Single-Photon Detector & Metrology Efforts at NIST

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photon.jqi.umd.edu/spw2009

Keck Institute, CalTech, Pasedena, CA
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Single-Photon Detector Efforts

- Detectors
  - Deadtime reduction by
    - space multiplexing
    - avalanche photodiode- advanced electronics
    - smart processing
- Metrology
  - Correlated Photon Method
  - Transfer Standard Method
  - High-gain low-noise transfer standard to disseminate calibrations
  - Bridging the gap between cryogenic radiometry & photon counting
- Coincidence counting
  - Simple FPGA-based multi-coincidence analyzer

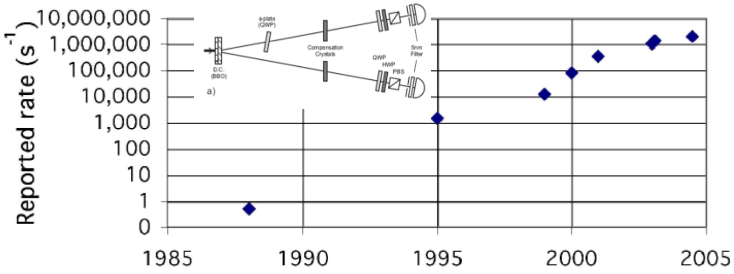
Detectors: The problem

(good news & bad news)

- Single photon & entangled photon sources are getting brighter

  ~5 MHz

History of Entangled Photon Pair Production



Kwiat, et al QCMC 2004

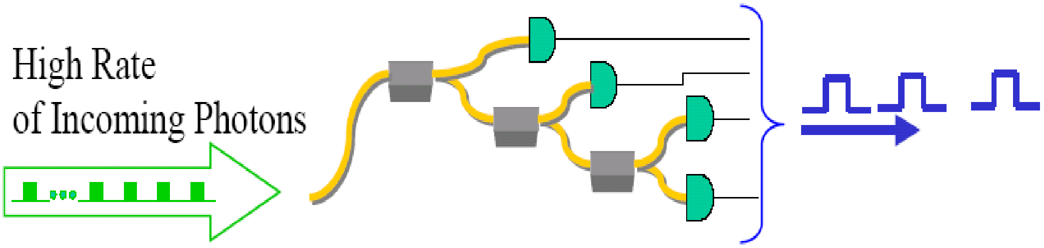
- Detector count rates are limited
  - absolute max rates ~5-15 MHz
  - practical max rates ~1 MHz
    - Deadtime ~50 ns(vis) 10 μs(NIR)
    - Afterpulsing ~1 – 10^{-3}

Overloading the system

Ways to reduce effective deadtime:

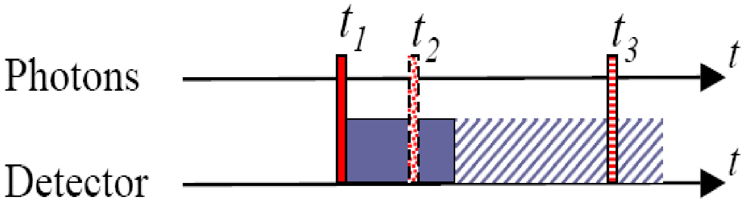
Detector Tree:

a detection apparatus based on a set of detectors used in “tree” configuration



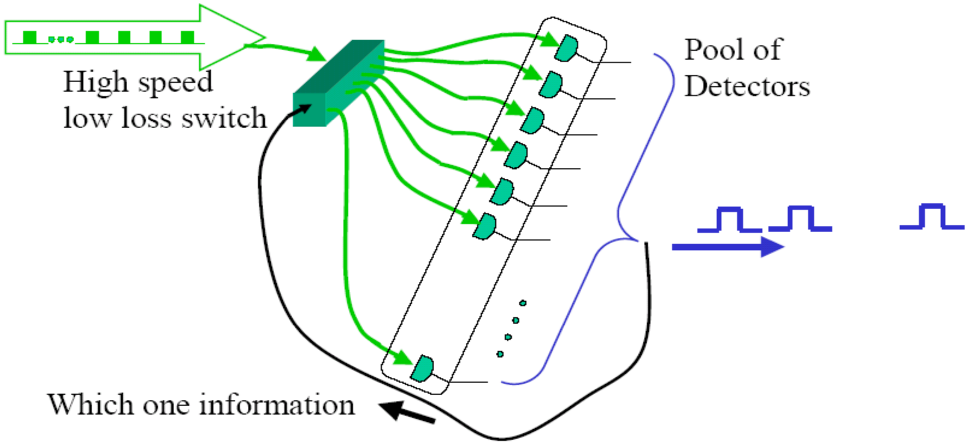
Improved Single Detector with Reduced Deadtime:

technological efforts to reduce the deadtime of the single detector

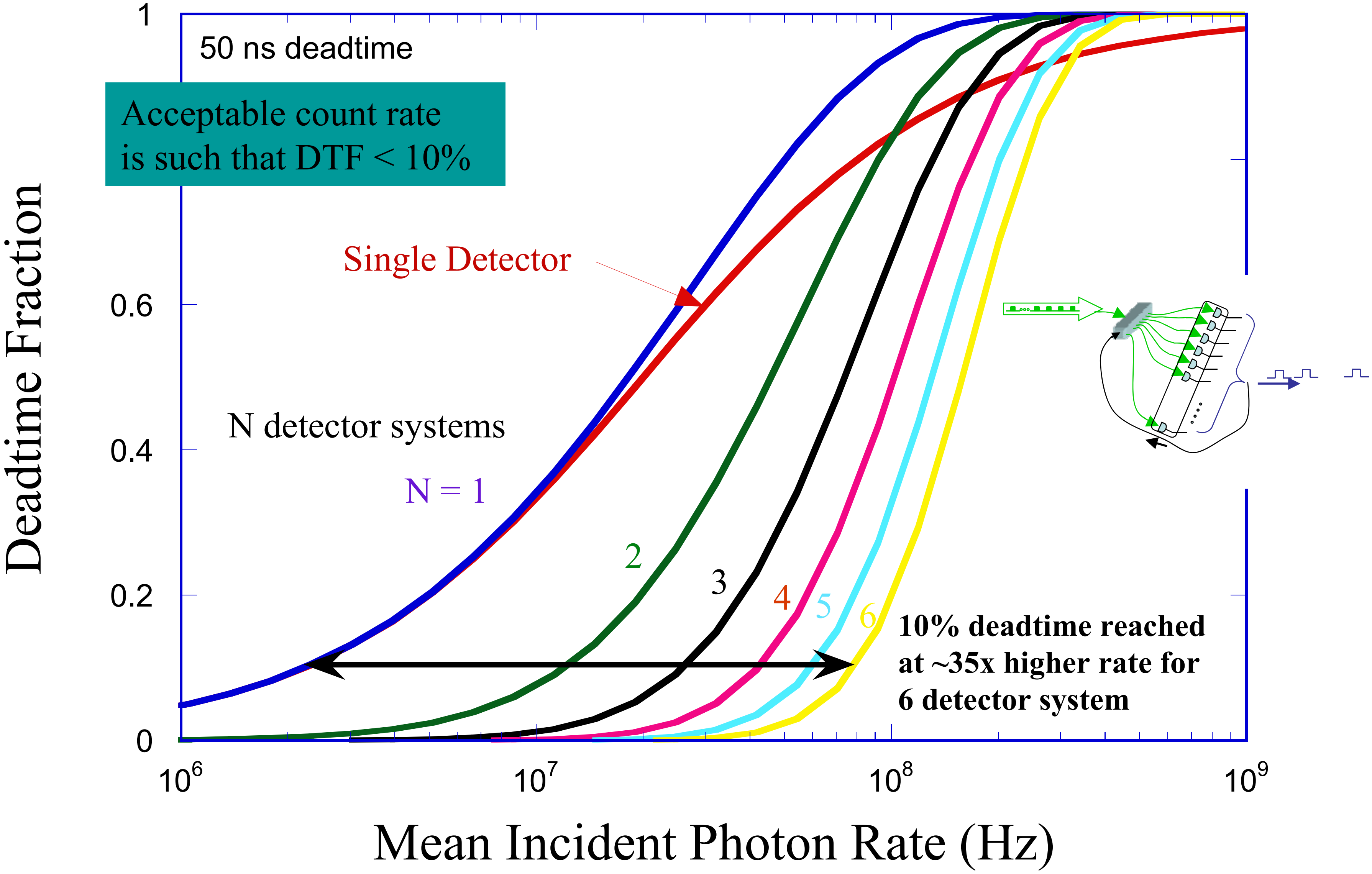


Multiplexed Detector Array:

a detection apparatus based on an active optical switch and an array of detectors



Deadtime Model of Multiplexed Detector Array



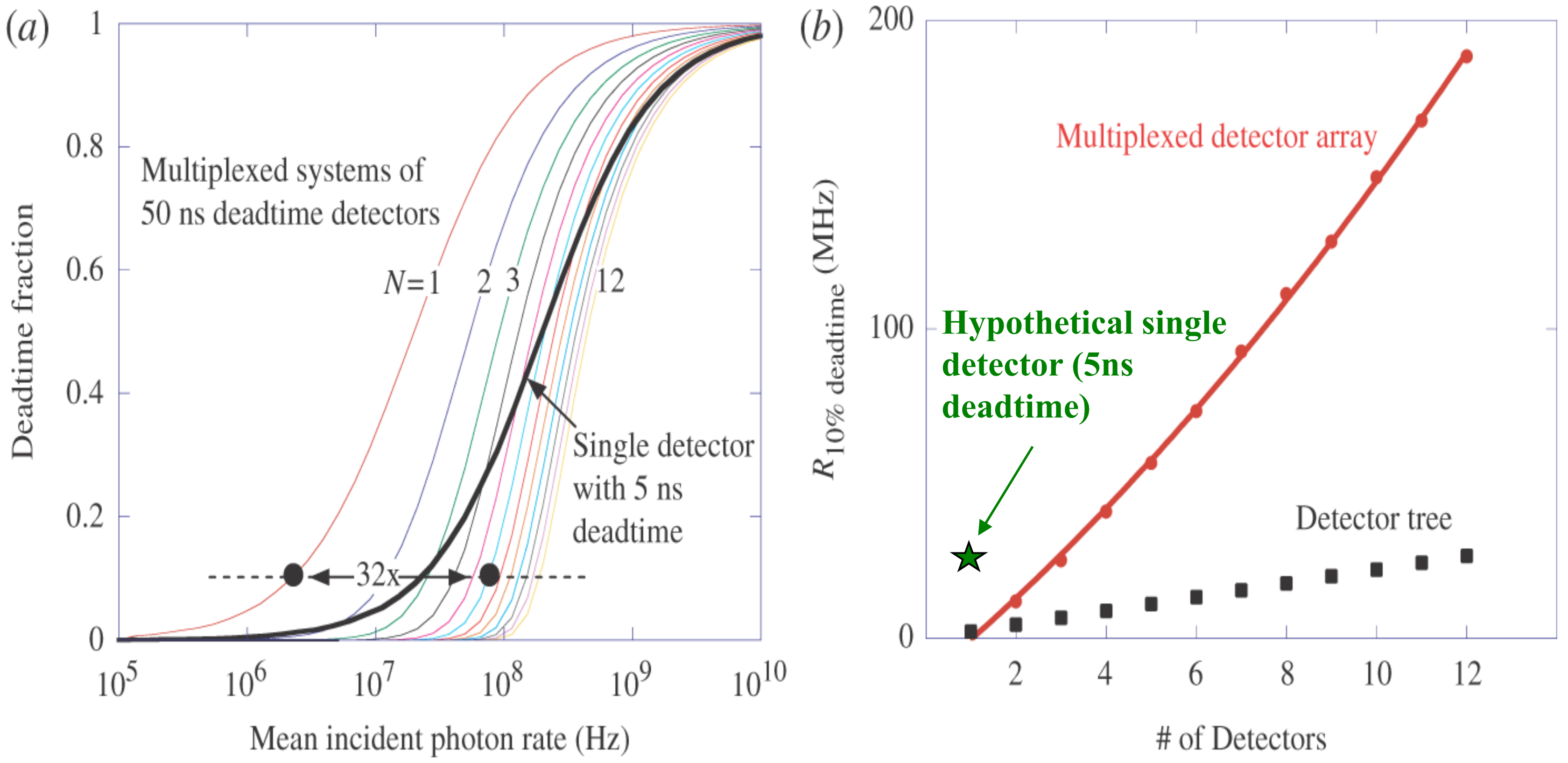
Acceptable count rate
is such that DTF < 10%

**10% deadtime reached
at ~35x higher rate for
6 detector system**

zero switch transition time

DTF and detection count rates

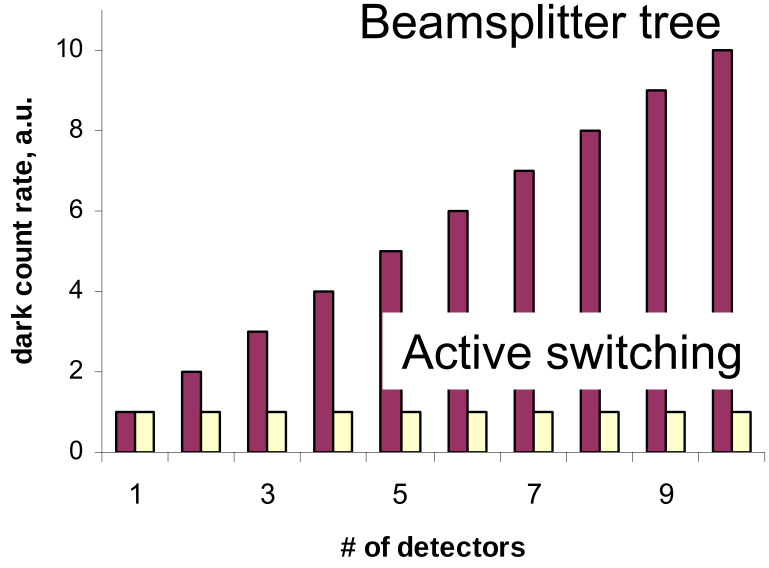
- In most cases an acceptable count rate is such that DTF < 10%



