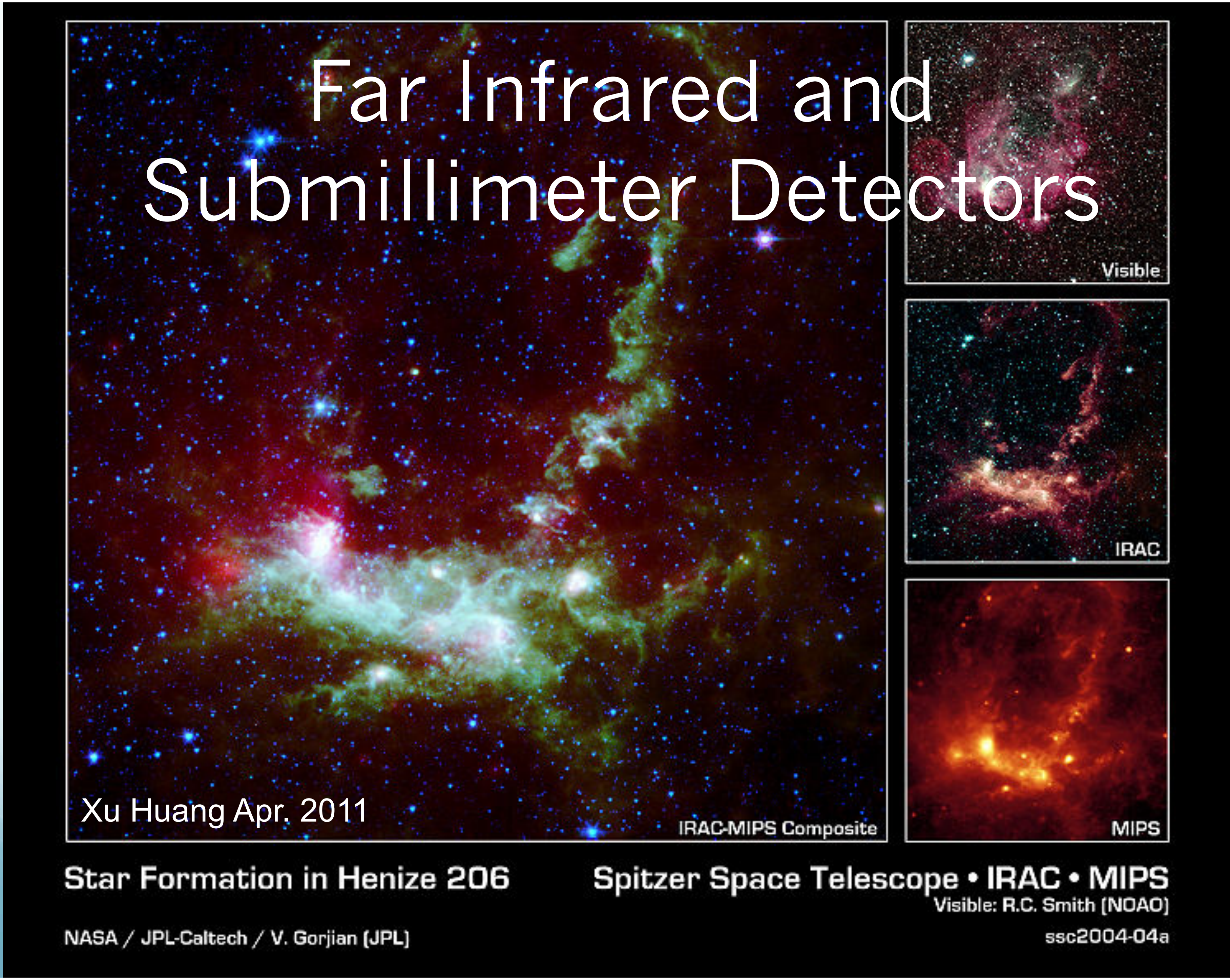
Far Infrared and Submillimeter Detectors

