Paris Centre for
Cosmological Physics

Superconducting Detectors for Cosmological Studies

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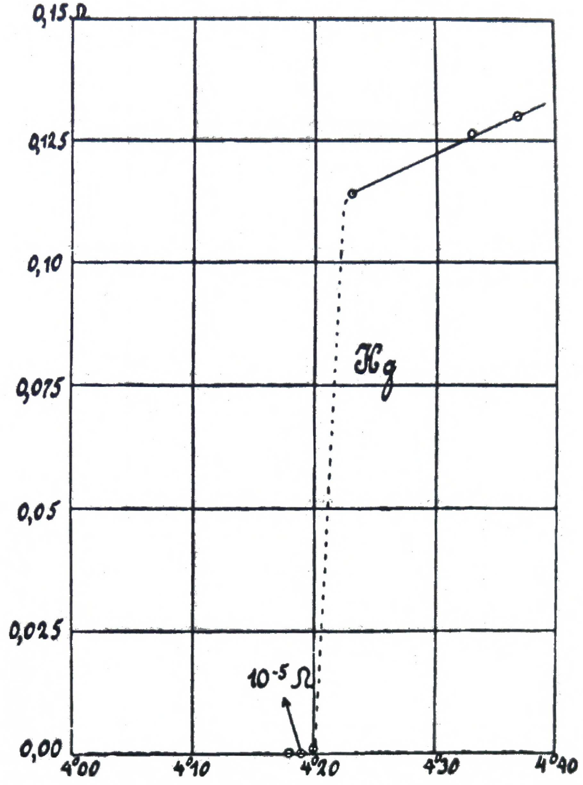
Outline

- What is a Superconductor?
  - 1911: the discovery
  - BCS description: the formation of Cooper pairs below Tc
  - The energy gap: semiconductor-like picture of SC energy bands
  - Energy conservation (Poynting theorem) and the kinetic energy of charge carriers
- Superconducting Detectors: a panoramic view
  - From mm-waves to X-rays: a list of current and future astrophysical application of SC detectors (with basic principles)
- The case of Kinetic Inductance Detectors
  - Basic Principles

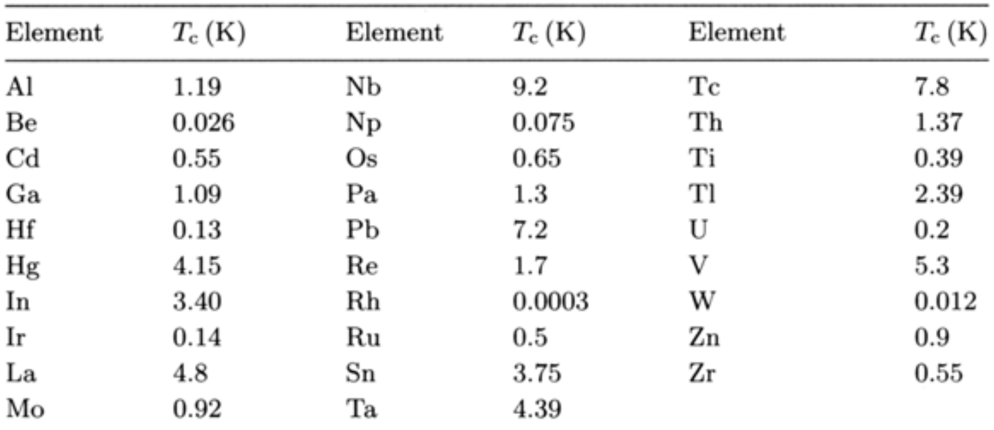
100 Years ago

Onnes, H. K. *Comm. Phys. Lab. Univ. Leiden*,
Nos. 119, 120, and 122, 1911.



Below a certain Tc, R≅0. Some metals, at different temperature, exhibit this sudden transition

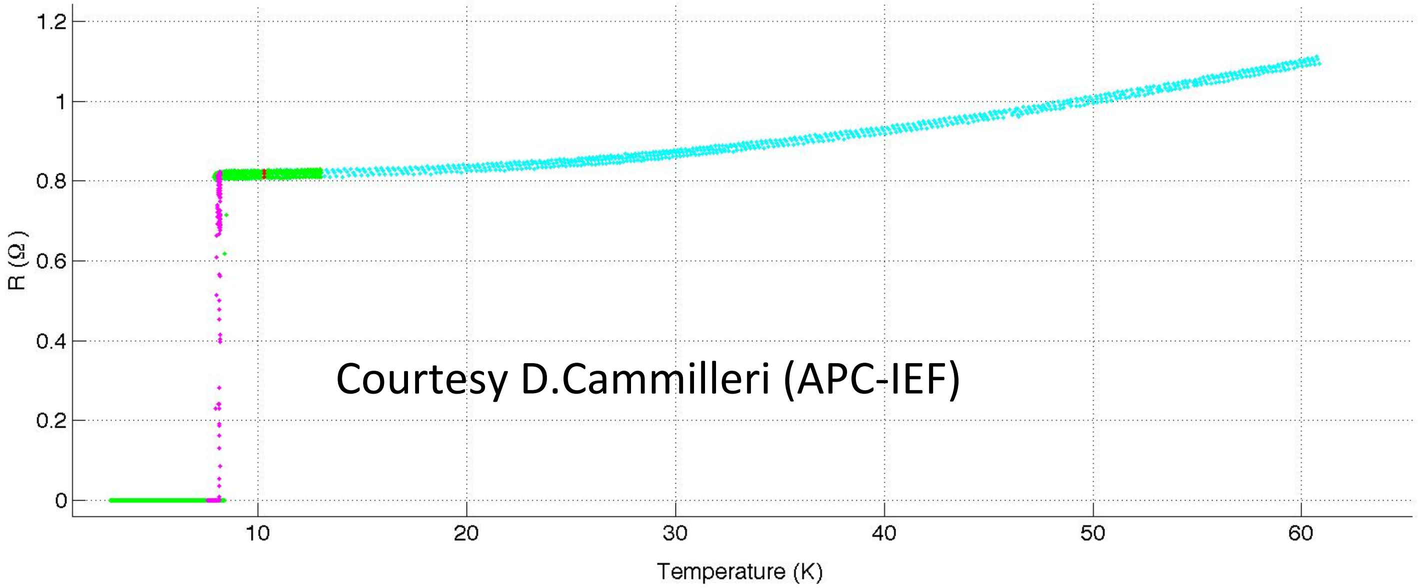
?



