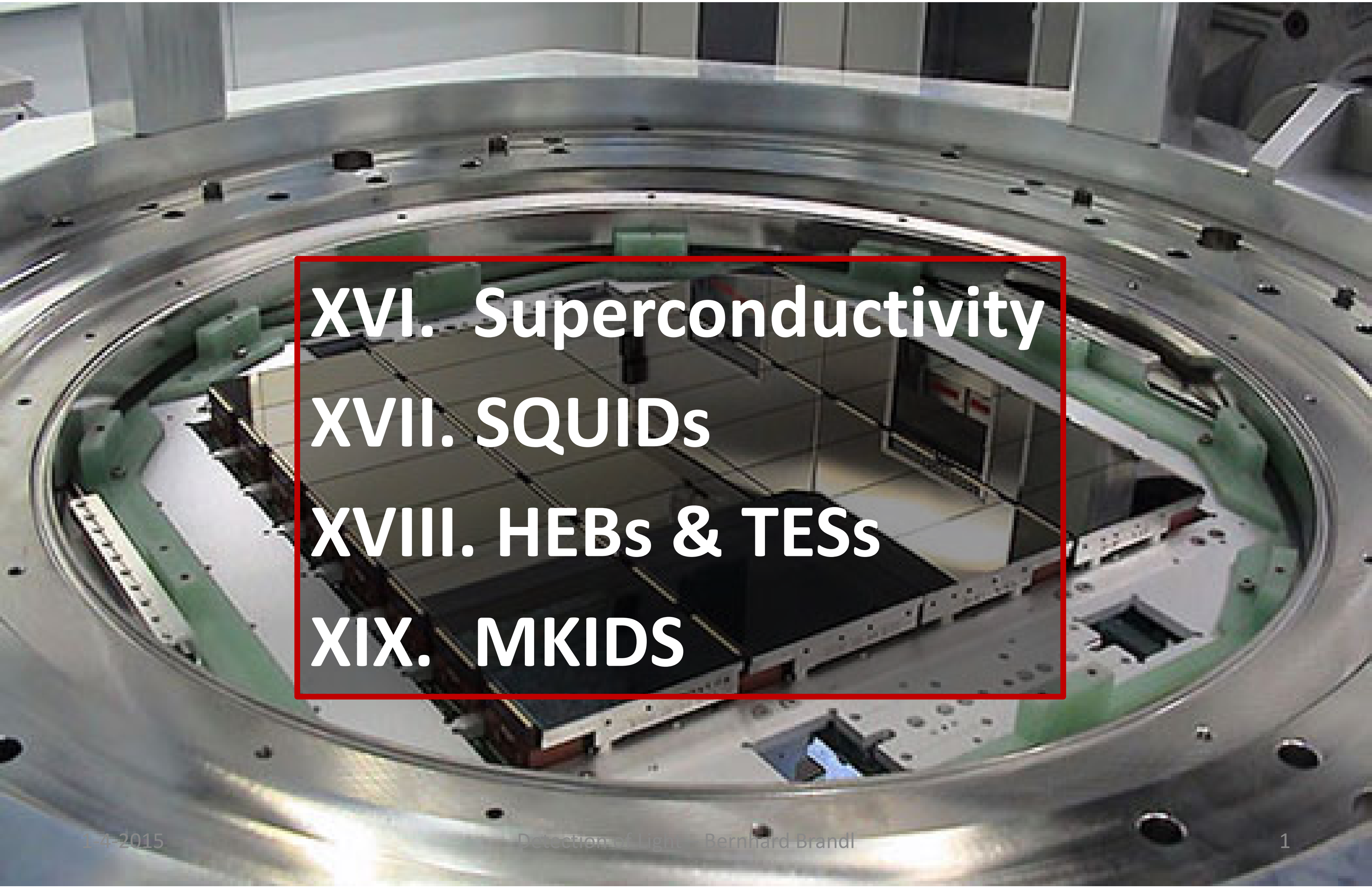
Detection of Light



XVI. Superconductivity

XVII. SQUIDs

XVIII. HEBs & TESs

XIX. MKIDS

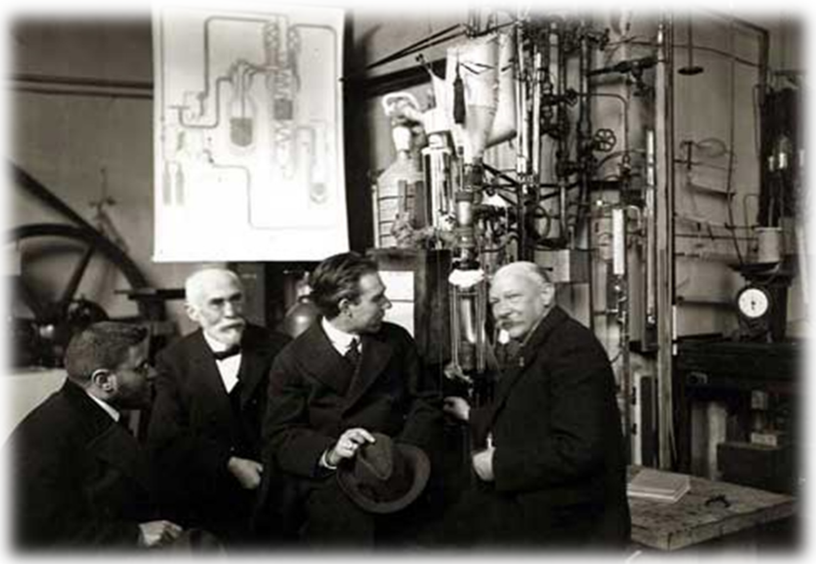
Basics of Superconductivity

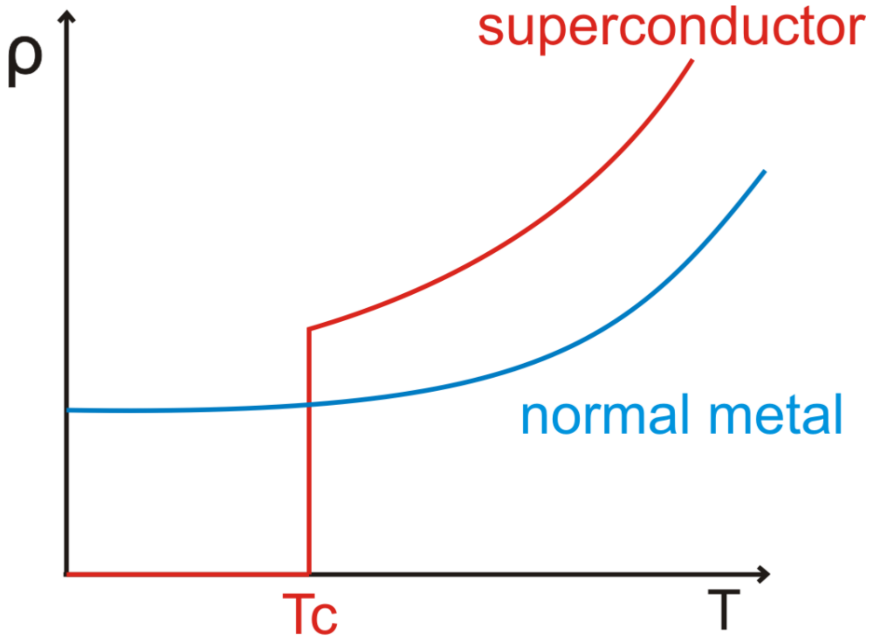
Superconductivity

Wikipedia:

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature.

It was discovered by Dutch physicist Heike Kamerlingh Onnes on April 8, 1911 in Leiden.

