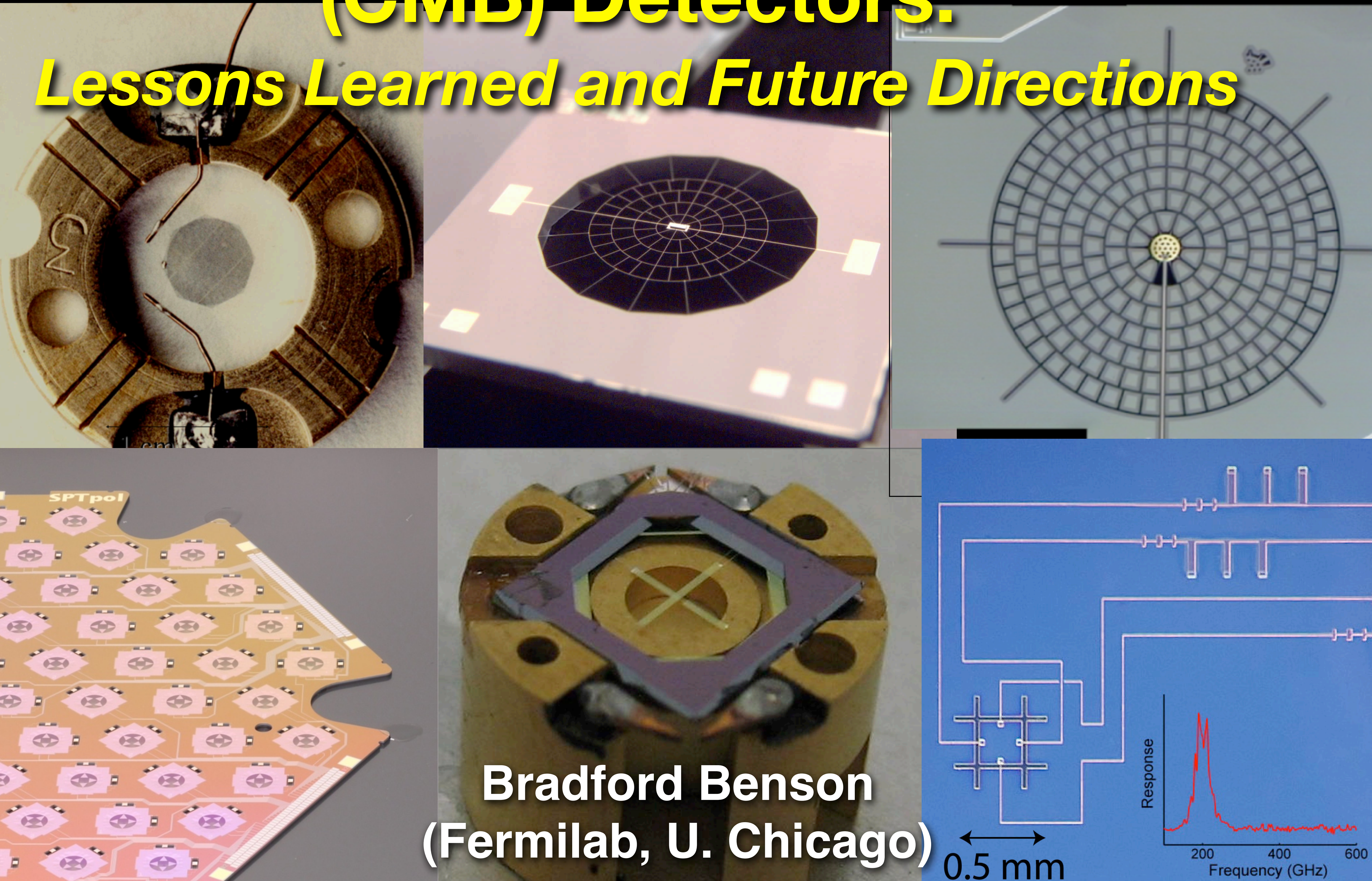
Cosmic Microwave Background (CMB) Detectors:

Lessons Learned and Future Directions



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**
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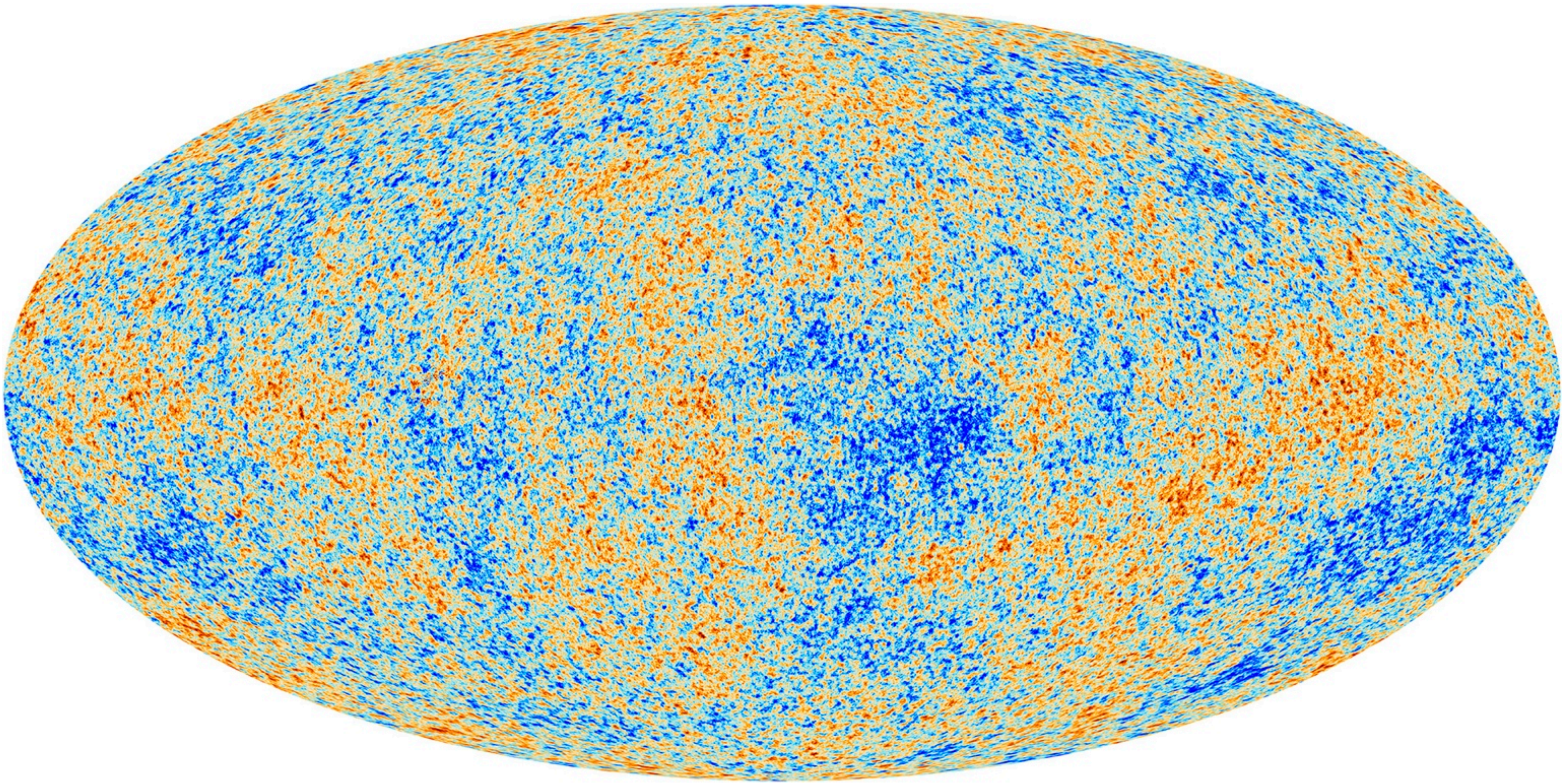
4. **Future Directions**
   - The path to CMB-S4

2013: Planck

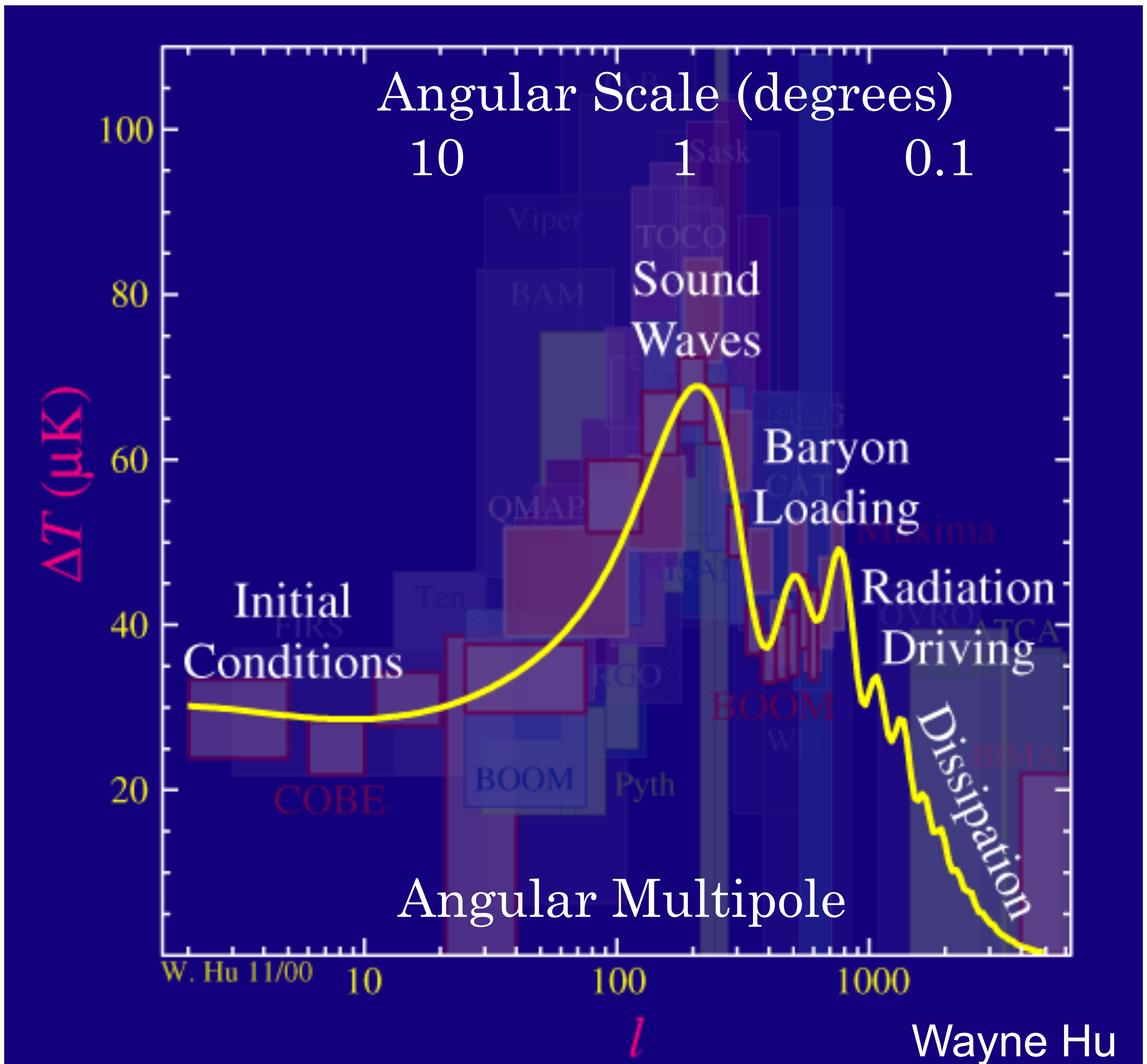
30μK RMS fluctuations on 3 K background

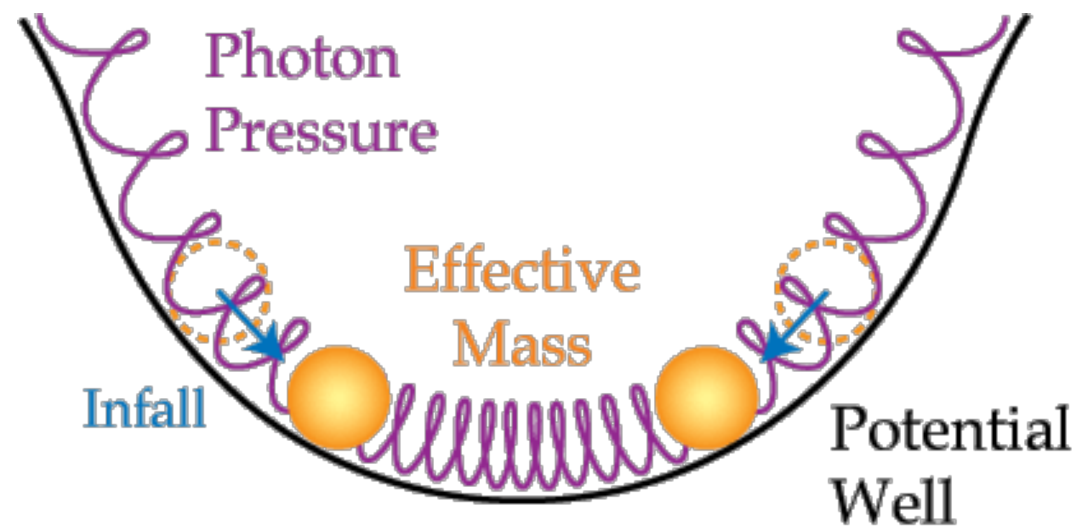


Credit: ESA (Planck)

The CMB Power Spectrum

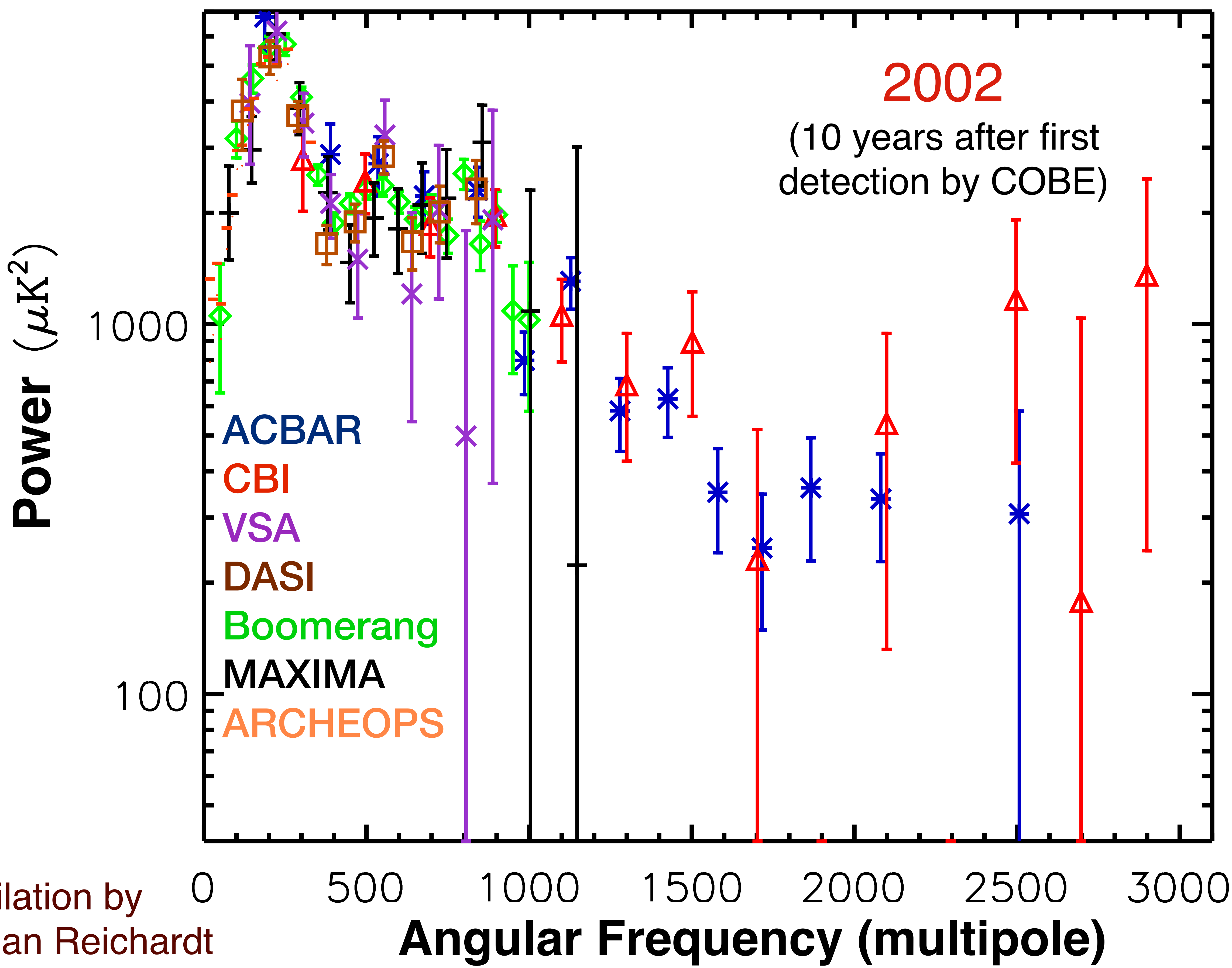
Encoded within the primordial CMB power spectrum is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (baryons, dark matter)





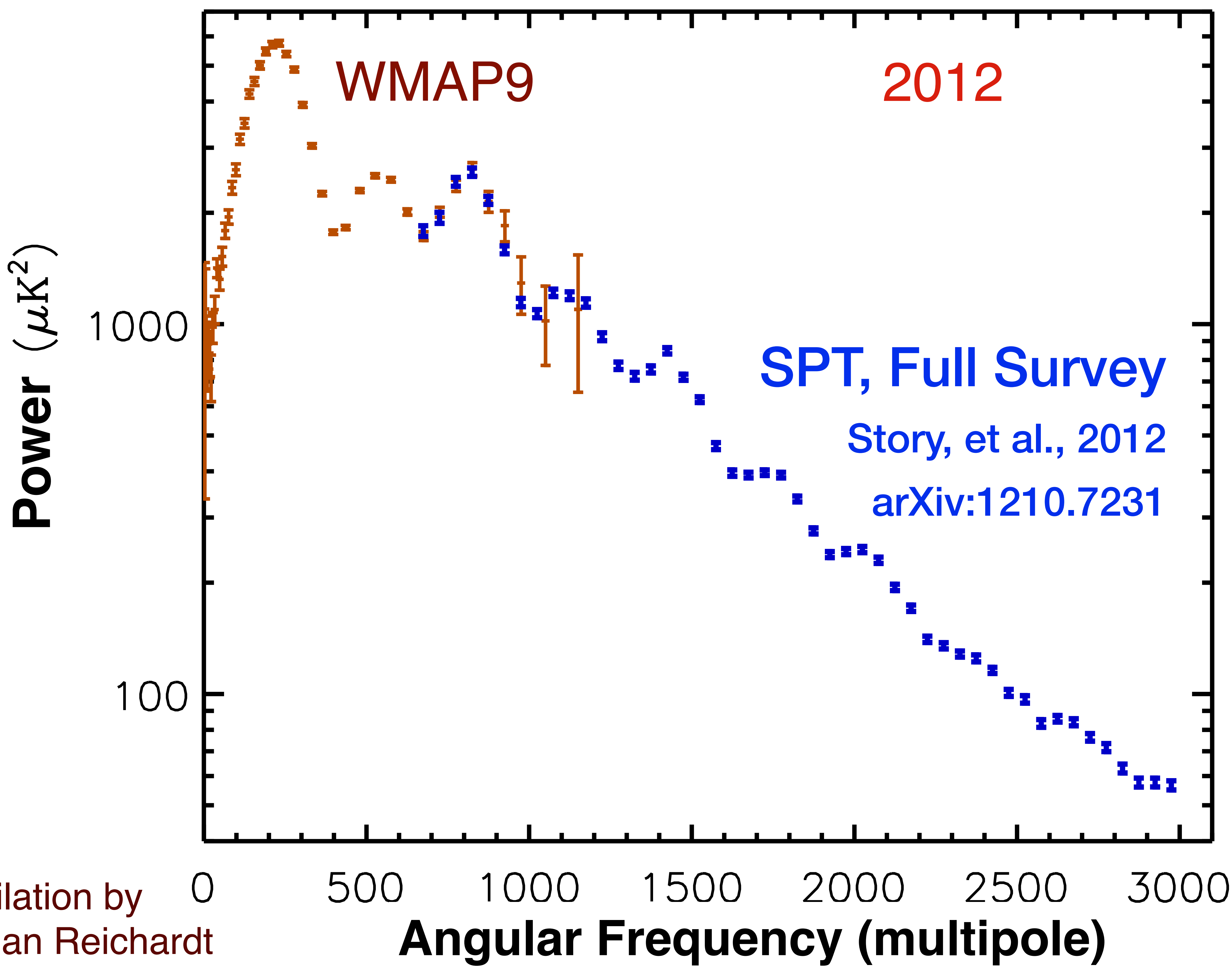
Peaks in power spectrum generated by acoustic oscillations in ~3000 K plasma

Evolution of CMB Power Spectrum Measurements



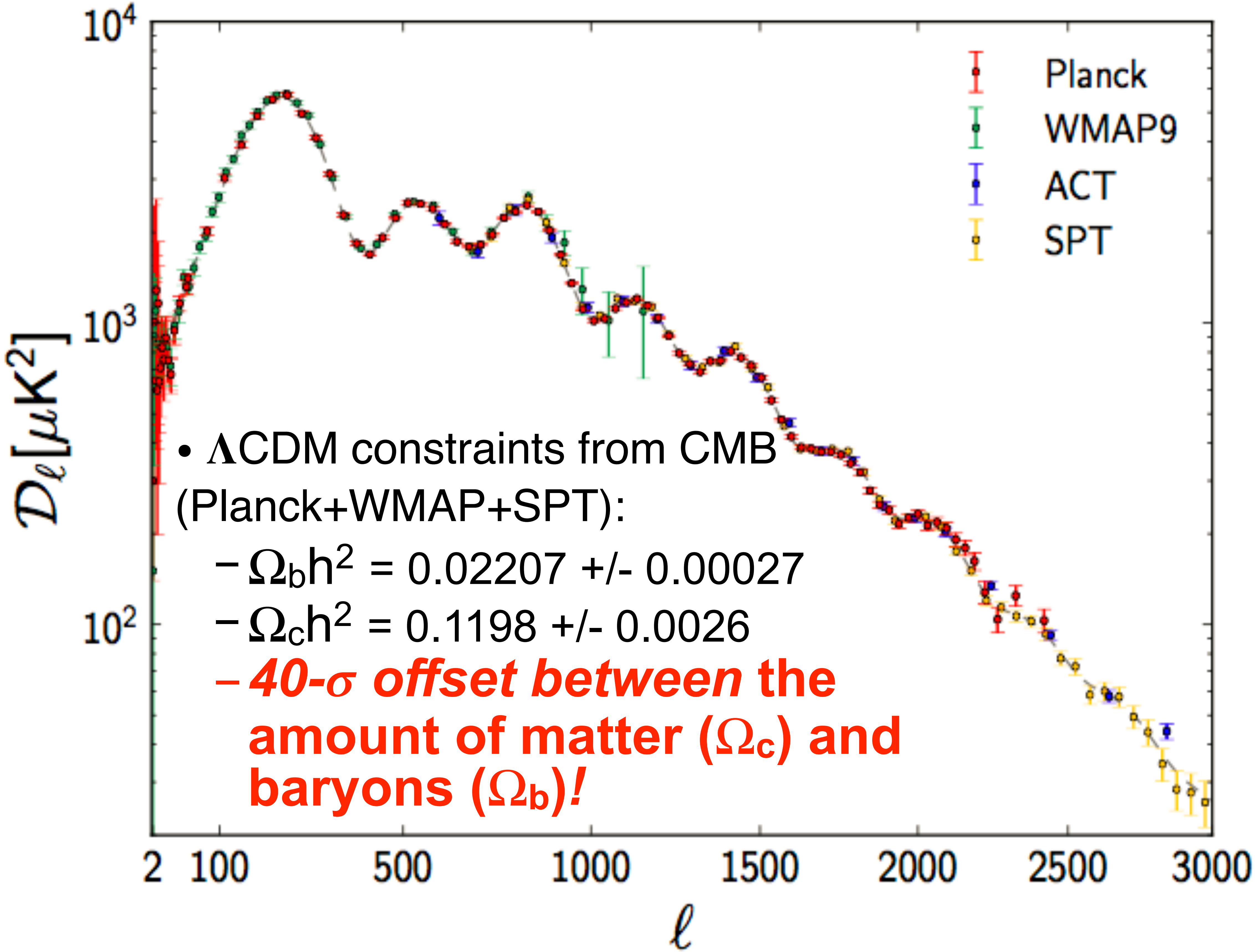
Compilation by
Christian Reichardt

Evolution of CMB Power Spectrum Measurements



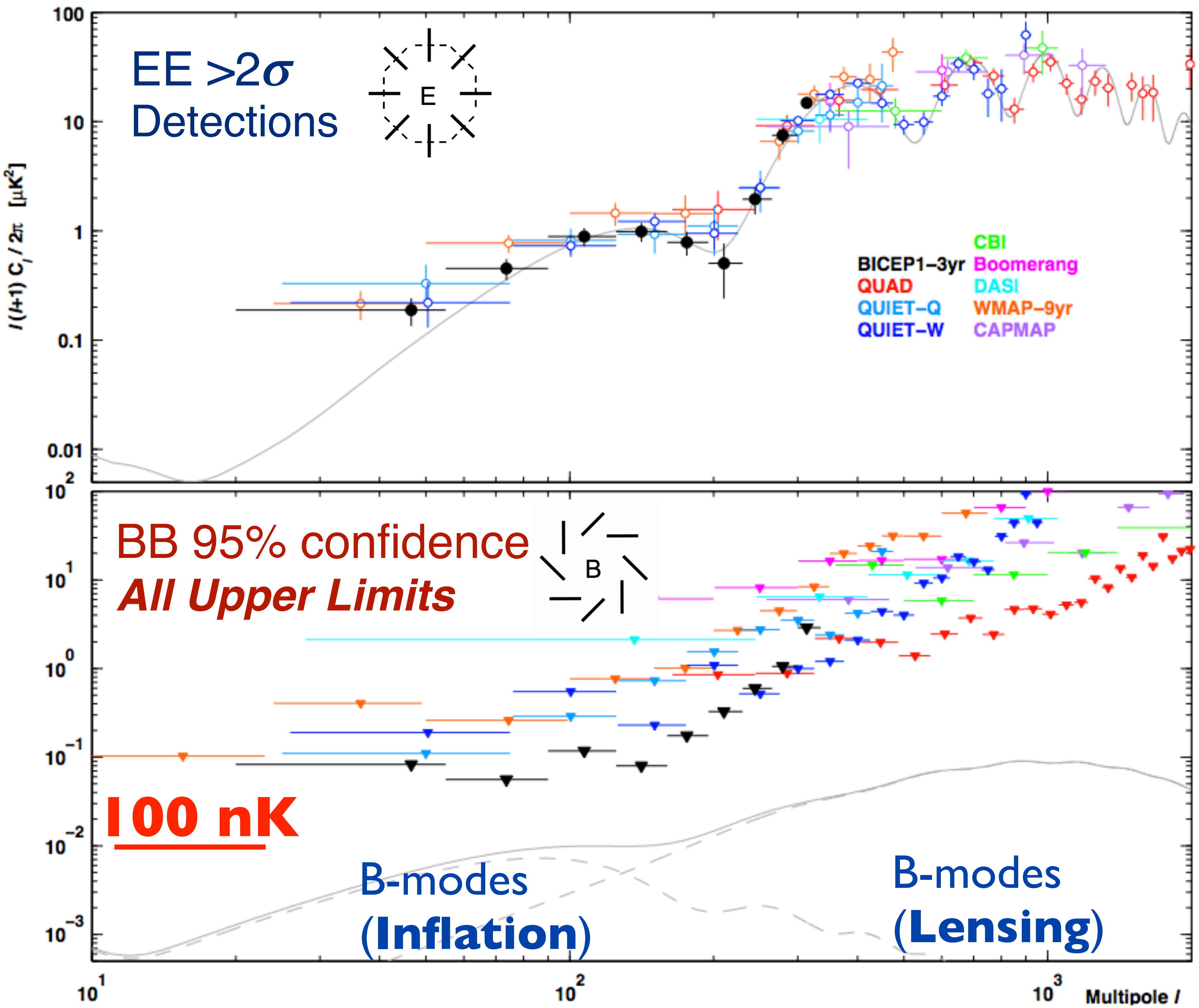
Compilation by
Christian Reichardt

Today: Outstanding agreement between CMB power spectrum measurements



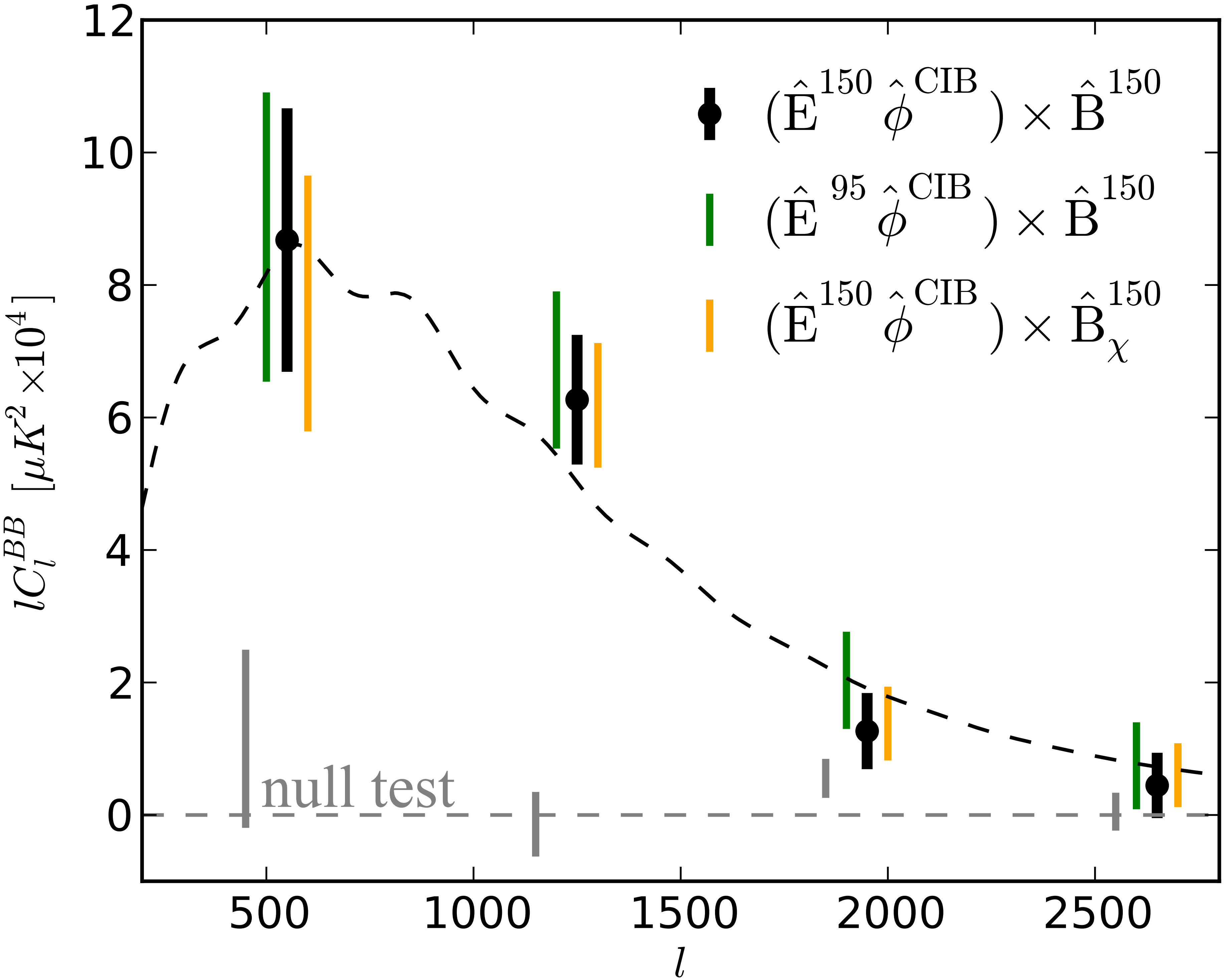
- ΛCDM constraints from CMB (Planck+WMAP+SPT):
  - $\Omega_b h^2$ = 0.02207 +/- 0.00027
  - $\Omega_c h^2$ = 0.1198 +/- 0.0026
  - ***40-σ offset between*** **the amount of matter (Ω_c) and baryons (Ω_b)*!***

