Single-Photon Detector Tutorial

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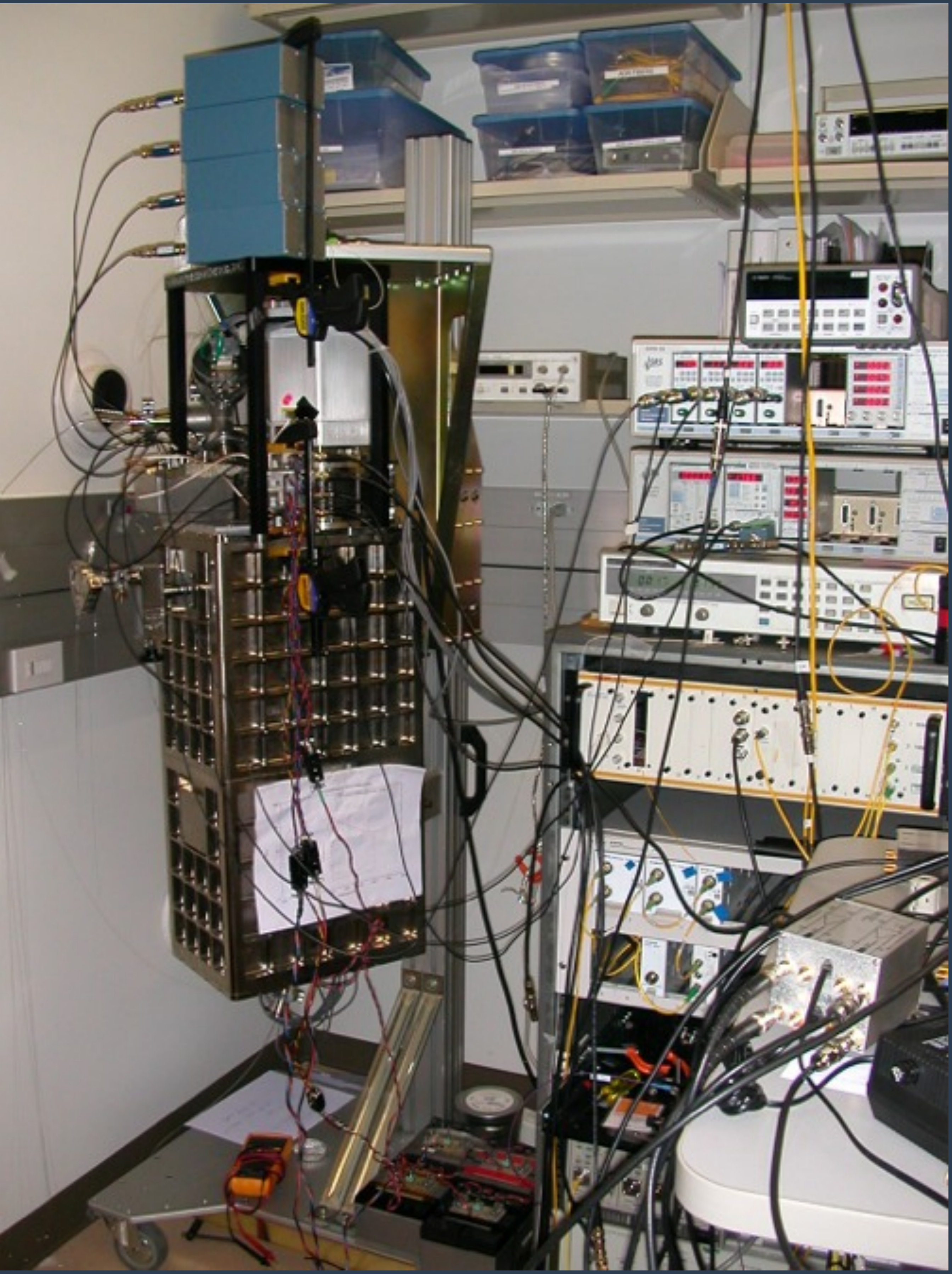
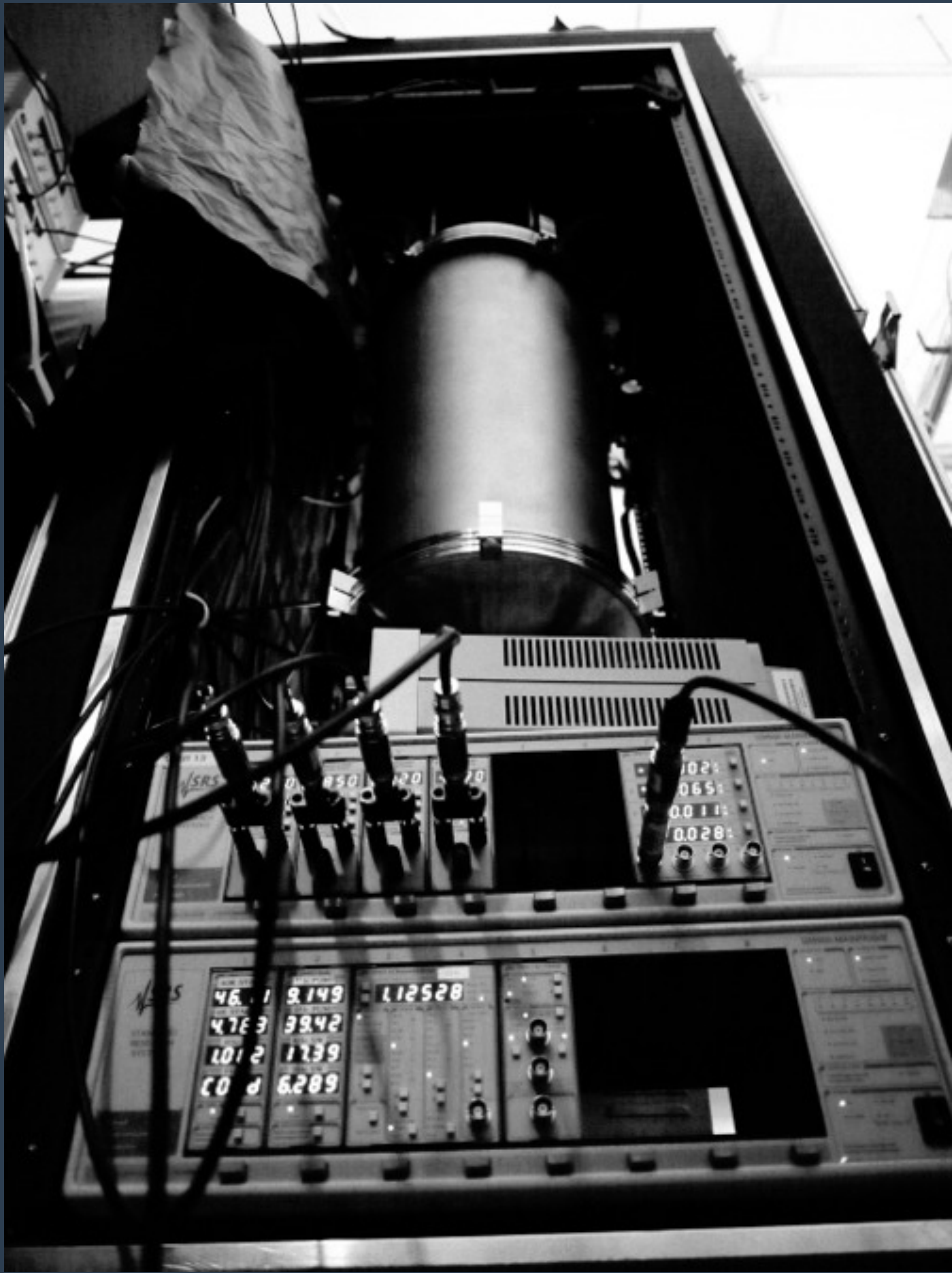
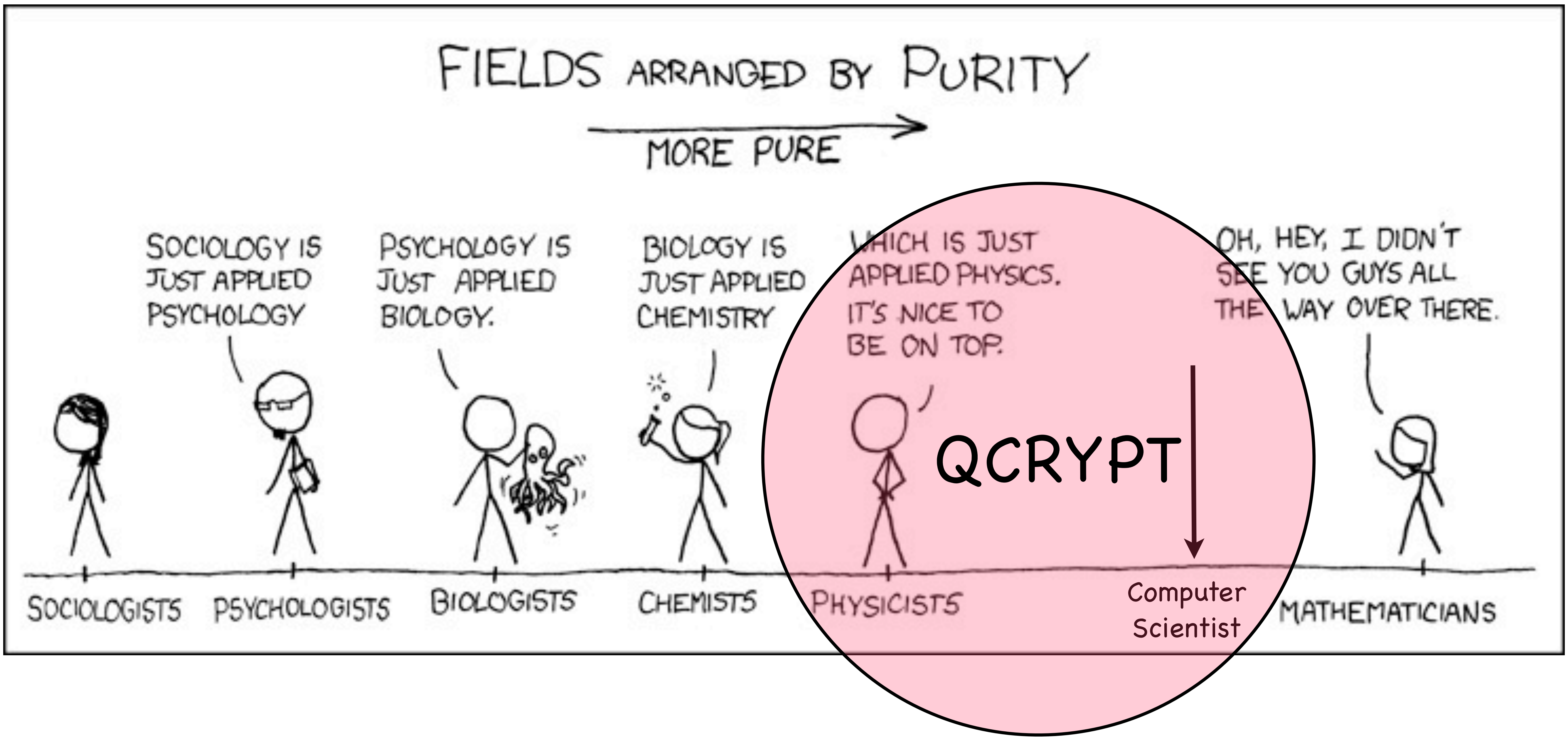
Have detectors. Will travel.






HPD



Source: http://imgs.xkcd.com/comics/purity.png

It is impossible to make anything foolproof because fools are so ingenious.

It is impossible to make anything hackerproof because hackers are so ingenious.

