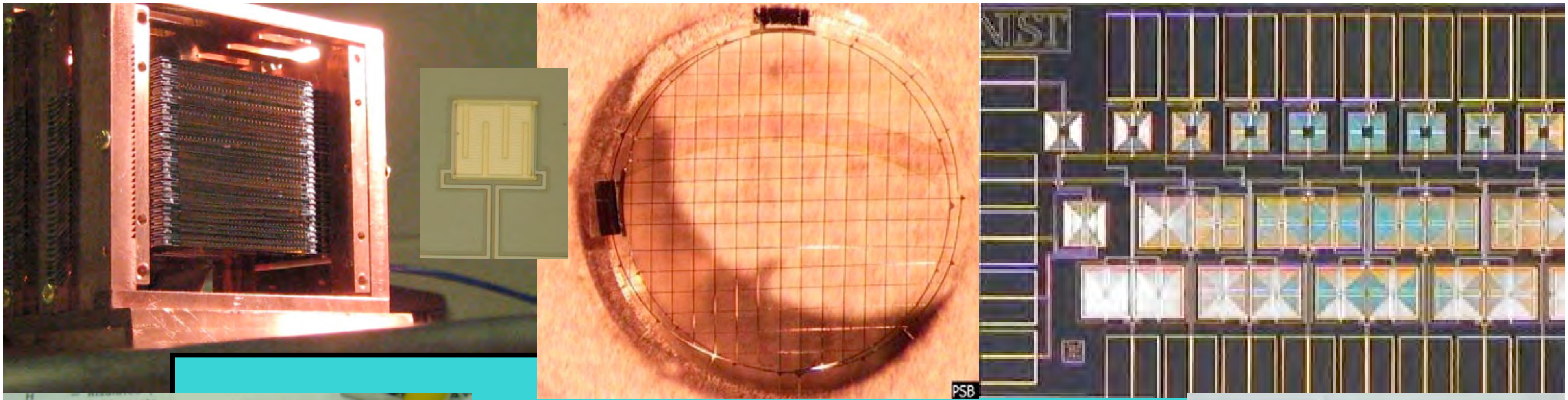
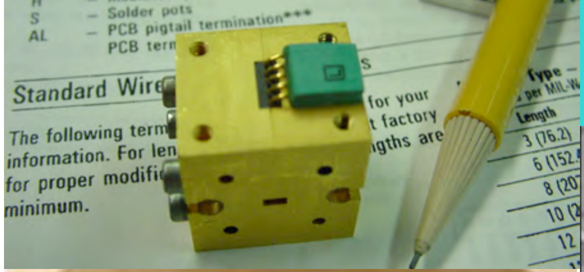
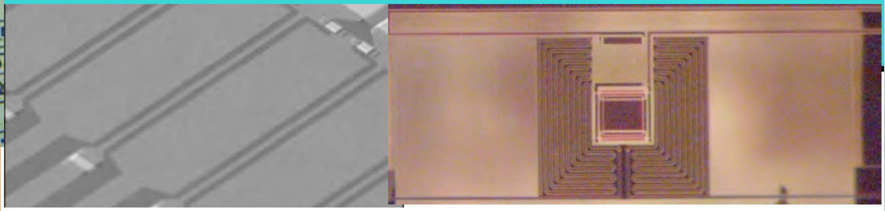
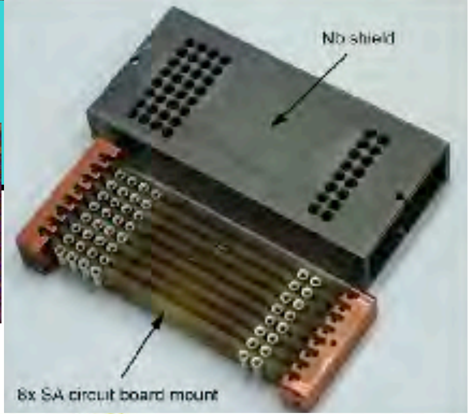
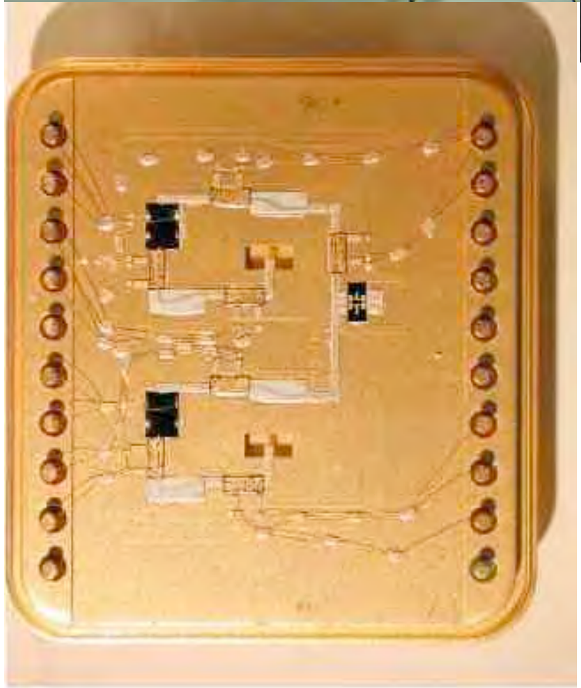




CMB Detectors



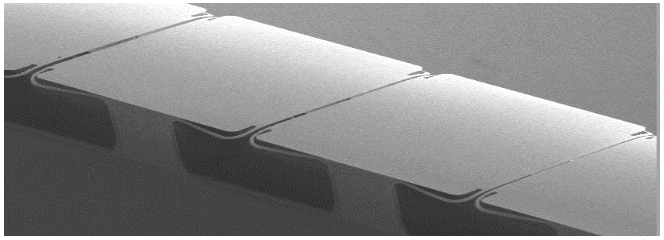


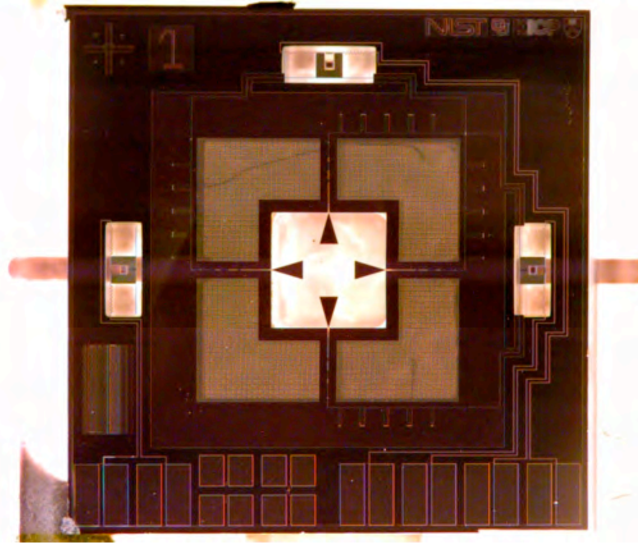


Suzanne Staggs

Princeton University

Gunma, Japan; 11 Feb 09





Properties of Radiation

- Stokes parameters: I, Q, U, V
  - INTENSITY
    - Frequency spectrum: $I(\upsilon)$
    - Intensity variations (I(x,y)): δT
  - POLARIZATION
    - Linear (Q(x,y), U(x,y)): δE and δB
    - Circular polarization (V(x,y))

Absolute Spectrum

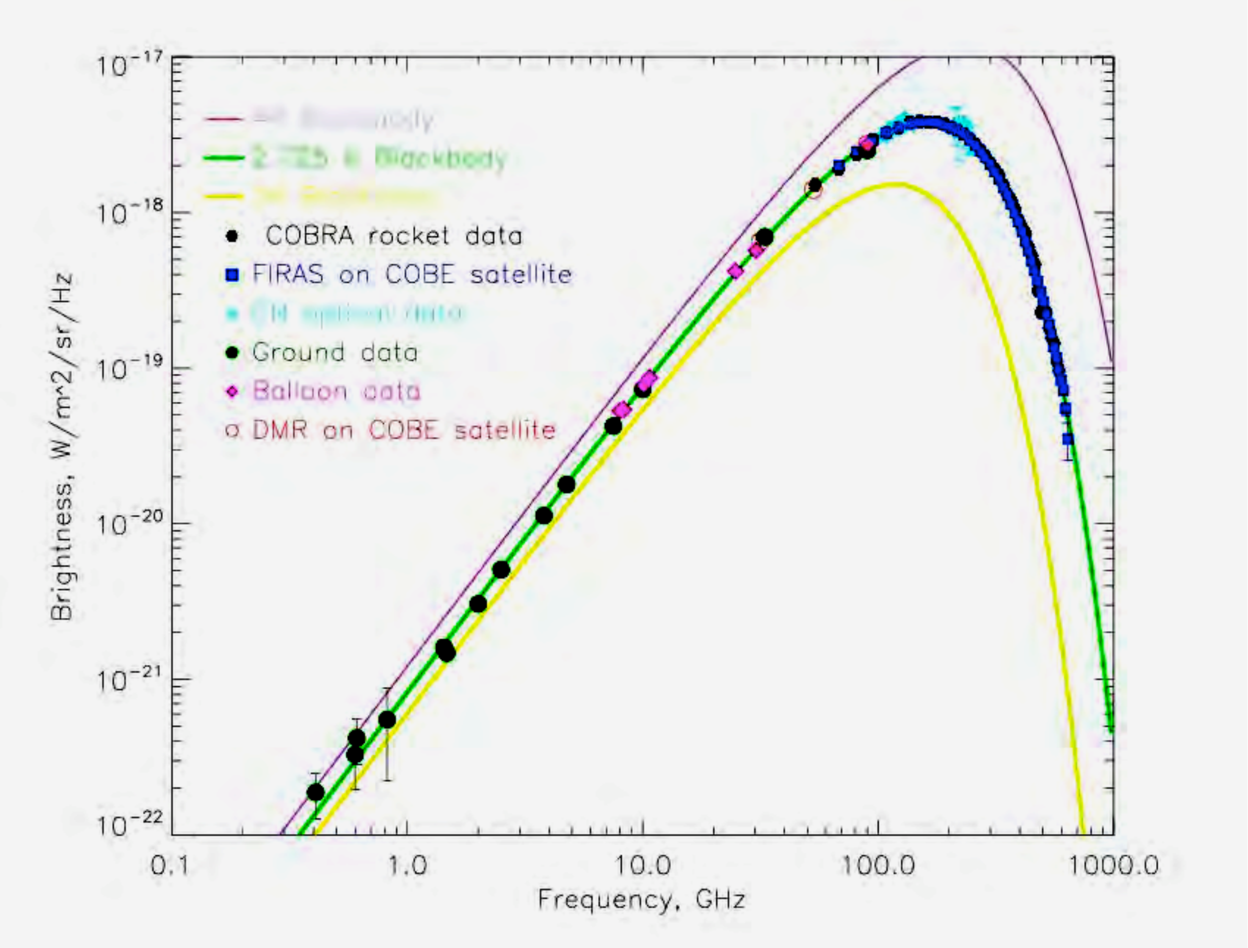


Figure from Samtleben,Staggs, Winstein, Ann. Rev. Nucl Part Sci 57, 245 (2007)

Measuring Temperature

- Blackbody brightness, using x=hυ/kT:

$$B_\nu = \frac{2h\nu^3}{c^2}\left(\frac{1}{e^x - 1}\right) \text{ W m}^{-2}\text{ sr}^{-1}\text{ Hz}^{-1}$$

- If x << 1 then e^x-1 ~ x: $$B_\nu \approx \frac{2\nu^2}{c^2}kT$$

- Define T_{RJ}: $$T_{RJ} = \frac{c^2}{2k\nu^2}B_\nu$$

(x << 1 is the Rayleigh Jeans limit)

- We call T the 'thermodynamic temperature.' Sometimes T_{RJ} is called 'antenna temperature'

