Bolometers for submm/mm-wave astronomy

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Presented at the 2nd NAIC-NRAO School on Single-Dish Radio Astronomy, Green Bank Observatory,
13th August 2003

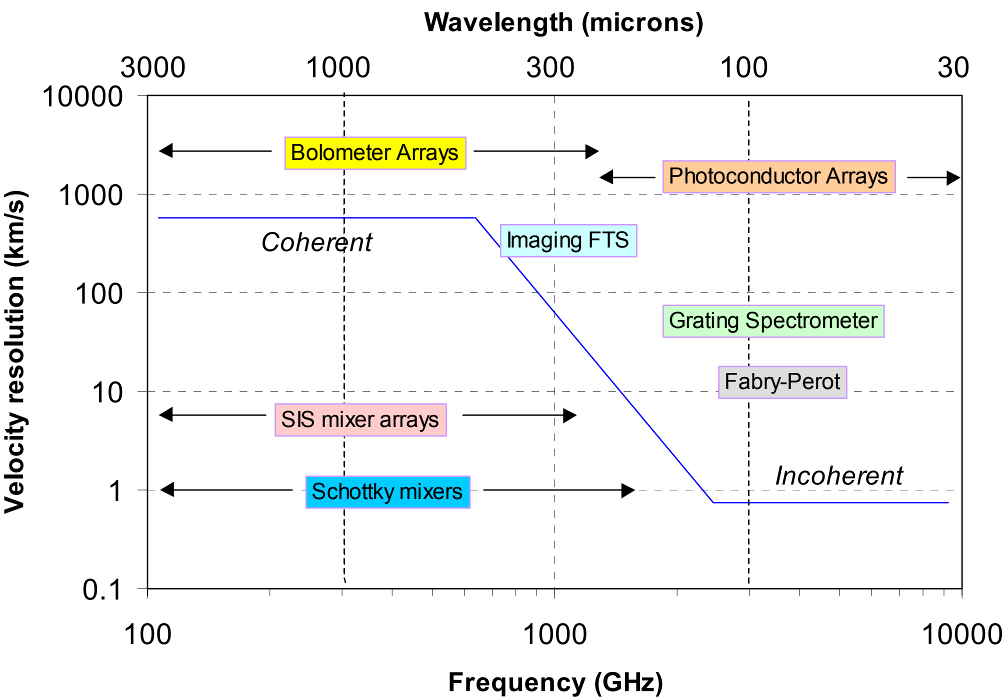
UK Astronomy Technology Centre

Talk outline

- Scientific rationale
  - Why do we need bolometers?
- Basic principles
  - How do bolometers work?
  - Characterising performance
- Bolometer technologies
  - Practical devices
  - Instrument design issues
- Recent developments and the future

Bolometers for submm/mm astronomy

★ A BOLOMETER is simply a *thermal* or *total power* detector



Why are they popular for submm/mm astronomy?

1. High sensitivity from a cooled device
2. Flat spectral response over a wide-bandwidth

In addition:

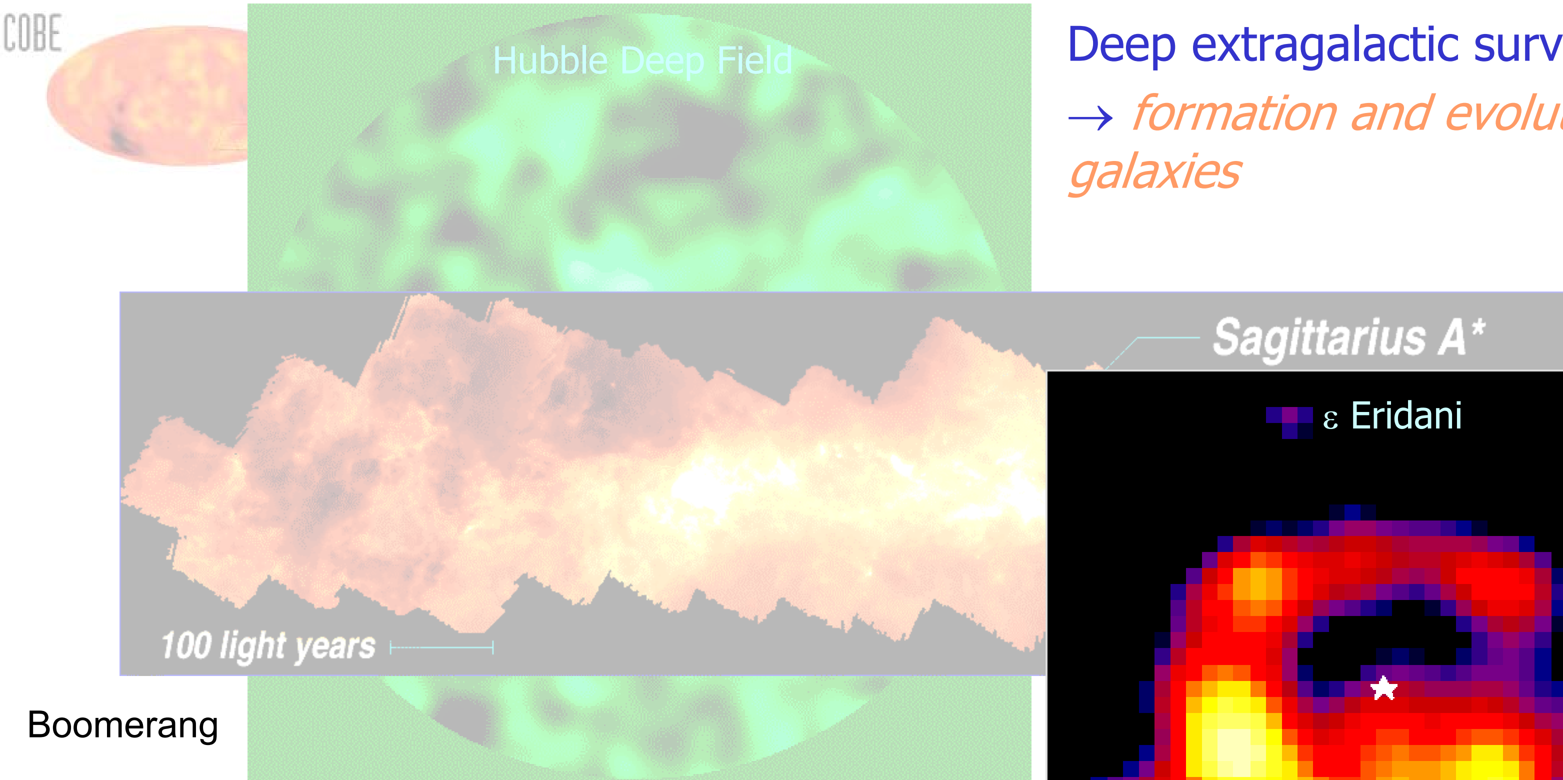
→ Relative ease of construction and optimization

→ Bolometers have a wide range of applications

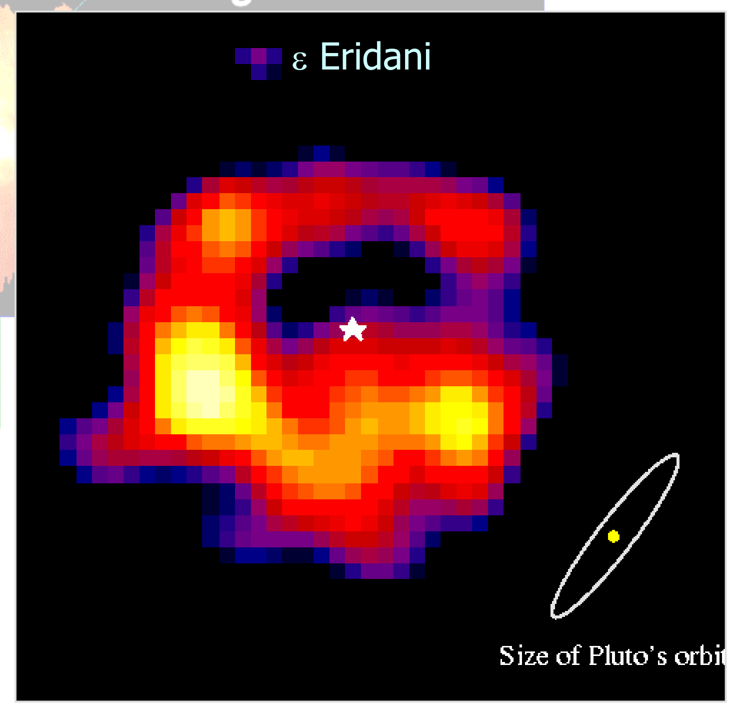
Why submm/mm astronomy?

