Single photon generation and detection technology

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Quantum Information …

- Encodes information in quantum mechanical states
- Involves the manipulation and measurement of quantum states

  - Atoms, Ions, Spins, Superconductors, Cavity-QED, **Photons**
  - We need a toolbox to generate, manipulate, and measure (detect) photons.

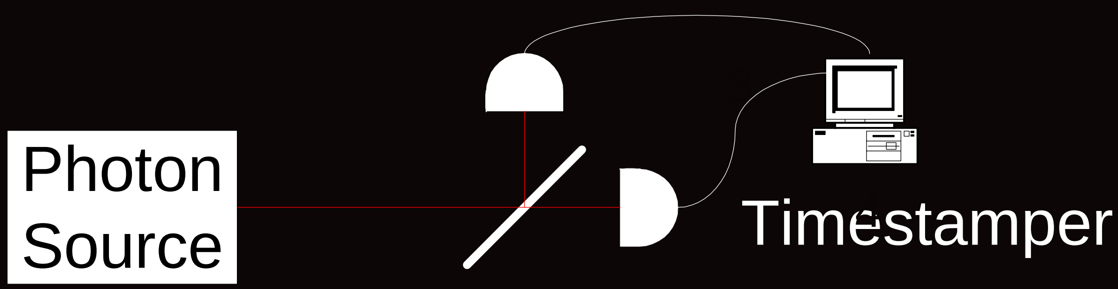
Single Photon Sources - Properties

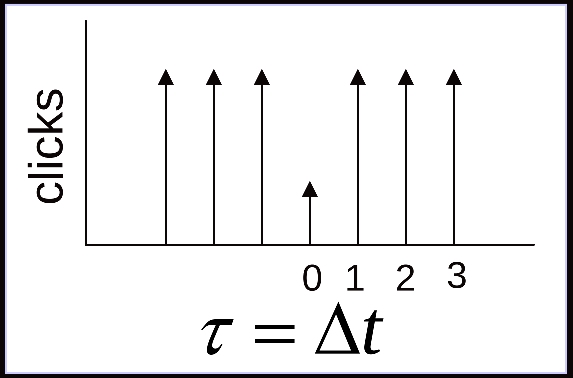
- One and only one
- Wavelength
- Efficient
- Timestamp / On demand
- Polarization
- Spatial Mode

- Commercially available / Manufacturable?

Metrology of Single Photon Sources

- Photon Number Resolving Detector
- Hanbury-Brown-Twiss Interferometer (HBTI)





$$g^{(2)}(\tau) = \frac{\langle I_3(t)(I_4(t+\tau))\rangle}{\langle I_3(t)\rangle\langle I_4(t)\rangle}$$

For a single photon source

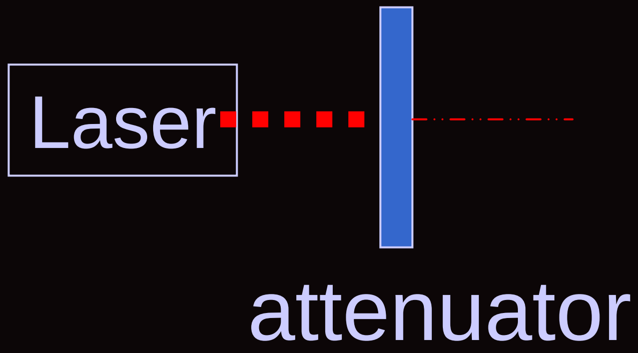
$$g^2(\tau = 0) = 0$$

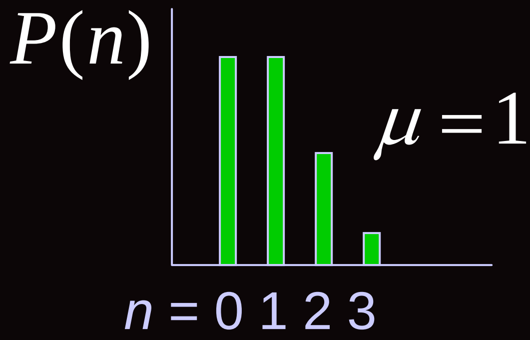
Single Photon Source Technologies

- Laser
- Single Atoms / Molecules
- Single “artificial” atoms
  - Quantum dots
  - Nitrogen vacancies in diamond
- Correlated photon sources (two-γ sources)
  - Spontaneous Parametric Downconversion
  - Four-wave mixing in fiber

Laser

Single γ's	$g^2(0) = 1$, Poisson
Wavelength	IR-visible
Efficiency	Electrically pumped, high
Timestamp	pulsed
Polarization	cavity
Spatial mode	cavity, optics

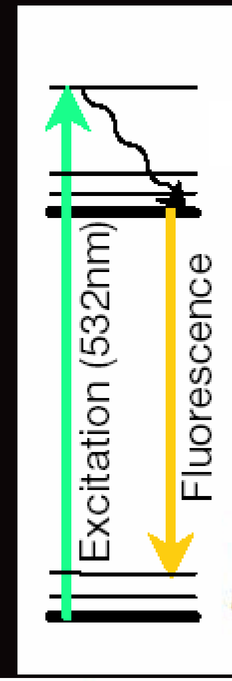


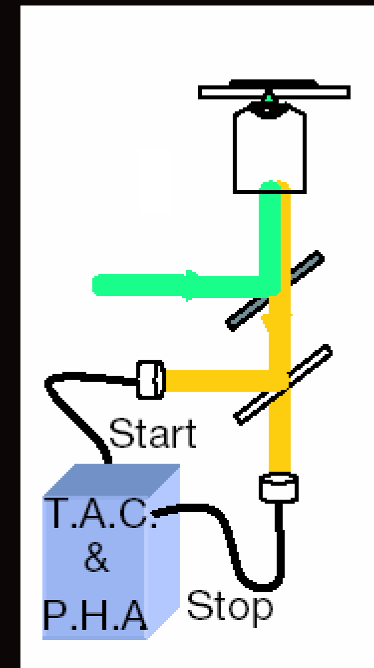


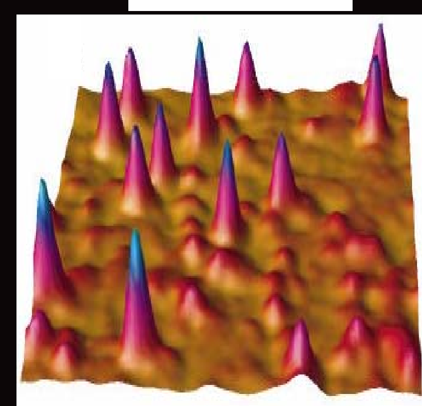
$$P(n) = \frac{\mu^n}{n!} e^{-\mu}$$

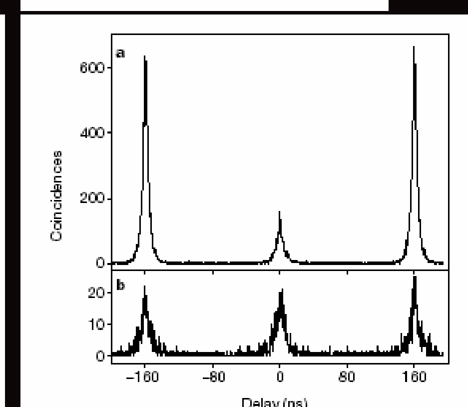
Atoms / Molecules

Single γ's	See plot
Wavelength	Atomic transition
Efficiency	6%
Timestamp	pulsed
Polarization	cavity
Spatial mode	cavity, optics





