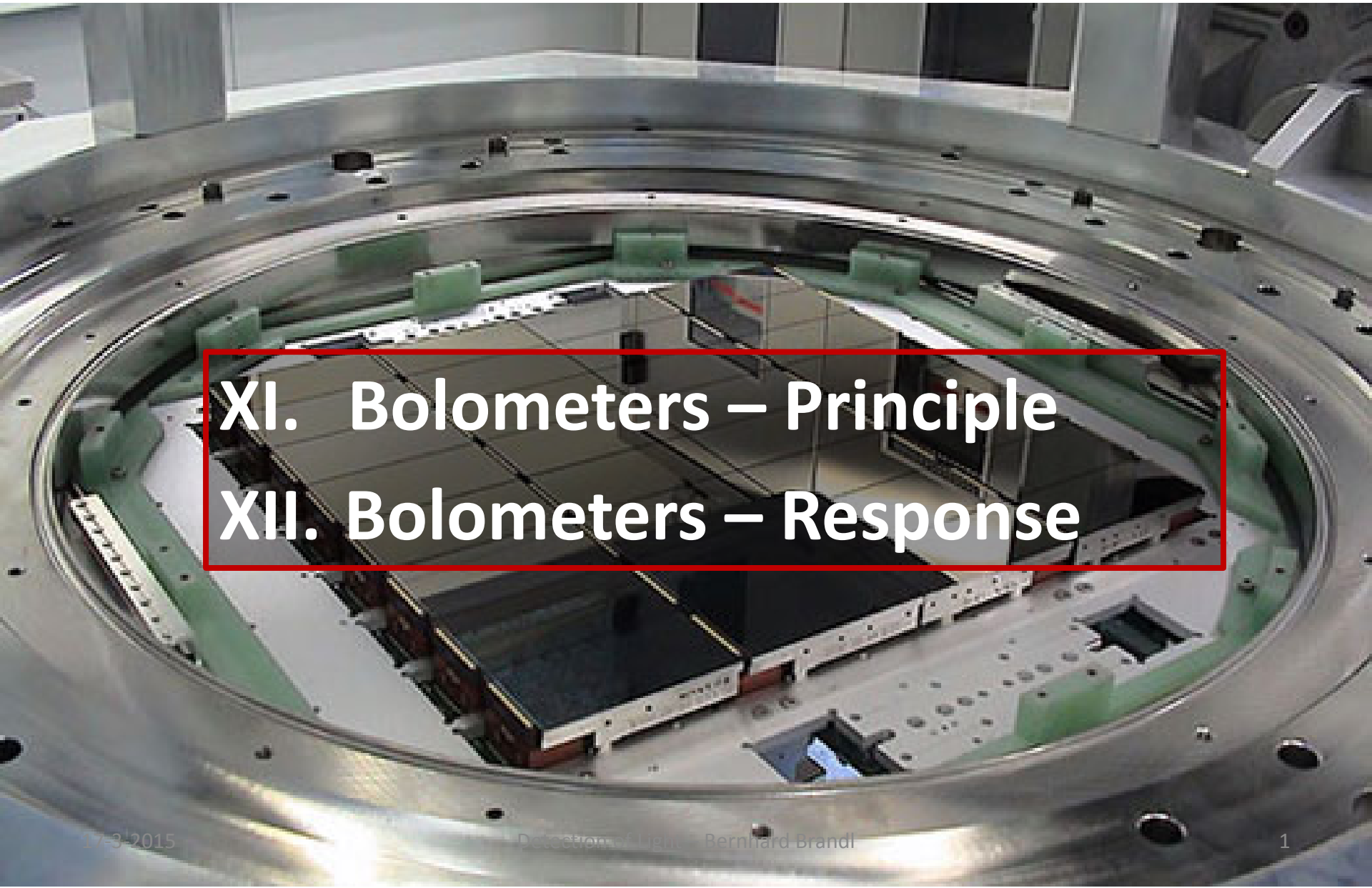
Detection of Light



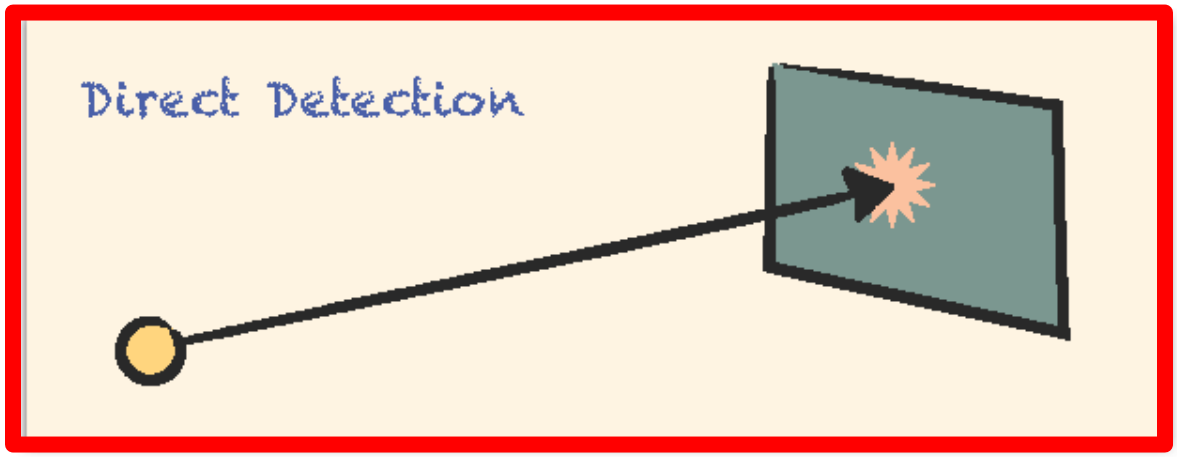
XI. Bolometers – Principle

XII. Bolometers – Response

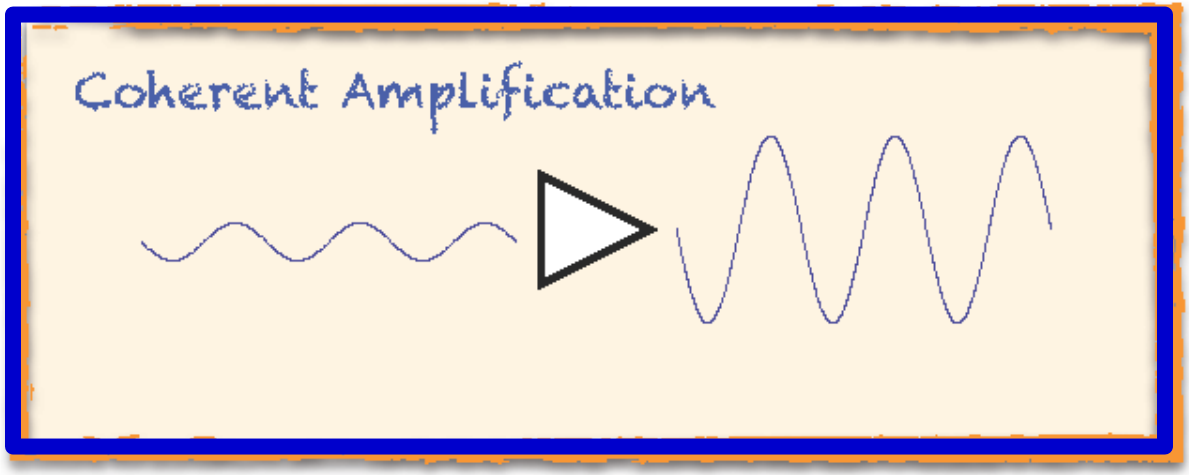
Fundamental Types of Detectors

Two Fundamental Principles of Detection

Respond to individual photon energy



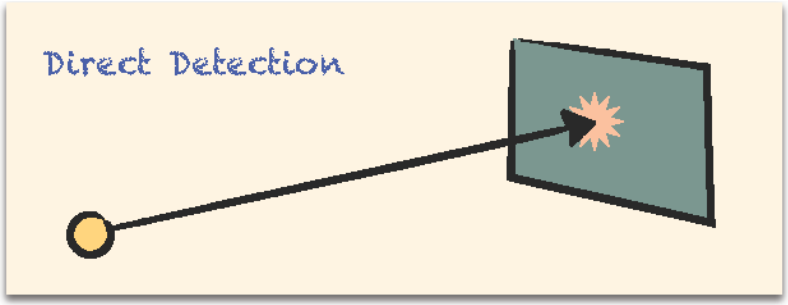
Photons



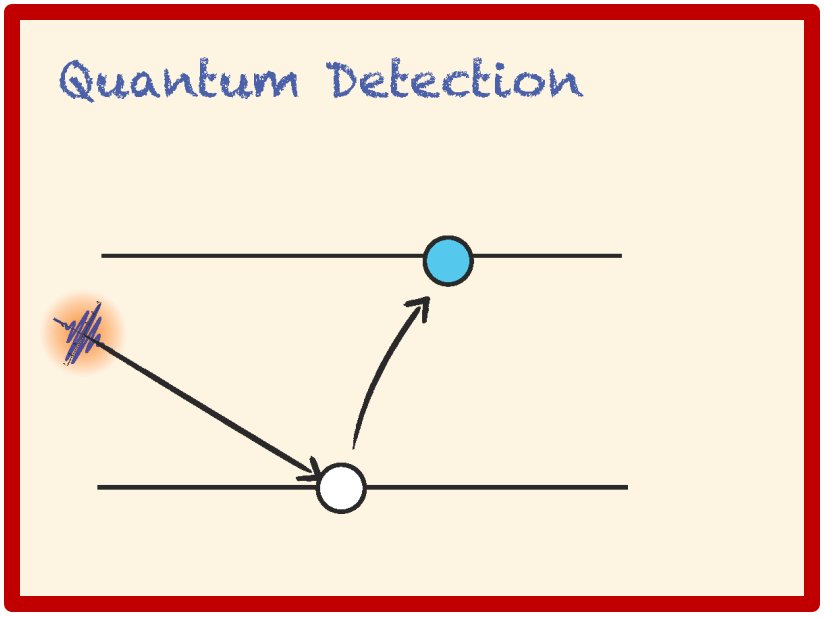
Waves

Respond to electrical field strength and preserve phase

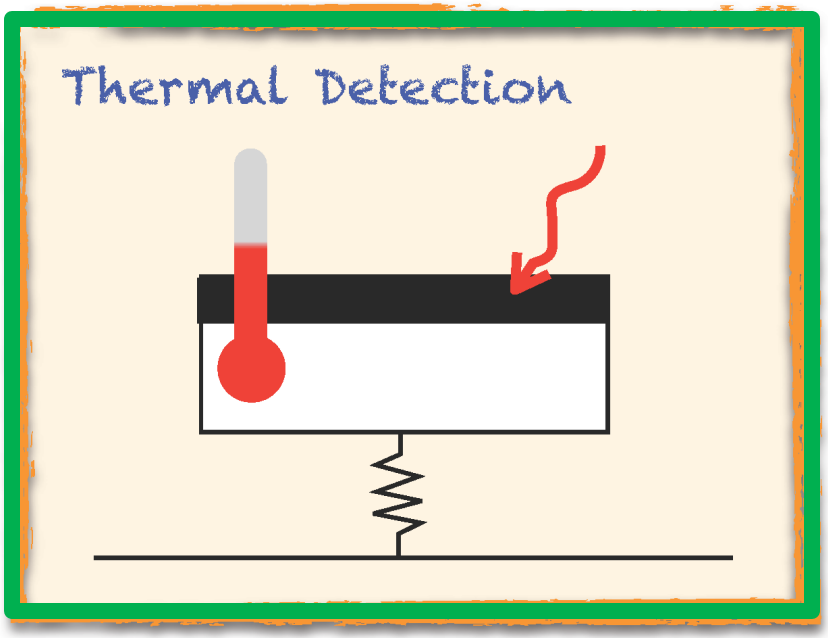
Two Types of *Direct* Detection



Based on photoelectric effect
(release of bound charges)



Thermalize photon energy



A Brief History of Bolometers

Bolometer Beginnings

The father of astronomical bolometers is Frank Low. He invented the Ge:Ga bolometer in 1961.

Frank Low
(1933 – 2009)

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

Low-Temperature Germanium Bolometer

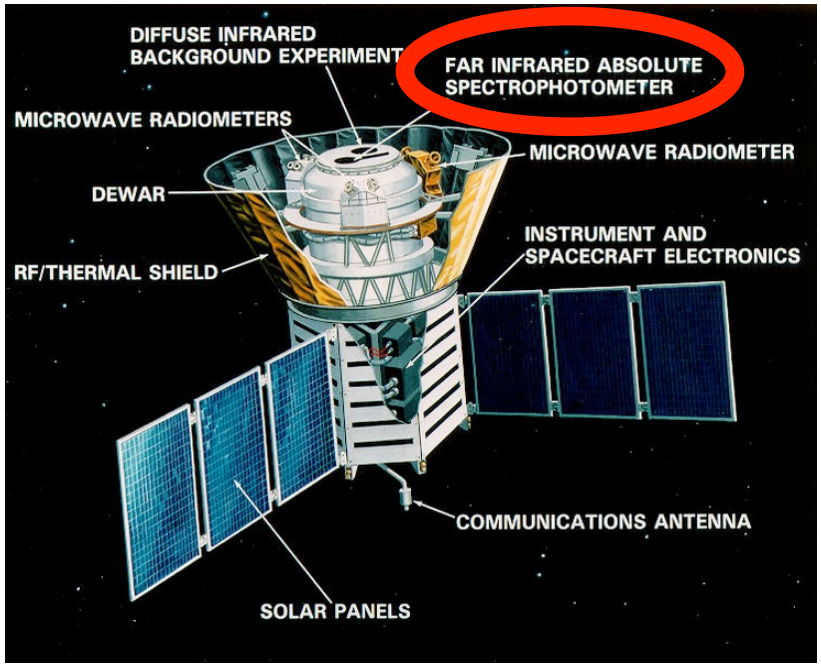
FRANK J. LOW
Texas Instruments Incorporated, Dallas, Texas