Element	T_c (K)	Element	T_c (K)	Element	T_c (K)
Al	1.19	Nb	9.2	Tc	7.8
Be	0.026	Np	0.075	Th	1.37
Cd	0.55	Os	0.65	Ti	0.39
Ga	1.09	Pa	1.3	Tl	2.39
Hf	0.13	Pb	7.2	U	0.2
Hg	4.15	Re	1.7	V	5.3
In	3.40	Rh	0.0003	W	0.012
Ir	0.14	Ru	0.5	Zn	0.9
La	4.8	Sn	3.75	Zr	0.55
Mo	0.92	Ta	4.39		

Incomplete list (only pure metals): but fine to our purposes.

In (our) lab today



Courtesy D.Cammilleri (APC-IEF)

What does it happen around T_c?

- Microscopic Bardeen-Cooper-Schrieffer (BCS) theory

- Macroscopic (thermodynamic): Ginzburg-Landau theory

➢ We only address a discussion on qualitative aspects necessary to understand detector physics

Microscopic view: qualitative

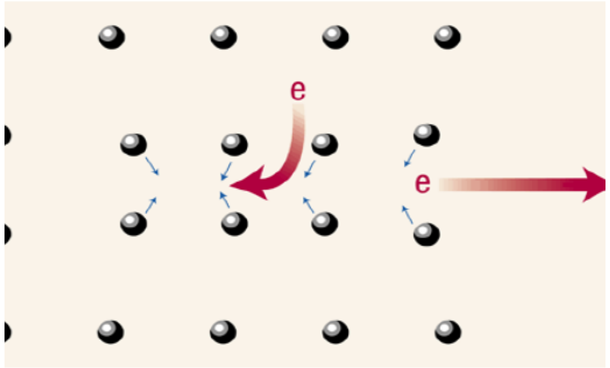
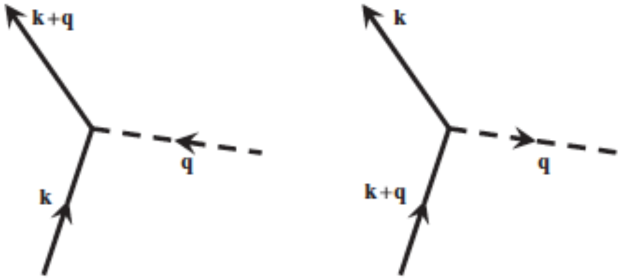


Image credit to: Indranil Paul (Néel-Grenoble)



Some facts:

1.Electrons Coulomb potential is screened in a crystal lattite (weaker repulsion)

2.Two electrons with energy close to the Fermi energy couple *via* phonon exchange

3. Typical energy of the phonon: $\hbar\omega_{Debye} = \hbar c_{sound}\sqrt[3]{6\pi^2 N / V}$

→ The resulting entity is a boson. It is called the “Cooper pair”.

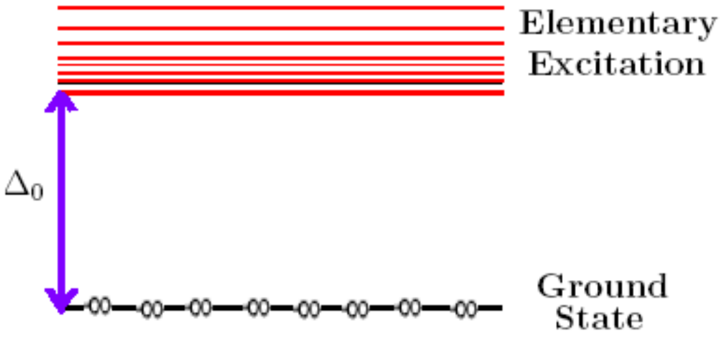
Cooper pair: identikit

- Mass = 2 m_e
- Charge = 2e
- Spin = 0 (singlet),1 (triplet)
- Statistics: Bose-Einstein
- Binding energy: 2Δ(T) ~ fraction of **m**eV (*)
- Size (coherence length): $\xi_0 = a\hbar v_F / \pi\Delta(T) \sim O(1\mu m)$ (**)
- Its motion through the crystal lattice is frictionless (= no ohmic losses)

(*) typical for our detector applications

(**) Values change metal by metal (a factor 100 from Al to Nb)

Energy bands



- ■ Elementary excitation: electrons (better: quasi-particles)

- ■ Ground state: paired electrons (Cooper pairs)

★At T=0K only Cooper pairs living in the ground state. At T=0K a photon with energy

$$E_\gamma = \hbar\omega = 2\Delta_0 \cong 3.5 k_B T_c$$

can break a Cooper pair and produce two quasi-particles

Macroscopic view

- It describes the SC transition as a phase transition occuring when **$T \sim T_c$**
- The main object of the theory is the so-called order parameter $\psi = |\psi| e^{i\theta}$
- At T=0K the order parameter represents the state of all the Cooper pairs in a superconductor (allowed: CP are bosons!)

Poynting theorem

$$\vec{E} \bullet \left\{ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \right\} - \vec{H} \bullet \left\{ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \right\}$$

$$\Downarrow$$

$$-\nabla \bullet (\vec{E} \times \vec{H}) = \vec{E} \bullet \frac{\partial \vec{D}}{\partial t} + \vec{H} \bullet \frac{\partial \vec{B}}{\partial t} + \vec{E} \bullet \vec{J}$$

Poynting theorem

If our box contains normal metals, then $\vec{J} = \vec{J}_e$

and the term $E \bullet J = \rho \left| J_e \right|^2$ just means: ohmic losses!

