Title: Review of Photon Counters

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Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

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Review of Single-Photon Avalanche Diodes

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Workshop on Intensity Interferometry for Astronomy
Perimeter Institute, Waterloo, Ontario, 10/31/2024

Outline

- SPAD Introduction and Fundamentals
- Design, Internal Behavior and External Characteristics
- Types of SPADs and Quenching Circuits
- Conclusions

Executive Summary

1. SPADs offer high performance single-photon detection in every* metric.
2. But not all metrics are achieved in a single device; there are always tradeoffs.
3. The tradeoffs can be strong, but SWAP and fab capabilities often makes up for them.

*caveats about wavelength range and perhaps ultra-low noise

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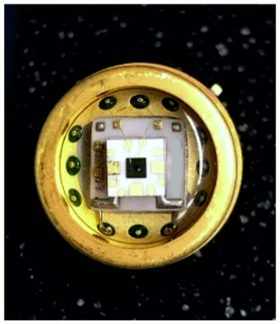
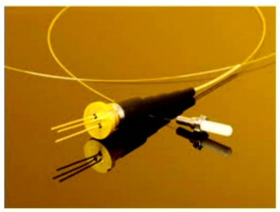
Single-Photon Avalanche Diodes (SPADs)





Avalanche diodes voltage reverse biased above breakdown
→ a single photogenerated electron-hole pair can trigger an exponential growth in current through runaway impact ionization

- Low cost, compact, low power
- Room temperature (… well, TE cooled to reduce dark counts)
- Diameters from < 10 μm to 500 μm
- System detection efficiencies > 85% in Si, > 50% in InGaAs
- Dark count rates can be < 10 s^{-1} in Si, < 10^3 s^{-1} in InGaAs
- FWHM jitter < 10 ps in small area devices
- Max count rates > 10^8 s^{-1} in Si and gated InGaAs
- CMOS compatible: large arrays, integration, 3D ToF imagers

- Trade-offs in S.D.E/Jitter/Area, DCR/Afterpulsing
- Afterpulsing << 1% in Si, much worse in InGaAs (unless gated)

Disclaimer: The mention of any commercial product does not imply recommendation or endorsement by the U.S. National Institute of Standards and Technology.

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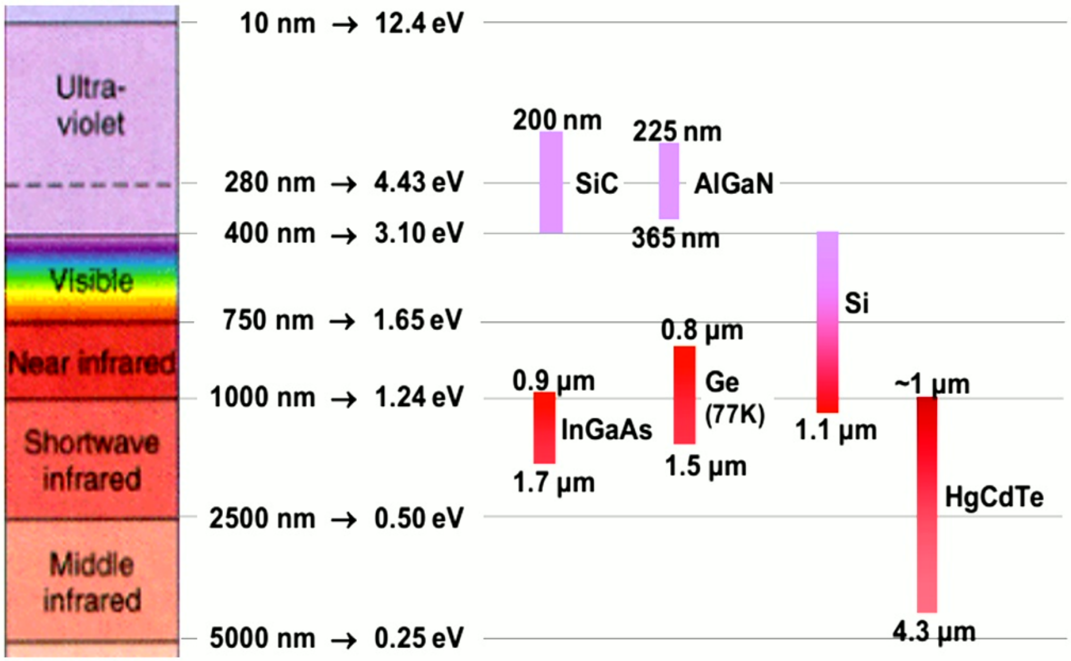
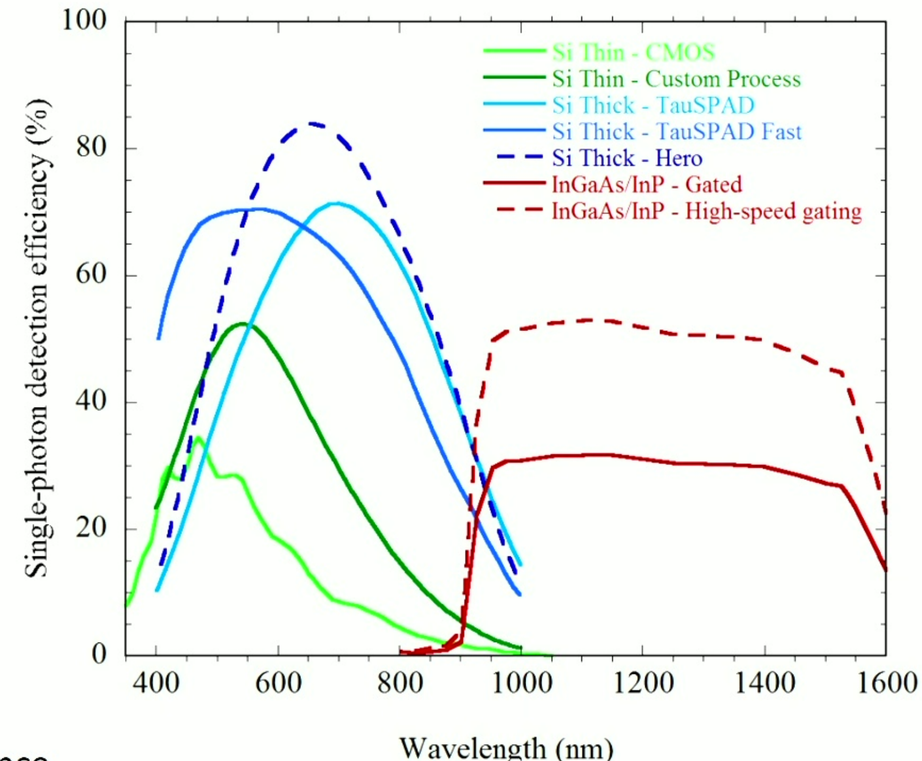
Semiconductor SPAD Materials





- active development of III-V SPADs, seeking to improve performance
- active development of Si SPAD arrays with greater functionality and performance (e.g. gated arrays, individually controlled)
- nascent UV SPAD development

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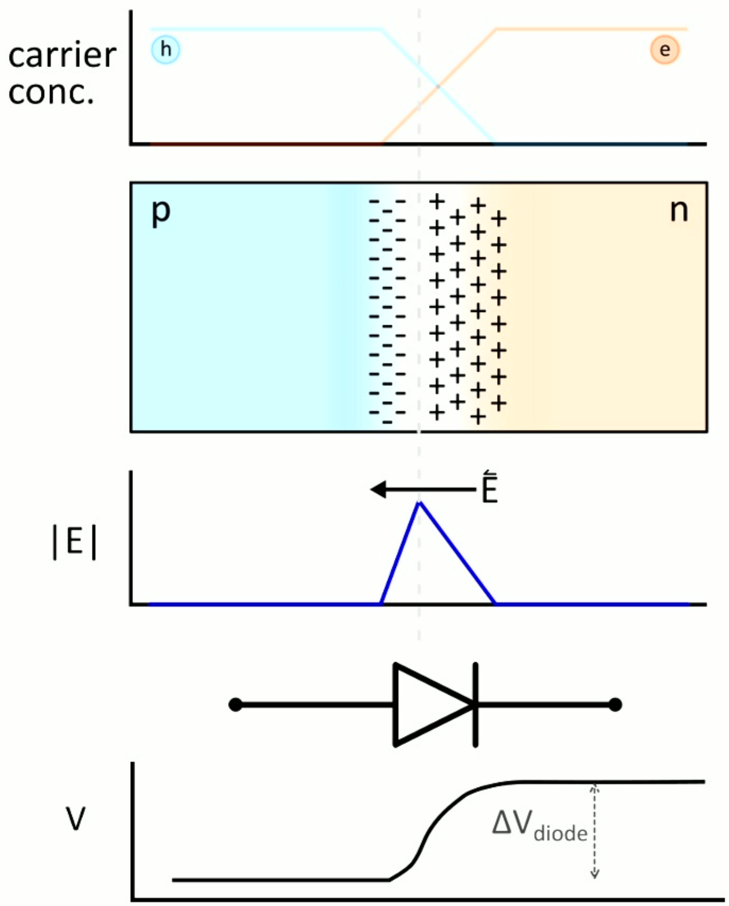
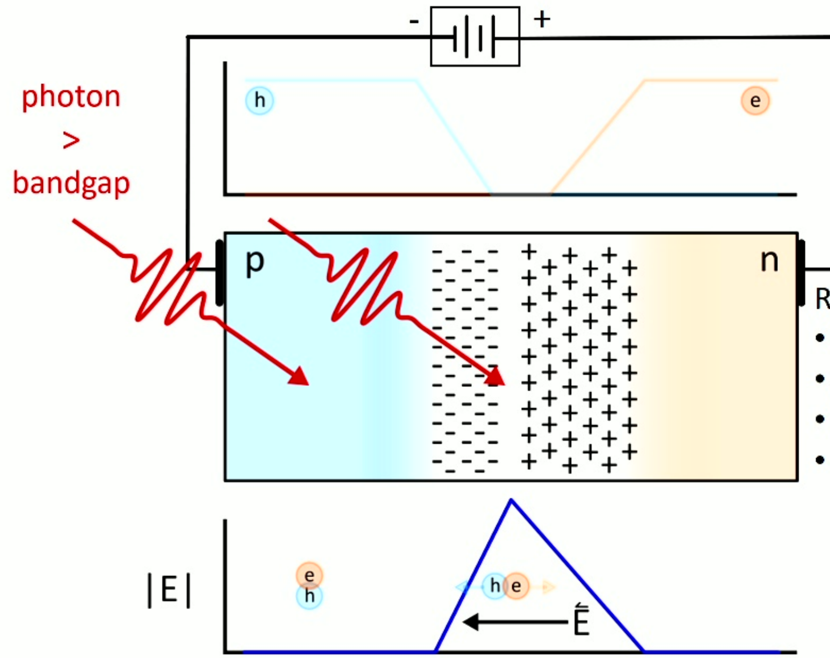
Si Avalanche Photodiode Fundamentals



Forward bias:
conductor w/
diode drop ΔV



Reverse bias:
- insulator
- depletion width ↑
- field ↑
- capacitance ↓

- Carriers in depletion region move apart due to E
- Carriers outside depletion, E = 0, diffuse & recombine
  - ➢ For efficiency, increase bias to fully deplete absorption region

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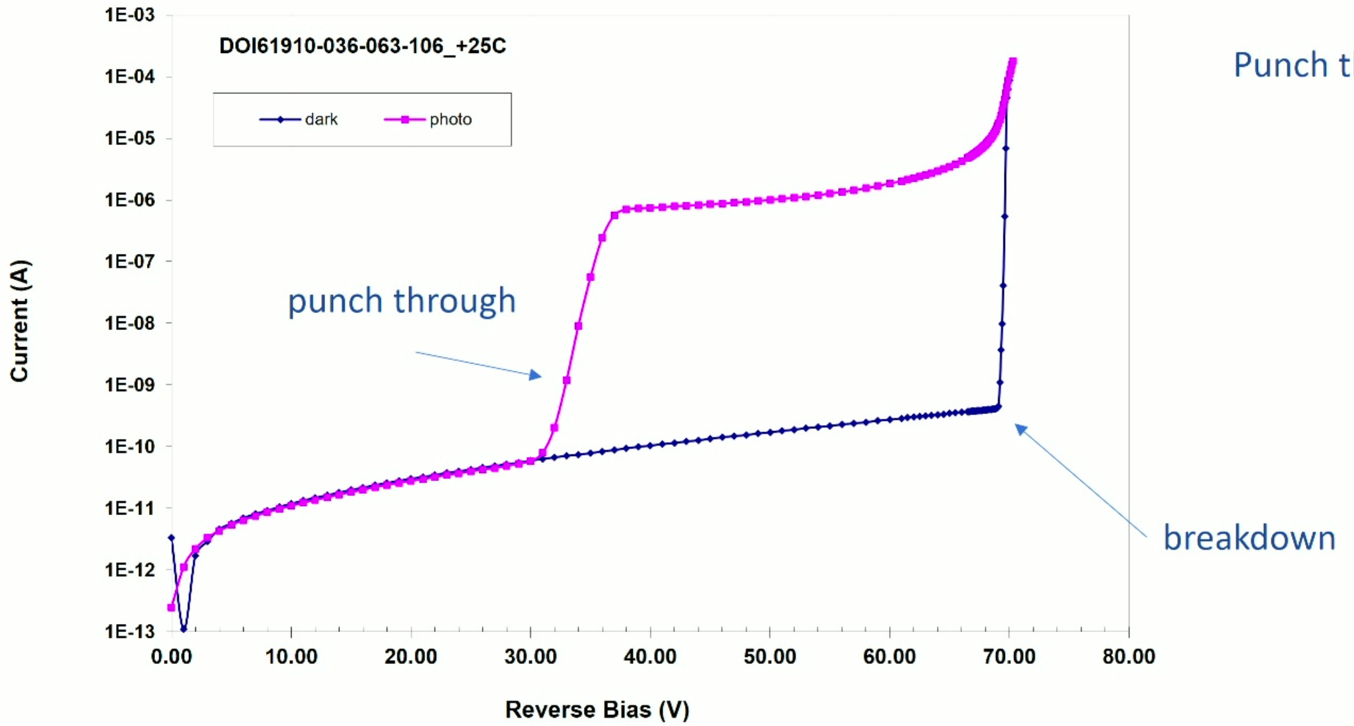
SPAD I-V Curve



Punch through = fully depleted

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6

Si **Linear** Avalanche Photodiode Fundamentals

- With high E, carrier energy > Si bandgap between collisions ➔ Impact Ionization, liberating another carrier (pair)
  - Internal gain mechanism, or "avalanche"
- A toy model: single-photon generates e-h pair. Say the probability of ionization through device is α. The mean gain is

$$M = 1 + \alpha + \alpha^2 + \alpha^3 + \cdots = \frac{1}{1-\alpha}$$
$$\alpha \to 1, M \to meaningless$$

  - Runaway impact ionization when the field is above breakdown ("Geiger mode;" gain is undefined)
  - Breakdown depends on doping/field profile, but a *very* rough figure of merit is 100 V for 10 µm thickness.

- Avalanche gain is ***a highly stochastic*** process and, when starting from a single e-h pair, can self-terminate
  - energy losses to lattice, probabilistic ionization → fluctuating gain gives large "excess noise factor"
  - no "linear-mode" photon counting

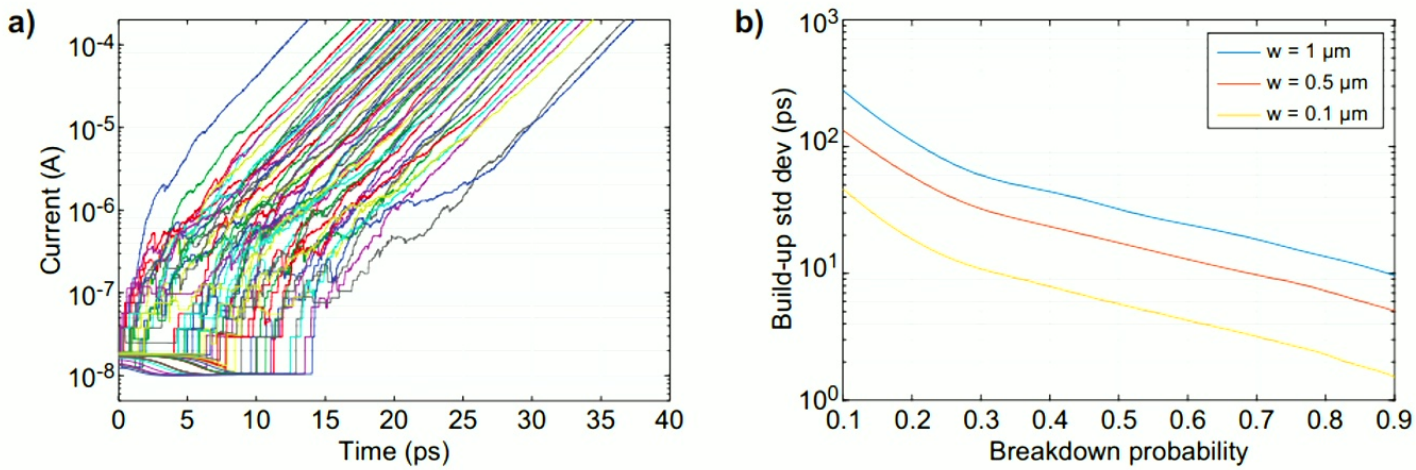
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-19, NO. 6, JUNE 1972 703

The Distribution of Gains in Uniformly Multiplying Avalanche Photodiodes: Theory

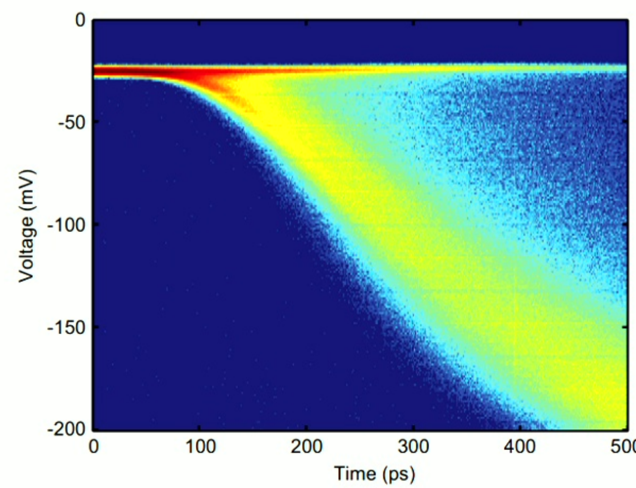
ROBERT J. McINTYRE, SENIOR MEMBER, IEEE

➔ Result: To reduce excess noise it is better to have one type of carrier do all the ionizing
- Triggering probability

Models of Avalanche Growth



- Models are for qualitative understanding; not quantitatively predictive
- Stochastic nature of avalanche growth contributes to triggering efficiency and timing resolution
  - Thinner avalanche regions improve timing resolution



