Efficient Multiple Photon Discrimination

Limits and Limitations

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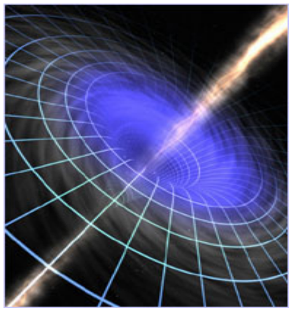
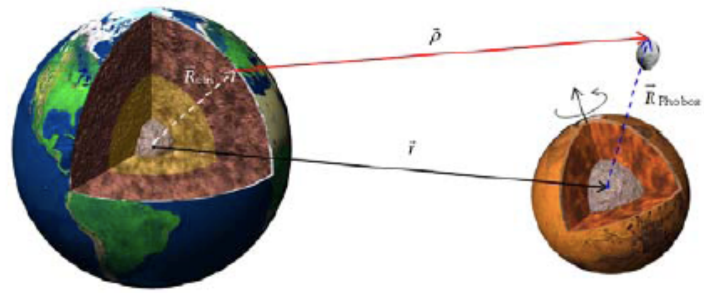
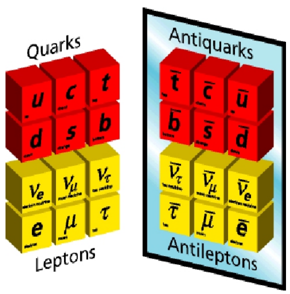


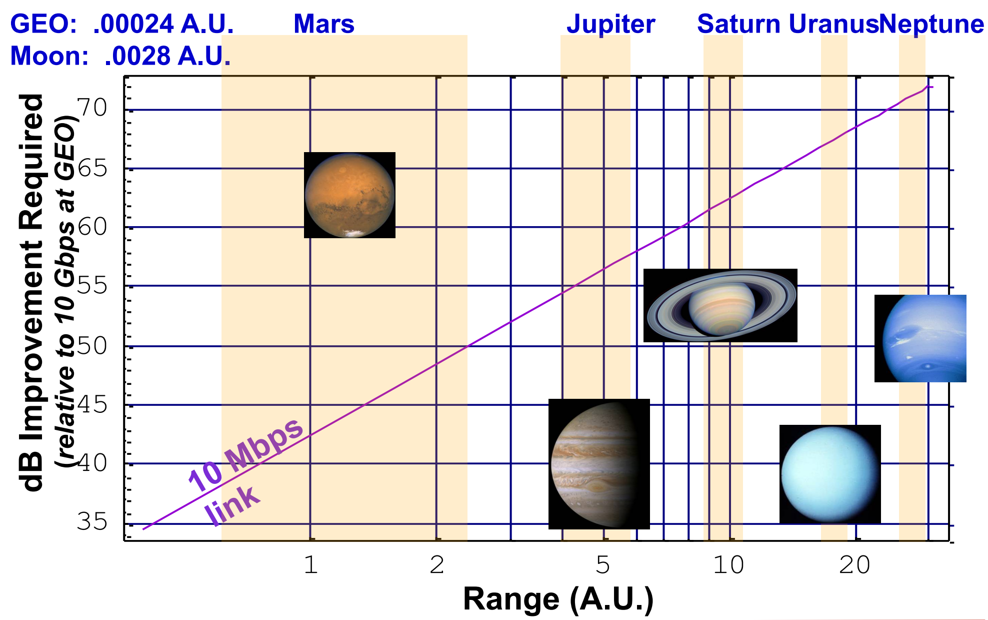
- **Interplanetary Ranging for Tests of Gravitation and Relativity**
  - Tests of Parametric Post-Newtonian gravitational theories
  - Tests of strong and weak equivalence principles
  - Determination of planetary interiors



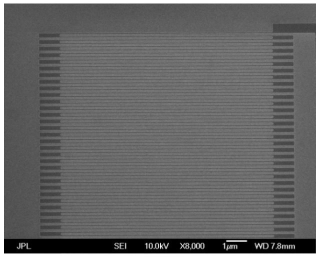


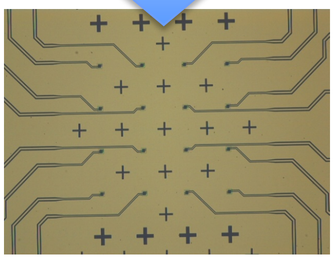
- **Interplanetary Light Science for Tests of Fundamental Physics**
  - Physics beyond the standard model
  - Tests of time variation of fundamental physics constants

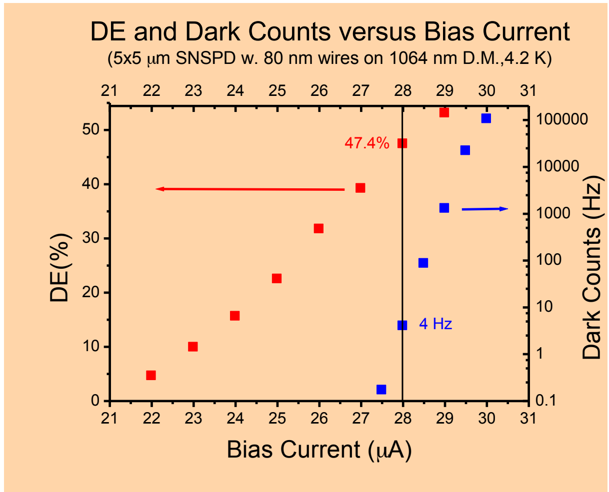
- **Interplanetary Optical Communications**
  - To increase data volume returns and reduce spacecraft burden, as compared to present RF technologies