And if we have also a Cooper pair current?

$$\vec{E} \bullet \vec{J} = \rho \left| \vec{J}_e \right|^2 + \frac{\partial}{\partial t} \left(\frac{1}{2} \Lambda \vec{J}_{cp}^{\,2} \right)$$

Kinetic energy!

Poynting theorem

A practical consequence:

In a superconducting circuit the current allows to store energy in the form of kinetic energy and magnetic energy, that is $E=1/2\ L_k i^2 + 1/2 L_m i^2$

Bibliography

- Tinkham: “Introduction to Superconductivity”
- Van Duzer-Turner: “Superconductive devices and circuits”
- J.F.Annett: ”Superconductivity, Superfluids and Condensates”

Historical:

- Van Delft, Kes: “The discovery of superconductivity”, Physics Today (2010)

A prophetic connection

Press Release
17 October 1978

The Royal Swedish Academy of Sciences has decided to award the 1978 Nobel Prize for Physics in two equal parts: one to Professor **Piotr Leontevitch Kapitsa**, Institute of Physical Problems, USSR Academy of Sciences, Moscow, **for his basic inventions and discoveries in the area of low-temperature physics**;
and the other, to be shared equally between Dr **Arno A. Penzias** and Dr **Robert W. Wilson**, Bell Telephone Laboratories, Holmdel, New Jersey, USA, **for their discovery of cosmic microwave background radiation**.

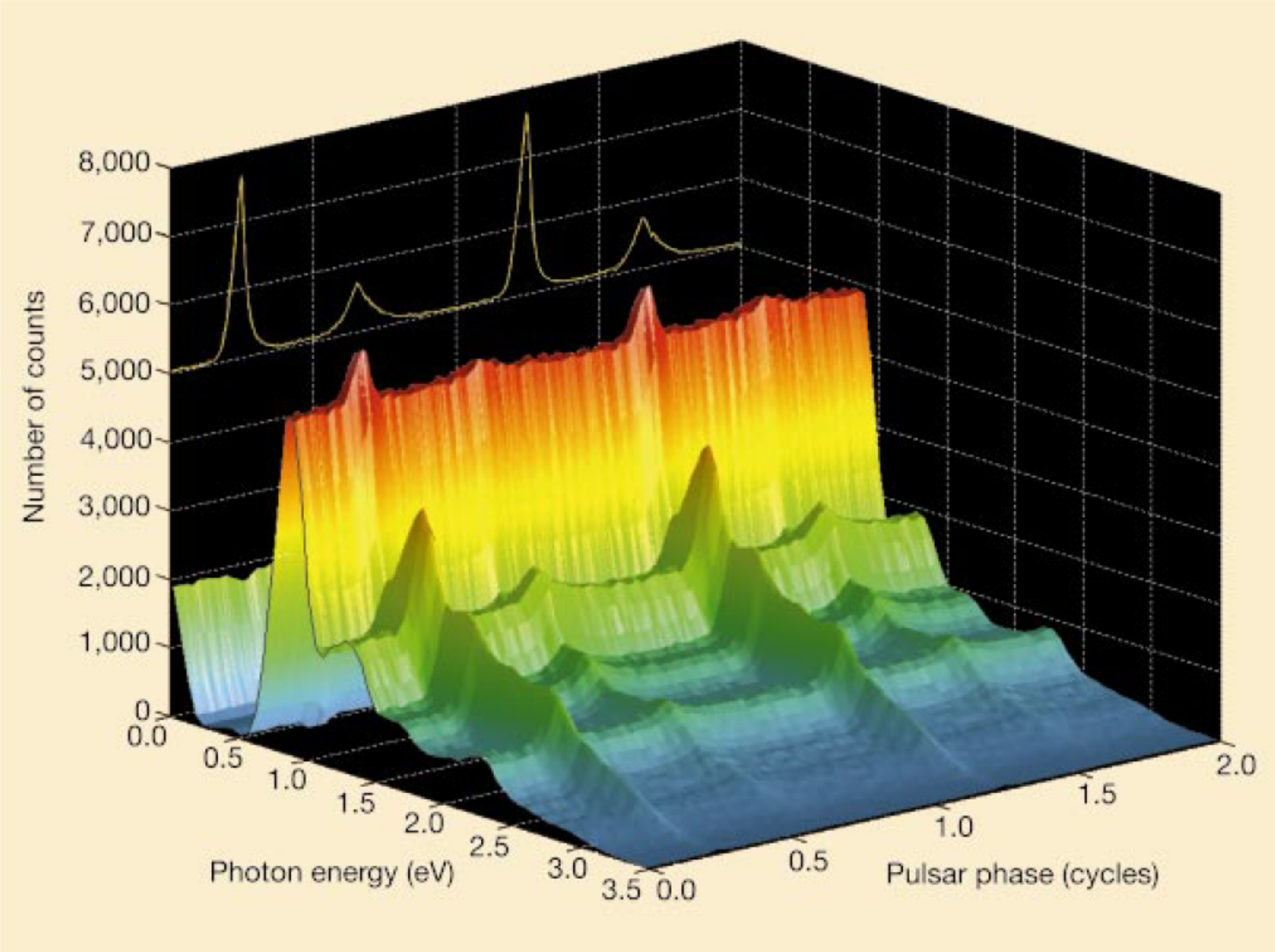


Figure 1 How to catch photons from a spinning pulsar. Time-resolved spectrum of the Crab nebula pulsar recorded by Romani *et al.*[1] using a superconducting microcalorimeter. An arriving photon heats the electrons in the superconductor, which is cooled just below its superconducting transition, thereby producing measurable changes in the superconducting current. (Reproduced from ref. 9.)

Superconducting detectors: panorama I

From mm-waves to X-rays, with almost continuous frequency coverage, cryogenic superconducting detectors have been proposed to explore Cosmic Microwave Background, the earliest galaxies and their evolution, rapidly varying optical sources, compact objects. And, looking at particles, superconducting detectors have been proposed to explore rare nuclear phenomena (related to neutrino physics) and to search for Dark Matter.