Measuring Temperature

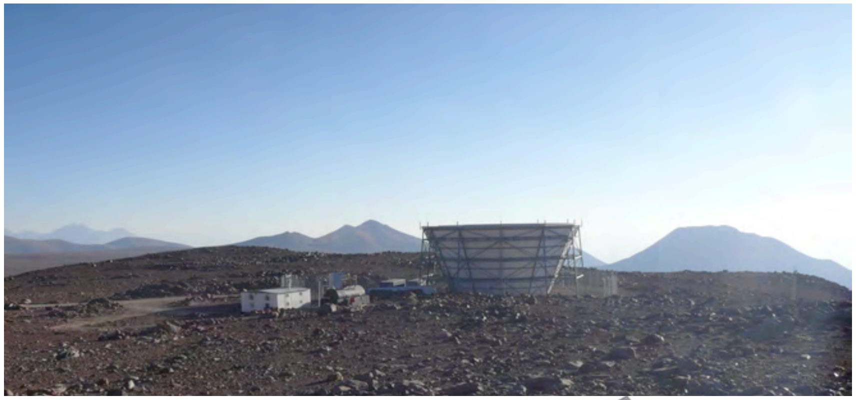
- We defined $x = h\upsilon/kT$
- For the CMB with T=2.728 K, x=1 for υ=59 GHz.
- Most calibration sources have T high enough that x <<1 for CMB frequencies of interest
- We can relate T and T_{RJ}:

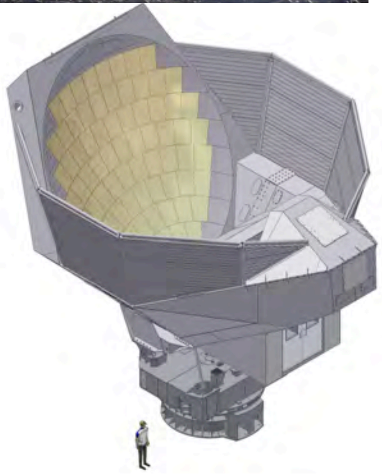
$$T = T_{RJ}\left(\frac{e^x - 1}{x}\right)$$

- When measuring temperature anisotropies, must differentiate:

$$\delta T = \delta T_{RJ}\left(\frac{(e^x - 1)^2}{x^2 e^x}\right)$$

Measuring Microwaves





Most CMB instruments are surrounded by huge groundscreens.

(The Atacama Cosmology Telescope, ACT is an example.)

- Since 3 K << 300 K, CMB measurements are sensitive to thermal emission from their environments
- CMB telescopes are specially designed to be very directional, but 300 K in the sidelobes is always a worry
- The atmosphere also emits thermal radiation, so high dry sites are preferred.
- Balloon-borne platforms evade the atmosphere but suffer from ground and balloon emission.
- Space platforms have special advantages.

ACT at night (courtesy Mark Devlin)

The Radiometer Equation

- A receiver has a system temperature T_{sys}
  - $T_{sys} = T_{rec} + T_{cmb} + T_{atm} + T_{gnd} + \dots$
- The detection bandwidth is $\Delta\upsilon$
- Make N measurements each with integration time τ
- The variance of those is δT^2
- Define the sensitivity S by $\delta T^2 = S/\tau$
- The Radiometer Equation is:

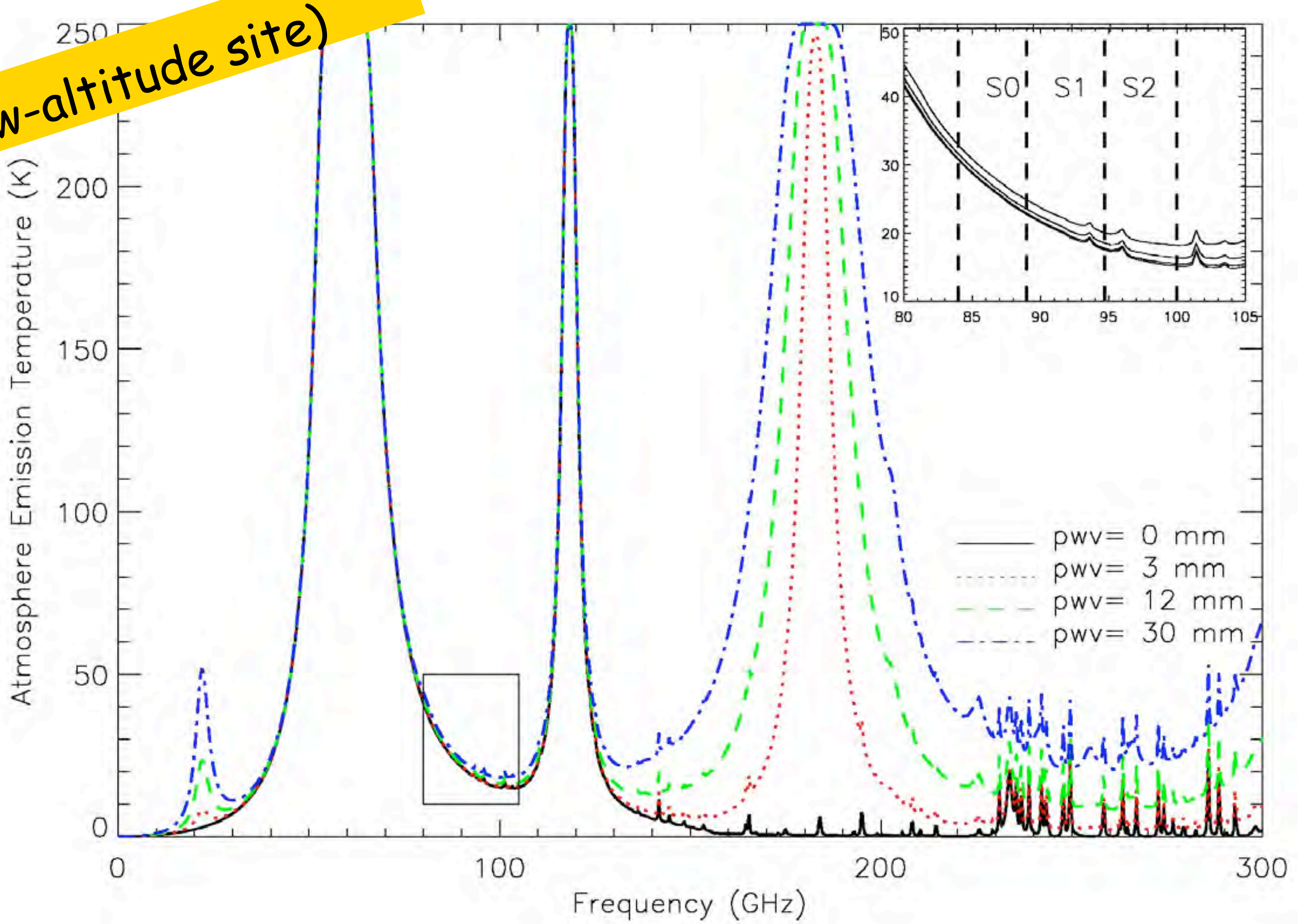
$$\delta T = \frac{bT_{sys}}{\sqrt{\Delta\nu\,\tau}}$$

  - where b is a constant near unity depending on the type of radiometer. (Note that $S = bT_{sys}/\Delta\upsilon$.)

Going to a high dry site reduces Tatm and so improves S!

Atmosphere

From NJ (a wet low-altitude site)

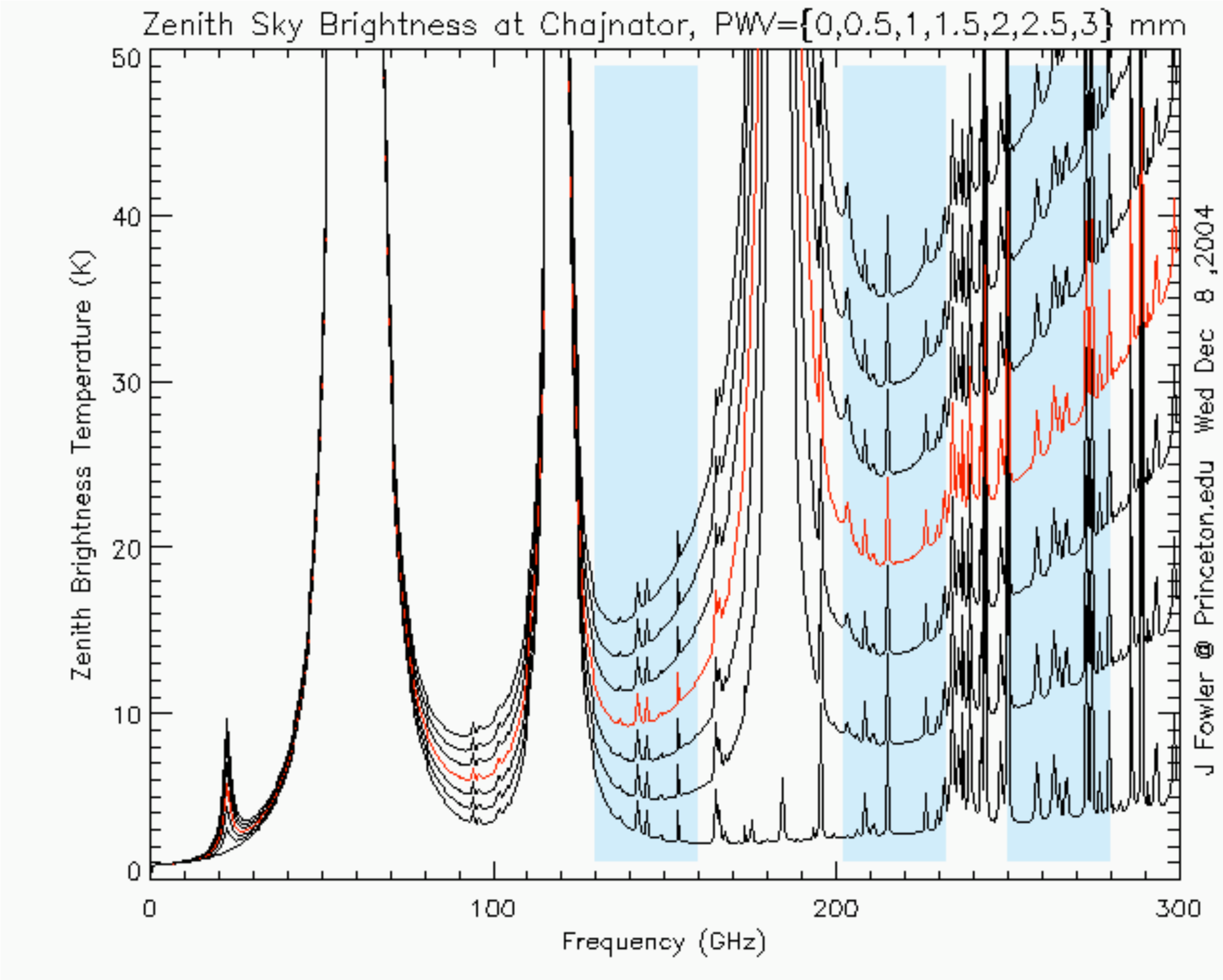


Oxygen and water lines in the atmosphere limit microwave bands observable from ground.

(Note that the CAPMAP experimented measured CMB polarization from NJ where pwv~ 4-8 mm!)

Atmosphere

From Chile Chajnantor plateau (site of ALMA, ASTE, QUIET, and ACT): note vertical scale is 50x lower



Location, location, location!