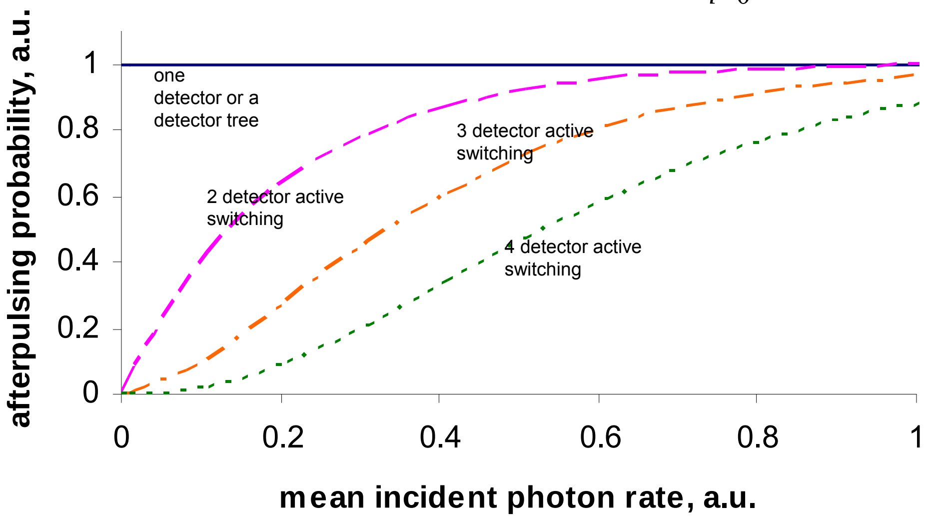
zero switch transition time

Benefits Beyond Deadtime:

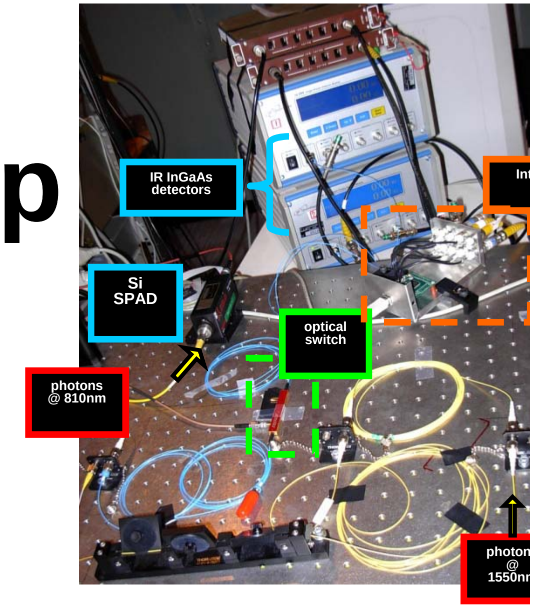
dark counts & afterpulsing

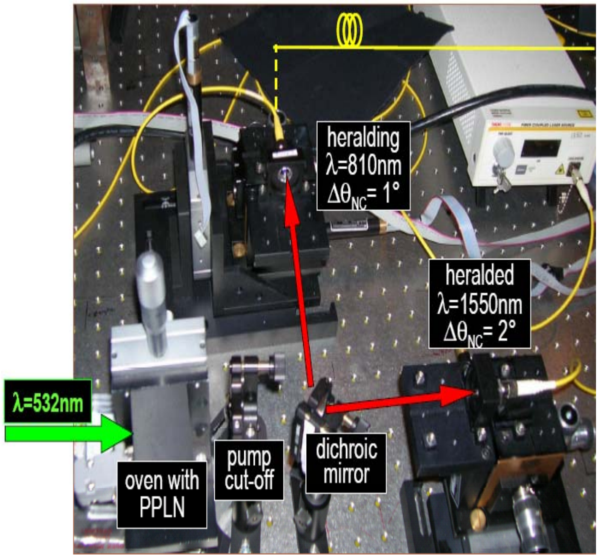


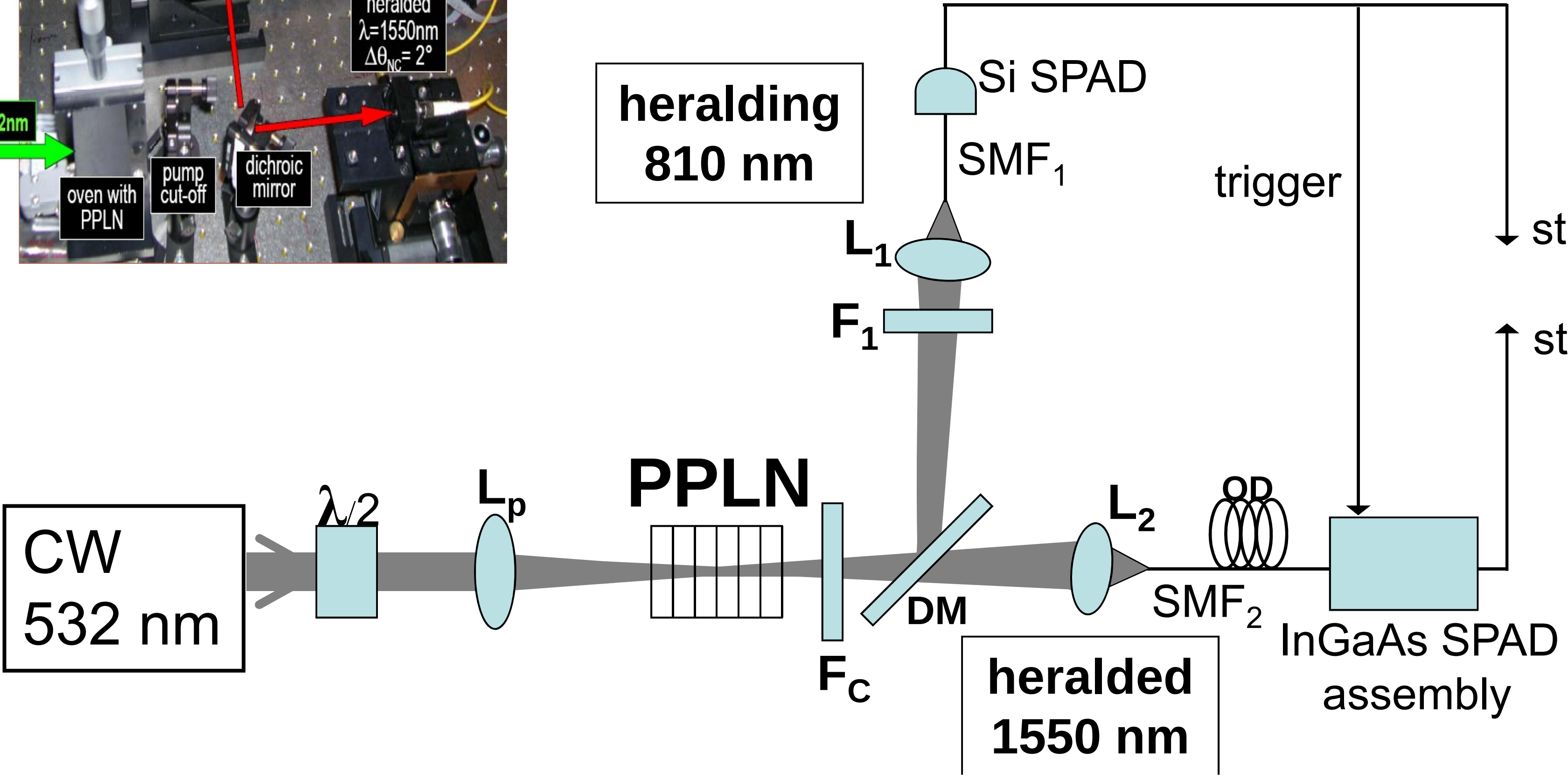
$$P(n \ge N-1) = 1 - \exp(-\lambda T_\mathrm{d}) \sum_{i=0}^{N-2} (\lambda T)^i / i!$$



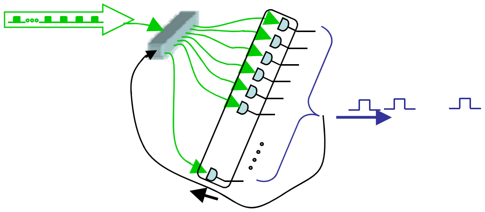
Experimental setup







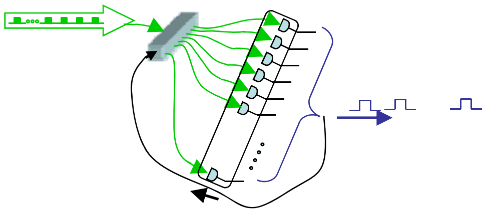
Realism



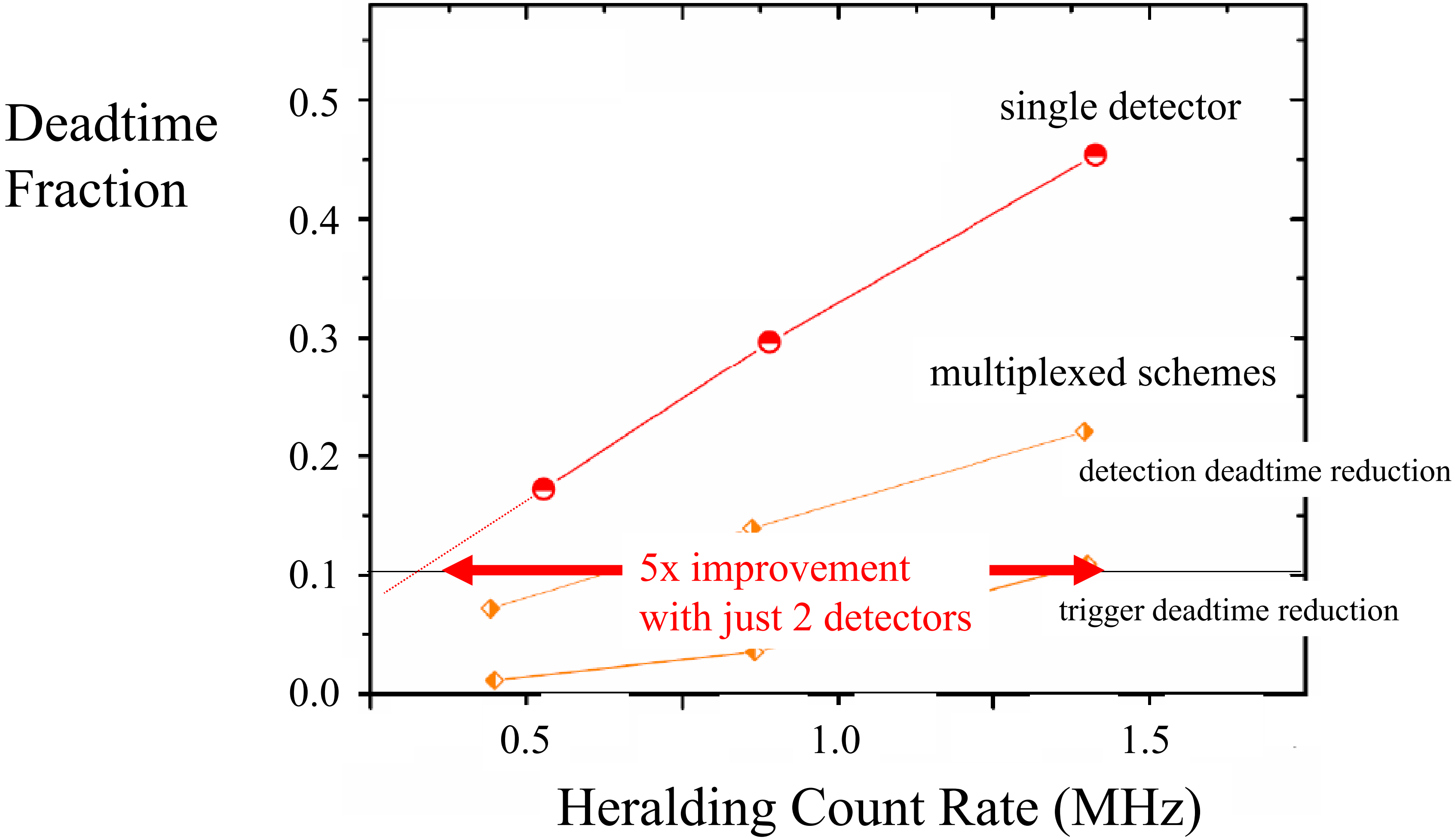
- Switch transition time $\neq 0$ includes:
  - Switch latency time
  - Switch propagation time
  - $T_{\text{switch}} \sim 100$ ns is practical for $T_{\text{dead}} \sim 1\ \mu\text{s}$

- Gate deadtime,
  - deadtime $\neq 0$ for no detection
  - $T_{\text{gate}} \sim 200$ ns in our setup

Latest Result



Trigger Electronics Deadtime:
deadtime when it does not fire



5x improvement
with just 2 detectors

Scalable multiplexed detector system for high-rate telecom-band single-photon detection Rev. Sci. Instr. **80**, 116103 (2009)

