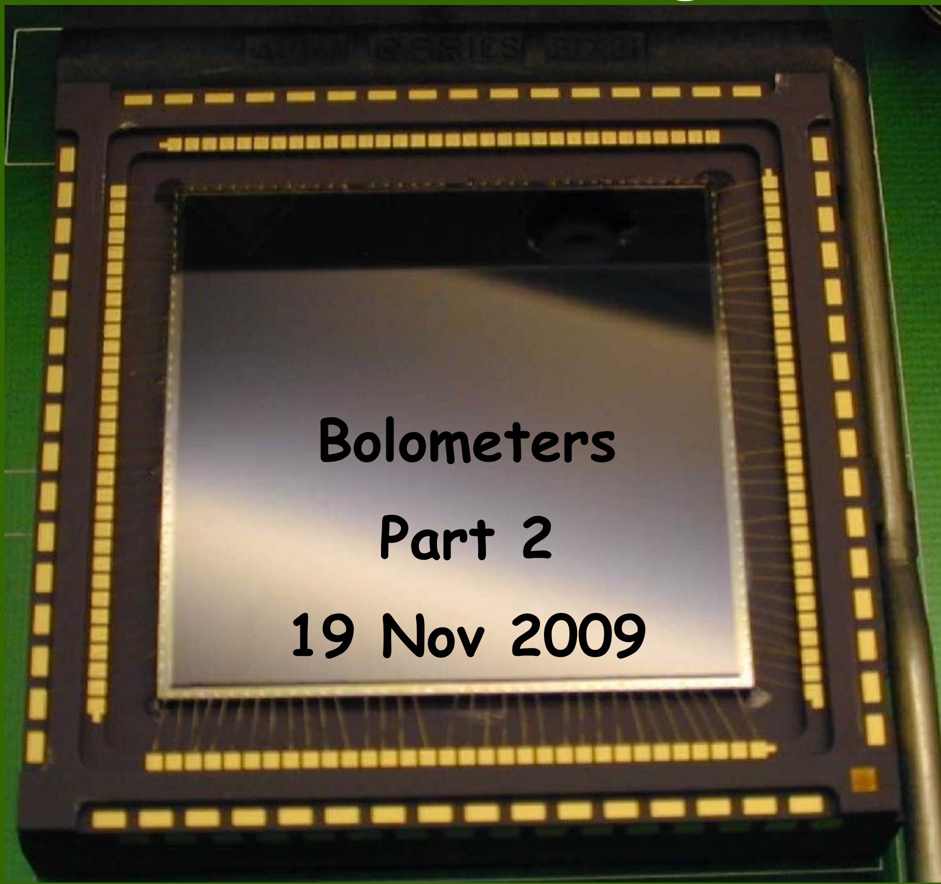
Detection of Light



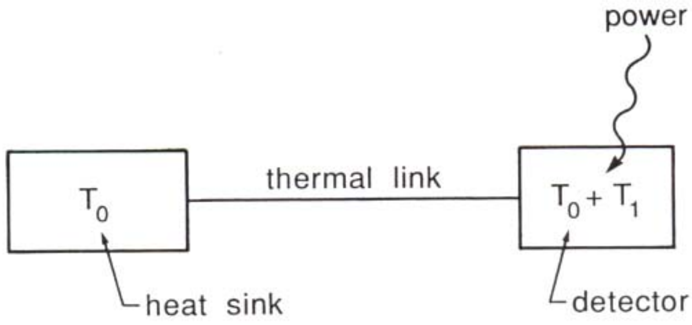
See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Reminder: Bolometer Basics

Basic Operation

Detector connected via a weak thermal link of thermal conductance $G = P / T_1$ to a heat sink of temperature T_0.

A constant power (background) raises the temperature of the detector by T_1.