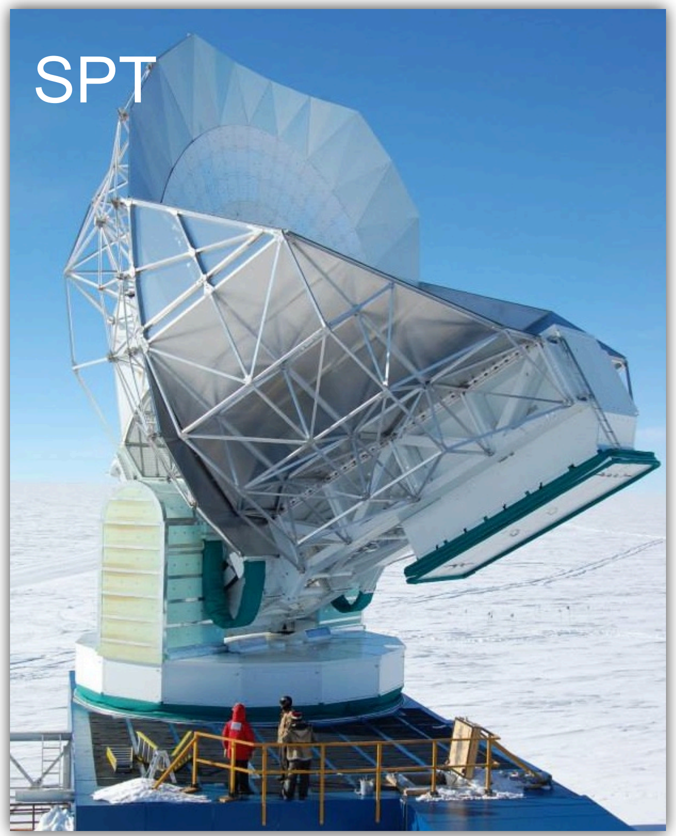
mid-2013: CMB Polarization Measurements

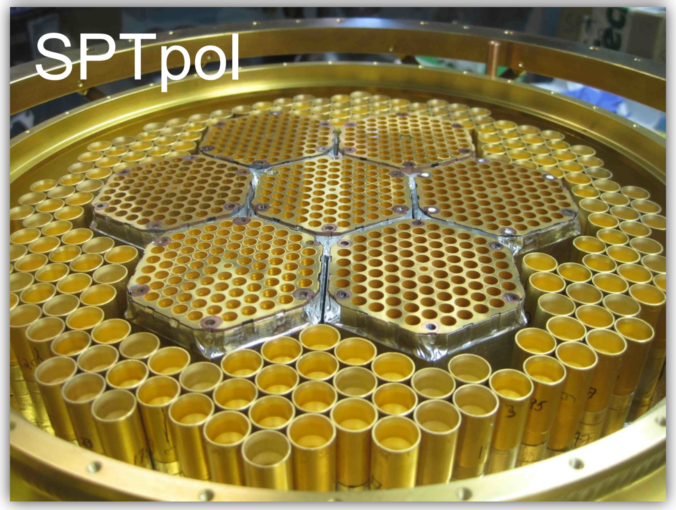


BICEP (Barkats et al. 2013, arxiv:1310.1422)

July 2013: SPTpol Detection of Lensing B-modes

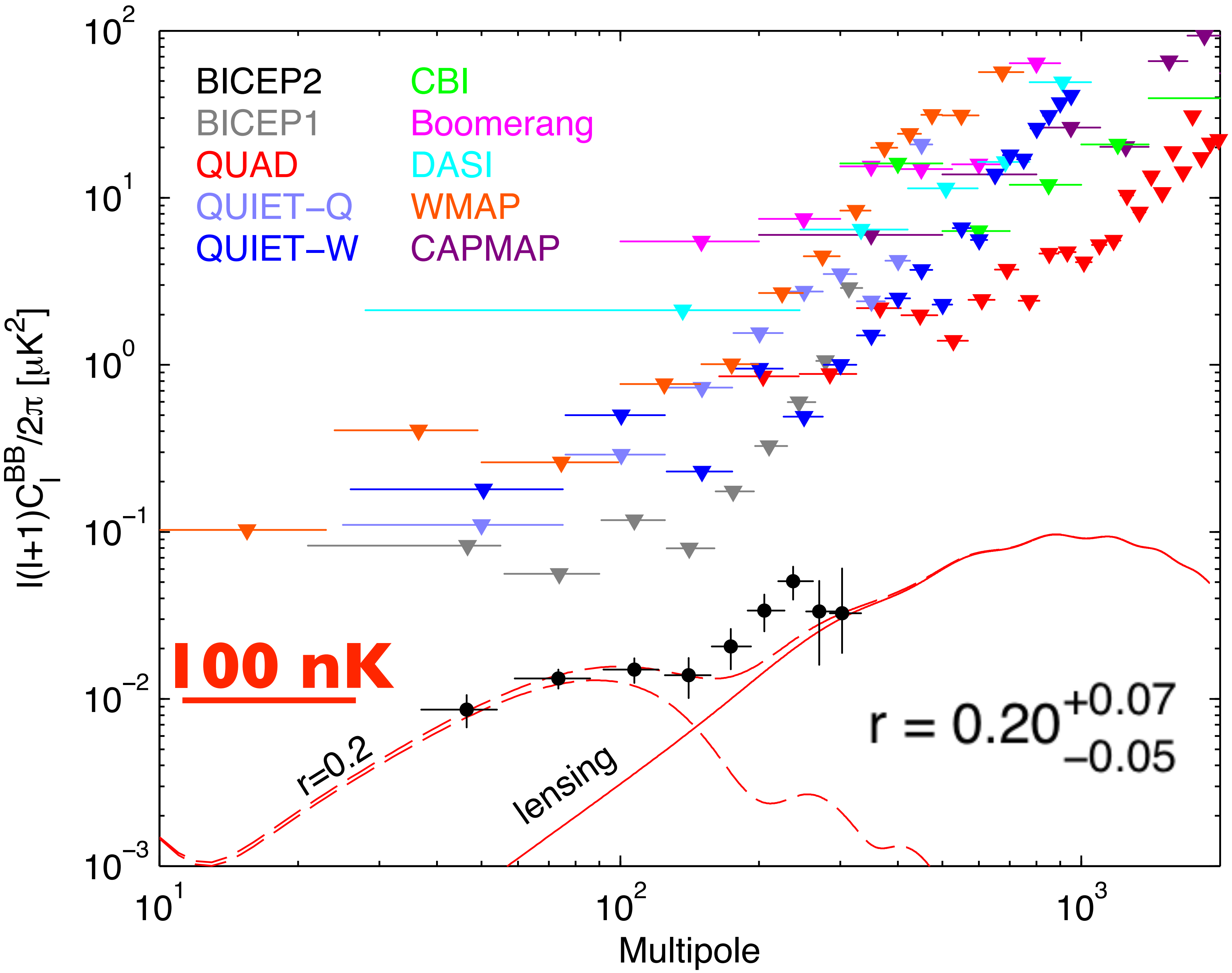


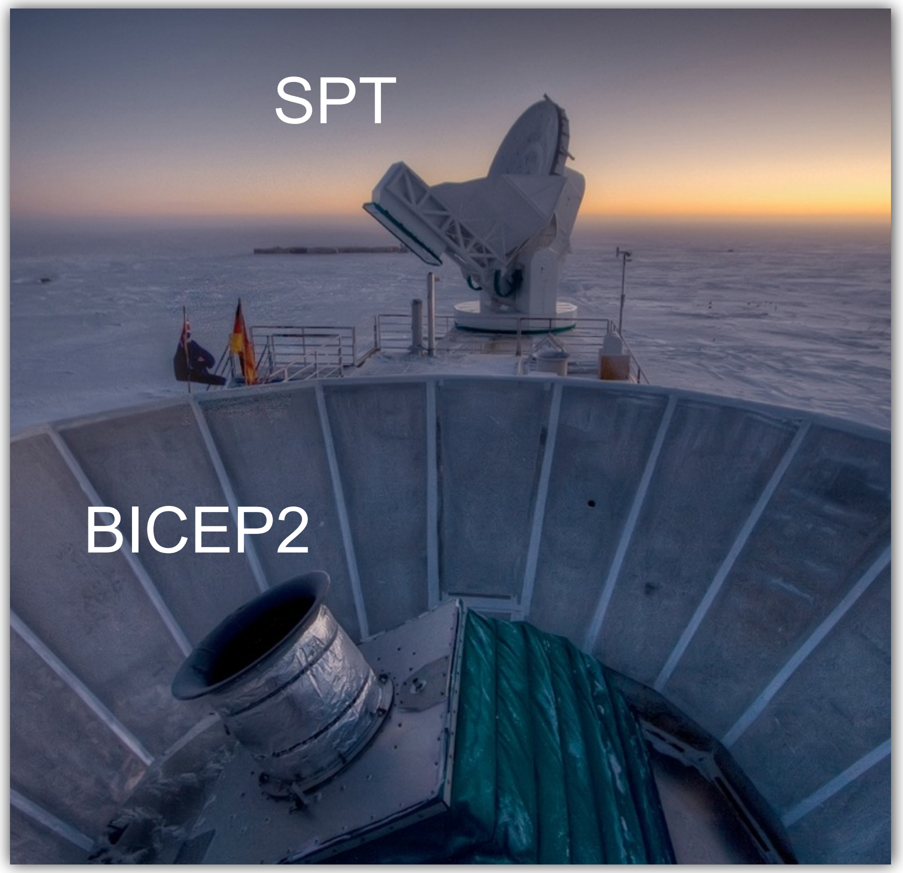


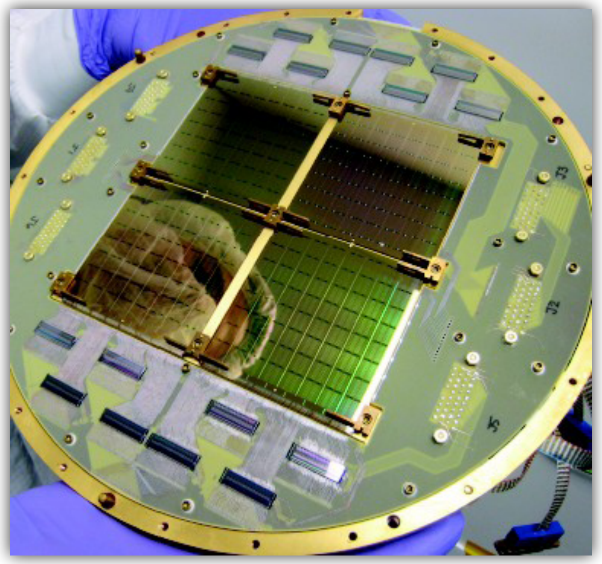


SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also recently detected by Polarbear arXiv:1312.6645, 1312.6646, 1403.2369

March 2014: BICEP2 Detection of B-modes!





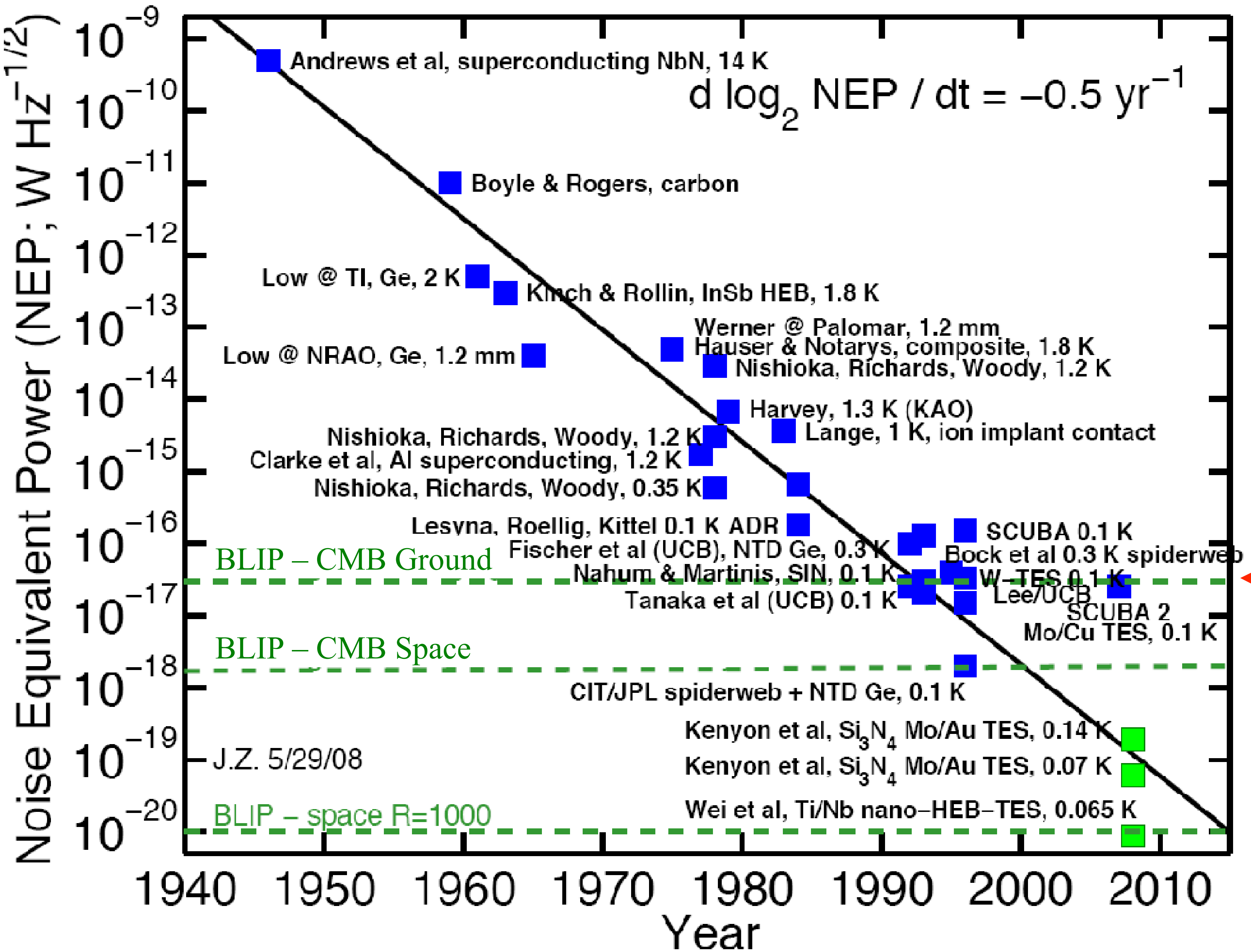


BICEP2: 512 detectors
150 GHz made by JPL

BICEP2 Collaboration (arXiv:1403.3985, arXiv:1403.4302)

Evolution of Detector Sensitivity

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



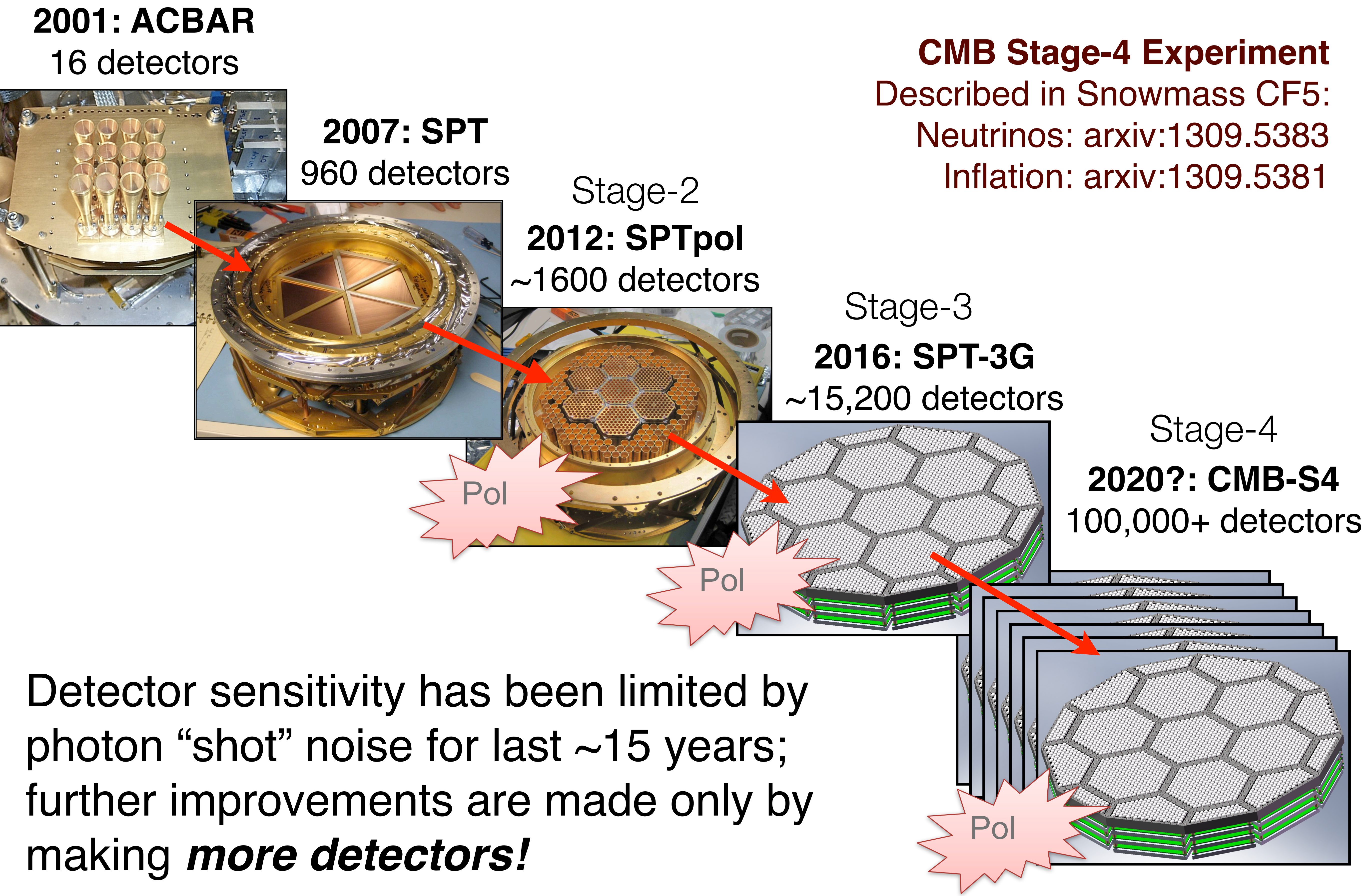
Photon ("shot") noise limit from ground-based observations

NEP ~
50×10^{-18} W Hz$^{-1/2}$

Plot from J. Zmuidzinas

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!***

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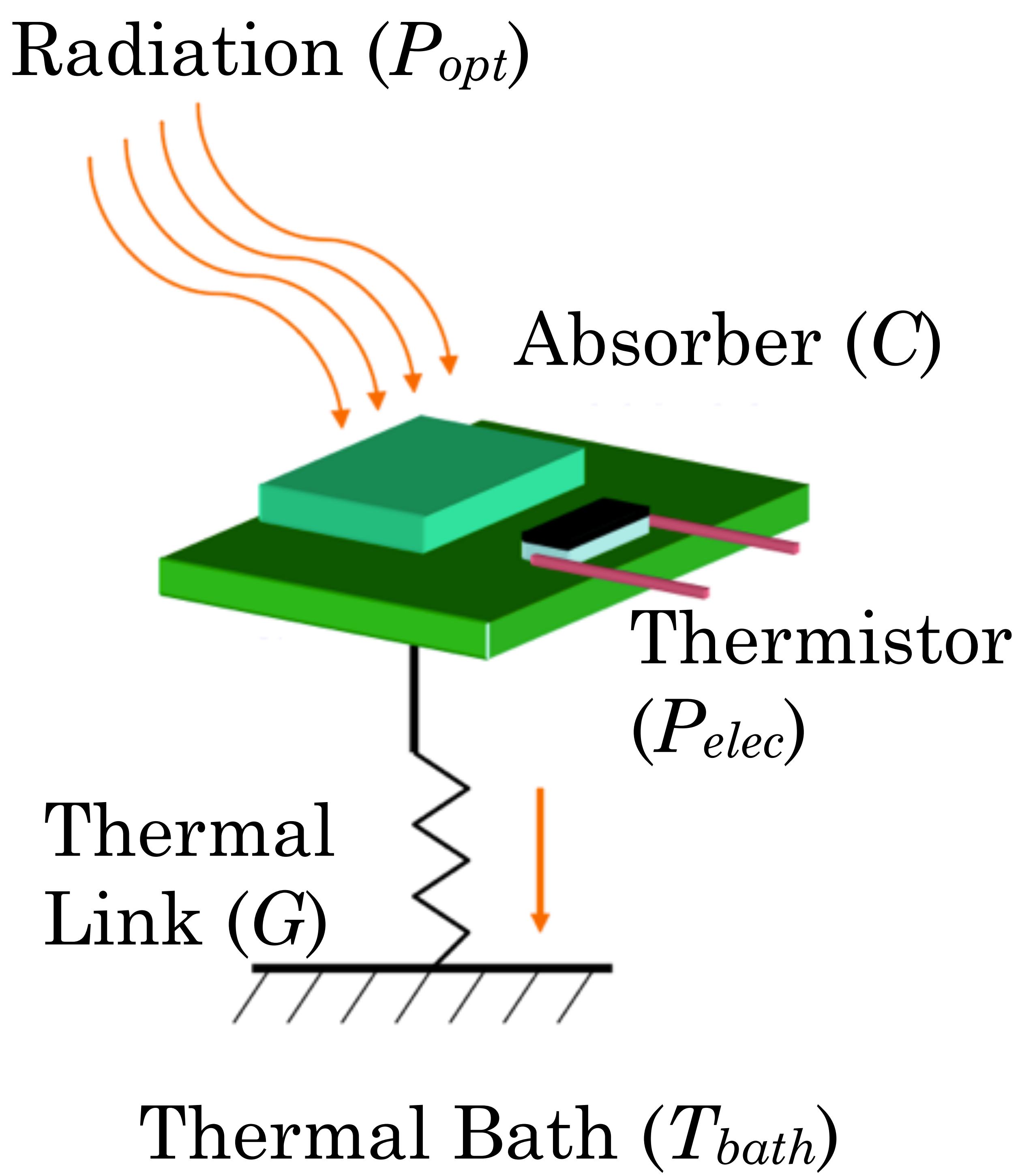
The Bolometer

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:

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

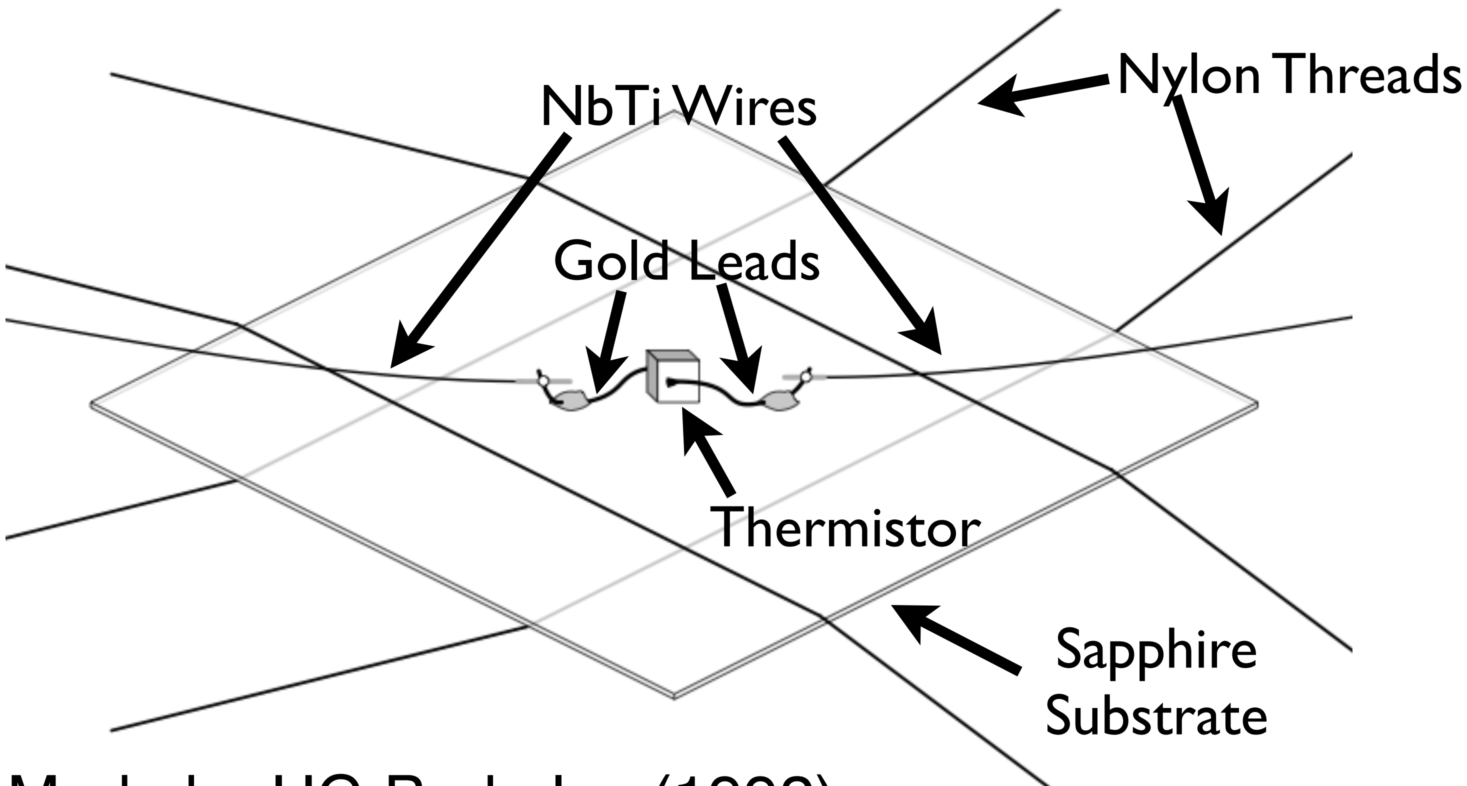
- Photon Noise:

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

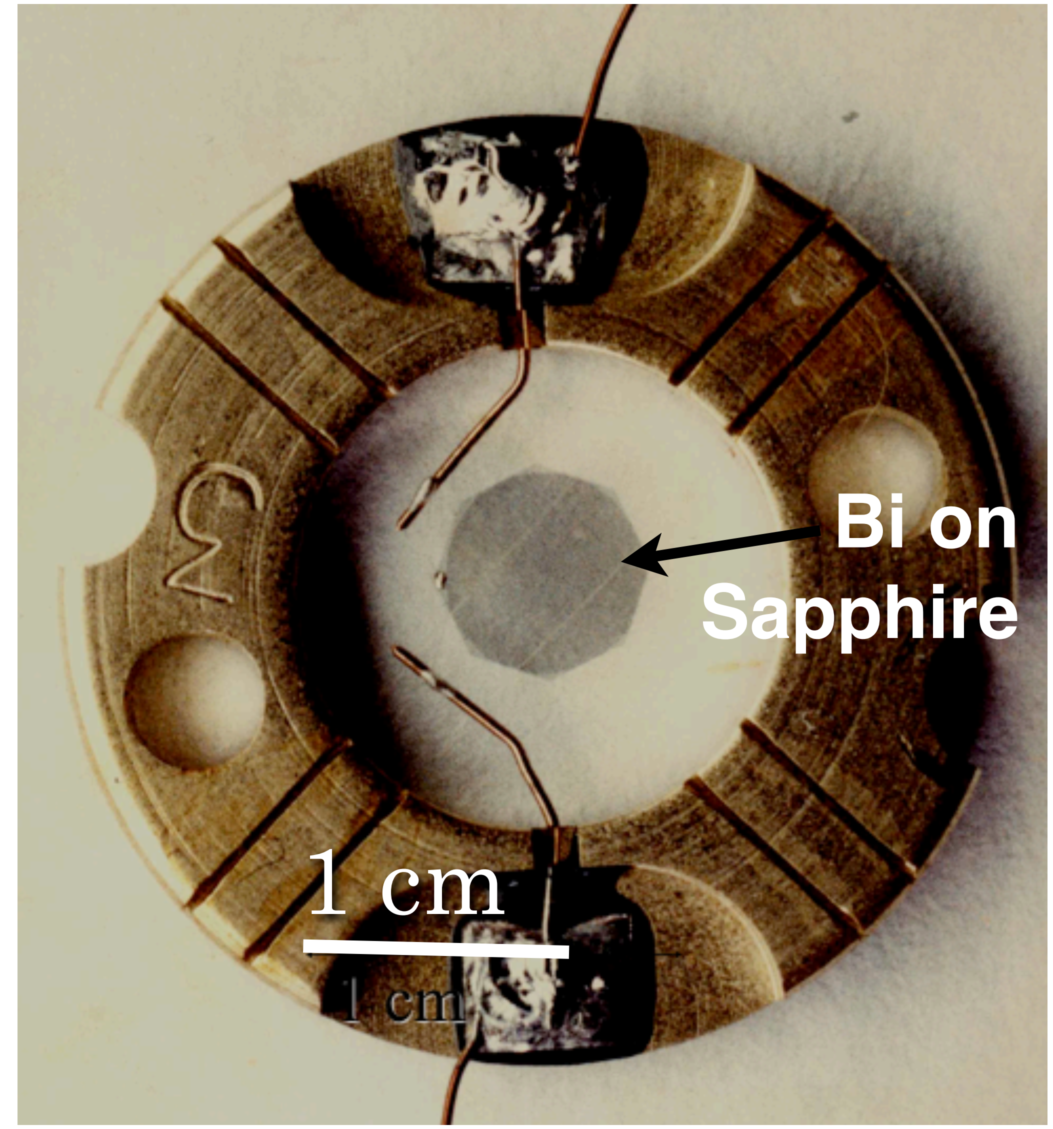
Goal: Design G, Tc such that thermal noise < photon noise.

SuZIE Bolometers (1992-1997)

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



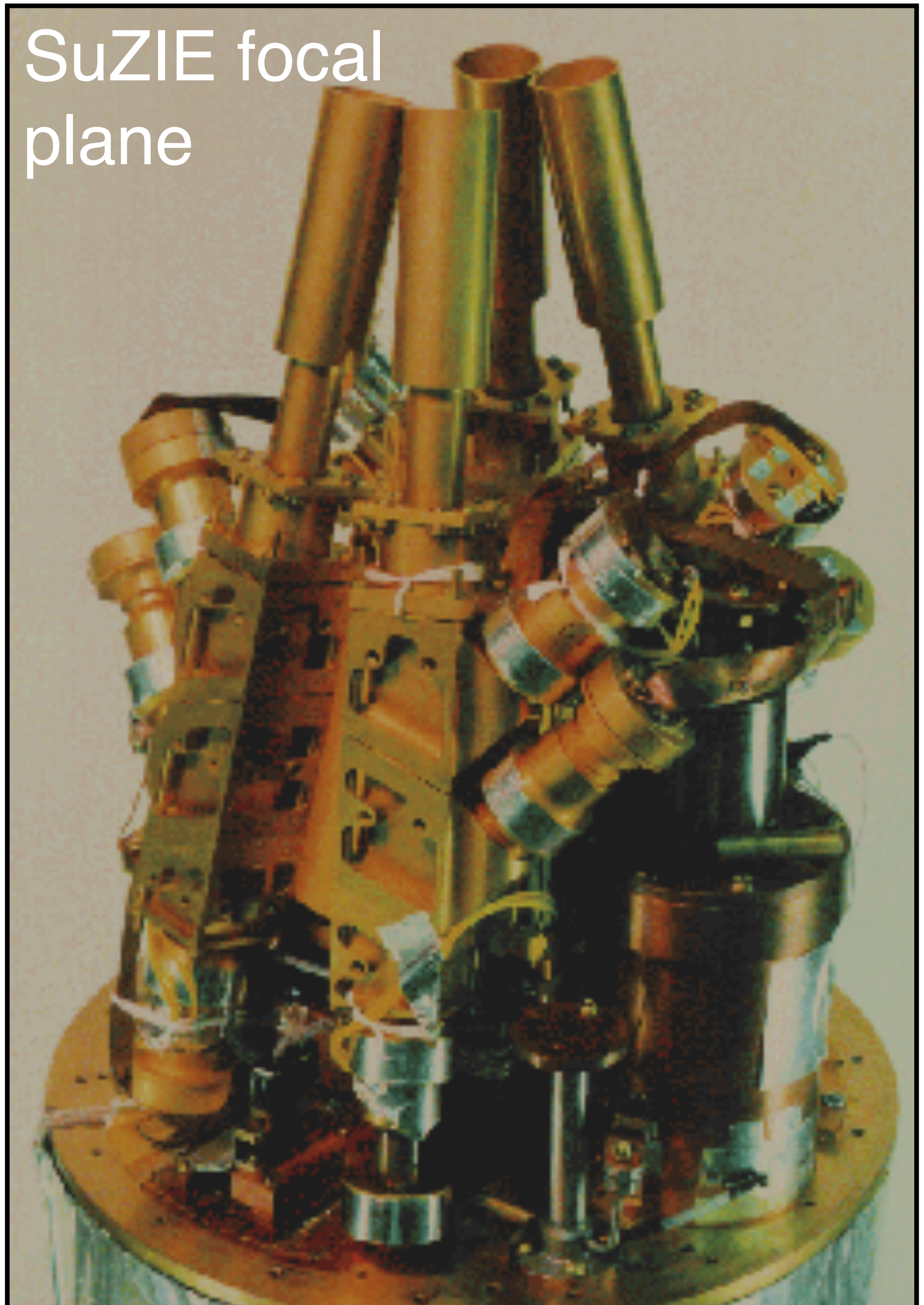
Made by UC-Berkeley (1992)

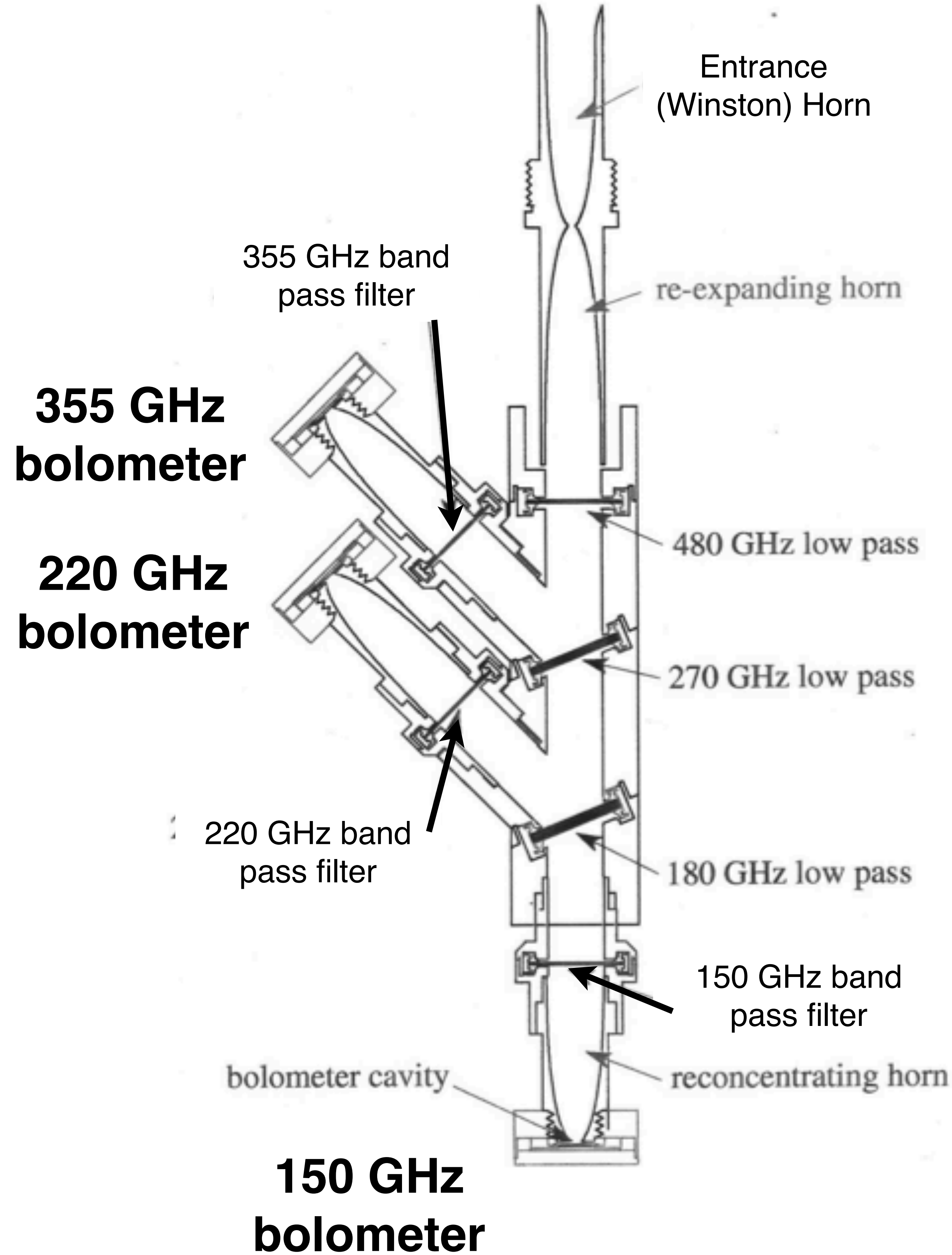


A Hand-Made bolometer!

