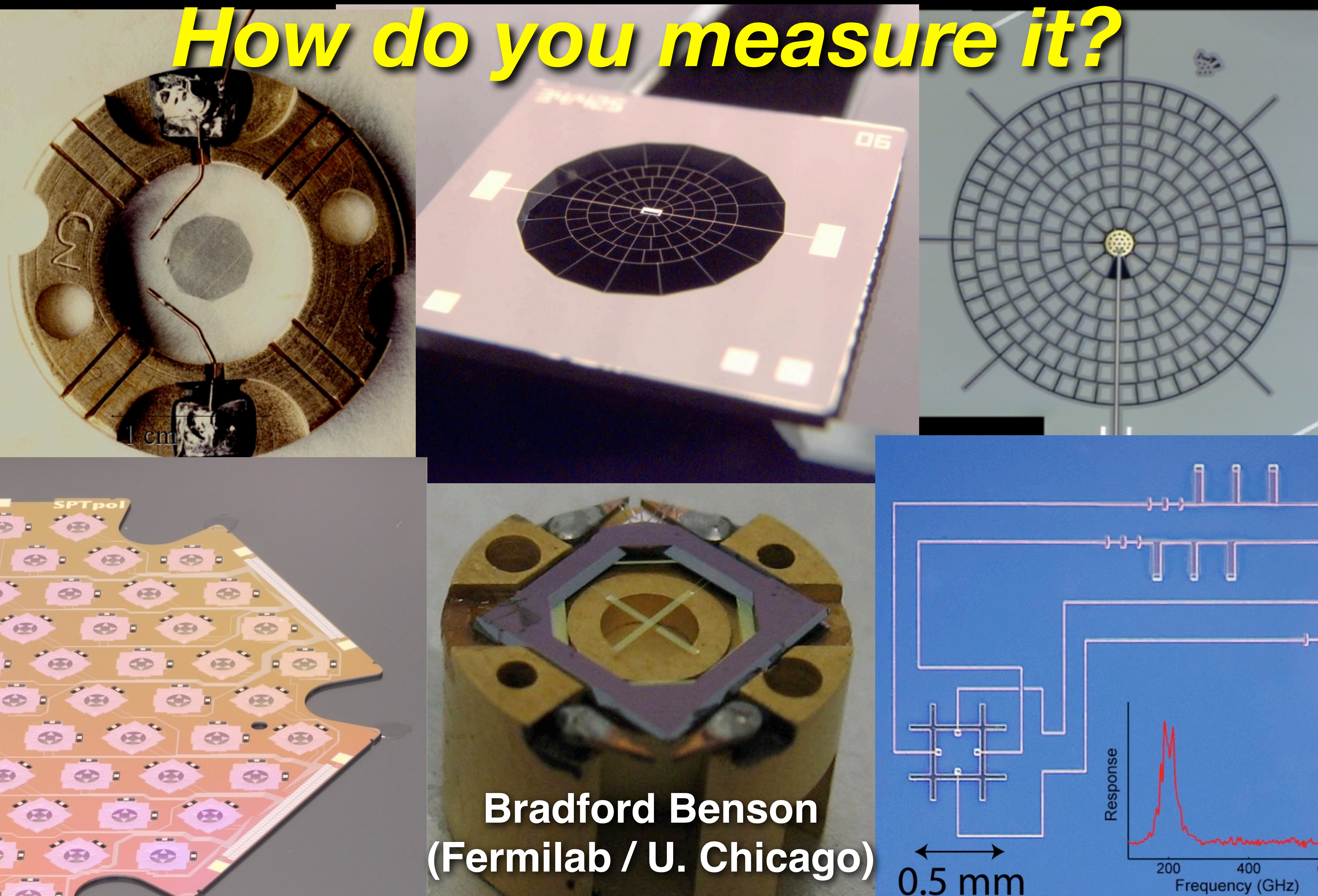
The Cosmic Microwave Background:

How do you measure it?

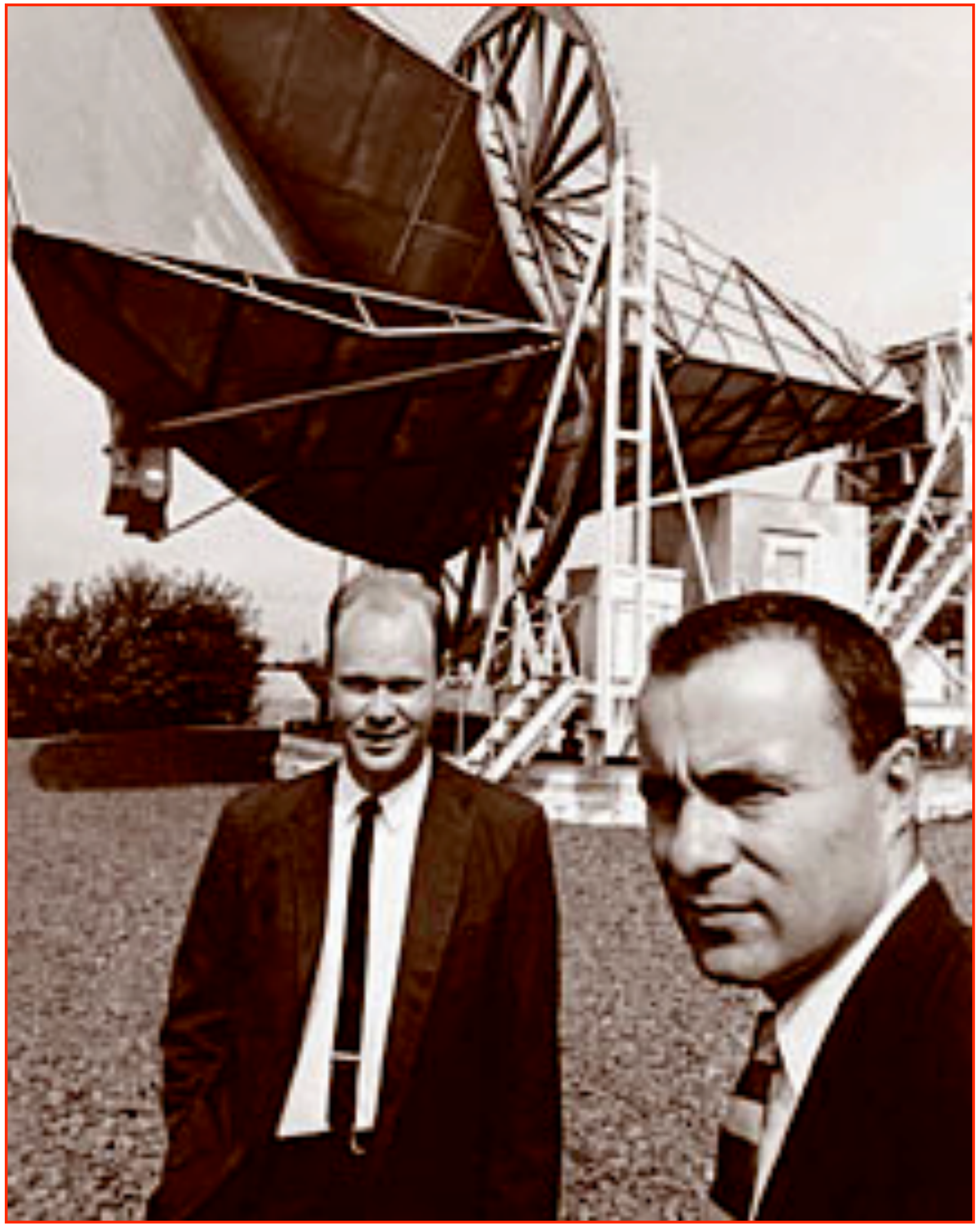


Bradford Benson
(Fermilab / U. Chicago)

Outline

1. **Science Motivation**
   - Fundamental physics and astrophysics from the CMB
2. **Total Intensity Bolometers**
   - From hand-made bolometers to single pixels to arrays
3. **The Polarization-Sensitive Bolometer**
   - From Hand-made bolometers to single pixels to arrays
4. **Future Directions**
   - Multi-chroic pixels, MKIDs, sub-mm and optical arrays

1965: Discovery of the Cosmic Microwave Background (CMB)



Arno Penzias & Robert Wilson in front of the 20 ft Bell Labs antenna used to discover the microwave background in 1965

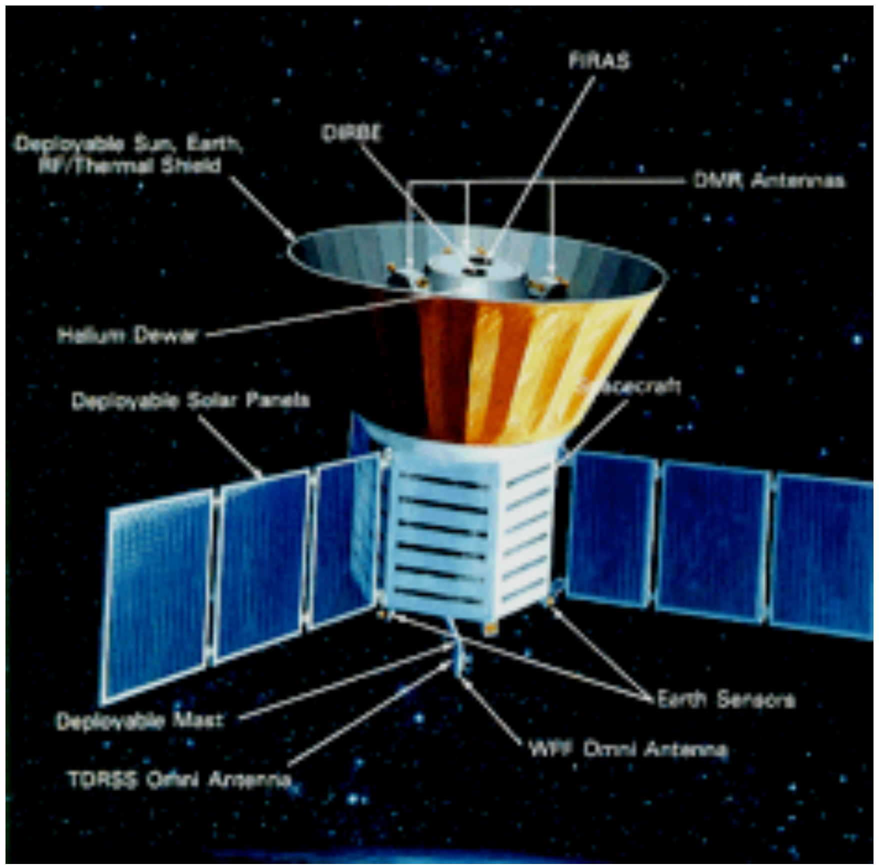
"Smoking Gun" evidence for the Big Bang

Received 1978 Nobel Prize

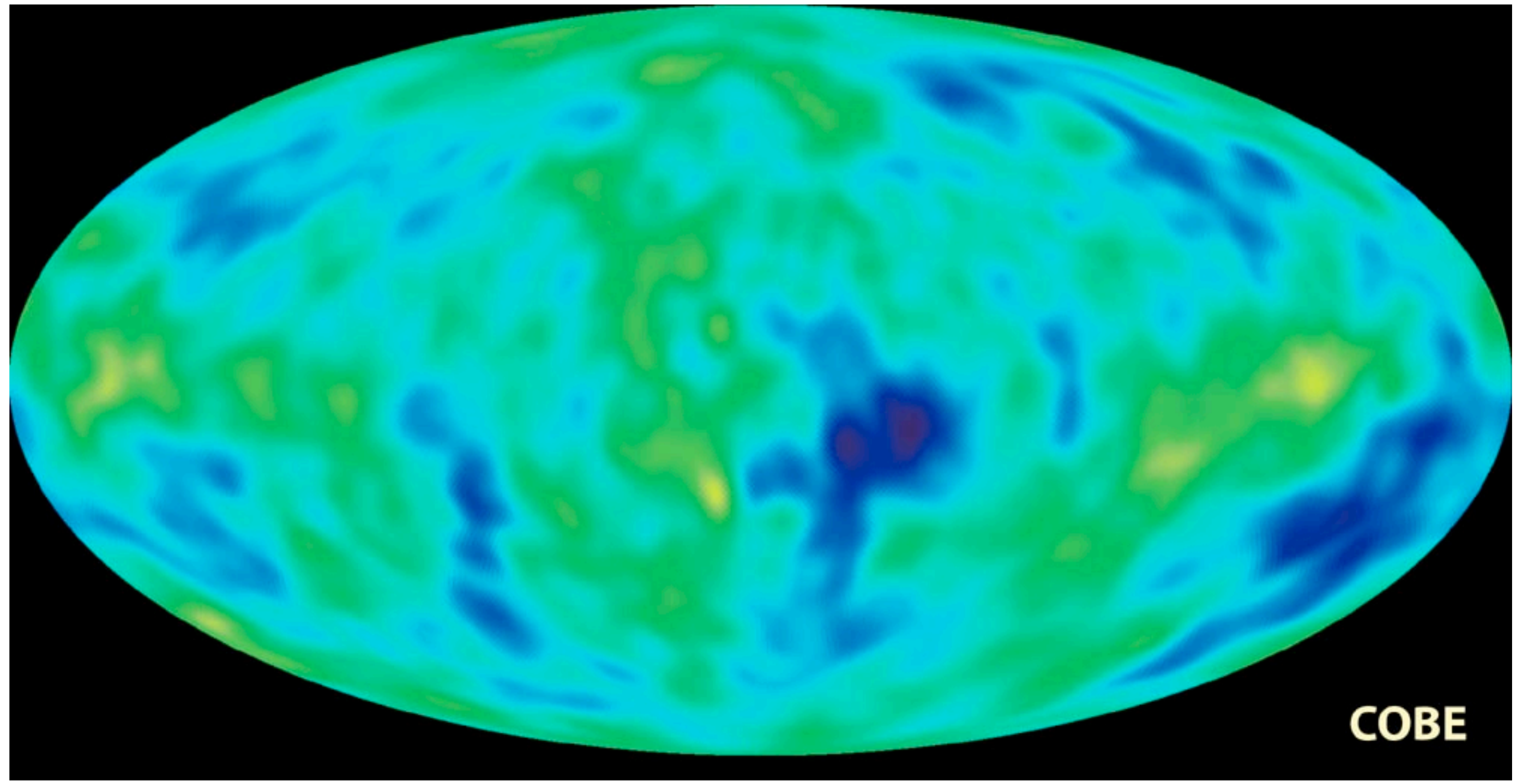
Enormous Impact on Cosmology

1992: Structure in Background Discovered

COBE Satelite
(launched 1987)



Map of the CMB

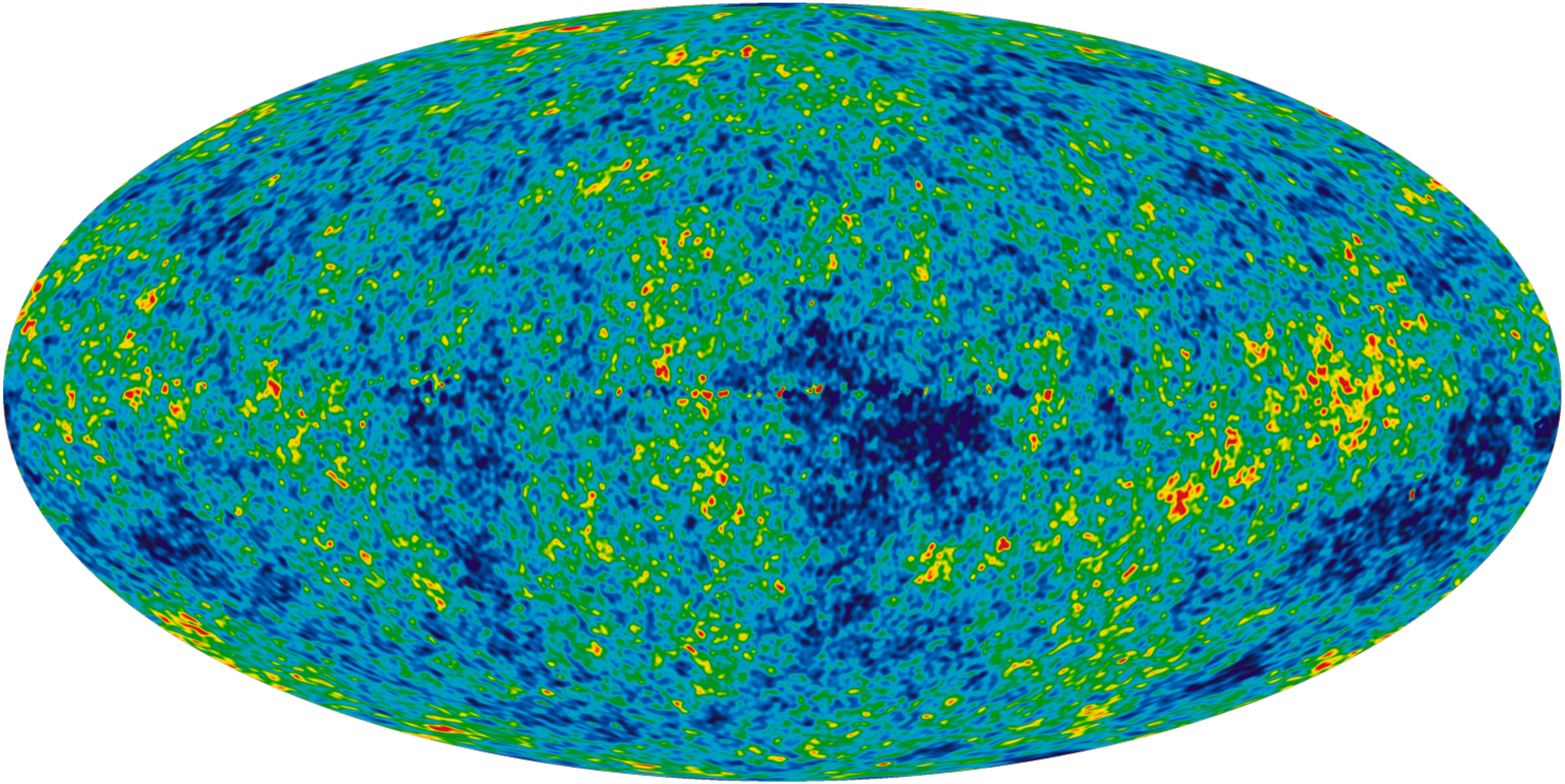


1 part in 100,000 variation
of a ~3 K blackbody

COBE team leaders
John Mather & George Smoot
Received 2006 Nobel Prize

2001-2010: WMAP

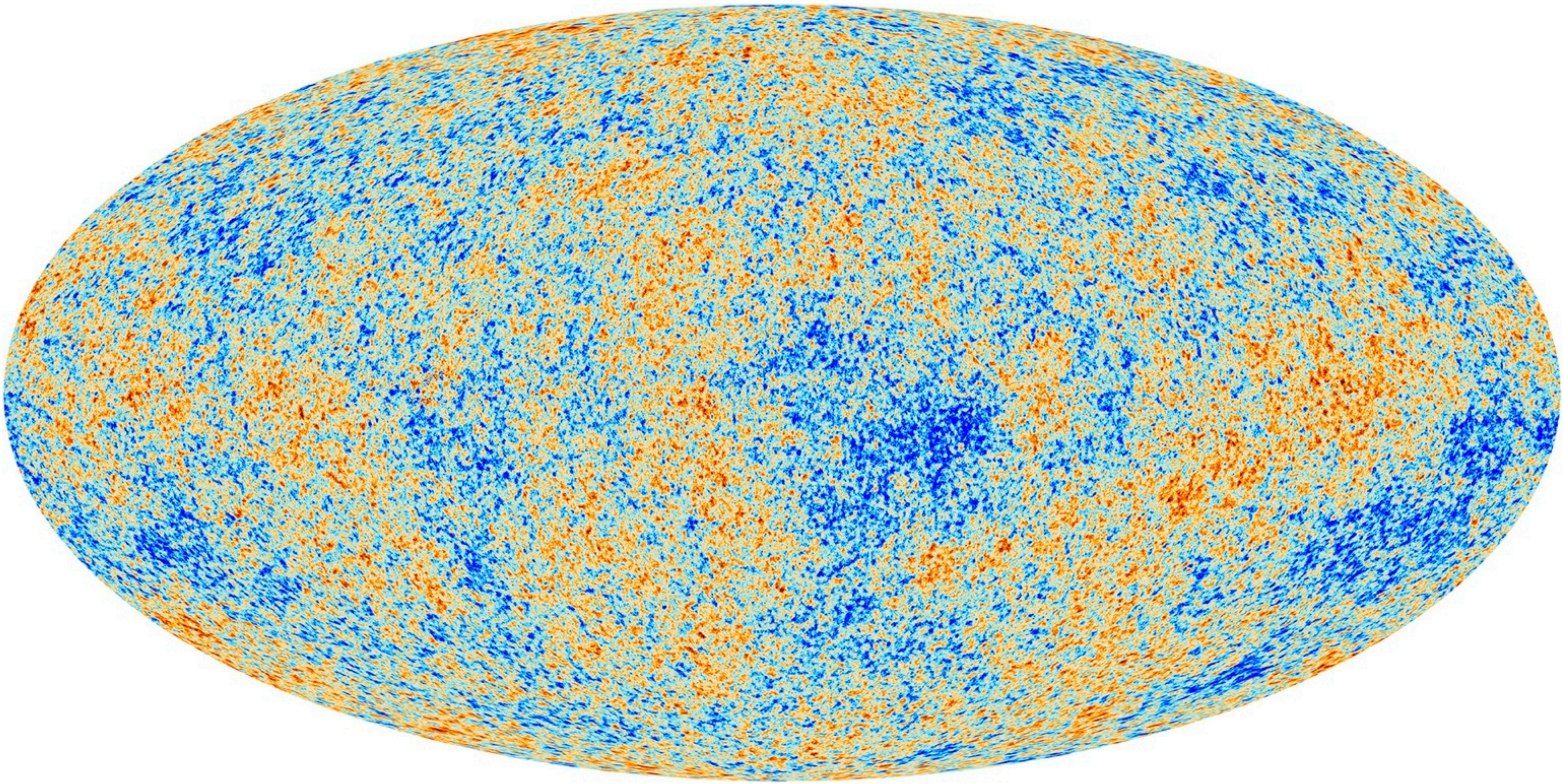
30μK RMS fluctuations on 3 K background



Credit: NASA (WMAP)

2013: Planck

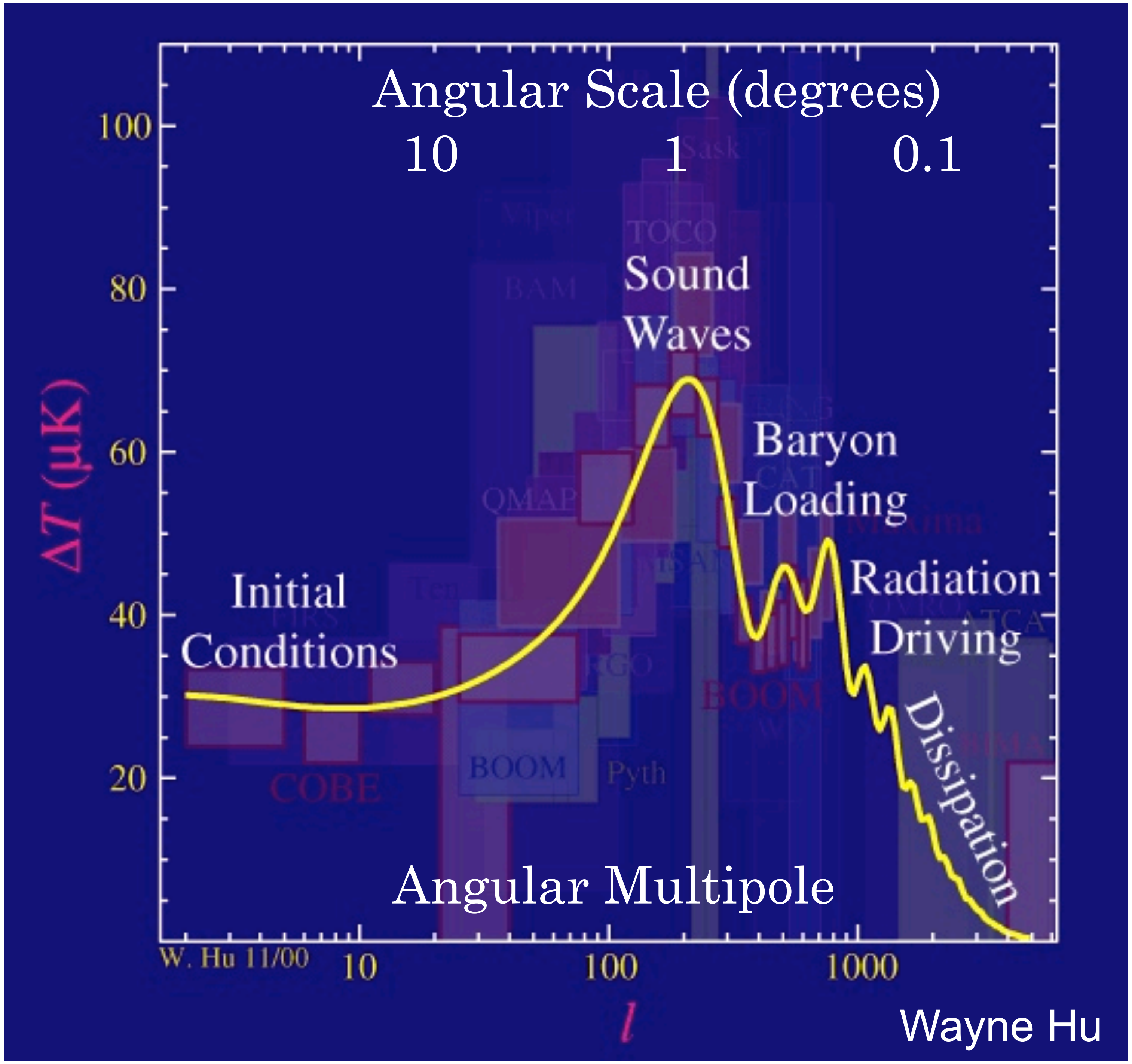
30μK RMS fluctuations on 3 K background

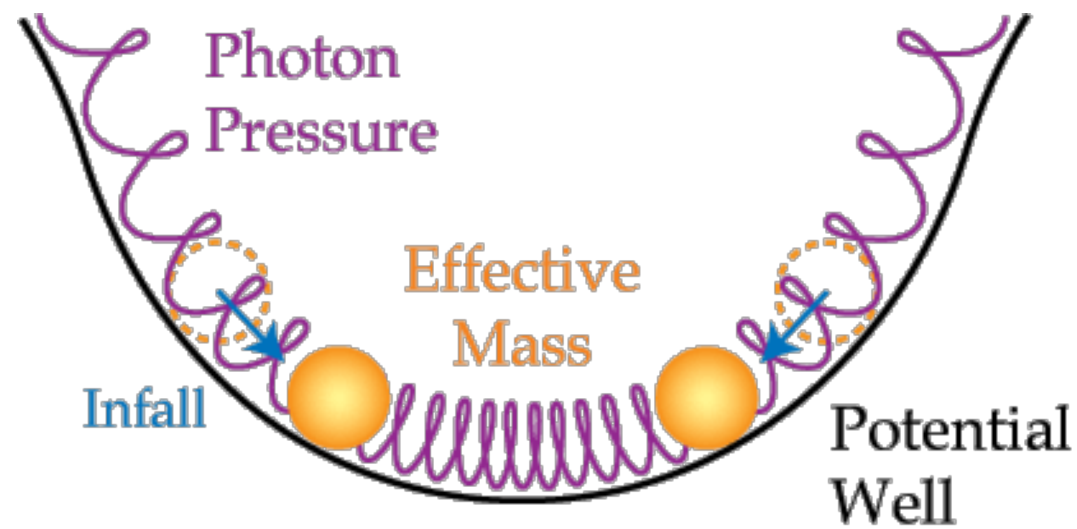


Credit: ESA (Planck)

The CMB Power Spectrum

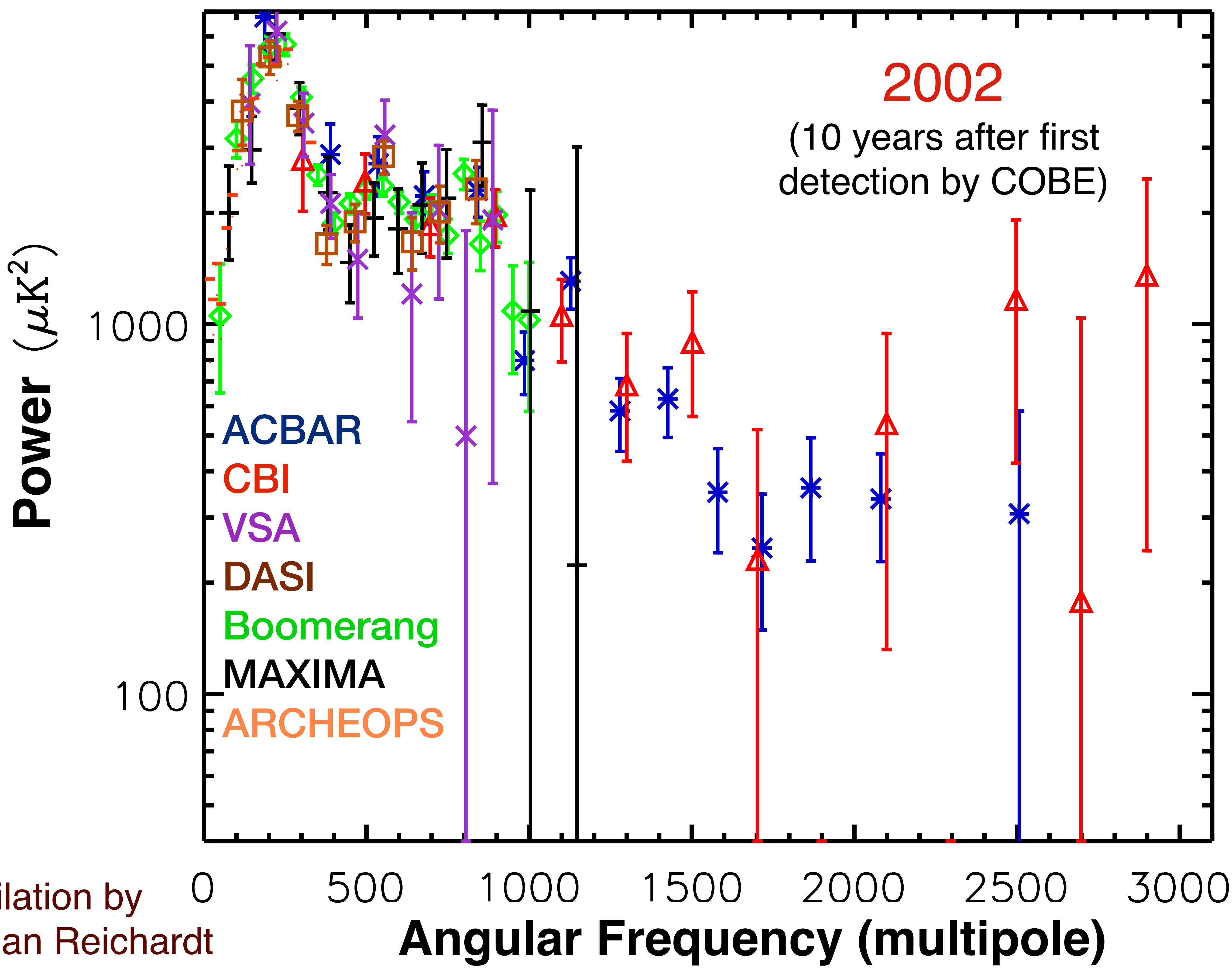
Encoded within the primordial CMB power spectrum is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (baryons, dark matter)





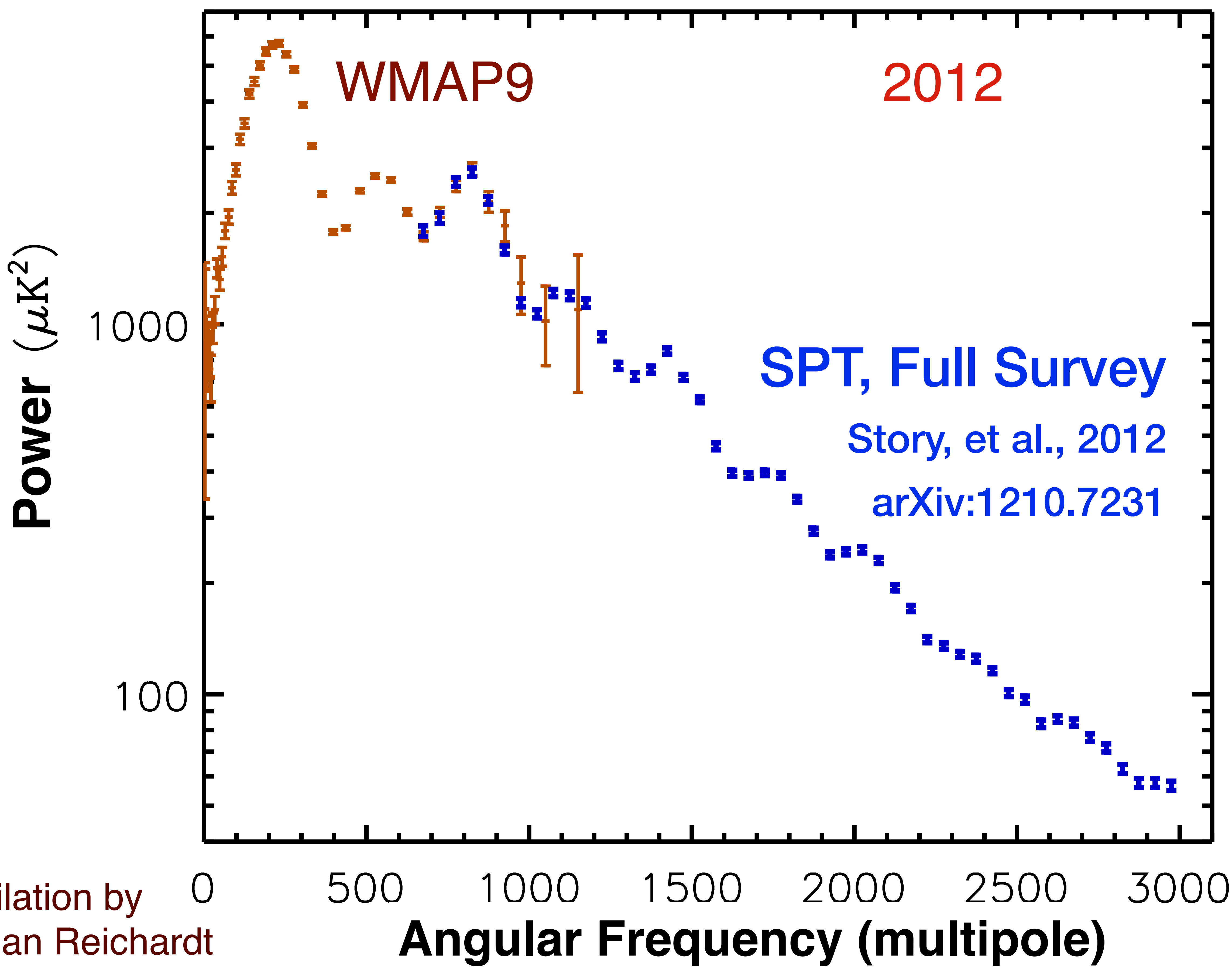
Peaks in power spectrum generated by acoustic oscillations in ~3000 K plasma

Evolution of CMB Power Spectrum Measurements



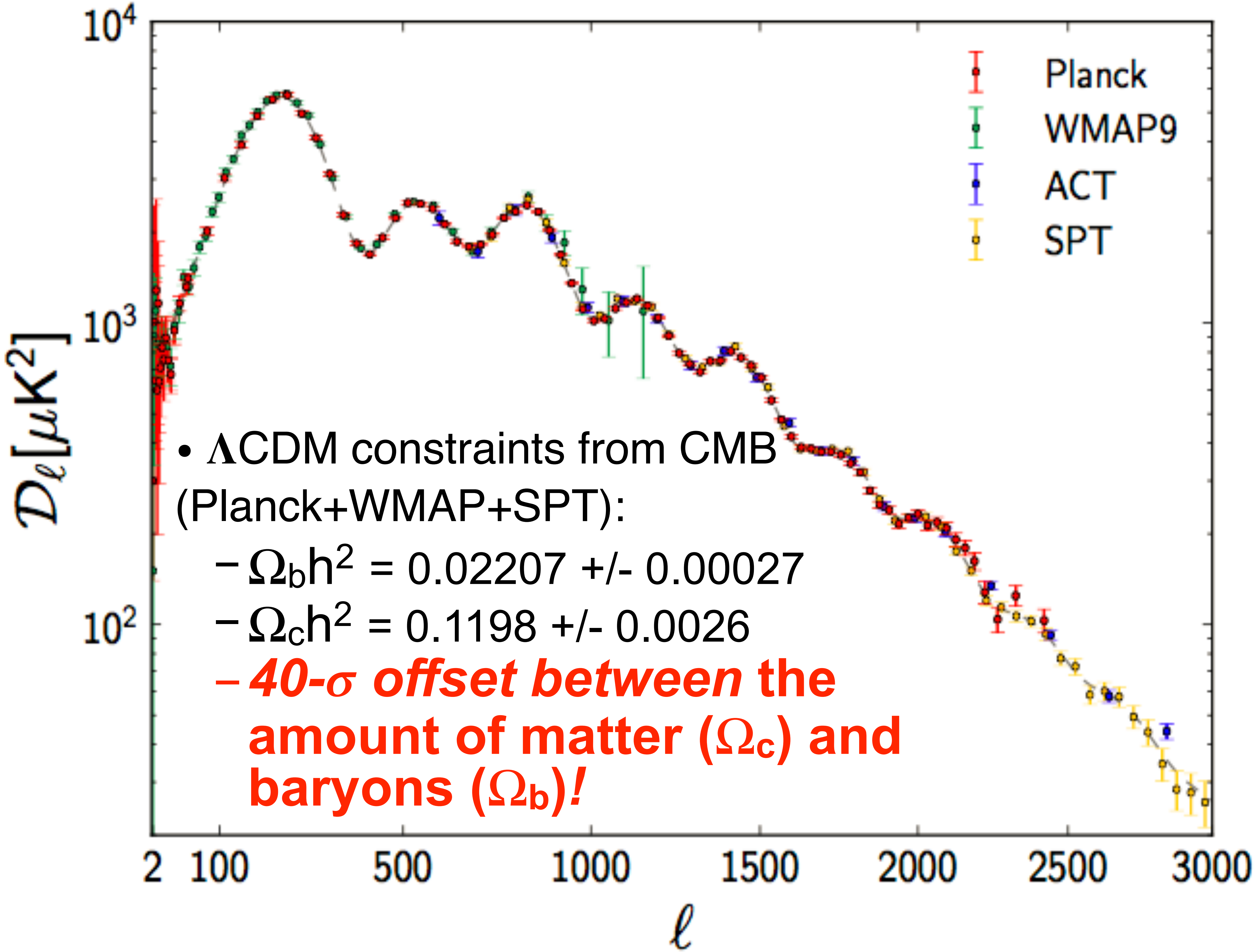
Compilation by Christian Reichardt

Evolution of CMB Power Spectrum Measurements



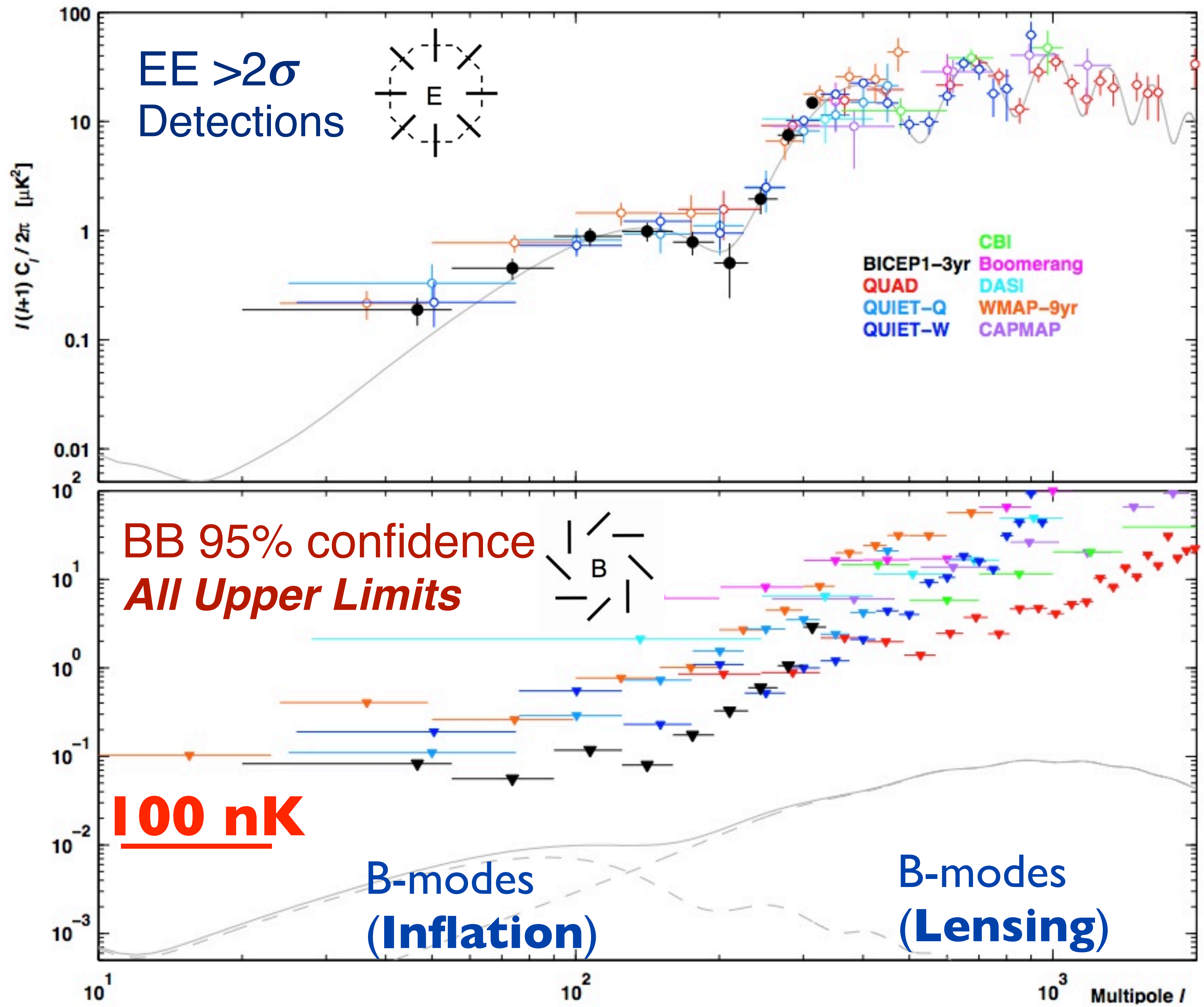
Compilation by
Christian Reichardt

Today: Outstanding agreement between CMB power spectrum measurements



- ΛCDM constraints from CMB (Planck+WMAP+SPT):
  - $\Omega_b h^2$ = 0.02207 +/- 0.00027
  - $\Omega_c h^2$ = 0.1198 +/- 0.0026
  - ***40-σ offset between*** **the amount of matter (Ω_c) and baryons (Ω_b)*!***

Current CMB Polarization Measurements



BICEP (Barkats et al. 2013, arxiv:1310.1422)

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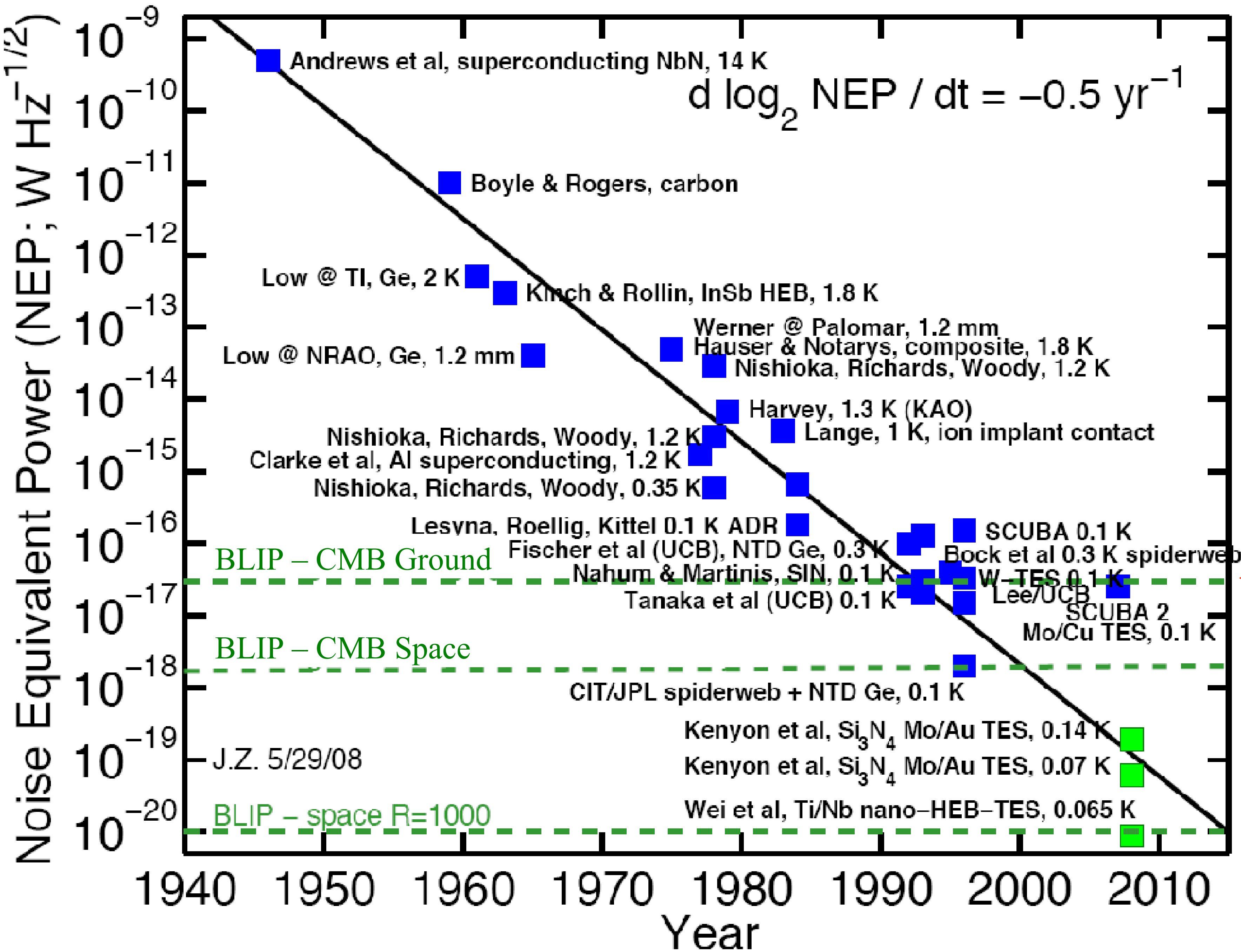
Evolution of Detector Sensitivity