Now we add an additional, variable component $P_V(t)$ =(astronomical signal) → the temperature will change, according to

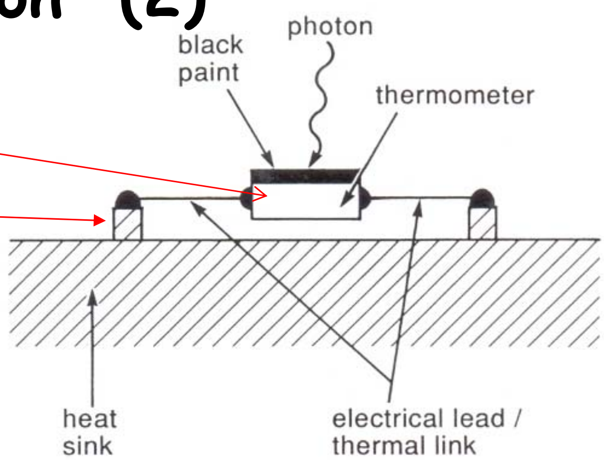
$$\eta P_V(t) = \frac{dQ}{dt} = C\frac{dT_1}{dt}$$

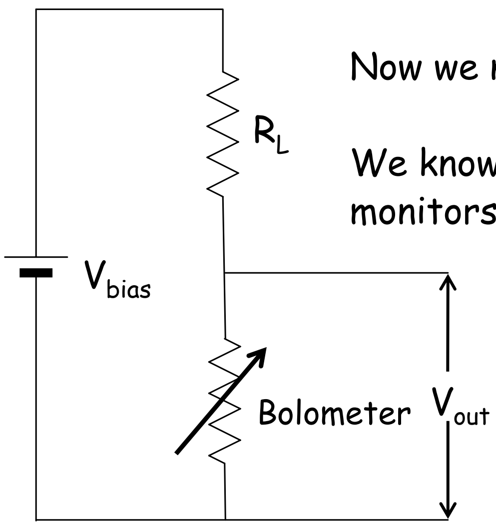
where η = quantum efficiency, Q = thermal energy, and $C = dQ/dT_1$ = the heat capacity [J/K].

Basic Operation (2)

Chip of doped silicon or germanium

Mounts to the heat sink must provide good thermal contact and electrical isolation.

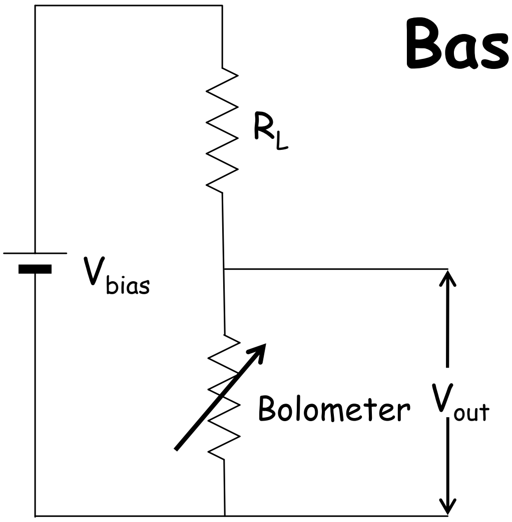




Now we need to measure the temperature change – How?

We know, R = f{T} → high input impedance amplifier monitors the voltage (-changes) across the detector.

Basic Operation (3)



Problem: apply voltage V_{bias} to measure R → current

$P_I = I^2 \times R(T)$ is the electrical dissipated power, which we need to correct for.

But: $P_I \sim R = f\{T\}$ and changes with an electrical time constant of: $\tau_E = \dfrac{C}{G - \alpha(T) P_I}$

(with the temperature coefficient of resistance α).

The detector cools exponentially with a thermal time constant of $\tau_T = C / G$.

Since $\alpha(T) < 0$ *for semiconductors*
→ $\tau_E < \tau_{th}$ → electrothermal feedback (→ faster response)

➔ Frequency response: $S(f) = \dfrac{S(0)}{\left[1 + (2\pi f \tau_E)^2\right]^{1/2}}$, where S_0 is the low frequency responsivity

