Experimental Techniques for Strong Interaction between Photons and Atoms

AQIS'15 – KIAS, Seoul, 24-27 August 2015

Christian Kurtsiefer

Centre for Quantum Technologies

National University of Singapore

WARNING

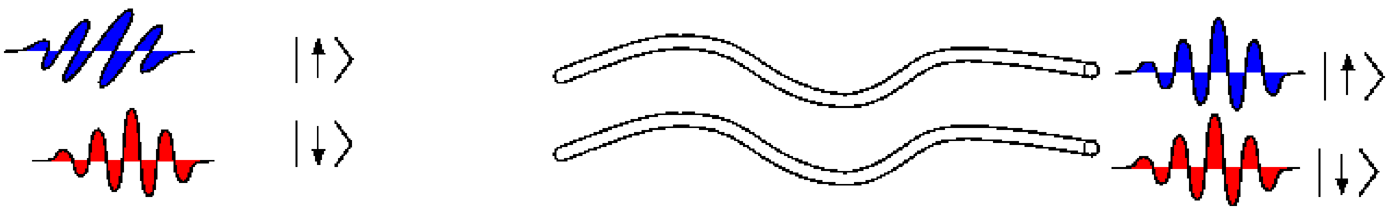
This talk is very experimental

Why bother?

- Any implementation of quantum information operations needs real physical systems
- A hard physical property to find are nonlinear responses at the single quantum level
- We need a good balance between controlled interactions between individual qubits and isolation from an environment
- Any scalable system would likely require a coherent interconnection mechanism

Why optical photons?

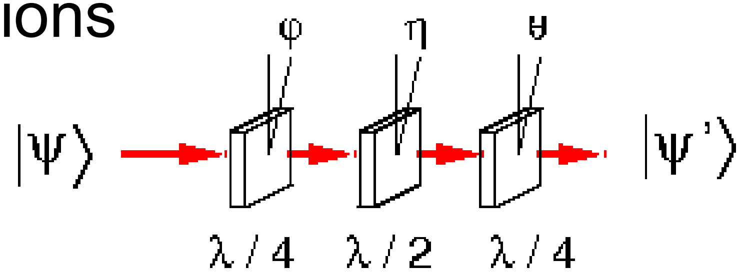
- Nice transport, nice qubits



- Low coupling to environment, easy detection, low noise

$$\hbar\omega / k_B T \approx 40..50$$

- Simple 1-qubit operations



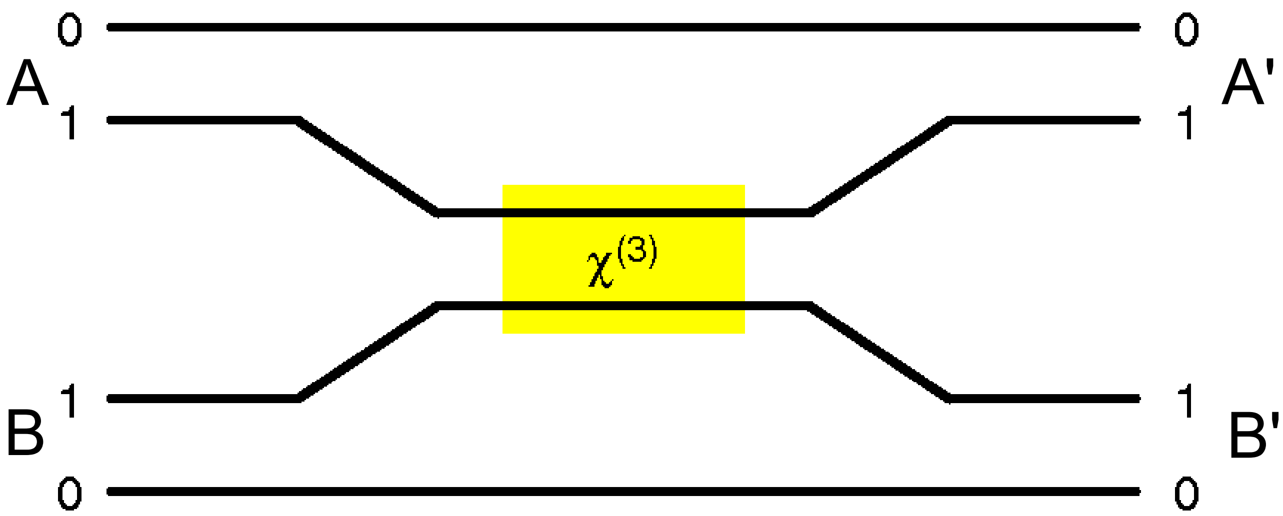
- Some simple interesting 2-qubit primitives:
  Entangled parametric conversion sources for a few qubits

Why atoms / ions / color centers ?

- Good isolation from environment, low decoherence
- Nice qubits (2-level systems)
- Localized
- Simple 1-qubit operations
- Compatible with optical photons, reasonable coupling

Gates between photons ?

- Use atoms as nonlinear elements for photons



A, B	A', B'
0,0	0,0
0,1	0,1
1,0	1,0
1,1	(1,1) $e^{i\varphi}$

- Requires strong interaction between single photons and atoms; traditionally: realm of cavity QED

Where do we want to be ?

$$\hbar / T_1 < \hbar g_0 \ll \hbar \omega$$

Lifetime of a qubit $\qquad \hat{E}_0 \cdot \hat{d}$

- Many atoms → large *d* (Ensemble of atoms)
- Large E_0 for a single photon
  → cavity QED, field mode engineering

Outline

- **Part I**: Interaction between atoms and photons in the strong focusing regime

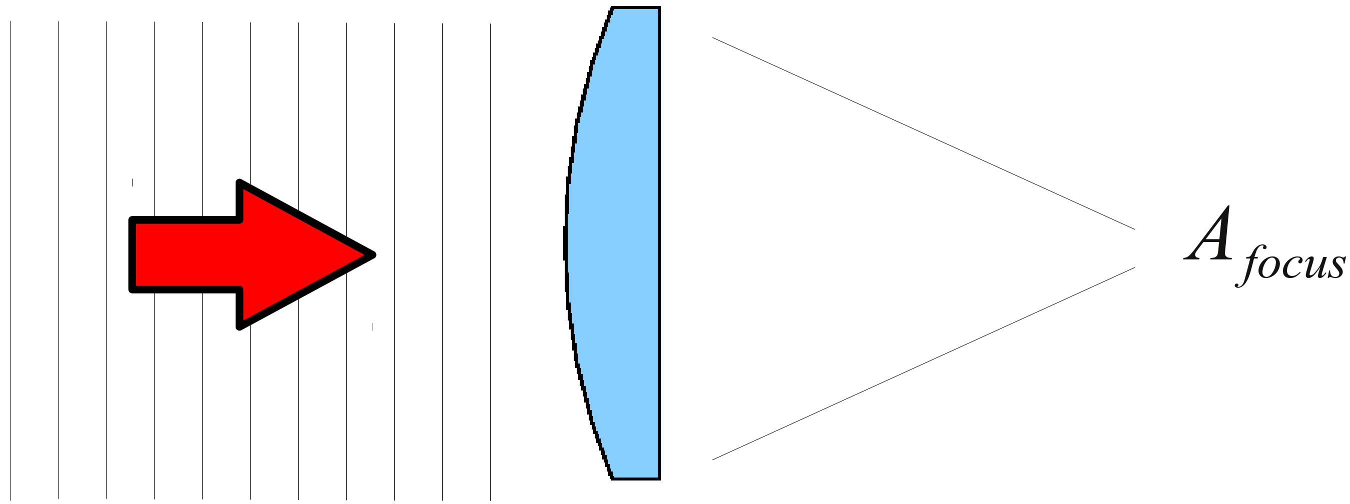
  - propagating optical modes
  - discrete modes in an unusual cavity geometry

- **Part II**: A photon pair source compatible with atomic transitions

  - narrow bandwidth photon pairs
  - heralded single photons
  - funny field envelopes

- **Part III**: Combine the two systems: Hong-Ou-Mandel interference

Part I: Alternative to cavity-QED



- Diffraction limit: $A_{focus} \approx \lambda^2 / \left(NA^2\right) \cdot something$

- For large numerical aperture: $A_{focus} \approx \sigma_{max}$ or $R \approx 1$

Strong coupling?

Focused Gaussian beam

paraxial approximation

$$R_{sc}=\frac{P_{sc}}{P_{in}}=\frac{3\lambda^2}{\pi w_L^2}\left(\frac{E_A}{E_L}\right)^2\approx\frac{3\lambda^2}{\pi w_f^2}=3u^2\approx\sigma_{max}/A$$

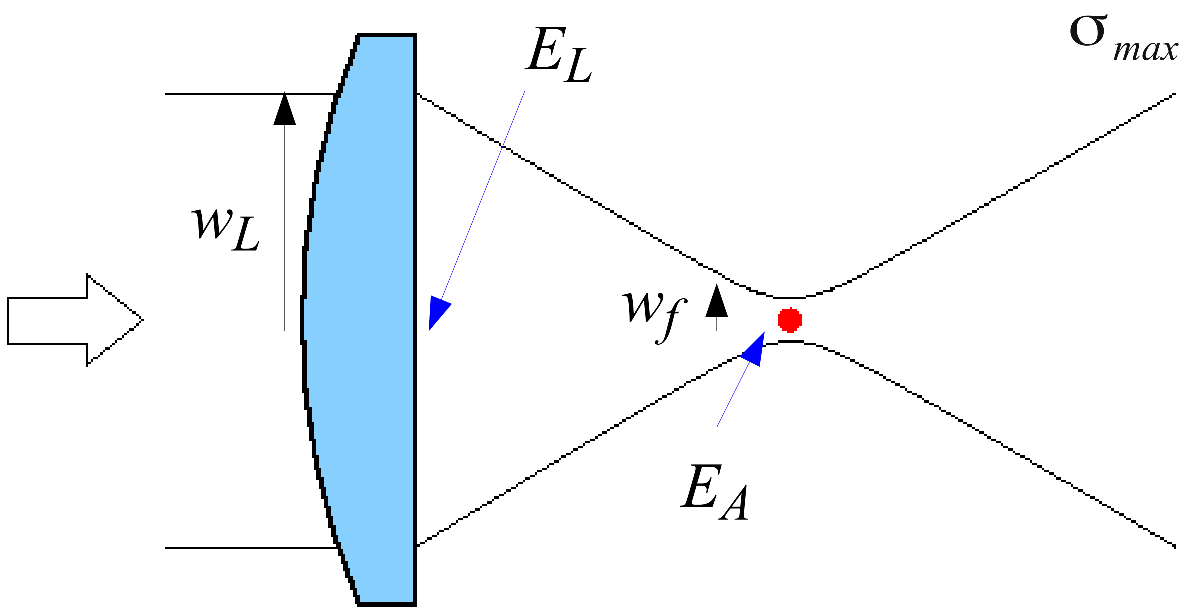
focal area

$$A\approx\pi w_f^2/2$$

focusing strength $u:=w_L/f$

atomic scattering cross section

$$\sigma_{max}=3\lambda^2/2\pi$$

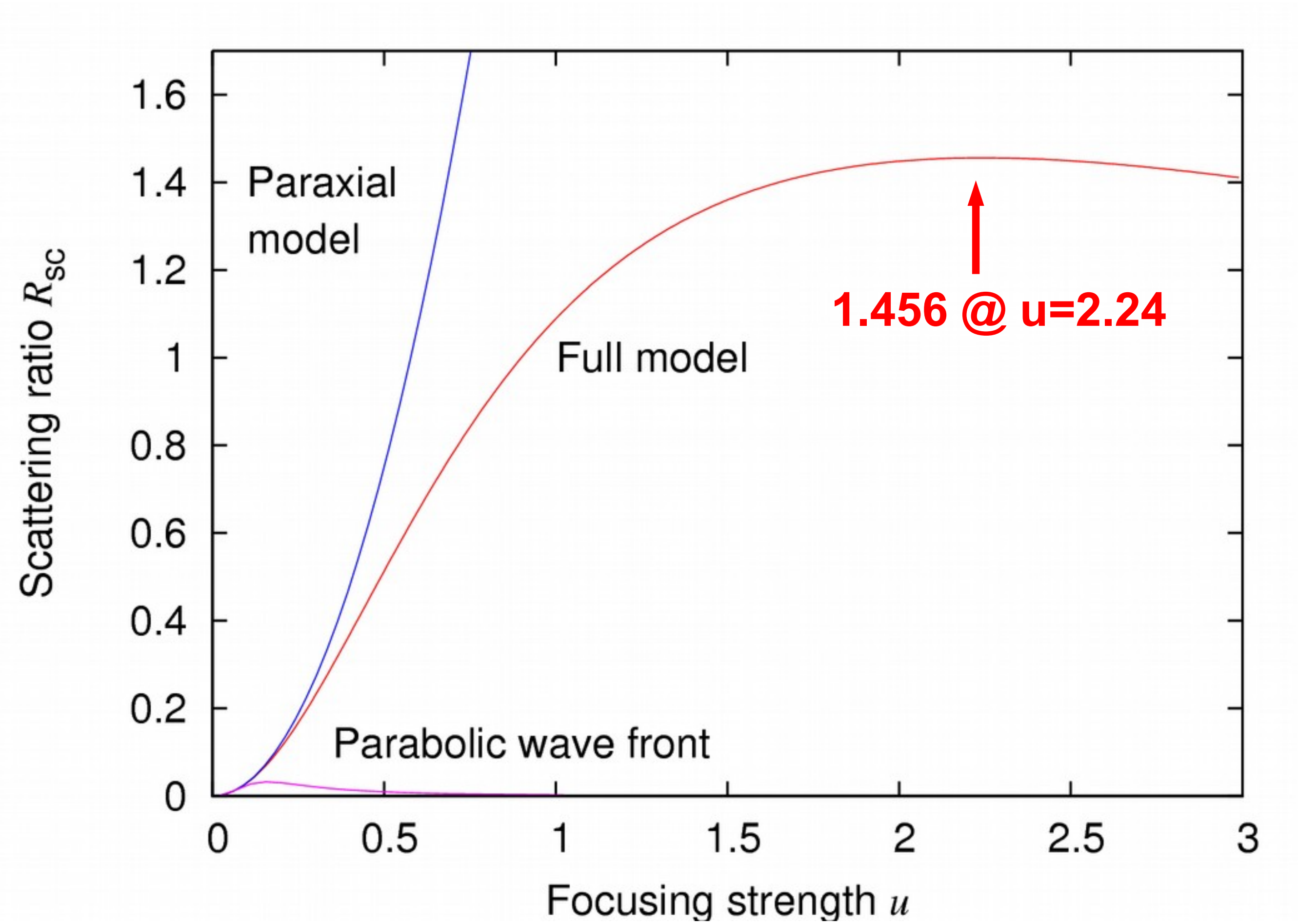


E_A diverges, use full expression for field

Focused Gaussian beam (exact)

- scattering “ratio” like in plane wave excitation mode:

$$R_{sc} := \frac{P_{sc}}{P_{in}} = \frac{3}{4u^3} e^{-2/u^2} \left[\Gamma\left(-\frac{1}{4}, \frac{1}{u^2}\right) + u\,\Gamma\left(\frac{1}{4}, \frac{1}{u^2}\right) \right]^2$$



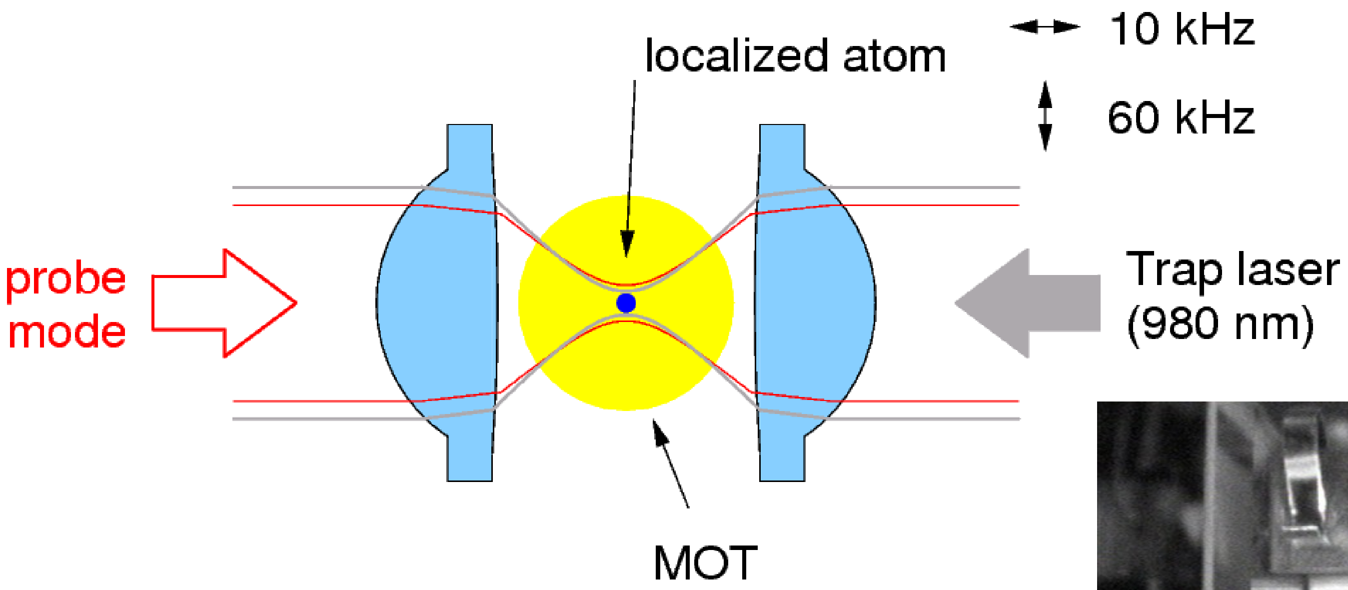
Richardson/Wolf limit:

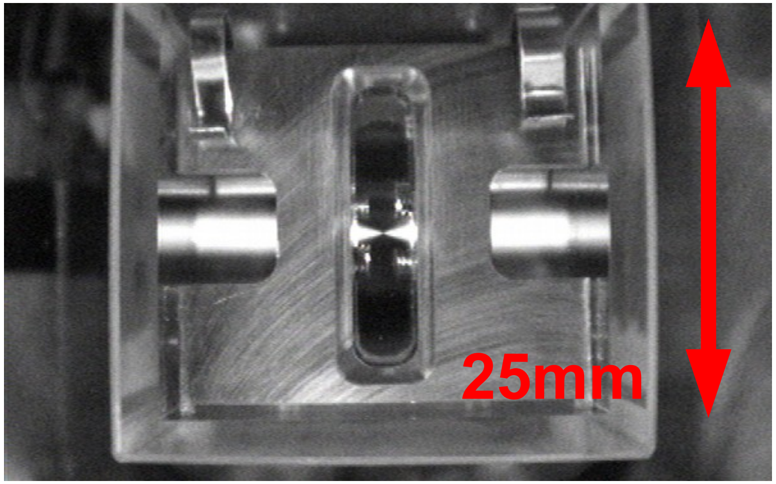
$$R_{sc} \leq 2$$

*M. K. Tey, G. Maslennikov, T.C.H. Liew et al., NJP **11**, 043011 (2009)*

No-cavity Experiment

One Rb-87 atom in an optical dipole trap



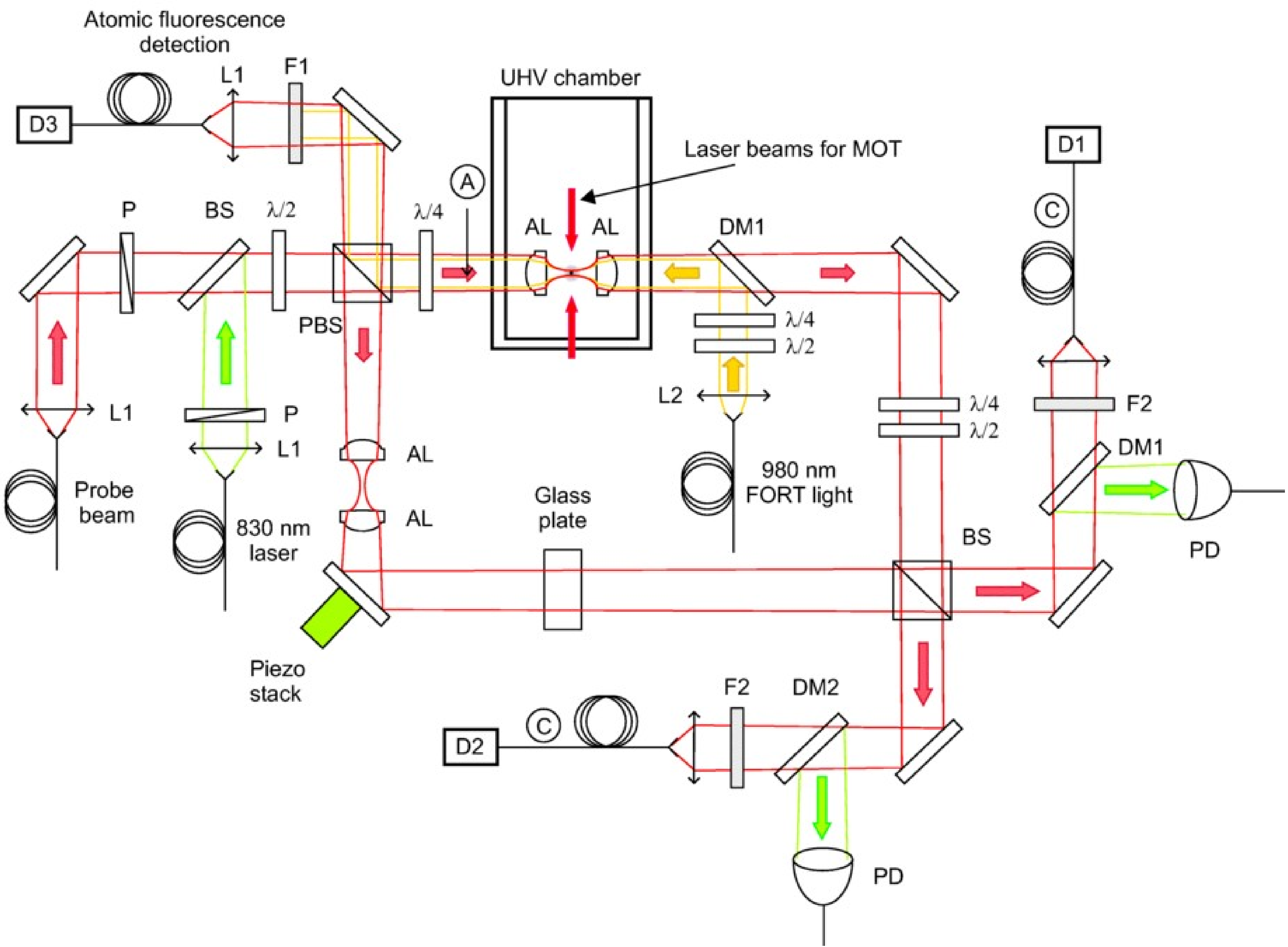


- Extinction >10% for with probe mode collected into single mode fiber

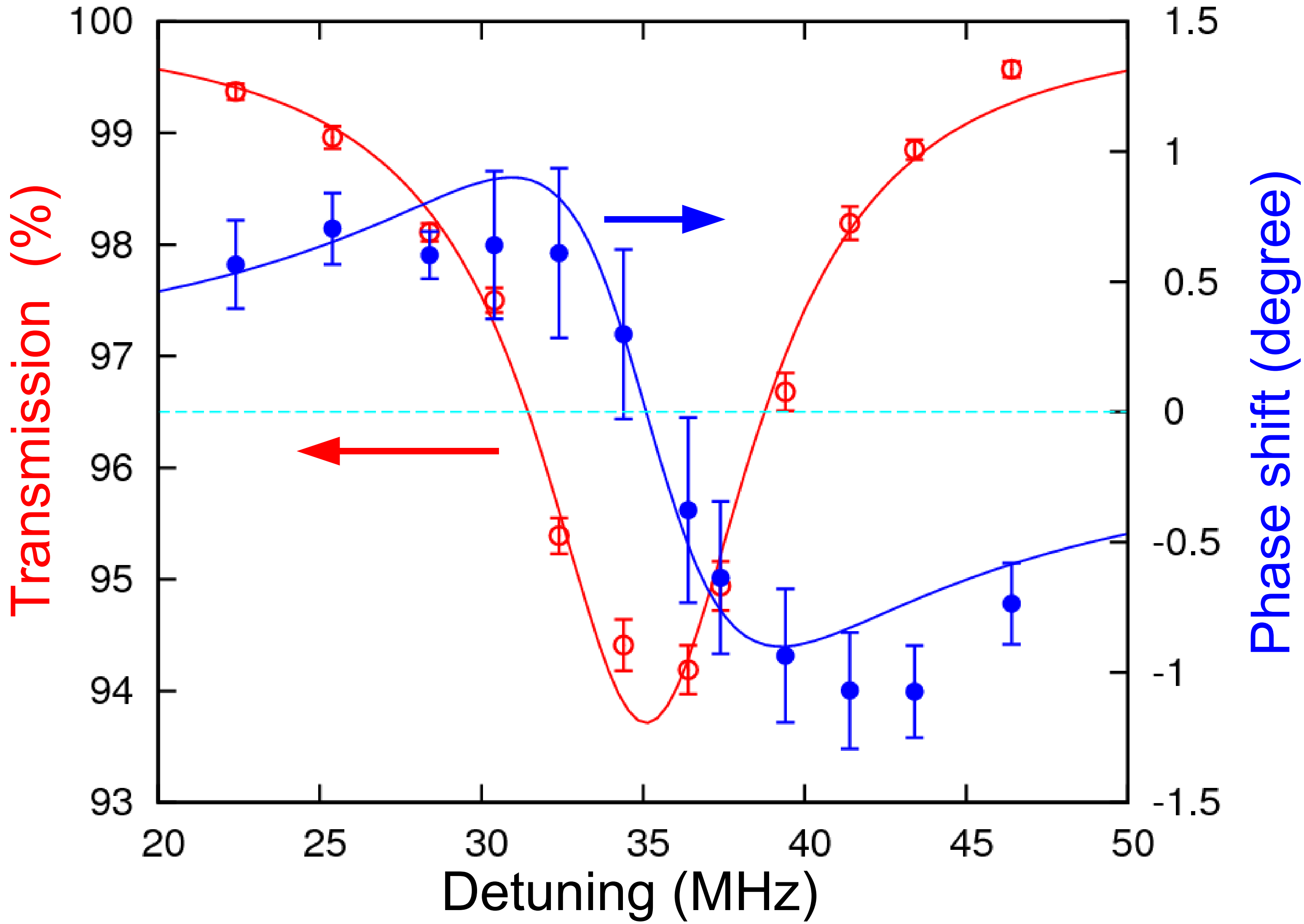
M. K. Tey, Z. Chen, S.A. Aljunid, B. Chng, F. Huber, G. Maslennikov,C. K.
nature physics ***4****, 924 (2008)*

Experiment, almost real

Mach-Zehnder interferometer with one atom



Phase shift / Transmission

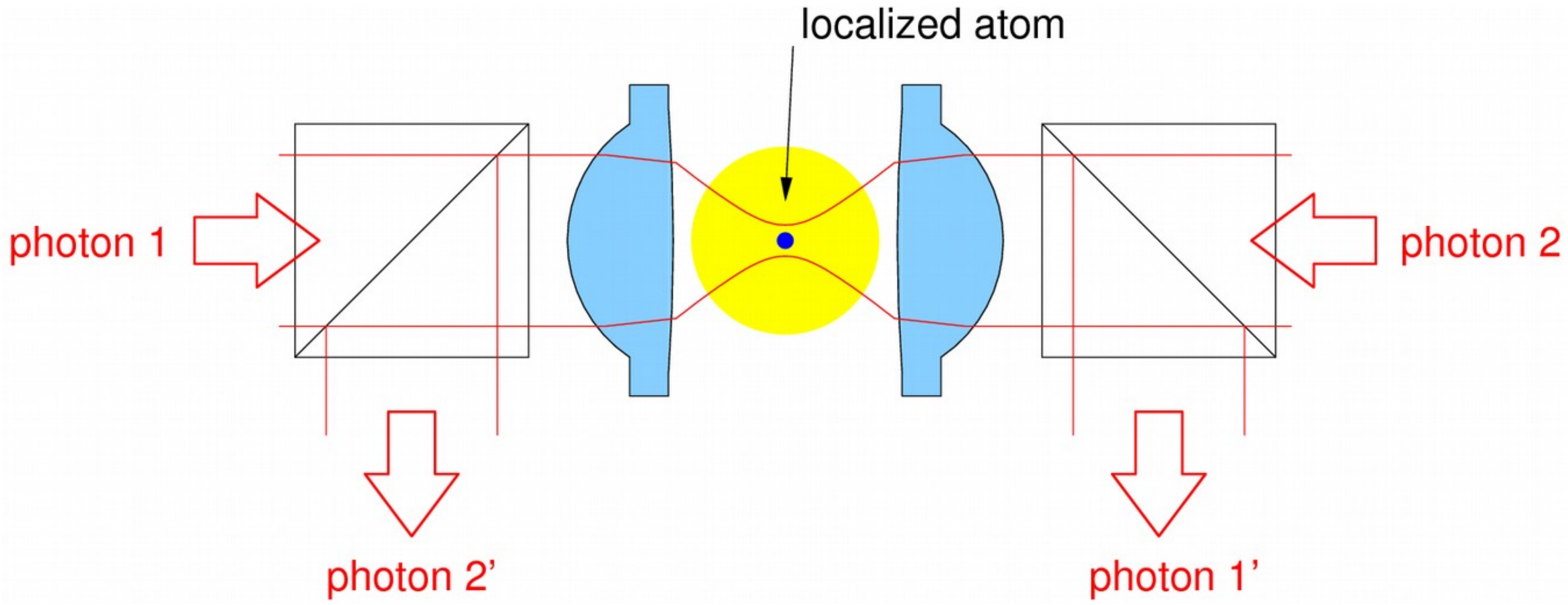


phase shift within factor 2..3 of prediction by stationary atom model!

*S.A. Aljunid et al. PRL **103**, 153601 (2009)*

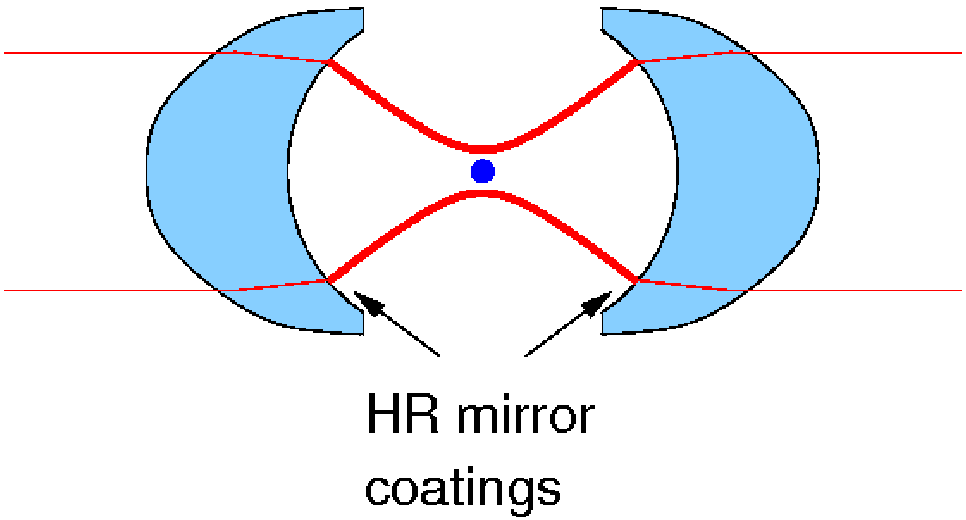
Dreams...

- Try to see conditional phase gate....



Combine focusing & cavity

- Get easier into “strong coupling” regime



S.E. Morrin, C.C. Yu,
T.W. Mossberg,
*PRL **73**, 1489 (1994)*

A. Haase, B. Hessmo,
J. Schmiedmayer,
*Opt. Lett. **31**, 268 (2006)*

Recently: many nice papers from Jakob Reichel group

Electrical field operator (single freq):

$$\hat{\boldsymbol{E}}(x,y,z)=i\sqrt{\frac{\hbar\omega\pi}{\epsilon_0 L 3\lambda^2}R_{sc}}\left(\boldsymbol{g}(x,y,z)\hat{a}^+-\boldsymbol{g}^*(x,y,z)\hat{a}\right)$$

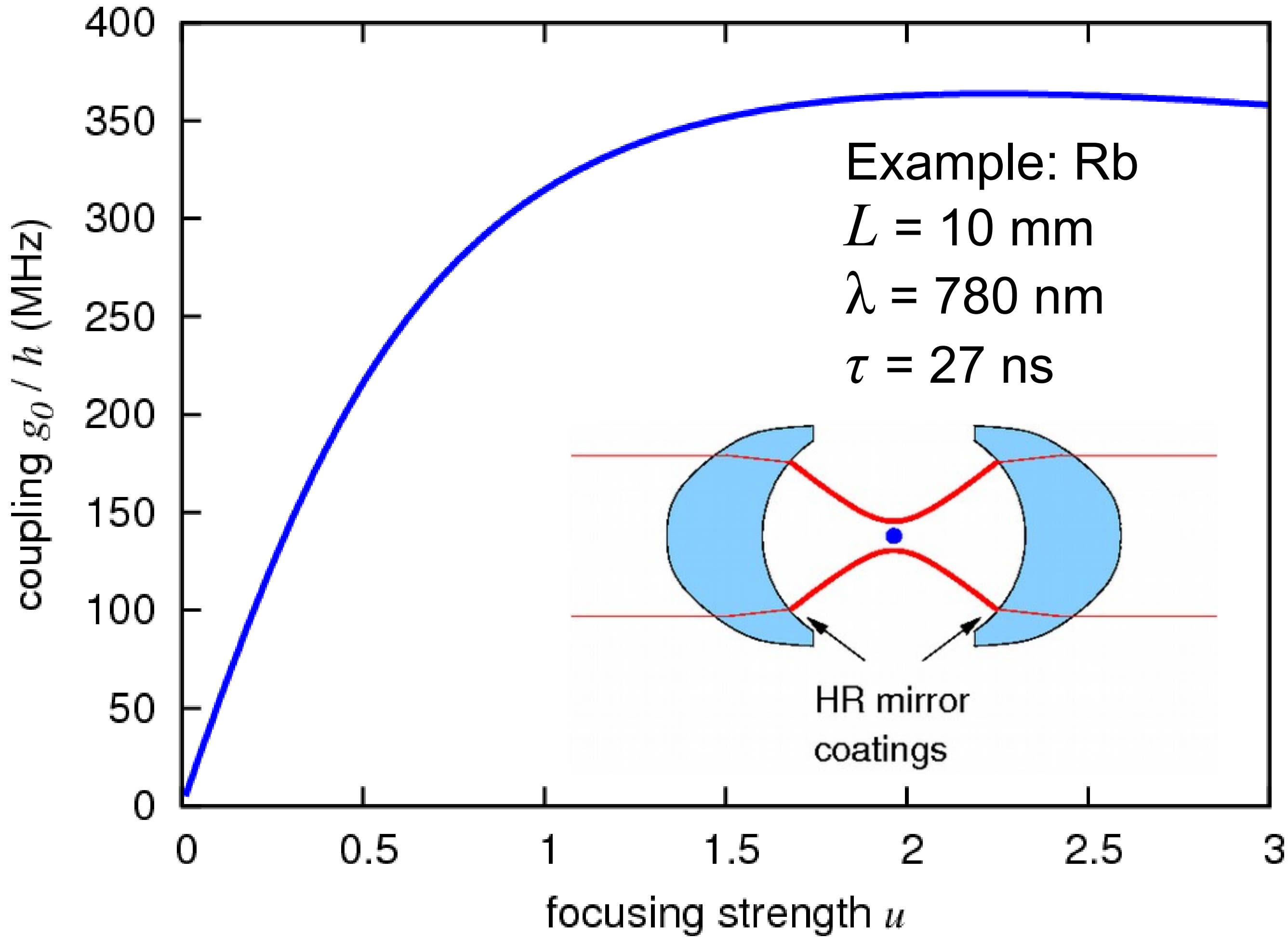
Scattering ratio, 0...2

mode function, g=1 at focus

Effective mode volume: $V=L\lambda^2/R_{sc}$

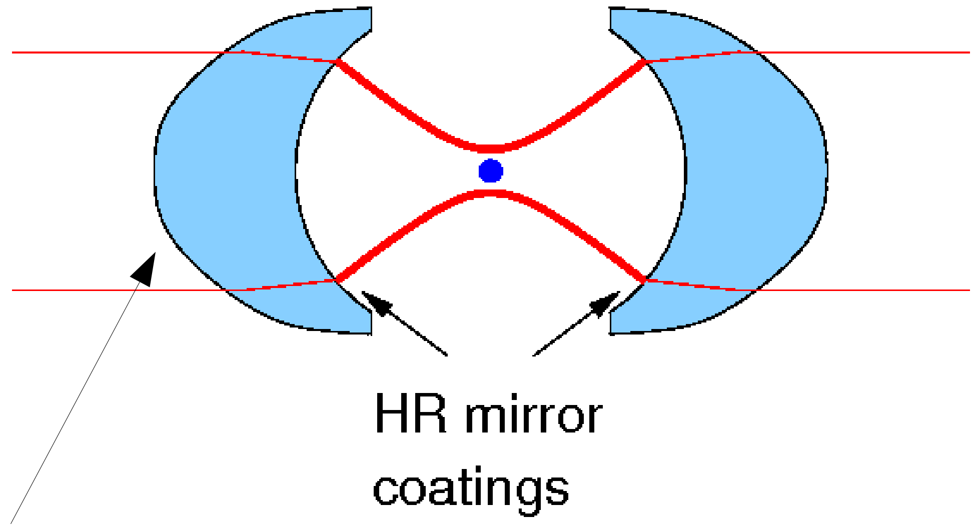
Weak cavity – strong coupling?

Coupling strength: $g_0 = \hbar \sqrt{\frac{\pi c R_{sc}}{\tau L}}$



S.A. Aljunid et al., J. Mod. Opt. ***58****, 299-305 (2011)*

Coupling to outside modes



Ideal “anaclastic” lens with ellipsoidal surface:

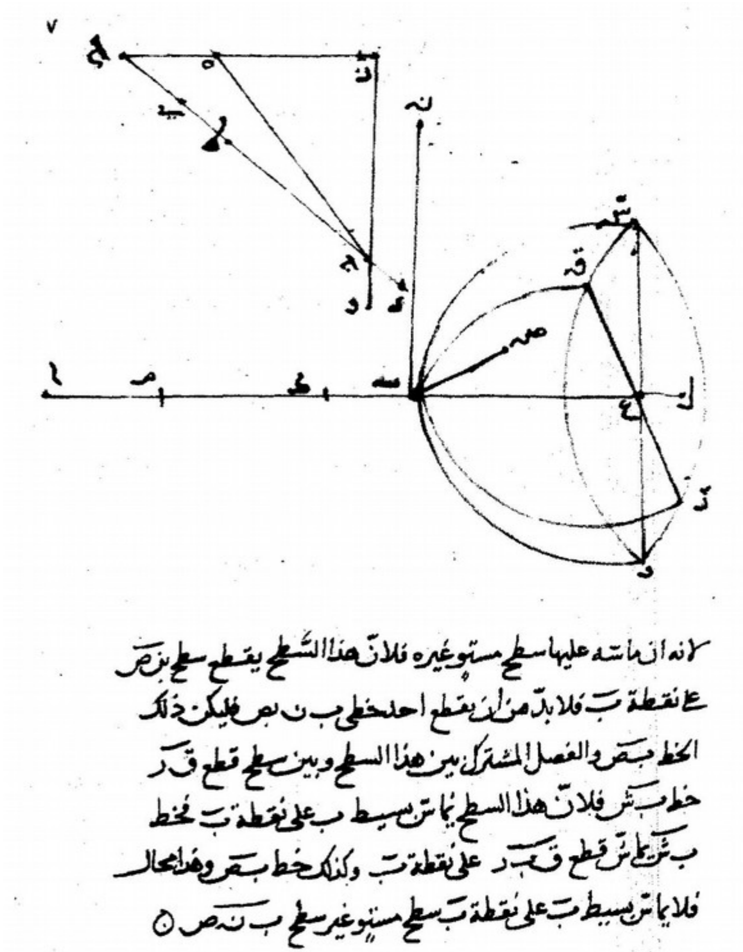
Half axis in longitudinal direction: $fn/(n+1)$

Half axis in radial direction: $f\sqrt{(n-1)/(n+1)}$

S.A. Aljunid, B. Chng, J. Lee, K. Durak et al., J. Mod. Opt. ***58****, 299 (2011)*

Not exactly a new idea...

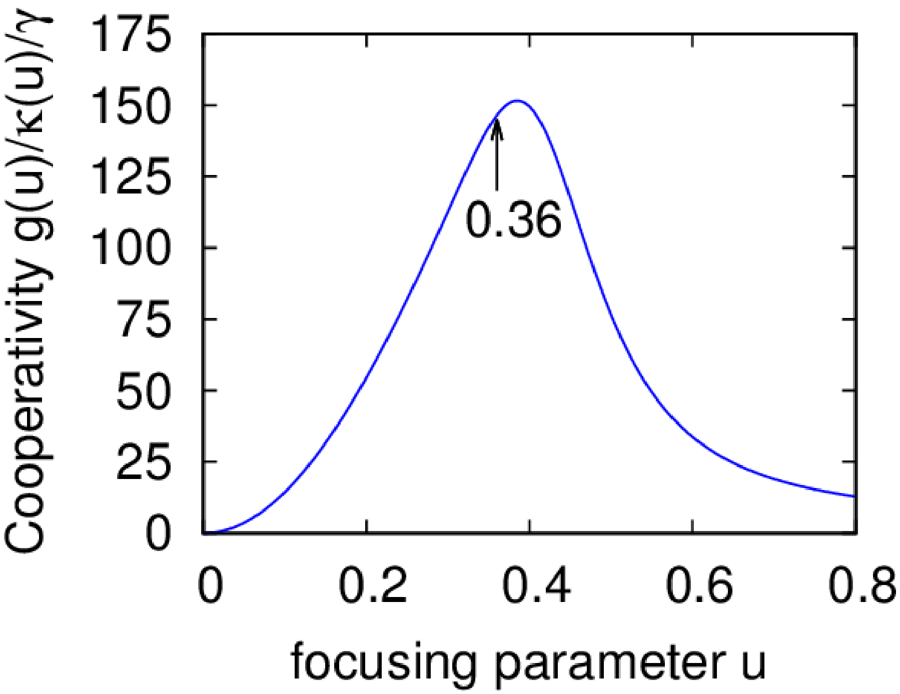
- Ibn Sahl, ~ 984: optimal focusing



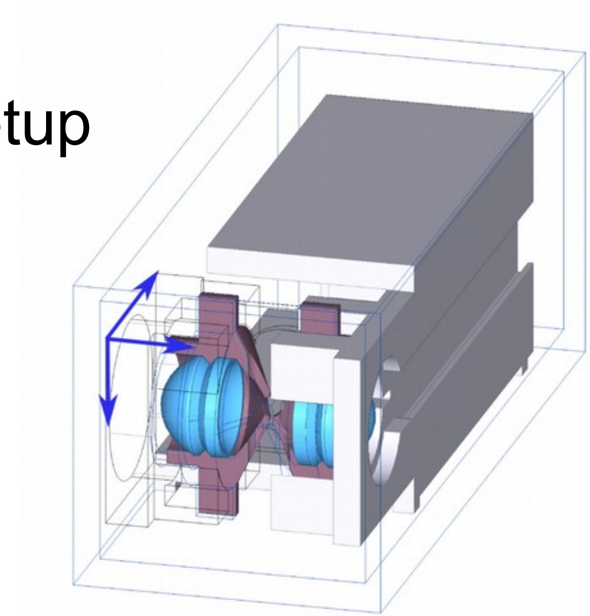
- Today's version of an anaclastic lens

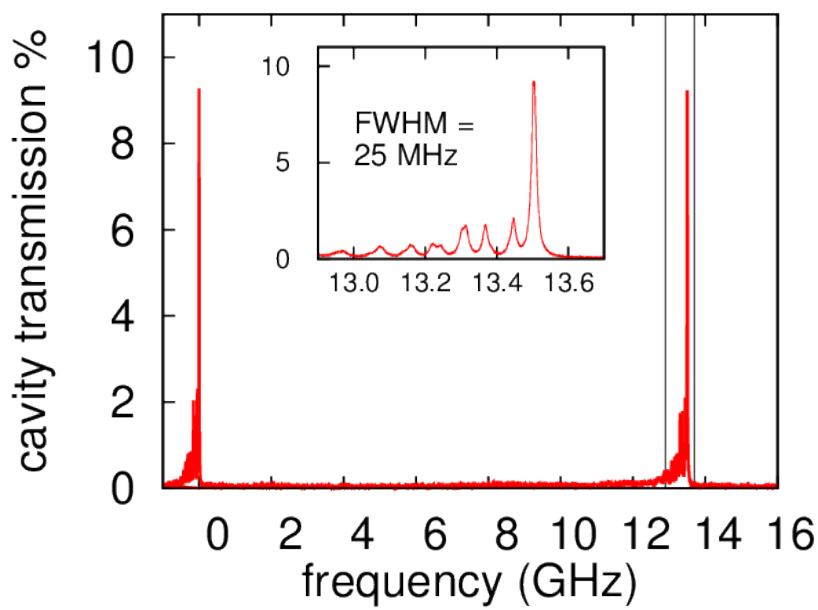
Cavity at critical point

- What is realistic?