CMB science has been driven by advances in detector technology; ***detector speed has ~doubled every year for 50 years!***



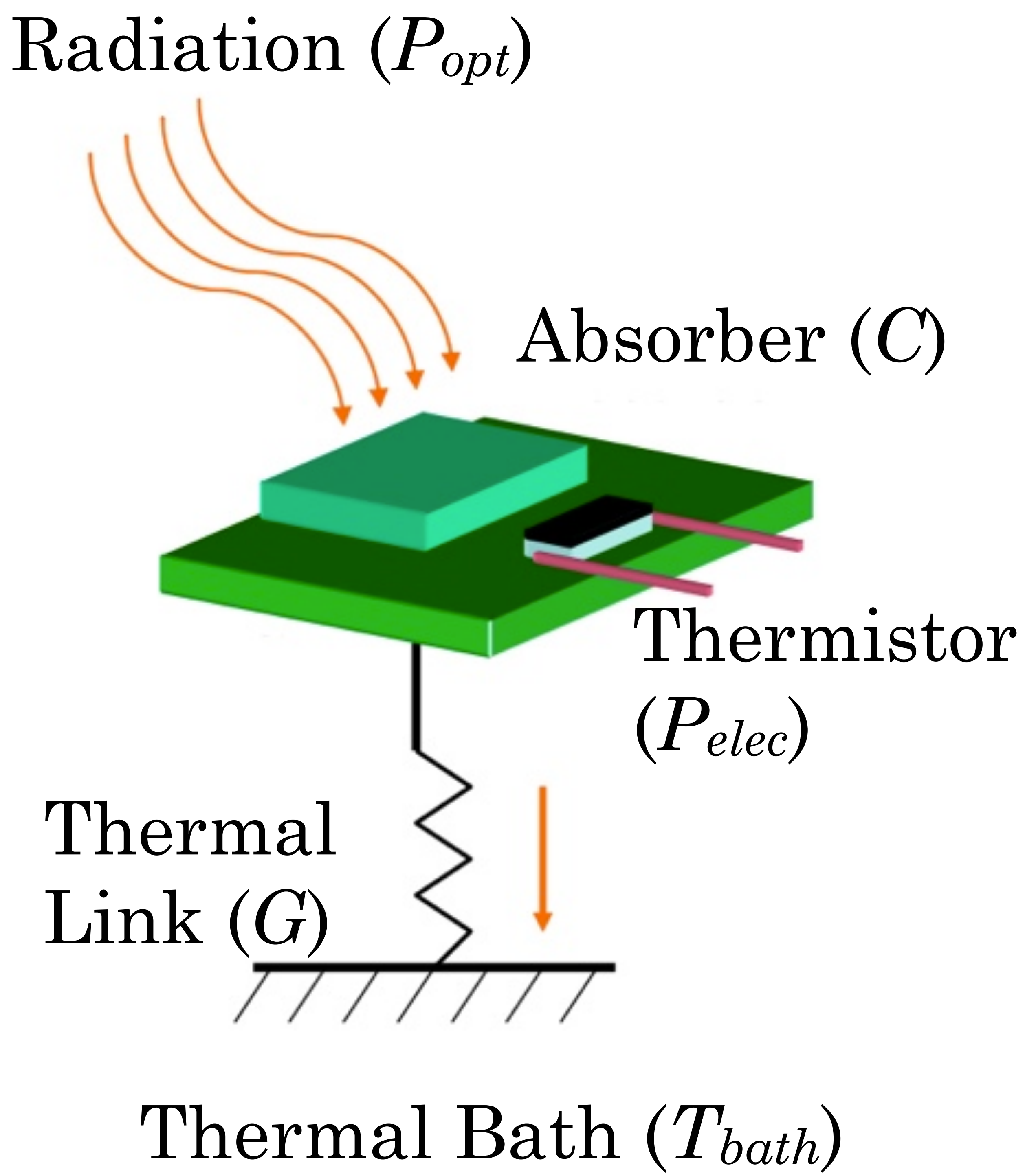
Photon ("shot") noise limit from ground-based observations

NEP ~ 50×10^{-18} W Hz$^{-1/2}$

Plot from J. Zmuidzinas

The Bolometer

A bolometer is the most sensitive ~mm-wavelength detector



Bolometer Design / Noise Properties:

- Optical Power: P_{opt}
- Thermal Conductivity: $G \sim P_{tot}/\mathrm{d}T$
- Thermal Noise:

$$NEP_G^2 \approx 4kT_c^2\overline{G}$$

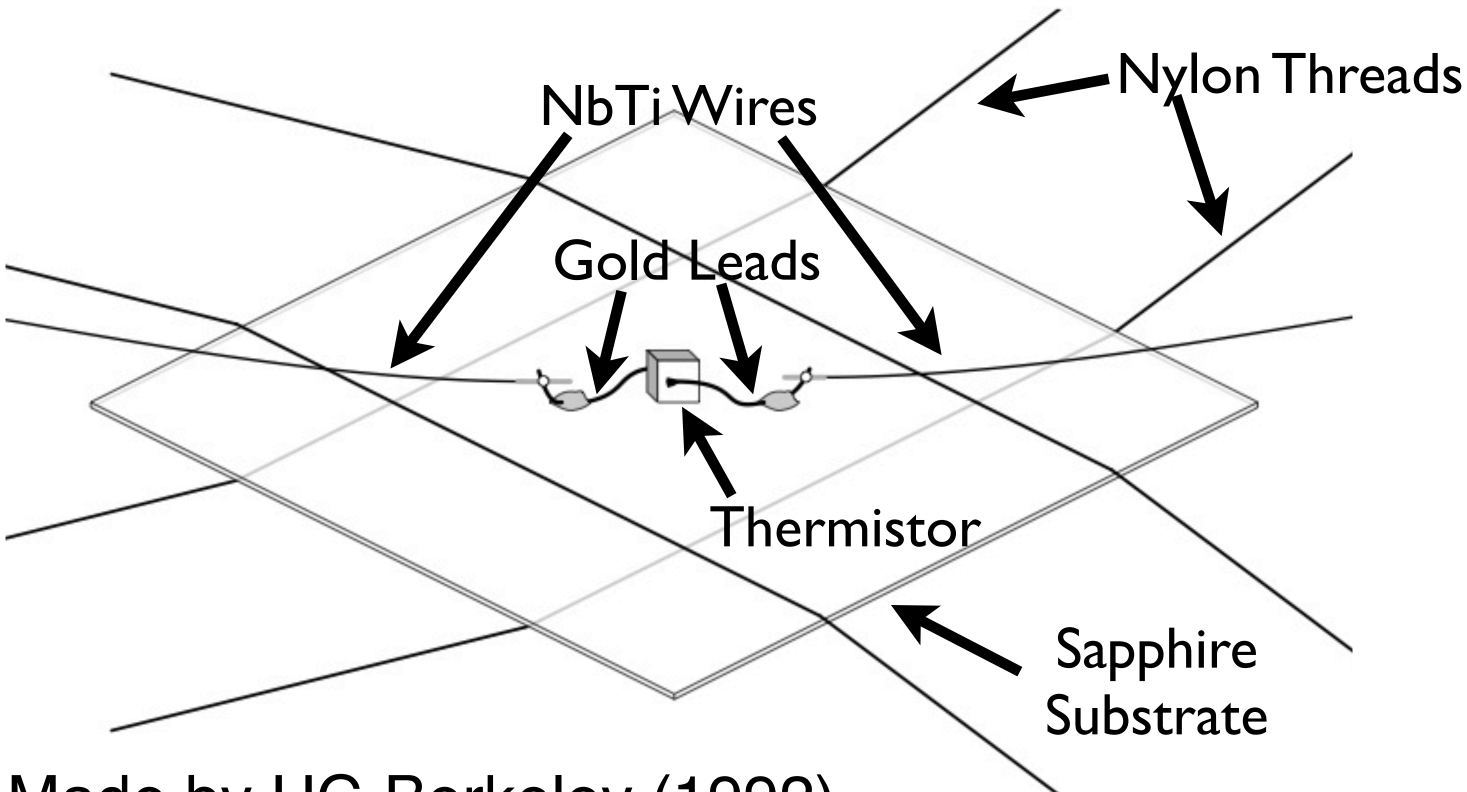
- Photon Noise:

$$NEP_\gamma^2 \approx 2h\nu_0 P_{opt}$$

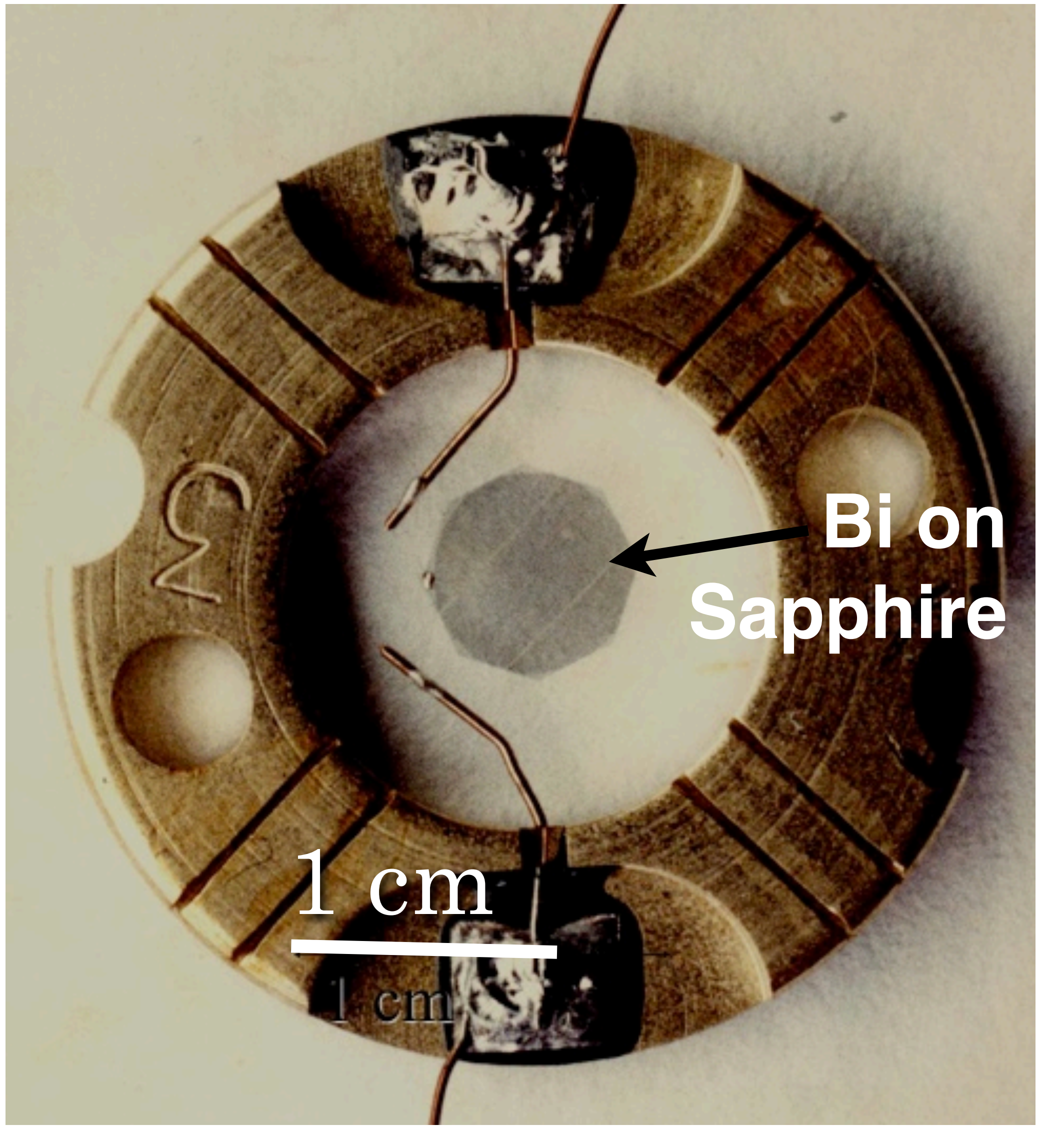
Goal: Design G, Tc such that thermal noise < photon noise.

SuZIE Bolometers (1992-1997)

SuZIE was my thesis project
(***PIs: Sarah Church, Andrew Lange***)



Made by UC-Berkeley (1992)

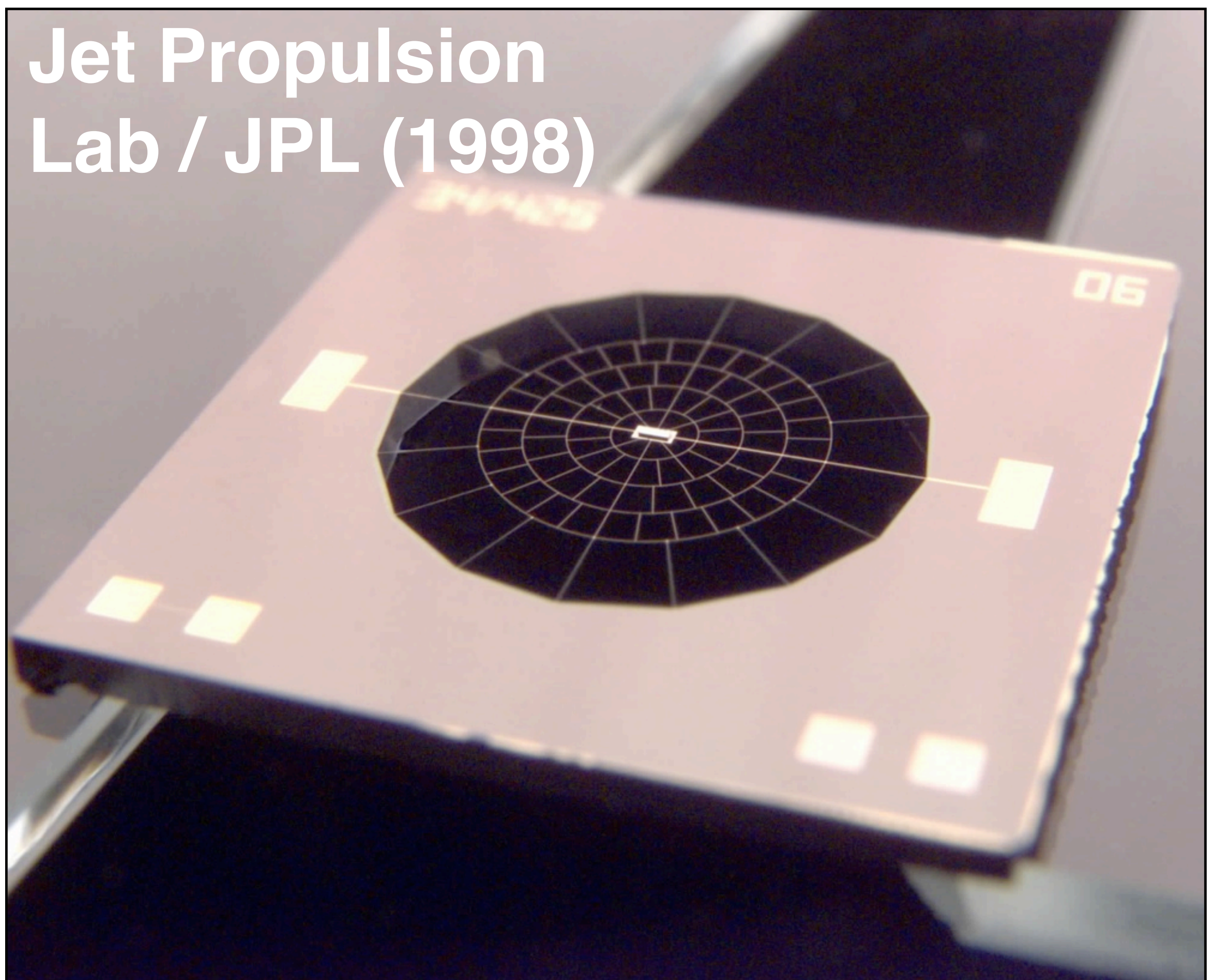


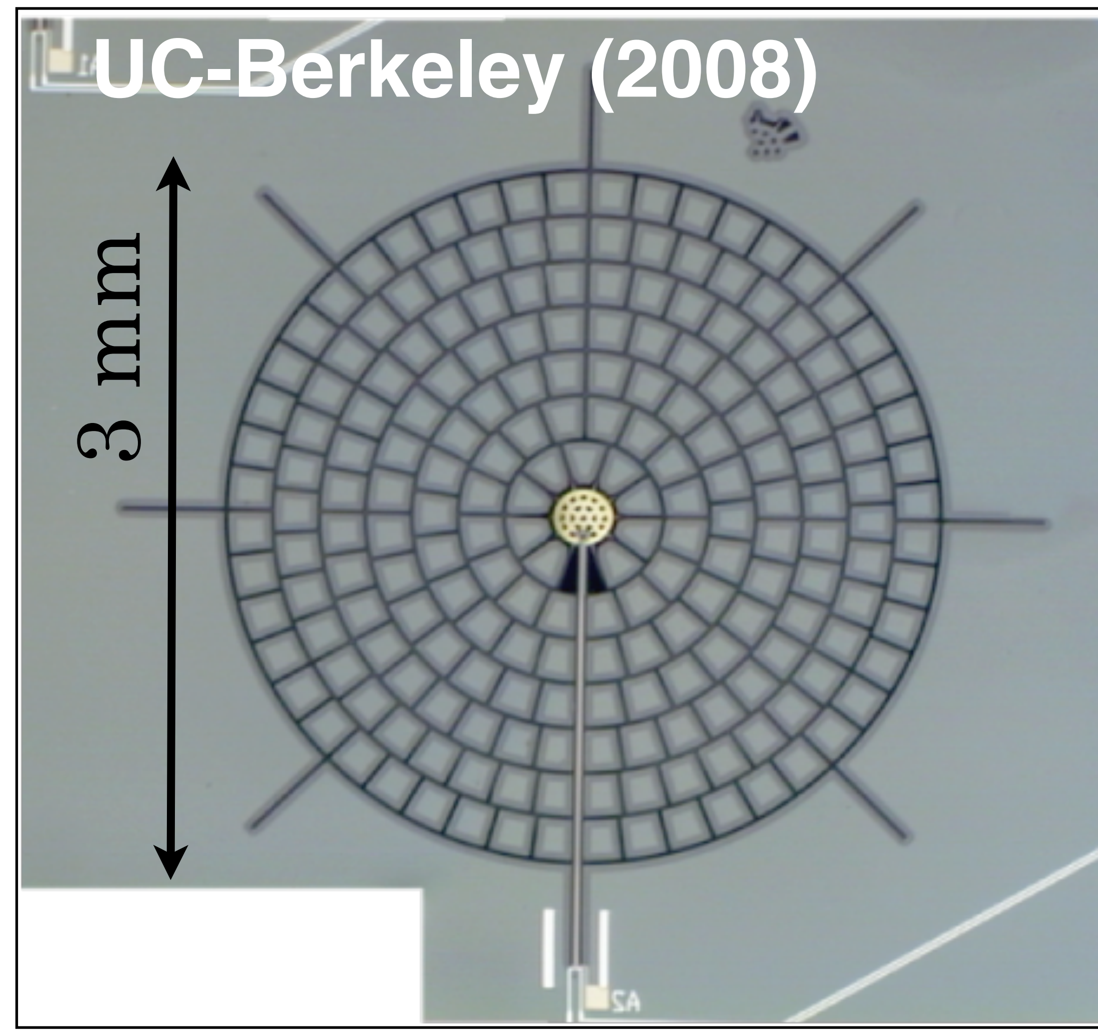
A Hand-Made bolometer!

- 100 nm thick bismuth absorber on sapphire substrate suspended by nylon wires which set the thermal conductivity (G)
- NTD Germanium thermistor epoxied to center of bolometer
- Cooled to 300 mK, ***NEP was within a factor of three of photon limit!***

The Spider-Web Bolometer

- ***SuZIE was the first experiment to use a "spider-web" bolometer!***
  - Same JPL design later used for ***ACBAR, Boomerang, Planck*** experiments
- For the South Pole Telescope, UC-Berkeley incorporated a transition edge sensors (TES) as the thermistor, operated on its superconducting transition





Evolution of CMB Focal Planes

2001: ACBAR
16 detectors

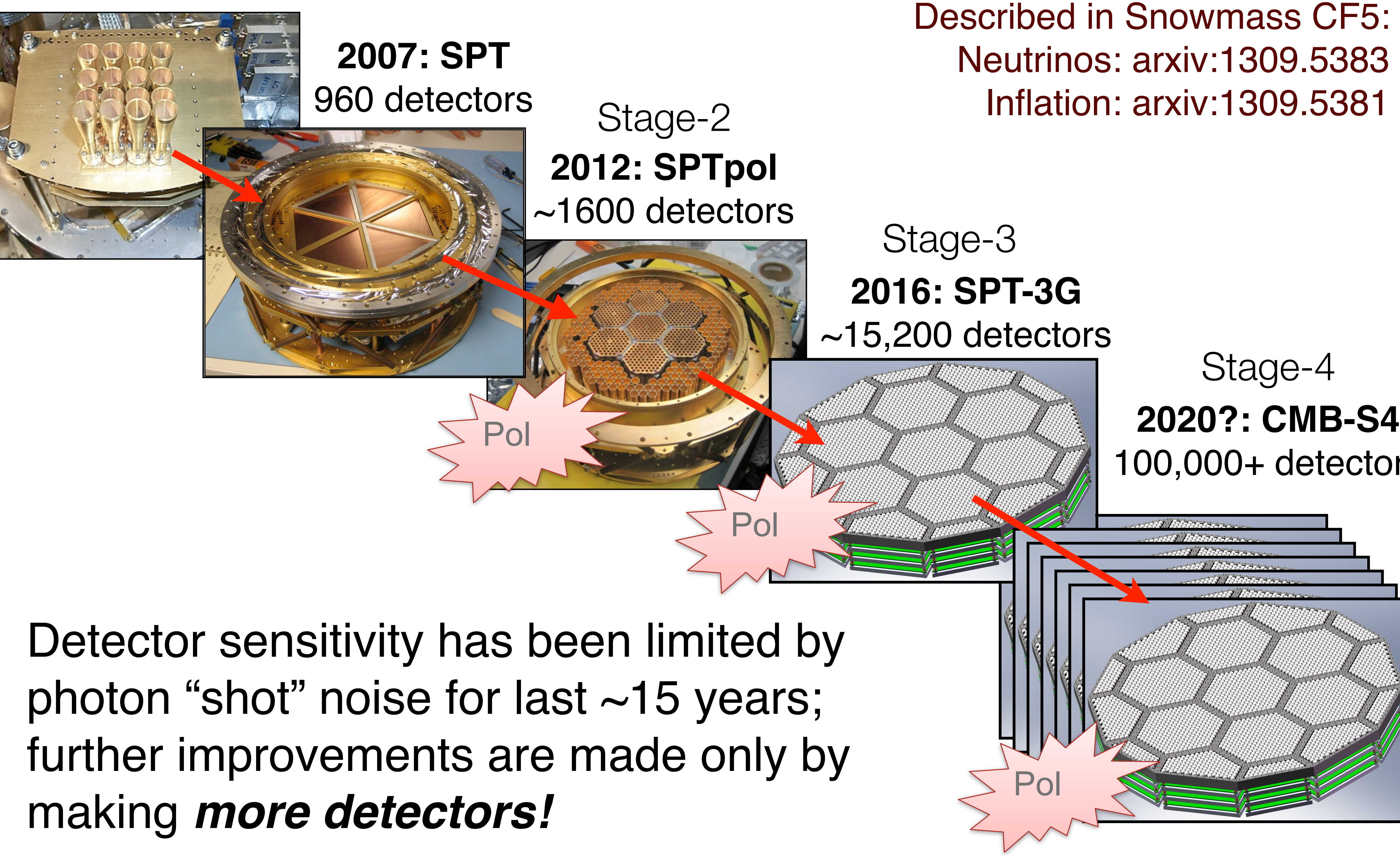
2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors

Stage-3
2016: SPT-3G
~15,200 detectors

Stage-4
2020?: CMB-S4
100,000+ detectors

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

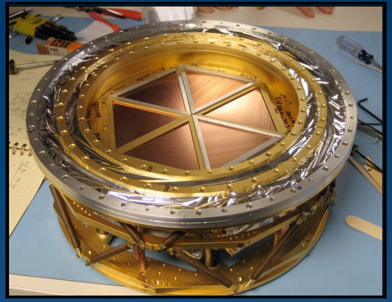


Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***

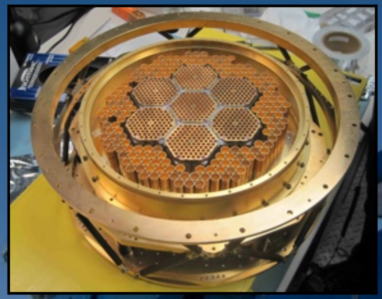
The South Pole Telescope (SPT)

- 10-meter sub-mm quality wavelength telescope
- At 100, 150, 220 GHz, angular resolution of 1.6, 1.2, 1.0 arcmin

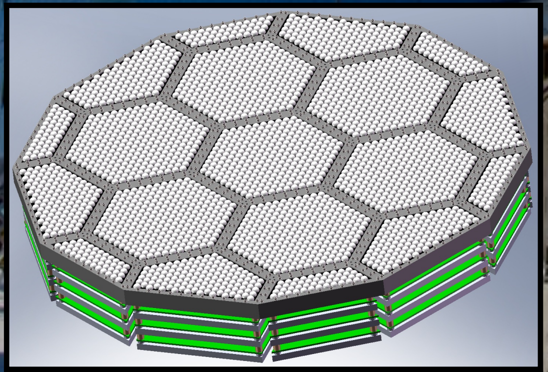
2007: SPT-SZ
960 detectors
100,150,220 GHz



2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization



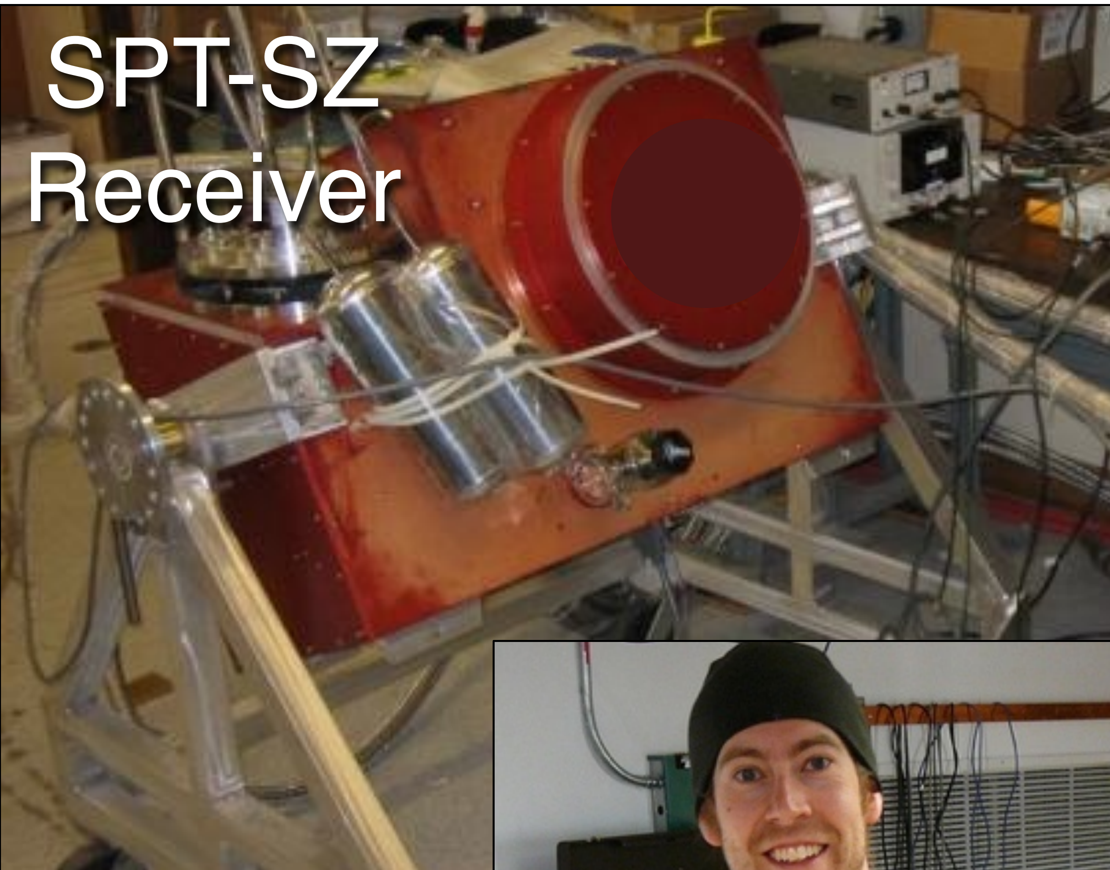
The South Pole is the best place in the world to observe the CMB

South Pole Environment

- **High Altitude (~10,000 ft)**
- **Extremely Dry**
  - Precipitable water vapor in winter is ~4x less than Chile, ~6x less than Hawaii
- **Stable Atmosphere**
  - During 6-month night, the sky is ~30x more stable than ALMA-site in Chile

The South Pole has been home to world-leading CMB experiments for the past decade

SPT-SZ Receiver (2004-2008)

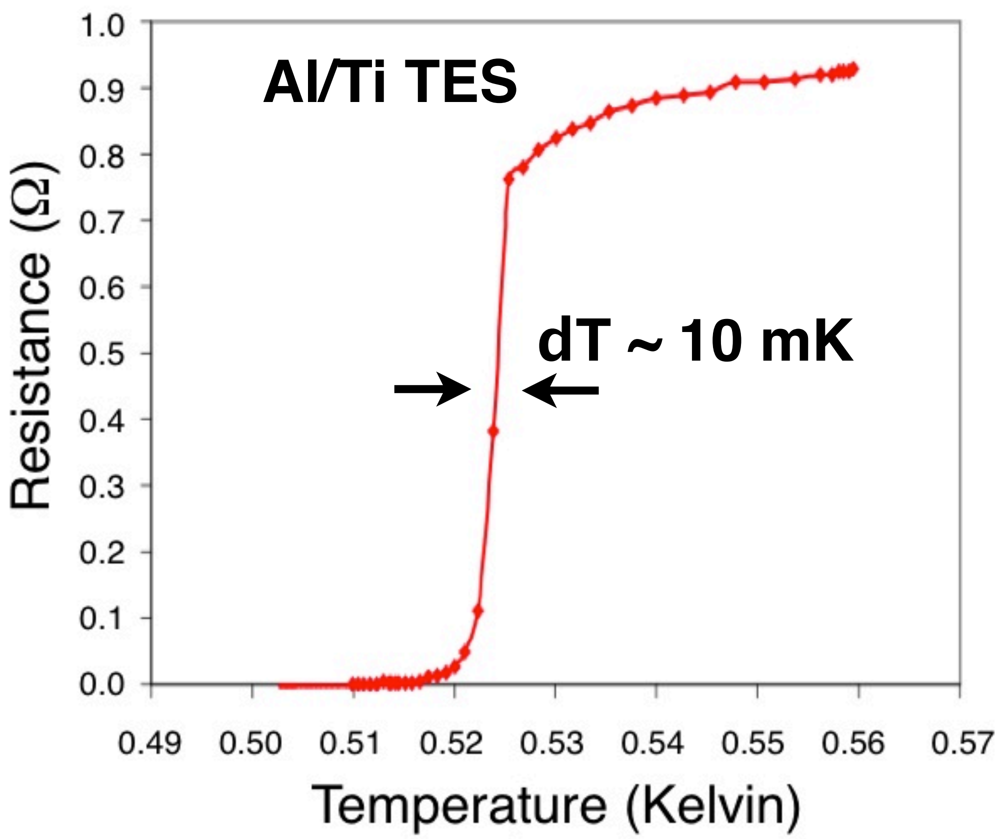


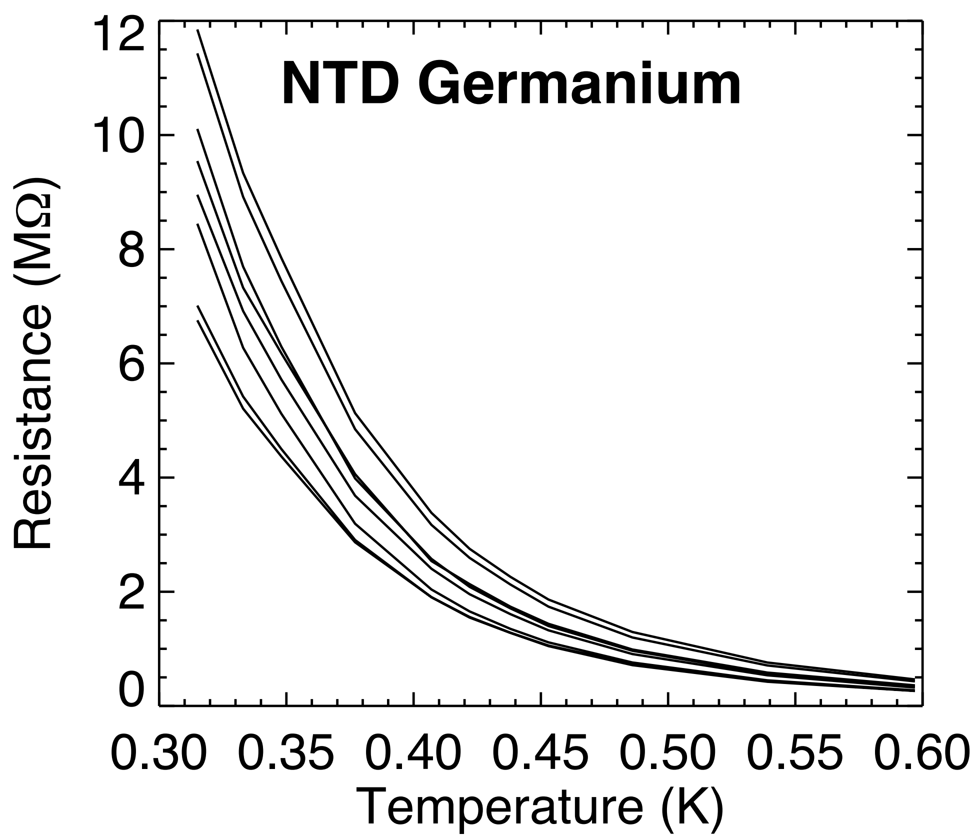
SPT-SZ Focal Plane

- Develop “scalable” detector technology to increase focal plane mapping speed
- Built and designed at UC-Berkeley
- Required development of several key technologies:

  1) Pulse Tube Coolers
  2) Superconducting (TES) bolometer arrays
  3) Multiplexed low-noise SQUID readout electronics

Superconducting Transition Edge Sensor (TES)





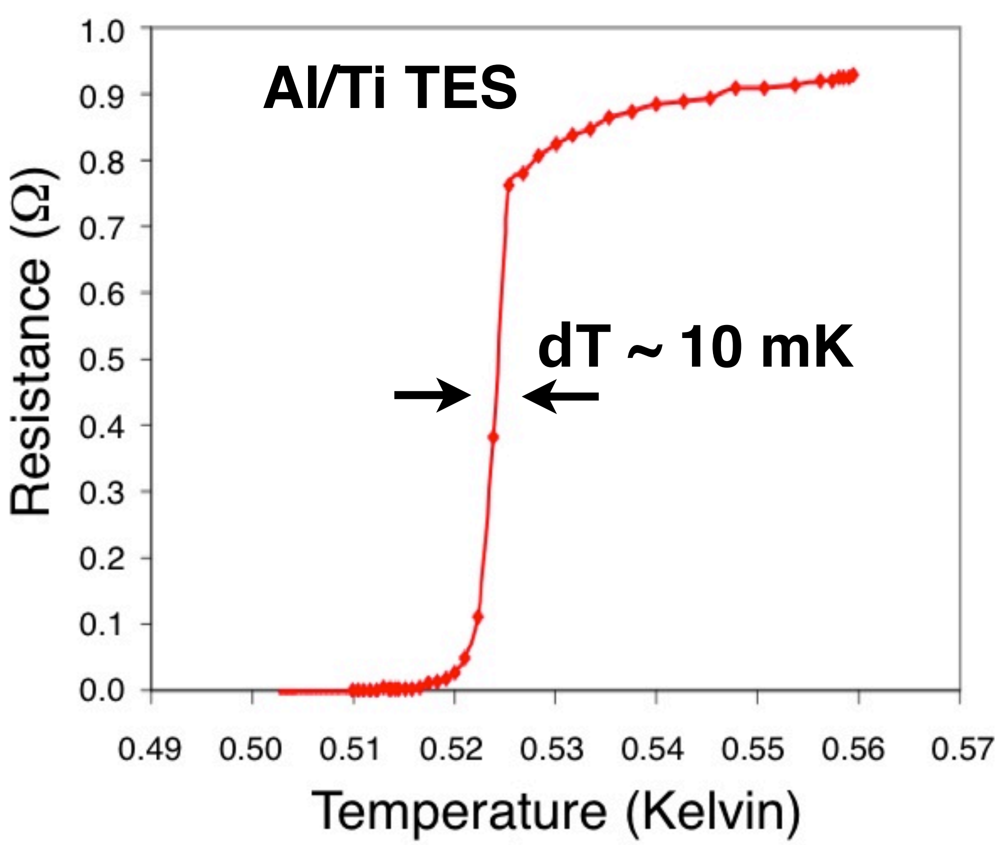
Transition Edge Sensors (TES)

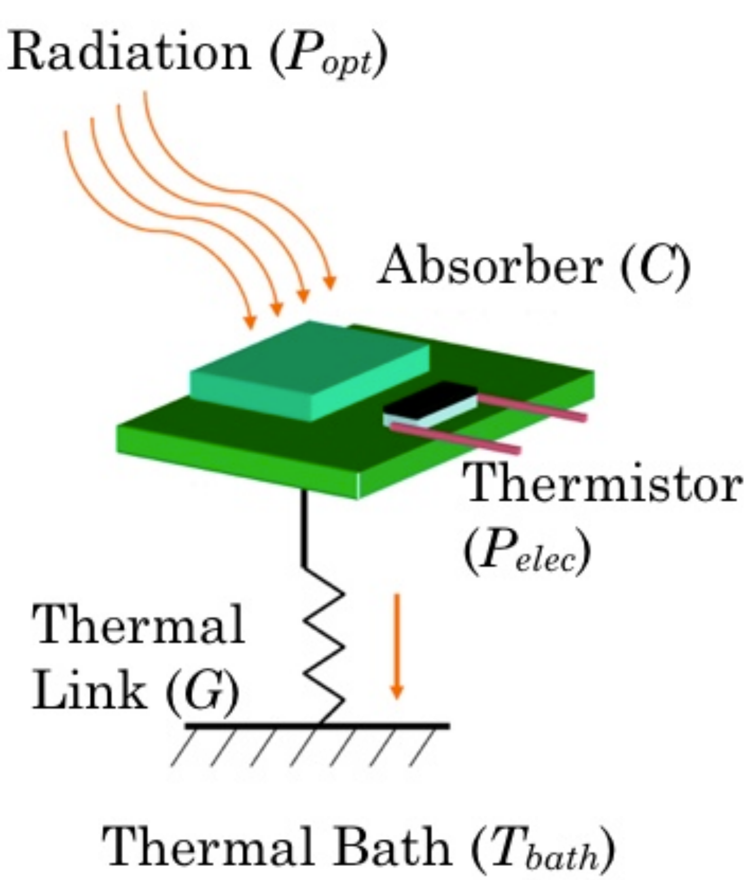
- A normal-metal/superconducting bi-layer
- Typical combinations (e.g., Al/Ti, Mo/Au,Al/Mn) require ~30-100 nm film thickness for transitions of ~500 mK

Thermistor: TES vs NTD Germanium

- Steepness of $R(T)$ curve determines strength of electrothermal response
- Sign of dR/dT determines if current or voltage bias provides negative electrothermal feedback (for stability and linearity)
- TES ~1 Ohm
  NTD Germanium ~ 2-10 M-Ohm

Superconducting Transition Edge Sensor (TES)





Bolometer Design Properties:

- Thermistor provides electrical power to balance optical power on bolometer:

$$P_{opt} + P_{elec} = \int_{T_{base}}^{T_{bolo}} G(T)\, dT$$

- Electrical feedback determined by slope of *R(T)* curve, parameterized by α parameter:

$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

TES **~ 20-1000**
NTD ~ 3-10

- Can define a "loop gain" in analogy to electronic feedback circuits:

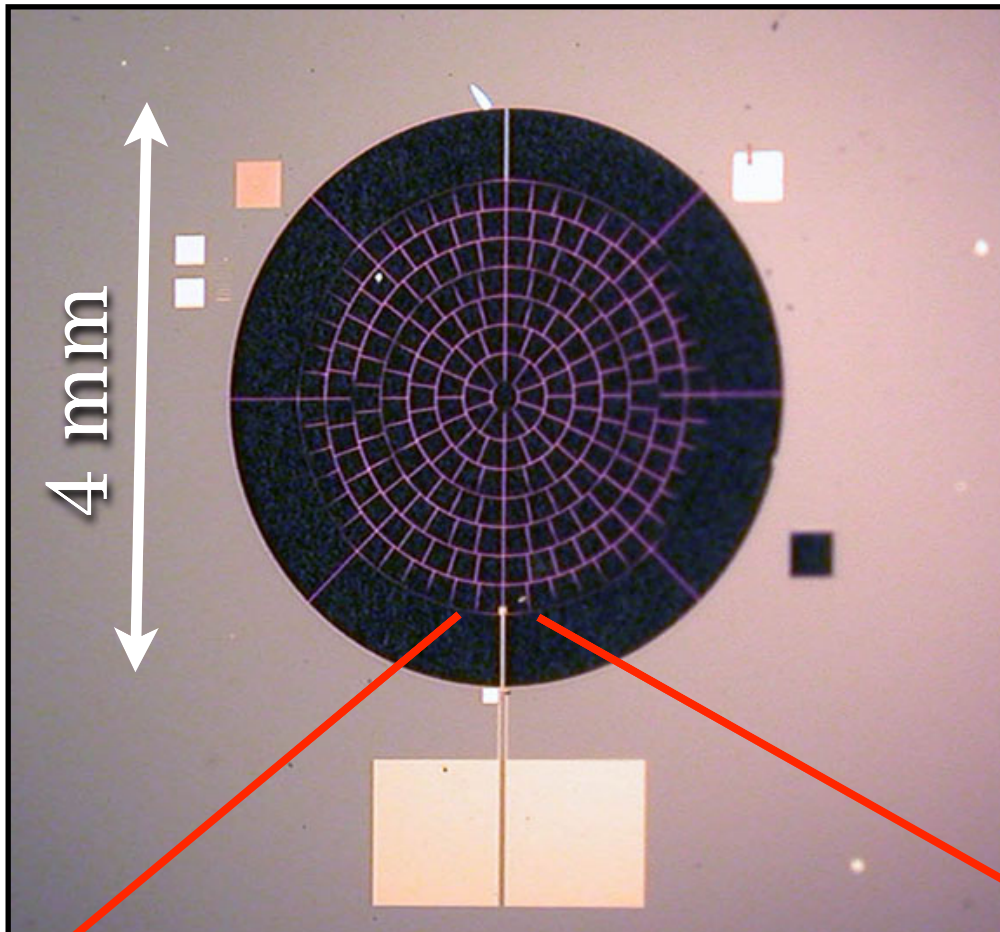
$$\mathcal{L} = \frac{\alpha P_{elec}}{G T_b}$$

