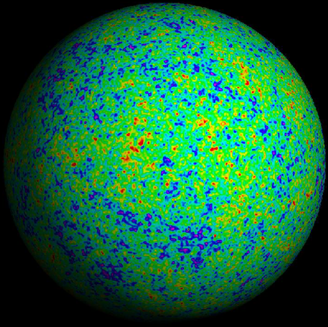
Survey of CMB Polarization Experiments

Clem Pryke

IUCAA Lectures - Pune India

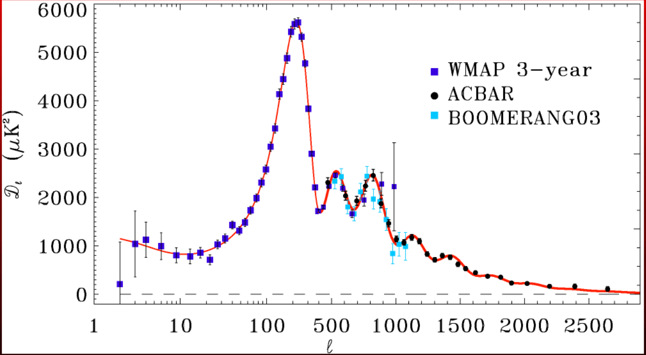
4 August 2008

Temperature Anisotropy of the CMB



CMB T is a sample of the density structure on a shell cut through the 400,000 year old Universe.

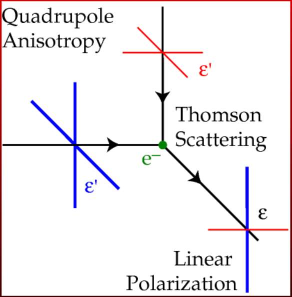
Current Total Intensity (T) Results



From Reichardt et al, astro-ph/0801.1491

Beautiful confirmation of predicted acoustic oscillations in plasma...

Polarization by Thompson Scattering



- If electrons are exposed to incoming radiation which has a quadrupole moment the re-radiated light will be (partially) polarized.

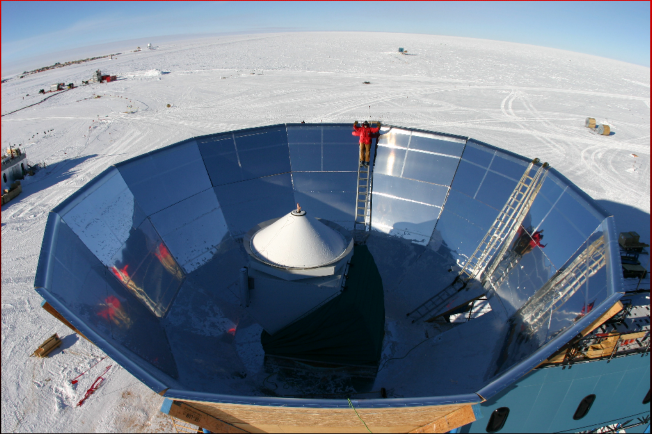
"First Order" Polarization of the CMB

- Density perturbations at last scattering produce T anisotropy.

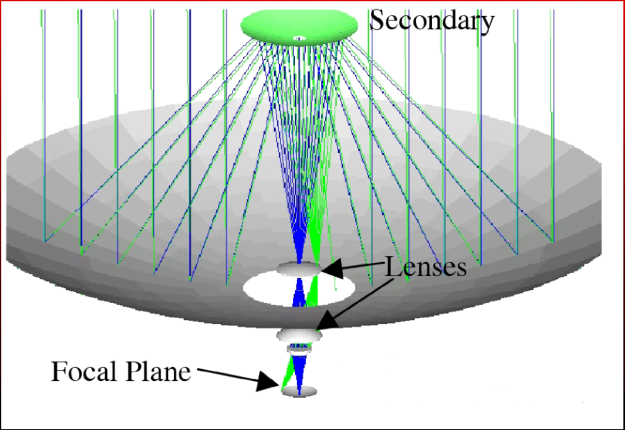
- Material flowing along gradients in the density field
  - Resulting polarization pattern aligned with its gradient (E-modes) and has zero curl (B-modes).
  - Since density perturbations produce the motions there is TE cross correlation.

- Given T spectrum and standard cosmological model can predict expected E and TE spectra.
  - ...if measurements don't match the whole framework falls apart! - Critical test!

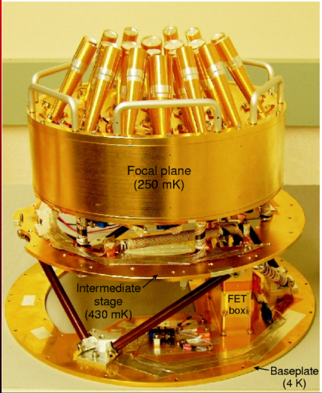
QUaD at South Pole Feb 2005



Optical Path

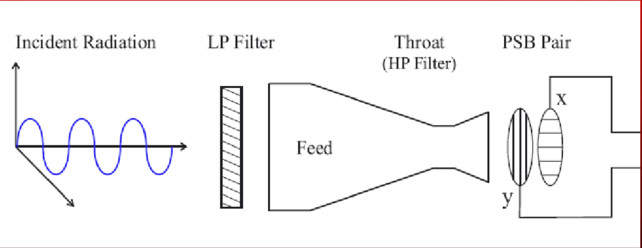


Receiver Focal Plane



12 feeds @ 100GHz (6 arcmin), 19 @150GHz (4 arcmin)

Polarization Sensitive Bolometers



- Two orthogonal absorber grids read out independently
  - Sum measures total intensity
  - Difference measures polarization
- 12 pairs @ 100GHz, 19 pairs @ 150GHz

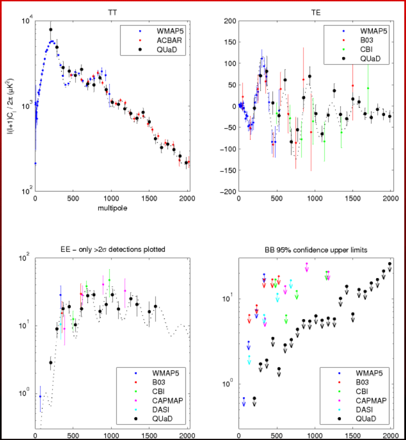
How QUaD Works

- Bolometer temperature coupled to temperature of incoming radiation from small "spots" on the sky

- Whole telescope moves (scans), sweeping the set of pencil beams around on the sky

- We read out the *changing* bolometer temperature as a function of pointing position - called timestream data...
  - any change in bolometer temperature appears in readout...
    - need an outrageously stable system!

Current Status of Polarization Results



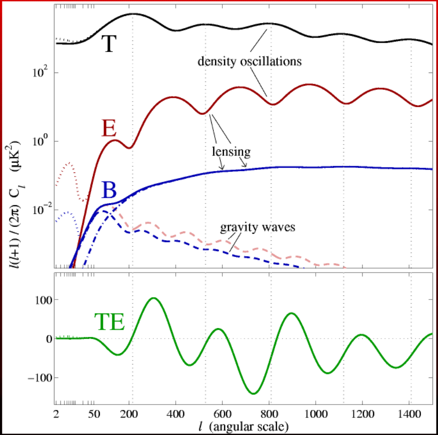
"Second Order" Polarization of the CMB

- Lensing by large scale structure between last scattering and us distorts the polarization pattern...
  - mixes E into B to a small extent.
    - Called "Lensing B-modes"

- Gravity waves propagating through the primordial plasma add to all spectra...
  - based on existing T data we know contribution small.
    - Called "Gravity Wave B-modes"

- When Universe re-ionizes additional scattering occurs
  - generates extra large scale anisotropy.
    - Called "Re-ionization Signature"

Location of Polarization Effects



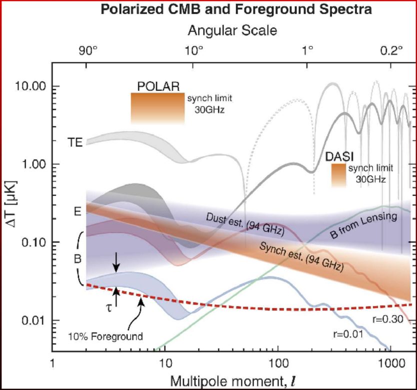
Why Make Further Measurements?

- At $l>150$
  - Refine measurements of E and TE to further test paradigm
  - Try to detect lensing B to get info on neutrinos and dark energy
- At $30<l<150$
  - Try to detect gravity wave B
- At $l<30$
  - Refine measurements of E and TE to constrain re-ionization
  - Try to detect gravity wave B

How Much Sky is Needed for Grav B?