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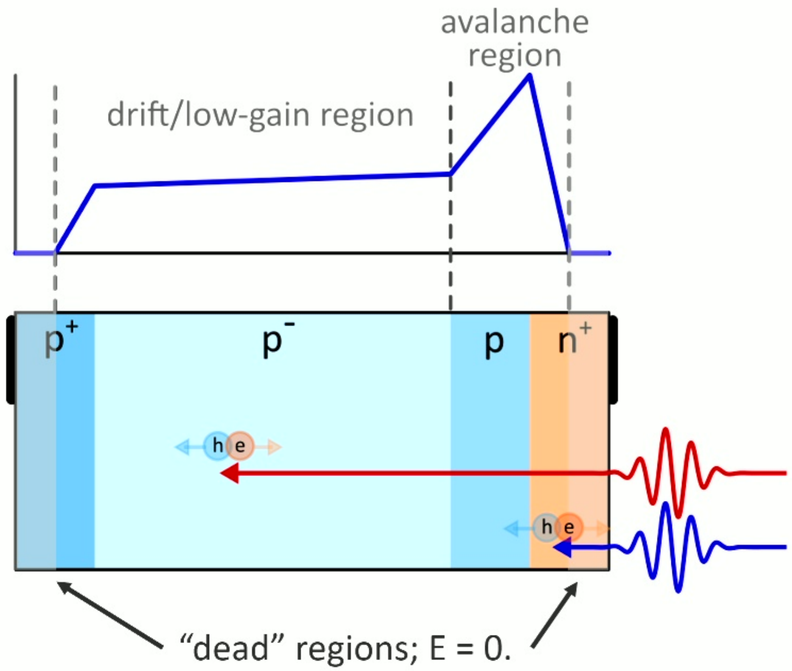
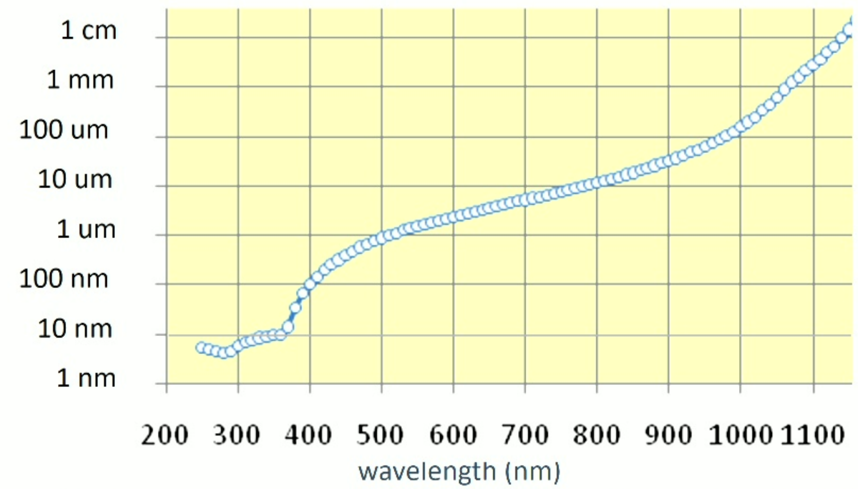
[Acconcia et al., Optics Express **31**, 33963 (2023)]

Si SPAD Fundamentals

- In Si, α_{elec} is larger than α_{hole}
- Can achieve low k devices, where $k = \alpha_{hole}/\ \alpha_{elec}$, by having *some* multiplication throughout the device, but having the multiplication peak very close to the cathode where the hole density is low
  - The SLiK[TM] device; $k \approx 0.002$ [Dautet et al., Appl. Opt. **32**, 3894 (1993)]





[M. A. Green, Prog. Photovoltaics: Research and Applications **3**, 189 (1995)]

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9

Detection Efficiency: Thick Si SPAD

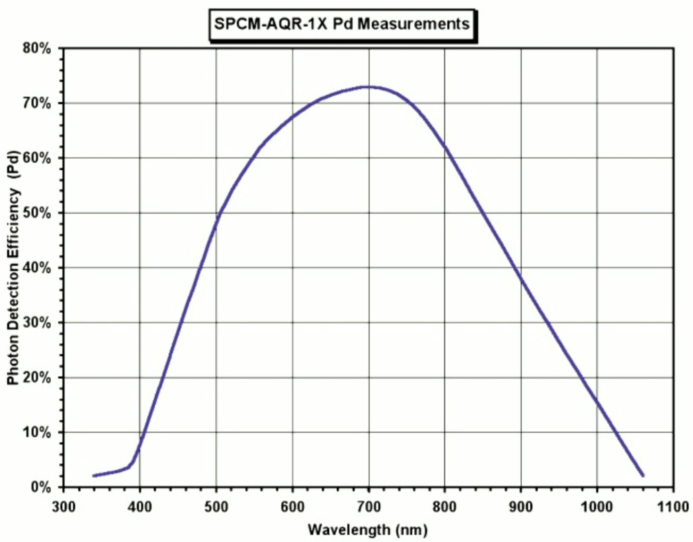
$$SDE = (1 - R_{in}) \times P_{abs} \times P_{trig}$$

$R_{in} \equiv optical\ reflection$

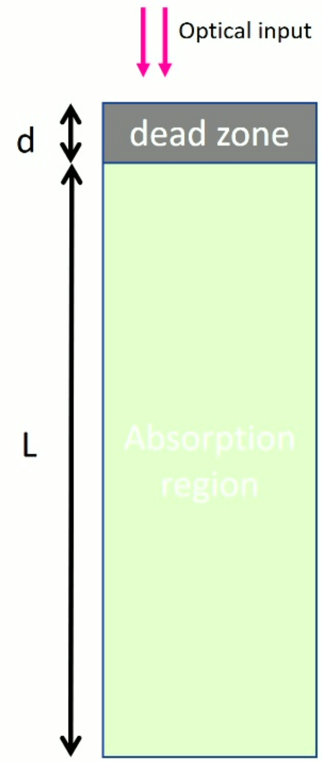
$P_{abs} \equiv absorption\ prob.$

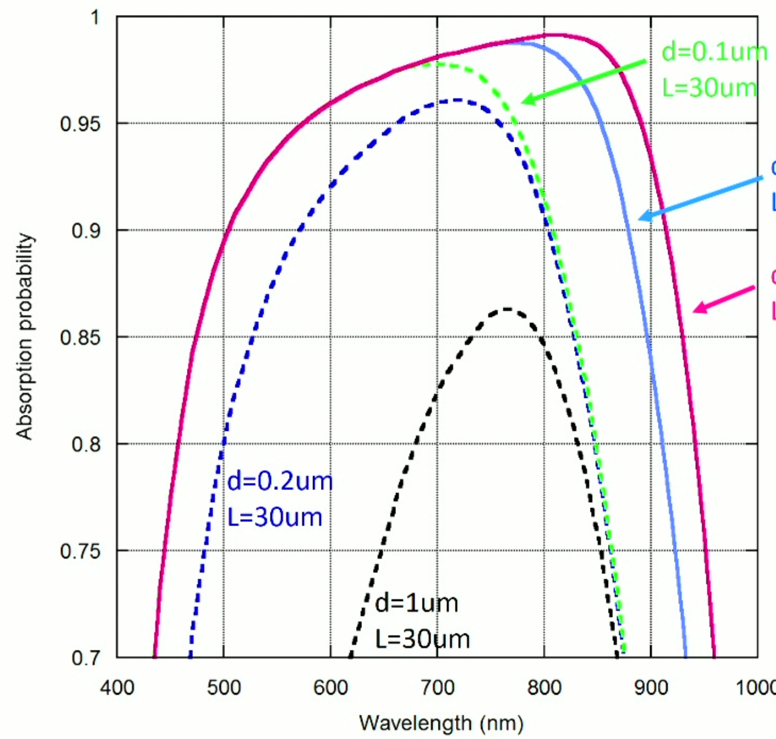
$P_{trig} \equiv avalanche\ prob.$

Ptrig



[PerkinElmer SPCM-AQR Datasheet, 2008]





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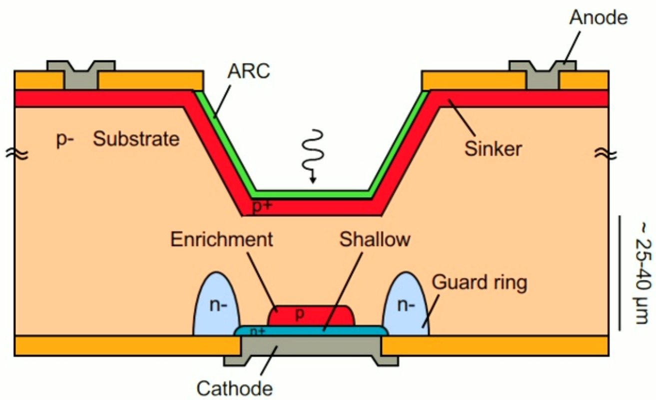
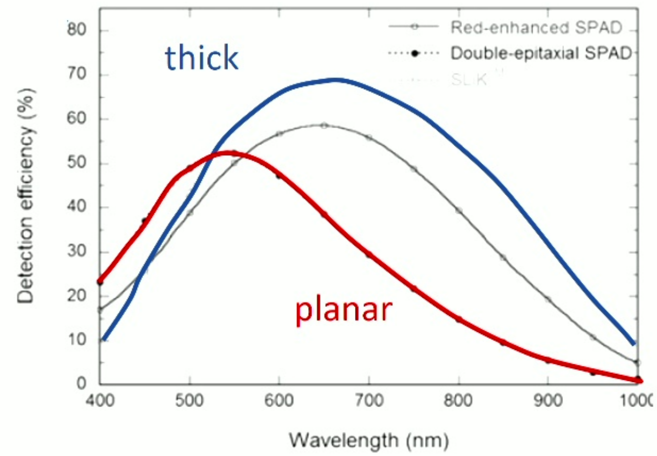
Two families of Si SPADs:

Thick “Reach-Through” SPAD

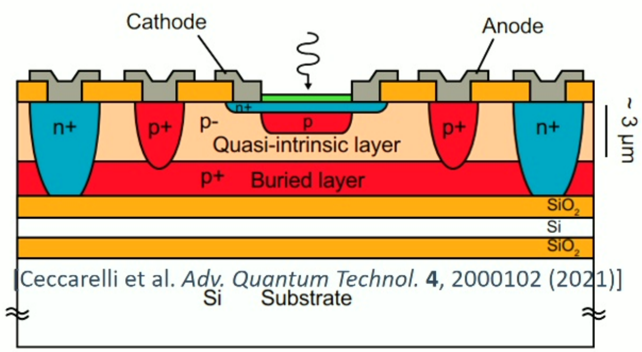
- Processing on both sides of wafer
- Anode and cathode are on opposite sides.
- Thick, high efficiency
- Single element



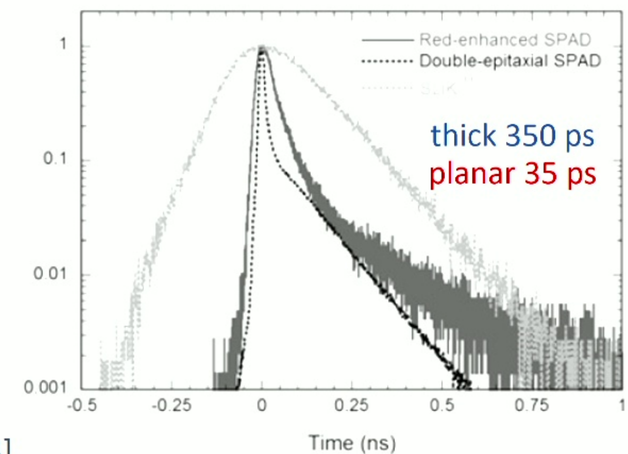


Thin “Planar” SPAD

- Processing on top only
- Anode (p^+) connects w/ sinkers
- Thin
- Back reflector: avoid absorption in deep low field regions
- Suitable for arrays



[Ceccarelli et al. *Adv. Quantum Technol.* **4**, 2000102 (2021)]



[Single-Photon Generation and Detection, Elsevier, 2013]

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Timing Resolution (Jitter)

Consider a d = 10 um thick absorption region (pretty thick)
Optical transit time = $d \times n/c \approx$ 14 fs
Carrier transit time = $d\ /v_{sat} \approx$ 10 ps

Additional jitter from variance in avalanche buildup

- Perversely, a *high* ratio of ionization coefficients is better for jitter

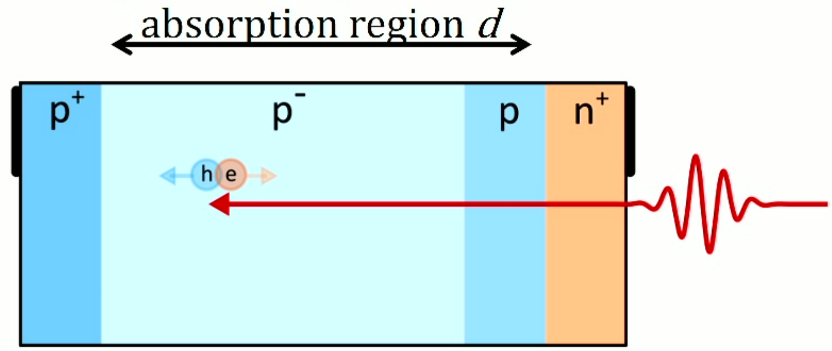
Other issues that can impact timing resolution:

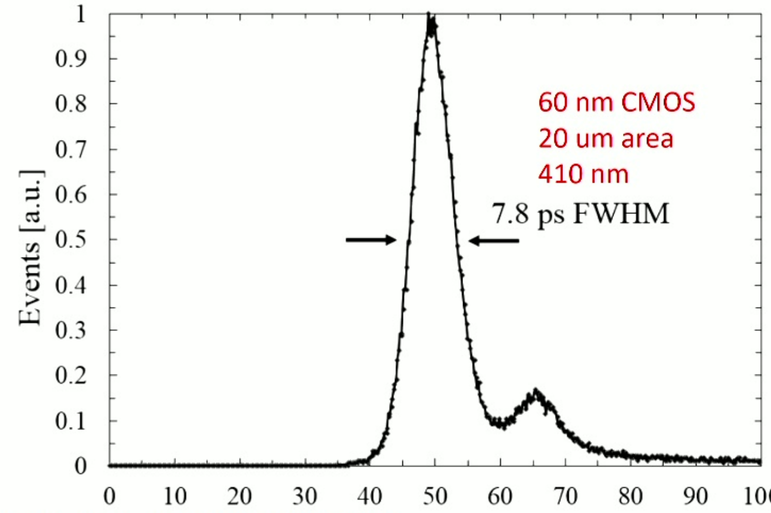
- junction RC, limiting the slope (dV/dt) of the output current
- readout electronics

Thick Si SPAD ≈ 150 ps FWHM, 600 ps FW(1%)M

Thin Si planar SPAD ≈ 20 ps to 30 ps FWHM, <400 ps FW(1%)M

CMOS planar SPAD < 20 ps FWHM





[Nolet *et al.*, *Instruments* **2** (4), 19 (2018)]

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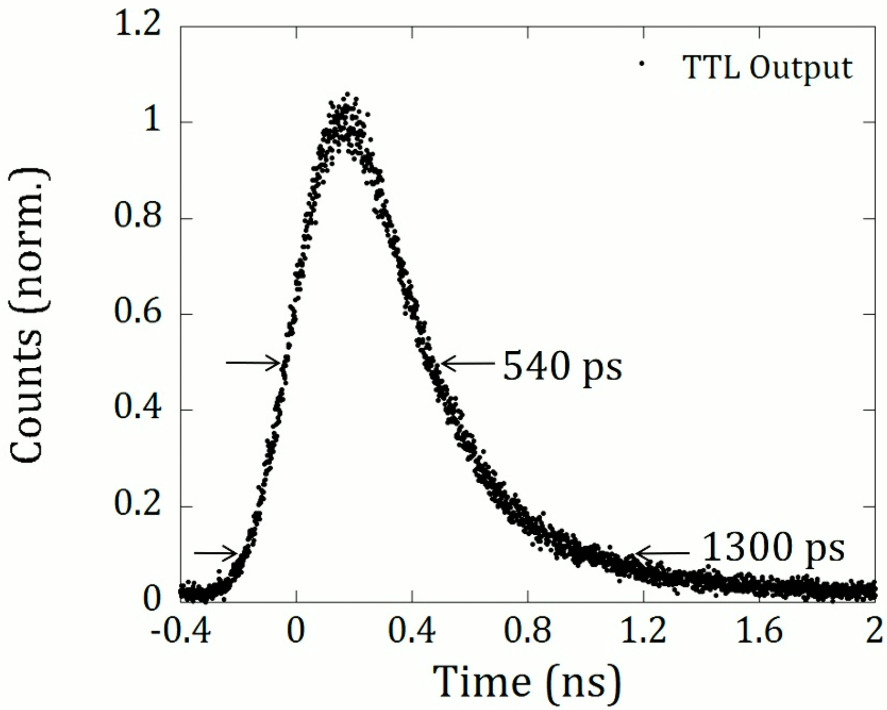
Readout Electronics: A story from the QKD days

Thick SPAD measured < 350 ps FWHM in lab.

But over FSO link timing resolution degraded significantly.



Original temporal resolution insufficient for low-error QKD.

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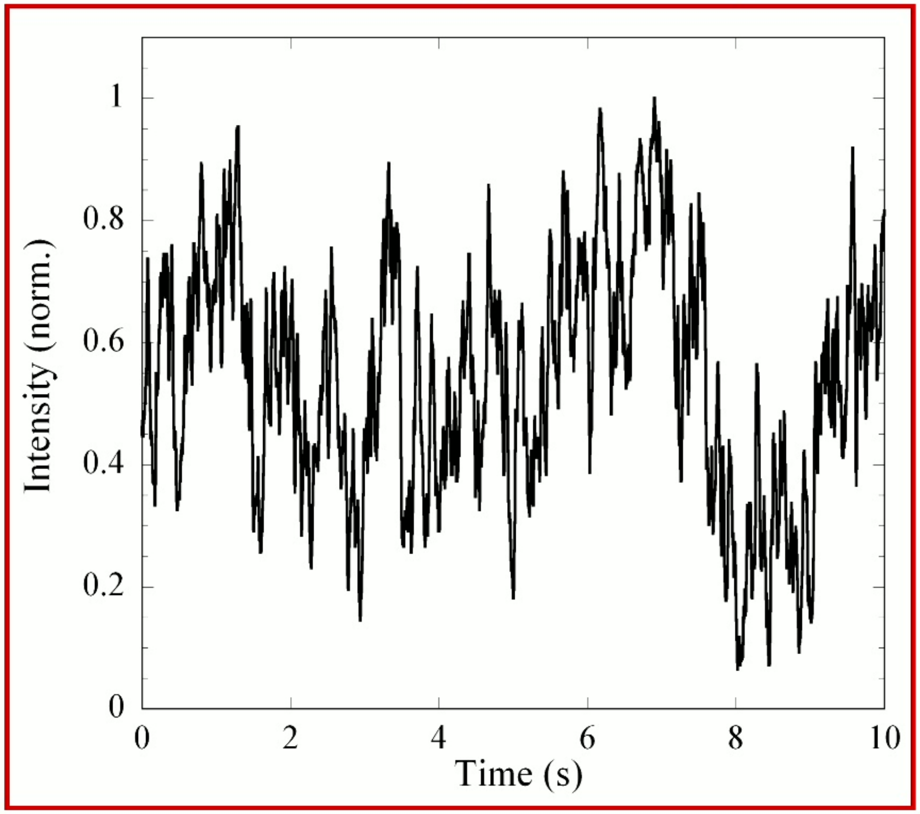

Original temporal resolution insufficient for low-error QKD.

Scintillation-induced **count-rate fluctuations** contributed timing jitter.