- 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!***

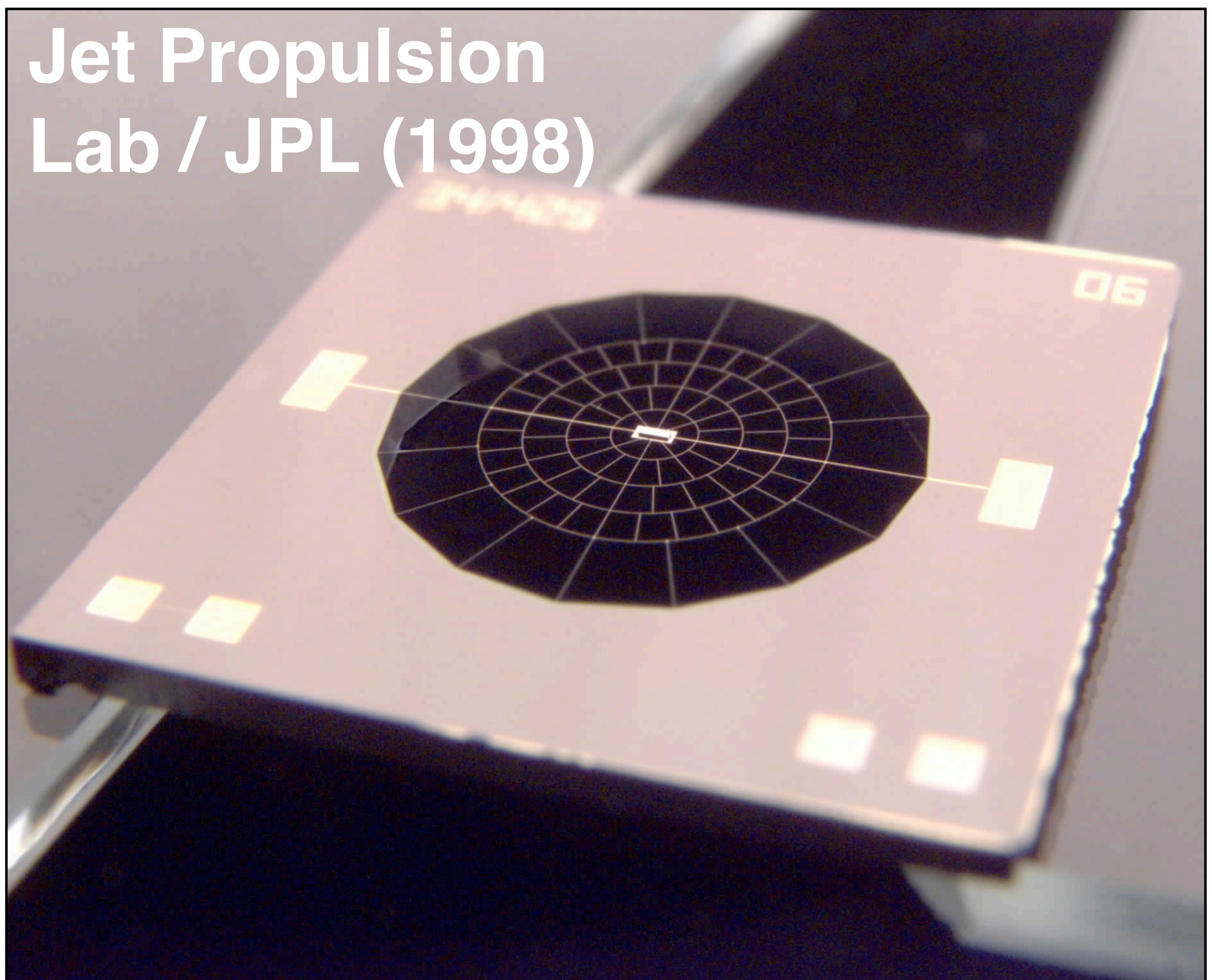
The SuZIE Photometer

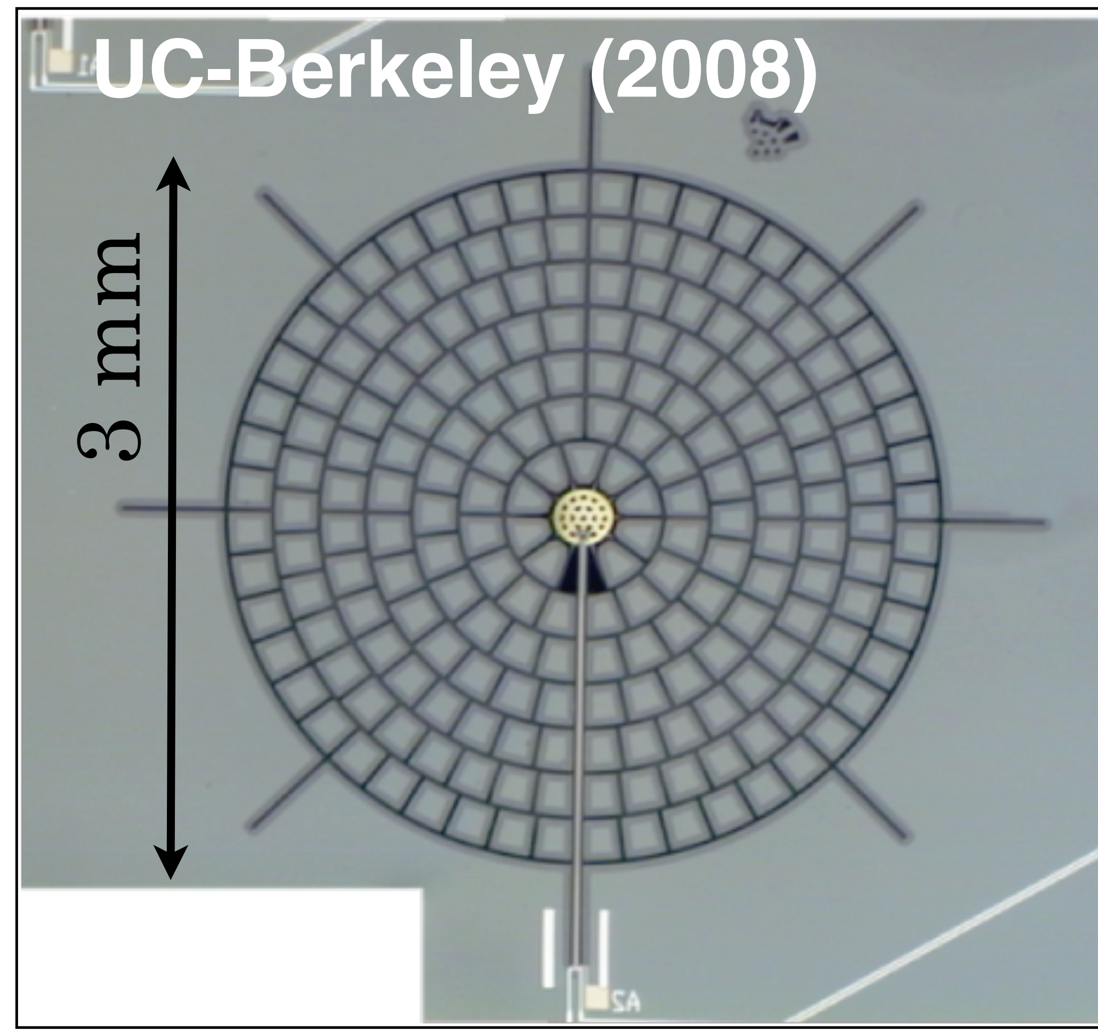




The Spider-Web Bolometer

- ***SuZIE was the first experiment to use a JPL "spider-web" bolometer!***
  - Silicon nitride substrate with gold absorber and NTD germanium thermistor
  - Same JPL design later used for *ACBAR, Boomerang, Planck* experiments
- ***For SPT, UC-Berkeley incorporated a transition edge sensors (TES)*** as the thermistor, operated on its superconducting transition





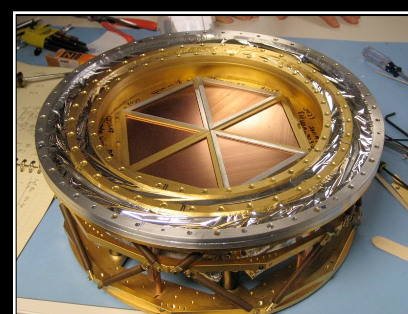
Fabricated by Erik Shirokoff!
(new faculty at U. Chicago)

The South Pole Telescope (SPT)

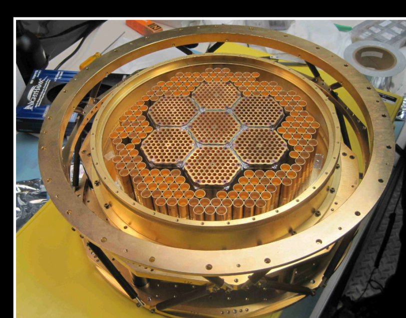
10-meter sub-mm quality wavelength telescope

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

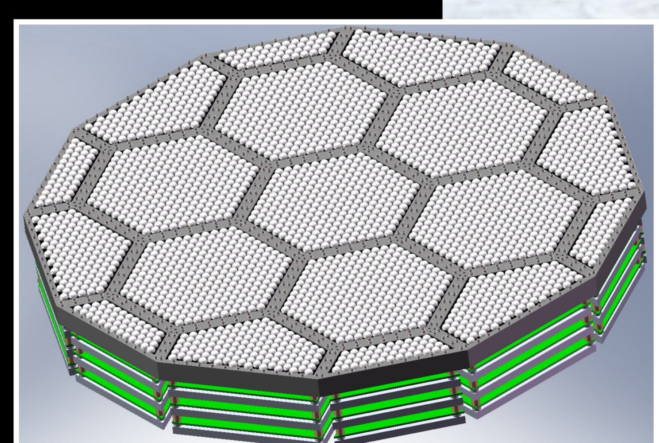
2007: SPT-SZ
960 detectors
100,150,220 GHz

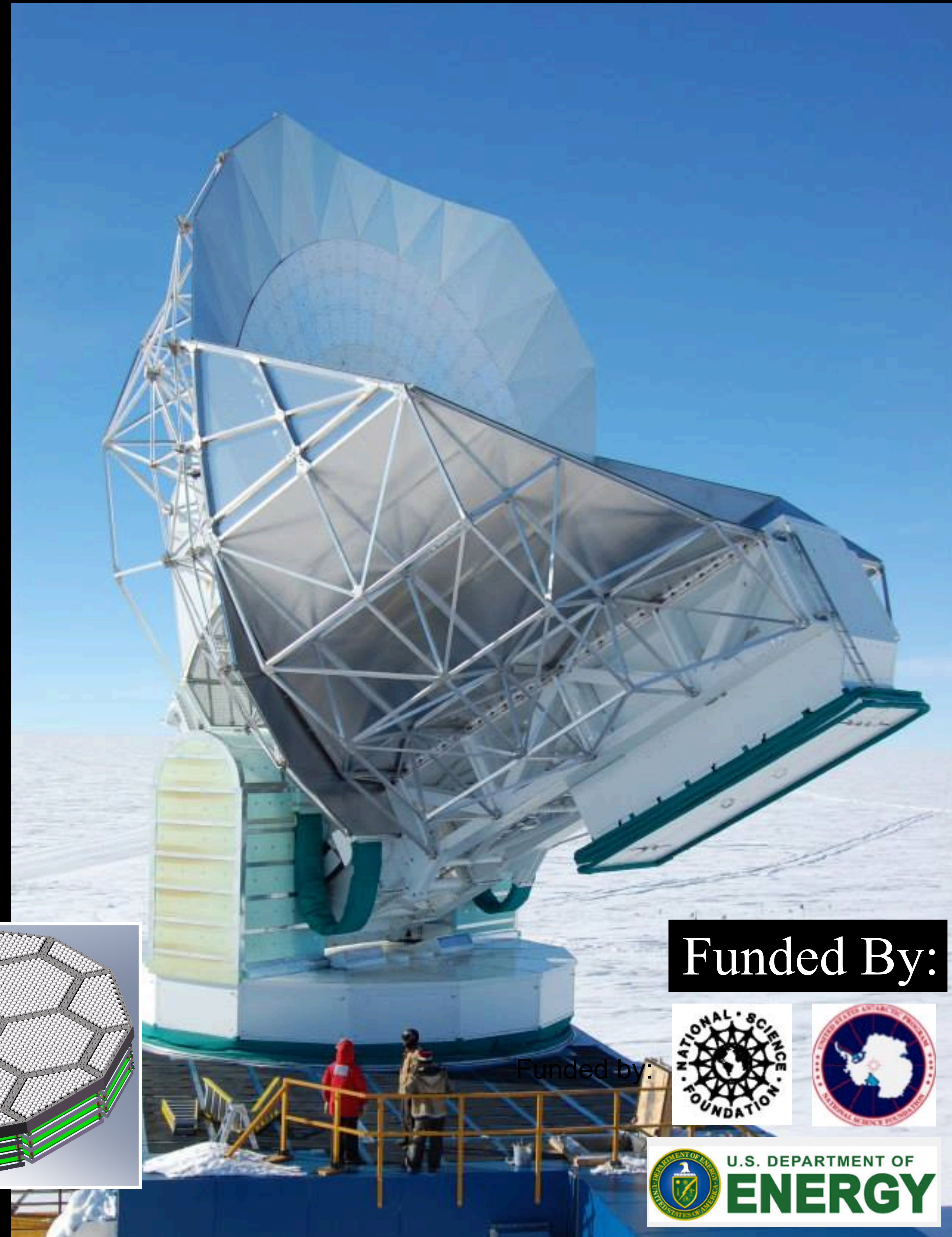


2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



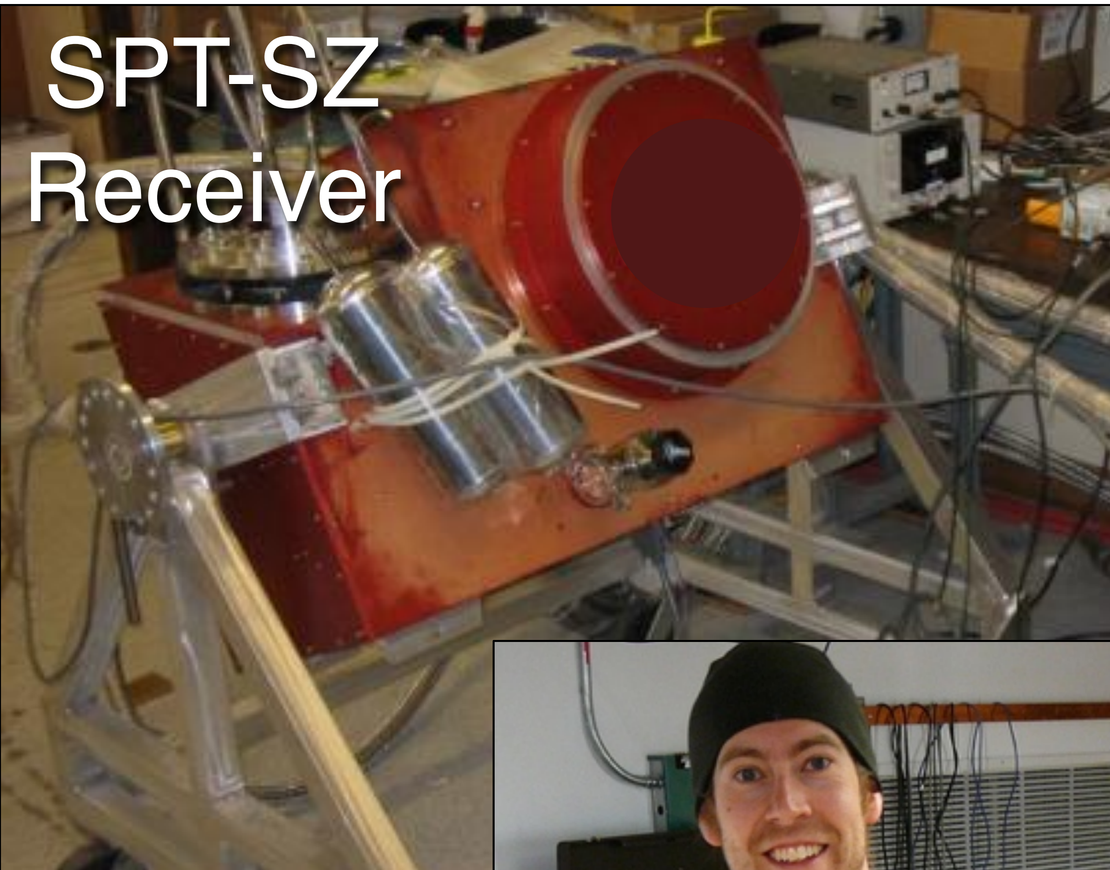
2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization





Funded By:

SPT-SZ Receiver (2004-2008)

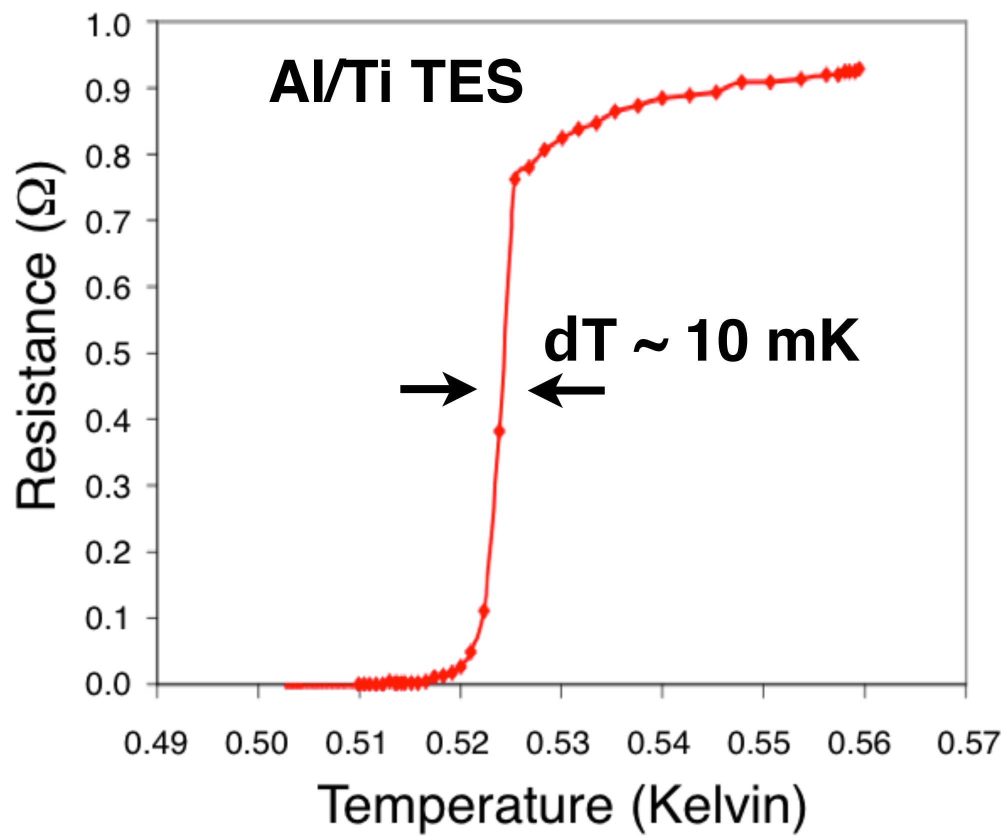


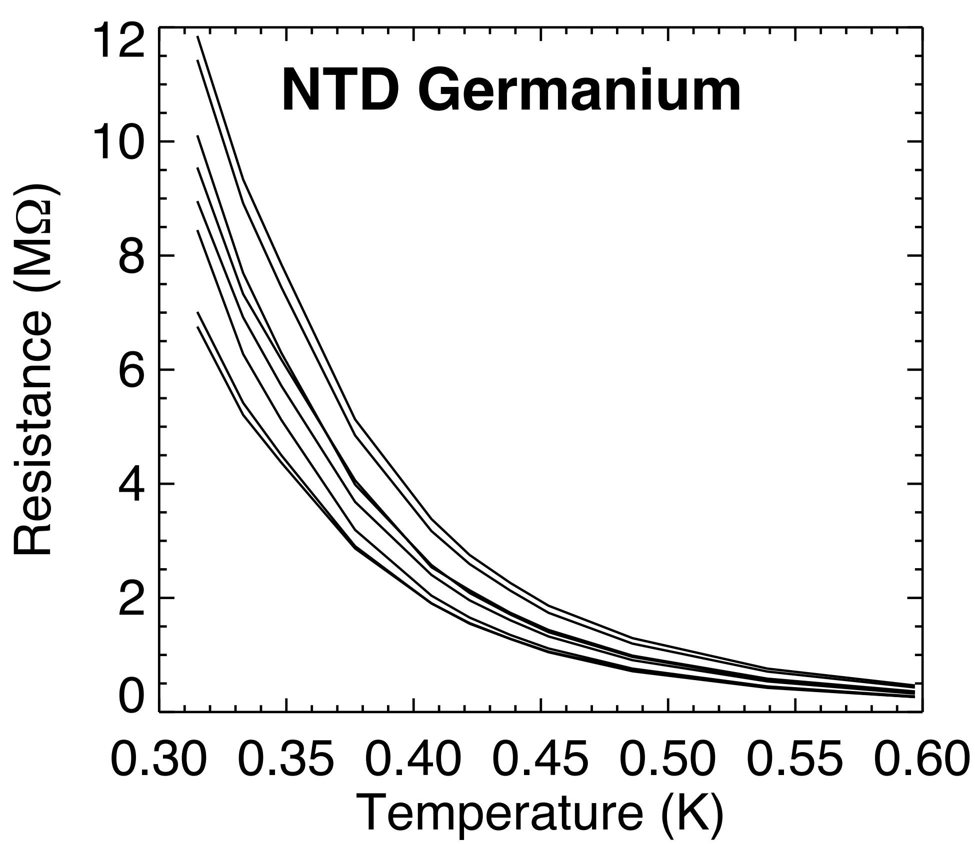
SPT-SZ Focal Plane

- 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)

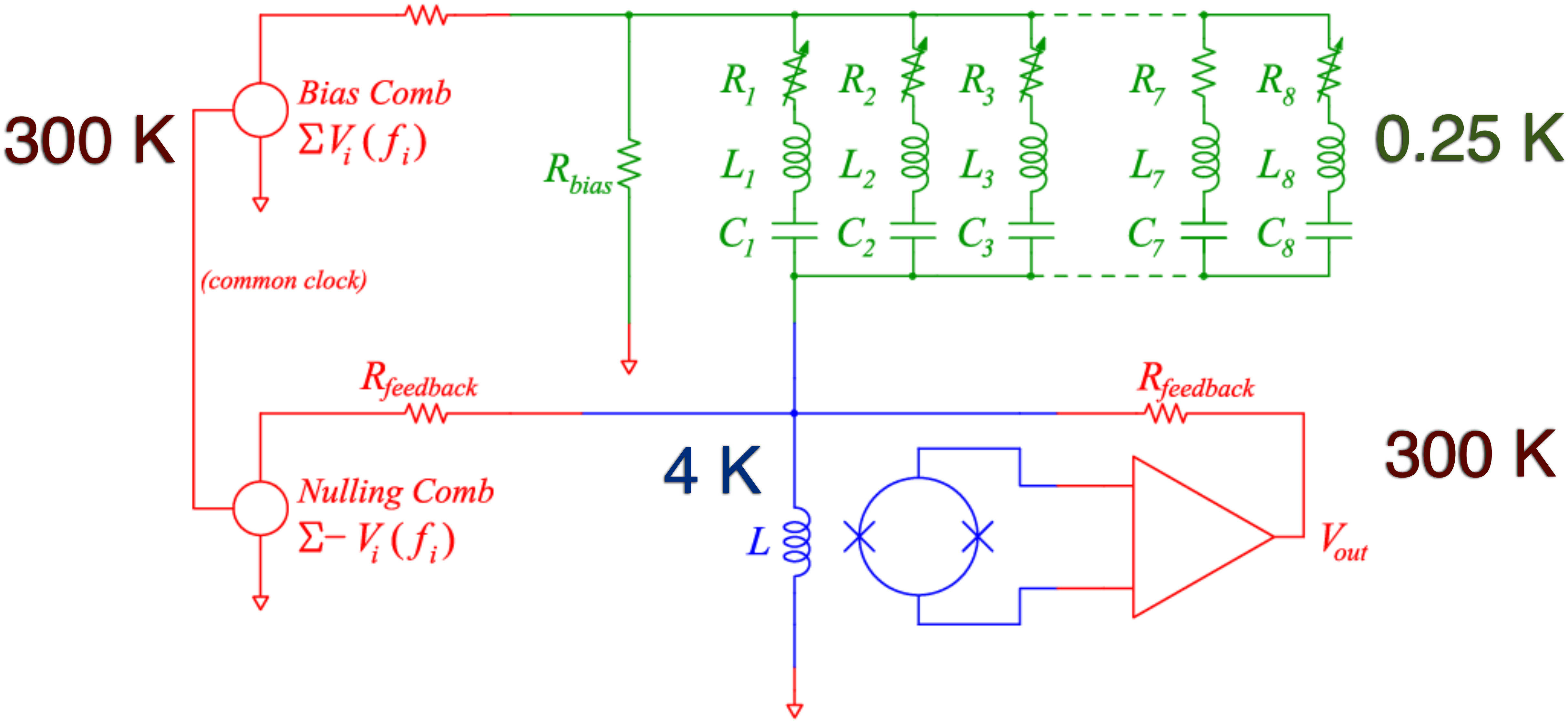
- Often a normal-metal/superconducting bi-layer
- Typical combinations (e.g., Al/Ti, Mo/Au,Al/Mn) require ~30-100 nm film thickness for transitions of ~500 mK

Thermistor: TES vs NTD Germanium

1) ***Fab*** - TES's can be fabricated on bolometer
2) ***Linearity*** - Steepness of $R(T)$ curve determines strength of electrothermal response
3) ***Microphonics*** - Low-impedance = low-microphonic response

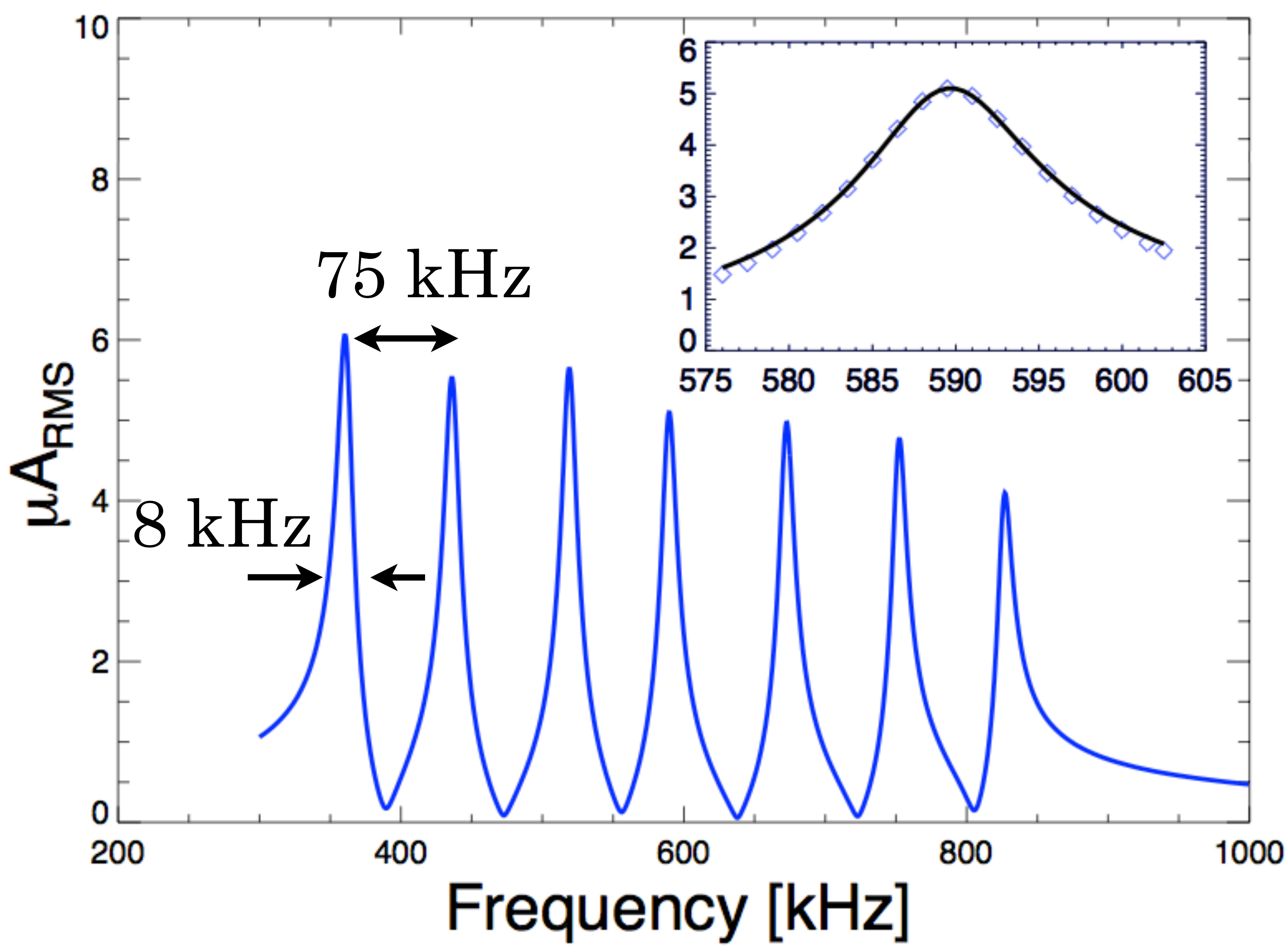
	Resistance (Ohms)	Electrical Loop Gain
NTD Germanium	~2-10 M	~1-5
TES	~1	~20-1000

Frequency Domain Multiplexing (fMUX)



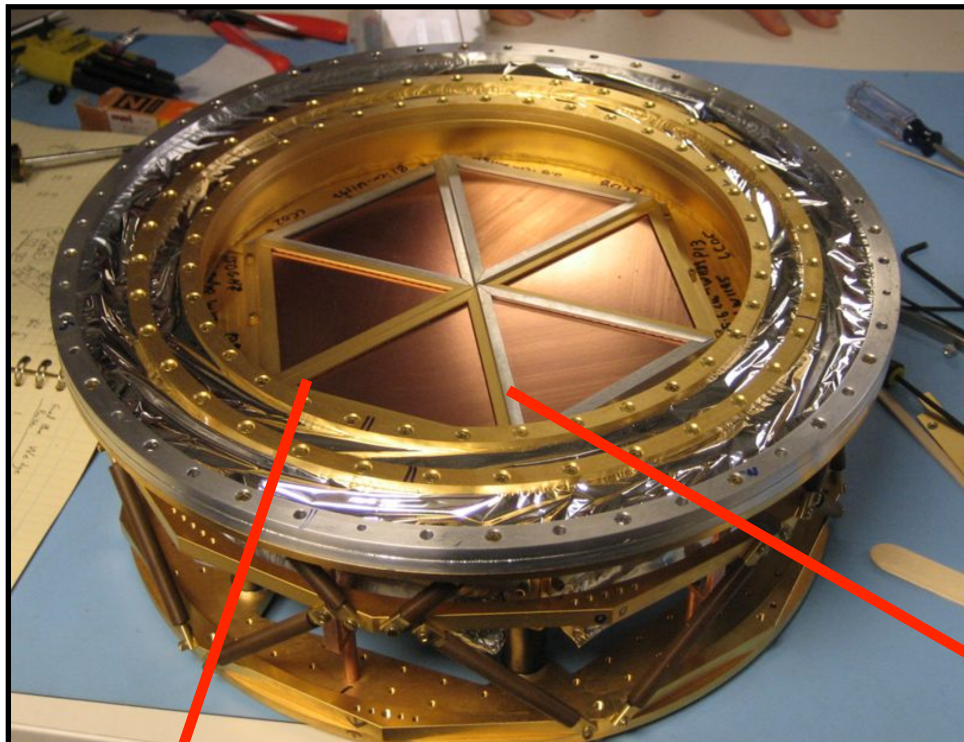
- Developed current summing fMUX SQUID readout at UC-Berkeley and Lawrence Berkeley Labs (LBL)
- AC Bias row of detectors with comb of frequencies between 300-1000 kHz at RLC filter resonances: $2\pi f_{\mathrm{filt}} = w_{\mathrm{filt}} = 1/(LC)^{1/2}$
- Crosstalk determined by Q of LC resonance (designed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