Superconducting detectors: panorama II

In this discussion we neglect a remarkable application of SC technology to astronomy: that is the realization of microwave/mm-wave/THz down-converters, like HEB and SIS mixers. We just concentrate on (some) direct detectors.

Transition Edge Sensors (TES)

They can be used to make **bolometers** to study the Cosmic Microwave Background
➔From mm-waves to far infrared radiation

Figure by D.Prêle (APC)

Principle of bolometric operation: electromagnetic energy is absorbed and converted into heat. A thermometer coupled to the absorber measures a temperature change. A weak thermal link towards a cold sink (thermal bath) allows to recover the initial equilibrium state.

Transition Edge Sensors (TES)

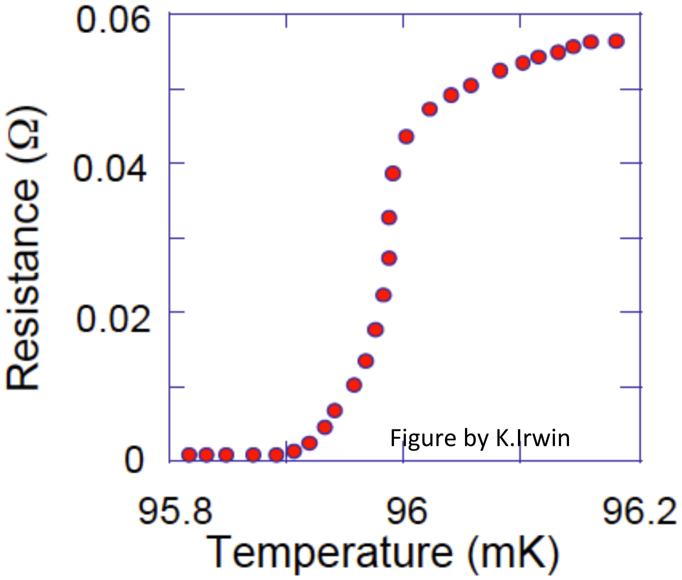


Figure by K.Irwin

Under voltage bias, since R=R(T), the current changes when temperature changes. <u>This current change is measured by an ammeter</u>. To be operated in condition of maximum stability and sensitivity, TES must be used within a negative **electro-thermal** feedback loop (Irwin, 1995).

Heat input:

R_{TES} ↑ $\delta R_{TES}>0$
Current ↓ $\delta I<0$

$$\delta P_{bias} = -\frac{V_{bias}^2}{R_{TES}^2}\frac{dR_{TES}}{dT}\delta T$$

N.B.: radiation can be optically coupled to the absorber. Otherwise, the absorber might be a matched load at the end of antenna terminals

Transition Edge Sensors (TES)

X-ray microcalorimeters

Non-dispersive spectrometer

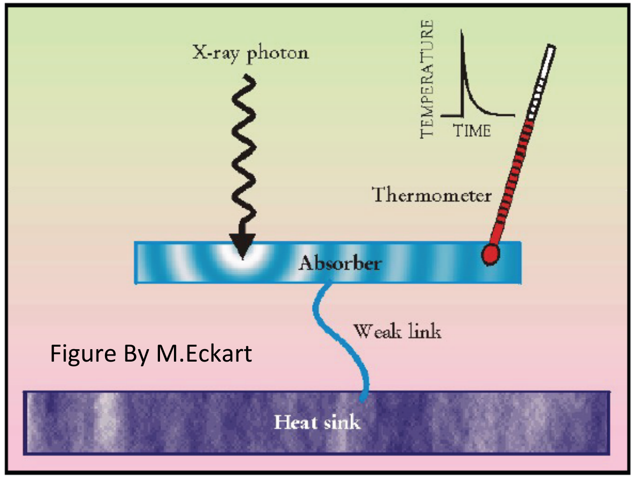
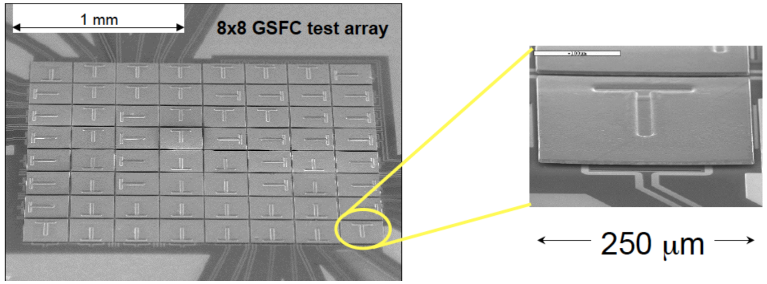


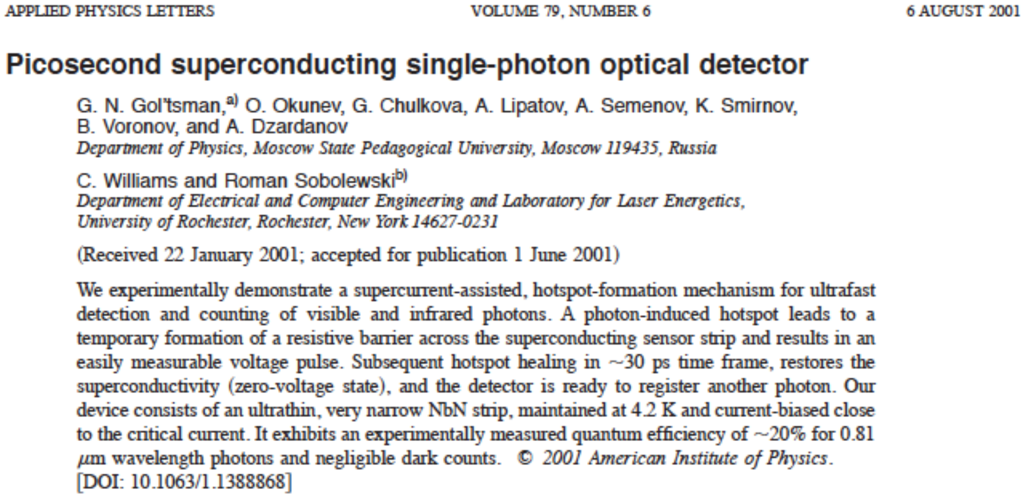
Figure By M.Eckart

Thermal detection of individual X-ray photons



Proposed for the Astro-H spectrometer. To be operated at ~50 mK. Kilopixel array. With resolution R~1000 (or better!).

