EBEX
The E and B EXperiment

Michael Milligan
University of Minnesota

Collaboration

APC – Paris
Radek Stompor

Brown University
Andrei Korotkov
John Macaluso
Greg Tucker
Yuri Vinokurov

CalTech
Tomotake Matsumura

Cardiff
Peter Ade
Enzo Pascale

Columbia University
Amber Miller
Britt Reichborn-Kjennerud
Will Grainger

Harvard
Matias Zaldarriaga

IAS-Orsay
Nicolas Ponthieu

Imperial College
Andrew Jaffe

Lawrence Berkeley National Lab
Julian Borrill

McGill University
Francois Aubin
Eric Bisonnette
Matt Dobbs
Kevin MacDermid

Oxford
Brad Johnson

SISSA-Trieste
Carlo Baccigalupi
Sam Leach
Federico Stivoli

University of California/Berkeley
Adrian Lee
Xiaofan Meng
Huan Tran

University of California/San Diego
Tom Renbarger

University of Minnesota/Twin Cities
Asad Aboobaker
Shaul Hanany
Clay Hogen-Chin
Hannes Hubmayr
Terry Jones
Jeff Klein
Michael Milligan
Dan Polsgrove
Ilan Sagiv
Kyle Zilic

Weizmann Institute of Science
Lorne Levinson

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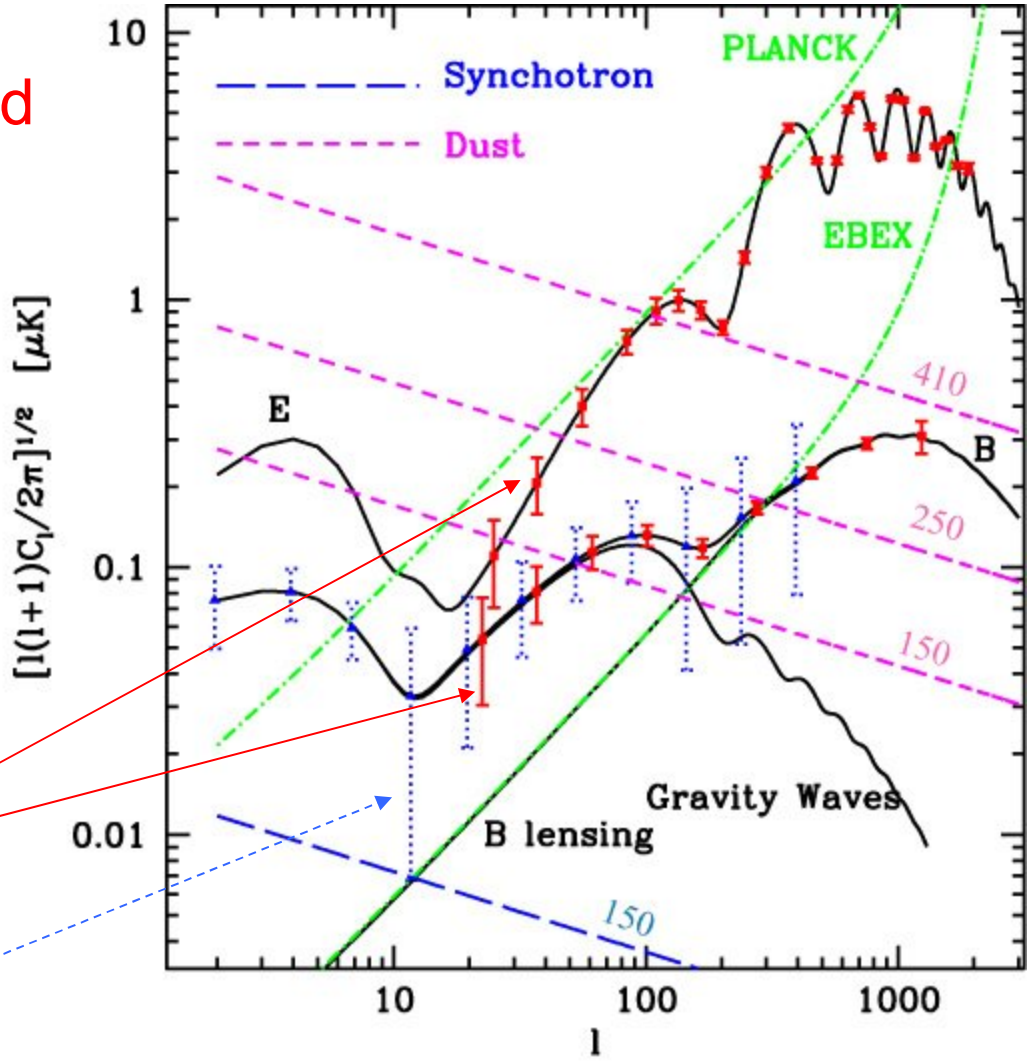
Science Goals

- Detect or set upper bound on inflation B-mode

  – Restrict T/S to ~x10 better than now:

  T/S<0.02 at 2σ

  (excluding systematic and foreground subtraction uncertainties)

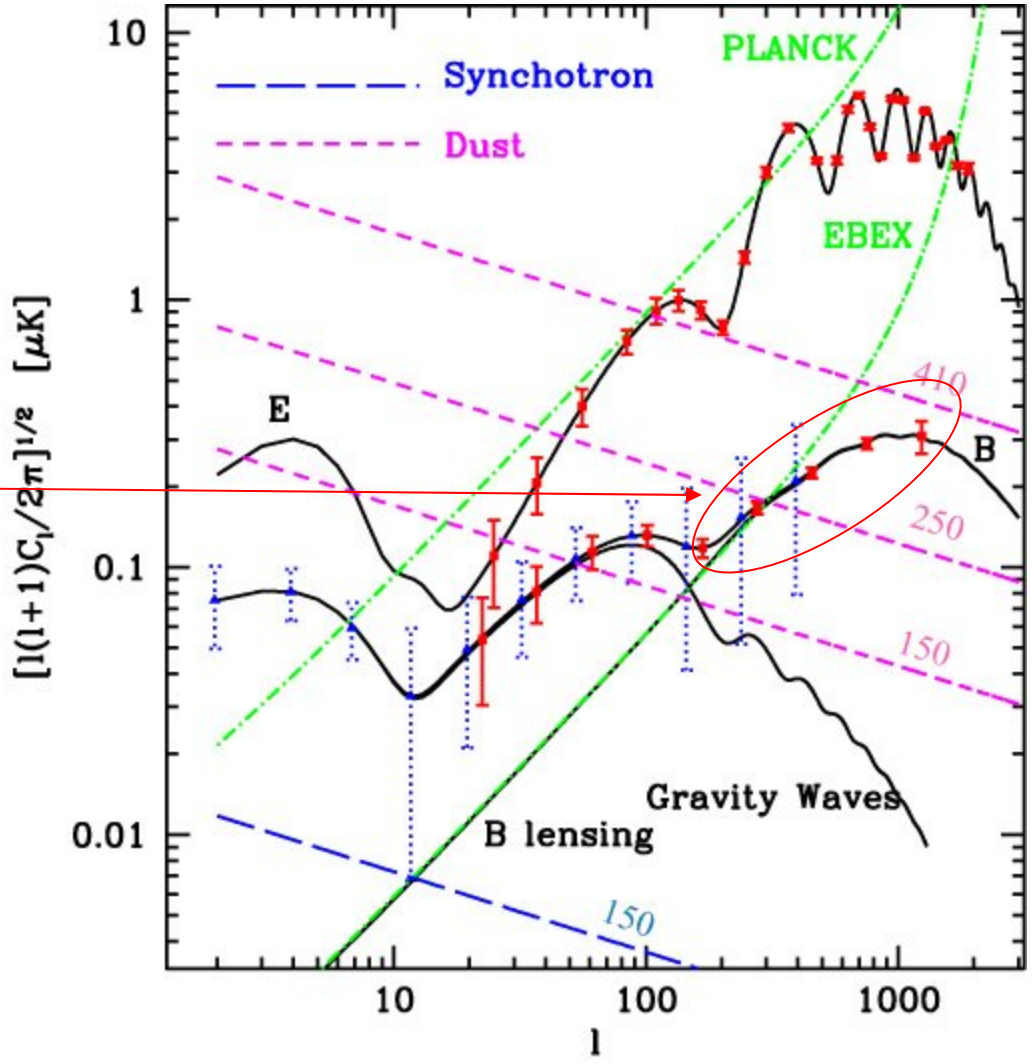


EBEX 14 days

Planck 1 year

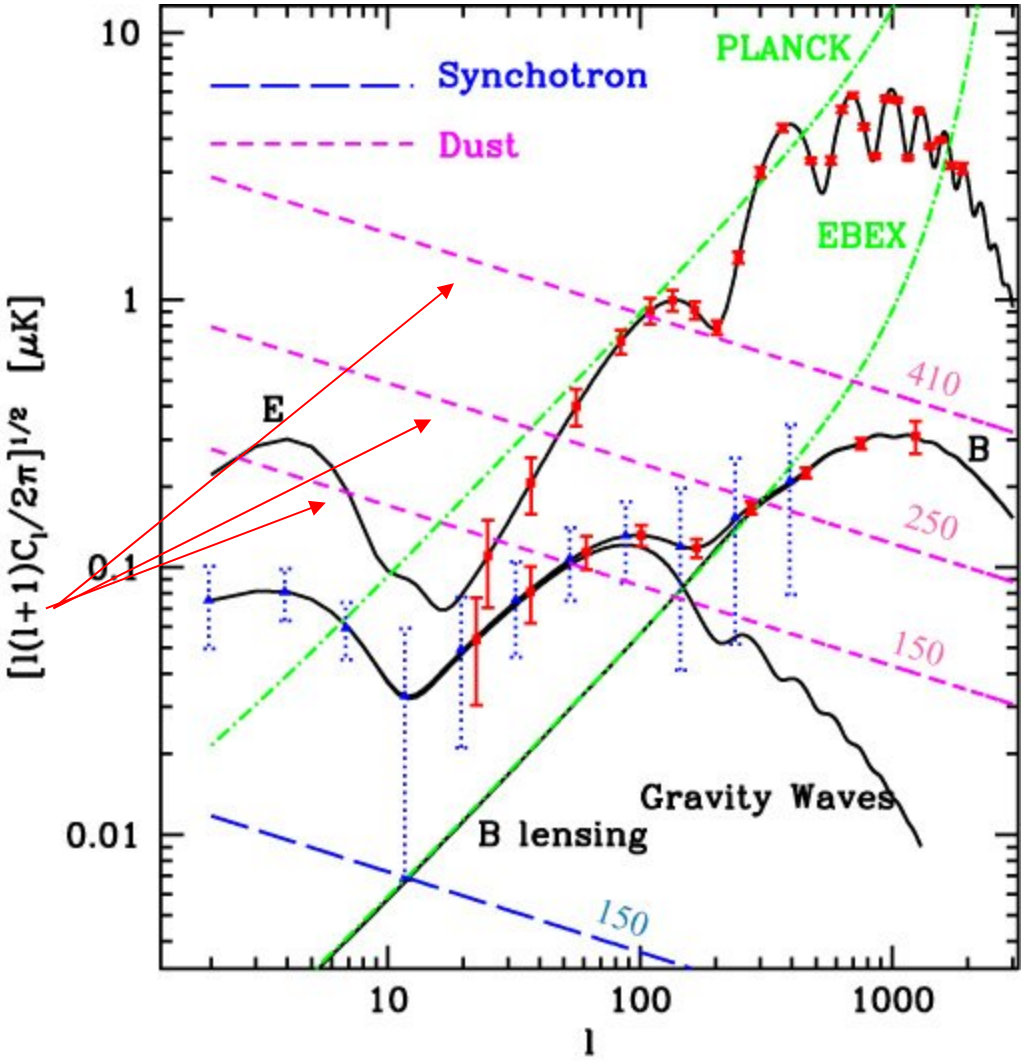
Science Goals

- Detect or set upper bound on B-mode
- Detect the lensing B-mode:
  - 5% error on amplitude of lensing power spectrum



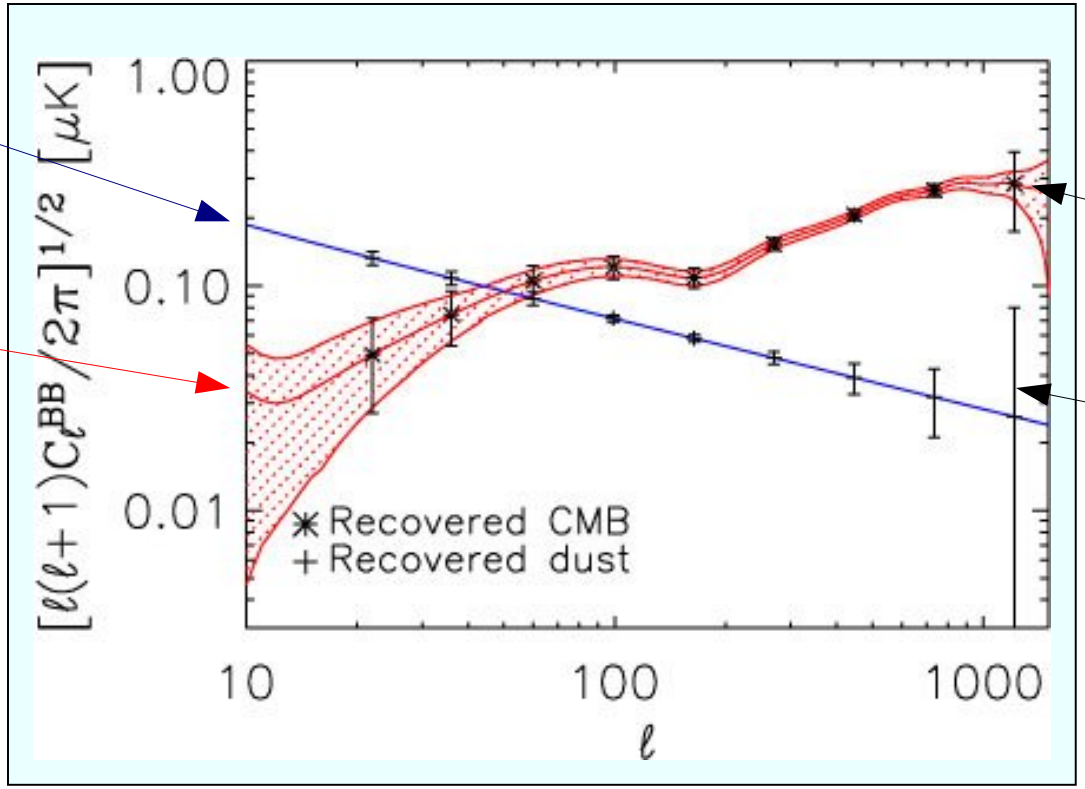
Science Goals

- Detect or set upper bound on B-mode
- Detect the lensing B-mode
- Determine properties of polarized dust