(Received March 29, 1961)

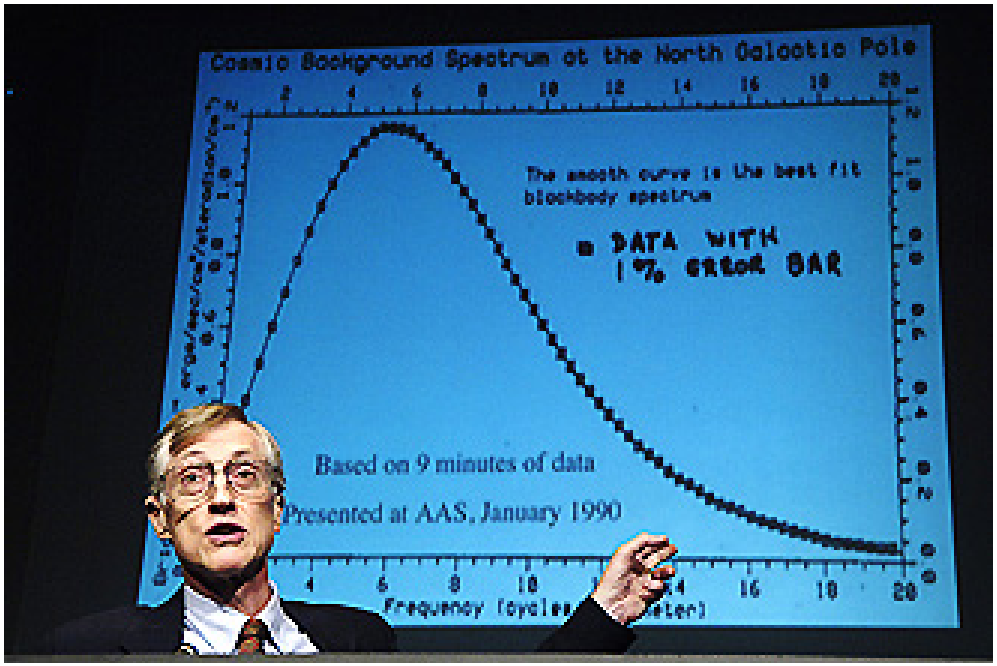
A bolometer, using gallium-doped single crystal germanium as the temperature-sensitive resistive element, has been constructed and operated at 2°K with a noise equivalent power of 5×10^{-13} w and a time constant of 400 μsec. Sensitivities approaching the limits set by thermodynamics have been achieved, 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^{-3} sec, is 10^{-15} w. The detector is suitable for use in both infrared and microwave applications.

The night sky has a large thermal emission at 10 microns
SOLUTION: rapid beam switching to remove the sky background

A milestone in the History of Bolometers

Many references to John C. Mather (Applied Optics 21, 1125, 1982):



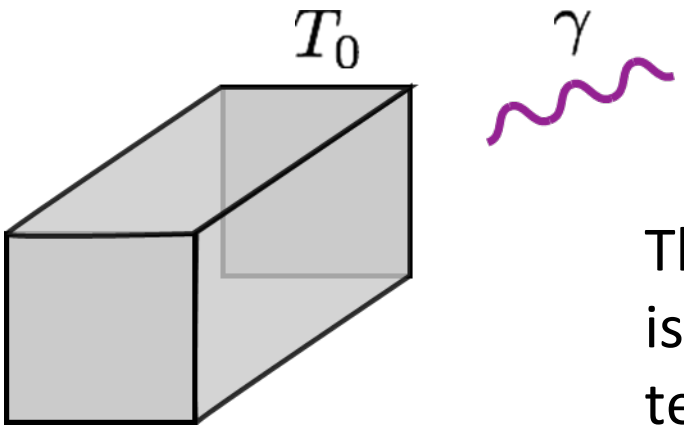


PI for Far Infra Red Absolute Spectrophotometer (FIRAS) on COBE

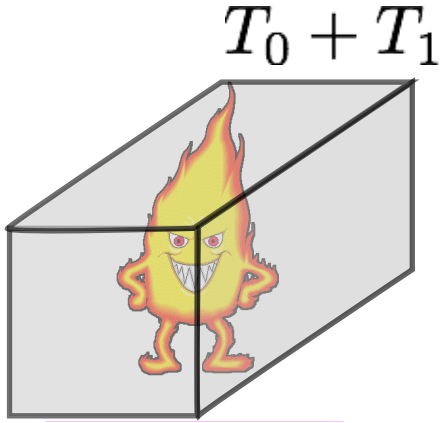
The Nobel prize in Physics 2006 (with George Smoot)

