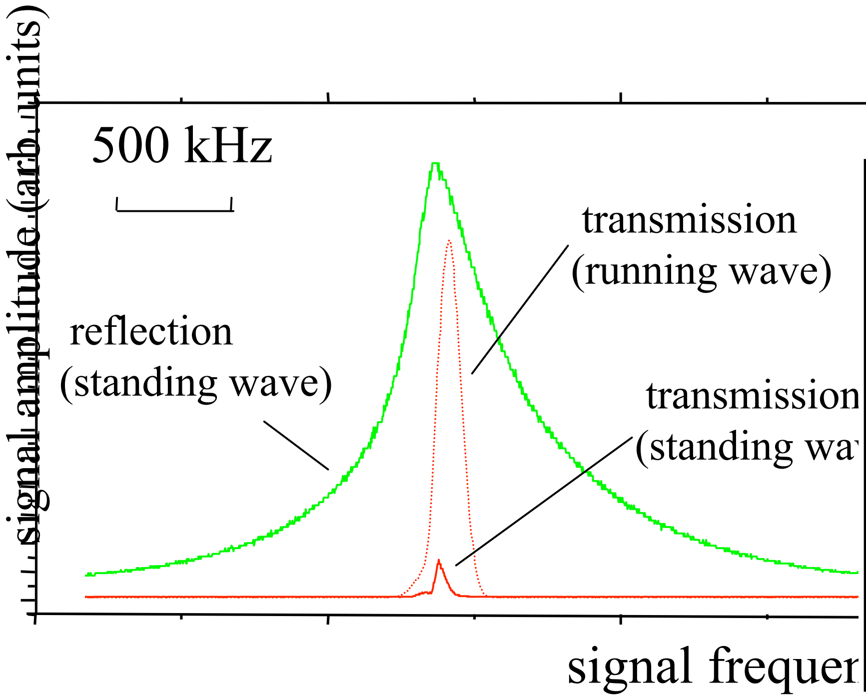
- ✓ … are modified by standing-wave control field:
  produces sharp modulation of atomic absorption in space



