CMB Balloons (& What Can LiteBIRD Learn)

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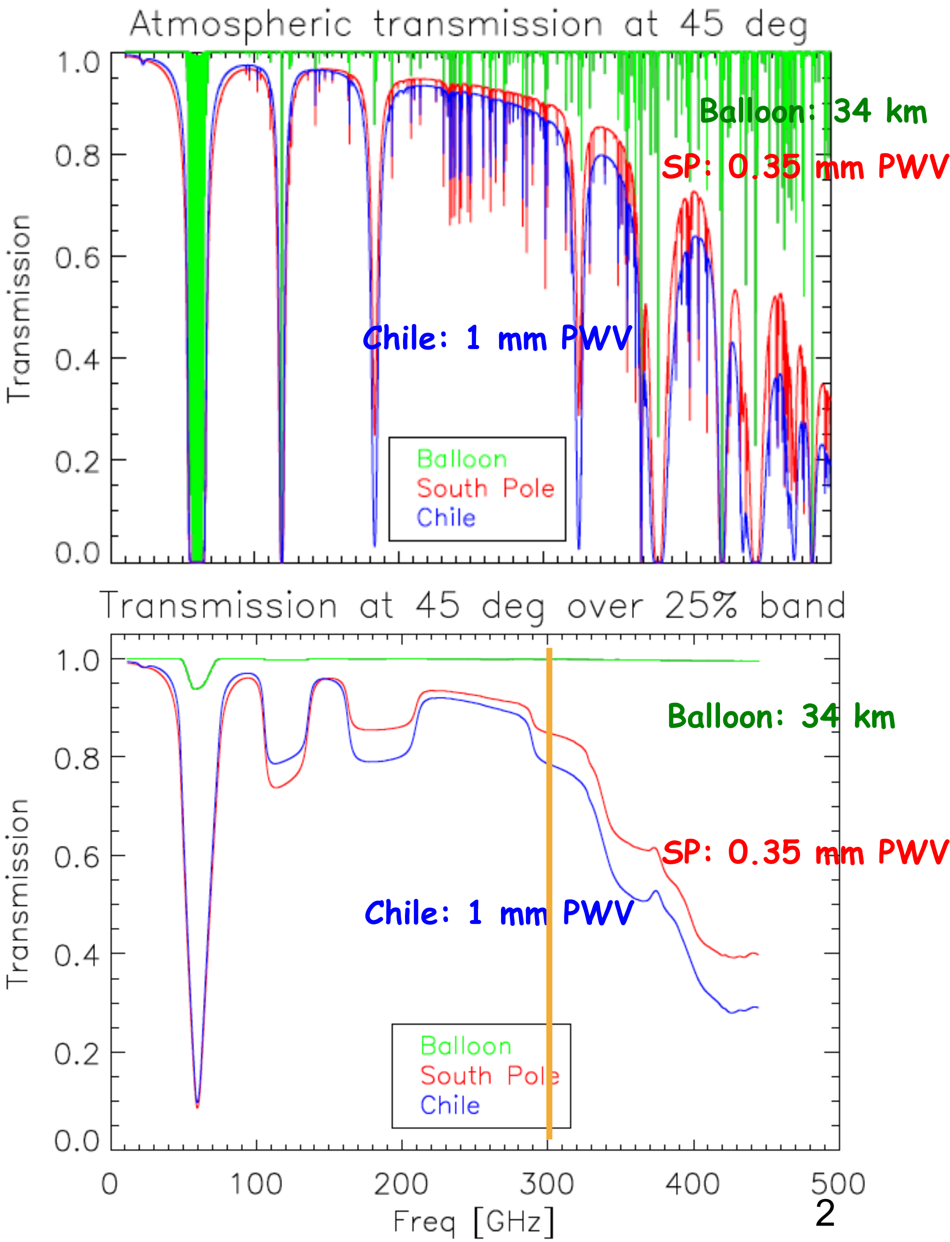
University of Minnesota/Twin Cities

(with contributions by B. Jones, A. Kogut, & P. deBernardis)

Why Balloons?

- Access to (near) space
    - Test technologies
    - Train new space scientists
    - Avoid the atmosphere
        - Signal attenuation
        - Noise



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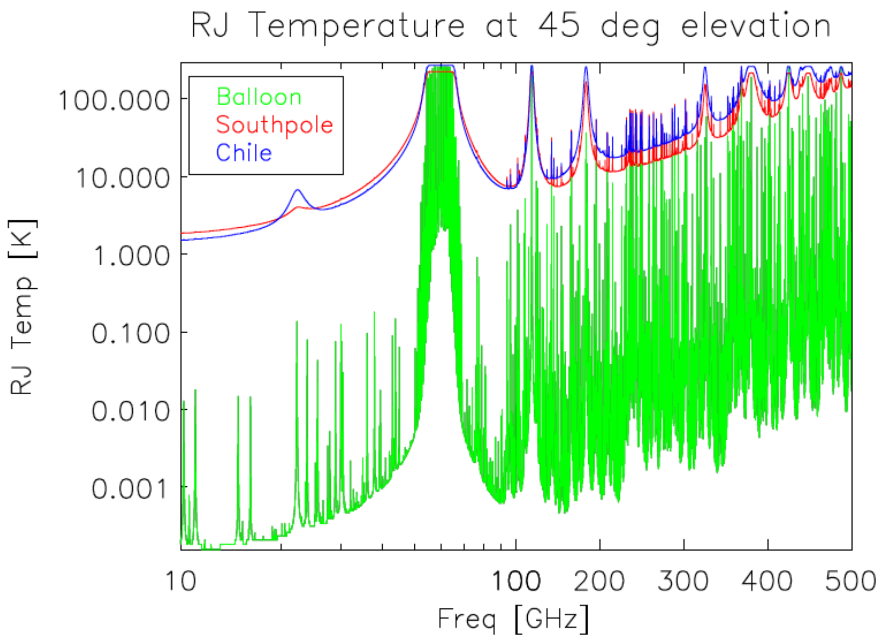
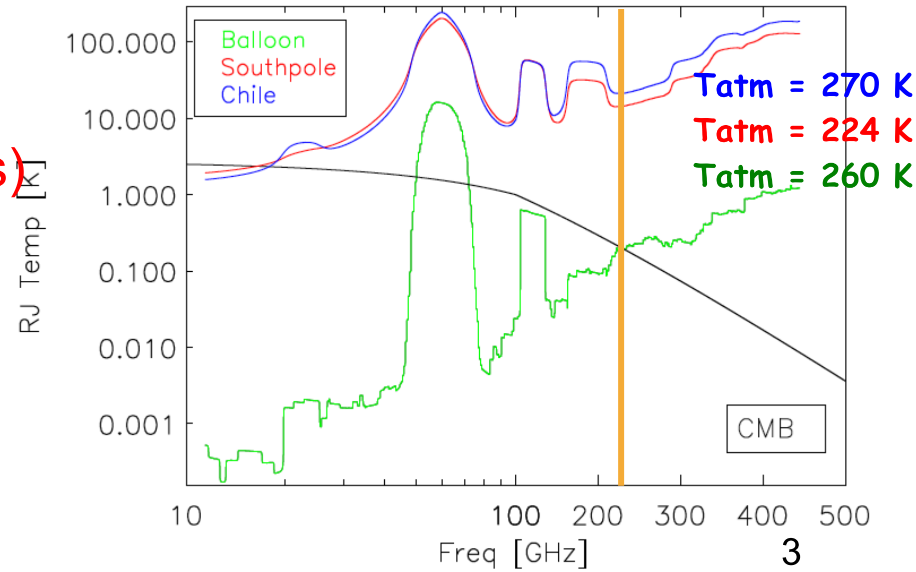
  - Train new space scientists
  - Avoid the atmosphere

    - Signal attenuation

    - Noise
      - Photon (white) noise
      - Turbulence (correlated noise @ low frequencies)





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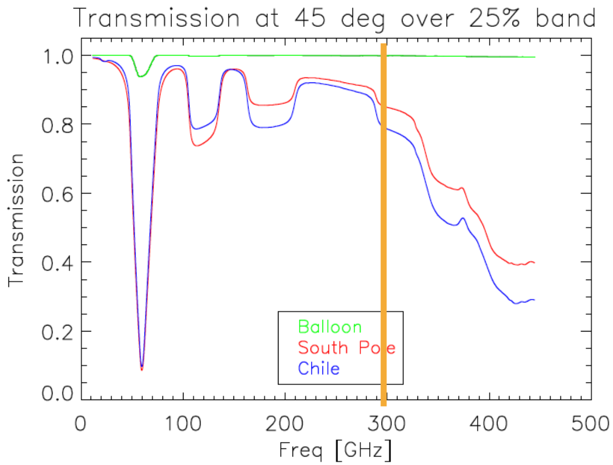
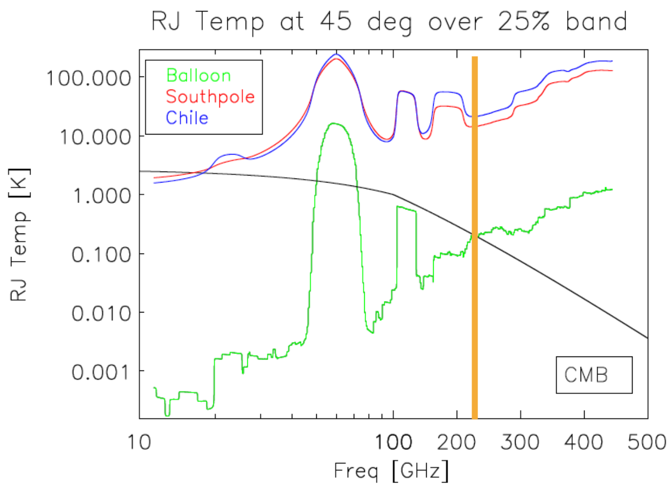




ν > 250/300 GHz, all angular scales
and
ell < 20 at all frequencies

Balloon Frequency and \ell coverage

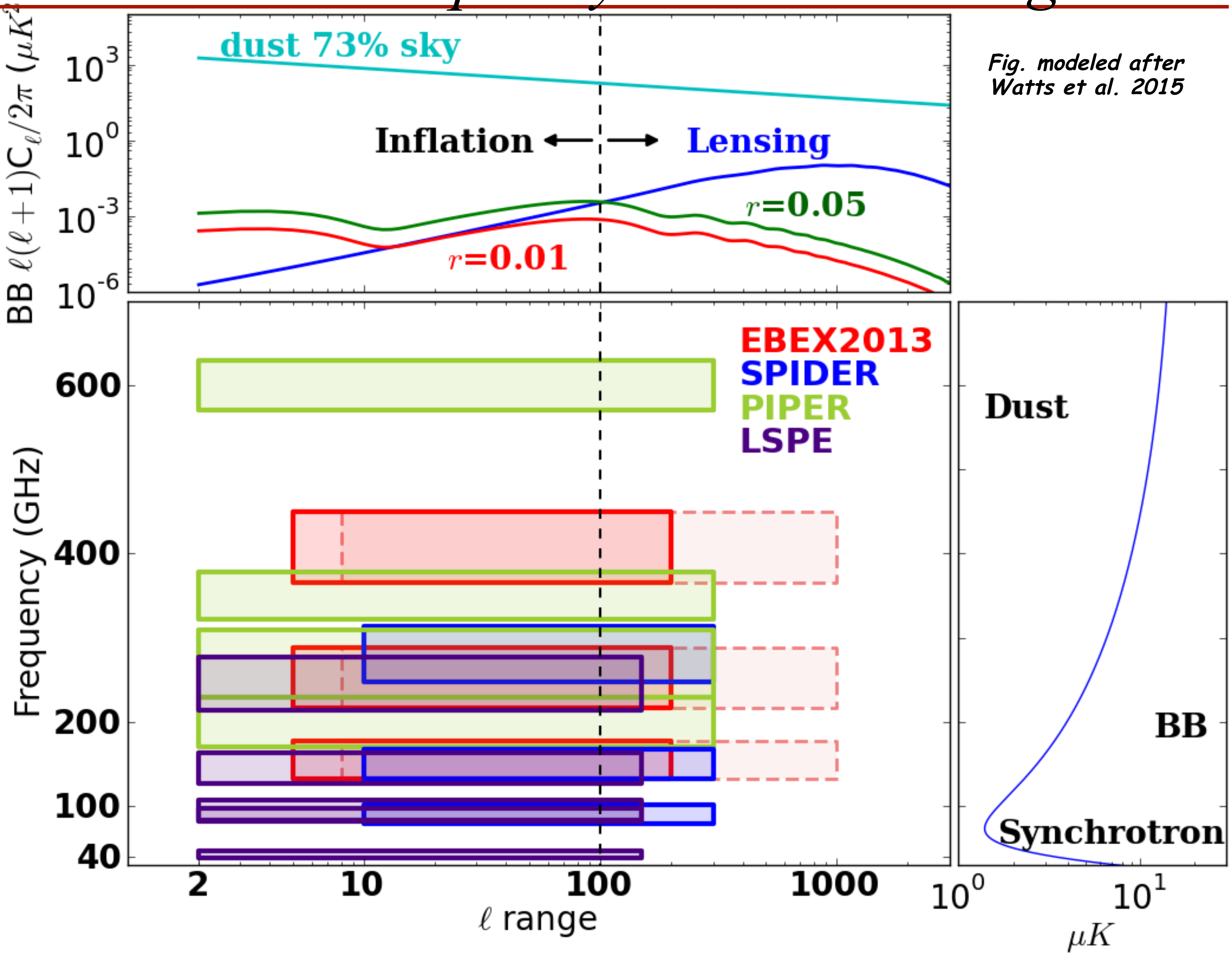


Fig. modeled after Watts et al. 2015


EBEX
Represented here by:
Adrian, Ben, Carlo, Hannes, Jacques, Josquin, Julian,
Mathieu, Matt, SH, Radek, Tomo
NASA
UNIVERSITY OF MINNESOTA
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
McGill
C.S.B.F.
PALESTINE, TEXAS
BROWN
THE UNIVERSITY OF CALIFORNIA
1868
BERKELEY LAB
CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD
NIST
APC
SISSA
Imperial College
London

EBEX in a Nutshell

- Antarctic long duration
- Using ~1000 bolometric TES (+ FDM)

- 3 Frequency bands: 150, 250, 410 GHz

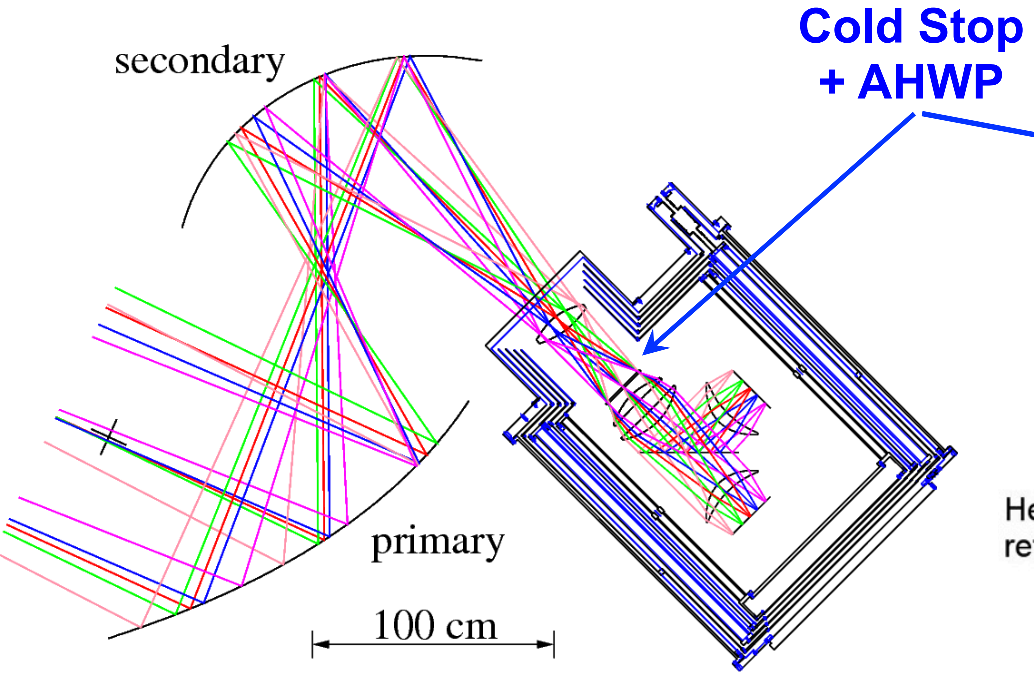
- Resolution: 8' at all frequencies

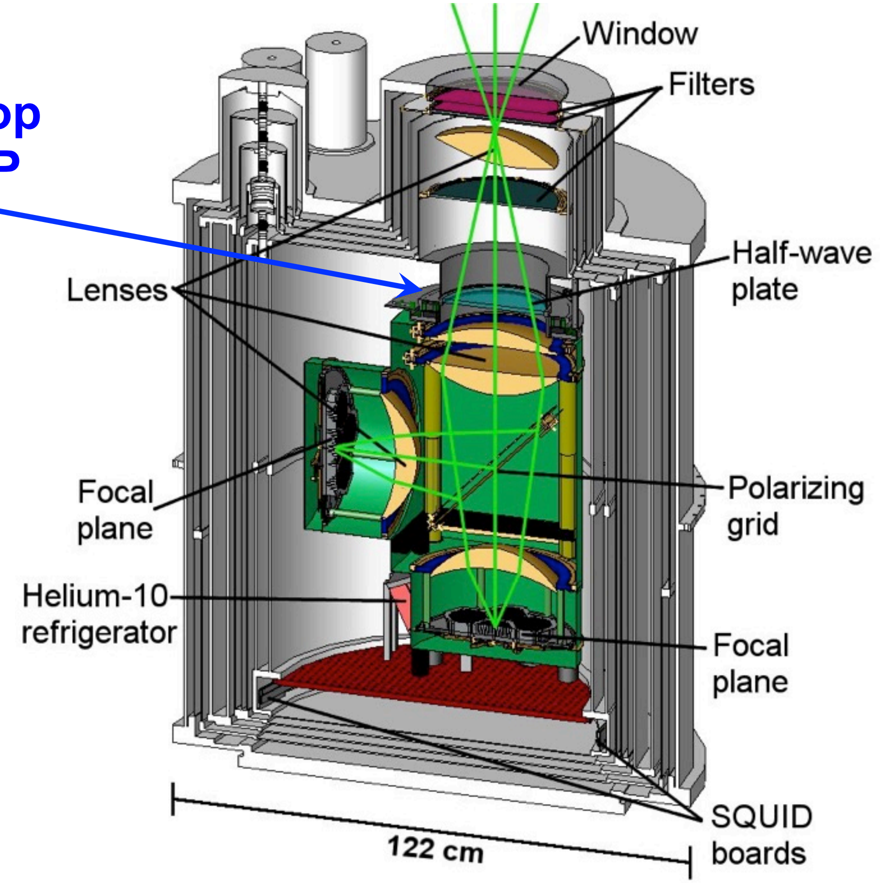
- Continuously rotating achromatic half wave plate (Separate talk on Monday)