- Most sensitive to cold gas and dust
  - this is the material at the "ORIGINS" of many phenomena, from primaeval galaxies to Galactic star and planet formation
  - emission from high-z dusty galaxies is red-shifted into the submillimetre $\rightarrow$ exploration of the early Universe
- Low opacities
  - can "see" into the centre of objects e.g. star forming cores
  - masses, geometries etc. are much less model-dependent than in the optical/IR
- Unexplored territory
  - mostly unexplored but contains the same amount of cosmic energy as in the optical/IR background

Recent discoveries



Deep extragalactic surveys
→ *formation and evolution of galaxies*

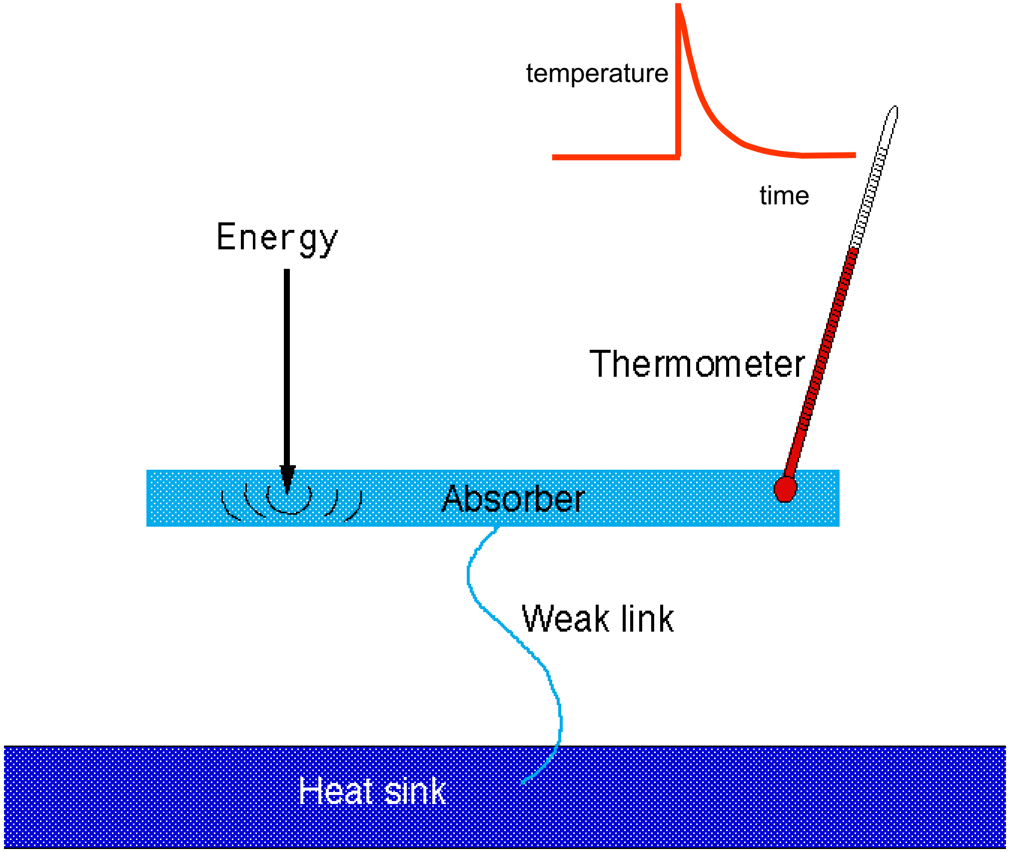


Cosmological surveys → *structure in the Primordial Universe*

Protoplanetary/debris dust disks → *formation of planets and planetesimals*

Basic principles

★ Two components: A *sensitive thermometer* and high cross-section *absorber*



- Thermometer and absorber are connected by a weak thermal link to a heat sink
- Incoming energy is converted to heat in the absorber:

$\Delta T = T - T_0 = E/C$

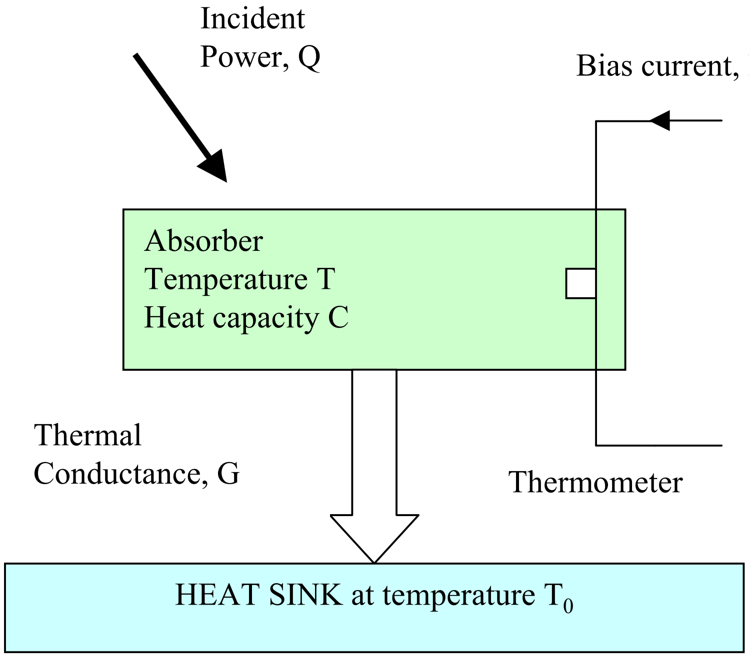
Temperature rise decays as power in absorber flows out to the heat sink

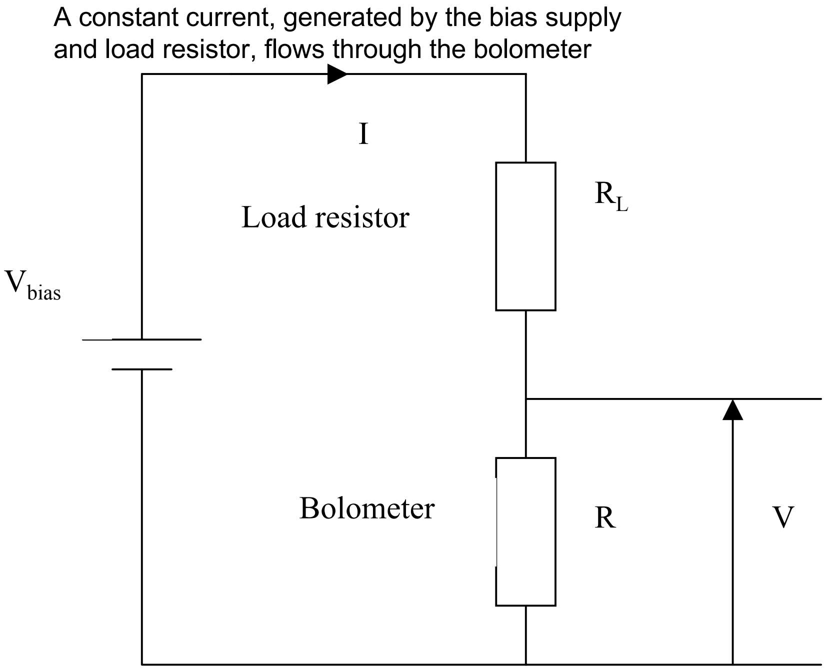
$\tau = C/G$

- Temperature rise is proportional to the incoming energy

Bolometer operation

★ Classical Germanium bolometer: Bias circuit with voltage source and load resistor





Provided the bias power remains constant: $T = T_0 + (Q + P_{bias})/G$

The temperature rise causes a change in bolometer resistance and consequently in the voltage across it

Performance parameters

- The Noise Equivalent Power (NEP) is the power absorbed that produces a S/N of unity at the bolometer output.

Can be written as: $NEP^2 = NEP^2\mathit{(detector)} + NEP^2\mathit{(background)}$

Ideal detector NEP consists of contributions from Johnson and Phonon noise.

Background NEP is due to photon noise power from the sky, telescope and instrument.

The overall NEP of a device can be written as:

$$NEP^2 = 4k_BTR/S^2 + 4k_BT^2G + 2Q(h\nu_0+\eta\varepsilon kT_{bk})$$

- The thermal time constant is a measure of the response time of the bolometer to incoming radiation.

Can be written as: $\tau = C/G$

Characterising ideal performance

Assumptions:

1. There are no excess noise sources present...

2. Resistance is a simple function of temperature: $R = R_* e^{(T_g/T)^{0.5}}$

3. Thermal conductivity follows a power law: $k(T) = k_o (T/T_o)^{\beta}$

4. Performance can be characterised by 3 dimensionless parameters:

ϕ = T/T_0 **Bias parameter**

$\gamma = \eta Q/(GT_0)$ **Loading parameter**

δ = Tg/ T0 Material parameter

However, in practice...

★ To achieve good sensitivity a practical device will have a wide bandwidth

However…

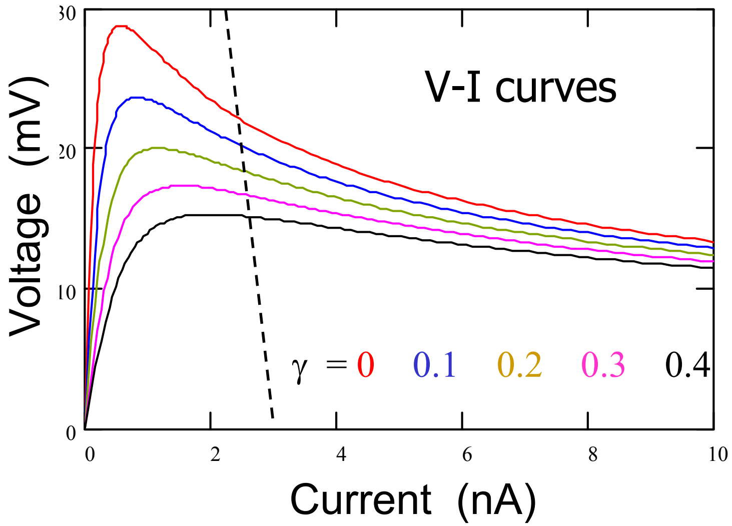
In this case the bolometer performance can *degrade* due to power loading from the background

