Single photons

how to create them, how to see them

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Intro

- light is quantum
- light is cheap
- let’s use the quantum properties of light

Little interaction with the environment ☺

We can send them across long distances

Little interaction with the environment ☹

Hard to detect and to store

Outline

Photon: elementary, cheap, powerful

How would you like your photons?

Generating single photons

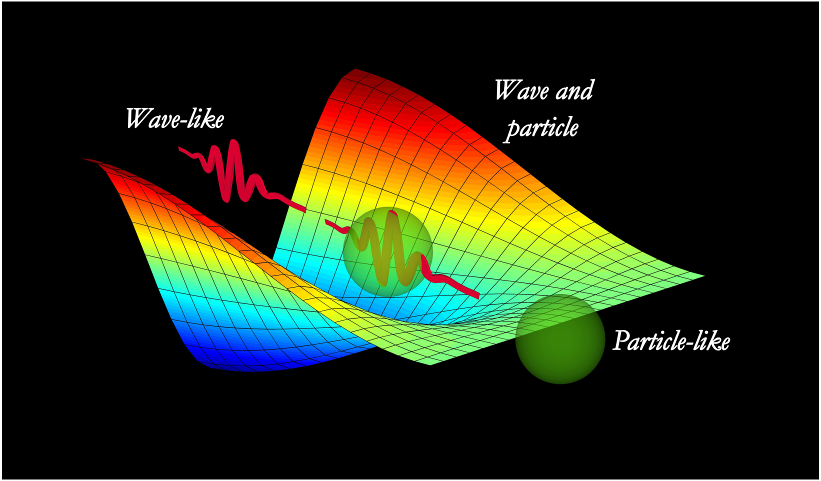
Photon

An elementary particle, the quantum of all forms of electromagnetic radiation.

Including light.

source: Wikipedia

Photons are quantum objects



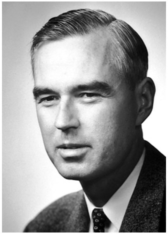
source: www.photonics.com

Anti-photon

W.E. Lamb, Jr.

Optical Sciences Center, University of Arizona, Tucson, AZ 85721, USA

Received: 23 July 1994 / Accepted: 18 September 1994



I suggested that a license be required for use of the word "photon," and offered to give such a license to properly qualified people.

sources: Lamb, Appl. Phys. B 60, 77 (1995);
Photo: wikipedia.

“Seeing” photons is a destructive process

- Conversion of photon into electrical pulses
- Limited efficiency η
- Counting the number of photons?

Outline

Photon: elementary, cheap, powerful

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Generating single photons

Quantized Electromagnetic Field

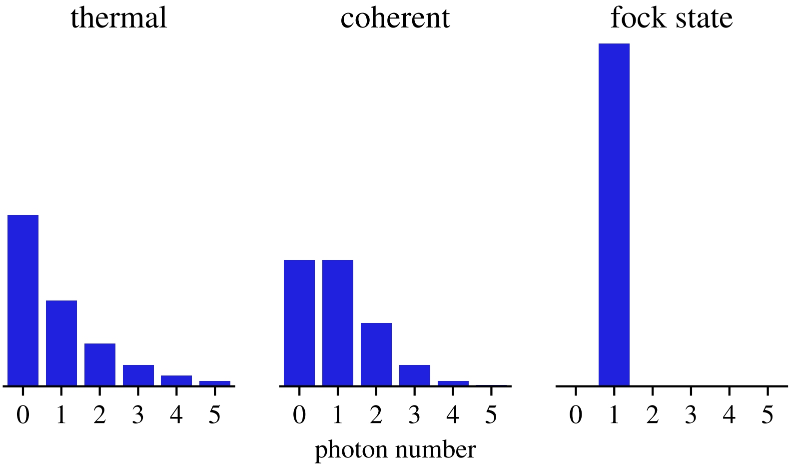
In a finite volume L^3, we can directly quantize an EM field mode

