Bolometric vs. MMIC Arrays for CMB Observations

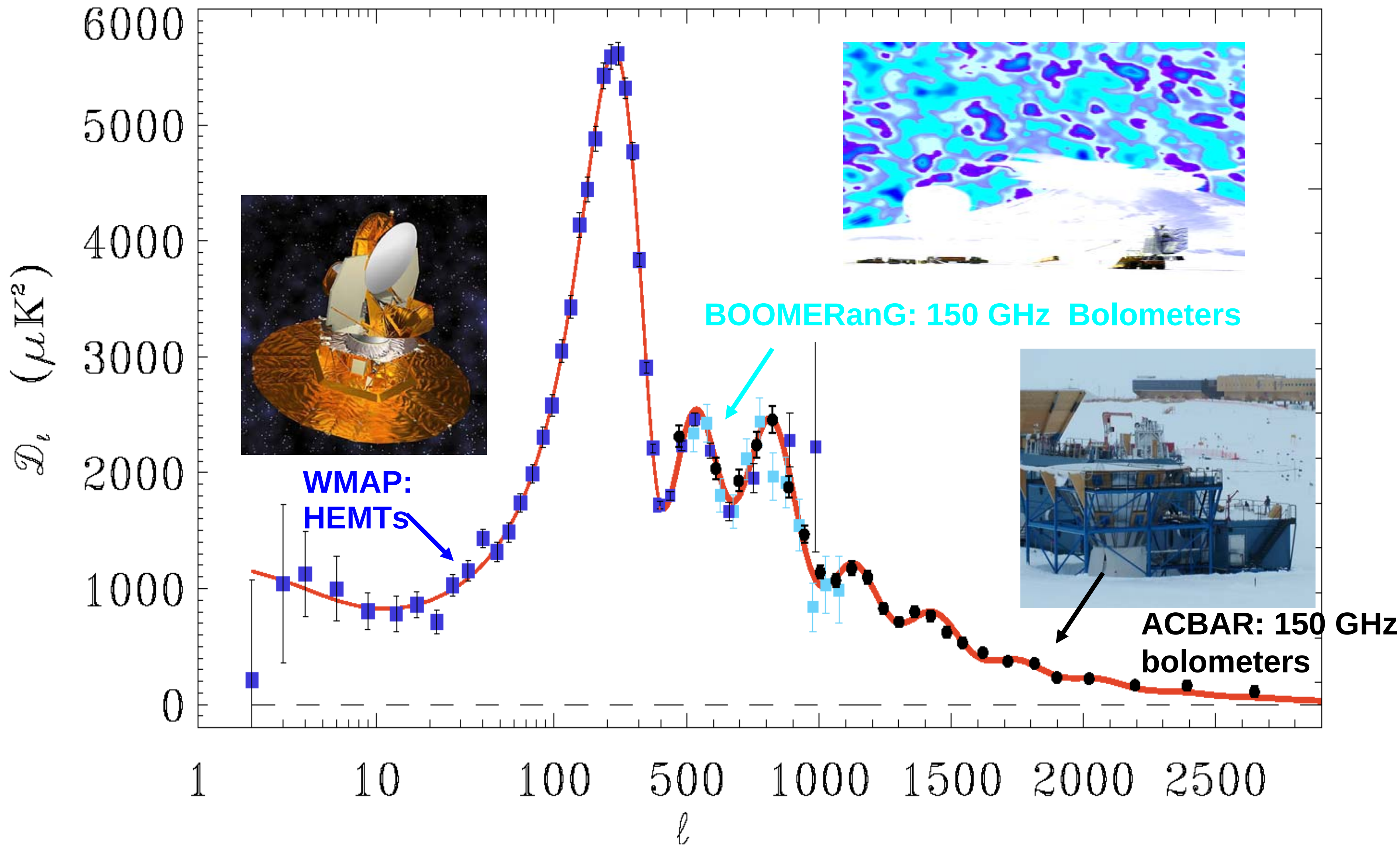
Andrew Lange

Caltech / JPL

A Physicist's History of the Universe:

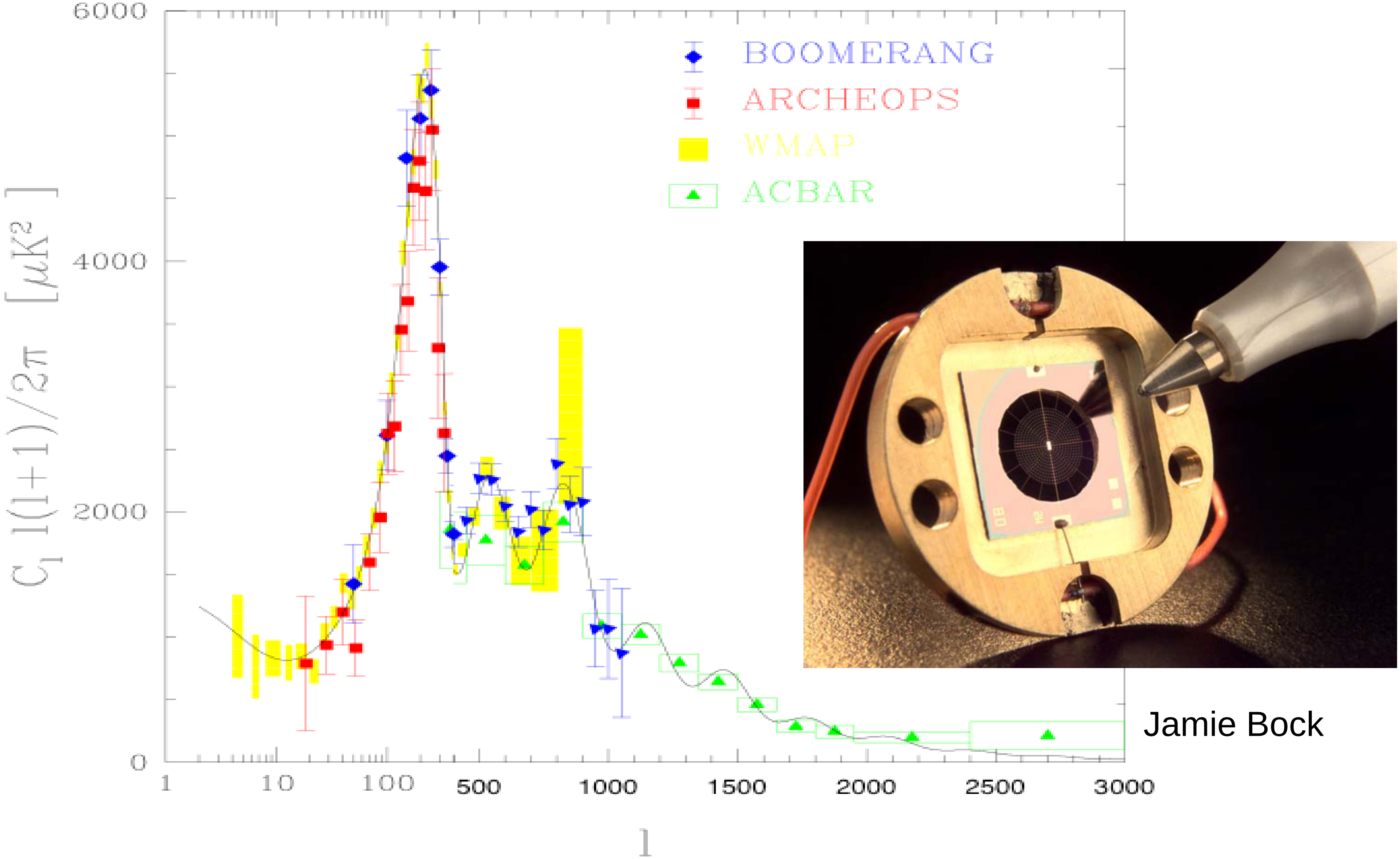
14 billion yr	400,000 yr	1 hour	<< 1 s
telescopes	atoms	nuclei	**????**

We have now seen a peak and 4 harmonics!



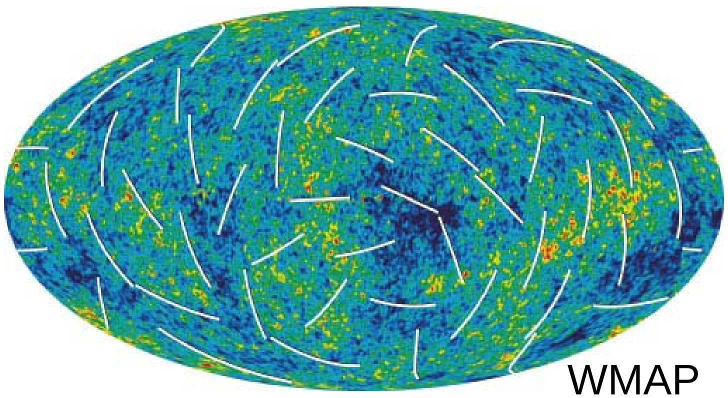
Reichardt et al. astro-ph 0801.1491

JPL detectors mapped the basic features

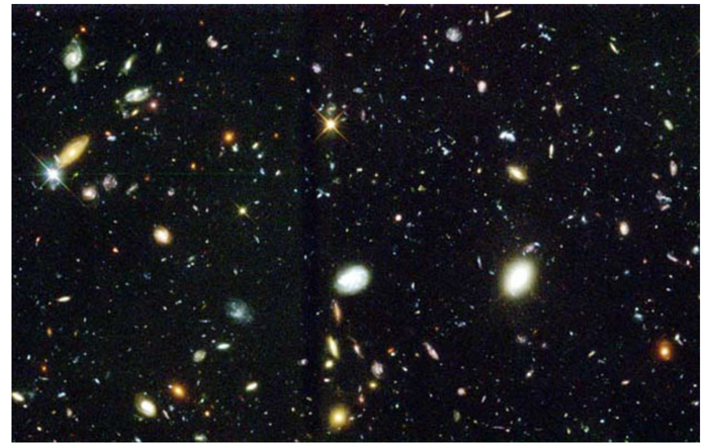


Jamie Bock

What have we learned?



WMAP



The Universe "INFLATED" at t << 1 sec(?!)

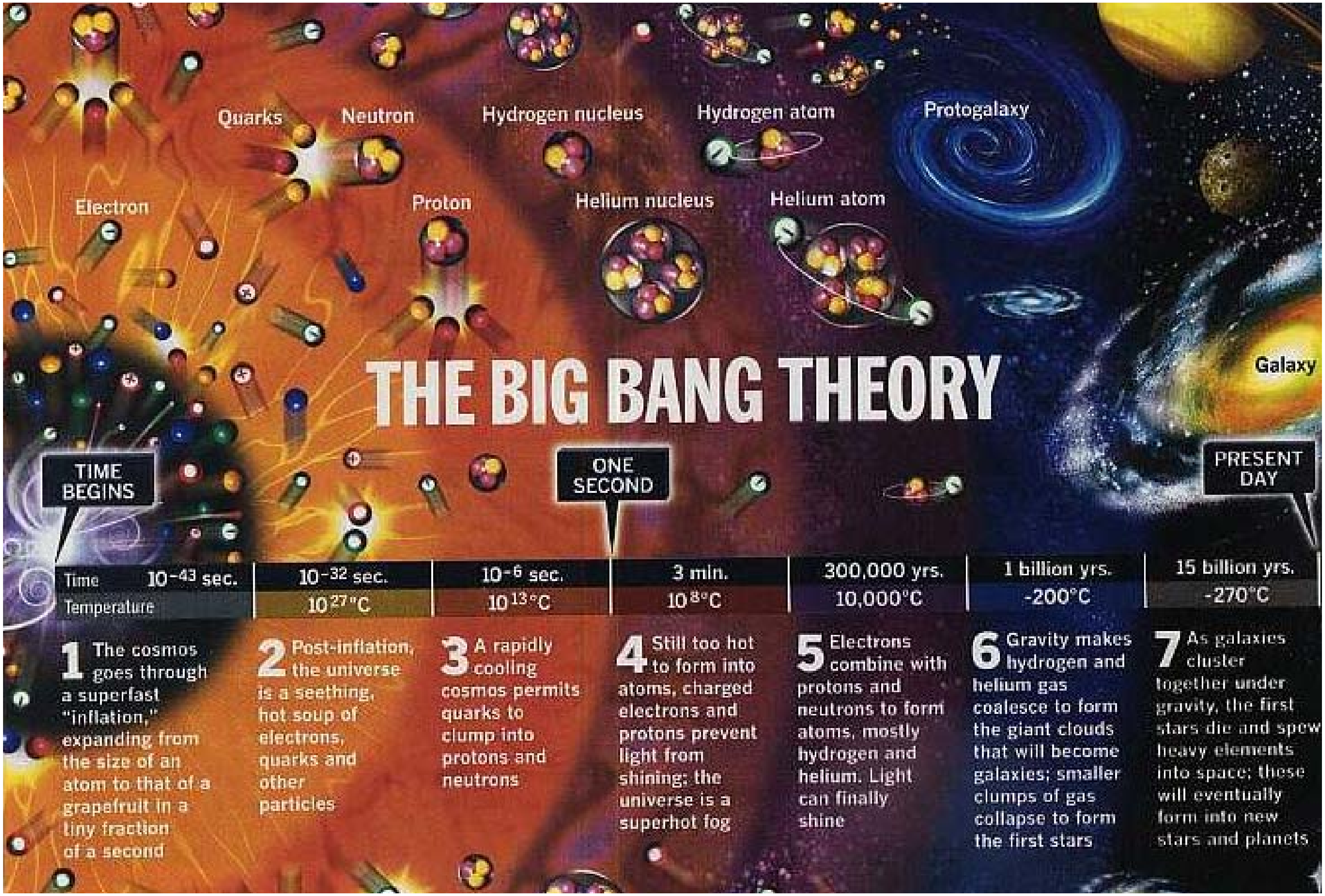
and is now 13.7 +/- 0.1 Gyrs old

The recipe for the Universe is:

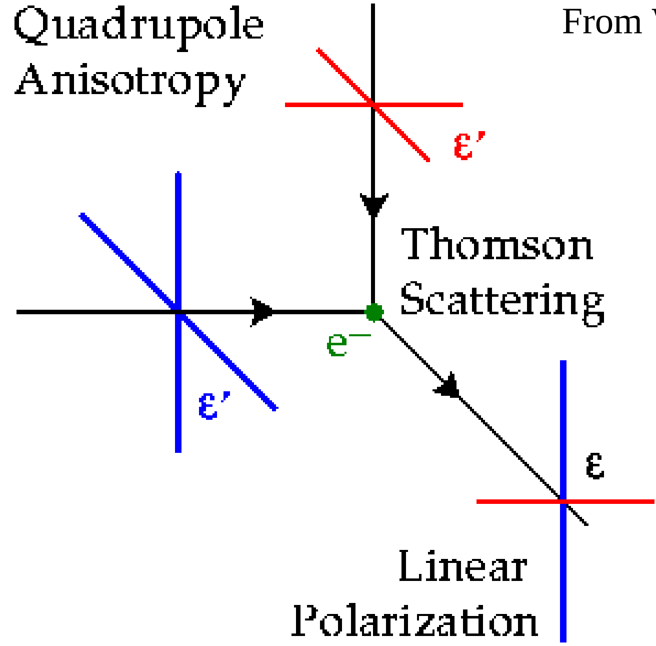
4.6 % ordinary matter [atoms: you, me, planets, stars]
23% some unknown type of cold dark matter
72% some unknown type of *DARK ENERGY*
(enormous tension - accelerating the expansion!)