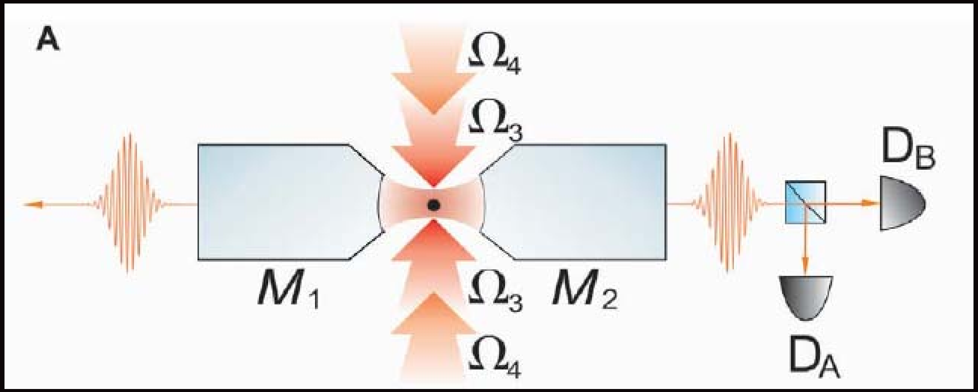




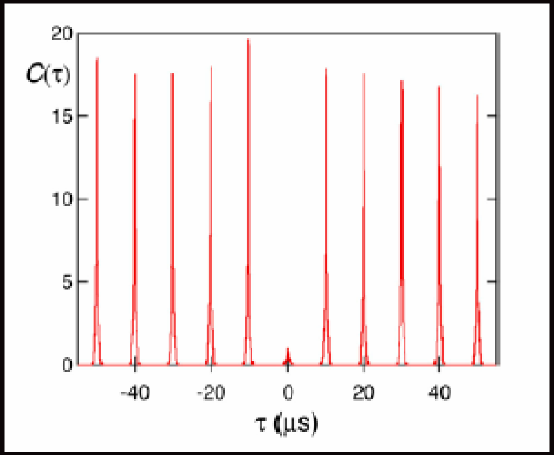
F.D. Martini, et al., Phys. Rev. Lett. 76, 900 (1996).
Treussart, et al., Phys. Rev. Lett. **89**, 093601 (2002)

B. **Lounis** and WE **Moerner**, Nature, 407, 491-493 (2000)

Single Atoms



Kimble et. al, Cal Tech



- Trap Single Cs Atom
- Pump with external field
- Use a cavity to control spatial mode
- See talk later today

published online February 26, 2004; 10.1126/science.1095232 (Science Express Reports)

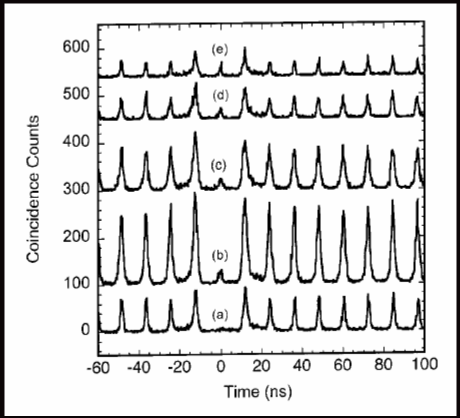
Artificial Atoms: Quantum Dots

Single γ's	See plot
Wavelength	Material dependent
Efficiency	
Timestamp	Pulsed
Polarization	
Spatial mode	

3D confined electron gas
Discrete energy levels
"Aritifical atom"

Self-assembled (most common):

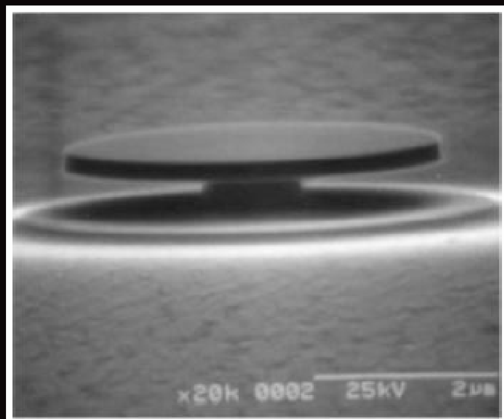
InAs/GaAs
InAs/InP
InGaAs/GaAs
CdSe/ZnSe