$$\hat{\mathrm{E}}(\vec{\mathrm{r}})_{\vec{\mathrm{k}},\vec{\epsilon}} = \underbrace{i\sqrt{\frac{\hbar\omega_k}{2\varepsilon_0 L^3}}\,\vec{\epsilon}\,\hat{\mathrm{a}}^{\dagger}_{\vec{\mathrm{k}},\vec{\epsilon}}\,e^{i\left(\vec{\mathrm{k}}\cdot\vec{\mathrm{r}}-\omega_k t\right)}}_{\hat{\mathrm{E}}^{(-)}} + \underbrace{\quad \text{c.c.} \quad}_{\hat{\mathrm{E}}^{(+)}}$$

where

$\vec{\mathrm{k}}$	wave vector
ω_k	angular frequency. In vacuum $\omega_k = c\left\|\vec{\mathrm{k}}\right\|$
$\vec{\epsilon}$	polarization
$\hat{\mathrm{a}}^{\dagger}$	creator operator

Light classification



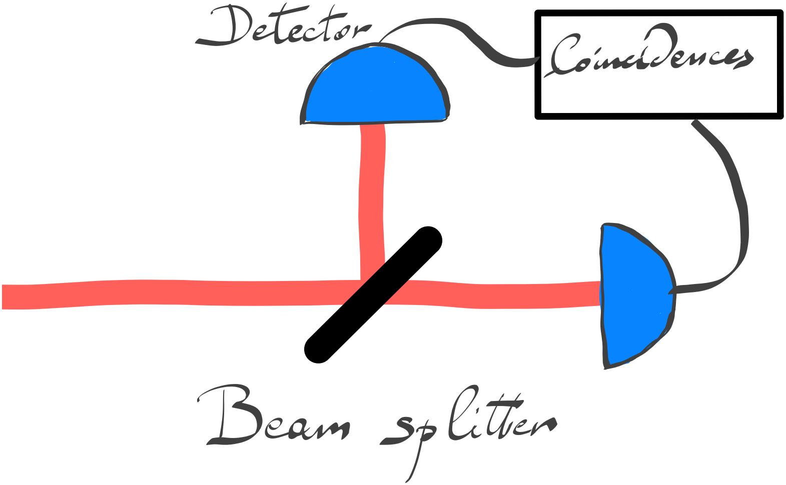
The second-order correlation function

Different light sources present different statistical properties (coherence).

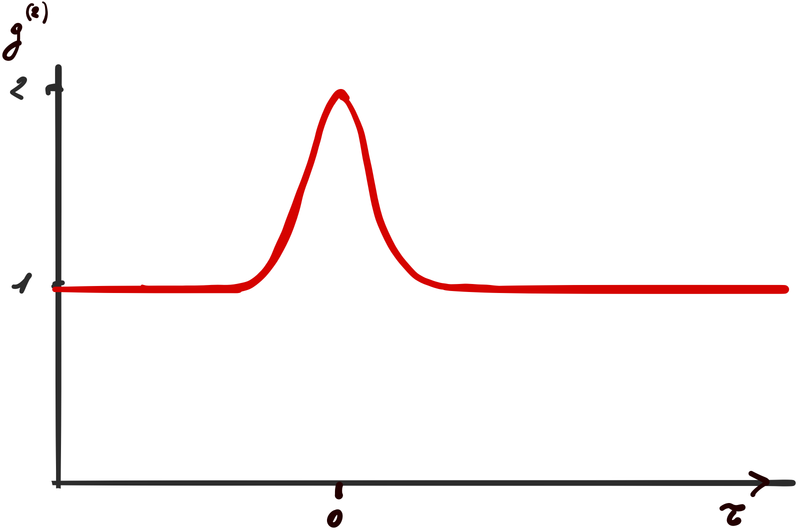
We are particularly interested in second-order correlation function

$$g^{(2)}(\tau) = \frac{\left\langle \hat{E}^{(-)}(t)\,\hat{E}^{(-)}(t+\tau)\,\hat{E}^{(+)}(t+\tau)\,\hat{E}^{(+)}(t) \right\rangle}{\left\langle \hat{E}^{(-)}(t)\hat{E}^{(+)}(t) \right\rangle^{2}}$$