What comes next?

The ultimate high energy physics laboratory…

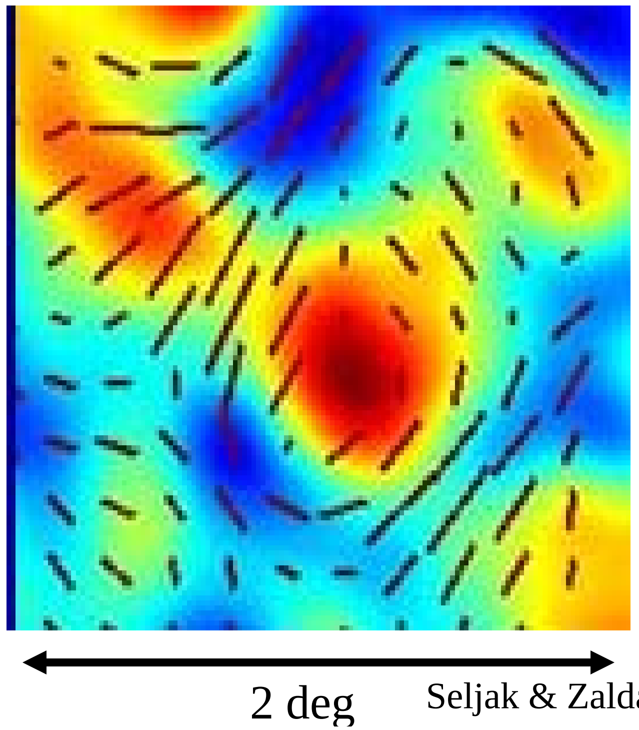


CMB Polarization



From Wayne Hu

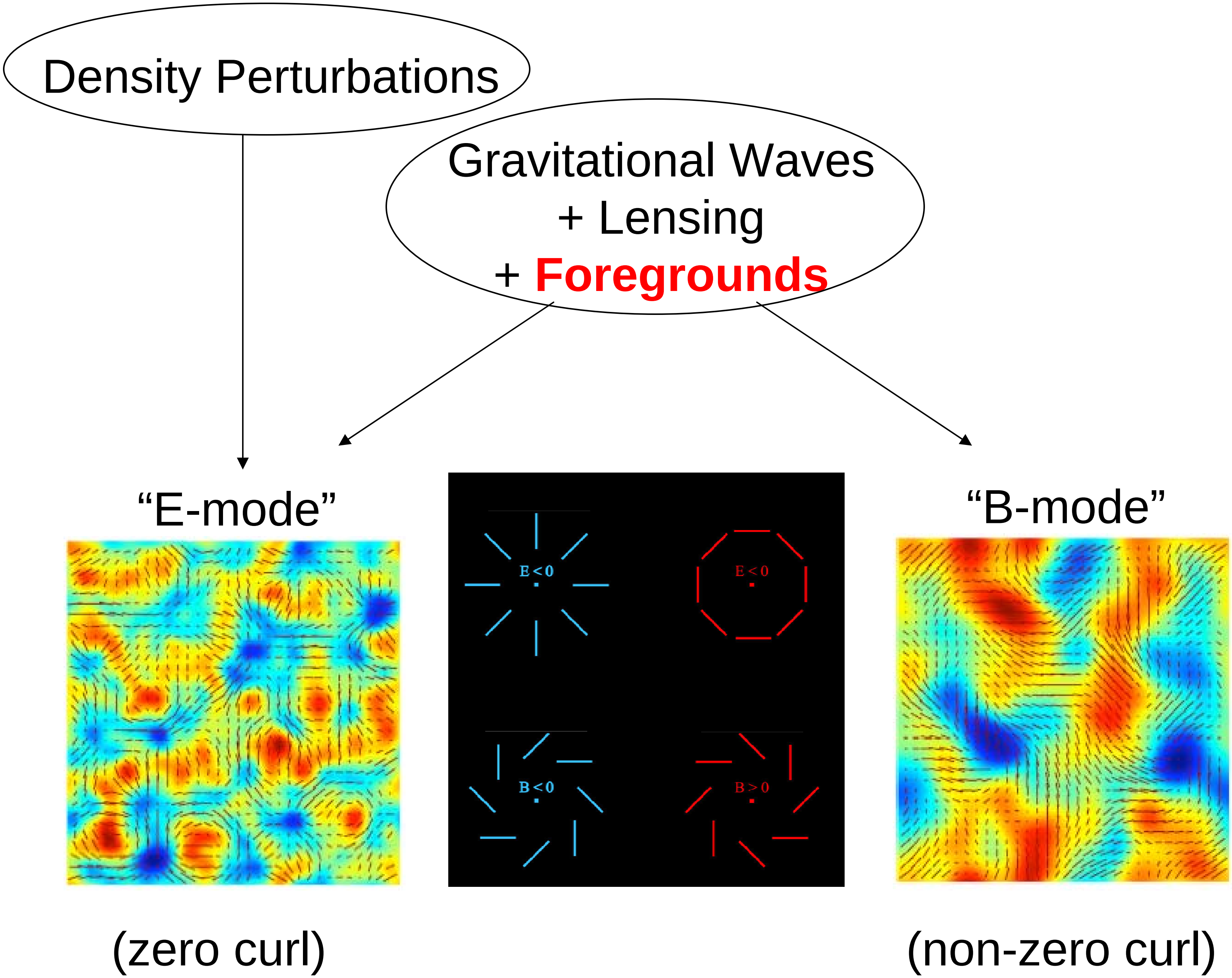
The CMB is polarized by Thompson scattering of a quadrupolar radiation pattern.



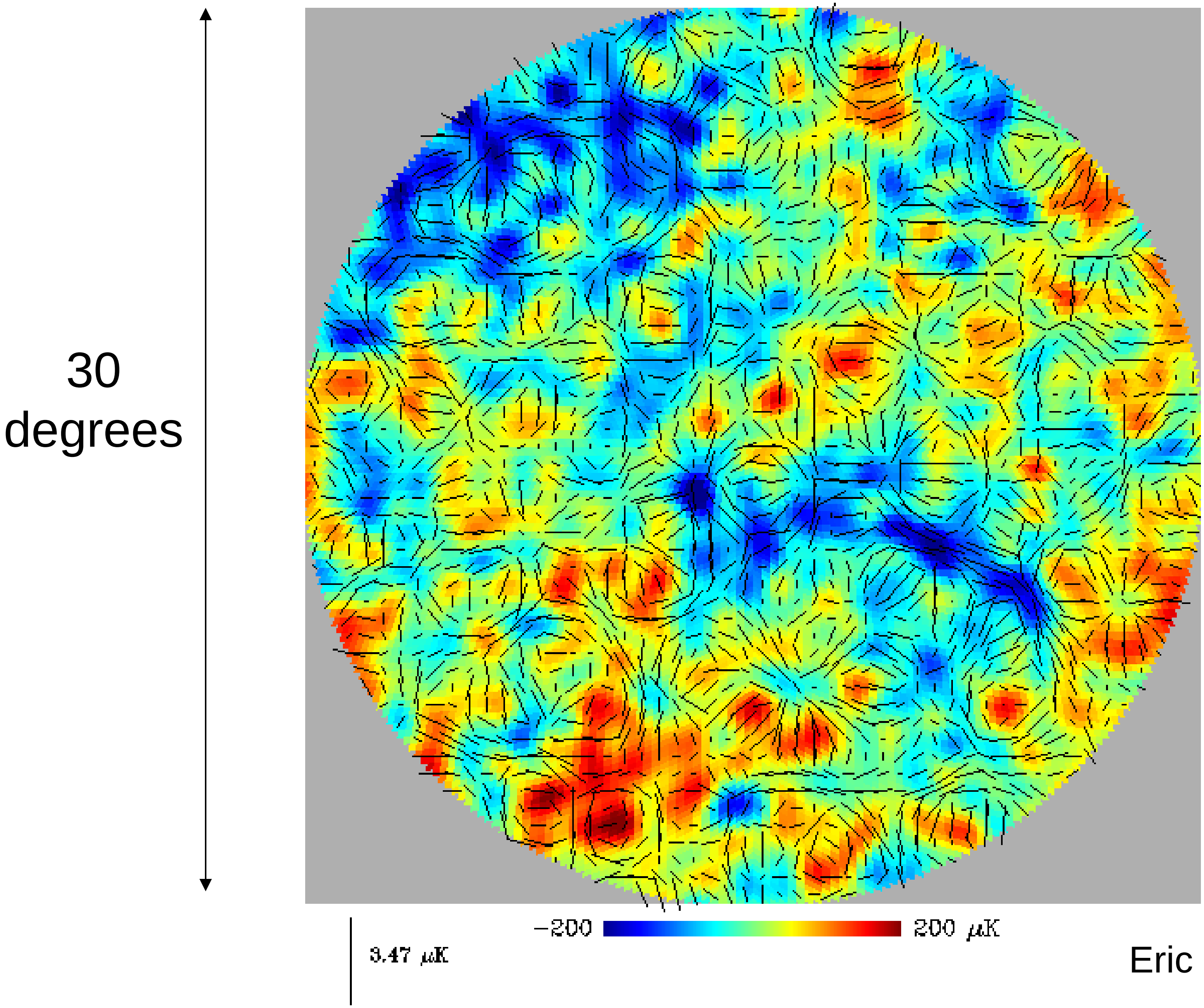
Seljak & Zaldarriaga

Density perturbations produce polarization with a special symmetry.

Gravitational waves produce polarization with a different symmetry.

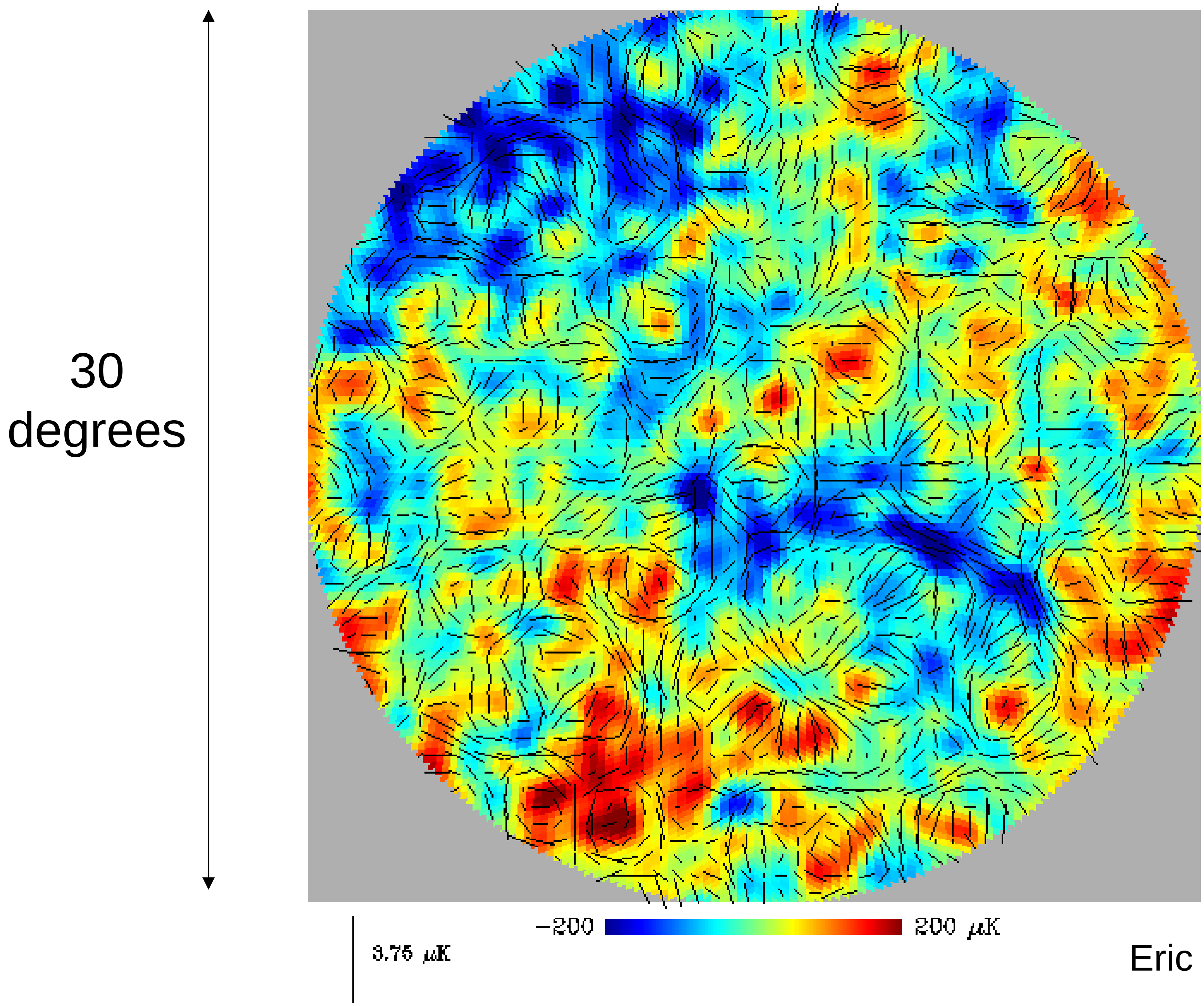

Density Perturbations
Gravitational Waves
+ Lensing
+ Foregrounds
“E-mode”
E<0
E<0
B<0
B>0
“B-mode”
(zero curl)
(non-zero curl)