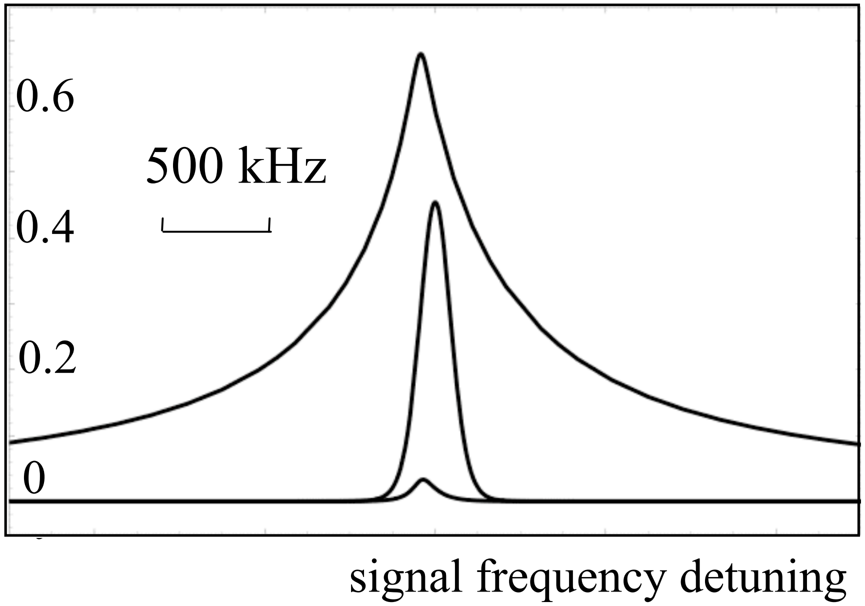


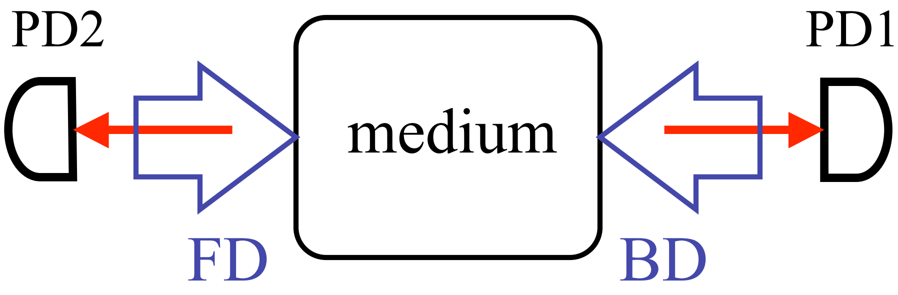
- ✓ Such medium becomes high-quality Bragg reflector

EIT spectra: running vs. standing wave control



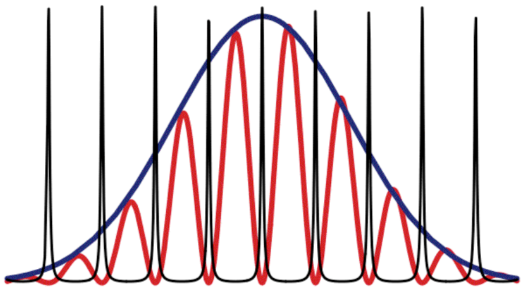
Theory:



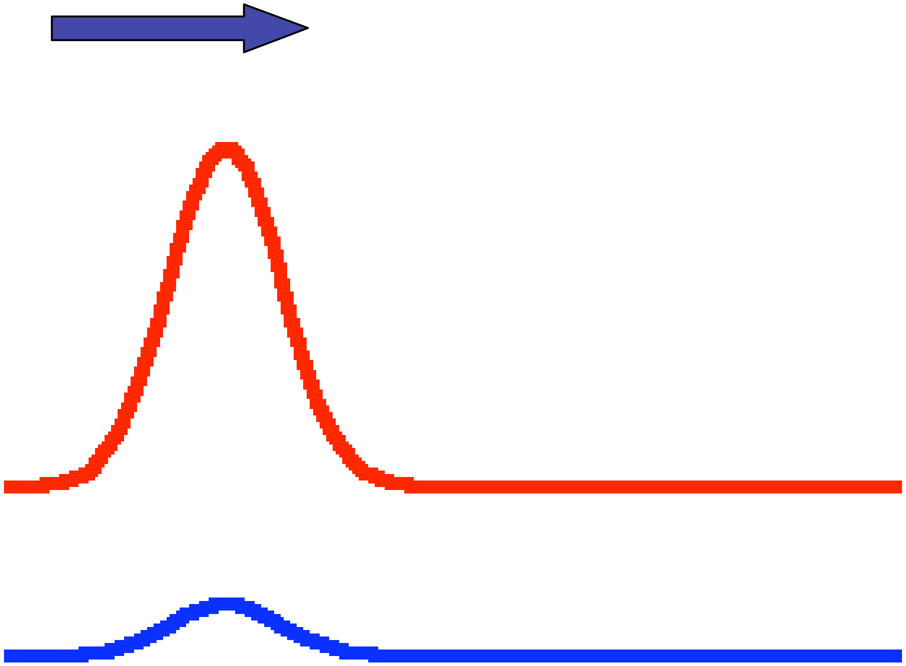


Idea of this work

✓ Releasing stored spin wave into modulated EIT medium creates light pulse that can not propagate