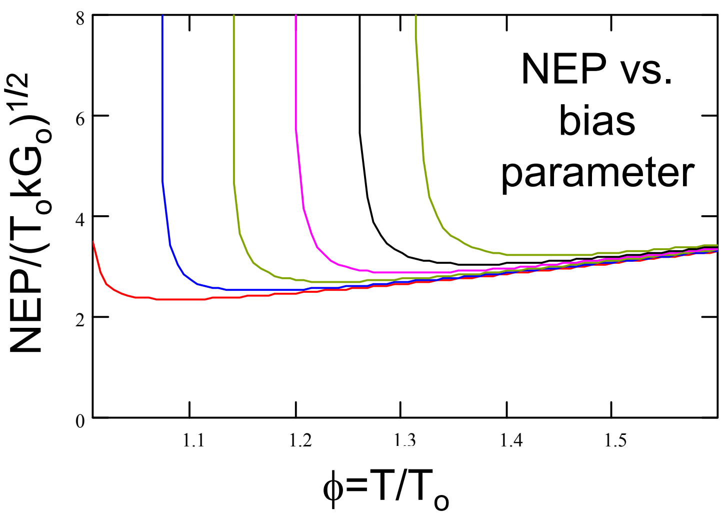
I.e. not only does the background contribute photon noise but it also heats up the (cooled) device

The overall NEP becomes:

$$NEP^2 = NEP^2(\textit{detector}) + NEP^2(\textit{loading}) + NEP^2(\textit{photon noise})$$

Operation in variable background





V-I curves are important diagnostics for bolometers

In the presence of variable background power the bolometer becomes a significantly non-linear device

The bias point moves to a different curve

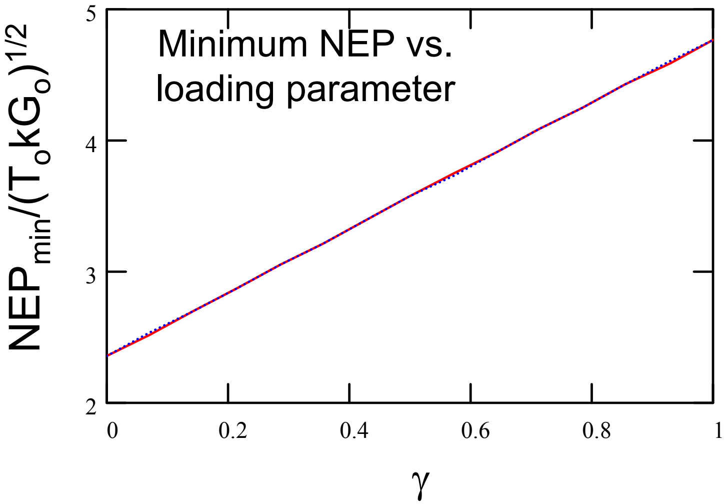
Broad *minimum* in the NEP around an optimum ϕ

Under-biasing - large increase in NEP
Over-biasing - little degradation in NEP

Optimum bias point shifts to higher values as the power loading increases.

Advantageous to overbias

Operation in variable background



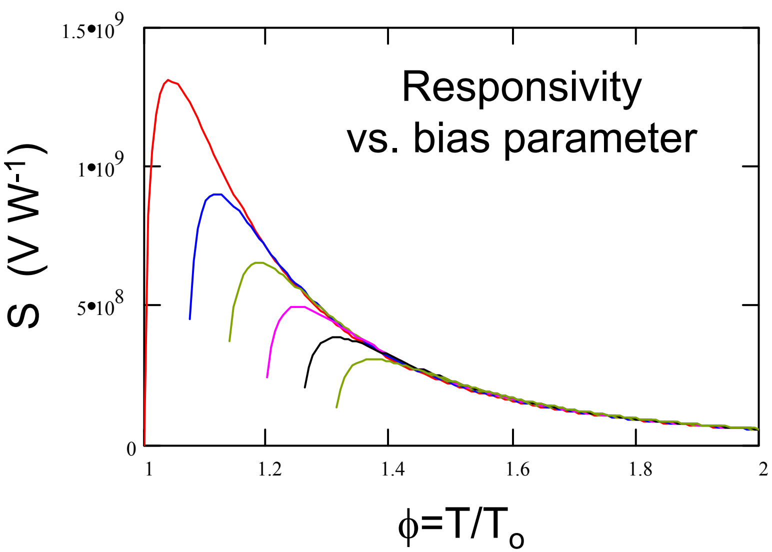
Can write the minimum NEP as:

$NEP_{min} \propto TG^{1/2} + Q/G^{1/2} + (photon\ noise)$

Low G – low NEP_{det} *but larger heating...*

High G – poor NEP_{det} *but less heating…*

Compromise!



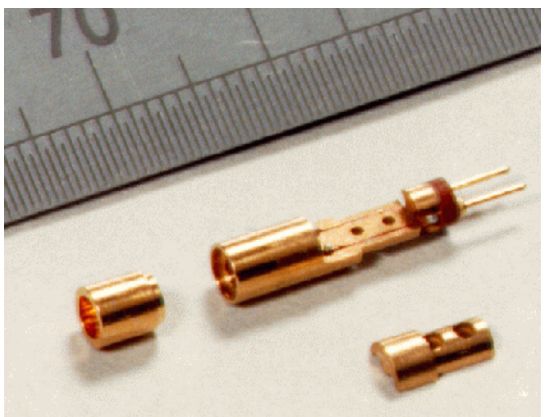
Responsivity *drops dramatically* as the power loading increases

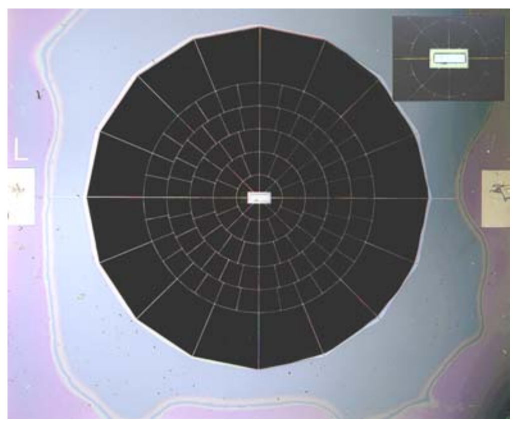
Less sensitive as ϕ is increased

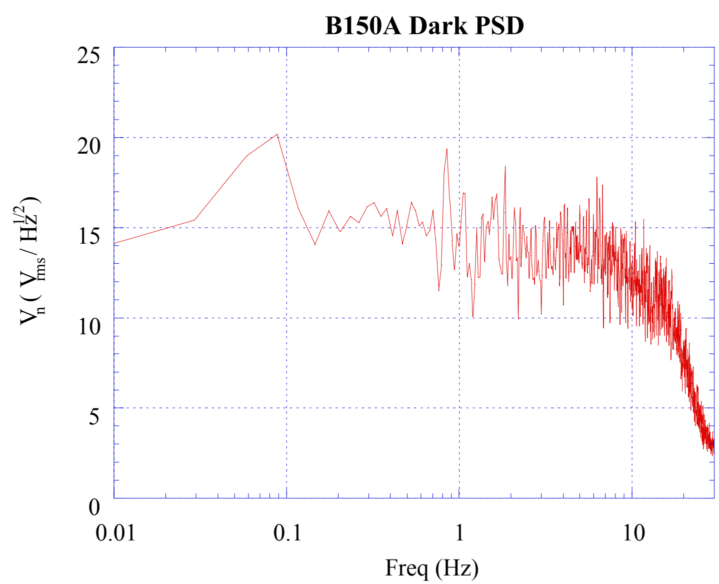
Must *calibrate out* changes in responsivity at time of observation

“Classical” semiconductor bolometers

- Composite design:
  - Metal-coated dielectric as absorber
  - Semiconductor resistance thermometer
- Used on ground-based telescopes for many years
- Theory and practice well understood
- Current state-of-the-art: “Spider-Web” composite bolometers

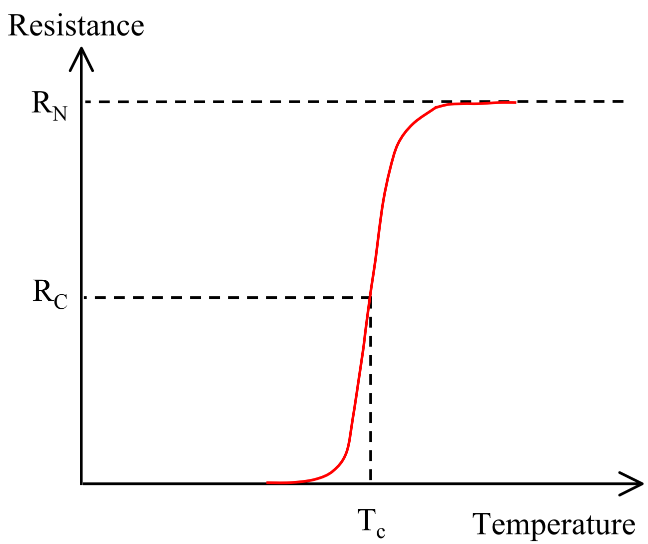


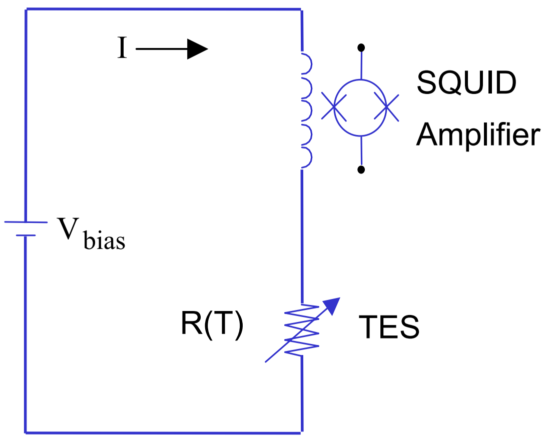




- Low thermal conductivity - high sensitivity
- No 1/f noise down to 20 mHz
- Low absorber heat capacity - fast response time
- Low-cosmic ray cross-section (few %)
- Minimal suspended mass - robust