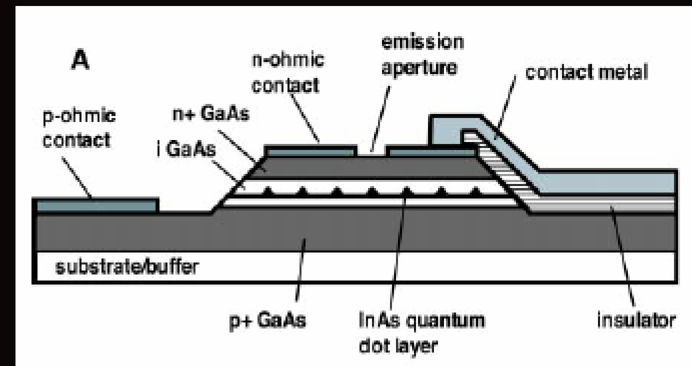
InGaAs/GaAs

Mirin, APL, vol.84, no.8 : 1260-2, 23 Feb. 2004

Cavities, Electrically pumped

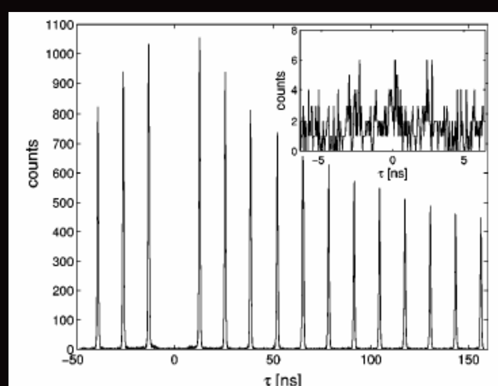


P. Michler,et al, Science 290, 2282 (2000)

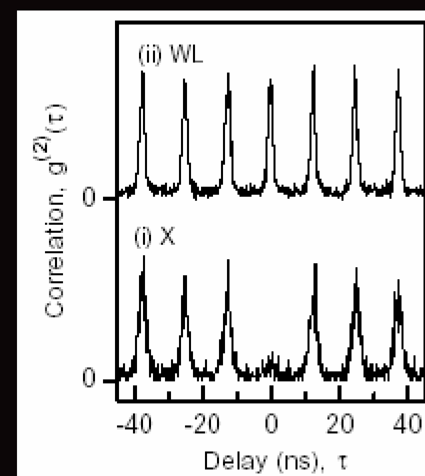


Z. Yuan,et al, Science 295, 102 (2002)

M. Pelton et al., PRL, 89, 233602 (2002)

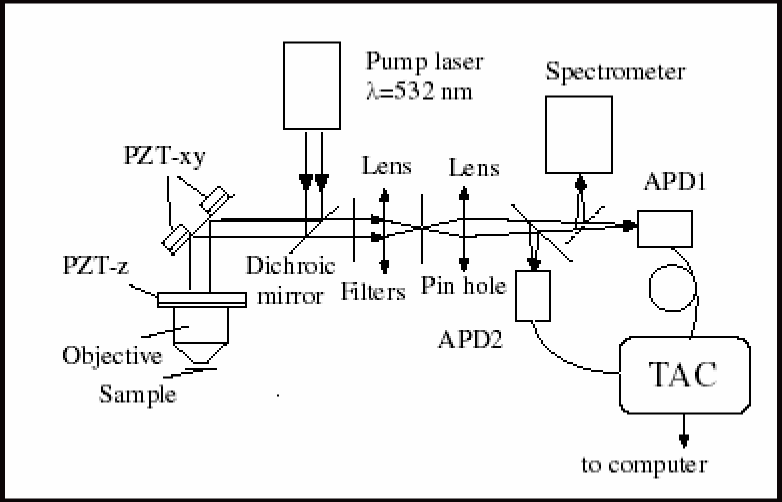


J. Vuckovic et al., APL, 82, 3596 (2003)

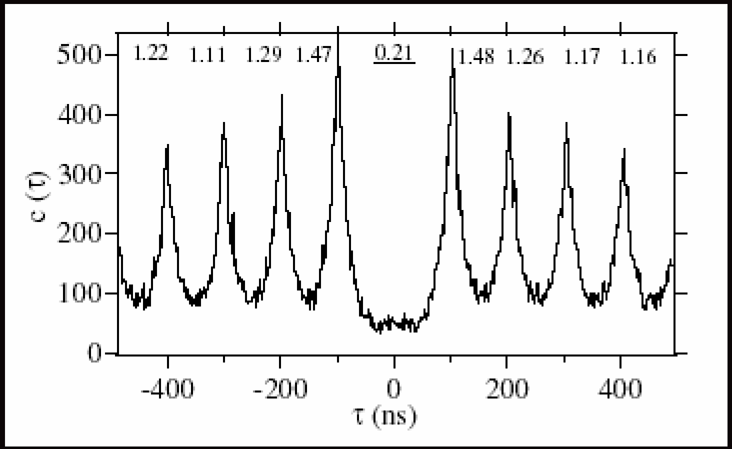


Artificial Atoms: NV in diamond

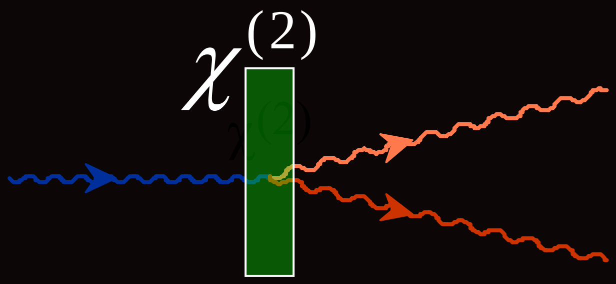
Single γ's	See plot
Wavelength	Band gap of the material
Efficiency	0.001
Timestamp	Pulsed
Polarization	
Spatial mode	



A. Beveratos, et. al, Eur. Phys. J. D 18, p. 191.



Spontaneous Parametric DownConversion



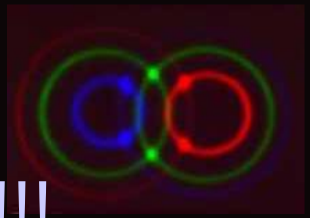
$$\omega_p = \omega_s + \omega_i$$

$$\vec{\kappa}_p = \vec{\kappa}_s + \vec{\kappa}_i$$

Single γ's	Heralded by other photon
Wavelength	IR-visible
Efficiency	
Timestamp	pulsed pump
Polarization	cavity?
Spatial mode	cavity?, optics?

Varieties:

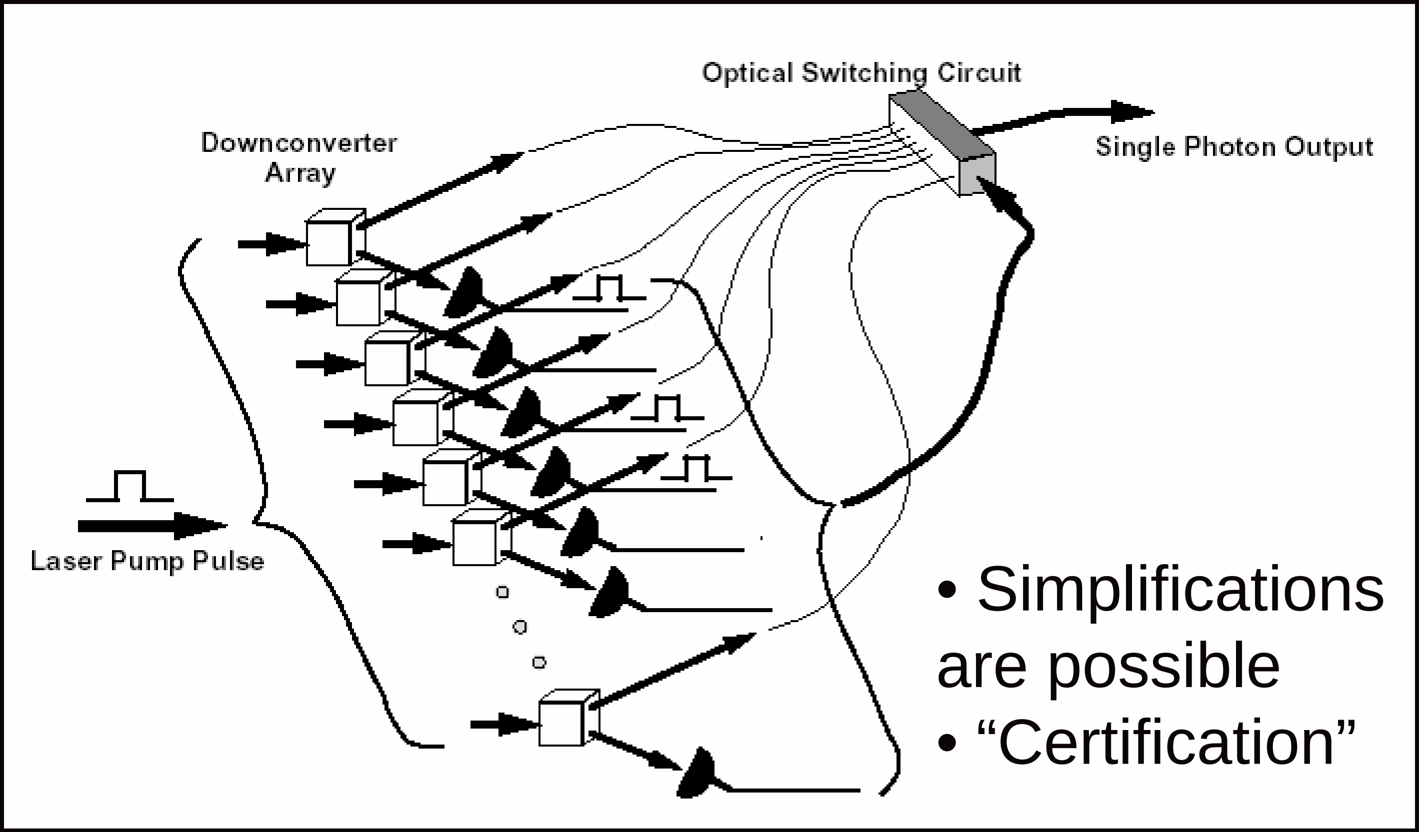
- Type I or II (polarization)
- Non-colinear, colinear



