Ultrafast Optics group

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Physics of Complex Systems
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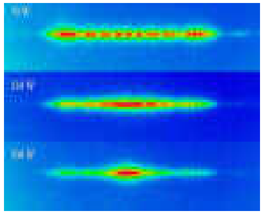
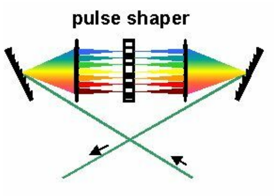
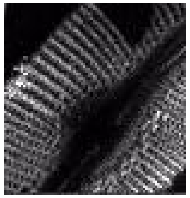


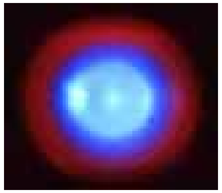
Optical Solitons



Coherent Quantum Control



Nonlinear Microscopy



Nonclassical Light

On the Shape of the Photon:

Quantum Coherent Control with
Single Photons

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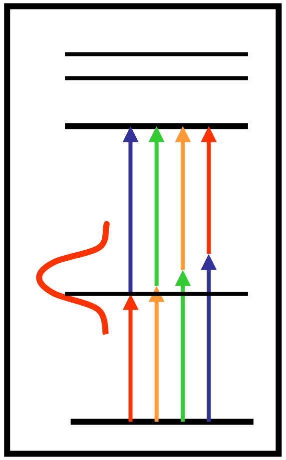
Cargese August 2008

Narrow Transitions, Broad Light

Atomic transitions ~ 1 GHz

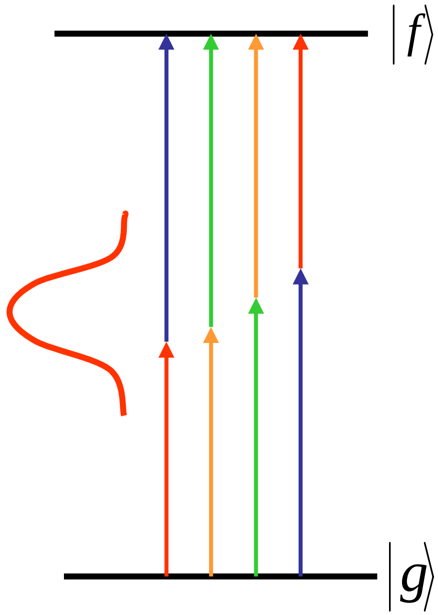
10 fs pulse ~ 100,000 GHz



Nonresonant Two-Photon Absorption

Perturbation analysis yields:

$$a_f(\infty) \propto \int \varepsilon^2(t)\exp(i\omega_{fg}t)dt$$



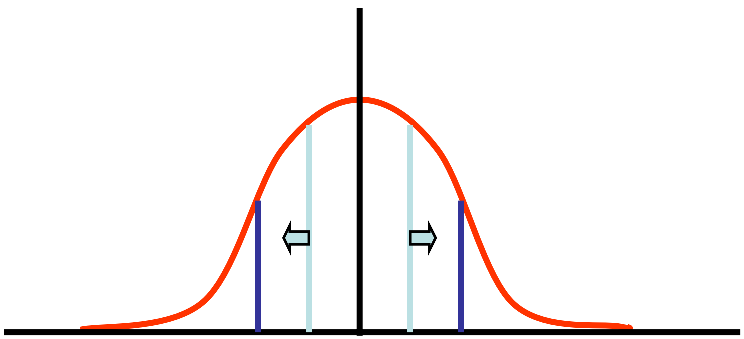
Transition is induced by interference of many trajectories:

$$a_f(\infty) \propto \int E(\omega)E(\omega_{fg}-\omega)d\omega$$

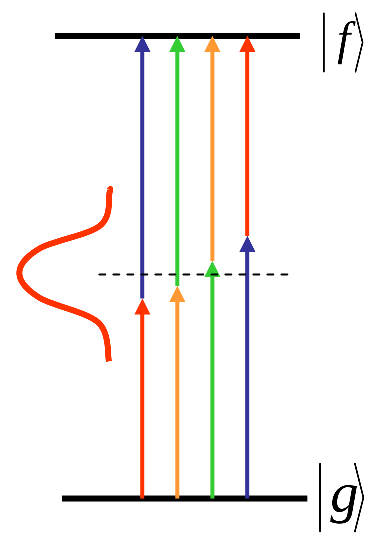
Nonresonant TPA

$$a_f(\infty) \propto \int d\delta\omega\, E(\omega_0 + \delta\omega) E(\omega_0 - \delta\omega) =$$

$$= \int d\delta\omega \left|E(\omega_0 + \delta\omega)\right| \left|E(\omega_0 - \delta\omega)\right| \cdot \underline{e^{i[\Phi(\omega_0+\delta\omega)+\Phi(\omega_0-\delta\omega)]}}$$



$\omega_0 = \omega_{fg}/2$



Transform limited pulses are most efficient, but:

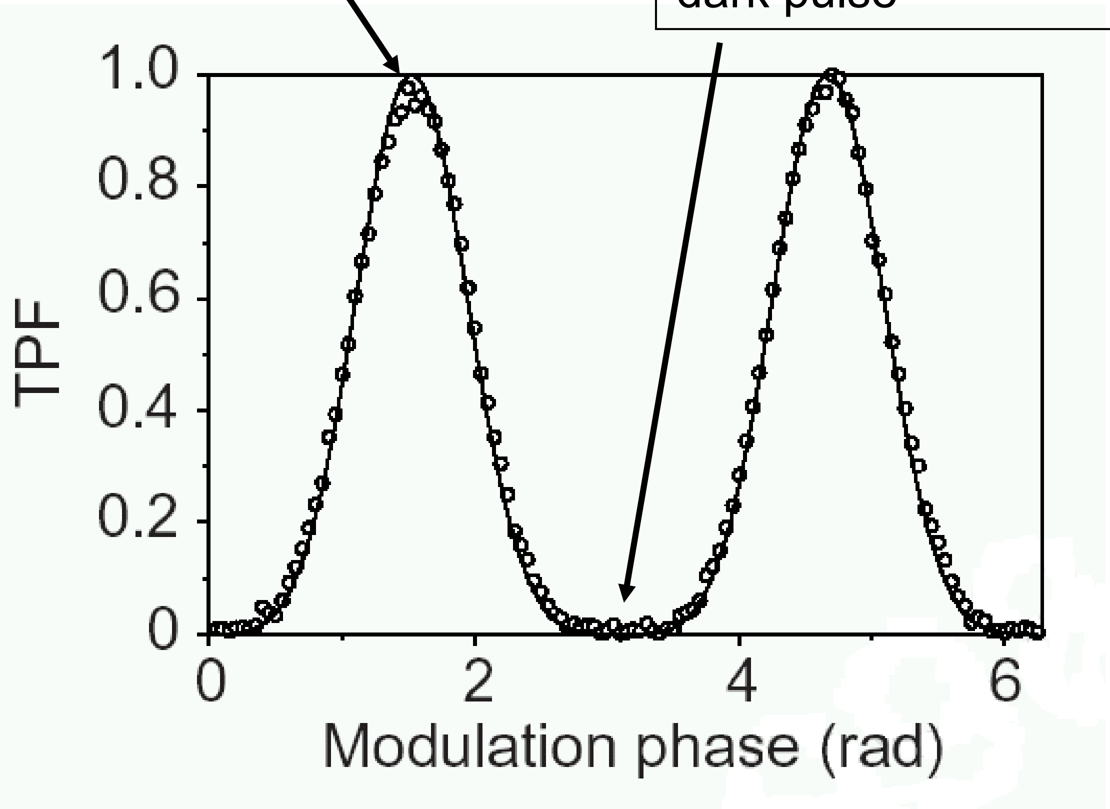
Antisymmetric phase has no effect on transition probability

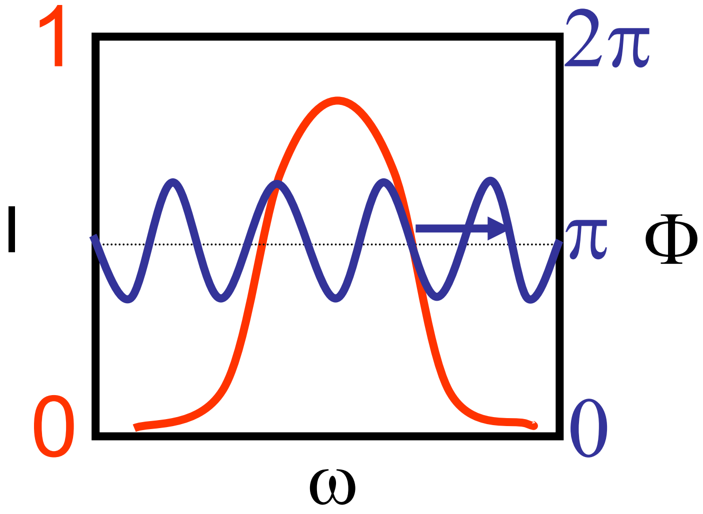
Nonresonant TPA

scan of a periodic phase mask

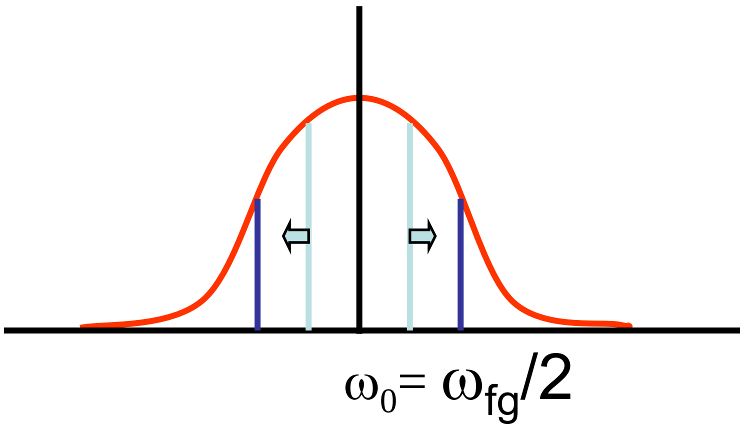
Sinusoidal (antisymmetric) phase

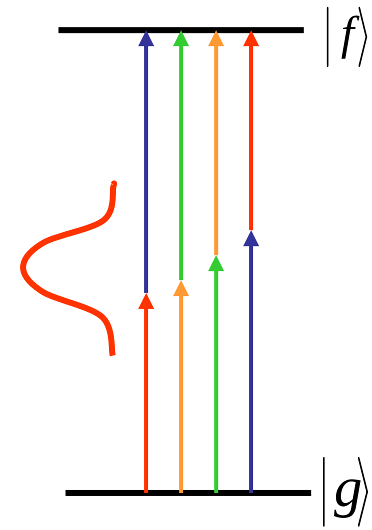
Cosinusoidal (symmetric) phase – dark pulse





Anti-Symmetric Phase Modulation





$$E(\omega_0 - \Delta) = E(\omega_0 + \Delta)^*$$

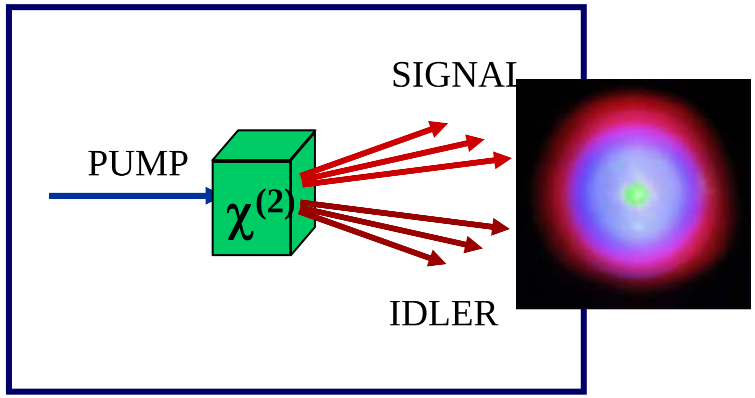
$$A(t)\cos(\omega_0 t)$$

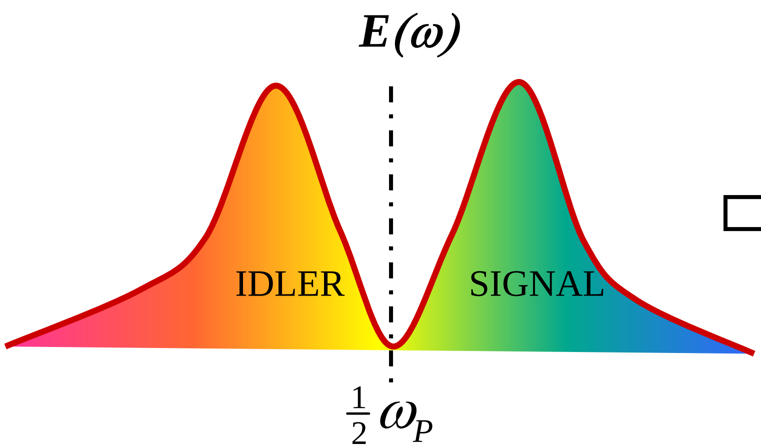
Long, weak **AM modulated** pulses induce TPA just like transform limited pulses with the same energy

How long is long?

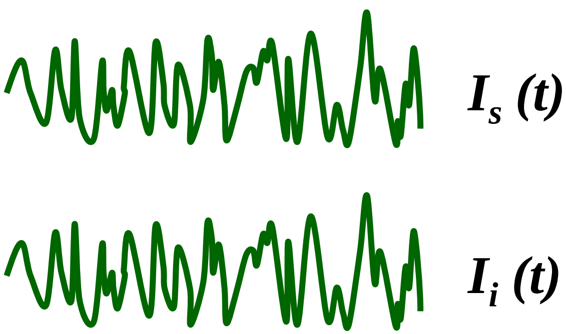
20 fs pulse modulated by a shaper could becomes ~10 ps

Broadband down-converted light (squeezed vacuum)

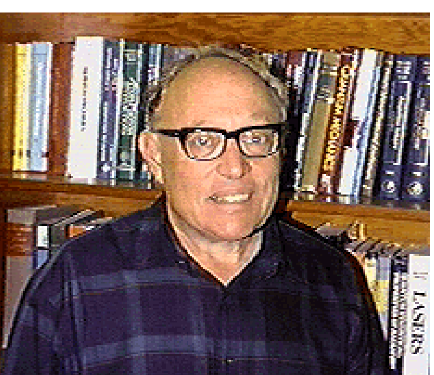




⇨



⇨ $A_i(t) = A_s(t)^*$



S. E. Harris, M. K. Oshman, and R. L. Byer, "Observation of Tunable Optical Parametric Fluorescence," *Phys. Rev. Lett*. **18**, 732-734 (May 1967).

TPA with SPDC Light

Broadband down-converted light beams can induce TPA just like an ultrashort pulse with the same bandwidths

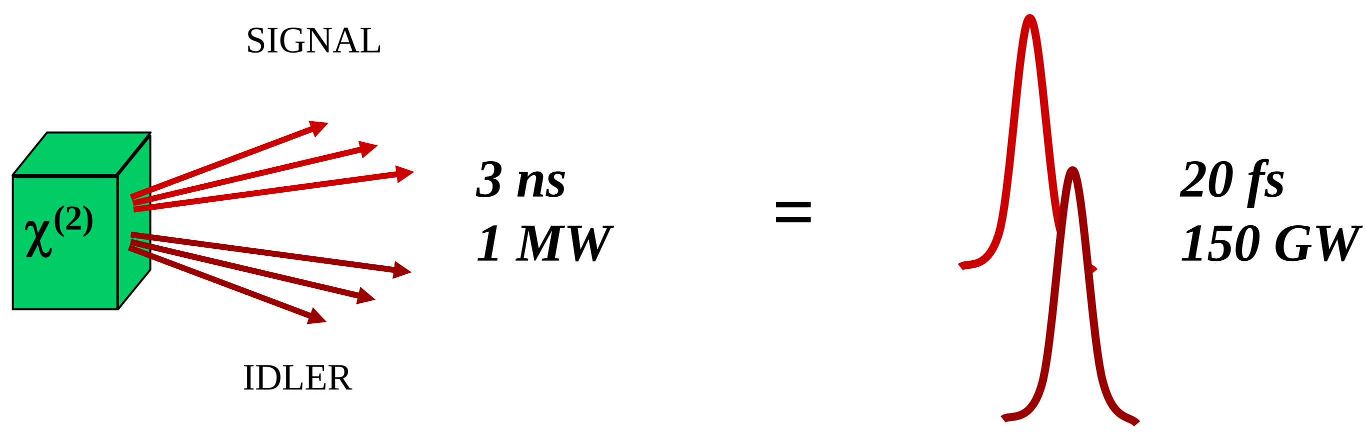
$$E_I\left(\tfrac{1}{2}\omega_P-\Delta\right)\propto E_S\left(\tfrac{1}{2}\omega_P+\Delta\right)^*$$

when the pump frequency ω_p is tuned to the two-photon overall frequency ω_{fg} :

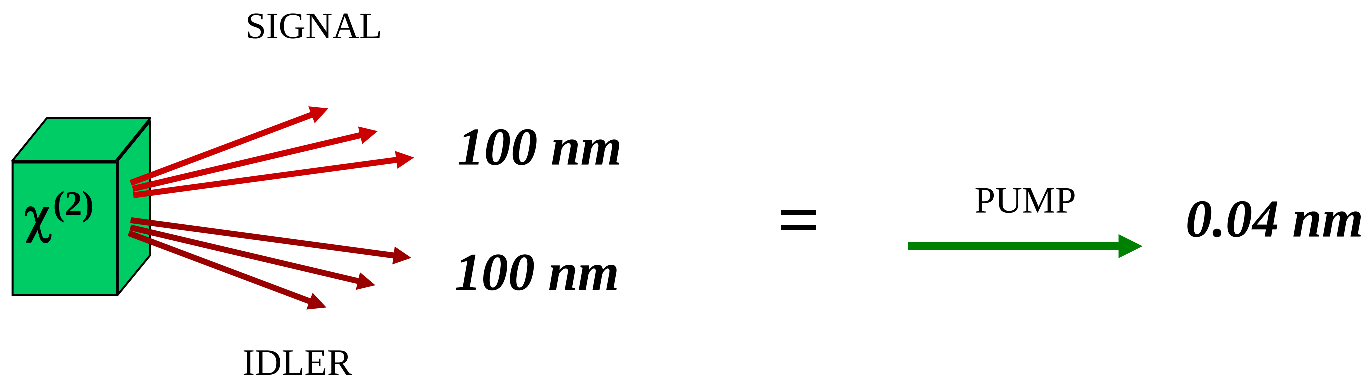
$$p_f\propto\left|\int\left|E_S(\omega)\right|^2 d\omega\right|^2$$

A complete constructive interference, just like with a transform-limited pulse

Broadband down-converted light beams induce TPA just like a pair of ultrashort pulse with the same bandwidths