Superconducting TES bolometers

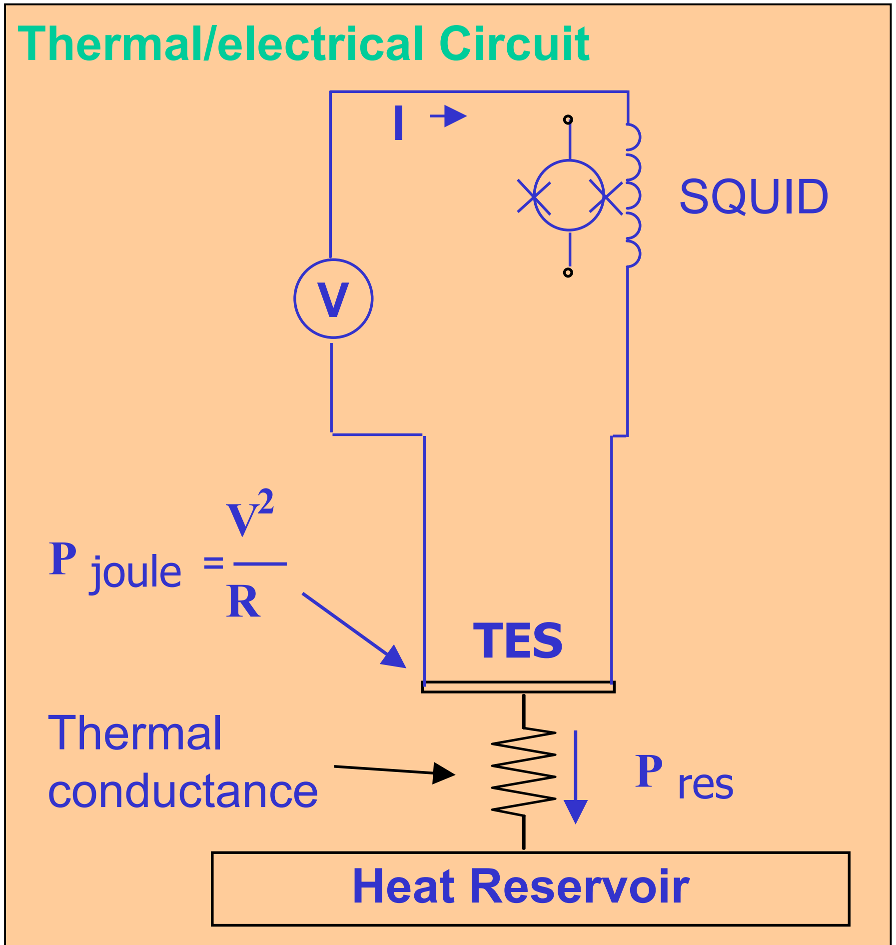




- TES = Transition Edge Sensor
- Voltage-biased on normal - superconducting transition
- Resistance has a very steep dependence on temperature in transition region
- Film held at constant voltage bias - change in resistance results in a change in current through the film

  - Low noise, low power (~ 1nW) SQUID ammeter readout
  - Under development at NIST/GSFC, JPL, UC Berkeley, SRON

Electrothermal feedback



- Bias power or Joule heating depends on resistance of the superconducting film
- As the film cools, its resistance drops and the Joule heating increases
- The Joule heating provides negative feedback raising the film temperature
- A stable equilibrium occurs when the Joule heating matches the heat loss

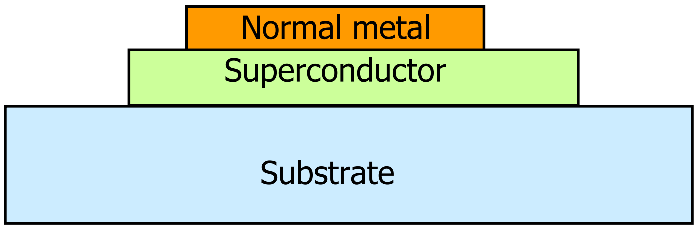
Temperature Self-Regulation

Reduced Johnson Noise

Faster Response

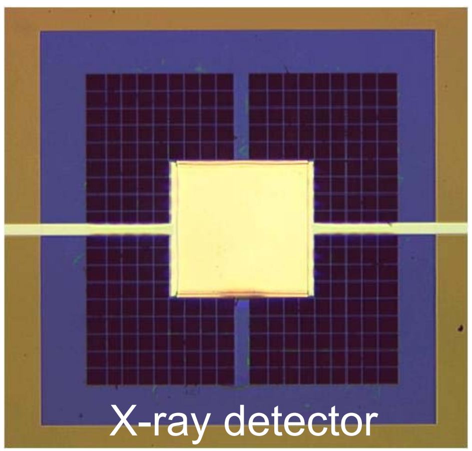
More Linear response, Larger Dynamic Range

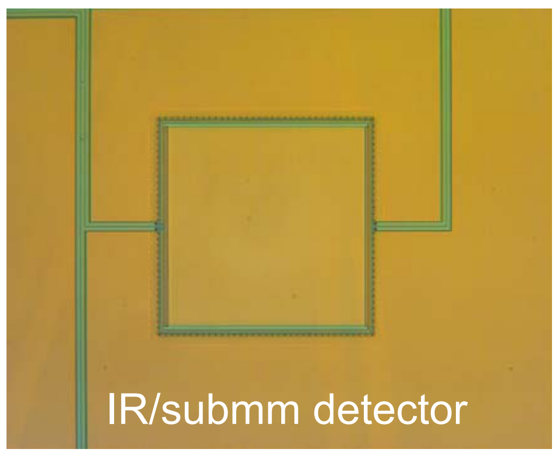
Practical TES bolometers

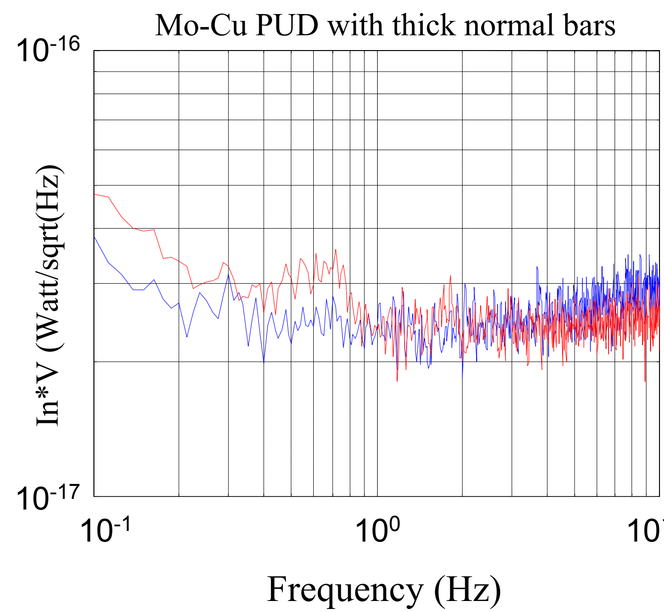


Cross-section of a proximity effect TES

- A bilayer of thin superconducting film and a thin normal metal act as a single superconductor
- By choosing the film thickness can reproduce TES devices with sharp (~2mK) tuneable transitions







- Very sharp transition - big change in R for a small change in T
- Low Johnson noise - high sensitivity
- Low heat capacity -- fast response time
- Self-biasing – easy to bias arrays
- Signals can be read out by multiplexed SQUID amplifiers

Bolometer performance

- Ideally the overall NEP should be dominated by the photon noise from the thermal background

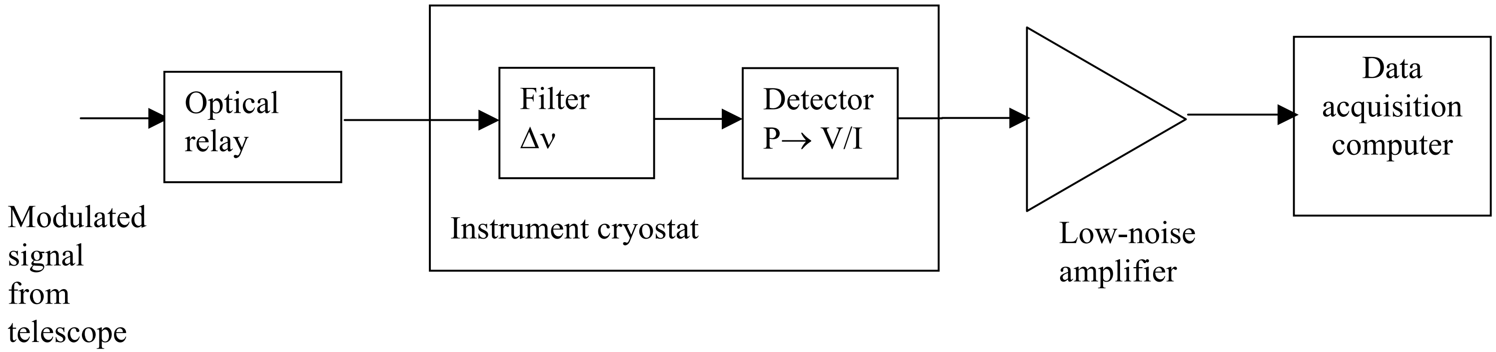
i.e. $NEP(det) < (2Qh\nu_0)^{1/2}$

Requirements for typical instruments:

Instrument	λ range (μm)	NEP_{det} (W/√Hz)	τ (ms)	$NEP\tau^{1/2}$ ($\times 10^{-19}$ J)	
SCUBA	350-850	1.5×10^{-16}	6	9	→ High background, needs reasonable τ
SCUBA-2	450-850	7×10^{-17}	1-2	1	→ Lower background, need faster τ
BoloCAM	1100-2000	3×10^{-17}	10	3	→ Lower background, slower device okay
SPIRE	250-500	3×10^{-17}	8	2.4	→ Space background, slowish device okay
Planck-HFI	350-3000	1×10^{-17}	5	0.5	→ Lowest background, need quite fast τ

Compromise between response time and NEP...

