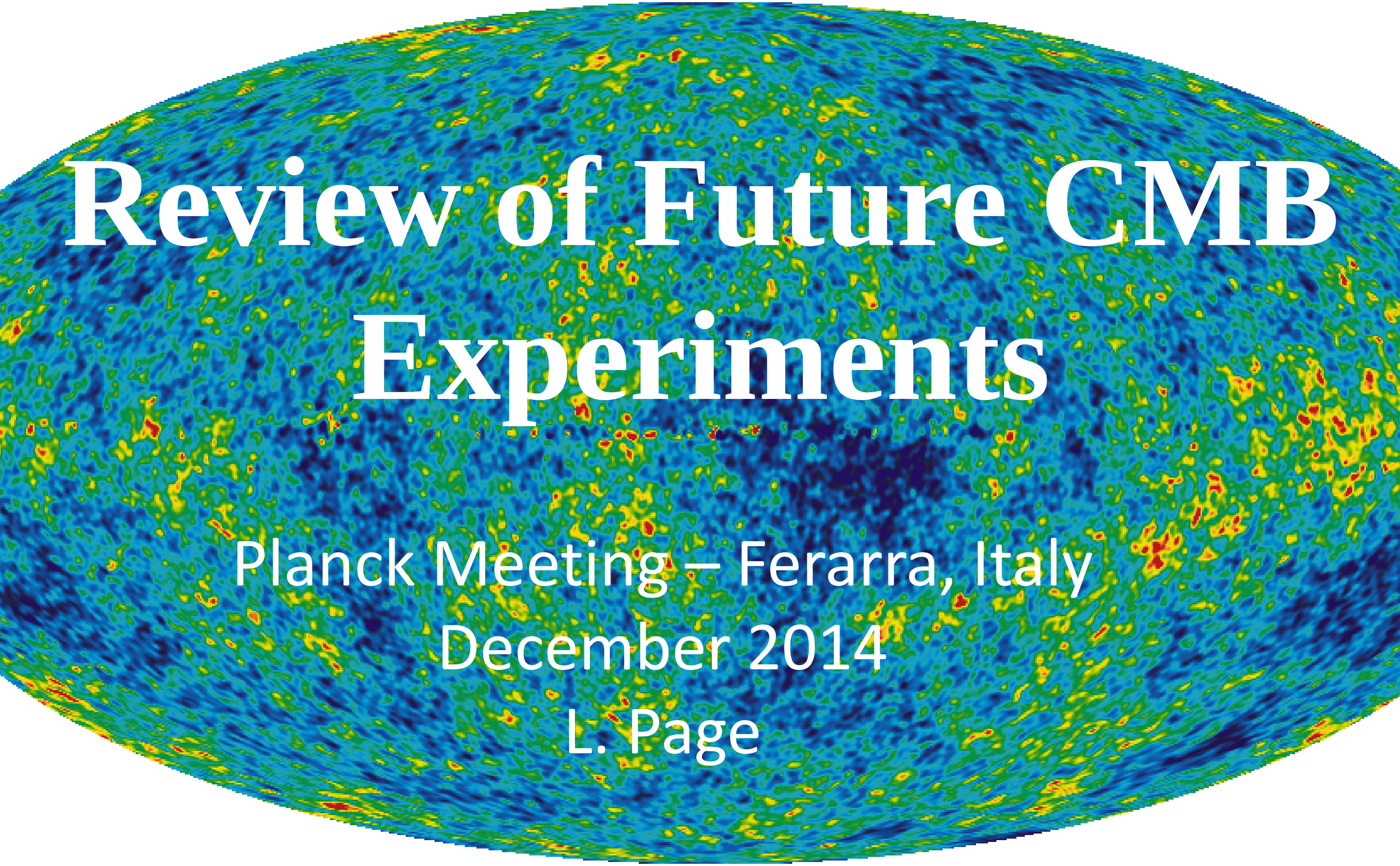
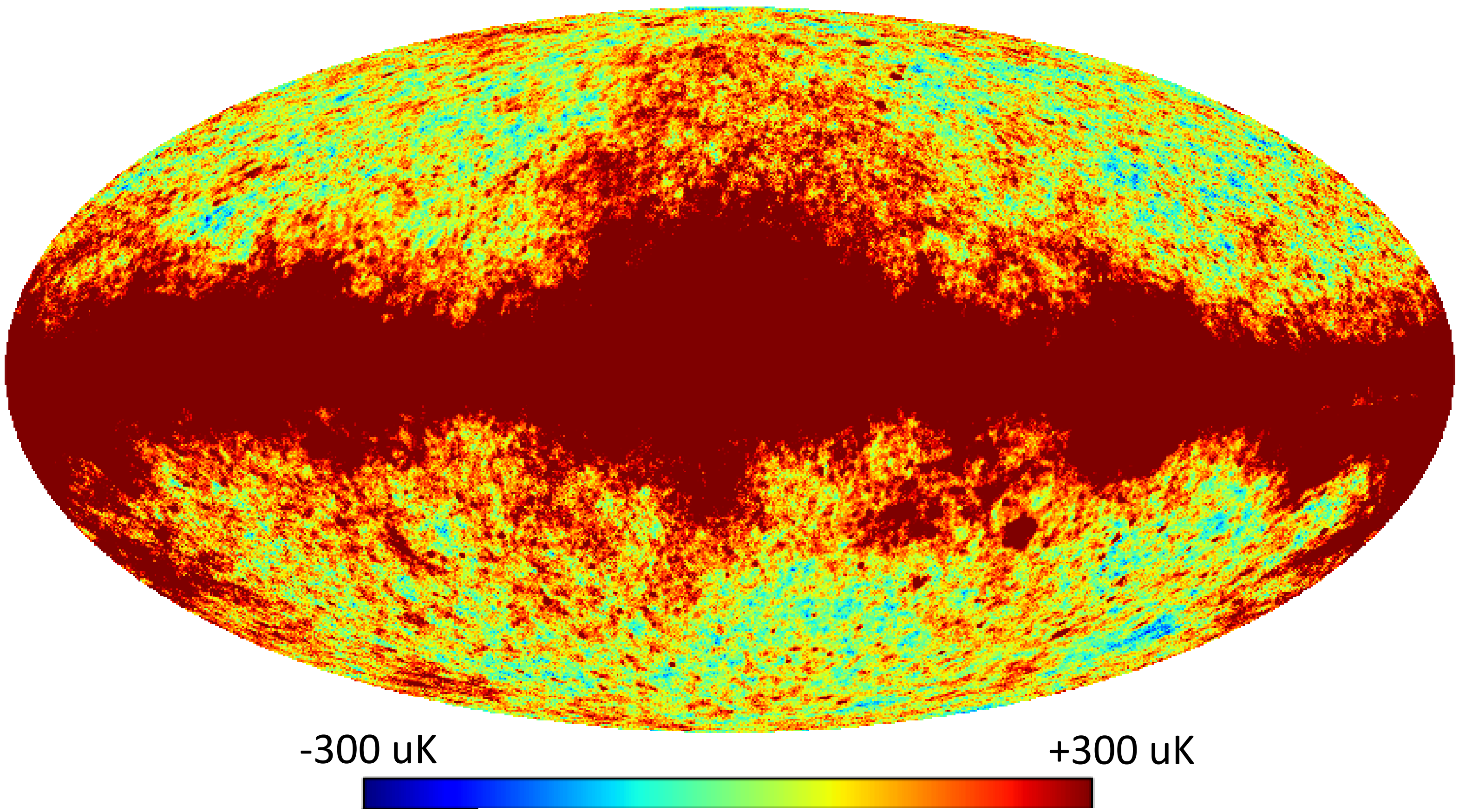


Review of Future CMB Experiments

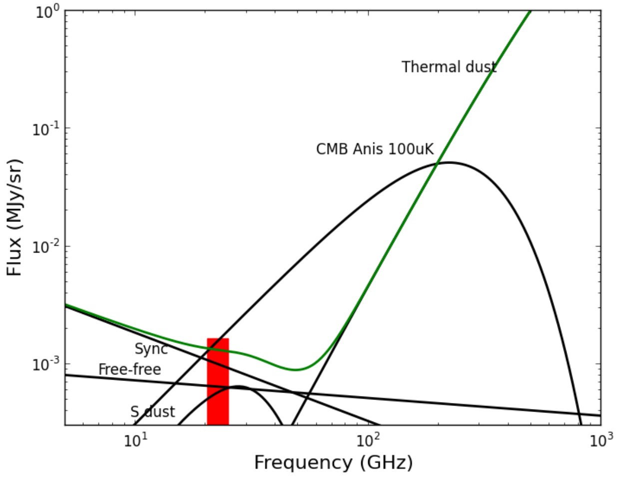
Planck Meeting – Ferarra, Italy
December 2014

L. Page

K band res9

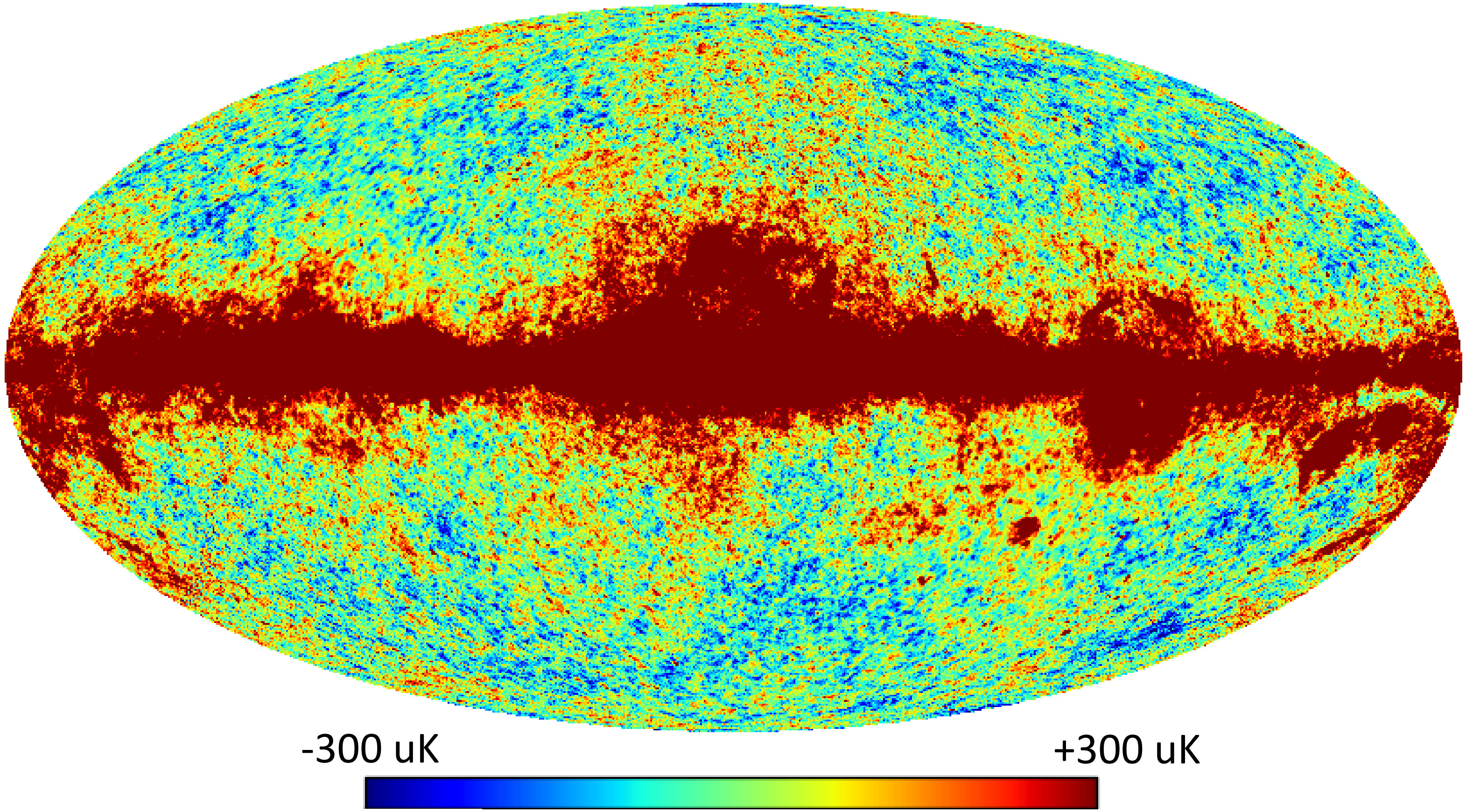


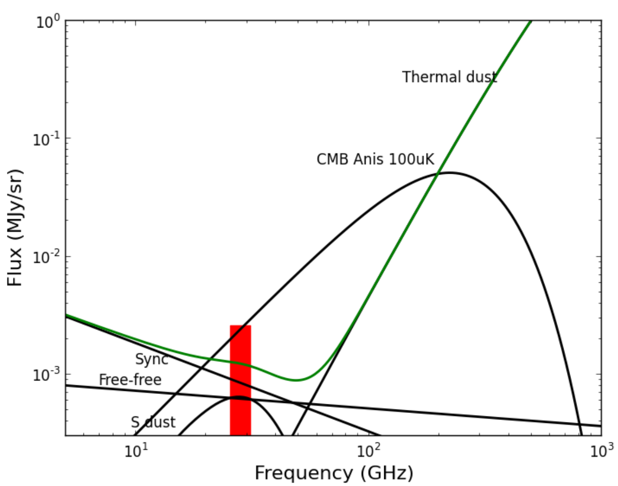
-300 uK
+300 uK

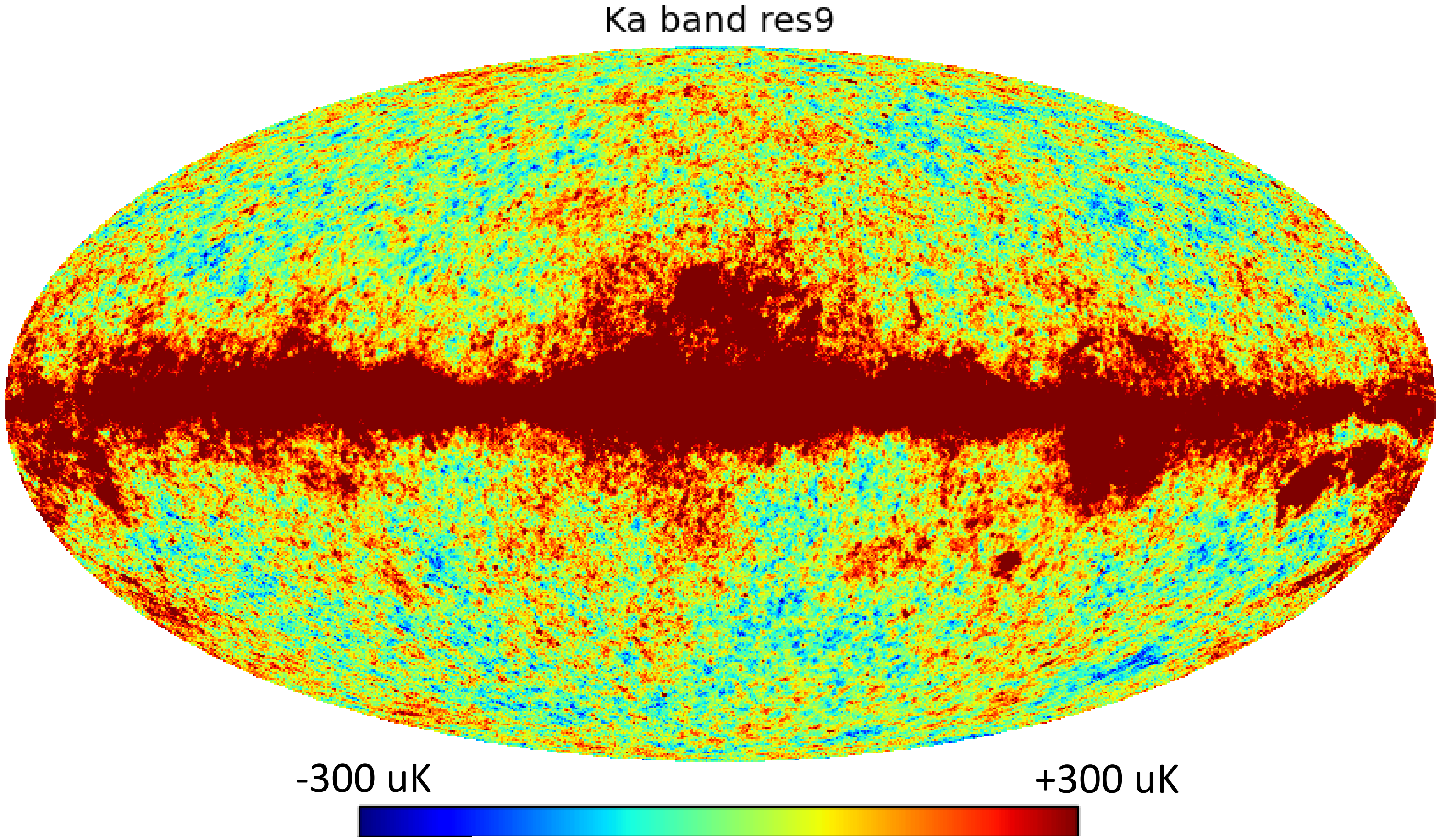


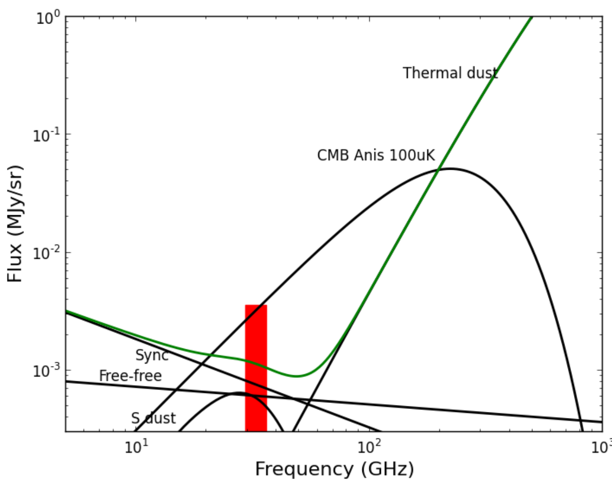
Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