Tutorial Topics

a. Single-photon sources and the properties of light

b. Photo multiplier detectors

c. Single-photon avalanche detectors

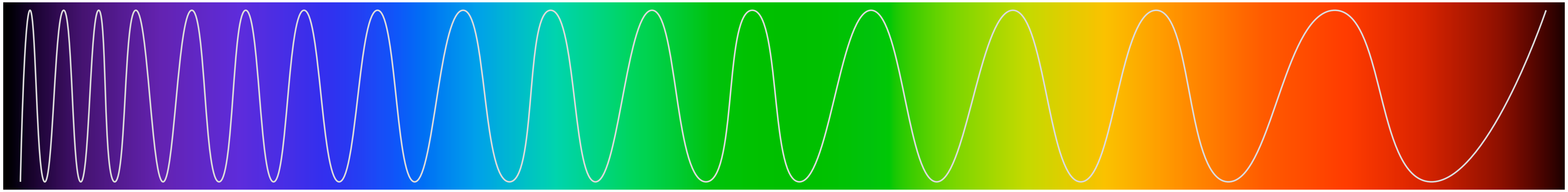
d. Detector properties and definitions

e. Transition edge sensors

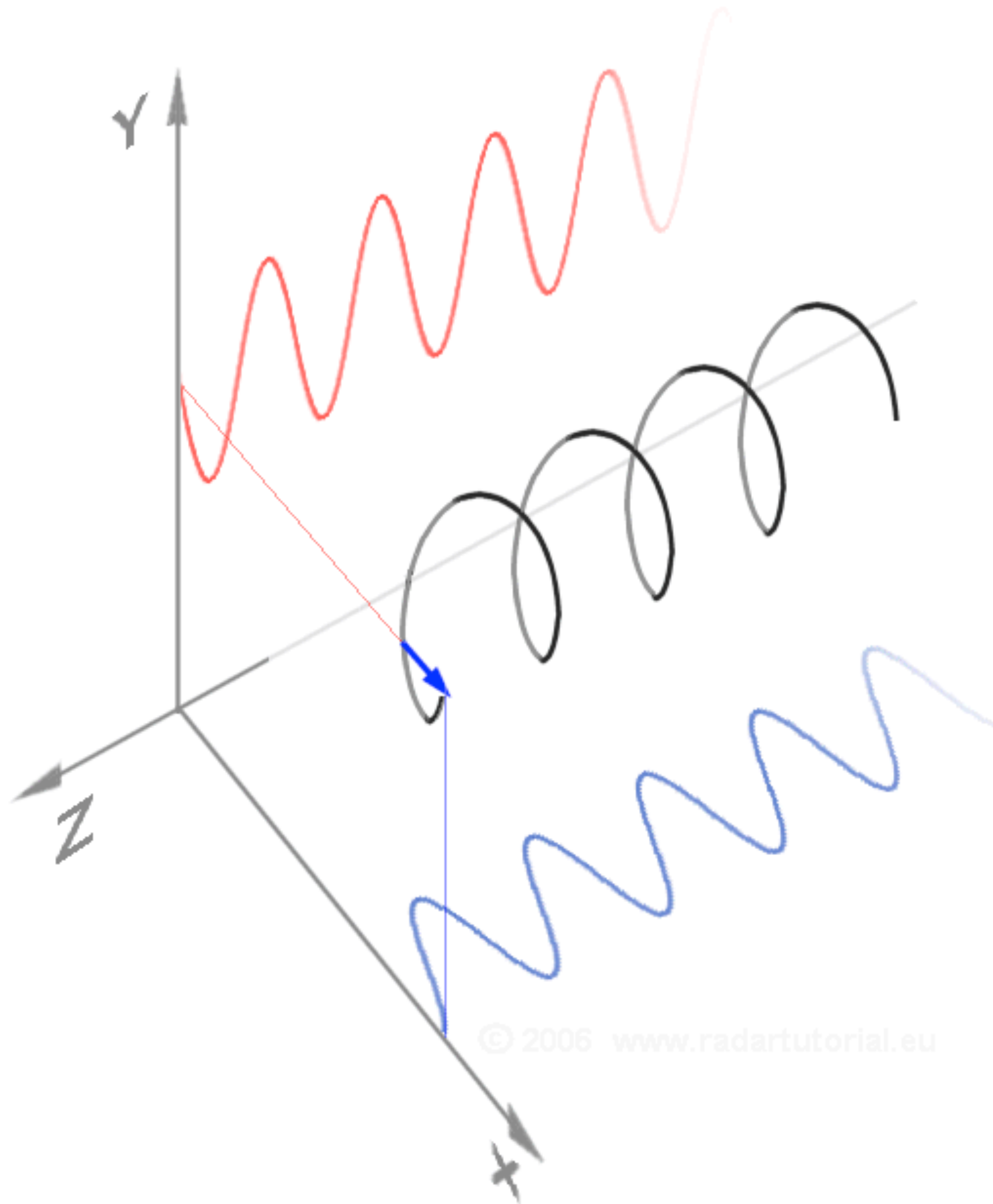
a. Single-photon nanowire detectors

f. Hack attacks

Color

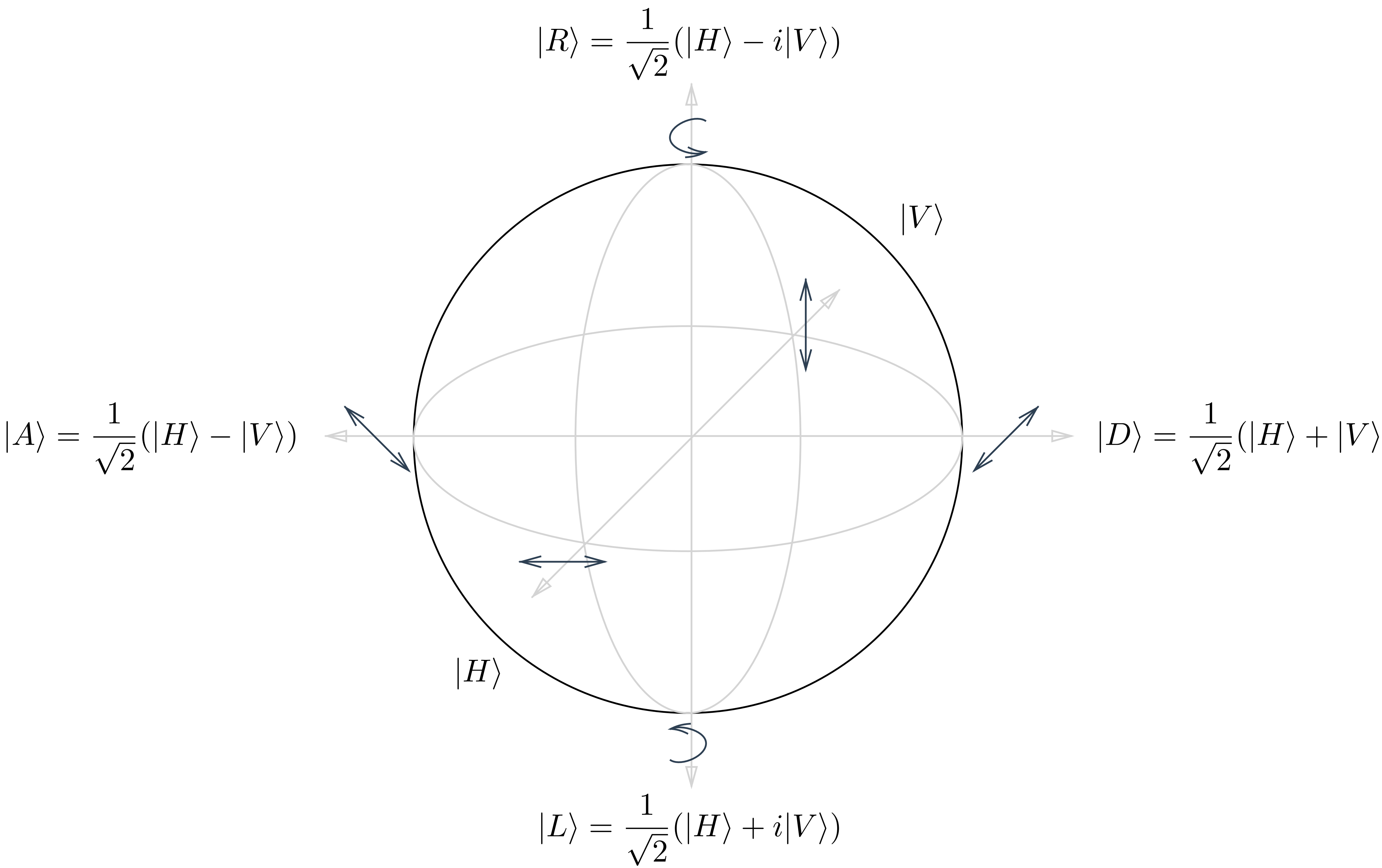


Polarization

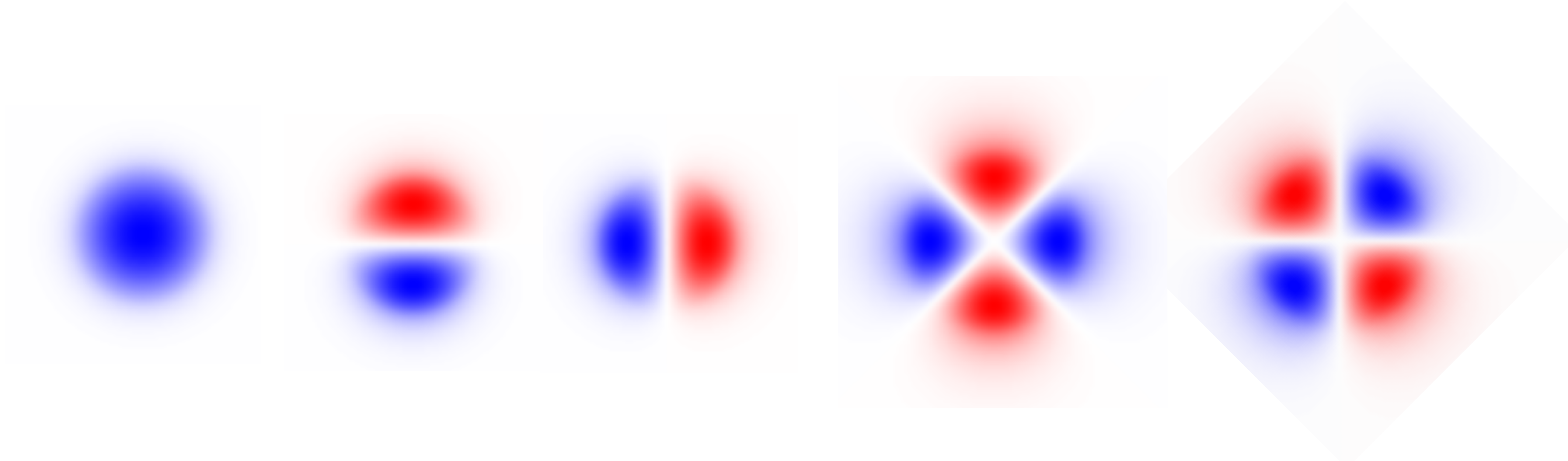


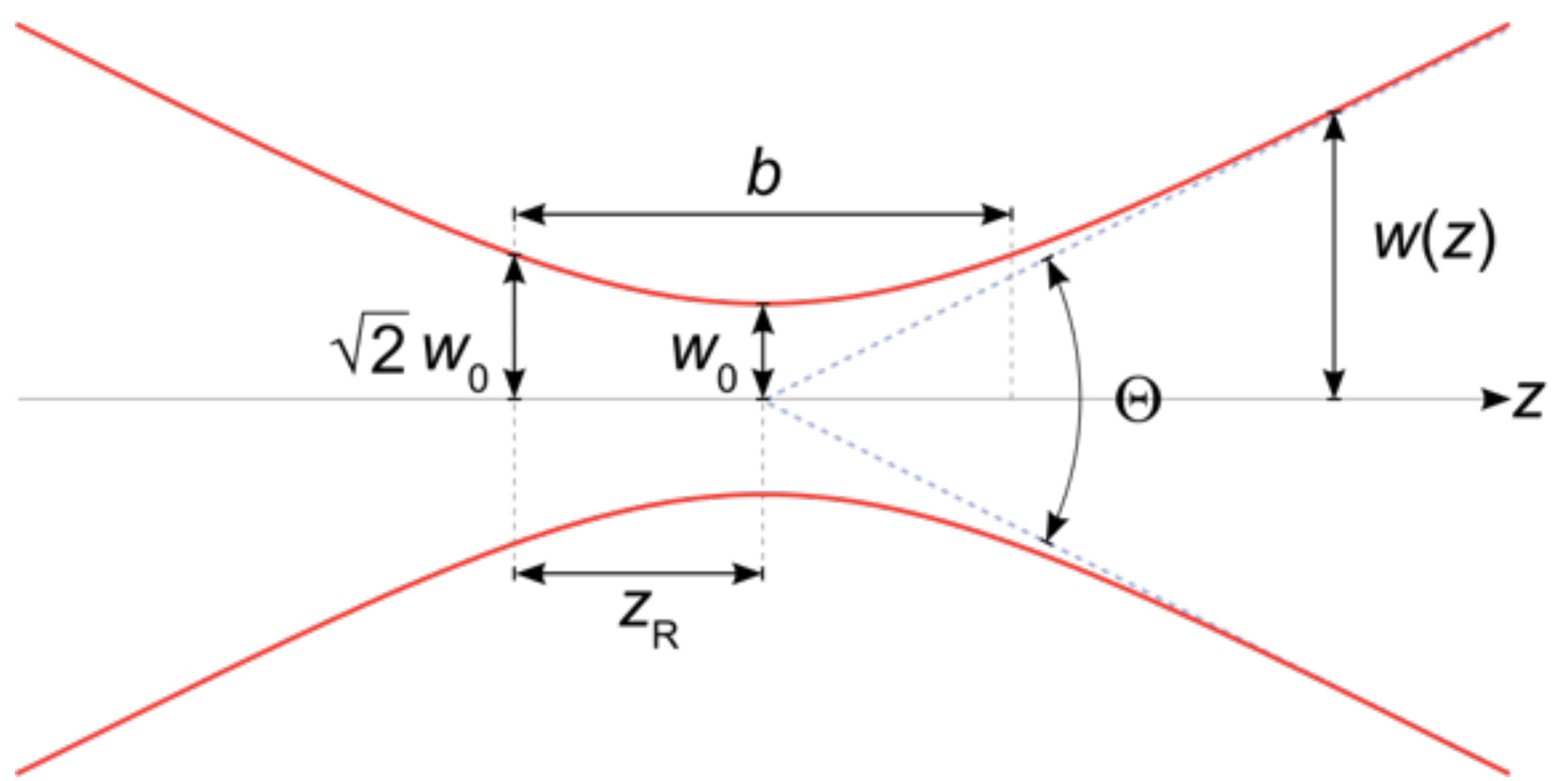
http://en.wikipedia.org/wiki/File:Rising_circular.gif