Frequency Domain Multiplexing (fMUX)

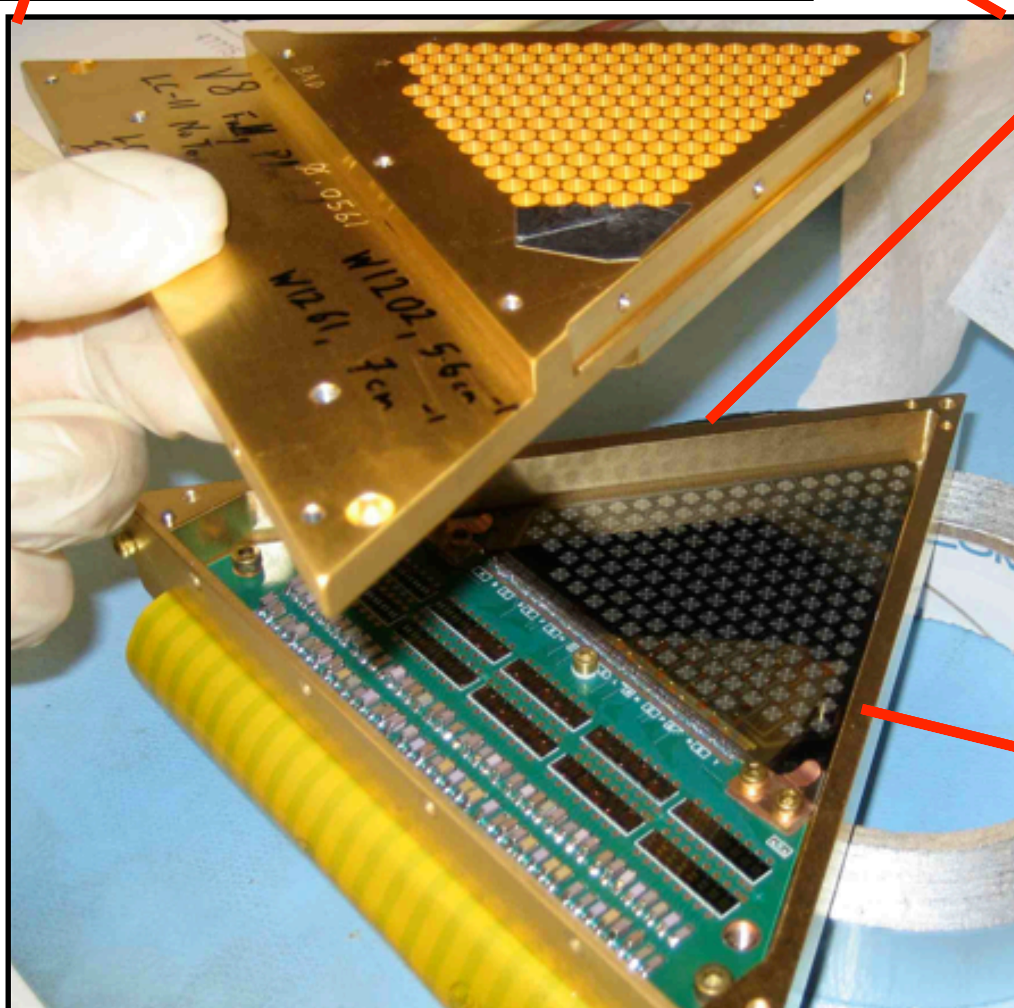


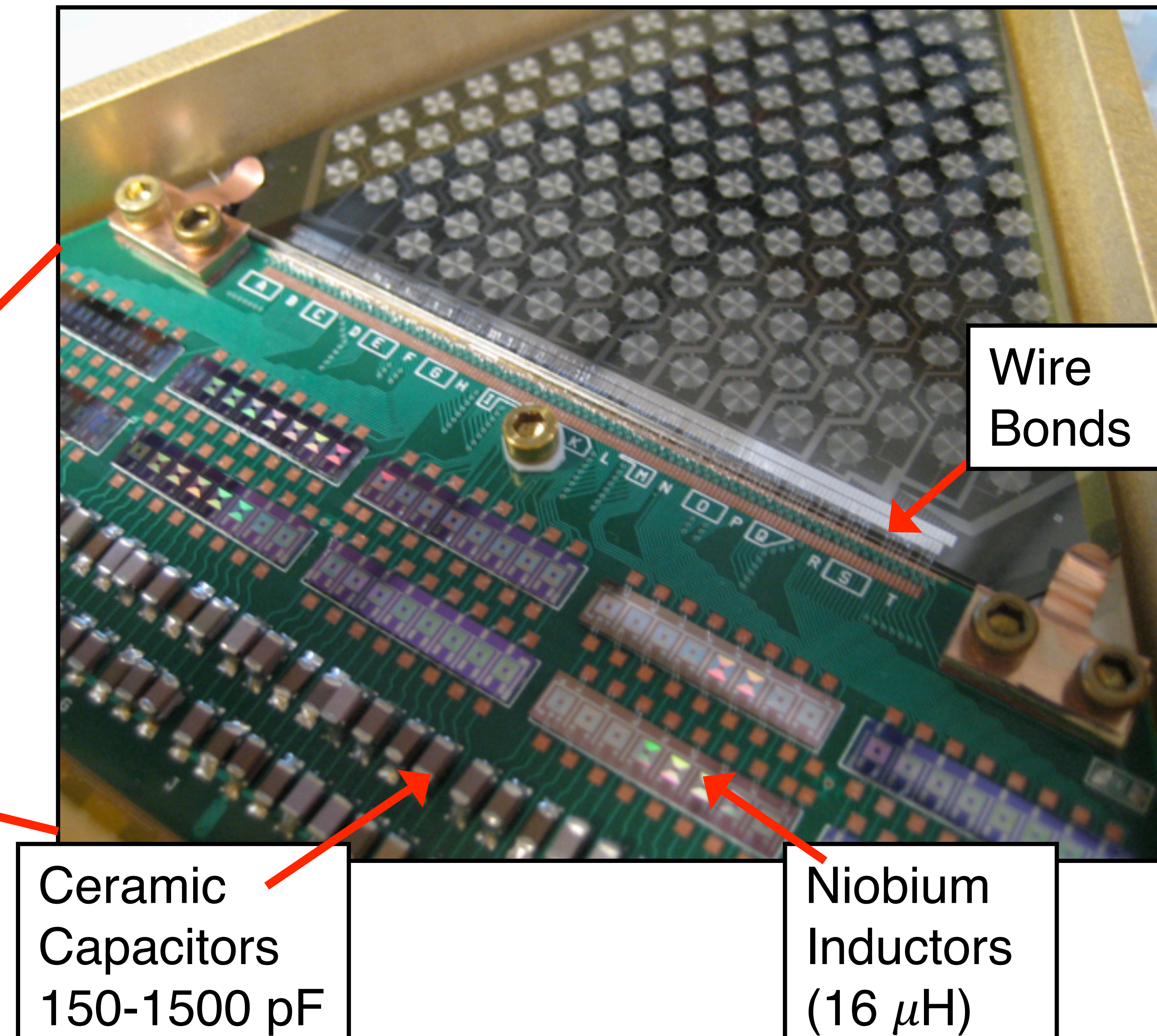
- AC Bias row of detectors with comb of frequencies between 300-1000 kHz at RLC filter resonances: $2\pi f_{\text{filt}} = w_{\text{filt}} = 1/(LC)^{1/2}$
- Crosstalk determined by Q of LC resonance (designed to be < 1%): $\Delta w_{\text{filt}} = R/L$, therefore $Q = (L/RC)^{1/2}$

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)





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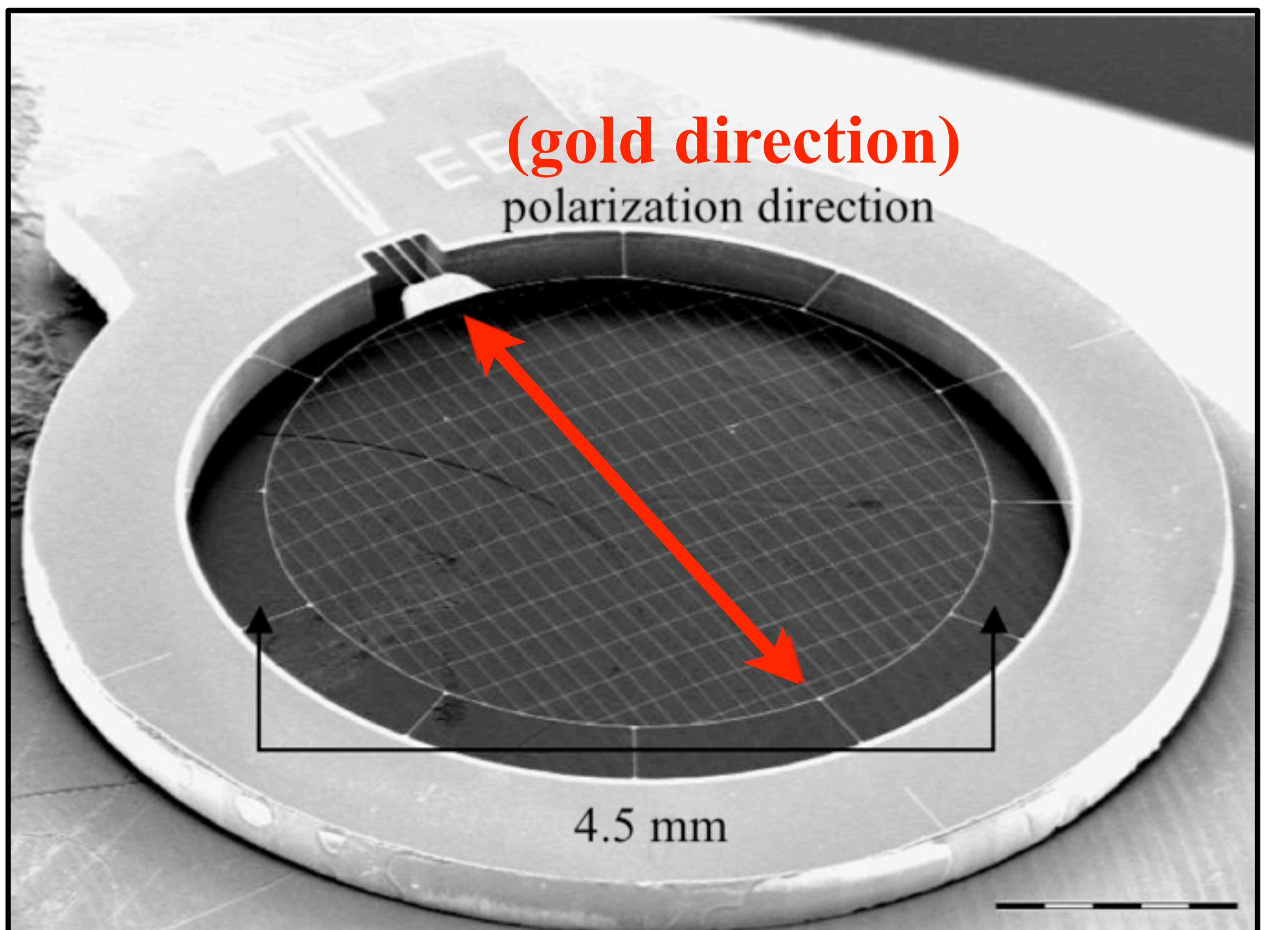
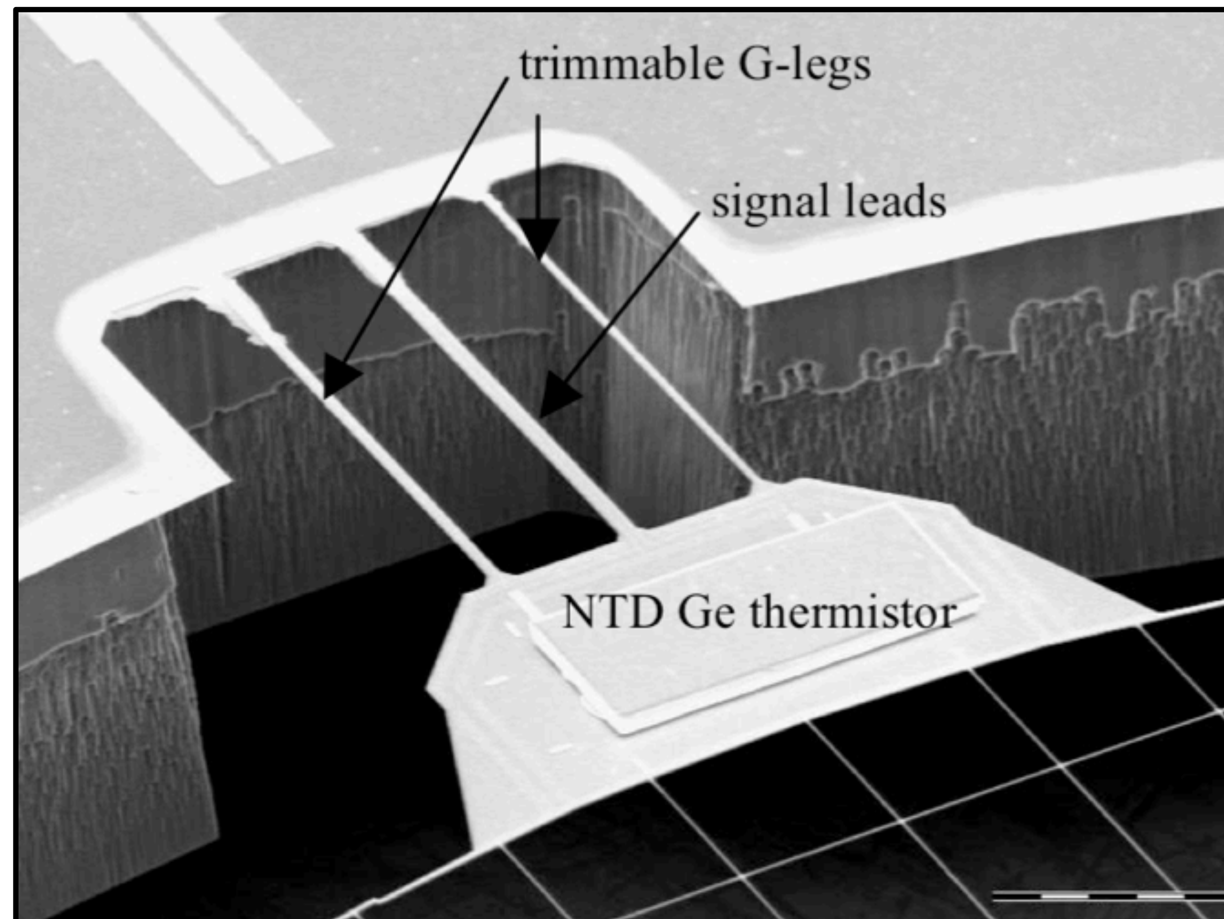
   - The path to CMB-S4

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

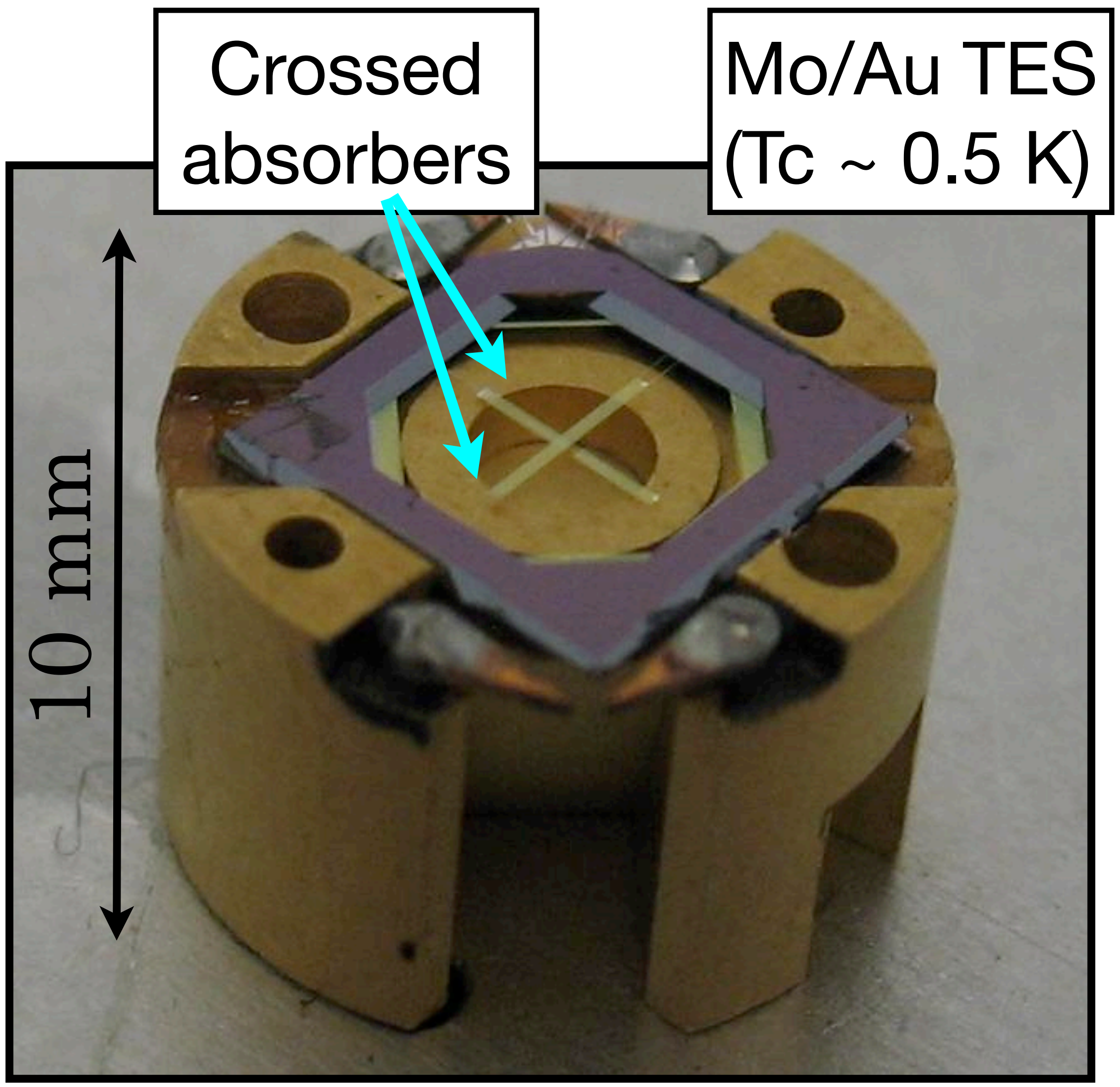


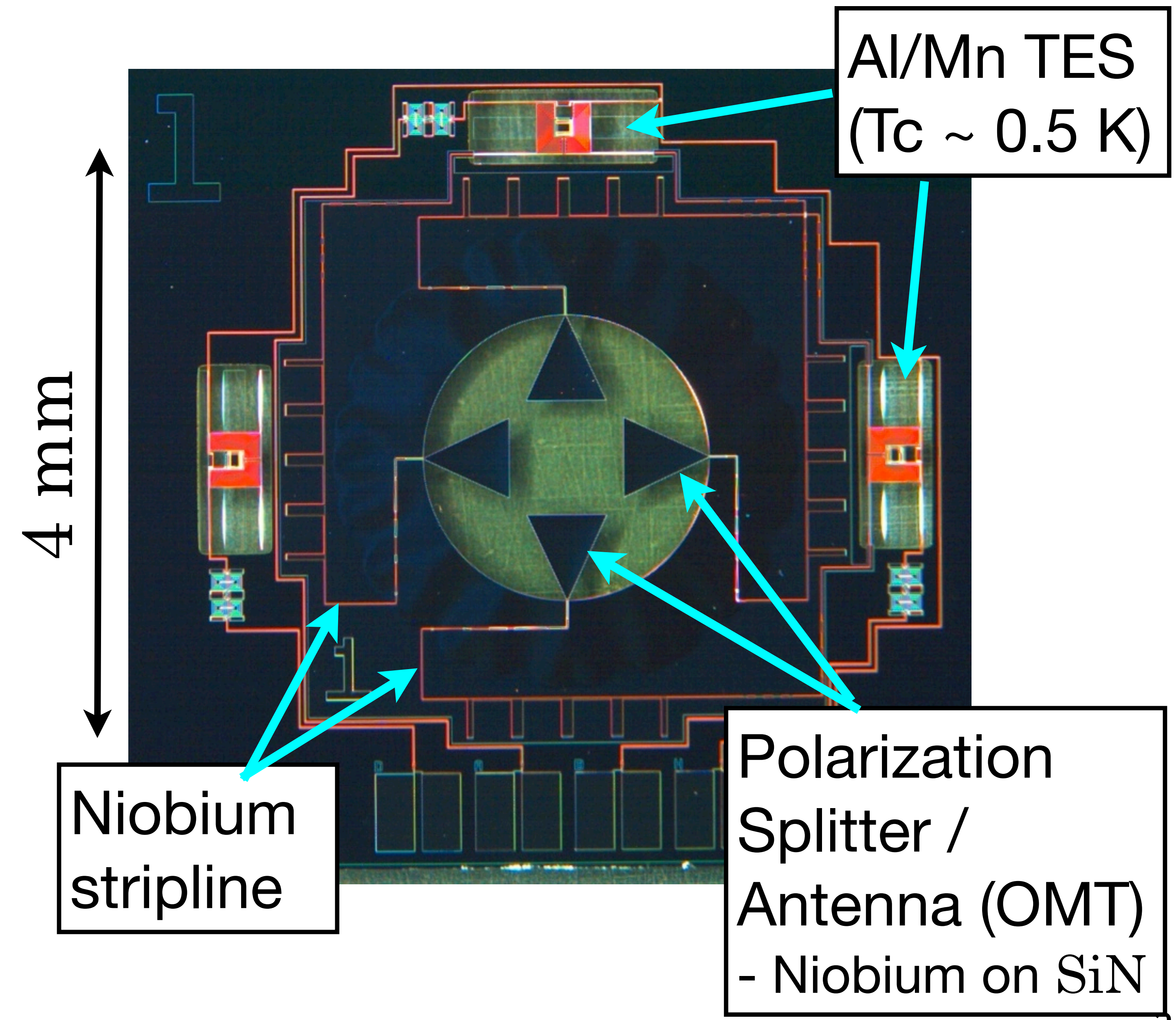


SPTpol: Detectors

For SPTpol, we scaled the PSB concept to ~1000 pixel array, using 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)



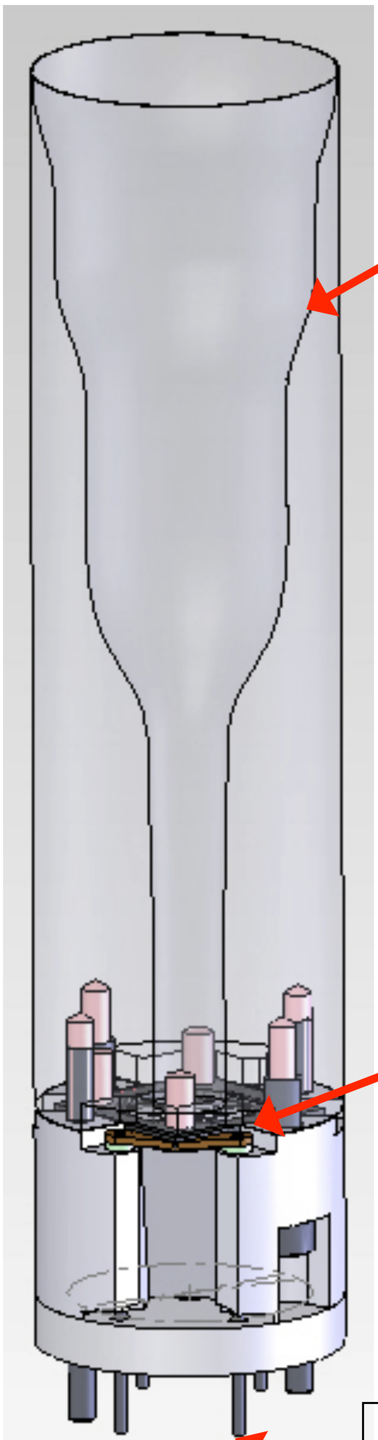


Argonne NATIONAL LABORATORY

95 GHz Single Pixel PSBs

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

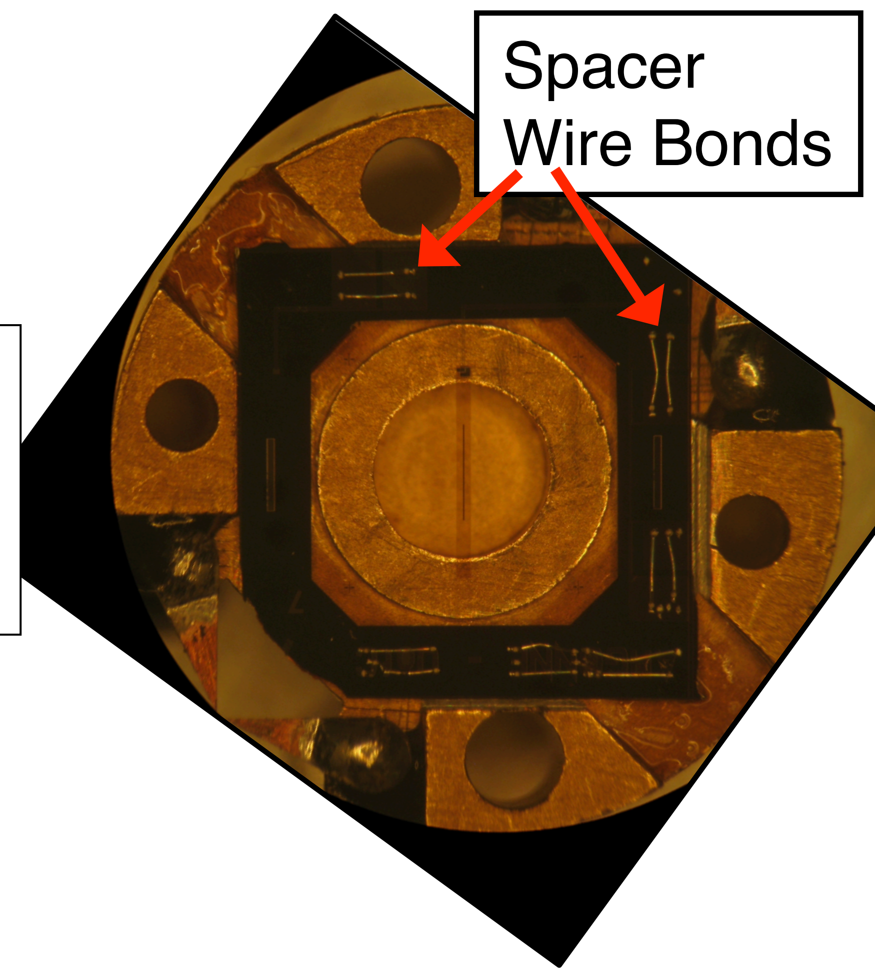
- SPTpol 95 GHz array of 190 pixels
- Crossed absorbers with TES's in waveguide behind contoured feed horn with a $\lambda/4$ backshort
- Wire-bonds maintain ~50 um separation between crossed absorbers



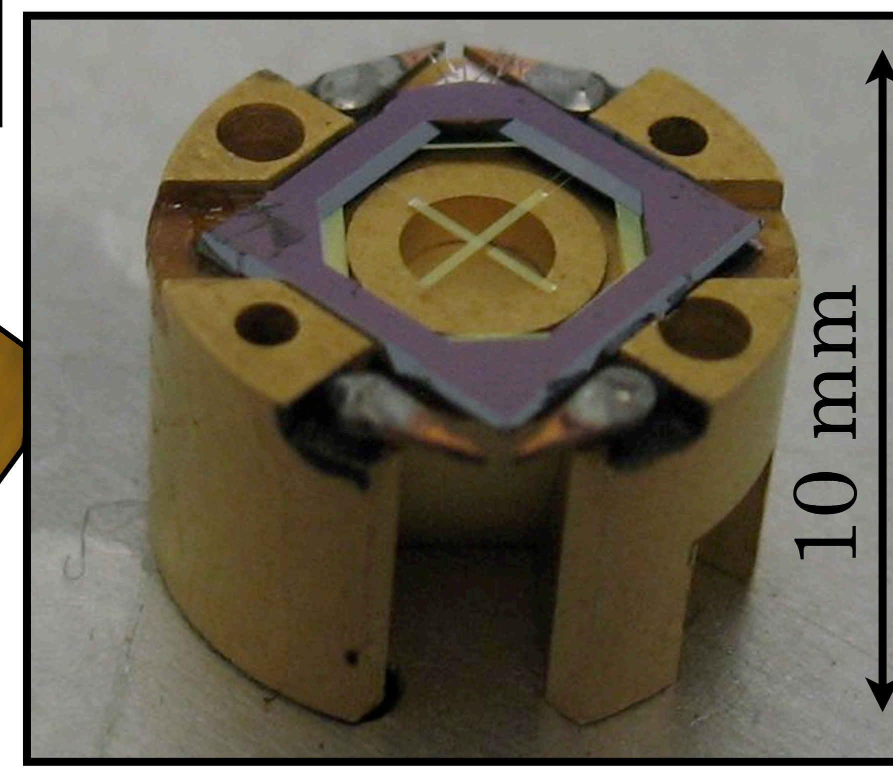
Contoured feed horn; maintains polarization angle

