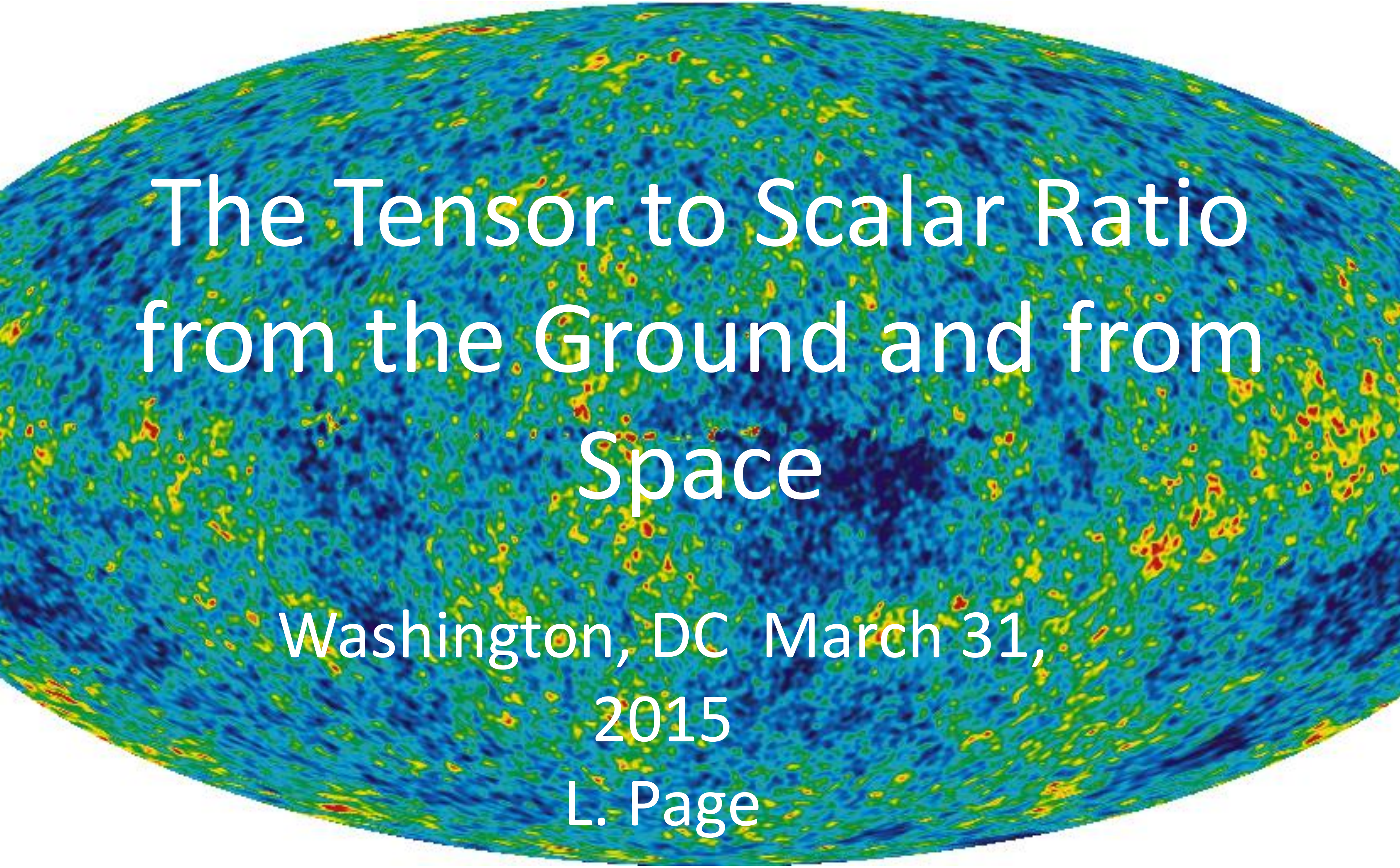


The Tensor to Scalar Ratio from the Ground and from Space

Washington, DC March 31, 2015

L. Page

Why?

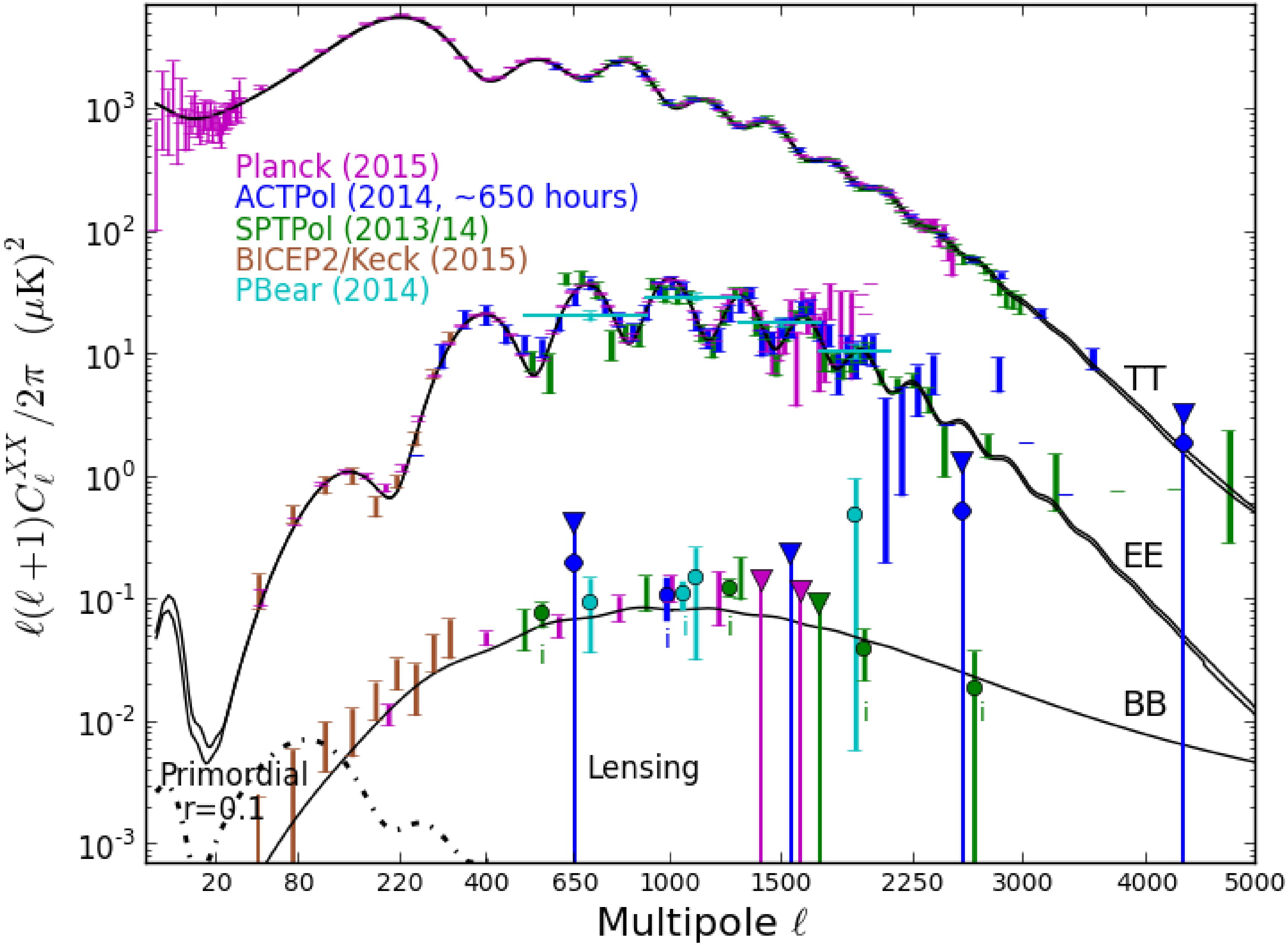
Measuring *primordial* CMB B-modes is likely our best opportunity for directly observing gravity operating on a quantum scale.

A detection would revolutionize fundamental physics.

The importance and challenges are well known.

We have a well-established model standard model of cosmology.

- Universe is flat, and described by six cosmological parameters: $\Omega_b h^2$, $\Omega_c h^2$, Ω_Λ, τ, n_s, Δ_R^2
- **Perturbations (*i.e.* fluctuations) are super-horizon, nearly scale invariant, Gaussian, and adiabatic.**
- Theory of **General Relativity** describes gravity.
- The model is so good we can observe departures from it to determine the **sum of neutrino masses** and test GR among other things.



Planck (2015)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2/Keck (2015)
PBear (2014)
TT
EE
BB
Lensing
Primordial
r=0.1
$\ell(\ell+1)C_\ell^{XX}/2\pi \quad (\mu K)^2$
Multipole ℓ
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

Cosmological Purturbations I

$$C_\ell \propto \int P(k)T^2(k)dk$$

Initial power spectrum from, e.g., inflation

Transfer function (acoustic oscillations etc.)

Scalars: $\delta\phi/\phi$, $\mathrm{P(k)} \propto k^{n_s}$

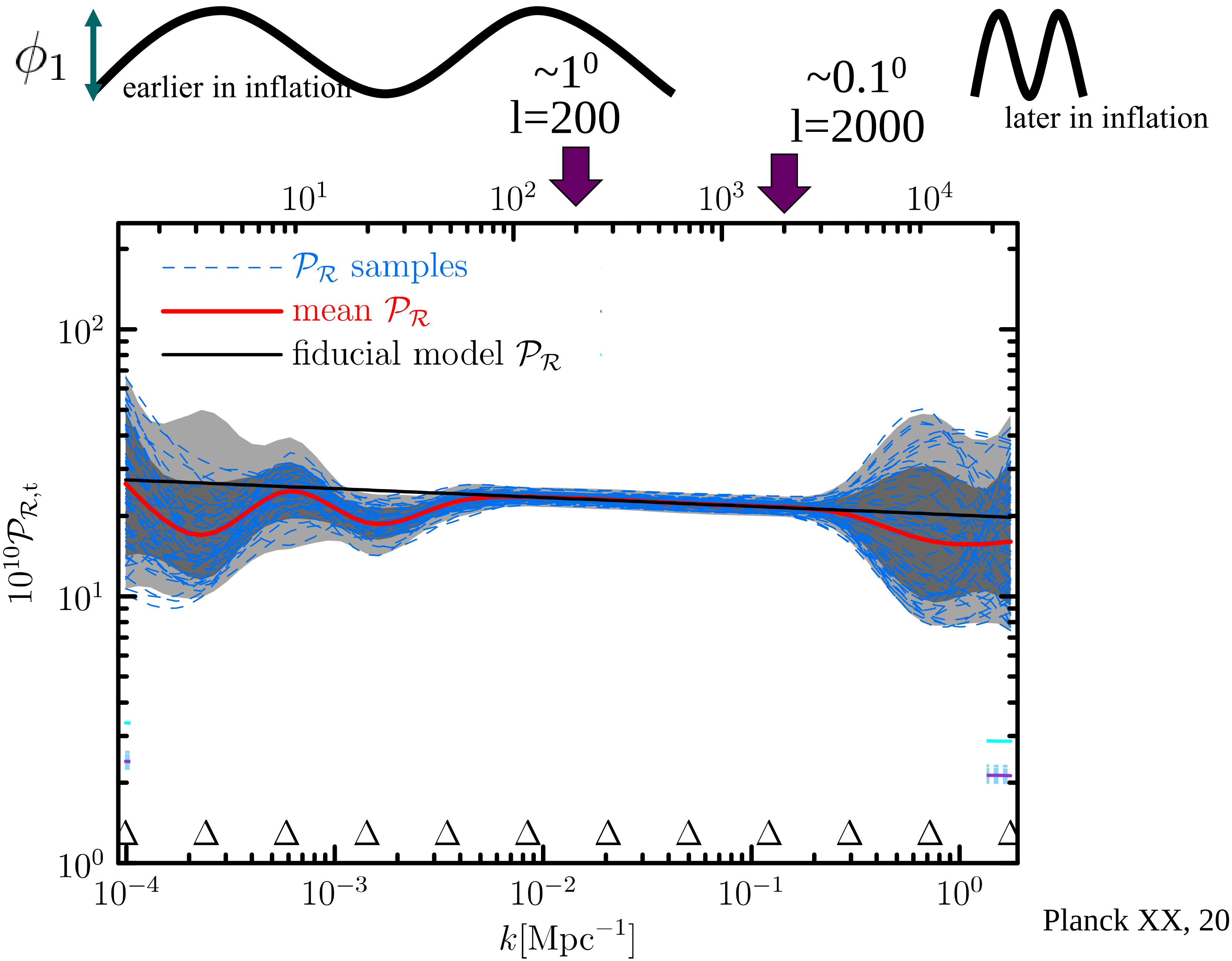
Temperature

E polarization

n_s, the scalar spectral index, is a prediction of early universe theories.

n_s = 0.986 +/- 0.006 (Planck '15)

P(k)/k



Planck XX, 2015

Cosmological Perturbations II

Tensors: *h* (GW strain)

- Temperature
- E-mode polarization
- B-mode polarization

$$r = \frac{\mathrm{Var(Tensors)}}{\mathrm{Var(Scalars)}}$$

"Generic" (1980's) predicted r~0.2

r<0.1 Planck (95% cl)

- In tension with simple models of inflation.

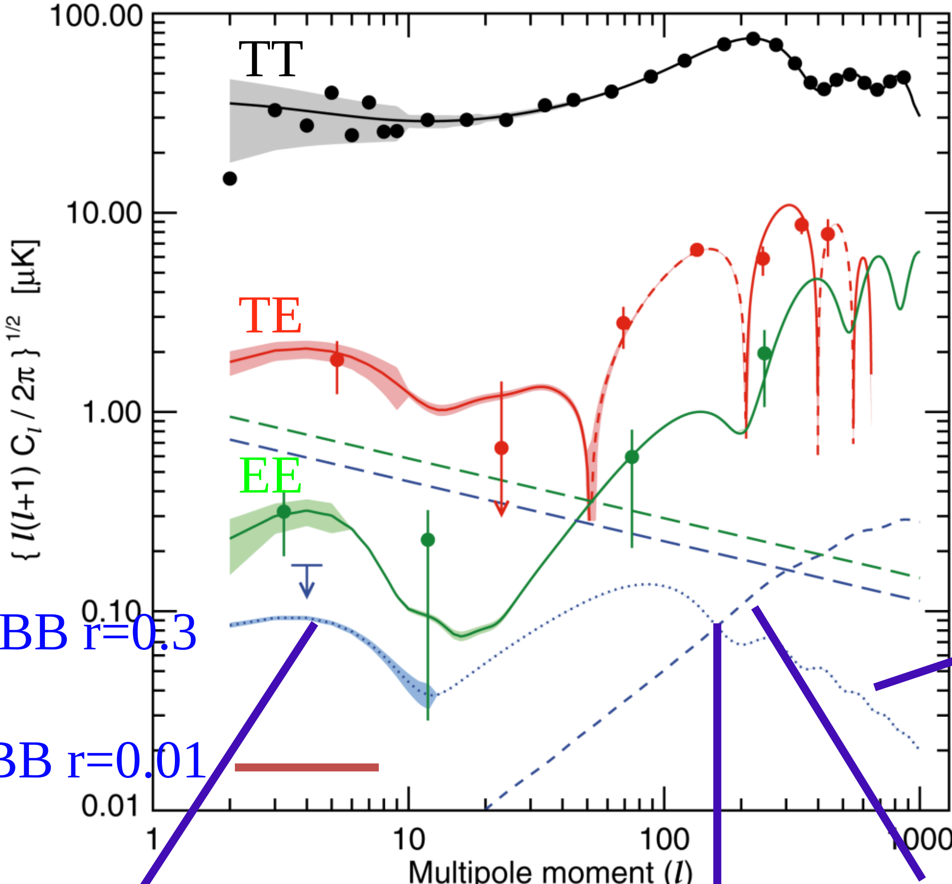
r~0.01 (95% cl)

- "Sure bet" from balloons/ground.

r~0.0001, 0.003, 0.1

- Some current predictions.

Polarization Landscape from the Weiss Report: 2005/6



EE from decoupling

EE from reionization

Approx EE/BB foreground averaged over 75% of the sky.

BB from GWs

BB r=0.3

BB r=0.01

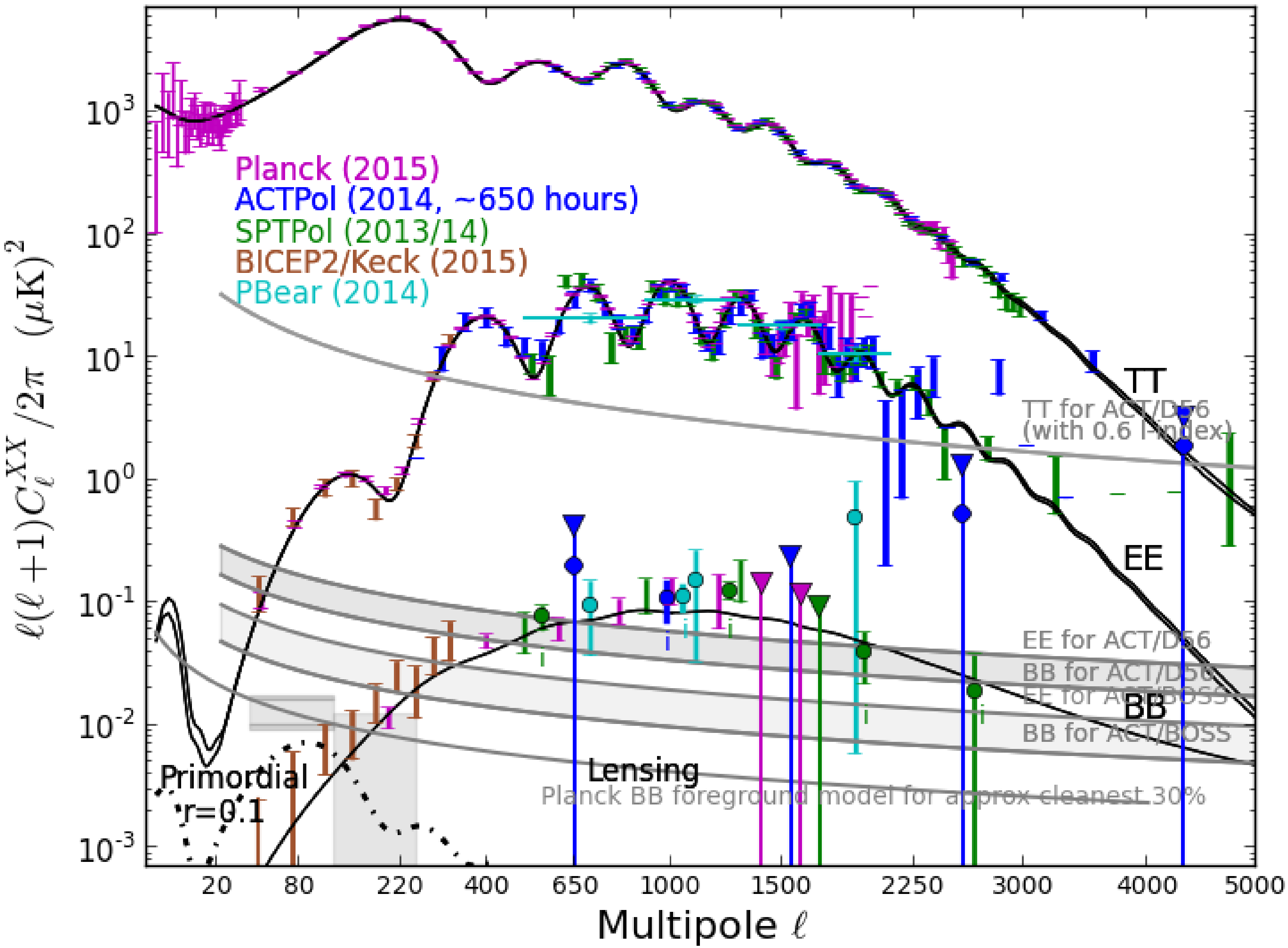
G-waves decay once inside the horizon.

BB from lensing of E-modes (not primordial)

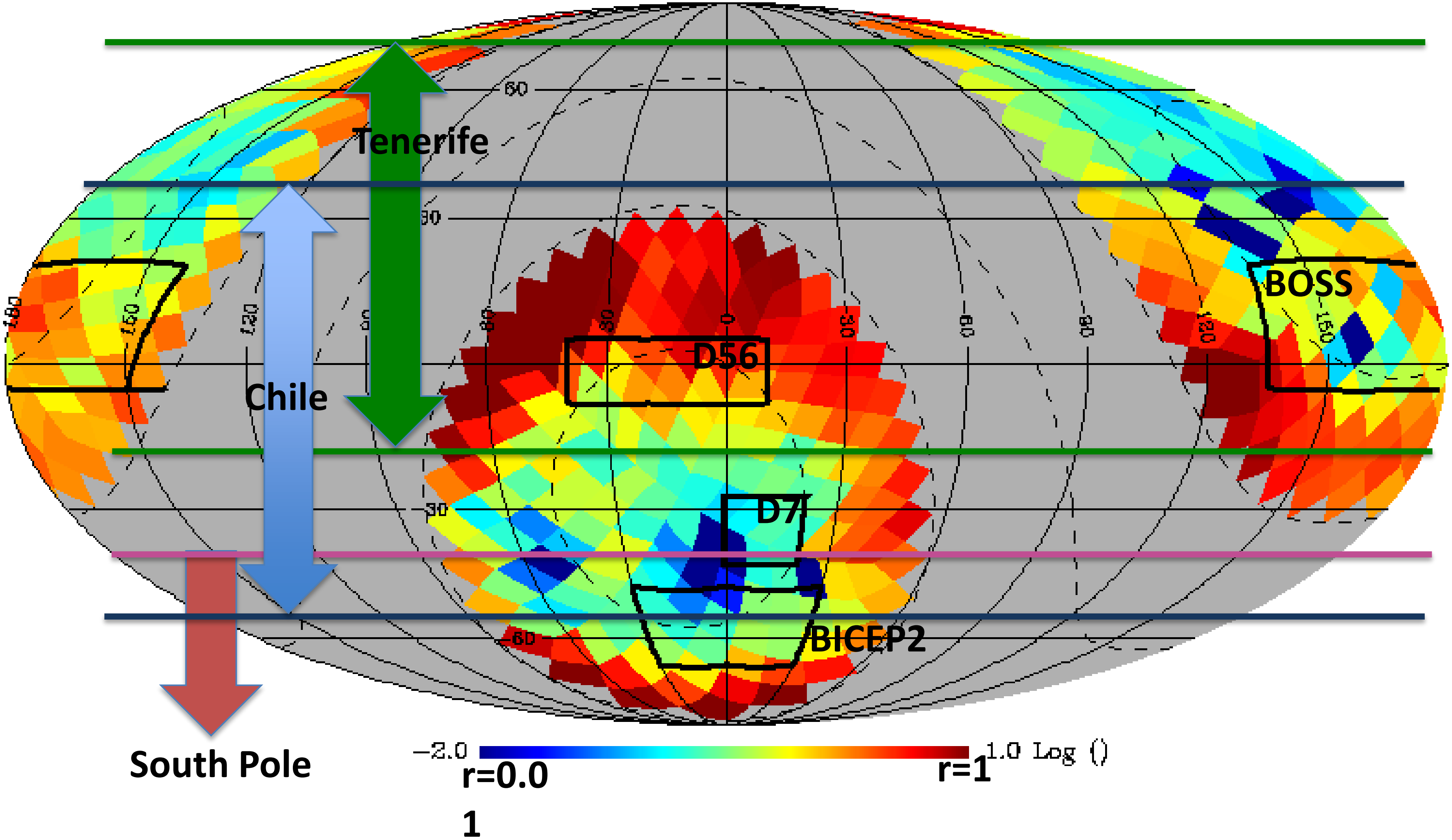
Reionization peak (z_r=10)

Horizon size at decoupling ($\theta_H \sim 1.2^0$)

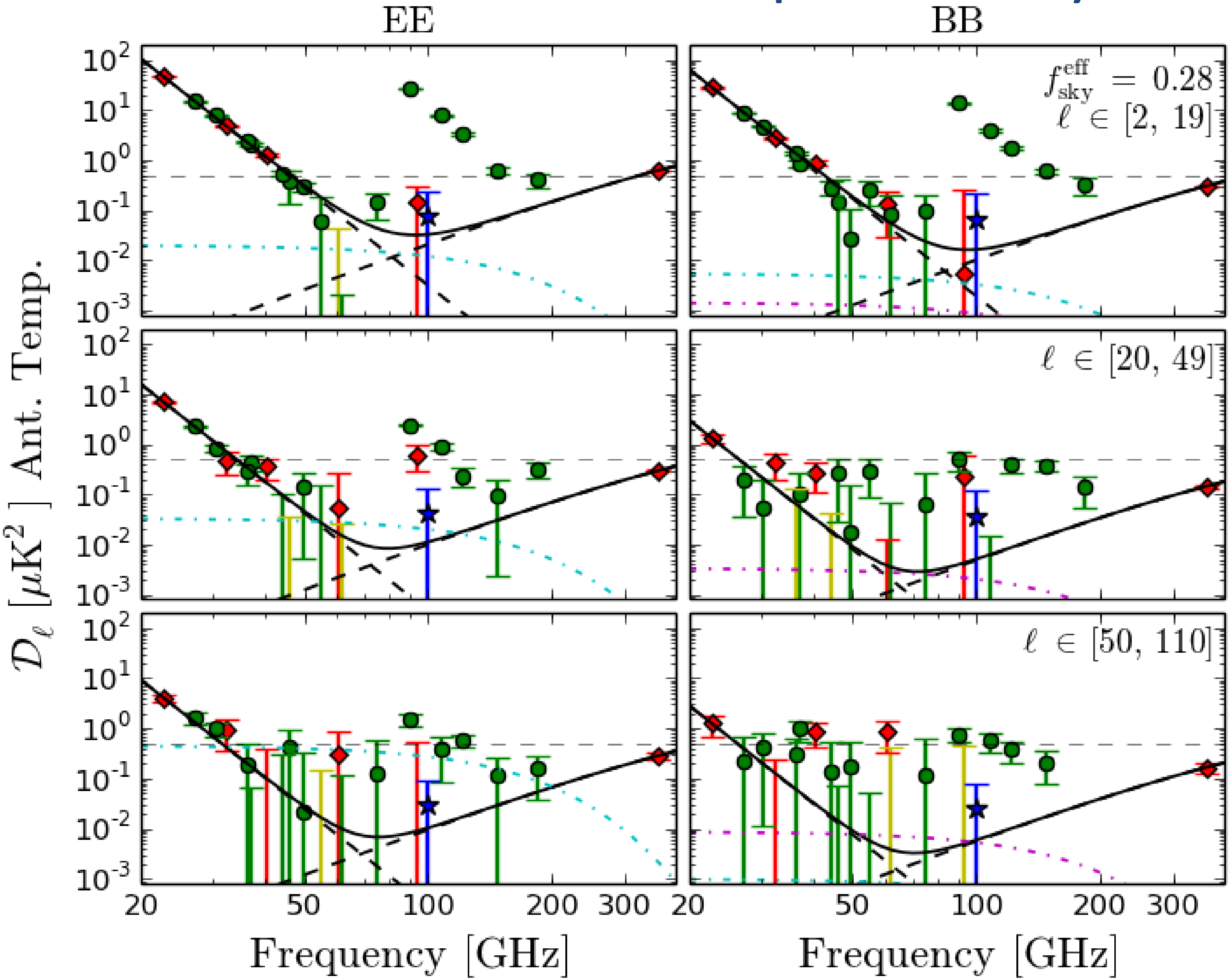
Foregrounds at 150 GHz



Planck guide to low dust polarization level in effective r



From Steve Choi--preliminary

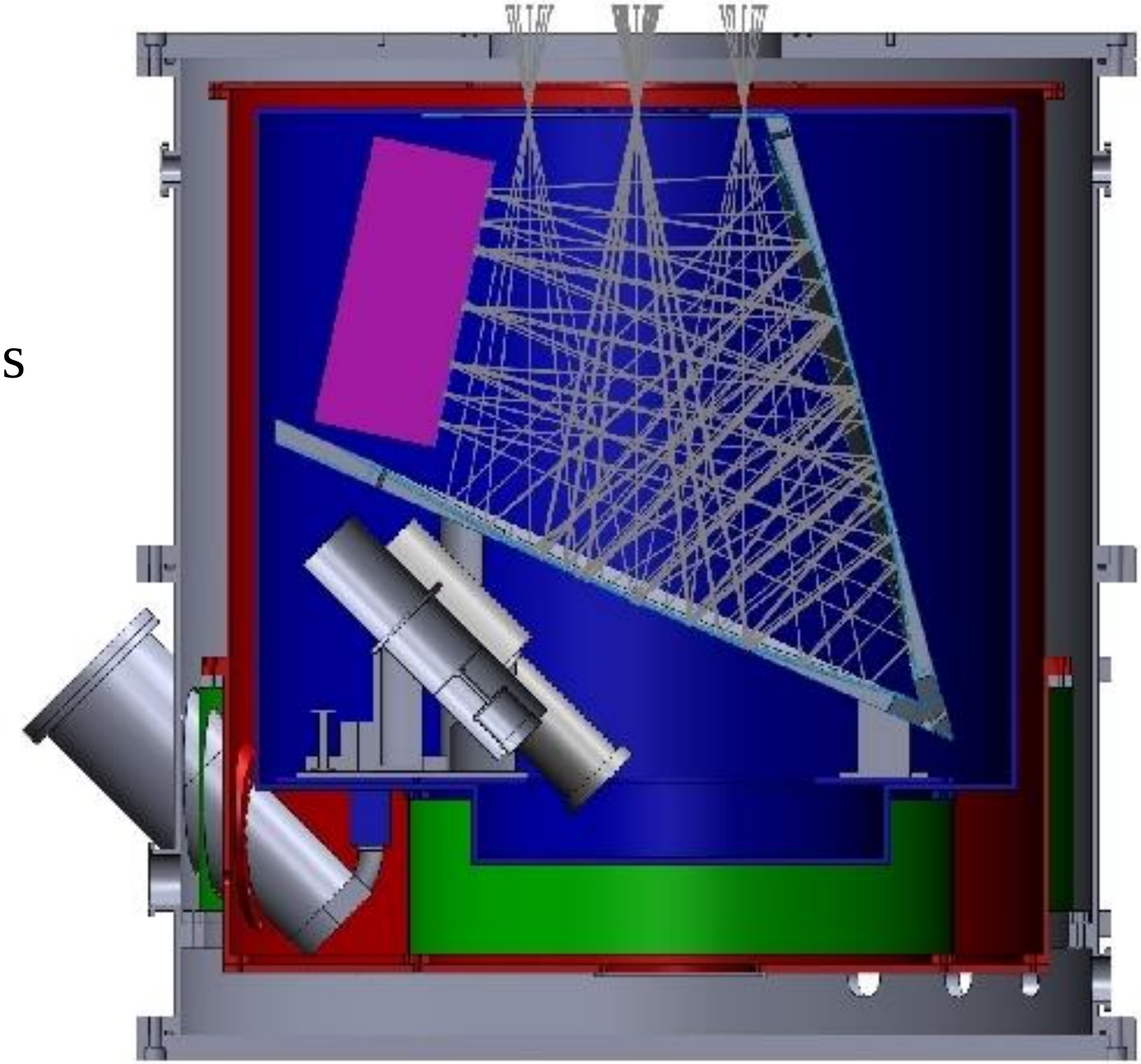


Ground Based

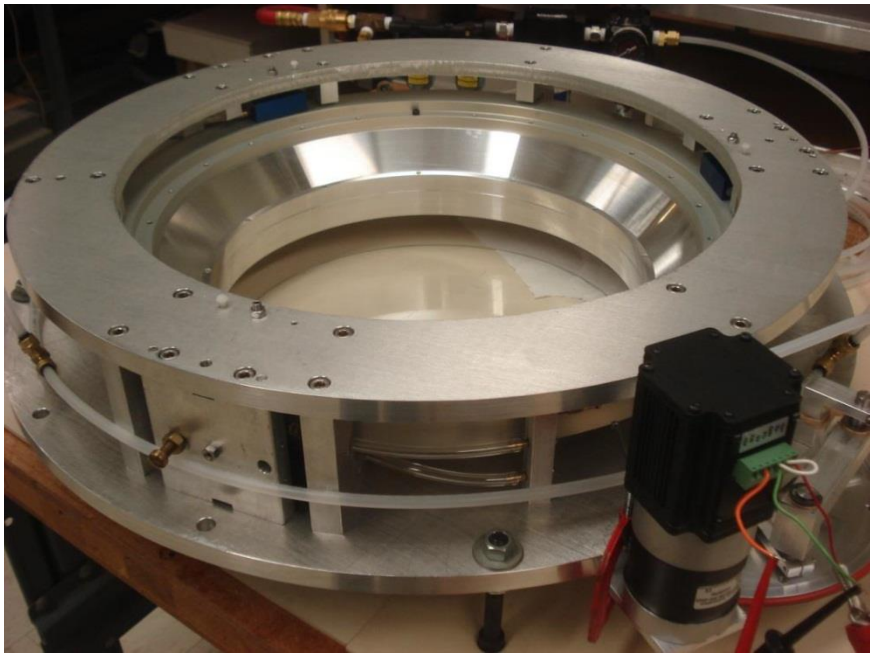
		Have data		Current or planned freqs
	Chile			
	ABS			145 GHz
HR	ACTPol/AdvACt			30, 40, 90, 150, 230 GHz
HR	POLARBEAR			90, 150 GHz
	CLASS			40, 90, 150 GHz
	Antarctica			
	BICEP/KECK			90, 150, 220 GHz
HR	SPTPol			90, 150 GHz
	QUBIC-Bolo int.	2016		90, 150, 220 GHz
	Elsewhere (for now)			
	B-Machine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