Superconducting Single-Photon Detectors (SSPD)



APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 6 6 AUGUST 2001

Picosecond superconducting single-photon optical detector

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(Received 22 January 2001; accepted for publication 1 June 2001)

We experimentally demonstrate a supercurrent-assisted, hotspot-formation mechanism for ultrafast detection and counting of visible and infrared photons. A photon-induced hotspot leads to a temporary formation of a resistive barrier across the superconducting sensor strip and results in an easily measurable voltage pulse. Subsequent hotspot healing in ~30 ps time frame, restores the superconductivity (zero-voltage state), and the detector is ready to register another photon. Our device consists of an ultrathin, very narrow NbN strip, maintained at 4.2 K and current-biased close to the critical current. It exhibits an experimentally measured quantum efficiency of ~20% for 0.81 μm wavelength photons and negligible dark counts. © *2001 American Institute of Physics*. [DOI: 10.1063/1.1388868]

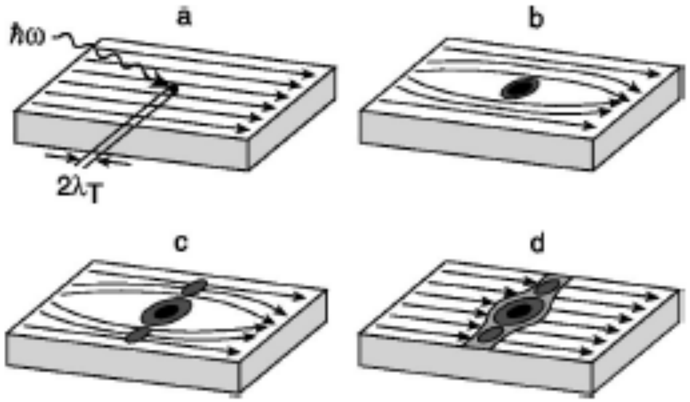


FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

Current biased SC nanowires can be used as photon counters from IR to Optical.
Not yet observing the sky, but see Feautrier et al. EUCAS 2007 for potential space applications

Superconducting Tunnel Junctions (STJ)

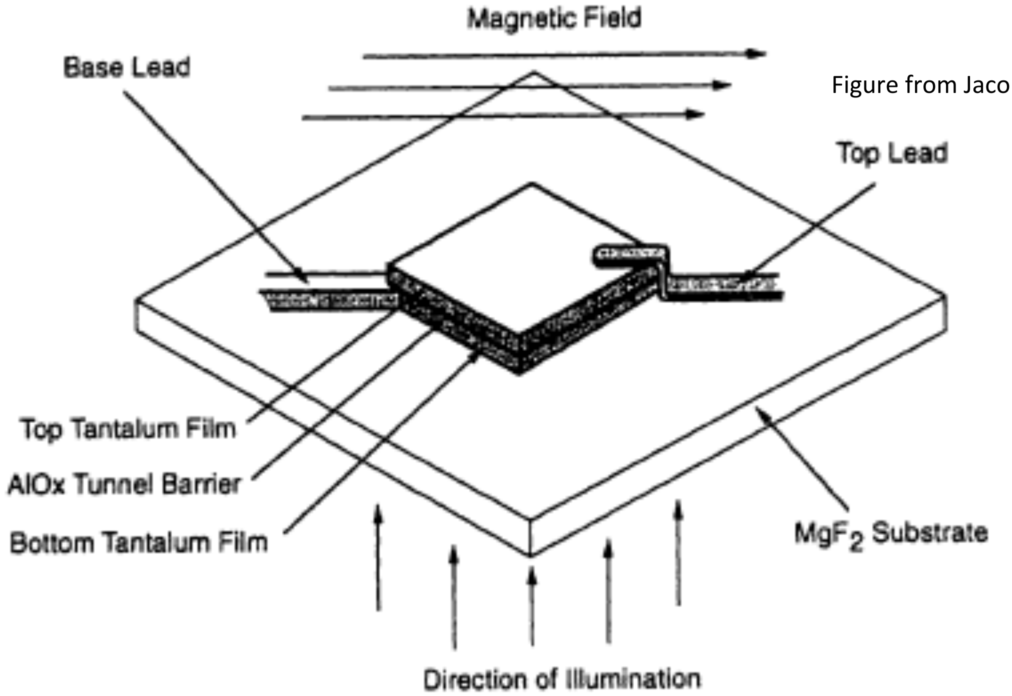


Figure from Jacobsen ASPC 1999

Reference: A.Peacock et al. Single opticalal photon detection with a superconducting tunnel junction, Nature 1996

A photon hits an electrode of the junction. Quasi-particles are generated. A small bias voltage assists their tunneling across the junction. The charge pulse is finally extracted from the device (proportionality between charge and photon energy). Optical, UV.