The Radiometer Equation

- The expression $S = bT_{sys}/ \Delta\upsilon$ gives the best (lowest) sensitivity a given receiver can have
- Post detection noise can increase S
- Responsivity (or gain) variations can increase S
- Define the responsivity R in terms of the change in the output detector voltage, δV, in response to the change in the sky temperature, δT: $\delta V = R\,\delta T$.
- The generalized radiometer equation is:

$$\delta T = bT_{sys}\sqrt{\frac{1}{\Delta\nu\,\tau} + \left(\frac{\delta R}{R}\right)^2}$$

The Radiometer Equation

- The generalized radiometer equation is:

$$\delta T = bT_{sys}\sqrt{\frac{1}{\Delta\nu\,\tau} + \left(\frac{\delta R}{R}\right)^2}$$

- Note that if δR/R increases with time -- as with classic 1/f noise -- integrating for a longer τ does not decrease the error!
- All receivers suffer from 1/f noise at some time scales, so CMB measurements require MODULATION, often in the form of scanning the telescope, which allows an AC measurement

The Radiometer Equation:

Caveats

- The expression $S = bT_{sys}/ \Delta\upsilon$ (sometimes called the Dicke equation) is valid for most of radioastronomy.
- In fact, the Dicke equation is only complete in the limit of large photon mode occupancy (where $x=h\upsilon/kT$):

$$n_\gamma = \frac{1}{e^x - 1} << 1$$

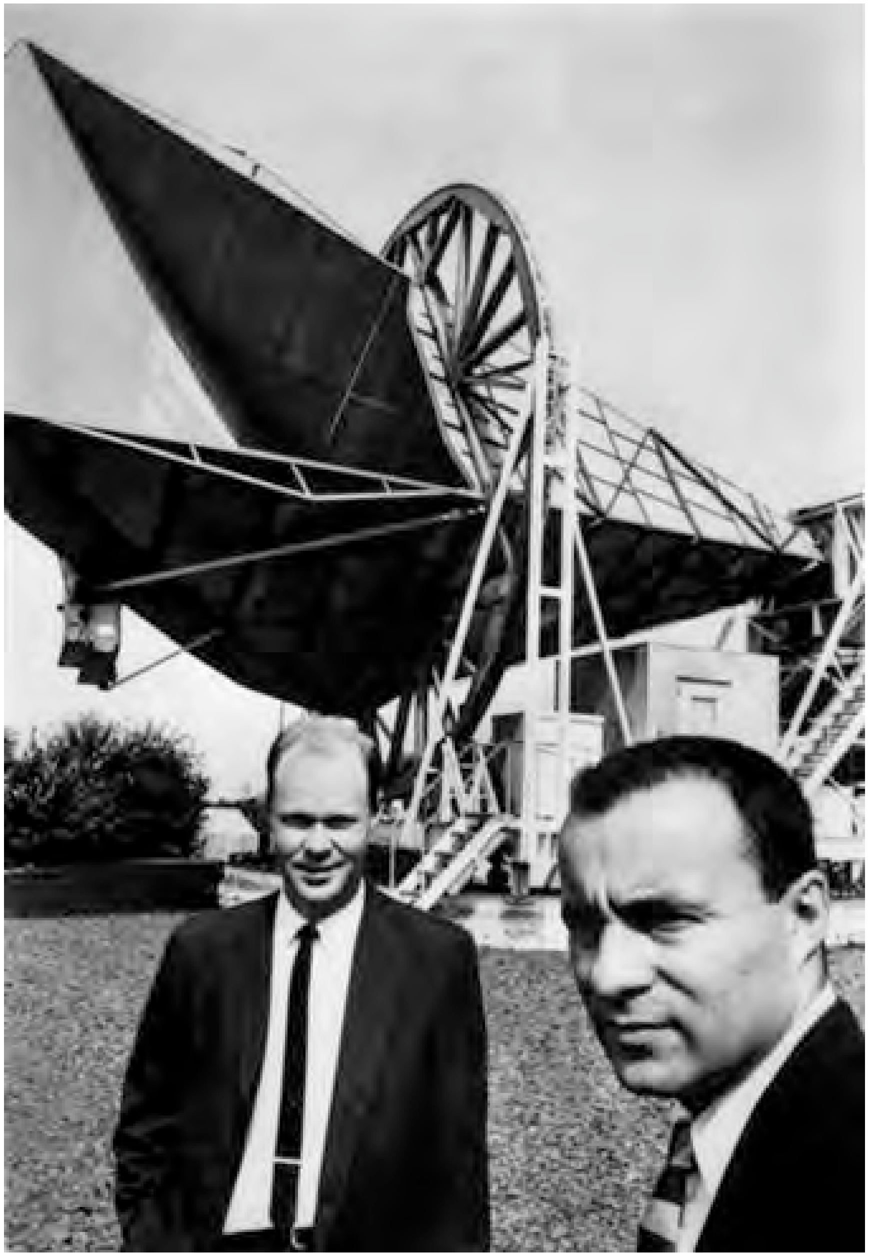
- For smaller mode occupancy (as in many bolometer receivers), photon shot noise can dominate:

$$S \propto \sqrt{T_{sys}}$$

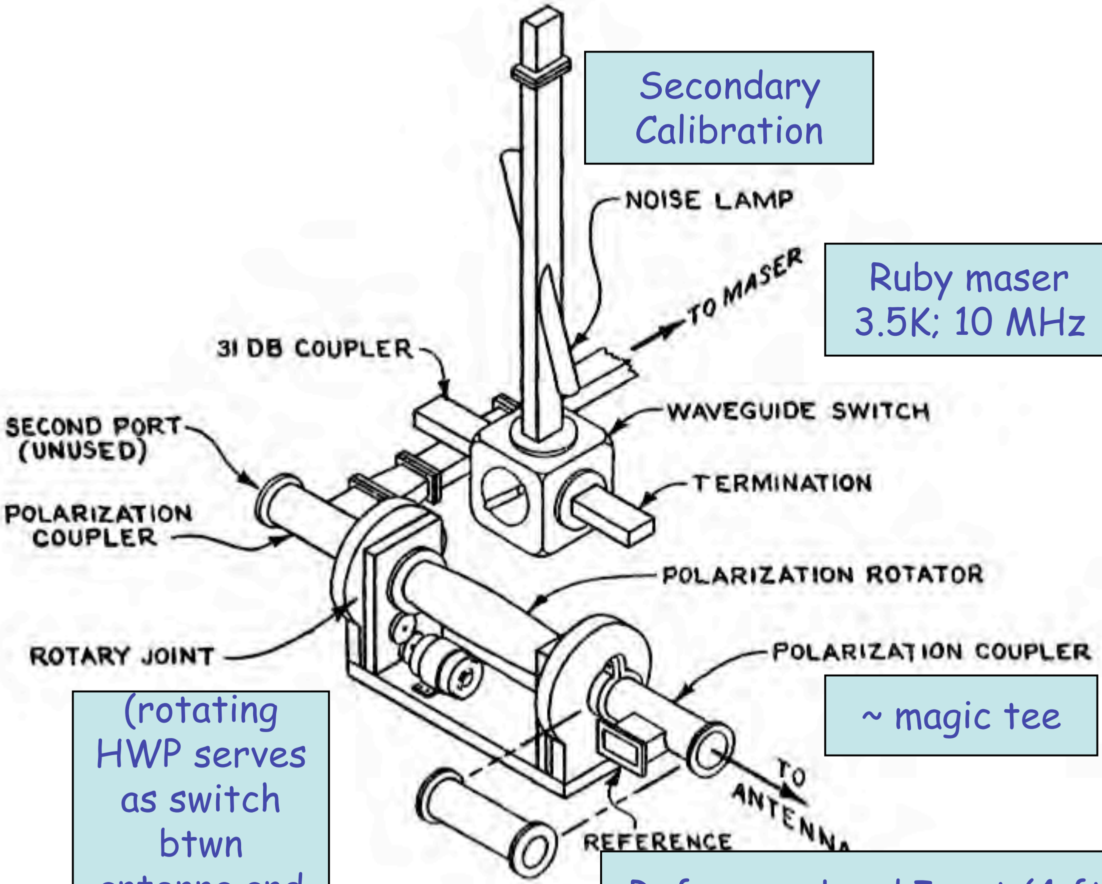
- More on bolometer noise later!

CMB DETECTION

- Penzias & Wilson, 1965 ApJ 142, 419
  - "A Measurement of Excess Antenna Temperature at 4080 Mc/s"
  - Isotropic & unpolarized 'within the limits of our observations'
  - $T_{cmb} = 3.5 +- 1$ K
- Nobel Prize, 1978 (shared with Kapitsa)



The First CMB Receiver



Secondary Calibration

Ruby maser 3.5K; 10 MHz

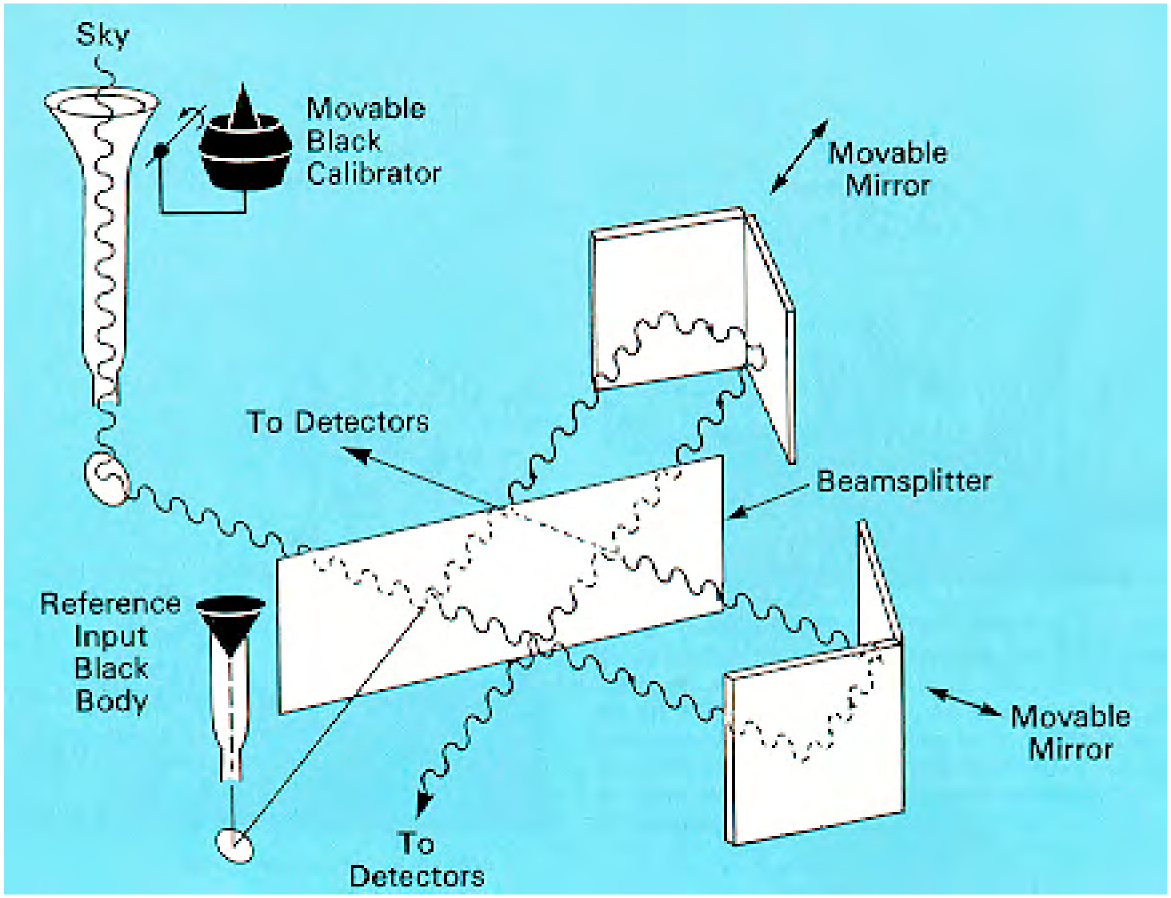
~ magic tee

(rotating HWP serves as switch btwn antenna and reference laod)

Reference Load Input (4 ft long piece of brass waveguide in Lhe dewar with absorber cone at the bottom.) See Penzias, RevSci Instr, 36, 68 (1965)

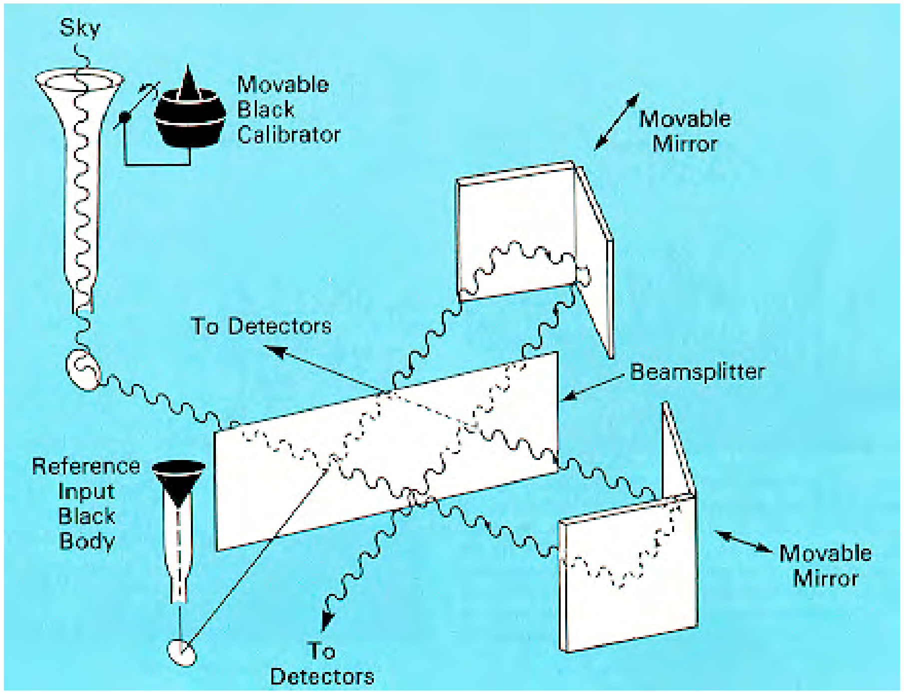
- Penzias & Wilson, 1965, ApJ 142, 1149.
- Tsys = 20 K
- Expected S = 5 mK $s^{-1/2}$
- Helium bubbling in the maser caused gain fluctuations
- Achieved S = 25 mK $s^{-1/2}$
- Totally adequate for measuring T=3 K!