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

Readout from back via pins

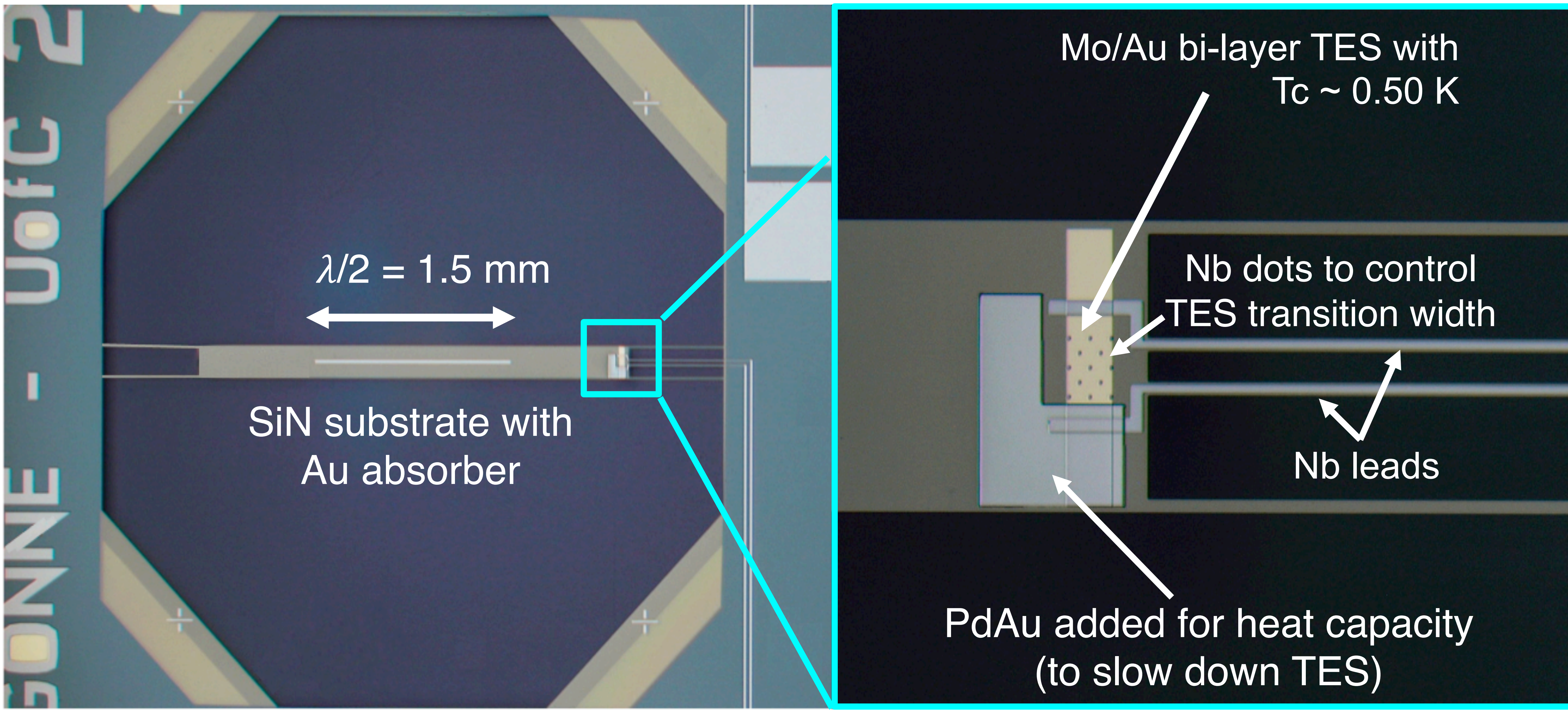


Spacer Wire Bonds



Fabricated by Vlad Yefremenko at ANL

95 GHz Single Pixel PSBs



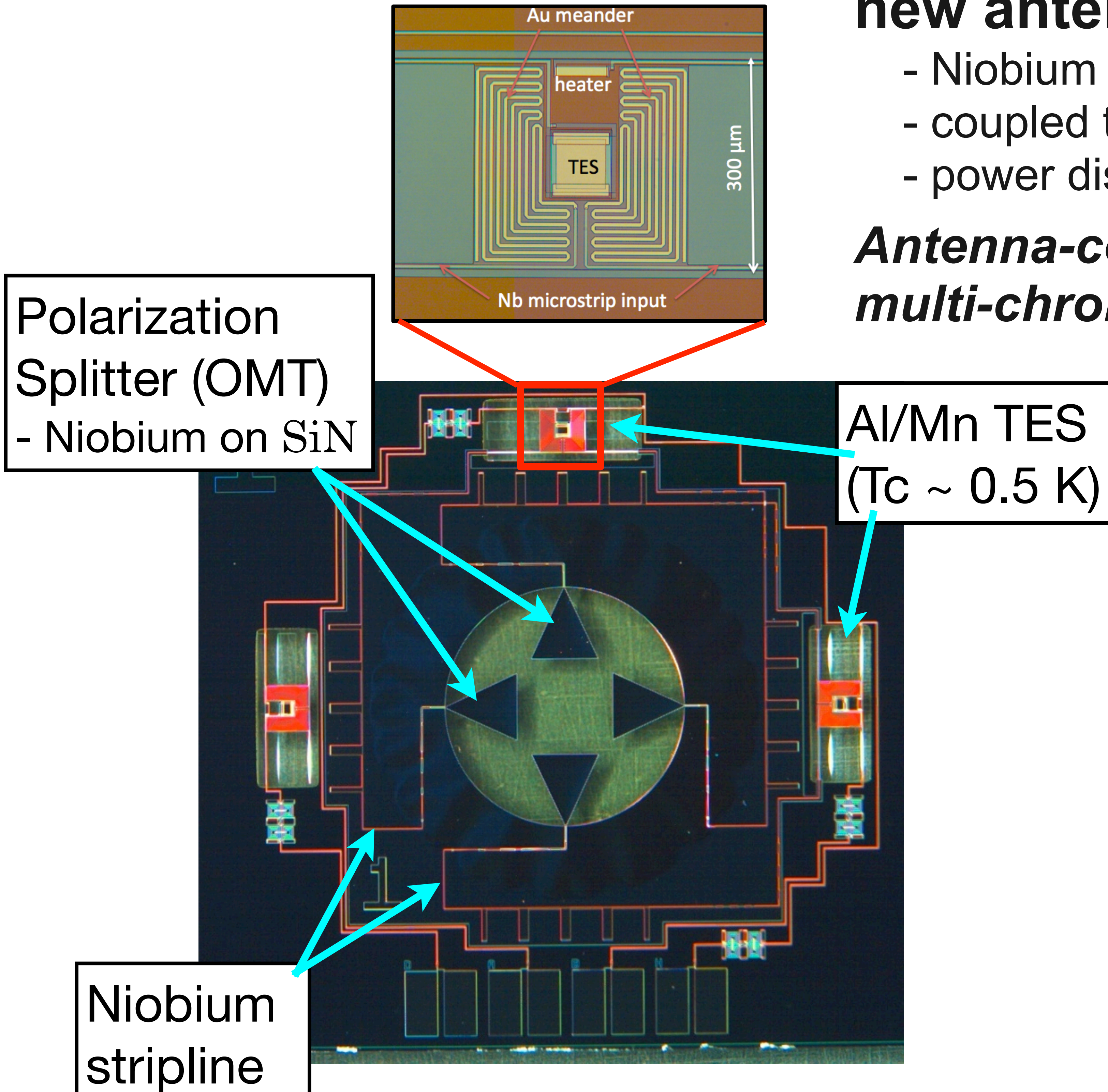
150 GHz Array PSBs

Fabricated by Dale Li, Sherry Cho at NIST

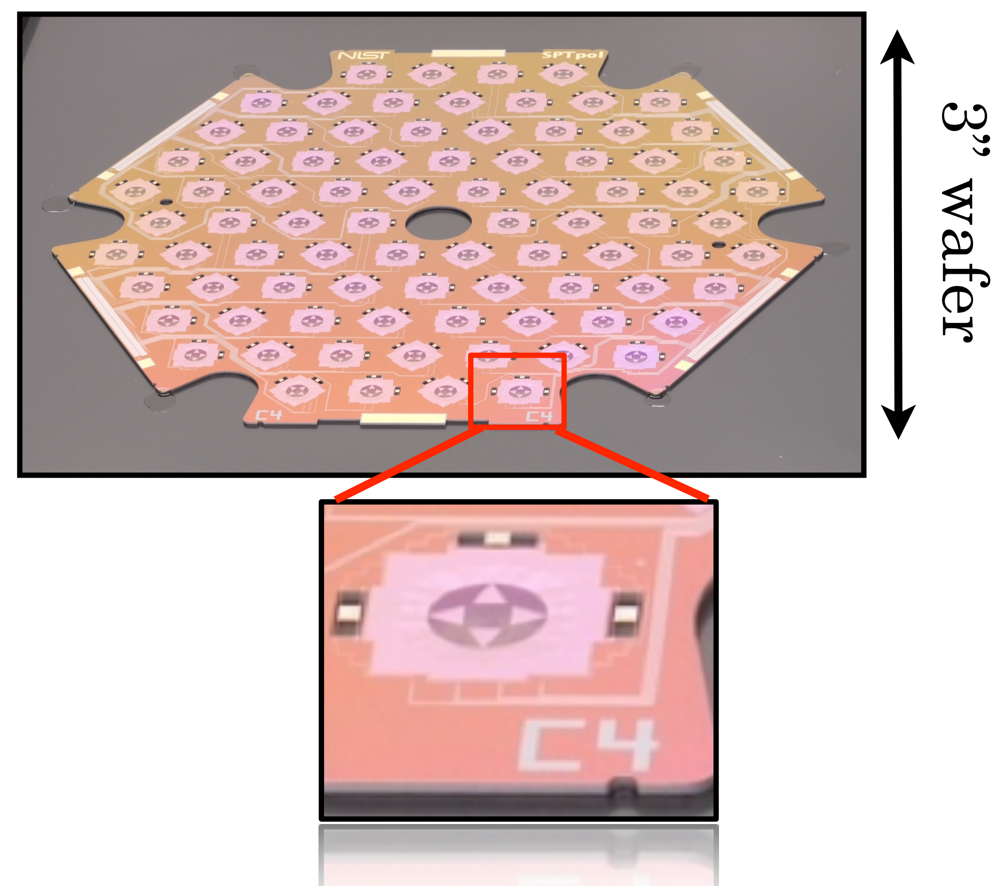
NIST 150 GHz detectors uses a new antenna-coupled TES design

- Niobium OMT antenna
- coupled to microstrip, leading to TES island
- power dissipated via lossy Gold meander

Antenna-coupled design is scalable to multi-chroic pixels!

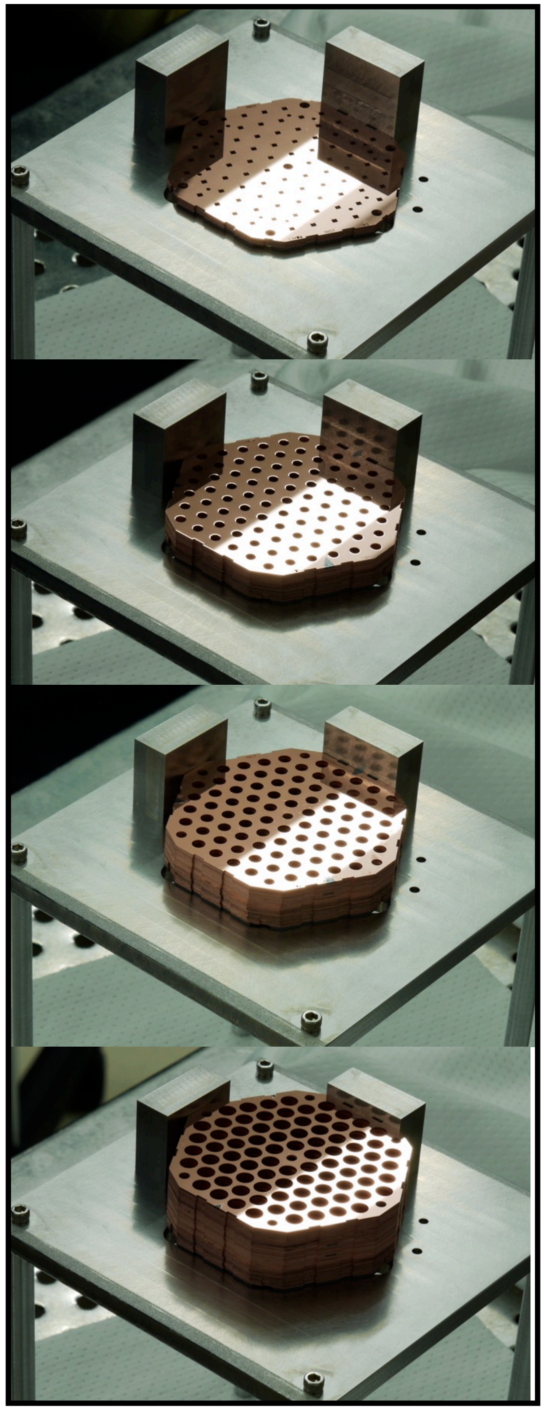


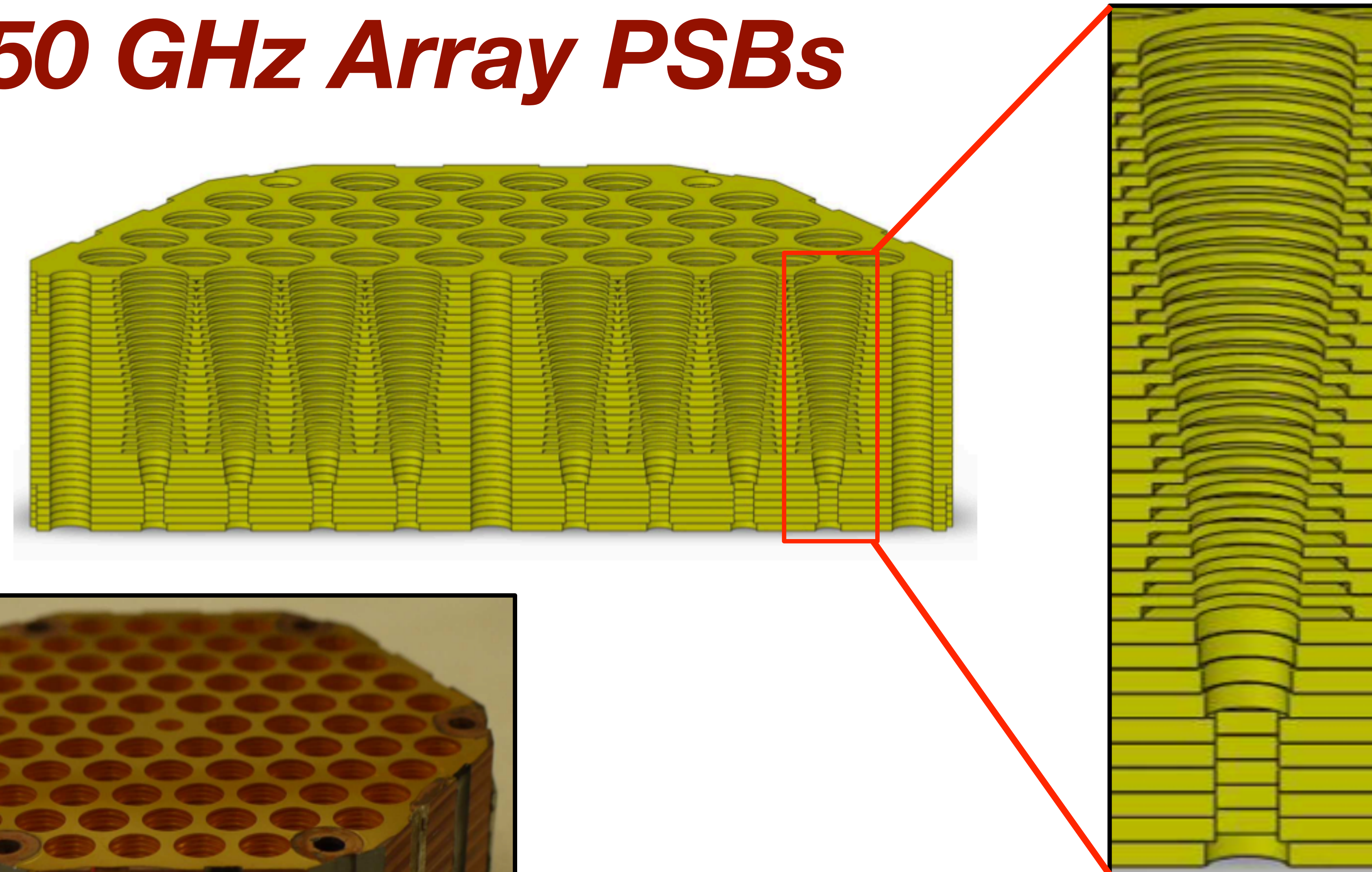
SPTpol 150 GHz Detector Array

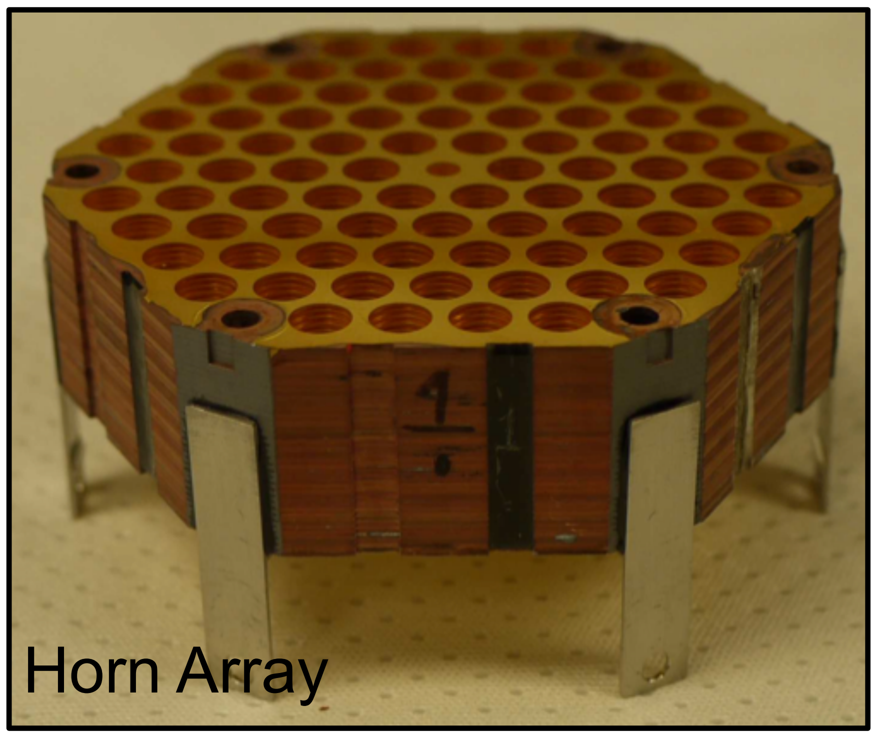


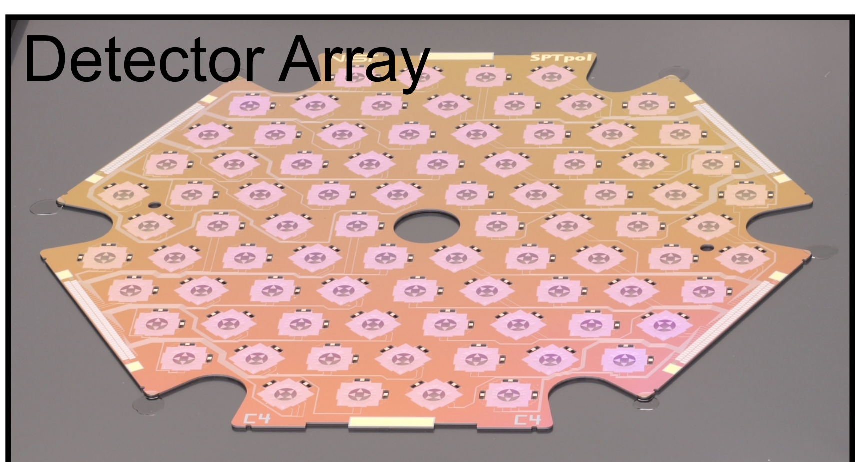
150 GHz Array PSBs

Horn Assembly









Corrugated feed horn array

- Stack of 33 silicon (500 μm) wafers, deep-etched into horn profile and gold-plated
- 84 pixels per array
- Excellent beam and RF pickup systematics control

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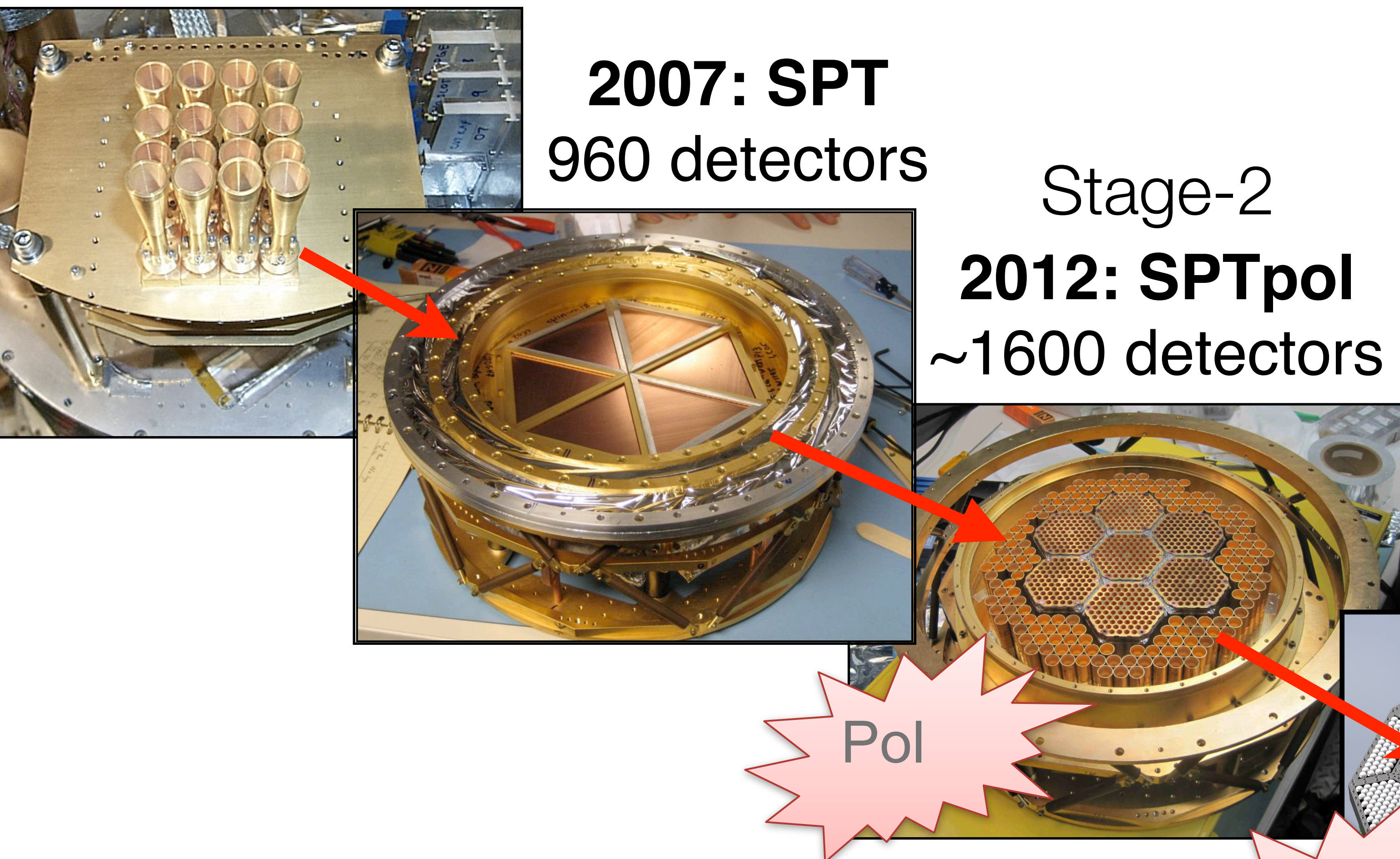
Evolution of CMB Focal Planes

2001: ACBAR
16 detectors

2007: SPT
960 detectors

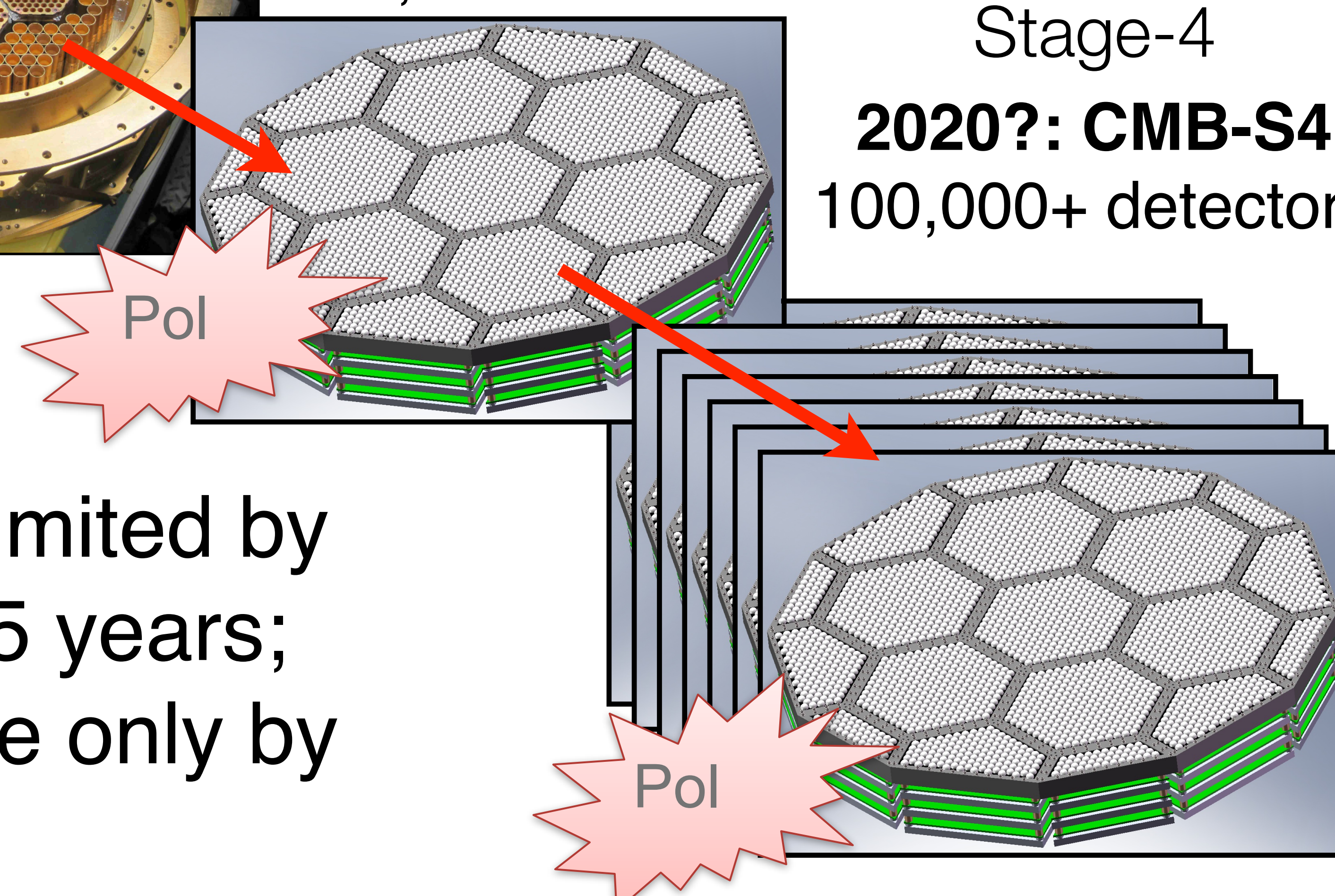
Stage-2
2012: SPTpol
~1600 detectors



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

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

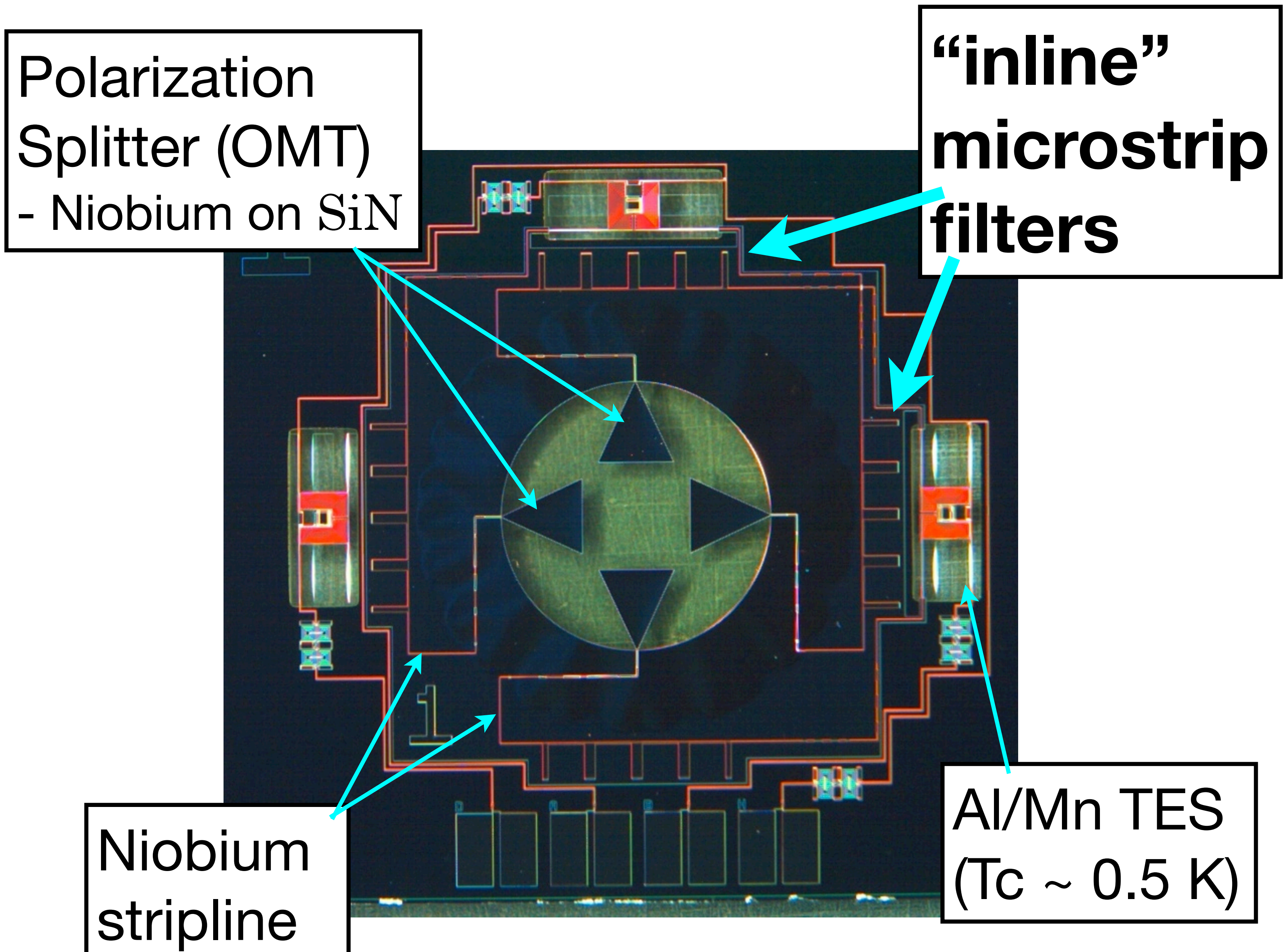
Stage-4
2020?: CMB-S4
100,000+ detectors



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

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



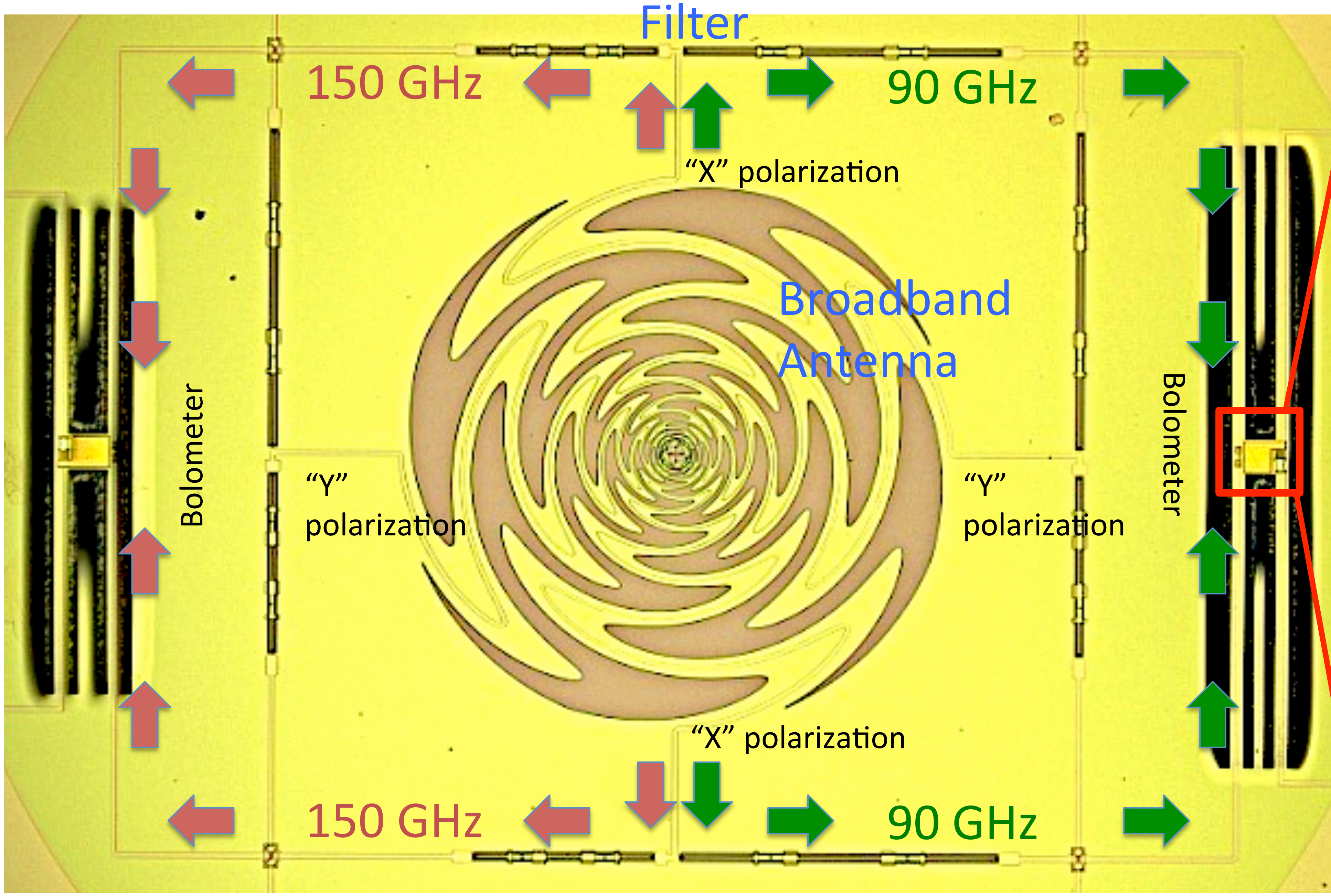
NIST

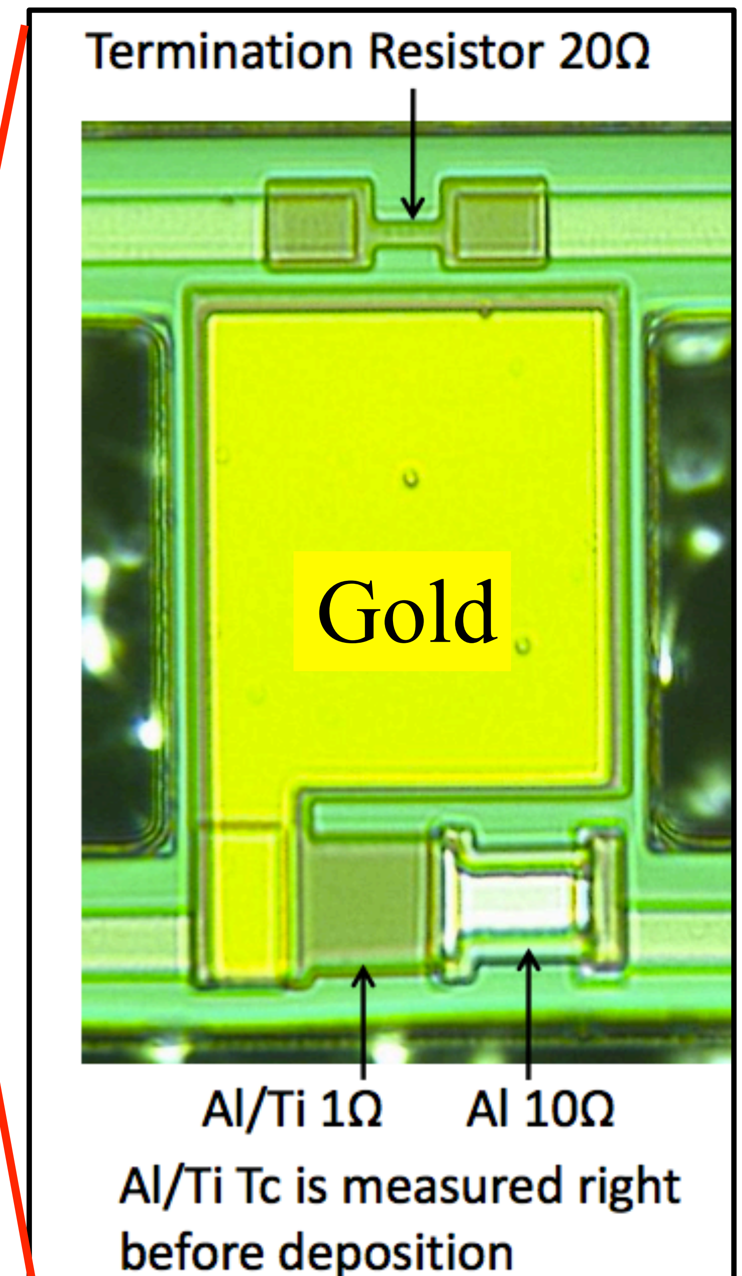
Fabricated by Dale Li, Sherry Cho at NIST