Dust Determination and Subtraction

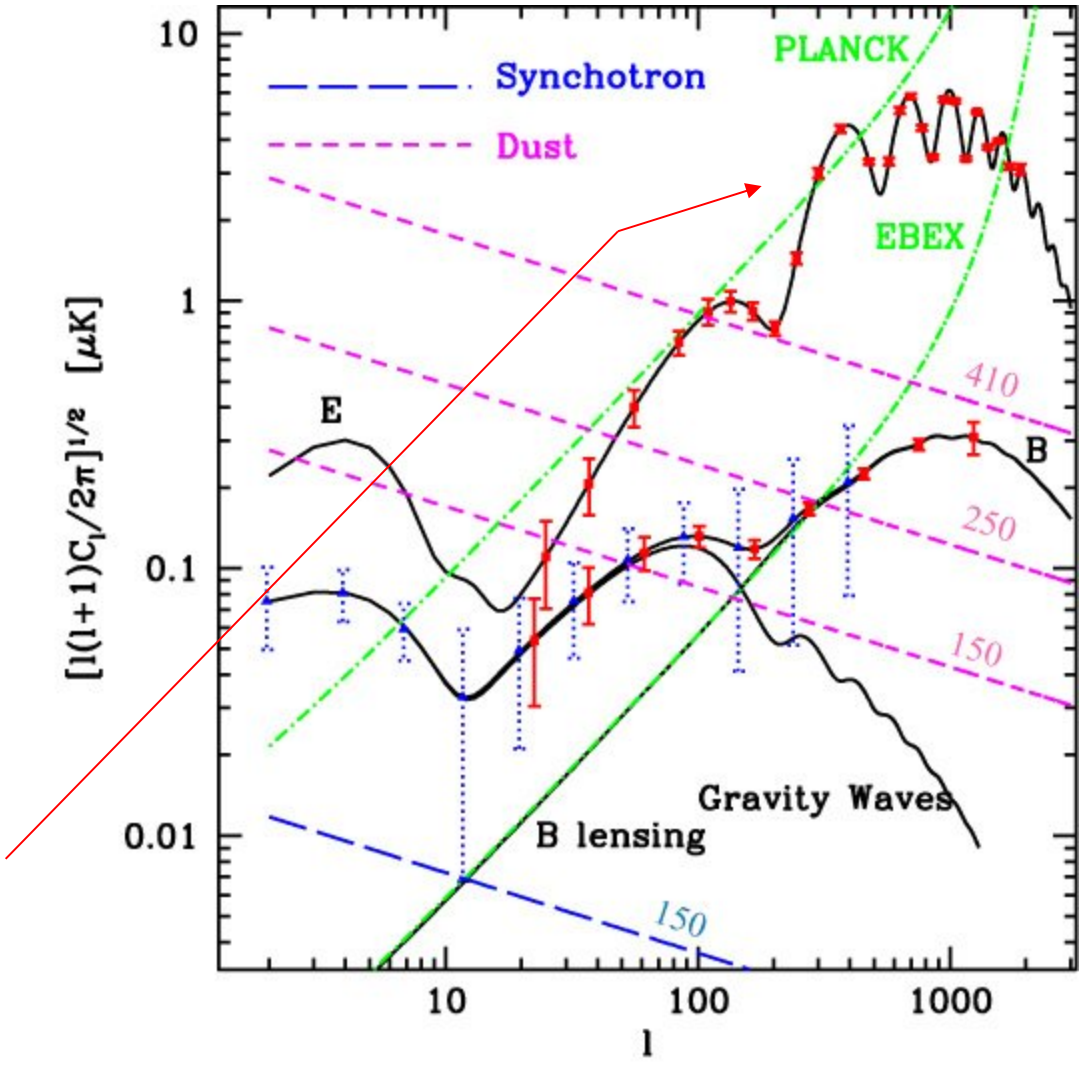
Simulated CMB+Dust Reconstruction



- Simulate observed sky from dust + CMB + instrument noise (at three EBEX frequency bands)
- Systematic uncertainties not simulated
- Reconstruct dust + CMB maps (using parametric estimation)
- Less than 1/3 σ penalty in CMB reconstruction for ℓ < 900
- Unbiased recovery of CMB and dust power spectra

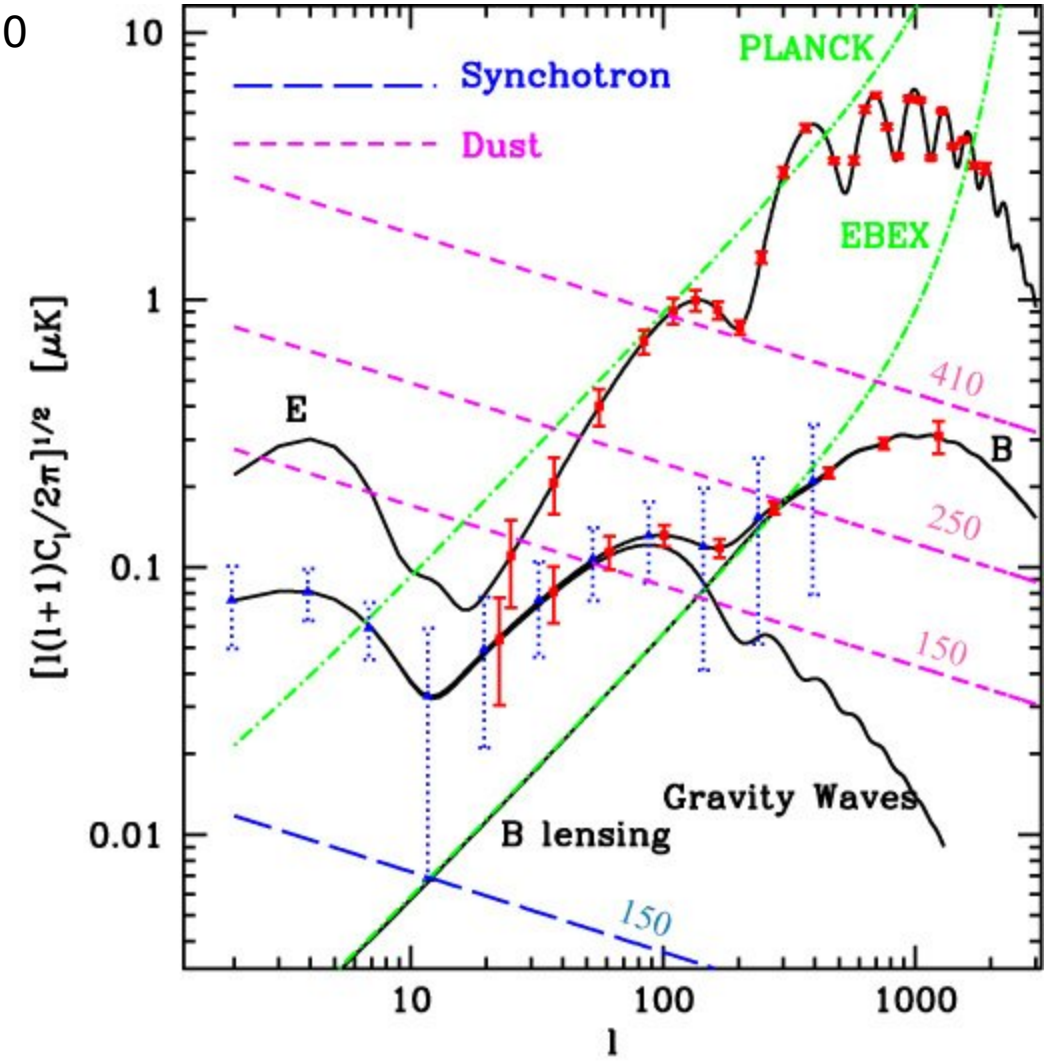
Science Goals

- Detect or set upper bound on B-mode
- Detect the lensing B-mode
- Determine properties of polarized dust
- Improve accuracy of cosmological parameters:
  e.g. x2 improvement in limit on running of n



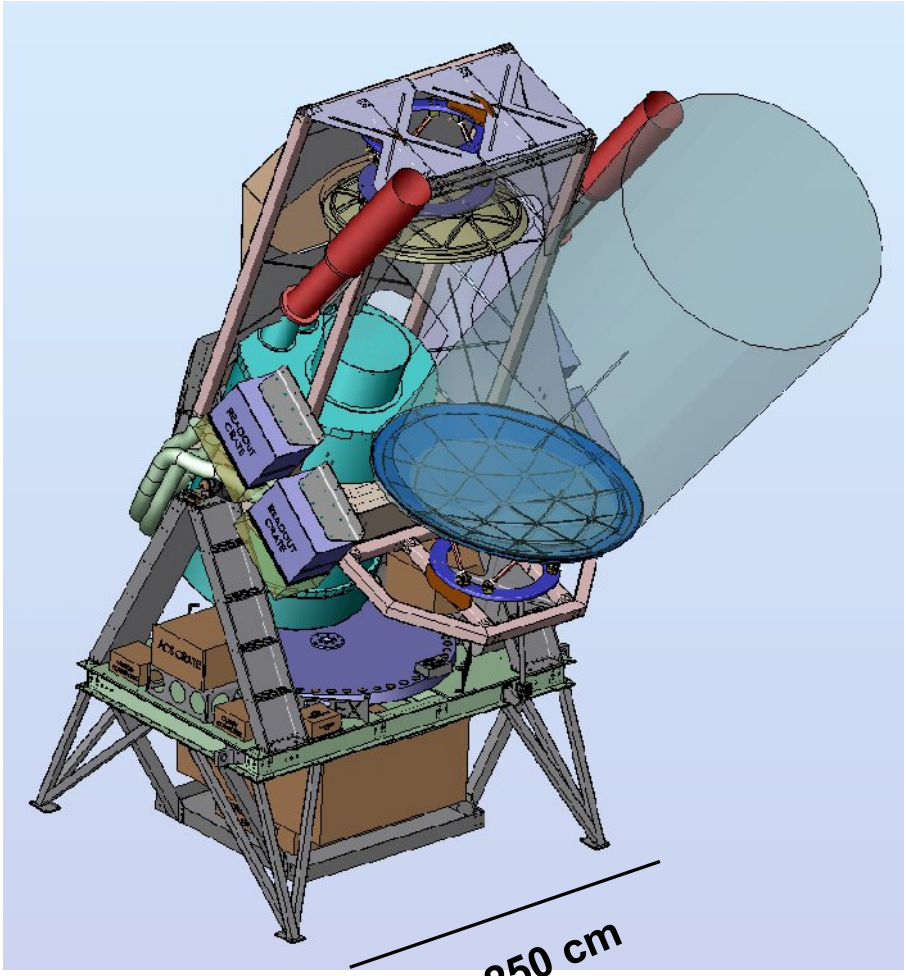
Design Principles

- concentrate on $20 < \ell < 1500$
- Detect B lensing signal: ~x5 stronger than dust
- Deal with only one foreground
- Use balloon to get firm handle on dust foreground
- Provide strong rejection of polarimetric systematics
- Use available technologies where practical