Practical instrument design



Important considerations in the instrument design:

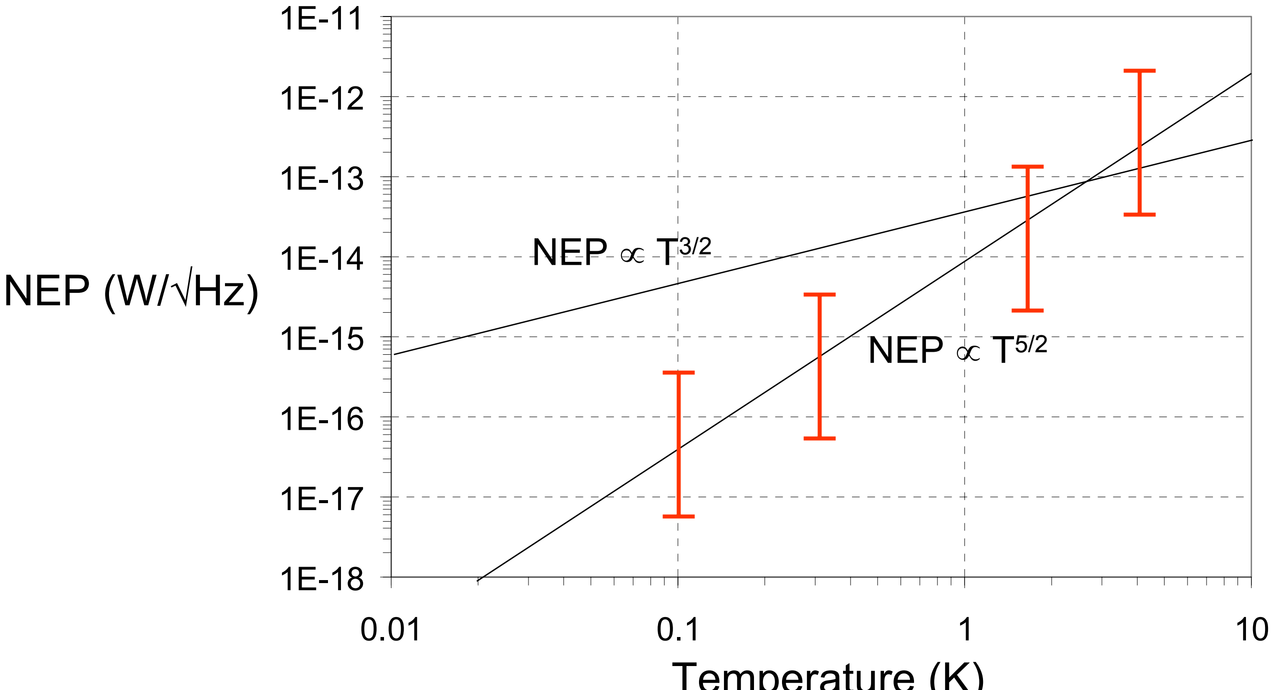
- **Detector operating temperature**
- **Optical coupling**
- Wavelength selection
- Low-noise electronic readouts
- Data acquisition system
- Environmental issues - microphonic pick-up, RFI,grounding, stray light

Operating temperature

For a fixed response time, the detector NEP is $\propto TC^{1/2}$

Typical bolometers have materials which have heat capacities which are proportional to T (metals) and T^3 (dielectrics)

So can write detector NEP as: $NEP \propto T^{3/2} - T^{5/2}$



Low-temperature refrigeration

To achieve background limited NEPs the bolometers have to be cooled to below 0.5K

There are three basic types of fridge:

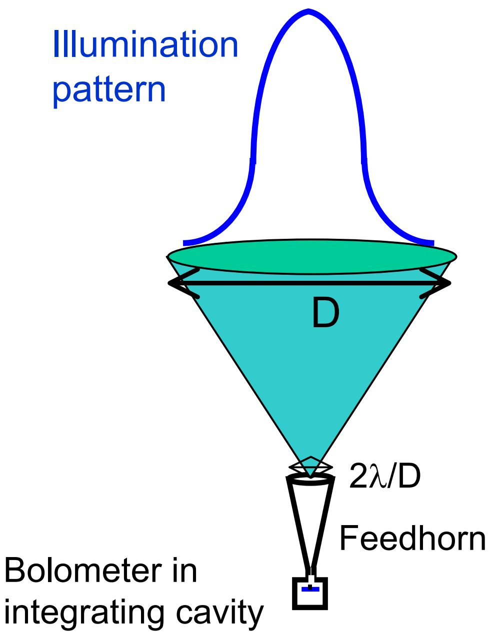
- ^{3}He systems
- Adiabatic demagnetization refrigerator
- Dilution refrigerator

Refrigerator Type	Operating temperature (mK)	Cooling Power at T_{op} (μW)	Size / Complexity	Magnetic field	Cryo-free?	Cycling
^{3}He system	300	~10	Compact design	No	No	Every day
ADR	<100	2–10	Reasonably Compact	Yes	Yes	Every day / Continuous
Dilution	<100	20–100	Bulky and complex	No	Custom	Continuous operation

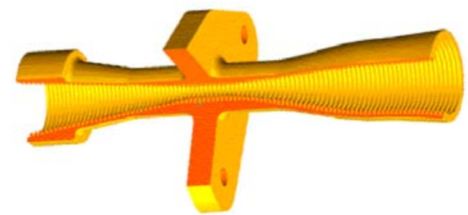
Optical coupling

Size of a bolometric detector (typically a few mm) is small compared to the telescope diffraction spot at submm/mm wavelengths.

There are two basic ways of coupling this radiation onto the detector:



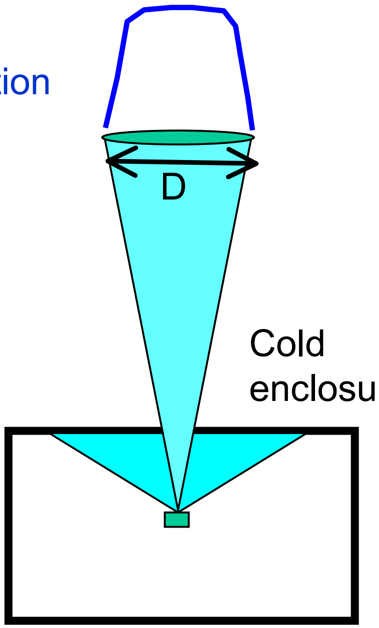
Conical horn with section of cylindrical waveguide



- Horn defines the detector field-of-view
- Gives a tapered (~Gaussian) illumination of the telescope
- Maximum aperture efficiency when horn diameter = $2\lambda/D$
- Throughput is single-moded, i.e. $A\Omega=\lambda^2$
- Beam on the sky is close to the diffraction limit ($\sim\lambda/D$)

Optical coupling

Alternative is to dispense with feedhorns and simply have a bare pixel in the focal plane:



Bare pixel with cold aperture stop

- Pixel field-of-view is large (~π steradians)
- Illumination to the telescope is defined by a cold stop
- Results in a near top-hat illumination of the telescope

Imaging arrays

★ Until the mid-1990s most bolometers instruments were single-pixel devices

→ Mapping extended regions of sky was very slow...

→ Instrument sensitivity was usually *detector-noise* limited

Next logical step was to have more than one detector in the focal plane.