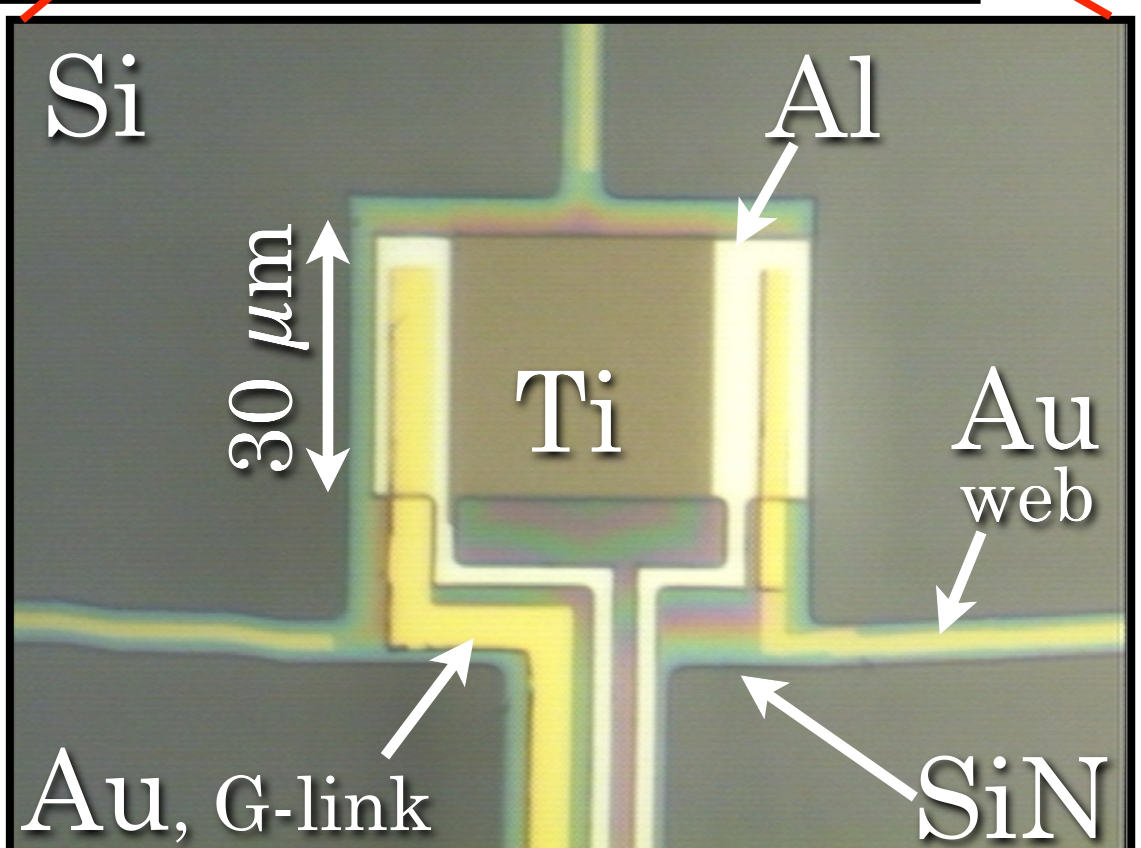
TES **~ 20-1000**
NTD ~ 1-5

- Increased loop gain improves the linearity (in responsivity) and speed of the detector:

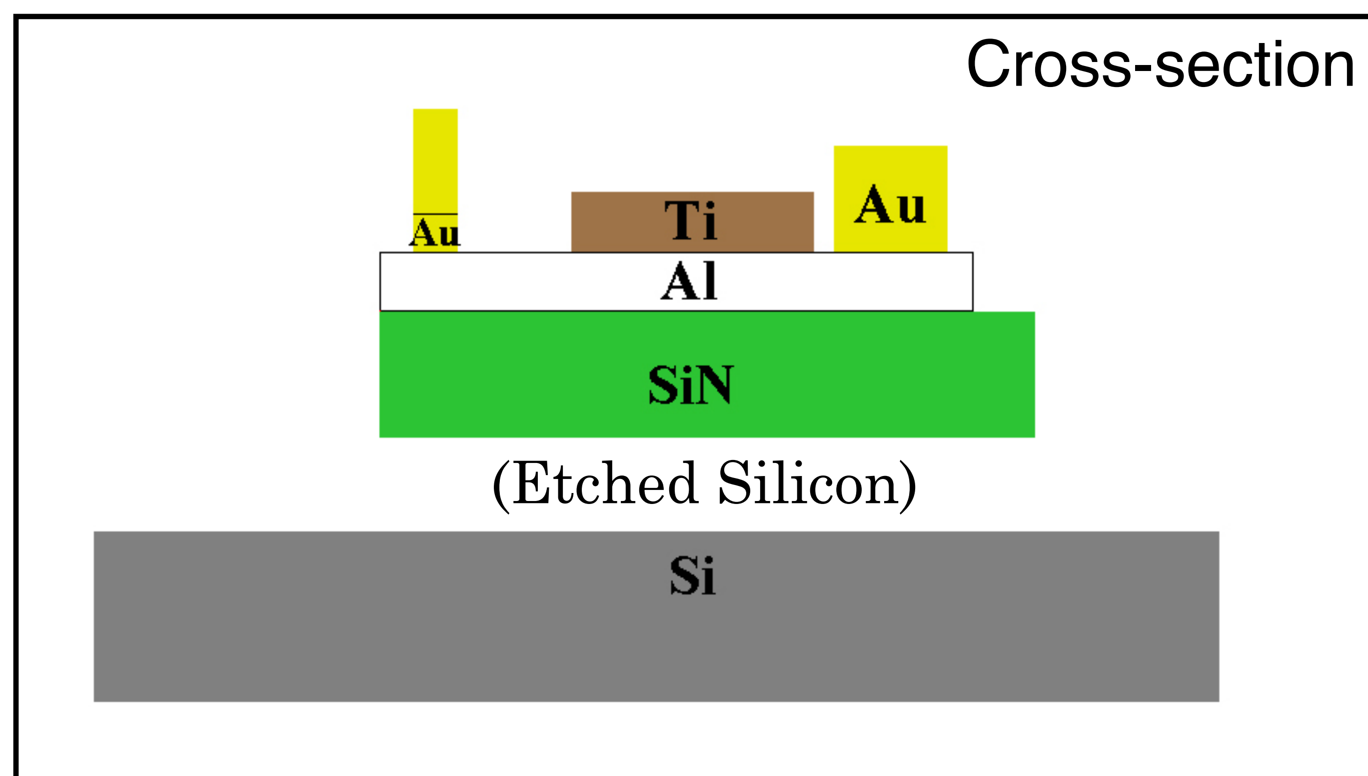
$$S_I = \frac{\delta I}{\delta P} = \frac{-1}{V_b}\frac{\mathcal{L}}{1+\mathcal{L}} \qquad \tau = \frac{\tau_0}{1+\mathcal{L}} = \frac{C/G}{1+\mathcal{L}}$$

SPT-SZ TES Single Pixel

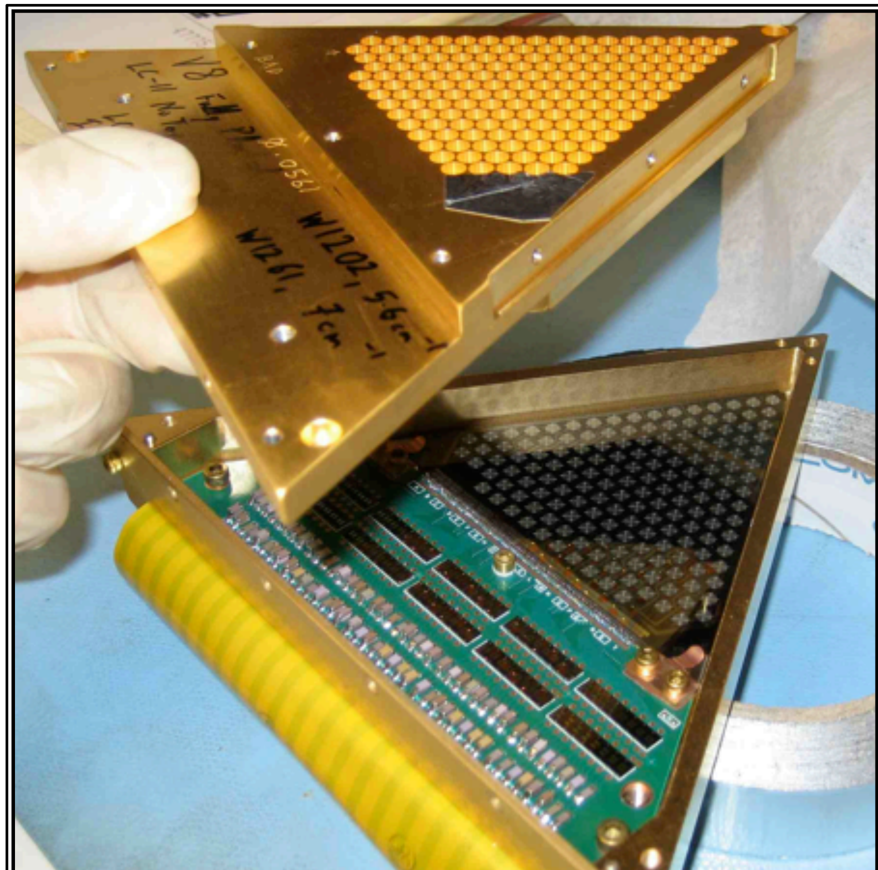


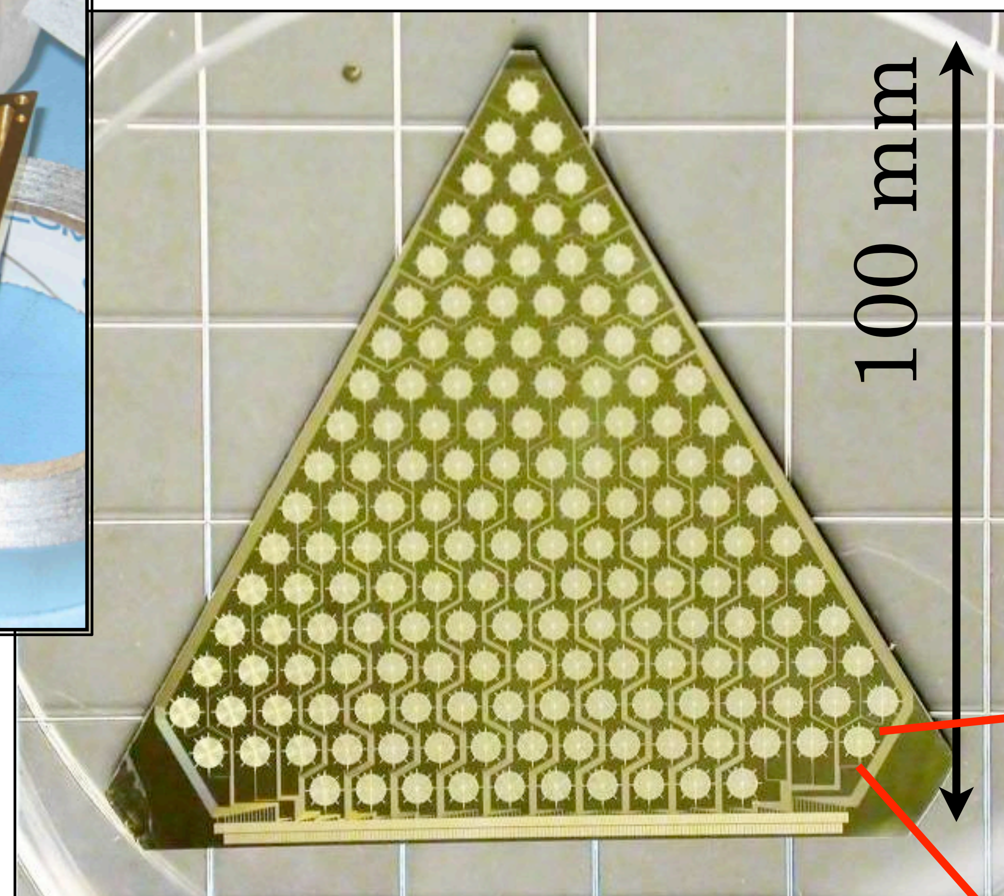


- Made at UC-Berkeley
- Used JPL spider-web absorber design;
  - suspended 1mm thick Silicon Nitride (SiN) substrate with 12 nm thick Gold (Au) absorber
- Replaced NTD Germanium with TES Aluminum/Titanium (Al/Ti) bilyaer;
  - Film thickness 40 nm Al, 80 nm Ti, gives a superconducting transition (T_c) of ~ 0.5 K
- "G" set by gold finger to TES

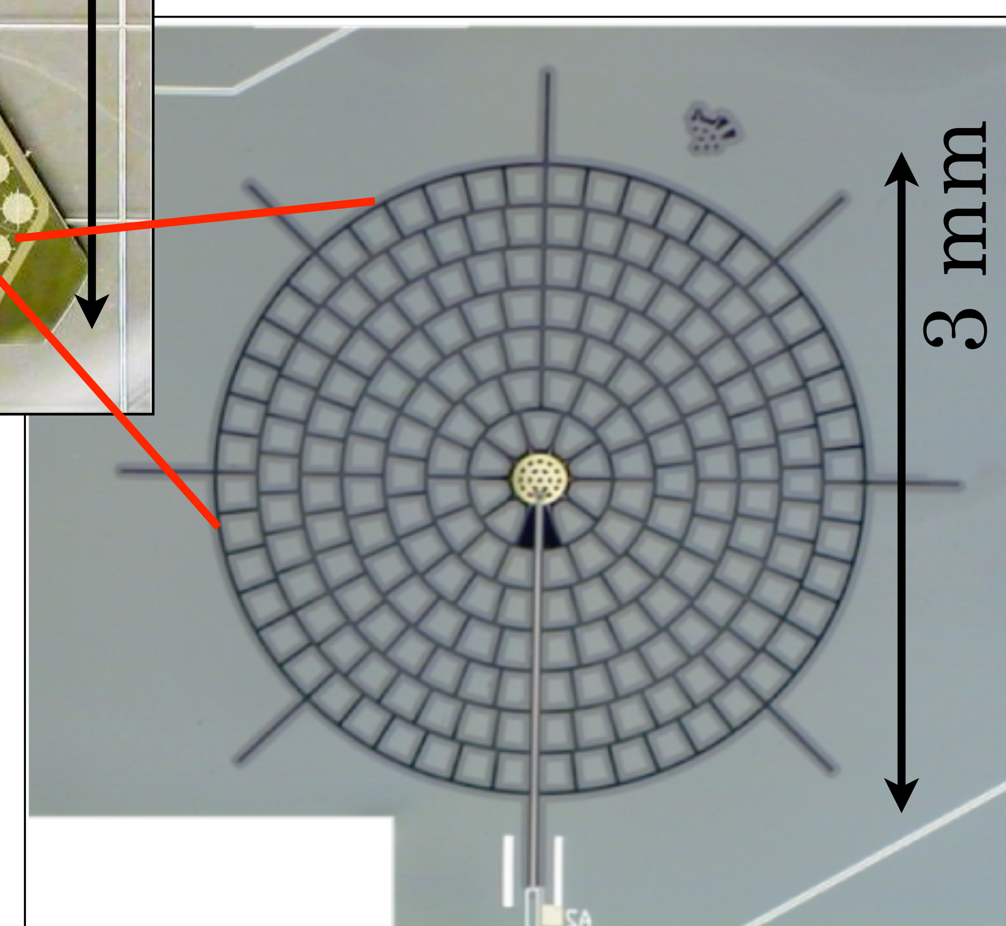


SPT-SZ Bolometer Array





Fabricated at UC-Berkeley by Sherry Cho and Erik Shirokoff (new faculty at U of Chicago)

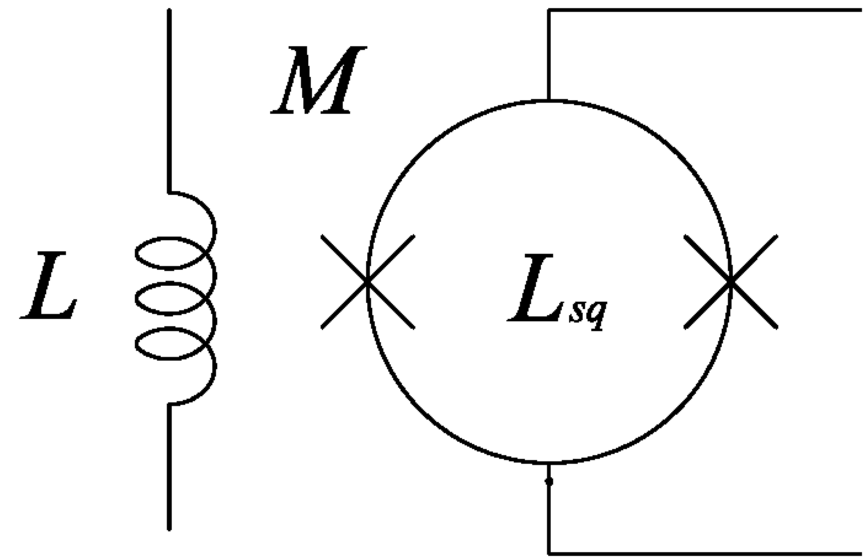


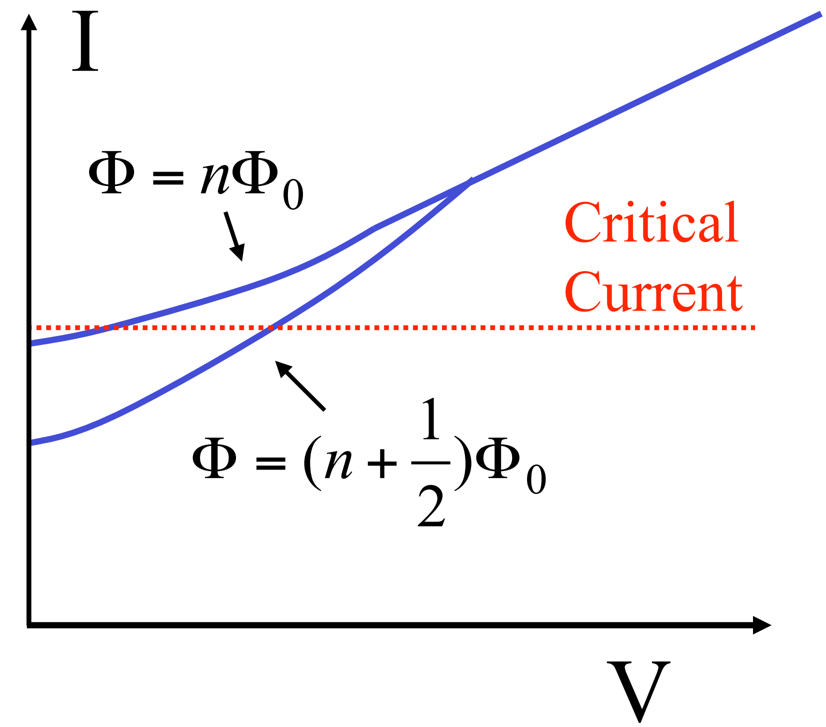
An SPT-SZ 160 bolometer array;
SiN substrate with gold absorber, and a Al/Ti transition edge sensor (TES) superconductor with a transition temperature of 500 mK

SQUID Bolometer Readout

Requirements:

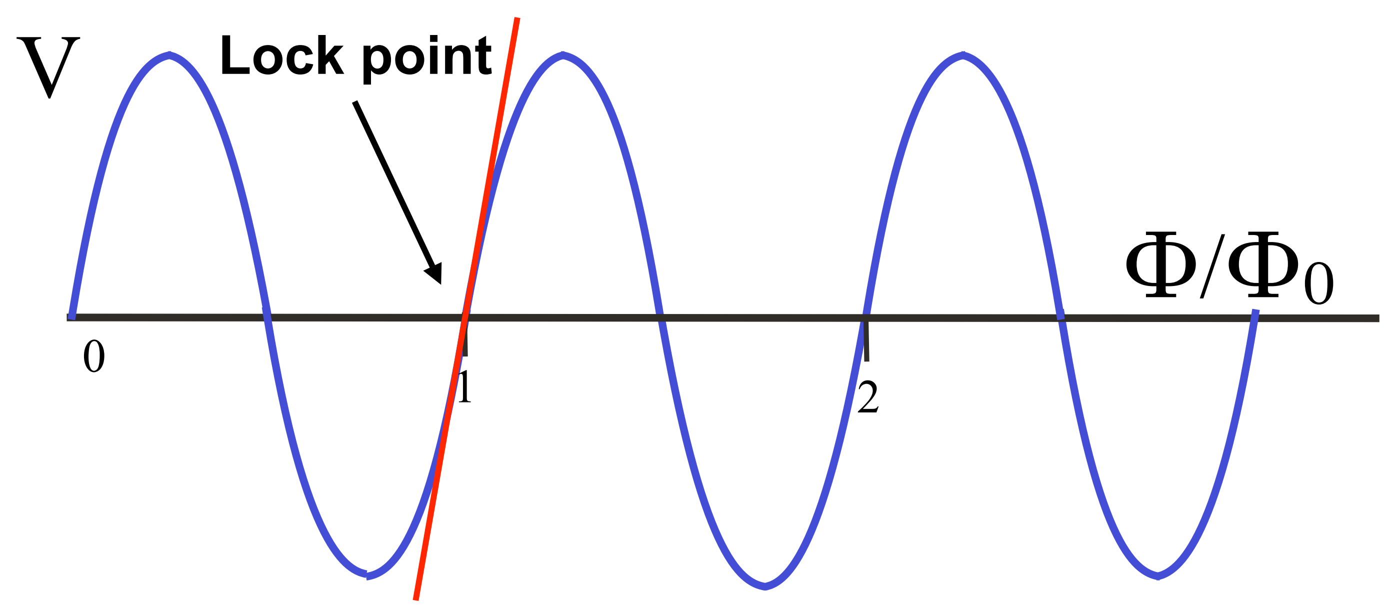
- Low input impedance
- Low power dissipation
- High bandwidth
  - ~100 MHz
- Low noise. At 4 K:
  - 3 pA/rtHz
  - 0.2 nV/rtHz



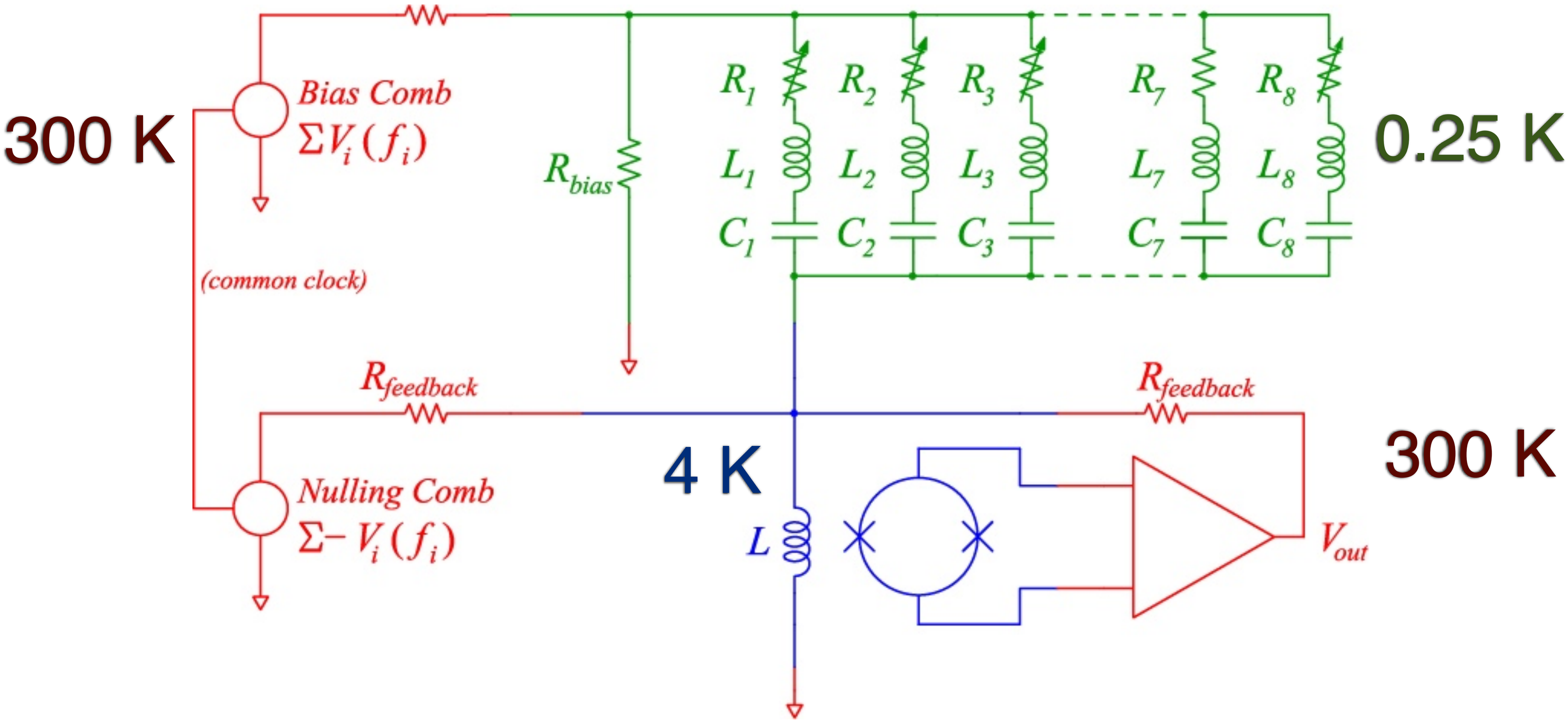


Implementation:

- Use DC SQUID as an ammeter (Superconducting Quantum Interference Device)
- Current->Flux->Voltage transducer

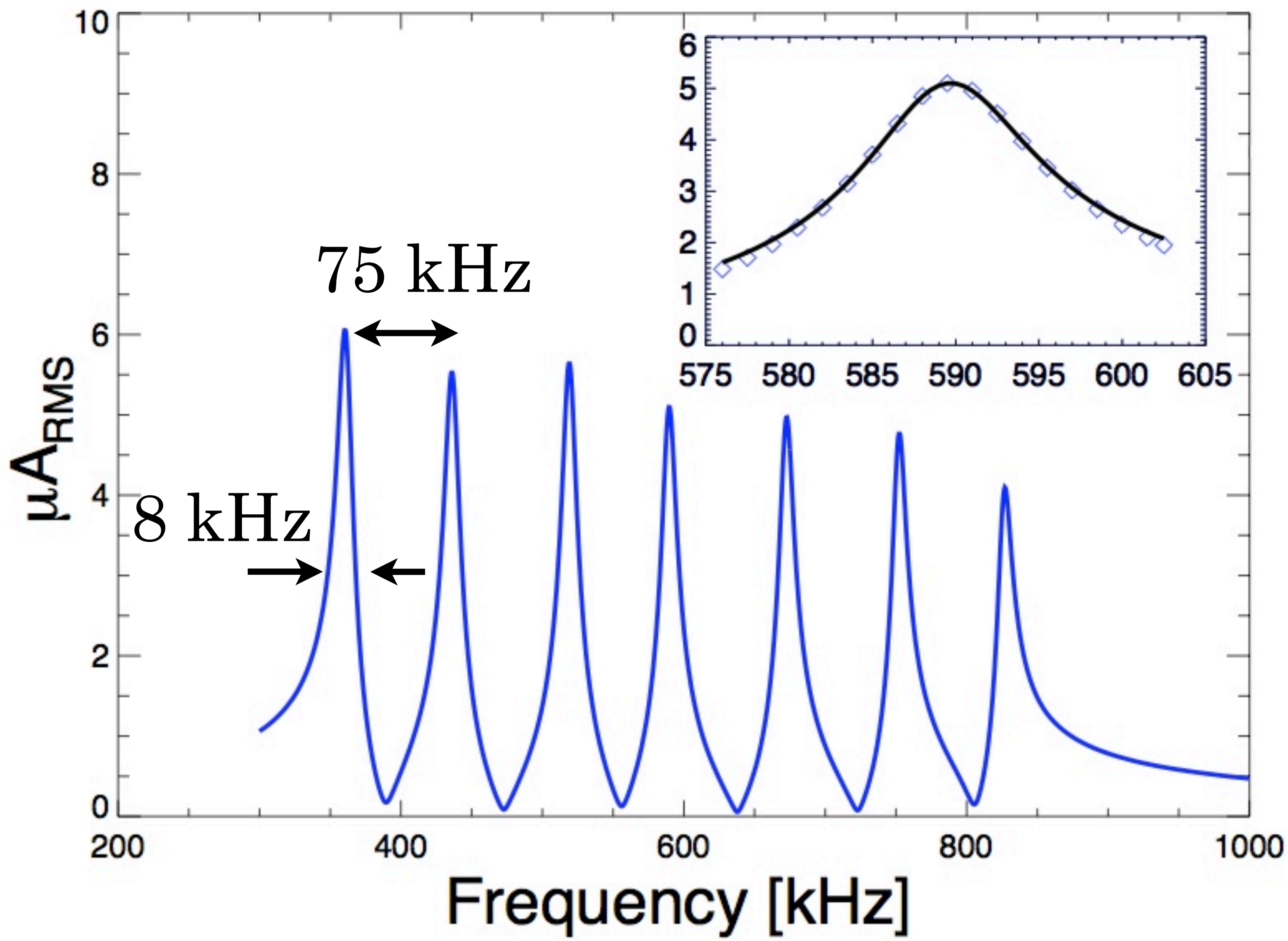


Frequency Domain Multiplexing (fMUX)



- Developed current summing fMUX at UC-Berkeley and Lawerence Berkeley Labs (LBL)
- AC Bias row of detectors with comb of frequencies between 300-1000 kHz at RLC filter resonances: $2\pi f_{\mathrm{filt}} = \omega_{\mathrm{filt}} = 1/(LC)^{1/2}$
- Crosstalk determined by Q of LC resonance (designed to be < 1%): $\Delta\omega_{\mathrm{filt}} = R/L$, therefore $Q = (L/RC)^{1/2}$

Frequency Domain Multiplexing (fMUX)



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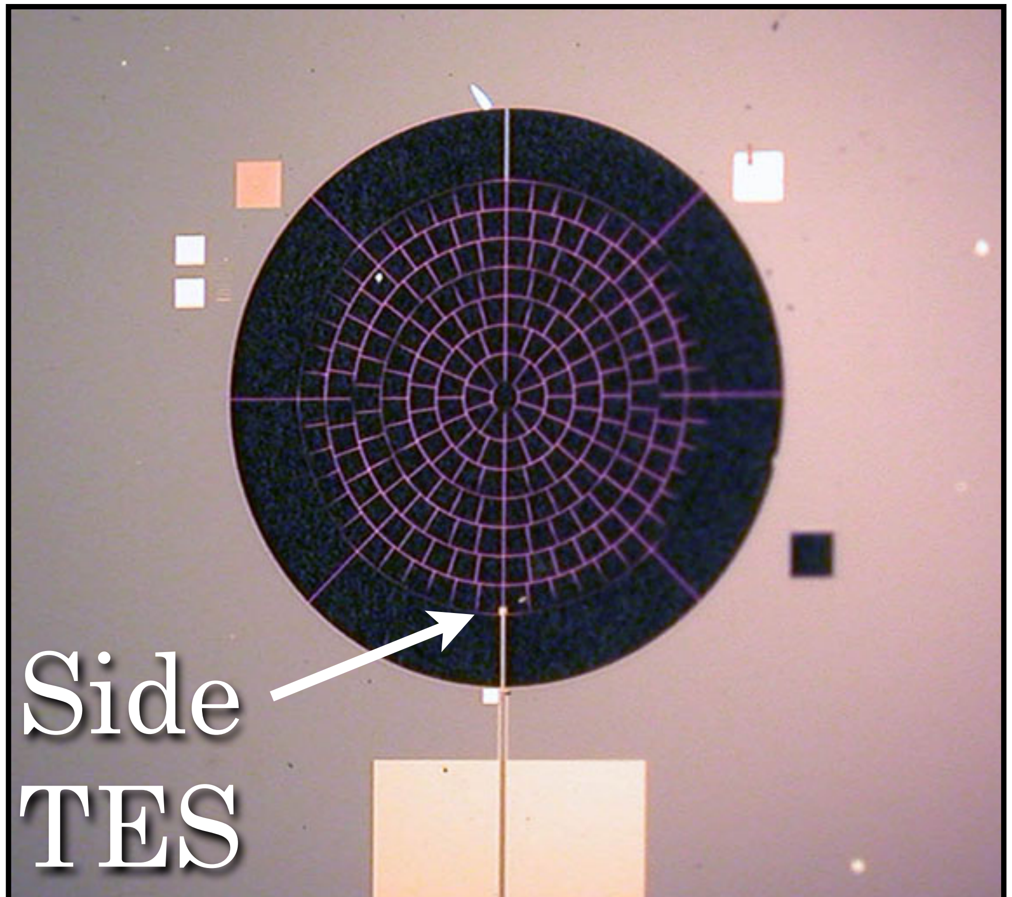
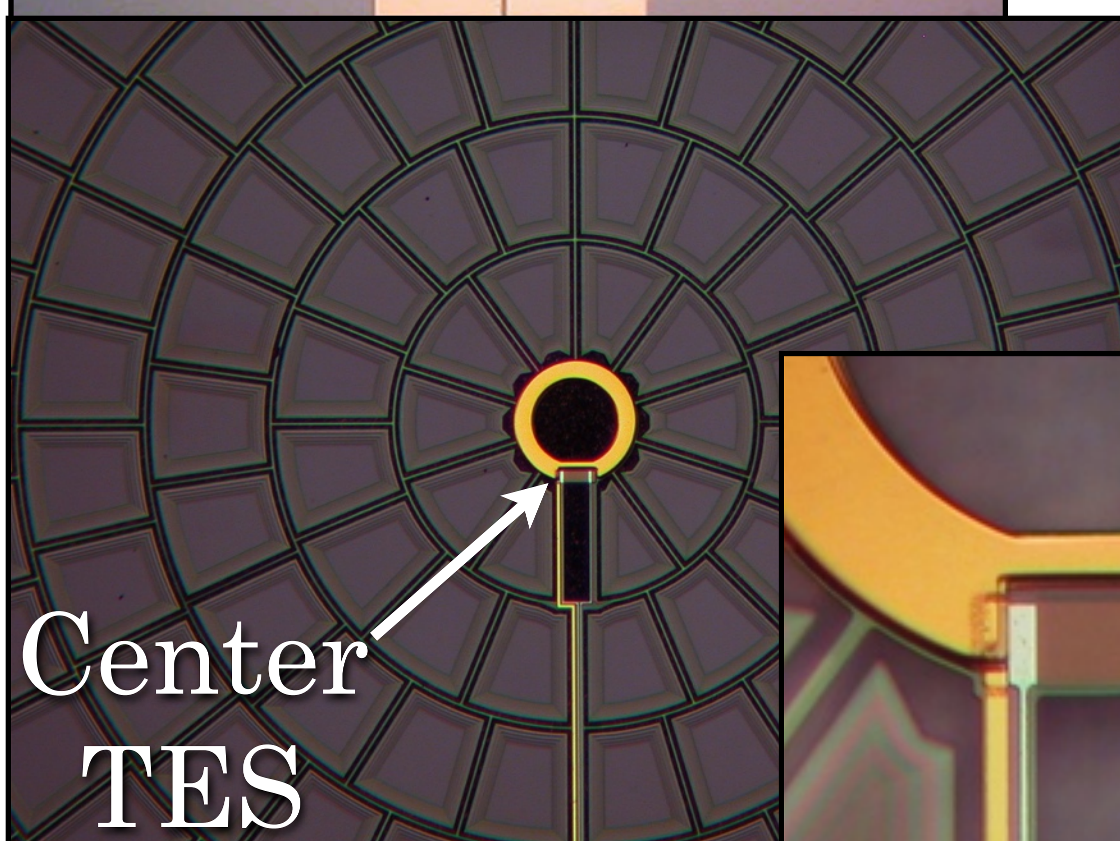
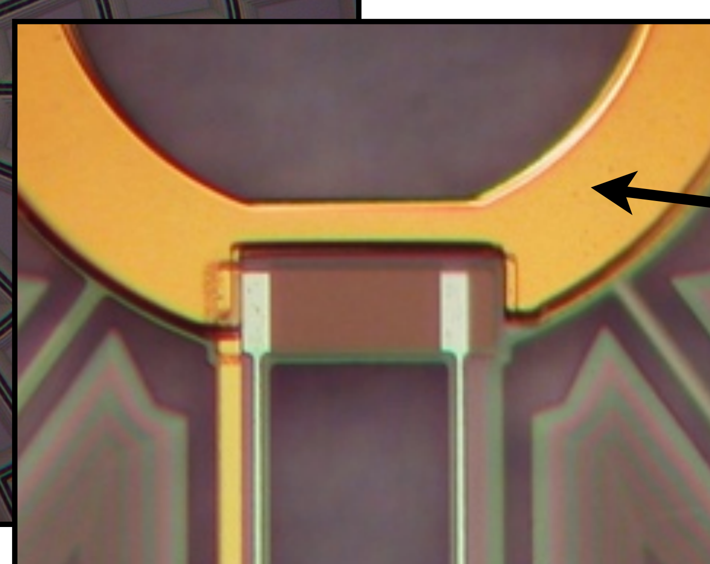
TES Time Constant and Stability







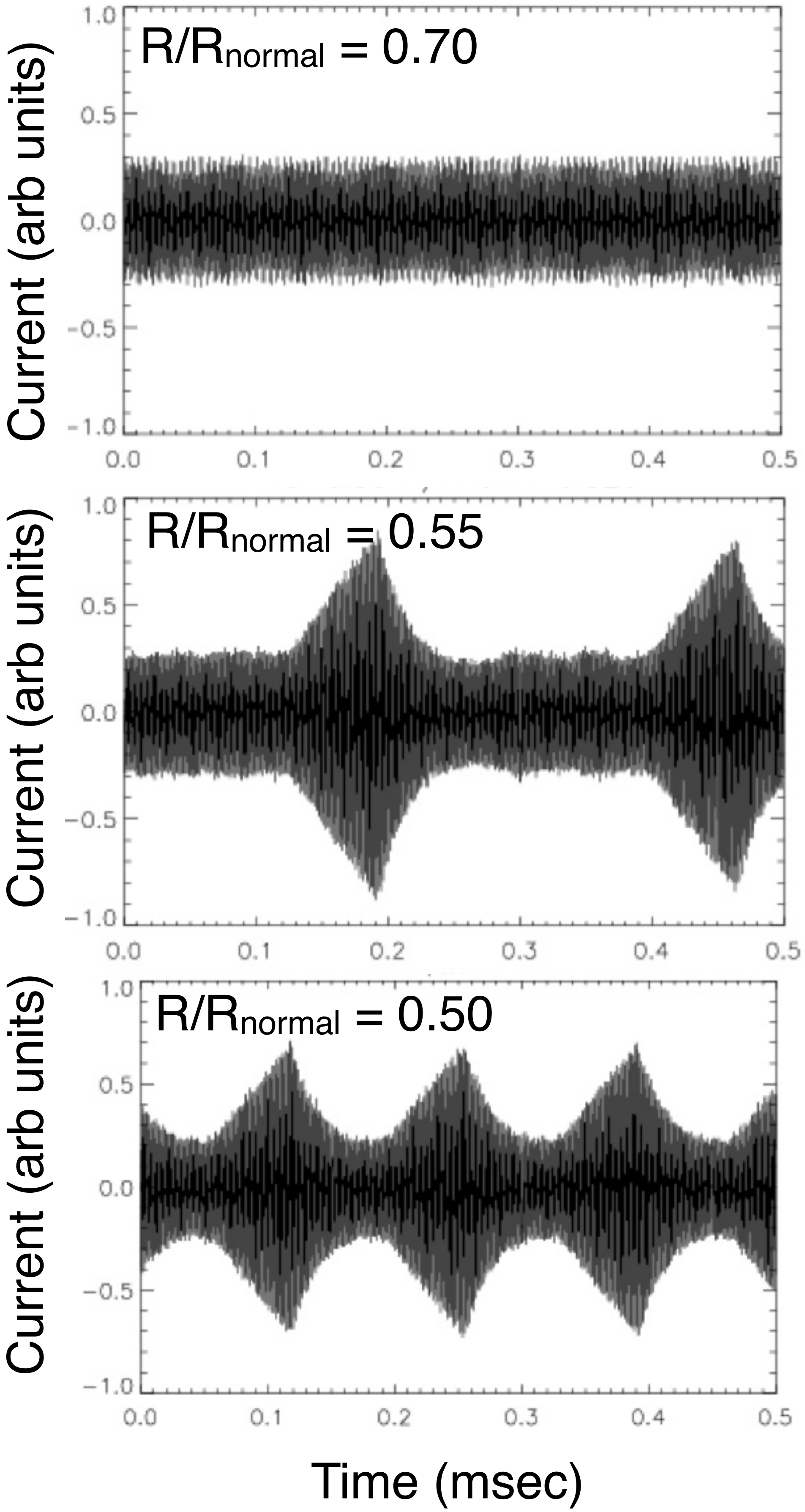
Side-TES design was ***too fast*** electrically, TES stability requires:

1) Bandwidth requirement for bolometer stability:
   TES bandwidth < 5.8 fMUX bandwidth
2) Given RLC filter bandwidth, this implies:
   0.2 msec < t_{TES} < 5 msec
3) TES speeds up as loop gain increases [$t_{TES} = t_0 / (1 + L)$], so assuming L ~ 10-30:
   6 msec < t_0 < 50 msec

Side-TES had a t_0 < 0.1 msec! became unstable as soon as TES went into its transition.

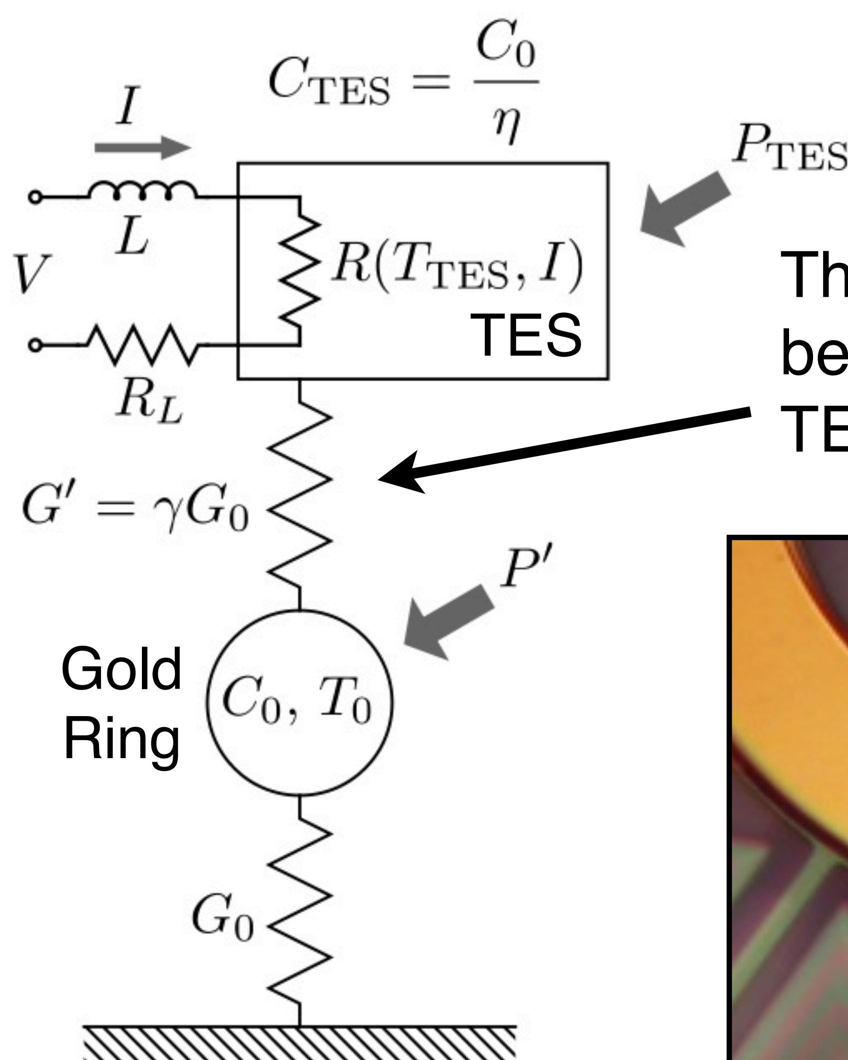
Gold Ring added for heat capacity to slow down bolometer to t_0 ~ 20 msec.

Thermal Decoupling of TES and Ring

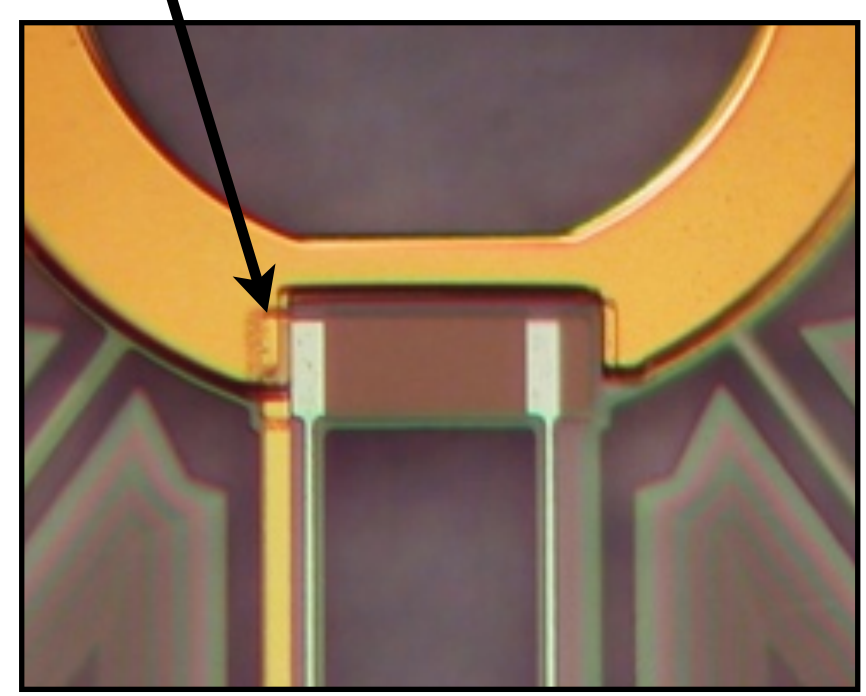


SPT-SZ 2007 focal plane used design with center-TES and gold ring.