Setup





Cavity length 11mm
BK7-like glass

K. Durak et al., NJP. ***16****, 103002 (2014)*

Part II: Narrowband photons

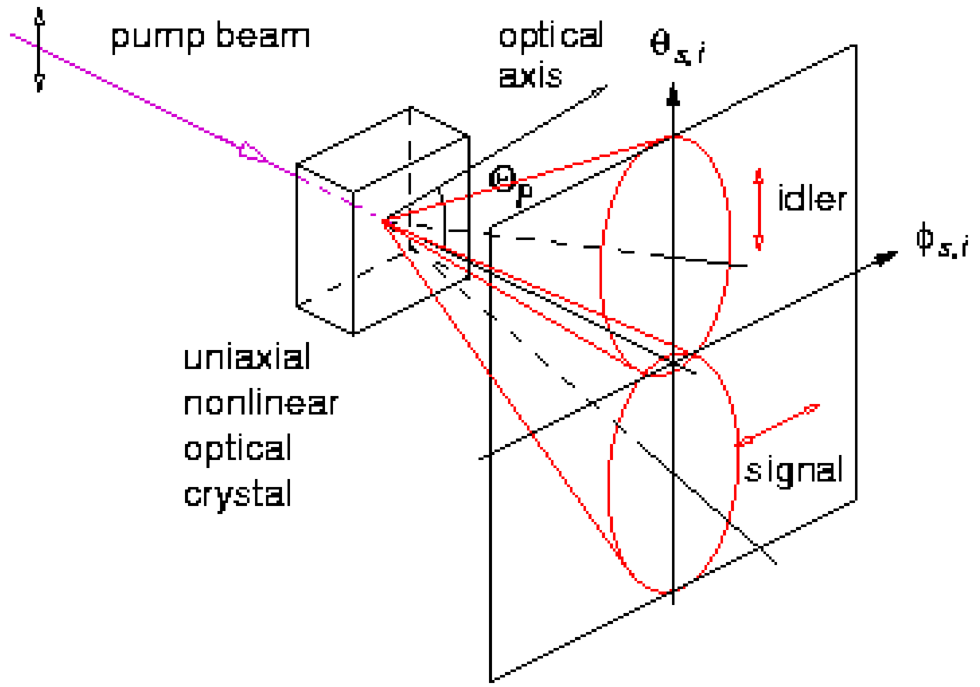
- Optical bandwidth of atomic transitions:

  1..20 MHz

- Optical bandwidth of “standard” down conversion sources:

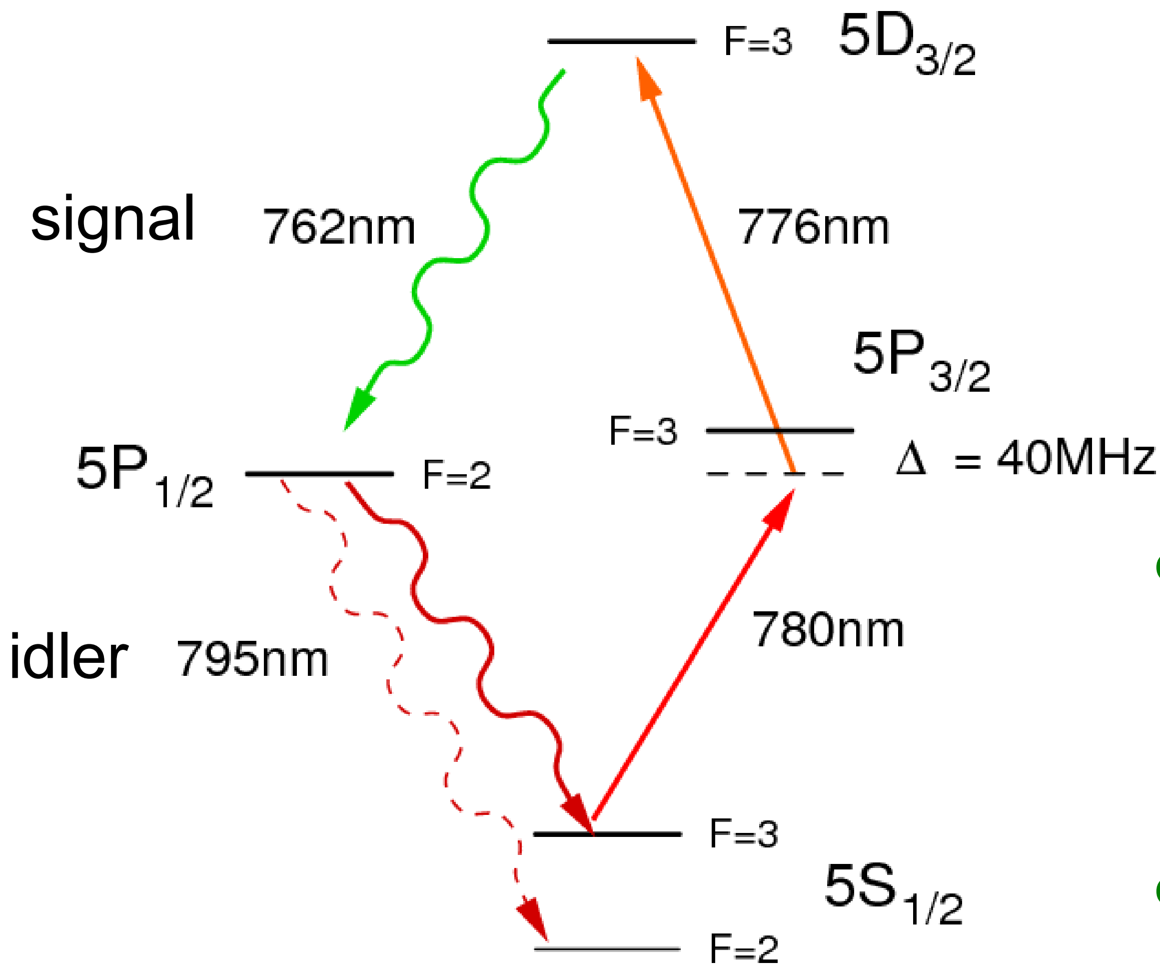
  0.1...5 nm

  (10^4 too wide)



- Temporal profile?

Narrowband Photon pairs - Idea

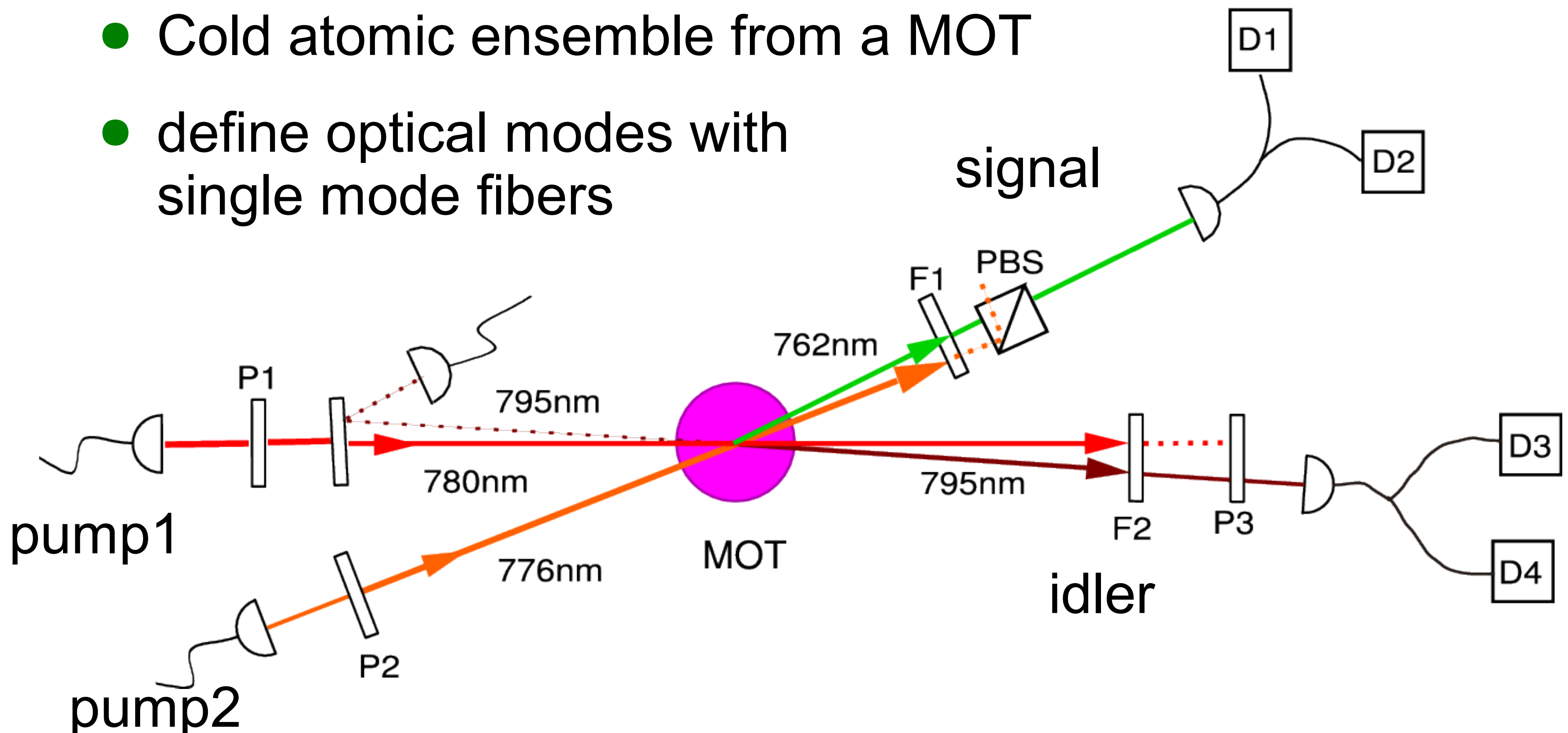


- Spatial extent: momentum conservation
  $$\vec{k}_{p1}+\vec{k}_{p2}=\vec{k}_s+\vec{k}_i$$
- Many atoms: superradiance

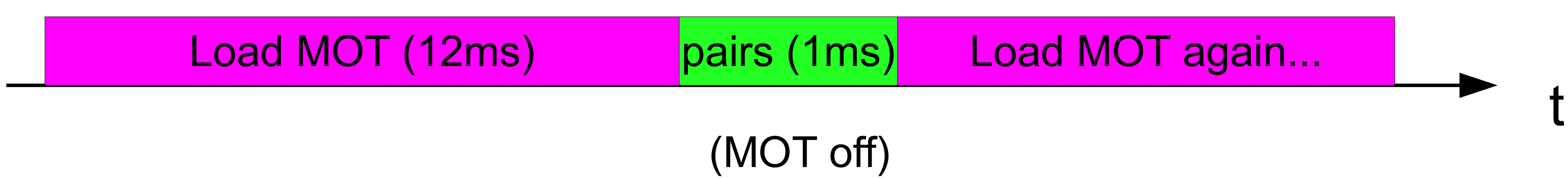
T. Chaneliere, D. N. Matsukevich, S. D. Jenkins, T. A. B. Kennedy, M. S. Chapman, and A. Kuzmich, Phys. Rev. Lett. ***96****, 093604 (2006)*

Experimental setup

- Cold atomic ensemble from a MOT
- define optical modes with single mode fibers

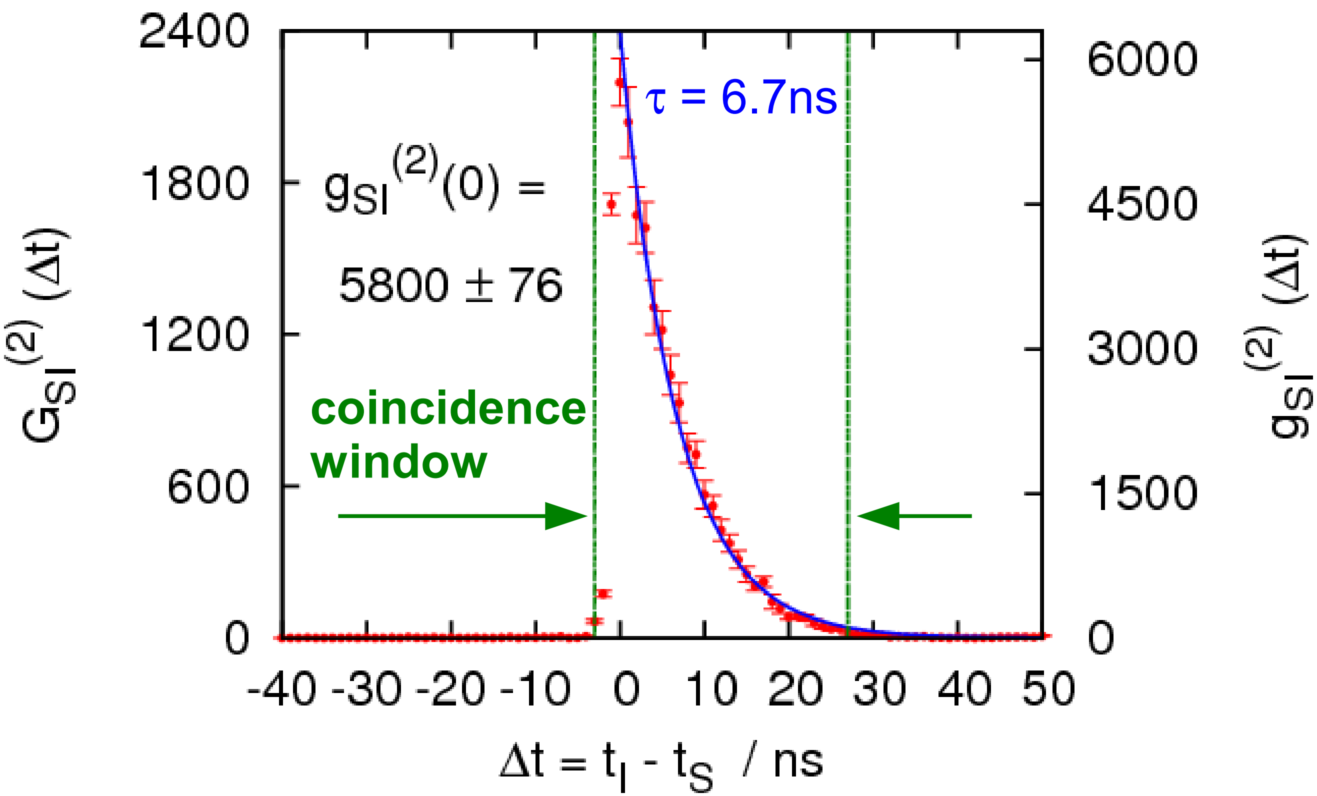


- Experimental sequence:



Observing Paired Photons

- Temporal correlation between signal and idler photons:



(measured at OD_{780} ~32)

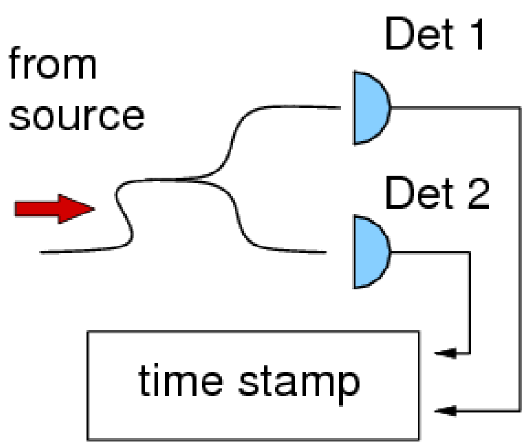
- Pair rate up to 18,000 s^{-1} (at 1/13 duty cycle)
- Efficiency (pair/sing): η_1 = 15%, η_2 =23%
- Decay time $\tau < \tau_0$ (superradiance)

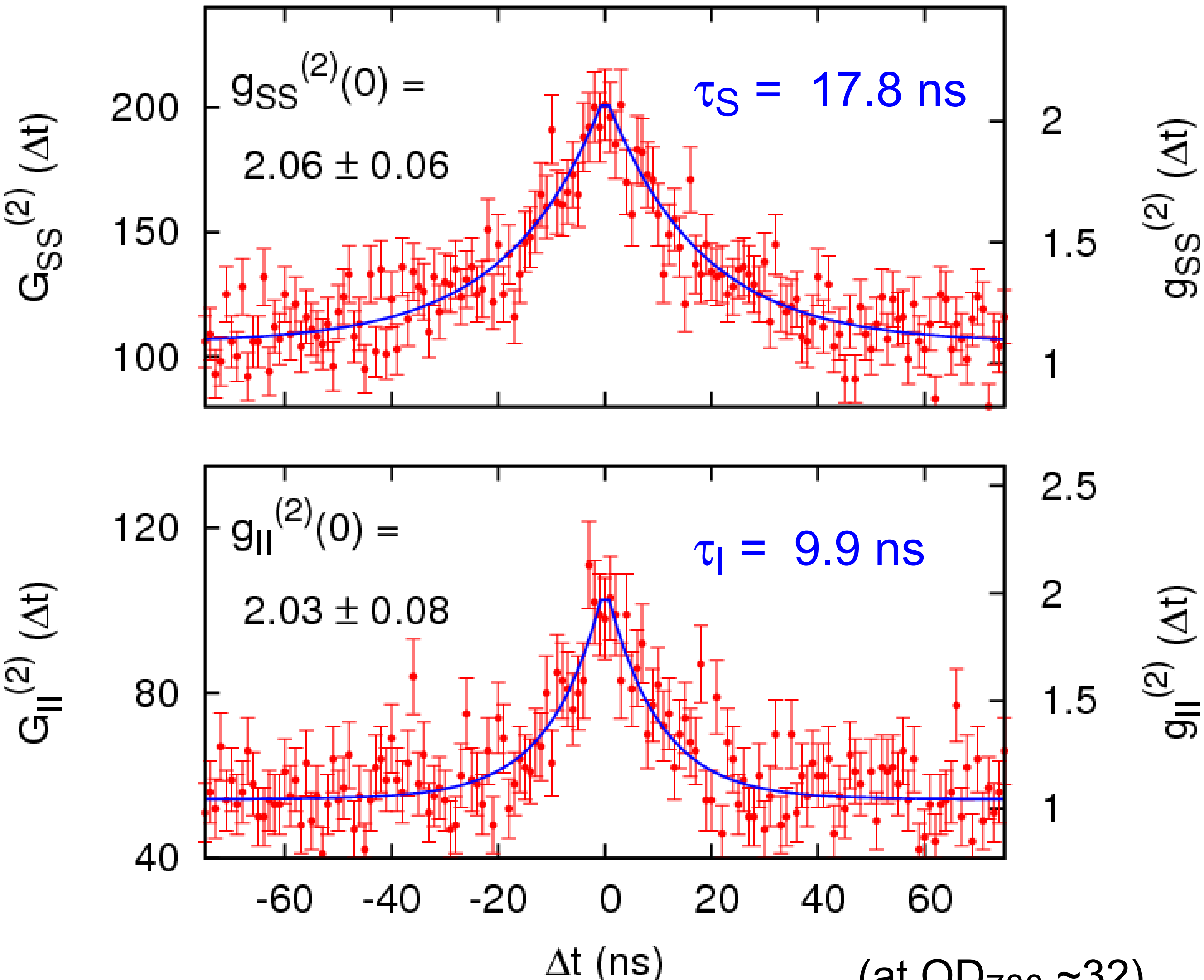
$$g(2) \Leftrightarrow \frac{\text{true coindic}}{\text{accidental coinc}}$$

*B. Srivathsan, G.K. Gulati et al., PRL **111**, 123602 (2013)*

Old School Quantum Optics

- Hanburry-Brown – Twiss experiment on signal or idler:





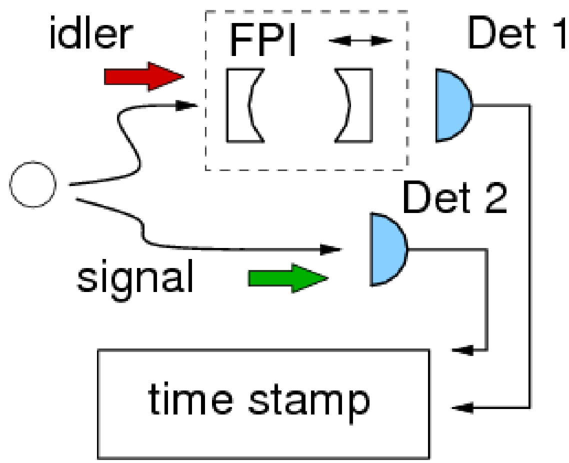
- Thermal light!

