Balloon-borne CMB Experiments to mid-decade and Beyond

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with a great deal of input from the community!

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Overview

- Heritage of scientific and technical synergy between sub-orbital and orbital programs
- Status of CMB polarization observations
- Prospects for balloon borne missions in the near- and mid-term
- Milestones and future missions

NASA's sub-orbital heritage

Sub-orbital (balloon and ground based) programs

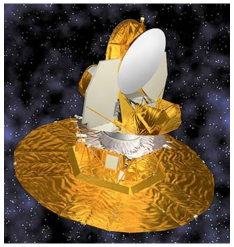
- Return extremely cost effective science
- Complement the scientific capabilities of orbital missions
- Provide foundational technology development
- Provide a unique training ground for future leaders

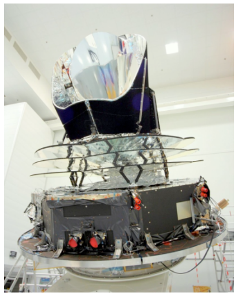
NASA’s sub-orbital heritage

The overwhelming successes of each of NASA’s orbital CMB missions are directly traceable to the heritage of sub-orbital experiments.

“This [the balloon-borne demonstration of receiver technology] provided the confidence and heritage needed to improve the COBE DMR receivers”

-George Smoot, Nobel Lecture



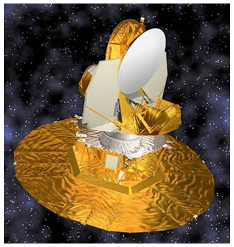


NASA’s sub-orbital heritage

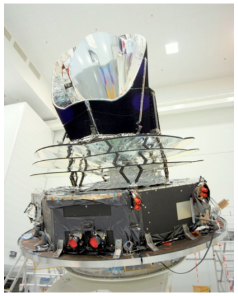
The overwhelming successes of each of NASA’s orbital CMB missions are directly traceable to the heritage of sub-orbital experiments.

Lubin & Villela [balloon borne technology demonstration] **DMR**

Meyer, Cheng & Page (1991), Ganga et al (1993) [balloon borne data] **DMR**
Mather, Woody and Richards, Gush [balloon borne, rocket, technology demonstration] **FIRAS**



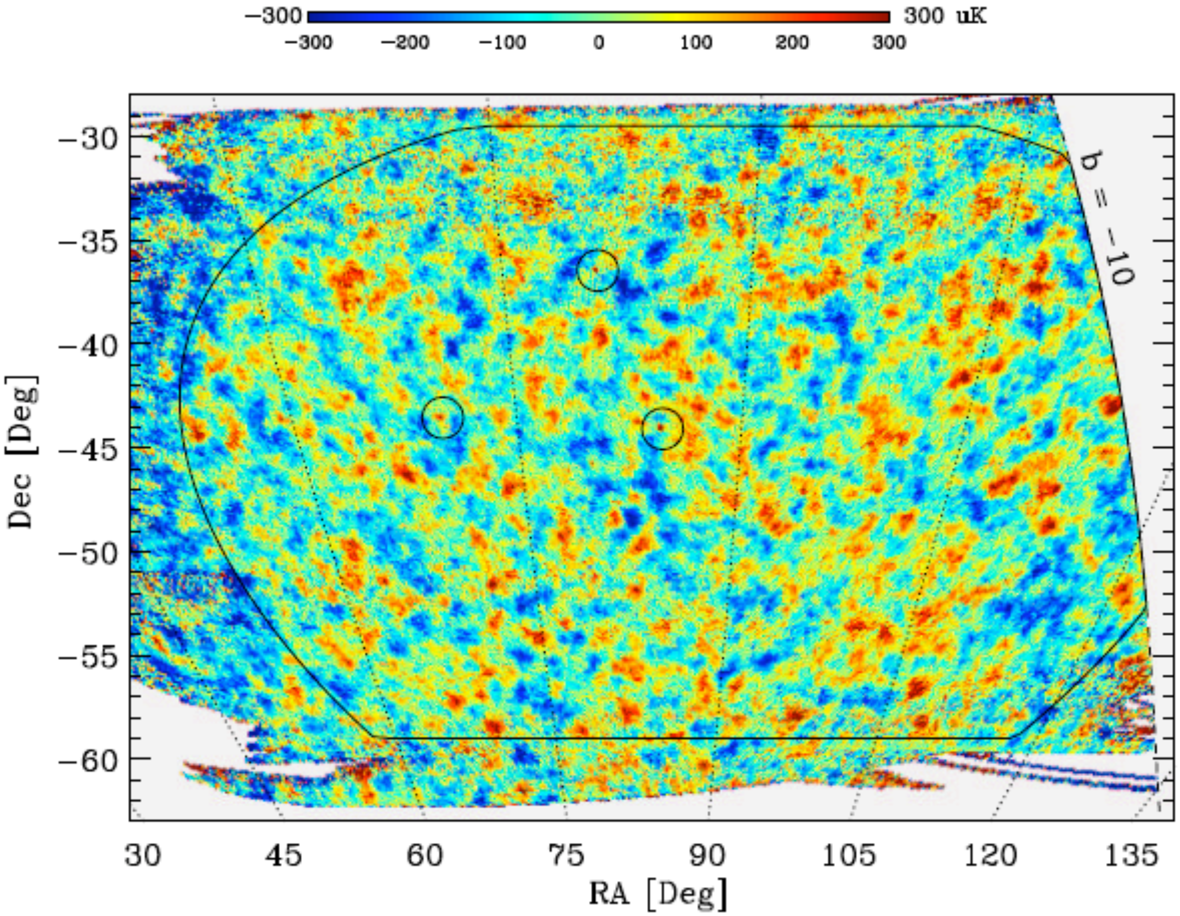
Saskatoon, TOCO [suborbital science and technology demonstration]



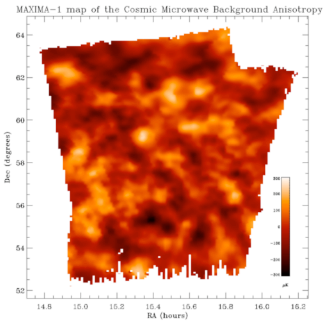
Boomerang, Maxima, Archeops [balloon borne science and technology demonstration]