No gravitational waves (r = 0)



Eric Hivon

Gravitational waves (r = 0.3)



Eric Hivon

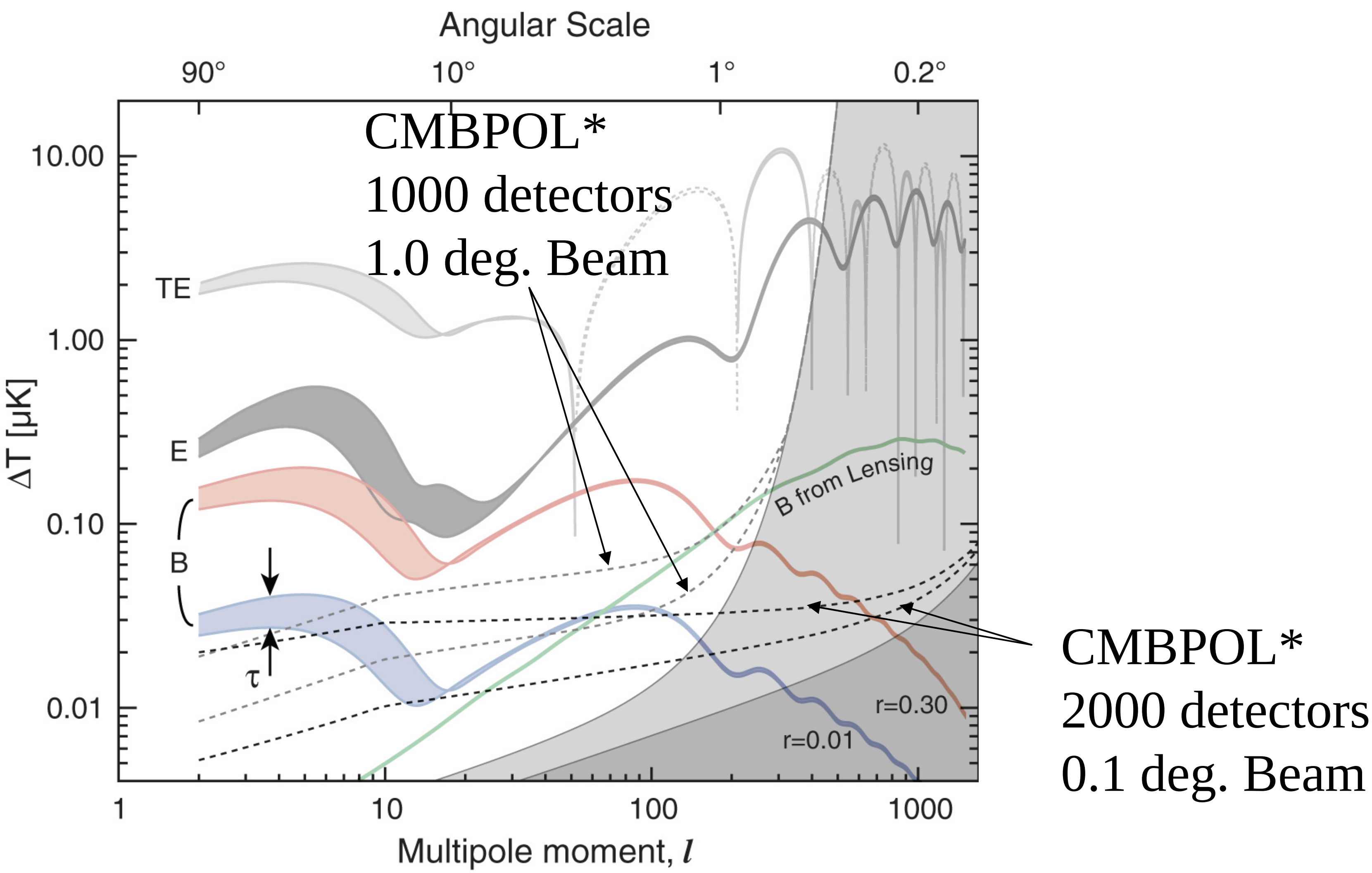
Task Force on CMB Research

- Google: “cmb task force”
- Convened by NASA/NSF/DOE in 2003
- 14 members (3 from our Project Team)
- Final Report July 2005
- Findings & Recommendations:
  - “A unique CMB polarization signal directly tests inflation. As our highest priority, we recommend a phased program to measure this signal to the limit set by astrophysical foregrounds.”
- Envisioned a satellite launched in 2018.

Highest Technical Priority from Task Force Report:

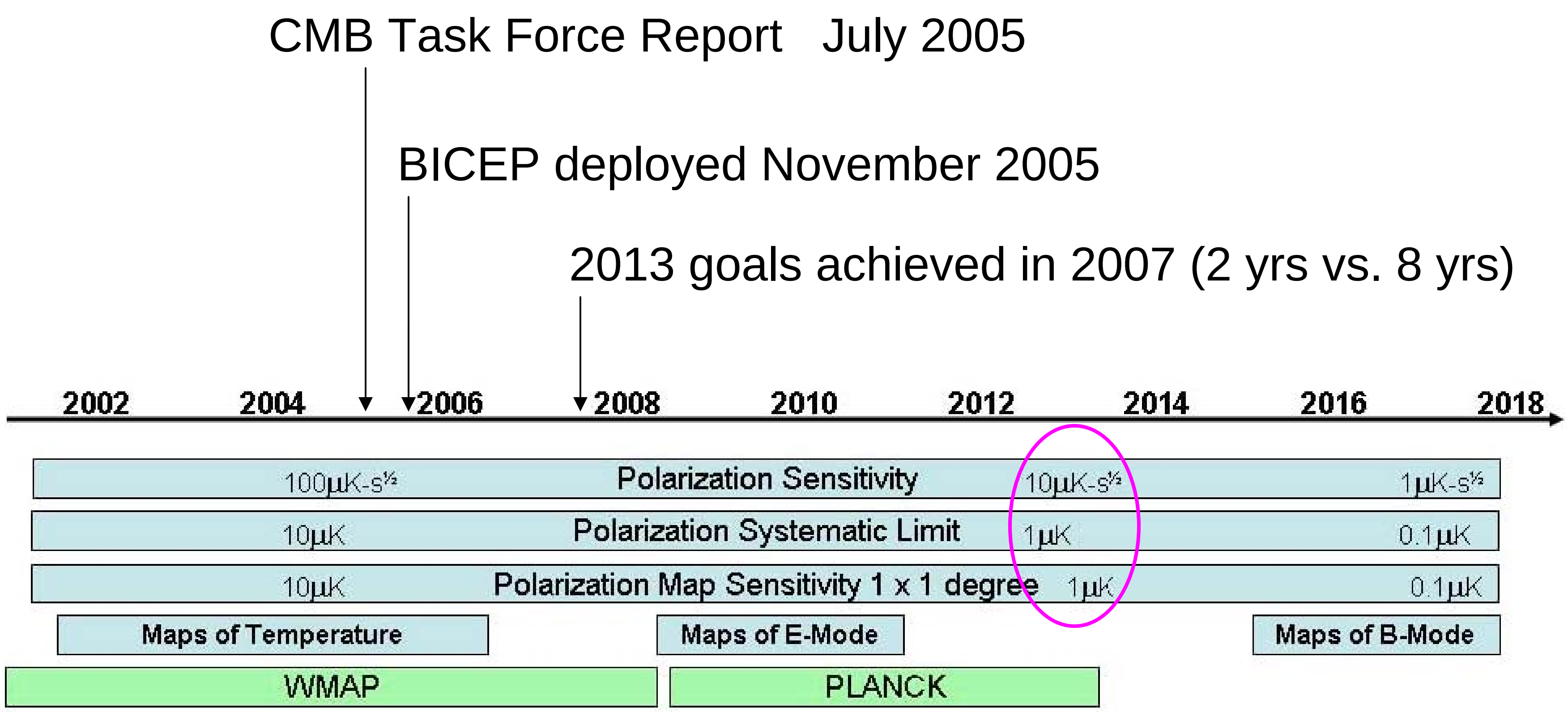
- **T1) We recommend detector development, leading to polarization sensitive receivers incorporating a thousand or more detectors, and adequate support of facilities to produce them**
  - Recommendation T1 requires maintaining core capabilities at NASA-supported centers for detector development and substantial support for detector development at DoE, NIST and University groups as well.