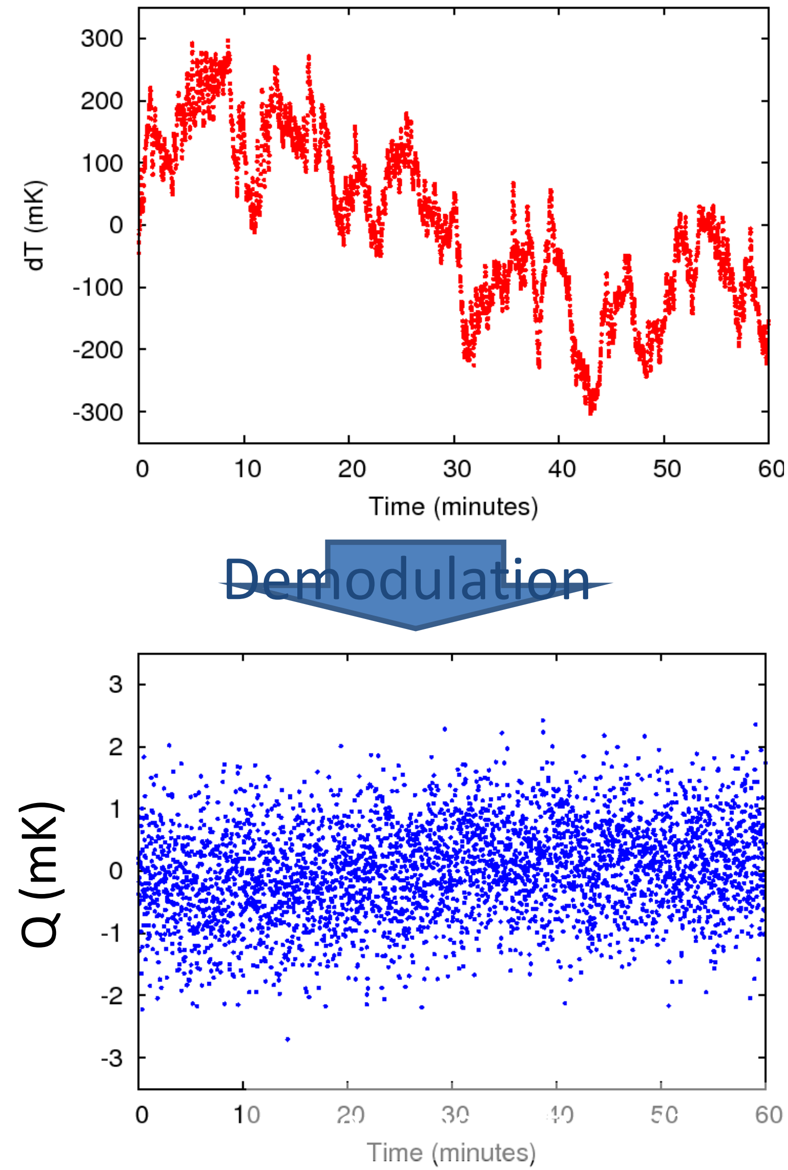
Atacama B-mode Search

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



Continuously 2.5 Hz rotating warm half-wave plate with ABS





Kusaka, Essinger-Hileman , et al 2014

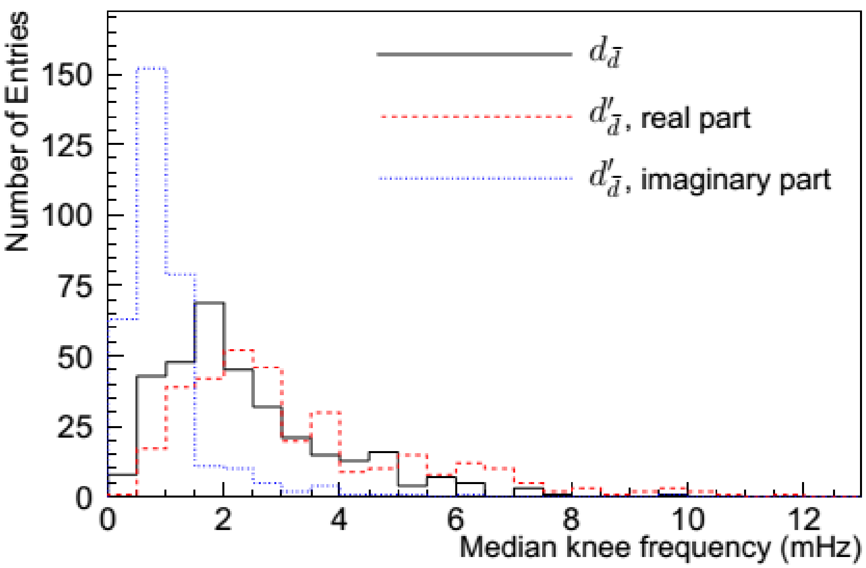
Demodulated timestream

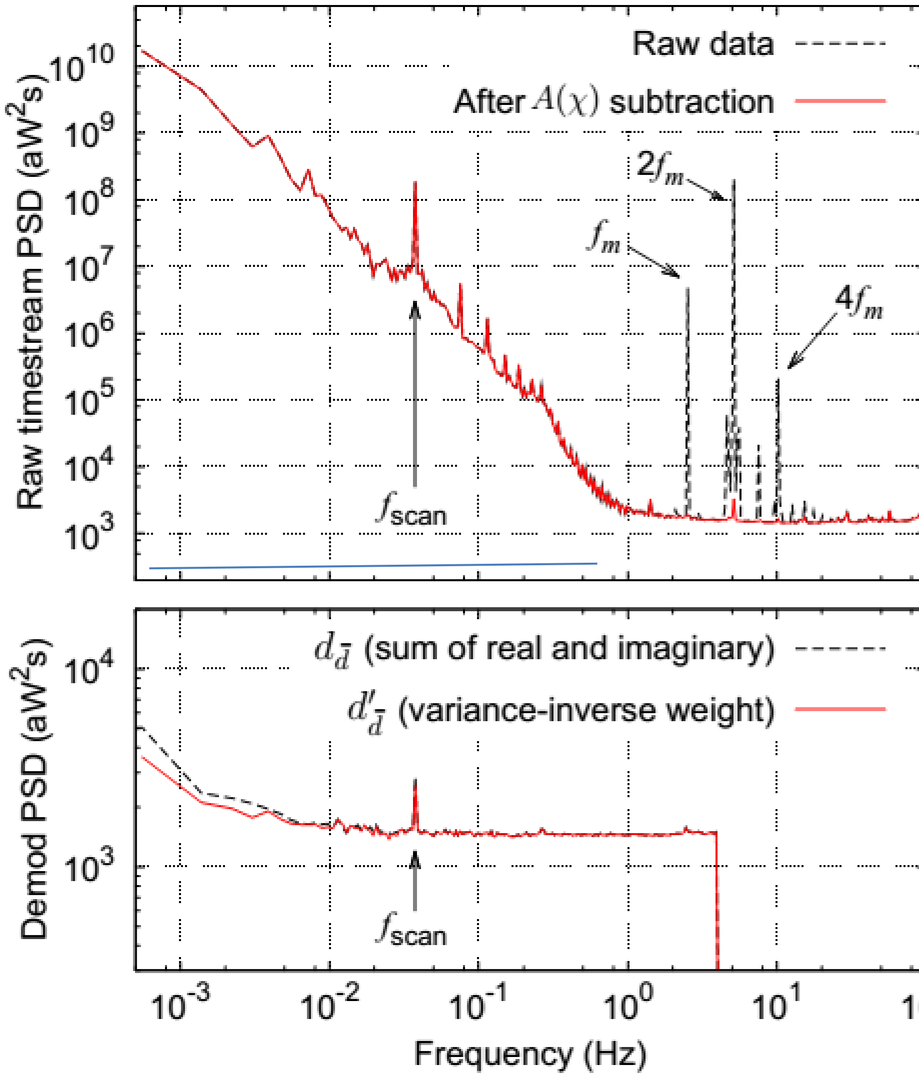
f_{knee}~ 1mHz

~1000 sec

~3^0 sky rotation

=>/~60

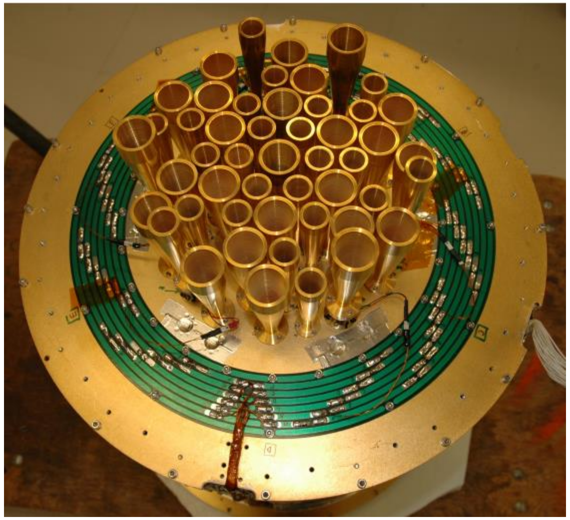


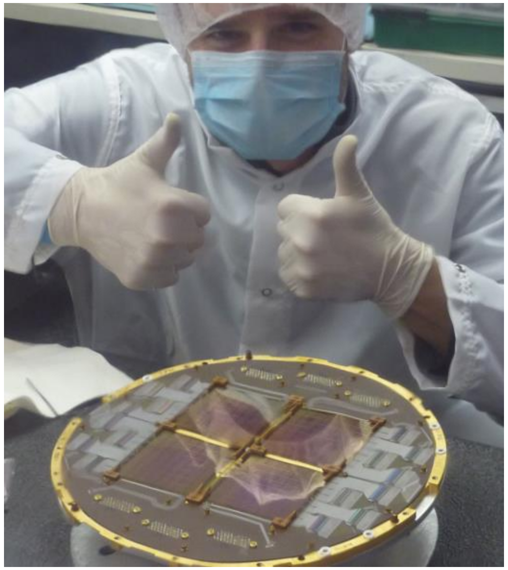


BICEP/Keck Experiments

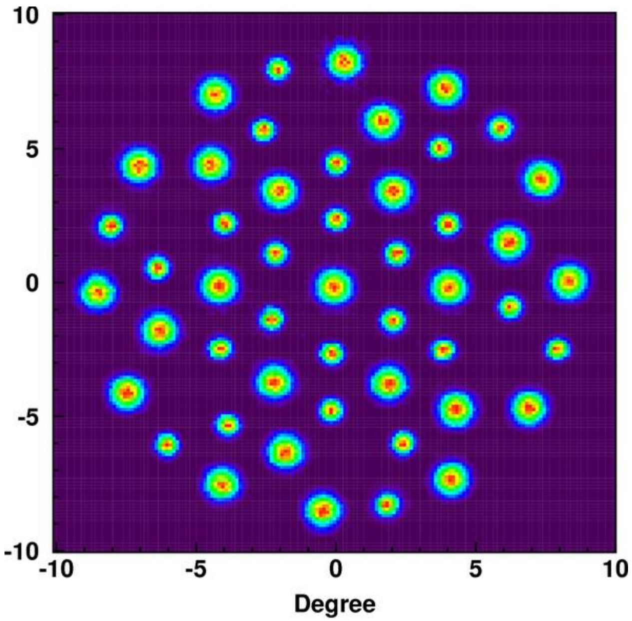
- BICEP1, observed 2006-2008
  - Initial result from first 2 seasons --> tightest constraint on r from B-modes:
    $r = 0.03 \pm 0.3$ $r < 0.72$ (95% conf.)   **Chiang et al. 2010 (0906.1181)**
  - Full 3-year results coming in 2011:   **Barkats et al.**
- BICEP2, observing since Jan 2010
  - good 1st 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), more bands (100, 150, 220 GHz)
  - Predict r<0.06 in 2015/16

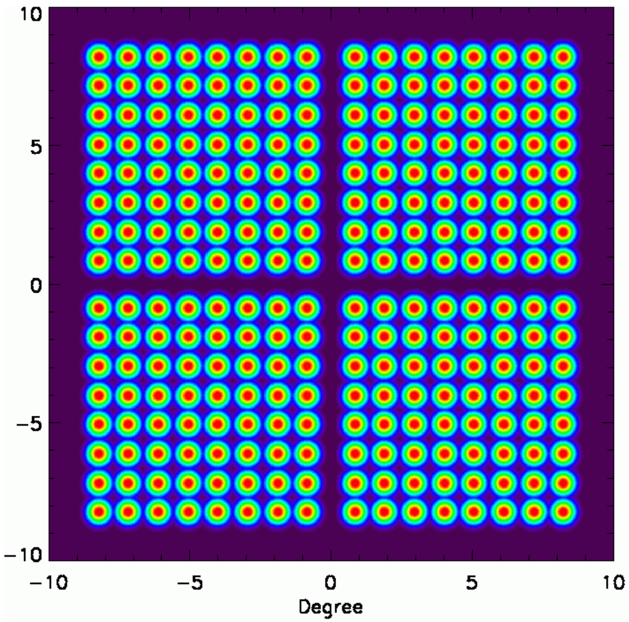
More detectors: **BICEP2**





Justus Brevick (BICEP2 grad student, at Pole 2009)

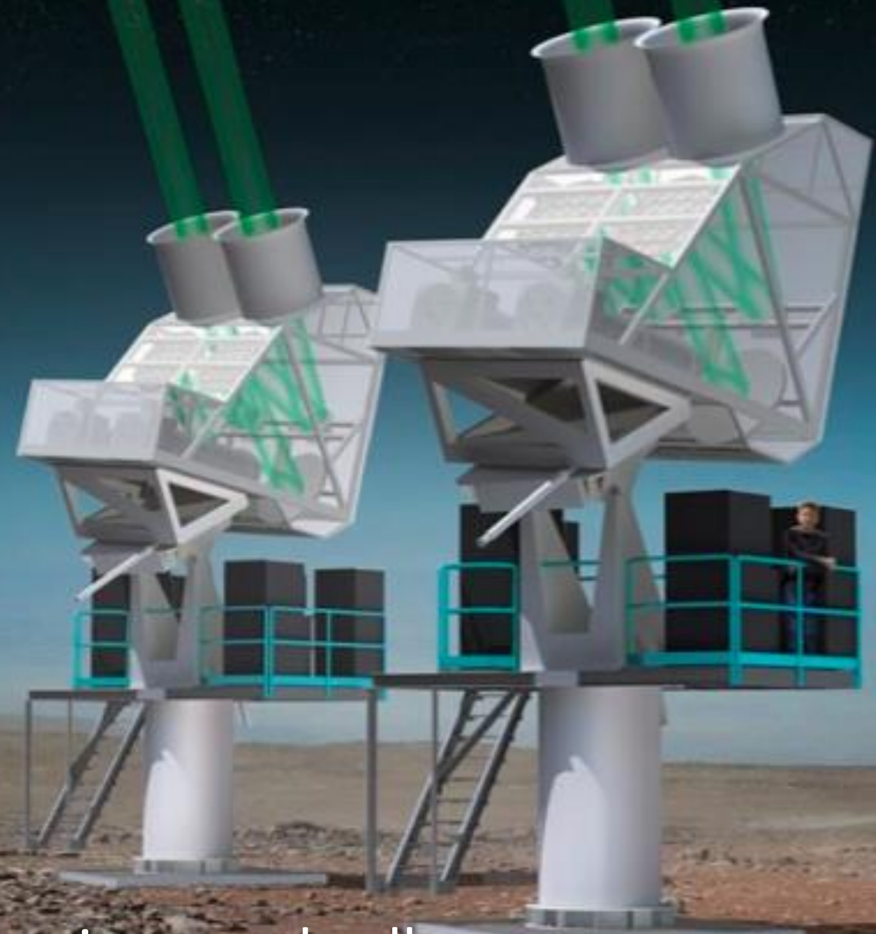




BICEP1 **98 detectors** → **BICEP2** **512 detectors**

Cosmology **L**arge **A**ngular **S**cale **S**urveyor

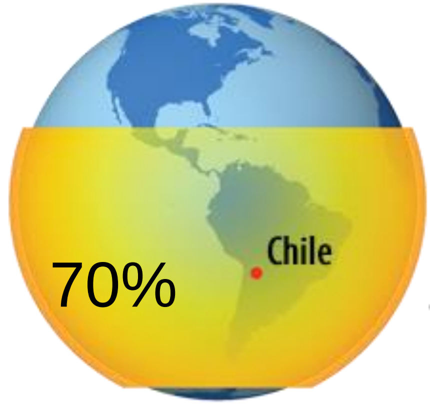
JOHNS HOPKINS UNIVERSITY

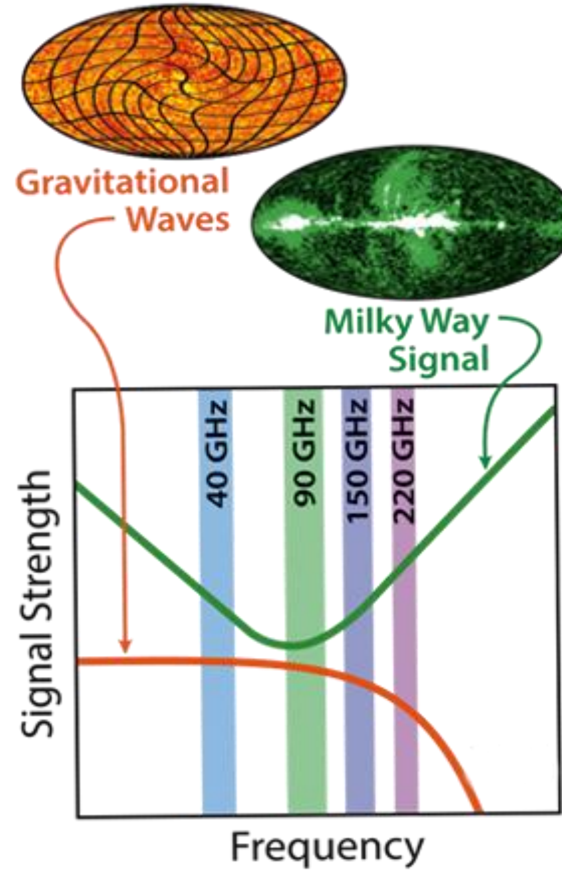


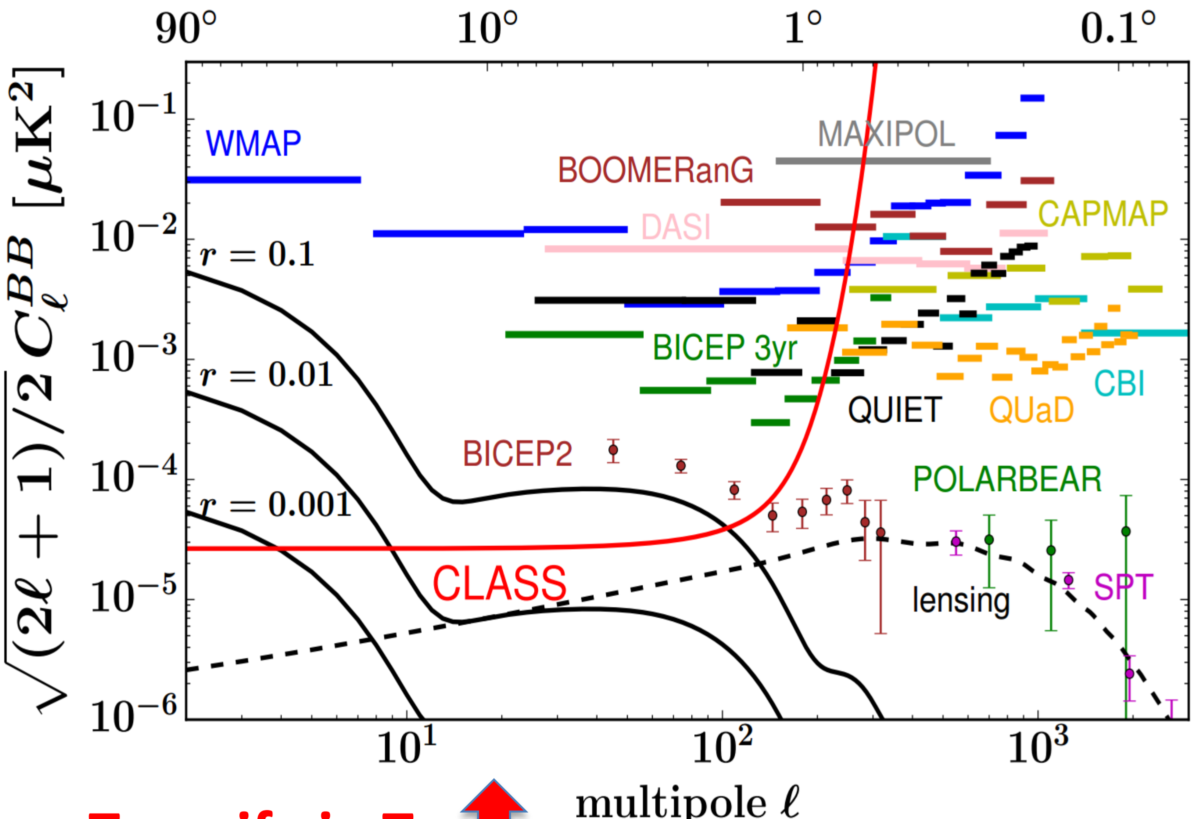
Chuck Bennett, Toby Marriage, and colleagues

CLASS

- ✓ Inflation
- ✓ Reionization

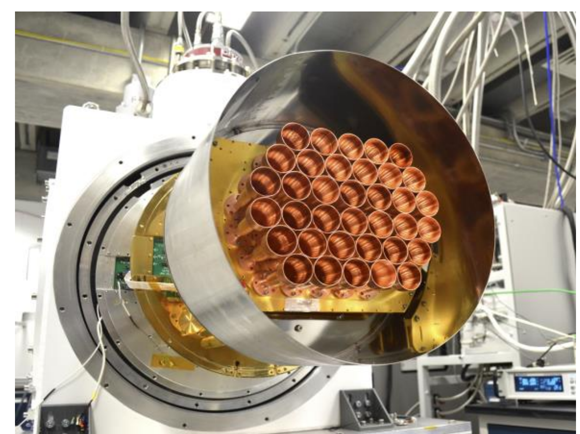






Tenerife in T

40 GHz Focal Plane



Upcoming Polarimeter Deployments

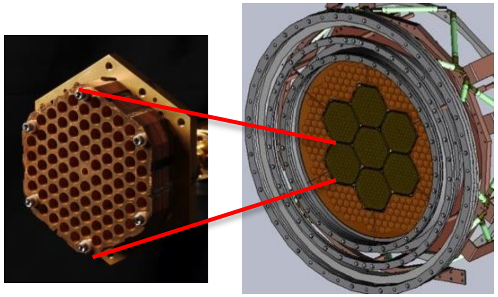
Detectors
NIST
NASA/GSFC
NASA/JPL
Berkeley
ANL

SQUIDs
NIST

Mux readouts
UBC
Berkeley
McGill

Filters
Cardiff

South Pole 10m Telescope



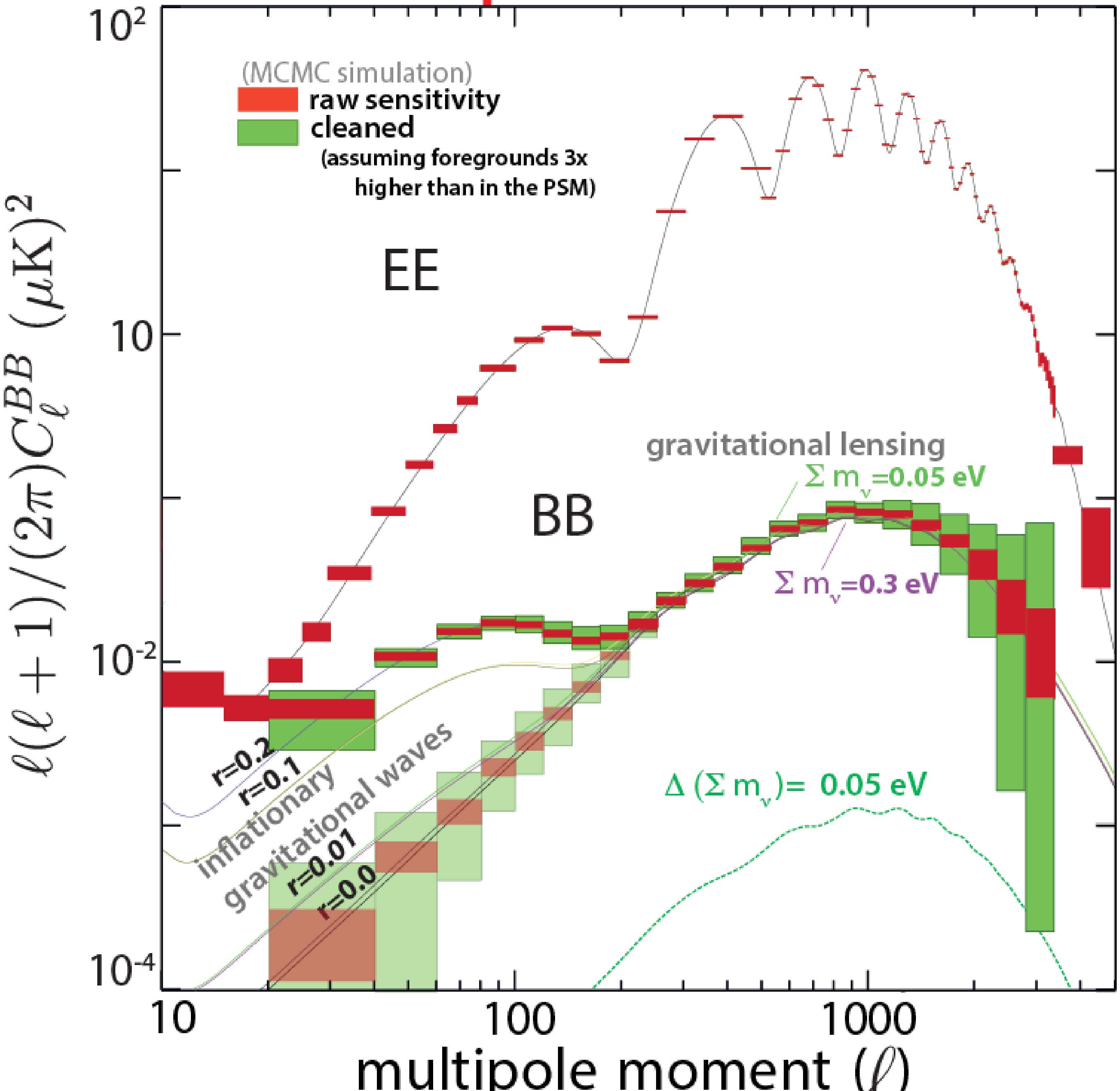
(J. McMahon et al., LTD 2009)

Atacama Cosmology 6m Telescope

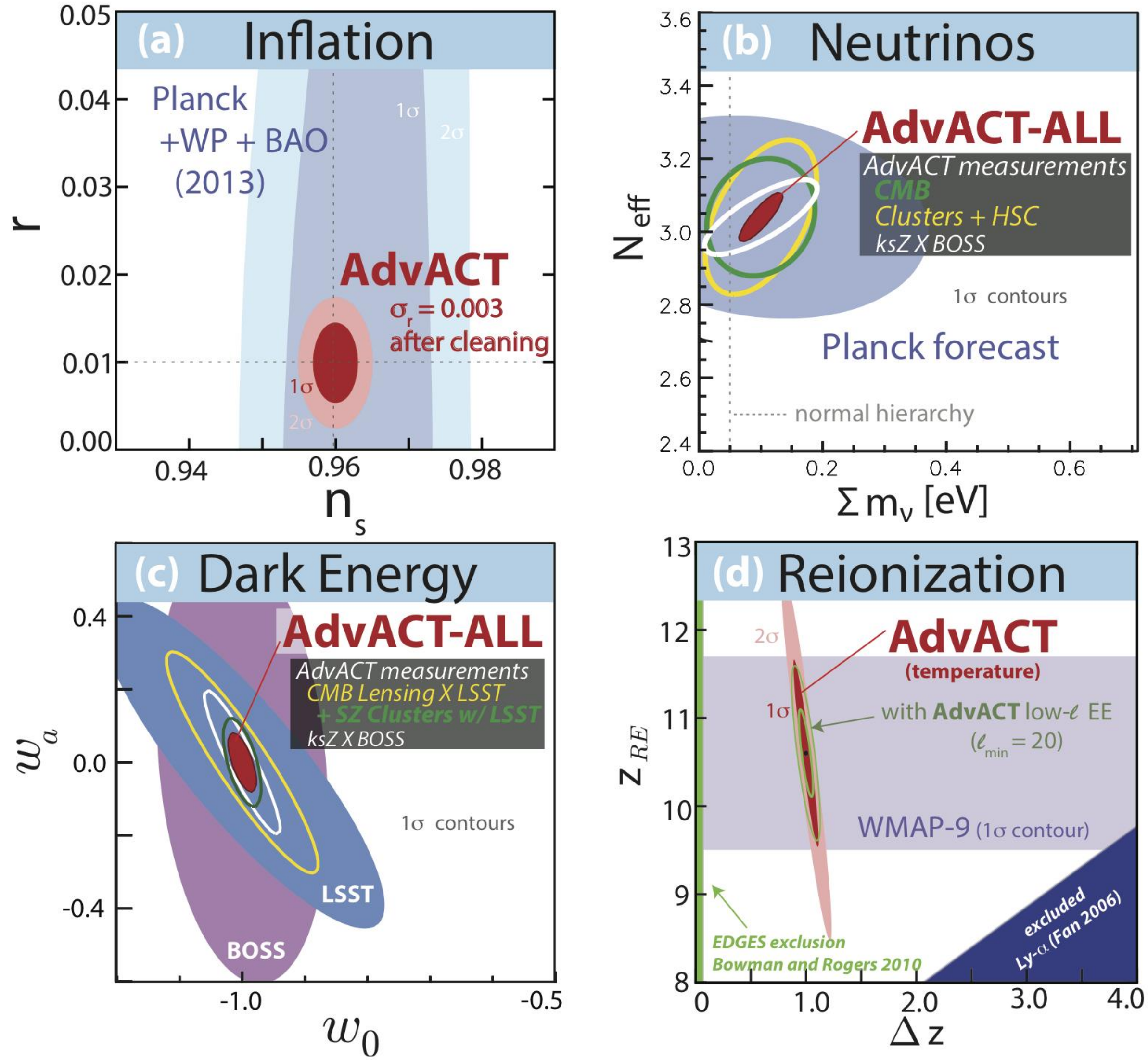
(Niemack et al., SPIE 2010)

The ACT Neighborhood

AdvACT polarization forecast



With AdvACT+other (non-CMB) surveys



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
B-FORE	Proposal	?	

SPIDER: Probing the early Universe with a suborbital polarimeter.

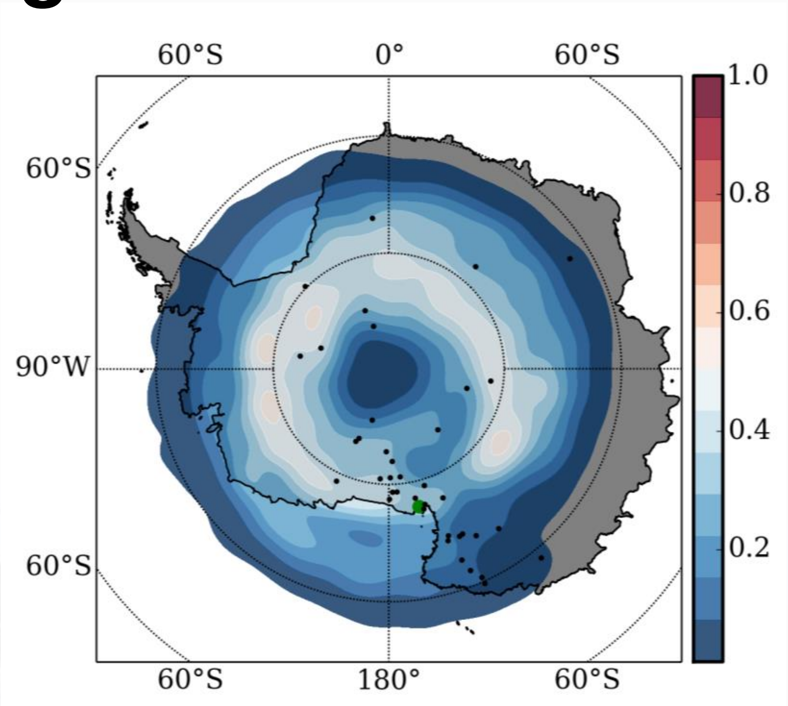
Long Duration Ballooning

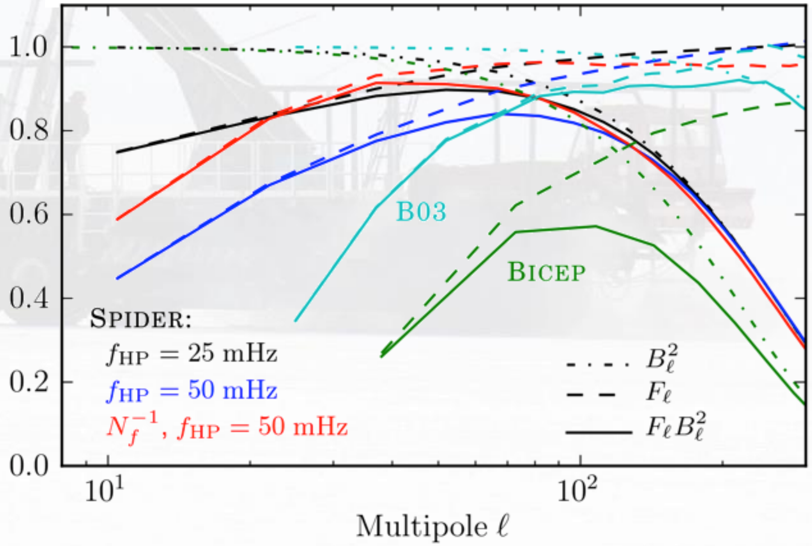
Why Ballooning? Access to space.

- Wider frequency windows
  - Atmosphere makes > 150 GHz difficult
- Space-like loading (NET)
- Fidelity to large angular scales
- Flight heritage for new technology

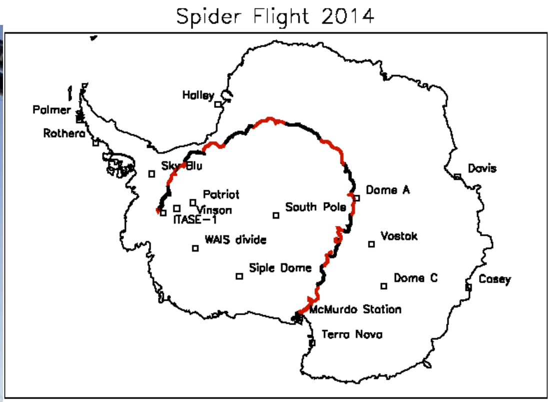
At what price?