Ebex, Spider, Piper and GB will lay the groundwork for the Inflation Probe

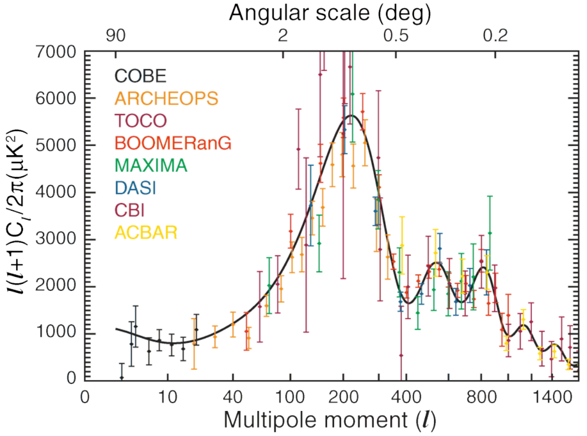
NASA's sub-orbital heritage



Boomerang98

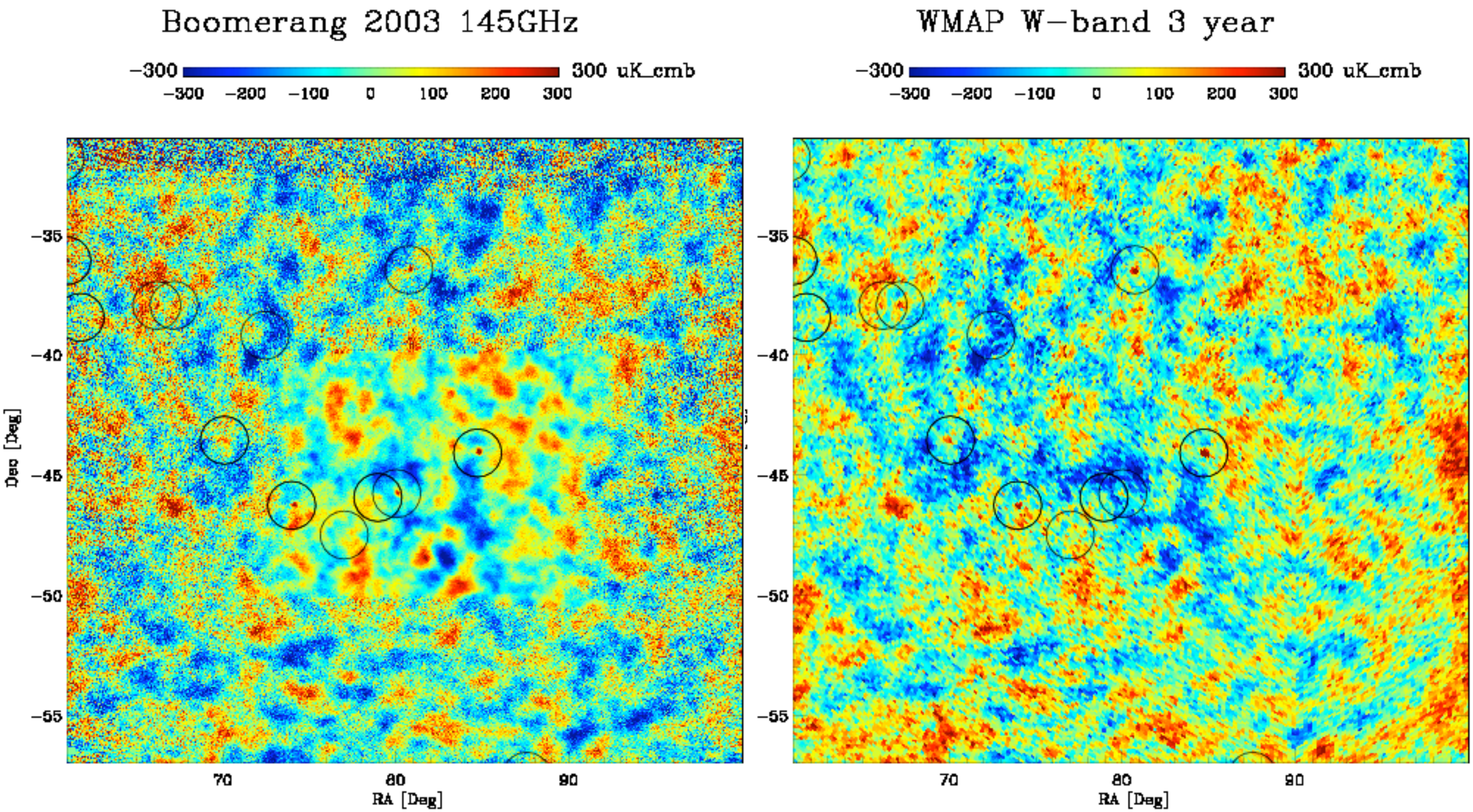


Maxima

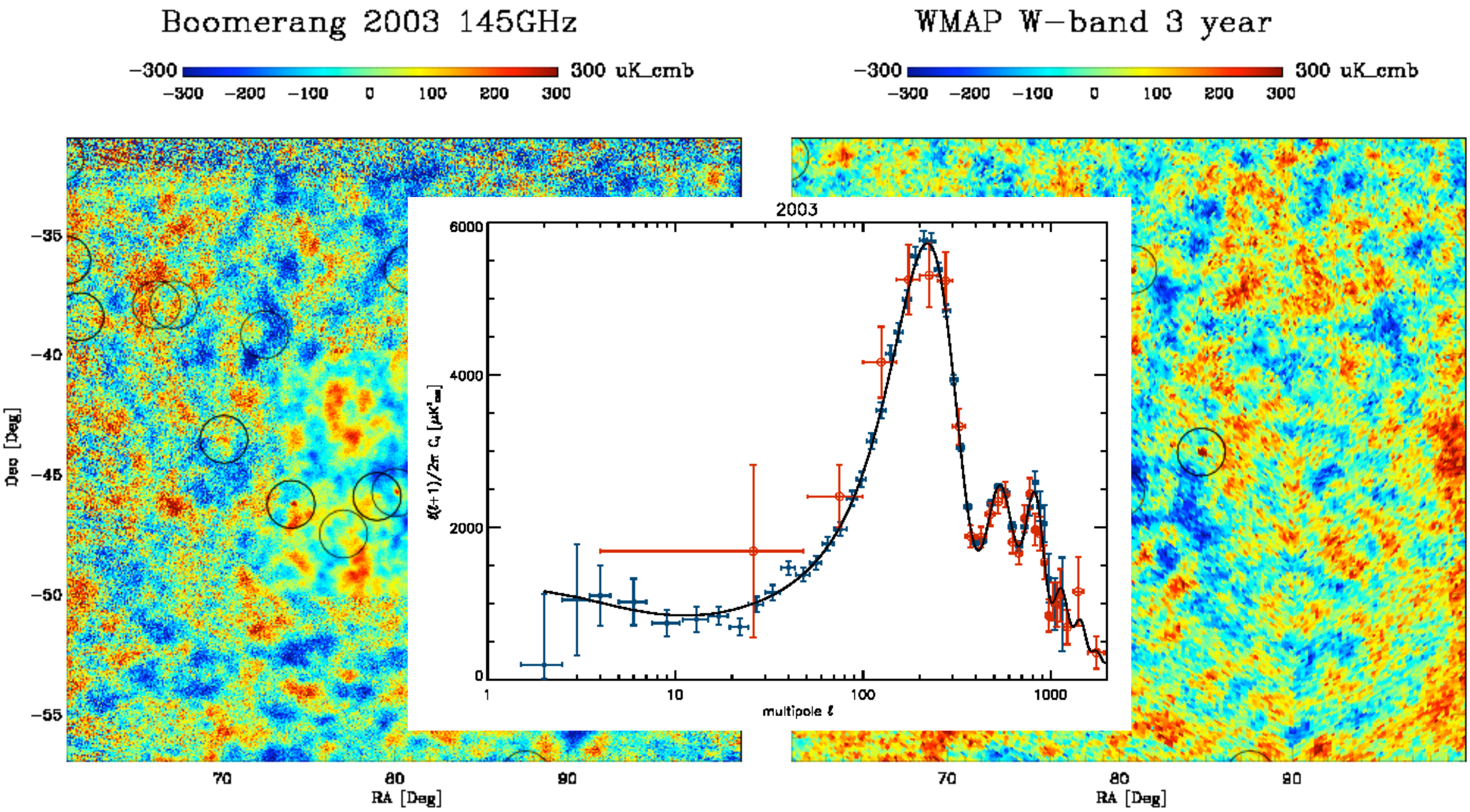


Hinshaw et al (2003)