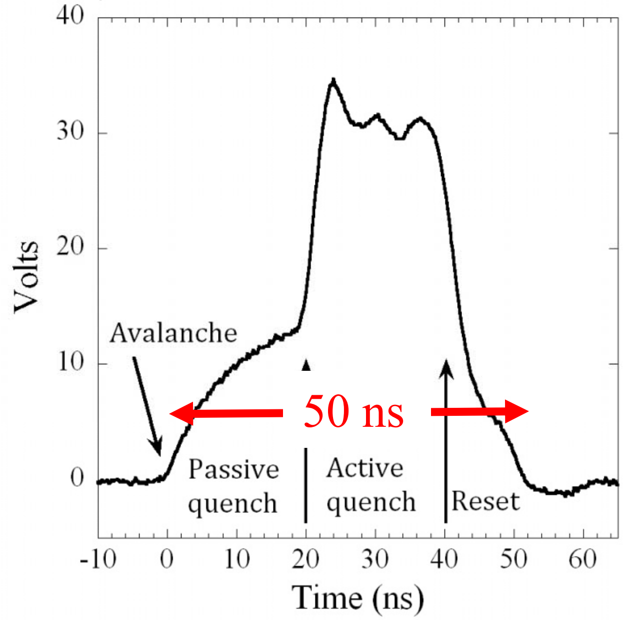
APD- Advanced Electronics

Getting the most out of existing detectors

Joshua Bienfang
Allesandro Restelli

Active gating and quenching Si APDs

Typical thick-Si-APD anode

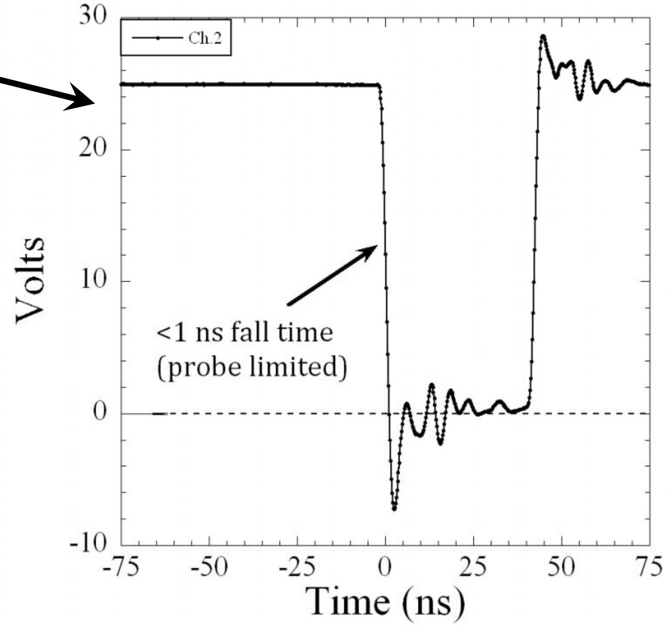


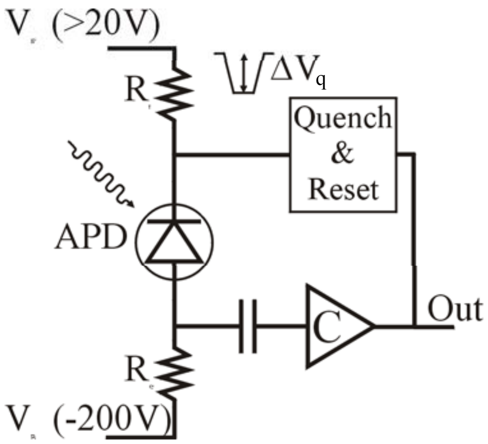
All useful information is acquired at onset of avalanche

- Combination of passive & active quenching
  → latency in recovery time
- Any means to shorten recovery benefits count rate

Sub-nanosecond control of Si APD bias can enable nanosecond gating, and reduce charge flow and after-pulsing.

Requires switching >20 V in less than a nanosecond

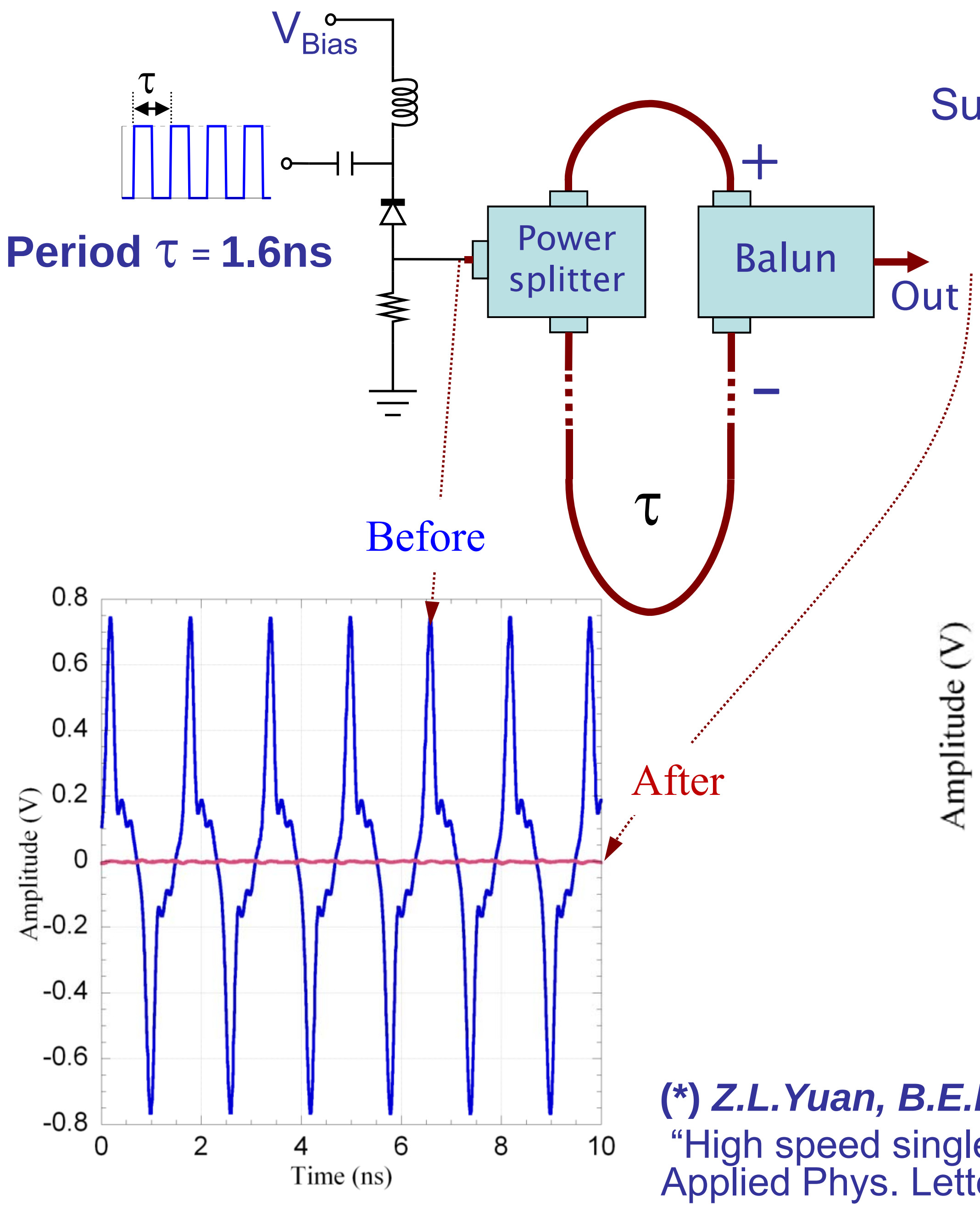




10x reduction in charge with quench 500 ps after avalanche

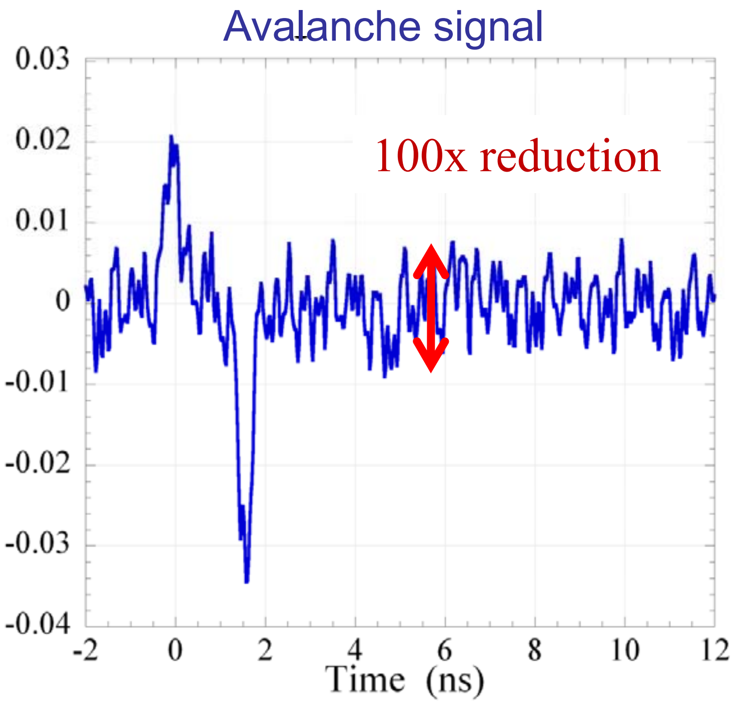
- GHz logic can provide <200ps propagation delay
- next issue: APD package high frequency compatibility

Front-end electronics for Geiger-mode InGaAs/InP detectors (requires gated operation)



Sub-nanosecond gating
(with self differencing scheme*)

Short gates &
Low overbias 0.7 v



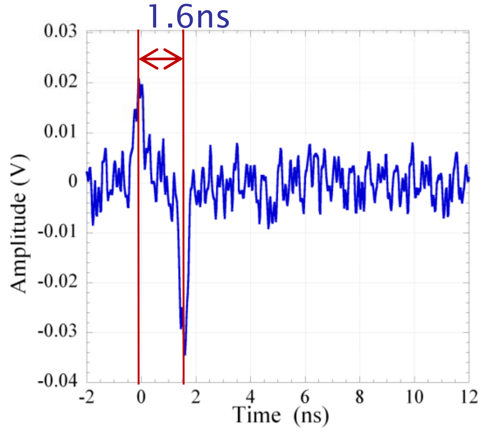
(*) Z.L.Yuan, B.E.Kardynal, A.W.Sharpe, and A.J.Shields
"High speed single photon detection in the near infrared"
Applied Phys. Letters, 2007.

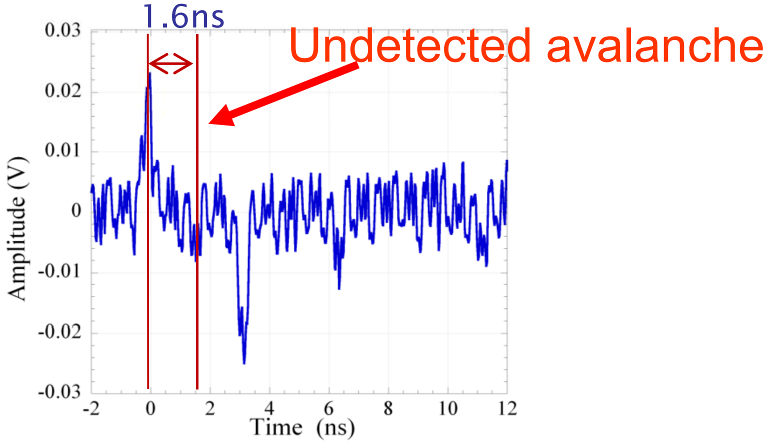
Front-end electronics for Geiger-mode InGaAs/InP detectors.

Detection efficiency is limited by afterpulsing!

In addition…

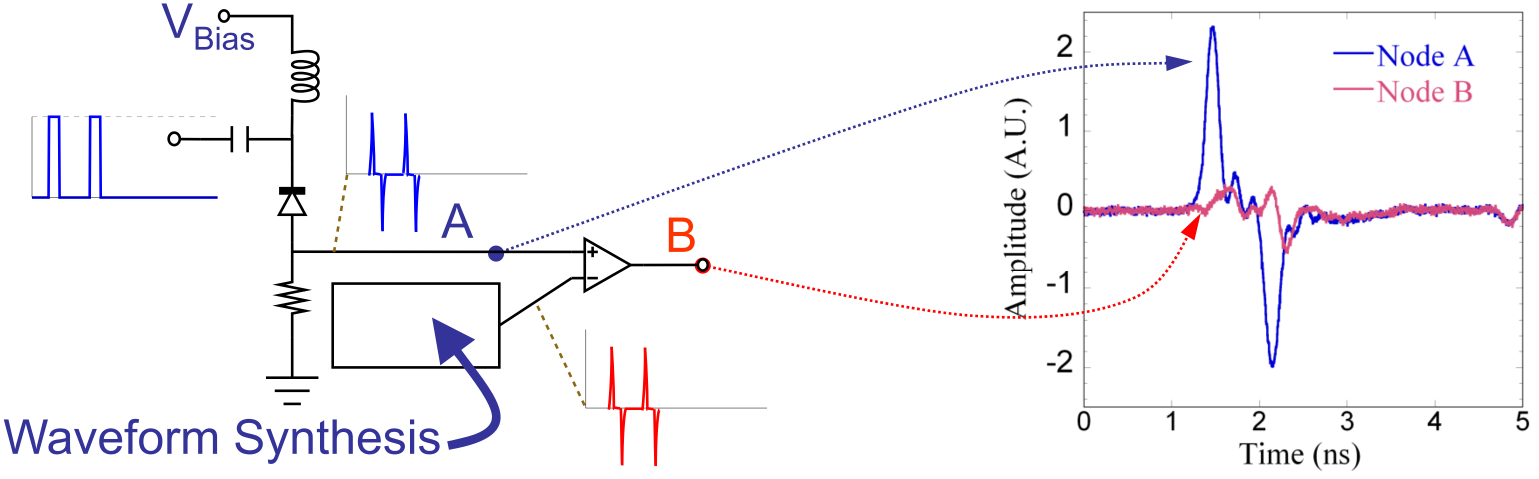
1. Avalanche current flow in adjacent gates can be masked ☹



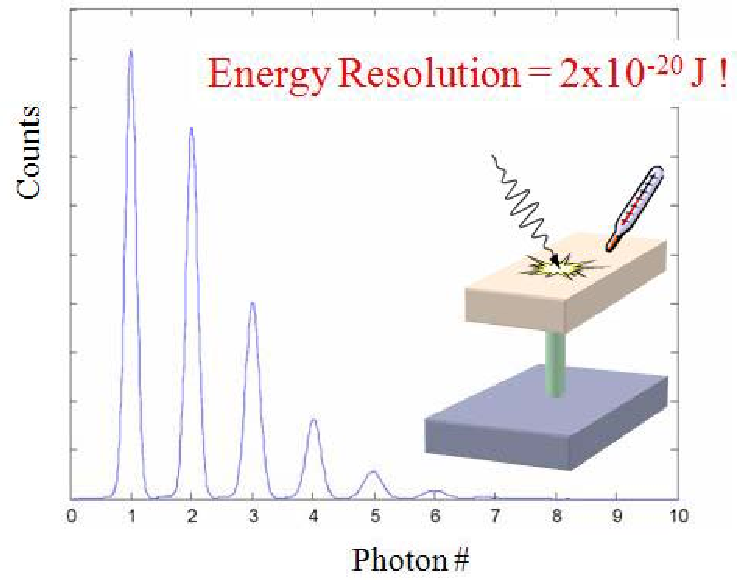


2. The gate ***has*** to be periodic:
   - No possibility to introduce a dead-time longer than the gate period to reduce the afterpulsing.