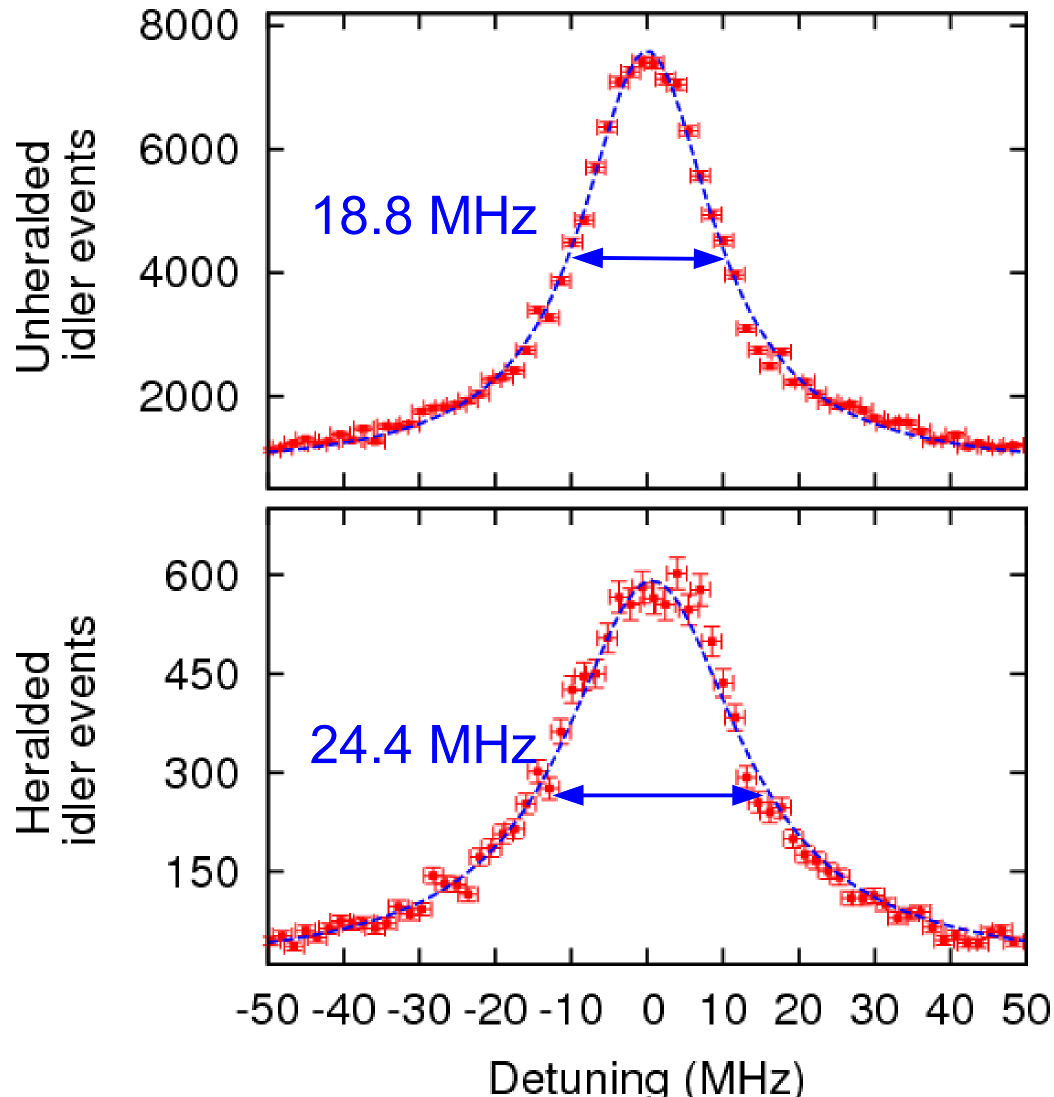
- From decay:
  $\Delta f_S = 1 / 2\pi\ \tau_S$
  $= 8.9$ MHz

(at OD_{780} ~32)

Narrow Optical Bandwidth

- Direct optical spectroscopy





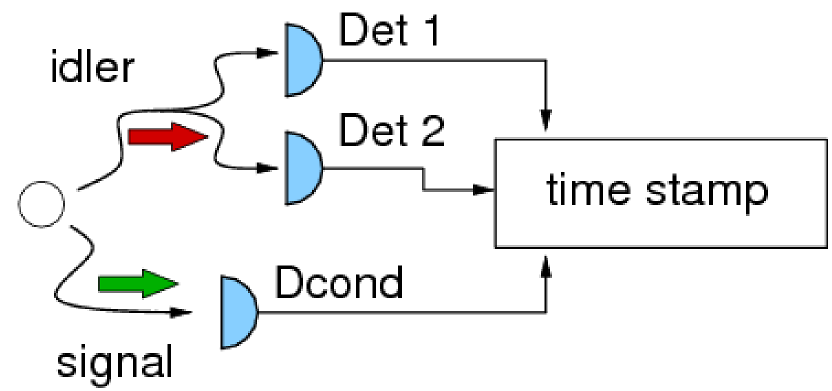
- Heralded bandwidth compatible with coherence time
  transform-limited heralded photons
- Heralded bandwidth exceeds unheralded BW (two step decay)

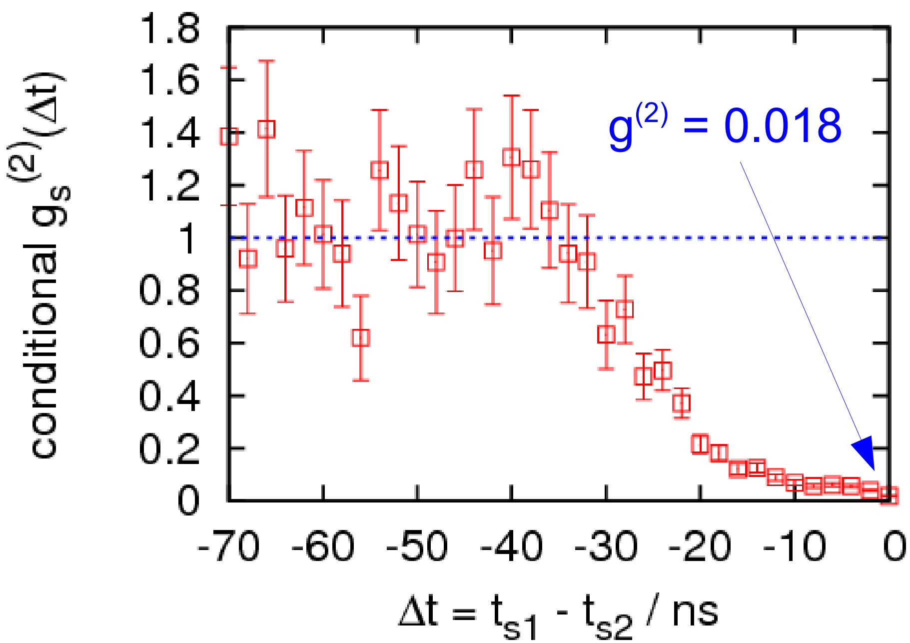
*B. Shrivathsan, G.K. Gulati et al., PRL **111**, 123602 (2013)*

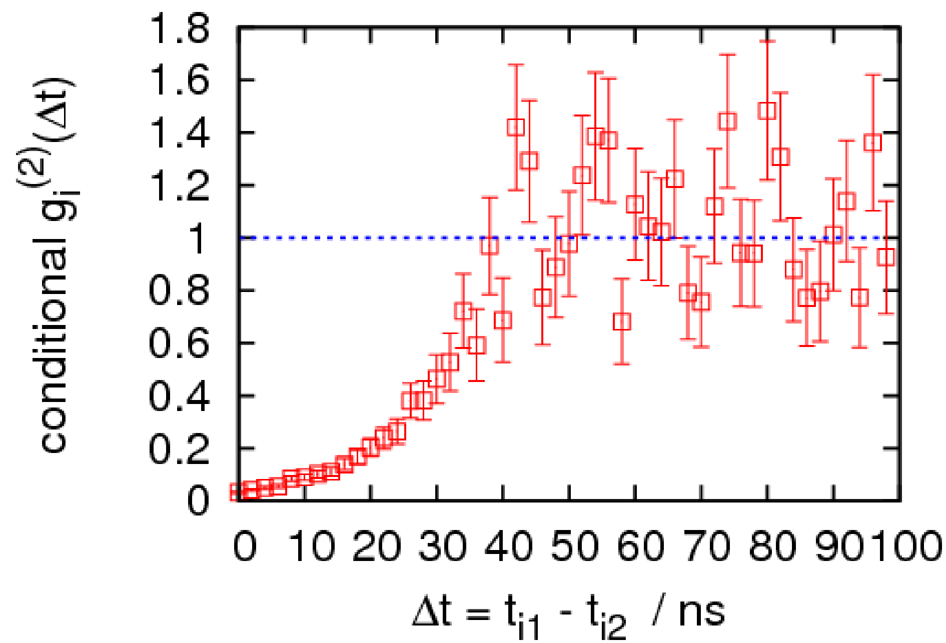
Narrowband Single Photons

- Conditional photon antibunching:

Indication of "single photons"



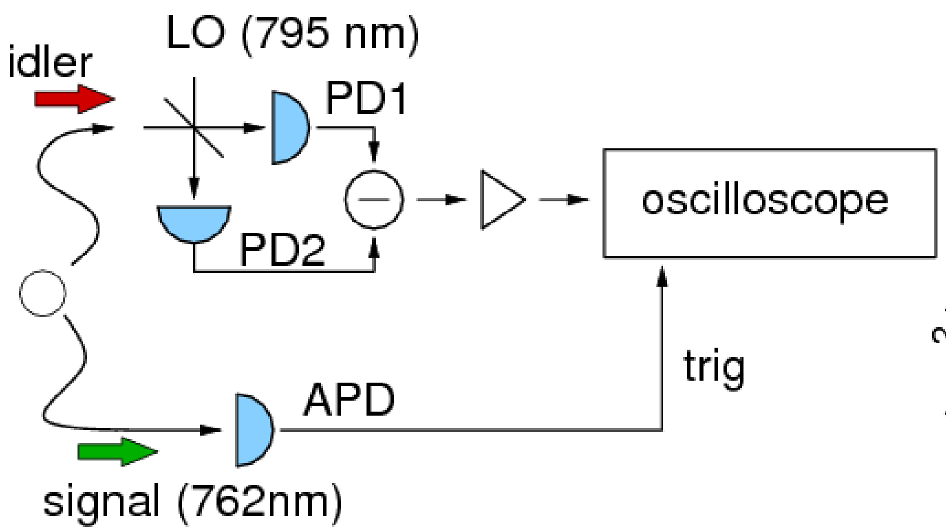


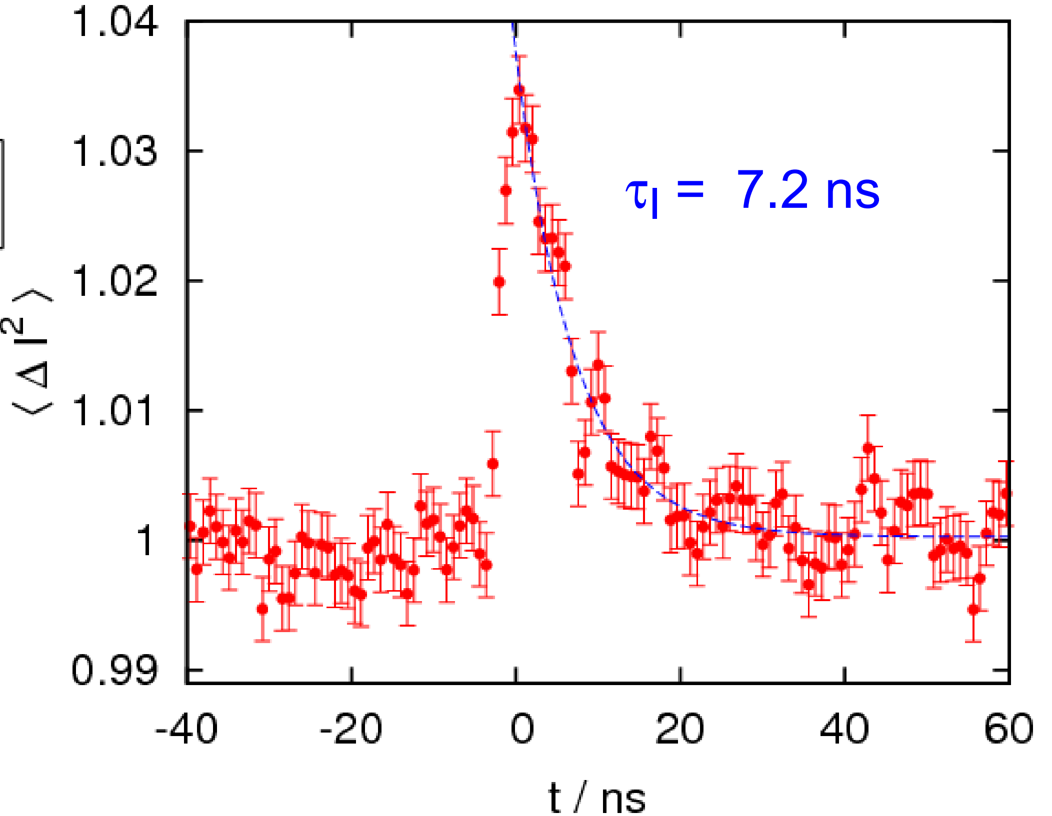


*G.K. Gulati, B. Srivathsan et al., PRA **90**, 033819 (2014)*

Field of a Photon

- Time scales compatible with photon counting and homodyning



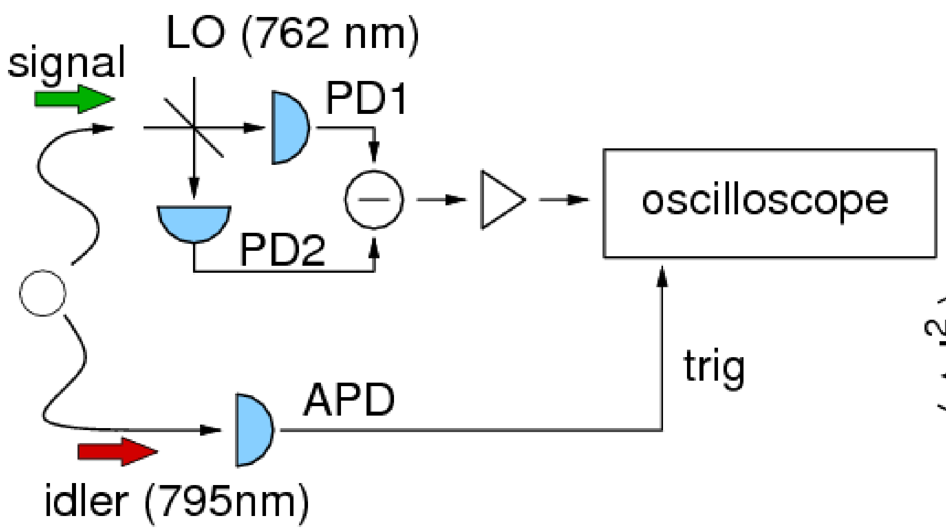


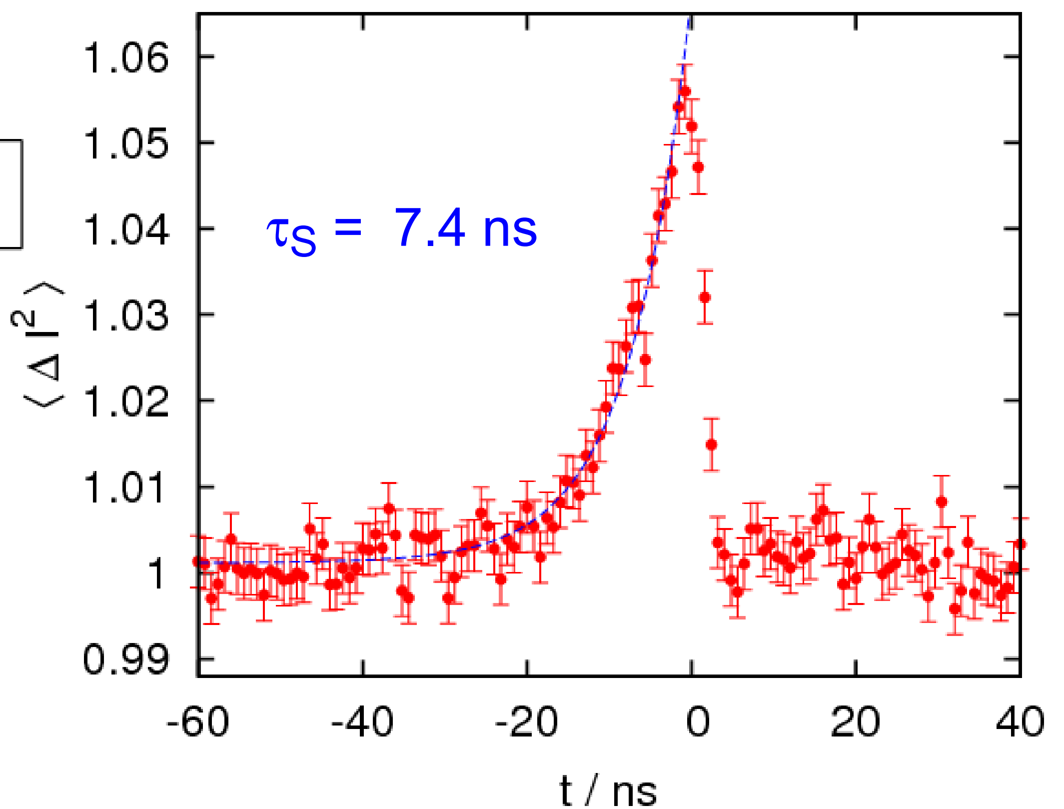
(Average over 20000 traces)

- Field variance decays according to superradiant decay on 795nm transition

The other one...

- Swap trigger and homodyne photon...

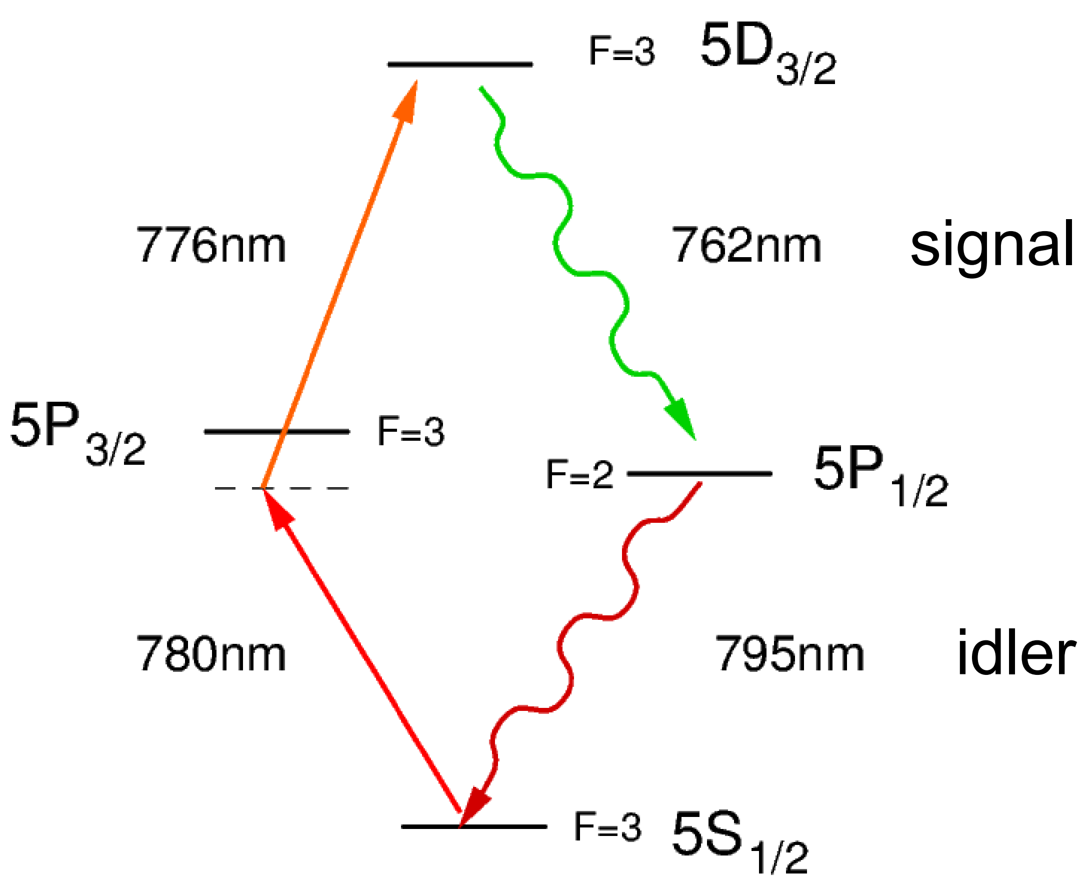




- Heralded single photon state with exponentially rising field variance

???