NASA's sub-orbital heritage



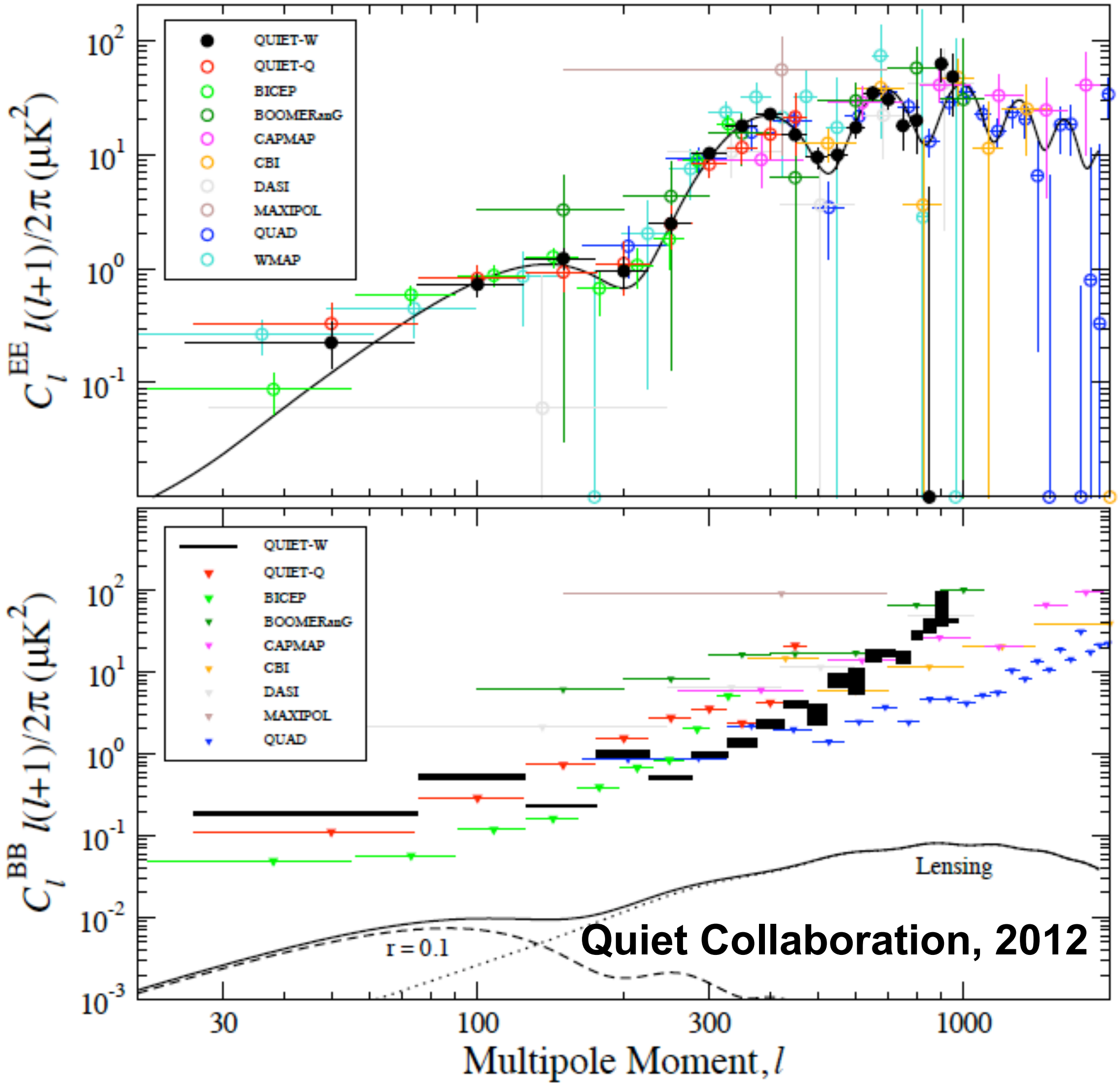
NASA’s sub-orbital heritage



Status of CMB Polarization Observations

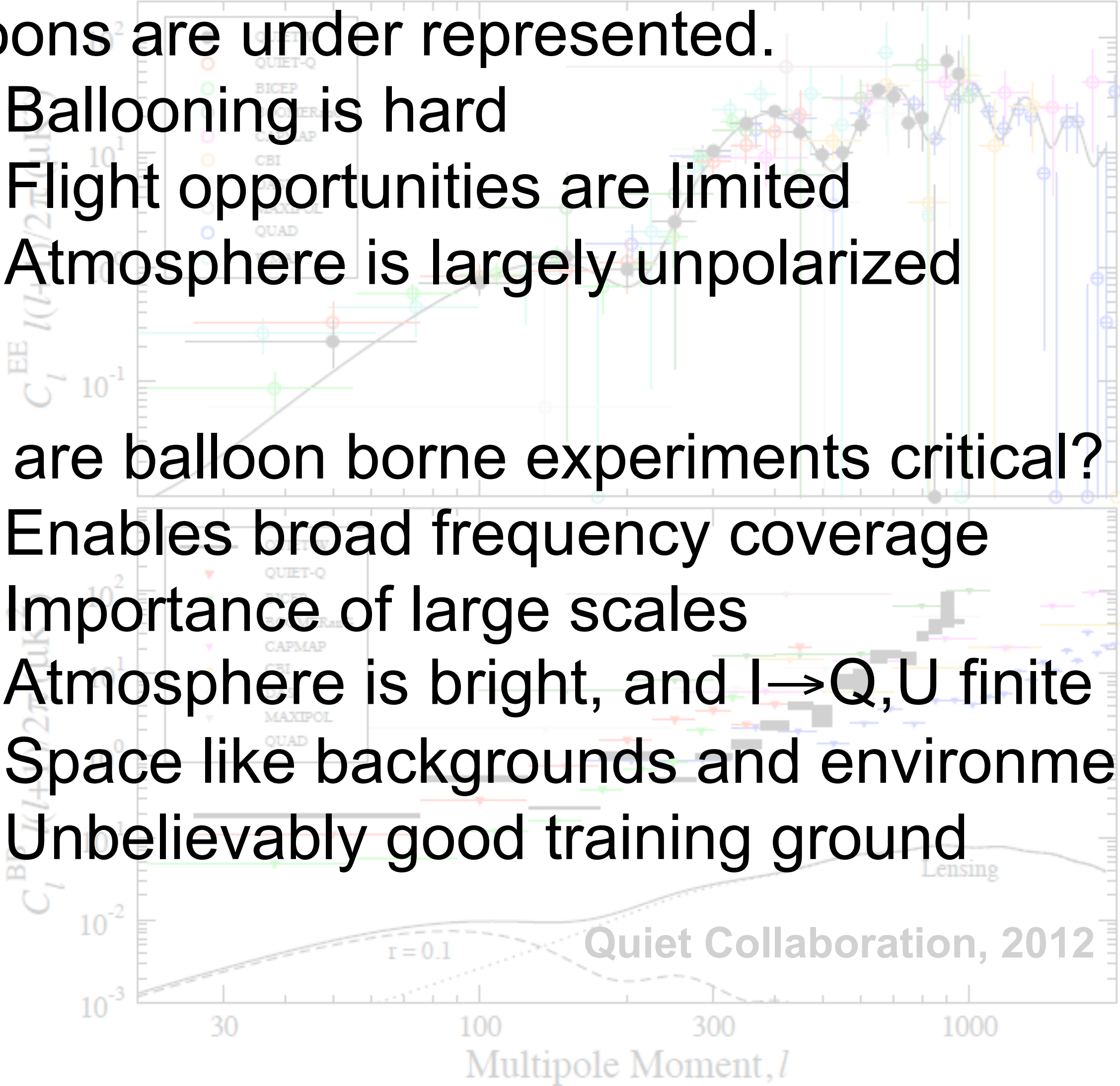
Balloon:
- Boomerang
- Maxipol
- Ebex
- Spider
- Piper

Ground:
- DASI
- CBI
- QUAD
- Bicep1/2
- CAPMAP
- QUIET
- Keck Array
- ABS
- PolarBear
- CLASS



Quiet Collaboration, 2012

Observational Status



Balloon:
Boomerang
Maxipol
Ebex
Spider
Piper

Ground:
DASI
CBI
QUAD
Bicep1/2
CAPMAP
QUIET
Keck Array
ABS
PolarBear
CLASS

Balloons are under represented.

- Ballooning is hard
- Flight opportunities are limited
- Atmosphere is largely unpolarized

Why are balloon borne experiments critical?

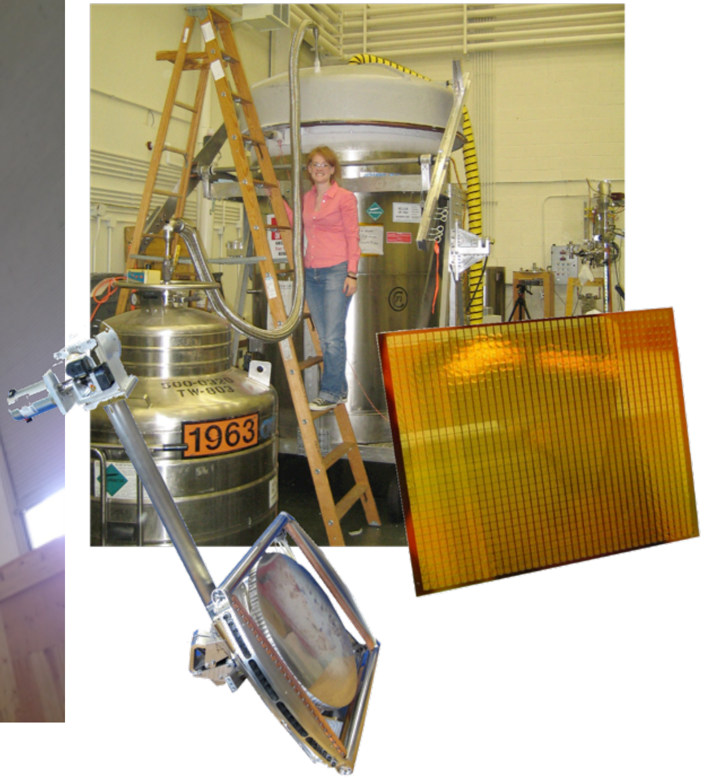
- Enables broad frequency coverage
- Importance of large scales
- Atmosphere is bright, and I→Q,U finite
- Space like backgrounds and environment
- Unbelievably good training ground