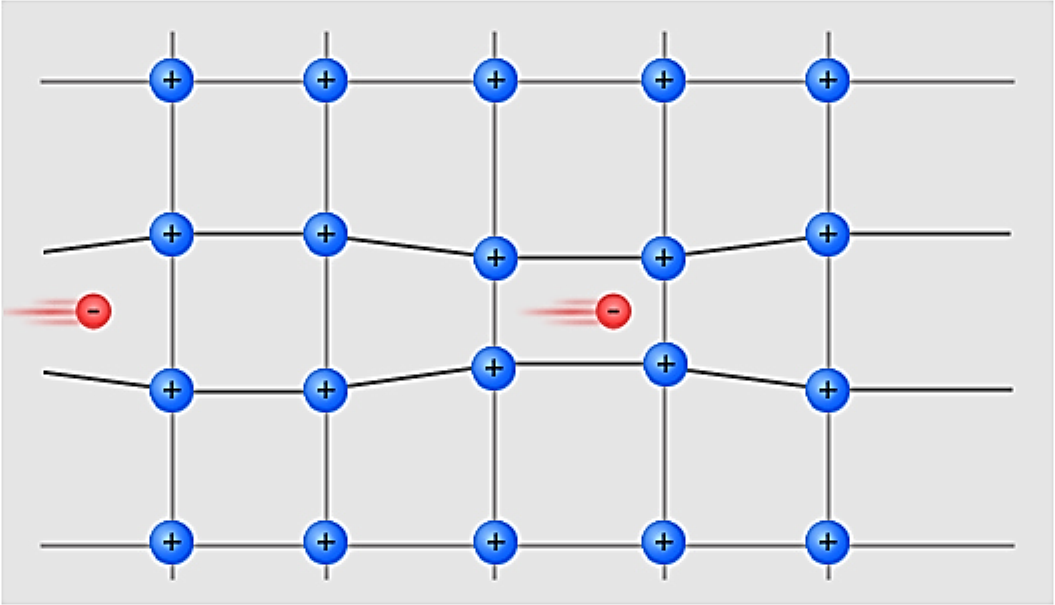




Wikipedia:

Cooper Pairs (1)

a Cooper (or BCS) pair is a pair of electrons bound together at low temperatures in a certain manner. In 1956, Leon Cooper showed that an arbitrarily small attraction between electrons in a metal can cause a paired state of electrons to have a lower energy than the Fermi energy, which implies that the pair is bound.

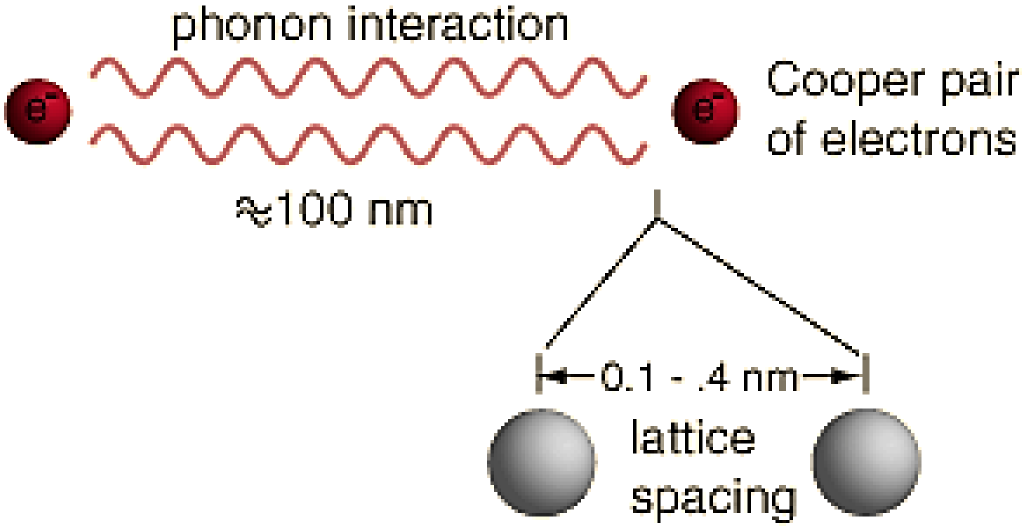


Cooper pairs make super conductors

At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

Cooper Pairs (2)

The energy to break Cooper pairs is very small (← long wavelength detectors?), and their range is many 100 times the lattice spacing.



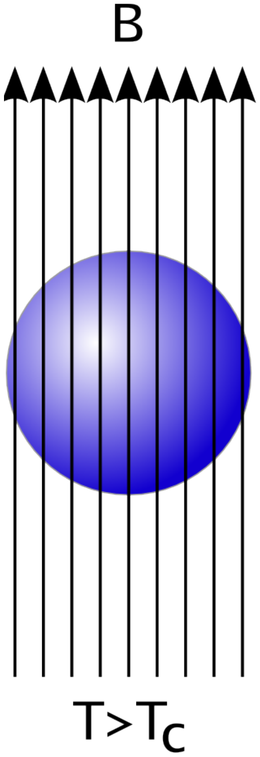
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/coop.html#c4

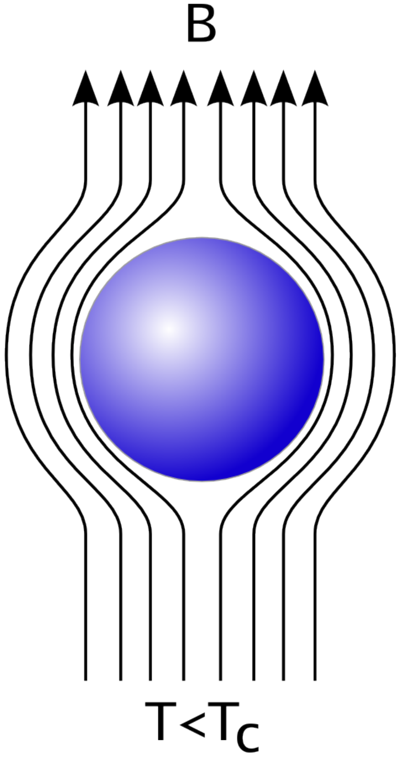
This is classical superconductor theory, called BCS theory. It does not explain high T_C superconductors.

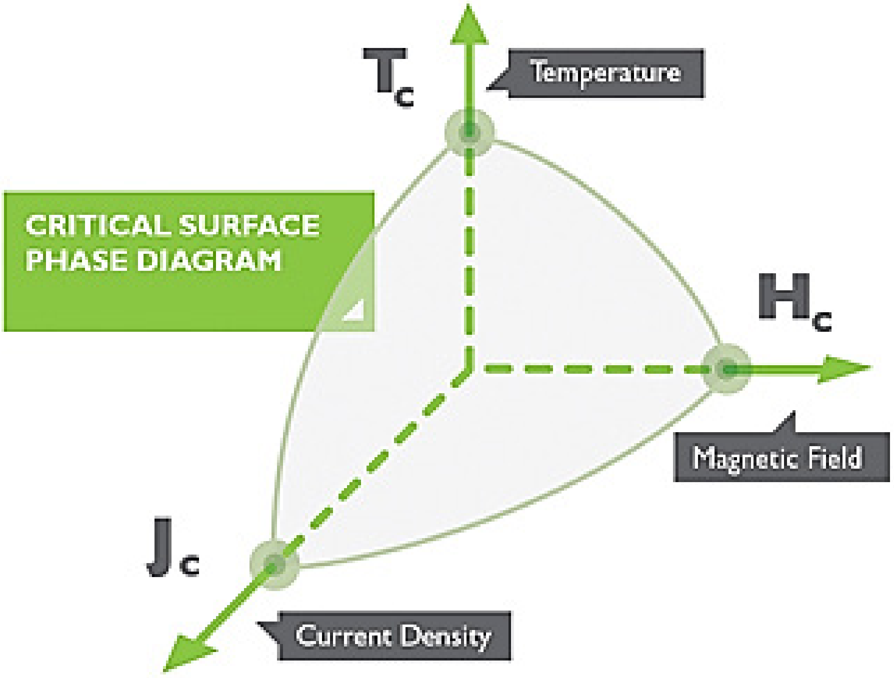
Magnetic Fields

Wikipedia:

In 1933 Meissner and Ochsenfeld discovered that when a superconductor is placed in a weak external magnetic field *H*, and cooled below T_C the magnetic field is ejected. (Actually, the Meissner effect does not cause the field to be completely ejected but instead the field penetrates the superconductor but only to a very small distance.)