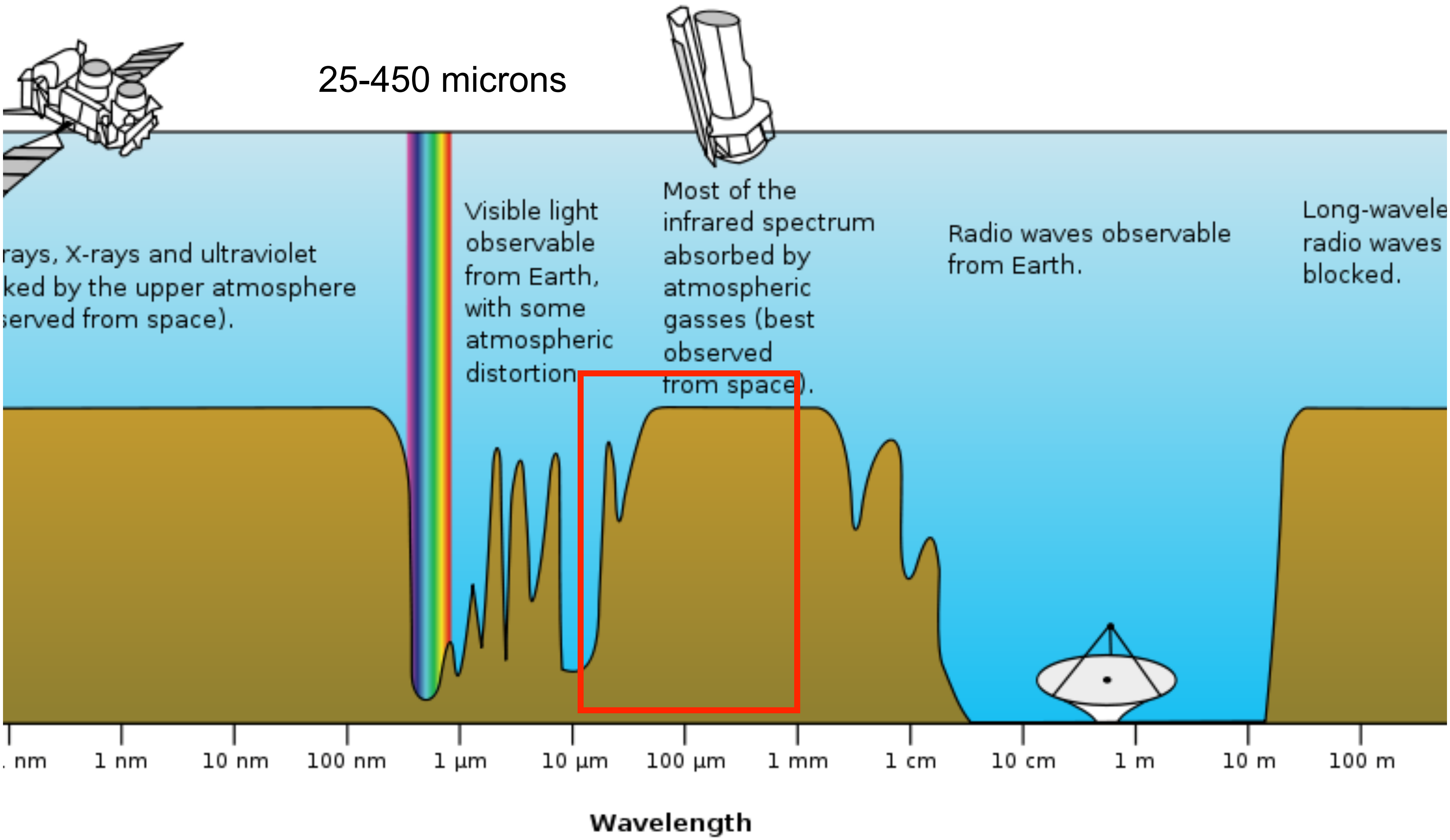


Xu Huang Apr. 2011

Outline

- Background
- Devices
  - Photoconductors
  - Bolometers
  - Heterodyne Receivers
- Case study-Herschel