Source of Entangled Photons!!!

Paul Kwiat, UIUC

Spontaneous Parametric DownConversion – Multiplexed

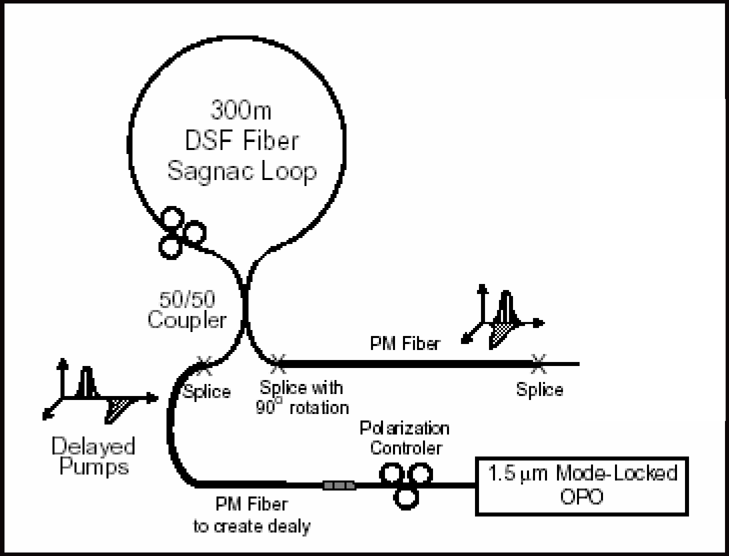


- Simplifications are possible
- “Certification”

Alan Migdall, NIST

Four Wave Mixing in Fiber

Single γ's	Entangled pair
Wavelength	~1550nm
Efficiency	
Timestamp	pulsed
Polarization	Pump dependent
Spatial mode	Fiber



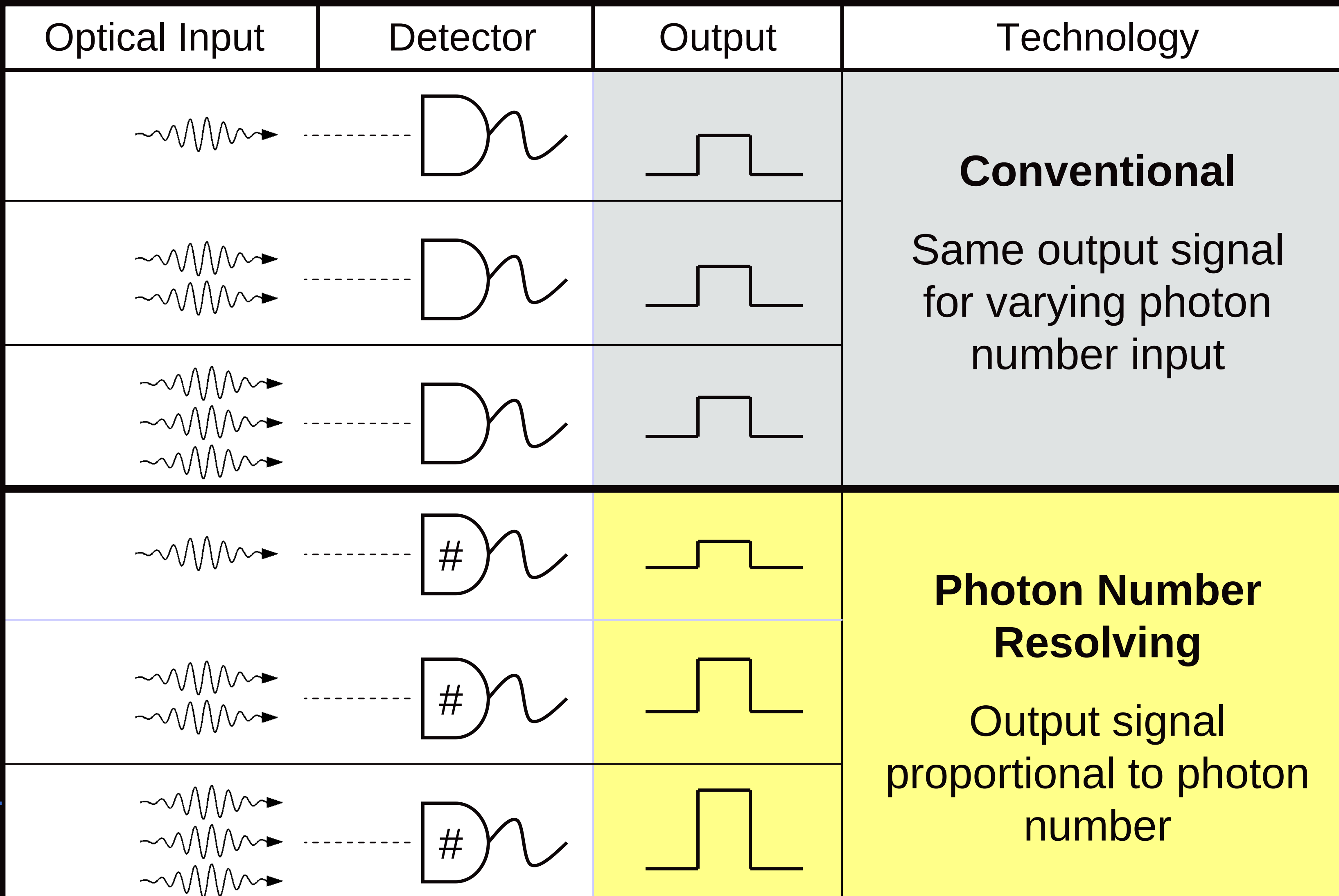
X. Li, et al. , QTuB4 in QELS'03 Technical Digest

$$2\omega_p = \omega_i + \omega_s$$

Single Photon Detectors - Properties

- High Quantum Efficiency (as close to 100%)
- Broadband (100nm to 2000nm)
- Low Dark Count rate
  - No false counts
  - No afterpulsing
- Speed
  - Fast recovery
  - Fast rise / pulse pair resolution
- Energy Resolving / Photon Number Resolving