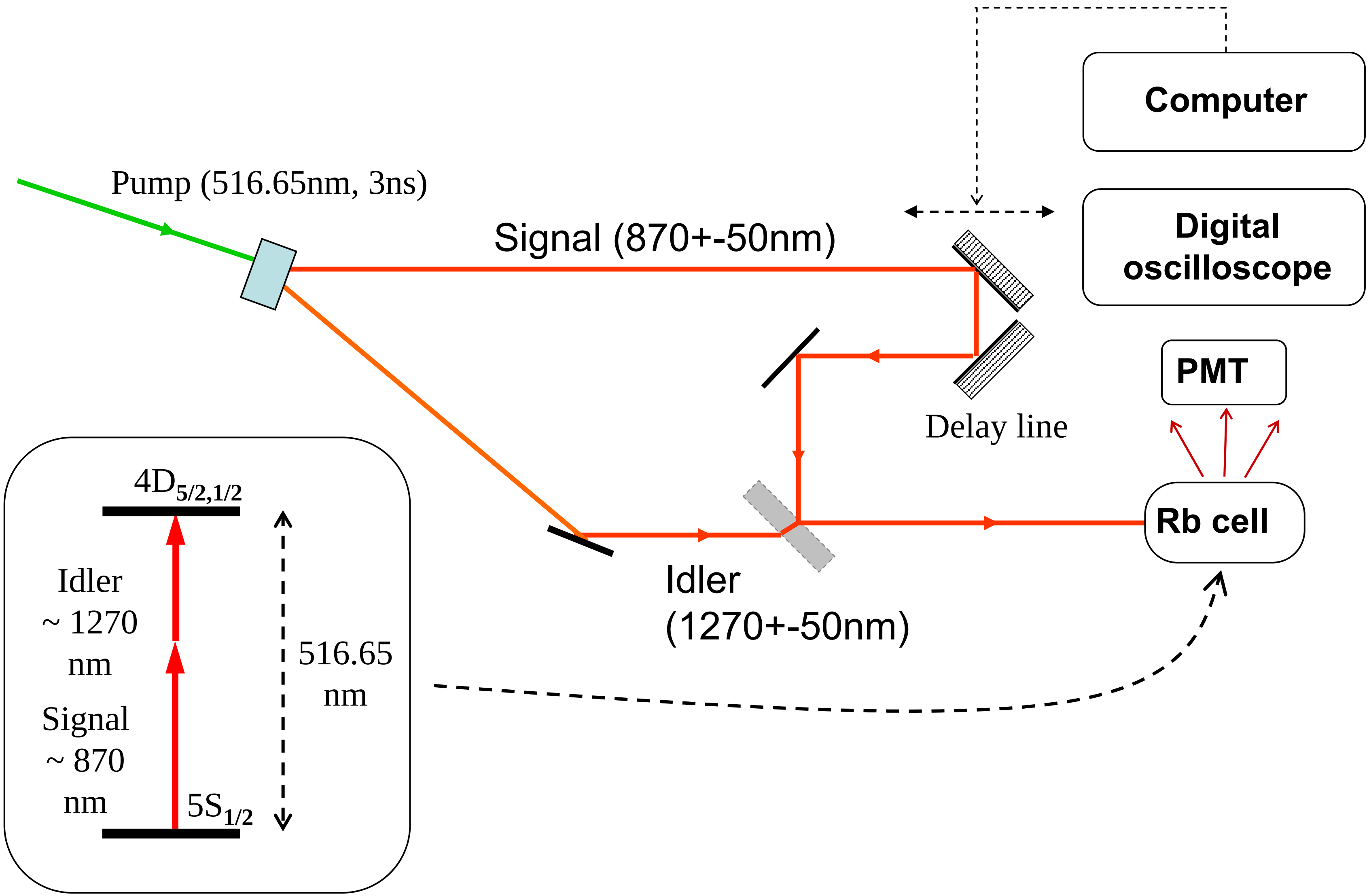
But :



Temporal resolution of ultrashort pulses (though the light can be continuous)

Spectral resolution of a narrowband laser (though the light is as broadband as a pulse)

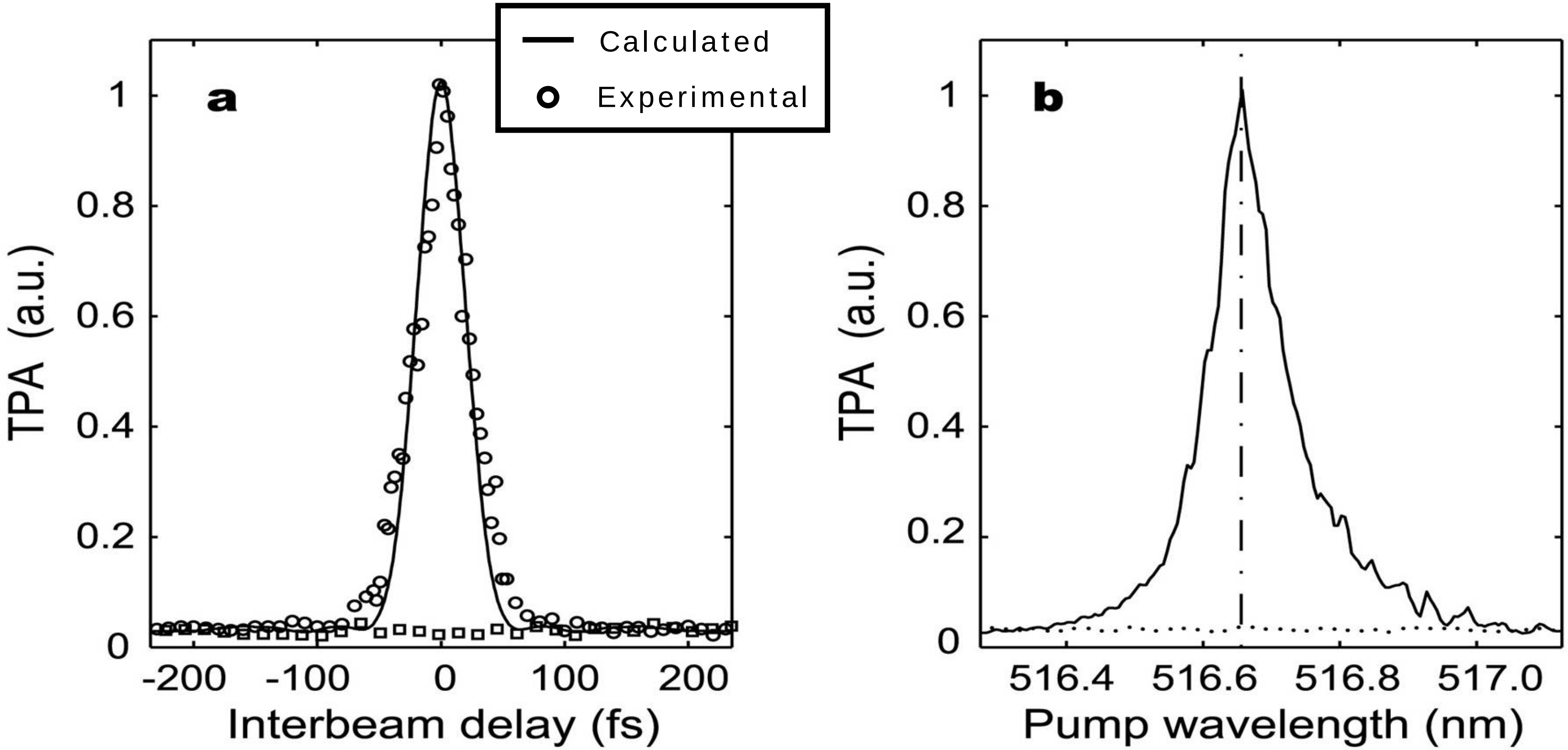
TPA with down-converted light



Experimental Results

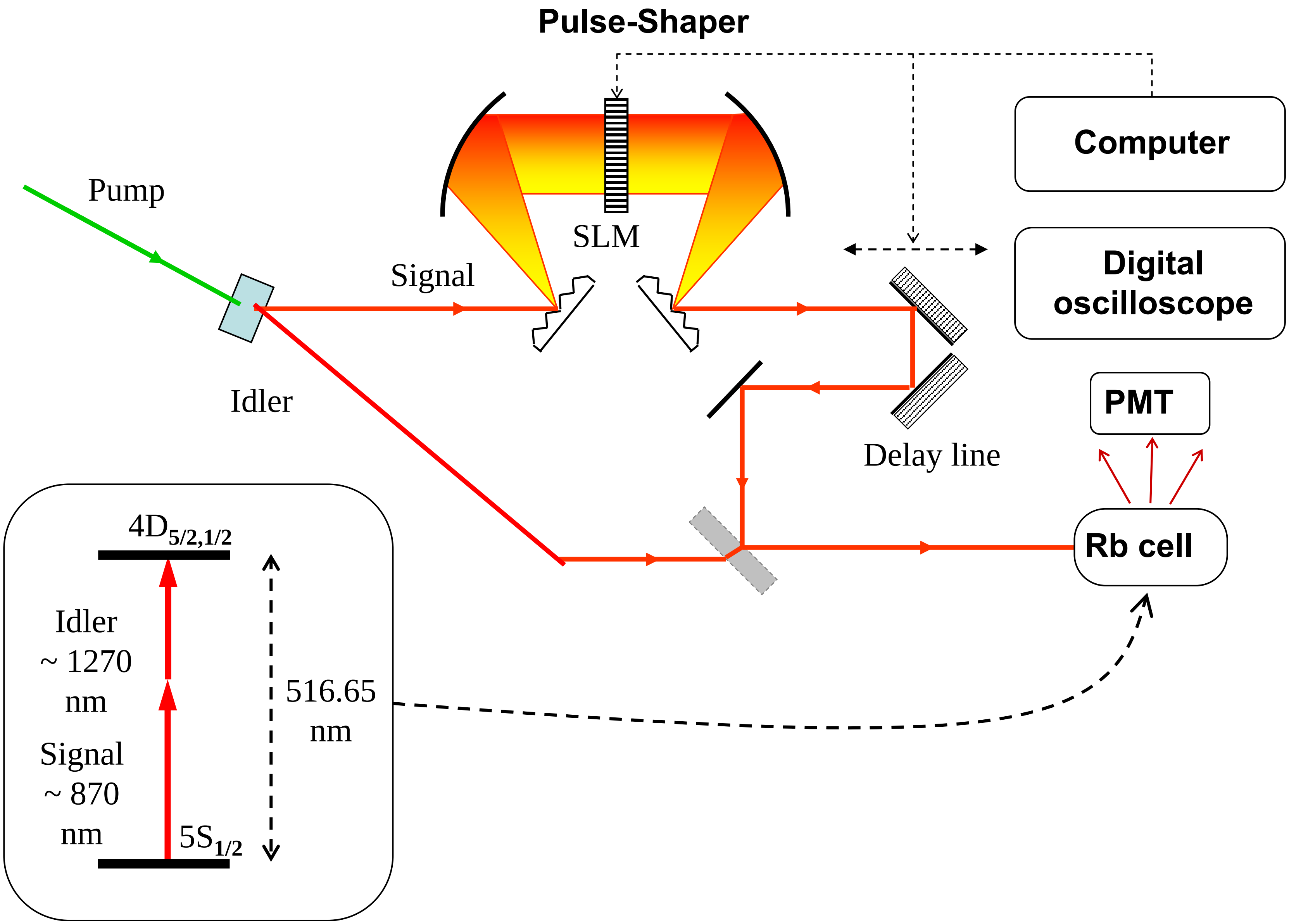
Temporal resolution as of *23 fs* pulses,
5 orders of magnitude
Below the duration of the light (*3 ns*).

Spectral resolution as of the pump (0.04nm)
3 orders of magnitude
Below bandwidth of light (~100nm / beam)

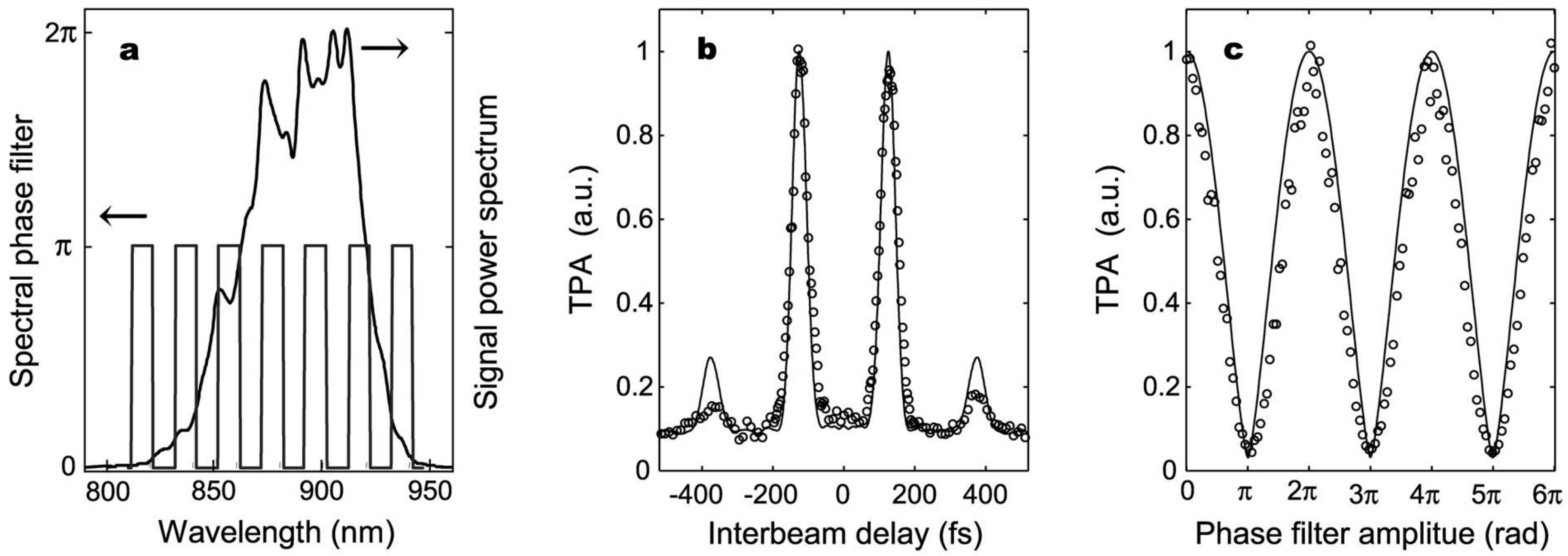


B. Dayan, A. Pe'er, A.A. Friesem, Y. Silberberg, *Phys. Rev. Lett*, 93, 023005 (2004)

Controlling TPA



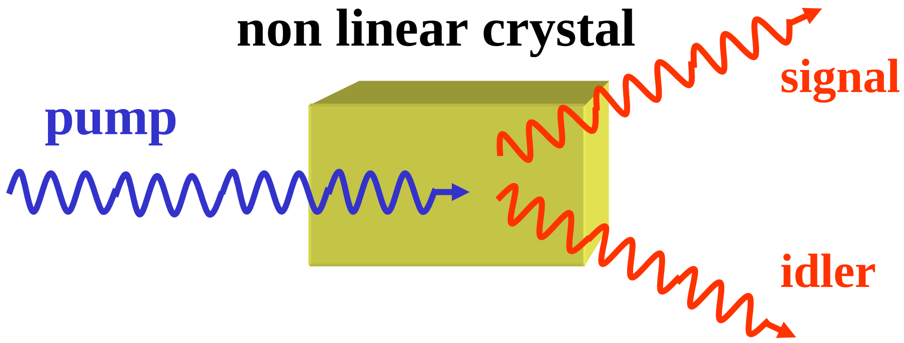
Controlling TPA



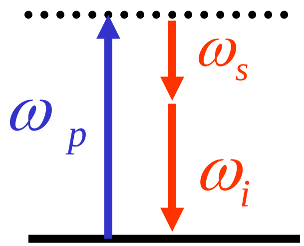
B. Dayan, A. Pe'er, A.A. Friesem, Y. Silberberg, *Phys. Rev. Lett*, 93, 023005 (2004)

Spontaneous Parametric Down-Conversion - the bi-photon source

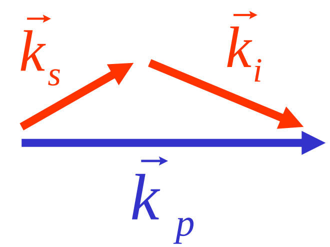
a pump photon is spontaneously converted into two lower frequency photons



energy conservation



momentum conservation (phase matching)



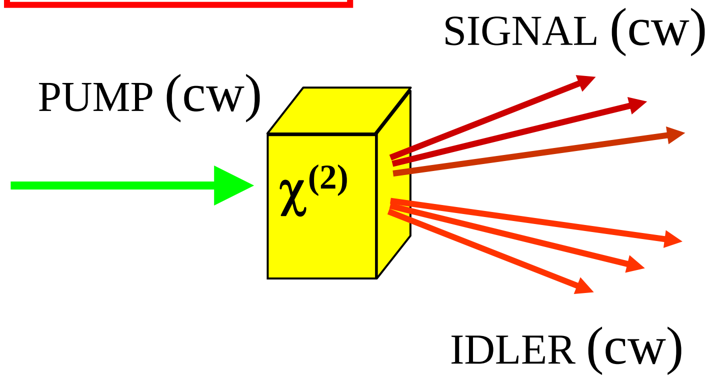
QCC with Non-classical Light

Can we shape a single photon?
Can we control with single photons?

Spontaneous Down-Conversion:

Time-Energy Entangled Photons

$\delta_p \approx 5\ MHz$

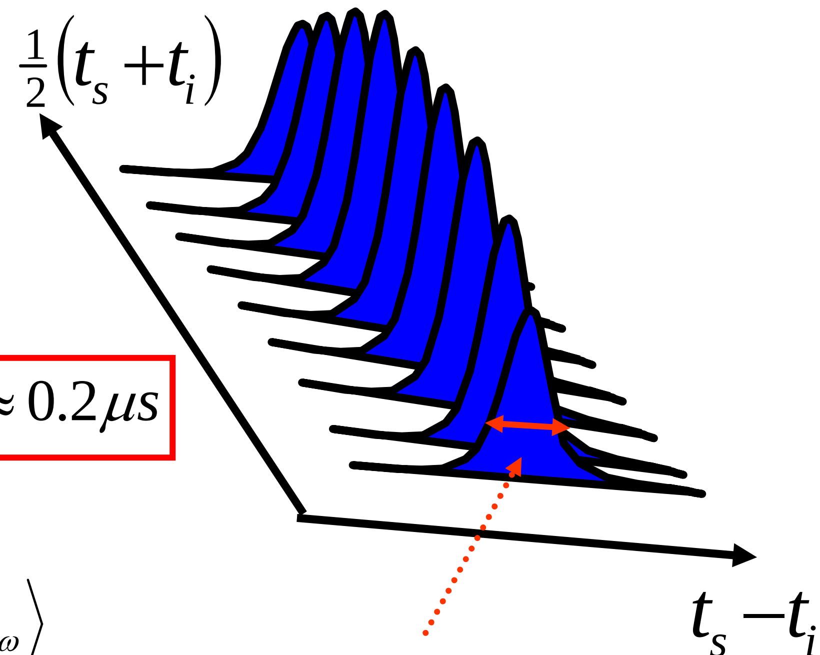


$\Delta \approx 30nm \approx 10THz$

$1/\delta_p \approx 0.2\mu s$

The two-photon wavefunction

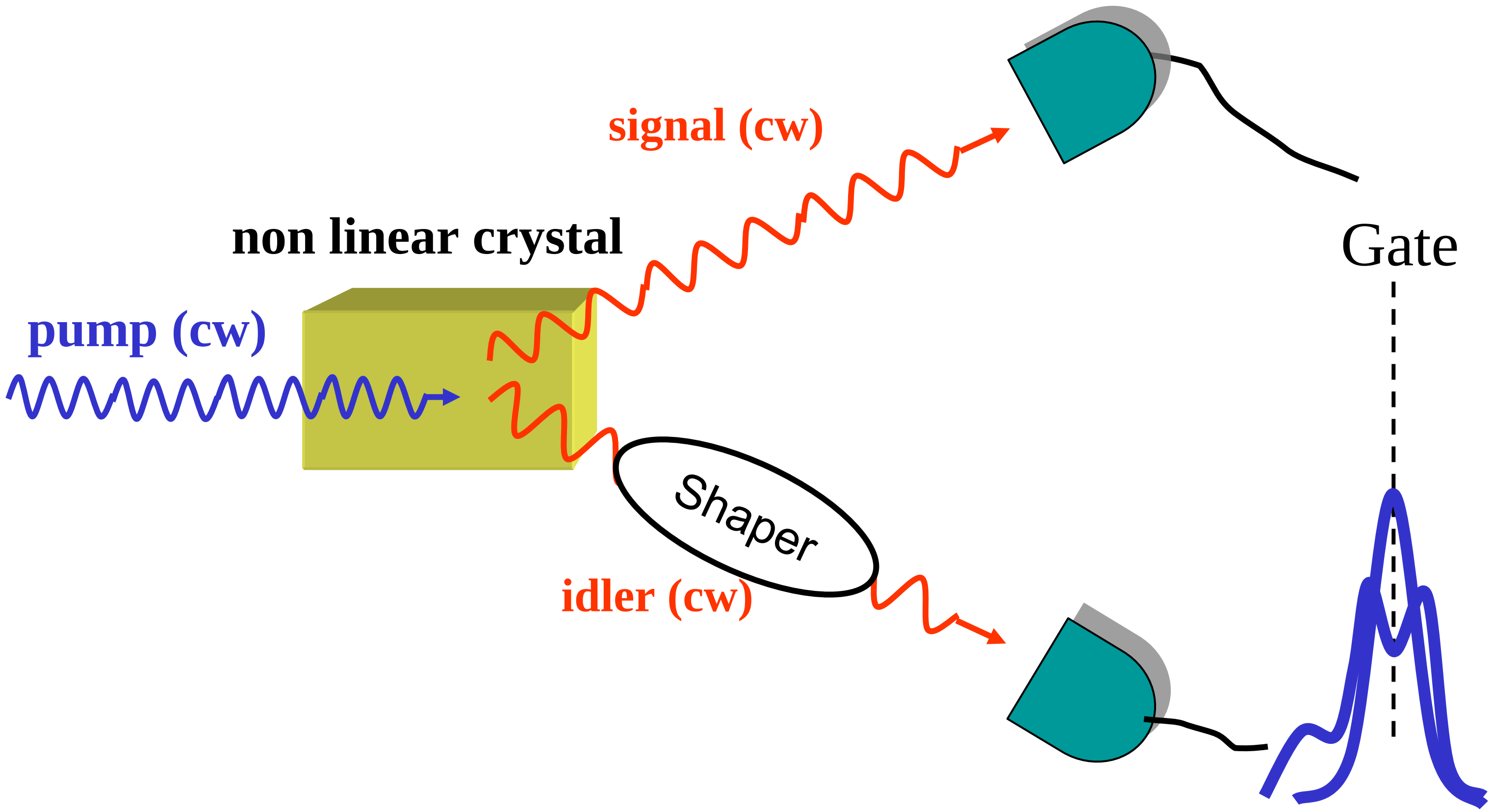
$$\Psi(t_s, t_i) = \langle 0 | E_s^+(t_s) E_i^+(t_i) | \varphi \rangle$$