25-450 microns



http://en.wikipedia.org/wiki/Optical_window

A Short History

- 1878 Langley- bolometer theory
- After 1959, modern bolometers-carbon resistor
- 1970 The first molecular line CO 115GHz

GaAs Schottky-barrier diode mixer

- 1970th superconductor bolometers
- 1979 first SIS Mixer
- 1992 first Nb SIS Mixer, 492GHz

Devices

- **Photoconductors**
- **Bolometer**
- The distinguishing characteristic is that in a thermal detector the excitations generated by the photons relax to a thermal distribution at an elevated temperature (in the thermometer) before they are detected.
- In the photon detector, the nonthermal distribution of excited electrons (e.g., in the conduction band) is detected before it relaxes (e.g., to the conduction band).
- **Heterodyne Receiver**

Photoconductors

Ge:Ga

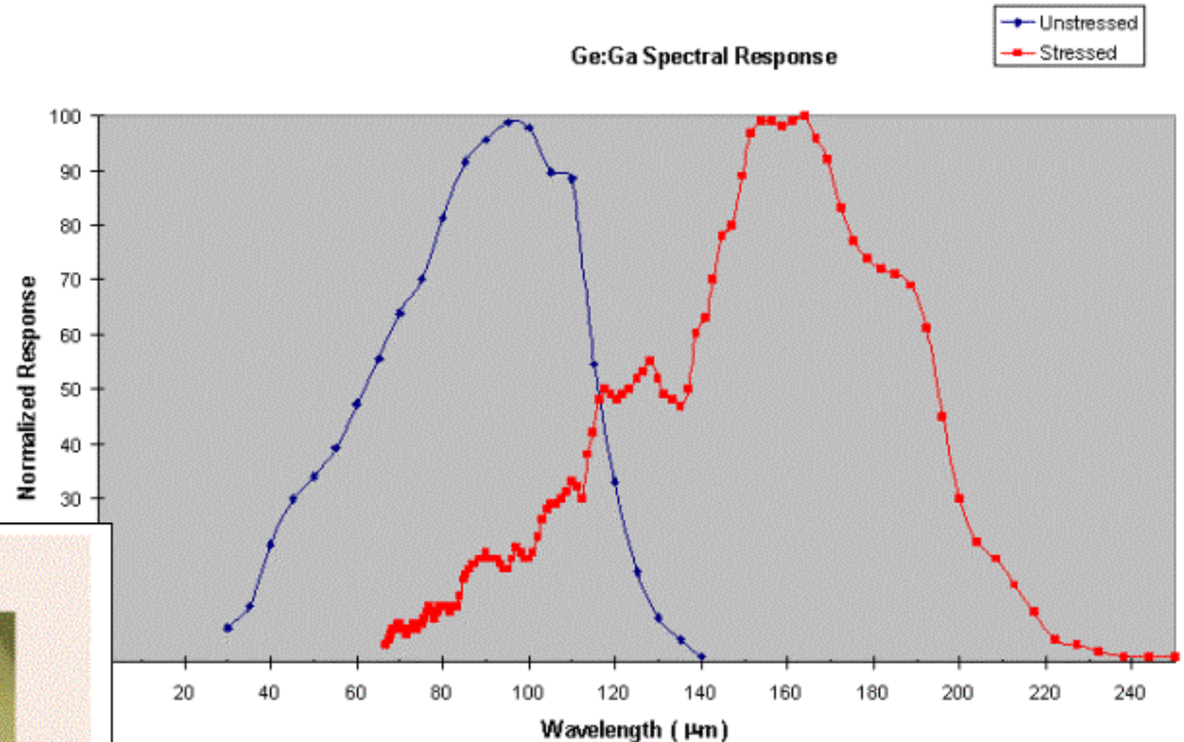


Figure 2. Spectral Response for Stressed and Unstressed Ge:Ga.