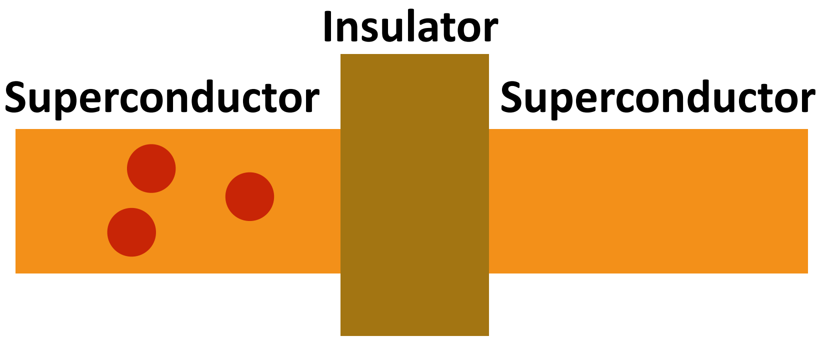




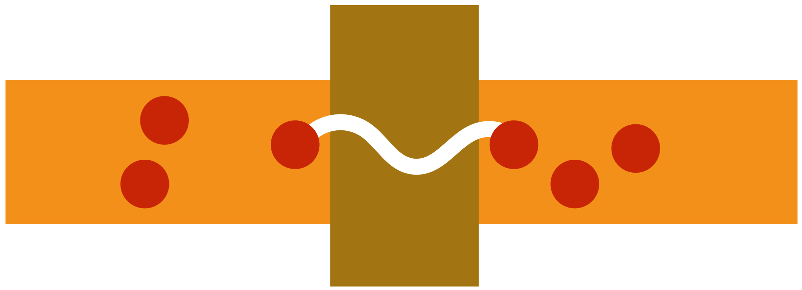
SIS Junctions and SQUIDS

Josephson Junctions

Consider the following junction:



Cooper pair wave functions can extend across the insulator:

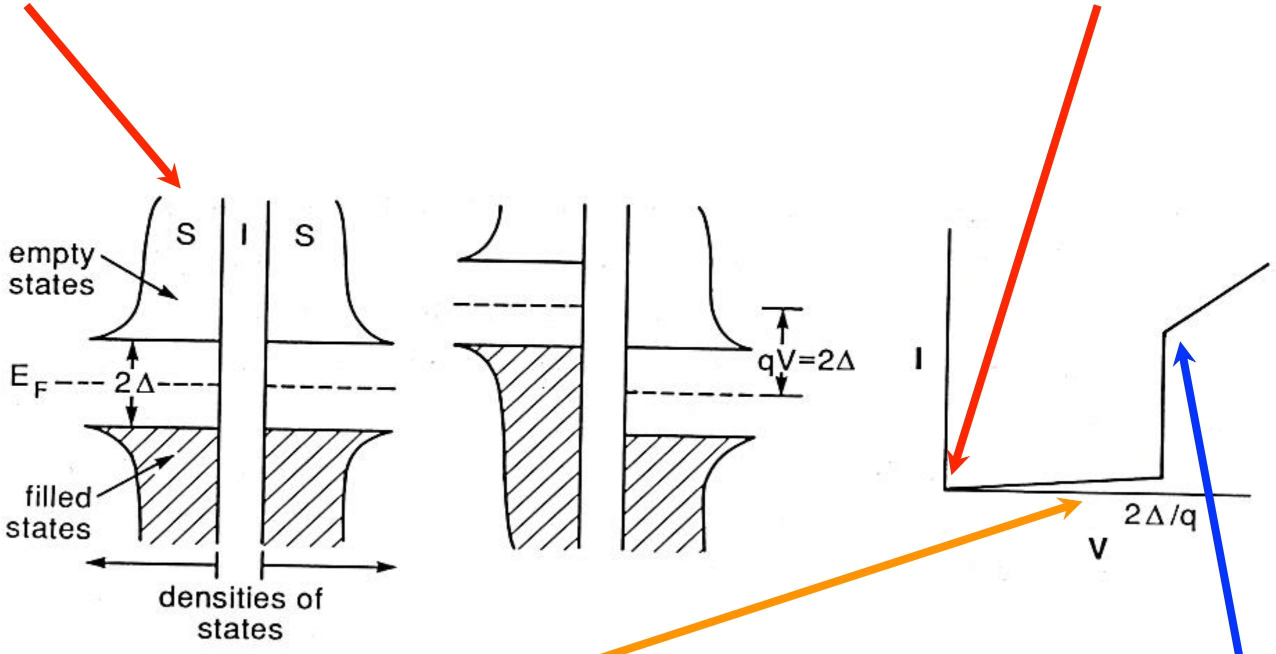


With bias voltage applied, they tunnel across the junction. The insulator must be thinner than the tunneling distance of a Cooper pair.

Biased SIS Junctions

Superconductor – Insulator – Superconductor (SIS):

NO VOLTAGE: Cooper pairs can flow and carry small currents (Josephson effect)



SMALL VOLTAGE: Energy states shifted, but insulator still blocks normal currents.

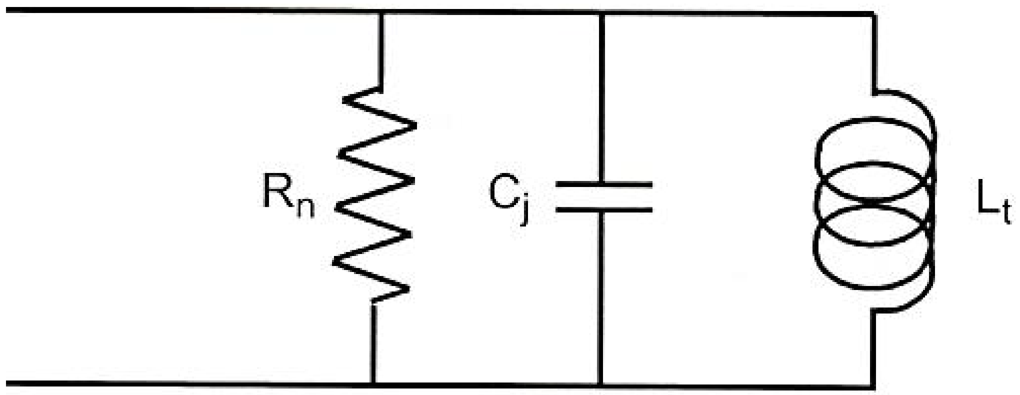
LARGER VOLTAGE: Voltage just exceeds the energy gap and you get *nonlinear* behaviour.

Problem of high Capacitance

SIS junctions typically have 10 times higher capacitance than Schottky diodes.

→ Cancel out the capacitance with an inductance

This inductance is provided with a superconducting stripline



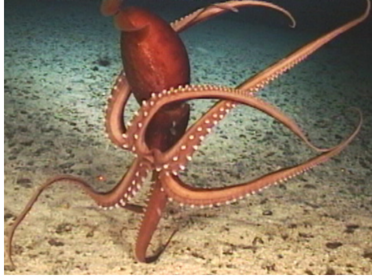
Schematics:

R_n = normal mixer resistance

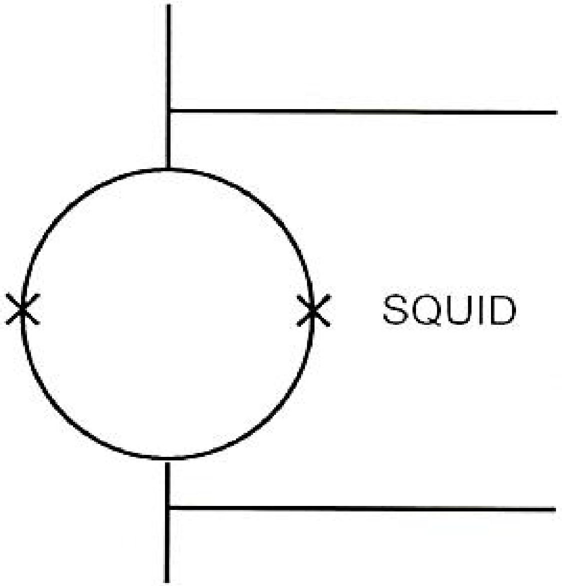
C_j = junction capacitance

L_t = stripline tuning inductance

SQUIDs (1)



Superconducting QUantum Interference Devices (SQUIDs) are based on the Josephson effect.



In SQUIDs two Josephson junctions are connected in a loop.