$1/\Delta \approx 100\ fs$

$$|\varphi\rangle = \sqrt{(1-\varepsilon)}|0\rangle + \sqrt{\varepsilon}\int d\omega\, g(\omega)\left|1_{\omega_{p/2}-\omega}, 1_{\omega_{p/2}+\omega}\right\rangle$$

Time-Energy Entangled Photons



- The time DIFFERENCE between the photons behaves as a fs pulse

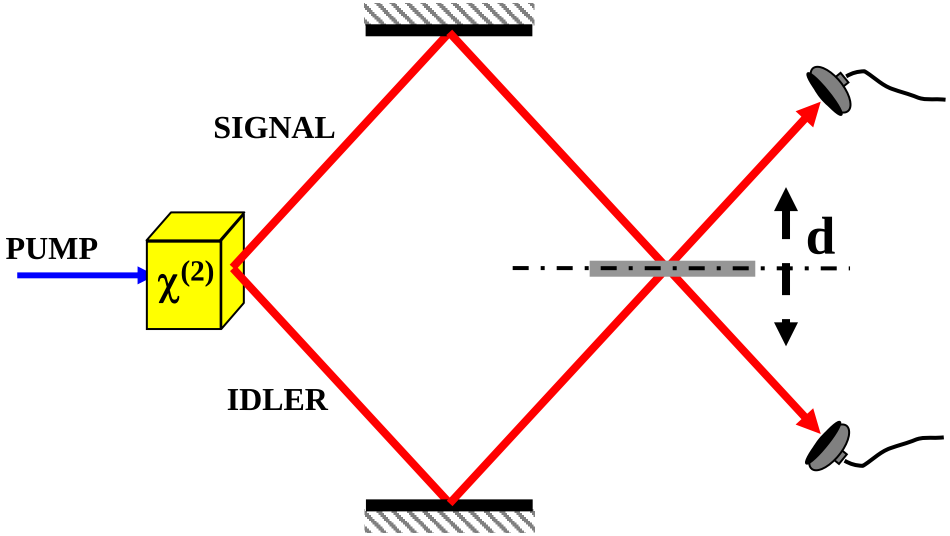
  … so lets shape the two-photon correlation function !

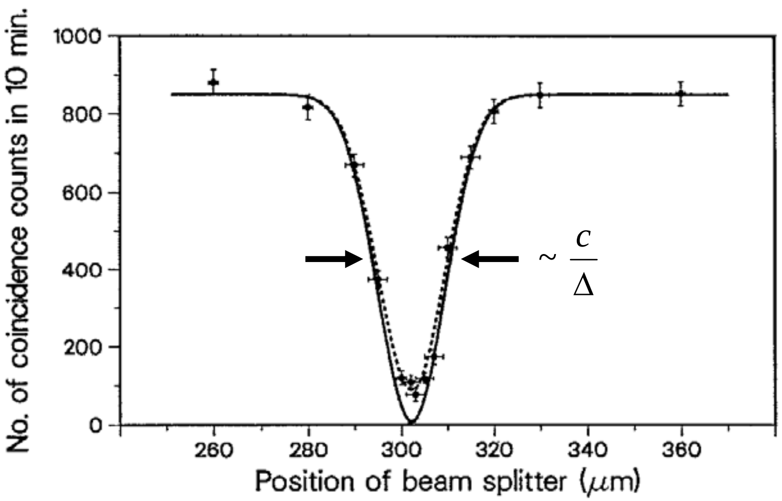
- But electronics limits temporal resolution to ~ns

Two-Photon Coincidence Interference : Hong-Ou-Mandel Dip

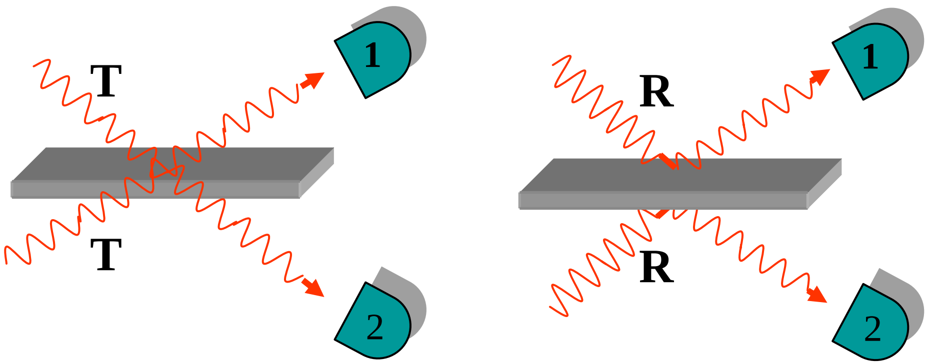
"Measurement of Subpicosecond Time Intervals between Two Photons by Interference"

C.K. Hong, Z.Y. Ou and L. Mandel, PRL 59 (1987)





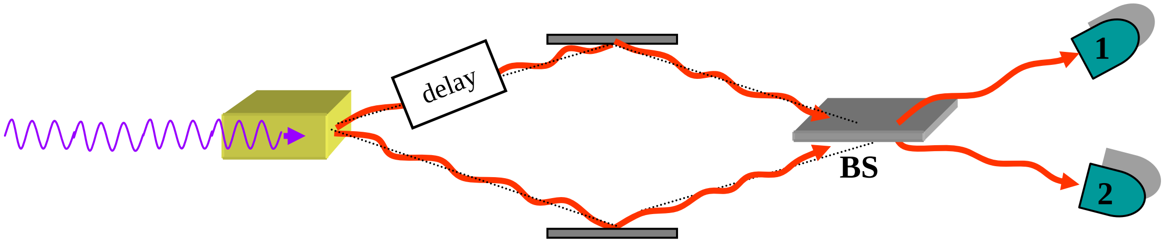
Indistinguishable Paths



$$\frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} \quad + \quad \frac{i}{\sqrt{2}} \cdot \frac{i}{\sqrt{2}} \quad = \quad 0$$

Indistinguishable paths which lead to the same event interfere

→ destructive interference → no coincidence



delay → distinguishable paths → no interference

Two-Photon Coincidence Interference :
Hong-Ou-Mandel Dip

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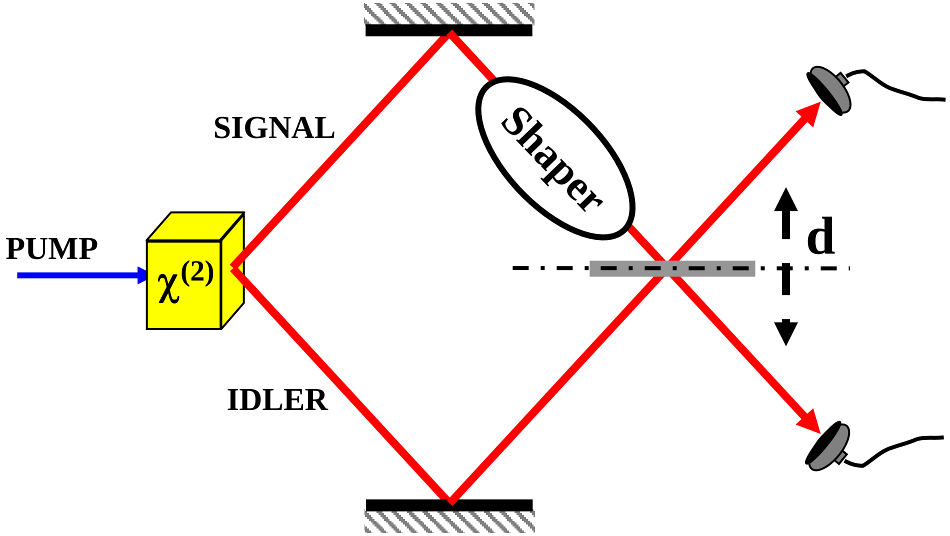
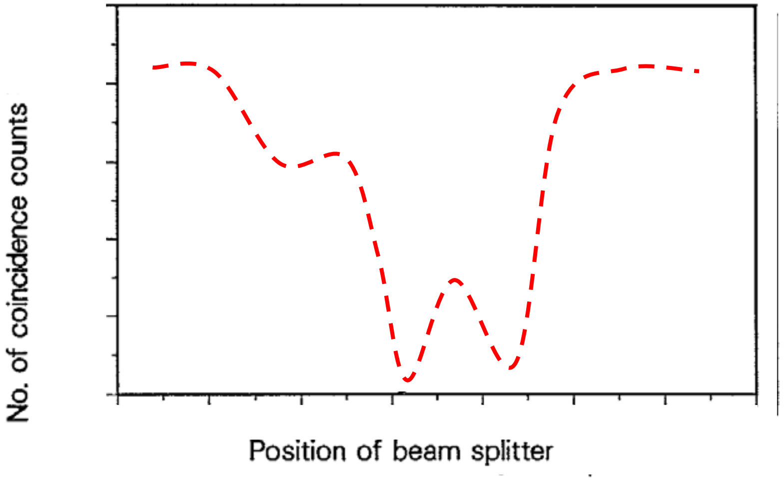




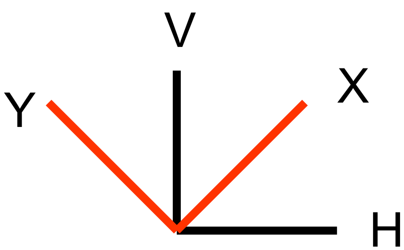
HOM in polarization

2 type-I crystals generate polarization entanglement and broad spectrum

$$\frac{1}{\sqrt{2}}\left(|H\rangle_s|H\rangle_i + e^{i\varphi}|V\rangle_s|V\rangle_i\right)$$

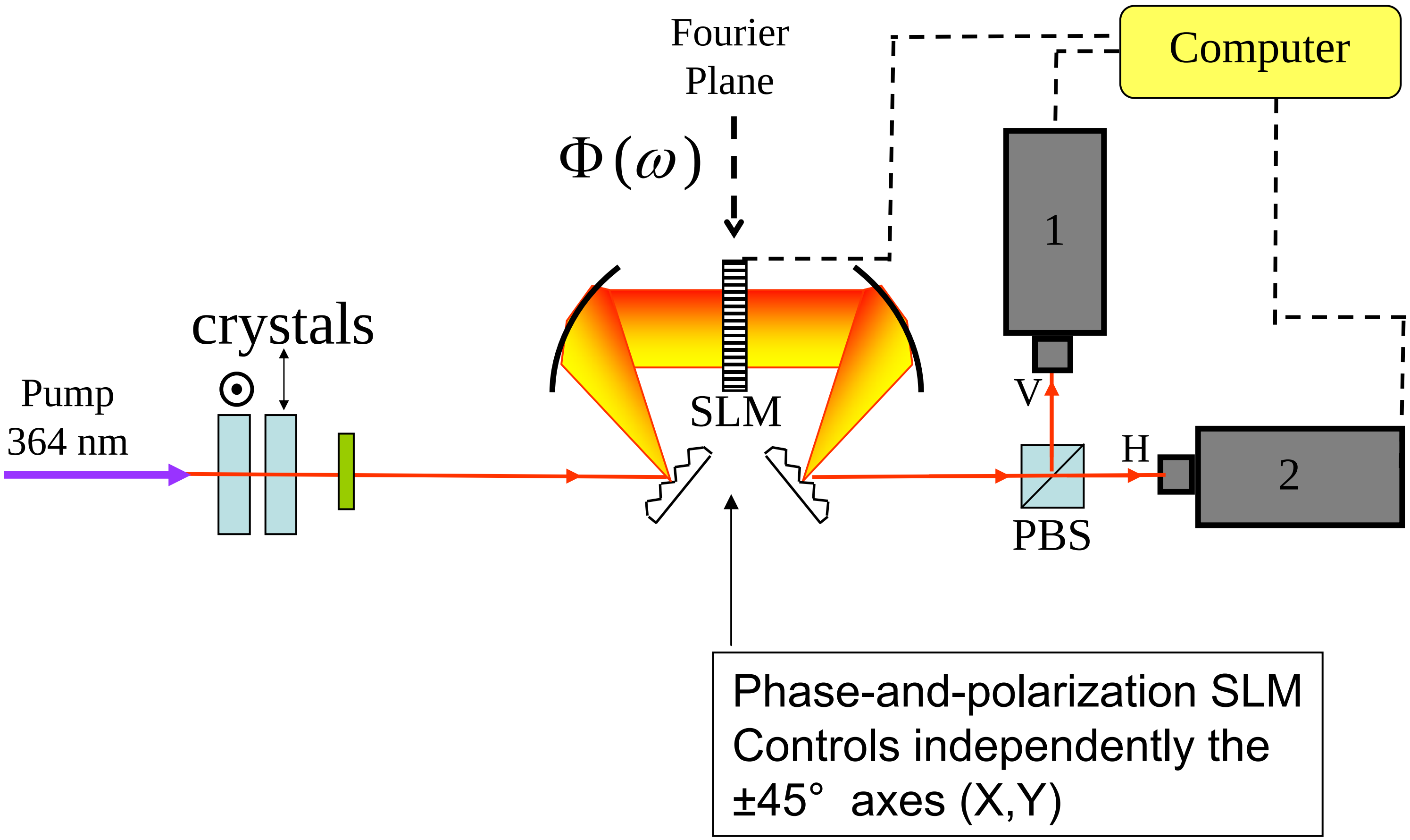
$$\frac{1}{\sqrt{2}}\left(|H\rangle_s|H\rangle_i - |V\rangle_s|V\rangle_i\right)$$

$$= \frac{1}{\sqrt{2}}\left(|X\rangle_s|Y\rangle_i + |Y\rangle_s|X\rangle_i\right)$$

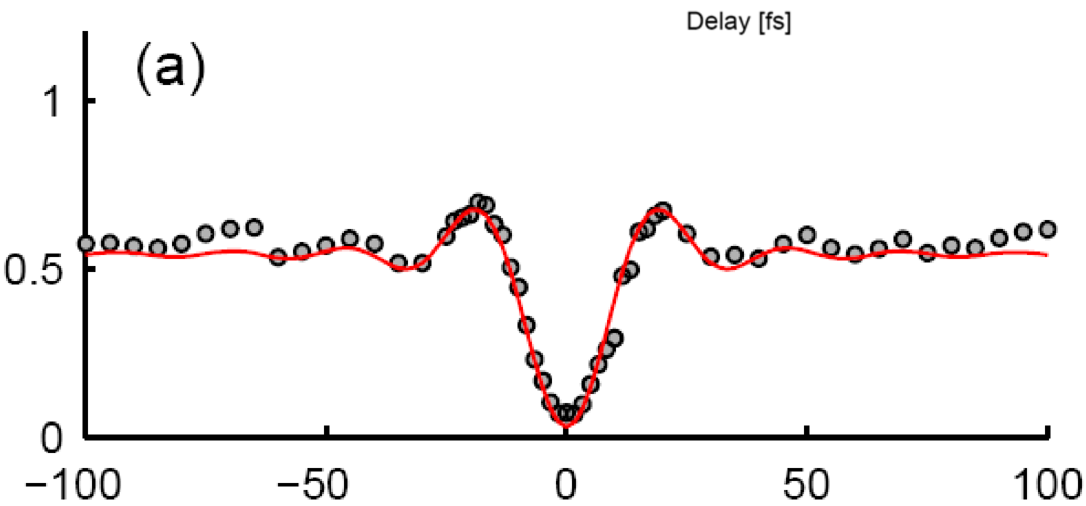


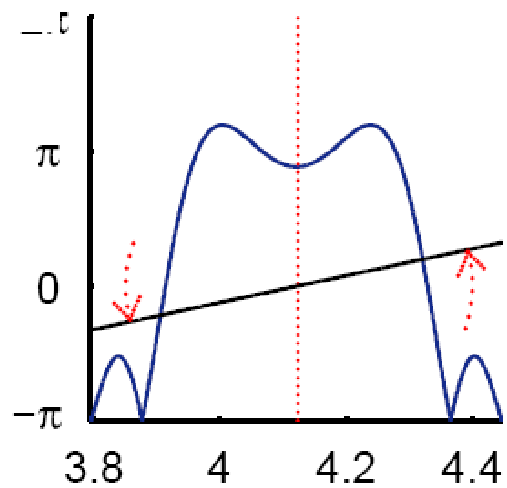
A. V. Burlakov *et. al.* , PRA **64,** (2001)