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





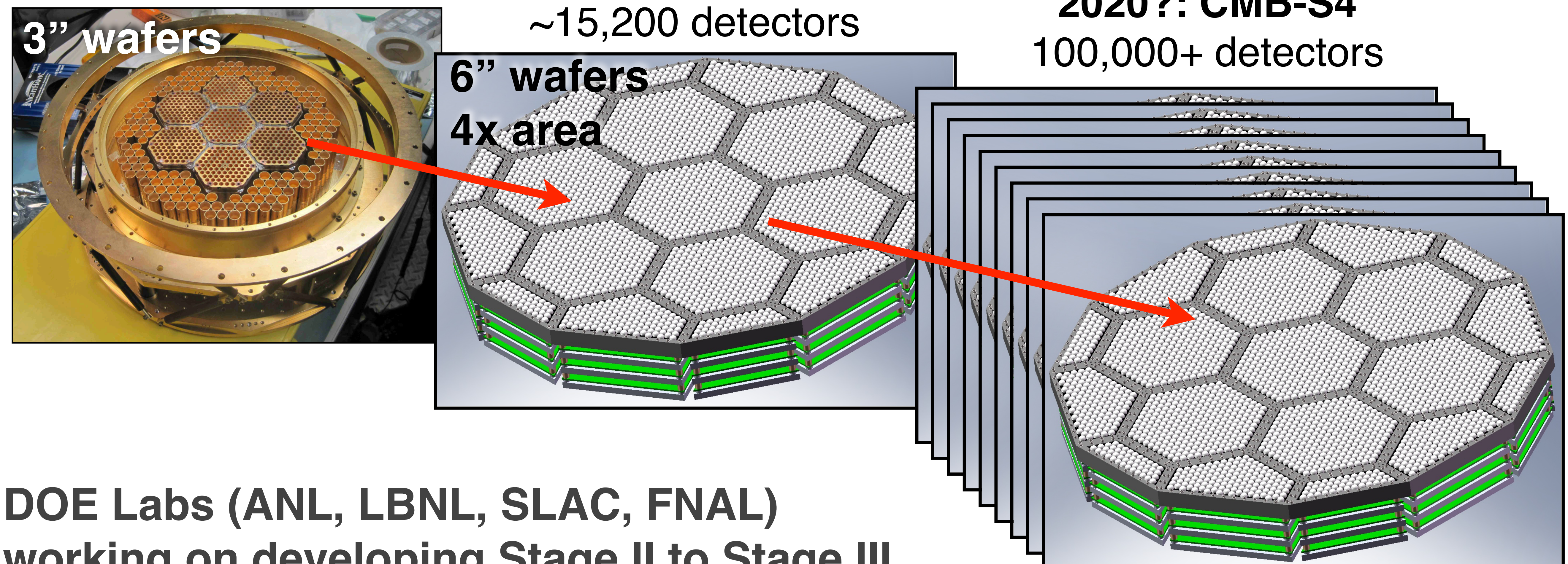
~4 mm

Evolution of CMB Focal Planes

Stage-2
2012: SPTpol
~1600 detectors

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

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

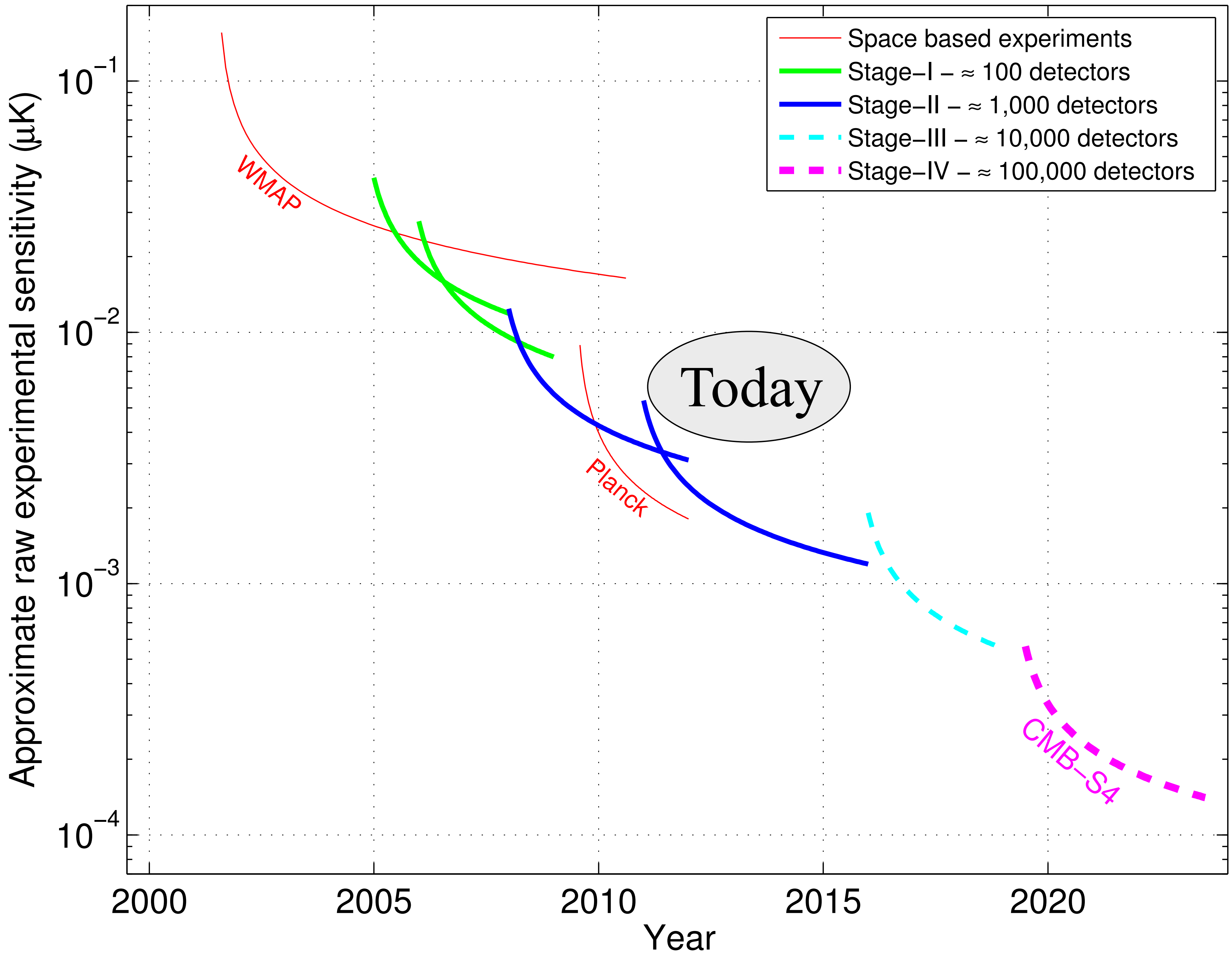


DOE Labs (ANL, LBNL, SLAC, FNAL) working on developing Stage II to Stage III detector based on 3-band, dual polarization pixel.

- Background limited performance per detector
- Uniform properties with high-fab-throughput
- Consistent fabrication on 6" wafers

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

CMB Experimental Stages



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

~200x faster than today's Stage 2 experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB-based Cosmological Constraints

	$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$ (meV)
Current CMB	**0.05**	**0.34**	**117**
Stage 2	0.03	0.12	96
Stage 3	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:

- $\sigma(r) \sim 0.001$; Differentiate between large vs small field inflation.
- $\sigma(N_{\mathrm{eff}}) \sim 0.02$; Precision constraint of relativistic energy density; search for deviations from standard model prediction of 3.046.
- $\sigma(\Sigma m_\nu) \sim 16$ meV ; Cosmological detection of neutrino mass.

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

Summary and Big Questions

This science is just beginning!

- First detection of CMB B-mode polarization in the past year!
- Advances in measurements driven by detector technology
- Experimental challenge today is to increase detector counts
- Antenna-coupled TES detectors are the baseline technology for next-generation experiments

This science is exciting! CMB experiments are trying to answer fundamental questions about the Universe:

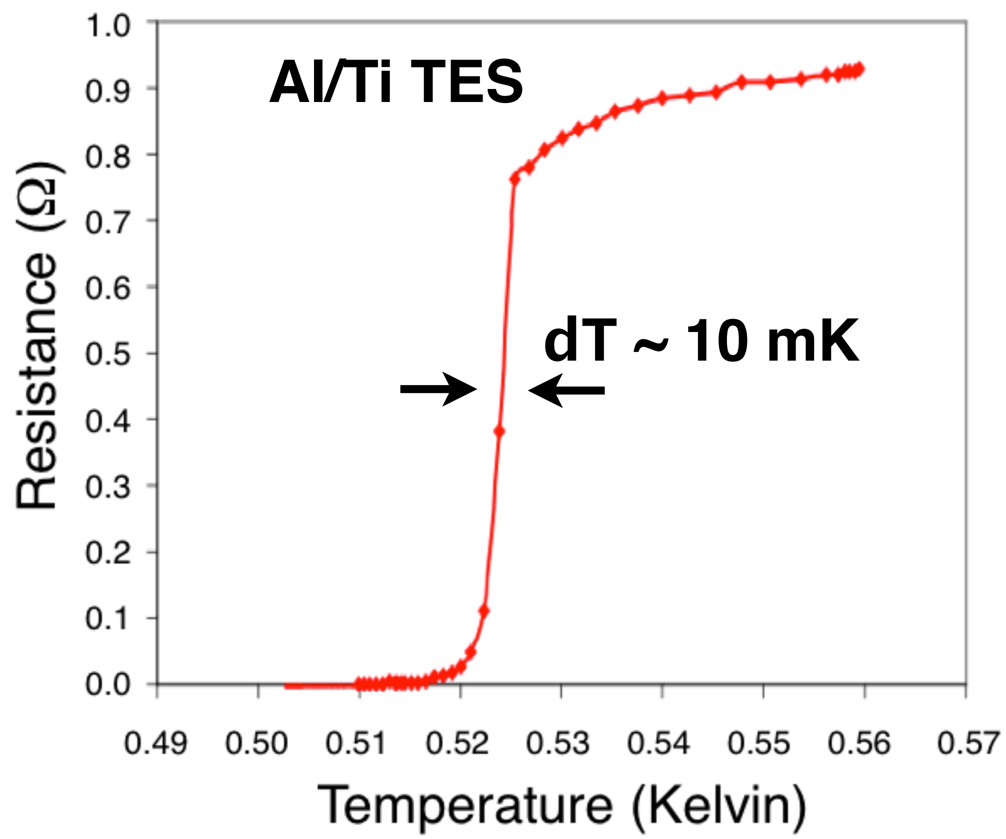
Did the universe start with an epoch of inflation?

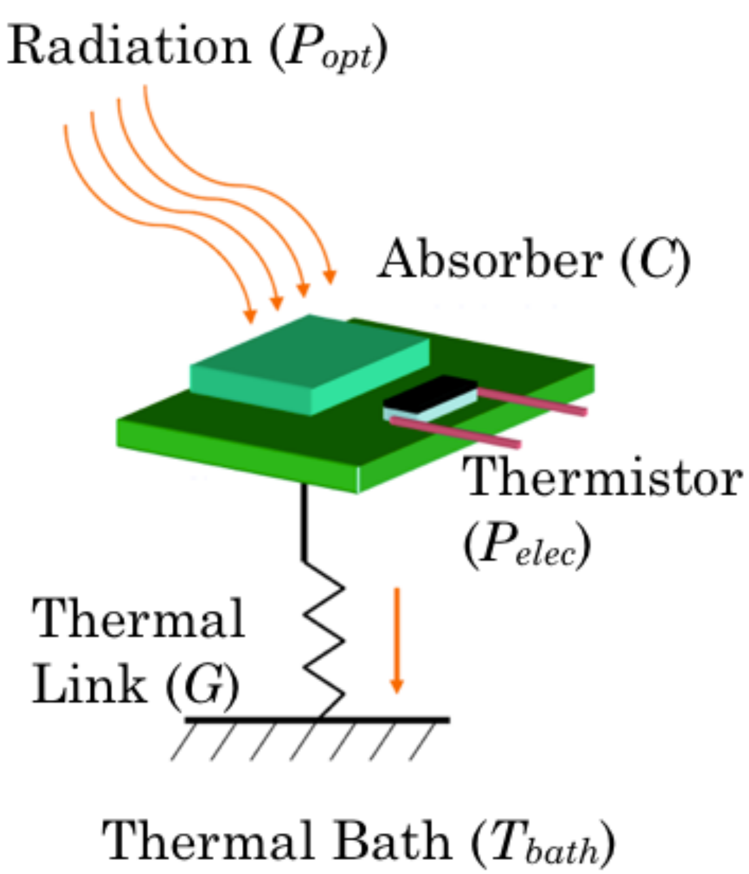
What is the energy scale of inflation?

Is there any "dark radiation"?

What is the sum of the neutrino masses?

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:

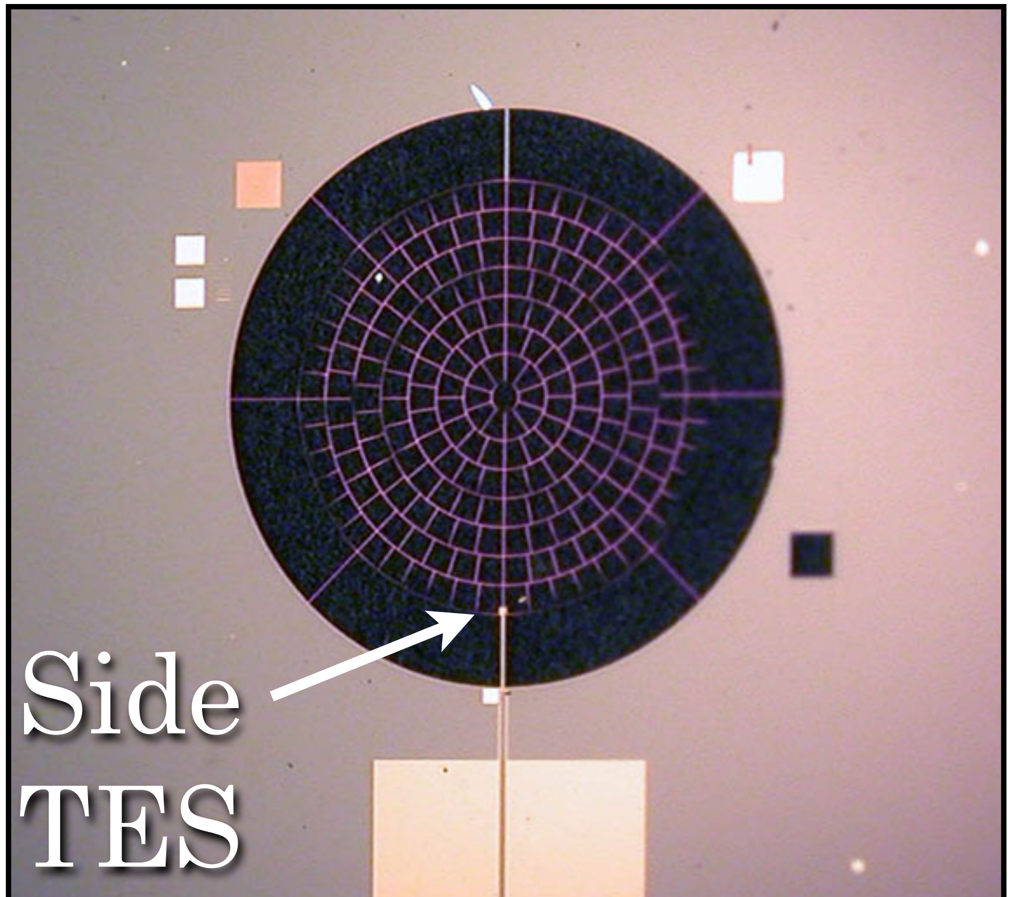
$$\mathcal{L} = \frac{\alpha P_{elec}}{G T_b}$$

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

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

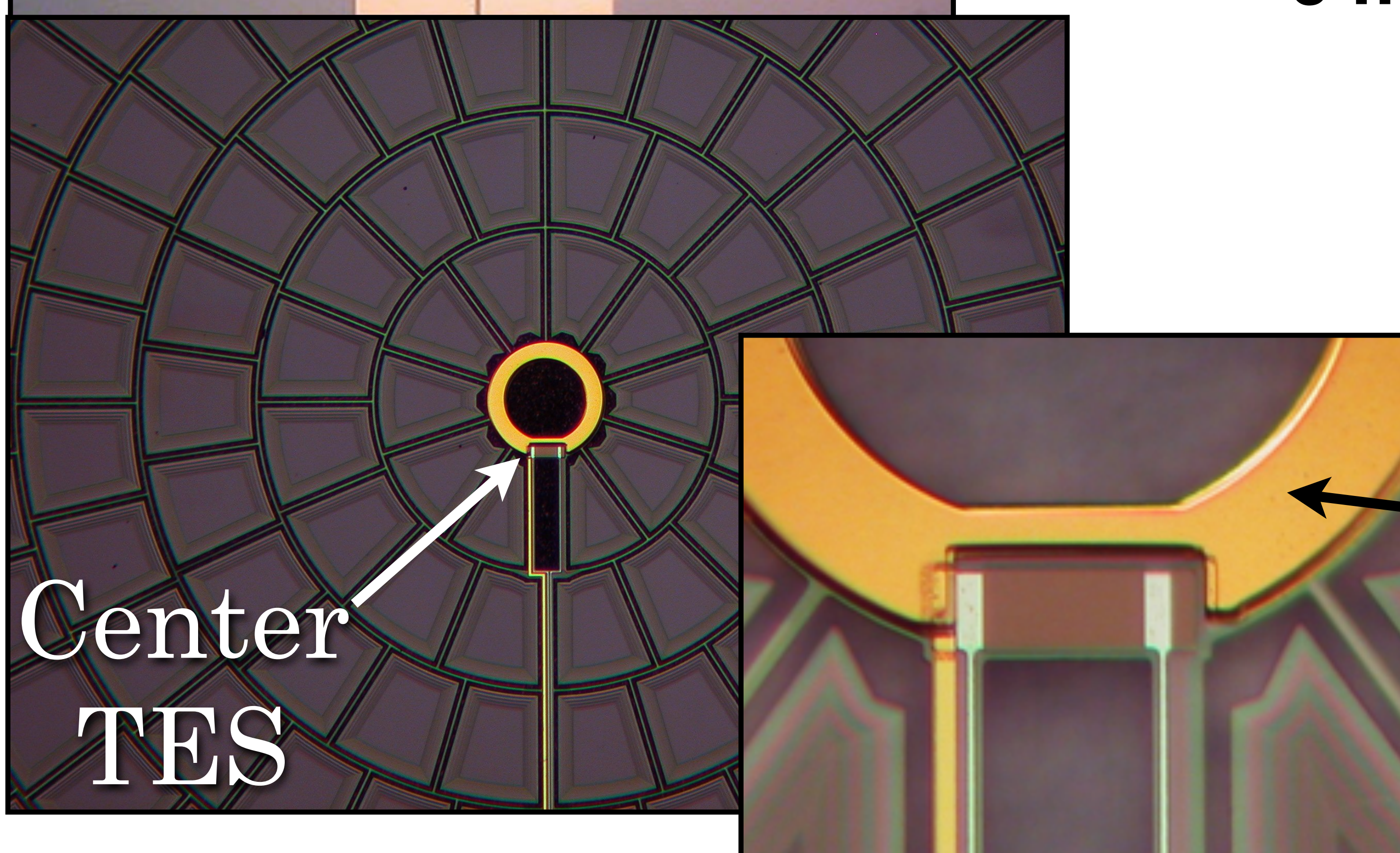
$$S_I = \frac{\delta I}{\delta P} = \frac{-1}{V_b}\frac{\mathcal{L}}{1+\mathcal{L}} \qquad \tau = \frac{\tau_0}{1+\mathcal{L}} = \frac{C/G}{1+\mathcal{L}}$$

TES Time Constant and Stability



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

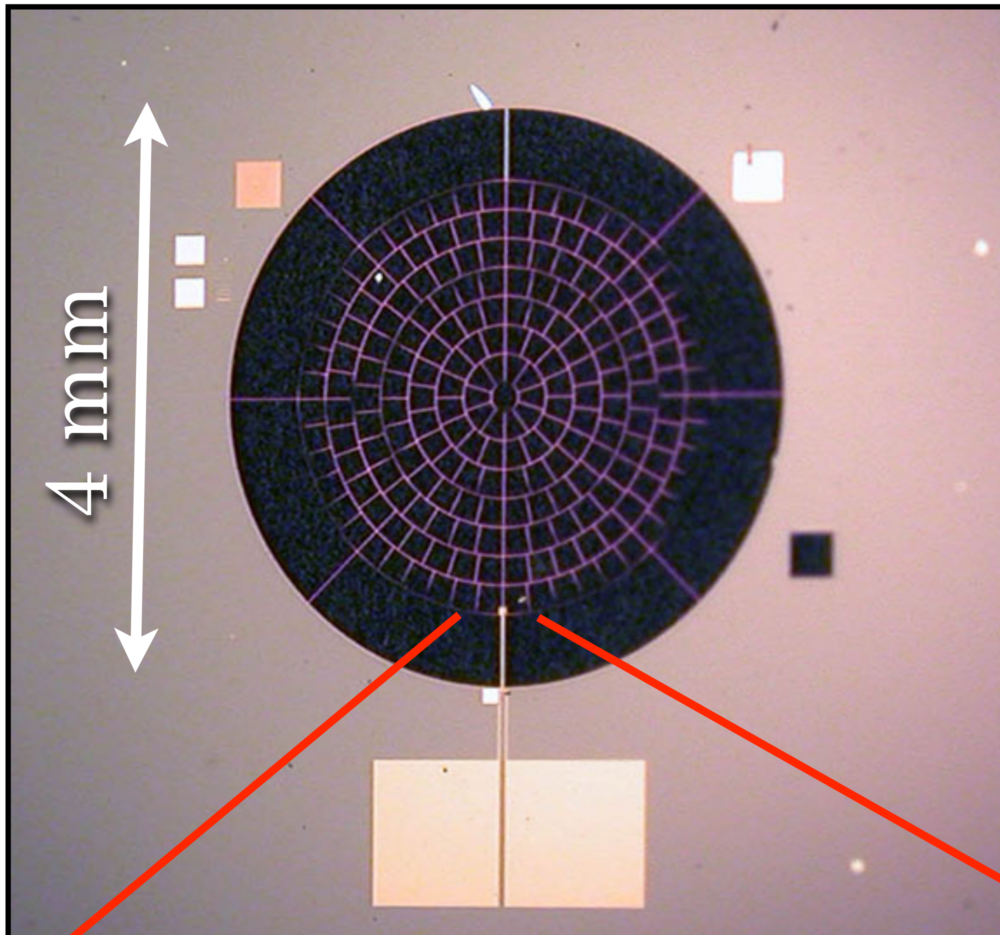
1) Bandwidth requirement for bolometer stability:
   TES bandwidth < 5.8 fMUX bandwidth
2) Given RLC filter bandwidth, this implies:
   0.2 msec < t_{TES} < 5 msec
3) TES speeds up as loop gain increases [$t_{TES} = t_0 / (1 + L)$], so assuming L ~ 10-30:
   6 msec < t_0 < 50 msec

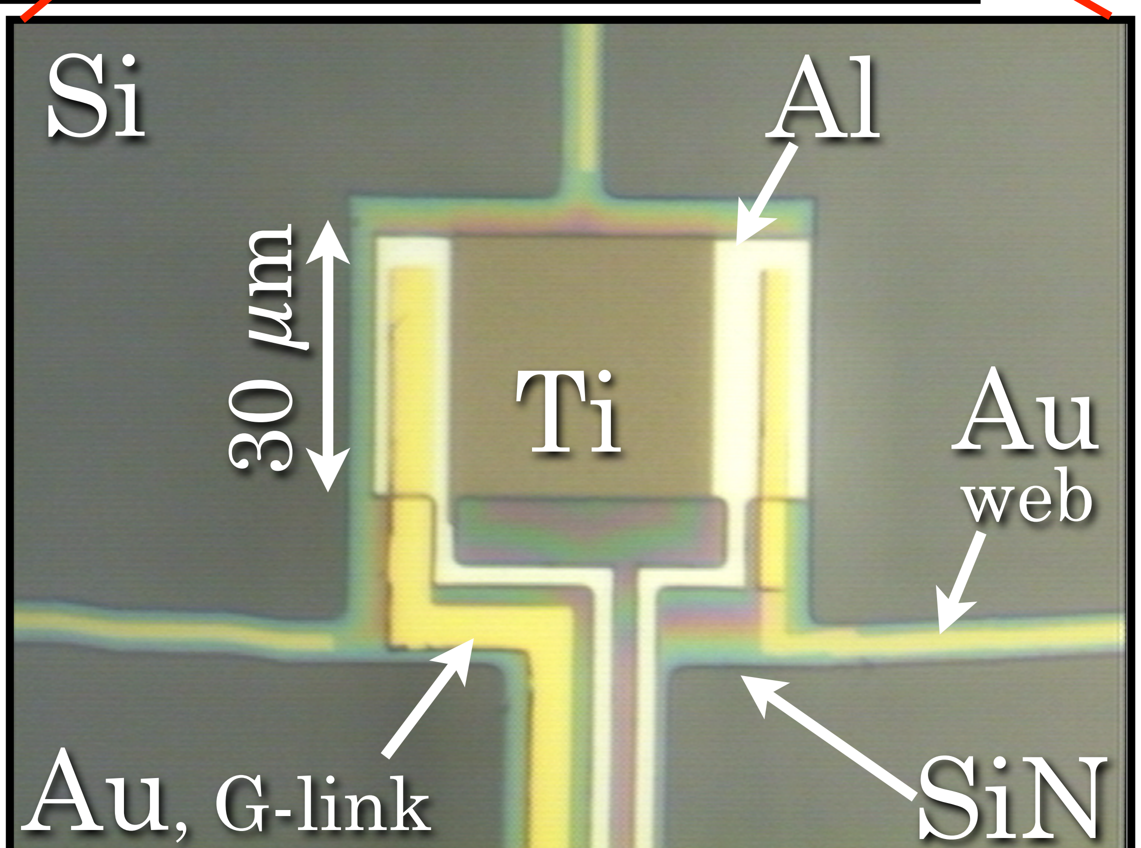


Side-TES had a $\mathbf{t_0}$ < 0.1 msec! became unstable as soon as TES went into its transition.

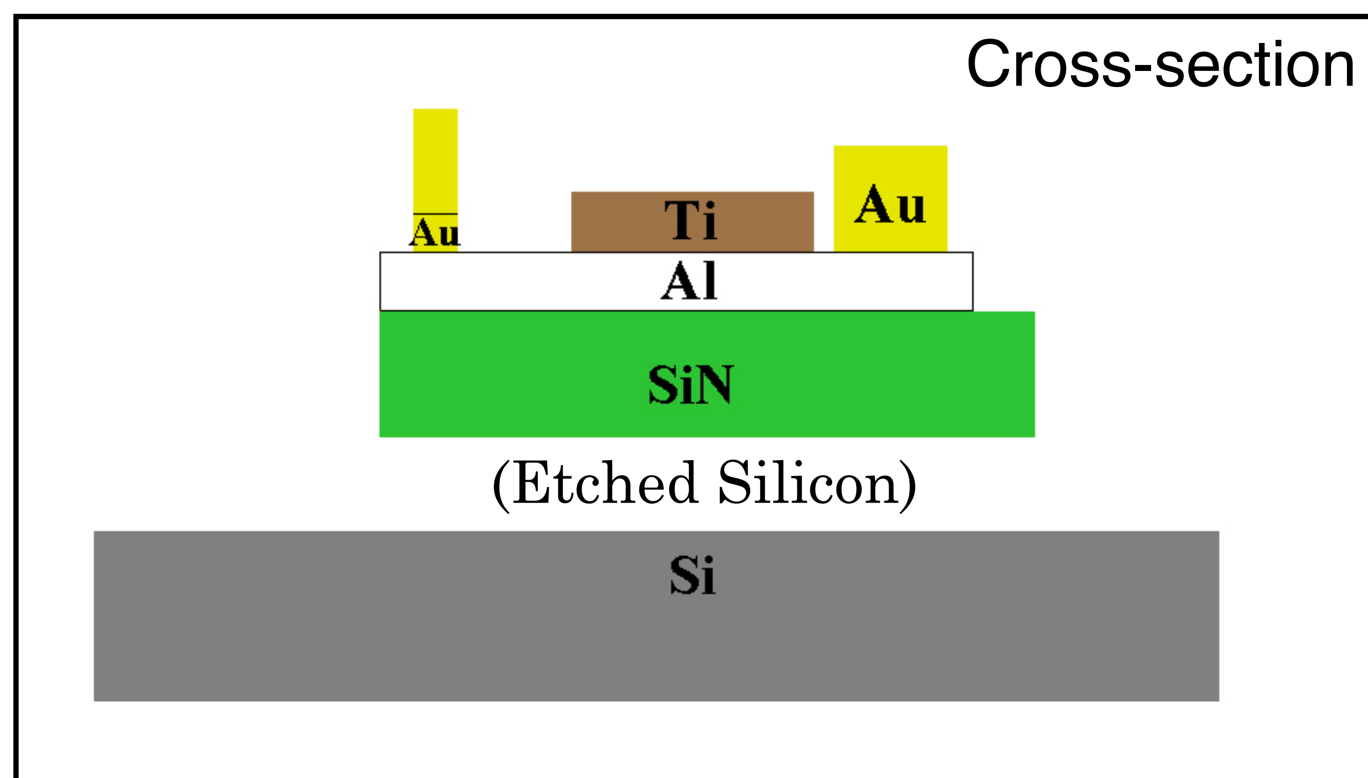
Gold Ring added for heat capacity to slow down bolometer to $\mathbf{t_0}$ ~ 20 msec.