Status
- 10 days of data collected in 1/2013 and are being analyzed

Optics

- 1.5 m aperture Gregorian Dragone telescope (ambient temp.)
- Cold aperture stop + 4 polyethylene lenses

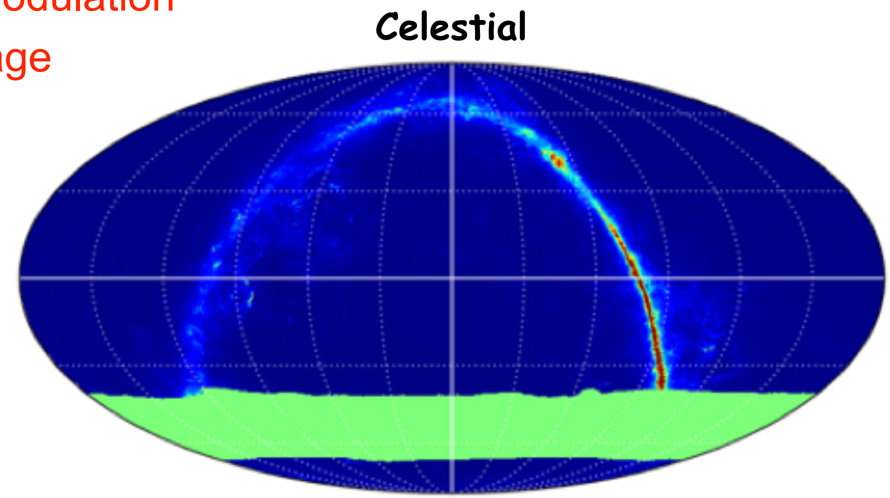


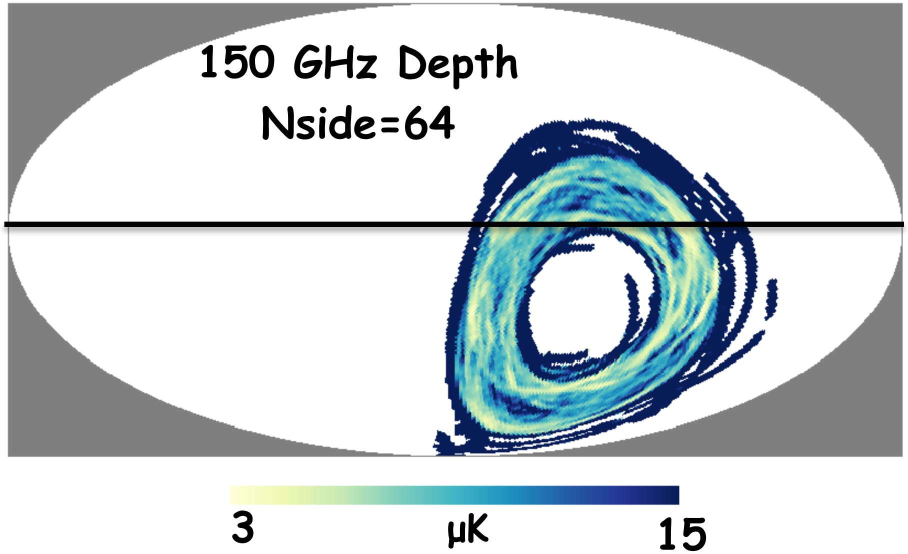


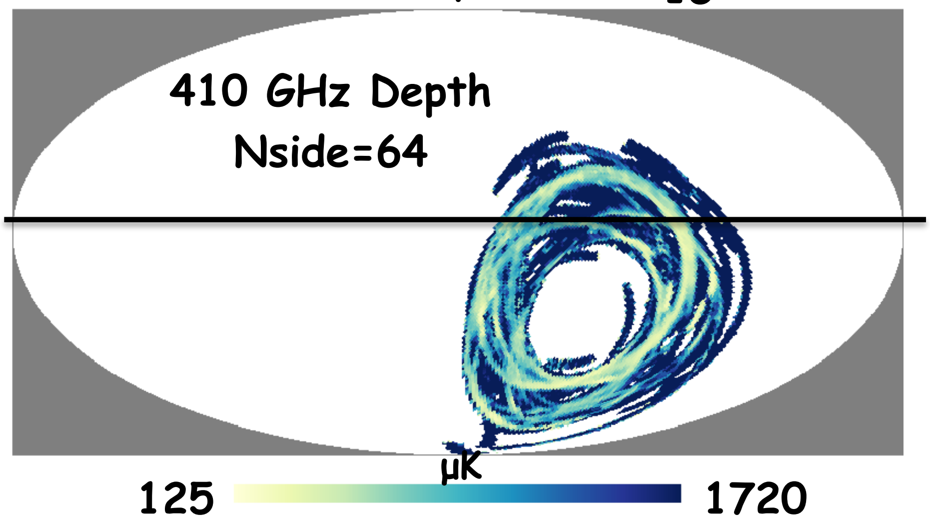
- Achromatic Half wave plate + polarizing grid
- Two focal planes for two orthogonal polarization states

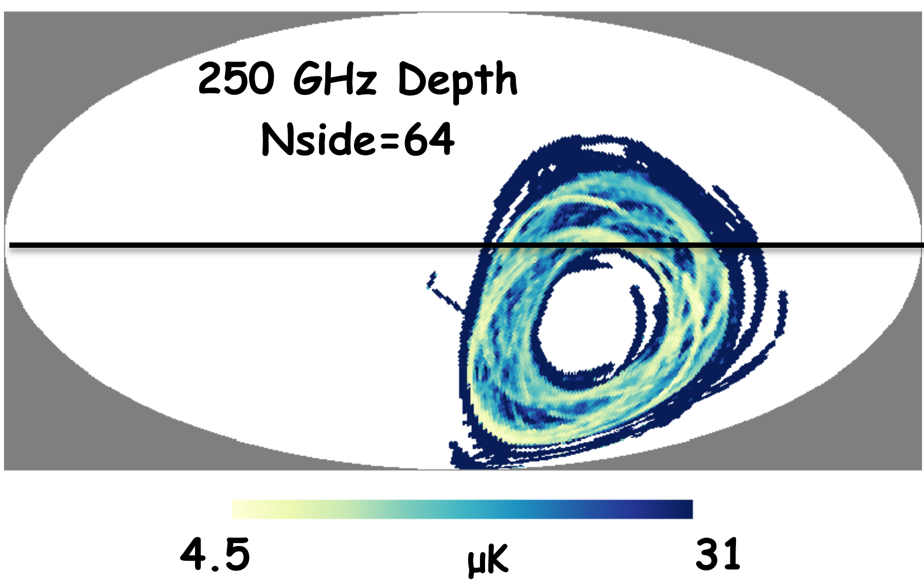
2013 Flight

- Constant elevation, full 360 rotations, + azimuth modulation
- ~6000 sq. deg. constant DEC, non-uniform coverage

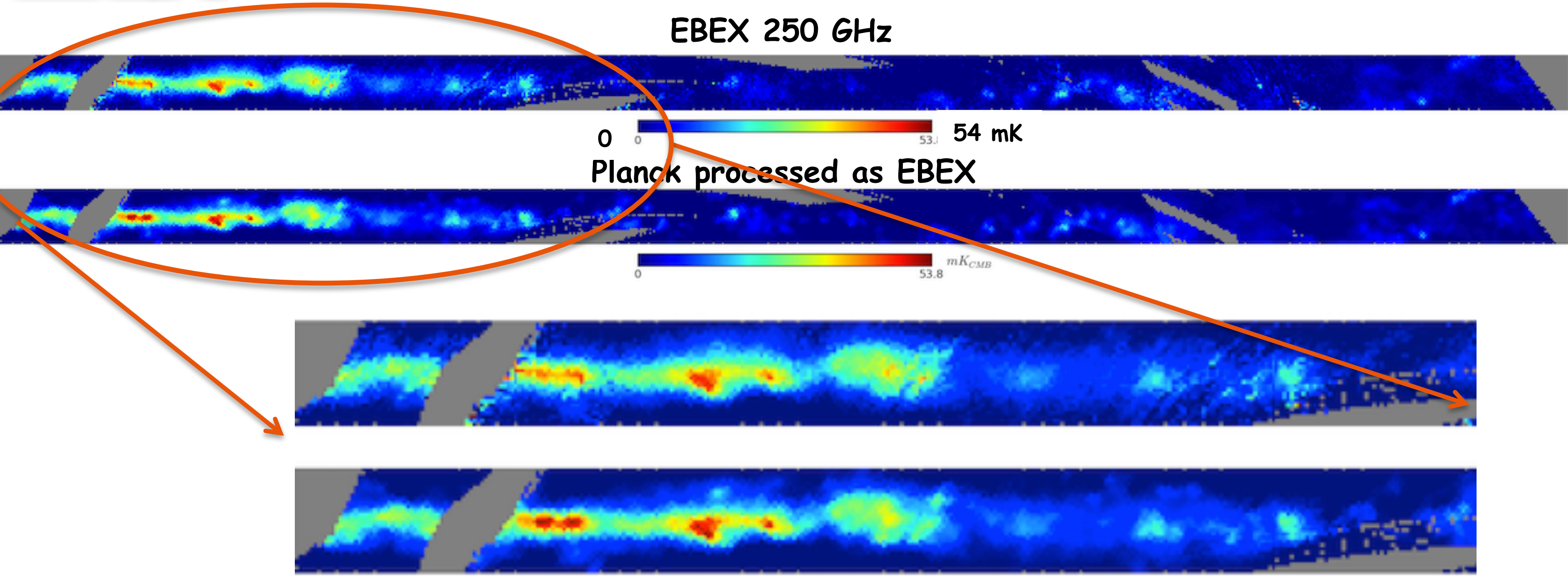




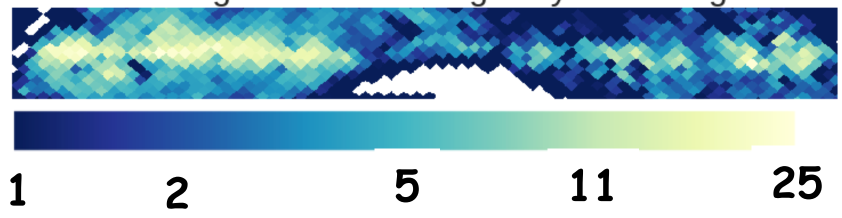




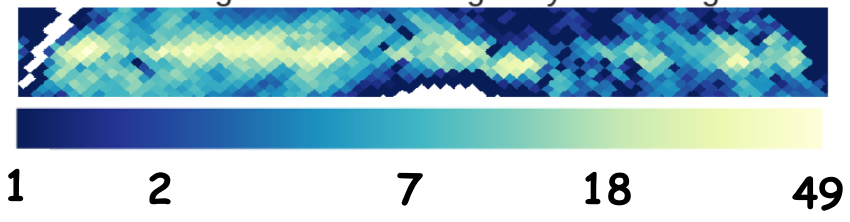
2013 Flight



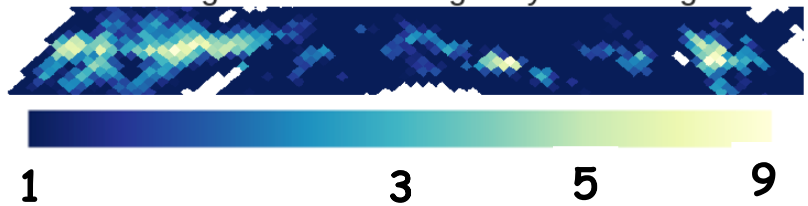
Pol Signal to Noise on galaxy at 150 log



Pol Signal to Noise on galaxy at 250 log

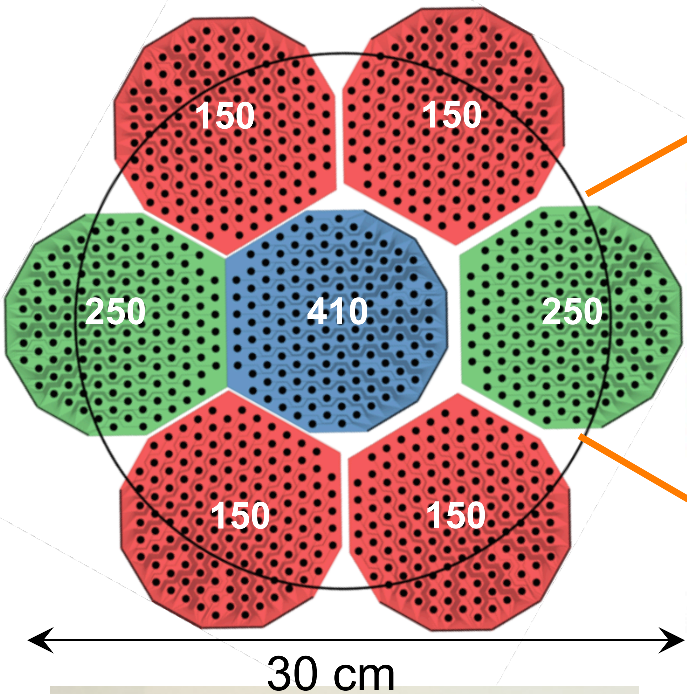


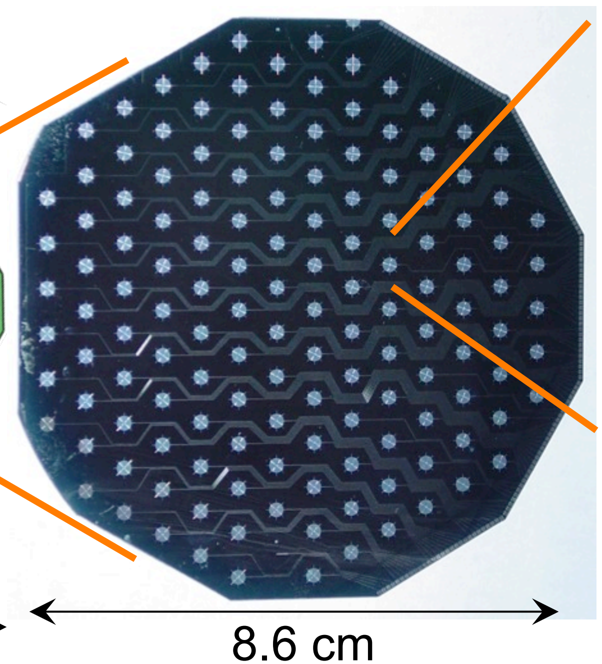
Pol Signal to Noise on galaxy at 410 log

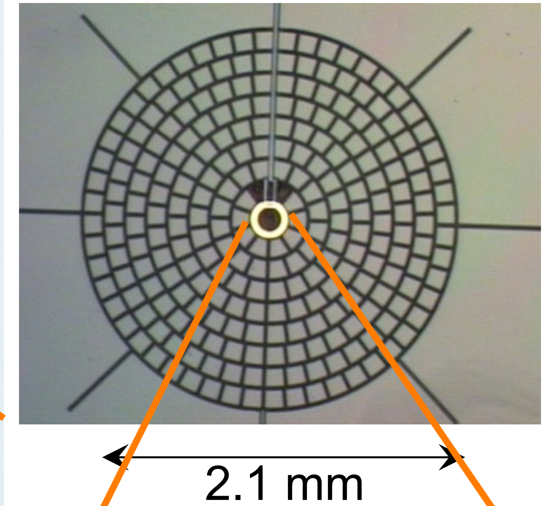


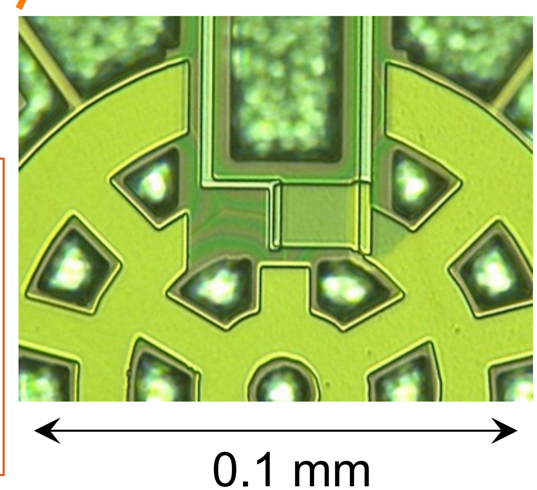
Focal Plane + Readout

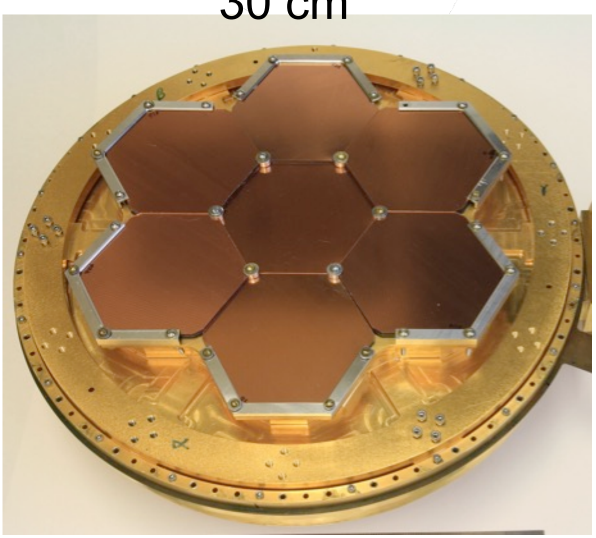
A. Lee, UCB











<u>Readout</u>

- Digital FDM (McGill)
- x10 lower power than analog
- Running in x16 mode

Focal Plane Arrays

Big Picture on Yield:

- 14 wafers x 140 detectors each = 1960 detectors
- We could have operated only 1735 detectors

- UCB fabricated >50 wafers

- We chose 14 wafers, 1043 ‘known IVs’

- At float, first tune: 955 valid IVs

Yield reduction:

- Bad wafers
- Low yield wafers
- Bad detectors
- Bad squids, bad wiring
- Unusually High noise
- One wafer close to saturation

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> - More lead time
> - Dedicated, high quality fab
> - High throughput test + characterization facility

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Multiple end-to-end integrations + testing

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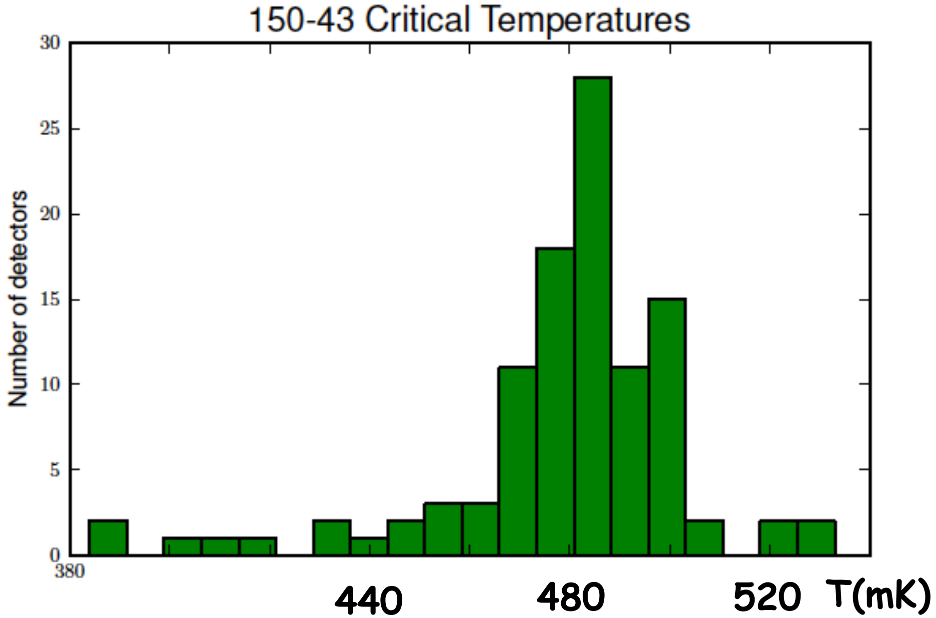
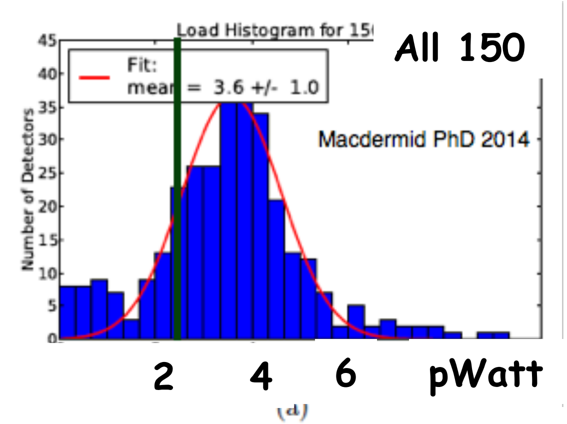
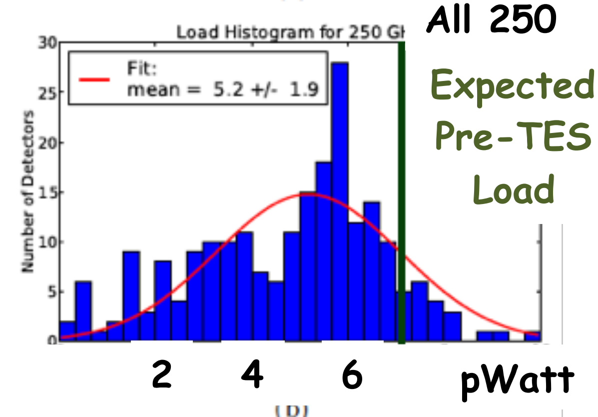
Multiple end-to-end integrations + testing
In full flight configuration

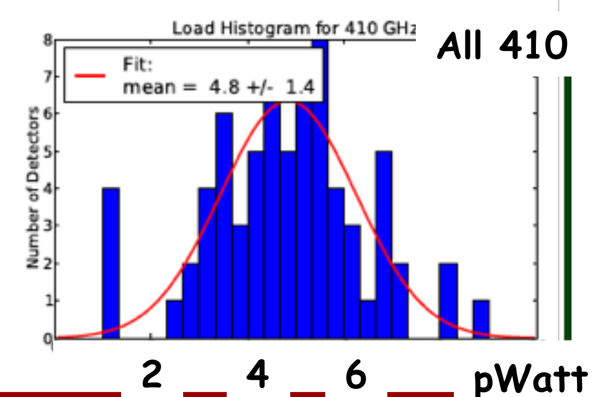
Bolometer Array Performance

- In Flight loading:
    - Excess load of ~2 pW@150 GHz (~80% abs. efficiency)
    - Load ~as expected @250 GHz (~75% abs. efficiency)
    - Load ~as expected @410 GHz (~40% abs. efficiency)





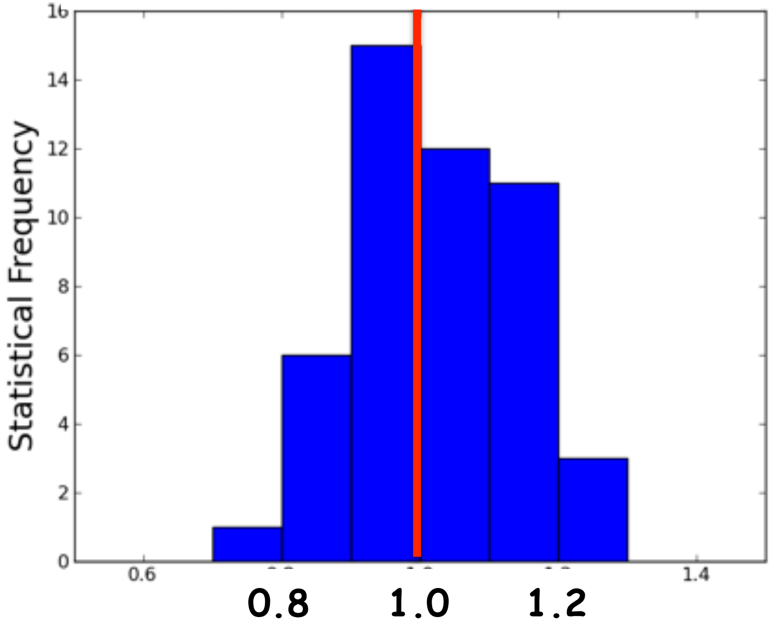




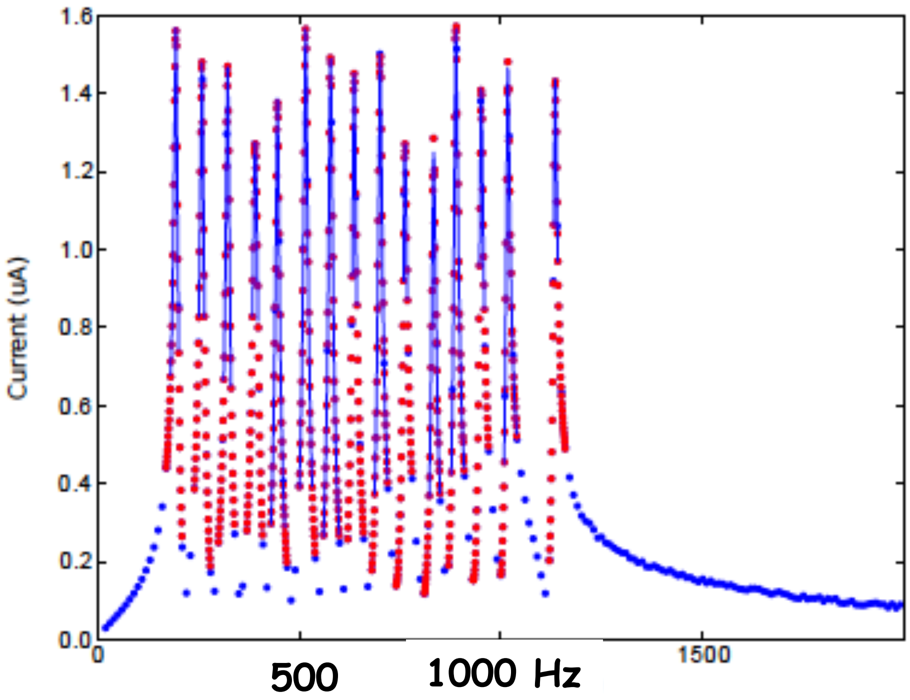
Readout

- Developed digital FDM
- Running in x16 mode

Ratio of measured to predicted electronic noise

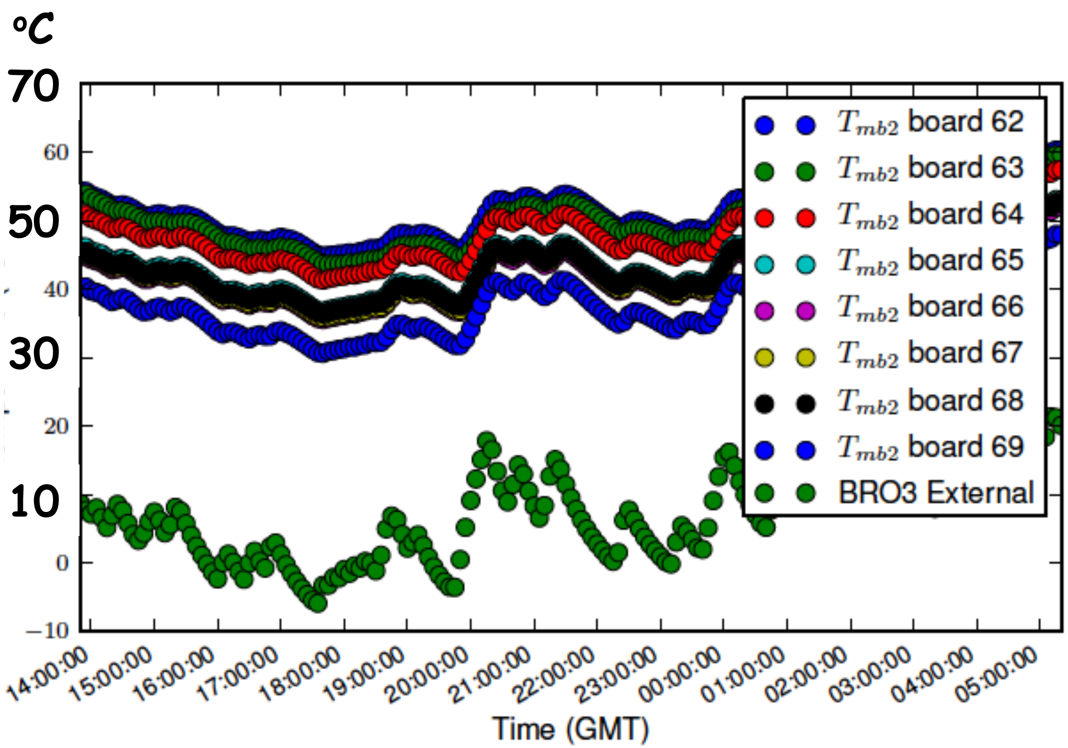


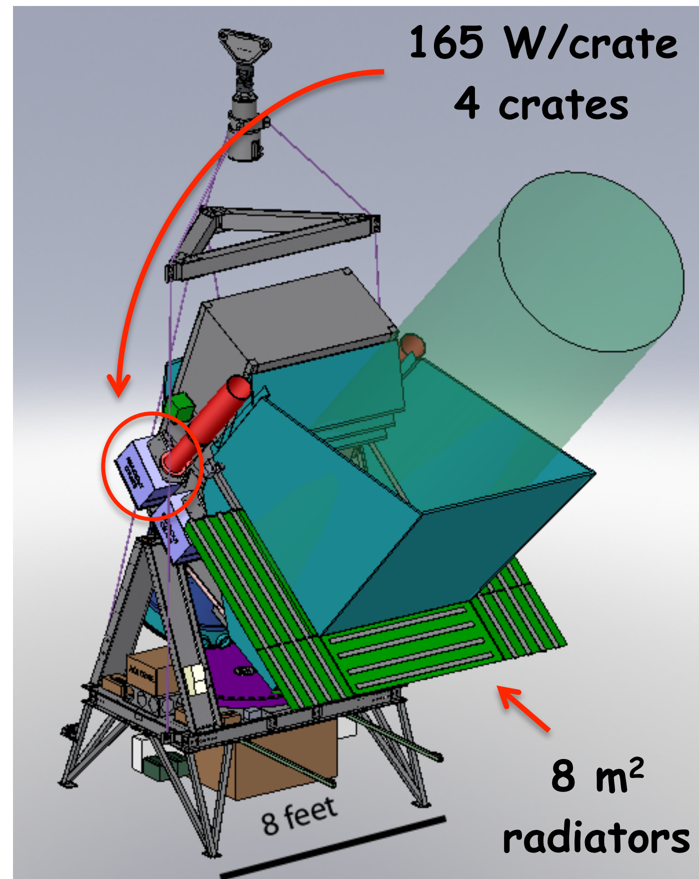
150-43 Network Analysis



Readout - Power

- ~650 W; x10 lower power compared to analog
- But still required active cooling
- And consumed significant intellectual effort





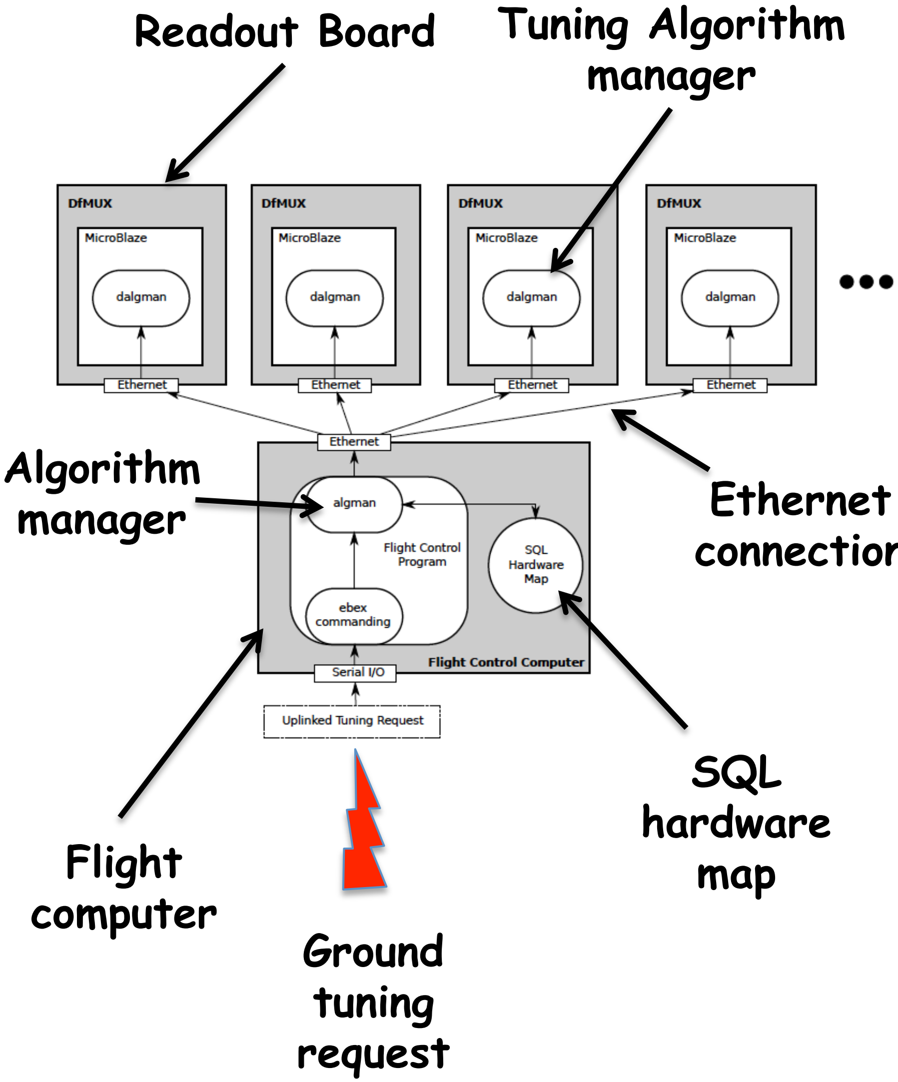
Readout - Software/Firmware/Visualization

<u>A balloon platform:</u>

- Requires high tuning efficiency
- Must accommodate low- to non- TM rate
- Has limited computing resources

<u>Solutions:</u>

- Executed tuning automatically with fridge cycles
- Stored all tuning parameters on an SQL database on-board
- Moved tuning algorithm execution from computer to individual boards



MacDermid Ph.D.

