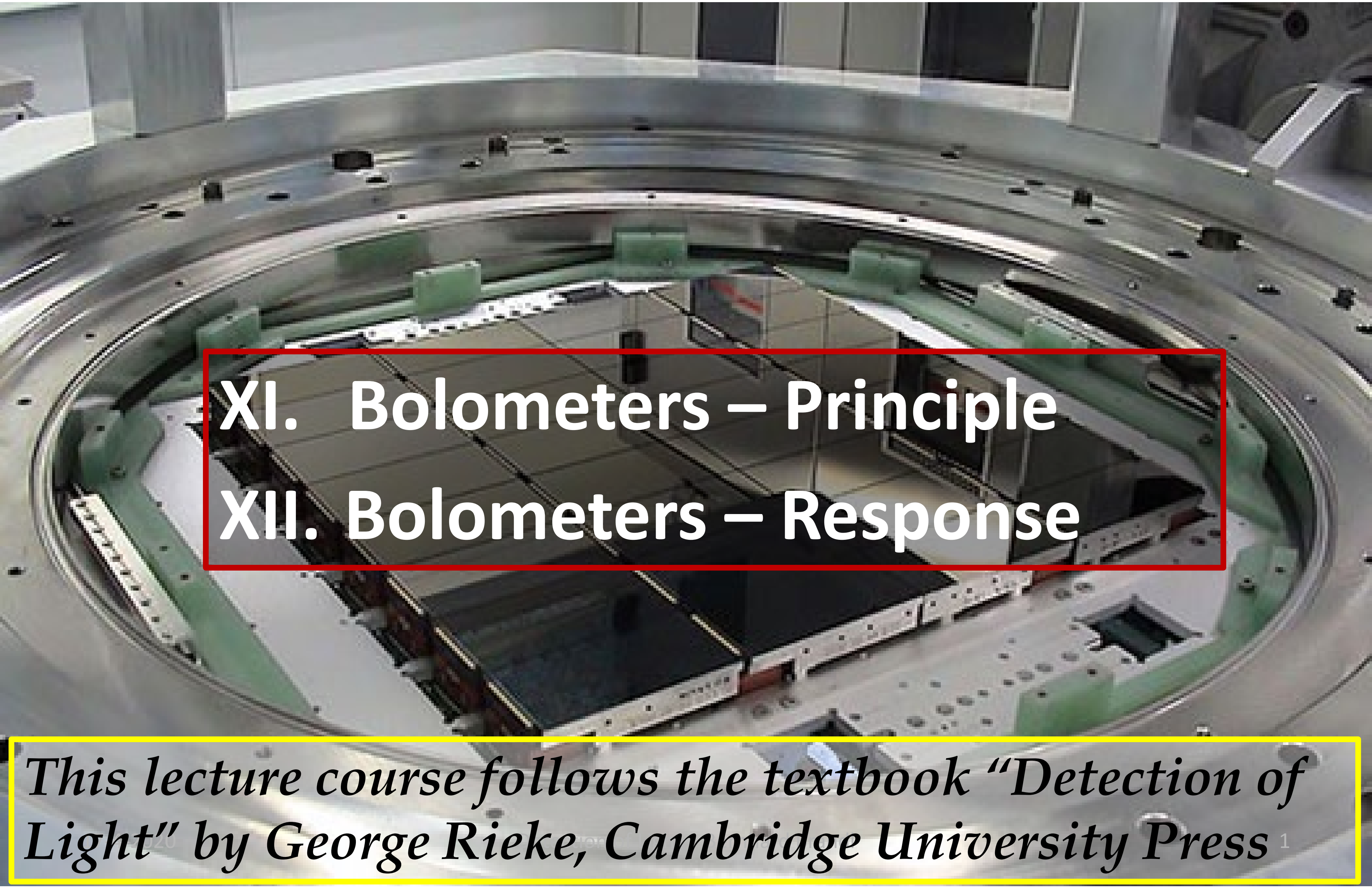
Detection of Light



XI. Bolometers – Principle

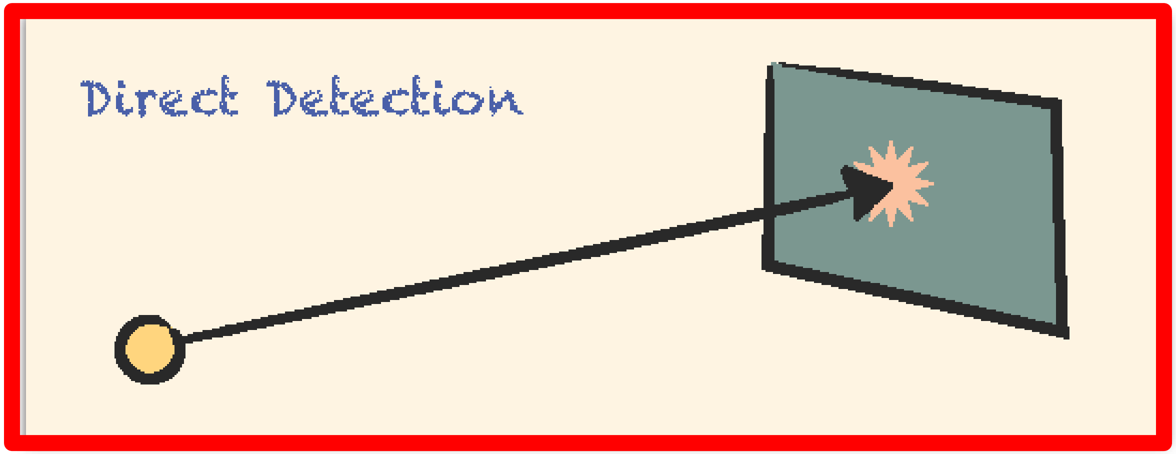
XII. Bolometers – Response

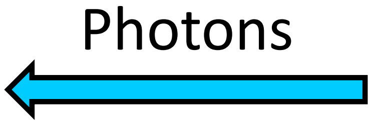
This lecture course follows the textbook "Detection of Light" by George Rieke, Cambridge University Press