Experimental Setup

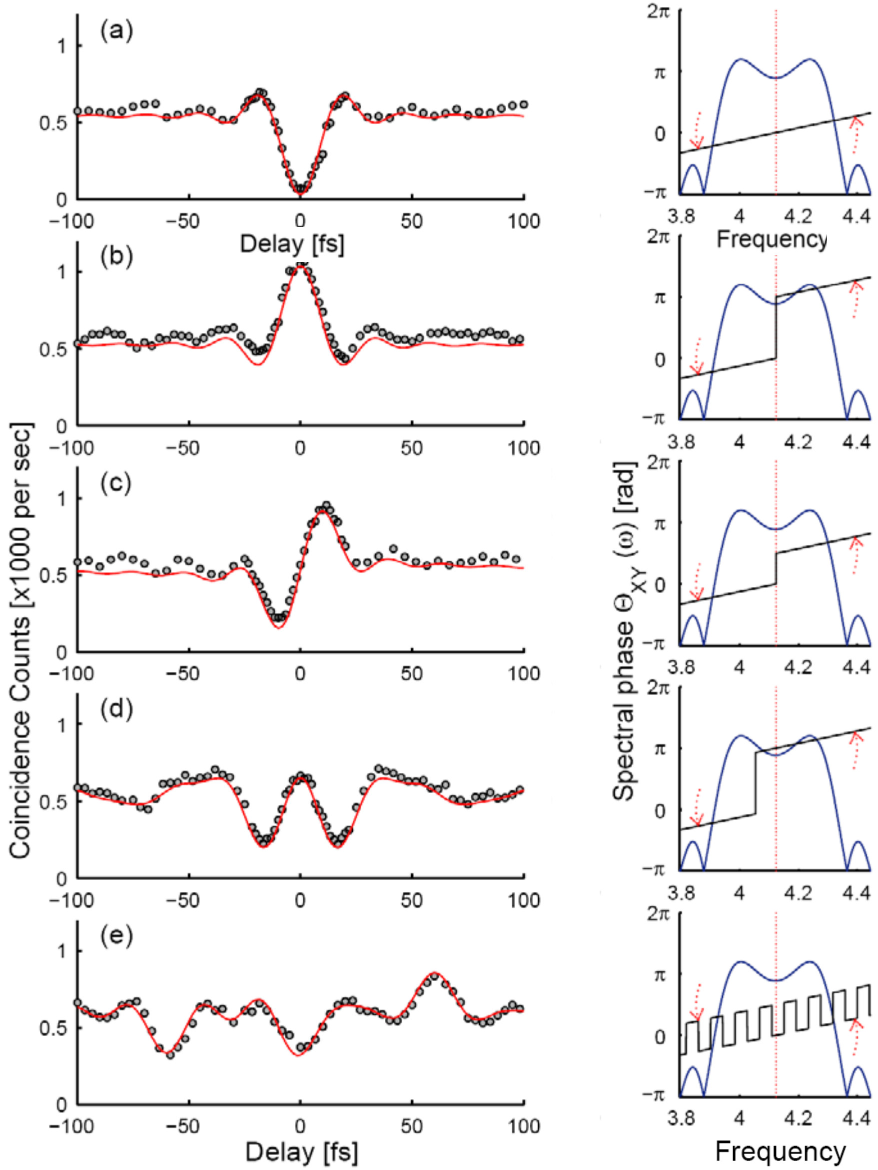


Experimental Results





Experimental Results



We can shape the two-photon correlation function

Polarization Bell States

Entanglement of signal ($\omega > \omega_p/2$) and idler ($\omega < \omega_p/2$) photons

$$\Phi^{(-)} = |\uparrow\rangle|\uparrow\rangle - |\rightarrow\rangle|\rightarrow\rangle$$

$$\Psi^{(-)} = |\uparrow\rangle|\rightarrow\rangle - |\rightarrow\rangle|\uparrow\rangle$$

π step with SLM

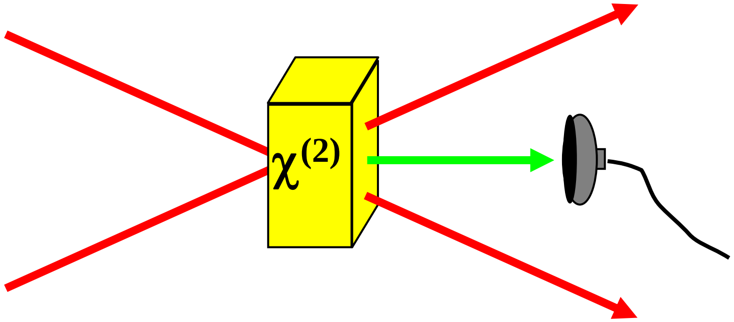
π phase with LCC

$$\Phi^{(+)} = |\uparrow\rangle|\uparrow\rangle + |\rightarrow\rangle|\rightarrow\rangle$$

$$\Psi^{(+)} = |\uparrow\rangle|\rightarrow\rangle + |\rightarrow\rangle|\uparrow\rangle$$

Nonlinear Optics with Single Photons ?

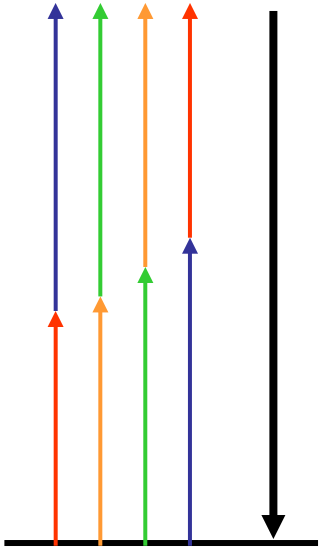
HOM correlations are nice, but wouldn't it be nicer to have direct detection of photons ?



TPA ?   SFG ?

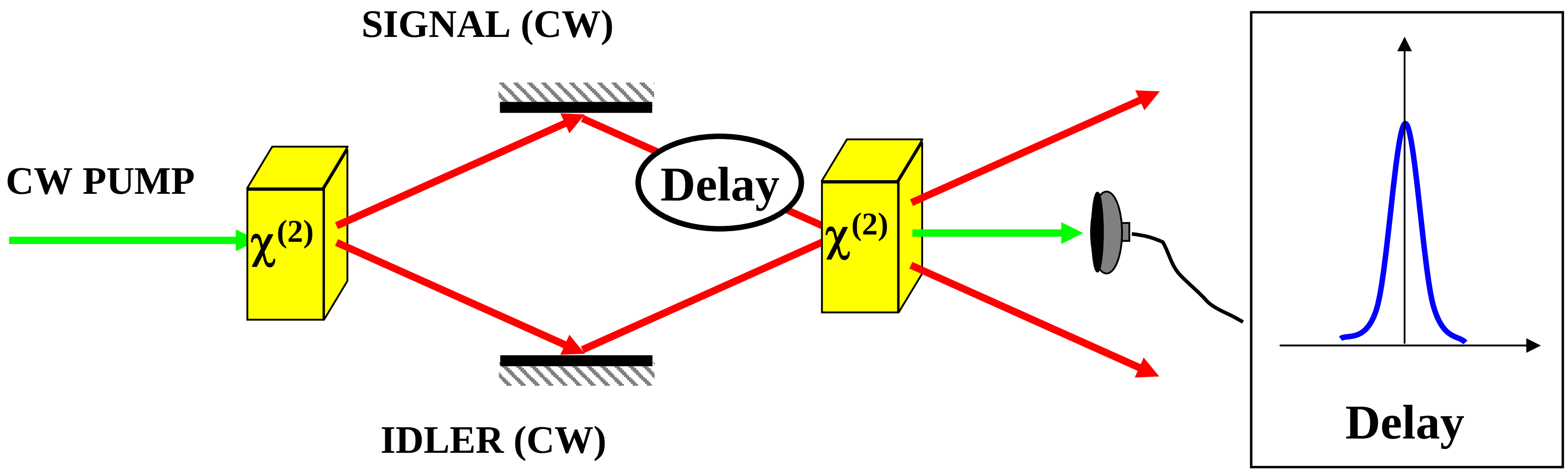
Nonlinear Optics with Single Photons

Sum-Frequency Generation



$$E(\Omega) \propto \int E(\omega) E(\Omega - \omega) d\omega$$

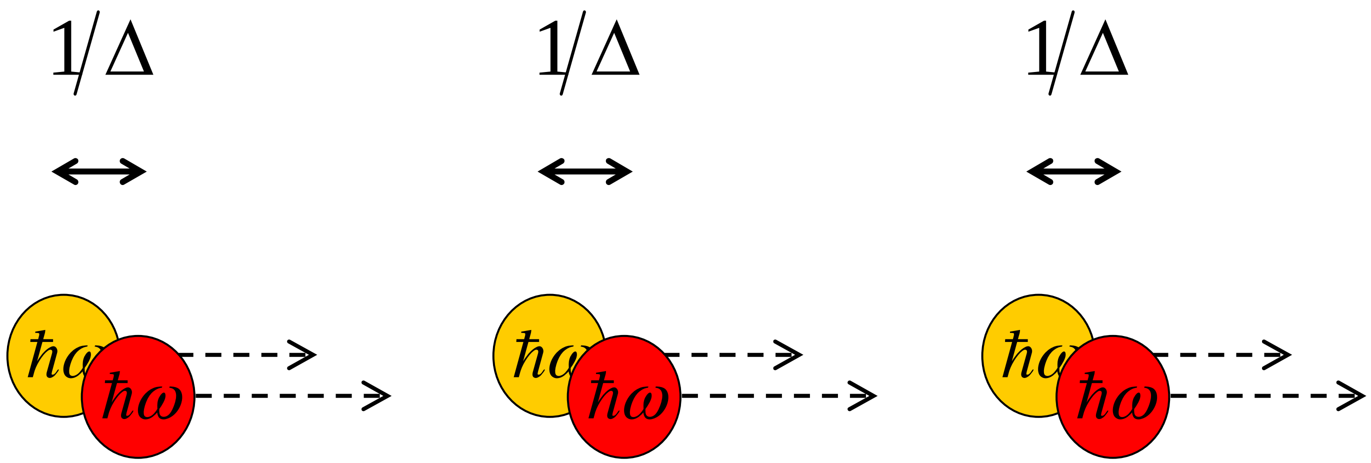
Coincidence detection through Sum-Frequency Generation (SFG)



typical flux		SFG efficiency	SFG signal
$\sim 10^{6}\ s^{-1}$	$\times$	$\sim 10^{-9}$	$\approx 10^{-3}\ s^{-1}$

How many 'single photons' can arrive in one second ?

(How high can 'low light levels' be ?)

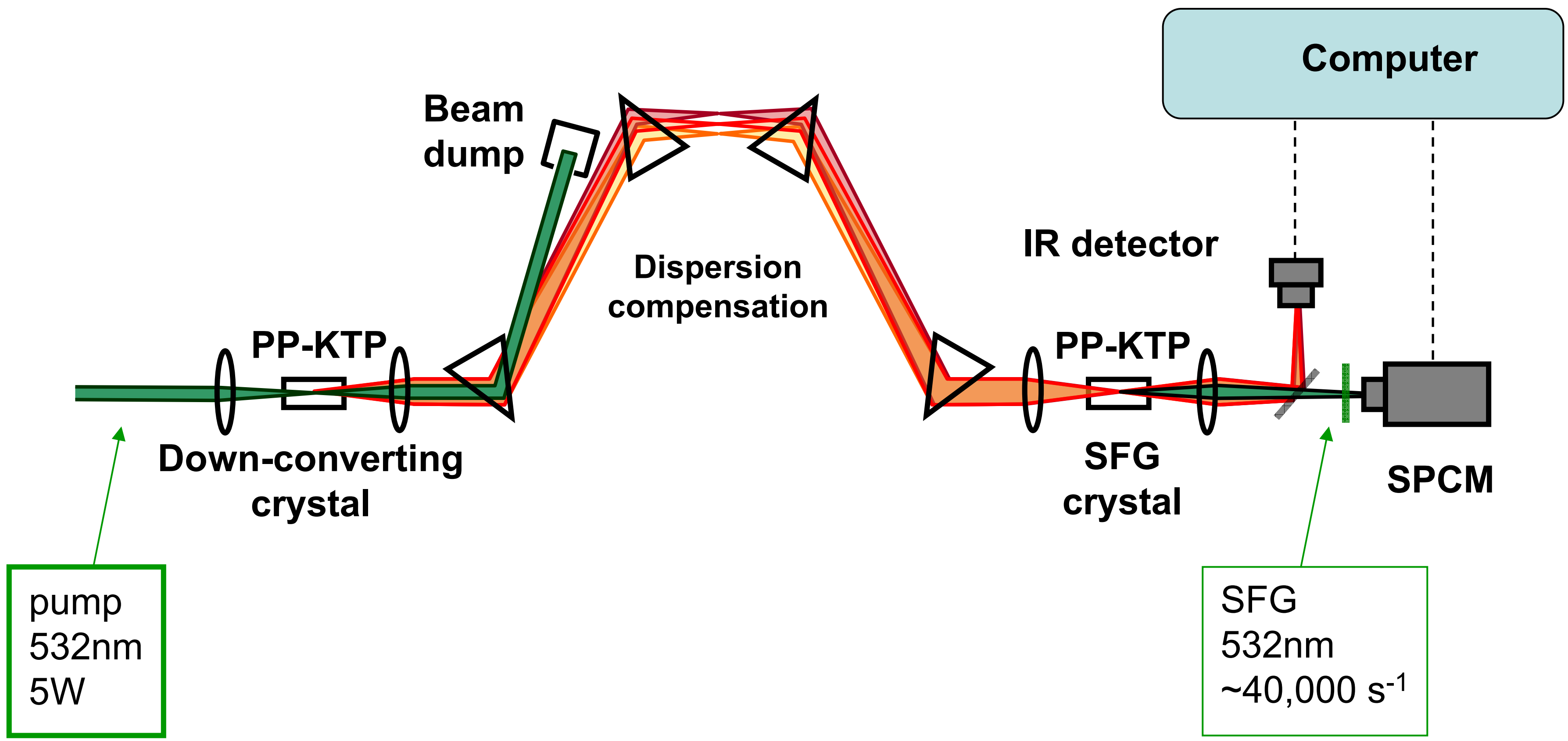


The photon-pair arrives within 1/Δ

A photon-pair per time-bin ⟷ n=1 photon per mode

$$\Phi_{max} \approx \Delta \approx 10^{13}\,\mathrm{s}^{-1} \approx 2\mu W\,!!$$

SFG with Entangled Photons



Quantum mechanical analysis of SFG

$$R_{SFG} \propto \alpha\, n_0^2 + \alpha\, n_0$$

$\propto I^2$

Classical

$\propto I$

Entangled photons

n_0 - photons per mode

Nonclassical Excitation for Atoms in a Squeezed Vacuum

N. Ph. Georgiades, E. S. Polzik,*, K. Edamatsu,† and H. J. Kimble
Norman Bridge Laboratory of Physics, California Institute of Technology 12-33, Pasadena, California 91125

A. S. Parkins‡
Department of Physics, University of Konstanz, Konstanz, Germany
(Received 21 April 1995)

The two-photon transition $6S_{1/2} \rightarrow 6D_{5/2}$ is investigated for trapped atomic cesium excited by squeezed light. The rate R of two-photon excitation versus intensity I is observed to be consistent with the functional form $R = \beta_1 I + \beta_2 I^2$, extending into a region with slope 1.3. This departure from the quadratic form for classical light sources is due to the fundamental alteration of atomic radiative processes by the nonclassical field.

PACS numbers: 42.50.Dv, 32.80.-t

1995: Kimble's group measures a slope of 1.3 at low photon numbers

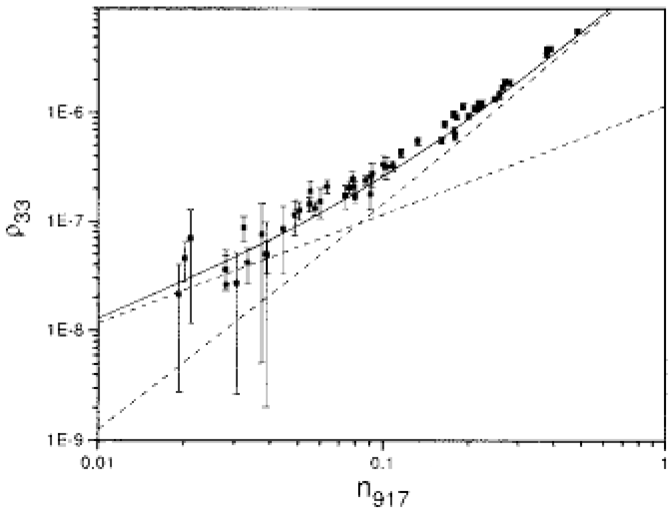
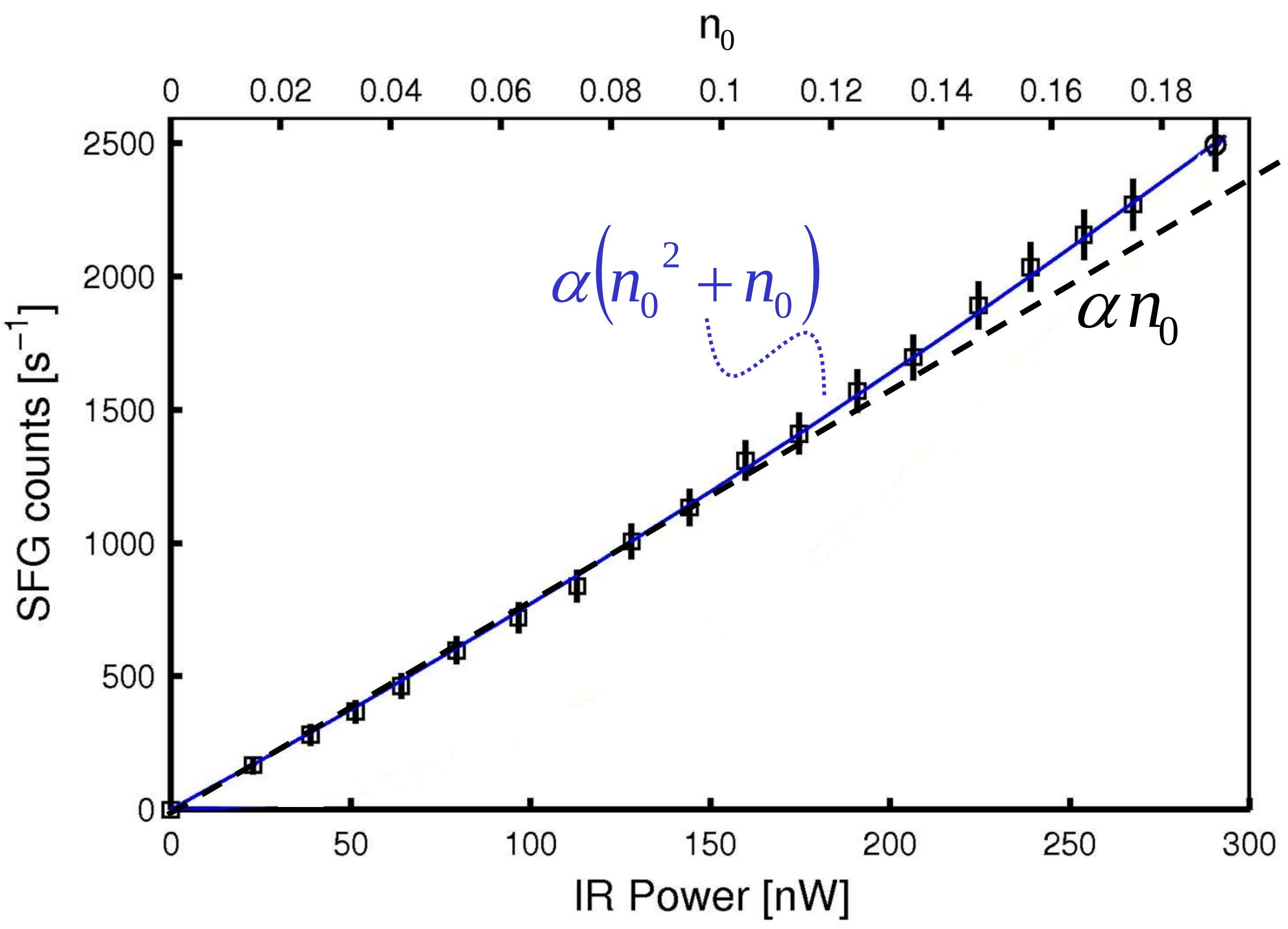


FIG. 5. Level 3 population ρ_{33} due to two-photon excitation versus intracavity photon number n_{917} at 917 nm. The counting data (R_1, R_2) from five experiments have been scaled as discussed in the text. The full curve is obtained from a numerical solution of the master equation, with the linear and (almost) quadratic components indicated.