FIRAS



- Mather et al 1999: T_{cmb} = 2.728+-0.002 K
- No distortions to blackbody at 50 ppm
- Nobel Prize, 2006 (shared with Smoot)

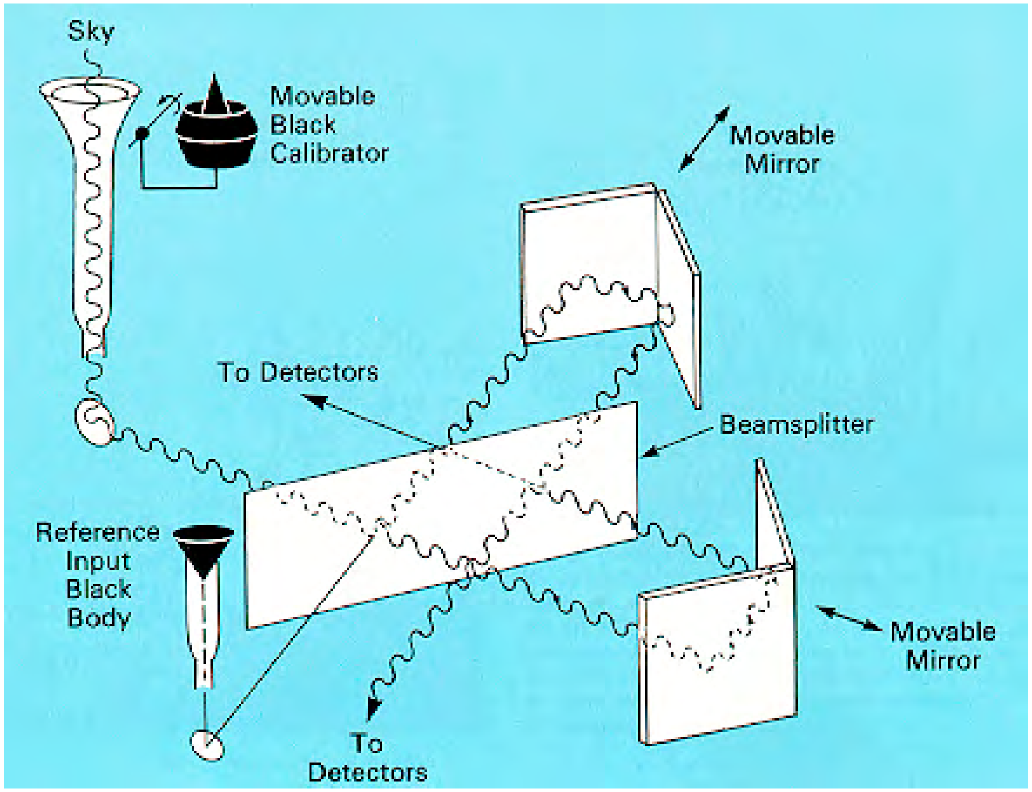
FIRAS



- Beamsplitter = wire grid (reflects one polarization; transmits the other)
- Dihedral (rooftop) mirrors rotate polzn
- Inherently differential*: output is $I_{sky}(\upsilon)$ -$I_{ical}(\upsilon)$
- Input blackbody (ICAL) has its temperature set to null the output!

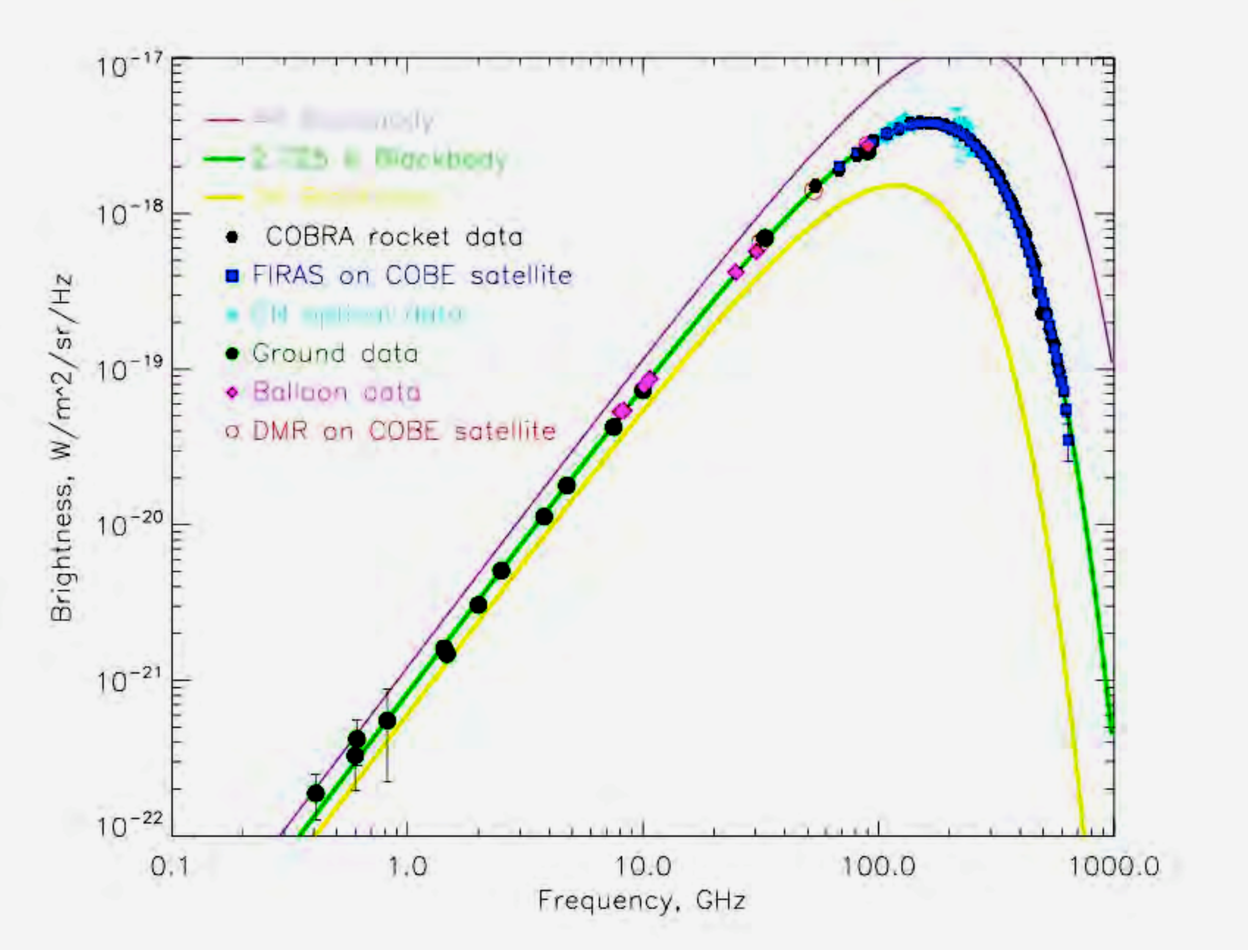
*drawing is simplified; real instrument has two beam splitters (and other steering and collimating elements)

FIRAS



- υ = 60 GHz to 3 THz
- 7^{o} FOV
- Detectors are bolometers at 1.6K
- NEP = 4×10^{-15} W $Hz^{-1/2}$ (about 100x worse than typical 300 mK ground-based bolometers now)
- Calibration: periodically replace sky with Xcal: emissivity > 0.9999

Absolute Spectrum

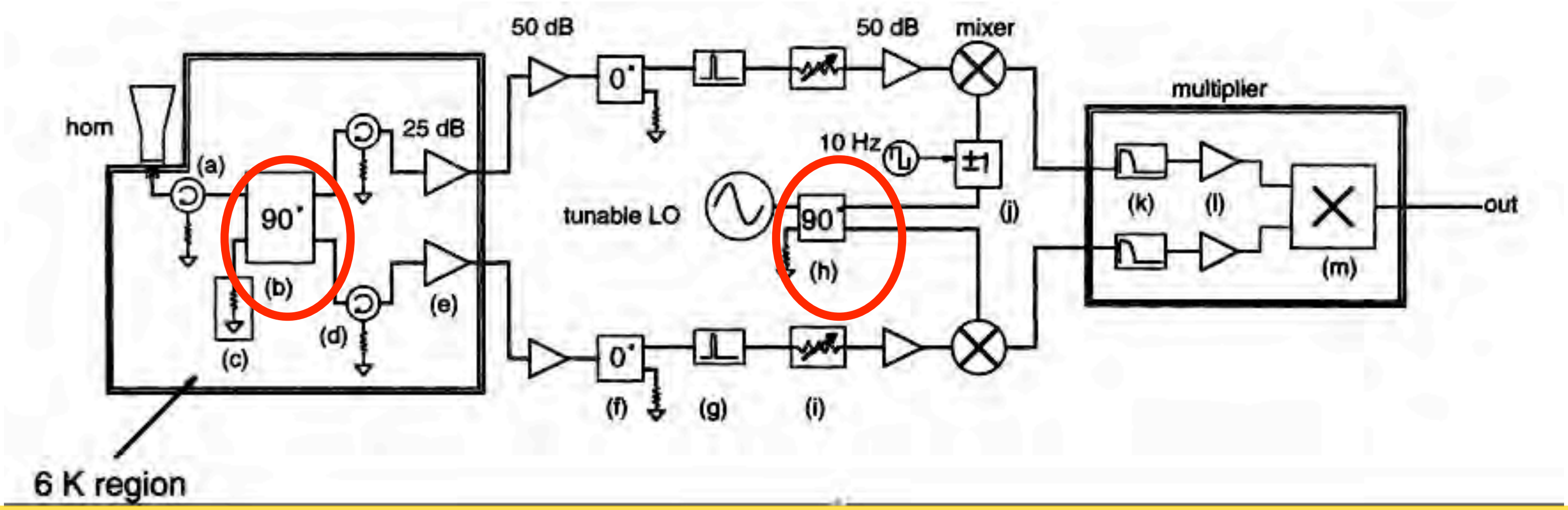


BLUE LINE shows the FIRAS data with greatly inflated errors: distortions from blackbody are less than 50 ppm!

