Quantum optics with an intracavity Rydberg gas

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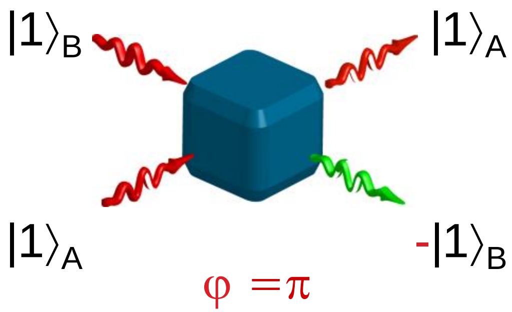
Photonic interactions

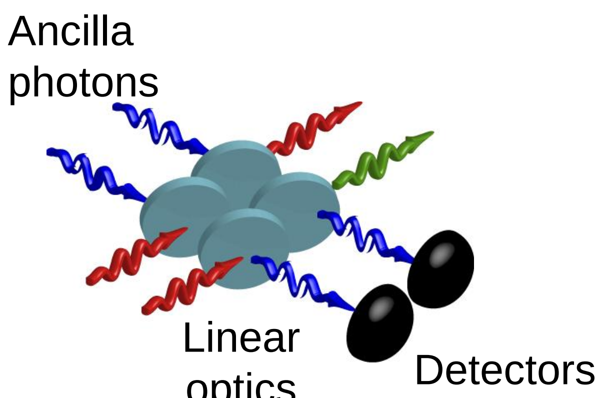


Example: photon A shifts phase of photon B

Classical non-linear media: $\varphi < 10^{-6}$ before photons are lost

« Established » methods

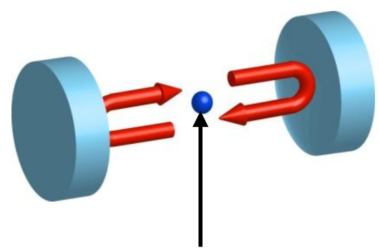
Projective measurements



⇒ Entanglement

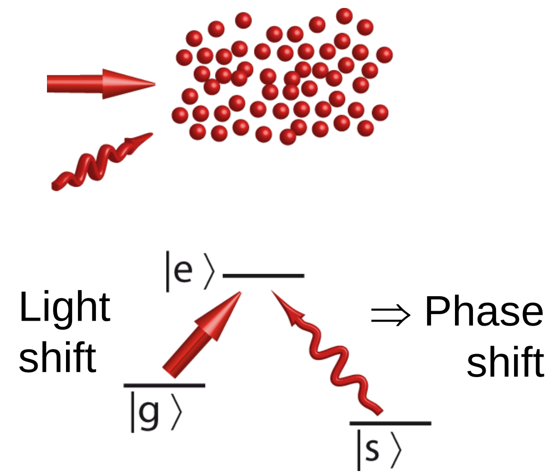
Cavity QED

2-level « atom »
+ high-finesse cavity

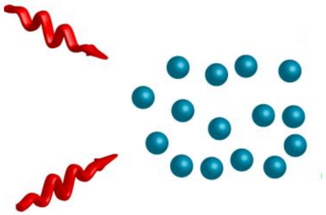


Absorbs/emits
one photon at a time

Dense atomic ensembles



Our approach



Photons:

Injected in
a cold gas

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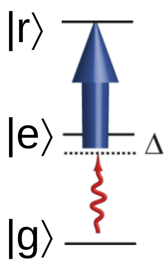
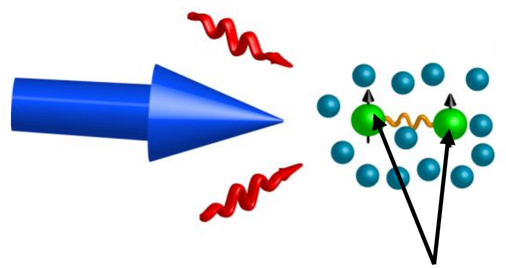


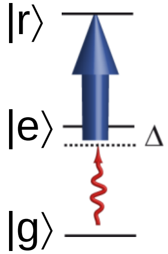


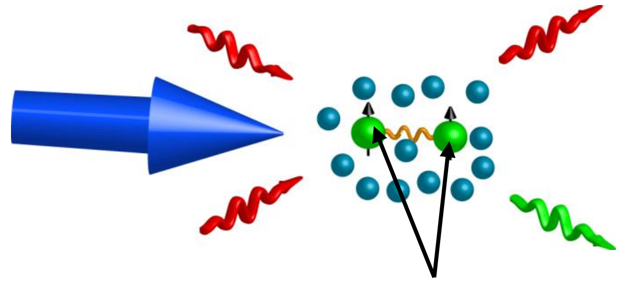
Rydberg atoms |r⟩, n~50-100:
Long lifetimes (~100μs)
Strong interactions $V \propto C_6 / r^6 \propto n^{*11}$

Photons:

Injected in a cold gas $\rightarrow$ Interact via Rydberg excitations

Our approach





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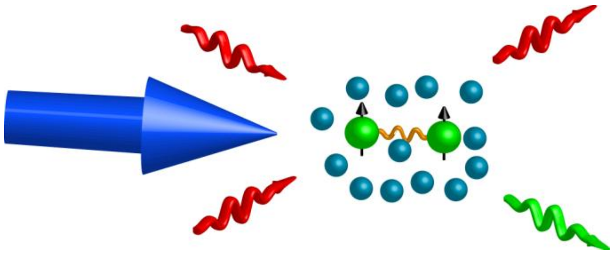
Long lifetimes (~100μs)
Strong interactions $V \propto C_6 / r^6 \propto n^{*11}$

Photons:

Injected in a cold gas → Interact via Rydberg excitations → Retrieved in desired mode

Outline



Atomic physics:
create
non-linear effects

Part I

Quantum optics:
Manipulate & detect
quantum states

Part II

Rydberg-mediated
photonic interactions

Part III

Outline

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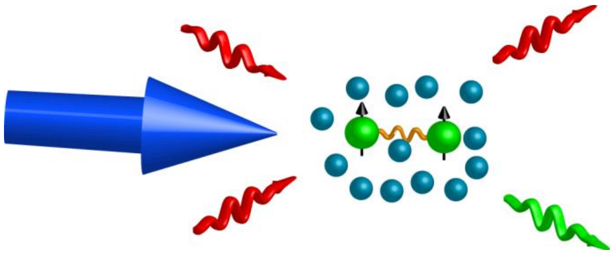

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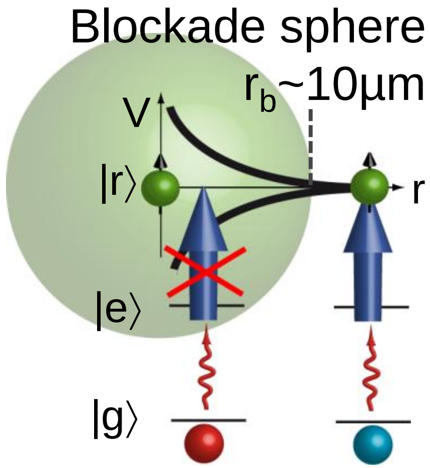
Rydberg blockade



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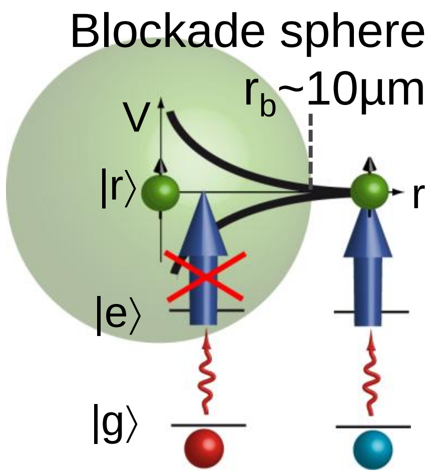
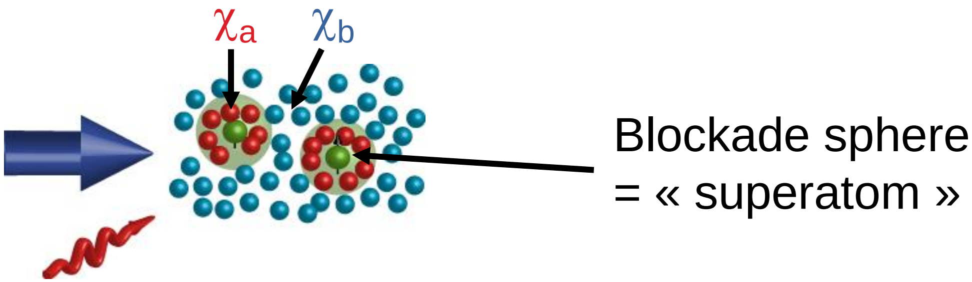


Optical susceptibility:

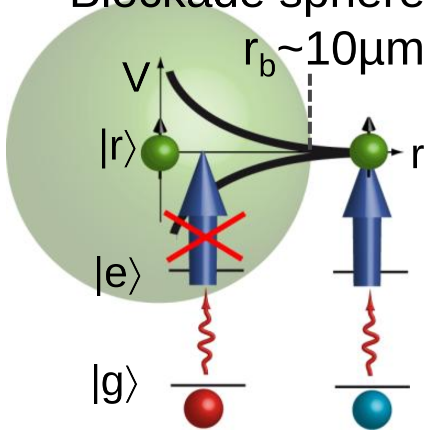


↗ photons ⇒ ↗ Rydberg atoms ⇒ ↗ blockade spheres

⇒ ≠ transmission / phase

Rydberg blockade

Blockade sphere



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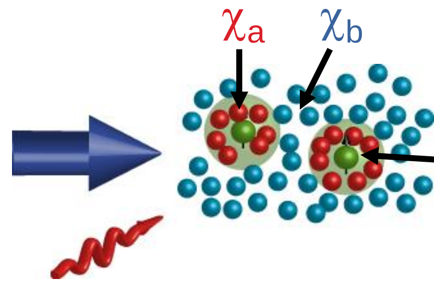

Blockade sphere
= « superatom »

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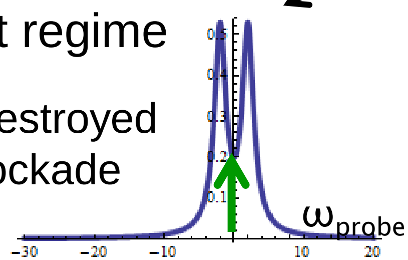
⇒ ≠ transmission / phase

Resonant regime

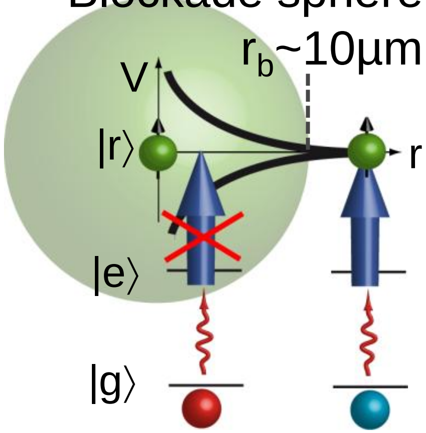
EIT destroyed
by blockade



Pritchard *&al,* PRL **105,** 193603 (2010)
Ates *&al*, PRA **83**, 041802(R) (2011)

Rydberg blockade

Blockade sphere



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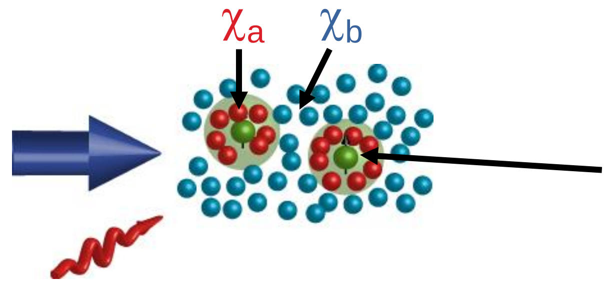

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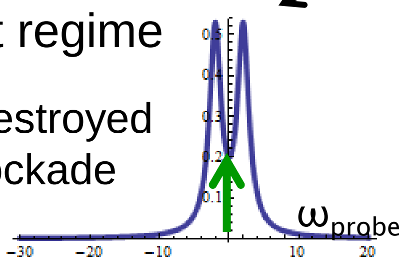
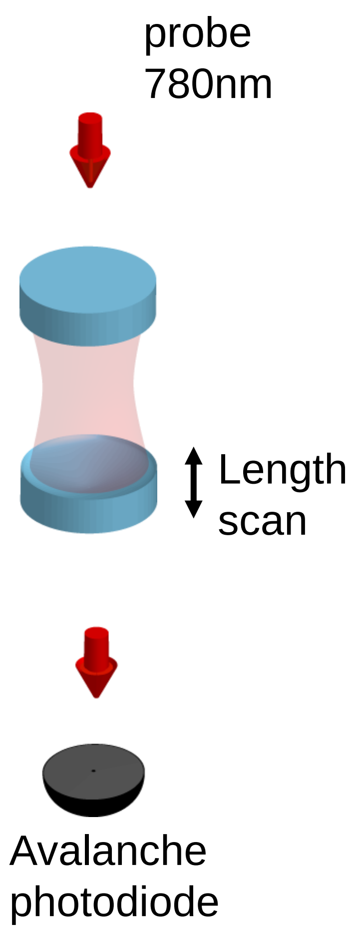


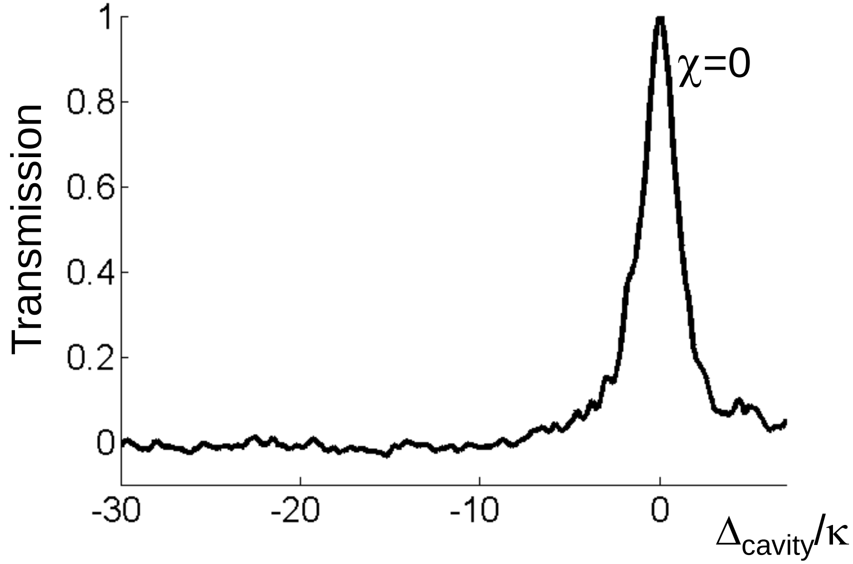
Off-resonant regime?

