Bridging the Gap:
Radiometry from Watts to Single-Photons

A. Migdall
B. Calkins
C. Cromer
M. Dowell
J. Fan
T. Gerrits
J. Lehman
A. Lita
D. Livigni
R. P. Mirin
S. W. Nam
S. V. Polyakov
M. Stevens
N. Tomlin
I. Vayshenker

NIST, Boulder & Gaithersburg

Outline

- Existing Radiometry and The Gap

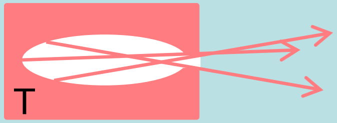
  (What this talk is and is not about)

- Bridging the Gap efforts (review)
- Hope: Single-Photon Tools
- Issues and concerns

Absolute Radiometric Standards

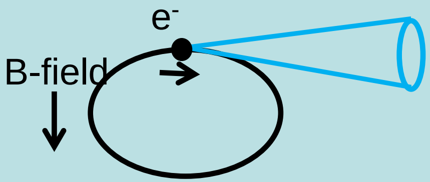
Sources

Blackbody



Temperature → Radiance

Synchrotron

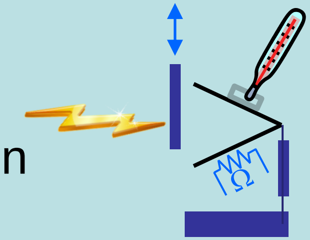


B-field, current, energy → Radiance

Detectors

Trap: Radiometer

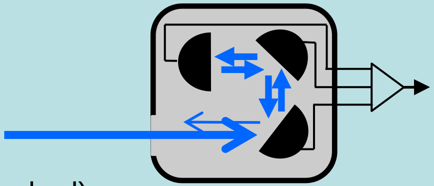
Electrical Substitution



Radiant power

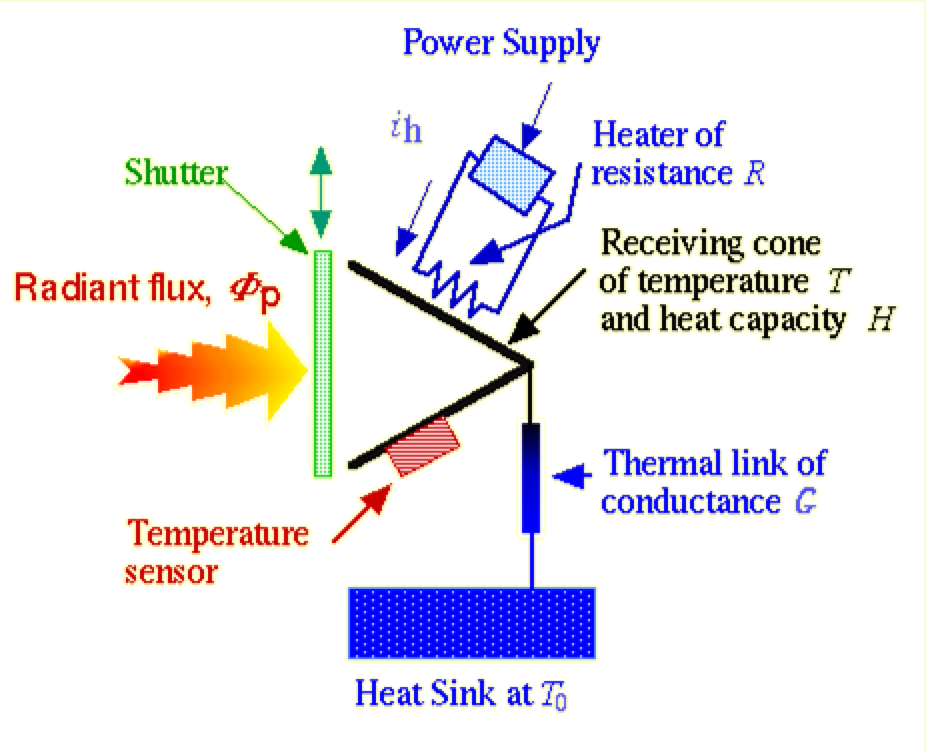
Trap:

Semiconductor



Radiant power (transfer standard)

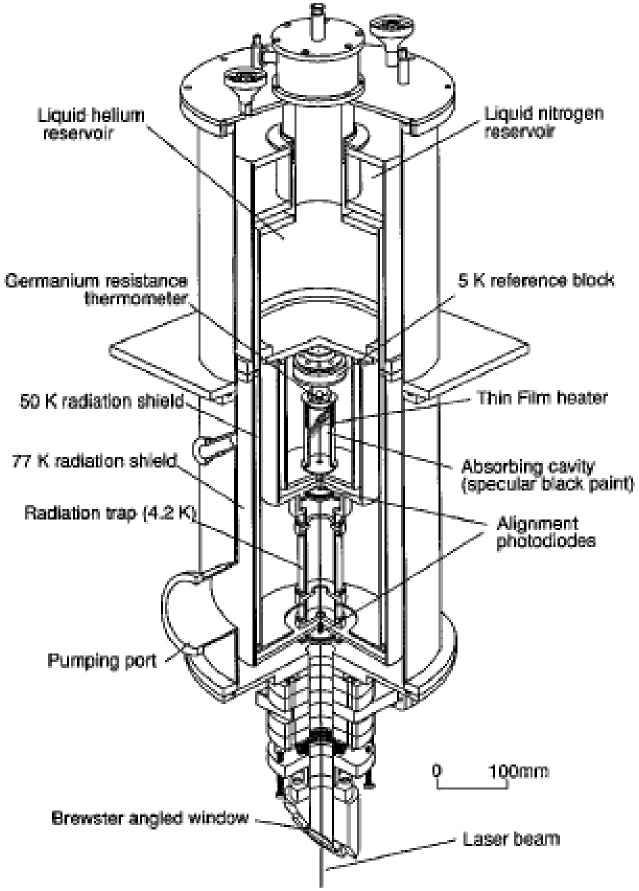
Electrical Substitution Radiometry



From NIST Technical Note 1421, A. Parr

Optical Power = Electrical Power

High-Accuracy Cryogenic Radiometer (HACR) 1980s



Laser Optimized Cryogenic Radiometer (LOCR) 1990s

Present Limits:

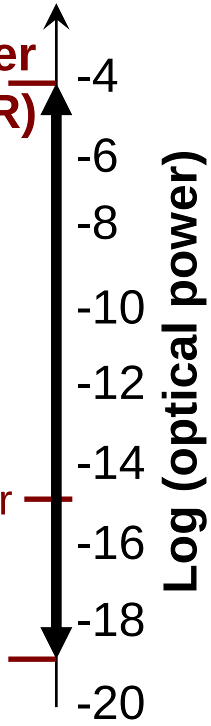
- **“World’s best” cryogenic radiometry is U = 0.01%**
- **Primary standards (cryogenic radiometers) operate over limited range and relatively “high” powers**
  - Typical operation is **~100 uW to ~1 mW**
  - Dissemination to customers degrades due to transfer standard limits ~1%
  - Optical power traceability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

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

The gap

15 order-of-magnitude gap

between cryogenic radiometry and single photon metrology



Cryogenic Radiometer minimum (LOCR)

Highest efficiency single-photon detector @ 10 kHz count rate

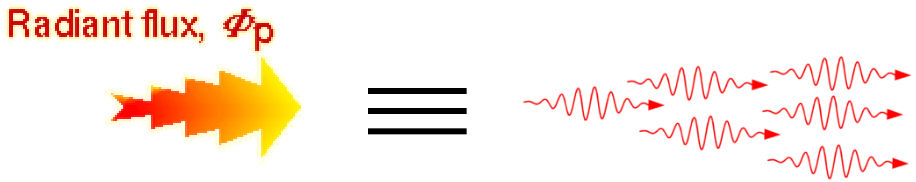
1 photon/s

For λ = 1 µm photons
E=2x10^{-19} J

Attempt to close the gap by comparing calibrations done classically and with a heralded photon source (2007)

No traceability between conventional radiometry and photon counting

Opportunity: Single Photon Tools for the Gap



Light arrives in packets (quanta – photon)

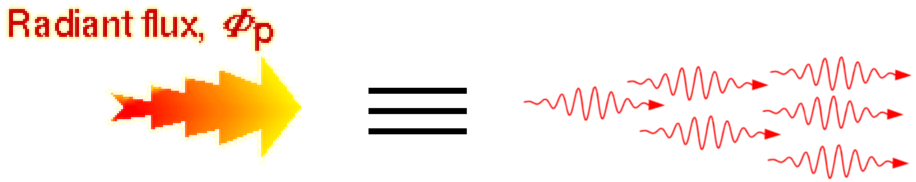
$$\textit{Optical Power} = \textit{Energy}_{\text{photon}} \times \textit{rate}$$

$$= h \times \nu \times \textit{rate}$$

Relies only on Planck’s constant, measurement of wavelength, and accurate measurement of rate

Independent of existing radiometry

Opportunity: Single Photon Tools for the Gap



Light arrives in packets (quanta – photon)

$$Optical\ Power = Energy_{\mathrm{photon}} \times rate$$

$$= h \times \nu \times rate$$

Source: that emits a known number of photons
Detector: that counts a known number of photons

Independent of existing radiometry standards &
Inherently single photon

Caution!

This talk:

- What this talk *is* about:
  - “Bridging the gap” between cryogenic radiometry & photon counting
- What this talk is *not* about:
  - “Quantum Candela”

Bridging-the-Gap efforts

Nuclear Instruments and Methods in Physics Research A 610 (2009) 183–187

Contents lists available at ScienceDirect

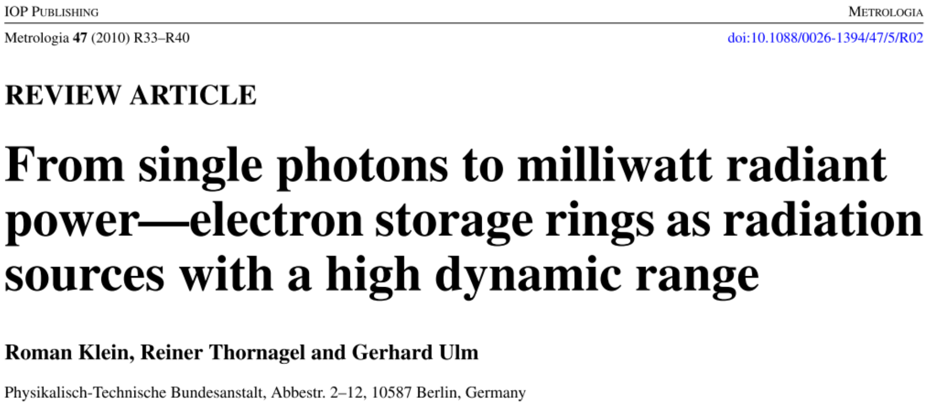
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Providing reference standards and metrology for the few photon–photon counting community

Andrew R. Beaumont, Jessica Y. Cheung *, Christopher J. Chunnilall, Jane Ireland, Malcolm G. White



IOP PUBLISHING METROLOGIA

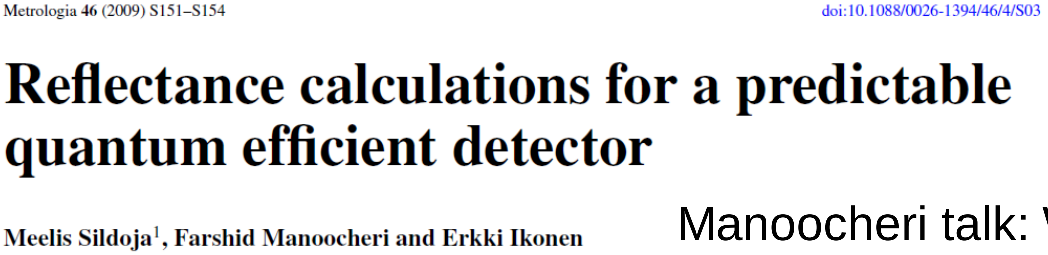
Metrologia **47** (2010) R33–R40 doi:10.1088/0026-1394/47/5/R02

REVIEW ARTICLE

From single photons to milliwatt radiant power—electron storage rings as radiation sources with a high dynamic range

Roman Klein, Reiner Thornagel and Gerhard Ulm

Physikalisch-Technische Bundesanstalt, Abbestr. 2–12, 10587 Berlin, Germany



Metrologia **46** (2009) S151–S154 doi:10.1088/0026-1394/46/4/S03

Reflectance calculations for a predictable quantum efficient detector

Meelis Sildoja[1], Farshid Manoocheri and Erkki Ikonen

Manoocheri talk: Wed

Few-Photon Metrology (many talks) at *NEWRAD & Single Photon Workshop* 2011

- Brida: Toward Traceable Few Photon Radiometry (NEWRAD)
- Arp: Calibration Of Photomultiplier Tubes For Few Photon Applications Using Synchrotron Radiation (NEWRAD)
- Gerrits: Extending Single-Photon Optimized Superconducting Transition Edge Sensors Beyond the Single-Photon Counting Regime (NEWRAD & SPW)
- Smith: Quantum-enhanced metrology in the real world: Losses, decoherence, and noise make life on the quantum edge challenging (SPW)
- Müller: Towards Traceable Calibration of Single Photon Detectors Using Synchrotron Radiation (NEWRAD & SPW)
- Rastello: Metrology Towards Quantum-Based Photon Standards (SPW)
- Porrovecchio: A transfer standard for the low power / few photon regime – the trap detector plus switched integrator amplifier (NEWRAD & SPW)
- Schmunk: Relative detection efficiency calibration of single photon avalanche photo detectors using non-classical light (SPW)
- Lehman: Fiber-Coupled Cryogenic Radiometer with Carbon Nanotube Absorber (NEWRAD)
- Götzinger, Single-photon sources with near unity efficiency (NEWRAD)
- Kück, Towards novel AlN and GaN based single photon sources (NEWRAD)

New Bridging-the-Gap efforts

Traceability for single-photon sources

The development of highly efficient quantum light sources at the single photon level and the development of entanglement assisted measurement techniques would enable classical measurement limits to be overcome. These new traceable photon sources will underpin the growth of several emerging technologies, such as optical devices for quantum communication, computing, microscopy, nanosciences, nanofabrication and other new production technologies, as well as fundamental metrology.

