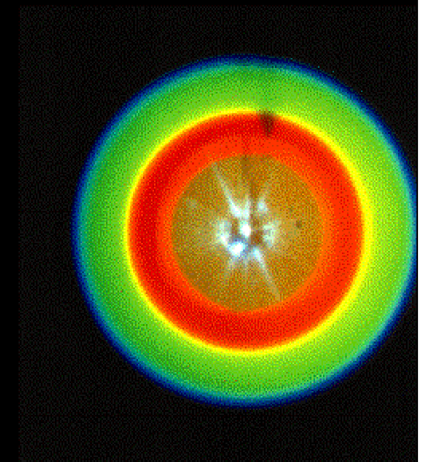
Single Photon Source with Individualized Single Photon Certifications

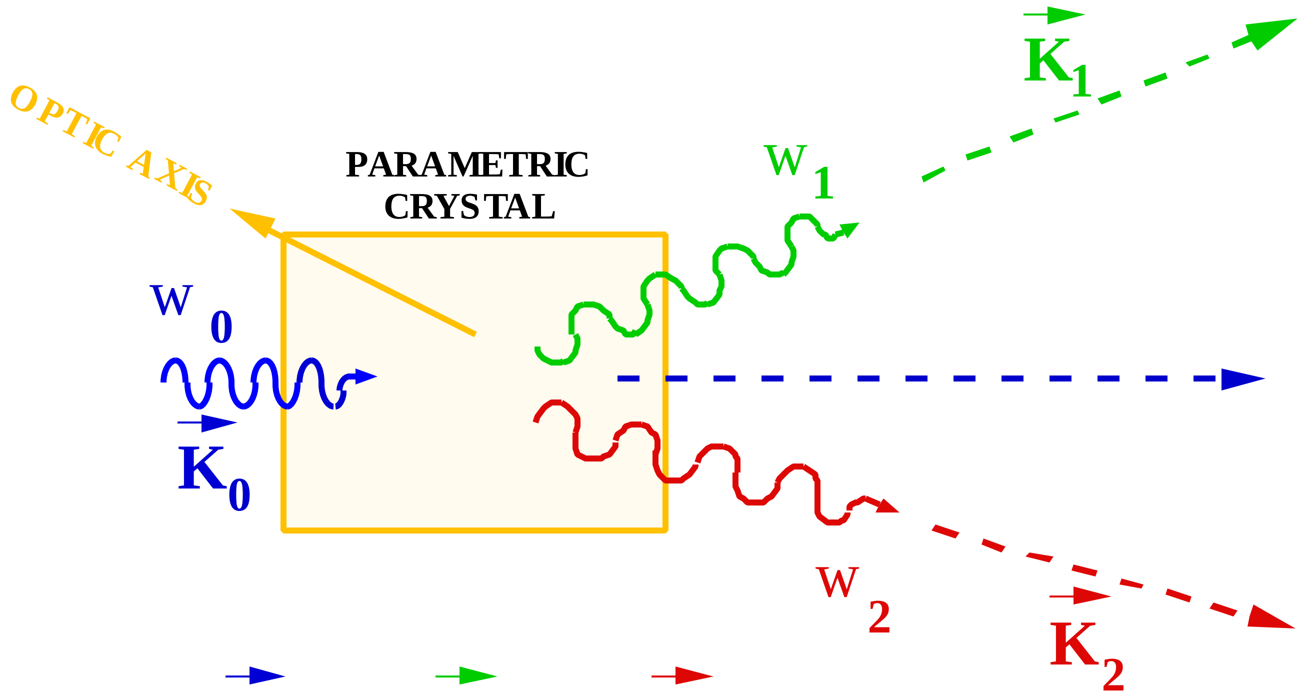


Alan Migdall

Stefania Castelletto, IEN Italy
Michael Ware

Optical Parametric Downconversion

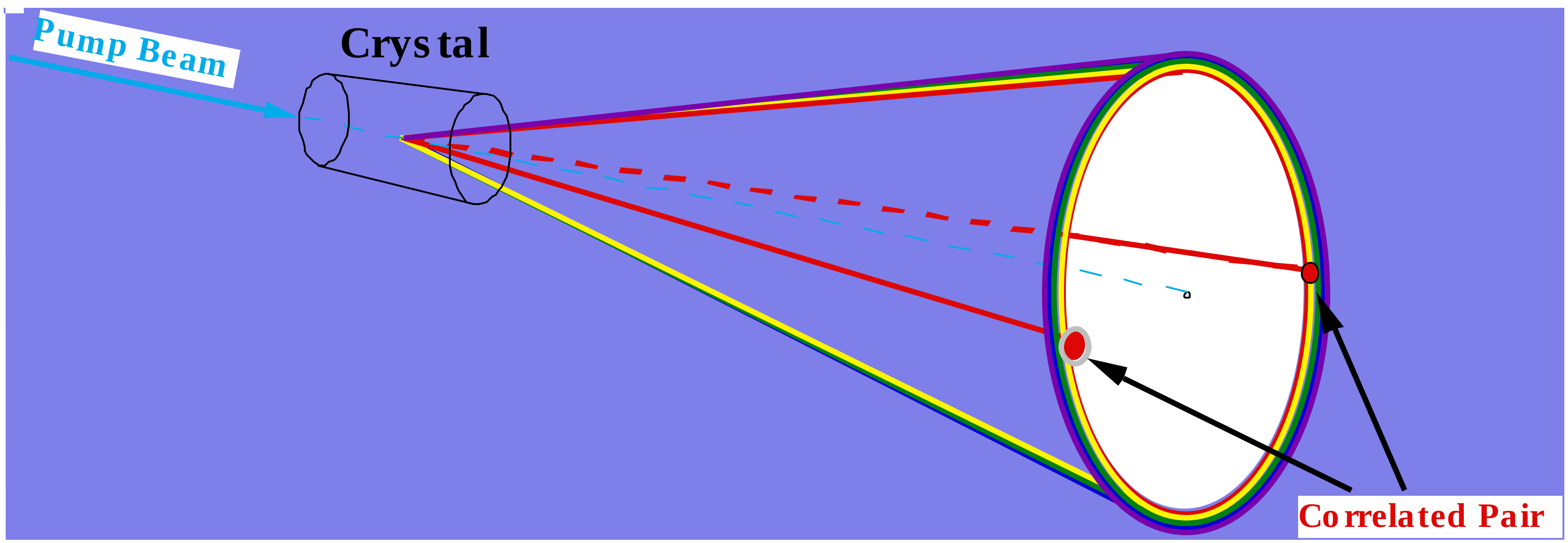
One in - two out

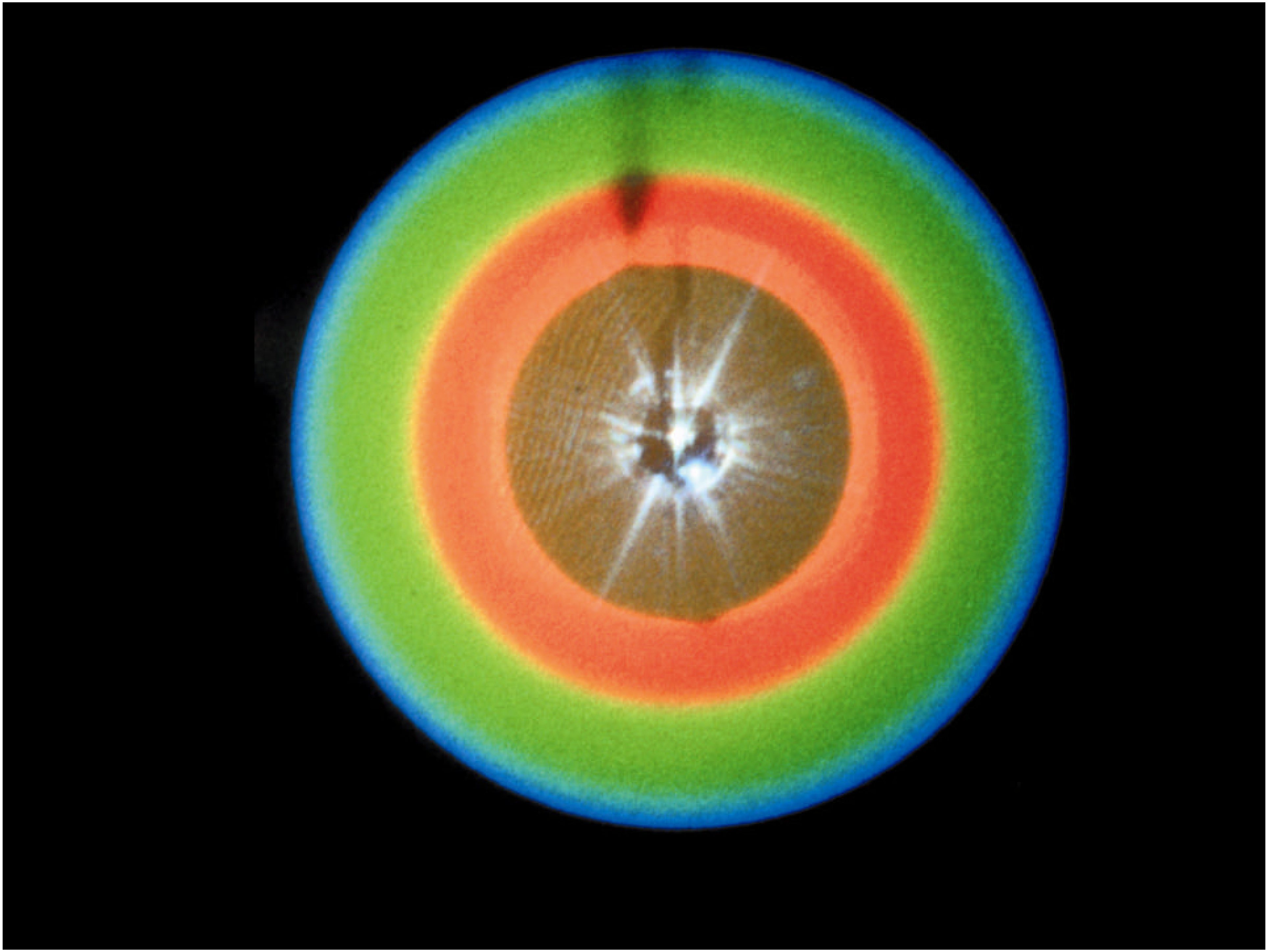


$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2$$

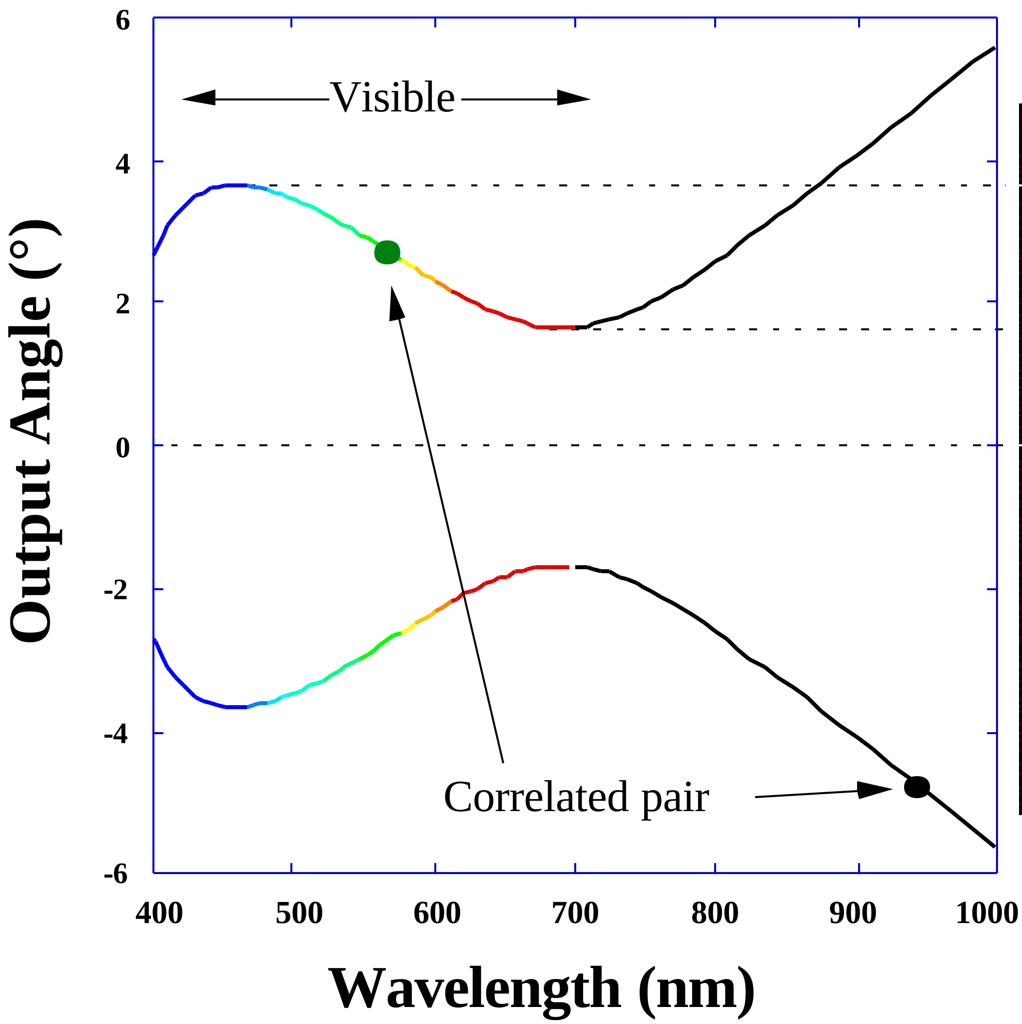
$$W_0 = W_1 + W_2$$