Propagation dynamics: storage in spin states

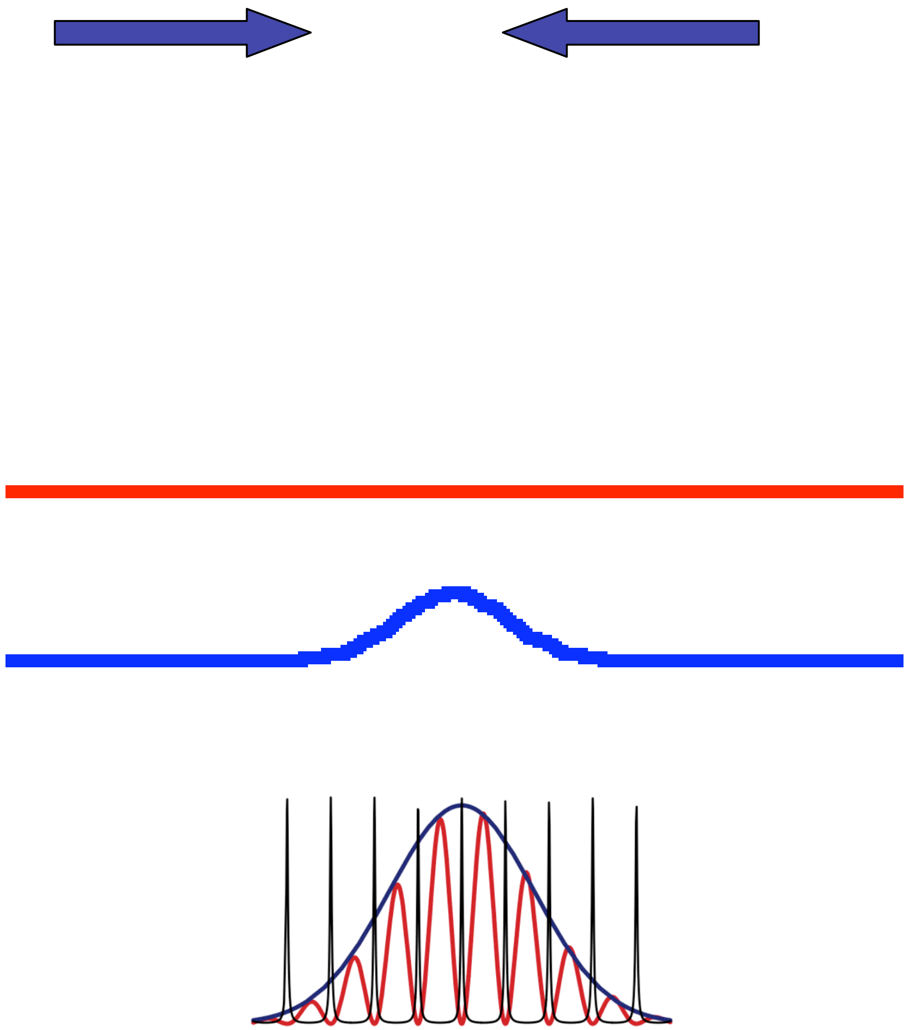


control light

signal light

spin coherence

Propagation dynamics: release in standing wave

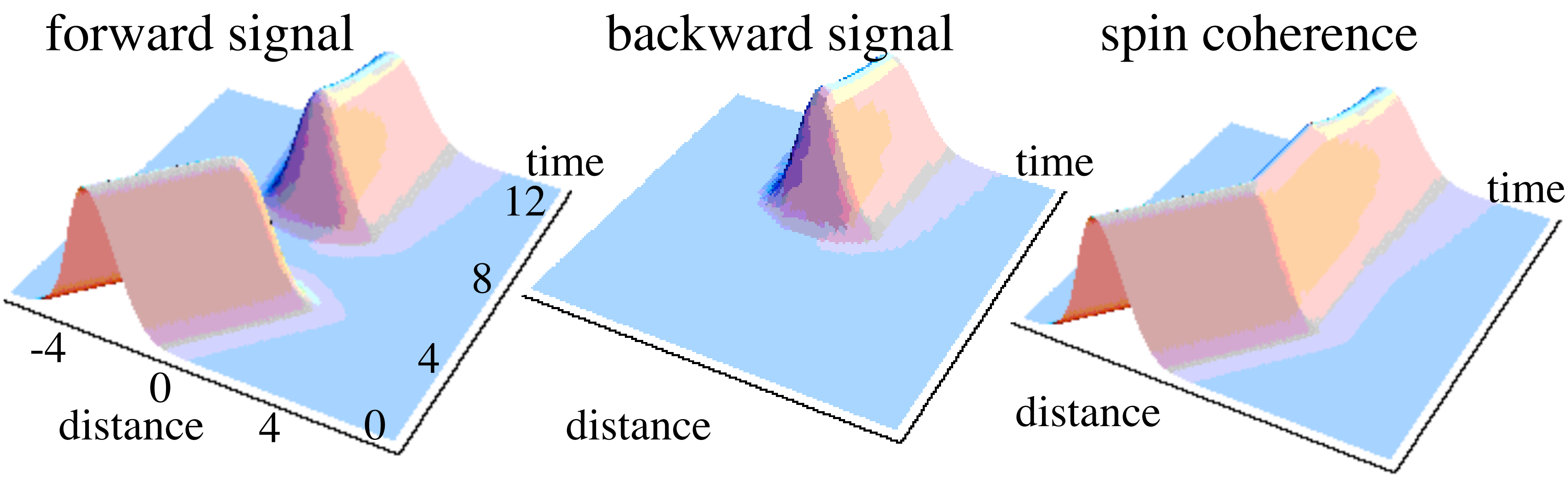


control light