- It depends on the ell you wish to measure!
  - With limited sensitivity it is highly inefficient to measure the full sky
- To obtain a detection we should concentrate all our sensitivity on the smallest possible patch of sky
  - The size of this patch is then determined by the minimum ell we wish to measure
- The lowest ell's require the full sky...
  - ...which means going into space...
  - ...but even there much of the sky is corrupted by foregrounds...
- But can target the $l=70$ gravity wave bump using order 600 sq deg patch from the ground

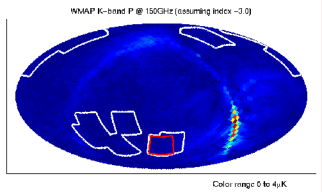
Foregrounds?

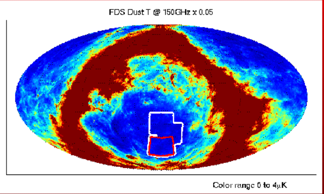


Beware - these plots assume large fractions of the sky!

CMB Task Force Report Figure 4.2

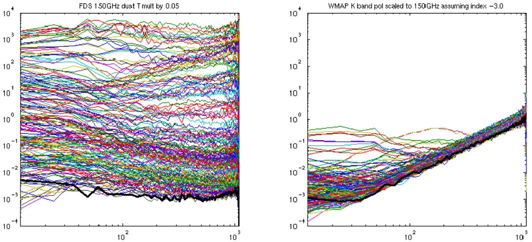
Cleanest Sky Regions





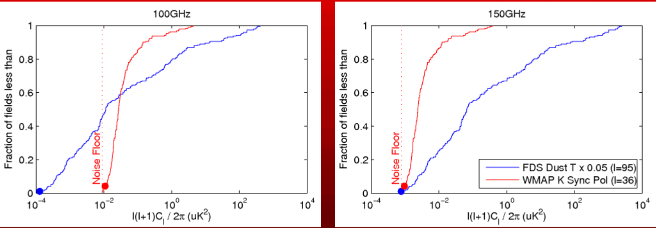
- We wish to find the cleanest sky regions, and how clean they actually are
- Available data is limited:
  - For dust use FDS map and assume 5% polarization
  - For synchrotron use WMAP K-band polarization maps, and assume spectral index of -3
- Take set of 192 equally spaced points on the sky and pull out a 30x30 deg square maps centered on each (healpix ring nside=4 pixel centers).
- Appodize and take the power spectra

Power Spectra



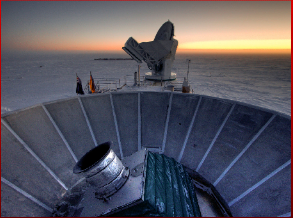
- Dust varies by 7 orders of magnitude across the sky
- WMAP sync maps are noise dominated except at lowest ell
- Read off the value of these curves at some ell and look at the integral distributions...

Foreground Avoidance



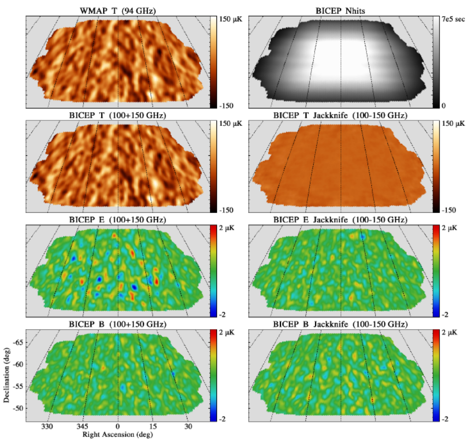
- For cleanest regions best frequency is 150GHz
- Foreground level in these regions is around 0.001 uK^2
- This is comparible to gravity wave signal for r=0.01
  - We can get down to this level without foreground removal!

QUaD's Sister - BICEP



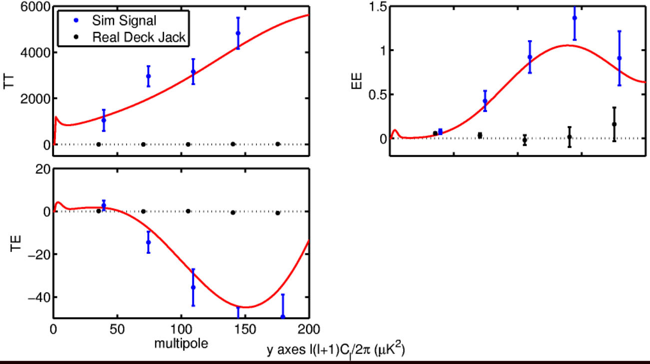
- First experiment to optimize for gravity B detection - refracting "telescope in a can" for excellent systematic control, modularity and low cost
  - all cold optics and black fore-baffle
    - super low sidelobes
  - downside is big beam - 0.9/0.6 deg @ 100/150GHz
- Three years of data in the can and under analysis

BICEP Maps



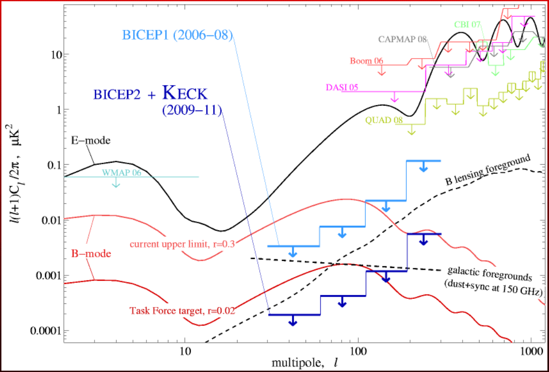
WMAP T (94 GHz)
150 μK
-150
BICEP Nhits
7e5 sec
0
BICEP T (100+150 GHz)
150 μK
-150
BICEP T Jackknife (100-150 GHz)
150 μK
-150
BICEP E (100+150 GHz)
2 μK
-2
BICEP E Jackknife (100-150 GHz)
2 μK
-2
BICEP B (100+150 GHz)
2 μK
-2
BICEP B Jackknife (100-150 GHz)
2 μK
-2
-65
-60
-55
-50
Declination (deg)
330
345
0
15
30
Right Ascension (deg)

Sim and Jackknife BICEP Spectra



Early days and looking good…(Caltech Post-doc Denis Barkats)

The Quest for Gravity Wave B-Modes



Health warning: theorists refuse to say how small this signal may be!

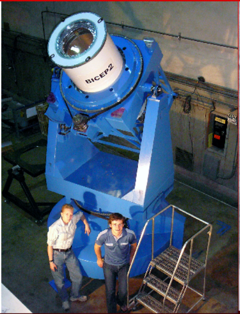
Future Experiments

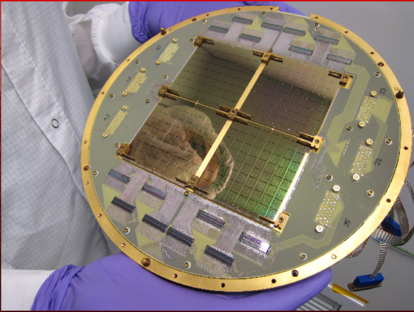
- Gravity wave B is very exciting science
  - Many experiments are going after it!

- Ground based:
  - BICEP2 / Keck array
  - QUIET
  - Clover
  - Polarbear
  - SPTpol
  - (Also MBI, Poincare, ABS...)

- Balloon:
  - EBEX
  - SPIDER

BICEP2 Under Construction

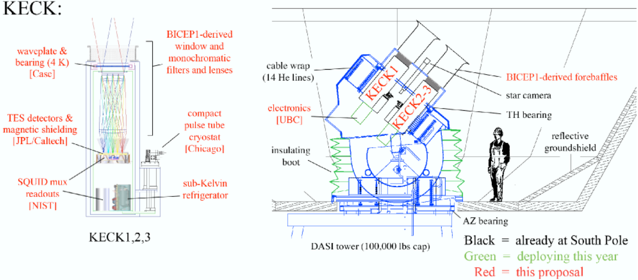




256 dual pol pixels (antenna coupled)

B-mode Array on the DASI Platform

KECK:



- First pulse tube receiver on DASI platform fall 2009
  - Funded by NSF
- Another three fall 2010
  - Proposed to Keck Foundation
- Ultimately six at a mix of frequencies

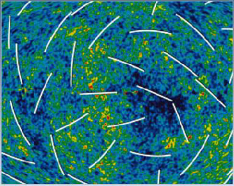
Meeting Last Week

Mitigating Systematic Errors in Space-based CMB Polarization Measurements

July 28 - 30, 2008 • Annapolis, Maryland

CMB POLARIZATION Systematic Errors

OVERVIEW | PROGRAM | LOGISTICS | CONTACT US | INTERNAL



CMBPol Mission Concept Study

The workshop will cover systematic effects relevant to measuring primordial B-modes in the CMB and using them to constrain Inflation. We will discuss sources, simulations, instrument designs and observing strategies. A review of the current "state of the art" from suborbital and orbital platforms will feed into our discussion of issues of particular relevance for CMBPol. The output of this workshop will be a written document that will become part of the full CMBPol Mission Concept Study.