Photon Counter vs. Photon Number Resolving



Single Photon Detector Technologies

- "Photon Counter"
  - Avalanche Photodiodes
  - Photomultiplier Tubes
  - Quantum Dots
  - Upconversion
  - Superconducting Single Photon Detector
- "Photon Number Resolving"
  - N-splitters and photon counters
  - Photomultiplier
  - Visible Light Photon Counter / Solid State Photomultiplier
  - Low Temperature Superconducting Detectors

Avalanche Photodiodes (APD)

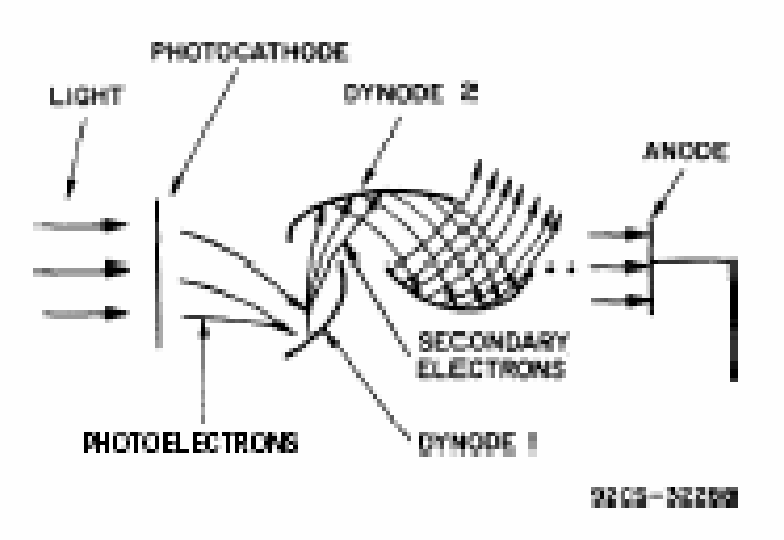
- Reverse Biased Diode
- Geiger Mode
- Impact Ionization continually amplifies uncontrollably
- Active/Passive Quench to reset
- Afterpulsing

Material	Si	InGaAs
Wavlength	300-1100 nm	1000-1700nm
Q.E.	70%	20%
Dark Count	100 Hz	10's kHz
Count Rate	5 MHz	100 kHz
Timing	1 ns	1 ns

Commercial Devices: Perkin Elmer, Sensors Unlimited, Amplification Technologies, JDS Uniphase, Fujitsu

Research: UT-Austin, UCSD, NovaCrystals

Photomultiplier Tube (PMT)

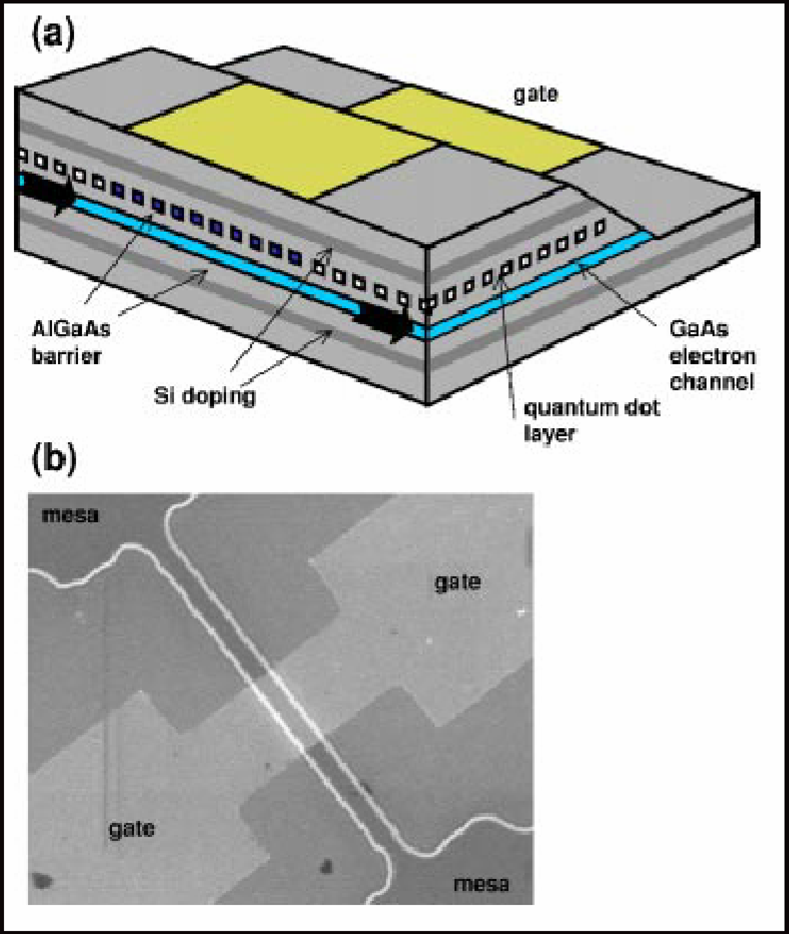


Wavelength	200-1700
Q.E.	10%
Dark Count	100 Hz – 100kHz
Count Rate	100 MHz
Timing	<1 ns

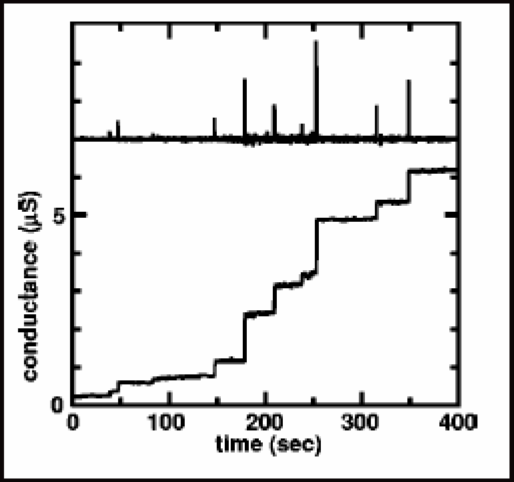
- Photocathode determines sensitivity
- Afterpulsing

Commercial Devices: Hamamatsu, Burle
~$20,000

Quantum Wells/Dots in FETs



1. Electron-hole pair is generated by absorption of a photon
2. Electron / hole is trapped by a quantum dot / well
3. Modulate the resistance of a FET channel.