Figure from Samtleben,Staggs, Winstein, Ann. Rev. Nucl Part Sci 57, 245 (2007)

CORRELATION RECEIVERS

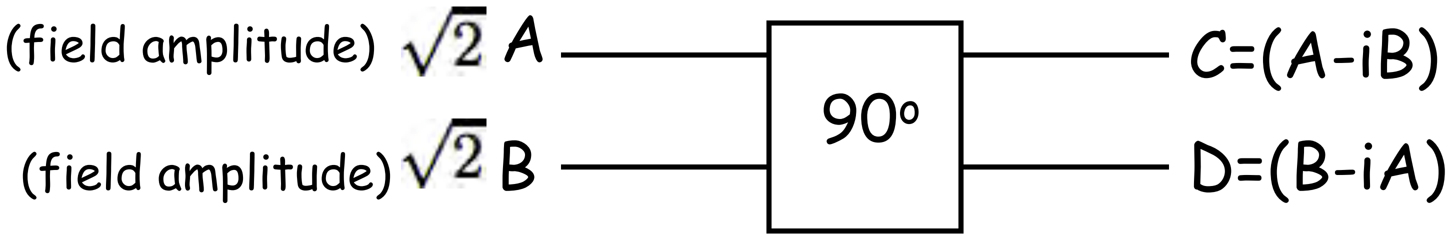
Example: 20 cm absolute experiment (Staggs, et al 1996).



Correlation technique reduces sensitivity to gain fluctuations because output is Tsky-Tref ~ zero; you read the temperature of the reference load to find T_{sky}.

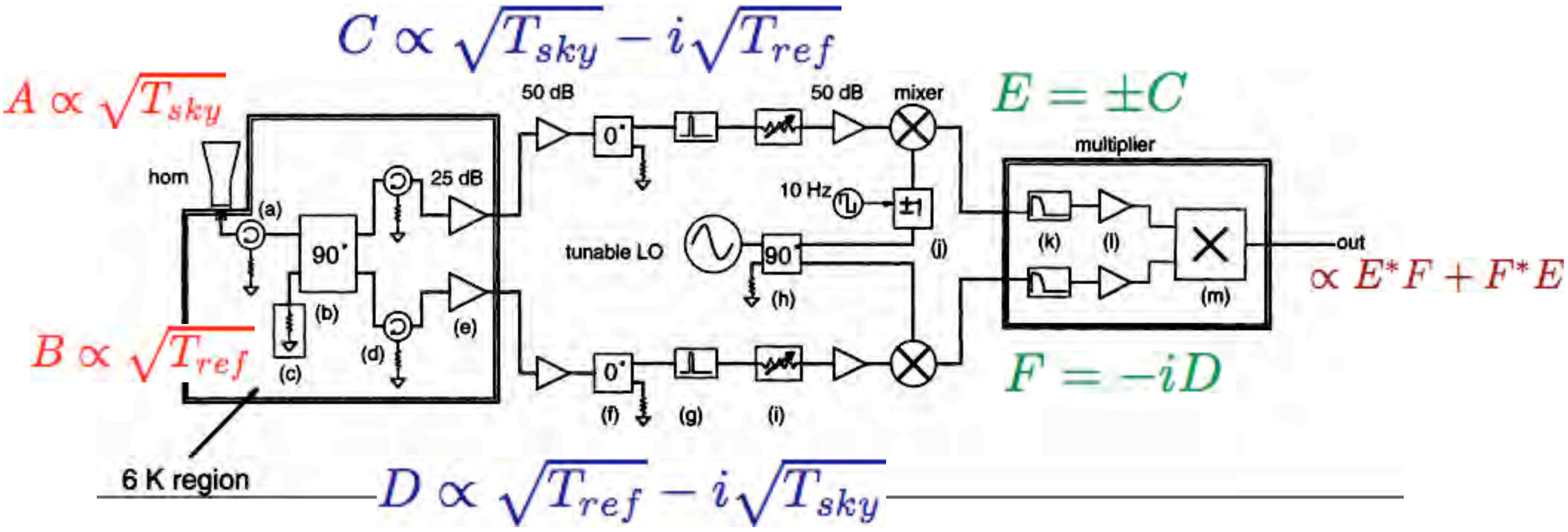
CORRELATION RECEIVERS

The 90° 3 dB hybrid coupler:



$T_{sky} \propto I_{sky} \propto E^2_{sky}$, so the amplitude from the sky horn is $\propto \sqrt{T_{sky}}$.

CORRELATION RECEIVERS



$C \propto \sqrt{T_{sky}} - i\sqrt{T_{ref}}$

$A \propto \sqrt{T_{sky}}$

$E = \pm C$

$B \propto \sqrt{T_{ref}}$

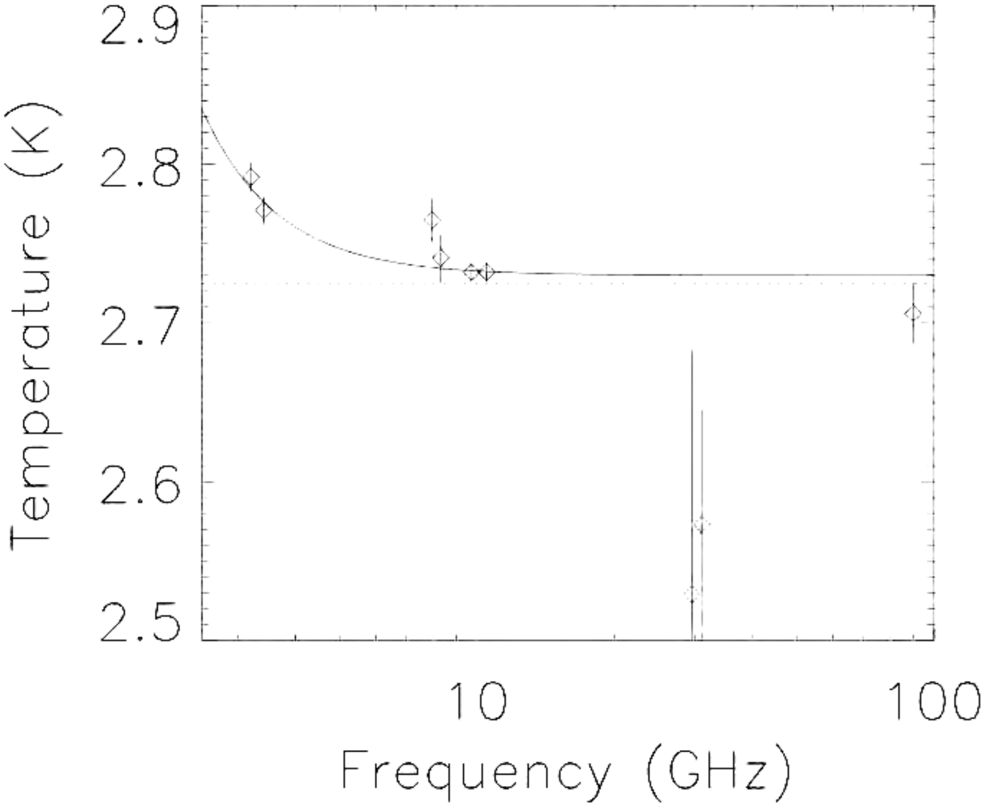
$\propto E^*F + F^*E$

$F = -iD$

$D \propto \sqrt{T_{ref}} - i\sqrt{T_{sky}}$

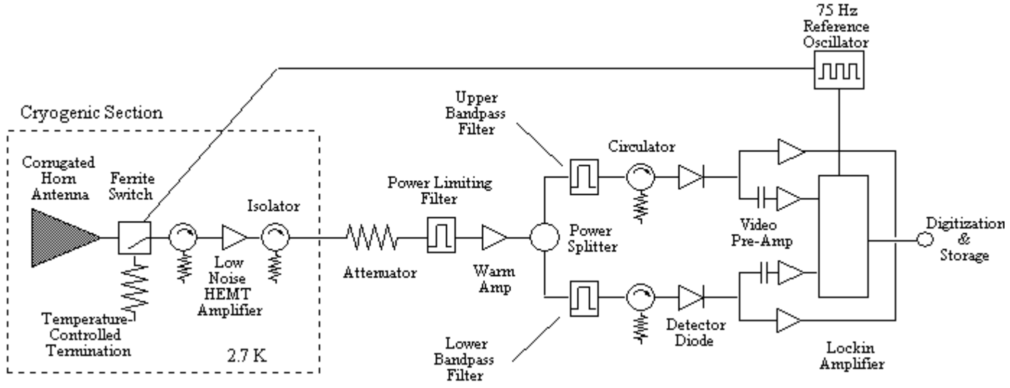
$$\text{Output} \propto E^*F + F^*E \propto \mp(T_{sky} - T_{ref})$$

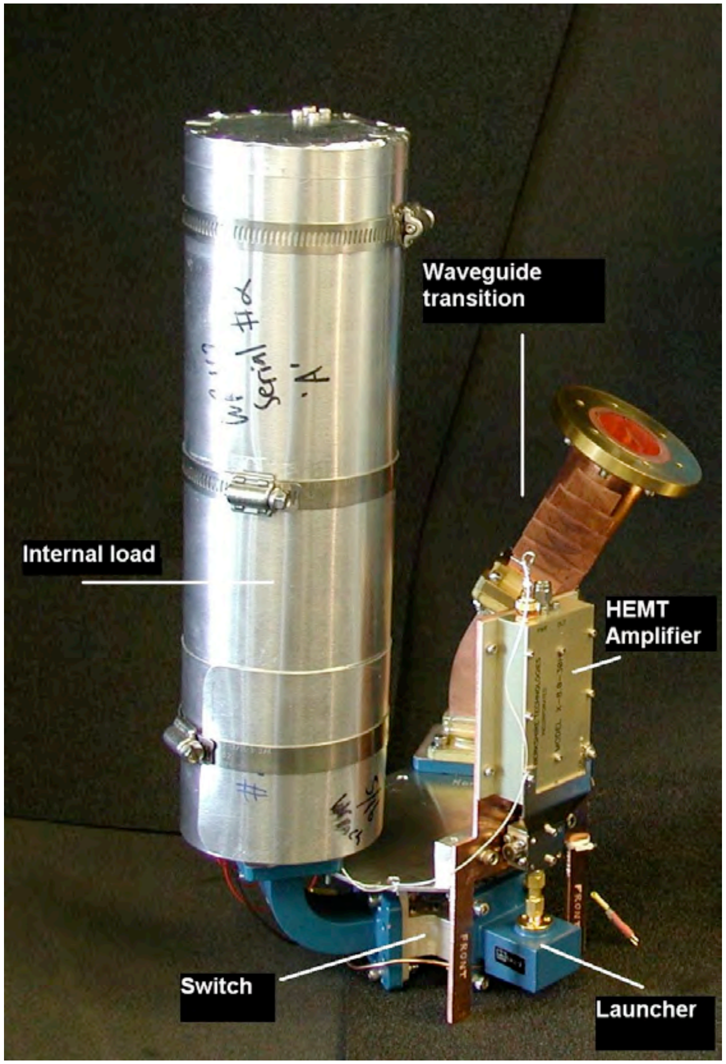
Absolute Spectrum:
New Results



- **ARCADE 2** (balloon flight)
- Fixsen et al, 2009, arXiv:0901.0555v1
- (Also observe power-law-spectrum extragalactic excess amounting to ~60 mK at 3.3 GHz)

Absolute Radiometer: ARCADE





Six frequency bands: 3, ~~5~~, 8, 10, 30, 90 GHz

Chop between horn and load at 75 Hz

Load functions as transfer standard, but is black enough (ε>0.999) for absolute reference

External calibrator (ε>0.99997) nulls any remaining instrument asymmetry and provides absolute temperature scale