RELATED WORKSHOPS ▸▸ CMBPol Theory and Foregrounds, 2008 CMBPol Technology, 2008

Following slides stolen from talks given at this meeting…

The QUIET Experiment

Bruce Winstein
The University of Chicago

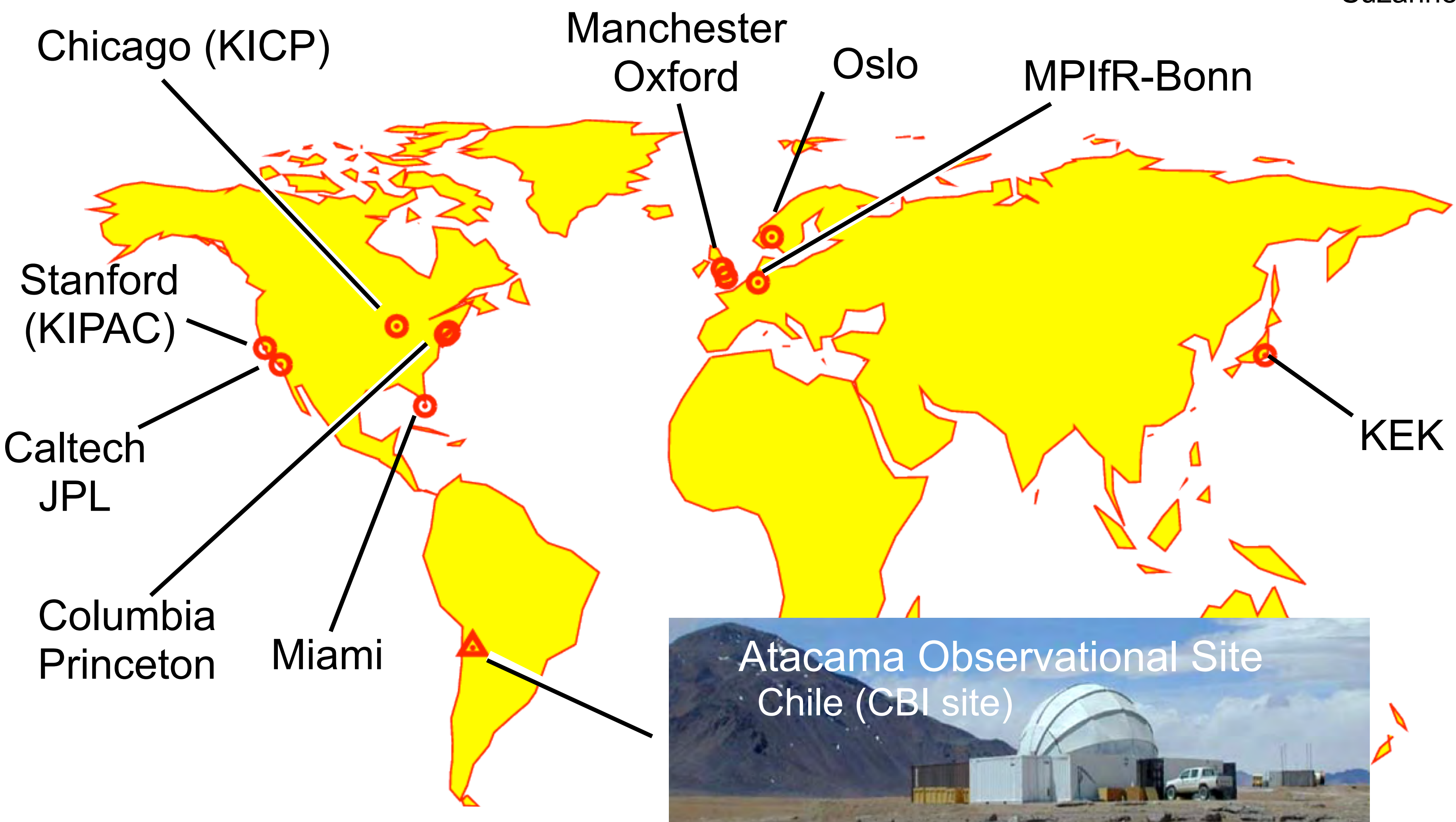
Inflation Probe Systematics Workshop

Annapolis, MD July 28-30

Collaboratoration

(http://quiet.uchicago.edu)