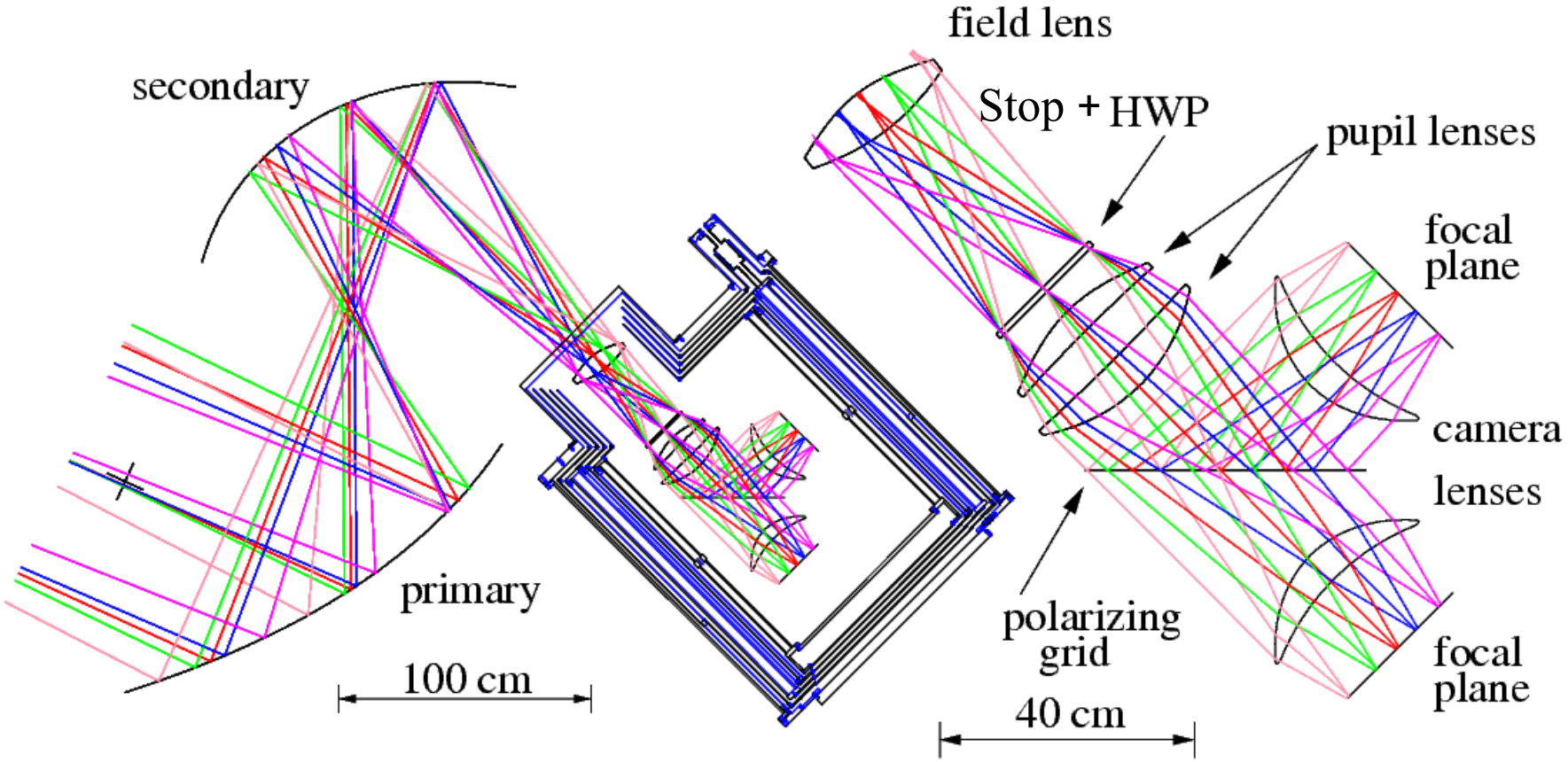
EBEX in a Nutshell

- Long duration balloon borne
- Use 1476 bolometric TES
- 3 Frequency bands: 150, 250, 410 GHz
- Resolution: 8’ at all frequencies
- Polarimetry with half wave plate
- BLAST (+ BOOM, MAXIMA) balloon technologies



Optics

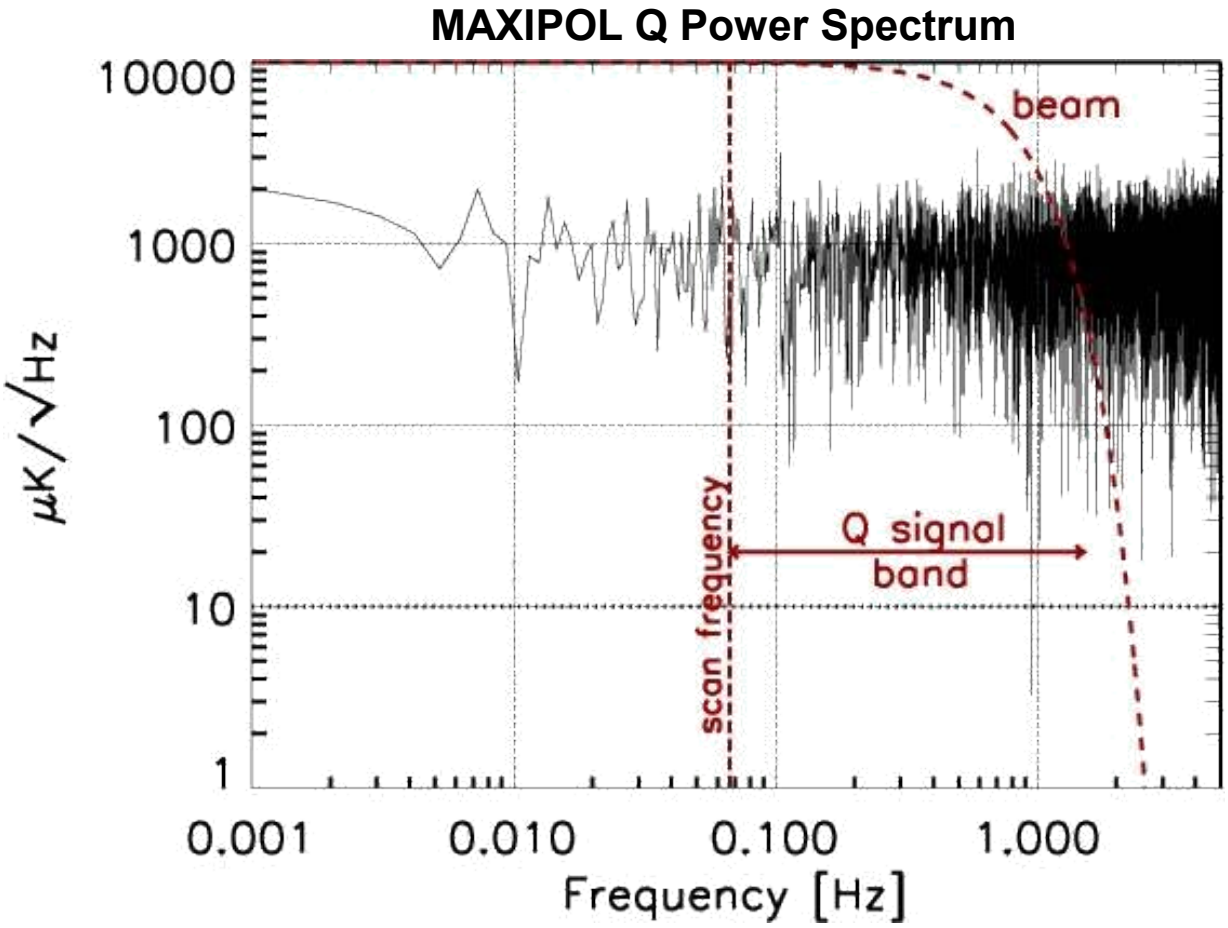
- Lensing B-mode: Reflecting Gregorian Dragone telescope
- Control of sidelobes: Cold aperture stop



- Polarimetry: Half Wave Plate + Grid
- Efficiency : Detection of two orthogonal states

Half Wave Plate Polarimetry

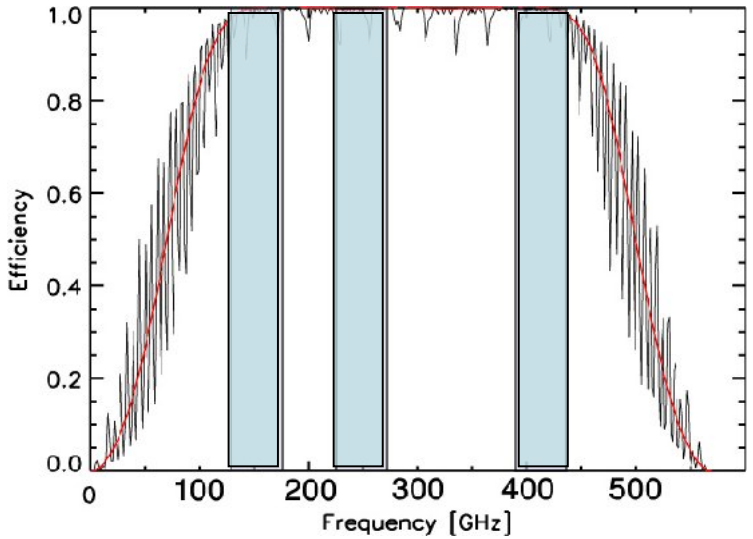
- Modulation via continuous rotating HWP
- Sky signals appear at sidebands of 4*f*
- Signal bandwidth defined by beam size and scan frequency

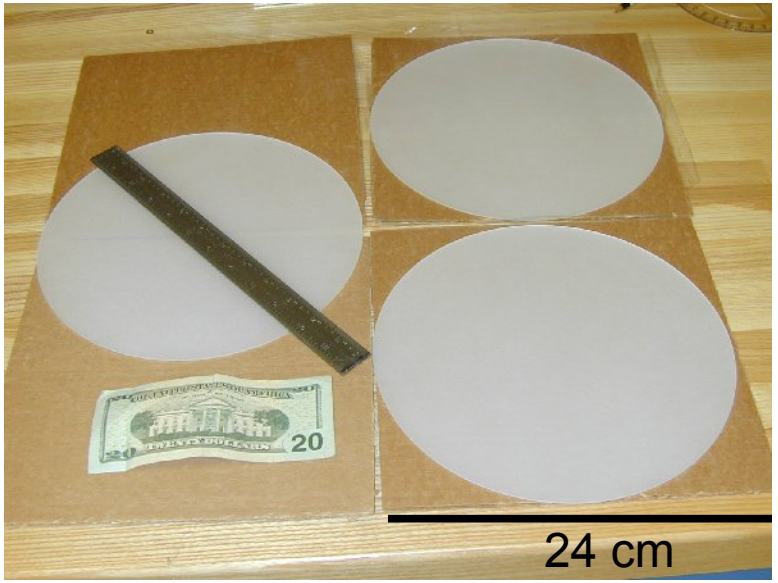


MAXIPOL:
- **Q, U power spectra consistent with white noise to ~few mHz**
- **Level consistent with expected detector noise**

Half Wave Plate Polarimetry

AHWP Modulation Efficiency

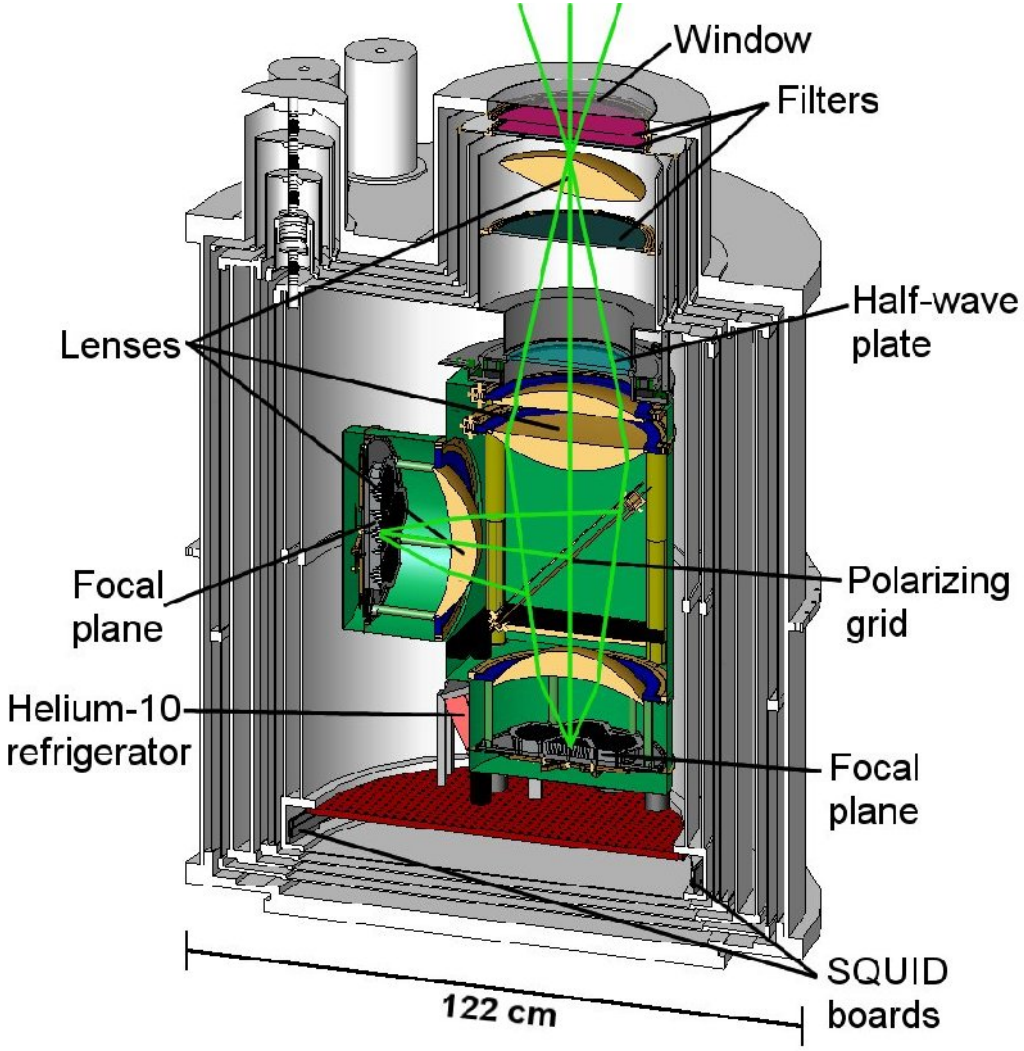




EBEX:
- 5 stack achromatic HWP
- 0.98 efficiency for 120< ν < 420 Ghz
- Rotates at 5 Hz
- Sky signal in ~5 Hz sidebands of $4f$ = 24 Hz

- HWP prototype bonded + thermally cycled
- ARC prototype bonded + thermally cycled
- AHWP now being bonded @ Cardiff
- Superconducting magnetic bearing tested end-to-end