Slide courtesy of Al Kogut

The Absolute Spectrum
&
The Experimental Platforms

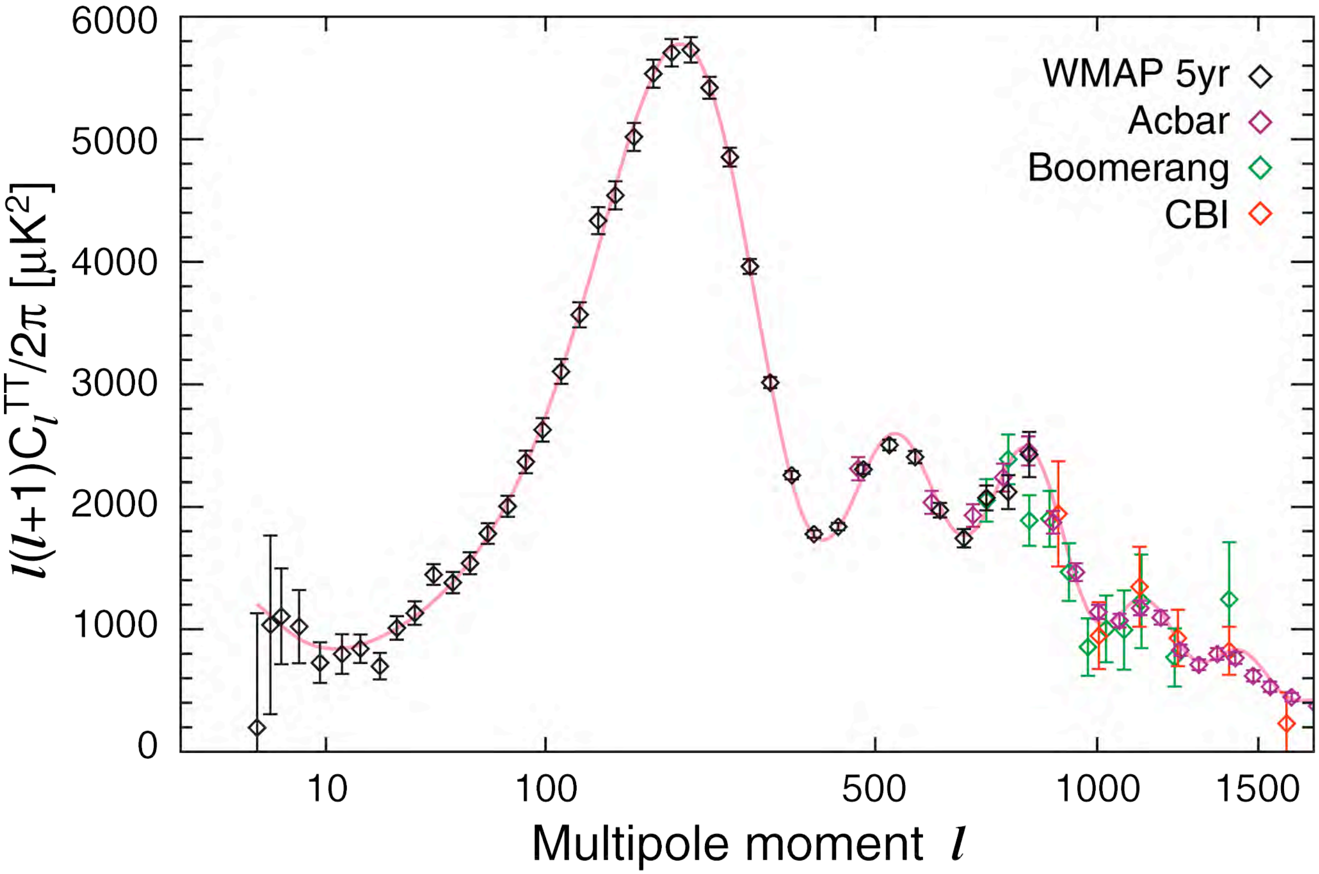
Best measurements from space:	2 mK errors
Best measurements from balloons:	10 mK errors
Best measurements from ground:	200 mK errors

(The comparisons for CMB temperature anisotropy and for CMB polarization anisotropy are not so stark!)

Properties of Radiation

- Stokes parameters: I, Q, U, V
  - INTENSITY
    - Frequency spectrum: I(υ)
    - Intensity variations (I(x,y)): δT
  - POLARIZATION
    - Linear (Q(x,y), U(x,y)): δE and δB
    - Circular polarization (V(x,y))

Temperature Power Spectrum



Staggs; 3rd Asian School of Particles
Strings & Cosmology, Feb 09

Nolta et al 2009.

The Basics

- Sensitive detectors are needed (and low-systematics techniques)
- Back of the envelope:
  - Record N beam-sized patches of sky into vector d; beam size is x_b
  - Noise on each measurement is σe
  - Multipoles sampled are approximately:

$$\ell_{min} = \frac{1}{x_b}; \text{ and } \ell_{max} = \frac{1}{N x_b}$$

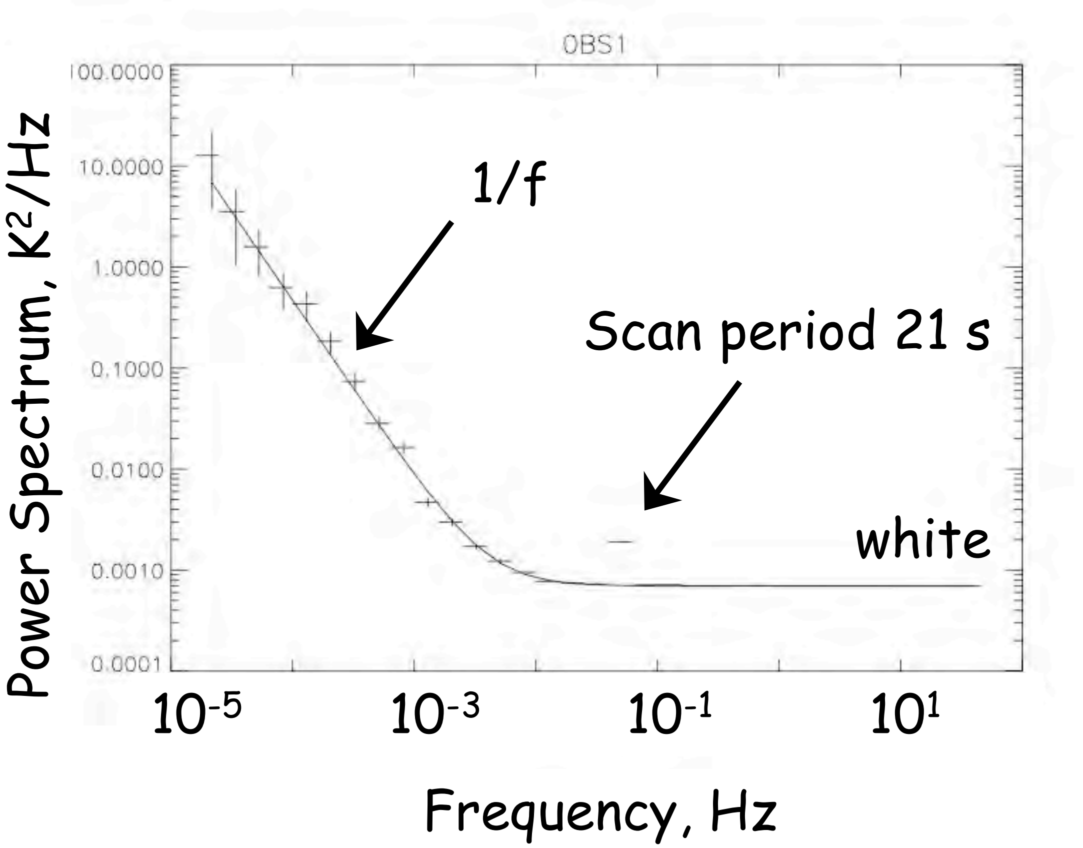
  - Define $\Delta\ell = \ell_{max} - \ell_{min}$ and ℓ_c as their average.
  - Assume the ps is white with average level ΔT^2 over $\Delta\ell$
  - If neglect σe (and sky curvature) then the variance in d is:

$$\sigma_d \approx \Delta T^2 \frac{\delta\ell}{\ell_c}$$

  - For $\Delta\ell / \ell_c \sim 1$, might then have $\sigma_d \sim (6000\ \mu K^2)^{-1/2} = 70\ \mu K$.
  - For $S = 1\ mK\ s^{-1/2}$, after 10 minutes $\sigma_e \sim 40\ \mu K$ on a single one of those N patches
- THIS WAS ALL FOR THE PEAK OF THE TEMPERATURE POWER SPECTRUM! It only gets worse for fine-scale CMB and polarization.

Modulation & the Postdetection Power Spectra

- An example postdetection power spectrum (the square of the Fourier transform of the timestream)
- Note the 1/f portion of the spectrum, which meets the white noise floor around 0.001 Hz (several minutes)
- from CAPMAP (using HEMT-based correlation polarimeters)
- Even in NJ, S~1 mK $s^{-1/2}$



Slide courtesy of
C. Bischoff

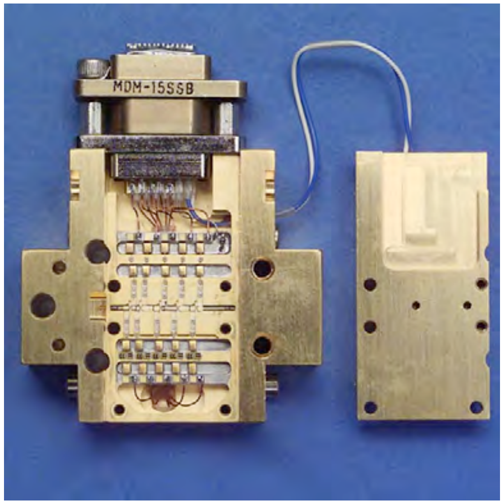
CMB Detector Classes

- Coherent (phase-preserving amplification of the voltages from incoming fields)
  - HEMT low noise amplifiers (HEMT LNAs)
  - SIS mixers followed by LNAs
  - Permits correlation techniques*
- Incoherent (direct measurement of intensity without ampification)
  - Bolometers
  - MKIDs (measurement of kinetic inductance changes when superconductors absorb microwaves)

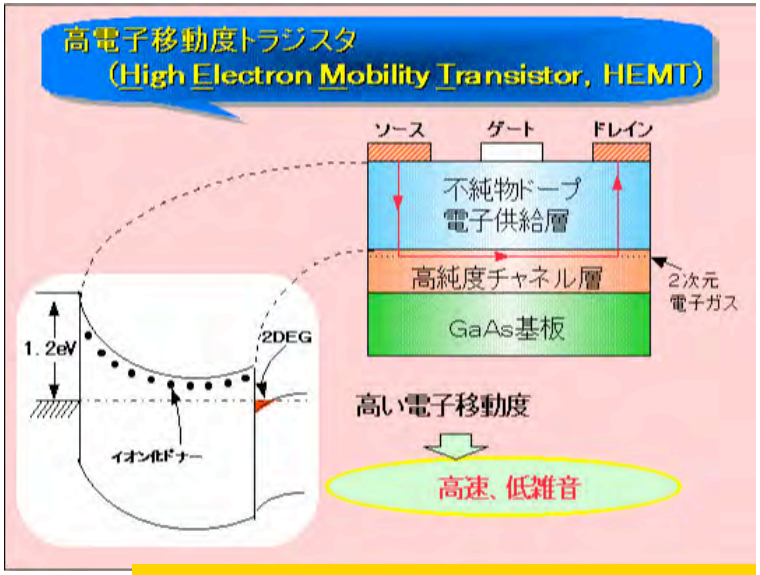
*Amplification is not necessary for correlation techniques, so 'coherent' and 'correlation' are not synonymous

HEMT amplifiers

- High electron mobility transistor (HEMT amplifiers)
- Commonly available in frequency bands from 1 GHz to 100 GHz
- Higher frequency bands in development
- Operate at 10-20 K
- Used recently in WMAP, QUIET, DASI, CBI, CAPMAP*



V-band MIC HEMT from WMAP: 50 micron wide gates, 5 stages of amplification. Pospieszalski, IEEE MTT-S Digest, 2000, 25