The Poincaré Sphere



Spatial properties

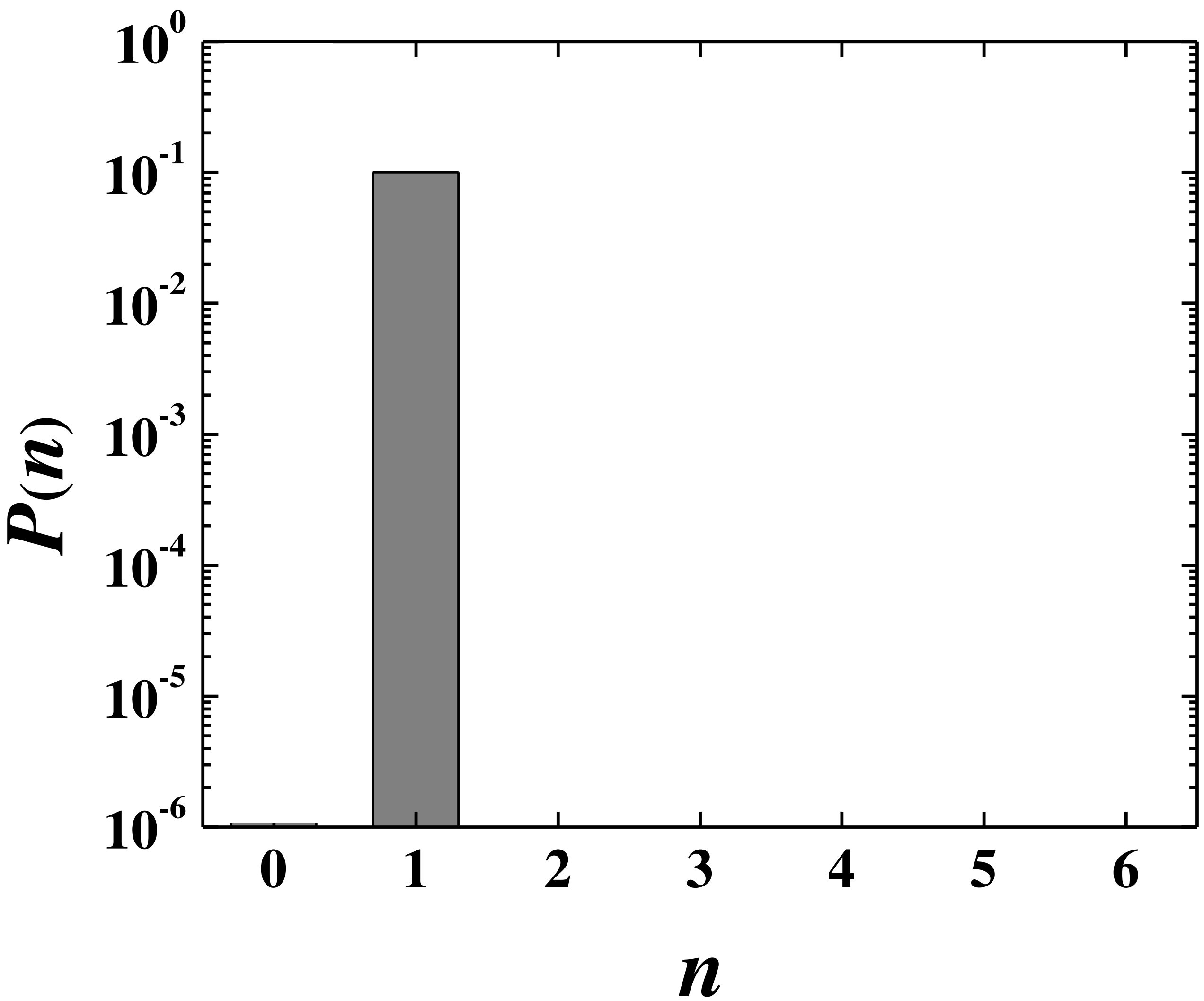


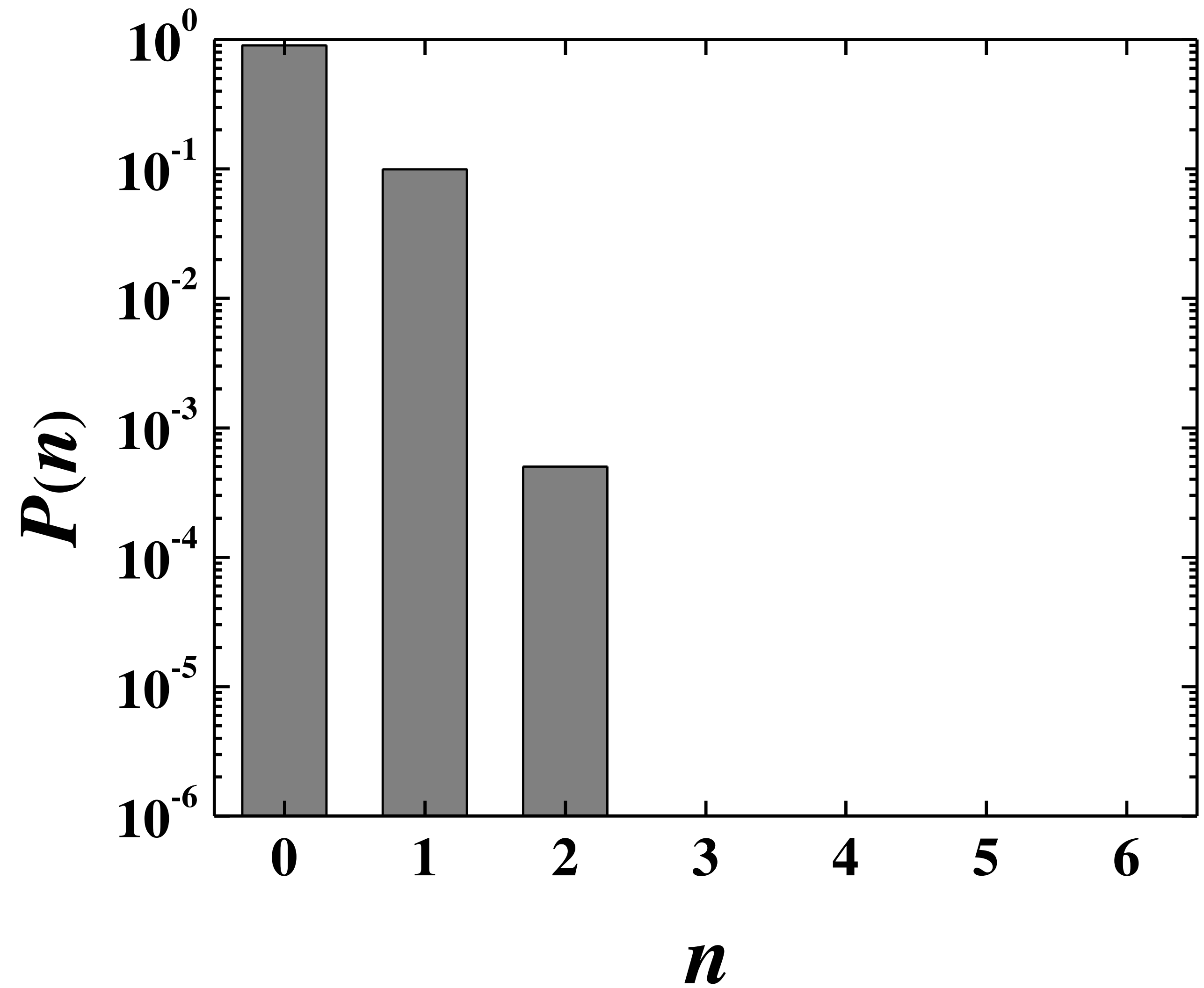


http://en.wikipedia.org/wiki/File:GaussianBeamWaist.svg

Number/Fock States

$$|n\rangle = \frac{1}{\sqrt{n!}}(\hat{a}^\dagger)^n|0\rangle$$

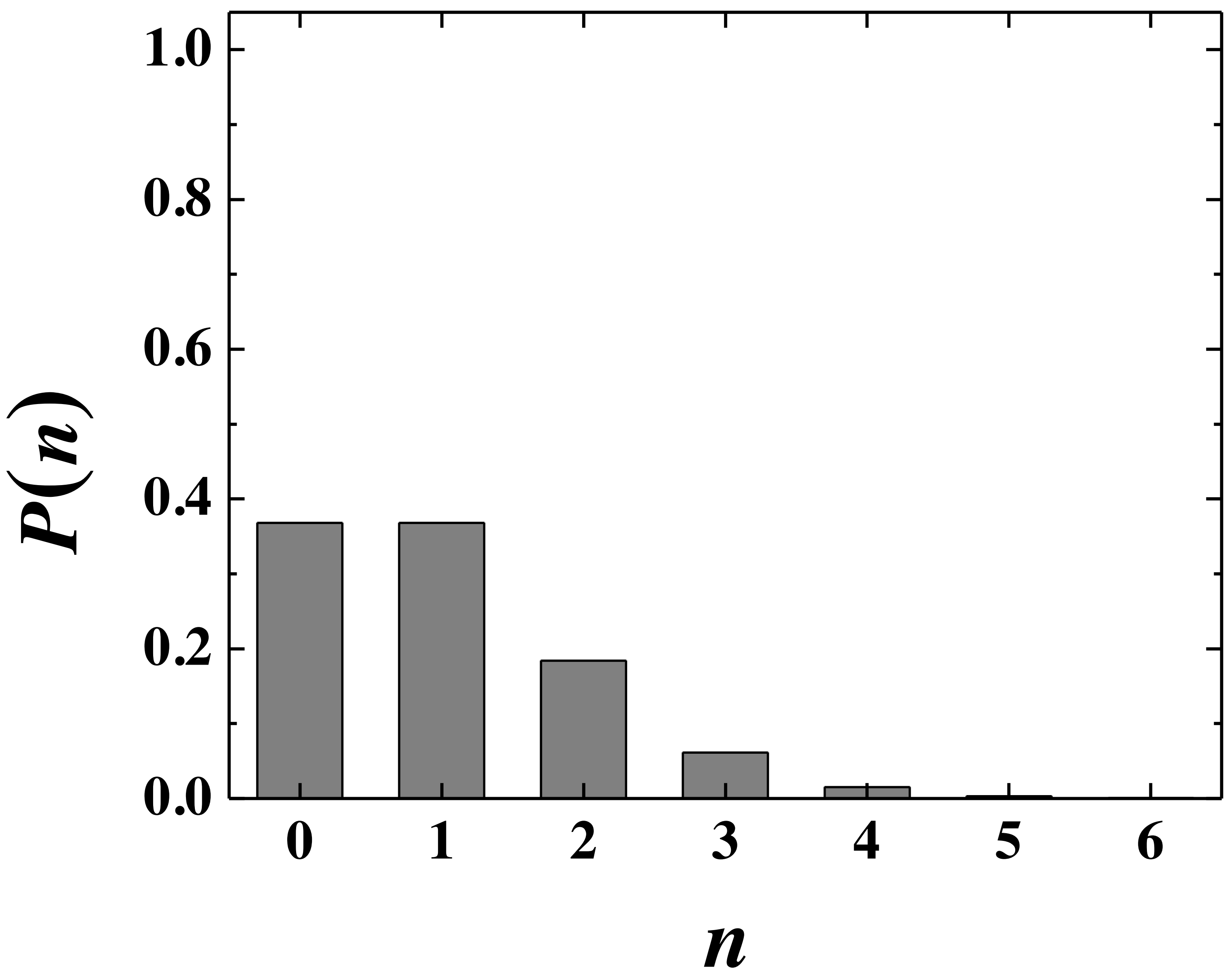




R. J. Glauber, Phys. Rev. 130, 2529–2539 (1963)

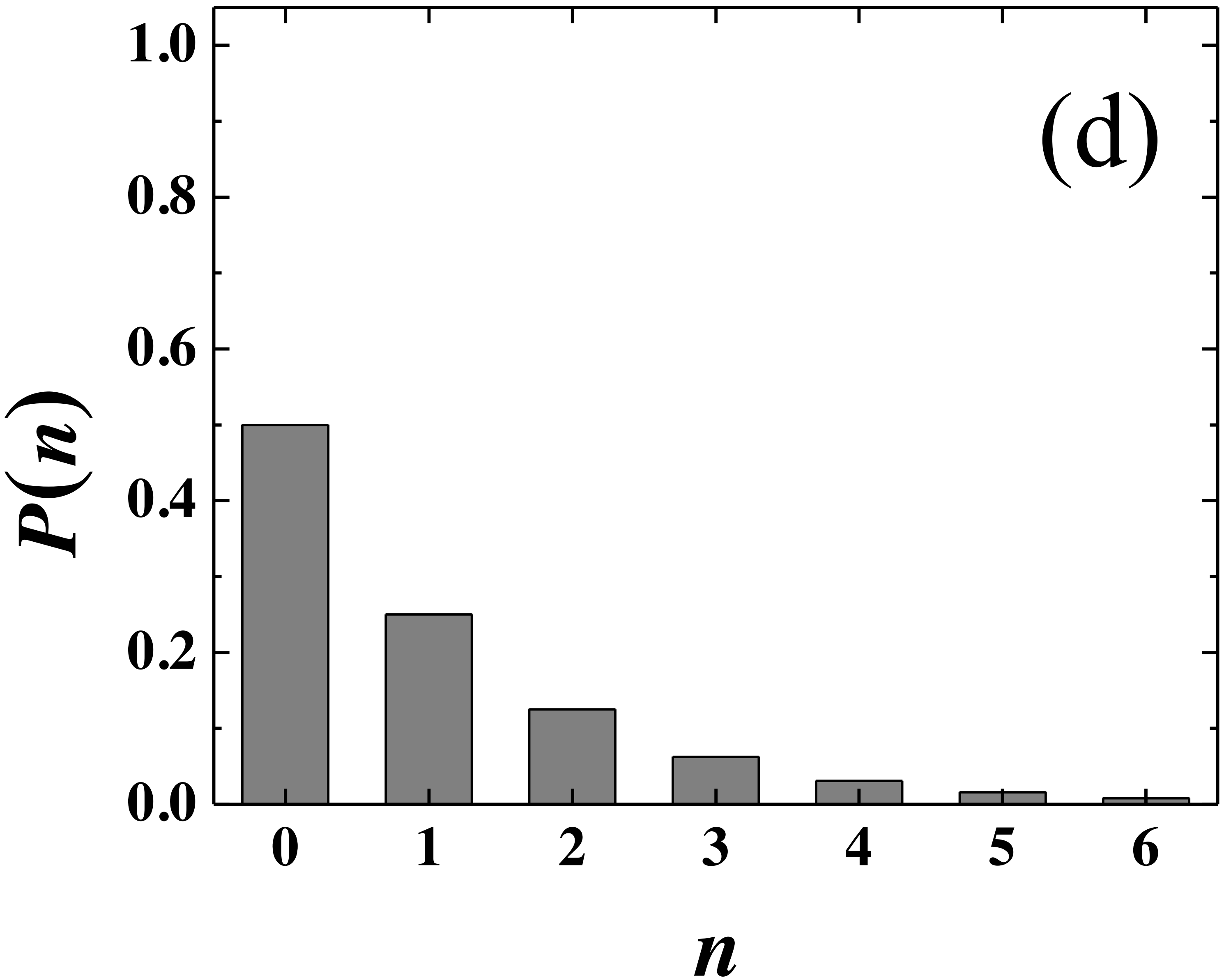
Coherent State

$$|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$



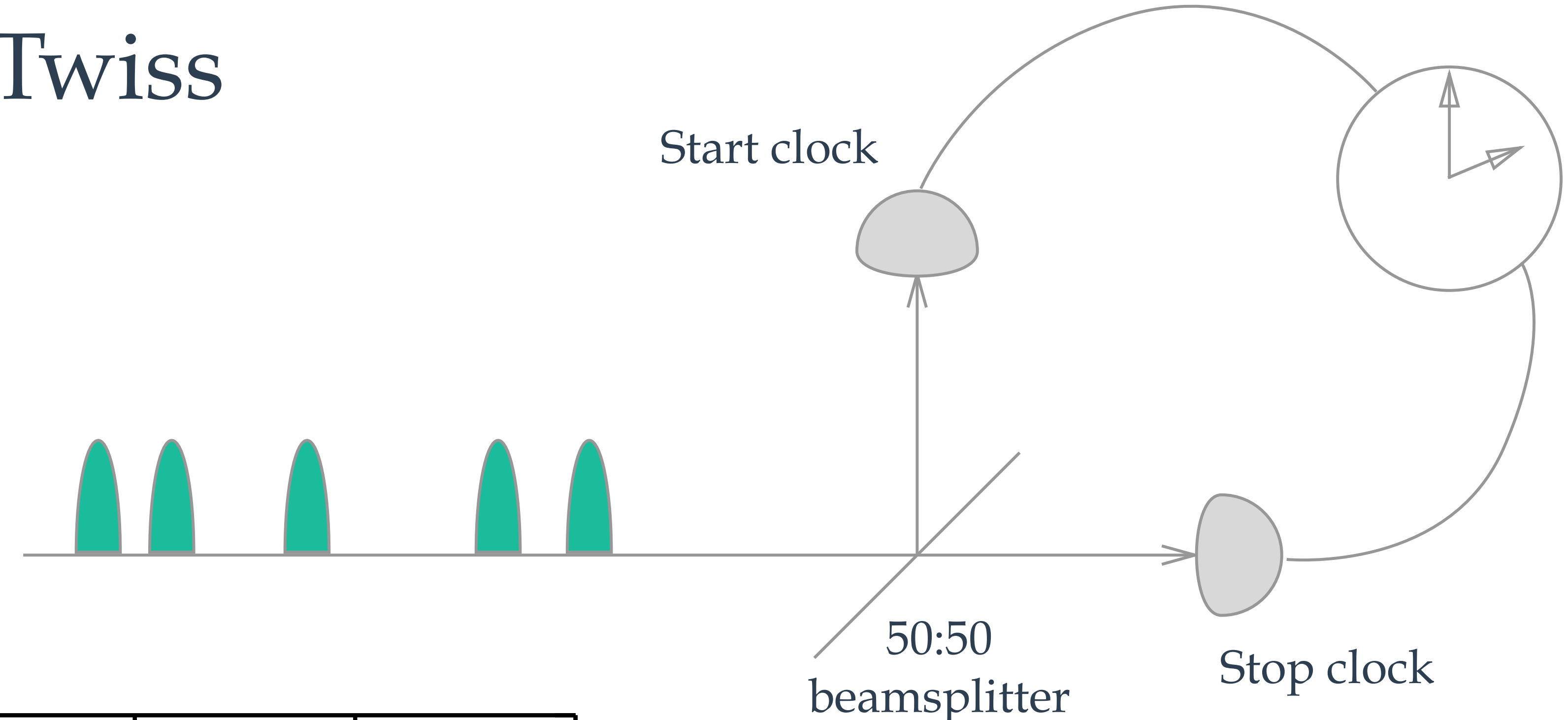
Thermal State

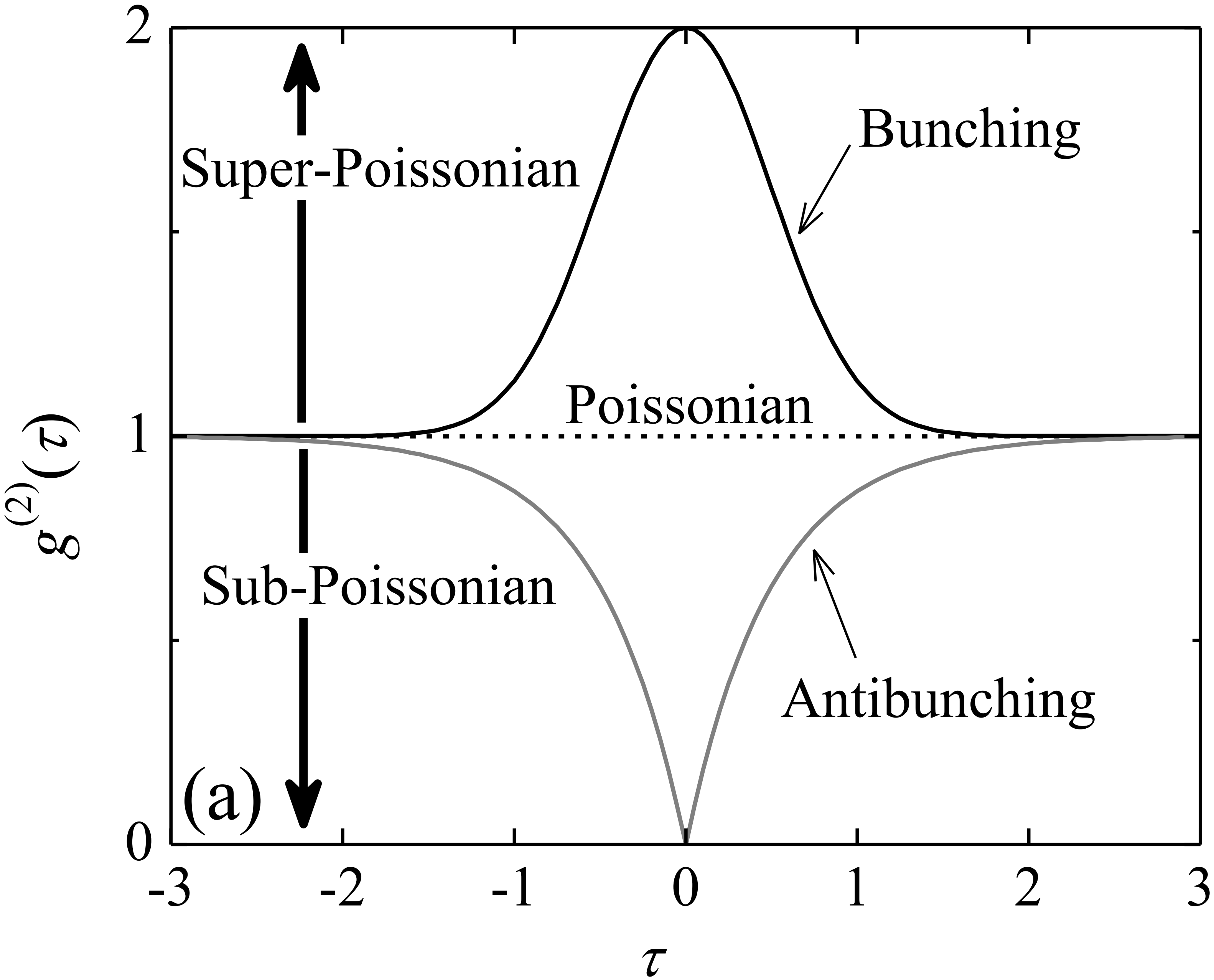
$$P(n) = \frac{\mu^n}{(1+\mu)^{n+1}}$$



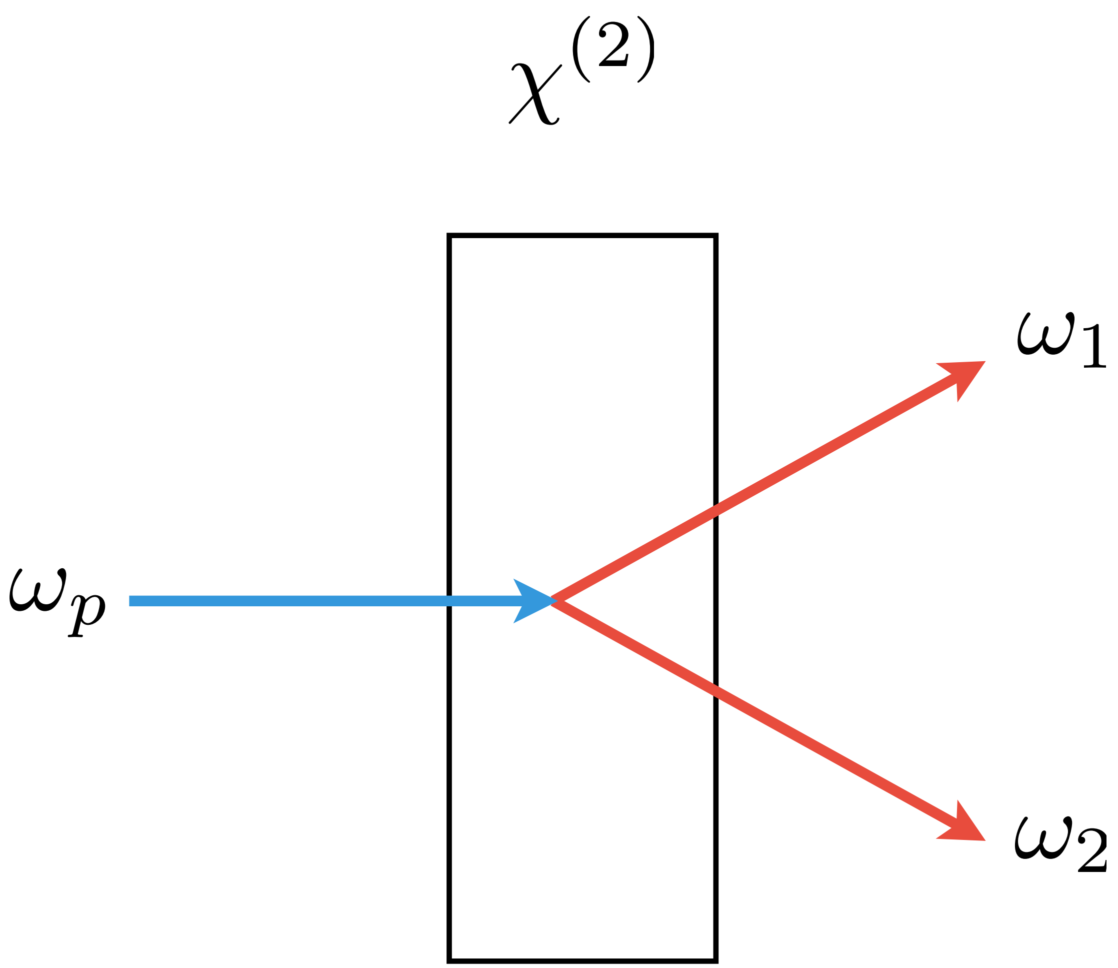
Photon bunching is directly related to the boson sampling problem by Scott Aaronson and Alex Arkhipov

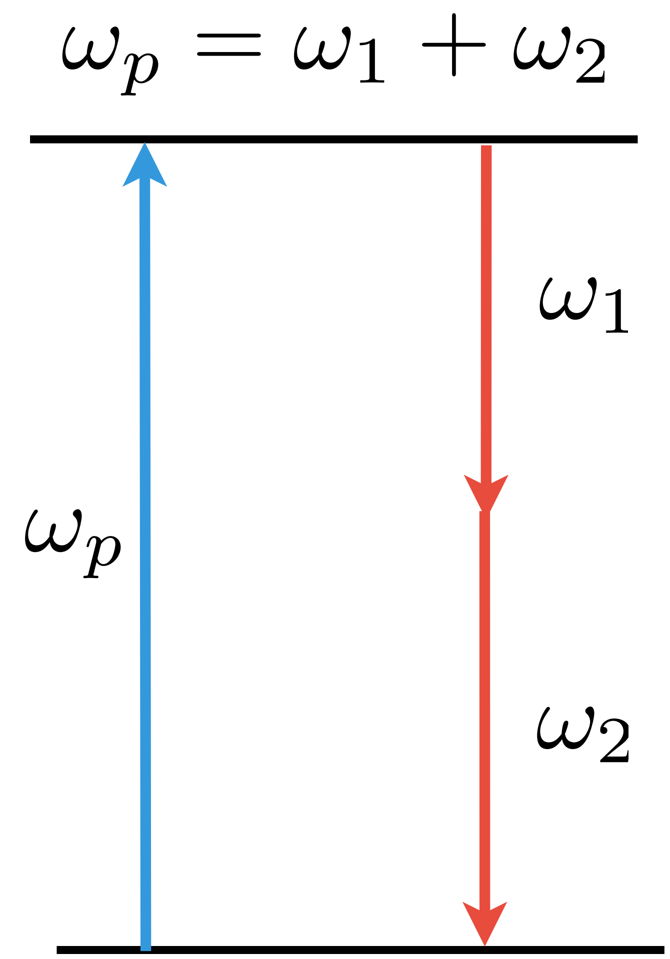
Hanburry Brown and Twiss Interferometer

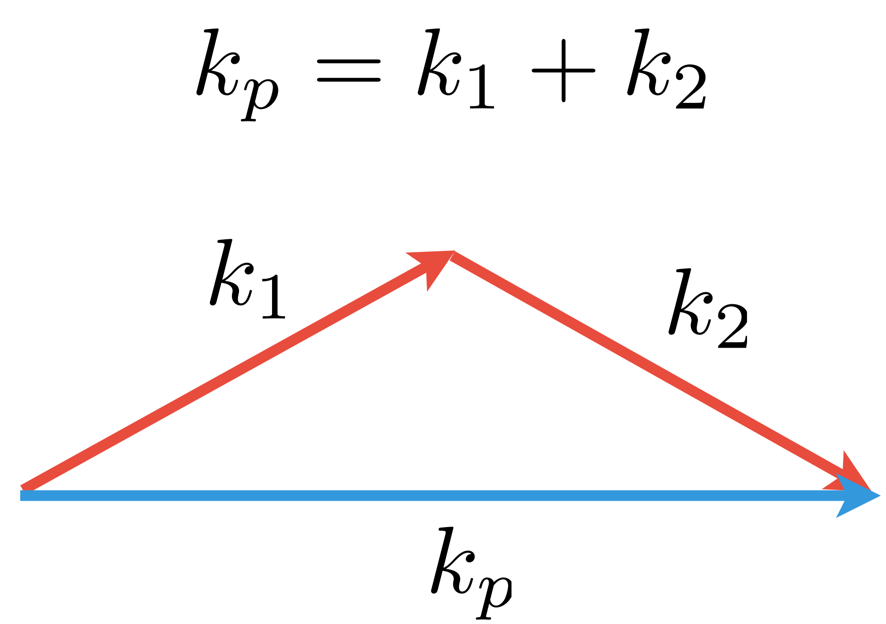




Spontaneous Parametric Downconversion





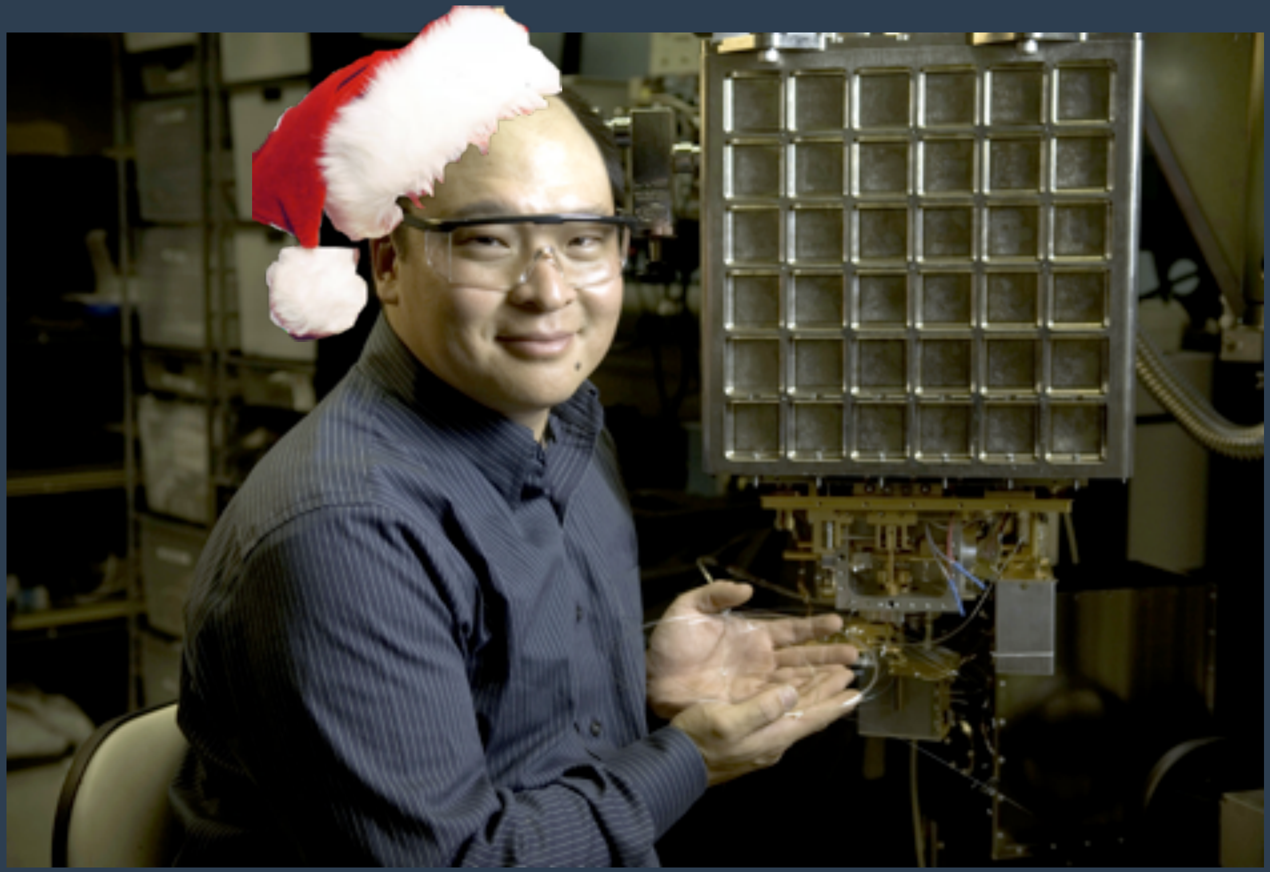


SPDCalc

http://www.dancingphysicist.com/spdcalc

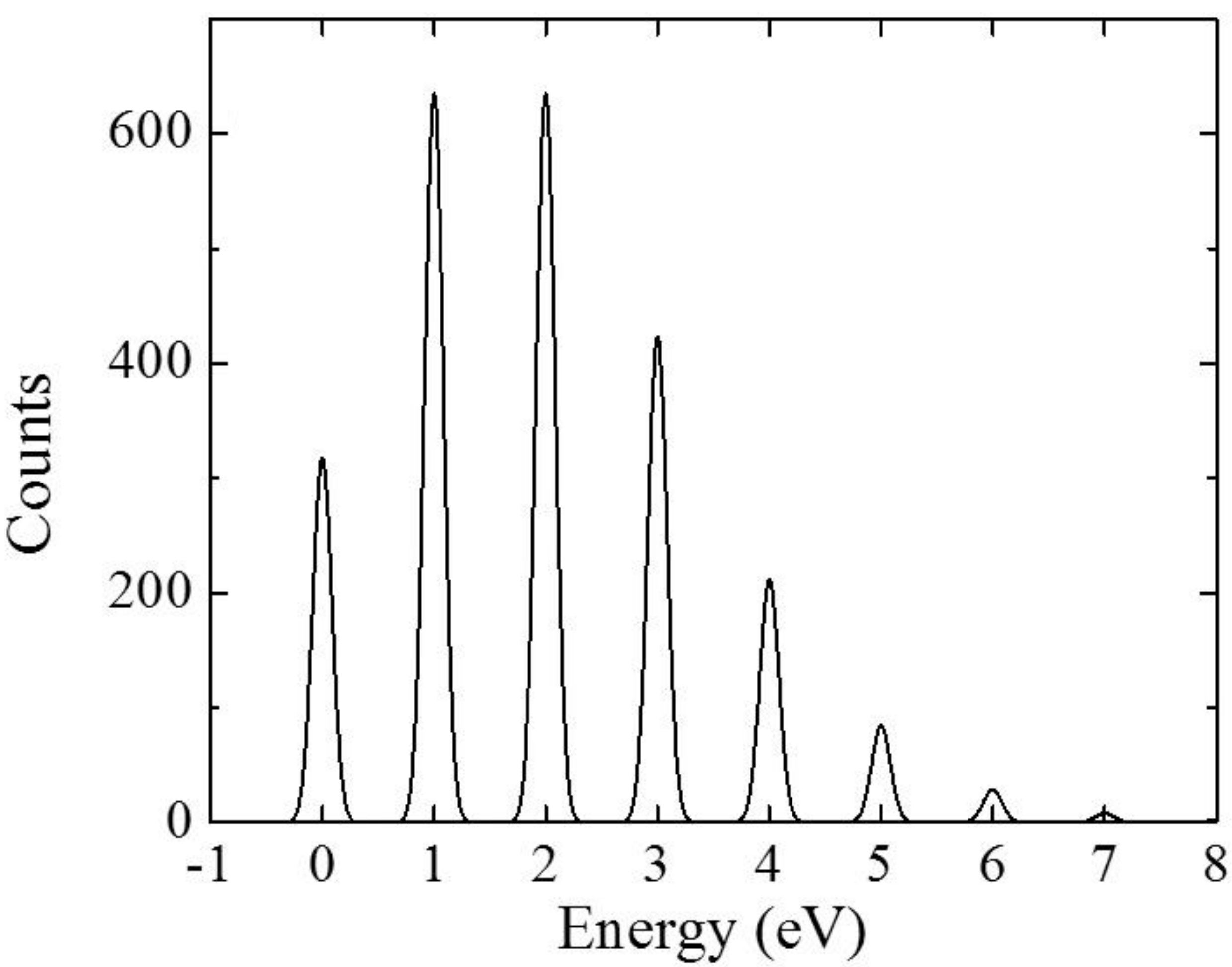
Properties of an ideal photon detector

- Detects all the incident light
- Insensitive to wavelength
- No noise
- Insensitive to polarization
- Can resolve the number of photons hitting it
- Good timing information (jitter)