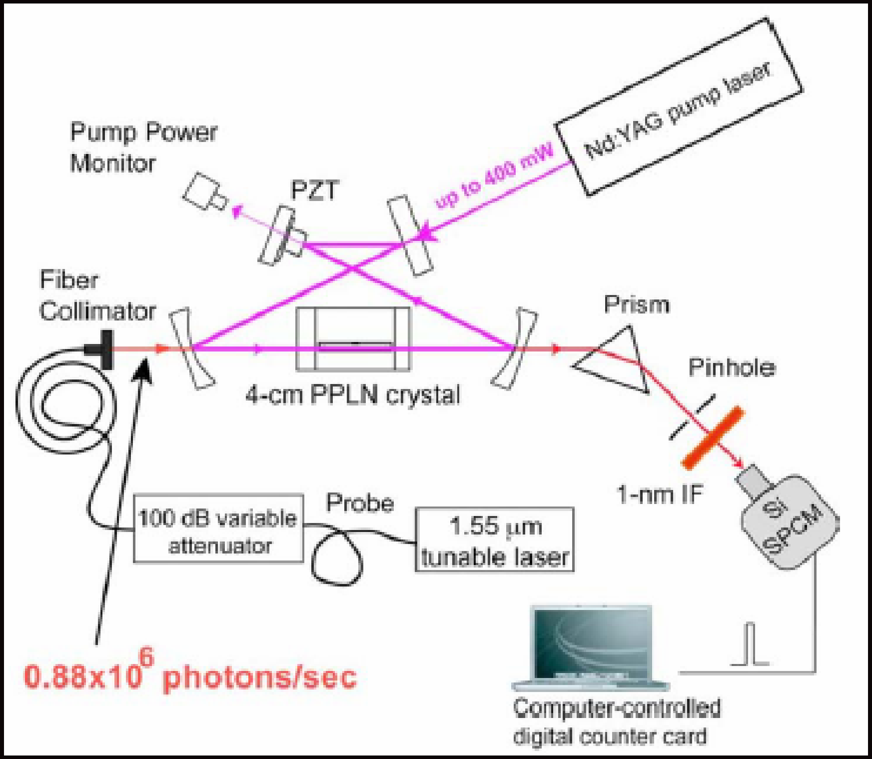


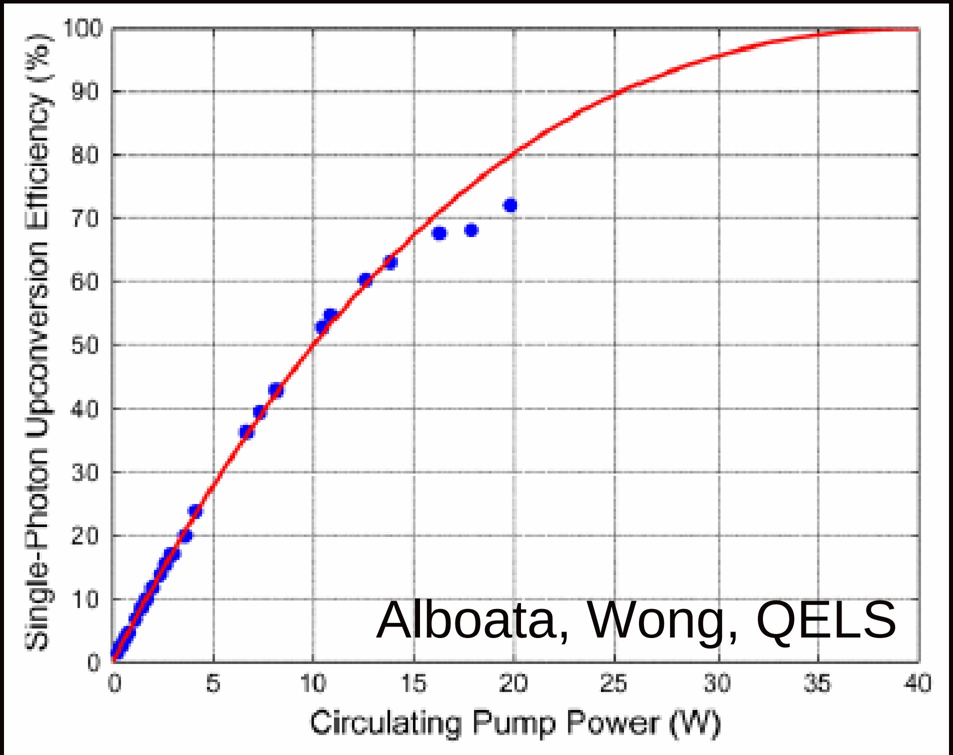
A.J. Shields, APL, vol 76, no. 25, p. 3673-5.

Yablonovitch UCLA, Mirin - NIST

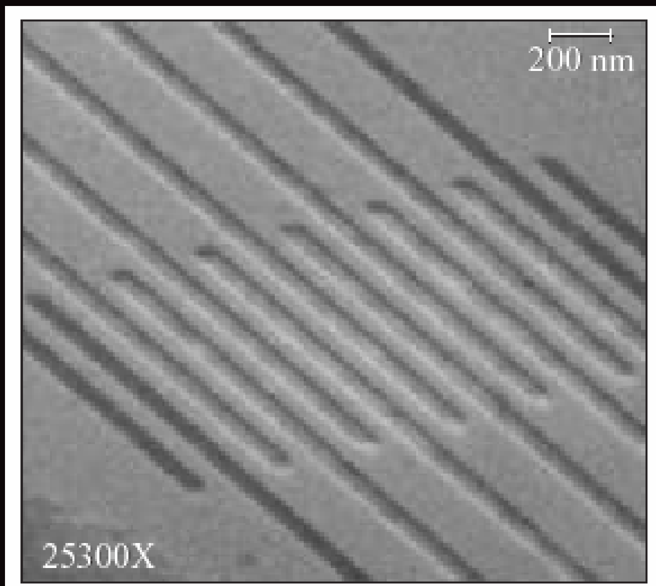
Upconversion

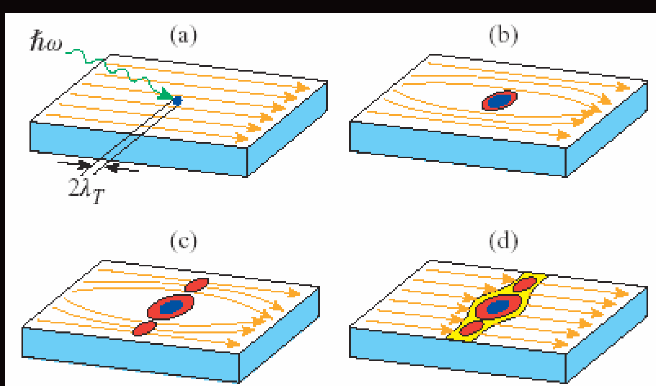
- Transform the detection problem from the IR to the visible.
- Downconversion in reverse!!!