Focal Plane

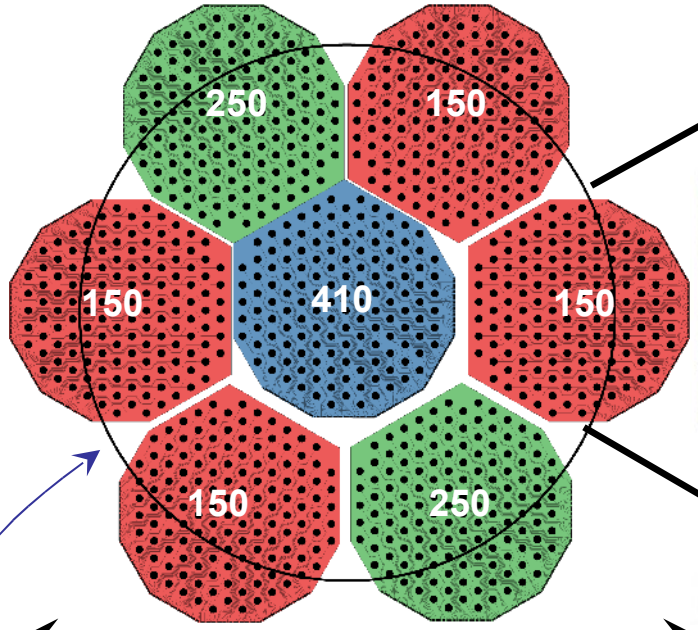

Window
Filters
Lenses
Half-wave plate
Focal plane
Polarizing grid
Helium-10 refrigerator
Focal plane
SQUID boards
122 cm

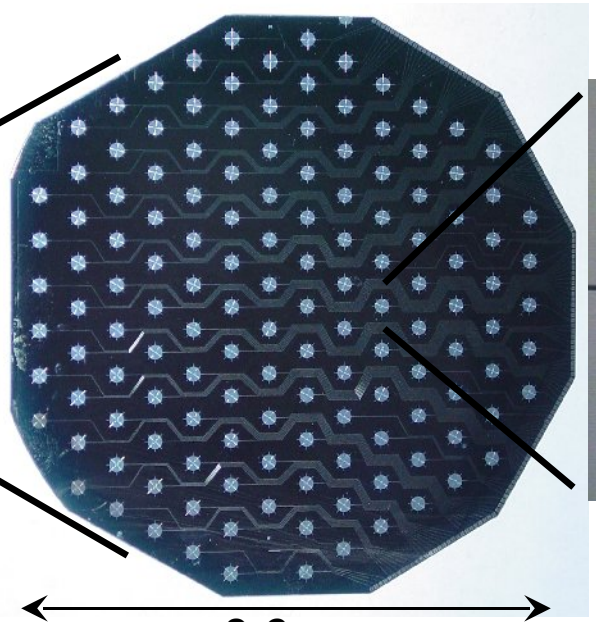
Focal Plane

738 element array

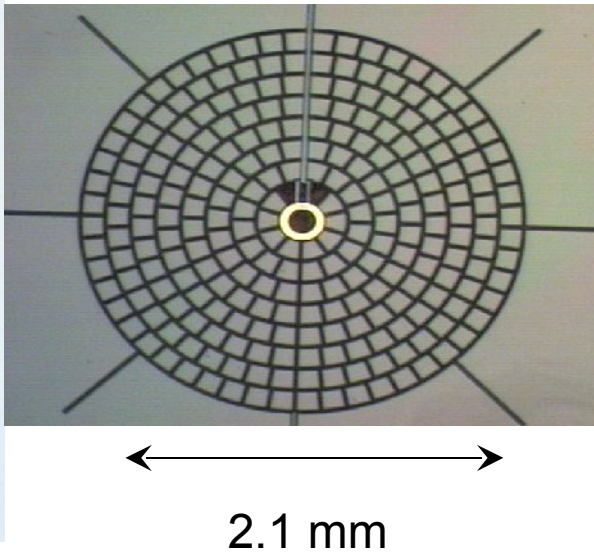
139 element decagon

Single TES





Meng, Lee, UCB



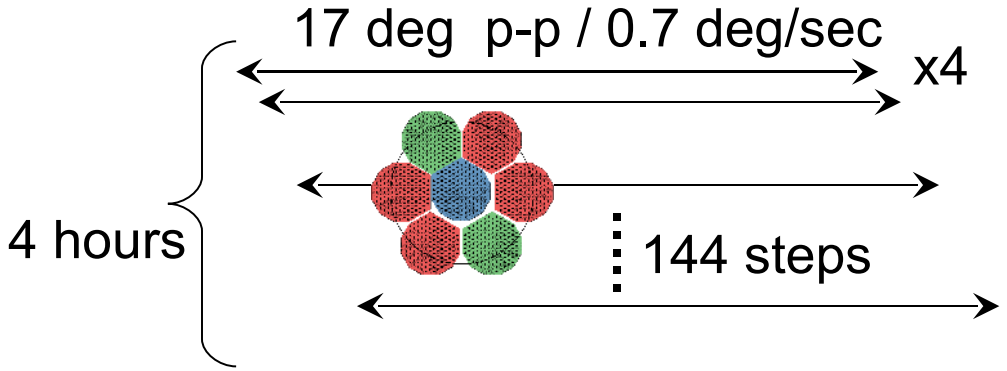
Strehl>0.85 at 250 GHz

- Total of 1476 detectors
- Maintained at 0.27 K
- 3 frequency bands/focal plane

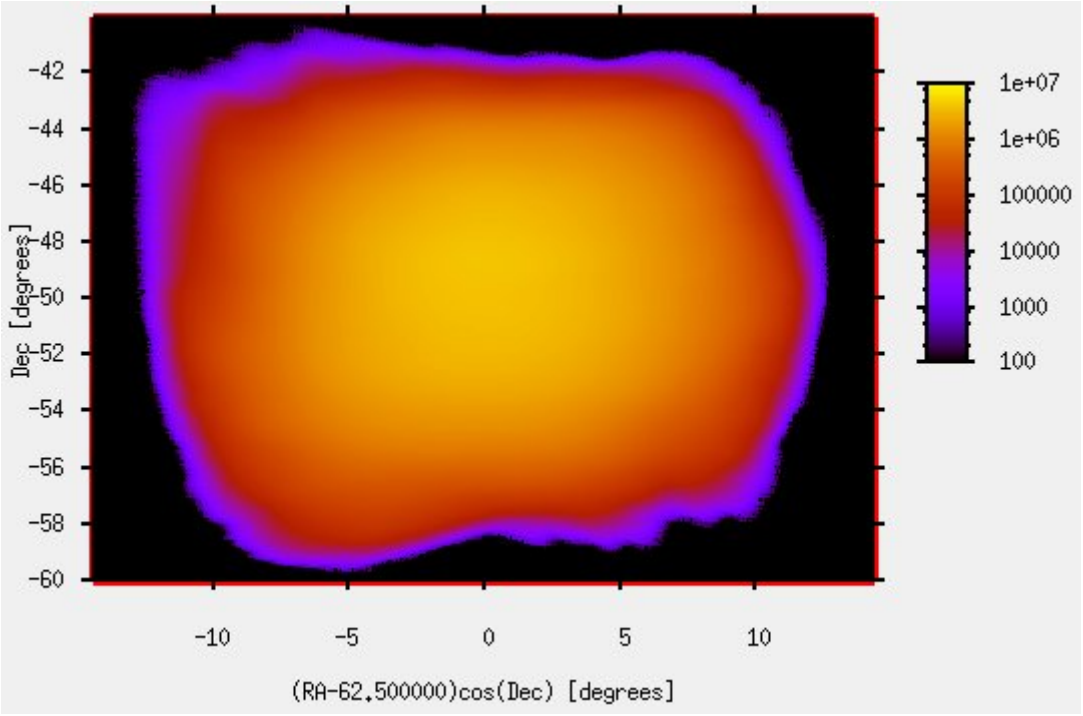
- G = 10 pWatt/K
- NEP = 1.1e-17 W*rt(sec) (150 GHz)
- NEQ = 136 μK*rt(sec) (150 GHz)
- $\tau = 3$ msec,

Scan

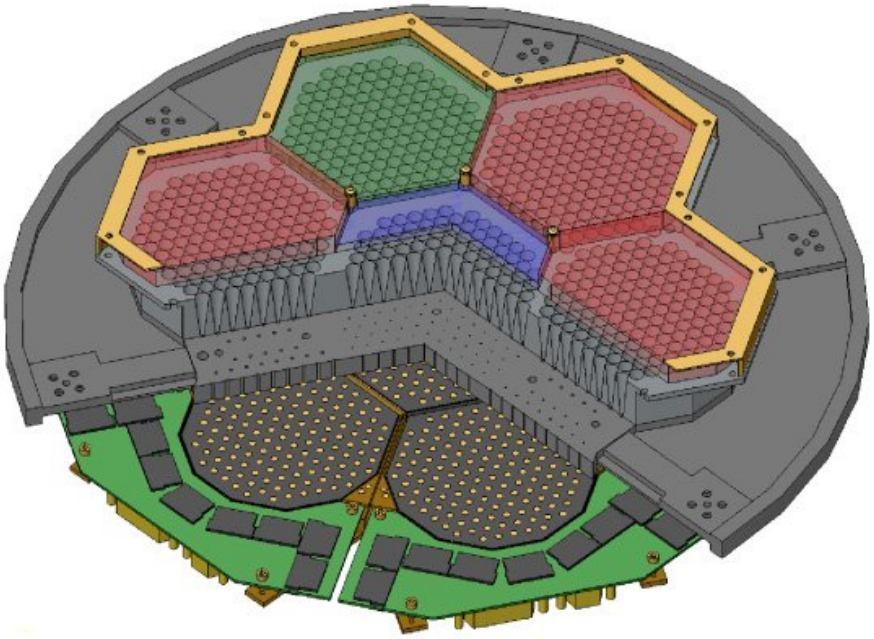
- Total 350 sq. deg
- Constant elevation
- Speed: one Q,U per 1/3 beam
- Multiple visitations per pixel
- **Relatively uniform coverage**
- **Up to 10^8 samples/beam**

