CMB Experiment

Clarence Chang
HEP, Argonne National Lab and
Astronomy & Astrophysics, The University of Chicago

Graduate School: Mass, Spectra, Symmetry
Autumn Block Course 2014

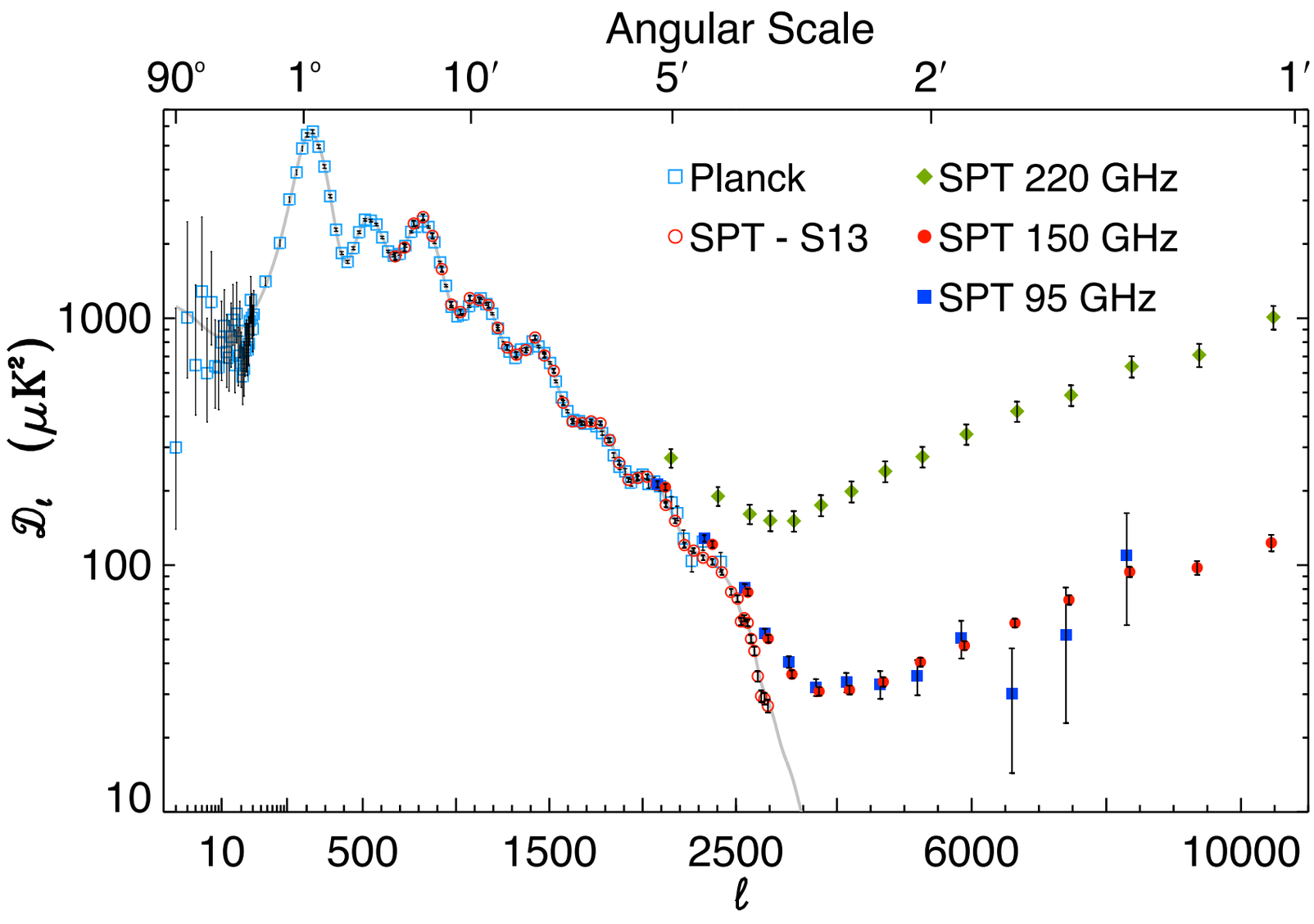
Three parts

- Part 1: “History” & Motivation - CMB past
- Part 2: Technology & Detectors - CMB present
- Part 3: Recent & anticipated results - CMB future

CMB present

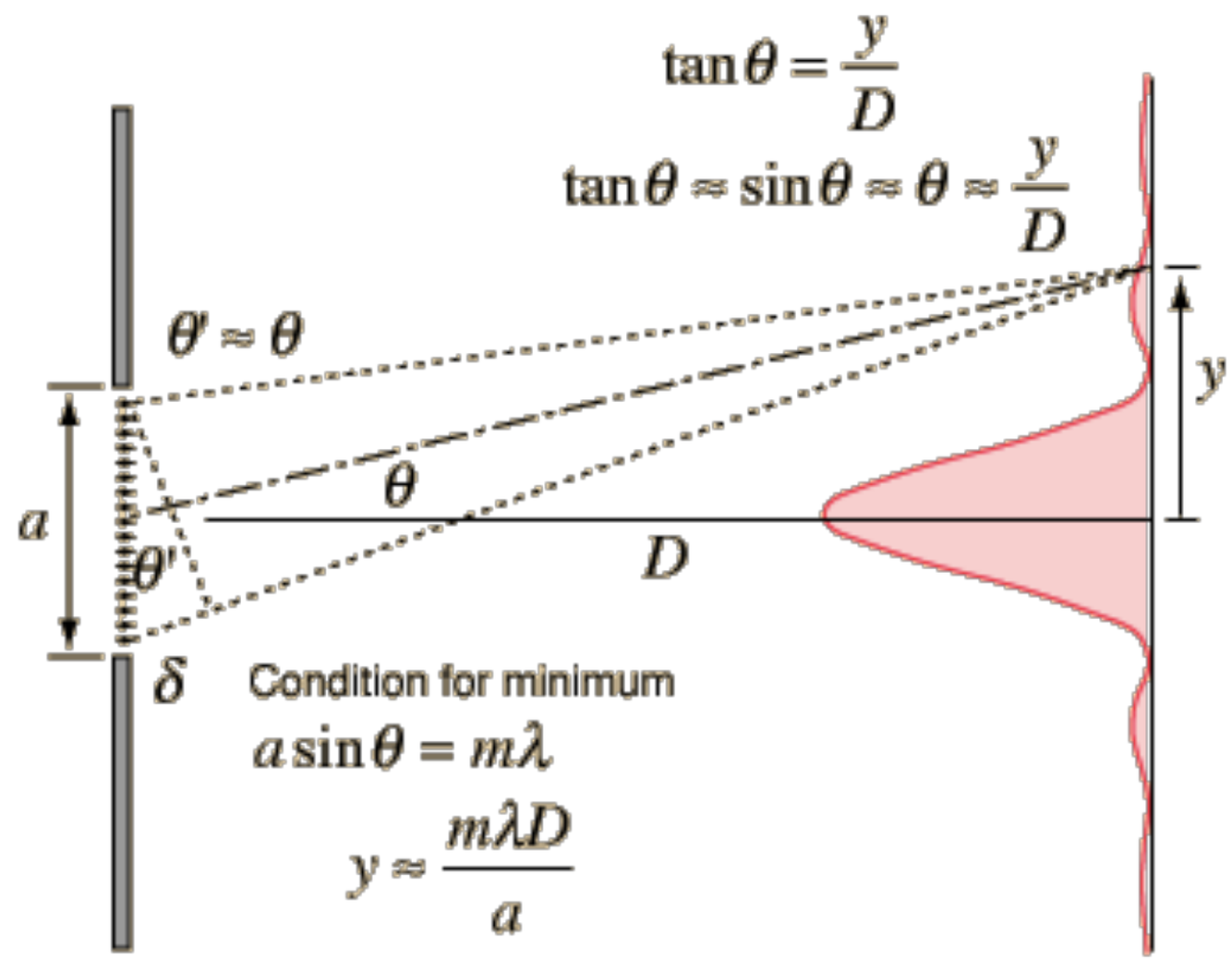
What limits your CMB experiment?

- What multipole range can your probe?
- What is your instrument's sensitivity?



High ell

- Single slit diffraction
- Angular resolution
  - λ/a
  - a is the aperture diameter



http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/sinslit.html

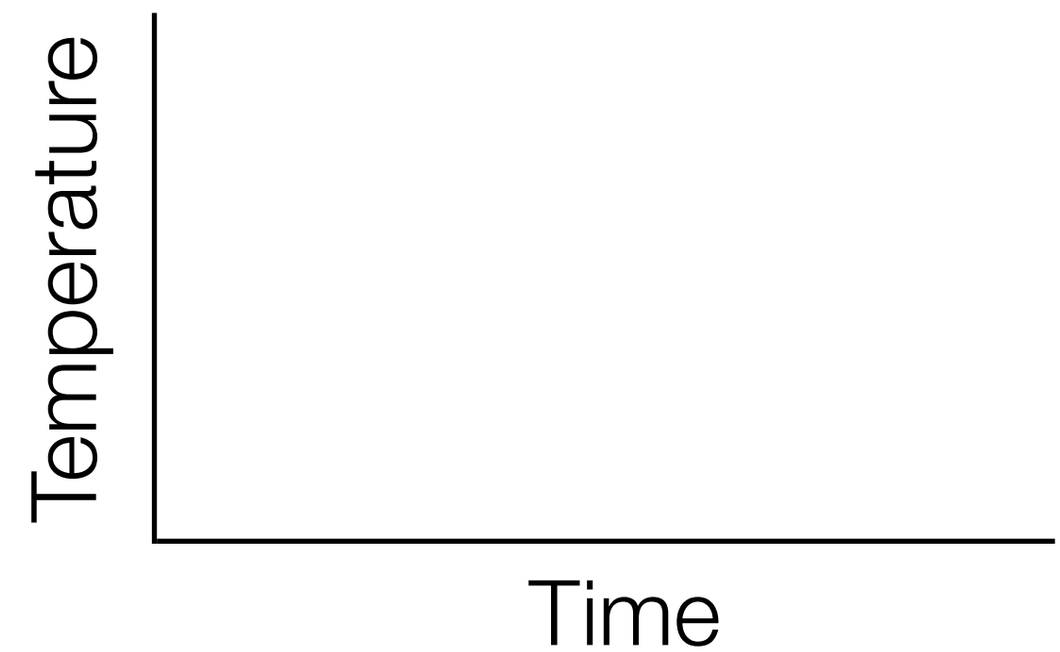
Low ell

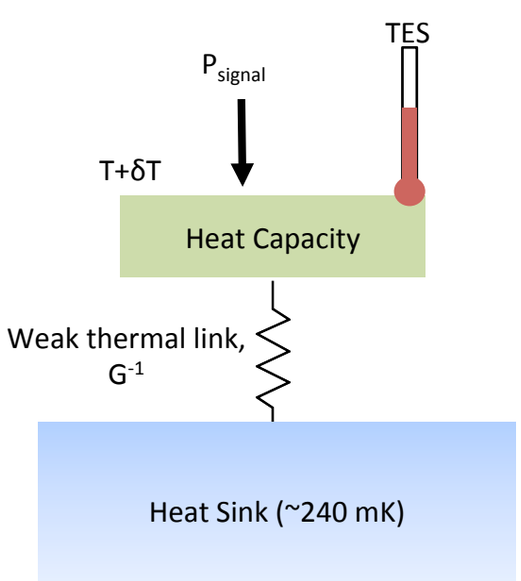
- Set by observed field size
- What is the largest mode you can measure for a given field size?