Microwave Kinetic Inductance Detectors (MKIDs)

P.Day et al. Nature 2003

Cooper pairs can store kinetic energy → kinetic inductance L_k

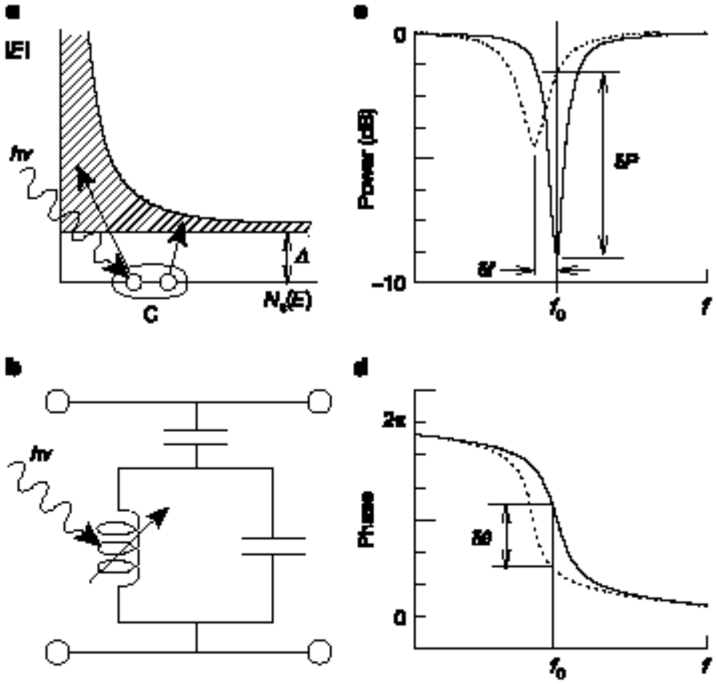
Therefore, a superconducting LC circuit has a resonant frequency $1/\sqrt{C(L_m+L_k)}$

A photon hitting the resonator breaks Cooper pairs → change in L_k & onset of ohmic losses

1. Shift in the resonance frequency (lowering) 2. Degradation of the quality factor

MKIDs

Another Cooper-pair breaking detector! $N_{qp} = \eta h\nu / \Delta$

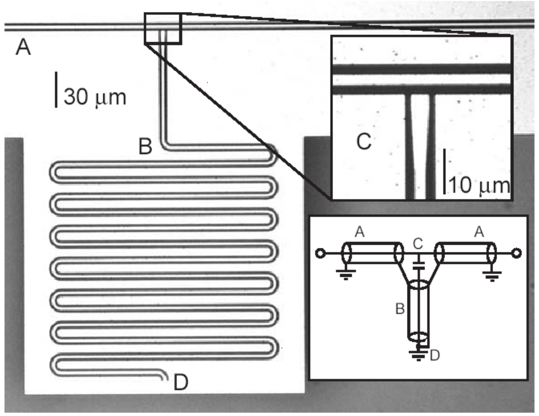


P.Day et al. Nature 2003

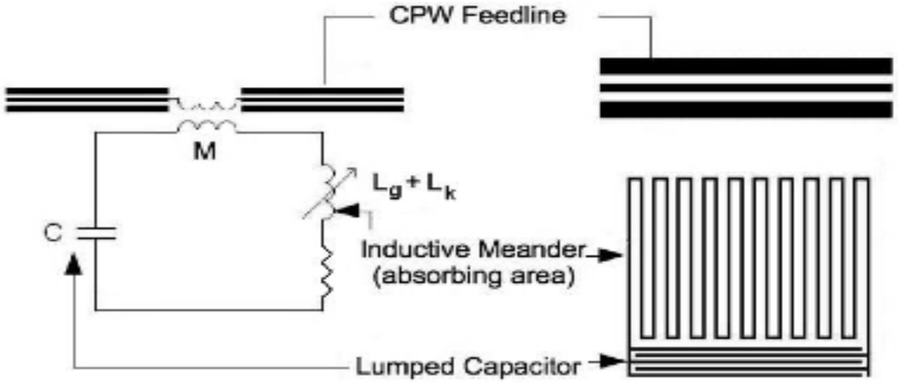
MKIDs

Making a superconducting LC resonator

Short-circuit λ/4 line (Mazin)



Lumped element (Doyle)