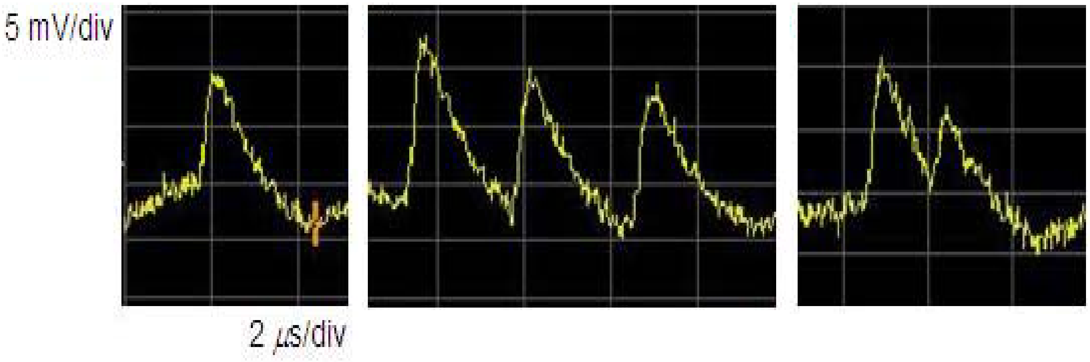
3. We are working on alternative setups to measure afterpulsing in the ns regime.



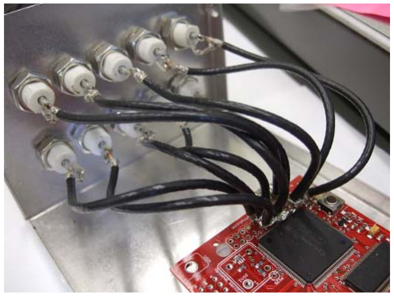
Smart TES signal processing



No inherent deadtime:

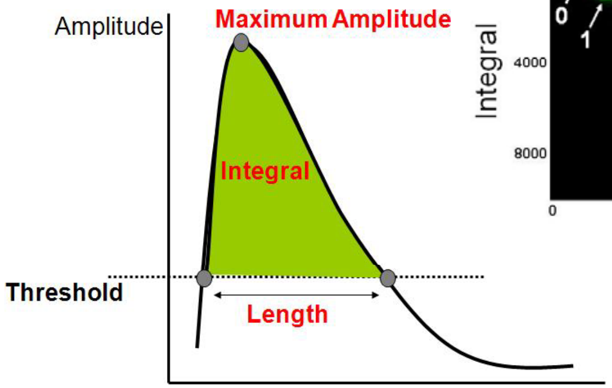


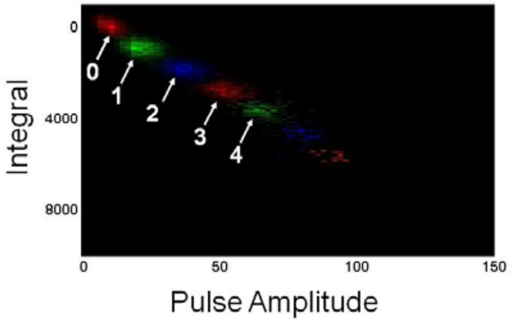
Deadtime-free processing:



Simple, cheap,
high throughput
signal processor

physics.nist.gov/Divisions/Div844/
FPGA/fpga.html



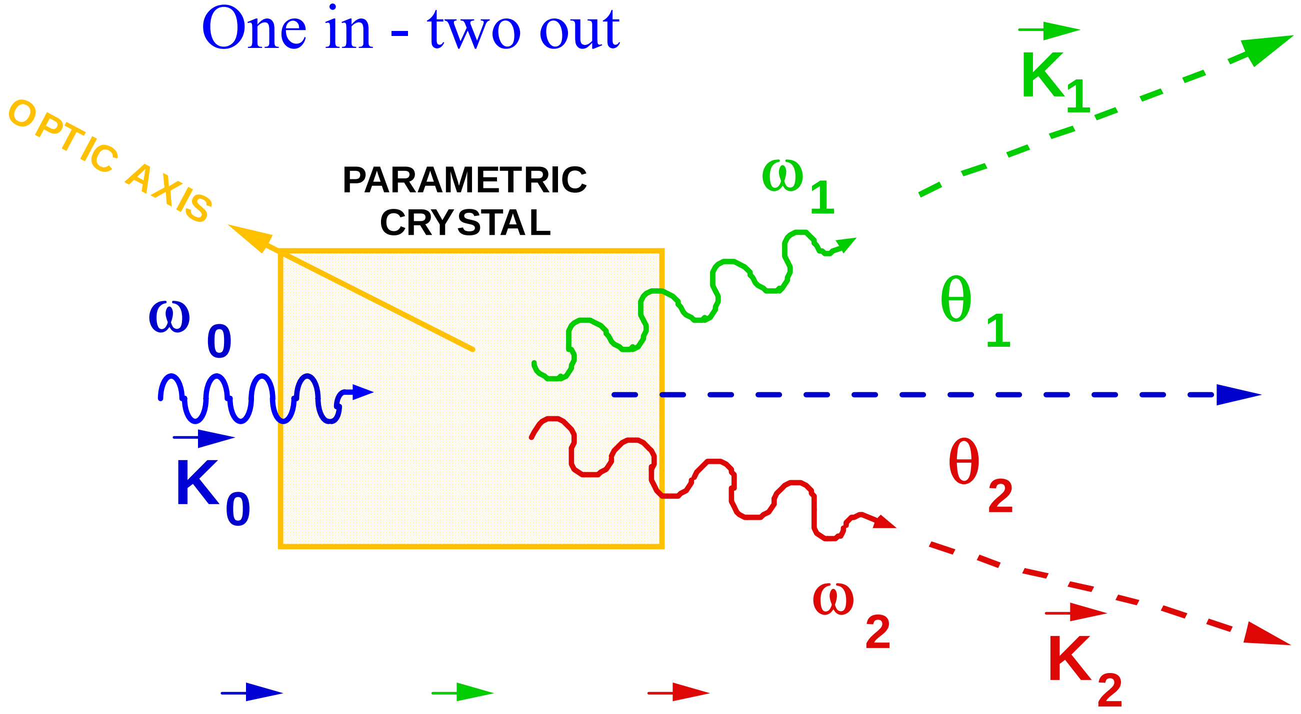


Photon-Counting Metrology

Based on creating light two photons at a time

Optical Parametric Downconversion

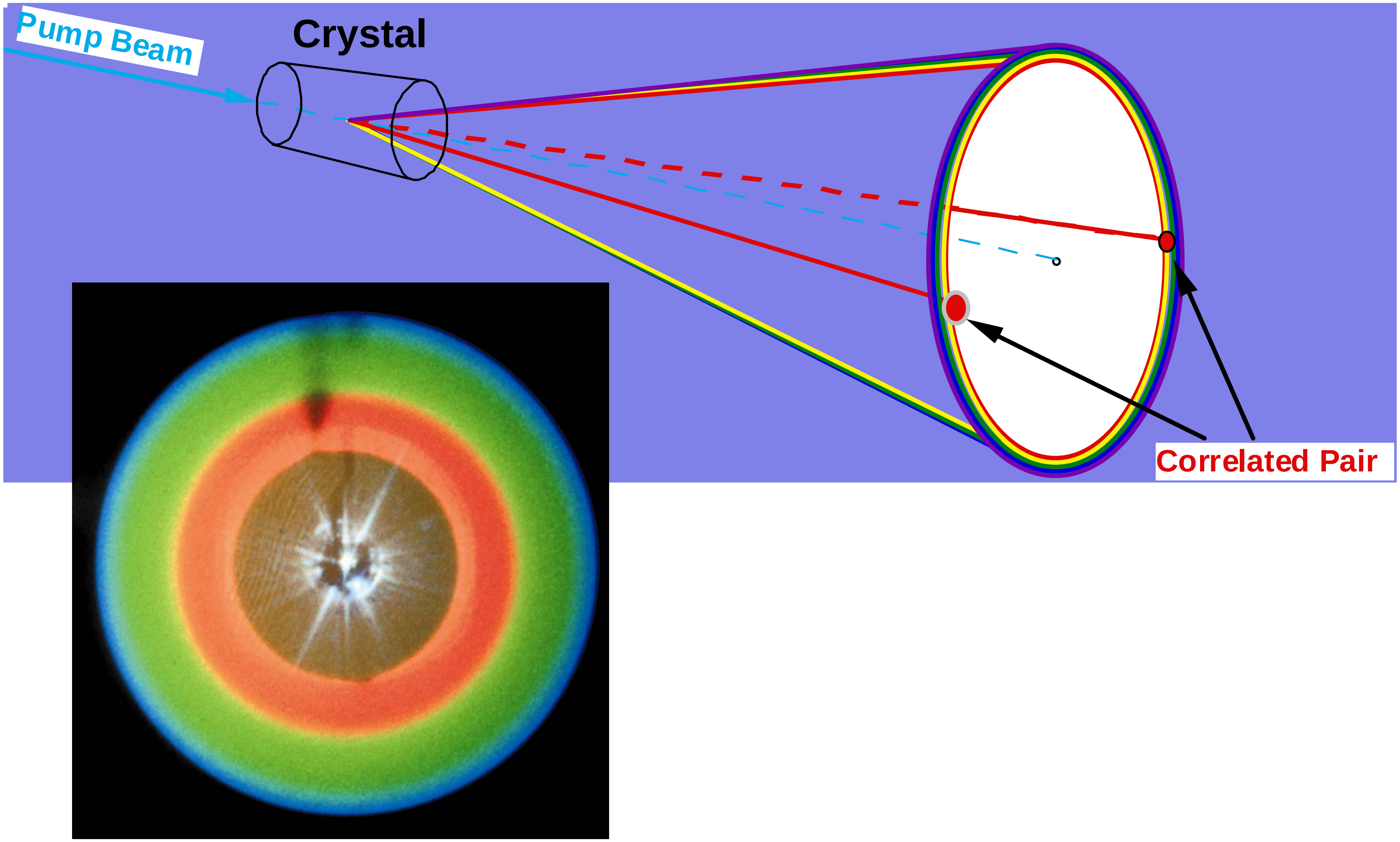
One in - two out



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

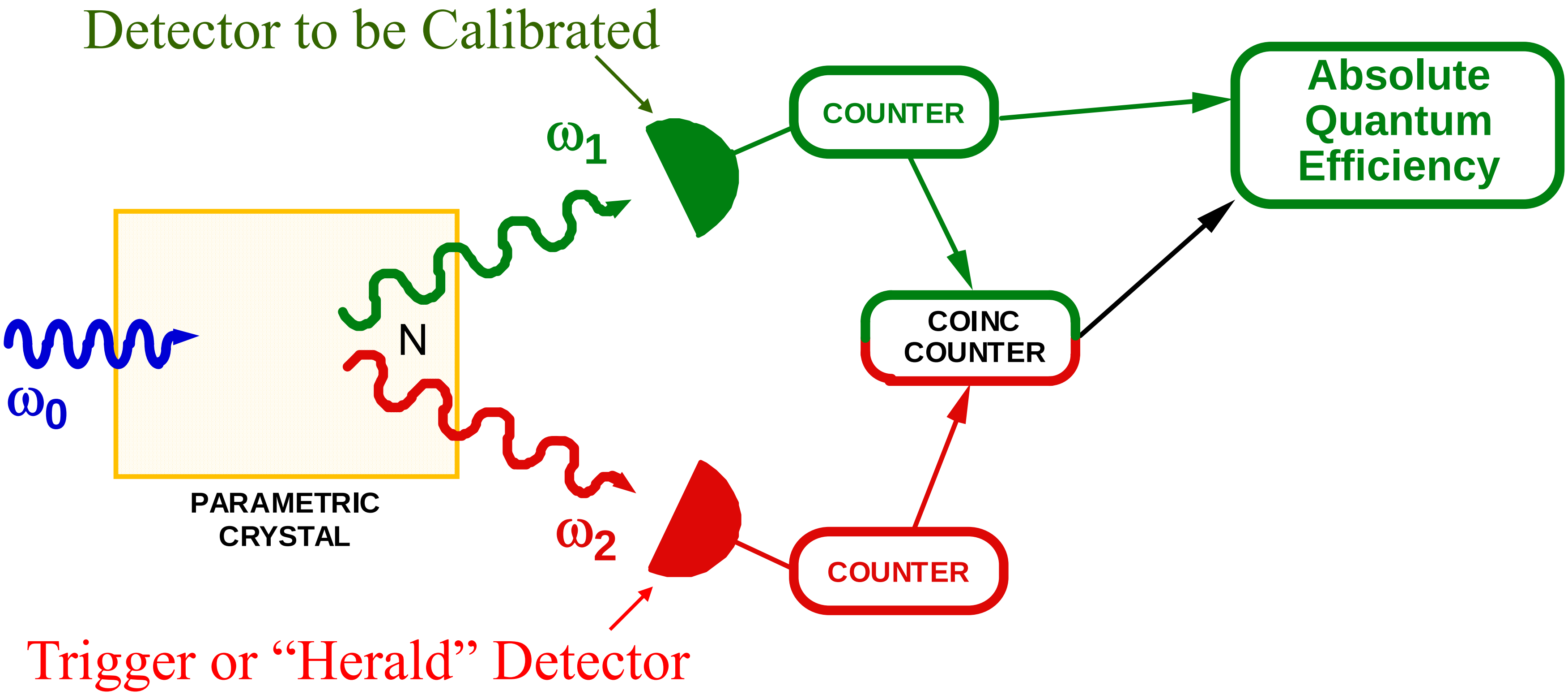
$$\omega_0 = \omega_1 + \omega_2$$

Optical Parametric Downconversion



Two-Photon Detector Efficiency Metrology

No External Standards Needed!