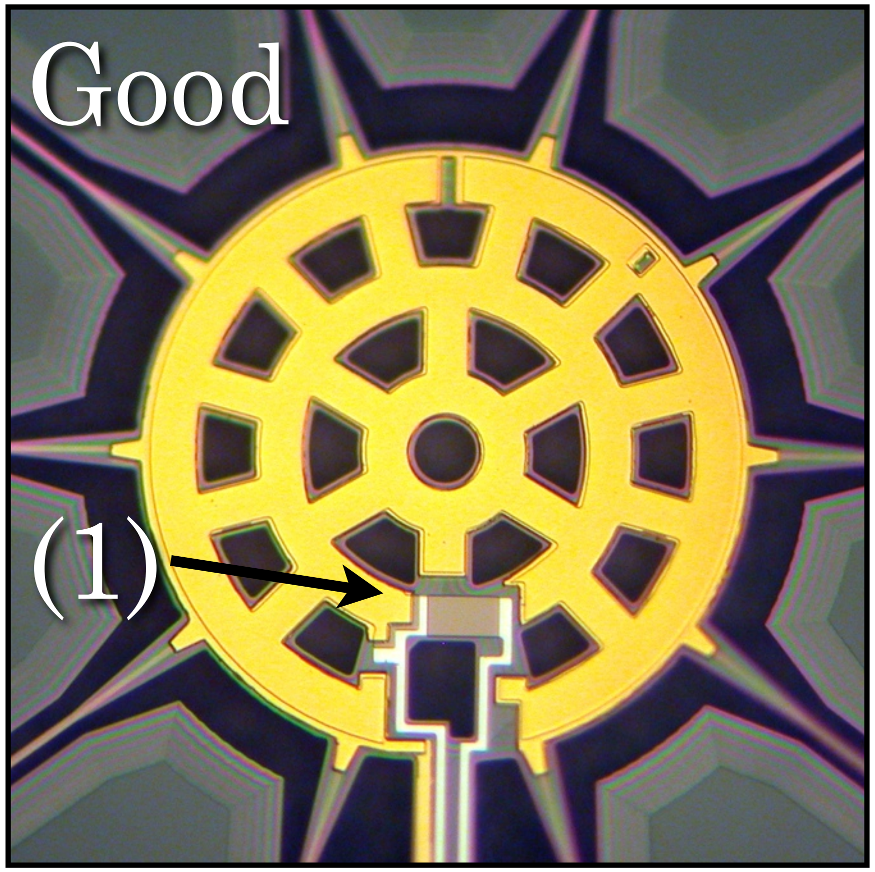
Unfortunately, design had additional instability from gold ring decoupling from the TES.



Thermal conductivity (G') between gold ring and TES is too small

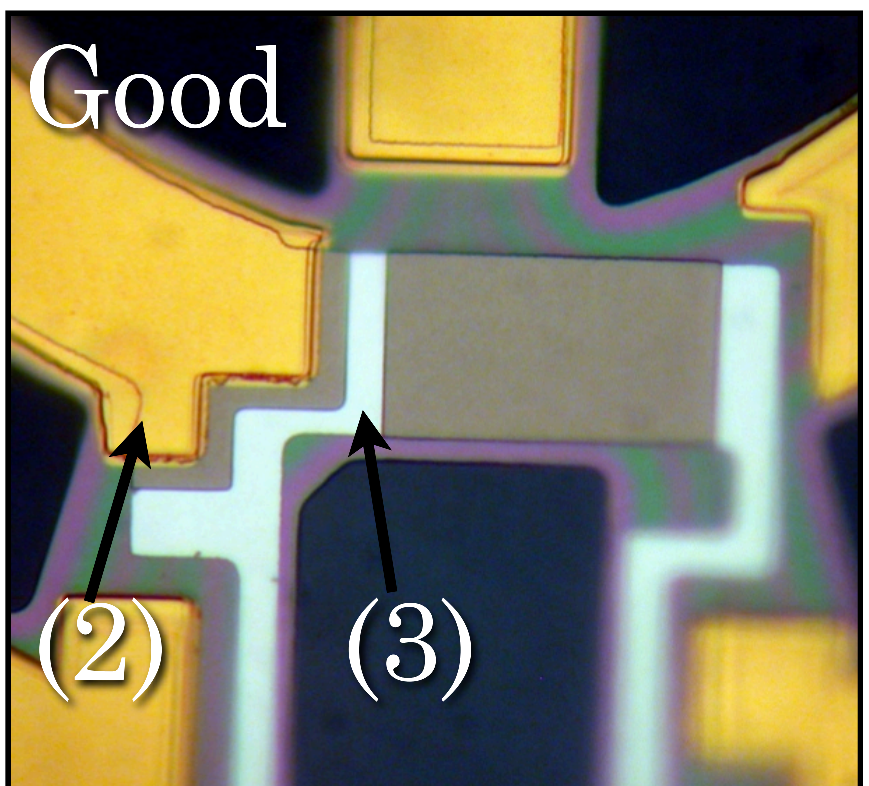


Alternative Gold Coupling Designs

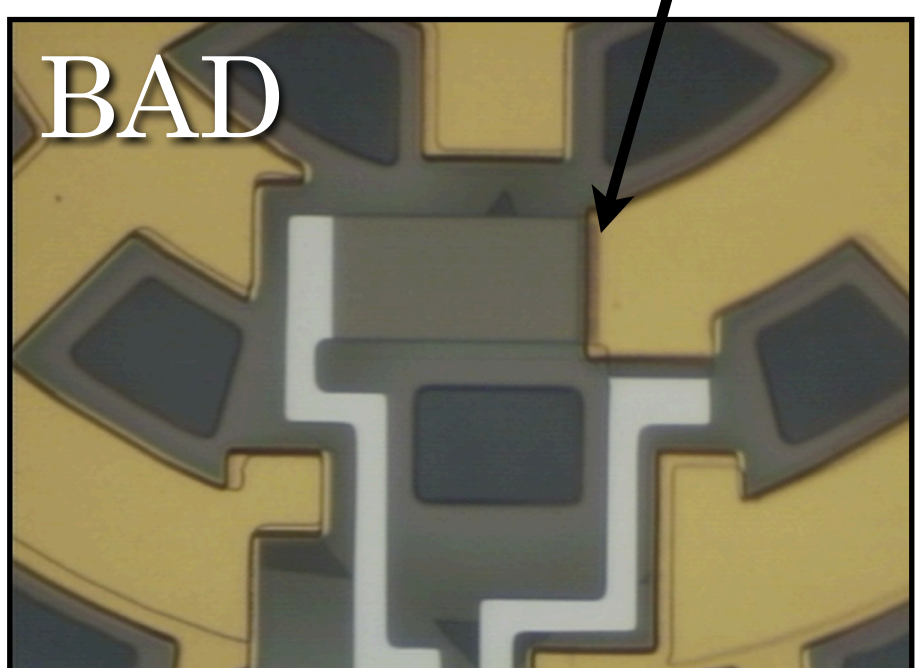


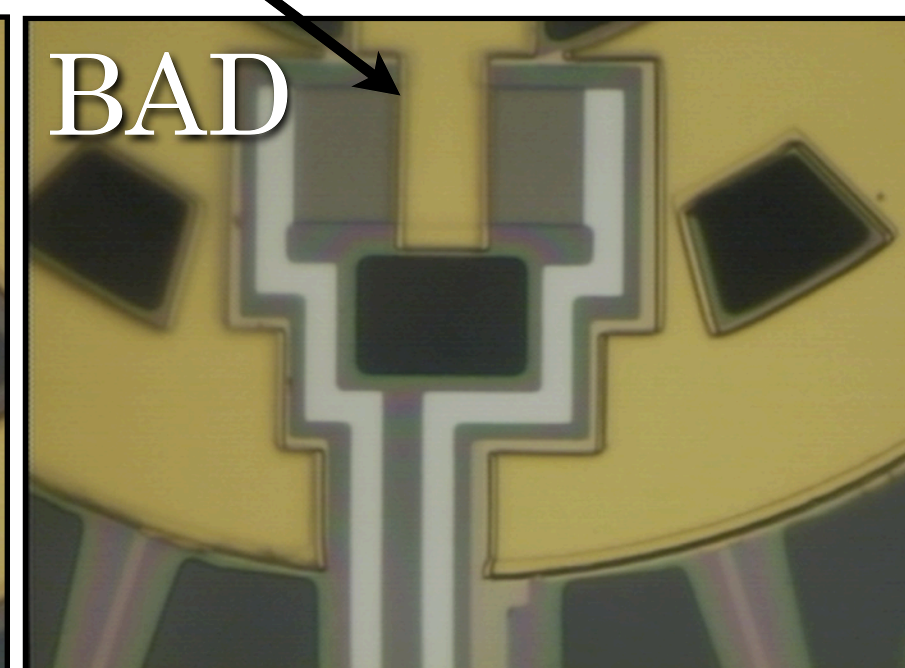
Improved TES-Gold Coupling:

1) Centered TES and increased gold connectivity,
2) Al/Ti bi-layer underlies gold,
3) Superconducting "Al" leads were narrowed,
4) Oxide layer cleaned with etch before gold deposition.

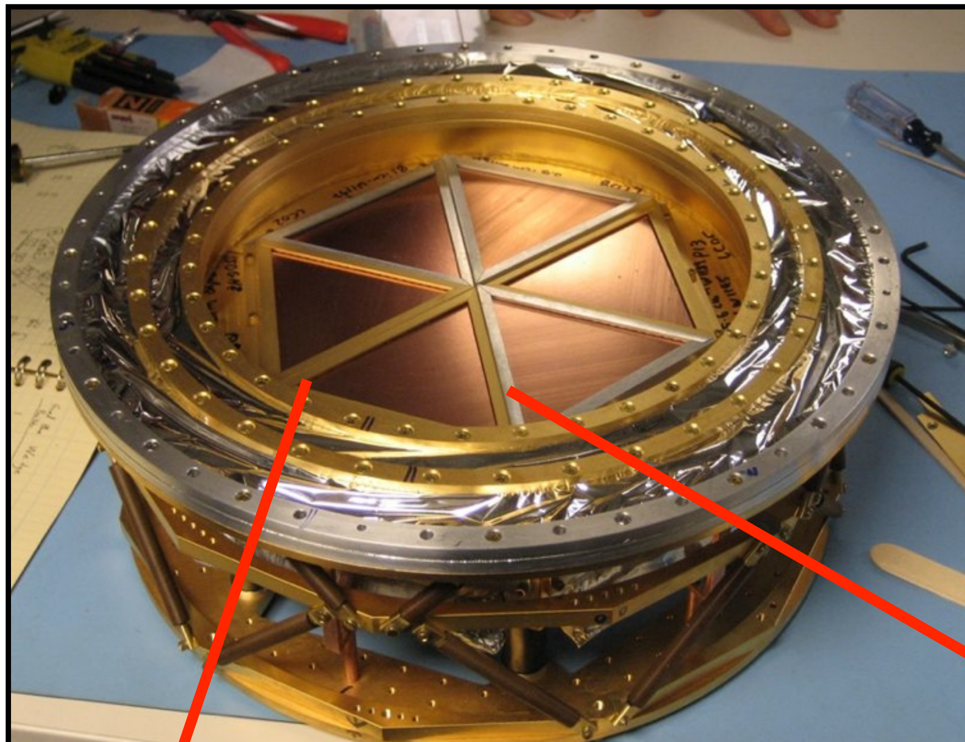


Designs that intercepted TES improved thermal coupling to gold, but broadened transition and lowered loop gain

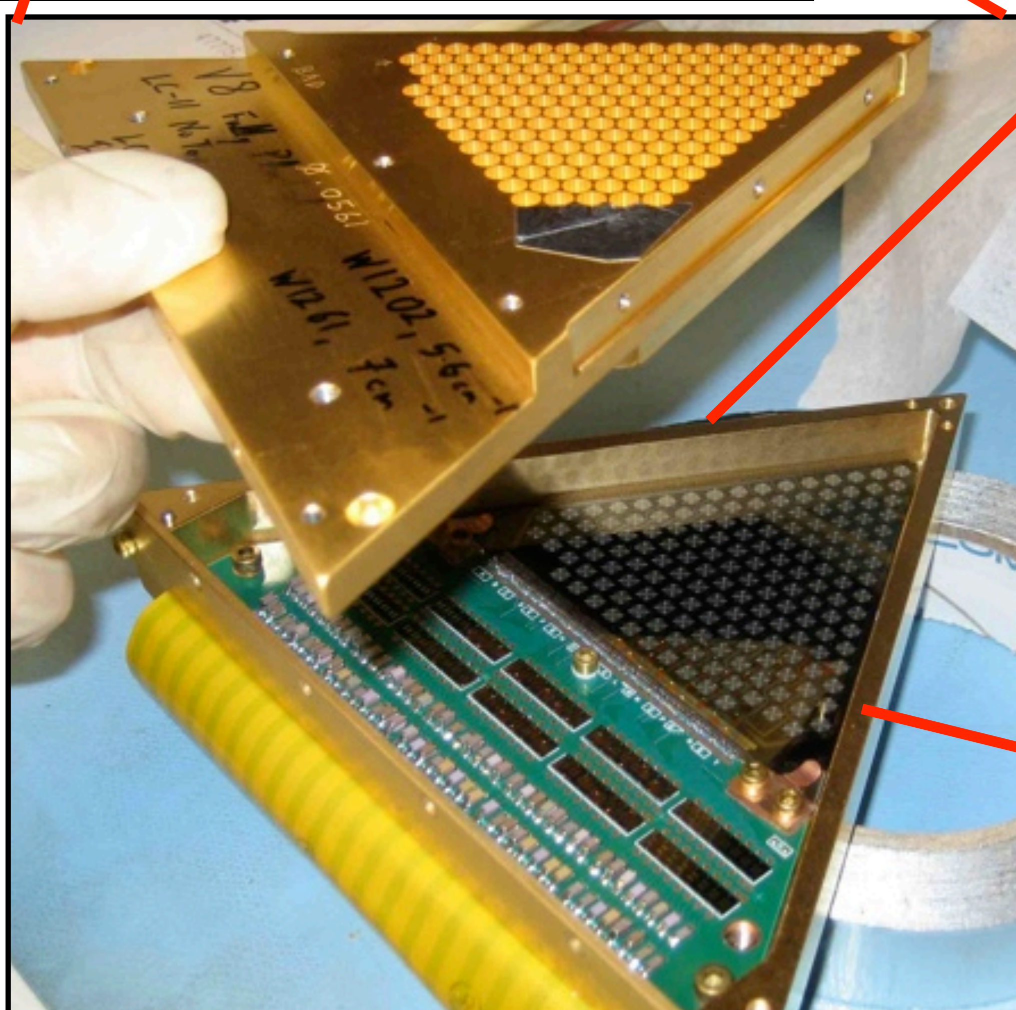


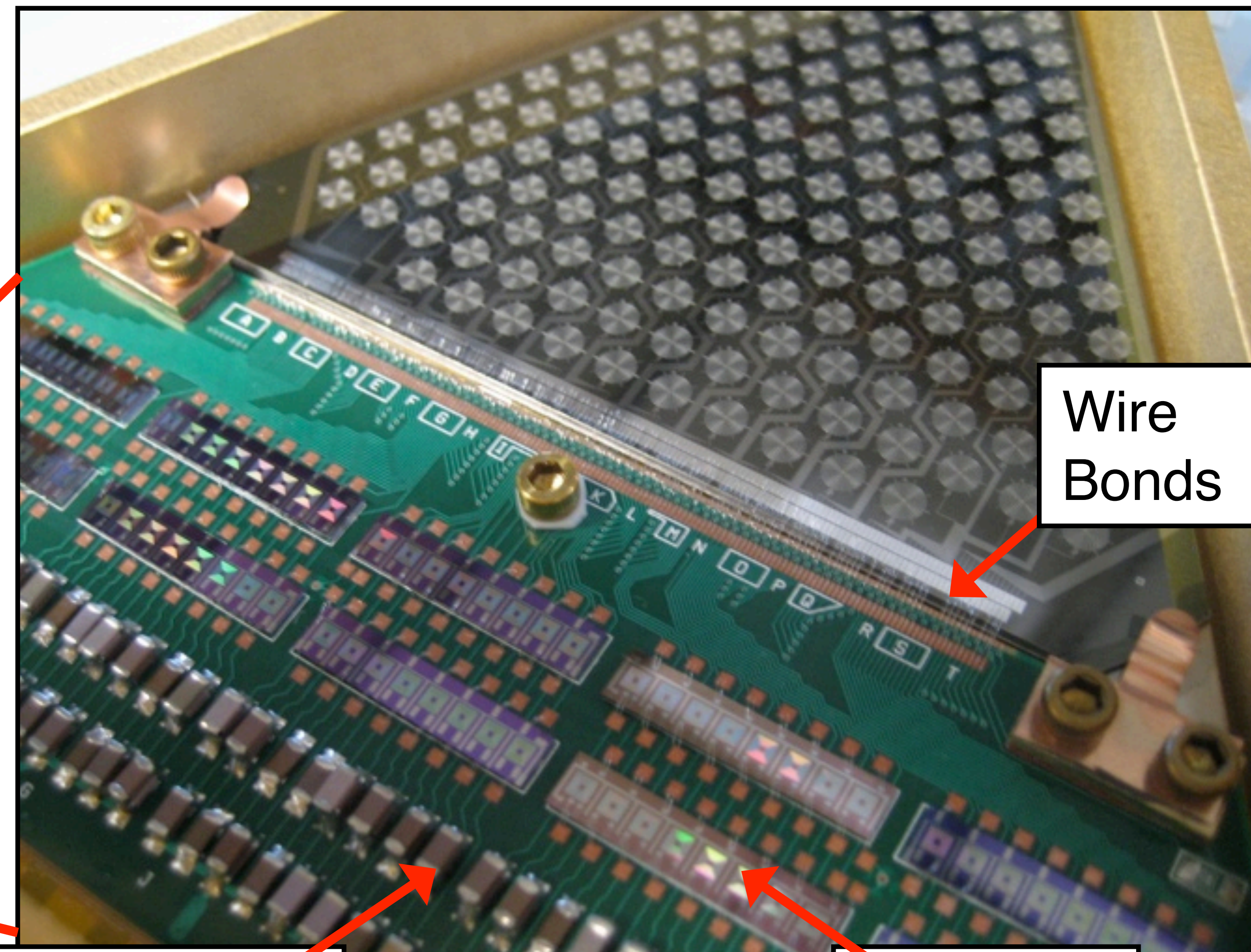


SPT-SZ Detector Module and LC Board

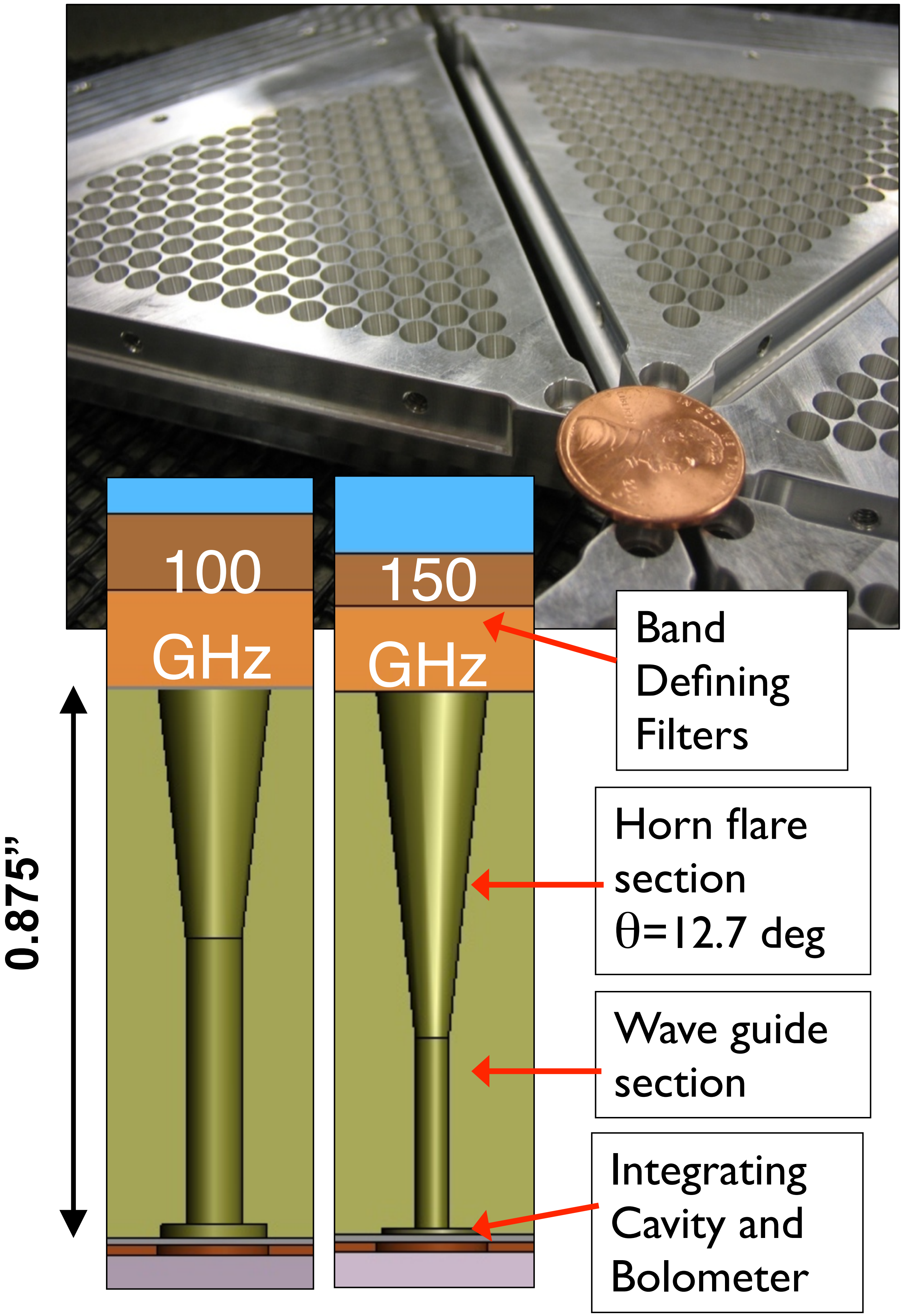


- Wafer wire-bonded to circuit board with LC circuit, which sets each bolometer's resonant frequency for frequency Multiplexing (fMUX)



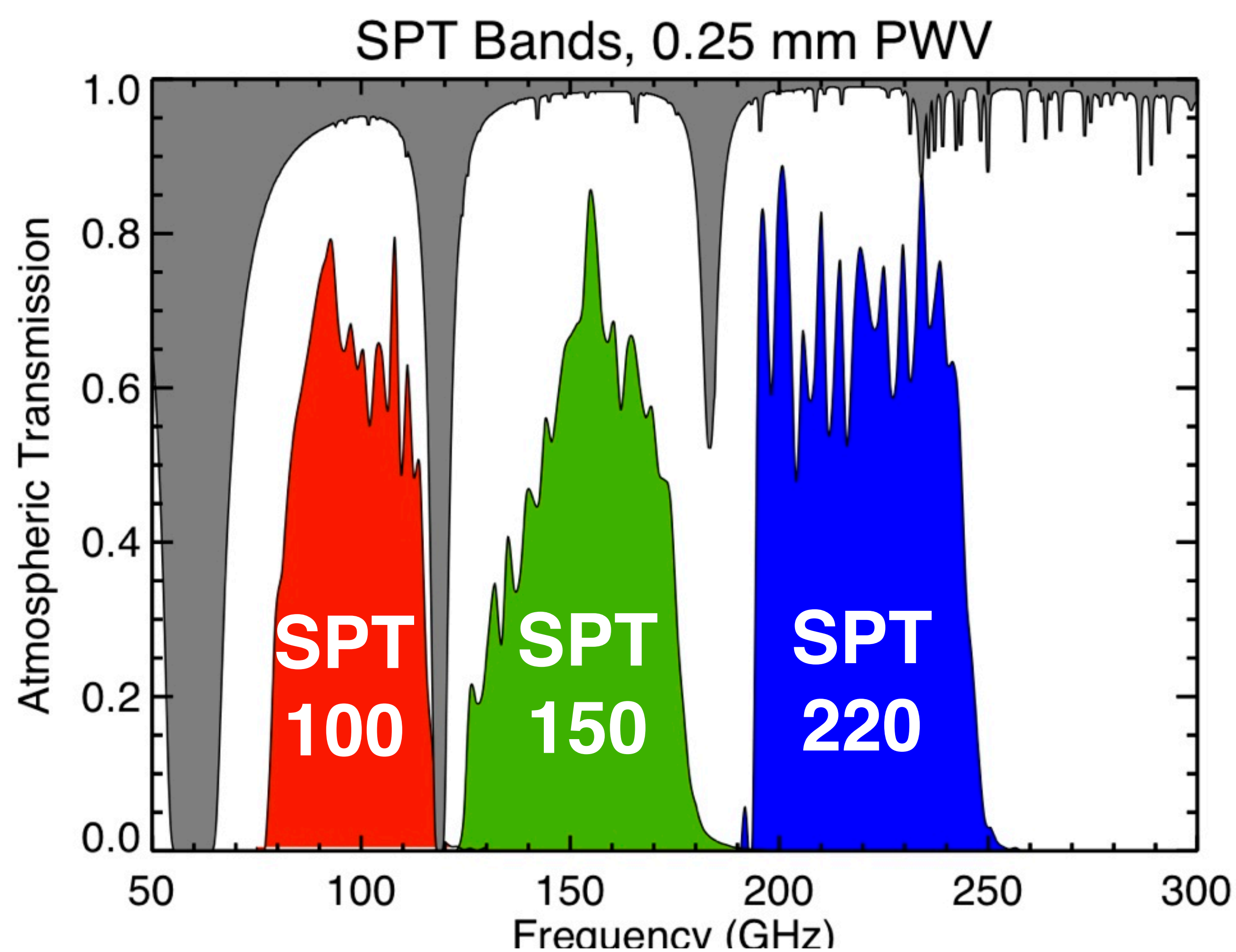


SPT-SZ Focal Plane Optics

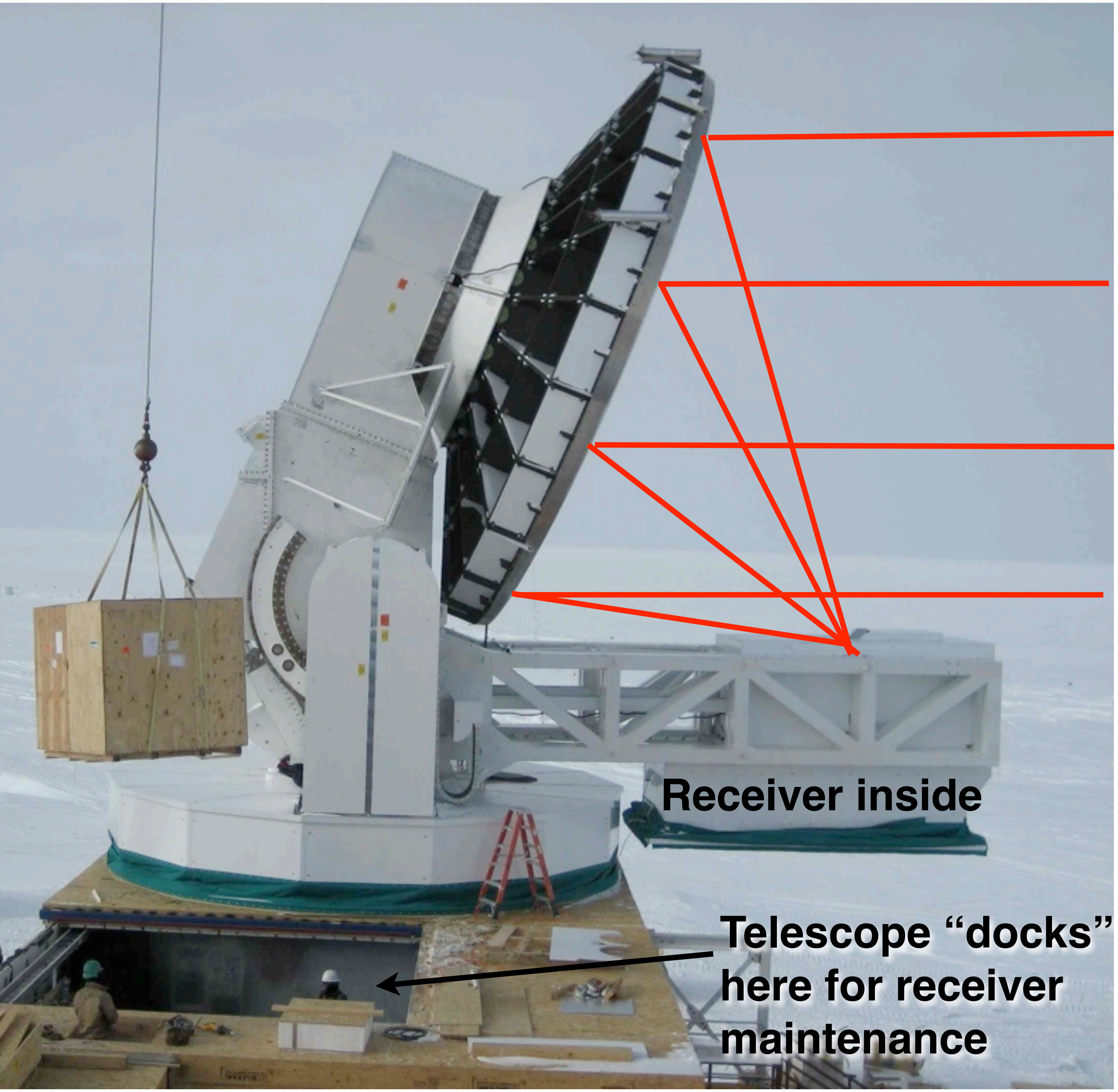


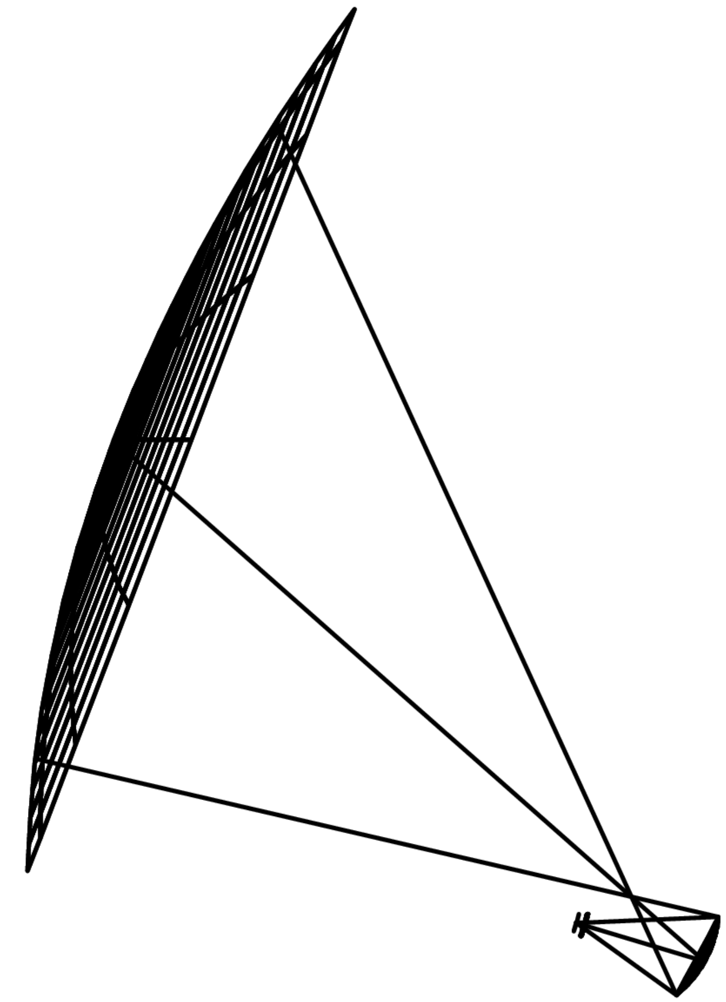
- Light coupled to the detectors thru a:
  1) ***machined conical horn array,***
  2) ***waveguide,*** and
  3) ***integrating cavity***

- Frequency response set by waveguide at low frequencies, and metal-mesh filters at high-frequency.
  - Waveguide also acts as RF seal to protect readout wiring



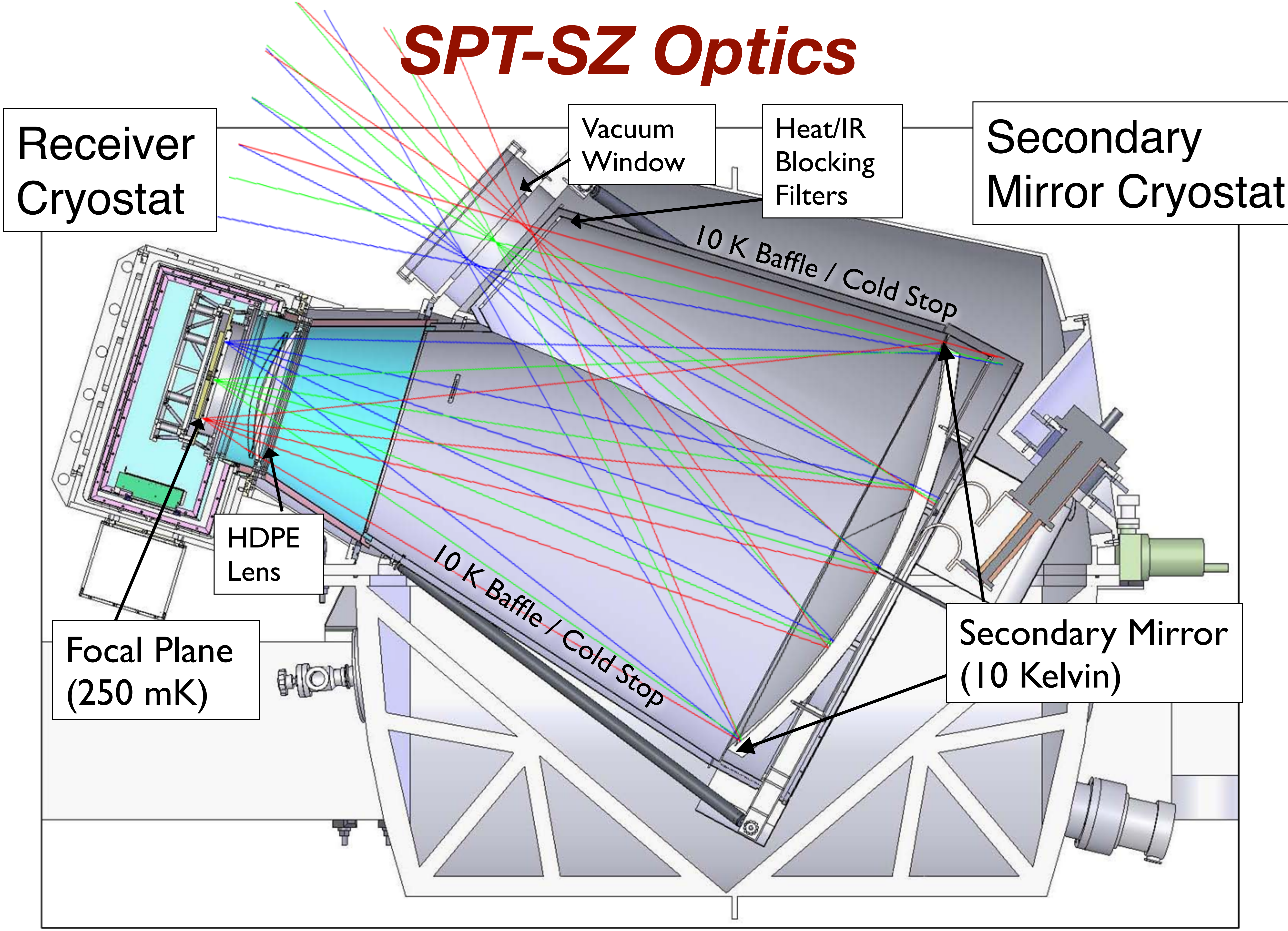
SPT-SZ Optics



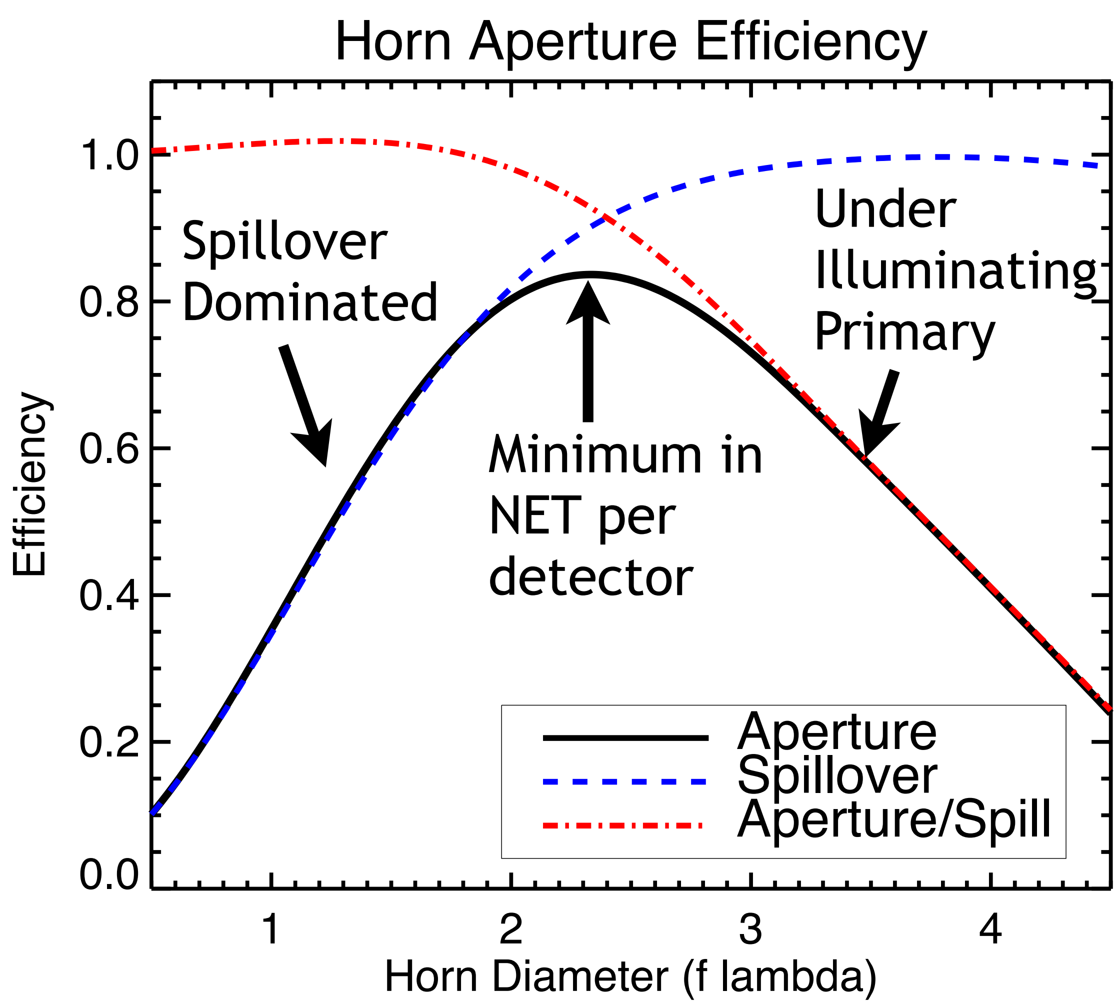


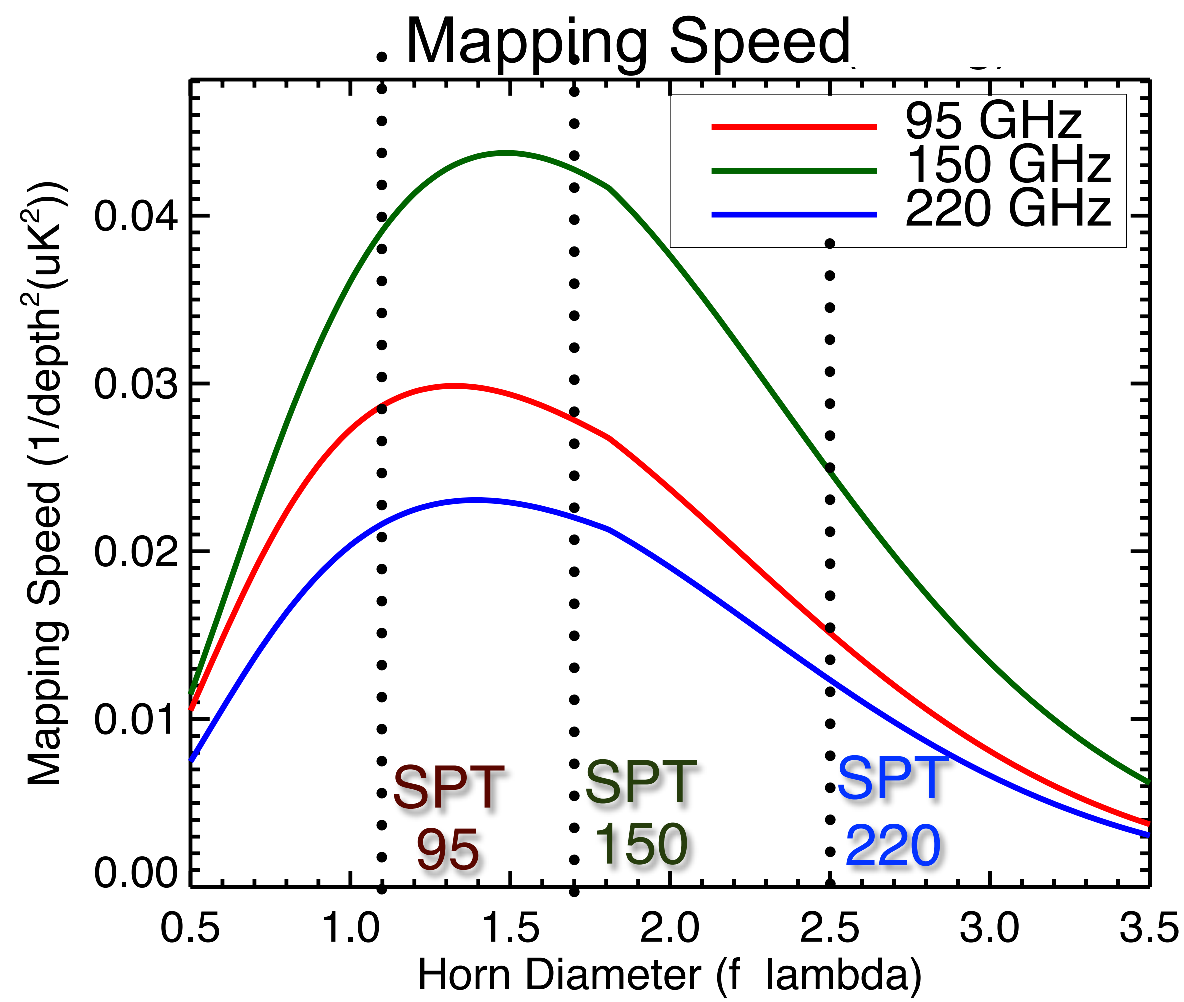
- Off-axis Gregorian design
- Fast optics = low-f number = large field-of-view = physically small pixels
- Secondary mirror and receiver in "cabin" that moves with the telescope

SPT-SZ Optics



Optimizing Mapping Speed





- Pixel size (or horn diameter) affects mapping speed
- Horn diameter of ***~ 2.2 f λ maximizes coupling to telescope per detector*** (matches pixel to Airy disk / diffraction-size of telescope), but ***number of detectors increases as 1 / (horn diameter)²***

→ **Mapping speed peaks at ~1.5 f λ horn diameter (4.2 mm at 150 GHz)**

- For SPT, we kept horn size the same at all frequencies to minimize fab complexity, and to bracket maximum speed at 95 and 150 GHz

Effect of Pixel Size on Focal Plane Speed

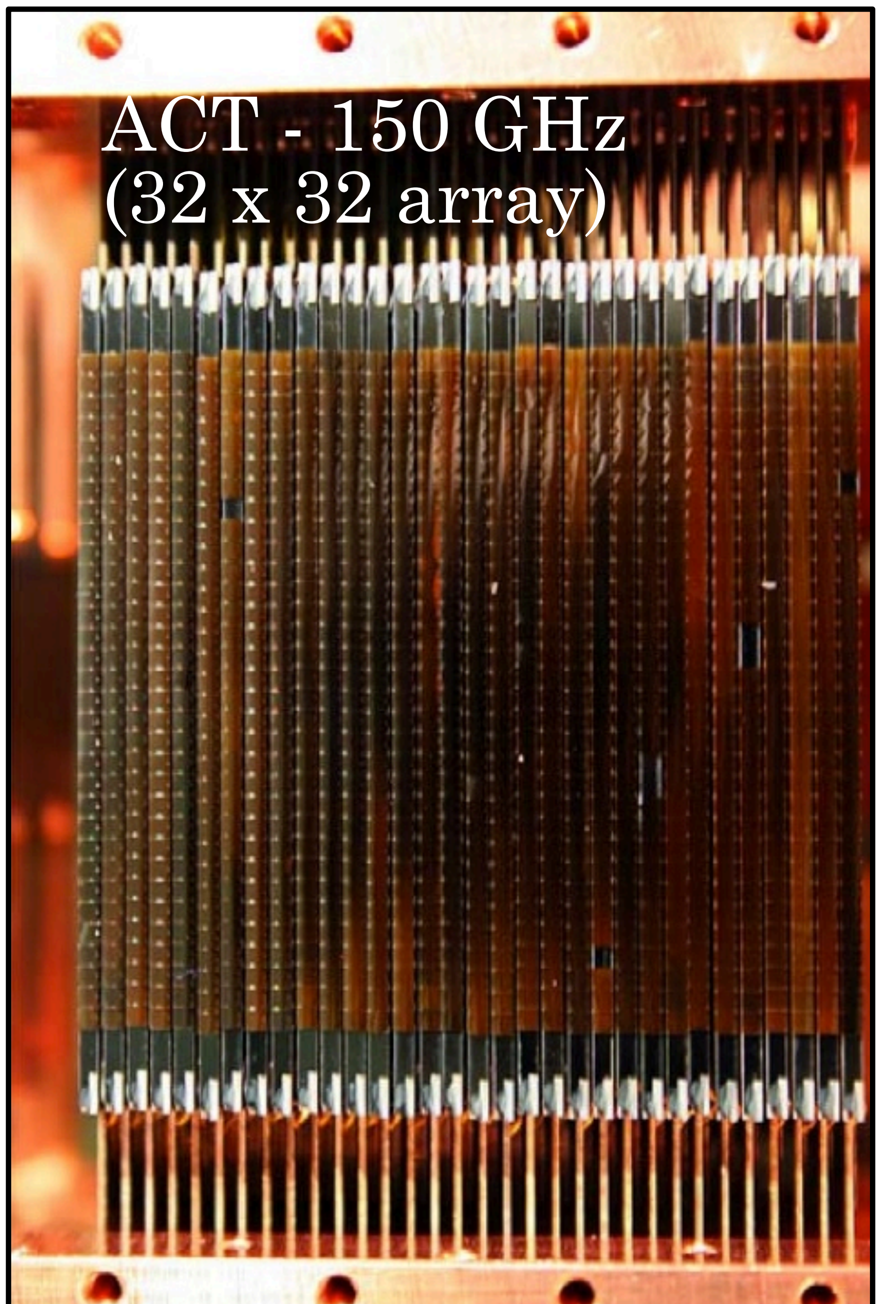
ACT 150 GHz focal plane
- 0.5 f λ pixel size
- NET_{bolo} ~ 900 mK $s^{1/2}$