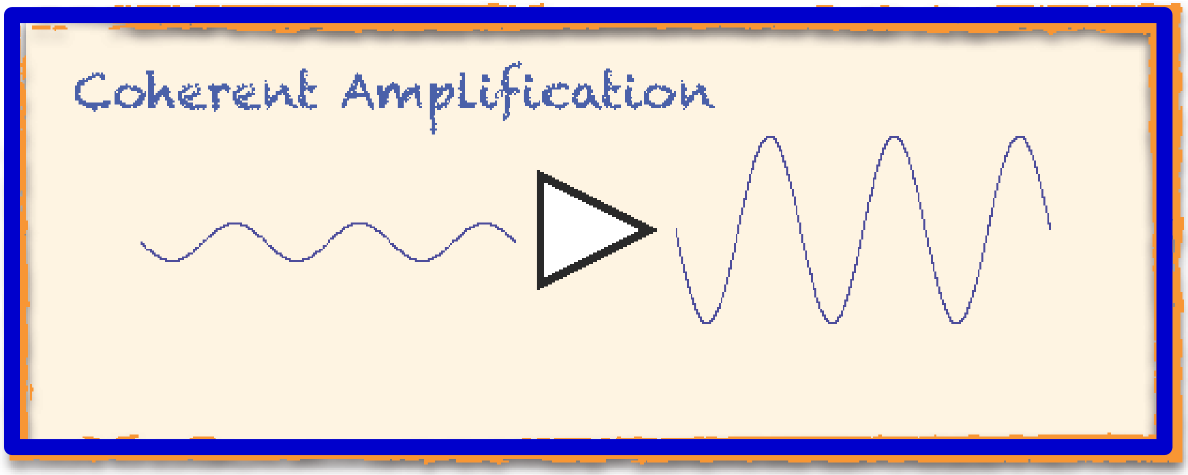
Fundamental Types of Detectors

Two Fundamental Principles of Detection

Respond to individual photon energy

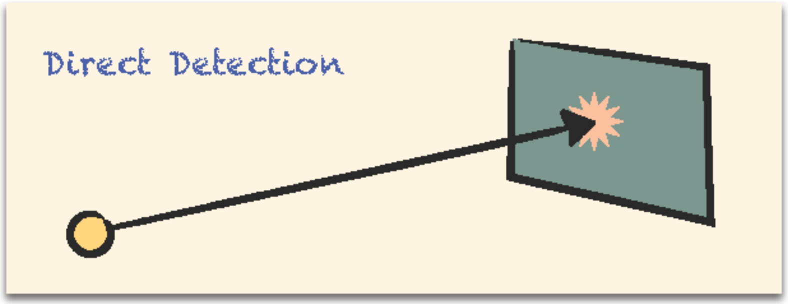




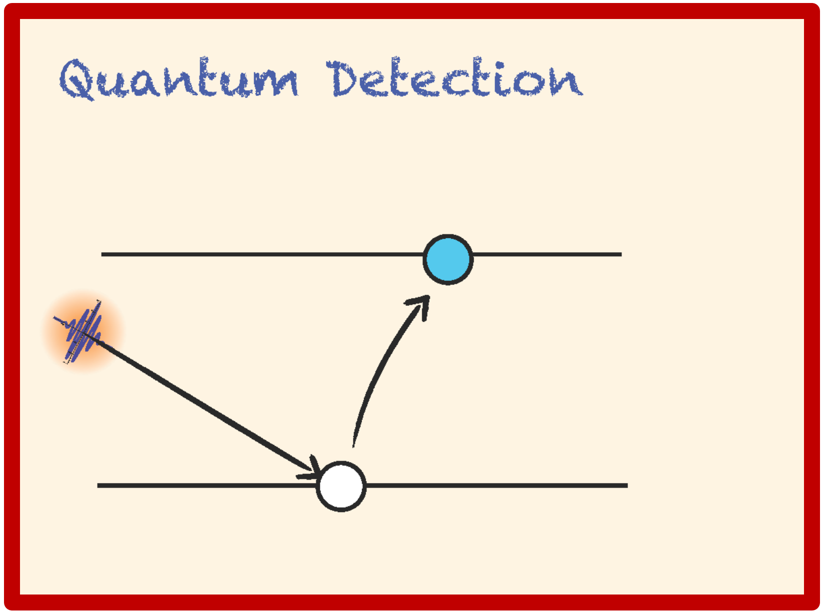


Respond to electrical field strength and preserve phase

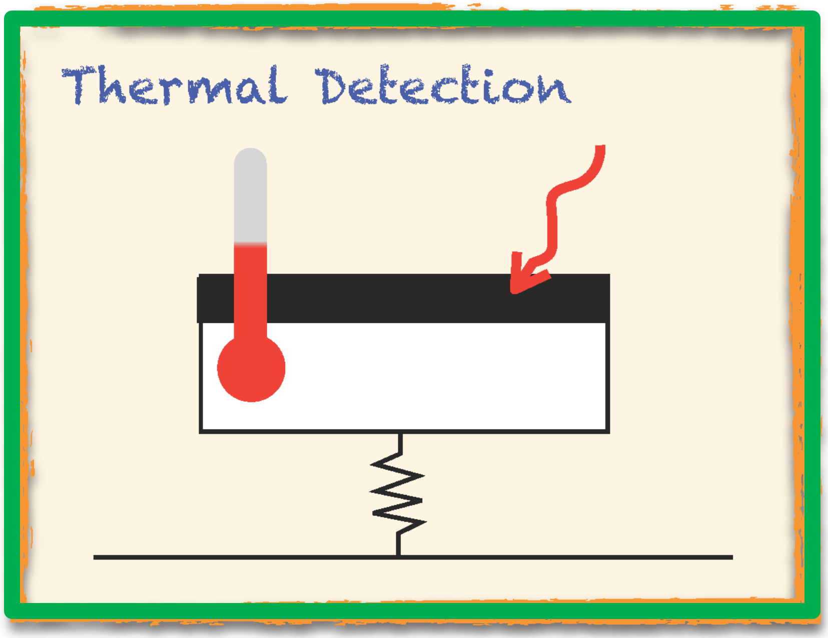
Two Types of *Direct* Detection



Based on photoelectric effect
(release of bound charges)



Thermalize photon energy



WIKIPEDIA
The Free Encyclopedia

Article Talk

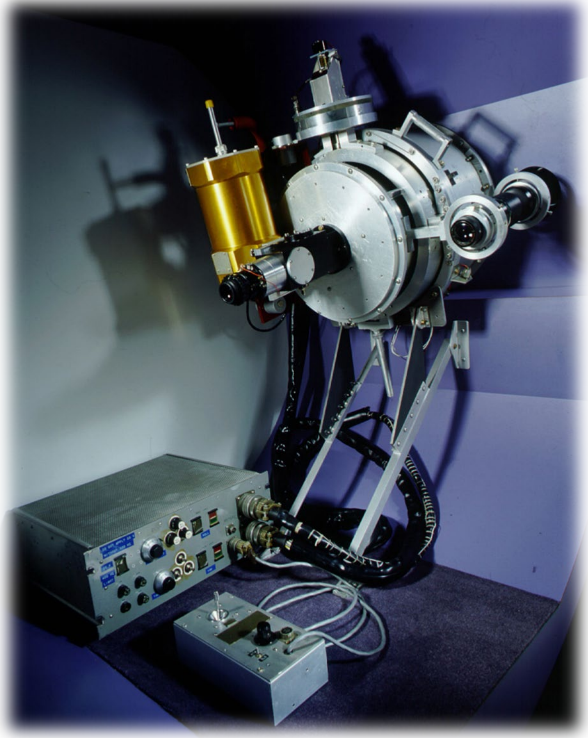
Bolometer

From Wikipedia, the free encyclopedia

Applications in astronomy [edit]

While bolometers can be used to measure radiation of any frequency, for most wavelength ranges there are other methods of detection that are more sensitive. For sub-millimeter wavelengths (from around 200 µm to 1 mm wavelength, also known as the far-infrared or terahertz), bolometers are among the most sensitive available detectors, and are therefore used for astronomy at these wavelengths. To achieve the best sensitivity, they must be cooled to a fraction of a degree above absolute zero (typically from 50 millikelvins to 300 mK). Notable examples of bolometers employed in submillimeter astronomy include the Herschel Space Observatory, the James Clerk Maxwell Telescope, and the Stratospheric Observatory for Infrared Astronomy (SOFIA).

A Brief History of Bolometers



The Beginnings

The father of astronomical bolometers is Frank Low (1933-2009). He invented the Ge:Ga bolometer in 1961.

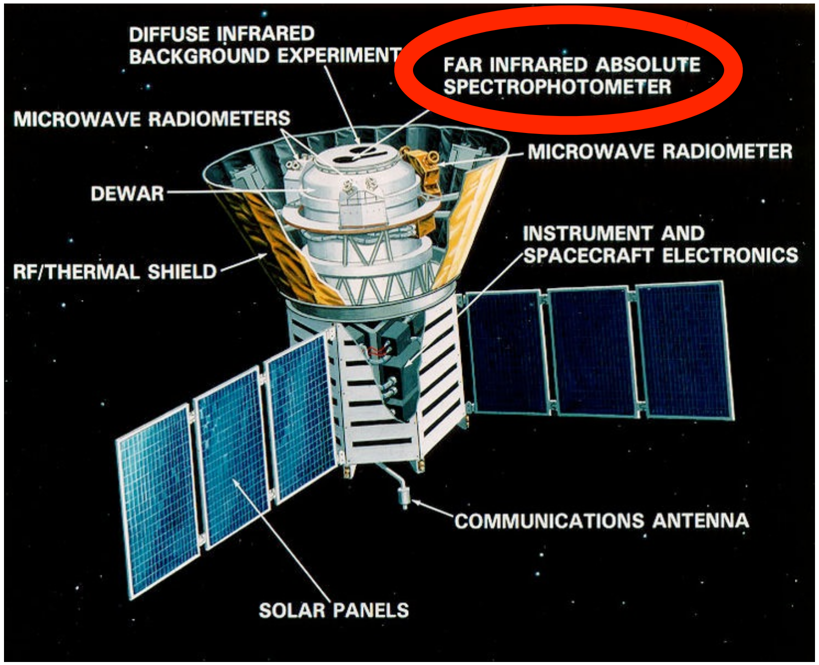
JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 51, NUMBER 11 NOVEMBER, 1961

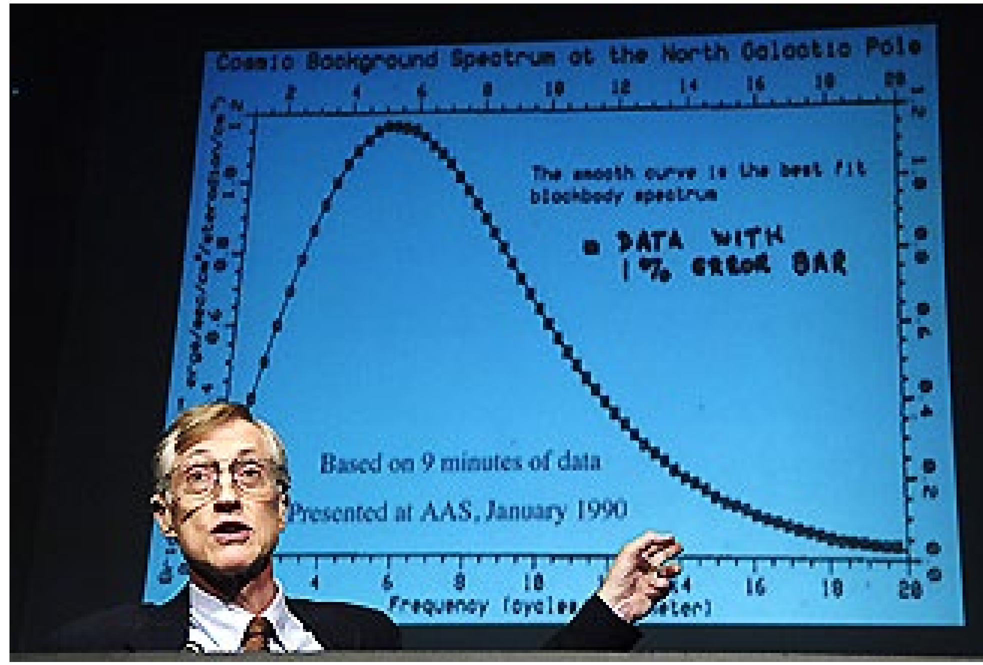
Low-Temperature Germanium Bolometer

FRANK J. LOW
Texas Instruments Incorporated, Dallas, Texas
(Received March 29, 1961)

A bolometer, using gallium-doped single crystal germanium as the temperature-sensitive resistive element, has been constructed and operated at 2°K with a noise equivalent power of 5×10^{-13} w and a time constant of 400 μsec. Sensitivities approaching the limits set by thermodynamics have been achieved, and it is shown that the background radiation limited or BLIP condition can be satisfied at 4.2°K. An approximate theory is developed which describes the performance of the device and aids in the design of bolometers with specific properties. The calculated noise equivalent power at 0.5°K, for a time constant of 10^{-2} sec, is 10^{-15} w. The detector is suitable for use in both infrared and microwave applications.

A milestone in the History of Bolometers

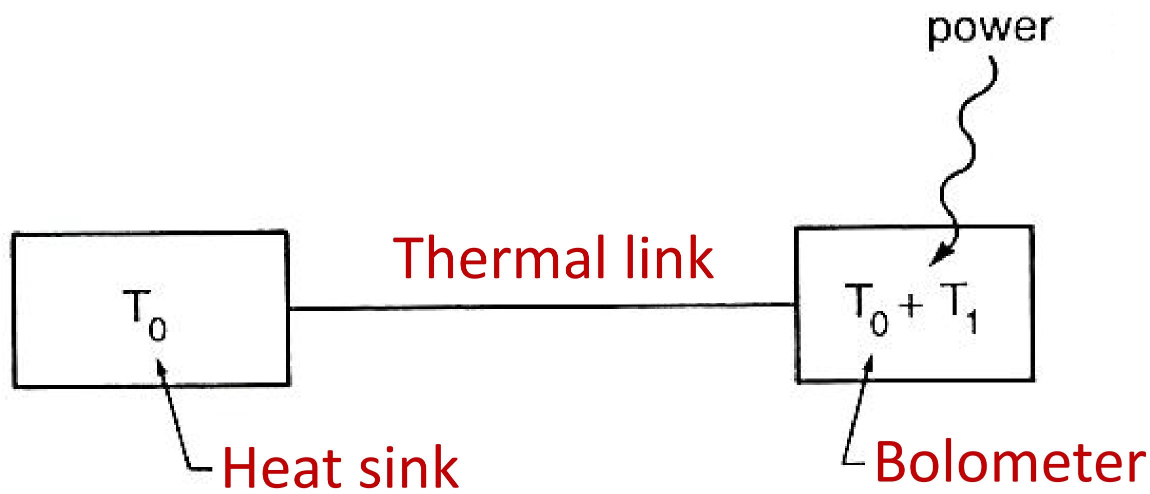




See John C. Mather (Applied Optics 21, 1125, 1982);
PI of the Far Infra Red Absolute Spectrophotometer (FIRAS) on COBE and Nobel prize winner in Physics 2006 (with George Smoot)