Detector to be Calibrated

ω_1

COUNTER

Absolute Quantum Efficiency

ω_0

N

COINC COUNTER

PARAMETRIC CRYSTAL

ω_2

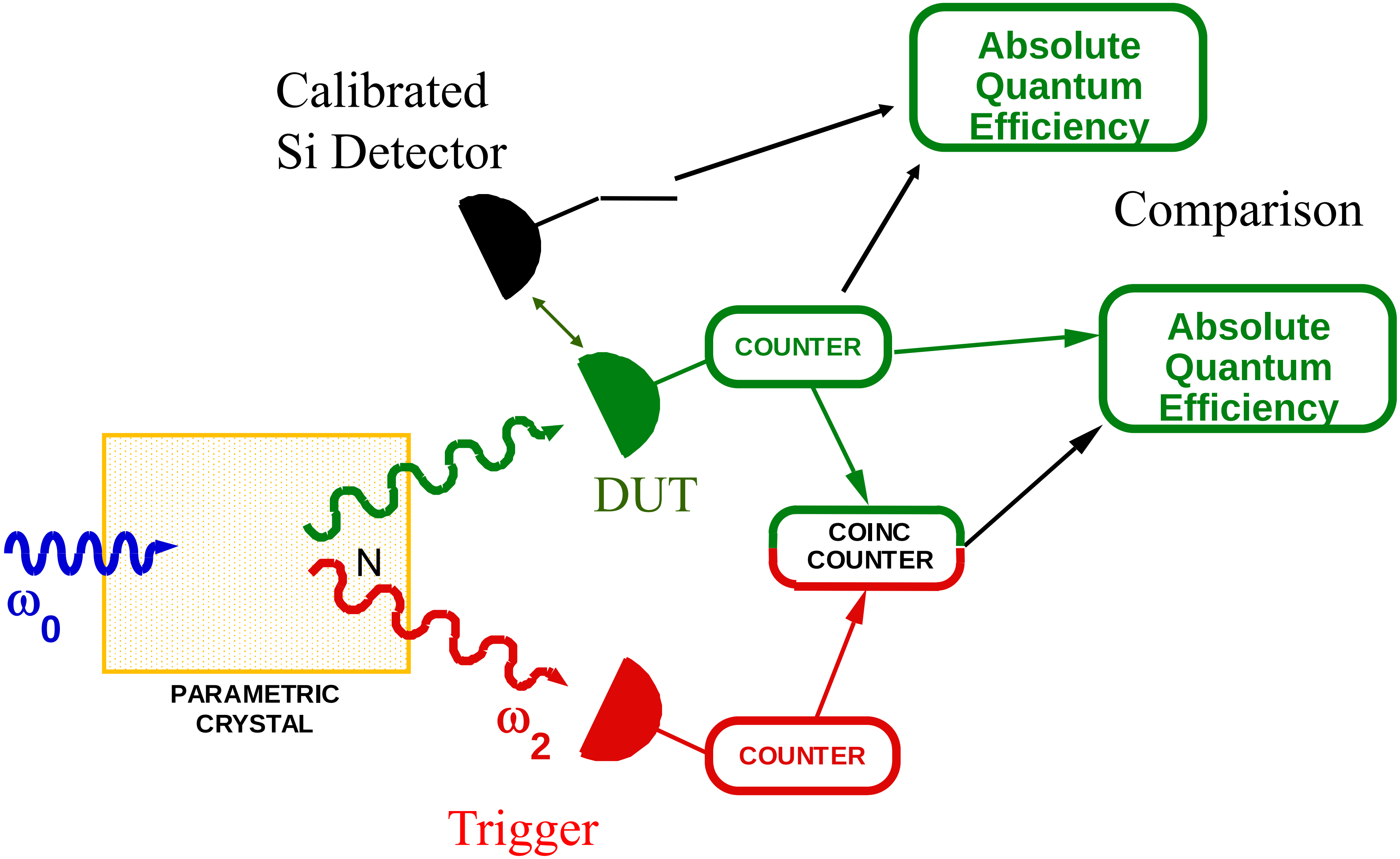
COUNTER

Trigger or "Herald" Detector

$N_1=\eta_1 N$ $N_2=\eta_2 N$ $N_C=\eta_1 \eta_2 N$

$$\eta_1 = N_C / N_2$$

Verifying the Method



Calibrated
Si Detector

Absolute
Quantum
Efficiency

Comparison

COUNTER

Absolute
Quantum
Efficiency

DUT

COINC
COUNTER

ω_0

N

PARAMETRIC
CRYSTAL

ω_2

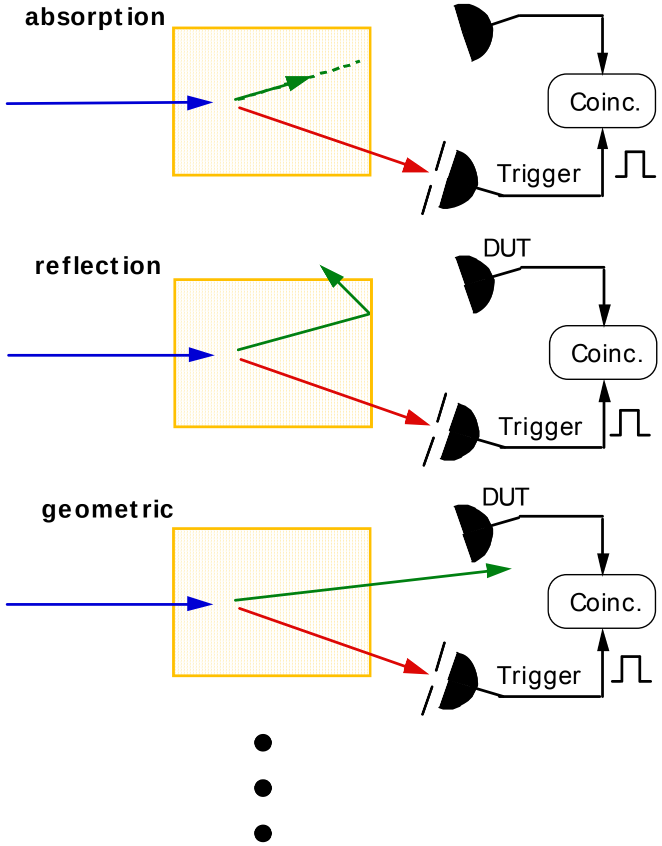
COUNTER

Trigger

Turning Two-Photon Method into Metrology

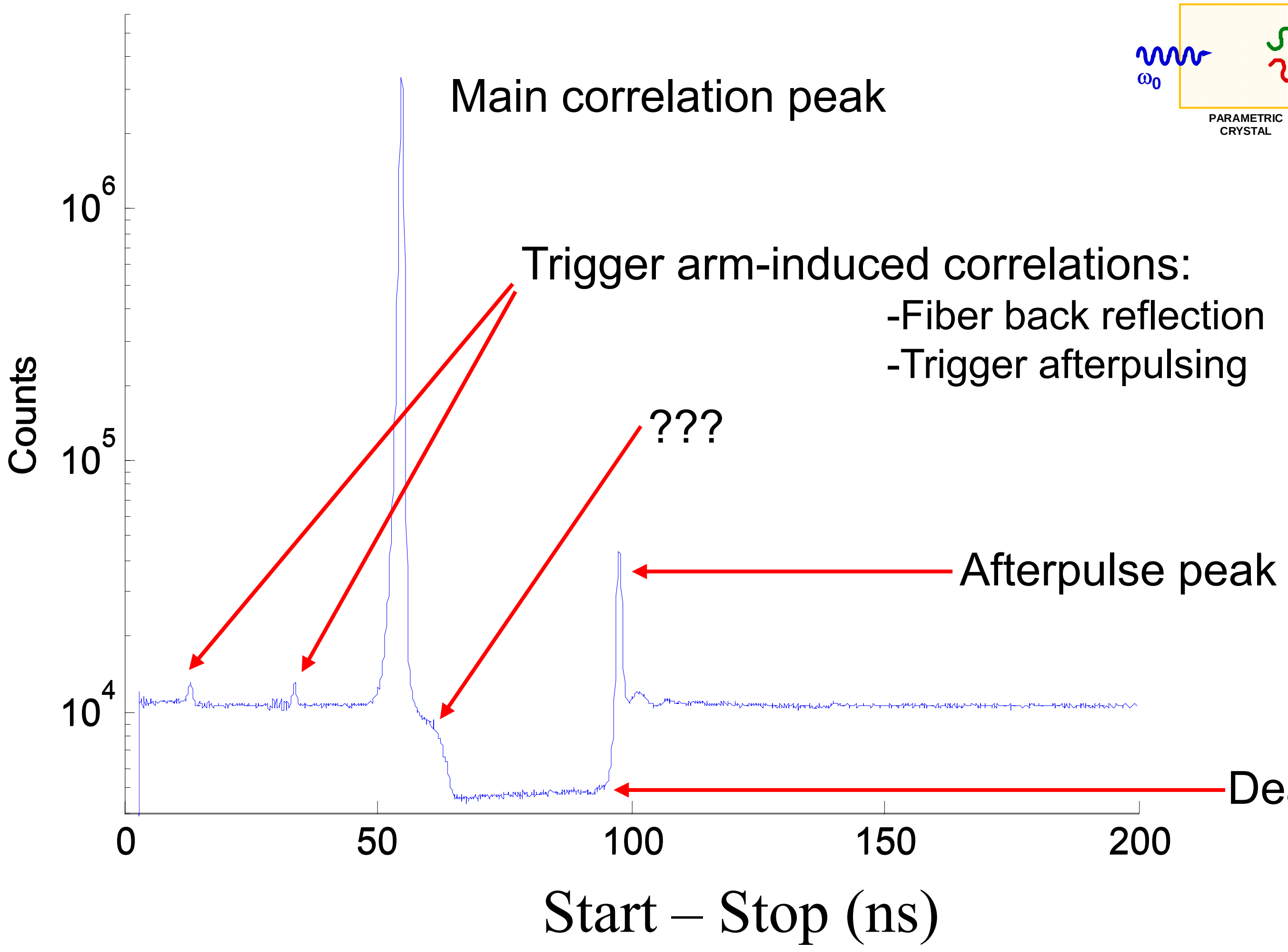
Sources of uncertainty:

DUT Collection Efficiencies
- **Spatial**
- **Angular**
- **Spectral**
- **…**



Trigger counting
Coincidence determination

Histogram and its Details



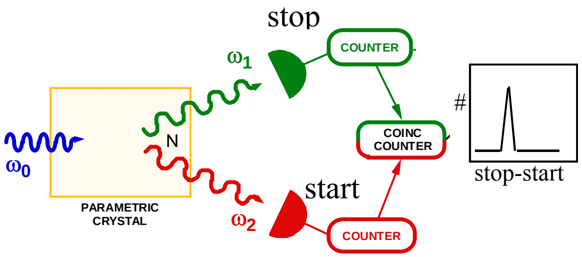
Main correlation peak

Trigger arm-induced correlations:
-Fiber back reflection
-Trigger afterpulsing

???

Afterpulse peak

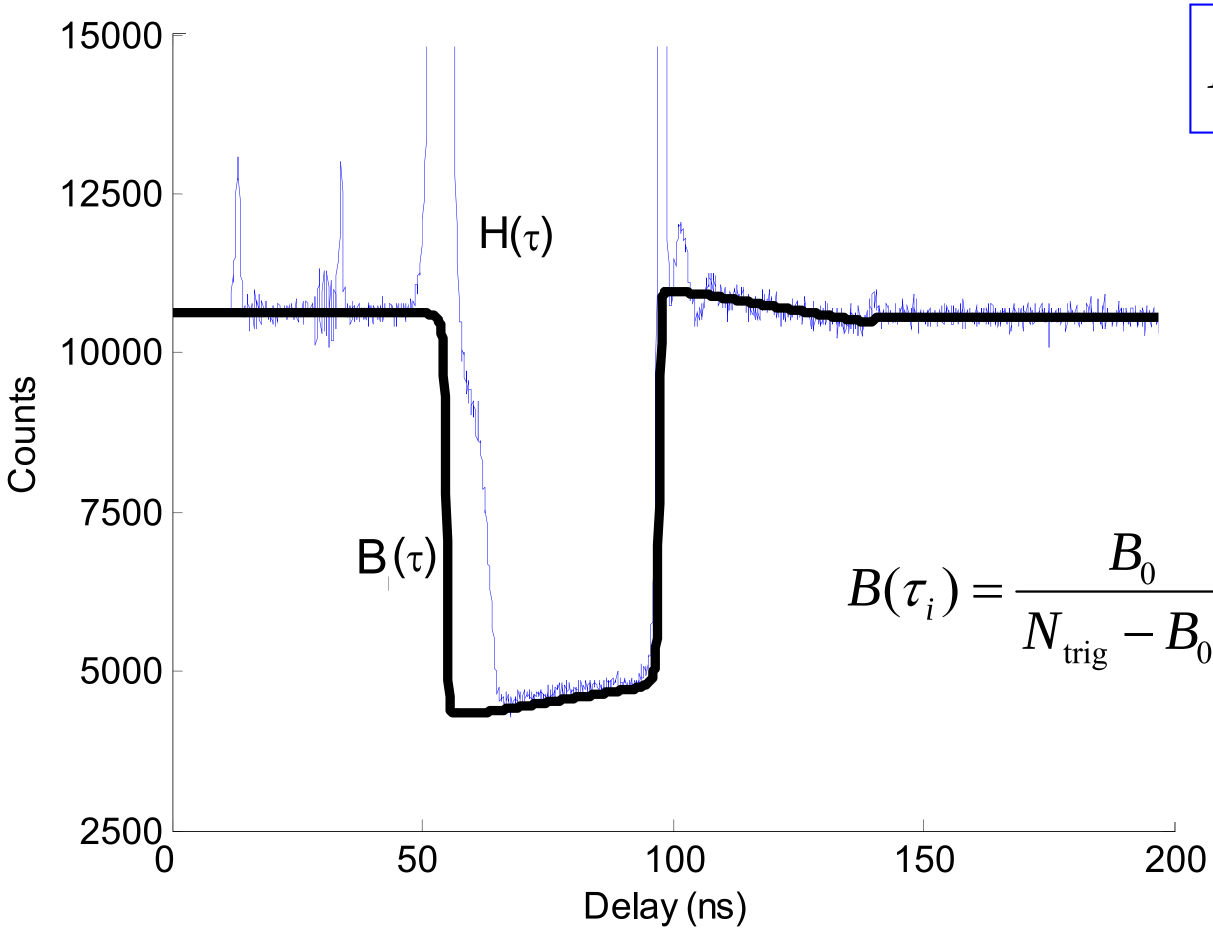
Deadtime



Ideal histogram

Real world

Signal and Background (we can model it)