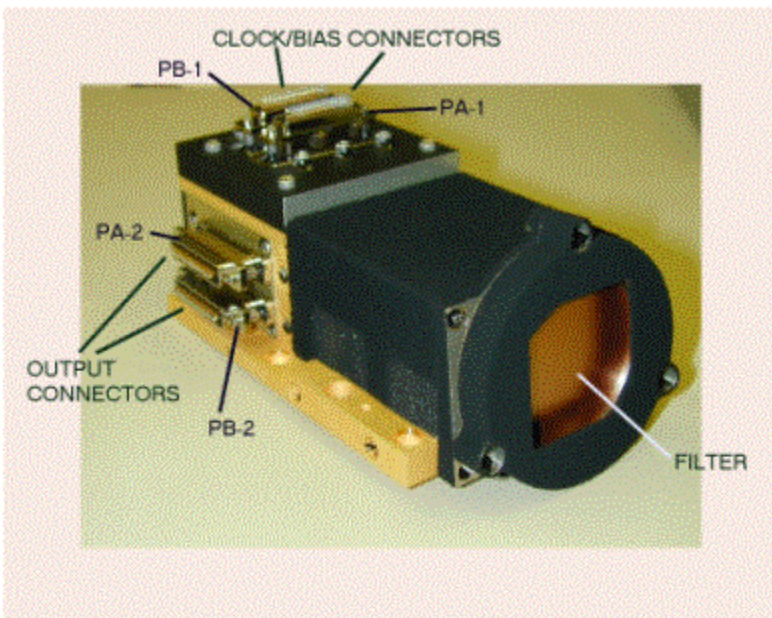


Figure 5. MIPS Flight 70 μm Array

E. T. Young, 2000

- **Table 1**. Typical Parameters for Unstressed Ge:Ga Photoconductors

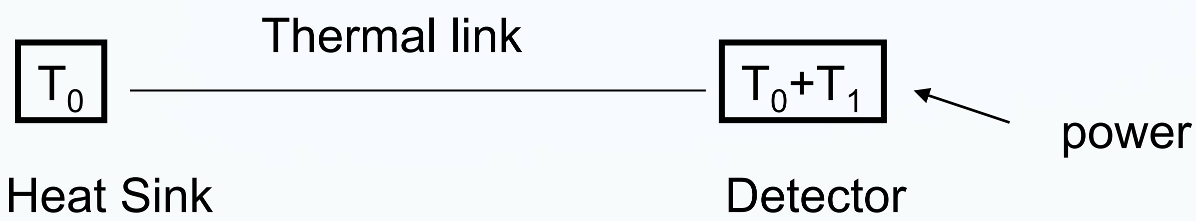
Acceptor Concentration	$2 \times 10^{14} cm^{-3}$
Donor Concentration	$<1 \times 10^{11} cm^{-3}$
Typical Bias Field	50mV/mm
Responsivity	7A/W
Quantum Efficiency	20%
Dark Current	$<200 e^{-}/s$
Operating Temperature	1.8K

E. T. Young, 2000

Bolometers

- Basic Operation
- Responsivity
- Noise
- Examples
- Superconductor TES Bolometers

Basic Operation



$$P_{in} = P_0 + \eta P_v(t) = GT_1 + C\frac{dT_1}{dt}$$

Heat capacity C
Thermal conductance *G*
Quantum efficiency η

$$T_1(t) = \begin{cases} \dfrac{P_0}{G}, \; t < 0 \\ \dfrac{P_0}{G} + \dfrac{\eta P_1}{G}\left(1 - e^{-t/(C/G)}\right), \; t \geq 0 \end{cases}$$

Thermal time constant

$$\tau_T = \frac{C}{G}$$

Responsivity (Voltage)

$$P_1 = I^2 R(T)$$ Electrical power dissipated in the detector

$$P_{in} = P_0 + \eta P_v(t) = GT_1 - \frac{dP_1}{dT} T_1 + C\frac{dT_1}{dt}$$

$$\alpha(T) = \frac{dP_1}{P_1 dT} = \frac{1}{R}\frac{dR}{dT} < 0$$ α(T) temperature coefficient of resistance