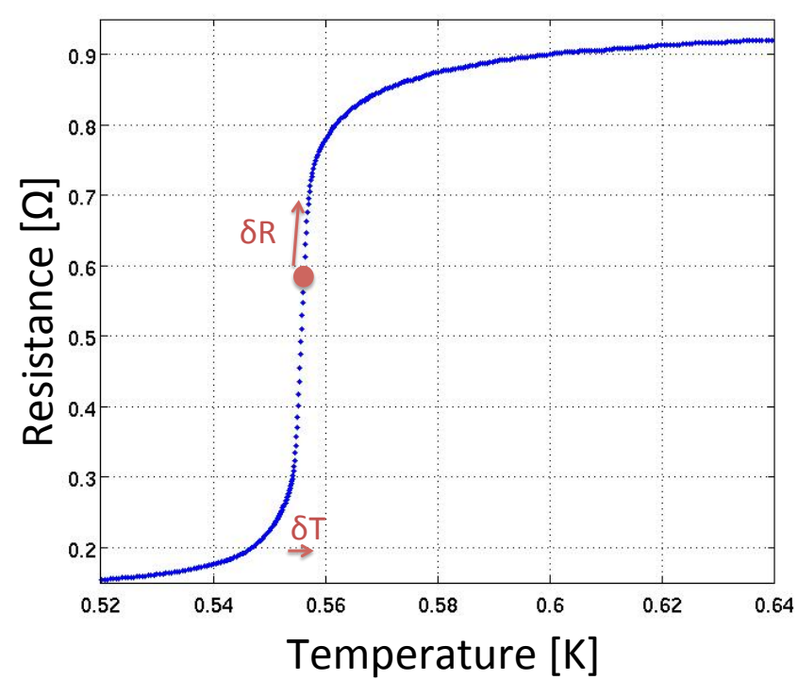
Sensitivity

Brighter

Dimmer



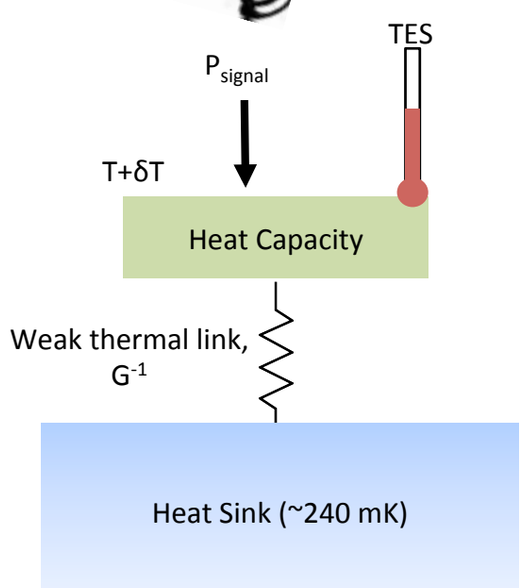


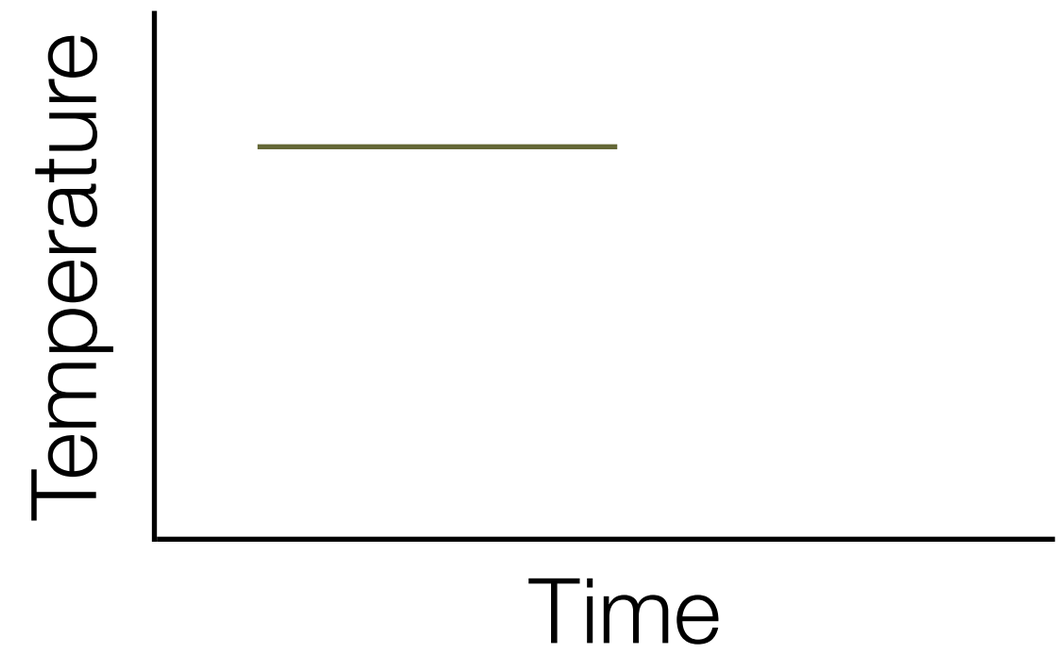


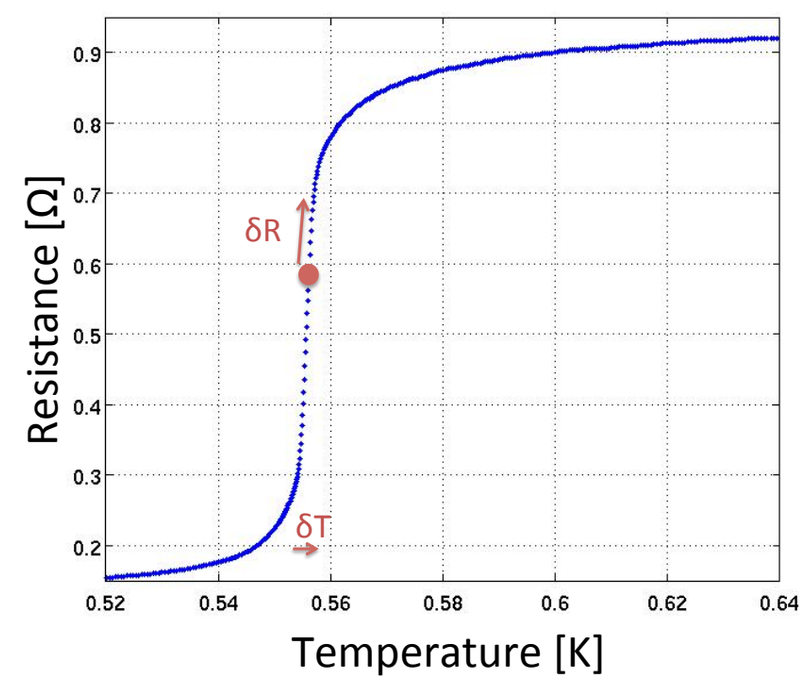
Sensitivity

Brighter

Dimmer



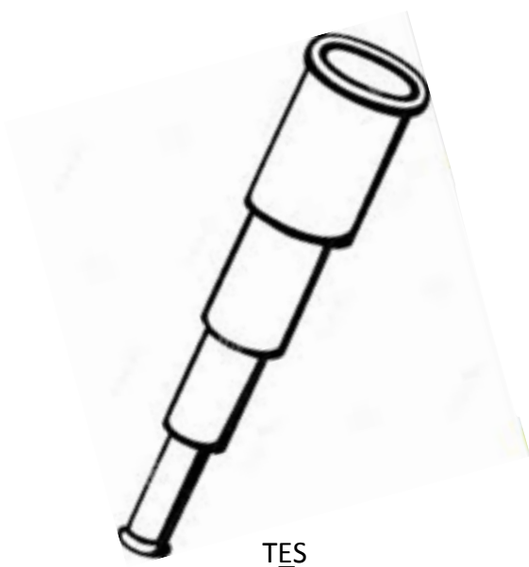


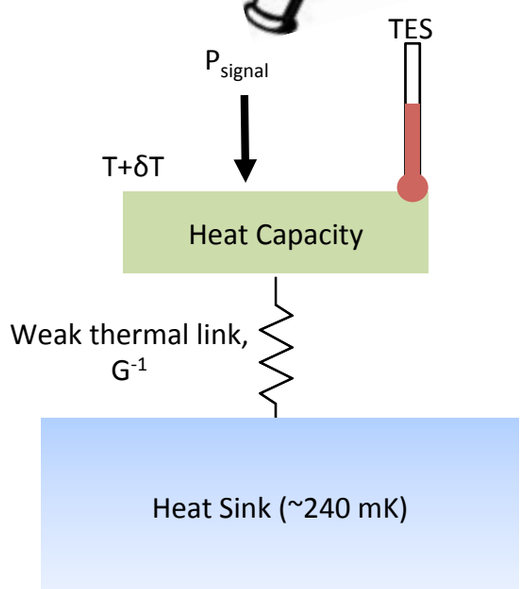


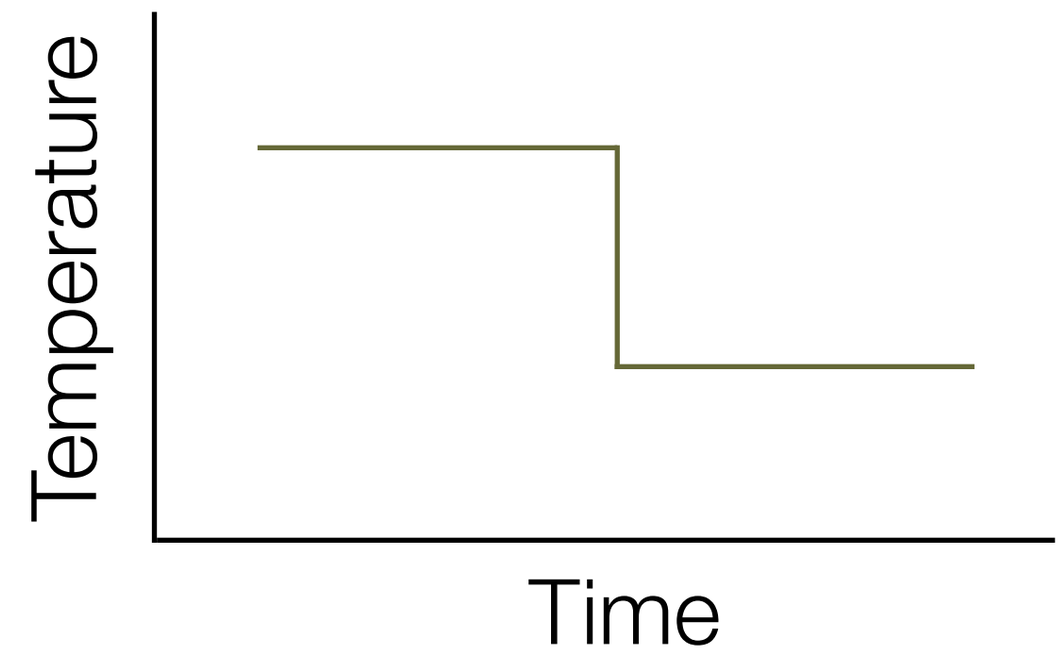
Sensitivity

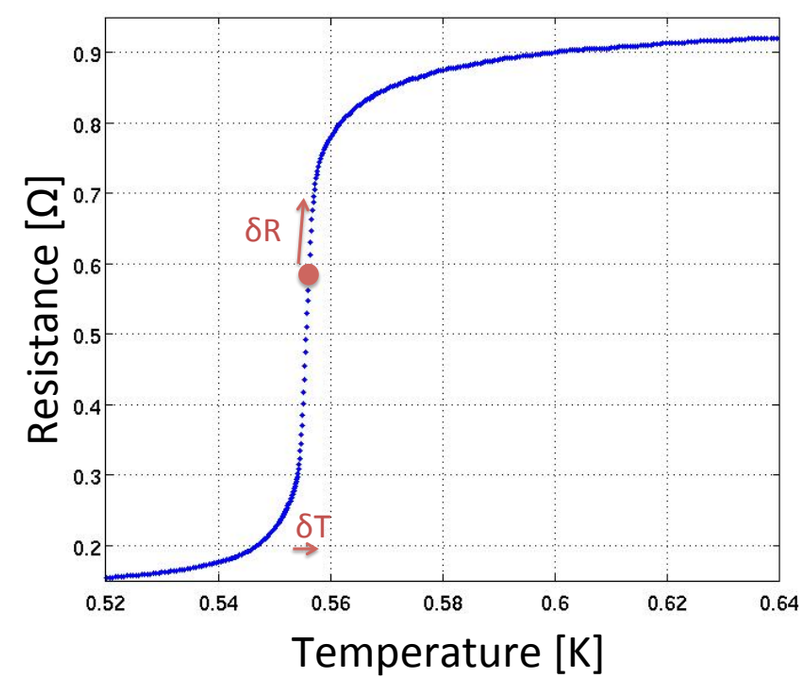
Brighter

Dimmer





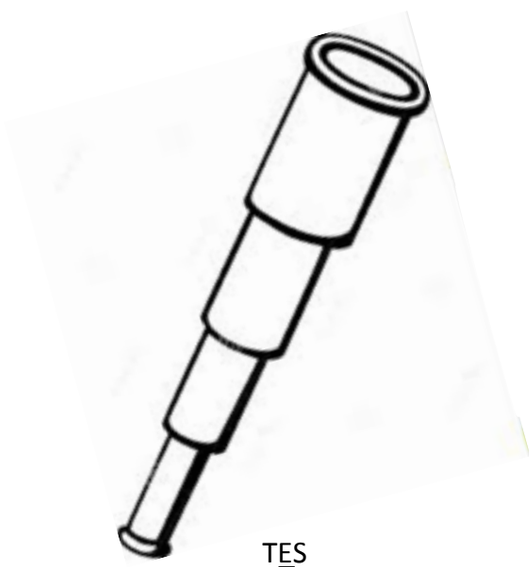


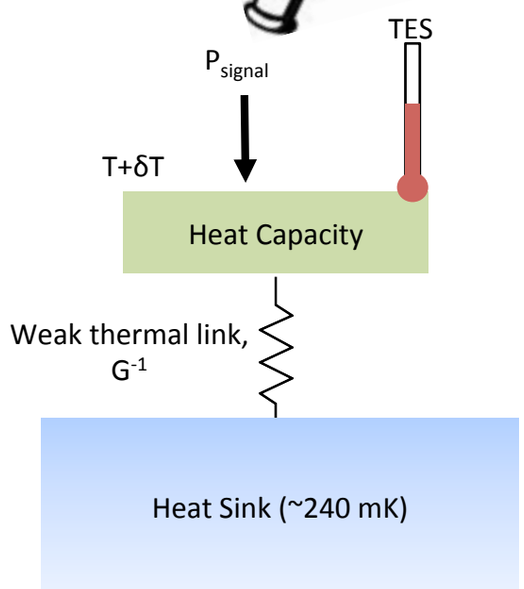


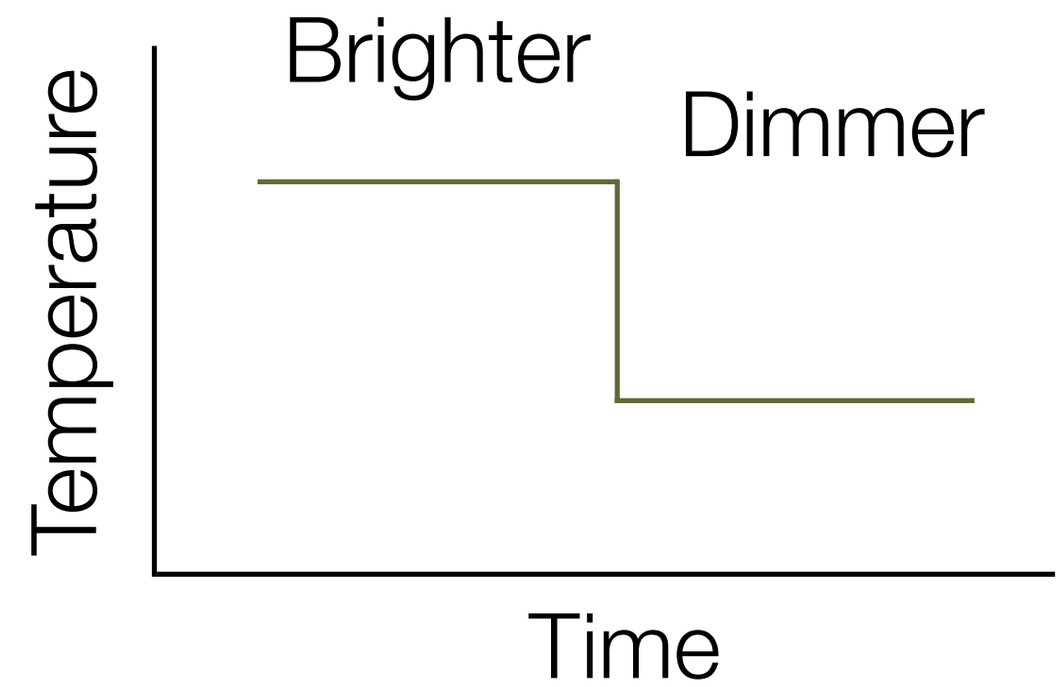
Sensitivity

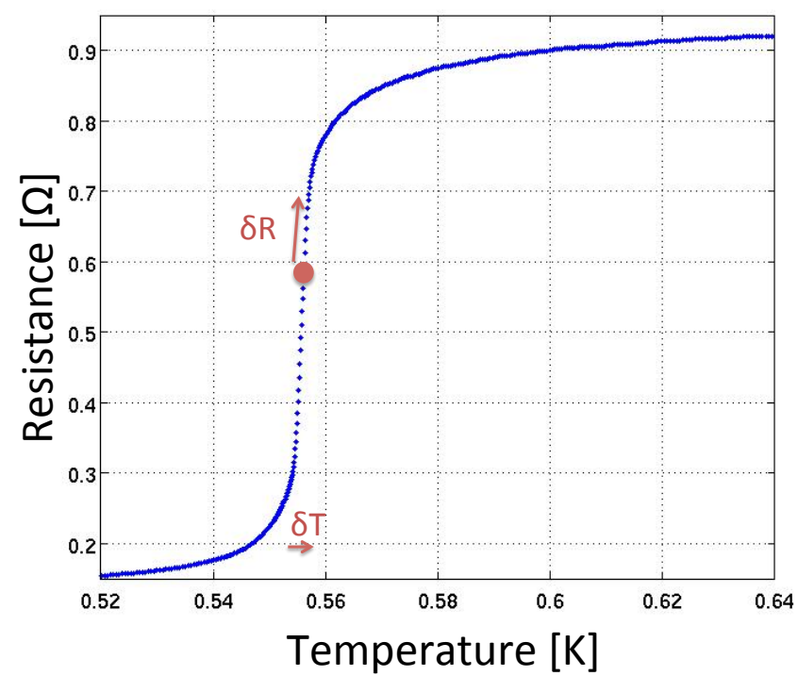
Brighter

Dimmer





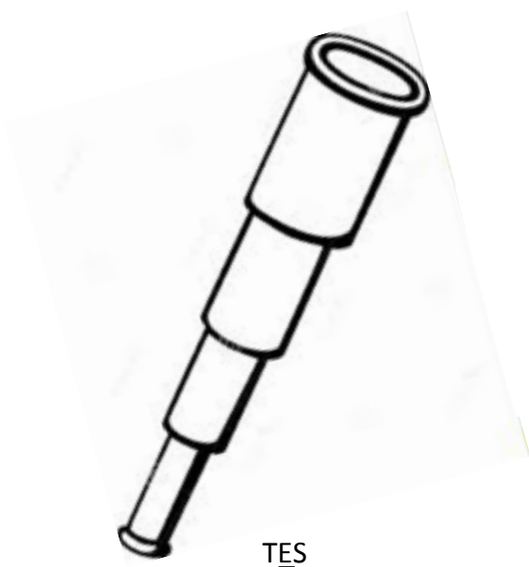


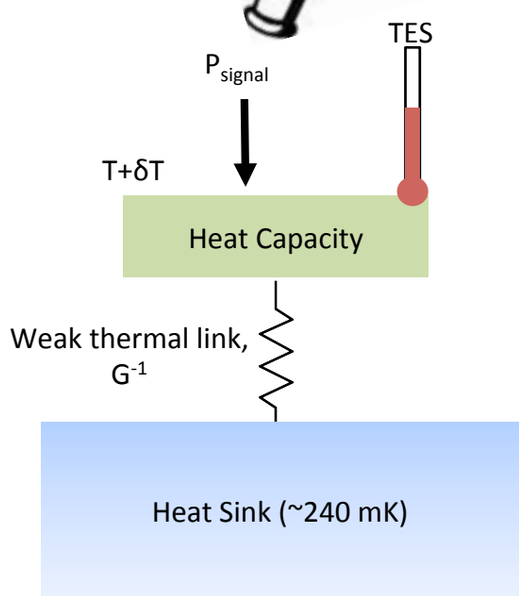


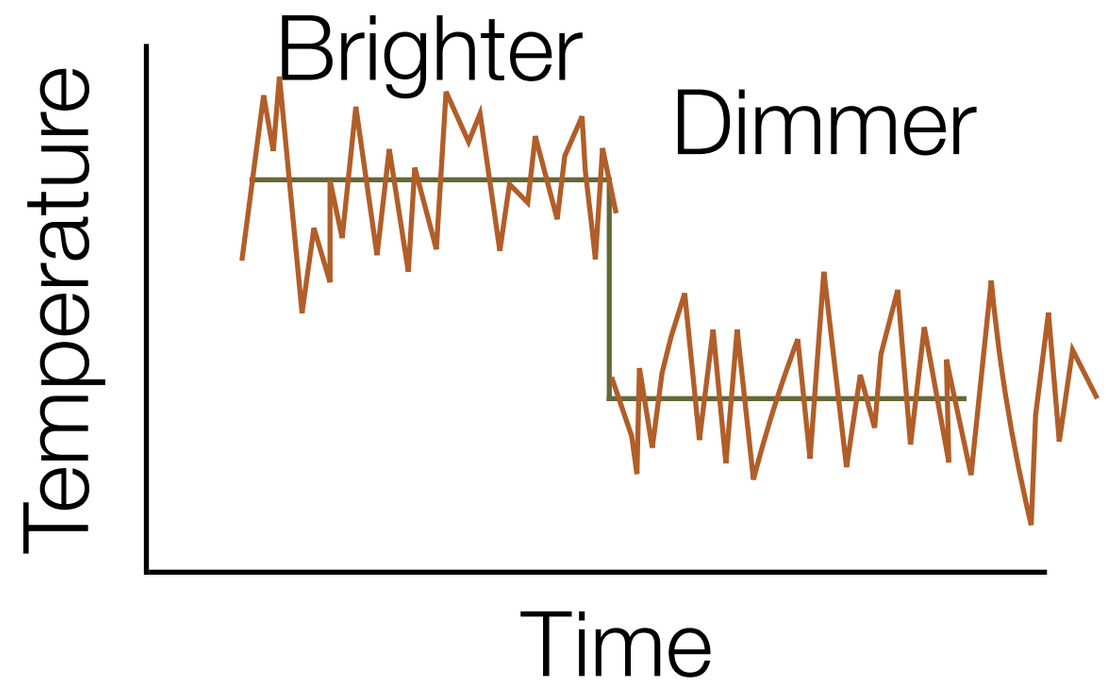
Sensitivity

Brighter

Dimmer

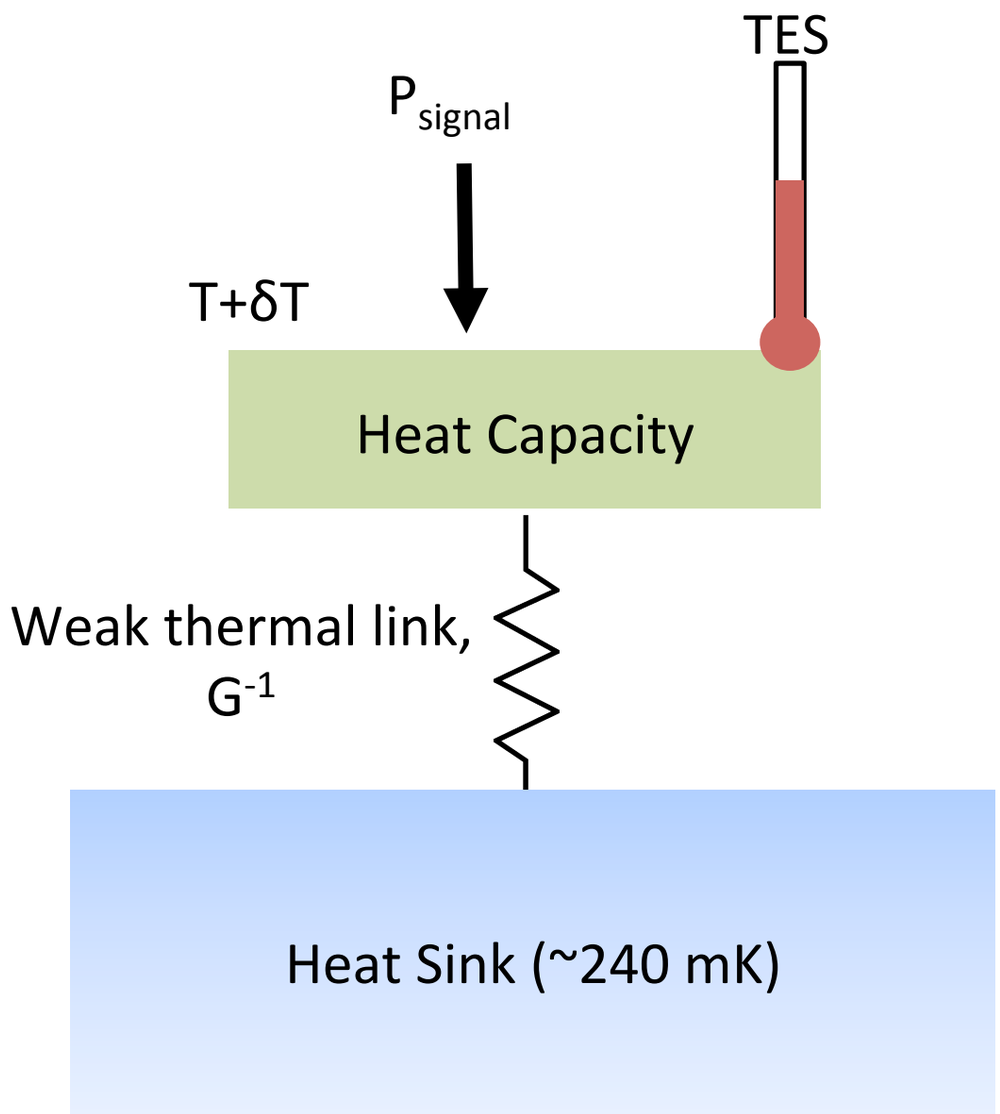


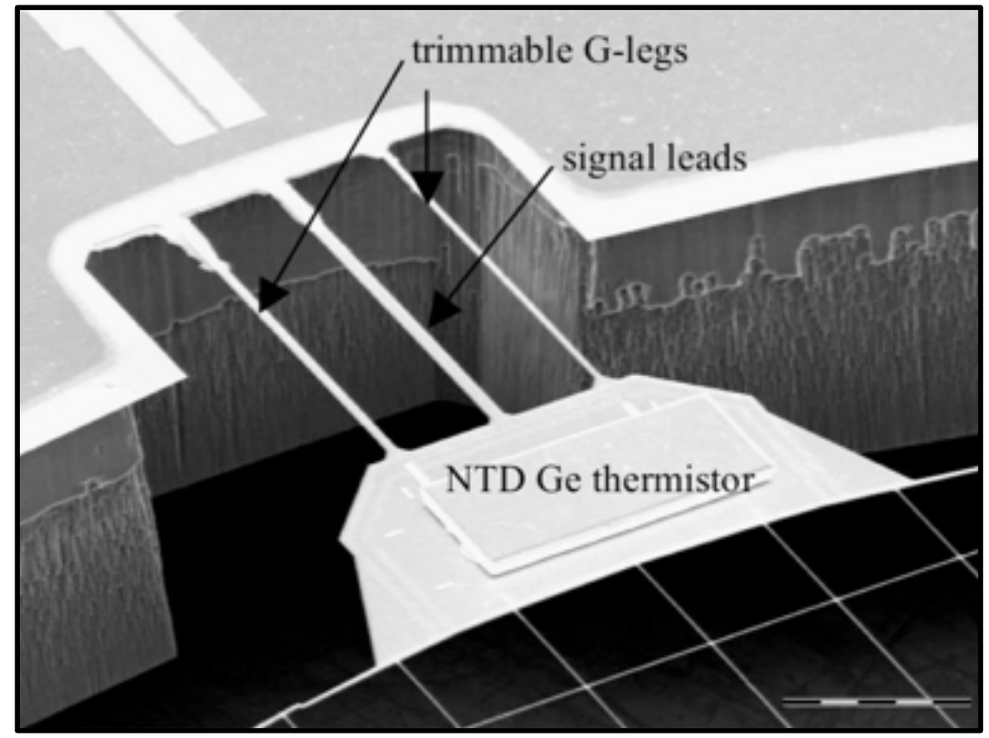


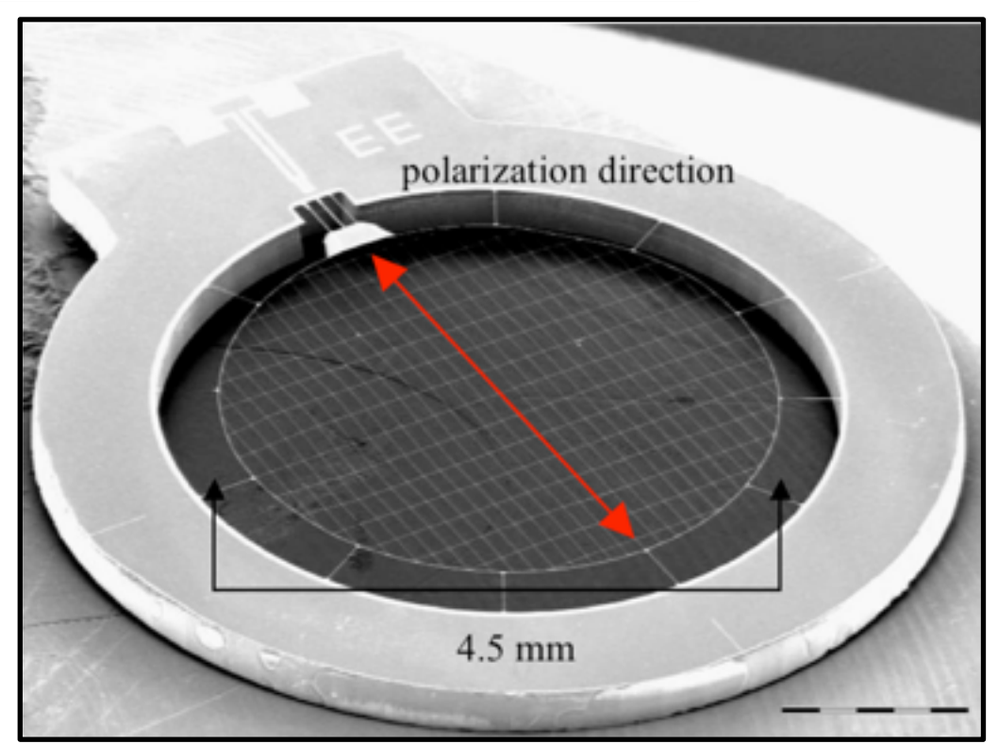


- Measured flux gives temperature along pointed direction.
- Noise in measurement limits the sensitivity.

Basic bolometer

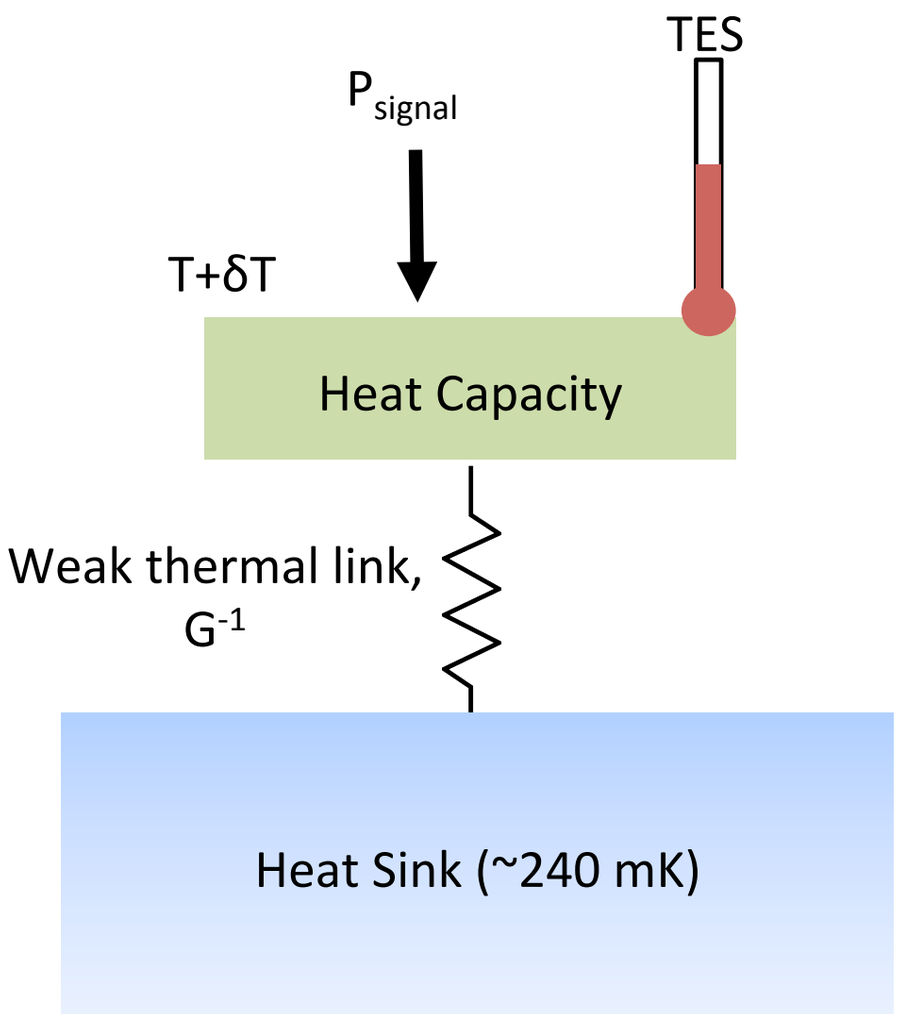


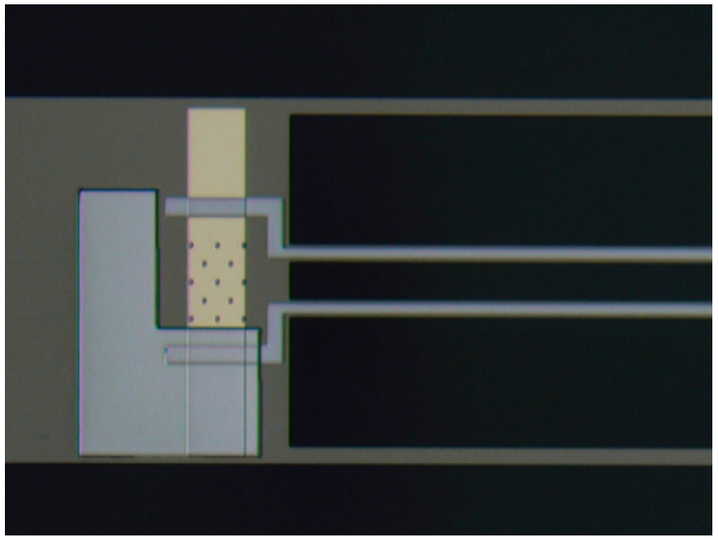


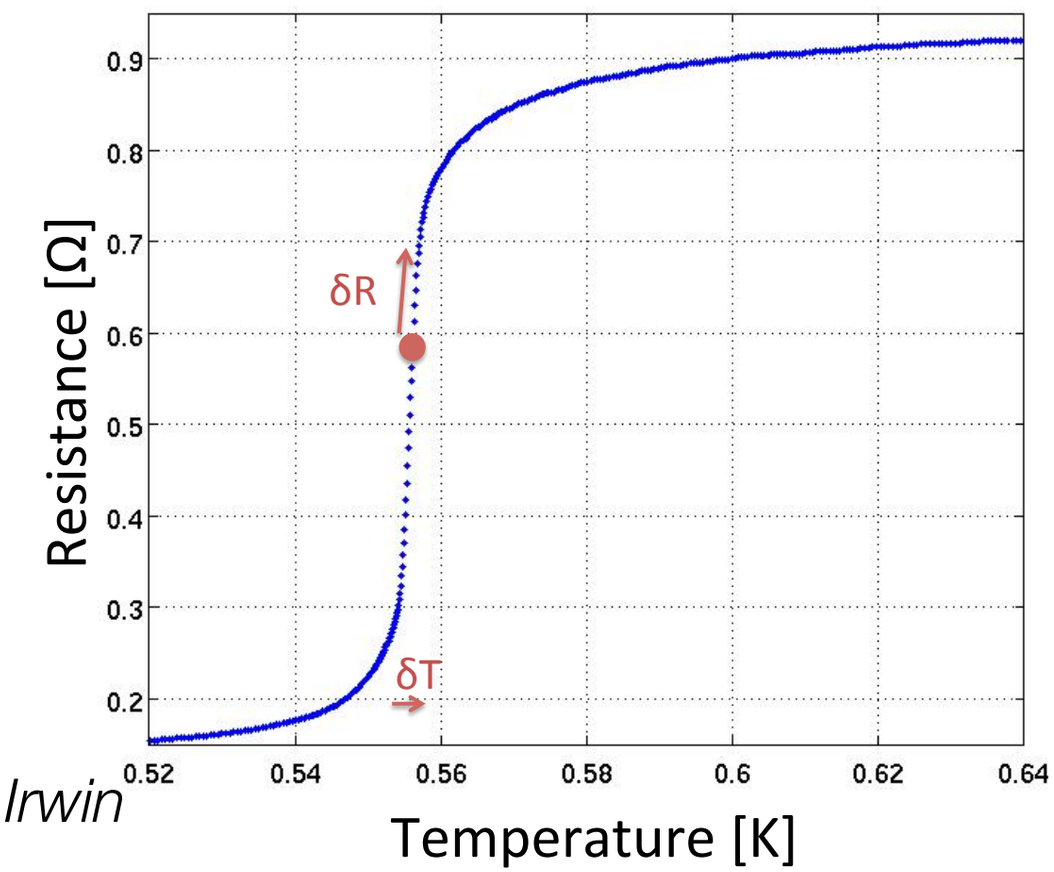


Jones, W. C., Bhatia, R. S., Bock, J. J., Lange, A. E. Proceedings of the SPIE, 4855, 227-238, 2003.

The Modern Transition Edge Sensor

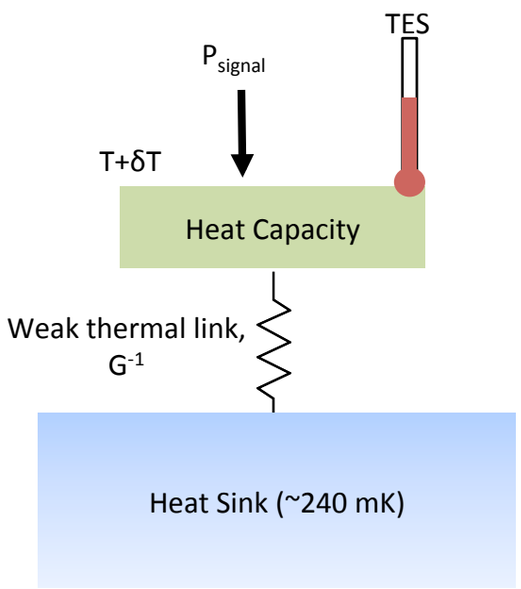




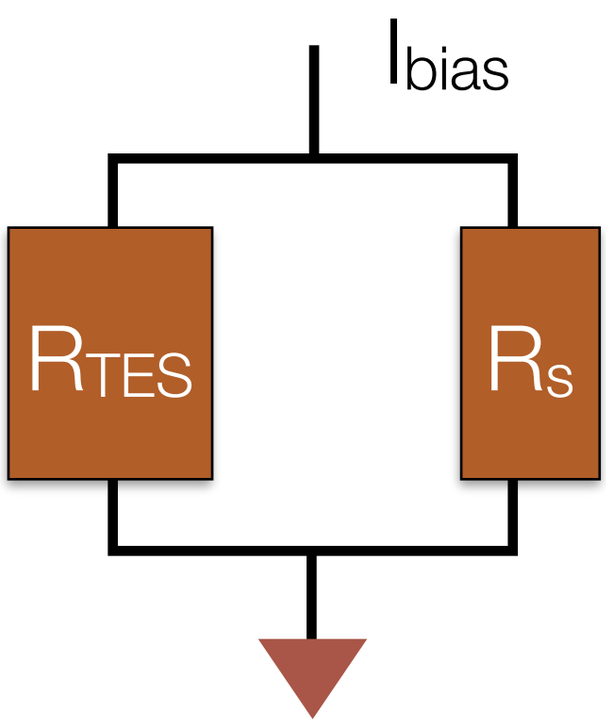


KD Irwin
Appl. Phys. Lett., 66, 1998 (1995)
AT Lee, PL Richards, SW Nam, B Cabrera, KD Irwin
Applied Physics Letters 69 (12), 1801-1803

Resistively shunted voltage bias



$$C\,(dT/dt) = P_{signal} + I_{TES}^{\,2} R_{TES} - P_{cool}$$



$$I_{TES}\, R_{TES} = (I_{bias} - I_{TES})\, R_s$$

Eq. of Motion: coupled electric & thermal circuits

$$C\,(dT/dt) = P_{signal} + I_{TES}^{\,2} R_{TES} - P_G$$

$$I_{TES} R_{TES} = (I_{bias} - I_{TES})\, R_s$$

- $P_{signal} = P_0 + \delta P e^{i\omega t}$
- $I_{TES} = I_0 + \delta I e^{i\omega t}$
- $T = T_0 + \delta T e^{i\omega t}$
- $R_{TES} = R_0 + \delta R = R_0 + \alpha(R/T)\, \delta T e^{i\omega t}$

$$\alpha \equiv d\ln R / d\ln T$$

Electrothermal feedback

$$C\,(dT/dt) = P_{signal} + I_{TES}^{\,2} R_{TES} - P_G$$

$$I_{TES} R_{TES} = (I_{bias} - I_{TES})\, R_s$$

- $G = dP_{cool} / dT$
- $\tau_0 = C/G$
- $L = \alpha\, I_0^2 R_0 / G T_0$

$\delta I = S(\omega)\delta P;$ $$S(\omega) = \frac{-1}{R_0 I_o}\left(\frac{L}{L+1}\right)\left(\frac{1}{1+i\omega\frac{\tau}{L+1}}\right)$$

Fundamental noise limits

- Only two sources of noise outside of readout electronics
- G-noise: $\sigma_G = 4k_BGT^2$; shot noise of thermal carriers
- Photon noise

Photon noise

- Recall partition function $$Z = \sum_n e^{-\beta\epsilon_\nu} = \frac{1}{1 - e^{-\beta\epsilon_\nu}}$$
- Energy is then $$\bar{E}_\nu = -\frac{\partial \log Z}{\partial \beta} = \frac{\epsilon_\nu}{e^{\beta\epsilon_\nu} - 1}$$
- Planck's law $$\bar{E} = \frac{8\pi\nu^2 h\nu}{c^3(e^{h\nu/kT} - 1)}\Delta\nu V \equiv h\nu\mathcal{N}_p$$
- Variance is $$-\frac{\partial \bar{E}}{\partial \beta} = \overline{(E^2)} - (\bar{E})^2 = \overline{(\Delta E)^2}$$
- Non-zero! $$\overline{(\Delta E)^2} = h\nu\bar{E} + \frac{c^3}{8\pi\nu^2\Delta\nu V}\bar{E}^2 = (h\nu)^2\mathcal{N}_p + \frac{\bar{E}^2}{\mathcal{N}_w}$$

$$2\frac{4\pi\nu^2}{c^3}d\nu V \equiv \mathcal{N}_w$$

Photon noise

- True in general for all photons (not just Black Body)
- Uncertainty in power after time τ

$$\sigma_P = \frac{h\nu\sigma}{\eta} = \frac{h\nu}{\sqrt{\Delta\nu\tau}} \sqrt{\frac{n_0(1+\eta n_0)}{\eta}} \Delta\nu$$

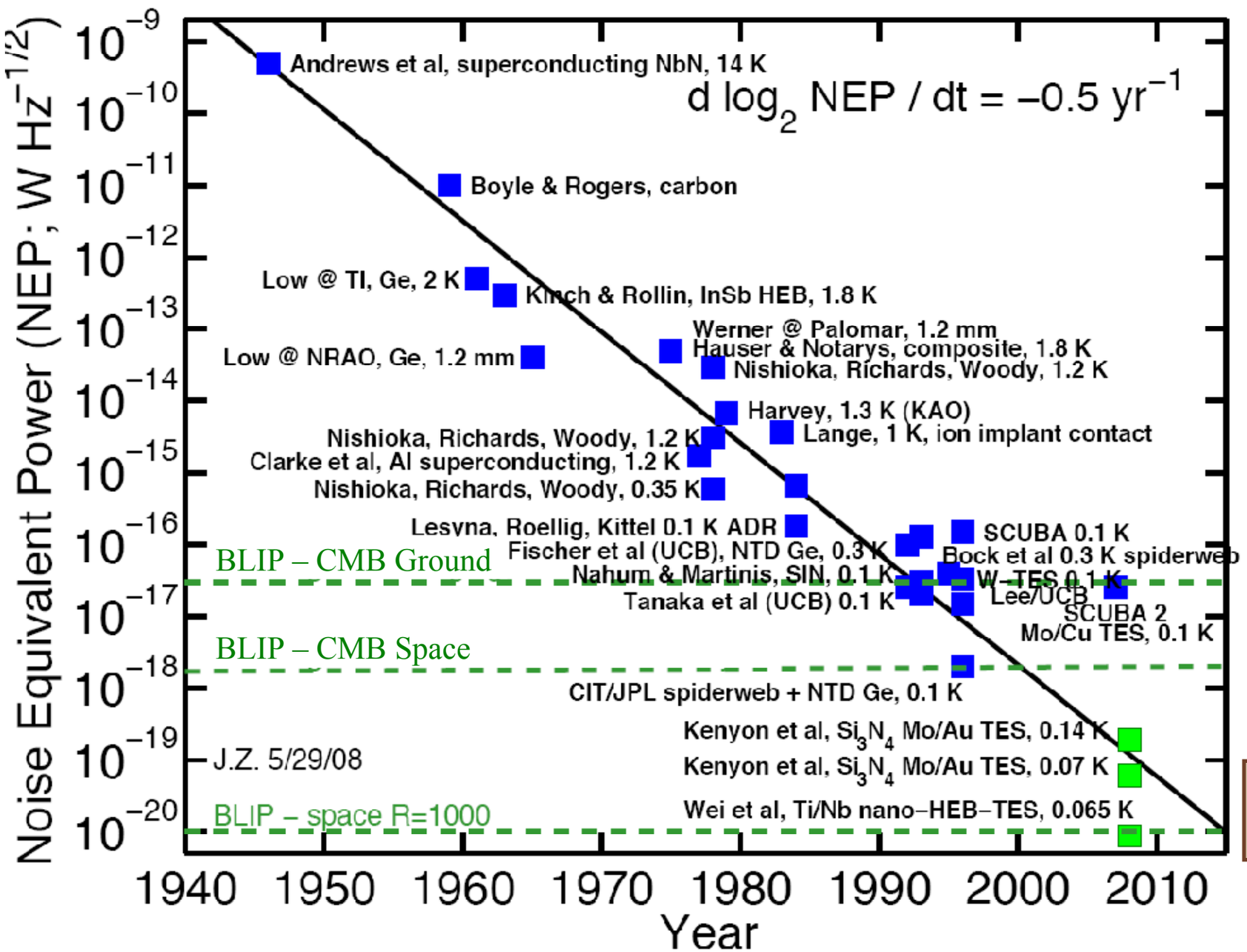
- Long way of saying, if you have any photons, you have noise from the photon statistics.