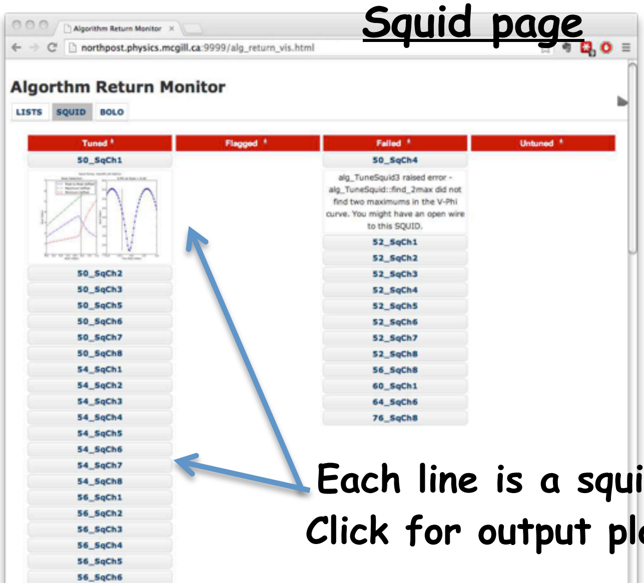
Readout - Software/Firmware/Visualization

Limited observing time requires rapid data monitoring => data analysis and visualization challenge

Solutions:

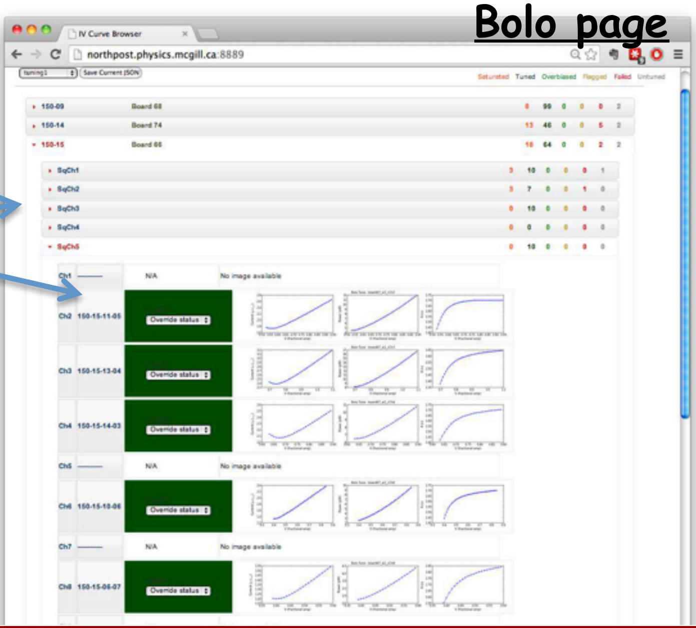
- Developed automated flagging for which squids/bolo tunes are successful, or not
- Web based / easy to use – accessible over internet to entire team

Squid page



Each line is a squid. Click for output plots

Bolo page



Each line is a comb. Click for output plots. Green is: "good IV"

This, too, consumed quite a bit of intellectual effort and time

Primordial Inflation Polarization Explorer (PIPER)

PI: Al Kogut (Goddard)

Sensitivity

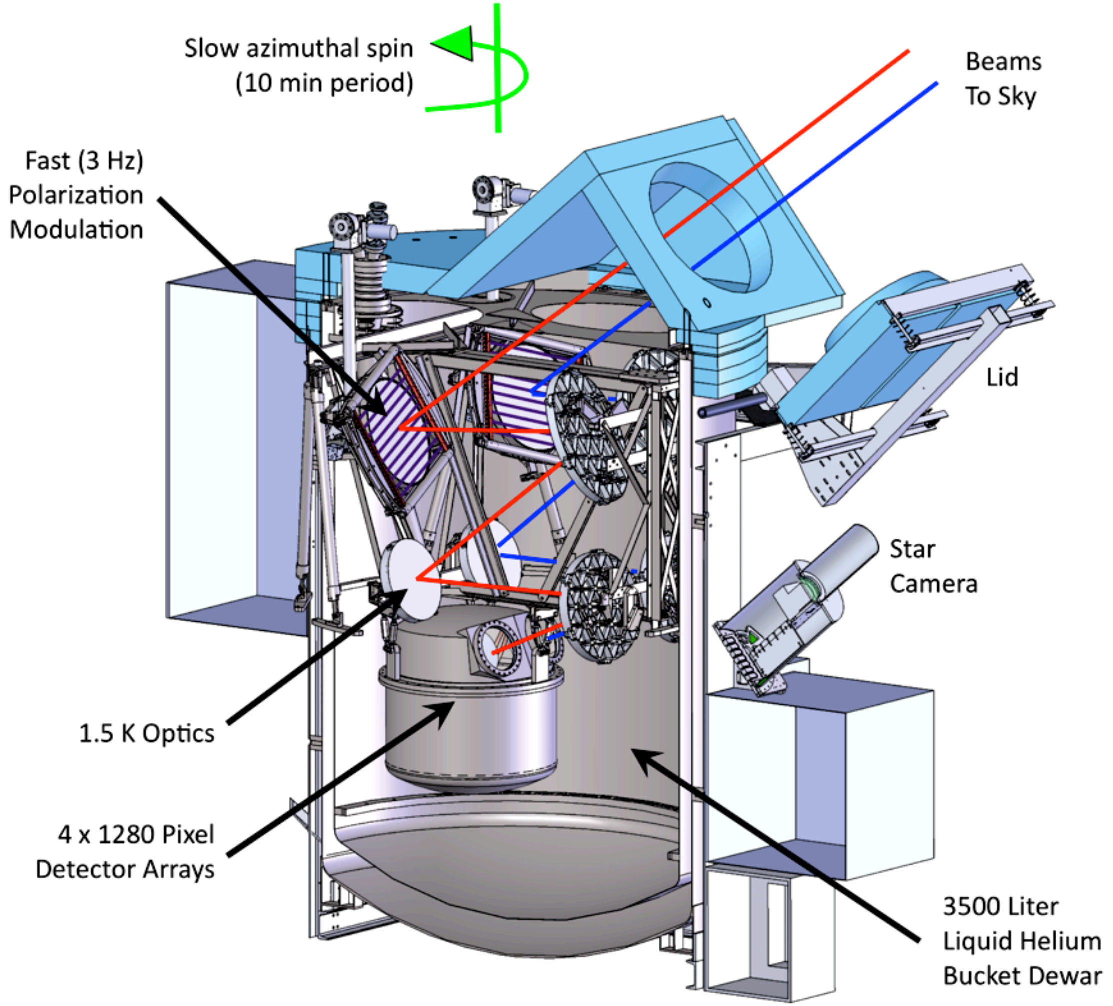
- 5120 TES bolometers:
  943@200 GHz; 1550@270 GHz
  2270@350 GHz; 3760@600 GHz
- 1.5 K optics with no windows
- NEQ < 2 μK $s^{1/2}$ at 200, 270 GHz

Systematics

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

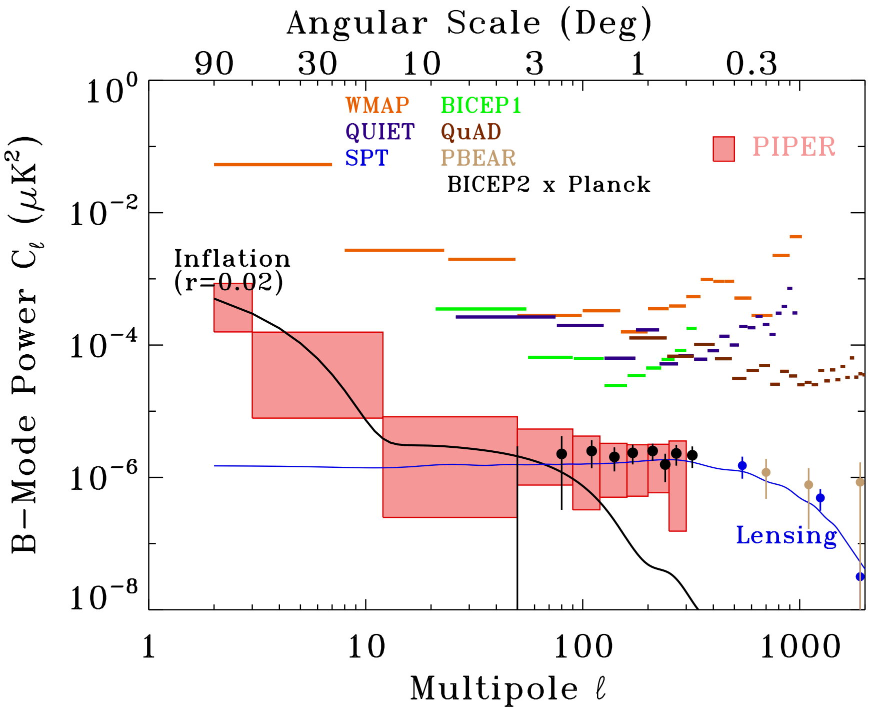
Foregrounds

- Clearly separate dust from CMB



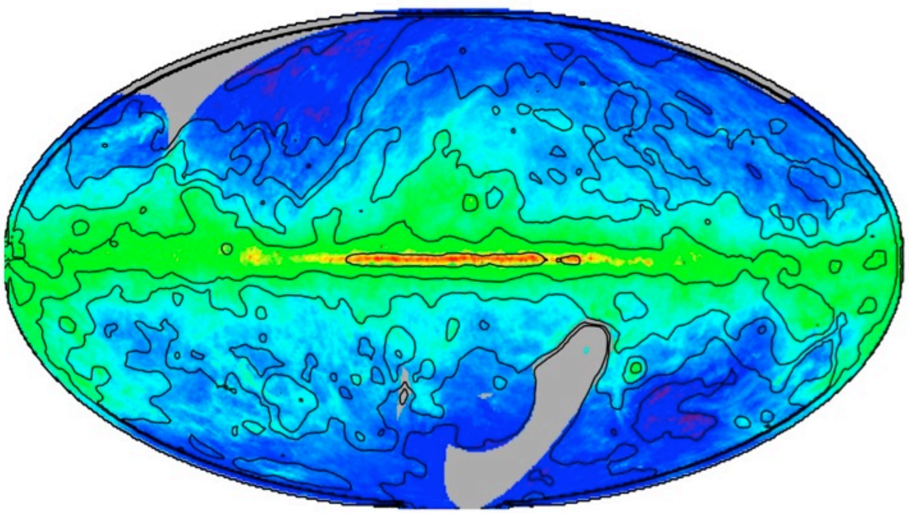
Goal: Detect Primordial B-Modes with r < 0.01

PIPER Sky Coverage and Sensitivity



Sensitivity r < 0.007 (2σ)

PIPER Sky Coverage:
2 short duration flights/year
Northern + Southern =~ 80% sky



LSPE (PI: Paolo deBernardis)

Two Instruments

- STRIP: 44/90 GHz (49/7 horns)
- SWIPE: 140/220/240 GHz

(110 TES bolometers/frequency band)

Angular resolution: 1.4 deg

Target sensitivity: 10 muK*arcmin

Systematics

- OMT (STRIP)
- Stepped Polarization Modulator
- Twin telescopes in bucket dewar

Sky Coverage: 20-25%/flight

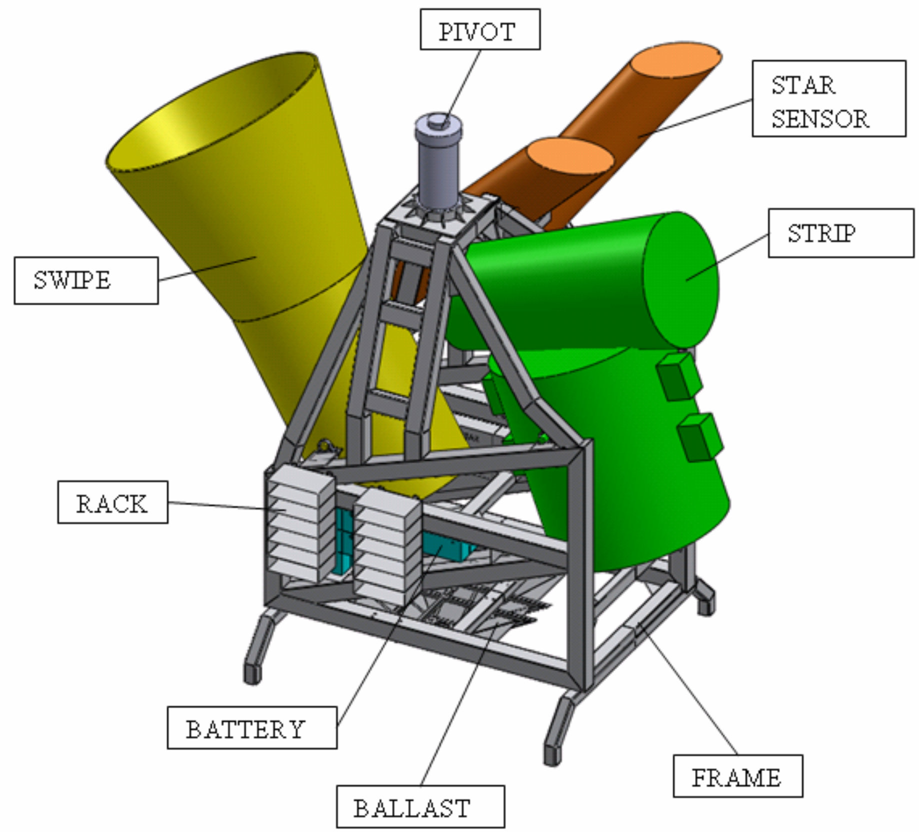


Figure 1 - The Gondola of the LSPE Experiment

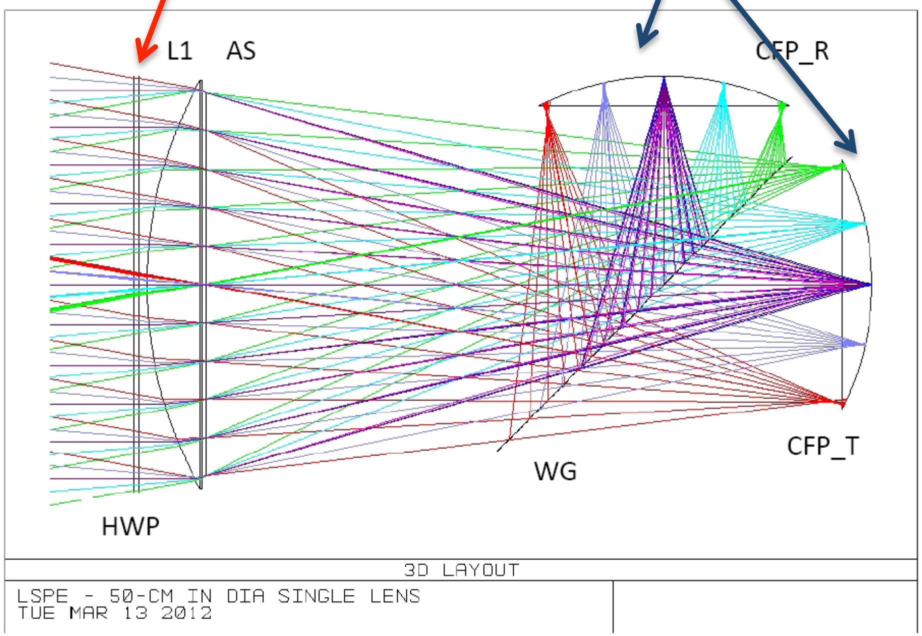
Goal: reionization peak at r ~ 0.01

SWIPE
(PI: P. deBernardis)

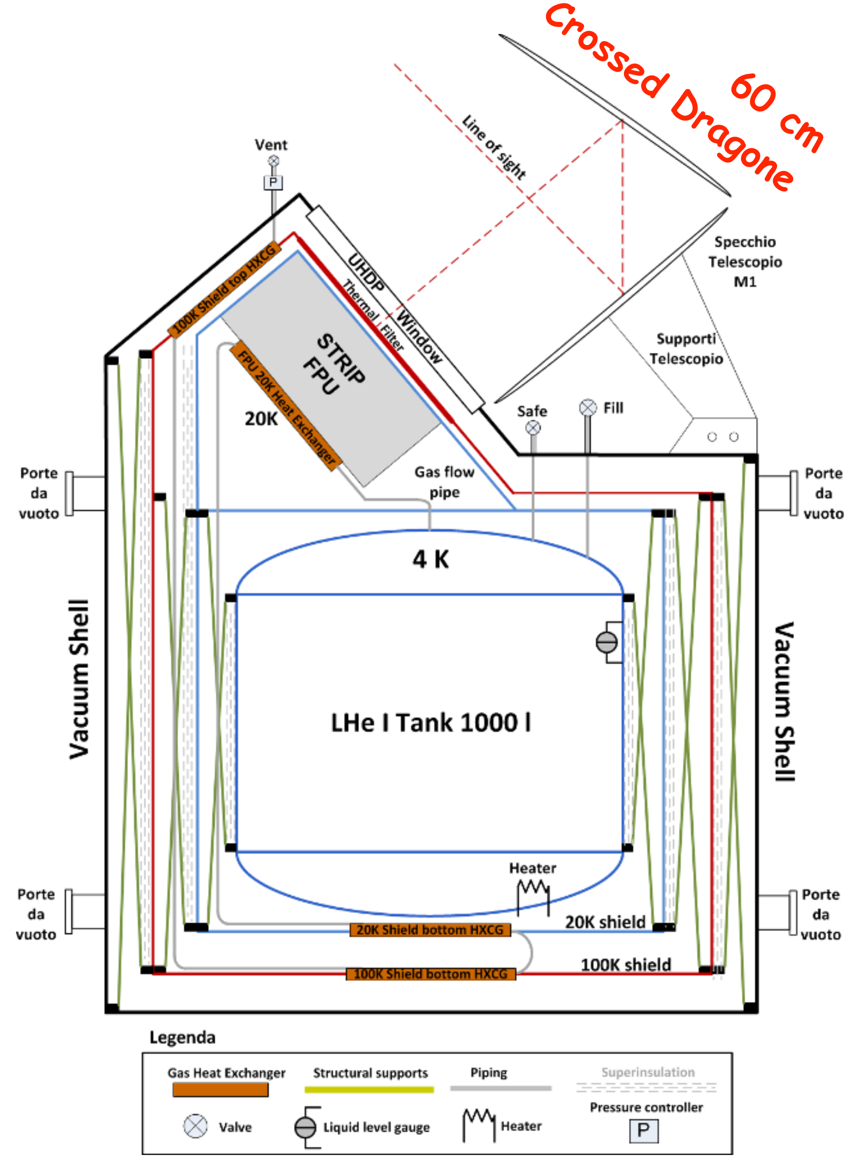
STRIP
(PI: M. Bersanelli)

