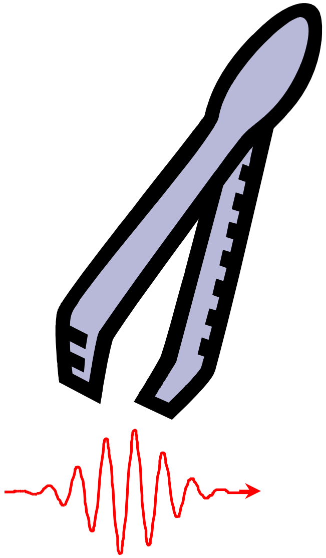
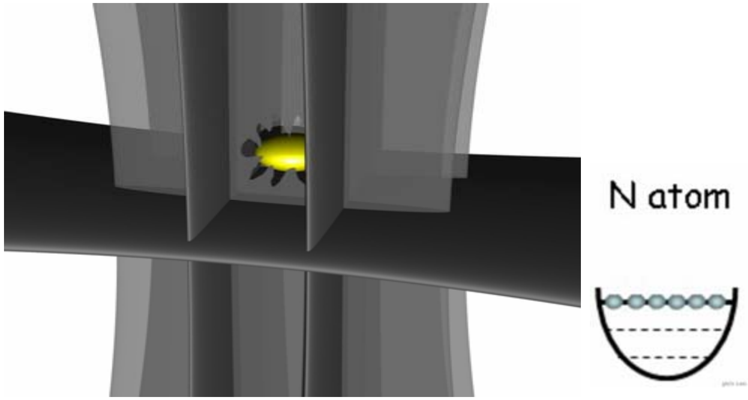
# Probing and manipulating photon wavefunctions

Chih-Sung Chuu 褚志崧

Edward L. Ginzton Laboratory
Stanford University

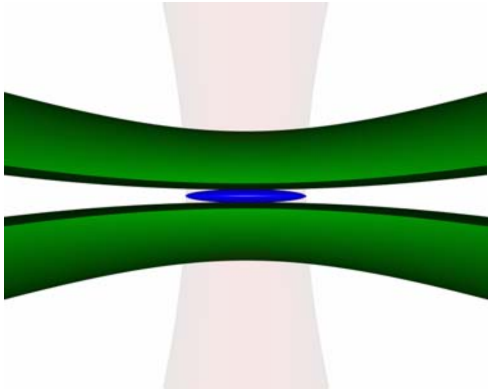


Number squeezing in BEC

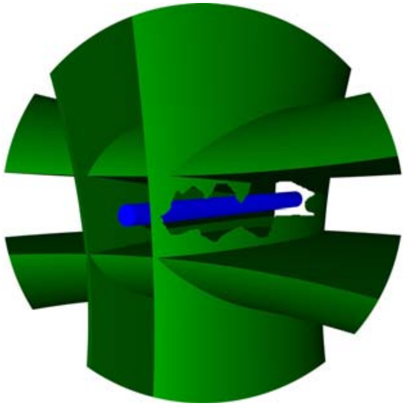



PRL 95, 260403 (2005)

2D BEC

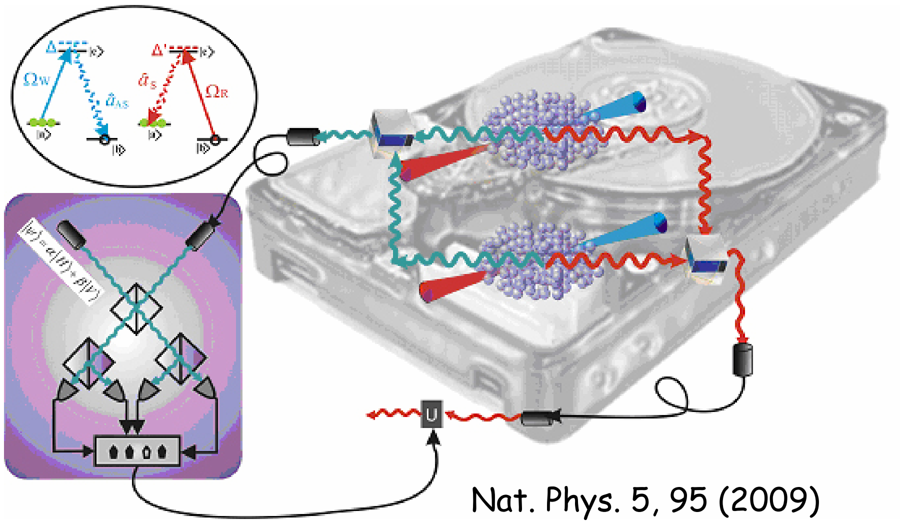


1D BEC



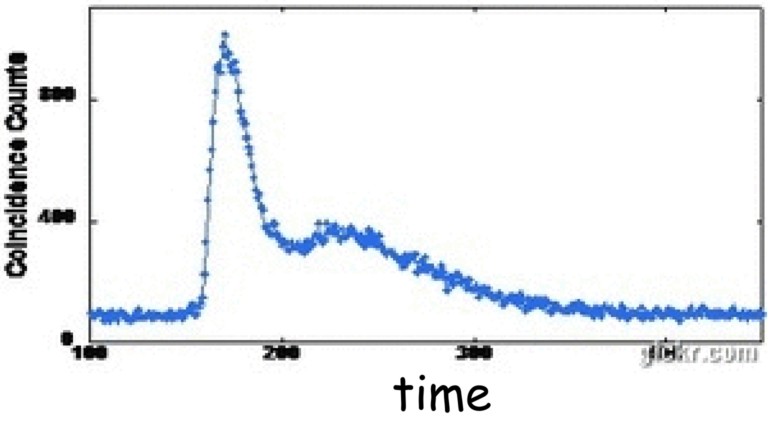
PRA 71, 04160(R) (2005)
Opt. Exp. 13, 2843 (2005)

Quantum teleportation and quantum memory



Nat. Phys. 5, 95 (2009)
Nat. Phys. 4, 103 (2008)
PRL 101, 120501 (2008)

Manipulating photon wavefunction




PRL 104, 223601 (2010)
PRA 80, 031803(R) (2009)

# Quantum information science and photon manipulation

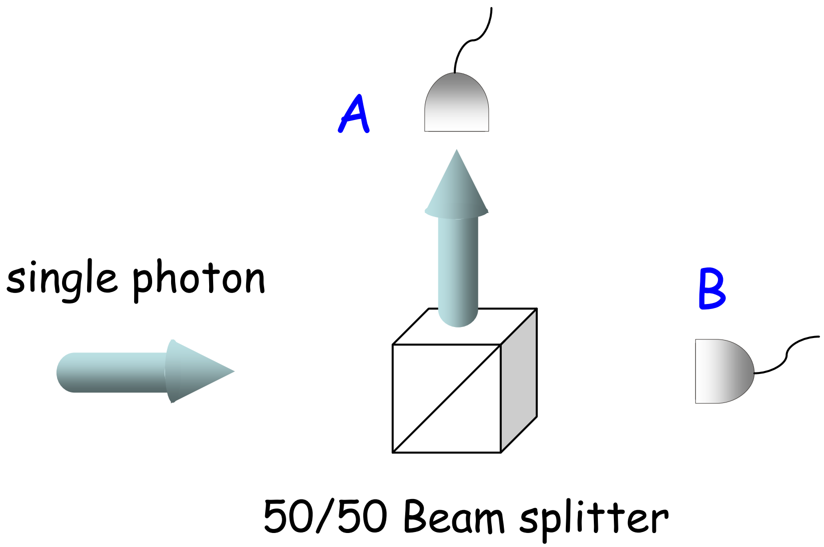
- Quantum teleportation, quantum cryptography, … etc.
  → polarization-entangled states
- Quantum imaging, entanglement concentration, … etc.
  → spatial shape of momentum-entangled states
- Long-distance quantum communication, clock synchronization, … etc.
  → spectral shape of frequency-entangled states
- ………