Amber
Charles
Kris
Michele
Osamu
Suzanne



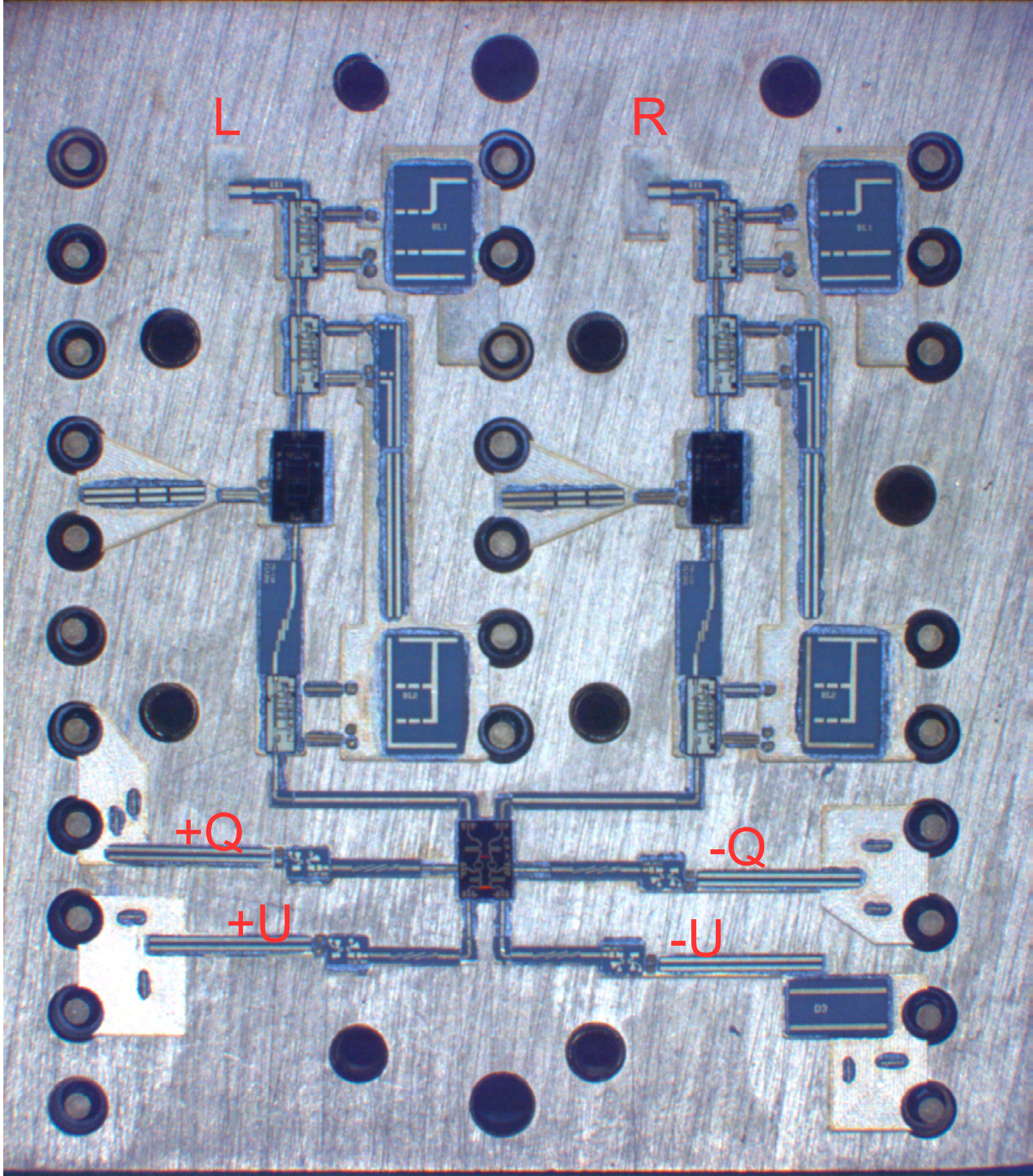
5 countries, 12 institutes, ~30 people

Experiment Details: QUIET Phase I

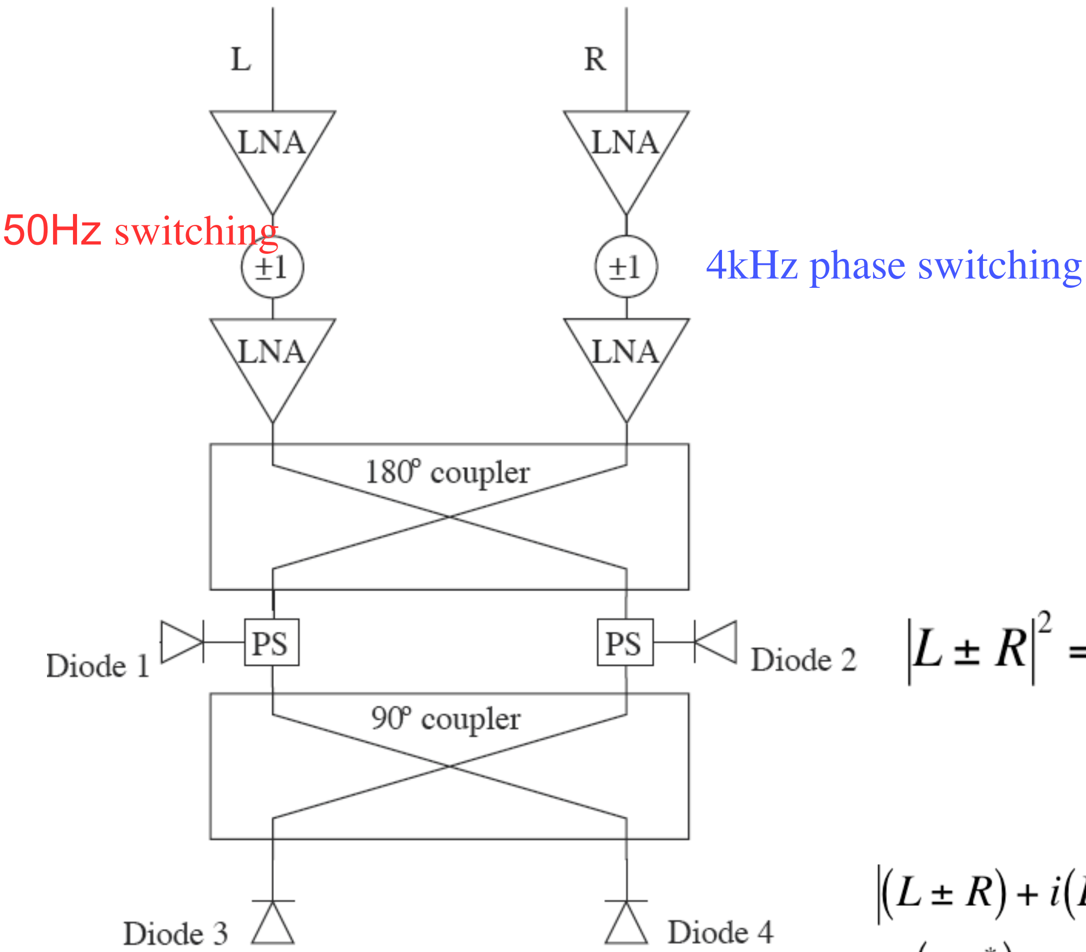
Angular resolution	Q:28/W:12	Arcminutes
Frequency Coverage	44/90	GHz
Sky Coverage	4x400	Square Degrees
Multipole Coverage	~ 60-450/60-1000	-
Polarization Modulation?	Phase switching PA sky rotation Dec angle rotation Rapid scanning	-
Types of Detectors	MMIC based	-
Location	Atacama Desert	Ground
Instrument NEQ	70/60 (from lab measurements)	$\mu K\ s^{1/2}$
Expected limit on *r*	~0.15 (?)	(no foregrounds)
Status	Phase I Funded	(Funded/Proposed/Future)

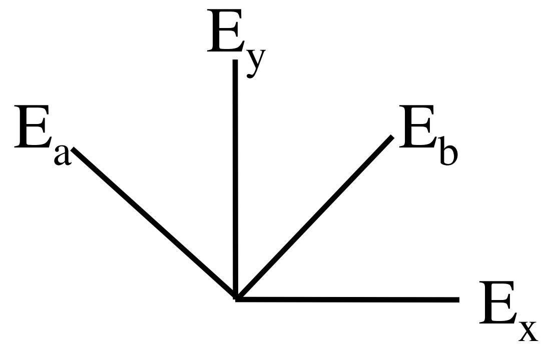
90 GHz Module
Automatic Assembly

Simultaneous
Q/U detections



QUIET L/R Correlator: Simultaneous Q/U measurements





$$\left|L \pm R\right|^2 = \left|\left(E_x + iE_y\right) \pm \left(E_x - iE_y\right)\right|^2 = \underline{4E_x^2, 4E_y^2}$$

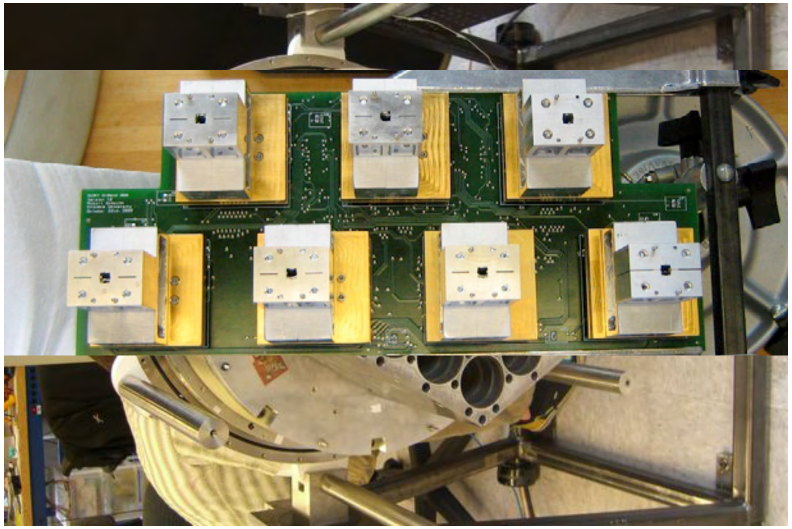
Q

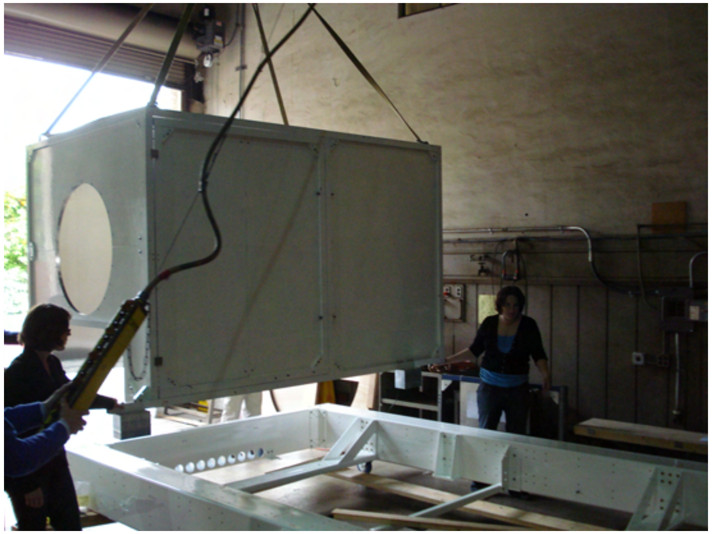
$$\left|\left(L \pm R\right) + i\left(L \mp R\right)\right|^2 = \left|L \mp iR\right|^2 = \left|L\right|^2 + \left|R\right|^2 \mp 2\,\mathrm{Im}\left(RL^*\right)$$

$$\mathrm{Im}\left(RL^*\right) = \mathrm{Im}\left(E_x + iE_y\right)^2 = 2E_xE_y = \underline{E_a^2 - E_b^2}$$