Superconducting Single Photon Detector (SSPD)



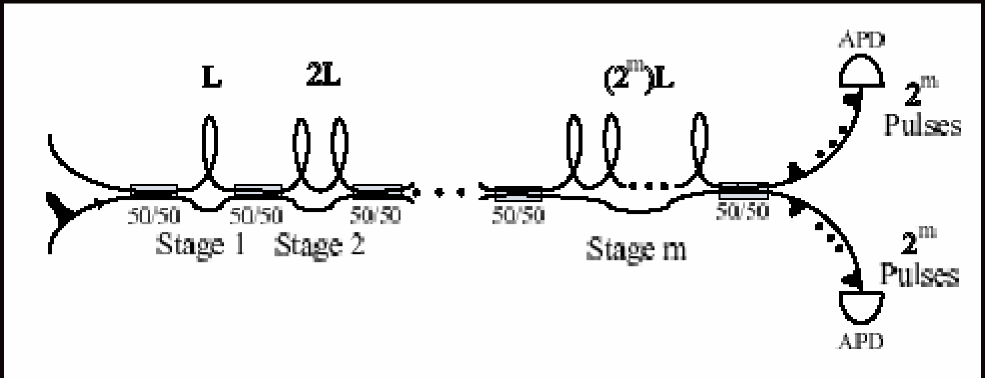


Wavelength	200-1700
Q.E.	5%
Dark Count	10kHz
Count Rate	1 GHz
Timing	<100 ps

Sobolewski, Univ. of Rochester

Spatial or Time multiplexing

- Spatial Multiplexing
  - Multiple beam splitters + multiple detectors
  - Careful analysis of the output to estimate photon number
- Time multiplex
  - Divide the photons into time bins
  - Slower effective count rate



D. Achilles, et al., quant-ph/0310183

PMT for Photon Number Resolving

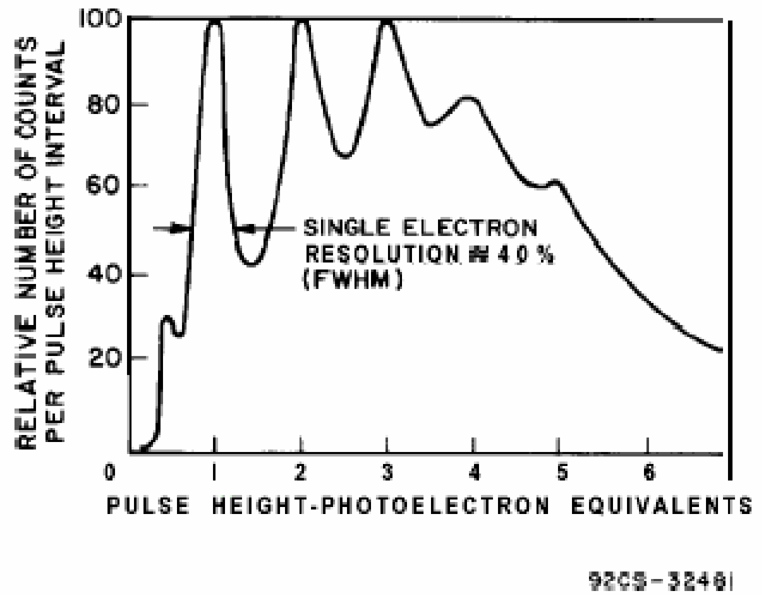


Fig. G-8 - Typical photoelectron pulse-height spectrum for a photomultiplier having a GaP first dynode.

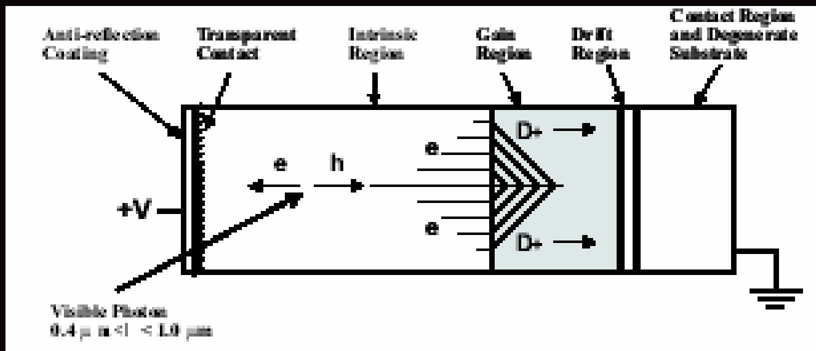
855 nm photons on a RCA-8852 from Photomultiplier Handbook, RCA, Lancaster, PA 1980, p168.

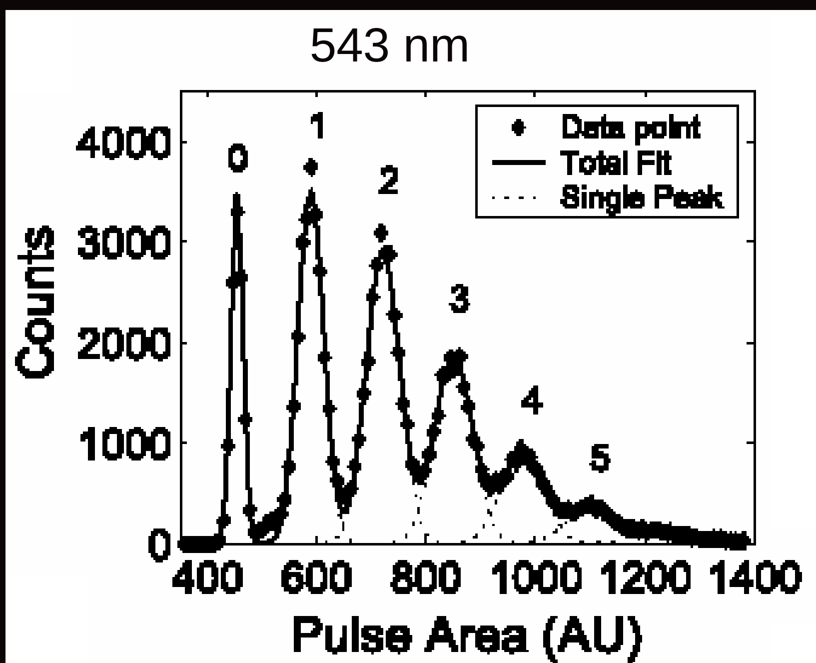
- Low Noise Amplification
- Single shot estimate of photon number is difficult

Examples of use to look at photon statistics of lights sources:

R. Charvin, *Opt. Acta,* vol. 28, 397(1981)
R. S. Bondurant, *Optics Letters*, vol. 7, 529(1982)

Visible Light Photon Counter



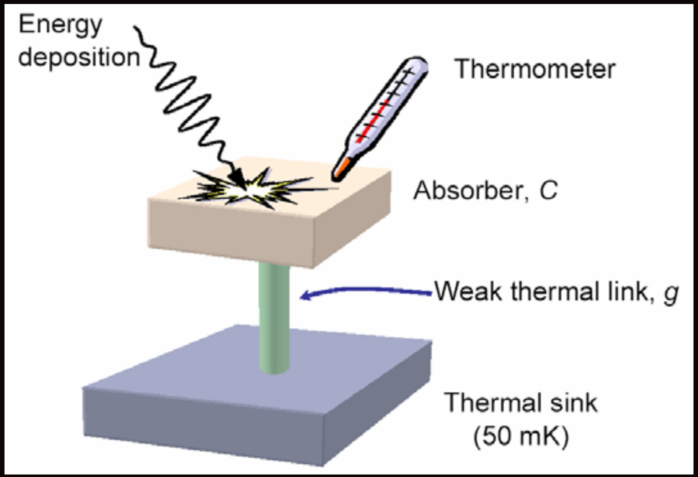


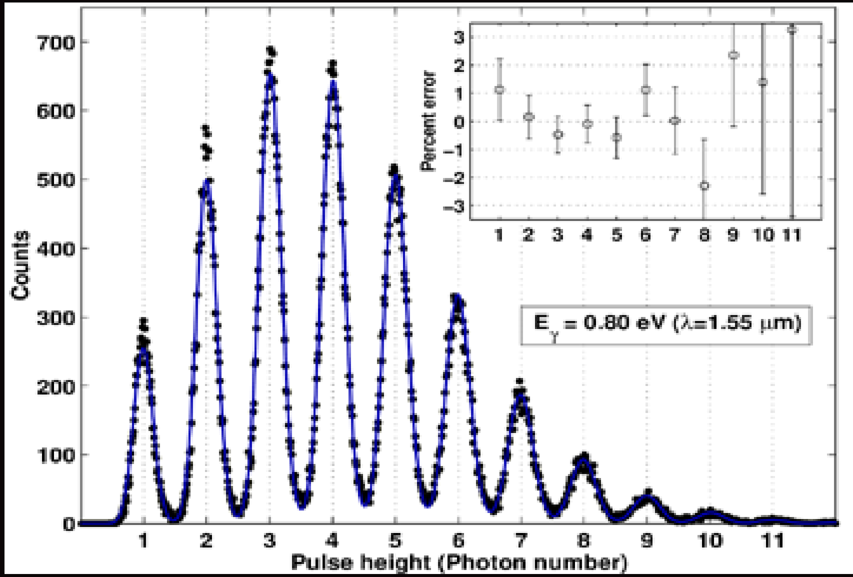
Wavelength	400-1000 nm
Q.E.	90%
Dark Count	30kHz
Count Rate	~1 MHz
Timing	<100 ps

Commercially available with a special fabrication run (Rockwell / DRS)

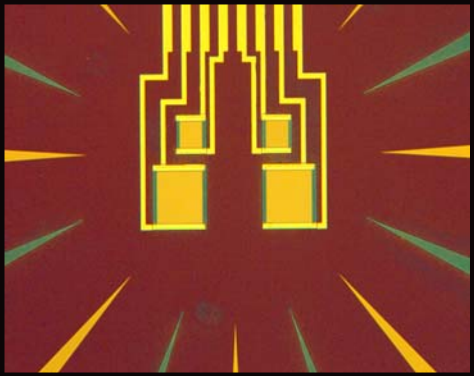
E. Waks, et al., quant-ph/0308054

Transition-edge Sensor





Wavelength	200-1700 nm
Q.E.	20%
Dark Count	0
Count Rate	10-50 kHz
Timing	~1 μsec



QE > 90% with a resonant cavity

Metrology problem

A.J. Miller, et al, APL, v. 83, 791-793 (2003)

ARDA

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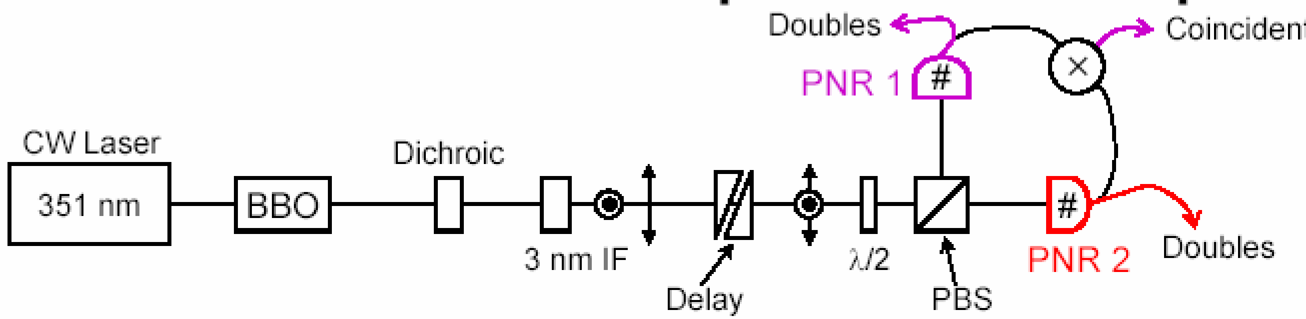
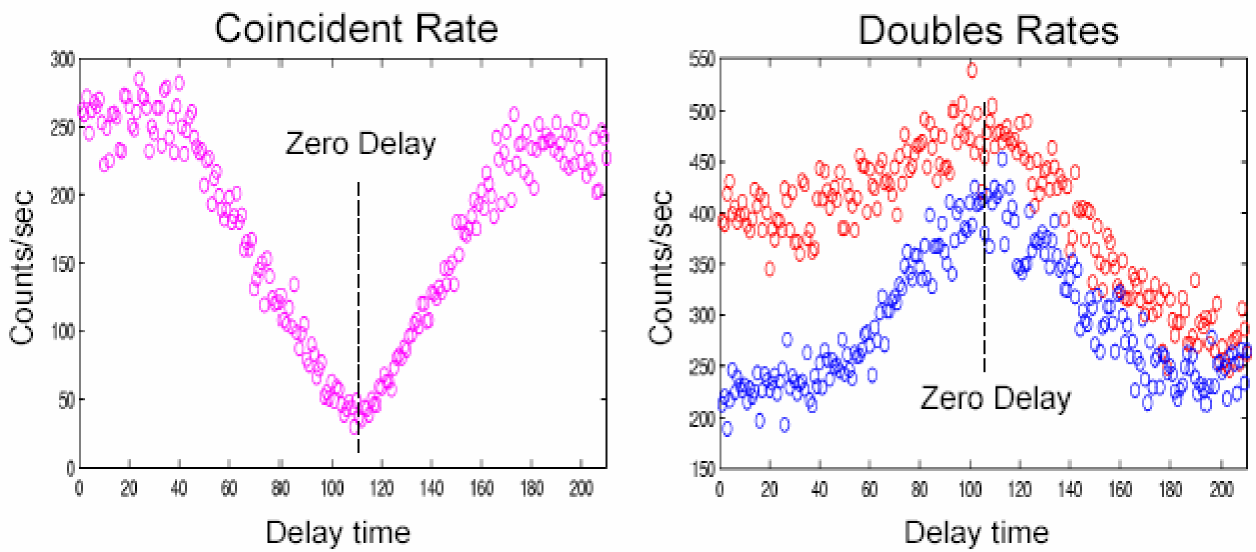
BU: Quantum Optical Setup





NIST

BOSTON UNIVERSITY

QuIST

Summary

- Toolbox for generation and detection of photons is not complete
- Good tools are available, lots of improvements are being developed
  - Very exciting work that is fast moving
- As our tools improve, better metrology is needed
- Expect impact in tests of quantum physics, quantum key distribution, LOQC