Task Force strawman mission: ~ 15 to 30 x sensitivity of Planck



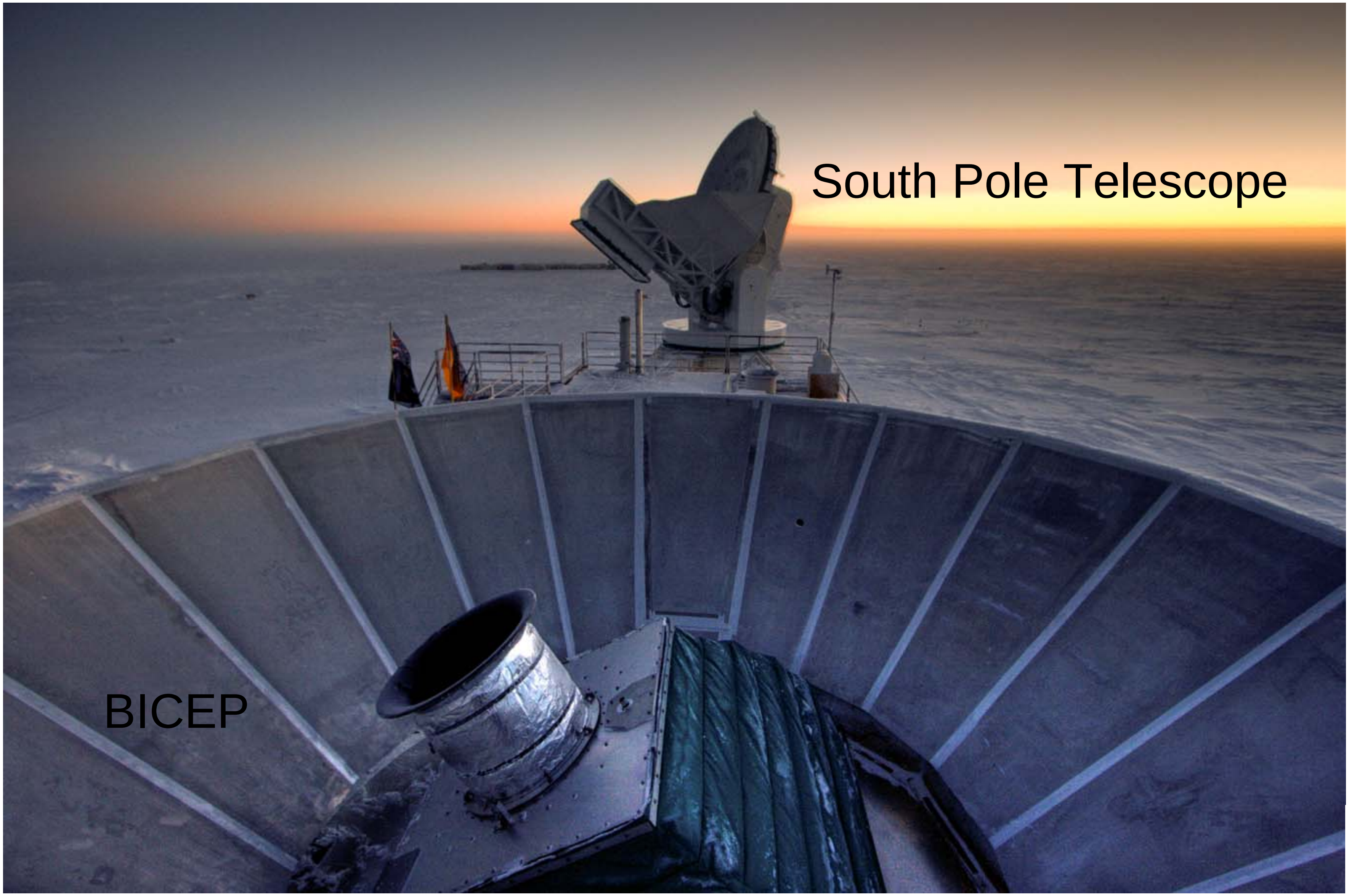
*2 lines span foreground uncertainty

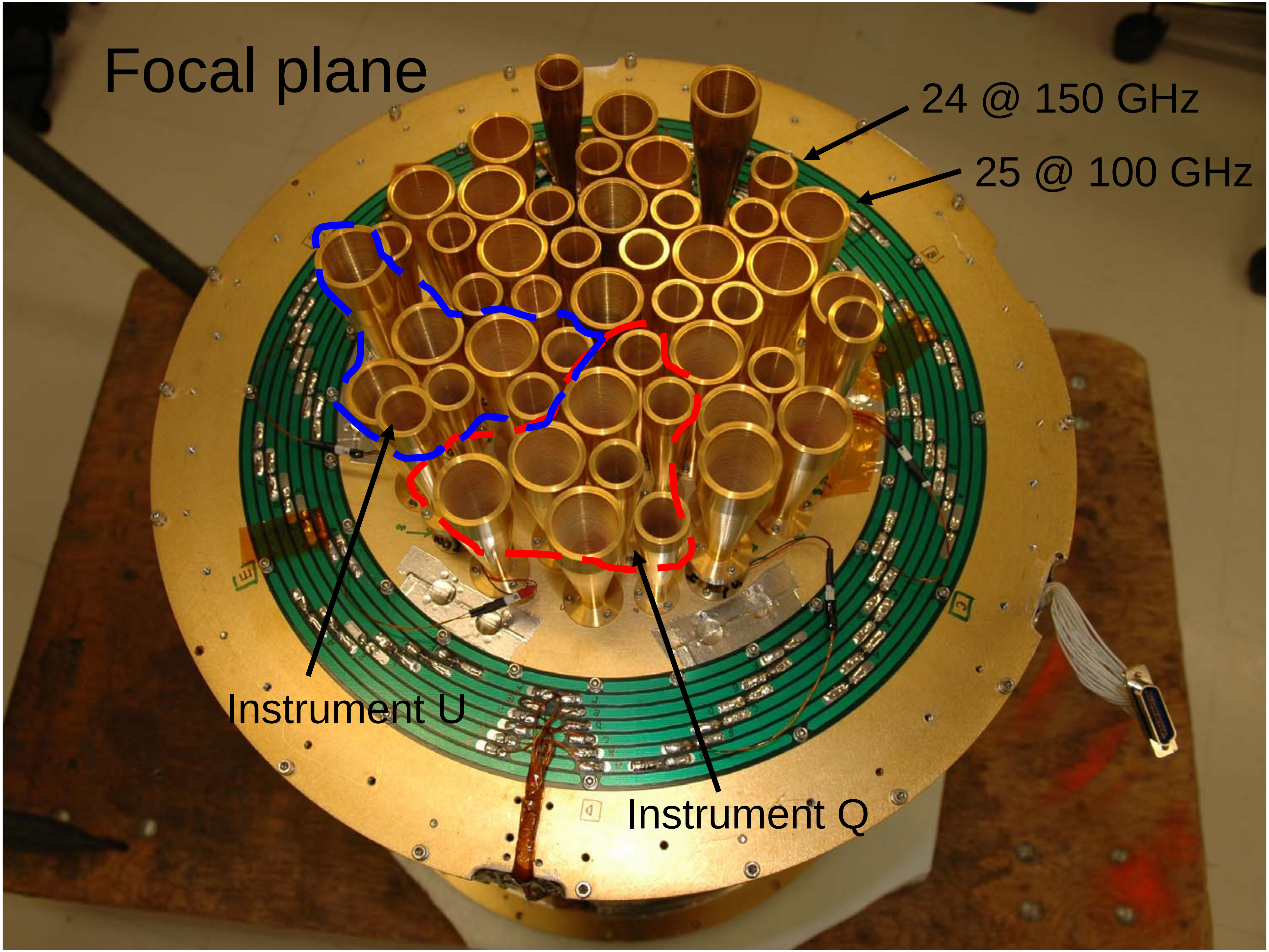
3 years later: progress has been much faster than expected!



CMB Task Force Report , Fig. 10.2

A good orbital pathfinder environment

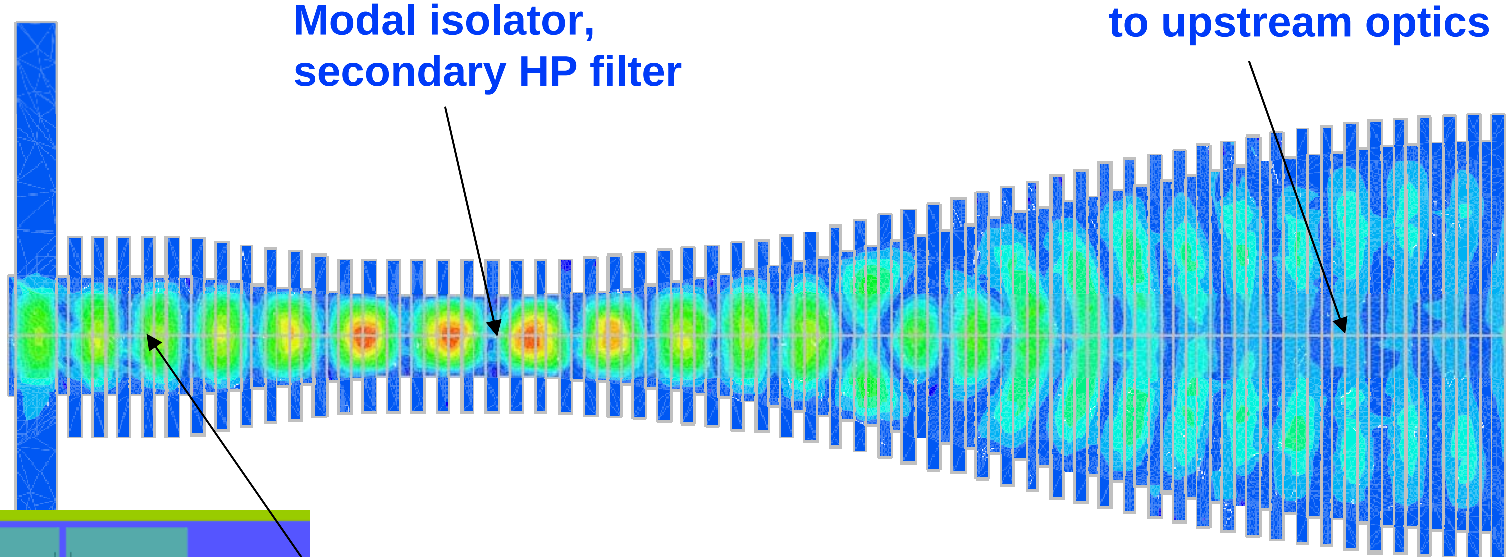



Focal plane
24 @ 150 GHz
25 @ 100 GHz
Instrument U
Instrument Q

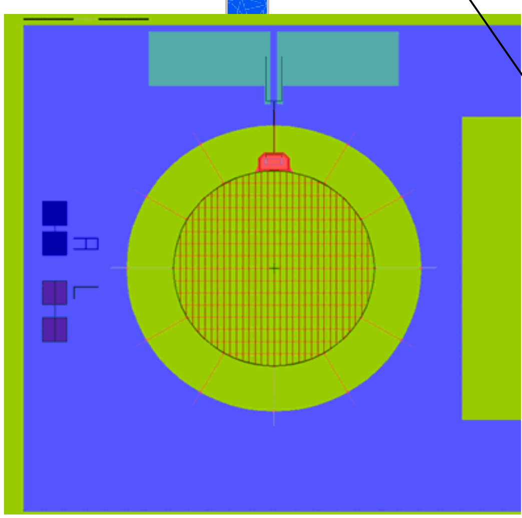
PSB Electrical Design and Waveguide Coupling

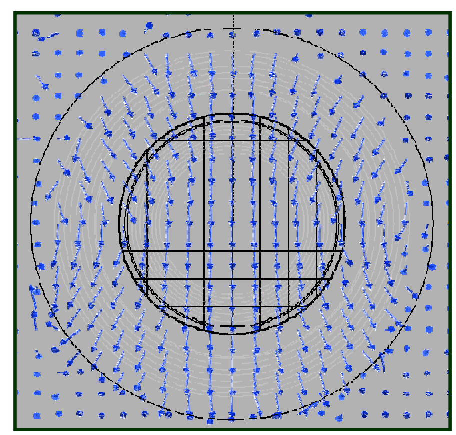
Modal isolator,
secondary HP filter

Determines coupling
to upstream optics

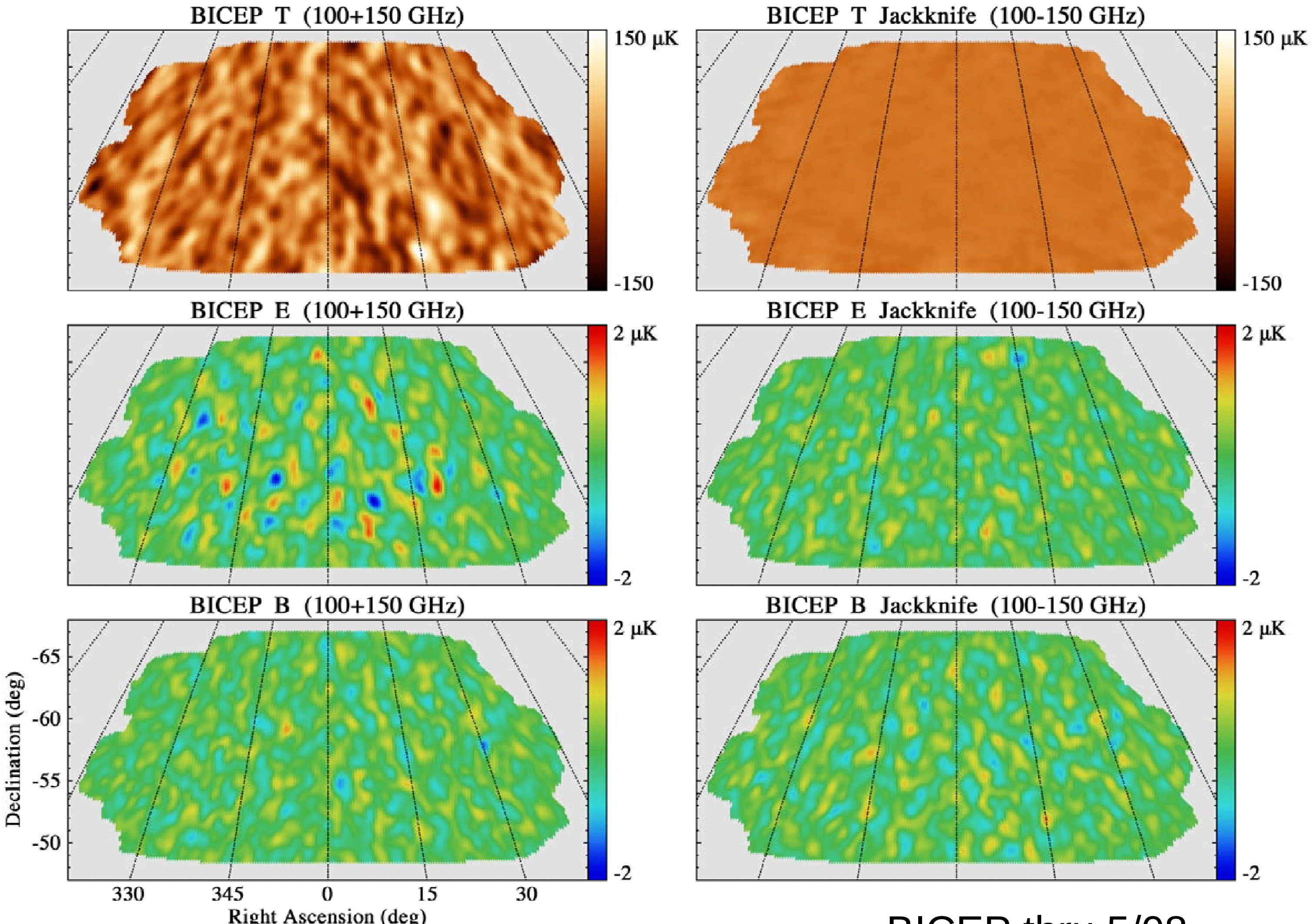


Provides the linear vector
field distribution and
determines polarised
bandwidth and the impedance
match to bolometers





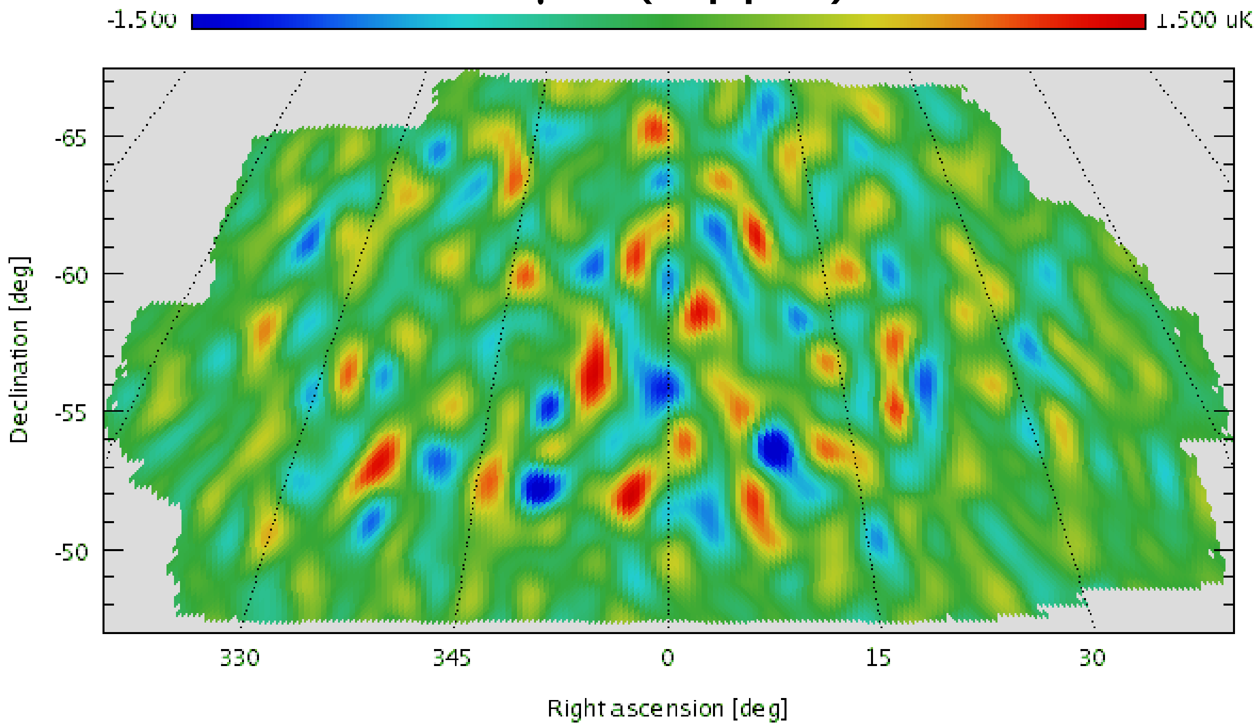
End-to-end demonstration:



BICEP thru 5/08

E-mode 100+150

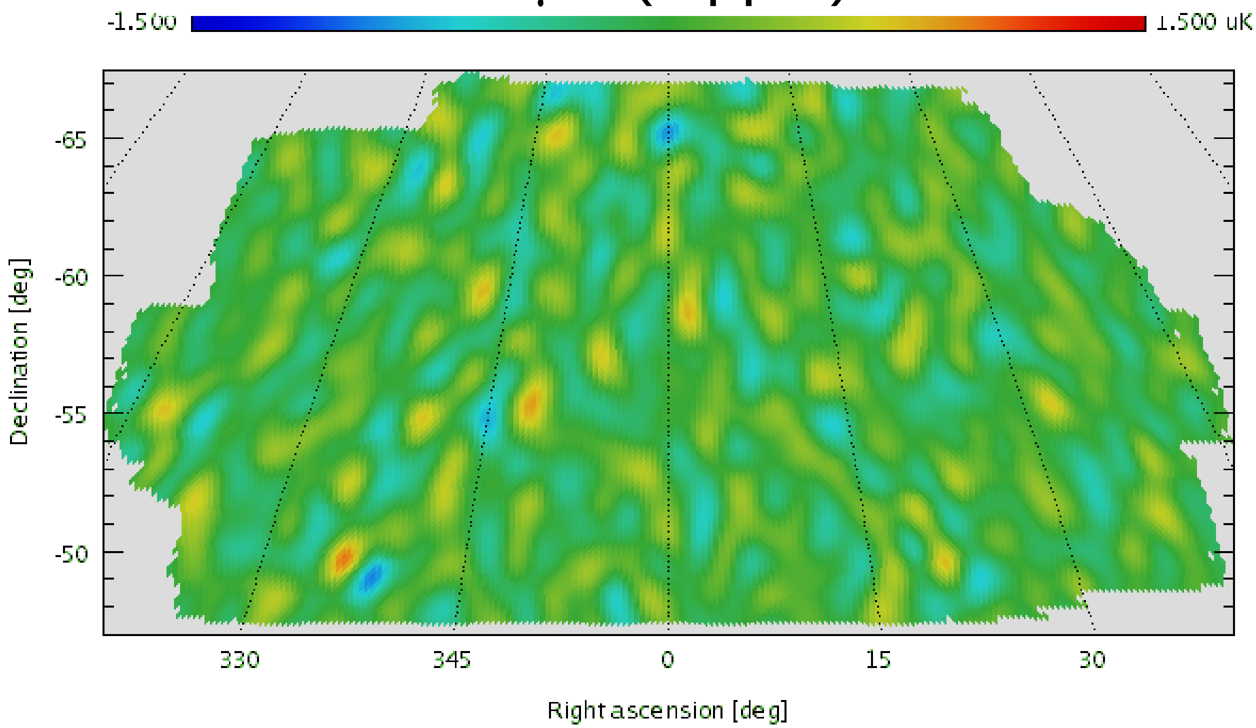
<---------- 3 μK (1 ppm) ----------->



BICEP thru 11/08

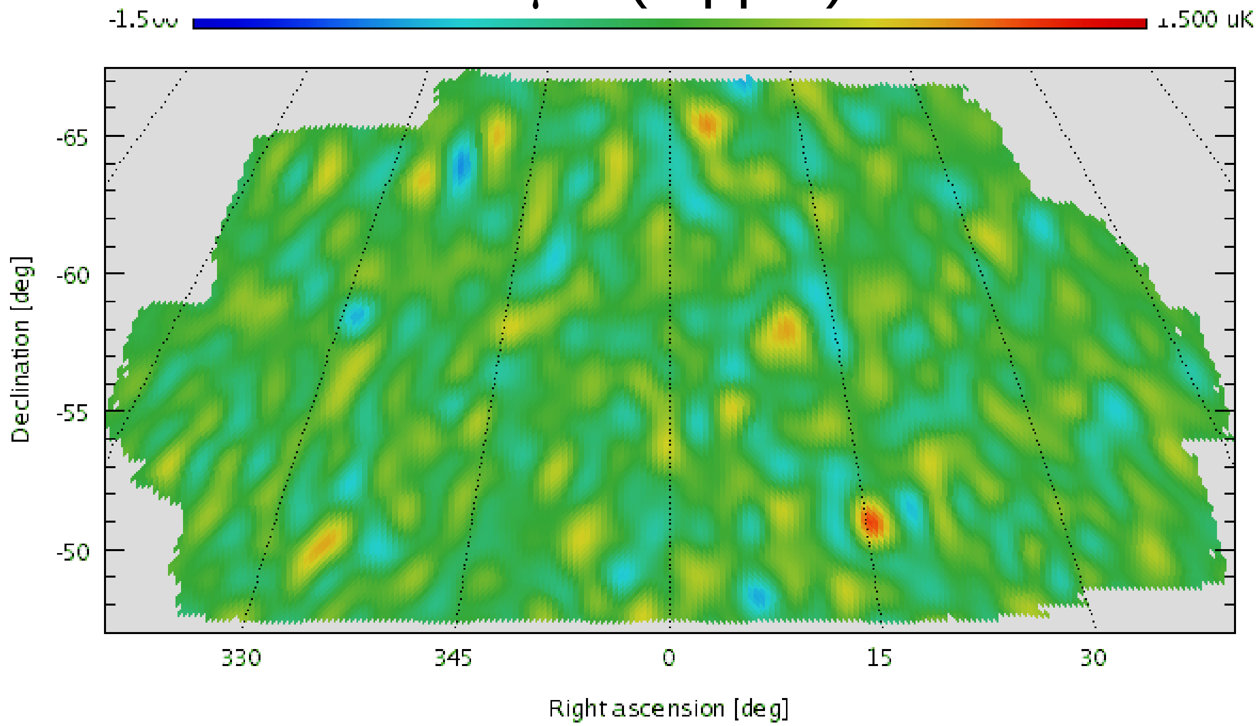
E-mode 100 -150

<---------- 3 μK (1 ppm) ---------->



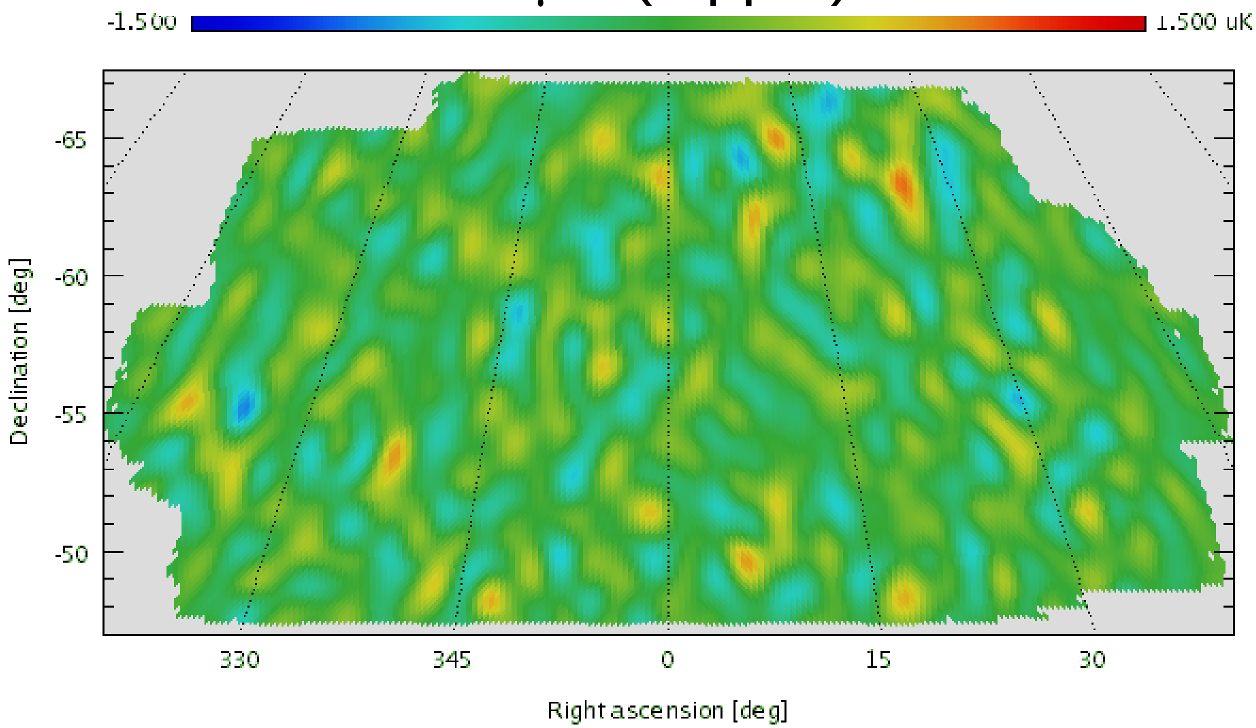
B-mode 100+150

<---------- 3 μK (1 ppm) ----------->



B-mode 100 -150

<---------- 3 μK (1 ppm) ----------->



Relevant Detector Properties

	Bolometers	MMIC HEMTs
• **Sensitivity**	**great**	**good @ < 100 GHz**
• **Response time**	**~ msec -> sub-msec**	**fast**
• **Frequency Coverage**	**comprehensive**	**limited**
• **Cooling Requirements**	**little P at low T**	**large P at higher T**
• **Linearity**	**adequate**	**excellent**
• **Gain Stability**	**excellent**	**poor**
• **Offset Stability**	**excellent**	**good**
• **Focal Plane Density**	**better**	**feedhorn limited**
• **Polarization Sensitivity**	**good**	**good**
• **EMI / RFI / B-field / microphonic susceptibility**	**adequate**	**better**
• **Array Uniformity**	**good**	**???**
• **MUX**	**adequate**	**good**

Planck

- 20K HEMT amplifiers at 30, 45, 70 GHz
  - ~ 20 amplifiers
- 100 mK bolometers at 100 -> 850 GHz
  - ~ 50 bolometers
- Demonstration of feasibility of cooling
  - 100 mK could sustain 1000's of bolometers
  - Not so for 20K and HEMT amplifiers

Limiting Factors (from Weiss report):

Table 7.2. Sensitivities of Bolometer and HEMT-based detection schemes

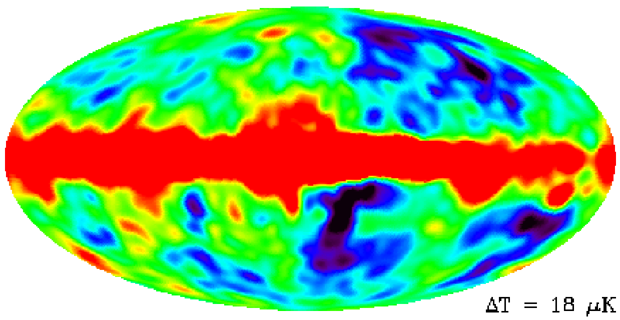
Frequency [GHz]	***WMAP*** [μK ¦(sec)]	**PLANCK** [μK ¦(sec)]	**Bolometer** [μK ¦(sec)]	**3xQL HEMT** [μK ¦(sec)]
20	**700**		55	**66**
30	**700**	**350**	49	**64**
45	**900**	**350**	44	**53**
70	**1000**	**480**	42	**74**
100	**1500**	90	43	**90**
150		80	51	**136**
220		110	80	**272**
350		360	290	**1286**

Notes: (a) All sensitivities are per detector, numbers in **bold** *are HEMTs based on the NRAO design, others are bolometers. (b) WMAP sensitivities are those achieved in orbit. (c) PLANCK sensitivities are current best estimates, based on laboratory measurements of flight detectors. (d) Future bolometer sensitivities assume 2K RJ instrument emission, 30% fraction bandwidth, 50% optical efficiency, and bolometers designed to operate at 100 mK with a 10mK temperature rise under the total background. (e) HEMT sensitivities assume* $T_{sys} \geq 3h\nu/k_B$*, 2K RJ instrument emission, and 30% fractional bandwidth. The values shown are ¦ 2 less than the sensitivity for each detector, under the assumption that both* **Q** *and* **U** *are extracted from the amplified signal, and in order to provide a fair basis of comparison with the other systems, for which each detector measures only one of* **Q** *or* **U.**

Planck (polarized) bolometers already within ~ 2x as well as we will ever do.

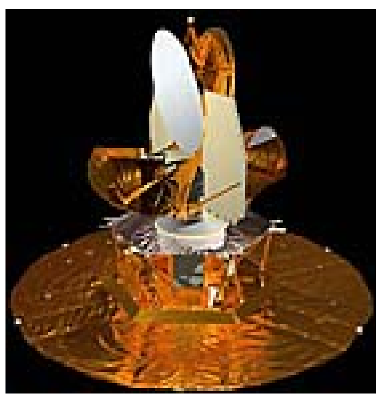
Moore’s Law for CMB Detectors:

CMBPol



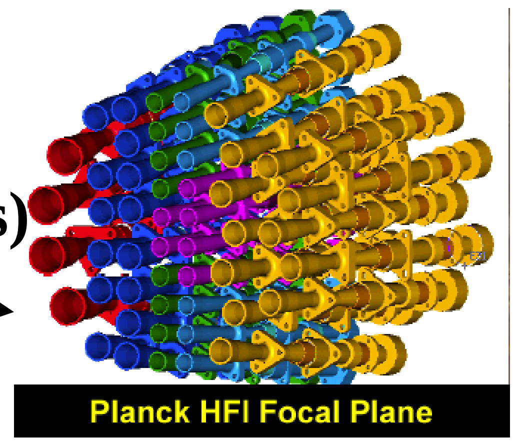
COBE

× ~ 2^5 (12 years)



MAP

× ~ 2^5 (7 years)



×~ $2^{3->5}$ (4 to 12 years past Planck)??