Jonas Zmuidzinas
Applied Optics, Vol. 42, Issue 25, pp. 4989-5008 (2003)

Noise cont'd

- Minimize photon noise by reducing photon "loading"
  - baffle with low emissivity shielding at cryogenic temperatures
  - From ground, reduce atmospheric emission with choice of site (dominant emission from water)
- G noise less than photon noise for T~0.5K

Background limited detectors



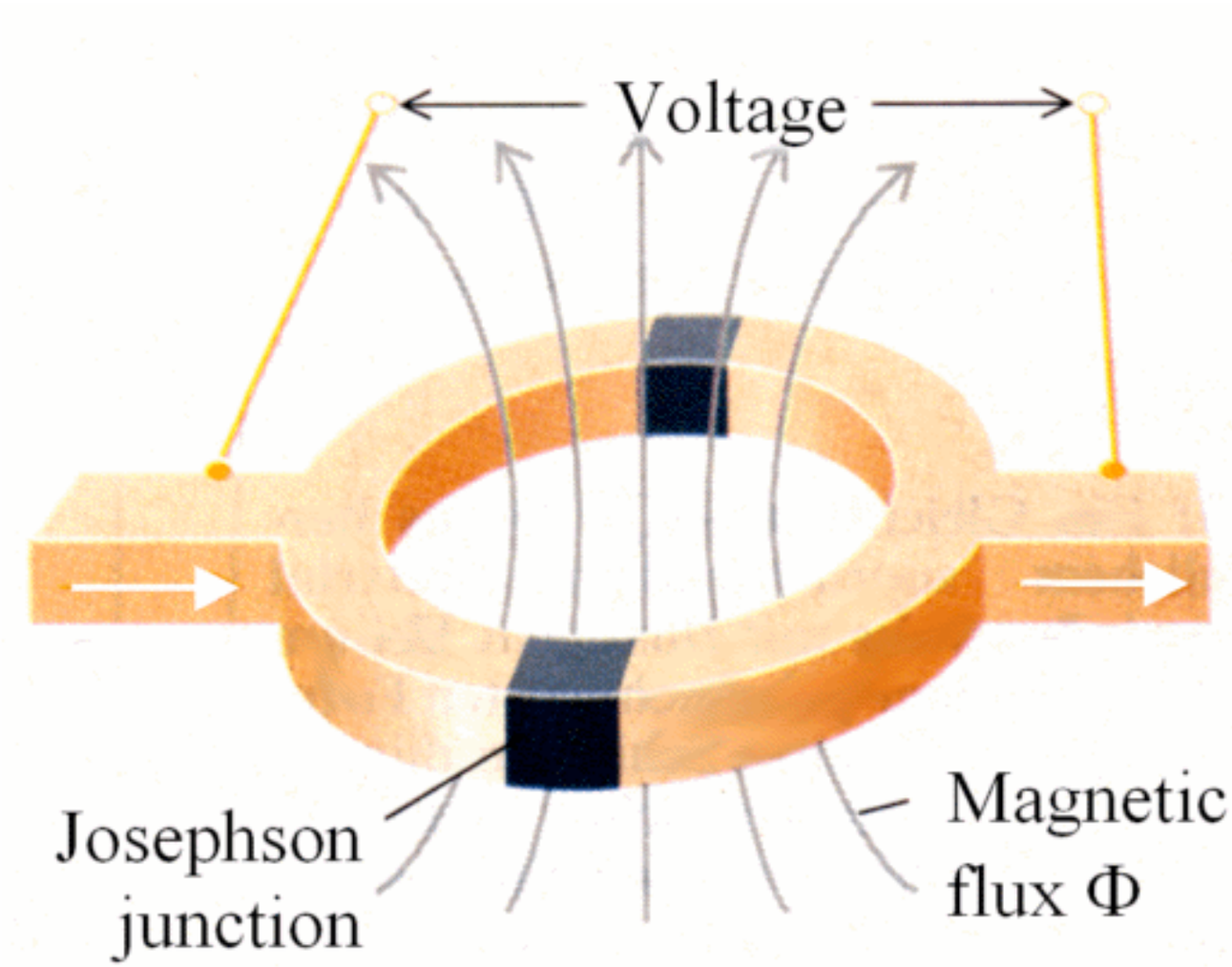
Photon noise

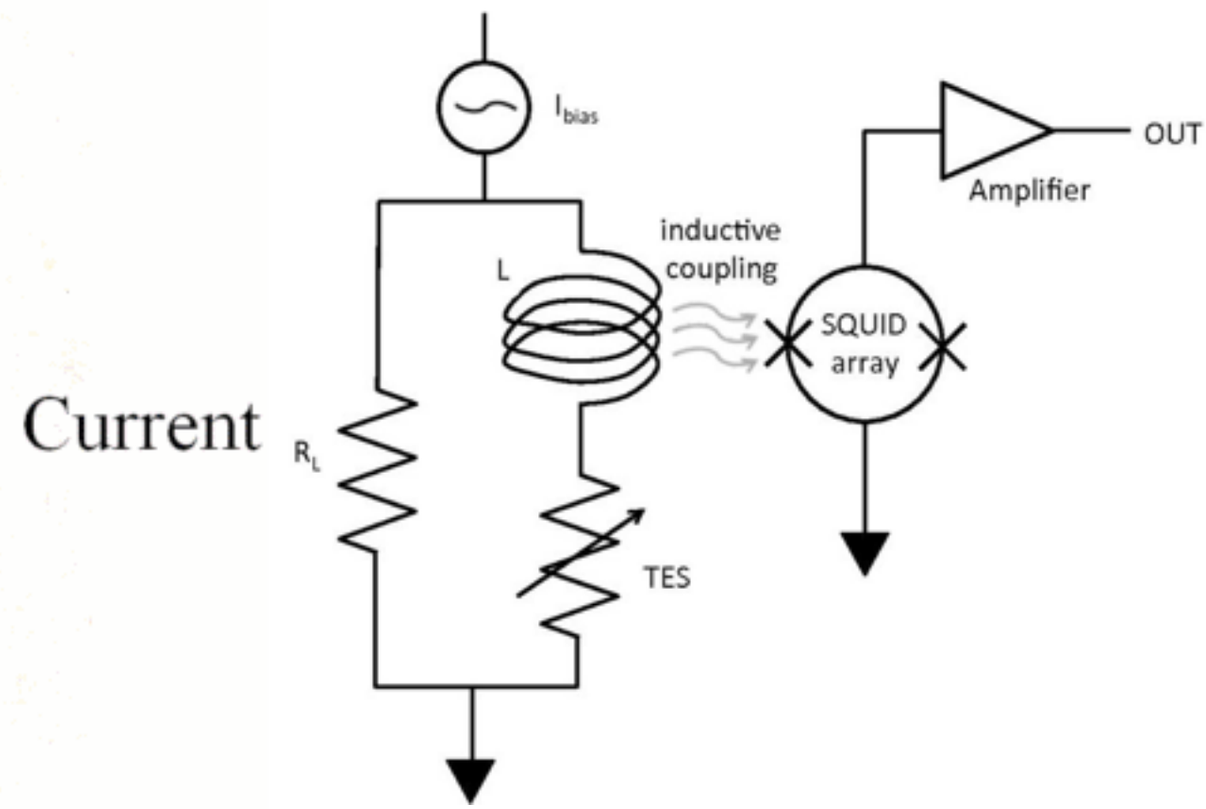
- Ground
- Space

Need more bolos!

Plot from J. Zmuidzinas

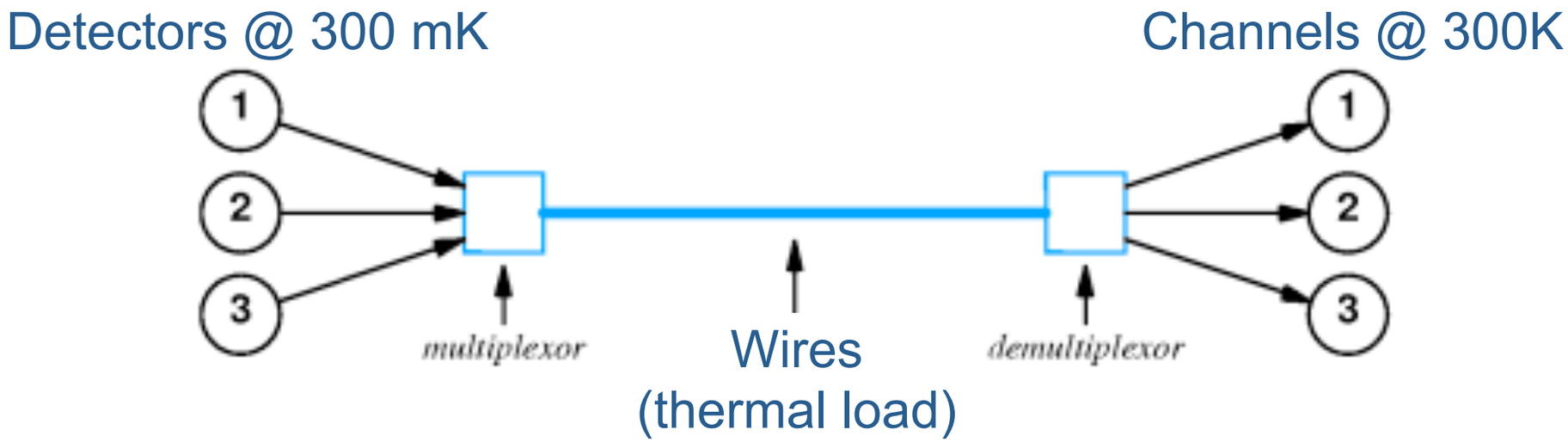
Superconducting QUantum Interference Device