Pritchard *&al,* PRL **105,** 193603 (2010)
Ates *&al*, PRA **83**, 041802(R) (2011)

Dispersion measurement



Cavity:
Finesse ≈ 120
Length ≈ 64mm



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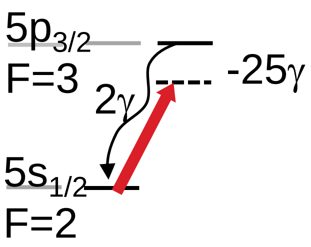

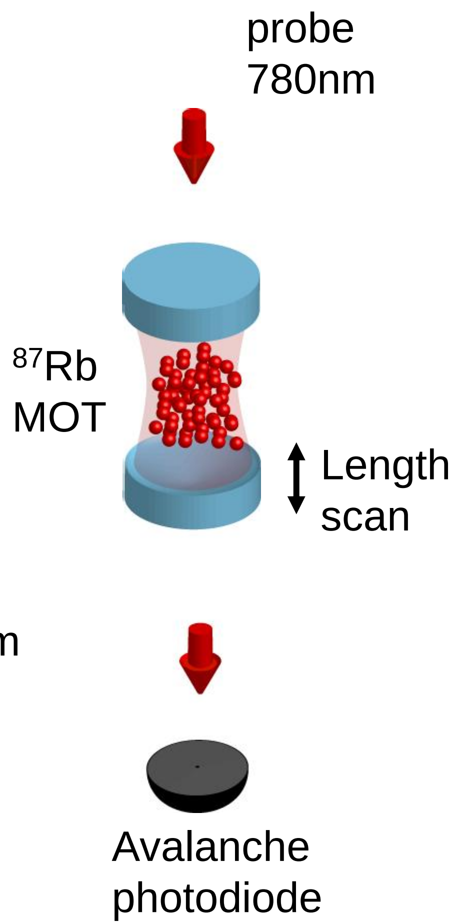

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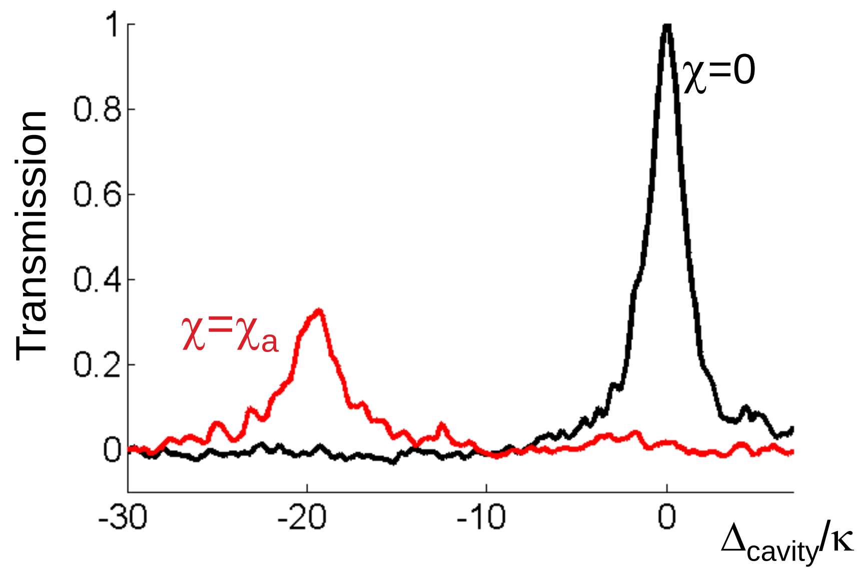

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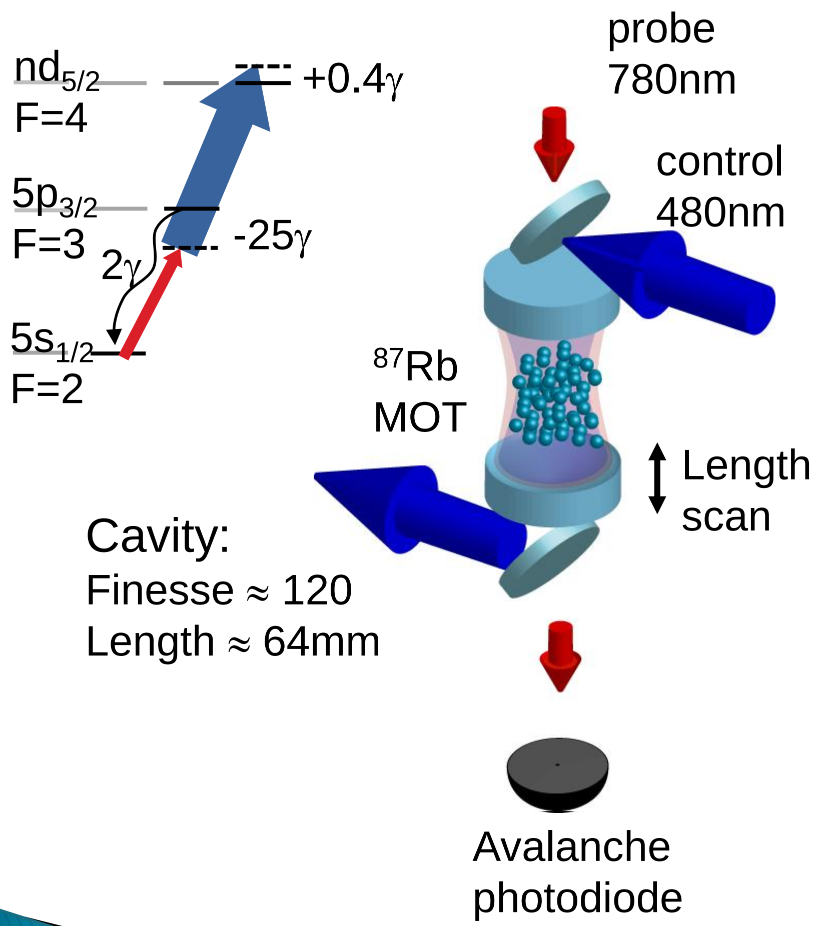

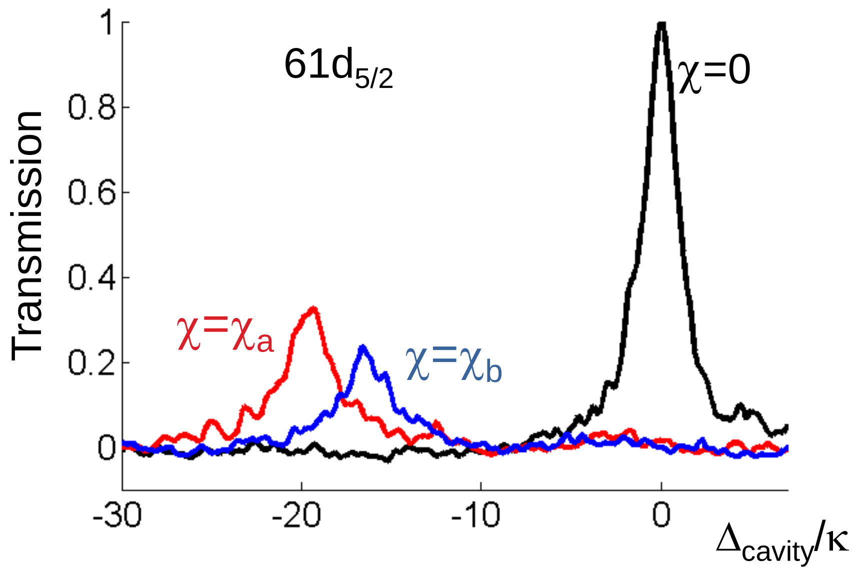

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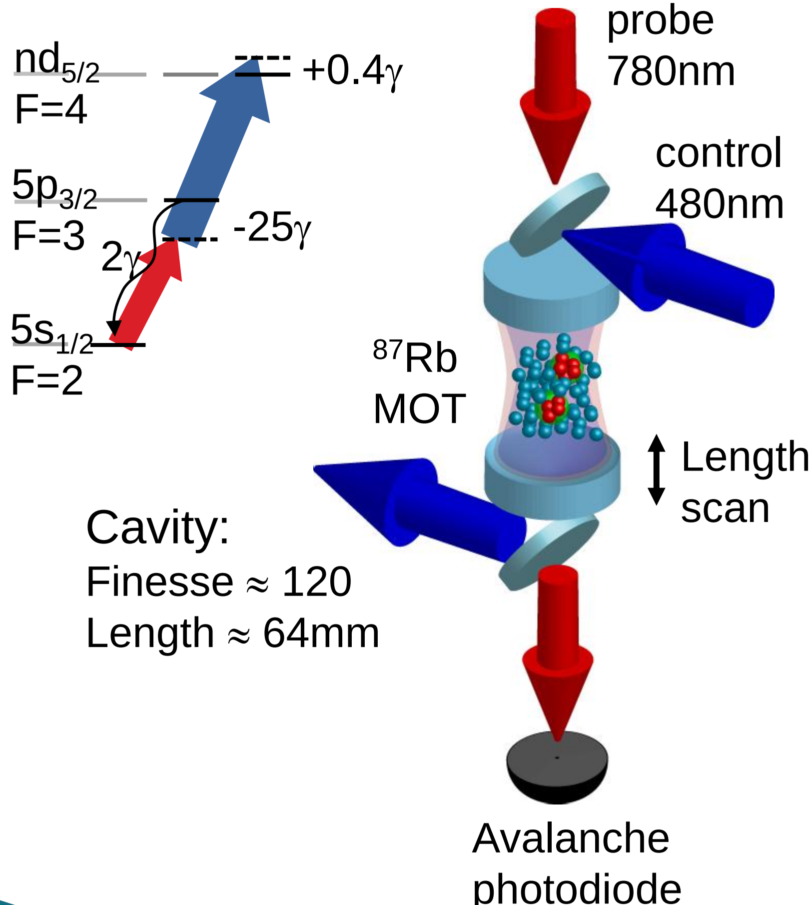
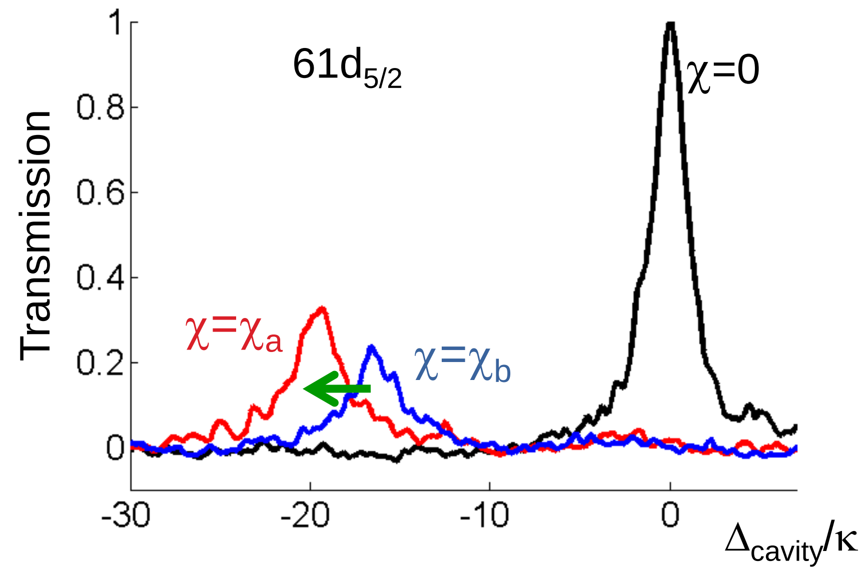
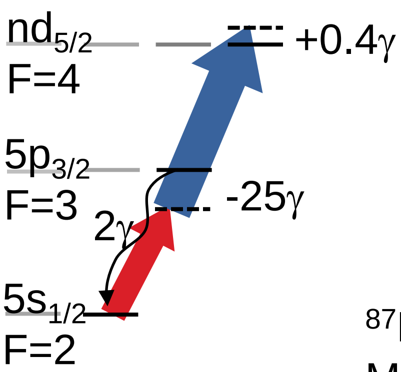
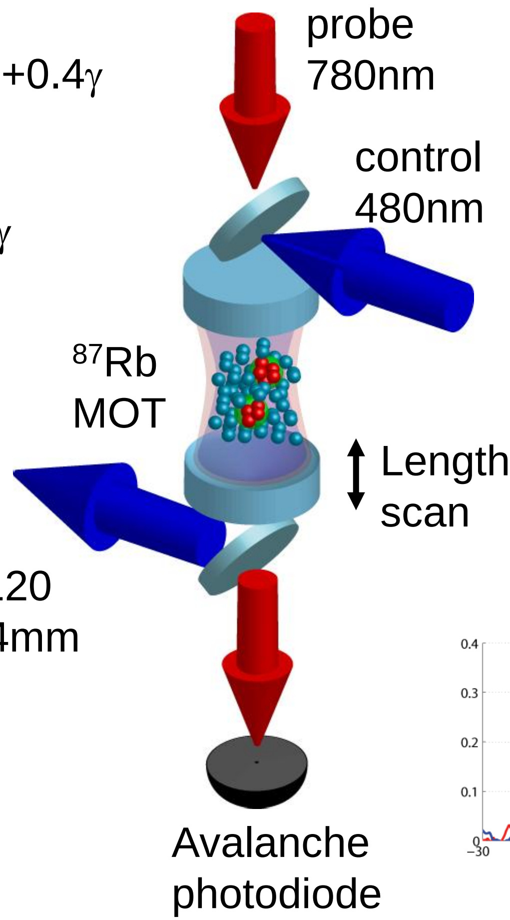




Expected bistability… saw ions
⇒ weaker driving, faster scan.