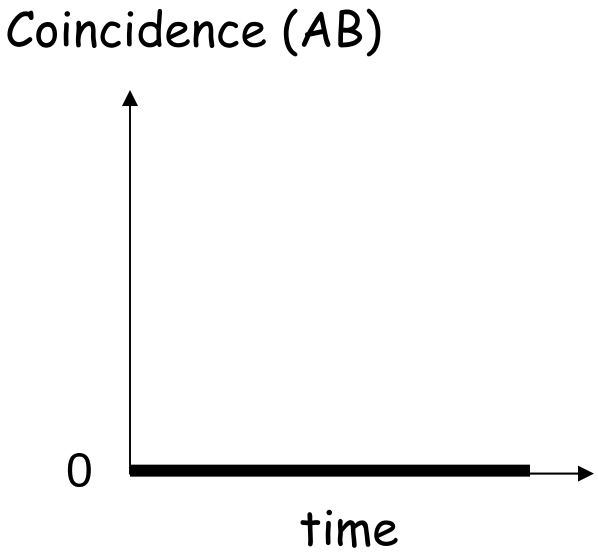
# Outline

- Single photon and time-energy entangled photons (biphoton)
- Measurement of short entangled photons
- Transmission of a single photon through noisy environment
- Summary
- Outlook

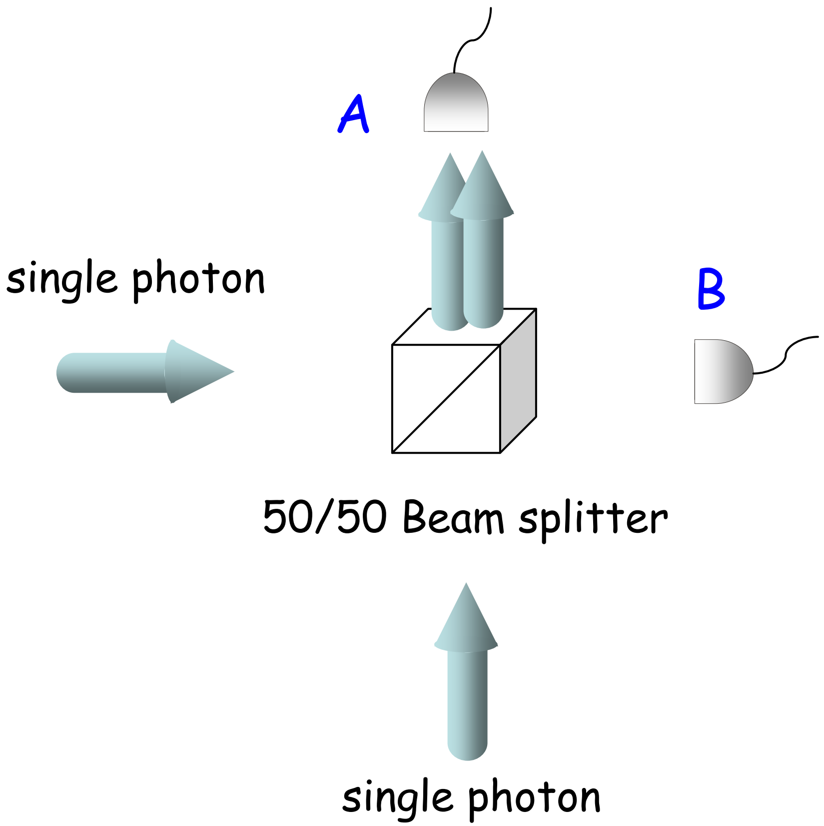
# Single photon and time-energy entangled photons (biphoton)

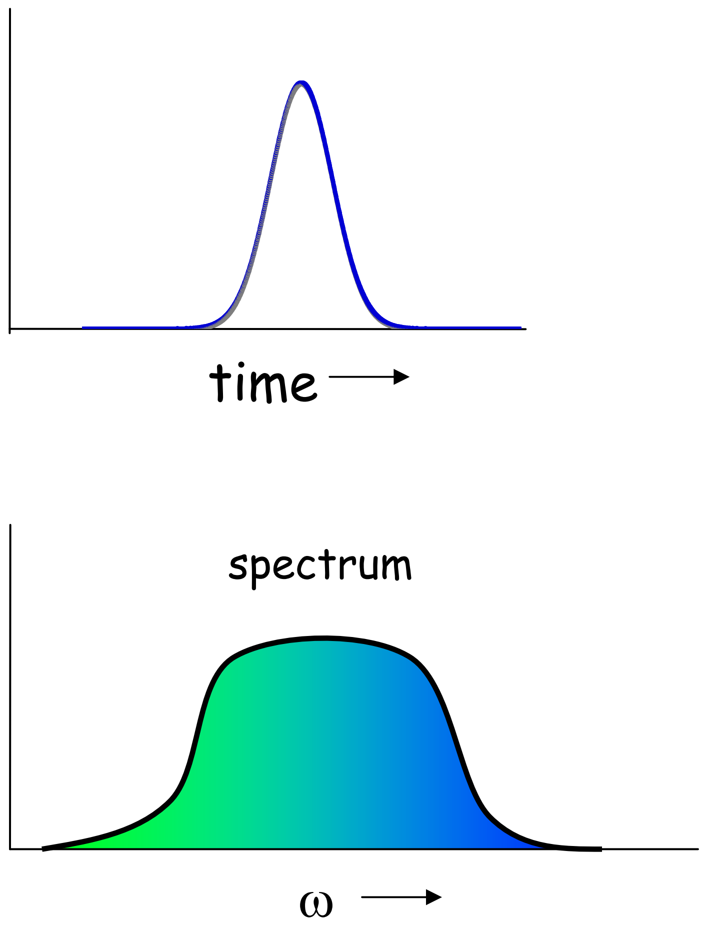
# Single photon



# Single photon



# Time-energy entangled photons (biphoton)

If photon 1 and photon 2 are time-energy entangled,

Photon 1: $E_1, \; t_1$

Photon 2: $E_2, \; t_2$

$$\Delta E \, \Delta t \geq \hbar$$

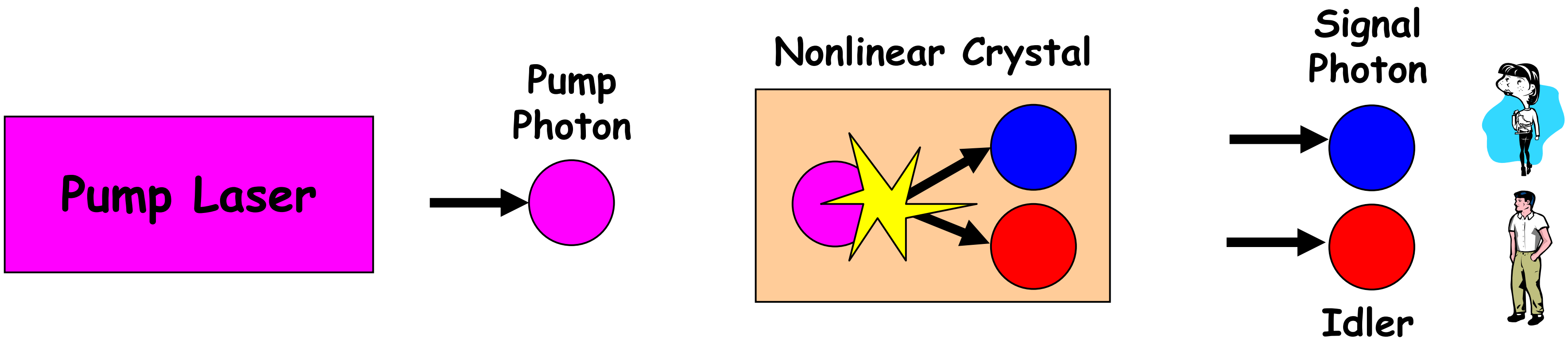
$$\Delta(E_1 + E_2) \; \Delta(t_1 - t_2) \rightarrow 0$$

Measurements of $E_1 + E_2$ and $t_1 - t_2$ are not limited by the Heisenberg uncertainty principle.

This distinguishes entangled photons from photons that are **correlated but not entangled**.