Objectives:
Traceability for single-photon sources

The JRP shall focus on the traceable measurement and characterisation of source-based standards for photon metrology spanning the range 1 photon/s to 10^8 photons/s.

The specific objectives are:

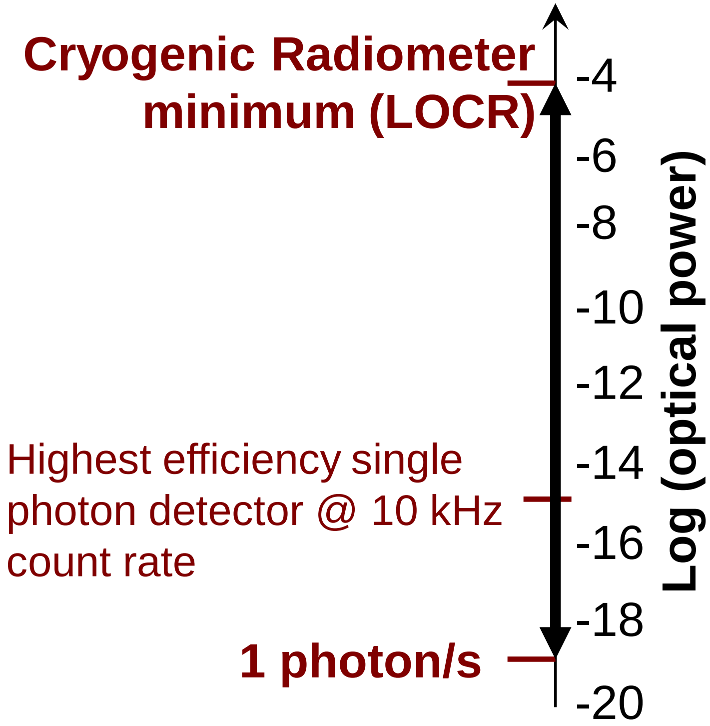
1. To develop absolute and calculable single photon sources with high dynamic range at both telecom and visible wavelengths.
2. To develop efficient single-photon sources, to support for SI traceable photon radiometry.
3. To develop quantum optical state sources for entanglement enhanced measurements.
4. To develop optimised photon-coupling strategies and methods between source and detector.

The sources developed in objectives 1-3, should be characterised for photon flux, and by appropriate metrics in terms of statistics, anti-bunching, indistinguishability, degree of entanglement and sub-shot-noise as required by the application.

Why is there cause for hope?

15 order-of-magnitude gap

between cryogenic radiometry and single-photon metrology



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Highest efficiency single photon detector @ 10 kHz count rate

1 photon/s

For λ = 1 µm photons
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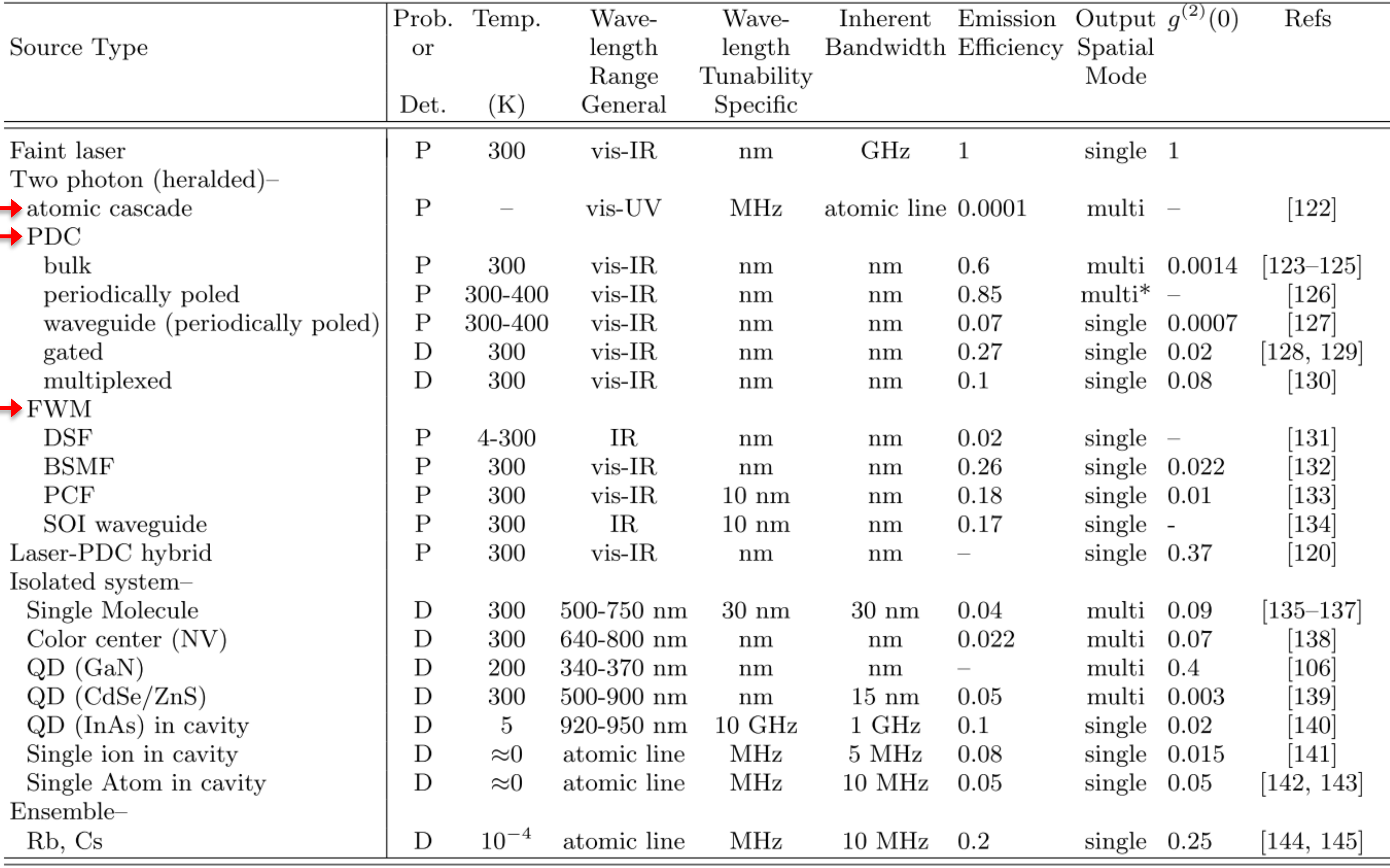
Single-Photon Sources

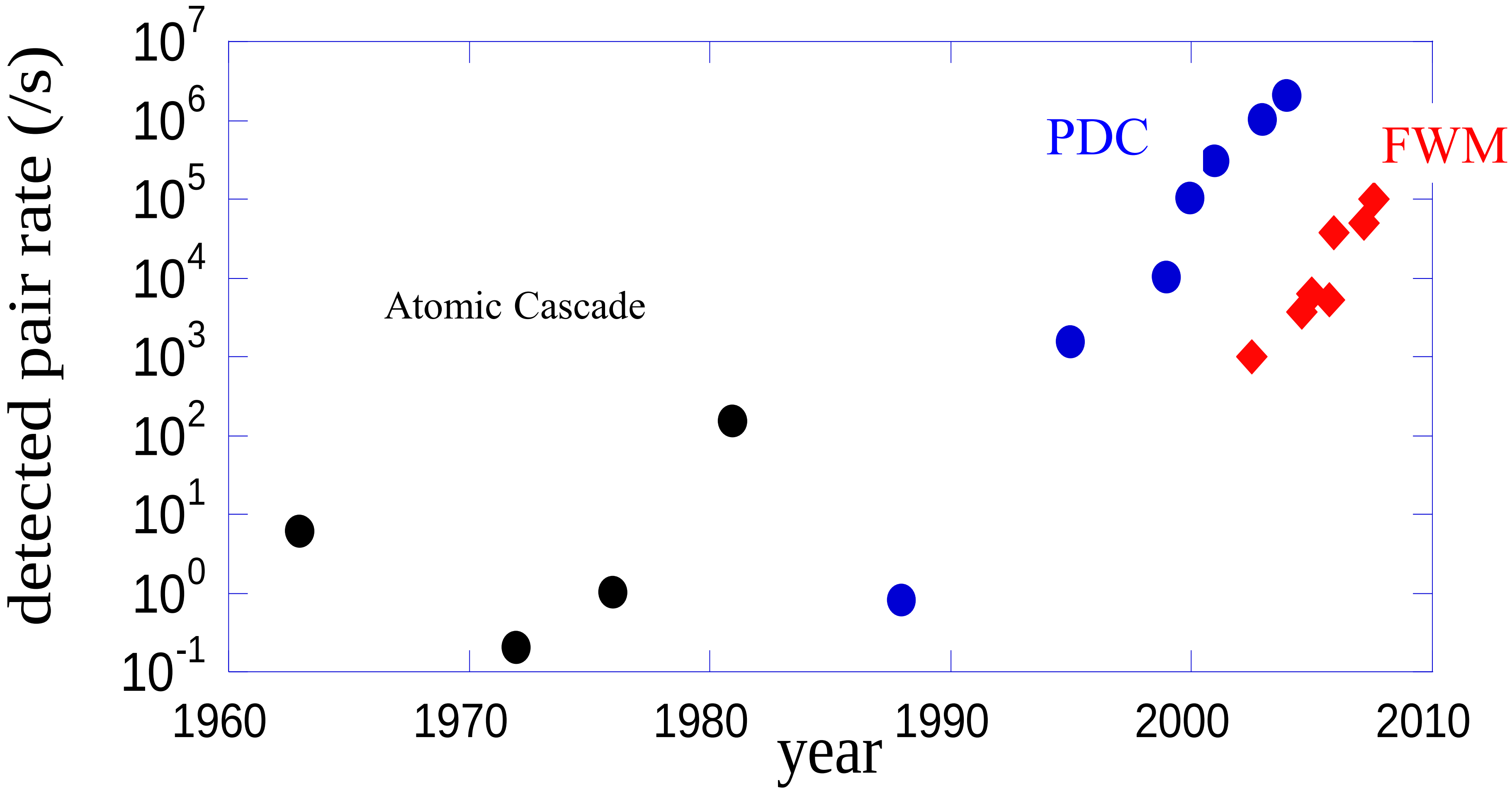
RSI **82**, 071101(2011)



Source Type	Prob. or Det.	Temp. (K)	Wave-length Range General	Wave-length Tunability Specific	Inherent Bandwidth	Emission Efficiency	Output Spatial Mode	$g^{(2)}(0)$	Refs
Faint laser	P	300	vis-IR	nm	GHz	1	single	1	
Two photon (heralded)–									
atomic cascade	P	–	vis-UV	MHz	atomic line	0.0001	multi	–	[122]
PDC									
bulk	P	300	vis-IR	nm	nm	0.6	multi	0.0014	[123–125]
periodically poled	P	300-400	vis-IR	nm	nm	0.85	multi*	–	[126]
waveguide (periodically poled)	P	300-400	vis-IR	nm	nm	0.07	single	0.0007	[127]
gated	D	300	vis-IR	nm	nm	0.27	single	0.02	[128, 129]
multiplexed	D	300	vis-IR	nm	nm	0.1	single	0.08	[130]
FWM									
DSF	P	4-300	IR	nm	nm	0.02	single	–	[131]
BSMF	P	300	vis-IR	nm	nm	0.26	single	0.022	[132]
PCF	P	300	vis-IR	10 nm	nm	0.18	single	0.01	[133]
SOI waveguide	P	300	IR	10 nm	nm	0.17	single	-	[134]
Laser-PDC hybrid	P	300	vis-IR	nm	nm	–	single	0.37	[120]
Isolated system–									
Single Molecule	D	300	500-750 nm	30 nm	30 nm	0.04	multi	0.09	[135–137]
Color center (NV)	D	300	640-800 nm	nm	nm	0.022	multi	0.07	[138]
QD (GaN)	D	200	340-370 nm	nm	nm	–	multi	0.4	[106]
QD (CdSe/ZnS)	D	300	500-900 nm	nm	15 nm	0.05	multi	0.003	[139]
QD (InAs) in cavity	D	5	920-950 nm	10 GHz	1 GHz	0.1	single	0.02	[140]
Single ion in cavity	D	≈0	atomic line	MHz	5 MHz	0.08	single	0.015	[141]
Single Atom in cavity	D	≈0	atomic line	MHz	10 MHz	0.05	single	0.05	[142, 143]
Ensemble–									
Rb, Cs	D	10^{-4}	atomic line	MHz	10 MHz	0.2	single	0.25	[144, 145]

Progress of Single-Photon Sources

(limited by detector saturation)