Dispersion measurement





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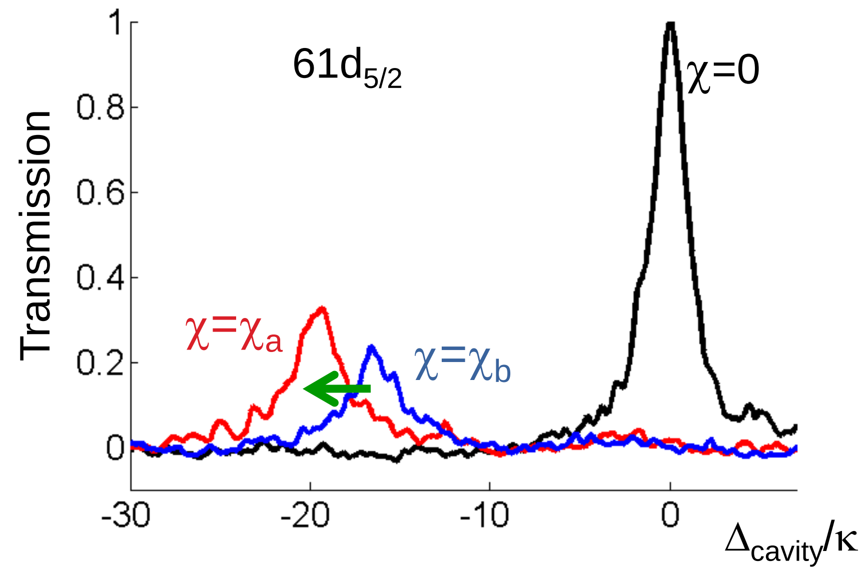
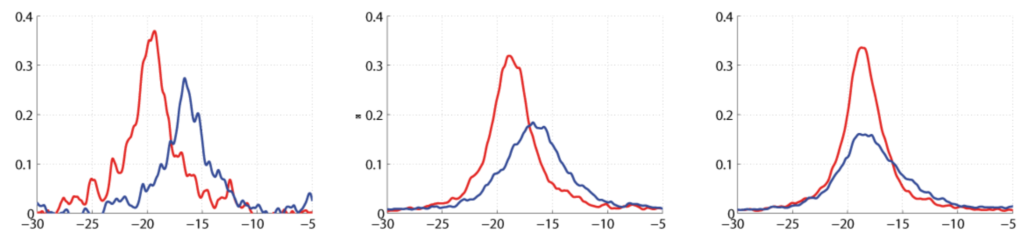
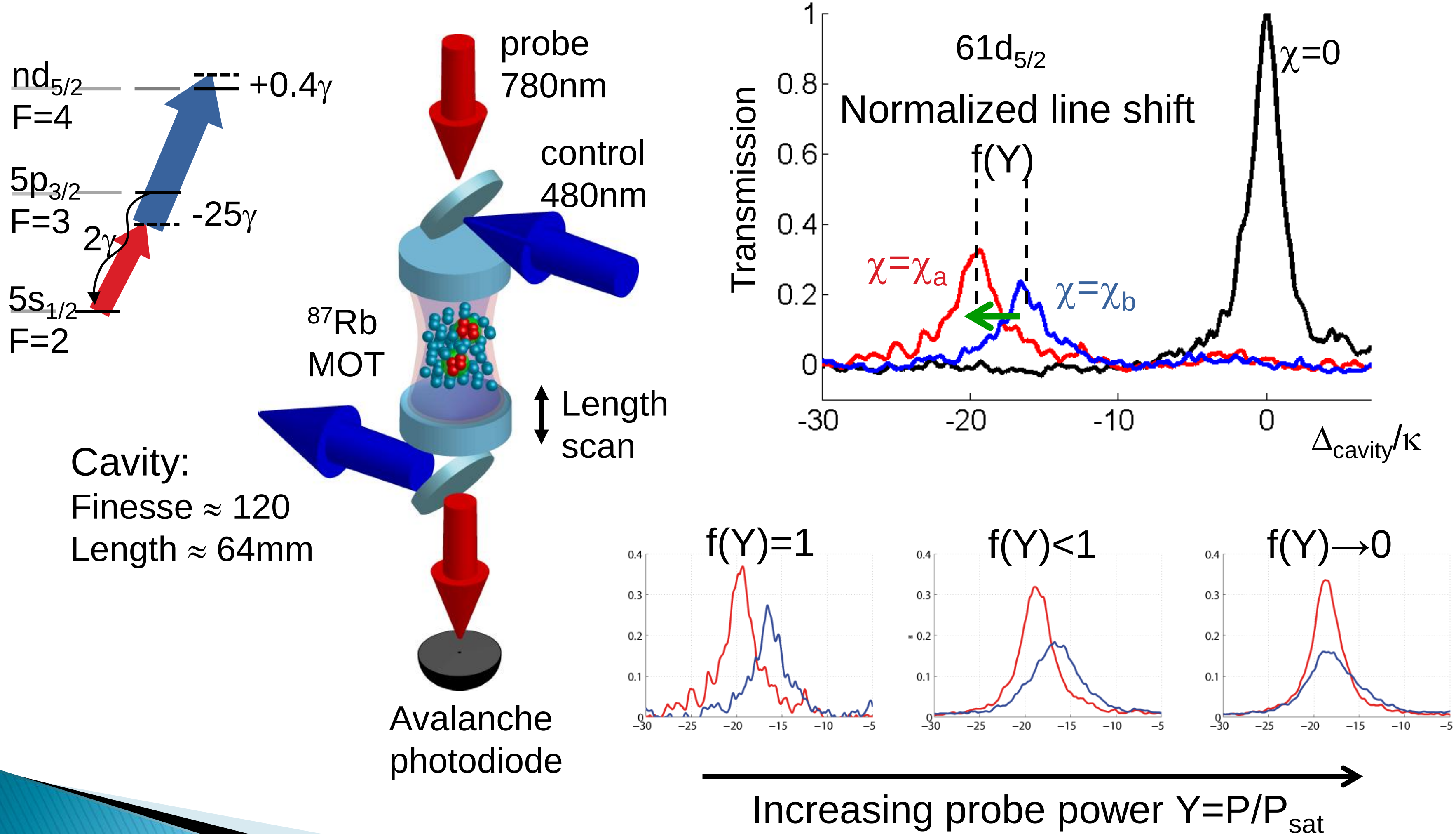




Increasing probe power $Y=P/P_{sat}$

Dispersion measurement



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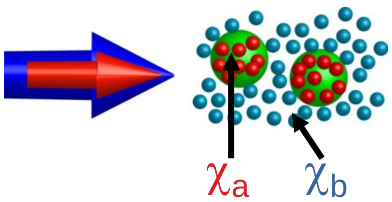


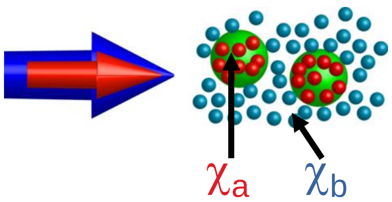
Normalized line shift f(Y):

$$\frac{df}{dY}(0) \propto n_{block} = \rho\, V_{sphere}$$

Atomic density

Volume of a blockade sphere $\propto \sqrt{C_6} \propto (n^*)^{5.5}$

Dispersion measurement



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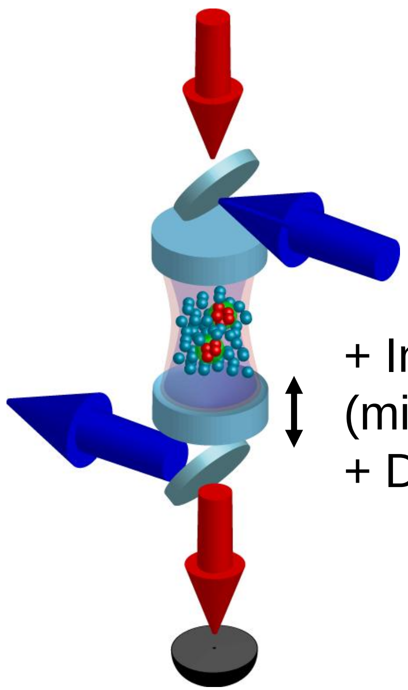
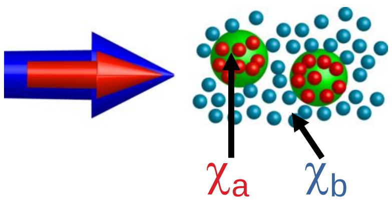


+ Inhomogeneous beams
(mismatched standing waves & transverse profiles)
+ Dynamics

Dispersion measurement



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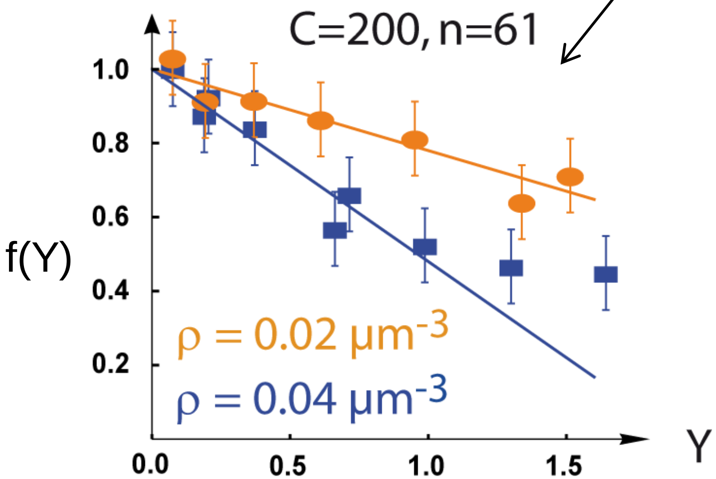
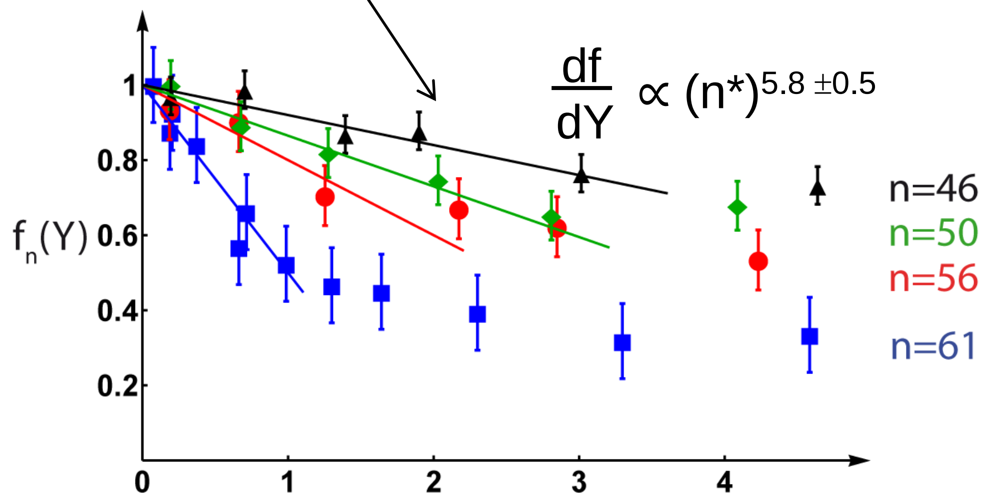
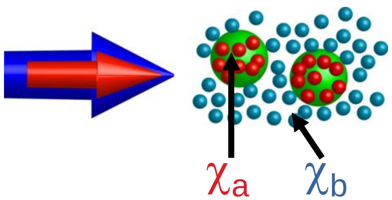