Contemporary Balloon Borne CMB Polarization Experiments

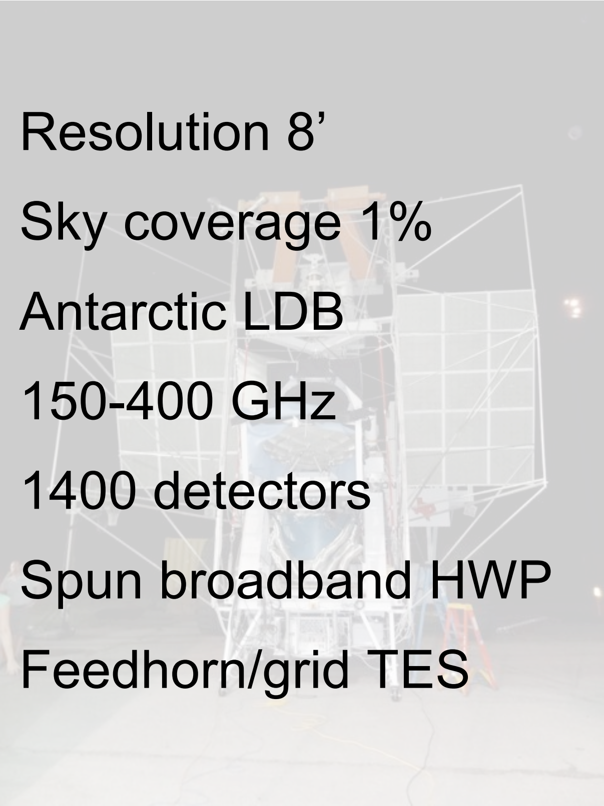
EBEX

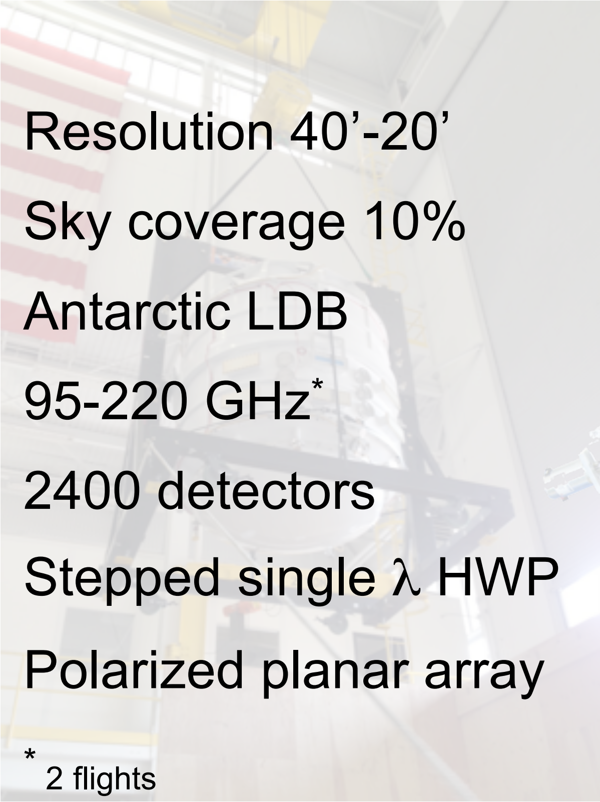
Spider

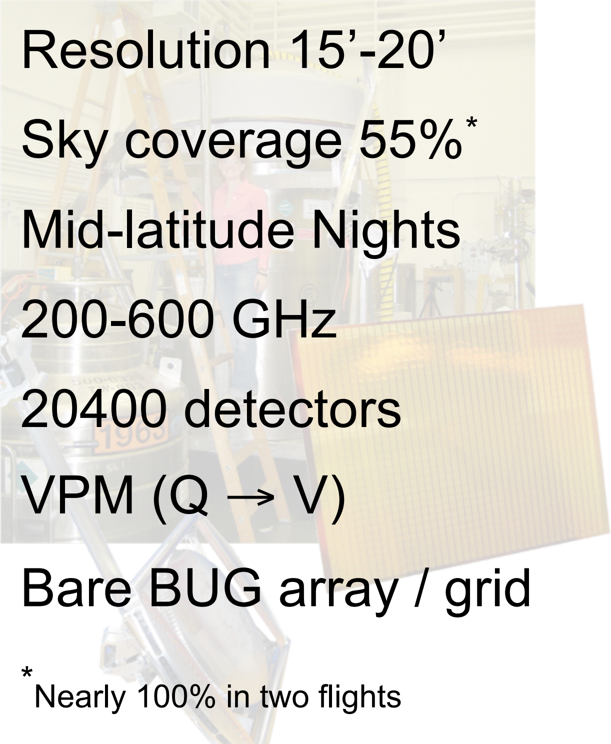
Piper



Contemporary Balloon Borne CMB Polarization Experiments

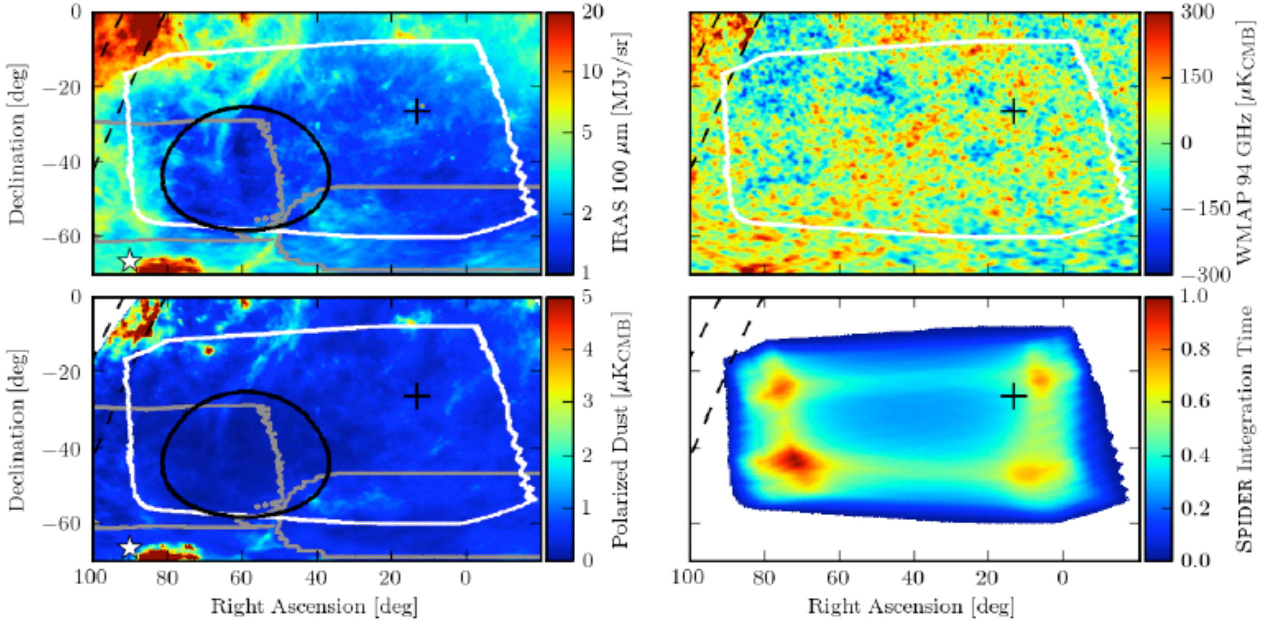


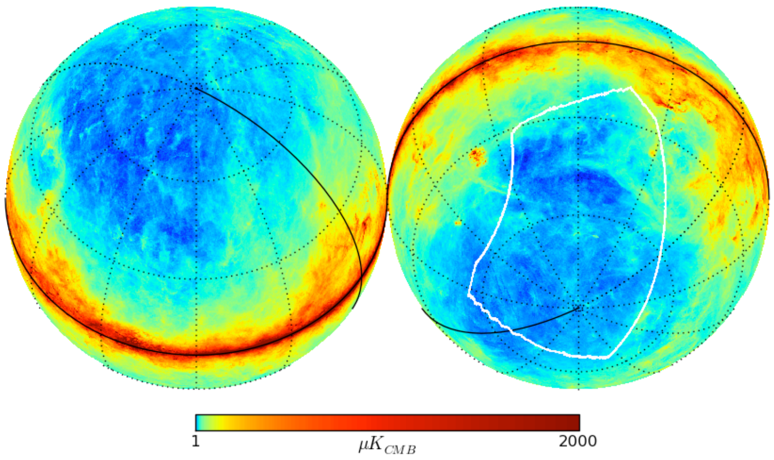




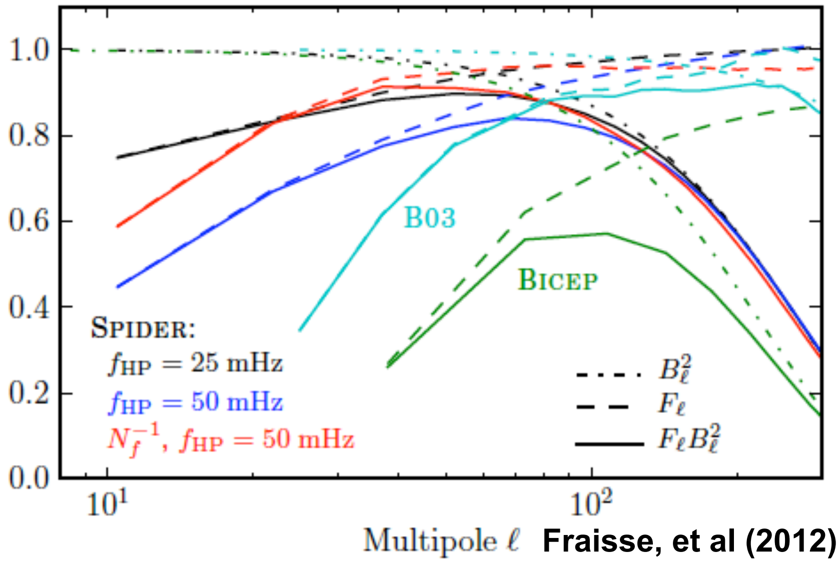
EBEX	Spider	Piper
Resolution 8’	Resolution 40’-20’	Resolution 15’-20’
Sky coverage 1%	Sky coverage 10%	Sky coverage 55%*
Antarctic LDB	Antarctic LDB	Mid-latitude Nights
150-400 GHz	95-220 GHz*	200-600 GHz
1400 detectors	2400 detectors	20400 detectors
Spun broadband HWP	Stepped single λ HWP	VPM (Q → V)
Feedhorn/grid TES	Polarized planar array	Bare BUG array / grid
	* 2 flights	*Nearly 100% in two flights
arxiv:1007.3672	arxiv:1106.3087	Kogut et al, SPIE 2012