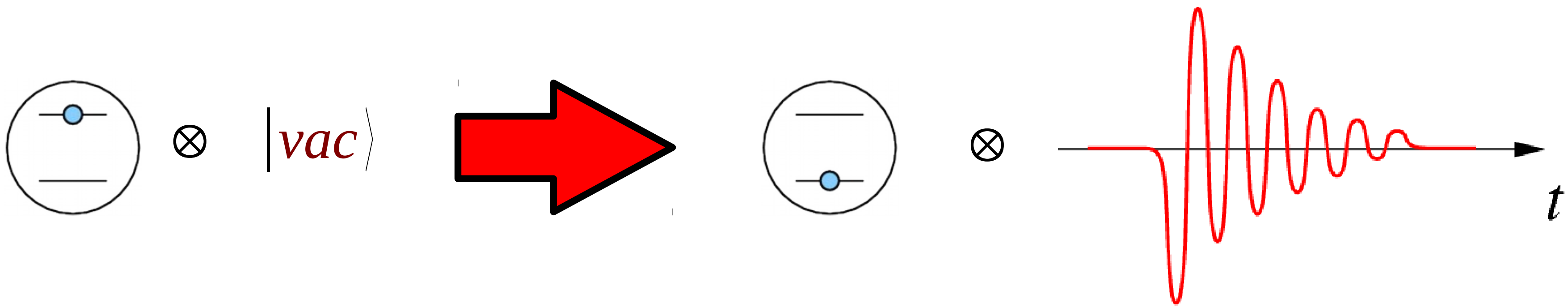
Wrong photon is "rising"..



- Signal is herald:
  idler has exponentially falling envelope
- Idler is herald:
  signal has exponentially rising envelope
- Atoms in ground state absorb idler photons

Spontaneous Emission

- Weisskopf-Wigner solution: excited atom at *t=0*



$$|\Psi(t)\rangle = a(t)|e\rangle|vac\rangle + \int d\rho\, b_\rho(t)|g\rangle|n_\rho=1, n_{\rho'\neq\rho}=0\rangle$$

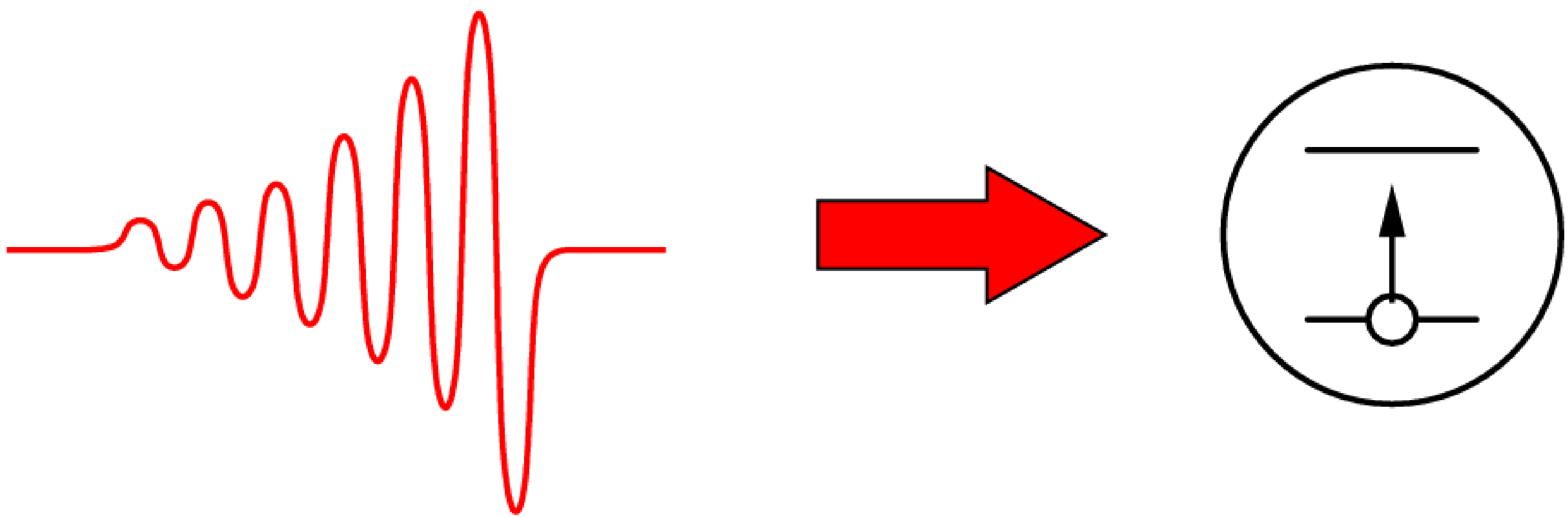
$$a(t) = e^{-\gamma t/2}, \qquad \gamma = 1/\tau$$

$$b_\rho(t) = \frac{w_{eg}^{\rho}}{\hbar} \cdot \frac{e^{-\gamma t/2} - e^{i(\omega_\rho - \omega_{eg})t}}{i\gamma/2 + \omega_{eg} - \omega_\rho}$$

*V. Weisskopf and E. Wigner, Proc. Roy. Soc. London (A), **114**, 243, 710 (1927)*

Reverse Spontaneous Emission

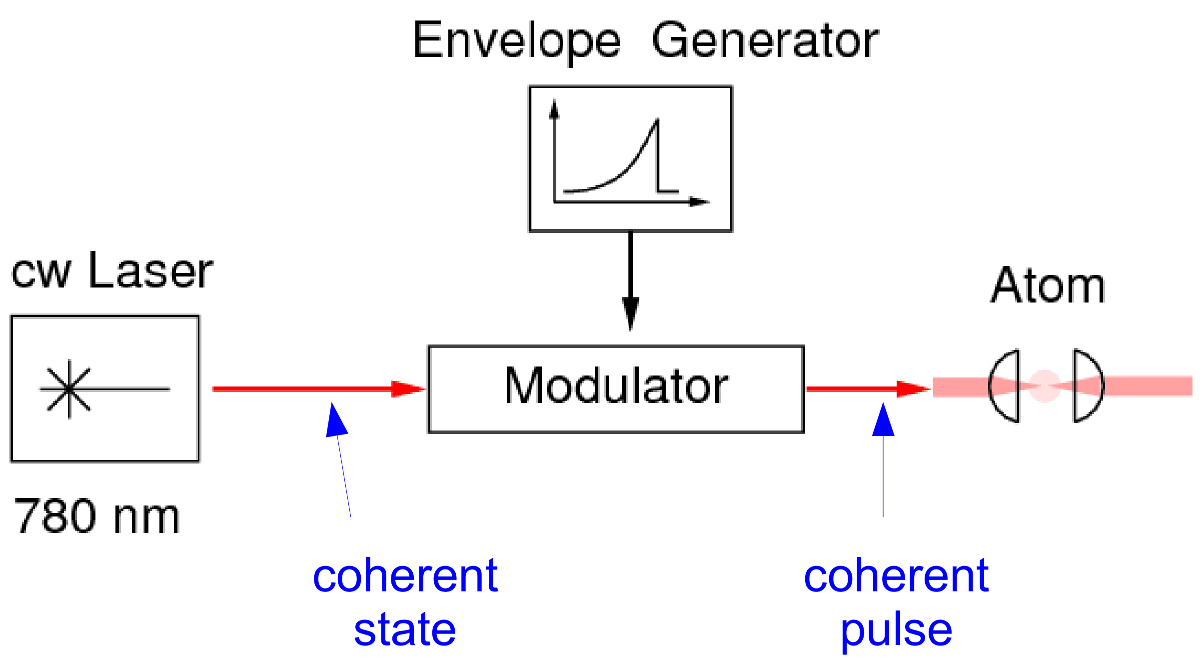
- Optimal absorption process:
  Time-reversed Wigner-Weisskopf solution
- Requires photon with a shaped mode



M. Sondermann, R. Maiwald, H. Konermann et al. Appl. Phys. B ***89****, 489 (2007)*

Creating a "reverse" photon

- A single field excitation is difficult to make
- Let's start with shaping a coherent state

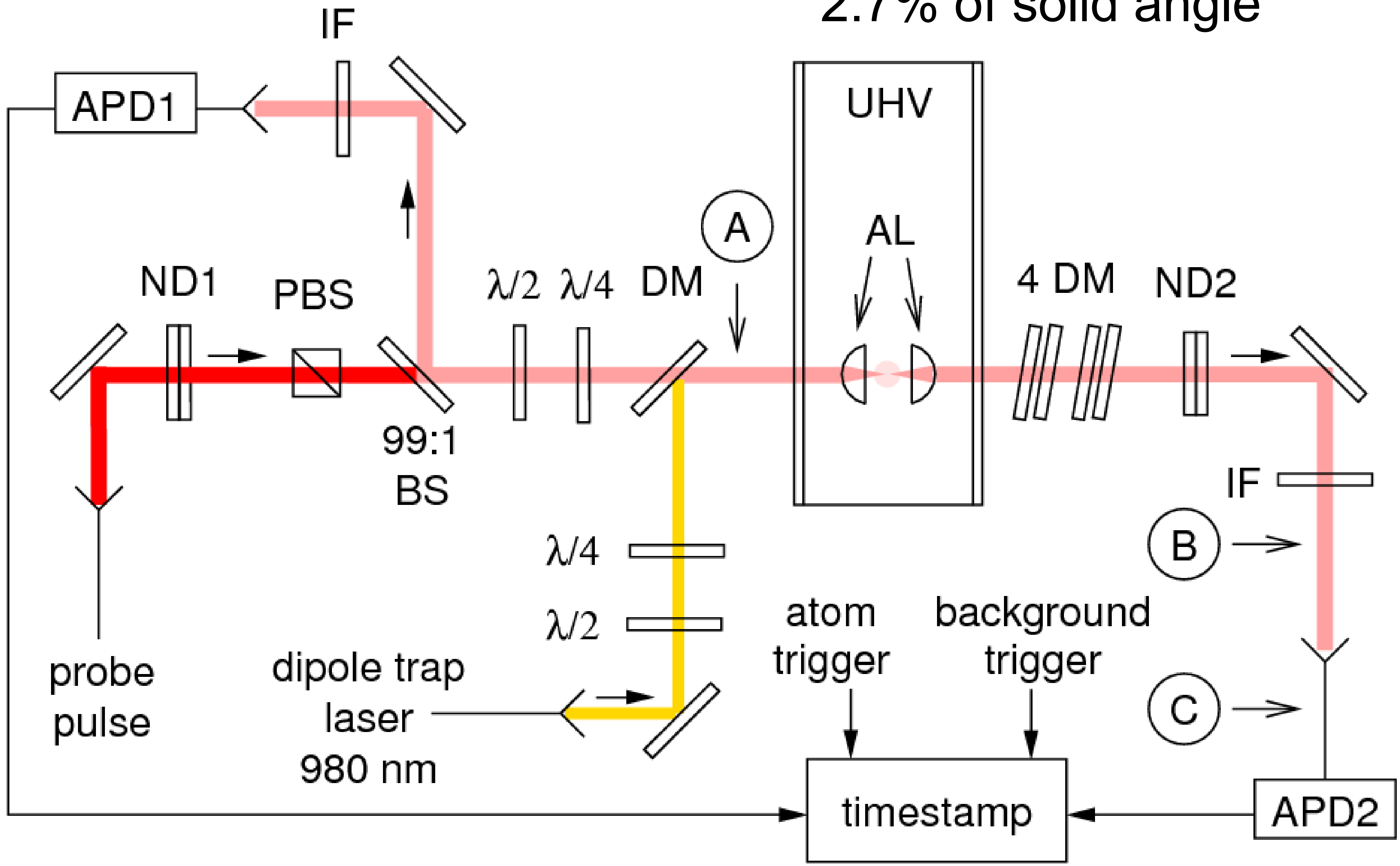


Dao Hoang Lan, S.A. Aljunid, G. Maslennikov, C.K., Rev. Sci. Instr. ***83****, 083104 (2012)*

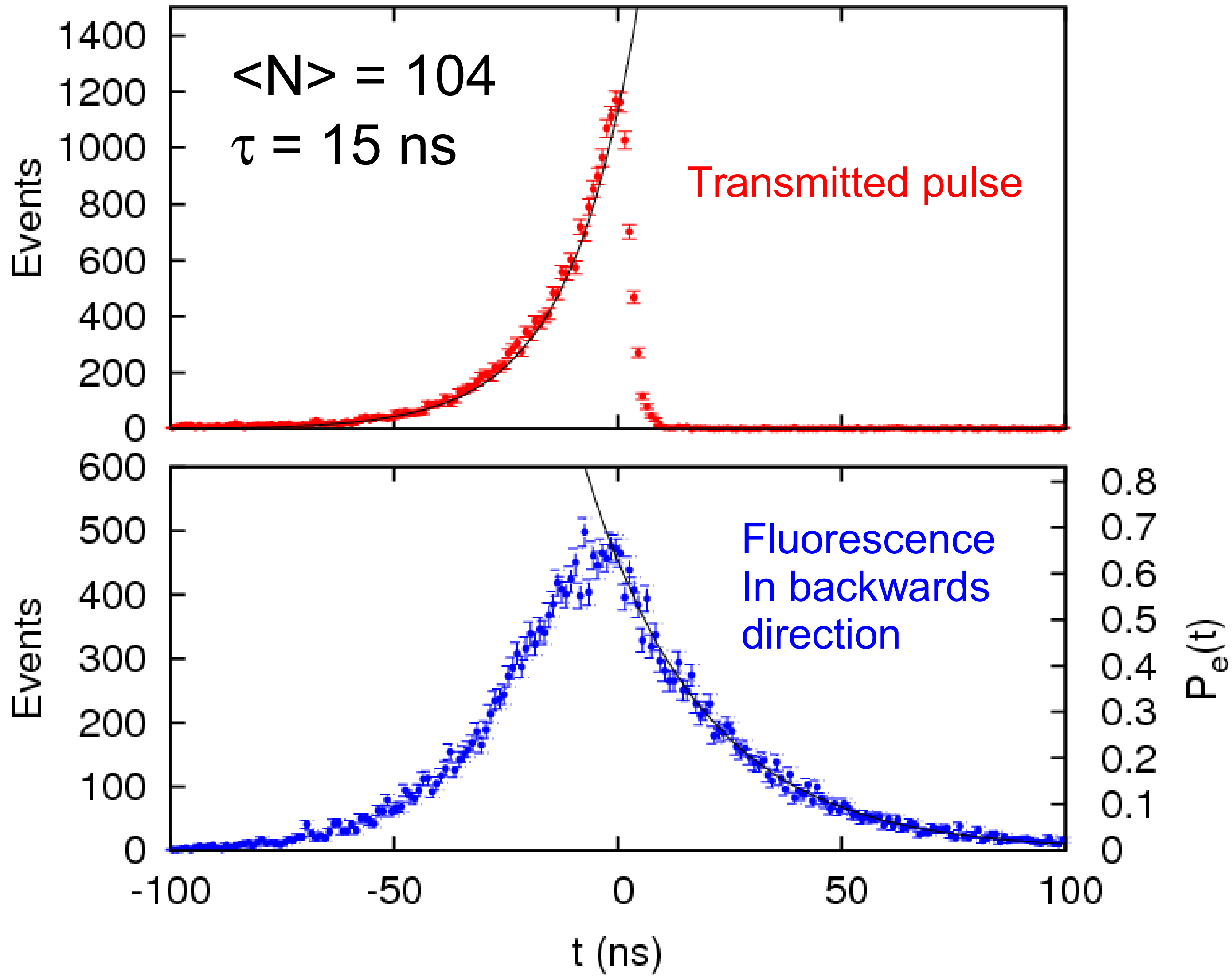
Theoretical support:Y. Wang, L. Sheridan, V. Scarani, Phys. Rev. A ***83****, 063842 (2011)*

Excitation setup

- Capture of fluorescence: 2.7% of solid angle



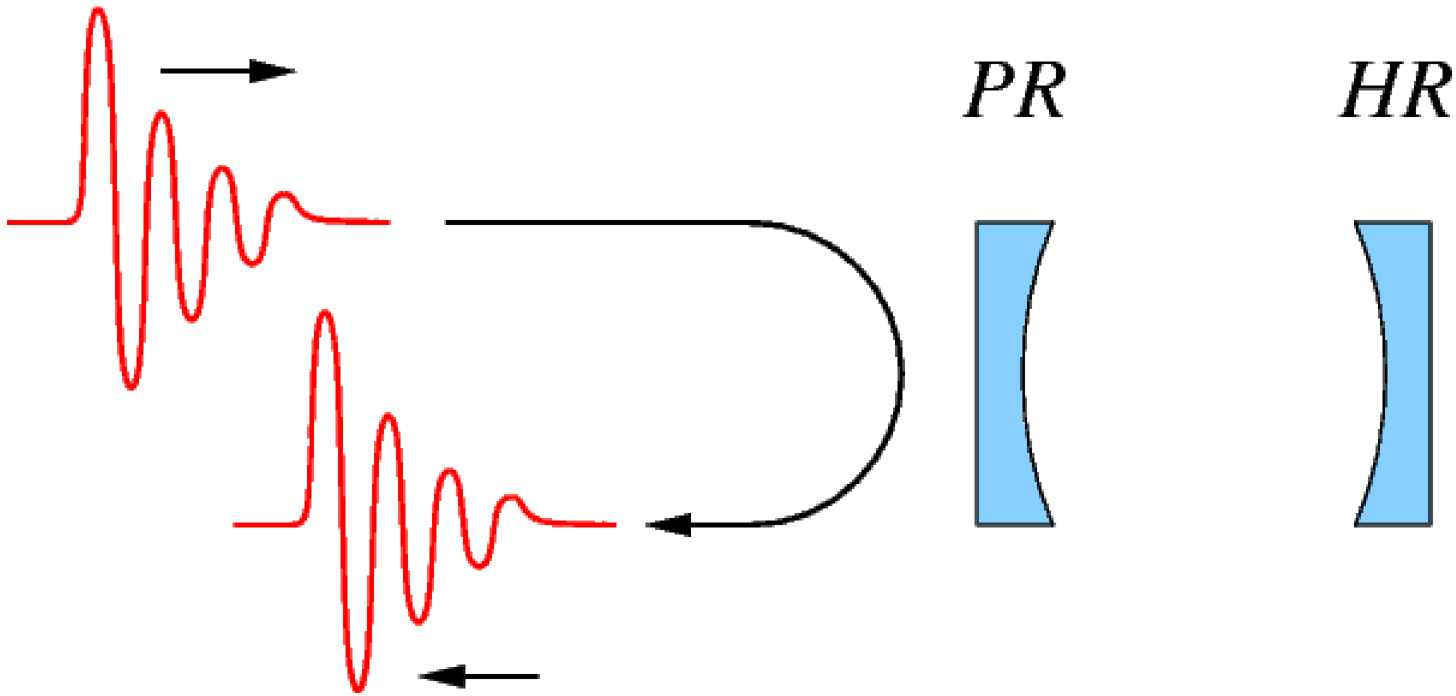
Atomic fluorescence



- Excitation probability rises and falls exponentially

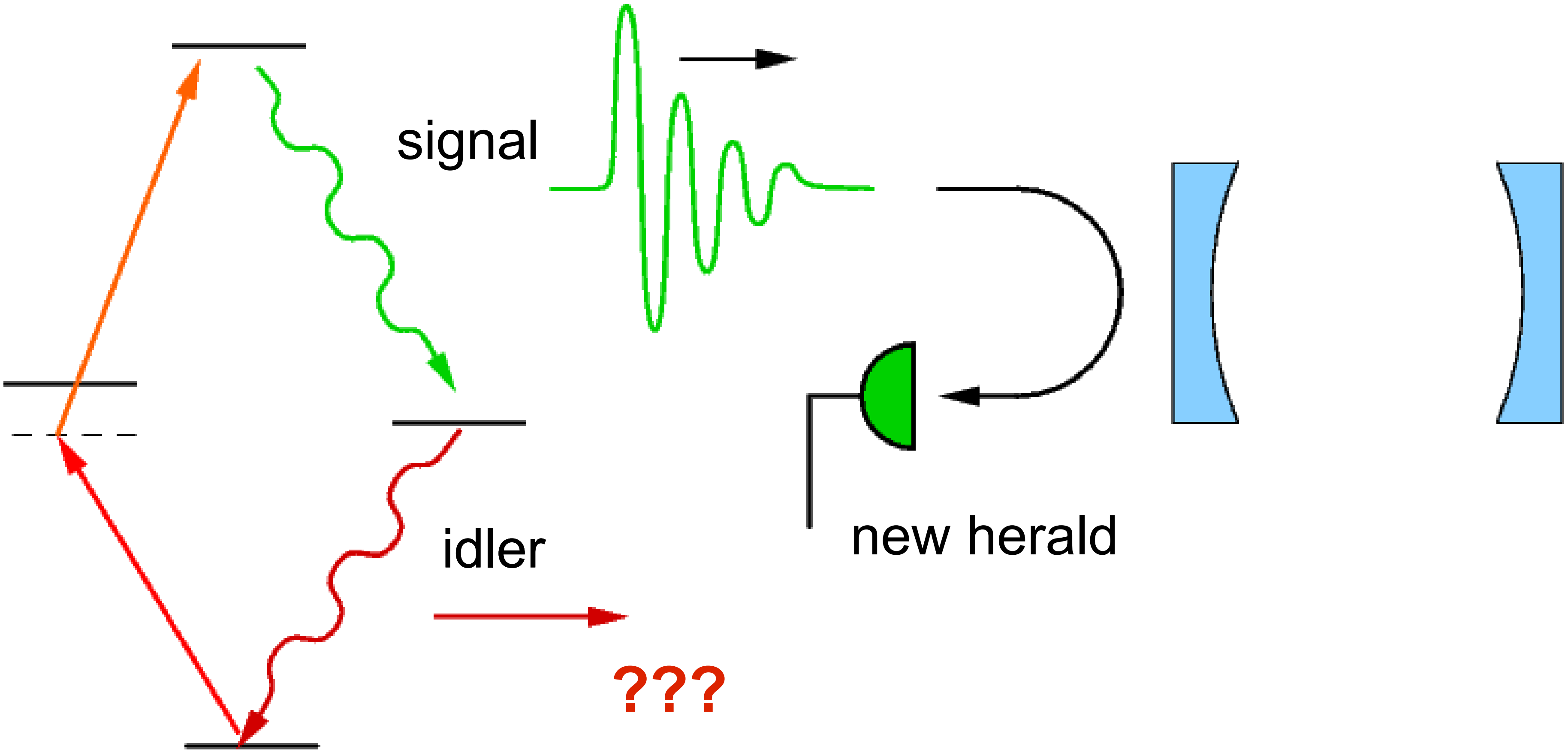
Use a smart insight

- A half-sided cavity can reverse an exponentially rising light pulse



*M. Bader, S. Heugel, A. L. Chekhov, M. Sondermann, and G. Leuchs, NJP **15**, 123008 (2013)*

Reverse herald, look at idler



- Does this really reverse the idler photon envelope?