signal light

spin coherence

Stationary pulses of light bound to atomic coherence


forward signal

backward signal

spin coherence

Physics:

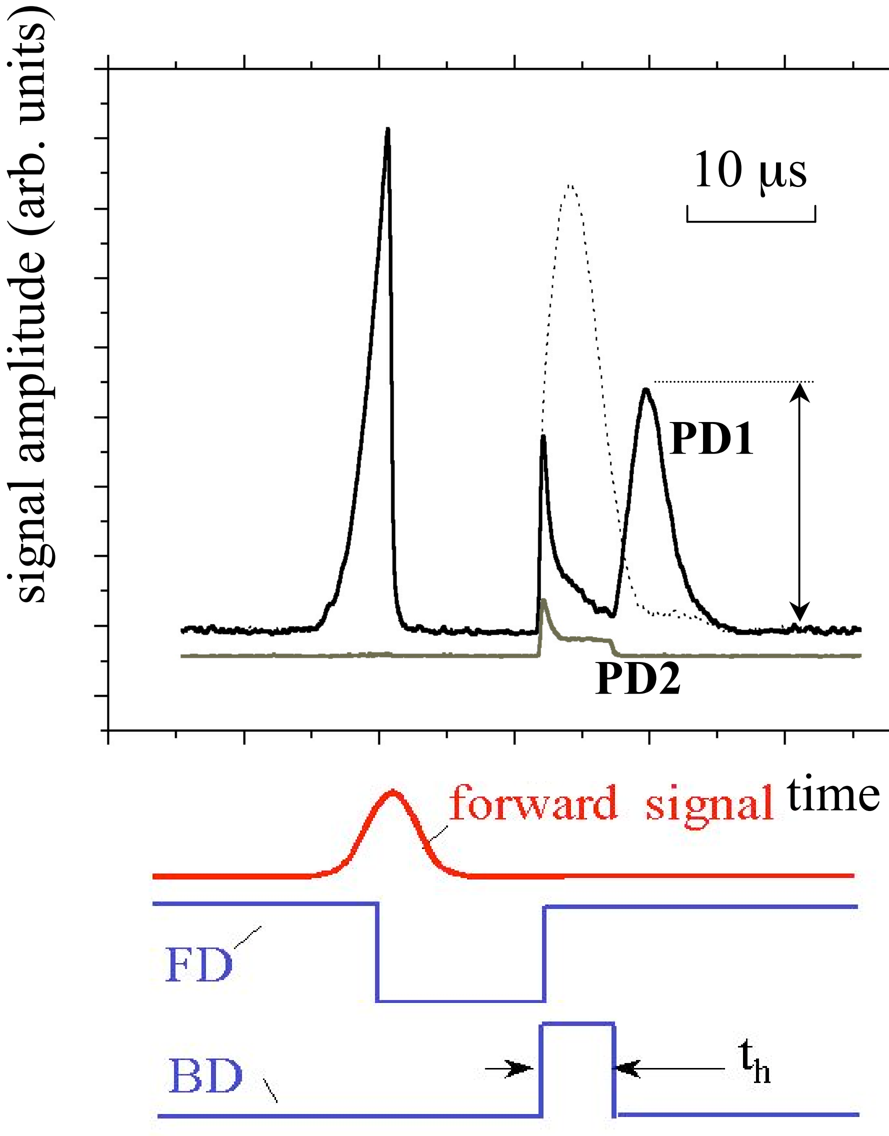
analogous to “defect” in periodic (photonic) crystal:

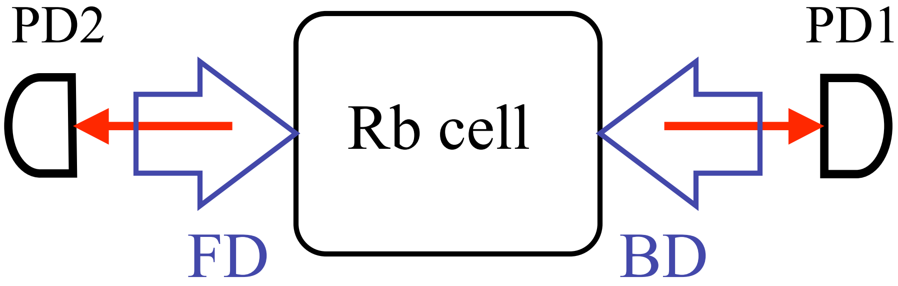
fines (ℱ) of localized mode determined by optical depth

- ✓Localization, holding, release completely controlled
- ✓In optimal case, no losses, no added noise, linear optical technique

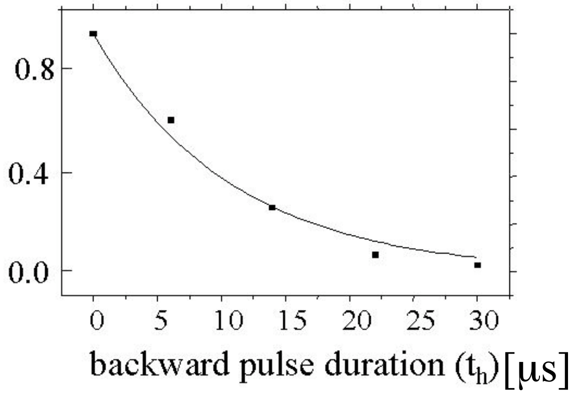
Theory: A.Andre & MDL Phys.Rev.Lett. 89 143602 (2002)