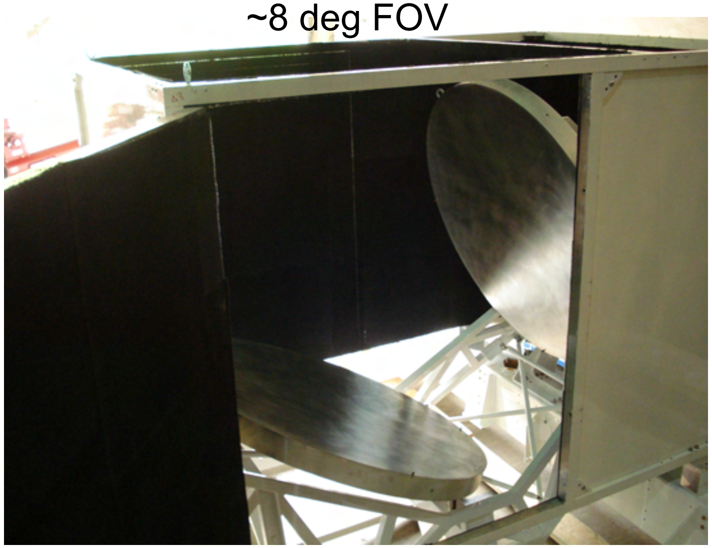
U

Q-band Receiver/Telescope Integration

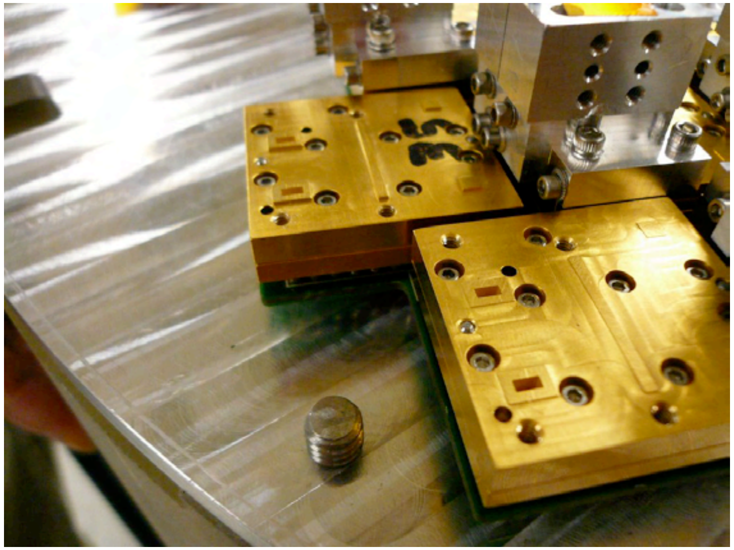


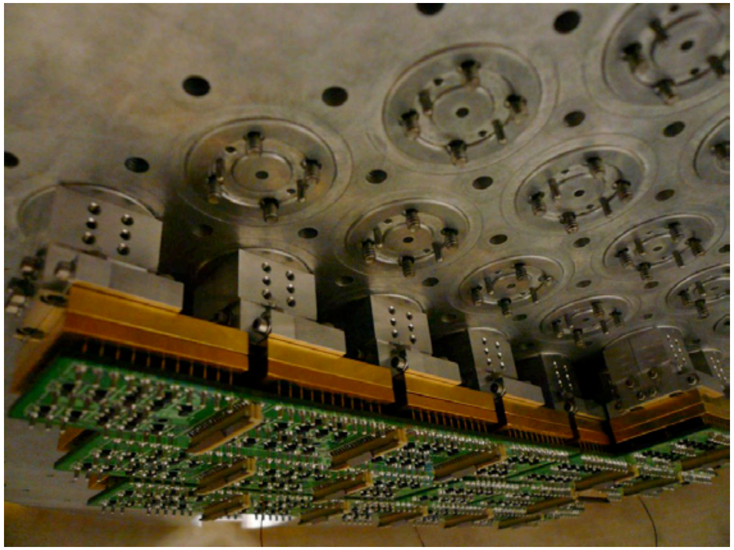


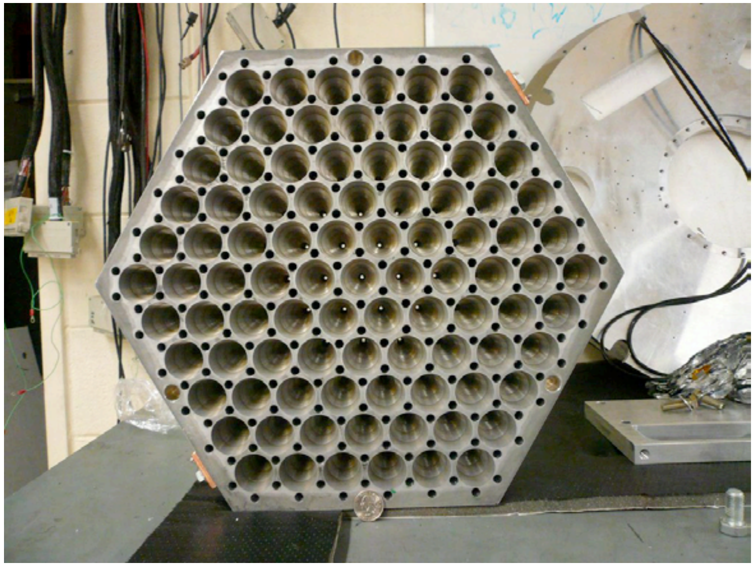
~8 deg FOV

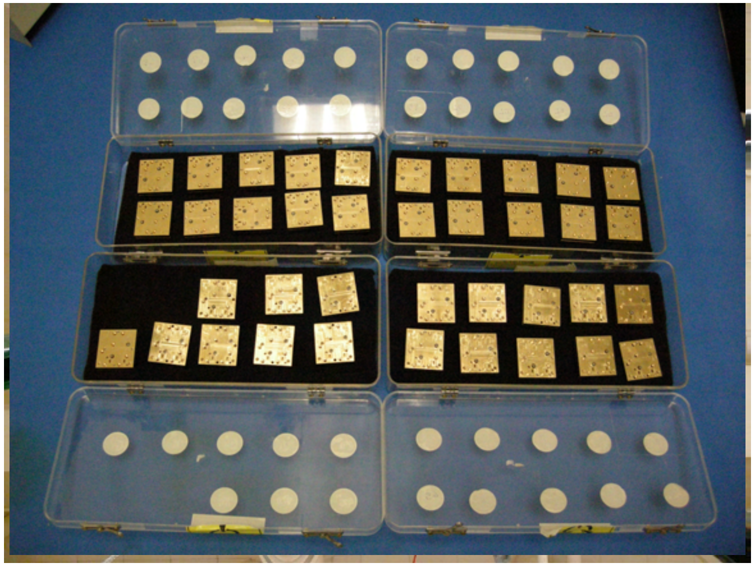


W-band Receiver Integration



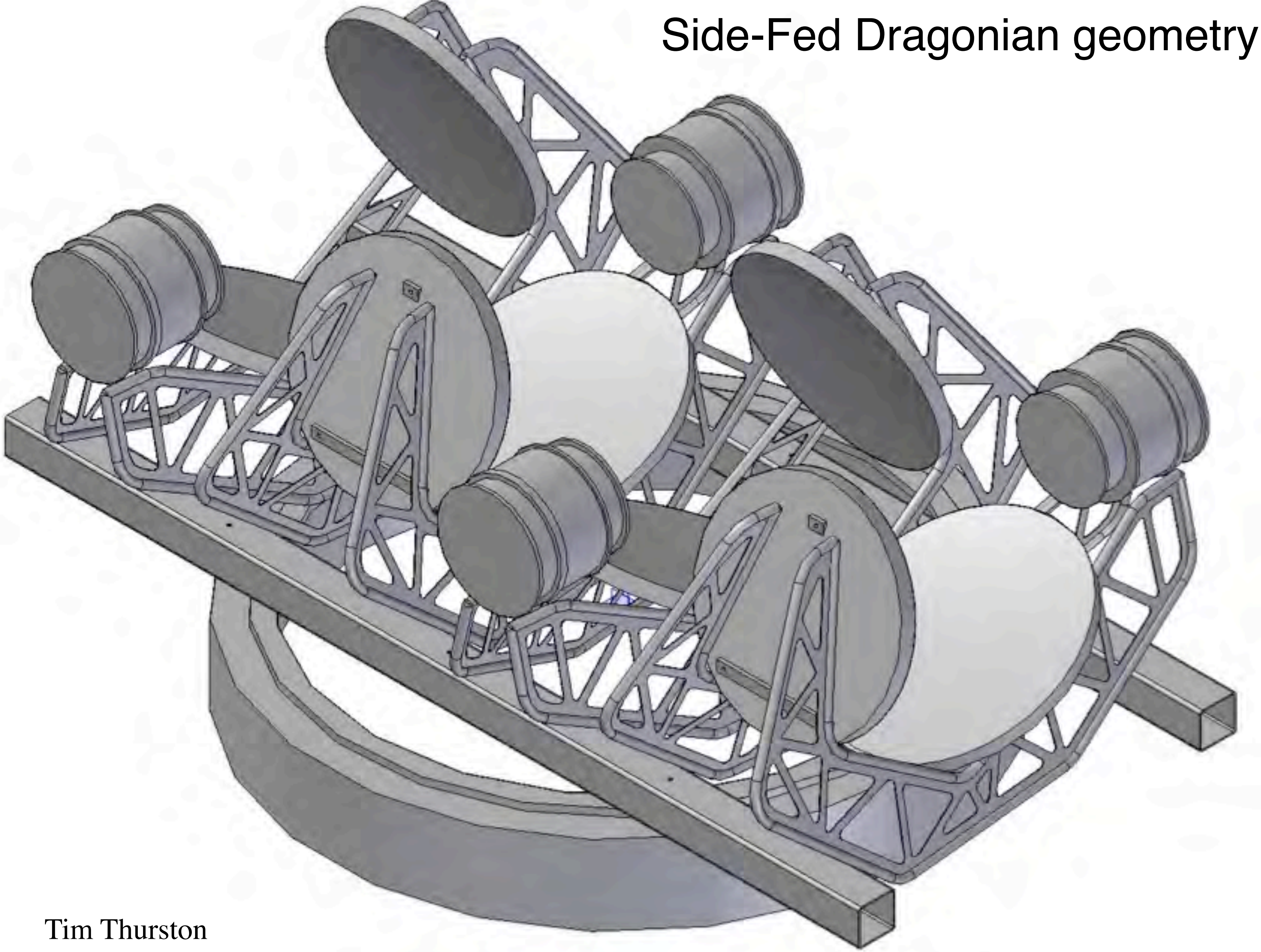






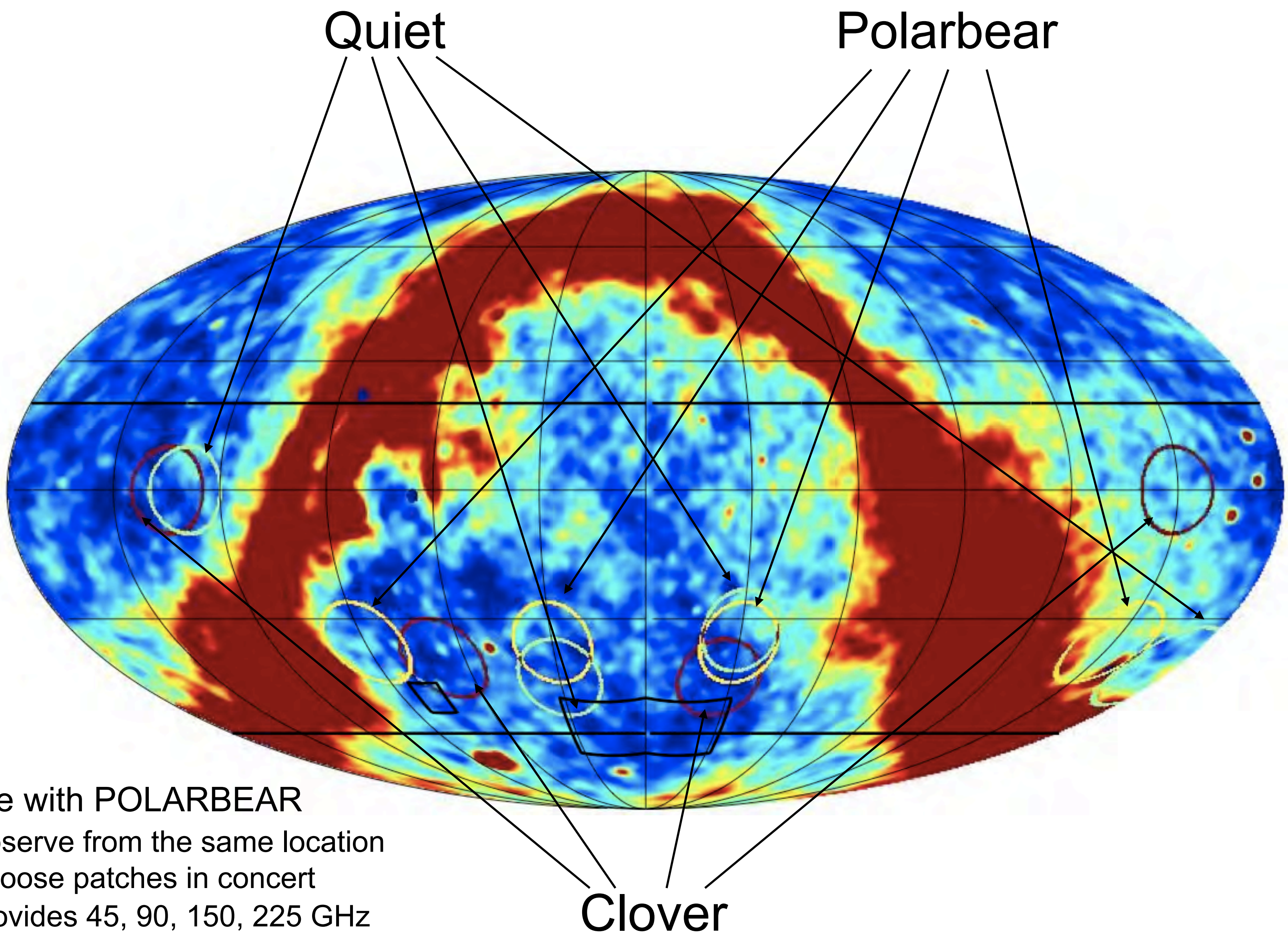
W-band should ship in January

Side-Fed Dragonian geometry