Responsivity $$S_A = dV/dP = \alpha(T)V(dT/dP) = \alpha(T)V/(G - \alpha(T)P_1)$$

Does not depend on wavelength

Electrical time constant $$\tau_E = \frac{C}{G - \alpha(T)P_1}$$

Source of Noise

Noise Equivalent Power (NEP) (W Hz$^{-1/2}$)

$$\frac{S}{N} = \frac{P_s}{NEP(df)^{1/2}}$$

- a) Johnson noise – randomly fluctuating potential energy on the capacitor
- b) Thermal noise – fluctuations of entropy across the thermal link
- c) Photon noise – Poisson statistics of the incoming photon stream

$$NEP_J \approx \begin{cases} GT^2 (if\, \alpha(T) \approx T^{-3/2}) \\ GT^{3/2} (if\, \alpha(T) \approx T^{-1}) \end{cases}$$

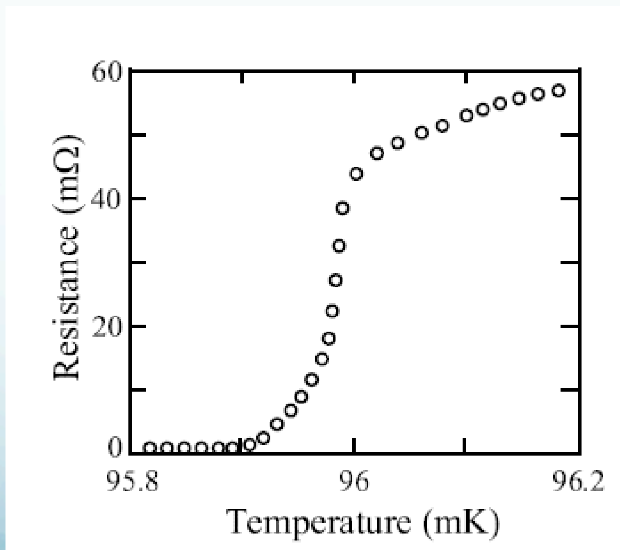
$$NEP_T = \frac{(4kT^2G)^{1/2}}{\eta}$$

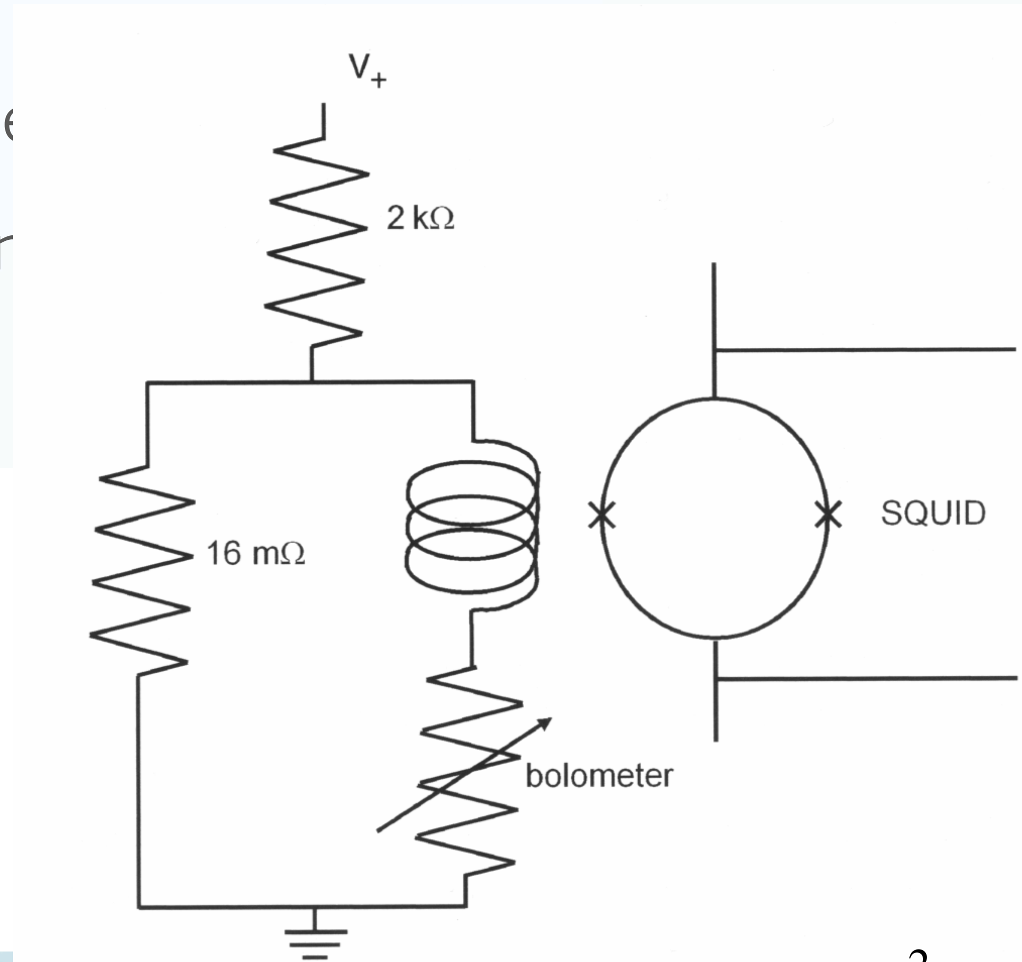
$$NEP_{ph} = \frac{hc}{\lambda}\left(\frac{2\varphi}{\eta}\right)^{1/2}$$