Observational Strategy

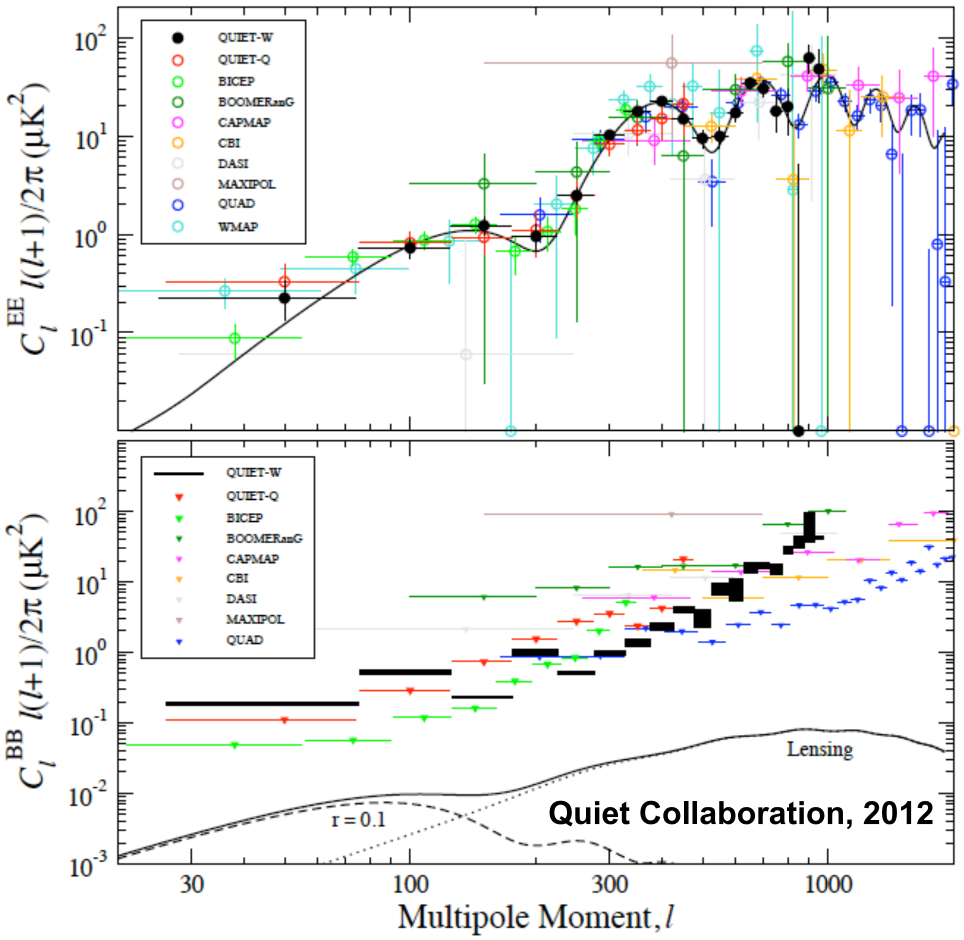




Observational Strategy



Fraisse, et al (2012)



Quiet Collaboration, 2012

f_{sky} ~ 10 % (balloon)

f_{sky} ~ 2 % (balloon)

f_{sky} ~ 2 % (ground)

Ebex Summary

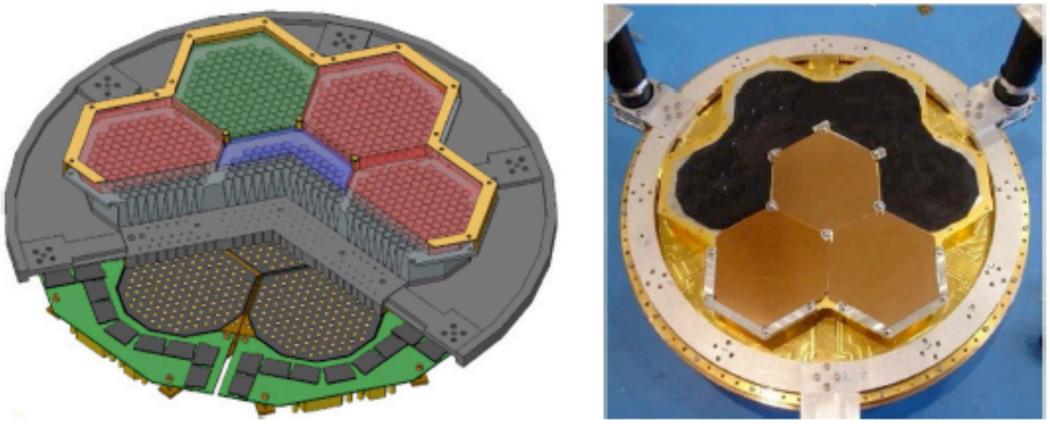
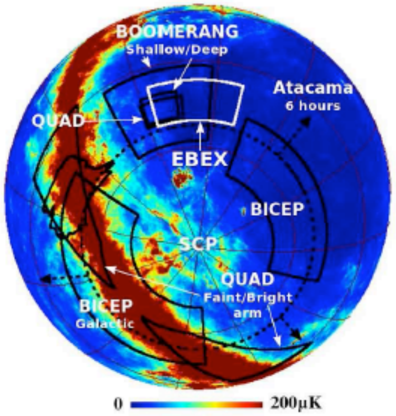

(a) (b)

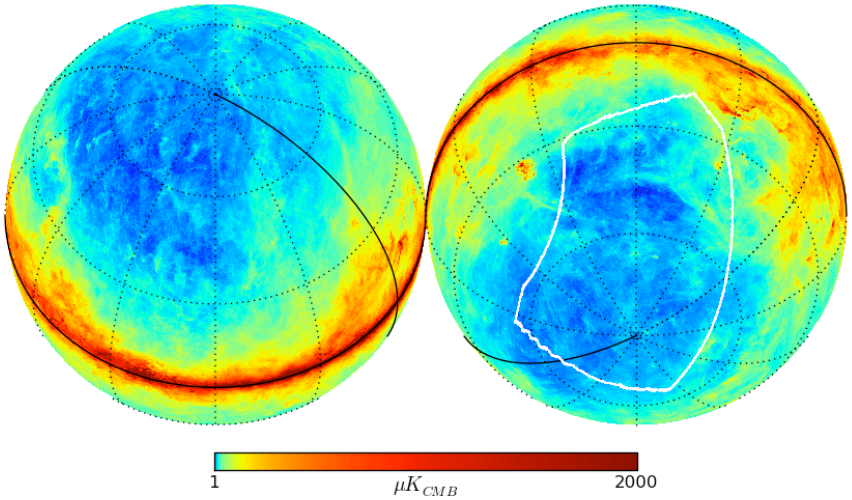
Figure 5. *a:* Three dimensional CAD drawing of the EBEX focal plane. The colors encode the frequency of the band defining filters; red is 150 GHz, green is 250 GHz, and blue is 410 GHz. *b:* The partially populated EBEX focal plane in the engineering flight configuration with three TES wafers and band defining metal mesh filters installed.