Observing stationary pulses of light



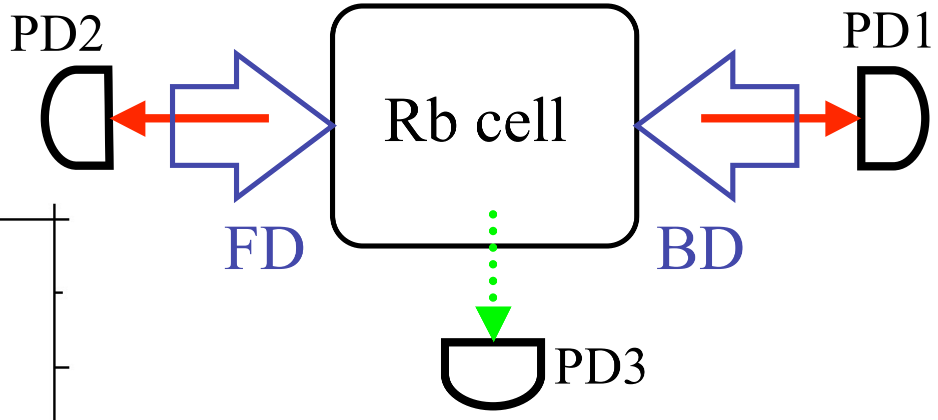


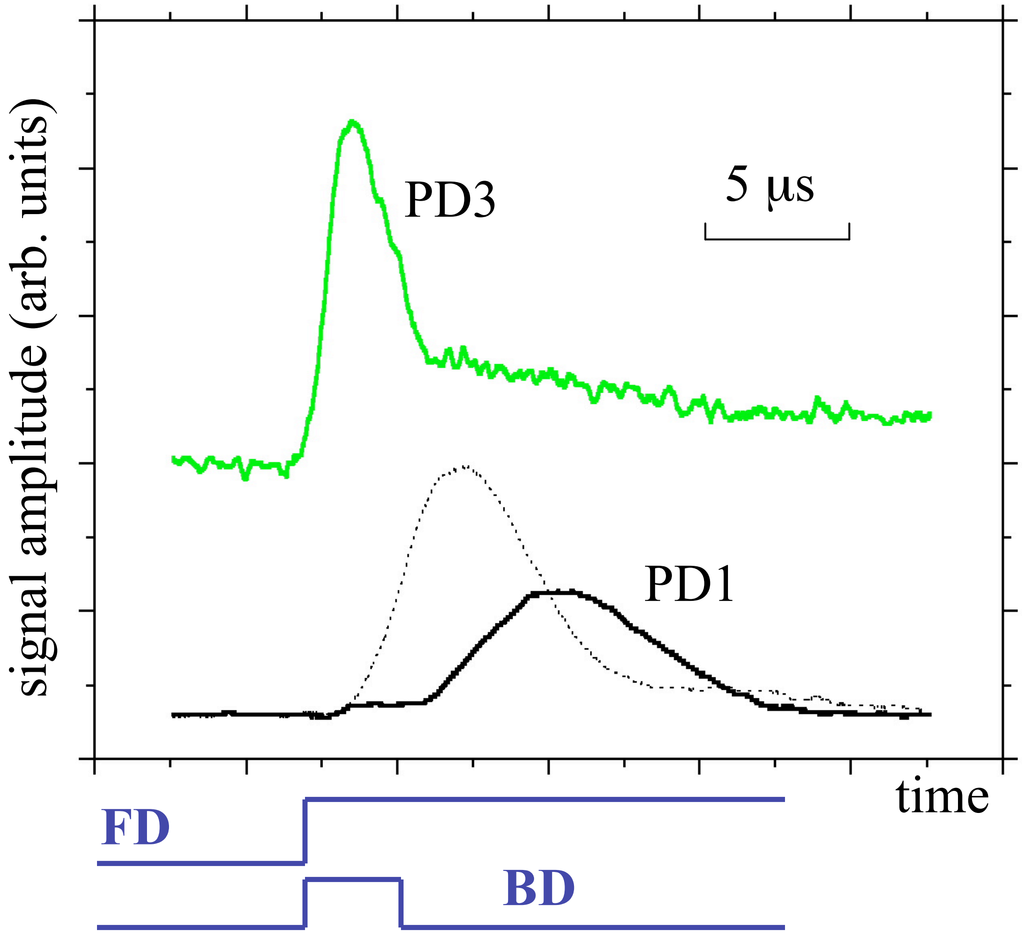
Released pulse amplitude



Proof of stationary pulses

Fluorescence measurement



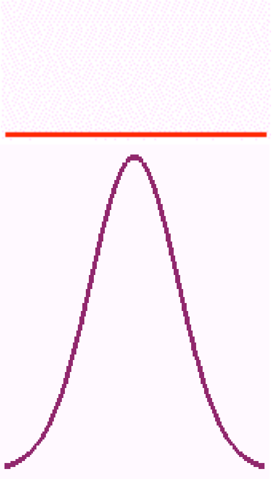


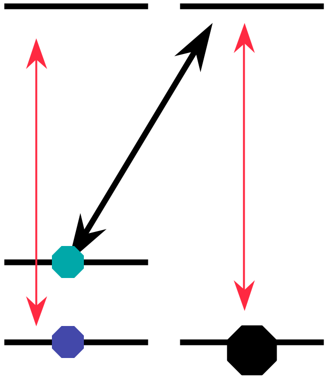
- measure fluorescence caused by the stationary light pulse