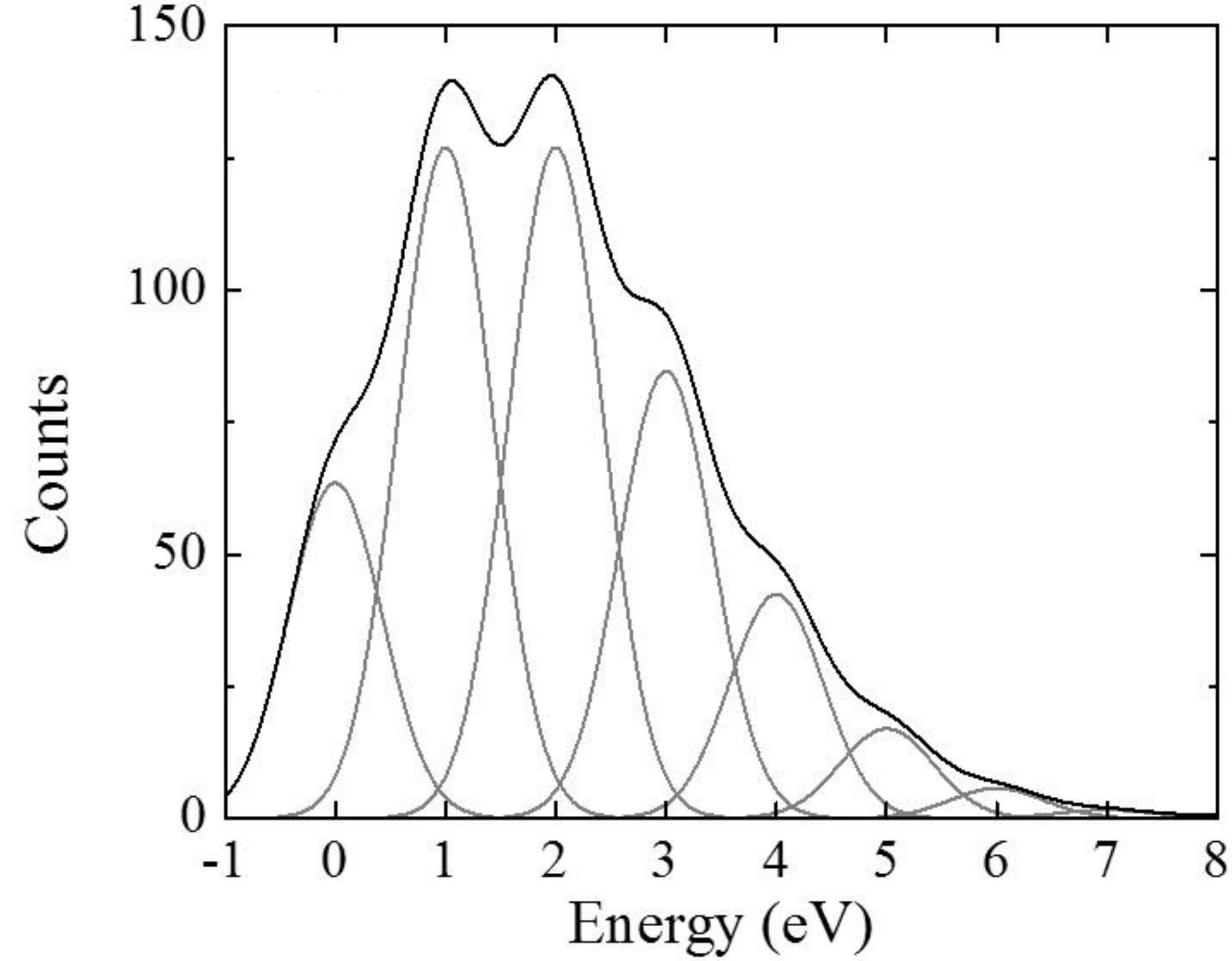


Photon number resolution: *can the detector distinguish the number of photons hitting it.*

Good

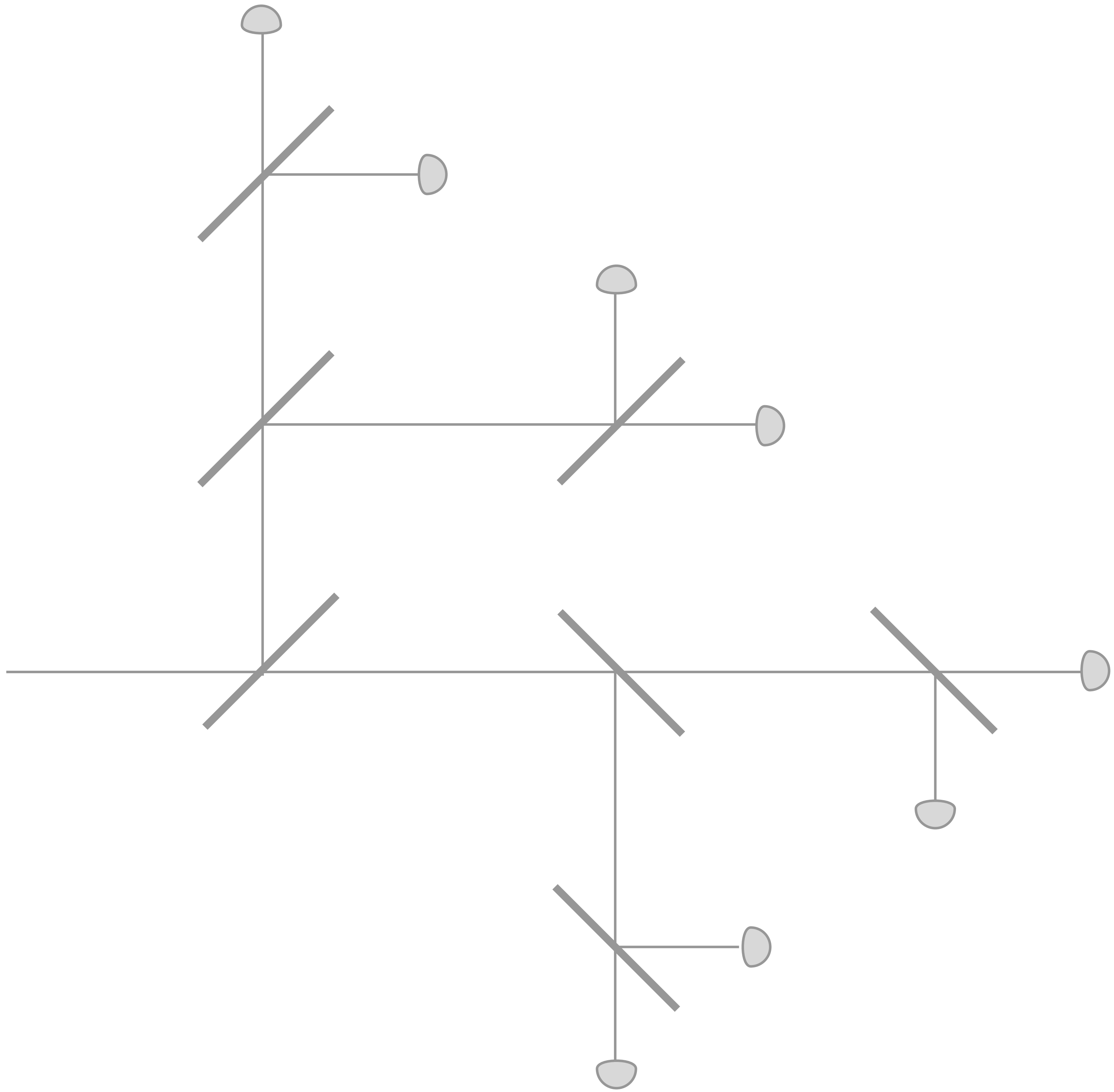


Not Good

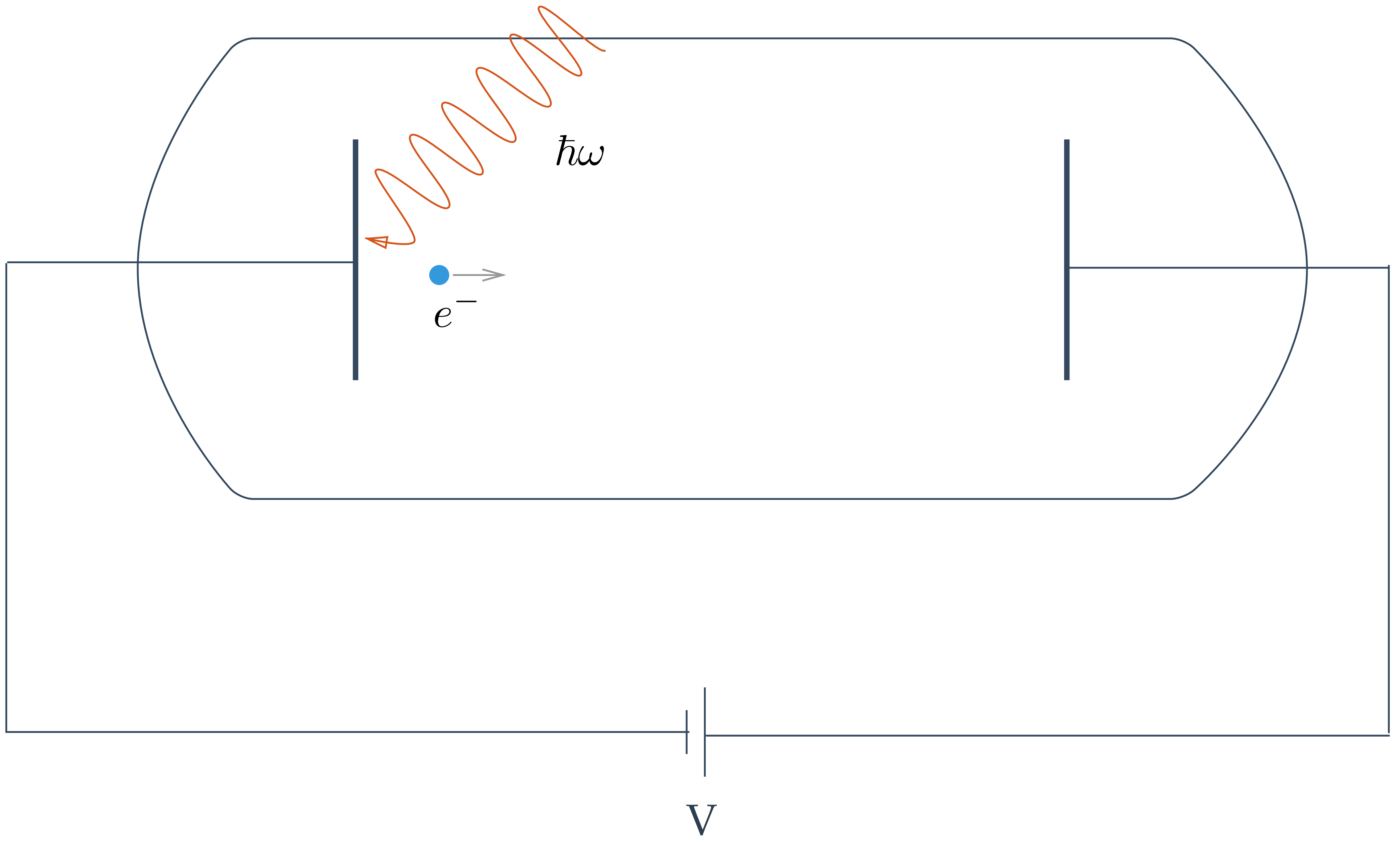


"Click" detectors: *Can only tell the difference between the presence of photons and no photons.*

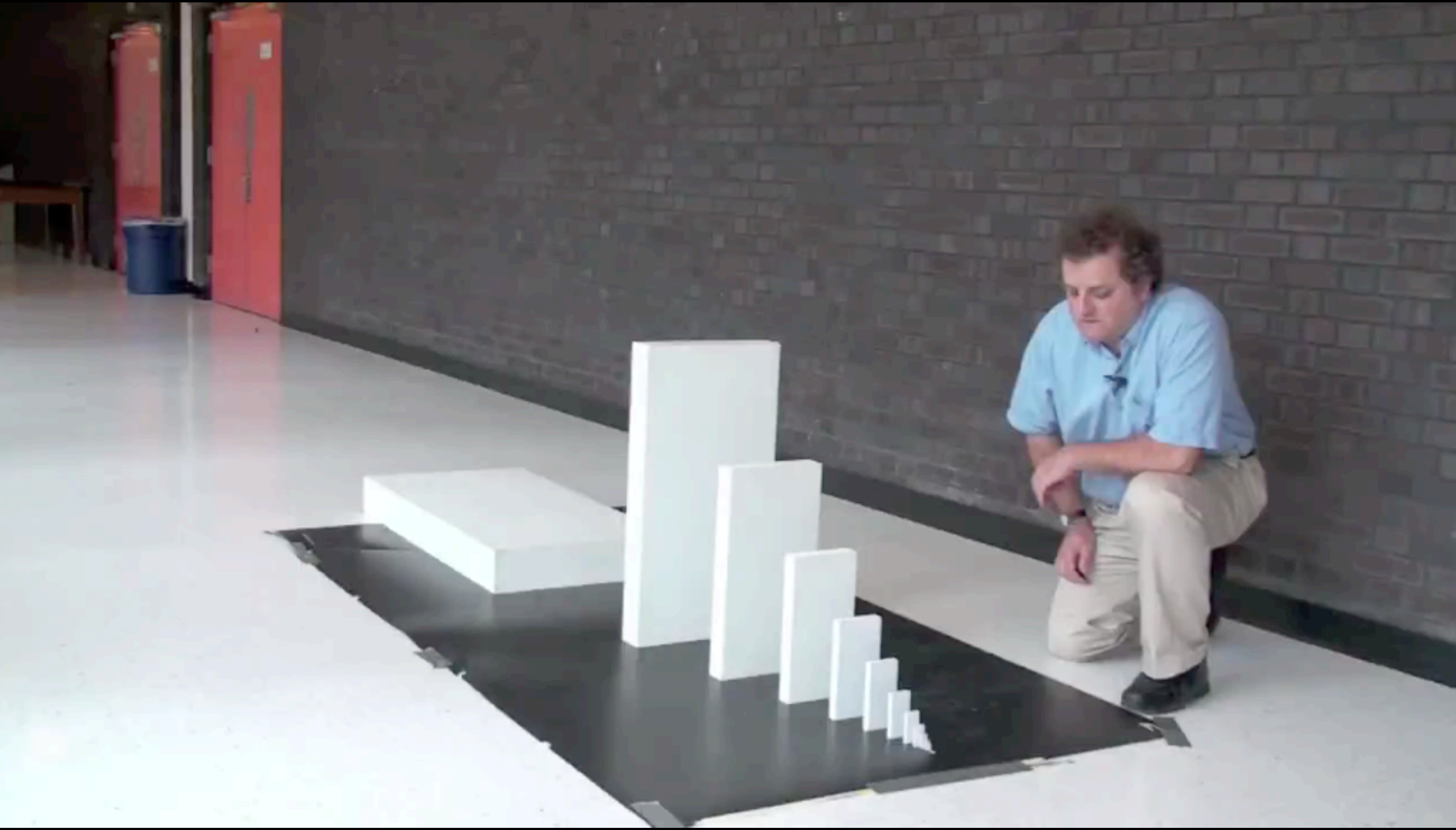
Using multiple “click” detectors to obtain number resolution