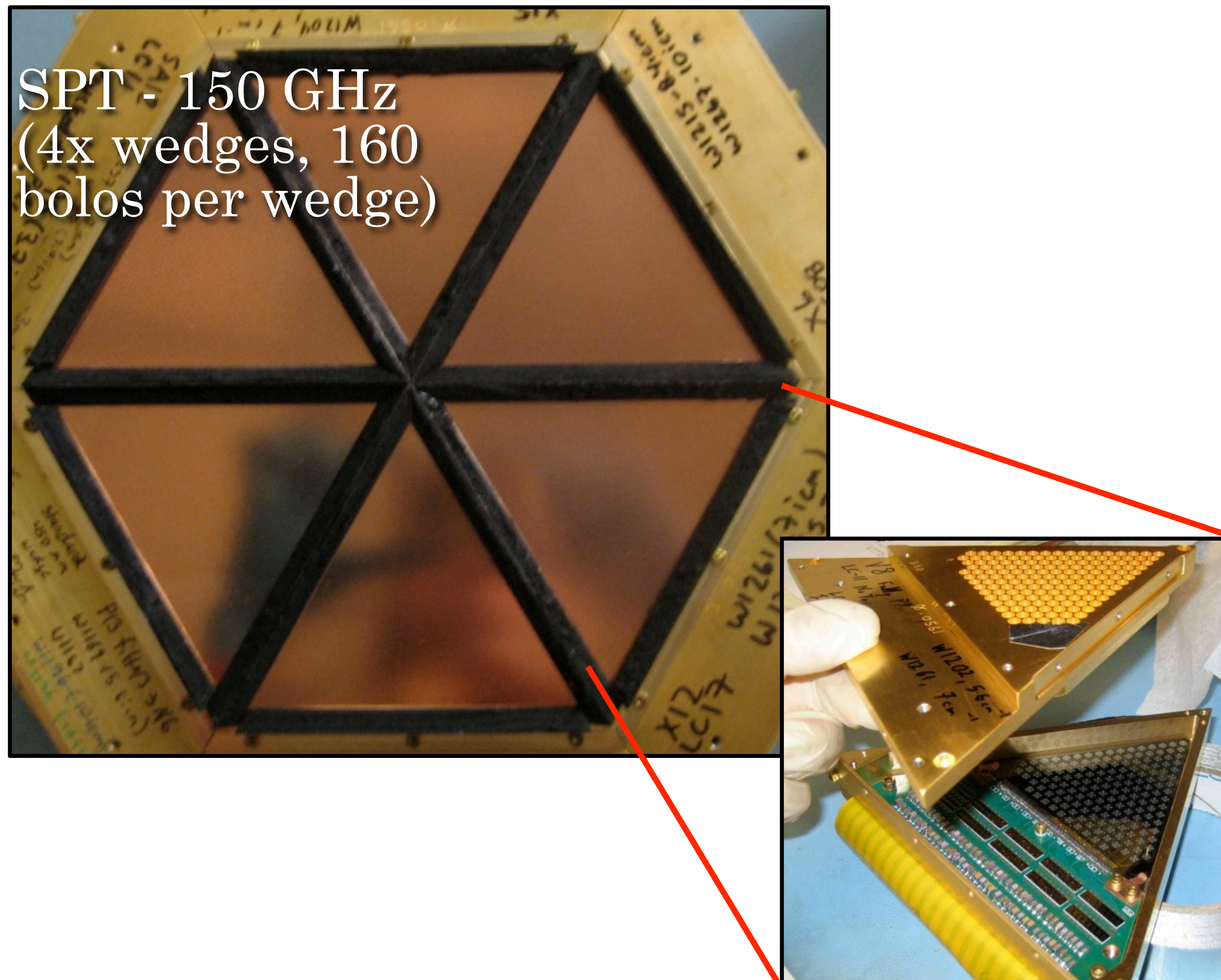
~700 "working" bolometers
- NET_{150} ~ 35 mK $s^{1/2}$

SPT 150 GHz focal plane
- 1.7 f λ pixel size
- NET_{bolo} ~ 450 mK $s^{1/2}$

~450 "working" bolometers
- NET_{150} ~ 20 mK $s^{1/2}$

→ **SPT was ~3x faster than ACT, largely from more efficient bolometer spacing!**





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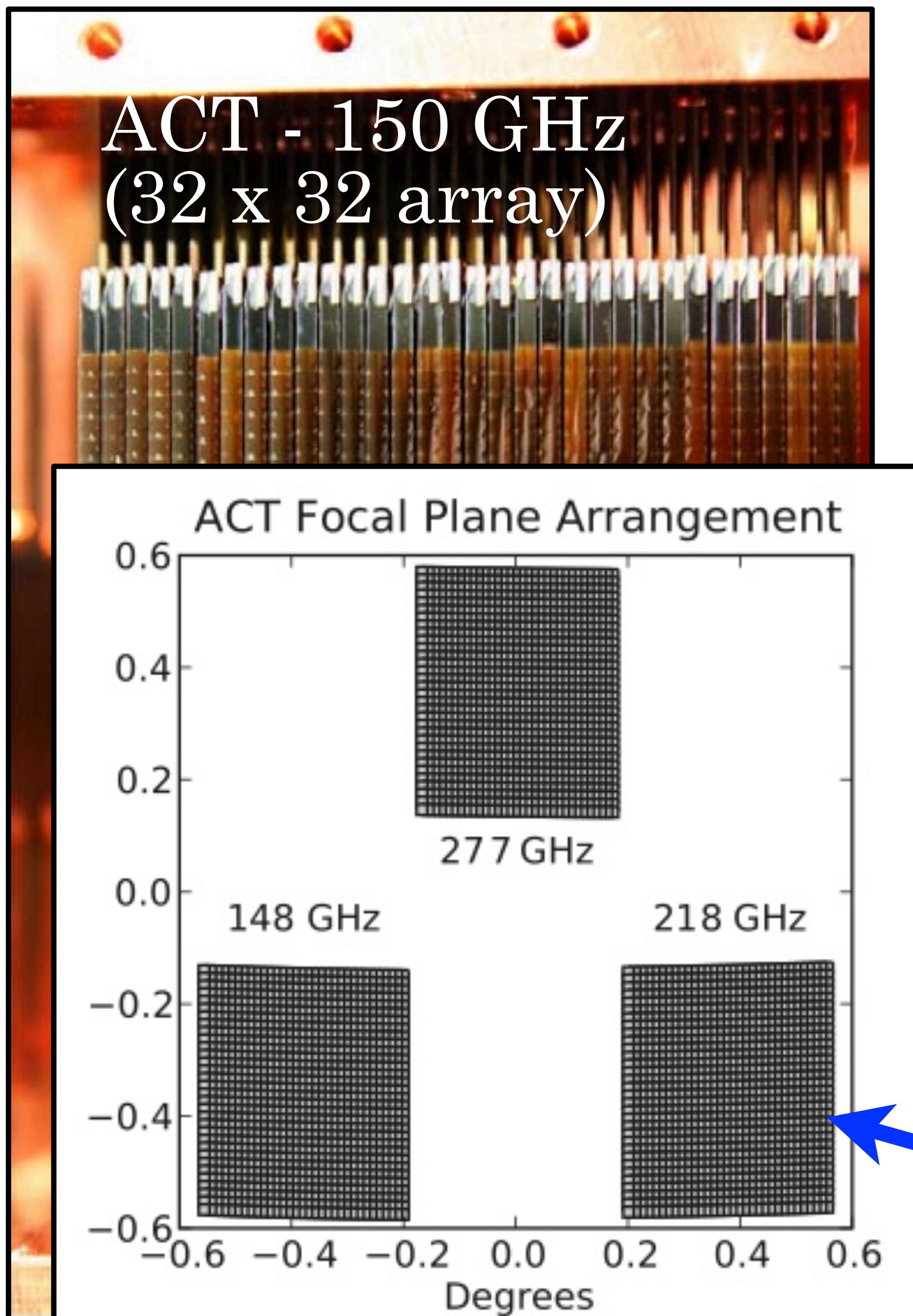
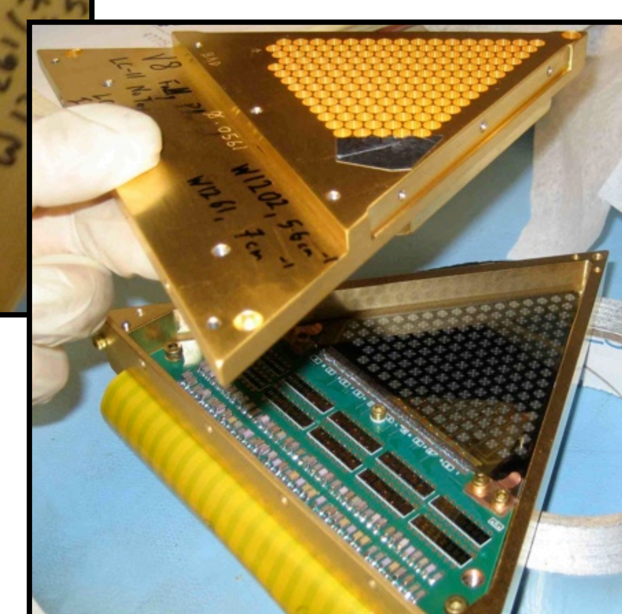


GOOD use of detectors and focal plane space



BAD use of detectors and focal plane space

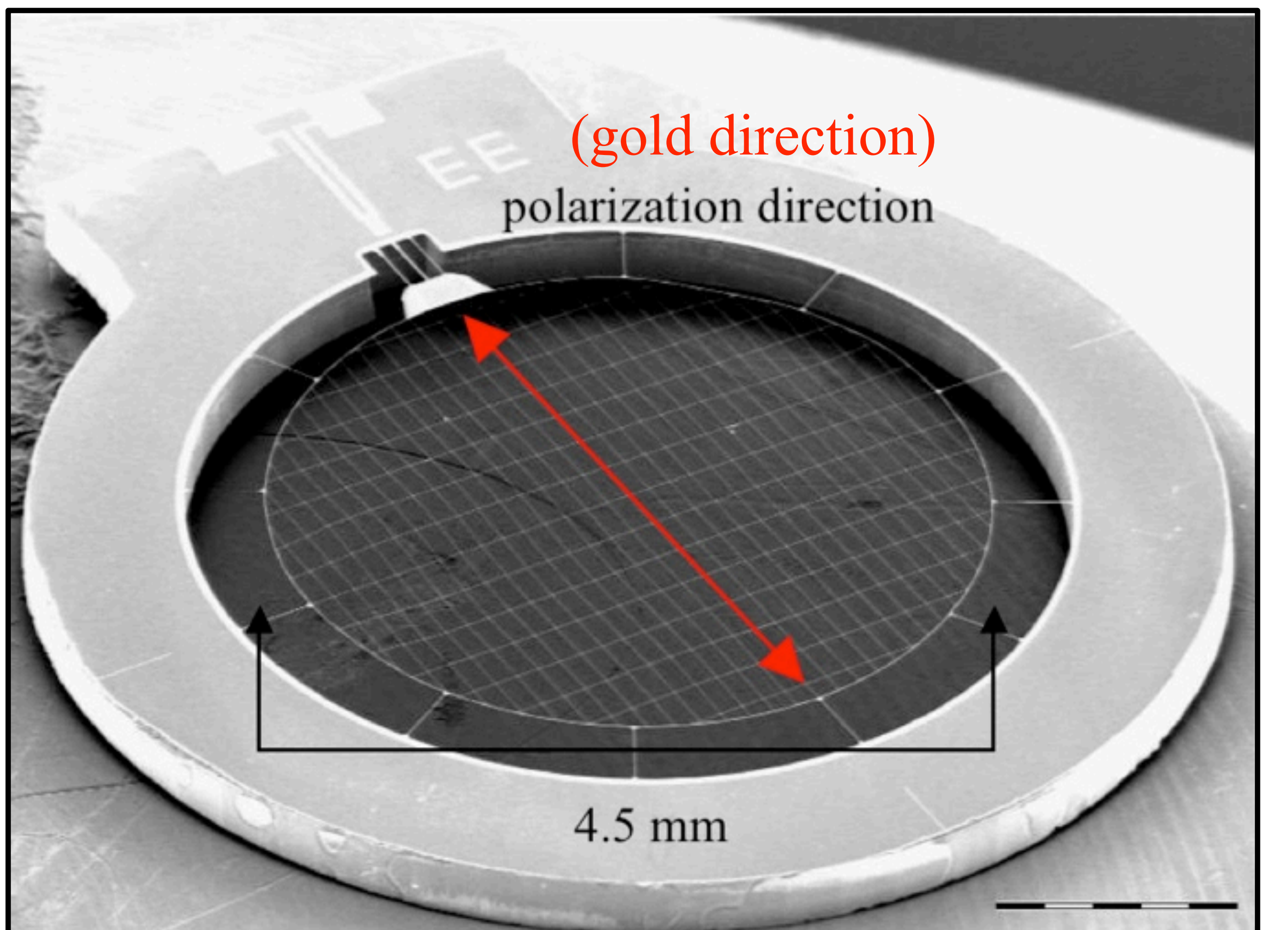
Outline

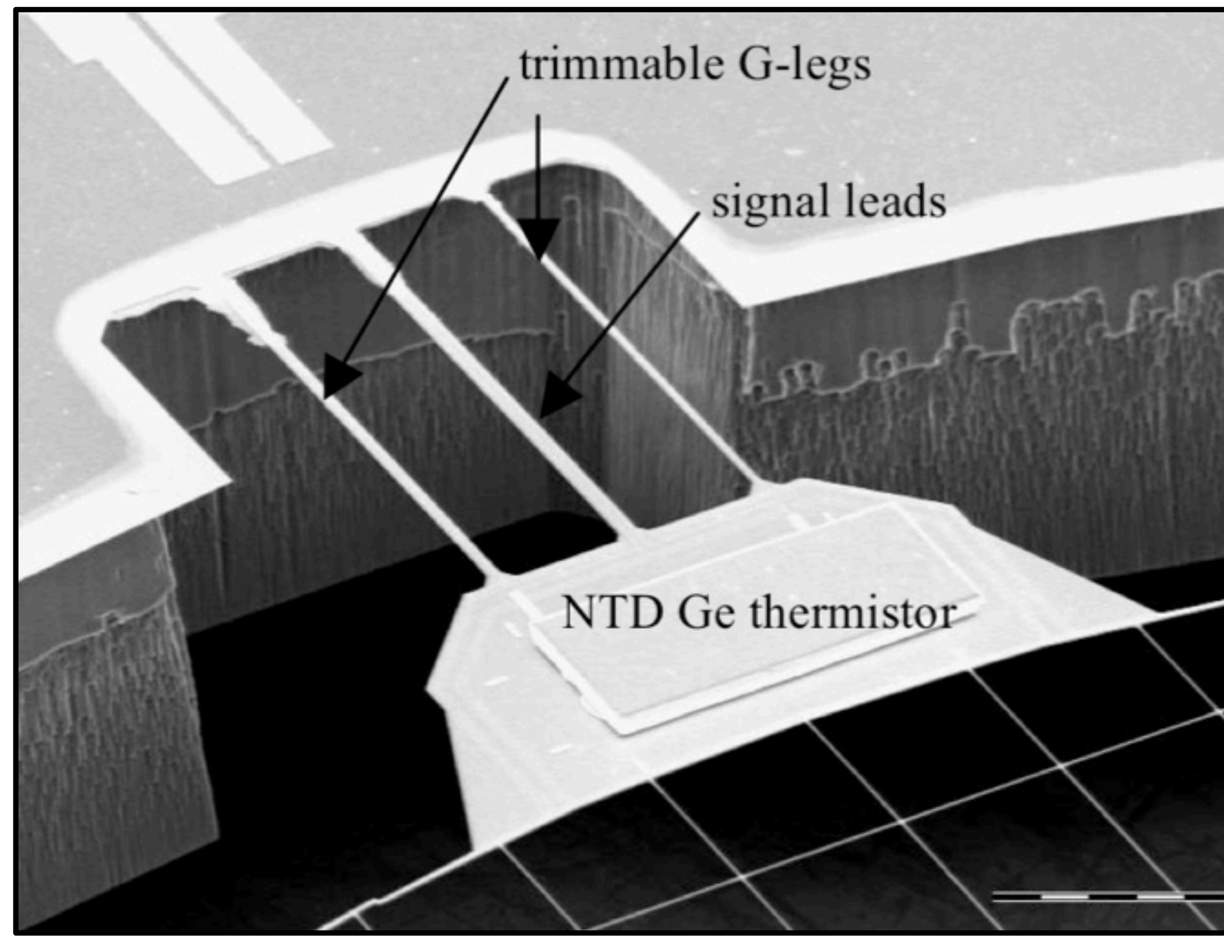
1. **Science Motivation**
    - Fundamental physics and astrophysics from the CMB
2. **Total Intensity Bolometers**
    - From hand-made bolometers to single pixels to arrays
3. **The Polarization-Sensitive Bolometer**
    - From Hand-made bolometers to single pixels to arrays
4. **Future Directions**
    - Multi-chroic pixels, MKIDs, sub-mm and optical arrays

Polarization Sensitive Bolometers (PSBs)

JPL modified spider-web concept to add polarization sensitivity

- SiN substrate with linear crossed pattern, gold added only along one direction
- NTD thermistor on edge of absorber, to minimize cross-polar response
- Design used for ***QUAD, BICEP, Boomerang2k,*** *and* ***Planck*** experiments
- Single-pixel concept needs to be scaled up for ~1000 element focal planes





SPTpol Receiver (2008-2011)

SPTpol Receiver at Chicago (2011)

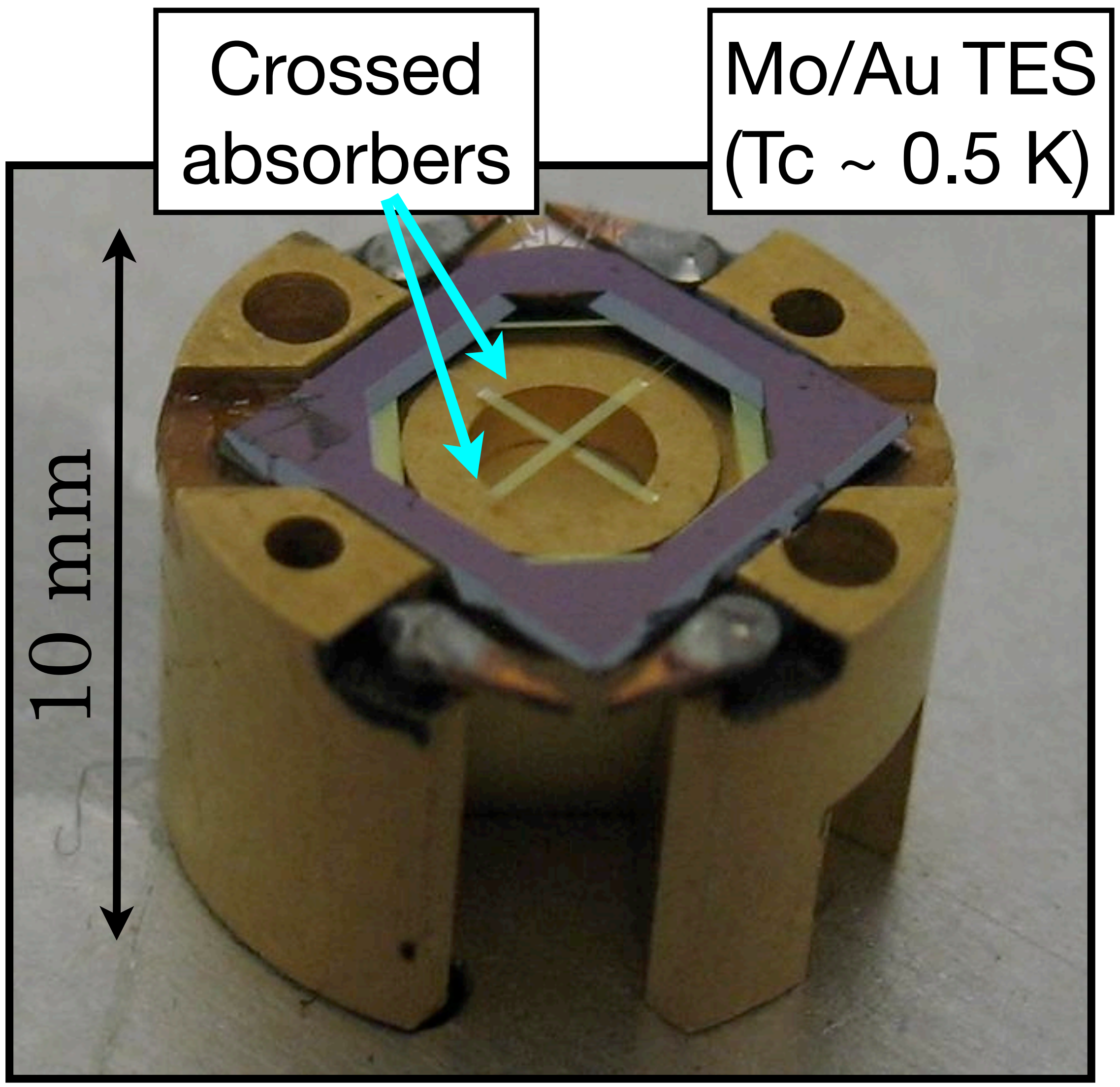
Assembled SPTpol Focal Plane at South Pole (2012)

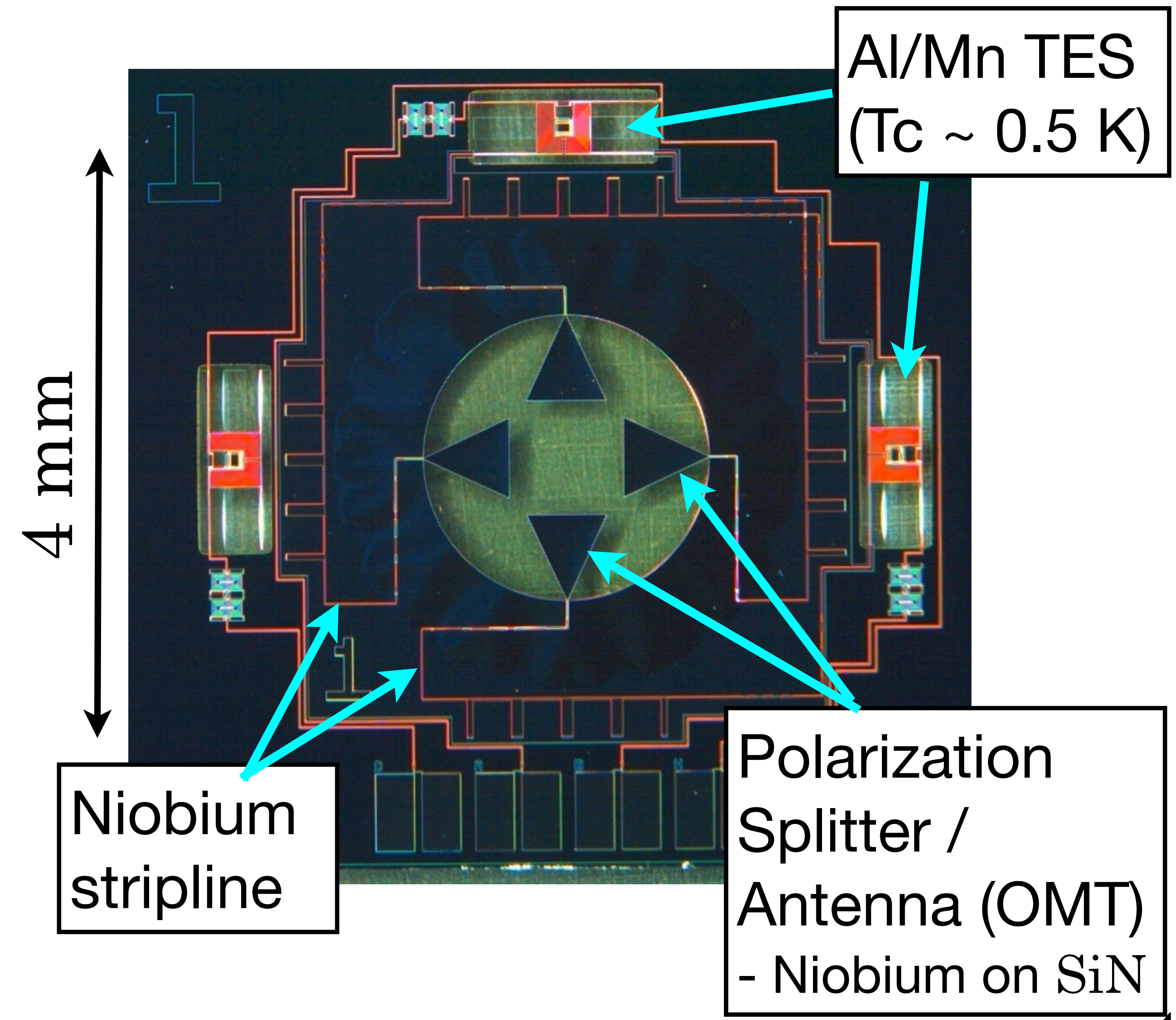
- Develop ~1000 pixel focal plane for CMB polarization science
- Receiver built at U. Chicago
- Collaborated with Argonne National Labs (ANL) and NIST (Boulder) to develop new polarization sensitive bolometers

SPTpol: Detectors

SPTpol used two different detectors technologies;

- At 90 GHz, single pixel, crossed absorbers with TES made at Argonne
- At 150 GHz, array of antenna-coupled TES made at NIST (Boulder)



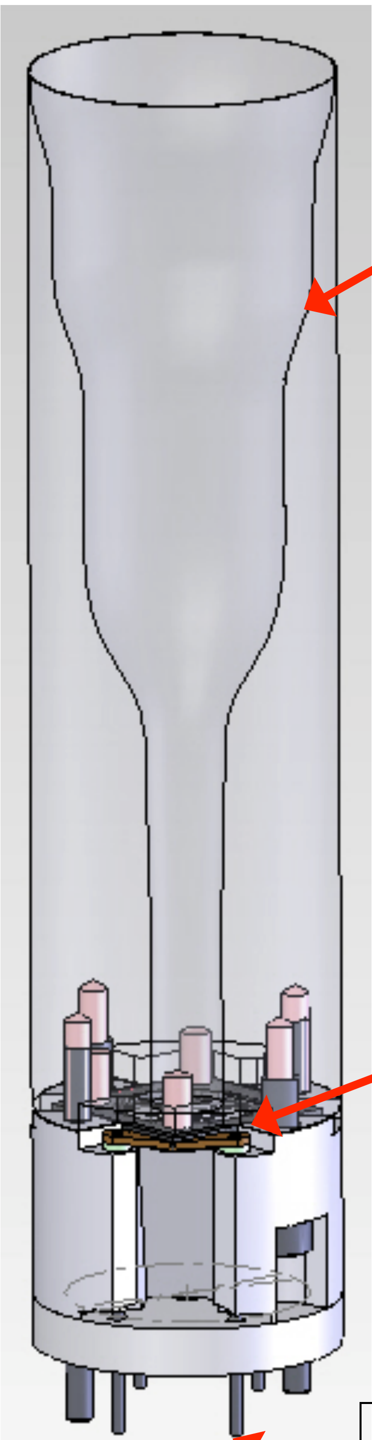


Argonne NATIONAL LABORATORY

95 GHz Single Pixel PSBs

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

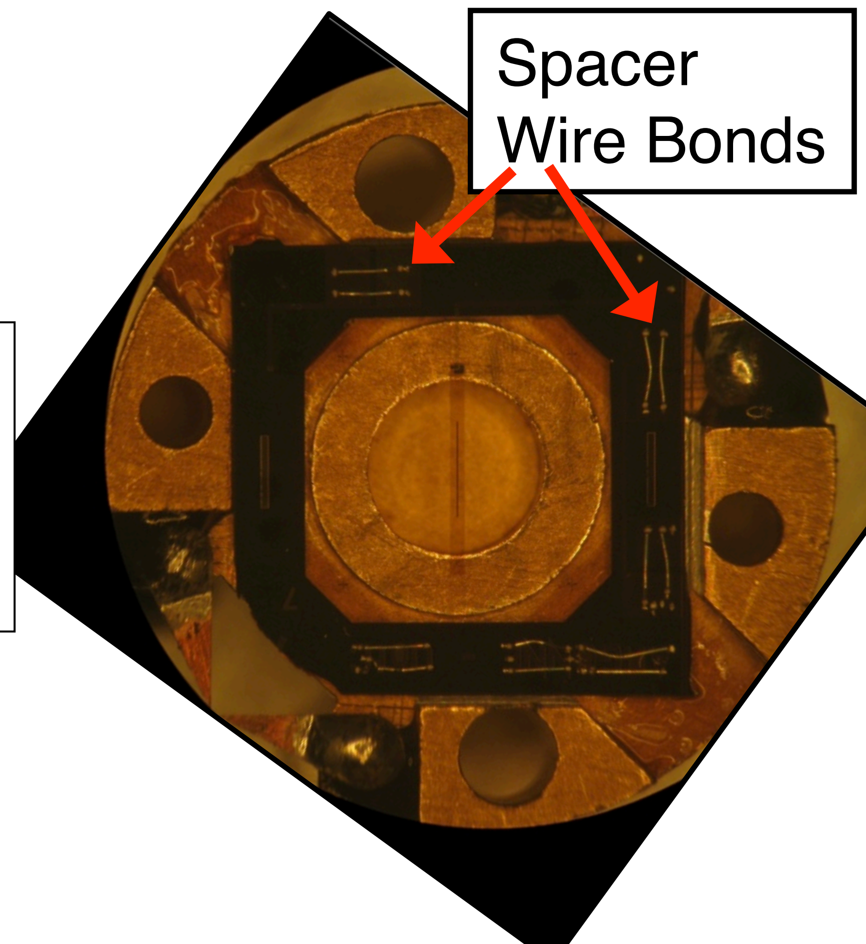
- 190 pixels at 95 GHz
  - few enough pixels, so that single-pixel design was possible, also matched ANL capabilities at the time
- Crossed absorbers with TES's in waveguide behind contoured feed horn with a $\lambda/4$ backshort
- Wire-bonds maintain ~50 mm separation between pixels



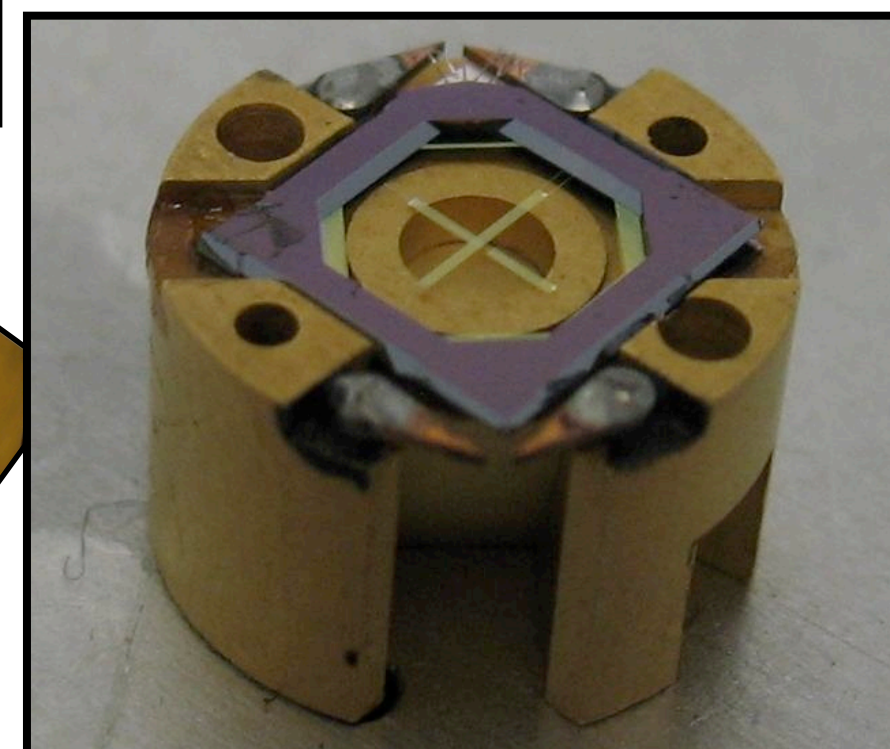
Contoured feed horn; maintains polarization angle

Detector in wave-guide section with $\lambda/4$ backshort

Readout from back via pins

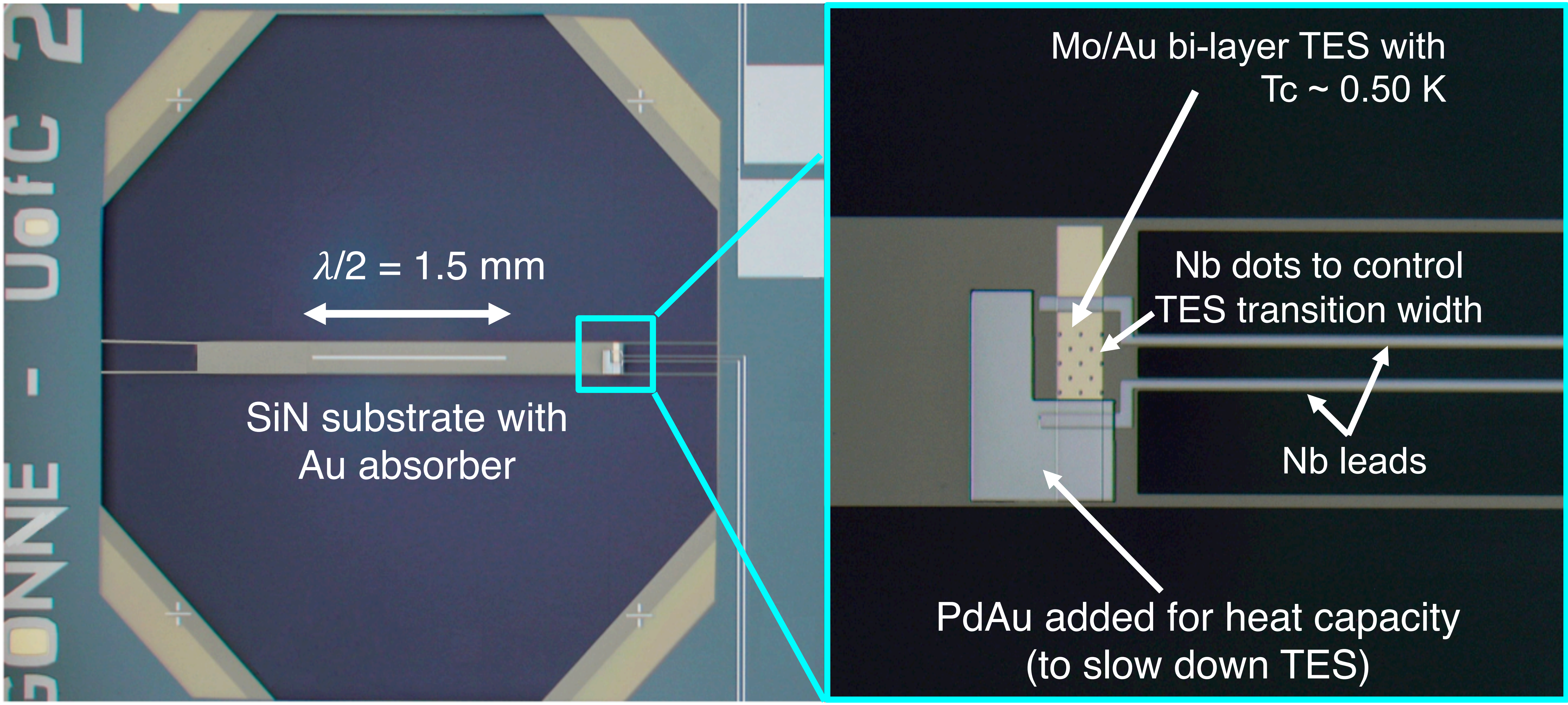


Spacer Wire Bonds



Fabricated by Vlad Yefremenko at ANL

95 GHz Single Pixel PSBs

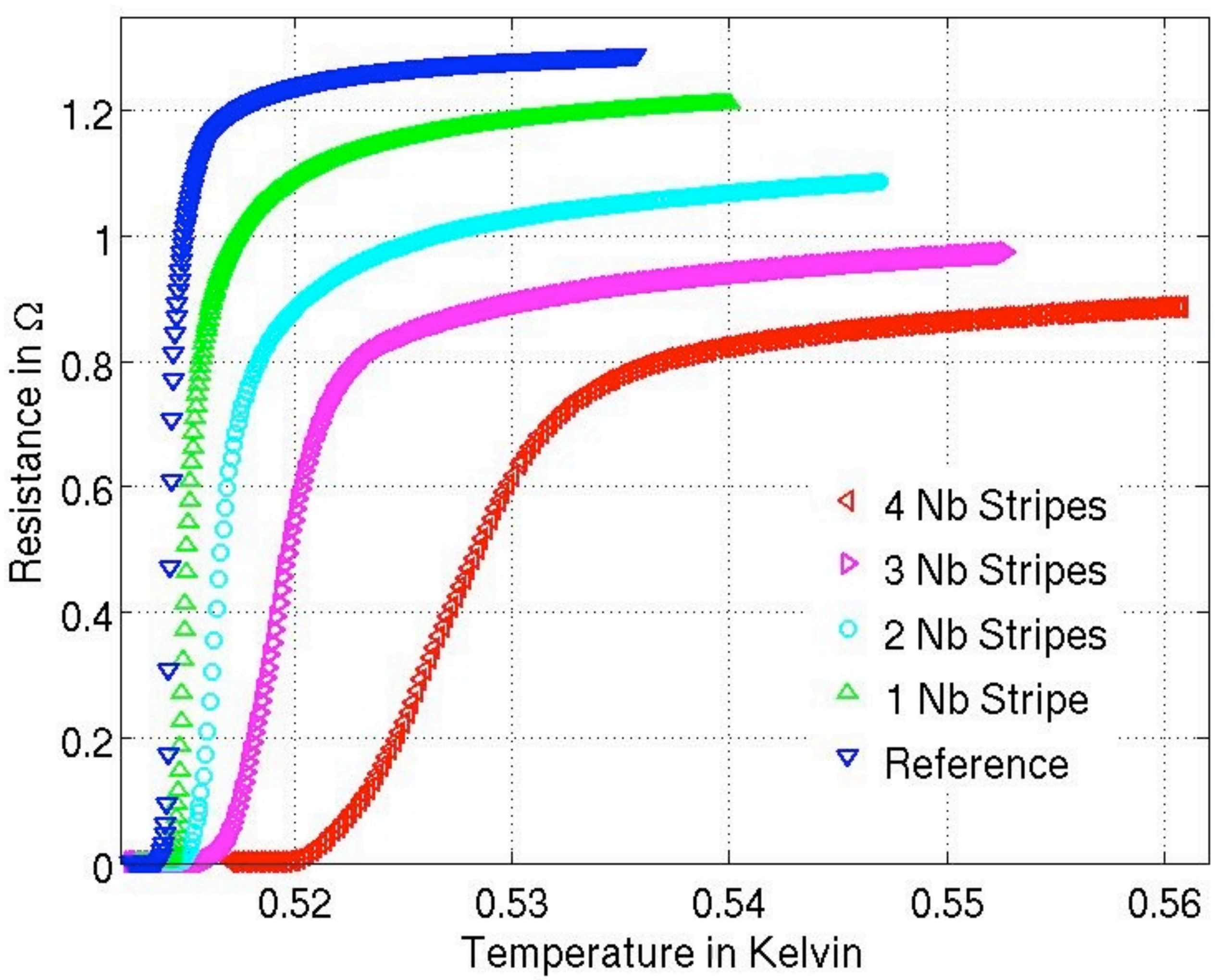


95 GHz Single Pixel PSBs

$R(T)$ curve:

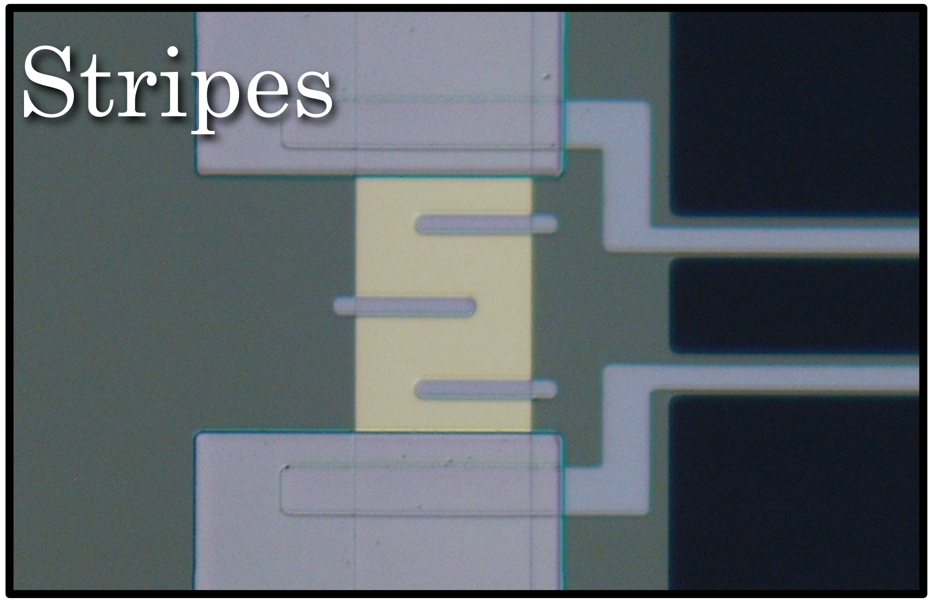
Steeper = Faster, more linear

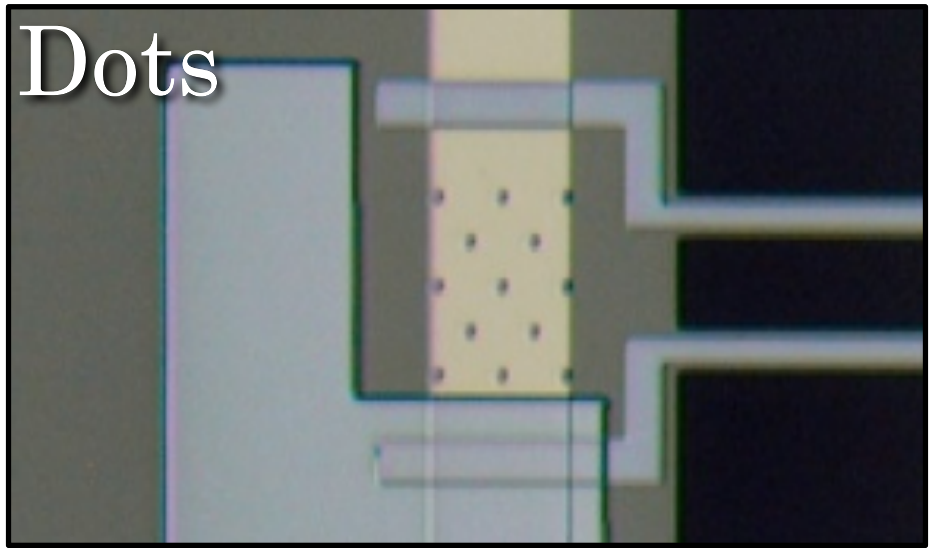
Broader = More stable



Engineer TES speed and responsivity

- Palladium-Gold (PdAu) added head capacity to slow detectors (ala SPT-SZ)
- Tested superconducting stripe and dot architecture on TES to **"soften"** $R(T)$ **curve** and **add responsivity high in the transition**