Tim Thurston

Observed Patches

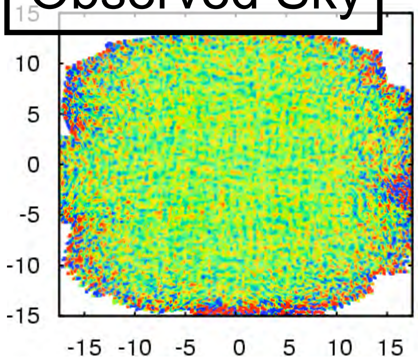


Alliance with POLARBEAR
- Observe from the same location
- Choose patches in concert
- Provides 45, 90, 150, 225 GHz

CMB Power, QUIET Sensitivity

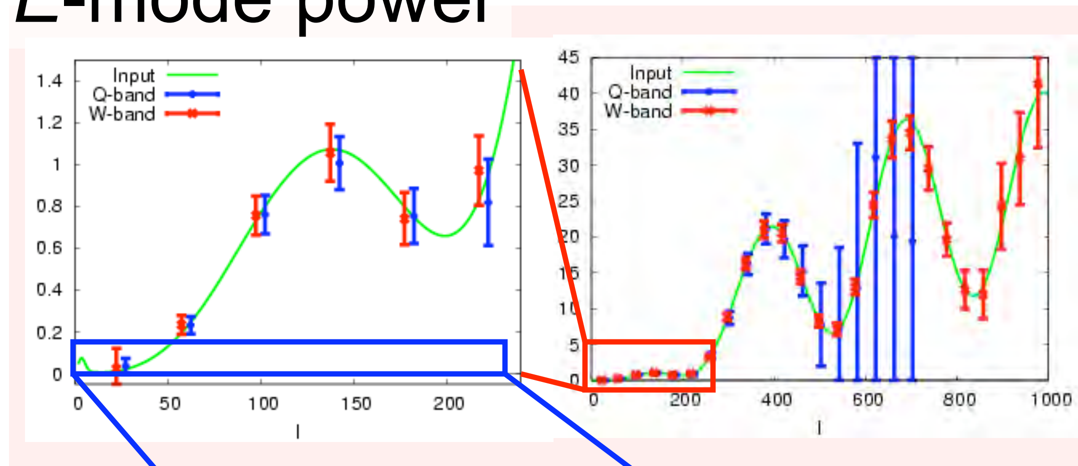
A. Kusaka

Observed Sky

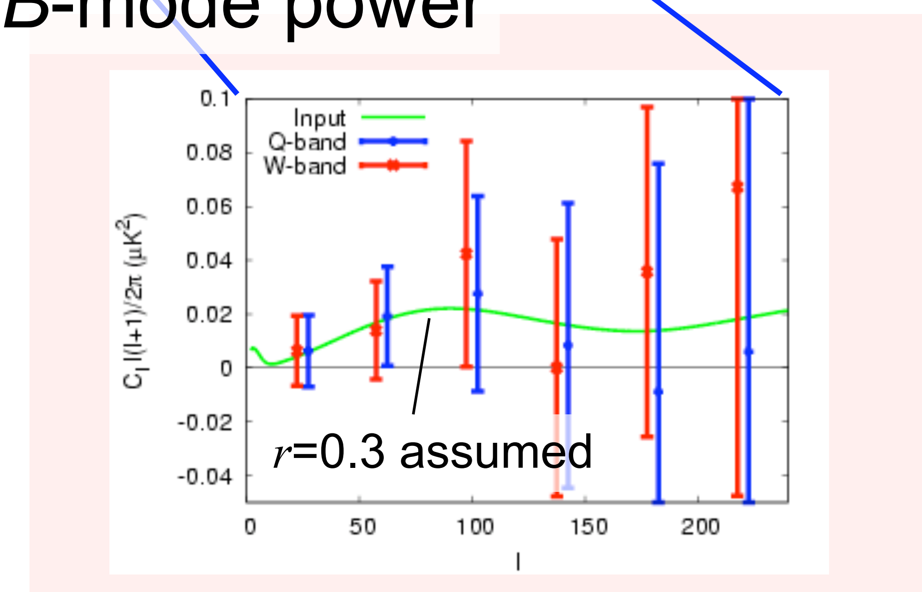


Auto Correlation

E-mode power



B-mode power



QUIET sensitivity
(10 months, 50% duty)