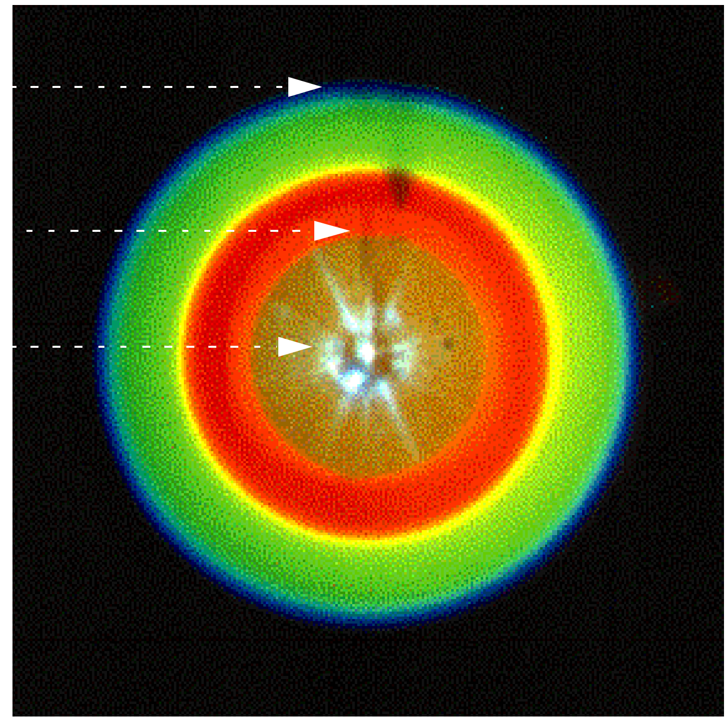
Optical Parametric Downconversion

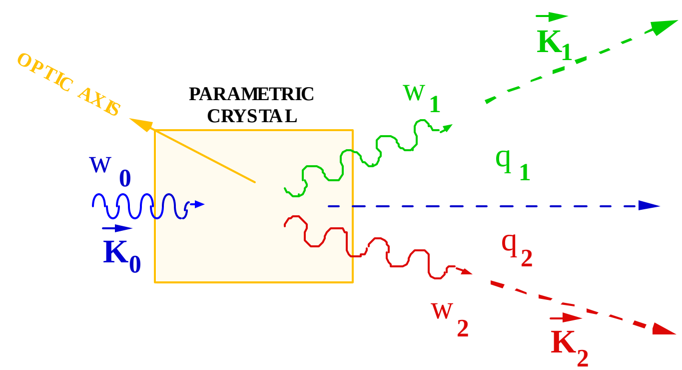




KDP (50.4°) pump wavelength 351 nm

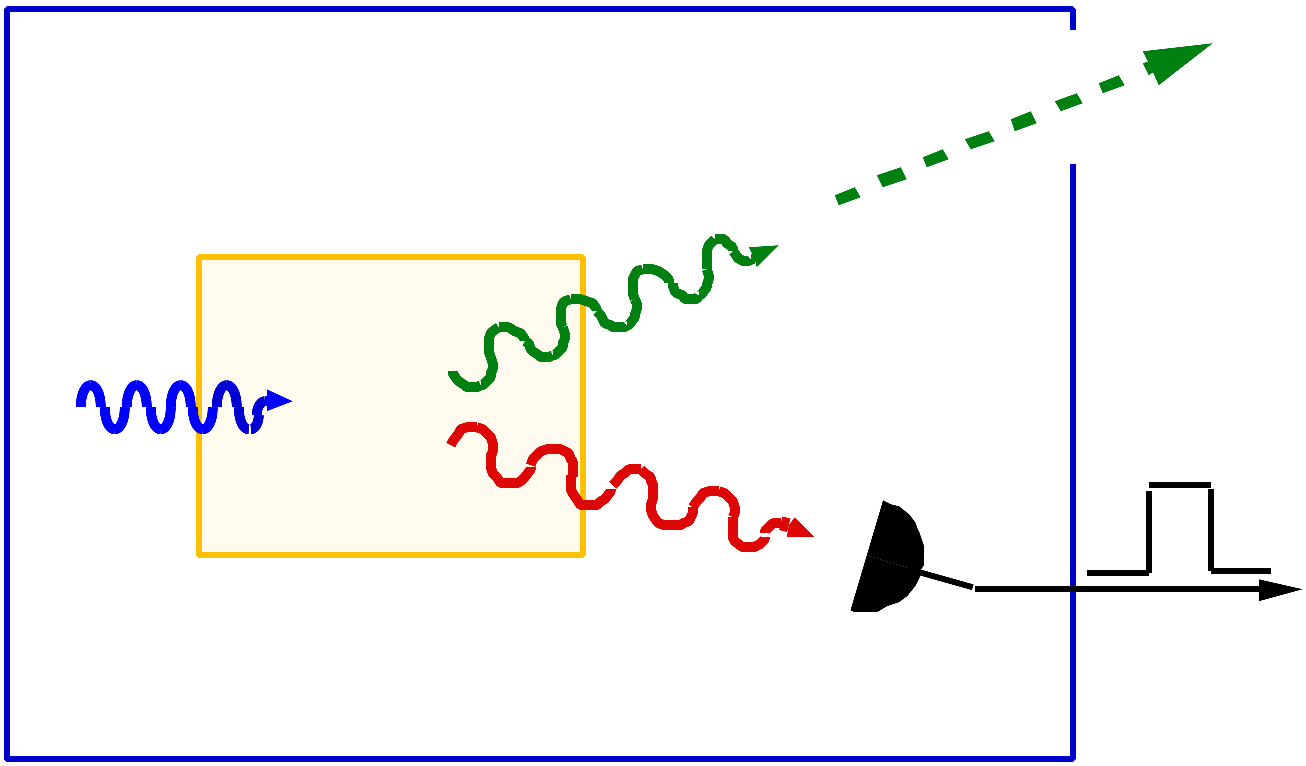






$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2 \qquad W_0 = W_1 + W_2$$

Absolute Light Source



Output characteristics :

photon #	**➔ known**
photon timing	**➔ known**
wavelength	**➔ known**
direction	**➔ known**
polarization	**➔ known**