SPT-SZ TES Single Pixel

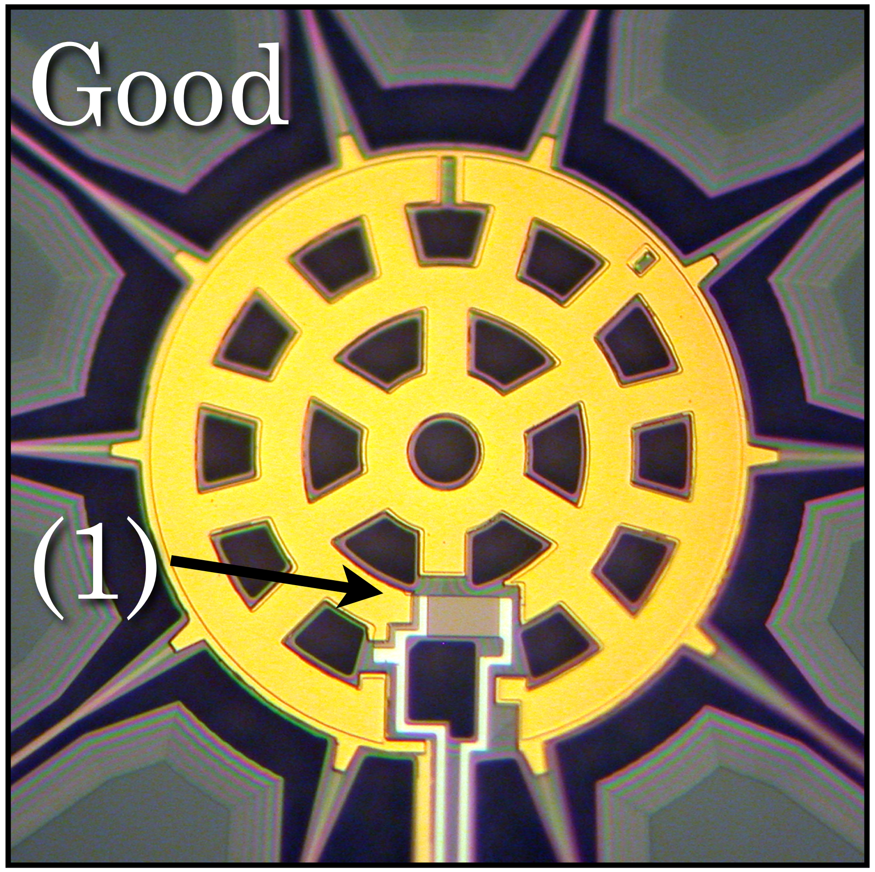


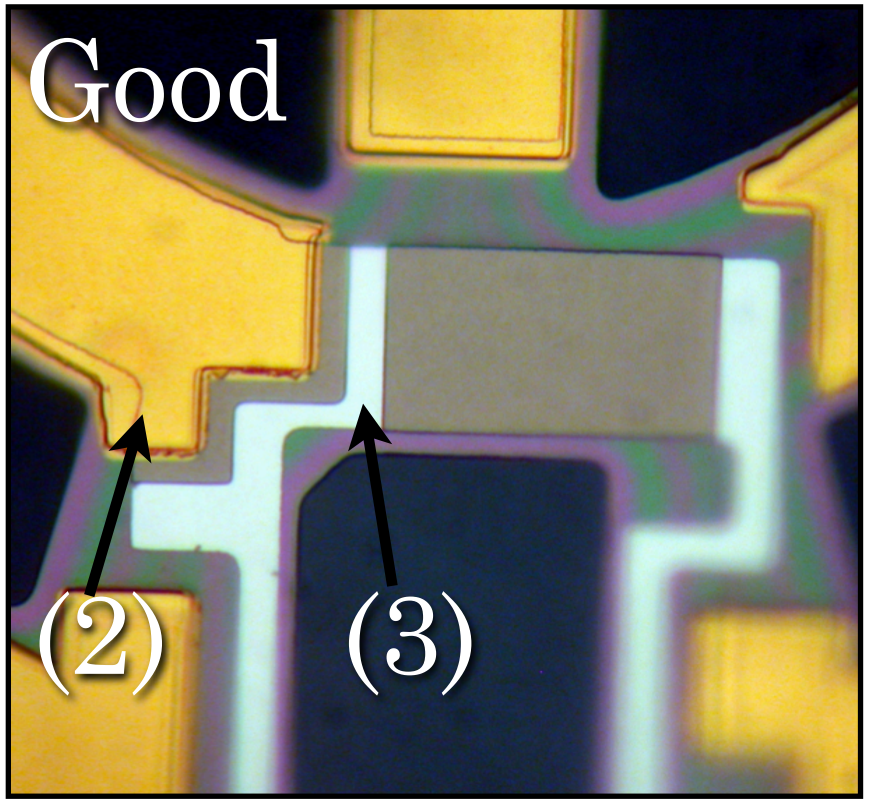


- Made at UC-Berkeley
- Used JPL spider-web absorber design;
  - suspended 1mm thick Silicon Nitride (SiN) substrate with 12 nm thick Gold (Au) absorber
- Replaced NTD Germanium with TES Aluminum/Titanium (Al/Ti) bilyaer;
  - Film thickness 40 nm Al, 80 nm Ti, gives a superconducting transition (T_c)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



Alternative Gold Coupling Designs

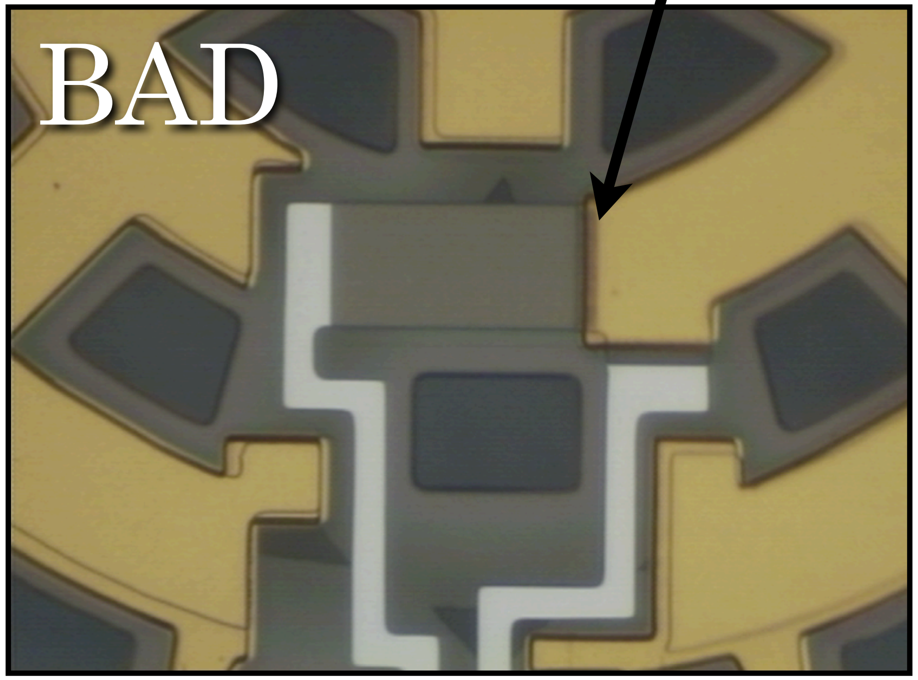


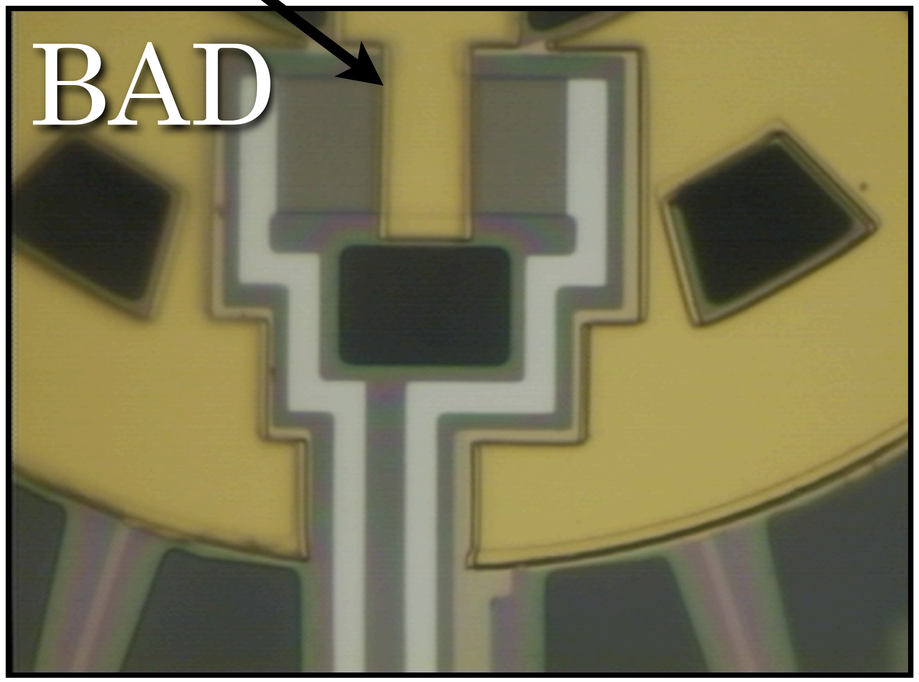


Improved TES-Gold Coupling:

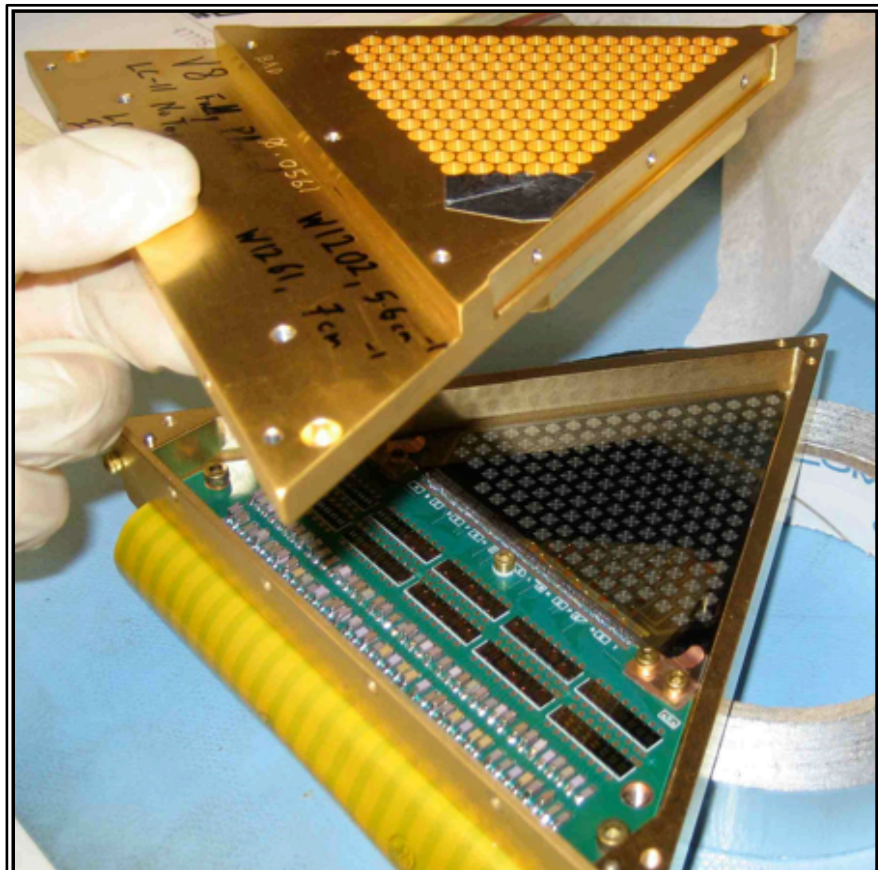
1) Centered TES and increased gold connectivity,
2) Al/Ti bi-layer underlies gold,
3) Superconducting "Al" leads were narrowed,
4) Oxide layer cleaned with etch before gold deposition.

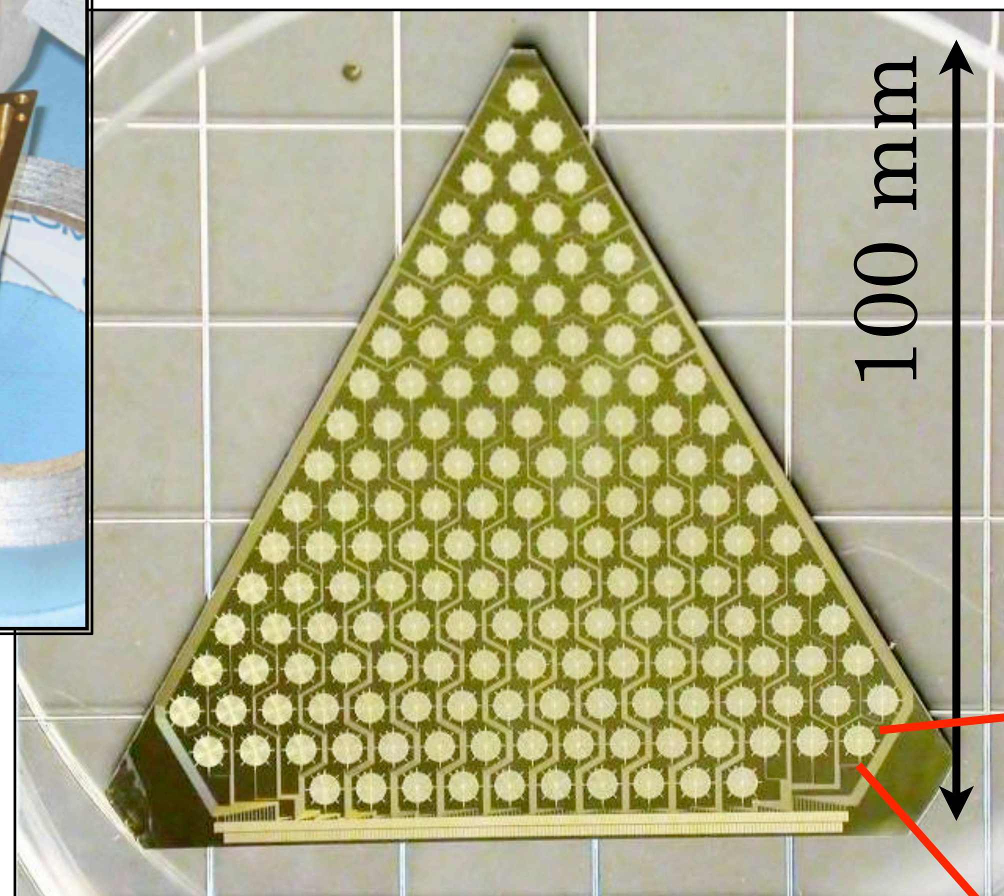
Designs that intercepted TES improved thermal coupling to gold, but broadened transition and lowered loop gain



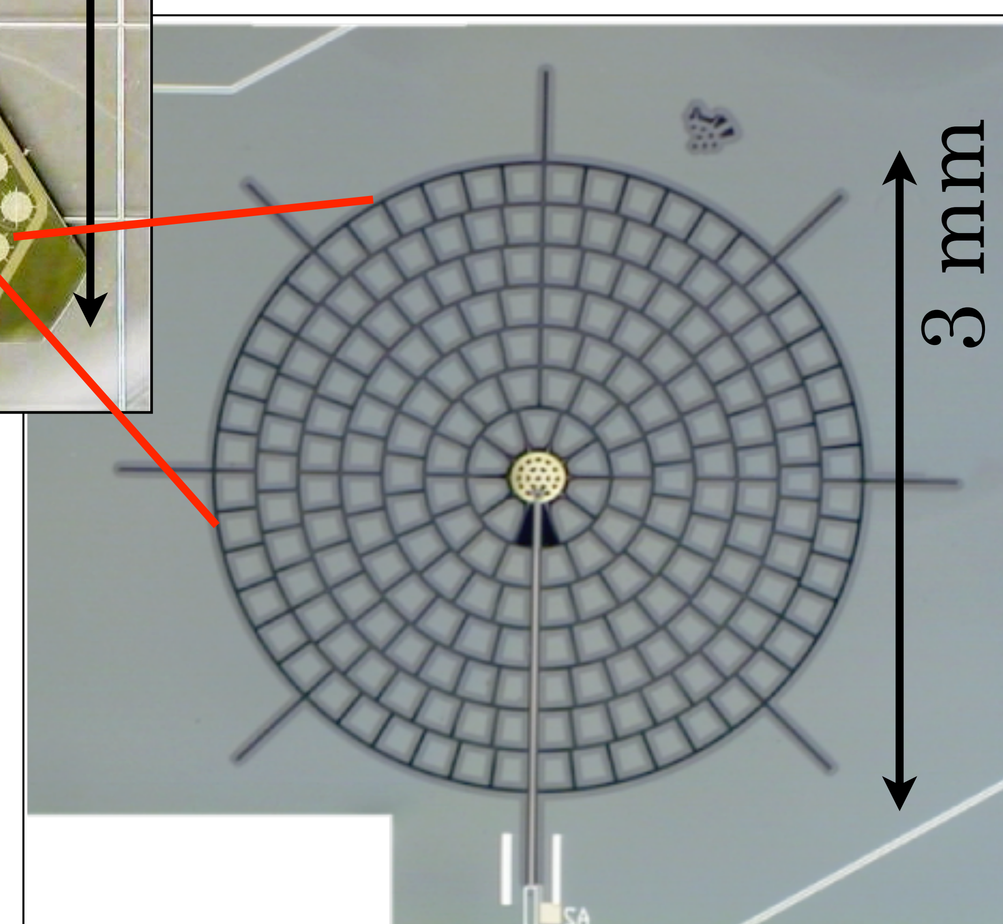


SPT-SZ Bolometer Array





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

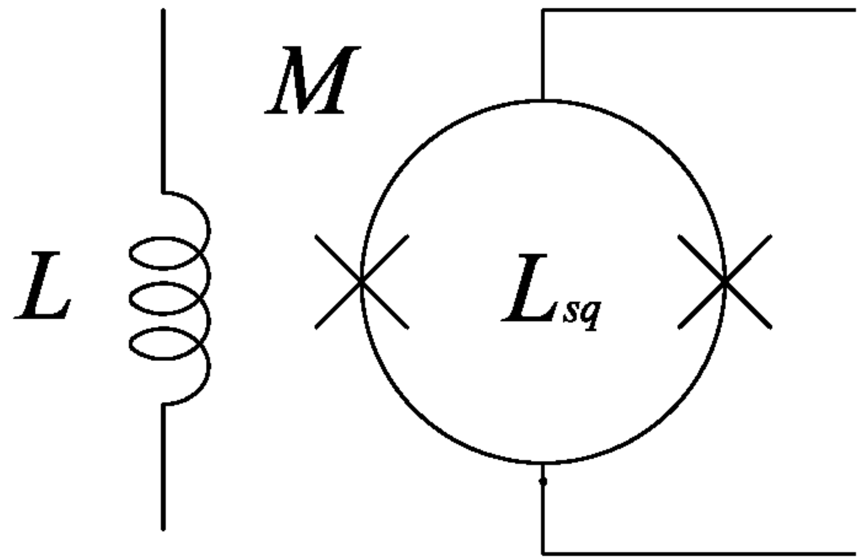


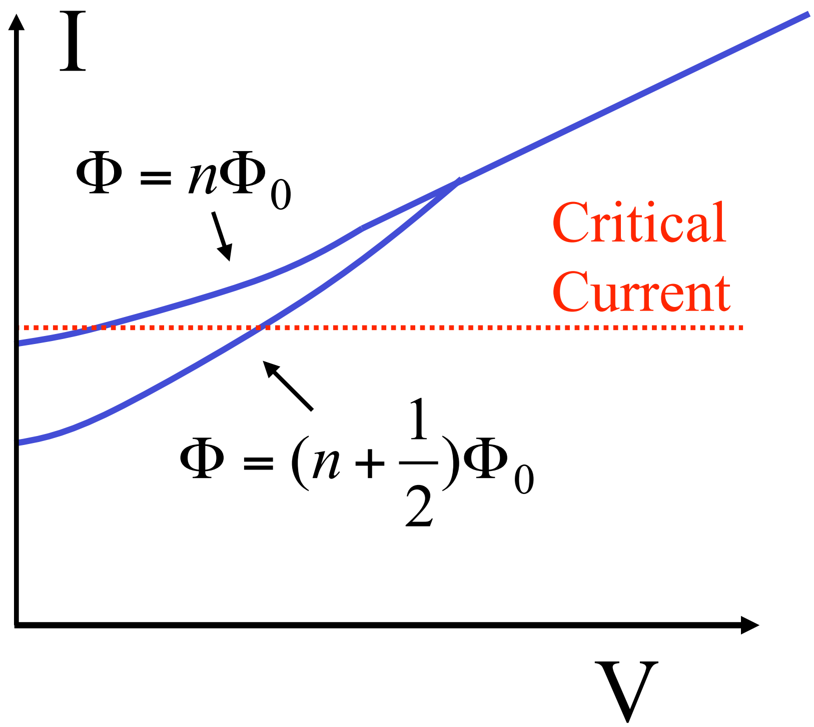
An SPT-SZ 160 bolometer array;
SiN substrate with gold absorber, and a Al/Ti transition edge sensor (TES) superconductor with a transition temperature of 500 mK

SQUID Bolometer Readout

Requirements:

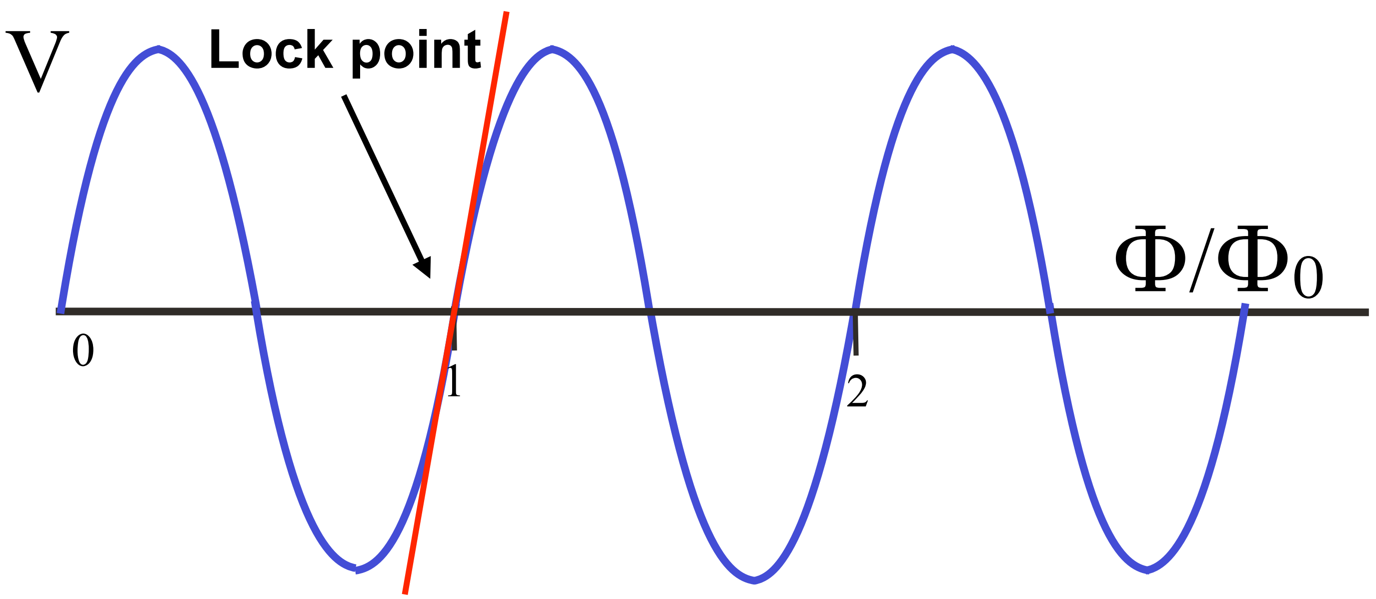
- Low input impedance
- Low power dissipation
- High bandwidth
  - ~100 MHz
- Low noise. At 4 K:
  - 3 pA/rtHz
  - 0.2 nV/rtHz





Implementation:

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

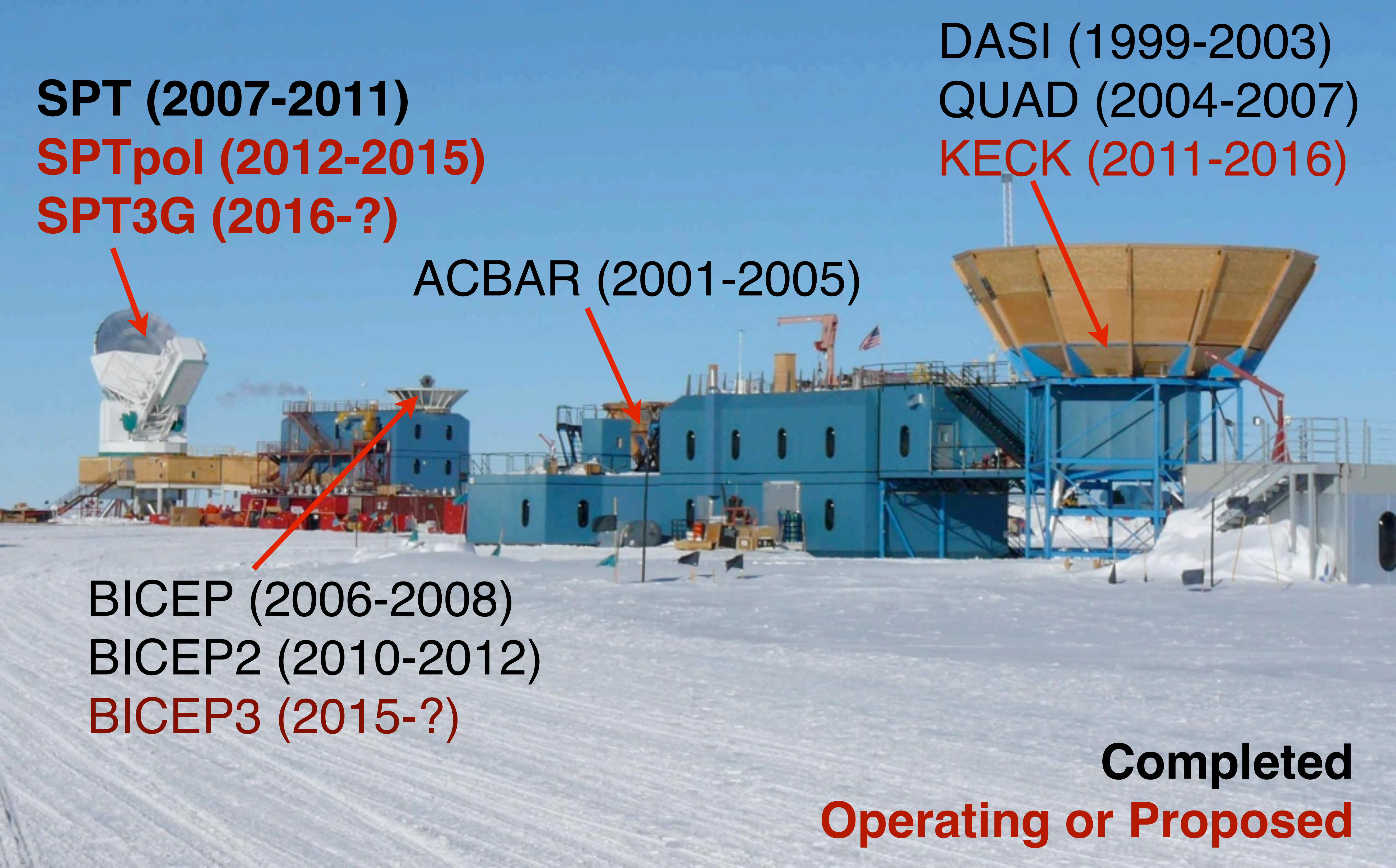


The South Pole is the best place in the world to observe the CMB

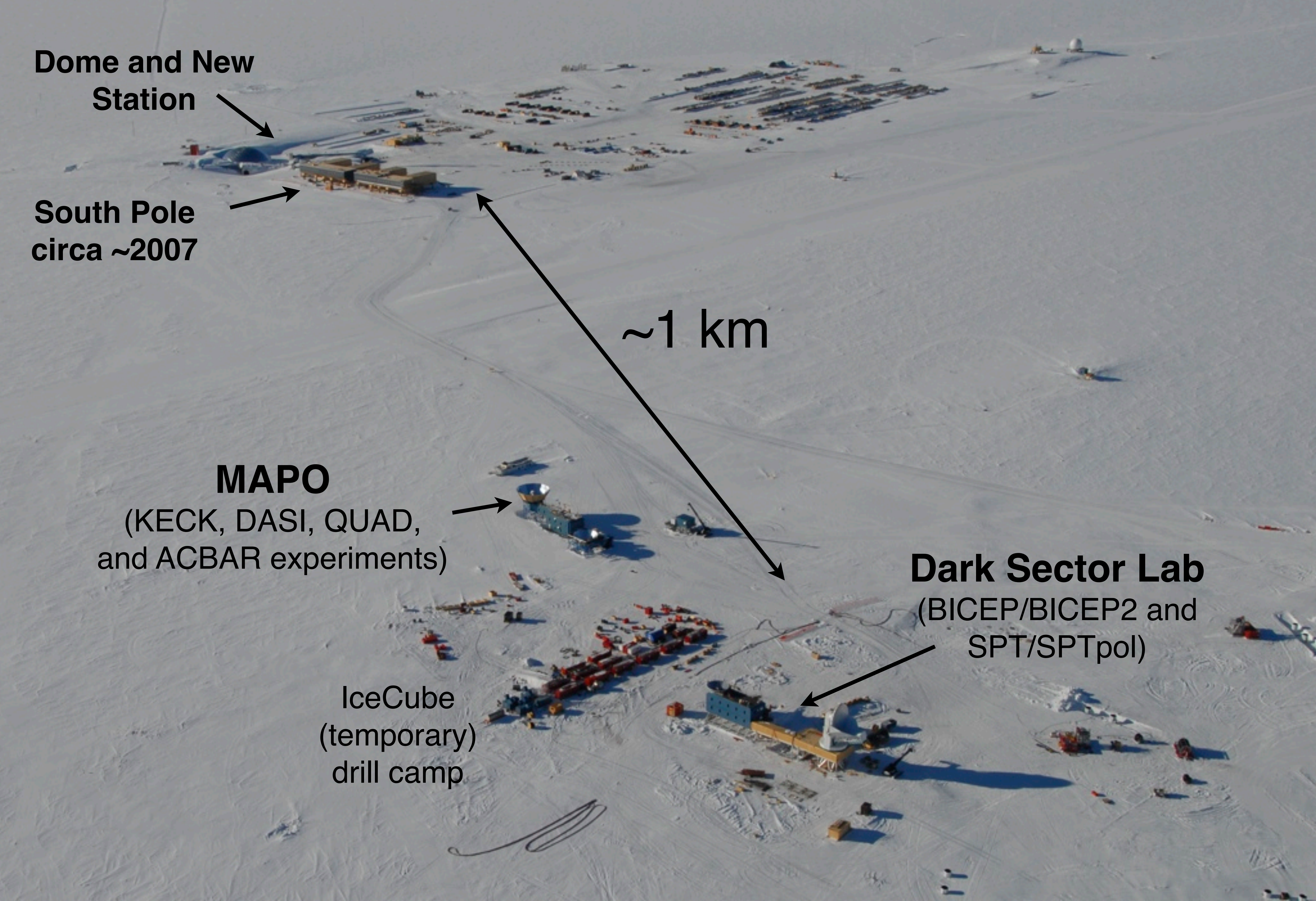
South Pole Environment

- **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

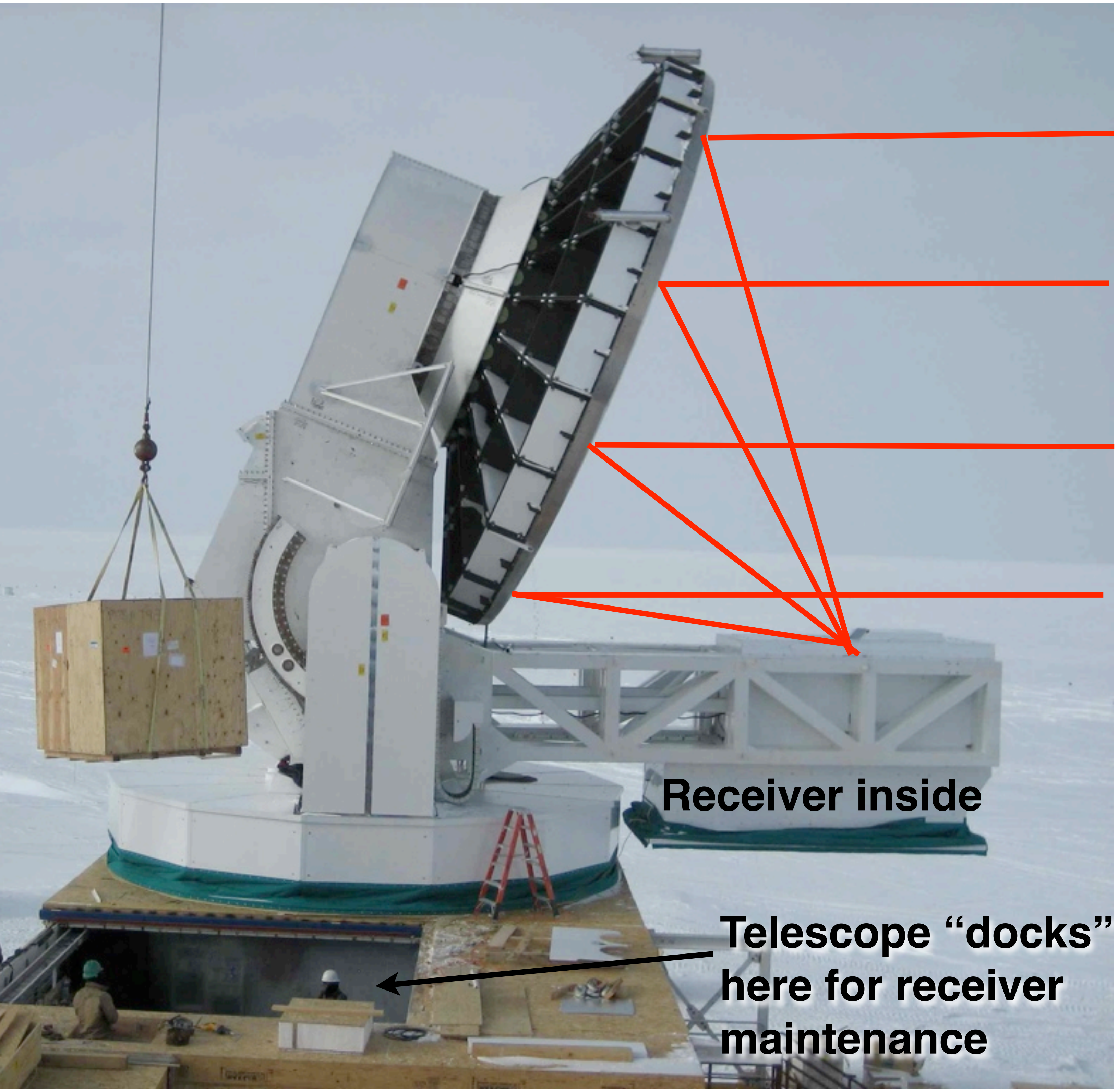
The South Pole has been home to world-leading CMB experiments for the past decade