Polarization sensitivity 25μK per 5 arcmin pixel to Q and U

A lot of the sensitivity increase for MAP and Planck has come from improvements in detector sensitivity, but Planck is close to the background limit …..

Can a 15 -> 30 fold sensitivity increase be achieved?

- ×**2** via lower noise/detector (?)
  - **Requires a cold telescope (10K) and careful control of stray-light**
- ×**2** via increased mission life (?)
  - **4 - 8 years vs. 1 - 2 years**
- ×**5 -> 10** via (25 to 100 x) more detectors
  - **Requires arrays of 100's of polarization-sensitive detectors at each frequency**
  - **Large frequency muxed and/or multiple focal planes**
  - **Monolithic, muxed focal planes must have high uniformity and yield**

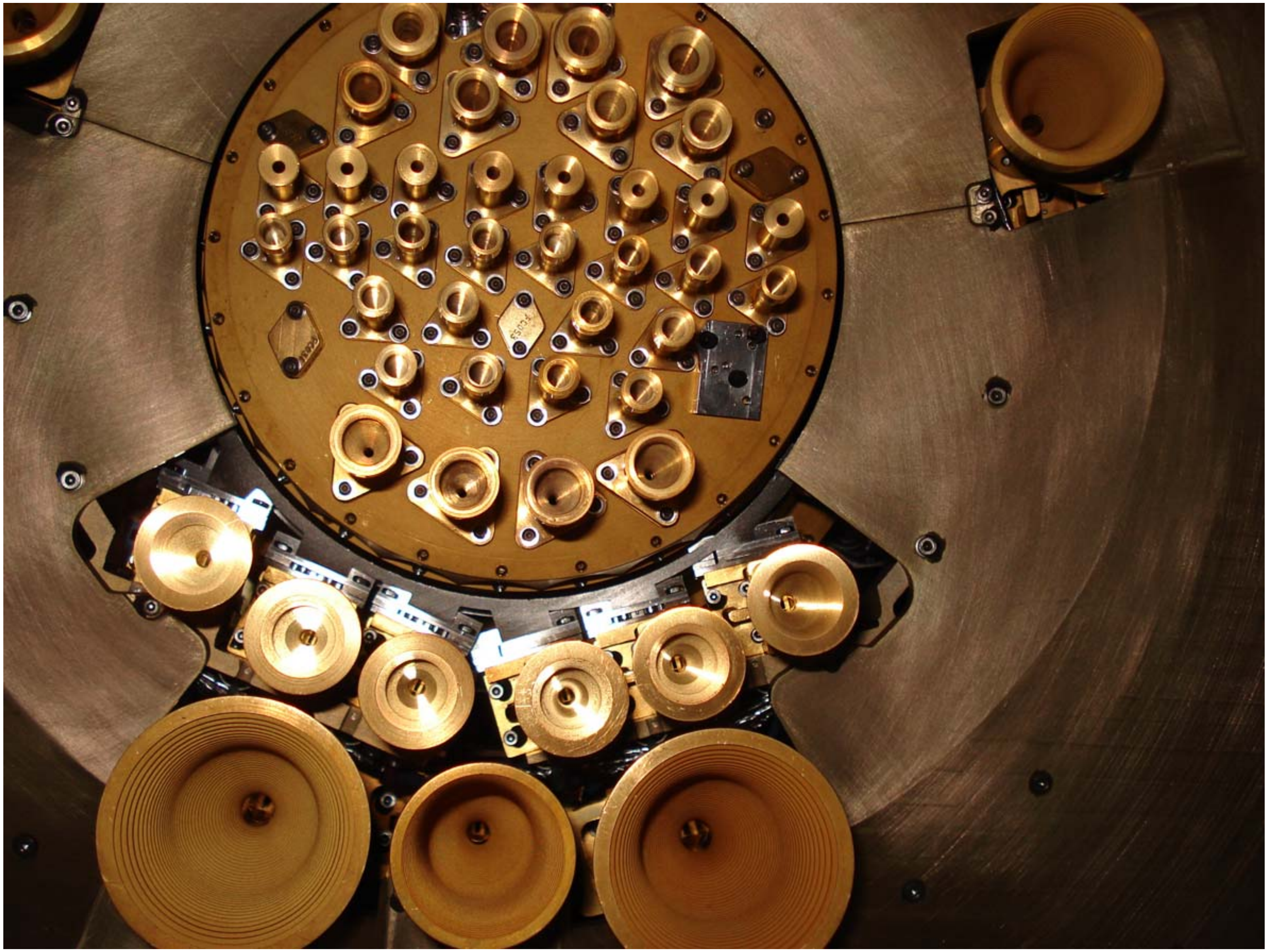
=> $$$

The focal plane will need to be large and densely packed...

ν	P_CMB	dP_CMB/ dT_CMB	NEQ/cm 3xQL HEMT	NEQ/cm real bolo
[GHz]	[fW]	[fW/K]	[μK rtsec/cm]	[μK rtsec/cm]
30	264	123	99	112
45	343	180	69	63
70	416	261	51	35
100	432	330	45	23
150	365	372	46	17
220	223	315	63	16
350	59	130	189	34

Planck HFI has NEQ (143 GHz) ~ **20 μK sec $^{0.5}$**

The Planck focal plane is not densely packed….

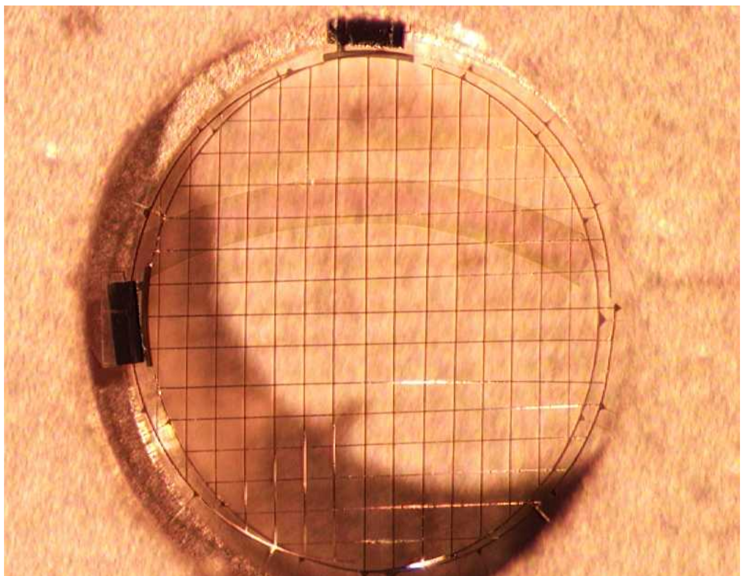


Polarization-Selective Bolometers for BICEP

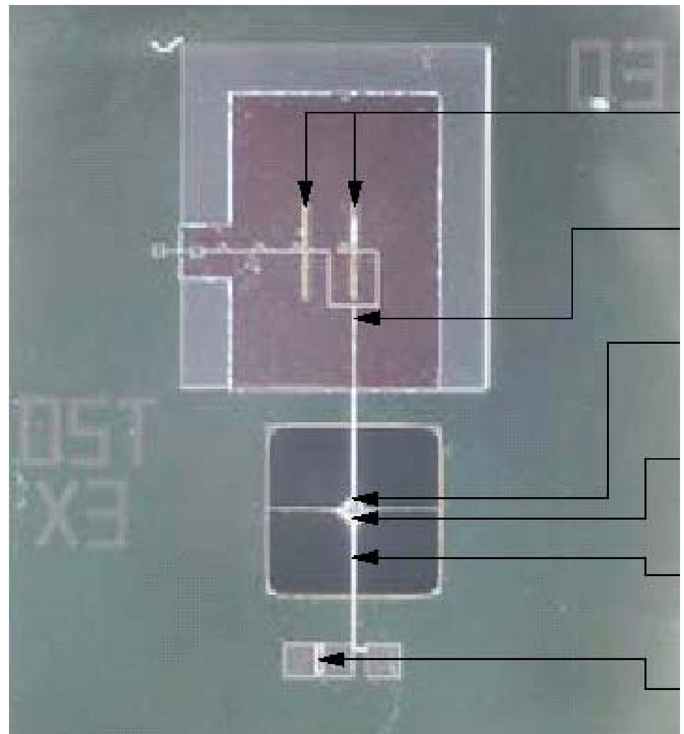
- Arrays of 200 detectors
- Hand-assembled semi-conducting detectors
- Absorber-coupled architecture

Superconducting detectors for CMBPOL

- Arrays of 1000+ detectors
- Superconducting detectors and readouts
- Novel "antenna-coupled" architectures



The First Pair of Polarization-Selective Bolometers

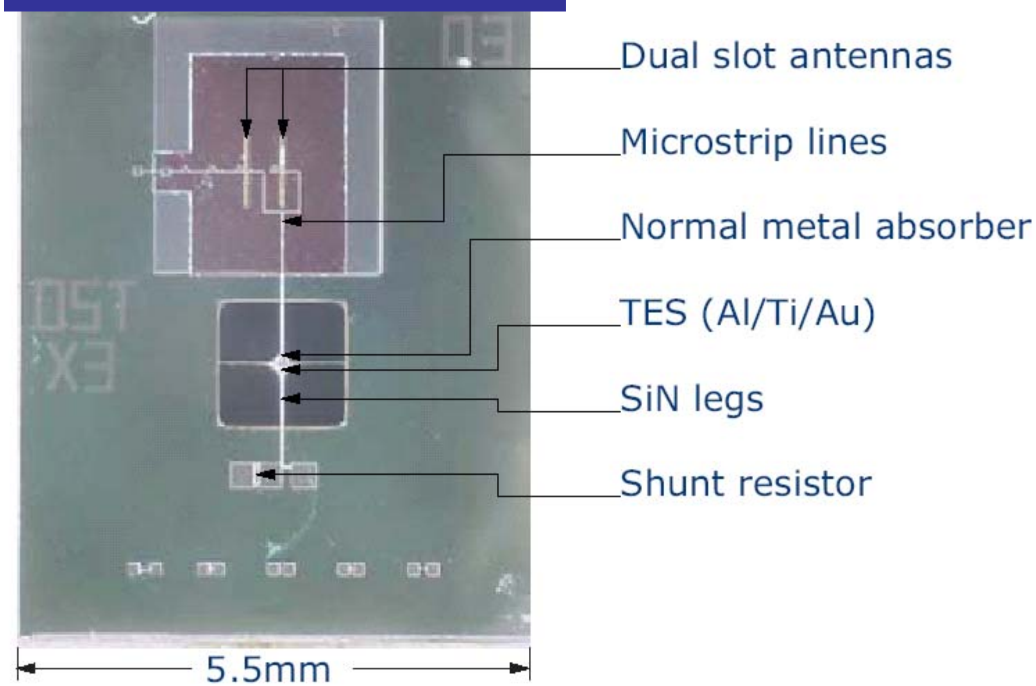


Antenna-Coupled Superconducting Bolometer

Antenna-Coupled Bolometers for CMB Polarimetry

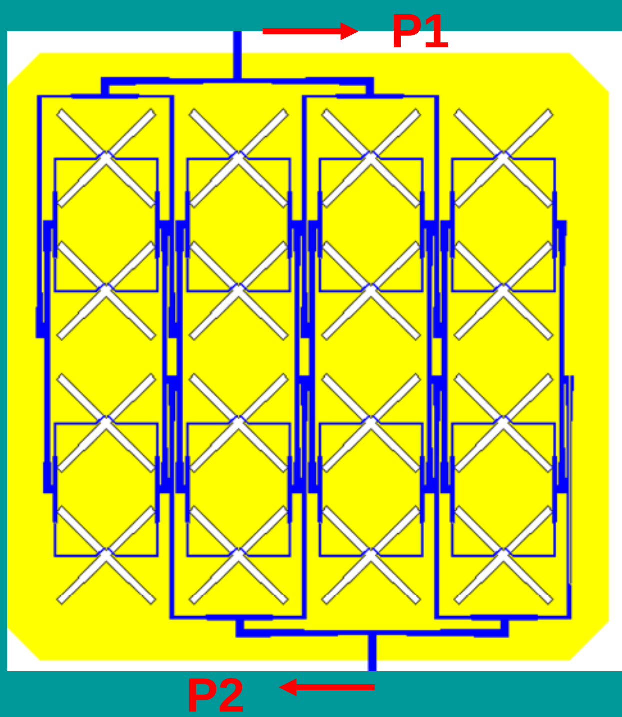
Challenges for mm-wave Arrays	Antenna-Coupled Bolometers
• Large formats	• TES readout + SQUID MUX
• Directed beams	• Antennae define beams
• Massive focal planes	• Antennae eliminate feedhorns
• Large pixels	• Large antennae, small active volume
• Straylight and filtering	• Integrated filters & phase switches