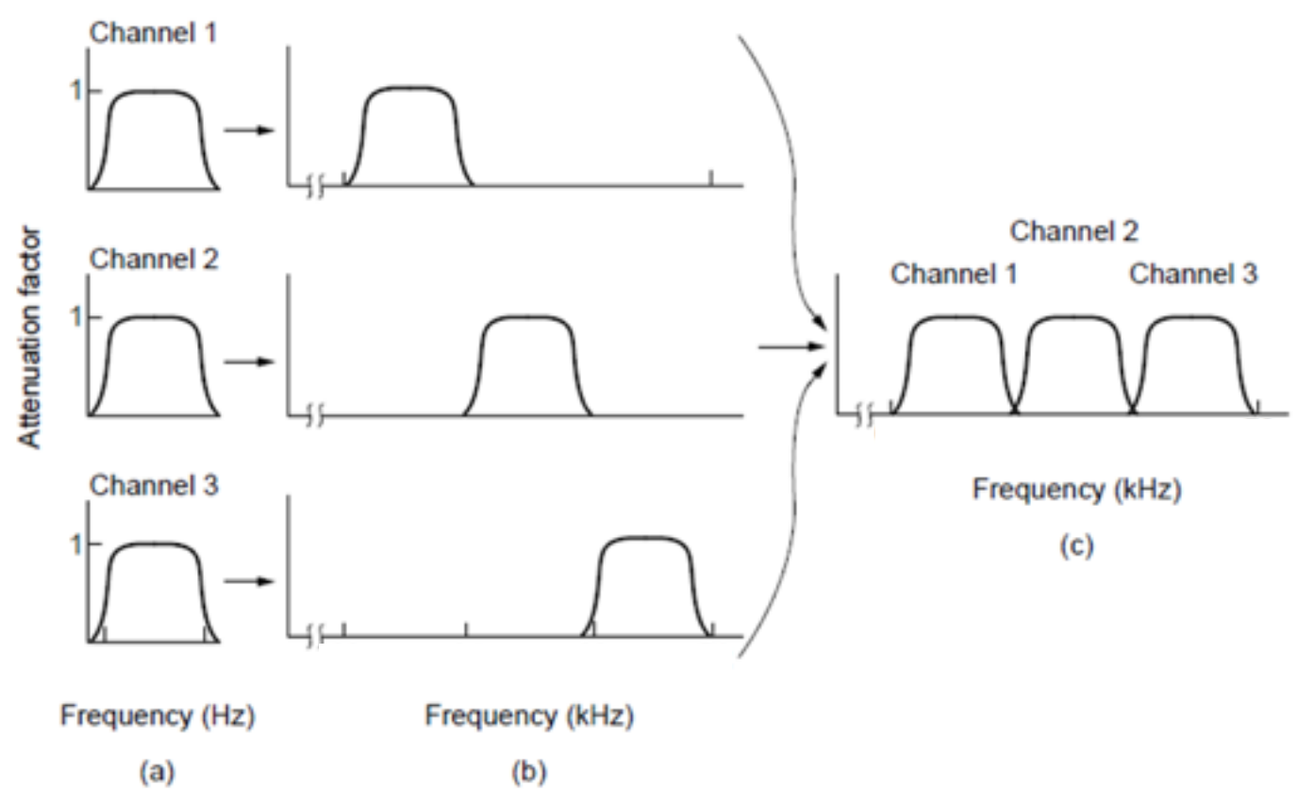




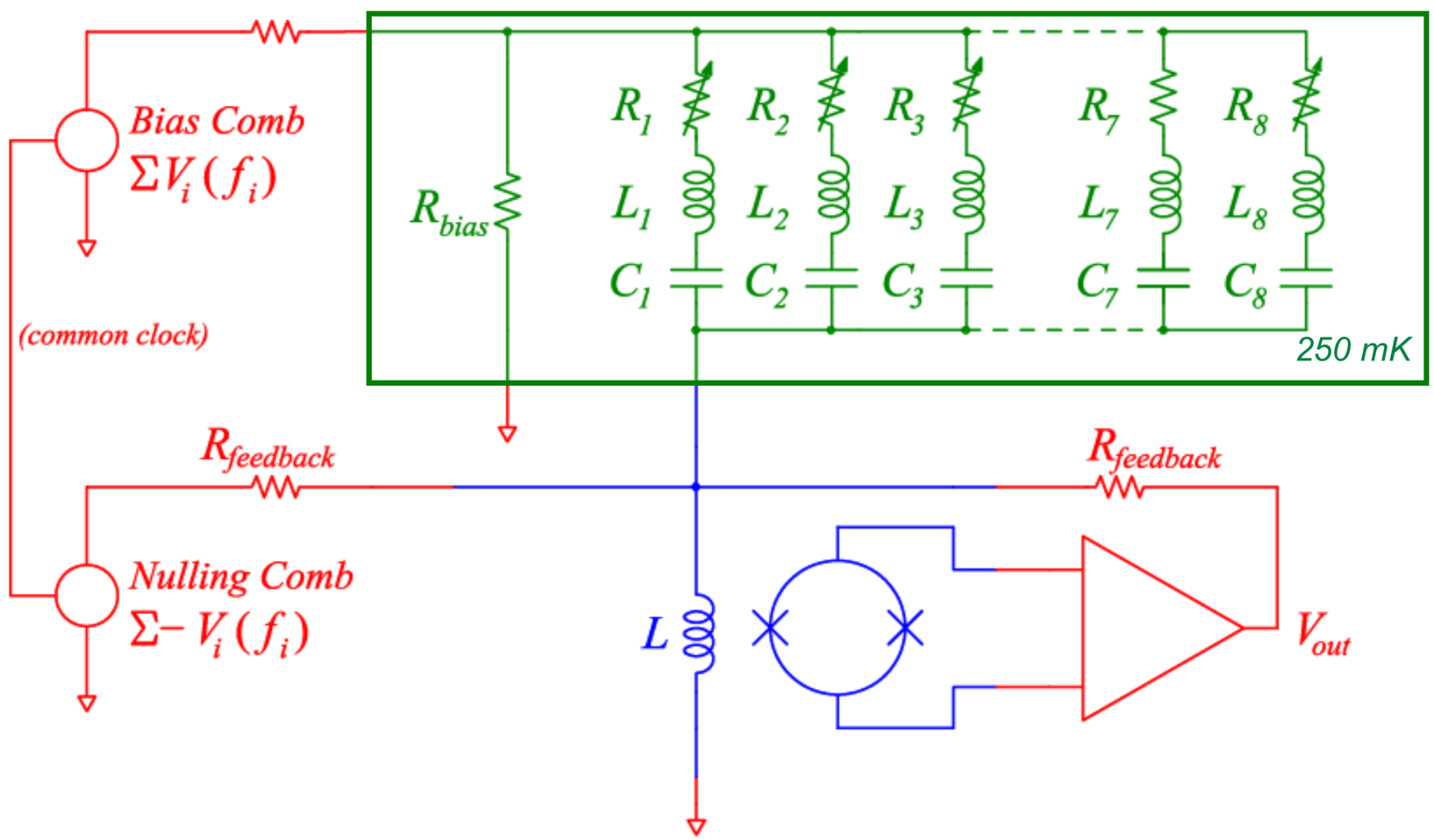
Bandwidth ~100 MHz

Multiplexing

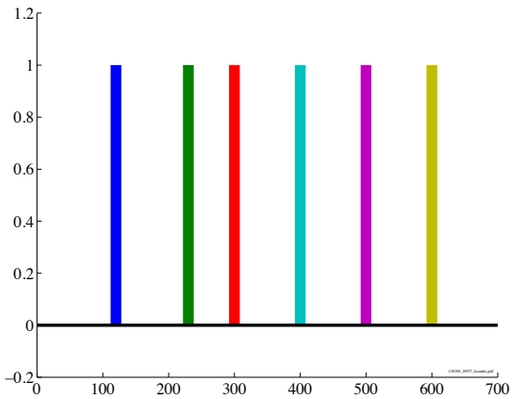


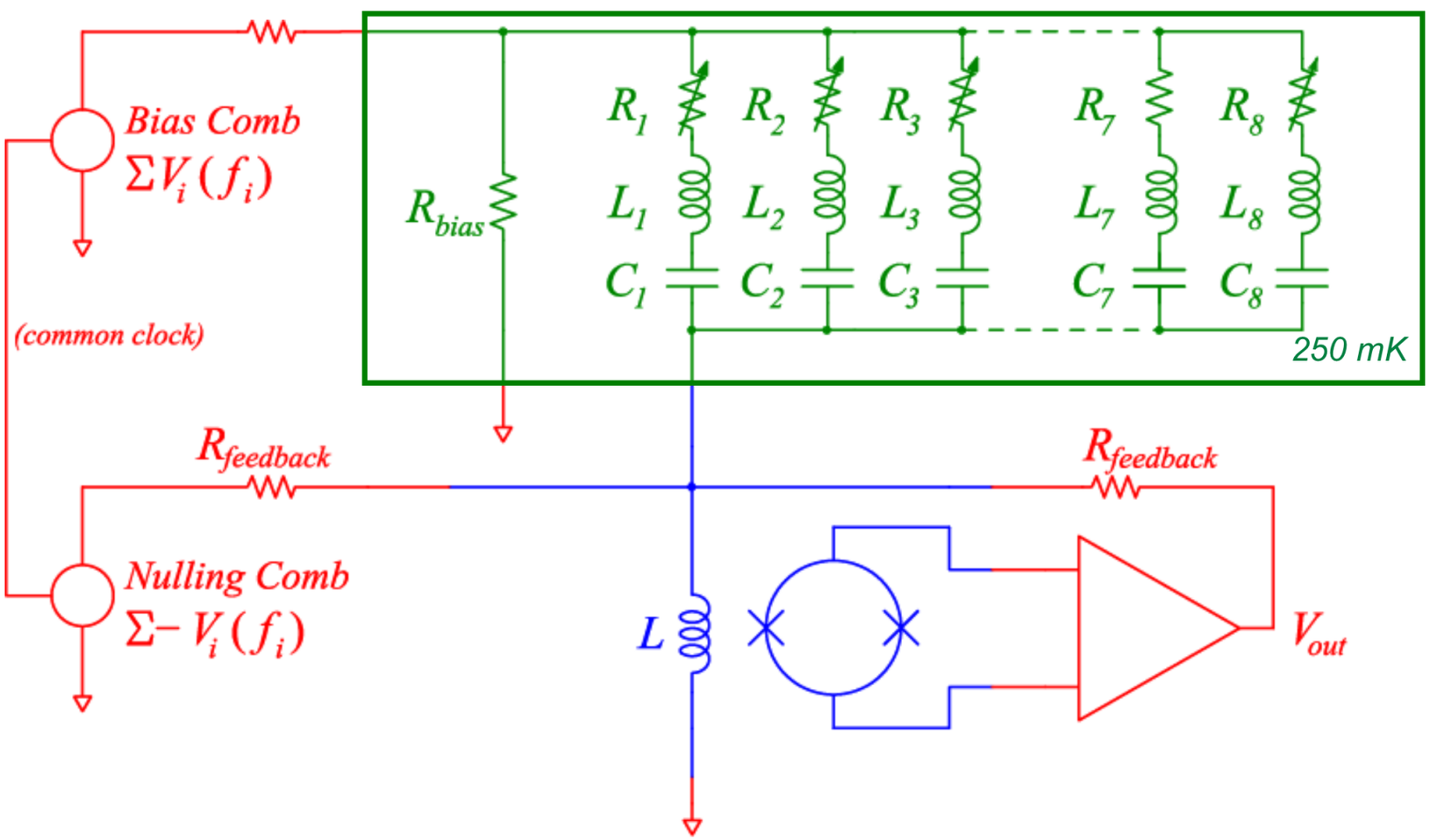


SQUID multiplexing

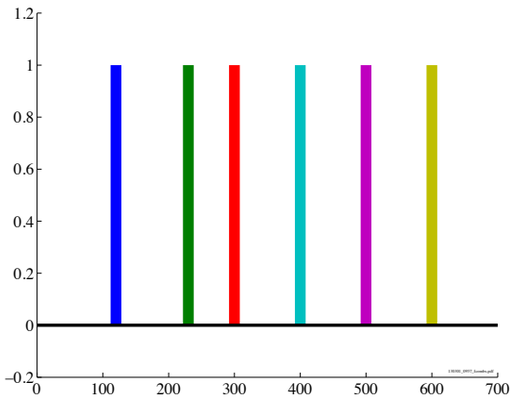


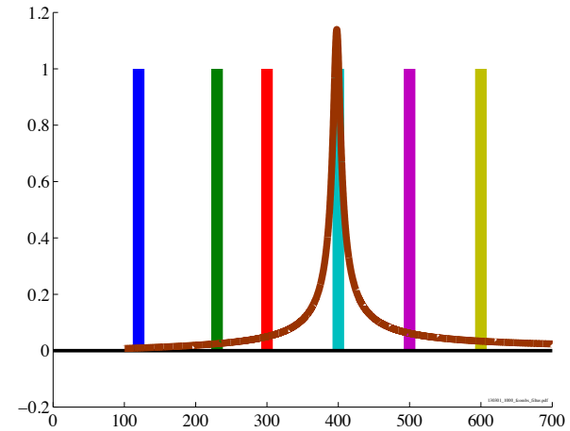
SQUID multiplexing

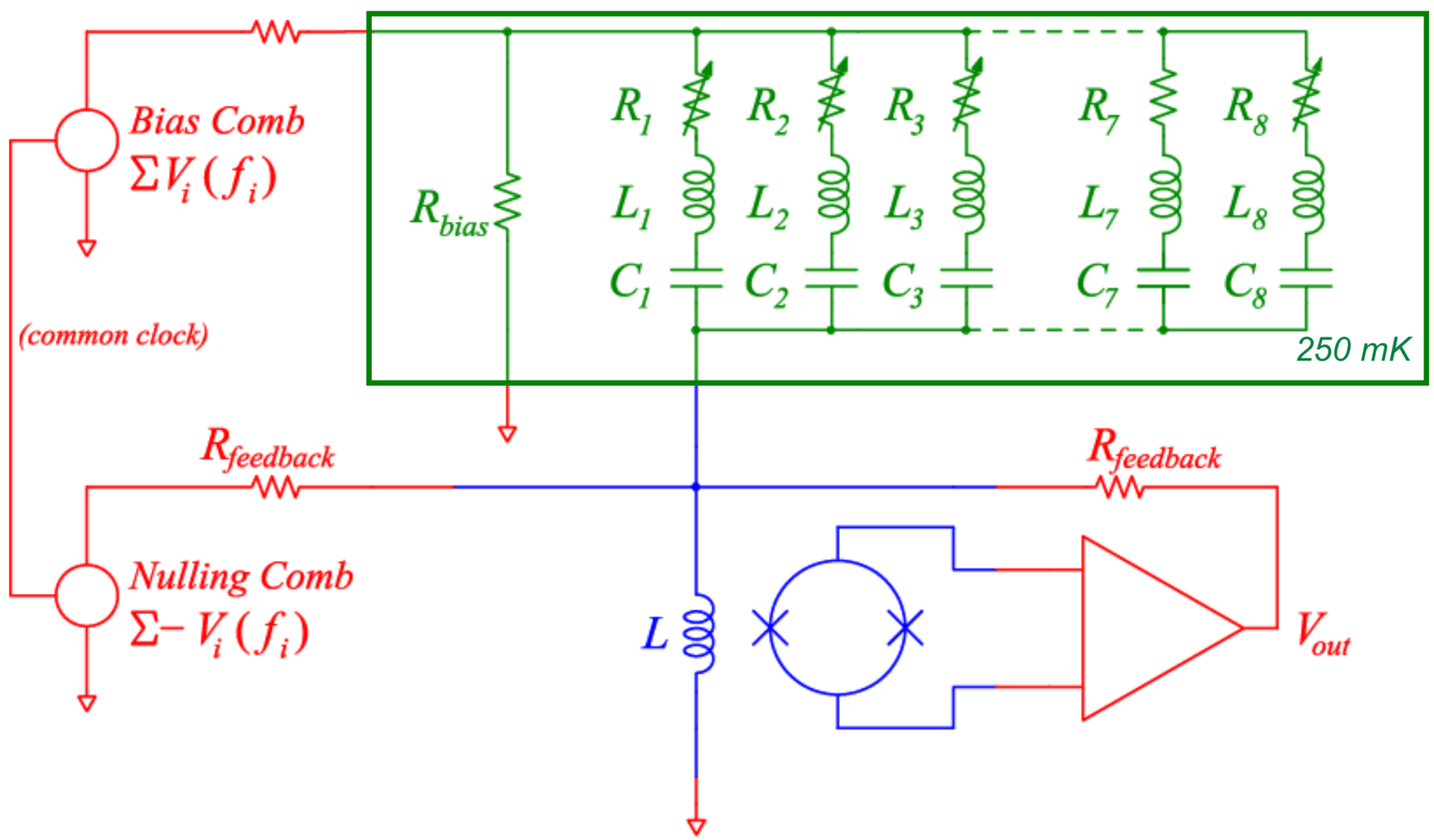




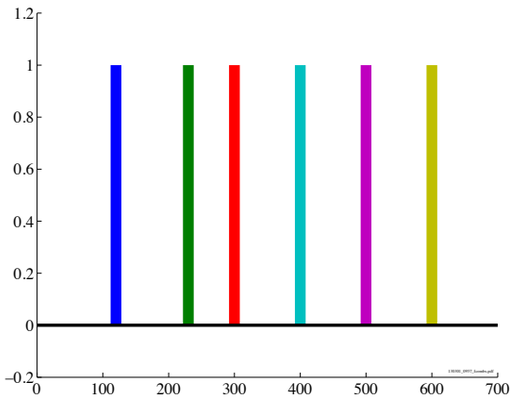
SQUID multiplexing

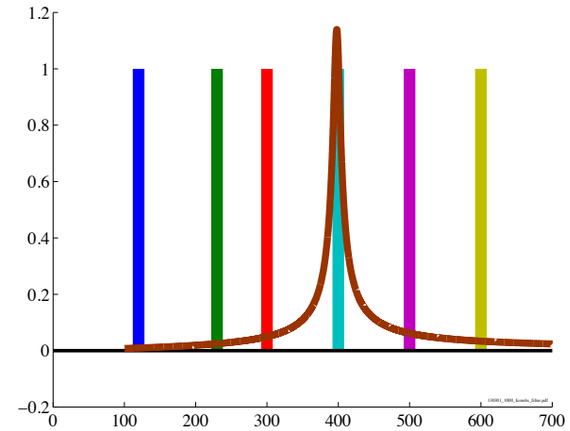


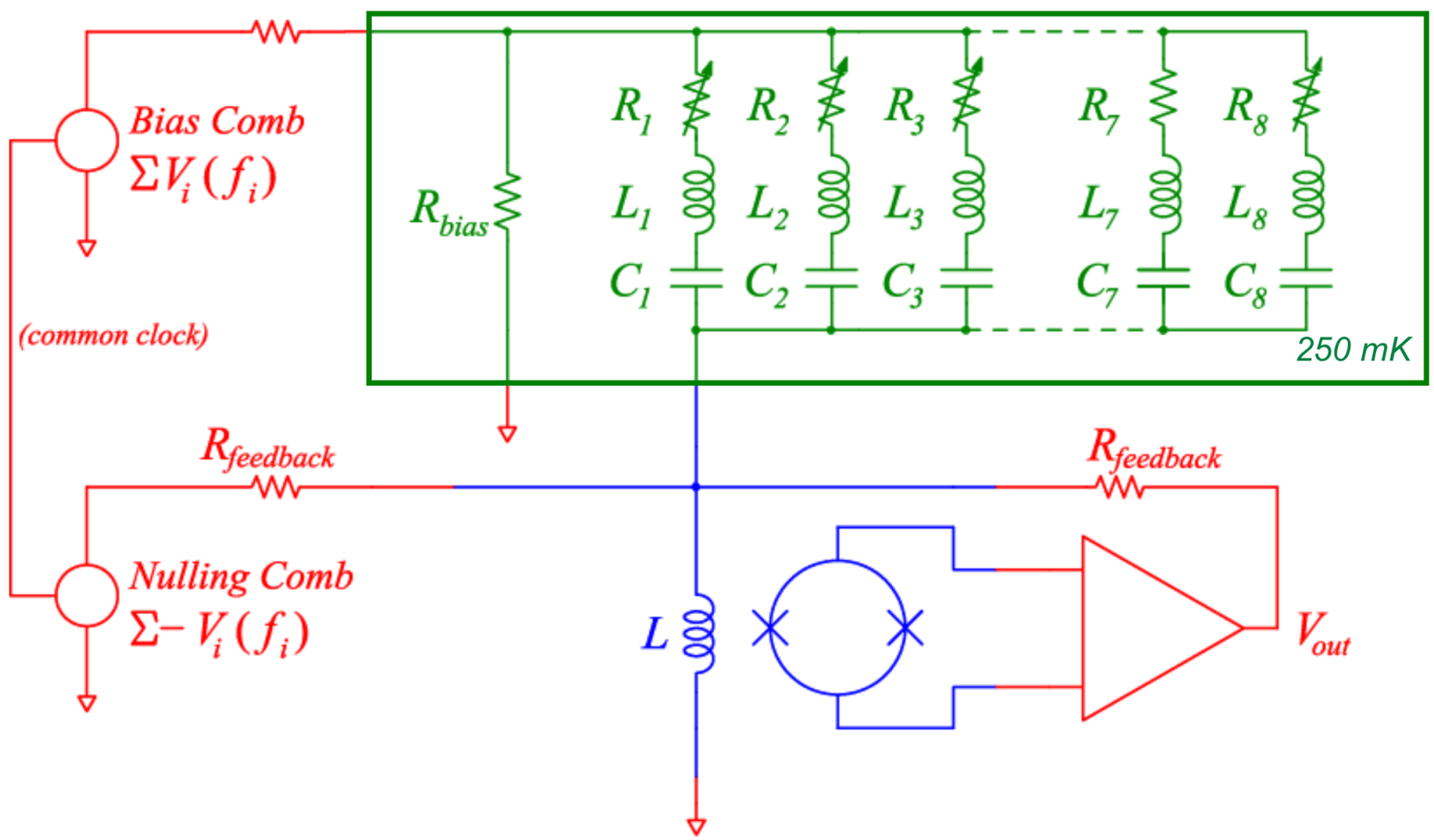




SQUID multiplexing

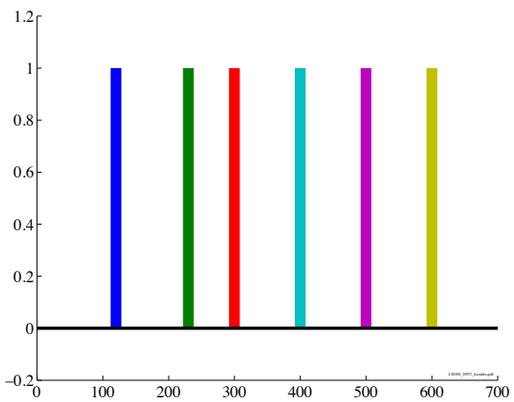


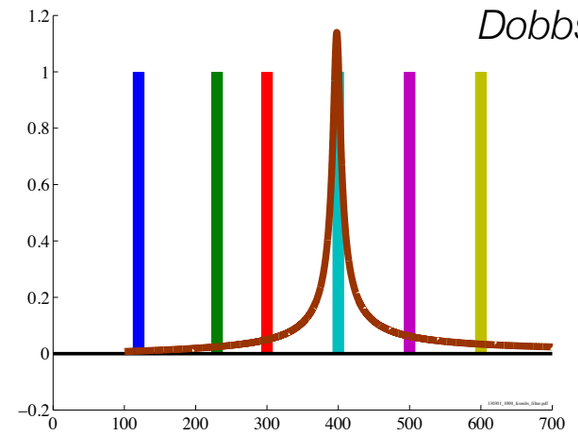




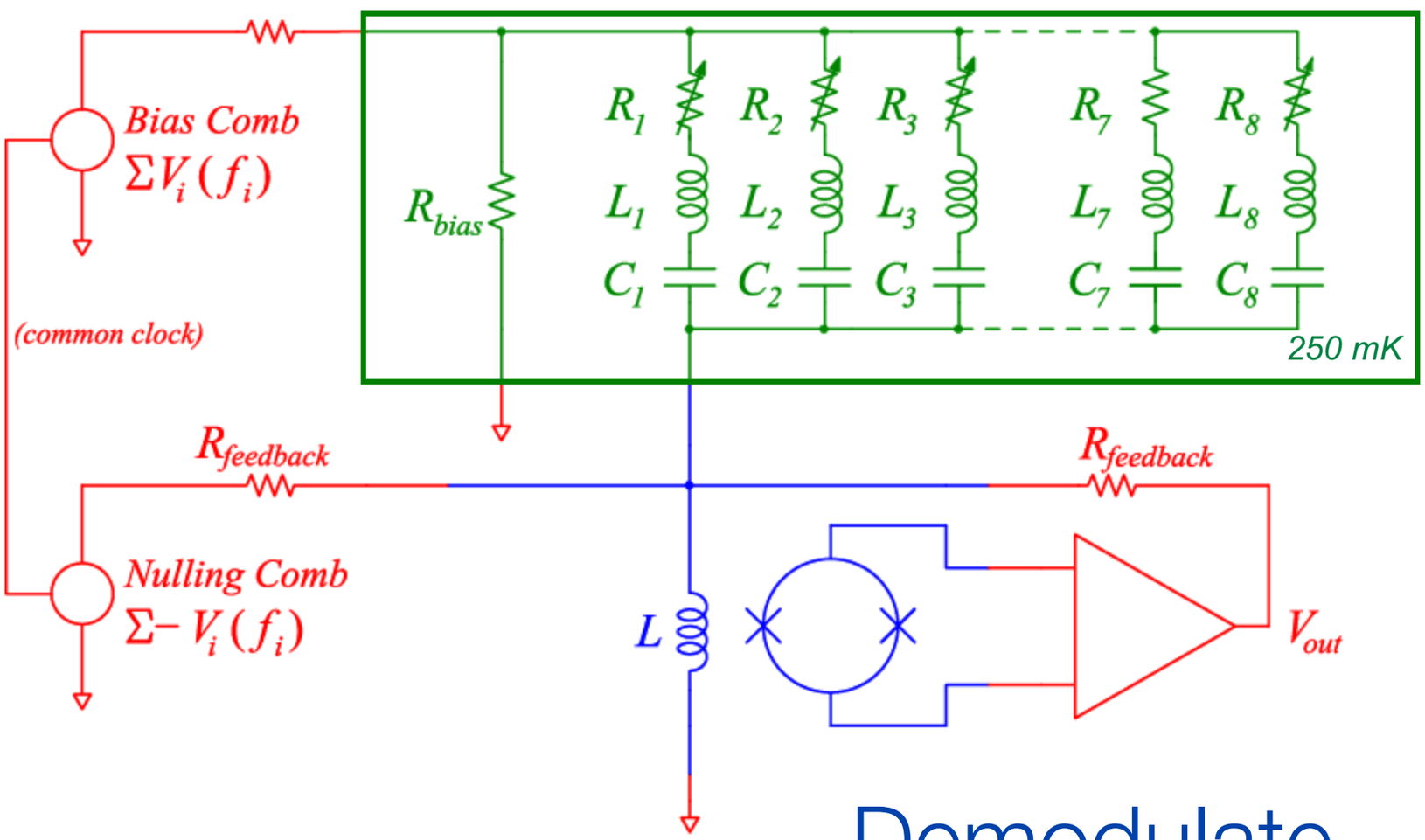
$$I_i = \frac{1}{R_i(t)} V \cos(f_i t)$$

SQUID multiplexing





Dobbs et al., Rev. Sci. Instrum. 83, 073113 (2012)

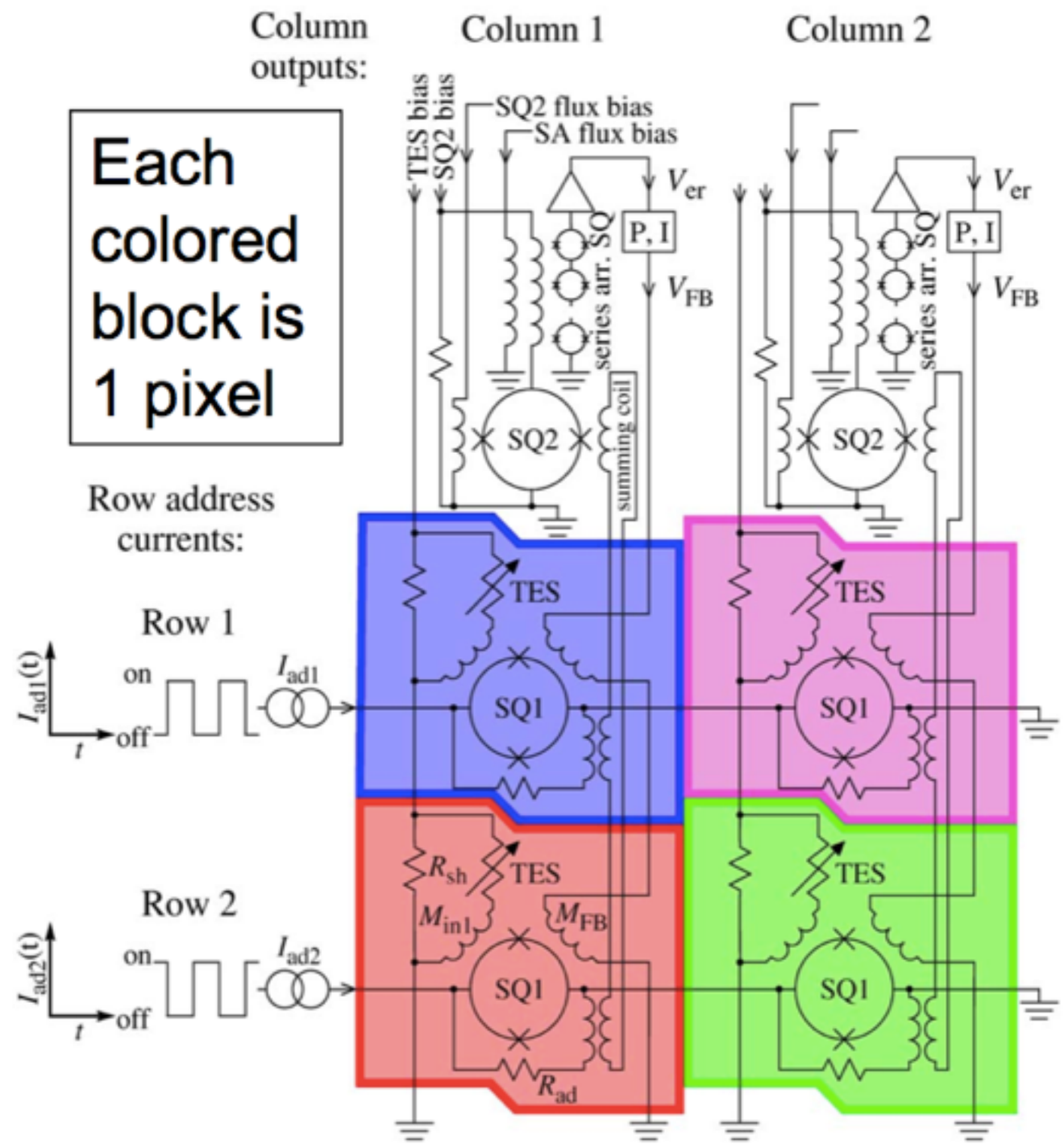


$$I_i = \frac{1}{R_i(t)} V \cos(f_i t)$$

Demodulate... just like AM radio

SQUID Multiplexing

- Alternative scheme using fast switching.
- Each bolometer readout in narrow time window.
- Similar to cell phone TDMA.

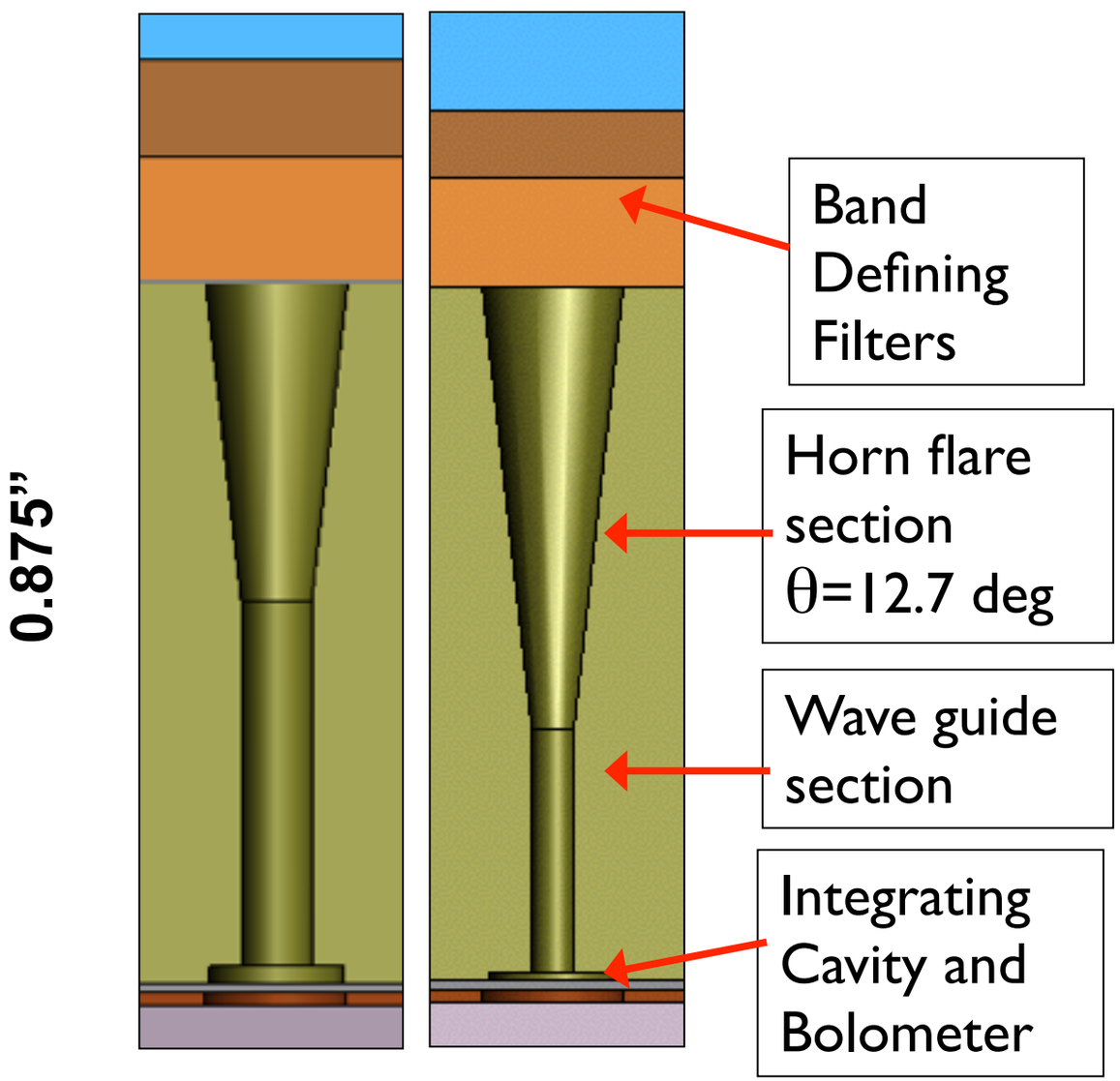


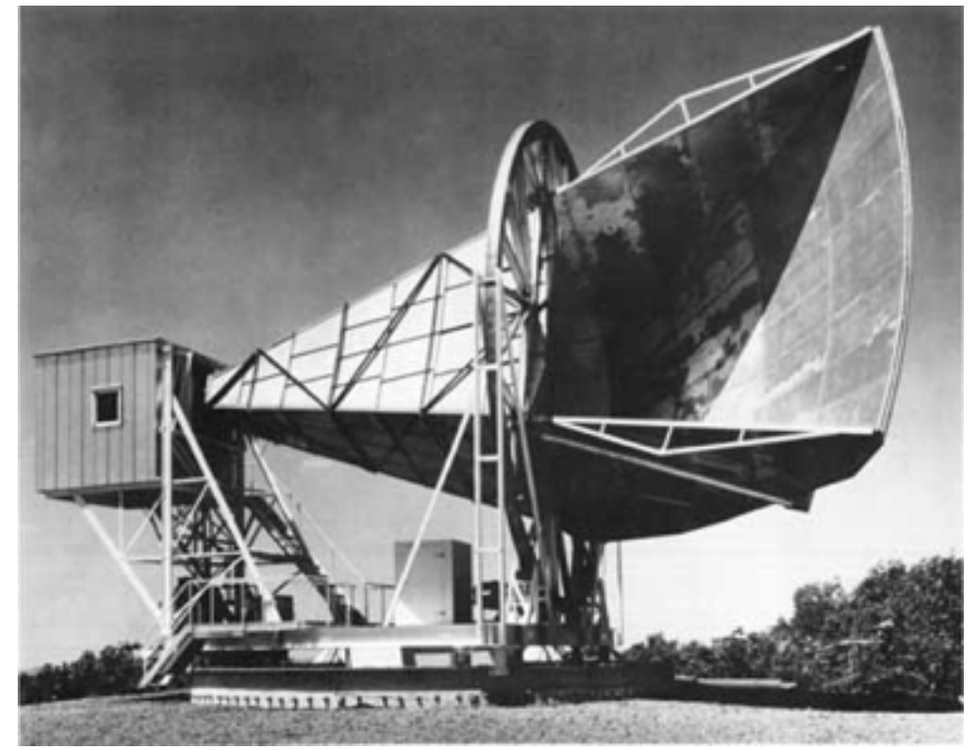
Summary

- Range in multipole determined by aperture size and field size
- Sensitivity limited by photon noise. Minimized by baffling and choice of site
- Background limited means large bolometer arrays required to increase sensitivity
- Multiplexing critical for implementing arrays in cryogenic systems

Optical coupling

- Feedhorn defines excellent beam
- λ/4 backshort to form resonant cavity. Radiation absorbed on bolometer

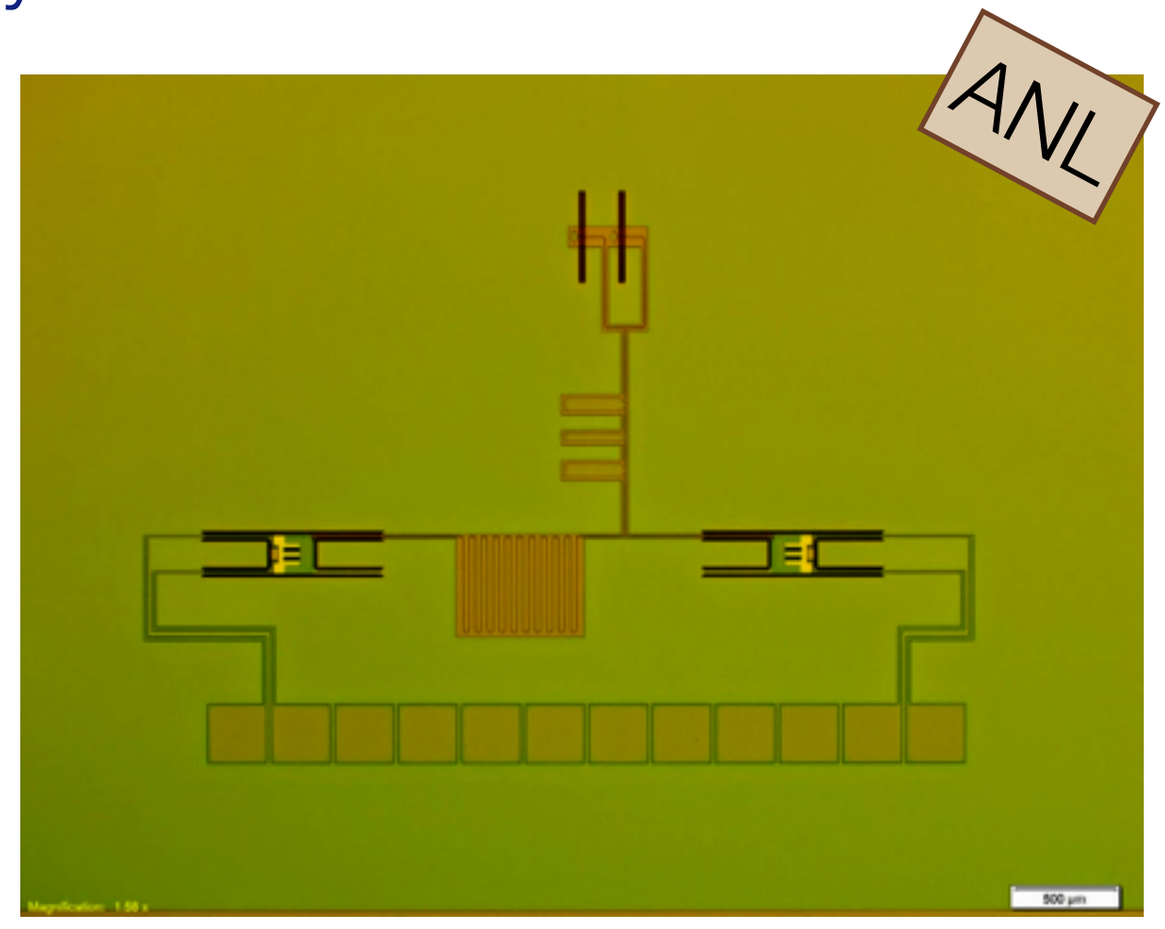




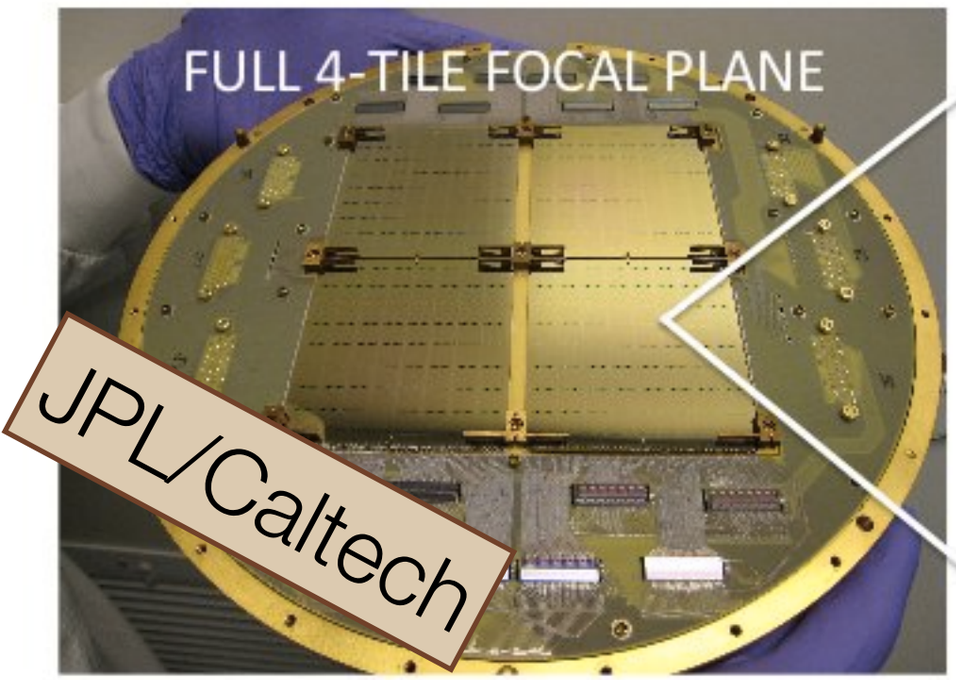
Optical coupling

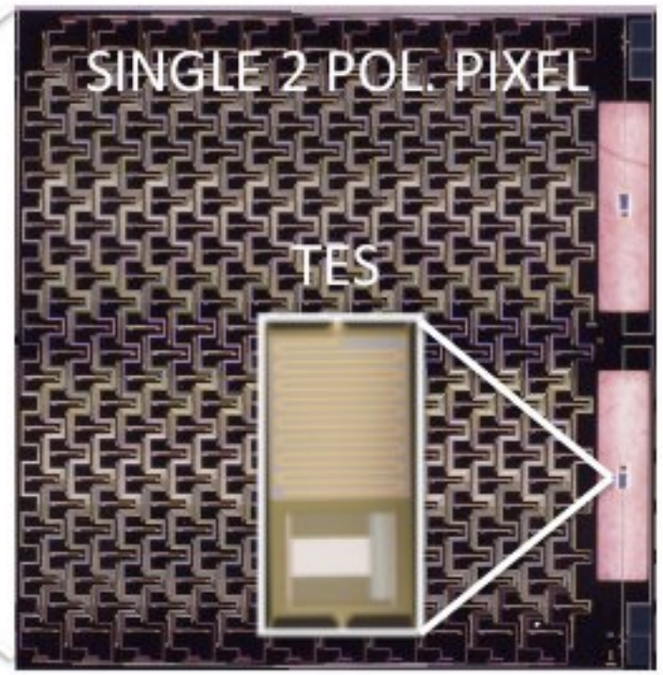
- Microstrip coupling - use planar antenna structure to couple free space radiation into planar transmission line