Source of Single Photons *On-Demand*

Problem:

"Given a path of potential applications for quantum information processing, how can it be achieved in real physical systems?….

… a major difficulty has been producing *single photons on demand*; experimentalists have instead opted to use schemes which produce single photons 'every now and then', at random, and wait for such an event to occur. "

M. Nielsen & I. Chuang, "Quantum Computation and Quantum Information"

Not single photon

or

Not on-demand

Source of Single Photons *On-Demand*

Who needs single photons?

Quantum Information

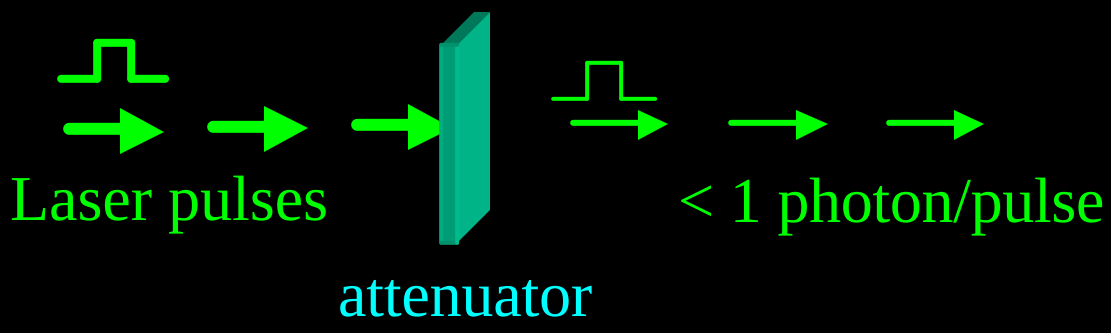
- Cryptography
  - unknown quantum state cannot be cloned
  - fundamental protection from surreptitious eavesdropping
- Computation
  - potential to crack current encryption schemes
  - ….

Arms race -->> you gotta do it

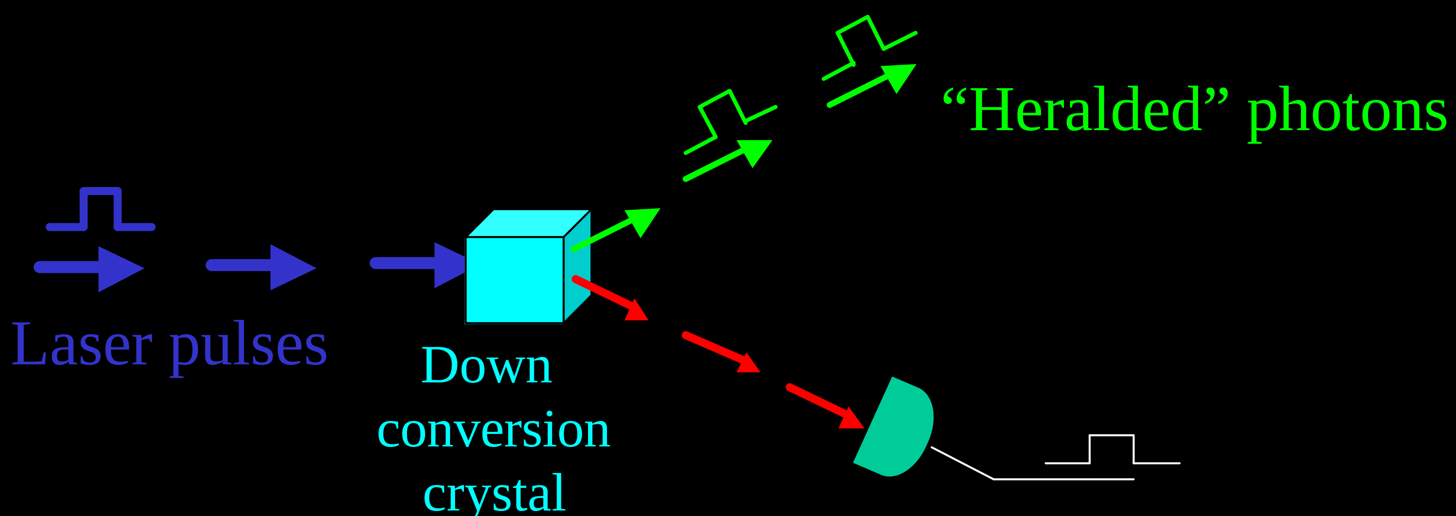
How do you make a source of single photons on demand?

Scheme	Trick
Faint laser Downconversion	pulsed pump + low photon rates
Quantum dots Single fluorescent molecule N vacancy in diamond	single quantum systems