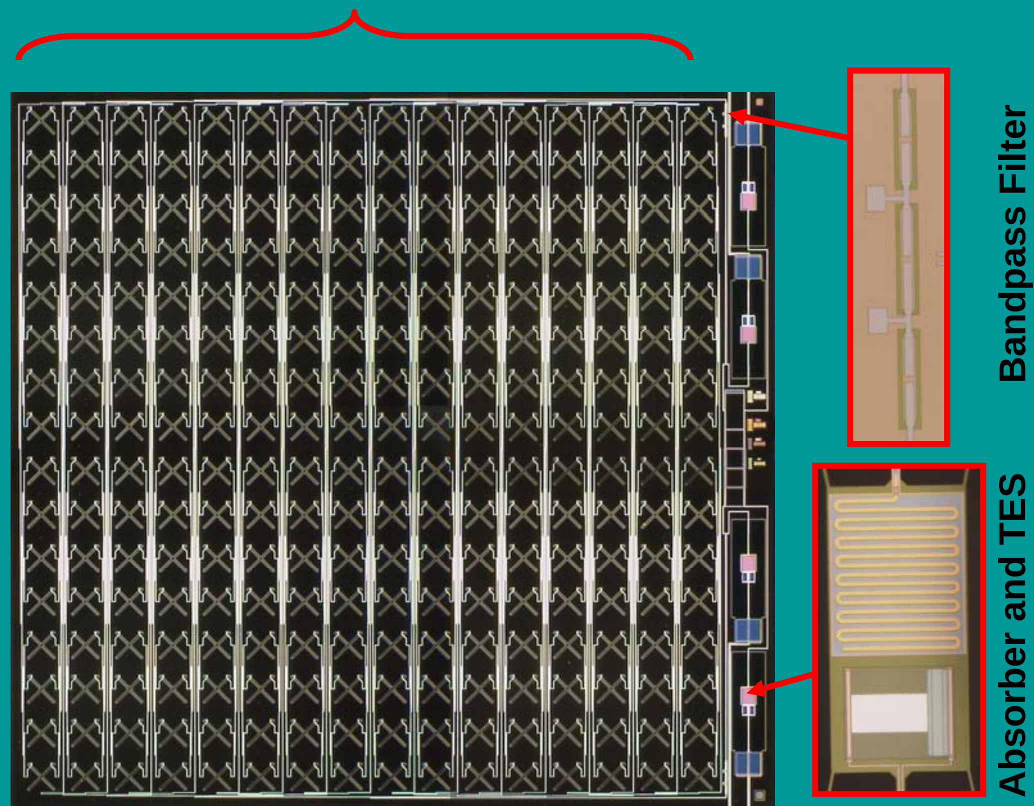
Dual-slot TES bolometer

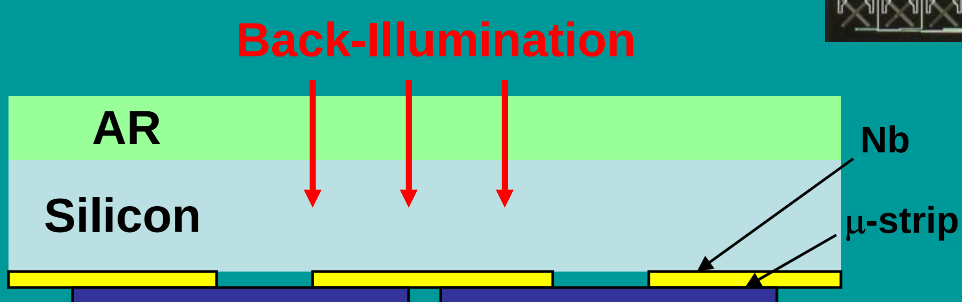


Antenna-Coupled 'Polarimeter On a Chip'

Dual Polarization, Single Band





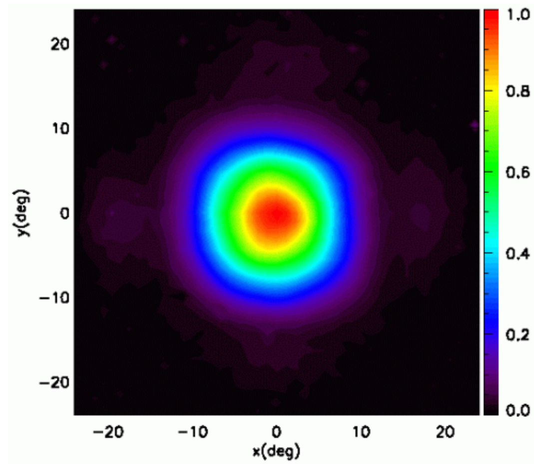


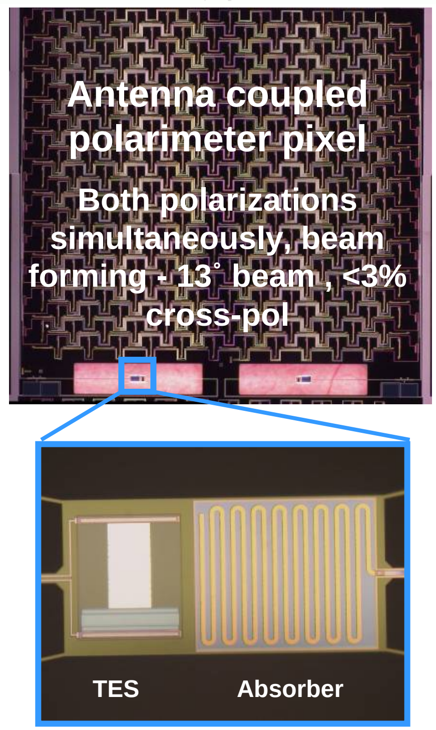
7X
R&TD HiLite
Rick Leduc
Jamie Bock

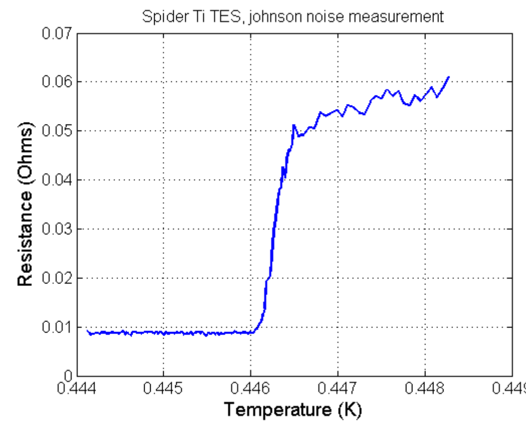
Antenna Coupled TES

Recent Progress

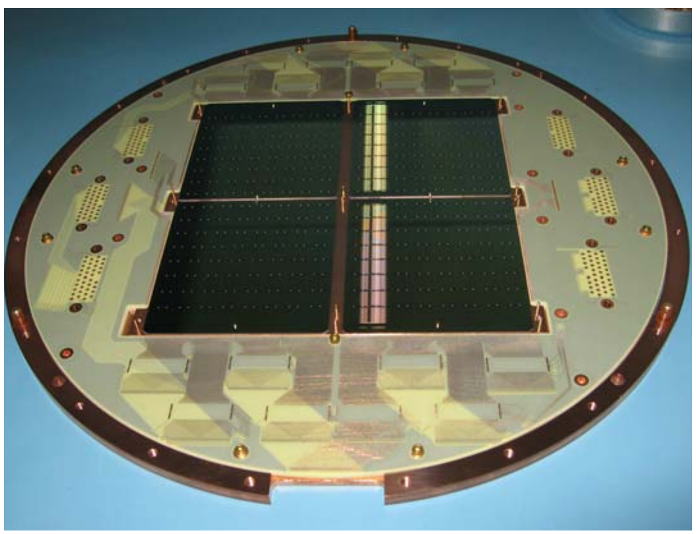
- Measured Al TES performance
- Measured 1/f knee to 40 mHz
- Measured high QE (~60 %)
- Measured matched beam shapes
- Arrays fabricated for BICEP2



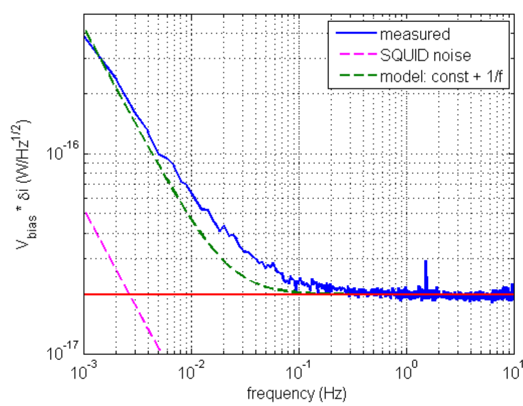




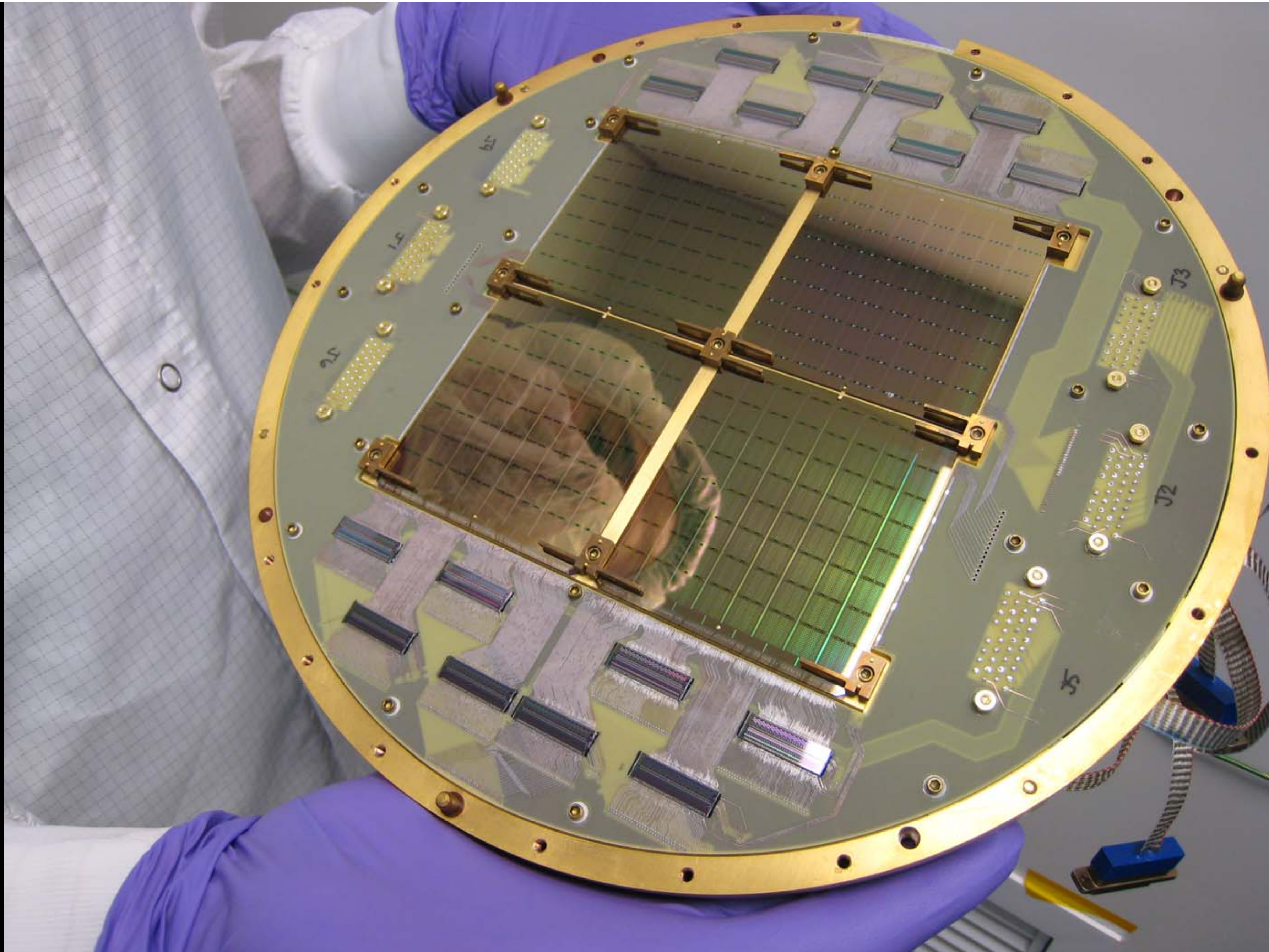
TES transition curve measured using Johnson noise. T_c~446mK, α~1500