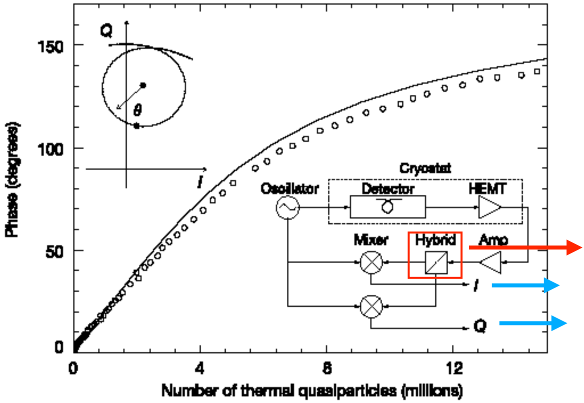


MKIDs: readout

Intrinsically frequency multiplexed readout

$$V(t) = \sqrt{I^2 + Q^2}$$

$$\theta(t) = atan(Q/I)$$



$\pi/2$, 3dB

In-phase

Quadrature

B.Mazin et al., NIM A, **559**, 2006

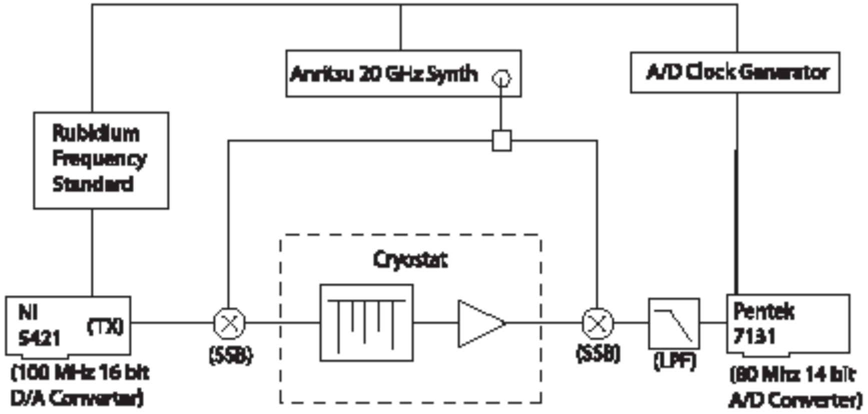
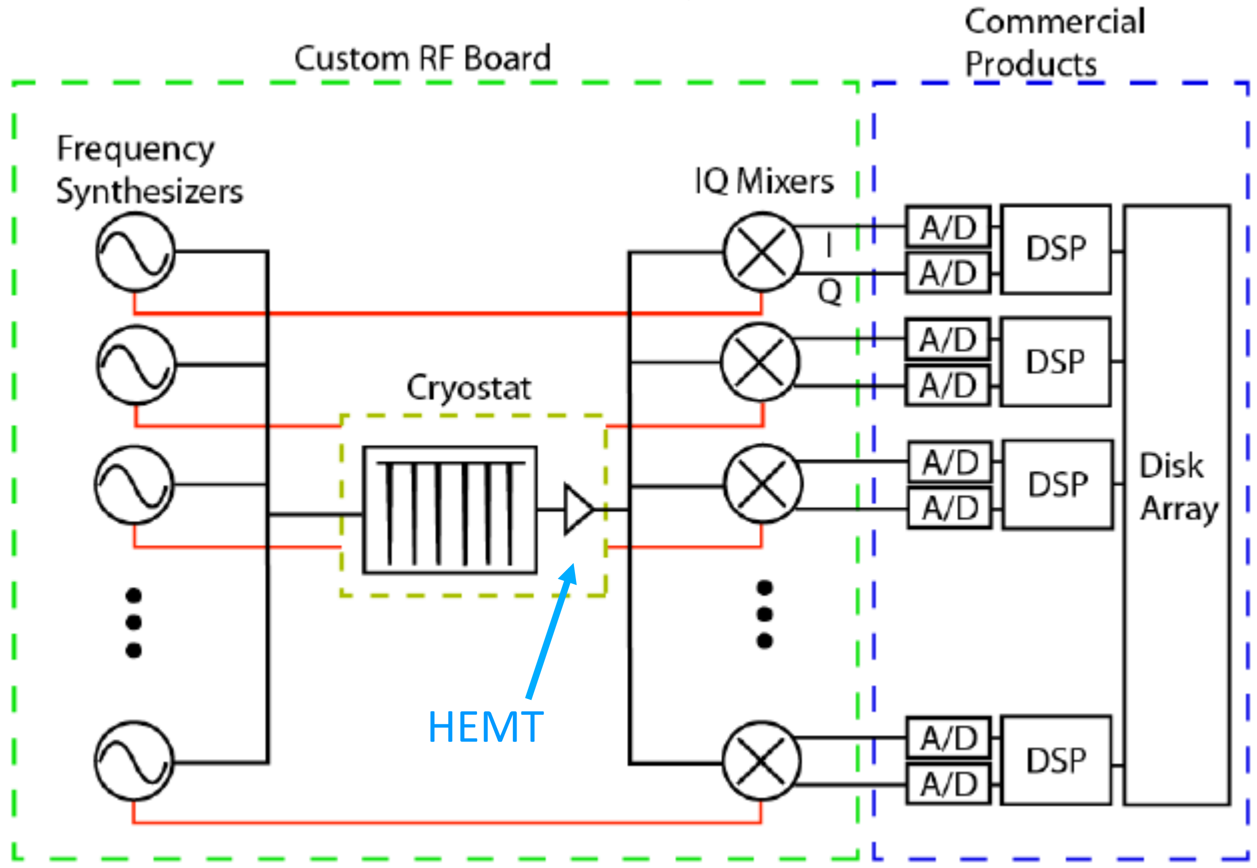


Fig. 1. The physical hardware of the software radio readout used for data acquisition in this paper.

MKIDs: Multiplexing (Mazin thesis)



N resonators amplified by 1 low noise amplifier

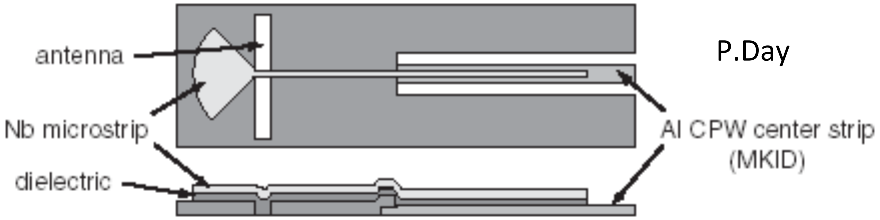
How big N?

1. Ideal limit ⟶ $N \approx Q(T, \varepsilon''_{diel}, \ldots) \bullet \Delta\nu_{hemt} / \nu_0$
2. Thechnological limit ⟶ $\delta L = .2\ \mu\mathrm{m}$ ⟶ 250 kHz

MKIDs

Coupling mm-wave photons to the resonator

1. Anntennas



P.Day

2. Lumped element pixel matched to free space impedance at 377 Ω

Noadays impressive degree of maturity of MKIDs for mm and sub-mm wave Astronomy (NIKA, SuperSpec, MUSIC). Moreover, look at ARCONS camera for Optical/UV.