Basic Principle

A simple thermal Model (1)

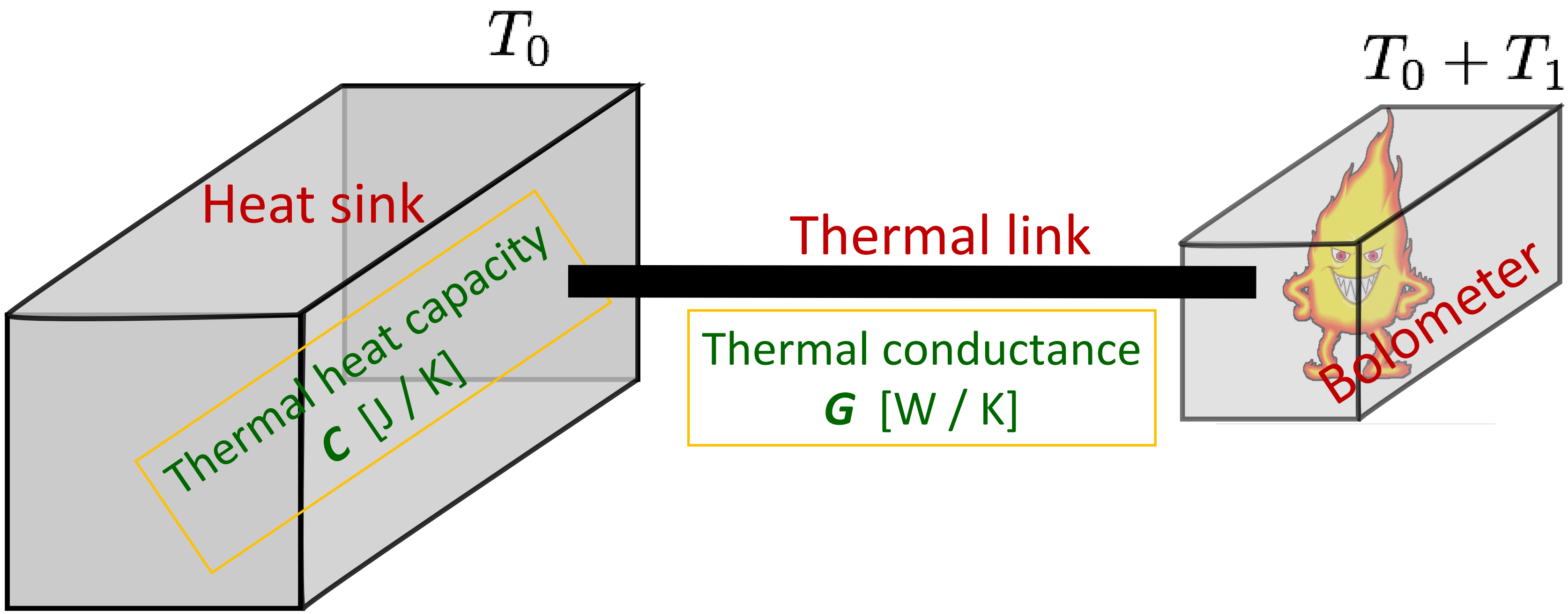


- A detector is connected by a weak thermal link to a heat sink at T_0
- From its environment, the detector absorbs a constant power P_1 so that $T_0 \rightarrow T_0 + T_1$
- The thermal link has a thermal conductance $G = \frac{P_0}{T_1}$ which counteracts that temperature increase.

For Reference:

- P_0: zero-point heat load of the bolometer (analogous to dark current in photoconductors)
- P_1: constant (generic) external power on the bolometer.
- P_V: time-variable power, due to the *absorbed* photon flux (i.e., the signal we want to detect)
- P_T: total power of all components
- P_I: power due to the sensing current through the bolometer

A simple thermal Model (2)

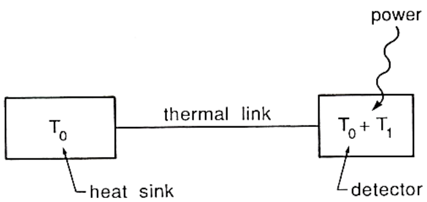


- Now we introduce a time-variable power component $P_V(t)$ – *the photon flux we want to detect*

$$\eta P_V(t) = \frac{dQ}{dt} = C\frac{dT_1}{dt}$$

where η is the quantum efficiency, and Q is the thermal energy.

A simple thermal Model (3)



The total power absorbed by the detector is then:

$$P_T(t) = P_0 + \eta P_V(t) = GT_1 + C\frac{dT_1}{dt}$$

We switch the signal on/off so that: $\begin{cases} P_V = 0 & t < 0 \\ P_V = P_1 & t > 0 \end{cases}$

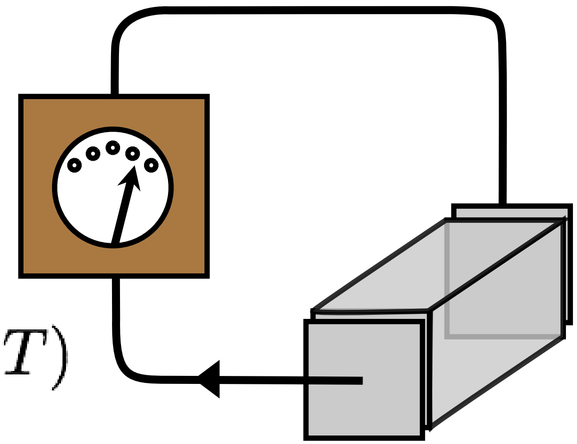
Then the solution is:

$$T_1(t) = \frac{P_T}{G} - \frac{\eta P_V}{G} = \begin{cases} \frac{P_0}{G} \text{ for } t < 0 \\ \frac{P_0}{G} + \frac{\eta P_1}{G}\left(1 - e^{-t/(C/G)}\right) \text{ for } t > 0 \end{cases}$$

→ The signal response changes exponentially with the thermal time constant $\tau_T = \frac{C}{G}$

Electrical Time Constant

Besides the thermal time constant $\tau_T = \frac{C}{G}$ there is also the electrical heating from the current sensing in the thermometer P_I:



$$P_I = I^2 \times R(T)$$

The electrical power changes with an electrical time constant τ_E

$$\tau_E = \frac{C}{G - \alpha(T) P_I} < \tau_T = \frac{C}{G}$$

Since $\alpha(T) < 0^*$, this term is always positive: $\tau_E < \tau_T$

*see slide #20

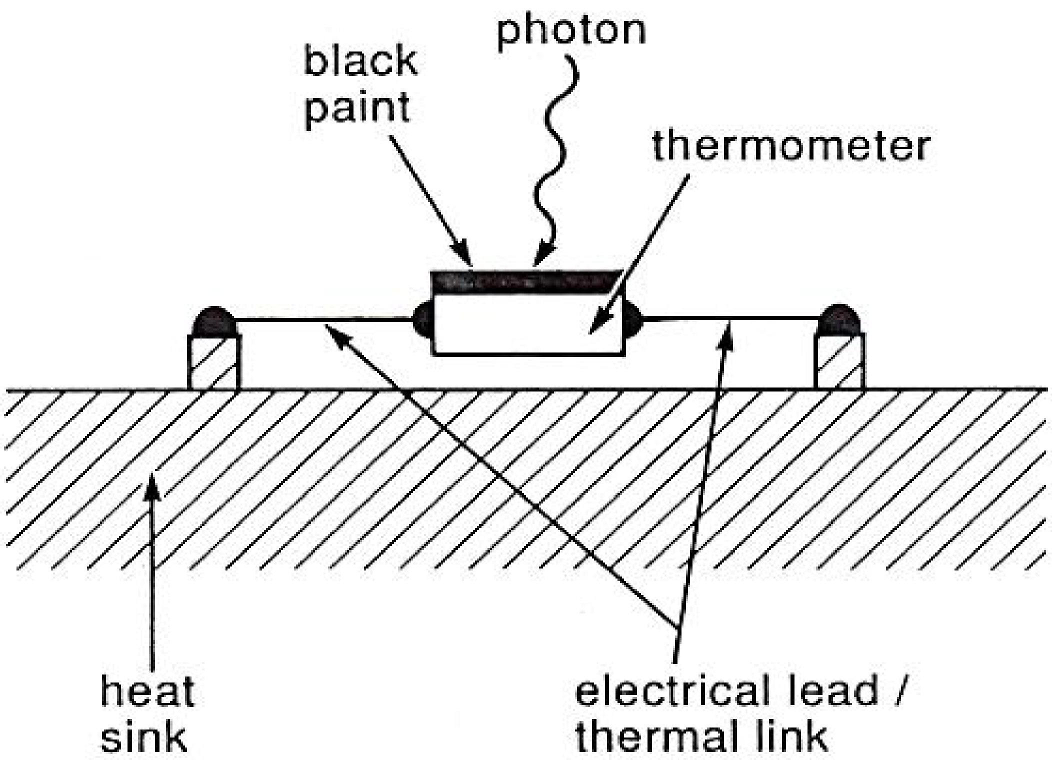
Conclusion

For $t \gg \tau_T$ and $\tau_T > \tau_E$, the temperature T_1 is proportional to $(P_0 + \eta P_1)$.

In other words, *if you measure the temperature then you know the power, and, after calibration, you know the source brightness*.