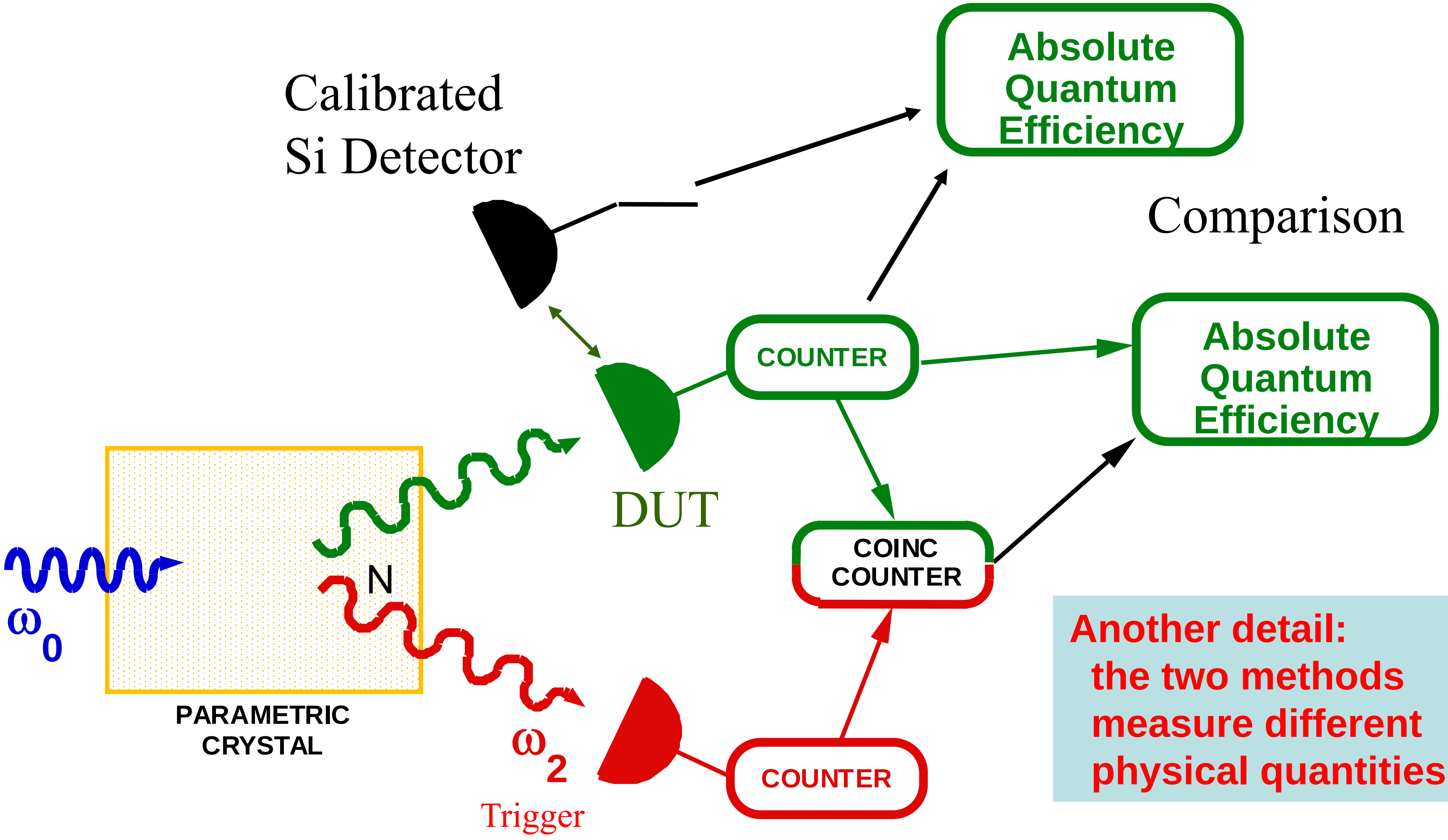
$$\boxed{H(\tau_i)} = C(\tau_i) + \boxed{B(\tau_i)}$$

$$B(\tau_i) = \frac{B_0}{N_{\text{trig}} - B_0 d}\left[N_{\text{trig}} - \sum_{j=i-d}^{i-1} H(\tau_j)\right]$$

Correlated photon calibration method uncertainty budget

Physical property	Value	Relative uncertainty of value (%)	Sensitivity	Relative uncertainty of DE (%)	
Crystal reflectance	0.09249	0.2%	0.1	0.02%	Optical losses
Crystal transmittance	0.99996	0.009%	1	0.009%	
Lens transmittance	0.97544	0.0027%	1	0.0027%	
Geometric collection (raster scan)	0.9995	0.05%	1	0.05%	
DUT filter transmittance	0.9136	0.1%	1	0.10%	
Trigger bandpass to virtual bandpass/wavelength				0.07%	
Histogram background subtraction				0.03%	Histogram
Coincidence circuit correction	0.0083	10.0%	0.008	0.084%	
Counting statistics				0.08%	
Deadtime (due to rate changes with time)				0.02%	
Trigger afterpulsing	0.0025	25.0%	0.003	0.06%	Trigger
Trigger background, & statistics	175000	0.3%	0.035	0.01%	
Trigger signal due to uncorrelated photons	0	0.07%	1	0.07%	
Trigger signal due to fiber back reflection	0.00202	1.60%	0.002	0.003%	
Total				**0.18%**	

Verifying the Method



Calibrated
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Absolute
Quantum
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Comparison

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Absolute
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DUT

COINC
COUNTER

ω_0

N

PARAMETRIC
CRYSTAL

ω_2

Trigger

COUNTER

Another detail:
the two methods
measure different
physical quantities!

Comparison/Results

- NIST implementation of High Accuracy SPD Calibration methods

Method	**Absolute uncertainty**
Two-photon	0.18%
Substitution	0.17%

- Uncertainty of each individual comparison:

0.25%

- Overall mean difference between the two methods:

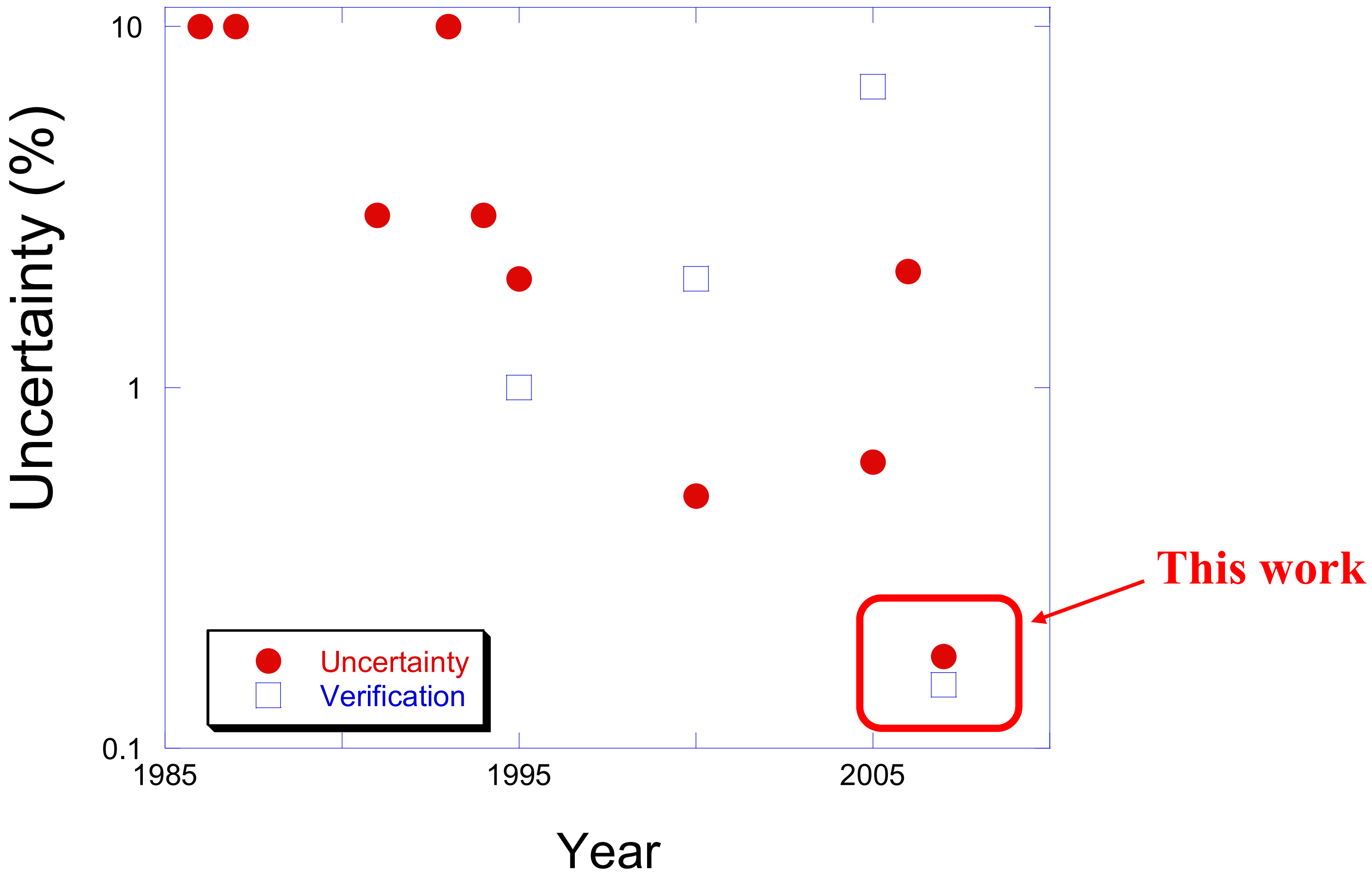
0.15%±0.14% $(\eta_{\text{sub.}} > \eta_{\text{2-photon}})$

Highest accuracy verification of the 2-photon method yet achieved

2-Photon Metrology Progress

		Uncertainty of		
Year	1st author	Method	Verification	External Comparison
1970	Burnham	~35%		Calibrated lamp
1981	Malygin	-		
1986	Bowman	~10%		
1987	Rarity	~10%		HeNe + attenuation
1991	Penin	> 3%		
1993	Ginzburg	~10%		Published values
1994	Kwiat	~3%		
1995	Migdall	< 2%	1%	Calibrated Si Detector
2000	Brida	~0.5%	2%	Calibrated Si Detector
2005	Ghazi-Bellouati	1.1, 0.62%	6.8%	French cryoradiometer
2006	Wu	2.1%		
2007	Polyakov	0.18%	0.15%	Calibrated Si Detector

Metrology Progress



Single Photon Metrology

Goal: 0.5% photon counting calibration to the masses

- Metrology
  - Correlated Photon Method
  - Transfer Standard Method
- Compared the two
- Lessons Learned
- Dissemination Effort
  - High-gain low-noise transfer standard

Transfer standard design

Goal: 0.5% uncertainty
disseminated to users

Desires: Bridging photon-counting to analog levels

- Detector:
  - Visible
  - Stable response vs temperature
  - Spatially uniform response
  - Low Noise for photon counting levels

- Amplifier
  - High gain for photon-counting levels
  - Lower gain for analog calibration levels
  - Thermal stability
  - Gain stability & precision for calibration ease