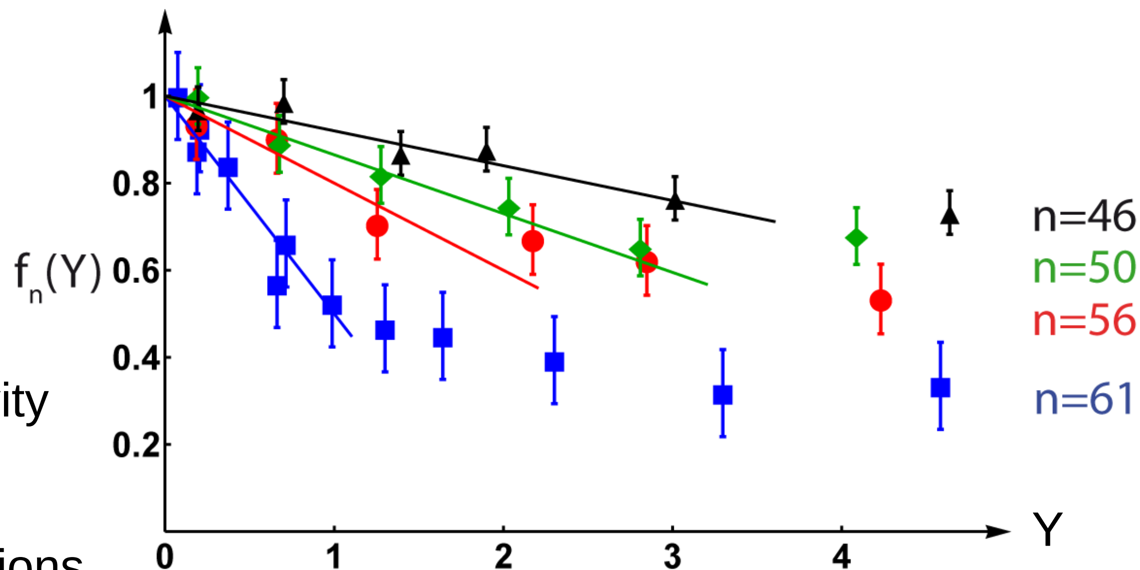


Parigi *et al*, PRL **109**, 233602 (2012)
Stanojevic *et al*, PRA **88**, 053845 (2013)

Blockade model validity



Low-power $\chi^{(3)}$ regime $(Y<<1)$:

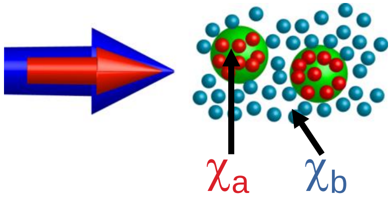


$\chi \approx \chi_b + (\chi_a - \chi_b)sX$

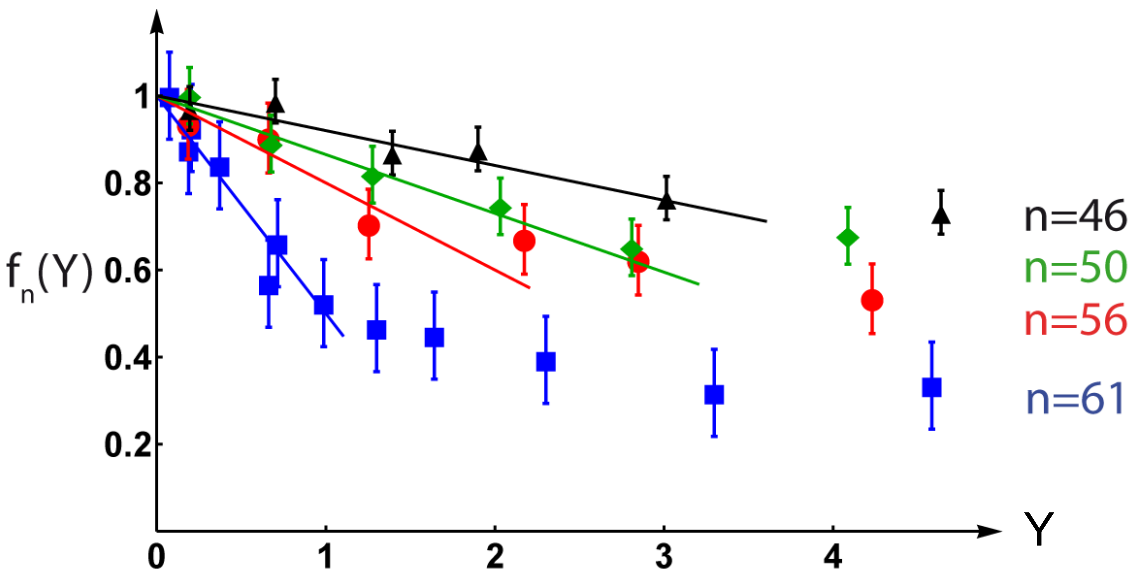
Intracavity power

3-level optical Bloch equations
(lowest-order expansion)
+ spatial inhomogeneities
+ dynamics

Blockade model validity



Saturated regime ?



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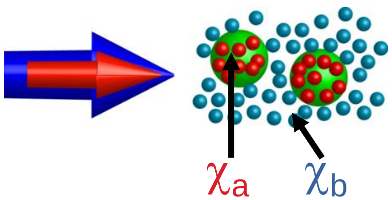
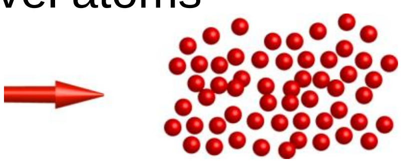
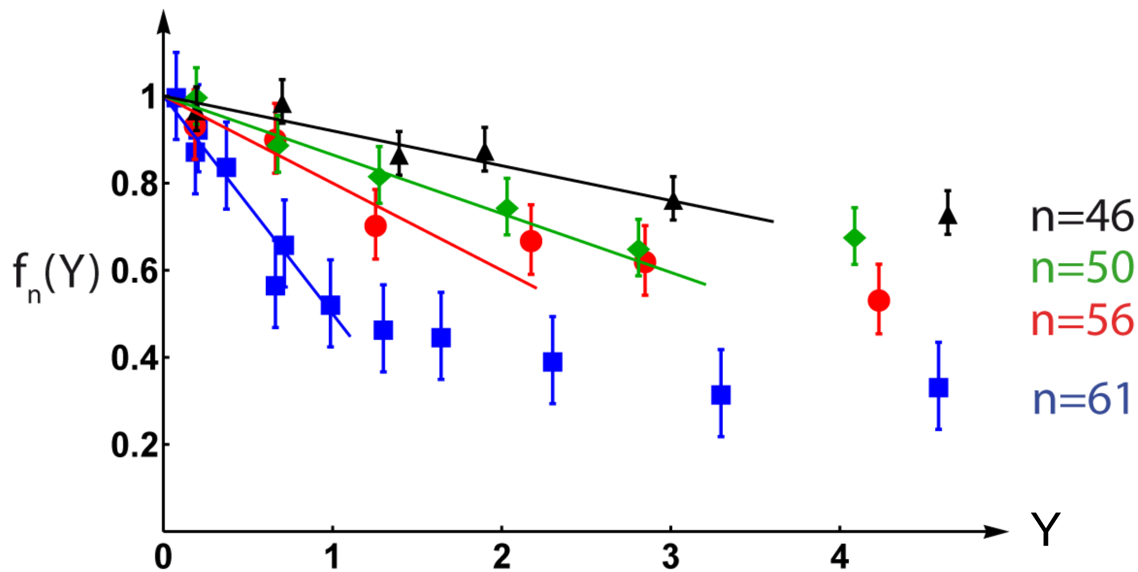


2-level atoms



$$\chi = \frac{\chi^{(1)}}{1+sX}$$

Saturated regime ?



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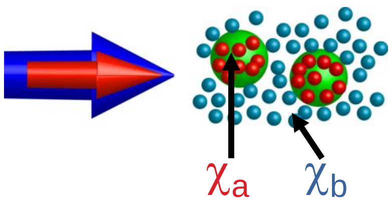

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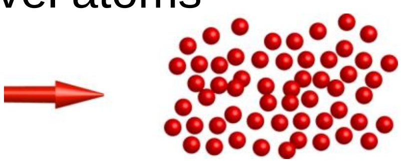

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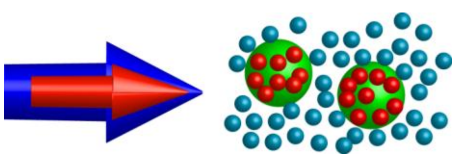
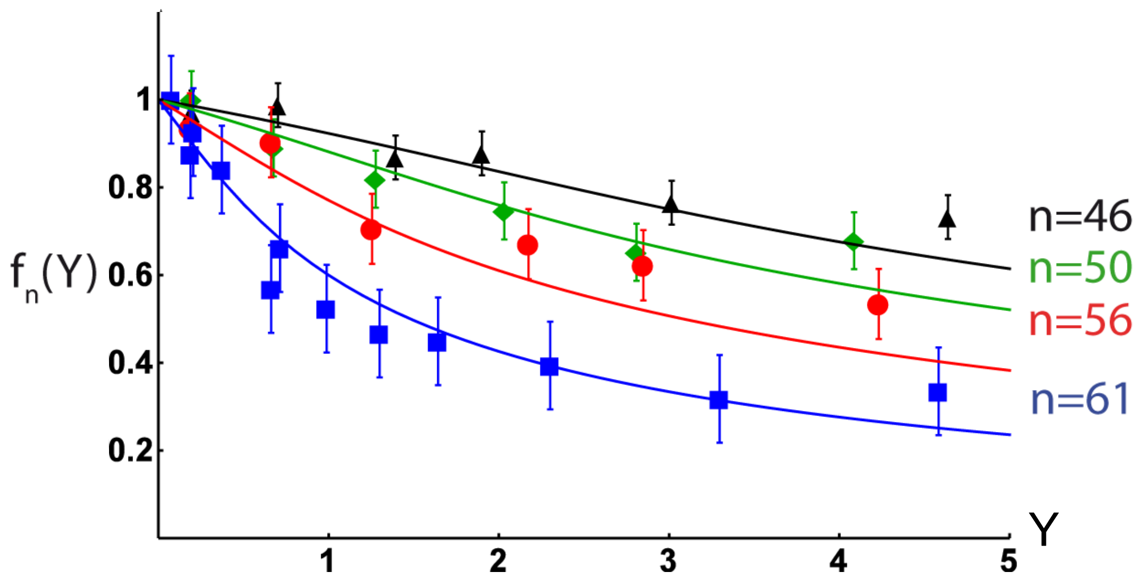
Rydberg « superatoms »



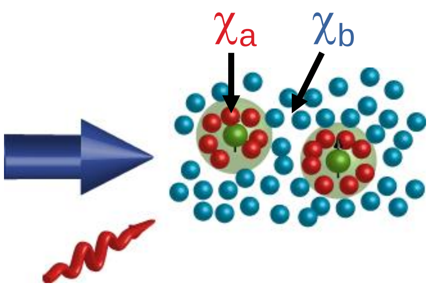
$$\chi - \chi_a = \frac{\chi_b - \chi_a}{1+sX}$$

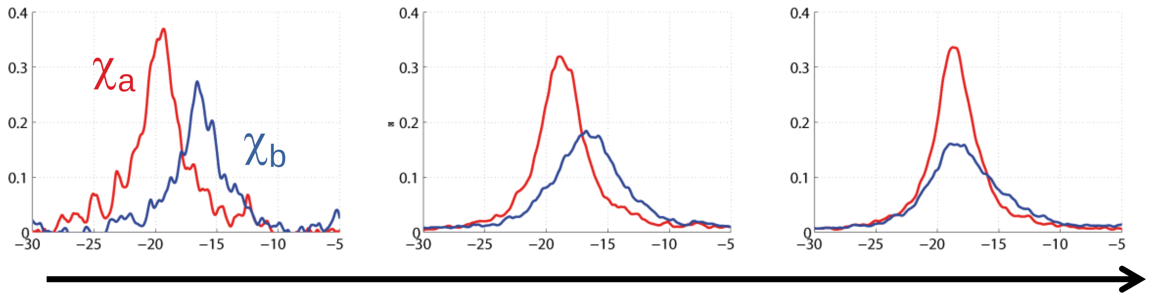
Saturated regime ?