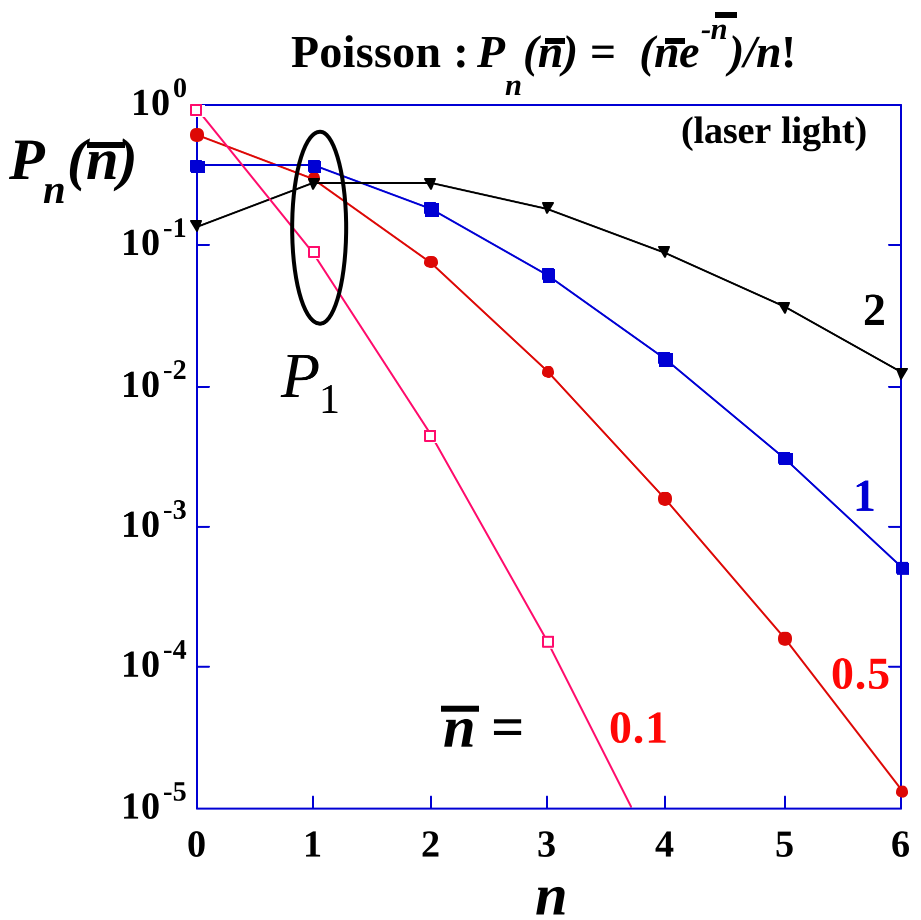
Faint laser source

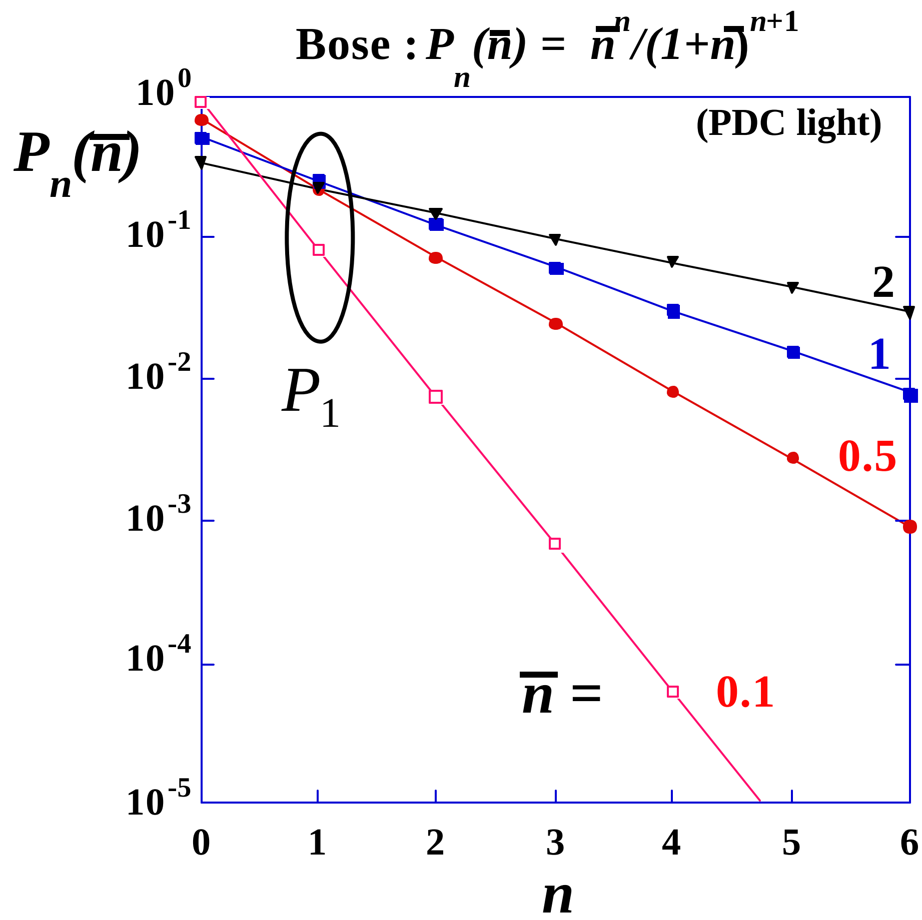


Parametric down conversion source



Problem of getting just one





$P_{>1} \sim P_1^2$

Prob of exactly 1 photon

Prob of more than 1 photon

So you can have either

"photons" but not "single photons"

or

"single photons" but mostly "no photons"

Not single photon

or

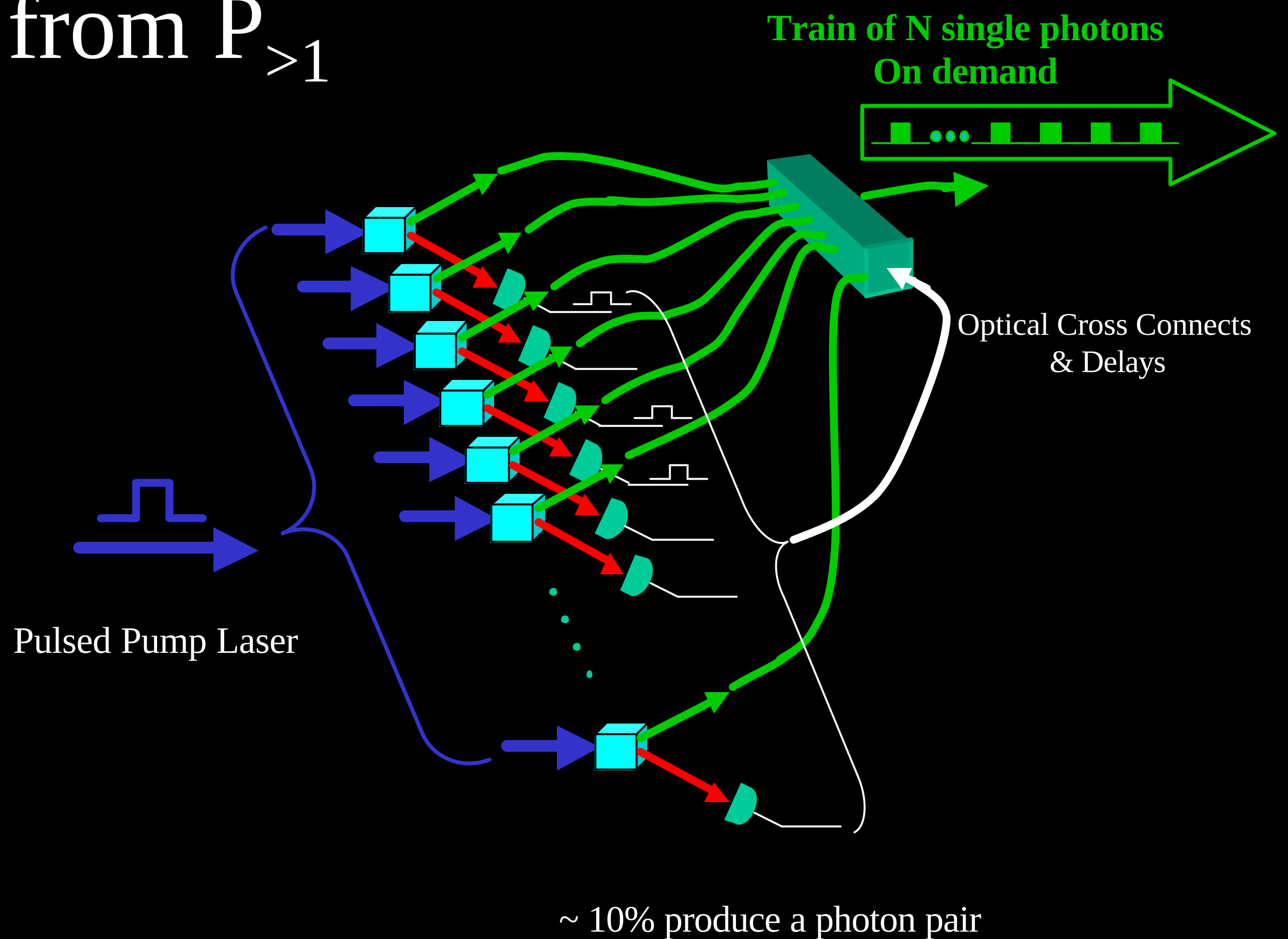
Not on-demand

Solution:

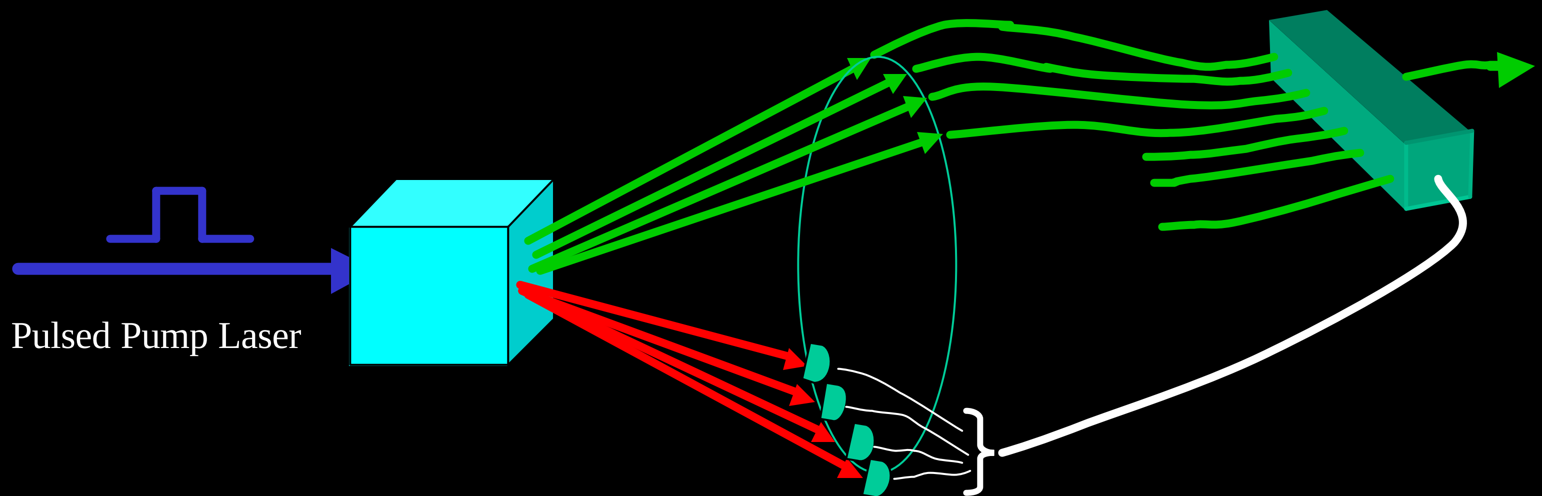
Multiplexed PDC

Separates

P_1 from $P_{>1}$



Simplification #1 - azimuthal PDC symmetry allows single PDC crystal + many azimuthal planes -->> virtual PDC array.