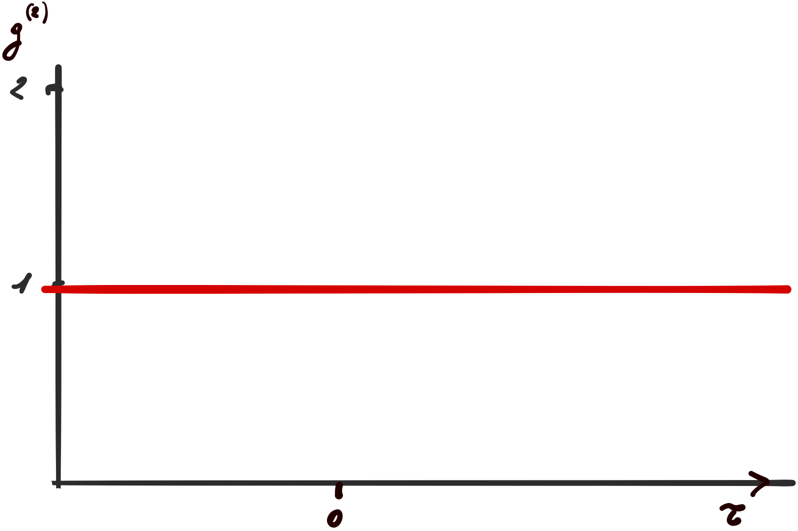
Hanbury Brown and Twiss interferometer



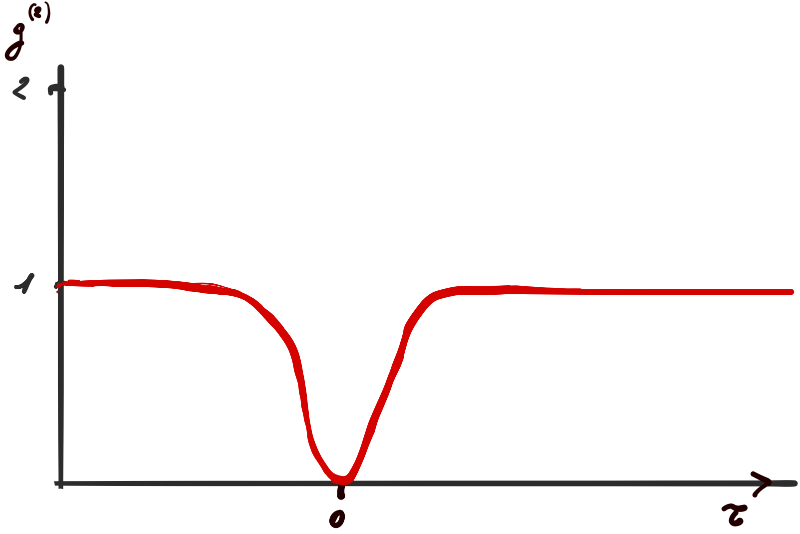
Coherence classification - thermal



Coherence classification - coherent



Coherence classification - anti-bunched (non-classical)



It's a multimode, free space world

We set some operative conditions to define what's a single photon in free space, and its usefulness.

Brightness
: The probability of getting a click in response to an excitation. Low B messes up the purity: the state is a mixture of vacuum and $|1\rangle$.

Purity
: It's a vague term, everyone uses it they way they prefer. IMHO: the description is closer to $|\psi\rangle$ than $\sum_i |\psi\rangle$. But it can also be associated to the fidelity of the output to the ideal $|1\rangle$.

Indistinguishability
: All emitted photons are the same. We can test it with Hong-Ou-Mandel interference.