BICEP2 Engineering Focal Plane
512 Detectors

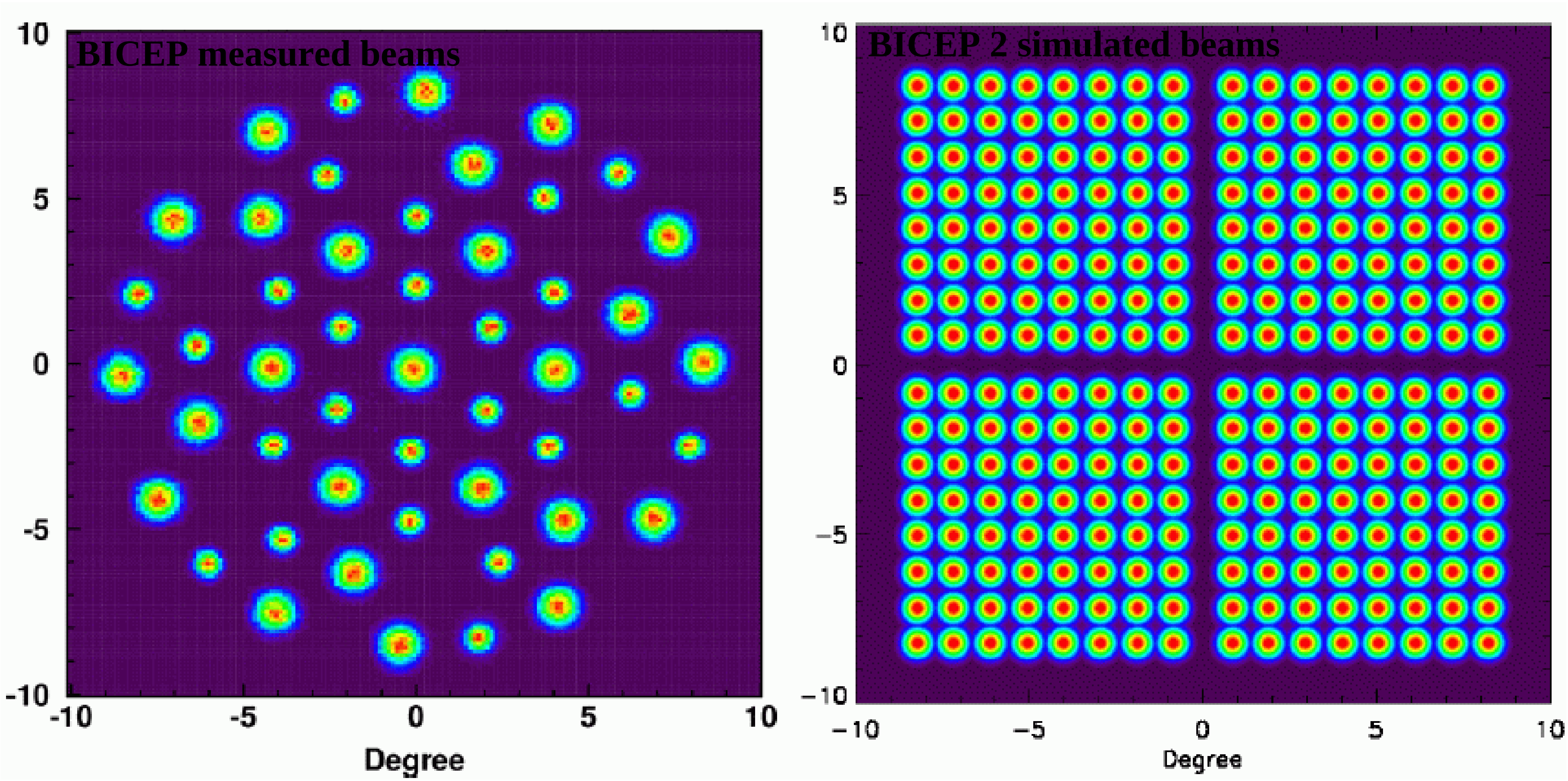


TES dark noise. NEP~$2x10^{-17}$ W $Hz^{-1/2}$, 1/f noise knee ~40mHz



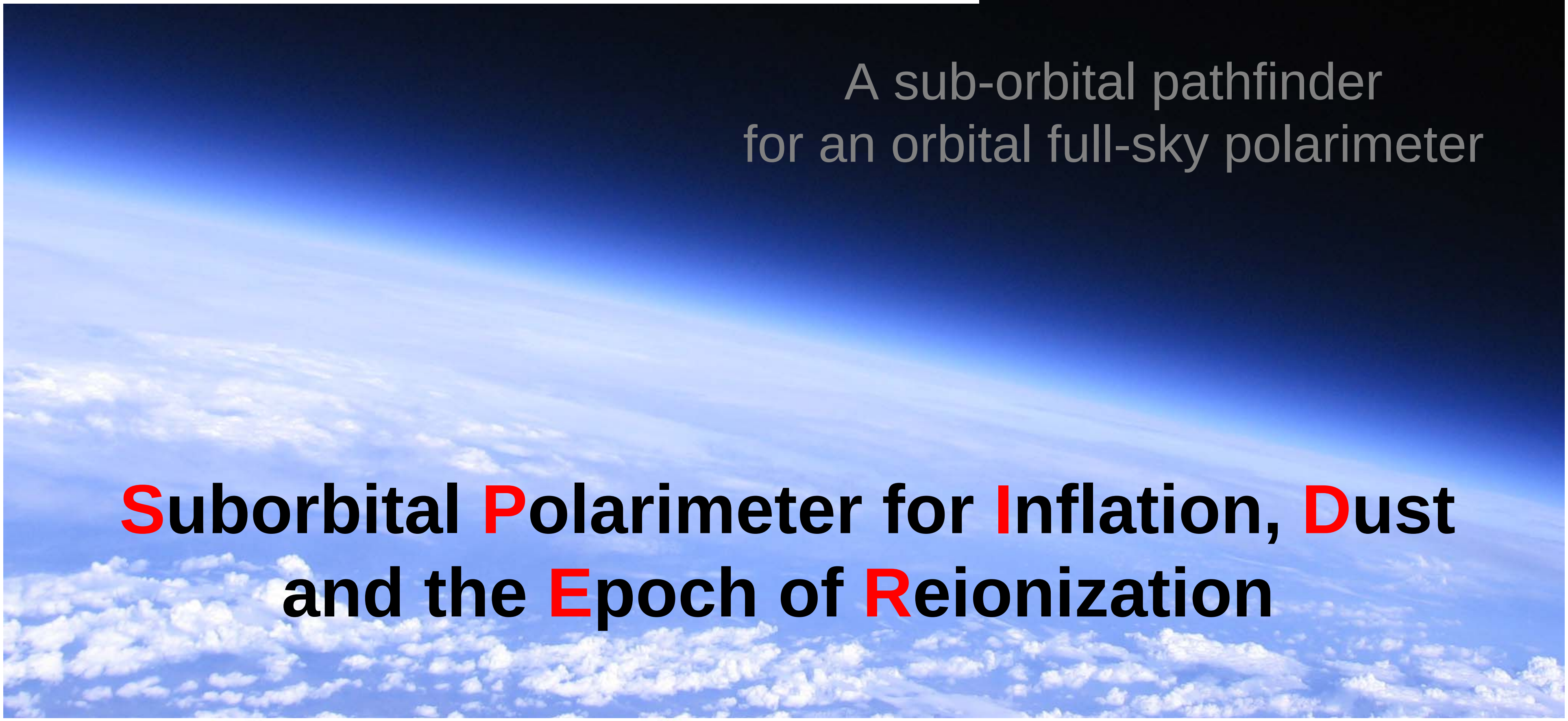
BICEP2 focal plane, May 2008

Getting more pixels on the sky …



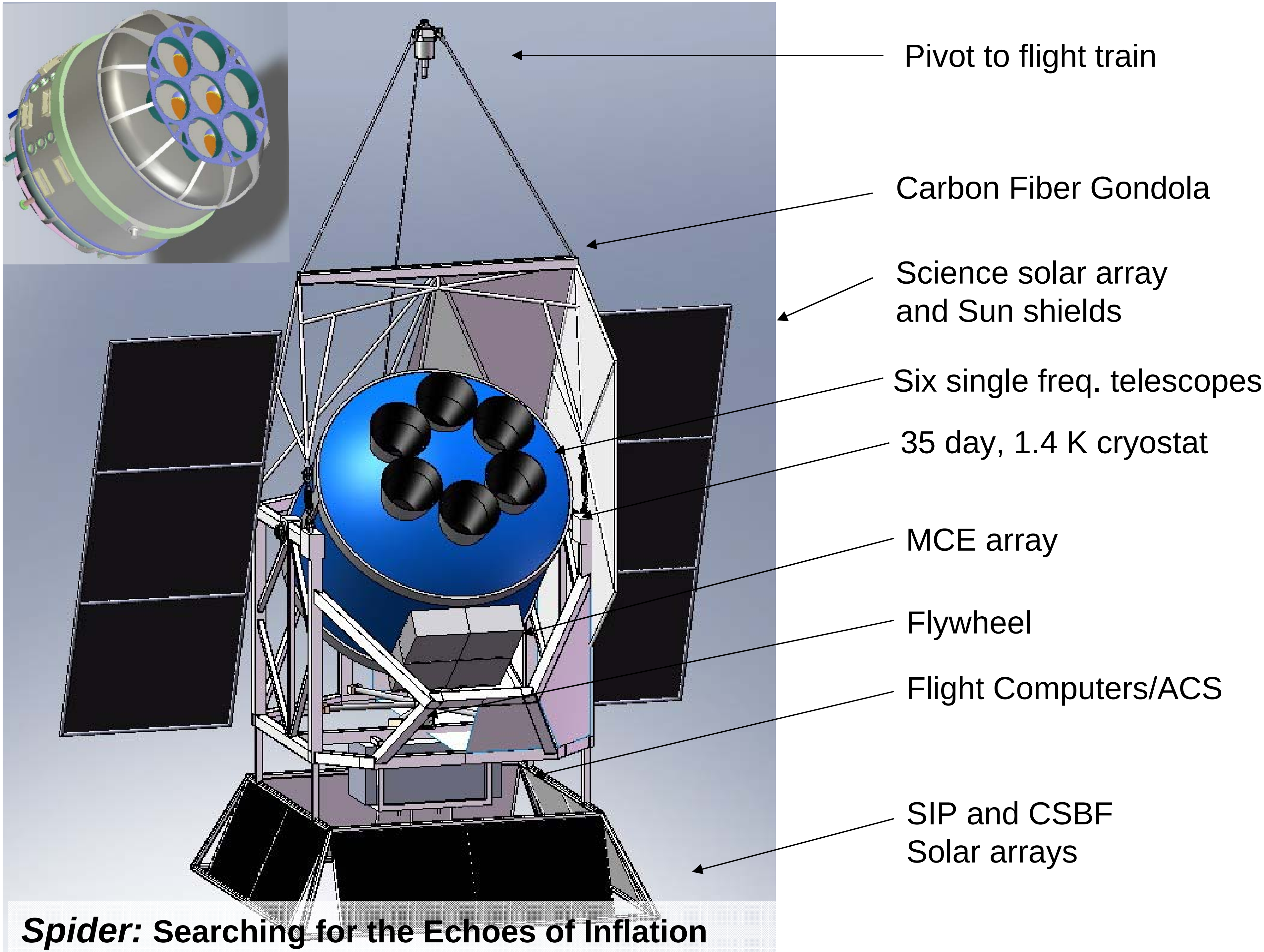
2008 SPIDER

SEARCHING FOR THE ECHOES OF INFLATION



A sub-orbital pathfinder
for an orbital full-sky polarimeter

Suborbital Polarimeter for Inflation, Dust and the Epoch of Reionization

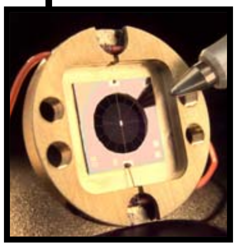


Spider: **Searching for the Echoes of Inflation**

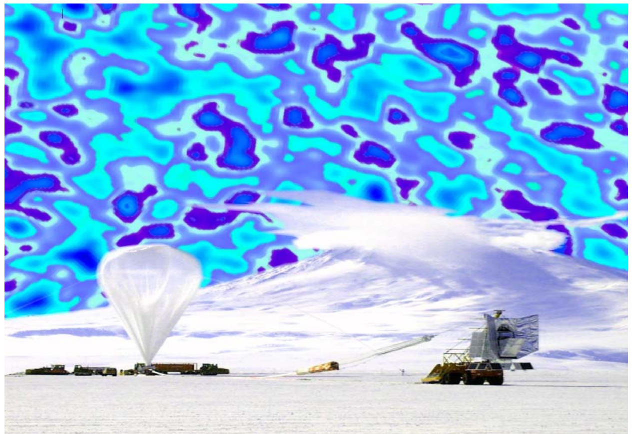
Detector and Focal Plane Sensitivities

	Single Detector NET	Focal Plane NET
Bicep	450	70
Bicep2 (150)	450	25
Spider 225	315	10
Spider 150	120	4
Spider 96	105	5
HFI 353P	290	102
HFI 217P	82	29
HFI 143P	47	17
HFI 100P	53	19

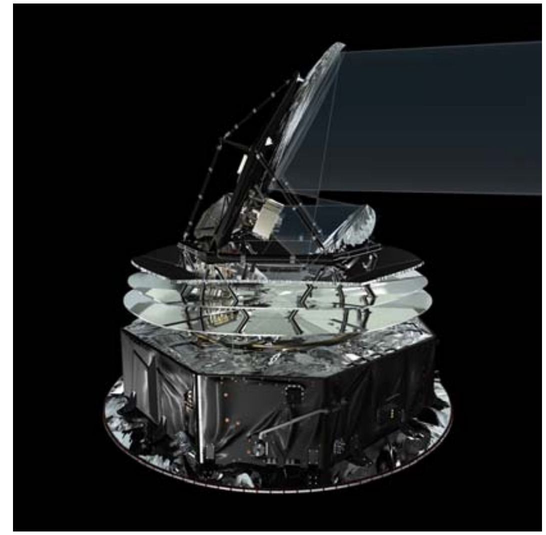
Spider web Bolometer



1995

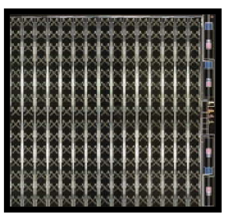


BOOMERanG 1998 (2000)



Plank 2008 (2012)

Antenna-coupled TES



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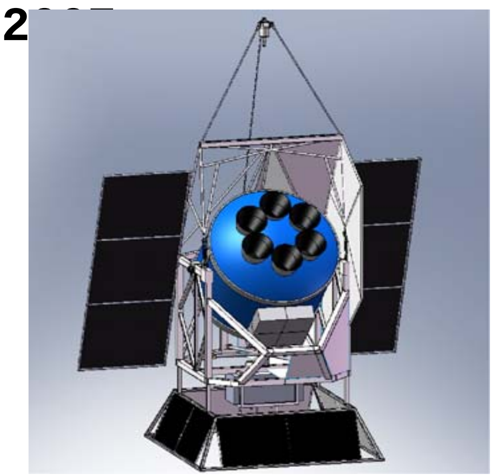
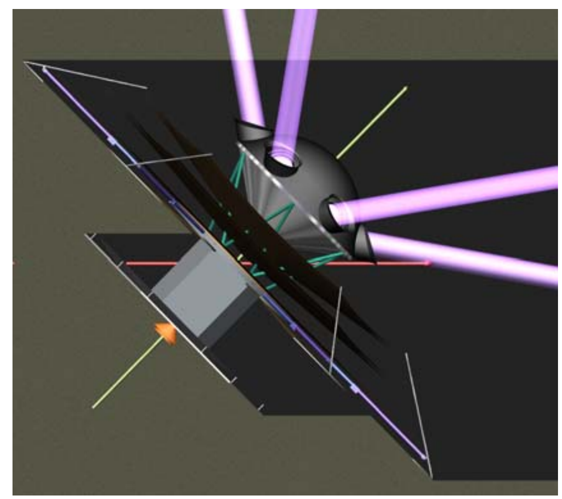


SPIDER 2010 (2012)



EPIC 2020 (2024)

Conclusions (taken from an ancient talk)

- **We need to sustain existing efforts (~ $5M/yr)**
  - **A necessary and sufficient condition!**
  - Antenna-coupled bolometers: **GSFC / JPL / NIST / UCB**
  - MMIC HEMTs: **JPL**

- **We need to deploy these detectors in real receivers and learn how to observe with them (currently several x $10M/yr)**
  - Modulators (on-chip, Faraday, waveplate)
  - Optics (cold refractors, warm mirrors, filters, feeds)
  - scan strategies
  - systems engineering (RFI, microphonics, B-fields…)