Basic Setup

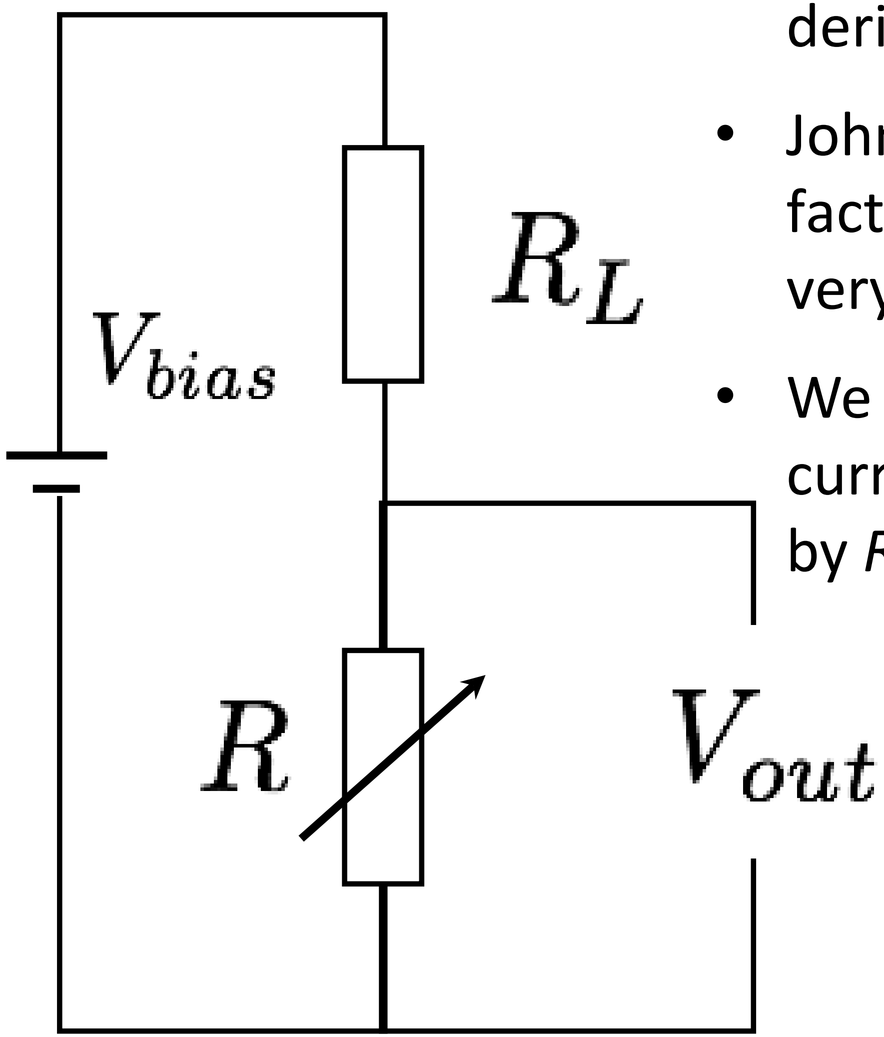
General Layout of Semiconductor Bolometer



- A chip of doped silicon or germanium acts *both* as bolometer detector *and* thermometer.
- High input impedance amplifier measures the voltage → voltage depends on resistance → resistance depends on temperature.

Electrical Properties

Bolometer Readout Circuit



- We can use this circuit to measure V_{out} to derive the bolometer resistance *R*.
- Johnson noise is usually not the limiting factor for bolometers so we don't need a very high resistance *R* for the bolometer.
- We assume that $R_L >> R$ so that the current through the bolometer is limited by R_L.

Temperature Coefficient of Resistance (1)

Bolometer temperature ⇔ electrical resistance
→ temperature coefficient of resistance α:

$$\alpha = \alpha(T) = \frac{1}{R}\frac{dR}{dT}$$ (in units of Kelvin^{-1})

The sign of α leads to very different behavior for a bolometer.

A positive/negative temperature coefficient (PTC/NTC) refers to materials that experience an increase/decrease in electrical resistance when their temperature is raised.

Material	α/°K
Silicon	-0.075
Germanium	-0.048
Carbon	-0.0005
Manganin	0.000002
Constantan	0.000008
Nichrome	0.0004
Mercury	0.0009
Copper	0.0039
Aluminum	0.0039
Tungsten	0.0045
Iron	0.005
Lithium	0.006

http://www.resistorguide.com/temperature-coefficient-of-resistance/

Temperature Coefficient of Resistance (2)

To make sure that there are good electrical properties for this very low temperature, the doping is so heavy that hopping is the dominant mode.

If $T \ll \Delta$, and the semiconductor is heavily doped, the electrical resistance for hopping can be described by:

$$R = R_0 e^{(\Delta/T)^\epsilon}$$

where $\epsilon \approx ½$ and $\Delta \approx 4 - 10$ K is a characteristic temperature.

Substituting the hopping resistance into the above equation yields:

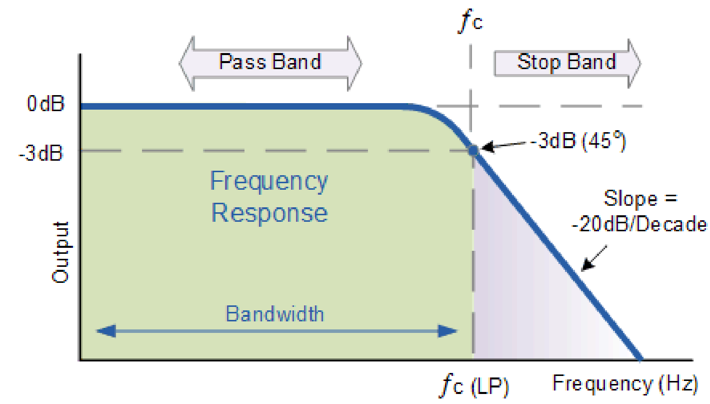
$$\alpha(T) = \frac{1}{R}\frac{dR}{dT} = \frac{1}{R_0 e^{(\Delta/T)^{1/2}}}\frac{d}{dT}\left(R_0 e^{(\Delta/T)^{1/2}}\right) \approx \boxed{-\frac{1}{2}\left(\frac{\Delta}{T^3}\right)^{1/2}}$$

Bolometer Responsivity

Frequency Response

The frequency response of a classical RC-circuit is given by (Rieke 1.38):

$$|V_{out}(f)| = \frac{v_0}{\left[1+(2\pi f \tau_{RC})^2\right]^{1/2}}$$



https://www.electronics-tutorials.ws/filter/filter_2.html

Similarly, the frequency response of a bolometer is given by:

$$S(f) = \frac{S(0)}{[1+(2\pi f \tau_E)^2]^{1/2}}$$

where *S*(0) is the low frequency responsivity in [V / W] and τ_E is the electrical time constant.

Electrical Responsivity

Let *dR*, *dT* and *dV* be the changes in resistance, temperature and voltage across the bolometer, caused by the absorbed power *dP*.

$$dV = I\,dR = I[\alpha(T)R\,dT] = \alpha(T)V\,dT = \frac{\alpha(T)V\,dP}{G - \alpha(T)P_I}$$

$$\alpha(T) = \frac{1}{R}\frac{dR}{dT}$$

with Rieke p.244

$$dT = \frac{dP}{G - \alpha(T)P_I}$$

with Rieke p.245

So, we get for the electrical responsivity: $S_E = \frac{dV}{dP} = \frac{\alpha(T)V}{G - \alpha(T)P_I} = \frac{1}{2I}\left(\frac{Z}{R} - 1\right)$

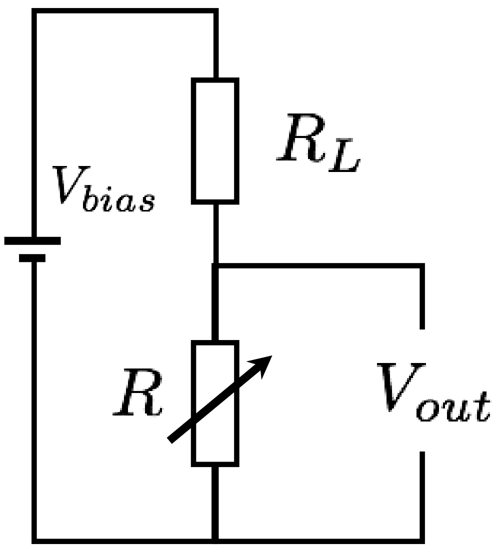
S_E is completely determined by the electrical properties of the detector.

S_E electrical responsivity
$\alpha(T)$ temperature coefficient of resistance [K^{-1}]
V voltage [V]
G thermal conductance [W/K]
P_I power from sensing current [W]

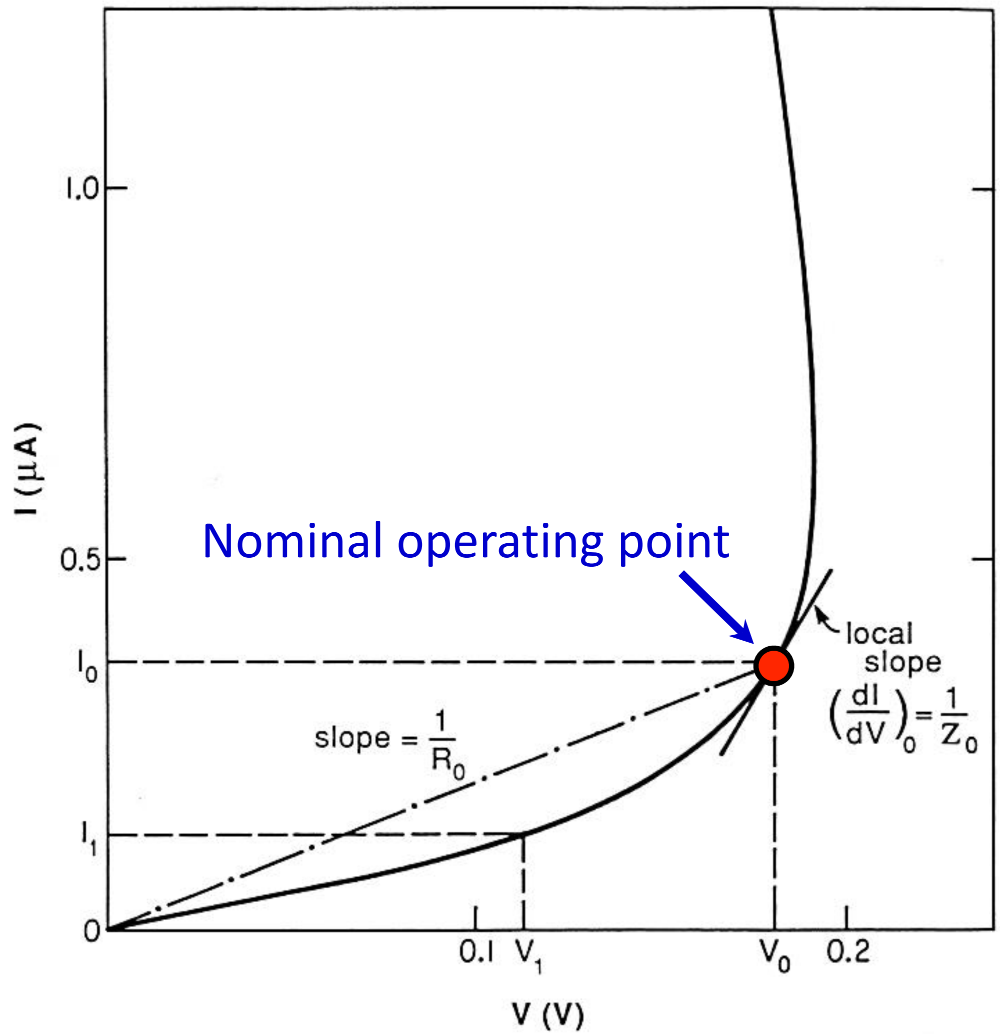
Measuring Electrical Responsivity

The detector properties *G* and *α* are not always known → need to determine them by measurement.