The output voltage of a biased SQUID is:

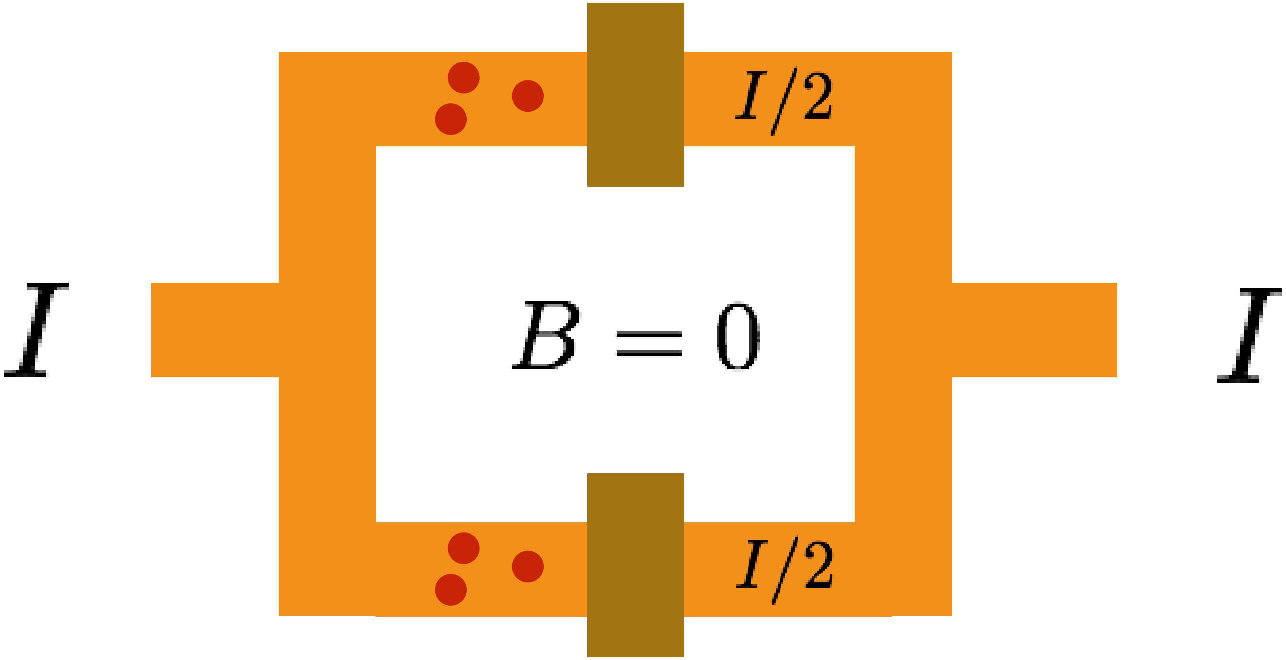
$$V = \frac{R}{2}(I^2 - [2I_0 \cos(\pi\phi/\phi_0)]^2)^{1/2}$$

where *R* is the resistance of the junctions, *Φ* is the magnetic flux, and I_0 the maximum current through the junctions at zero voltage.

If the SQUID is biased close to $2I_0$, very small changes in *I* can be detected at the SQUID output. It acts as a low input impedance amplifier.

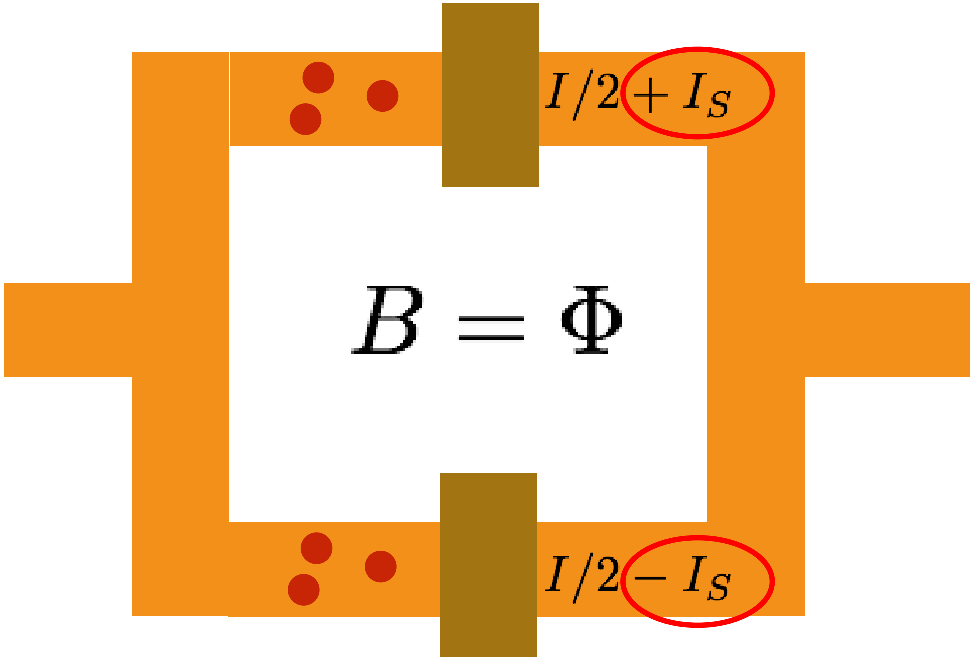
SQUIDs (2)

Two Josephson junctions in parallel with a current flowing through them. Current is split evenly between them.



SQUIDs (3)

A SQUID is essentially a very, very sensitive magnetometer: A magnetic field passing through the hole will generate an opposite circulating current.

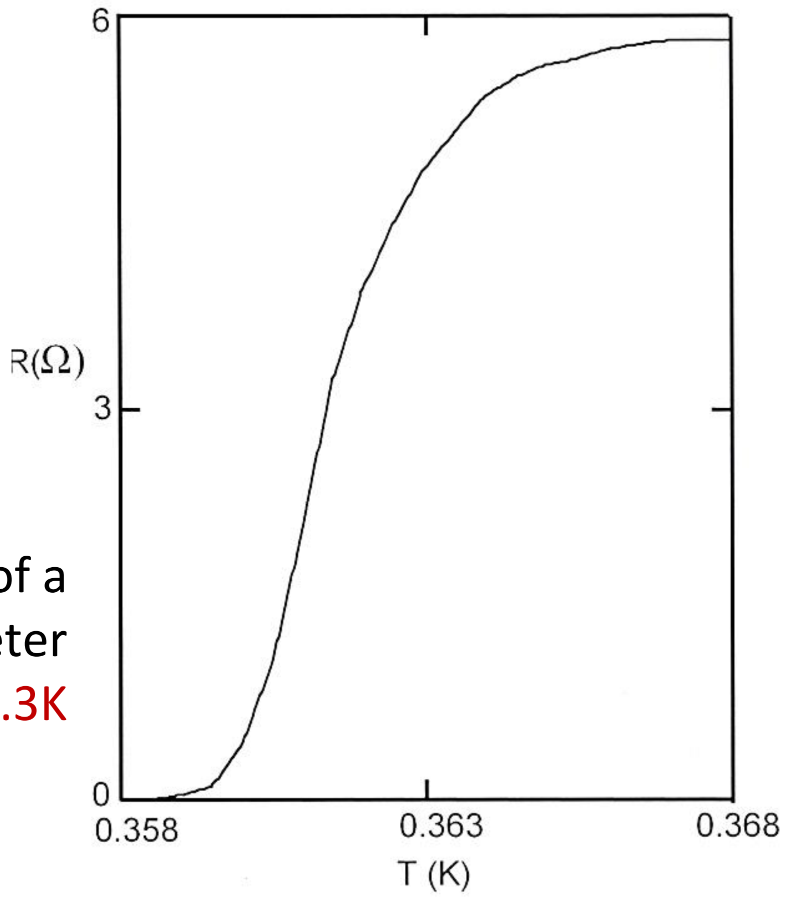


Superconducting and Hot Electron Bolometers

Superconducting Bolometers

Superconducting films are suitable as bolometers.

The steep gradient in $R = f\{T\}$ around T_C makes them very sensitive devices.



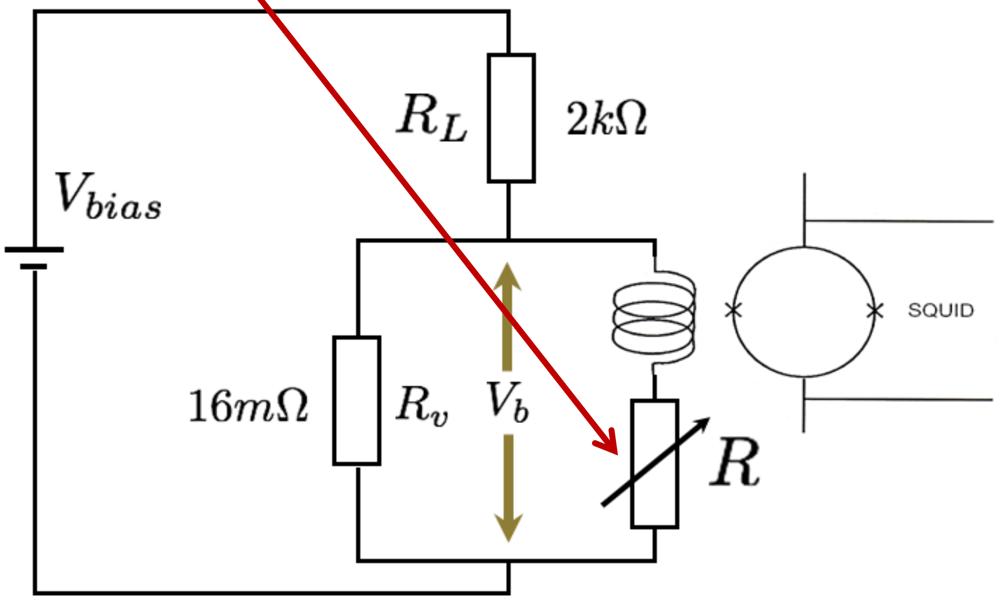
Resistance of a superconducting bolometer with a heat sink at 0.3K

Superconducting bolometers can be much faster than semiconducting bolometers.