- Stringent limits on mass, power
- Complexity of automation
- Insane integration schedule
- Narrow, and scarce, flight windows
- Risky recovery



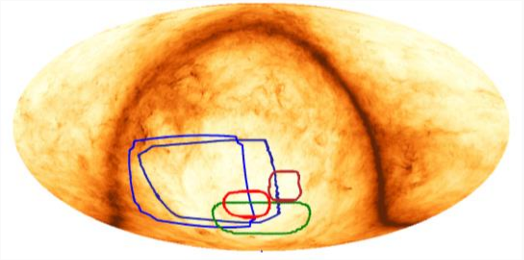


SPIDER 2015 flight summary



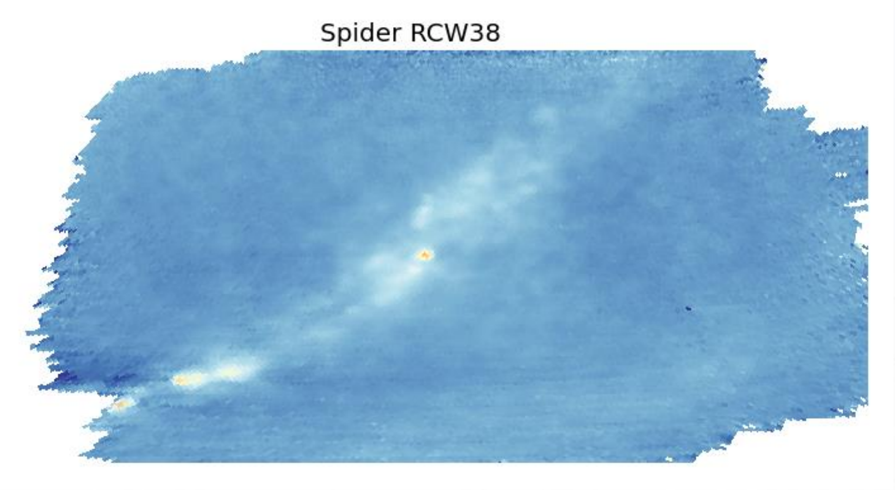
Campaign summary

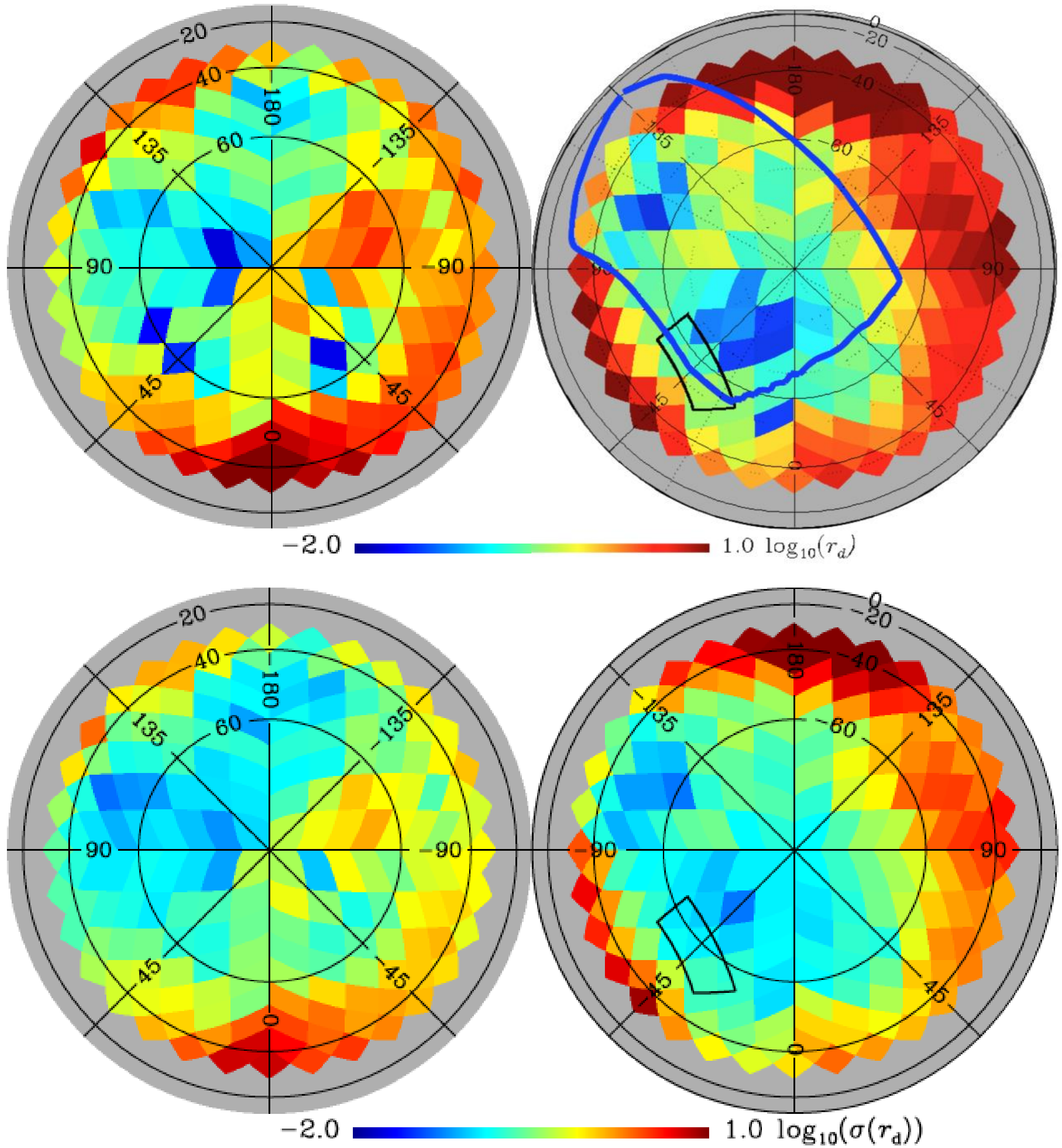
- Launched January 1
- 16 days of observations from 36km
- All systems operated nominally
- Data recovery only
- Full recovery planned via traverse in late 2015



Science Summary

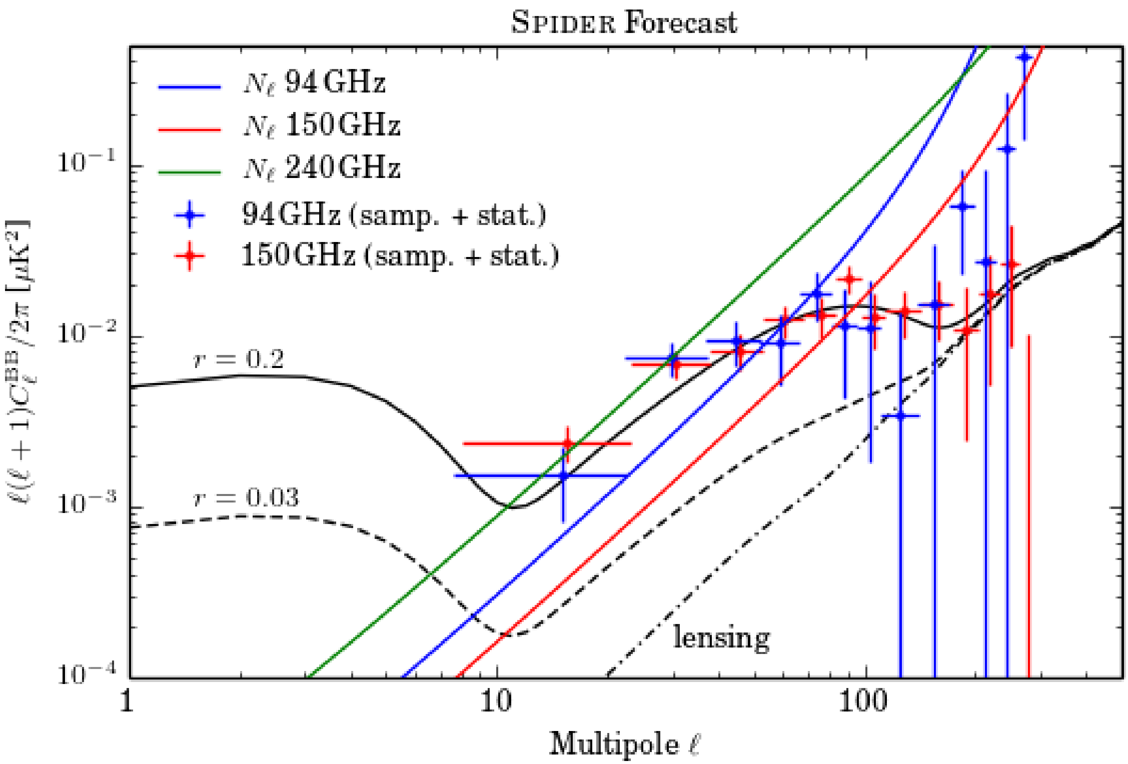
- 5-7 x higher instantaneous sensitivity than Planck
- 10x lower noise in maps, over 10% of the sky
- Signal dominated maps of polarization at 94 and 150 GHz (E&B), at ½ degree resolution
- Sample variance limited EE at low multipole
- B-mode search limited by Galactic foregrounds
- With the addition of 280 GHz data (2017), can achieve a limit $r < 0.03$ with expected foregrounds

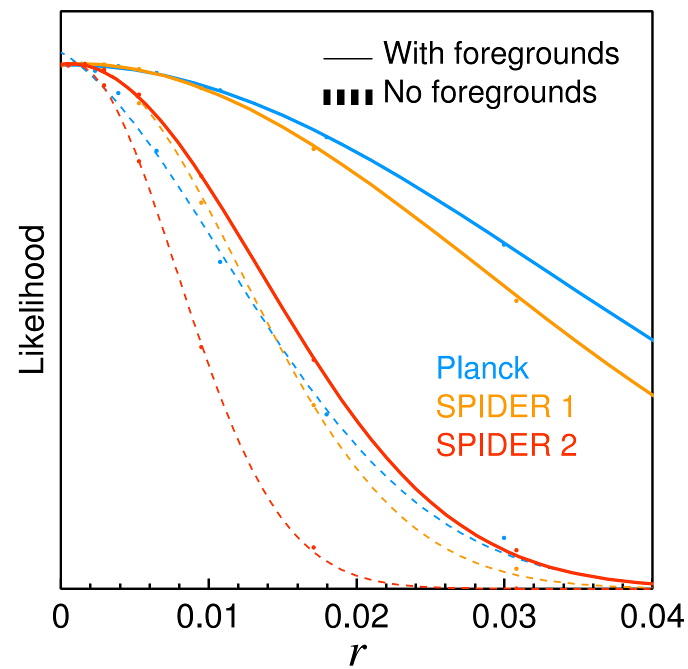



20
40
60
180
135
90
45
0
−2.0
1.0 log10(r_d)
−2.0
1.0 log10(σ(r_d))

Expected Sensitivity

- Jan 2015: 3x (90 GHz, 150 GHz)
  - r<0.03 (99%CL) without FG for the 16-day flight
- Jan 2017 (TBD) : 2x (90 GHz, 150 GHz, 280 GHz)
  - r<0.02 (99%CL) without FG, r<0.03 (99%CL) with FG

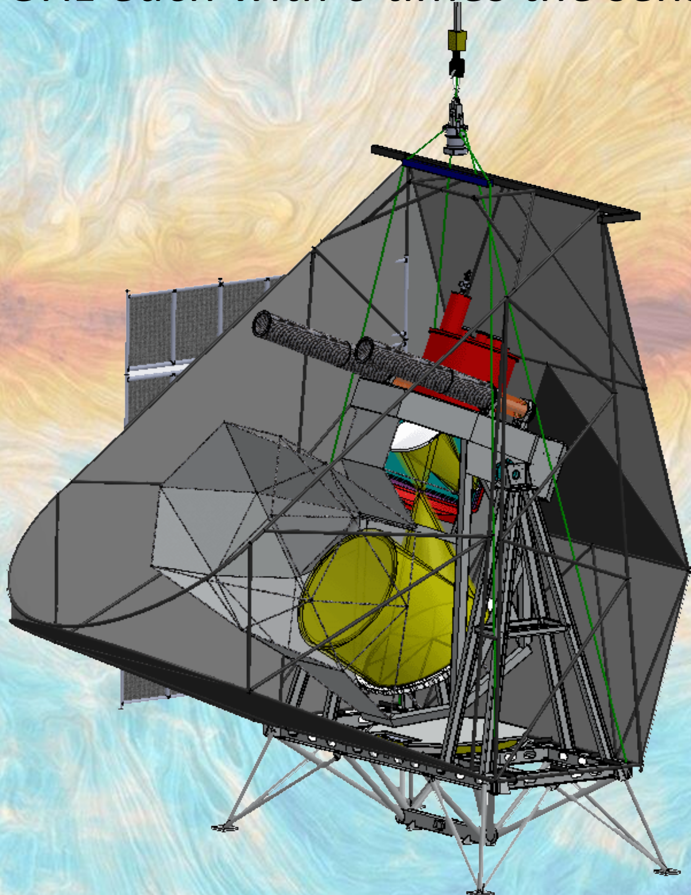




The B-mode Foreground Experiment

BFORE

"A sub-orbital balloon mission to map the polarized dust foreground at 270, 350, and 600 GHz each with 6 times the sensitivity of Planck 353 GHz over 10,000 deg^2."



Key Features

Detectors: 11,800

7,840 TES detectors at 270, and 350 GHz

4,960 KID detectors at 600 GHz

Telescope:

1.35 meter primary –> 1.7 to 4.2 arcmin

4 K secondary

Flight:

28+ days above Antarctica

10,000 deg^2 overlapping ACT, BICEP2, CLASS, PolarBear and SPT

First flight – December 2018 (proposed)

Background: Planck/ESA

Satellites

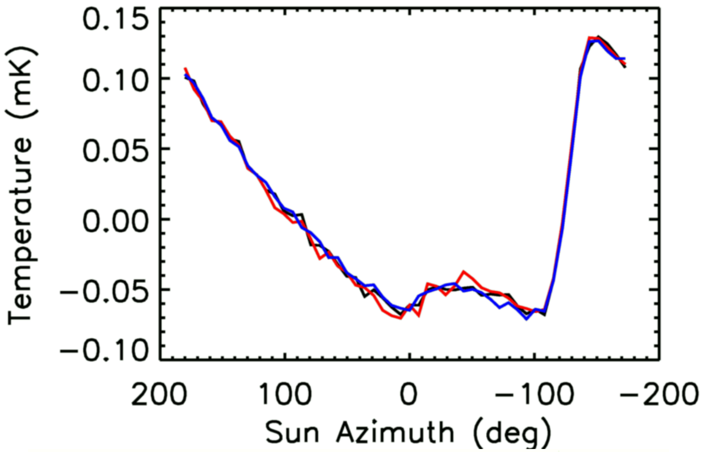
LiteBIRD		Hazumi et al., 50-320 GHz
PIXIE		Kogut et al., 30-6000 GHz
EPIC		Bock et al. , 30-850 GHz
EPIC	?	Timbie et al.
CORE		de Bernardis et al.

Why Space?

For a definitive measurement, space is the place.
Difficult to get l<10 any other way.

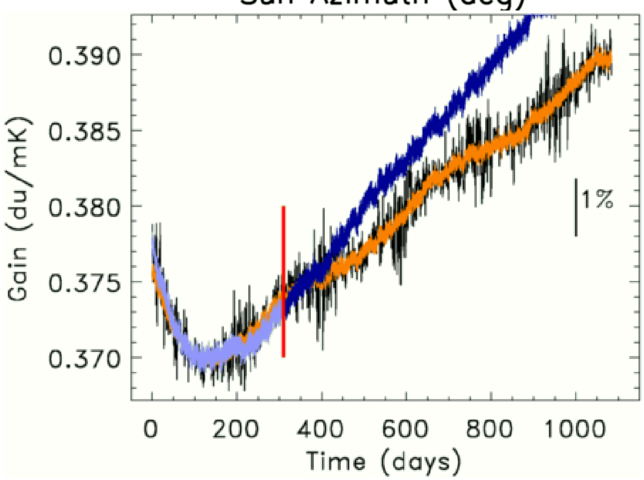
Stability.

WMAP



Physical temperature of B-side primary over three years. This is the largest change on the instrument.

WMAP



Three parameter fit to gain over three years leads to a clean separation of gain and offset drifts.

Jarosik et al.

Why Space?

Full sky coverage with unique scan strategies.

No other platform can tie together large and small angular scales with as much precision.

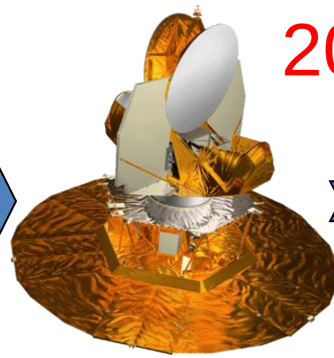
Knowledge of the instrument and of noise.

I believe a space mission is *required* to make maps that will withstand close scrutiny for decades hence, but the case is more subtle than for other fields.

From Jamie Bock:
How Sub-Orbital Program Benefits a Satellite Mission

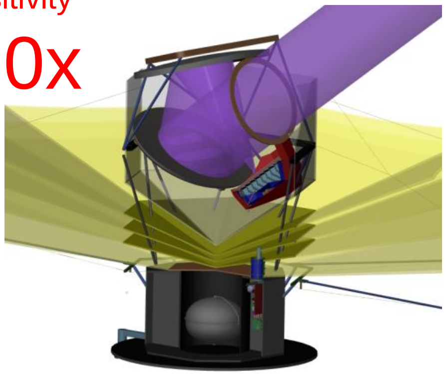
Satellite Mission

Sensitivity 60x



Sensitivity 20x

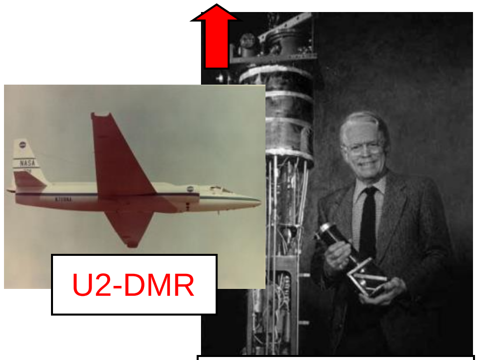
Sensitivity >20x



100 μK | 1 μK | 100 nK | few nK

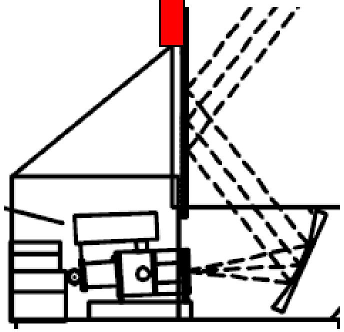
COBE	WMAP	Planck	CMBPOL
1989	2001	2009	2020+

Sub-Orbital Precursor

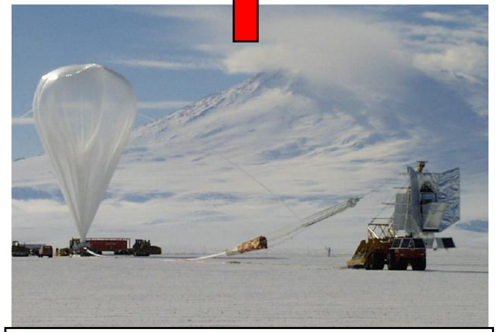


U2-DMR

Woody-Richards



QMAP, SK, TOCO



Archeops, Boomerang, Maxima

Multiple

Ground-based

&

Balloon-borne

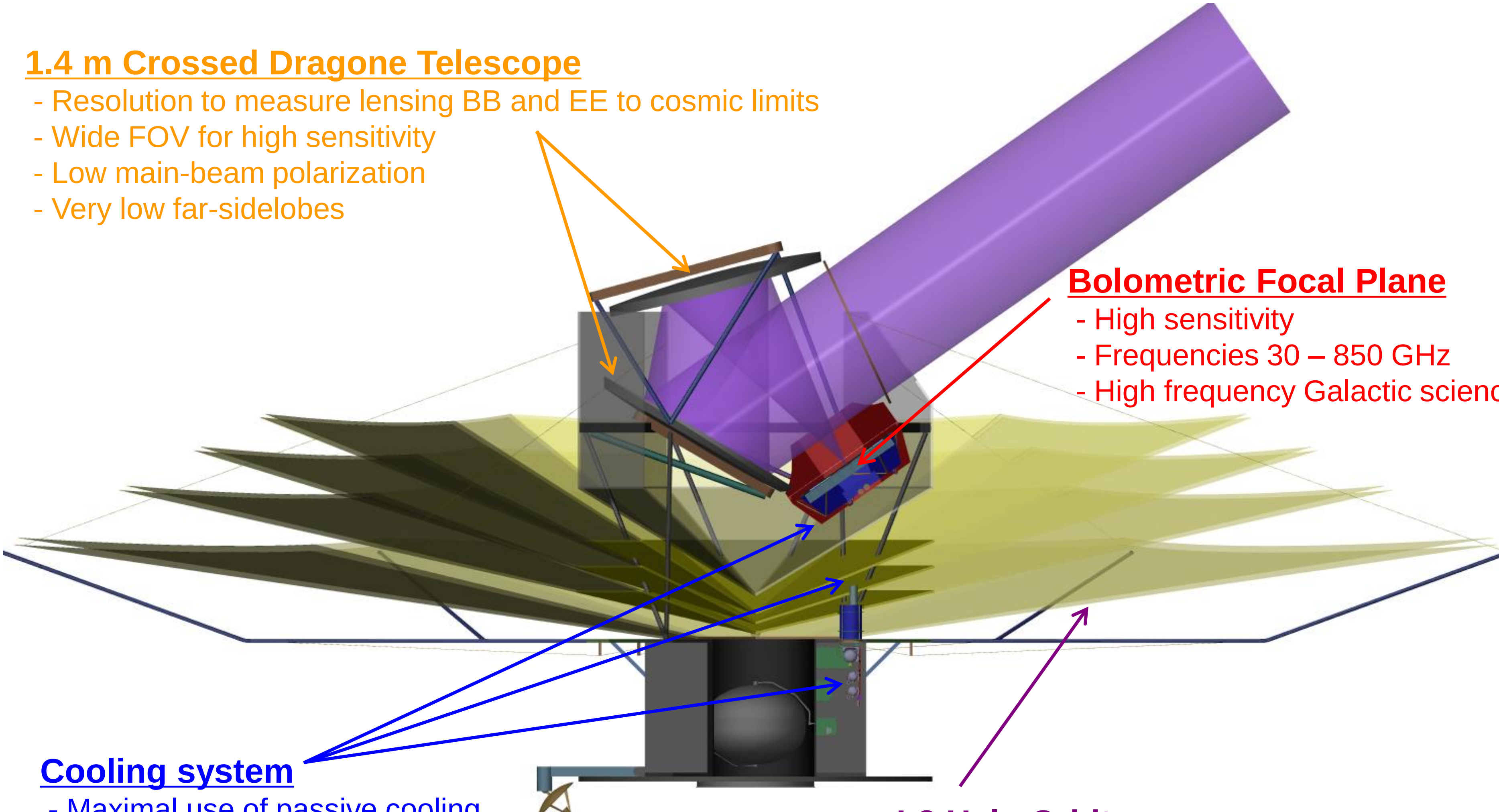
Historical Interplay: Suborbital Experiments serve to

- **Shape scientific objective of a space mission**
- **Train leaders of future orbital missions**
- **Develop experimental methodologies**
- **Develop technologies at systems level**

The EPIC-IM Concept in a Nutshell

Experimental Probe of Inflationary Cosmology – Intermediate Mission

1.4 m Crossed Dragone Telescope
- Resolution to measure lensing BB and EE to cosmic limits
- Wide FOV for high sensitivity
- Low main-beam polarization
- Very low far-sidelobes



Bolometric Focal Plane
- High sensitivity
- Frequencies 30 – 850 GHz
- High frequency Galactic science

Cooling system
- Maximal use of passive cooling
- Efficient 4 K cryocooler (~MIRI) cools telescope
- Continuous 100 mK cooler (~Planck) cools focal plane

L2 Halo Orbit
- Ideal scan strategy for polarization
- Extremely stable thermal environment
- Simple operations, conventional spacecraft

The EPIC-IM Concept: Main Features

- **Maximum Cosmology**
  - high sensitivity to measure CMB polarization to cosmological (or astrophysical) limits
  - 5 arcminute resolution to go deeply into CMB lensing polarization
  - 1 arcminute resolution for Galactic science

- **Simple and Flexible Construction**
  - no cold moving parts, uses 1/f stability of detectors and readouts
  - simpler cooling chain to 100 mK than *Planck*
  - single enabling technology: sensitive detector arrays
  - descopes: smaller sunshield, smaller focal plane, 30 K optics
  - frequency coverage set only by focal plane design

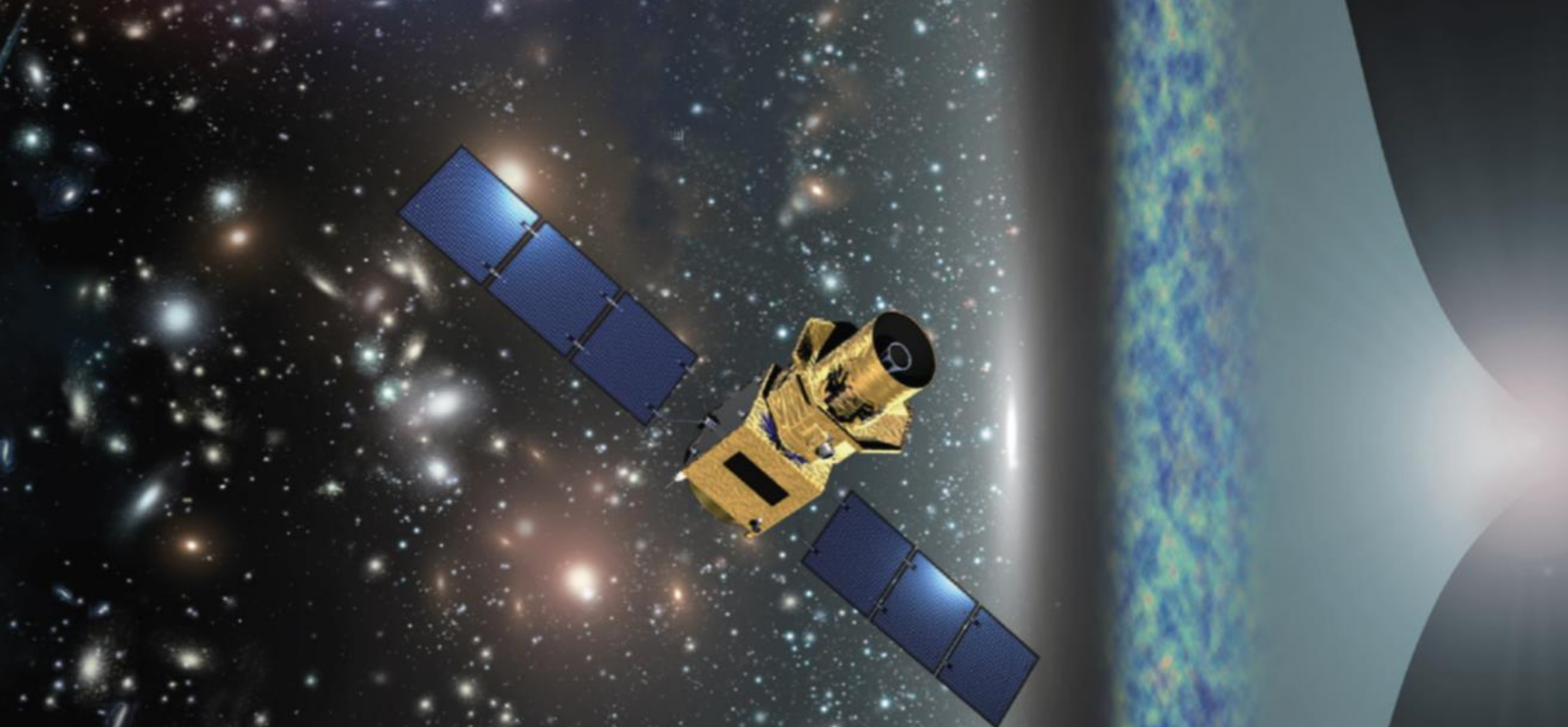
- **Systematic Error Control**
  - simple pair differencing
  - scan strategy: perfectly isotropized scan angles, daily ½ sky maps
  - incorporates direct experience from *Planck*

Small aperture concept……… J. Bock *et al*. arXiv 0805.4207
1.4 m IM concept:……………. J. Bock *et al*. arXiv 0906.1188

LiteBIRD !

PI Masashi Hazumi (KEK/Kavli IPMU)

Lite(Light) satellite for the studies for ***B***-mode polarization and ***I***nflation from cosmic background ***R***adiation ***D***etection



LiteBIRD working group

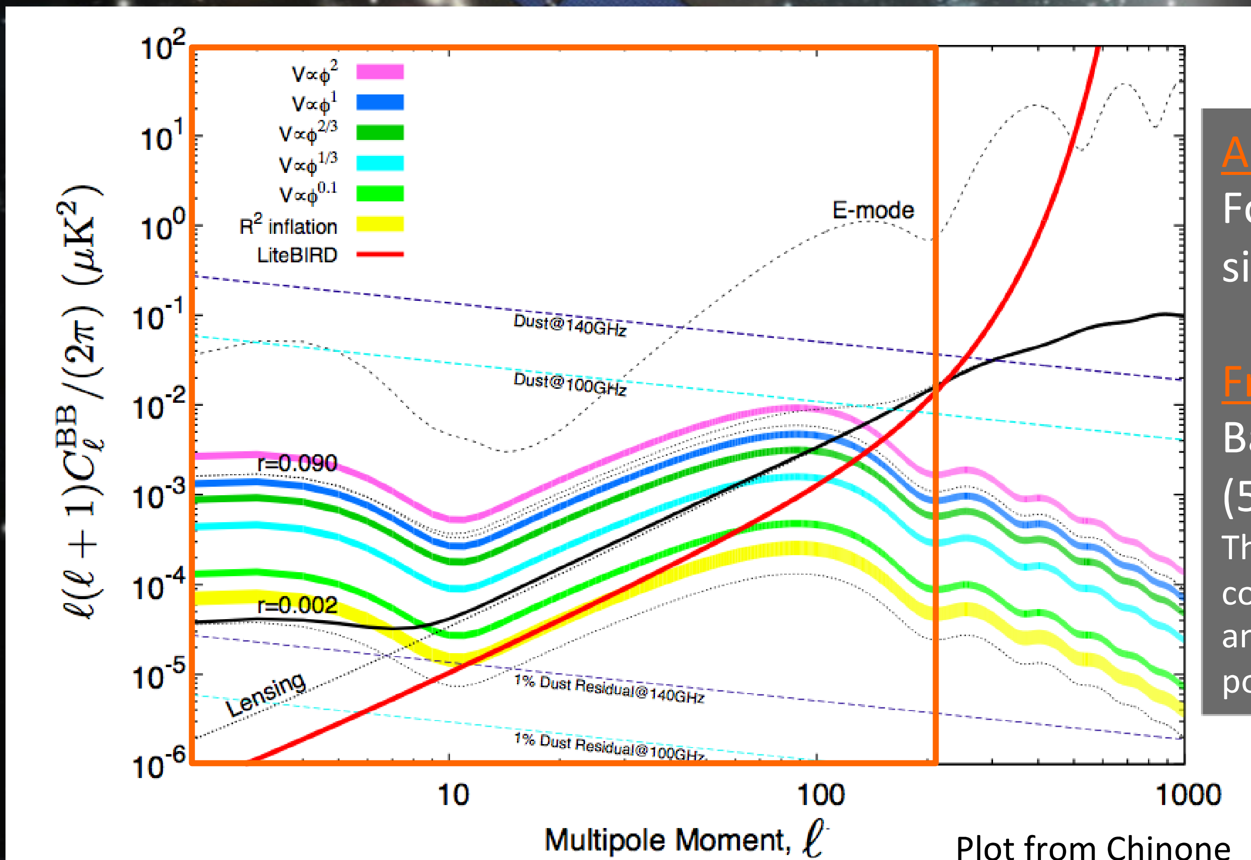
APC Paris
JAXA
Kavli IPMU
KEK
Konan Univ.
LBNL
McGill Univ.
MPA
NAOJ
NICT
NIFS
NIST
Osaka Univ.
Okayama Univ.
Osaka Pref. Univ.
RIKEN
Saitama Univ.
Stanford Univ.
Sokendai
Tohoku Univ.
UC Berkeley
Univ. of Colorado
UCSD
Univ. of Tsukuba
Yokohama Natl. Univ.

LiteBIRD!

Lite(Light) satellite for the studies for ***B***-mode polarization and ***I***nflation from cosmic background ***R***adiation ***D***etection

Science goal!!

LiteBIRD is a next generation CMB polarization satellite to probe the inflationary Universe. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio, r =0.002, with 2σ sensitivity.



Plot from Chinone

Angular coverage

Focusing the primordial B-mode signal with l<200.

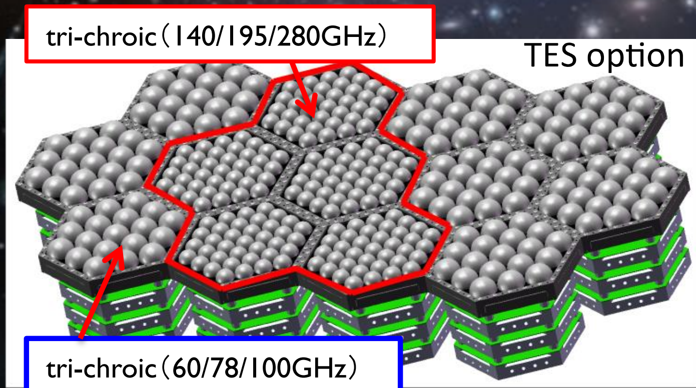
Frequency coverage

Baseline band of ≧ 6 bands (50-320GHz).

There is a room to extend the frequency coverage if necessary based on the analysis using the upcoming Planck polarization data/model.

Mission overview

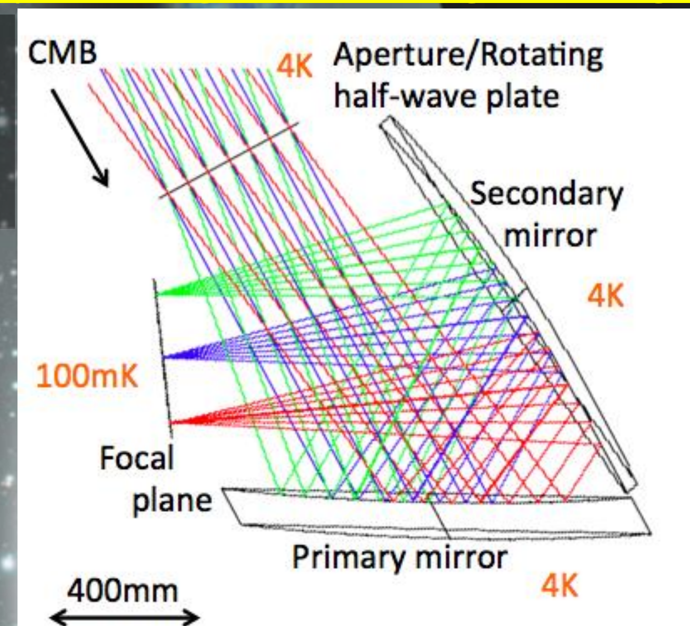
Superconducting detector array

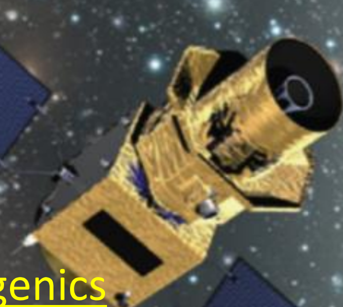


UC Berkeley (Heritage from PB1,2/SA)
The multi-color pixels for two sets of band.
The total # of TES is 2022 with 64 DfMUX readout using SQUID.

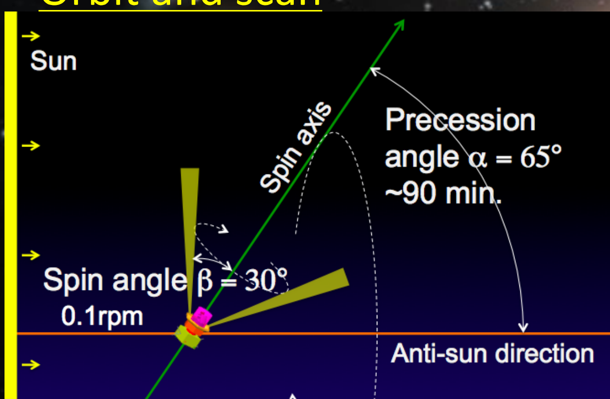
Optics using crossed-Dragone design

The compact and wide FOV. The heritage from QUIET and ABS for CMB pol. exp.





Orbit and scan

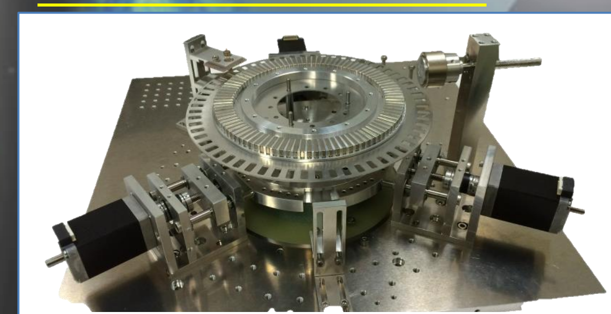


Observing at L2with spin and precession to optimize the full sky coverage and the systematics.

Cryogenics

Stirling cooler + 4K Joule-Thomson cooler to achieve 4K. Strong heritage and R&D from Akari, Smiles, Suzaku, Astro-H, and SPICA. The sub-K stage is ADR.

Polarization modulator



Achromatic half-wave plate to mitigate the system 1/f and differential systematics. Heritage from EBEX pol. modulator.

Status(and(prospect(

- LiteBIRD WG has proposed to the JAXA strategic large mission and the result is to be announced.!

- LiteBIRD WG has proposed to the NASA MO for the FPU and sub-K cryogenics development and the result is to be announced.!