Outline

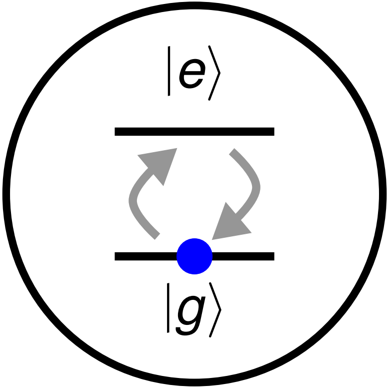
Photon: elementary, cheap, powerful

How would you like your photons?

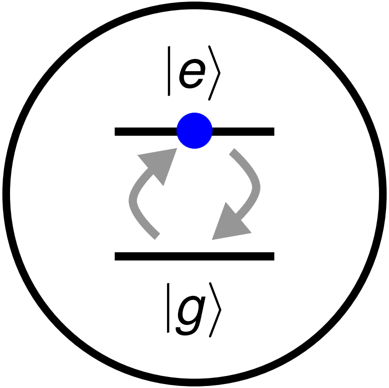
Generating single photons

- Single emitter
- Pairs of photons

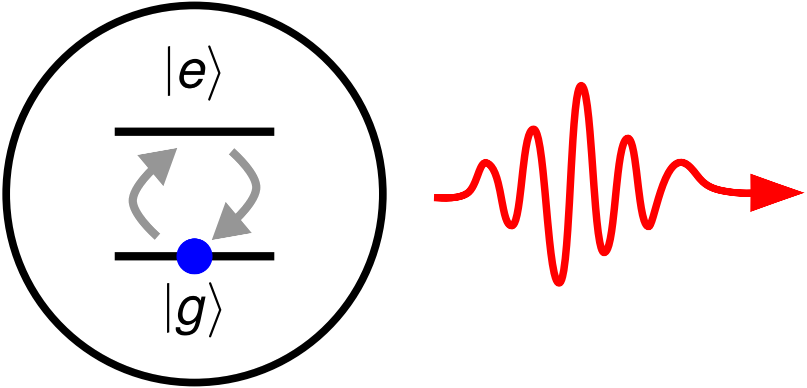
Single photons from a single "atom"



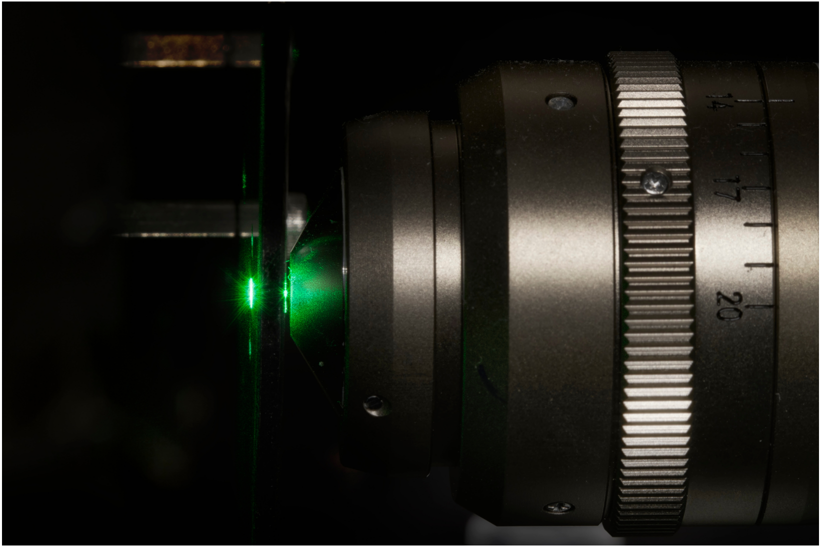
Single photons from a single “atom”