http://web.physics.ucsb.edu/~bmazin/Mazin_Lab/Projects/Projects.html

MKIDs for X-rays

B.Mazin, PhD thesis & cond-mat/0610130, 04/10/2006

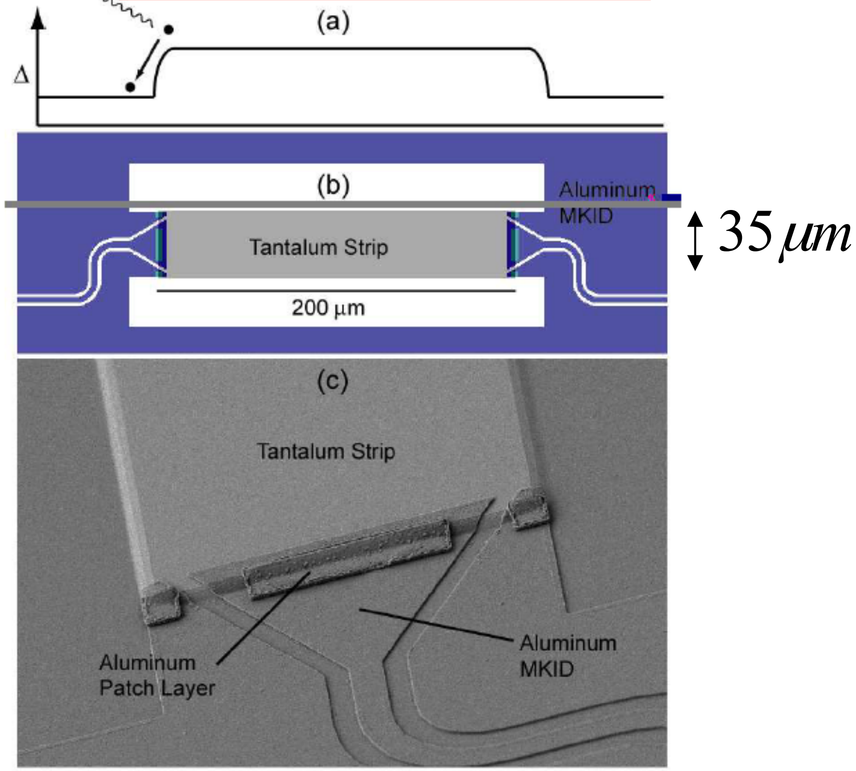
0.1~10keV energy resolved single photon detection at 150 mK and P_{rf}=-73 dbm

Long-strip (Ta) detectors + 2 lateral Al-MKIDs (traps)

$$d\theta/dN_{qp} = 1.63 \times 10^{-7} \alpha Q/V$$

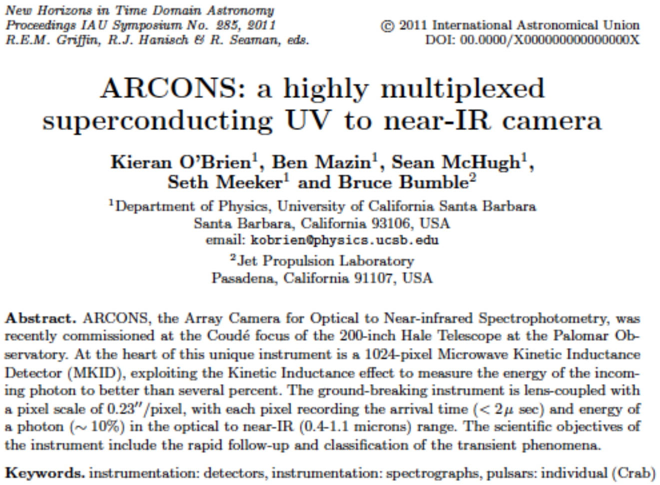
$\Delta_{Ta} = 0.67$ meV

$\Delta_{Al} = 0.18$ meV



QP pulses → phase pulses

MKIDs for IR-Optical



New Horizons in Time Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

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ARCONS: a highly multiplexed superconducting UV to near-IR camera

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Abstract. ARCONS, the Array Camera for Optical to Near-infrared Spectrophotometry, was recently commissioned at the Coudé focus of the 200-inch Hale Telescope at the Palomar Observatory. At the heart of this unique instrument is a 1024-pixel Microwave Kinetic Inductance Detector (MKID), exploiting the Kinetic Inductance effect to measure the energy of the incoming photon to better than several percent. The ground-breaking instrument is lens-coupled with a pixel scale of 0.23″/pixel, with each pixel recording the arrival time ($< 2\mu$ sec) and energy of a photon ($\sim 10\%$) in the optical to near-IR (0.4-1.1 microns) range. The scientific objectives of the instrument include the rapid follow-up and classification of the transient phenomena.

Keywords. instrumentation: detectors, instrumentation: spectrographs, pulsars: individual (Crab)

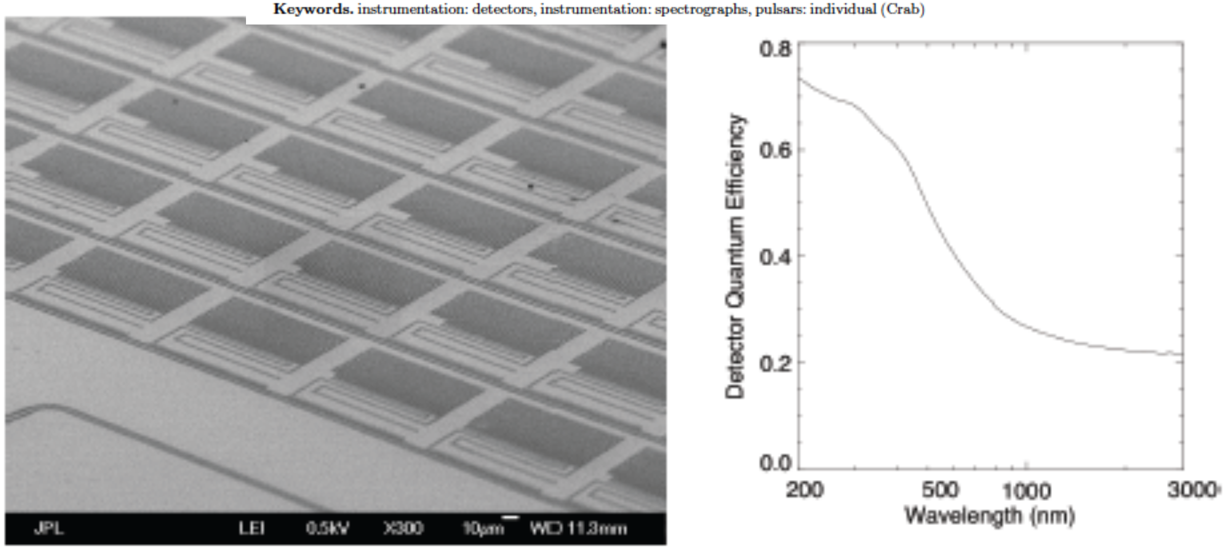

Figure 2. Left, Image of a section of the science array. The individual pixels can been seen to have a slightly different length meandered section in order to tune the resonant frequency, enabling the highly multiplexed read-out. Right, the measured quantum efficiency of the TiN lumped element detector.