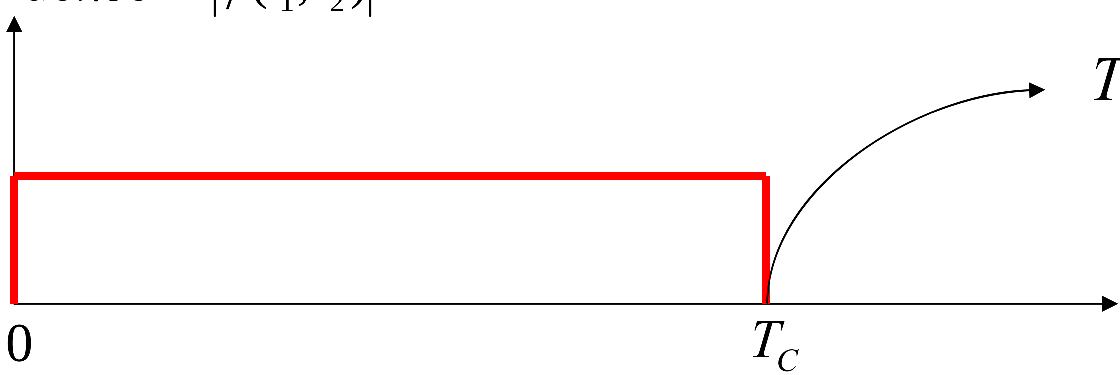
# Generation of time-energy entangled photons (biphotons)

The most common way to generate biphotons is by a process called spontaneous parametric down conversion in a nonlinear optical crystal.