Important design criteria for array instruments:

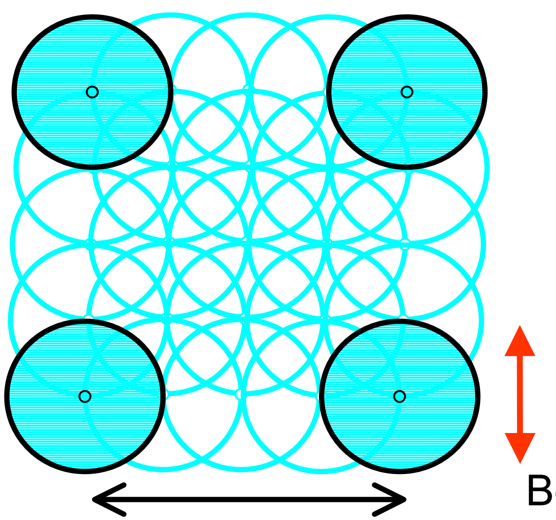
- **Pixel architecture - observing modes**
- Read-out schemes (multiplexing)
- “Array-ability”
- Uniformity (mass-production)

Array pixel architecture

For array receivers there are two possible approaches to the pixel architecture:

1. Under-sample the image with a feedhorn array
2. Fully-sample the image with a filled array

For undersampled arrays using feedhorns:



Beam separation = $2\lambda/D$

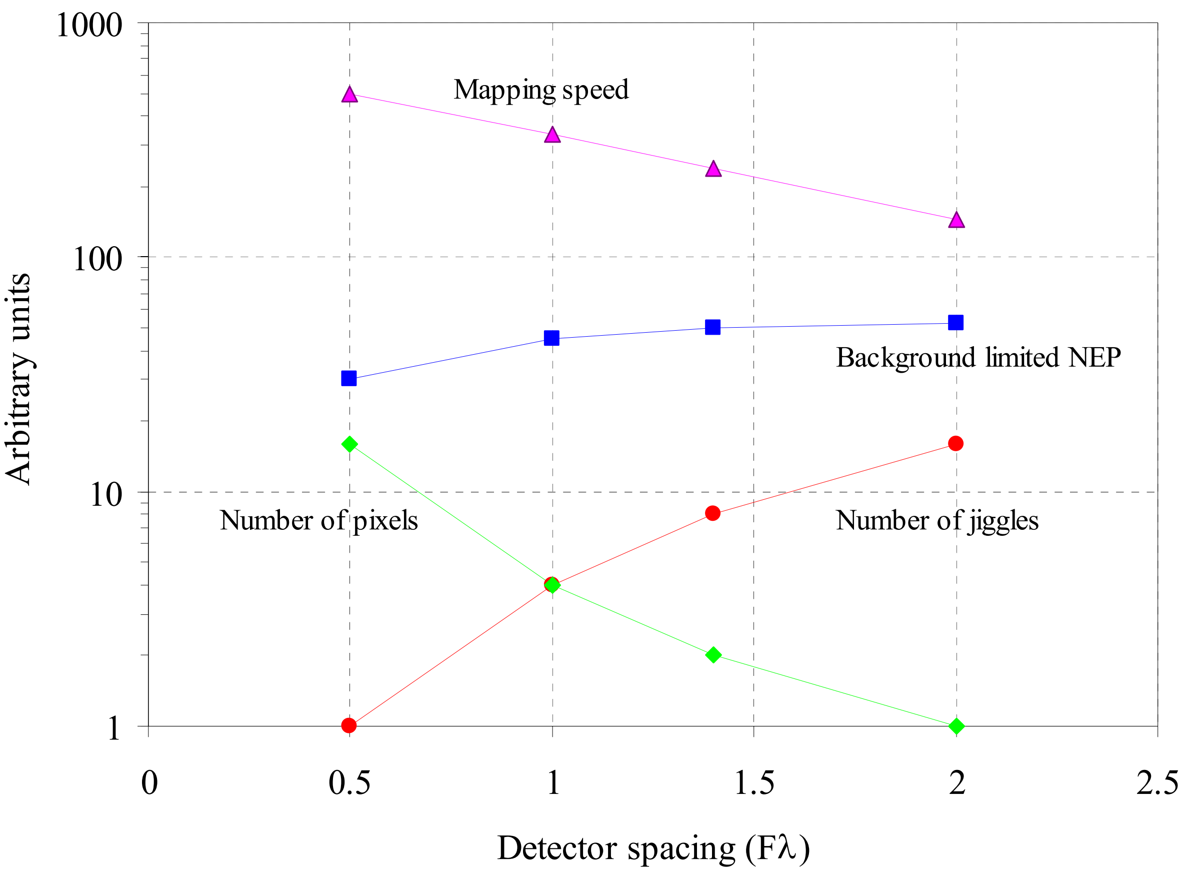
Beam FWHM = λ/D

Main beams on the sky don't overlap $\Rightarrow$ the image is not fully sampled without scanning or "jiggling" of the telescope pointing

16 pointings needed for fully-sampled image

Array pixel architecture

Relative trade-offs in pixel architecture:



Other things to consider:

1. Filled arrays allow instantaneous ("snap-shot") imaging of an object.

Observing modes should be easier...

2. Easier to control the field-of-view of a feedhorn-coupled bolometer than a bare pixel.

Stray light control...

Telescope performance

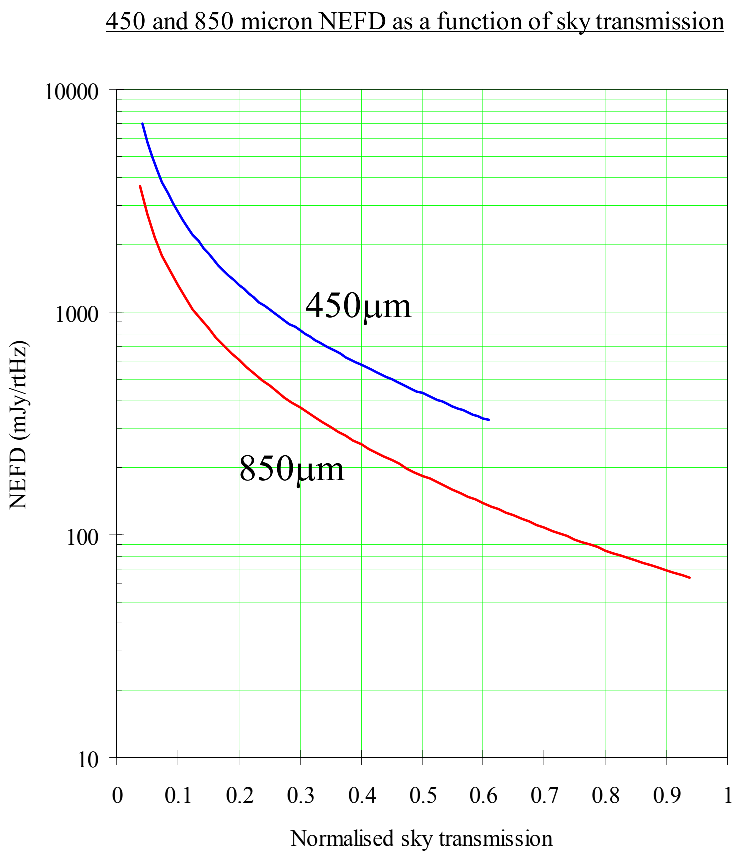
Performance on the telescope is represented by the Noise Equivalent Flux Density (NEFD)

This is the flux density that produces a signal-to-noise of unity in one second of integration:

$$NEFD = \frac{NEP}{\eta_c \eta_t A_e e^{-\tau A} \Delta \nu} \quad \text{(mJy/}\sqrt{\text{Hz}}\text{)}$$

- NEFD depends very much on the weather and varies with sky transmission

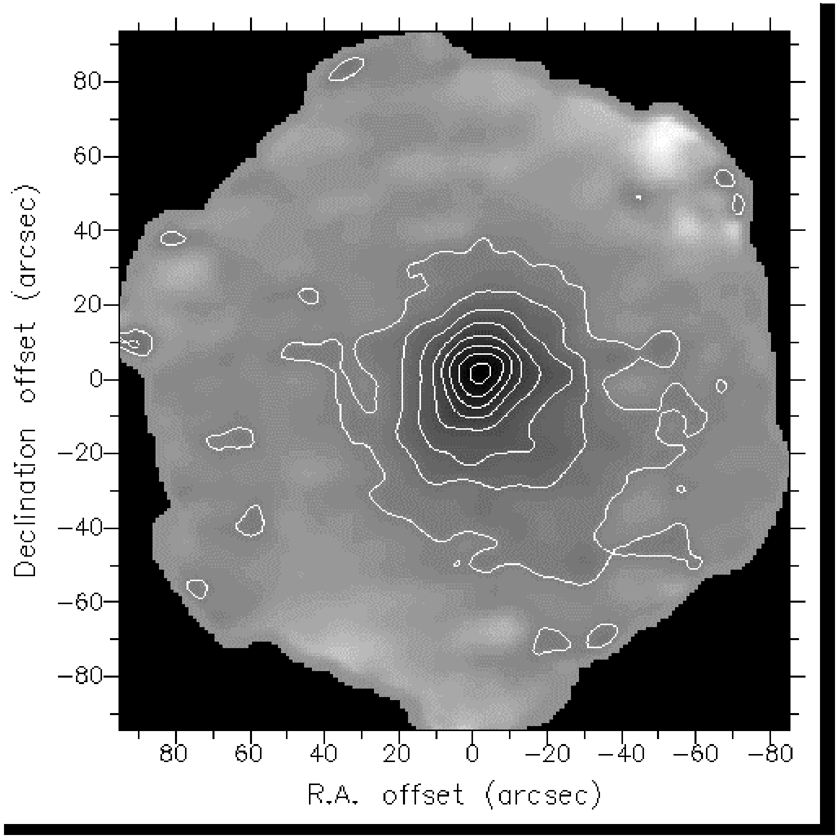
- On many occasions the fundamental sensitivity limit is set by sky-noise.



Sky-noise

Sky noise manifests itself in a DC offset and in spatial and temporal variations in the emmissivity of the atmosphere.

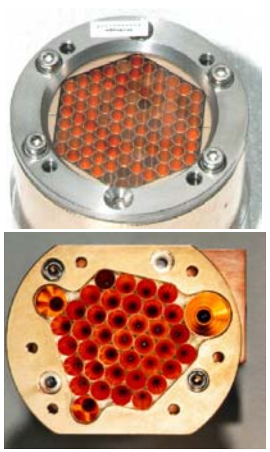
- It can degrade the NEFD by more than an order of magnitude!
- Standard observing techniques like sky chopping and telescope nodding remove *most* of the DC offset.
- Chopped beams travel through slightly different atmospheric paths so there is still some residual...
- If sky-noise arises from features that are larger than the array it is possible to remove the effects to high order.