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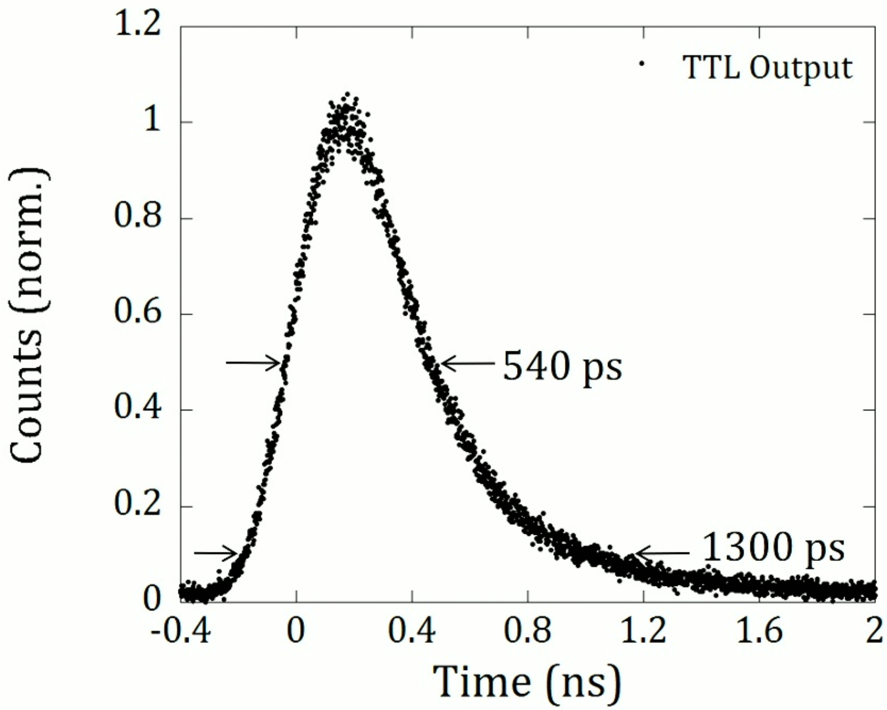

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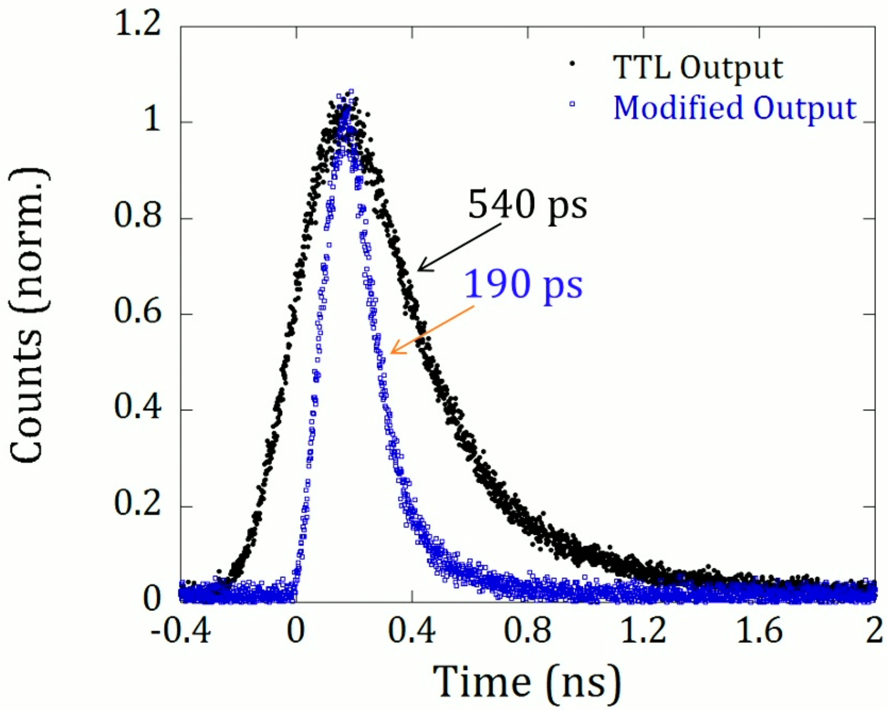

Original temporal resolution insufficient for low-error QKD.

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Detector timing circuitry modified in collaboration with *Politecnico di Milano*

[I. Rech, *Rev. Sci. Instrum.* 77, 033104-1-5 (2006)]

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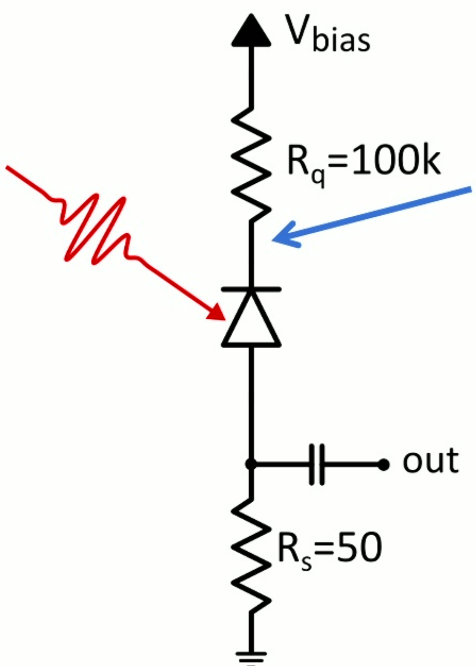
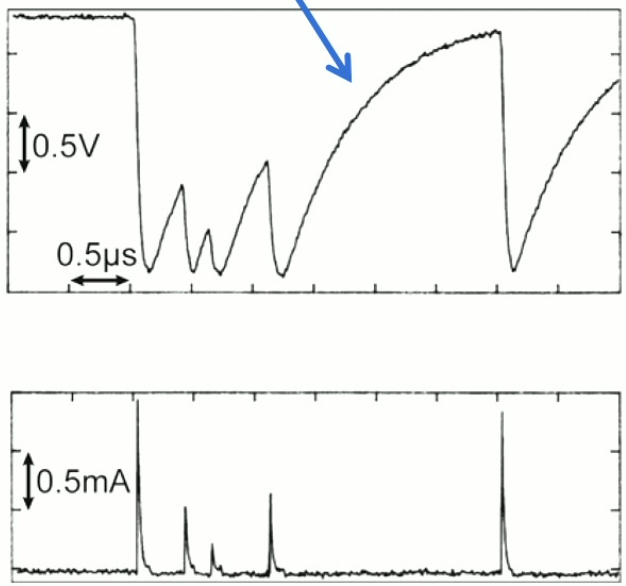
Quenching Circuits

SPADs must operate in a control circuit.

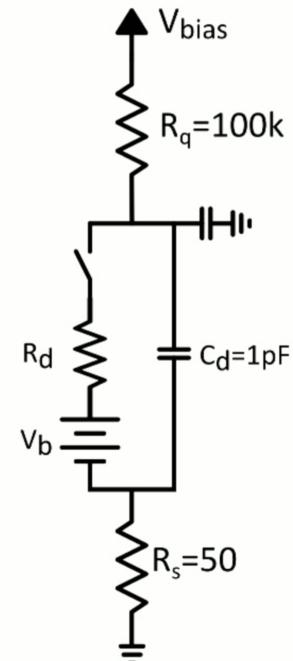
Passive Quenching
Current through large load resistor drops reduces bias until avalanche terminates



Cathode recharges as R_qC_d



Equivalent circuit



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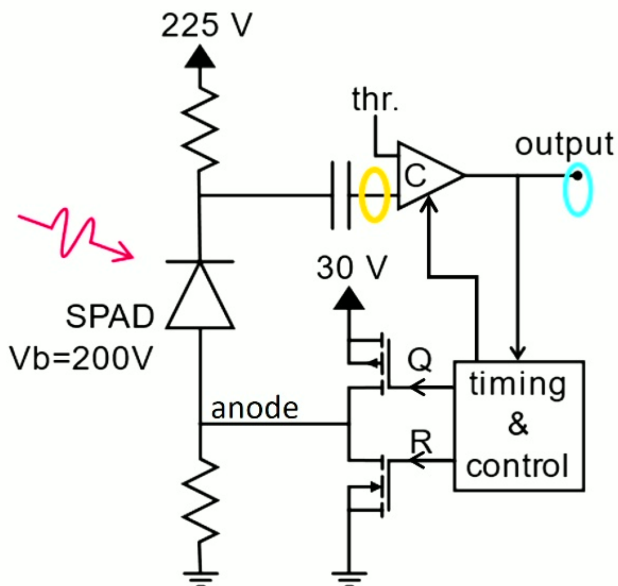
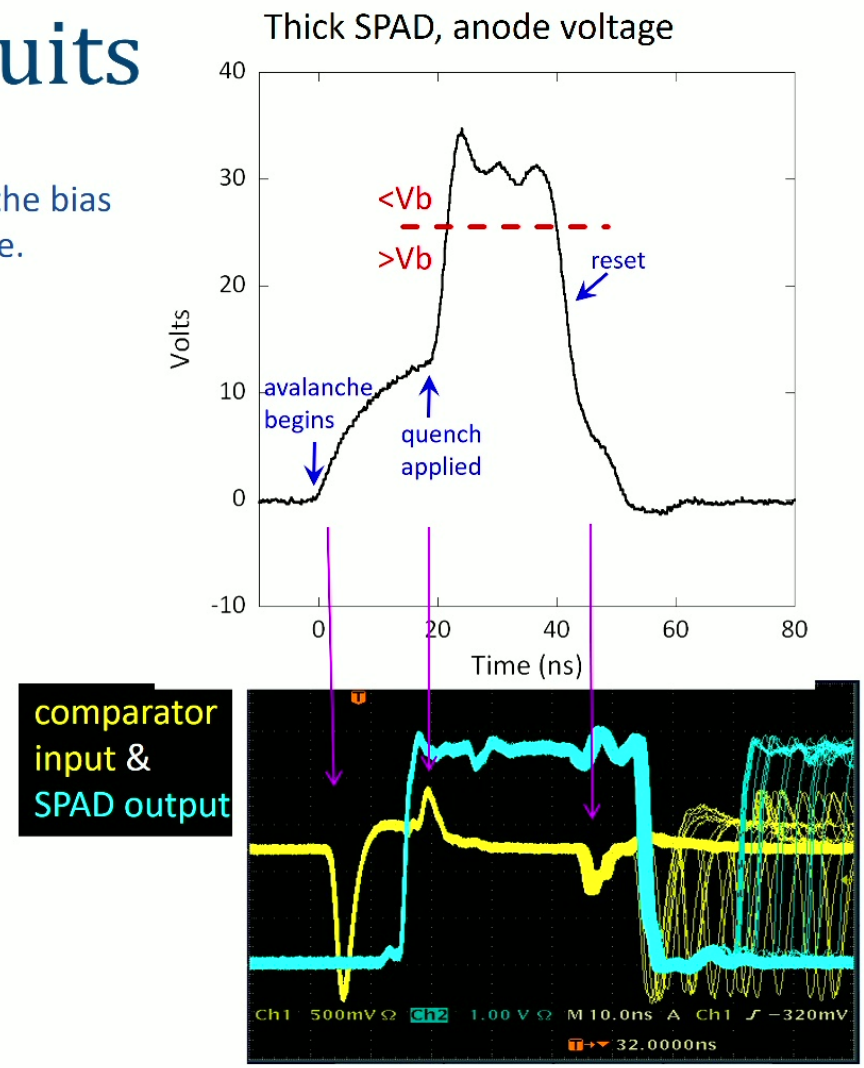
Quenching Circuits

Active Quenching
The avalanche is detected and triggers an active feedback to reduce the bias across the SPAD below breakdown, actively terminating the avalanche.
This is a vastly higher performance system.





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Quenching Circuits

ASICs can greatly improve performance

- Reduced capacitance & faster response times
- Thick SPAD recovery time improved from > 50 ns to < 10 ns

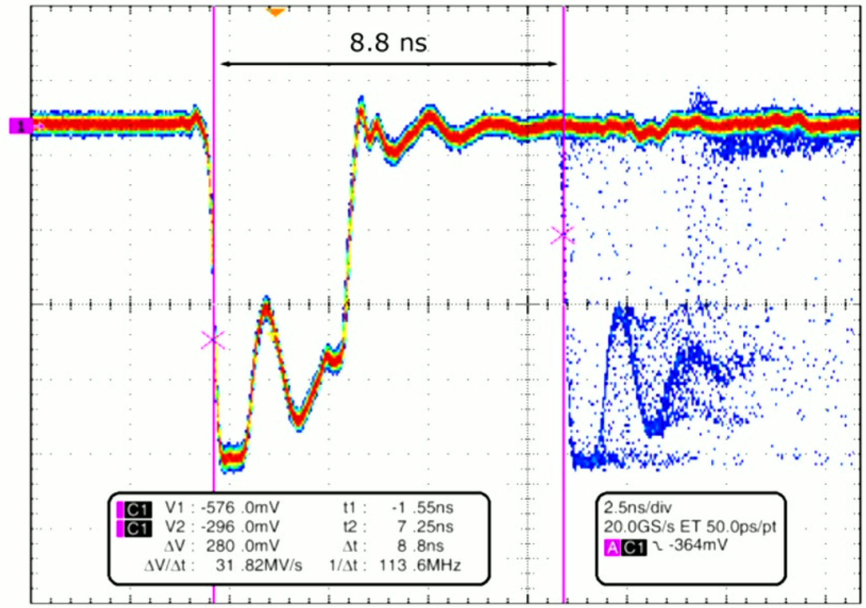

FIG. 2. Oscilloscope image of the RT-SPAD timing output (NIM standard) with direct bonding between the device and the AQC. A minimum time interval of 8.8 ns is observed between two subsequent pulses. The measurement has been performed with the same overvoltage (22 V) and the same temperature conditions of the original module.

[Farina et al. Rev. Sci. Instrum. 93, 053102 (2022)]

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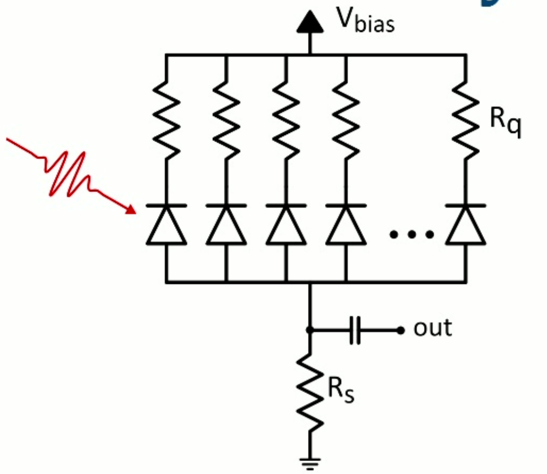
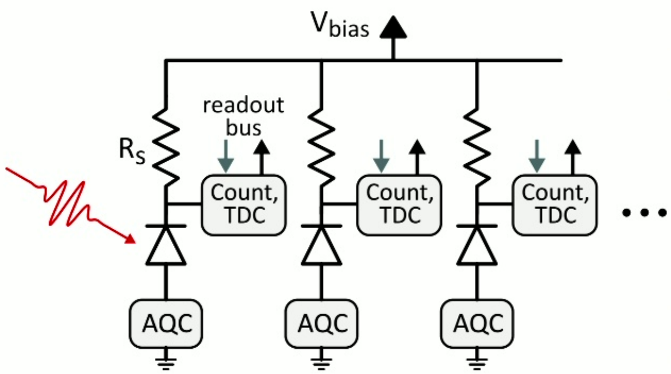
SPAD arrays: SiPM vs. Imaging

SiPM:



- > 10 mm² "Silicon Photomultiplier" (SiPM; replacing PMTs)
- High fill factor
- Avalanche current is additive; quasi-number-resolving
- DCR is sum over all pixels (up to $10^6\ s^{-1}/mm^2$)

Imaging:



- Actively or passively quenched (AQC drawn here)
- Readout system varies
  - random
  - gated counter (e.g. 10 bit);
  - TDC, or shared TDC
  - both
- 3D single-photon imaging
- Fill factor is issue
- Readout limits size & functionality

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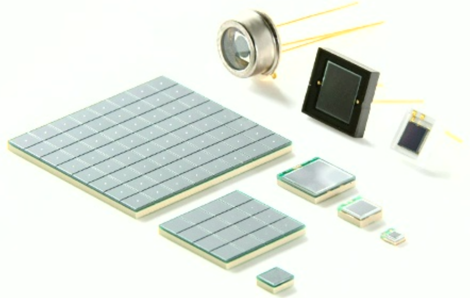
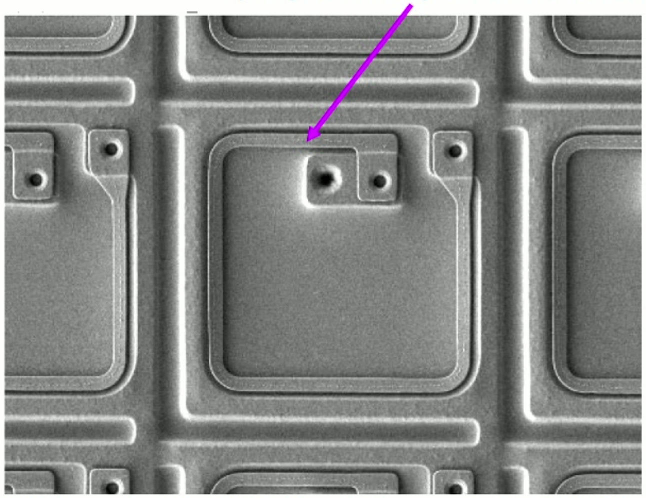
SPAD arrays: SiPM

Large format, high fill factor



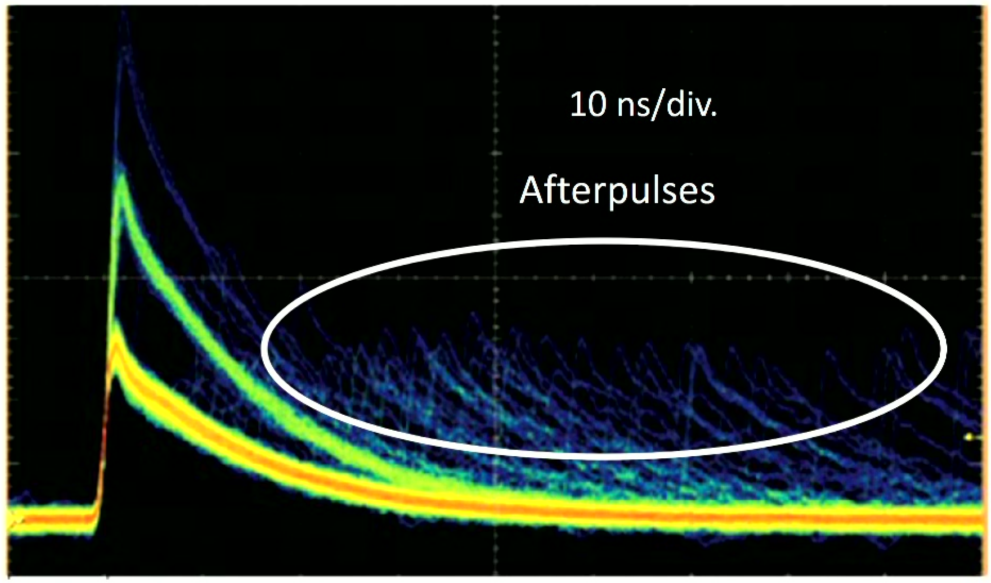
polysilicon quench resistor



[A. Ghassemi et al., *MPPC Manual*, Hamamatsu K.K. (2022)]

e- ionization efficiency is higher than *h* in Si, and red/NIR absorption length is longer

- red/NIR: n-on-p (*e*- generated deep and travel up to n)
- blue/UV: p-on-n (*e*- generated shallow and travel down to n)



- Fast edge: typically AC coupled readout
- Low jitter → ToF sensor
- Noise can be discriminated by thresholding on multiple detections
  - pretty high noise ***single***-photon detector