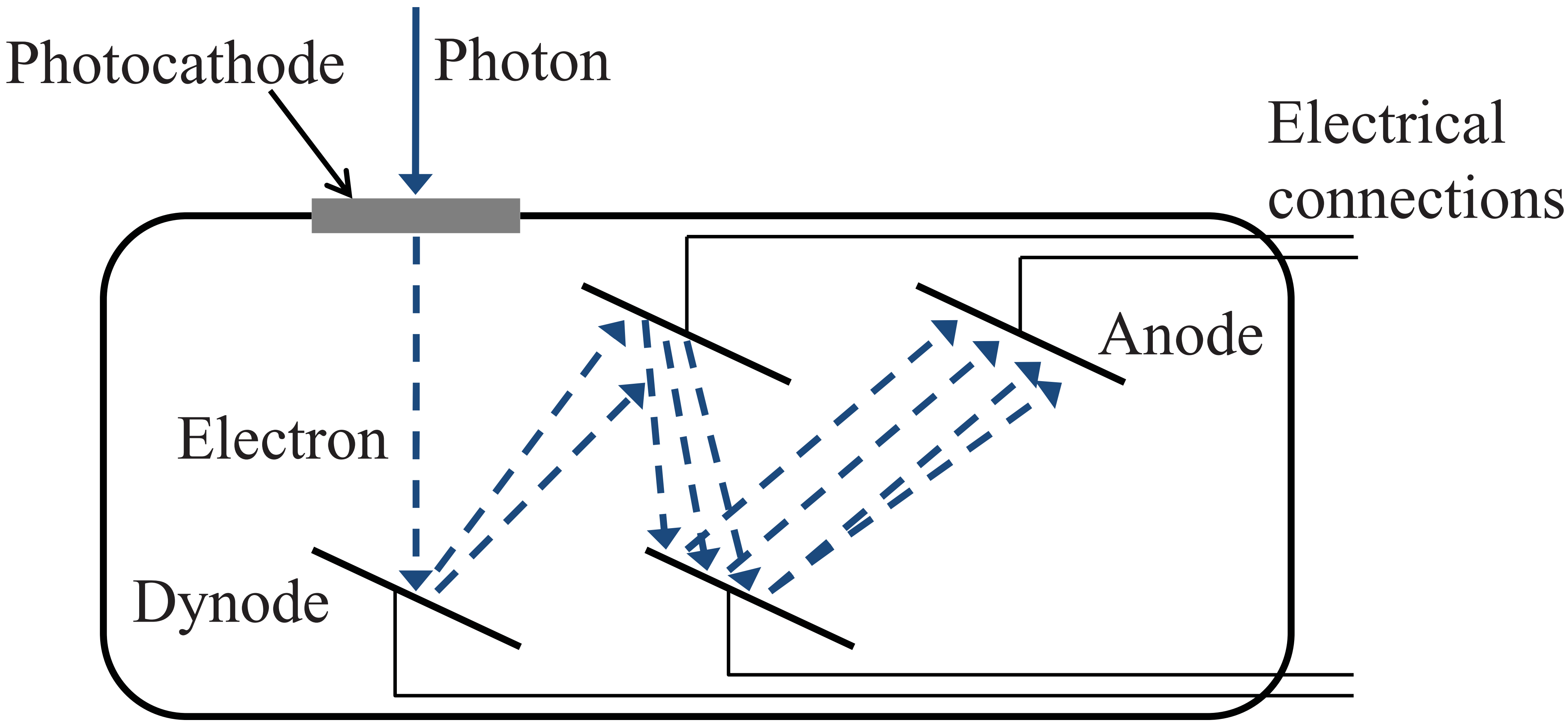
Photoelectric Effect



http://www.youtube.com/watch?v=5JCm5FY-dEY

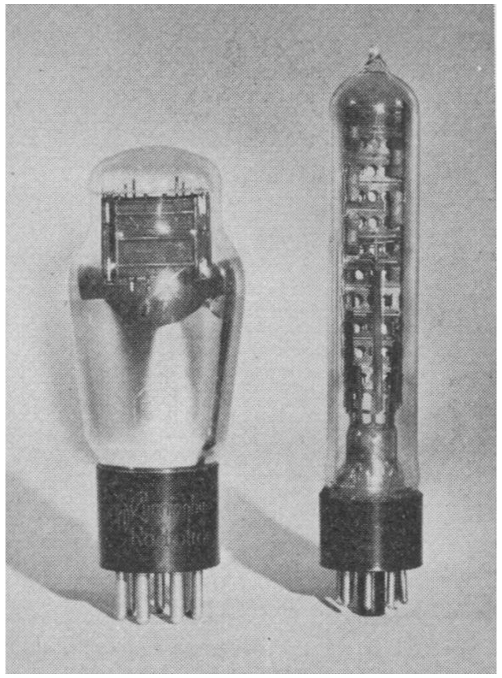


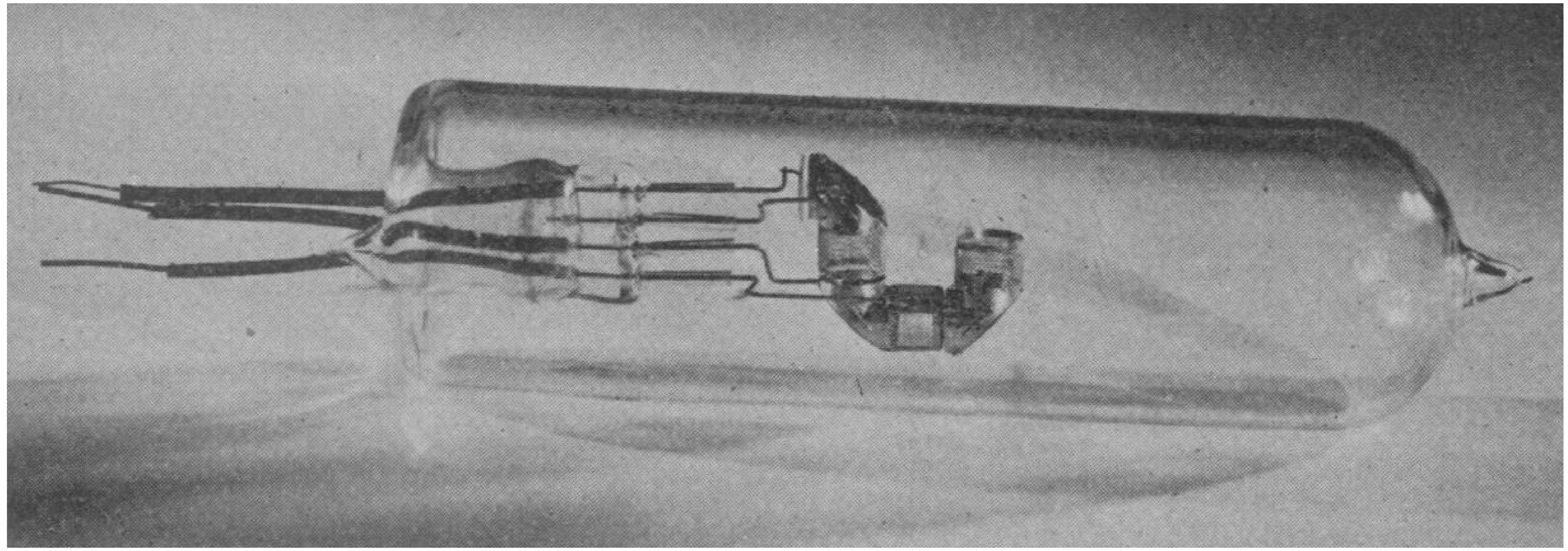
Photomultiplier tubes

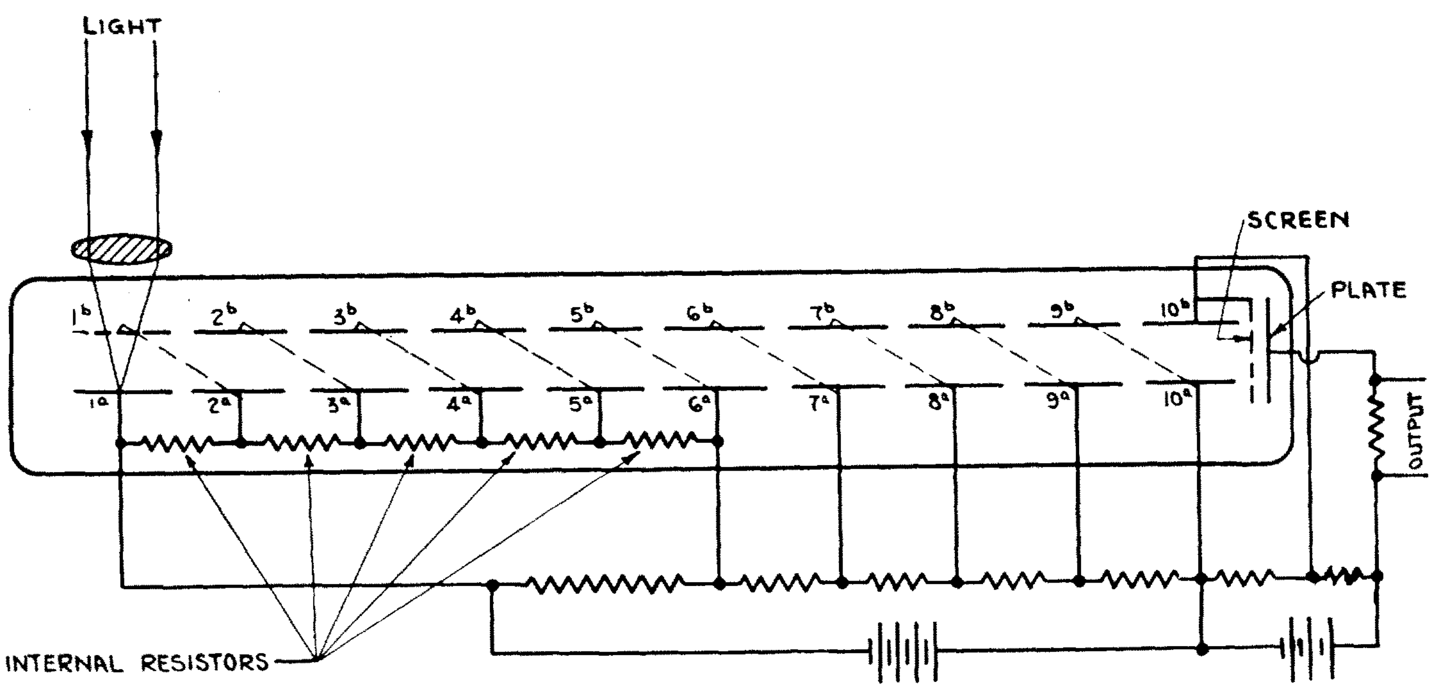


Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011);
doi: 10.1063/1.3610677

Photomultiplier tubes







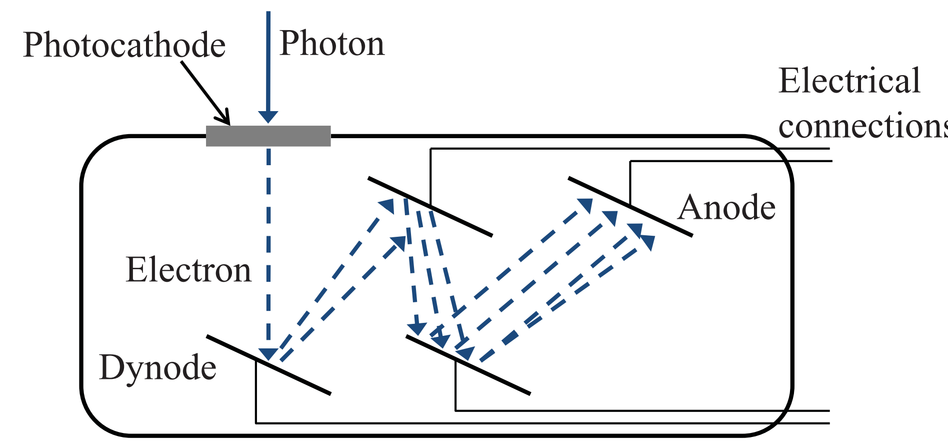
H. Iams and B. Salzberg, Proc. IRE 23, 55 (1935)

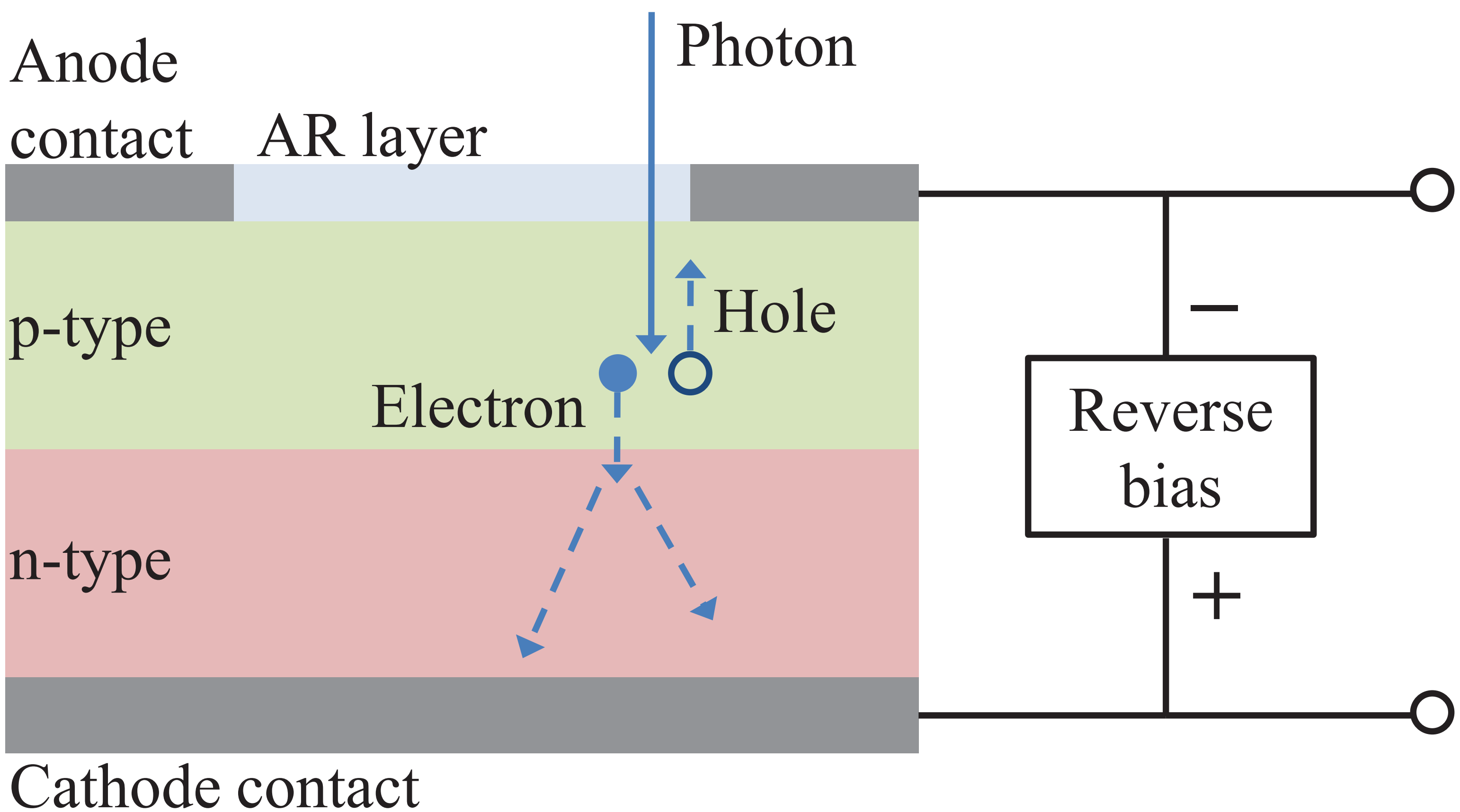
V. Zworykin, G. Morton, and L. Malter, Proc. IRE 24, 351 (1935).

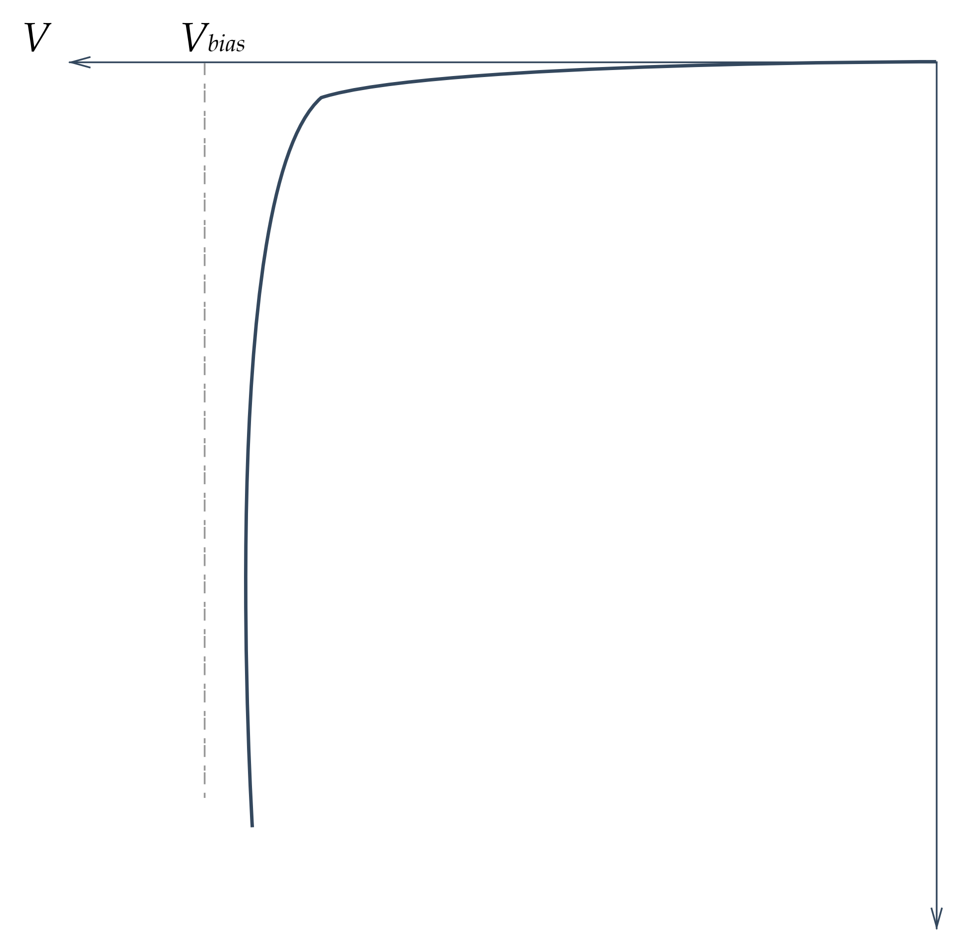
L. A. Kubetsky, Proc. Inst. Radio Eng. 254, 421 (1937).

J. S. Allen, Phys. Rev. 55, 966–971 (1939).

Single-Photon Avalanche Diodes (SPAD)



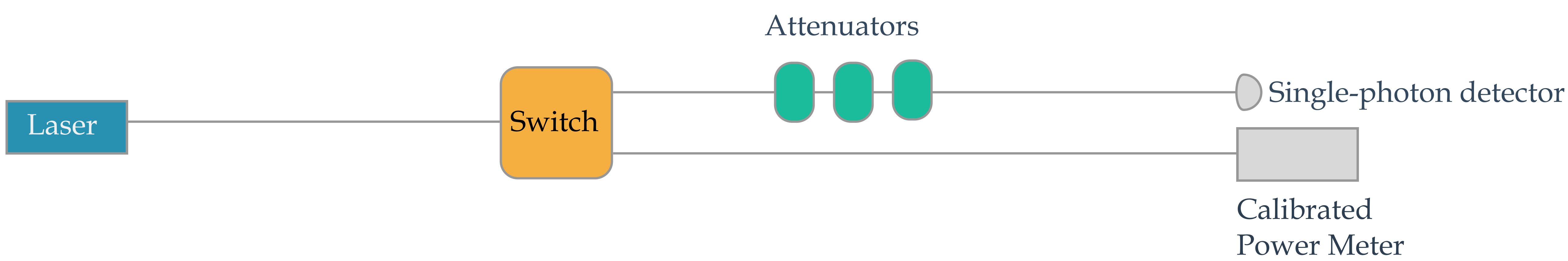




Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011);
doi: 10.1063/1.3610677