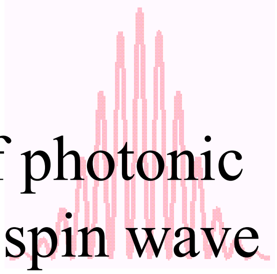
M.Bajcsy, A.Zibrov & MDL
Nature, 426, 638 (2003)

Outlook: novel techniques for nonlinear optics

✓ Efficient nonlinear optics as a sequence of 3 linear operations

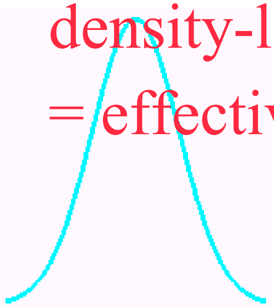






✓Nonlinear shift results from interaction of photonic components of stationary pulse with stored spin wave

$$\phi_{NLN} \sim \frac{\lambda^2}{A} n_{photon} \times \mathcal{F} \longrightarrow$$

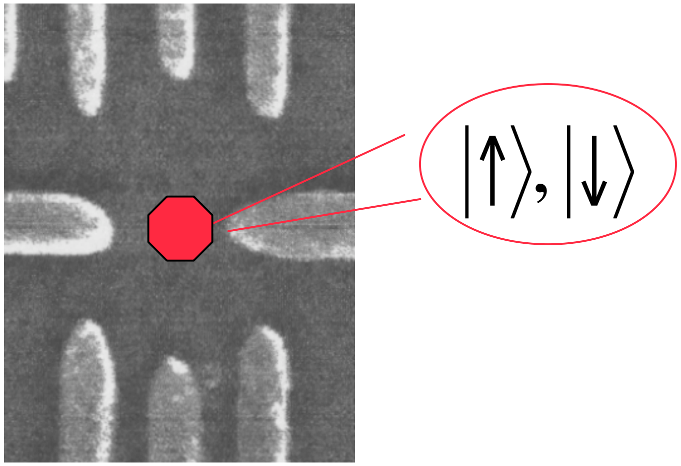


density-length

= effective $\mathcal{F}$

✓ Nonlinear processes at a few-photon level are realistic

Example from condensed matter:
controlling mesoscopic environment in solid state



$|\uparrow\rangle, |\downarrow\rangle$

- Short coherence time: limiting factor for solid-state quantum control
  e.g. for electron spins in GaAs dots ~ fraction of μs

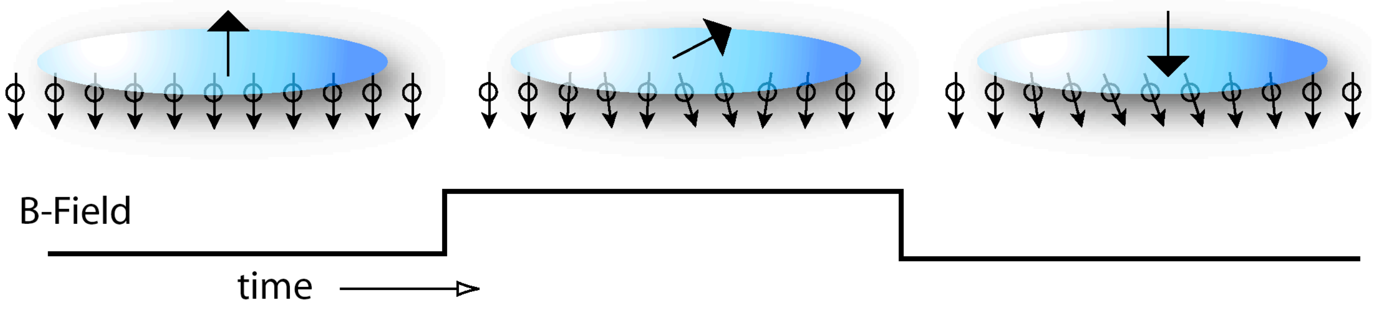
✓ Reasons: … interaction with surrounding ensemble of nuclear spins