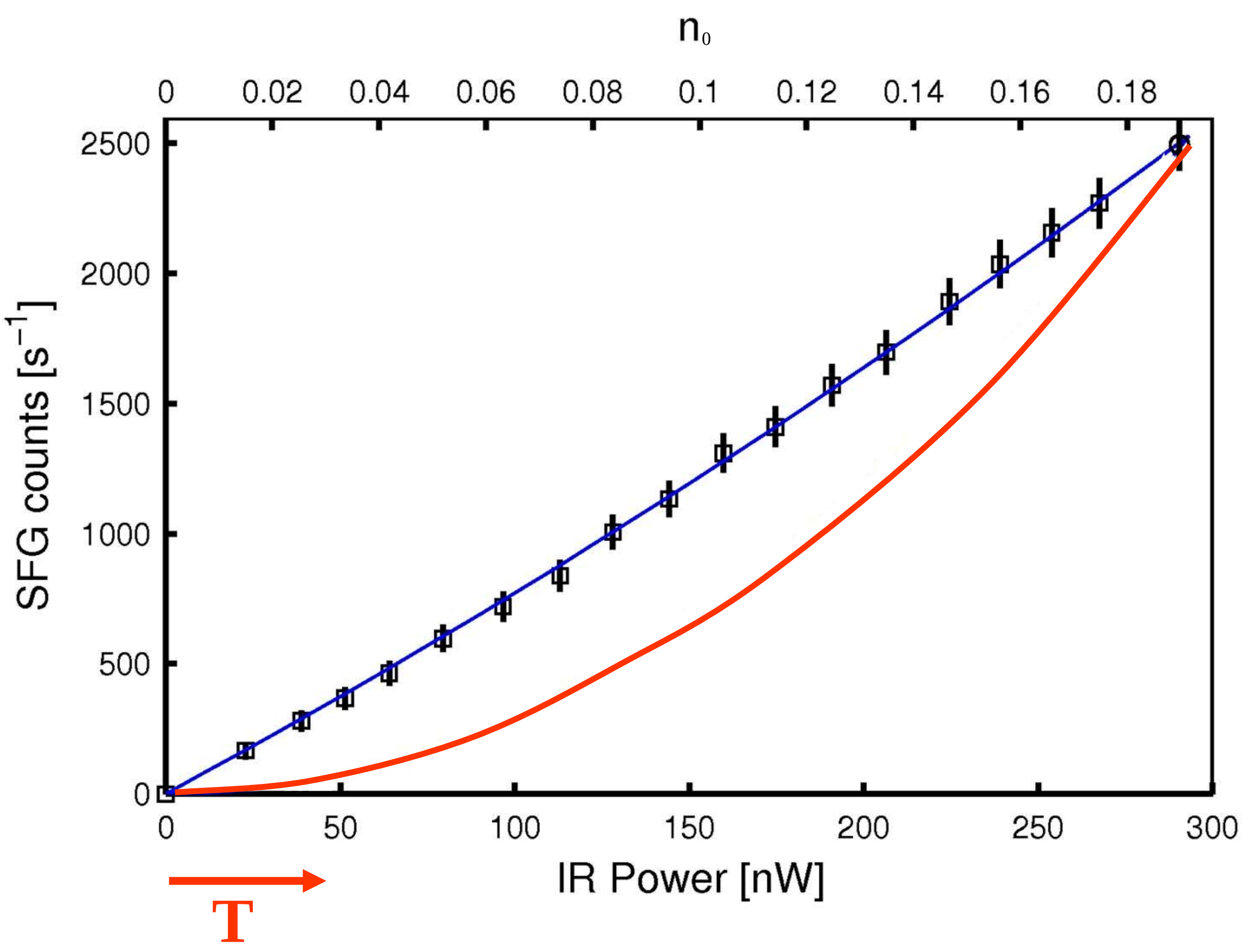
Intensity Dependence of SFG with Entangled Photons

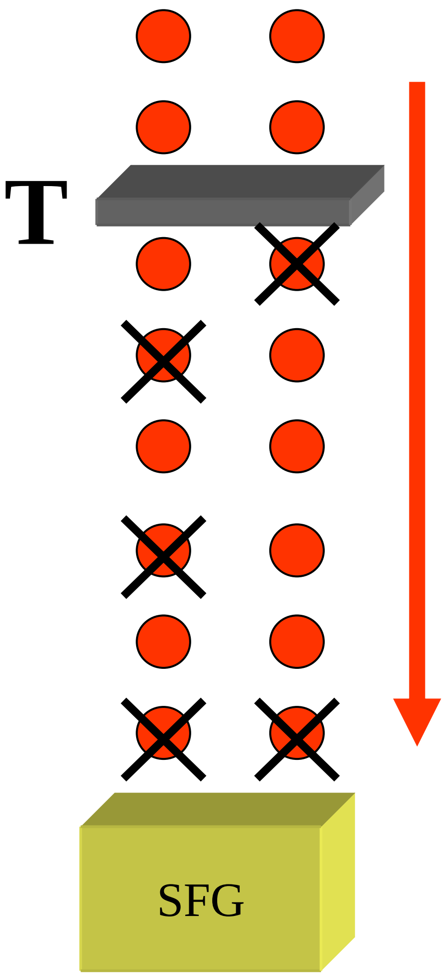


"Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons",

B. Dayan, A. Pe'er, A.A. Friesem and Y. Silberberg, Phys. Rev. Lett. **94**, 043602 (2005)

Intensity Dependence of SFG with Entangled Photons





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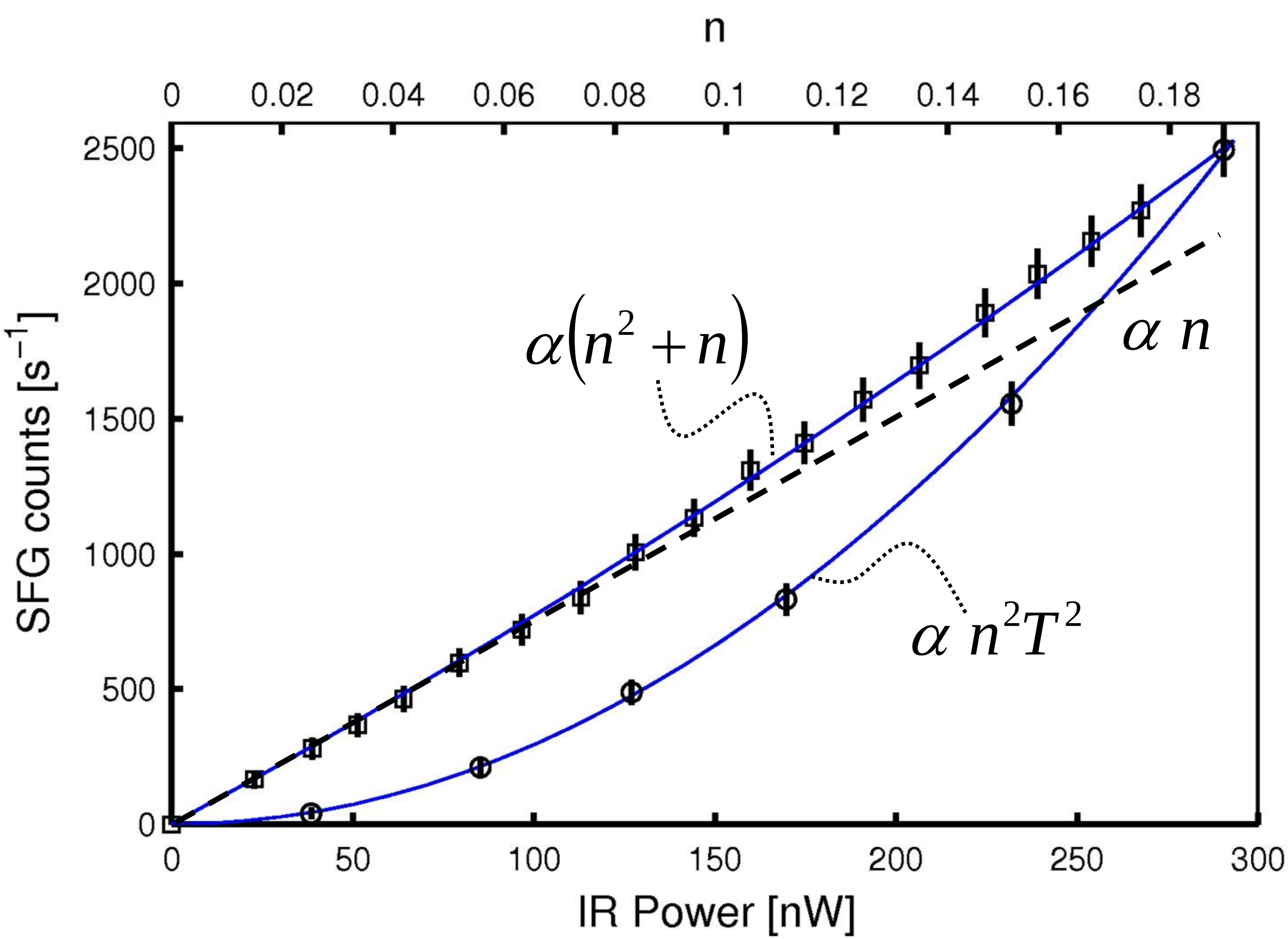
Intensity dependence of SFG with entangled photons



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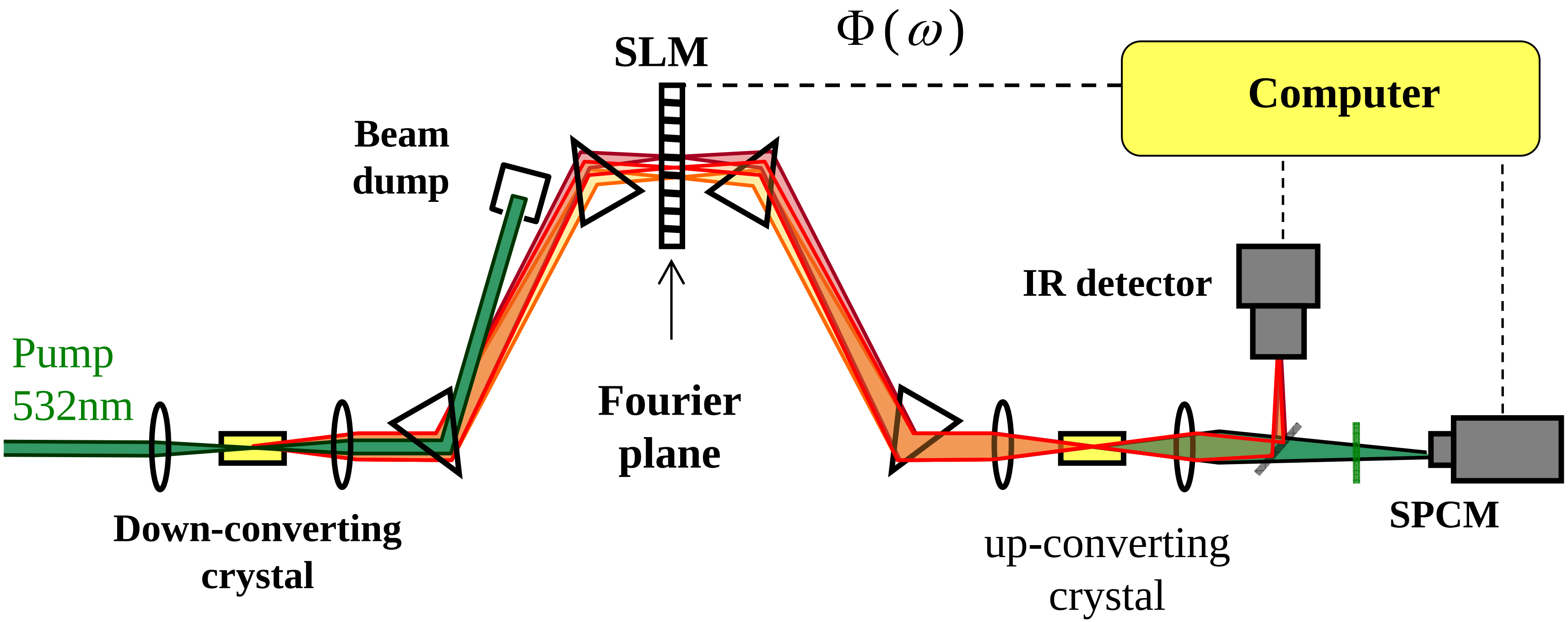
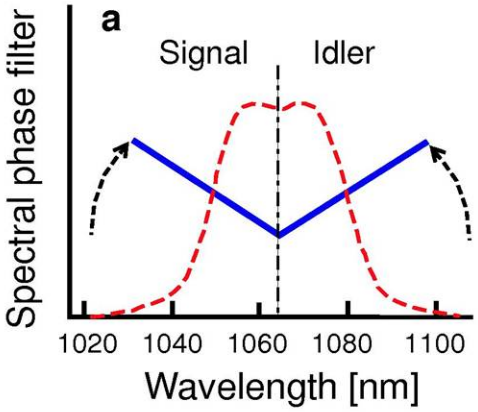
B. Dayan, A. Pe'er, A.A. Friesem and Y. Silberberg, Phys. Rev. Lett. **94,** 043602 (2005)

Shaping of Entangeled Photons

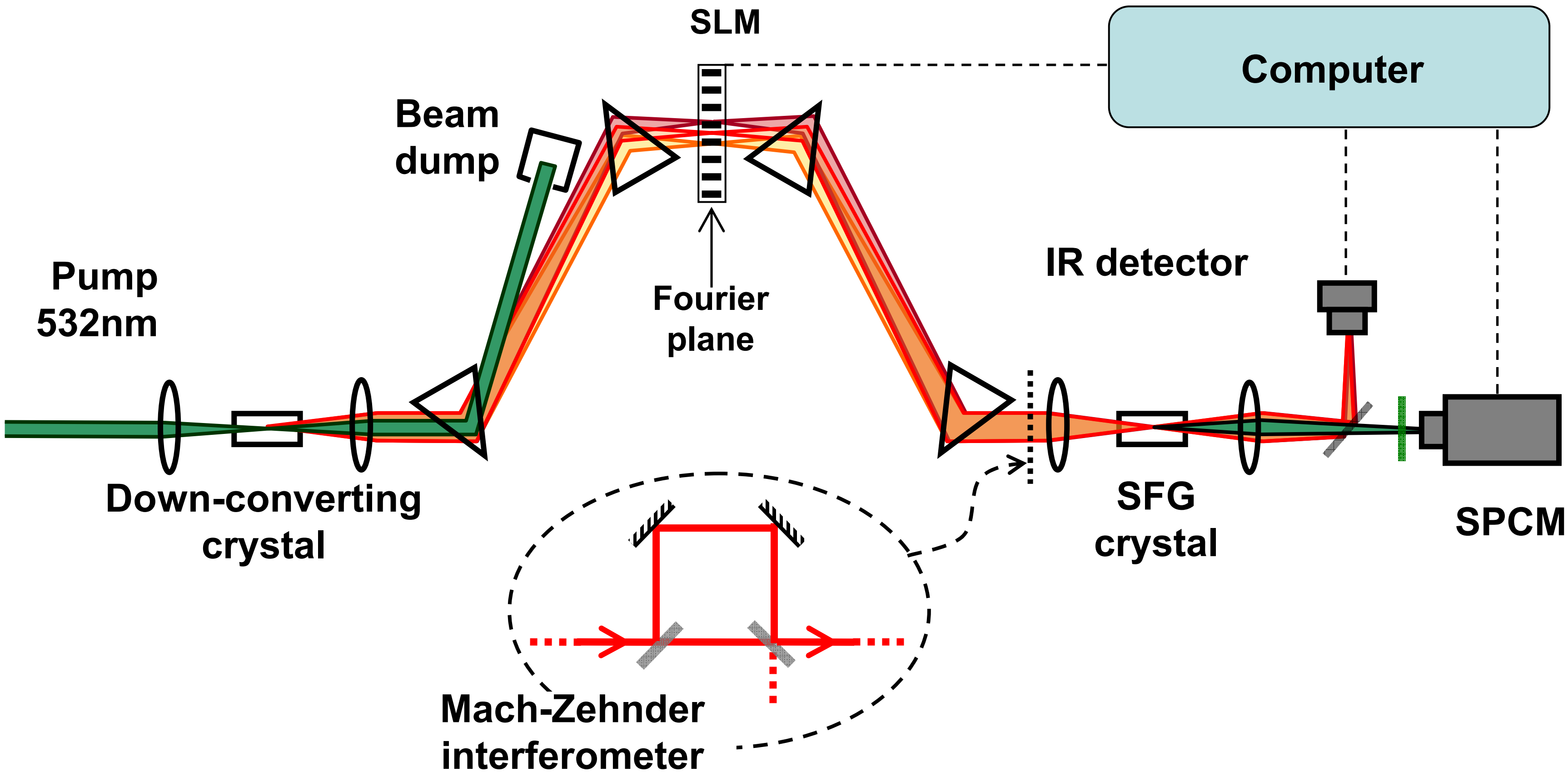


Temporal shaping of the two-photon wavefunction



"Temporal Shaping of Entangled Photons",
A. Pe'er, B. Dayan, A.A. Friesem and Y. Silberberg, Phys. Rev. Lett. **94,** 073601 (2005)