50 cm Metamaterial HWP

Multi-Moded Horns + 8 mm spiders + Mo-Au TES (INFN-Genoa)



Crossed Dragone 60 cm



(Frequency Domain Multiplexing)

Target ~25% of sky/Flight

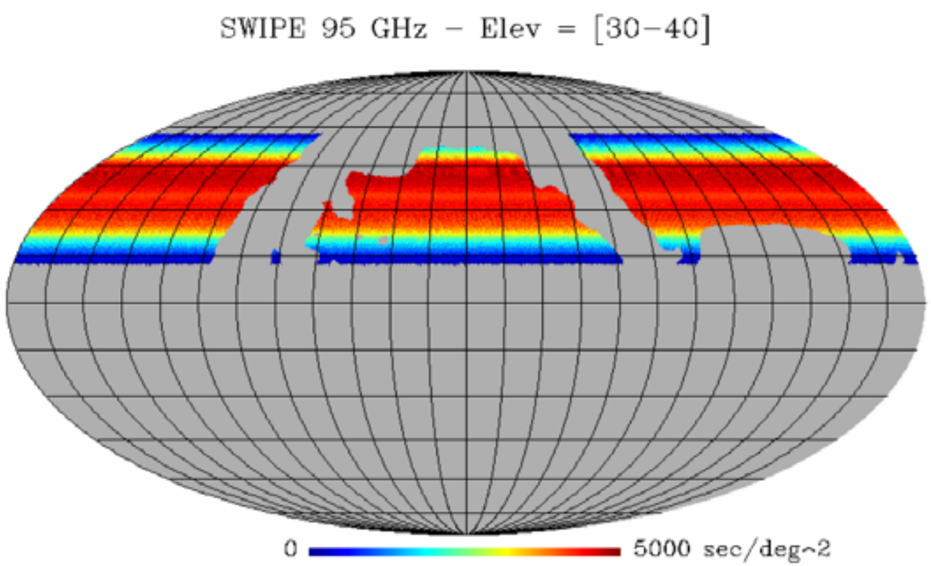
1st Flight: 12/2017

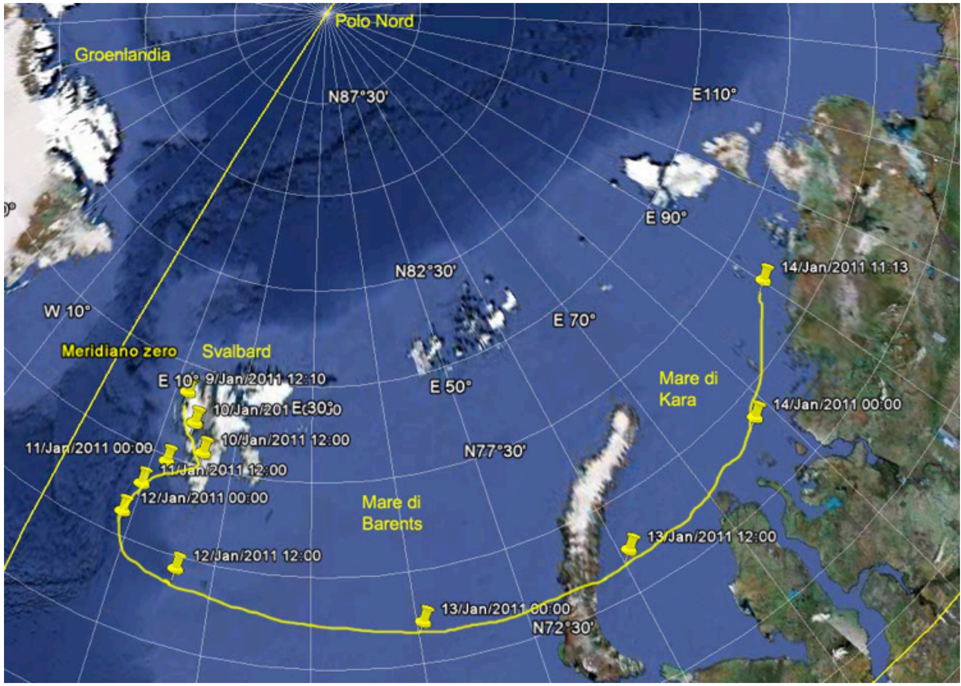
Launch from Svalbard (Norway)

Or Kiruna (Sweden)

December: Polar night flight

Power = lots of batteries





SPIDER: Suborbital Polarimeter for Inflation, Dust and the Epoch of Reionization (PI: B. Jones, Princeton)

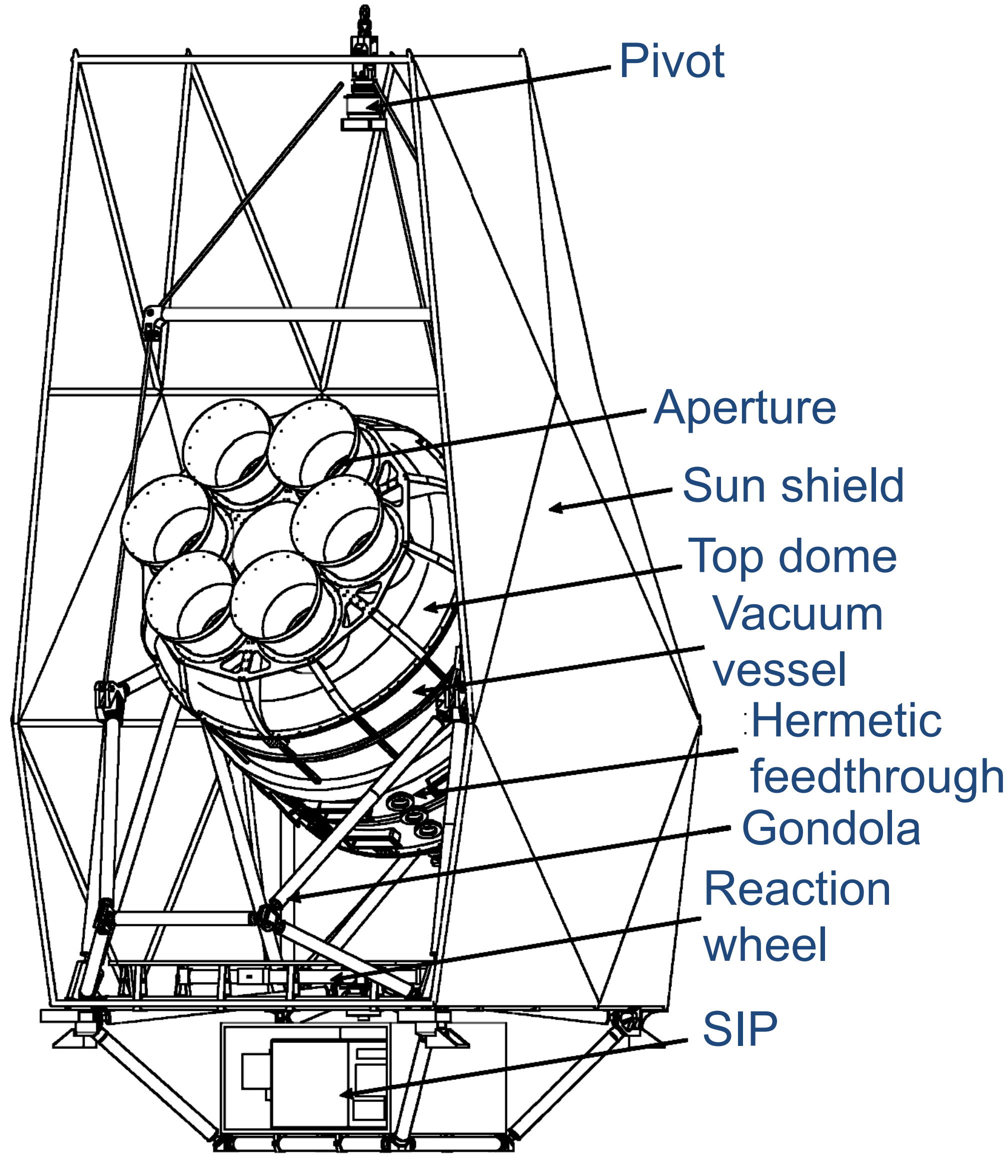
NASA
NSF
C.S.B.F. PALESTINE, TEXAS
CSA ASC
NSERC CRSNG
JPL
the David & Lucile Packard Foundation
Alfred P. Sloan Foundation
California Institute of Technology
University of Toronto
Case Western Reserve University EST. 1826
Cardiff University Prifysgol Caerdydd
UBC
NIST
Princeton University
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique
Imperial College London

Spider: Overview

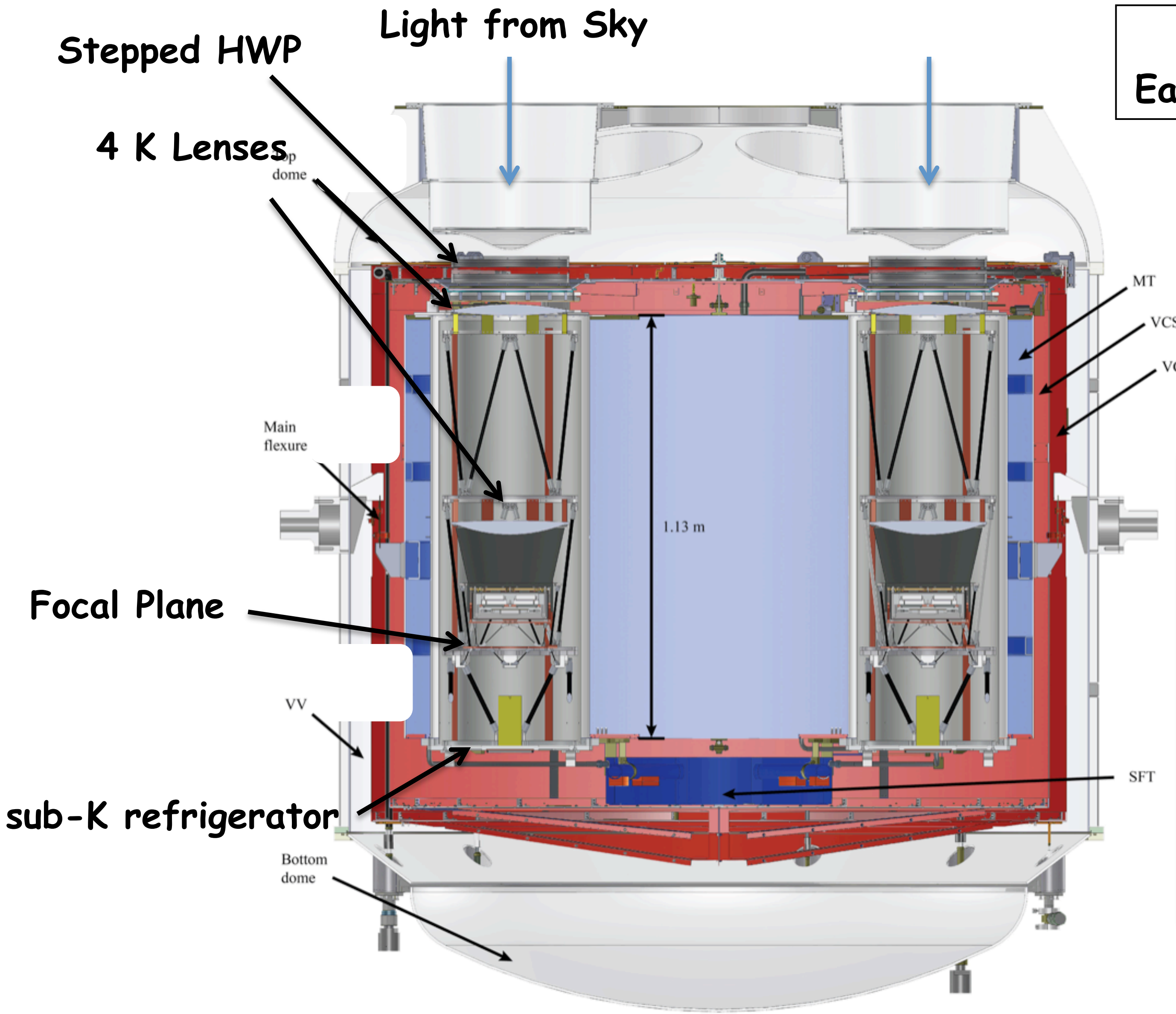
Frequencies (GHz)	94	150
Telescopes	3	3
Bandwidth [GHz]	22	36
Optical efficiency	30-45%	30-50%
Angular resolution* [arcmin]	42	28
Number of detectors†	601 (816)	863 (1488)
Optical background‡ [pW]	≤ 0.25	≤ 0.35
Instrument NET† [μK·rts]	6.0	5.7
*FWHM. †Only counting those currently used in analysis ‡Including sleeve, window, and baffle		

Sky coverage	About 10 %
Scan rate (az, sinusoid)	3.6 deg/s at peak
Polarization modulation	Stepped cryogenic HWP
Detector type	Antenna-coupled TES
Multipole range	$10 < \ell < 300$
Observation time	16 days at 36 km
Limits on r†	0.03

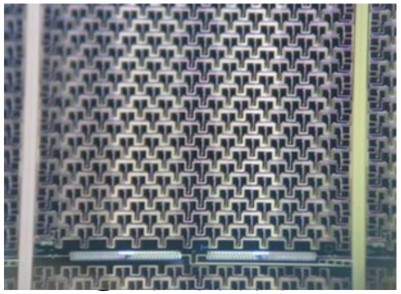
† Ignoring all foregrounds, at 99% confidence



SPIDER Design



6 identical inserts
Each is single frequency



Detectors

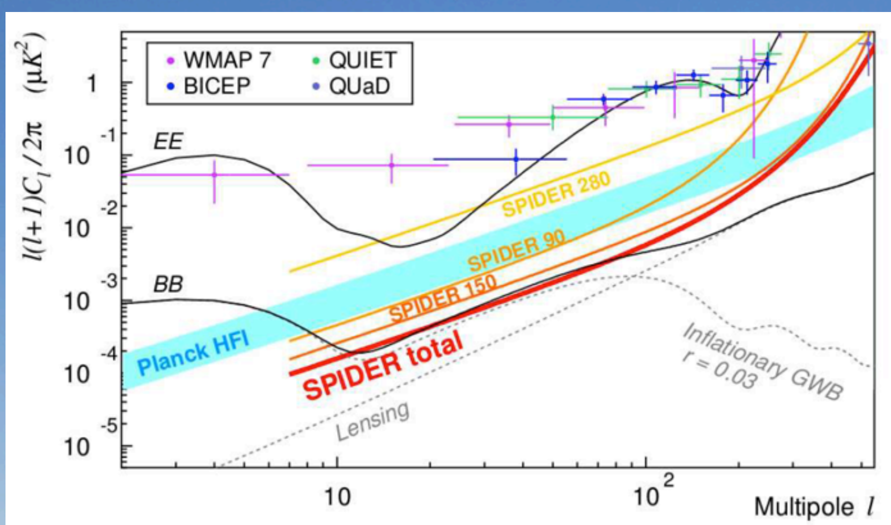
Antenna Phase-Array with TES (JPL/Caltech)

Readout:

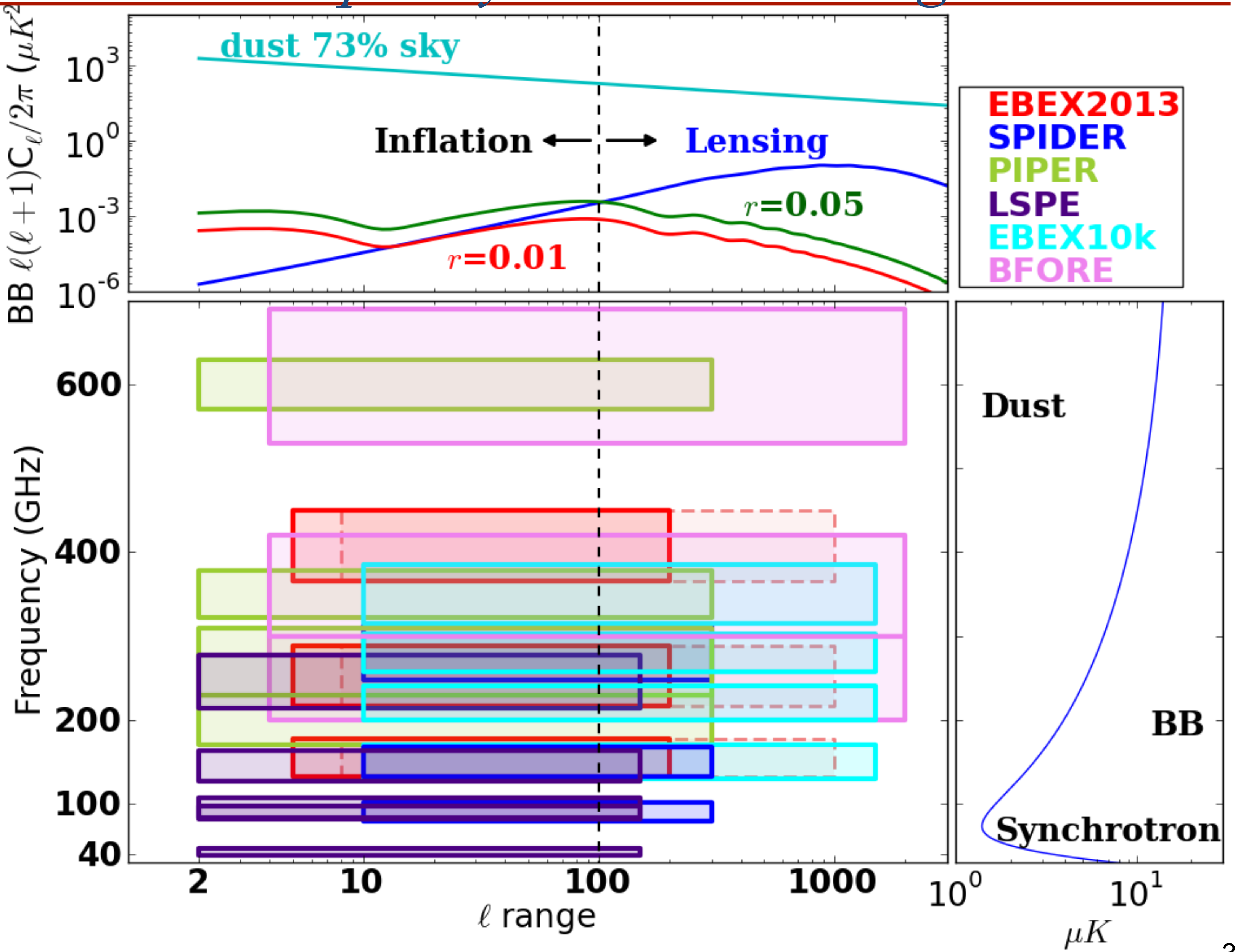
Time Domain Mux (Halpern, Canada)

Future plans

- Payload has been recovered!
- 3 new NIST 285 GHz cameras
- Second flight: 2017/18

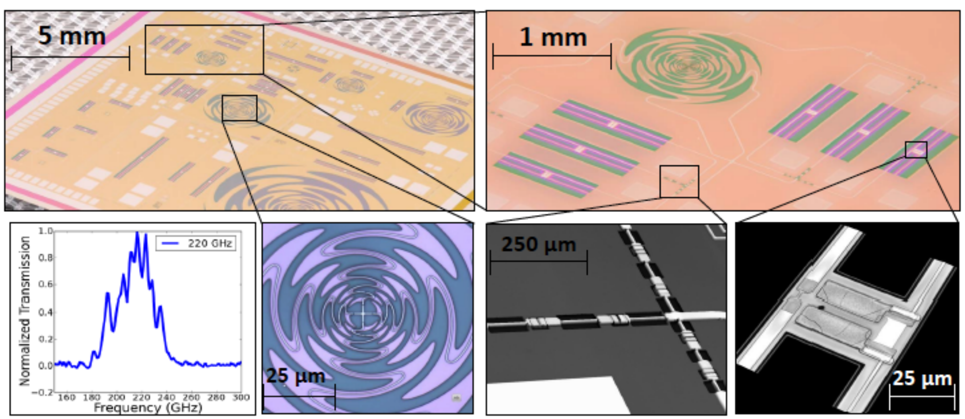


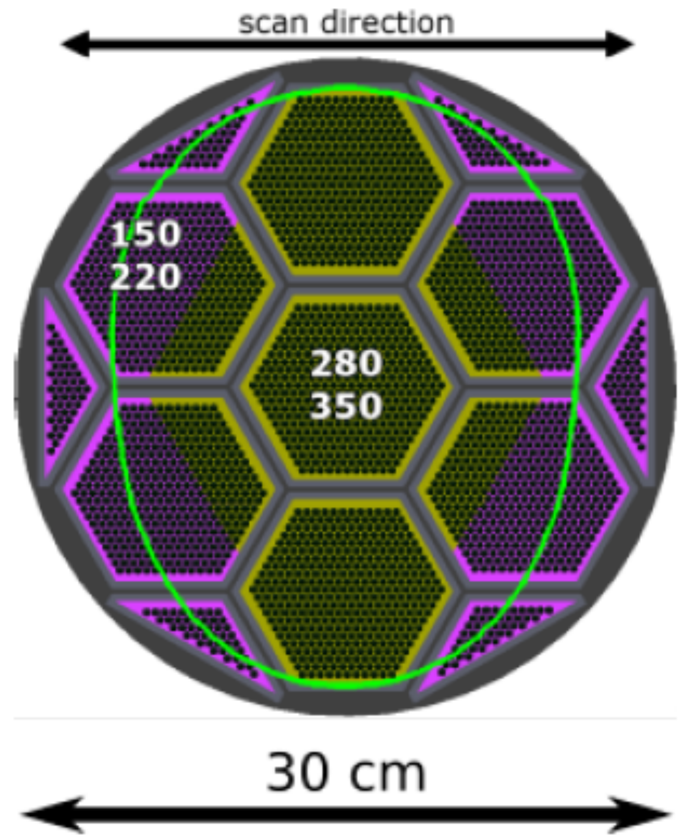
Frequency and \ell coverage



EBEX10K

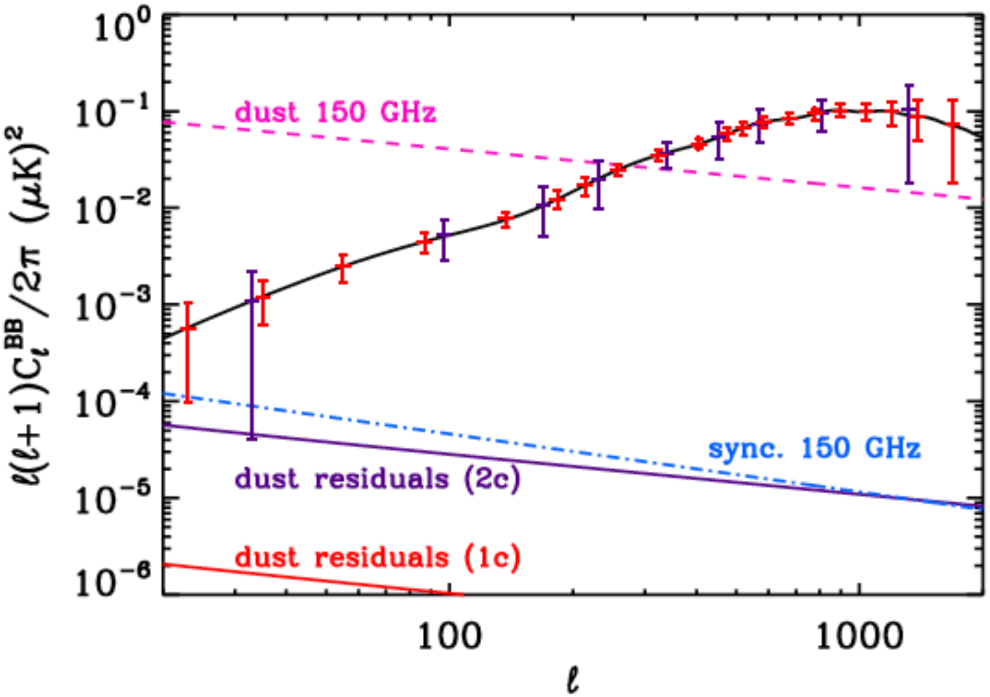
- 4 bands: 150, 220, 280, 350 GHz
- 2% of sky (~800 sq. deg)
- Sinuous Antenna Dual Frequency Pixels (150,220), (280,350) GHz (PB2, SPTPol, LiteBIRD)

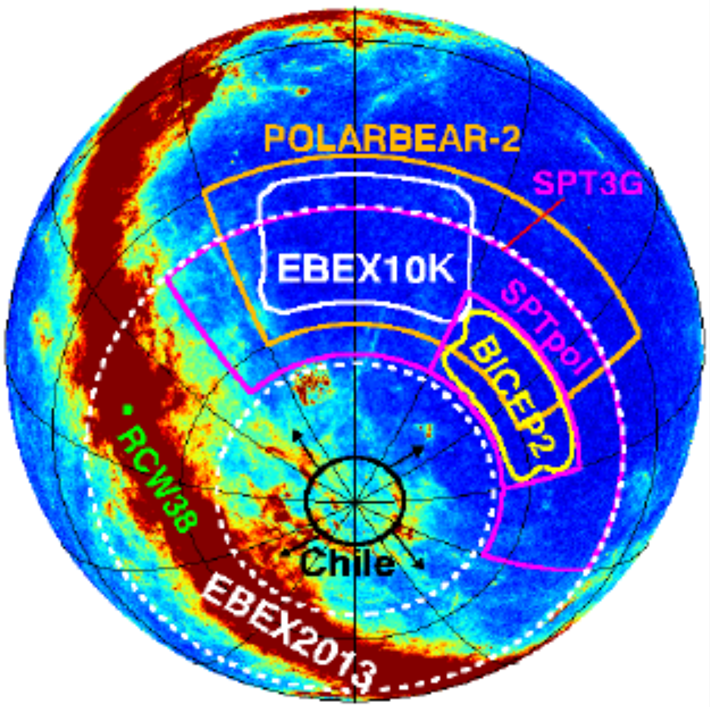




- 11,160 detectors
  - 46% at 150-220 GHz
  - 54% at 280-350 GHz

EBEX10K





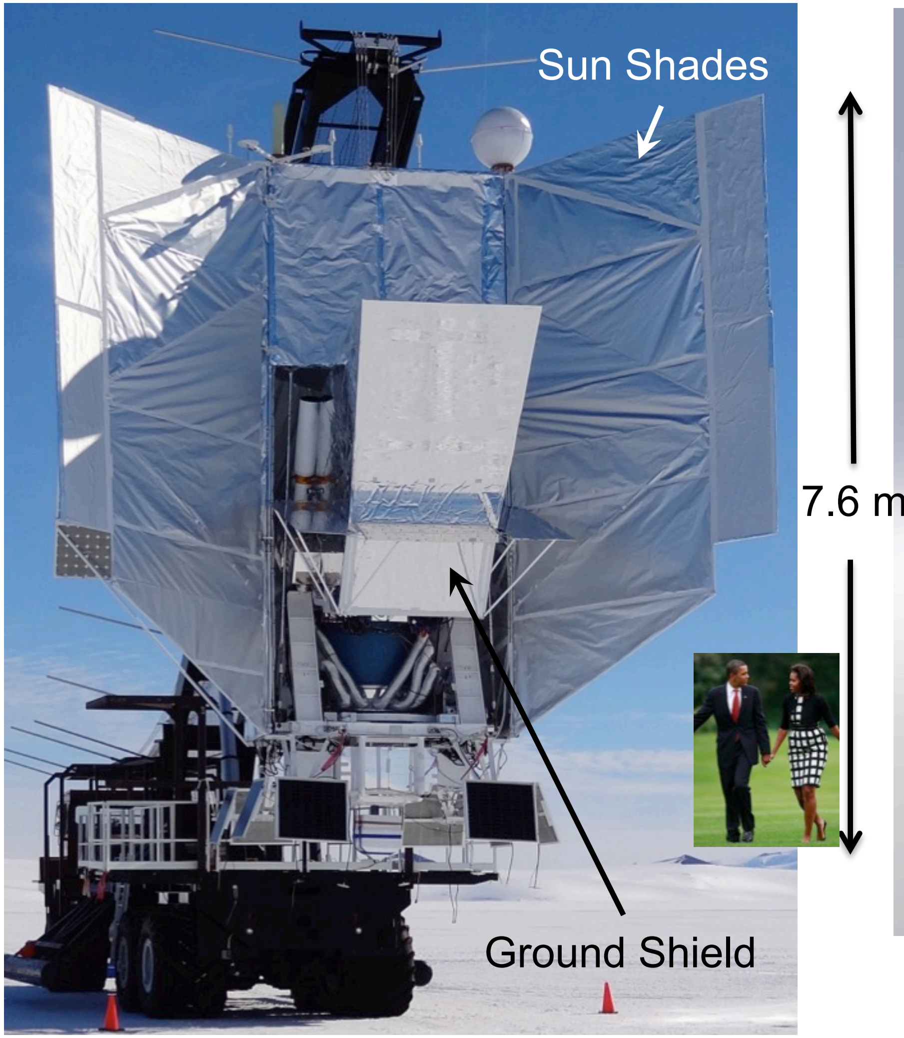
r<0.009 (2σ) EBEX10K alone,
Δβ=0.05%

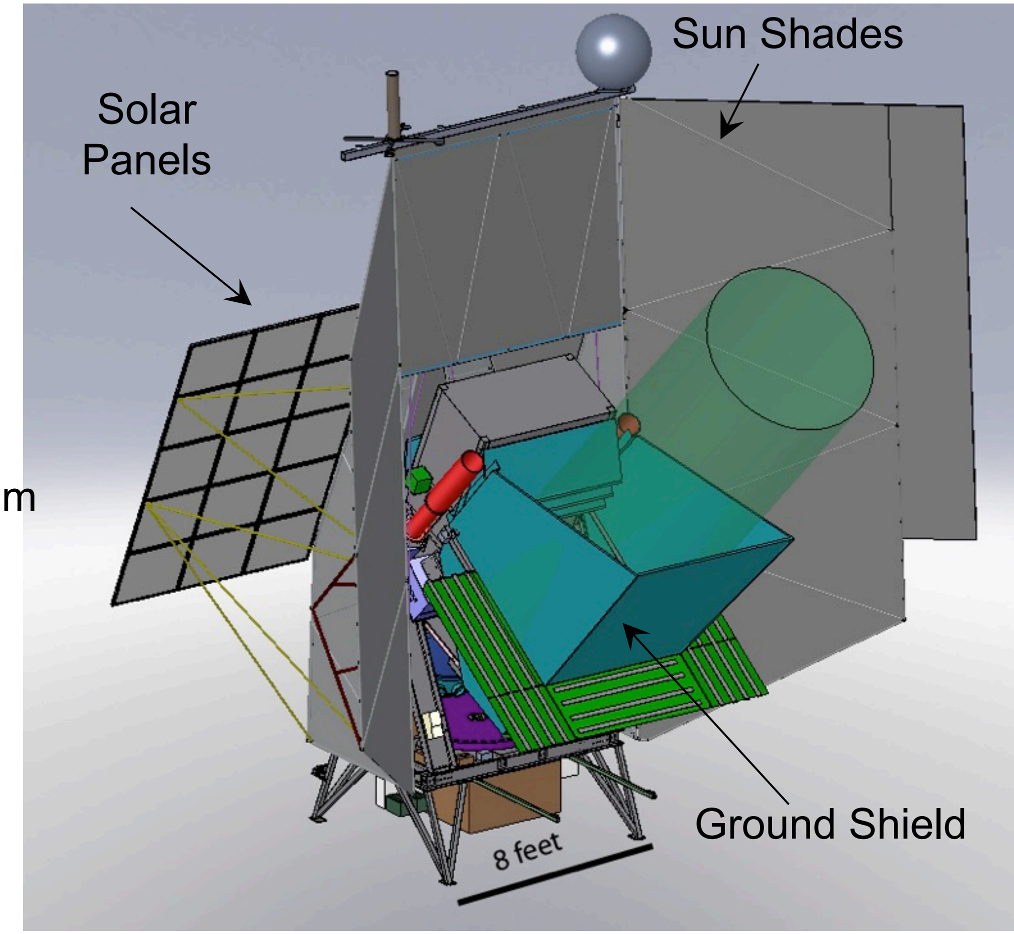
Summary

- Balloons are essential for probing high frequencies on all angular scales.
- They have strong benefits at the largest angular scales for all frequencies
- By mid-next decade limits will push r=~0.01 + more information on polarization of galactic dust.
- Balloons = ‘single shot’: no evolutionary improvements => different approach for hardware implementation
- New technologies consume intellectual effort and require time to mature – choose essentials, and leave ample time
- Complex receivers require more time for end-to-end integration and testing.