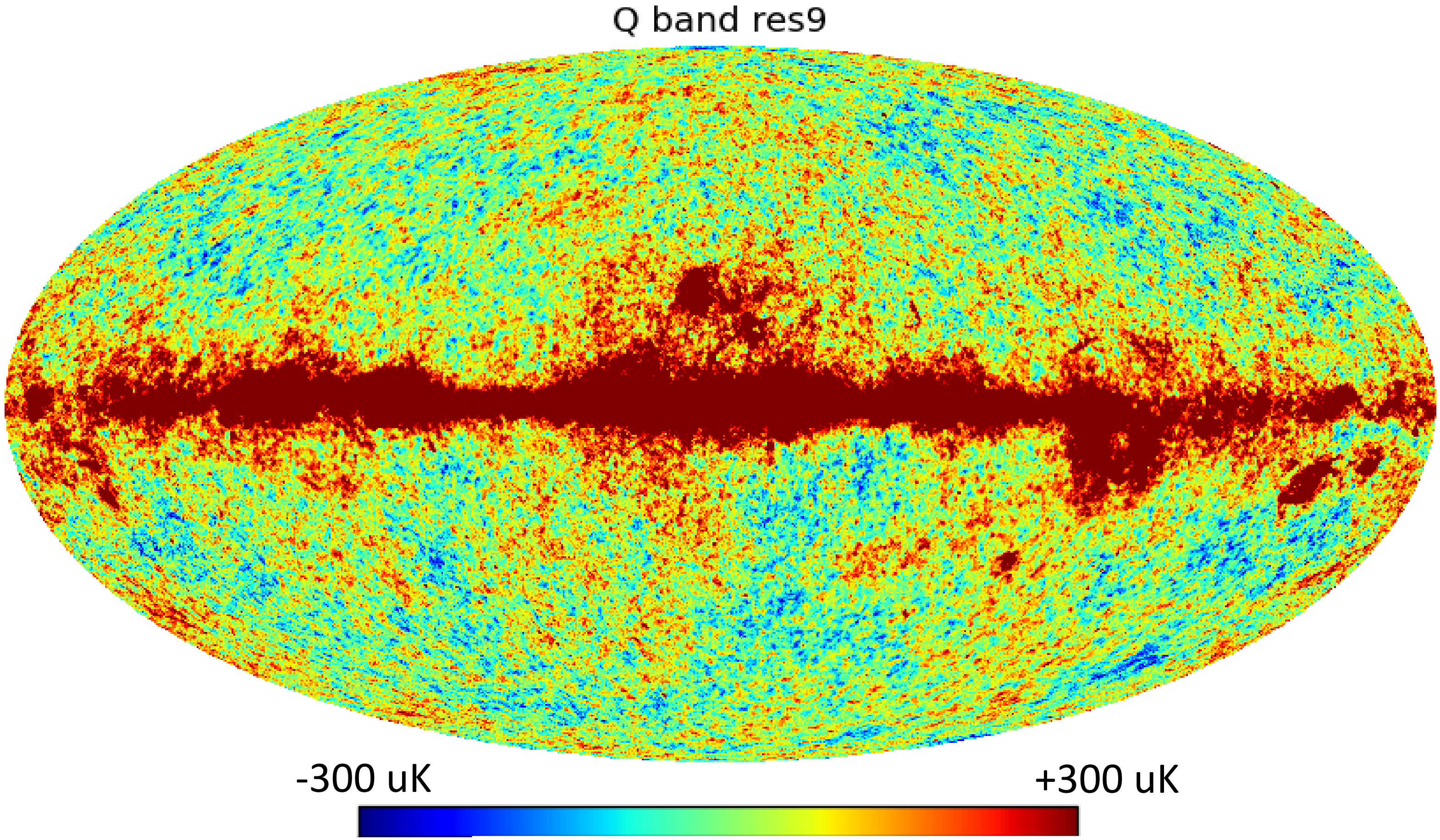
Planck 30 res9

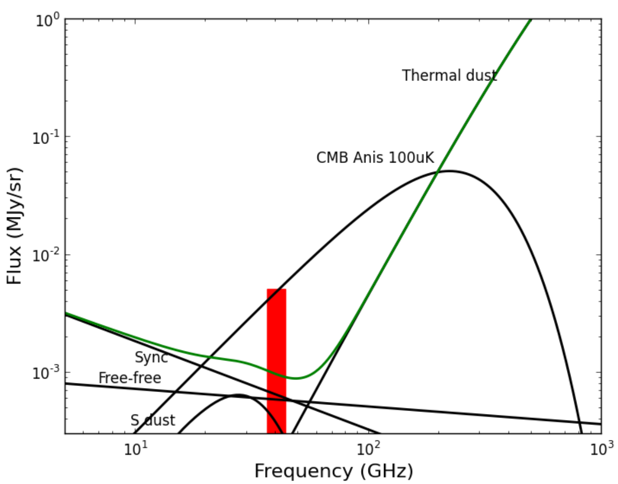




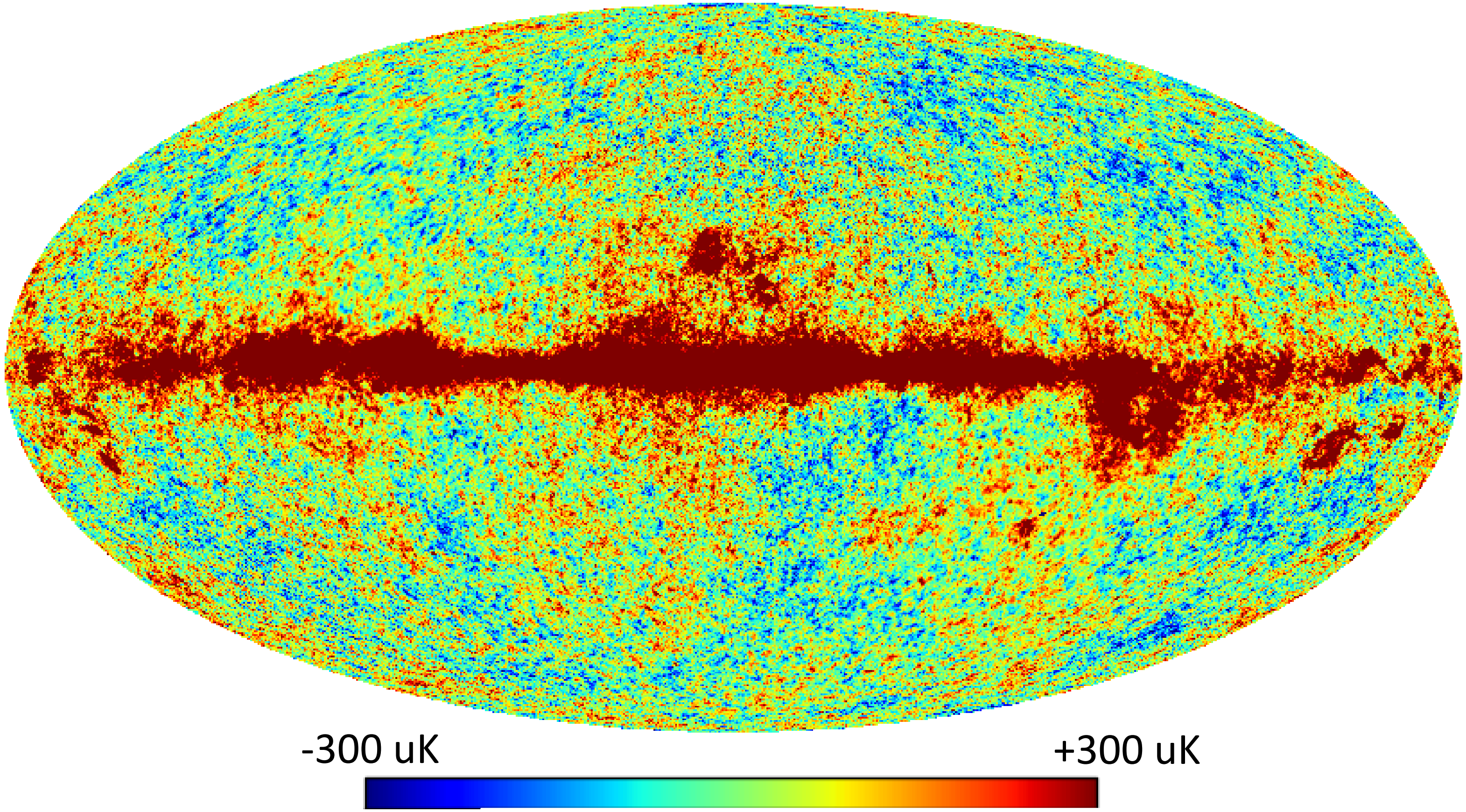

Ka band res9
-300 uK
+300 uK

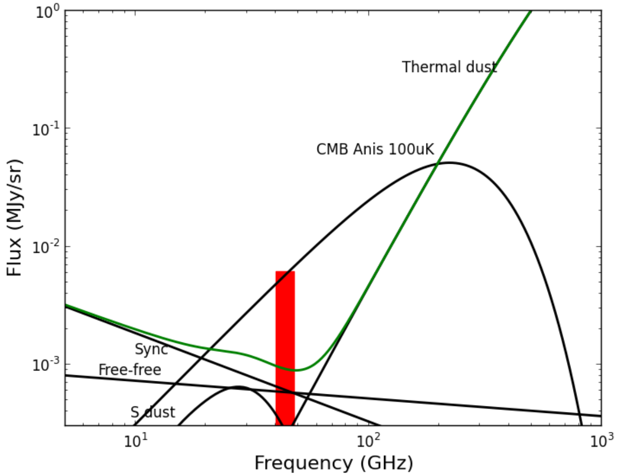

Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)


Q band res9
-300 uK
+300 uK

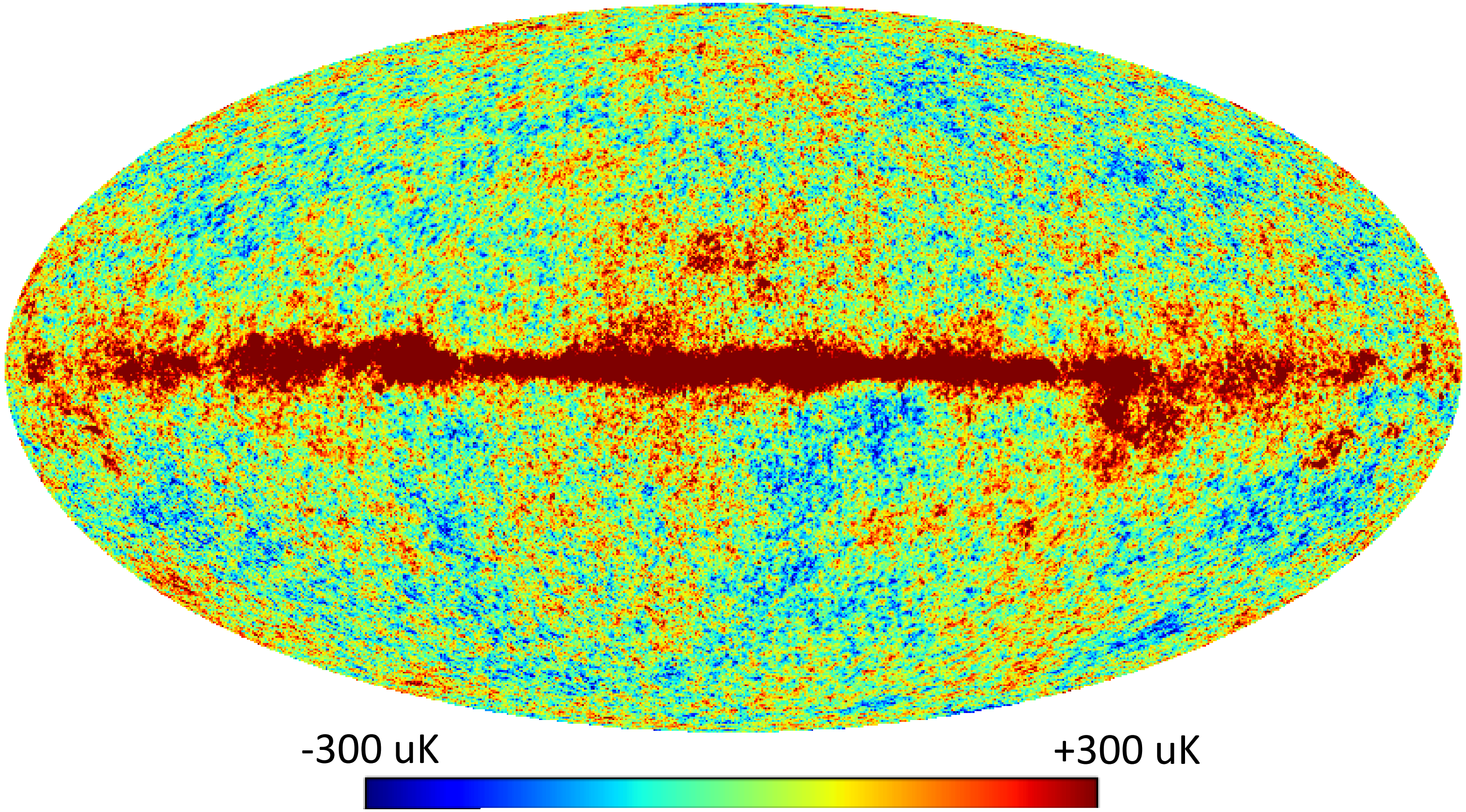

Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3

Planck 44 res9

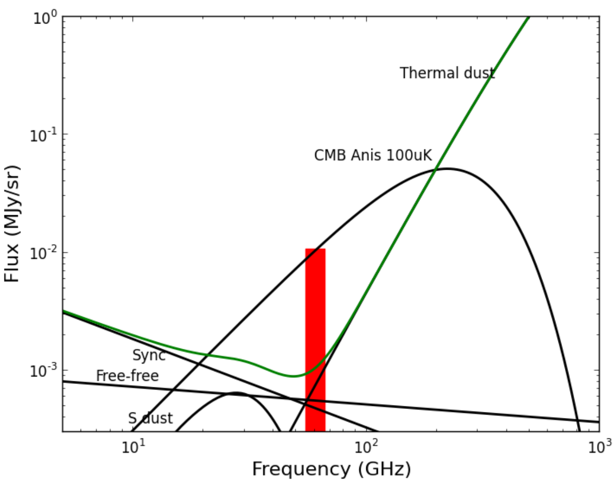




V band res9 I

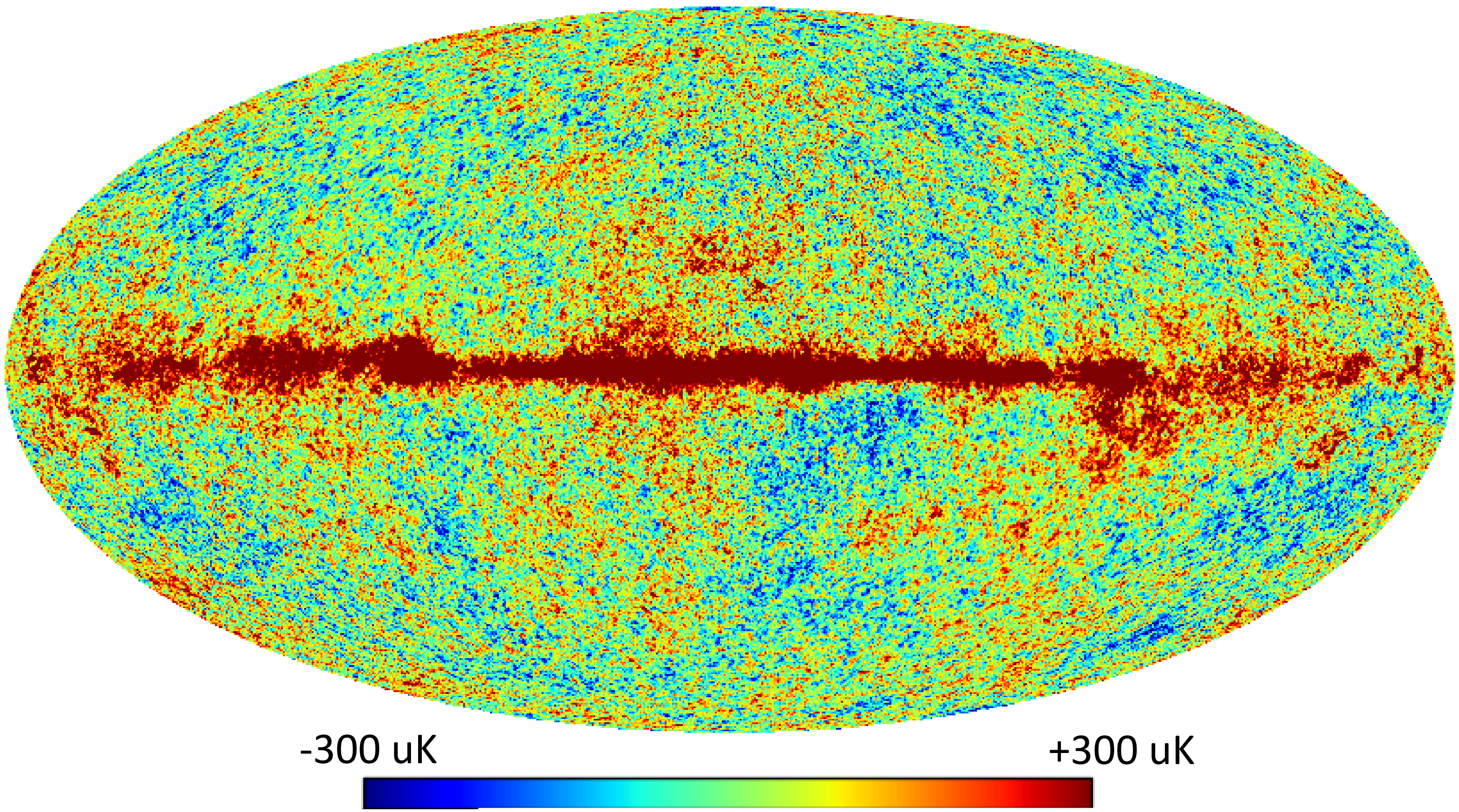


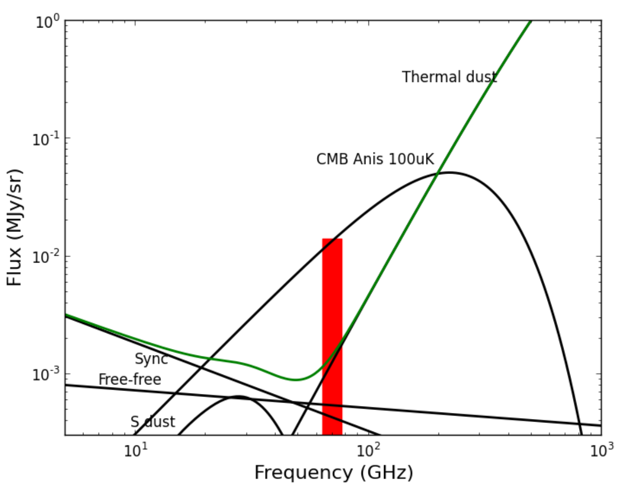
-300 uK
+300 uK



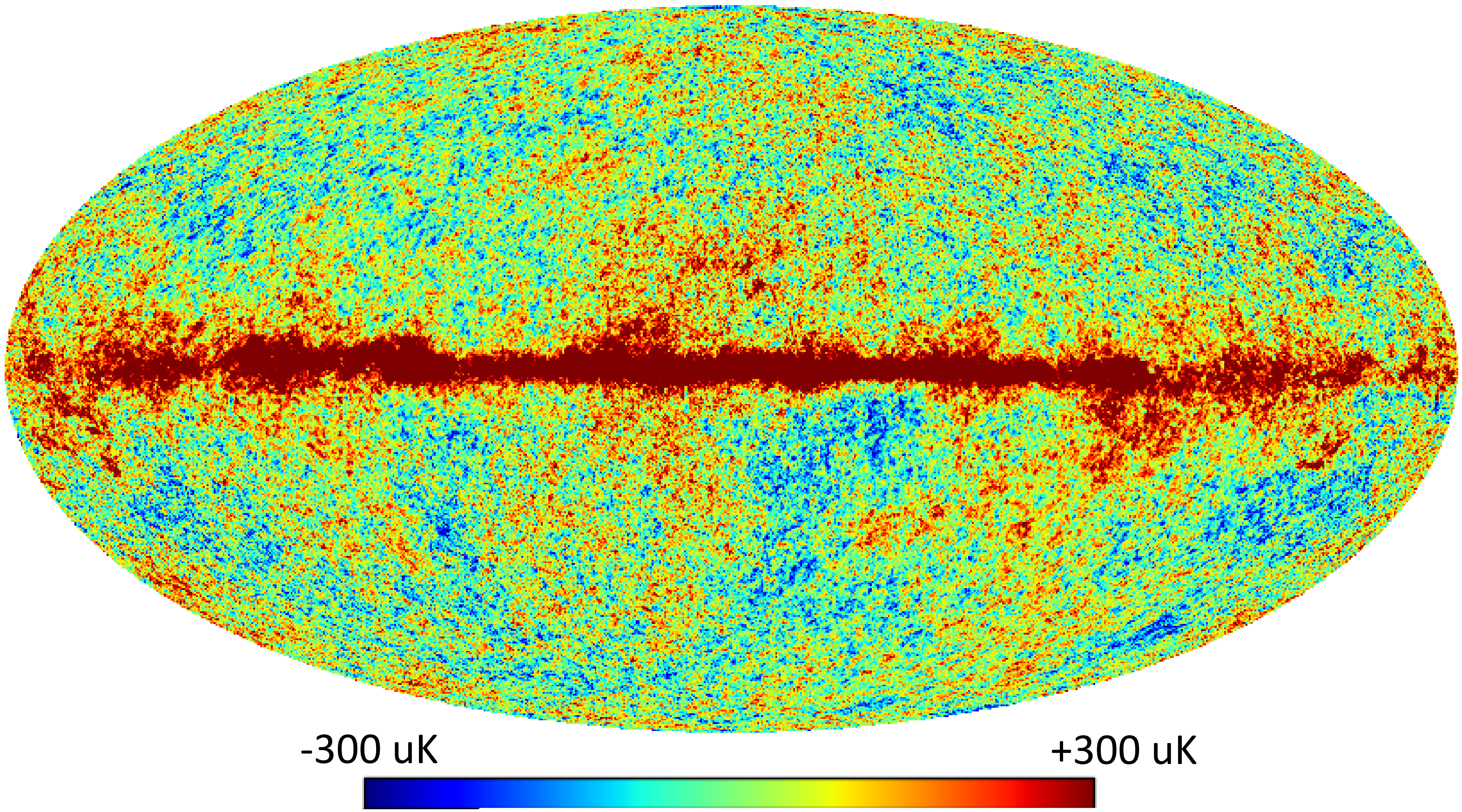
Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