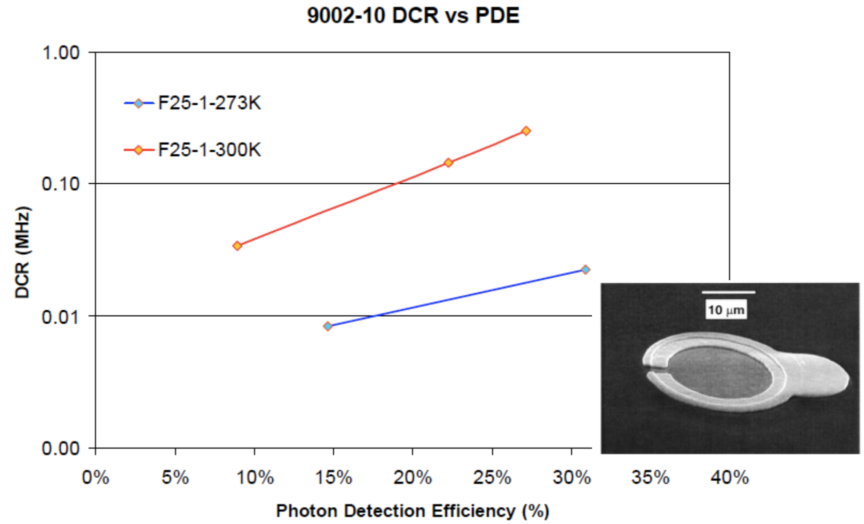
The Big, the Not So Good, and the Ugly



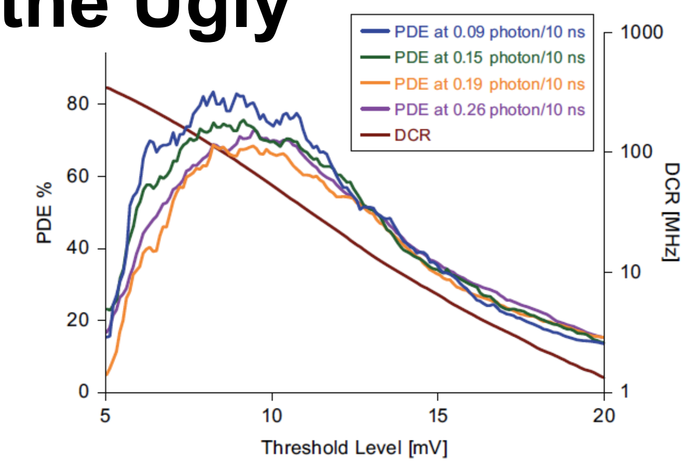




The Not So Good…



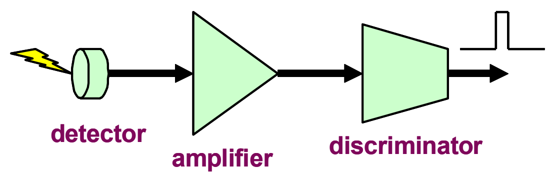
…and the Ugly



The Big…

Ideal photon counting detector performance:

- Detect every photon
  - *100 % detection efficiency*
  - *Perfect photon number resolution*
  - *Resolve photon energy too?*
- No false detections
  - *Zero dark count rate*
  - *Zero after-pulsing*
- Photon energy limited bandwidth ($\Delta E \Delta t$)
  - *Zero timing jitter*
  - *Zero recovery time*
- Infinite dynamic range



Parameter		Description	Units
Quantum Efficiency	QE	Ratio of generated primary photocarrier rate to incident photon rate	% (*unitless*)
Detection Efficiency	DE	Ratio of rate of distinguishable electrical output pulses to incident photon rate	% (*unitless*)
Dark Count Rate	DCR	Rate of distinguishable electrical output pulses (at a given DE operating point) with no optical input	Hz
After-Pulsing Ratio	APR	Ratio of correlated secondary distinguishable electrical output pulses to primary distinguishable electrical output pulses (at a given DE point)	% (*unitless*)
Single Photon Jitter	SPJ	Timing uncertainty between arrival of incident photons to distinguishable electrical output pulses	s
Recovery Time	RT	Time after a photon detection event for the DE to recover to a specified fraction of the limiting (low rate, maximum) DE value	s

Some Common Photon Counting Detector Performance Metrics

Photon Number Resolution (PNR)

- **First requirement: *single photon sensitivity***
- **However, with a linear system and "single" photon detectors, you do not absolutely resolve photon number***
  - In reality photon number cannot be measured at a specific time or position
  - Even with perfect detection efficiency and no noise
  - Closest approximation is true "linear" (gain) mode single photon detectors
    - Intensified Photodiode (IPD)
    - Linear mode HgCdTe with anomalous low gain variance

*For instance: P. Kok, IEEE Sel. Top. Quantum Electronics 9, (2003)