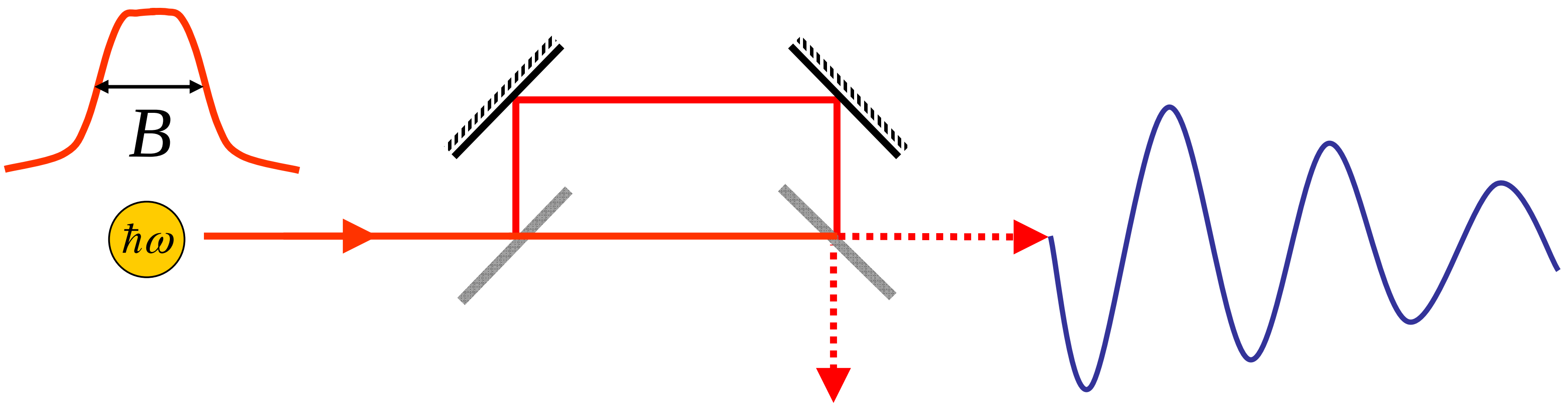
Two-photon interference



Two-photon interference

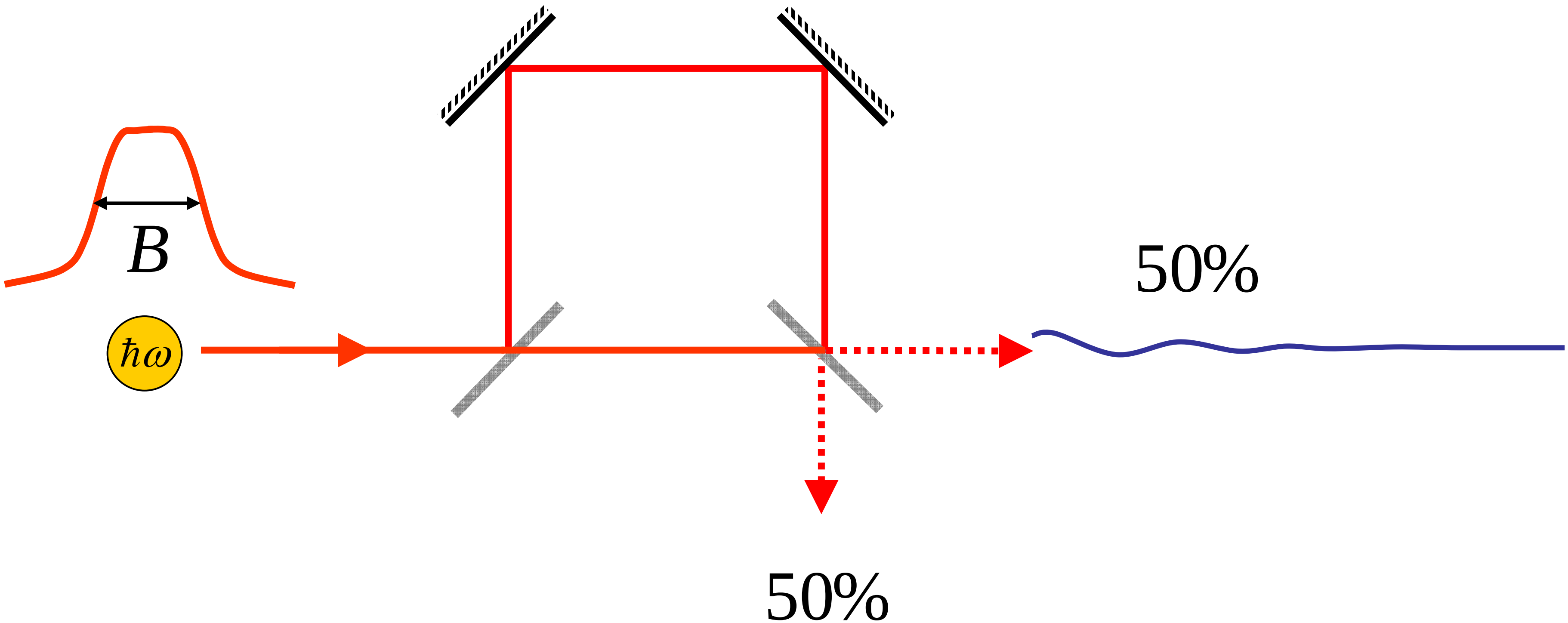
Two-photon interference

Mach-Zehnder
interferometer



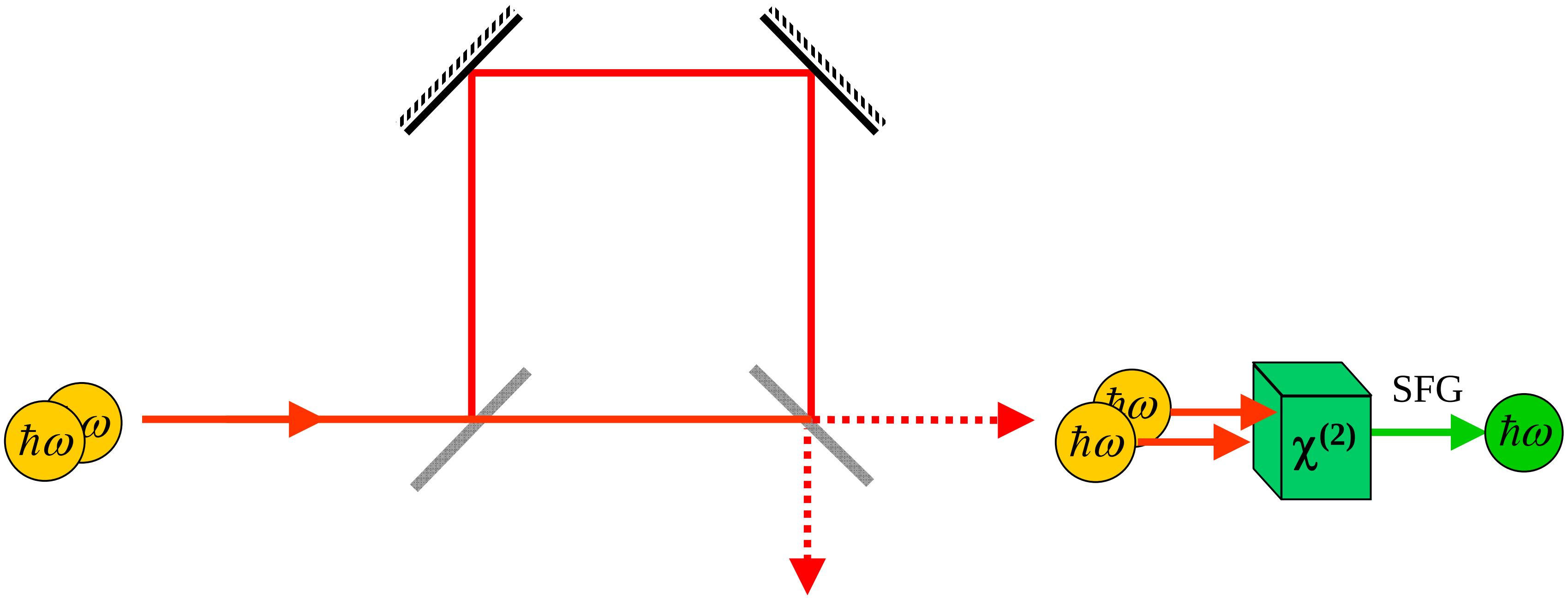
Two-photon interference

for $\Delta\tau >> 1/B$:



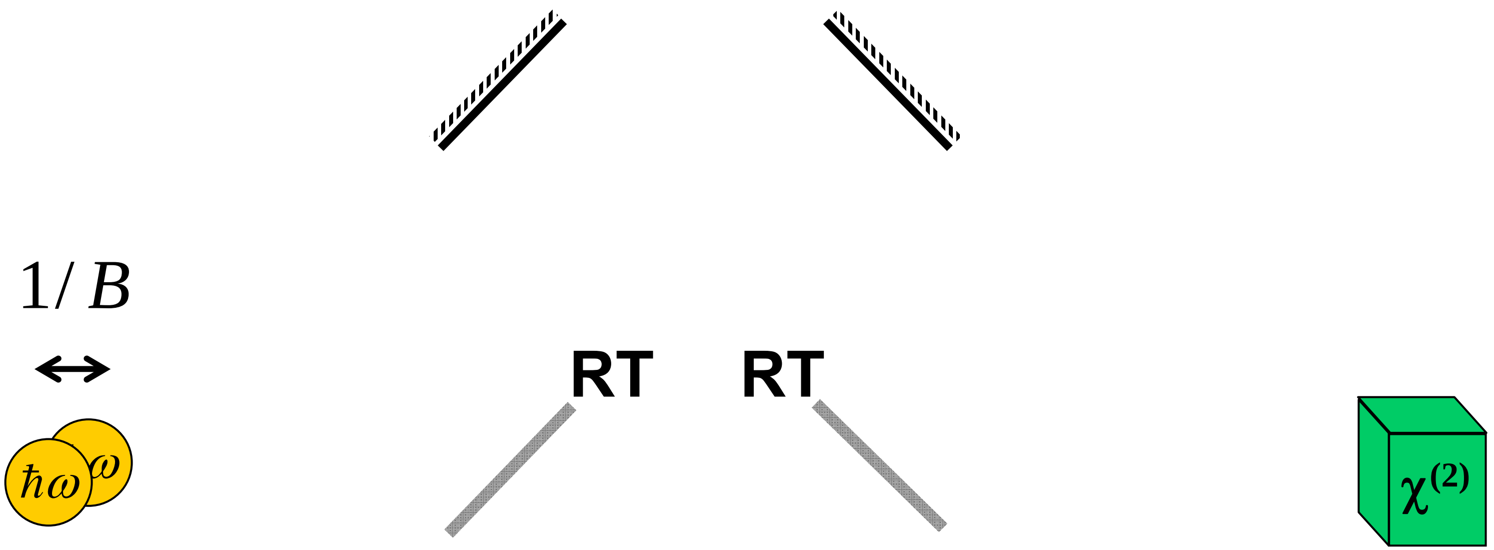
Two-photon interference

for $\Delta\tau >> 1/B$:



Two-photon interference

for $\Delta\tau >> 1/B$:

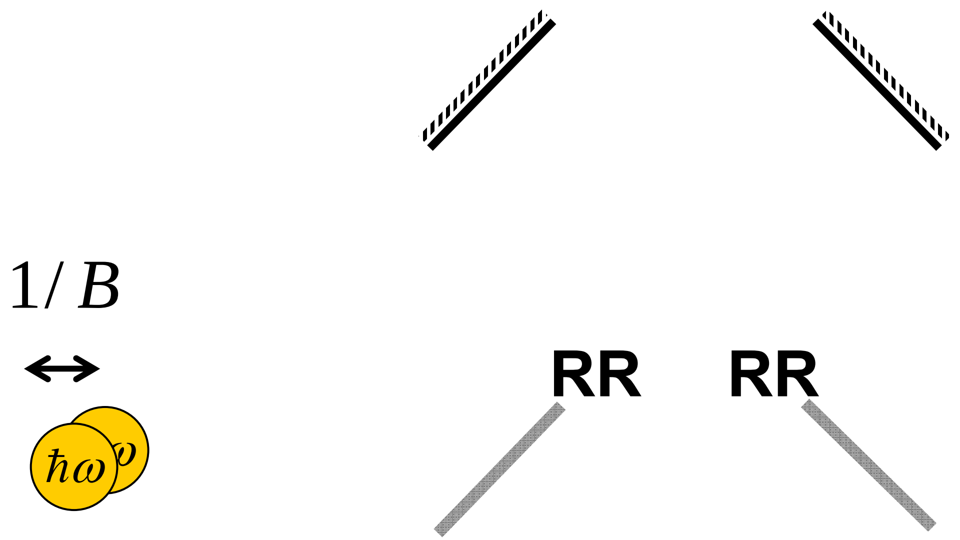


Electronic detection is not fast enough,

…But SFG is !

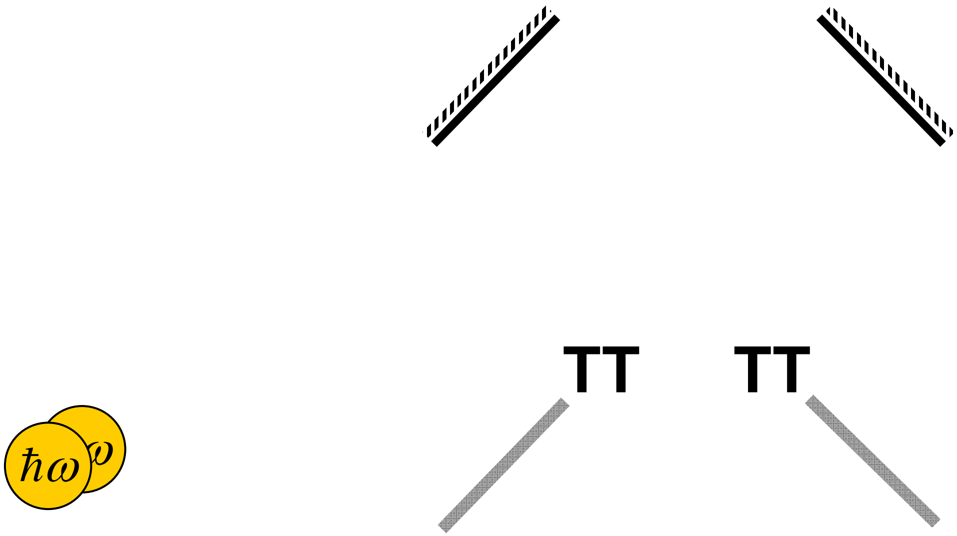
Two-photon interference

for $\Delta\tau >> 1/B$:



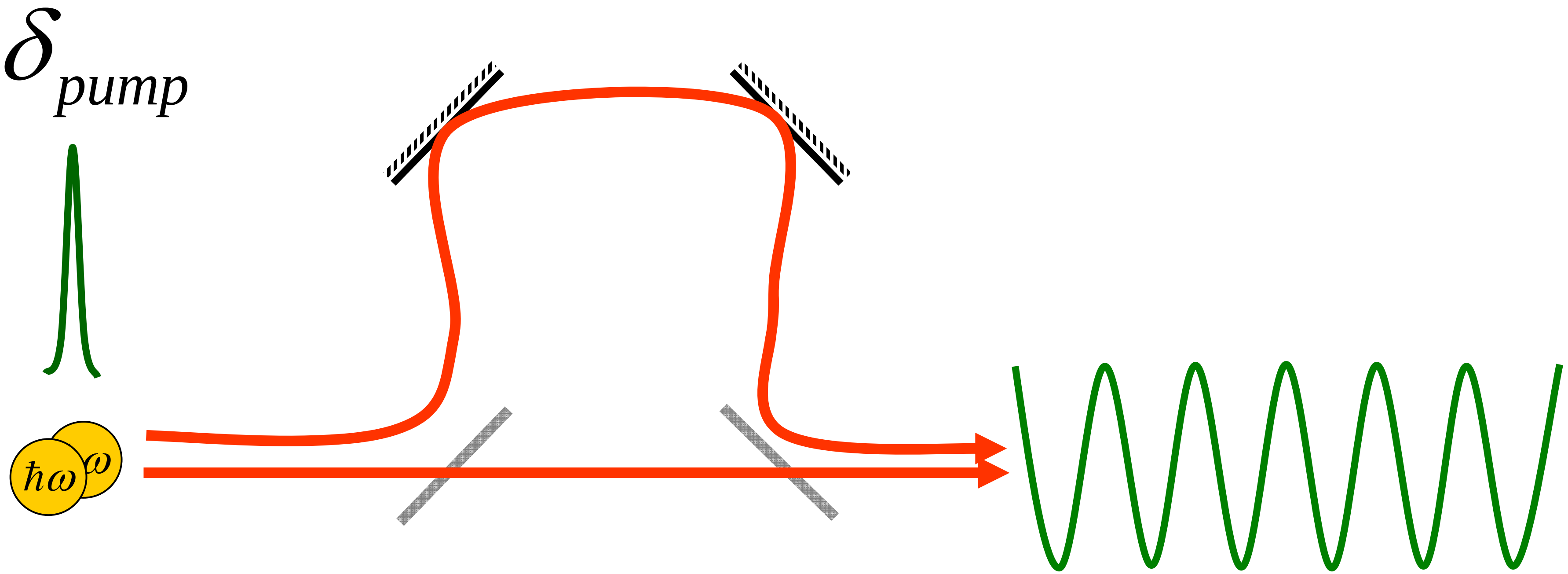
Two-photon interference

for $\Delta\tau >> 1/B$:

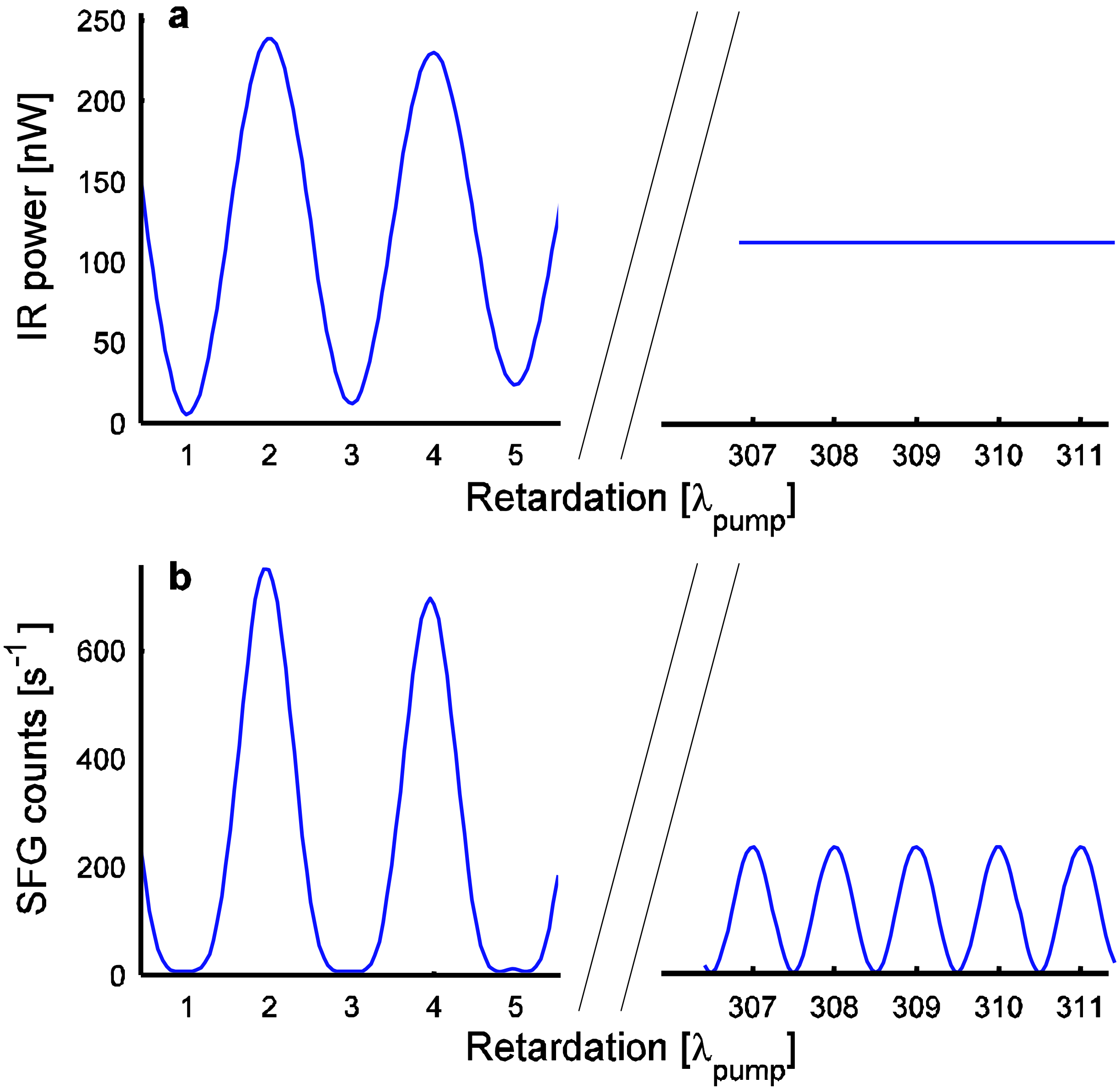


Two-photon interference

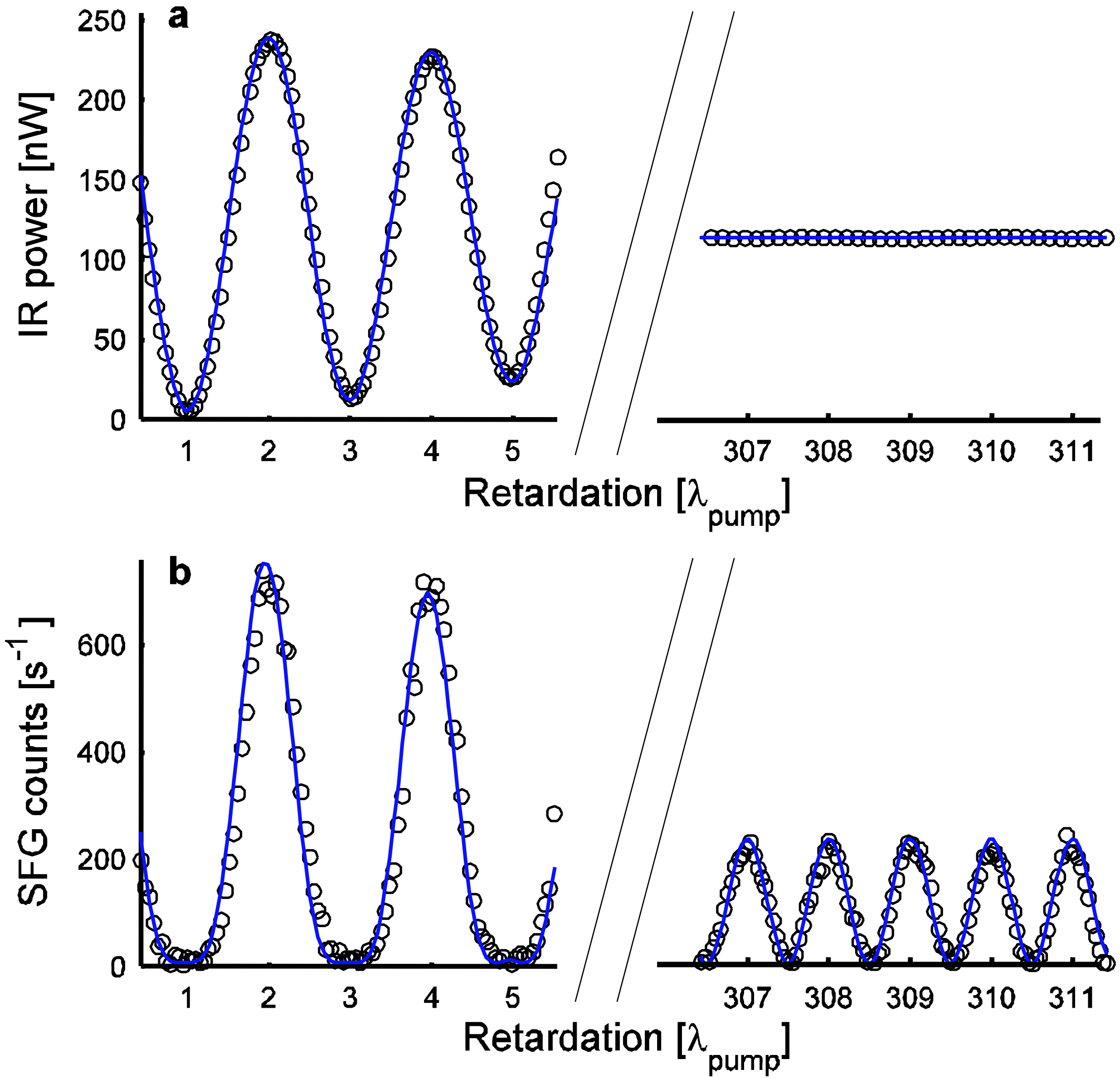
for $\Delta\tau >> 1/B$:



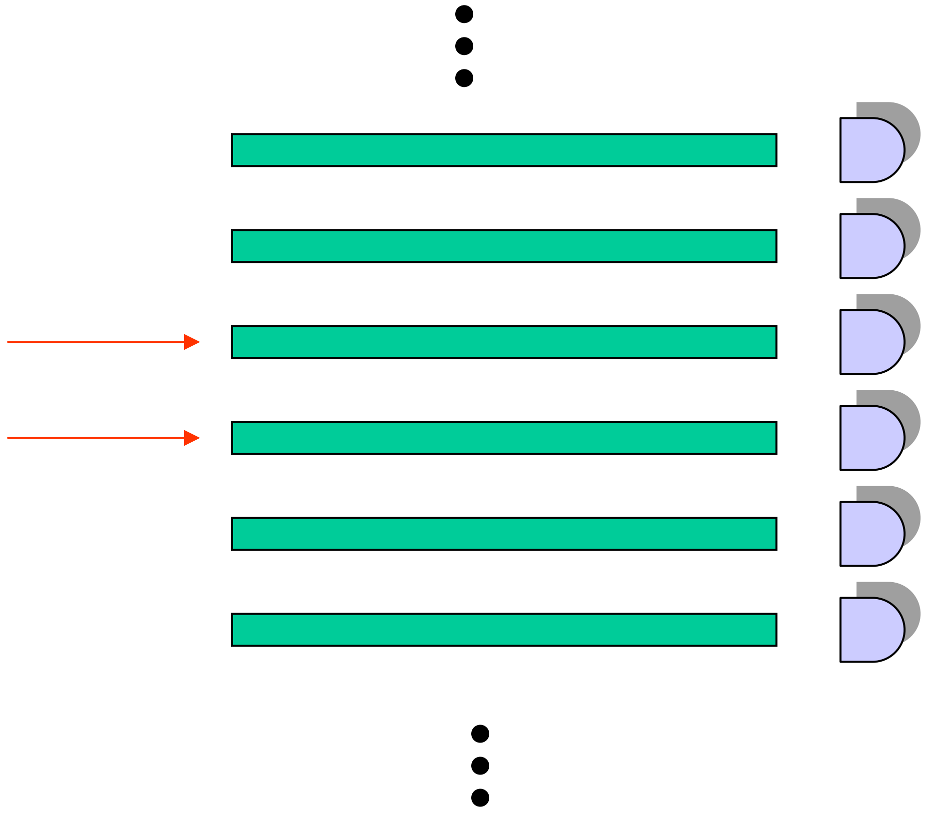
Background-free two-photon interference oscillations



Background-free two-photon interference oscillations

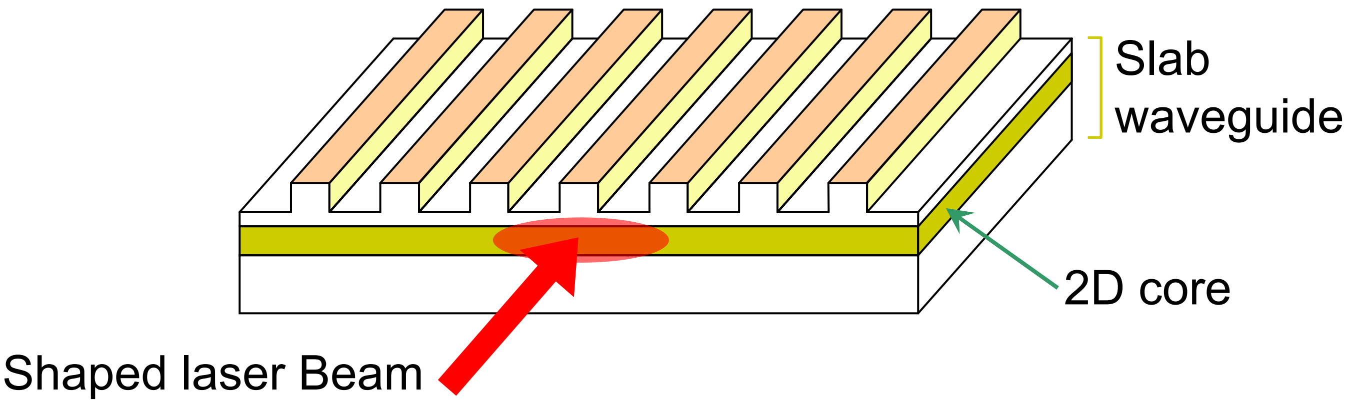


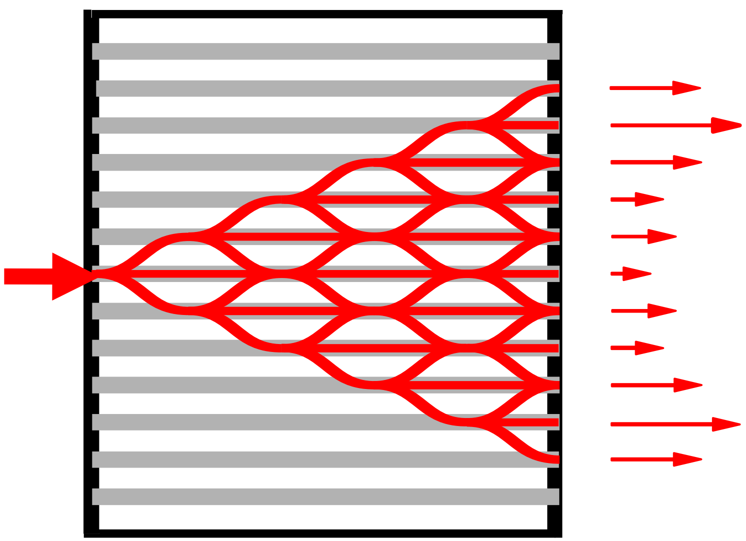
HOM Interference in a coupler



In coupled waveguides there is a $\pi/2$ phase between light in adjacent waveguides

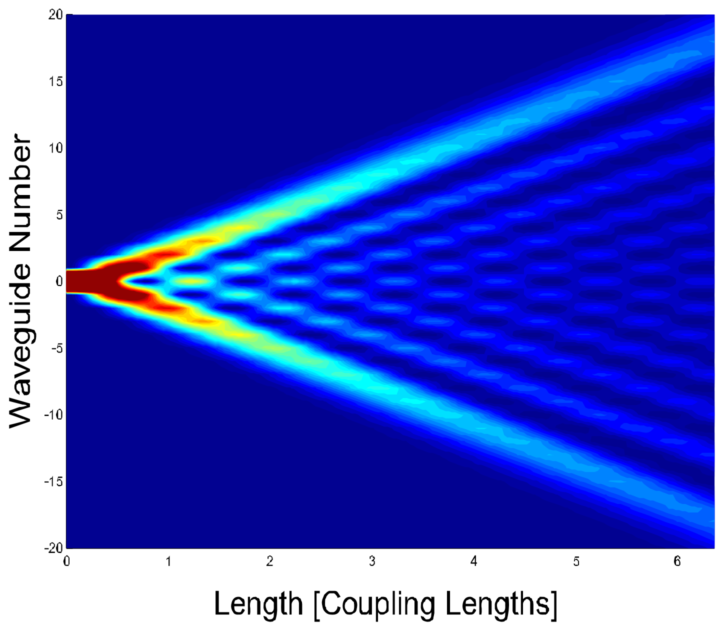
Discrete Diffraction





Discrete diffraction

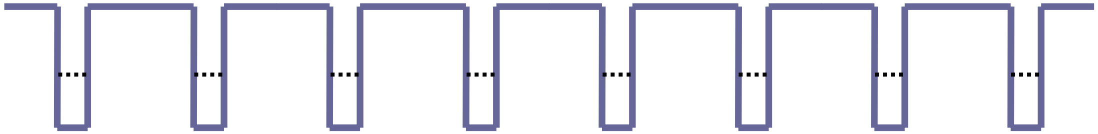
Linear propagation

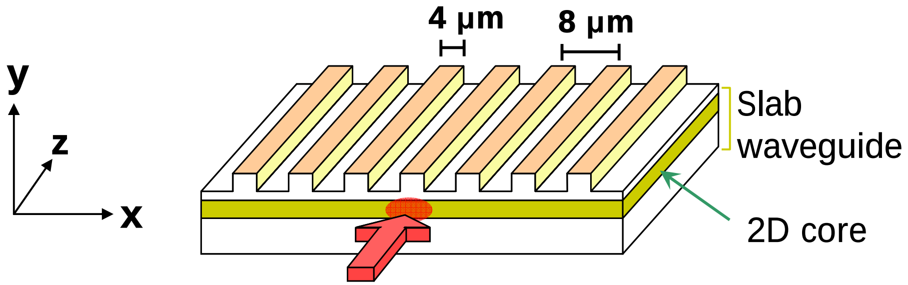


The 1d waveguide lattice

- The Tight Binding Model (Discrete Schrödinger Equation)

$$-i\frac{\partial \psi_n}{\partial t} = E_n \psi_n + T_{n,n\pm1}\left[\psi_{n+1} + \psi_{n-1}\right]$$





- The discrete nonlinear Schrödinger equation (DNLSE)

$$i\frac{\partial U_n}{\partial z} = \beta_n U_n + C_{n,n\pm1}\left[U_{n+1} + U_{n-1}\right] + \underline{\gamma |U_n|^2 U_n}$$

Key Results:

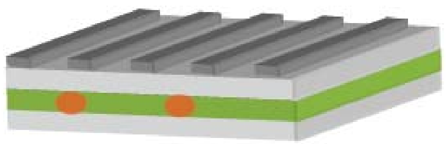
Periodic Lattices:

Discrete Spatial Optical Solitons (1998)
Diffraction Management, (2000).
Self-Focusing and Defocusing, **dark solitons** (2001).
Modulational Instability (2002**)**
Vector Solitons (2003)
Band Structure and Floquet-Bloch Solitons (2003).
Gap solitons (2004)
Surface states (2006)
Spatio-temporal effects (x-waves) (2007)
Quantum & Classical Correlations (2008**)**

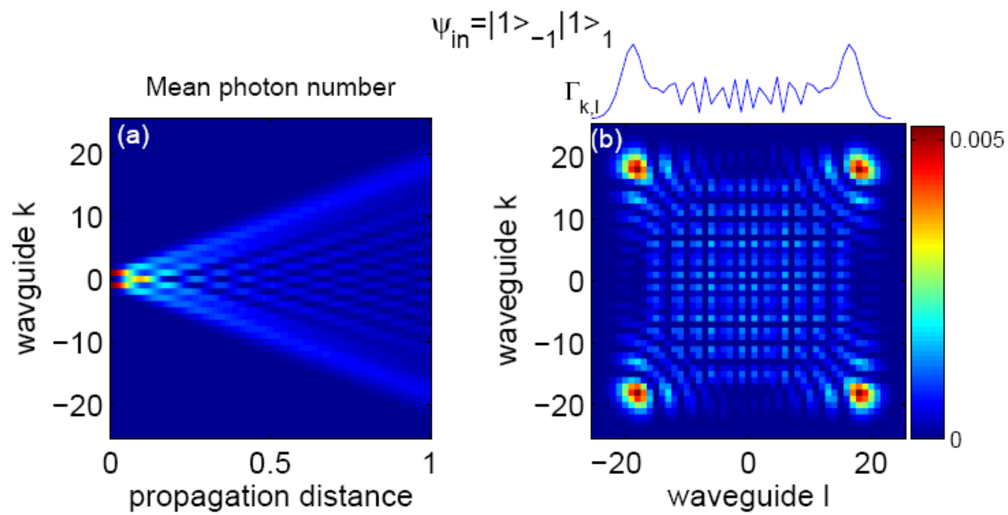
Non-uniform arrays

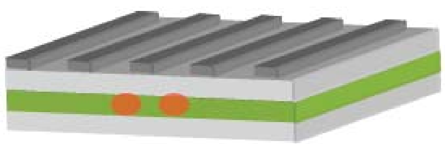
Bloch Oscillations (1999).
Defect States (1999).
Binary Arrays (2004)
Anderson Localization (2007)

Quantum Correlations in Arrays

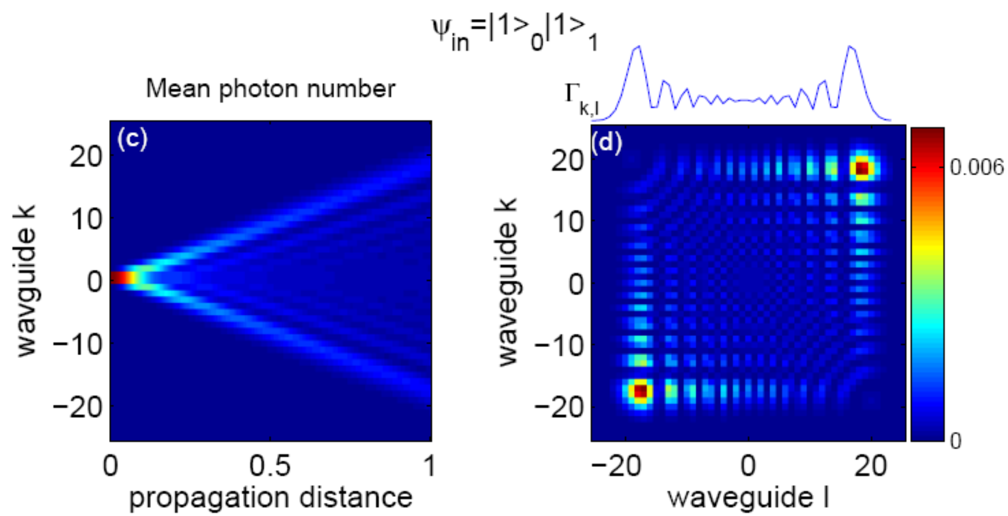


IOI input





II input



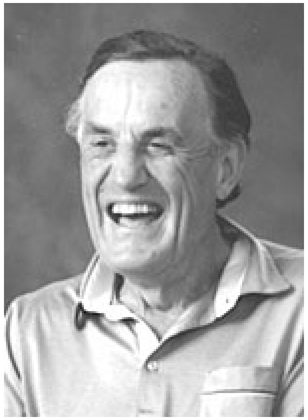
Two-Photon Correlations

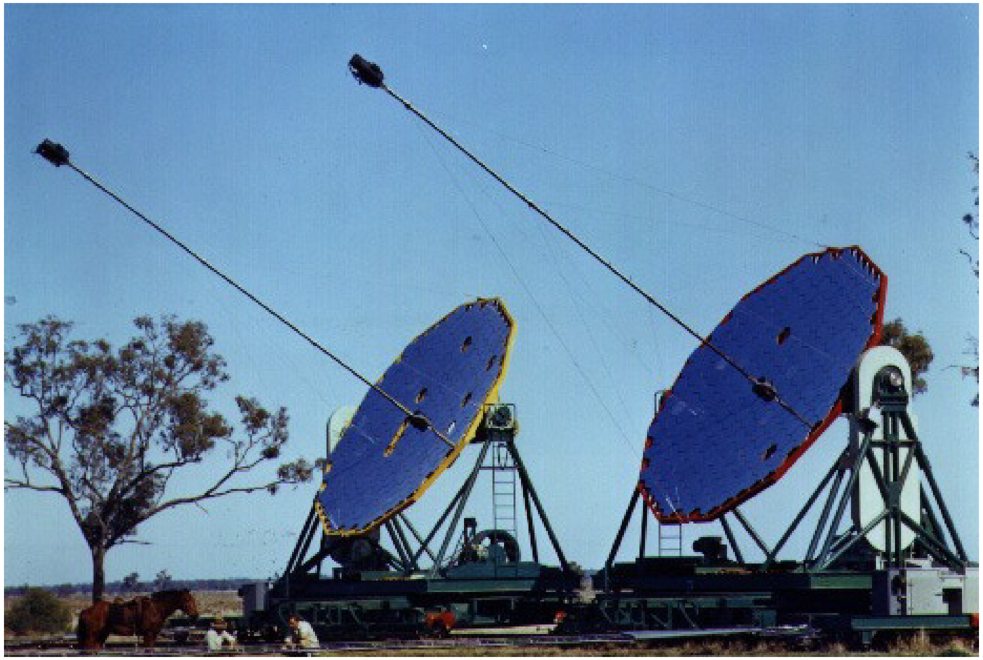
Experiments with entangled photons in waveguide arrays are tough

But there is a simple classical version…

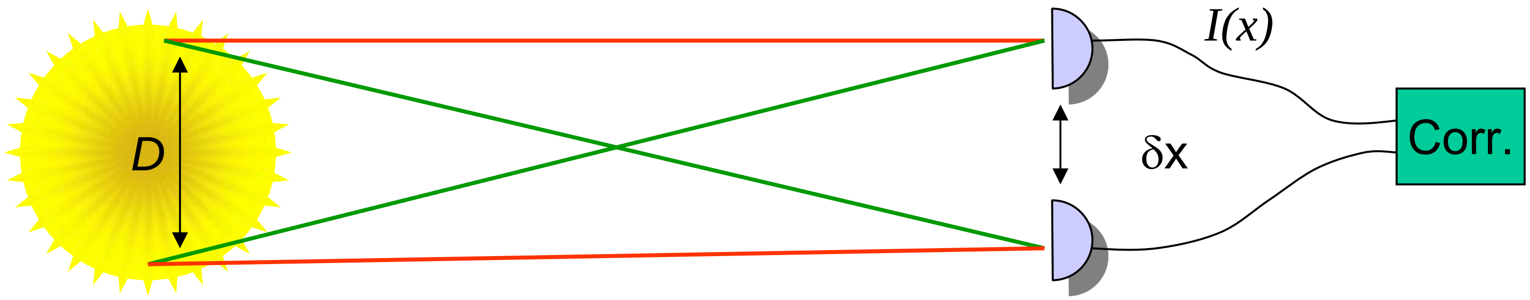
1956

HB&T claim that they have measured the angular size of Sirius by intensity correlations

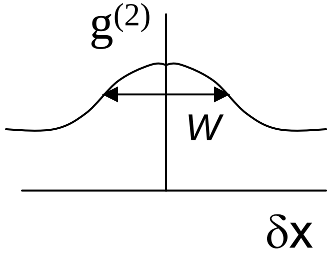




The HBT experiment



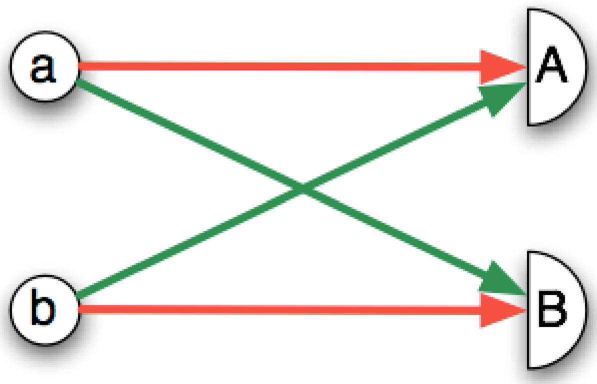
$$g^{(2)}(\delta x) = \frac{\langle I(x) I(x+\delta x) \rangle}{\langle I(x) \rangle^2}$$

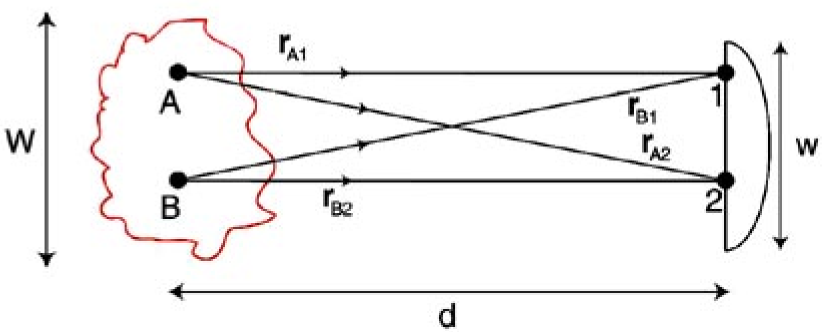


$$\delta\theta = D/L \approx \lambda/W$$

How could photons generated at two different sides of a star interfere?