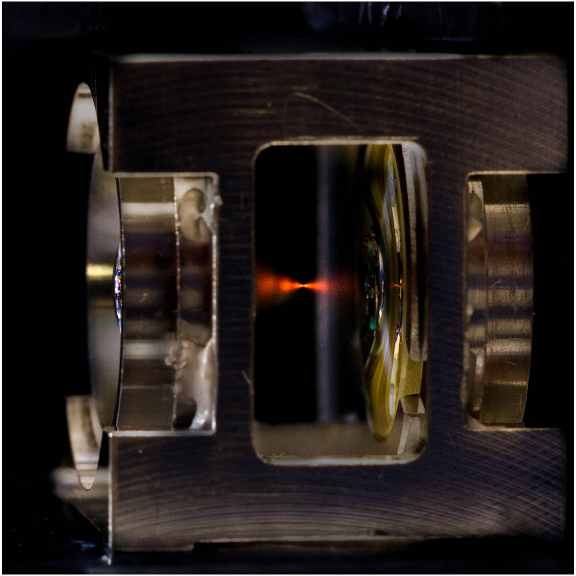
Single photons from a single "atom"



Localize the emitter



Localize the emitter



Stages of photon generation

1. excite the transition of interest
   - electrical pulse
   - optical pulse

2. collect the emission

3. repeat

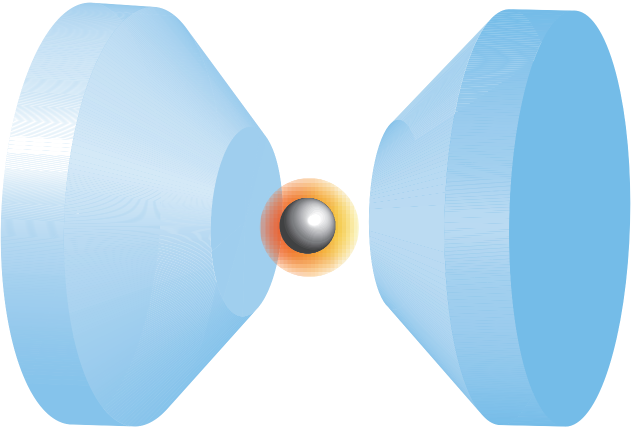
Stages of photon generation

1. excite the transition of interest
   - electrical pulse
   - optical pulse

2. collect the emission
   the emission in a large solid angle

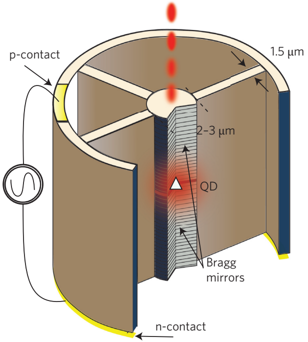
3. repeat

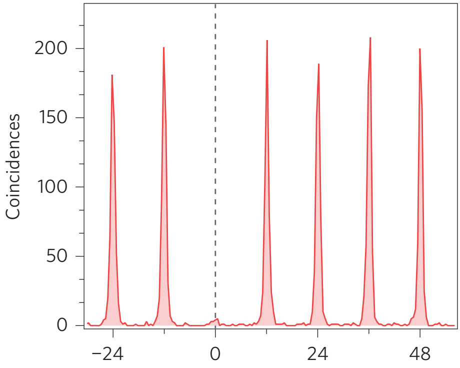
We can change the mode structure



source: S. Ritter, et al., Nature **484**, 195 (2012).

Quantum Dot in cavity





source: N. Somaschi, et al., Nature Photonics **10**, 195 (2016).

Single emitter

Pros

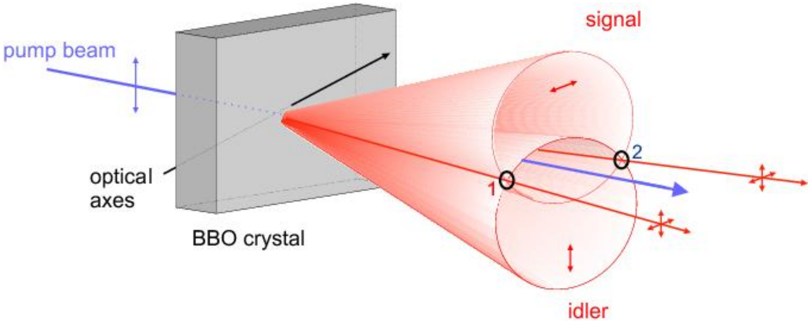
- High brightness (with cavity)
- good purity (filtering)