- **Reasonable proxies**
  - Energy resolving detectors
    - TES, x-ray (silicon PIN)
  - High bandwidth photon counting
    - SNSPD, resonant SPAD
  - Arrays of single photon detectors
    - "cascade" signal splitting across discrete arrays
    - "linear mode" detectors

- **Other major issues**
  - Overlap with spatial-temporal mode
    - Fiber or free-space coupling?
  - Detection efficiency and gain variance
  - Dark rate
    - Thermal, inter-band traps, tunneling
    - Ultimately limited by internal blackbody radiation of detector

"Good Enough" PNR is very application dependent

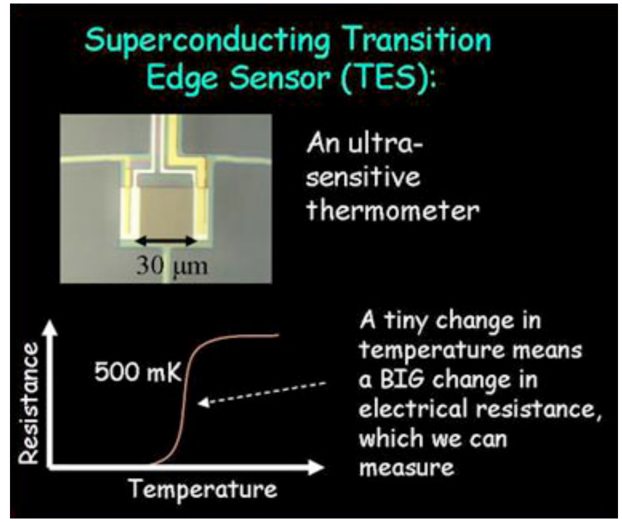
Single Photon Detector Technologies

	Superconductor		Semiconductor						Photocathode	
ABSORBER	W, Ti, …	Nb(Ti)N, $W_{(1-x)}$, Si_x, VaN, …	Si, SiC, InGaAs(P), InSb, GaN, …						metallic / semi-metallic	
			Extrinsic As, B, …	Intrinsic						
GAIN	Broken Cooper Pairs		Non-Markovian Impact Ionization			Photo-conductive		Markovian Impact Ionization	Dynode Chain / Micro-channels	Kinetic Ionization
RECOVERY	Weak Thermal Link	Fast Phonon + Kinetic Inductance	Tunneling and / or Carrier Diffusion					External Current Quench	Electron Diffusion	
	Transition Edge Sensor TES	Superconducting Nanowiire SSPD, SNSPD, SNA, SNDA	Si:As Photon Counter SSPM, VLPC, NIPC	Heavy hole / electron APD HgCdTe,	Negative Avalanche Feedback DAPD, TCB, NFAD	Semiconductor Nanowire	Quantum-dot FET QDOFET	Geiger-Mode Avalanche Photodiode (GM-APD, SPAD, SPM, SSPM, MPPC, …)	Photo-multiplier (PMT, MCP, RULLI)	Intensified Photodiode (IPD, HPD, HPMT)
PNR METHOD	energy	array	linear					array	array	linear

MCT LM-APD DAPD NIPC SPAD GM-APD QDOFET SSPM VLPC RCE GM-APD SNSPD IPD PMT

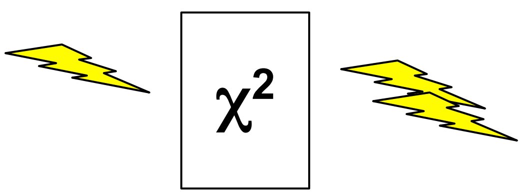
- **Transition Edge Sensor (TES)**
  - \+ Can achieve >95% DE with resonant cavity
  - \+ Zero DCR
  - – KHz count rates, ~100 ns pulse widths
  - – < 100 mK operating temperature