Bloch equations + inhomogeneities + dynamics

Blockade model validity



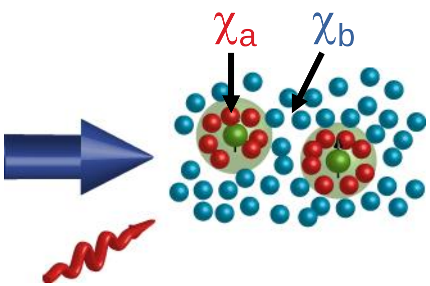


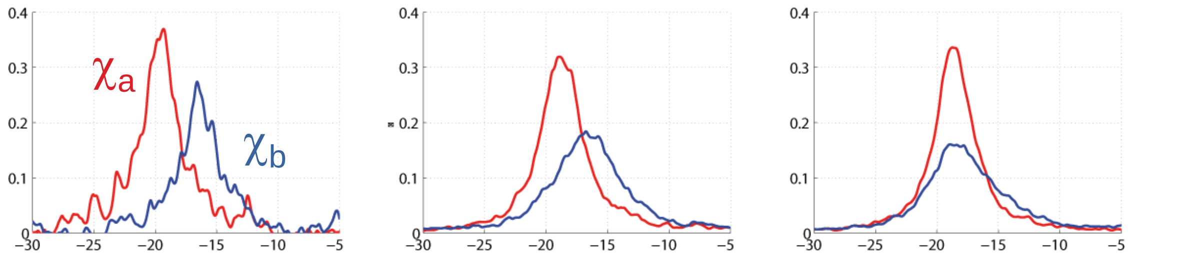
Increasing probe power $Y=P/P_{sat}$

Dispersion $\propto Re(\chi)$: OK

Absorption $\propto Im(\chi)$: Additional losses

Blockade model validity





Increasing probe power $Y=P/P_{sat}$

~~Hard-core~~
~~Isotropic~~

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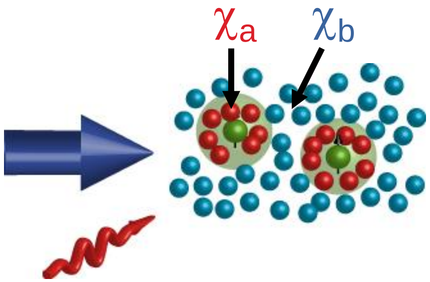
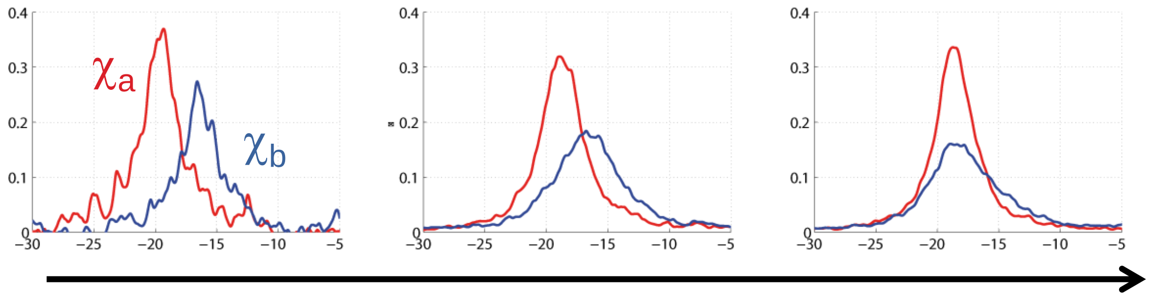
Blockade model validity





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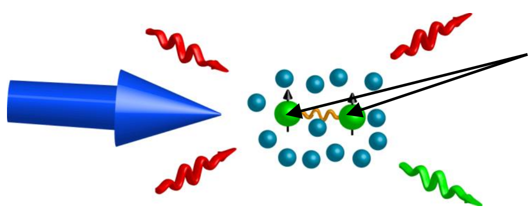
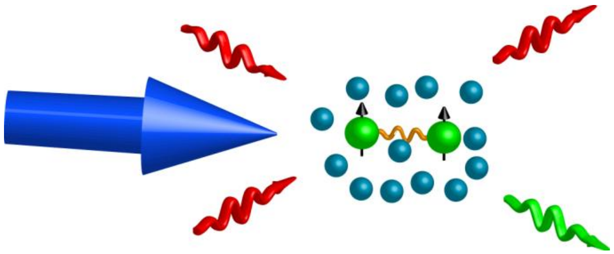


- Phase shift $\varphi(t)=t^*C_6/r^6$
  r random $\Rightarrow$ dephasing
  Dudin & Kuzmich, Science **336,** 887 (2012)
- d states $\Rightarrow$ angular dependence $\Rightarrow$ dephasing

Outline



Atomic physics:
create
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Rydberg-mediated
photonic interactions

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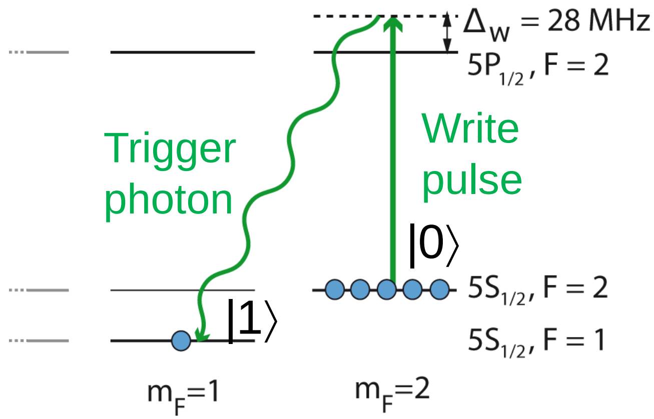
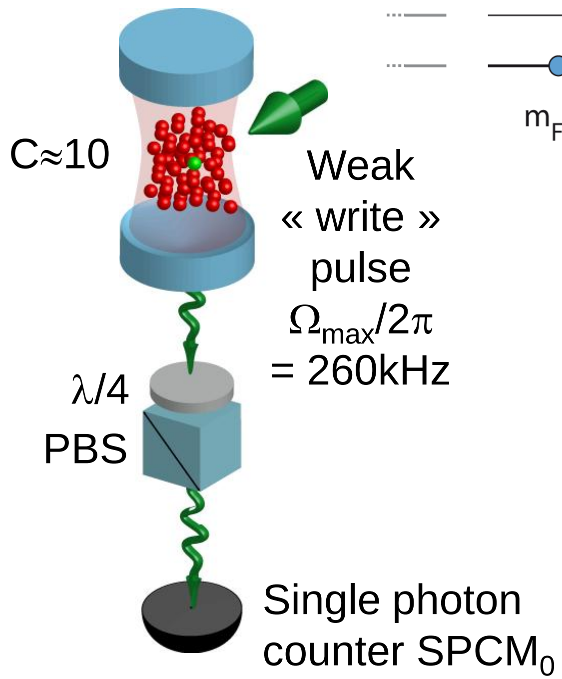
Single photon source (DLCZ)





Write step:

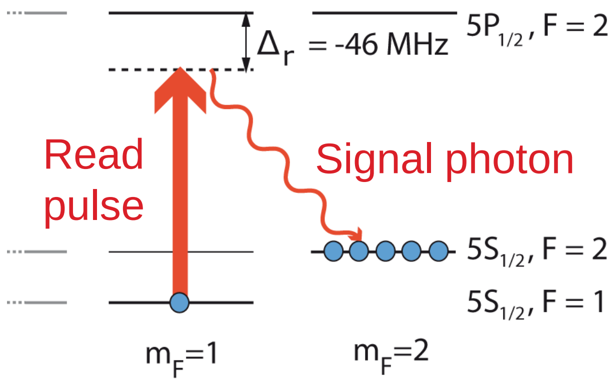
Creates a single collective excitation

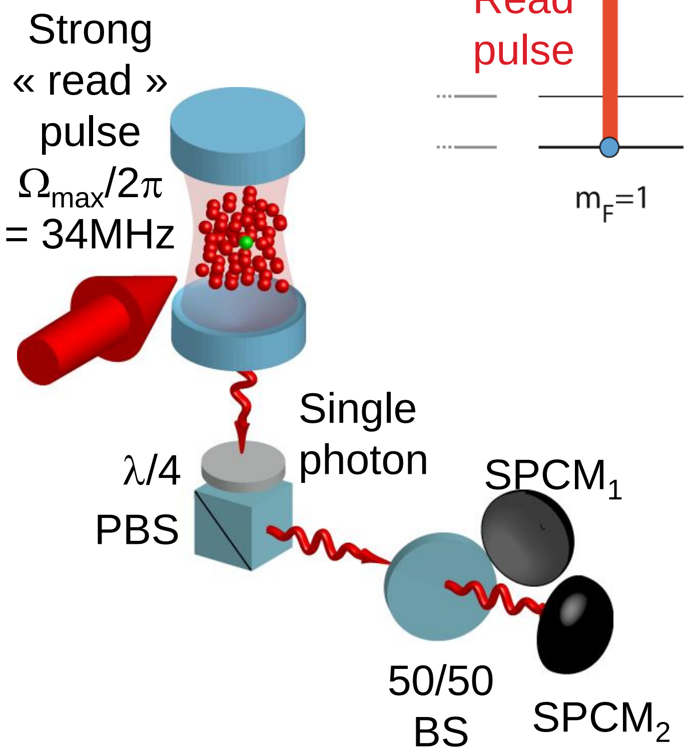
$$e^{i(\vec{k_T}-\vec{k_W}).\vec{r_1}}\left|100...0\right\rangle + e^{i(\vec{k_T}-\vec{k_W}).\vec{r_2}}\left|010...0\right\rangle + ...$$

Trigger probability ~1/1000 (rate ~100/s)

Duan & al, Nature **414**, 413 (2001)

Single photon source (DLCZ)





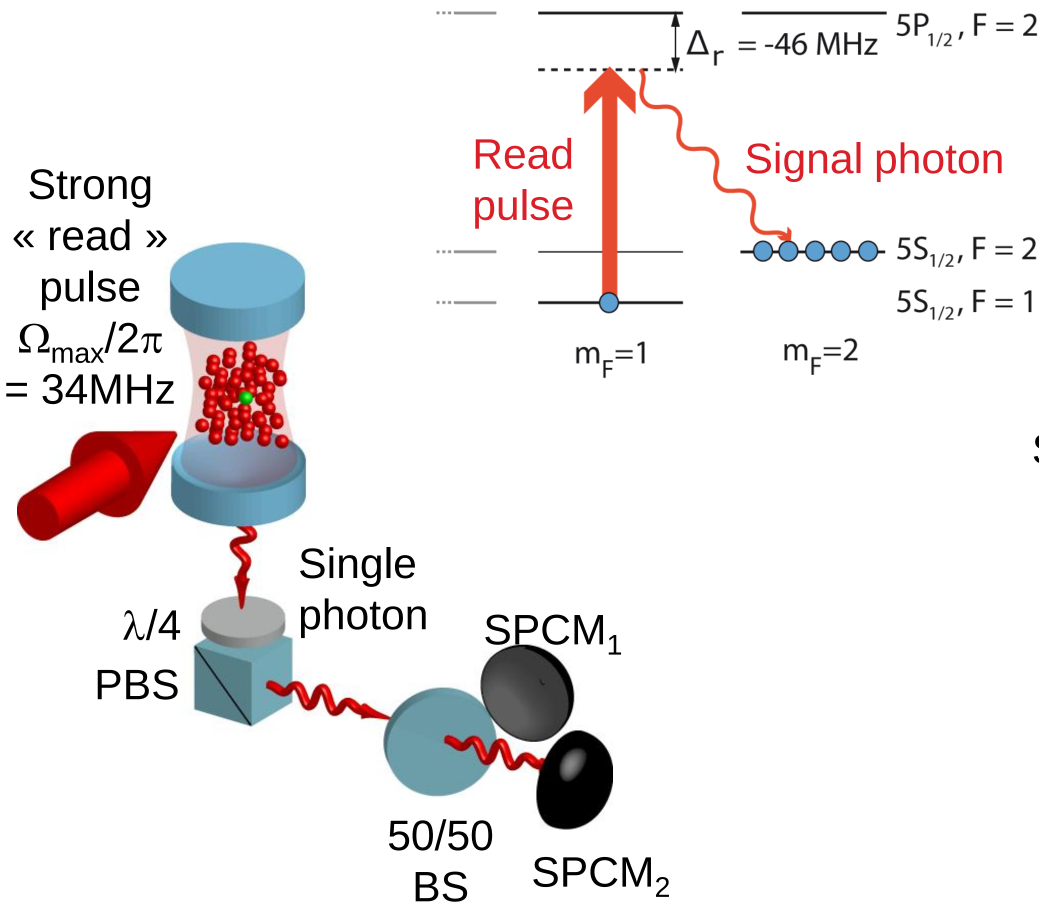
Read step:
Spin excitation retrieved as a photon
Collective phase-matched process

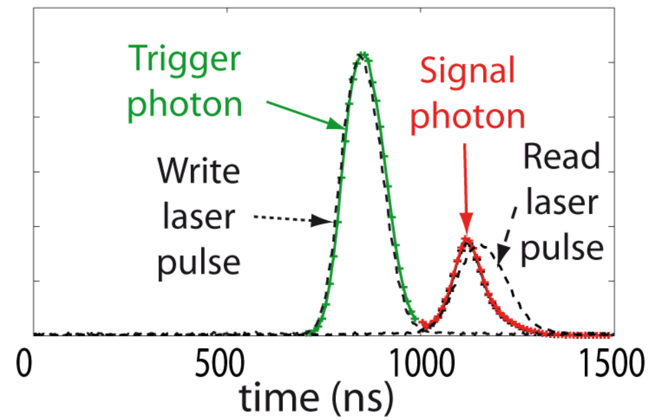
$$\vec{k}_{Trigger} - \vec{k}_{Read} = \vec{k}_{Signal} - \vec{k}_{Write}$$

Emitted in (another) cavity mode

Duan & al, Nature **414**, 413 (2001)

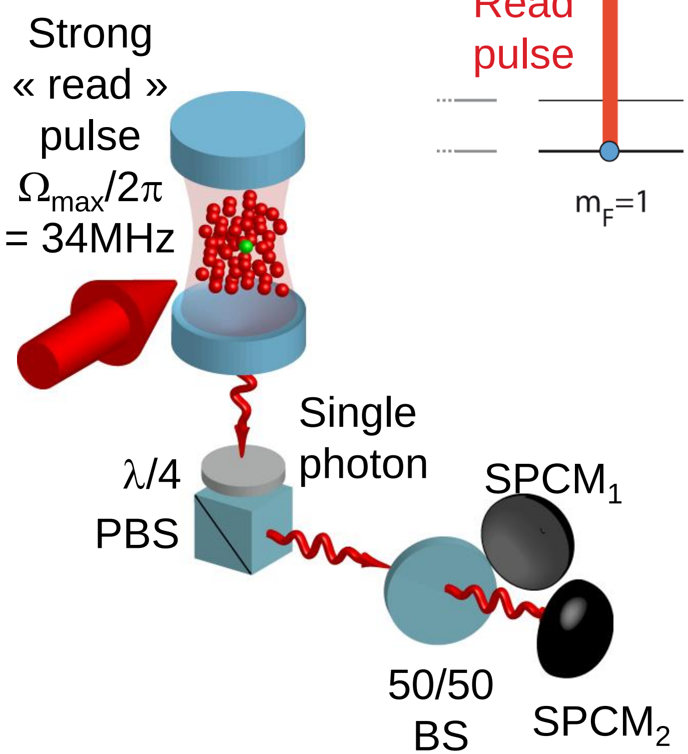
Single photon source (DLCZ)