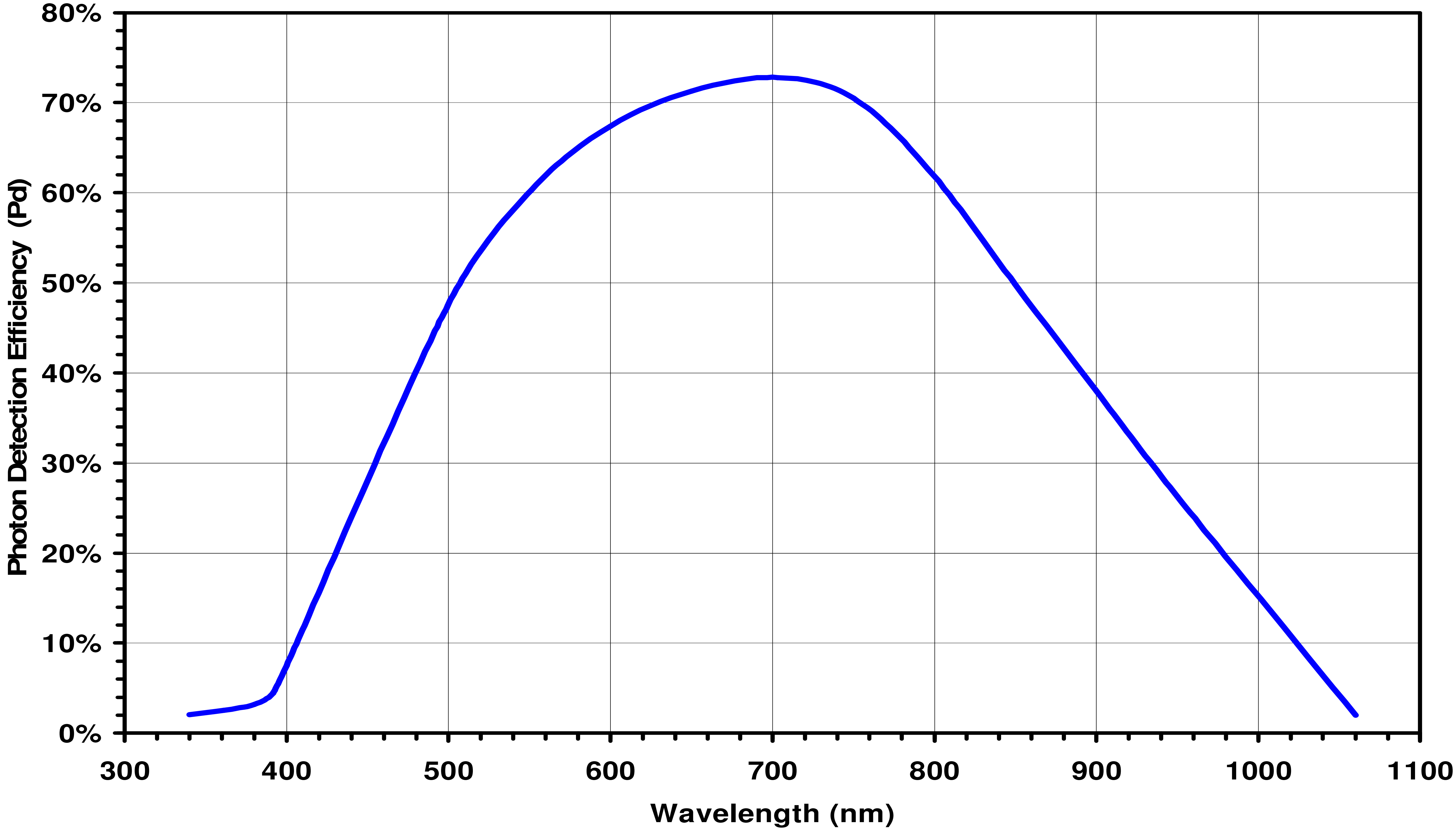
Detector properties and terminology

Efficiency: *probability that a photon will be detected.*



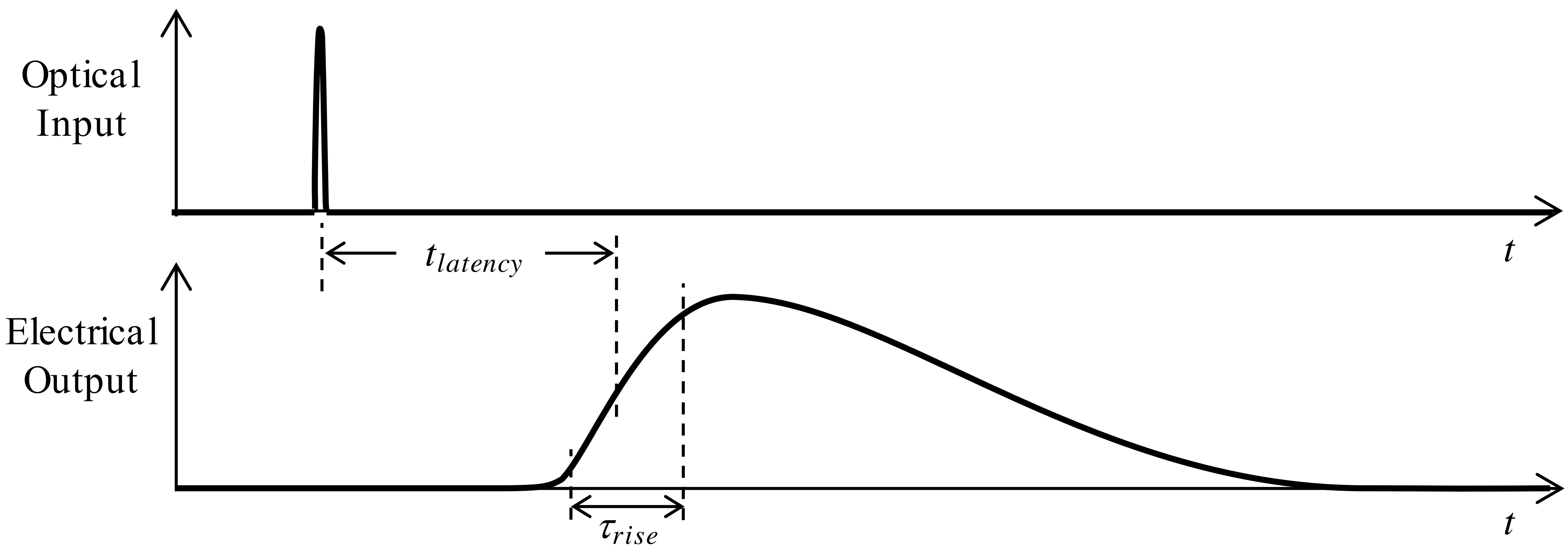
Igor Vayshenker

Typical Silicon based SPAD efficiency curve

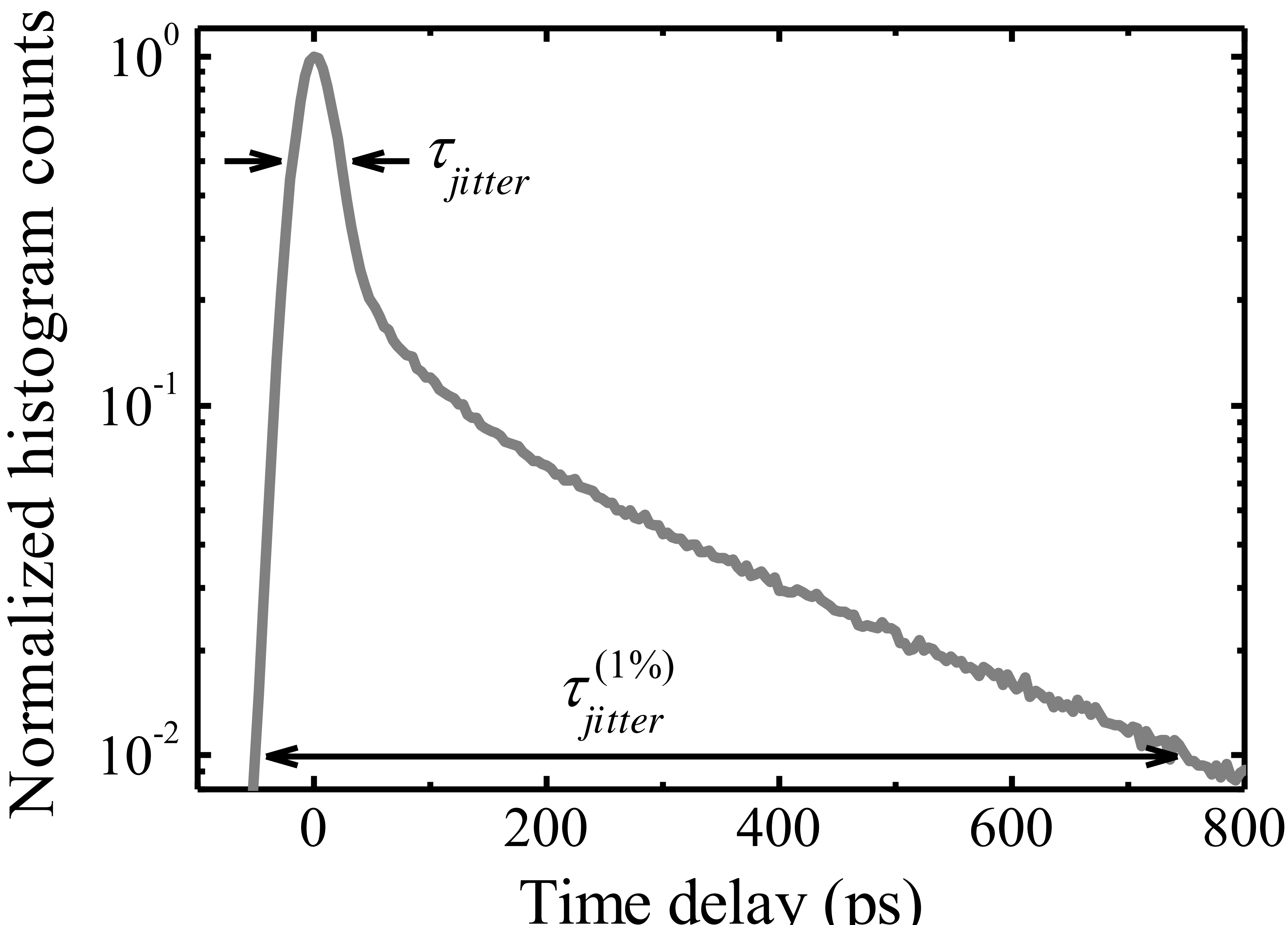


http://www.perkinelmer.com/CMSResources/Images/44-12462DTS_SPCM%20AQRH.pdf

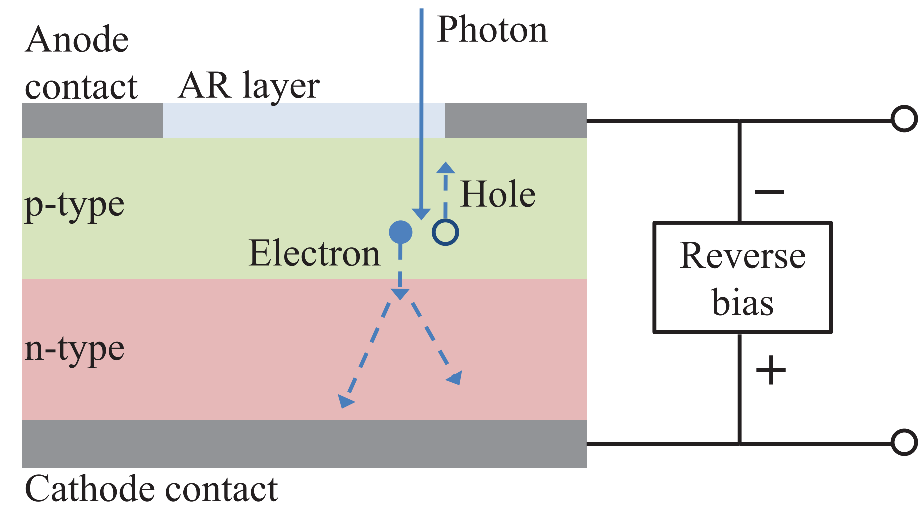
Timing latency: *how long it takes from the photon being absorbed until the electrical pulse can be measured.*



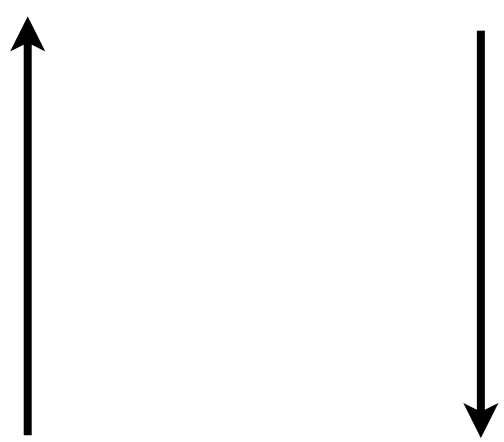
Jitter: *variation in the detection time of a detector.*



SPAD Tradeoff

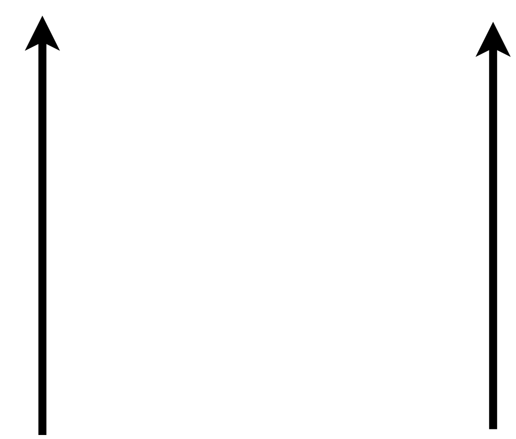


Want



Efficiency Jitter

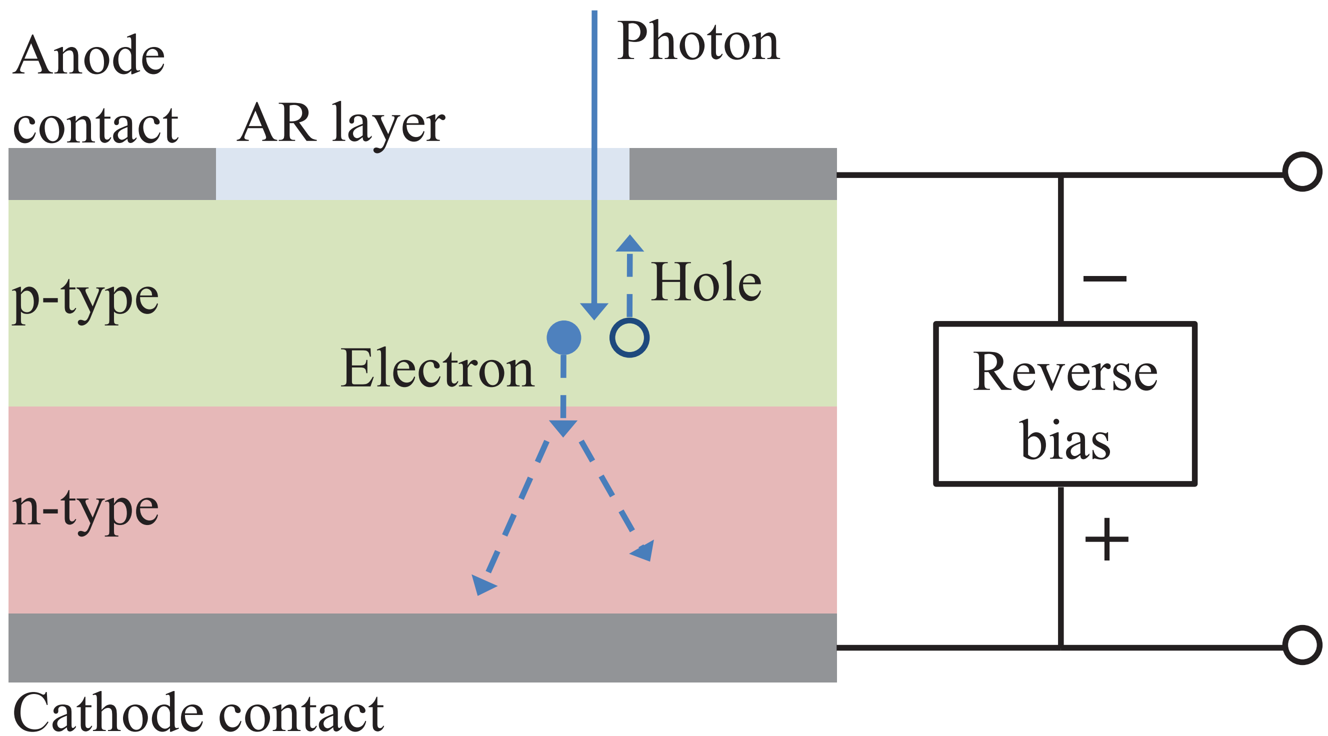
Reality



Efficiency Jitter

For commercial devices can get efficiency of ~70% with a jitter of ~400 ps or efficiency of ~30% with a jitter of 50 ps (at 700 nm).

Dark Counts: *counts a detector registers when no light from our source is incident on it.*

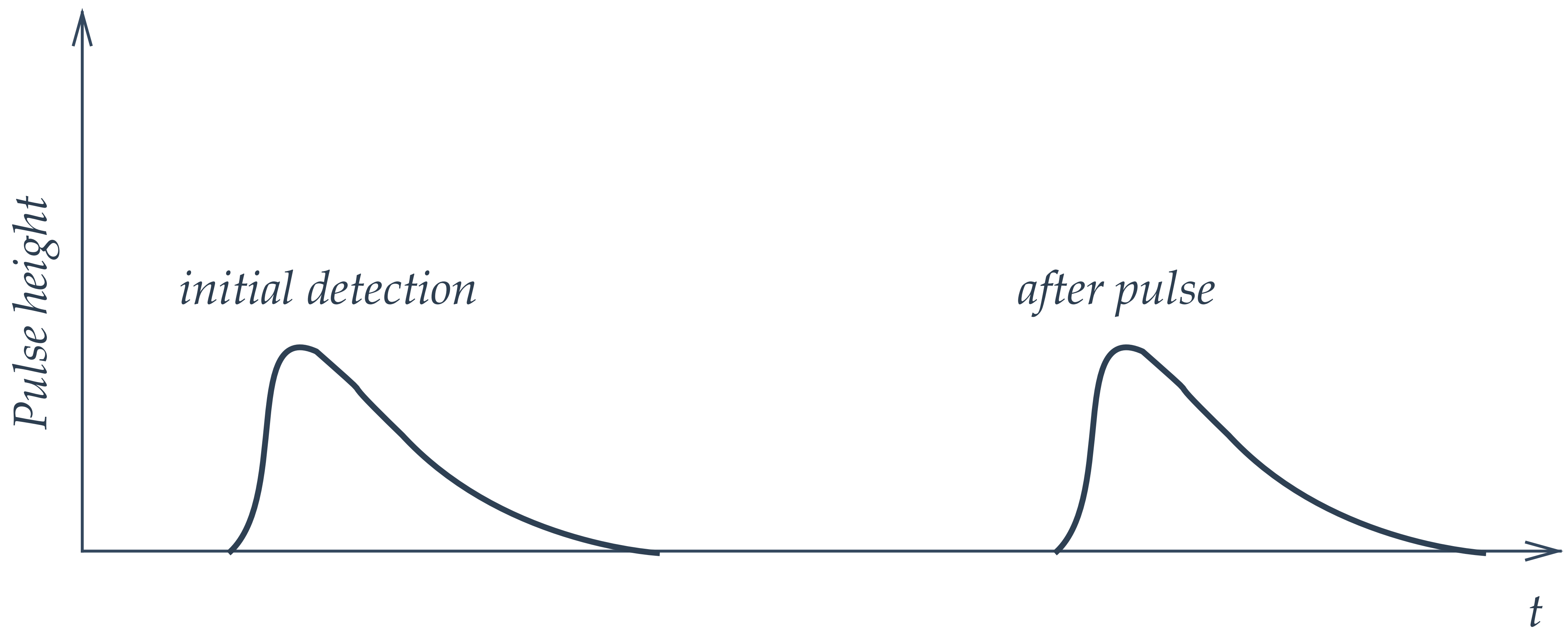


1) Stray light

2) Thermal fluctuations creating spurious e-h pairs that trigger the device

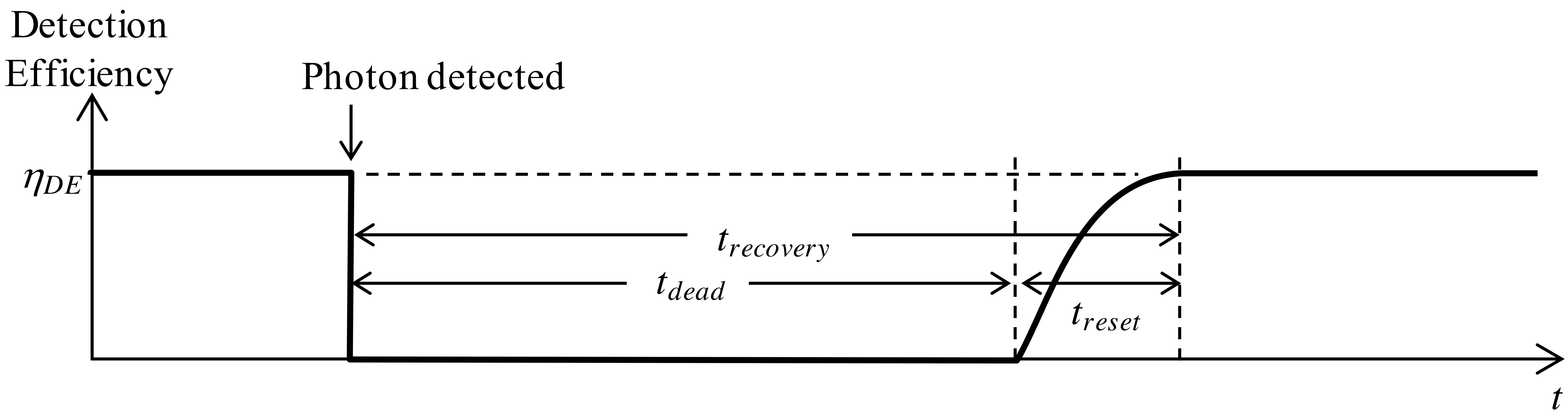
Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011); doi: 10.1063/1.3610677

After Pulsing: *correlated false counts that happen some time after the initial detection event.*



Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011);
doi: 10.1063/1.3610677

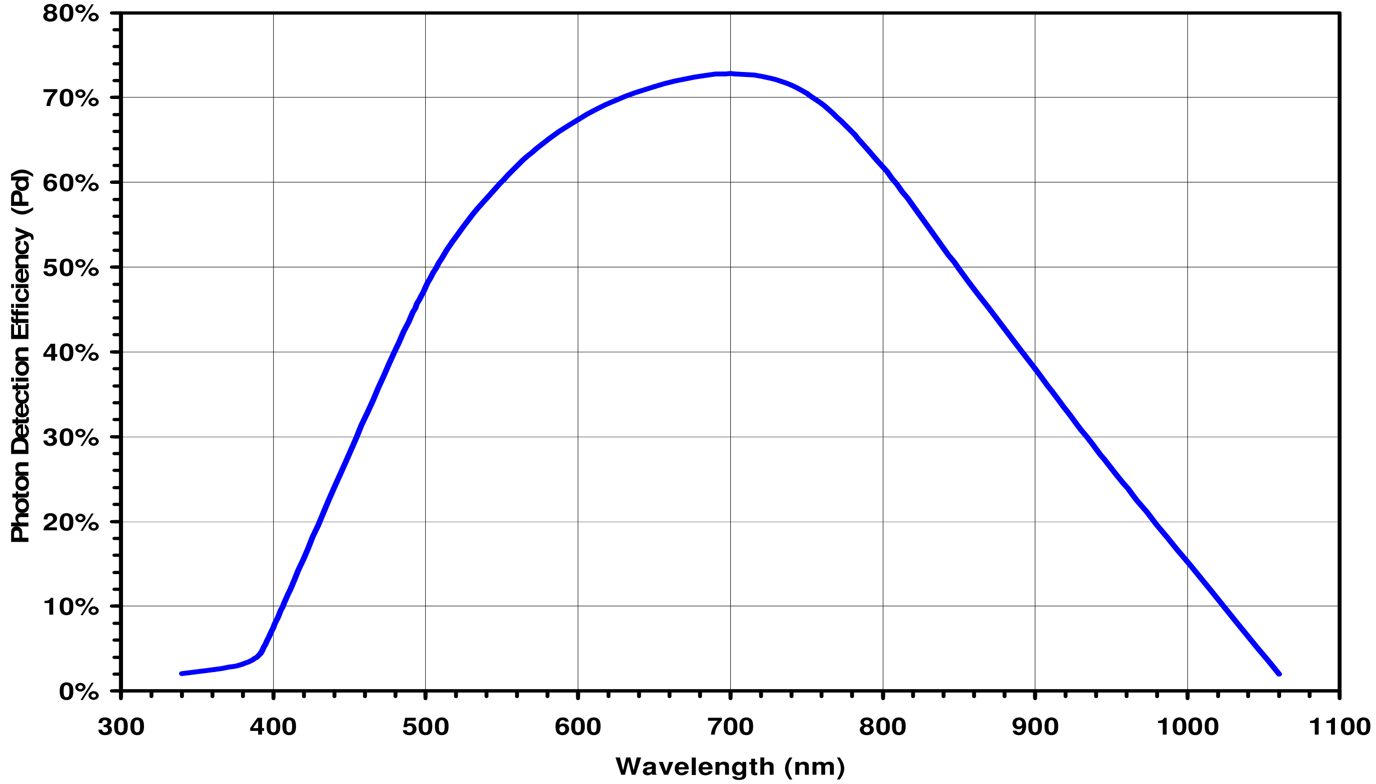
Recovery time: *how long it takes before a detector is ready to detect the next photon.*



