Detection Beyond 100µm

- Photon detectors no longer work ("shallow", i.e. low excitation energy, impurities only go out to equivalent of 100µm)
- A few tricks let them stretch a little further (like stressing) but this is basically a dead end
- Back to the detector store:

Types of Detectors

- **γ ray to 100µm: photon detectors**
  - Photoconductor
  - Photodiode
  - Photoelectric effect
  - Photography

- **X ray to 1mm: thermal detectors**
  - Semiconductor bolometer
  - Superconducting bolometer
  - Hot electron bolometer

- **100µm to 10m: heterodyne receivers (coherent)**
  - Photomixer
  - Schottky diode mixer
  - SIS mixer
  - HEB mixer

- Let's try thermal detectors, or "bolometers"

Bolometers operate on a different principle from photon detectors. Photons are absorbed and thermalized, and the resulting energy is sensed.

Bolometers are based on an absorber that is isolated by a thermal link from a heat sink. Photons incident on the absorber raise its temperature, causing a
sensitive thermometer attached to it to change resistance, producing a signal that can be amplified to achieve a detection. A bolometer detects any photon that it absorbs - it is not wavelength specific at all.

![Diagram of a bolometer](image)

This historic bolometer illustrates the various parts in a working detector.

The strength of the thermal link is $G$ (in W/K). The thermal time constant of the bolometer if $\tau = C/G$, where $C$ is the heat capacity. Making a high performance bolometer requires making $G$ very small (so a given signal causes a larger temperature swing), but to keep the speed reasonable $C$ must also be kept small.

Real bolometers generally behave in a way that is well understood theoretically. The challenge is to control the material properties to achieve the theoretical results. It is tremendously beneficial to operate them very cold. One obvious reason is that many materials when cold obey "Debye theory", which says their specific heat goes as $T^3$. 
Another reason is thermal noise. Bolometer performance is usually described in terms of "Noise Equivalent Power" (NEP). The NEP is the signal power that yields a rms signal to noise of unity into a frequency bandwidth of 1 Hz (the smaller the NEP, the better the performance of the detector at low light levels). Low temperatures suppress thermal noise that arises due to thermodynamic fluctuations in the flow of energy across the thermal link:

\[
NEP_T = \frac{(4kT^2G)^{1/2}}{\eta},
\]

where \(k\) is Boltzmann's constant, \(T\) is the temperature, and \(\eta\) is the quantum efficiency. Bolometers can be designed and operated so the thermal noise is the ultimate limit, but bolometer noise may also have a significant contribution from Johnson noise, and the corresponding NEP is roughly proportional to \(T^2G\). Empirically, it is found that the achievable NEP scales approximately as \(T^{2.5}\). To achieve photon-noise-limited performance requires temperatures of \(\sim 0.3K\) on the ground and \(\sim 0.1K\) when using cold optics in space.

Until recently, bolometers were built one at a time, or in small arrays, with individual amplifiers - that is, there was no multiplexer technology. The Herschel SPIRE instrument uses such devices. Recently, the first true bolometer arrays have been made, as in the Herschel PACS instrument. These arrays are made possible by "silicon micromachining," the ability to etch tiny, precise structures in silicon

The following picture shows one pixel of a PACS bolometer array.
The mesh is blackened with a thin layer of titanium nitride with sheet resistance matched to the impedance of free space (377 Ω/square section of film). This matching provides an efficiency of 50% over a broad band in absorbing submm or mm-wave photons. Quarter-wave resonant structures can tune the absorption to higher values over limited spectral bands. For each bolometer a silicon-based thermometer doped by ion implantation to have appropriate temperature-sensitive resistance lies at the center of the mesh. Large resistance values are used so the fundamental noise is large enough to utilize MOSFET readout amplifiers. A second silicon wafer is used to fabricate the MOSFET-based readouts, and the two are joined by indium bump bonding.

A single pixel in the Herschel/PACS bolometer array, pixel size about 750 μm.
However, the MOSFET readouts are relatively noisy and take considerable power (a real problem for the low operating temperatures), so a second approach is being developed rapidly. It is based on transition-edge-sensor (TES) arrays. A TES is a superconducting film held at its transition temperature so a tiny change in temperature results in a huge change in resistance. The transition temperature can be tuned by the "proximity effect", the influence of non-superconducting material on the superconductor properties.

The resistance of a TES is low, so it can deliver significant power only to low input impedance amplifiers. The signals are fed into superconducting quantum interference devices (SQUIDs). A SQUID consists of an input coil that is inductively coupled to a superconducting current loop.