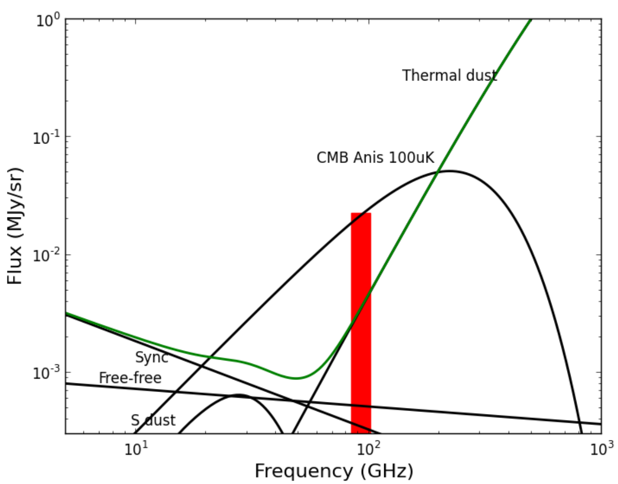
Planck 70 res9



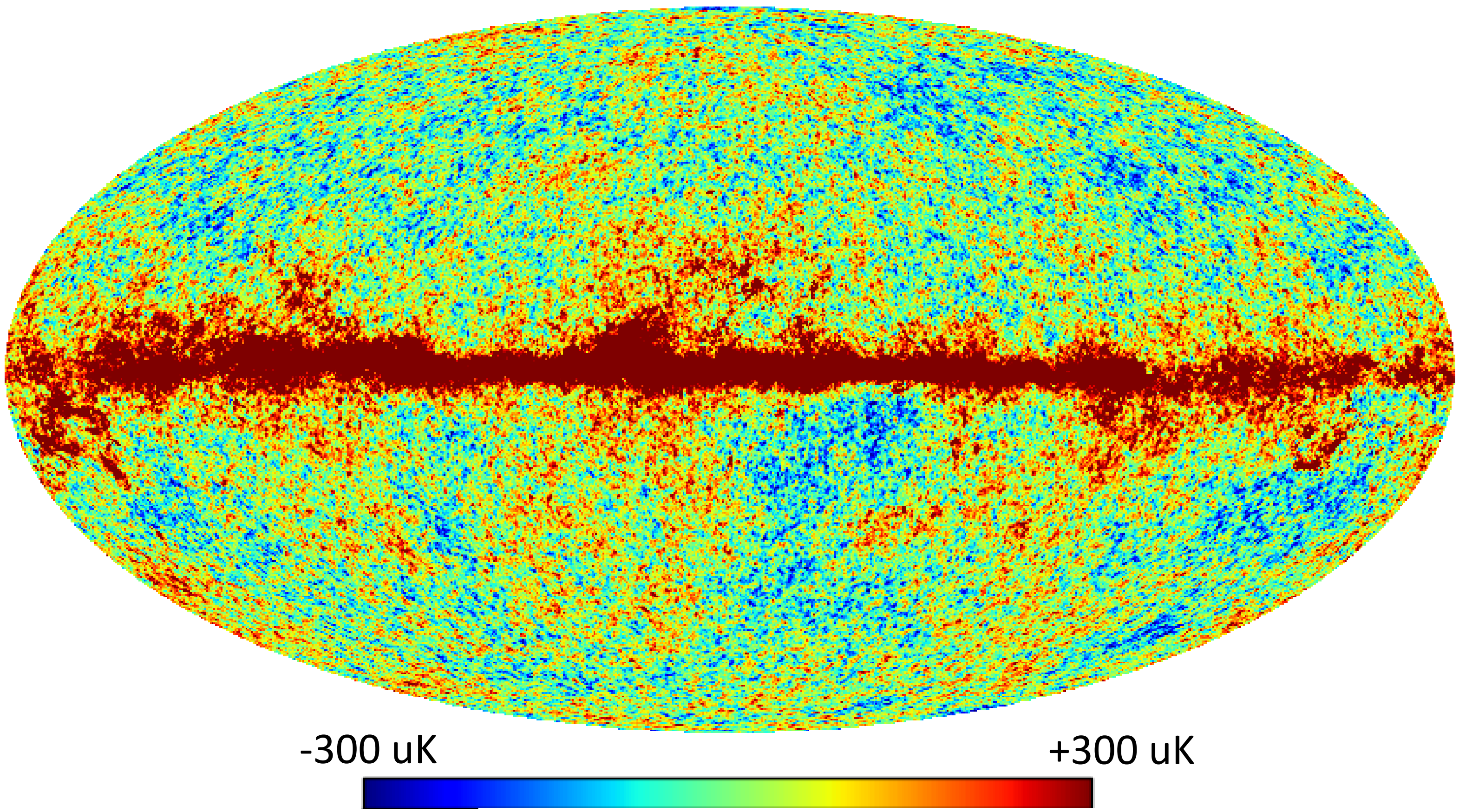


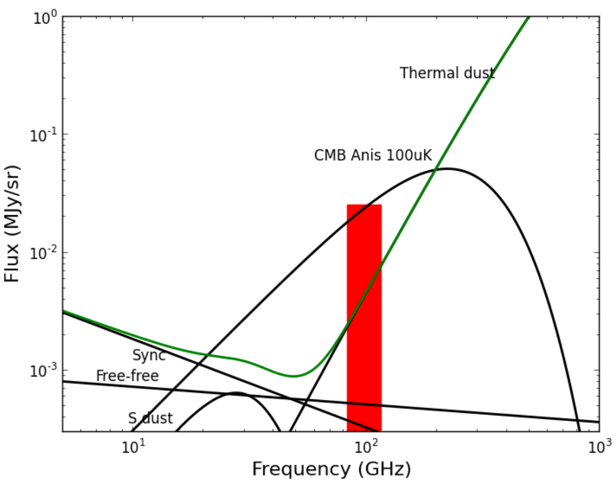
W band res9


-300 uK
+300 uK

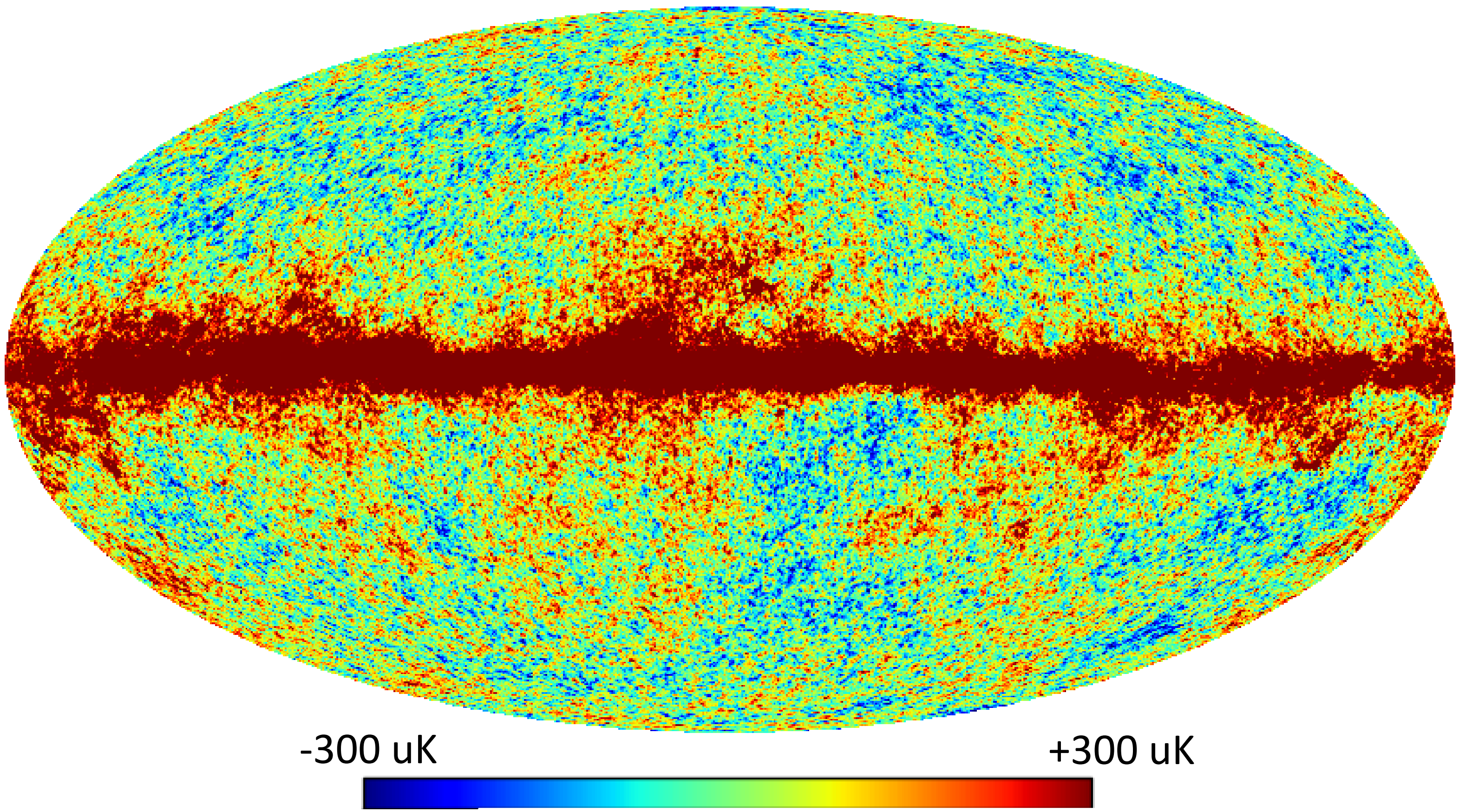

Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3

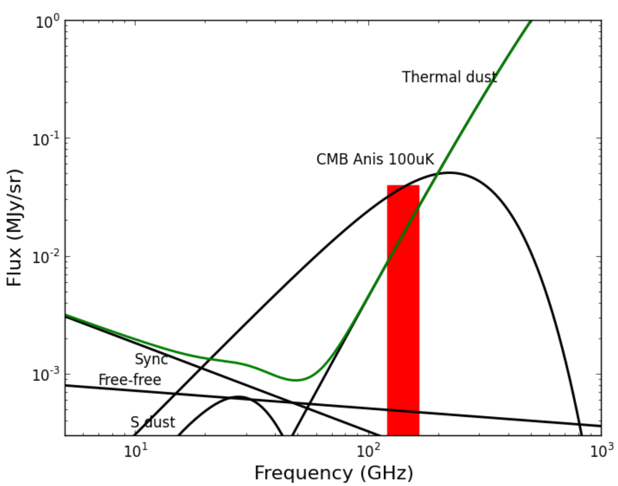
Planck 100 res9



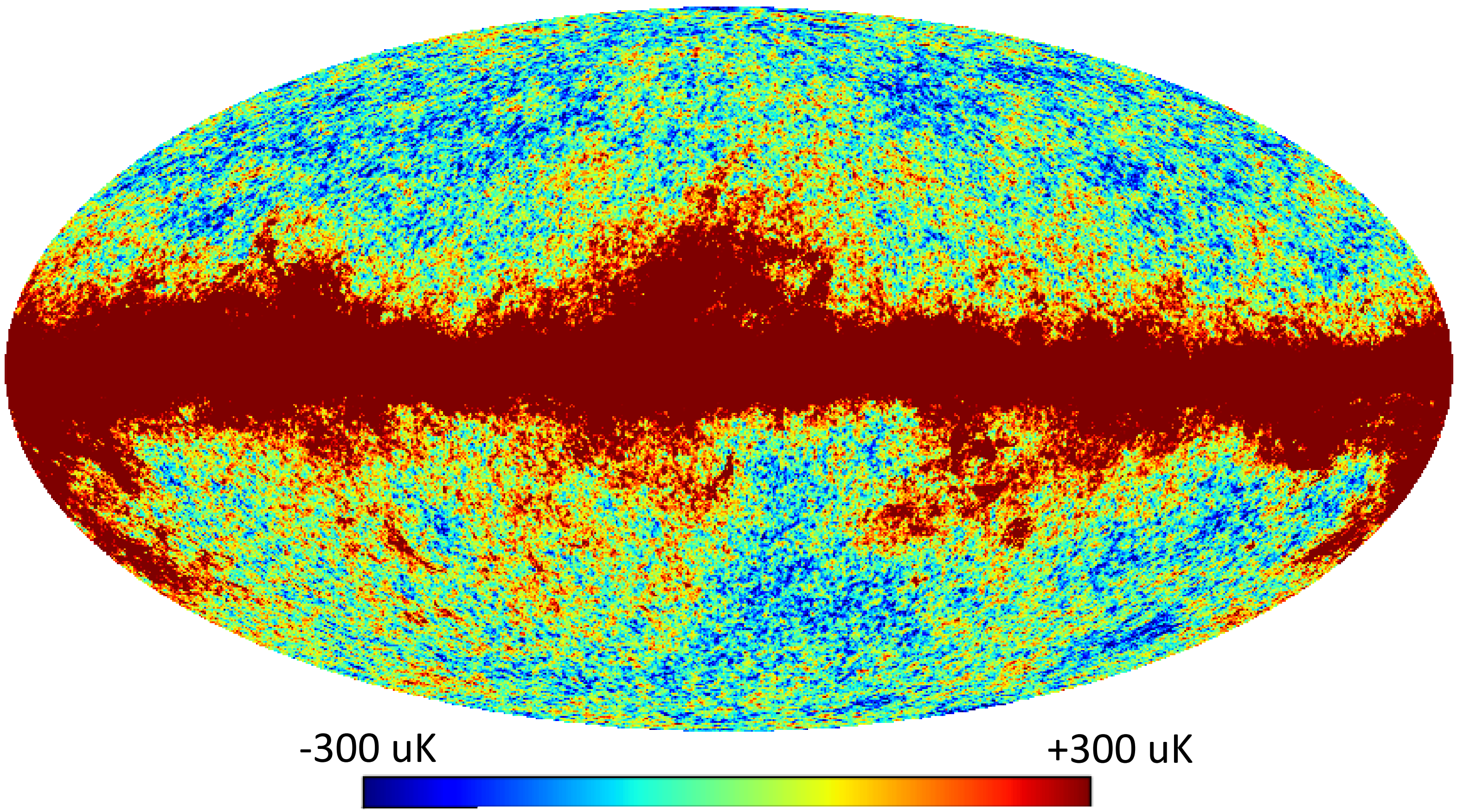


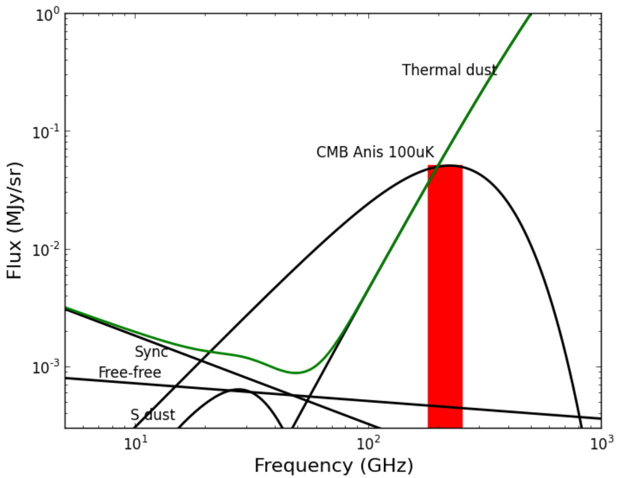
Planck 143 res9

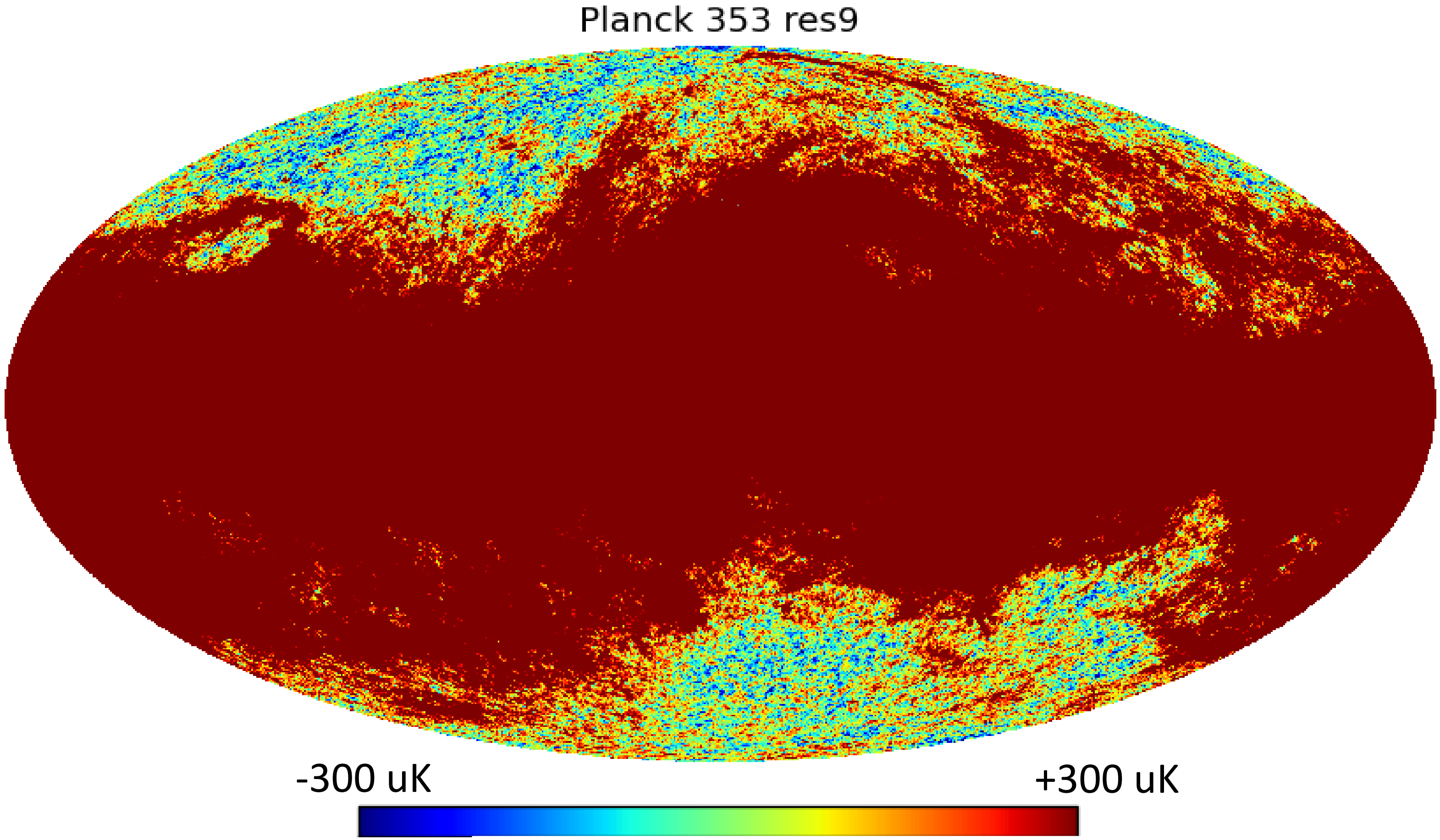


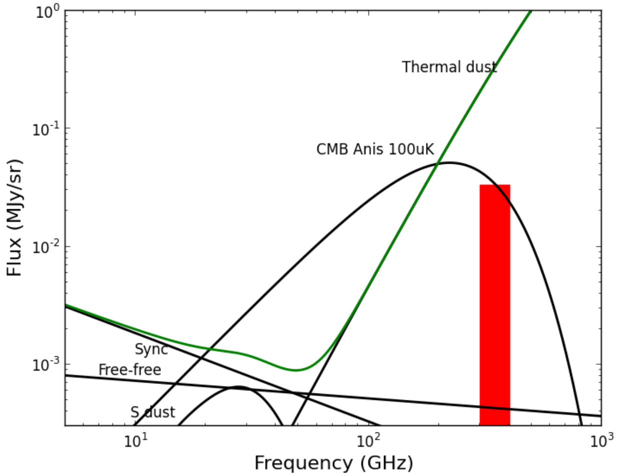


Planck 217 res9

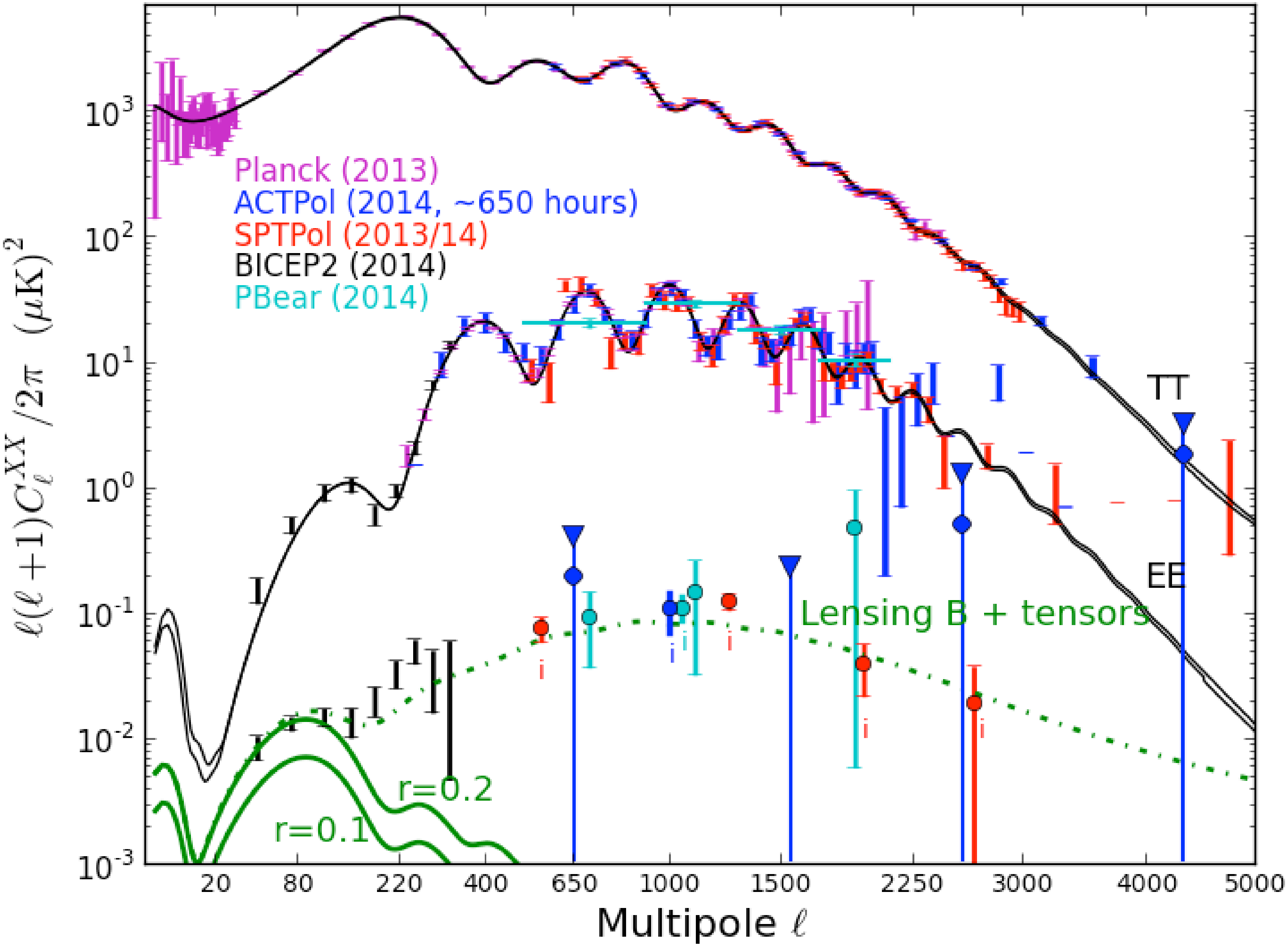


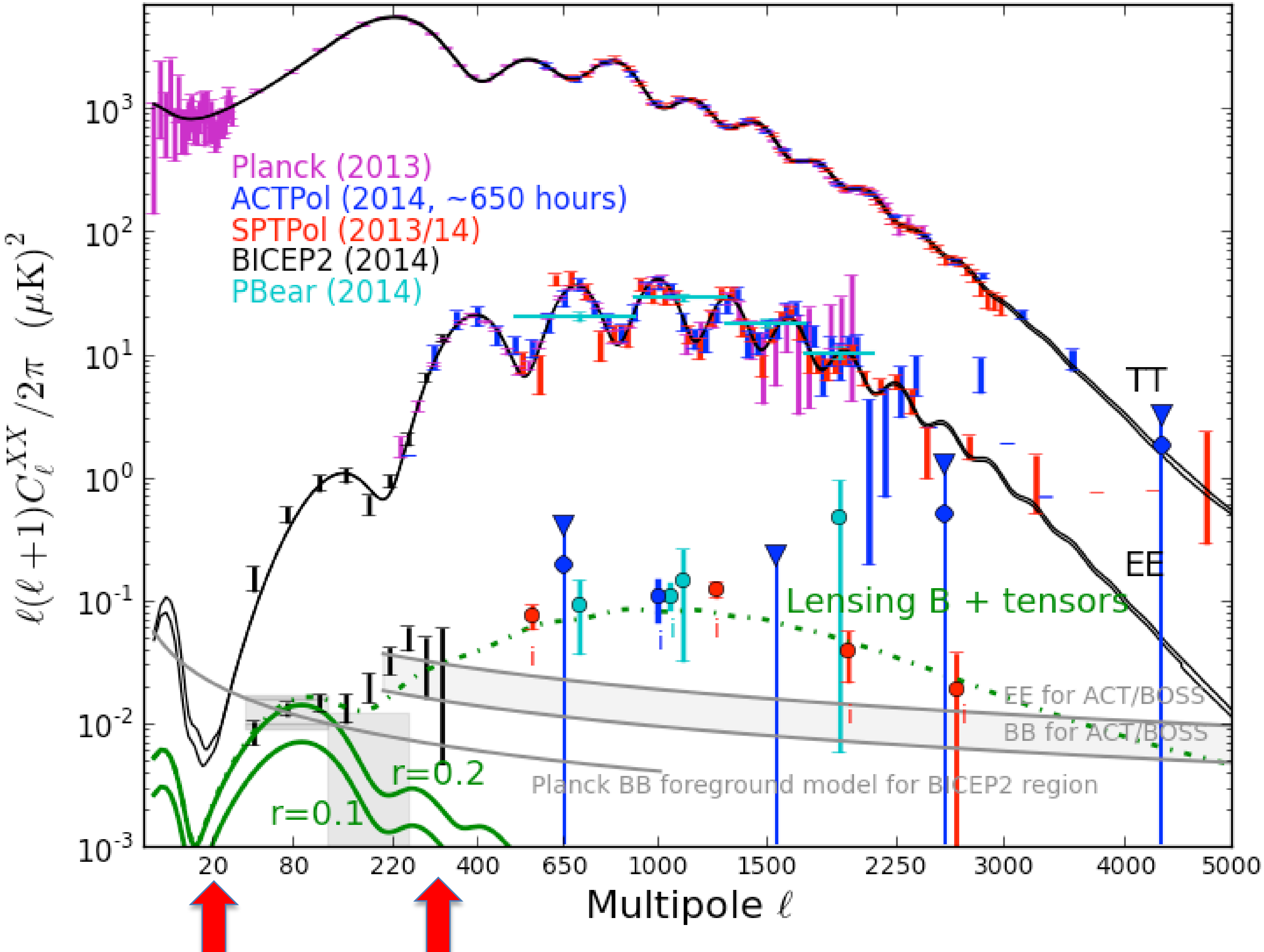



Planck 353 res9
-300 uK
+300 uK


Thermal dust
CMB Anis 100uK
Sync
Free-free
S dust
Flux (MJy/sr)
Frequency (GHz)