Single-Photon Detectors

η >50%

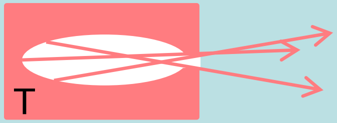
Detector Type	Operatio Temp. (K)	Efficiency Wavelength η(%), λ (nm)	Timing Jitter, δt(ns) (FWHM)	Dark-count Rate, D (ungated) (1/s)	Fig M	Max Count rate (10 /s)	PNR ıpability
PMT (visible–near-infrared) [271, 272]	300	40 @ 500	0.3	100	1.3×10^7	10	some
PMT (infrared) [273]	200	2 @ 1550	0.3	200000	3.3×10^2	10	some
Si SPAD (thick junction) [274]	250	65 @ 650	0.4	25	6.5×10^7	10	none
Si SPAD (shallow junction) [275]	250	49 @ 550	0.035	25	5.6×10^8	10	none
Si SPAD (self-differencing) [276]	250	74 @ 600	–	2000	–	16	some
Si SPAD (linear-mode) [277]	78	56 @ 450	–	0.0008	–	0.01	full*
Si SPAD (cavity) [278]	78	42 @ 780	0.035	3500	3.4×10^6	10	none
Si SPAD (multipixel) [279, 280]	290	40 @ 532	0.3	25000-500000	1×10^4	30	some
Hybrid PMT (PMT + APD) [281, 282]	270	30 @ 1064	0.2	30000	5×10^4	200	none
Time multiplexed (Si SPAD) [234]	250	39 @ 680	0.4	200	5×10^6	0.5	some
Time multiplexed (Si SPAD) [283]	250	50 @ 825	0.5	150	7×10^6	2	some
Space multiplexed (InGaAs SPAD) [284]	250	33 @ 1060	0.133	160000000	1.6×10^1	10	some
Space multiplexed (InGaAs SPAD) [285]	250	2 @ 1550	–	–	–	0.3	none
InGaAs SPAD (gated) [286]	200	10 @ 1550	0.370	91	3.0×10^5	0.01	none
InGaAs SPAD (self-differencing) [287]	240	10 @ 1550	0.055	16000	1.1×10^5	100	none
InGaAs SPAD (self-differencing) [267]	240	10 @ 1550	–	–	–	–	full
InGaAs SPAD (discharge pulse counting) [288]	243	7 @ 1550	–	40000	–	10	none
InP NFAD (monolithic negative feedback) [289, 290]	243	6 @ 1550	0.4	28000	–	10	some
InGaAs (self-quenching & self-recovery) [291]	300	– @ 1550	10	–	–	3	some
CIPD (InGaAs) [263]	4.2	80 @ 1310	–	–	–	0.001	full
Frequency up-conversion [292]	300	8.8 @ 1550	0.4	13000	1.7×10^4	10	none
Frequency up-conversion [254, 293]	300	56-59@ 1550	–	460000	–	5	none
Frequency up-conversion [294]	300	20 @ 1306	0.62	2200	1.5×10^5	10	none
VLPC [295]	7	88 @ 694	40	20000	1.1×10^3	10	some
VLPC [296]	7	40 @ 633	0.24	25000	6.7×10^4	10	some
SSPM [297]	6	76 @ 702	3.5	7000	3×10^4	30	full
TES(W) [298]	0.1	50 @ 1550	100	3	1.7×10^6	0.1	full
TES(W) [299]	0.1	95 @ 1556	100	–	–	0.1	full
TES(Ha) [300]	0.1	85 @ 850	100	–	–	0.1	full
TES (Ti) [301–303]	0.1	81-98 @ 850	100	–	–	1	full
SNSPD [304]	3	0.7 @ 1550	0.06	10	1.2×10^7	100	none
SNSPD (in cavity) [253]	1.5	57 @ 1550	0.03	–	–	1000	none
Parallel-SNSPD [262]	2	2 @ 1300	0.05	0.15	2.7×10^9	1000	some
STJ [258, 259, 305]	0.4	45 @ 350	2000	–	–	0.01	full
QD (resonant tunnel diode) [306]	4	12 @ 550	150	0.002	4×10^9	0.25	full
QDOGFET (field-effect transistor) [265, 307, 308]	4	2 @ 805	10000	150	10	0.05	full

>100 MHz

Radiometric Standards including single-photon tools

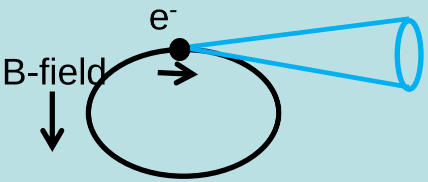
Sources

Blackbody



Temperature → Radiance

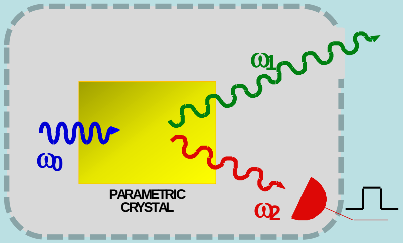
Synchrotron



B-field, current, energy → Radiance

Heralded Source

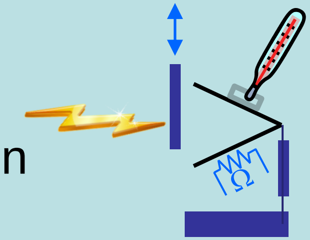
single photons



Detectors

Trap: Radiometer

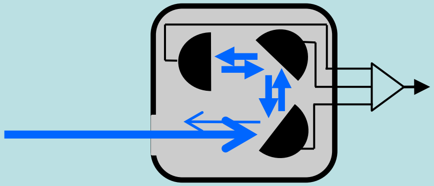
Electrical Substitution



Radiant power

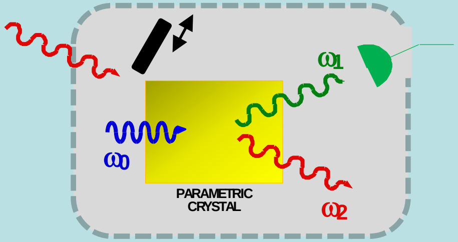
Trap:

Semiconductor



Radiant power

Radiance:

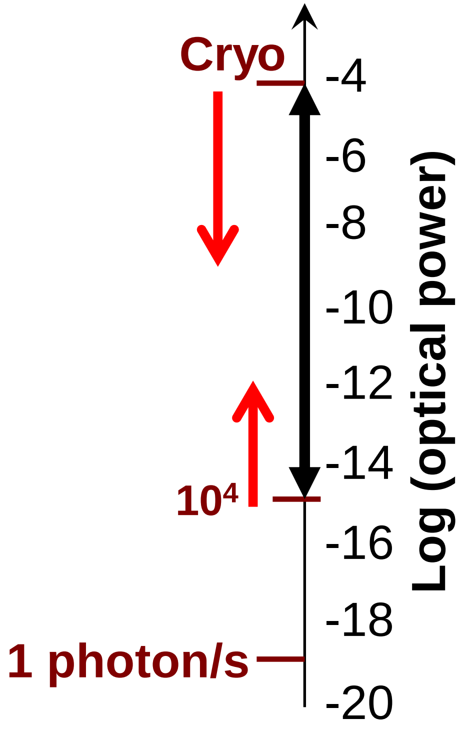


Bridging the Gap: from both ends

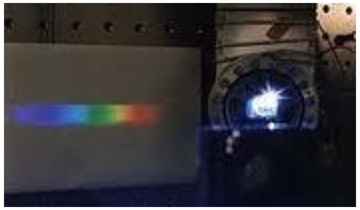
- Reaching downwards to photon counting levels
  - Cryogenic radiometers
  - Transfers from Cryogenic radiometers
  - Source standards
- Reaching upwards to cryogenic radiometry levels
  - Single photon sources-

    countable single photon generation rates
  - Single photon detectors-

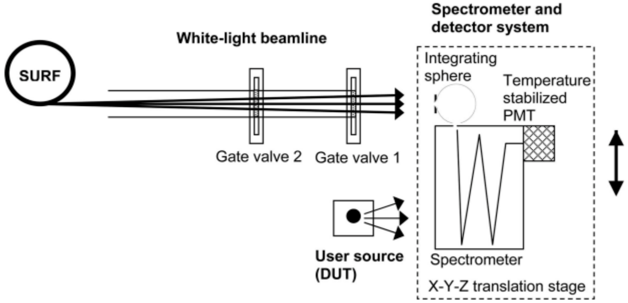
    countable single photon detection rates



Extending Source Dynamic Range Downward



Synchrotron linearity through
high dynamic range e$^-$ beam current



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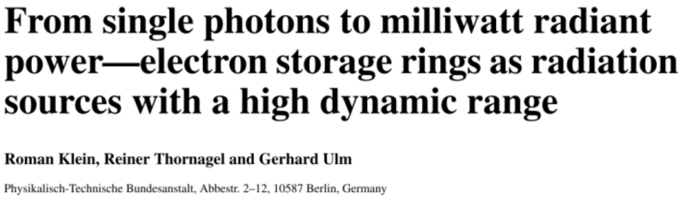
Metrologia **47** (2010) R33–R40

REVIEW ARTICI



From single photons to milliwatt radiant power—electron storage rings as radiation sources with a high dynamic range

Roman Klein, Reiner Thornagel and Gerhard Ulm

Physikalisch-Technische Bundesanstalt, Abbestr. 2–12, 10587 Berlin, Germany

11-Decade Dynamic Range achieved
Radiant intensity uncertainty 0.03%*
*Not including: Window transmittance, bandwidth

Irradiance uncertainty 0.36%
Appl. Opt. **46** 25(2007)

Source linearity through
high dynamic range Optical Density

OD=10 transmittance uncertainty=few %

Transmittance measurements for filters of optical density between one and ten

Z. M. Zhang, T. R. Gentile, A. L. Migdall, and R. U. Datla

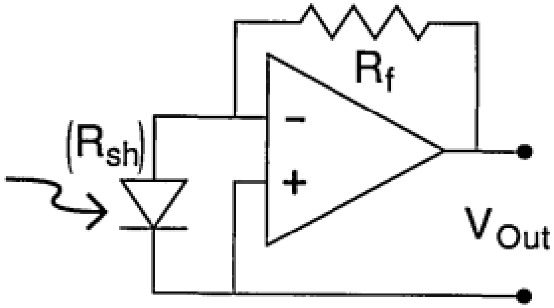
1 December 1997 / Vol. 36, No. 34 / APPLIED OPTICS 8889

Extending Detector Dynamic Range Downward

Si photodiode & amplifier

Noise= 800 photons/sec

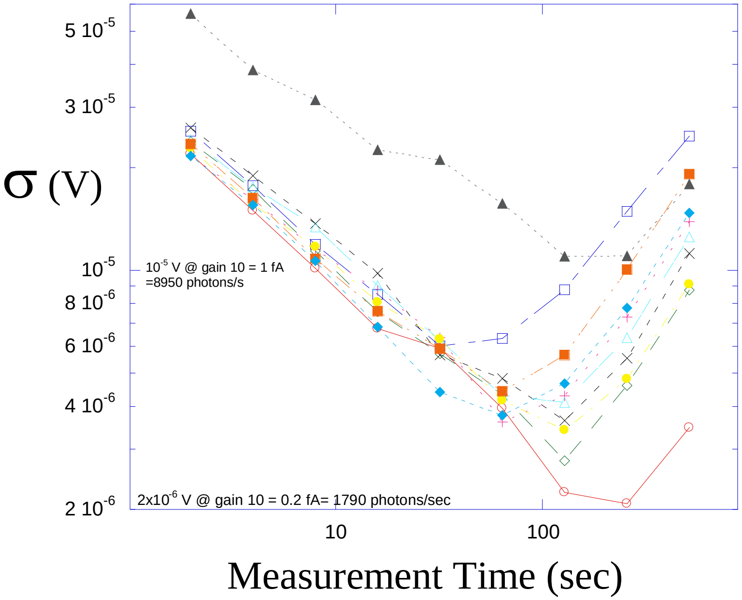
with 400 s measurement times



Fourteen-decade photocurrent measurements with large-area silicon photodiodes at room temperature

Appl. Opt. 30 3091(1991)

G. Eppeldauer and J. E. Hardis



equivalent
photon
noise

9000 photon/s

1800 photon/s

Extending Cryogenic Radiometer Dynamic Range Downward

- Typical Cryo Radiometer-
  - max power 1 mW
  - Noise 3 nW
  - Absolute accuracy 0.005%
- NIST pW-ACR (Carter et al. Metrologia 2009)
  - Temp sensor: noncontact TES magnetiza
  - Max power 20 nW
  - Noise 1 fW
  - Absolute accuracy 0.1%
- Fiber radiometer
  - < 1 nW noise
  - Flat absorber
  - Carbon nanotube

    (Lehman Tues. talk)

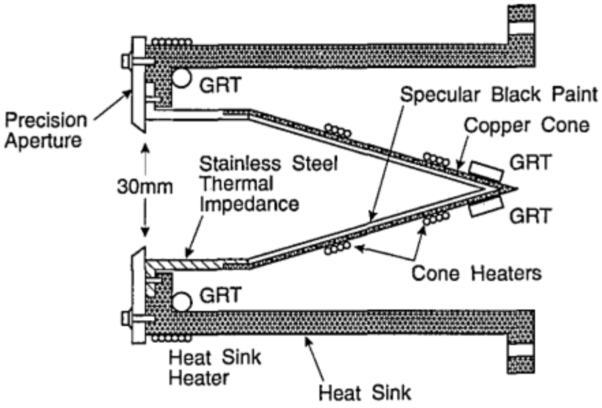


Fig. 5. ACR receiver subassembly.

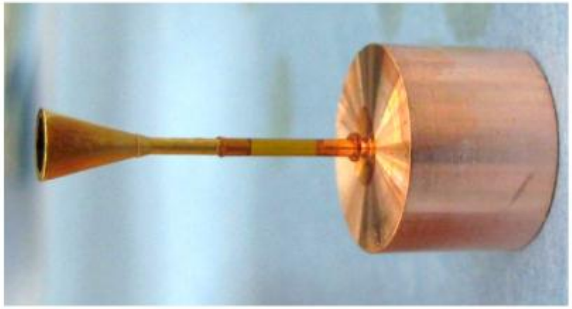
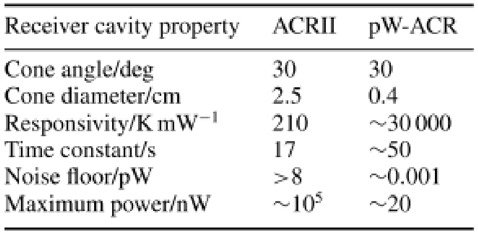


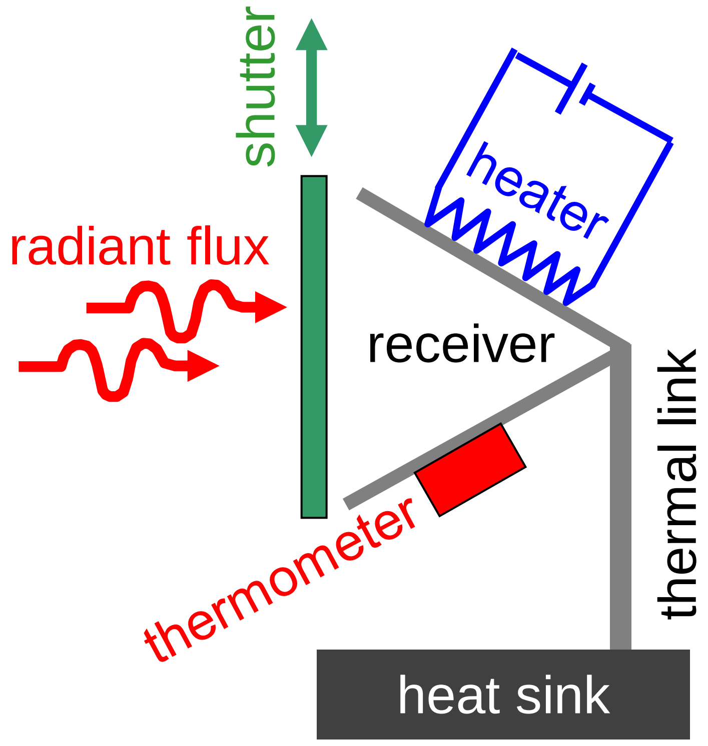
Figure 2. Photograph of a pW-ACR receiver cavity held in place by a thin Kapton tube. The receiver cone has a base diameter of 4 mm and is made from electroformed copper plated with gold. The Kapton has very low thermal conductance but is rigid enough to hold the cavity in place.