The biphoton is described by a biphoton wavefunction $\varphi(t_1, t_2)$

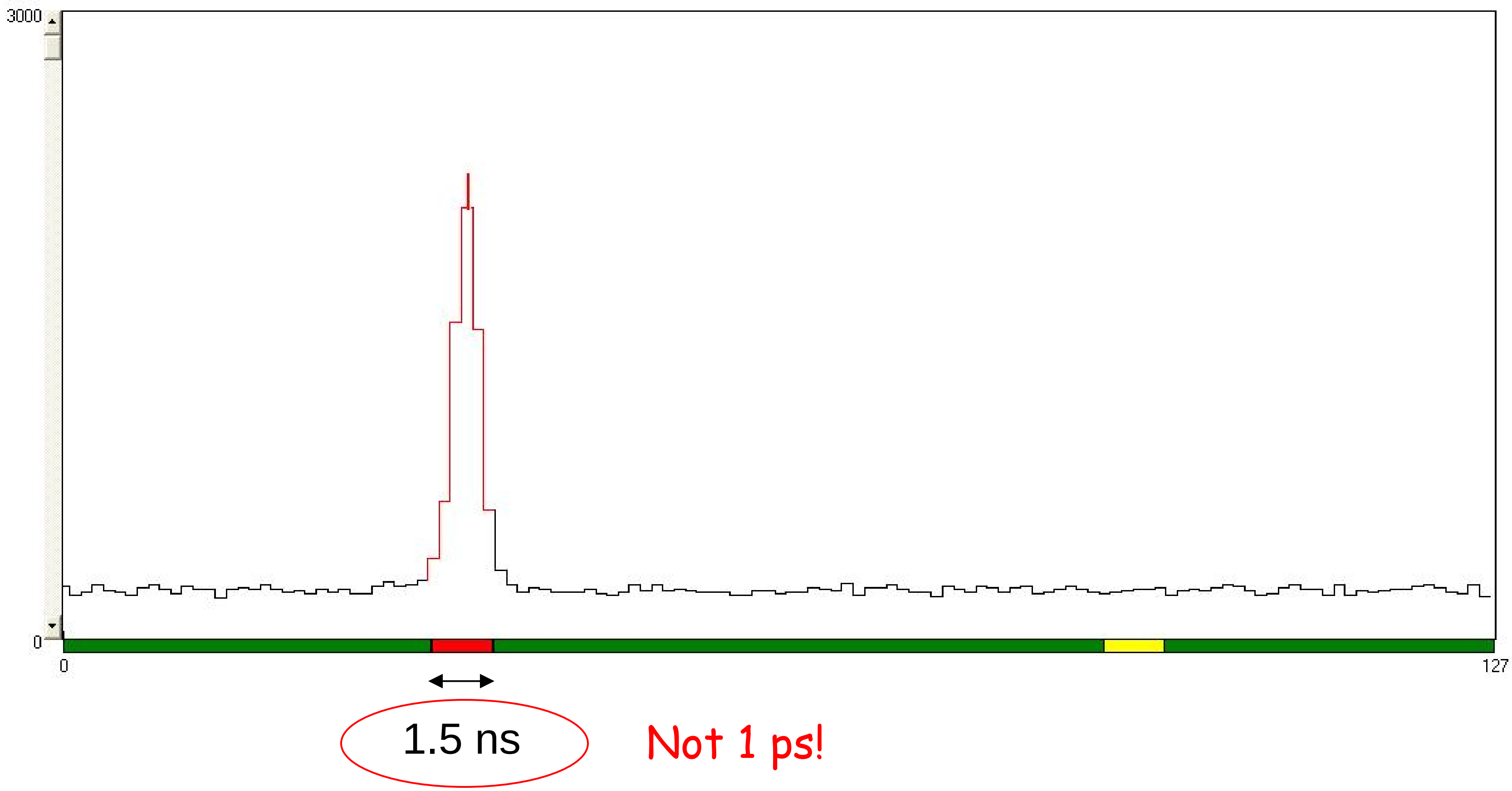
Coincidence ~ $|\varphi(t_1, t_2)|^2$



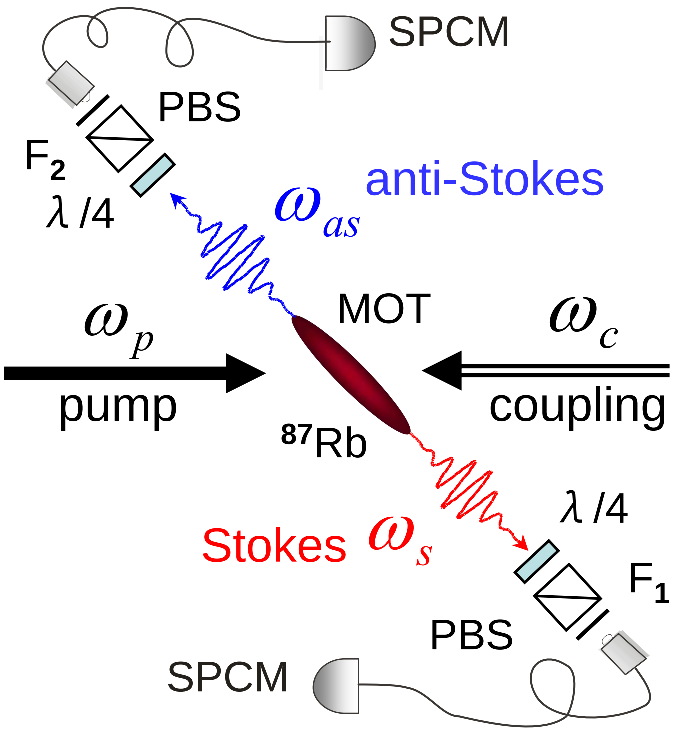

$$T_C = \frac{L}{v_1} - \frac{L}{v_2} = \frac{L\Delta v}{v_1 v_2}$$

# Measurement of short photons?

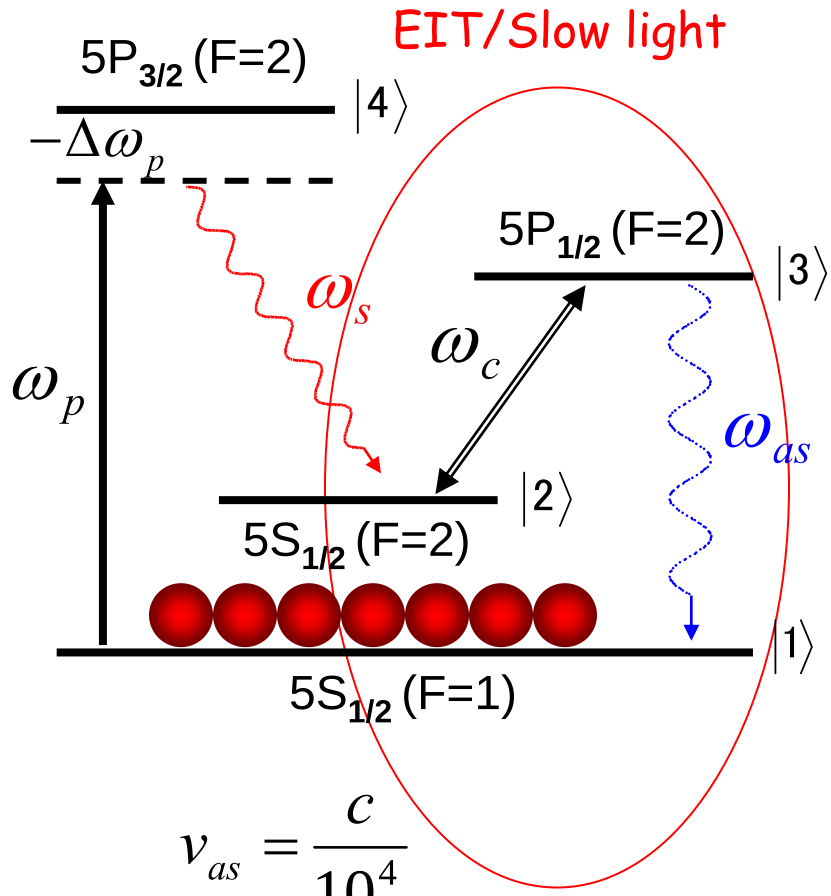
- Temporal length of biphoton ~ 1 ps
- Resolution of single photon detectors ~ 1 ns
- Photons are generated from a $LiNdO_3$ nonlinear crystal.



# Generation of time-energy entangled photons with four-wave mixing and slow light



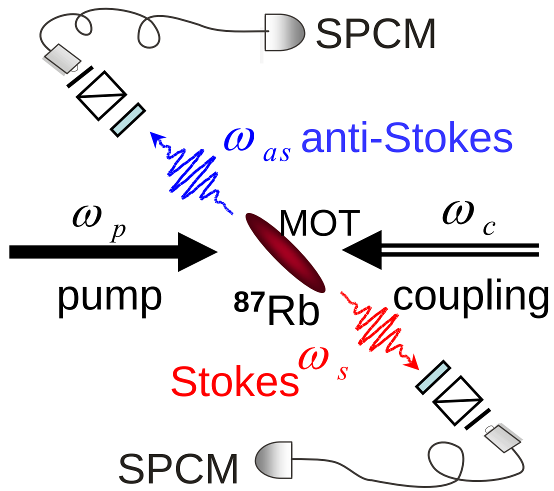

$$\omega_p + \omega_c = \omega_s + \omega_i$$

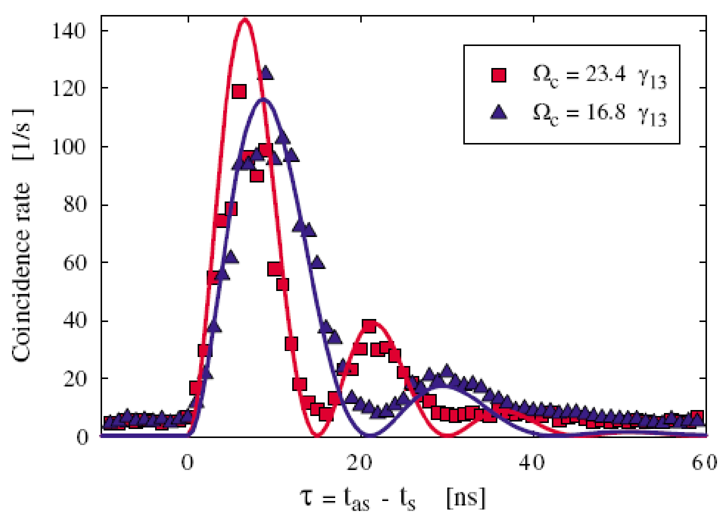


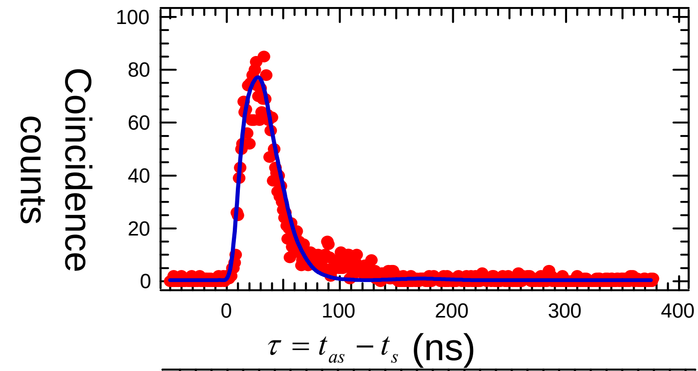

$$v_{as} = \frac{c}{10^4}$$

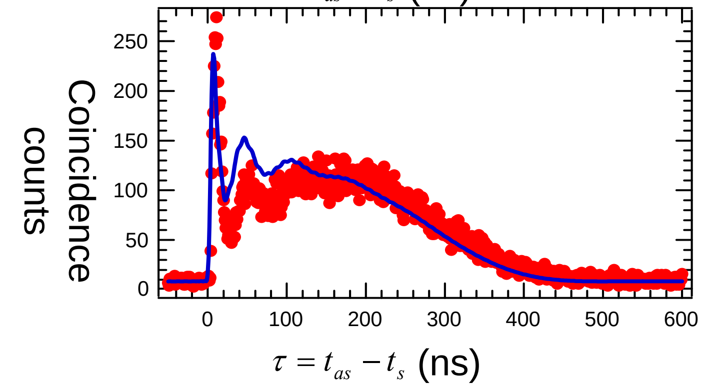
$$v_s = c$$

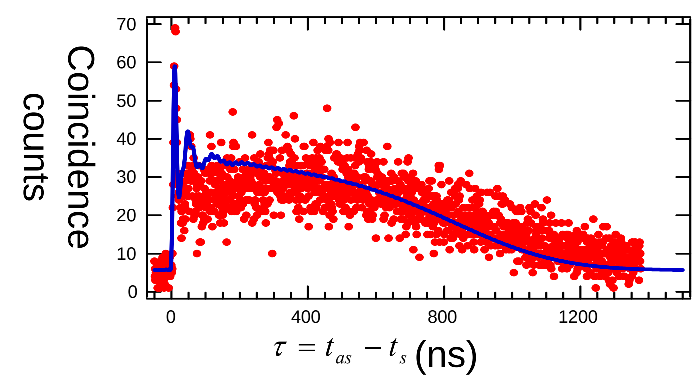
# Direct measurement of photon wavepacket $|\varphi(t_1, t_2)|^2$