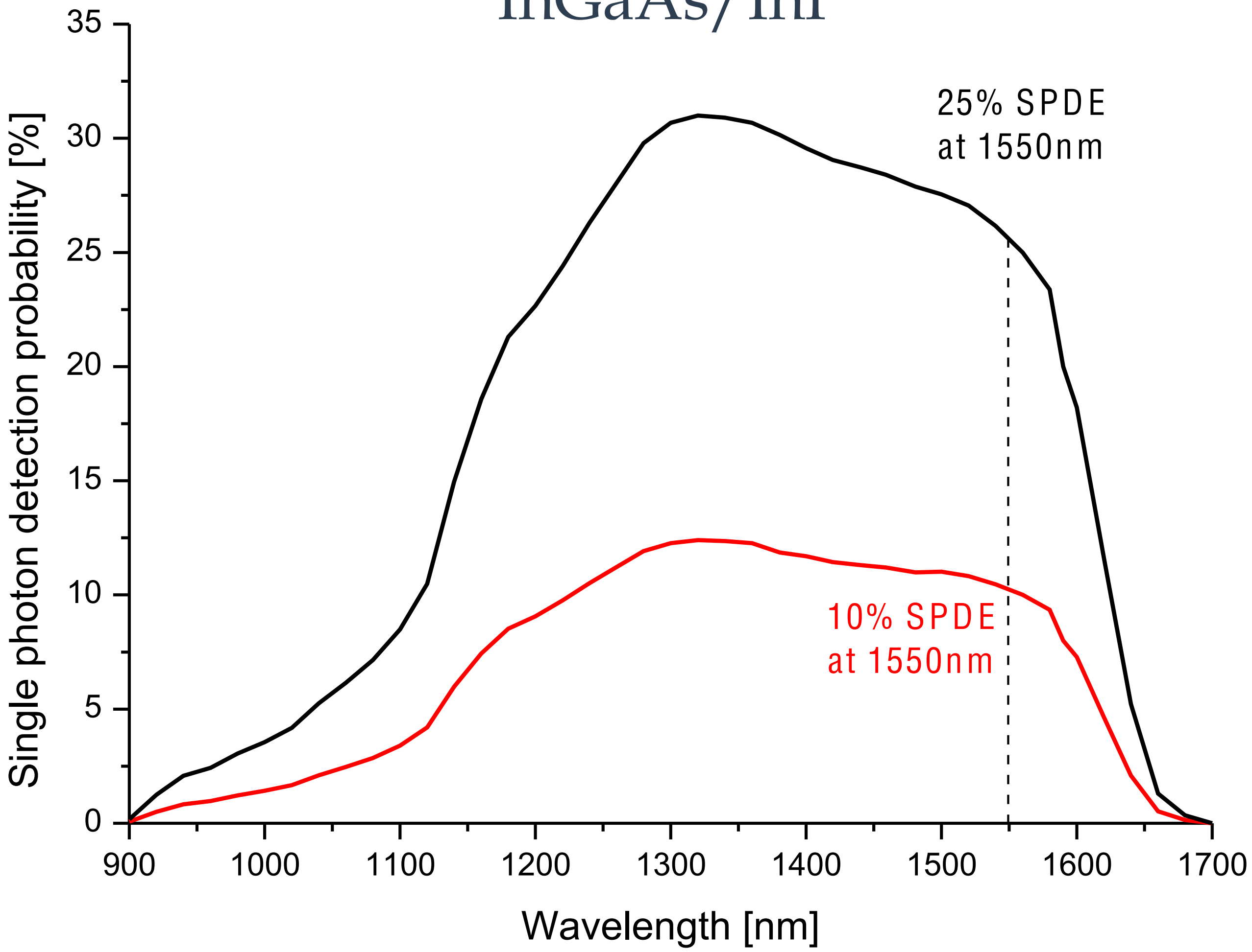
Quenching: *reduce the voltage bias so that trapped charges cannot trigger another avalanche.*

SPAD Tradeoff: *Lower operating temperatures leads to lower dark counts (good), but increases the probability of after pulsing (bad)*

Si



InGaAs/InP



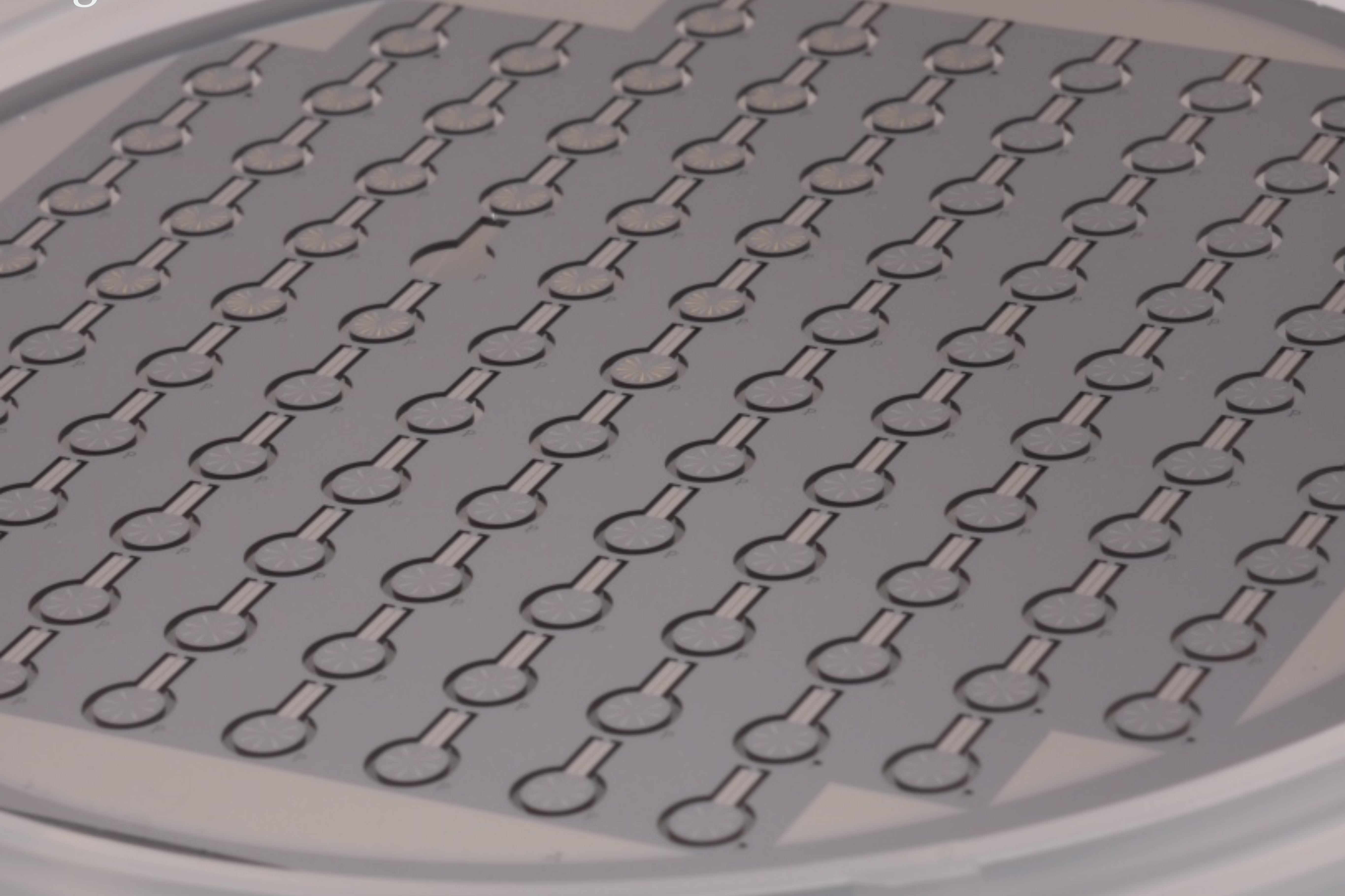
New: No Gating required

Yan et al., Rev. Sci. Instrum. 83, 073105 (2012)

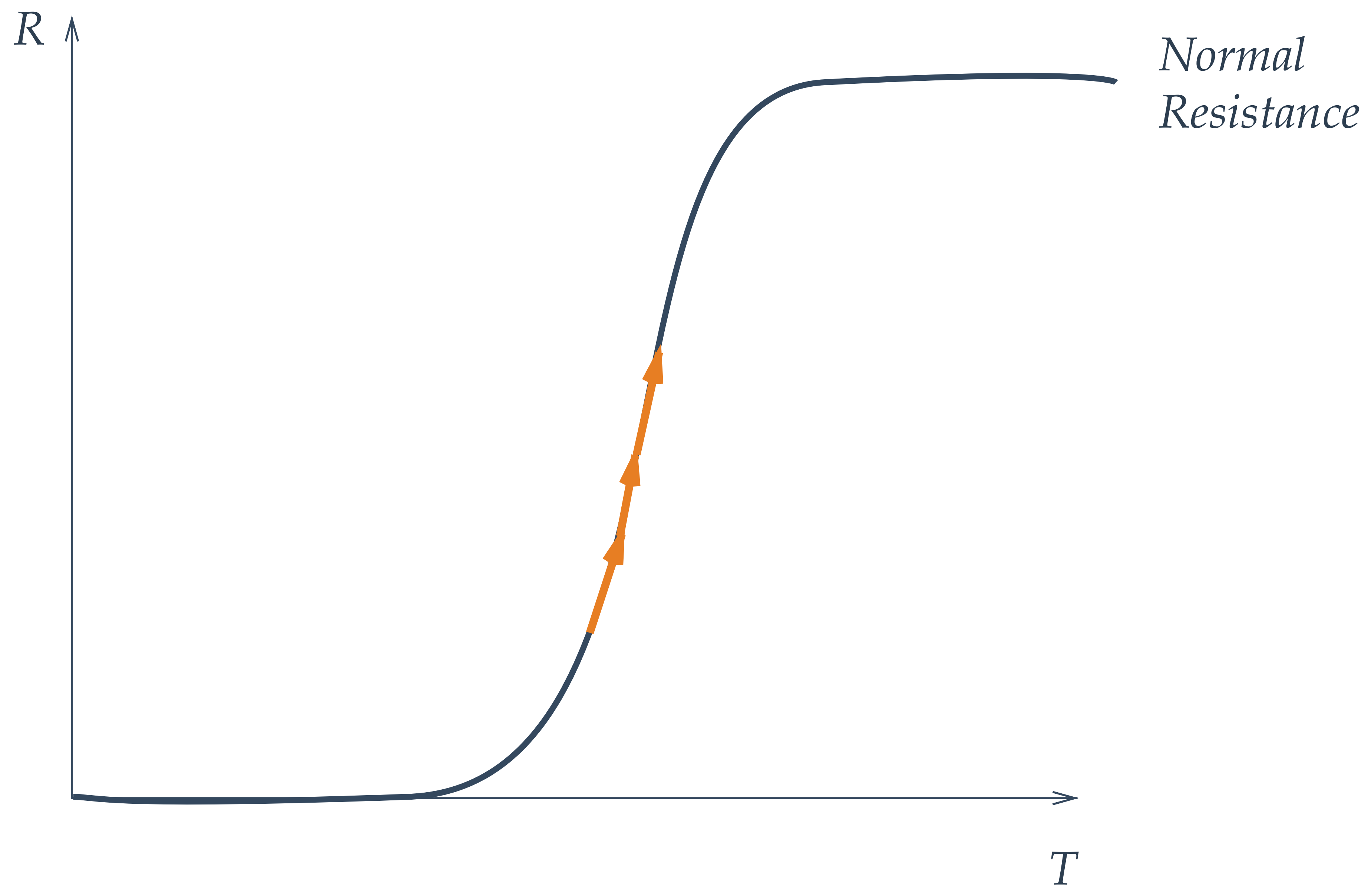
http://www.perkinelmer.com/CMSResources/Images/44-12462DTS_SPCM%20AQRH.pdf

http://www.idquantique.com/images/stories/PDF/id201-single-photon-counter/id201-specs.pdf

Superconducting Transition Edge Sensors

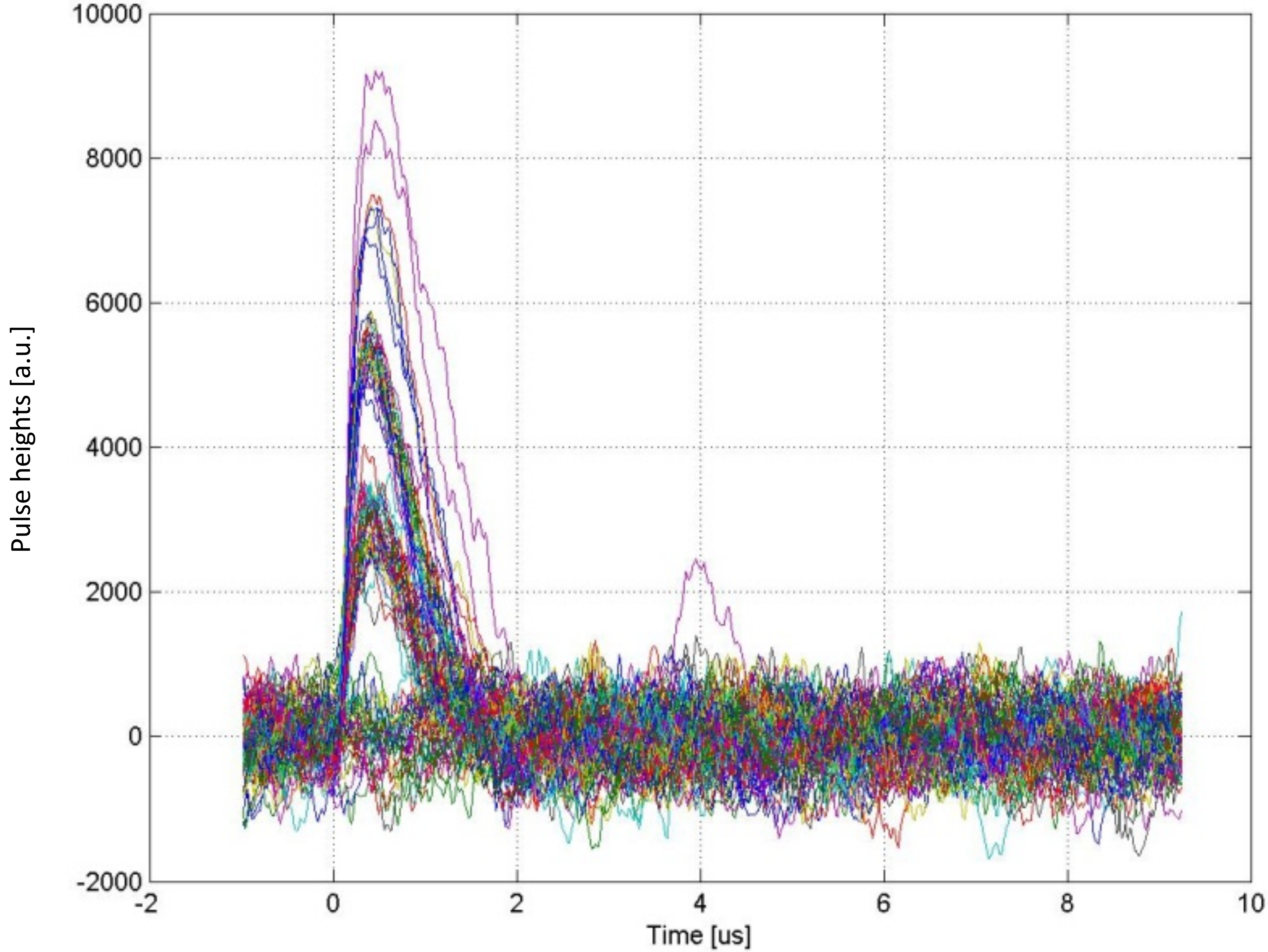


Superconducting Transition Edge Sensors



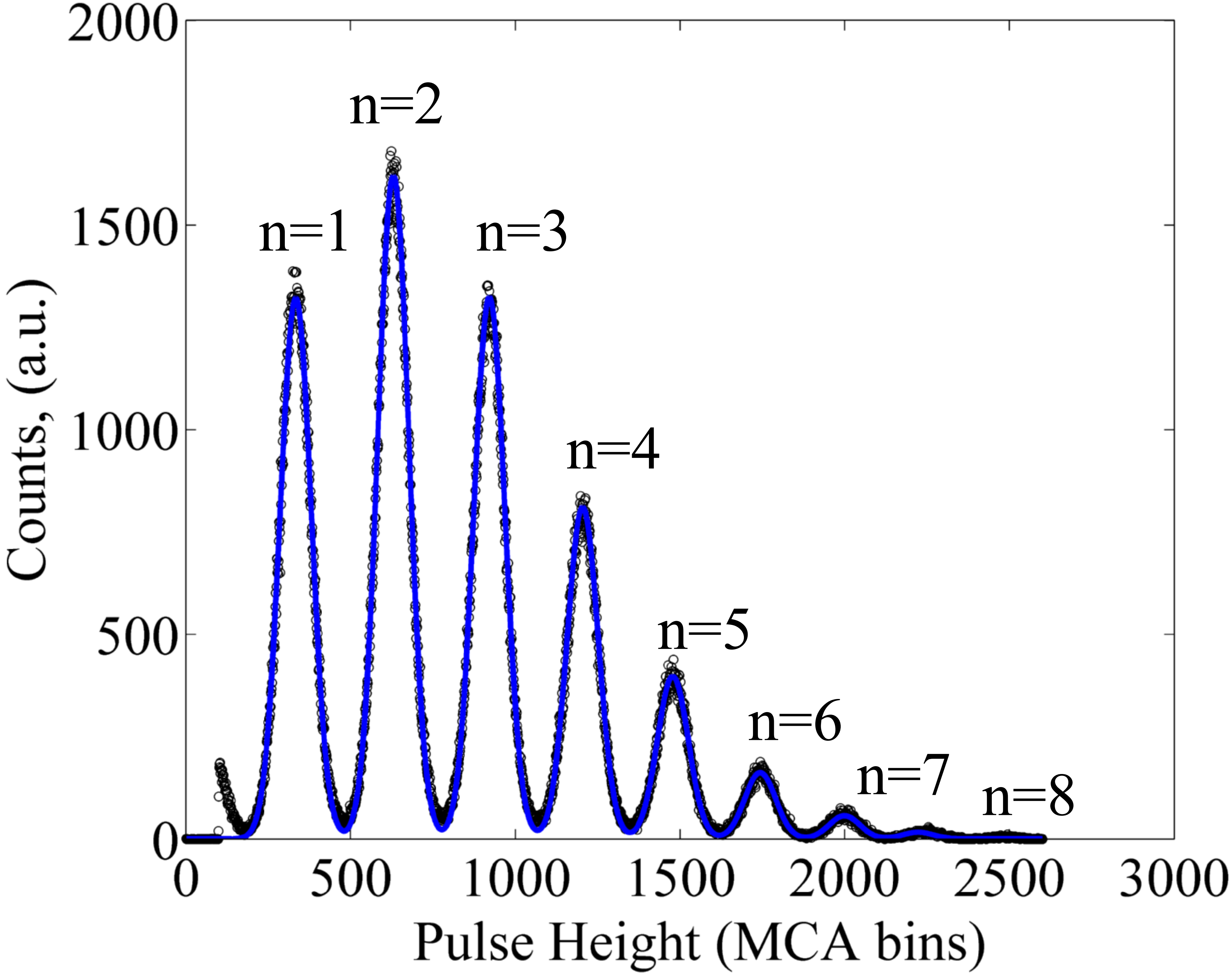
Number resolving capabilities. Detection efficiency of ~98% using a cavity structure from ~200-2000 nm. No intrinsic dark counts.