Measure the "load curve" of I-V by adjusting the load resistor R_L



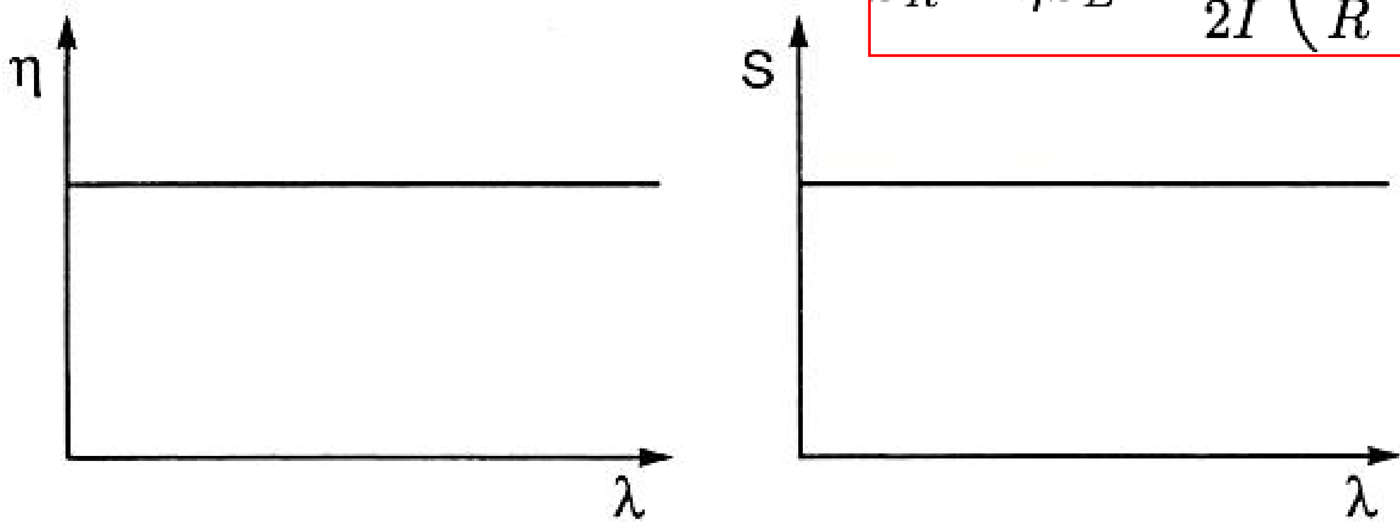
The Load Curve



Bolometer Detector Responsivity

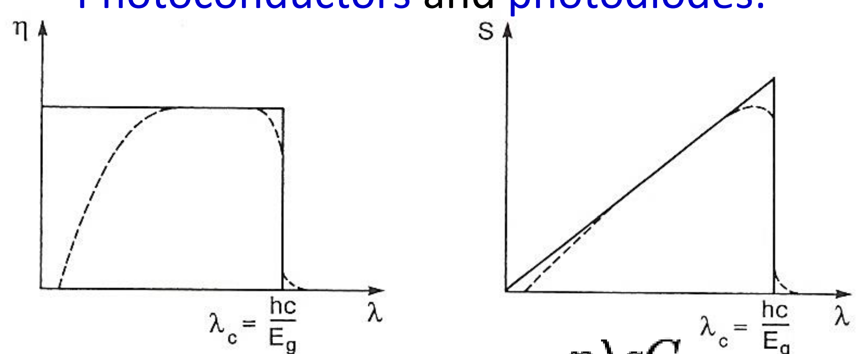
S_E is only the *electrical* responsivity. If we want to get the responsivity to incoming radiation we need to multiply S_E with the absorbed fraction η of the incoming radiation:

$$S_R = \eta S_E = \frac{\eta}{2I}\left(\frac{Z}{R} - 1\right)$$



Unlike photoconductors, the bolometer responsivity is independent of the wavelength λ (assuming the QE η is independent of λ).

Photoconductors and photodiodes:



$$S_{photoconductor} = \frac{\eta \lambda q G}{hc}$$

Noise and NEP

The total NEP (1)

Bolometers suffer from the same fundamental noise mechanisms as photoconductors *plus* the noise from thermal fluctuations:

Johnson noise can be characterized by the "noise voltage":

$$V_J = \langle I_J^2 \rangle^{1/2} R \quad \text{where} \quad \langle I_J^2 \rangle = \frac{4kT\Delta f}{R}$$

Johnson noise:

$$NEP_J \approx \begin{matrix} GT^2 \text{ for } \alpha(T) \approx T^{-3/2} \\ GT^{3/2} \text{ for } \alpha(T) \approx T^{-1} \end{matrix}$$

....due to fluctuations in the thermal motions of charge carriers (random currents due to Brownian motion).

The total NEP (2)

Thermal noise: $$NEP_T = \frac{(4kT^2G)^{1/2}}{\eta}$$

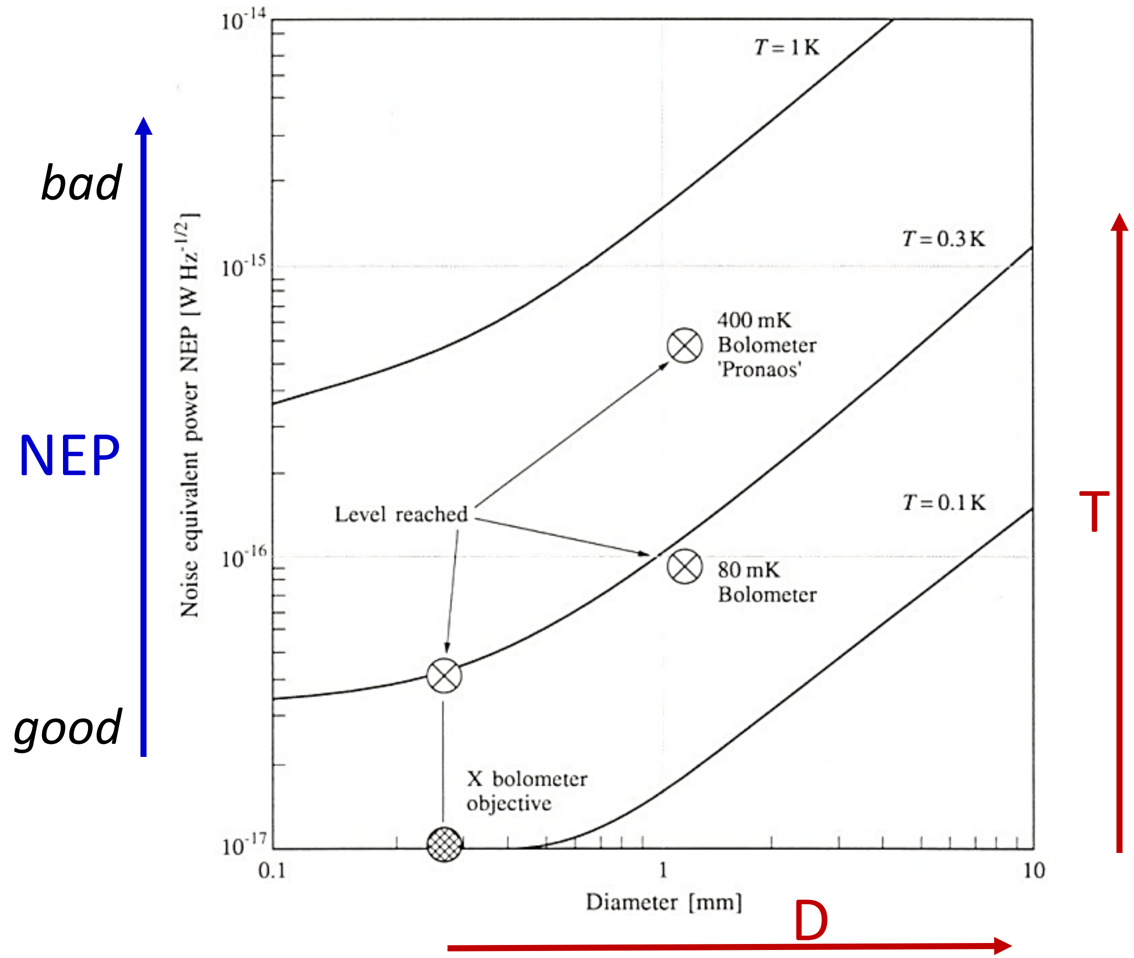
...due to fluctuations of entropy across the thermal link that connects the detector and the heat sink.

Photon shot noise: $$NEP_{photon} = \frac{hc}{\lambda}\left(\frac{2\varphi}{\eta}\right)^{1/2}$$

...due to fluctuations in the photon flux. *(Note: Bolometers do not have G-R noise since no particle pairs are being created or destroyed).*

Total NEP noise: $$NEP = \sqrt{(NEP^2_{photon} + NEP^2_{\tau} + NEP^2_J + ...)}$$

NEP Performance of Bolometers



(from Puget & Coron 1994 for the SAMBA mission).