Cons

- bad indistinguishability (solid state)
- requires trapping/cooling

Spontaneous parametric down conversion

generate photons in pairs



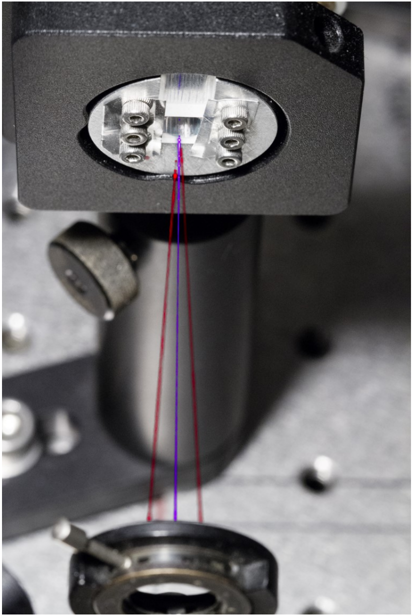
Conservations impose correlations

energy conservation

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

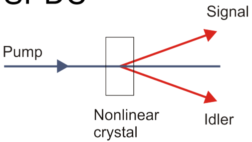
momentum conservation

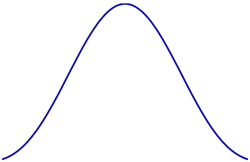
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$