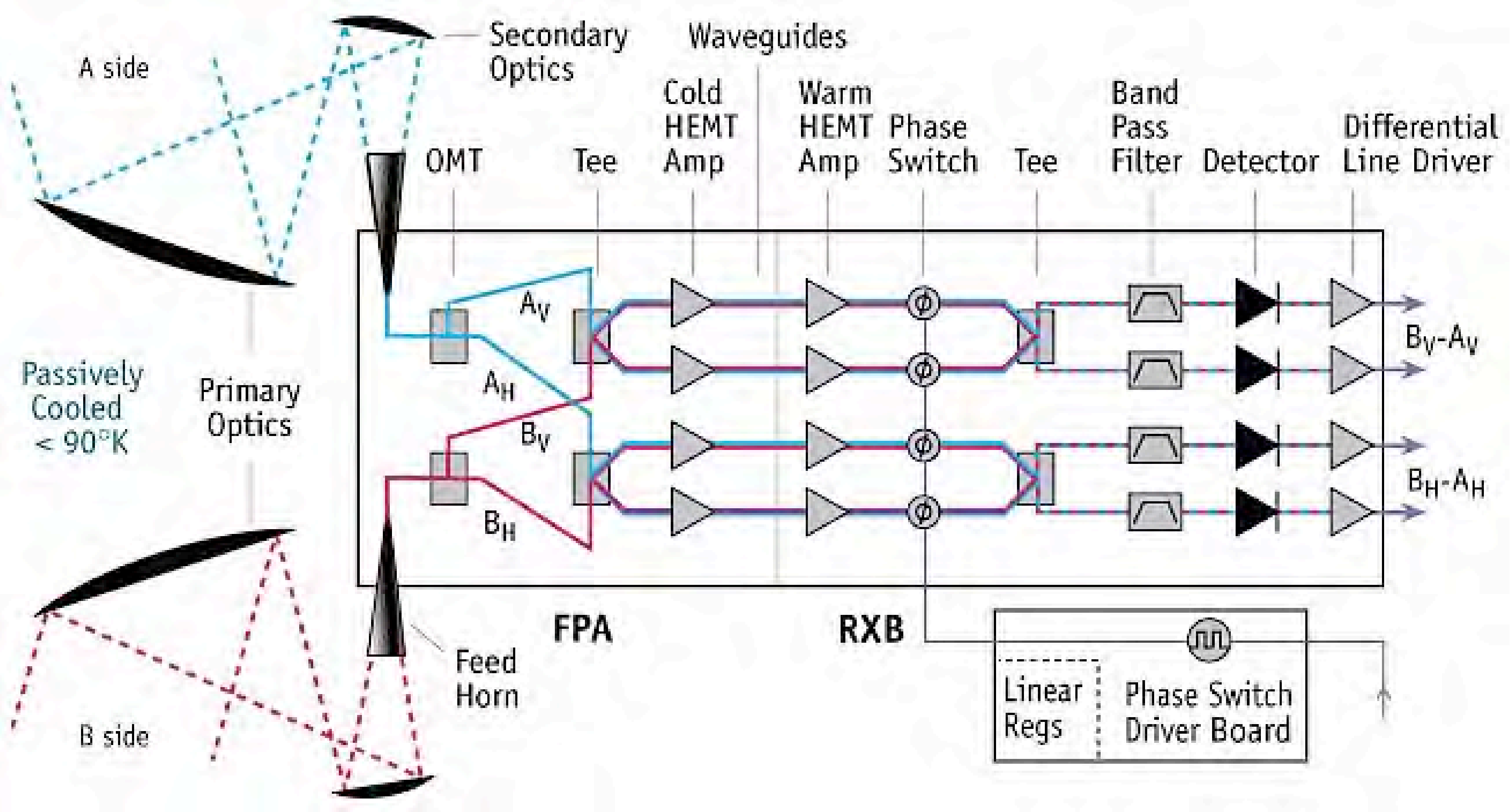


Fujitsu: first HEMT 1982

*All these used correlation techniques (DASI & CBI are interferometers)

WMAP

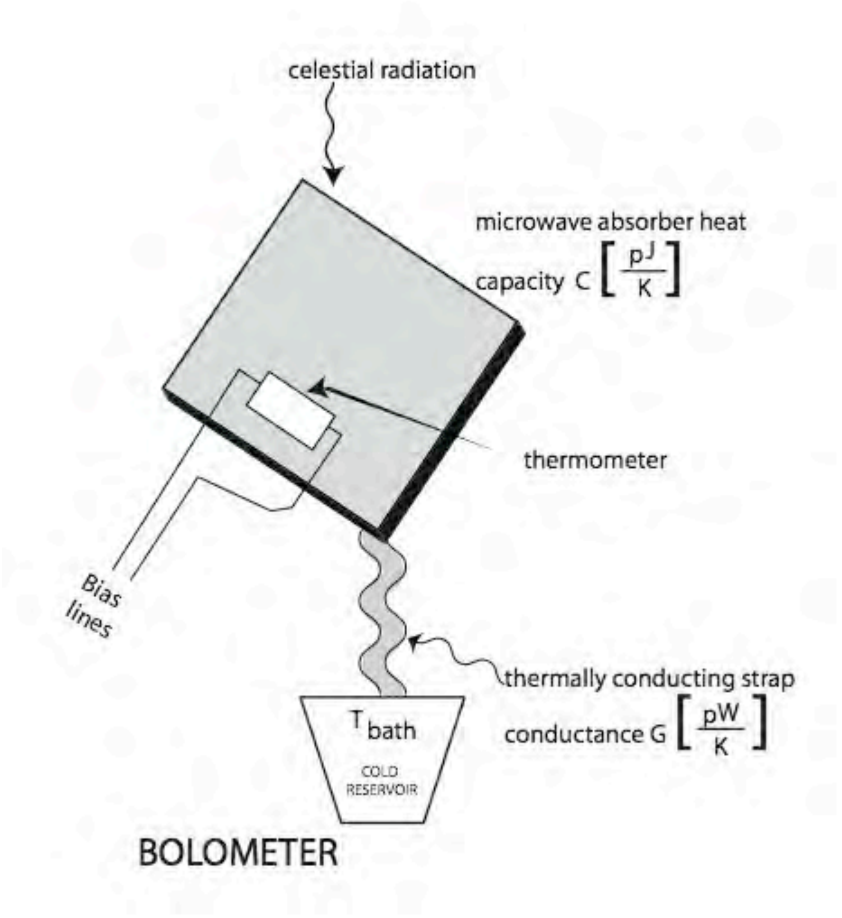
HEMT amplifiers used in novel correlation receiver configuration



HEMT Amplifiers

- PLUSES
  - Widely used for CMB and radioastronomy so well-understood
  - Correlation techniques can be used to reduce systematics
  - Naturally sensitive to a single linear polarization (rectangular waveguide)
  - Operate at 10-20 K (conventional cryocoolers)
  - Intrinsic time constant is fast enough to neglect
- MINUSES
  - Sensitivity suffers from the quantum noise limit of amplification of radiation: $T_{rec} > h\upsilon/k$
  - Therefore, HEMTs are less sensitive than bolometers at f > 100 GHz on the ground, and at f~100 GHz in space

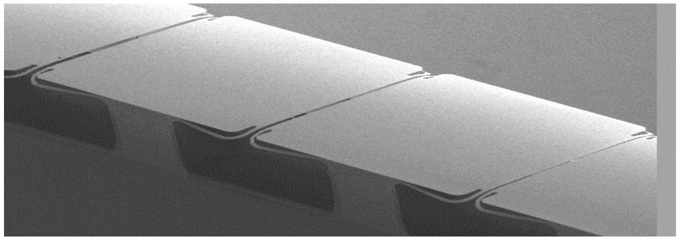
TES BOLOS



- Absorber is thermally isolated from environment (except for weak link to a thermal bath)
- Thermometer attached to absorber records incoming radiation intensity
- Thermal response time ~C/G.

Bolometers

Credit: JPL NASA
Technology web site



- Bolometers are sensitive to ALL incident radiation, including, eg, cosmic rays. Spiderweb absorbers reduce cross section to cosmic rays over large (~mm2) areas, and also reduce the absorber heat capacity.
- Ground-based bolometers have less cosmic ray flux; the 2nd picture shows plane-filling bolometers from GSFC.
- Bolometers must sit behind extensive IR and RF filters
- Bolometers have been used recently for CMB in BOOMerANG, ACBAR, SPT, QUAD, ACT< BICEP, PLANCK HFI (upcoming), & more

Bolometer Sensitivity

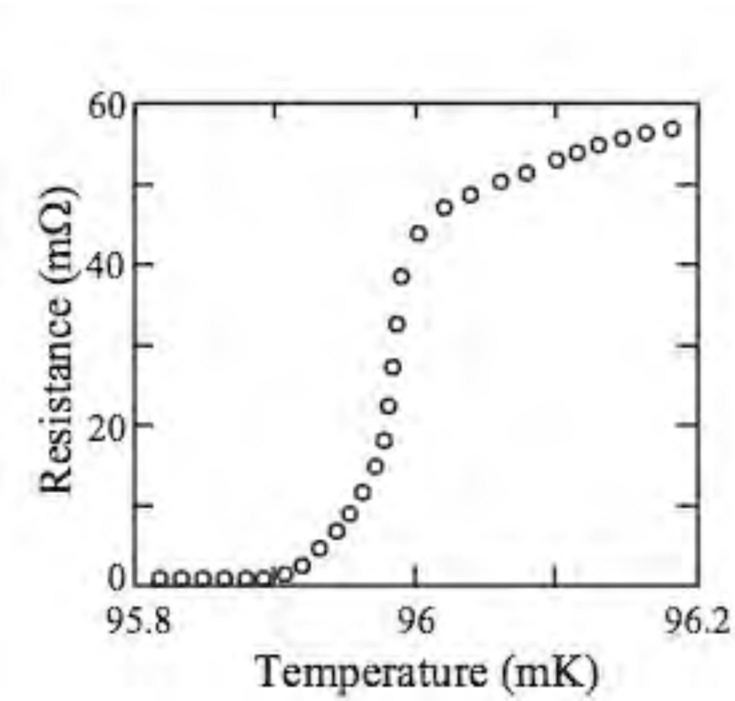
NOISE IN BOLOMETERS

- NEP = noise equivalent power in 1 Hz of bandwidth
- Sensitivity S proportional to NEP but depends on optical efficiency (the conversion from Watts absorbed at the bolometer to temperature)
- Noise from thermal fluctuations: $(NEPG)^2 = a2kT_c^2G$, where a ~1
- Photon shot noise contributes: $(NEPp)^2 = h\upsilon P$, where P is the photon power
- Other subdominant contributions from electrical Johnson noise, backend amplification noise, etc
- The total NEP from: $(NEP)^2 = (NEPG)^2 + (NEPp)^2 + (NEPx)^2$

Bolometers

- PLUSES
  - Very sensitive, especially in space (Planck HFI sensitivity between 70 and 150 GHz is 70 μK $s^{-1/2}$)
  - New generation (TES bolometers) are readily multiplexed
  - Advanced fabrication techniques permit highly integrated low-mass focal planes (with modest requirements on 4K cooling)
- MINUSES
  - Require more difficult cryogenics (300 mK on the ground [3He fridges] and < 100 mK from balloons and space [ADRs or dilution fridges].
  - Semiconductor bolometers have been most widely used, but they have high resistance and so suffer from microphonic pickup; TES do not, but they are an emerging technology.

TES Bolometers



Plot of R(T) for a Mo/Cu TES from Irwin & Hilton, 2005.

Transition Edge Sensors (TES) are superconductors used as thermometers near their critical temperatures

T_c and the normal resistance (R_n) an be tuned through the use of normal-metal-on-superconductor bilayers (and the proximity effect)

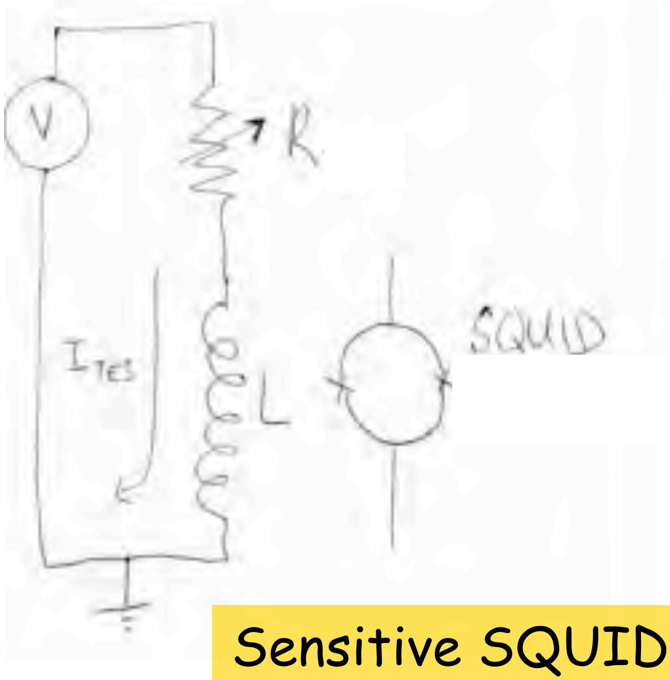
Essentially all new bolometer-based CMB experiments plan to use TES

- TES bolometers are being fabricated for CMB experiments at GSFC, NIST, JPL and Berkeley

TES Bolometers

- Bias the TES with a current I_b across a small shunt resistor R_{sh} in parallel with it (not shown)
- The TES operating resistance is R ($0<R<R_n$),
- For $R_{sh} \ll R$, the bias voltage is approximately constant, $V \sim I_b R_{sh}$
- The TES current is then $I_{TES}=V/R$
- Then R(T) is read out through I_{TES}:

$$\Delta I_{TES} = -\Delta R \frac{V}{R^2}$$



Sensitive SQUIDs can be used to read out ΔI_{TES} via the flux it couples through the series inductance L

TES Bolometers

- But wait, there's more!
- The bolometer absorbs the electrical power dissipated by the TES: $P_J=V^2/R$.
- As $T \uparrow$, $R \uparrow$, so $P_J \downarrow$
- This is ETF: electrothermal feedback
  - Stabilizes the TES over a wide range of bias voltages!
  - Speeds up its response to incident radiation over the thermal time constant, C/G.
- In fact, the TES can be modeled via coupled equations:

$$C\frac{dT}{dt} = -P_{bath} + P_J + P_\gamma$$

Here P_{bath} is the heat conducted to the thermal bath

$$L\frac{dI}{dt} = V - IR_{sh} - IR(T,I)$$

Here $R(T,I)$ is usually parameterized in terms of two ~ constant derivatives: d(ln R)/dT and d(ln R)dI.