Table 1. Comparison of critical construction and performance parameters between the current ACRII and the planned pW-AC

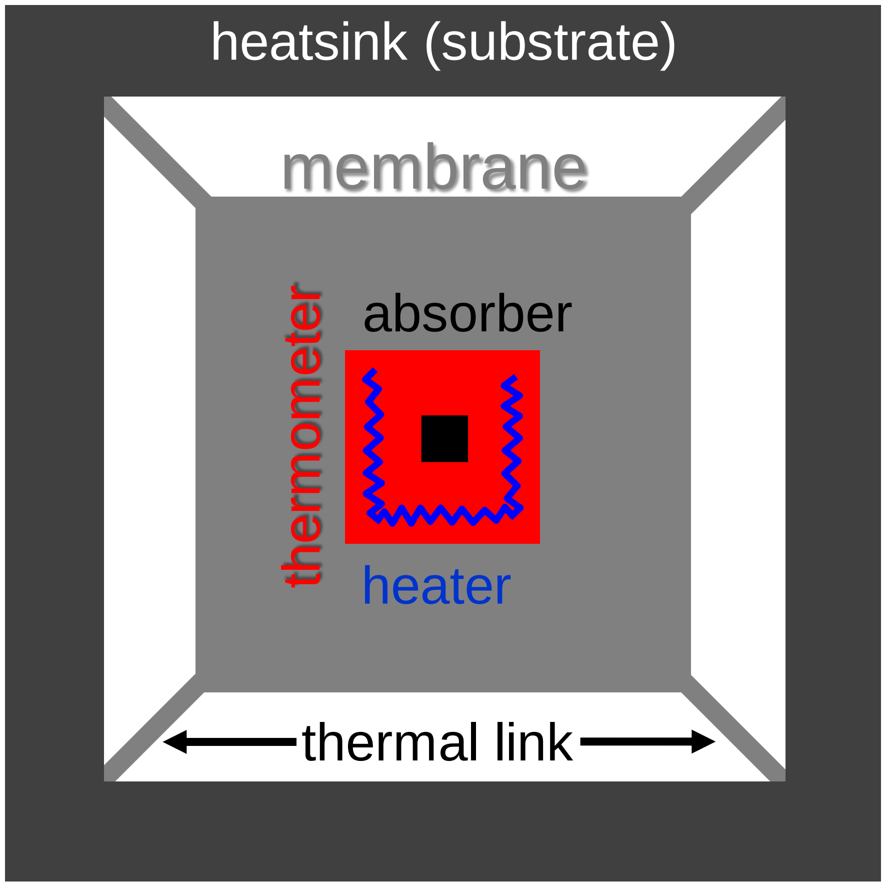


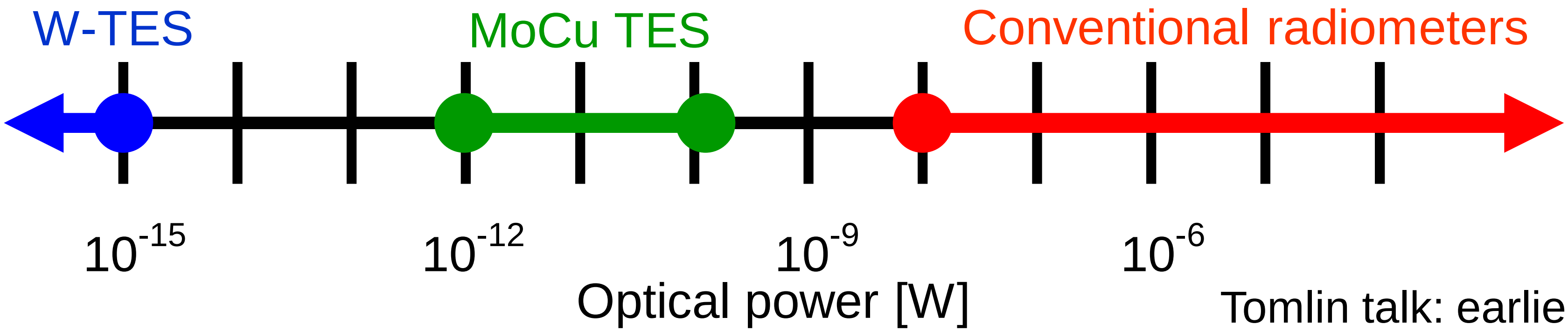
Receiver cavity property	ACRII	pW-ACR
Cone angle/deg	30	30
Cone diameter/cm	2.5	0.4
Responsivity/K mW^{-1}	210	~30 000
Time constant/s	17	~50
Noise floor/pW	>8	~0.001
Maximum power/nW	~10^5	~20

Conventional radiometer



pW-radiometer

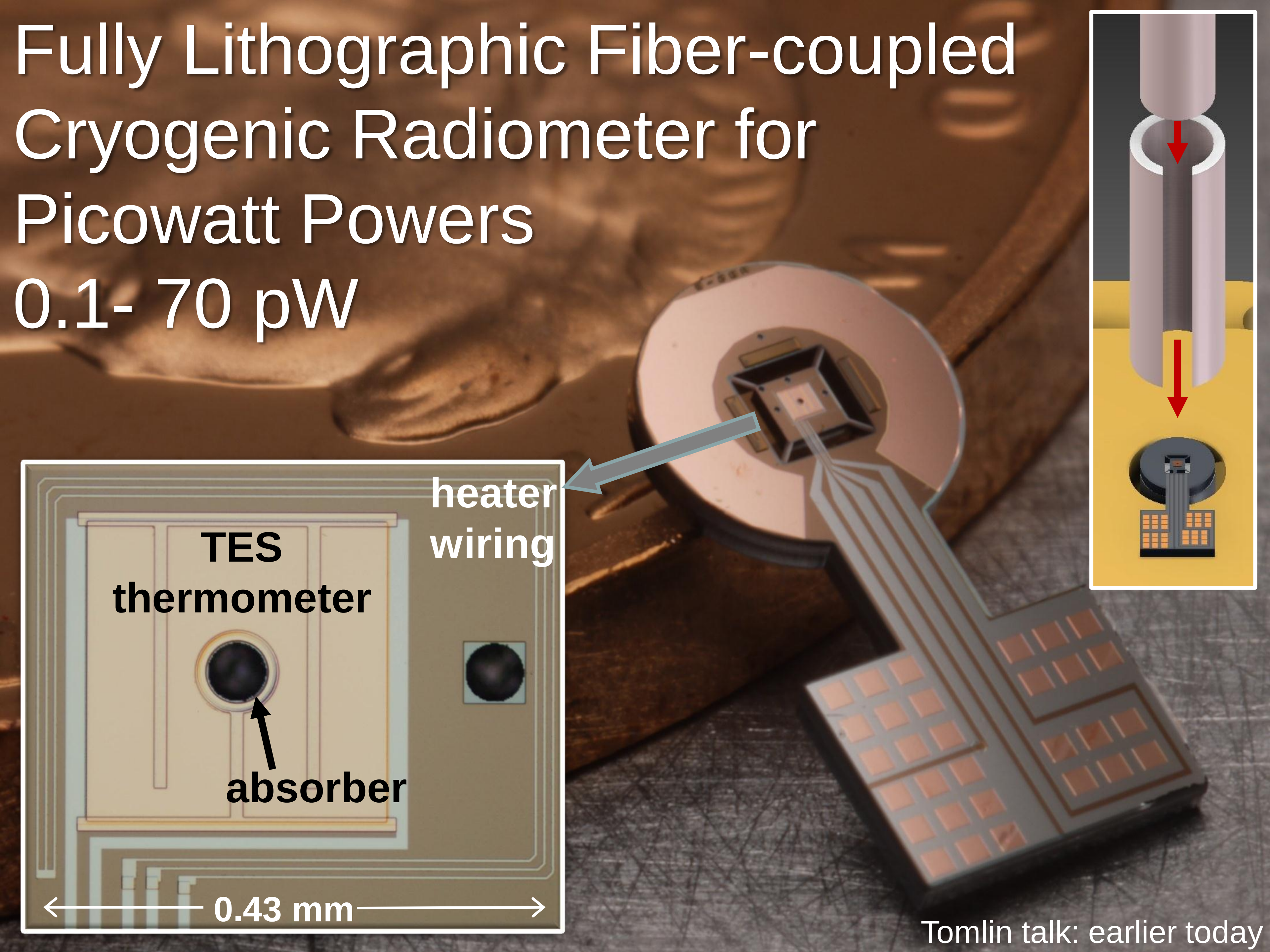




Tomlin talk: earlier today

Fully Lithographic Fiber-coupled Cryogenic Radiometer for Picowatt Powers

0.1- 70 pW

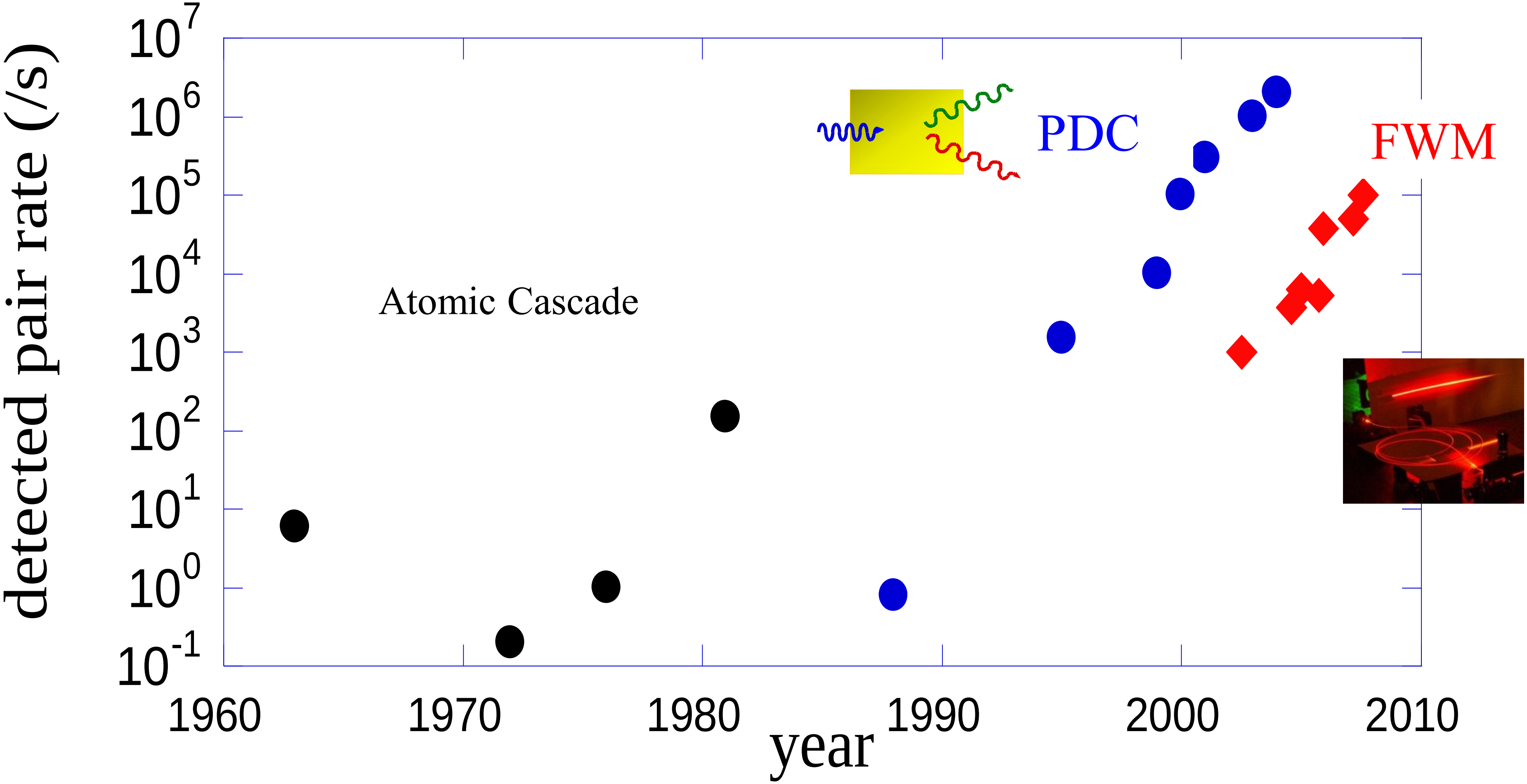


Tomlin talk: earlier today

Throwing Single Photon Tools at the Gap

Single Photon Sources Advancing

(limited by detector saturation)



Opportunity/ Dream

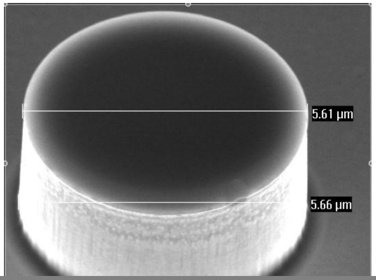
Return to a “standard candle” –
Single-photon devices that provide
Single-photons on demand

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

Turn present radiometry measurements into high accuracy counting measurements.

Change the way optical power is disseminated!!