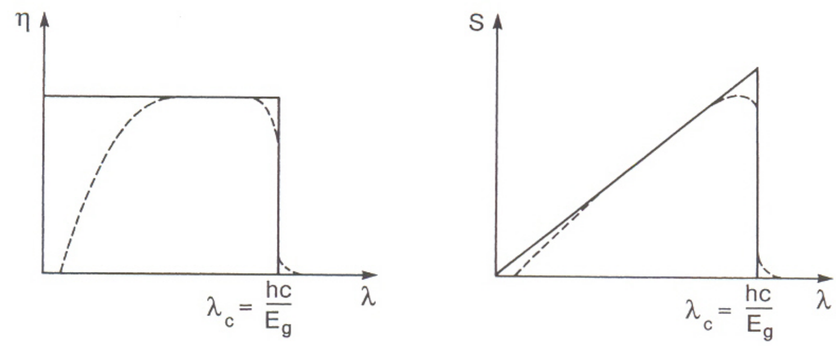
Performance

Photoconductor

$$S_{Ph-cond} = \frac{\eta \lambda q G}{hc}$$

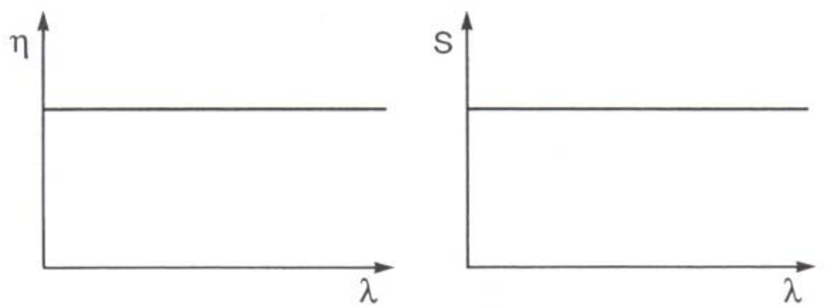
Photodiode:

$$S_{Ph-diod} = \frac{\eta \lambda q}{hc}$$



Bolometer:

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



Note: The bolometer responsivity is independent of the wavelength of operation (as long as the QE η is independent of λ)

Super-conducting Bolometers

Side note: Superconductivity

From Wikipedia: *Superconductivity is a phenomenon occurring in certain materials at extremely low temperatures, characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field (Meissner effect).*

- The electrical resistivity of a metallic conductor decreases gradually as the temperature is lowered. Even near absolute zero a real sample of copper shows a non-zero resistance.

- The resistance of a superconductor drops abruptly to zero when the material is cooled below its "critical temperature T_C". An electrical current flowing in a loop of superconducting wire can persist indefinitely with no power source.

- Superconductivity occurs in a wide variety of materials, including simple elements like tin and aluminum, various metallic alloys and some heavily-doped semiconductors. Superconductivity does not occur in noble metals like gold and silver, nor in most ferromagnetic metals.

- The crystal lattice deforms in a way allowing electrons to couple into "Cooper pairs" (BCS theory) that can move freely through the crystal lattice.

- Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes

Temperature Sensing

Consider a cylindrical wire:

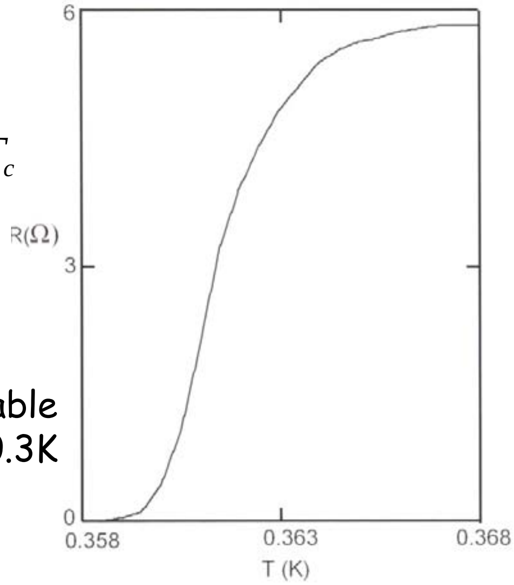
Ampere's law predicts a tangential magnetic field along a wire of radius r in which the current I flows.

Because of the Meissner effect superconduction can only occur below a critical magnetic field H_c. Because H_c is small the wire may be normally conducting at the surface but can be superconducting inside at smaller radii.

The electrical resistance of that wire is:

$$\frac{R}{R_n} = \frac{1}{2}\left\{1+\left[1-\left(\frac{T_c - T}{\delta T_c}\right)^2\right]^{1/2}\right\}, \qquad T_c - \delta T_c \le T \le T_c$$

where R_n is the normal resistance and I_c is the maximum current at which the wire is superconducting, and $\delta T_c = I(\mathrm{d}I_c/\mathrm{d}T)^{-1}$.