Transition Edge Sensors

A transition edge sensor (TES) is based on the strongly temperature-dependent resistance of the superconducting phase transition.

Detected photons heat up the SIS → current pulse goes through an inductor → generates magnetic field → sensed by SQUID.



- TES require one SQUID per pixel.
- TES are fiddly and tricky to manufacture and operate.
- TES are very difficult to multiplex in the 1000's.

Hot Electron Bolometers

Bolometers for sub-mm/mm wavelengths can use highly doped (n-type) InSb:

- Impurity levels ~ conduction band → 0.001 eV sufficient to create free electrons leading to a sea of free electrons.
- Incident photons are absorbed by the free electrons so absorption raises their energies above thermal equilibrium: "hot electrons".
- Lattice interaction is weak → de-excitation takes long time.
- Hot electrons significantly affect the mobility (and thus the conductivity) so measuring the resistance means monitoring the photon signal.

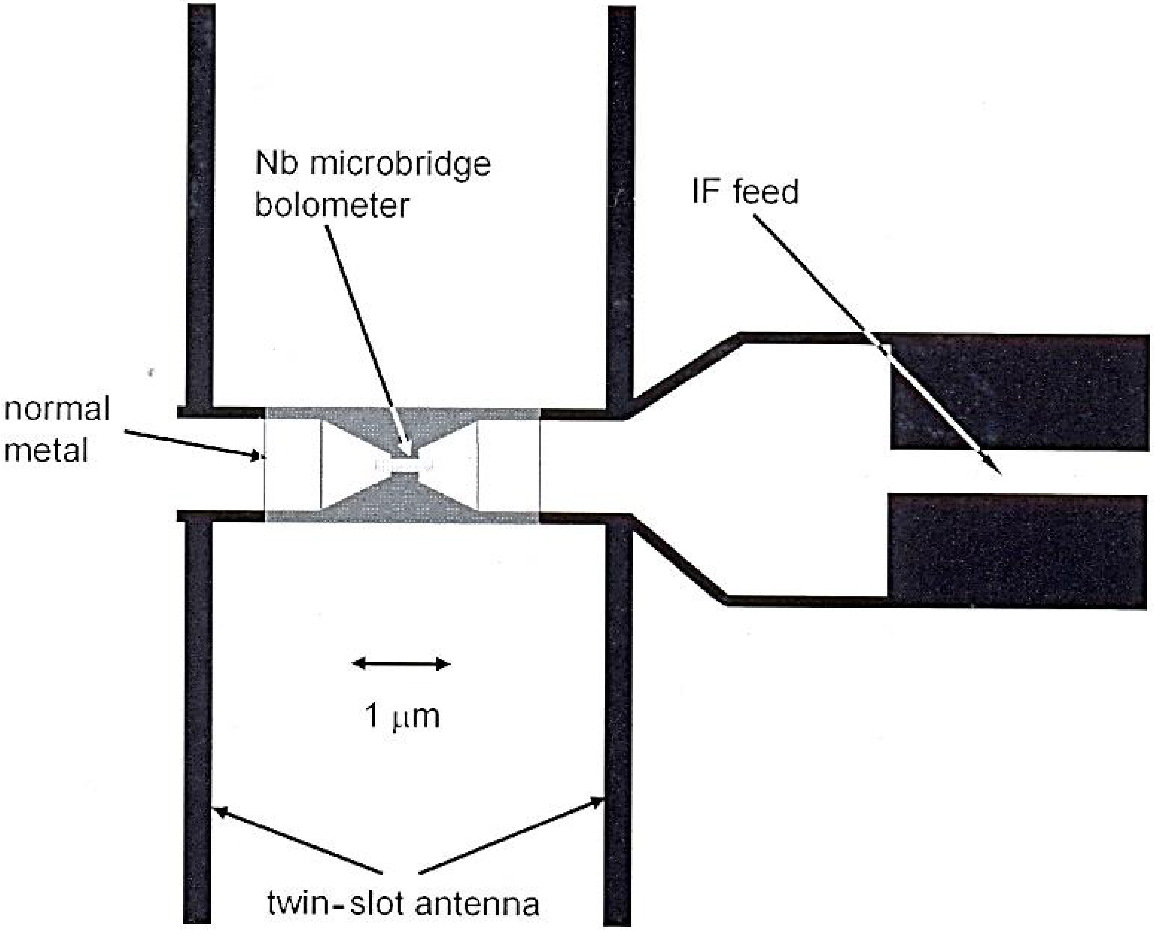
Example: thermal conductance $G = 5\times10^{-5}$ W/K
typical $n \sim 5\times10^{13}$ cm^{-3}
typical $\tau \sim 2\times10^{-7}$ s fast!
typical NEP ~ 2×10^{-13} W (Hz)$^{-1/2}$ low!

Superconducting Hot Electron Bolometers

The best of both HEB and superconductivity!

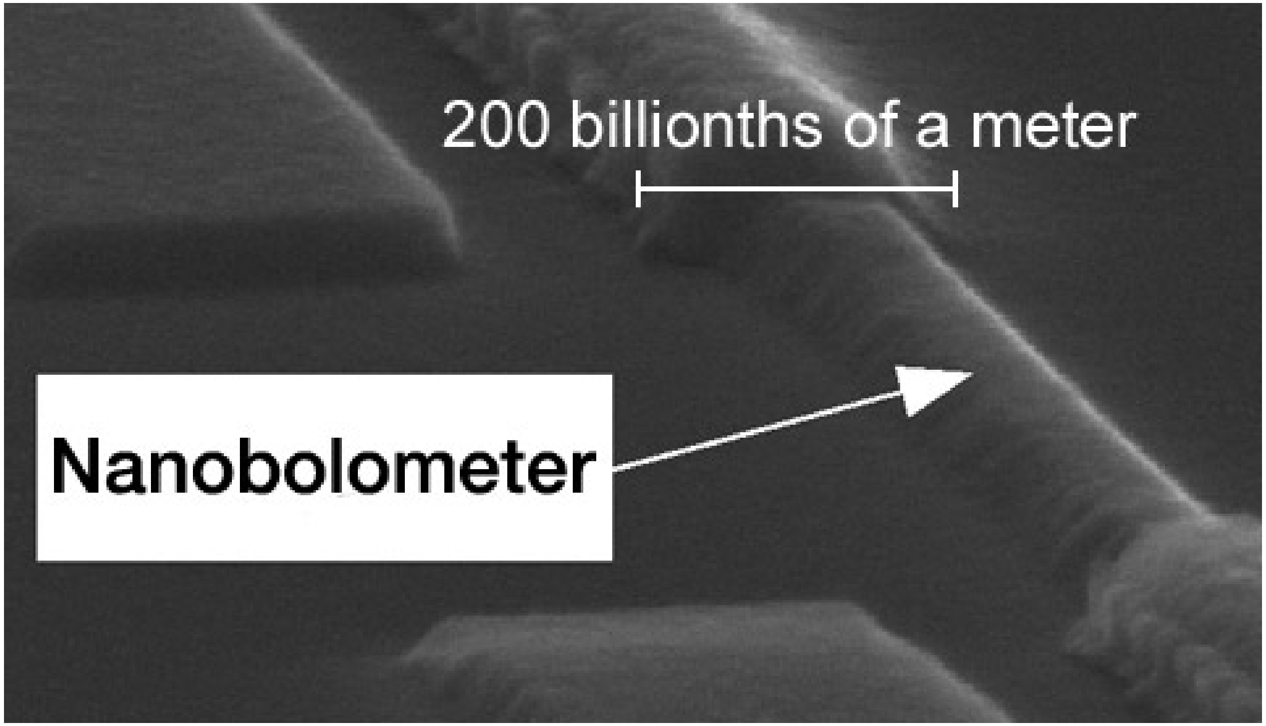
Make them small, so its a microbolometer.