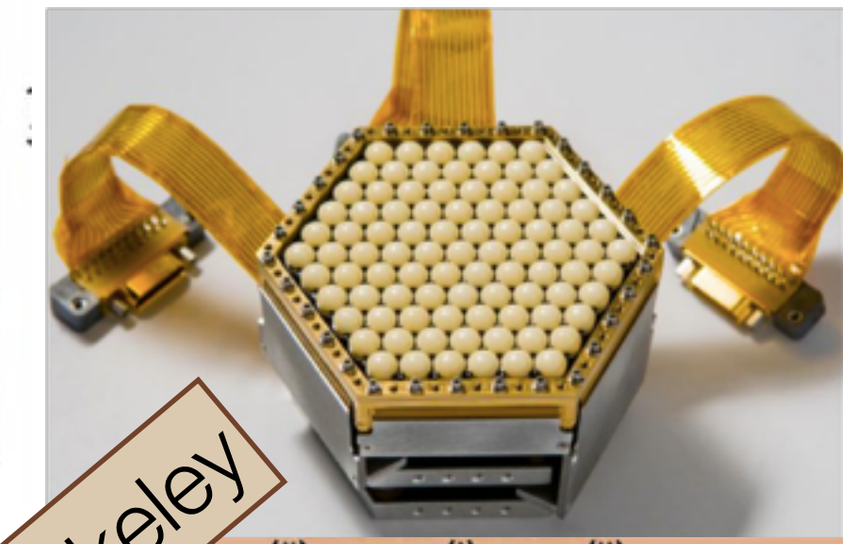
- Manipulate and filter radiation on transmission line before absorption by bolometer

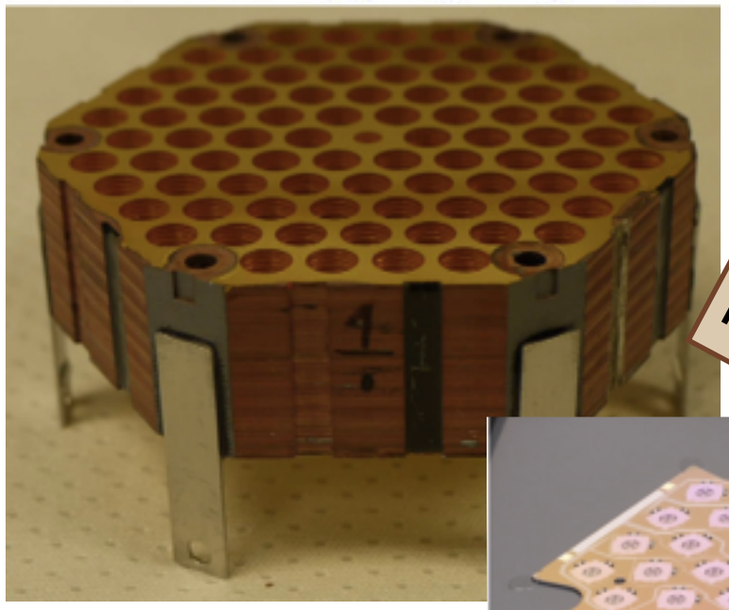


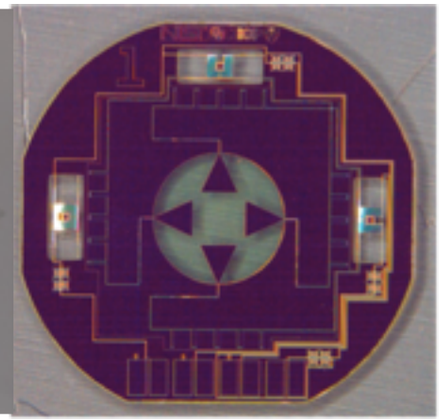
Optical coupling

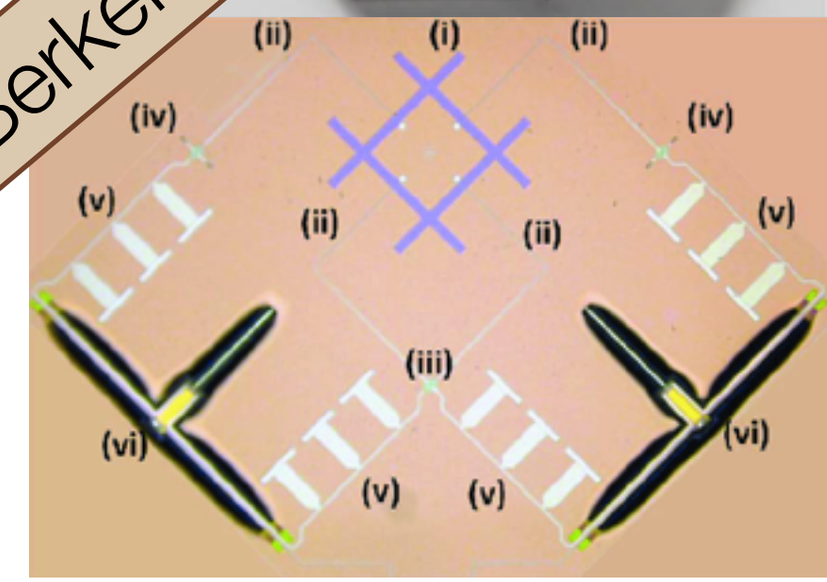




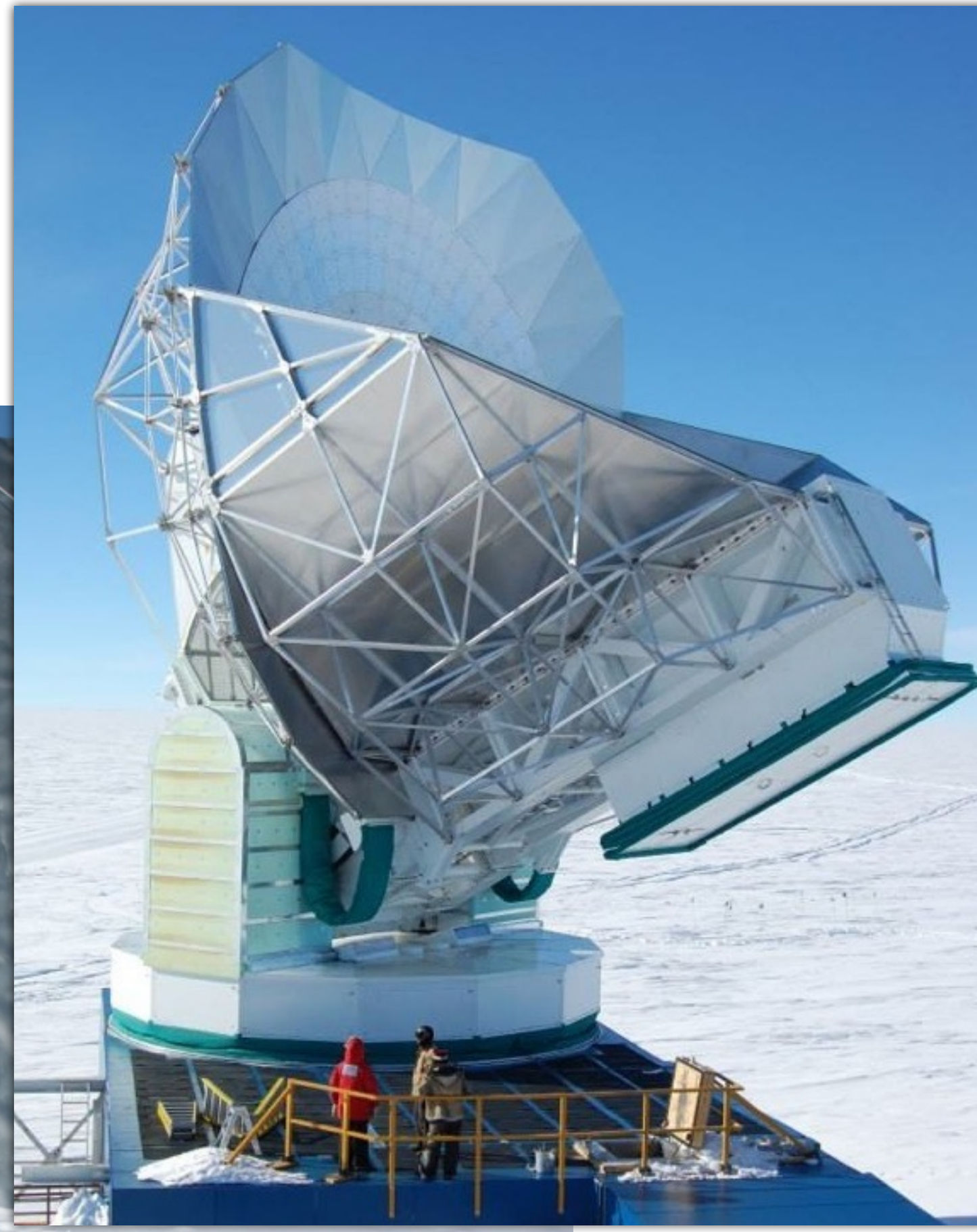






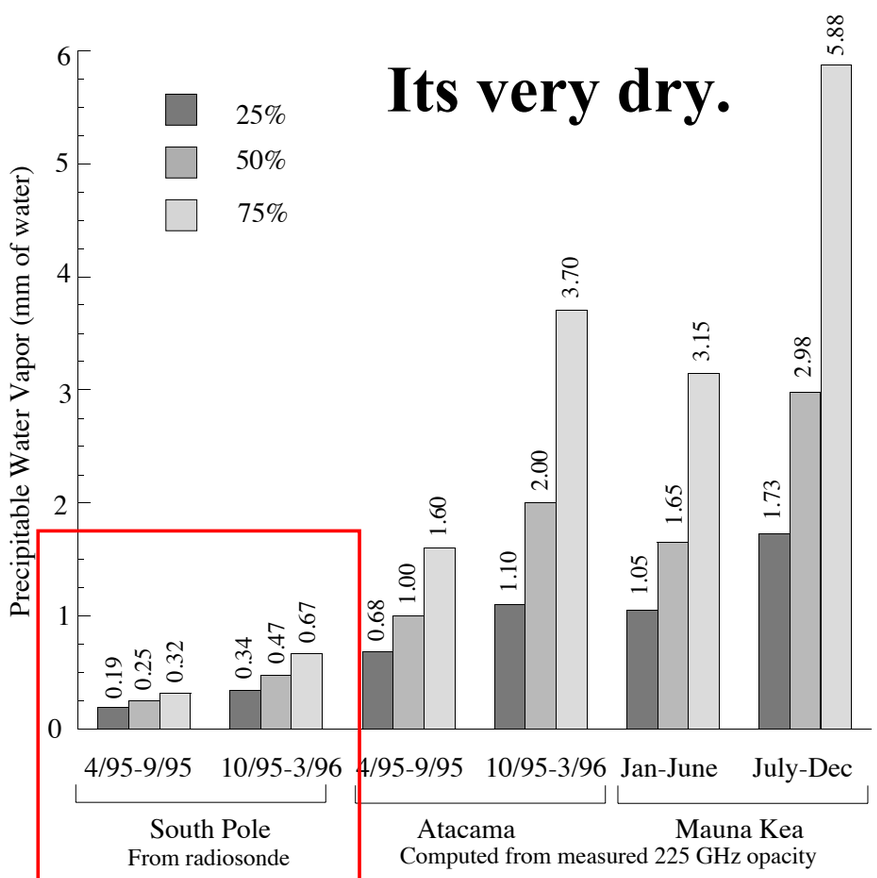


South Pole Telescope

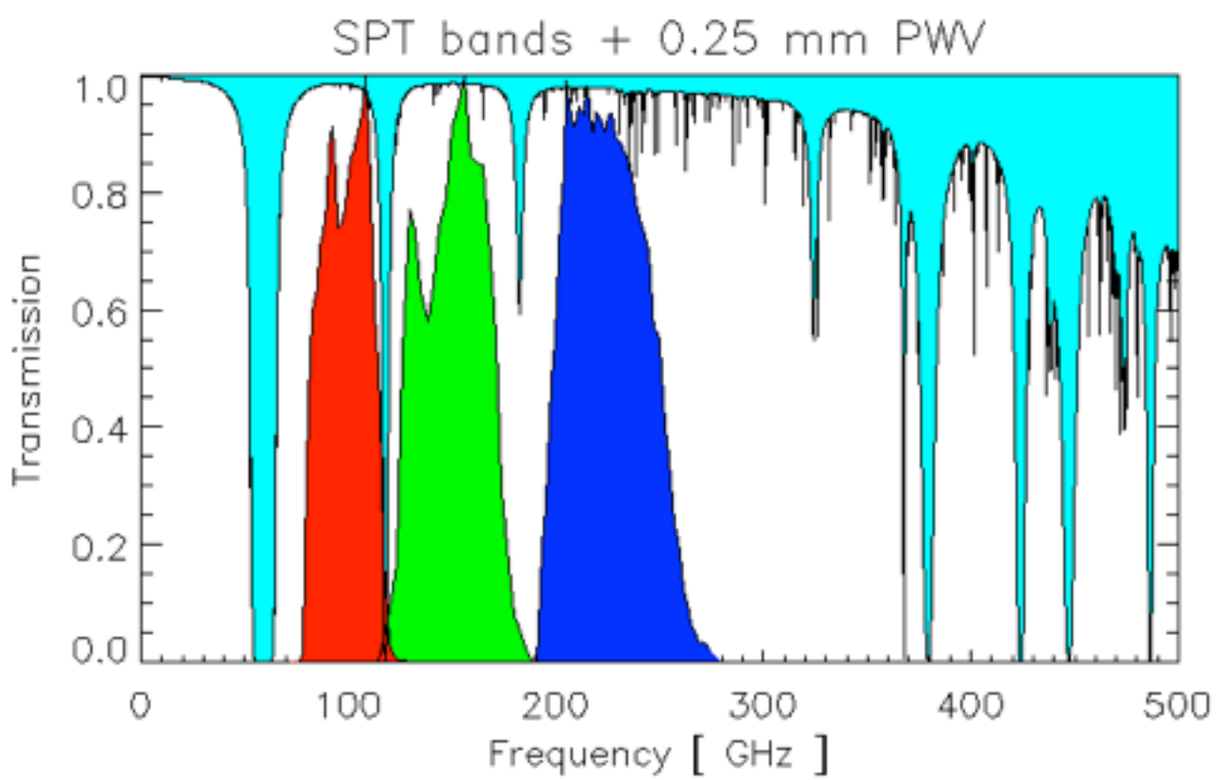


The South Pole Site

- Dry air for optimal atmospheric window
- Stable environment

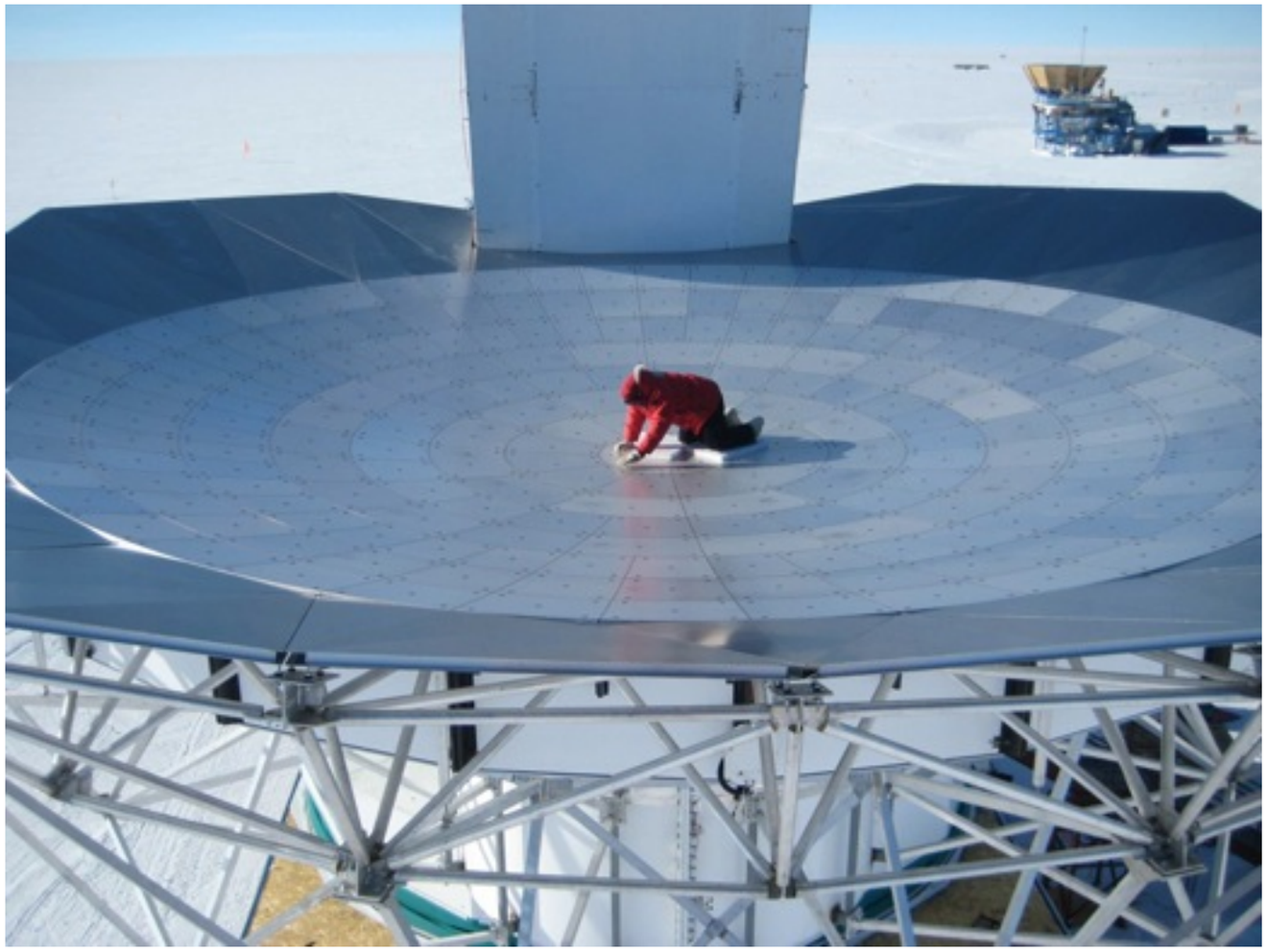


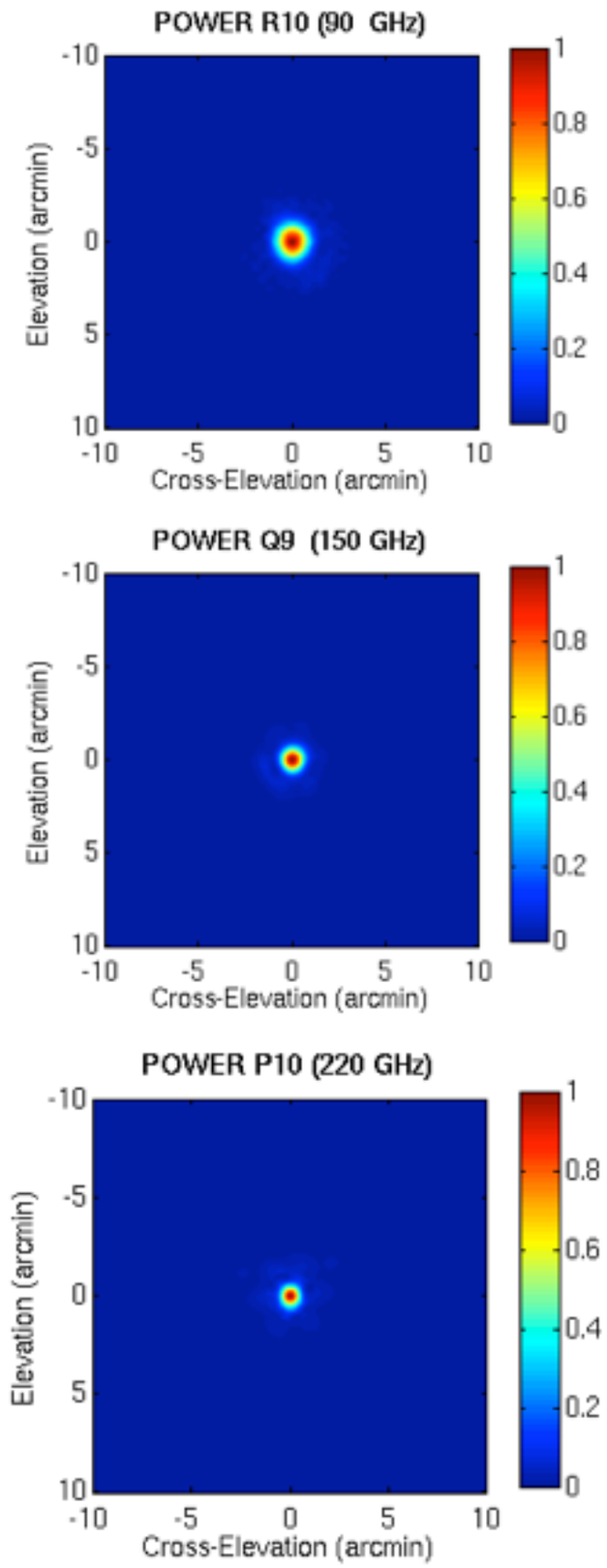
(A.P. Lane 1998)



Small angular resolution

- 10-m dish at 150 GHz gives ~1 arcmin beam (PSF)
- ~260 panels aligned to 25 μm rms over 10-m surface gives 95% efficiency at 220 GHz





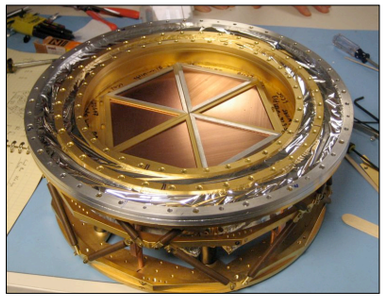
The South Pole Telescope (SPT)