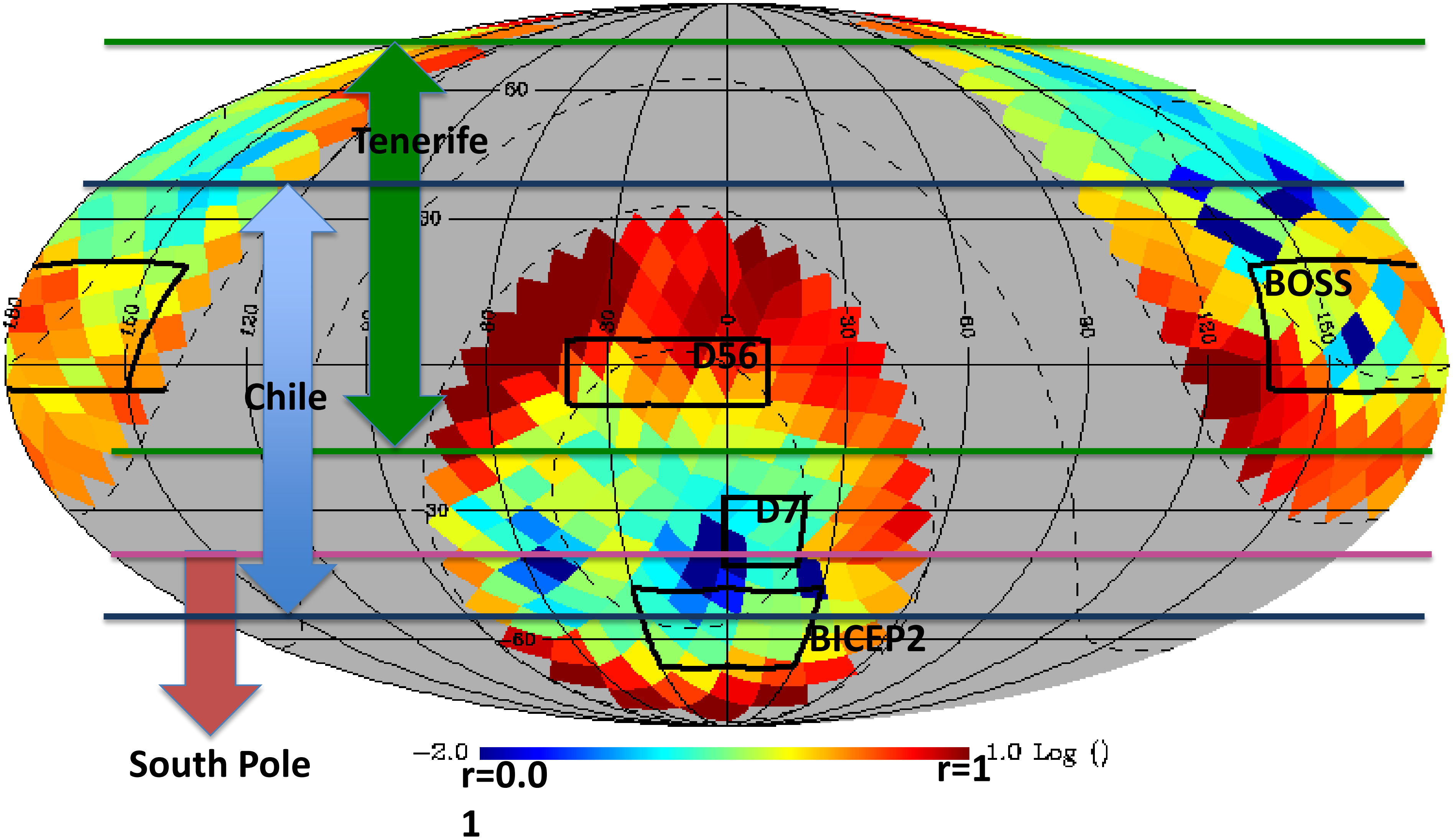
State of TT, EE, BB Nov 2014





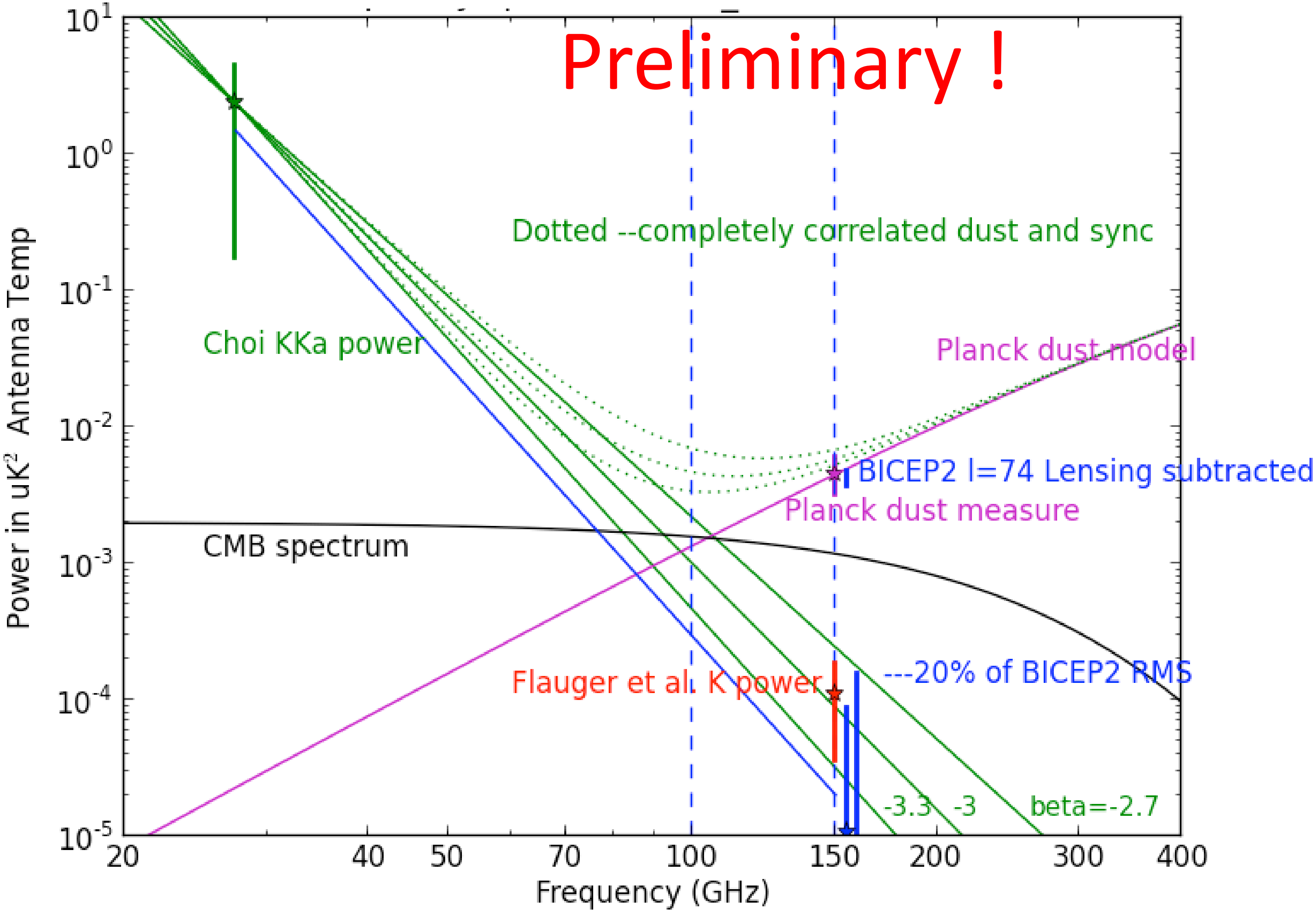
Planck (2013)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2 (2014)
PBear (2014)
TT
EE
Lensing B + tensors
EE for ACT/BOSS
BB for ACT/BOSS
Planck BB foreground model for BICEP2 region
r=0.2
r=0.1
$\ell(\ell+1)C_\ell^{XX}/2\pi\ \ (\mu K)^2$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
80
220
400
650
1000
1500
2250
3000
4000
5000
Multipole ℓ

Planck guide to low dust polarization level in effective r



Foregrounds at l=80 in BICEP2 region

Work in progress with Steve Choi and Ana Pop



“Sure bets” from the ground and balloons with experiments in progress

$r<0.01$ (or detection) $l<200$

Sum of neutrino masses to 0.06 eV $200<l<4000$

New tests of GR and the standard model through multiple cross correlations and the growth of structure. X-Corr

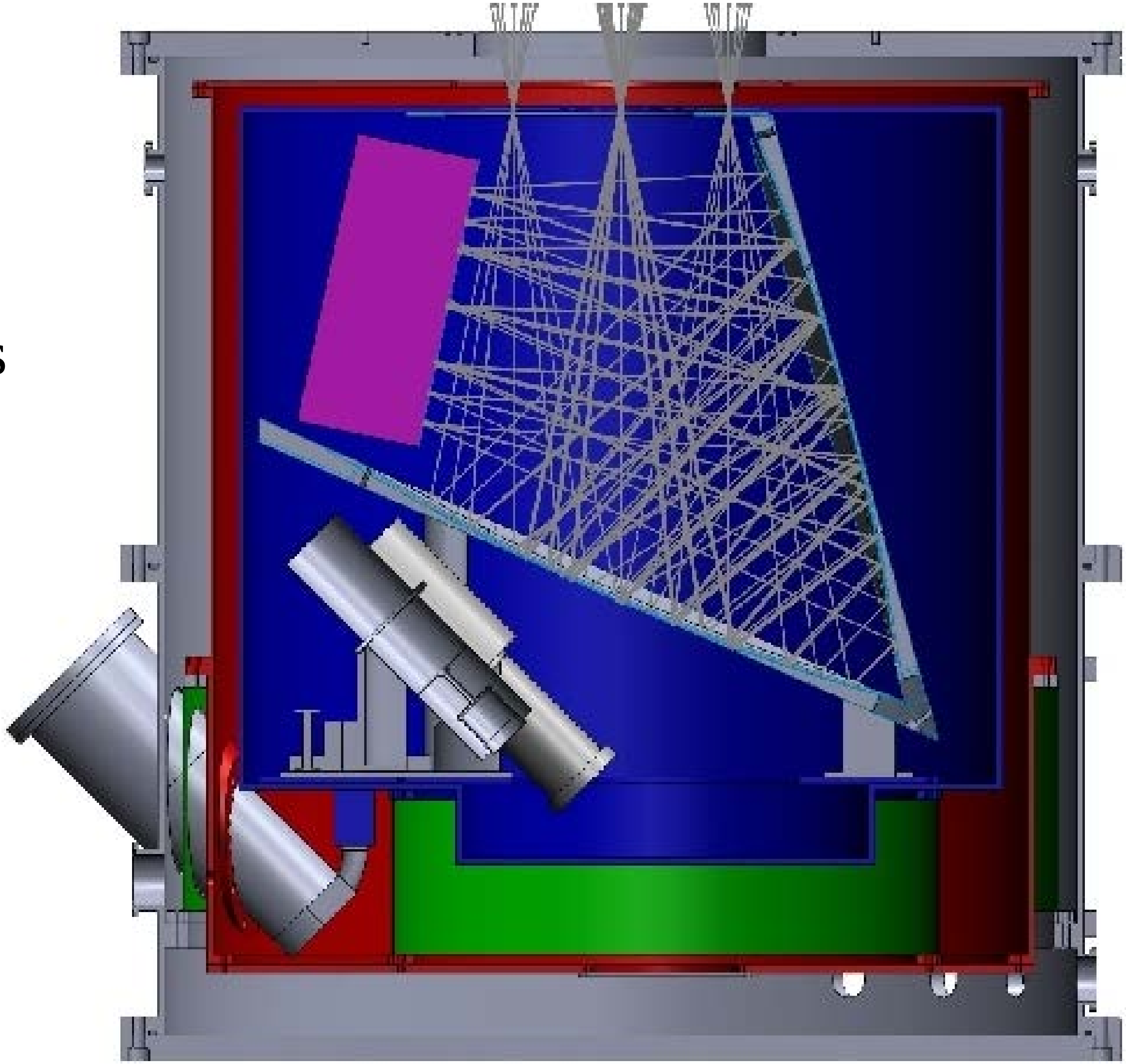
Technology: near term 1000s of bolometers, then to 10,000.
Currently single frequency pixels, multichroic in 2015.

Ground Based

		Have data	Current or planned freqs
	Chile		
*	ABS		145 GHz
	ACTPol/AdvACt		30, 40, 90, 150, 230 GHz
	POLARBEAR		90, 150 GHz
*	CLASS		40, 90, 150 GHz
	Antarctica		
*	BICEP/KECK		90, 150, 220 GHz
	SPTPol		90, 150 GHz
	QUBIC-Bolo int.	2016	90, 150, 220 GHz
	Elsewhere (for now)		
	B-Machine –WMRS		40 GHz
*	GroundBIRD, LiteBIRD	2016	150 GHz
*	GLP – Greenland	TBD	150, 210, 270 GHz
*	MuSE-Multimoded	TBD	44, 95, 145, 225, 275 GHz
	QUIJOTE –Canaries, HEM		11-20, 30 GHz

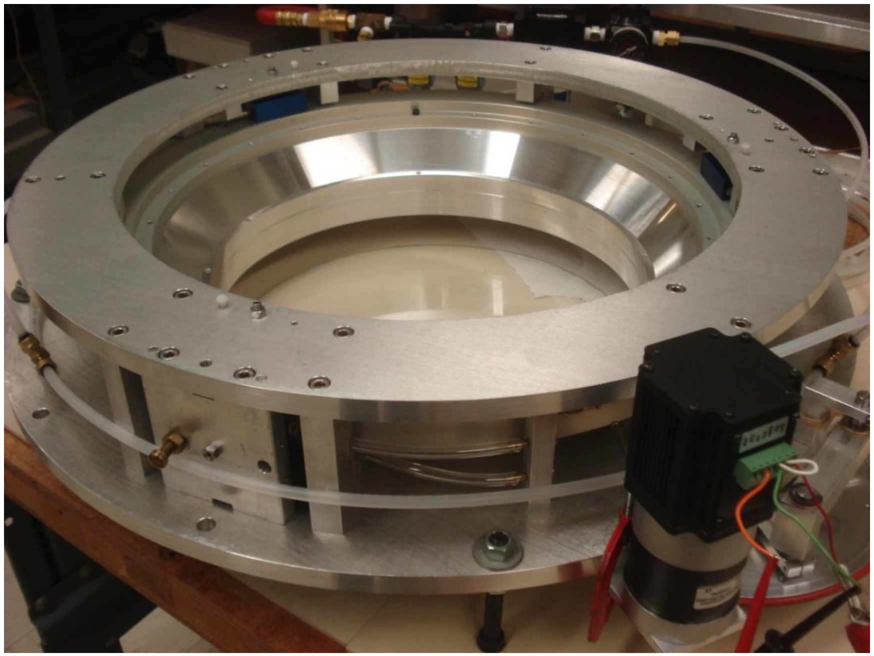
Atacama B-mode Search

- ⋆ 240 feeds
- ⋆ 270 K HWP
- ⋆ 4 K all reflective optics
- ⋆ 0.3 K detectors
- ⋆ Cryoperm/mu metal
- ⋆ 1 cubic meter
- ⋆ 145 GHz.

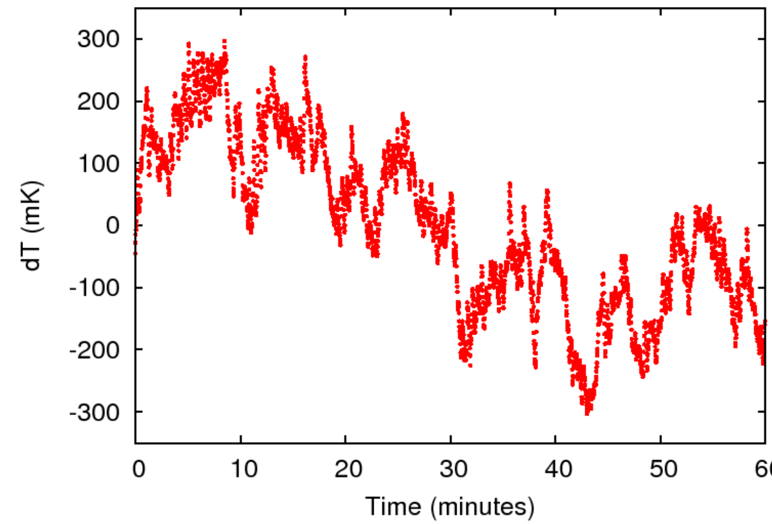


J
H
U

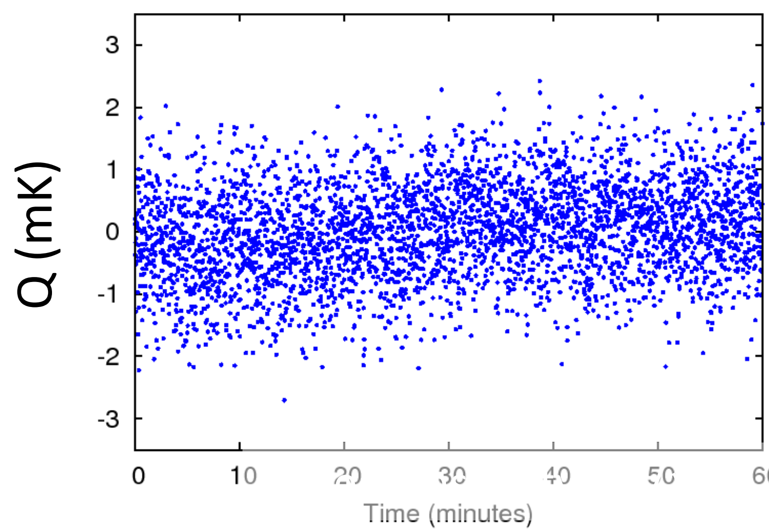
Continuously 2.5 Hz rotating warm half-wave plate with ABS