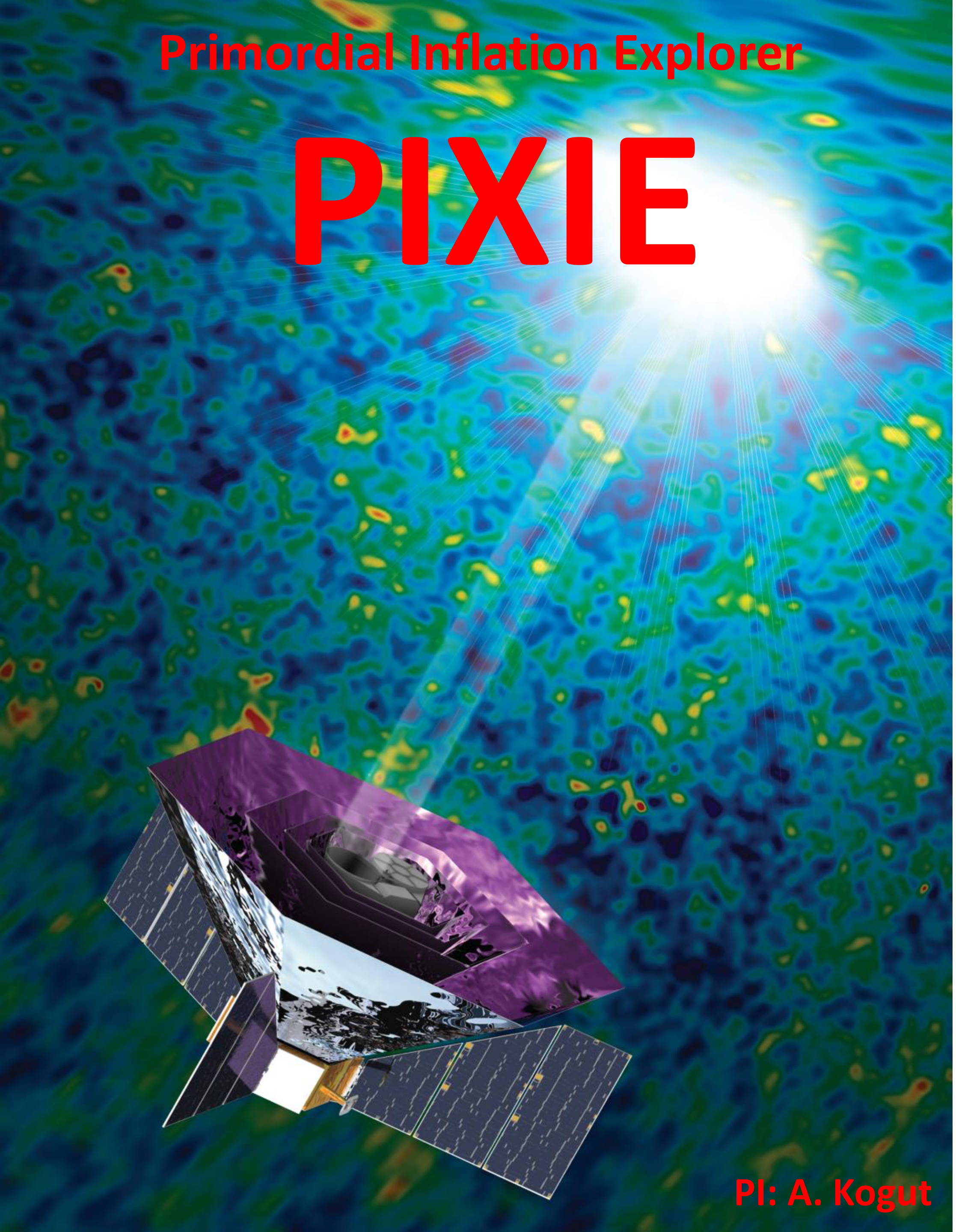
!

- LiteBIRD is selected as one of the prioritized projects in the master plan 2014 by Science Council of Japan.!

- LiteBIRD is chosen as one of ten new projects in MEXT Roadmap for Large-scale Research Projects.!

- Targeting the launch in early 2020s.!

(



Explorer mission to measure inflationary signal to limits imposed by cosmological foregrounds

- Probe inflation at $r < 10^{-3}$ (5σ)
- 400 frequency channels

30 GHz to 6 THz

1 cm to 50 µm

- Complex signal modulation

11 orders of magnitude in time

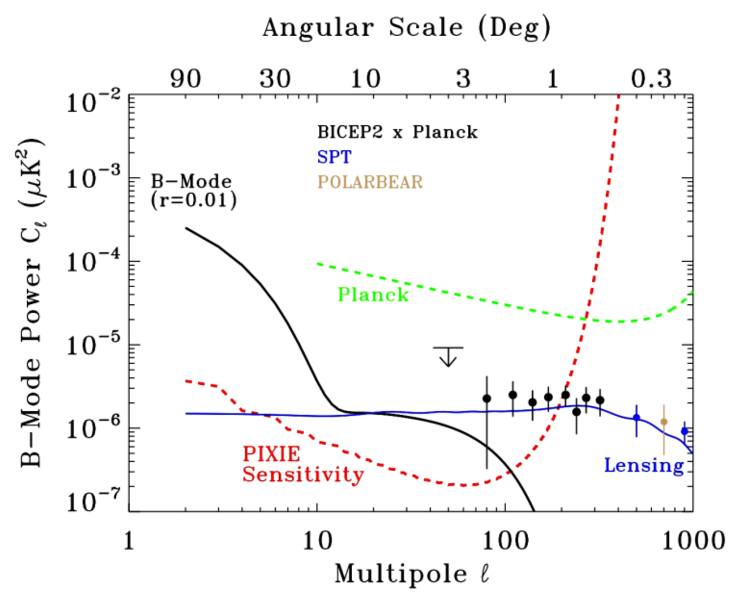
Multiple space/time symmetries

- Rich ancillary science

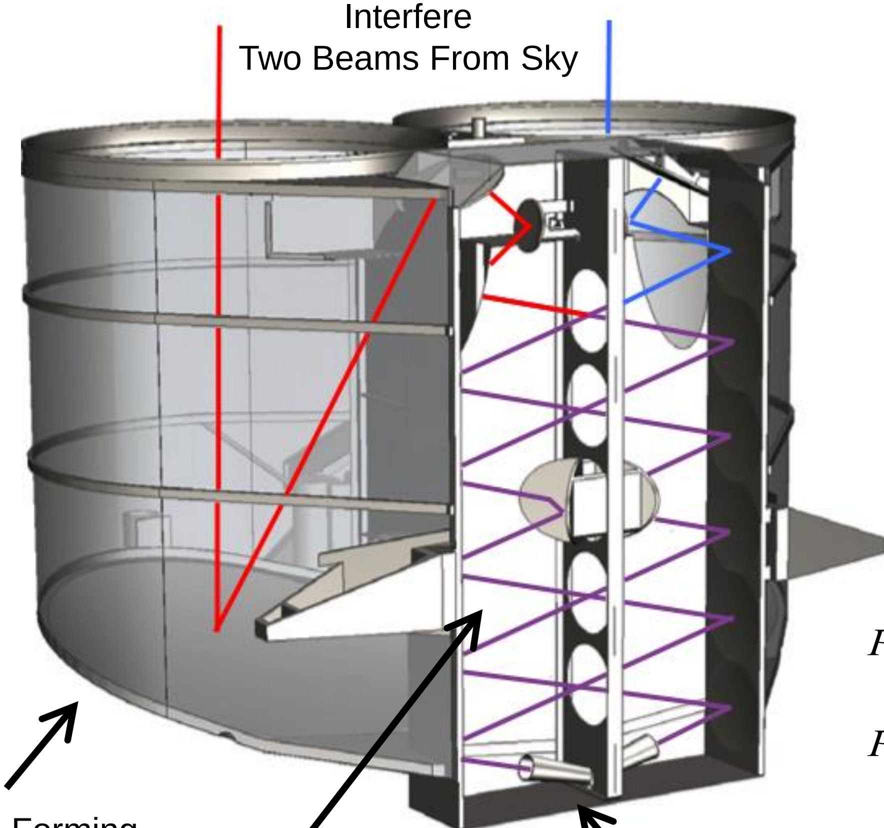
Epoch of reionization

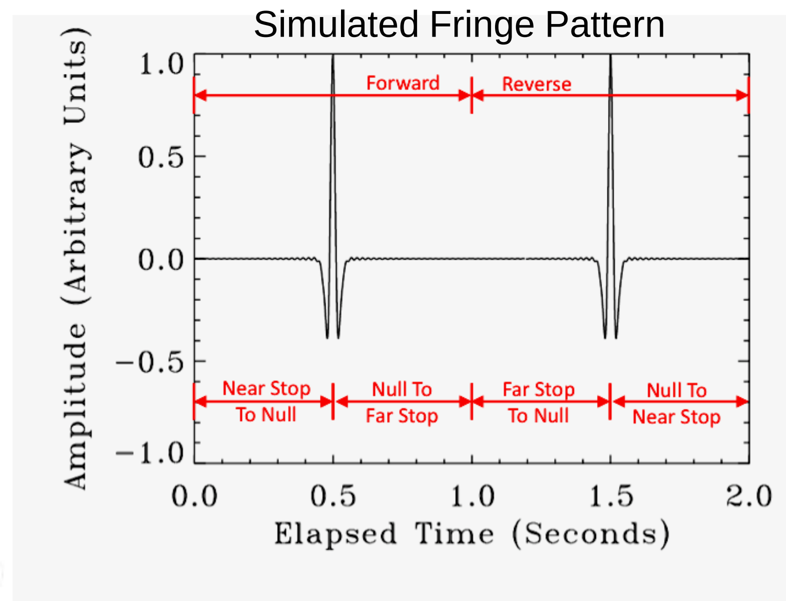
Cosmic IR background

Galactic astrophysics



PIXIE Nulling Polarimeter





$$P_{Lx} = \frac{1}{2} \int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right) \cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2} \int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right) \cos(z\omega/c)\, d\omega$$

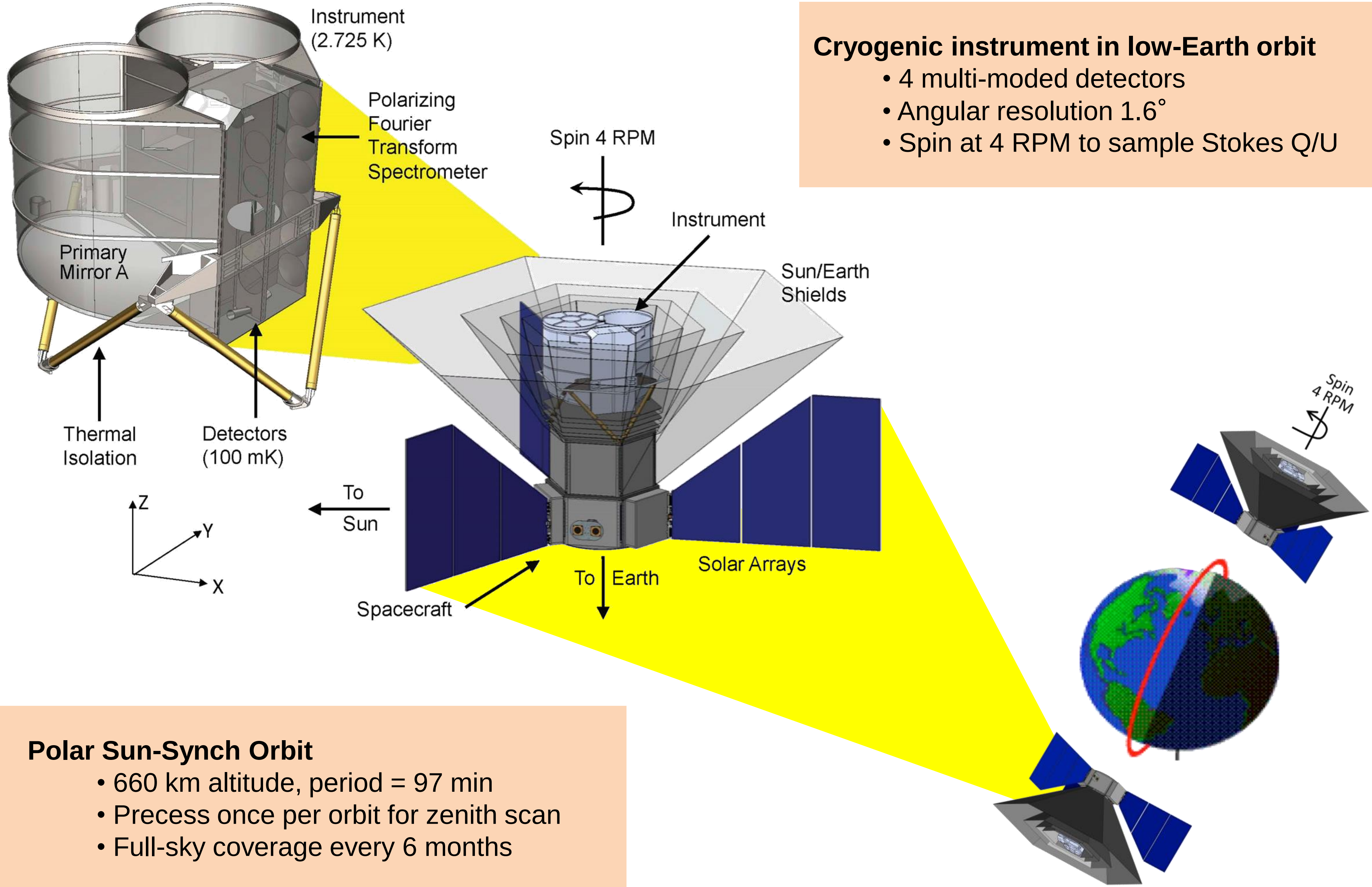
Stokes Q

Measured Fringes Sample Frequency Spectrum of Polarized Sky

Instrument and Observatory

Cryogenic instrument in low-Earth orbit

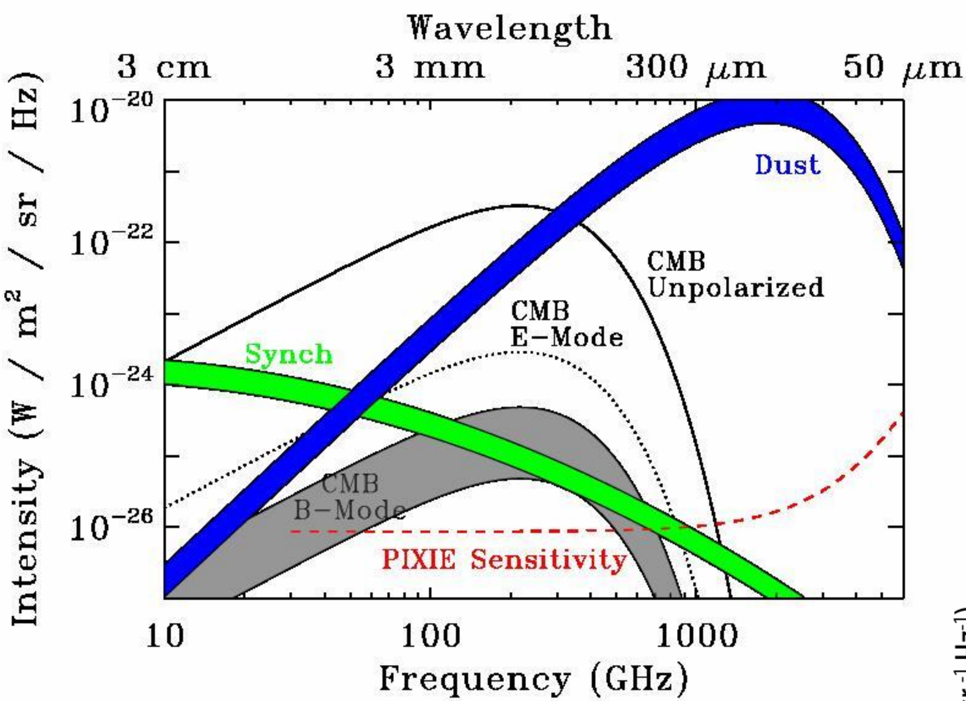
- 4 multi-moded detectors
- Angular resolution 1.6°
- Spin at 4 RPM to sample Stokes Q/U



Polar Sun-Synch Orbit

- 660 km altitude, period = 97 min
- Precess once per orbit for zenith scan
- Full-sky coverage every 6 months

PIXIE "Foreground Machine"



Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz

400 channels with mJy sensitivity per channel

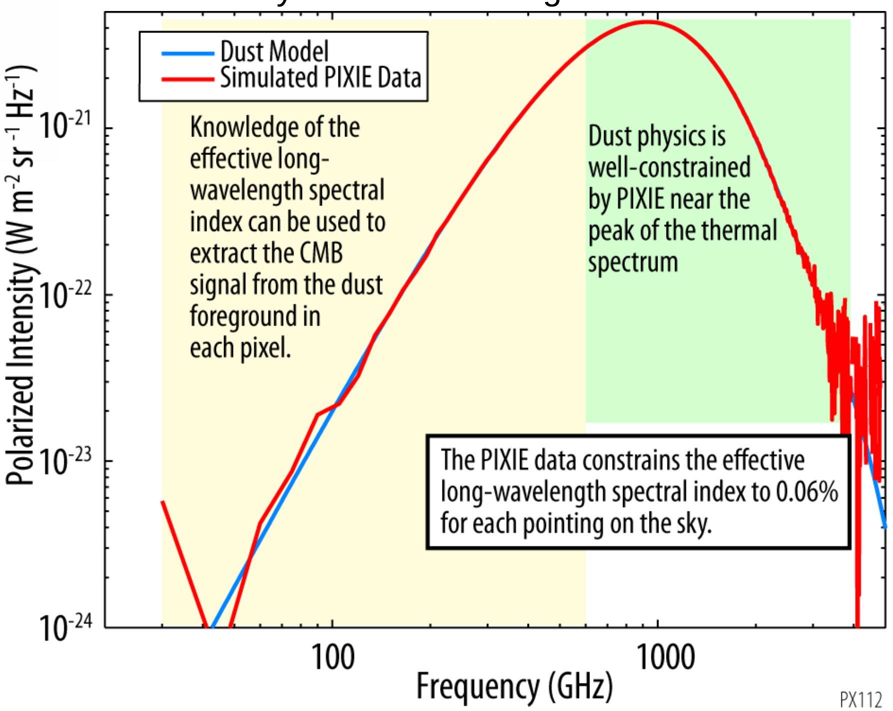
Sensitivity plus broad frequency coverage

Foreground S/N > 100 in each pixel and freq bin

Spectral index uncertainty ±0.001 in each pixel

If PIXIE can't figure out the foregrounds, it probably can't be done!

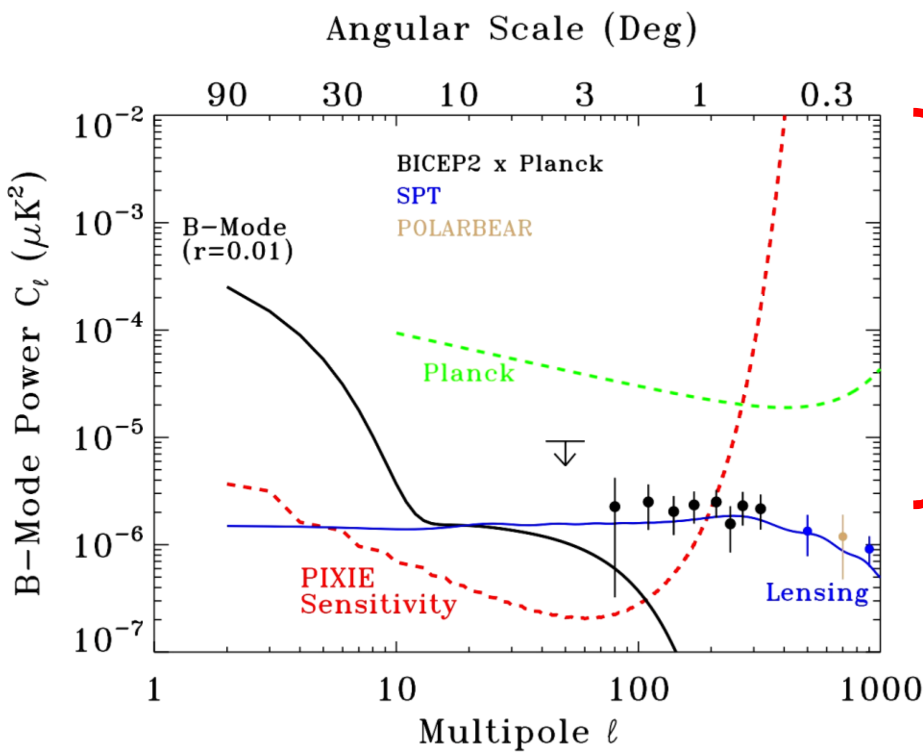
Dust Physics Inform Foreground Subtraction



PX112

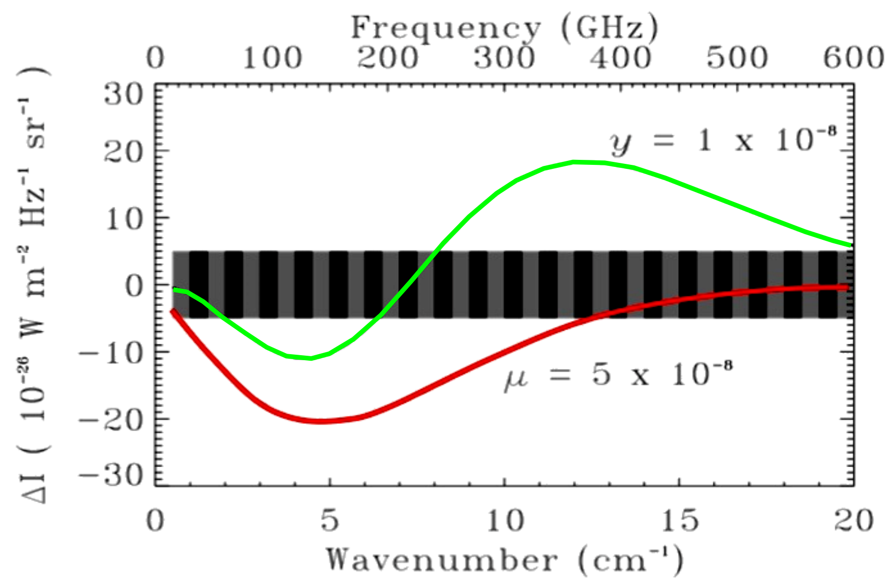
PIXIE Data and Science Goals

Measure Inflationary Signature to Cosmological Limit



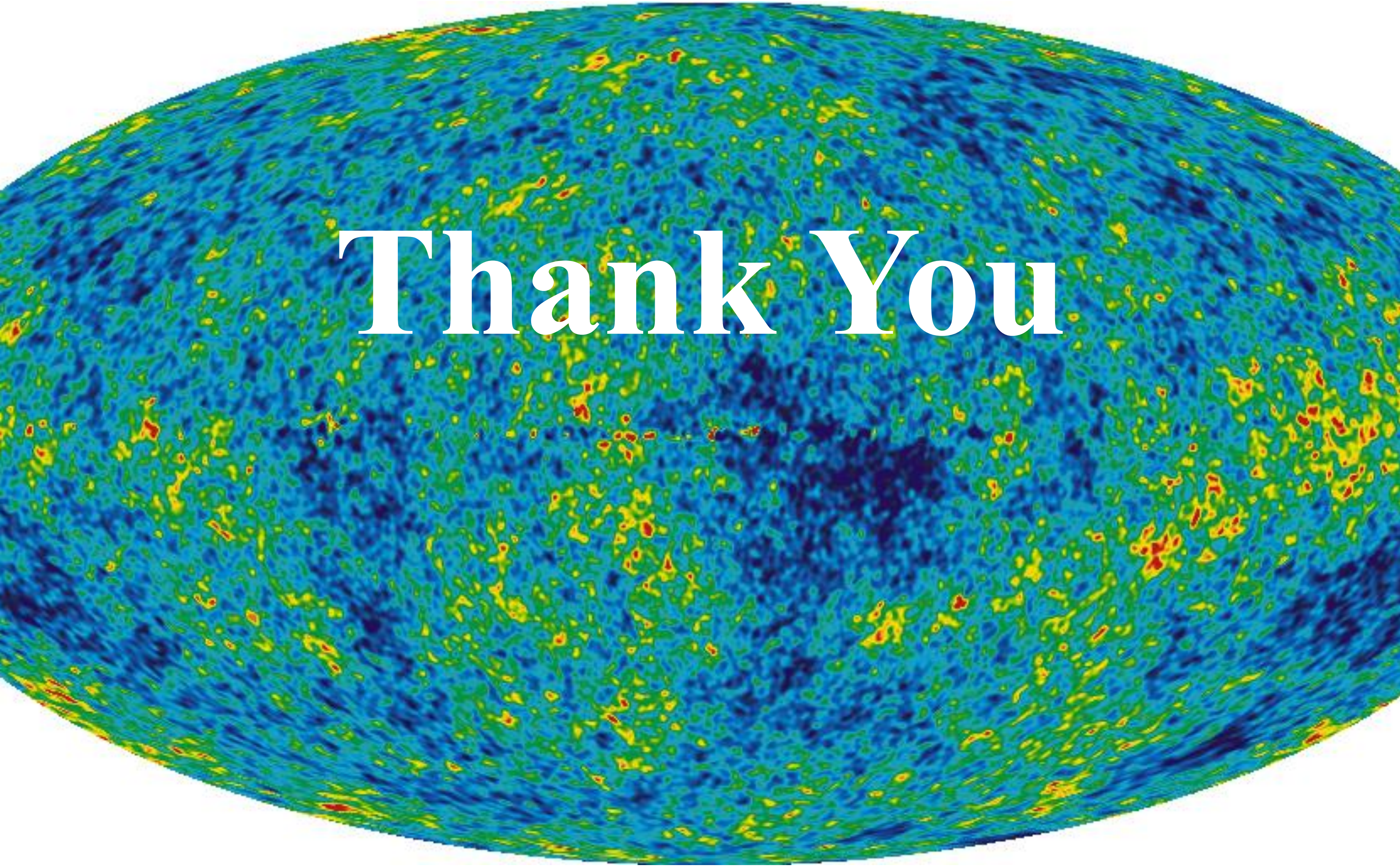
Inflationary Physics: $r < 10^{-3}$ at 5σ

- 70 nK rms noise per 1 deg pixel
- Measure GUT energy scale (10^{16} GeV)
- Probe physics to Planck scale (10^{19} GeV)
- Fully characterize competing foregrounds



Blackbody Spectral Distortions

- Improve COBE limits by factor of 1000
- Cosmological signals must exist at this level
- Inflation, dark matter, reionization
- Recombination lines and primordial He

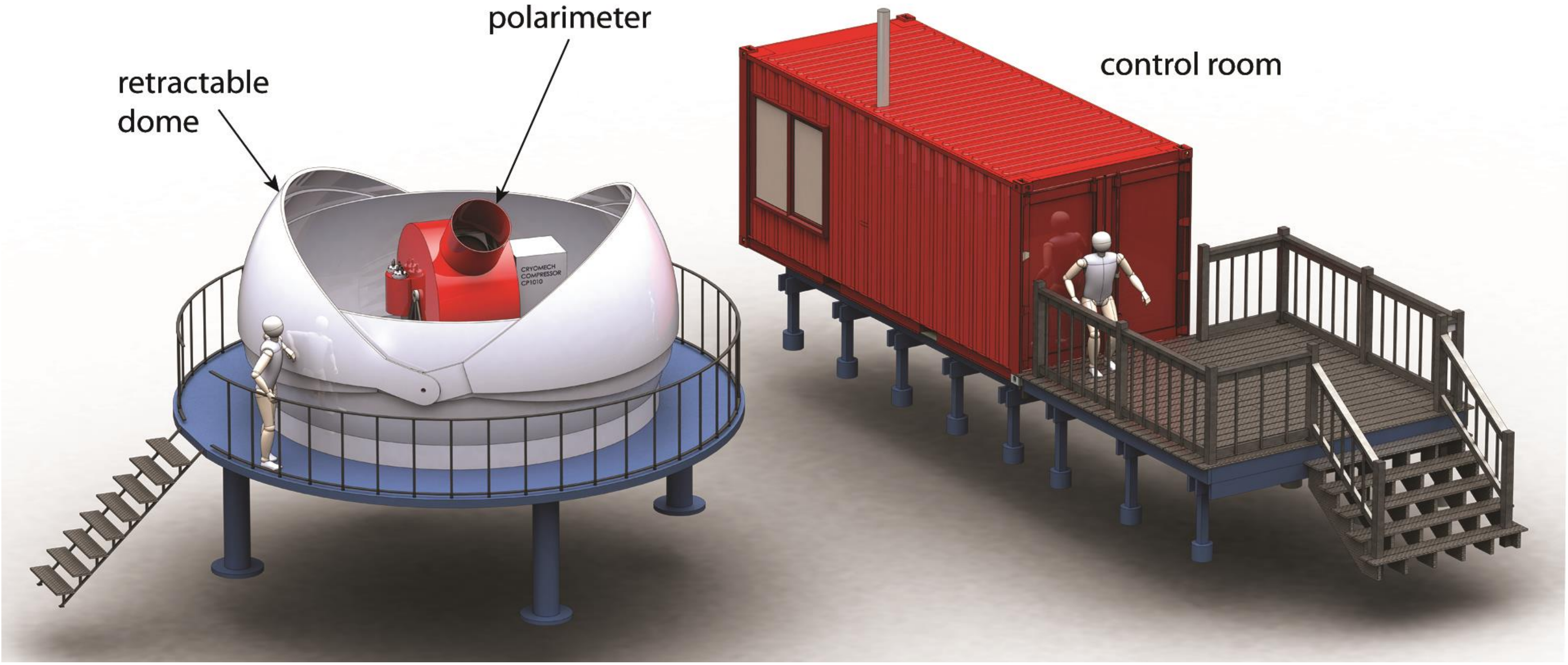

Thank You

Ground based

From Amber Miller

The Greenland LEKID Polarimeter

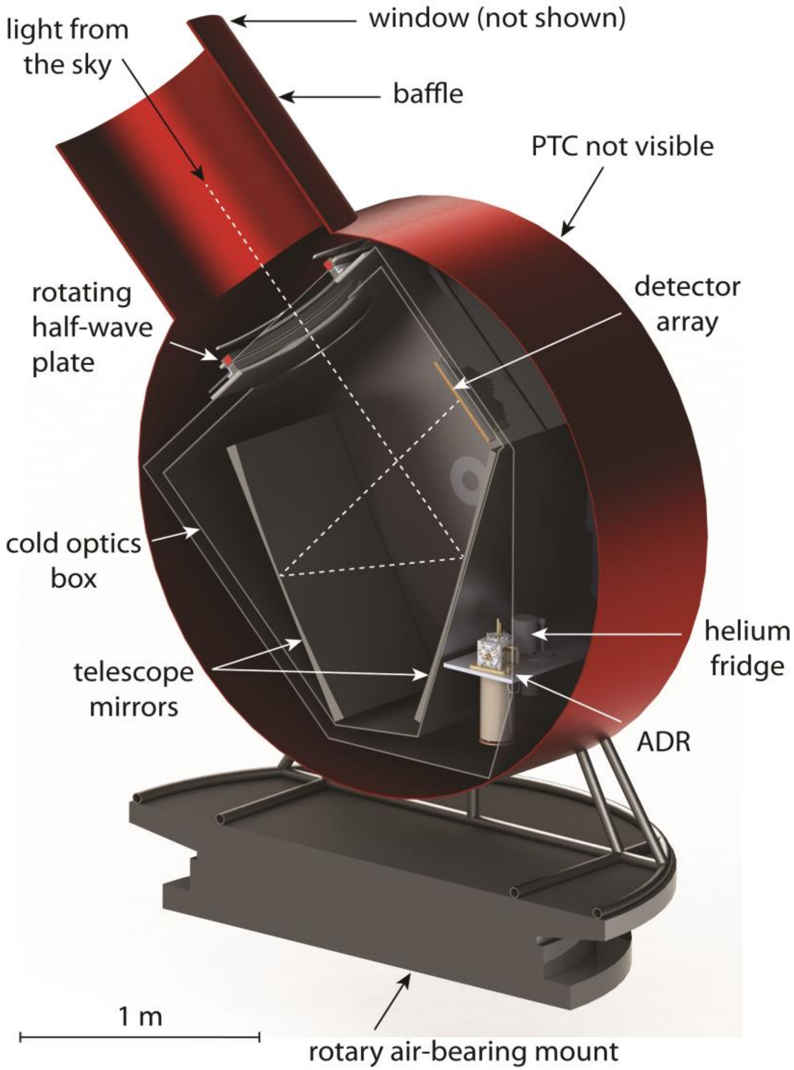
Compact LEKID-based spinning telescope for deployment to Greenland



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*

The Greenland LEKID Polarimeter



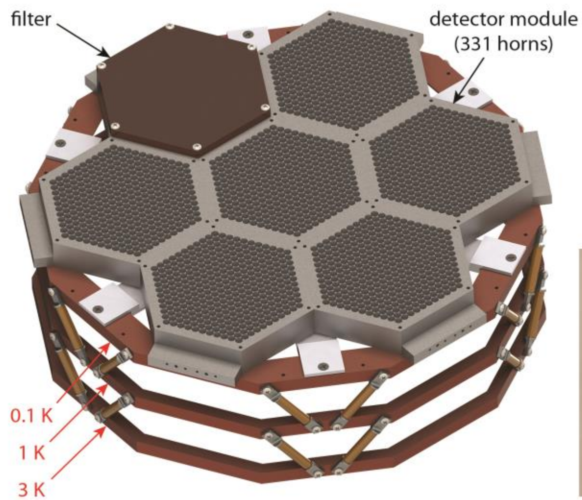
	Option 1	Option 2
Spectral Band Centers [GHz]	150	210, 267
Spectral Bandwidth [$\delta\nu/\nu$]	0.27	0.14, 0.22
Number of Detectors	2317	938, 2345
Total Number of Detectors	2317	3283
Detector NET [$\mu K\sqrt{sec}$]	418	1040, 1480
Instrument NET [$\mu K\sqrt{sec}$]	8.68	34.0, 30.6
Aperture Diameter [mm]	500	500
Horn Spacing ($D/F\lambda$)	1.0	1.2, 1.5
Beam FWHM [arcmin]	14.5	10.5, 8.4
Total Sky Coverage [deg^2]	12,400	12,400
ℓ Range	5 to 1000	5 to 1000
Observation Program [years]	2	2
Time on CMB Patch [years]	0.70	0.70
Total Duty Cycle [%]	37	37
Map Noise [μK arcmin]	14.	56., 50.
T sensitivity per 1° pixel [μK]	0.17	0.92, 0.83
Q sensitivity per 1° pixel [μK]	0.24	1.3, 1.2
Minimum r (99% confidence)	0.01	

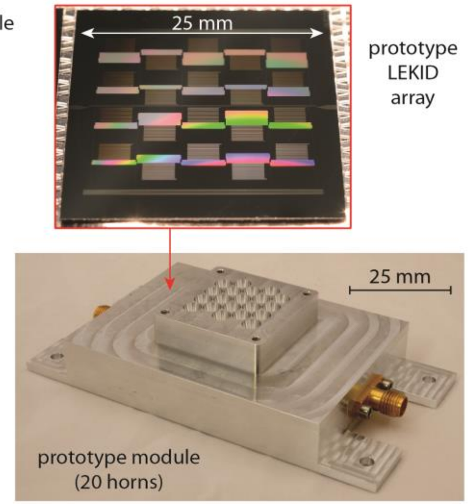
Performance values for two instrument configurations computed assuming the telescope is sited in Greenland and spinning continuously at a rate of 2° per second (on the sky) for 24-hour-long scans. The telescope elevation is fixed within each scan but varies between 30° and 75° among scans.