A very high-tech 10-meter submm wave telescope

100, 150, 220 GHz
1.6, 1.2, 1.0 arcmin resolution

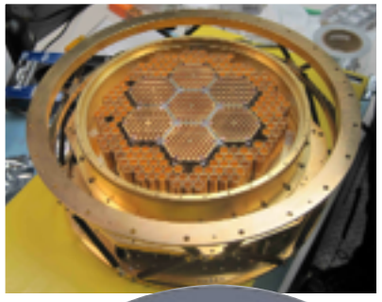
2007: SPT-SZ

960 detector receiver
built at UC Berkeley
95,150,220 GHz



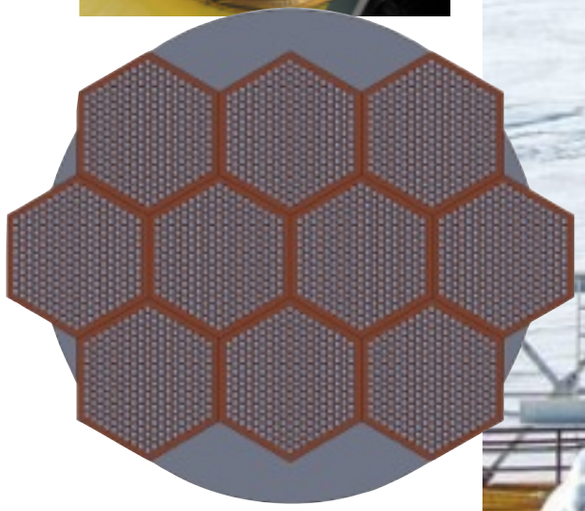
2012: SPTpol

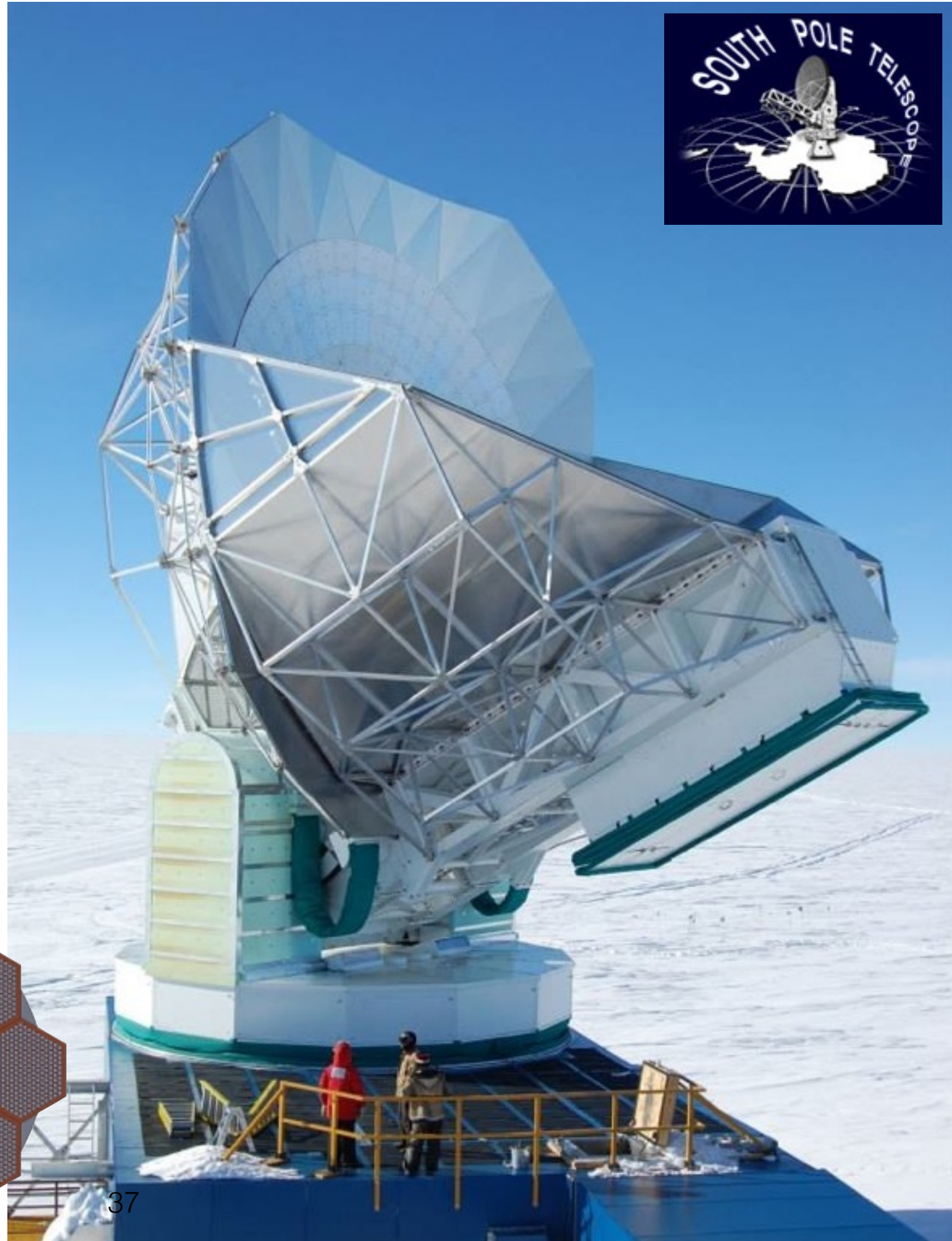
1600 detectors
95,150 GHz
+Polarization



SPT-3G

16,260 detectors
95,150,220 GHz
+Polarization

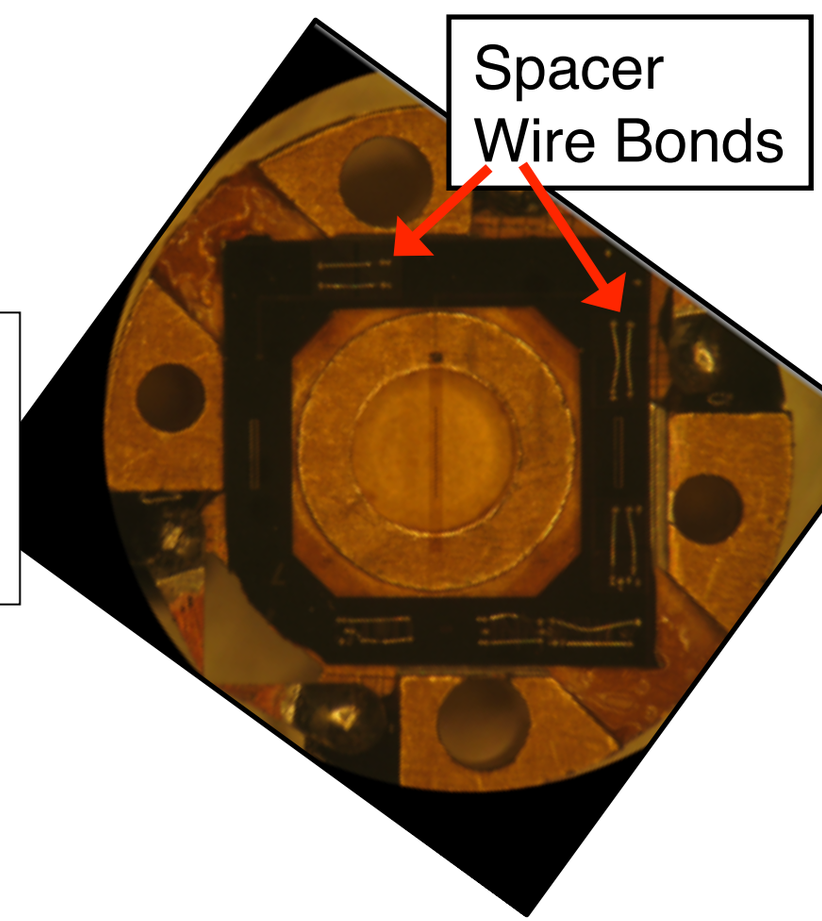


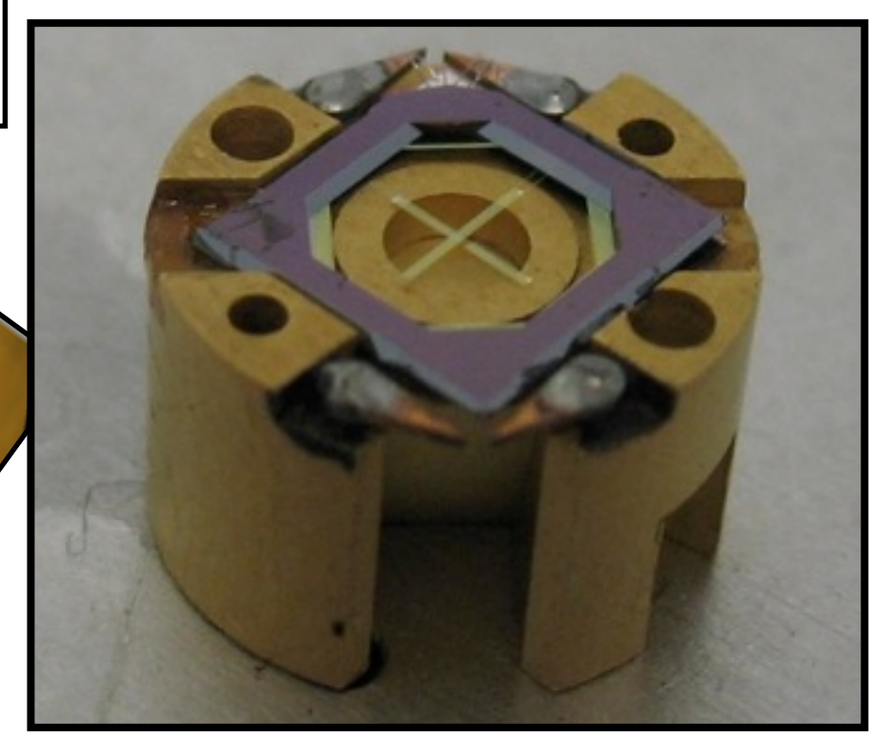


95 GHz Single Pixel PSBs

95 GHz pixels made in collaboration with Argonne National Labs (ANL)

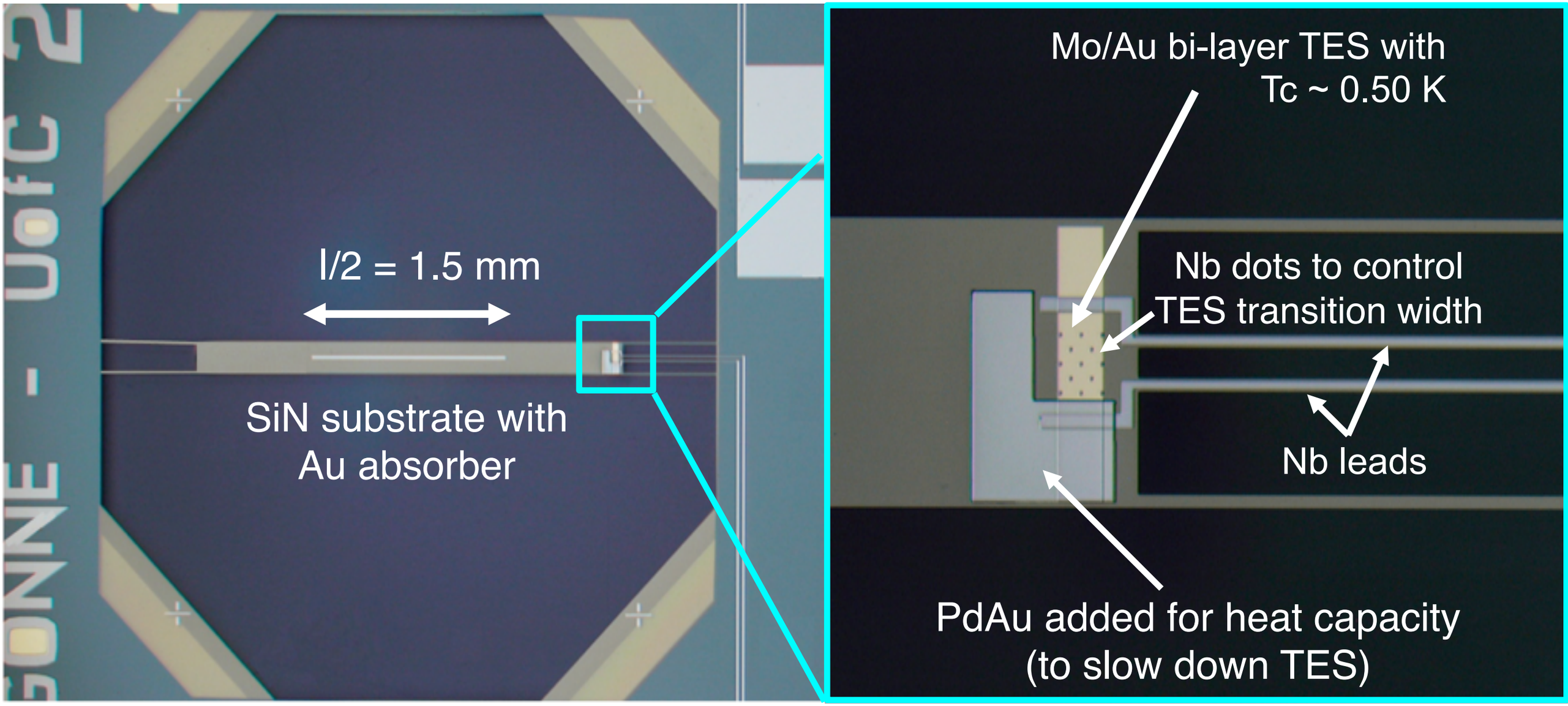
- 190 pixels at 95 GHz
  - few enough pixels, so that single-pixel design was possible, also matched ANL capabilities at the time
- Crossed absorbers with TES's in waveguide behind contoured feed horn with a l/4 backshort
- Wire-bonds maintain ~50 mm separation between pixels





Fabricated by Vlad Yefremenko at ANL

95 GHz Single Pixel PSBs

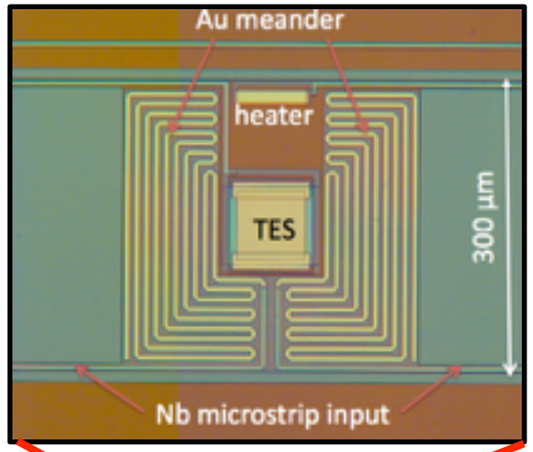


150 GHz Array PSBs

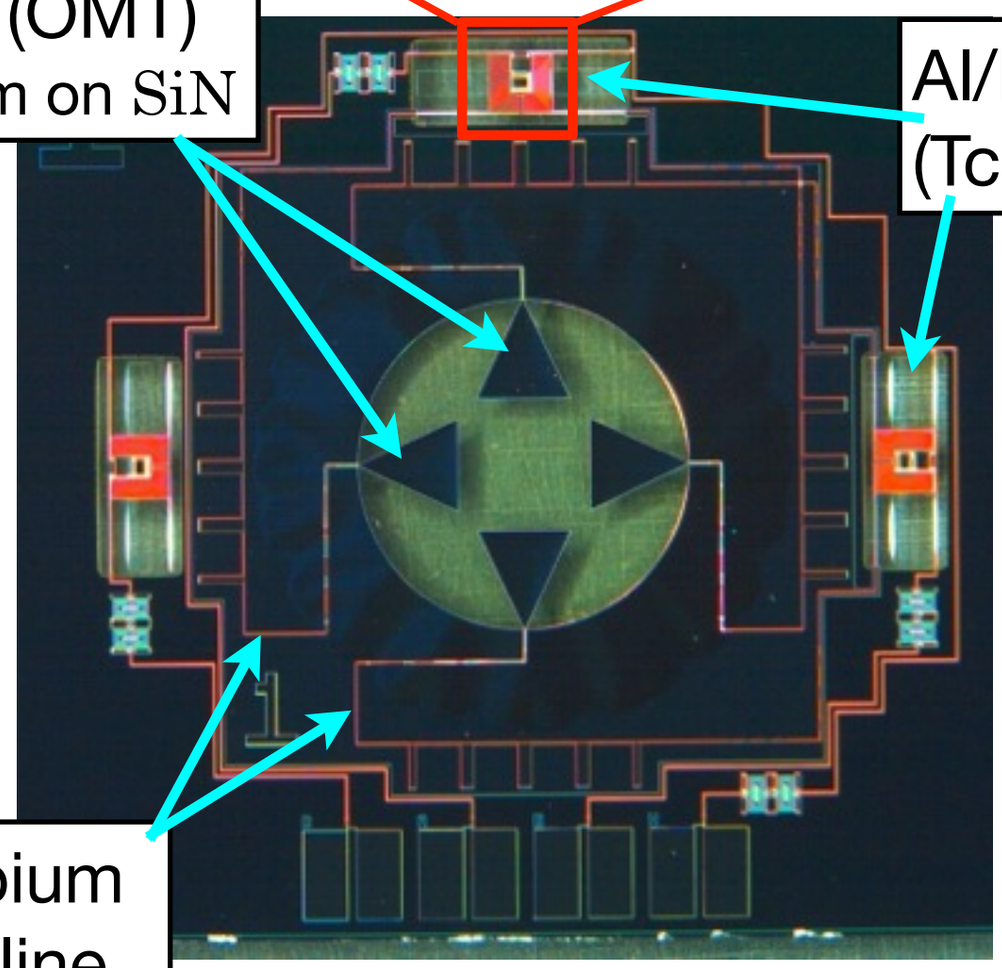
Fabricated by Dale Li, Sherry Cho at NIST

NIST 150 GHz detectors uses a new antenna-coupled TES design

- Niobium OMT antenna splits light into two polarizations, fed through strip-lines to TES island, where heat is dissipated through lossy Gold (Au) meander
- ***Antenna-coupled design is also scalable to multi-chroic pixels!***



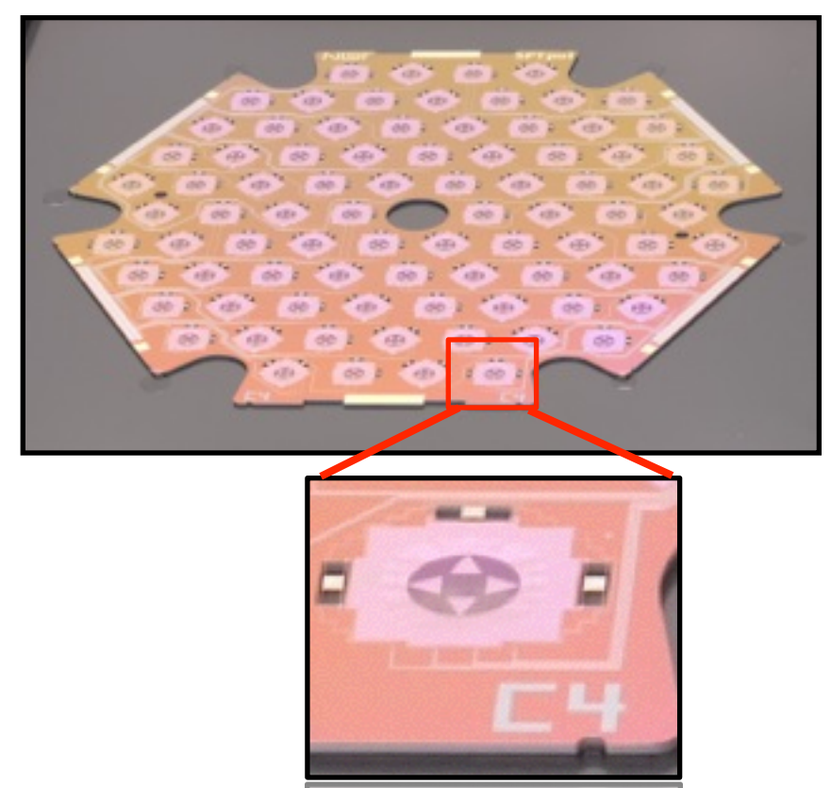
Polarization Splitter (OMT)
- Niobium on SiN



Al/Mn TES (Tc ~ 0.5 K)

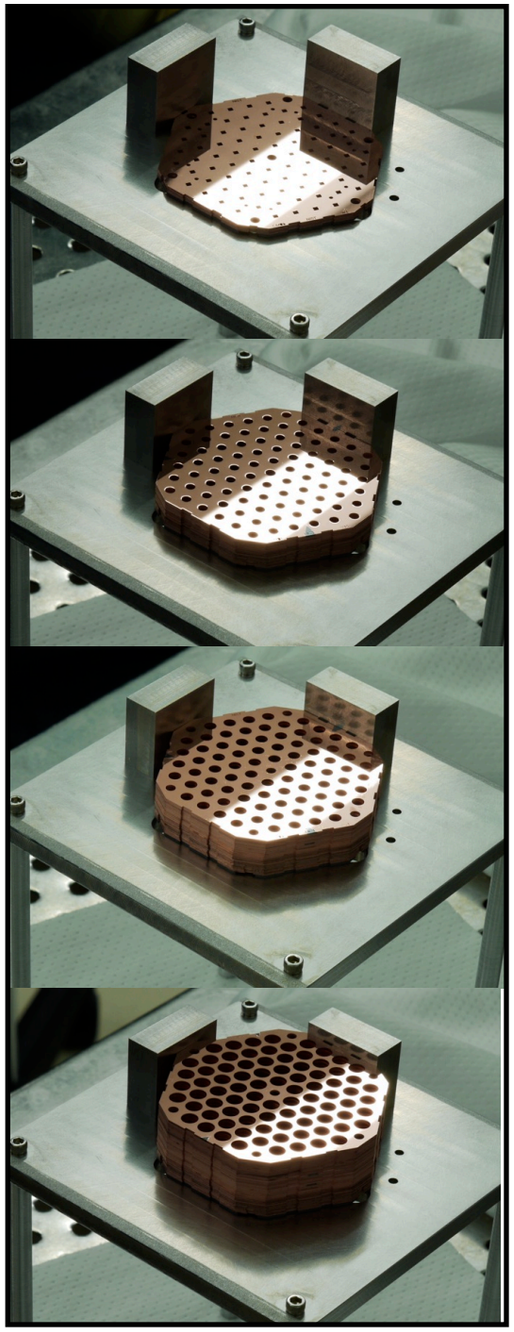
Niobium stripline

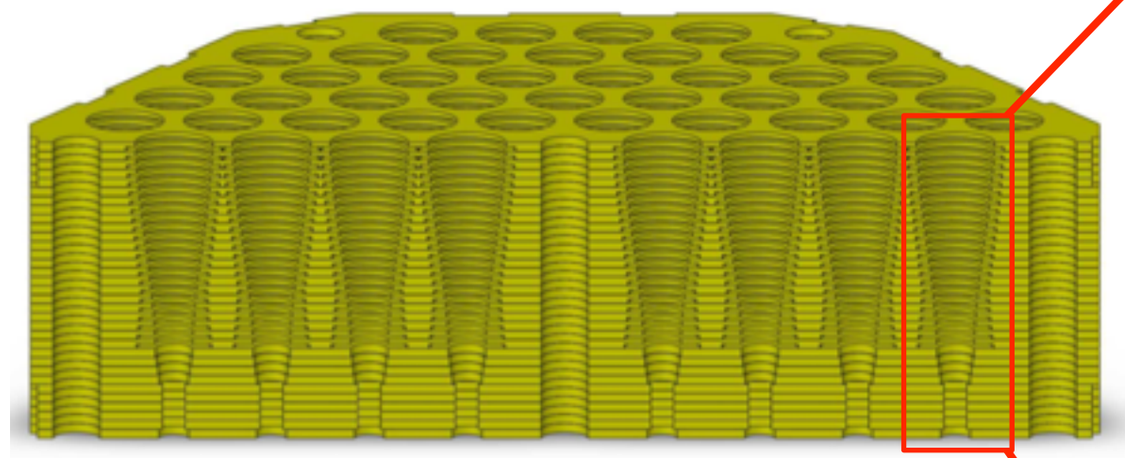
SPTpol 150 GHz Detector Array

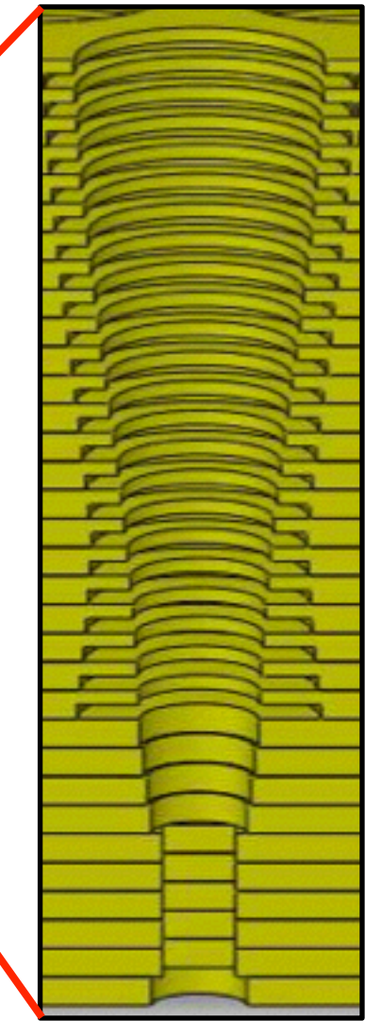


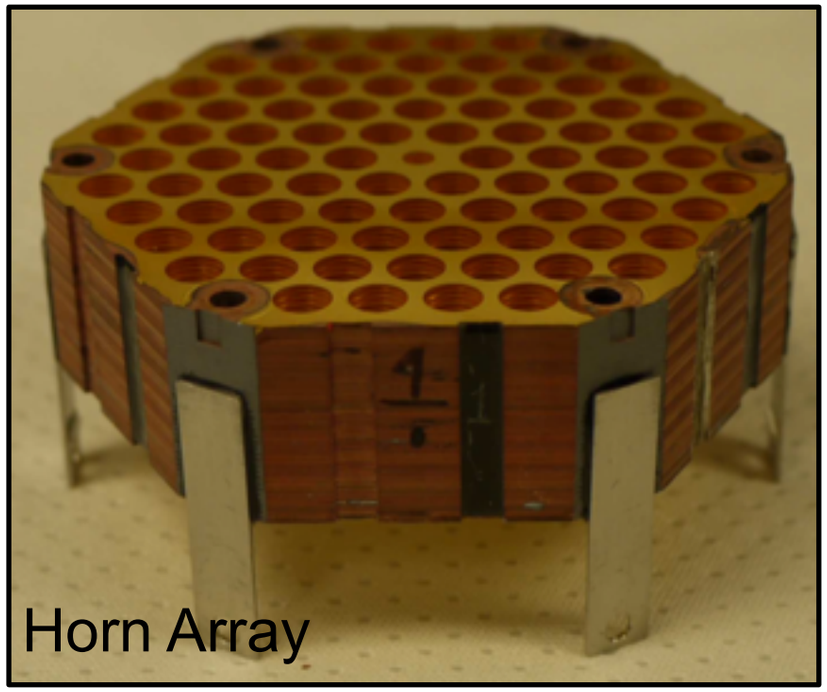
150 GHz Array PSBs

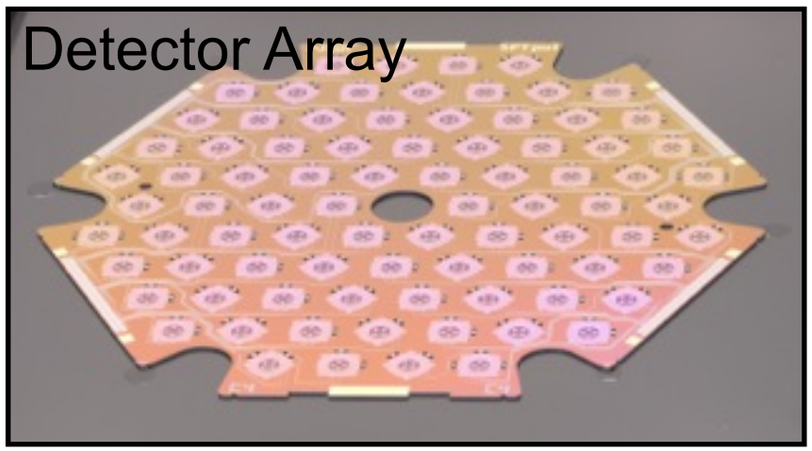
Horn Assembly







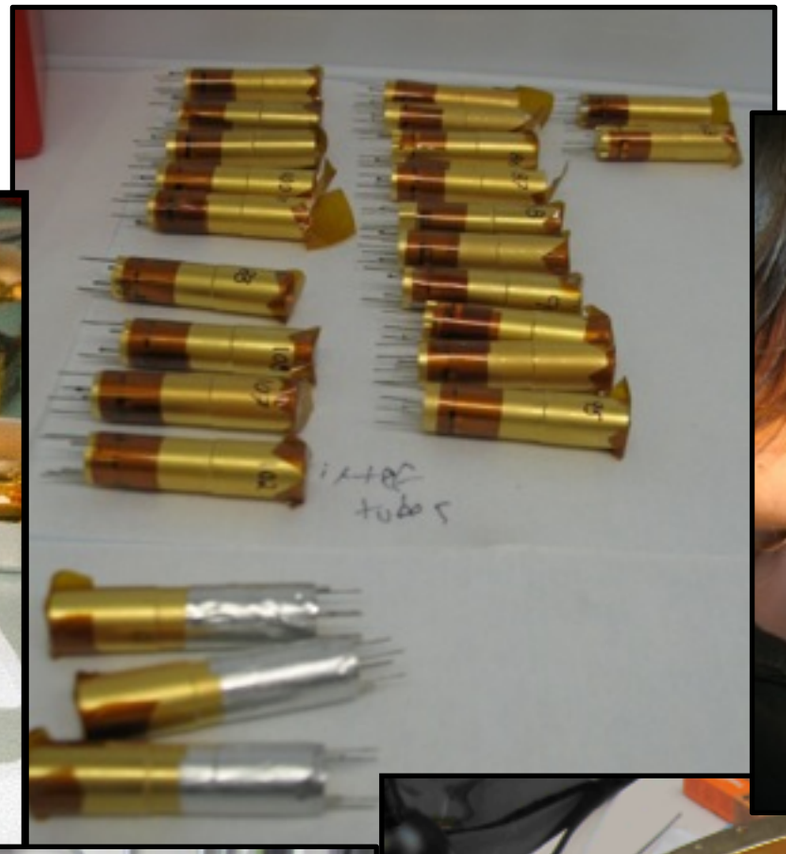


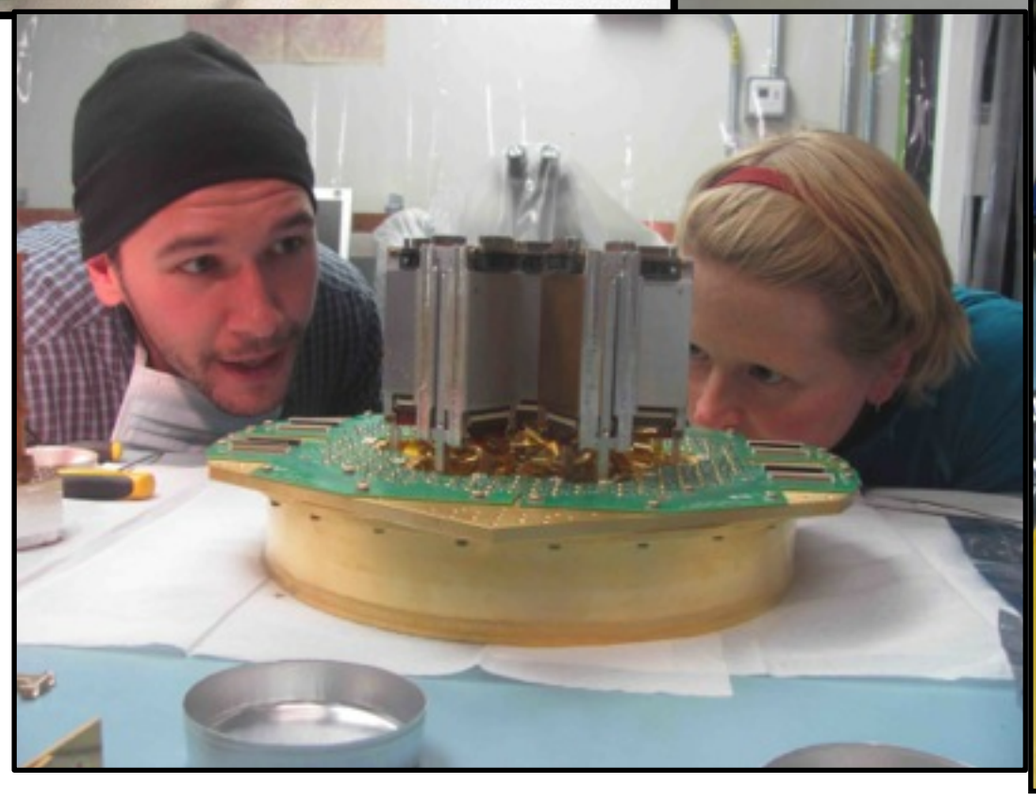


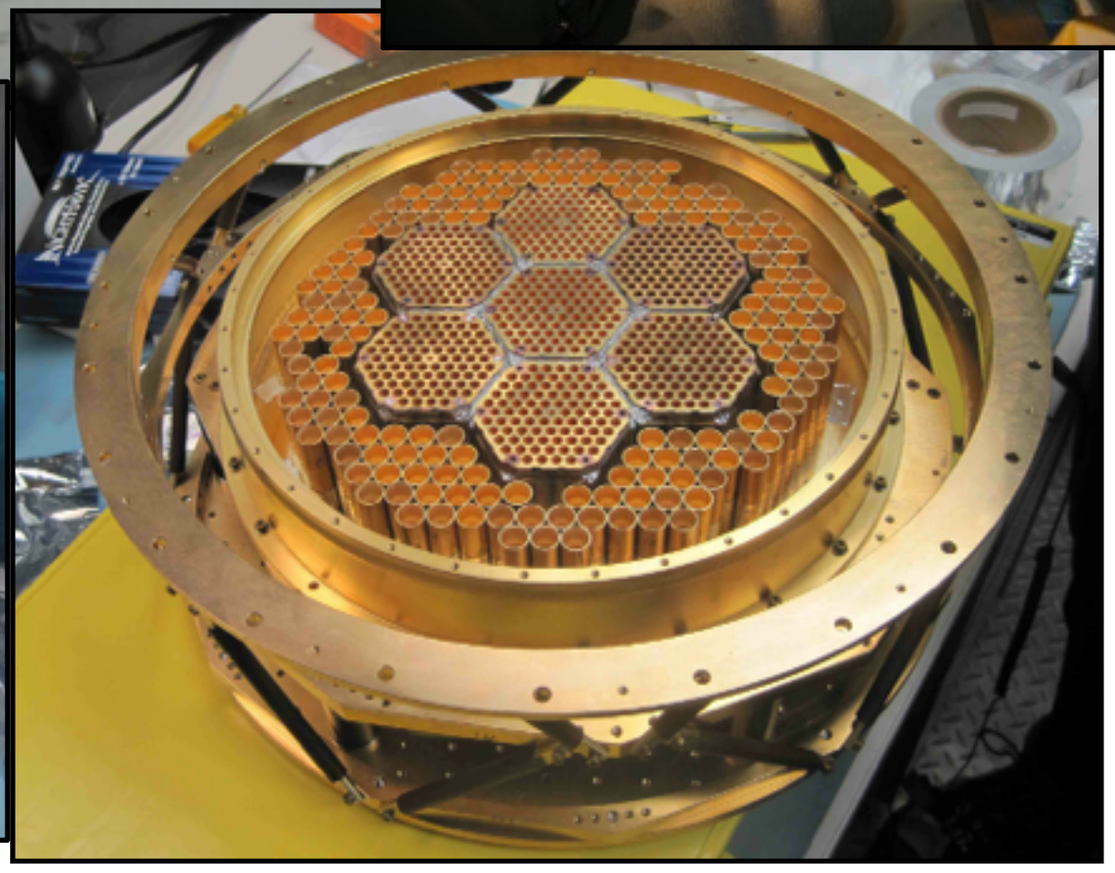
Corrugated feed horns

- Excellent beam and RF pickup systematics control
- 84 pixel gold-plated, silicon horn array with optimal 1.5 f l spacing
- Stack of 33 silicon wafers (500 mm), deep-etched in shape of horn profile, stacked, and gold-plated
- Thermal contraction naturally matched to Silicon detector array