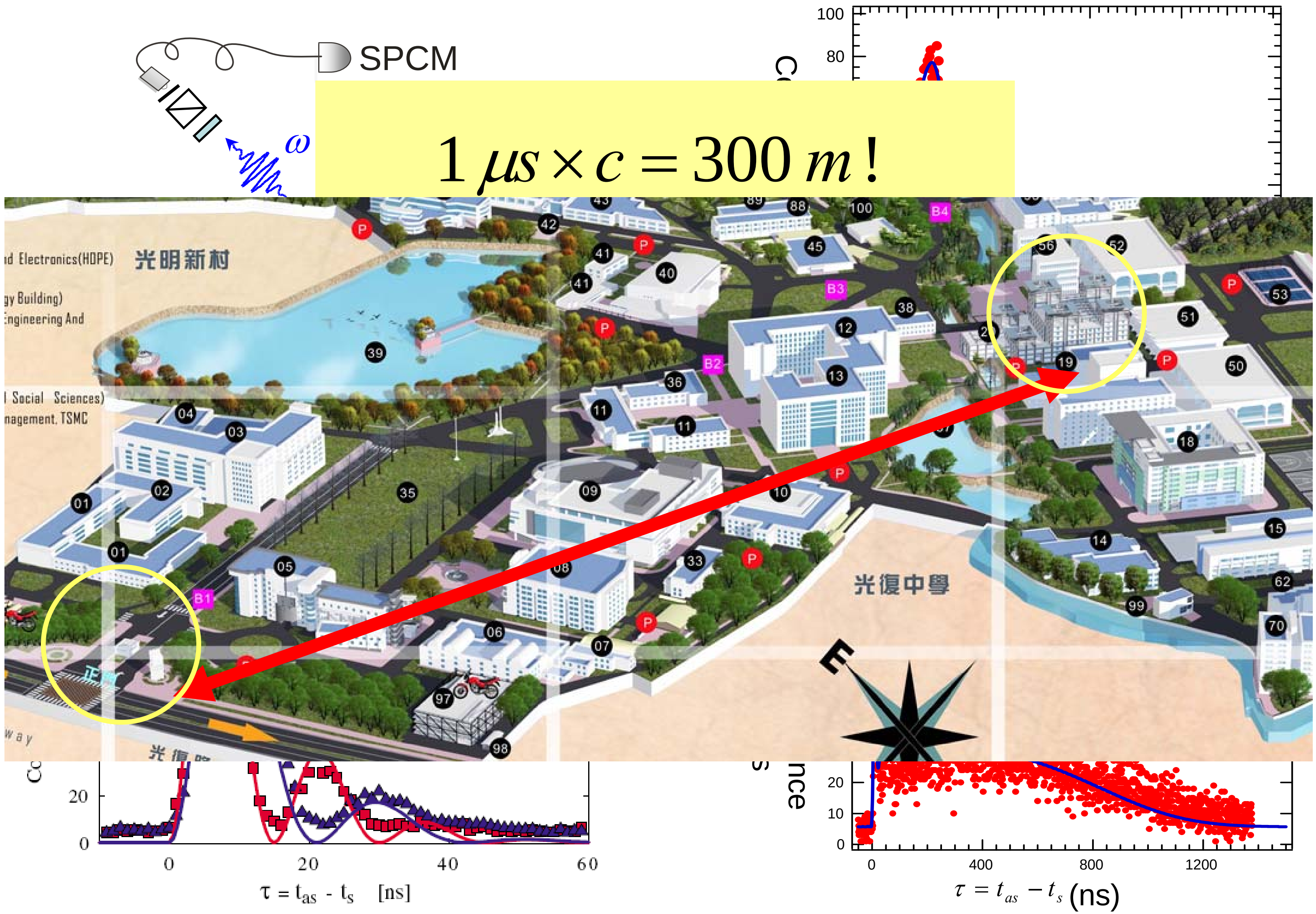



# Direct measurement of photon wavepacket $\left|\varphi(t_1, t_2)\right|^2$

$$1\,\mu s \times c = 300\,m\,!$$



# Measurement of short entangled photons

# Measurement of short entangled photons?

For a short entangled photon wavepacket $G(\tau)=\left|\varphi(t_1,t_2)\right|^2$ ,

measurement by slow detectors only gives $\int_0^\infty G(\tau)\,\mathrm{d}\tau$ but not $G(\tau)$ .

Lets use the following trick:

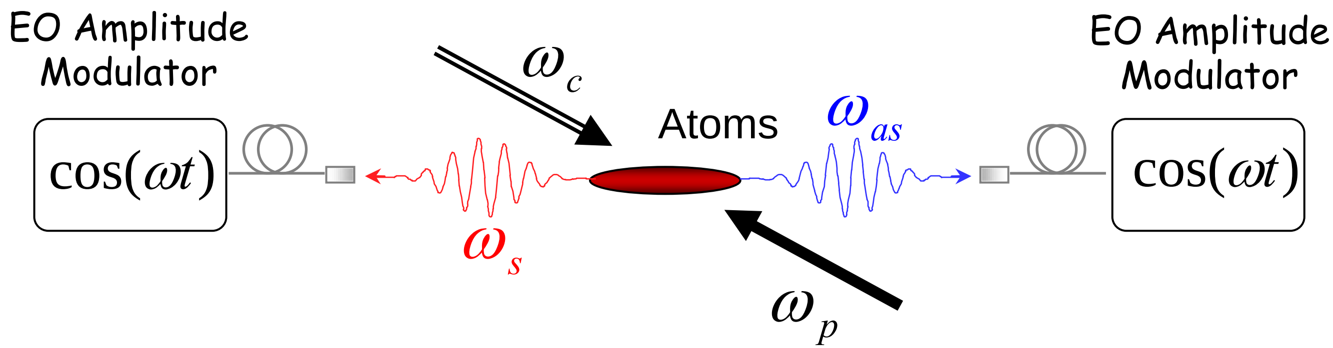
$$\int_0^\infty G(\tau)\,\mathrm{d}\tau \rightarrow \int_0^\infty G(\tau)\cos(\omega\tau)\,\mathrm{d}\tau$$

Now we have the Fourier transform of $G(\tau)$ .

We just need to take the inverse Fourier transform and obtain $G(\tau)$ !

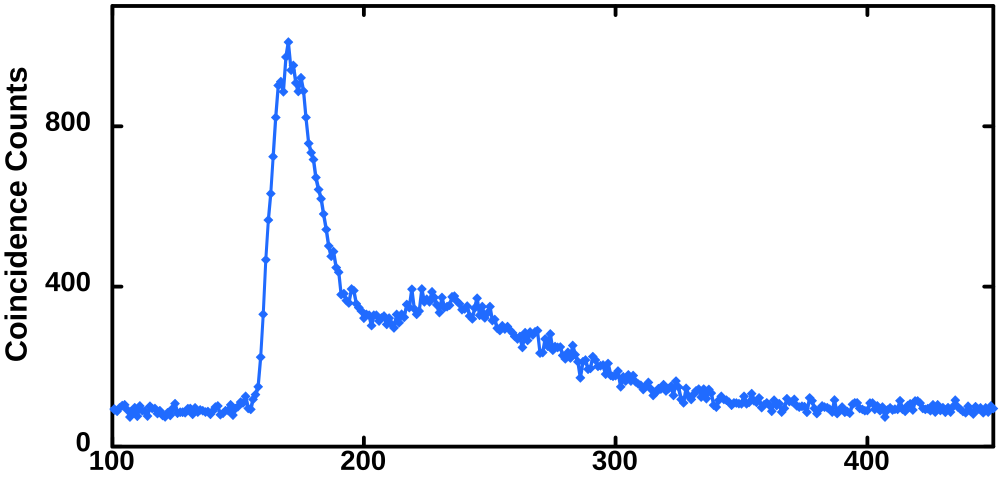
But, how do we add $\cos(\omega\tau)$ in our measurement?

# Amplitude modulation of entangled photons!

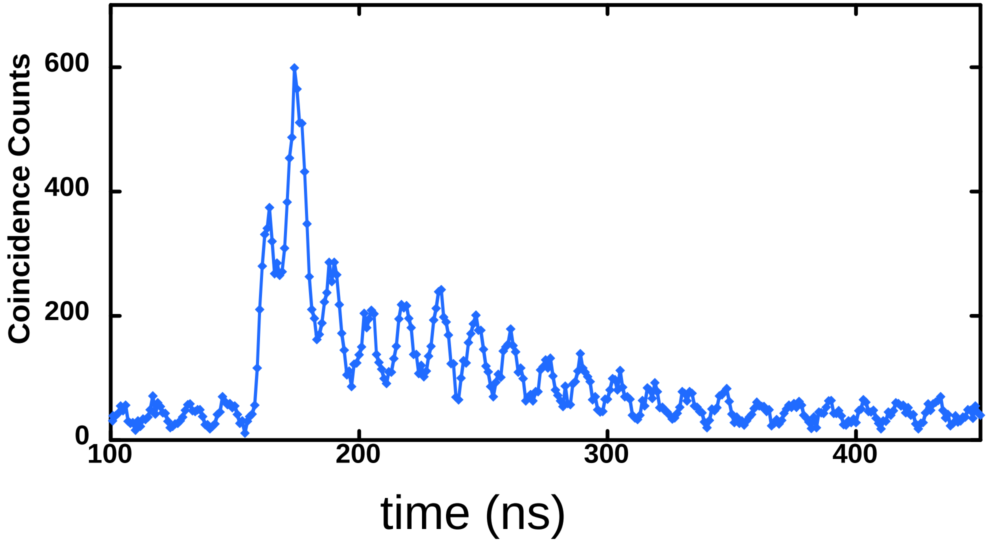



$$\int_0^{T_C} G(\tau)\cos(\omega t)\cos(\omega(t+\tau))dt = G(\tau)\cos(2\omega\tau) + \text{constant}$$