Kusaka, Essinger-Hileman , et al 2014

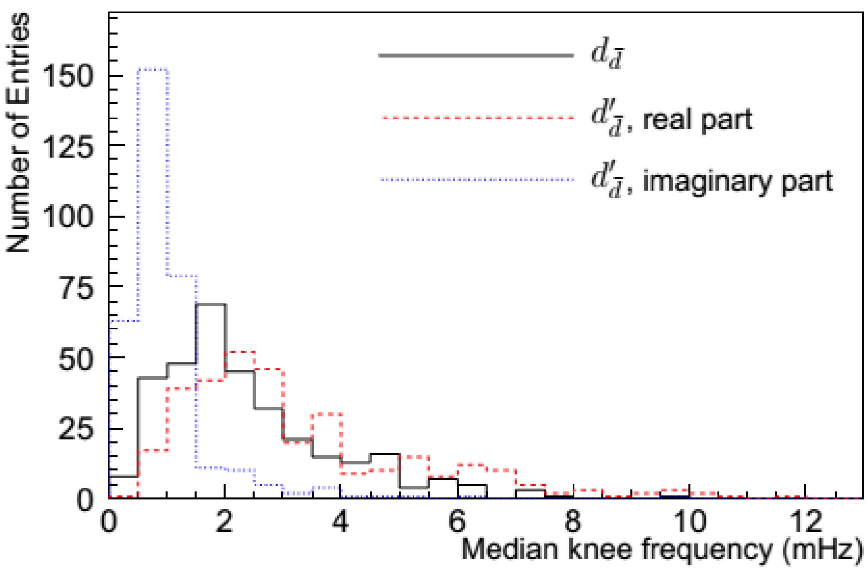


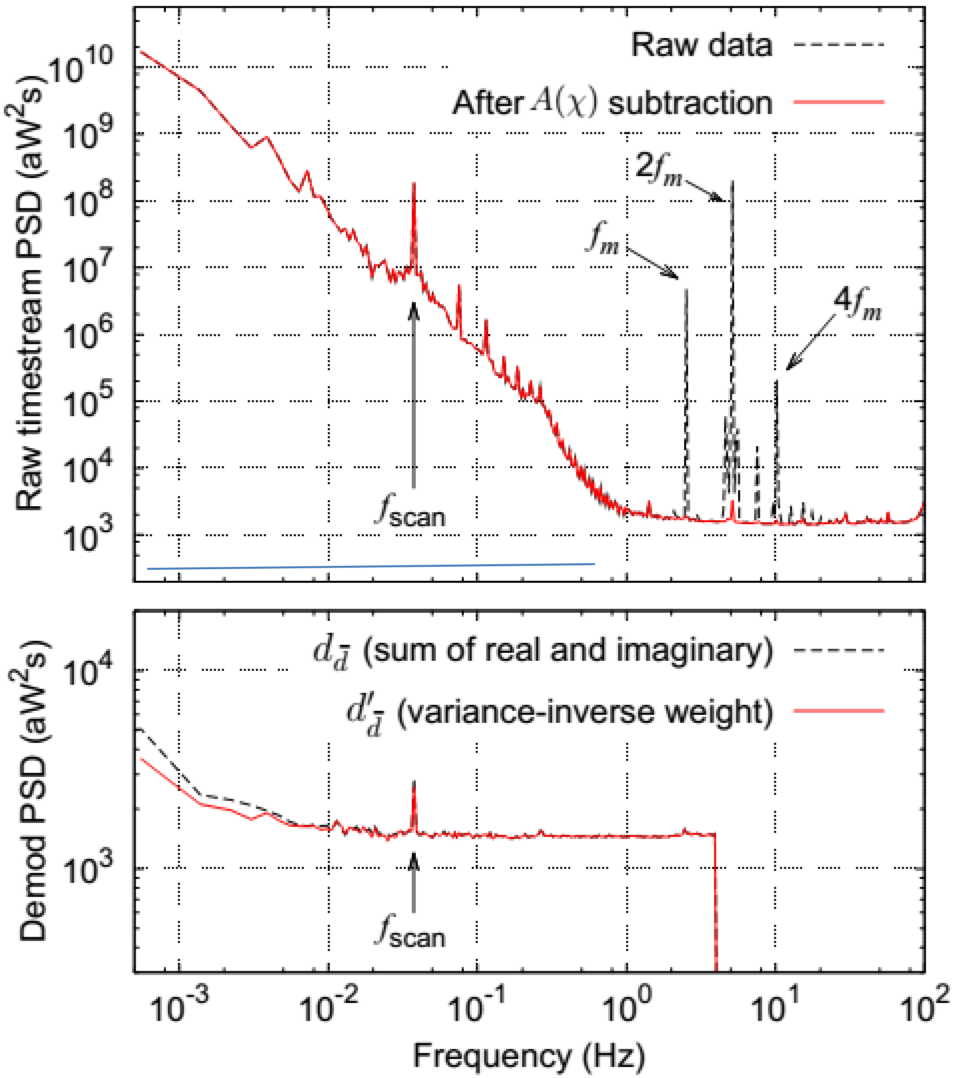
Demodulation



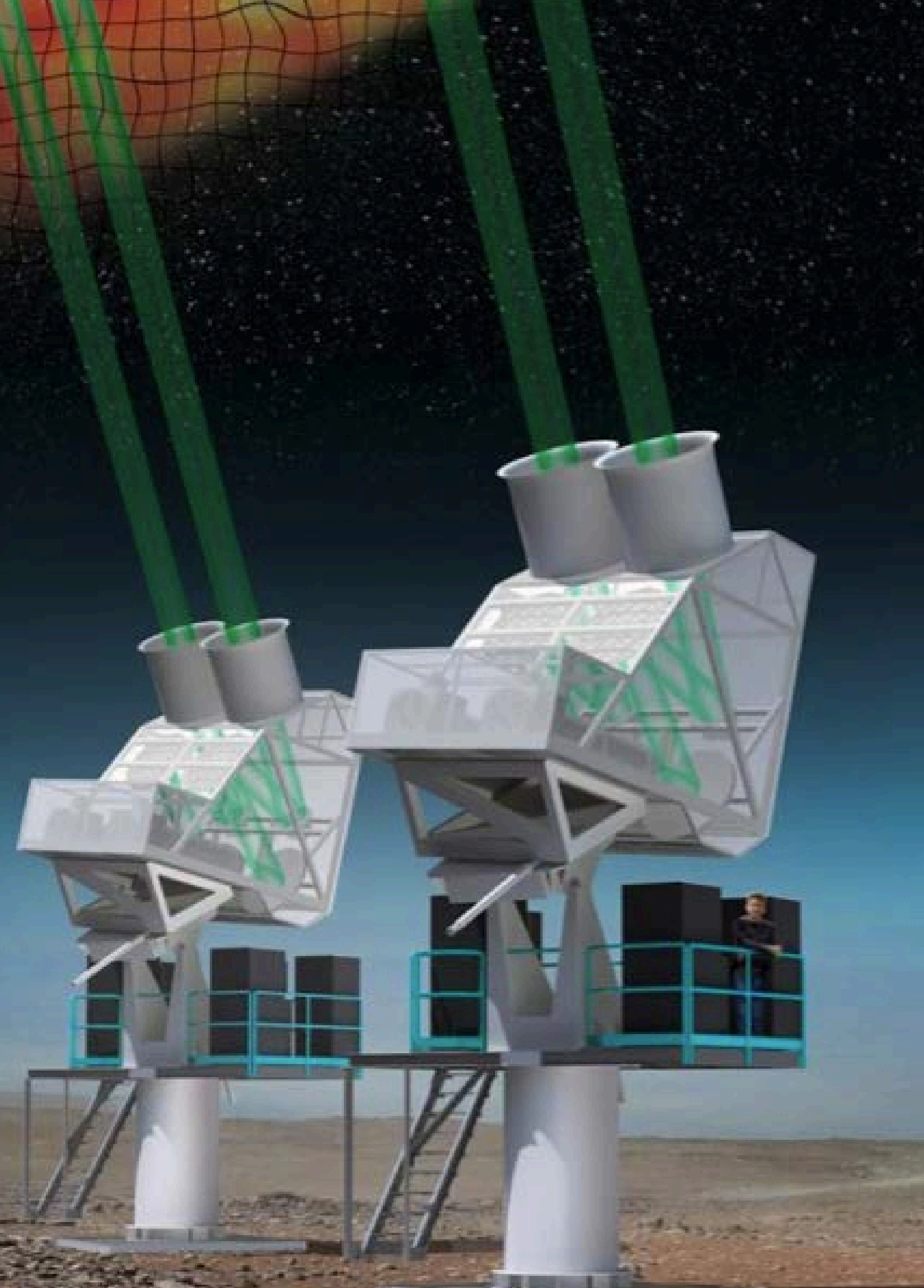
Demodulated timestream

f_{knee}~ 1mHz
~1000 sec
~3^0 sky rotation
=>/~60





Cosmology
Large
Angular
Scale
Surveyor

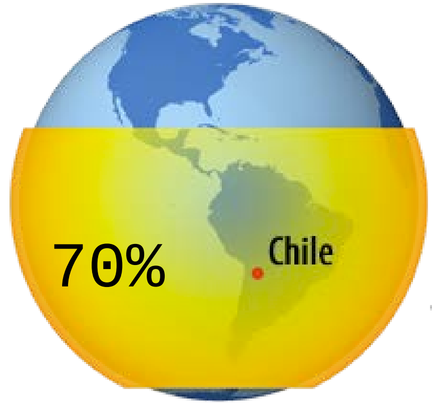


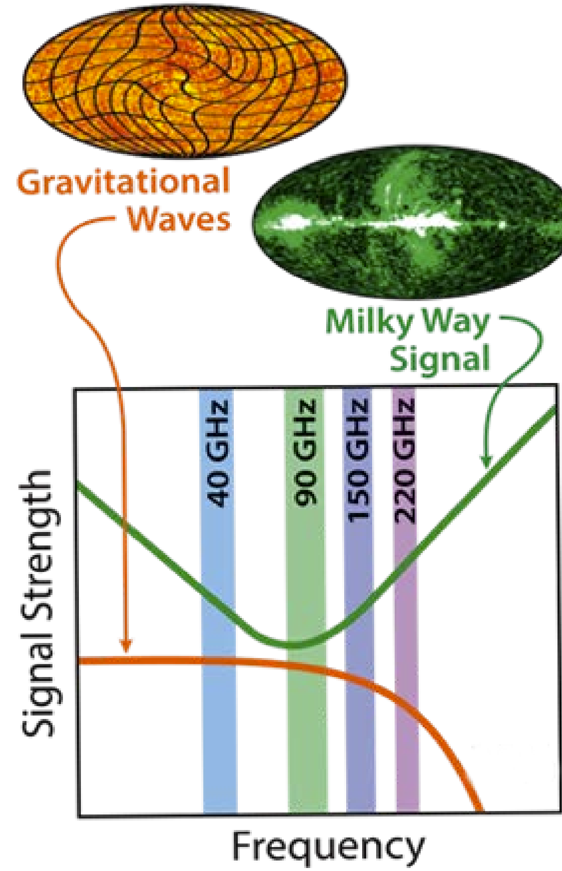
UNIVERSITY

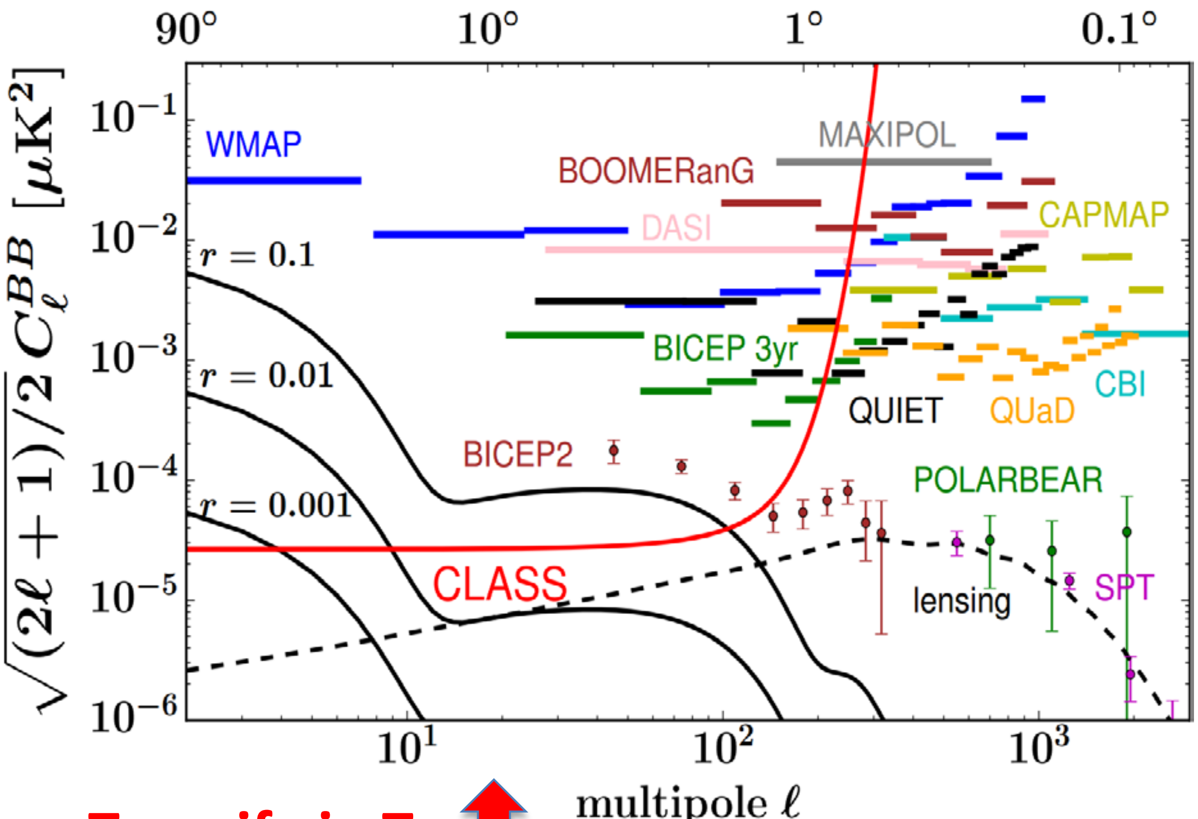
Chuck Bennett, Toby Marriage, and colleagues

CLASS

✓ Inflation
✓ Reionization

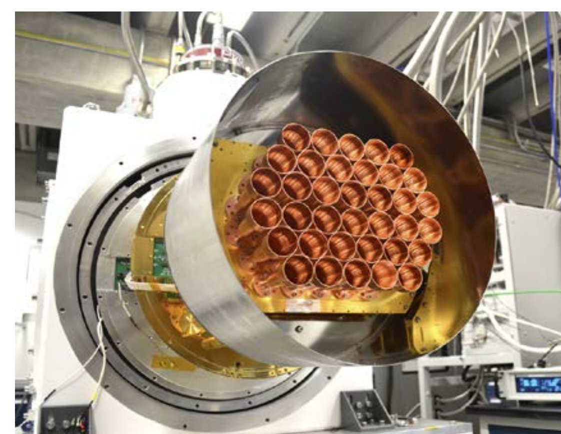






Tenerife in T

40 GHz Focal Plane

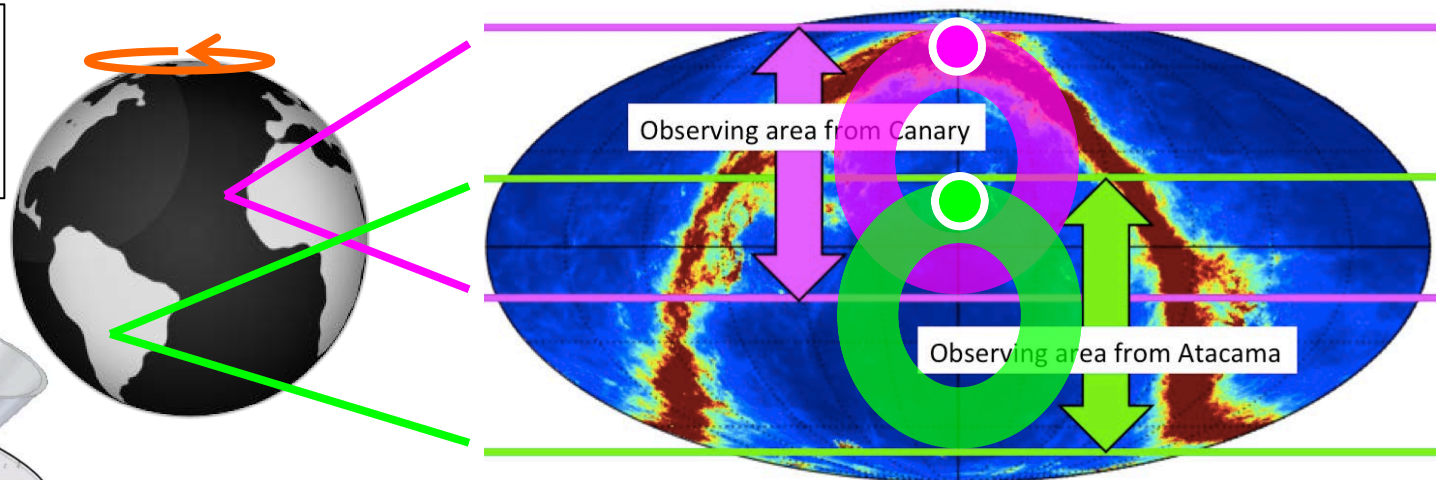


From Osamu Tajima

GroundBIRD – *Satellite-like scan on the ground, but **super high-speed !***

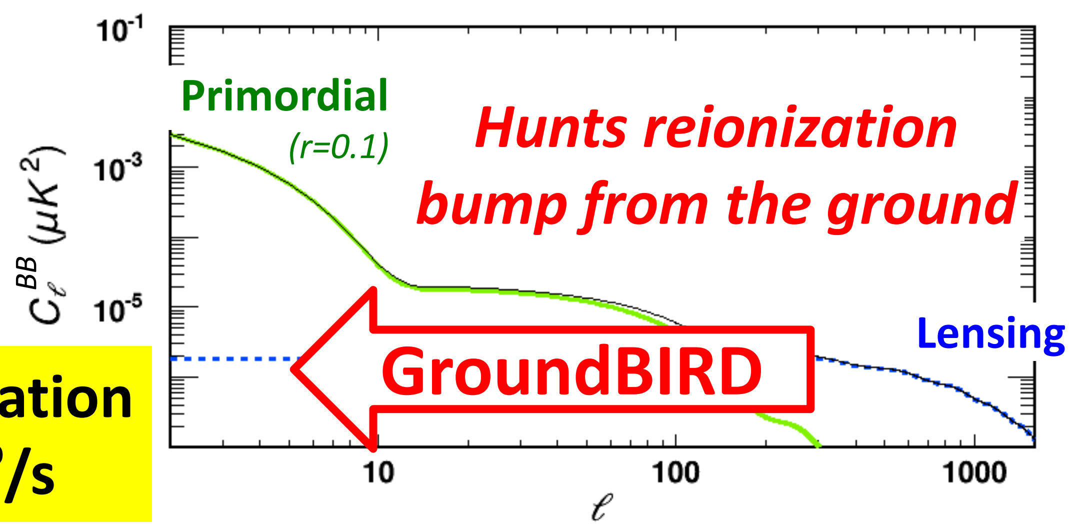
KEK, NAOJ, RIKEN, U-Tokyo, Tohoku U., and Korea U.

Would start CMB observation from 2016 – 2017



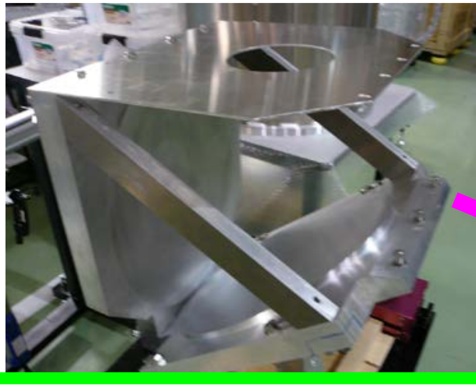
High-speed rotation scan + Earth rotation → Large field obs.
f_{sky} > 0.8 with two sites, e.g., Atacama Chile + Canary Islands

High-speed rotation scan of 120°/s



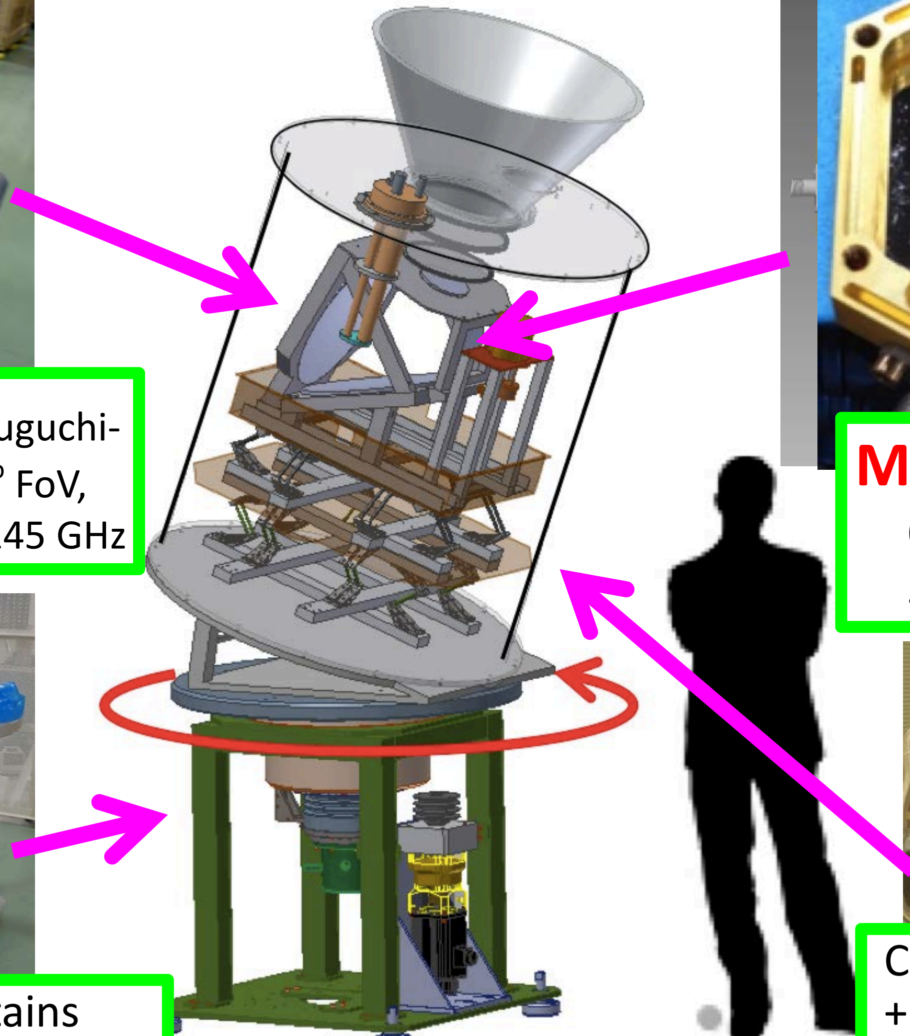
GroundBIRD – *Instrument features*

Details are described in J. Low Temp. Phys. 176, 691 (2014), and Proc. SPIE 8452, 84521M (2012).

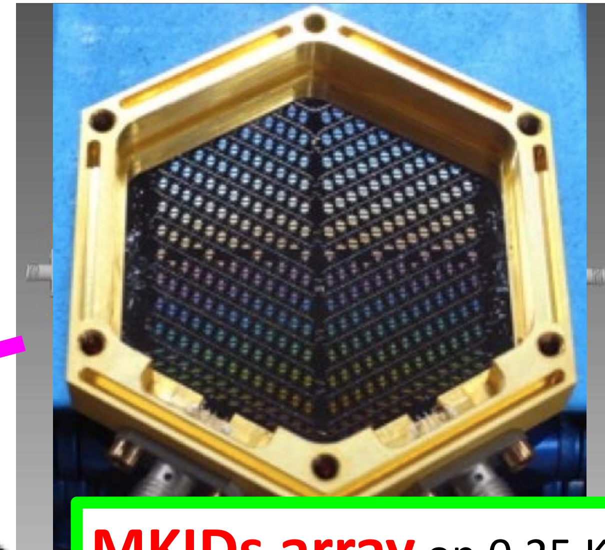


Cold optics at 4 K, Mizuguchi-Dragone dual-reflector, 20^{o} FoV, angular resolution of 0.6^{o} at 145 GHz

Rotation mount maintains
high-speed rotation scan
Scan speed of 120^{o}/s, i.e., 20 rpm



+ Continuous calibration with sparse-wire



MKIDs array on 0.25 K
612 kids for **145 GHz**,
354 kids for **220 GHz**.