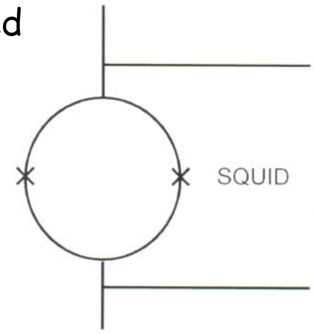
Resistance of a superconducting film – suitable for a bolometer with a heat sink at 0.3K

Generally, superconducting bolometers can be much faster than semiconducting ones.

SQUIDs

SQUID = superconducting quantum interference device, based on the Josephson effect:
If two pieces of superconductor separated by a thin layer of insulator a supercurrent can flow between them.

In SQUIDs two of these Josephson junctions are connected in a loop.



The output voltage of a biased SQUID is:

$$V = \frac{R}{2}\left\{I^2 - \left[2I_0 \cos\left(\pi\Phi/\Phi_0\right)\right]^2\right\}^{1/2}$$

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 (acts as a low input impedance amplifier).

SQUIDs are the analogon to transistors for superconducting electronics.

Construction and Operation

Heat Capacity

Contributions to the heat capacity of low-T bolometers:

- semiconductors: heat capacity of the crystal lattice
- metals: free electrons

T > 1K: heat capacity of the crystal lattice dominates → Si bolometers

T < 1K: electronic contribution dominates → Ge bolometers preferred

For superconductors below T_C the specific heat drops with T^3.

Generally, the heat capacity can be minimized by choice of material and minimizing the volume.

It is important to minimize also the heat capacity of the leads by making them of dielectric material with thin metal films.

Thermal Conductance

The performance critical parameters of:

- time response
- responsivity
- NEP

all depend on the conductance of the thermal link, *G*.

The thermal conductivity of metals is described by the Wiedemann-Franz relation:

$$k_e \approx \left(\frac{\pi^2 k^2}{3q^2}\right)\sigma T$$

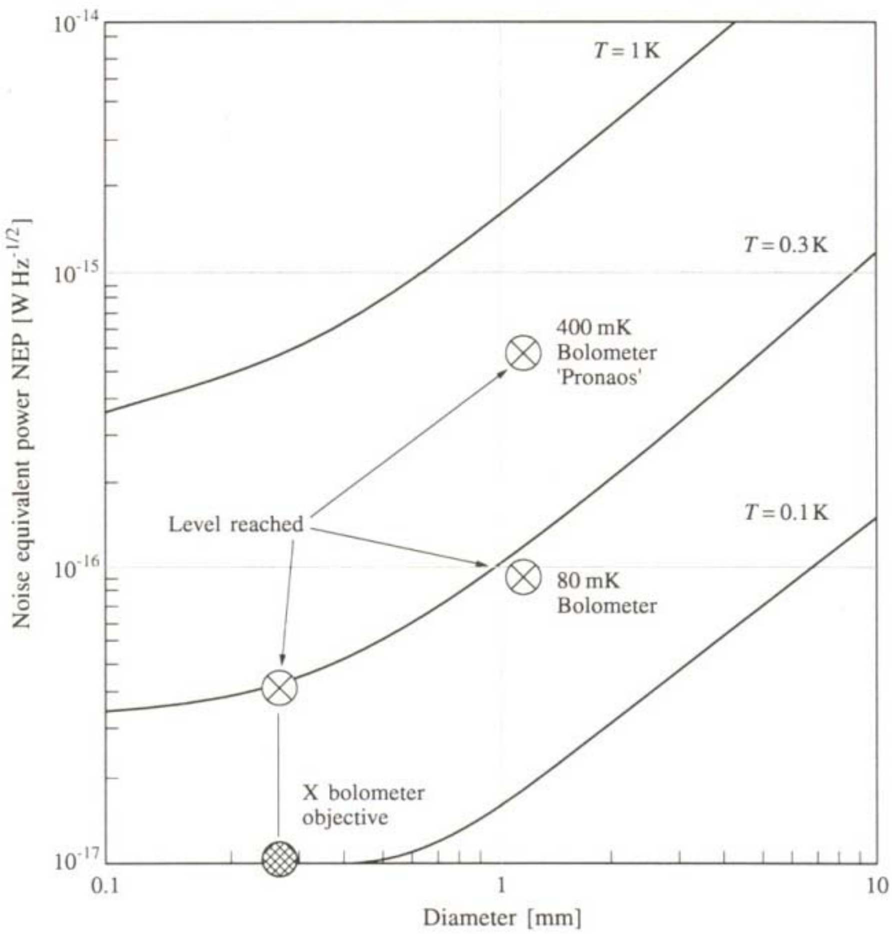
with the Lorentz number $\frac{\pi^2 k^2}{3q^2} \approx 2.45 \cdot 10^{-8} W\Omega K^{-2}$ and the electrical conductivity σ.