# Amplitude modulation of entangled photons!

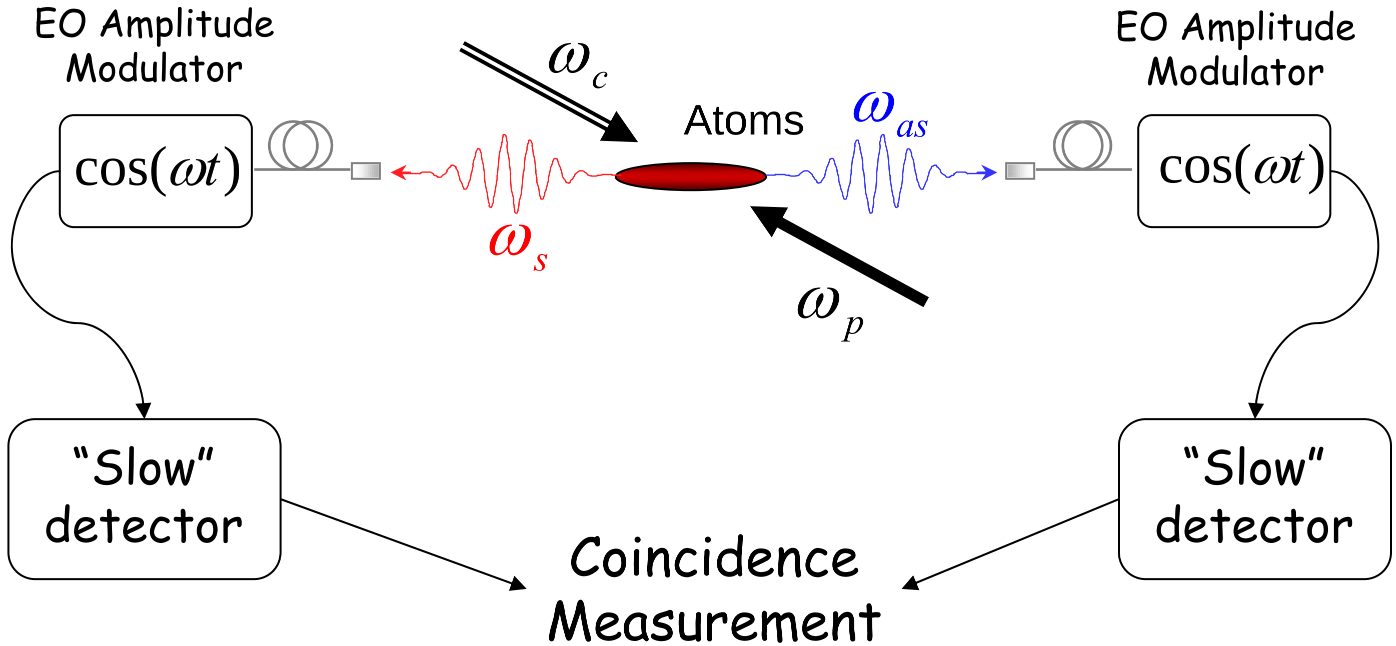



$$G(\tau)$$



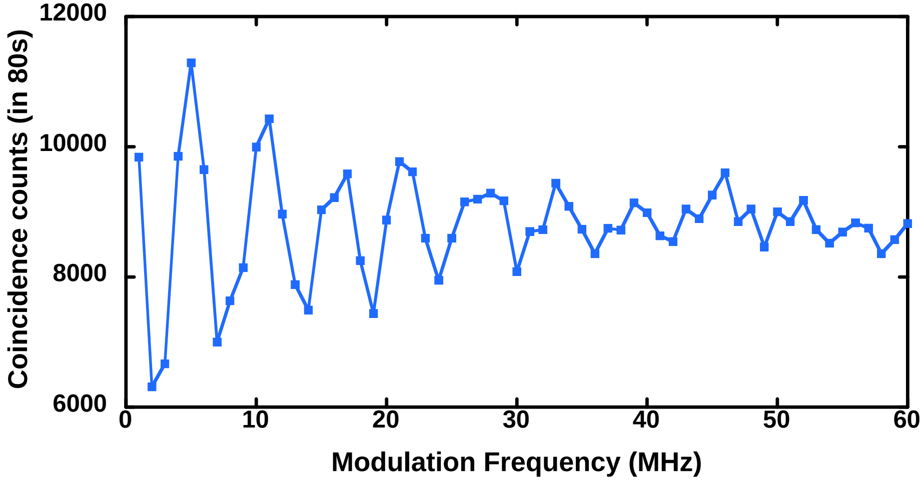

$$G(\tau)\cos(2\omega\tau)$$

# Amplitude modulation of entangled photons!

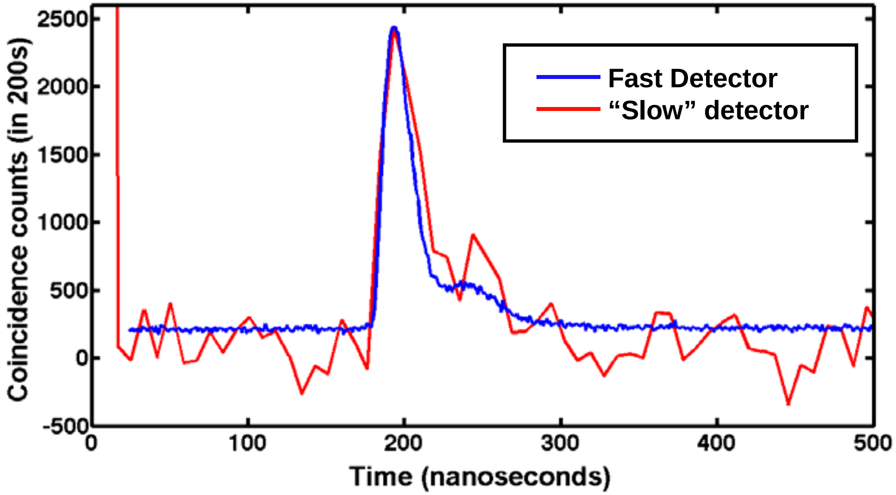



$$G(\omega) = \int_0^\infty G(\tau)\cos(2\omega\tau)\,\mathrm{d}\tau$$

# Measurement of "short" entangled photons with "slow" detectors



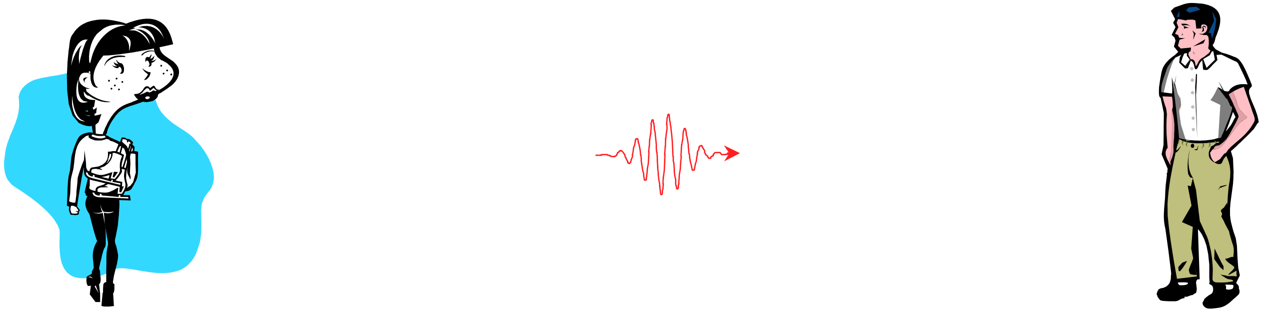