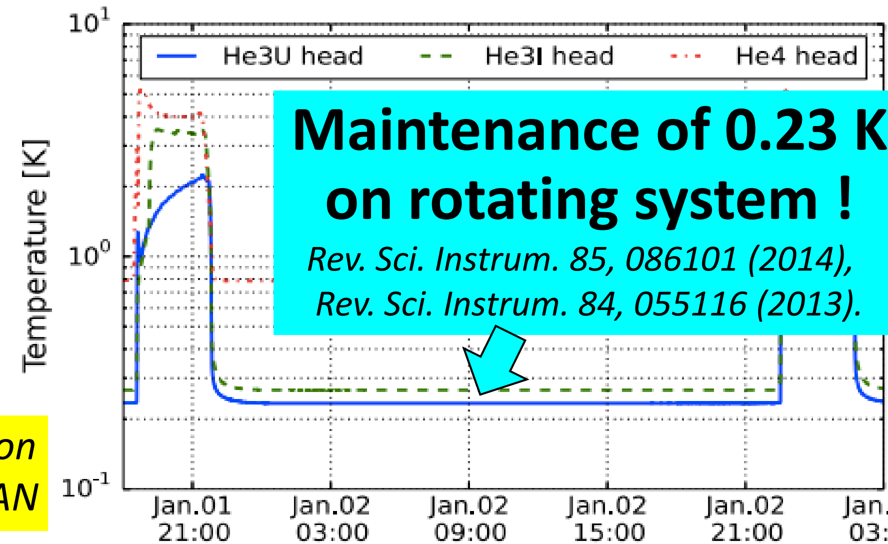
Cryostat cooled by PTC
+ Helium sorption cooler
Boresight rotation
(stepwise)

GroundBIRD – *Inventions to realize high-speed scan with high sensitivity*

Vacuu
f

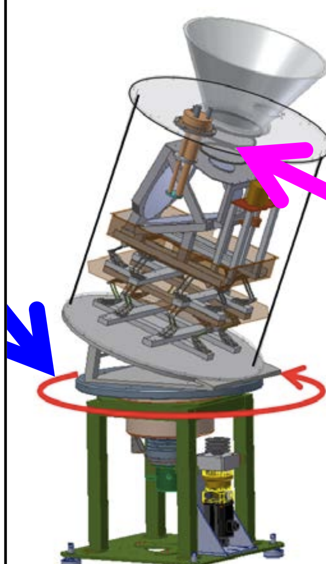
Rotati
20 rpn

quisition
ess-LAN



Maintenance of 0.23 K on rotating system !

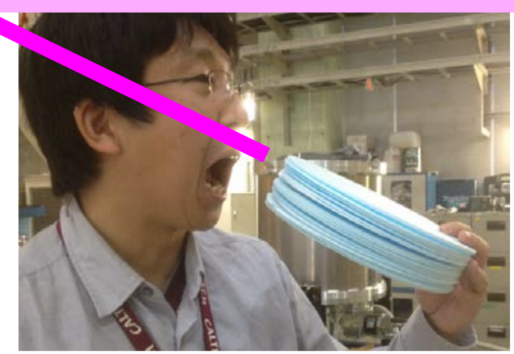
Rev. Sci. Instrum. 85, 086101 (2014),
Rev. Sci. Instrum. 84, 055116 (2013).



RT-MLI

radio-transparent thermal insulator

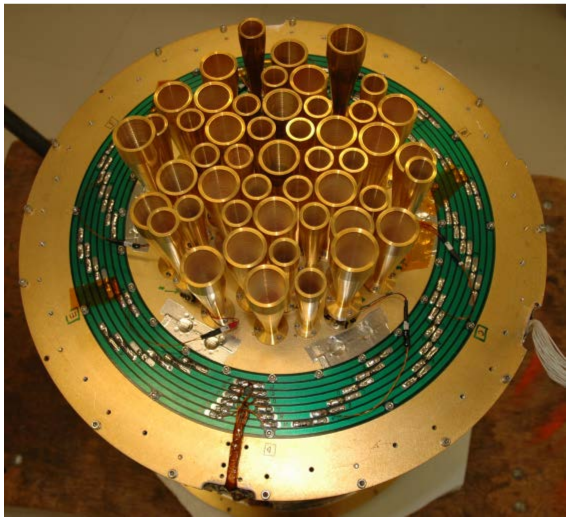
Rev. Sci. Instrum. 84, 114502 (2013).

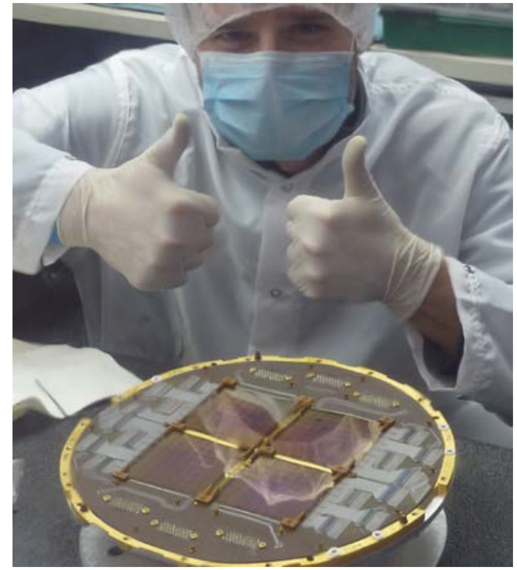


BICEP/Keck Experiments

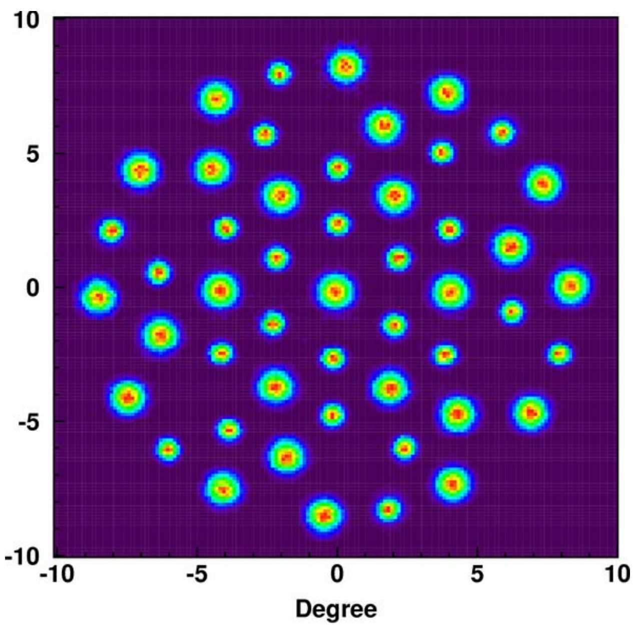
- BICEP1, observed 2006-2008
  - Initial result from first 2 seasons --> tightest constraint on *r* from B-modes:
    r = 0.03 +/- 0.3 *r* < 0.72 (95% conf.) **Chiang et al. 2010 (0906.1181)**
  - Full 3-year results coming in 2011: **Barkats et al.**
- BICEP2, observing since Jan 2010
  - good 1st season completed (>4500h)
  - 512 detectors, mapping speed 10x BICEP1
- Keck Array, observing since Feb 2011
  - 1st season config: 1500 detectors (3x BICEP2)
  - 2012-14 seasons: more receivers (5 max), more bands (100, 150, 220 GHz)

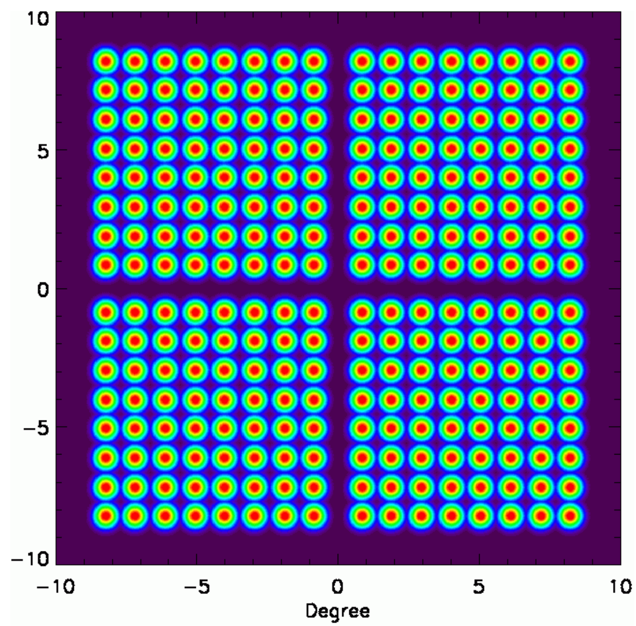
More detectors: **BICEP2**





Justus Brevick (BICEP2 grad student, at Pole 2009)





BICEP1 **98 detectors** → **BICEP2** **512 detectors**

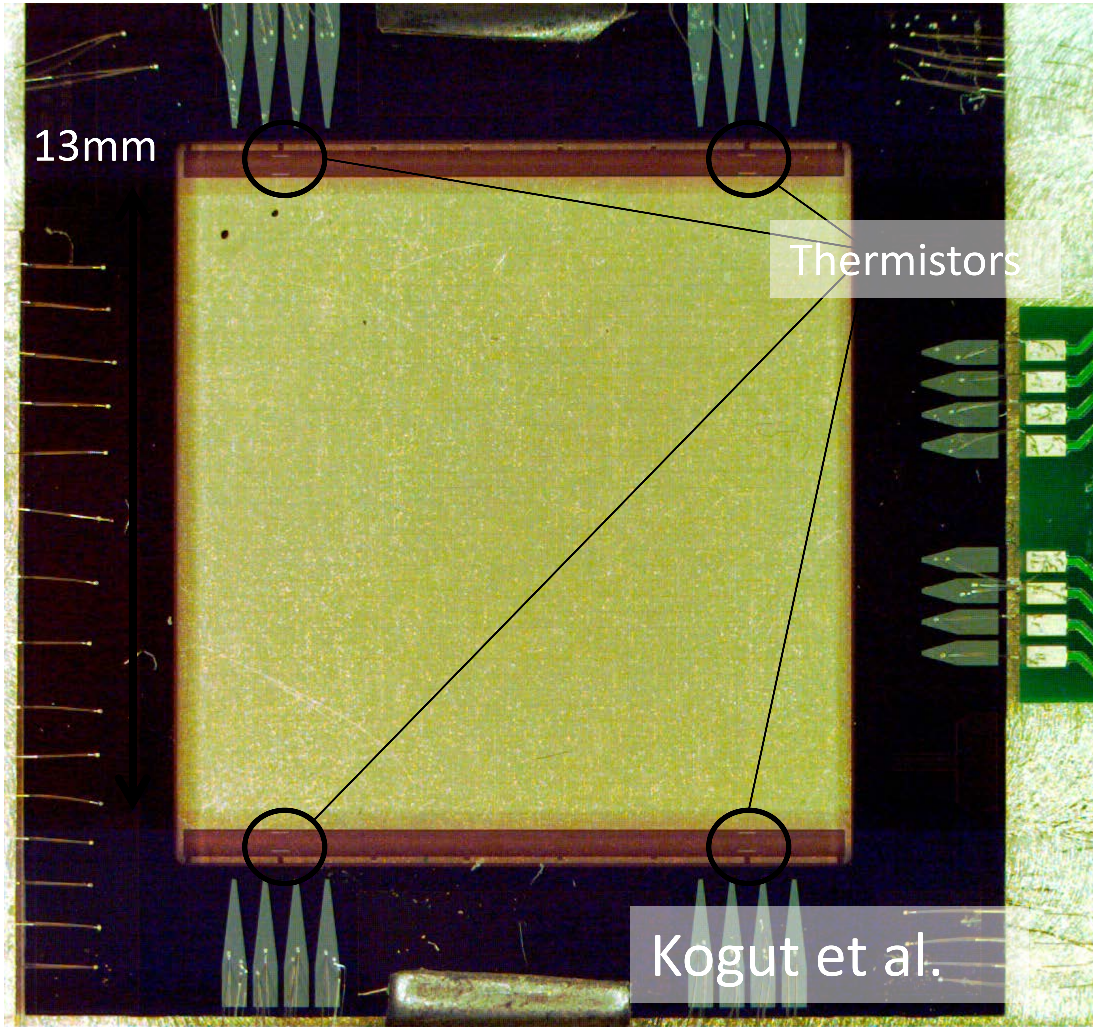
From Akito Kusaka

Multimoded Survey Experiment (MuSE)

Parameter	Value	Unit	Comment
Multimpole covarage	25 – 250		1.4m primary 1.1deg tophat
Frequency	44 / 95 / 145 225 / 275	GHz	
Bandwidth	0.23 / 0.27 / 0.25 0.22 / 0.18	Fractional	
Raw NEQ	4.5		95+145GHz
Foreground cleaned NEQ	8.0		Linear combination
# of pixels	50		8000 modes
Location	Ground		e.g., Atacama

Detector developed at NASA GSFC

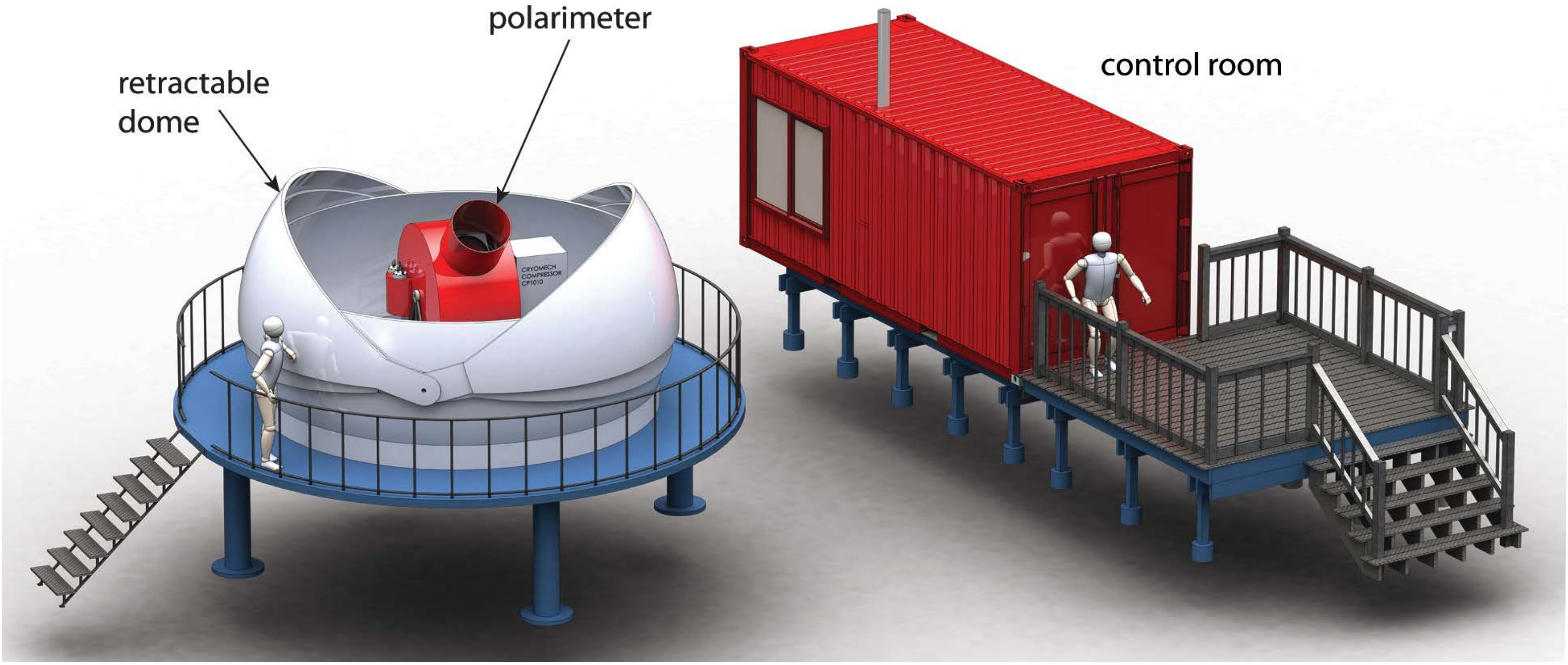
- Developed for PIXIE satellite proposal (Kogut et. al. 2011)
- Polarization selective absorbing strings
- Can be configured for narrow-band application
  - 87 modes/detector @145GHz
- Cryogenically testing at Princeton



From Amber Miller

The Greenland LEKID Polarimeter

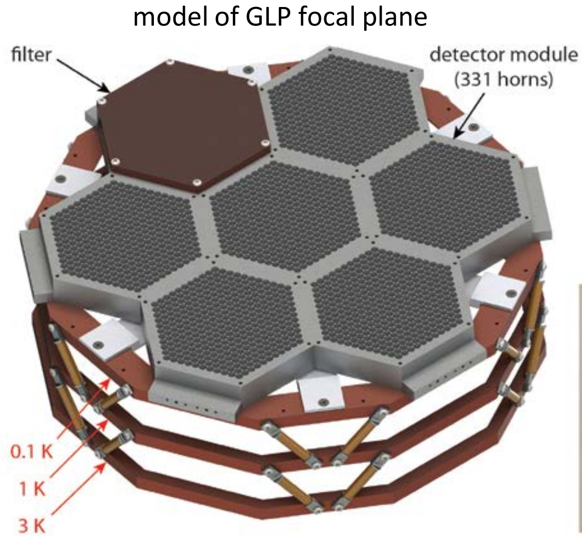
Compact LEKID-based spinning telescope for deployment to Greenland

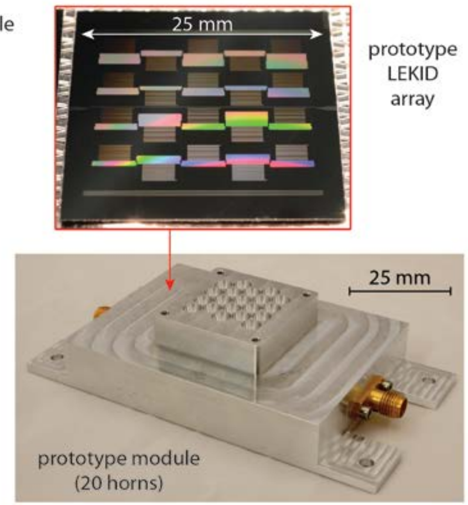


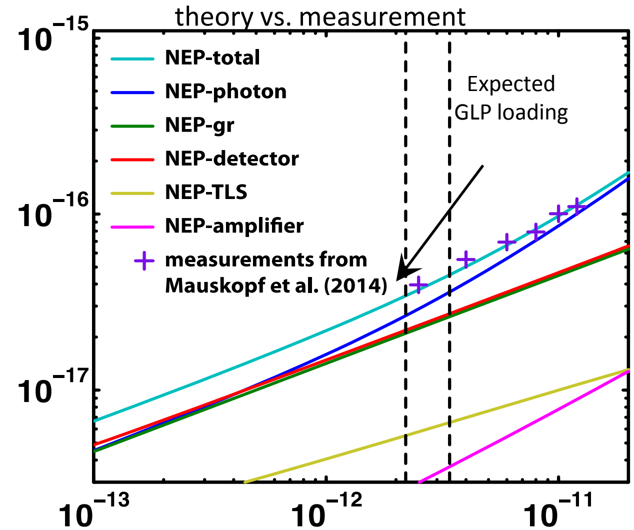
Miller (PI), Johnson (Co-I), Mauskopf (Co-I), Day (Co-I), Jones, Groppi, Limon, Zmuidzinas, Ade, Bond, Eriksen, Pen, Wehus

Araujo et al. (2014) in *Proc. SPIE*

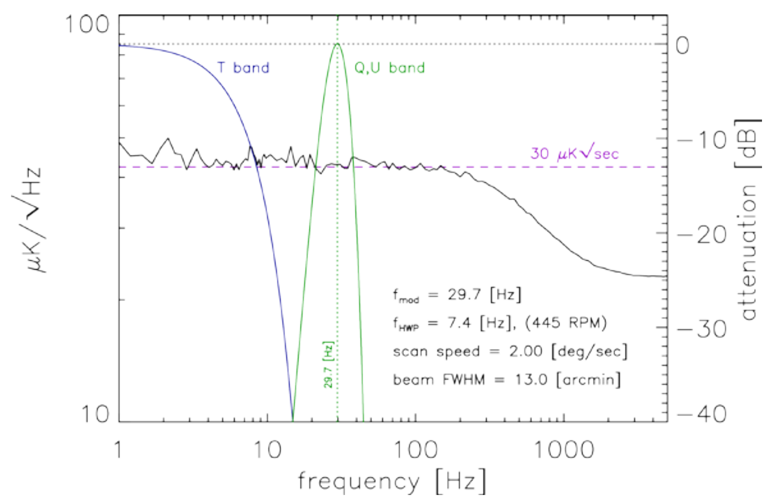
Focal Plane, LEKID Noise and NET







Laboratory measurements of noise from an array of horn-coupled prototype LEKIDs fabricated at Star Cryoelectronics show the NET = 26 +/- 6 μK √sec for a 4 K load. The T, Q and U signal bands for GLP are marked in blue and green.



Noise measurements are consistent with the theoretical calculations used for forecasting.