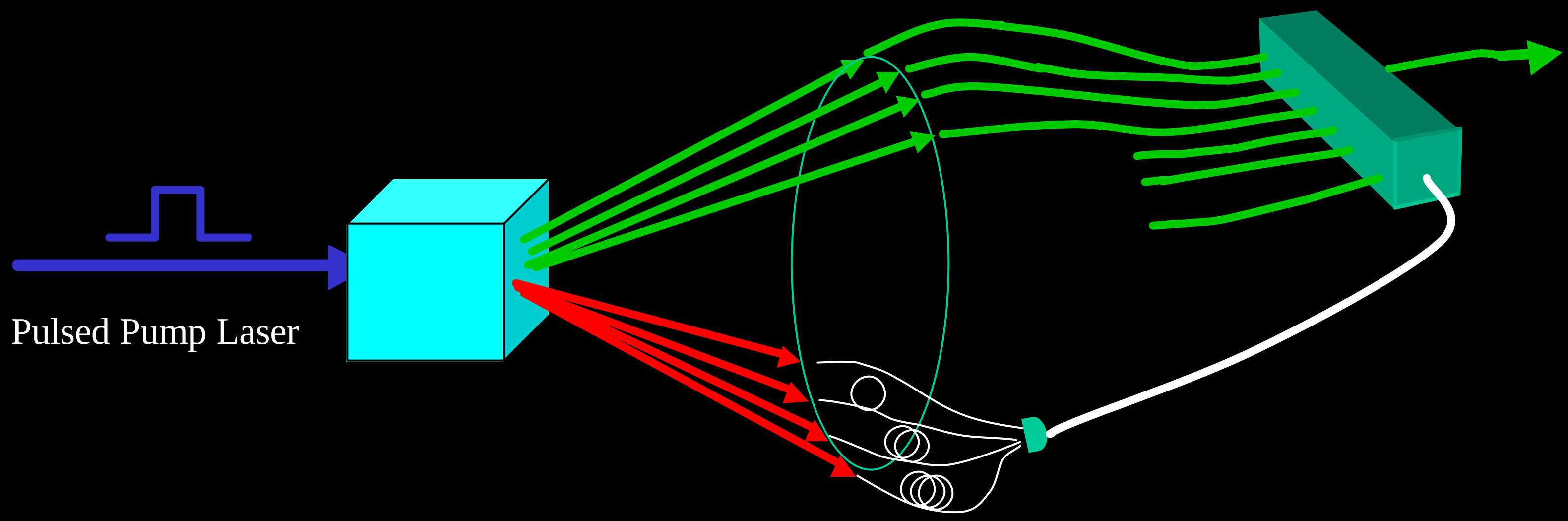


Simplification #2 -

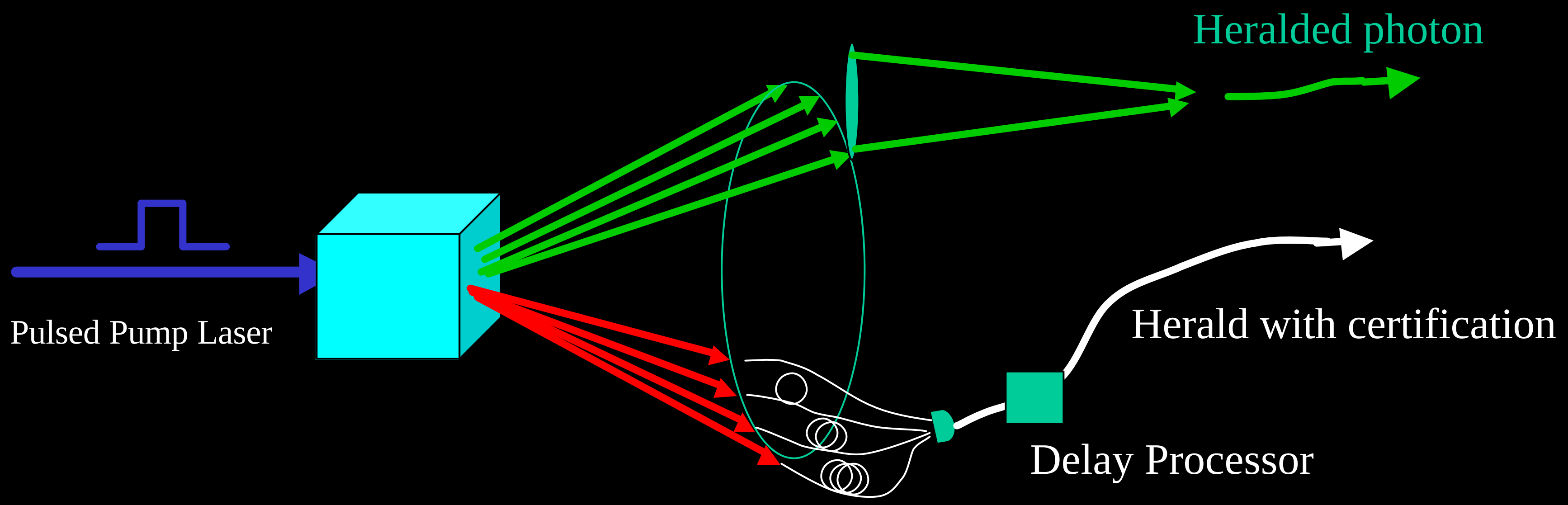
bundled trigger paths with staggered delays + single detector

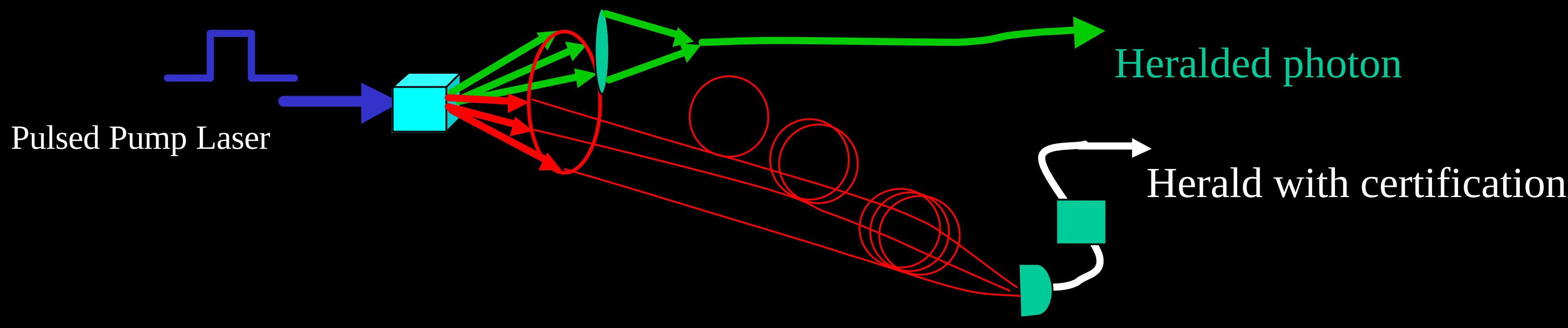
timing gives which path info.

-->> virtual detector array.



Simplification #3 - optical switching circuit eliminated single output collector -->> virtual detector array.





What does this arrangement buy?

Heralded Photons with *Single Photon Certification*

Each photon comes with probability of more than one photon

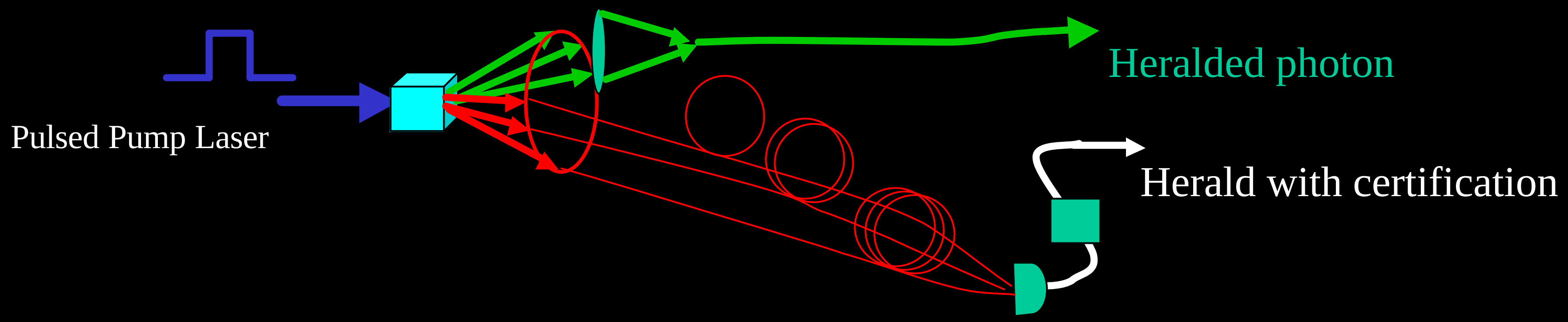
$P_{n>1}$ can vary, but it is known

and it is likely to be lower than $P_{n>1}$ for standard setup

vs.

Standard downconversion setup produces photons

with $P_{n>1}$ fixed by $P_{n=1}$



How does this work?