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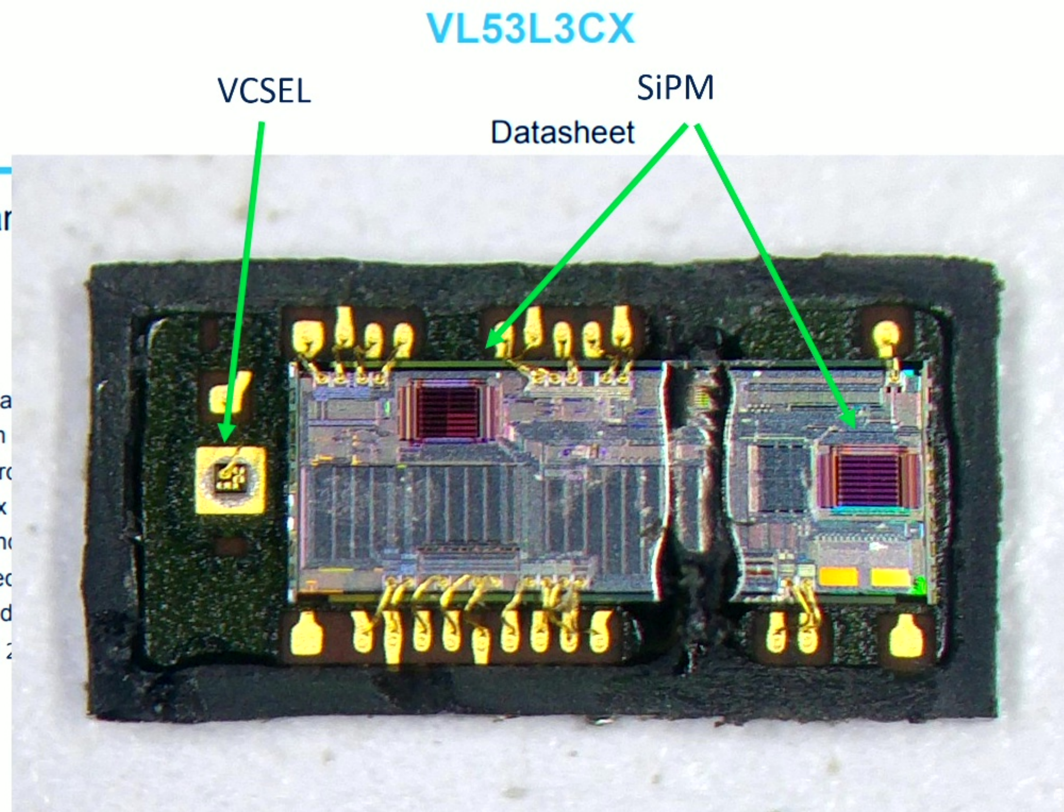
19

SPAD arrays: Ganged, ToF sensor

[https://www.st.com/resource/en/datasheet/vl53l3cx.pdf; accessed 2



[https://hackaday.io/project/25571-mappydot/log/148243-vl53l1x-teardown; accessed 2/10/23]

- < 10 mm range resolution (< 50 ps)
- Probably the least expensive SPAD(s) available

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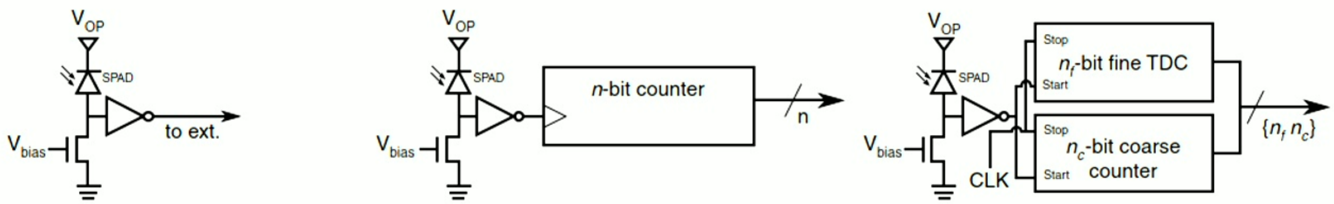
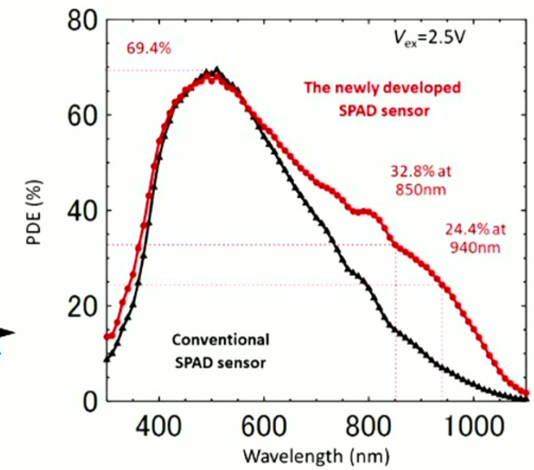
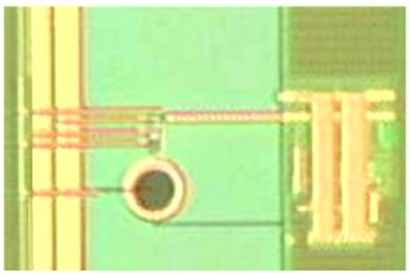
SPAD arrays: Imaging

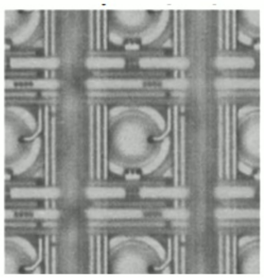
- Imaging SPADs are fabricated in CMOS → D.E. typically max. in the green
- Readout integration is incorporating more complex systems
- Fill factor



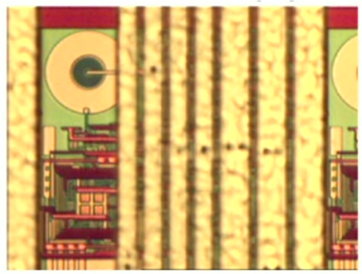




2011, AQC



2014, AQC, counter



50 ps AQC, TDC, & counter, 32x32, 2009

[Bruschini *et al.* Light: Science & Applications **8,** 87 (2019)]

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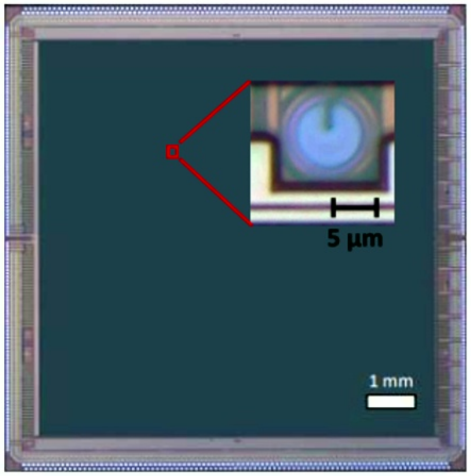
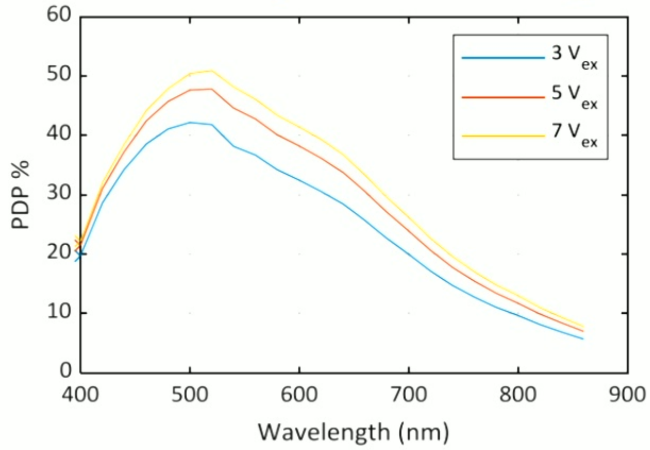
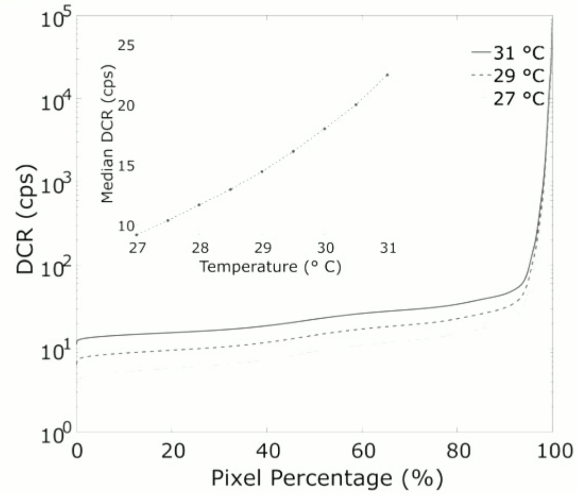
SPAD arrays: Imaging

Detailed example: 500 x 500 SPAD imager

- gated SPADs (1 ns min. gate duration)
- 88 kframes/s readout
- 6 um diameter SPADs, 16.4 um pitch
  - (10.5% fill factor)







0.003	0.010	0.021	0.003	0.001
0.013	0.028	0.050	0.026	0.009
0.018	0.055	100	0.050	0.022
0.007	0.024	0.046	0.026	0.007
0.004	0.004	0.015	0.006	0.002

Fig. 9. SS3 average crosstalk probabilities. The nearest neighbor pixels are below 0.06%, and the nearest diagonal is below 0.03%

[Wayne *et al.*, IEEE Trans. Electron. Dev. **69**, 6 (2022)]

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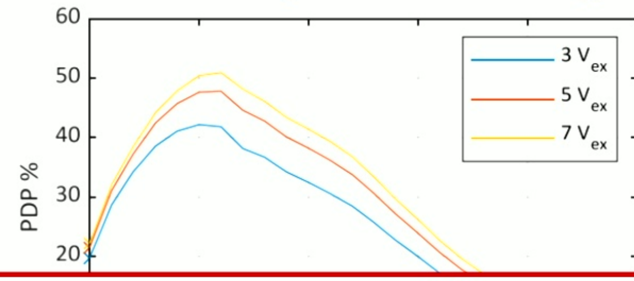
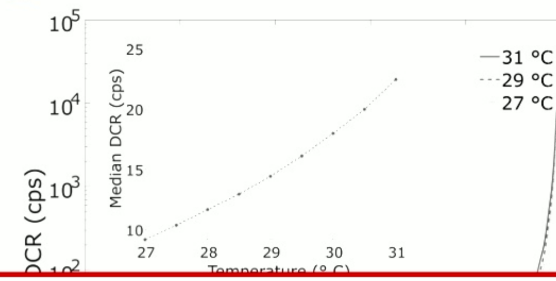
SPAD arrays: Imaging

Detailed example: 500 x 500 SPAD imager

- gated SPADs (1 ns min. gate duration)
- 88 kframes/s readout
- 6 um diameter SPADs, 16.4 um pitch
  - (10.5% fill factor)





	This Work	Ulku 2019 [11]	Morimoto 2020 [8]	Okino 2020 [32]	Dutton 2016 [22]	Parmesan 2015 [26]	Gyongy 2018 [27]	Burri 2014 [10]	Morimoto 2021 [31]	Henderson 2019 [6]
Proc. Tech (nm)	180 CMOS	180 CMOS	180 CMOS	65 CMOS	130 CIS	130 CIS	130 CIS	350 CMOS	90 / 40 3D	90 / 40 3D
Chip Size (mm²)	9.6 x 9.7	9.5 x 9.6	11 x 11	-	3.4 x 3.1	3.5 x 3.1	5 x 5	13.5 x 3.5	-	-
Pixels	500 x 500	512 x 512	1024 x 1000	1200 x 900	320 x 240	256 x 256	256 x 256	512 x 128	2072 x 1548	256 x 256
Pixel Pitch (µm)	16.38	16.38	9.4	6	8	8	16	24	6.39	9.2
Native Fill Factor (%)	10.5	10.5	7.0; 13.4	-	26.8	19.6	61	5	~100	51
Max. PDP (% @ nm)	50 @ 520	50 @ 520	10.5 @ 520 26.7 @ 520	-	39.5 @ 480	-	39.5 @ 480	46 @ 490	69.4 @ 510	23 @ 671
Median DCR (cps / px)	10.2	7.5	0.4; 2.0	-	47	50	6200	366	1.8	20
Max. Frame Rate (kfps)	49.8	97.7	24	0.45	16	4	100	156	0.06	0.76

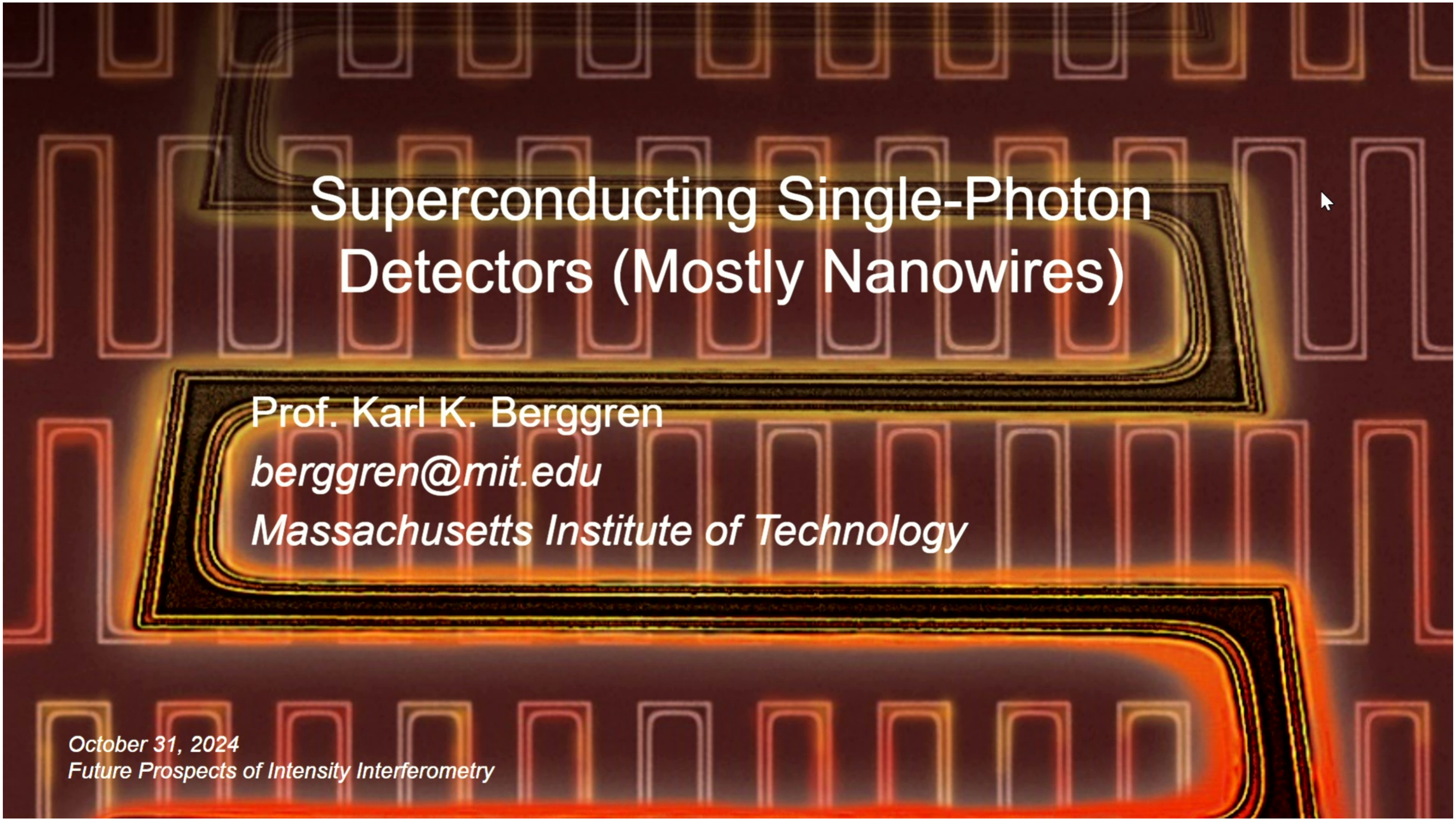
[Wayne *et al.*, IEEE Trans. Electron. Dev. **69**, 6 (2022)]

NIST

Conclusions & Take Aways

- SPADs are high performance single-photon detectors
  - Not all performance metrics have been achieved in a single device
- Two families of SPADs: thick reach through and thin planar.
- SPADs operate in control circuits that have a significant impact on their performance
- Majority of research in SPADs is in building active arrays (CMOS), improving timing resolution, and developing new materials & devices (e.g. waveguides)

NIST

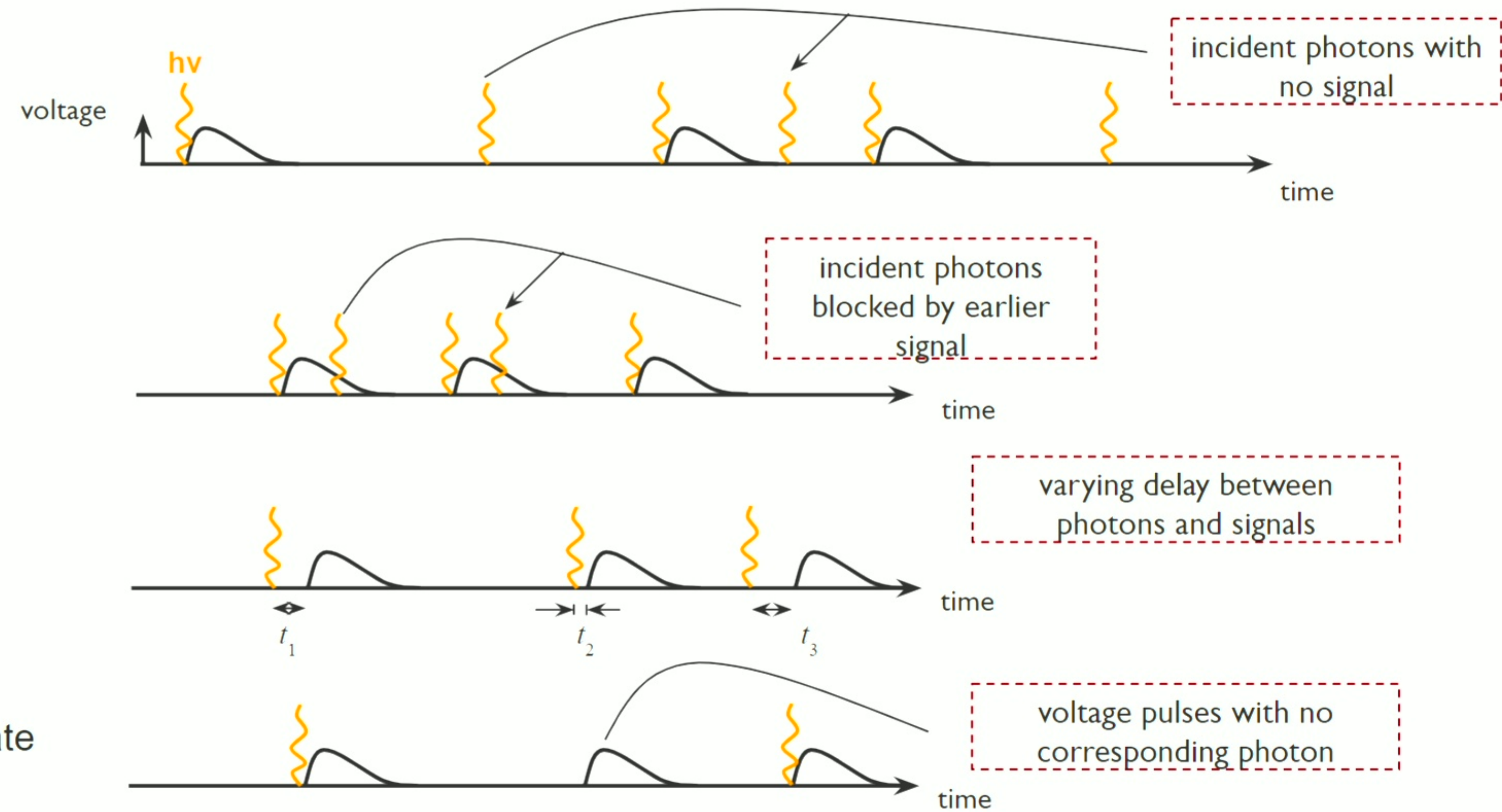

Superconducting Single-Photon Detectors (Mostly Nanowires)
Prof. Karl K. Berggren
berggren@mit.edu
Massachusetts Institute of Technology
October 31, 2024
Future Prospects of Intensity Interferometry

WHAT IS A PHOTON?