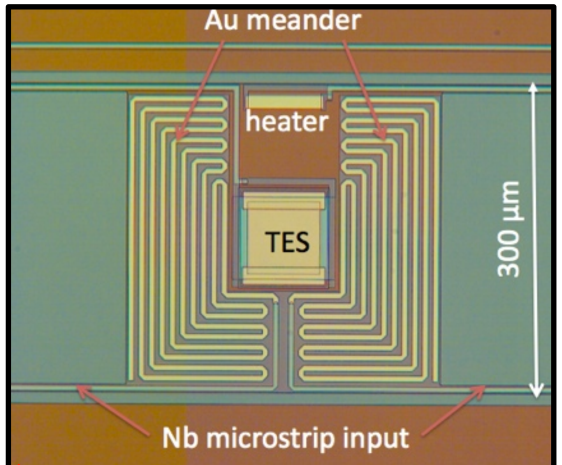


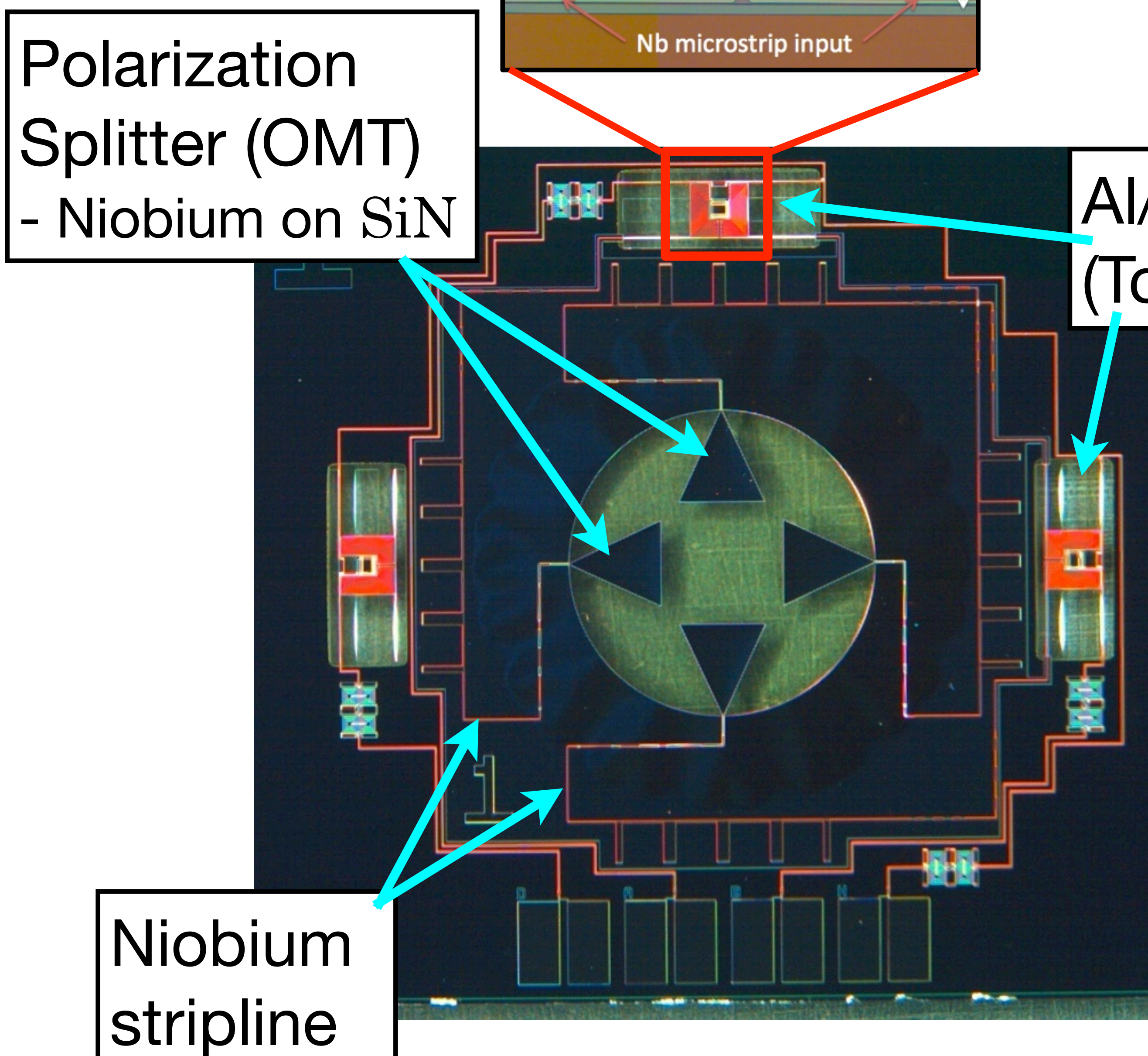
150 GHz Array PSBs

Fabricated by Dale Li,
Sherry Cho at NIST

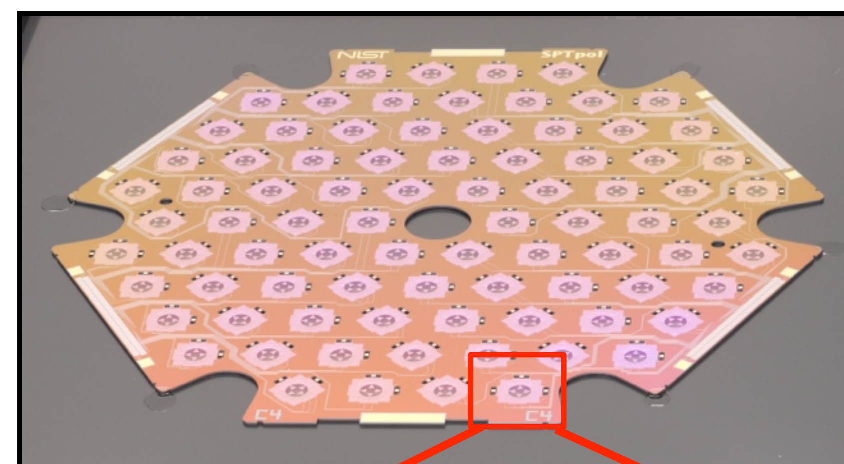
NIST 150 GHz detectors uses a new antenna-coupled TES design

- 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!***



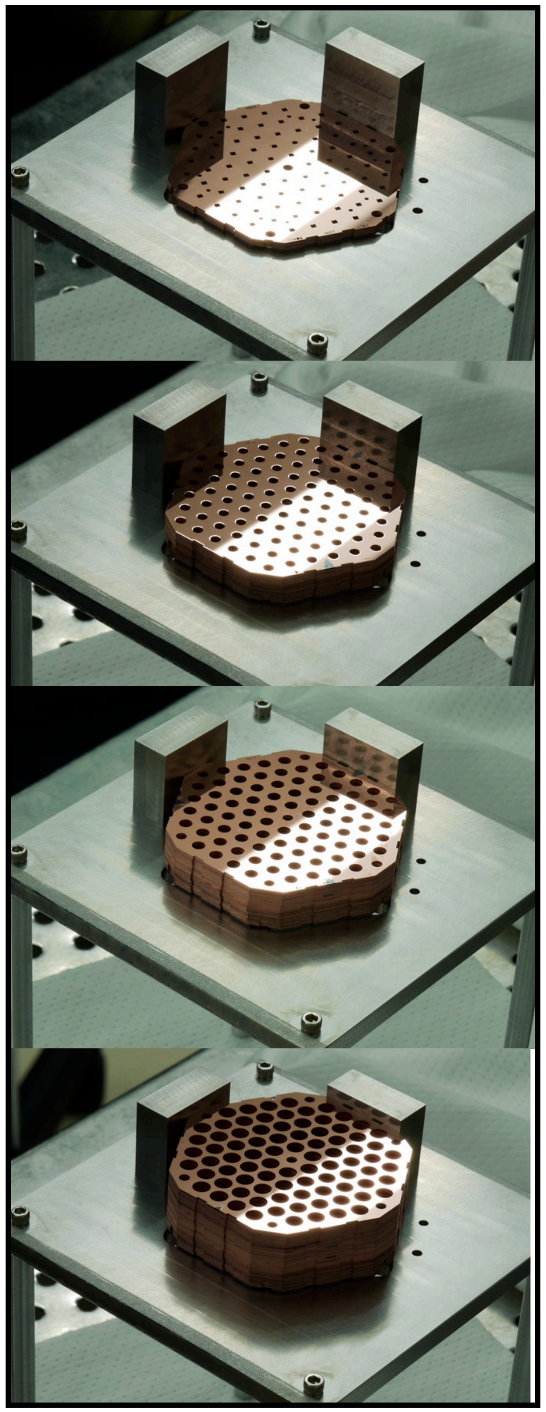


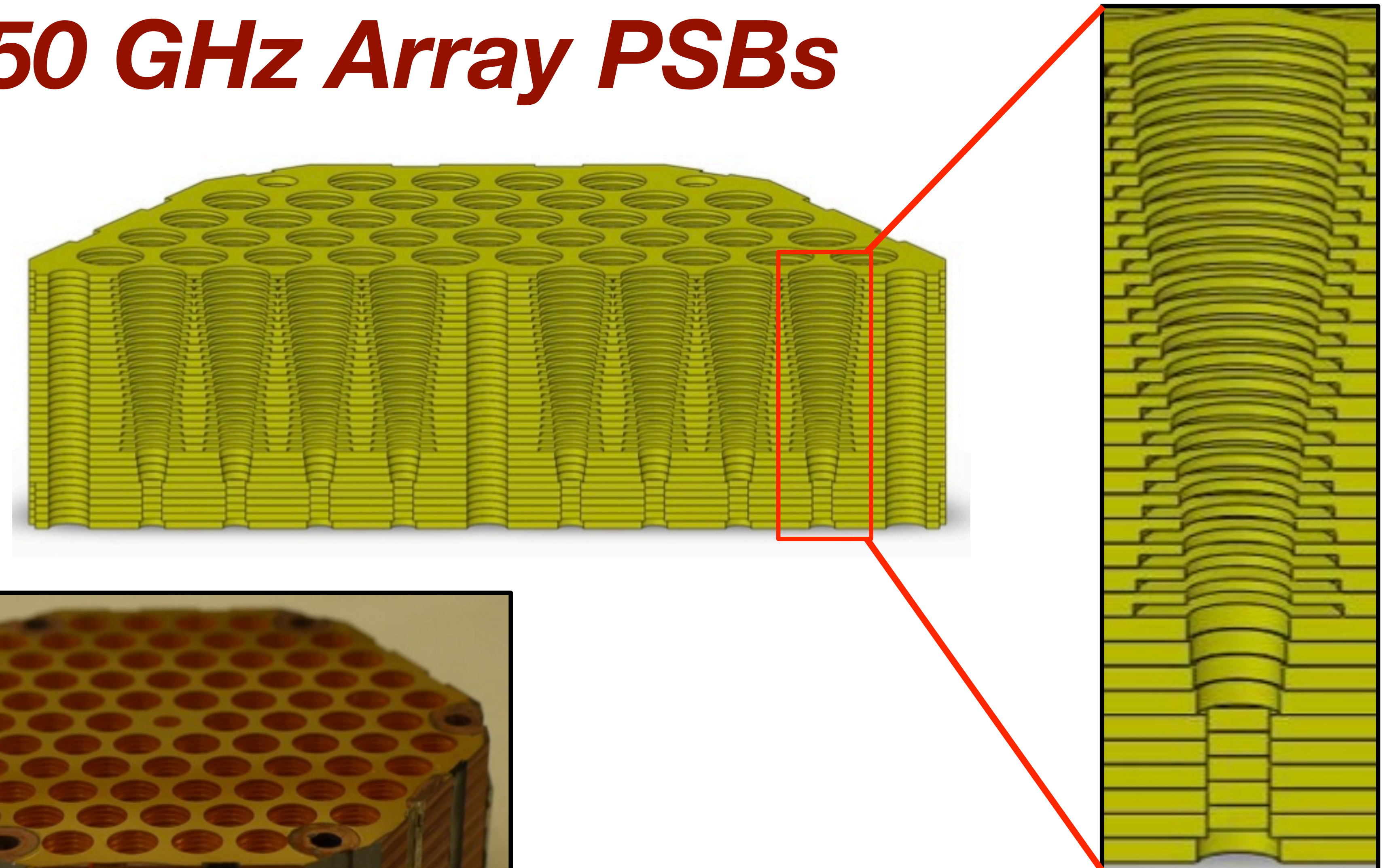
SPTpol 150 GHz
Detector Array

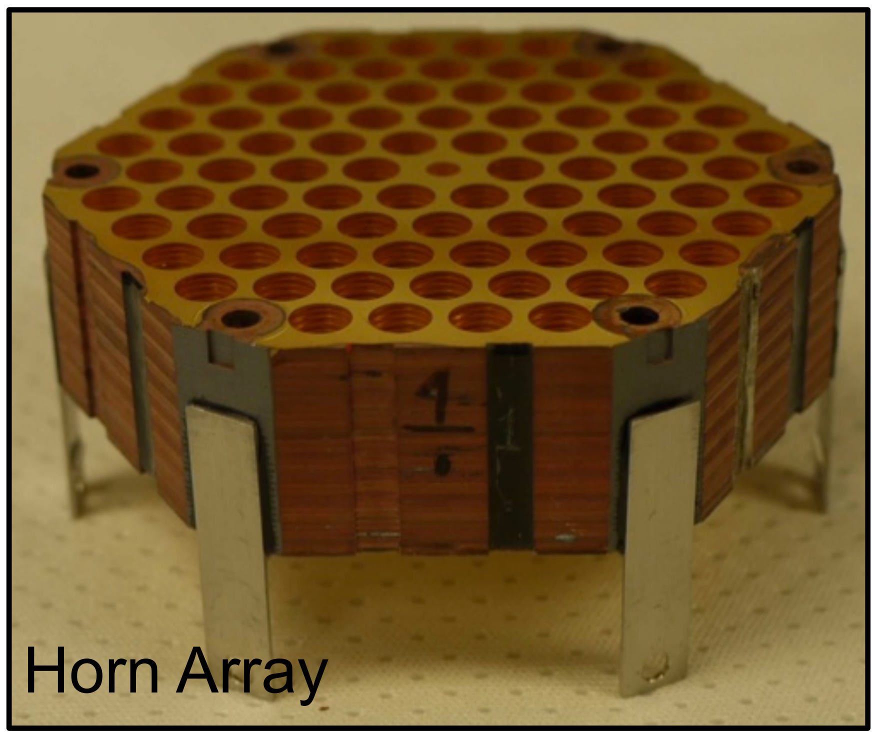


150 GHz Array PSBs

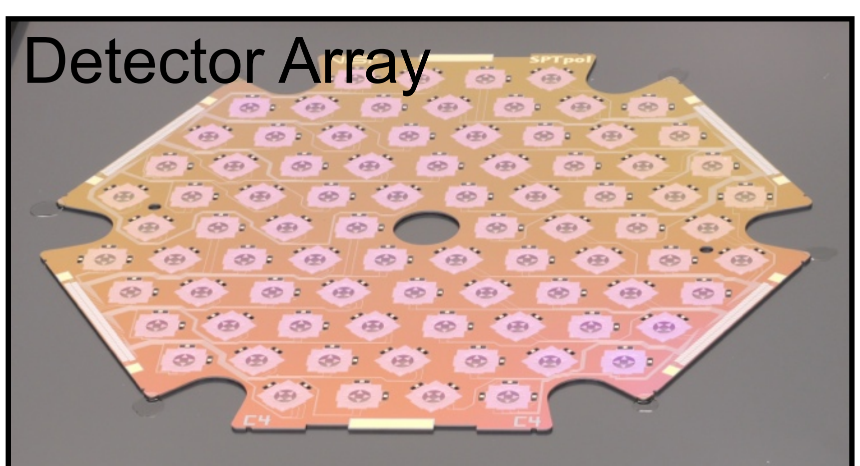
Horn Assembly







Horn Array

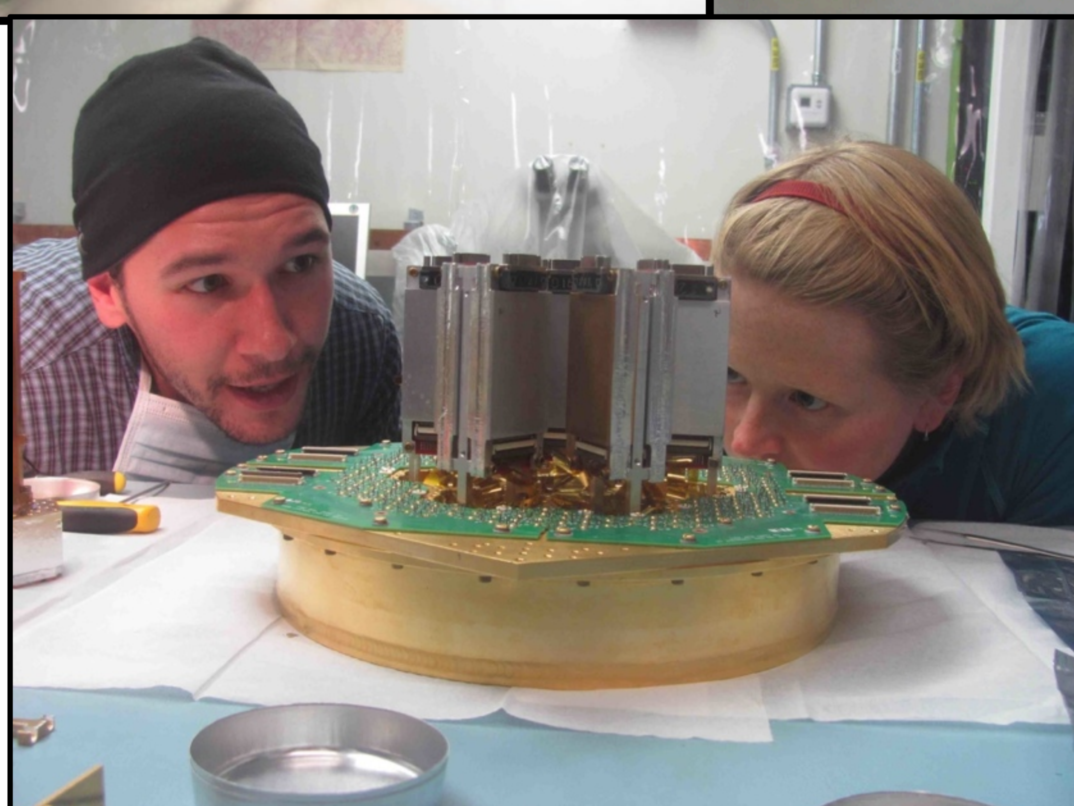


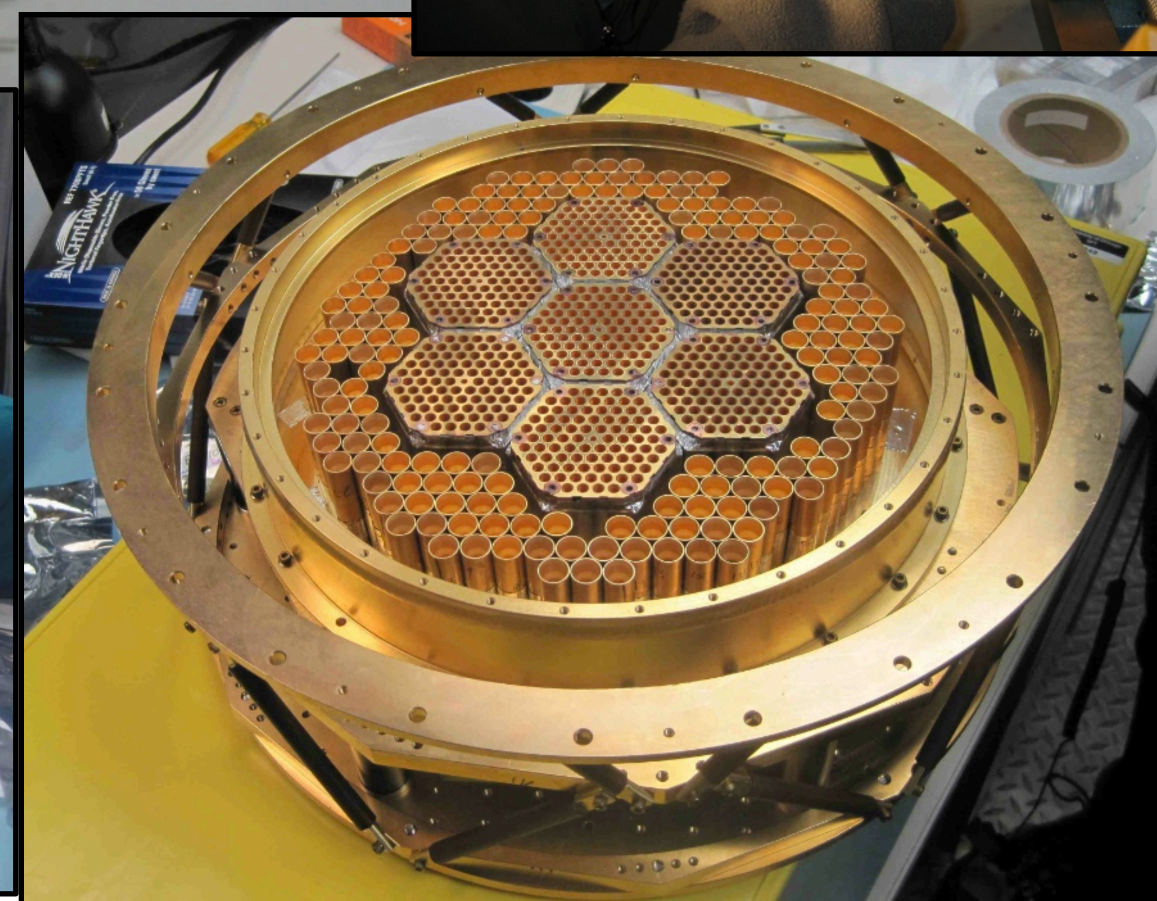
Detector Array

Corrugated feed horns

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

SPTpol Receiver





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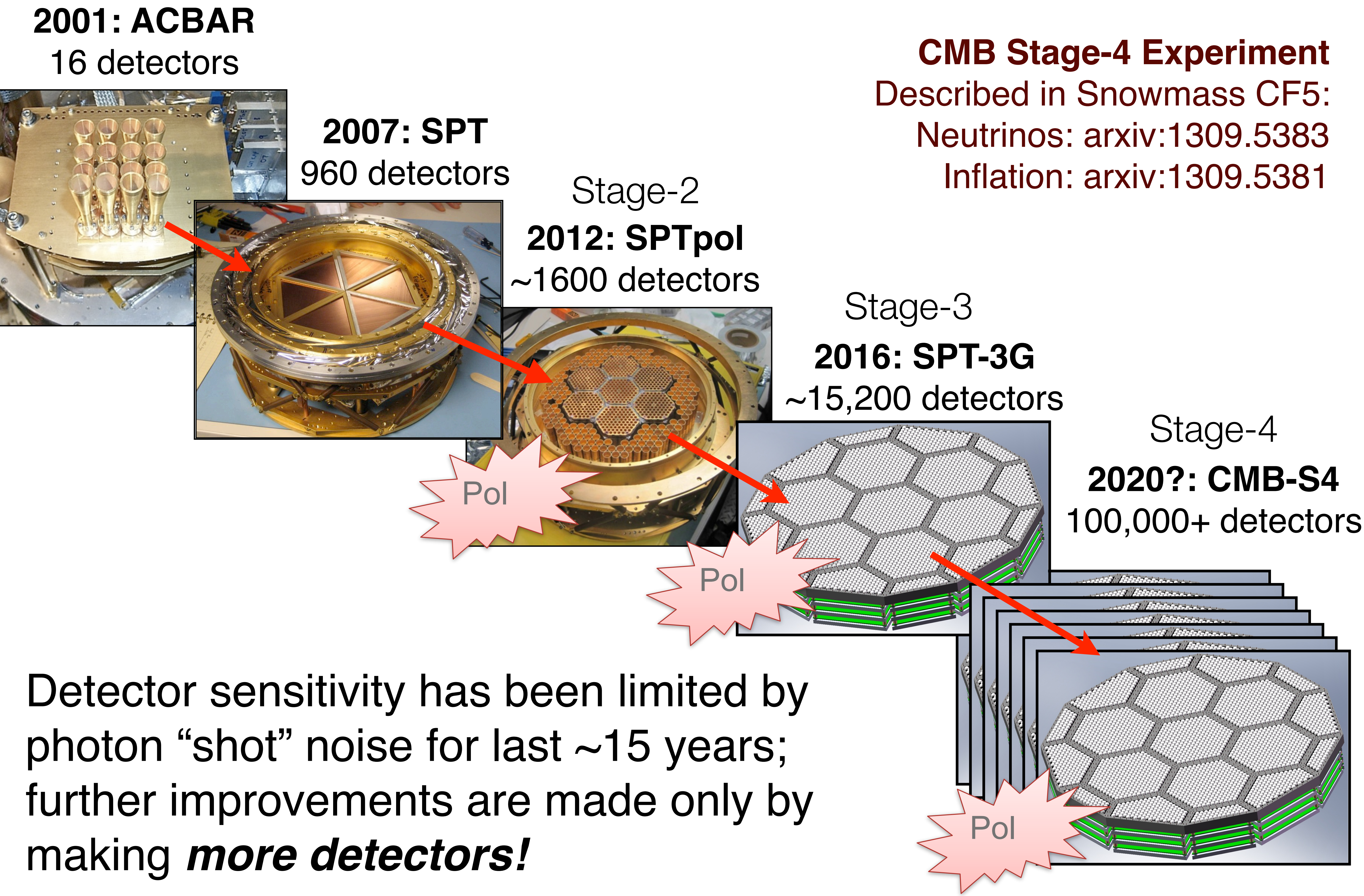
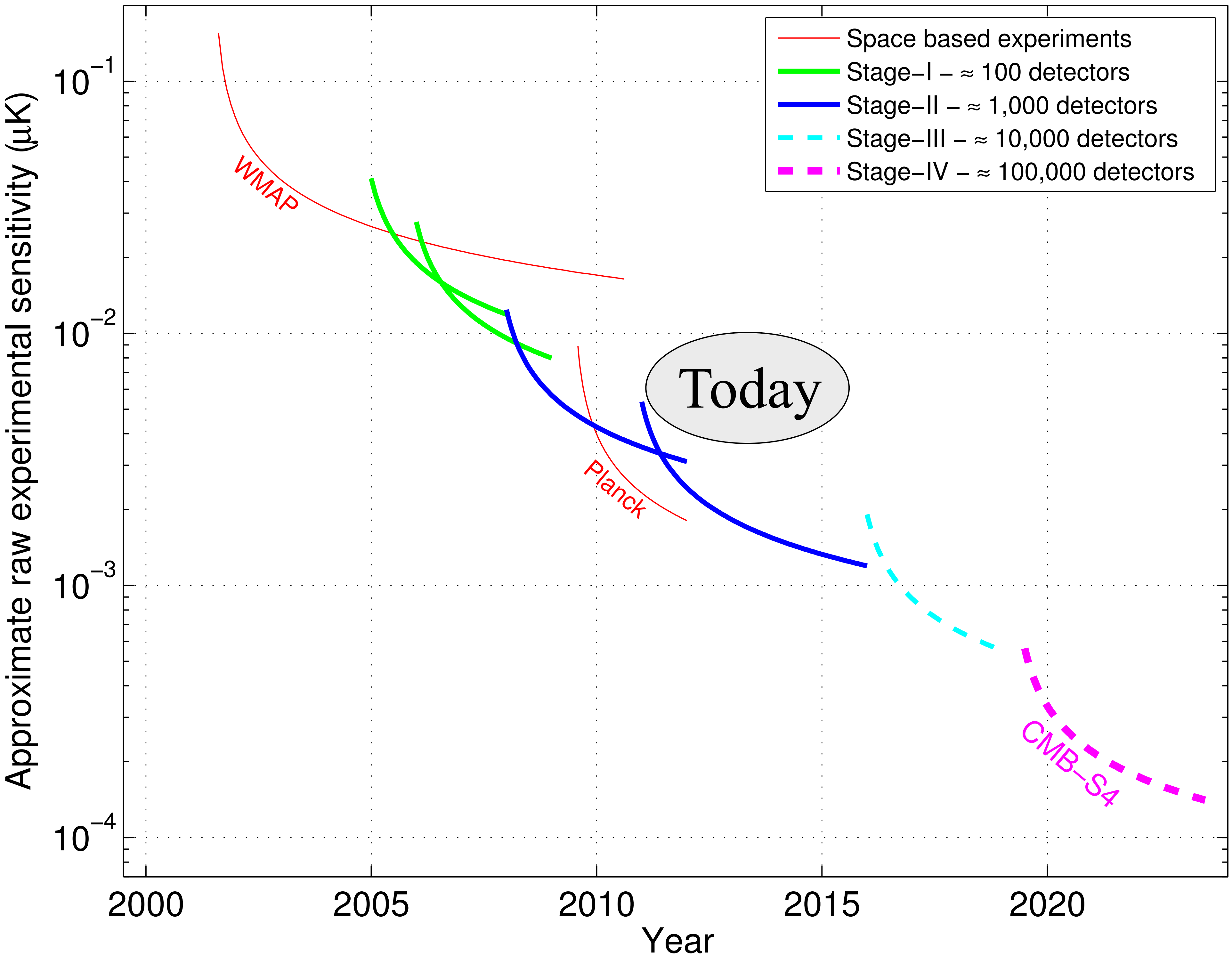
Whats next? Evolution of CMB Focal Planes

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381



Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***

CMB Experimental Stages



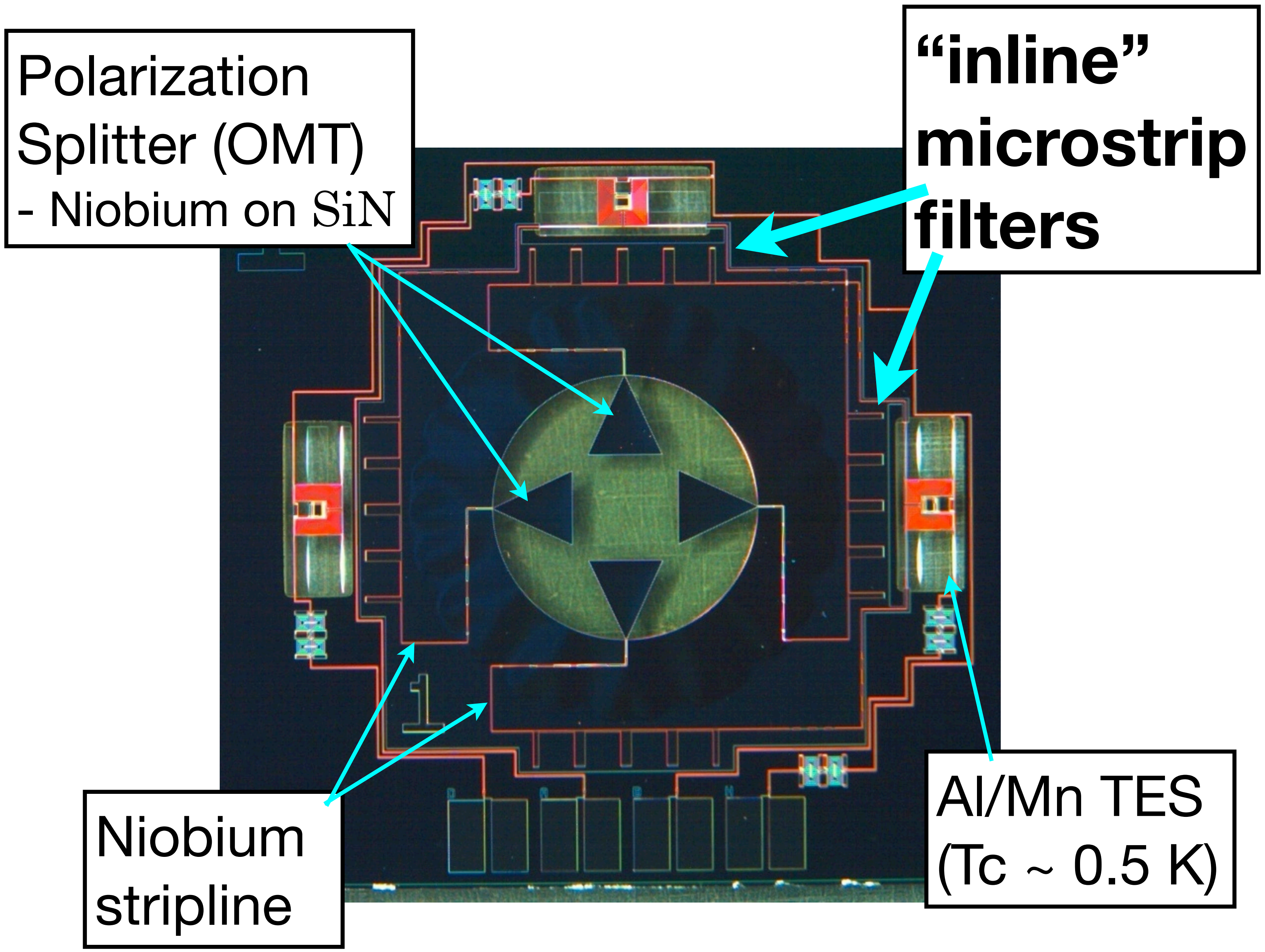
Stage-IV CMB experiment = **CMB-S4**

~200x faster than today's Stage 2 experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

SPTpol Detector: Antenna-coupled microstrip technology

Antenna-coupled architecture allows multiple detectors per pixel, **in-line microstrip filters act as band-defining filters**, therefore with a broadband antenna multiple frequencies also possible

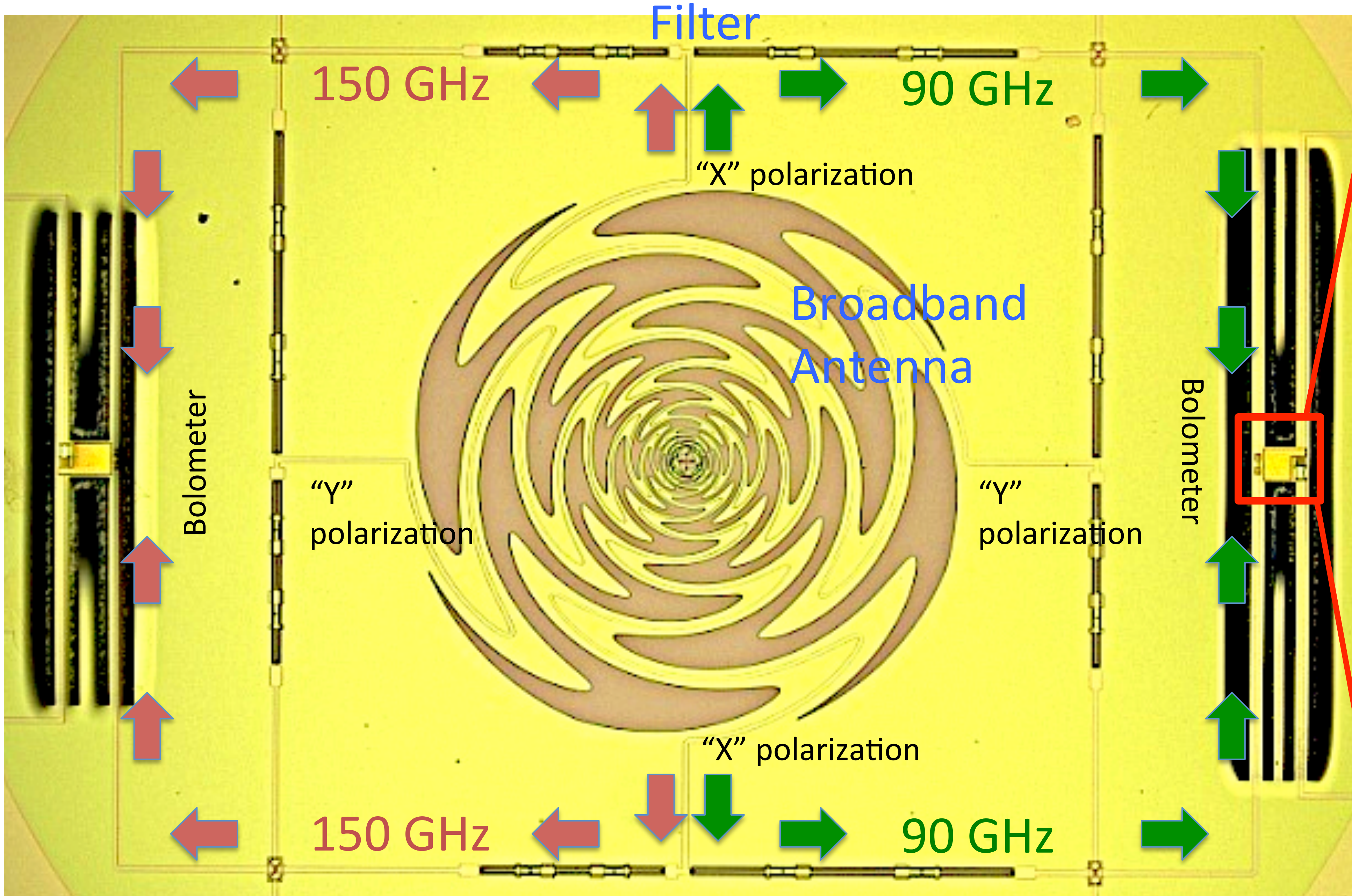


NIST

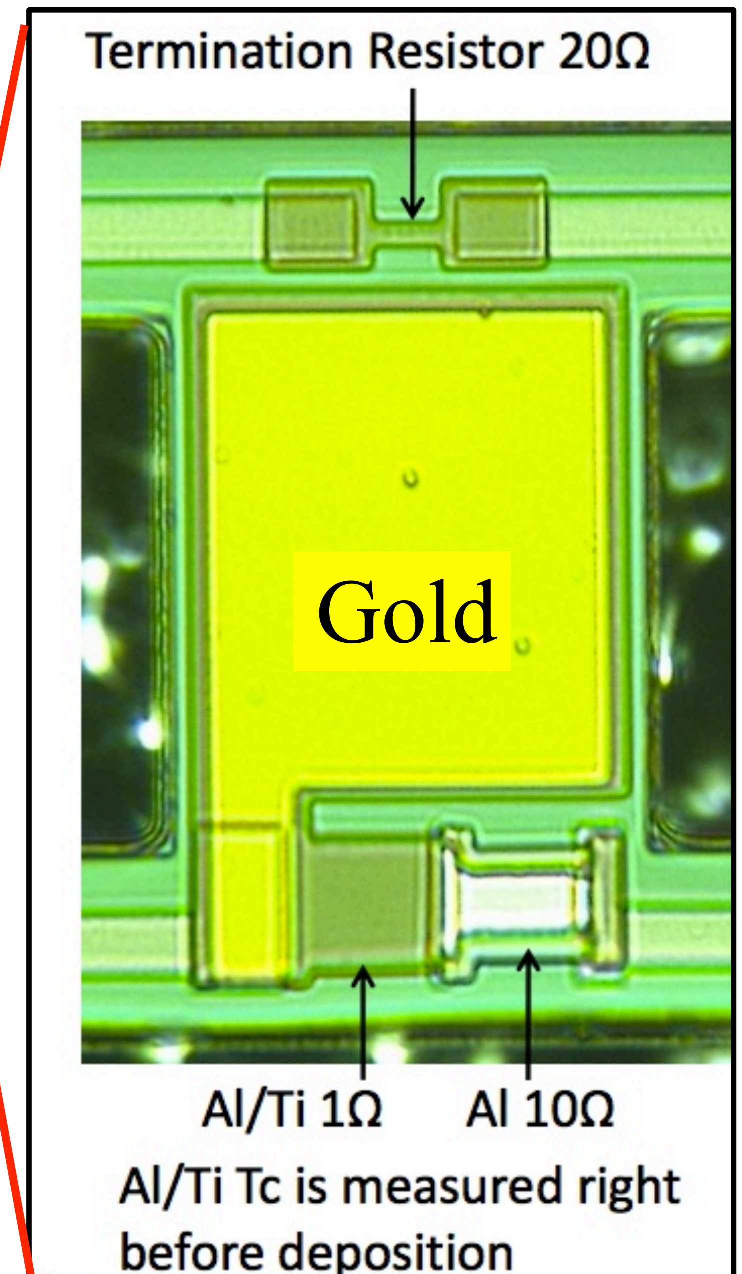
Fabricated by Dale Li, Sherry Cho at NIST

Prototype SPT-3G Multi-chroic Pixel

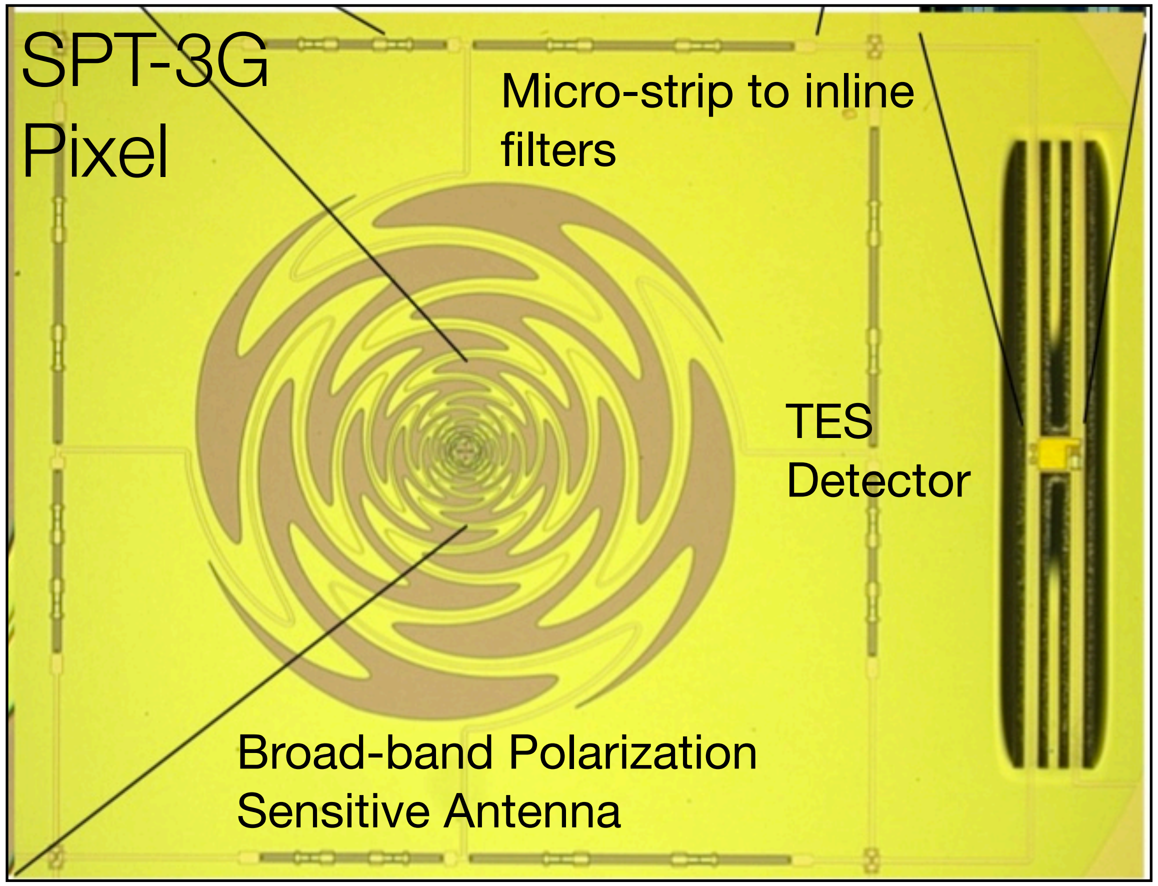
Prototype Polarbear2 / SPT-3G single-pixel. Broadband polarization-sensitive "sinuous" antenna at 90 and 150 GHz, (fabricated by Toki Suzuki at UC-Berkeley)

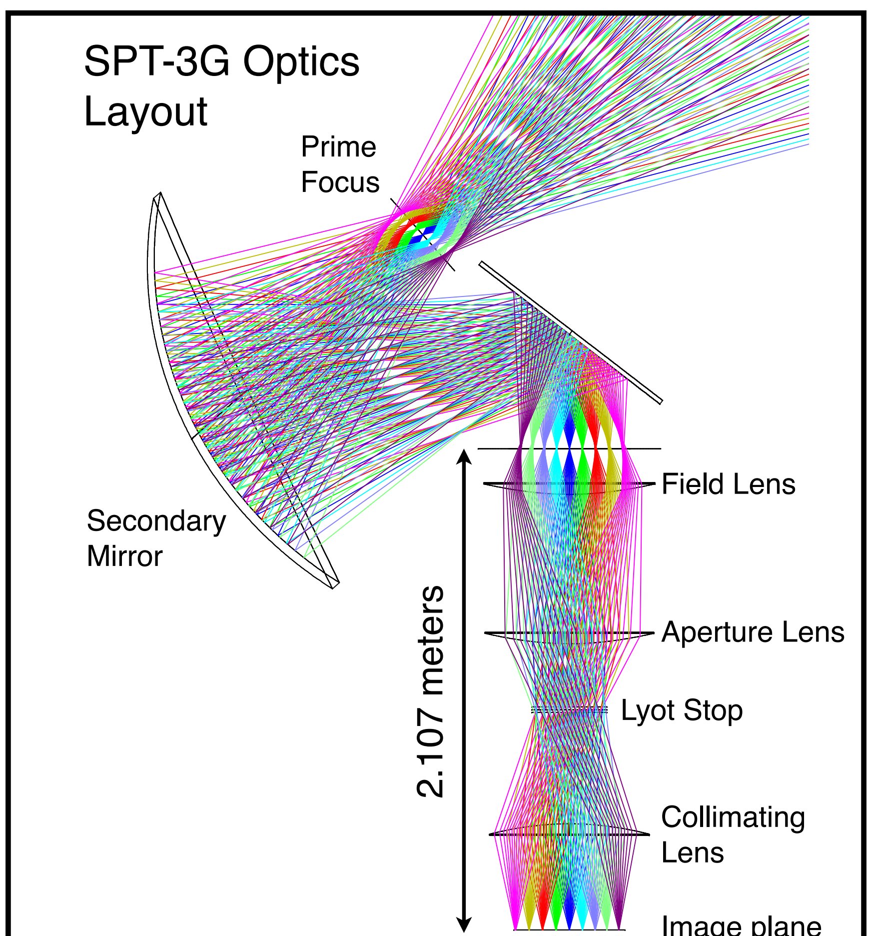


Silicon-Nitride
TES Island



SPT-3G: Focal Plane Design





SPT-3G Mapping Speed Increase:

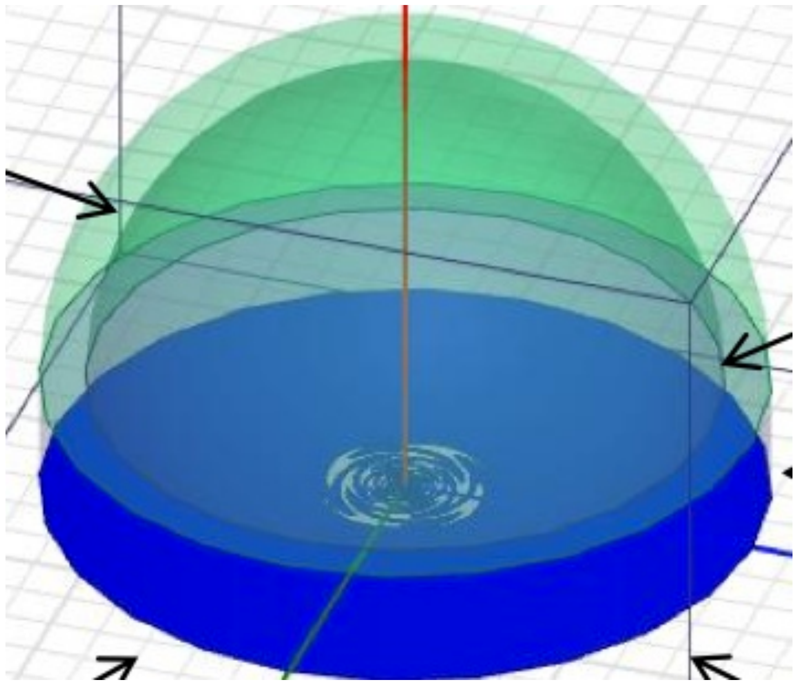
1) ***Multi-chroic pixels***
   - 3-bands: 95, 150, 220 GHz