Arrays on ground-based telescopes

Most bolometer instruments currently in operation have feedhorn coupled arrays.

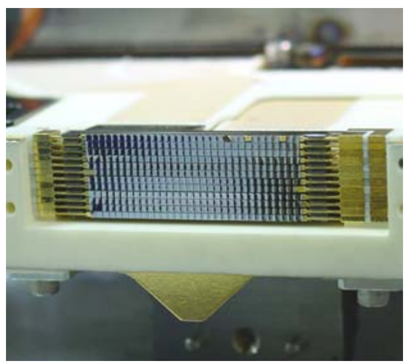
JCMT-SCUBA 450/850μm



91/37 pixels

300/65mJy/√Hz

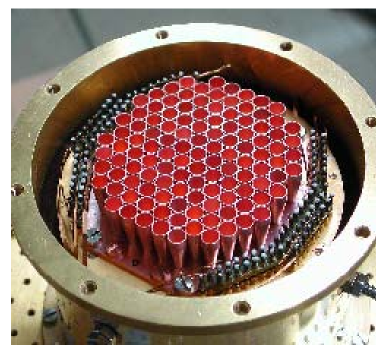
CSO-SHARCII 350μm



384 pixels

500mJy/√Hz

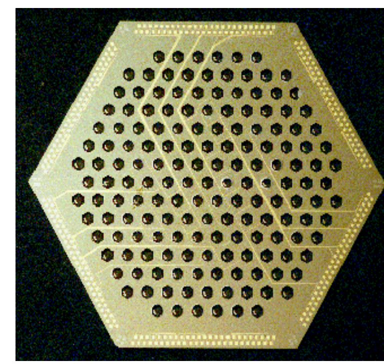
IRAM-MAMBO-2 1.2mm



117 pixels

60mJy/√Hz

CSO-BOLOCAM 1.4mm

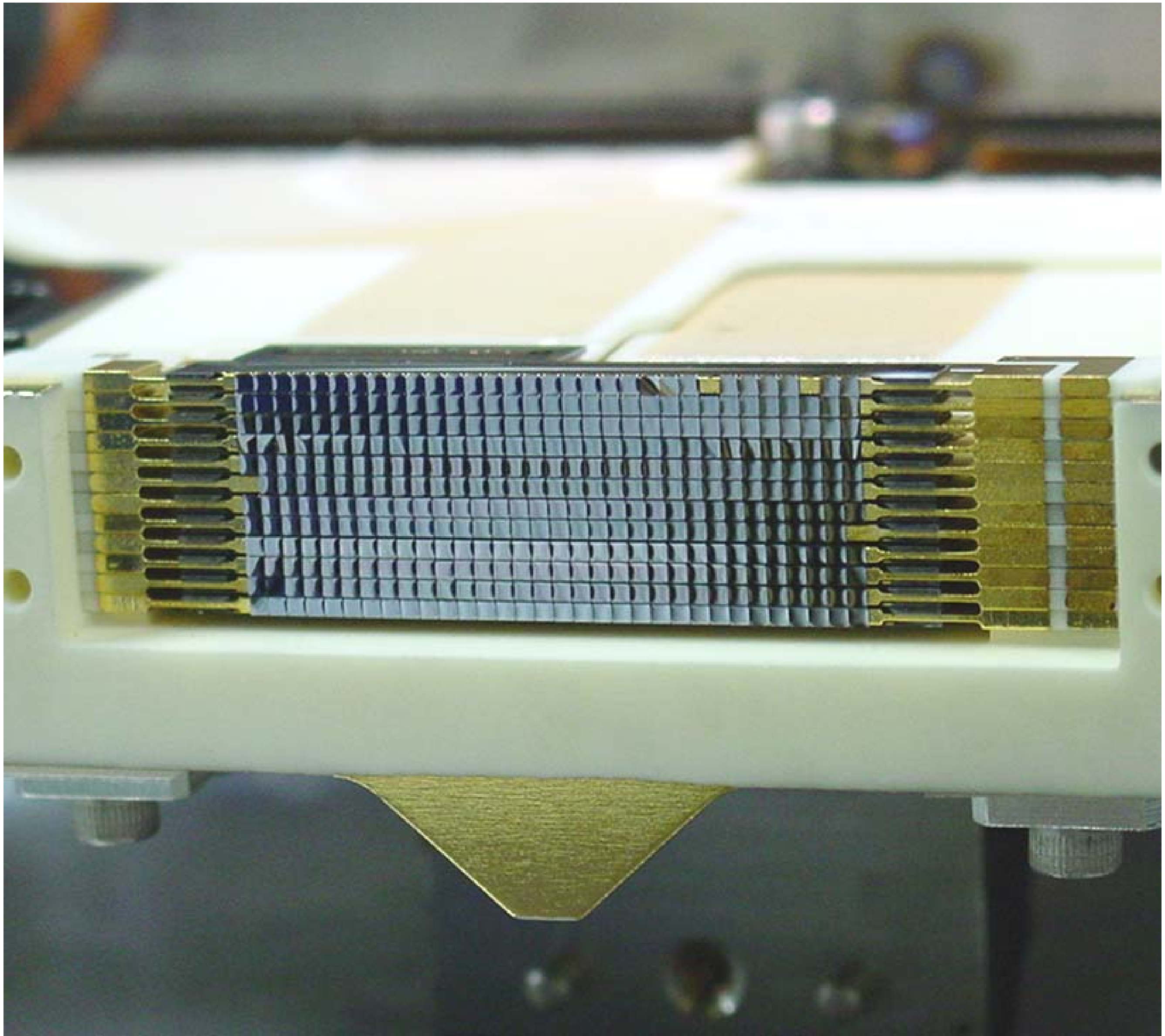


151 pixels

40mJy/√Hz

Arrays on ground-based telescopes

CSO-SHARCII
350μm



12x32 pixels
500mJy/√Hz

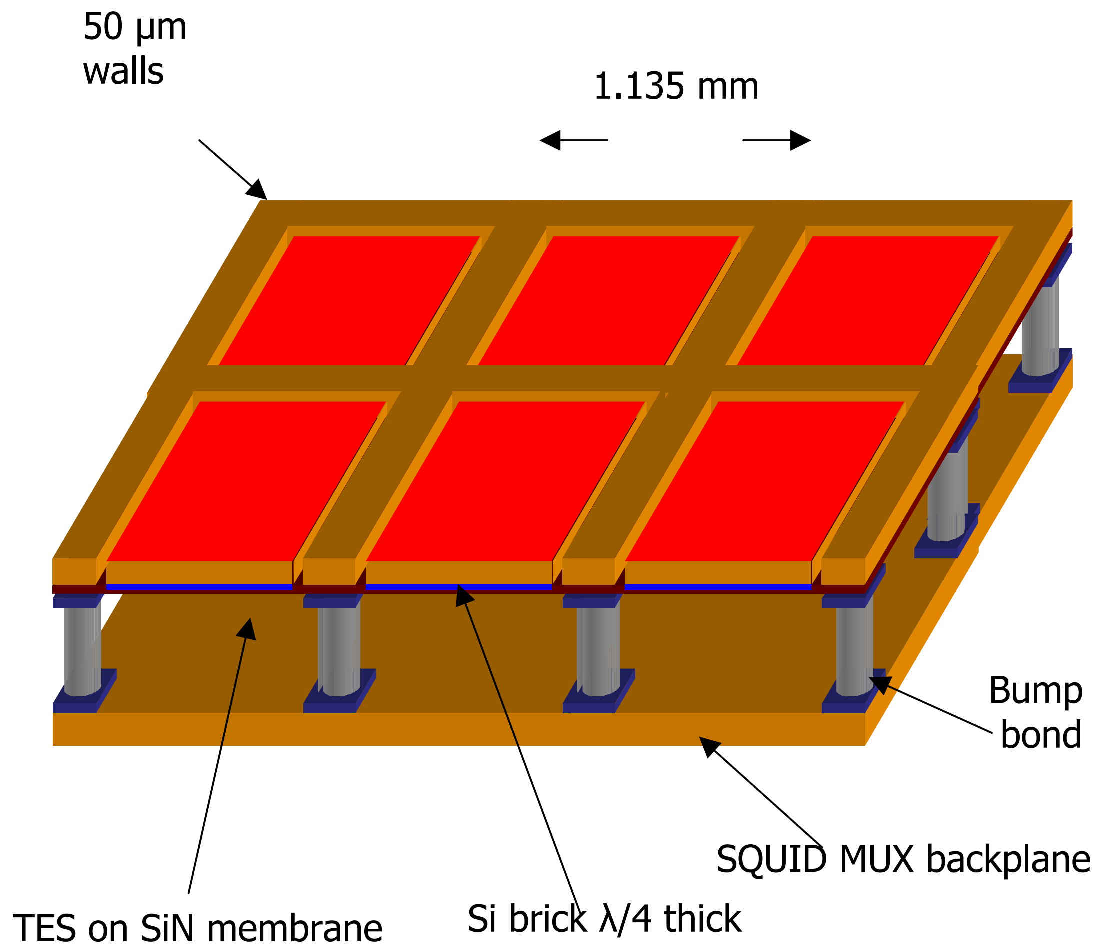
Large-format arrays

★ A number of groups are now developing arrays that will have many hundreds or even thousands of pixels