In the optical domain, a photon is approximately the amount of light from one pixel of an LCD screen that enters one of your eyes in one second if the light were held 1 km away from your face. It contains approximately 10^{-19} Joules of energy. It is an incredibly challenging technology to control and detect.

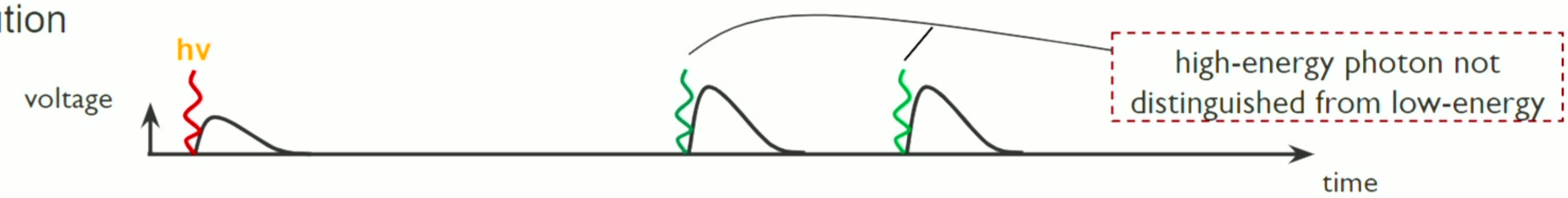
Characteristics of Photon Detectors

- Efficiency
- Reset time
- Jitter
- Dark count rate

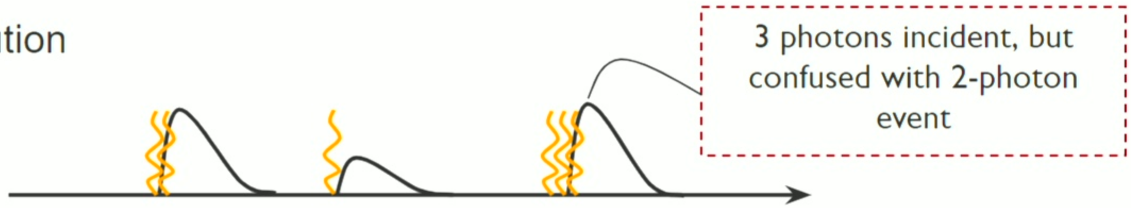


Characteristics of Photon Detectors

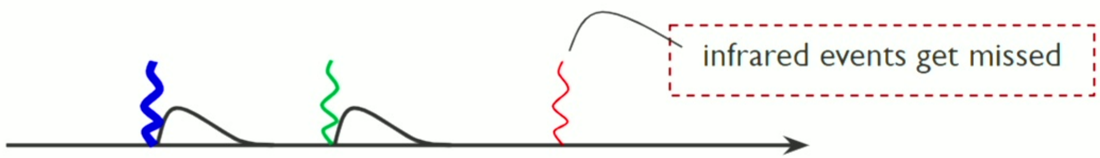
- Spectral Resolution



- Photon-Number Resolution



- IR Cut-Off



- Integration-scale for arrays
- Size, Weight, and Power consumption ("SWaP")

Proceedings of the Institute of Radio Engineers
Volume 24, Number 3 *March, 1936*

TECHNICAL PAPERS

THE SECONDARY EMISSION MULTIPLIER—A NEW ELECTRONIC DEVICE*

By
V. K. Zworykin, G. A. Morton, and L. Malter
(RCA Manufacturing Company, RCA Victor Division, Camden, New Jersey)

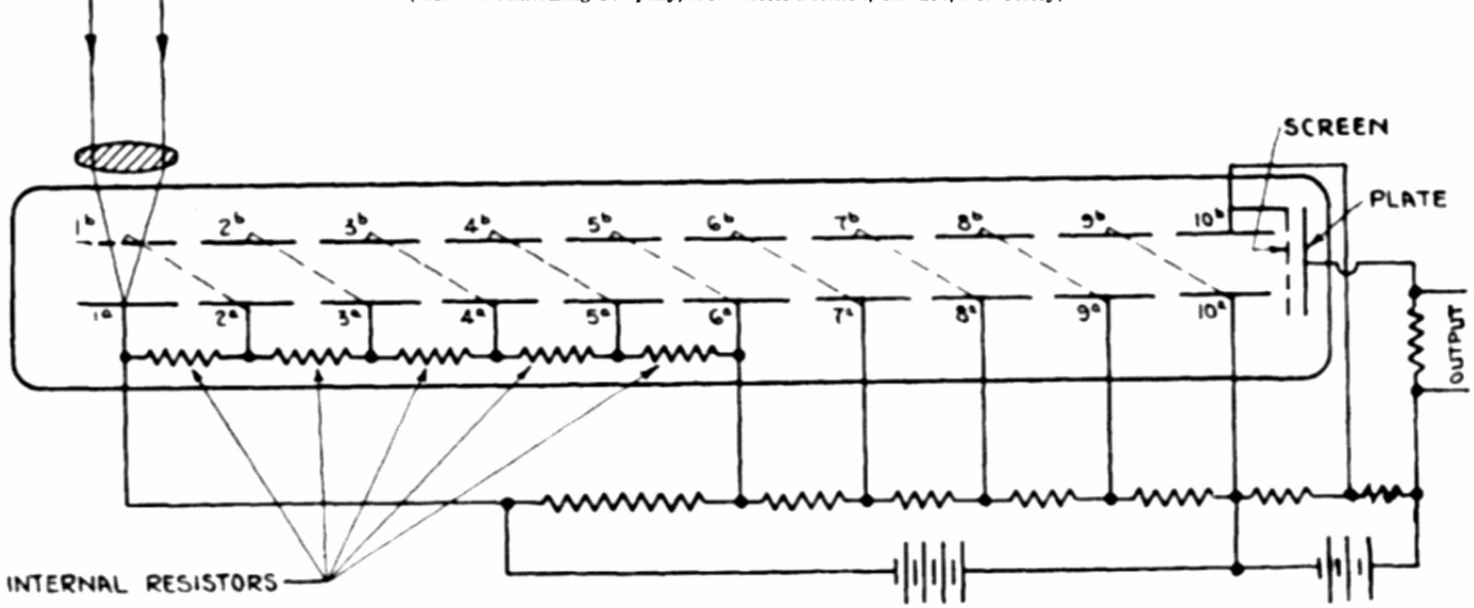


Fig. 9

WHAT IS A SUPERCONDUCTOR?

Has zero resistance at low temperature

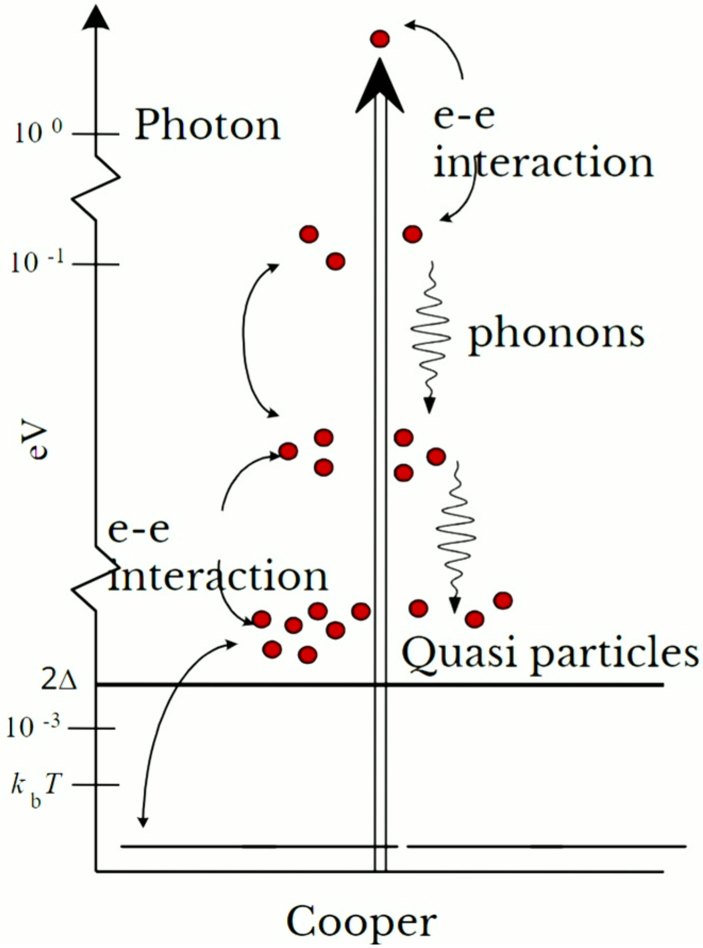
Most metals become superconductors at low enough temperature ("Critical Temperature")

Superconductors exclude magnetic field ("perfect diamagnets")

Superconductors exhibit sudden phase transition with increasing temperature, current, and magnetic field

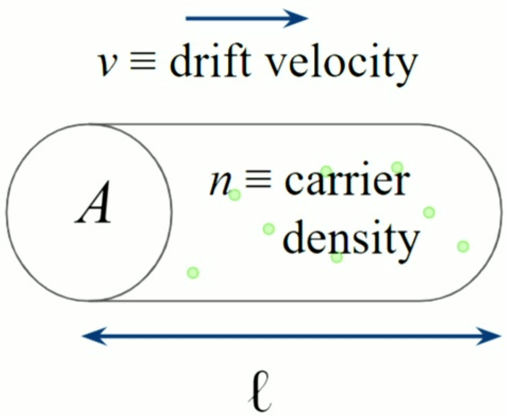
7

Band Picture of Superconductor



- Think of it as a semiconductor with a very very small gap (like 1 mV)
- Too many quasiparticles means suppress cooper pair density, and suppress gap

Kinetic Inductors



Inductive energy ≡ Kinetic energy

$$\Rightarrow \tfrac{1}{2} L_k i^2 \equiv \tfrac{1}{2} M v^2$$

$$i = A \cdot n \cdot (2e) \cdot v$$
$$M = \ell \cdot A \cdot m_e \cdot n$$

$$\Rightarrow \text{inductivity } [\mathrm{H} \cdot \mathrm{m}] \equiv \Lambda = m / (n\, e^2)$$

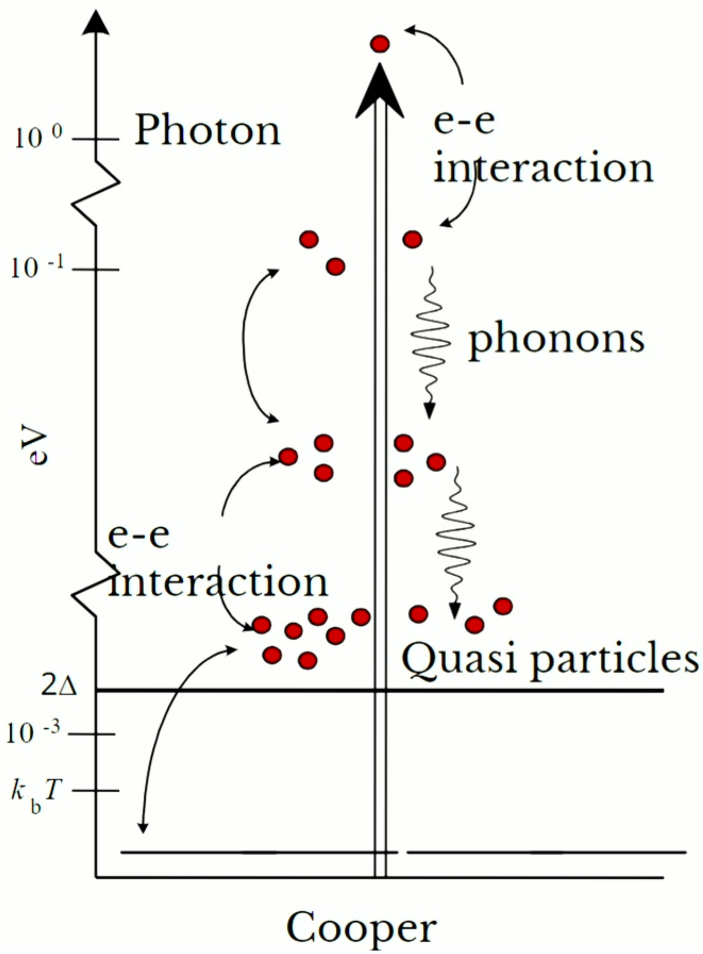
https://youtu.be/MAHkYROmriY

Resistive vs. Reactive Response of S/C

- Photons suppress superconductive energy gap and reduce carrier density
  - Reactive response:
    - Inductivity depends inversely on carrier density
    - Inductance increases, causing resonators to shift in frequency and phase
  - Resistive response
    - Phase slips and vortexes are generated
    - Vortex motion generates heat
    - Heat further suppresses superconductivity and resistive regions appear

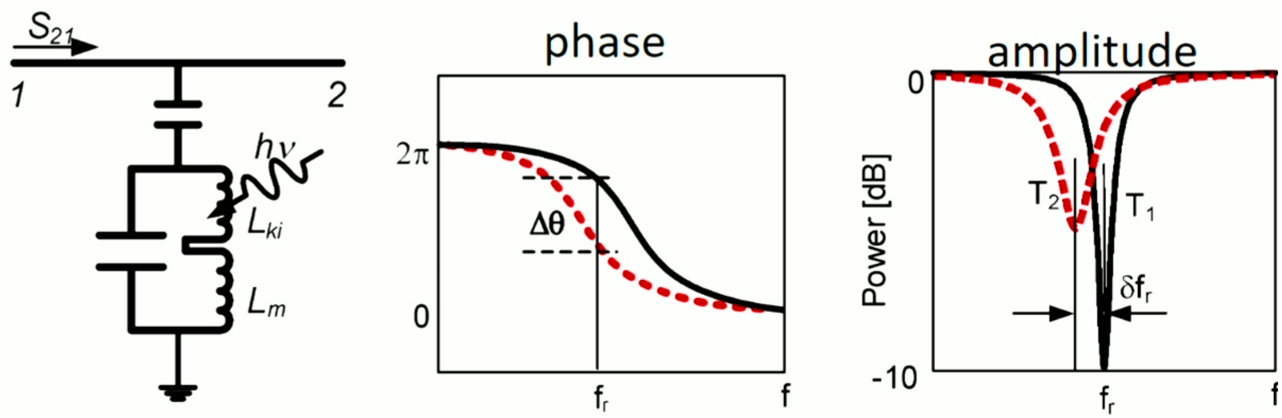
Slide courtesy of Sae-Woo Nam

MKID: principle of operation



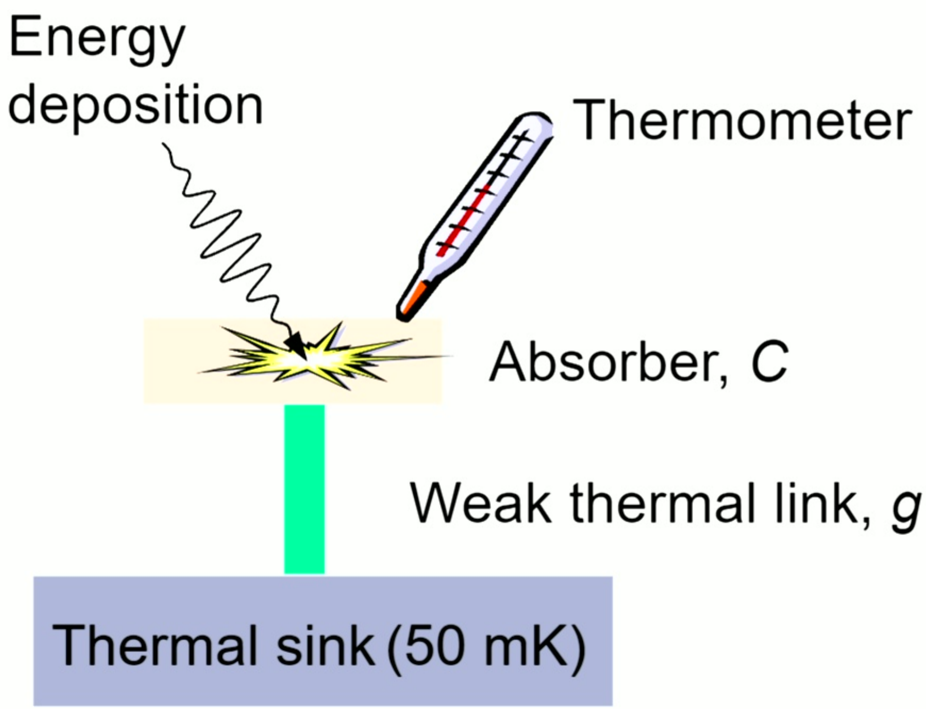
- Microwave Kinetic Inductance Detector
- Measure excess excitations, quasiparticles
- Inductance of a superconducting wire (kinetic inductance) rises in the presence of quasiparticles
- Readout by looking at the change in a resonator

https://doi.org/10.1038/nature02037



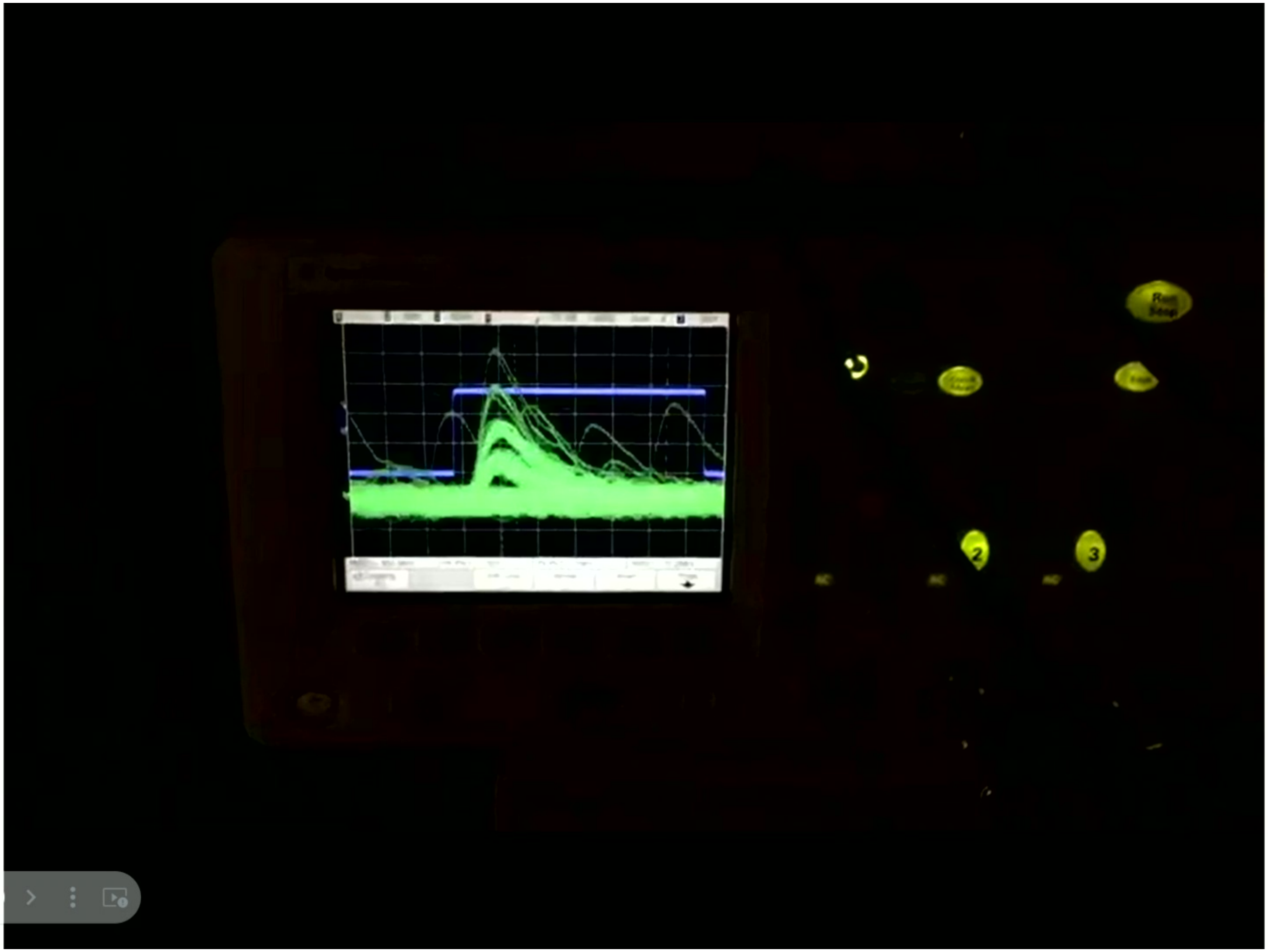
Slide courtesy of Sae-Woo Nam

Transition Edge Sensor (TES)