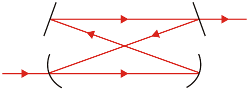
SPDC + Cavity

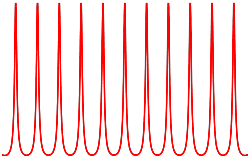
SPDC



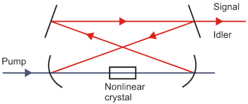


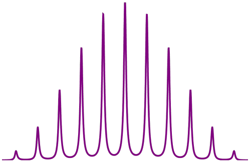
Cavity



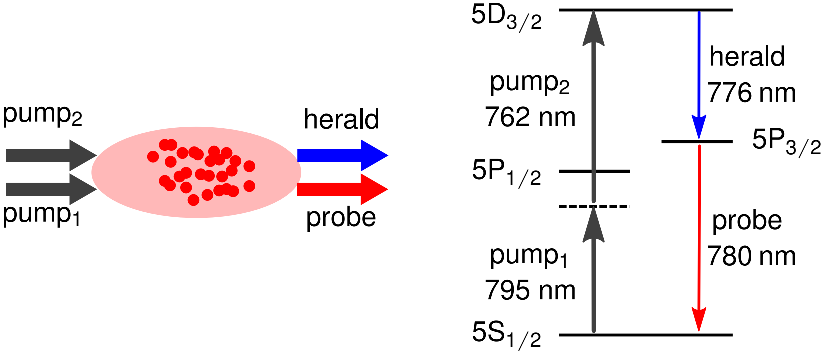


Combined

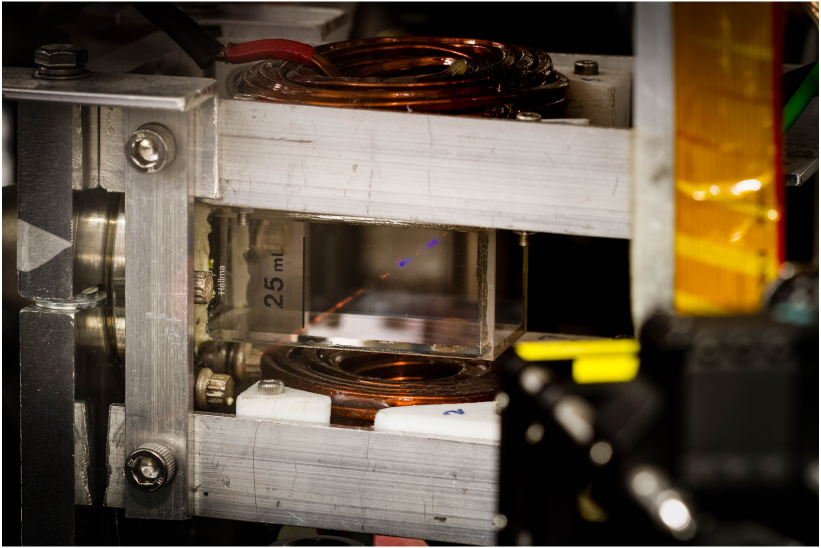




Four-wave mixing



FWM in cold atoms



Heralding

Pros

- wide range of wavelengths/bandwidths
- good purity (low brightness)
- great indistinguishability

Cons

- limited brightness
- poissonian process (high order pair generation)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quantumlah.org