- 2σ *B*-mode indication for r=0.3
- Precise measurement of *E*-mode

Measuring the Polarization of the CMB with CLOVER

Dr Bradley R Johnson

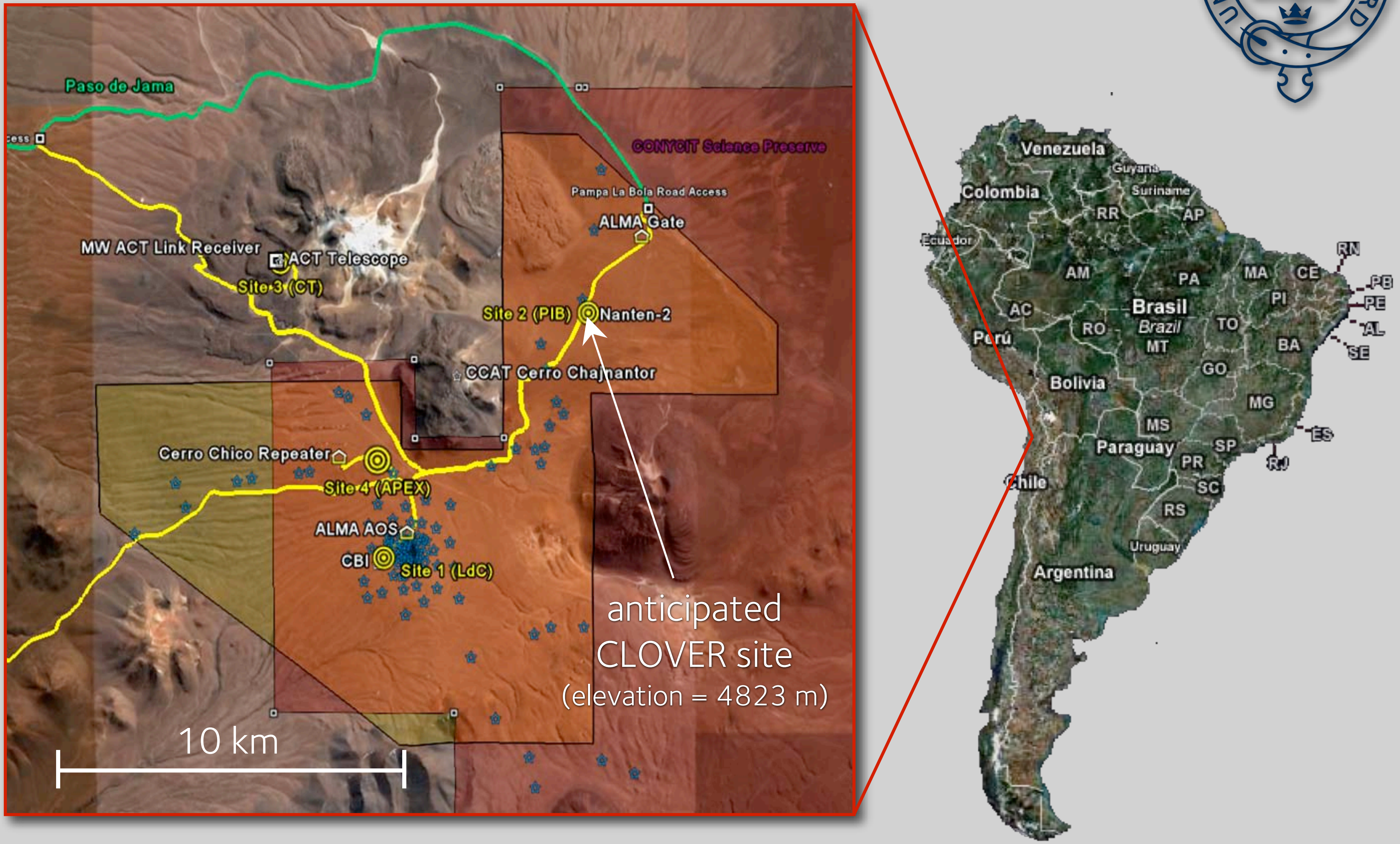
Postdoctoral Research Fellow
University of Oxford

CLOVER Collaboration

Cambridge	Cardiff	Manchester	Oxford
Damian Audley	Peter Ade	Colin Baines	Matthew Brock
Michael Brown	Paolo Calisse	Richard Battye	Pedro Ferreira
Anthony Challinor	Walter Gear	Adrian Galtress	Paul Grimes
Dorota Glowacka	Phil Mauskopf	Patrick Leahy	Brad Johnson
David J. Goldie	Stephen Parsley	Bruno Maffei	Michael Jones
Anthony N. Lasenby	Giorgio Savini	Simon Melhuish	Jamie Leech
Daniel O'Dea	Rashmi Sudiwala	Lucio Piccirillo	Chris North
David J. Titterington	Gustav Teleberg	Giampaolo Pisano	David Sutton
Vassilka Tsaneva	Carole Tucker	Bob Watson	Angela Taylor
Stafford Withington			Ghassan Yassin