$$NEP = (NEP_J^2 + NEP_T^2 + NEP_{ph}^2 + \ldots)^{1/2}$$

Superconducting Bolometers

- TES (Transition Edge Se
- SQUID (Superconductir amplifiers





$$P_1 = \frac{V^2}{R}$$

Heterodyne Receivers

- a) High quality, fast photon detectors are not available at wavelengths longer than the infrared.
- b) Efficient absorption of the energy of the photons by a device require the device to have dimensions at least comparable to the photon wavelength.
- c) Coherent receiver- measure and preserve phase information directly, easily adapted for spectroscopy, make interferometry between different receivers possible.

http://en.wikipedia.org/wiki/Heterodyne_detection

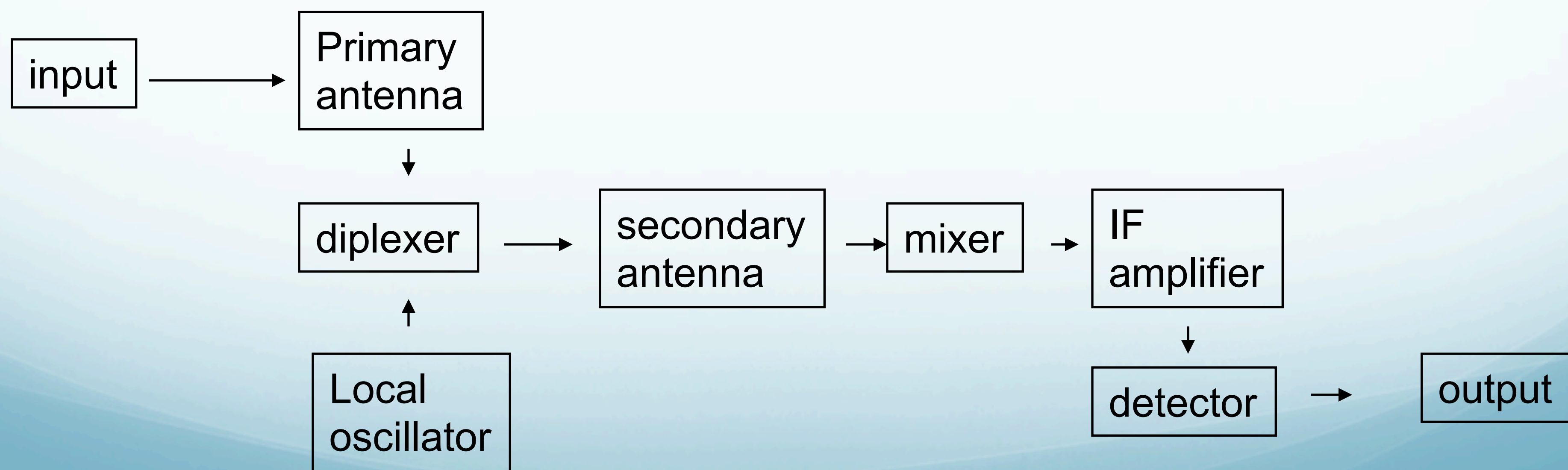
$$I \propto V^2 \propto P = (E_{sig}\cos(\omega_{sig}t+\varphi) + E_{LO}\cos(\omega_{LO}t))^2$$