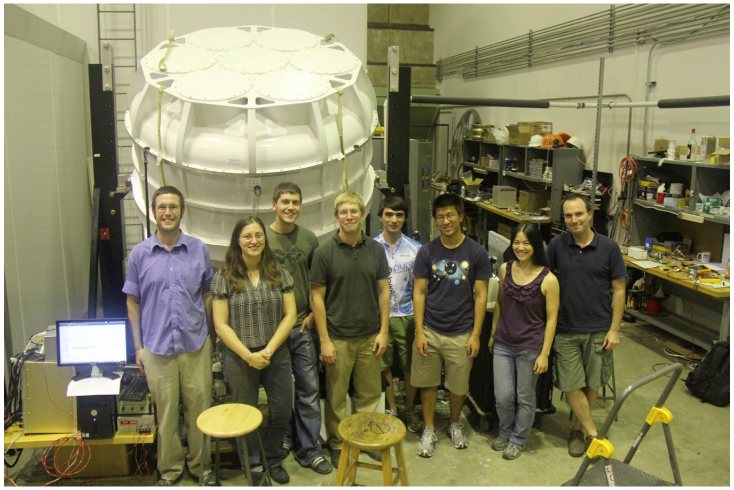


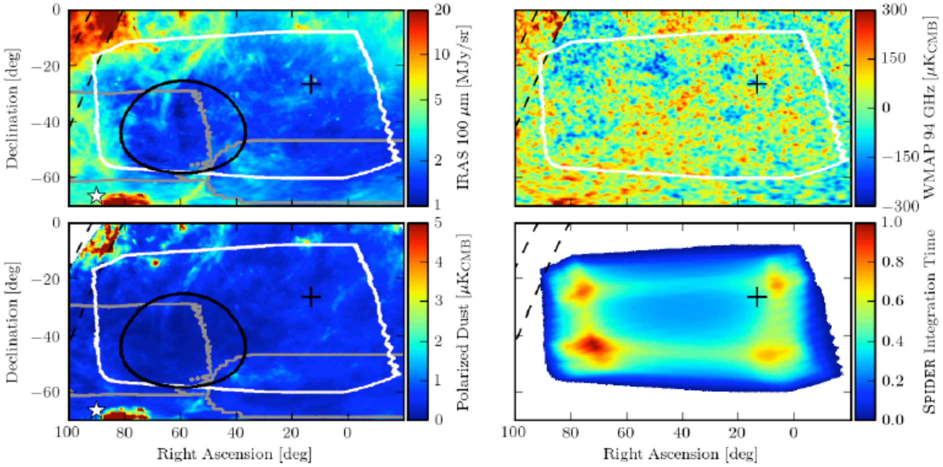
(a)

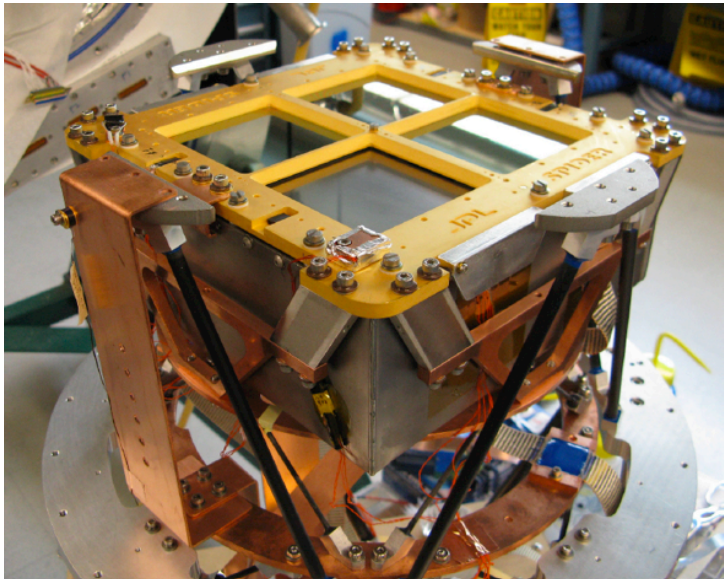
Nominal Band Frequencies (GHz)	150	250	410
Number of Detectors (Light)^a	768	384	280
Beam Size (arcmin)		8	
Error per beam size pixel^b (μK) Q/U, T		1.3, 0.9	
Total Sky Coverage (deg^2)		∼1% of the sky	
Flight Duration at Float^c (days)		14	

Spider Summary

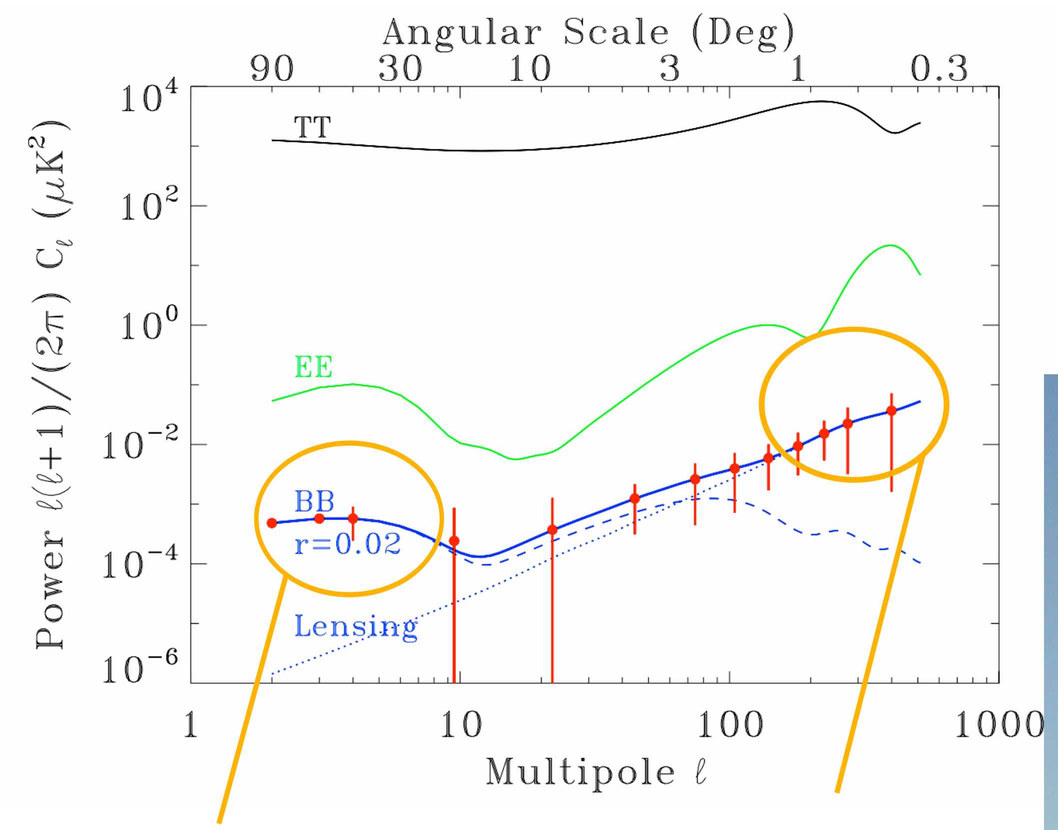








Piper Summary



l < 10: Amplitude of primordial signal

l > 200: Amplitude of lensing foreground

First flight scheduled 2013 (Ft Sumner, New Mexico)

Map linear and circular polarization

Map large and small scales

CMB and dust physics

Limit r < 0.007 (95% CL)

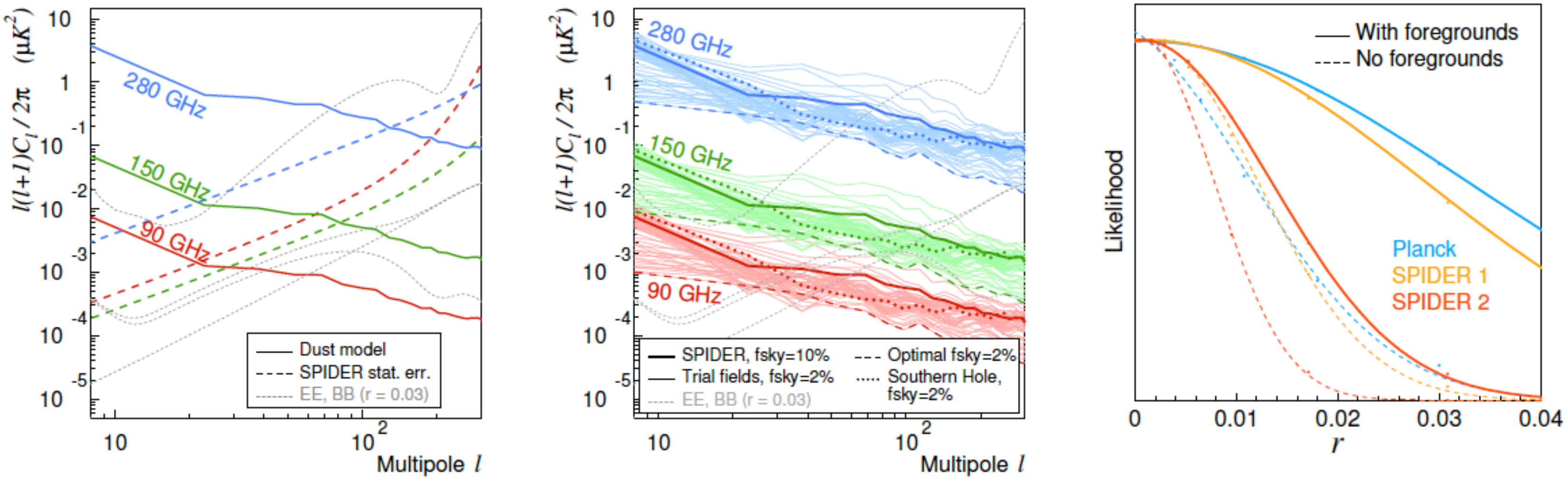
Milestones

If the simplest single field Inflation models apply, within 2-5 years

Multiple detections of B-mode power (~ few σ)