Sample Pulse traces, 1550 nm

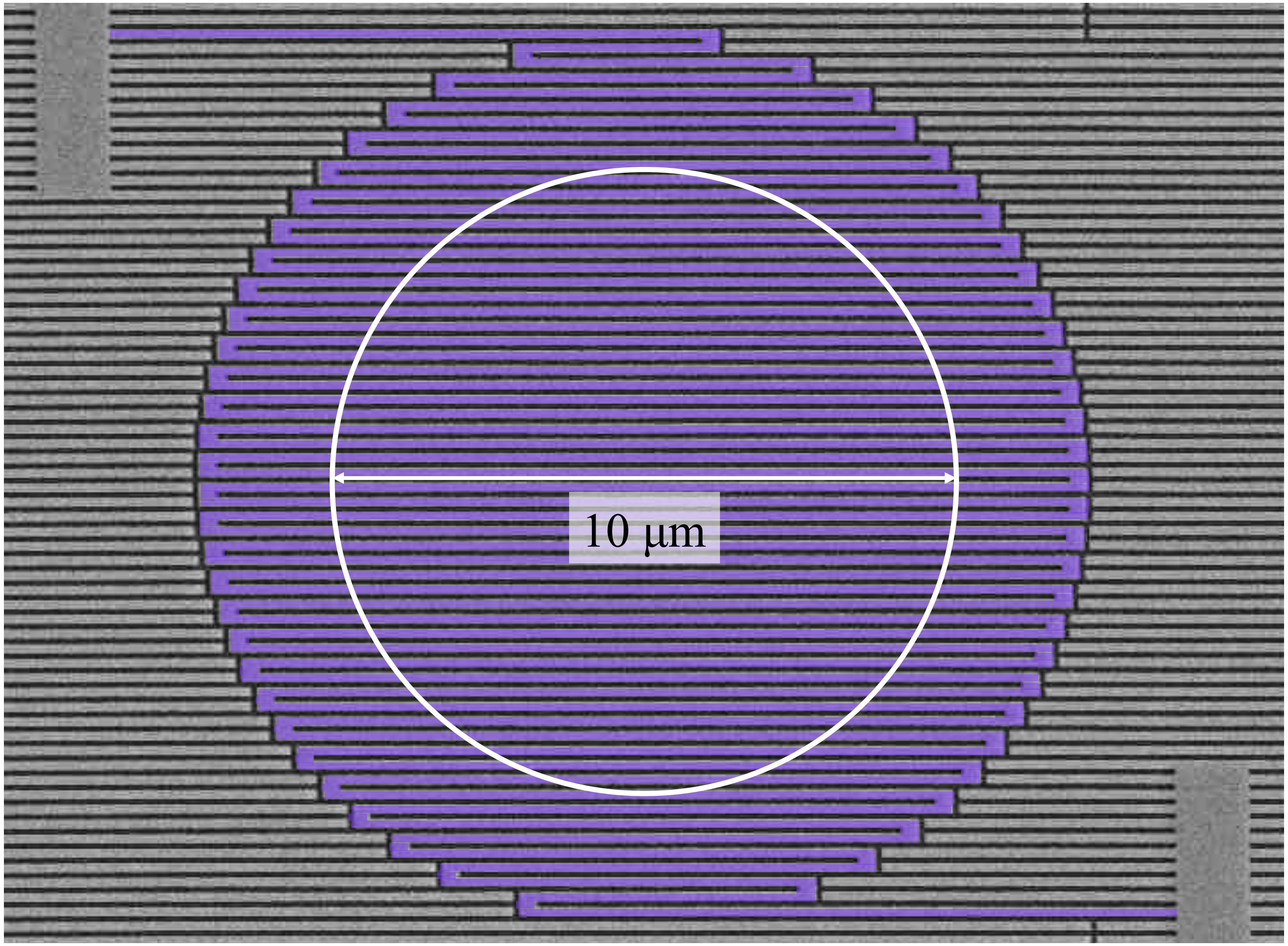


Jitter typically ~ 200+ ns. Can be made <10ns with special read out electronics. Can suffer from "pile up".

Photon number resolution

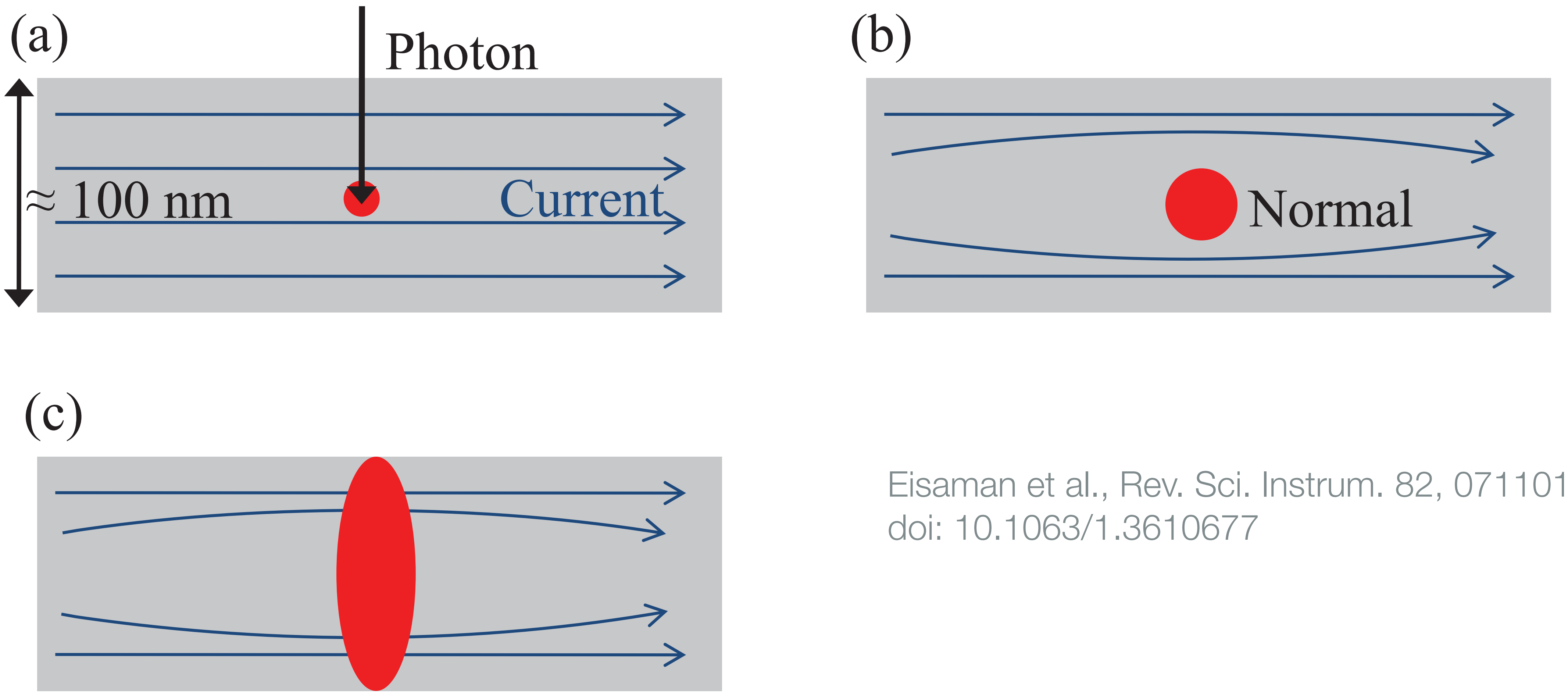


Superconducting Nanowire Detectors



Marsili et al.,Nature Photonics 7, 210–214 (2013)

Superconducting Nanowire Detectors



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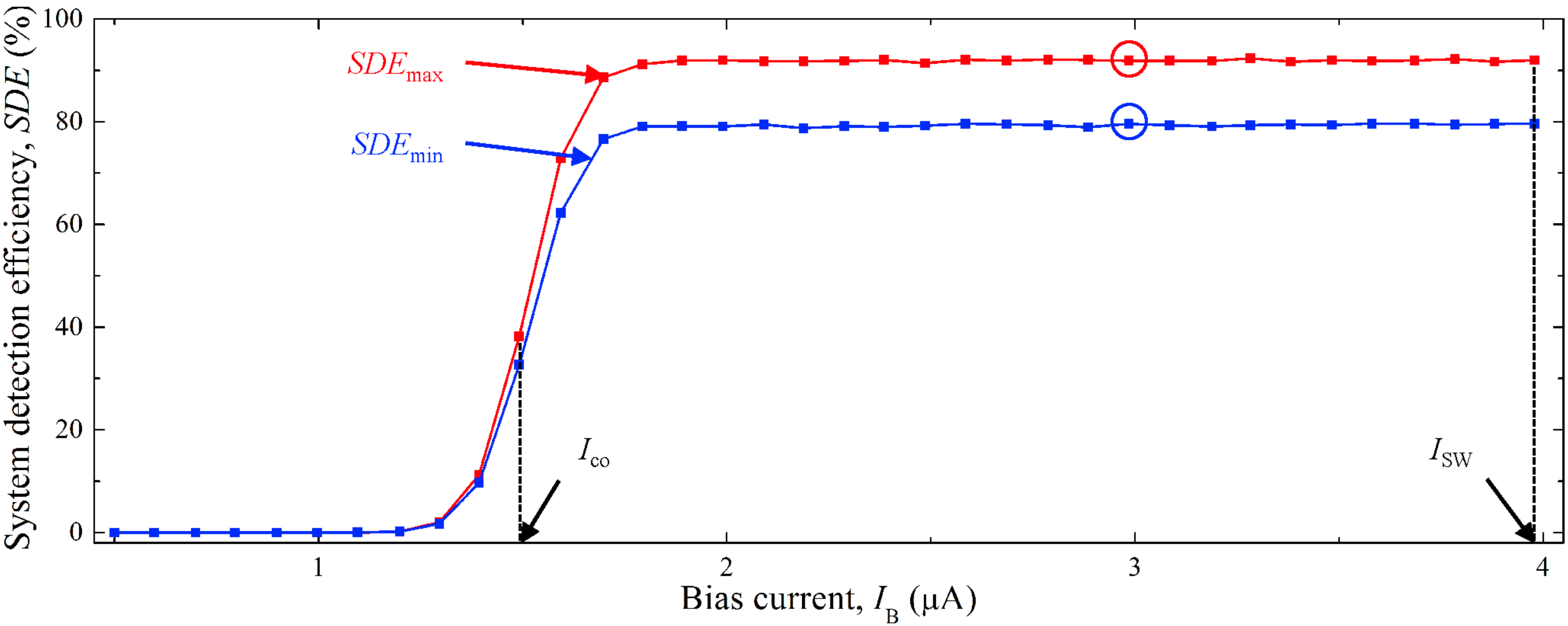
Superconducting Nanowire Detectors



Marsili et al.,Nature Photonics 7, 210–214 (2013)

Jitter <50 ps. Efficiency up to 93%. Fast recovery times. Broadband operation.
Downside: efficiency depends on polarization.

Table of properties

Detector Type	Efficiency	Dark Counts/s	Jitter	Max Count Rate (10^6)	Surface Area	Operating Temperature
PMT	40% @ 500 nm	100	~300 ps	10	~cm^2	300 K
Si APD	70% @ 700nm	25	~400 ps	10	~100 um^2	250 K
TES	98%	~0	100 ns (<10 ns)	0.1	~40 um^2	0.1 K
Nanowires	93% @ 1550nm	~100	30-50 ps	1000	~25 um ^2	1-3 K

Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011);
doi: 10.1063/1.3610677

Laser ON

Attack Vectors / Side Channels

Photon properties:

a. Wavelength
b. Polarization
c. Spatial mode
d. Photon statistics

Detector properties:

a. Efficiency
b. Jitter
c. Recovery time
d. Dark counts
e. After pulsing
f. Packaging / read out electronics

Holy sh*t! Smart toilet hack attack!

Free app lets anyone remotely harass toilet's occupant, run up water bill.

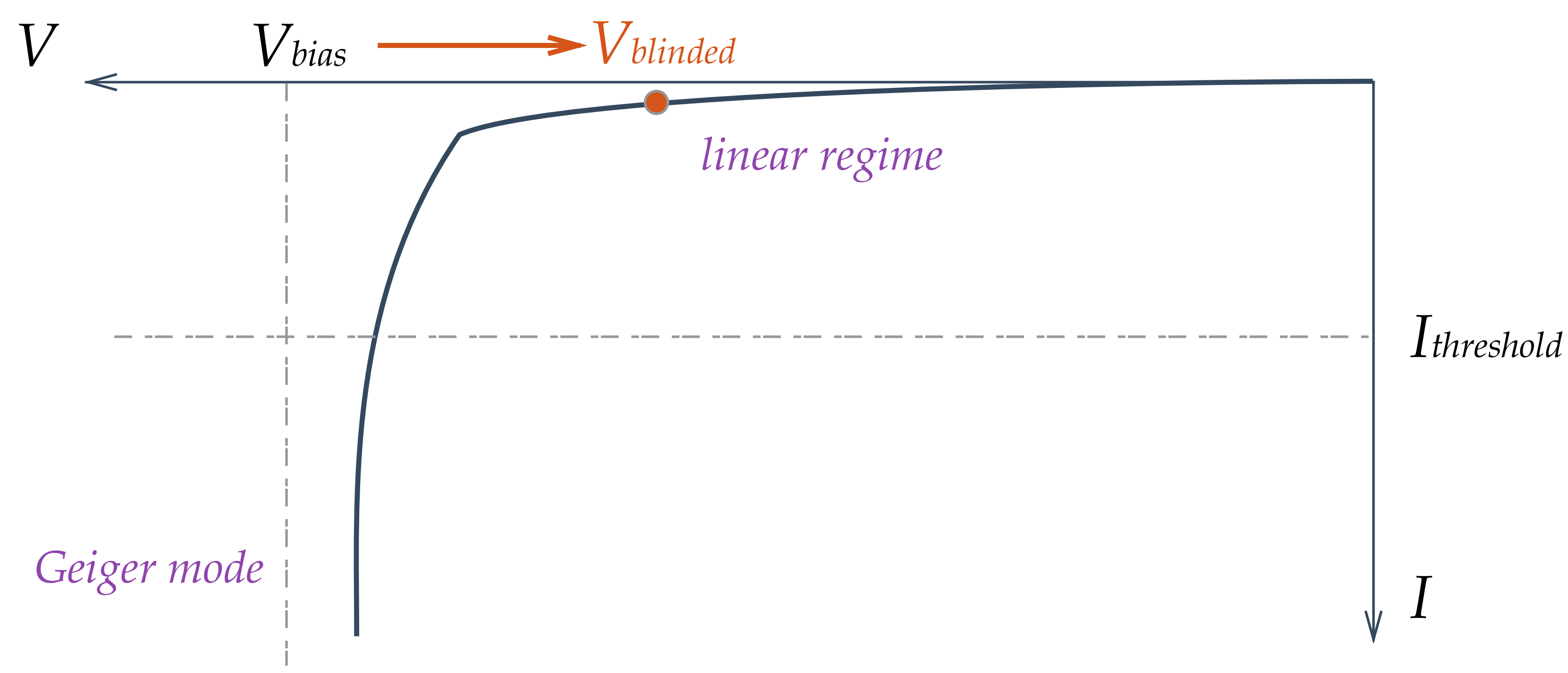
by **Sean Gallagher** - Aug 4 2013, 5:30pm EDT

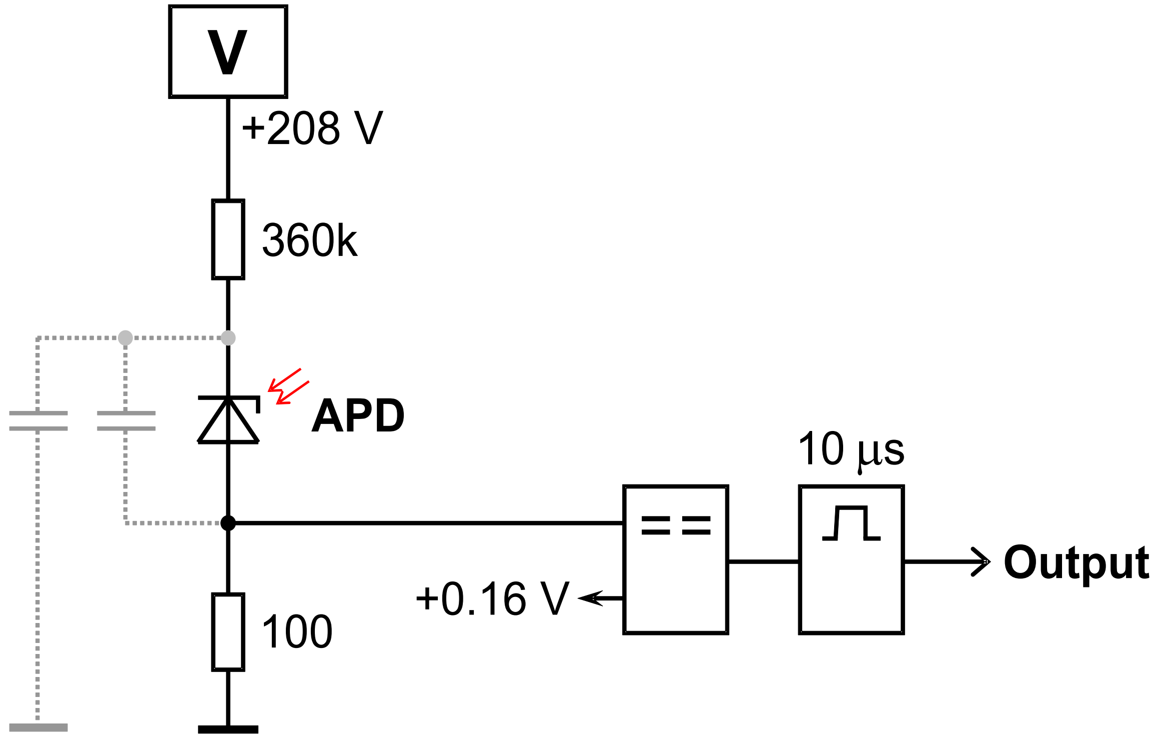
HACKING HARDWARE 51

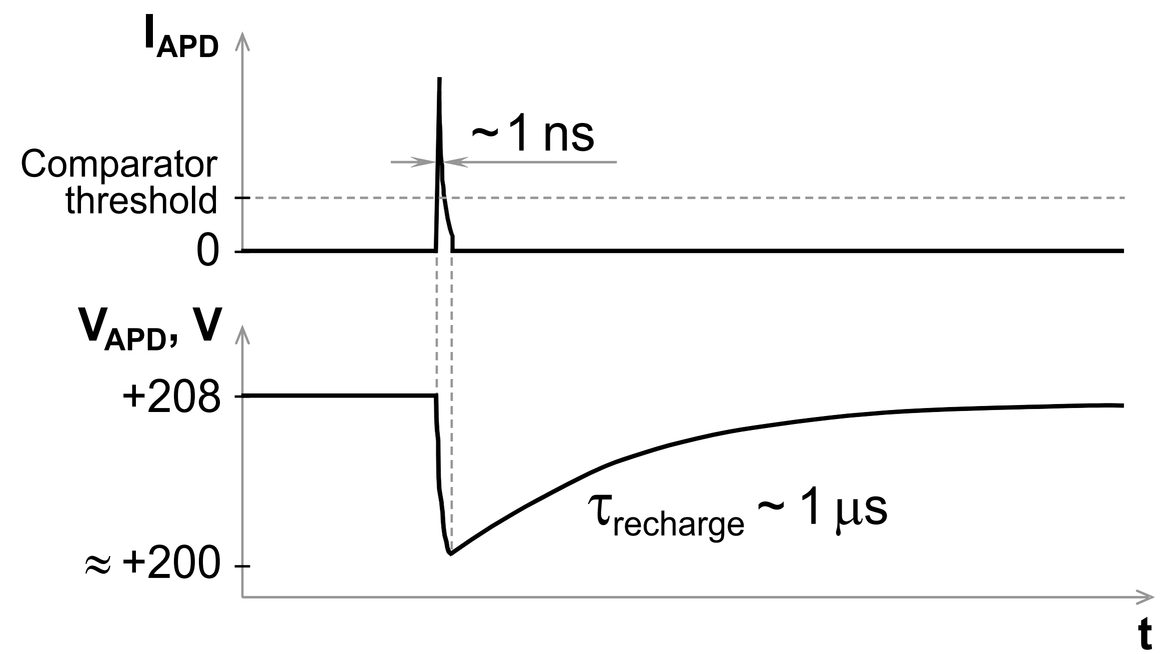
Information security firm Trustwave has reported a potential cyber-attack vector to a device you may have never expected the phrase "security vulnerability" would be applied (other than in reference to the end of a toilet paper roll, that is). In an advisory issued August 1, Trustwave warned of a Bluetooth security vulnerability in Inax's Satis automatic toilet.

http://arstechnica.com/security/2013/08/holy-sht-smart-toilet-hack-attack/

Blinding Attacks







V. Makarov, New J. Phys. 11 065003 (2009)

http://www.vad1.com/publications/

It is impossible to make anything hackerproof because hackers are so ingenious.

Moral: *we have some work to do.*