Basic Principle

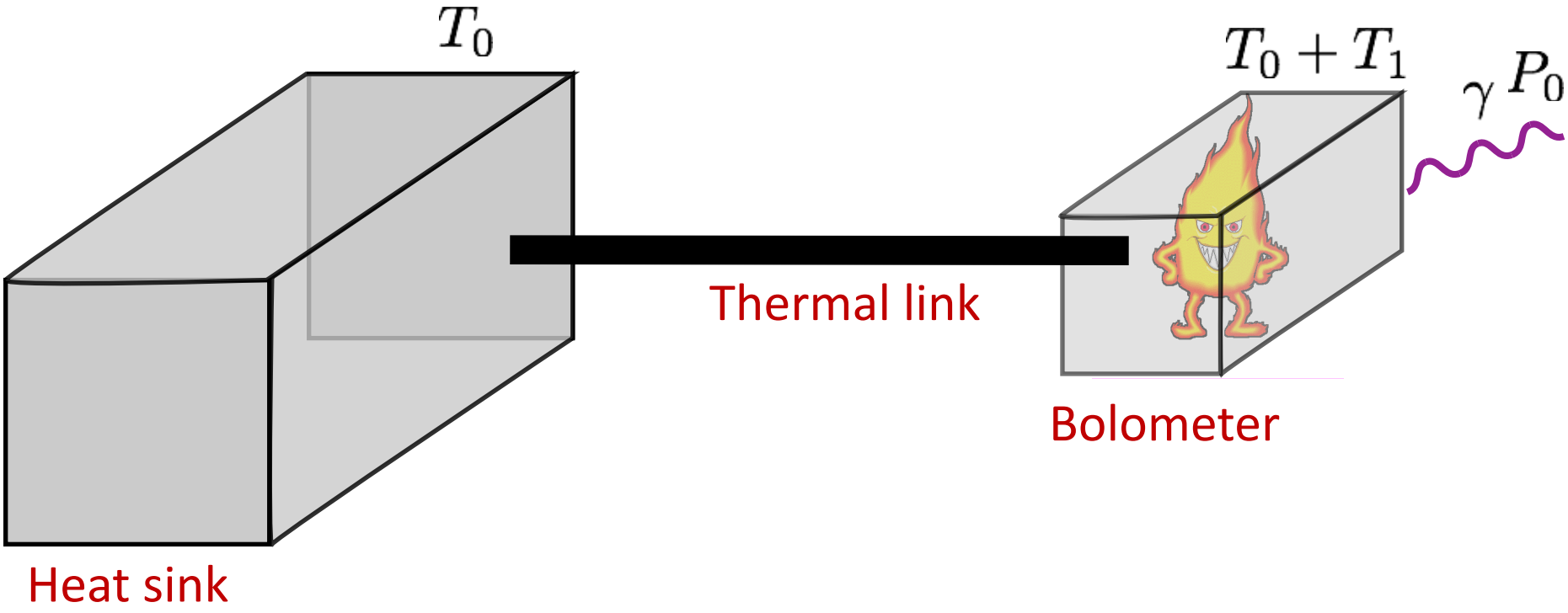
Basic Principle



The incoming photon energy $E_\gamma = hc/\lambda$ is absorbed as heat and increases the temperature of the absorber.

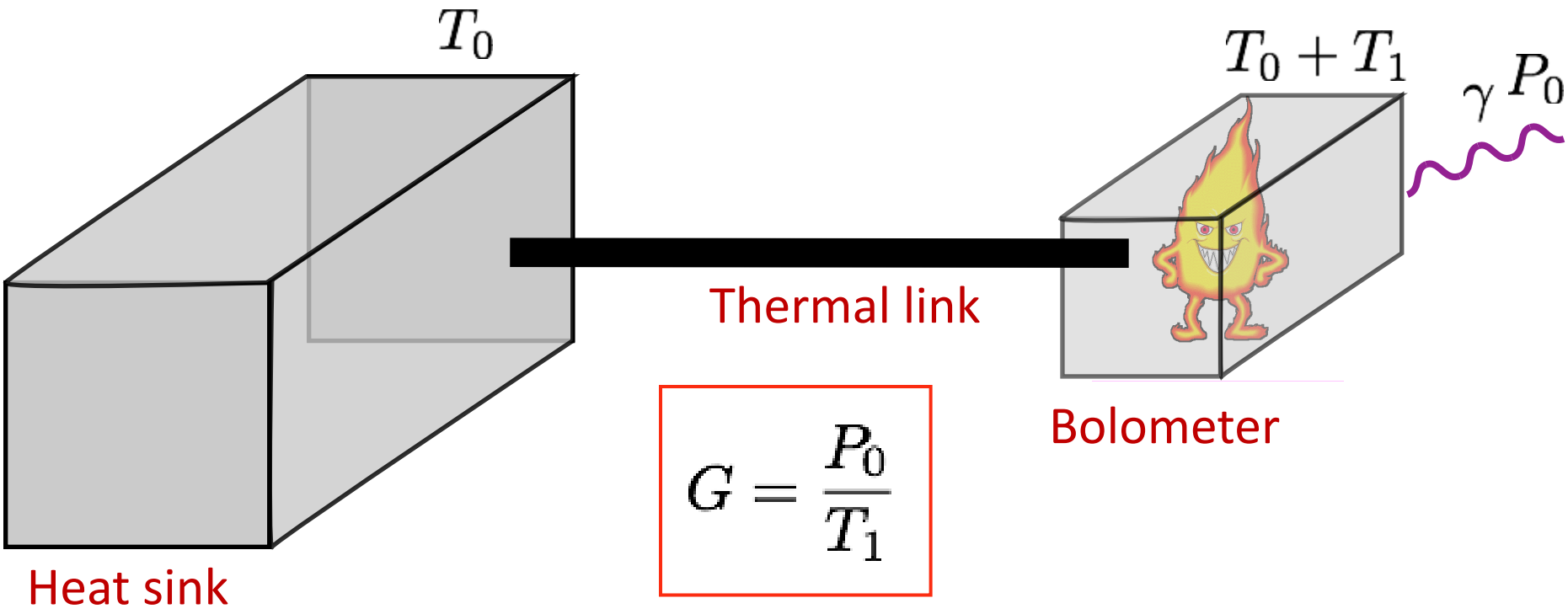


Steady State Operation of a Bolometer (1)



- Incoming photon power flux P_0 increases bolometer from equilibrium temperature T_0 to $T_0 + T_1$.

Steady State Operation of a Bolometer (2)

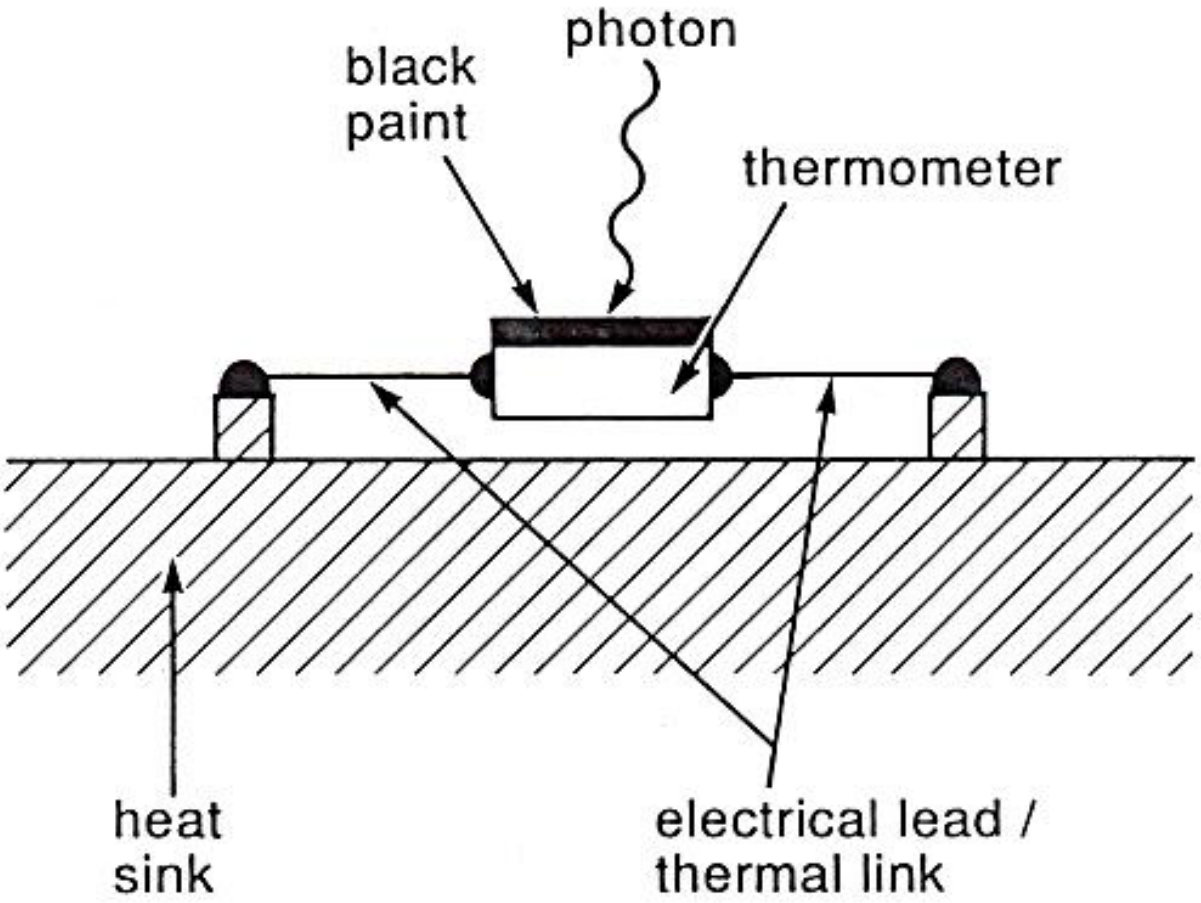


$$G = \frac{P_0}{T_1}$$

- A thermal link with thermal conductance G transfers power to a heat sink of temperature T_0