Superconducting thin film HEB extend to higher frequencies!



Hot Electron Nano-Bolometers

Titanium and Niobium metals, about 500nm long and 100nm wide at 0.1K



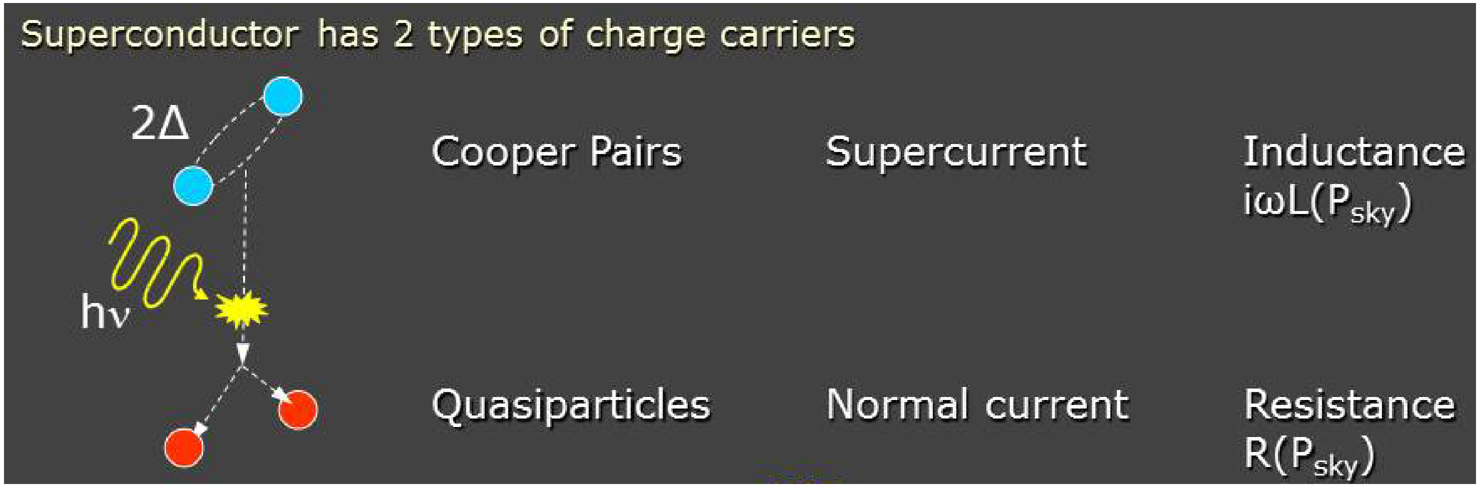
Photons heat the electrons in the Ti section, which is thermally isolated by superconducting Nb leads.

These devices can detect as little as a *single* photon of FIR light!

Microwave Kinetic Inductance Detectors (MKIDs)

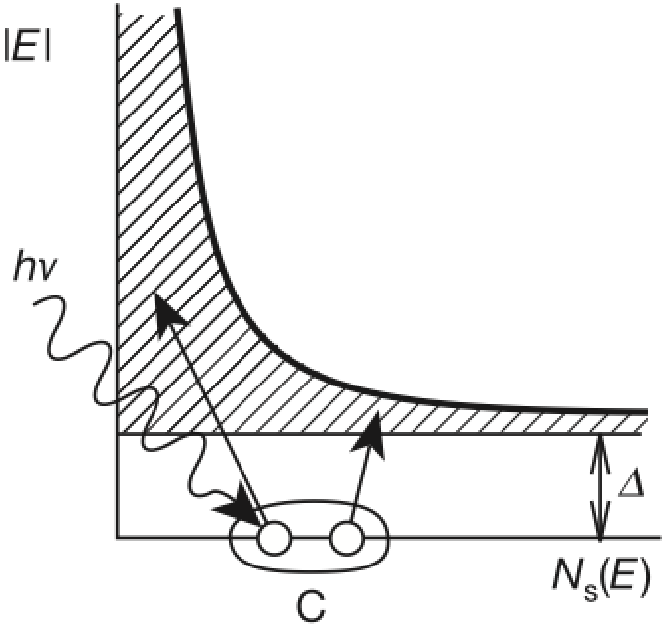
Detection Principle of MKIDs

Detected photons split Cooper pairs and create quasiparticles



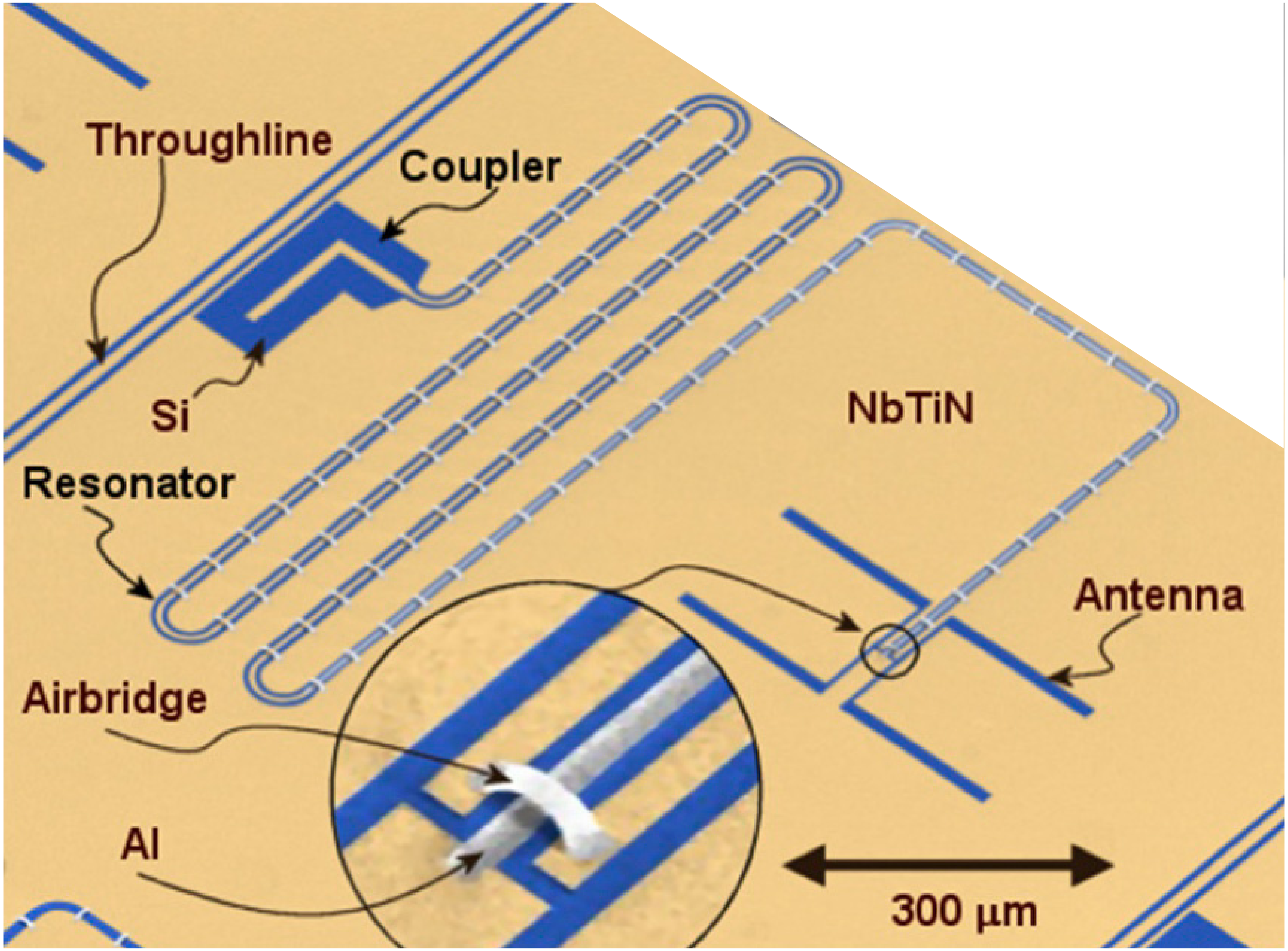
Superconductor has 2 types of charge carriers