For 2 delay channels & detector with deadtime

Case I: delay 1 fires, delay 2 no information

Case II: delay 1 does not fire, delay 2 fires

Case I: $P_{n>1}$ certification ~ conventional setup result

Case II: $P_{n>1}$ certification *better* than conventional setup result

as number of delay channels increase improvement increases

Additional information yields tighter limit on $P_{n>1}$ certification

Simple Implementation -

- one PDC crystal
- one trigger detector
- several delay paths
- no fast switch circuit

Advantages -

- simplicity
- single photon output pulses with
  - individualized single photon “certifications”
- some pulses with very good certifications
  - (and <u>known</u> to be very good)
- broken the usual dependence of P_1 and $P_{>1}$

Analysis

Trigger - each delay is a single mode (Bose statistics for PDC)
Output - a few modes (all modes correlated to trigger paths)
Trigger detector can only fire once per pump pulse
  due to dead time
Trigger detector quantum efficiency <1
  reduces knowledge of what happened

How does it work?
  i^{th} delay causes trigger to fire
    we know previous delays did not cause trigger
    we know nothing about subsequent delays
More information about trigger ->>
  more information about single photon likelihood

Given that a detector fired
the probability that *n* photons were incident

P of not *not* firing
If *n* photons incident

probability of
n photons incident

$$P^{\mathrm{F}}_{\overline{n},\eta}(n) = \frac{\left(1-(1-\eta)^n\right) \times P_{\overline{n}}(n)}{\sum_{k=1}^{\infty}\left(1-(1-\eta)^k\right) \times P_{\overline{n}}(k)}$$

For system of N_{D} delay paths &
the i^{th} delay caused trigger to fire
What is the probability that only a single photon was incident?

mean rate/delay chan

$$P_{\overline{n},\eta,N_{\mathrm{D}}}(i) = \left(1 - P^{\overline{\mathrm{F}}}_{\frac{\overline{n}}{N_{\mathrm{D}}},\eta}\right)^{i-1} P^{\mathrm{F}}_{\frac{\overline{n}}{N_{\mathrm{D}}},\eta}(1) \left(P_{\frac{\overline{n}}{N_{\mathrm{D}}}}(0)\right)^{N_{\mathrm{D}}-i}$$

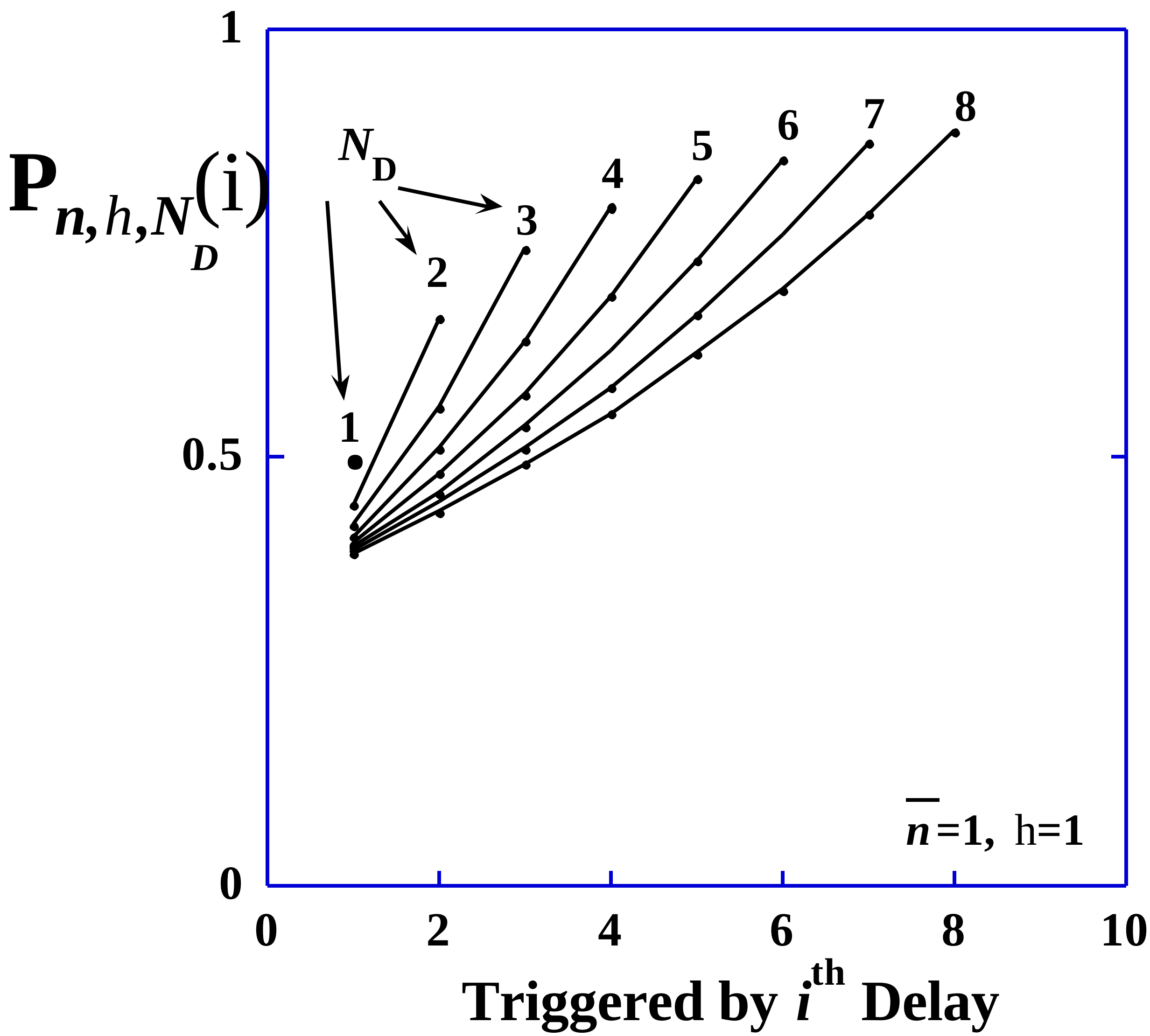
P of previous delays
not causing a firing
due to no photons incident

P of >0 photons incident
given no firing

P of i^{th} delay
having one photon

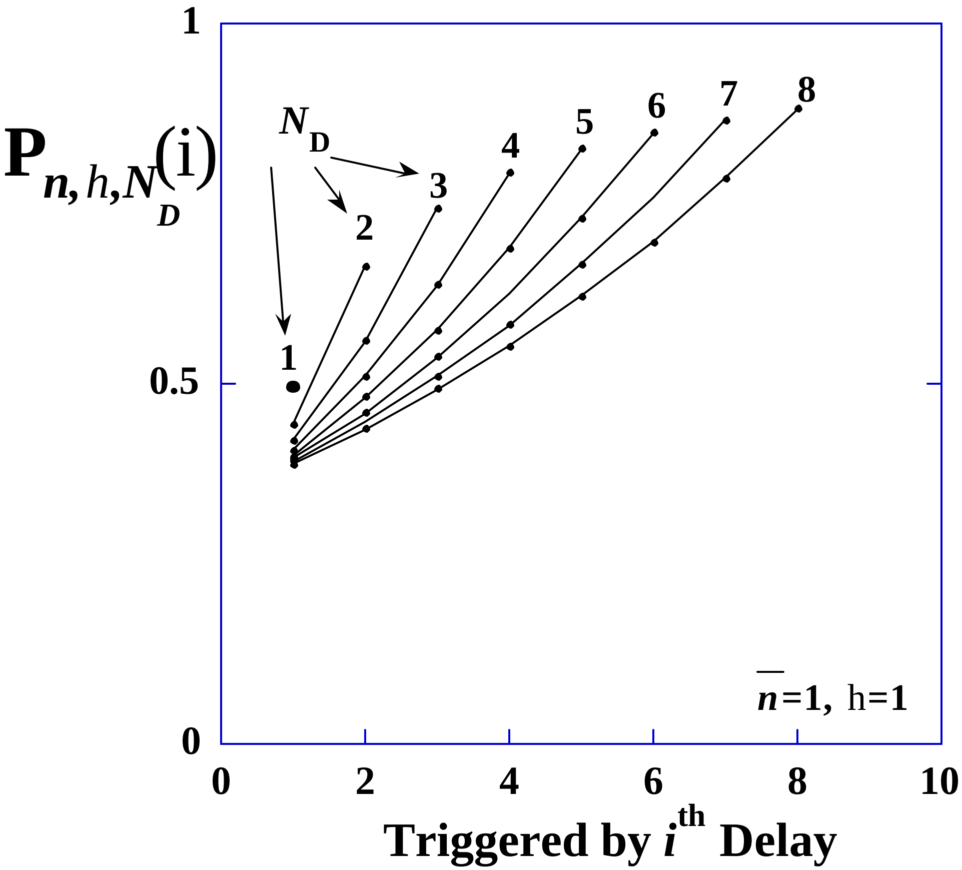
P of subsequent delays
not having any photons

Single photon "certifications" for systems of N_D delays given that the i^{th} delay caused the trigger to fire