McCarrick et al. (2014) in *Review of Scientific Instruments*

Balloons

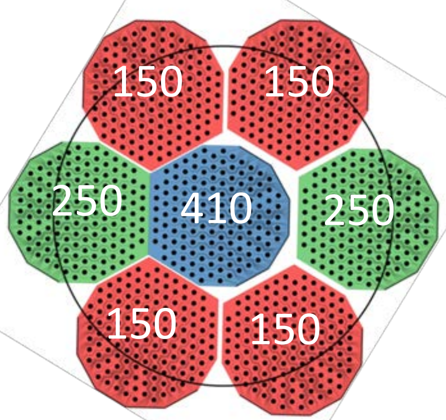
	Have data	Current or planned freqs
* EBEX		150, 250, 210 GHz
LPSE	TBD	5 chan 40-250 GHz
* PIPER	2015	200, 270, 350, 600 GHz
* SPIDER		90, 150, 280 GHz

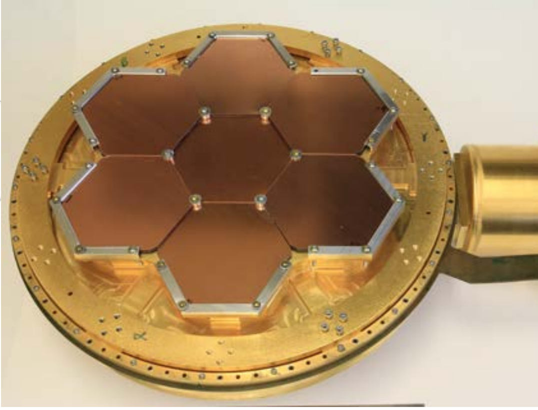
EBEX in a Nutshell

- A CMB Polarimeter
- Long duration balloon borne
- Use >1000 bolometric TES
- 3 Frequency bands: 150, 250, 410 GHz
- Resolution: ~10’ at all frequencies
- Polarimetry with continuously rotating half wave plate
- First flight in Antarctica 2012; 10 days of data

Antarctica Launch Dec. 29, 2012

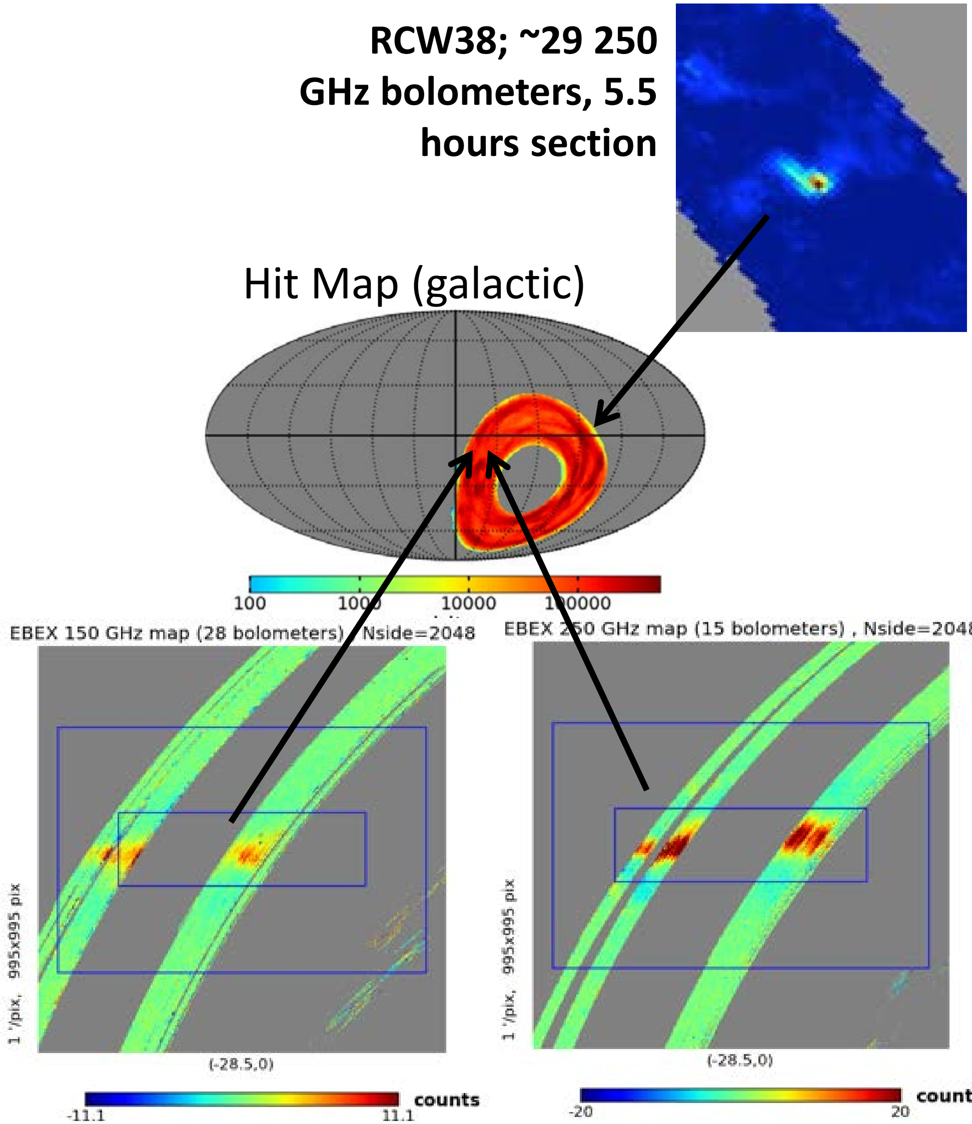
One of two (identical) focal planes





EBEX in a Nutshell

- First use of arrays of TES bolometers on a balloon platform
- First demonstration of digital frequency domain multiplexing
- First (and only) use of x16 FDM
- First use of superconducting magnetic bearing for astrophysical polarimetry
- Analyzing data from LD2012 flight; Total ~6000 square degrees

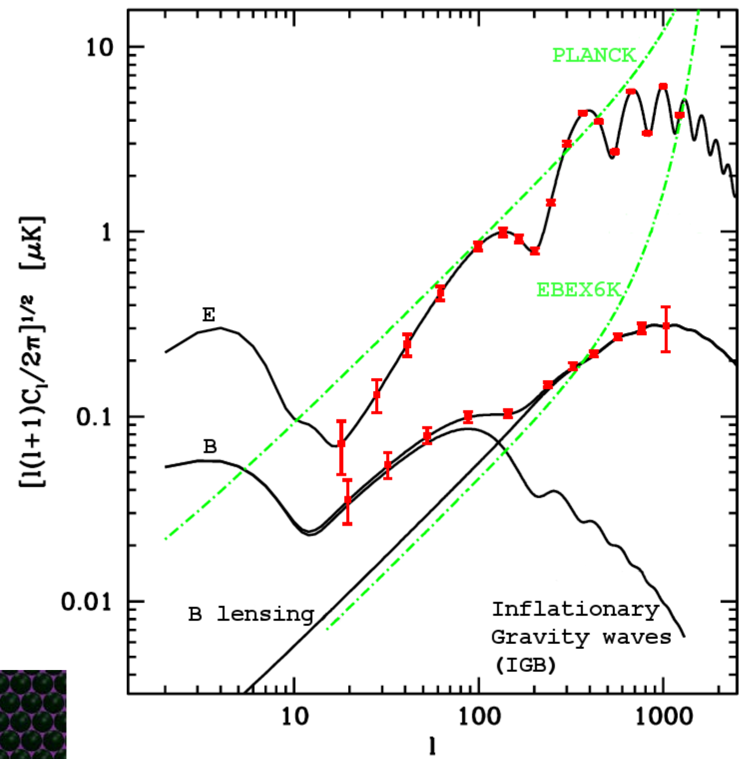


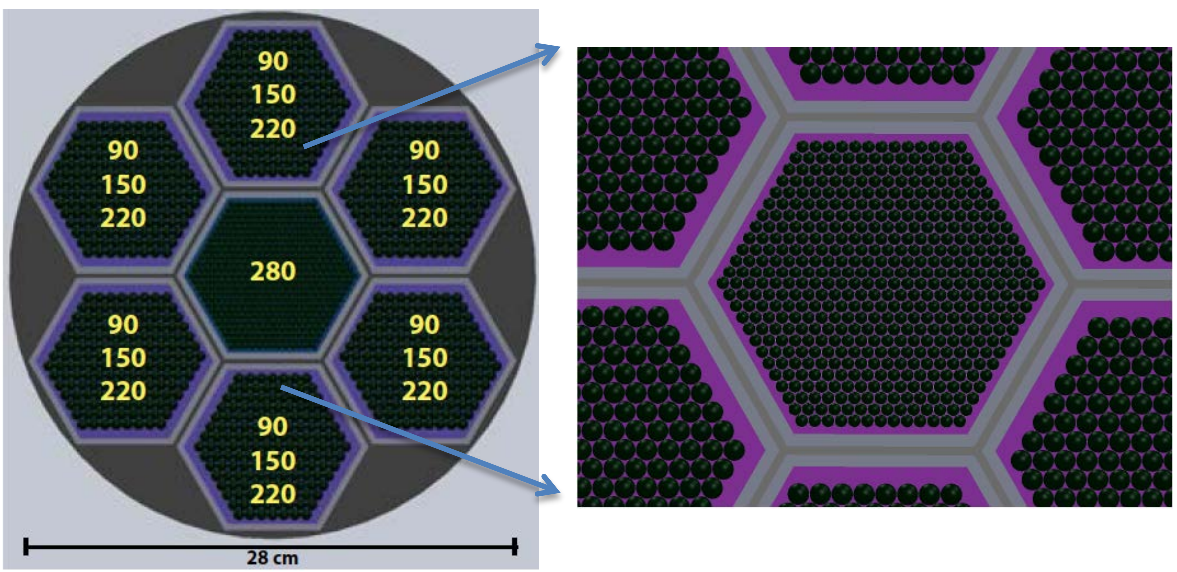
In Flight Galactic Signals
(one section, ~20 bolometers

EBEX6K

- 1048, 3-band multichroic pixels (90,150,220) + 1-band monochroic (280)
- Each pixel is dual polarization
- Sinuous-antenna design
- Total of 6048 detectors
- x64 muxing
- 5 μK*arcmin
- 2σ upper limit on r=0.007

  (excludes lensing cleaning, foregrounds, or systematic uncertainties)





Fly in 12/2018

Pending funding approval

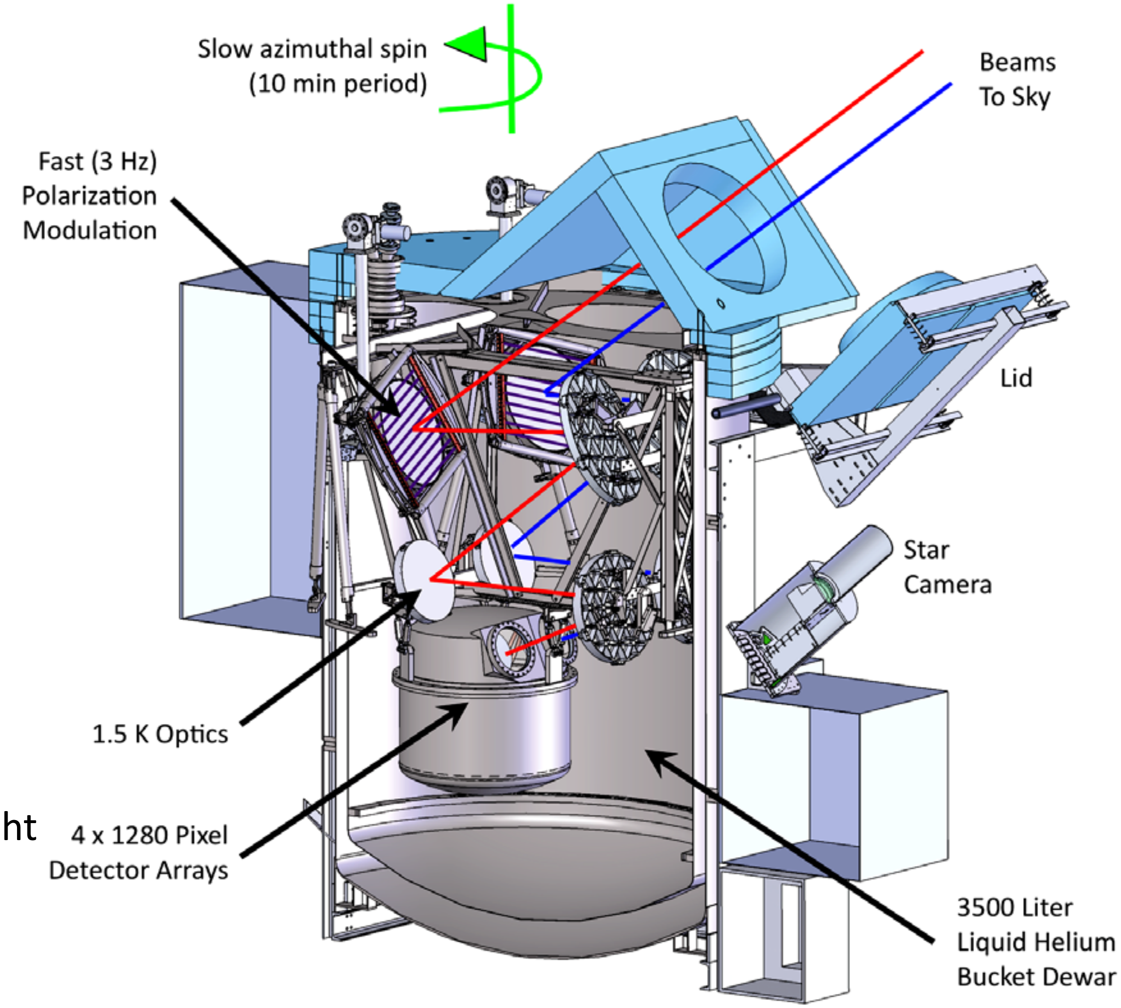
Primordial Inflation Polarization Explorer (PIPER)

Sensitivity
- 5120 Detectors (TES bolometers)
- 1.5 K optics with no windows
- NEQ < 2 μK $s^{1/2}$ at 200, 270 GHz

Systematics
- Front-End polarization modulator
- Twin telescopes in bucket dewar

Foregrounds
- 200, 270, 350, and 600 GHz
- Clearly separate dust from CMB

Sky Coverage
- Balloon payload, conventional flight
- 8 flights; half the sky each night



Goal: Detect Primordial B-Modes with r < 0.01

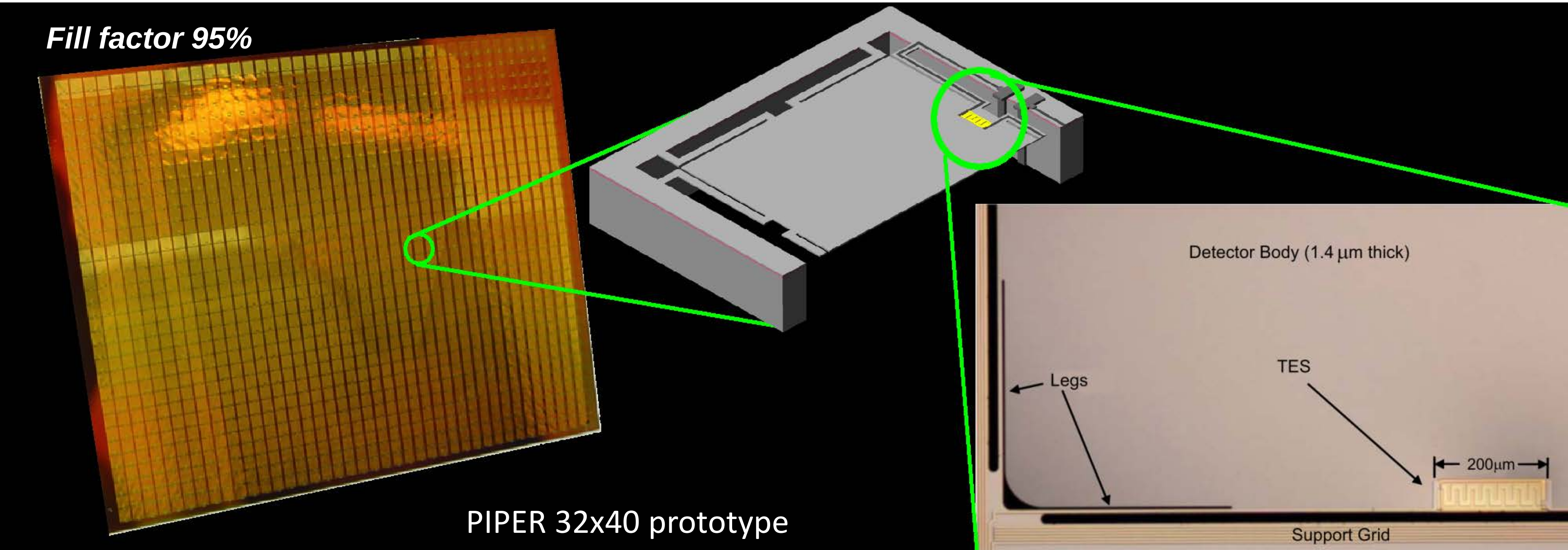
PIPER Detector Arrays

Parameter	Band 1	Band 2	Band 3	Band 4
Frequency (GHz)	200	270	350	600
Wavelength (μm)	1500	1100	850	500
Bandwidth $\delta\nu/\nu$	0.30	0.30	0.16	0.10
Beam Width (arc-min)	19	15	13	10
Optical Efficiency to Detector	0.55	0.52	0.50	0.42
Detector Absorption Efficiency	0.90	0.90	0.70	0.50
CMB Power (fW)	120	70	20	<1
Atmospheric Power (fW)[a]	20	90	150	230
Total Absorbed Power (fW)	200	190	190	250
Saturation Power (fW)	1200	1200	1200	1200
Photon NEP (W Hz$^{-1/2}$)	7×10^{-18}	8×10^{-18}	11×10^{-18}	13×10^{-18}
Phonon NEP (W Hz$^{-1/2}$)	4×10^{-18}	4×10^{-18}	4×10^{-18}	4×10^{-18}
Single-Detector NEQ (μK $\sqrt{s}$)	44	70	320	3800
Number of Detectors (phonon)	5120	5120	5120	5120
Number of Detectors (photon)	943	1550	2270	3760
Instrument NEQ (μK $\sqrt{s}$)	1.3	1.9	6.7	110
Instrument NEQ (mJy$\sqrt{s}$)	13	9	17	30

[a] Atmospheric values shown for float altitude 35 km

- Absorber-coupled TES bolometers at 100 mK
- 4 arrays each 32 x 40 pixels (5120 total)
- Backshort-Under-Grid (BUG) architecture
- Through-wafer vias put wiring UNDER array
- Bump-bond to NIST 32x40 tMUX chip

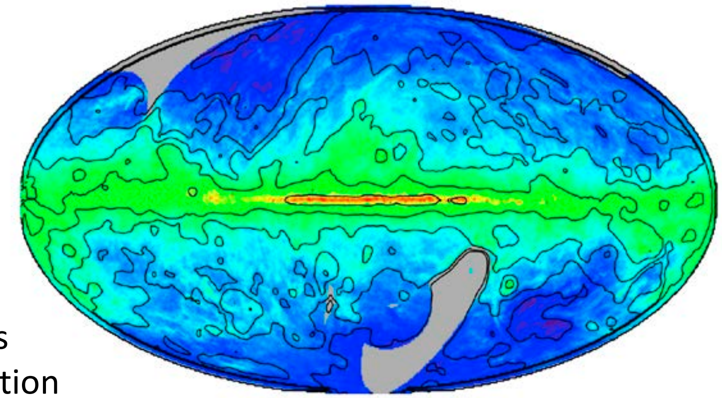
5120 detectors in each frequency band!



PIPER Sky Coverage and Sensitivity

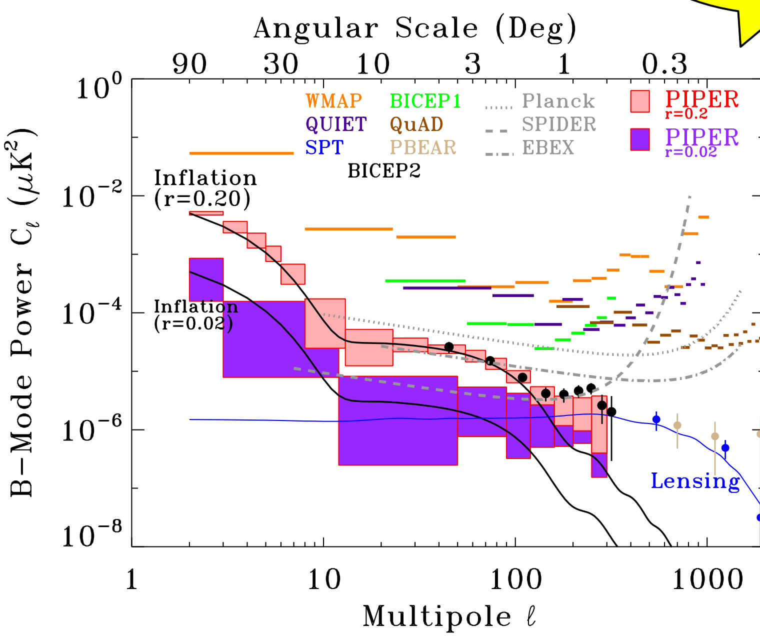
Cold optics improve mapping speed by a factor of 10 ...

Which allows overnight flights instead of Antarctic long duration flights ...