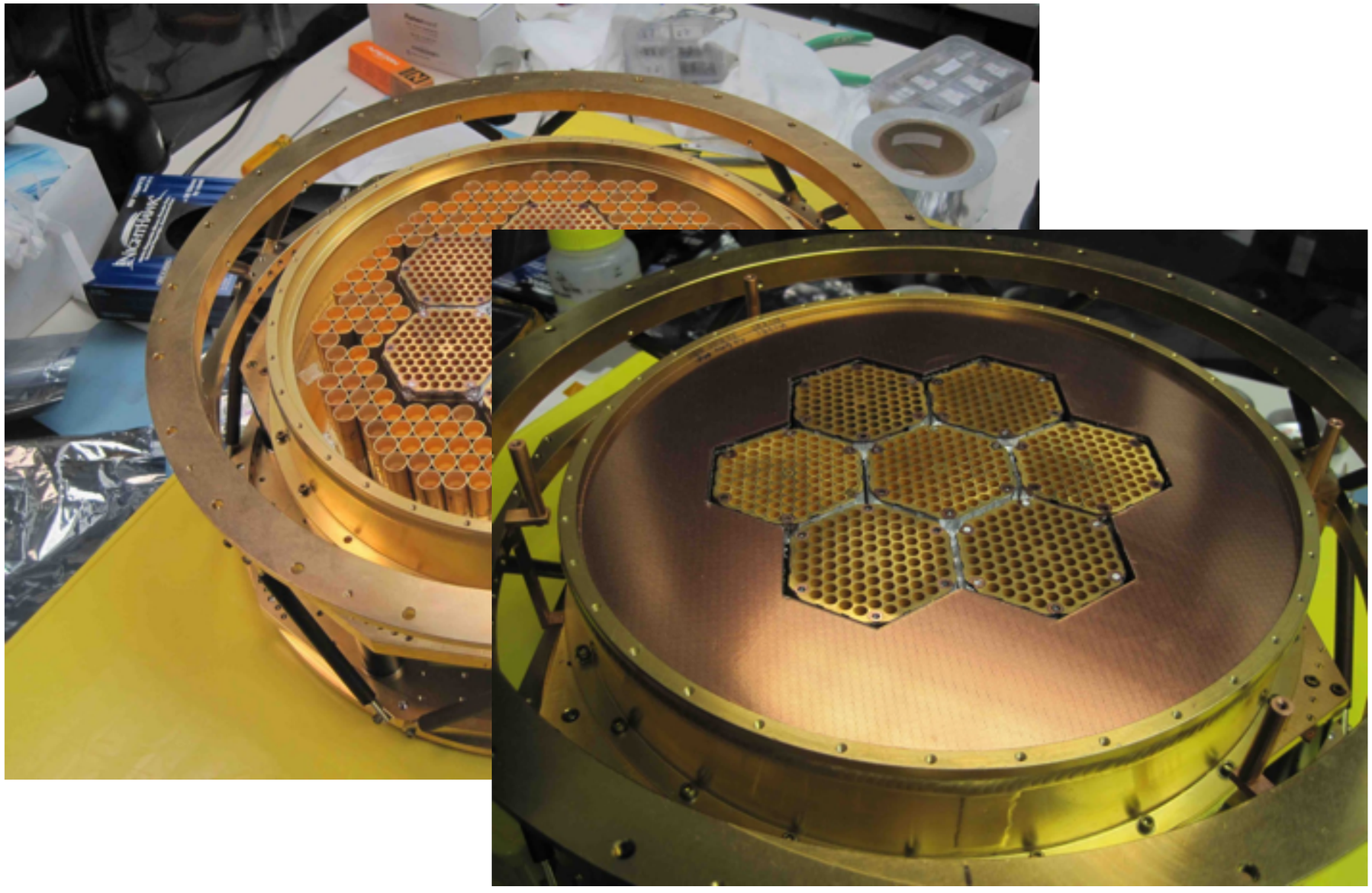
SPTpol Receiver



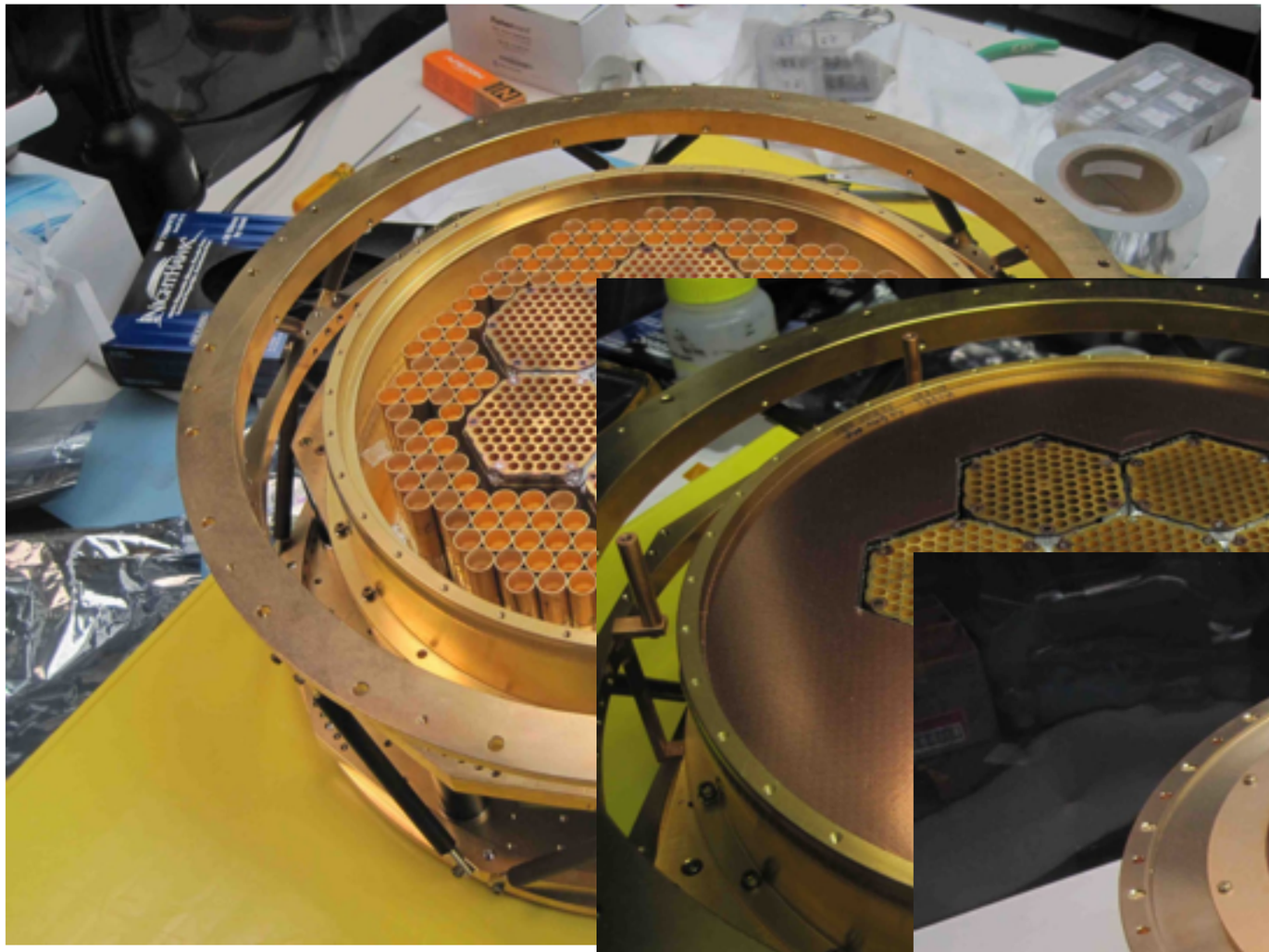


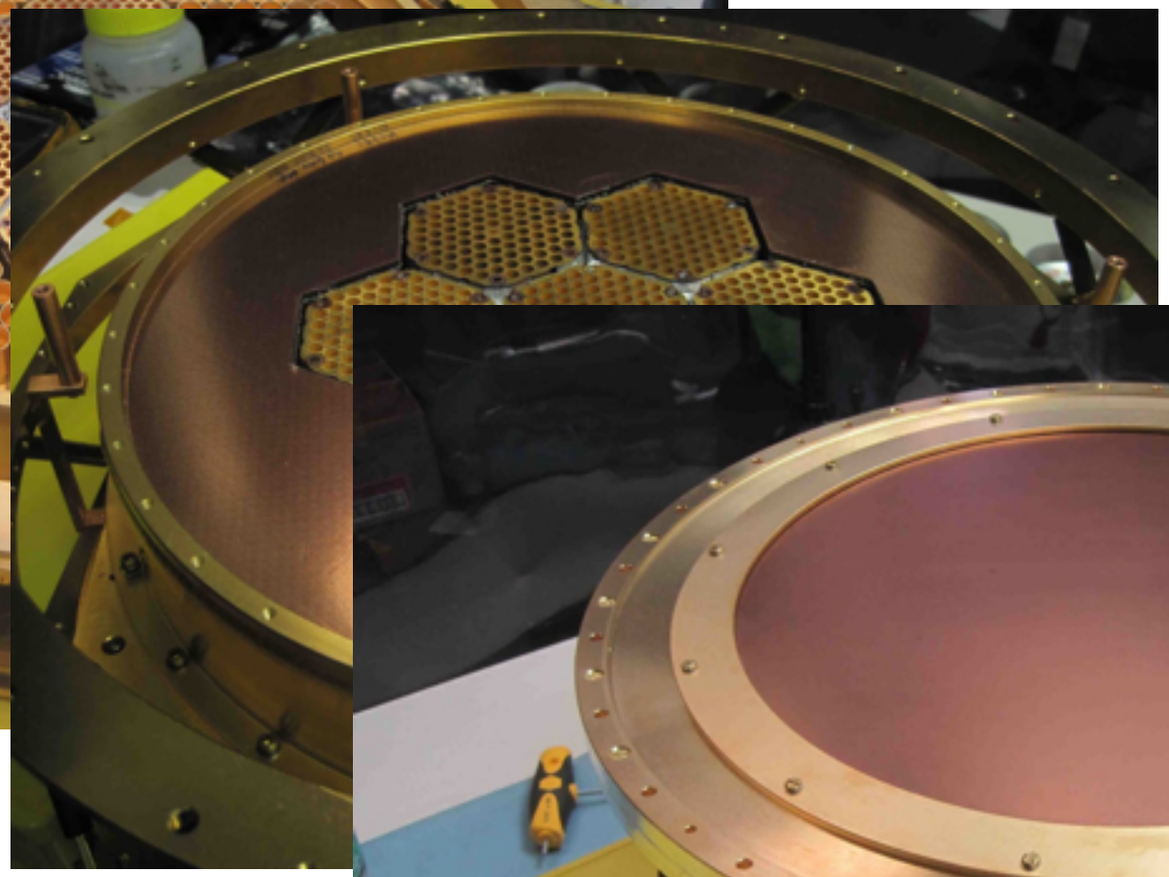


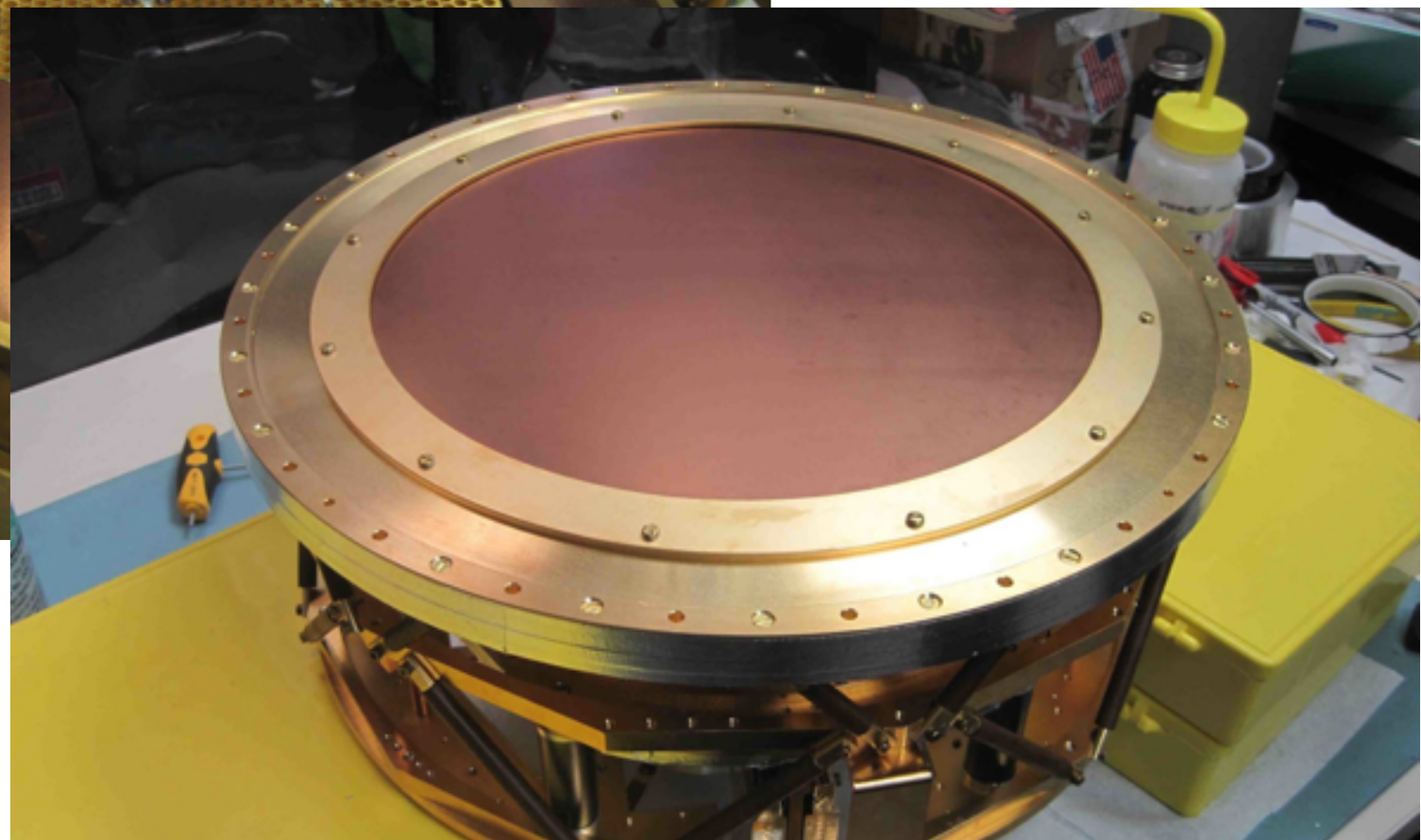
Install on SPT



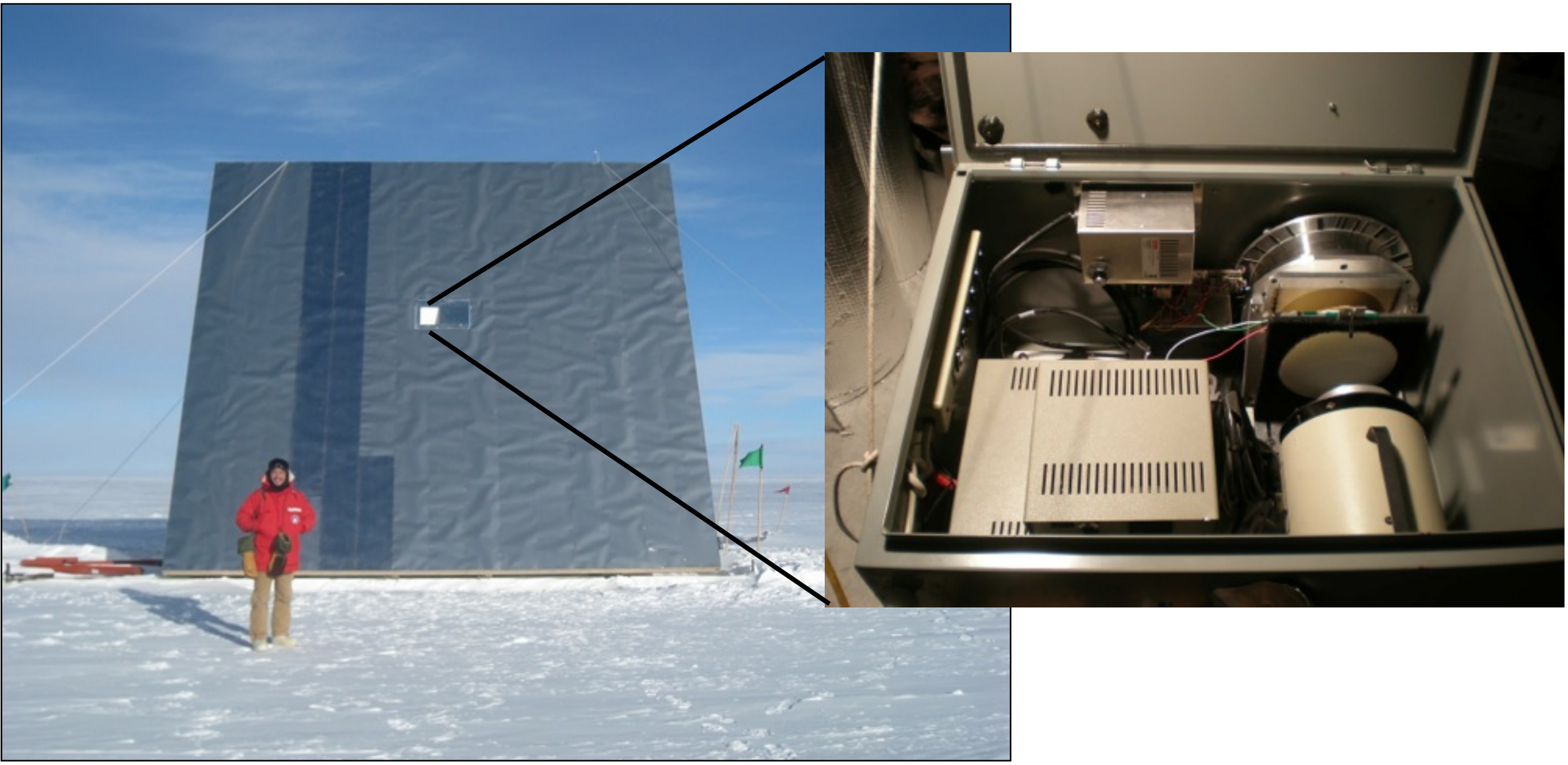
Install on SPT



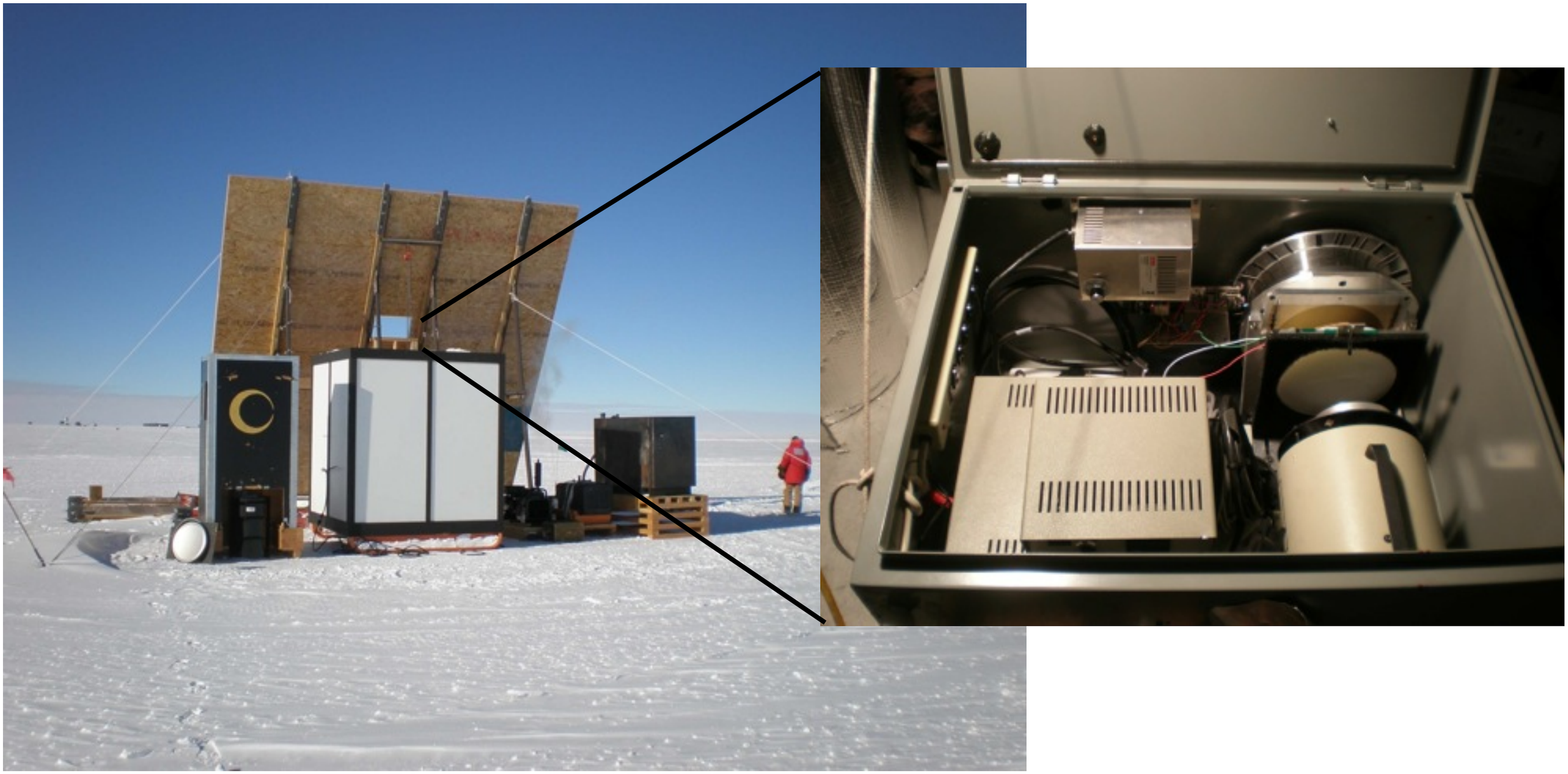




Angle Calibration

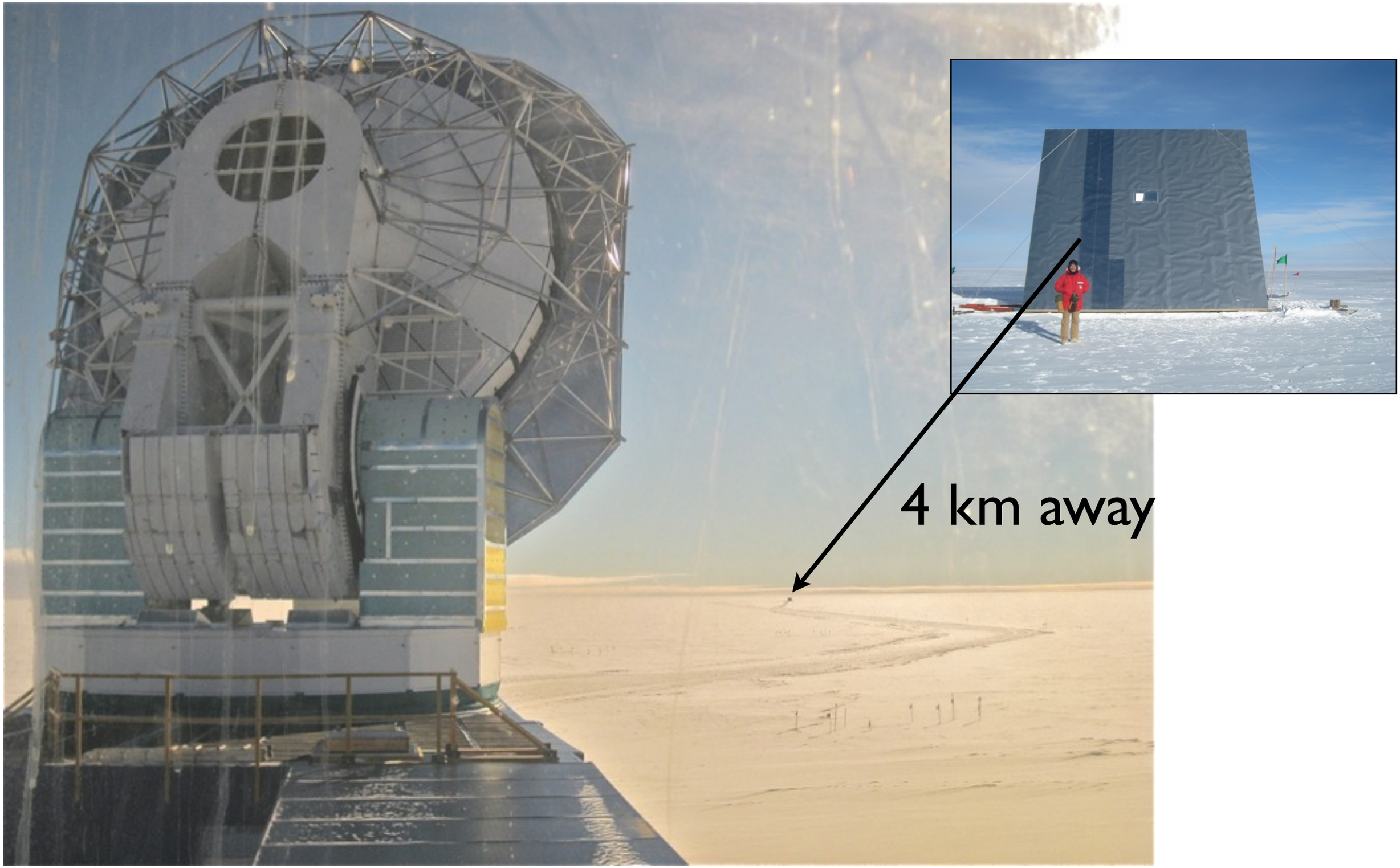


Angle Calibration



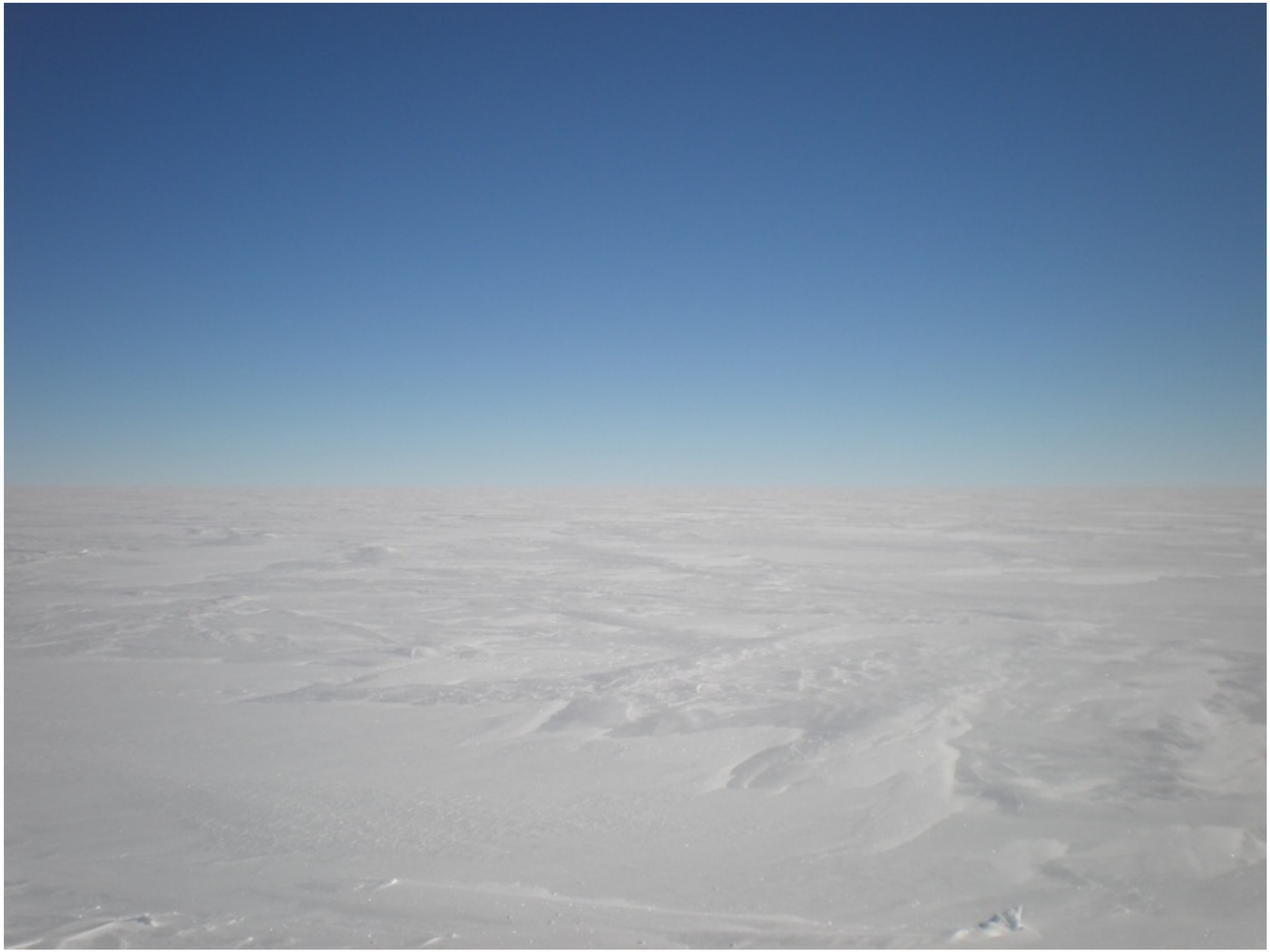
The commute out

Angle calibration



View of SPT from the source

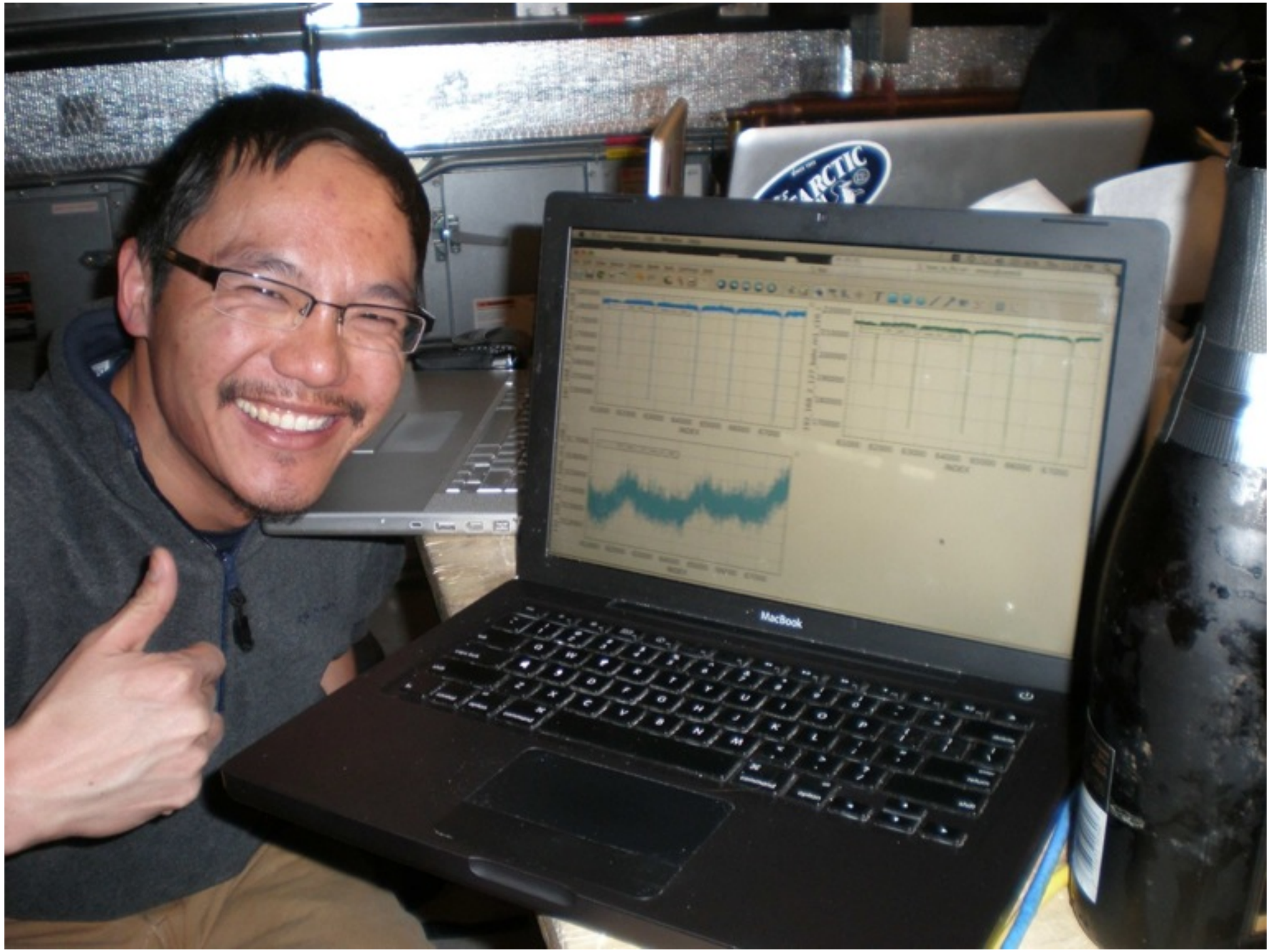