$$G(\omega) = \int_0^\infty G(\tau)\cos(2\omega\tau)\,\mathrm{d}\tau$$

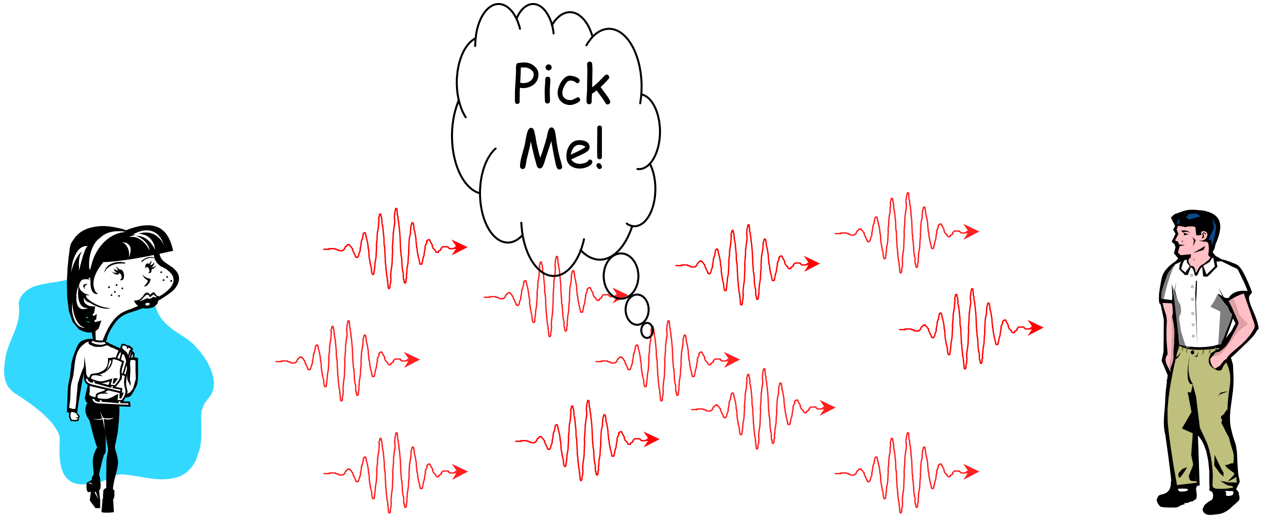



$$G(\tau) = \int_0^\infty G(\omega)\cos(2\omega\tau)\,\mathrm{d}\omega$$

## Transmission of a single photon through noisy environment

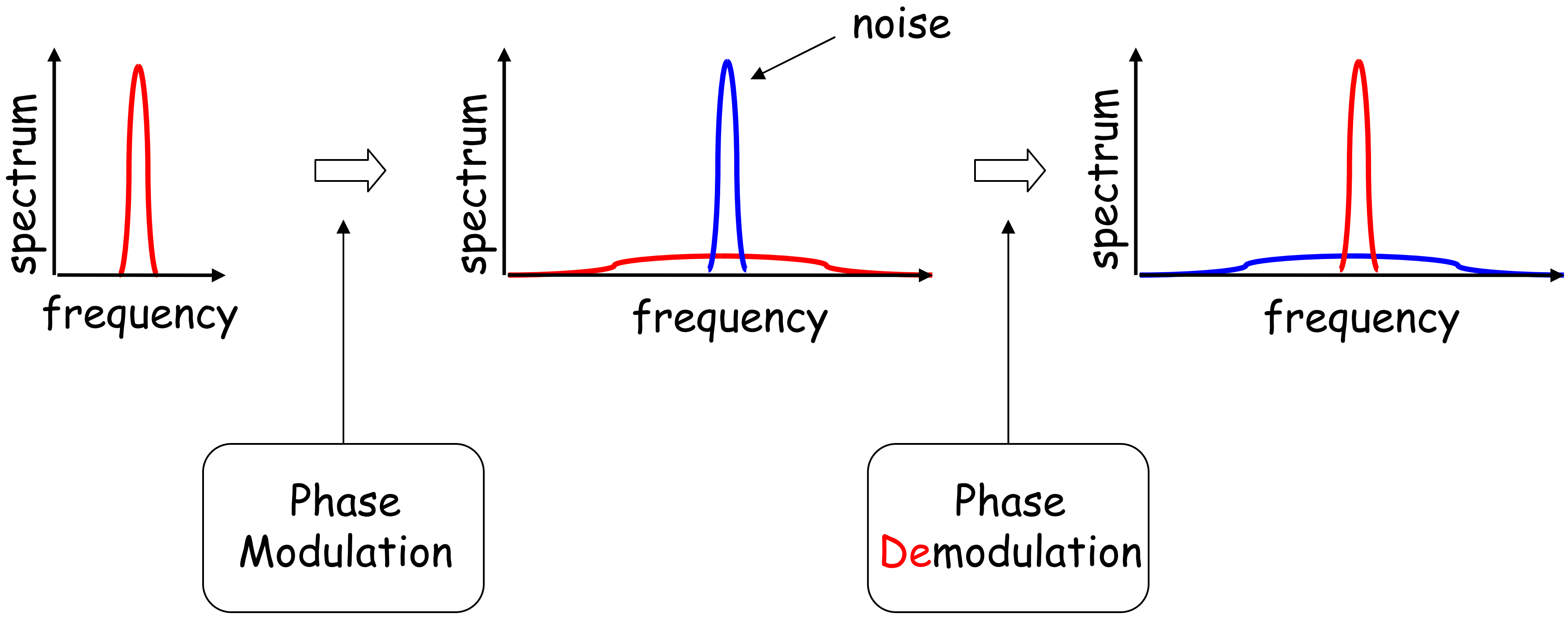
# Transmission of single photons through noisy environment?





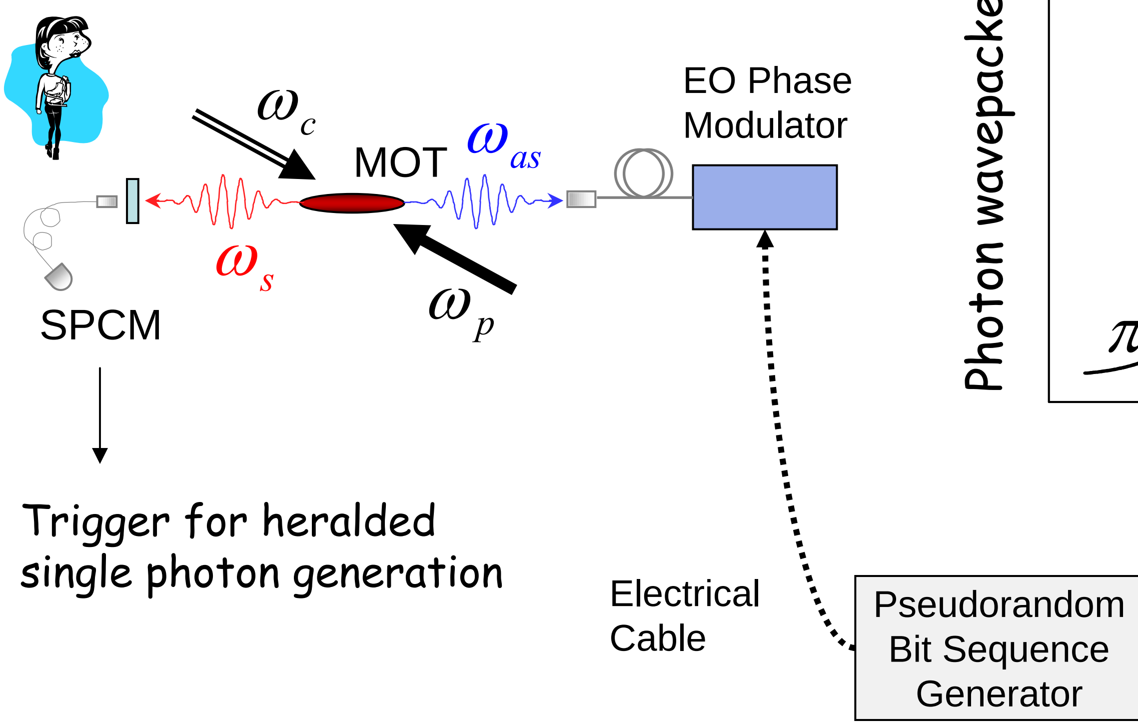
# Telecommunication through noisy environment