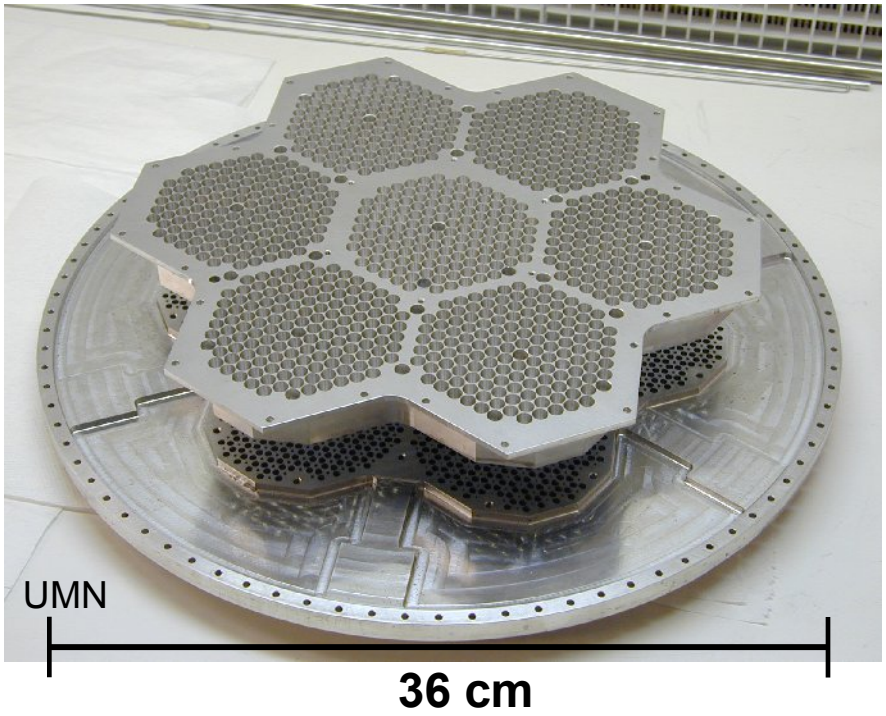


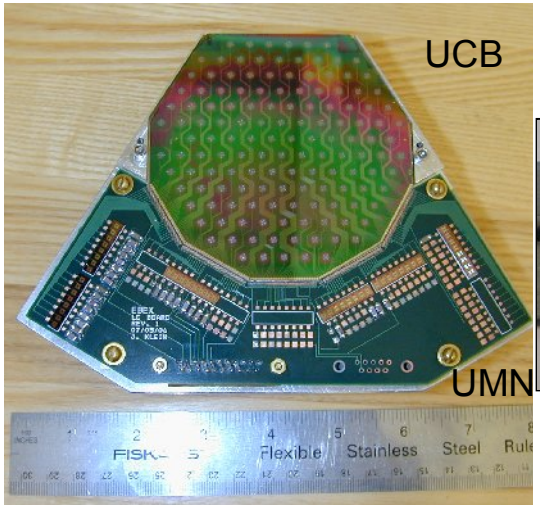
All (796) 150 GHz, 14 Day

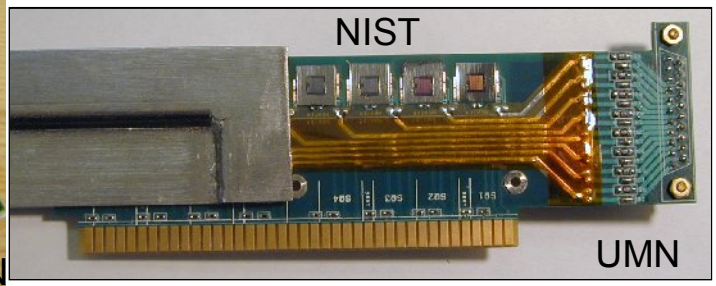


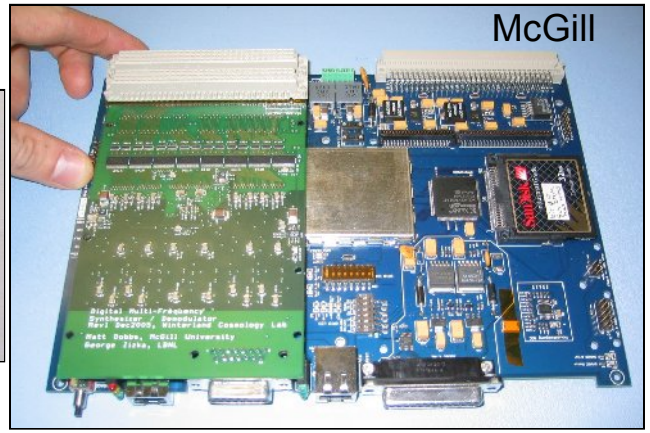
Focal Plane/Readout Assembly



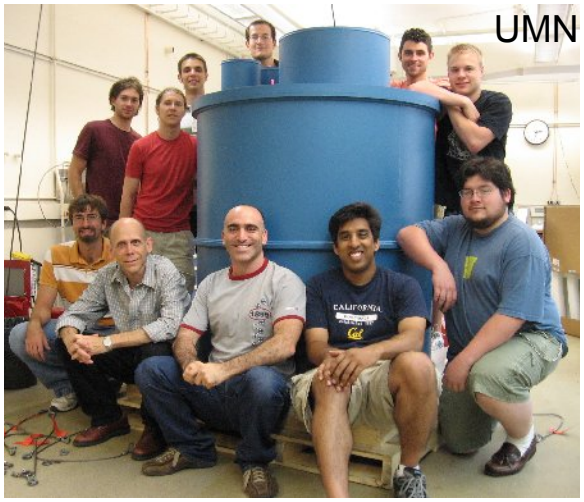




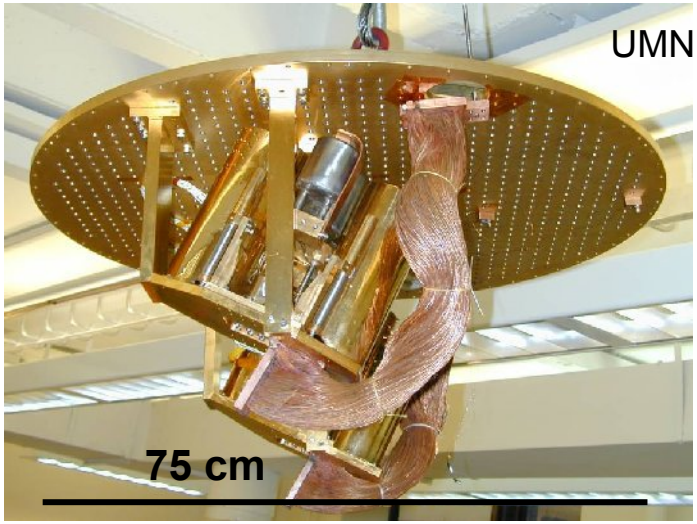


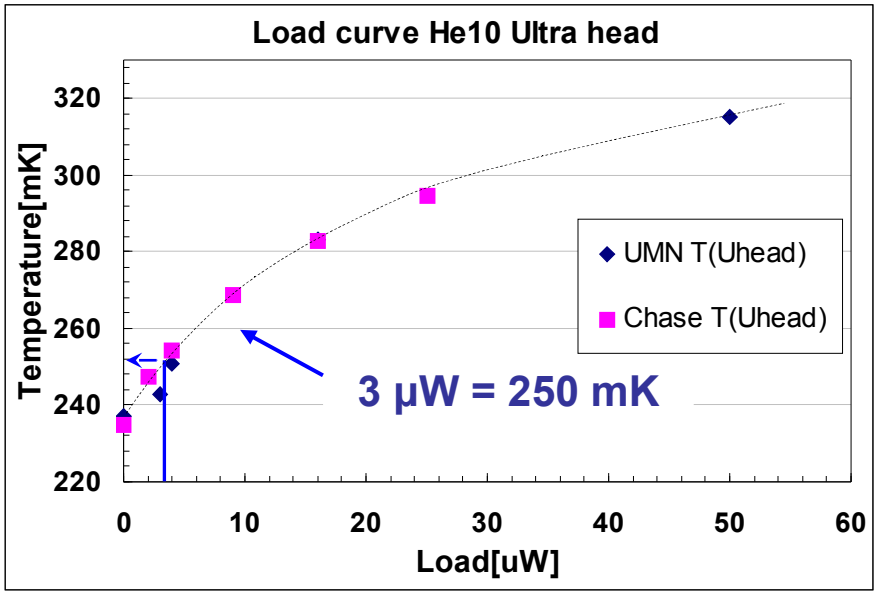


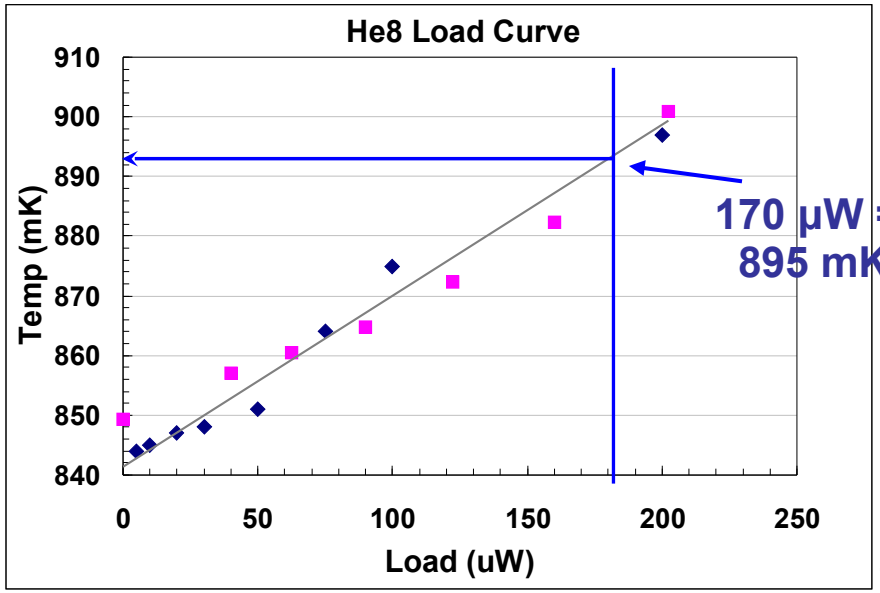
Cryostat, Cryogenics



LN2, LHe loads match design
LN2 hold time = 21 days (measured)
LHe hold time = 20 days (measured)



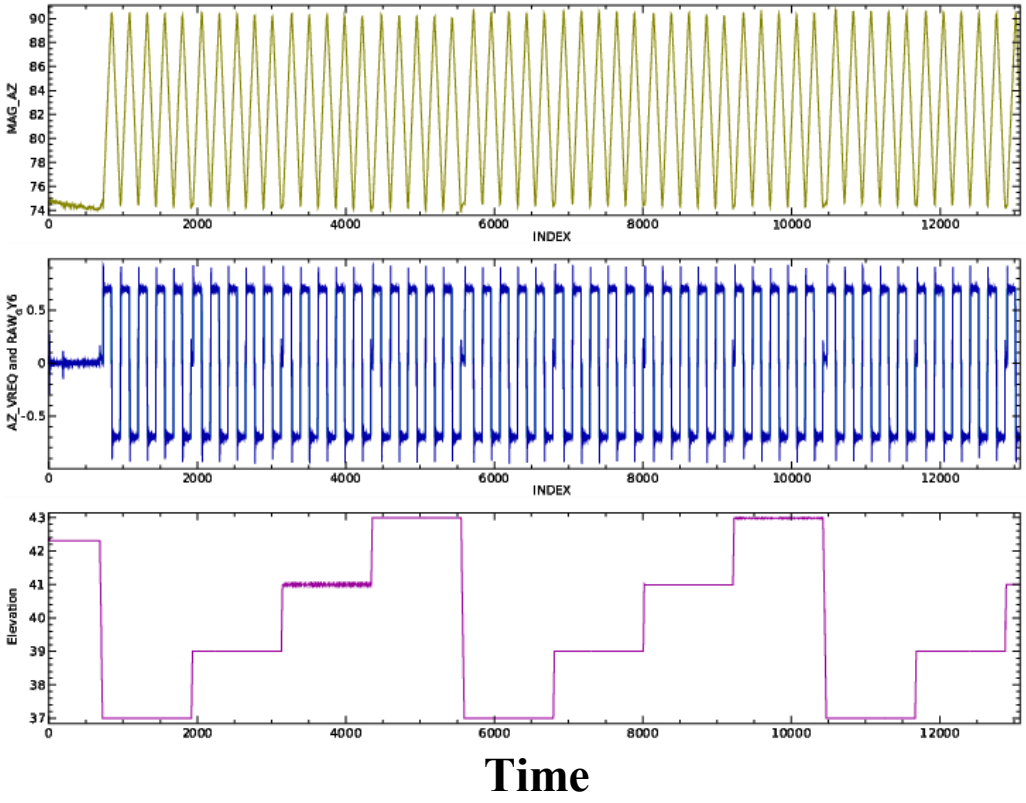




Gondola + Pointing

Cable Suspension (a-la BLAST)
Pointing System (BLAST, MAXIMA, Boom)
Gondola integrated at Columbia U.
Pointing tests ongoing

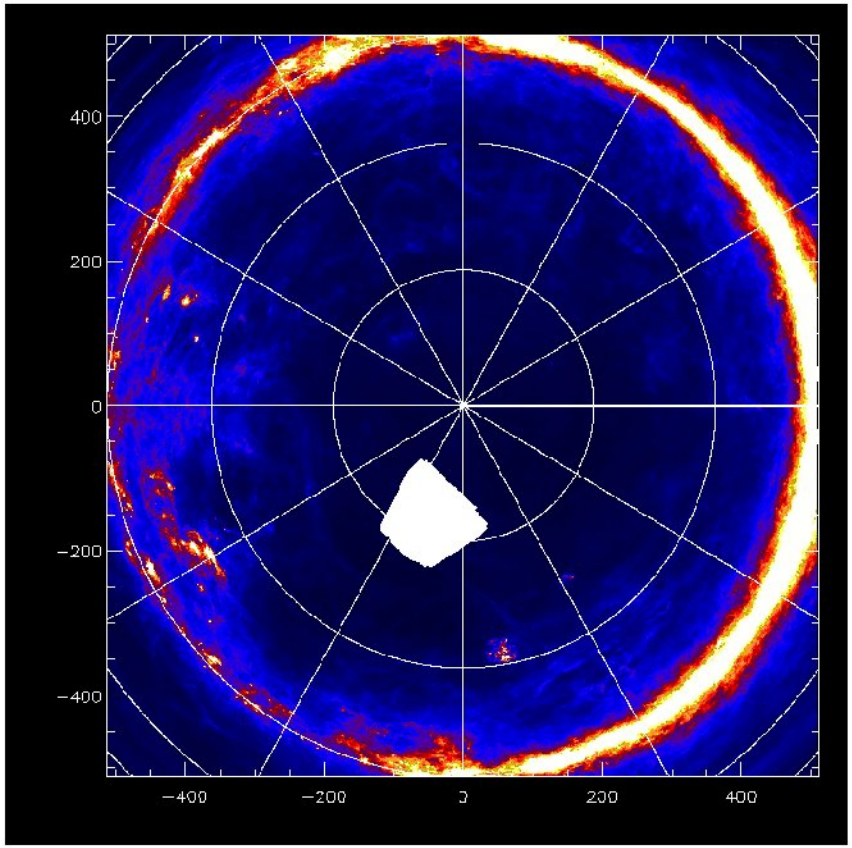
Science Scan Test



Summary + Schedule

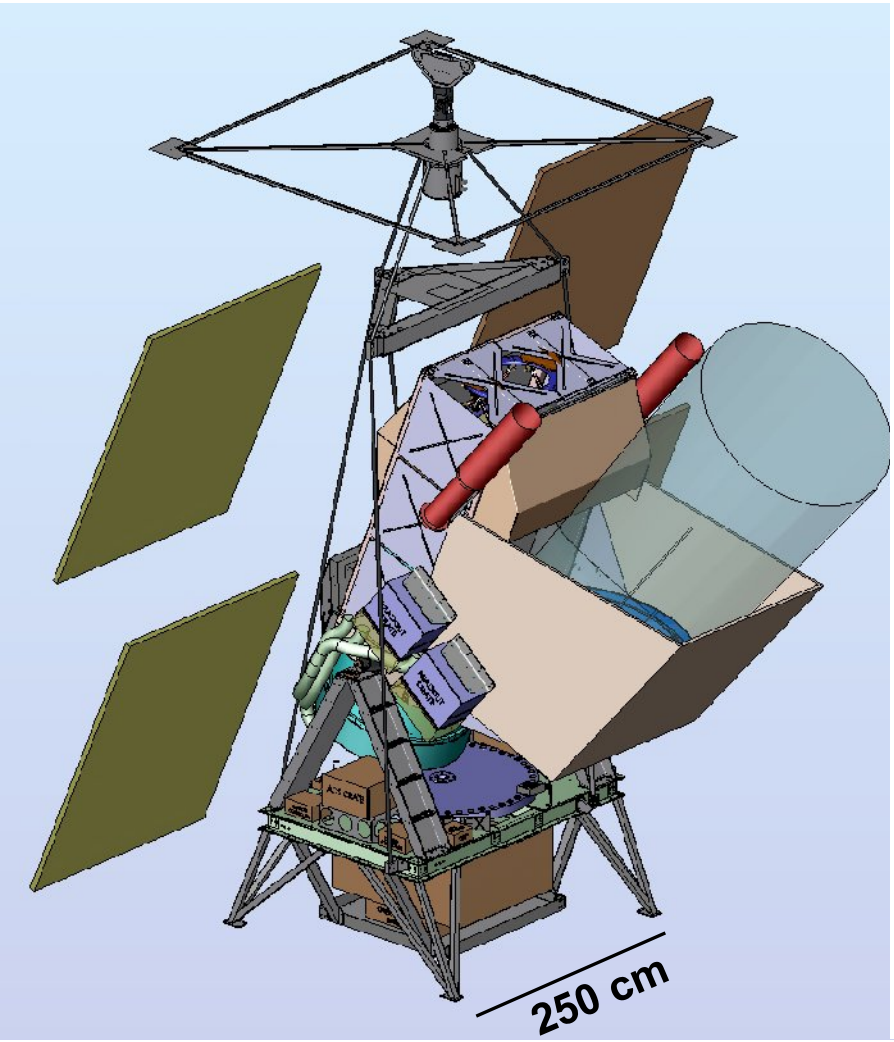
- 14 day flight
- 350 deg^2
- ~20,000 8’ pixels
- Low dust contrast (4μK rms)
- 796, 398, 282 TES detectors at 150, 250 ,410 GHz
- 0.6 μK/8’ pixel - Q/U;