If the bolometer is mounted on two leads of length *L* and cross section area *A*

the conductance is: $G = 2\frac{A}{L}k_e$

Generally, the leads must have much lower resistance than the thermometer.

Performance of bolometers for sub-mm detection in terms of diameter and temperature (from Puget & Coron 1994 for the SAMBA mission).

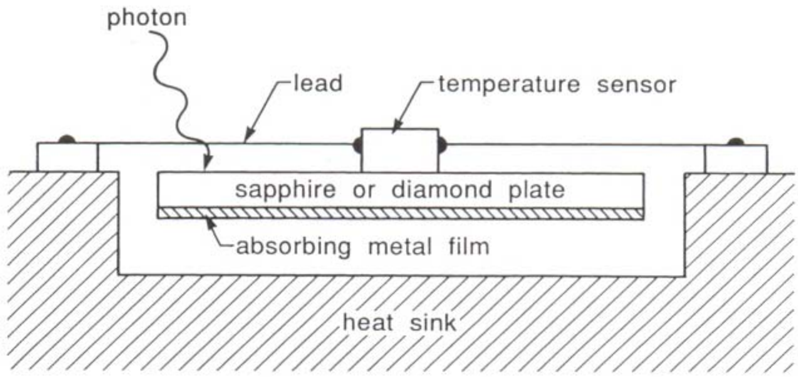


QE and Composite Bolometers

In some cases Si bolometers with high impurity concentrations can be very efficient absorbers.

In many cases, however, the QE is too low. 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 → composite bolometers.

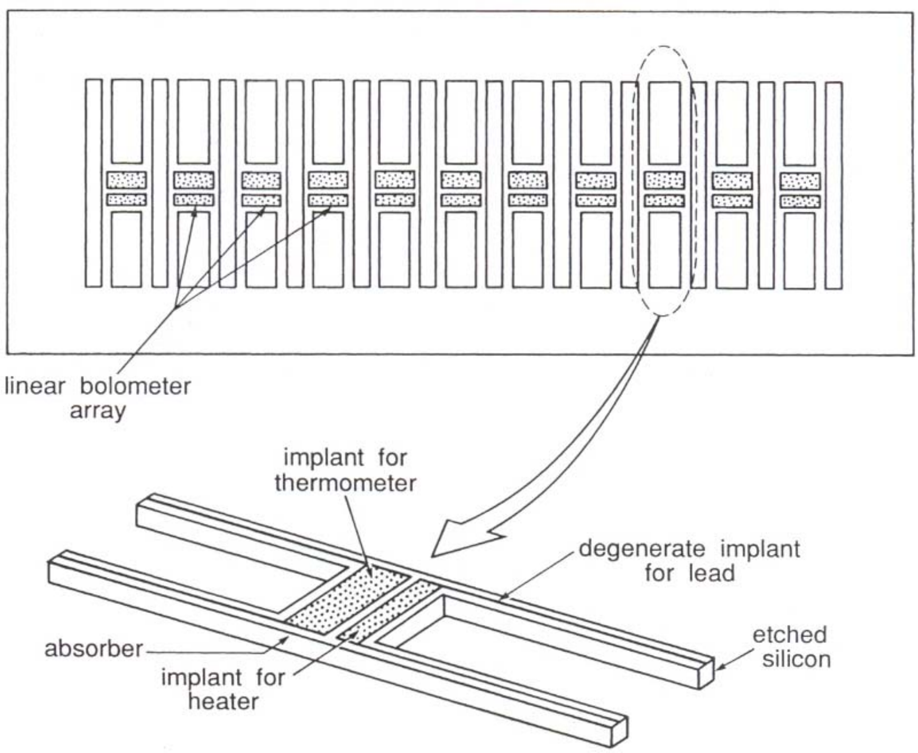


The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Etched Bolometers

The bolometer design has been revolutionized by precision etching techniques in Si