- Using silicon micro-machining, thin-film deposition, and hybridization techniques

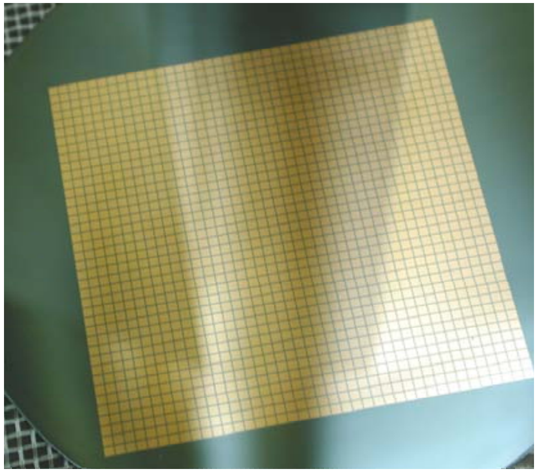
- Integrated SQUID multiplexers in the same plane as the detector chip

- For large-format arrays - wide-field cameras



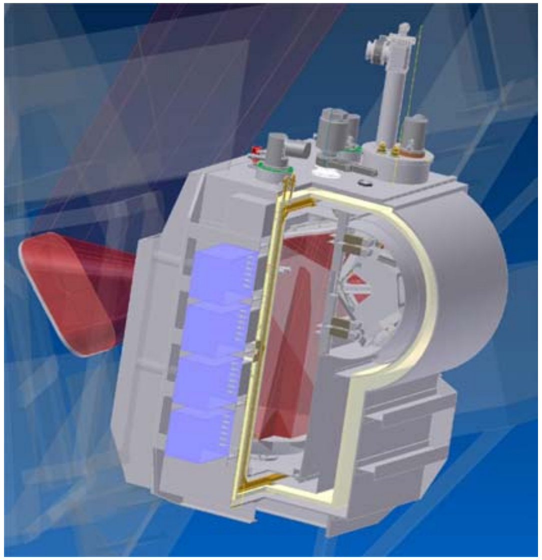
The future... SCUBA-2

★ SCUBA-2 is a 10,000 pixel camera under development for the JCMT:



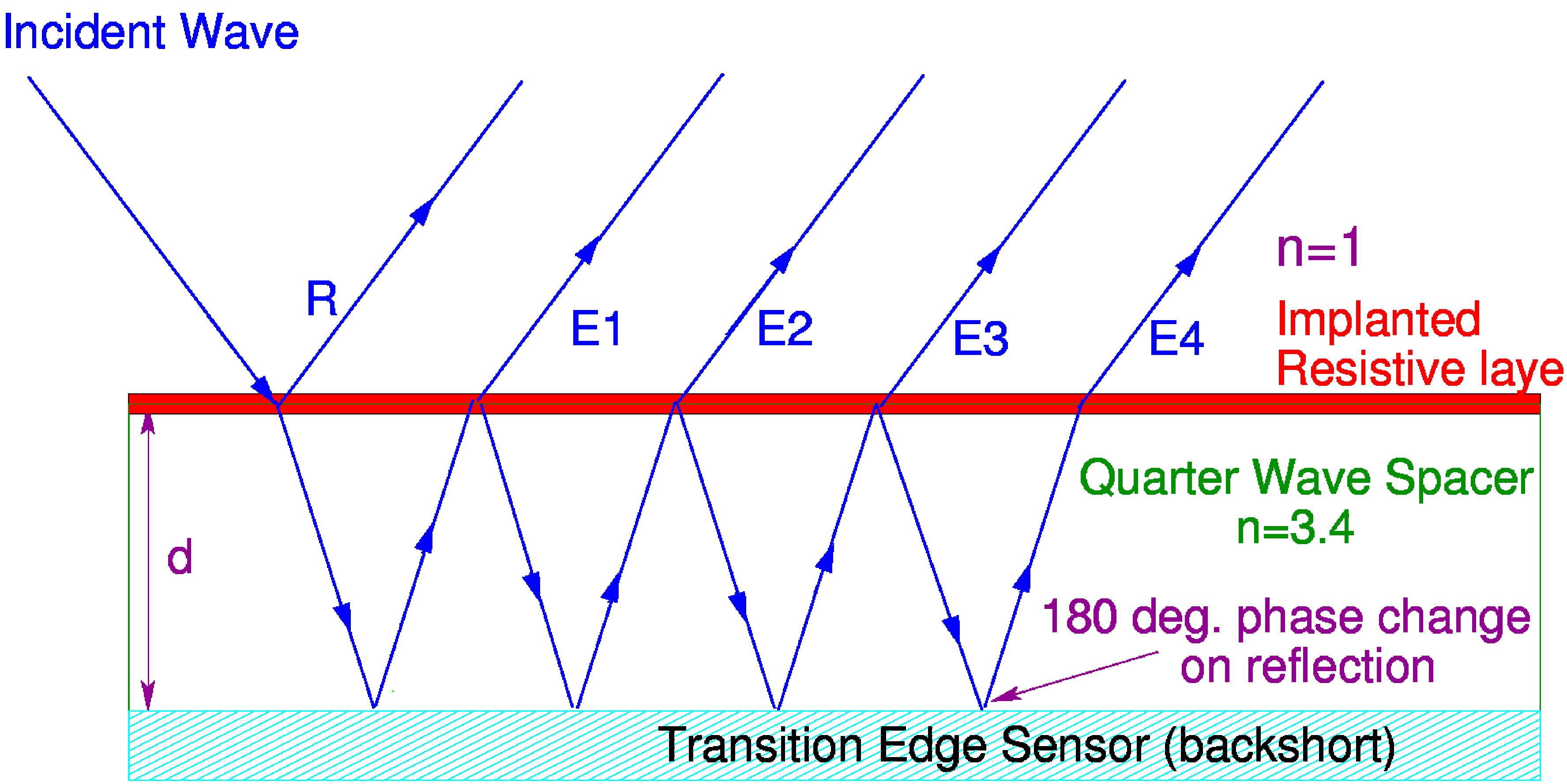
- Two cameras of TES devices – each with 4 sub-arrays
- Multiplexed SQUID readouts
- Fully-sample the 850μm image plane (450μm will be undersampled by a factor of 2)
- Operate at 450 and 850μm simultaneously
- ~8 × 8 arcmin field-of-view
- Background-limited sensitivity
- DC coupled arrays (no sky chopping)

SCUBA-2 will map large areas of sky *1000 times* faster than the current SCUBA to the same S/N.



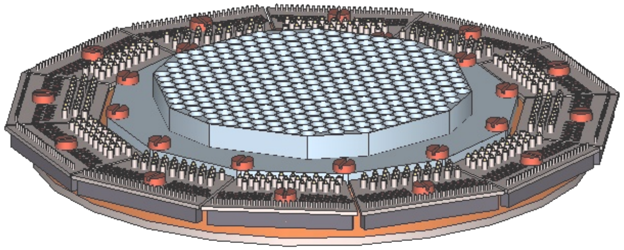
The future... SCUBA-2

How do we thermalize radiation from the telescope?

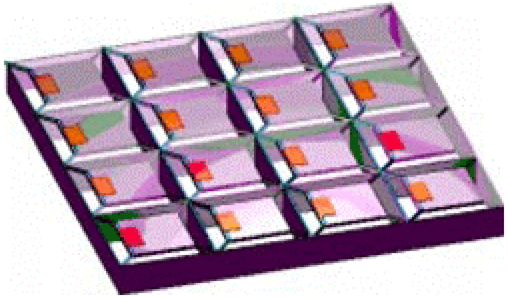


The future...

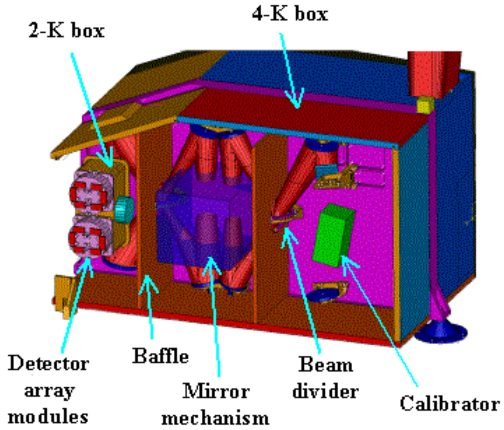
LABOCA - 870 microns, 313 pixels for the APEX telescope



UPenn Bolometer array - 3mm, 64 TES pixels for the GBT telescope (4 × 4 schematic shown)



SPIRE - 200-700 microns, 3 arrays of 43, 88 and 139 NTD Ge pixels for the Herschel space observatory



Conclusions

- Bolometers are the most sensitive total power detectors across a wide-range of wavelengths

- Although they are simple devices in principle, careful instrument design is needed to get the best performance

- The first generation bolometer arrays are now in operation on ground-based and balloon-borne telescopes

- Rapid developments in detector technology and readout circuitry will enable much larger arrays to be constructed – the first submm/mm "CCDs"

- Submm/mm astronomy is about to undergo a revolution similar to the introduction of integrated arrays in the infrared 20 years ago...

More Information

The Book pp 463—491

LOW TEMPERATURE DETECTORS: Ninth International Workshop on Low Temperature Detectors, AIP Conference Proceedings 603 (2002)

LTD-10 Proceedings coming out early 2004