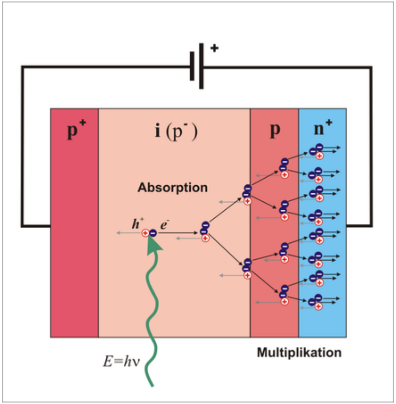
Outline

- Detecting single photons
  - Photoelectric effect
  - Thermal effect

Avalanche photodiodes

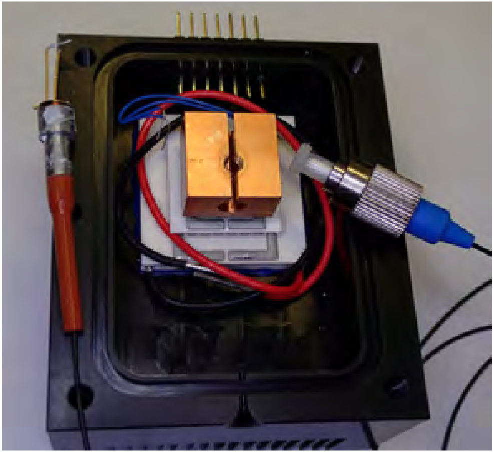
jitter: $\approx$ 500 ps

temperature: $\approx$ 230 K



source: http://www.wikiwand.com

APD is a mature technology



Different materials for different spectral regions

Si - visible range

400 nm to 1060 nm

Dark count rate: 20 - 2000 cps

InGaAs - telecom range

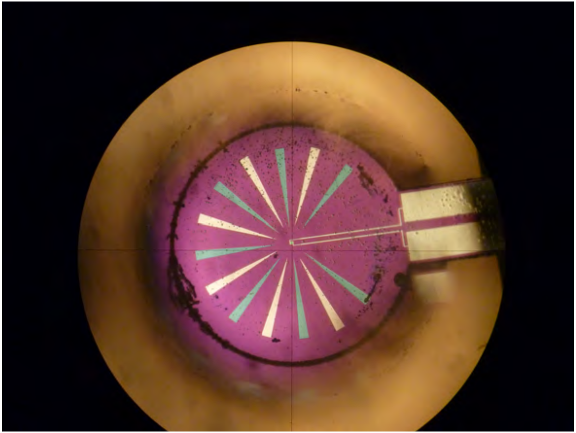
900 nm to 1700 nm

Dark count rate: $>$ 1kcps

Transition edge sensors - $\eta \approx 98\%$

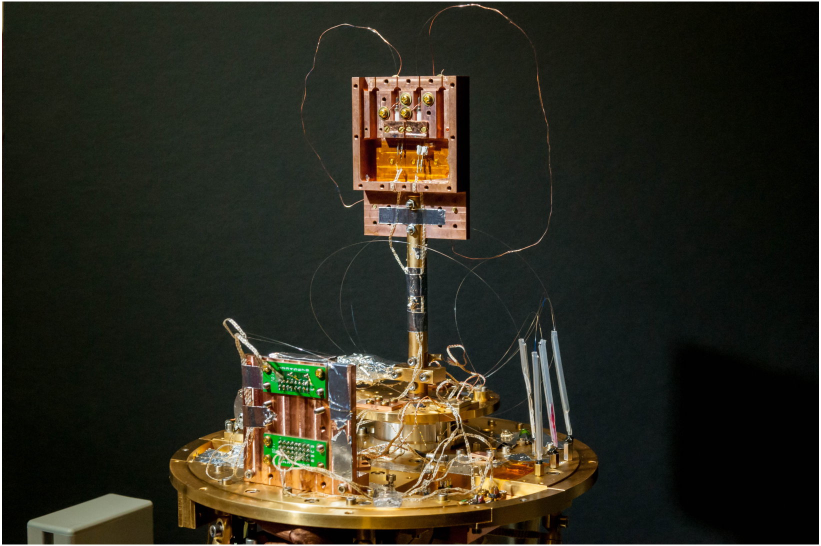
Slow: jitter
$>$ 100 ns

Very cold 100 mK

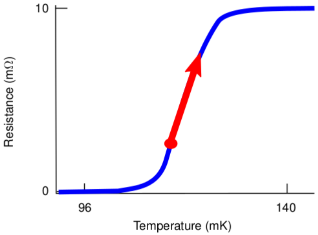


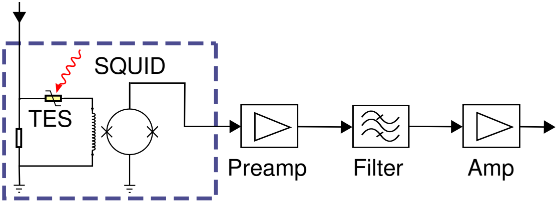
source: S. K. Joshi, Ph.D. thesis

We need to keep them very cold

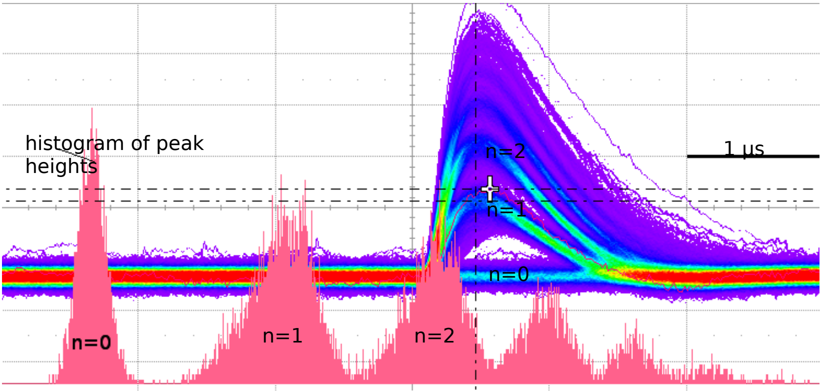


A very sensitive bolometer

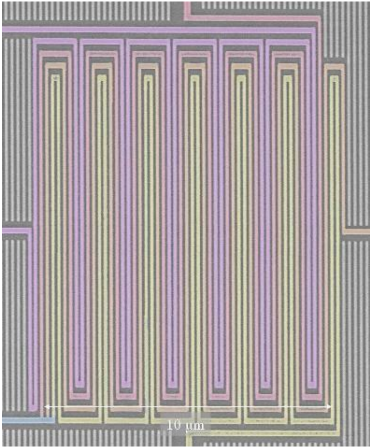




We can also count the number of photons



Superconducting nanowires - $\eta \approx 92\%$



Very fast: jitter$<$ 100 ps

“only” down to 4 K

source: MIT