Transfer standard design

Si detector/amplifier

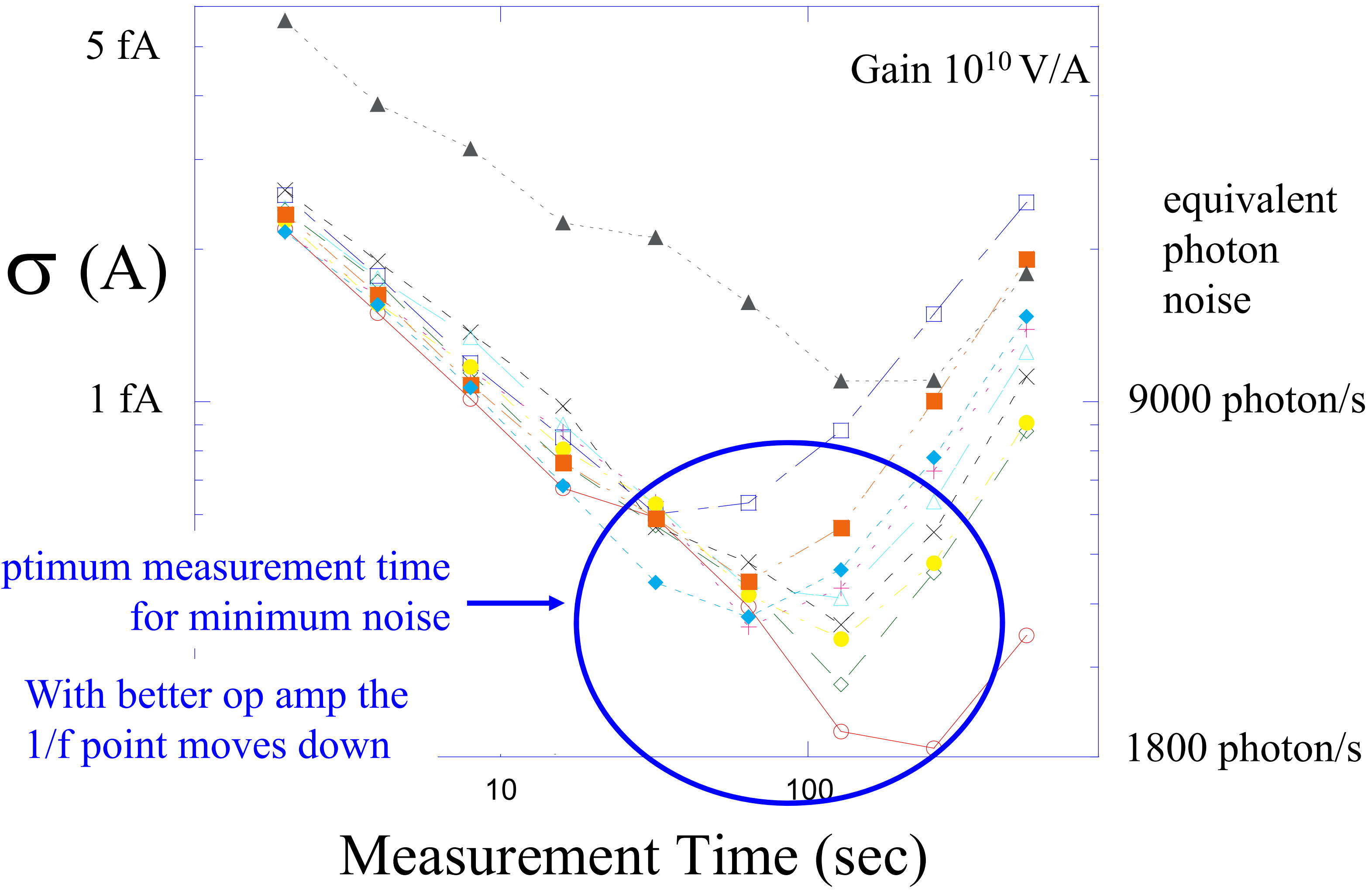
Goal: 0.5% uncertainty disseminated to users

- Detector: Si 5.8x5.8 mm Sapphire window (Hamamatsu S2592-04)
- Spatial response uniformity: 0.1%
- Cooled detector for
  - high shunt resistance: ~ 5 GΩ
  - high gain: 10^7, 10^8, 10^9, 10^{10} V/A
  - low noise: sub-fA

- Temperature stabilized for
  - low drift 0.1C gives < 0.1% response stability
- Gain: high precision nominal levels
  - 10^7, 10^8 V/A: 0.01% & 10 ppm/C
  - 10^9, 10^{10} V/A: 1% & 100 ppm/C
- Gain compatible with
  - Photon-counting levels (<0.1 pW, 10^6 photon/s, 10^9 ~ 10^{10} V/A)
  - Analog calibration levels (>0.1 μW, 10^7 ~ 10^8 V/A)

Transfer standard testing

Allen variance* analysis of 10 devices



Optimum measurement time for minimum noise

With better op amp the 1/f point moves down

* Deviation of adjacent differences: $\sigma_y^2 = ½<(y_{i+1} - y_i)^2>$

Can we get to 0.5% goal?

- For 100 s noise ~5000 photon/s
  Signal of 10^6 photon/s allows 0.5% uncertainty
- Scale transfer 0.1% (combined uncertainty)
- Gain range changes: 0.01% (gain 7,8) 1% (gain 9, 10)
- So far so good

- Further work
  - Better op amp temperature dependence
  - Frequency response for possible AC operation for lower noise
  - Gain range tolerance tests
  - Calibration
- Robust transfer standards for dissemination to user community

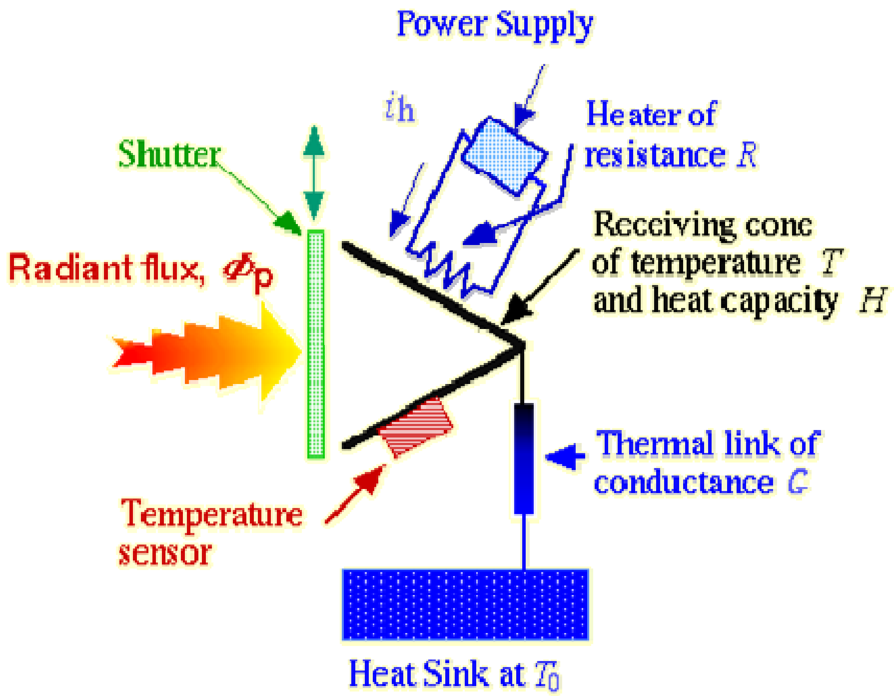
Thanks to IARPA for funding

Redefining optical power traceability: Bridging the gap from single-photons to tera-photons

Sae Woo Nam

John Lehman, Alan Migdall, & Rich Mirin

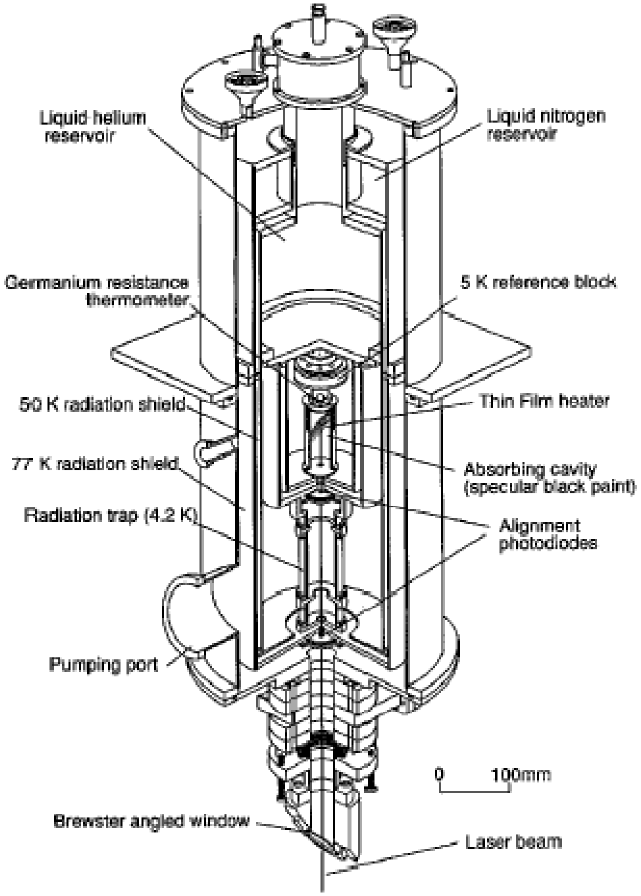
Electrical Substitution Radiometry



From NIST Technical Note 1421, A. Parr

Optical Power = Electrical Power

High-Accuracy Cryogenic Radiometer (HACR) 1980s

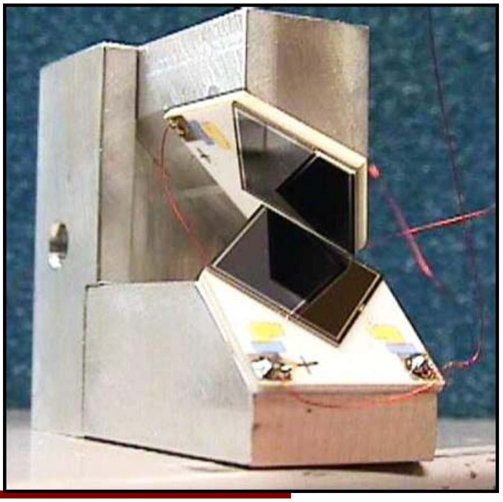


Laser Optimized Cryogenic Radiometer (LOCR) 1990s

Details:

- **“World’s best” cryogenic radiometry: Uncert = 0.01%**
- **Primary standards (cryogenic radiometers) operate over limited range and relatively “high” powers**
  - Typical operation is ~100 uW to ~1 mW
  - Dissemination to customers degrades due to transfer standard limits ~1%
  - Optical power traceability has the poorest uncertainty of major measurands
- **Difficult to link the lower range of optical powers used by industry to primary standards**

No formal connection between classical methods to measure optical power and new methods to measure single photons



What could the future look like?

Return to a "standard candle" –
Single-photon devices that provide
Single-photons on demand

- **Dial in the rate**
- **Dial in the wavelength**
- **"Known optical powers" on demand to calibrate devices**

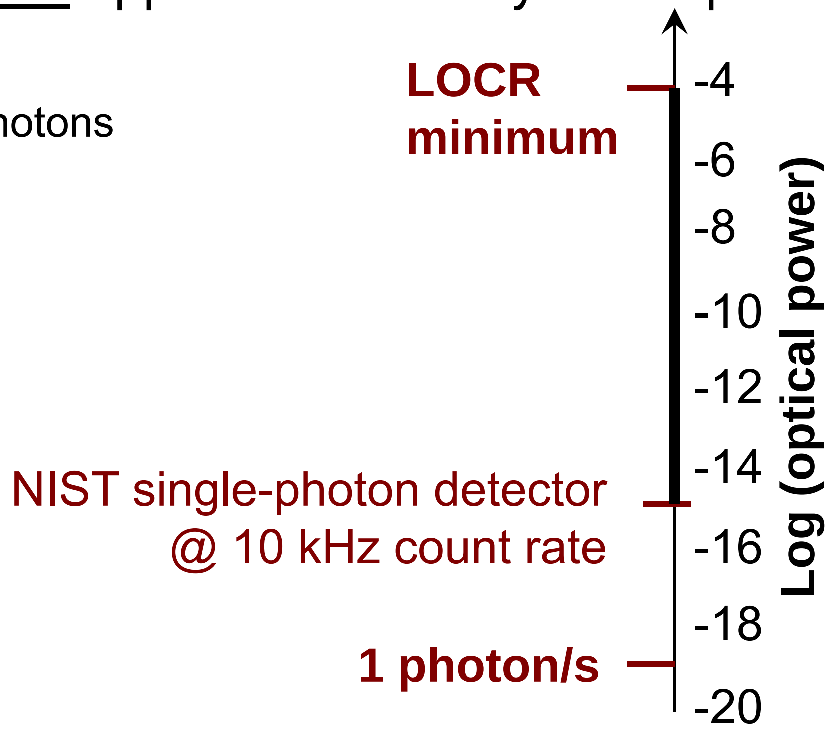
Change the way optical power is disseminated!!

Why is it hard? The power range is enormous

11 order-of-magnitude gap

between cryogenic radiometry and single photonics assuming
ideal application of today's best photon counting technology

For λ = 1 μm photons

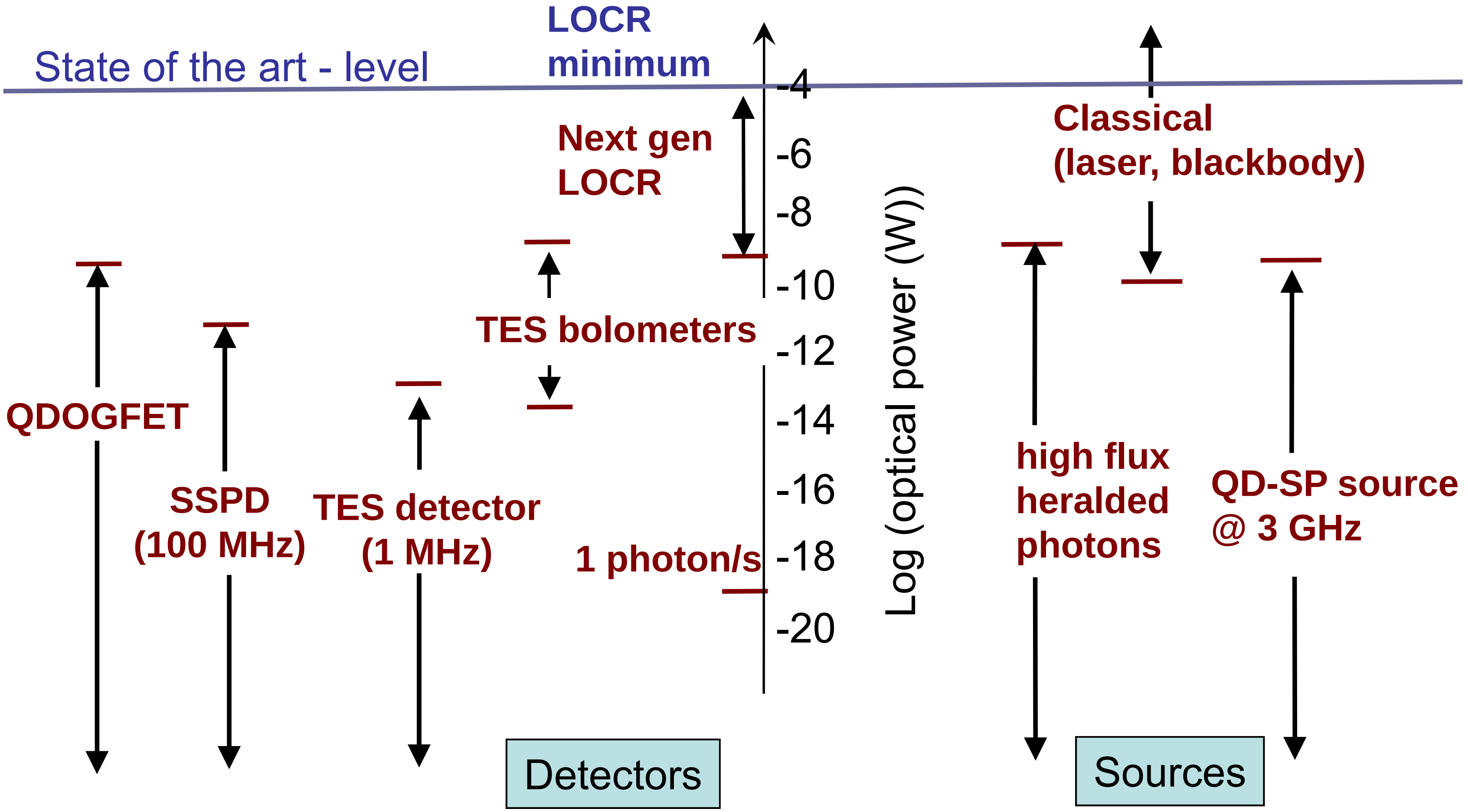


In 2007, first attempt to close the gap was done by comparing the calibrations done classically and with a heralded photon source

No traceability between conventional radiometry and photon counting

How do we bridge? Overlap power ranges

	Today	Ultimate Goal
gap:	**10^{15}**	**0**
best uncertainty:	**0.01 % (k=2)**	**0.001% (k=2)**



Simple and Inexpensive, Fast Time-Resolving Multichannel Coincidence Board

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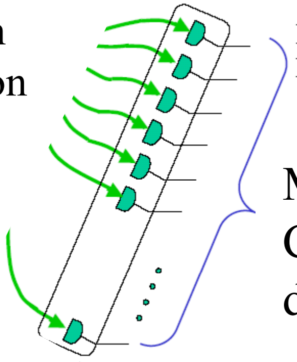
What?