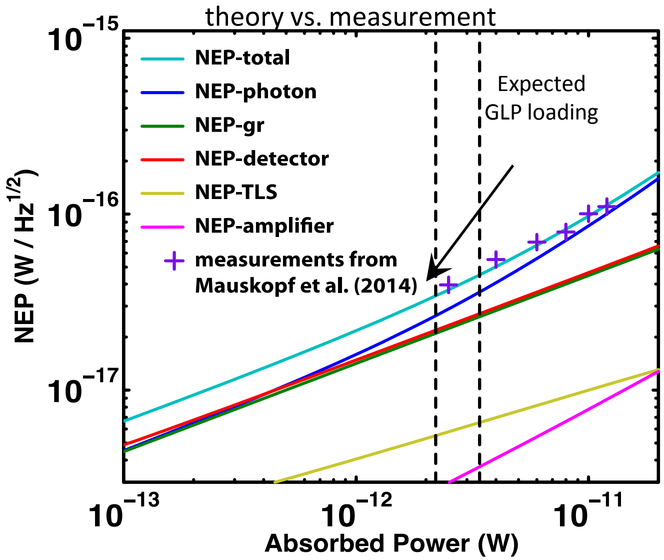
The 150 GHz NET values were computed assuming a typical loading of 3.0 pW and a total NEP of 4.9 x 10^{-17} W/√Hz.

Focal Plane, LEKID Noise and NET

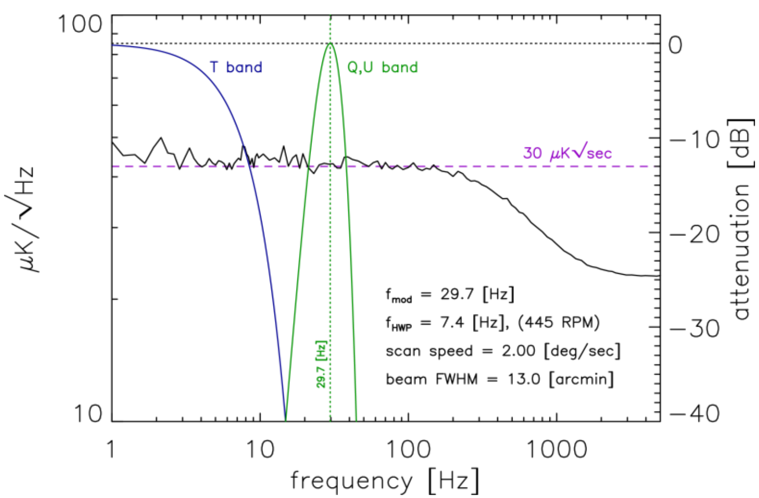
model of GLP focal plane







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*

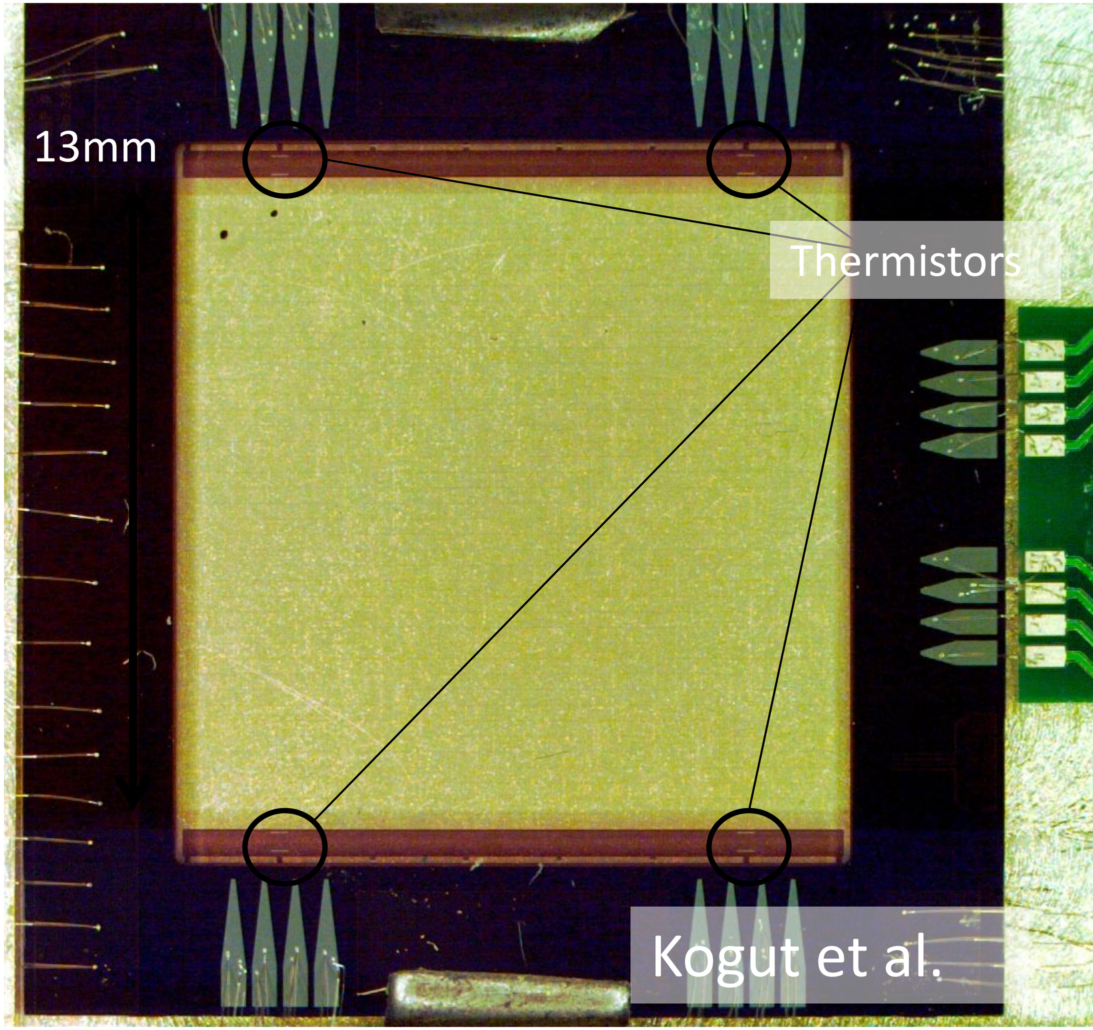
From Akito Kusaka

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

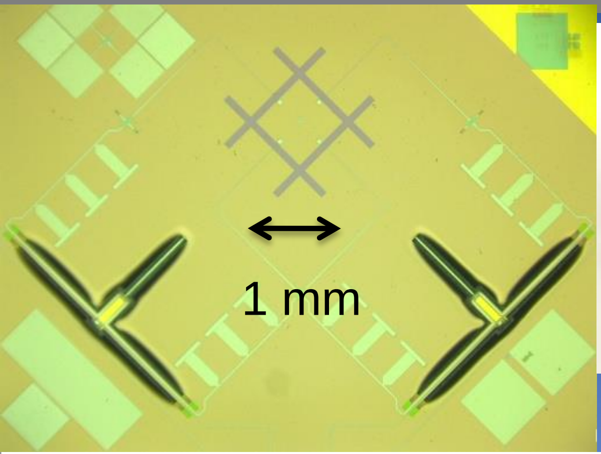
Detector developed at NASA GSFC

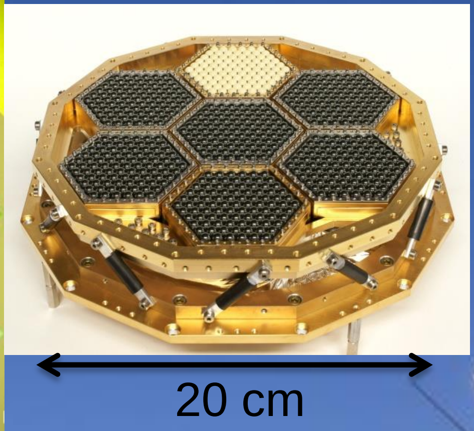
- Developed for PIXIE satellite proposal (Kogut et. al. 2011)
- Polarization selective absorbing strings
- Can be configured for narrow-band application
  - 87 modes/detector @145GHz
- Cryogenically testing at Princeton

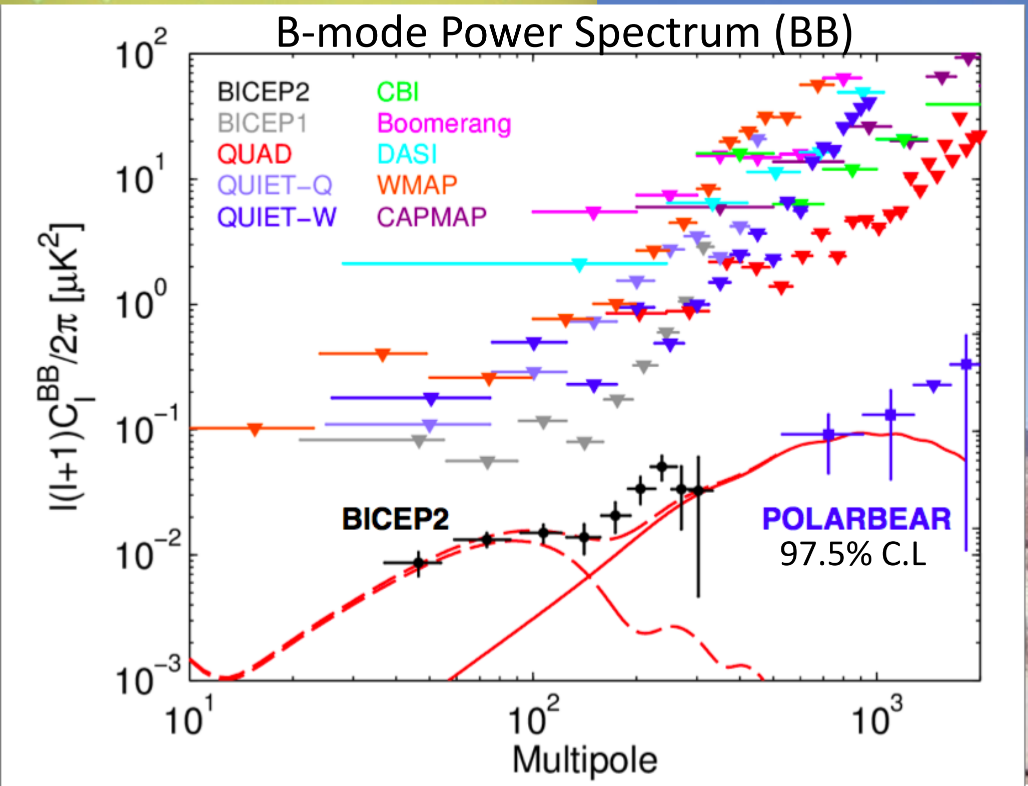


POLARBEAR-1: 4.7σ CMB-only detection of lensing B-modes

ANL, APC, Berkeley, Boulder, Cardiff, Dalhousie, IPMU, Imperial, JAXA,
LBNL, McGill, Melbourne, Princeton, NIFS, PUC, Sokendai, Trieste, KEK, UCSD

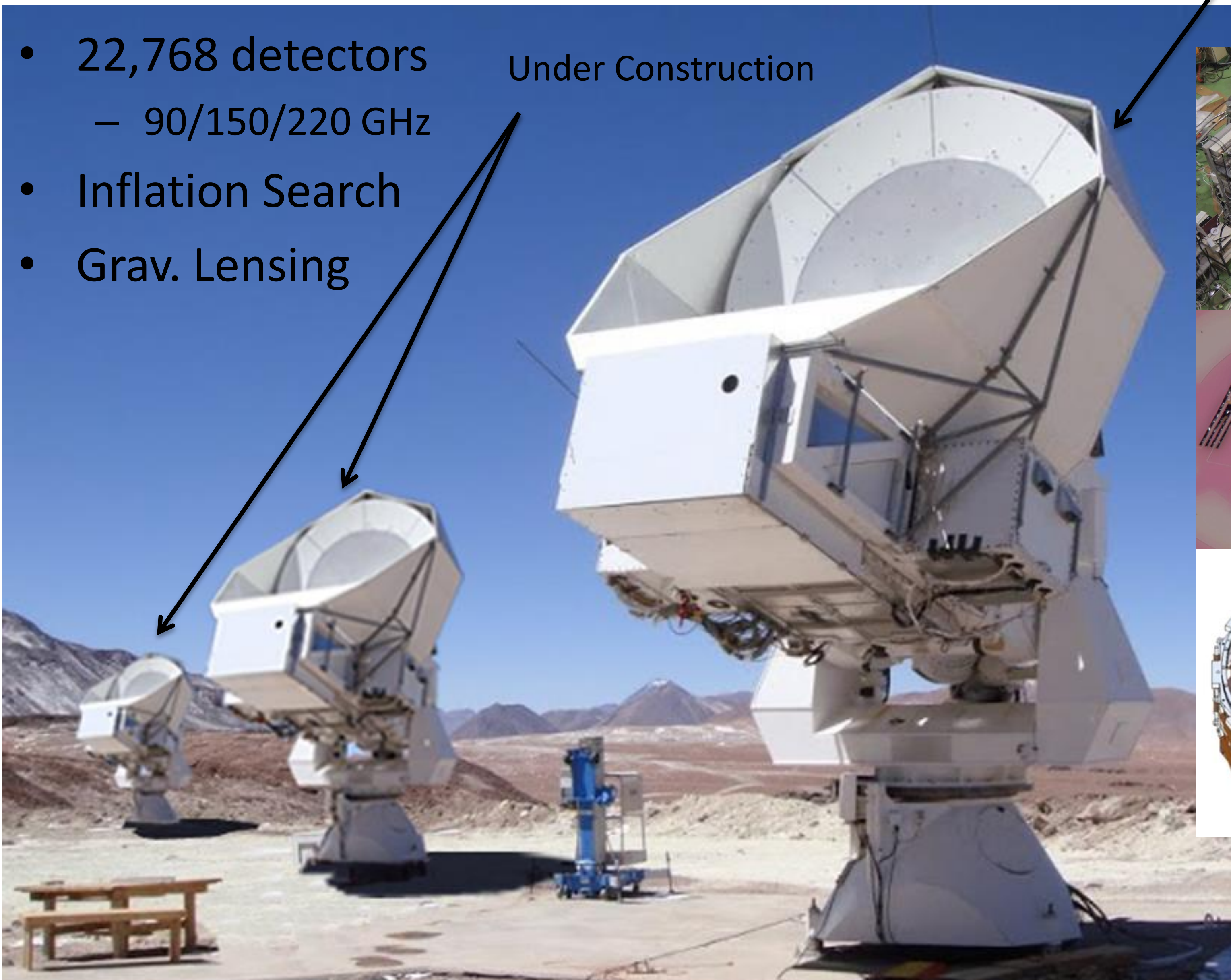


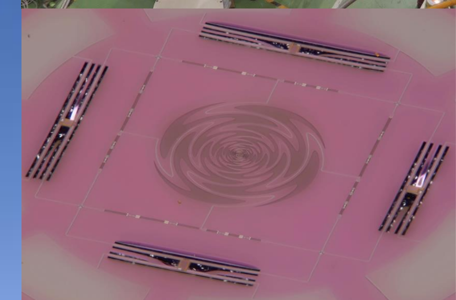




Simons Array (2016)

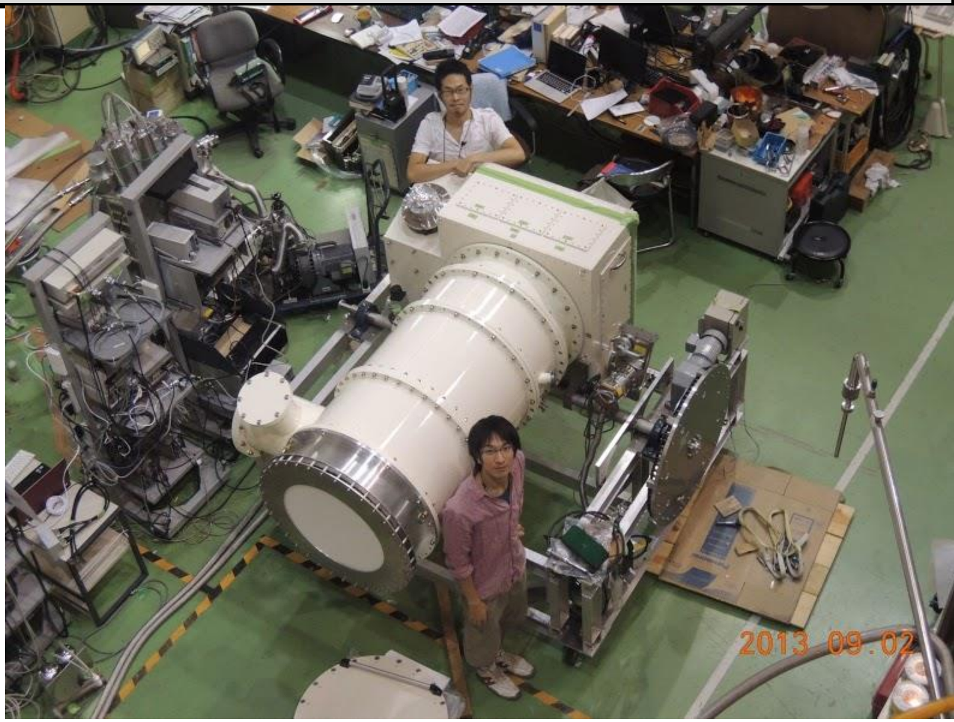
- 22,768 detectors
  - 90/150/220 GHz
- Inflation Search
- Grav. Lensing

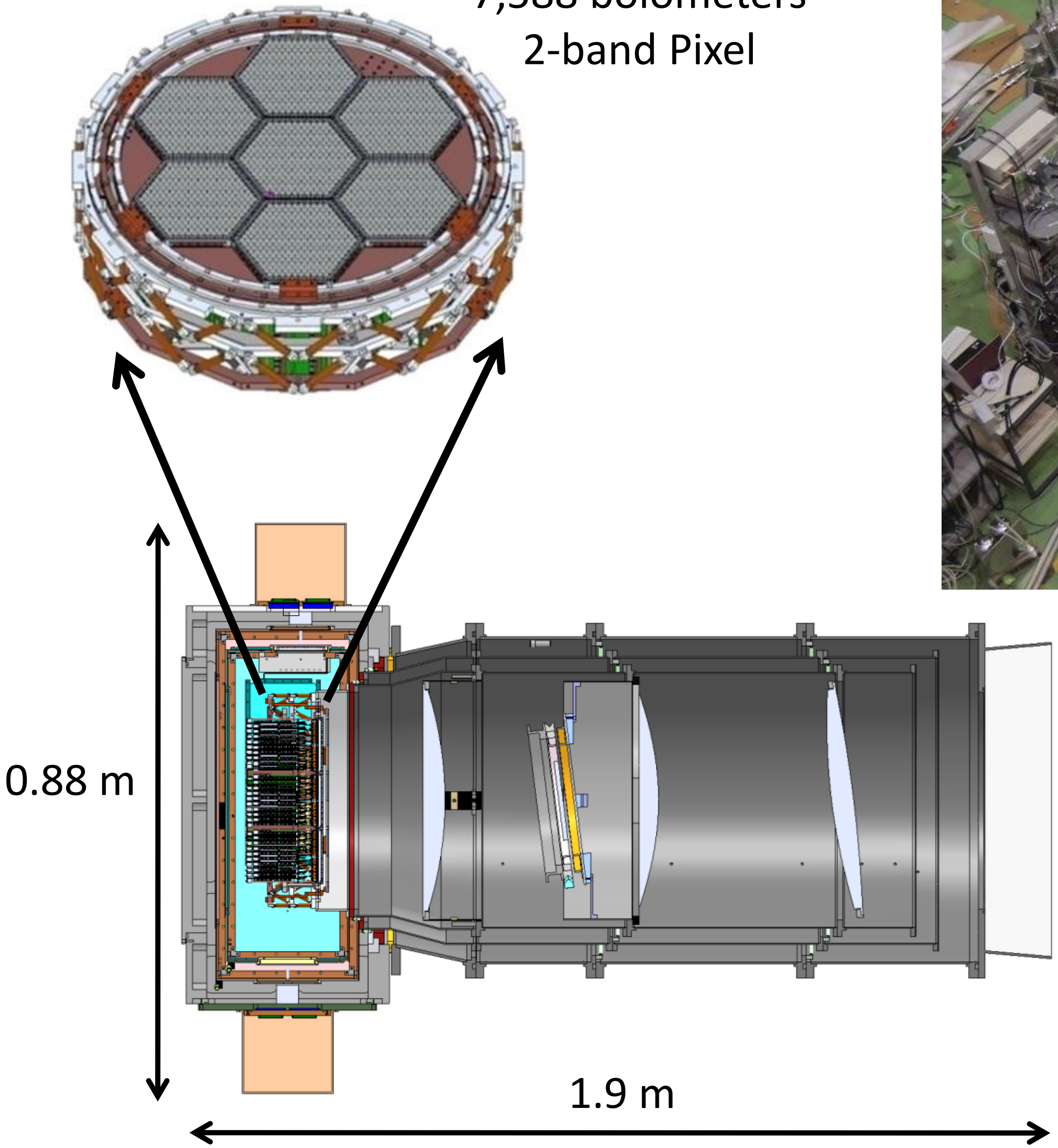




POLARBEAR-2 Receiver

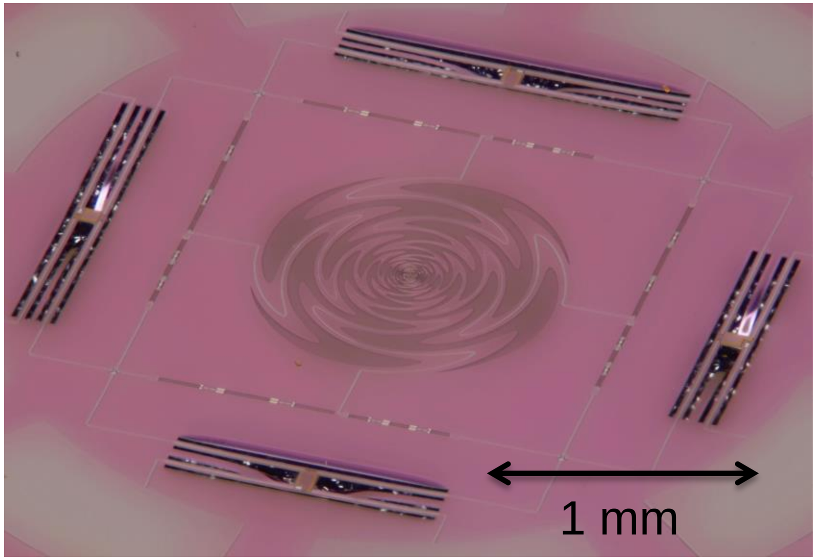
365 mm diameter focal plane
7,588 bolometers
2-band Pixel

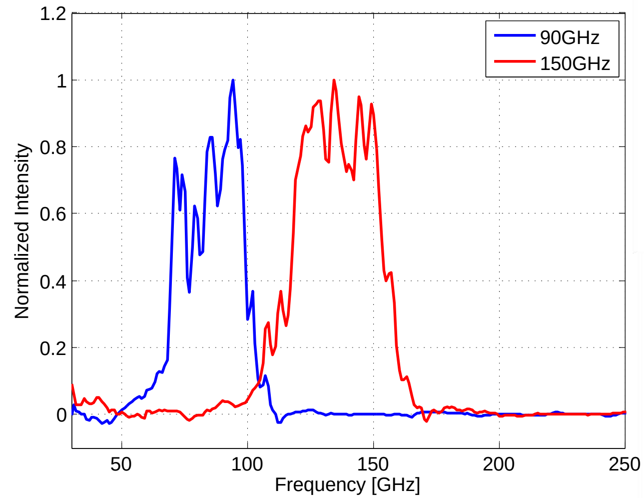


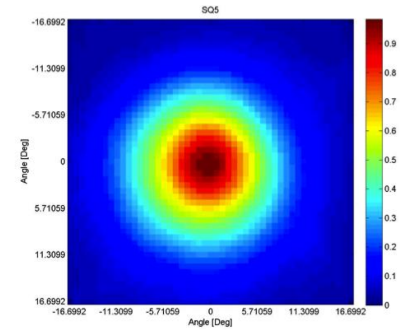


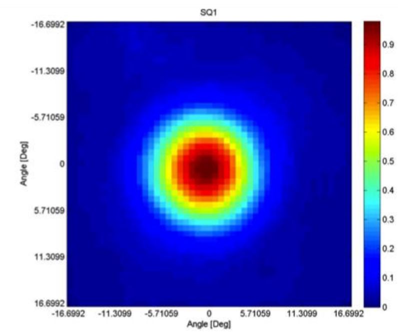
Multichroic Sinuous Antenna pixel

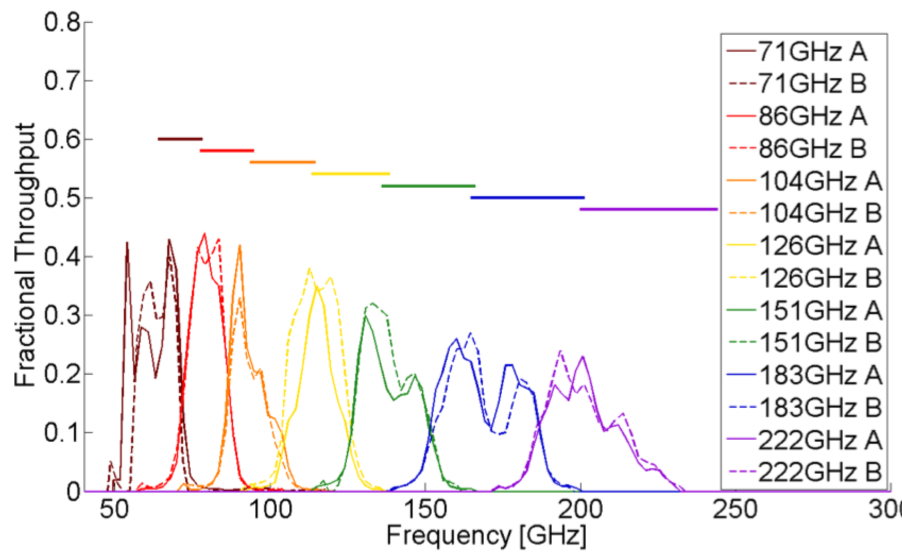
U.C. Berkeley, UCSD (Rebeiz), LBNL, Cardiff







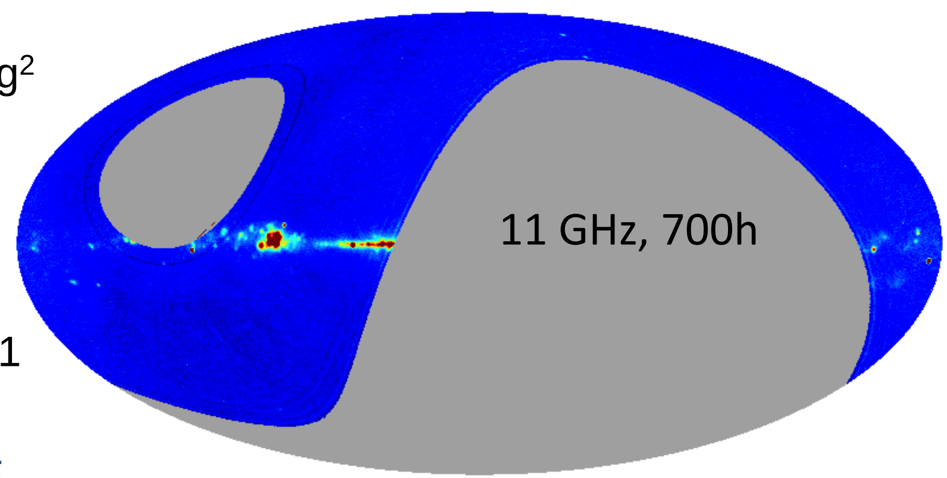




QUIJOTE

- **Q-U-I Joint Tenerife Experiment**
- Teide Observatory (Tenerife, Spain), 2.4km asl
- **Two telescopes** (both operative) and **three instruments**: MFI (10-20 GHz) -operative-, TGI (30 GHz) -early 2015- and FGI (40 GHz) -2016-
- 1-deg angular resolution.

- **Surveys**:
  - Wide survey: 20,000 deg^2, ≈15 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤3 μK/deg^2 @ 30, 40 GHz
  - Deep cosmological survey: 3×1,000 deg^2, ≈5 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤1 μK/deg^2 @ 30, 40 GHz (after 1 year)



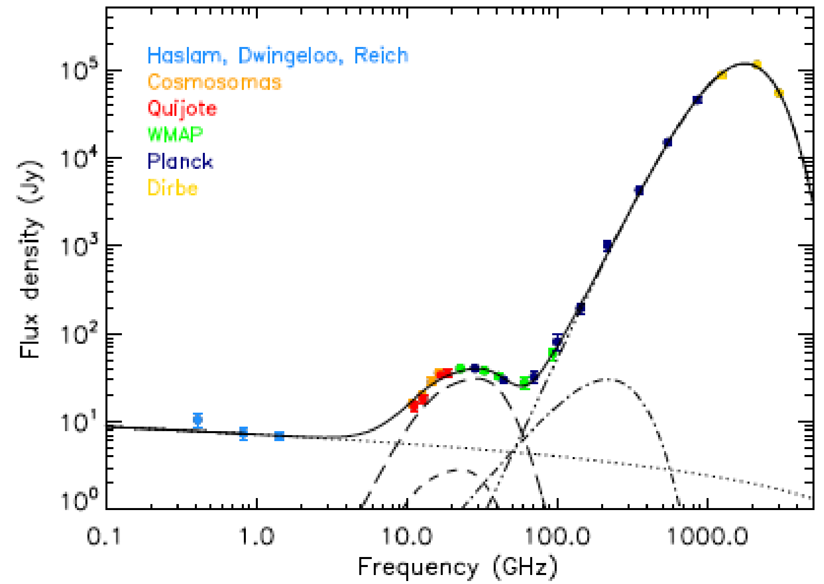
- **Scientific goals**:
  - B-modes down to r=0.05 (after 5 years), r=0.1 (after 1 year).
  - Characterization of the synchrotron and AME polarization.

QUIJOTE

- **MFI Instrument (10-20 GHz).**
- In operations since Nov. 2012.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- Sensitivities: ~400-600 μK $s^{1/2}$ per channel.

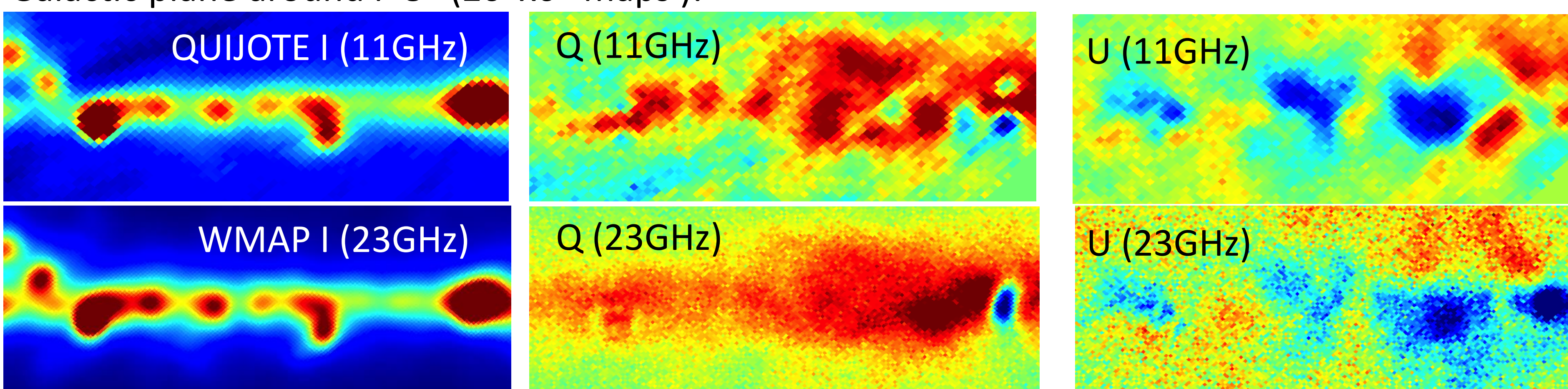
- **TGI (30 GHz) and FGI (40GHz) instruments**:
- TGI: 31 pixels at 30GHz. Expected sensitivity: 50 μK $s^{1/2}$ for the full array.
- FGI: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array.

Perseus molecular complex

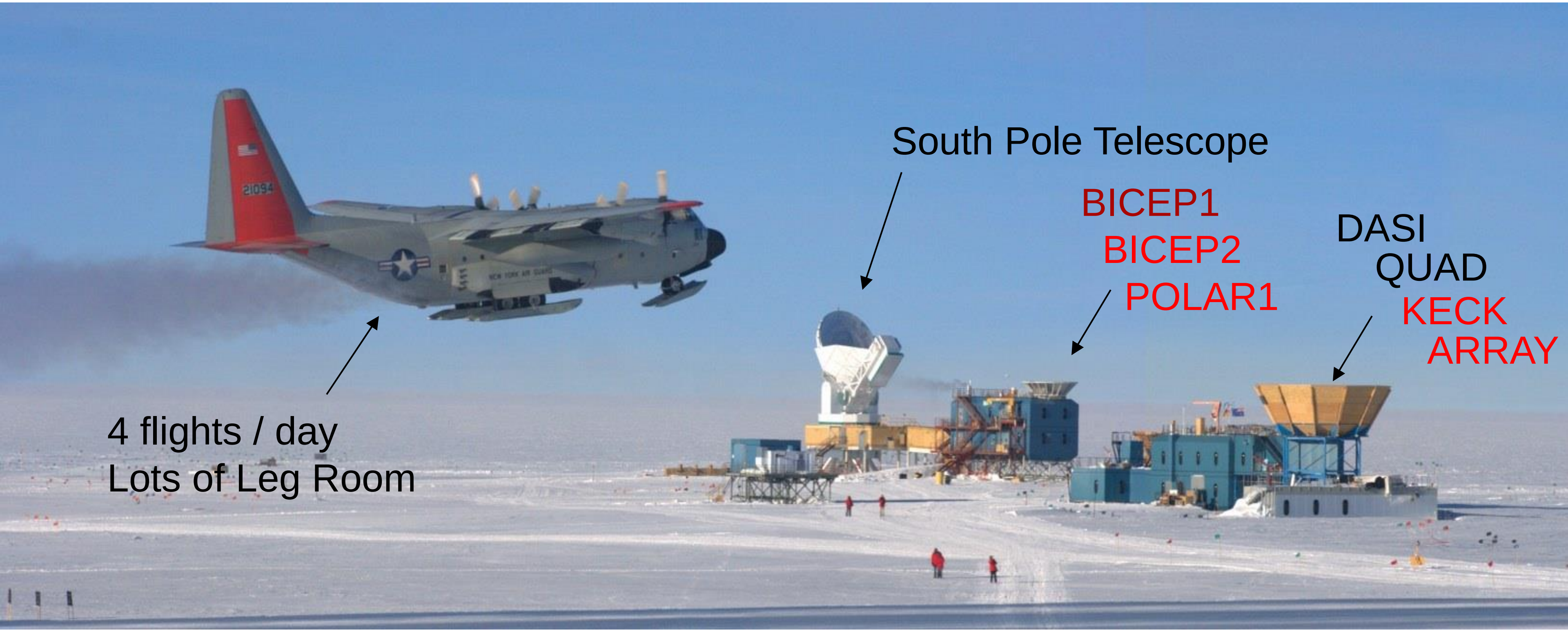


Génova-Santos et al. (2014) in prep.