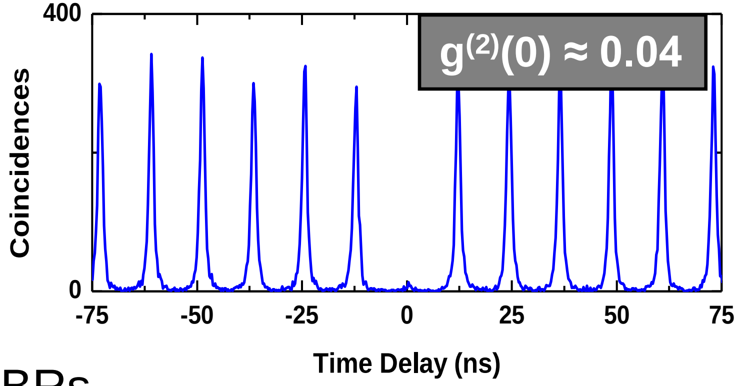
Quantum Dot single photon sources



Single QD in micropillar

Current limitations:	Goals:
emission rate (80 MHz)	3 GHz
emission efficiency (0.1%)	99%

First direct meas. of homogeneous linewidth; emission rate up to 10 GHz theoretically possible)



New Ideas

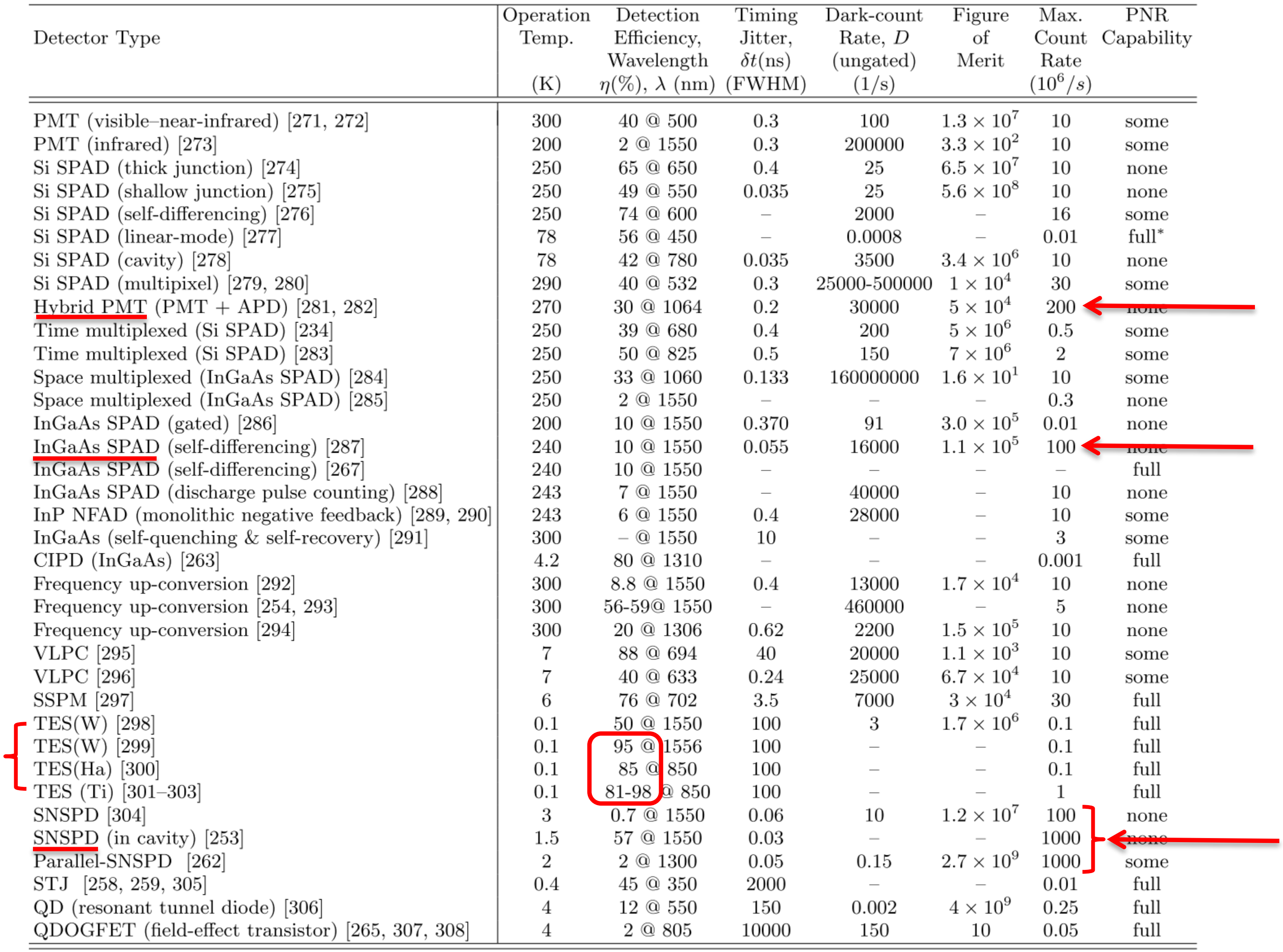
“inverse” QD single photon detector
(optical pump, electrical trigger)

3D microcavity: vertical oxide/semiconductor DBRs and transverse circular air/semiconductor DBRs

Ultimate outcome:

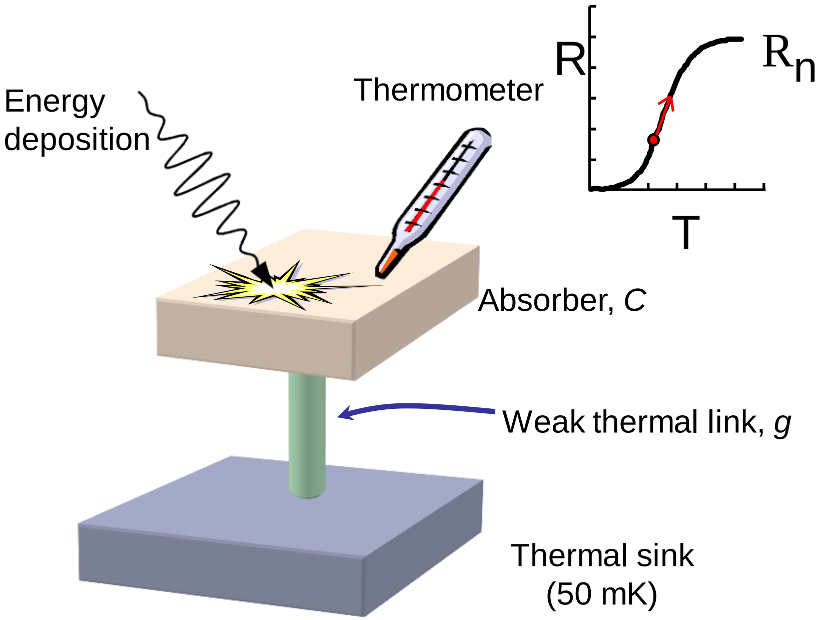
Countable photons-from-a-box for self-service traceability

Single Photon Detectors

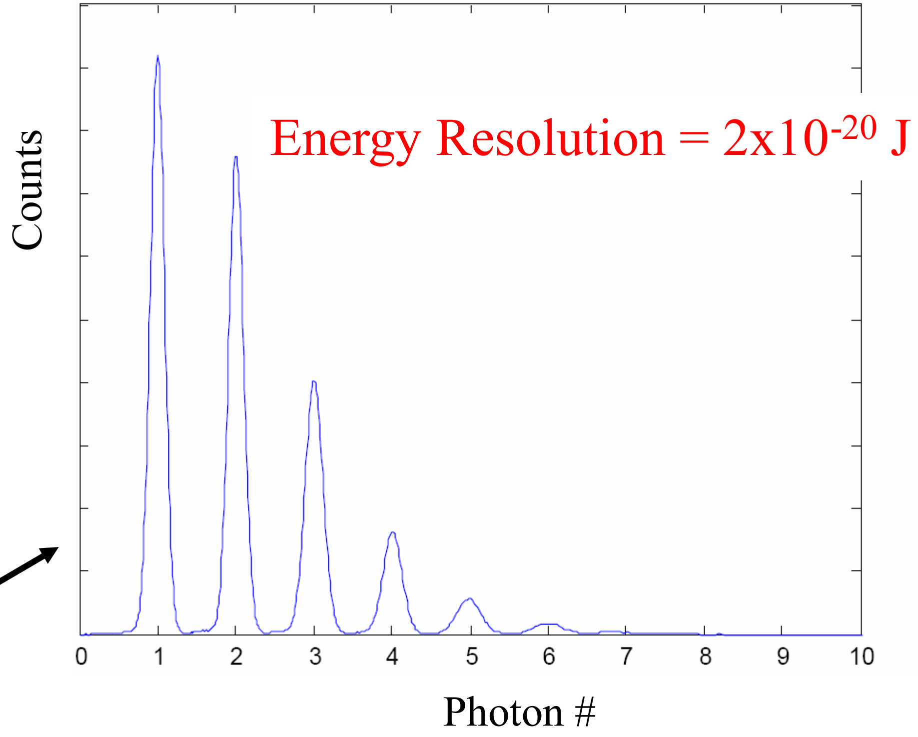


Detector Type	Operation Temp. (K)	Detection Efficiency, Wavelength η(%), λ (nm)	Timing Jitter, δt(ns) (FWHM)	Dark-count Rate, D (ungated) (1/s)	Figure of Merit	Max. Count Rate ($10^6/s$)	PNR Capability
PMT (visible–near-infrared) [271, 272]	300	40 @ 500	0.3	100	1.3×10^7	10	some
PMT (infrared) [273]	200	2 @ 1550	0.3	200000	3.3×10^2	10	some
Si SPAD (thick junction) [274]	250	65 @ 650	0.4	25	6.5×10^7	10	none
Si SPAD (shallow junction) [275]	250	49 @ 550	0.035	25	5.6×10^8	10	none
Si SPAD (self-differencing) [276]	250	74 @ 600	–	2000	–	16	some
Si SPAD (linear-mode) [277]	78	56 @ 450	–	0.0008	–	0.01	full*
Si SPAD (cavity) [278]	78	42 @ 780	0.035	3500	3.4×10^6	10	none
Si SPAD (multipixel) [279, 280]	290	40 @ 532	0.3	25000-500000	1×10^4	30	some
Hybrid PMT (PMT + APD) [281, 282]	270	30 @ 1064	0.2	30000	5×10^4	200	none
Time multiplexed (Si SPAD) [234]	250	39 @ 680	0.4	200	5×10^6	0.5	some
Time multiplexed (Si SPAD) [283]	250	50 @ 825	0.5	150	7×10^6	2	some
Space multiplexed (InGaAs SPAD) [284]	250	33 @ 1060	0.133	160000000	1.6×10^1	10	some
Space multiplexed (InGaAs SPAD) [285]	250	2 @ 1550	–	–	–	0.3	none
InGaAs SPAD (gated) [286]	200	10 @ 1550	0.370	91	3.0×10^5	0.01	none
InGaAs SPAD (self-differencing) [287]	240	10 @ 1550	0.055	16000	1.1×10^5	100	none
InGaAs SPAD (self-differencing) [267]	240	10 @ 1550	–	–	–	–	full
InGaAs SPAD (discharge pulse counting) [288]	243	7 @ 1550	–	40000	–	10	none
InP NFAD (monolithic negative feedback) [289, 290]	243	6 @ 1550	0.4	28000	–	10	some
InGaAs (self-quenching & self-recovery) [291]	300	– @ 1550	10	–	–	3	some
CIPD (InGaAs) [263]	4.2	80 @ 1310	–	–	–	0.001	full
Frequency up-conversion [292]	300	8.8 @ 1550	0.4	13000	1.7×10^4	10	none
Frequency up-conversion [254, 293]	300	56-59@ 1550	–	460000	–	5	none
Frequency up-conversion [294]	300	20 @ 1306	0.62	2200	1.5×10^5	10	none
VLPC [295]	7	88 @ 694	40	20000	1.1×10^3	10	some
VLPC [296]	7	40 @ 633	0.24	25000	6.7×10^4	10	some
SSPM [297]	6	76 @ 702	3.5	7000	3×10^4	30	full
TES(W) [298]	0.1	50 @ 1550	100	3	1.7×10^6	0.1	full
TES(W) [299]	0.1	95 @ 1556	100	–	–	0.1	full
TES(Ha) [300]	0.1	85 @ 850	100	–	–	0.1	full
TES (Ti) [301–303]	0.1	81-98 @ 850	100	–	–	1	full
SNSPD [304]	3	0.7 @ 1550	0.06	10	1.2×10^7	100	none
SNSPD (in cavity) [253]	1.5	57 @ 1550	0.03	–	–	1000	none
Parallel-SNSPD [262]	2	2 @ 1300	0.05	0.15	2.7×10^9	1000	some
STJ [258, 259, 305]	0.4	45 @ 350	2000	–	–	0.01	full
QD (resonant tunnel diode) [306]	4	12 @ 550	150	0.002	4×10^9	0.25	full
QDOGFET (field-effect transistor) [265, 307, 308]	4	2 @ 805	10000	150	10	0.05	full

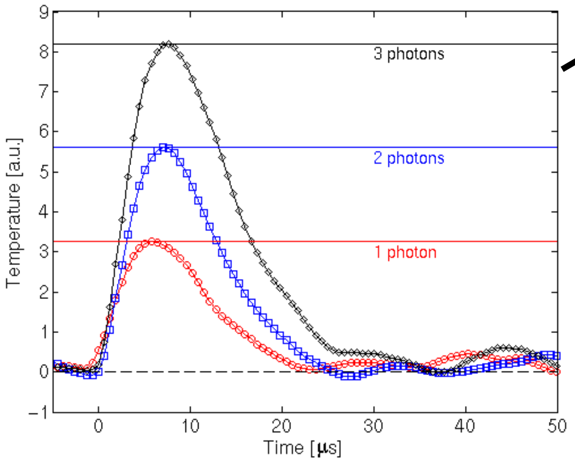
Transition Edge Sensor (TES) Microbolometer



Optimized for λ = 1550 & 810 nm, DE 98+%



Energy Resolution = 2×10^{-20} J !