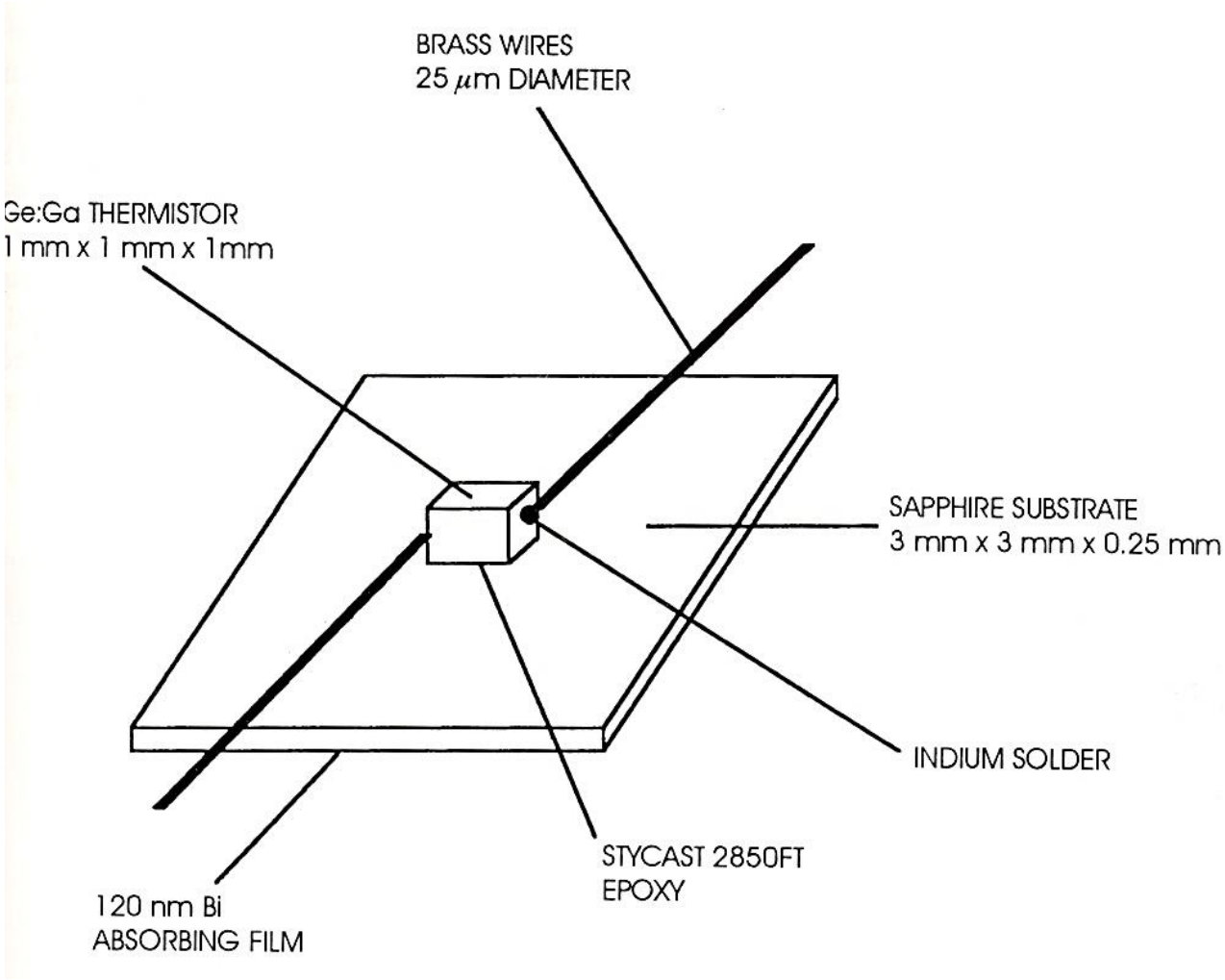
Thermal conductance ***G*** [W / K]
Thermal heat capacity ***C*** [J / K]

Physical Layout of Semiconductor Bolometer (1)



A chip of doped silicon or germanium acts both as bolometer detector and thermometer.

Physical Layout of Semiconductor Bolometer (2)

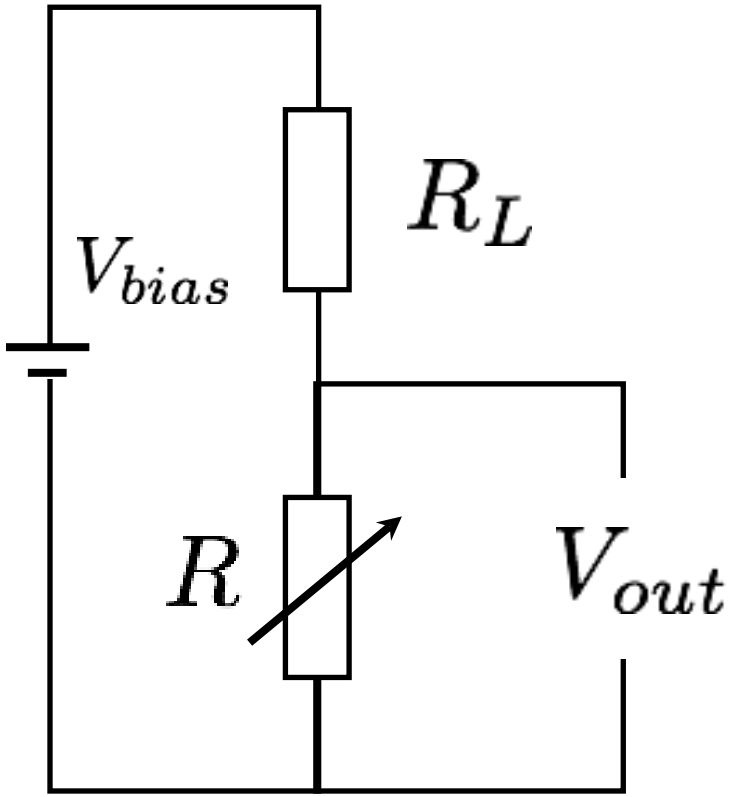


High input impedance amplifier measures the voltage → voltage depends on resistance → resistance depends on temperature.

Bolometer Readout Circuit

Johnson noise is NOT the limiting factor for bolometers so we don't worry about a high resistance *R*.

We can use this circuit to measure the bolometer resistance *R* (or what we actually measure is V_{out}.)



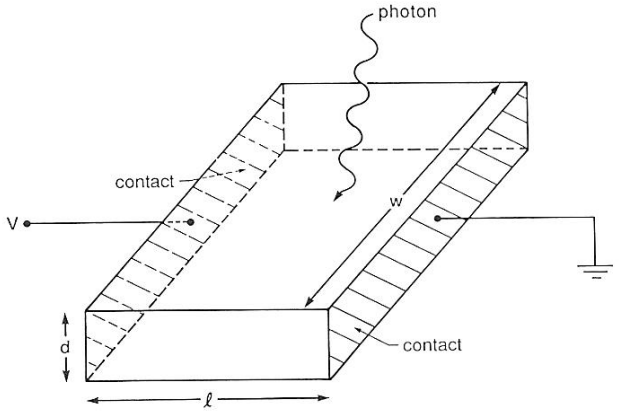
We assume that R_L >> *R* so that the current through the bolometer is limited by R_L.

Electrical Properties

R ⇔ T for intrinsic Semiconductors

From previous lectures, we know that the resistance R_d of a seminconductor is:

$$R_d = \frac{1}{\sigma}\frac{l}{wd} = \frac{1}{qn_0\mu_n}\frac{l}{wd}$$



...where the number of charge carriers is:

$$n_0 = 2\left(\frac{2m_n^* kT}{h^2}\right)^{3/2} e^{-(E_c - E_F)/kT}$$

So, *R* depends on the temperature as:

$$R = R_0 T^{-3/2} e^{B/T}$$

Temperature Coefficient of Resistance

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/

Low Temperatures = good Resistivity

Bolometers suffer from the same fundamental noise mechanisms as photoconductors PLUS the noise arising from thermal fluctuations.

➔ Keep temperature of the bolometer very low: $T < 5K$

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

Approximations for α

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.