http://pole.uchicago.edu/public/detectors.html



- ➢ **But is it two photons or one photon of twice the frequency?**

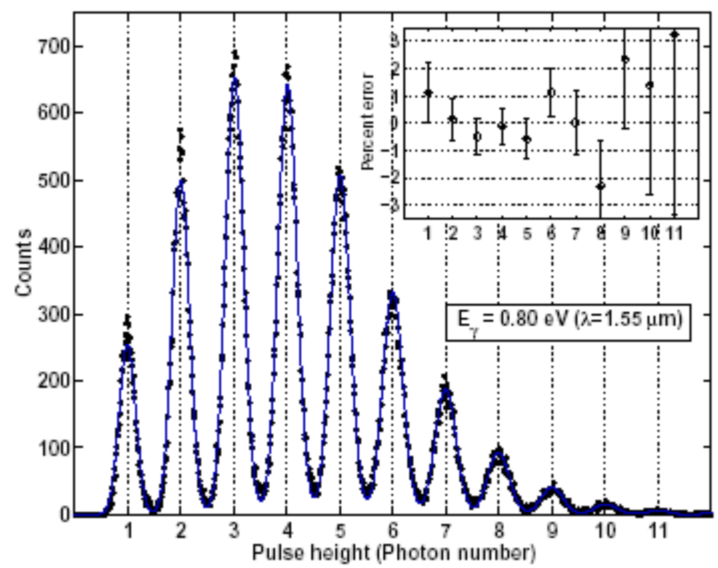
Co-linear degenerate DFG



$$\omega_1 \rightarrow \omega_2 + \omega_3$$

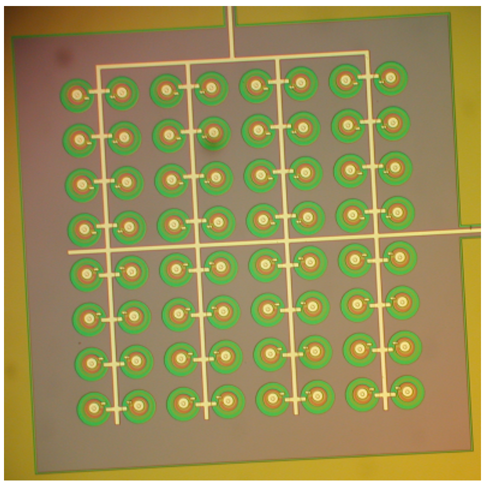
- ➢ **And when did they arrive?**

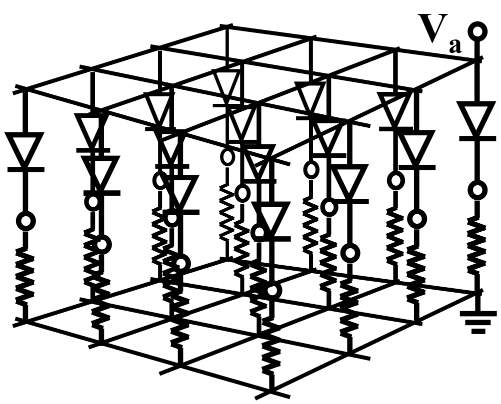
A. J. Miller, et al., Appl. Phys. Lett., 83, (2003).

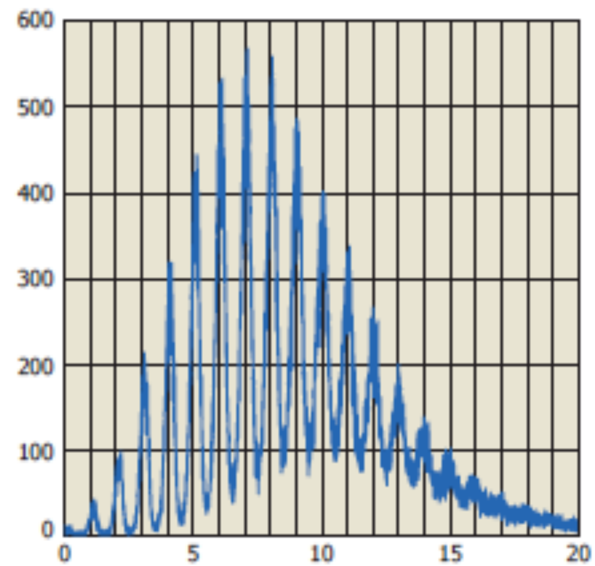


Photon Counting with Spatial Arrays

- **Generic approach: split input signal across many single photon pixels**
  - Pixels can be summed digitally after discrimination (1-bit ADC), or in some cases summed in the analog domain and then discriminated with a multi-bit ADC
  - Array mitigates individual detector pixel recovery times, but not timing jitter
  - **In semiconductor device arrays, optical cross-talk between pixels from photons emitted during the impact ionization gain process can be a significant noise source**