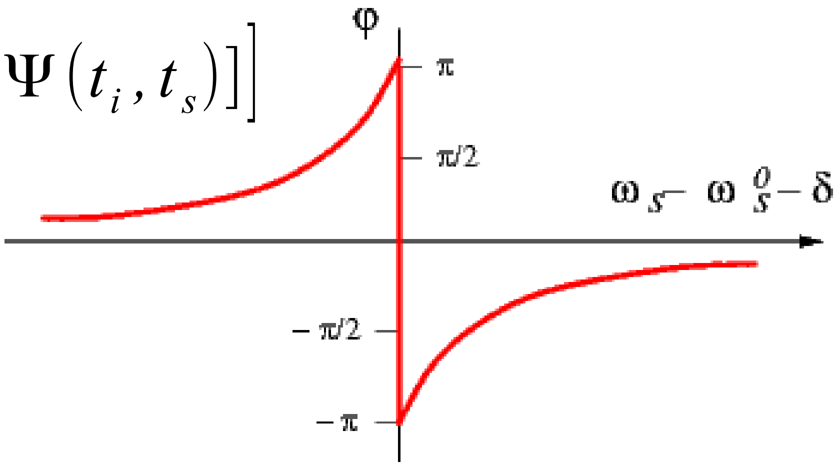
Yes, it does. Some Math...

- Use two-photon wave function:

$$\Psi(t_i, t_s) = A e^{-(t_i - t_s)/2\tau}\Theta(t_i - t_s)$$

- Transform signal part a la textbook:

$$\tilde{\Psi}(t_i, t_s) = F_s^{-1}\left[e^{i\varphi(\omega_s - \omega_s^0 - \delta)} F_s[\Psi(t_i, t_s)]\right]$$

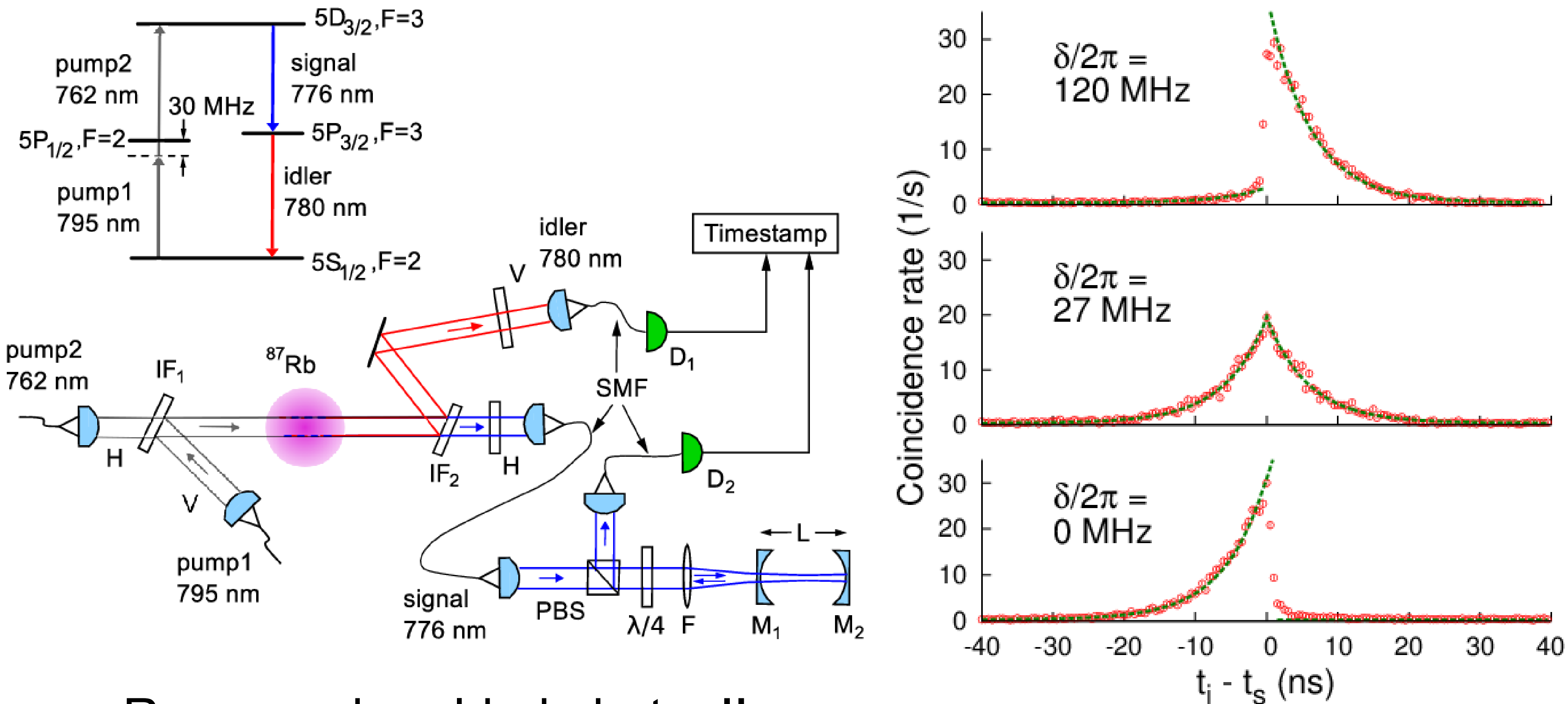


- Gives correct result for correct parameters:

$$\tilde{\Psi}(t_i, t_s) = \frac{A}{\sqrt{1 + 4\delta^2\tau^2}}\left[2\delta\tau e^{-(t_i - t_s)/2\tau}\Theta(t_i - t_s) + e^{(t_i - t_s)/2\tau}\Theta(t_s - t_i)\right]$$

It even works in the experiment

- Reverse heralding photon with cavity...

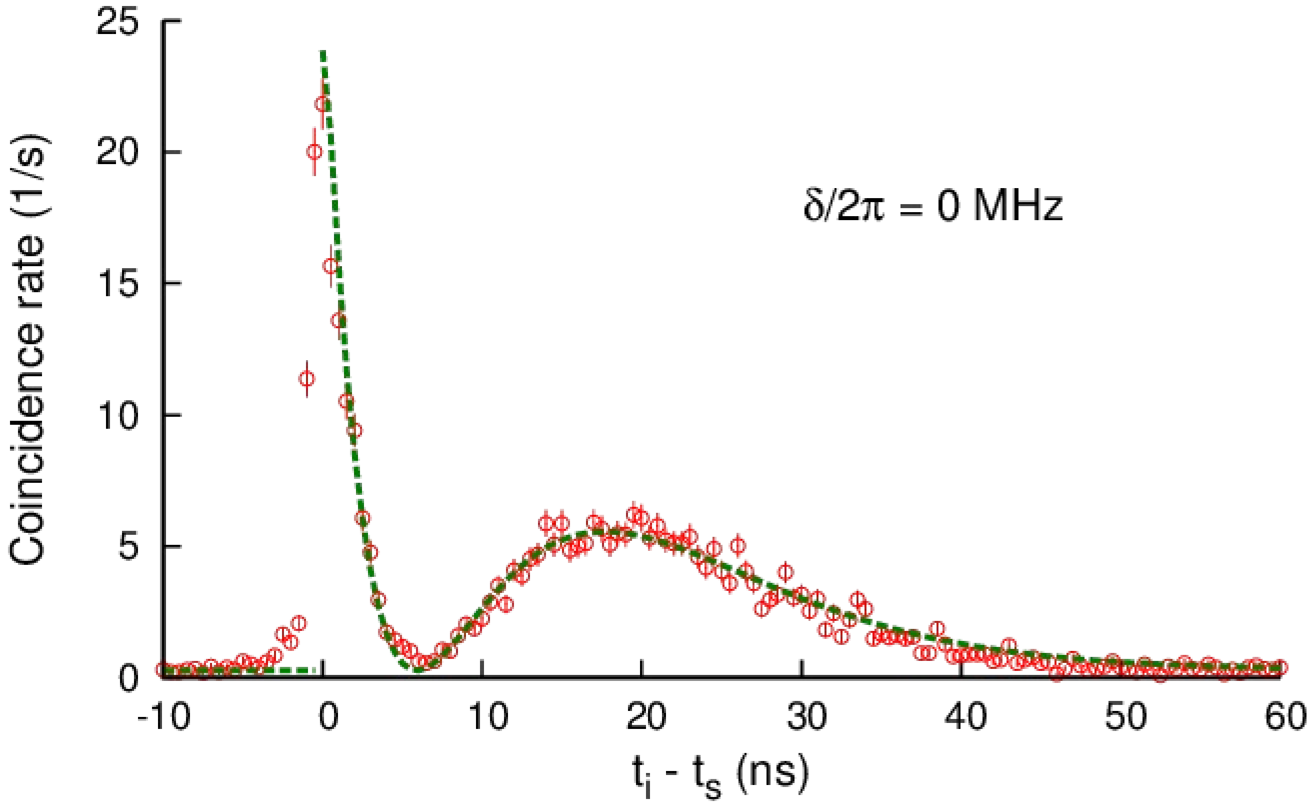


...Reverses heralded photon!!

B. Shrivathsan, G.K. Gulati et al., PRL ***113****, 163601 (2014)*

Small sanity check

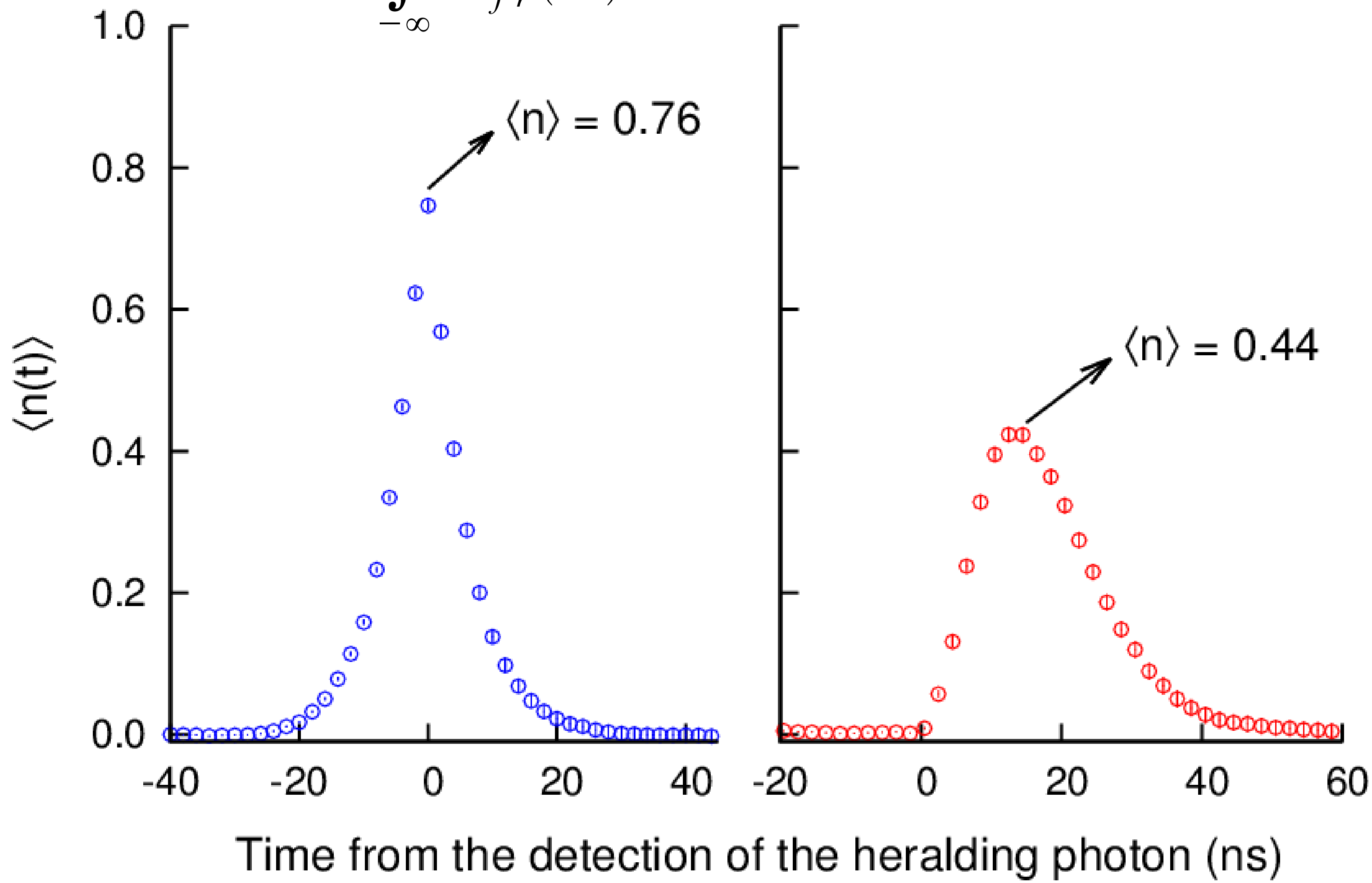
- reverse the idler with the cavity as a herald



Photon number in cavity

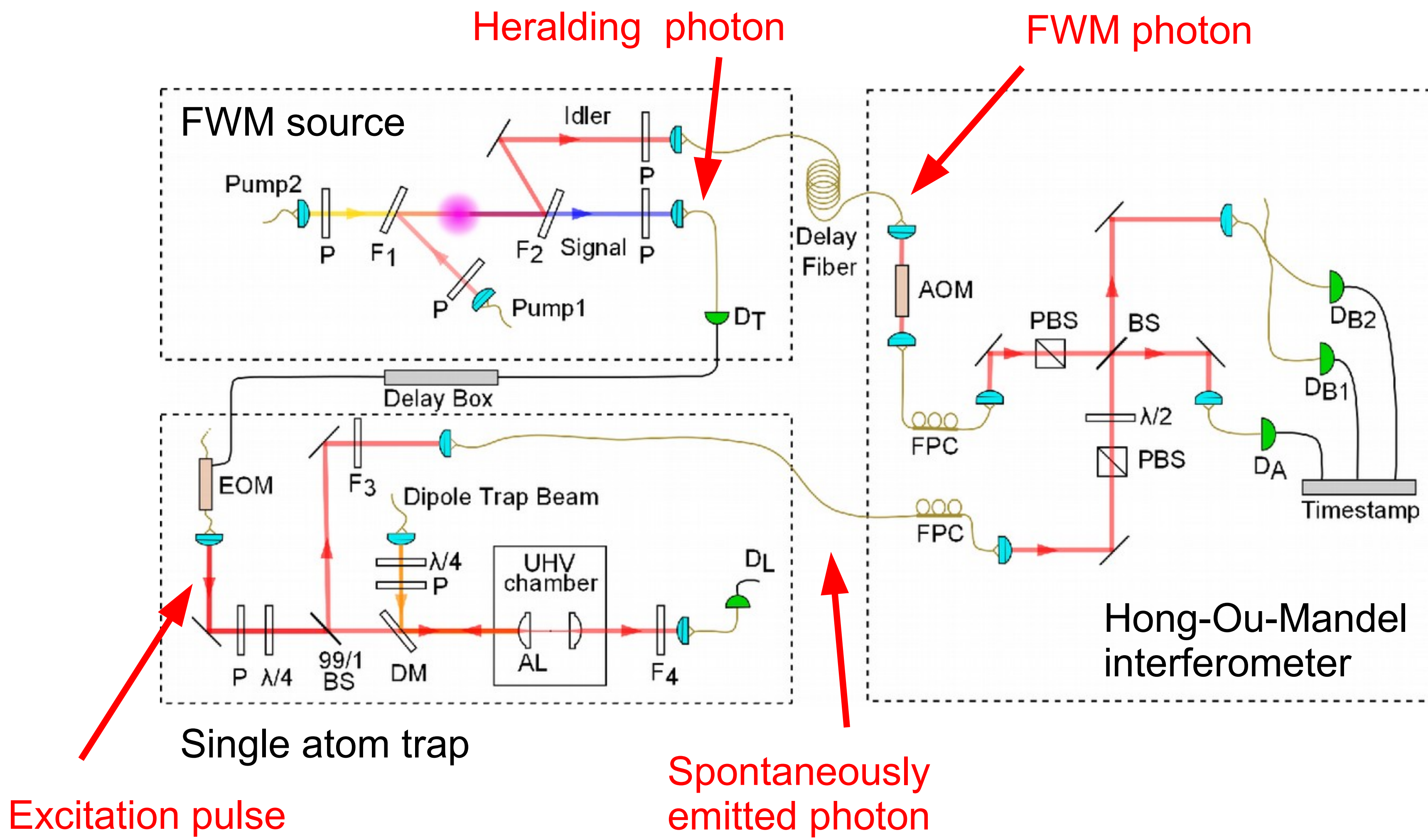
$$\langle n(t)\rangle = \frac{e^{-\eta t \Delta\nu_f} \int_{-\infty}^{t} \left[G^{(2)}_{fr}(t') - G^{(2)}_{or}(t') \right] e^{\eta t' \Delta\nu_f}\, dt'}{\int_{-\infty}^{+\infty} G^{(2)}_{fr}(t')\, dt'}$$

Also: M. Bader et al., NJP ***15****, 123008 (2013)*

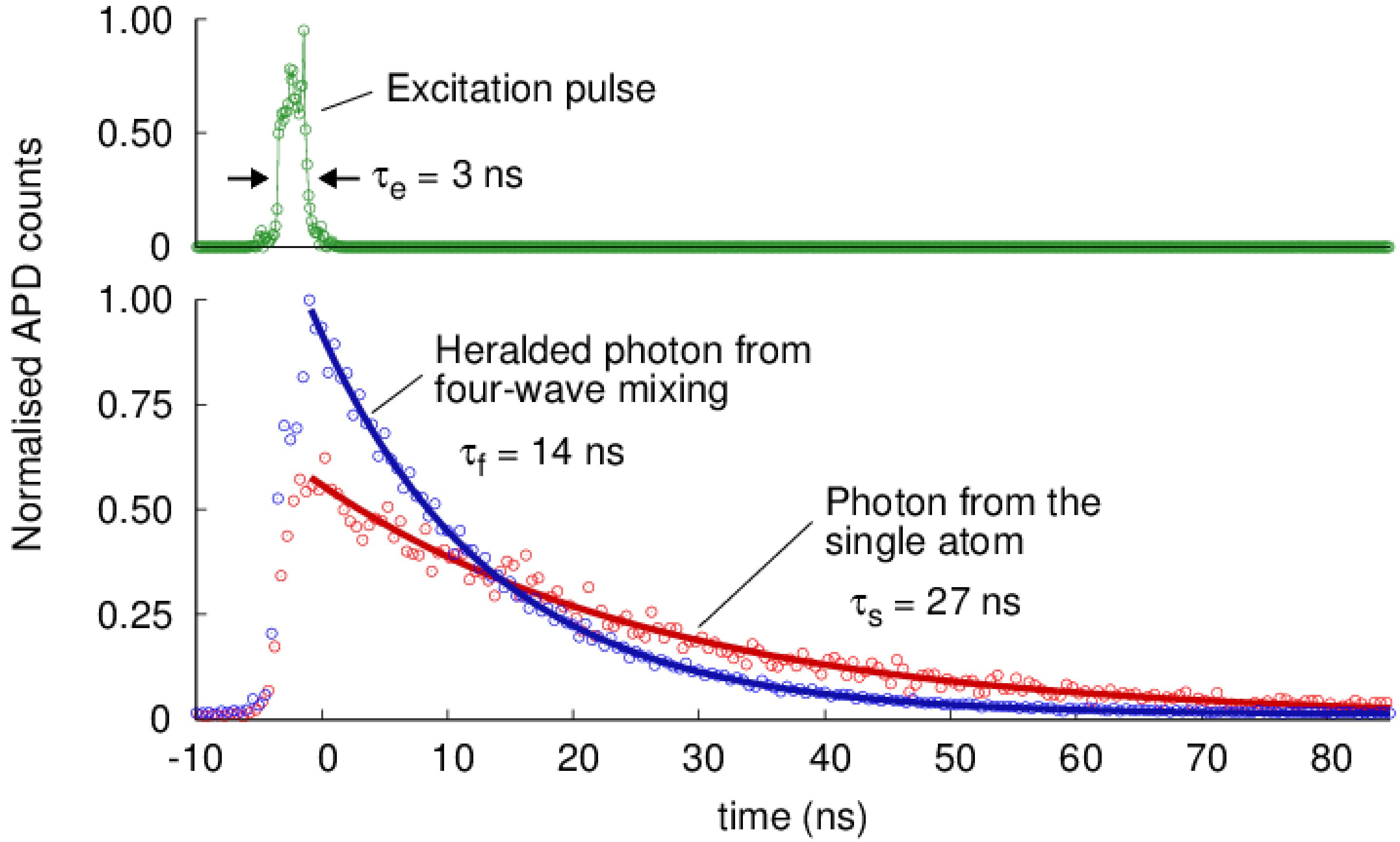


Part III: Interface different systems

- Combine photons from FWM and single atom trap:

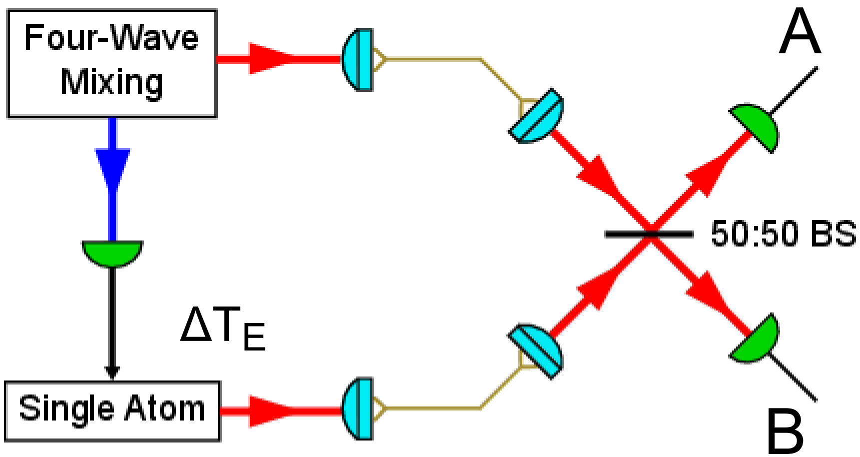


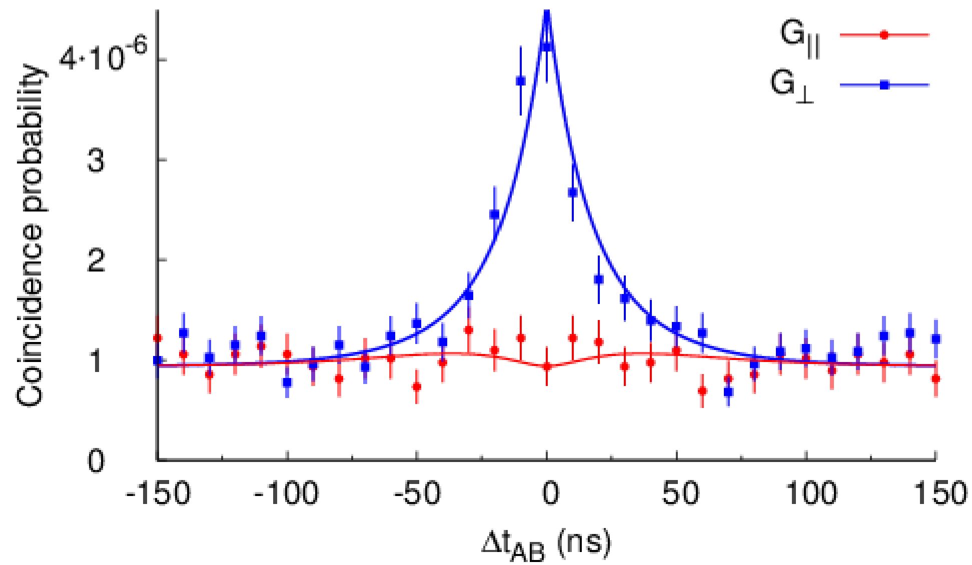
Similarly shaped Photons

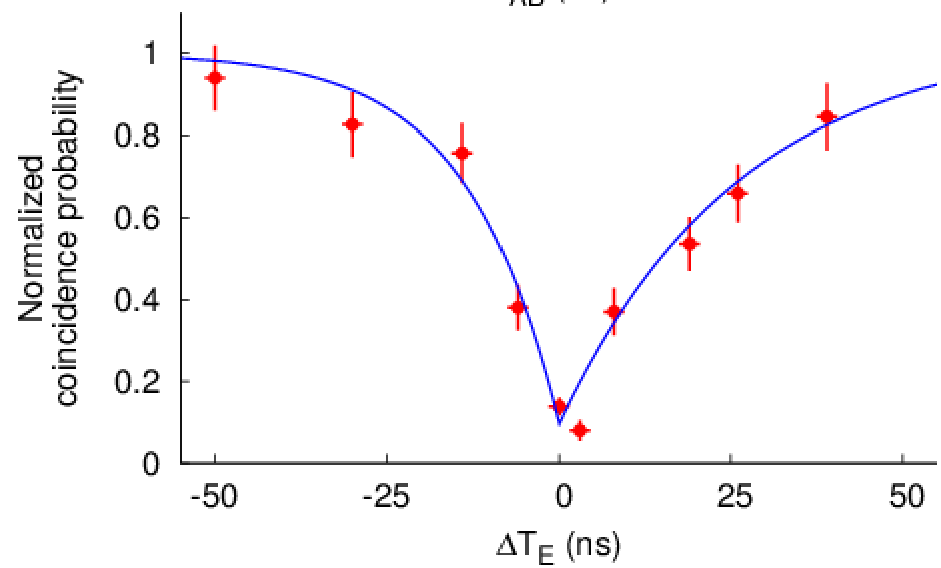


- Overlap of two envelopes: **90%** from time constants

Hong-Ou-Mandel interference







- HOM interference visibility:
  62 ± 4% uncorrected
  93 ± 6% background-corrected

*V. Leong, S. Kosen, B. Srivathsan, G.K. Gulati, A. Cerè, CK, PRA **91,** 063829 (2015)*

Take-home message

- Strong focusing leads to strong single atom-photon interaction

- Narrowband heralded single photons from parametric conversion in atomic cloud compatible with atomic transitions

- Different atomic systems can be connected together

Thank you!

http://www.qolah.org

Tey Meng Khoon
Syed Abdullah Aljunid
Bharath Shrivatshan
Gurpreet Kaur Gulati
Sandoko Kosen
Brenda Chng
Victor Leong
Kadir Durak
Chi Huan Nguyen
Wilson Chin, Mathias Seidler
Nick Lewty
Matthias Steiner
Alessandro Cere
Gleb Maslennikov, ***C.K****.*

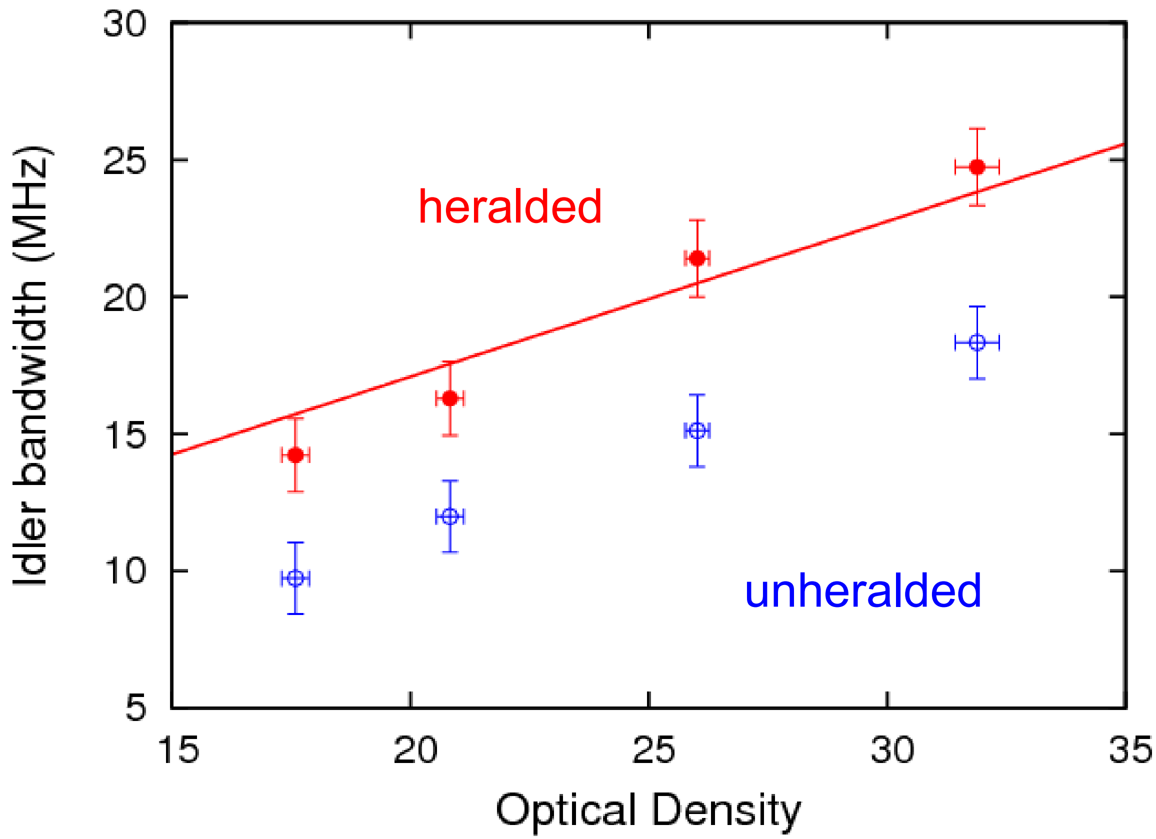
Theory Support:
Yimin Wang, Colin Teo,
Timothy Liew, ***Valerio Scarani***

Bandwidth vs. Optical Density

- Superradiance increases bandwidth with optical density

Expected:

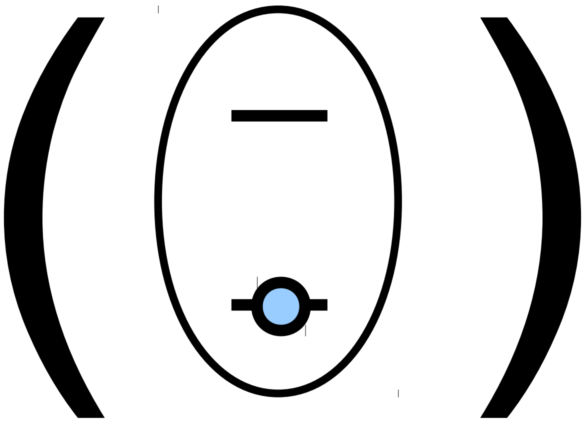
$$\Gamma=\Gamma_0\left(1+const\cdot OD_{795}\right)$$



$OD_{780,\,m}$ measured at 780nm in cloud center

A. Walther et al. PRA ***80****, 012317 (2009)*
H. H. Jen, PRA ***85****, 013835 (2012).*

Atom in cavities are nice..



- discrete mode spectrum
- 'textbook' field energy eigenstates

$$\hat{H}_{field} = \frac{\epsilon_0}{2} \int \left(\hat{\boldsymbol{E}}^2 + c^2 \hat{\boldsymbol{B}}^2 \right) dV = \hbar\omega\left(\hat{n} + \frac{1}{2}\right)$$

$$\hat{\boldsymbol{E}}(x,y,z) = i\sqrt{\frac{\hbar\omega}{2\pi\epsilon_0 V}} \left(\boldsymbol{g}(x,y,z)\hat{a}^{+} - \boldsymbol{g}^{*}(x,y,z)\hat{a} \right)$$

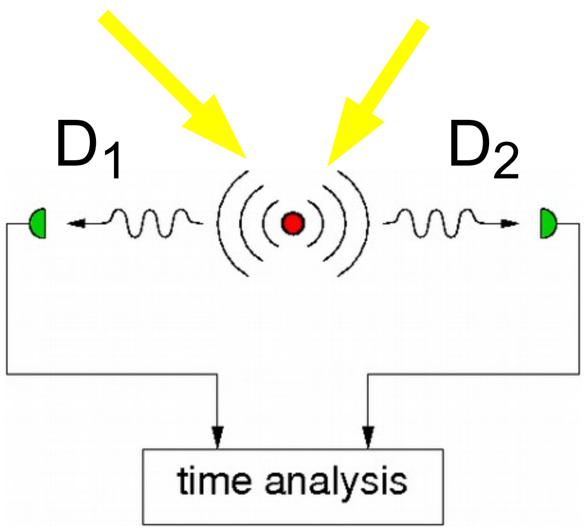
- electric dipole interaction $\hat{H}_I = \hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{d}}$ with $\hat{\boldsymbol{d}} = \boldsymbol{e}\, d_{eff} \left(|e\rangle\langle g| + |g\rangle\langle e| \right)$

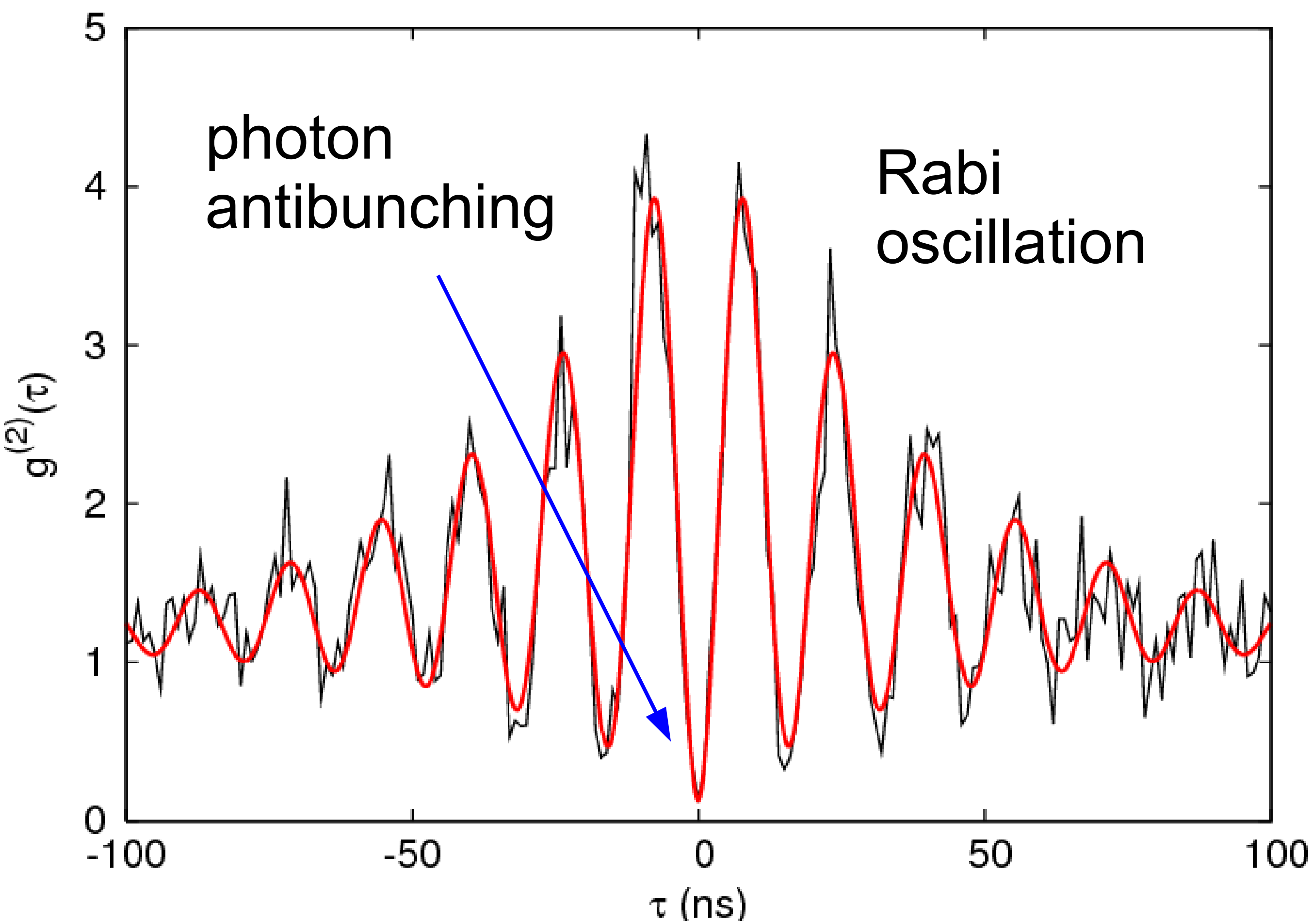
.....Jaynes-Cummings model with all its aspects

- treat external fields as perturbation/spectator of internal field

Single atom evidence

(almost) Hanbury-Brown—Twiss experiment on atomic fluorescence during cooling





Collection into Gaussian mode

- Project total field onto Gaussian mode of collection fiber

$$P_{out} = \left| \langle \vec{g}, \vec{E}_{Tot} \rangle \right|^2 \qquad \langle \vec{g}, \vec{E} \rangle := \int_{\vec{x} \in S} \vec{E}_{Tot}(\vec{x}) \cdot \vec{g}(\vec{x}) (\vec{k}_g \cdot \vec{n}) \, dA$$

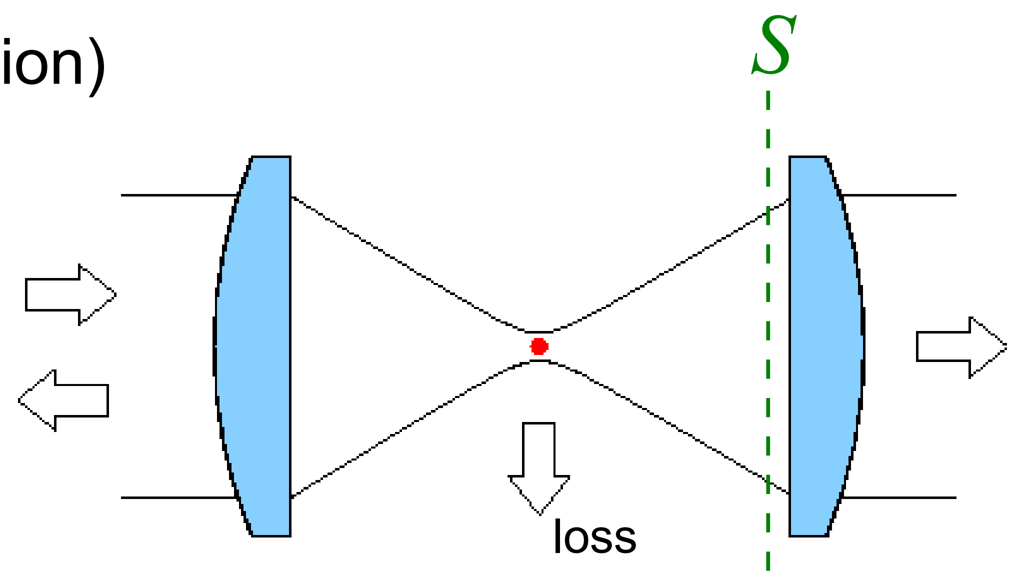
cross section fiber mode

- Forward transmission:

$$1 - \epsilon = \frac{P_{out}}{P_{in}} = \left| 1 - \frac{P_{sc} / P_{in}}{2} \right|^2$$

- Reflectivity (backward direction)

$$R = \frac{(P_{sc} / P_{in})^2}{4}$$

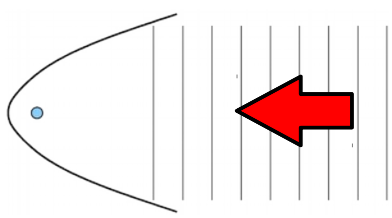


Related work

- Interaction with molecules
  Vahid Sandoghdar group - ETHZ, now MPL Erlangen

- Interaction with quantum dots
  Atac Imamoglu group - ETHZ

- Larger solid angle: ion trap in parabolic mirror
  Gerd Leuchs Group - MPL Erlangen



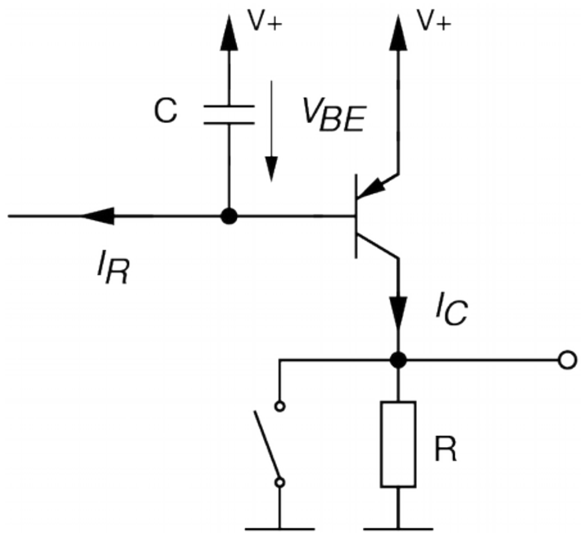
Large mode overlap
with π transition

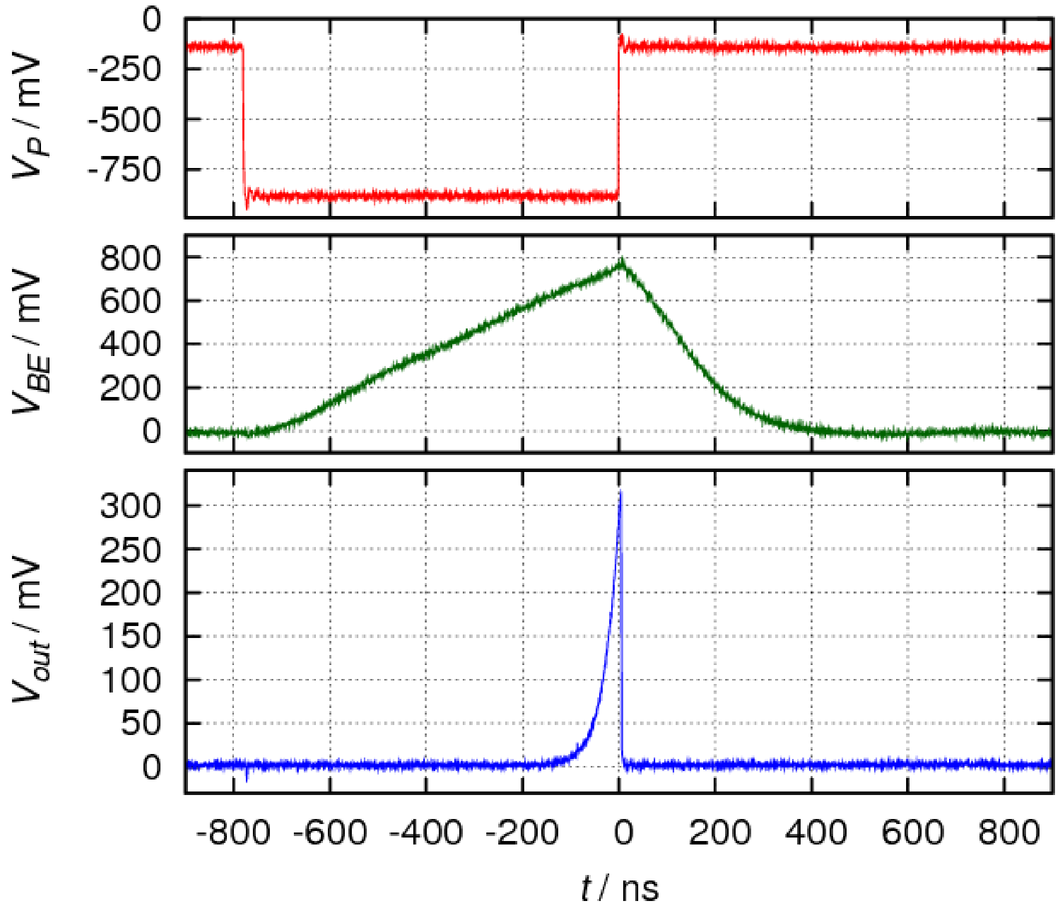
- Fiber cavities for small transverse optical modes
  Jakob Reichel group - LKB