- Confirm expected angular spectrum
- Confirm expected electromagnetic spectrum
- Rigorous internal systematic tests
- Demonstration of statistical isotropy

Measure of the polarized fraction of high latitude Galactic emission



Role of the MoO

The potential of balloon-borne missions of opportunity (30-55 M$) offer several challenges to the community:

Requires a level of project management that is costly (6-10 M$)

Requires a degree of project management discipline that may be incompatible with the student-driven culture of the balloon community - perhaps threatens the valuable role of developing talent

Increased budget is offset by margins and higher overhead - it is (fiscally) challenging to structure the support of a broad portion of the community under this budget

Future mission definition

After the current set of sub-orbital experiments return, we will be able to speak sensibly about how future missions (including the Inflation Probe, perhaps MoO) should look:

Angular resolution → internal de-lensing necessary?

Frequency coverage → close packed, wide throw, how many bands?

Sky coverage → about 20% in the two hemispheres

Challenges for the future (and present!)

Experiments are dramatically more complicated than MSAM/Boomerang/Maxima/Tophat

Realistic development timelines extend beyond 5 years
(difficult to reconcile with academic timelines, 1M$/yr budget)

Development costs are growing - 1M$/yr is not enough to develop detectors and design/build the payloads.

Detector funding has helped to bridge the gap, but the level of funding recommended in the Decadal has not materialized

Ground based programs play a key role, and leverage funding from other agencies.

If the Inflation Probe is to follow in the tradition of COBE, WMAP and Planck (revolutionary science, managed cost/schedule risk), then sustained support of the sub-orbital program is required.

Extra Slides

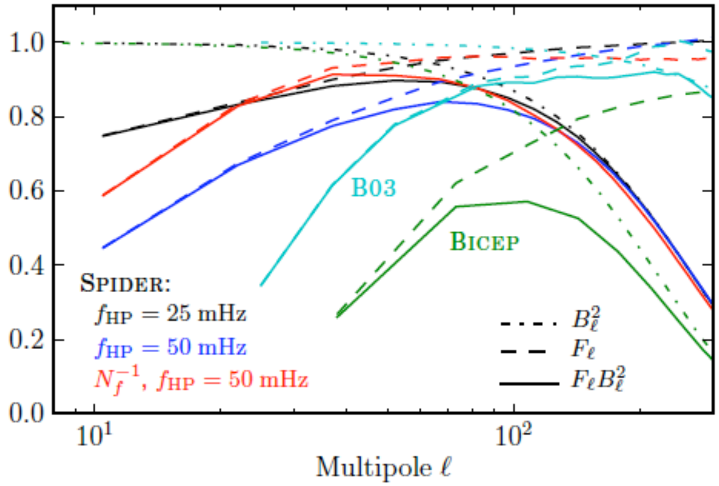


TABLE 4
SPIDER FPU FREQUENCY DISTRIBUTION AND PER-BAND CUMULATIVE NOISE

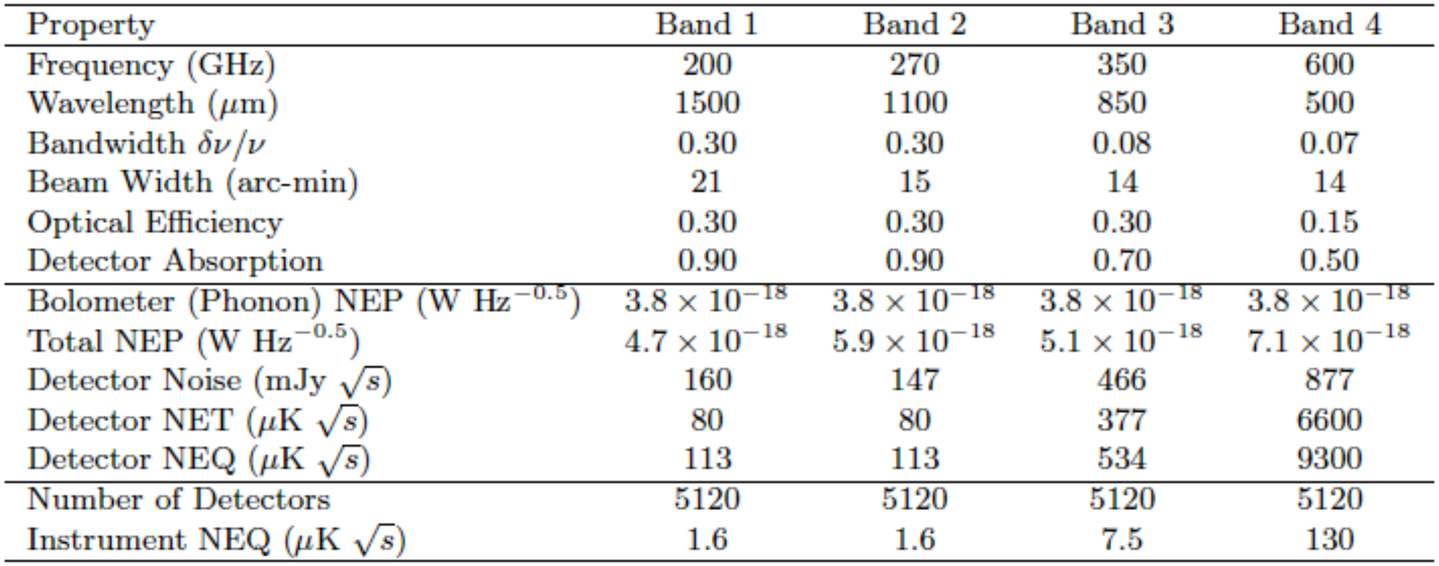
Flight	FPU Distribution	Cumulative Noise ($\mu K_{CMB}/deg^2$) 90 GHz	 150 GHz	 280 GHz
SPIDER 1	3 × 90 GHz; 3 × 150 GHz	0.27	0.20	···
SPIDER 2	2 × 90 GHz; 2 × 150 GHz; 2 × 280 GHz	0.21	0.16	0.62

TABLE 1
SPIDER OBSERVING BANDS, PIXEL AND DETECTOR COUNTS, AND SINGLE-DETECTOR AND SINGLE-TELESCOPE FPU SENSITIVITIES

Band Center (GHz)	Bandwidth (GHz)	Beam FWHM (arcmin)	Number of Spatial Pixels	Number of Detectors per FPU	Detector Sensitivity ($\mu K_{CMB}\sqrt{s}$)	FPU Sensitivity ($\mu K_{CMB}\sqrt{s}$)
90	22	49	144	288	150	10
150	36	30	256	512	150	7
280	67	17	256	512	380	18

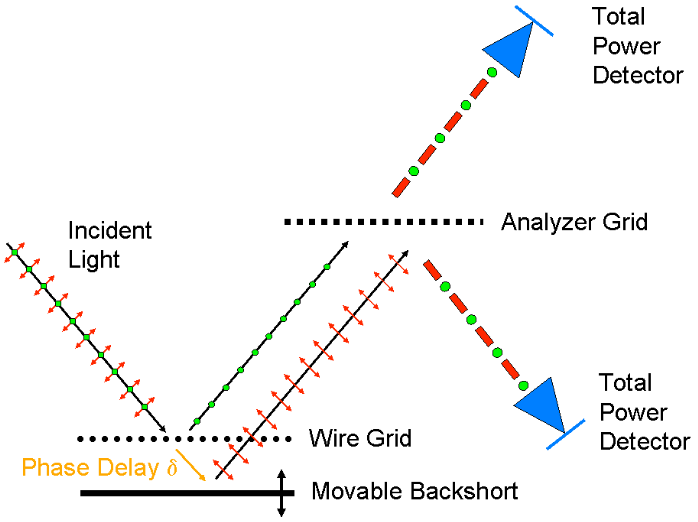
NOTE. — Each FPU sensitivity is obtained by dividing the corresponding single-detector sensitivity by $\sqrt{N_{det}}$, assuming a detector yield of 85%, slightly below the average of the delivered focal planes. The total experimental map depth at each frequency scales inversely as the square-root of the number of FPU-flights for that frequency. The quoted sensitivities at 90 GHz and 150 GHz are our current best estimate based on in-situ measurements of signal and noise using an aperture filling 4 K load. The 280 GHz sensitivity is scaled from the average in-flight sensitivity of BOOMERANG at 245 GHz and 345 GHz.