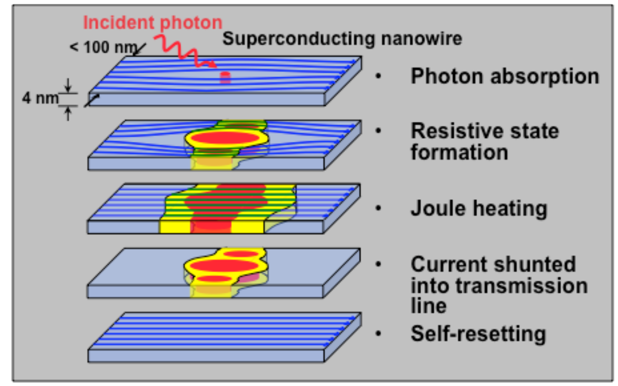


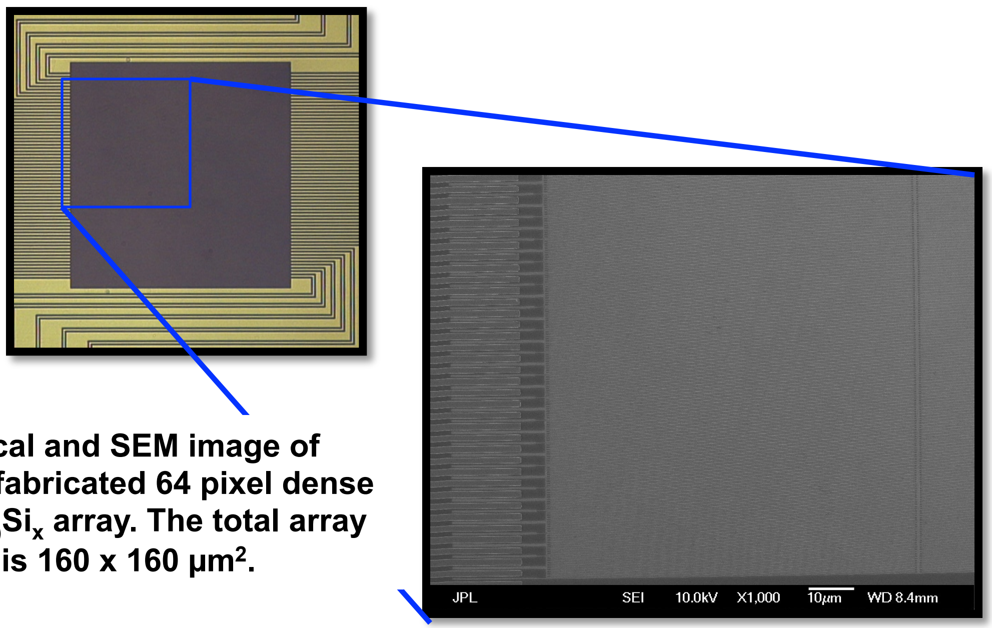


Common-Anode Passive Quenched Geiger Mode Avalanche Photodiode Array

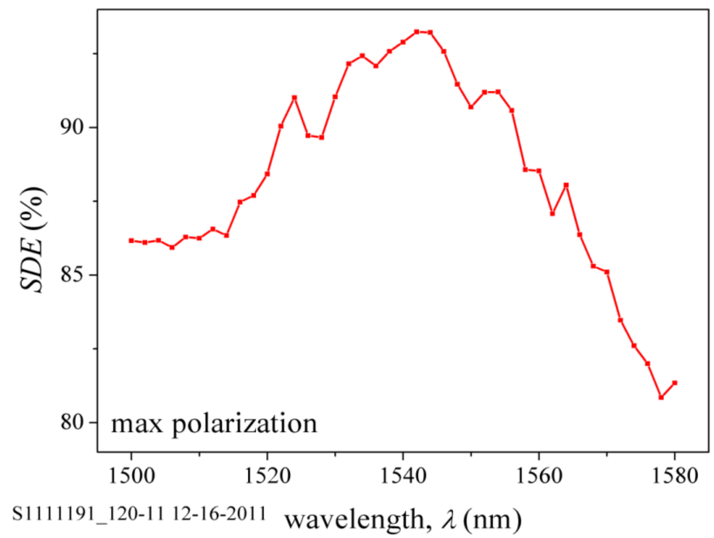
Superconducting Nanowire Arrays

- **Superconducting Nanowire Single Photon Detectors (SNSPD) can combine high detection efficiency with low dark rate and GHz bandwidths**
  - \+ > 80% DE with resonant cavities
  - \+ < 100 Hz dark rate is achievable
  - \+ < 50 ps jitter
  - – > 20 ns recovery time typical due to kinetic inductance
  - – < 4K operating temperature for Nb(Ti)N devices
  - – < 1K operating temperature for $W_{(1-x)}Si_x$ devices



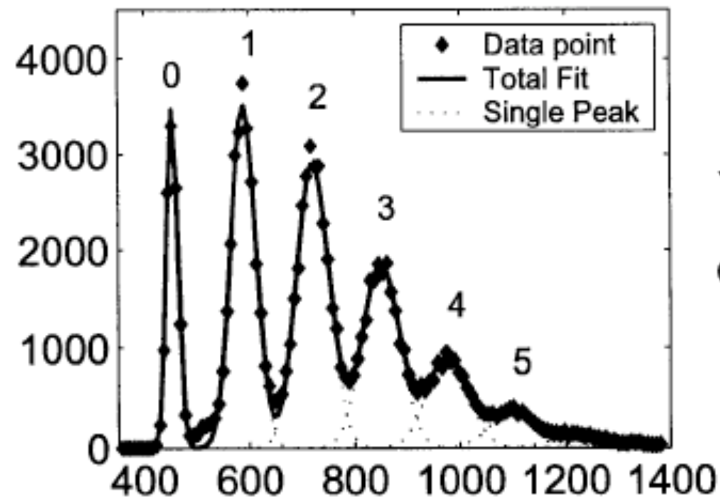


Optical and SEM image of JPL fabricated 64 pixel dense $W_{(1-x)}Si_x$ array. The total array area is 160 x 160 μm².