It Can Really Count Photons

- Optimized now for photon-number resolution, not speed (τ_{rise}~100 ns, τ_{fall}~few μs)
- Absorption events show good distinguishability
- Much slower than APDs

S. Nam

Transition Edge Sensors – Photon Number resolving

Current performance:

Detection efficiency >95% U = ?? at 1550nm

recovery times approaching 1μs

Strategy to reach goals:

Optical packaging

Coating design

Material science for compability of coatings with superconductors

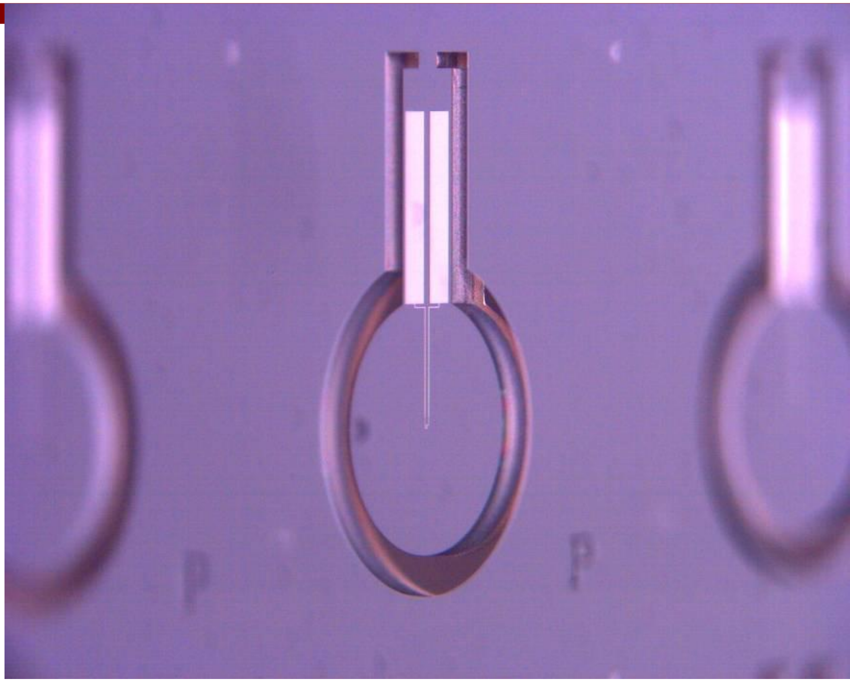
Fast electronics

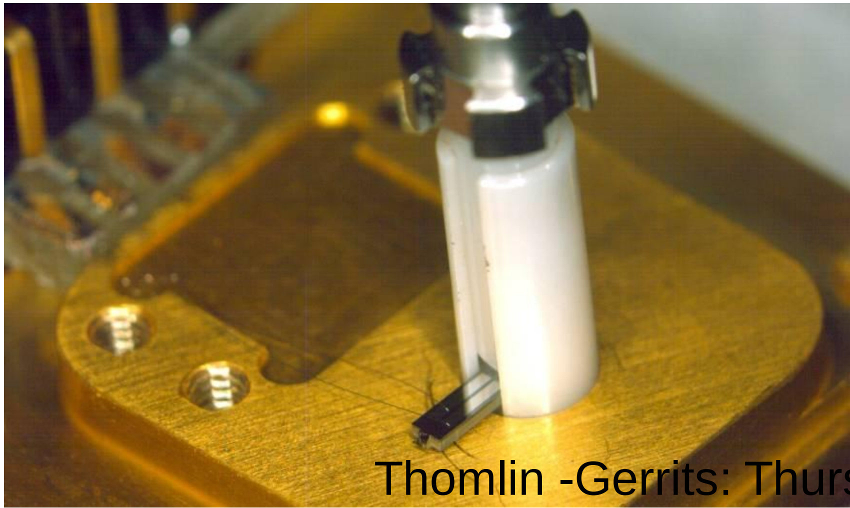
Possibility:

Recovery times < 1μs

Detection efficiency >99%

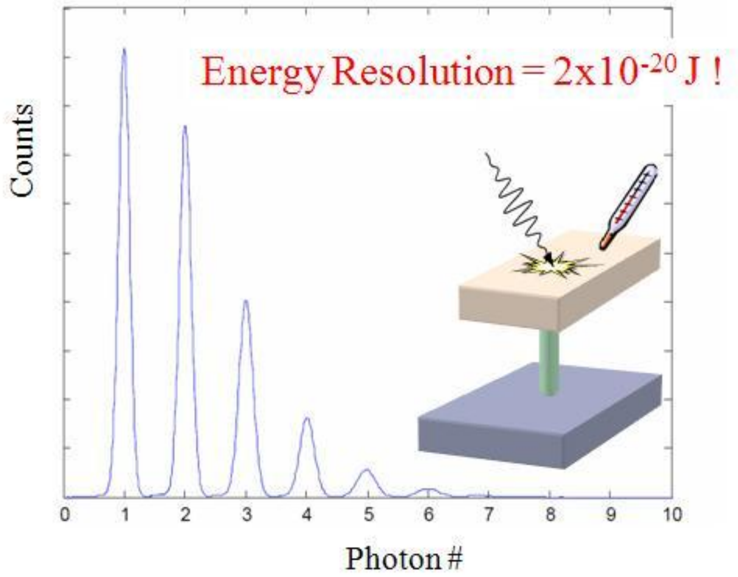
Plus ……



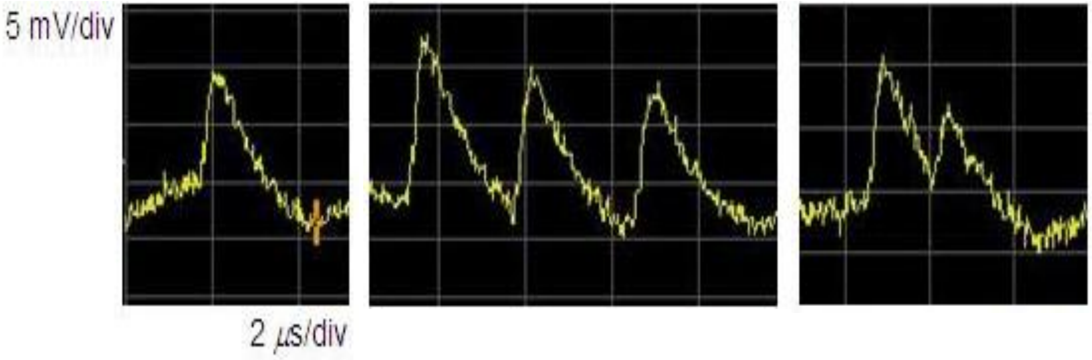


Thomlin -Gerrits: Thurs

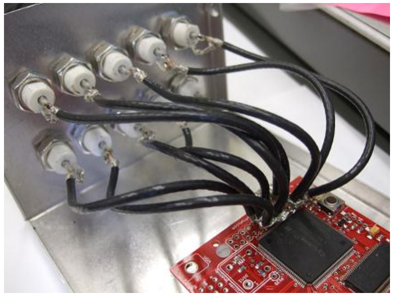
Smart TES signal processing



No inherent deadtime:

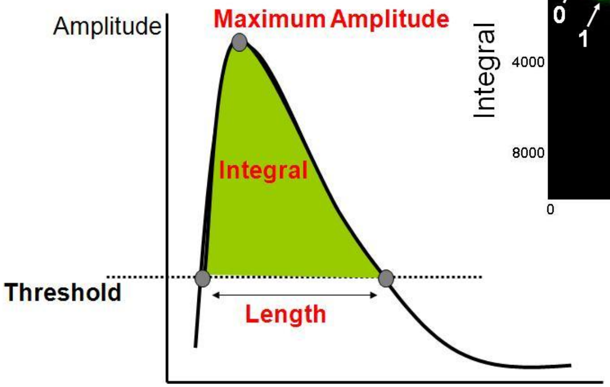


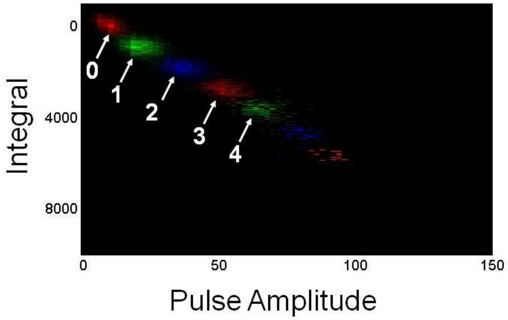
Deadtime-free processing:



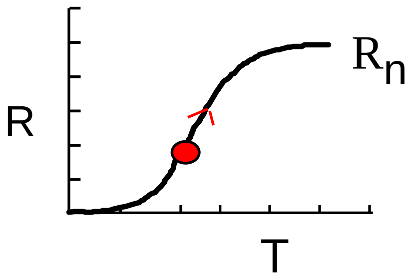
Simple, cheap, high throughput signal processor

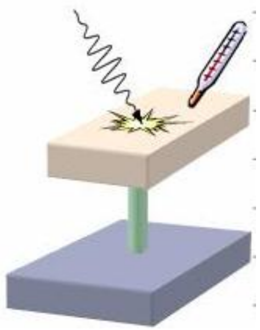
physics.nist.gov/Divisions/Div844/FPGA/fpga.html



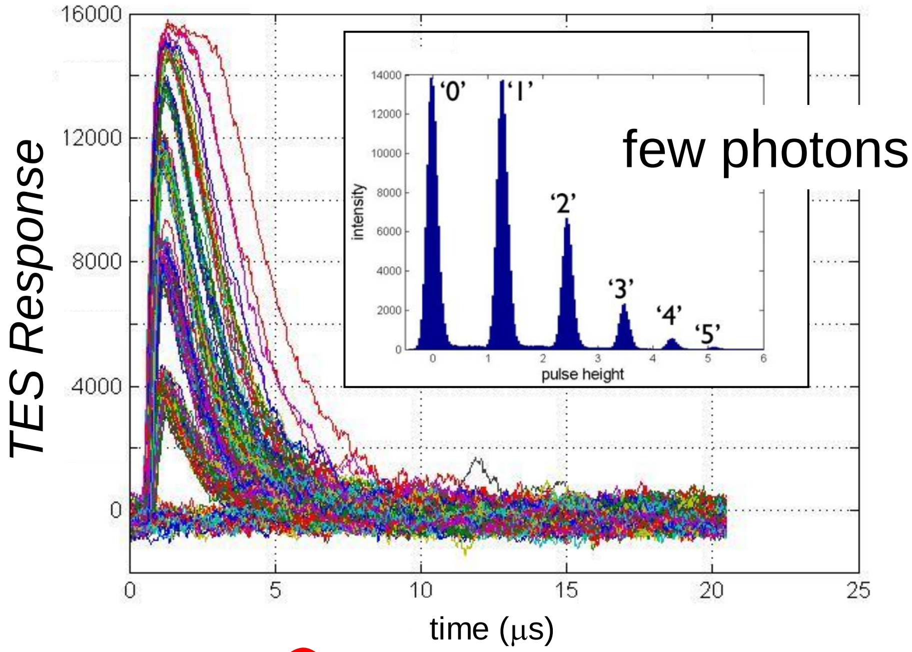


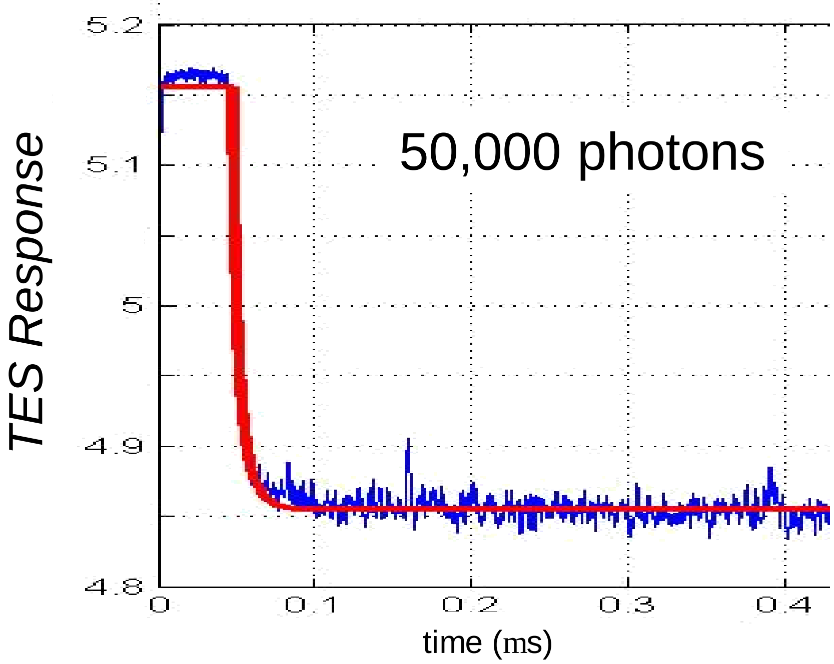
Transition Edge Sensor: Pushing the Limits

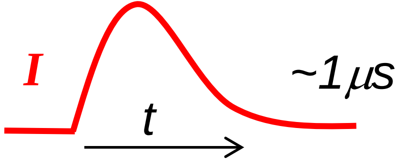




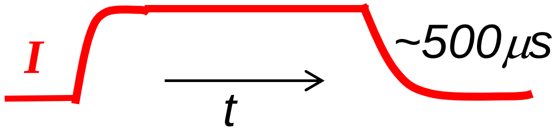
Thomas Gerrits
Talk by Tomlin
later today







Amplitude vs. Width



Superconducting Nanowire Single-Photon Detector (SNSPD)

Current performance:

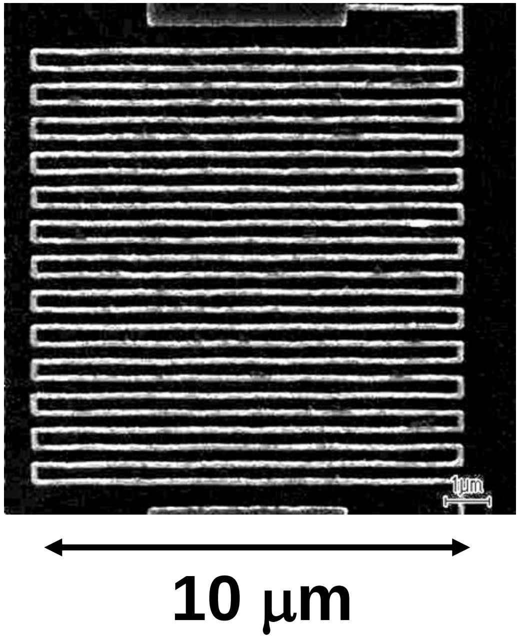
- Detection efficiency ~1% at 1550nm
- recovery times ~20ns

Strategy to reach goals:

- Make Detectors at NIST
- Optical packaging and coating design
- Coating design
- Material science for compability of coatings with superconductors
- Fast electronics

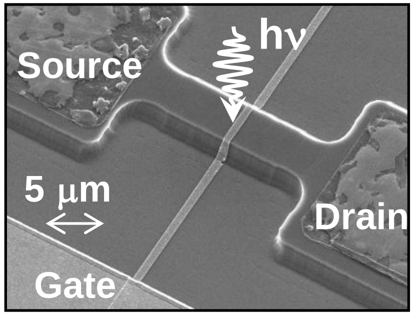
Outcomes:

- Detection efficiency >75%
- High count rates (>100 MHz)



Extremely challenging nanofabrication and material science problem

Quantum Dot Single-Photon Detector (QDOGFET)



Current limitations:	Goals:
detection rate: 400 kHz*	1 MHz – 10 MHz
counting: 10^3 photons	10^4-10^5 photons

$$10^4 \frac{\gamma}{\text{bunch}} \text{ X } 10^6 \frac{\text{bunch}}{\text{s}} = 10^{10} \text{ Hz}$$

*B. E. Kardynal, *et al.*, Appl. Phys. Lett. **84**, 419 (2004).