Extra Material

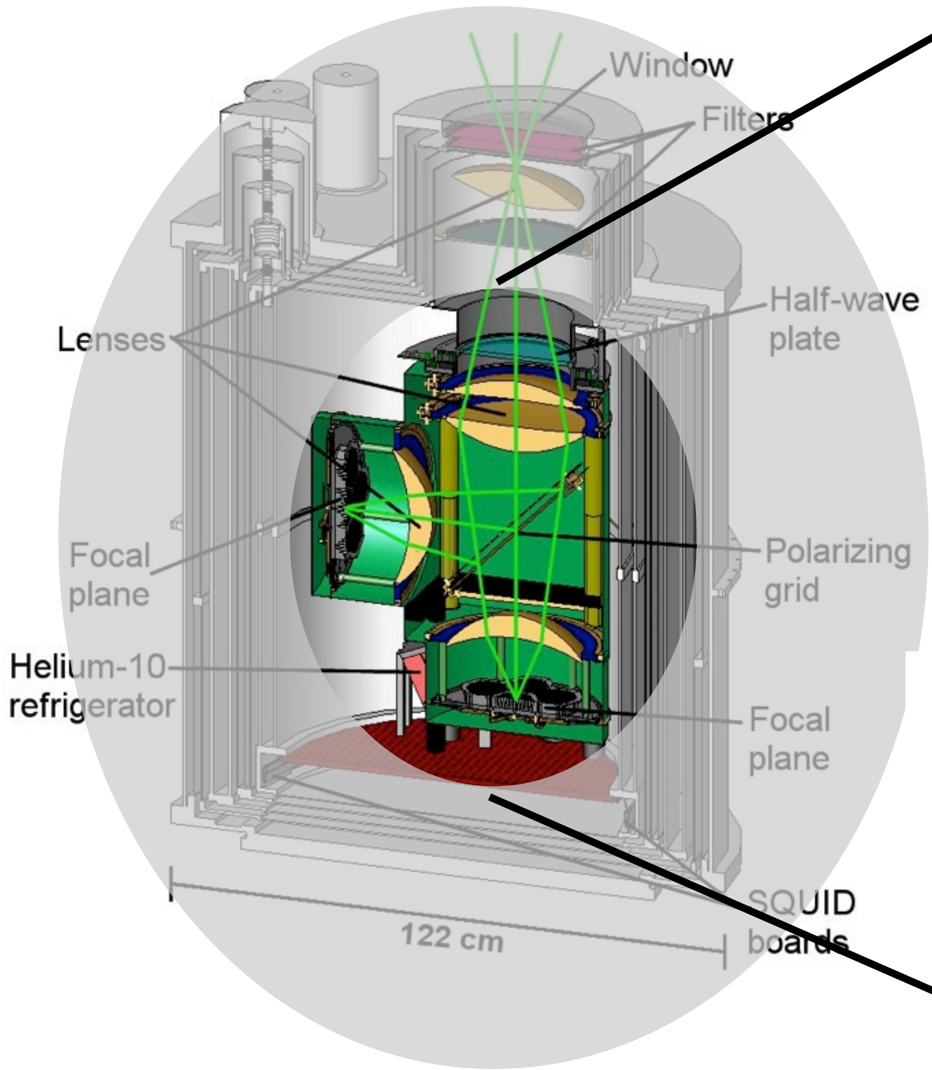
Instrument

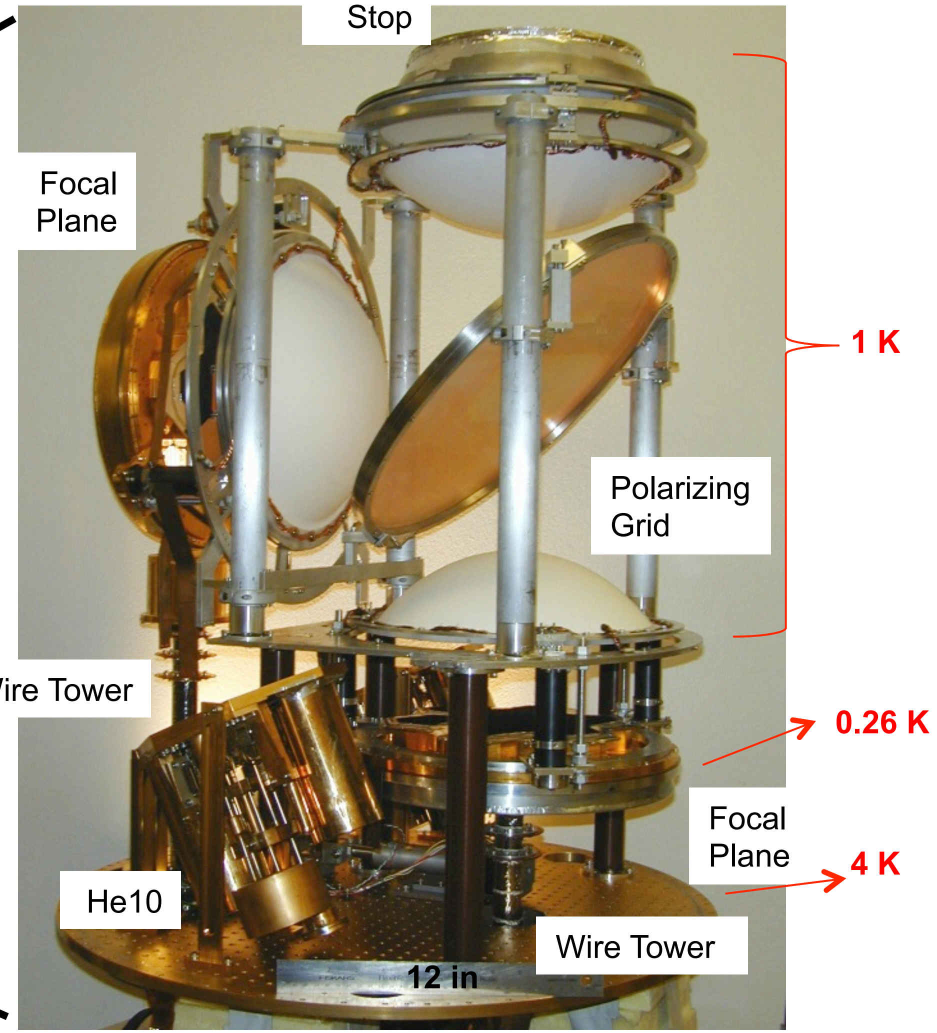




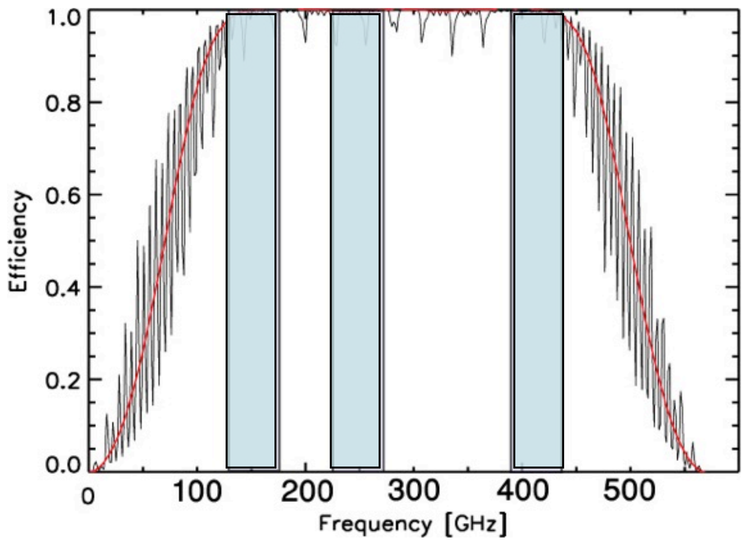
2725 kg Suspended Science Weight
2.6 kWatt max provided by panels

Instrument

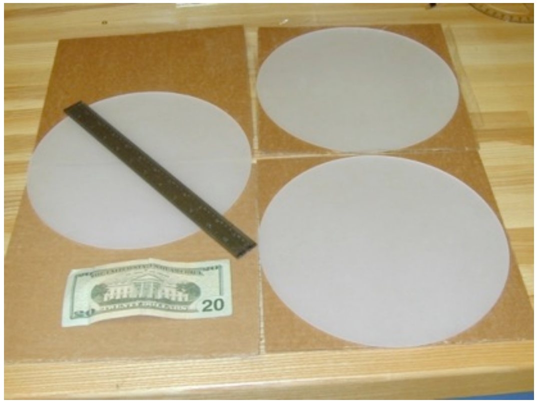

Window
Filters
Lenses
Half-wave
plate
Focal
plane
Polarizing
grid
Helium-10
refrigerator
Focal
plane
122 cm
SQUID
boards

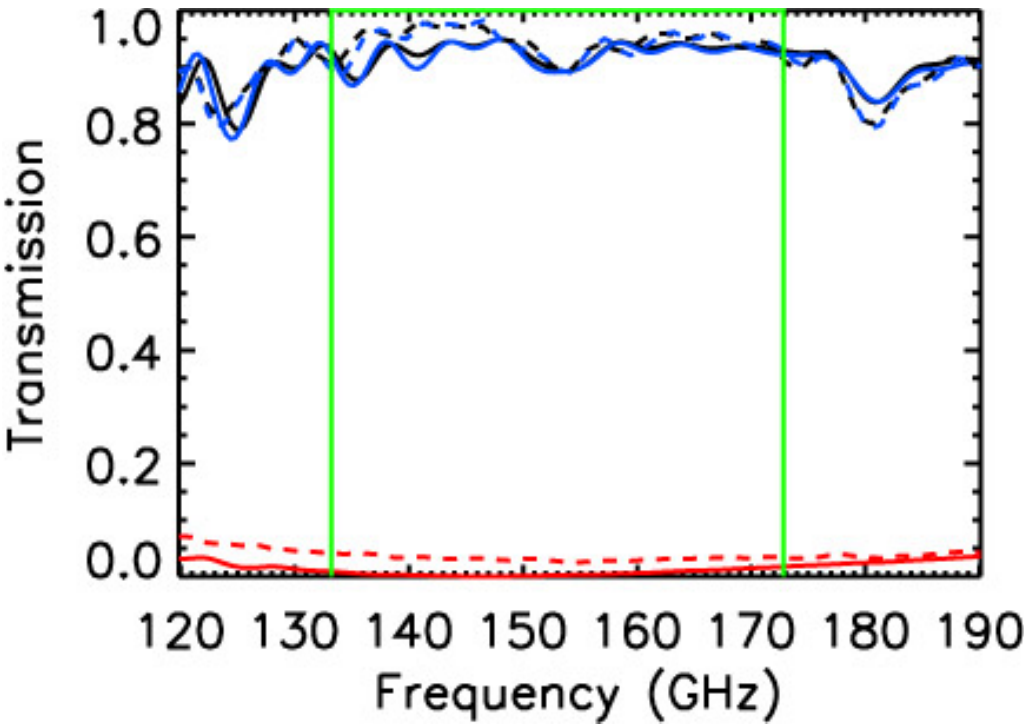

Stop
Focal
Plane
Polarizing
Grid
1 K
Wire Tower
0.26 K
Focal
Plane
4 K
He10
Wire Tower
12 in

Achromatic HWP



- 5 stack achromatic HWP
- Modulation Efficiency > 0.98
- 6 Hz rotation

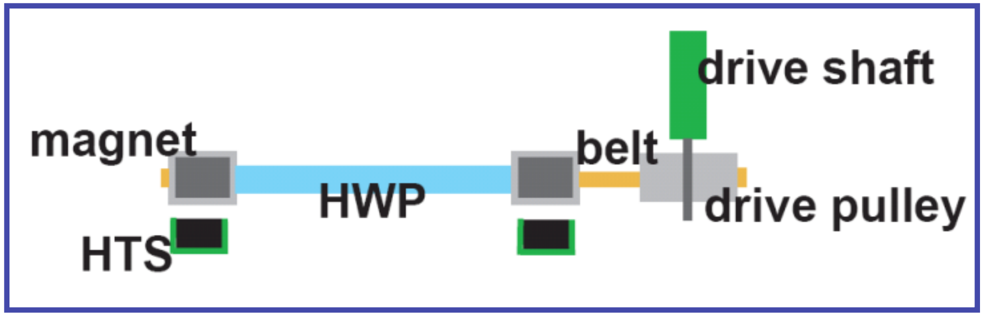


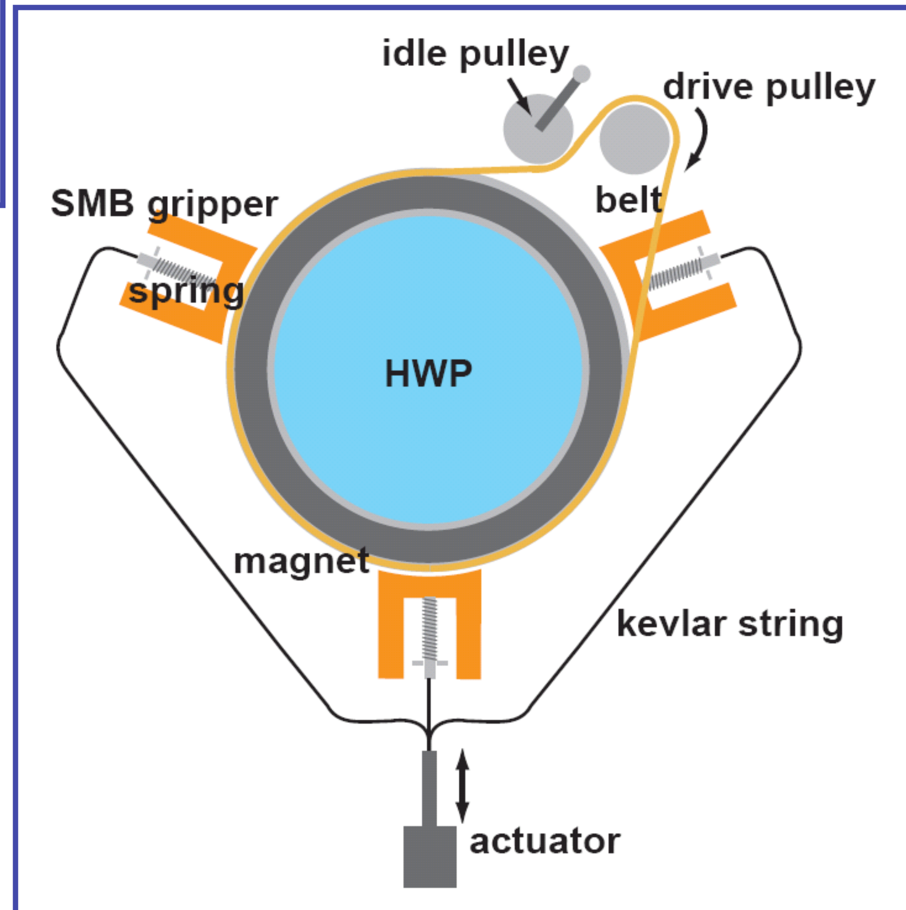


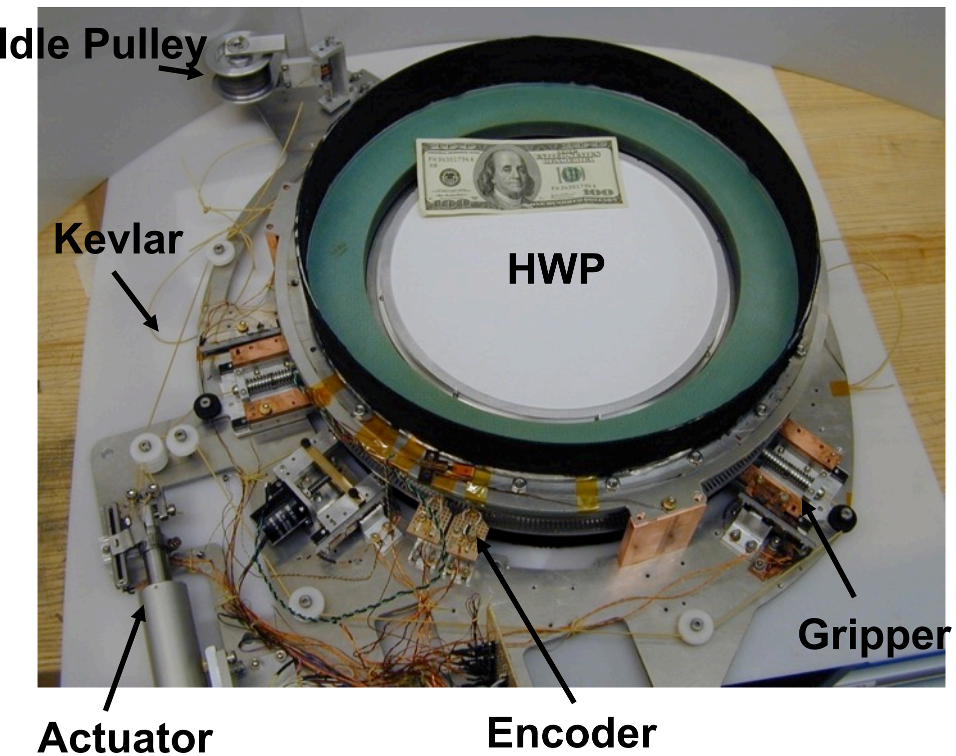
Warm measurement (Savini + Ade)
Dash = data; Solid = model
Black = 0°; Red = 45°; Blue = 90°