HBT and QO



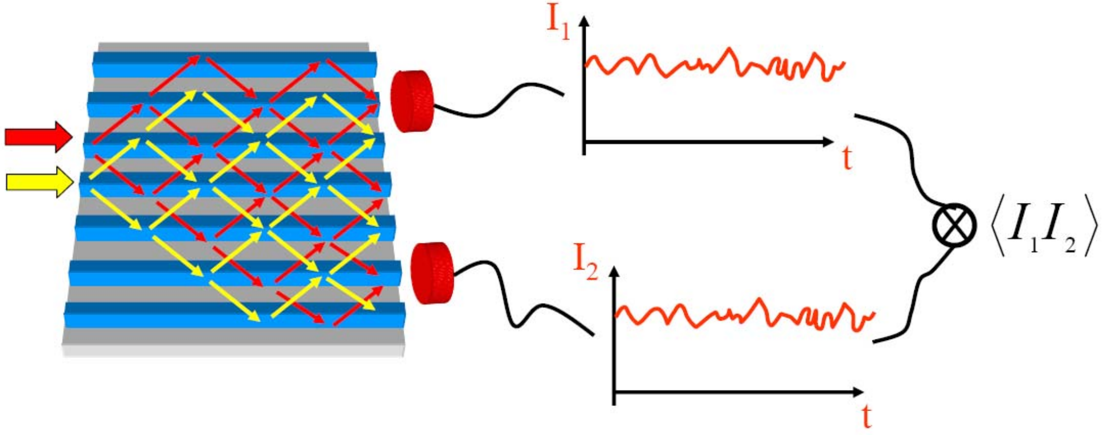


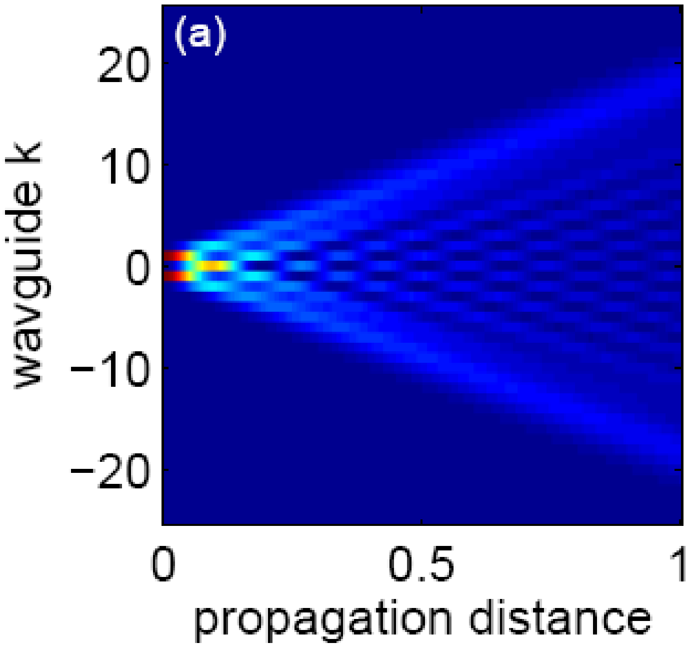
$$P = \left| \psi_A e^{i\phi_{A1}} \psi_B e^{i\phi_{B2}} \pm \psi_A e^{i\phi_{A2}} \psi_B e^{i\phi_{B1}} \right|^2$$

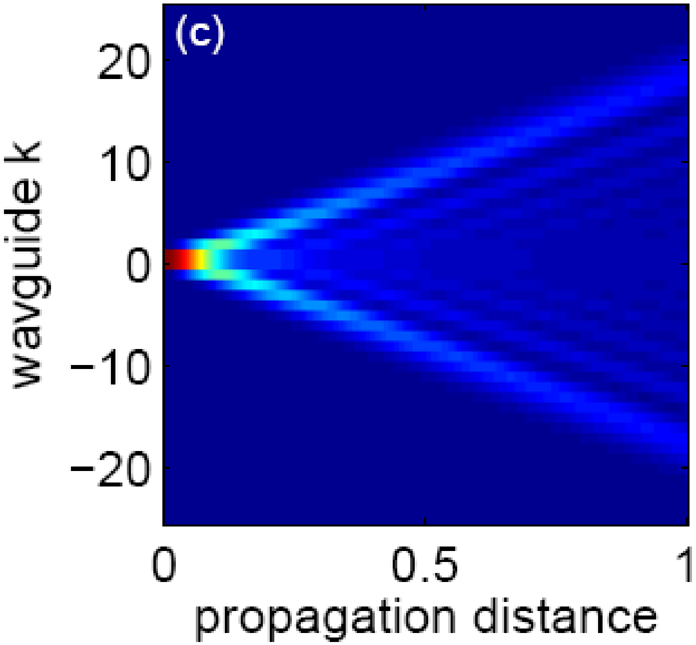
HBT was a key point in the development of quantum optics. It was later explained in terms of particle interference.

HBT has been demonstrated since with electrons, pions and matter waves. It reflects quantum statistics, leading to bunching (bosons) or anti-bunching (fermions).

Discrete HBT

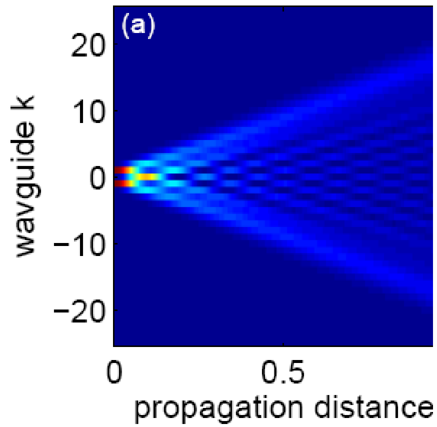


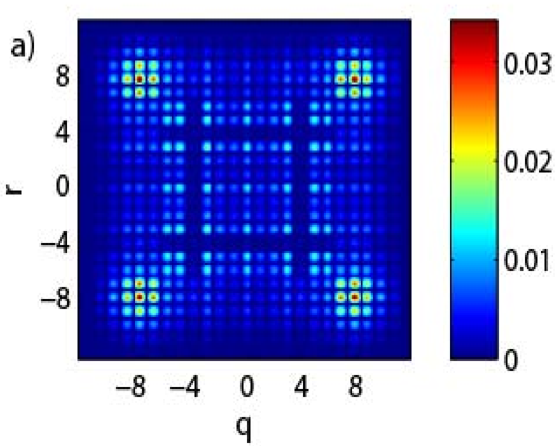




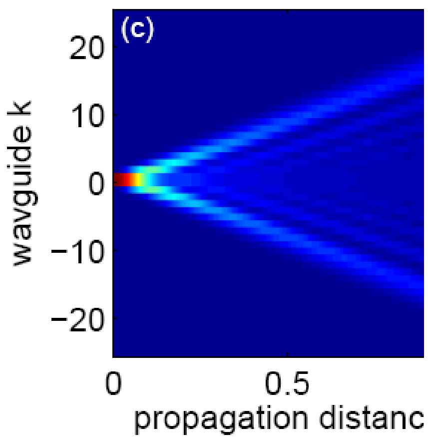
Discrete HBT Correlations

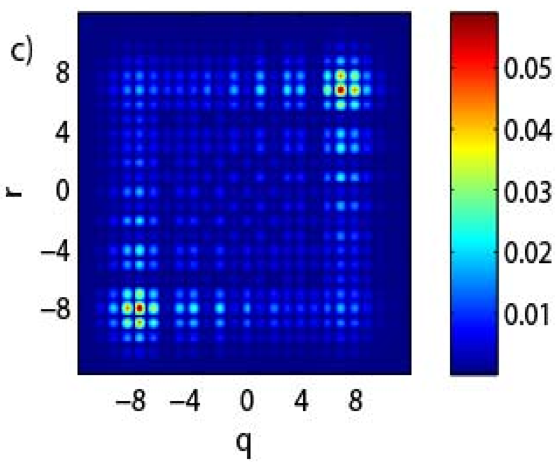
101





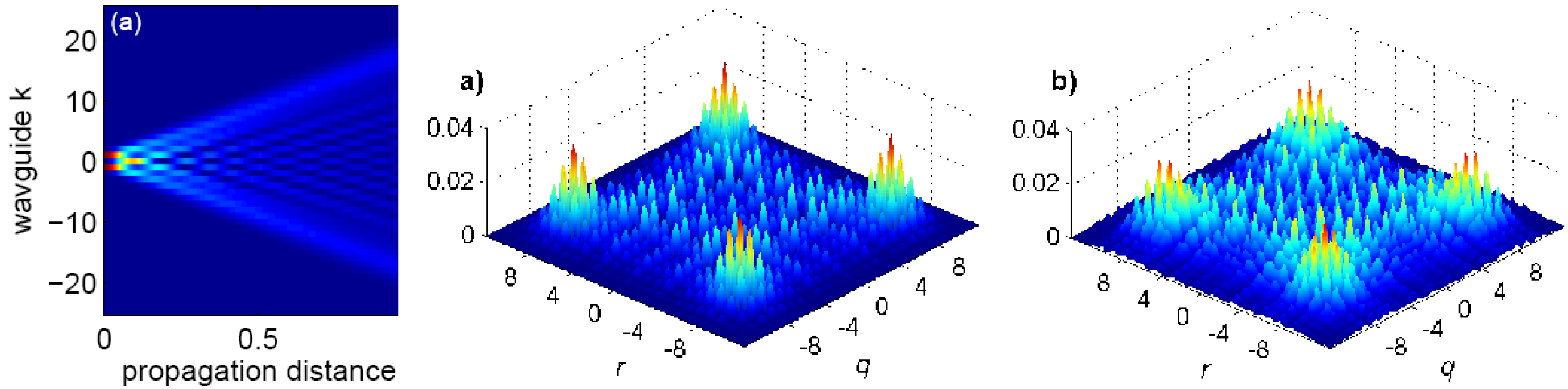
11





Discrete HBT Correlations

101



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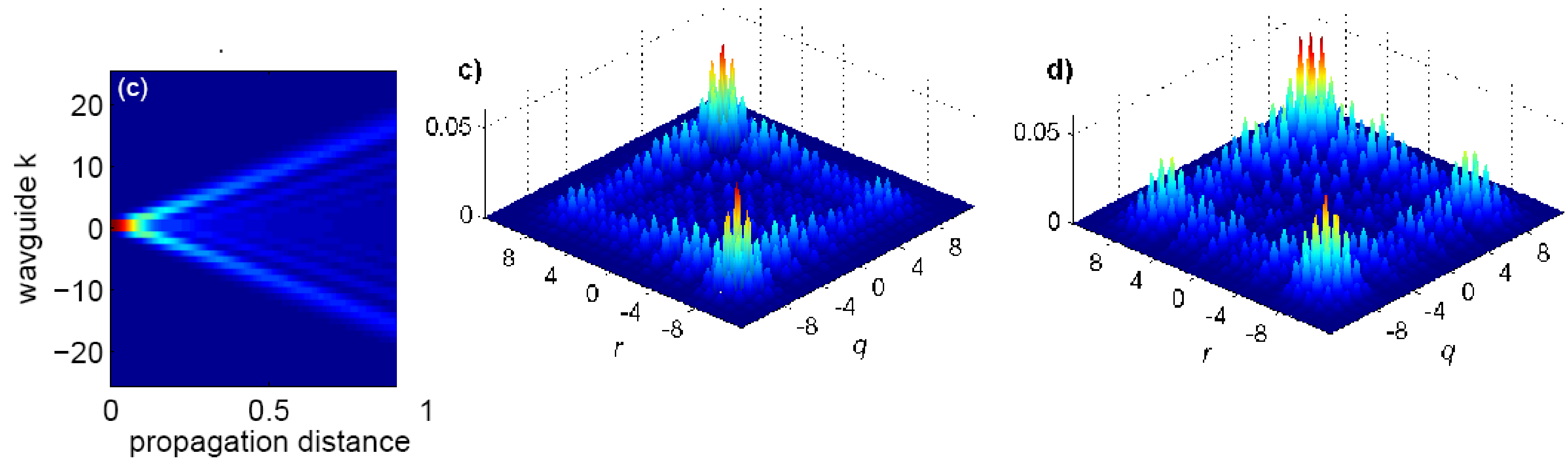
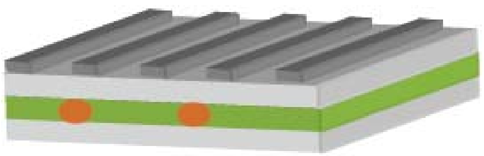
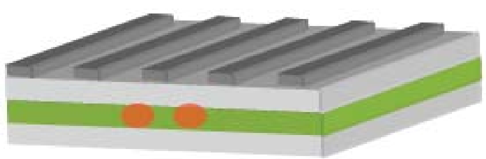


Nonlinear Discrete HBT !

$$\langle I_k I_l \rangle_\phi - \langle I_k \rangle_\phi \langle I_l \rangle_\phi$$

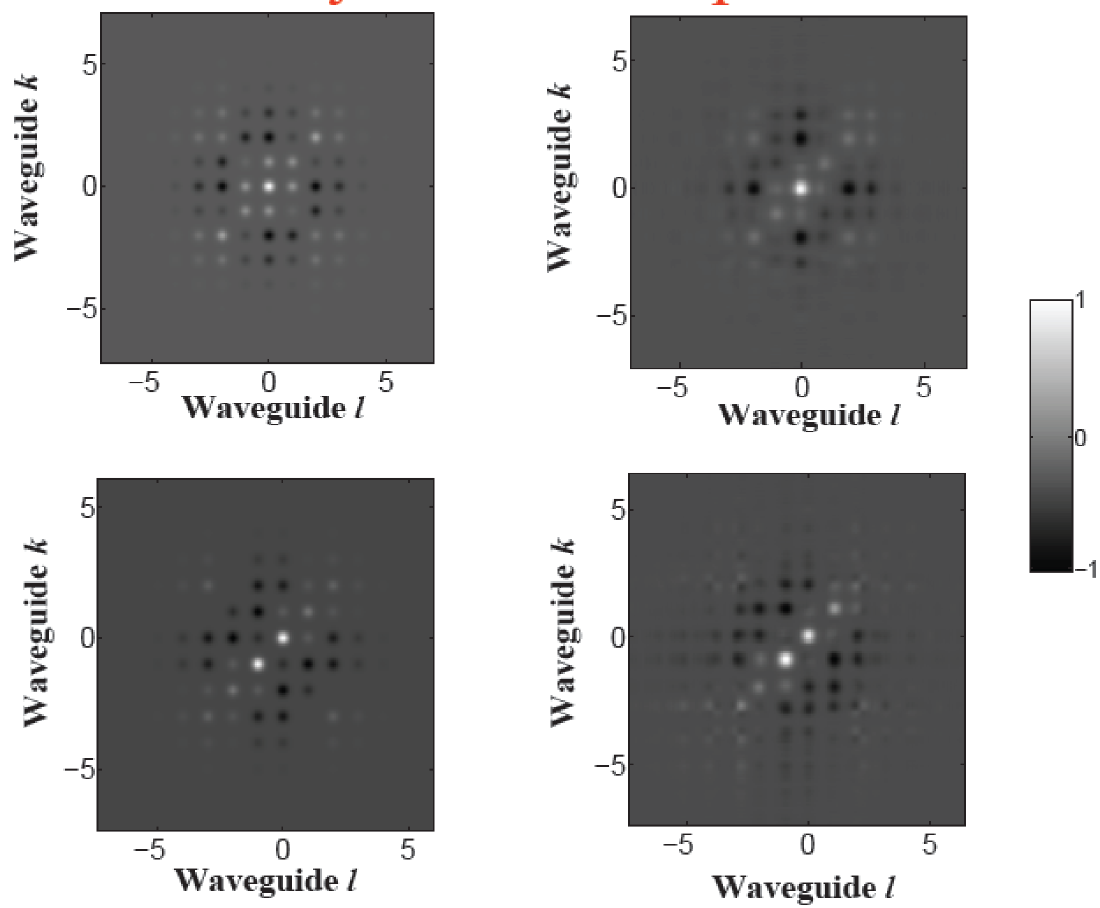


IOI input



II input

Theory | Experiment

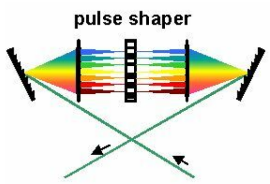


We have seen...

- Photon Correlations behave much like short pulses
- Shaping of photon correlations
- SFG for photon correlation measurements
- Quantum correlations in periodic structures

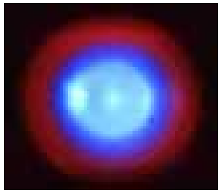
Ultrafast Optics group

Coherent Control:



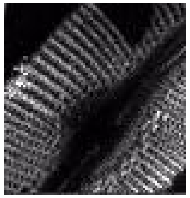
Doron Meshulach
Nirit Dudovich
Dan Oron
Thomas Polack
Evgeny Frumker
Adi Natan
Haim Suchowski
Barry Bruner
V Prabhudesai

Nonclassical Light:



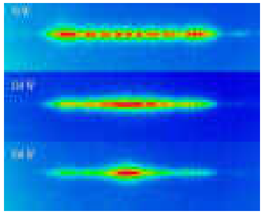
Barak Dayan
Avi Pe'er
Itay Afek

Microscopy:



Yaniv Barad
Dvir Yelin
Eran Tal
Ori Katz

Optical Lattices:



Hagai Eisenberg
Roberto Morandotti
Daniel Mandelik
Asaf Avidan
Yoav Lahini
Yaron Bromberg
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