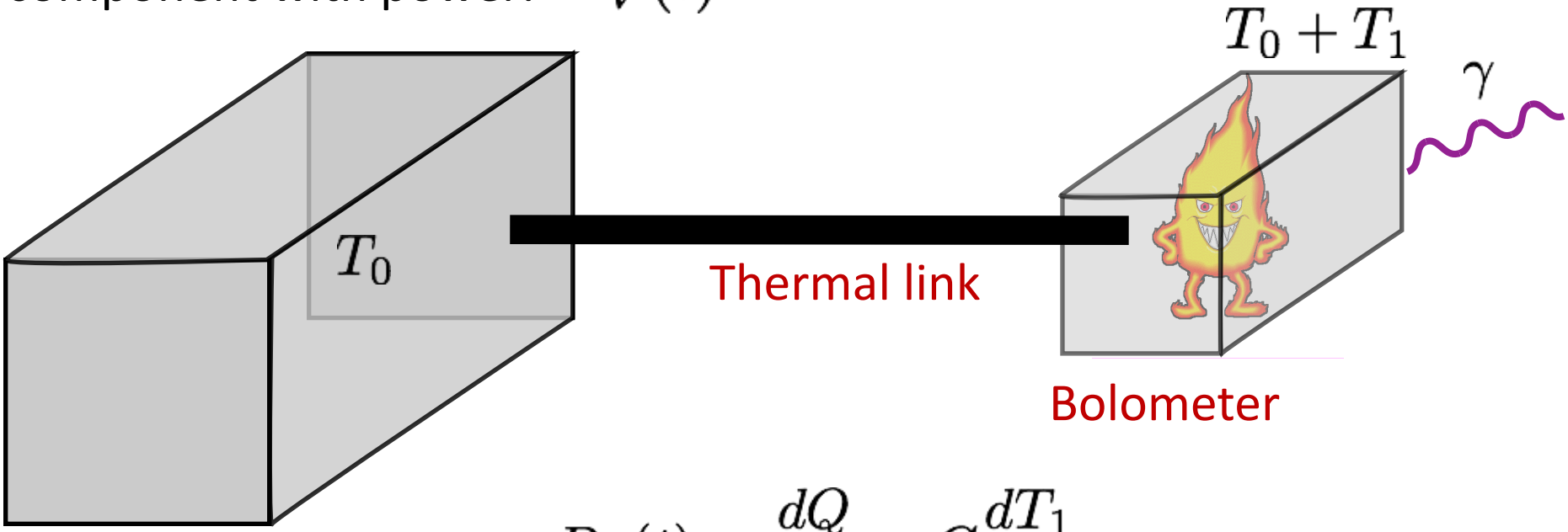
Substituting the hopping resistance into the above equation yields:

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

Time Response

Response of a Bolometer

Add an astronomical source represented as a time varying component with power: $P_V(t)$

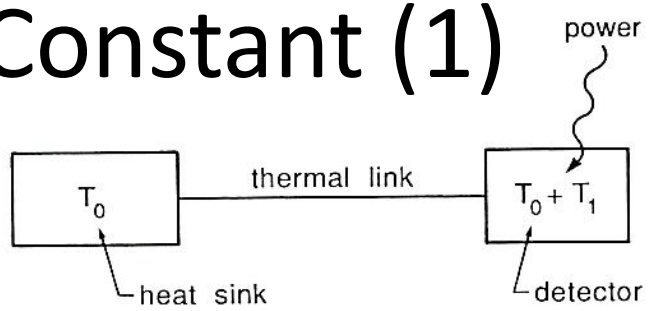


$$\eta P_V(t) = \frac{dQ}{dt} = C\frac{dT_1}{dt}$$

Thermal conductance ***G*** [W / K]
Thermal heat capacity ***C*** [J / K]
T-coefficient of resistance ***α*** [1 / K]

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

Bolometer Thermal Time Constant (1)



The total power absorbed by the detector is:

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

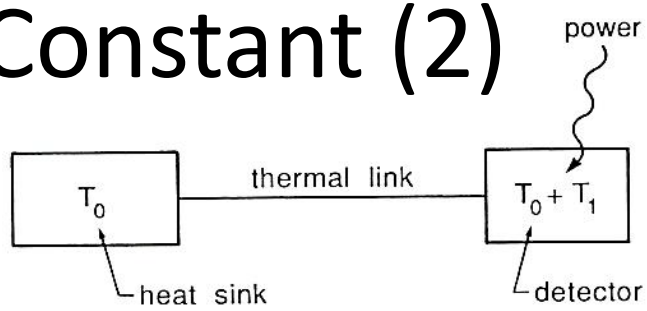
Now we turn on a signal so that:

$$P_V = 0 \quad t < 0$$
$$P_V = P_1 \quad t > 0$$

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

The signal changes exponentially with time constant $\tau_T = C/G$

Bolometer Thermal Time Constant (2)



$$T_1(t) = \frac{P_T}{G} - \frac{\eta P_V}{G} = \frac{P_0}{G} + \frac{\eta P_1}{G}\left(1 - e^{-t(C/G)}\right)$$

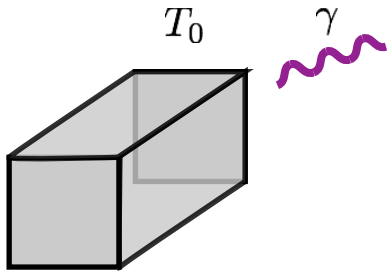
The signal changes exponentially with time constant $\tau_T = C/G$

For $t >> \tau_T$, the temperature $T_1 \sim (P_0 + \eta P_1)$

If you measure the temperature then you know the power.

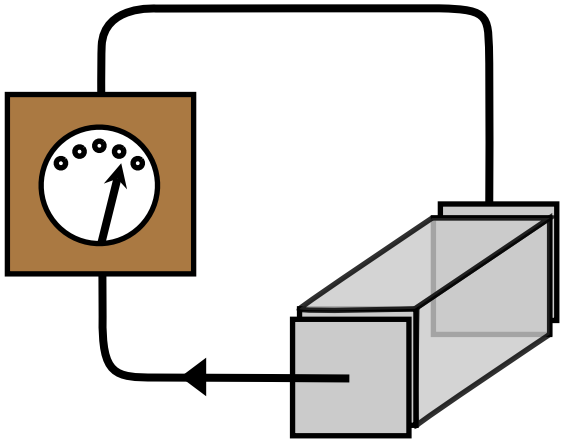
Two Sources of Bolometer Heating

1. Incoming (detected) photon flux produces $P_V(t)$:



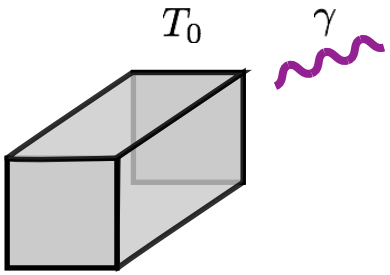
2. Electrical heating from the current sensing in the thermometer P_I:

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

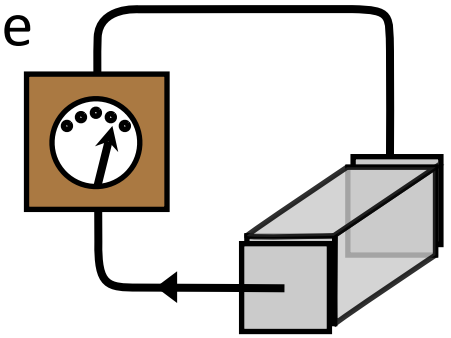


Two Sources = Two Time Constants

1. Heat flowing out of the bolometer through the thermal link gives rise to $\tau_T = \frac{C}{G}$



2. The electrical power changes with an electrical time constant $\tau_E = \frac{C}{G - \alpha(T) P_I}$



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

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

Frequency Response

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

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

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 [V / W].

Bolometer Responsivity

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

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

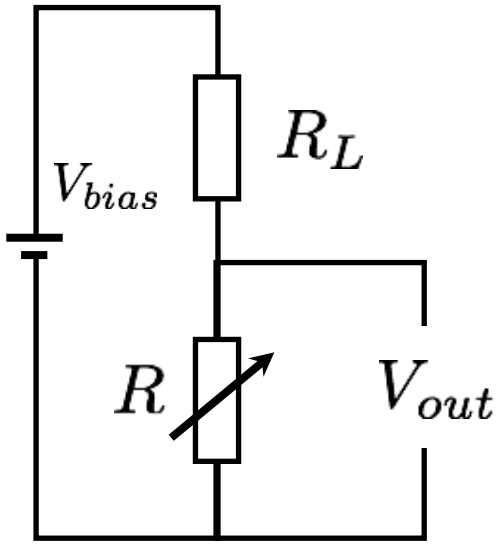
So, we get for the electrical responsivity: $S_E = \dfrac{dV}{dP} = \dfrac{\alpha(T)V}{G - \alpha(T)P_I}$