Generation of Envelope

- Linear slope, use transistor transfer function

$$I_C = I_0\left(e^{eV_{BE}/kT} - 1\right) \approx I_0 e^{V_{BE}/V_T}$$

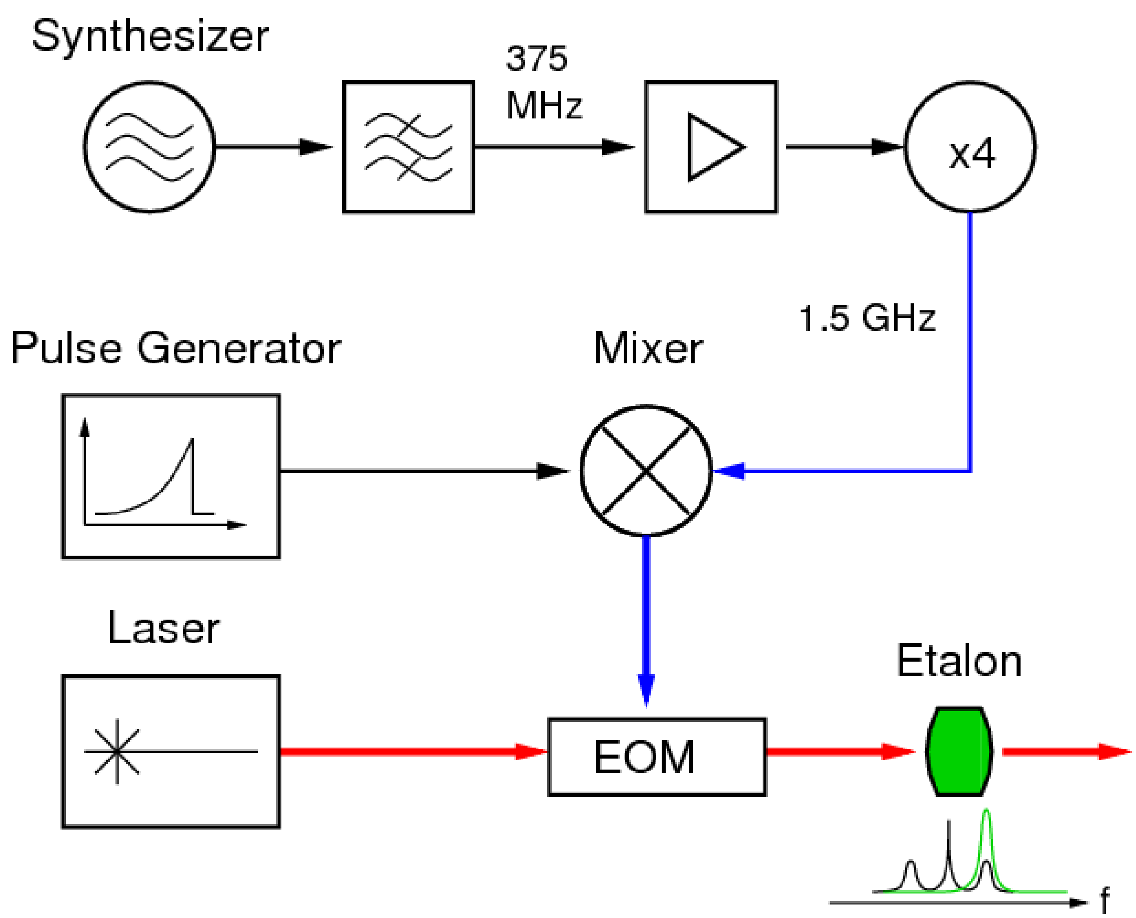




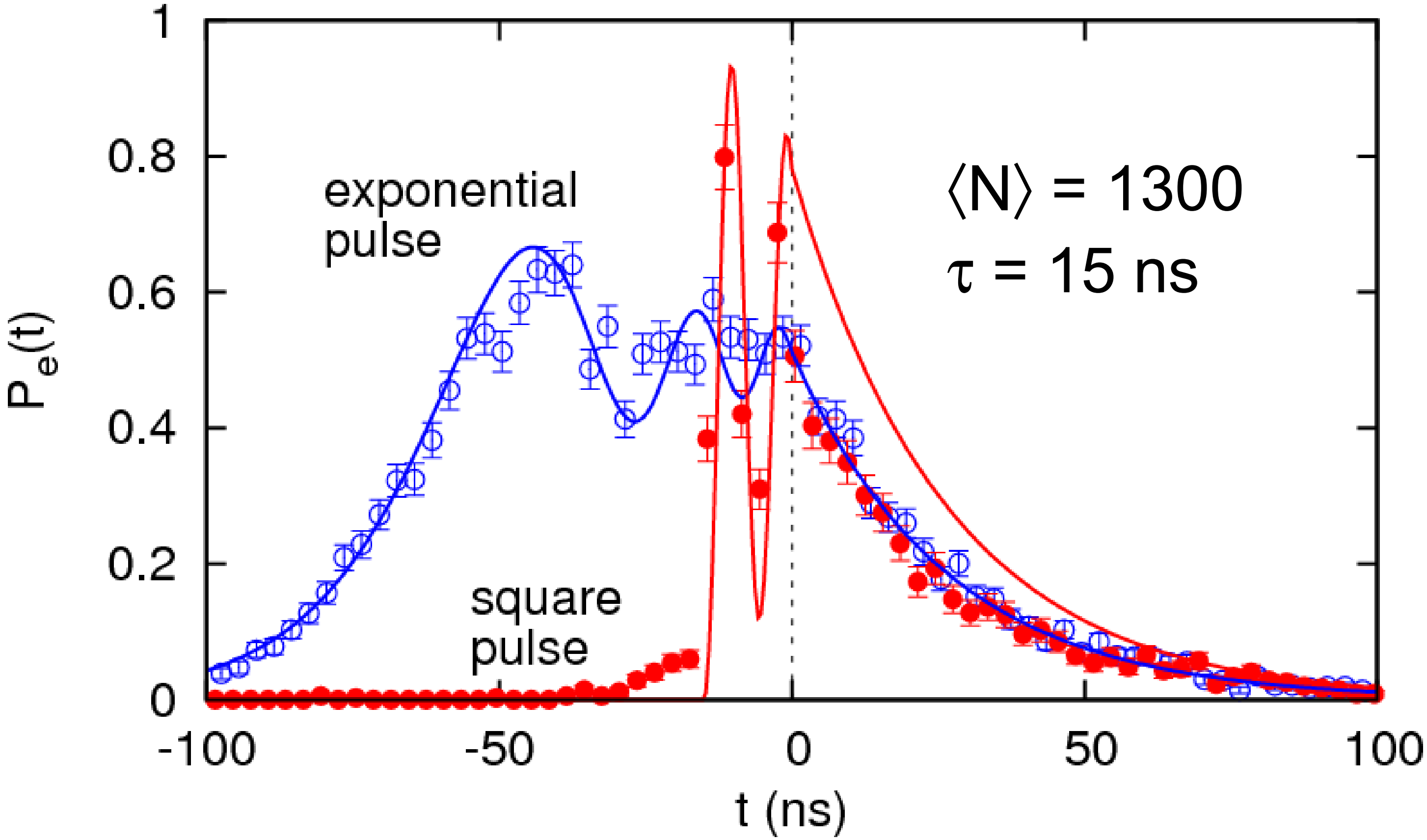
Dao Hoang Lan, S.A. Aljunid, G. Maslennikov, C.K., Rev. Sci. Instr. ***83****, 083104 (2012)*

Optical Pulse

- Generate electrical pulse
- Modulate RF carrier
- Generate optical sideband with EOM and filter with Etalon

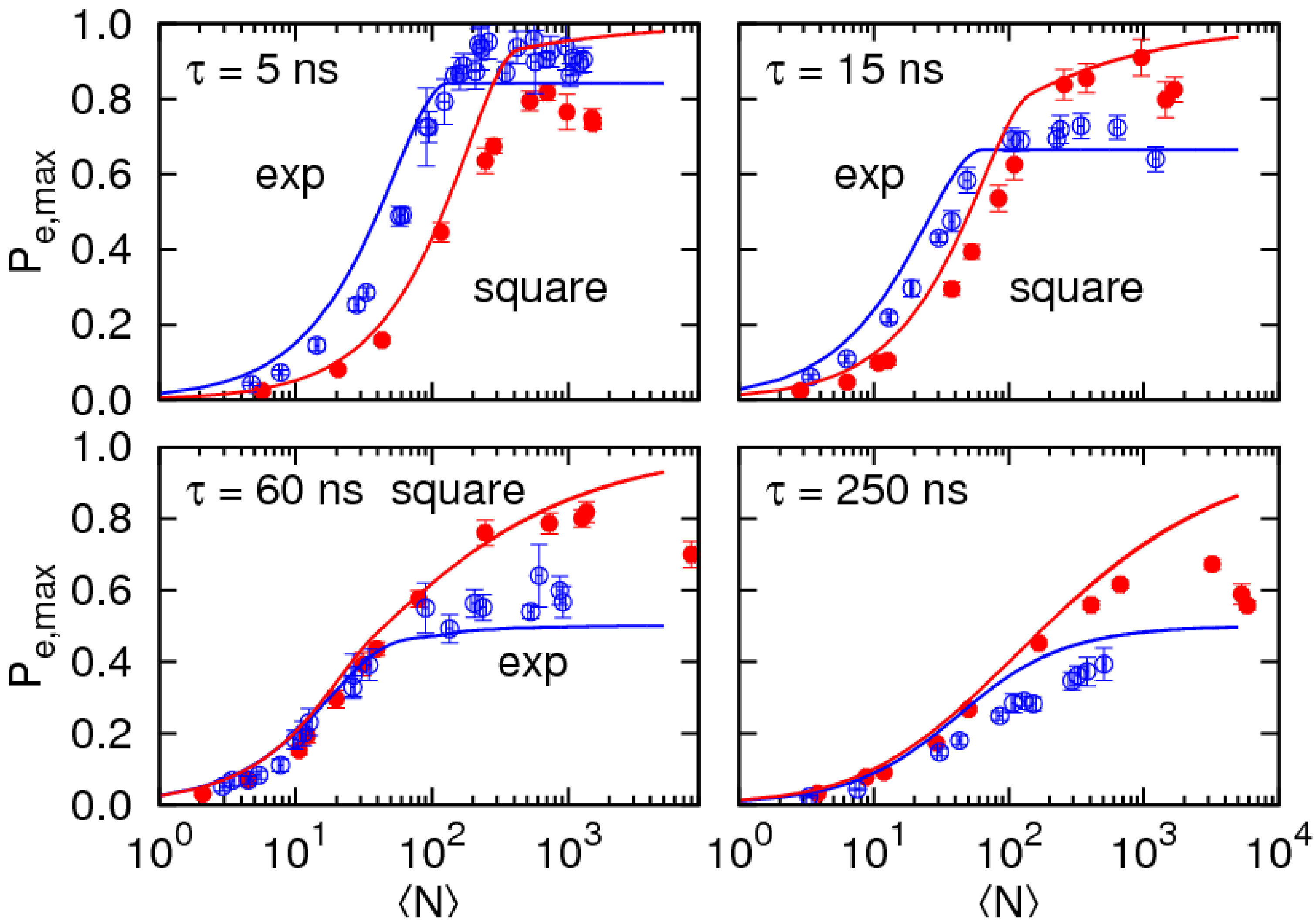


Stronger fields



- Onset of Rabi oscillations

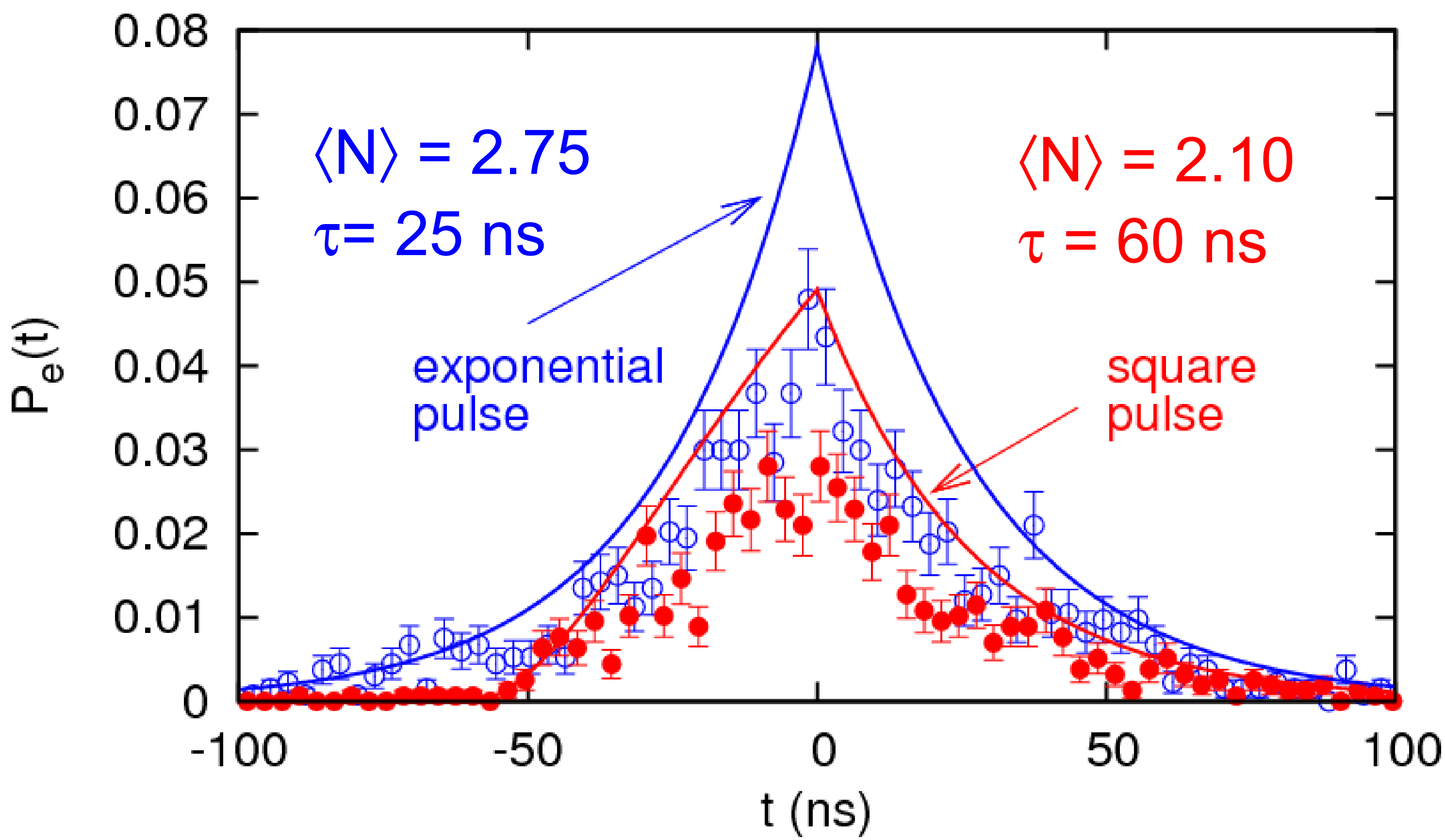
Saturating atomic transition



- Saturation of excitation with ~ 100 photons
- Rising exponential pulse shape does (a bit) better than square

Low photon number

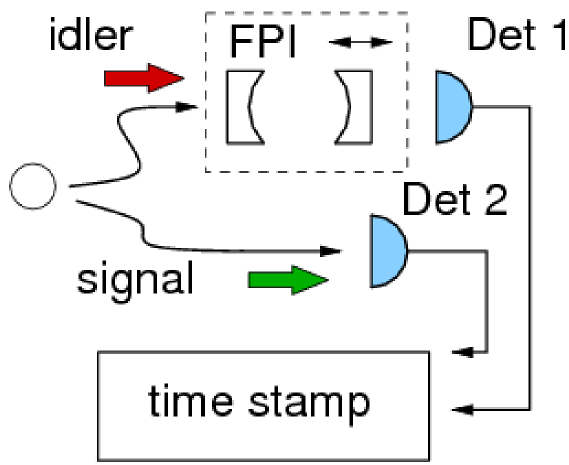
- Optimized τ for given pulse shape / geometry:



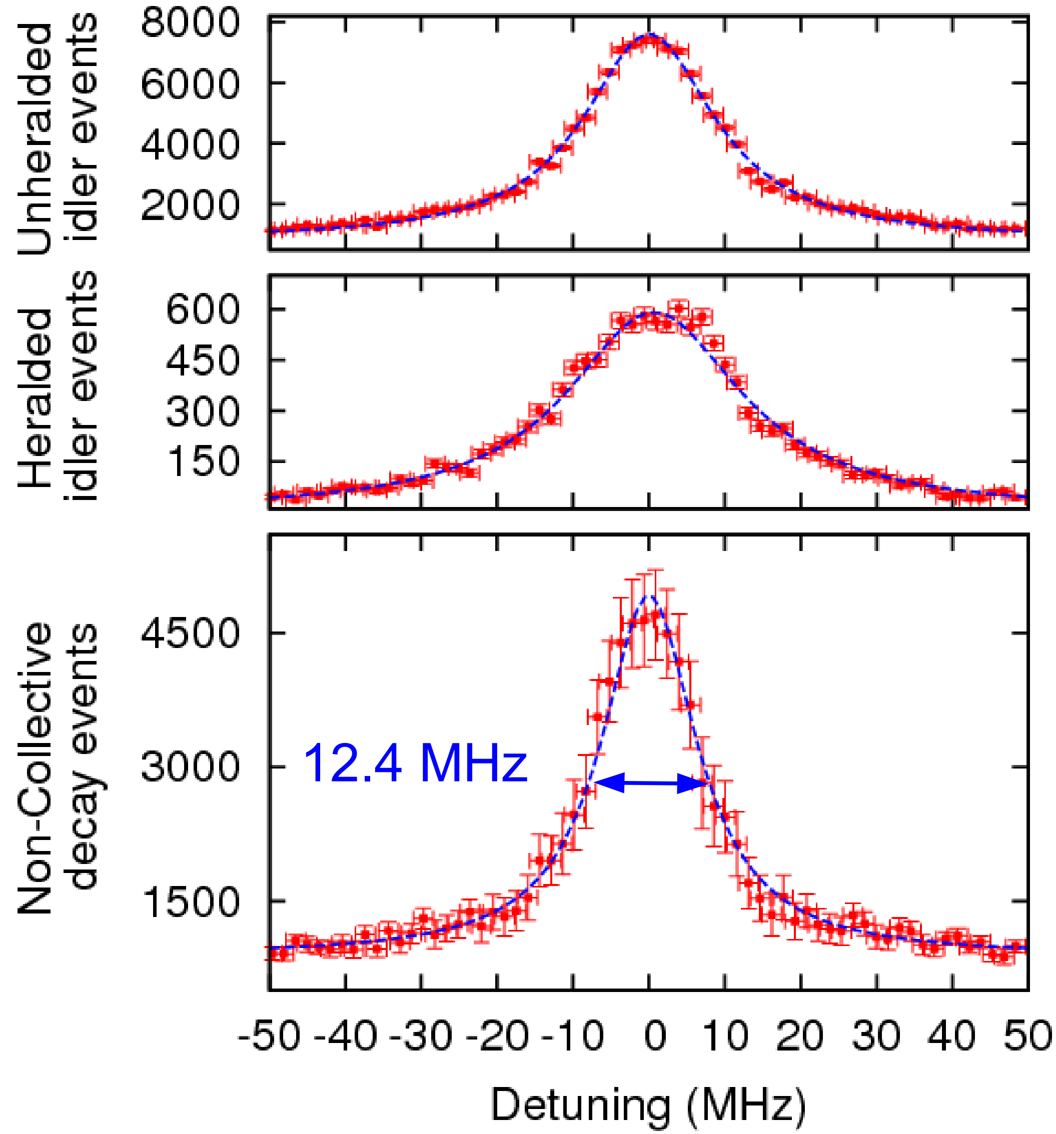
- Maximal excitation probability ~4.5% for <N>=2.75 for single atom

Bandwidth Measurement II

- Two-step vs. pair decay



- Correct unheralded for heralded photons, corrected for losses
- Bandwidth $\Gamma / 2\pi$ still larger than $\Gamma_0 / 2\pi$ due to absorption @ 795nm?



B. Shrivathsan et al., arXiv:1302:3706