Cooper Pairs	Supercurrent	Inductance $i\omega L(P_{sky})$
Quasiparticles	Normal current	Resistance $R(P_{sky})$



Credit: Jochem Baselmans (SRON/TUD)

Outline of one “Pixel”

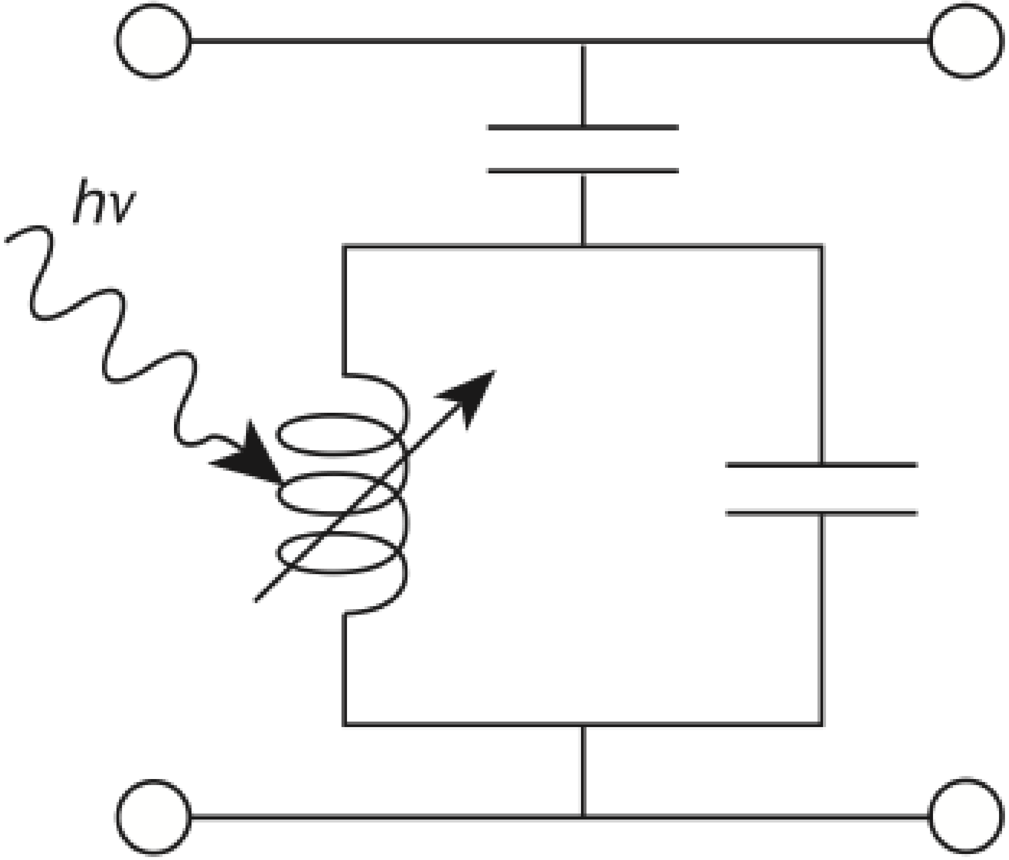


Credit: Jochem Baselmans (SRON/TUD)

Direct antenna coupled KID made from NbTiN (ground plane, resonator) and Al as radiation sensing element. This device works from 80 GHz to 1.2 THz.

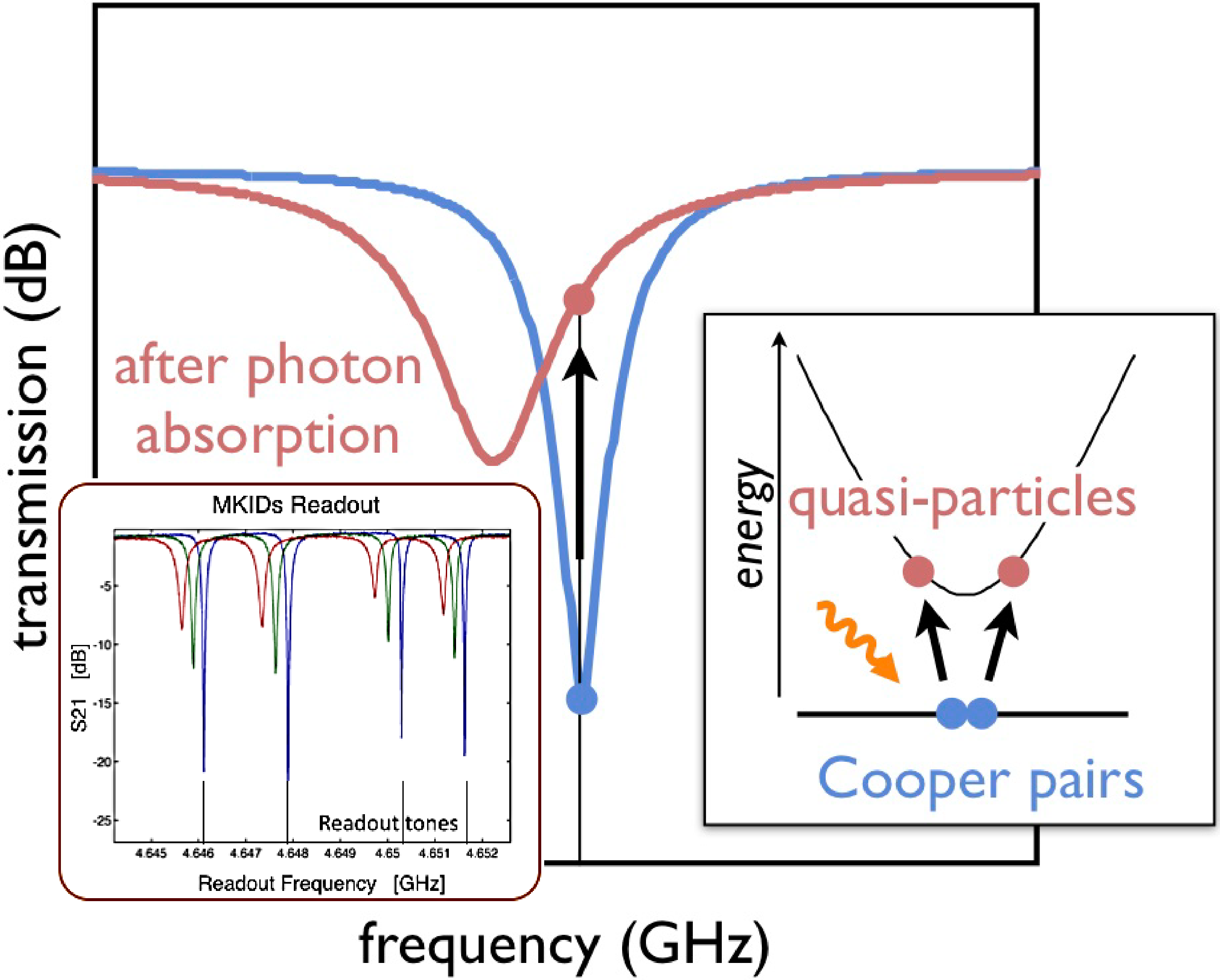
Readout Principle of MKIDs (1)

A resonator measures changes in the complex surface impedance ("kinetic inductance") due to quasiparticles.