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

Measuring Electrical Responsivity

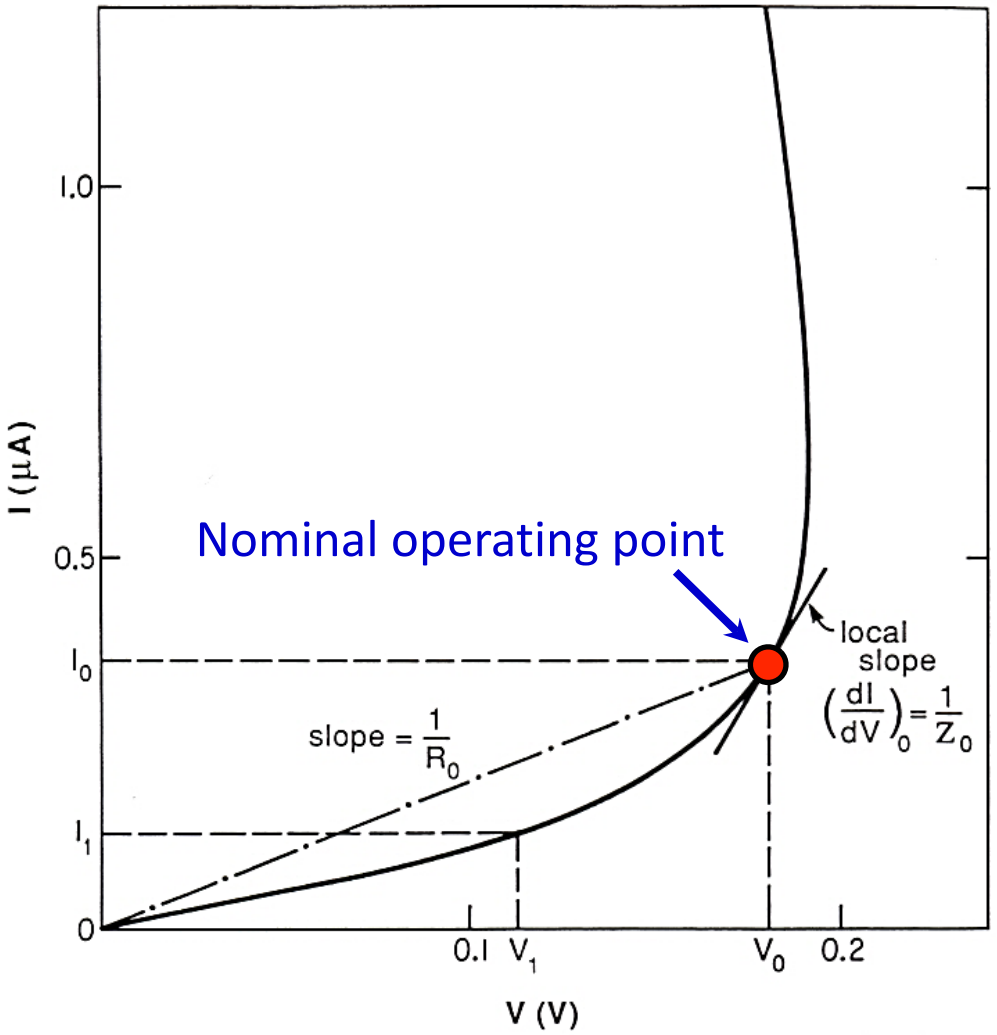
The detector properties *G* and *α* are not always known → need to determine them by measurement.

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



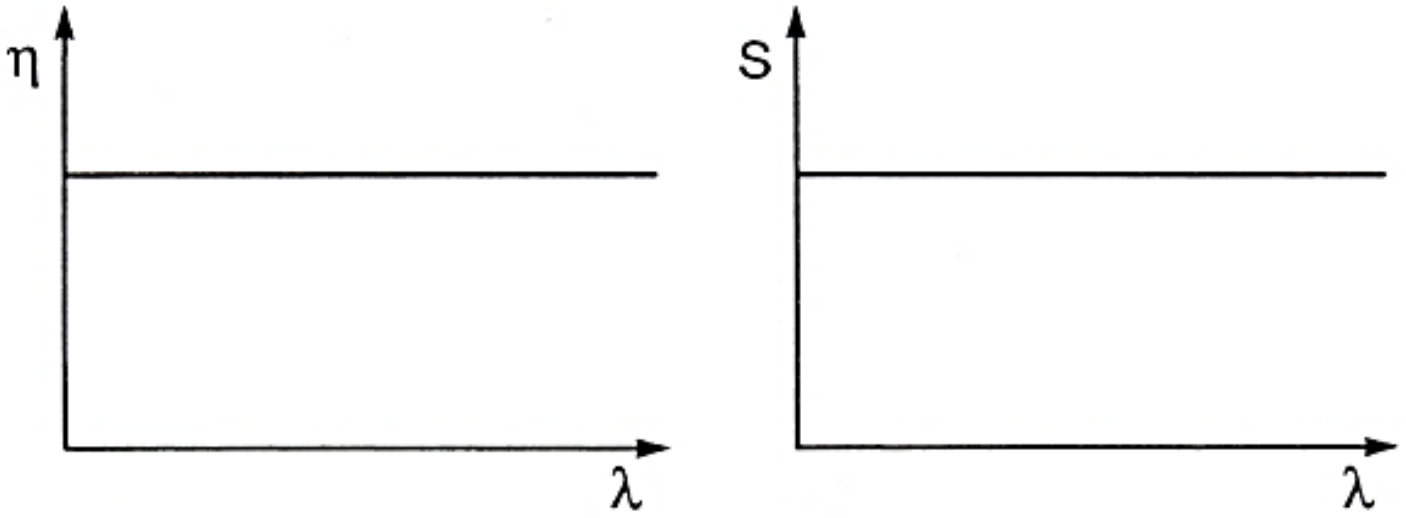
Note that the local slope is differe from "the resistance" R because o the non-linearity of the load curve

The Load Curve



Detector Responsivity ⇔ Electrical Responsivity

S_E is the electrical responsivity, but now we can derive the responsivity to incoming radiation (where only a fraction η of the incoming energy is absorbed):

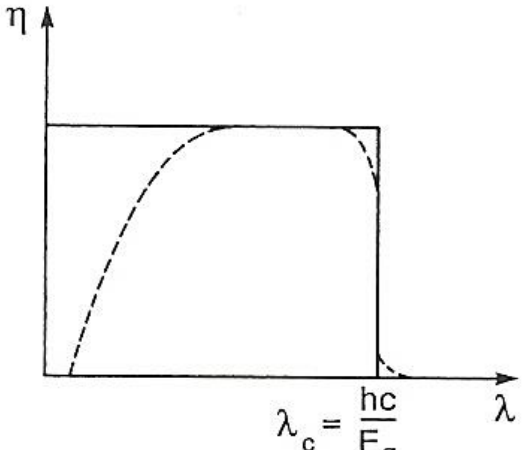


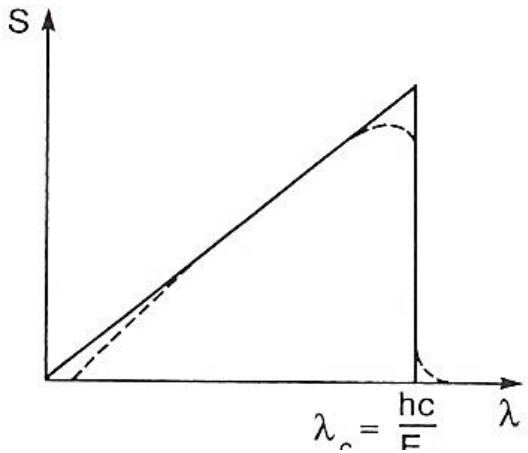
$$S_R = \eta S_E = \frac{\eta}{2I}\left(\frac{Z}{R} - 1\right)$$

Responsivity compared to Photodetectors

Photoconductor:

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



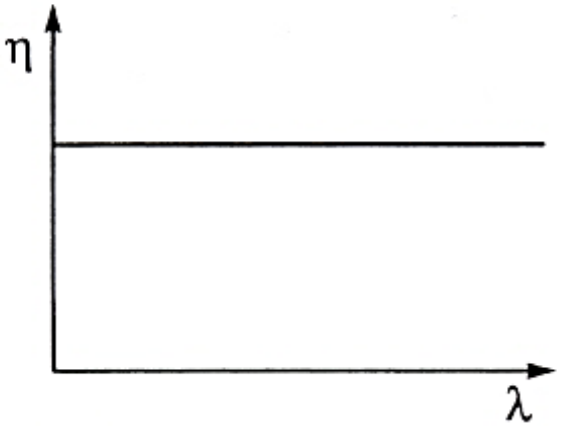


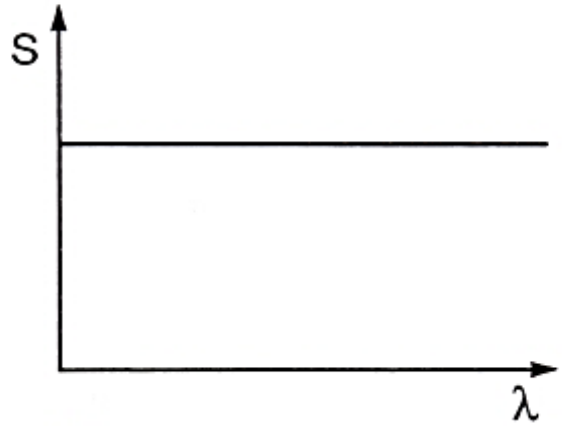
Photodiode:

$$S_{photodiode} = \frac{\eta \lambda q}{hc}$$

Bolometer:

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





The bolometer responsivity is independent of the wavelength λ (assuming the QE η is independent of λ).

Noise and NEP

Negative electro-thermal Feedback

Johnson noise can be characterized by the noise voltage

$$V_J = < I_J^2 >^{1/2} R$$

CASE 1: if V_J is added to the bias voltage, the dissipated power P increases and R decreases (because of the negative resistance coefficient) so the voltage across the detector decreases.

CASE 2: if V_J opposes the bias voltage, the dissipated power P decreases and R increases, so the net voltage across the detector still decreases.