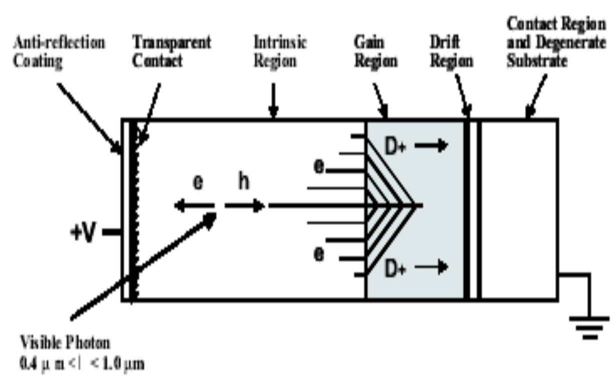


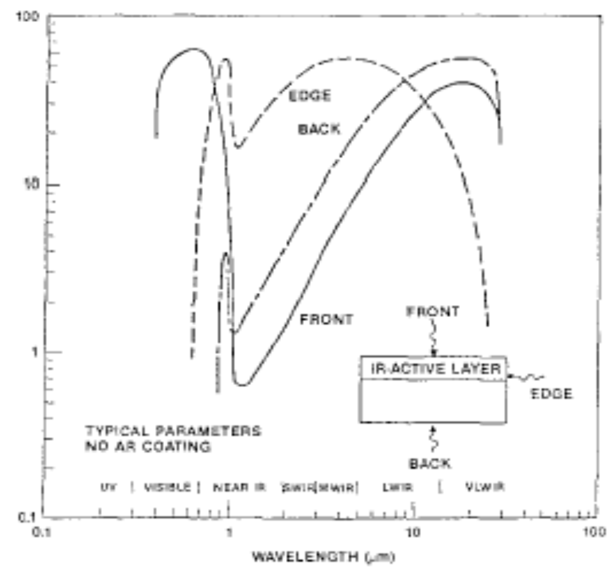
The Visible Light Photon Counter

- **The Arsenic doped Silicon VLPC detector has single photon sensitivity from 0.4 to 28 microns**
  - > 80% DE in the visible without optical cavity
  - 1 mm diameter active area with < 30 KHz DCR
  - 6 K nominal operating temperature
- **Non-Markovian gain process with localized avalanche volumes permits good photon number resolution**
  - Performance is limited by ~3 ms recovery time of local field reduction*



M. Petroff and M. Stapelbroek, *IEEE Trans. Nuclear Sci.*, 36, (1989)





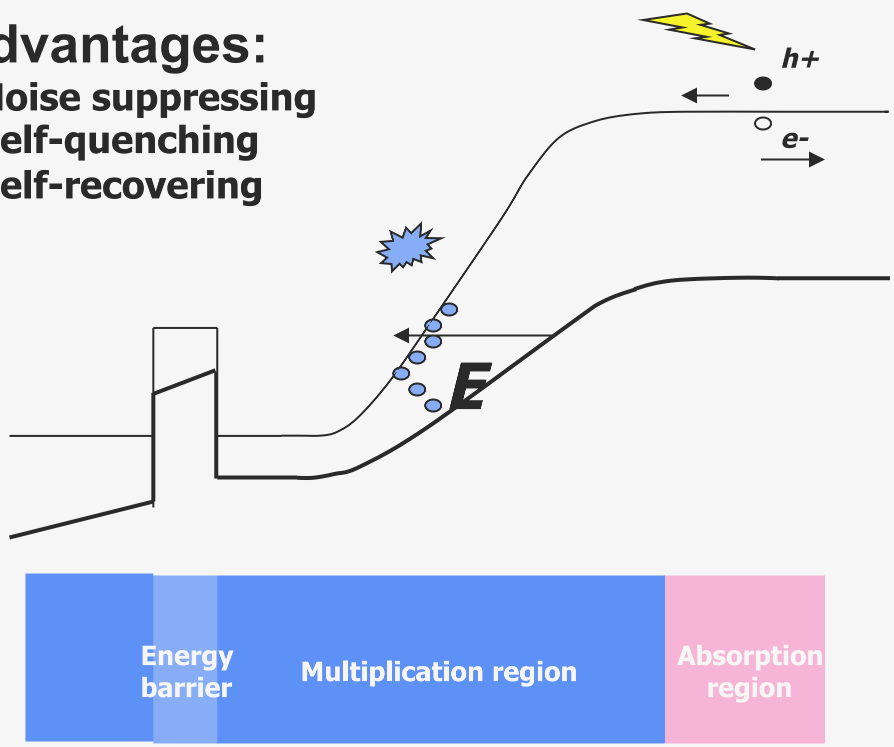
*A. Bross et al., Appl. Phys. Lett. 85, (2004)

InGaAs/InP Negative Avalanche Feedback APD

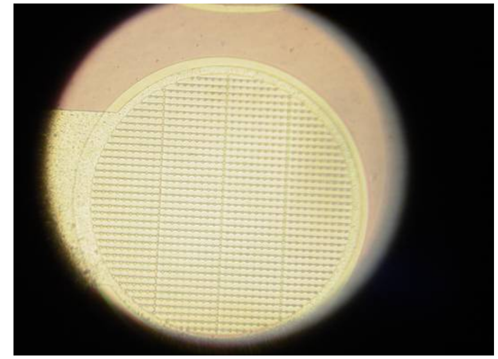
- **Negative Avalanche Feedback APD's extend the local field reduction concept to > 220K operation with InGaAs(P) devices**
- **Further work to reduce after-pulsing is required**
  - > 20% at 10 – 20% DE's

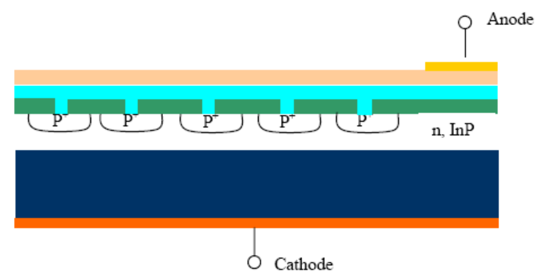
Advantages:

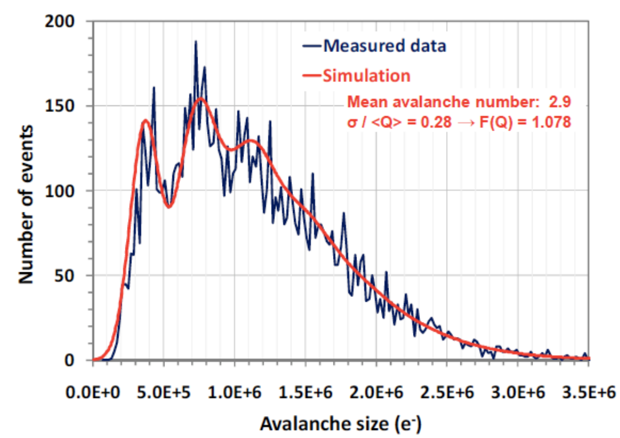
- **Noise suppressing**
- **Self-quenching**
- **Self-recovering**



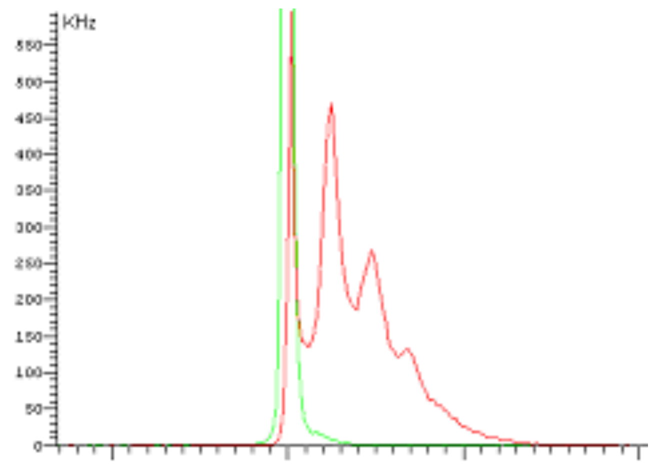
Micro-pixelated Detector Array



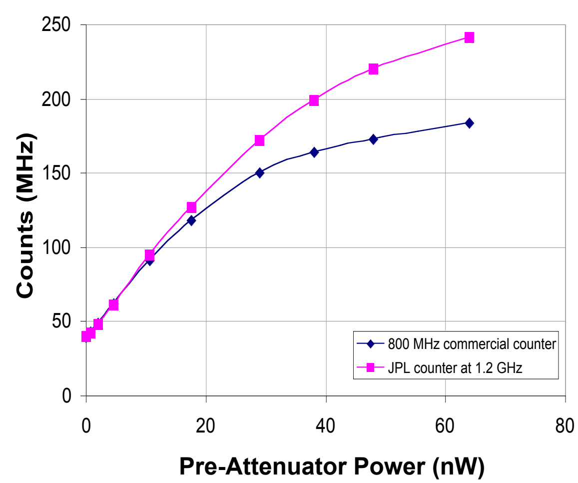


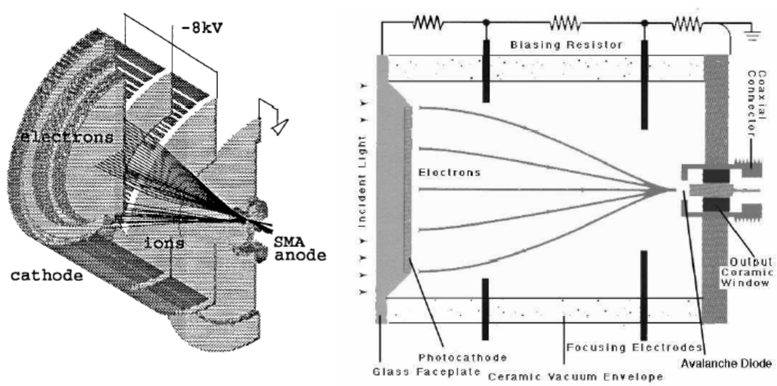


- **The Intensified Photodiode (IPD) uses a two-stage gain process to achieve single photon sensitivity**
  - Ultra-low noise gain on the order of 10^3 via energetic 8 KeV electrons onto an APD anode
  - Avalanche gain on the order of 10 within the high-field region of the APD
- **Photocathode limits device performance**
  - \+ > 200 MHz count rate per pixel
  - < 30% DE
  - < 100 ps with <20% DE, but jitter scales as square of photocathode thickness, whereas DE scales linearly
- **Future best concept for high-fidelity Photon Number Resolution?**