Galactic plane around l=8º (20ºx6º maps):



BICEP/KECK


South Pole Telescope
BICEP1
BICEP2
POLAR1
DASI
QUAD
KECK
ARRAY
4 flights / day
Lots of Leg Room

Background Imaging of Cosmic Extragalactic Polarization

Minimize polarization systematics

Azimuthal symmetry

Simple refractor, no mirrors

Optimize to $30 < \ell < 300$

Beam sizes ~ 0.9 deg, 0.6 deg

Field of view ~ 18 deg

Observed sky fraction ~ 2%

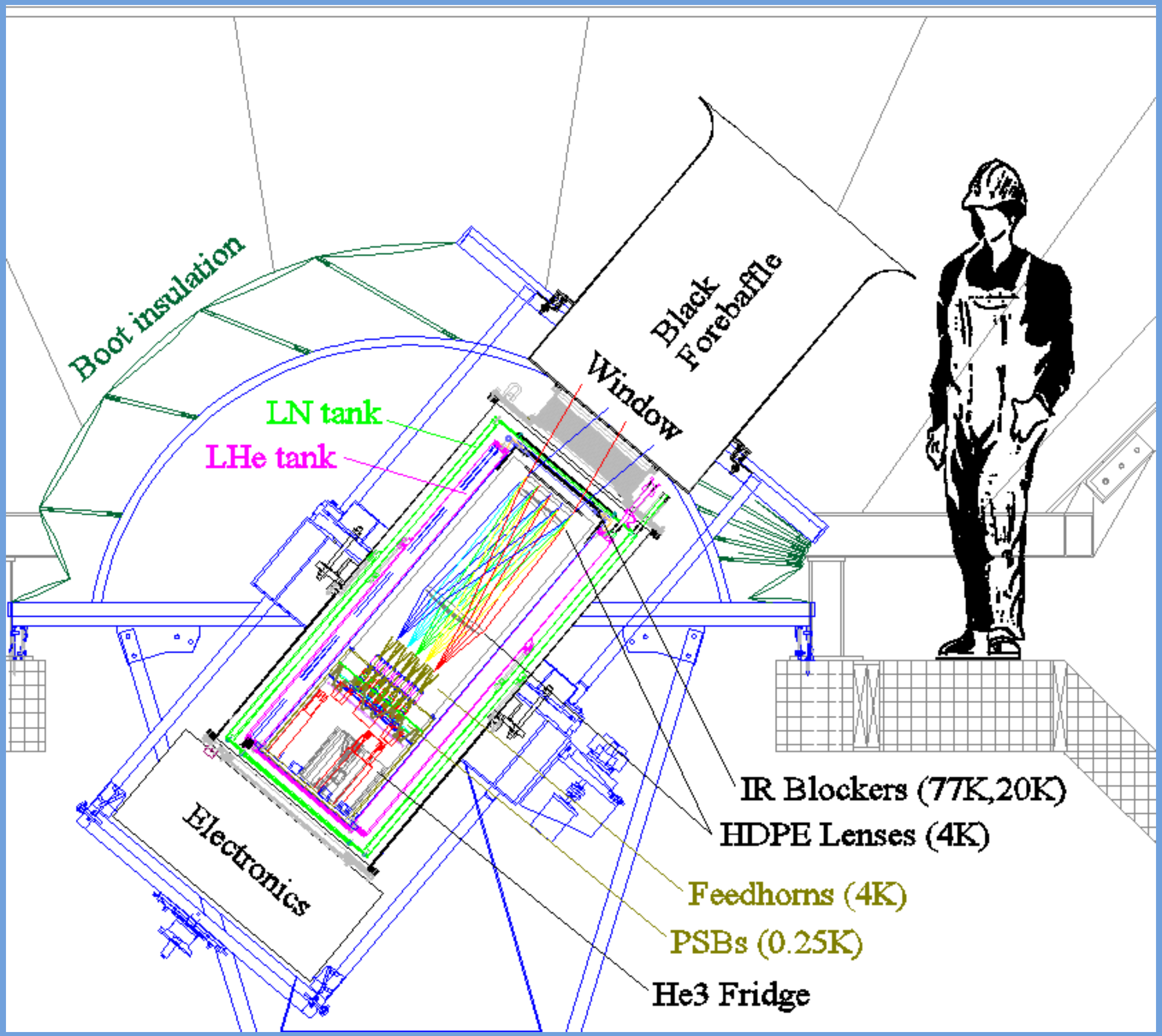
Frequency coverage

100 GHz: 25 pixels
150 GHz: 22 pixels
220 GHz: 2 pixels

Signal-to-noise considerations

PSB differencing

South Pole: long integration over contiguous patch of sky, reduced atmospheric loading

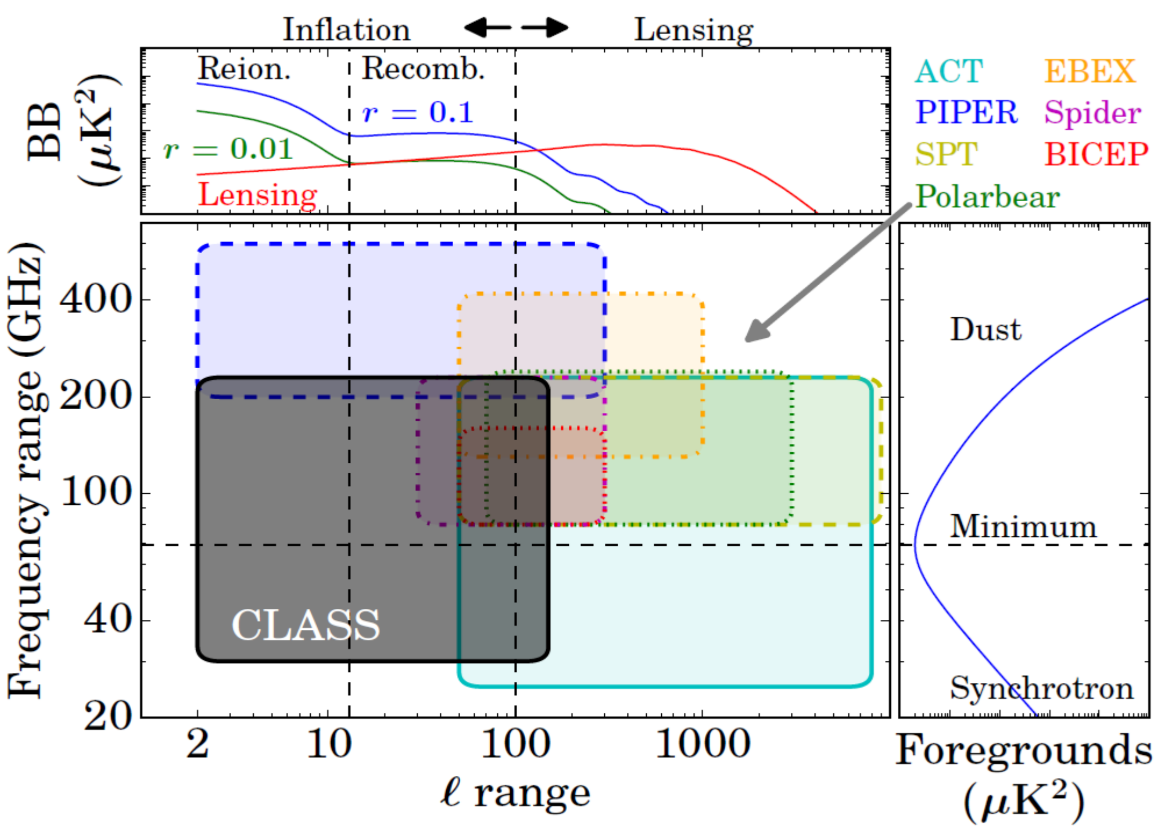


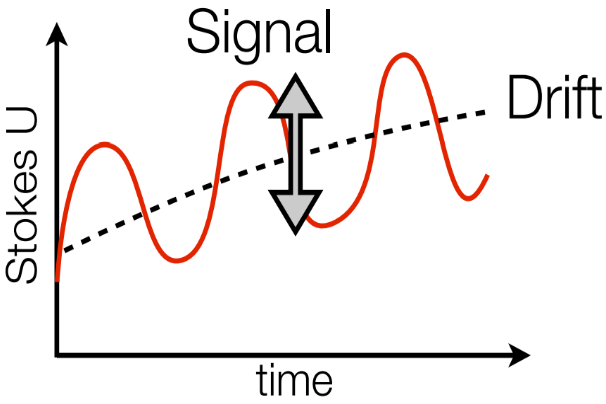
H. C. Chiang

CLASS

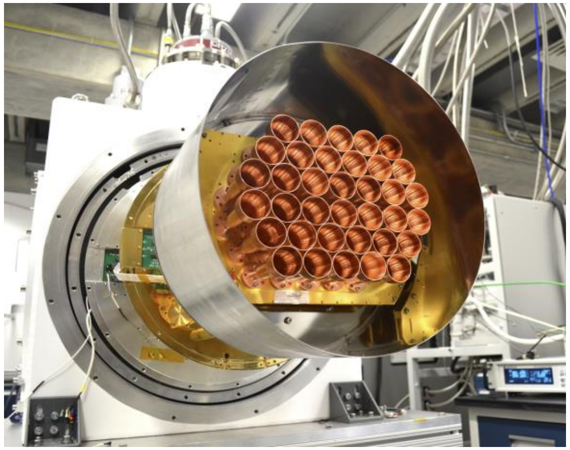
Rapid Front-end Modulation = DC-stable Large-scale Measurement

- ✓ Inflation
- ✓ Reionization





40 GHz Focal Plane

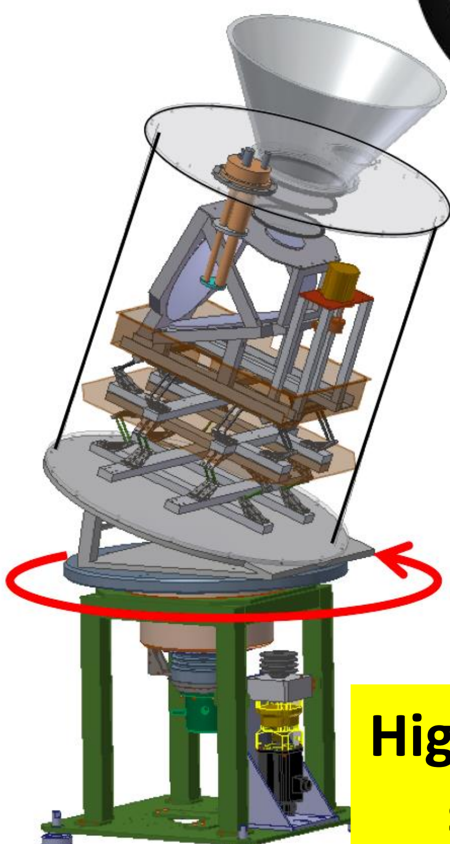


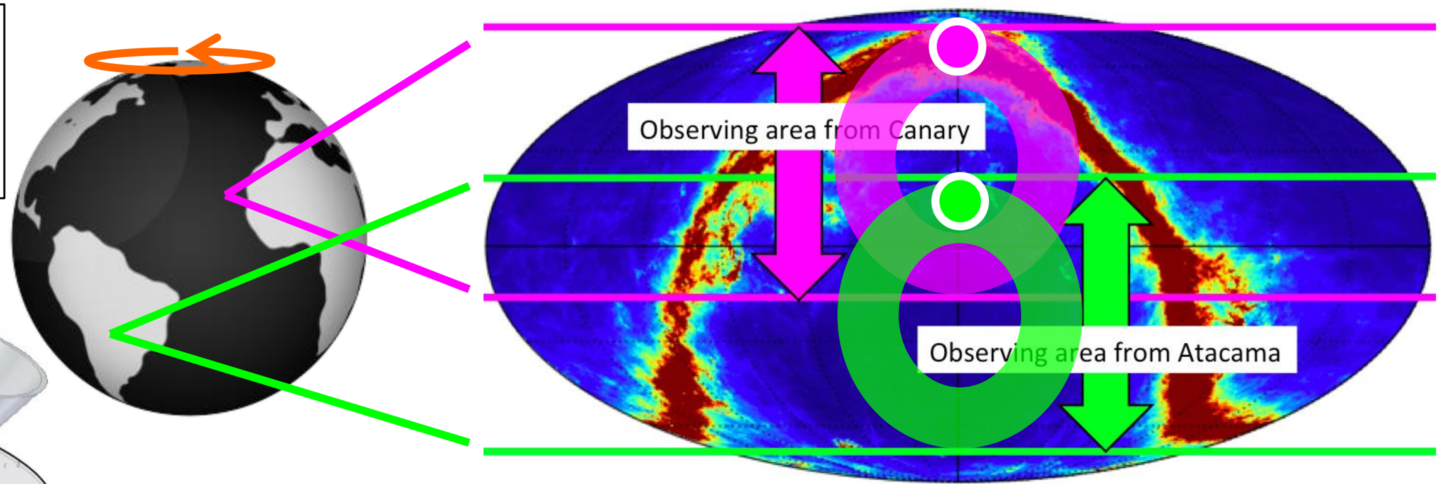
From Osamu Tajima

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

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

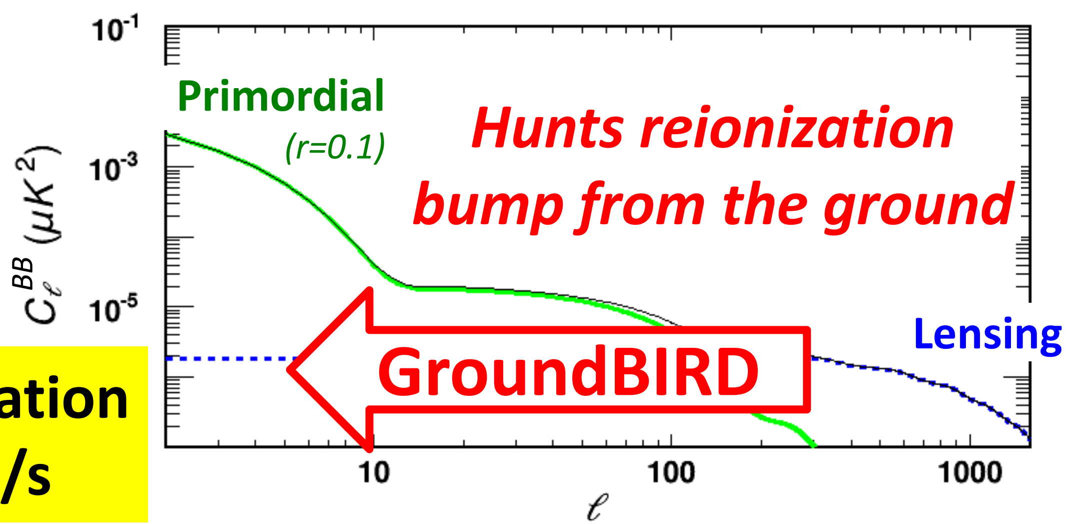
Would start CMB observation from 2016 – 2017





High-speed rotation scan + Earth rotation → Large field obs.

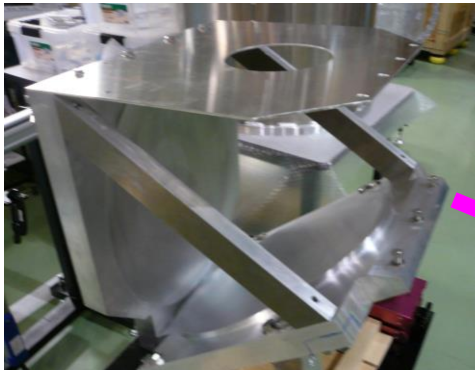
f_{sky} > 0.8 with two sites, e.g., Atacama Chile + Canary Islands



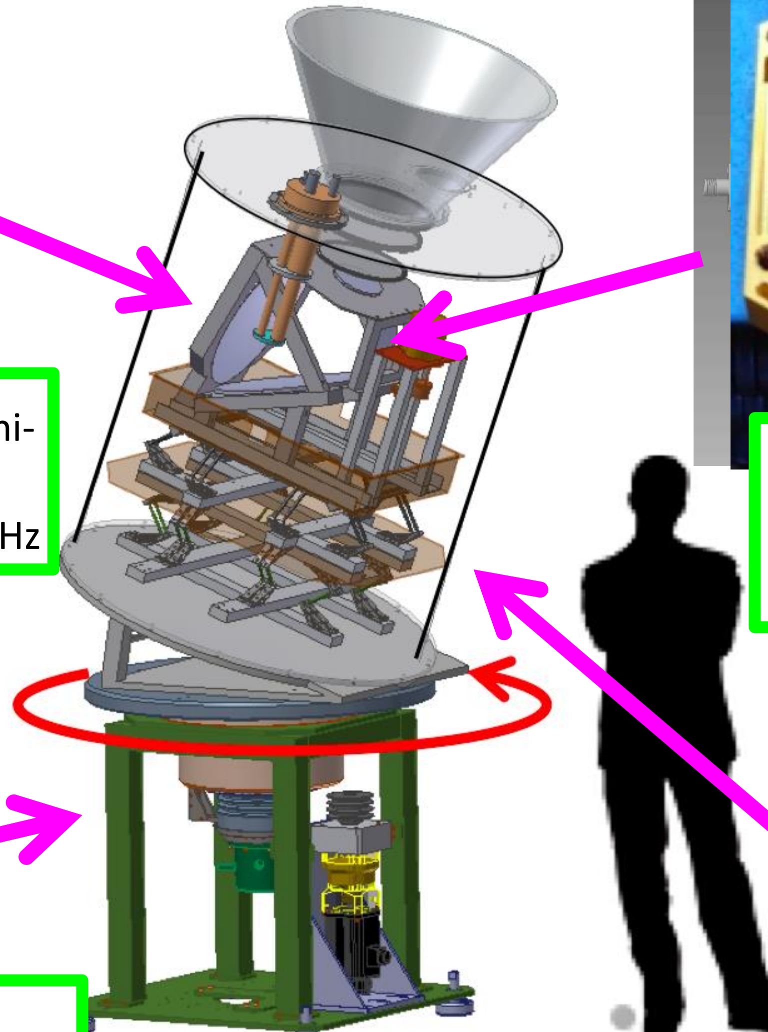
High-speed rotation scan of 120°/s

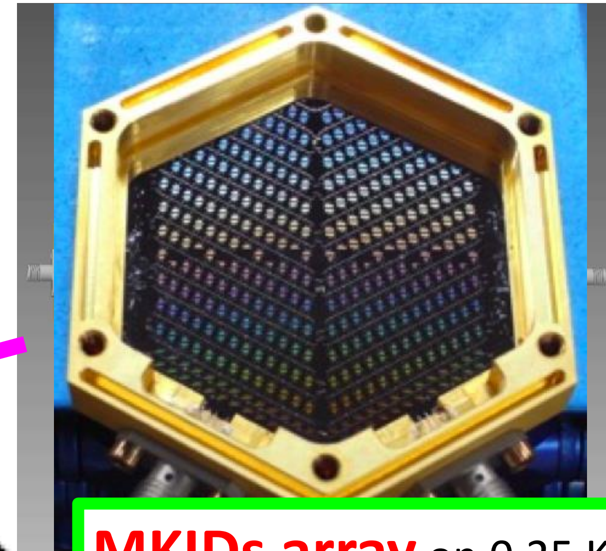
GroundBIRD – *Instrument* ***features***

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° FoV, angular resolution of 0.6° at 145 GHz





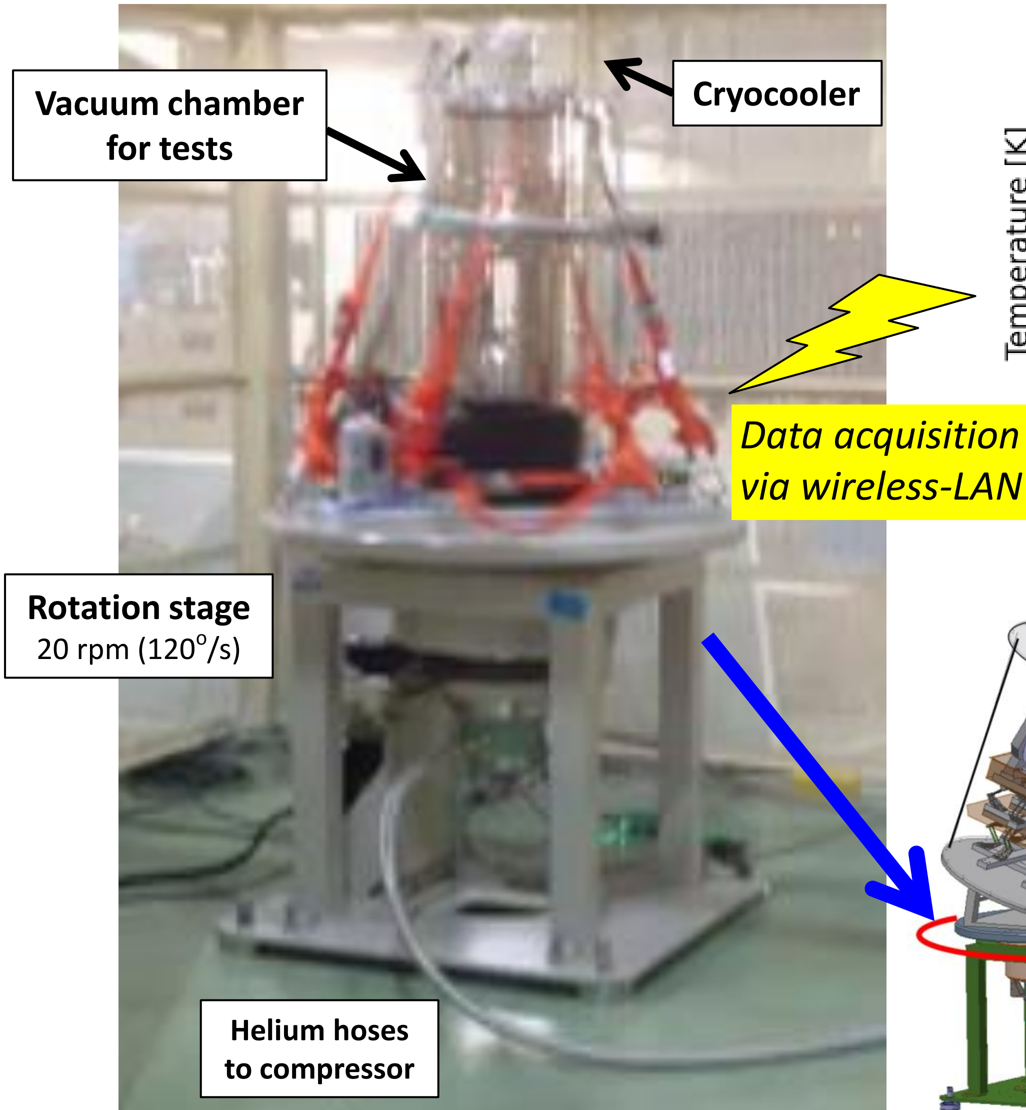
MKIDs array on 0.25 K
612 kids for **145 GHz**,
354 kids for **220 GHz**.

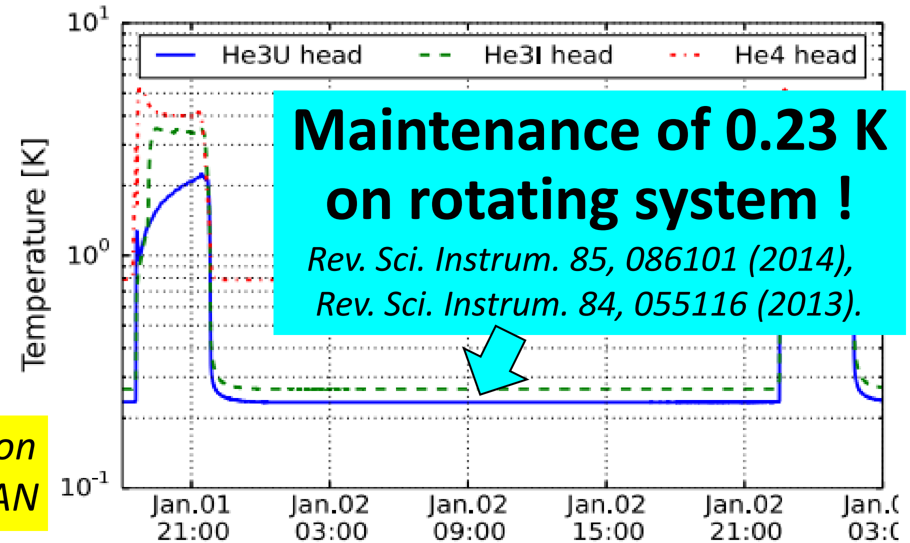
Rotation mount maintains
high-speed rotation scan
Scan speed of 120°/s, i.e., 20 rpm

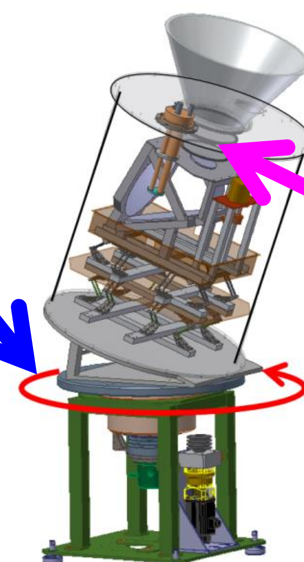
Cryostat cooled by PTC
+ Helium sorption cooler
Boresight rotation
(stepwise)

+ Continuous calibration with sparse-wire

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



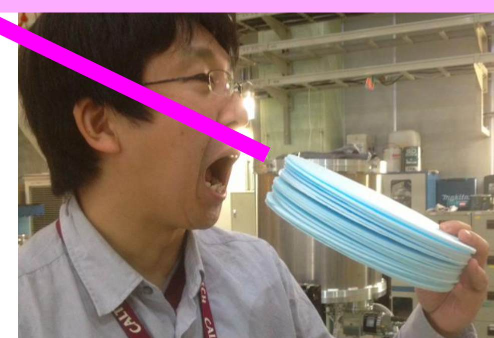




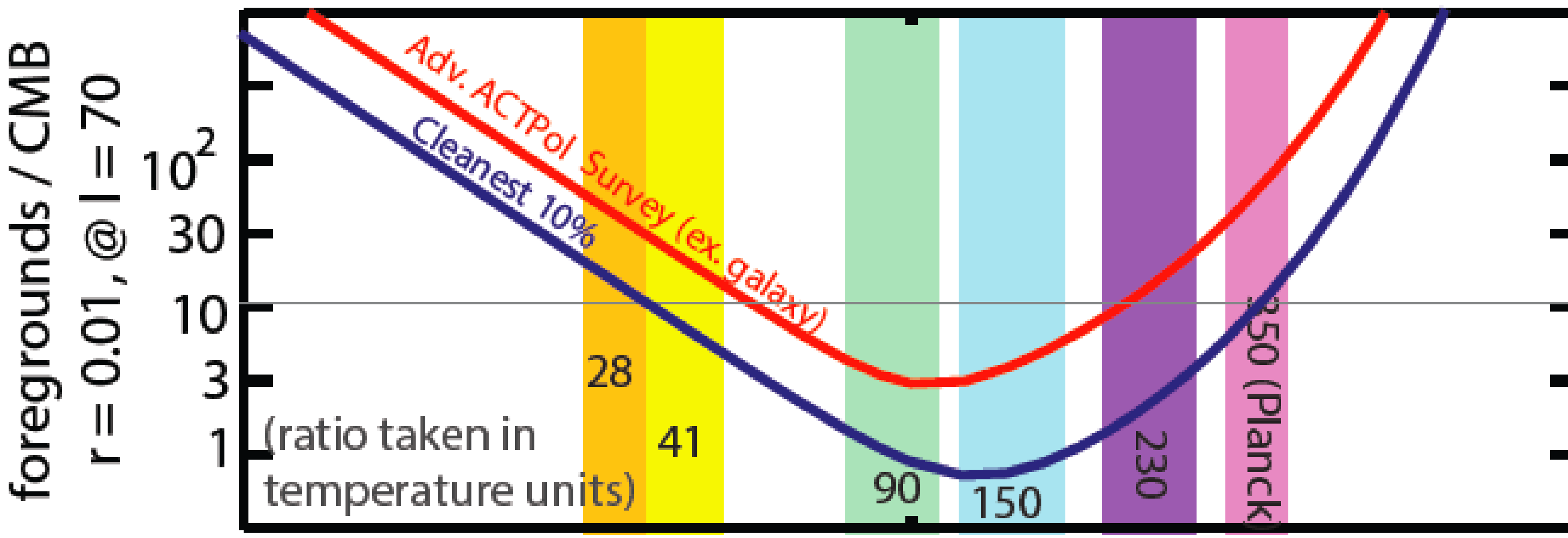
RT-MLI

radio-transparent thermal insulator

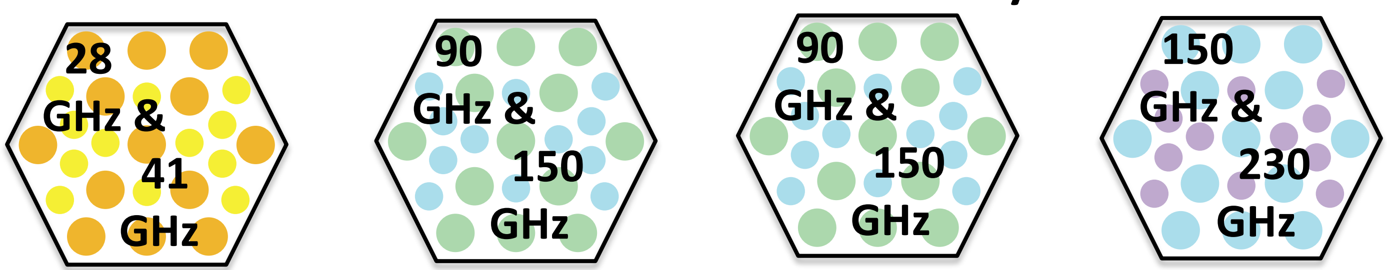
Rev. Sci. Instrum. 84, 114502 (2013).



Five bands from 30 to 230 GHz



Four multichroic arrays



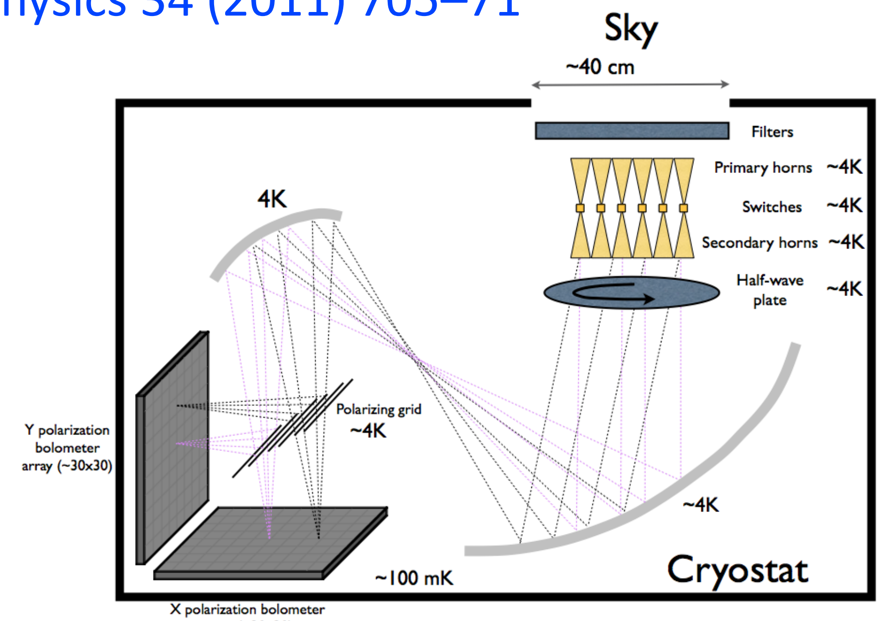
ACTPol will field first multichroic array this year

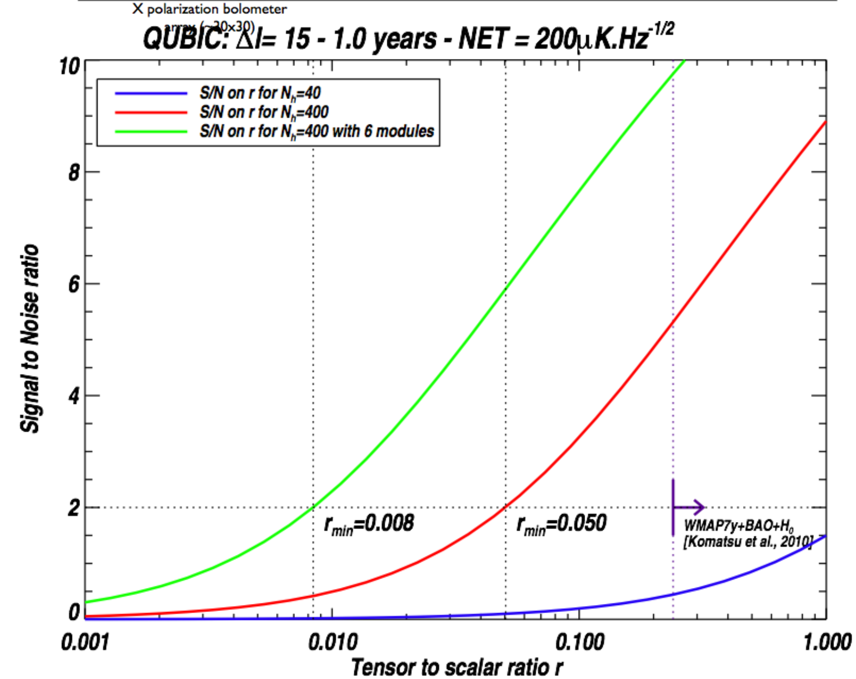
Low (28 & 41 GHz) and high (230 GHz + Planck 353 GHz) frequency channels allow detection and subtraction of synchrotron and dust foregrounds.