- Calorimetric detection of UV/optical/IR photons
- Temperatures are ~100 mK
  - low noise
  - high sensitivity.
- NIST – Tungsten Superconductor
- AIST – Titanium Superconductor

https://doi.org/10.1063/1.113674



Adriana Lita, NIST

History of Superconducting Wire Detectors

Phys. Rev. Lett. **8**, 438 – Published June 1962

SUPERCONDUCTING NUCLEAR PARTICLE DETECTOR

N. K. Sherman
Queen's University, Kingston, Ontario, Canada

J. Appl. Phy. 79, 7069 - Published 1996

Bolometric and nonbolometric infrared photoresponses in ultrathin superconducting NbN films

M. W. Johnson[a] and A. M. Herr
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
A. M. Kadin
Department of Electrical Engineering, University of Rochester, Rochester, New York 14627

Appl. Phys. Lett. **6**, 79– Published Aug. 2001

Picosecond superconducting single-photon optical detector

G. N. Gol'tsman,[a] O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov
Department of Physics, Moscow State Pedagogical University, Moscow 119435, Russia
C. Williams and Roman Sobolewski[b]
Department of Electrical and Computer Engineering and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627-0231

< 18 >

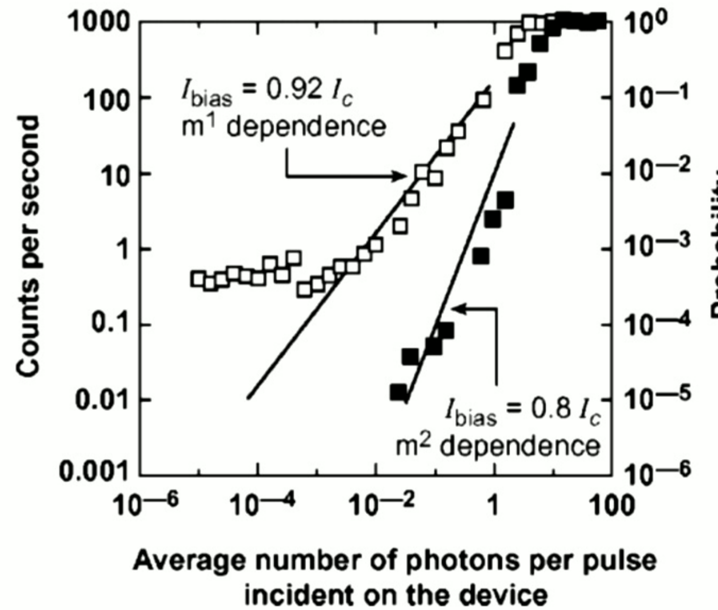
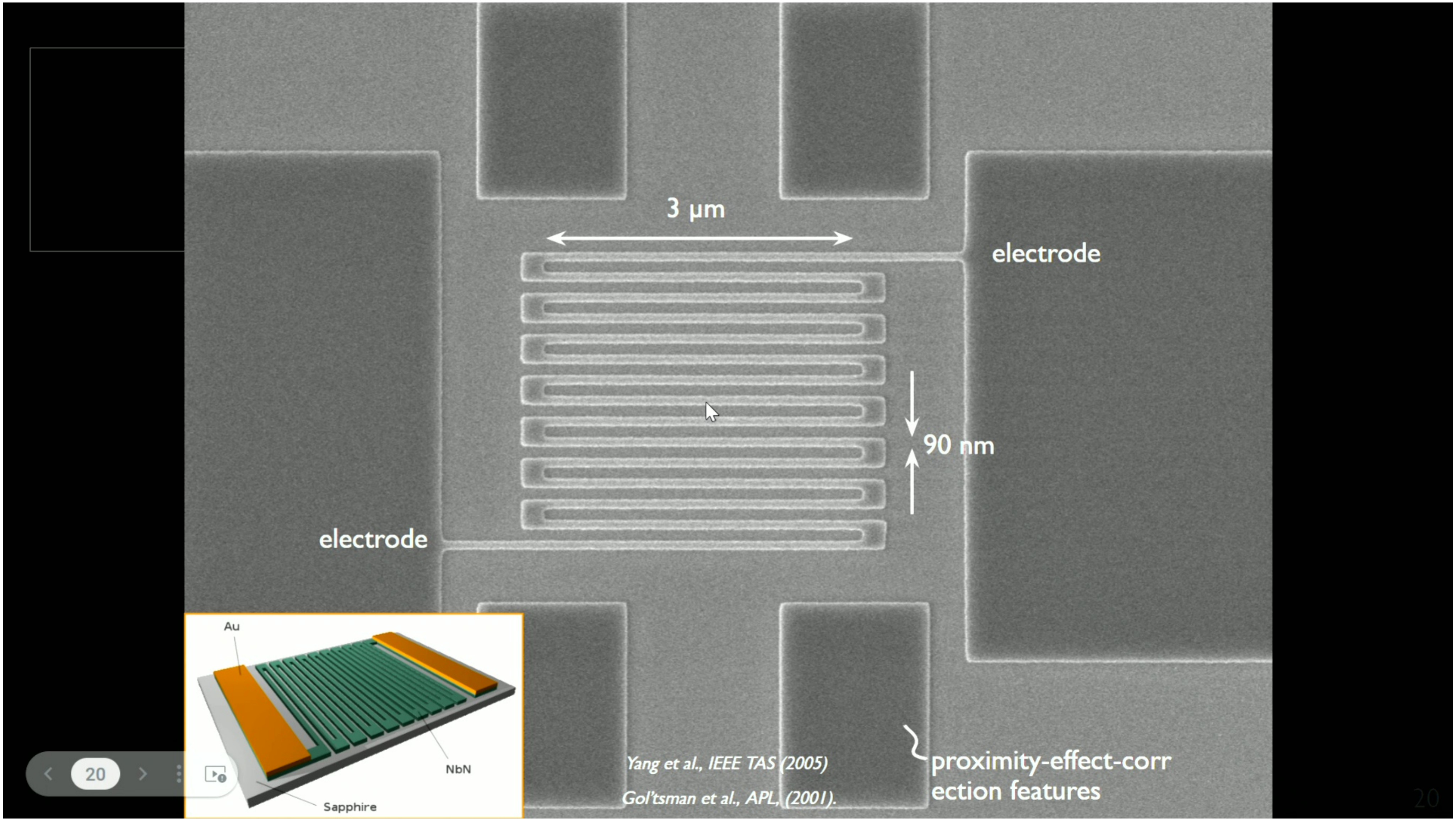
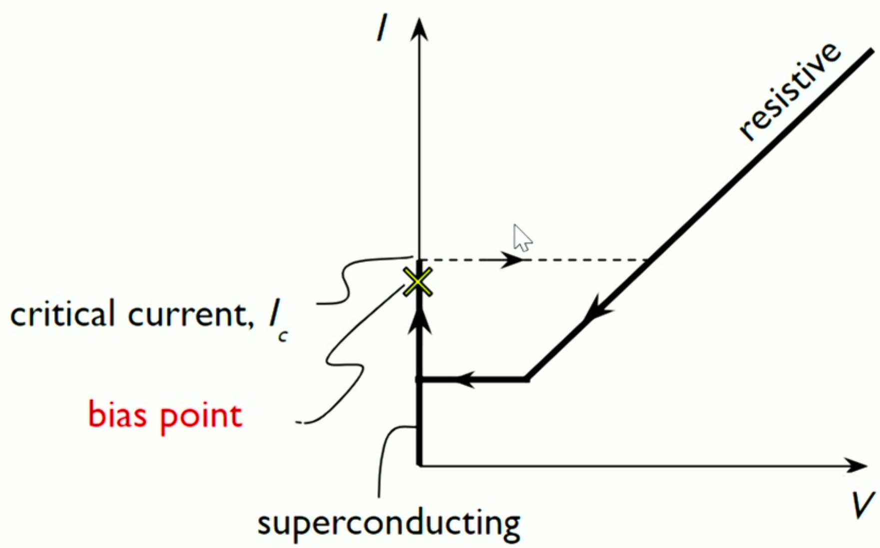


FIG. 3. Number of counts per second recorded by the NbN SPD versus the average number of photons per pulse incident upon the device, for two different bias current levels is shown. The solid lines correspond to the Eq. (4) theoretical predictions. The incident photon wavelength was 0.81 μm.

G. N. Gol'tsman et al., "Picosecond superconducting single-photon optical detector," doi: 10.1063/1.1388868.


3 μm
electrode
90 nm
electrode
Au
NbN
Sapphire
Yang et al., IEEE TAS (2005)
Gol'tsman et al., APL, (2001).
proximity-effect-corr
ection features
20

Comparison-Based Device



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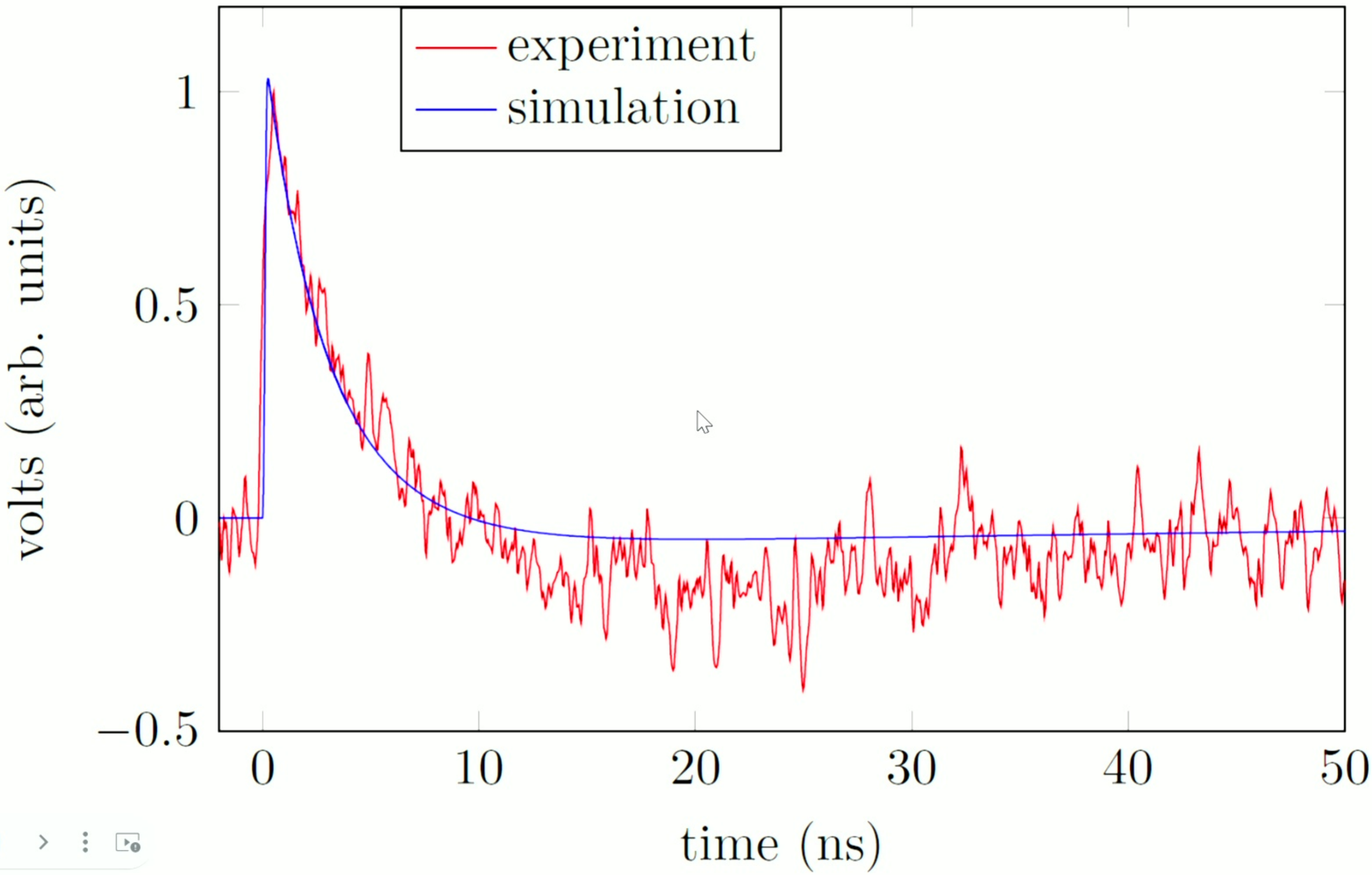
22


experiment
simulation
volts (arb. units)
1
0.5
0
−0.5
0
10
20
30
40
50
time (ns)

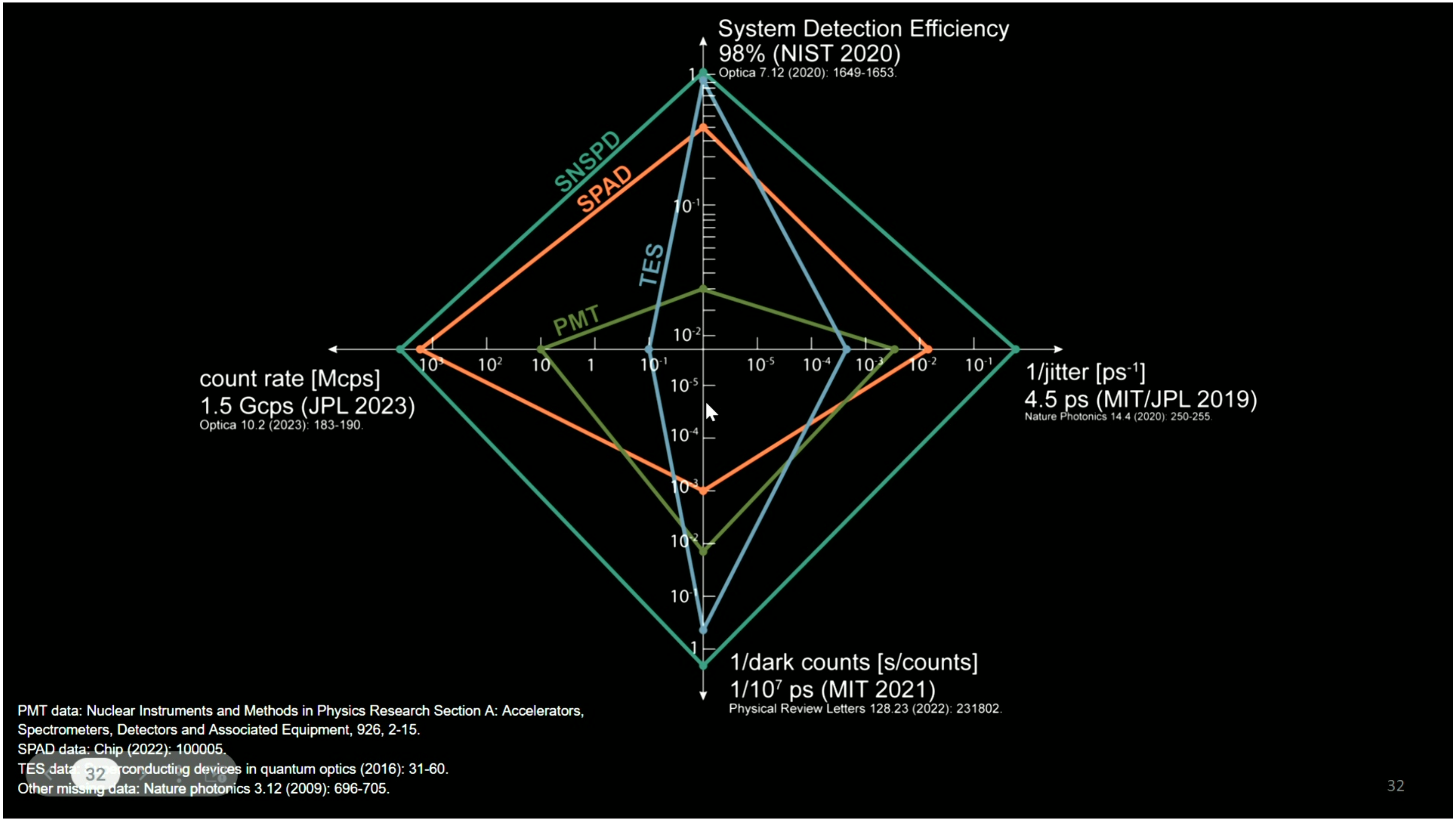
30

30

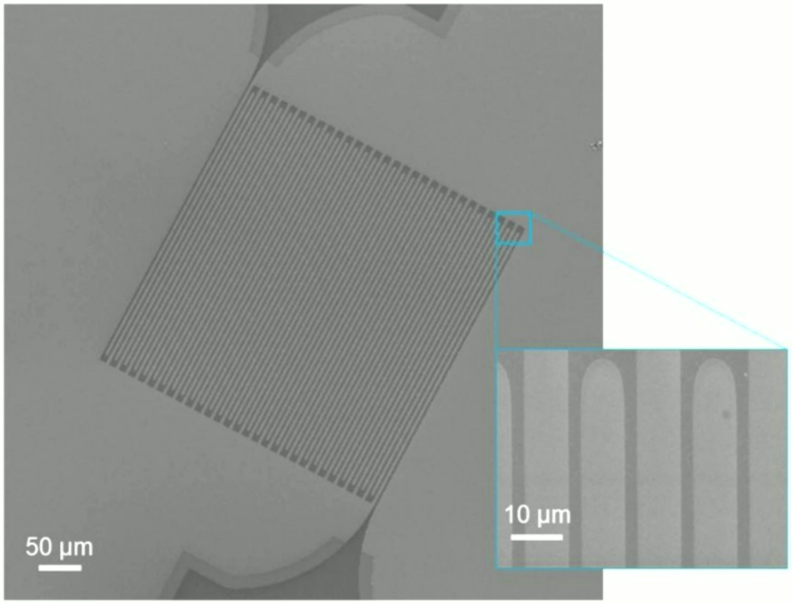
Why are Superconducting-Nanowire Single-Photon Detectors Special?