Multiplexing TES

- Both time-domain (TDM) and frequency-domain (FDM) methods have been proven for SQUID-based multiplexing the TES, to reduce the number of wires going from 300 K to 300 mK.

FDM (eg, SPT)

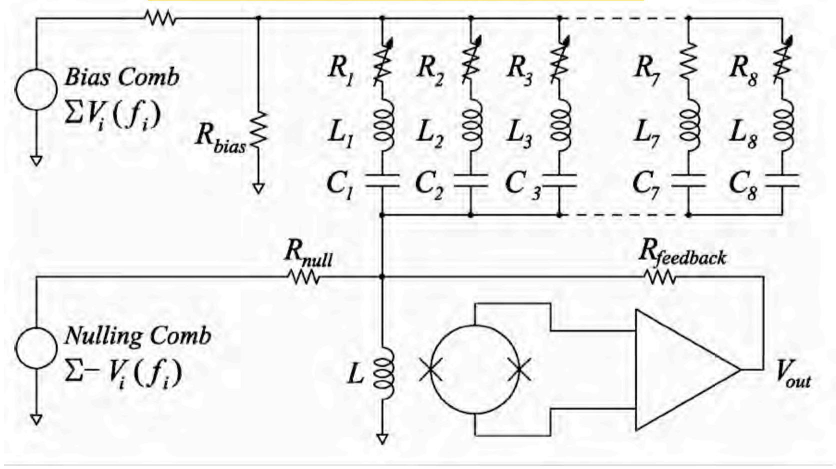
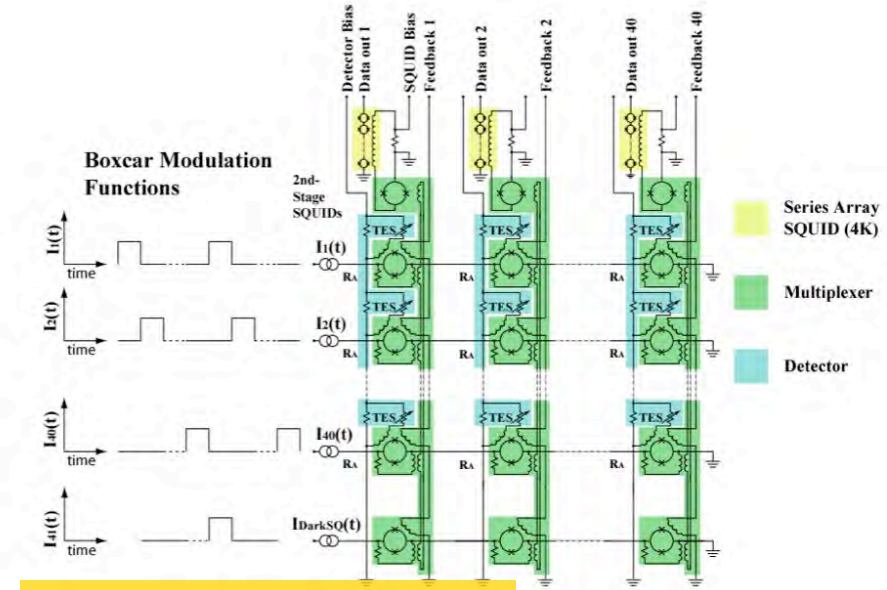


Figure from Lanting et al, IEEE Trans. Appl Superconductivity, 2005, 15, 567.



TDM (eg, ACT)

DC SQUIDs

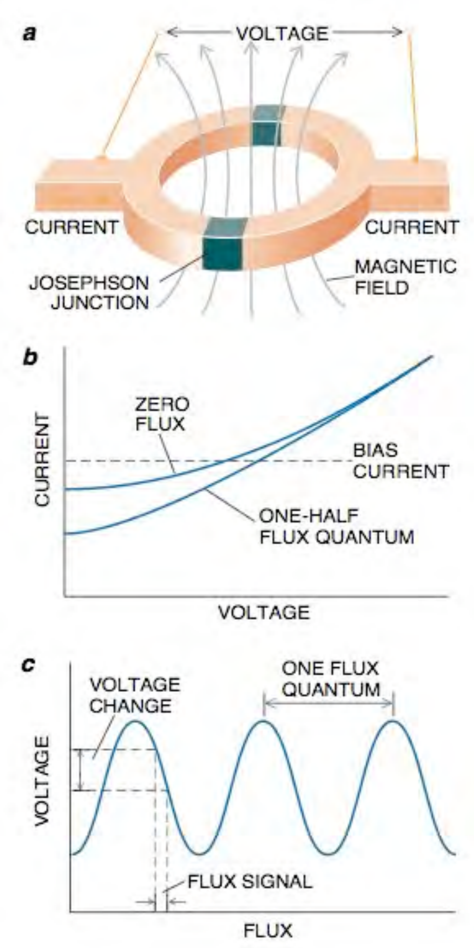


Figure :Clarke, SQUIDS, Sci Amer 1994

- TES readout is an emerging techology but great progress (Batistelli et al 2009, SPIE, for example.)
- Readout is via an FLL: flux-locked loop -- control loop zeroes the SQUID output by sending current through a 2nd inductor linked to it
- V(p) is multi-valued -- you don't know the absolute current (though you can get it with a sweep of the bias voltage)
- If you lock too near a max or min the output can flux-jump (by an integer number of flux quanta)

TES Parameters Example

- TYPICAL PARAMETERS FOR GROUND-BASED 150 GHz TES
  - G ~ 60 pW/K (dielectric legs few microns wide, few mm long)
  - Tc ~ 450 mK
  - C ~ 0.5 pJ/K (heat capacity of absorber plus TES)
  - $d(\ln R)/d(\ln T) = \alpha \sim 30\text{-}50$
  - NEP ~ 4×10^{-17} W $\mathrm{Hz}^{-1/2}$
  - S ~ 200 μK $s^{1/2}$
  - Thermal time constant $\tau \sim 25$ ms

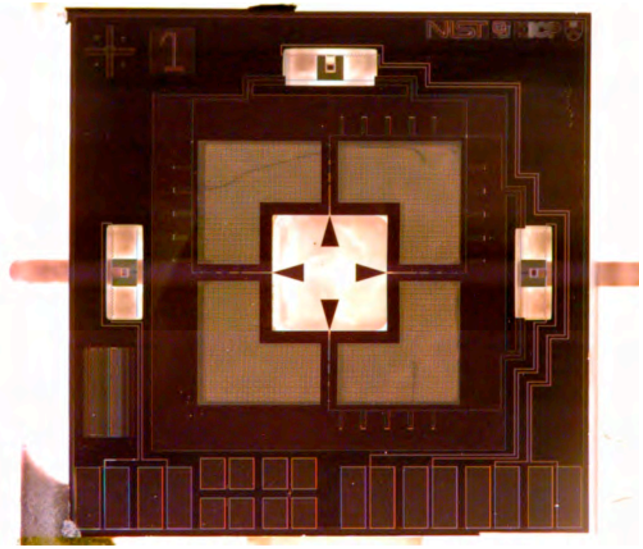
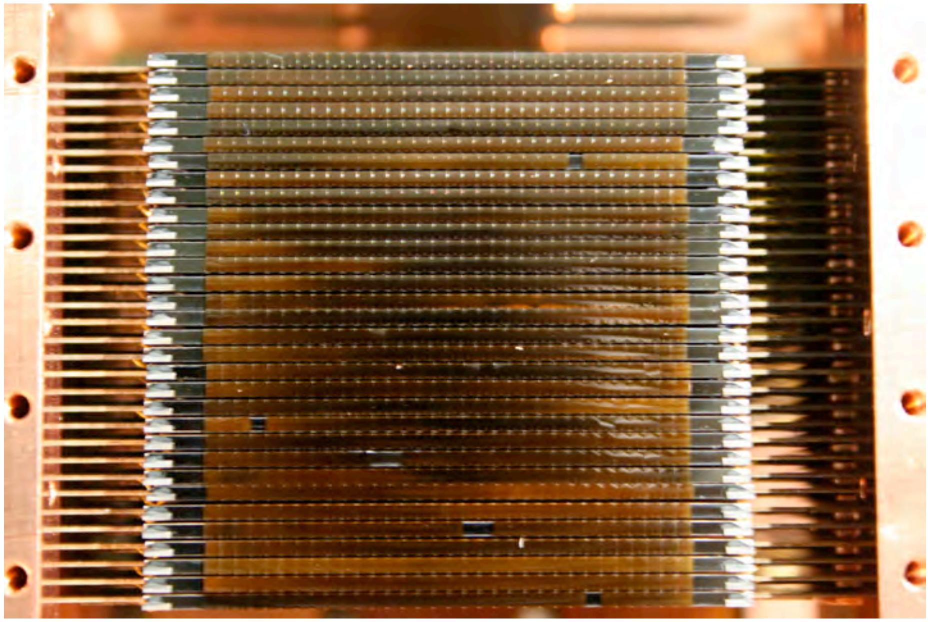
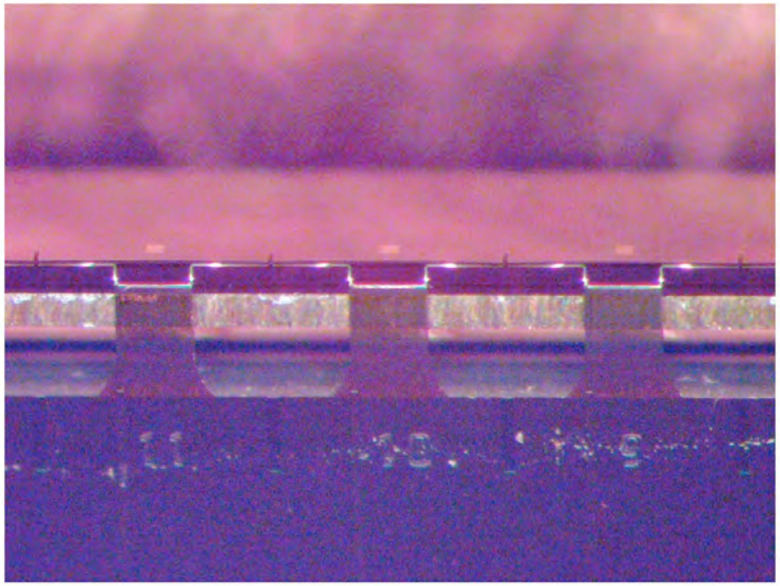


Photo of a bolometer with similar properties for use in the ABS CMB polarization experiment

Final Visuals



150 GHz ACT TES bolometer array (one of 3): 1024 detectors



Sideview of one column (1x32 detectors) showing how the legs bend out of the plane so the columns can be close-packed

END