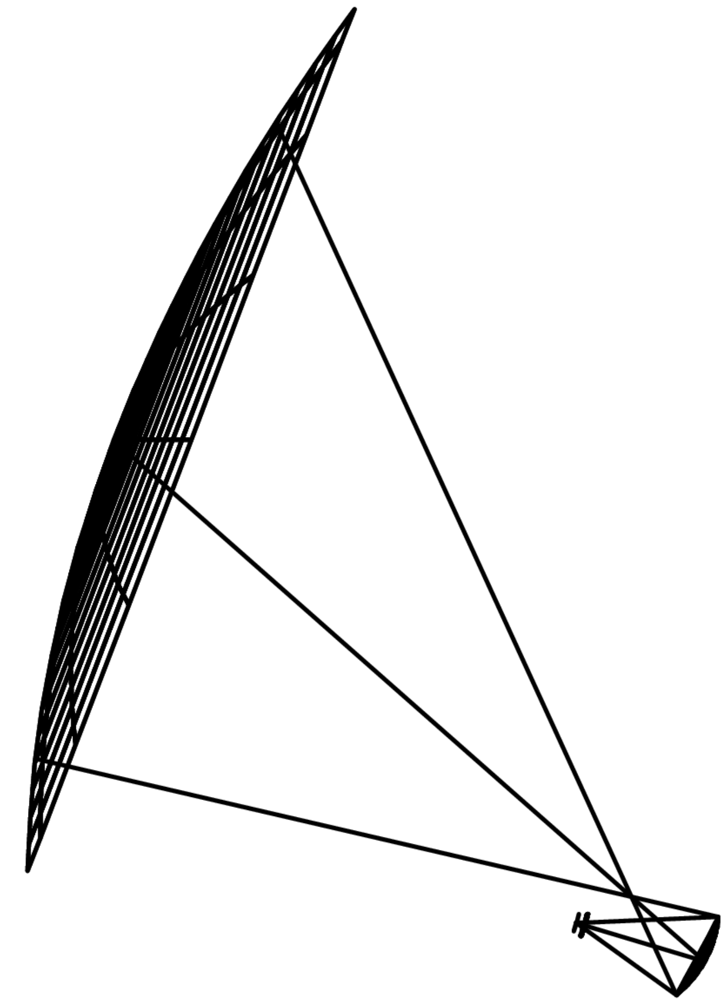


February 3, 2007: South Pole



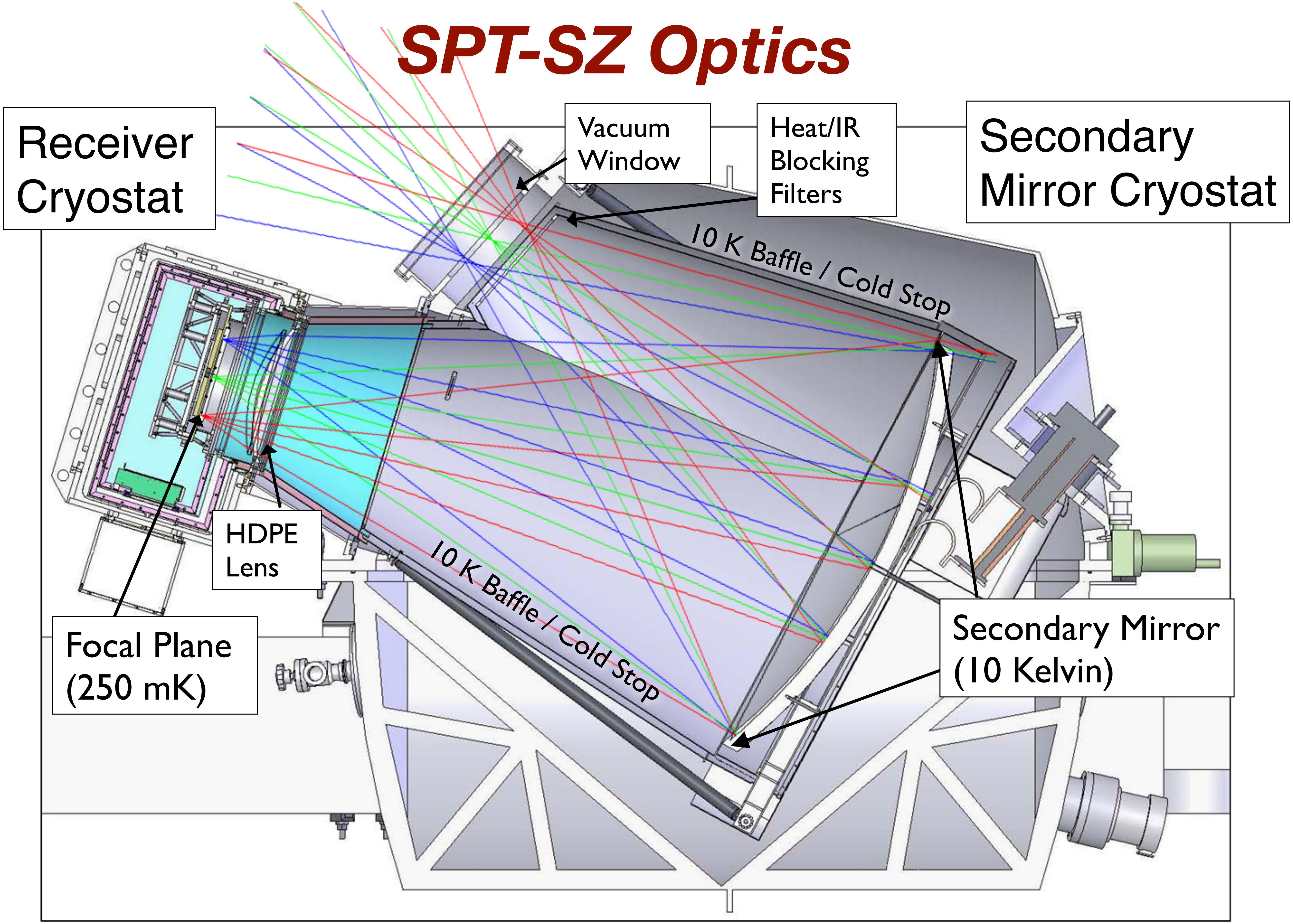
SPT-SZ Optics



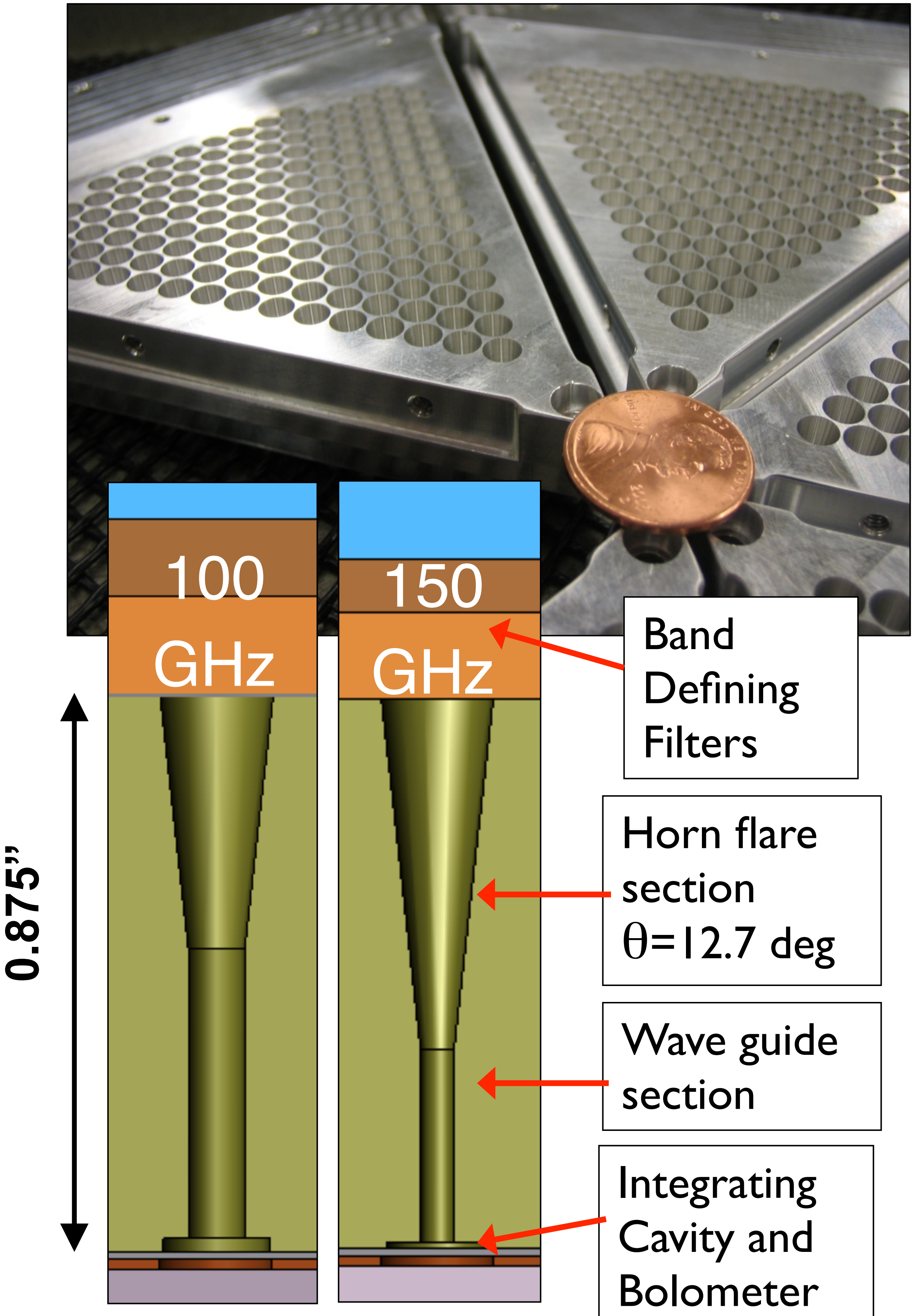


- Off-axis Gregorian design
- Fast optics = low-f number = large field-of-view = physically small pixels
- Secondary mirror and receiver in “cabin” that moves with the telescope

SPT-SZ Optics

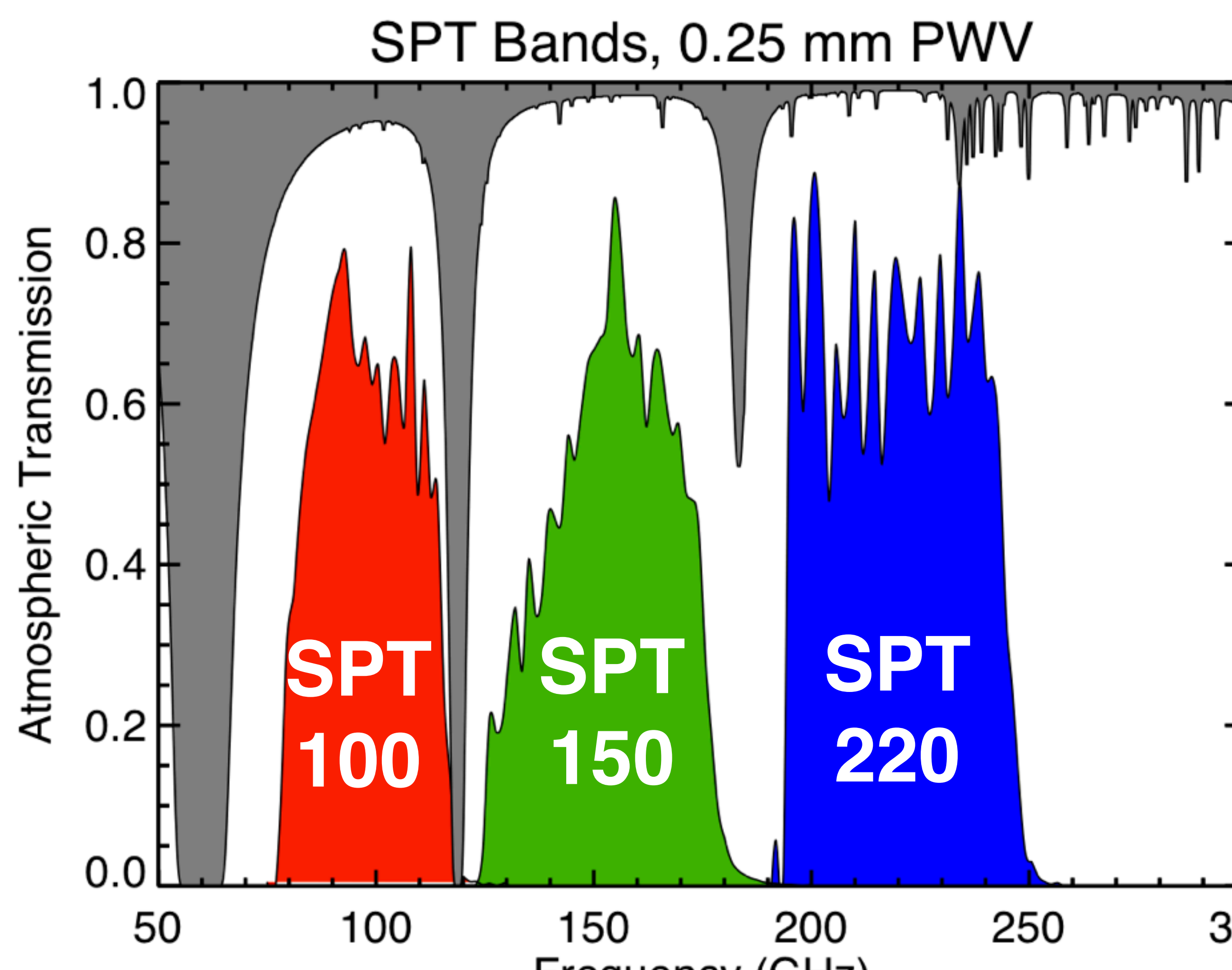


SPT-SZ Focal Plane Optics



- 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

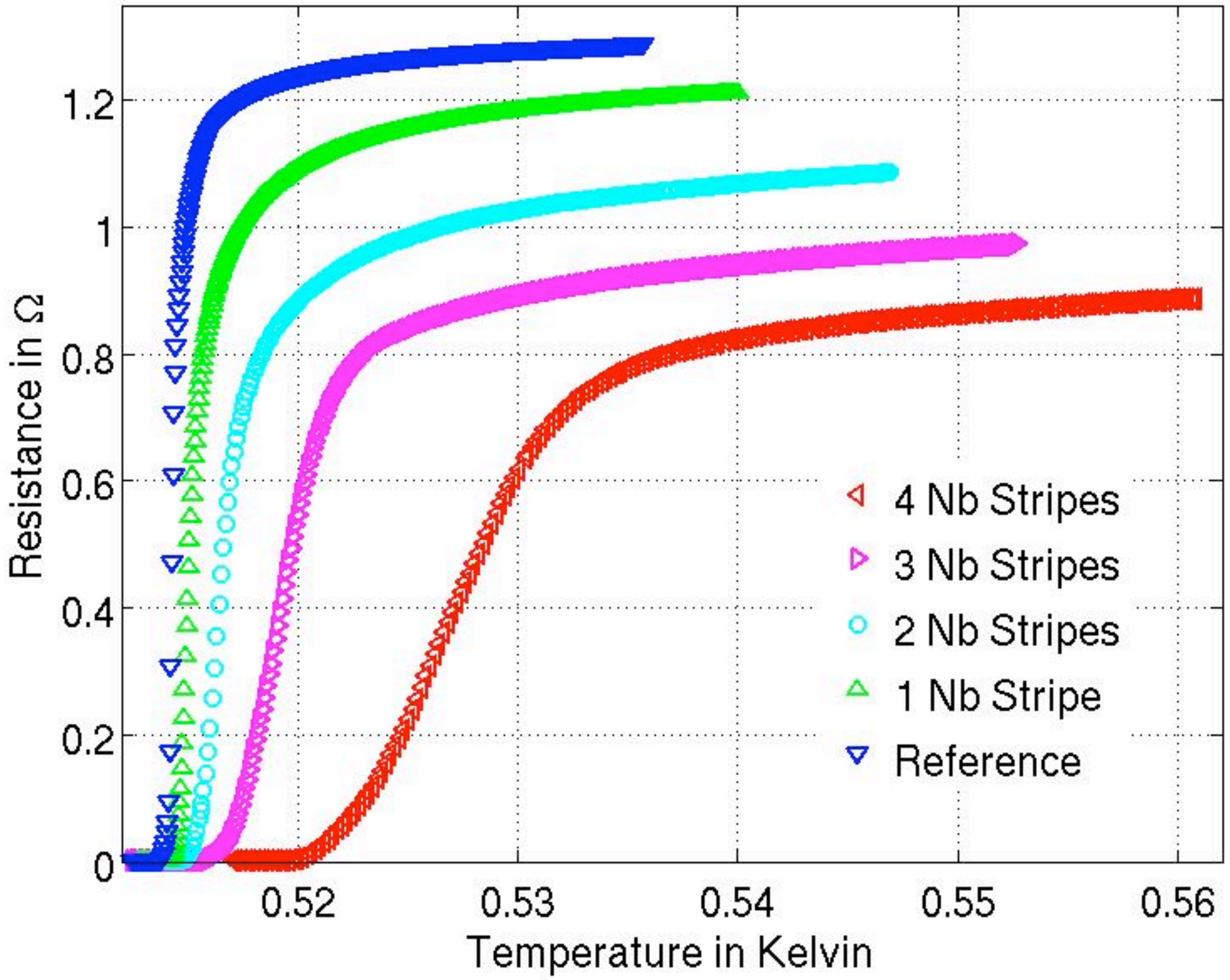


95 GHz Single Pixel PSBs

$R(T)$ curve:

Steeper = Faster, more linear

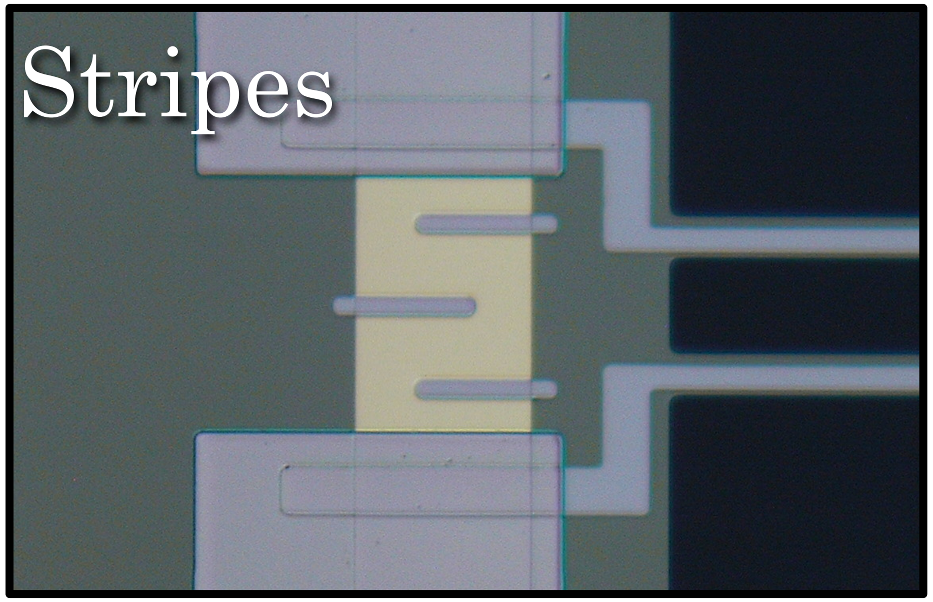
Broader = More stable

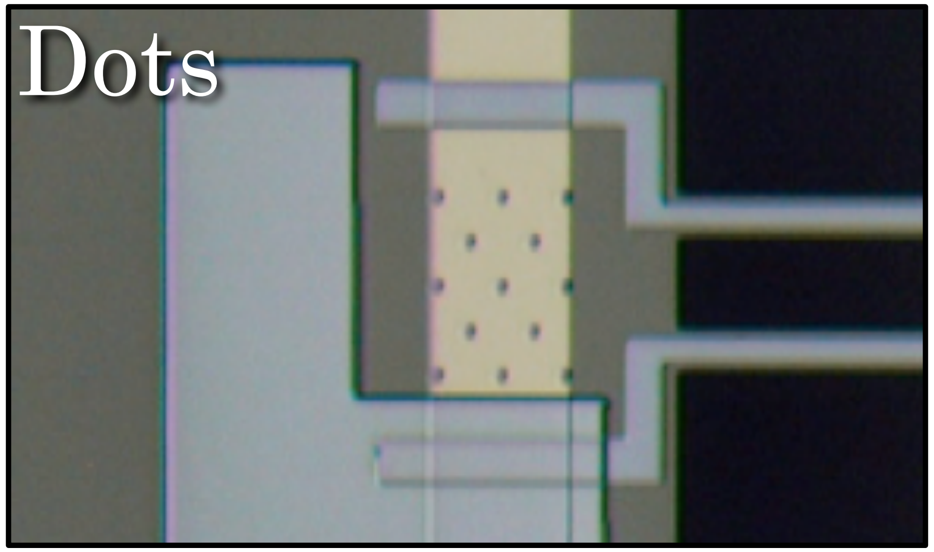


Engineer TES speed and responsivity

- 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**

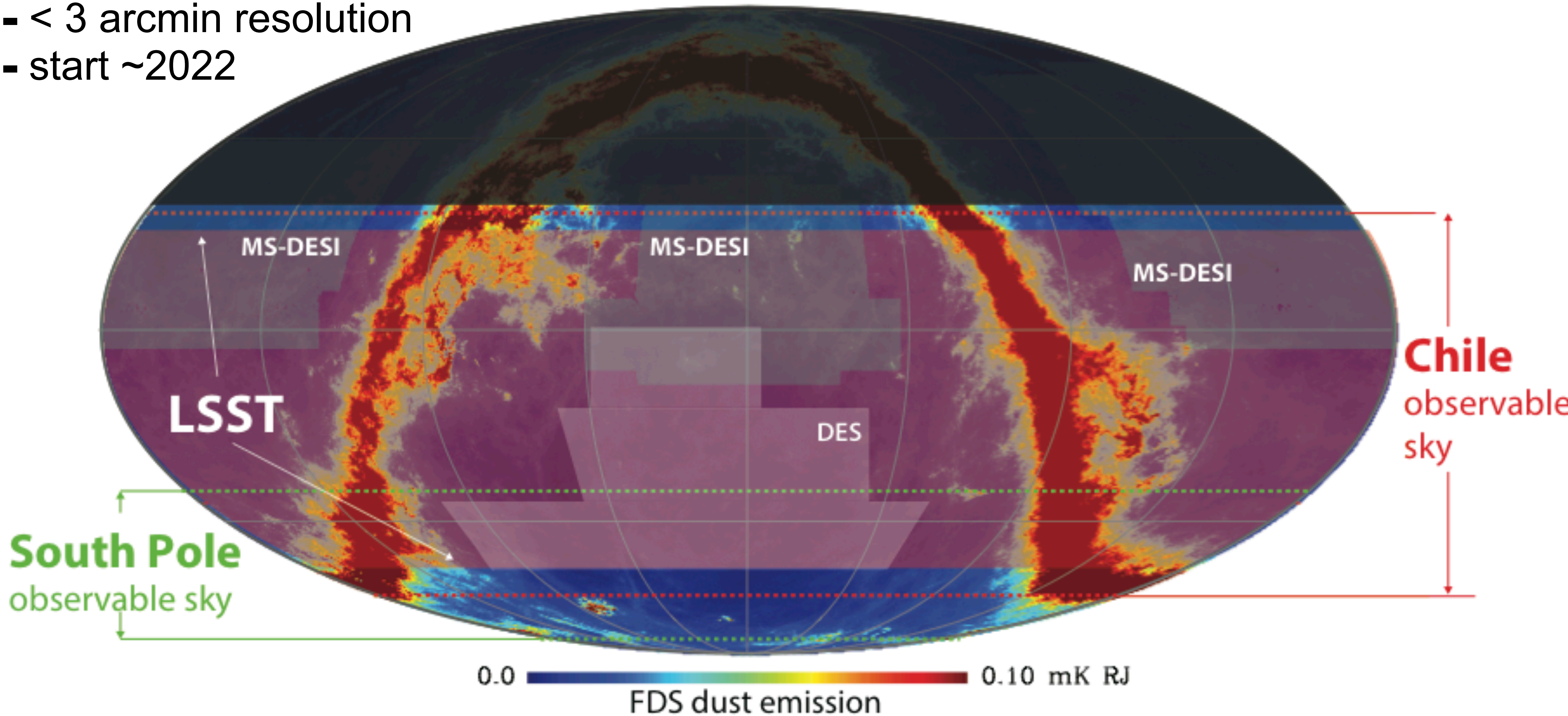




CMB-S4: A CMB Stage 4 Experiment

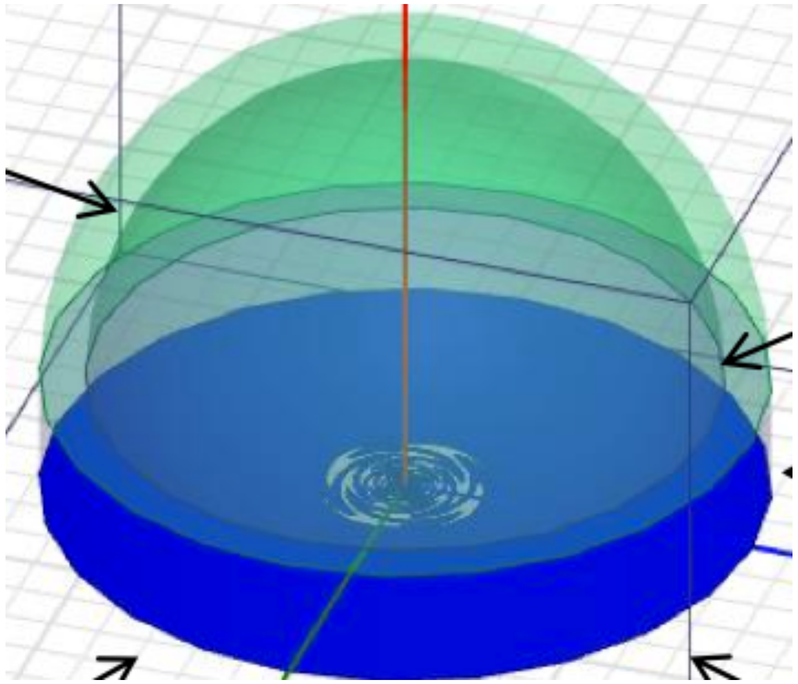
footprint overlap with DES, LSST, DESI, etc.

- 200,000 - 500,000 detectors on multiple platforms
- span 40 - 240 GHz for foreground removal
- target noise of ~1 uK-arcmin depth over half the sky
- < 3 arcmin resolution
- start ~2022

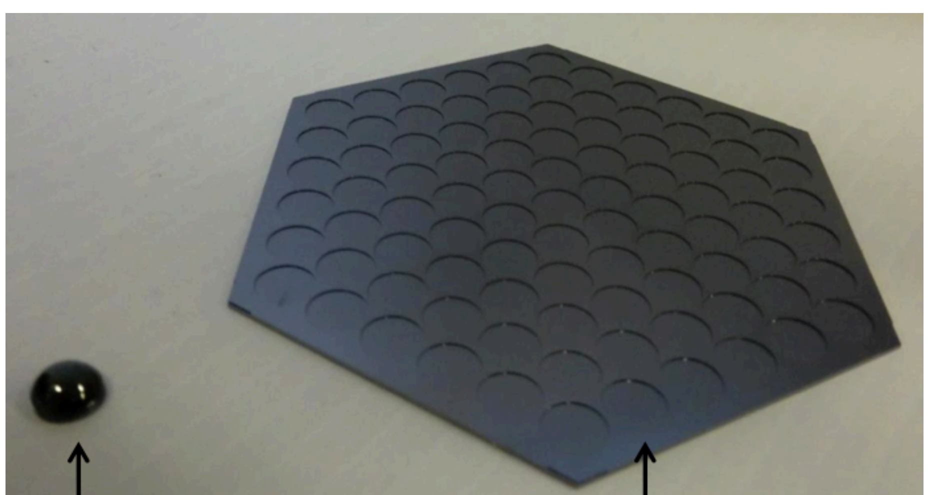


Primary technical challenge will be the scaling of the detector arrays

Lens-Coupled Antenna



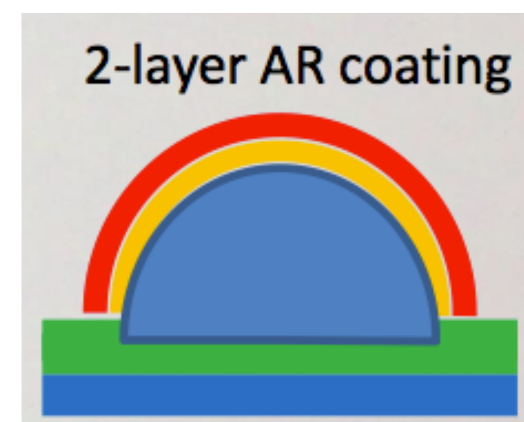
- **Contacting Si lens focuses beam pattern**
  - Surface of lens is analogous to horn aperture
  - Used for Herschel/HIFI, ALMA/SIS, Polarbear instruments
- **Antenna is small compared to lens**
  - Increases area under the lens for filters, TESs, ...
- **Anti-reflection (AR) coating needed**
  - Challenging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



Single-layer AR/epoxy coated lenslet

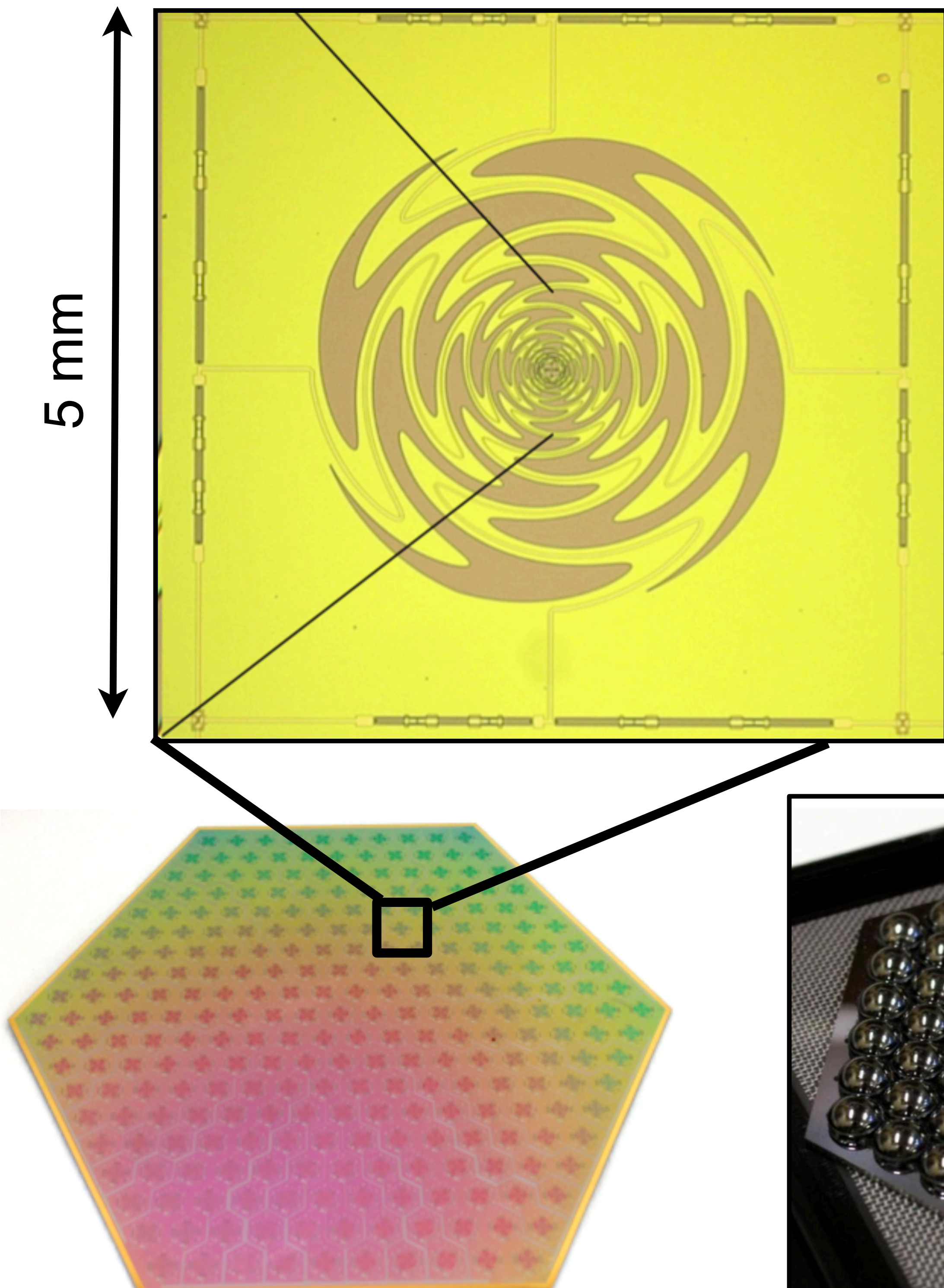
Spacer wafer with etched registration holes

Lenslet Array

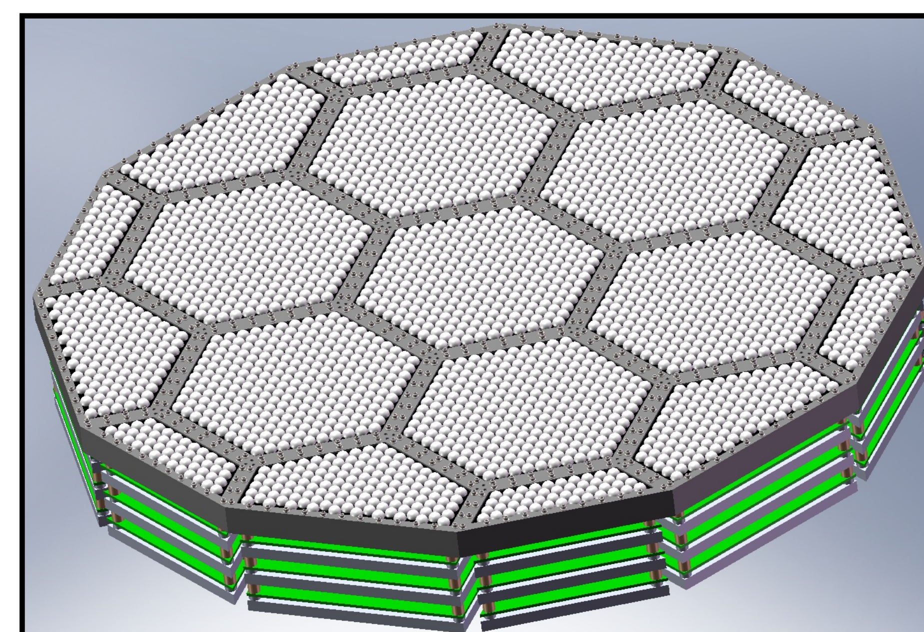


Credit: Toki Suzuki, Erin Quealy

SPT-3G Detector Module Assembly



- 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

SPTpol Receiver