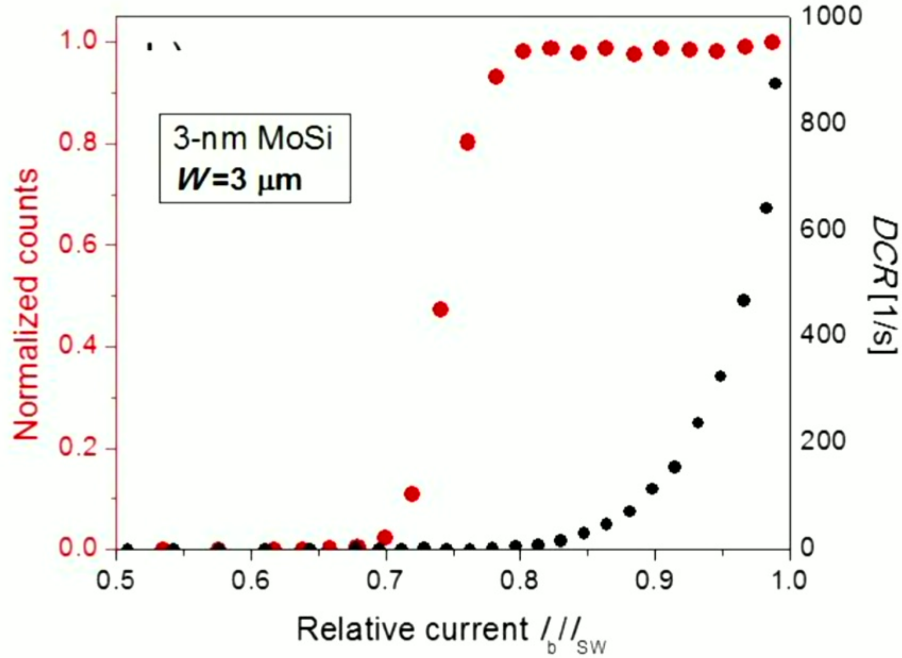
- Infrared efficiency for single photons (> 29 μm, JPL/NIST '23)
- Jitter < 3 ps: nothing else can match it for single photons (Korzh+, Nature Photonics 14 '20)
- Efficiency: Competes with transition-edge sensors (98%, Reddy+ CLEO/QELS '19)
- Count rate (~100 Mcps, i.e. 1-10 ns reset)
- Dark-count rate (~ 1 per day)
- Operates up to 20K, 7 T magnetic fields (Charaev 24, Marvinney 21)
- Convenient fabrication, no shielding, room-temp amplification, relatively higher temperature operation

31


System Detection Efficiency
98% (NIST 2020)
Optica 7.12 (2020): 1649-1653.
SNSPD
SPAD
TES
PMT
count rate [Mcps]
1.5 Gcps (JPL 2023)
Optica 10.2 (2023): 183-190.
1/jitter [ps-1]
4.5 ps (MIT/JPL 2019)
Nature Photonics 14.4 (2020): 250-255.
1/dark counts [s/counts]
1/10^7 ps (MIT 2021)
Physical Review Letters 128.23 (2022): 231802.
PMT data: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 926, 2-15.
SPAD data: Chip (2022): 100005.
TES data: Superconducting devices in quantum optics (2016): 31-60.
Other missing data: Nature photonics 3.12 (2009): 696-705.
32

Large-area microwire MoSi single-photon detectors





Thin 3-nm MoSi film, up to 3 µm-wide, operating T = 0.3 K, λ = 1550 nm

I. Charaev et al, Appl. Phys. Lett. *116, 242603 (2020)*


Quantum Opus
Wisconsin, US
California, US
Photon Spot
SINGLE QUANTUM
Excellence in photon detectio
The Netherlands
IDQ
Switzerland
SCONTEL
SUPERCONDUCTING NANOTECHNOLOGY
Moscow, Russia
赋同科技
PHOTEC
Shangai, China

What Does it Look Like?

Compressor unit fits under optical table.

Cryostat and electronics easily rack mountable.

Copyright © 2017 Quantum Opus, LLC

High-order temporal coherences of chaotic and laser light

Martin J. Stevens[1,*], Burm Baek[1], Eric A. Dauler[2,3], Andrew J. Kerman[3], Richard J. Molnar[3], Scott A. Hamilton[3], Karl K. Berggren[2], Richard P. Mirin[1] and Sae Woo Nam[1]

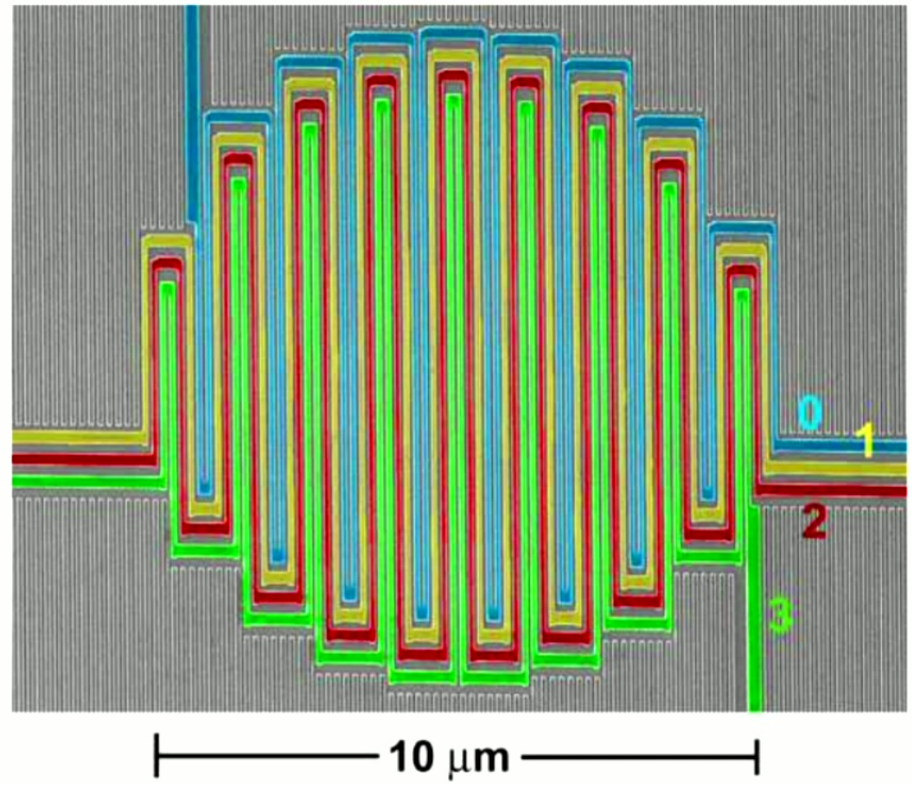


Fig. 1. Scanning-electron microscope image of the four-element SNSPD, with nanowire elements 0-3 traced out in color. Each element consists of a ~5 nm-thick × 80 nm-wide NbN nanowire on a sapphire substrate, with 60 nm gaps between wires. The 9.4 μm-diameter active area is well matched to the spatial mode of a single mode optical fiber, the cleaved end of which is held within ~10 μm of the detector surface. The interleaved design ensures that all four elements equally sample this spatial mode.

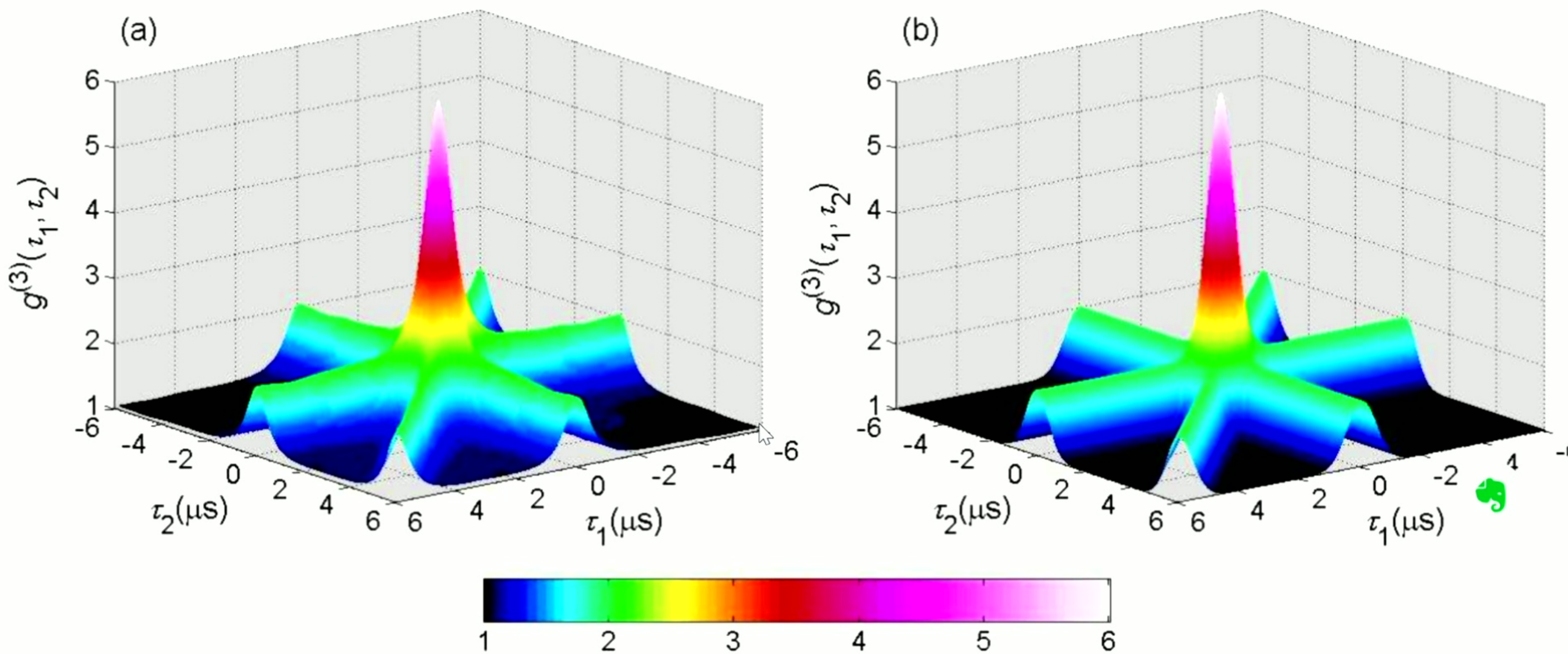
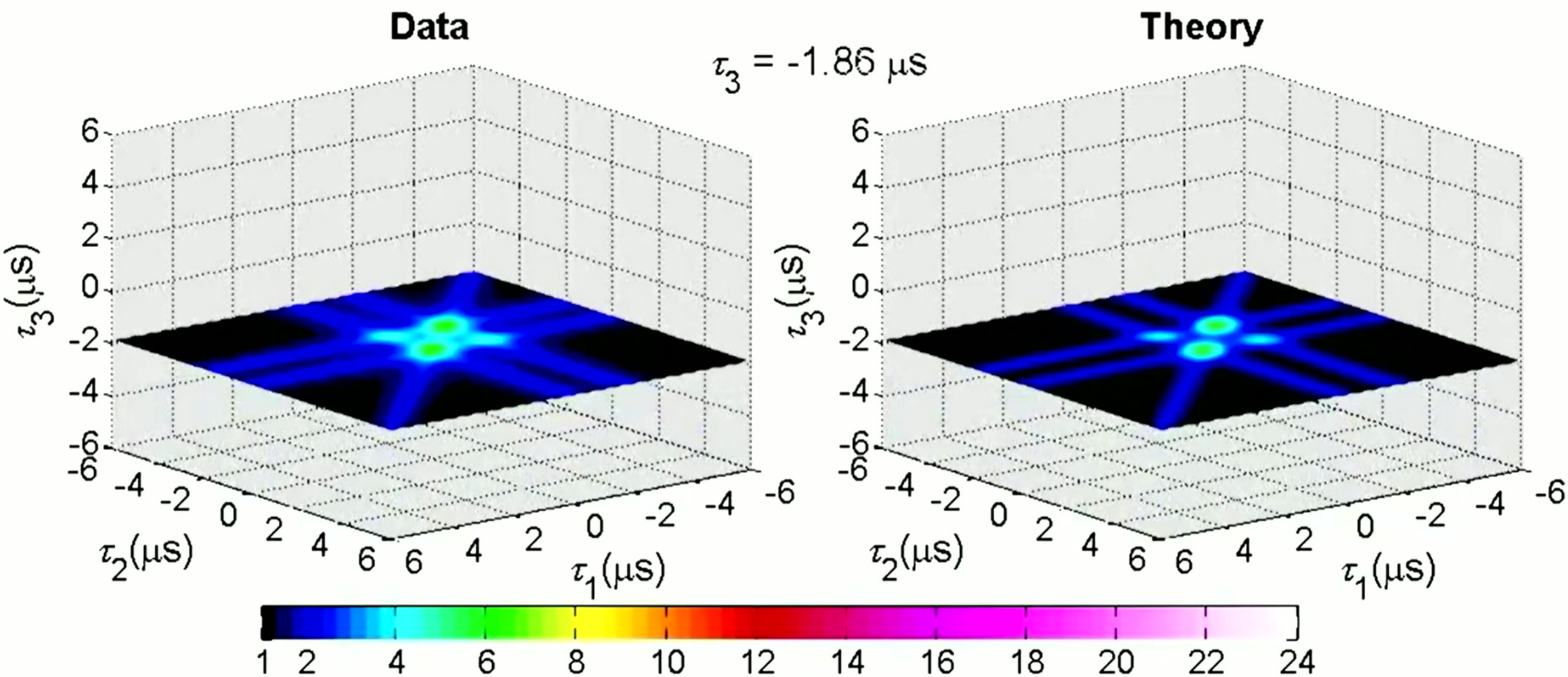


Fig. 3. (a) Measured third-order coherence from the chaotic source, where both color and height indicate measured value of $g^{(3)}$. The cross-section in Fig. 2(a) samples these data along a diagonal line (not shown) extending from the far left corner to the far right corner as plotted here. (b) Calculated third-order coherence for a chaotic source derived from an ideal Gaussian scattering process with a coherence time of 900 ns, as discussed in the text.

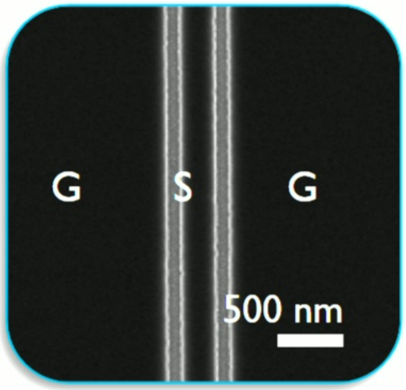
[Link to video]



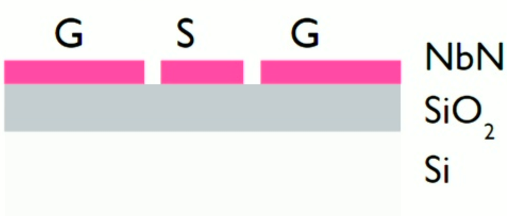
Kinetic Inductance: Superconductivity's Ugly Secret

Place for Speaker's video (5cm x 3.5cm)

Top view



Side view



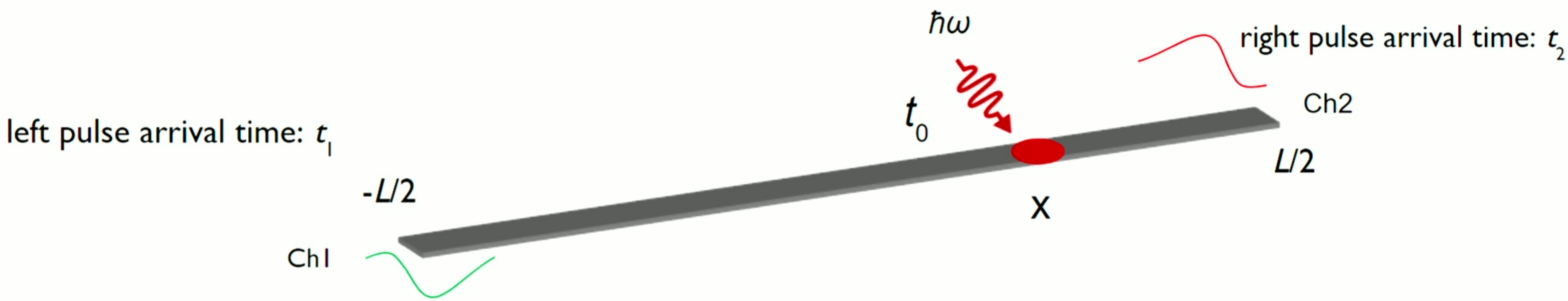
$$\begin{aligned}\text{Specific Inductance} &\equiv L_\text{S} \\ &= \mu_\circ \frac{\lambda^2}{\text{Area}} \\ &\approx 400\,\text{pH}\,\mu\text{m}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Specific Capacitance} &\equiv C_\text{S} \\ &\approx 3.3\epsilon_\circ \\ &\approx 30\,\text{aF}\,\mu\text{m}^{-1}\end{aligned}$$

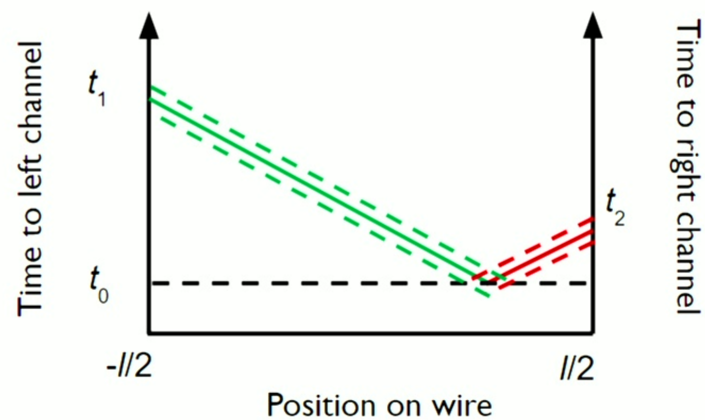
$$\begin{aligned}\text{Signal Speed} &= c_\text{eff} \\ &= \frac{1}{\sqrt{C_\text{S} L_\text{S}}} \sim \frac{c}{30} \\ &= 3\%\,c\end{aligned}$$

$$n_\text{eff} \sim 30$$

Spatial and temporal resolution in a wire



Photon position and arrival time can be detected simultaneously!