QUBIC: QU Bolometric Interferometer for Cosmology

arXiv:1010.0645 ~ Astroparticle Physics 34 (2011) 705–71

- Team: APC, Brown, IAS, IRAP, CSNSM, Manchester, Milan, NUI, Richmond, Rome, UW-Madison
- QUBIC Concept:
  - Image fringe patterns from 20x20 primary horns on focal planes
  - Frequency: 150 GHz, 25% Bandwidth
  - Polarization modulation: HWP
  - Horns FWHM: 14 deg. FoV
  - Optical combiner: Off-axis Gregorian 300 mm focal length
  - Detectors: 2x1024 NbSi TES with SQUID+SiGe ASIC mux readout
- Synthetic imager:
  - Fringe superposition results in synthesized beam ~0.5 deg FWHM
  - Scan sky with synthesized beam, make map and power spectra as with an imager
- Deployment plan:
  - 2011/12: R&D finalization on components
  - 2013: 1st module integration, first light in lab
  - 2014-...: 1st module observations from Dome C,
  - 2014-...: Other modules construction and installation (100 GHz and 220 GHz)



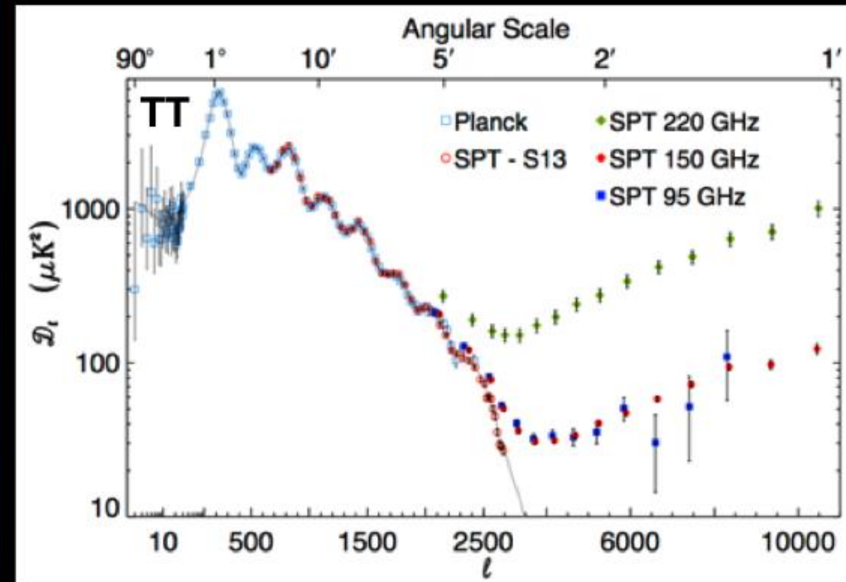


SPT: The 10-m South Pole Telescope

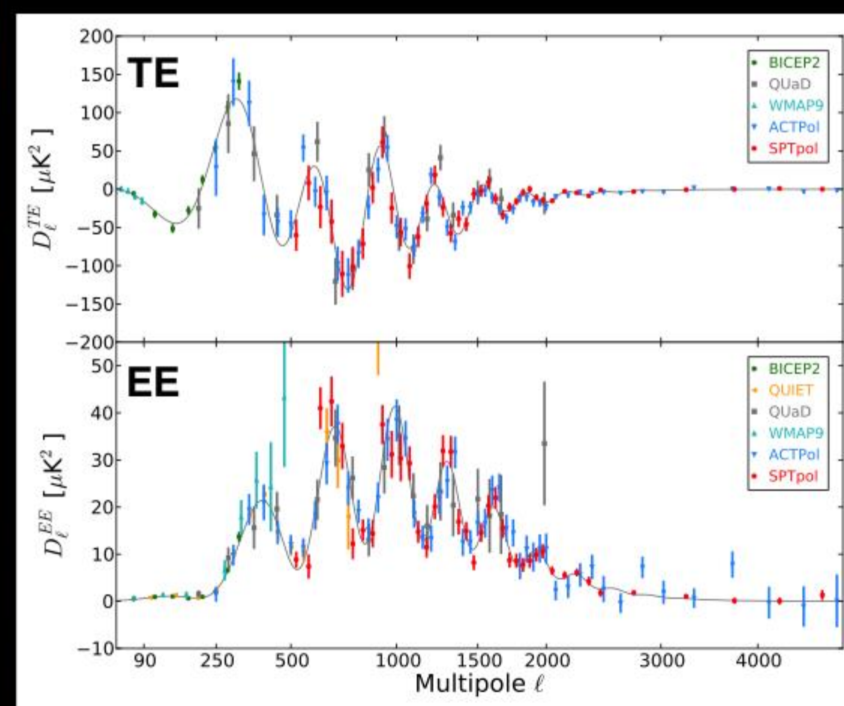
2007: SPT-SZ
960 detectors
100,150,220 GHz

2012: SPTpol
1600 detectors
100,150 GHz

2016: SPT-3G
16,200 detectors
100,150,220 GHz

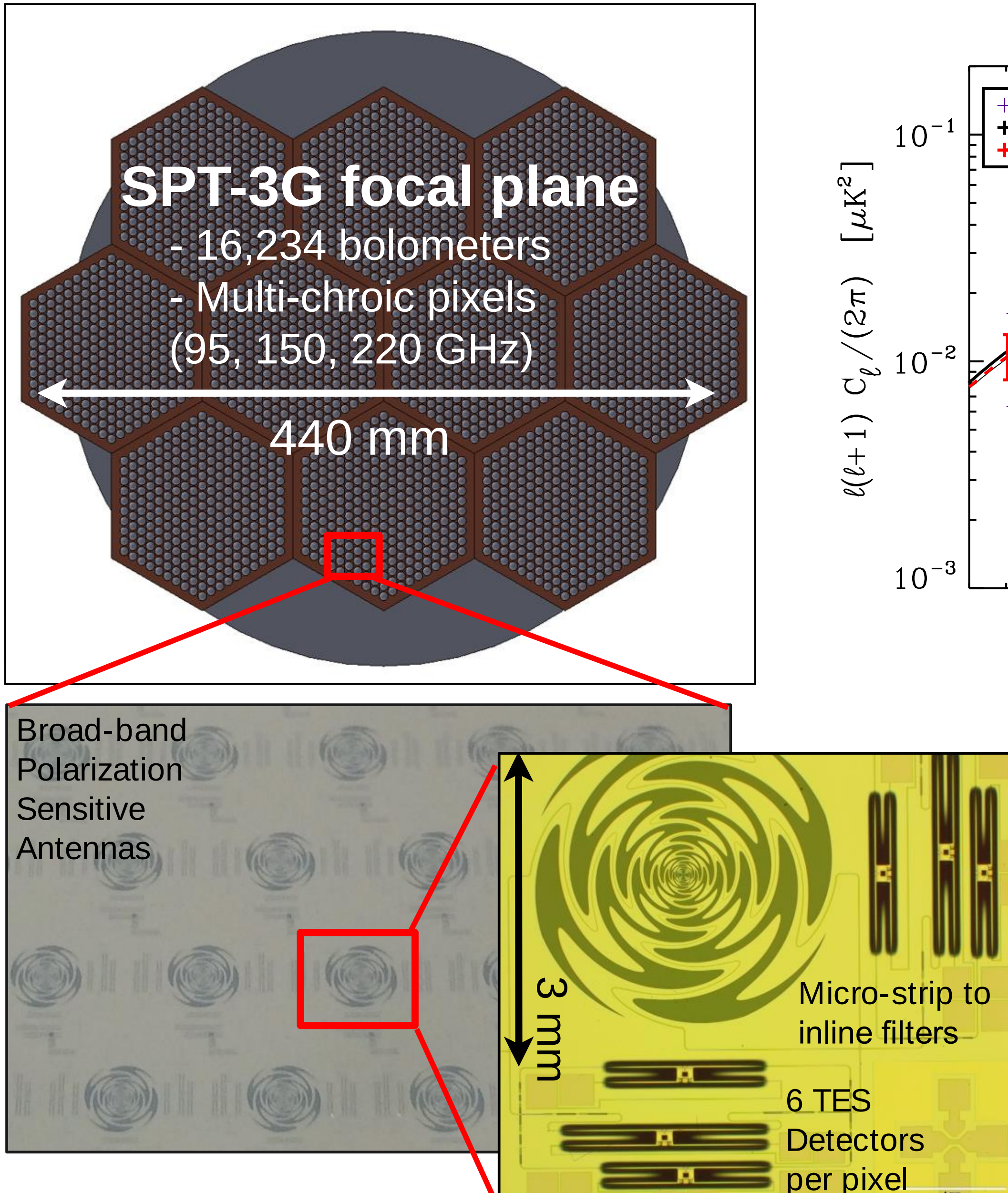


George et al 2014

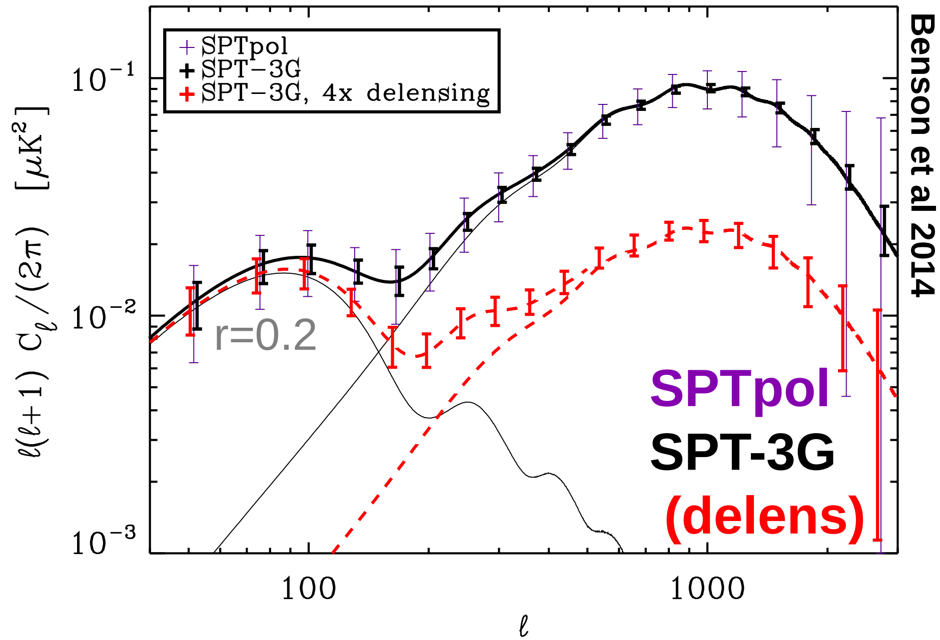


Crites et al 2014

SPT-3G: To Deploy in December 2015!



BB-Spectrum (projected)



Projections

(w/ Planck priors)

	SPT-3G (2019)
σ(r)	0.011
$\sigma(N_{eff})$	0.058
σ(! m#)	0.061 eV*

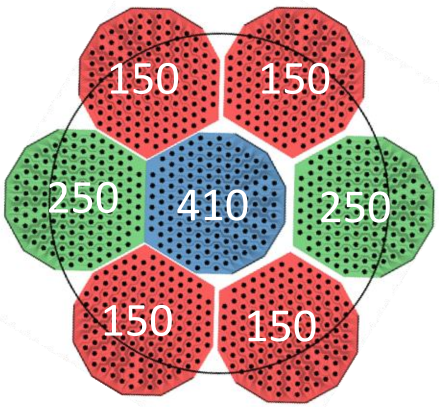
* Includes BOSS prior

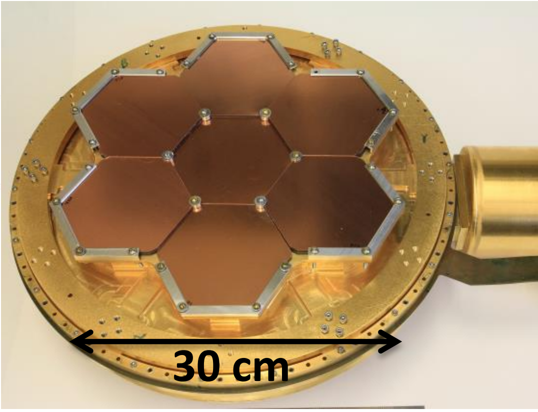
Balloon

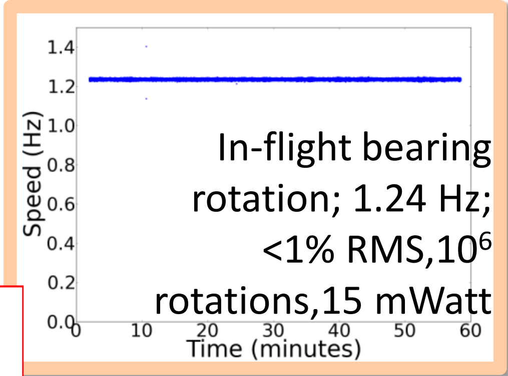
EBEX-2012 - Summary

- 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

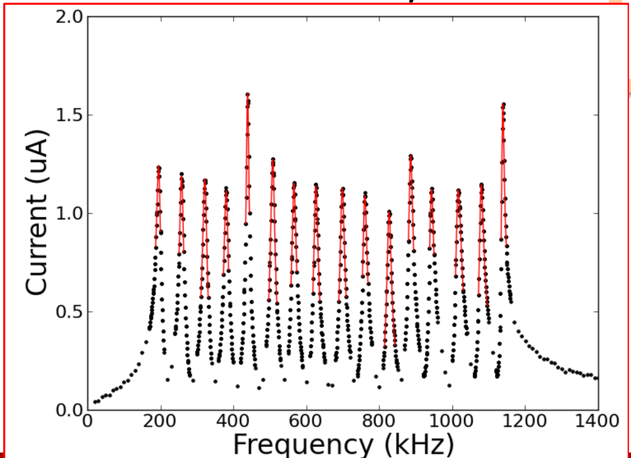
One of two (identical) focal planes

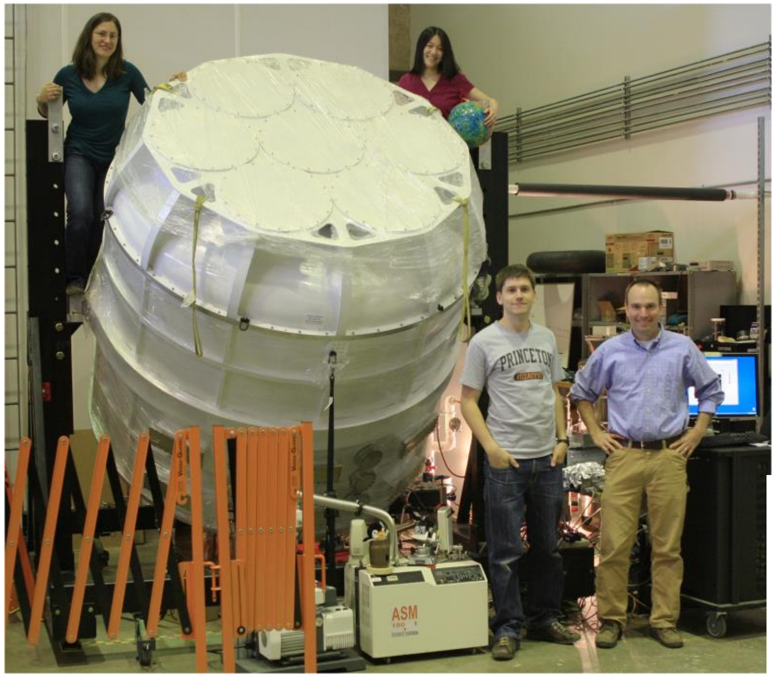






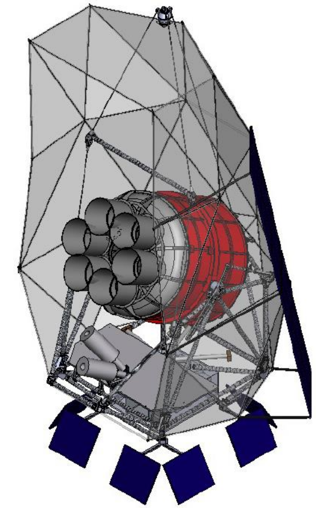
X16 FMUX; network analysis

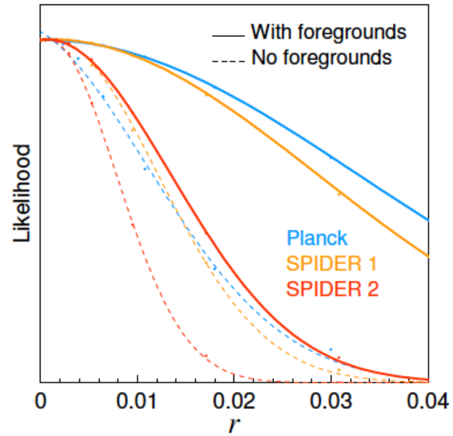




Spider:

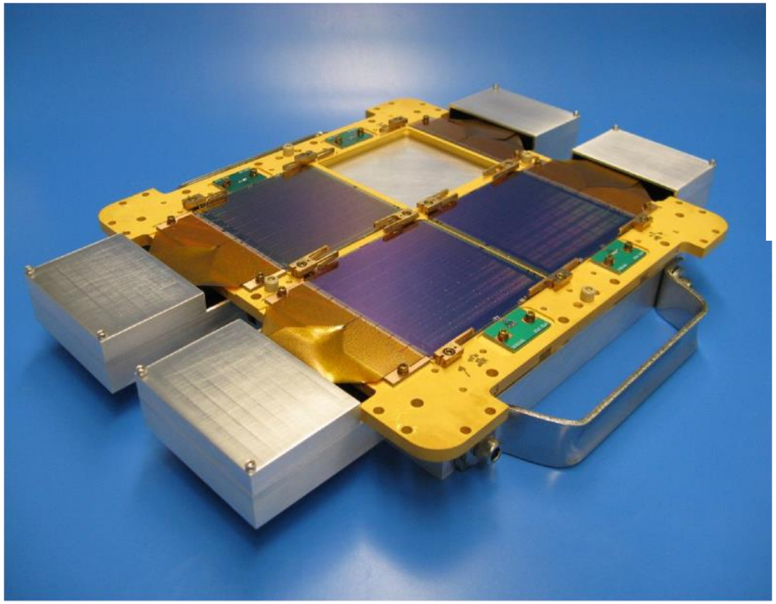
- Probing Inflation at r ~ 0.03
- Detecting weak lensing
- Detecting Galactic polarization
- Leading technology development





SCIP:

- Probing Inflation at r ~ 0.01
- Characterizing weak lensing
- Mapping the spectrum of Galactic polarization
- Space qualified technology

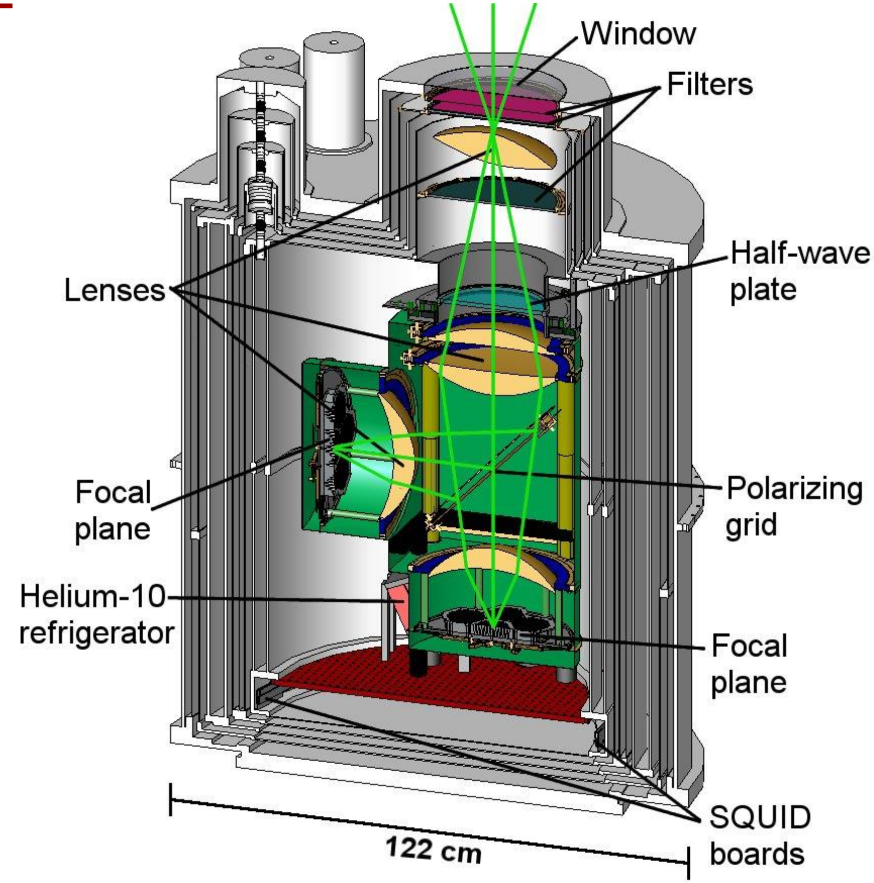


JPL Detectors

EBEX in a Nutshell

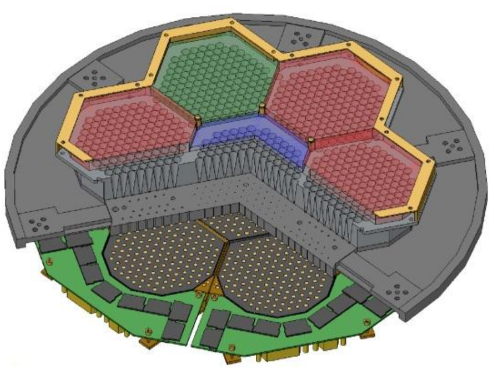
Science Goals

- T/S < 0.04 (2σ; includes dust subtraction)
- Detection of lensing B: S/N>10
- Detection of deflection angle power spectrum: S/N>20
- Determination of foreground:
  - 1.5% on dust spectral index
  - 2% on dust amplitude



Experimental Approach

- 1456 TES Bolometers
- 150, 250, 410 GHz
- 8’ resolution



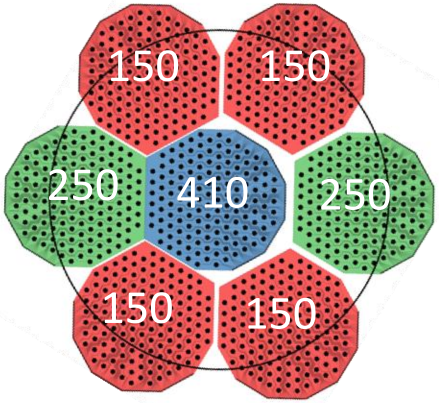
APC – Paris
Berkeley Lab
Brown Univ.
Cardiff
Columbia Univ.
GSFC
IAS-Orsay
IAS-Princeton
Imperial College
INRIA – Saclay
KEK- Japan
LAL-Orsay
McGill Univ.
NIST
SISSA-Trieste
Univ. California/ Berkeley
Univ. Minnesota/Twin Cities
Weizmann Institute of Science

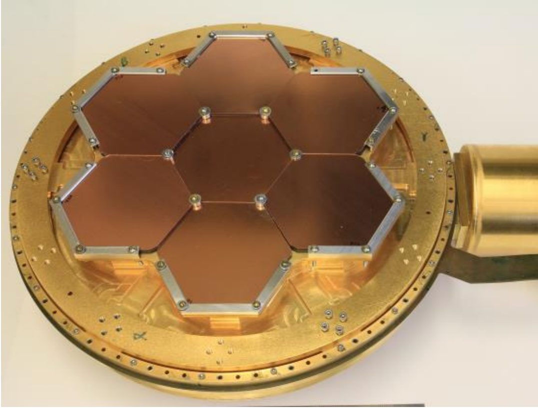
EBEX in a Nutshell

- 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

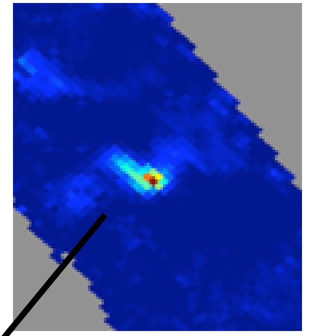


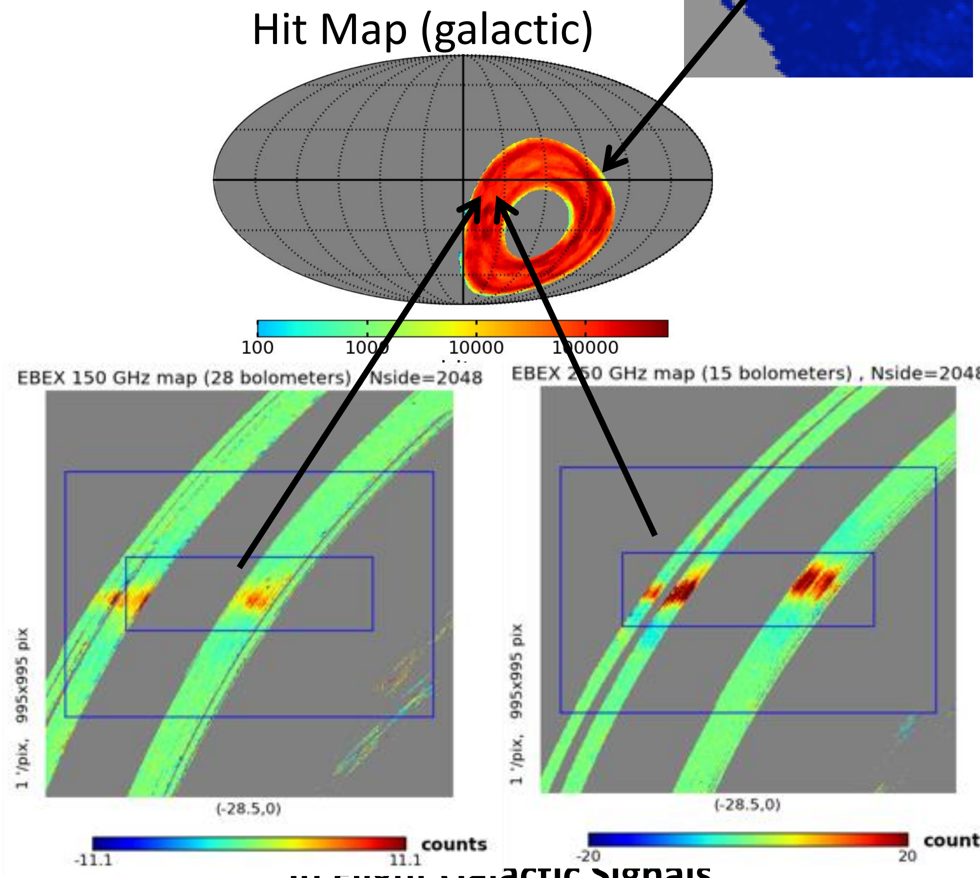


EBEX in a Nutshell

- 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

RCW38; ~29 250 GHz bolometers, 5.5 hours section



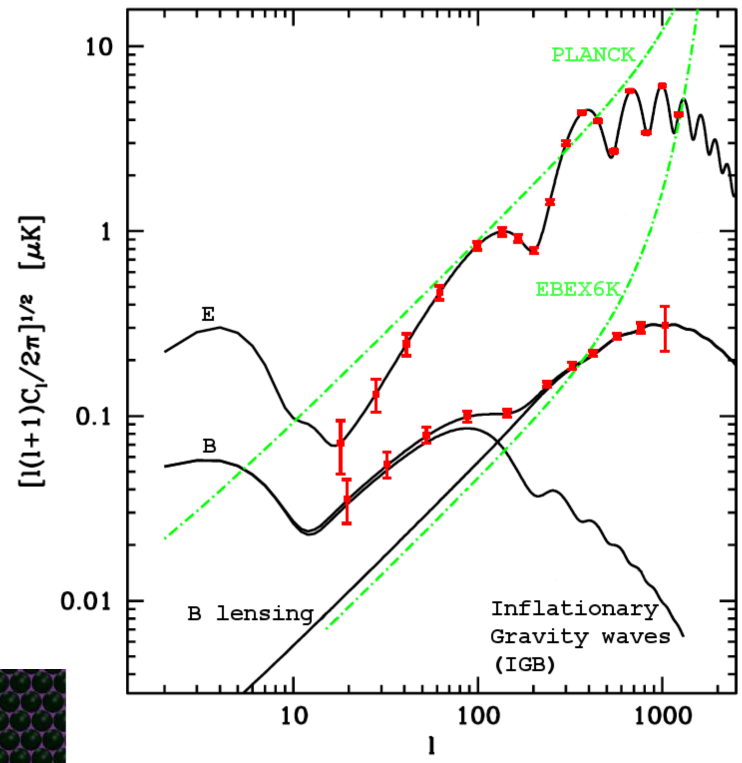


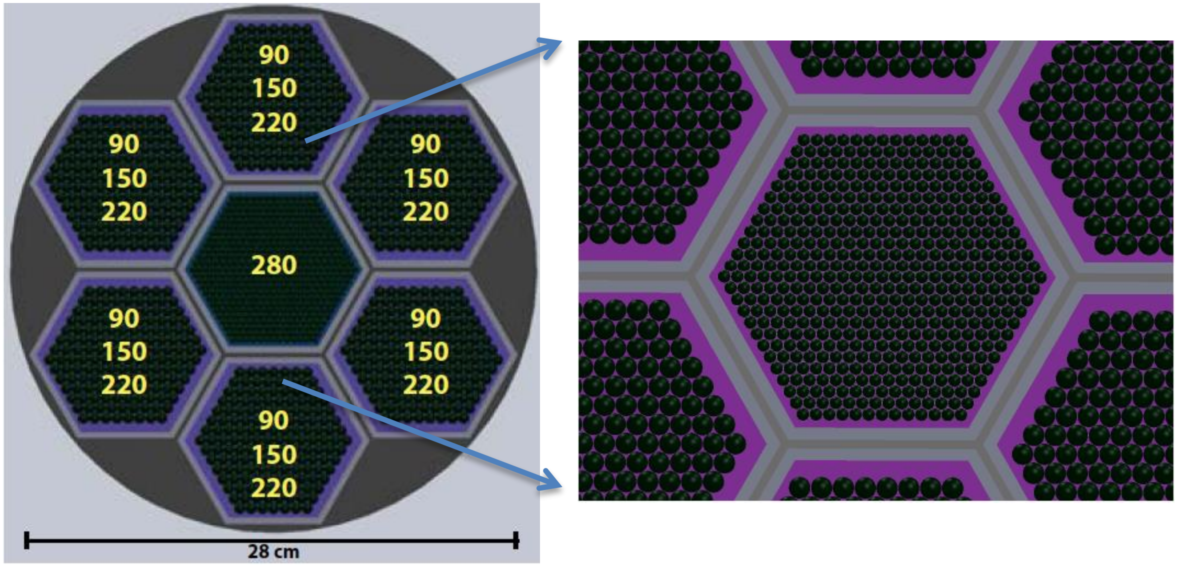
In Flight Galactic Signals (one section, ~20 bolometers

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)



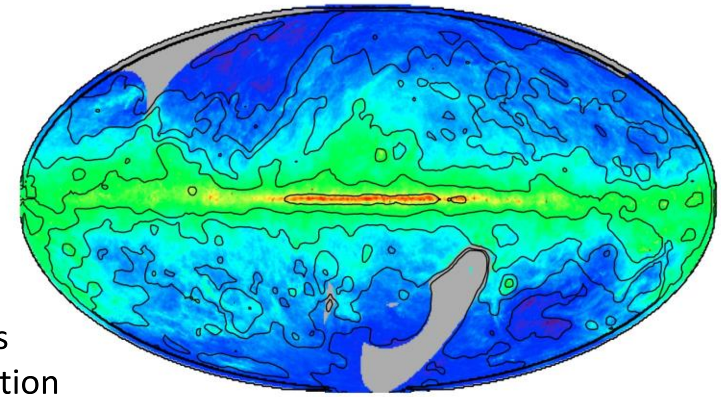


Fly in 12/2018
Pending funding approval

PIPER Sky Coverage and Sensitivity

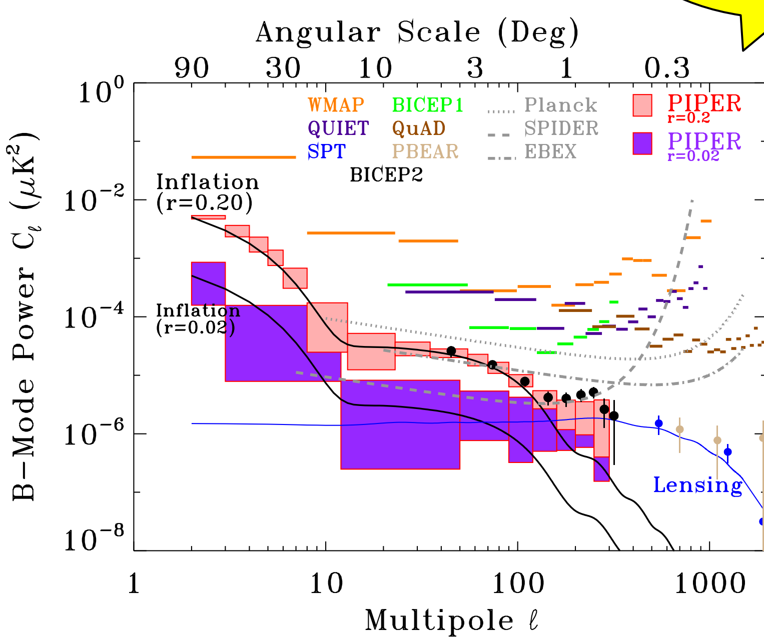
Cold optics improve mapping speed by a factor of 10 ...

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.