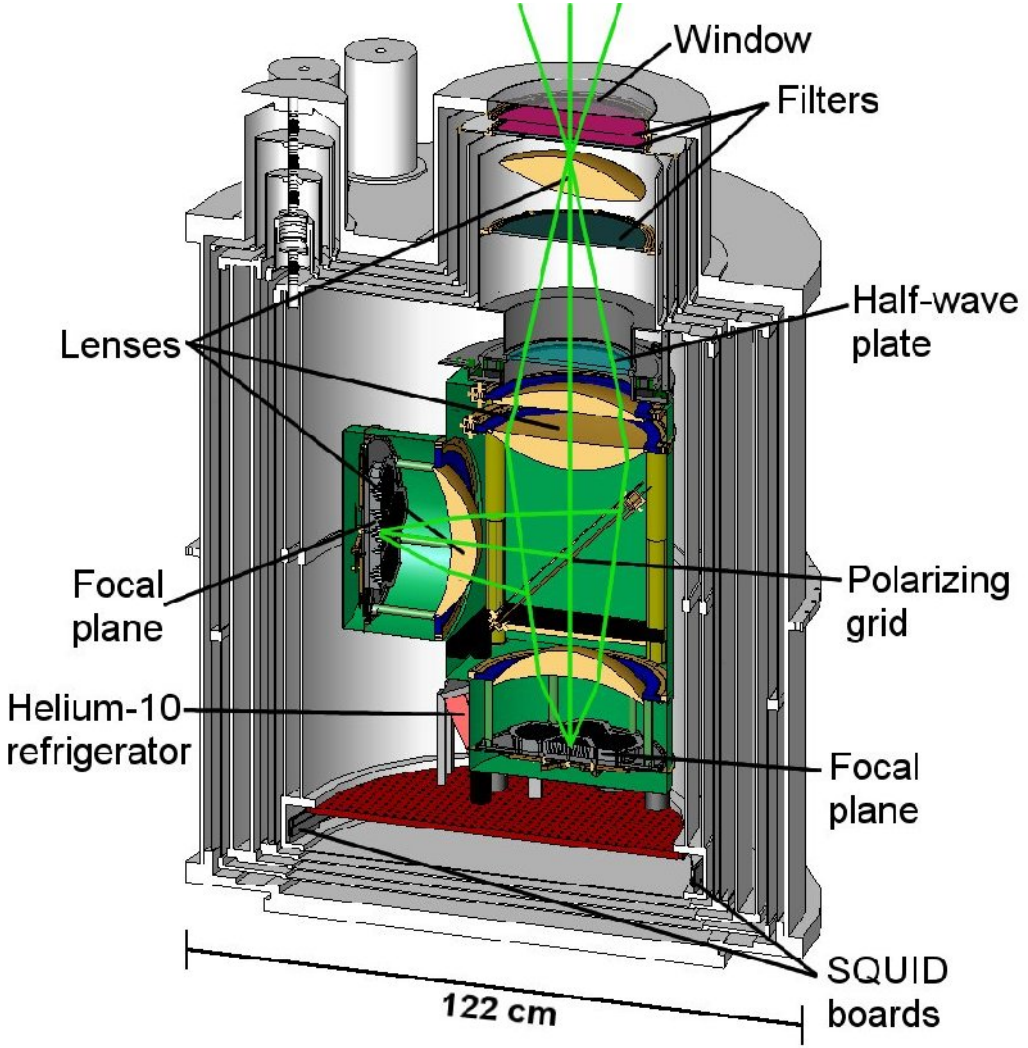
  0.5 μK/8’ pixel – T
- North American flight: 2008



Extra Material

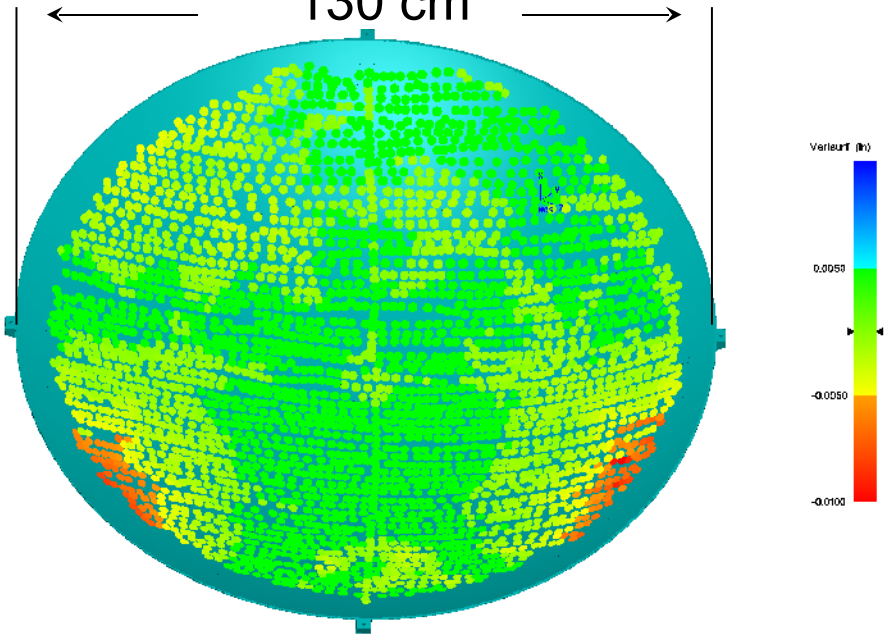
Design


250 cm

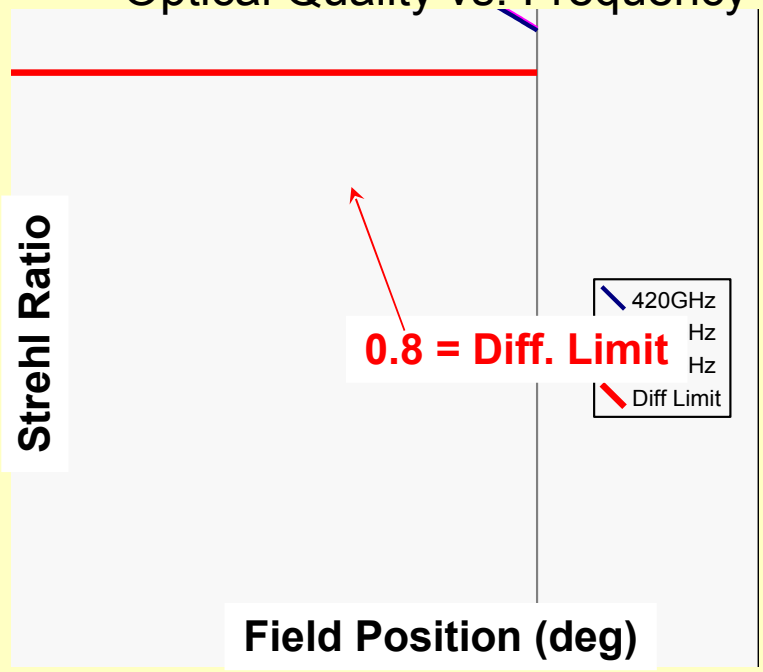

Window
Filters
Half-wave plate
Lenses
Focal plane
Polarizing grid
Helium-10 refrigerator
Focal plane
SQUID boards
122 cm

Optics

130 cm



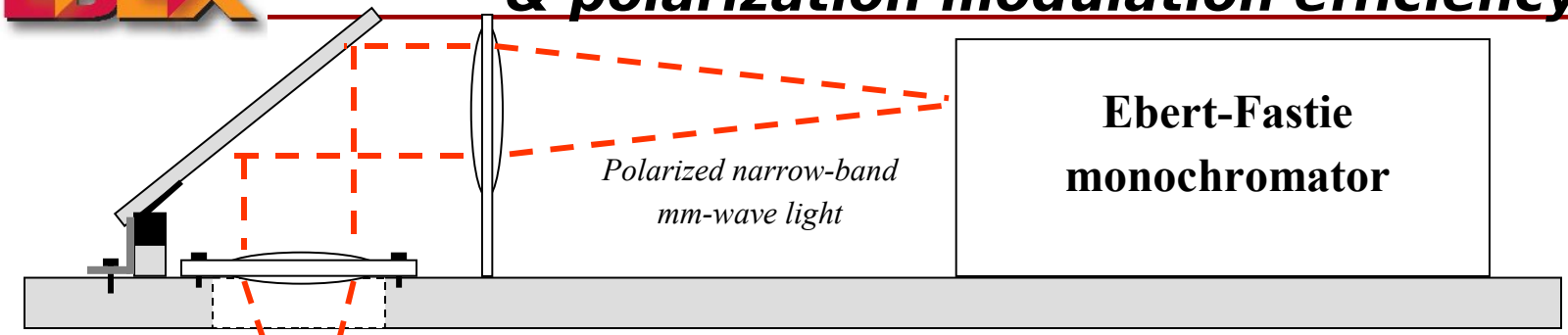
Measured RMS Figure < $\lambda_{420}/14$



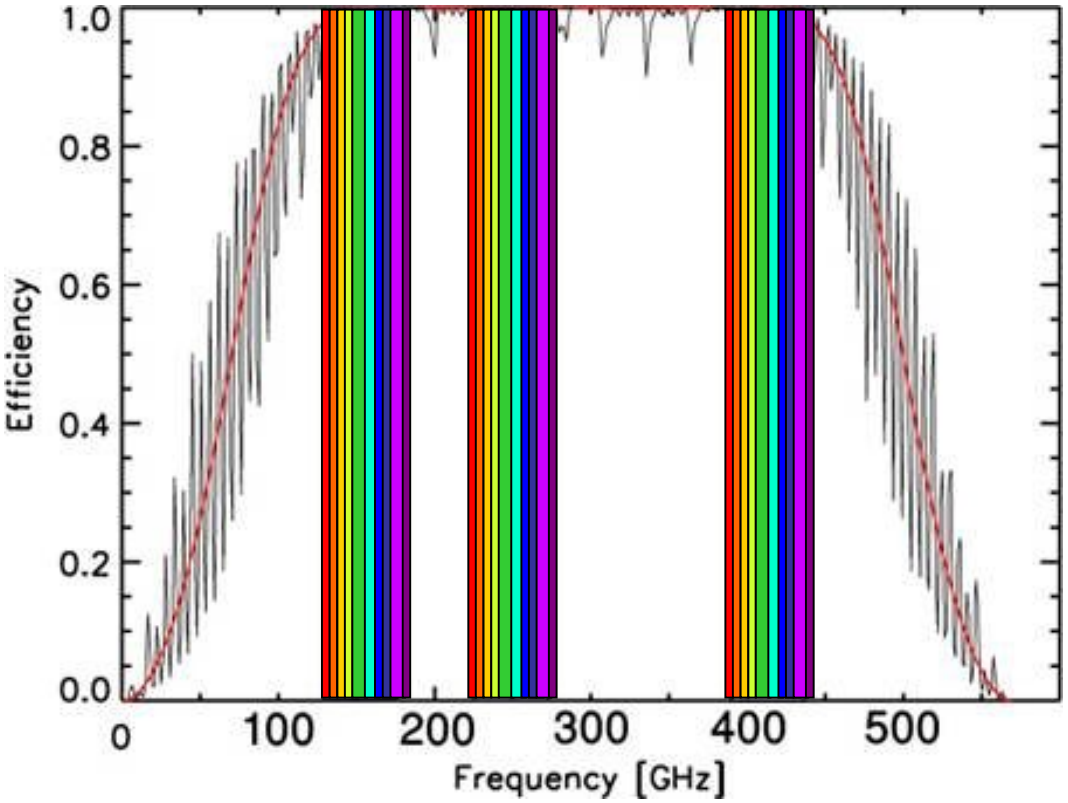
Over 6 Deg FOV

- 0.9 Strehl for 150 GHz
- 0.85 Strehl for 250, 420 GHz

Ground-based: relative polarization spectral response & polarization modulation efficiency



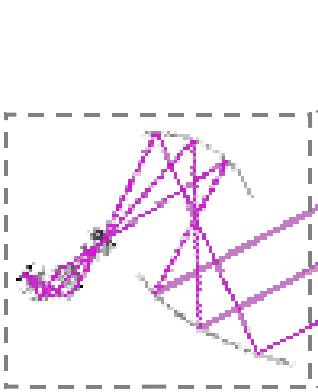
10 sub-bands per channel



Ground-based: antenna response (beam mapping), polarization rotation, coarse instrumental polarization