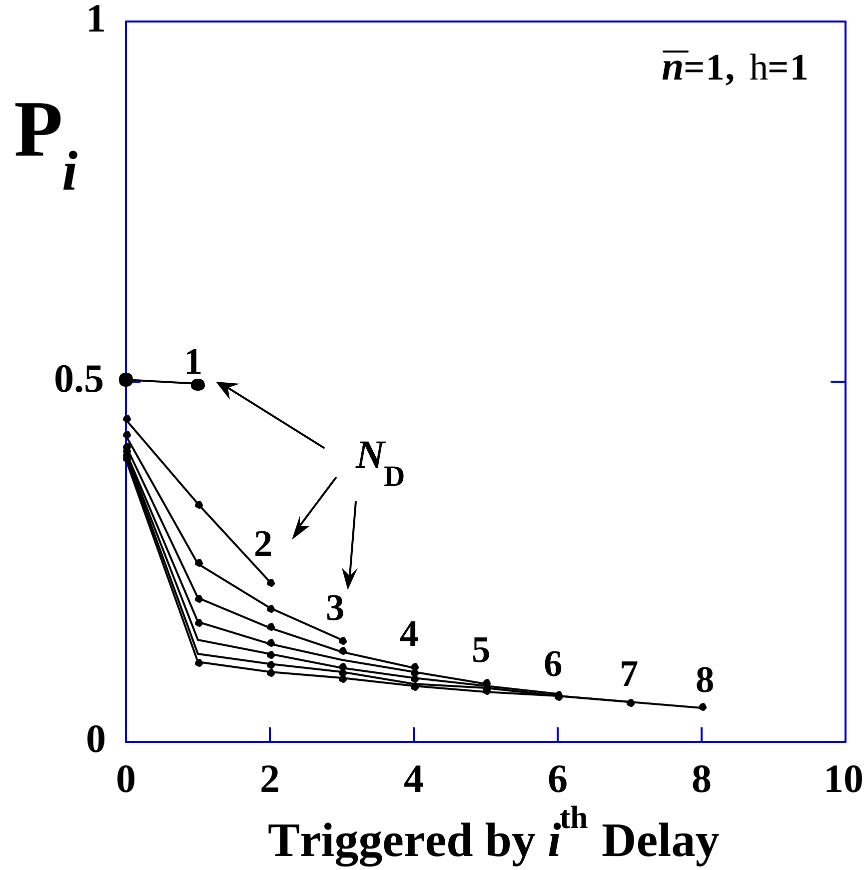


How often do you get good ones?

Prob of single photon "certification"



Prob of event occurrence



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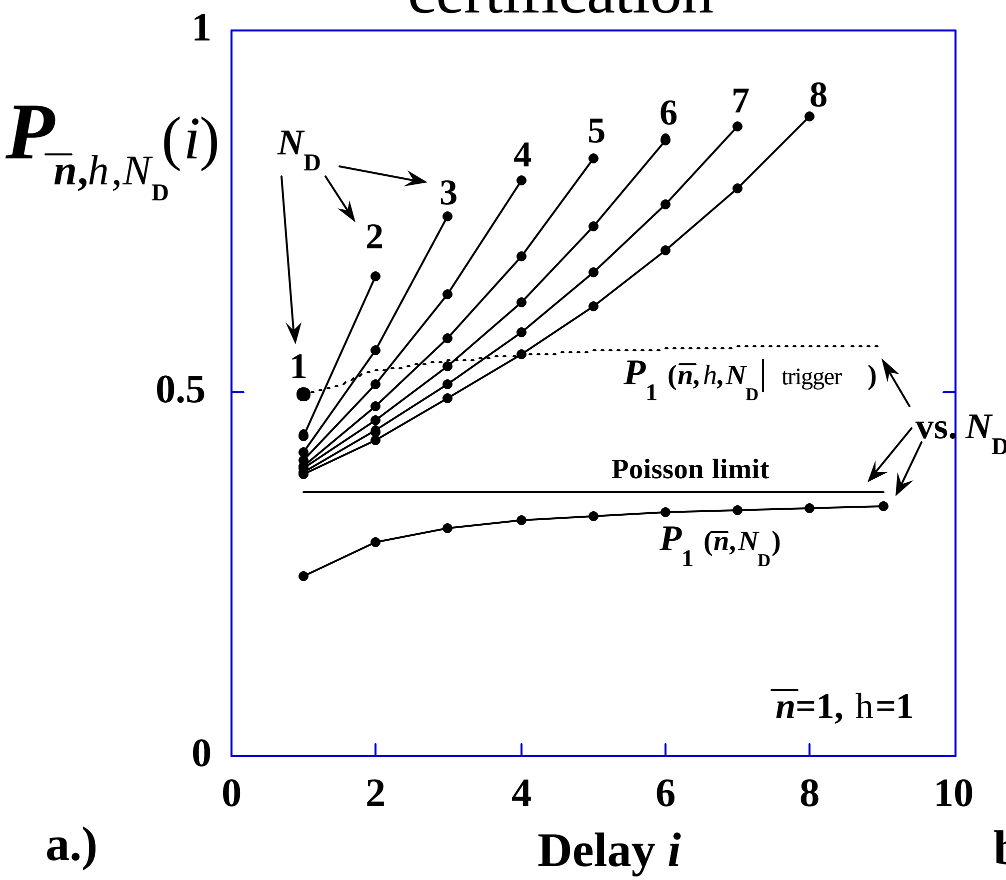
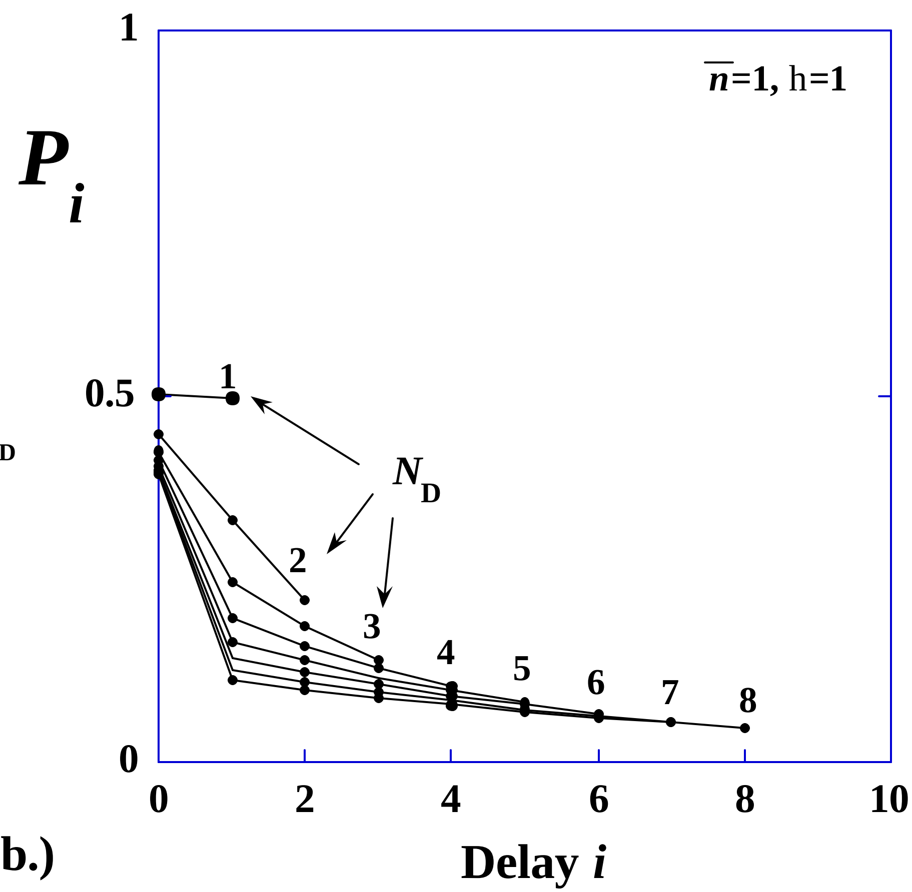


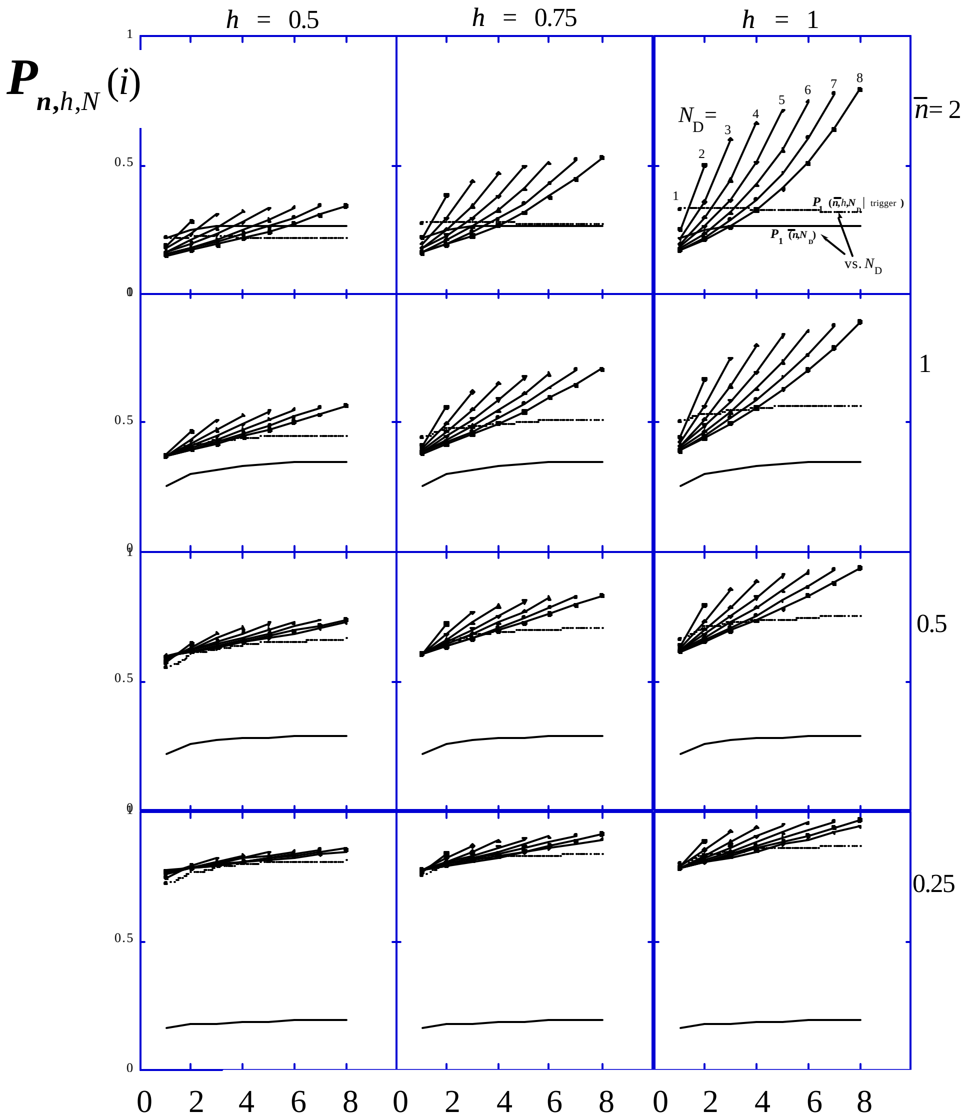
a.)