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

Sensitivity r < 0.007 (2σ)
First flight 2015

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

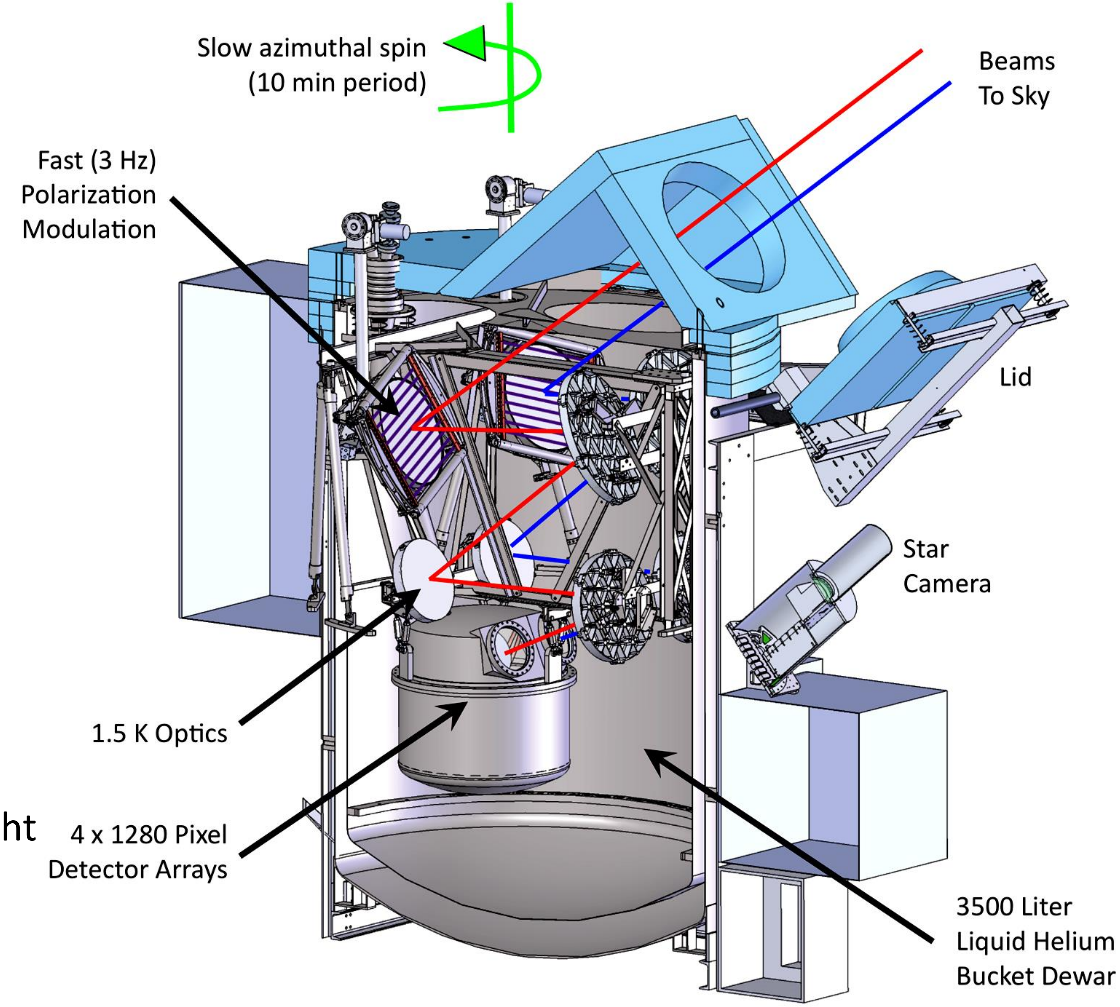
- Front-End polarization modulator
- Twin telescopes in bucket dewar

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

Primordial Inflation Polarization Explorer

Sensitivity

- 5120 Detectors (TES bolometers)
- Cold (1.5 K) Optics
- Background-limited performance

Systematics

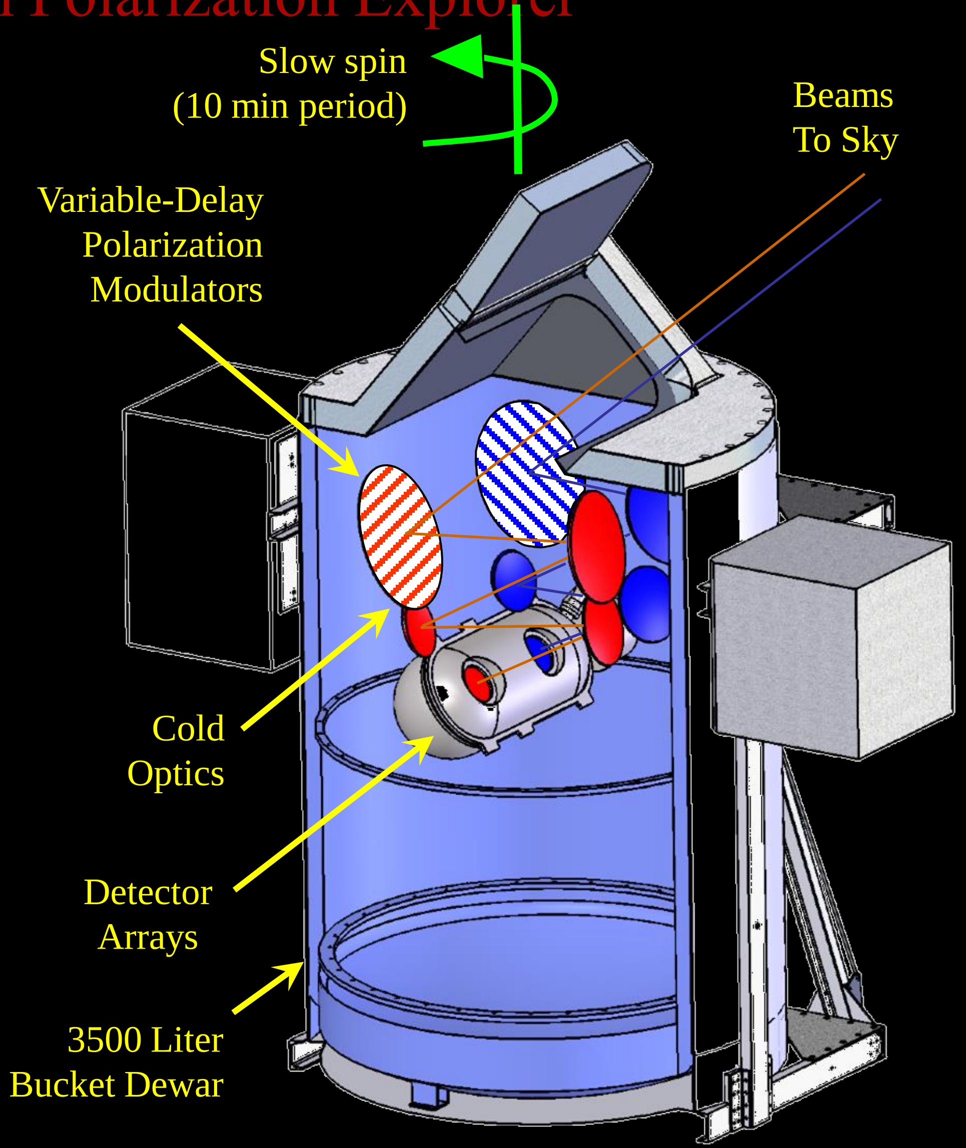
- Front-End polarization modulator
- Twin telescopes in bucket dewar

Foregrounds

- 1500, 1100, 850, and 500 µm
- Clearly separate dust from CMB

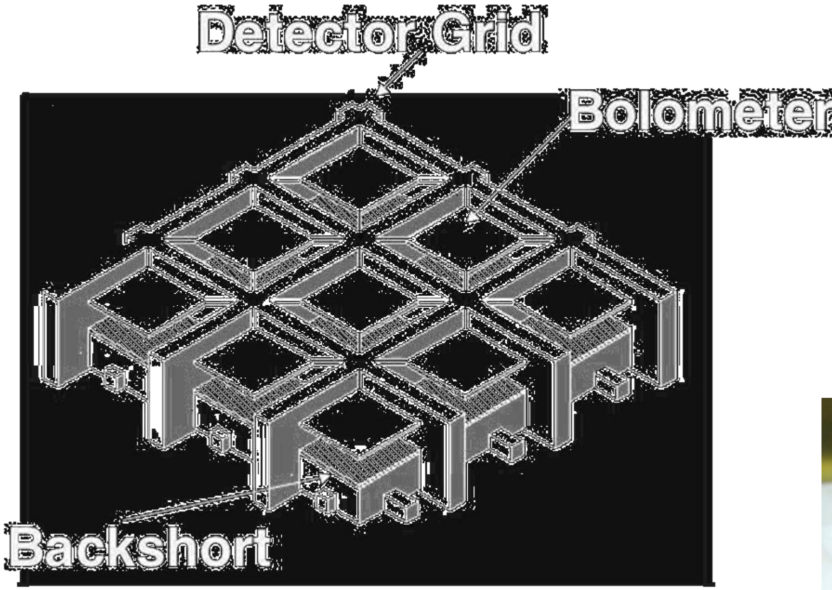
Sky Coverage

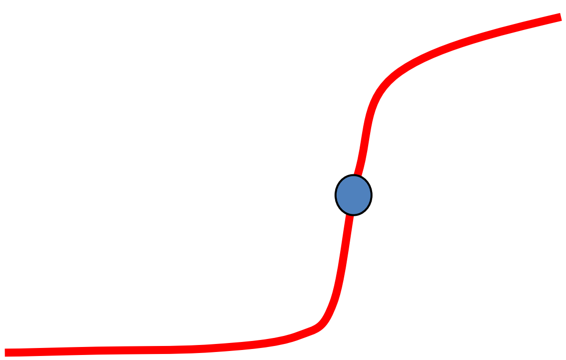
- Balloon payload, conventional flight
- 8 flights; half the sky each night

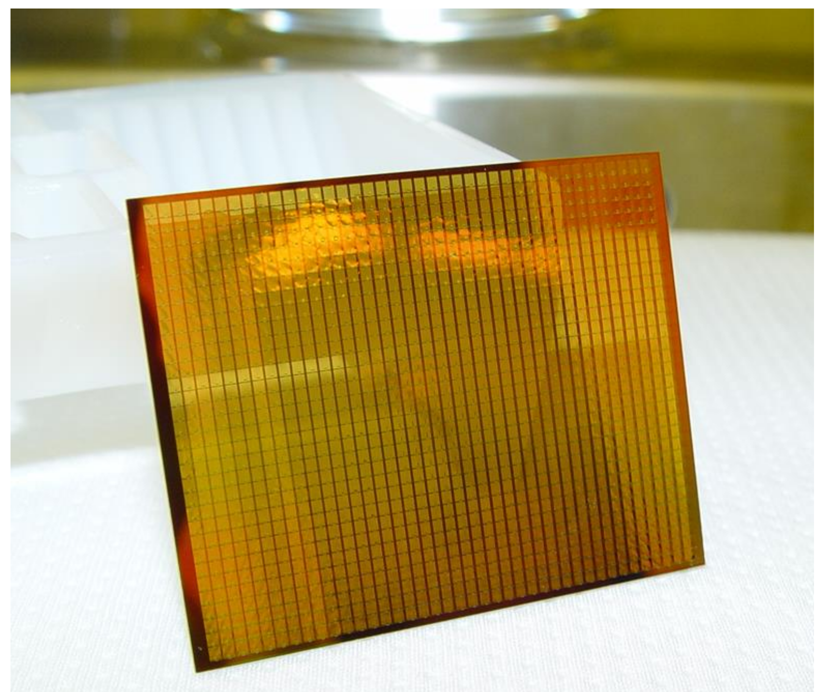


Goal: Detect Primordial B-Modes with r < 0.01

Detector Arrays







GISMO detector array

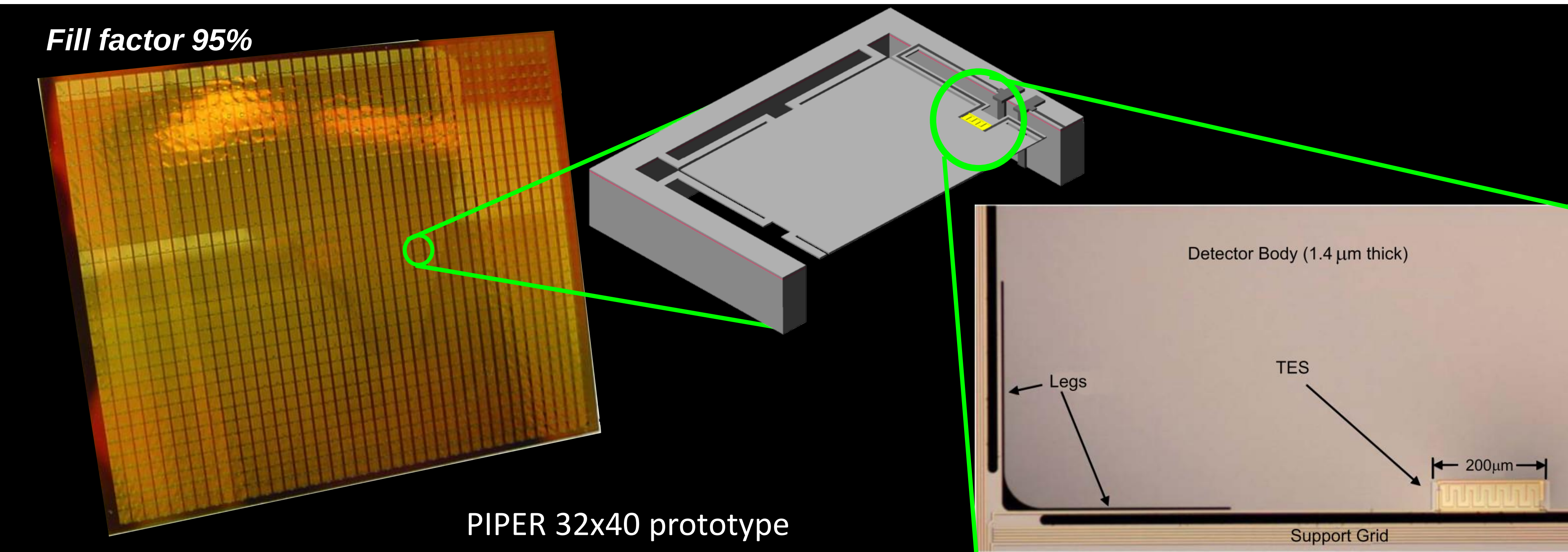
PIPER Detector Arrays

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

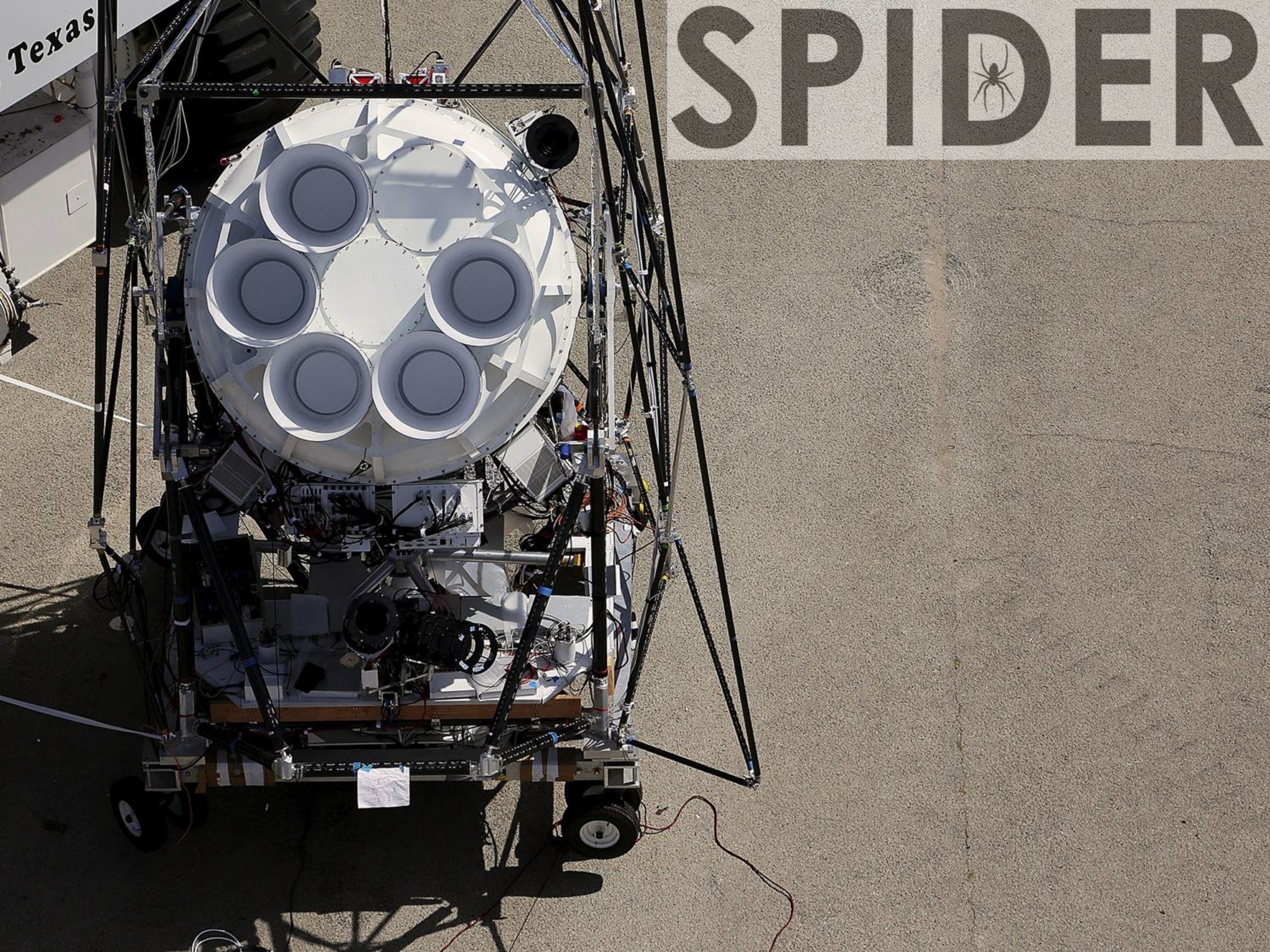
[a] Atmospheric values shown for float altitude 35 km

- 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!

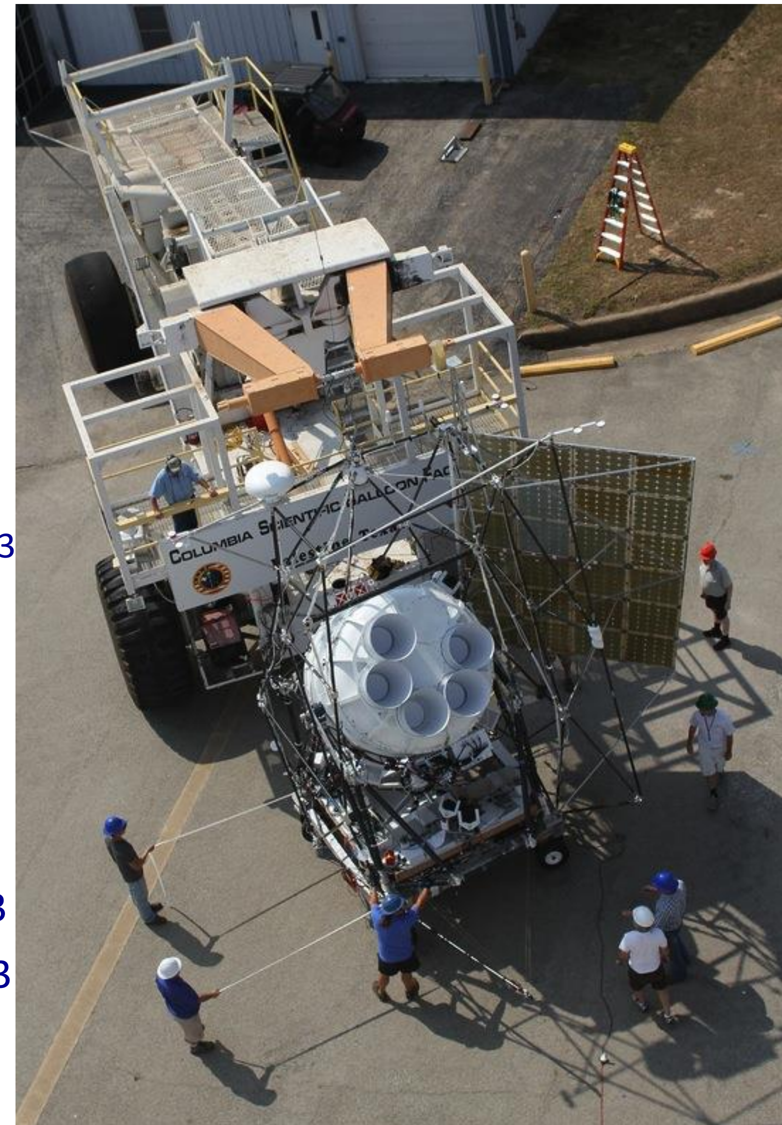


SPIDER



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)++



- Balloon borne polarimeter
- Science goals:
  - Set a limit on inflationary gravitational wave amplitude, ultimately at r < 0.03 at 99% confidence
  - Characterize polarized foregrounds
  - Sample variance limited EE at $\ell = 20$
  - Lensing B-modes
- Mapped the cleanest 10% (eff. f_{sky}= 6.5%) of the full sky.
- Half degree resolution.
  - $\ell = 10 – 300$
- Six telescopes 3/3 at 94/150 GHz
  - 694 + 1265 = 1959 detectors (plus darks)
- Two science flights: 2014/2017(?)

SPIDER Collaboration

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U. Toronto/CITA
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M. Farhang
L.M. Fissel
N.N. Gandilo
I. Padilla
J.A. Shariff

IAS - Orsay
J.D. Soler

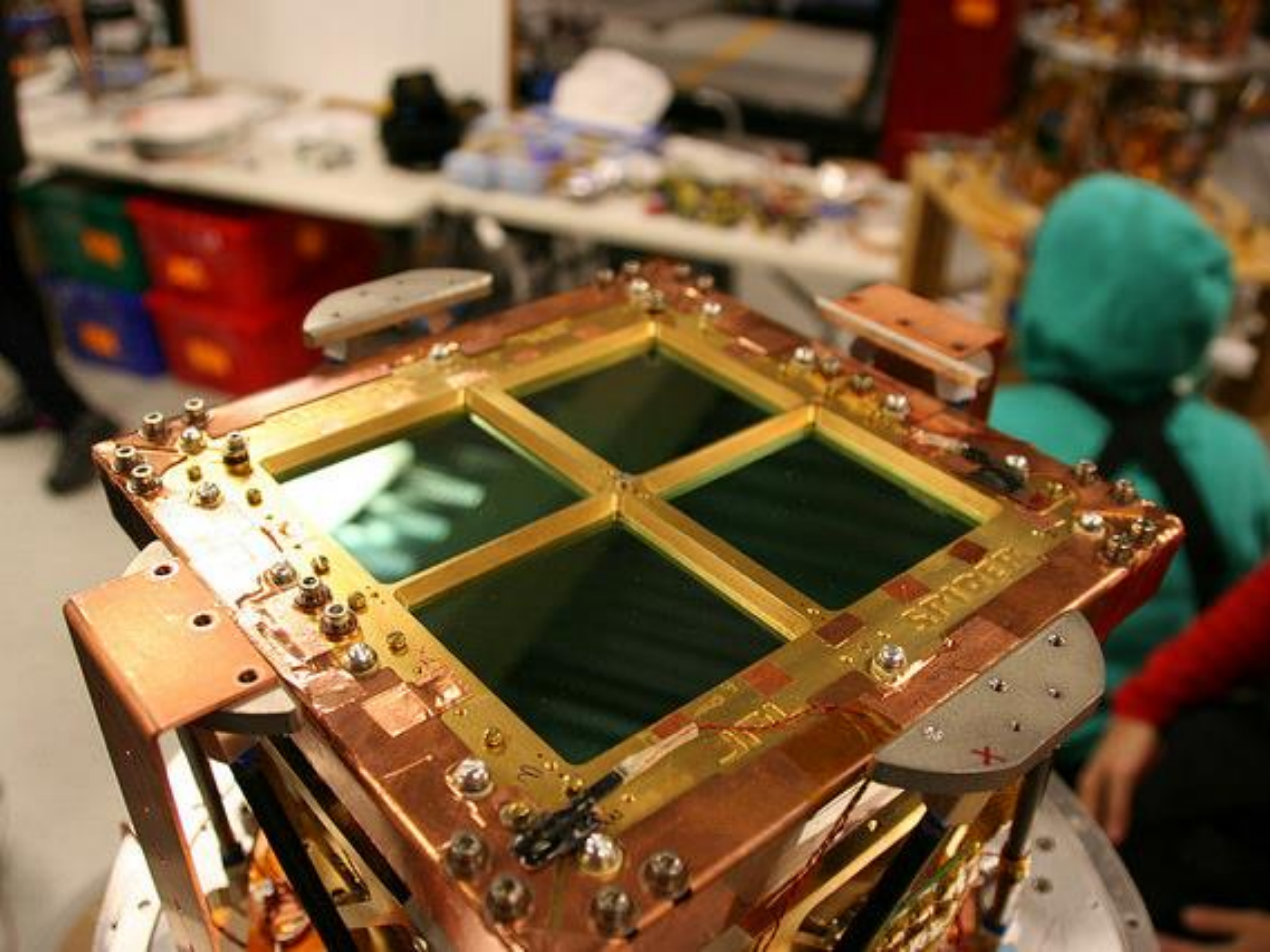
Stanford/SLAC
K.D. Irwin

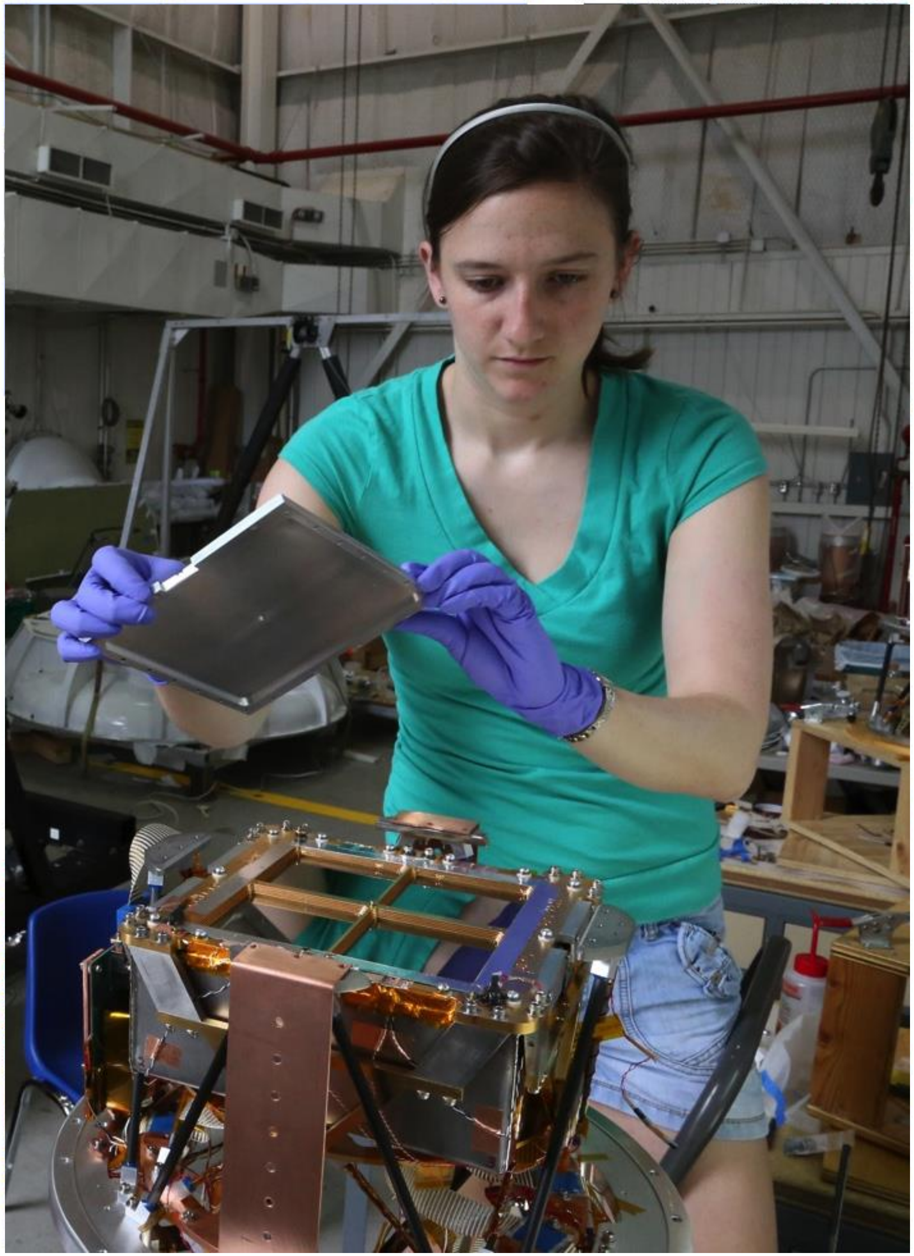
2015 Instrument Summary

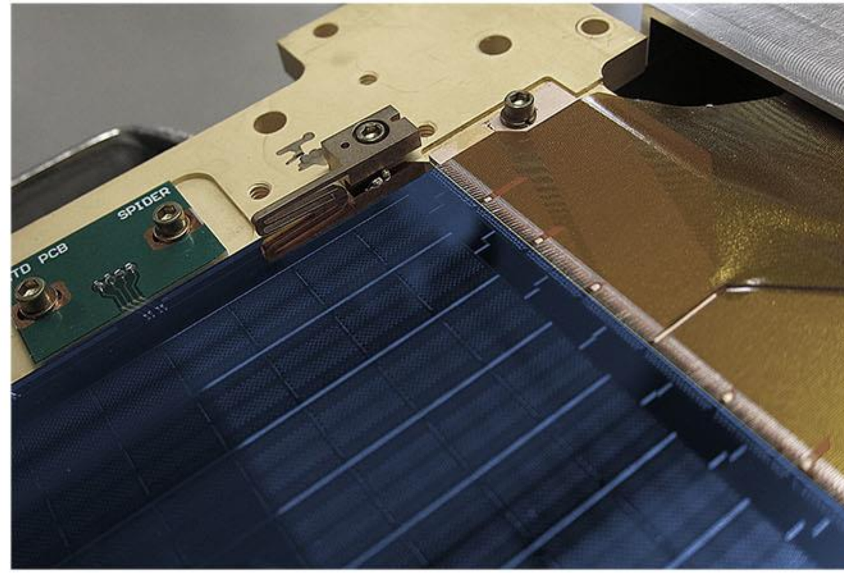
Band	**94 GHz**	**150 GHz**
Bandwidth [GHz]	22	36
Beam FWHM [arcmin]	42	30
# Optical Detectors	694	1265
NET per Detector [uK√s]	120-150	110-150
NET per band [uK√s]	4.5	3.4

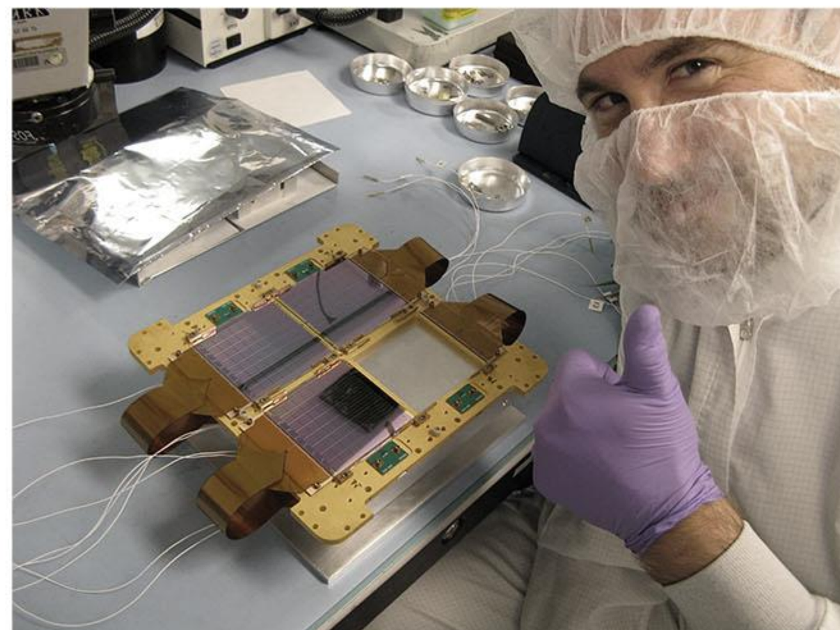
Instrument Summary

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

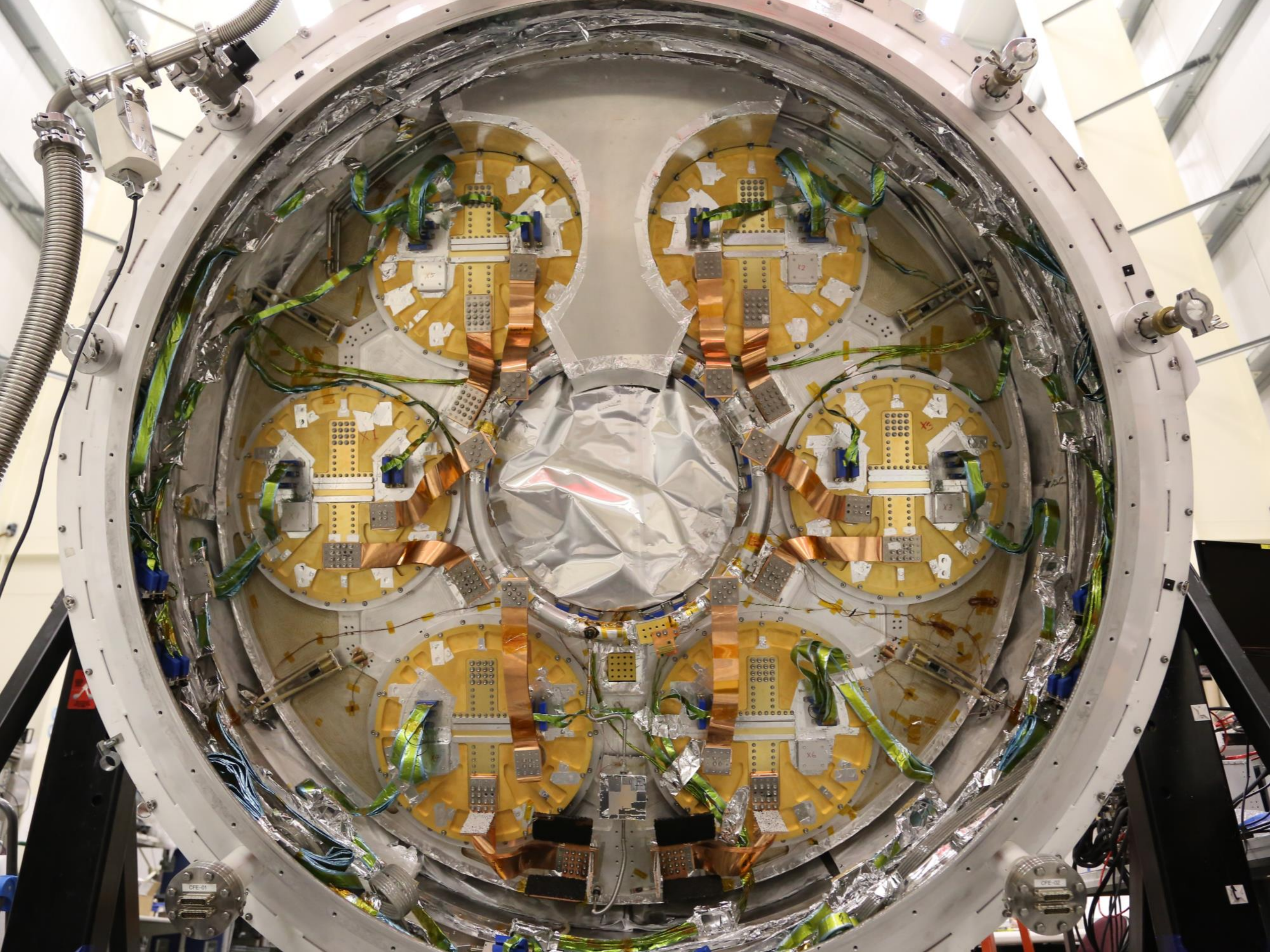


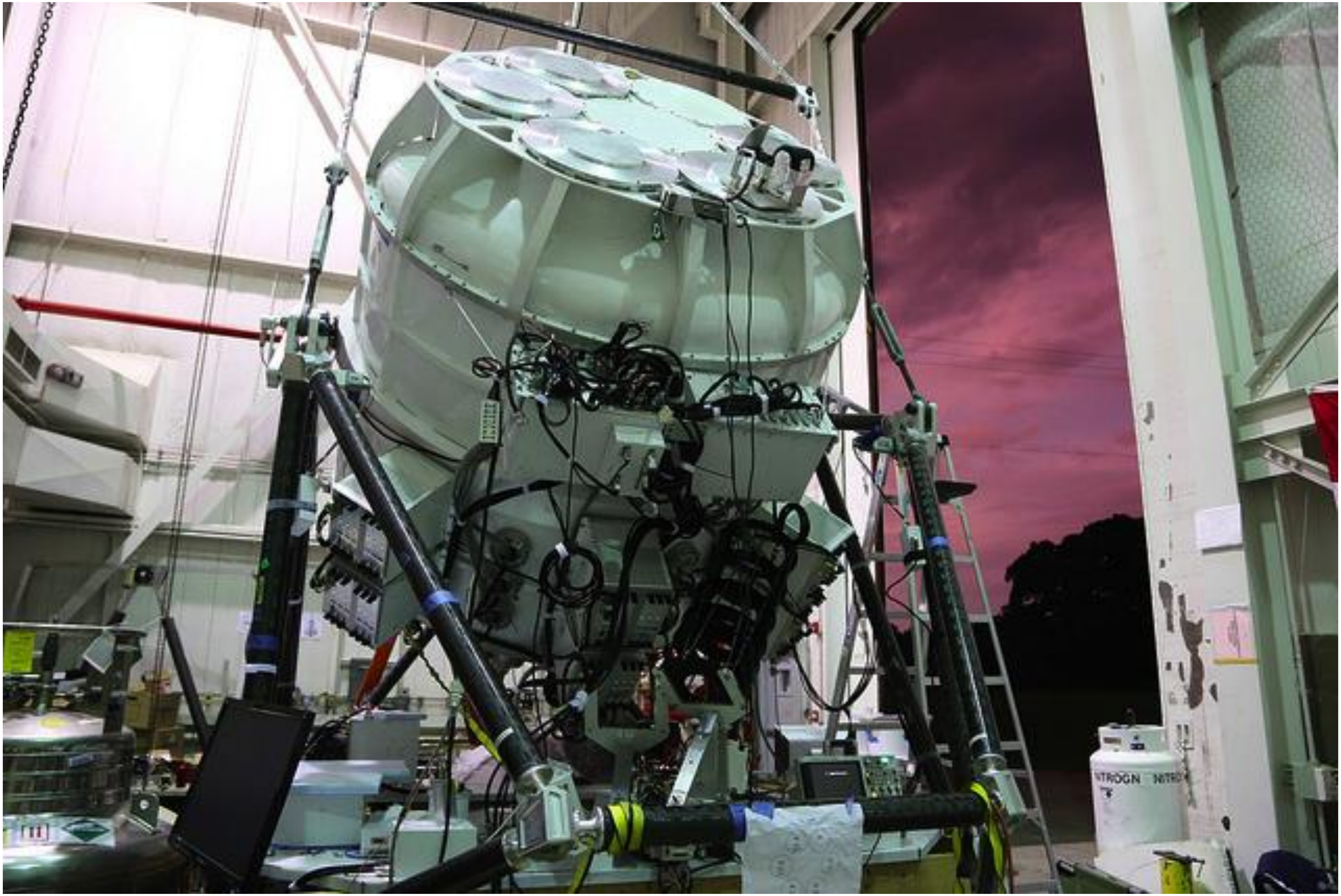



SPIDER
TD PCB



The Telescope(s)


CFE-01
CFE-02


NITROGN


TINY TIM