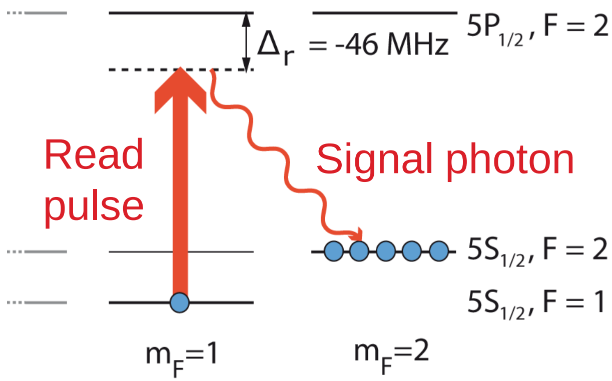


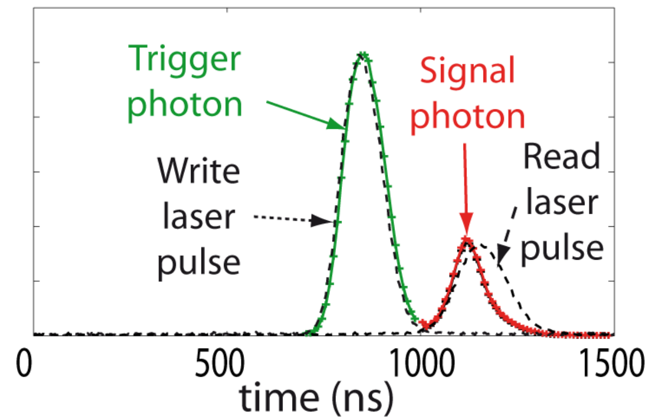


Stanojevic *et al*, PRA **84**, 053830 (2011)

Single photon source (DLCZ)

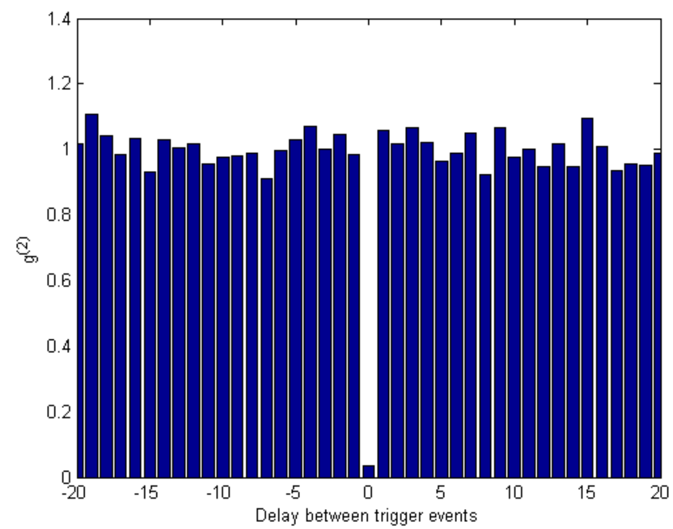






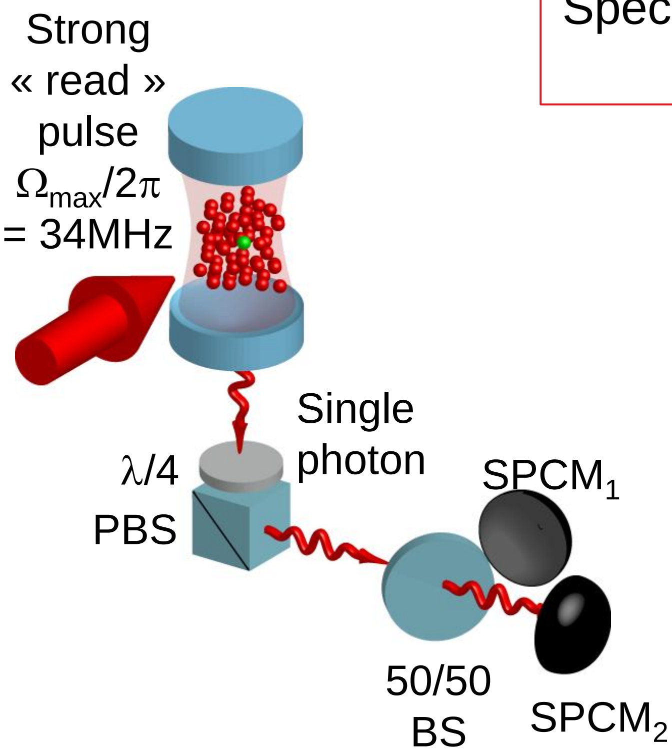
Stanojevic *et al*, PRA **84**, 053830 (2011)

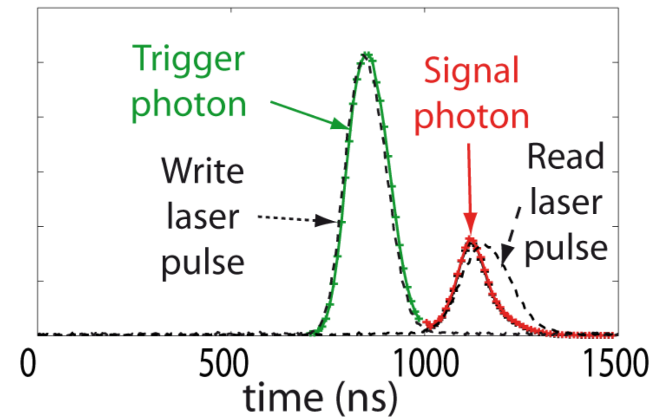
$$g^{(2)}(0) = \frac{\langle \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2} = 0.03$$



Single photon source (DLCZ)

Frequency ?
Chirp?
Spectral width?
…





Stanojevic *et al*, PRA **84**, 053830 (2011)

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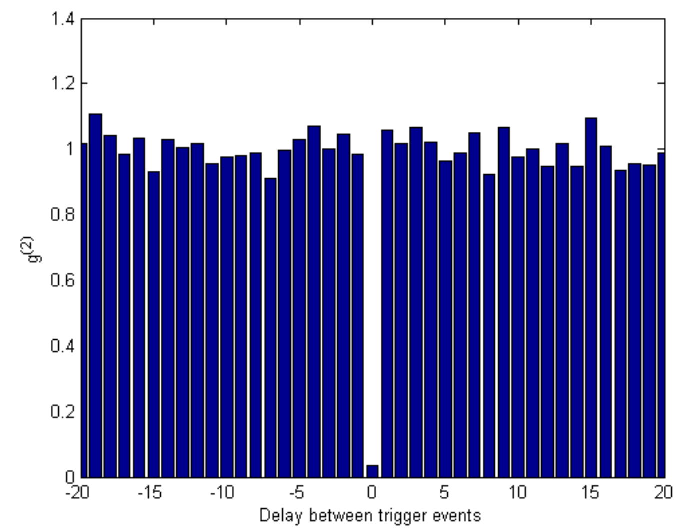
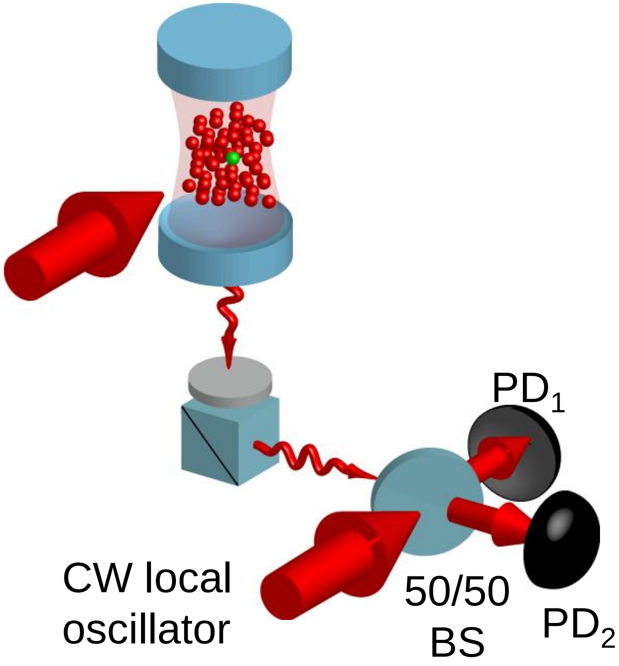


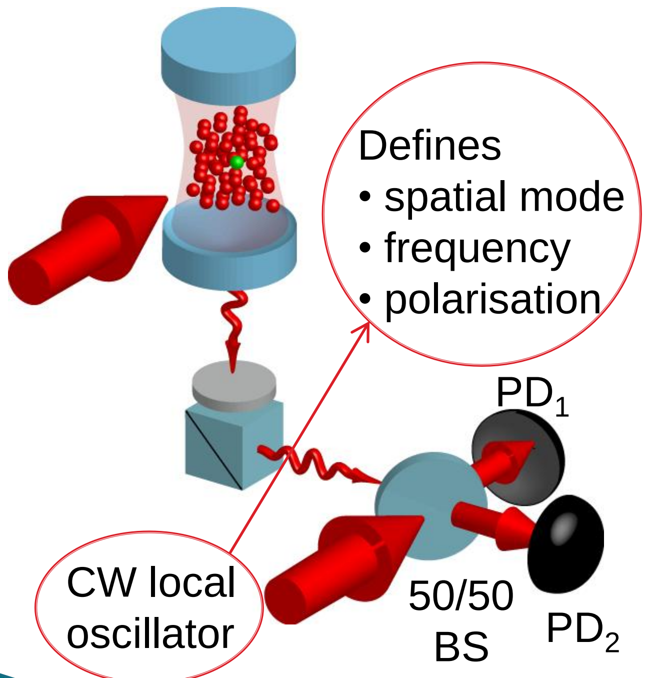
Homodyne tomography

$$I_1\text{-}I_2 \propto X = \frac{\hat{a}e^{-i\varphi}+\hat{a}^\dagger e^{i\varphi}}{\sqrt{2}}$$



Homodyne tomography

$$I_1 - I_2 \propto X = \frac{\hat{a}e^{-i\varphi} + \hat{a}^{\dagger}e^{i\varphi}}{\sqrt{2}}$$



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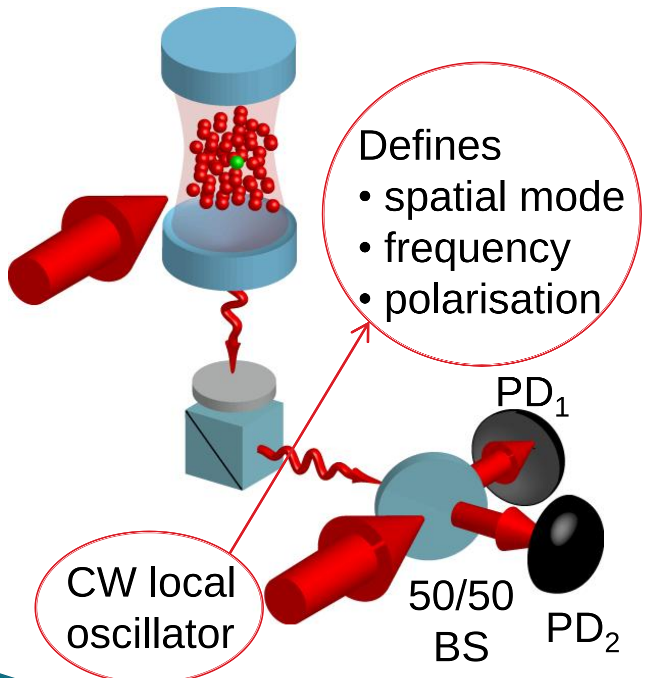
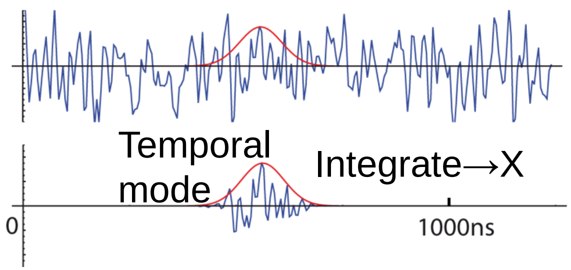


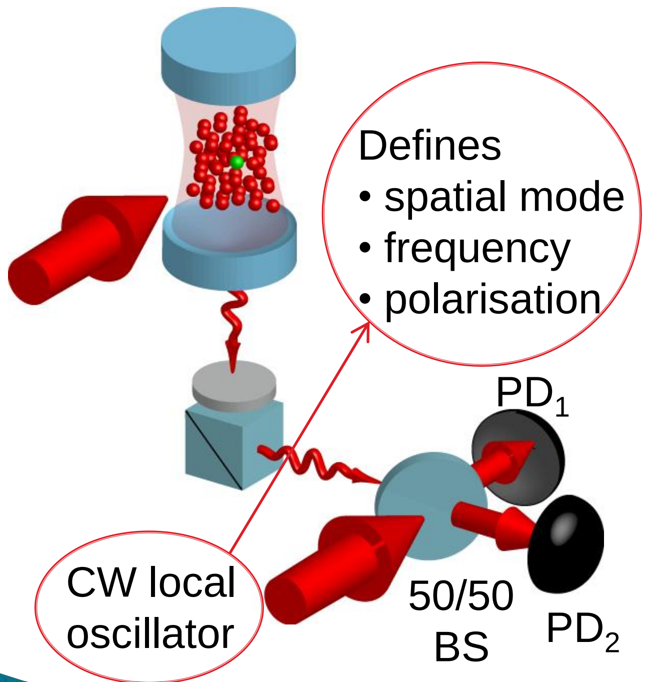
Homodyne signal



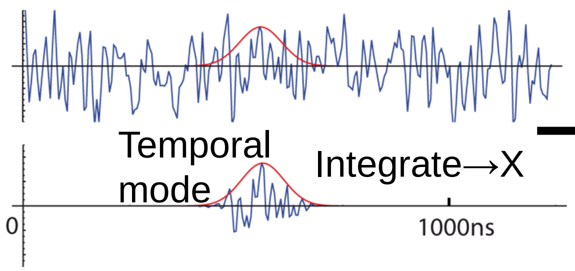
Bimbard *et al*, PRL **112**, 033601 (2014)