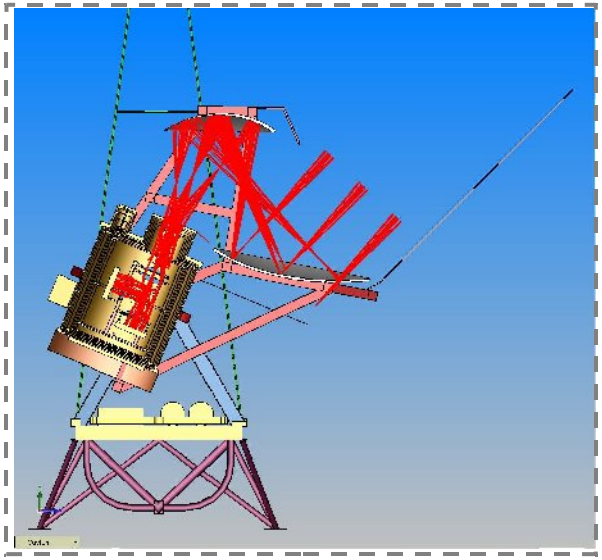
1.8 meter parabolic mirror on loan from BLAST

- surface quality
- beam size
- cost savings



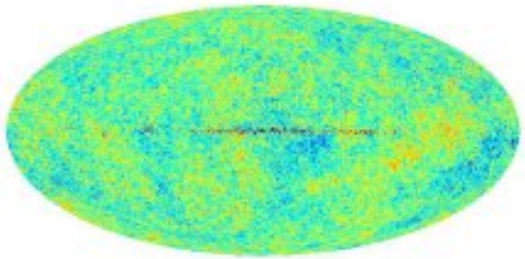
EBEX gondola

Mapping beam: scans source just like in-flight scan on sky

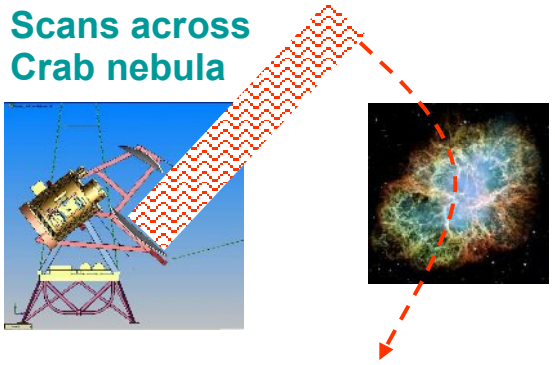


In-flight calibration: verifying ground-based measurements + absolute polarization spectral response

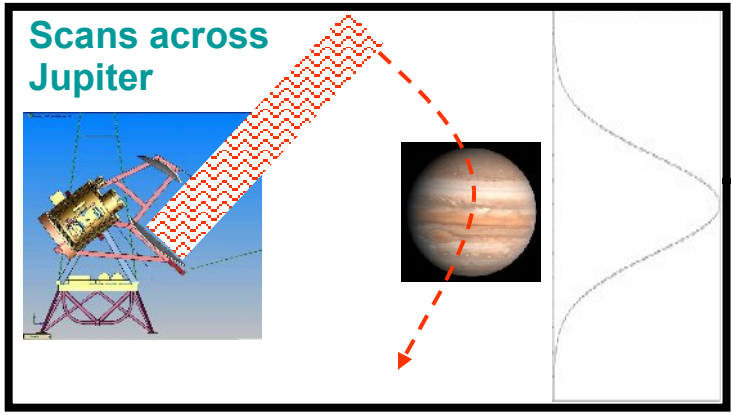
Comparison to WMAP temperature maps in EBEX scan area



Scans across Crab nebula

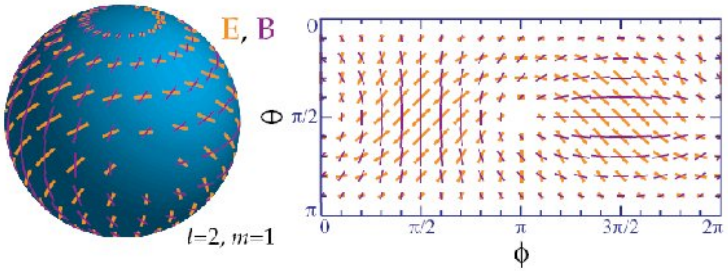


Scans across Jupiter

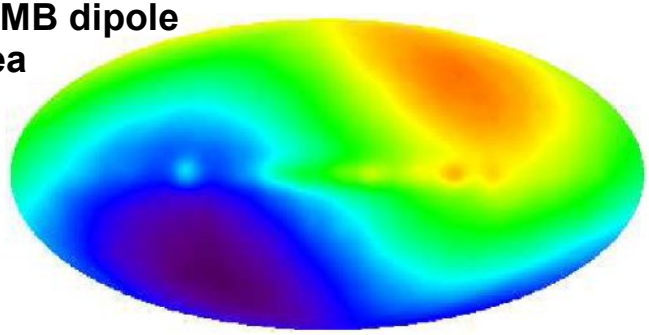


1. Absolute spectral response @ 150, 250 GHz
3. Polarization modulation efficiency
5. Beam map, absolute calibration @ 410 GHz
7. Instrumental polarization
9. Polarization rotation (a.k.a. cross-polarization)

Null correlation between E & B modes in EBEX data

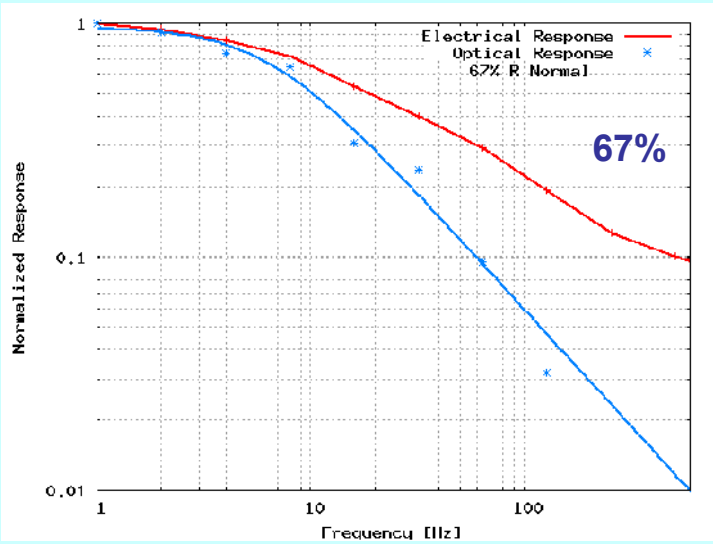


Comparison to CMB dipole in EBEX scan area

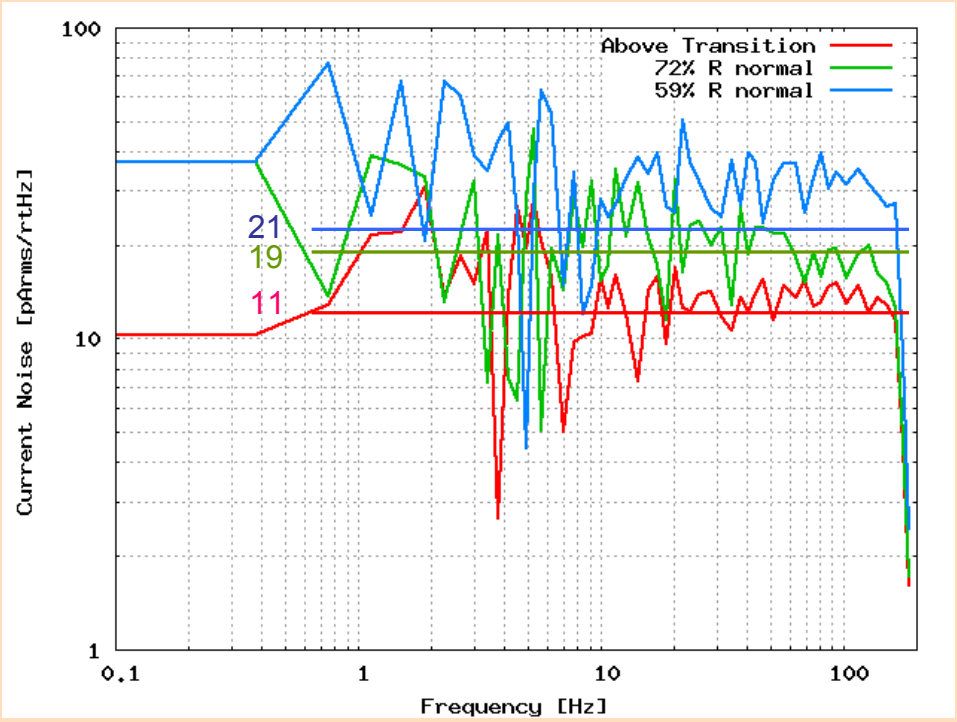


Time Constant, Noise, G

Thermal Conductance:
- Removed metallization; Changed geometry
- G_{target} = 30 pWatt/K
- $G_{measured}$ = 20, 23, 30, 80 pWatt/K



16 msec time constant (@50%) limited by TES heat capacity => reduce heat capacity (remove bling)

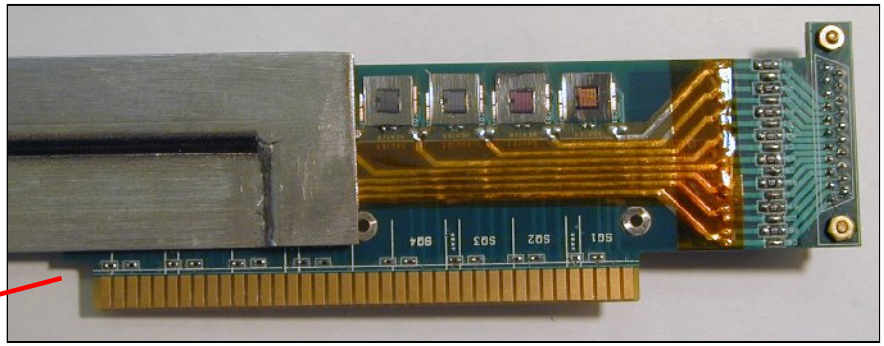


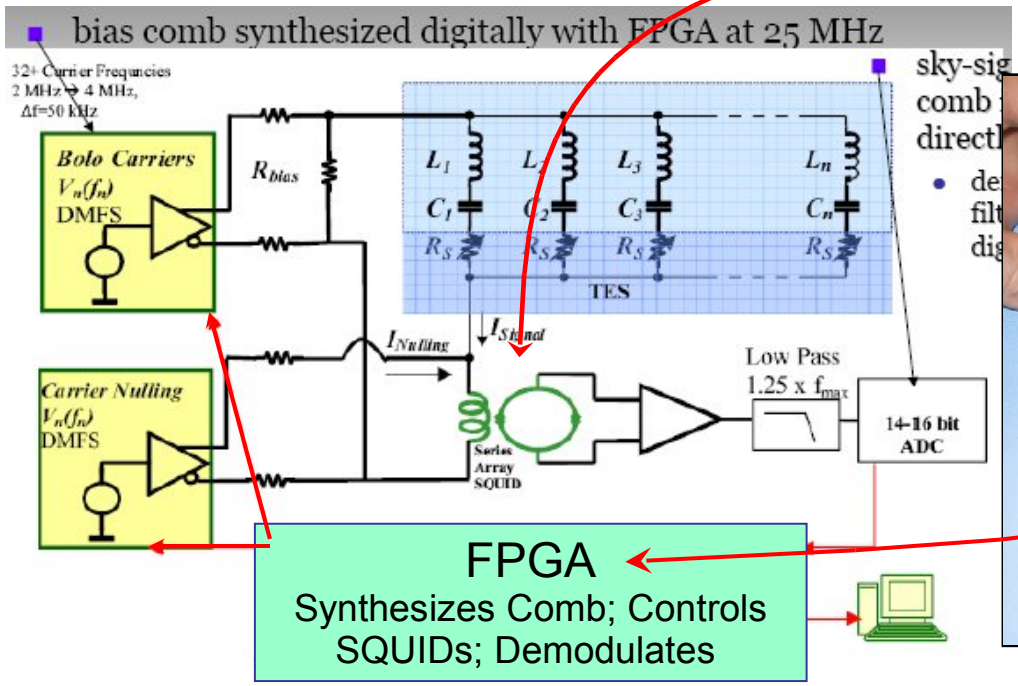
DFMUX noise < SQUID noise
SQUID Noise < Johnson noise

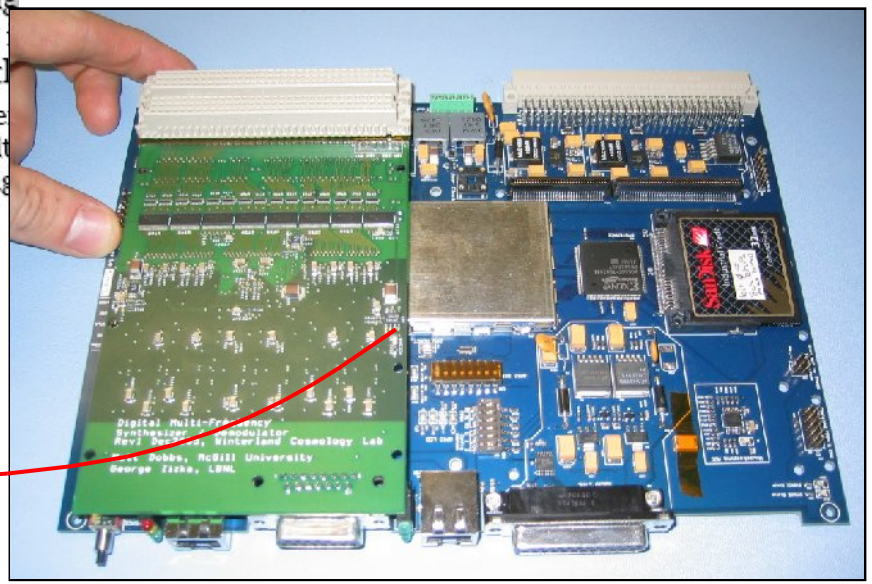
~x1.5 excess phonon noise (@~50%) under investigation