Conclusions:

- the colder, the better
- the smaller, the better

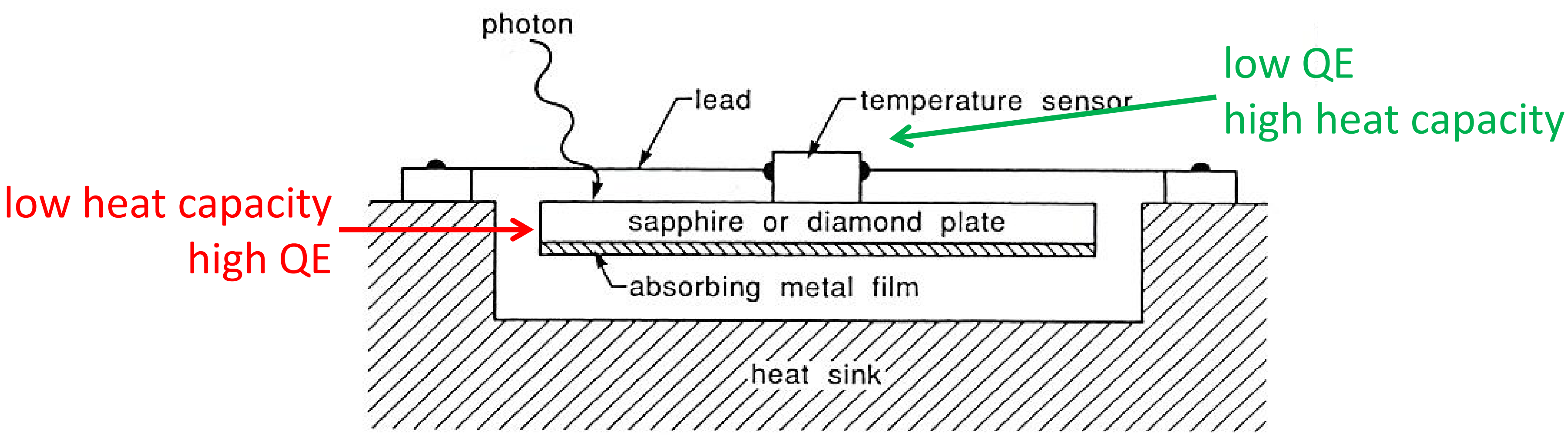
More sophisticated Bolometers

Composite Bolometers (1)

In some cases, Si bolometers with high impurity concentrations can be very efficient absorbers. In many cases, however, the QE is too low.

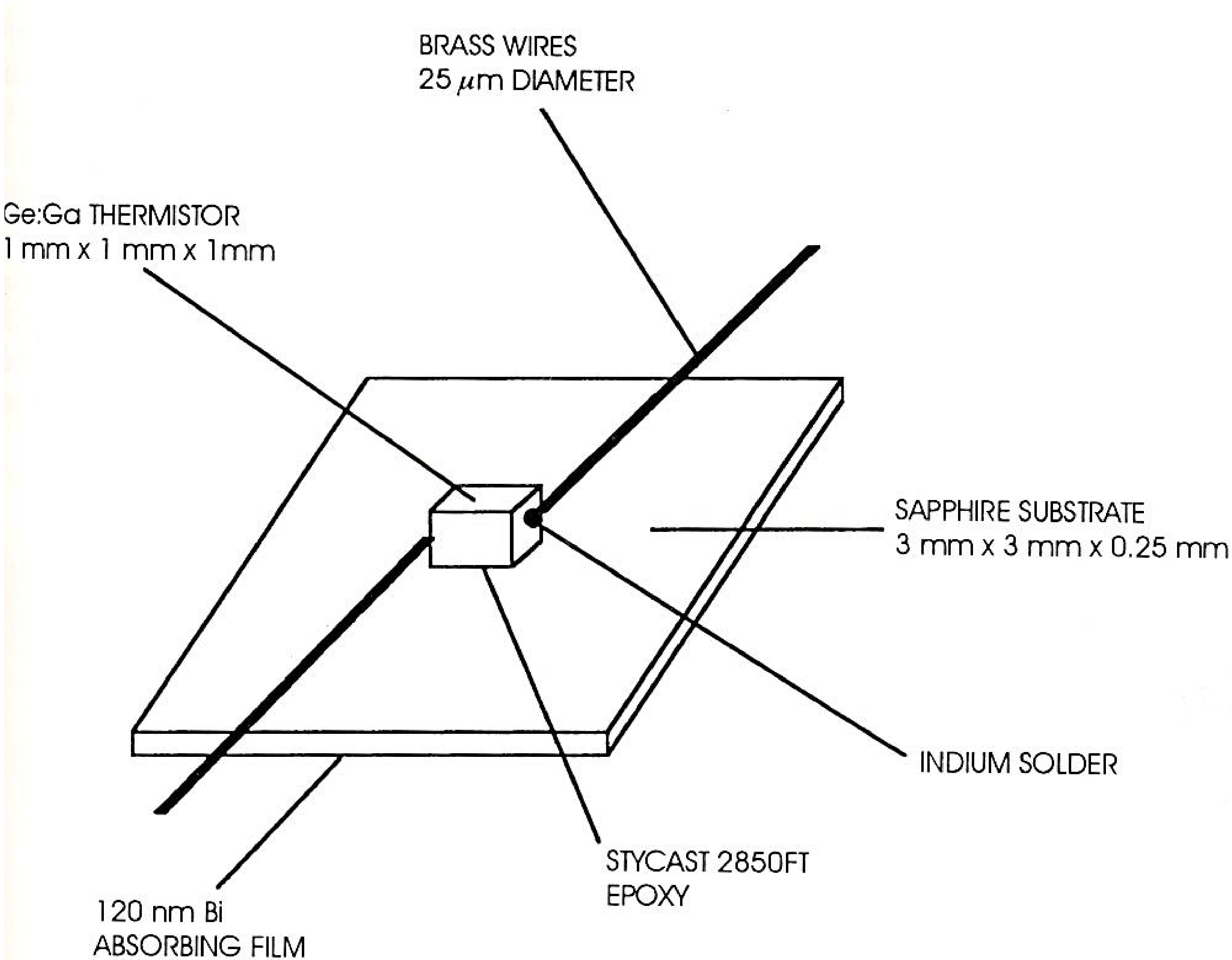
Quick solution: enhance absorption with black paint – but this will also increase the heat capacity.

A high QE bolometer for far-IR and sub-mm would have too much heat capacity hence composite bolometers.



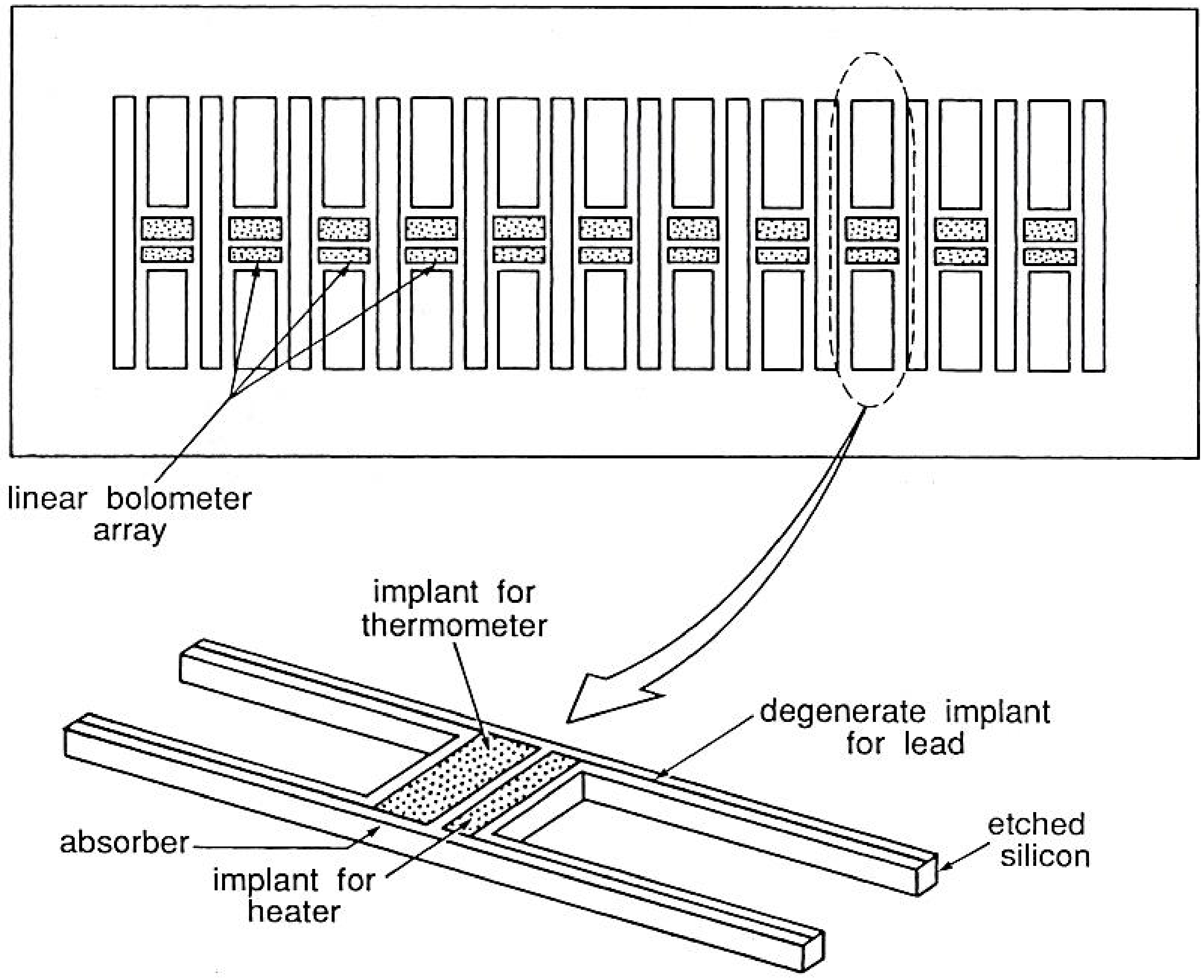
The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Composite Bolometers (2)



Etched Bolometers

Etching physical designs in Si means that you can make bolometer arrays and really reduce the thermal timescales.