Table 1. Instrument Summary



Property	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	0.08	0.07
Beam Width (arc-min)	21	15	14	14
Optical Efficiency	0.30	0.30	0.30	0.15
Detector Absorption	0.90	0.90	0.70	0.50
Bolometer (Phonon) NEP (W Hz$^{-0.5}$)	3.8×10^{-18}	3.8×10^{-18}	3.8×10^{-18}	3.8×10^{-18}
Total NEP (W Hz$^{-0.5}$)	4.7×10^{-18}	5.9×10^{-18}	5.1×10^{-18}	7.1×10^{-18}
Detector Noise (mJy $\sqrt{s}$)	160	147	466	877
Detector NET (μK $\sqrt{s}$)	80	80	377	6600
Detector NEQ (μK $\sqrt{s}$)	113	113	534	9300
Number of Detectors	5120	5120	5120	5120
Instrument NEQ (μK $\sqrt{s}$)	1.6	1.6	7.5	130

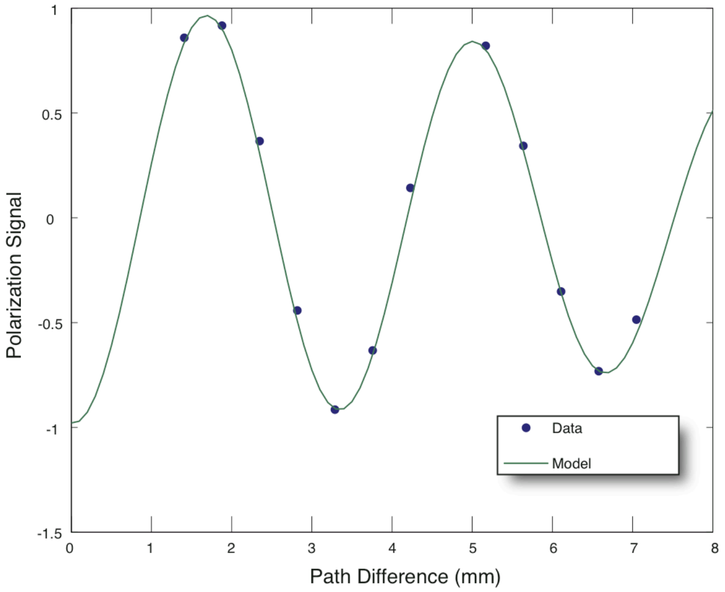
Variable-Delay Polarization Modulator

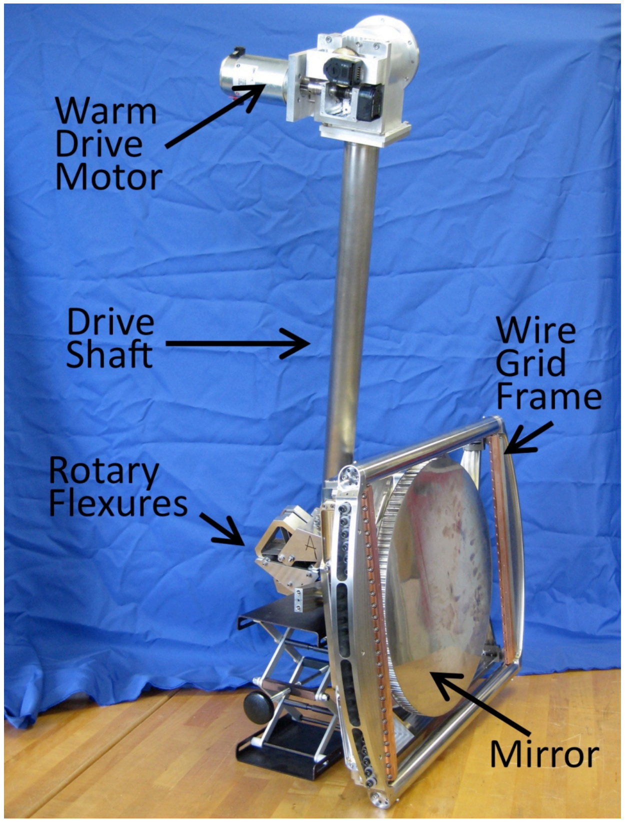


[illegible]

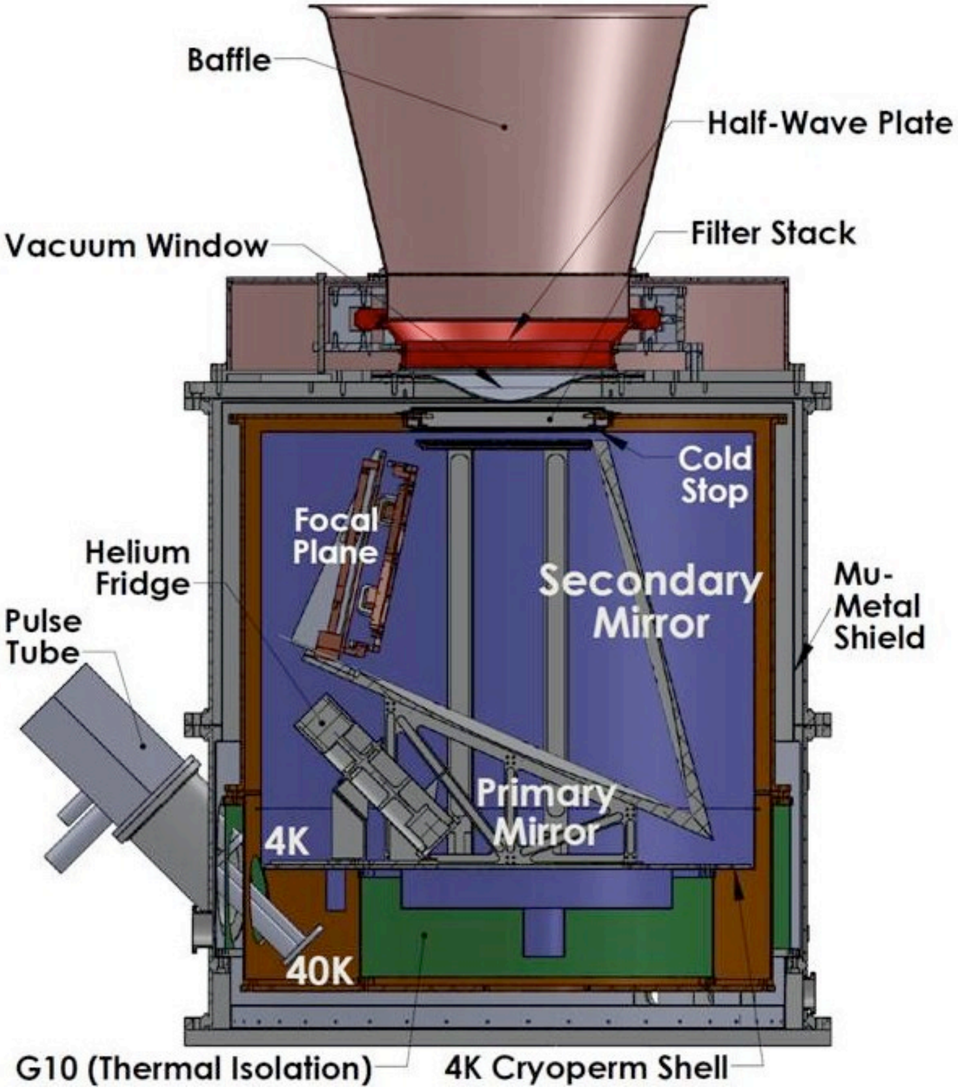
Measure linear and circular polarization!

[illegible]

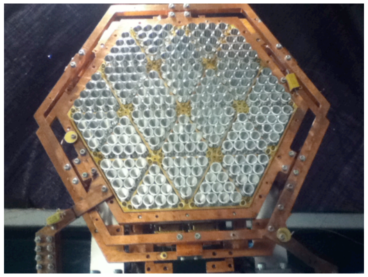




Atacama B-mode Search (ABS)



- 240 150-GHz feedhorns
- 480 TES bolometers at 300 mK
- Low foreground parts of sky
- ~ 35 microK rt(s)
- Cold mirrors
- Warm continuously rotating HWP
- Atacama desert: 5100 m elevation
- Target r < 0.03
- Status: taking data!



FOCAL PLANE