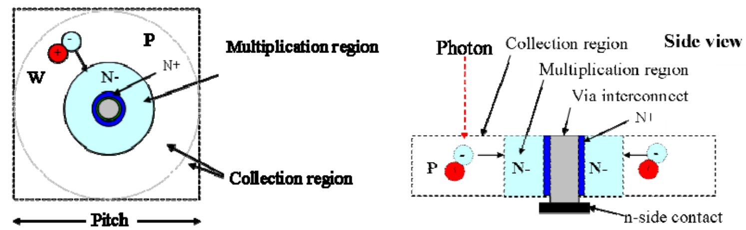
< 1dB compression at 200 MHz

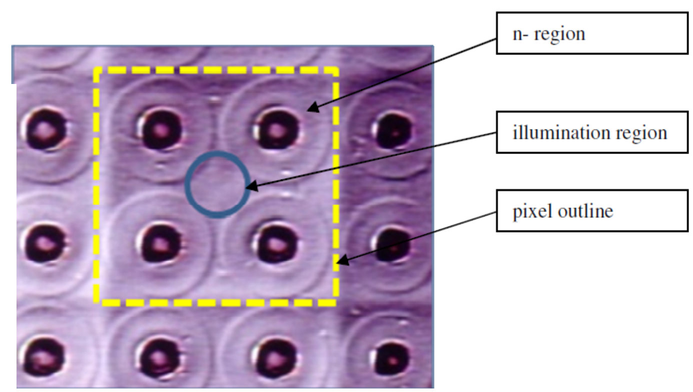


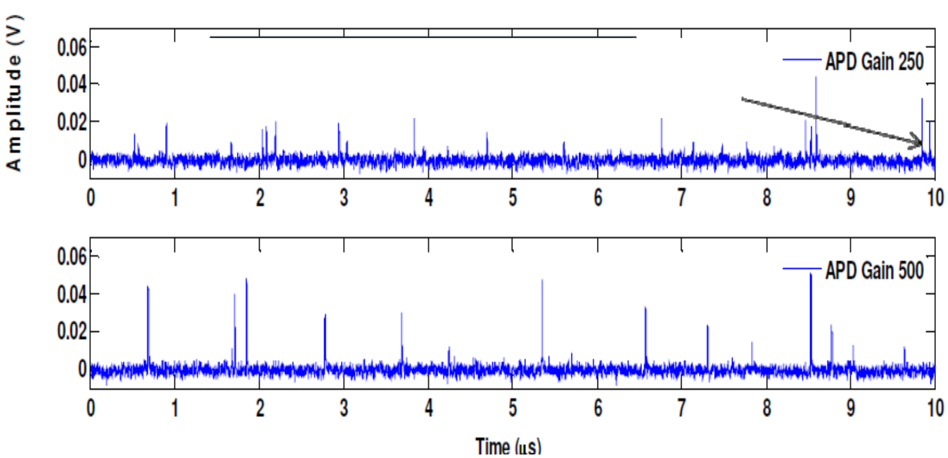


R. La Rue, et al., *IEEE Trans. Elec. Dev.*,44, (1997)

- **Linear mode photon counting demonstrated in 2010 by Raytheon and by DRS**
  - + 90% quantum efficiency at 1550 nm; >50% detection efficiency
  - – 1 MHz dark-count-rate, but photon emission from present amplifier is source of most of the dark counts
  - – Zero-field absorber region results in ~1 ns jitter
  - – 80K operating temperature







Proc. of SPIE, V. 8033 80330N-1

Detector Performance Comparisons

Single pixel "representative" values…

Technology	Peak DE	DCR	RT	Pulse Width	SDJ	PNR method	Relative False Count Probability *DCR RT*
TES	> 95%	~ 0	~ 1 ms	~100 ns		energy	~0
SNSPD	> 80%	~ 100 Hz	~ 20 ns	~10 ns	< 50 ps	array	2E-6
Si SPAD	> 50%	~ 100 Hz	~ 50 ns	~20 ns	~ 150 ps	array	5E-6
InGaAs SPAD	~ 50%	~ 100 KHz	~ 2 μs	~20 ns	~ 250 ps	array	0.2
VLPC	> 80%	~ 20 KHz	~ 100 ns / 1 mm dia.	~ 2 ns	~ 700 ps	linear	2E-3
IPD	~ 30%	~ 200 KHz	~ 1 ns pulse width	~ 1 ns	~ 200 ps	linear	2E-3
HgCdTe	> 50%	< 20 KHz intrinsic @ 80K	~ 2 ns pulse width	~ 2 ns	~ 1 ns	linear	4E-5

- **Near Term (1-5 years)**
  - Maturation of superconducting nanowire arrays
  - Faster TES detectors
  - Resonate-cavity enhanced semiconductor arrays
  - Monolithic hybrid semiconductor APD / FET pixels
- **Longer Term (5-10 years)**
  - After-pulsing reduction in InP/InAlAs avalanche photodiodes
  - New semiconductor material systems
  - Semiconductor nanowire single photon detector arrays
- **Blue Sky**
  - New photocathode concepts and miniaturized vacuum device arrays?
  - "Specialty" detectors, such as direct detection of OAM?

- **Single Photon Detectors are still far from "good enough"**
  - Unless you don't mind size and "wall-plug" power, in which case superconducting nanowire detectors are rapidly maturing
  - But for flight applications, NASA *does* mind "details" like size, weight, and power
- **Photon Number Resolution (PNR) is only approximate**
  - Can "true" PNR be achieved with future photocathode detectors?
- **Progress in detector development has been, and will continue to be slow**
  - Experience shows it can easily take \$5M -\$10M investment to bring a new detector technology variant to market at a useful level of performance
  - Difficult in a climate of tight technology funding
- **But progress *will* continue, as single photon detectors are "essential" for quantum future technologies**