Looking “North” away from SPT



Looking at yourself

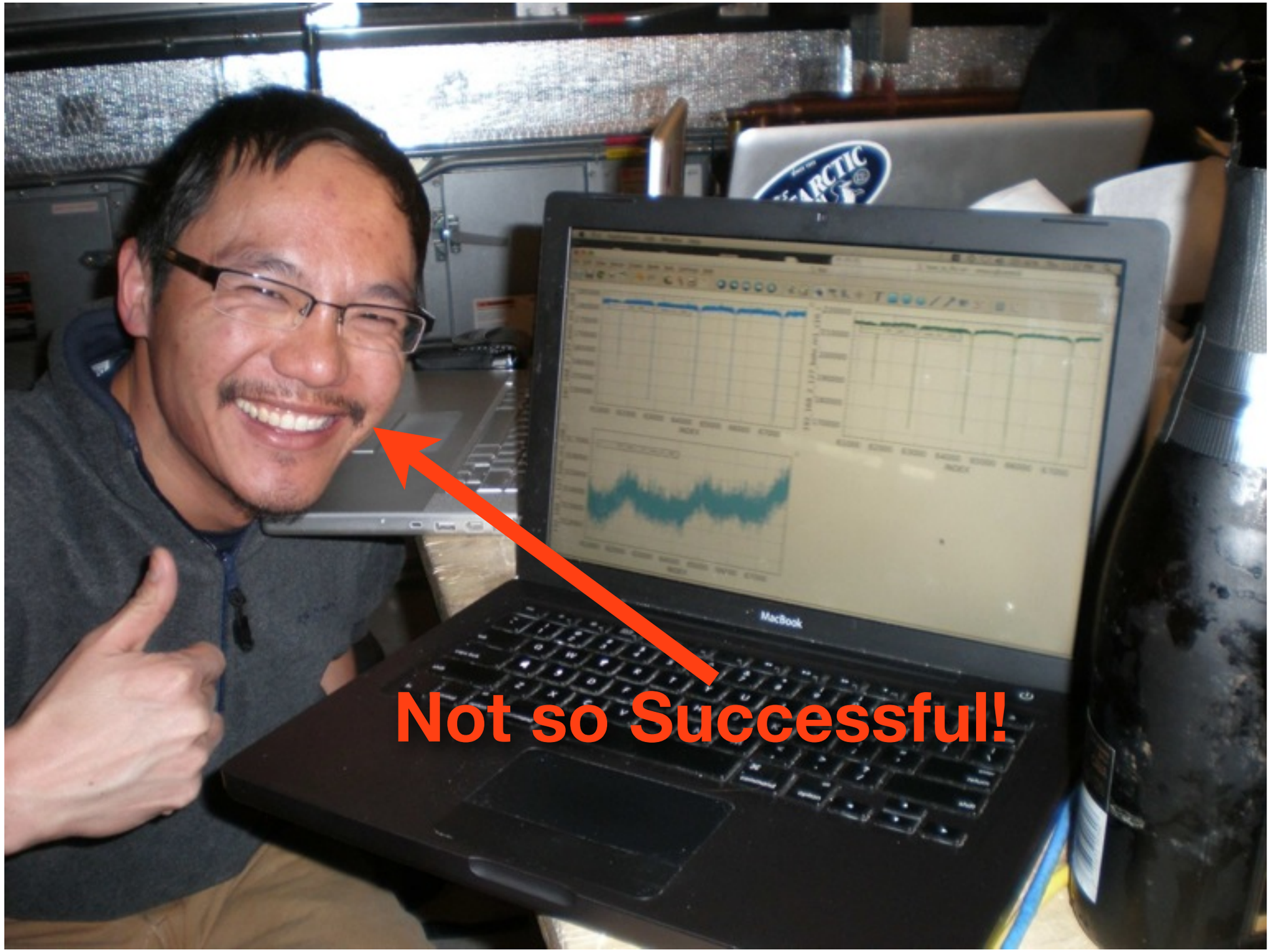
SPTpol 1st light January 2012

First light!



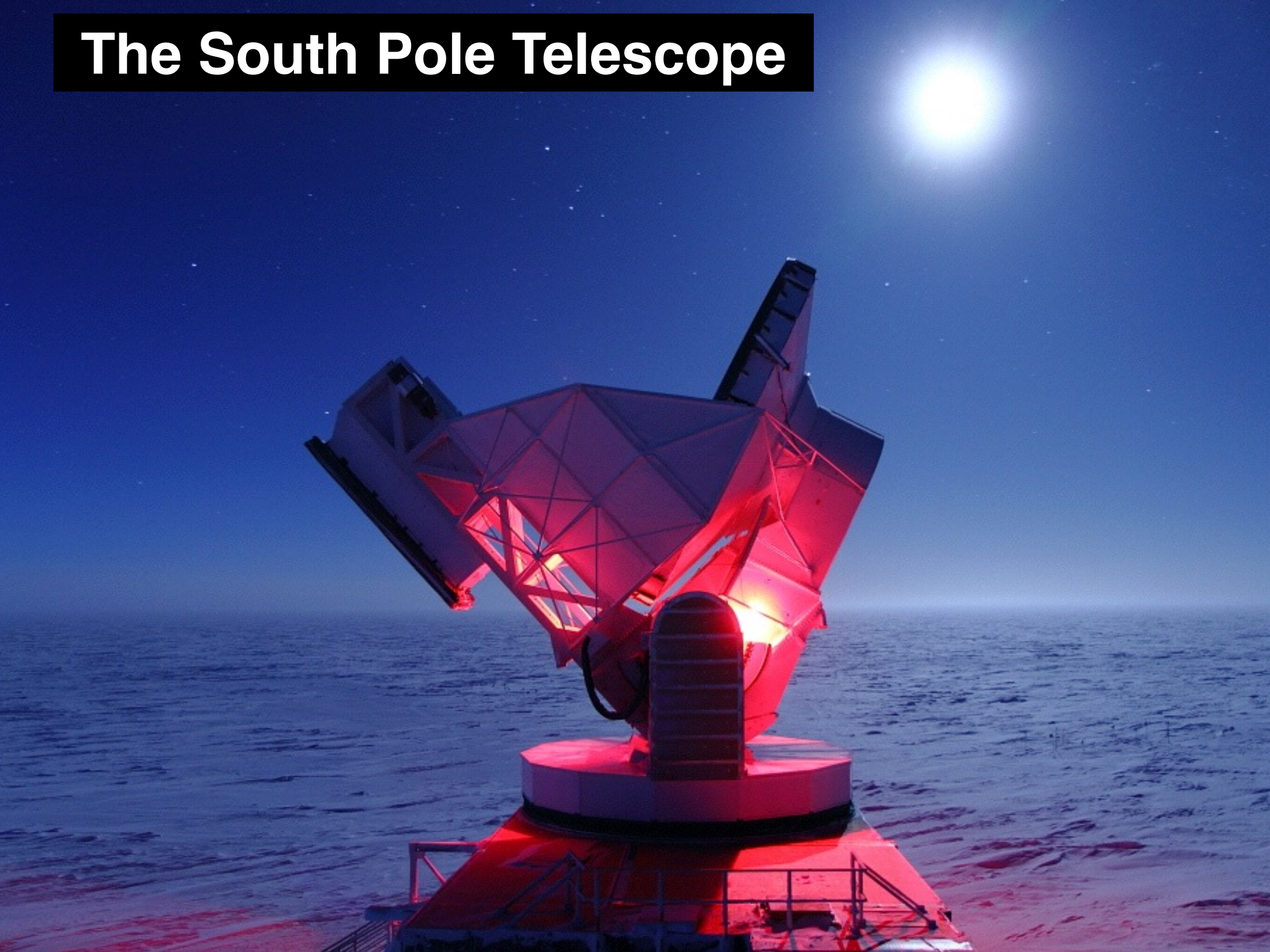
First light!

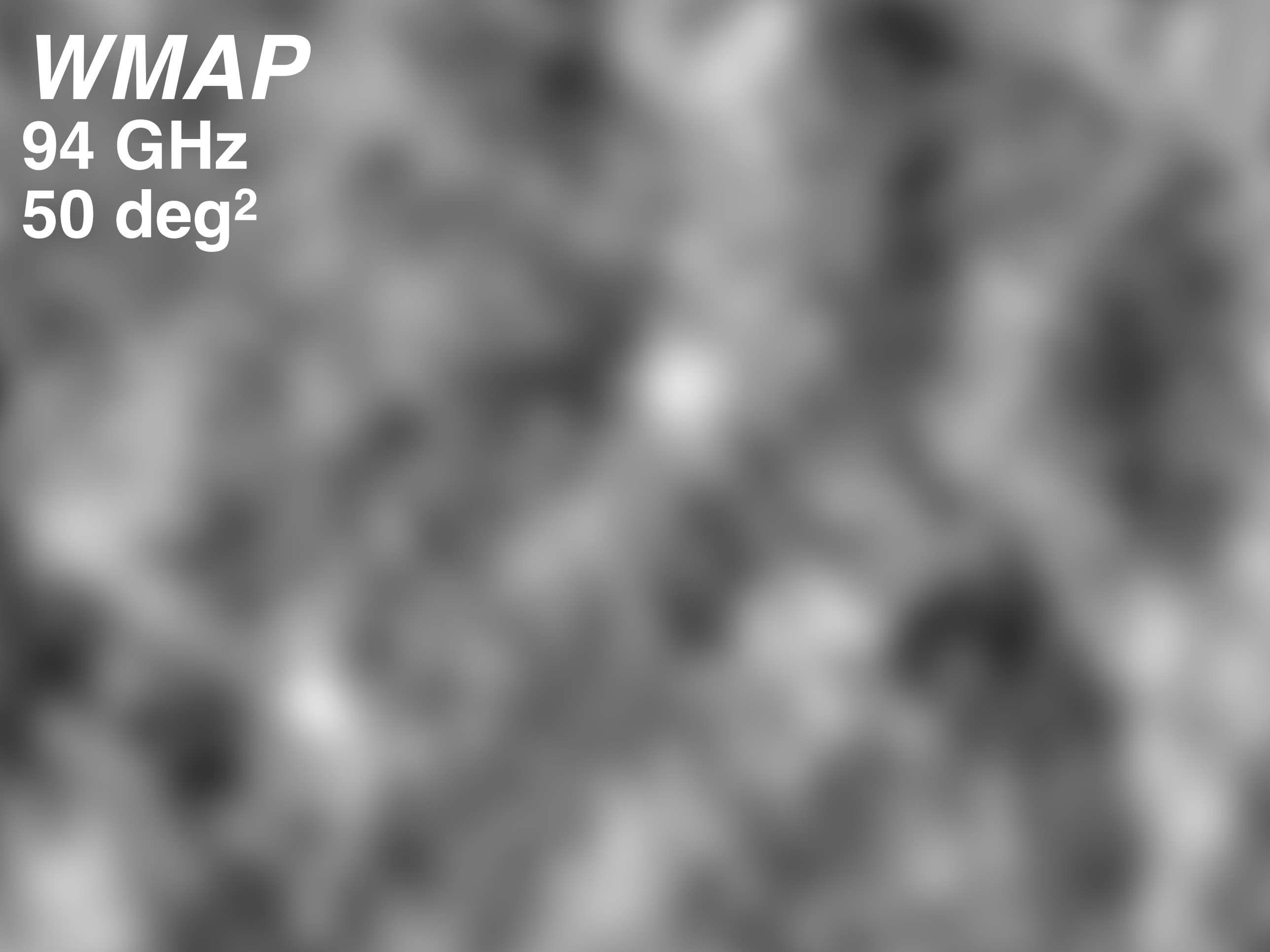
First light!

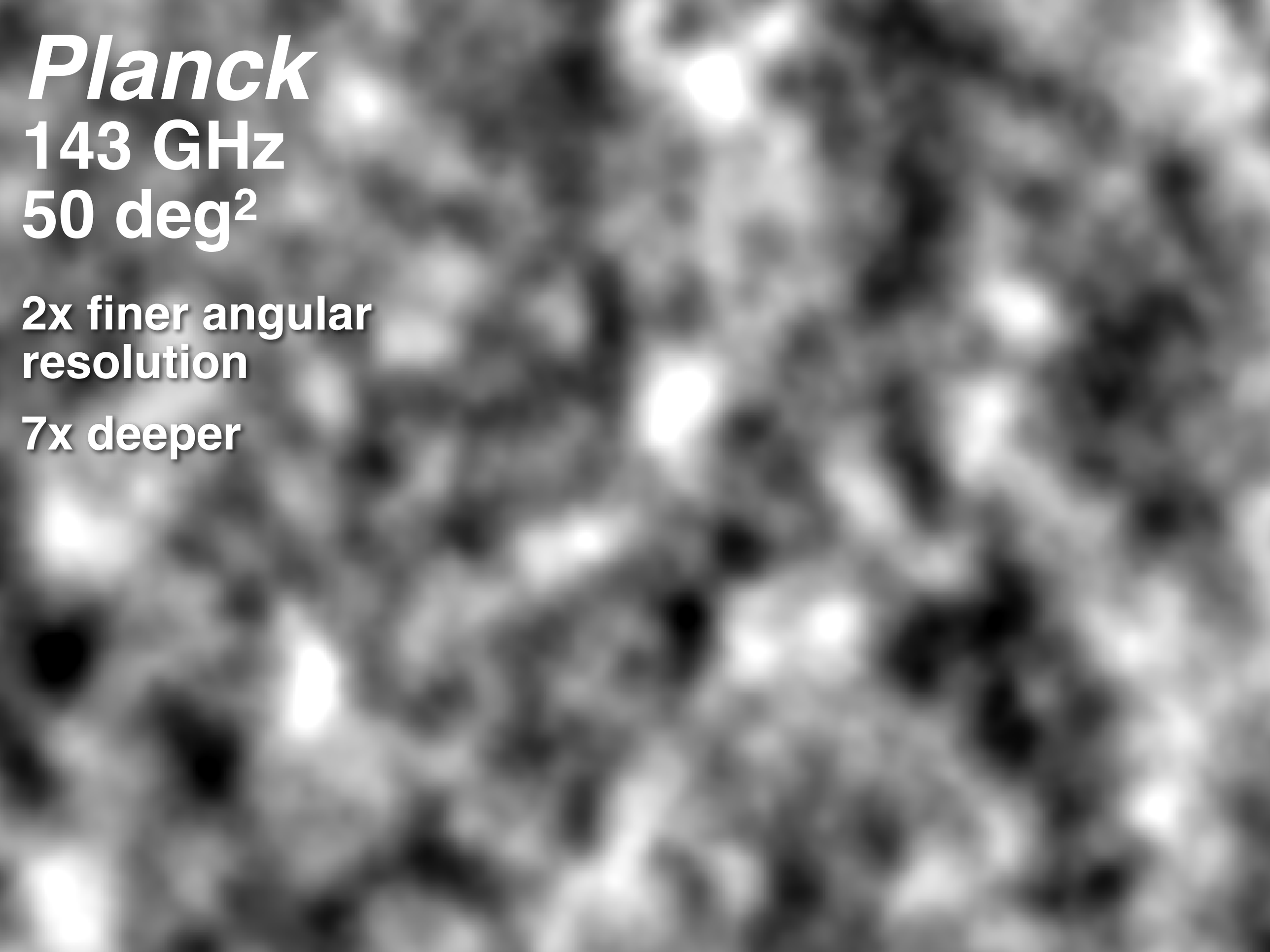


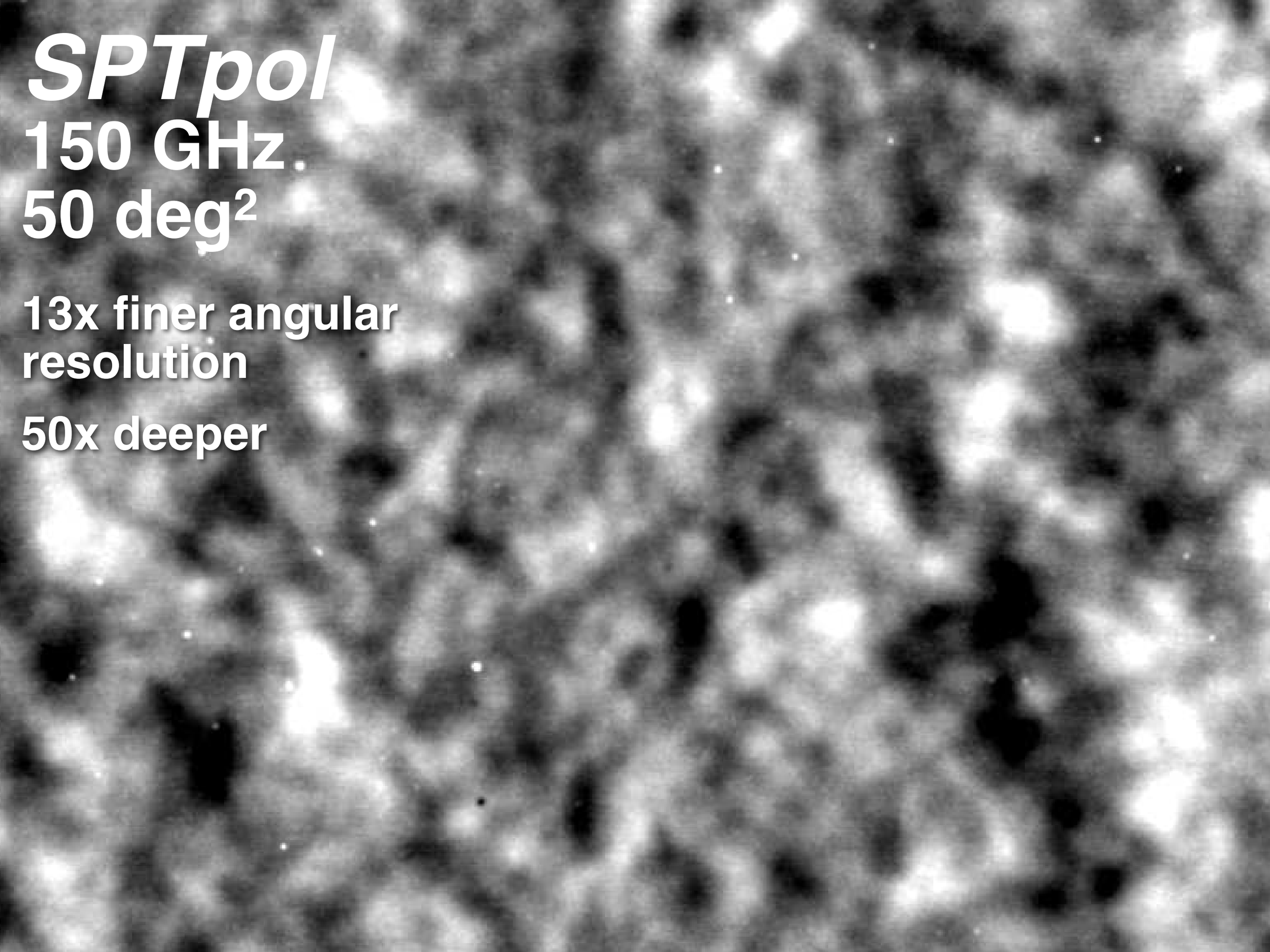
J. Dana Hrubes

The South Pole Telescope




WMAP
94 GHz
50 deg²


Planck
143 GHz
50 deg²
2x finer angular resolution
7x deeper


SPTpol
150 GHz
50 deg²
13x finer angular resolution
50x deeper