2) ***Increased field of view***
   - 2x increase
   - development of large aperture, low-loss alumina lenses

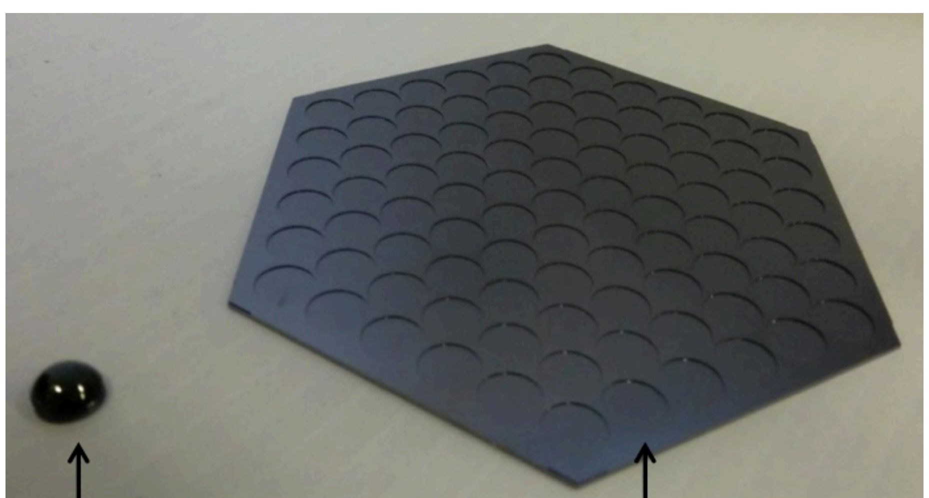
3) ***Reduce internal loading***
   - New large aperture ~100 K vacuum window

Each contributes a ~2x increase in mapping speed, totaling a 10x total increase

Lens-Coupled Antenna



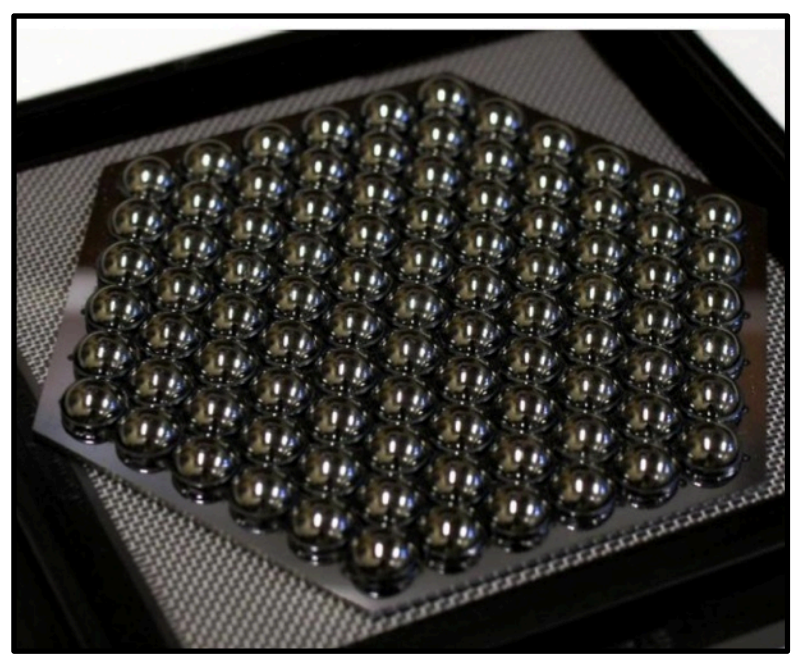
- **Contacting Si lens focuses beam pattern**
  - Surface of lens is analogous to horn aperture
  - Used for Herschel/HIFI, ALMA/SIS, Polarbear instruments
- **Antenna is small compared to lens**
  - Increases area under the lens for filters, TESs, ...
- **Anti-reflection (AR) coating needed**
  - Challenging for broad-band; 2 or 3 layer epoxy ok

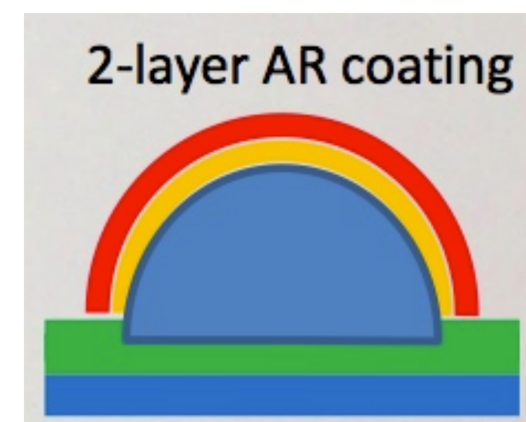


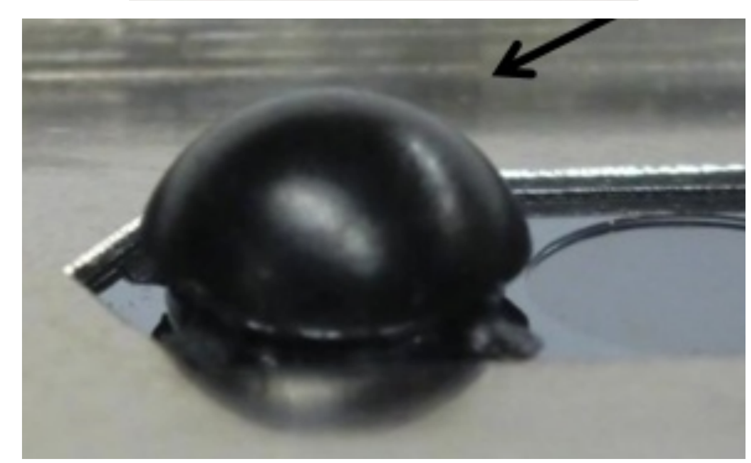
Single-layer AR/epoxy coated lenslet

Spacer wafer with etched registration holes

Lenslet Array



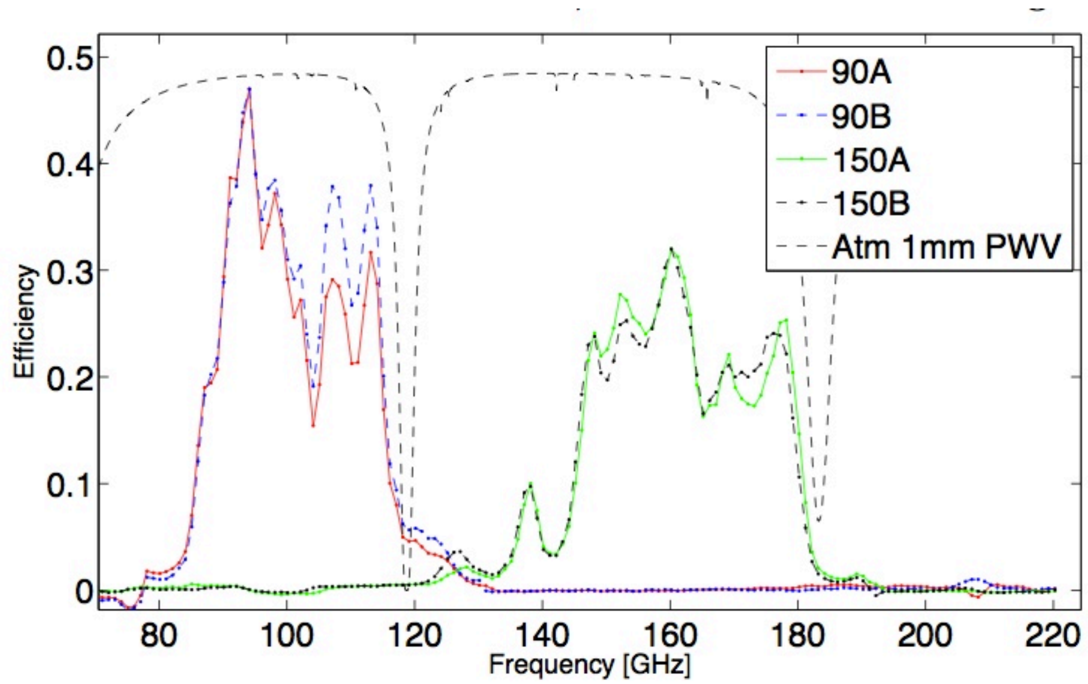




Credit: Toki Suzuki, Erin Quealy

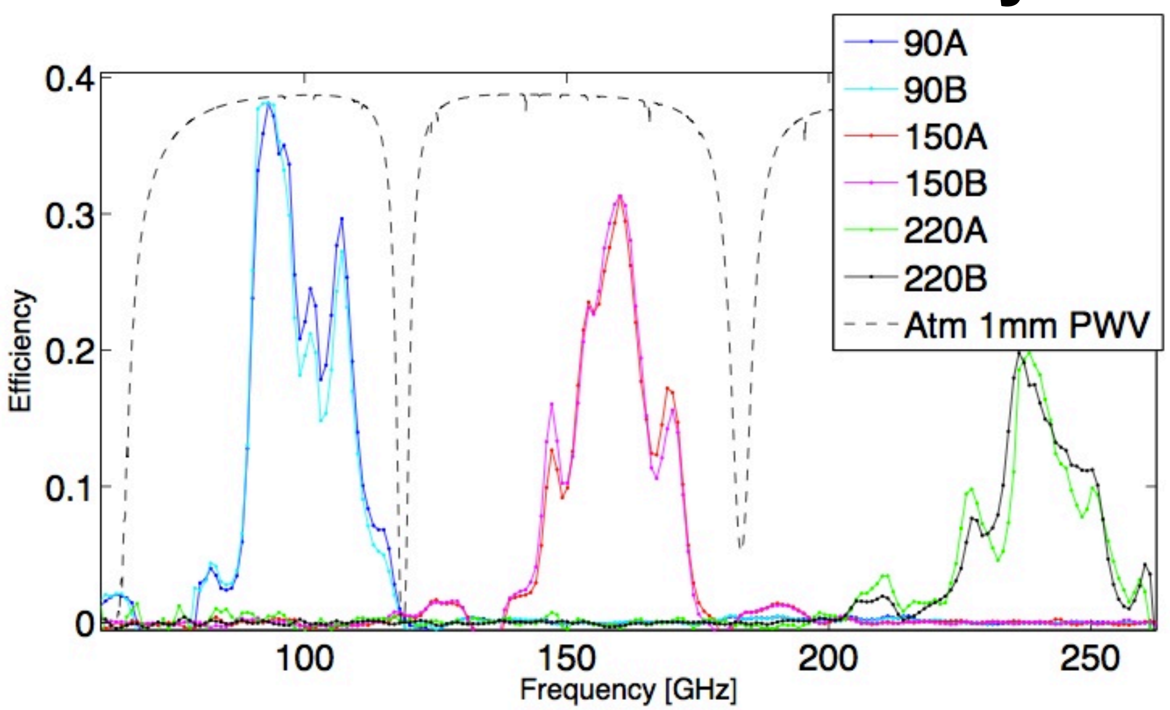
Bands, Efficiency, and Polarization Response

Two-Color Pixel Efficiency

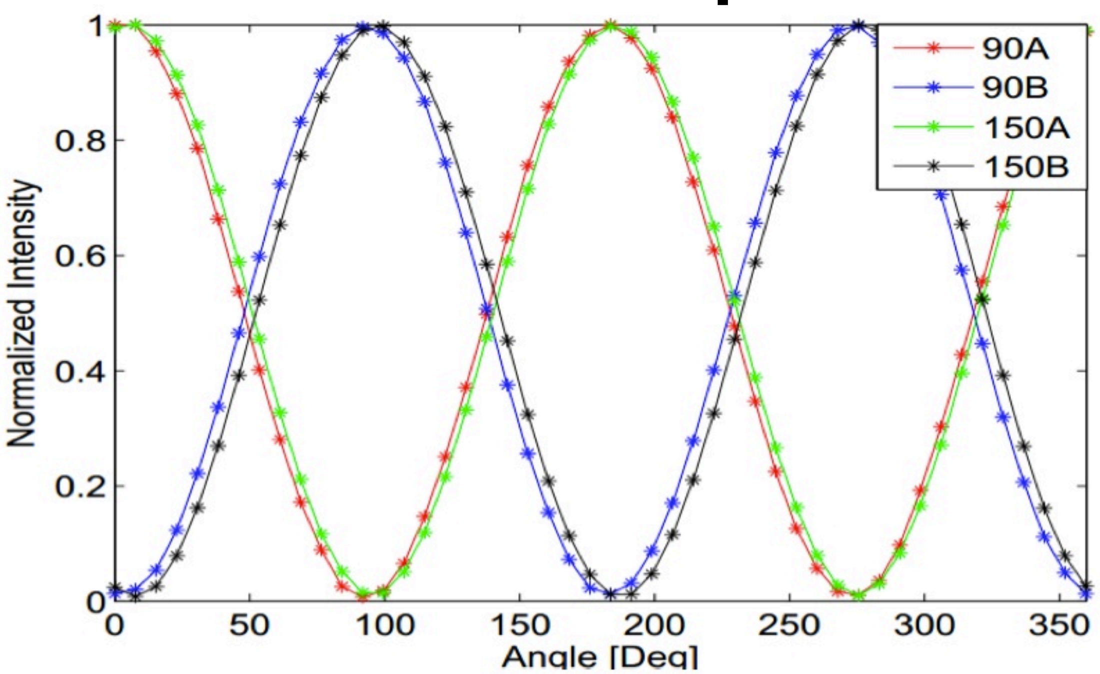


- Two and three-color prototype single-pixels show promising response
- Low (~1%) cross-polarization response
- Challenges:
  - Understand loss at higher frequencies; could be from Nb-microstrip, dielectric, radiative loss
  - scale up to 6” wafers, while maintaining uniformity

Three-Color Pixel Efficiency



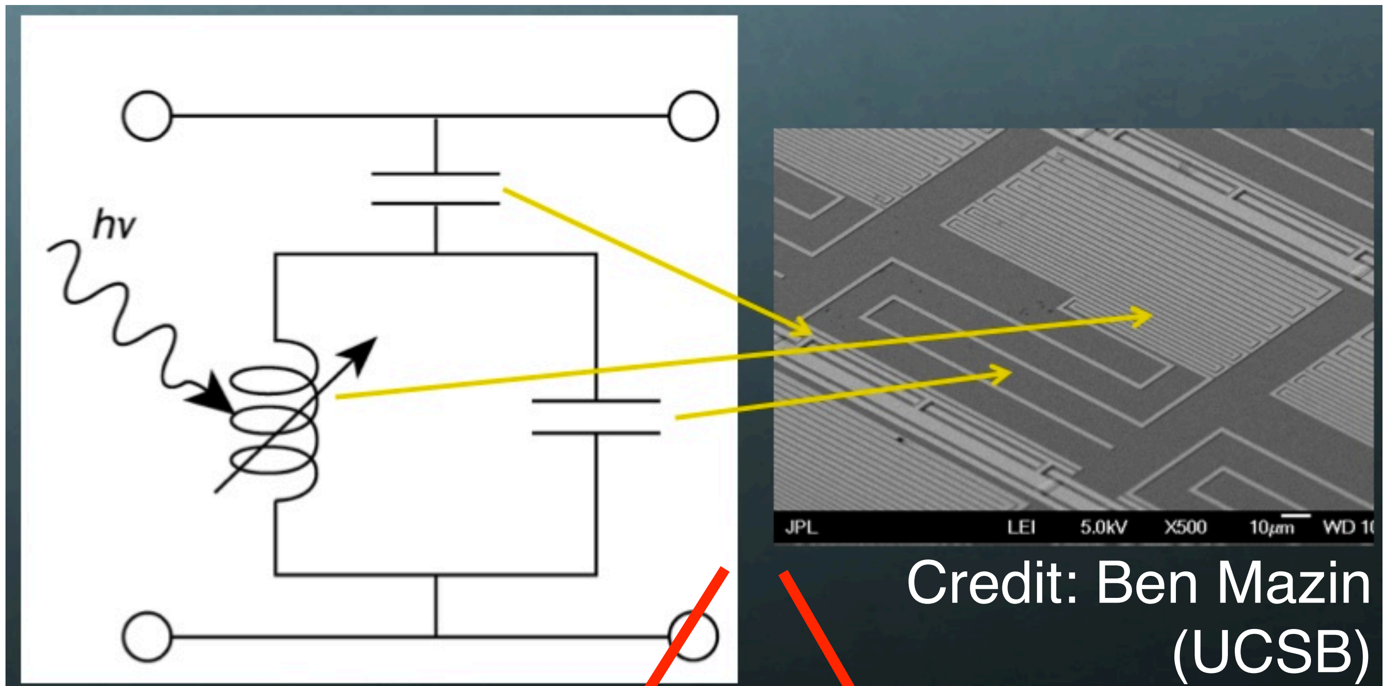
Polarization Response

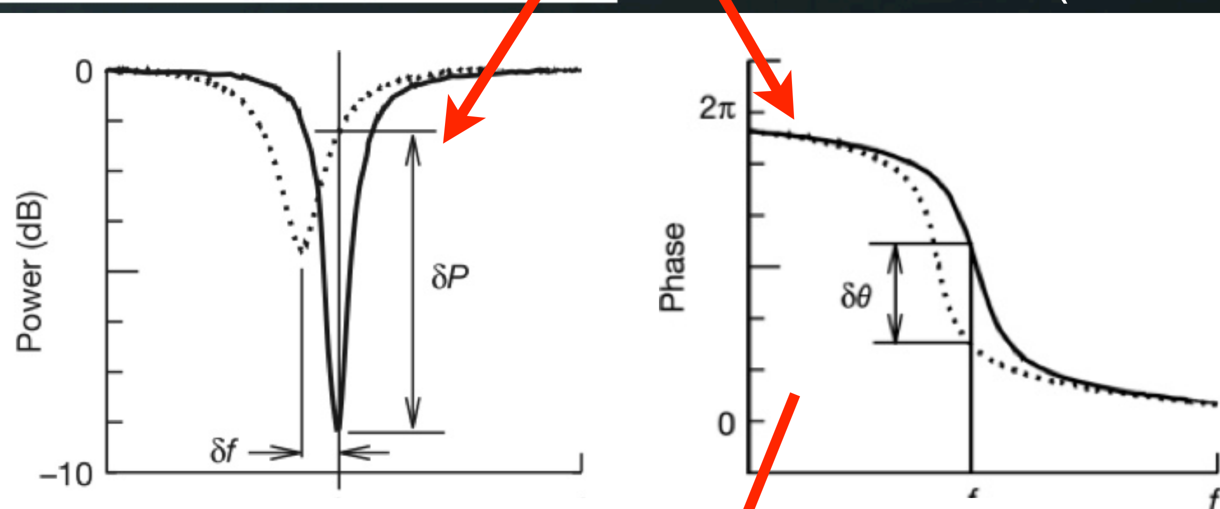


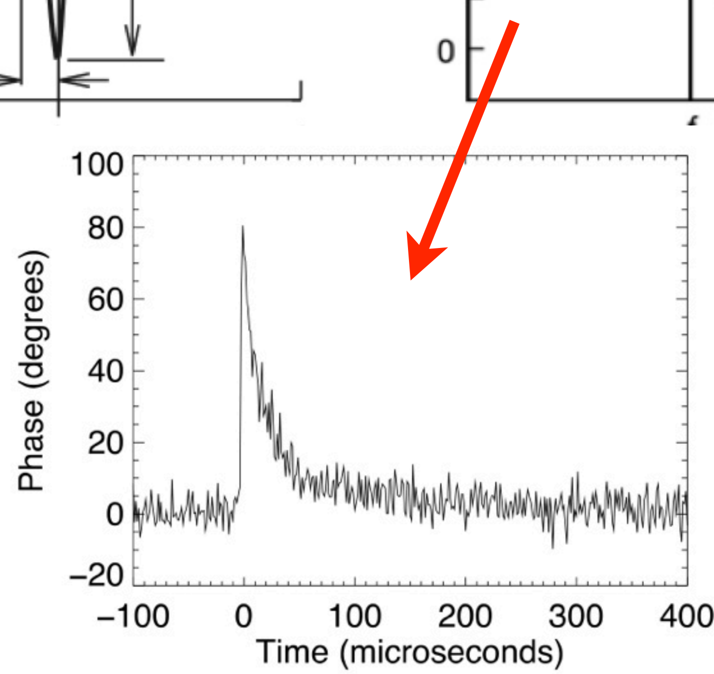
Credit: Toki Suzuki (UC-Berkeley)

MKIDS: Future Multi-Chroic Technology

MKID equivalent circuit







R~15 for a 260 nm optical photon!

- Processes developed at ANL for SPT-3G applicable to any detector that requires antenna-coupling, low-loss stripline, in-line filters, etc.

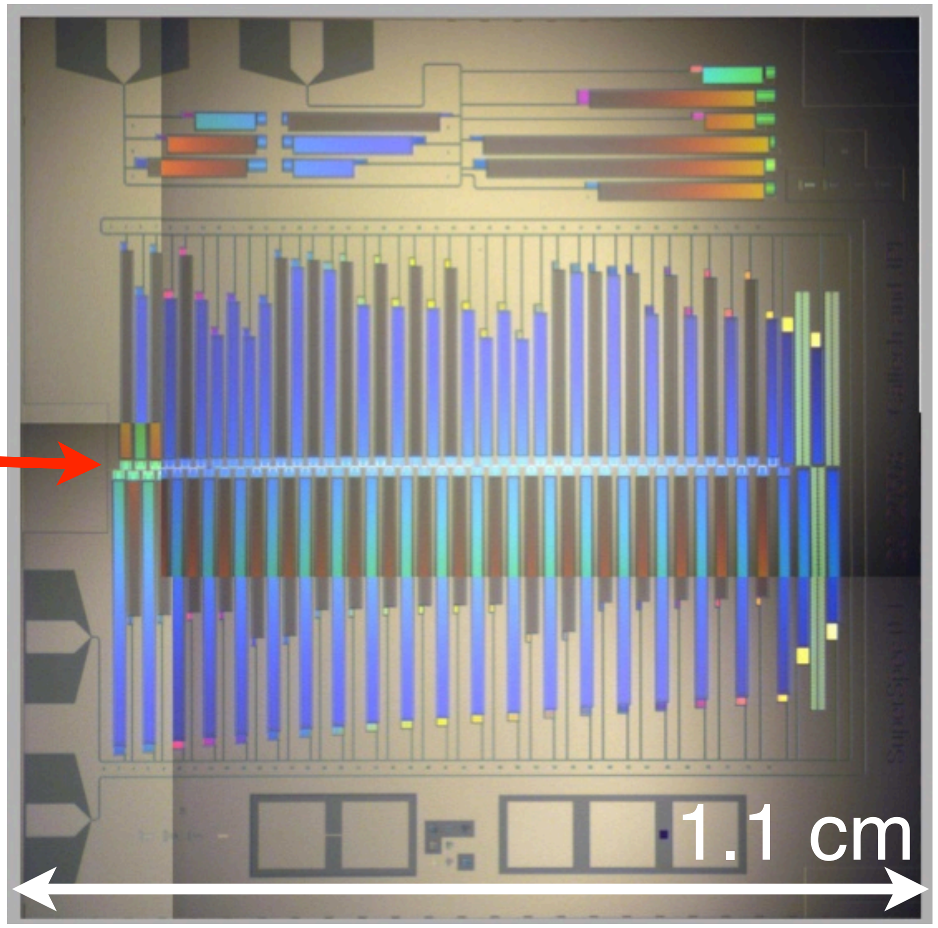
- **MKIDs (Microwave Kinetic Inductance Detectors)**; incoming photos break cooper pairs in a super-conductor changing its inductance

  - **Pros:** Single layer fab process, uses GHz readout, scalable to larger detector counts, ...
  - **Applications:**
    - Time-domain optical
    - Medium resolution spectrometer
    - Sub-millimeter spectrometer
    - X-rays
    - Cryogenic dark matter

MKIDS: Low-res mm-wave spectrometer

mm-wave MKID spectrometer on a chip

Horn/Antenna-fed



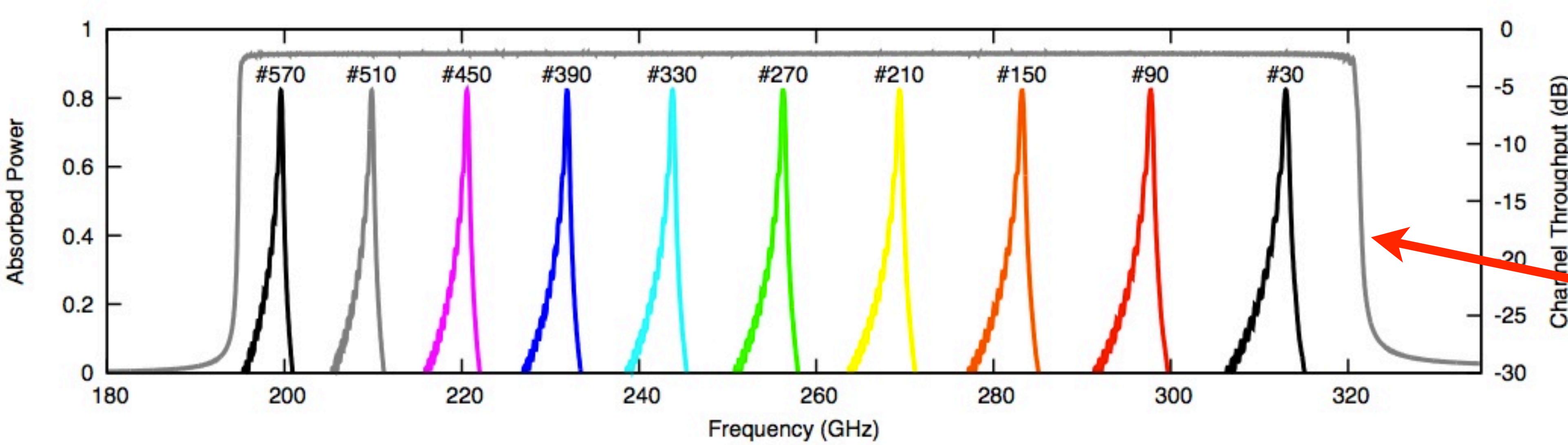
Shirokoff et al. 2012

- Dust-obscured galaxies at $z > 1$ responsible for bulk of star-formation in universe; little is known about their environment or redshift distribution

- 190-320 GHz window contains two or more CO lines for all galaxies at $z > 0.8$, and C+ 158 mm line at $4.9 < z < 8.7$
    - ***Tracer of structure growth to cross-correlate with 21 cm surveys during dark ages***

- ***SuperSpec***: single-pixel pathfinder for CSO (Kovacs, Zmuidzinas, Shirokoff et al.) to be deployed in next ~3 years

- Larger pixel camera would be powerful on CCAT or SPT



Resolution of $\mathcal{R} \sim 600$

Simulated Response (Kovacs et al. 2012)

Fermilab's Role on SPT-3G and CMB Detectors

1) SPT-3G Receiver Assembly and Testing

- *Summer 2014 expect SPT-3G cryostat parts to start arriving, and assembly and testing to begin*

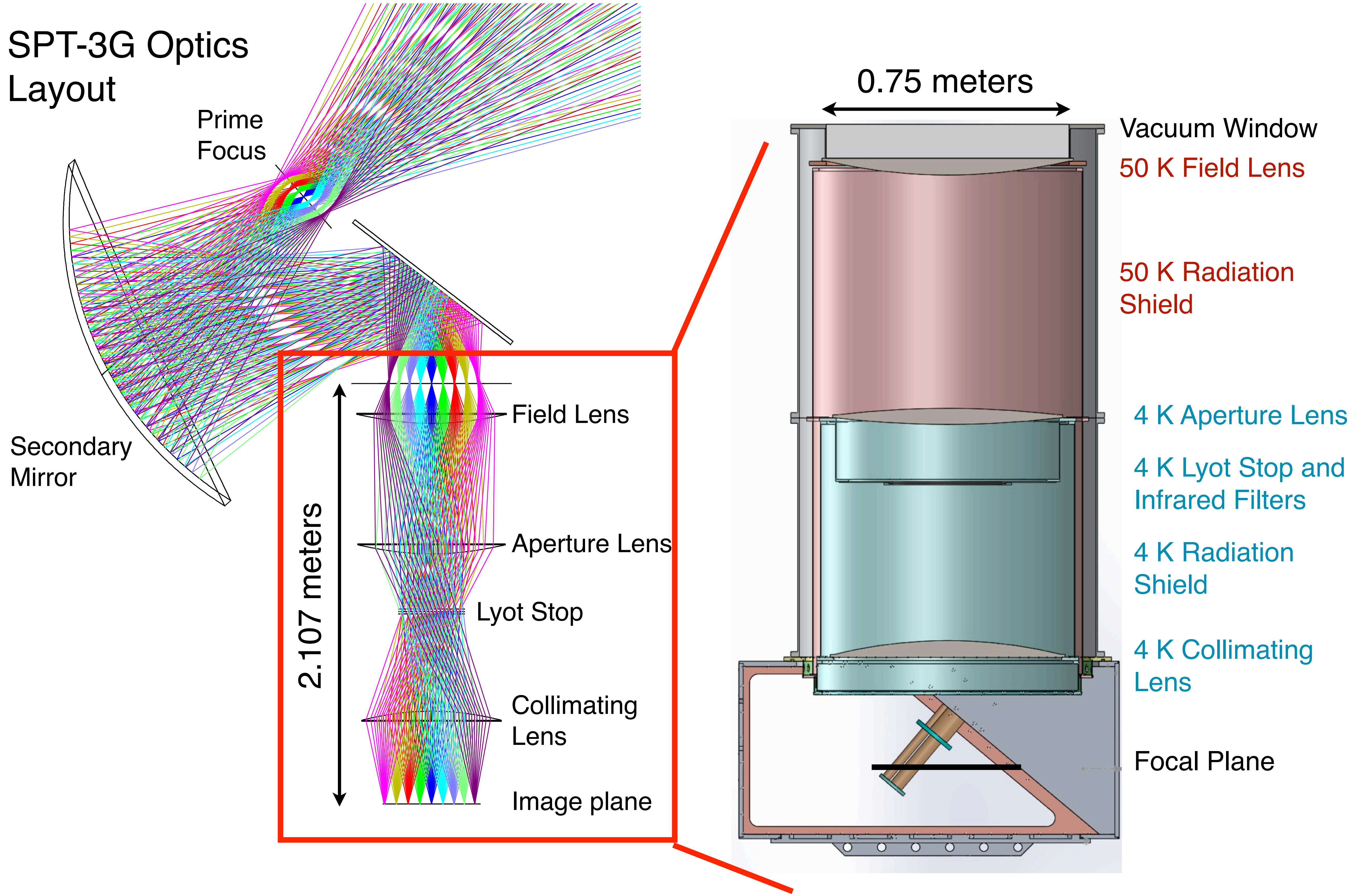
2) SPT-3G Detector Module Assembly

- *Detector arrays from Argonne wire-bonded and mounted with silicon lenslet arrays (begin Fall 2014)*

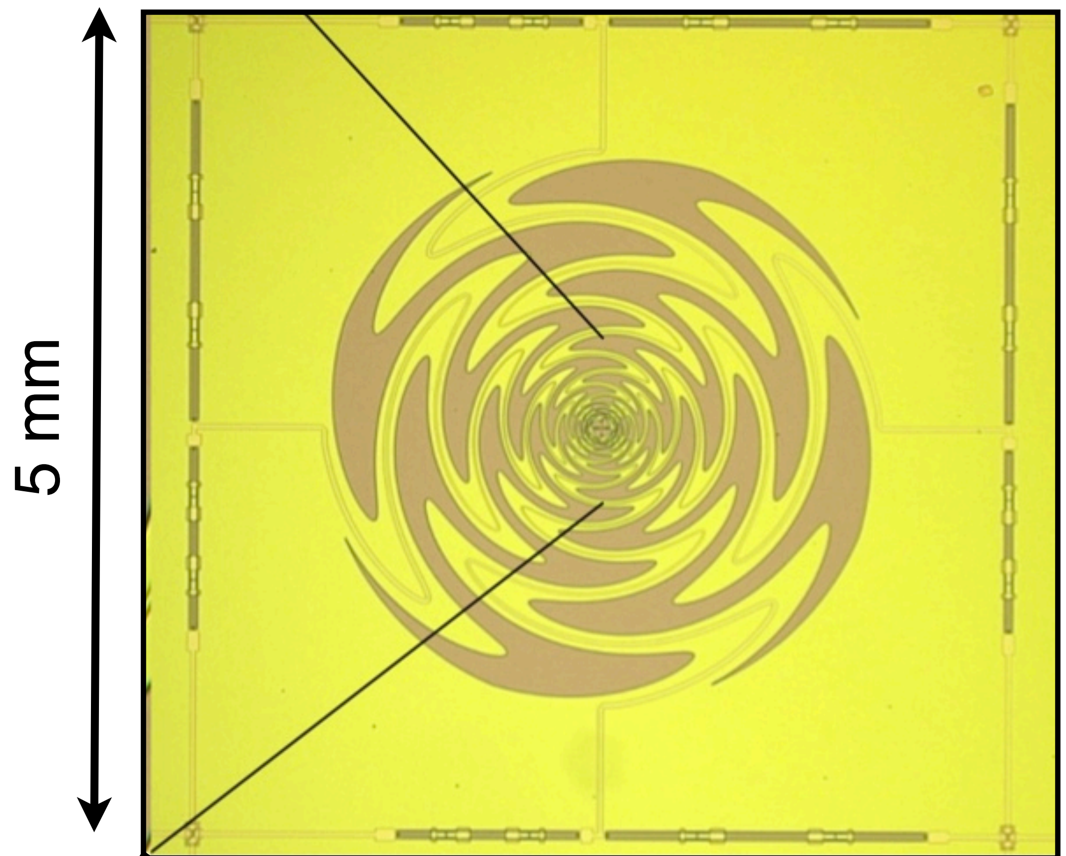
3) SPT-3G Detector Module Characterization

- *Commissioning of a new 250 mK cryostat detector module test cryostat, to provide feedback for fabrication of SPT-3G detectors by Argonne (Summer 2014)*

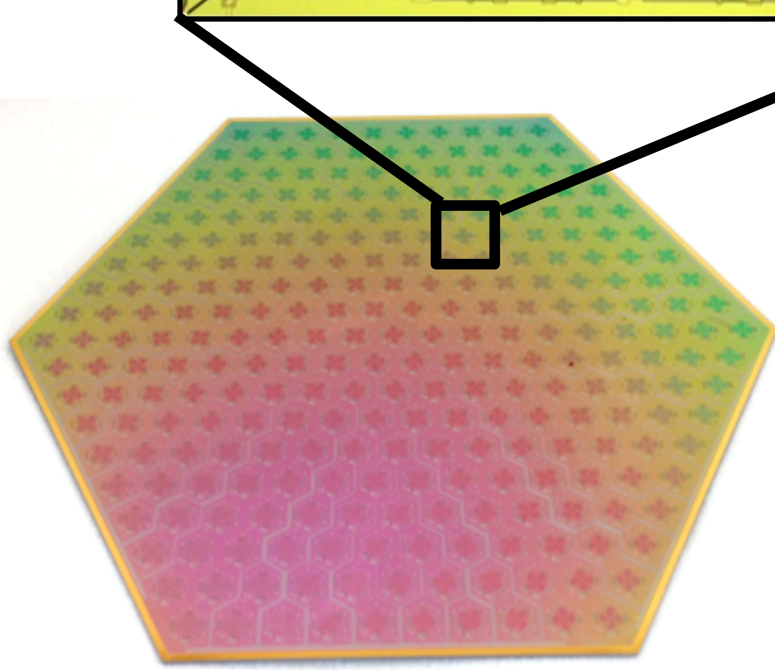
SPT-3G Receiver Assembly at SiDet



SPT-3G Detector Module Assembly

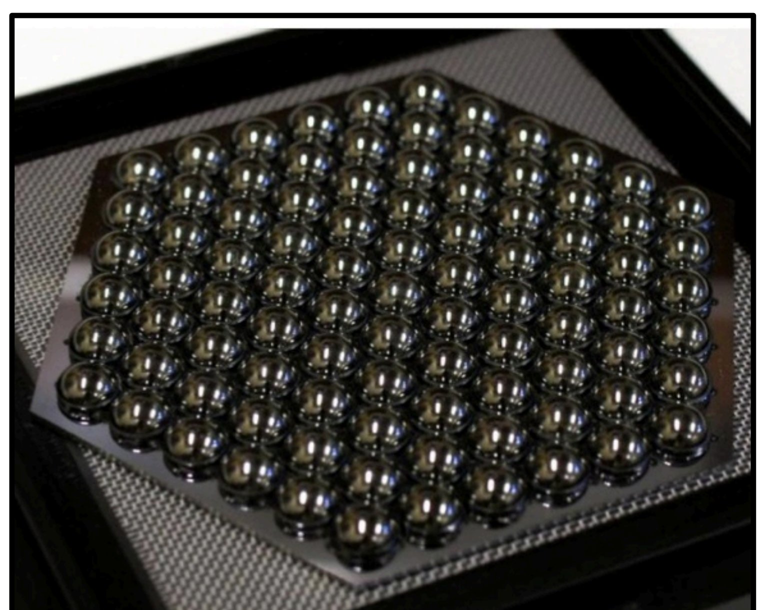


- ***FNAL will contribute detector module assembly, testing***
- ANL, U. Chicago, UC-Berkeley working in collaboration on 3-band, dual polarization pixel for SPT-3G
- Each SPT-3G detector module consists of 544 pixels, assembly will include:
  - >3,000 wire bonds per module
  - Packaging with silicon lenslet array



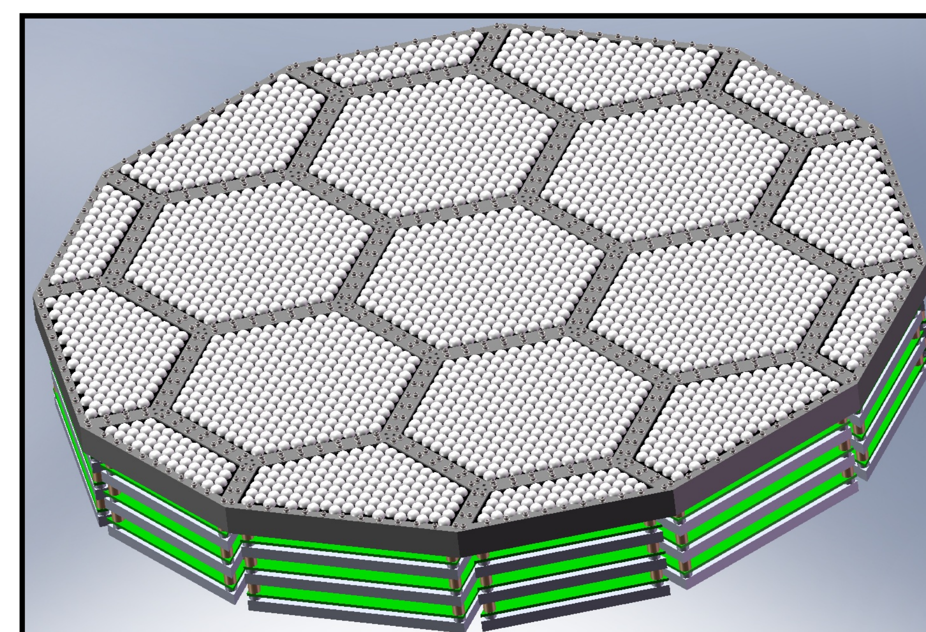
SPT-3G Prototype Array (6” wafer)

+



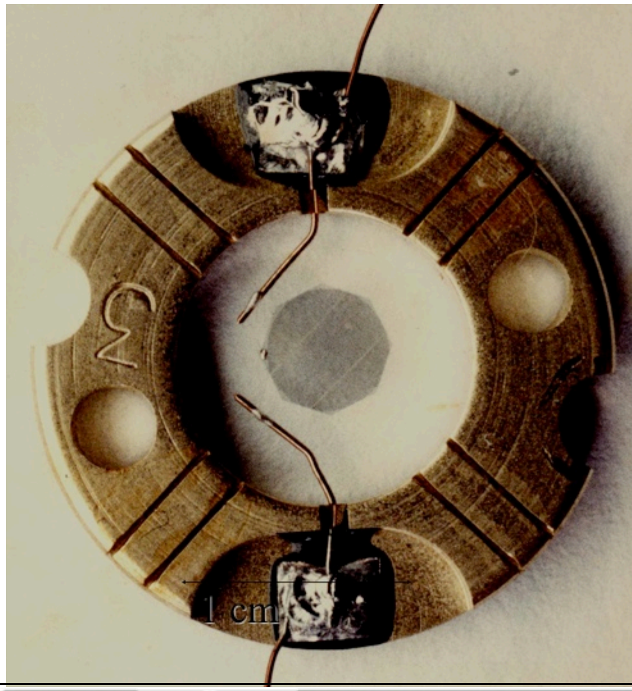
Silicon Lenslet Array

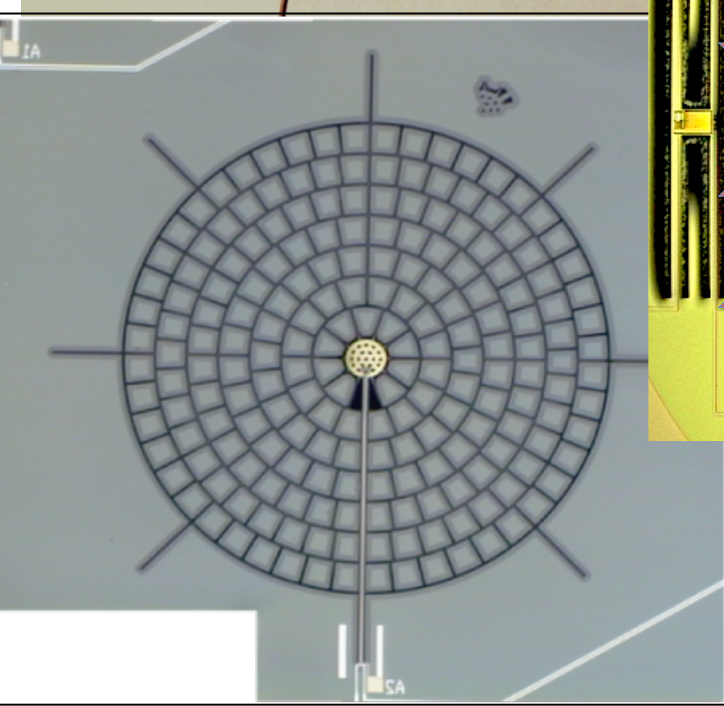
=

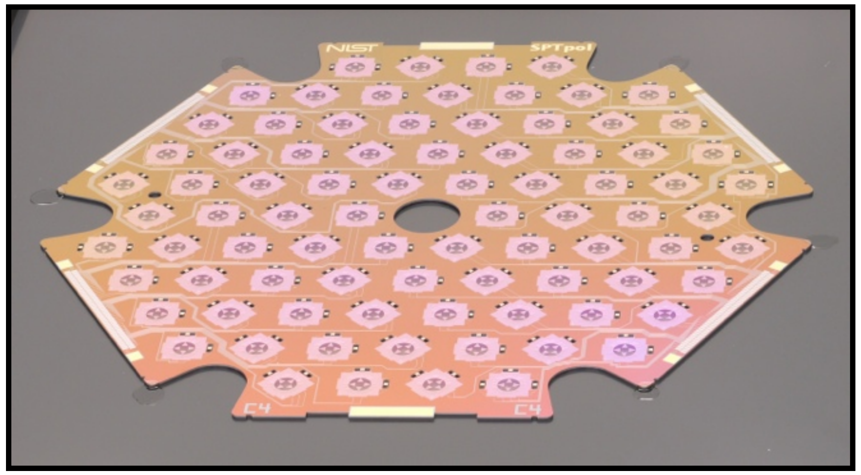


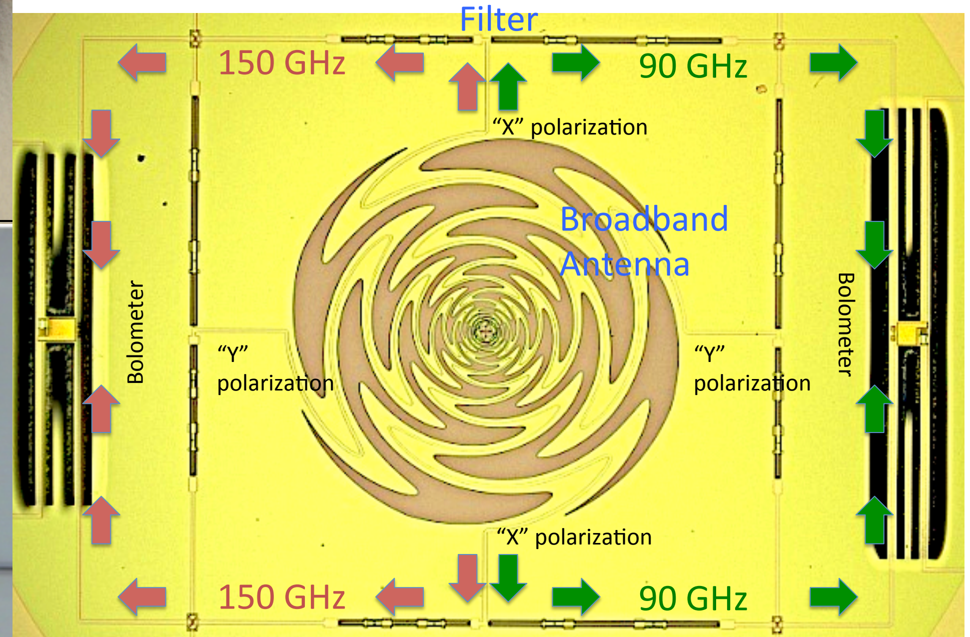
SPT-3G Focal Plane

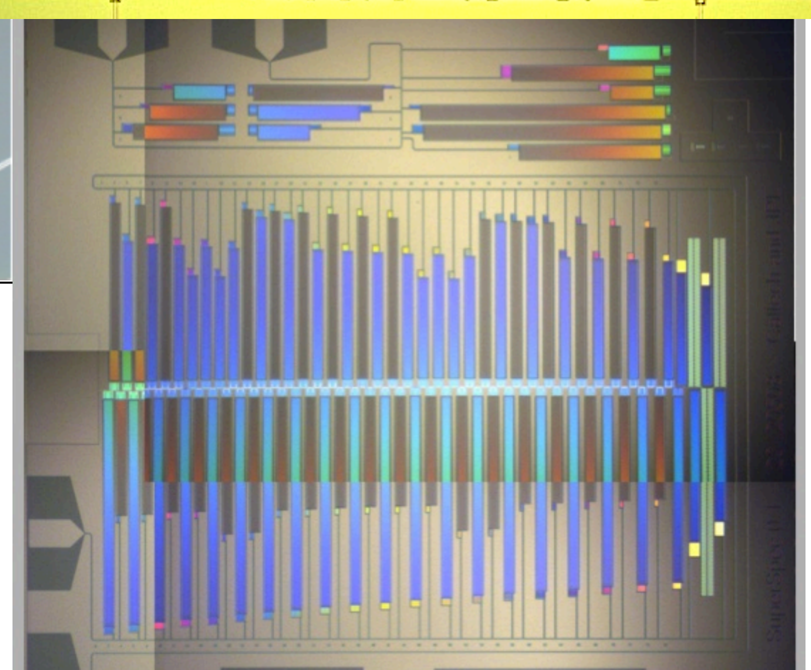
Summary











- Remarkable changes in thermal detectors over the last 20 years!