Predicted Efficiency >0.98

Magnetic Bearing

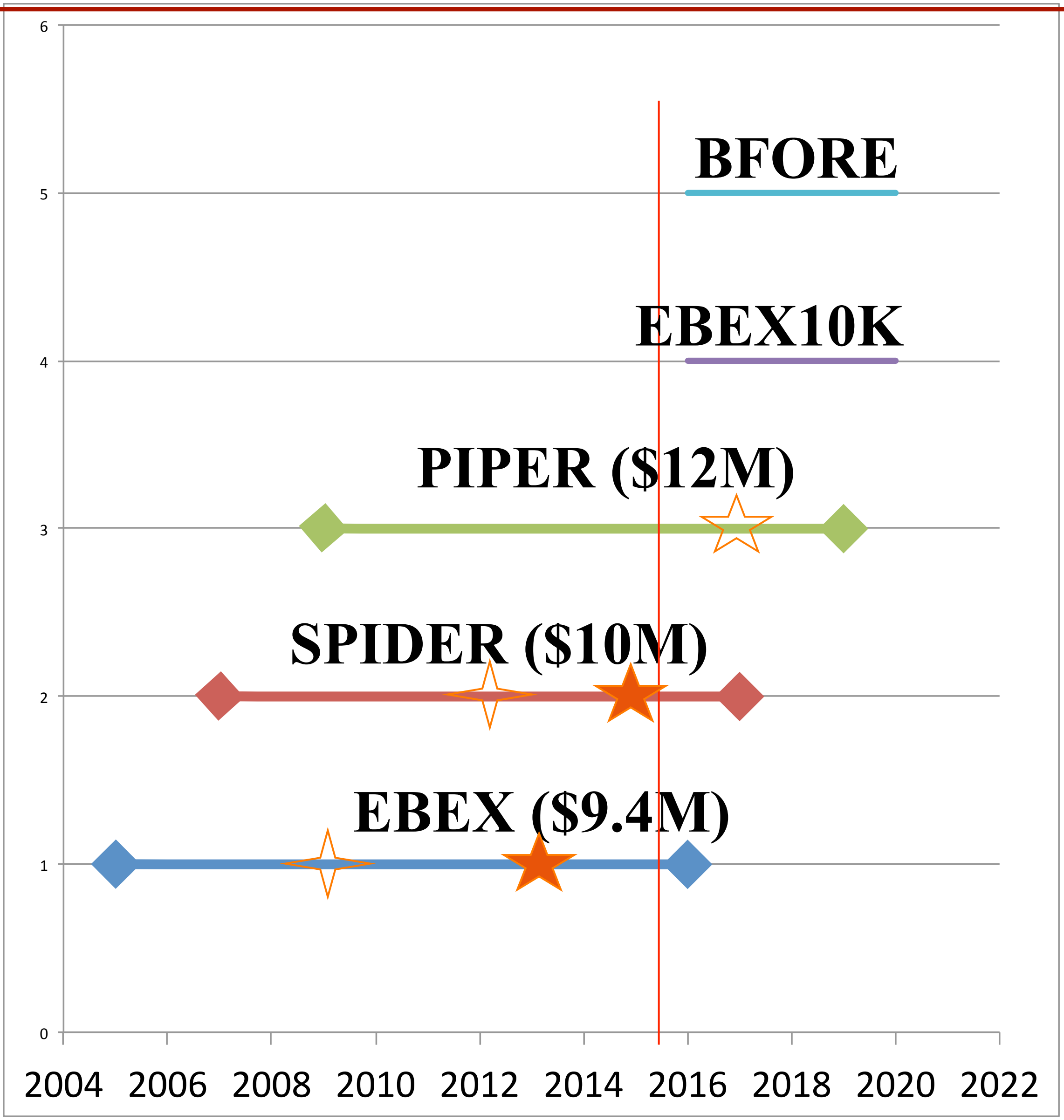






Hanany et al. 2003, Klein et al. 2008

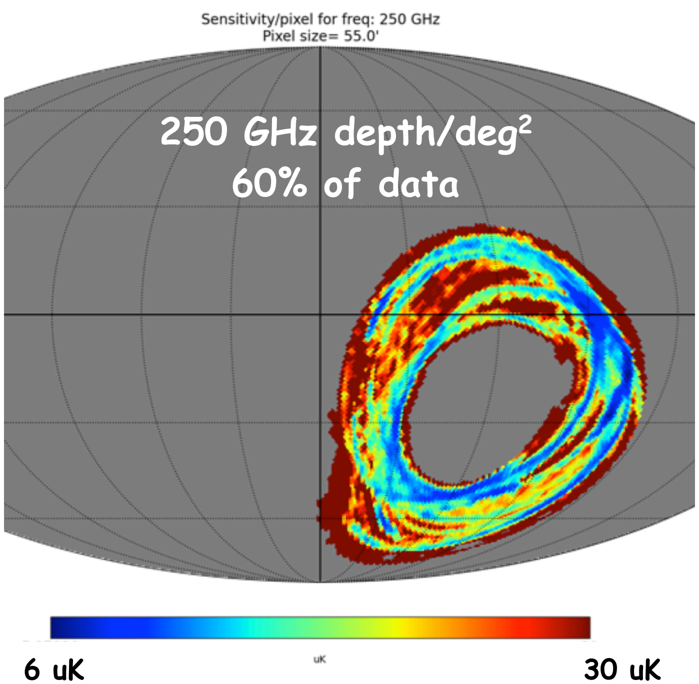
Timelines

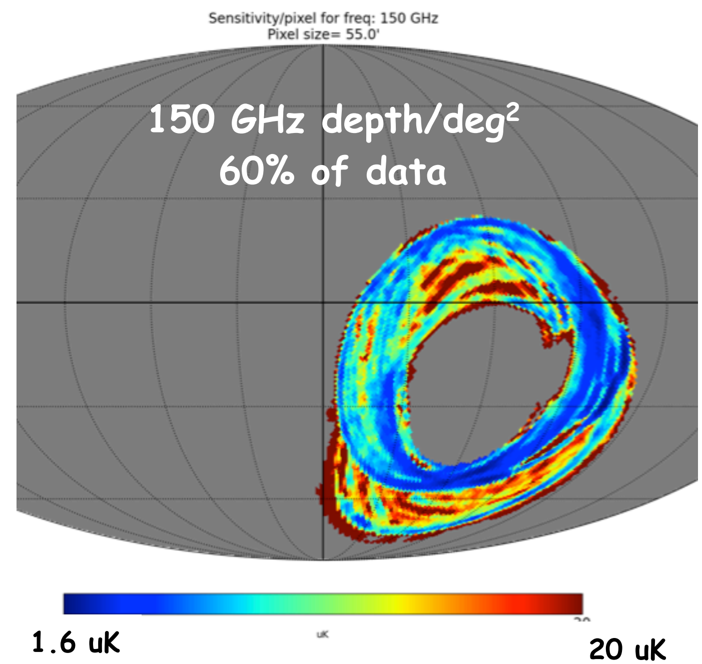


BFORE
EBEX10K
PIPER ($12M)
SPIDER ($10M)
EBEX ($9.4M)
0
1
2
3
4
5
6
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022

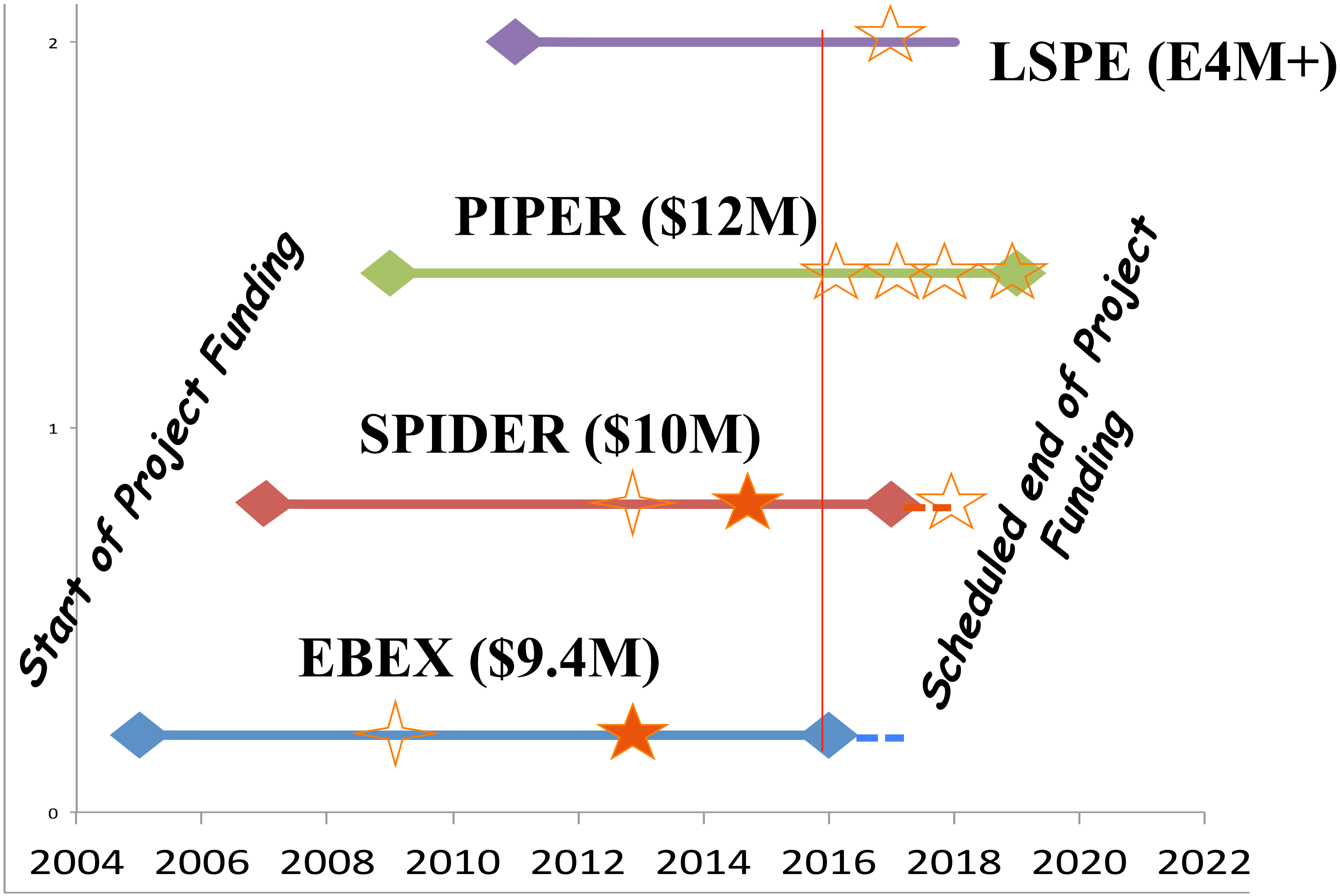
2013 Flight

- 10 days of data in January 2013
- ~6000 sq. deg. constant Dec
  - Overheating of az motor controller
  - Free rotations + az oscillations
  - Continuous pointing solutions; receiver worked well
  - Analysis in progress



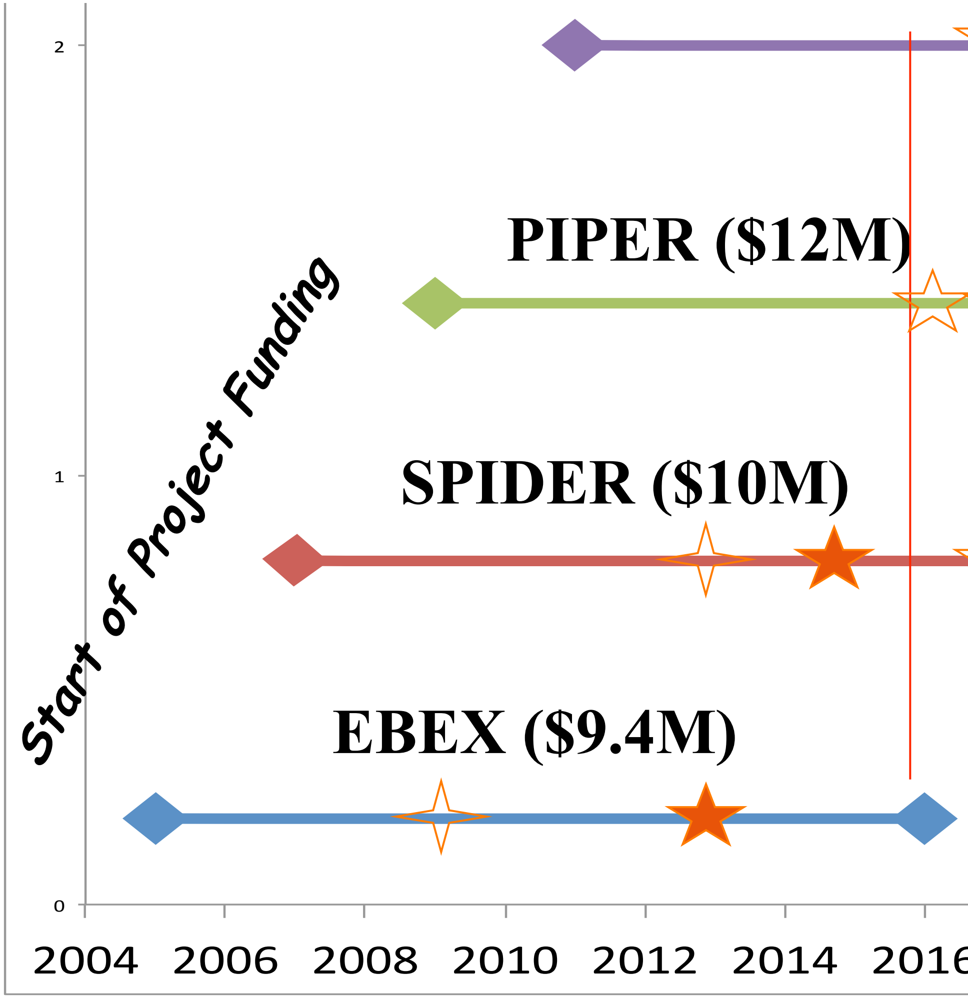


Currently Funded CMB - Timelines



- ~$1M/year; ~8 years to first dataset
- Compared to 20 years ago, complexity has increased (much) more than funding

Currently Funded CMB - Timelines



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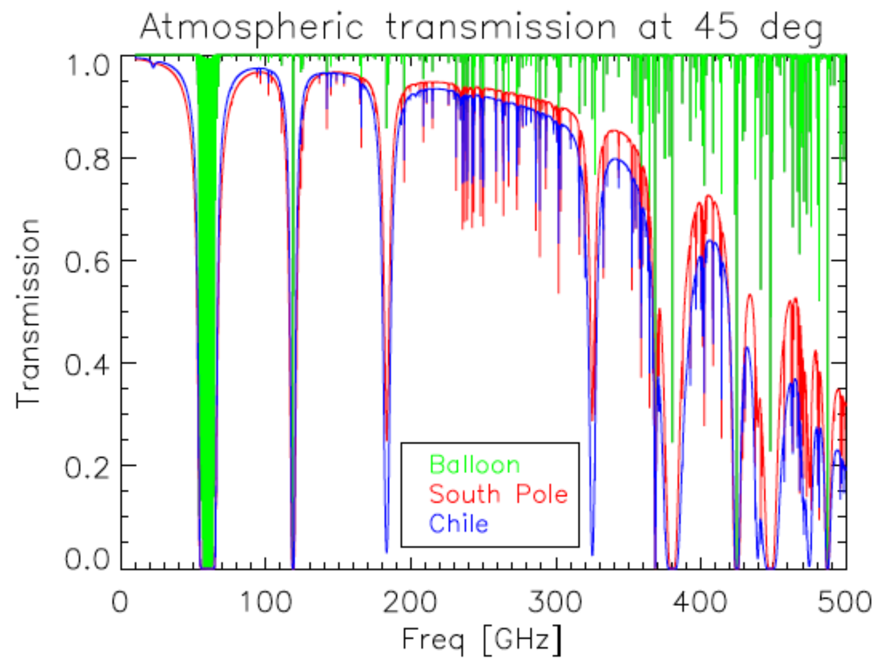
Why Balloons?

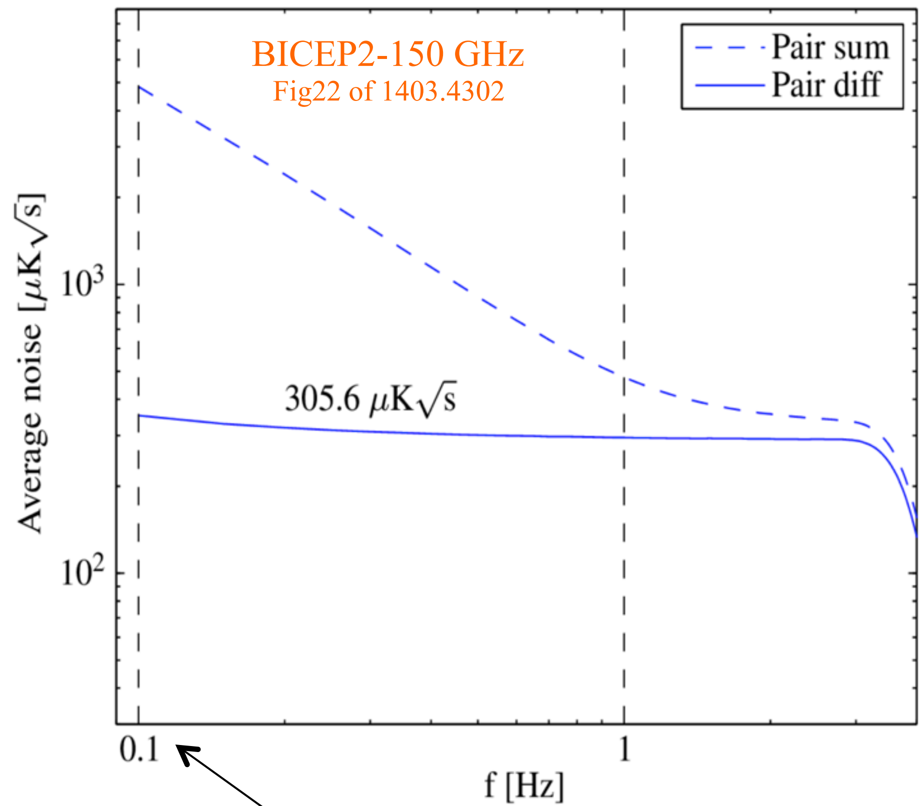
- Access to (near) space
  - Avoid the atmosphere



  - Increase TRL
    - Boomerang, MAXIMA, Archeops -> Planck
    - EBEX (TES, Frequency Domain MUX, Modulator) -> LiteBIRD
  - Train next generation space scientists

Why Balloons?

- Access to (near) space
  - Avoid the atmosphere
    - Signal attenuation
    - Noise
      - Photon (white) noise
      - Turbulence (1/f)



ell=~25