Hot Electron Bolometers

Hot Electron Bolometers

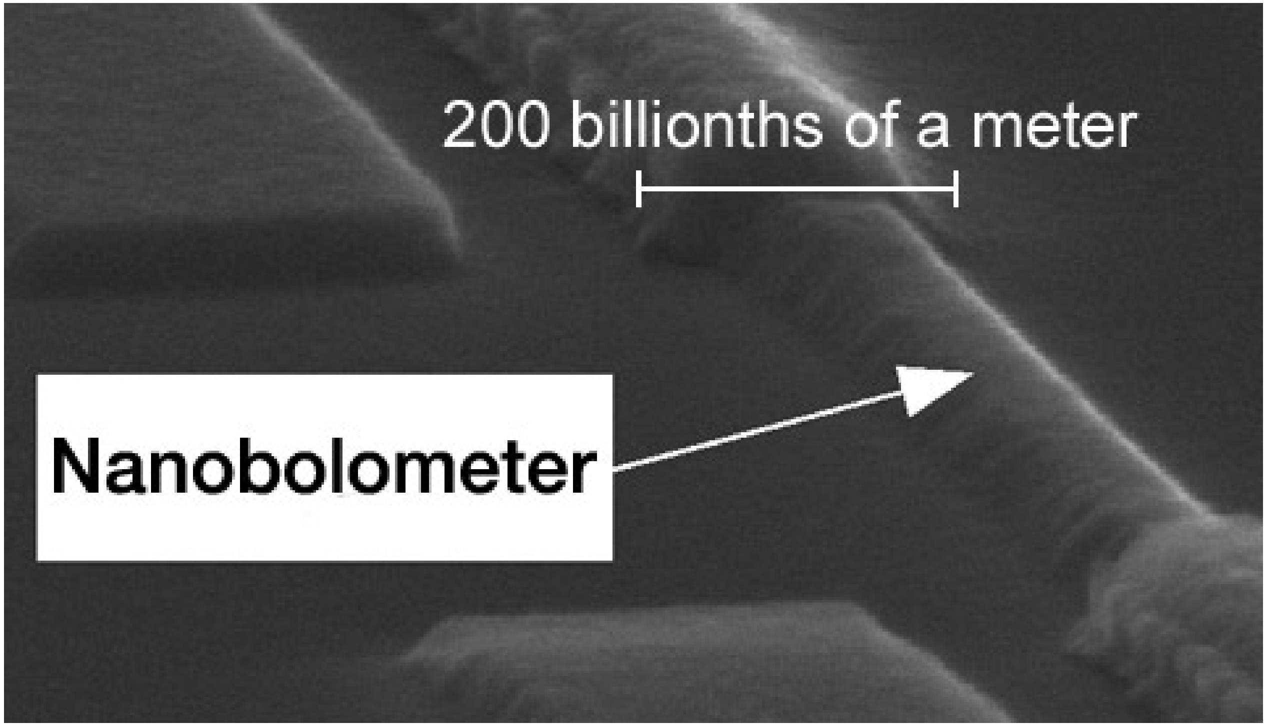
Bolometers for sub-mm/mm wavelengths can use highly doped (n-type) InSb:

- 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!

Hot Electron Nano-Bolometers

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



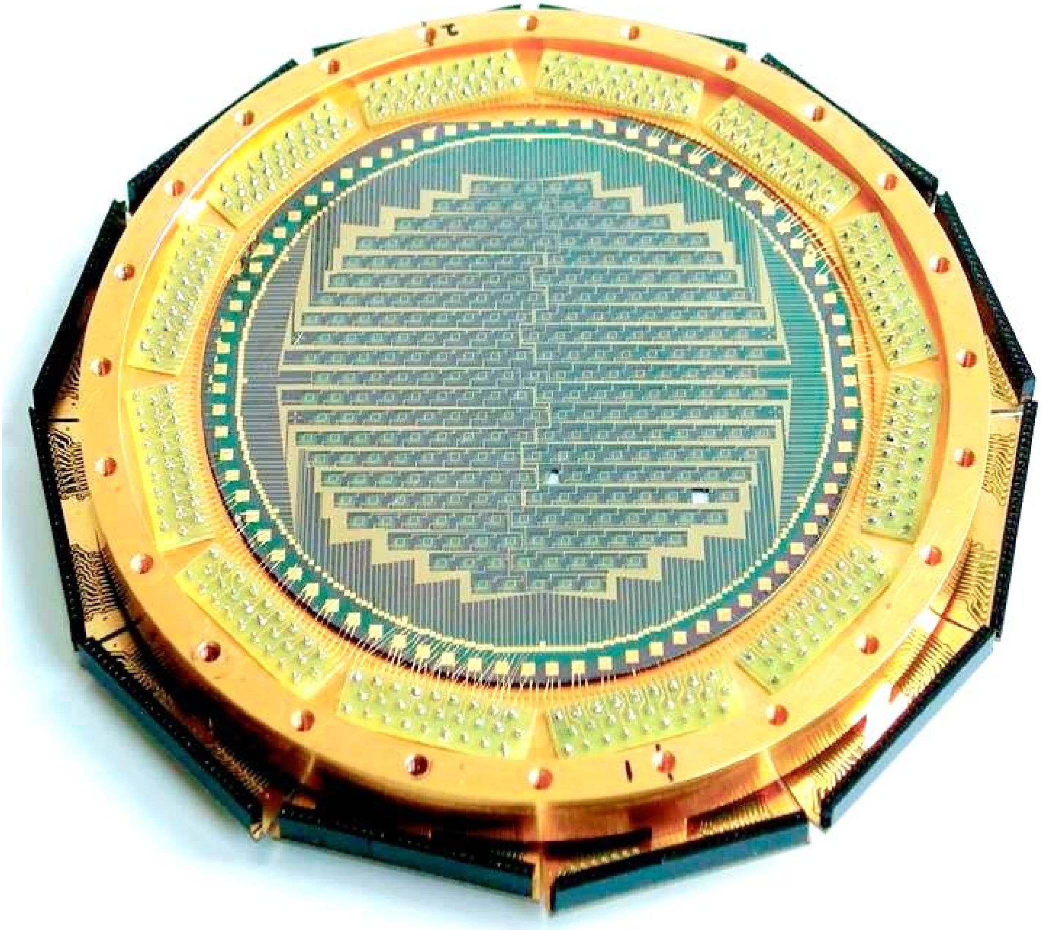
Photons heat the electrons in the Ti section, which is thermally isolated by superconducting Nb leads.

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

Instruments with modern Bolometers

LABOCA

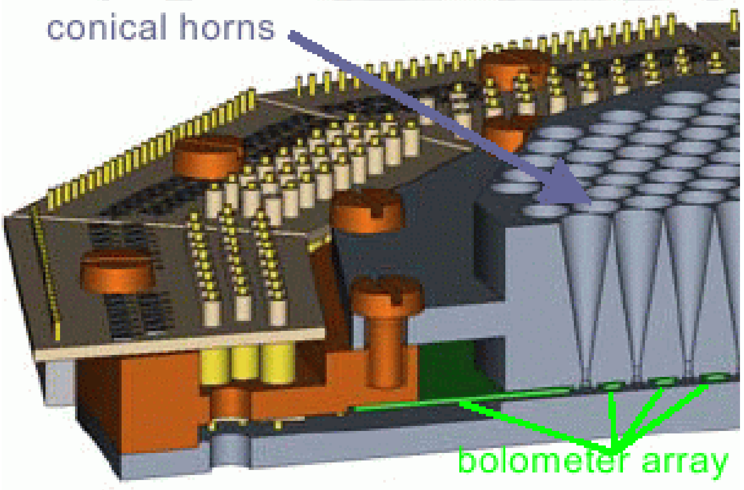
LABOCA – the multi-channel bolometer array for APEX operating in the 870 μm (345 GHz) atmospheric window.



The signal photons are absorbed by a thin metal film cooled to about 280 mK.

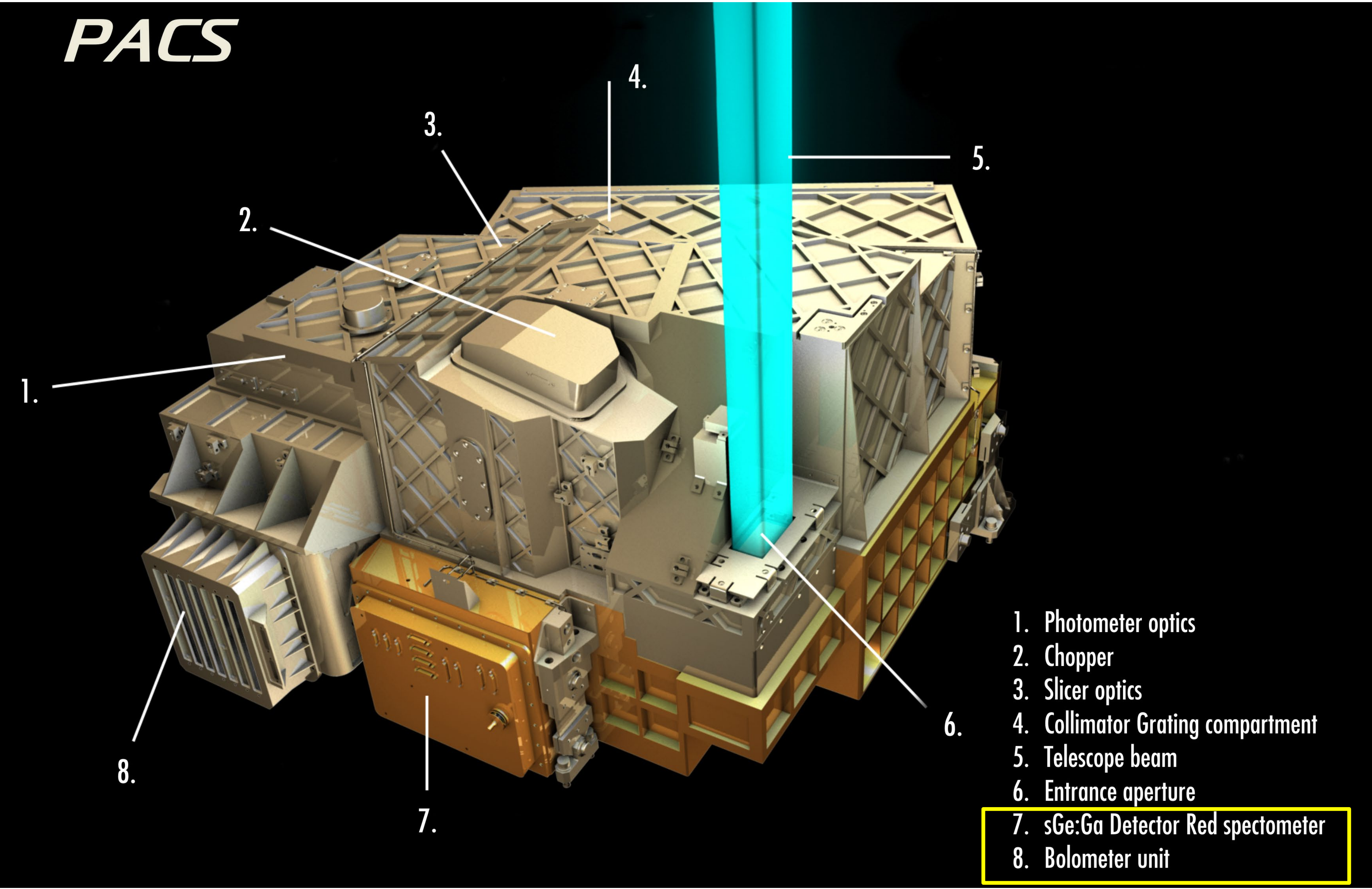
The array consists of 295 channels in 9 concentric hexagons.

The array is under-sampled, thus special mapping techniques must be used.