PIPER Sky Coverage

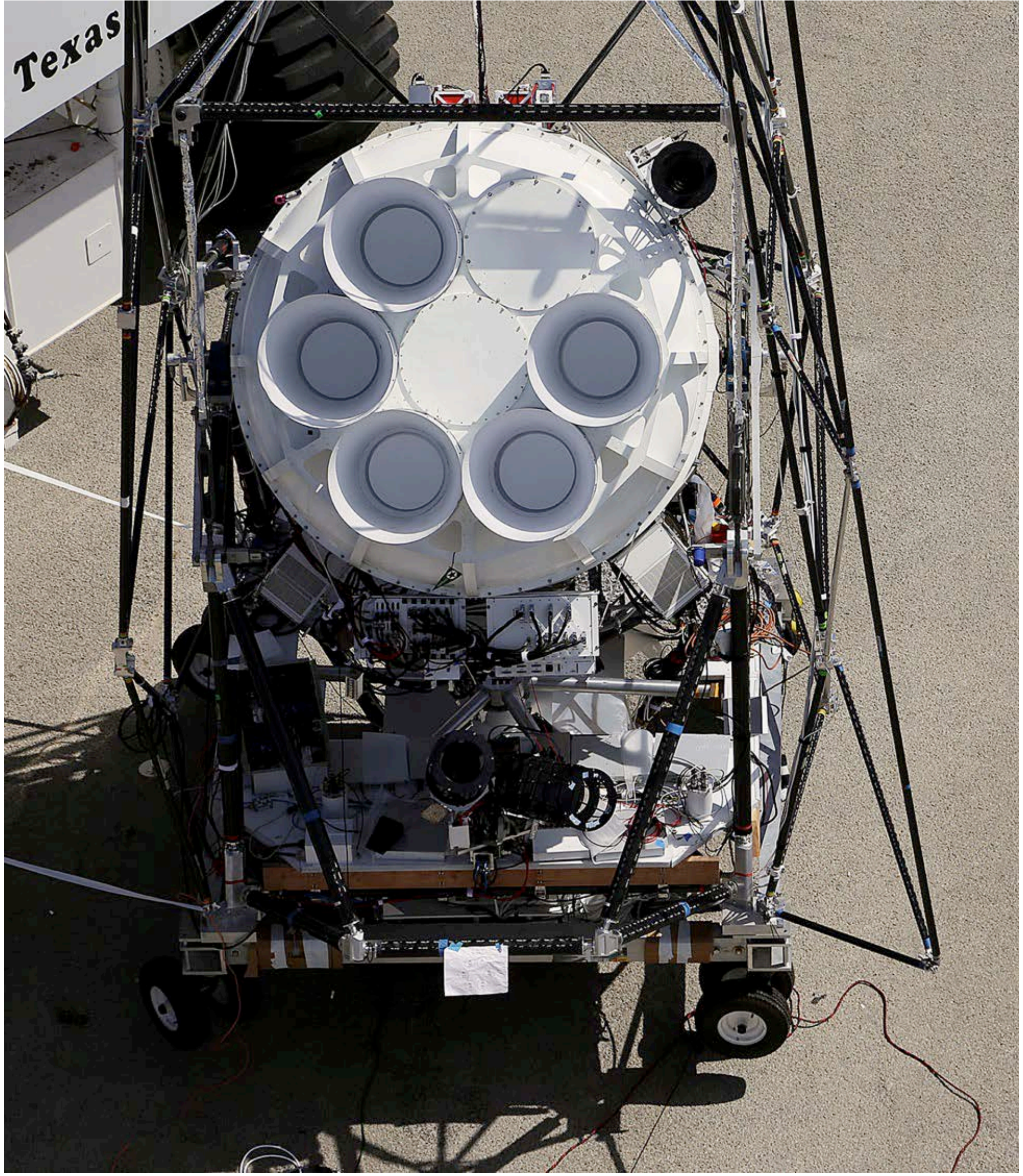
Observing with the sun set allows PIPER to view nearly the full sky. High sky coverage in turn allows detection of the inflationary signal on the largest angular scales where the signal is largest.



Sensitivity r < 0.007 (2σ)
First flight 2015

PIPER observes both the **inflationary signal** on large angular scales and the **lensing foreground** on small scales and will map the **polarized dust foreground**

SPIDER



PRINCETON UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

Imperial College London

UNIVERSITY OF TORONTO

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

STANFORD UNIVERSITY

CASE WESTERN RESERVE UNIVERSITY EST. 1826

NASA

C.S.B.F. PALESTINE, TEXAS

NSF

NIST

NSERC CRSNG

CSA ASC

JPL

the David & Lucile Packard FOUNDATION

UNIVERSITY OF KWAZULU-NATAL

UBC

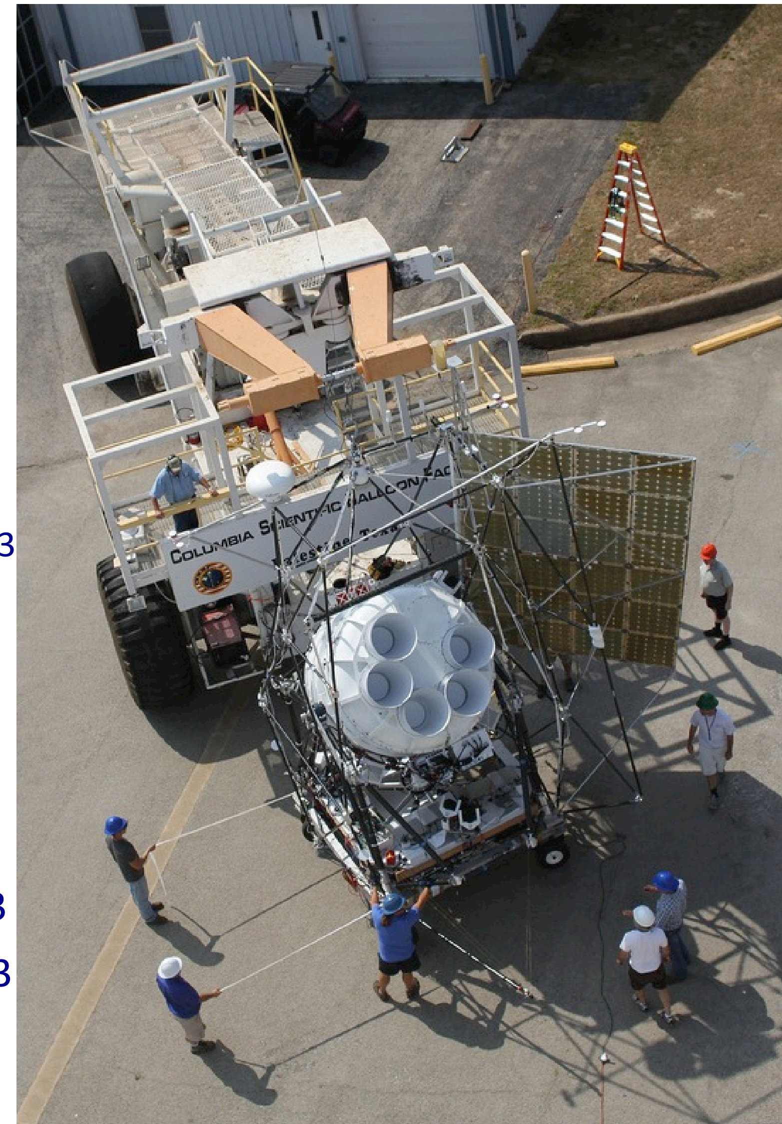
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

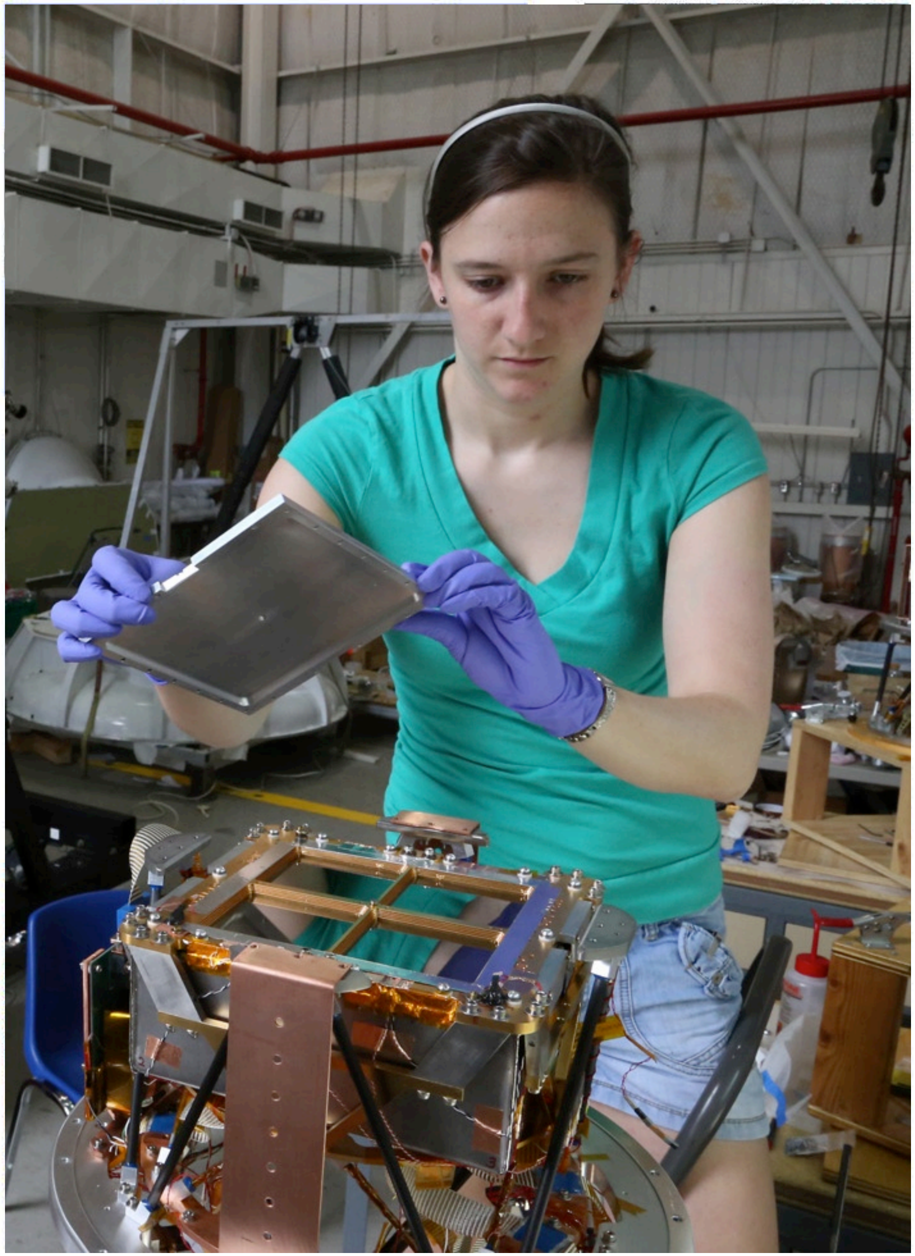
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

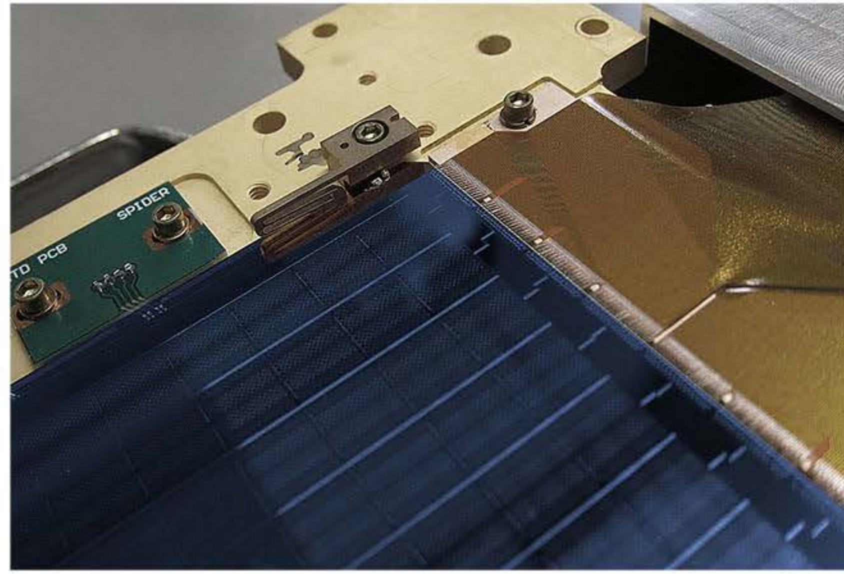
ALFRED P. SLOAN FOUNDATION 1934

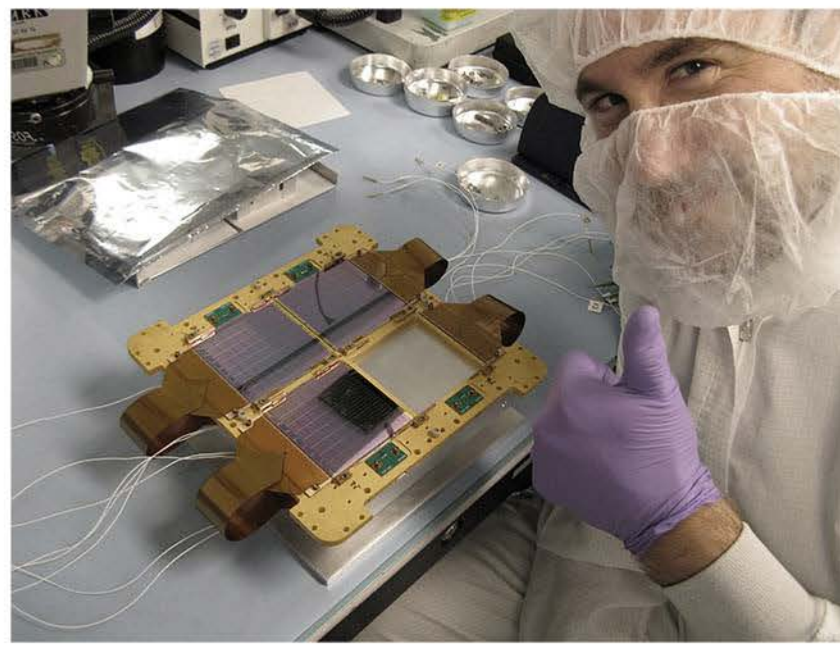
SPIDER

- A balloon borne polarimeter
- Will map the cleanest 8% of the full sky.
- Six telescopes 3/3 at 90/150 GHz
  - Approximately 2000 detectors (2376 w/80% yield)
- Half degree resolution.
  - $\ell = 10 - 300$
- Science goals:
  - Set limits on inflationary gravitational wave amplitude, $r < 0.03$ at 99% confidence
  - Characterize polarized foregrounds
  - Lensing B-modes
- Palestine, June 4 – August 28.
- Two science flights: 2013/2015
- Integrated, calibrated, and **deployed** to McMurdo Sep 2013
- Gov't shutdown eliminated the 2013/14 season in Oct 2013
- Spider **returned** to McChord AFB in December 2013.
- (Two science flights: 2013/2015)++






SPIDER
TD PCB

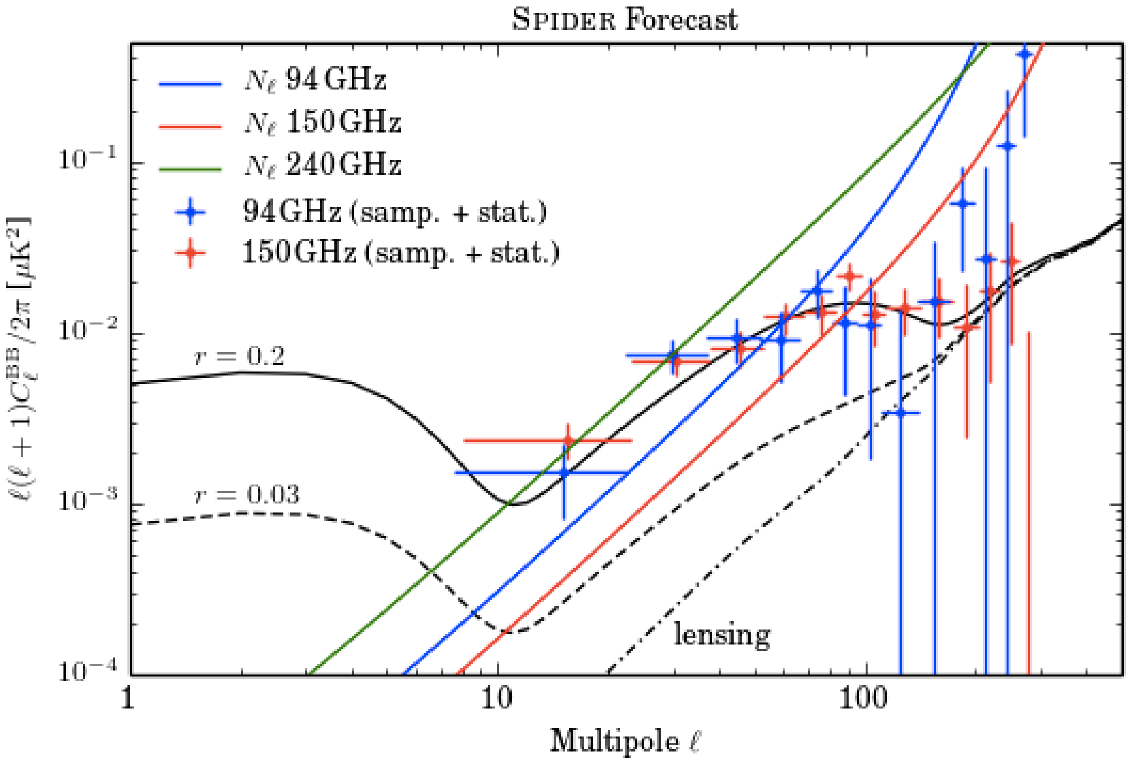


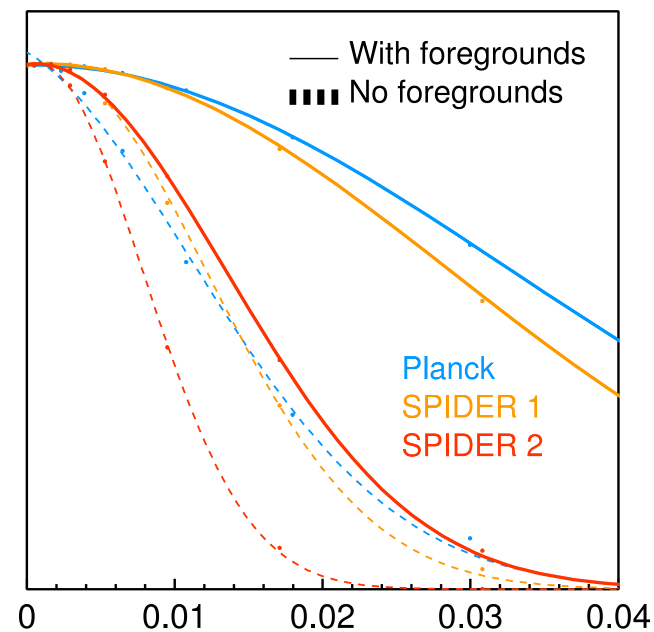
Instrument Summary

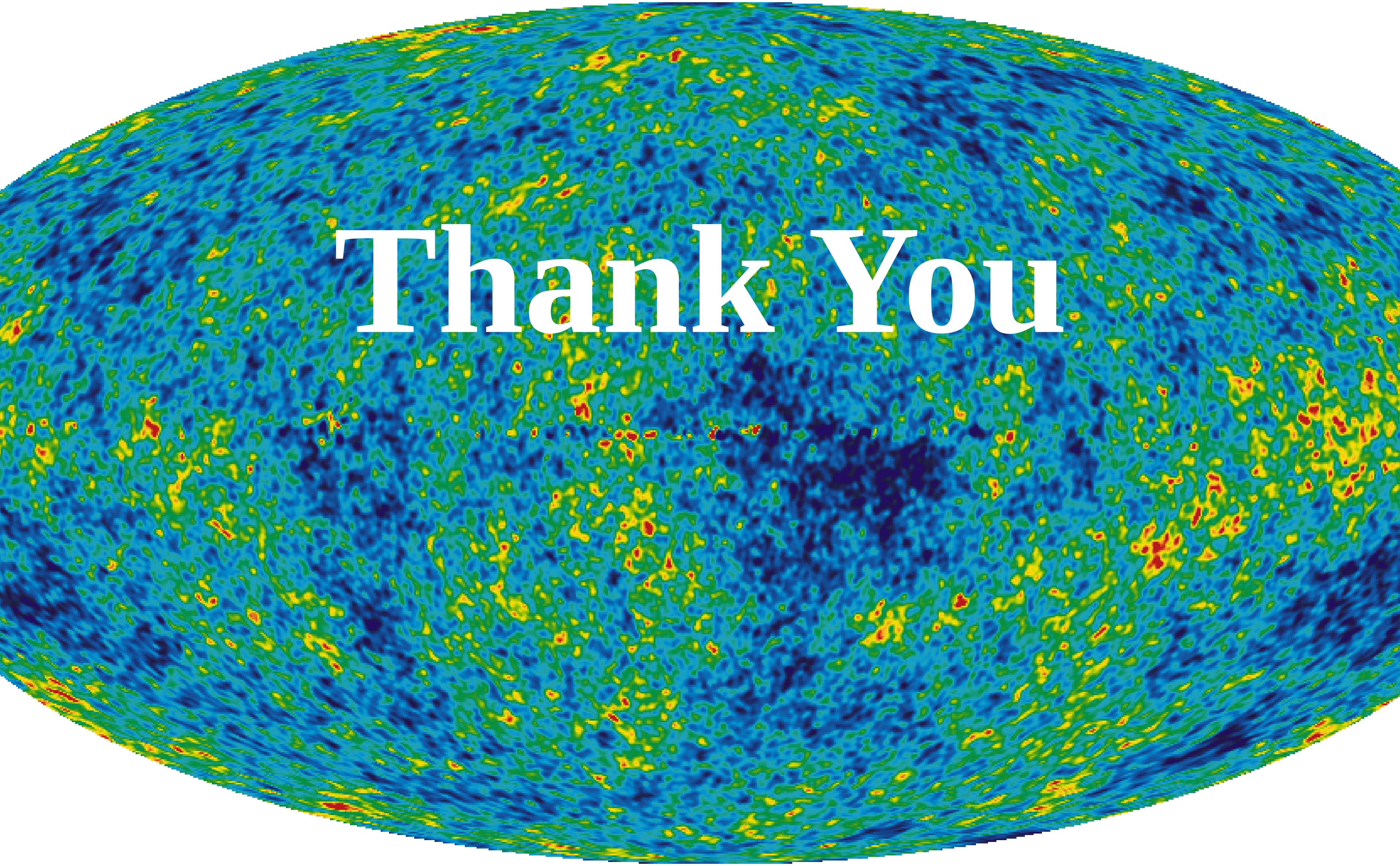
Band	90 GHz	150 GHz
Bandwidth [GHz]	22	36
Beam FWHM [arcmin]	42	30
# Detectors per Focal Plane	288	512
Yield	75-90%	75-90%
Optical Efficiency	30-40%	35-45%
NET per Detector [uK√s]	120-150	110-150
NET per Focal Plane [uK√s]	8-9.5	5.5-6.5

Expected Sensitivity

- Dec 2013: 3x (90 GHz, 150 GHz)
  - r<0.03 (99%CL) without FG for a 20-day flight
- Dec 2015: 2x (90 GHz, 150 GHz, 280 GHz)
  - r<0.02 (99%CL) without FG, r<0.03 (99%CL) with FG






Thank You