In both cases, the detector response opposes the ohmic voltage change resulting from Johnson noise → negative electro-thermal feedback.

$$< I_J^2 >= \frac{4kT\Delta f}{R}$$

The total NEP

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).

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.

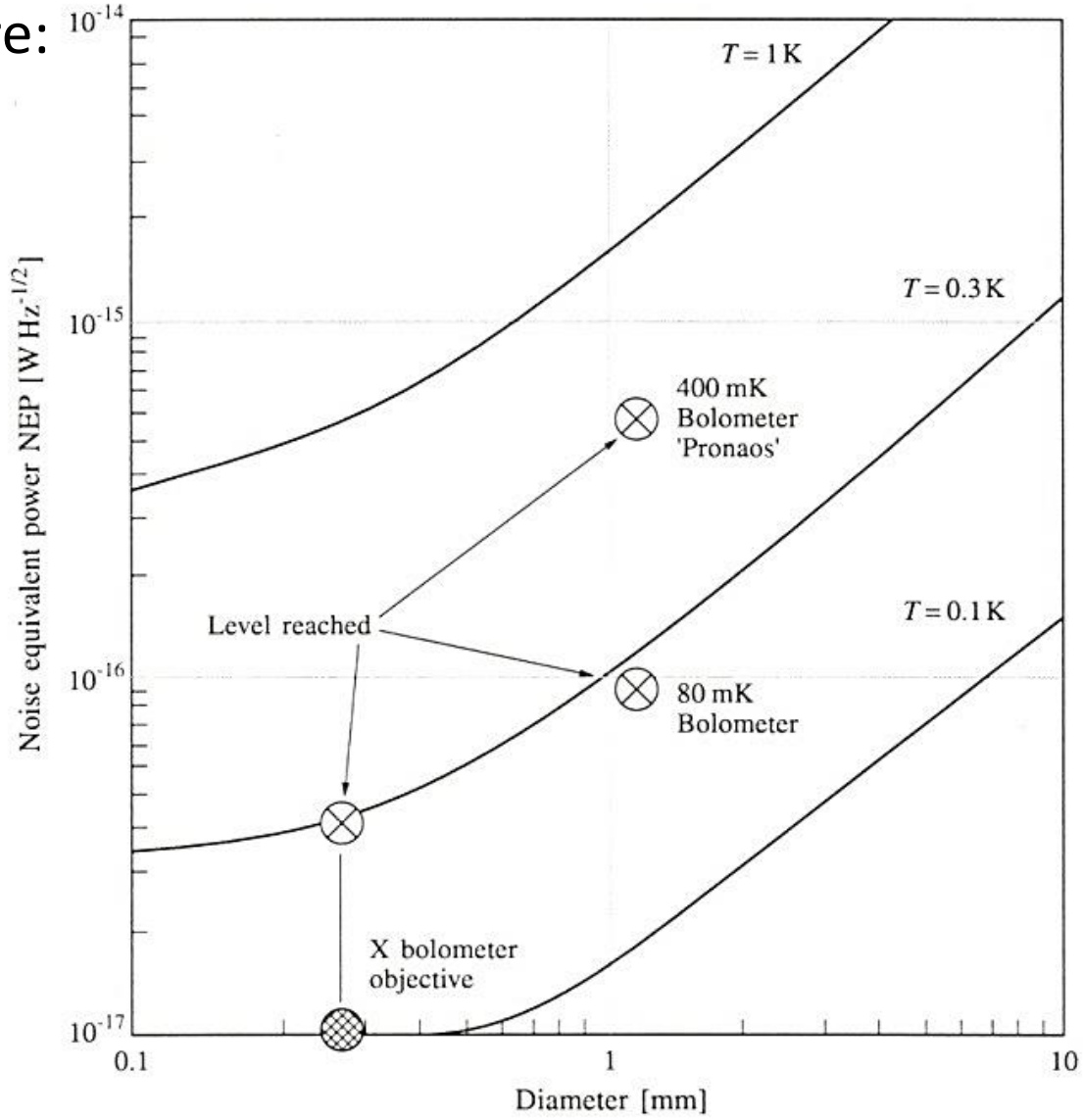
Photon noise: $$NEP_{photon} = \frac{hc}{\lambda}\left(\frac{2\varphi}{\eta}\right)^{1/2}$$

...due to fluctuations in the photon flux. *(Note: Bolometers no not have G-R noise – no particle pairs created/destroyed).*

Total NPE noise: $$NEP = \sqrt{(NEP_{photon}^2 + NEP_\tau^2 + NEP_J^2 + ...)}$$

NEP Performance of Bolometers

Performance of bolometers for sub-mm detection in terms of diameter and temperature:

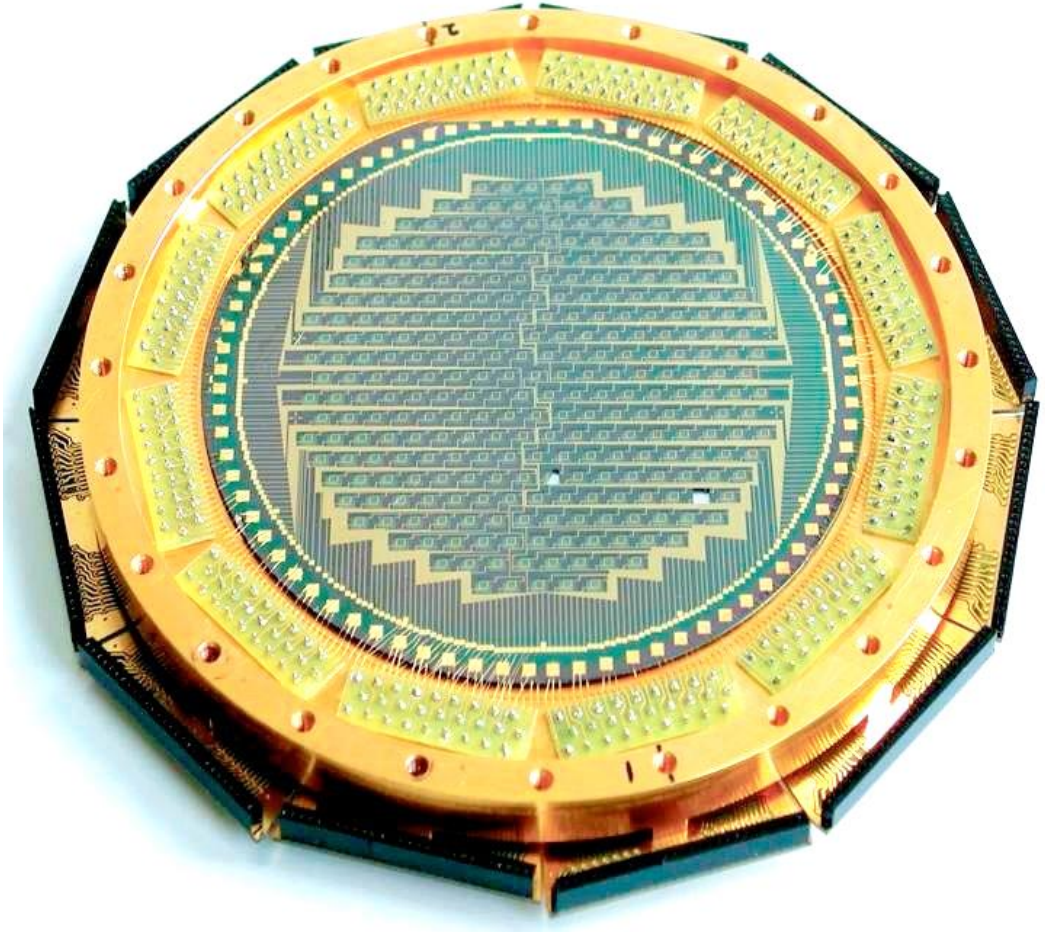


(from Puget & Coron 1994 for the SAMBA mission).