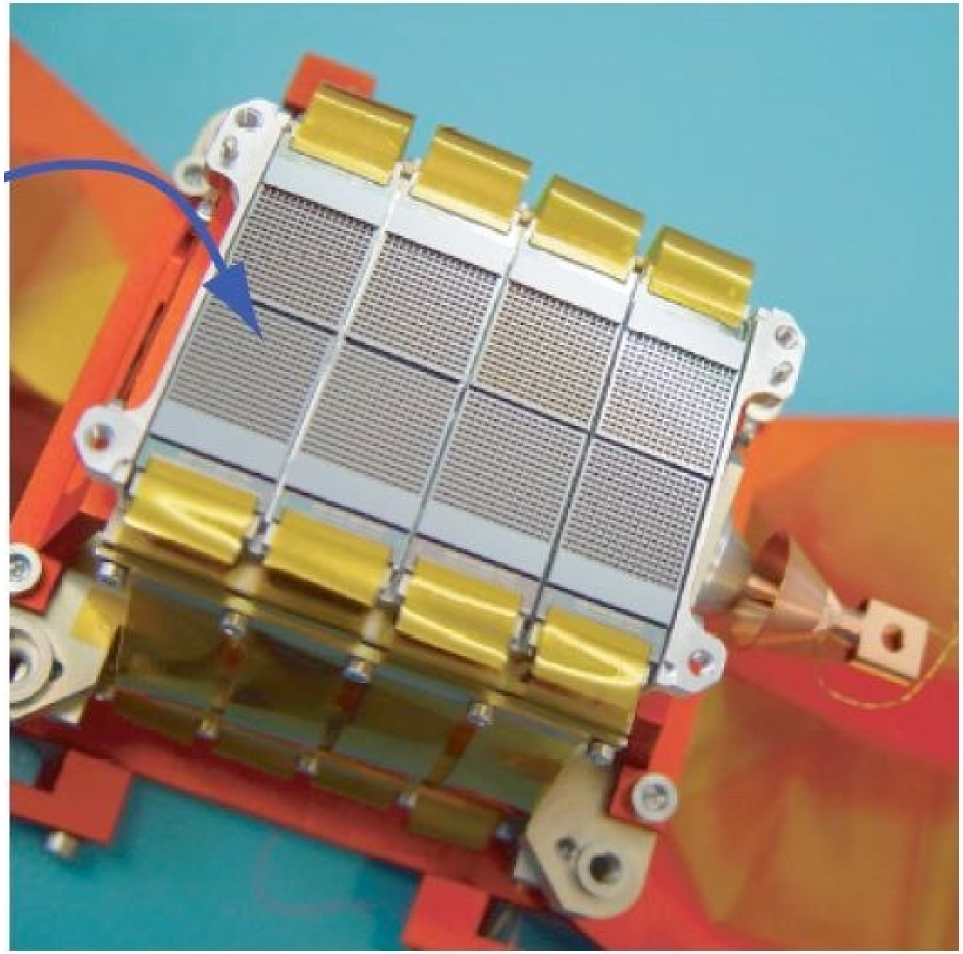


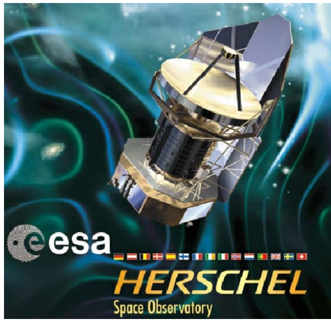
http://www.apex-telescope.org/bolometer/laboca/technical/

Herschel/PACS



Herschel/PACS





Herschel/PACS bolometer:
a cut-out of the 64x32 pixel bolometer array assembly.

4x2 monolithic matrices of 16x16 pixels are tiled together to form the short-wave focal plane array.

The 0.3 K multiplexers are bonded to the back of the sub-arrays. Ribbon cables lead to the 3K buffer electronics.

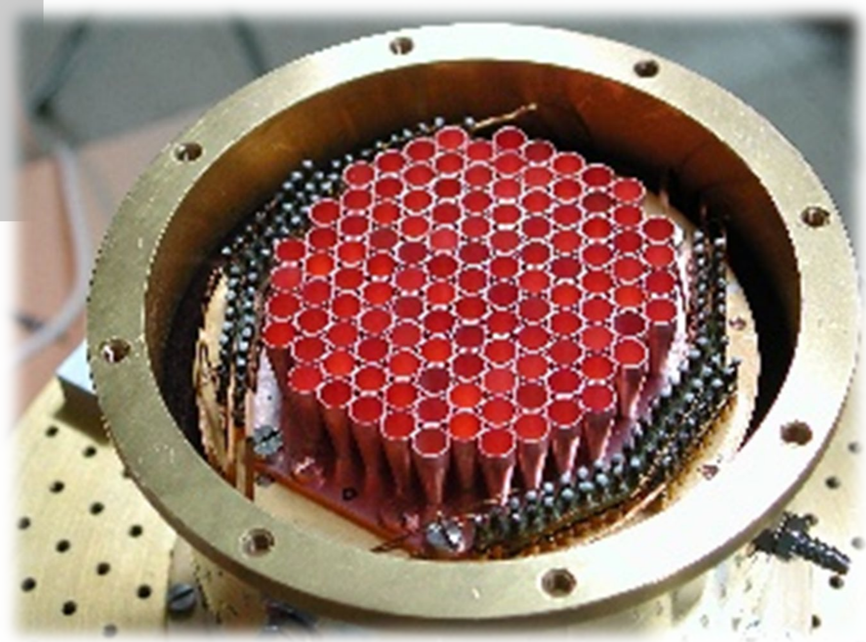
MAMBO

The **Ma**x-Planck **M**illimeter **Bo**lometer array is installed at the IRAM 30 m telescope on Pico Veleta, Spain. MAMBO's 37 channel array has been successfully used by many observers since the end of 1998. Winter 2001/2002 was the first season of the new MAMBO-2 version with 117 pixels. The 37 channel MAMBO is used at the 30 m telescope as a backup system now. Both systems work at 1.2 mm wavelength and have a He-3 fridge to operate the bolometers at a temperature of 300 mK.

Bolometer Development

at the MPIfR

Welcome to the home page of the Bolometer Development Group at the Max-Planck-Institut für Radioastronomie (MPIfR)!
We are part of the MPIfR Millimeter & Submillimeter Astronomy Group.



MUSTANG-2

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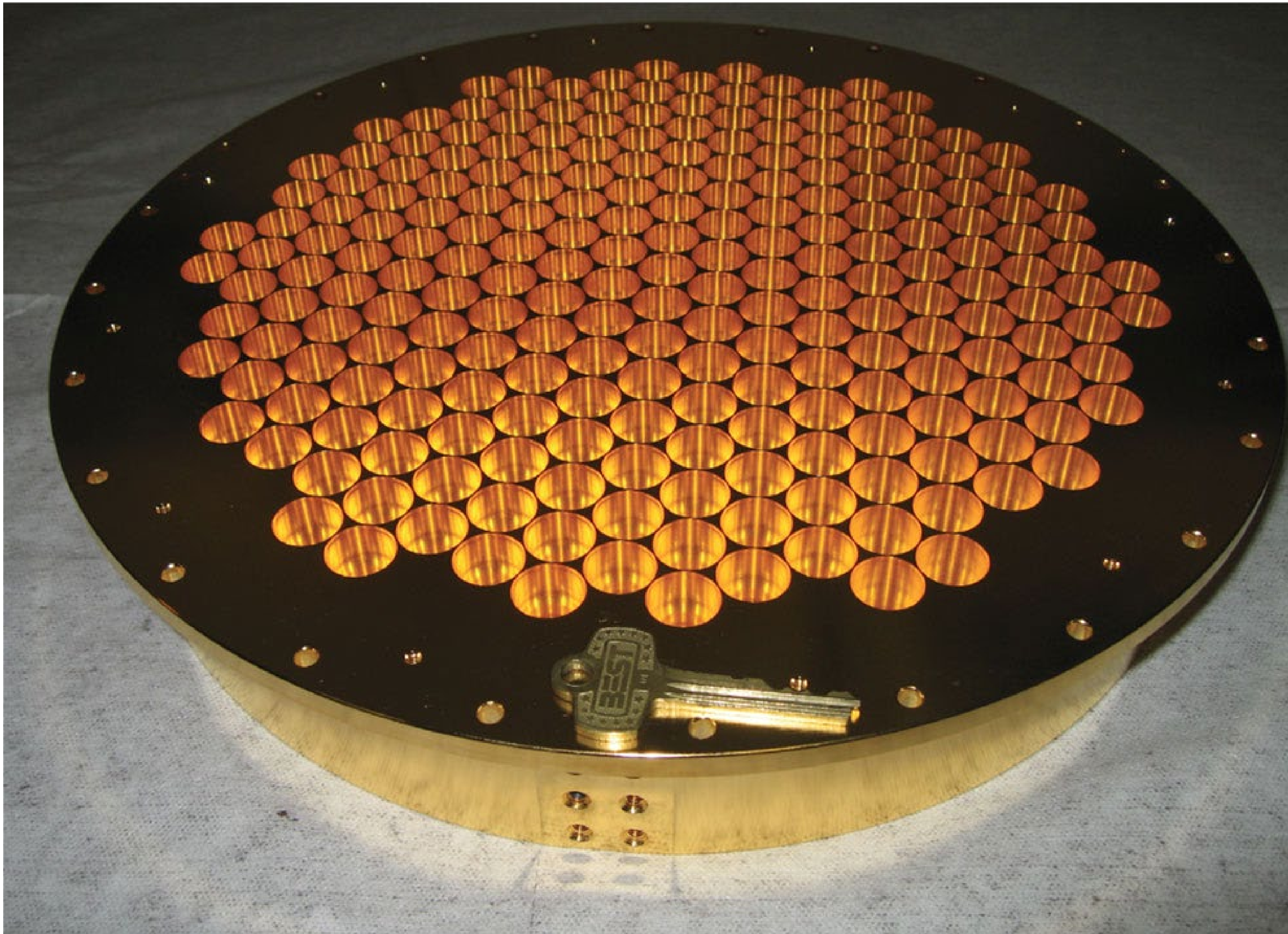
NRAO

New Bolometer Camera Deployed on GBT



University of California
Berkeley

ACBAR

- The Arcminute Cosmology Bolometer Array Receiver (ACBAR) produces high-resolution images of the CMB.
- The receiver is an array of 16 detectors in 3-millimeter wavelength bands near the CMB peak
- ACBAR is installed at the 2.1-meter Viper telescope at the South Pole Station in Antarctica.