Homodyne tomography

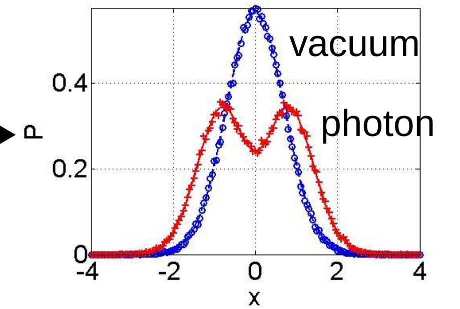
$$I_1 - I_2 \propto X = \frac{\hat{a}e^{-i\varphi}+\hat{a}^\dagger e^{i\varphi}}{\sqrt{2}}$$



Homodyne signal



Quadrature distributions



Bimbard *et al*, PRL **112**, 033601 (2014)

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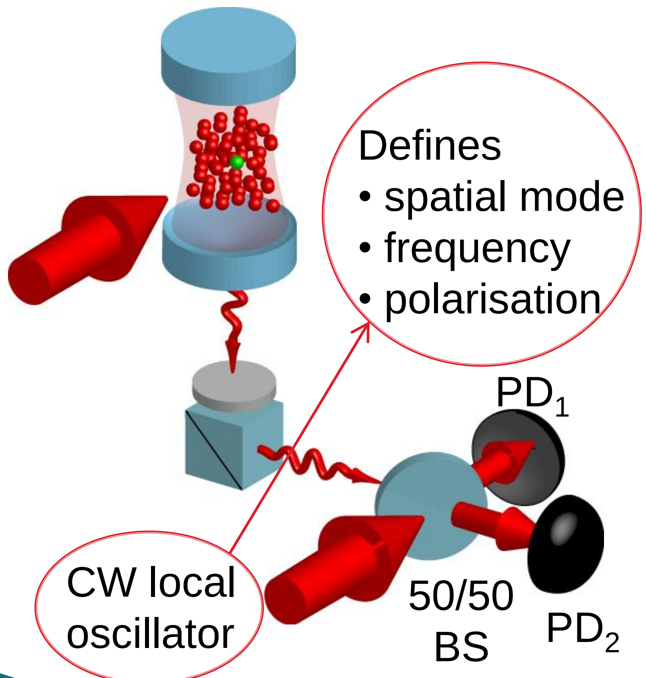
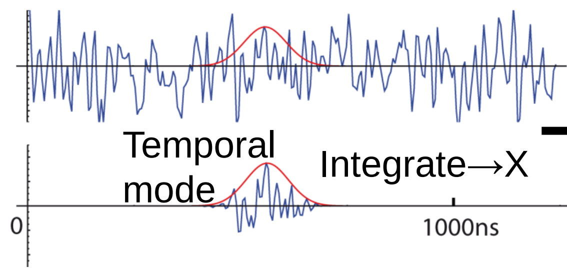
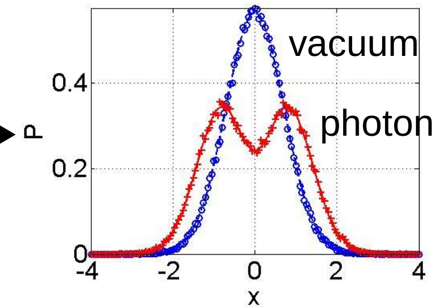


Homodyne signal

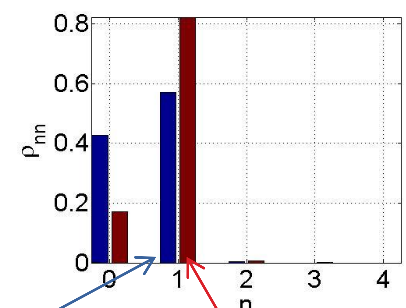


Quadrature distributions



maximal likelihood

Density matrix



Detector's efficiency:

- optical = 92%
- mode-matching = 97%
- quantum = 91%

\+ Electronic noise = 1%

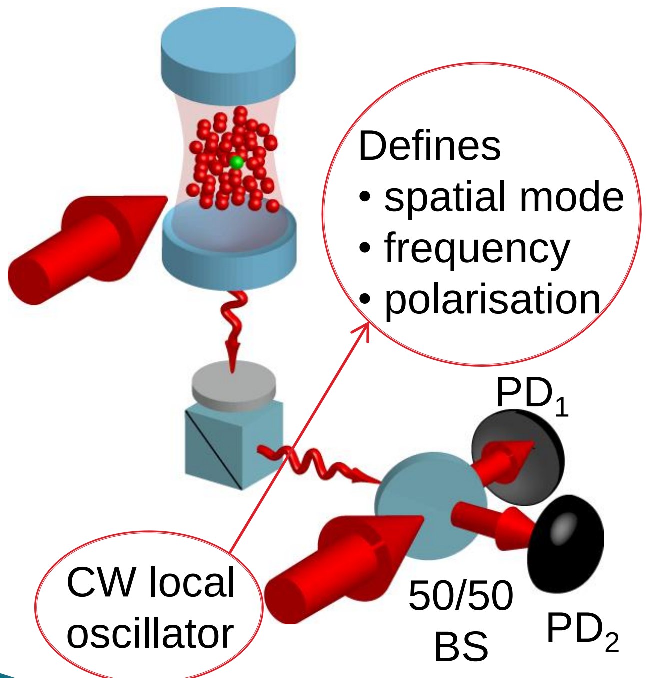
measured state: 57%

generated state: 82%

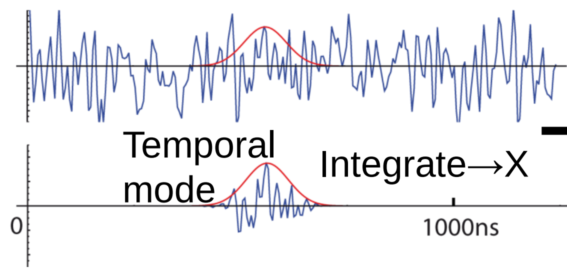
Bimbard *et al*, PRL **112**, 033601 (2014)

Homodyne tomography

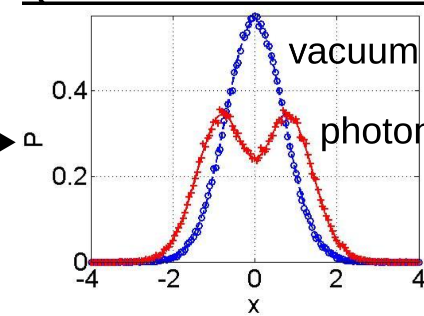
$$I_1 - I_2 \propto X = \frac{\hat{a}e^{-i\varphi}+\hat{a}^\dagger e^{i\varphi}}{\sqrt{2}}$$



Homodyne signal

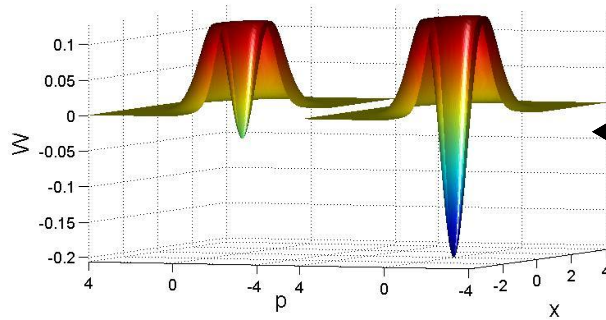


Quadrature distributions

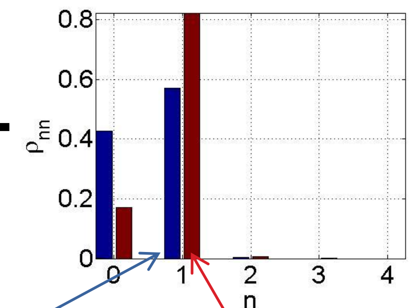


maximal likelihood

Wigner function



Density matrix



measured state: 57%

generated state: 82%

Bimbard *et al*, PRL **112**, 033601 (2014)

Efficiency limits

Homodyne/counting measurements consistent:

- Temporal mode $\exp(-t^2/2\tau^2)$, τ=40ns
- Generation efficiency η~80%

$$\eta = P_{Doppler}(t) * P_C * P_{Read} * P_{pump} * P_{mode} * P_{cav}$$

0.94 x0.97 x0.96 x0.965 x0.97 = 0.82

Polariton decoherence

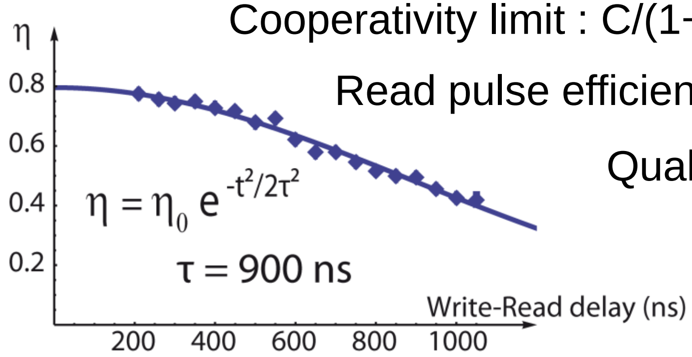
Cooperativity limit : C/(1+C)

Read pulse efficiency + defects

Quality of optical pumping

Amplitude and phase matching

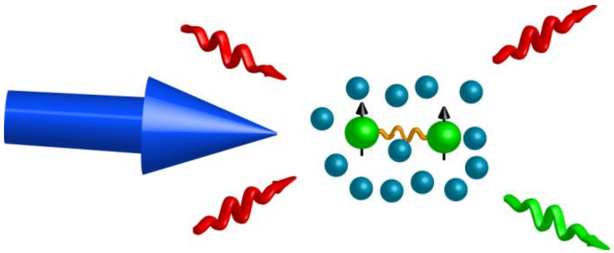
Cavity resonance condition



τ = Doppler decoherence time at 50 μK

Bimbard *et al*, PRL **112**, 033601 (2014)

Outline



Atomic physics:
create
non-linear effects

Part I

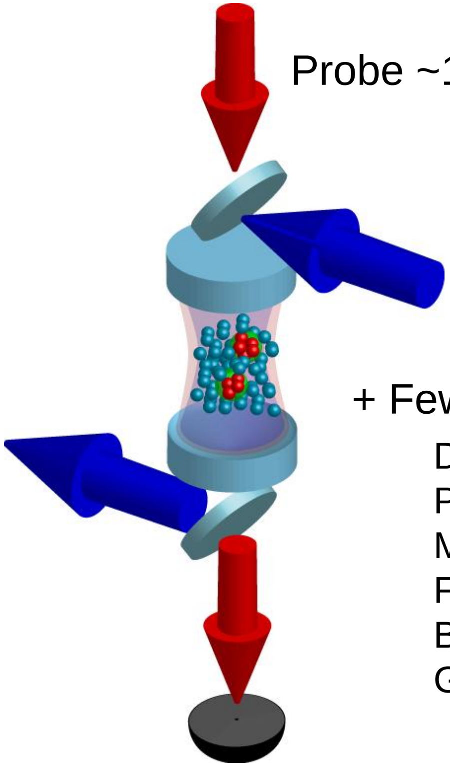
Quantum optics:
Manipulate & detect
quantum states

Part II

Rydberg-mediated
photonic interactions

Part III

Quantum effects?

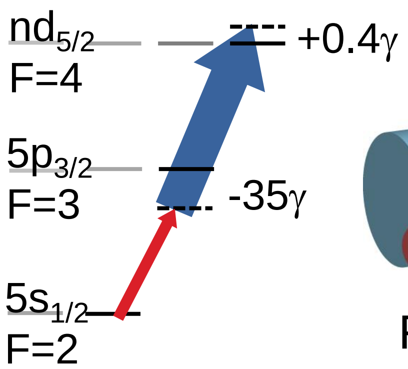


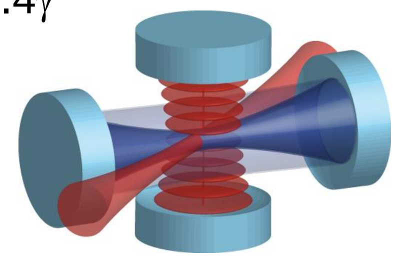
Probe ~1nW ~1000 photons ⇒ ~1 photon?

+ Fewer losses than previous experiments?