✓ Idea: use long nuclear memory to suppress decoherence and store the states of qubits

Idea of quantum memory: storing electron spin in collective nuclear spin states

- Controlled coupling of electronic and nuclear spins
  - contact hyperfine interaction, spin-polarized nuclei
  - control tool: effective magnetic field
  - allows for resonant spin-exchange and quantum state transfer

$$\boxed{\hat{H} = (\hbar g \underbrace{\mu_b B_0 - \sum A_i}_{\text{Zeeman+Overhauser}}/2)\hat{S}_z + \sum_i A_i \underbrace{(\hat{I}^i_+ \hat{S}_- + \hat{I}^i_- \hat{S}_+)}_{\text{Spin Exchange}}}$$



- Inverting the procedure maps the state back into the electron qubit

✓ In many way analogous to single atom + radiation field

Spin qubit storage in collective nuclear states

$$\left(\alpha|\uparrow\rangle+\beta|\downarrow\rangle\right)\otimes|\uparrow..\uparrow\rangle_N \xrightarrow{\Omega} |\uparrow\rangle\otimes\left(\alpha|\uparrow..\uparrow\rangle+\beta\sum_i A_i|\uparrow..\downarrow_i..\uparrow\rangle/\Omega_R\right)_N$$

spin qubit nuclei nuclear collective qubit

- Time scale for collective state transfer (GaAs, ~10^5 nuclei)
  - hyperfine coupling per nuclear spin ~ 0.1 GHz : fast!
- Dephasing mechanisms during storage
  - Inhomogeneous hyperfine coupling ~ fraction of MHz
    - Can be canceled by ESR of NMR pulse sequences
  - Nuclear dipole-dipole diffusion & dephasing ~4 KHz
    - Standard NMR pulse trains to cancel leading order

✓ Coherent storage times ~ seconds possible

Taylor, Marcus & Lukin
Phys.Rev.Lett., **90**, 206803 (2003)

✓Can be accomplished with low nuclear polarization

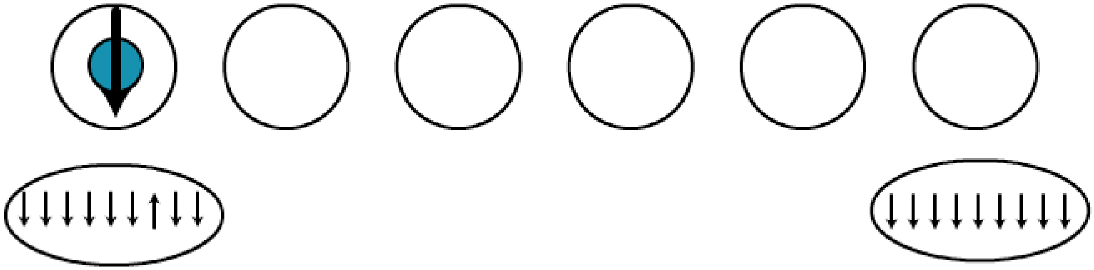
Taylor,Imamoglu & MDL,PRL (2004)

Quantum manipulation of nuclear ensembles

Based on spin degrees of freedom ONLY

- Single electron spin used to carry quantum information
- Local interactions between nuclear ensembles and electron spin (unharmonic system) are sufficient for entanglement

electron spin: transport



nuclei: memory

✓New techniques for quantum computation and
quantum communication in solid state

J.Taylor,A.Imamoglu, P.Zoller & MDL

Summary

- Quantum memory for light (photon state trapping) via EIT
- Raman scattering for preparation of non-classical states of atoms and light
  - shaping quantum pulses via Raman scattering & EIT
  - new techniques for long distance quantum communication

- Stationary pulses of light in atomic medium
  - proof of principle experiments
  - new nonlinear optical techniques

- Quantum state manipulation in solid state
  - long-lived memory for spins in q.dots

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http://qoptics.physics.harvard.edu