Two Josephson junctions - junctions of superconductors with an intervening insulator - Bias circuit for TES bolometer and SQUID readout (top circuit). The Josephson junctions are indicated with "X". The circuit is repeated three times with appropriate address lines to operate as a simple SQUID multiplexer.
interrupt the loop. The Cooper pair current across a Josephson junction is a sinusoidal function of the superconducting phase difference between the two sides of the junction. The superconducting phase around the current loop is also a function of the magnetic flux through the loop, and thus of the electrical current through the input coil. In a phenomenon analogous to a two-slit optical interferometer, interference of the superconducting wavefunction around the loop results in a voltage response on the output of the SQUID that is a very sensitive function of the current applied to the input coil. Thus, changes in the bolometer current produce a large modulation of the SQUID current.

Because of the steep temperature dependence of their resistance, TESs are most stable when biased with a constant voltage. In this state, when their temperature rises due to power from absorbed photons, their resistance rises, the bias current drops, and the electrical power dissipation in them decreases, partially canceling the effects of the absorbed power and limiting the net thermal excursion. This behavior is called electrothermal feedback. The steep temperature dependence of the resistance of a TES makes the effect very strong. This feedback expedites operating arrays with TESs because minor variations in the transition temperature can be overcome by the tendency of the feedback to force each device to a suitable operating point. Electrothermal feedback can also make the bolometers operate tens or even hundreds of times faster than implied by their thermal time constants.

TES bolometer arrays use SQUIDs for the same readout functions that we have discussed for photodiode and IBC detector arrays. The operation of a simple SQUID time-domain multiplexer is illustrated in the figure. The biases across the SQUIDs are controlled by the address lines. Each SQUID can be switched from an operational state to a superconducting one if it is biased to carry about 100\(\mu\)A. The address lines are set so all the SQUIDs in series are superconducting except one, and then only that one contributes to the output voltage. By a suitable series of bias settings, each SQUID amplifier can be read out in turn.
The design of the SCUBA-2 array is illustrated above. The detector elements are separated from their heat sinks by a deep etched trench that is bridged by only a thin silicon nitride membrane. The absorbing surface is blackened by implanting it with phosphorus to match the impedance of free space. The dimensions of the array pixels are adjusted to form a resonant cavity at the wavelength of operation, to enhance the absorption efficiency. The superconducting electronics that read out the bolometers are fabricated on separate wafers. The two components are assembled into an array using indium bump bonding.

- **Bolometer Variations**
  - Microcalorimeters: bolometers can be built to absorb X-rays. If the heat capacity is very low and the response fast, a single absorbed X-ray results in a "pulse" on the output, and the size of the pulse is proportional to the energy of the X-ray (remember, bolometers detect anything they absorb!).

Figures below from Wollman et al., NIST:
Microcalorimeter - except for the bismuth absorber (necessary for high efficiency with X-rays), it has all the elements of submm bolometers.

Energy resolution of the microcalorimeter, compared with a lithium drifted silicon detector.
Microcalorimeters are the core of the Constellation-X project (unfortunately indefinitely postponed).

- MM-wave bolometers with polarimetric and energy resolution.
  In the mm-wave range the pixel-based array geometry can be replaced with tiny antennae defined by photolithography. The antenna feeds respond to a single polarization, an advantage if the detectors are planned for a polarimeter. Antennae can be arranged in a single focal plane to measure several polarization angles simultaneously. Microstrip transmission lines can bring the antenna signals outside the sensitive area of the array (a microstrip consists of a miniature circuit trace on an insulator and over a ground plane that can be designed to have some of the characteristics of a waveguide). There, the signals can be sent to a bank of microstrip filters that separate them into multiple spectral bands. Microstrip transmission lines carrying the signals are then terminated with normally conducting metal resistors and TESs sense the temperatures of the resistors as a measure of the power received by the antennae in each band.

- Hot electron bolometers
  The absorber/variable temperature component of a bolometer need not be a piece of material - it can be a sea of hot electrons in a semiconductor. "Hot" electrons are electrons high up in the conduction band of a semiconductor;

![Diagram of electron bands](attachment:electron_bands.png)
When the hot electrons absorb energy, they are raised to higher energy levels. This is equivalent to changing their temperature, like an absorber in a standard bolometer. For some materials, it also changes the electrical properties so the temperature change can be sensed electrically. These bolometers are used as mixers in high frequency submm radio receivers. More about this topic in the next lecture!