$$= \underbrace{\frac{E_{sig}^2 + E_{LO}^2}{2}}_{\text{constant component}} + \underbrace{\frac{E_{sig}^2}{2}\cos(2\omega_{sig}t+2\varphi) + \frac{E_{LO}^2}{2}\cos(2\omega_{LO}t) + E_{sig}E_{LO}\cos((\omega_{sig}+\omega_{LO})t+\varphi)}_{\text{high frequency component}}$$

$$+ \underbrace{E_{sig}E_{LO}\cos((\omega_{sig}-\omega_{LO})t+\varphi)}_{beat\ component}$$

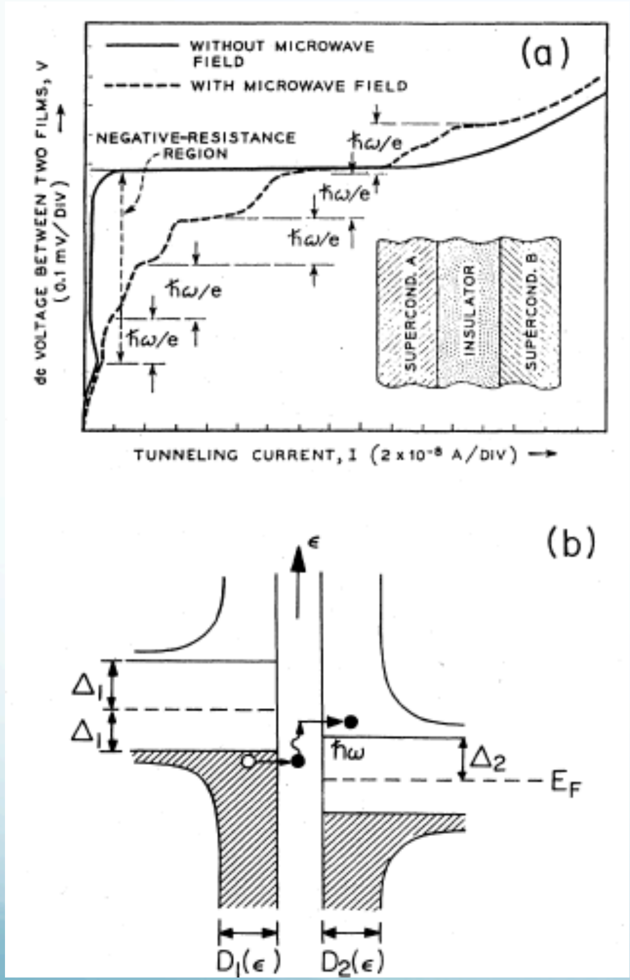
IF signal

Time response ~ $1/f_{IF}$ nanoseconds



SIS Mixers

Superconductor-Insulator-Superconductor



Photon-assisted tunneling of single electron quasiparticles

$$eV_0 > \Delta_1 + \Delta_2 - n\hbar\omega$$

Up frequency limit- Josephson tunneling

$$f_u = 2\Delta / h$$

Magnetic field to suppress tunneling current, $2f_u$

Nb 12×10^{11}Hz

J. R. Tucker & M. J. Feldman, 1985

Noise Temperature

Quantum limit $$T_N \approx \frac{h\nu}{k}$$

Thermal limit $$T_N \approx T_B$$

A matched blackbody at the receiver input at a temperature T_N produces: S/N=1

Mixer noise temperature $$T_M = \frac{e}{4k}\frac{1}{\Psi}$$

Figure of merit $$\Psi = \frac{d^2I / dV^2}{2dI / dV}$$

Detection of Light, G.H. Rieke.