State-of-the-Art Bolometers

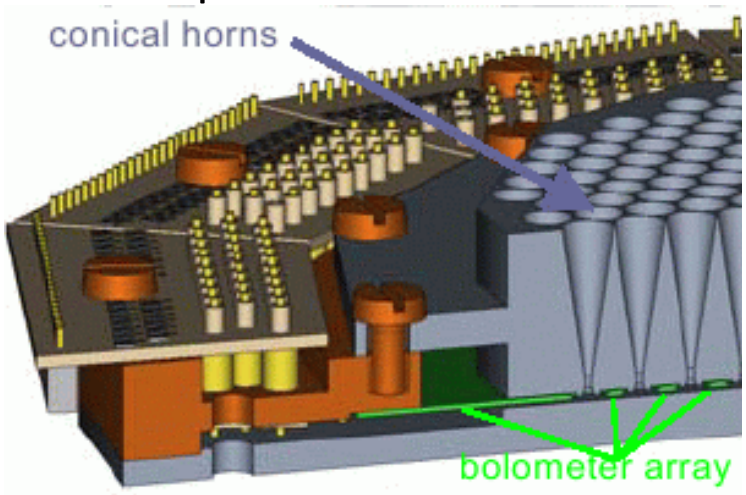
LABOCA

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



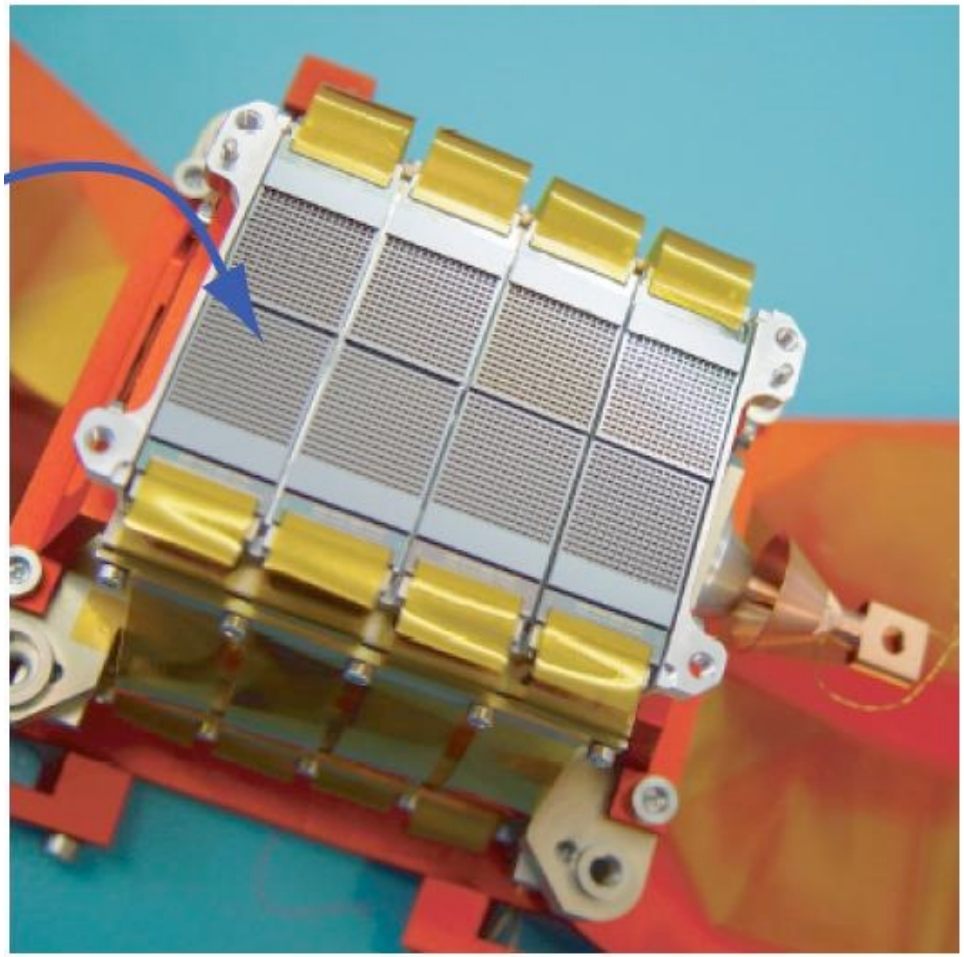
The signal photons are absorbed by a thin metal film cooled to about 280 mK.

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 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.

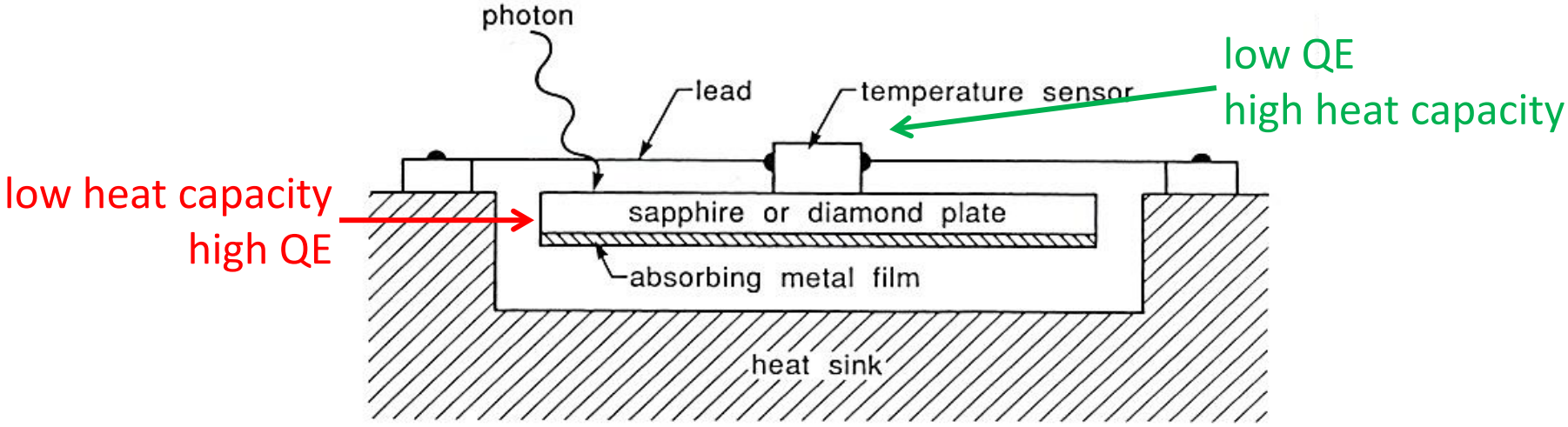
The 0.3 K multiplexers are bonded to the back of the sub-arrays. Ribbon cables lead to the 3K buffer electronics.

Composite Bolometers

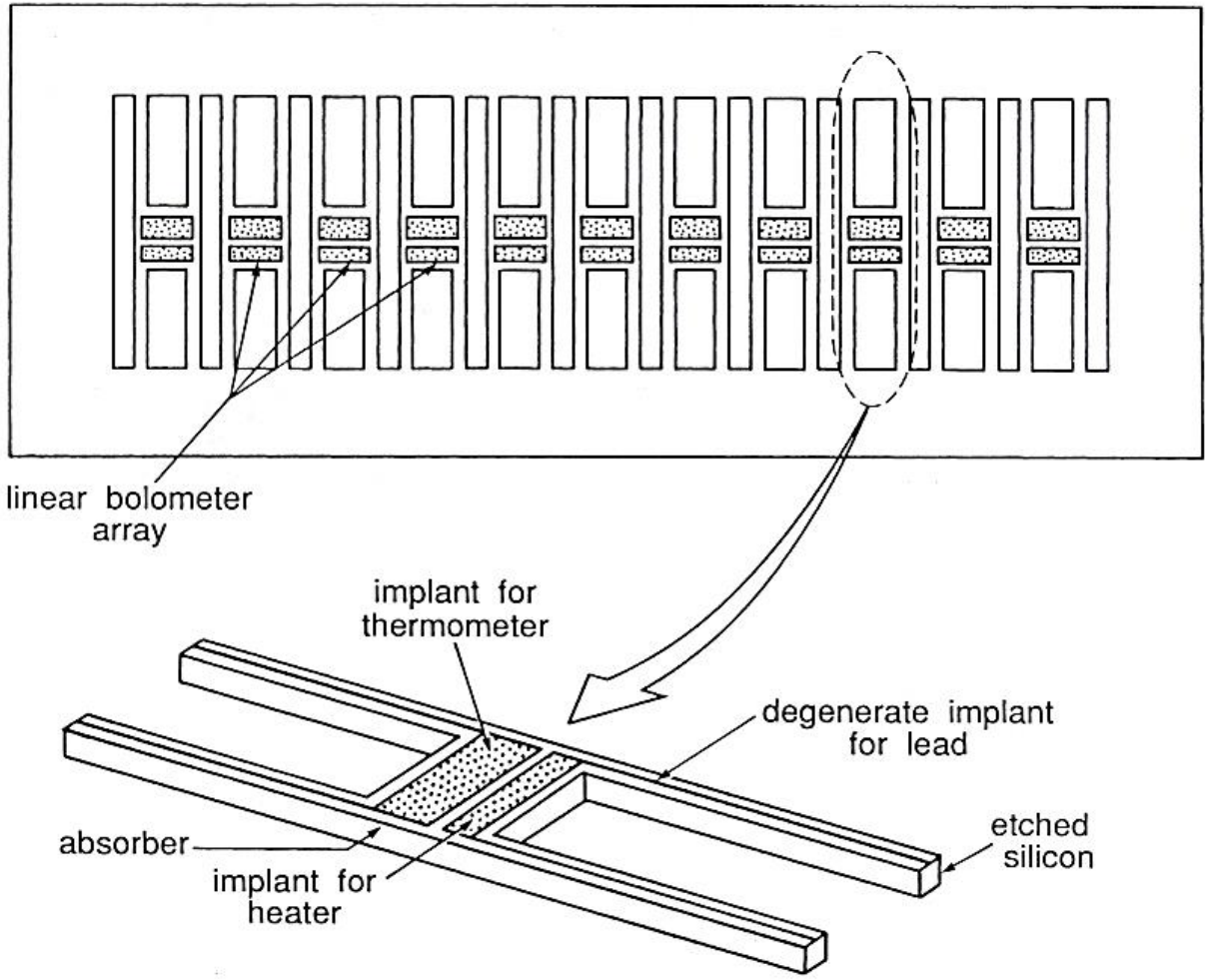
In some cases, Si bolometers with high impurity concentrations can be very efficient absorbers. In many cases, however, the QE is too low.

Quick solution: enhance absorption with black paint – but this will 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.

Etched Bolometers

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