Detector Readouts

- SQUID arrays (NIST)
- Digital Frequency Domain Multiplexing (McGill)



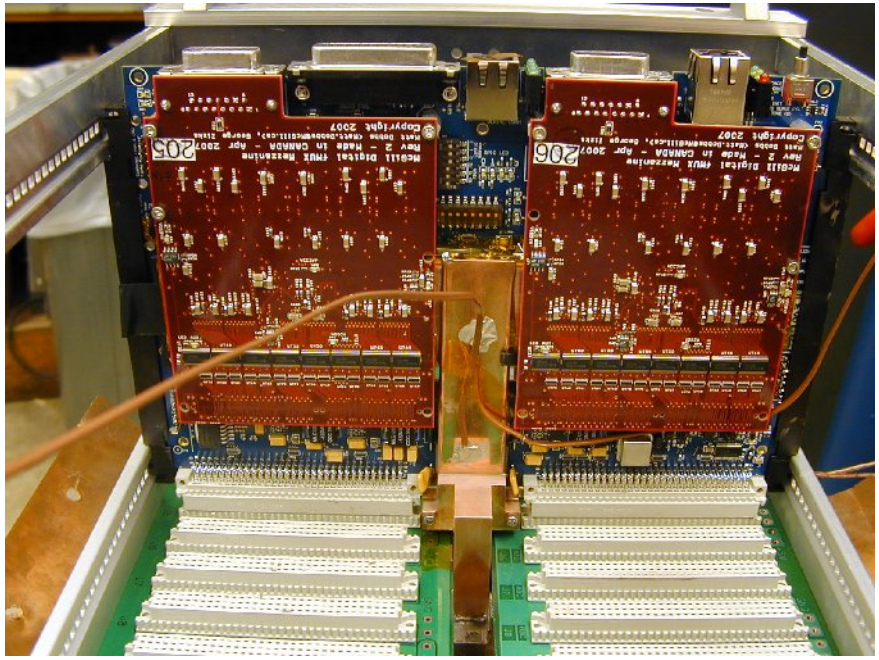


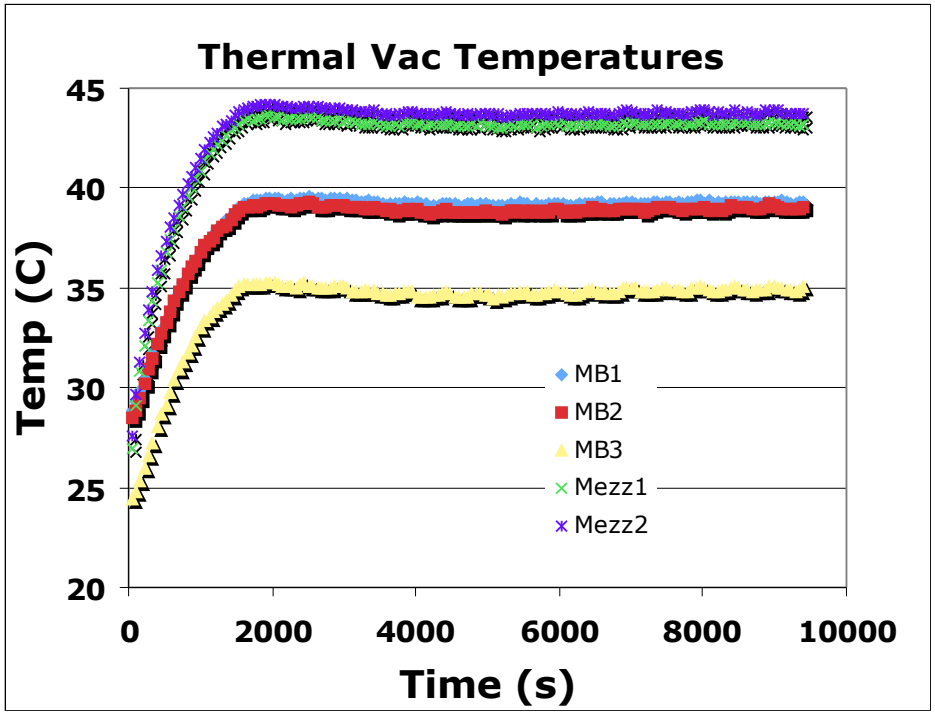


- LDB: 495 Watt for x12; 406 Watt for x16

Readout Thermal Design

- Measured 18.5 Watts/board
- Total of 495 Watt for LDB
- Flat heat pipes to conduct heat
- Constructed thermal model
- Tested heat sinking
- Baseplate at 17 C
- Results match simulations
- Warmest temperatures 43 C

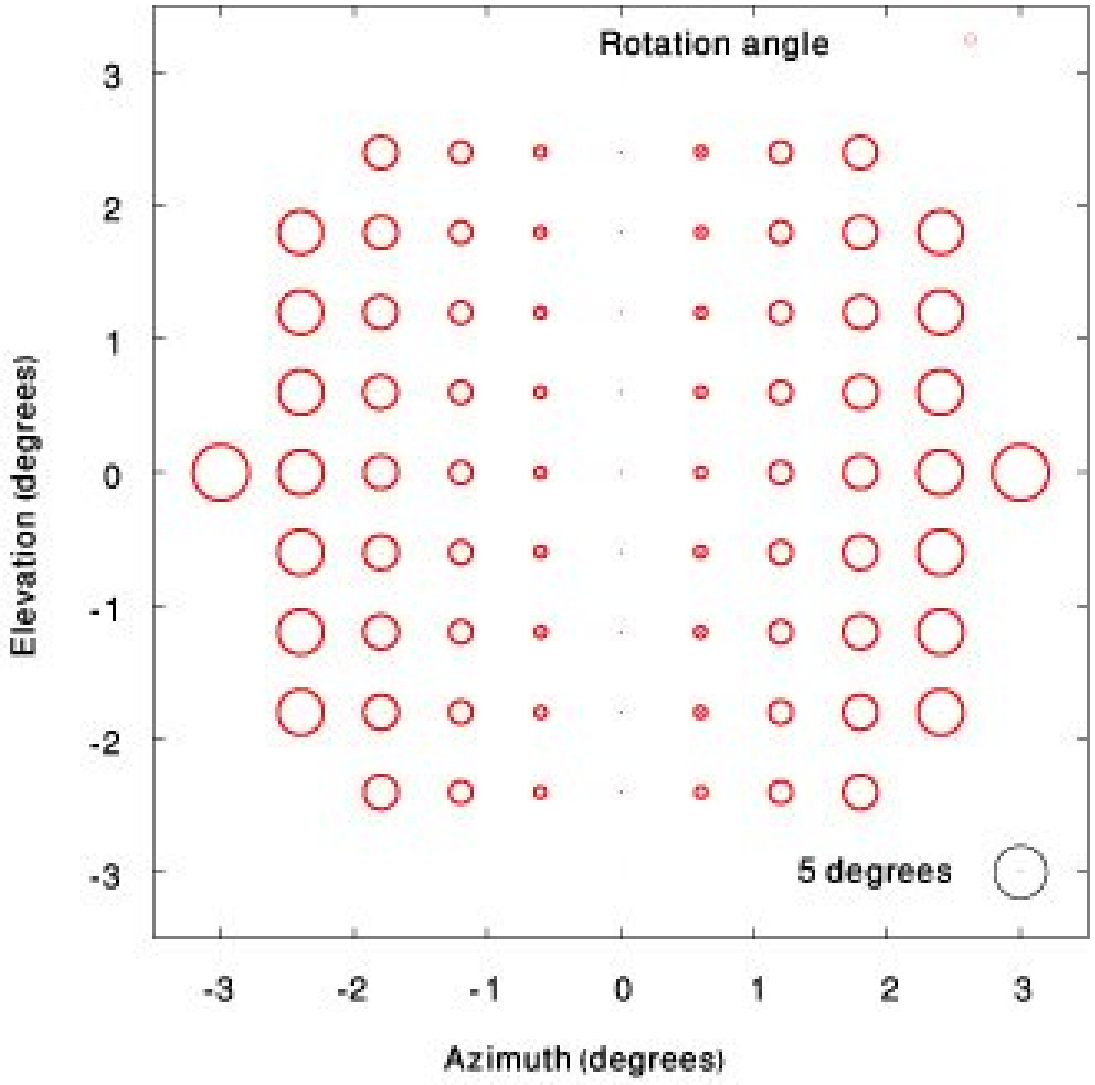




Pathfinder for a Space Mission

- Detectors at low backgrounds
- Readout (low power DfMUX)
- Information about Foregrounds
- Information about Systematics

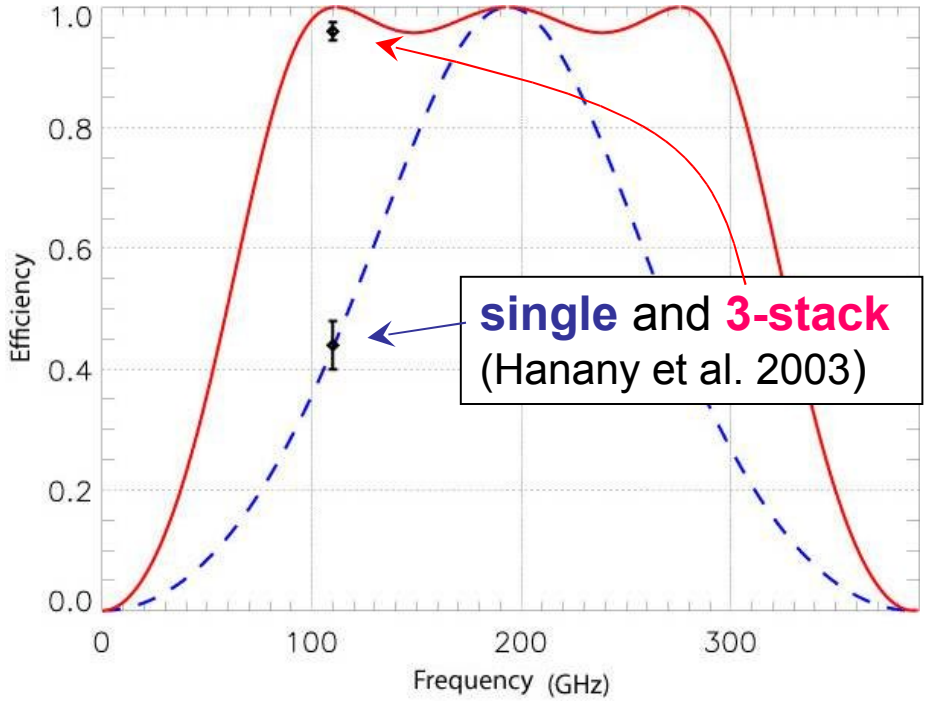
Polarization Rotation

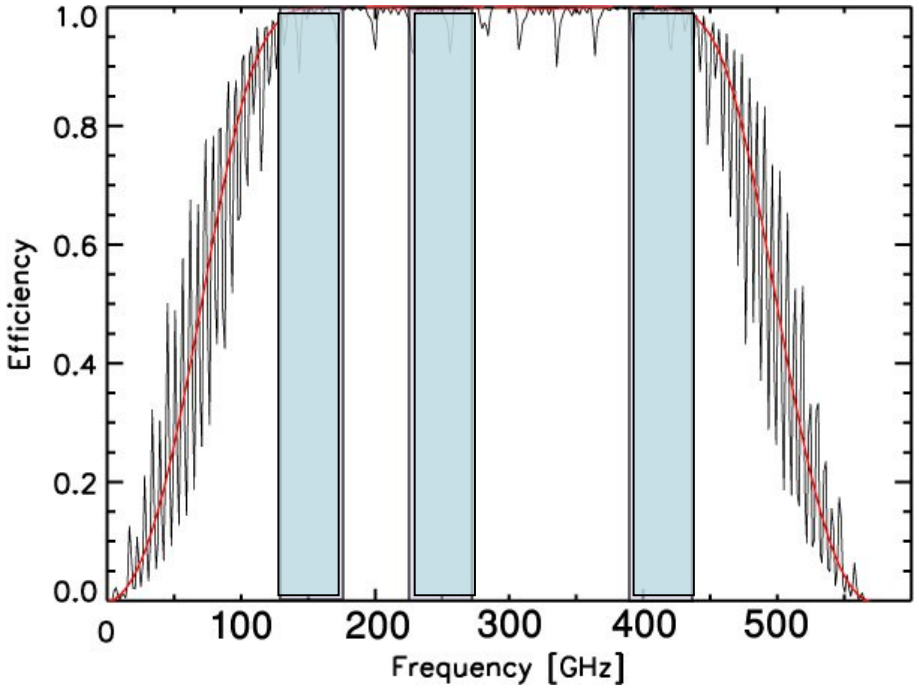


EBEX Half Wave Plate Polarimetry

- Half Wave Plate demonstrated successfully on MAXIPOL

- EBEX: 5-stack achromatic HWP; 0.98 efficiency for $120 < \nu < 450$ GHz





- Rotate at 6 Hz
- Signal at 24 Hz
- <10% attenuation from 3 msec time constant TES