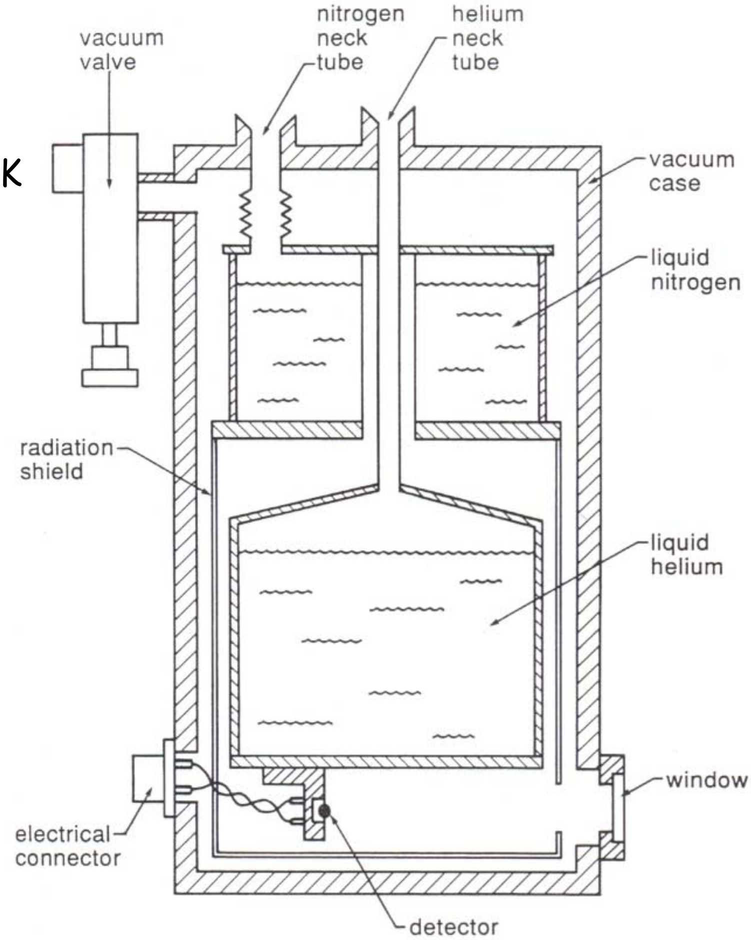
Thermal time response ~ C/G → small structures minimize the heat capacity C by reducing the volume of material.



Low Operating Temperatures (1)

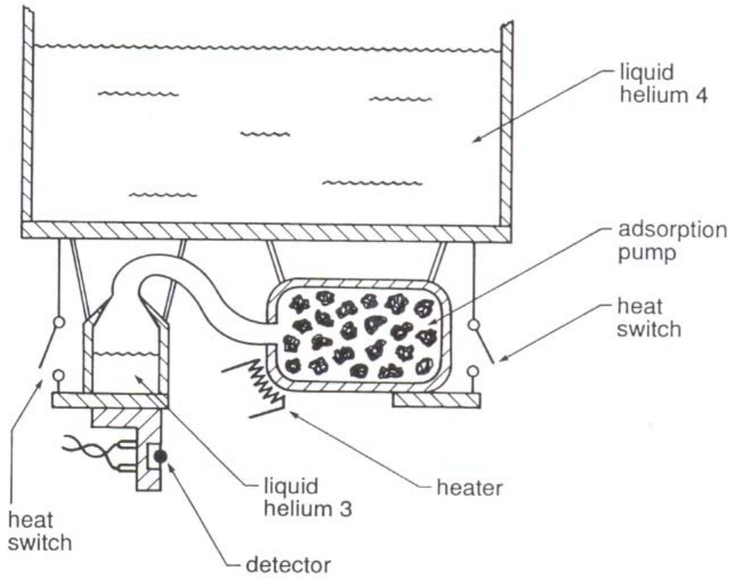
Four standard options to cool:

1. ^{4}He dewar (air pressure) → T=4.2K
2. ^{4}He dewar (pumped) → 1K< T<2K
3. …
4. …



Simplest solution is to use a two-stage helium dewar (here: model from Infrared Laboratories, Inc.)

Low Operating Temperatures (2)



Four standard options to cool:

1. ^{4}He dewar (air pressure) → T=4.2K
2. ^{4}He dewar (pumped) → 1K< T<2K
3. ^{3}He (closed-cycle) refrigerator → T~0.3K
4. adiabatic demagnetization refrigerator → T ~ 0.1K