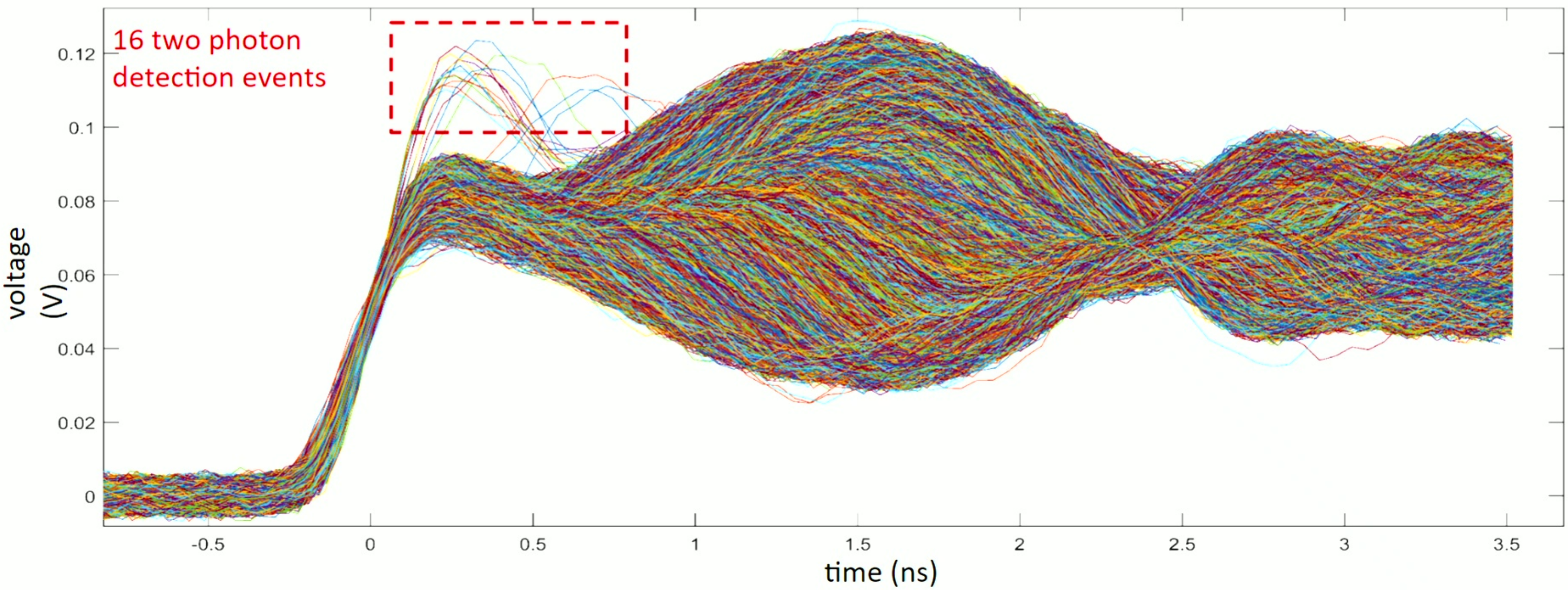
Location: $x = (t_1 - t_2)c'/2$ — differential time

Time: $t_p = (t_1 + t_2 - L/c')/2$ — sum time

spatial resolution = timing jitte

Detecting two-photon-firing events

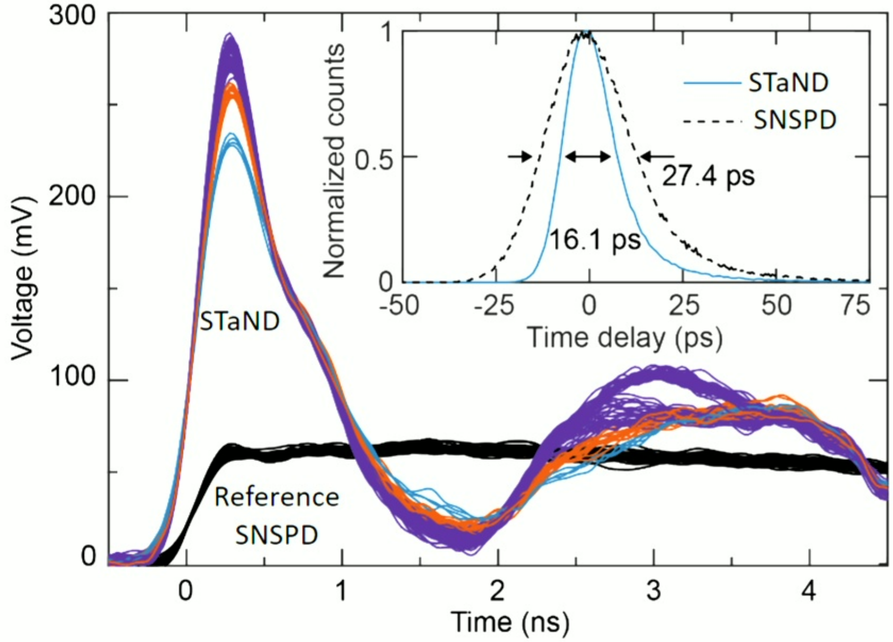
16 two-photon firing events among 50,000 photon detection events
(flood illumination over the entire area)



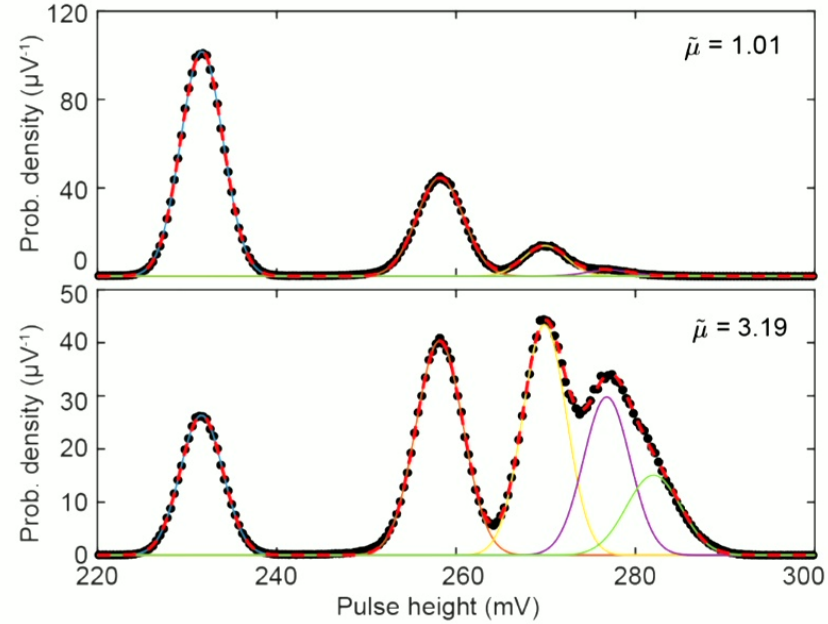
58

Photon Number Resolution

Jitter reduction



Photon number resolution



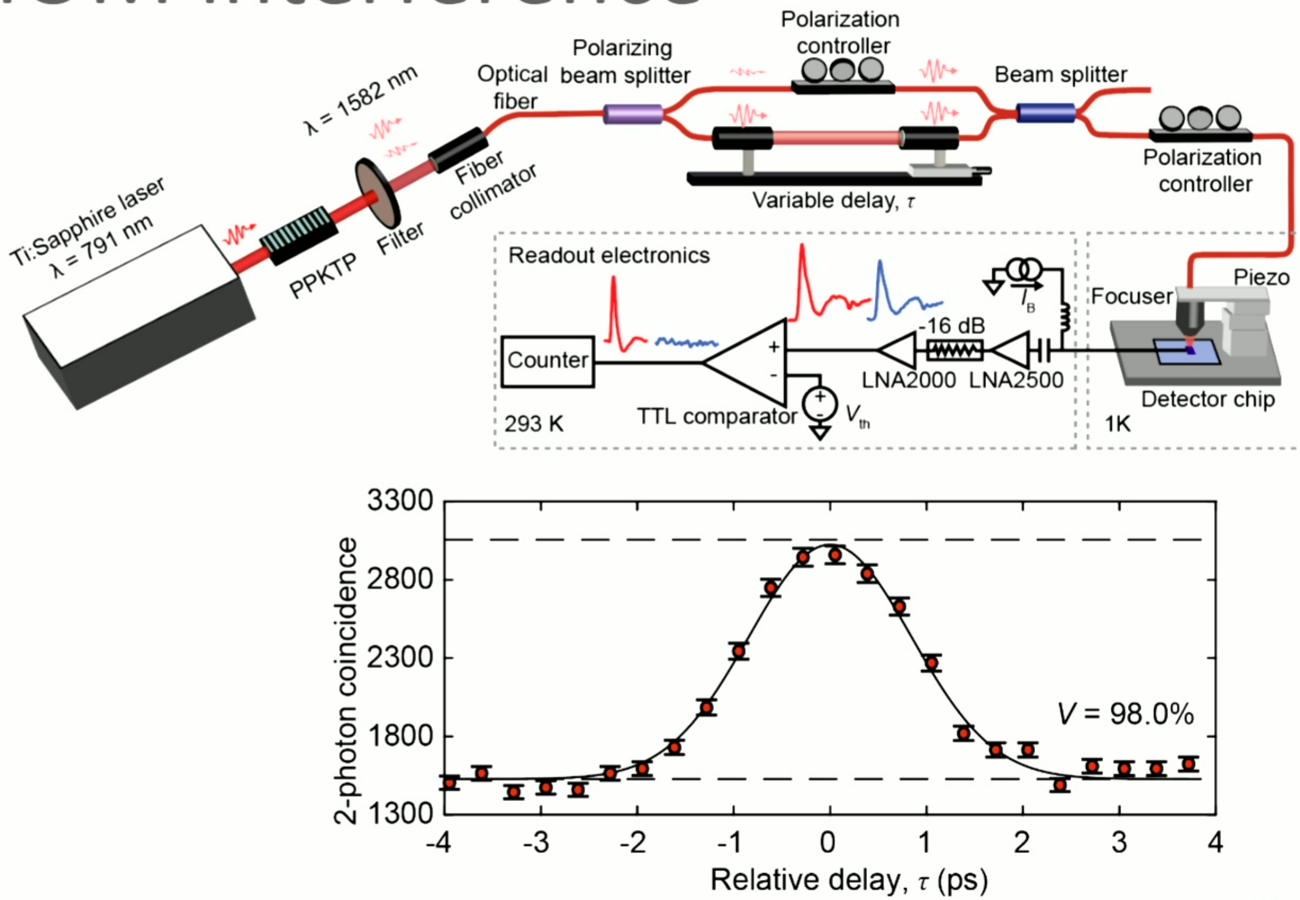
*Unpublished data

Tapered readout has also enabled:

1. 25 ps jitter in NbN SNSPD without amplifier (measured at JPL)
2. sub-5 ps jitter in WSi using cryogenic amplifiers (Korzh et al. CLEO 2018, paper FW3F.3)

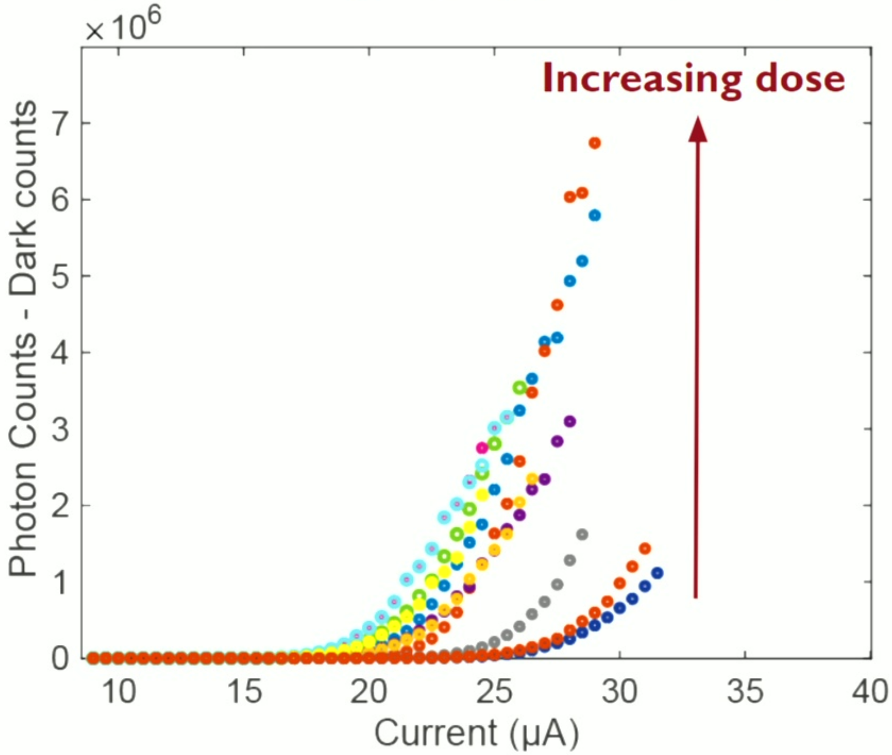
Direct measurement of photon bunching in HOM interference

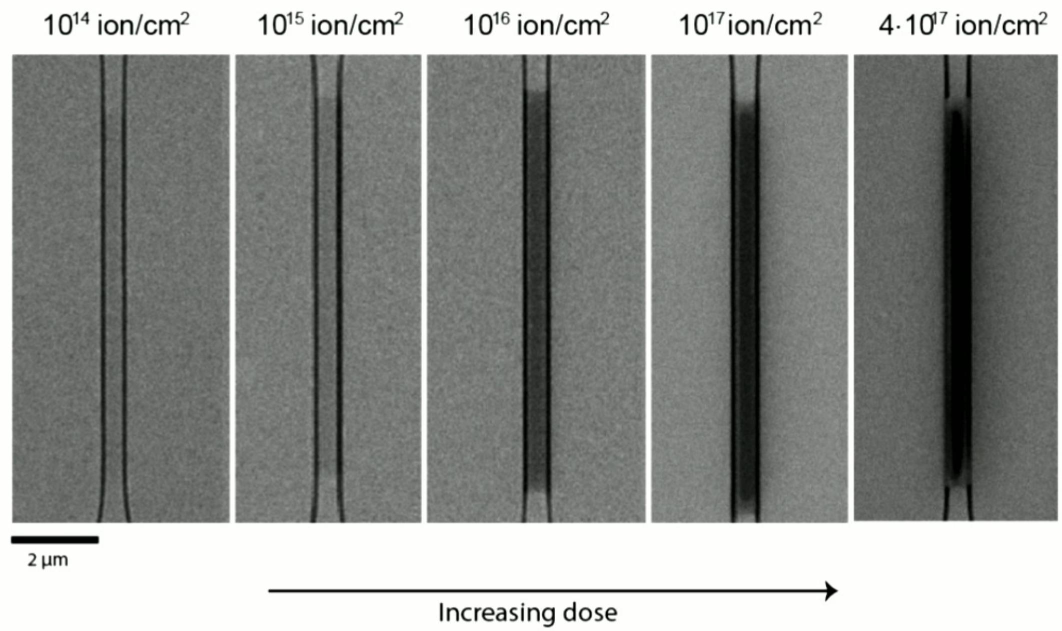
- Frequency degenerated entangled photon pairs generated through spontaneous parametric down conversion (SPDC)
- Comparator readout switches the STaND between single-photon-detector and coincidence-counter modes
- Measured HOM interference visibility of 98%



Effects of He ion irradiation on NbN SNSPDs

- Demonstration of an improved detection efficiency via defect engineering with He ion irradiation on NbN SNSPDs (first demonstration by Zhang et al., Physical Review Applied, 12(4):044040, 2019)

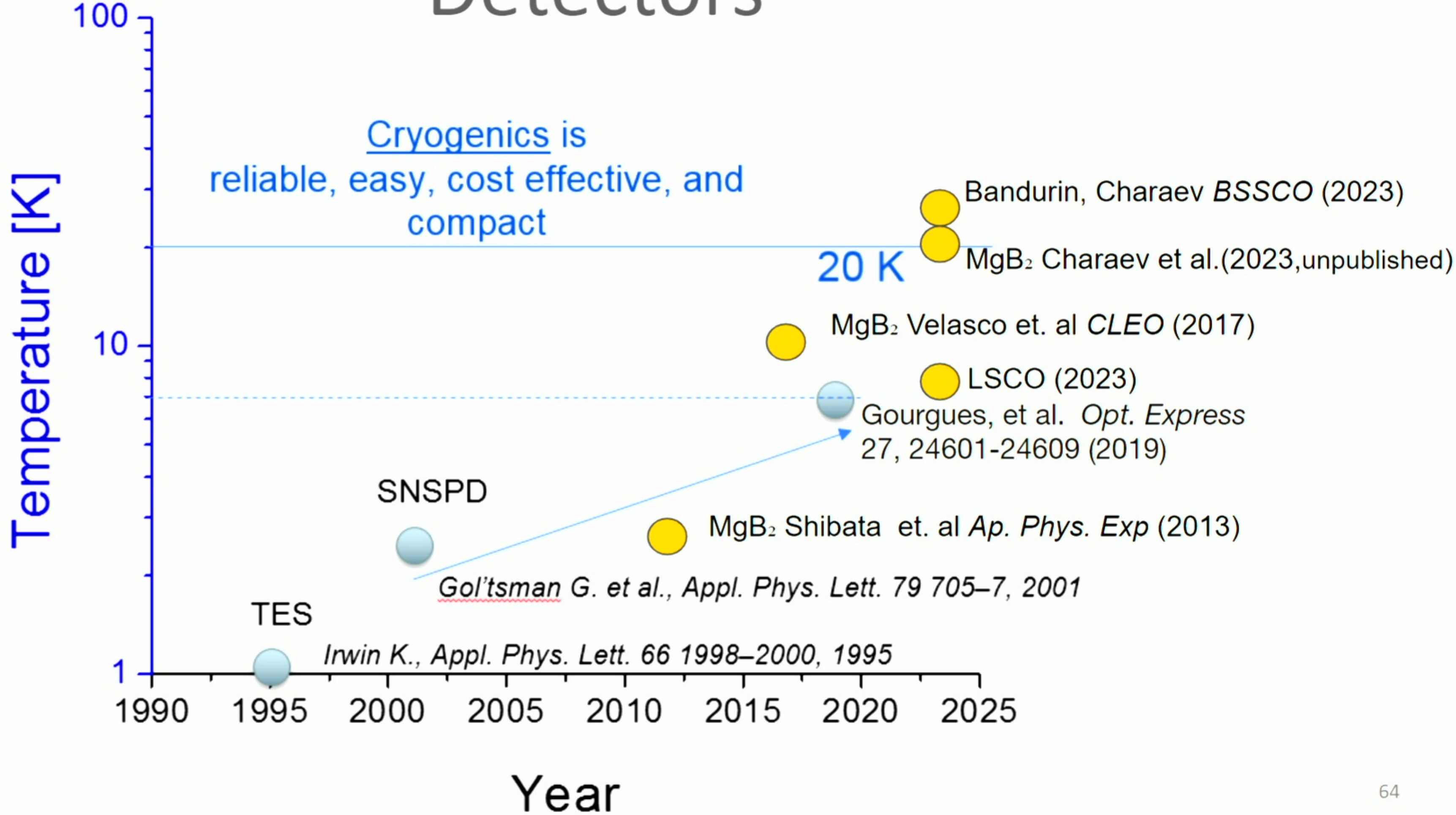




- For doses > $5\cdot10^{15}$ ions/cm^2 → post processing and enhanced detector metrics

Detection efficiency ∝ Light Counts - Dark Counts

Operating Temperature of Superconducting Detectors



64

Thank You!

- To the Perimeter Institute team and the conference organizer
- To the hundreds (thousands?) of PIs, post-docs, students, technicians who have supported this field over decades, and the thousands of administrators/facilities workers/family members who have supported them.
- The major institutions that have been involved in this field include (in random order).
    - Argonne National Lab, Caltech Jet Propulsion Laboratory, Chalmers University, Delft University of Technology, Eindhoven University of Technology, EPFL, Glasgow University, Heriot Watt University, Italian National Research Council (Rome, Naples)*, Karlsruhe Institute of Technology, KTH Royal Institute of Technology, Los Alamos National Lab, Michigan State University, MIT Lincoln Laboratory, Moscow State Pedagogical University, Nanjing University, National Institute of Information and Communications Technology (NICT) in Kobe Japan, National Institute of Standards and Technology, Shanghai Institute of Microsystem and Information Technology (SIMIT), SPIN (Naples), The Technion, U. of Naples, U. of Rochester, U. of Salerno, U. of British Columbia, U. of Roma TRE, U. of Waterloo, Yale University, and others that have slipped my mind…

Apologies to anyone I neglected to mention.