Performance Comparison

- a) Bolometer at background limit & Heterodyne receiver in the thermal limit (*hv<<kT*$_B$)

$$\frac{(S/N)_{coh}}{(S/N)_{inc}} = \left[\frac{1}{\eta}\frac{\Delta f_{IF}}{\Delta \nu}\frac{h\nu}{kT_B}\right]^{1/2}$$

- b) Bolometer at detector noise limit & Heterodyne receiver at quantum limit

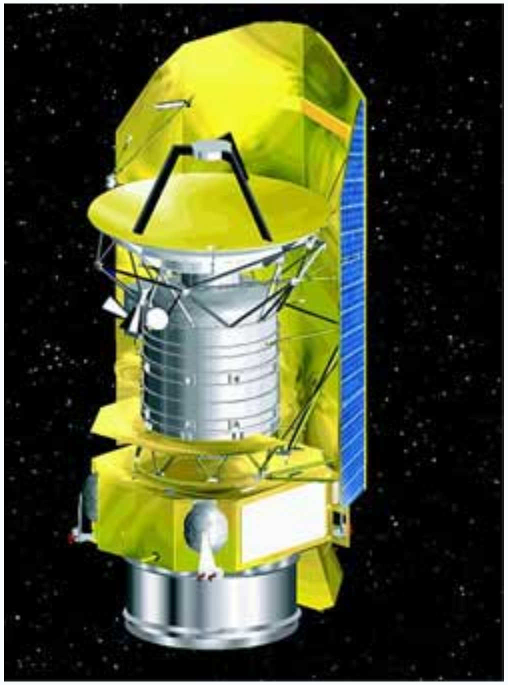
$$\frac{(S/N)_{coh}}{(S/N)_{inc}} = \frac{NEP(\Delta f_{IF})^{1/2}}{2h\nu\Delta\nu}$$

- c) Bolometer at background noise limit & Heterodyne receiver at quantum limit

$$\frac{(S/N)_{coh}}{(S/N)_{inc}} \approx \frac{2.6\times 10^{11}\,Hz}{\nu}$$

Detection of Light, G.H. Rieke.

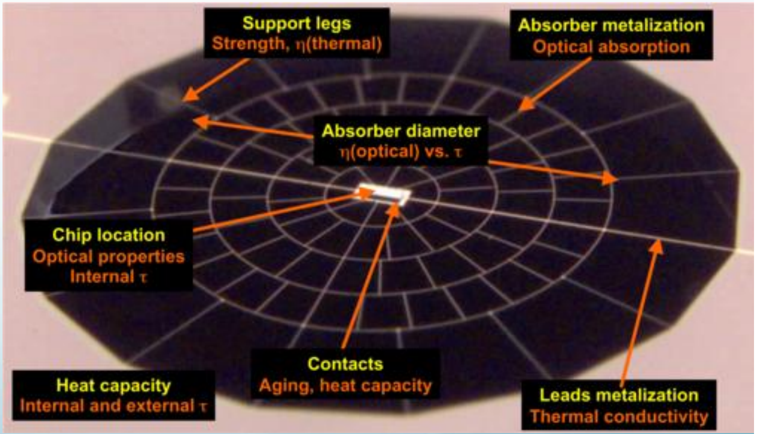
Herschel



PACS: (60-85, 85-130, 130-210 μm)
Bolometer Array for photometry
Ge:Ga photoconductor array for spectroscopy

SPIRE: (above 200 μm)
“Spider-web” bolometer arrays for long wavelength
Camera and low to medium resolution spectrometer

HIFI:
SIS mixer (480-1250GHz)
HEB mixer(1410-1910GHz)
Very high resolution heterodyne spectrometer



http://en.wikipedia.org/wiki/Herschel_Space_Observatory

Conclusion

- Exciting new area, fast developing
- **Detector of choice:**
- Photoconductors ($\lambda<160$micron)
- Bolometers (continuum detection)
- Heterodyne mixers (high resolution spectrum)
- **Expectation:** new superconducting material with better performance

Reference

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