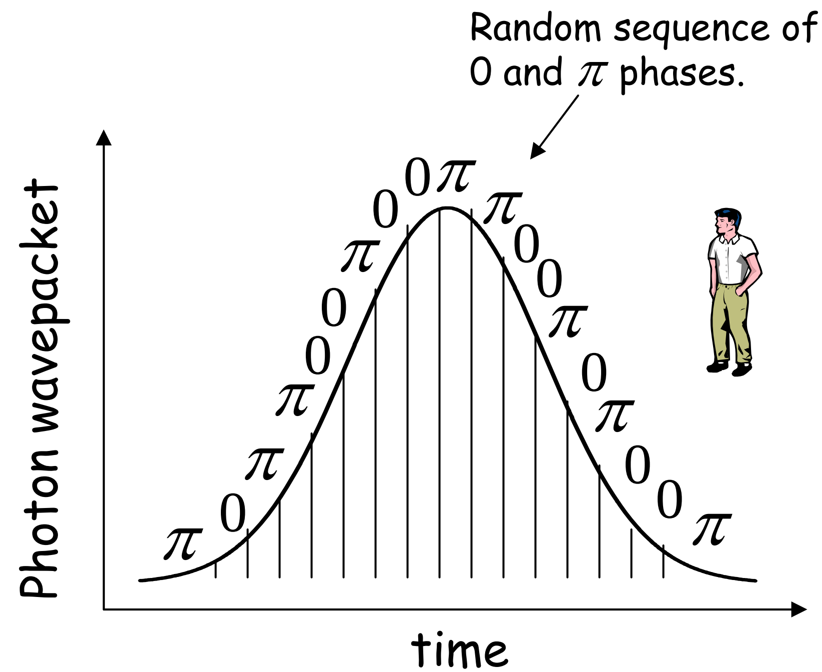
# Spread spectrum technology



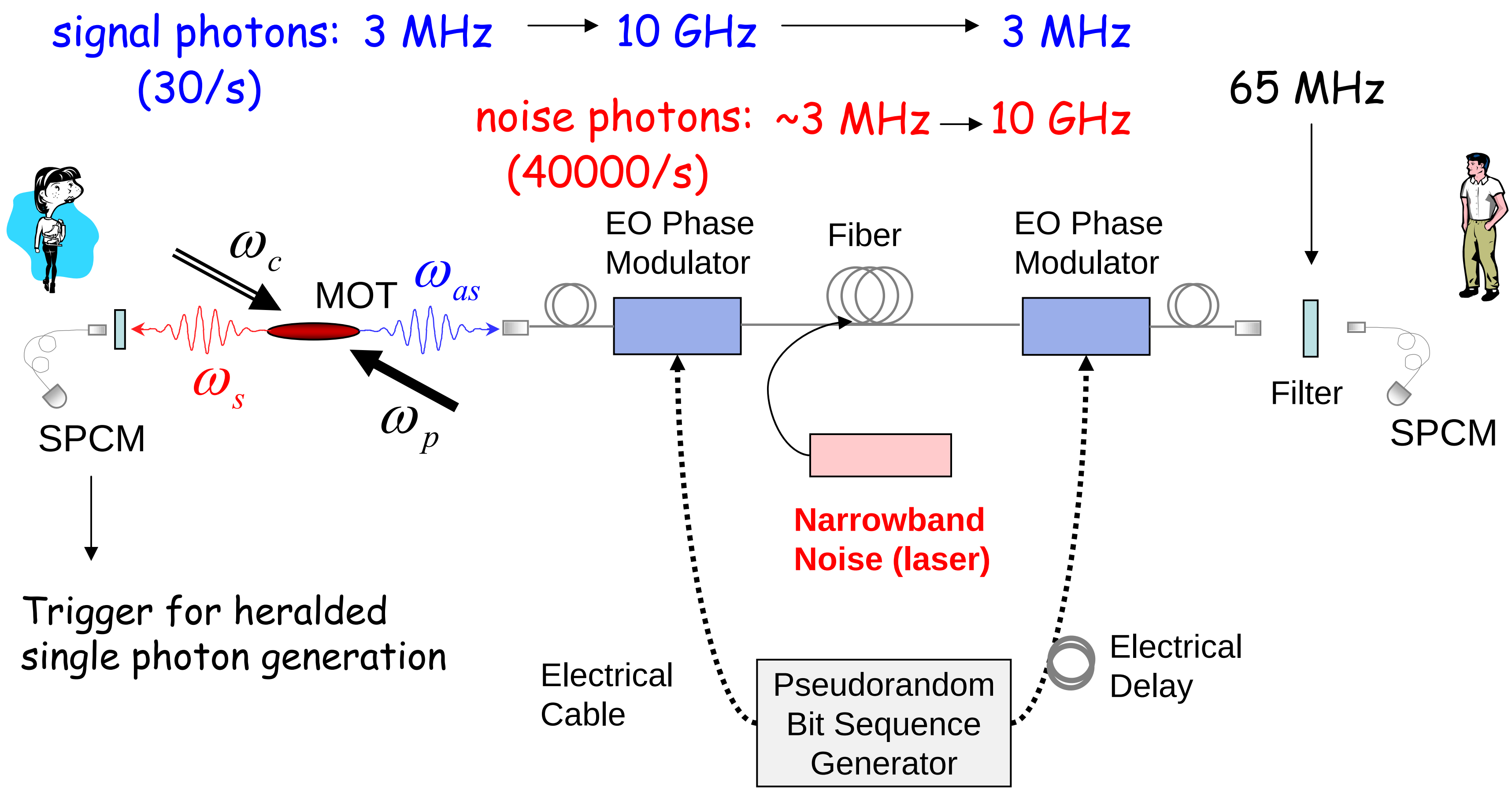
# Spread spectrum technology at single photon level

signal photons: 3 MHz → 10 GHz
(30/s)



# Spread spectrum technology at single photon level

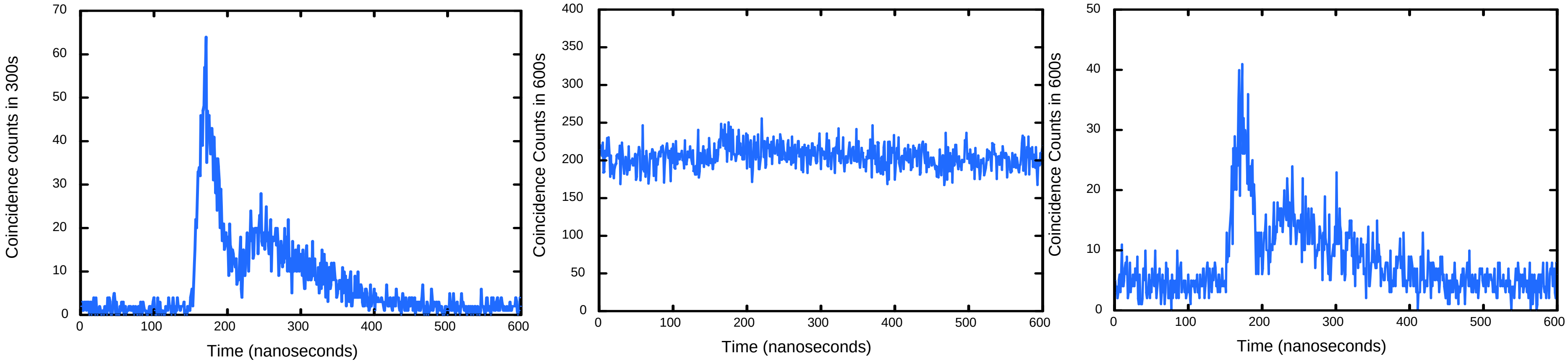


# Spread spectrum technology at single photon level

Without
SS technology

Without
SS technology
+ noise photons

With
SS technology
+ noise photons




Signal photon rate = 30/s
Noise photon rate = 40000/s

# Summary

- Long biphoton → heralded long single photon
- Amplitude modulation of time-energy entangled photons
  →Measurement of short entangled photons
- Phase modulation of single photons
  →Transmission of single photons through noisy environment

# Acknowledgements


**Stanford**
Prof. Steve Harris
Guan-Yu Yin
Chinmay Belthangady
Shengwang Du
Prof. Joseph Kahn

**Austin**
Prof. Mark Raizen
Florian Schreck
Todd Meyrath
Jay Hanssen
Gabriel Price

**Heidelberg**
Prof. Jian-Wei Pan
Prof. Joerg Schmiedmayer
Yu-Ao Chen
Bo Zhao
Prof. Shuai Chen
Zhen-Sheng Yuan
Markus Kohl
Thorsten Strassel
Xiao-Hui Bao
Xian-Min Jin

**NTHU**
Prof. Ite A. Yu


Thank you!