Prob of event occurrence



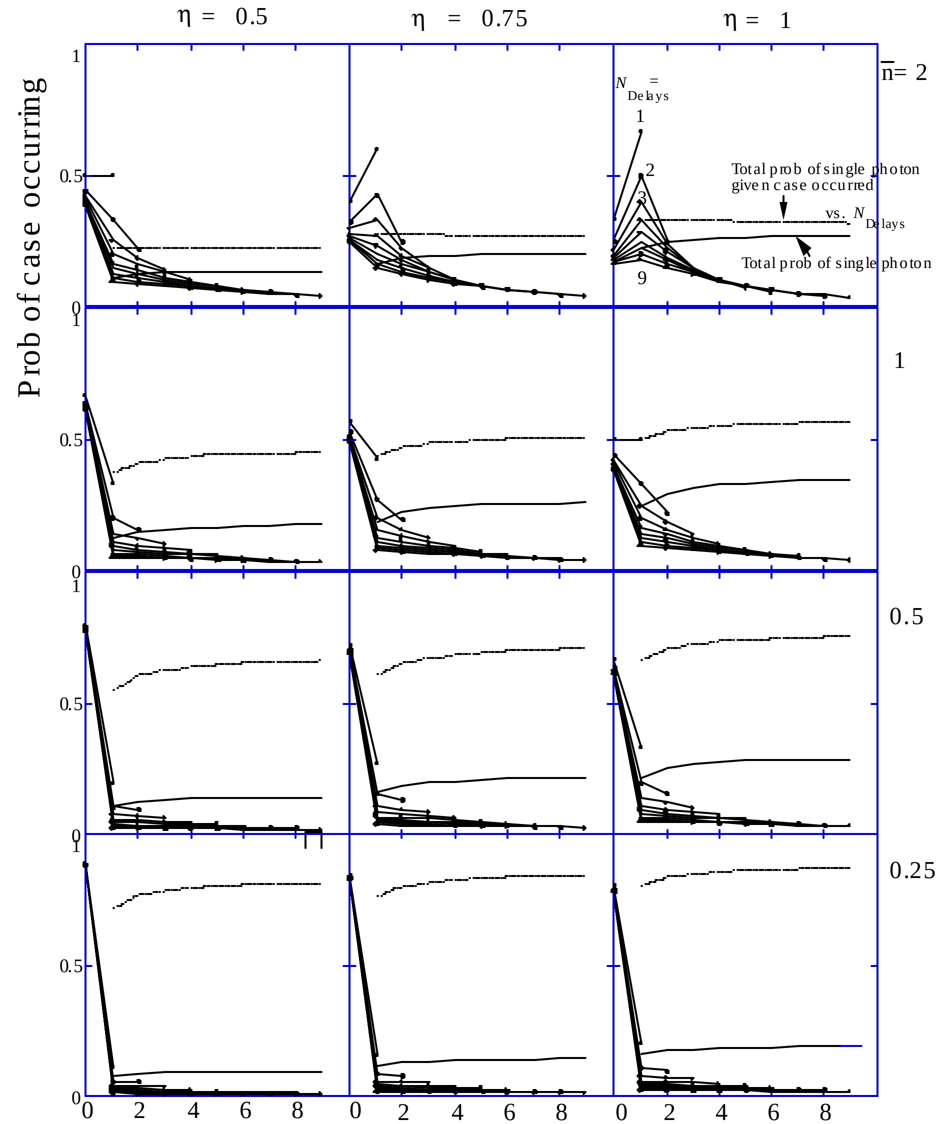
b.)

Single Photon “Certifications”



Triggered by the i^{th} Delay

Probabilities of Occurrence



Triggered by the i^{th} Delay

Single Photon Sources

Maximum single photon fractions possible

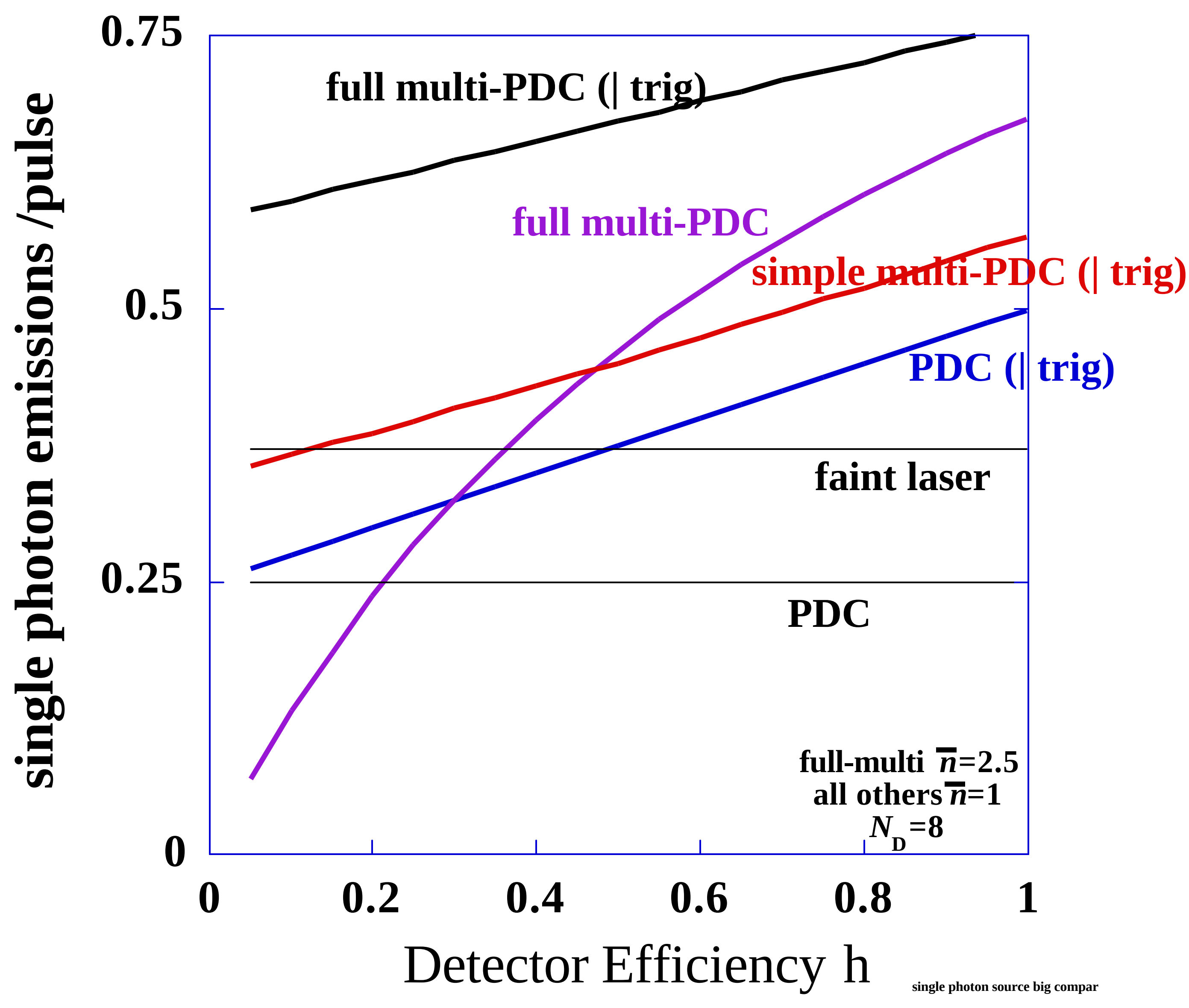
Faint Laser (Poisson) - 37%

Single PDC (Bose) - 25% overall
- 50% using herald information (for η=1)

Multiplexed PDC - 57% in simplest version (for η=1)
- 90+% full switched version (for η=1)

advantage - allows higher $\bar{n}$

Comparison of Single Photon Probabilities For Different "Single Photon Sources"



Status -

Pump source operational- (0.2 ns, 82 MHz Ar^{+})

Heralded photons observed

Timing resolution measured

Discrete component single photon source
with multi-delay channel array
-designed and under construction
-fast switching need pushed back

New simplified SPOD analyzed
-Paper submitted

Multi-delay line built

Next -

Tests of collection efficiency

Testing multi-delay line setup