Idea:

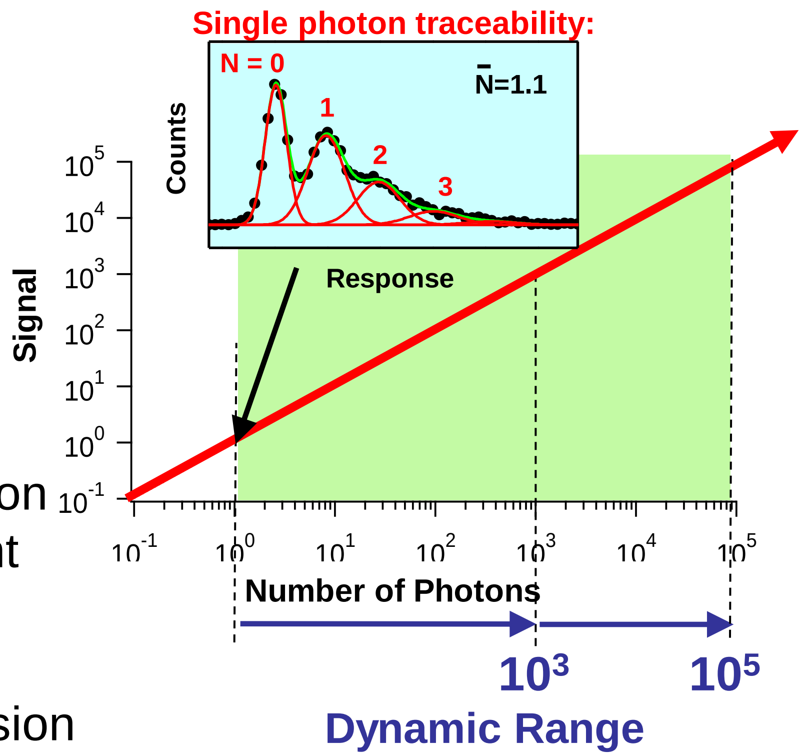
Use the QDOGFET's number sensitive ability (over a large dynamic range) to count bunches of photons. This way you don't have to count **so fast**!

Challenges:

Speed/noise: use on-chip cryogenic amplification

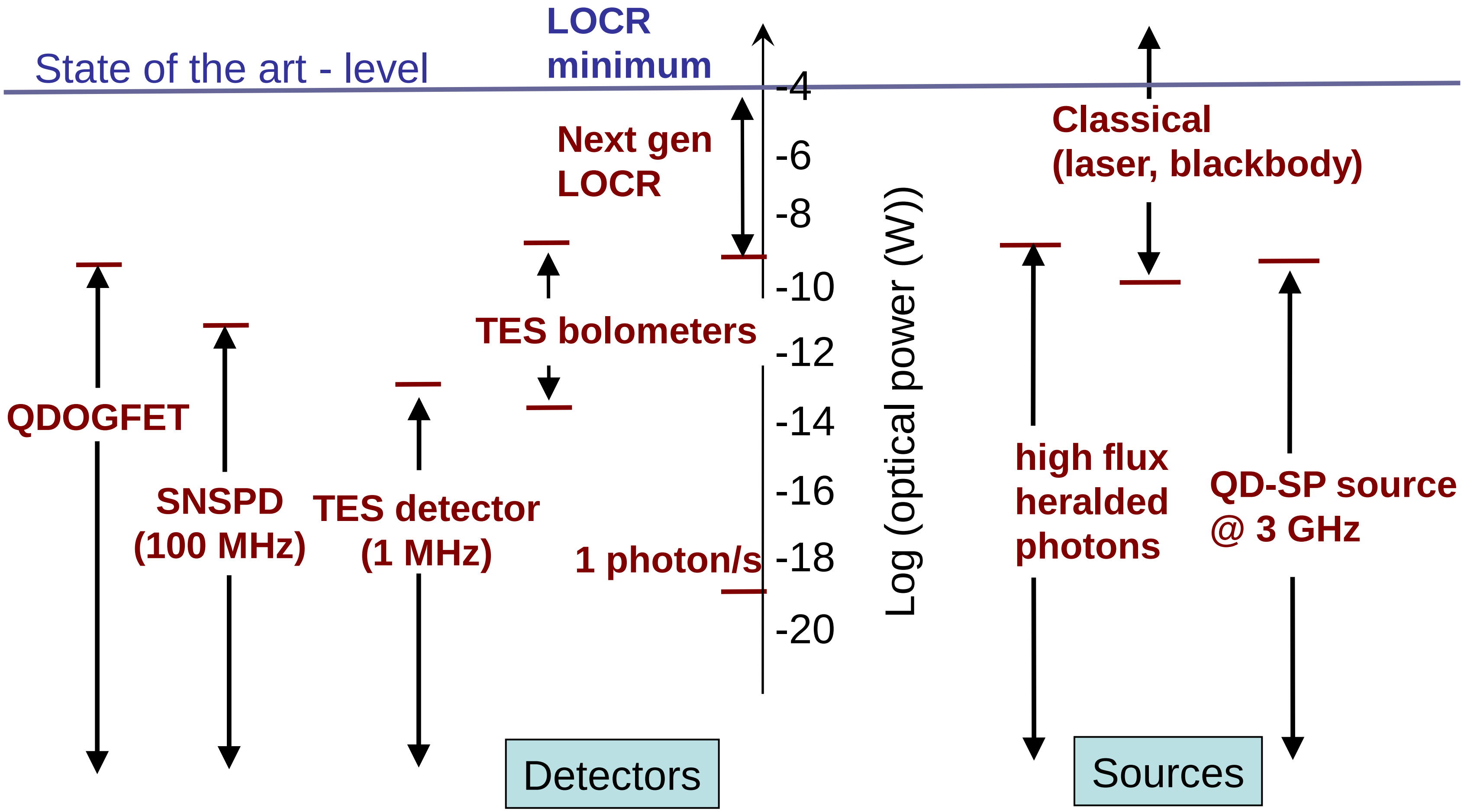
Overall detection efficiency: integrated resonant cavity design, solid emersion lens coupling, transparent gate

Understand the dynamic range with great precision



Bridge Plan: Overlap power ranges

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



LOCR minimum

Next gen LOCR

TES bolometers

QDOGFET

SNSPD (100 MHz)

TES detector (1 MHz)

1 photon/s

Detectors

Classical (laser, blackbody)

high flux heralded photons

QD-SP source @ 3 GHz

Sources

Promise and Concern

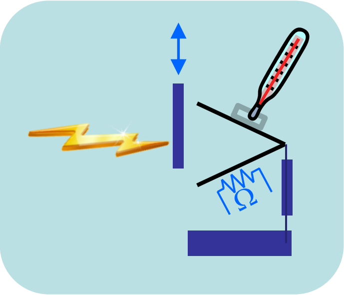
- Single Photon radiometry: holds promise of moving radiometry to counting problem

- Efficiencies remain an issue

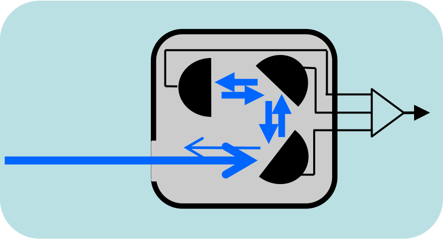
Common Issue: Efficiency

Trap:

Collection efficiency

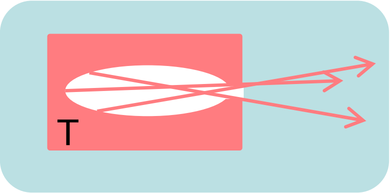


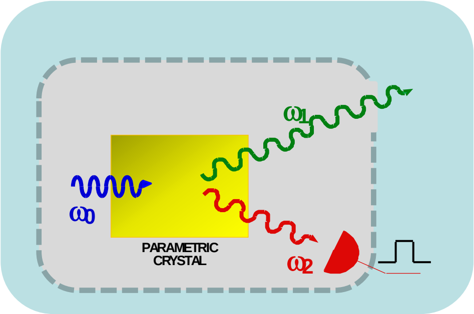
99.997(3)%



99.6(1)%

Extraction efficiency

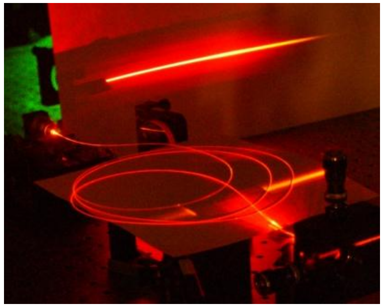


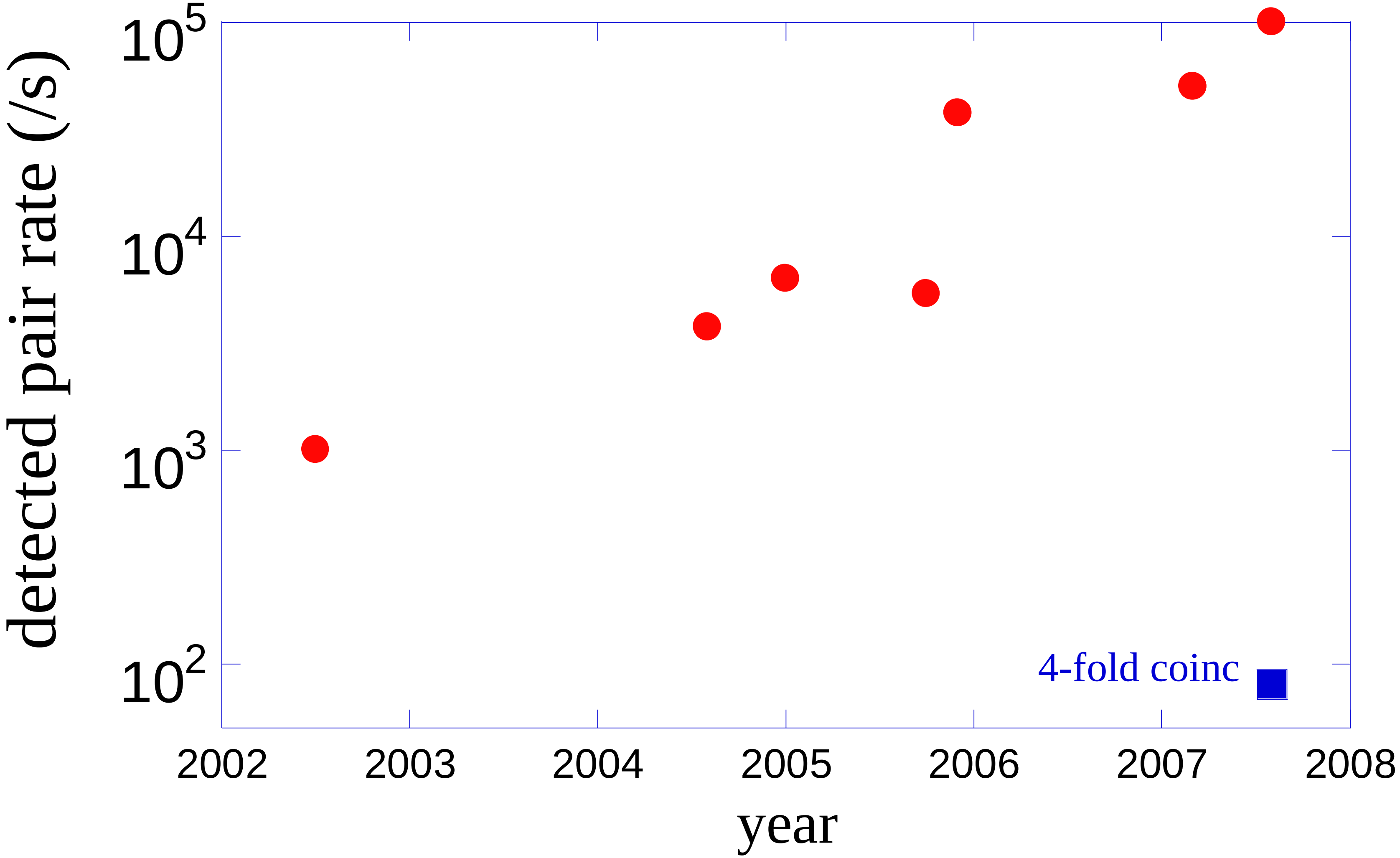


80.83(13)%

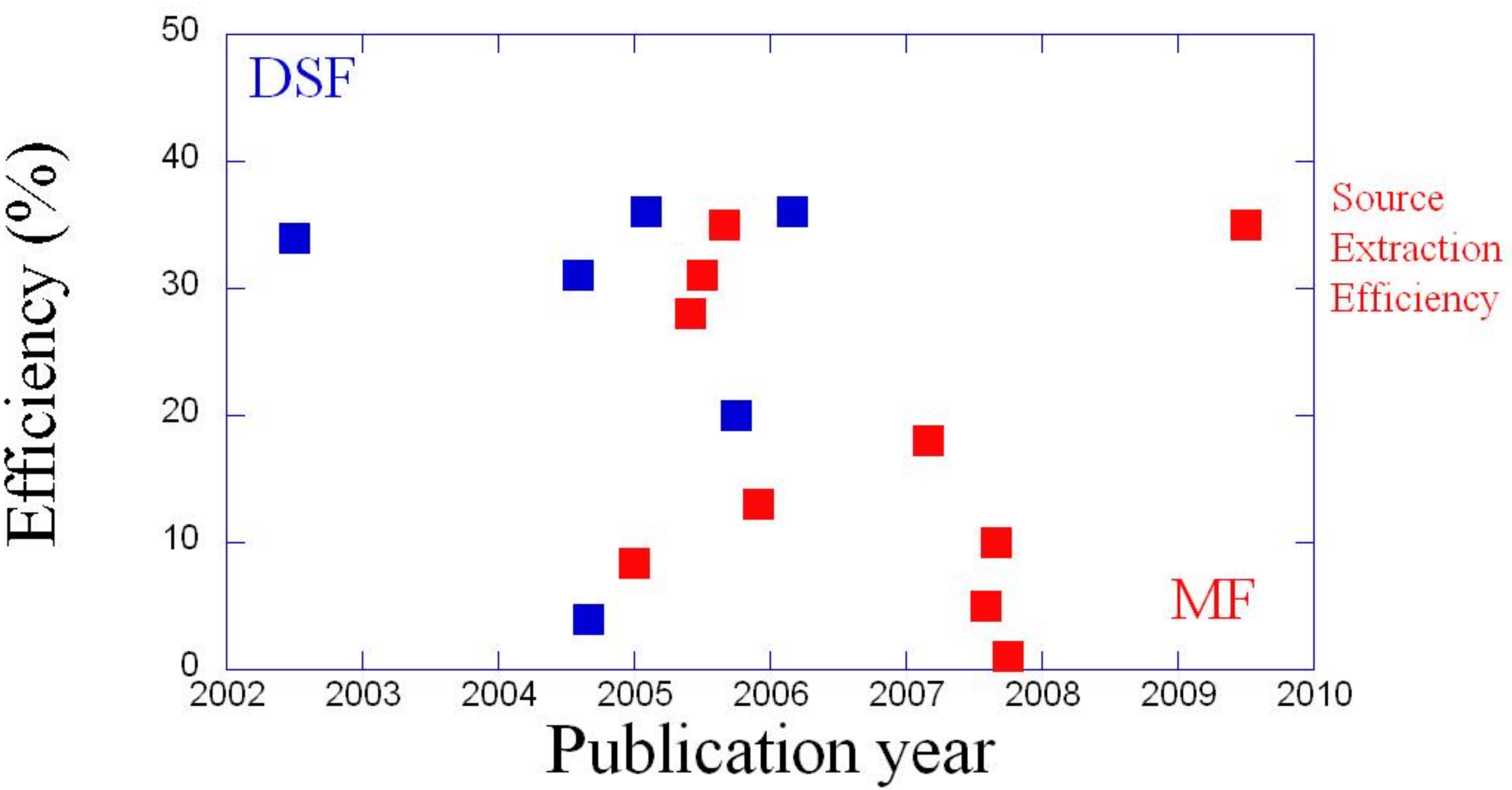
Single Photon Examples of Efficiency Issues

FWM Fiber Source Brightness Progress



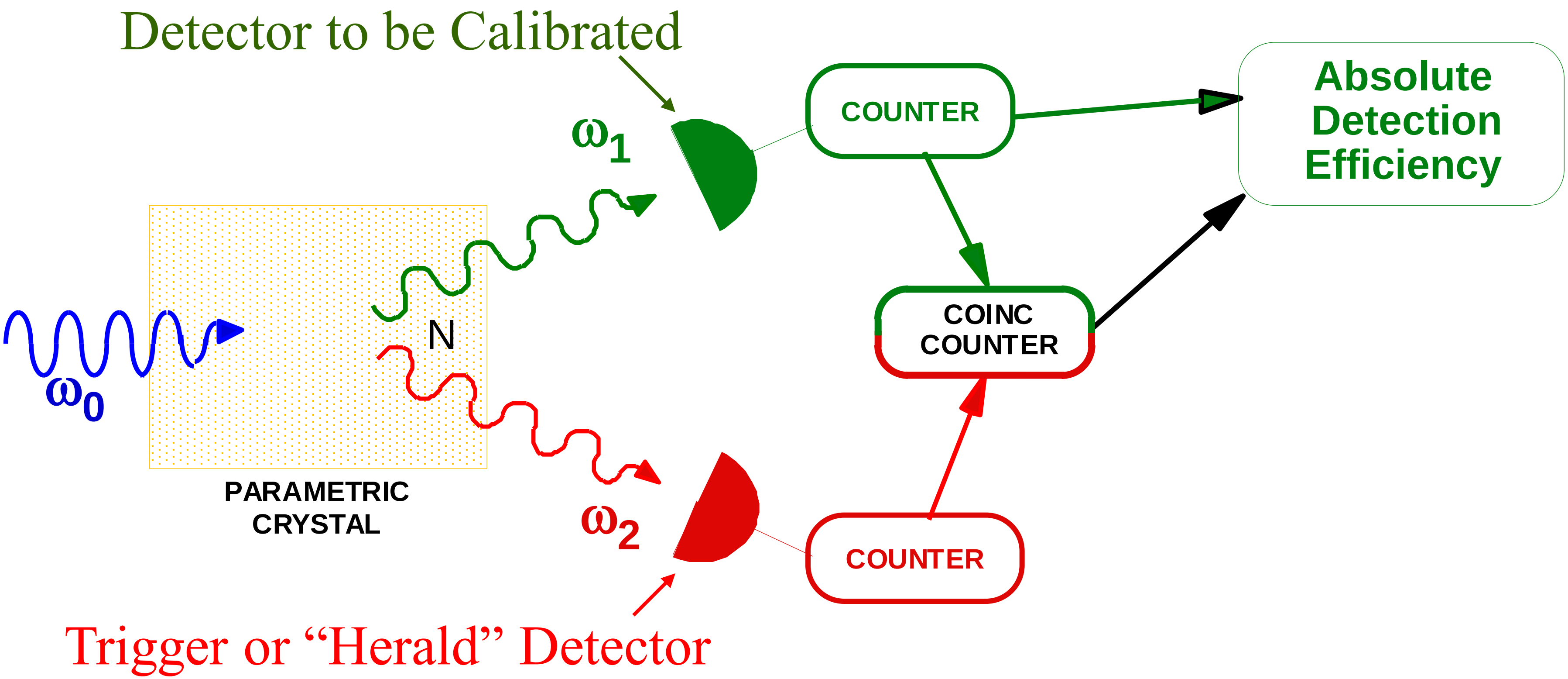


Fiber Source Efficiency Progress



Two-Photon Detector Efficiency Scheme

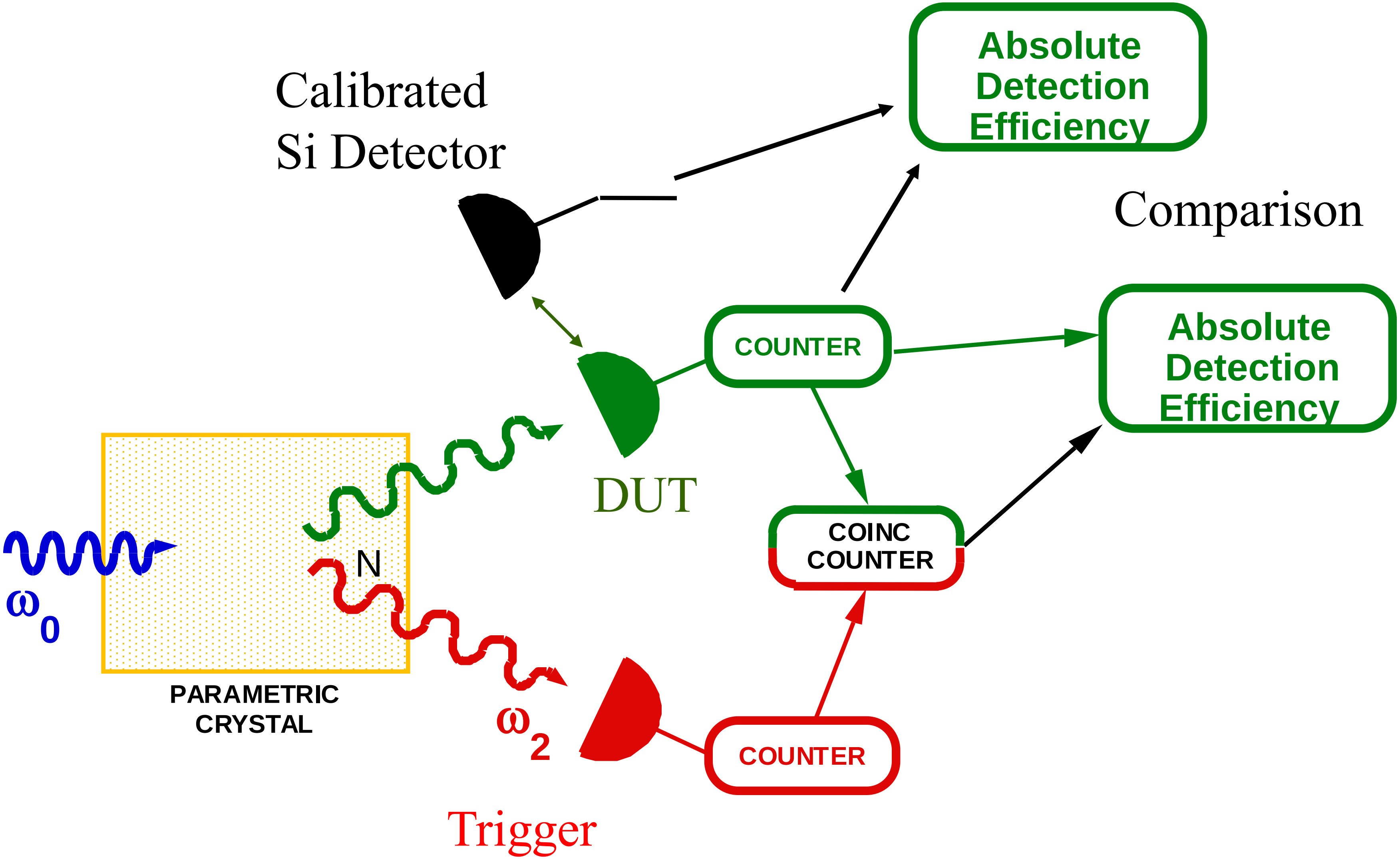
No External Standards Needed!



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

$$\eta_1=N_C/N_2$$

Verifying the Method

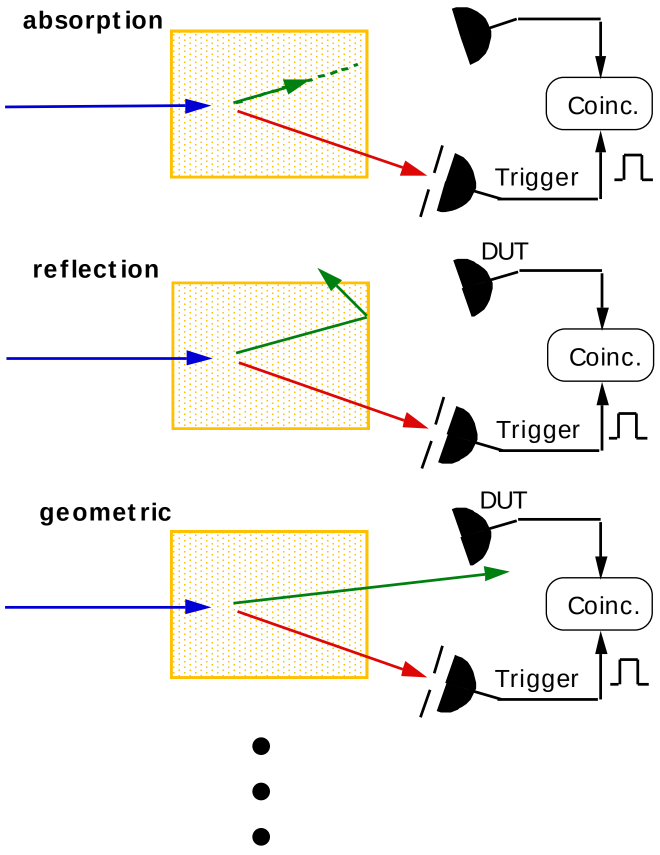


Two-Photon-Based SPD Detection Efficiency Calibration

Sources of uncertainty:

DUT Collection Efficiencies

- **Spatial**
- **Angular**
- **Spectral**
- **…**



Trigger counting

Coincidence determination

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%**	

Detector substitution calibration uncertainty budget

Physical property	Value	Relative uncertainty of value (%)	Sensitivity	Relative uncertainty of DE (%)
Analog transfer standard calibration (QE equivalent)	0.61906	0.10%	1	0.10%
Spatial nonuniformity at 700nm, (standard deviation of central responsivity)	1	0.025%	1	0.025%
Analog measurement statistics & drift				0.06%
Analog amplifier gain calibration	1.0022	0.050%	1	0.05%
Pinhole backside reflection	0	0.1%	1	0.10%
DUT signal & background statistics				0.003%
DUT afterpulsing	0.00322	11.6%	0.003	0.04%
DUT deadtime (due to rate changes with time)				0.02%
Total Uncertainty				**0.17%**

Summary of Single-Photon Promise and Concerns

- Single Photon radiometry: holds promise of moving radiometry to counting problem
- Efficiencies remain an issue
- Building bridges is good
- Burning a Candela requires caution