- Real-time recording and statistical processing of electrical pulses *(on-board processing)*
- Records and processes multiple-channel inputs
- Looks for coincidences between 2 or more channels *(any and all combinations detected)*



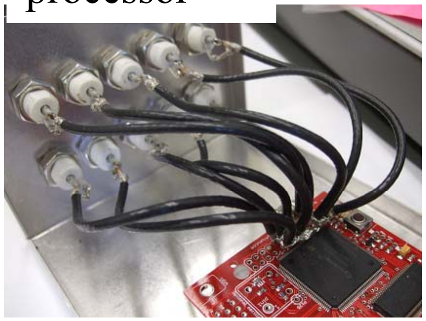
Quantum information system

Pool of Detectors

Multiple Coincidence data

ie. detectors 1, 4, 5 fired within same timebin

Our multiple coincidence processor



What’s new?

- Scalability to many channels <<big deal
  - Existing:
    - 2 channels coincidence boards run in parallel for more than two channel coincidence
- All n-fold coincidences can be detected (flexibility) <<big deal
  - Existing:
    - Fixed n-channel coincidence detection
    - No real time multicoincidence processing
- Single-chip design (allows very low cost)
- Internal clock synced to external experiment

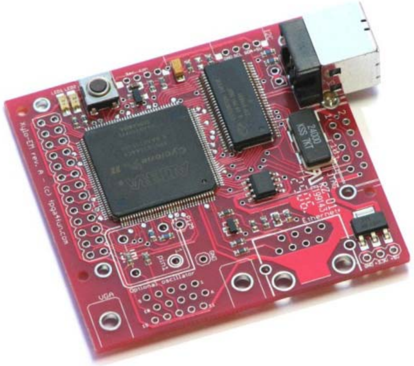
How it works

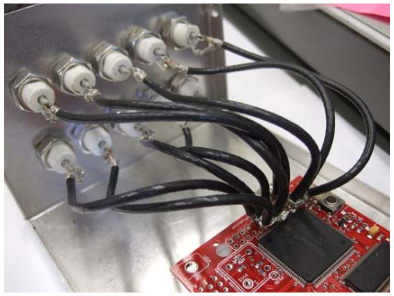
- FPGA & software:
  - Pulse edge detection
  - Synchronous timer
    - internal FPGA timer synchronized to external experiment timer
  - Many input channels
    - Inherent scalability for N-coincidence detection
  - High timing resolution

  - On-board processing:
    - Picks out multicoincidences
    - Transfers only desired events to pc

Solves the multiple-coincidence detection problem

Solves the data transfer problem





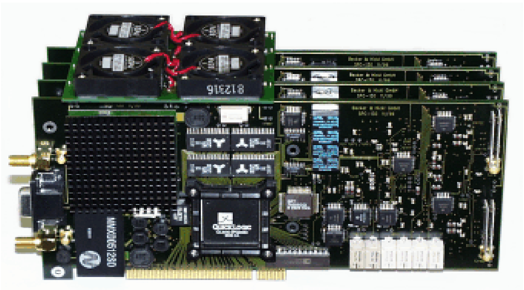
- Implemented with existing design board with:
  - Plug & Play USB2 connectivity with transfer rates to PC of >2 MHz

Problems it solves:
No real-time multicoincidence processing

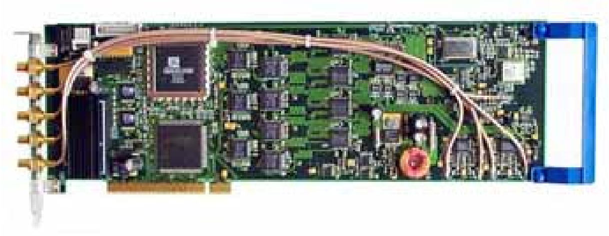
What we are stuck with:

PicoHarp 300 (Germany)
2 channel system

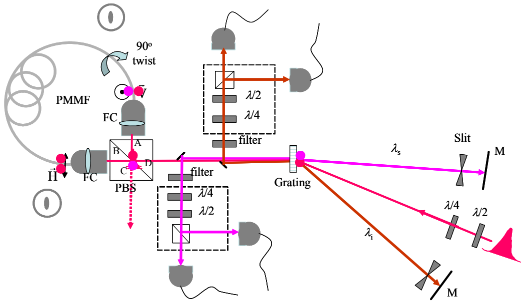
Becker & Hickl
GmbH SPC-134
1 start & 4 stops



Fast ComTec (Germany)
4 channel system
1 start & 4 stops



- These are inherently 2 channel devices that are ganged up
- Not scalable to more channels
- No real-time multichannel coincidence detection
- Too expensive
- Analysis deadtime
- Not designed for Quantum Information applications



Limitations of our approach

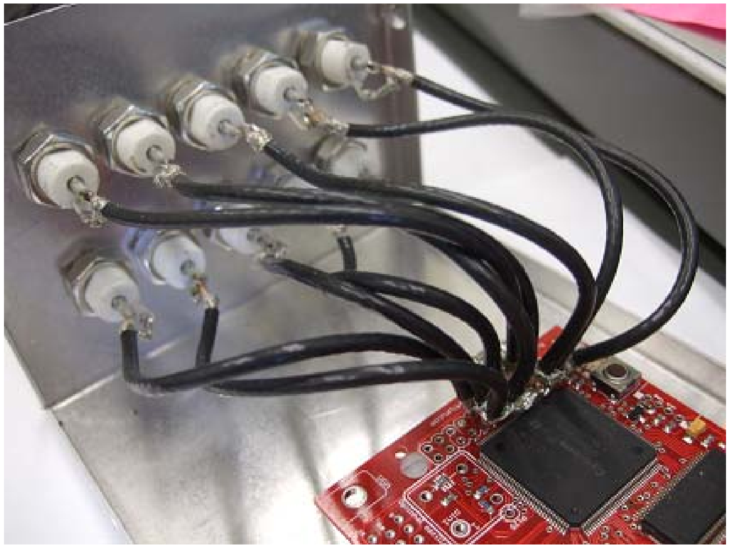
- *The time stamping rate limited by fastest toggle time of FPGA.*

    Current prototype: ~6.5 ns.

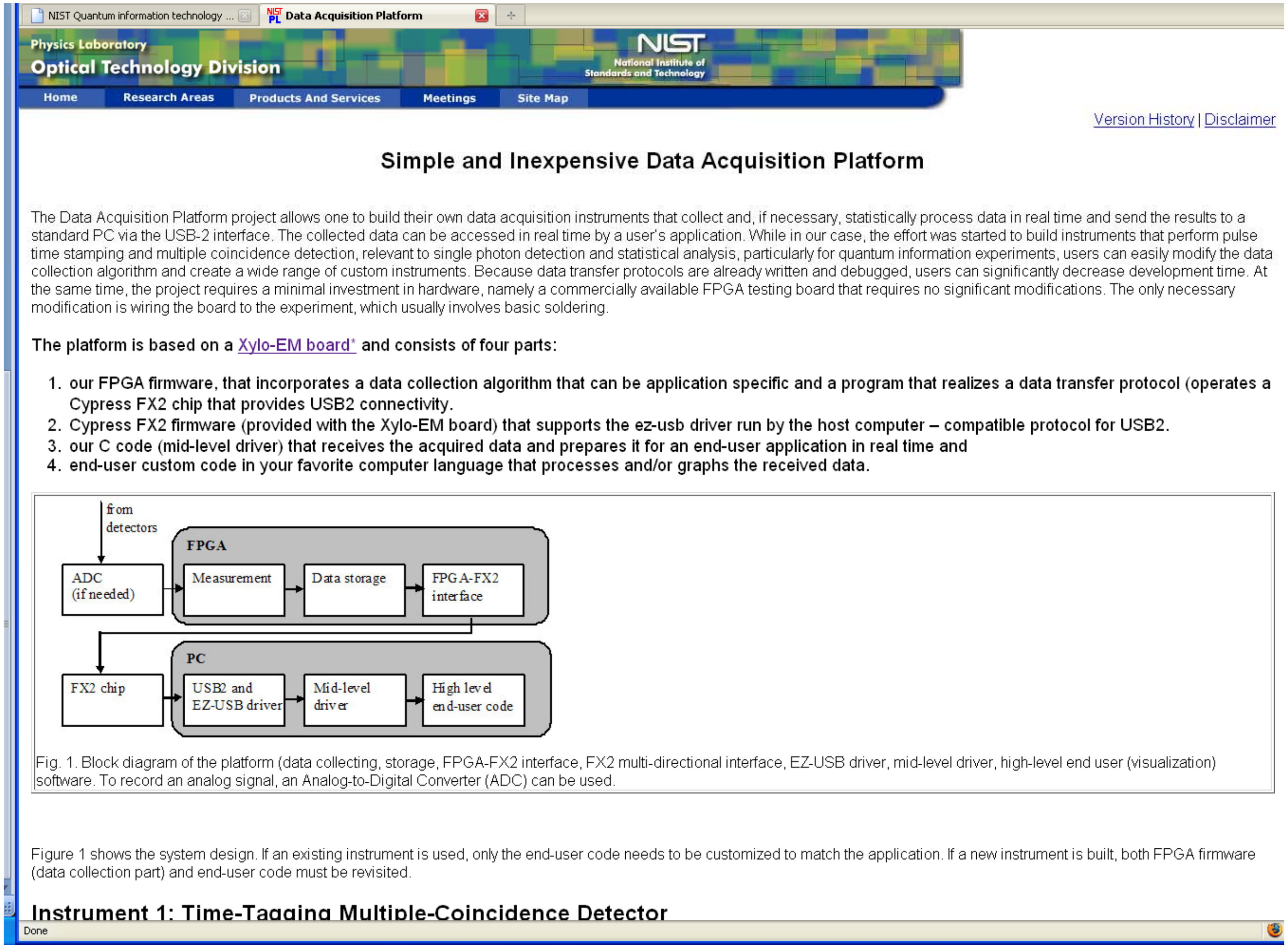
- *Underway: SBIR pushing to ~1 ns*

Multi-channel coincidence processor summary

- Novel technology for multiple channel coincidence detection
- Advantages
  - Scalable
  - Flexible
  - External synchronization
  - Robust (hardware is disposable)
  - Compact
  - Cost
- Dissemination-
  - physics.nist.gov\FPGA



System how to documentation



Simple and Inexpensive Data Acquisition Platform

The Data Acquisition Platform project allows one to build their own data acquisition instruments that collect and, if necessary, statistically process data in real time and send the results to a standard PC via the USB-2 interface. The collected data can be accessed in real time by a user's application. While in our case, the effort was started to build instruments that perform pulse time stamping and multiple coincidence detection, relevant to single photon detection and statistical analysis, particularly for quantum information experiments, users can easily modify the data collection algorithm and create a wide range of custom instruments. Because data transfer protocols are already written and debugged, users can significantly decrease development time. At the same time, the project requires a minimal investment in hardware, namely a commercially available FPGA testing board that requires no significant modifications. The only necessary modification is wiring the board to the experiment, which usually involves basic soldering.

The platform is based on a Xylo-EM board* and consists of four parts:

1. **our FPGA firmware, that incorporates a data collection algorithm that can be application specific and a program that realizes a data transfer protocol (operates a Cypress FX2 chip that provides USB2 connectivity.**
2. **Cypress FX2 firmware (provided with the Xylo-EM board) that supports the ez-usb driver run by the host computer – compatible protocol for USB2.**
3. **our C code (mid-level driver) that receives the acquired data and prepares it for an end-user application in real time and**
4. **end-user custom code in your favorite computer language that processes and/or graphs the received data.**

Fig. 1. Block diagram of the platform (data collecting, storage, FPGA-FX2 interface, FX2 multi-directional interface, EZ-USB driver, mid-level driver, high-level end user (visualization) software. To record an analog signal, an Analog-to-Digital Converter (ADC) can be used.

Figure 1 shows the system design. If an existing instrument is used, only the end-user code needs to be customized to match the application. If a new instrument is built, both FPGA firmware (data collection part) and end-user code must be revisited.

Instrument 1: Time-Tagging Multiple-Coincidence Detector

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