Dudin & Kuzmich, Science **336,** 887 (2012),
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)
Firstenberg *et al*, Nature **502**, 71 (2013)
Baur *et al*, PRL **112**, 073901 (2014)
Gorniaczyk *et al,* PRL **113**, 053601 (2014)

Off-resonant regime

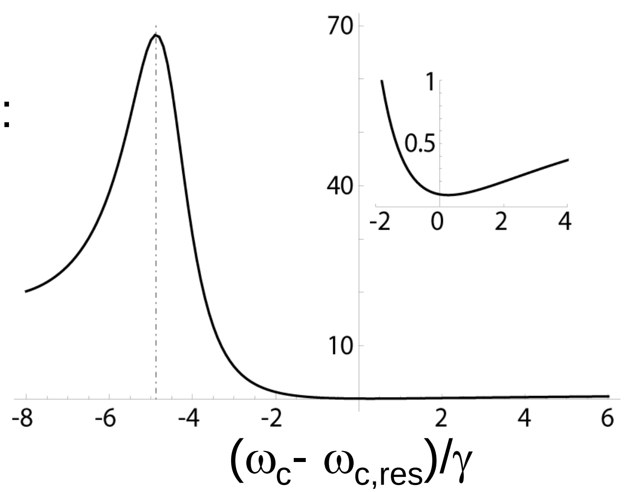




F = ~~100~~ 1000
w = ~~90~~ 15 µm

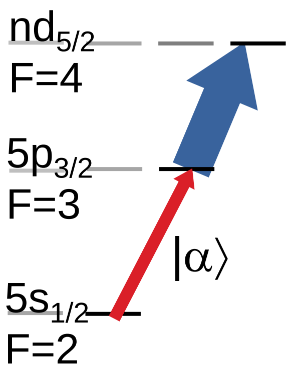
- ✓ Brigher, uniform control beam
  - → Buildup cavity (G~16)
- ✓ Smaller, denser cloud
  - → Dipole trap (σ~40µm)
- ✗ Higher cavity finesse & smaller waist

Expected $g^{(2)}$ of transmitted light:
(« Super-atom » model)

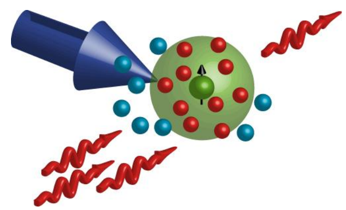


Grankin *et al*, NJP **16**, 043020 (2014)

Resonant regime



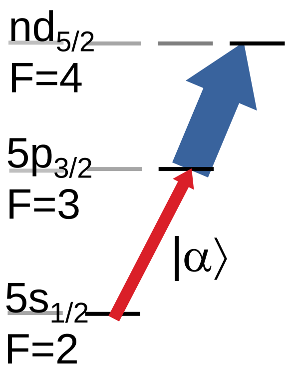
<u>Free space:</u>



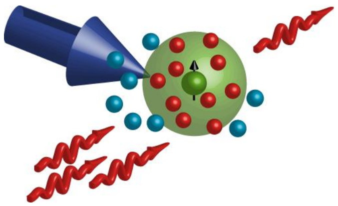
Non-linear losses ⇒ Single photon

Dudin & Kuzmich, Science **336,** 887 (2012),
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)

Resonant regime



Free space:



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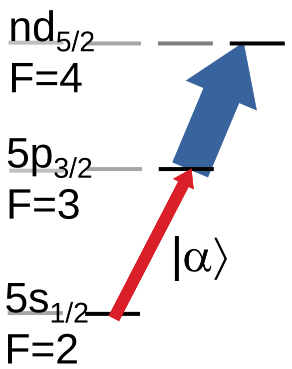
Dudin & Kuzmich, Science **336,** 887 (2012),
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)

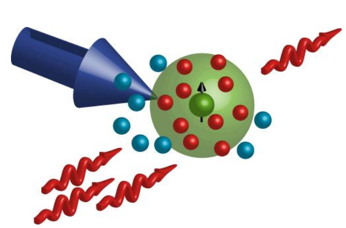
Cavity:

Turns losses into phase shift

Resonant regime



Free space:



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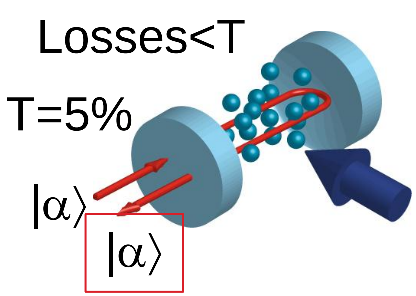
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)

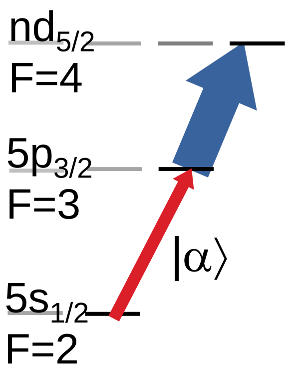
Cavity:

Turns losses into phase shift

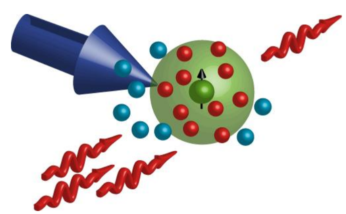
$|\alpha \ll 1\rangle$: EIT



Resonant regime



Free space:



Non-linear losses ⇒ Single photon

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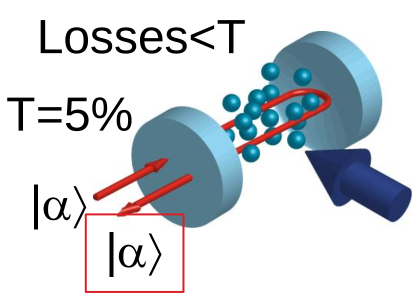
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)

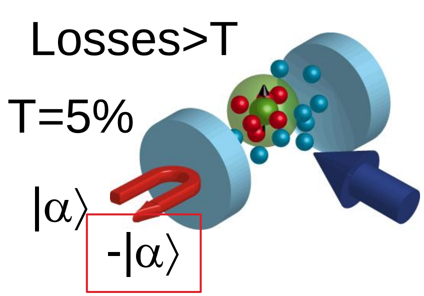
Cavity:

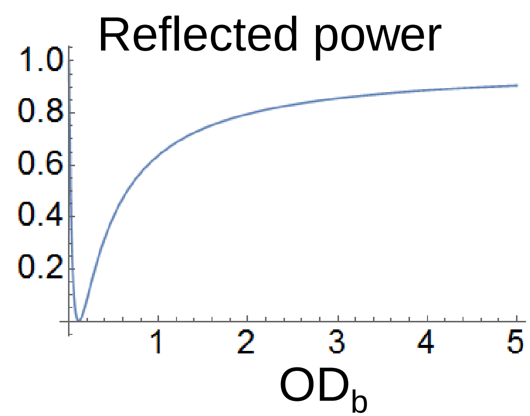
Turns losses into phase shift

$|\alpha \ll 1\rangle$: EIT

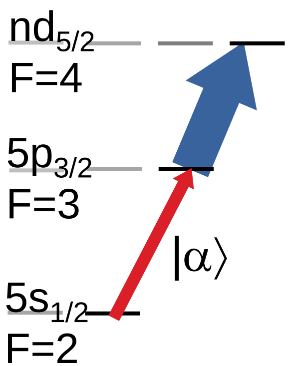


$|\alpha \gg 1\rangle$: Blockade

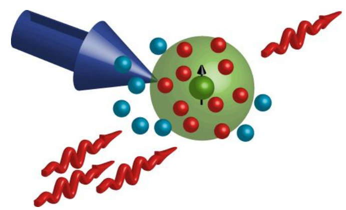




Resonant regime



Free space:



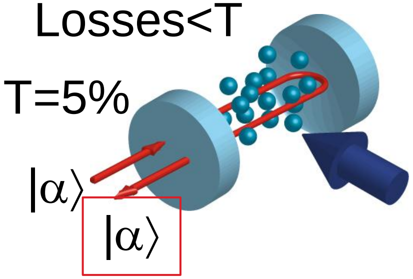
Non-linear losses ⇒ Single photon

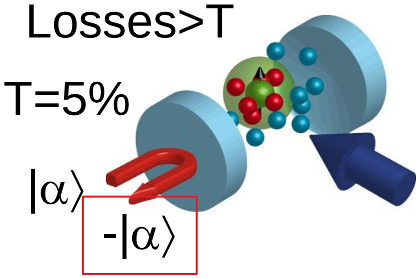
Dudin & Kuzmich, Science **336,** 887 (2012),
Peyronel *et al,* Nature **488**, 57 (2012)
Maxwell *et al,* PRL **110**, 103001 (2013)

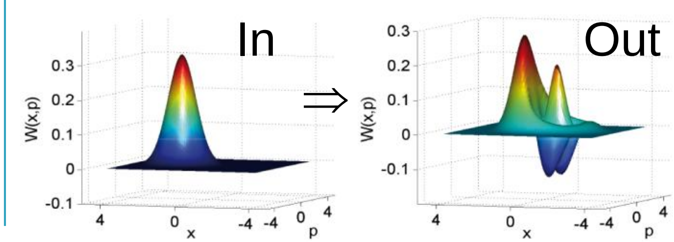
Cavity:

Turns losses into phase shift

|α<<1⟩: EIT	|α>>1⟩: Blockade	|α≈1⟩: Non-gaussian?
Losses<T	Losses>T	
T=5%	T=5%	







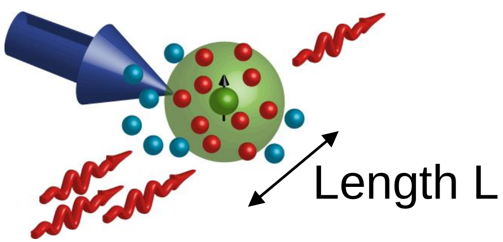
First experimental evidence of non-classical effects

No free lunch

- Additional technical complexity (OK)
- Specific theoretical models (OK)
- Temporal/spectral issues :

Can the tail of a photon enter the system before its head comes out?

Free space:

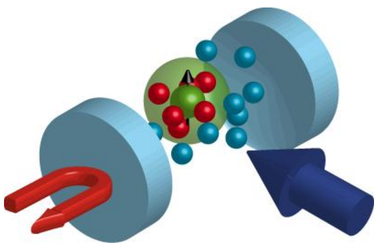


Time to cross the gas $\propto$ L

EIT linewidth $\propto L^{-1/2}$

$\Rightarrow$ OK

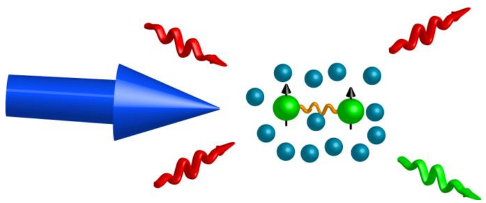
Cavity:



Storage time $\propto$ (linewidth)$^{-1}$ …

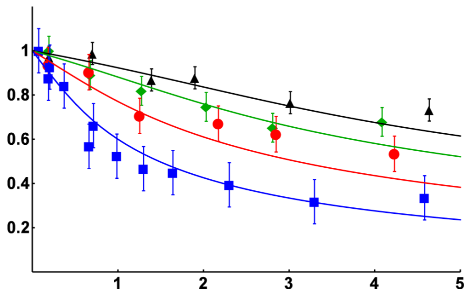
Dynamic control $\Rightarrow$ OK

Conclusion



Rydberg physics:
create
non-linear effects

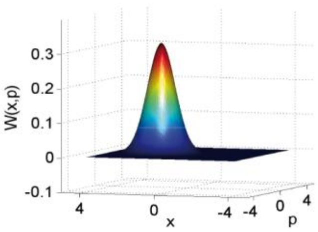
PRA **88**, 053845 (2013)
PRL **109**, 233602 (2012)

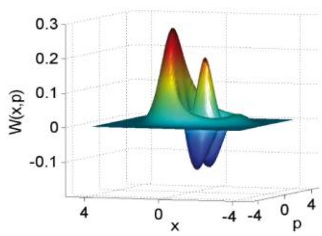


Rydberg-mediated
photonic interactions

PRA **86**, 021403(R) (2012)
NJP **16**, 043020 (2014)

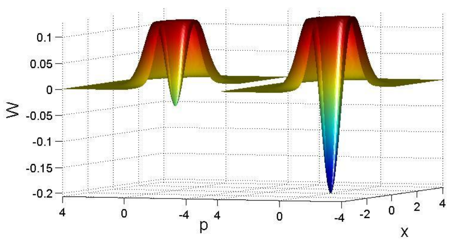
Work in progress



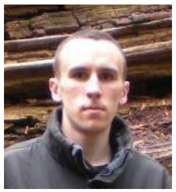


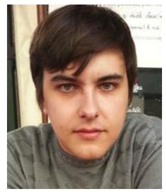
Quantum optics:
Manipulate & detect
quantum states

PRA **84**, 053830 (2011)
PRL **112**, 033601 (2014)



Thanks!



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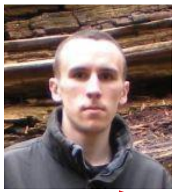  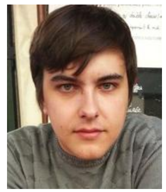 

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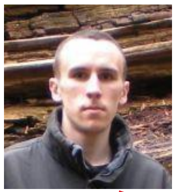

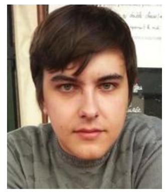


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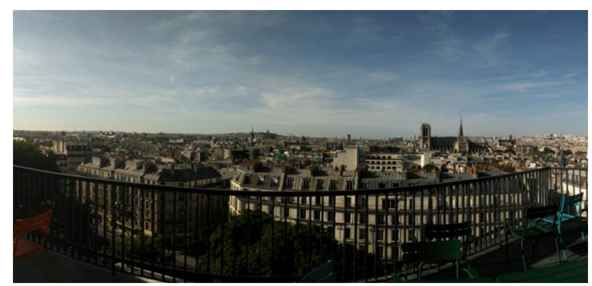

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