- Arrays of multi-chroic pixels are baselined for next-generation of CMB experiments (e.g., SPT-3G, Polarbear2)

- Technology will likely be used for latter mm-wave experiments (CMB-S4), and also applicable at other wavelengths (e.g., sub-mm, optical, X-rays)

CMB-S4: A CMB Stage 4 Experiment

- **Experimental Configuration:**
  - 100,000 - 500,000 detectors on multiple platforms
  - Spanning 40 - 240 GHz for foreground removal
  - < 3 arcmin resolution required for CMB lensing, neutrino science

- **Two Nested Surveys:**
  - Inflation survey (~few% of sky)
  - Neutrino survey (~half of sky)

- **Target noise of ~1 uK-arcmin depth over half the sky, starting in 2020**

Primary technical challenge will be from the scaling of the CMB detector arrays

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB-S4 Cosmological Constraints

	$\sigma(r)$	$\sigma(N_{\rm eff})$	$\sigma(\Sigma m_\nu)$ (meV)
Current CMB	**0.10**	**0.34**	**117**
Stage 2: SPTpol	0.03	0.12	96
Stage 3: SPT-3G	0.01	0.06	61*
Stage 4: CMB-S4	**0.001**	**0.02**	**16****

* Includes BOSS prior
** Includes DESI prior

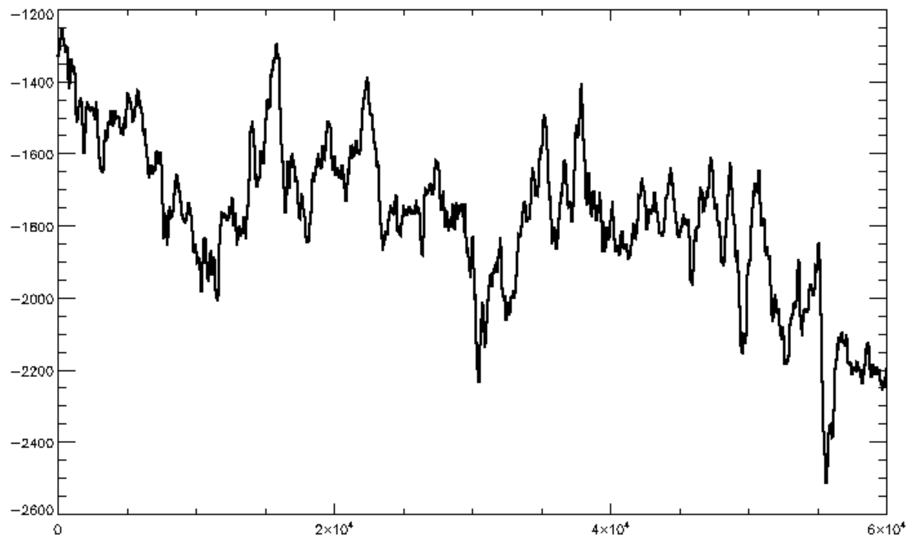
The CMB-S4 sensitivity would achieve important benchmarks:

- $\sigma(r) \sim 0.001$; large vs small field inflation?
- $\sigma(N_{\rm eff}) \sim 0.02$; new physics in neutrino or dark sector?
- $\sigma(\Sigma m_\nu) \sim 16$ meV ; cosmological detection of neutrino mass?

Snowmass: CF5 Neutrinos + Inflation Document
arxiv:1309.5383, 1309.5381

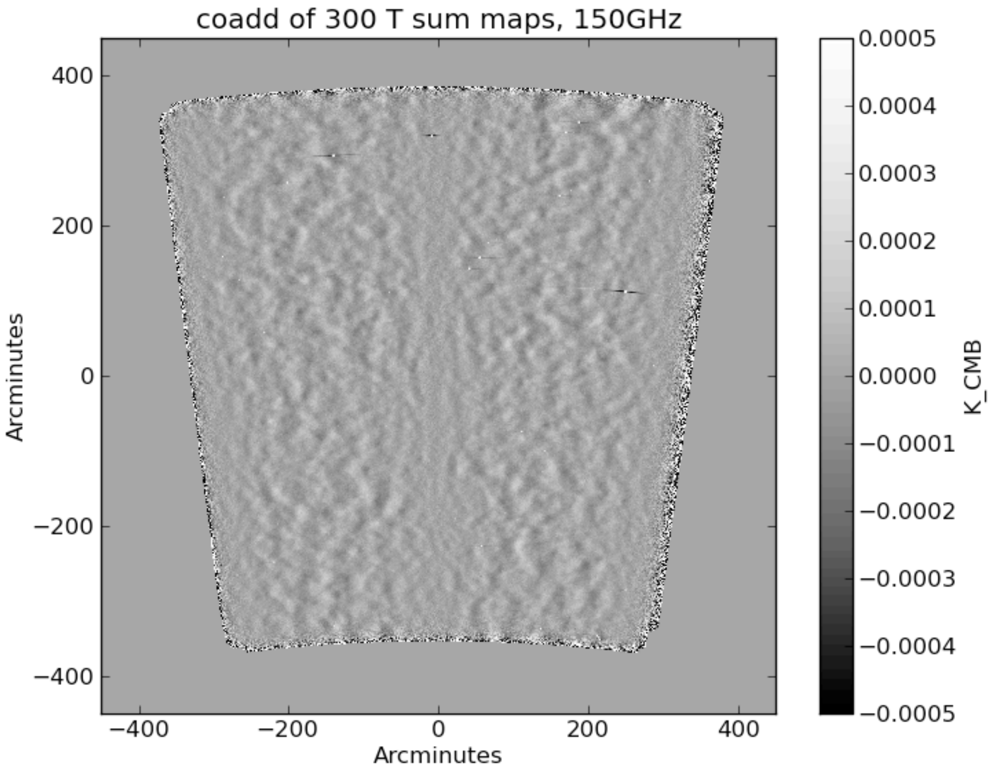
SPT Data: What is it?

- ❖ Fundamentally: voltages from O(1000) detector elements.



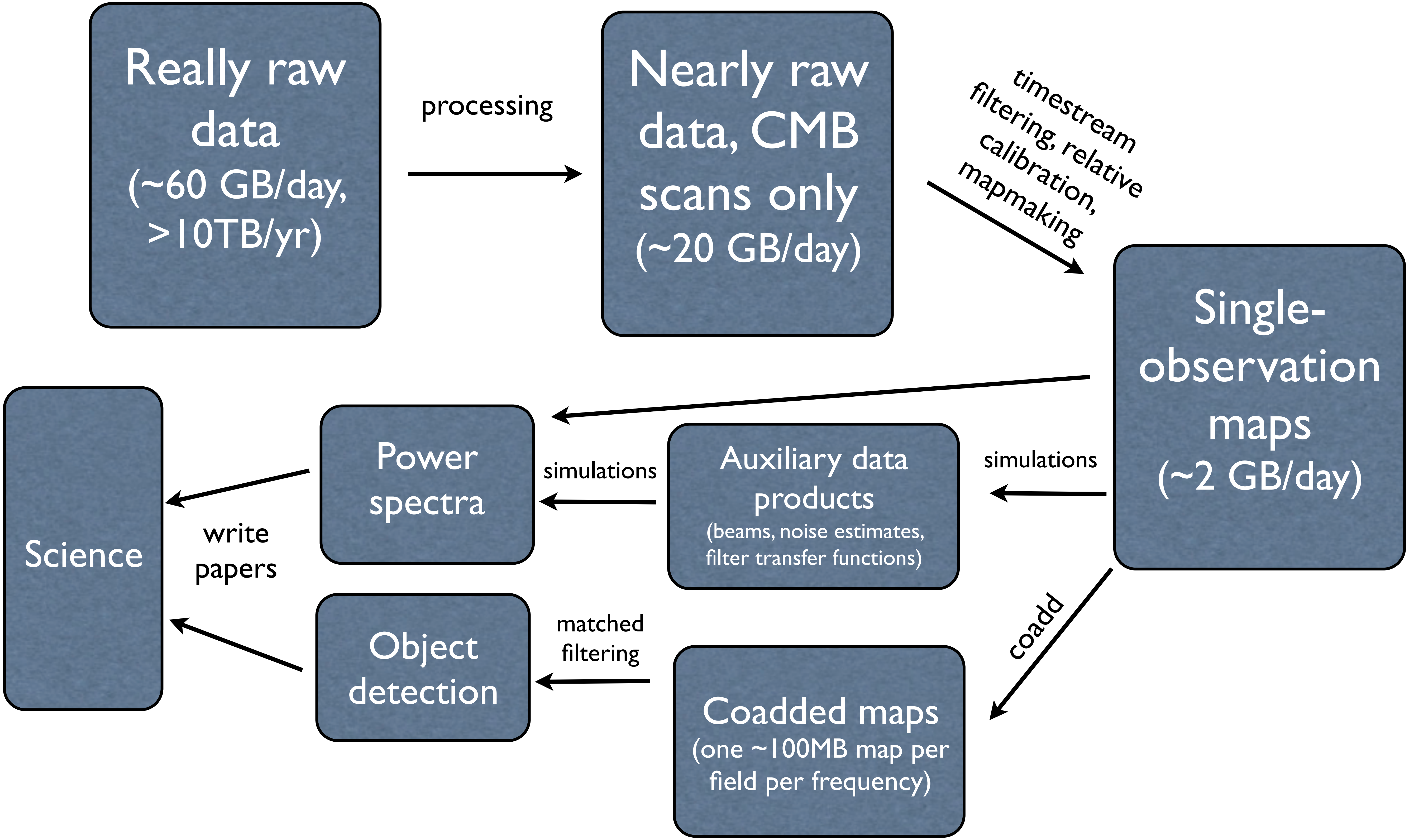
10 minutes of SPT-SZ data from a single bolometer

- ❖ Main pipeline products: best-fit temperature at pixelized locations on the sky: Maps.



100 deg^2 field observed by SPTpol for <1 month

The SPT-SZ / SPTpol Pipeline



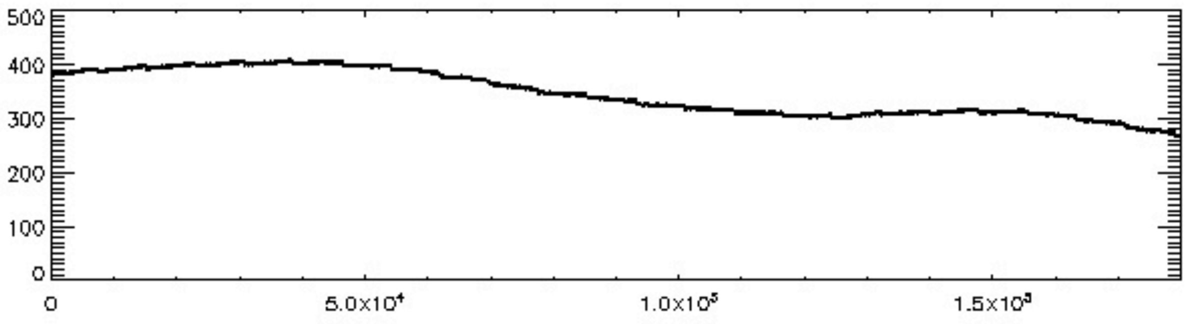
Data Processing

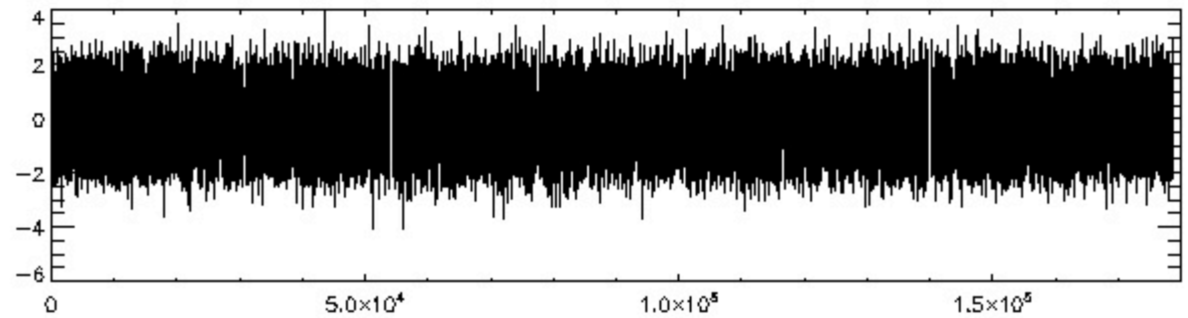
❖ Undo detector time response.

❖ De-spike.

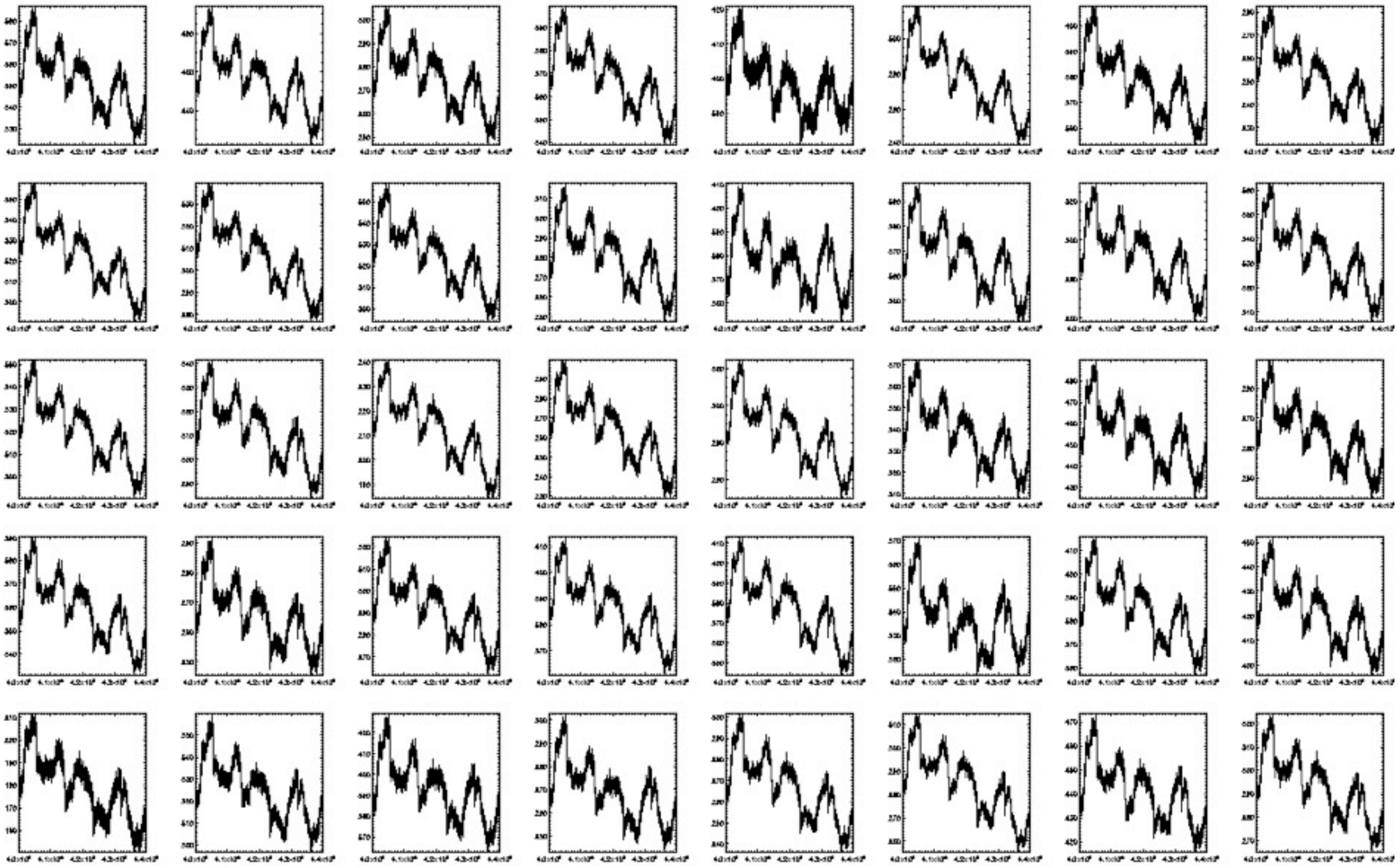
❖ Fourier-domain filtering (includes notching of spectral lines).

❖ Remove large-scale common mode and long-timescale drifts.

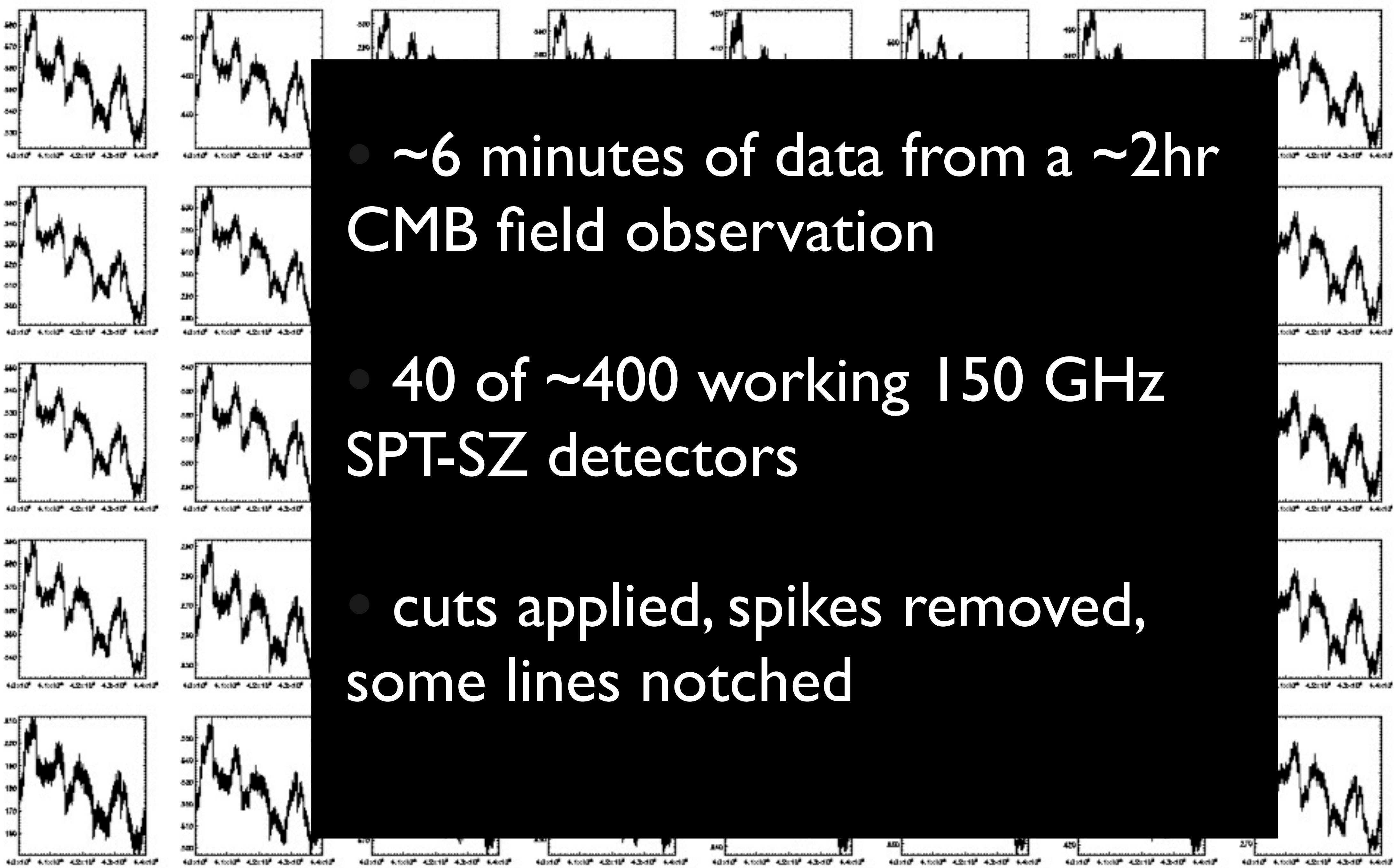




Minimally processed data

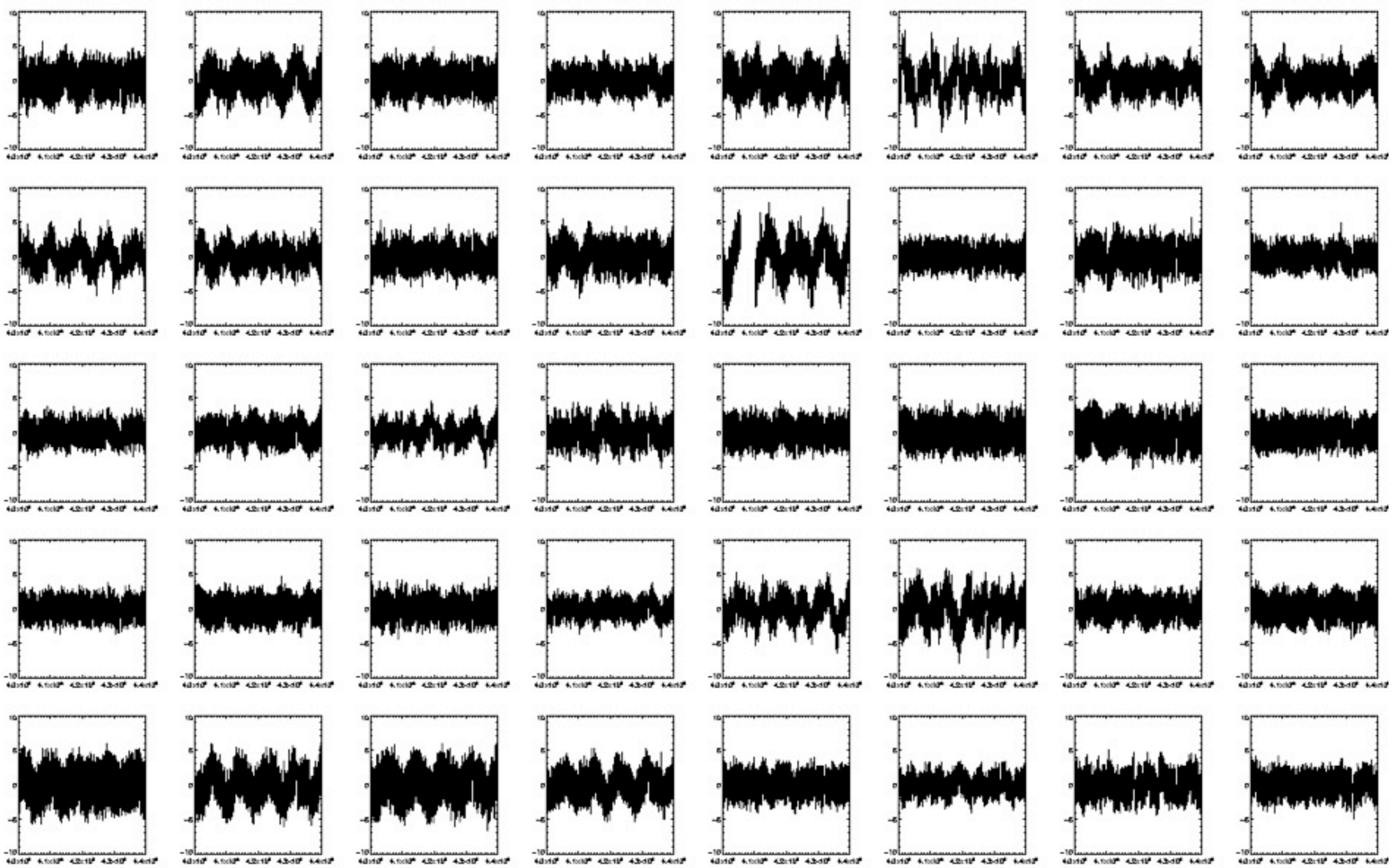


Minimally processed data

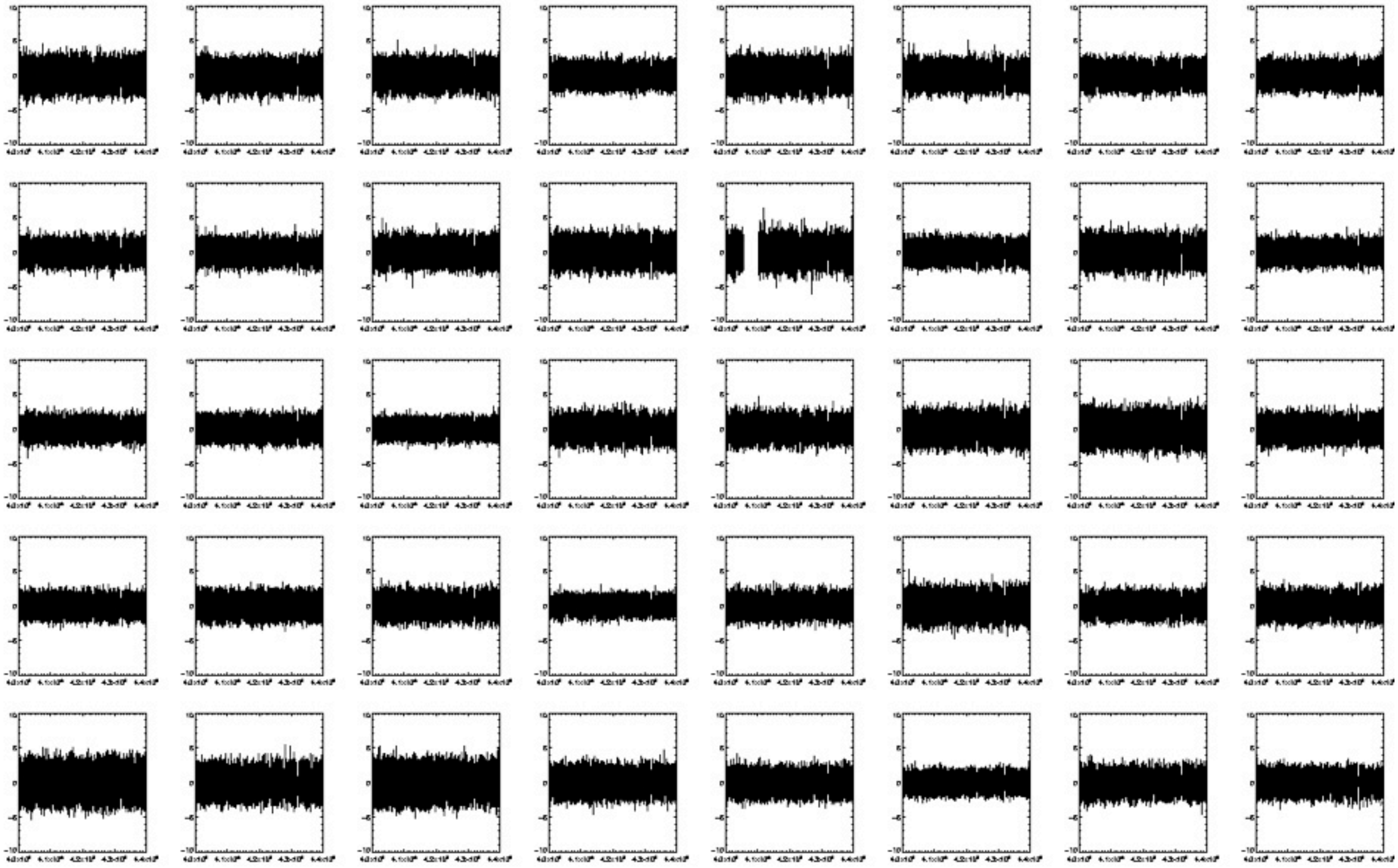


- ~6 minutes of data from a ~2hr CMB field observation
- 40 of ~400 working 150 GHz SPT-SZ detectors
- cuts applied, spikes removed, some lines notched

Common mode removed



High-order polynomial removed



Make Maps

- Calculate sky pointing for every detector at every timestream point.

- Apply calibration to each detector.

- Weight each detector's data by inverse variance (single number for SPT-SZ; 3x3 matrix for SPTpol).

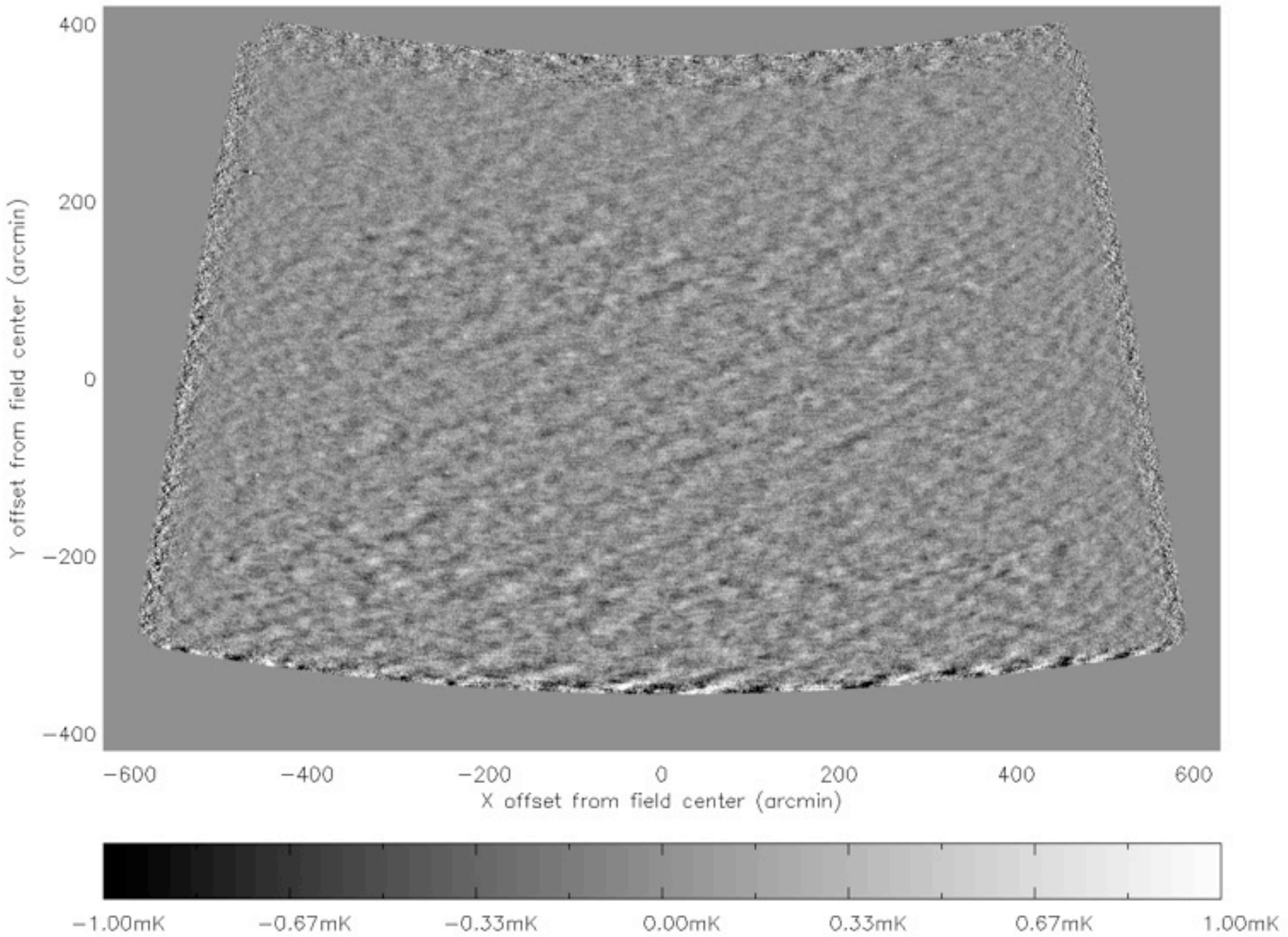
- Take weighted mean of all measurements of sky temperature/polarization at every (pixelized) observed sky location.

Make Maps

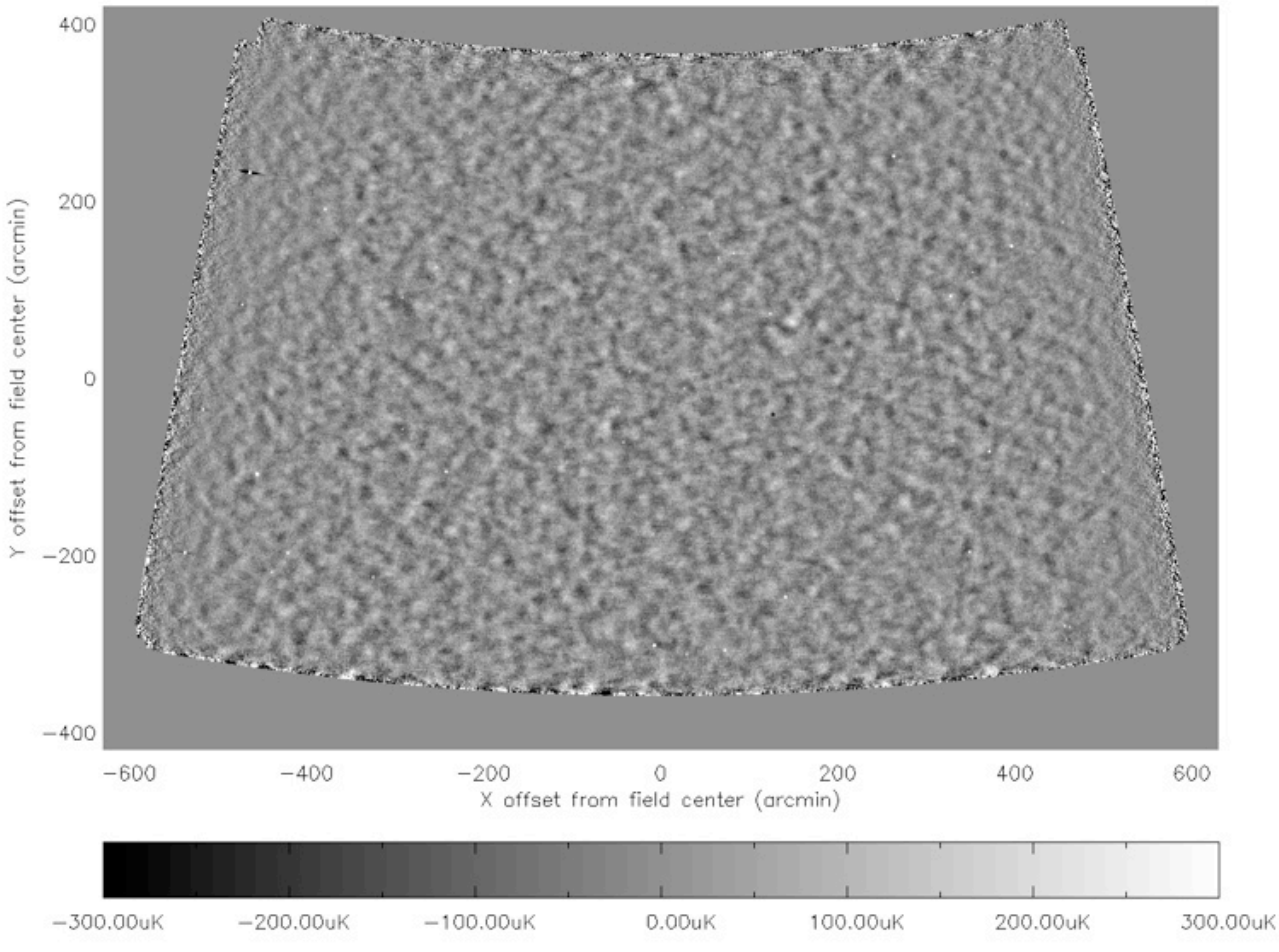
- ❖ Calculate sky pointing for every detector at every timestream point.
- ❖ Apply cali
- ❖ Weight ea … nce (single number fo
- ❖ Take weig … sky temperature/polarization at every (pixelized) observed sky location.

Mapmaking scheme is simple, but LOTS of effort into reconstructing pointing, optimizing calibration scheme, matching detectors within a polarization pixel, etc.

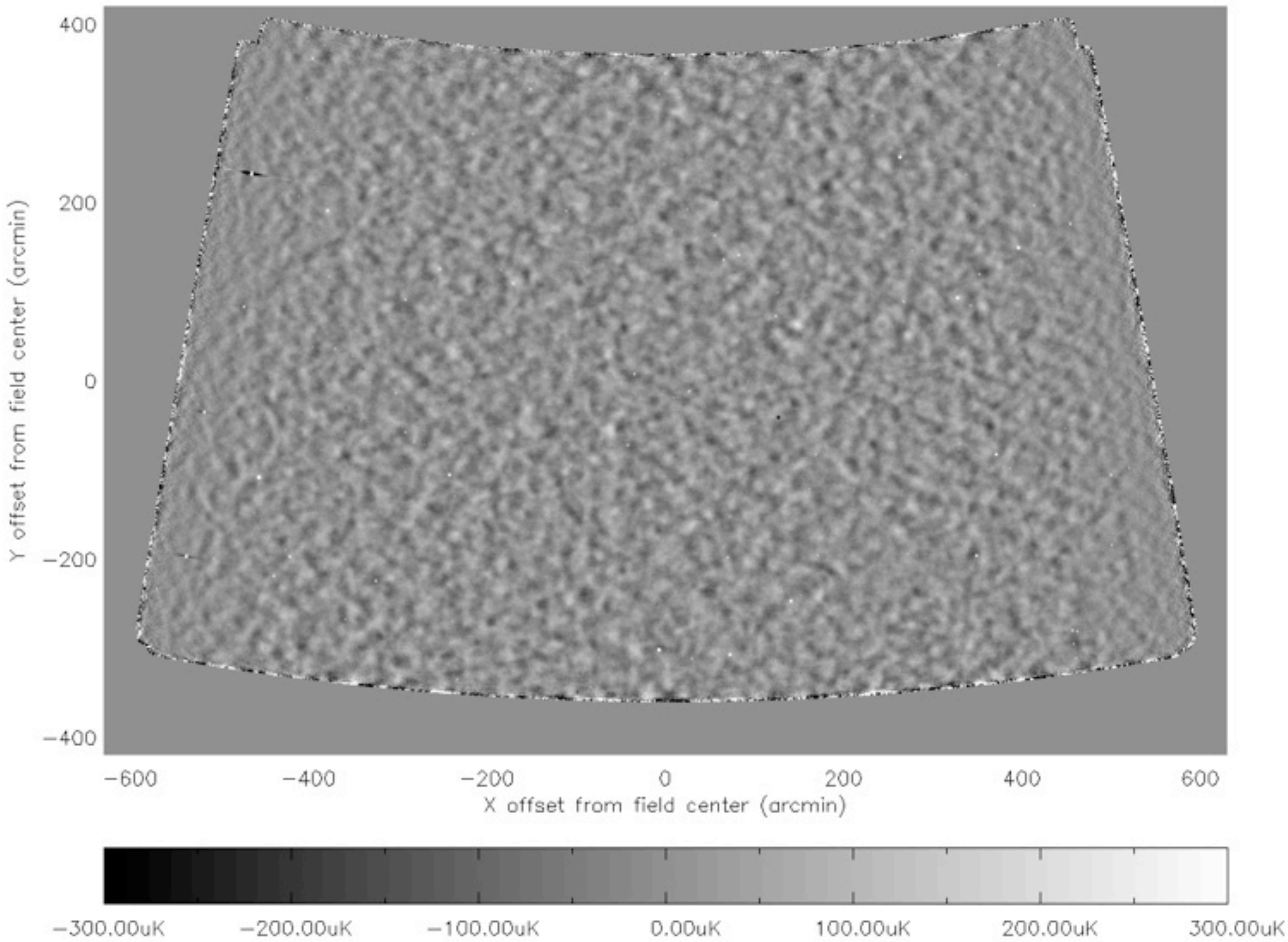
Single-observation Map



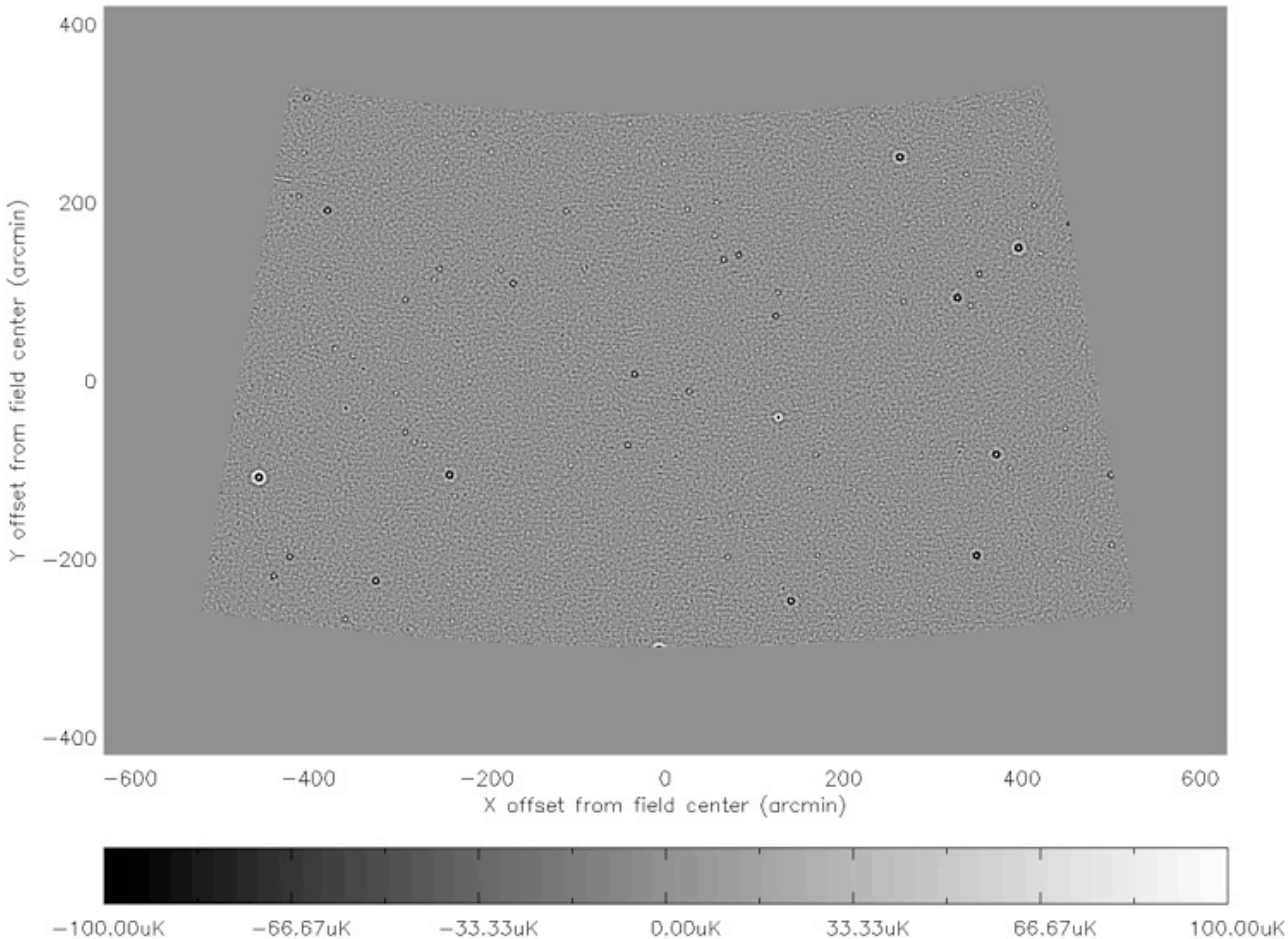
20 Observations



Full Coadd


400
200
0
−200
−400
Y offset from field center (arcmin)
−600
−400
−200
0
200
400
600
X offset from field center (arcmin)
−300.00uK
−200.00uK
−100.00uK
0.00uK
100.00uK
200.00uK
300.00uK

Post-map Analyses: Object Detection



Post-map Analyses: Power Spectra