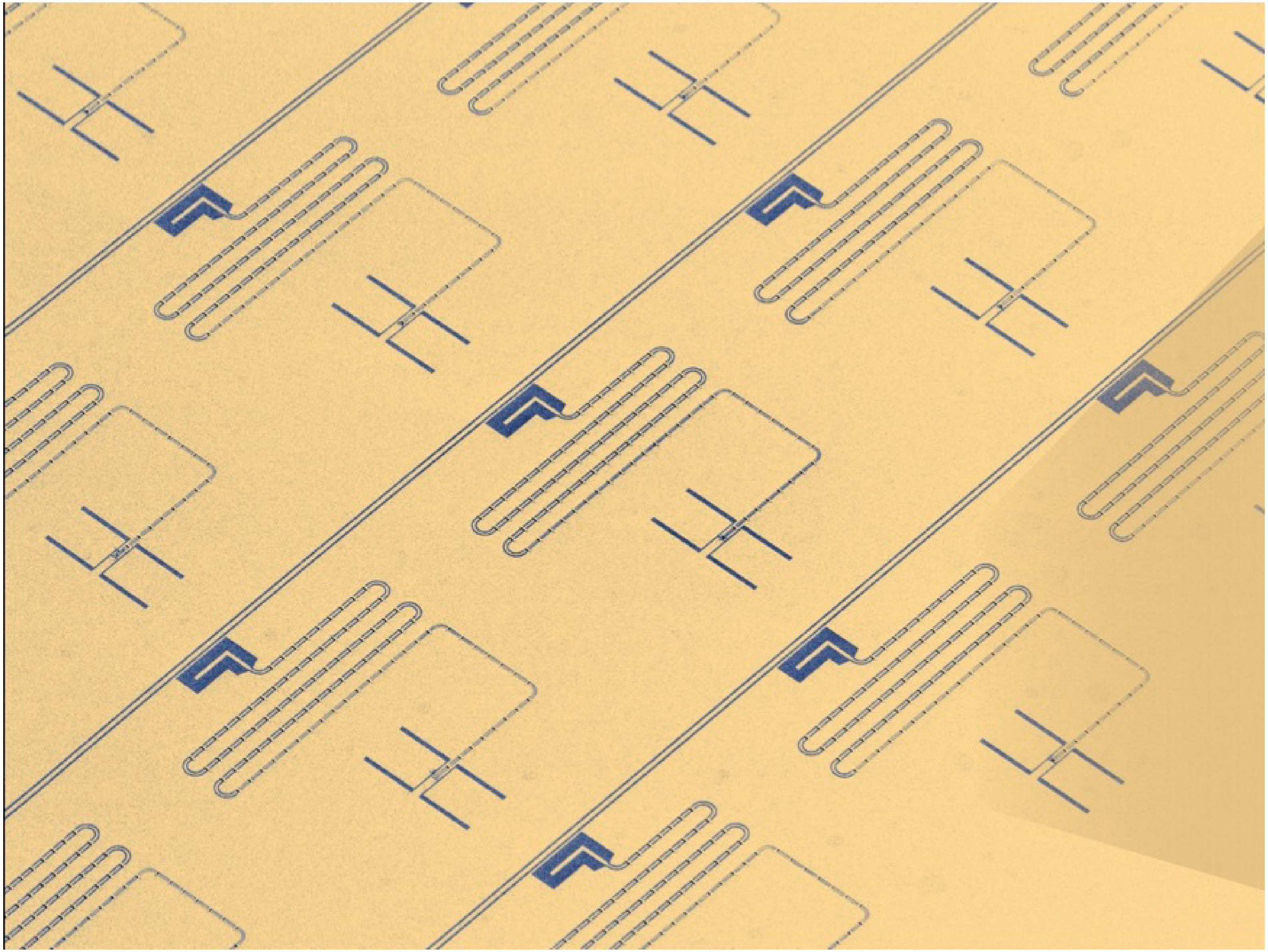
Readout Principle of MKIDs (2)

Change in tuned circuit is detectable with microwave line



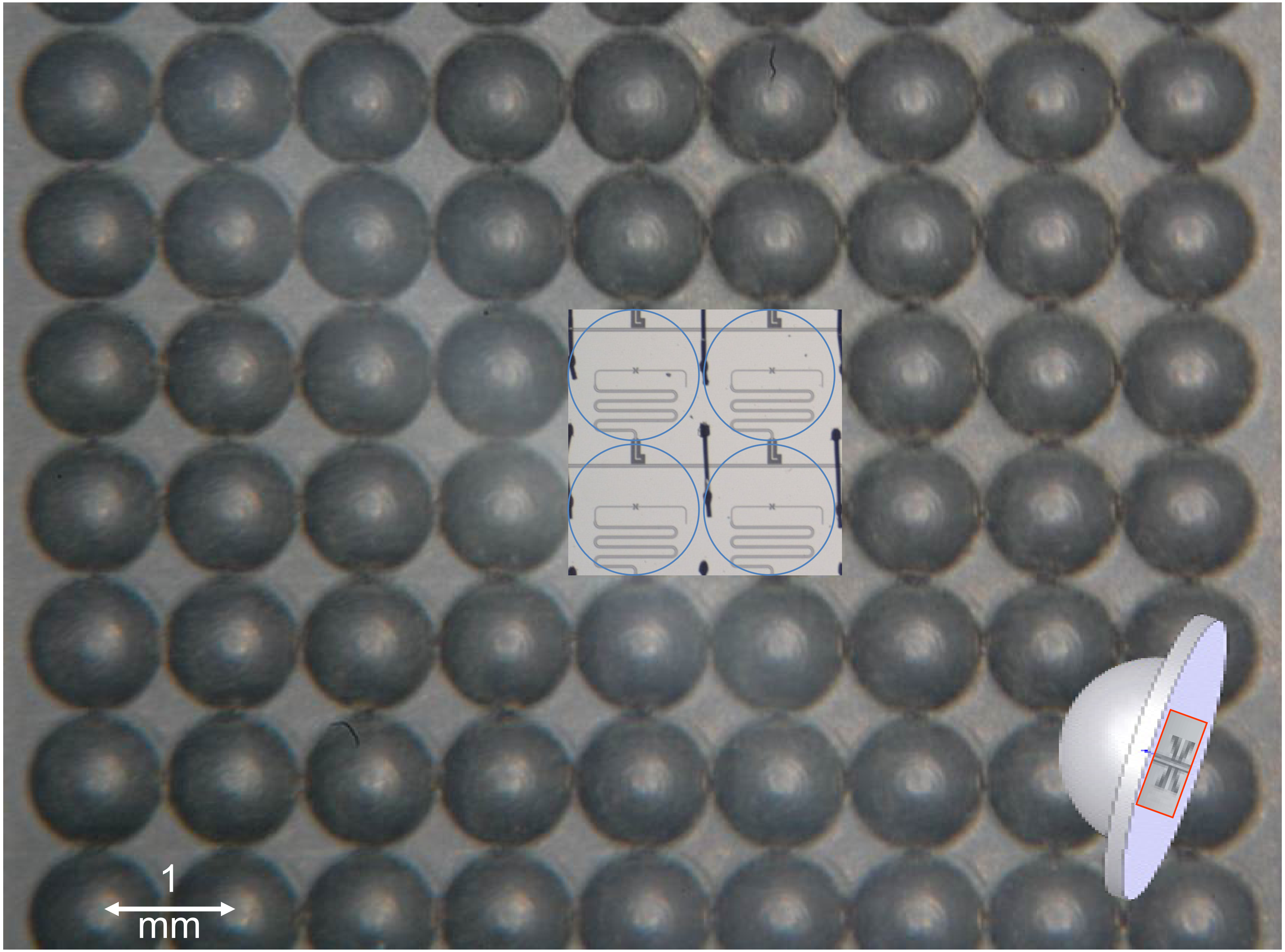
Credit: Jochem Baselmans (SRON/TUD)

“Easy” Multiplexing → MKID Arrays



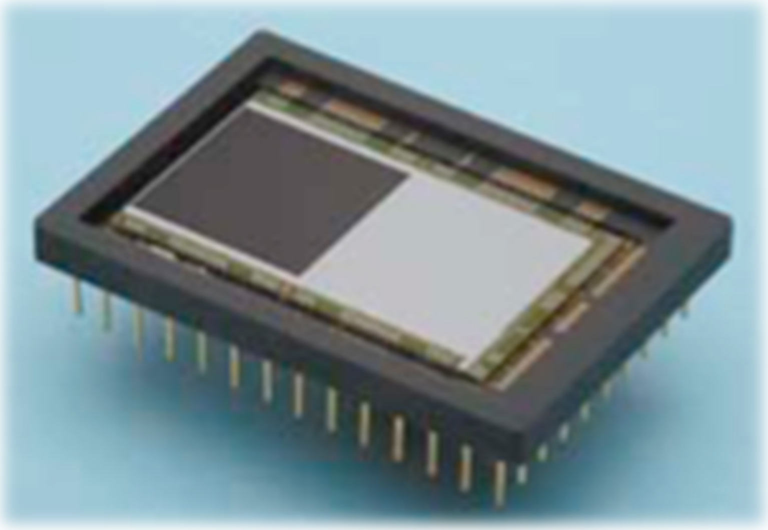
Credit: Jochem Baselmans (SRON/TUD)

Increasing QE with Lens-Antennae



Credit: Jochem Baselmans (SRON/TUD)

There are many more Detectors …



…and so little Time.

But don't forget:

Exam 13 April, 14:00hr