UBC	NIST
Mark Halpern	William Duncan
	Gene Hilton
	Kent Irwin
	Carl Reintsema

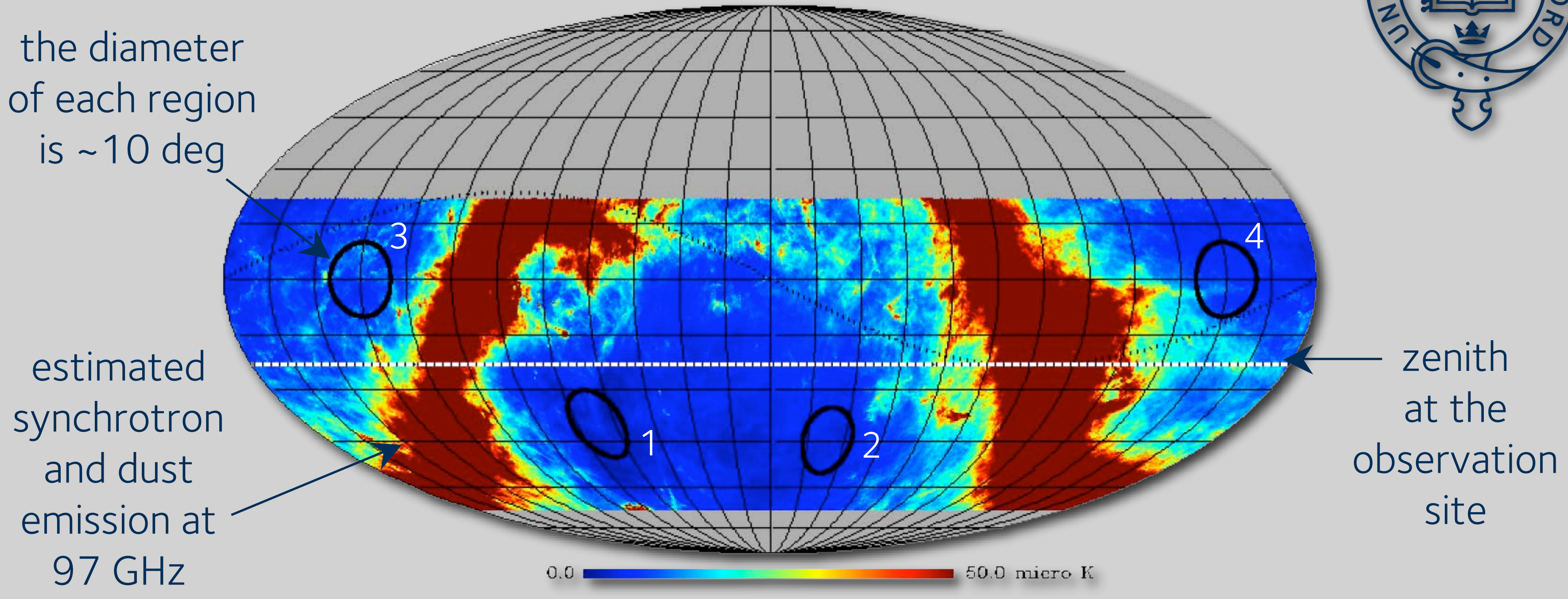
CLOVER Site: Atacama, Chile



Bradley R Johnson

January 29, 2008

CLOVER Observation Regions

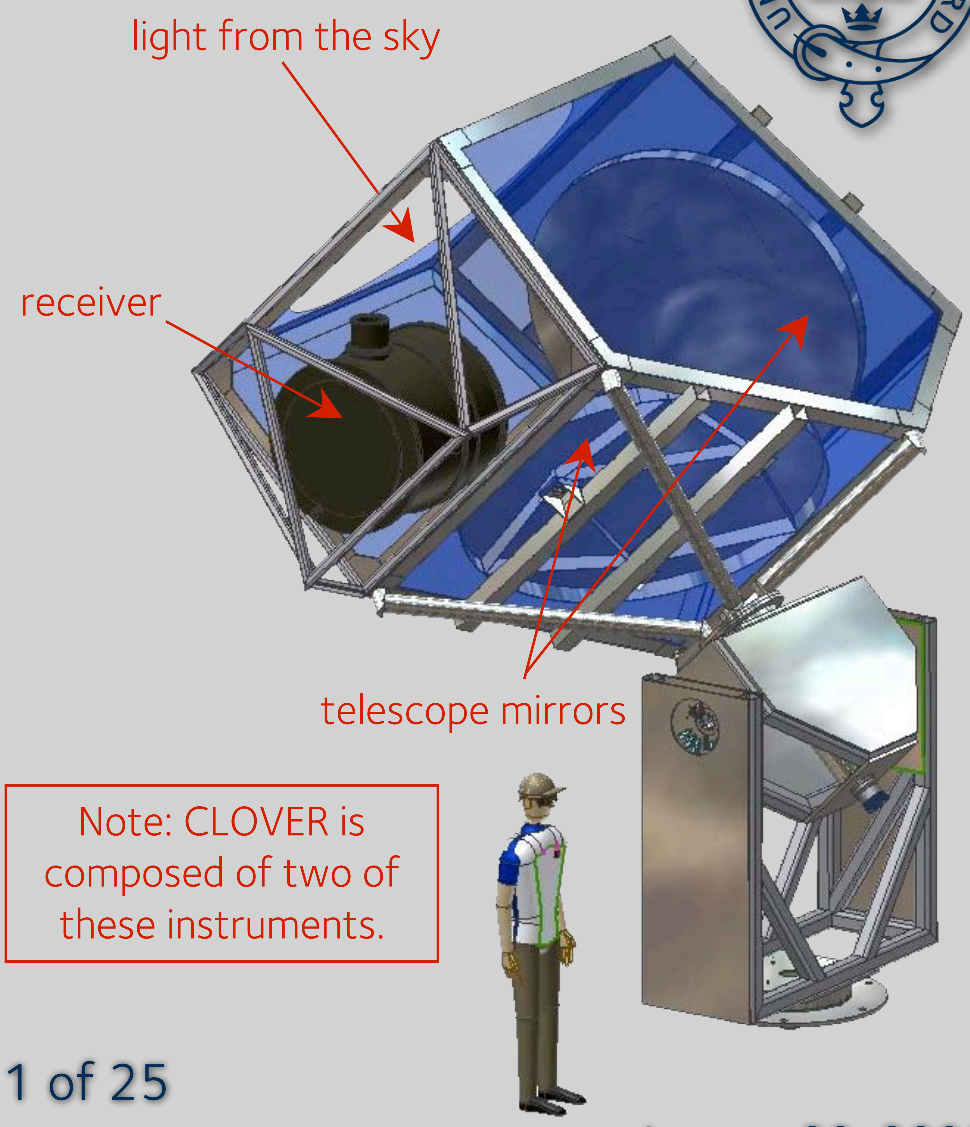


Region	1	2	3	4
RA [deg]	67.5	337.5	135.0	210.0
Dec [deg]	-40.0	-45.0	0.0	0.0
Dust/Synchrotron RMS [μK]	0.91/0.21	0.77/0.55	2.16/0.41	1.59/0.60

four regions together give 1000 deg^2 of coverage

CLOVER Experiment Characteristics

Band Centers [GHz]	97, 150, 225
Number of Single Polarization Detectors	192,192,192
NET [μK sec]	164, 254, 664
Beam FWHM [arcmin]	7.5, 5.5, 5.5
Sky Coverage [deg^2]	1000
l Range	20 to 1000
Operation Time [years]	2
Integration Time [years]	0.8
T Sensitivity per 8′ pixel [μK]	0.8
Q Sensitivity per 8′ pixel [μK]	1.1
Minimum r	0.03



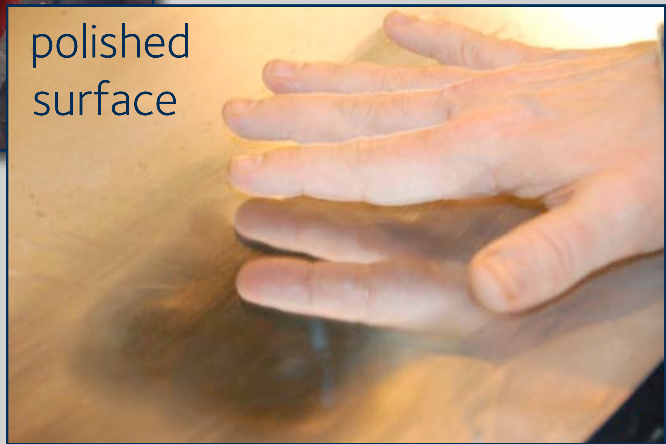
Note: CLOVER is composed of two of these instruments.

Bradley R Johnson

January 29, 2008

Mirror Fabrication

Mirror fabrication
is underway.

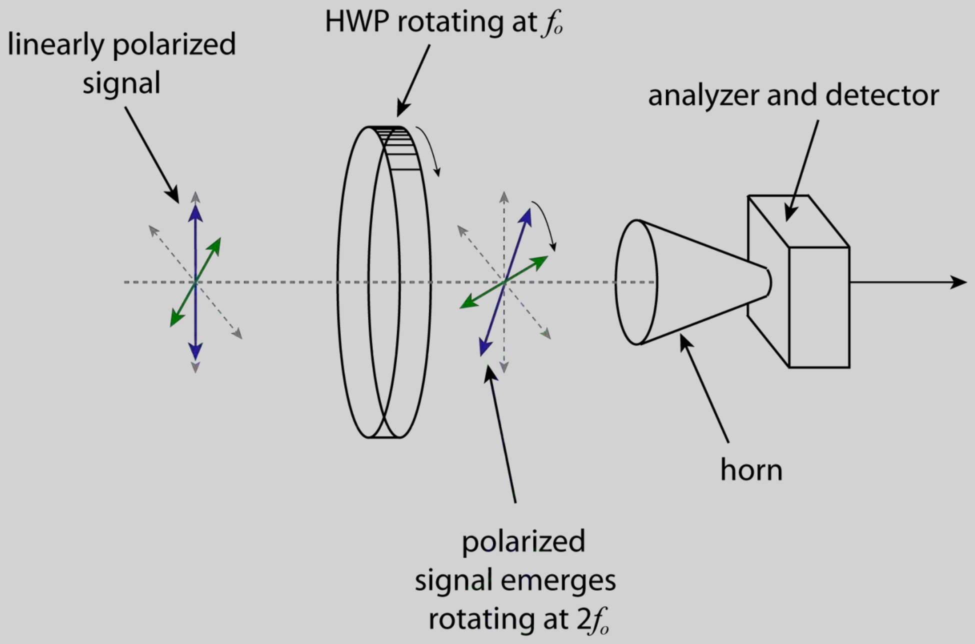


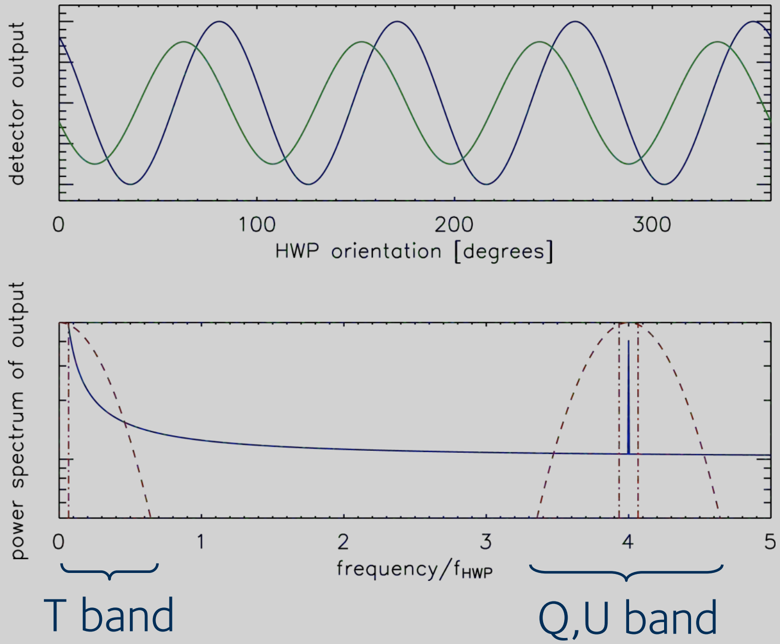
surface accuracy: < 50 μm (~λ/40 @ 259 GHz)

surface roughness: < 1 μm RMS

self weight deflection: 20 μm maximum

Half-Wave Plate Polarimetry





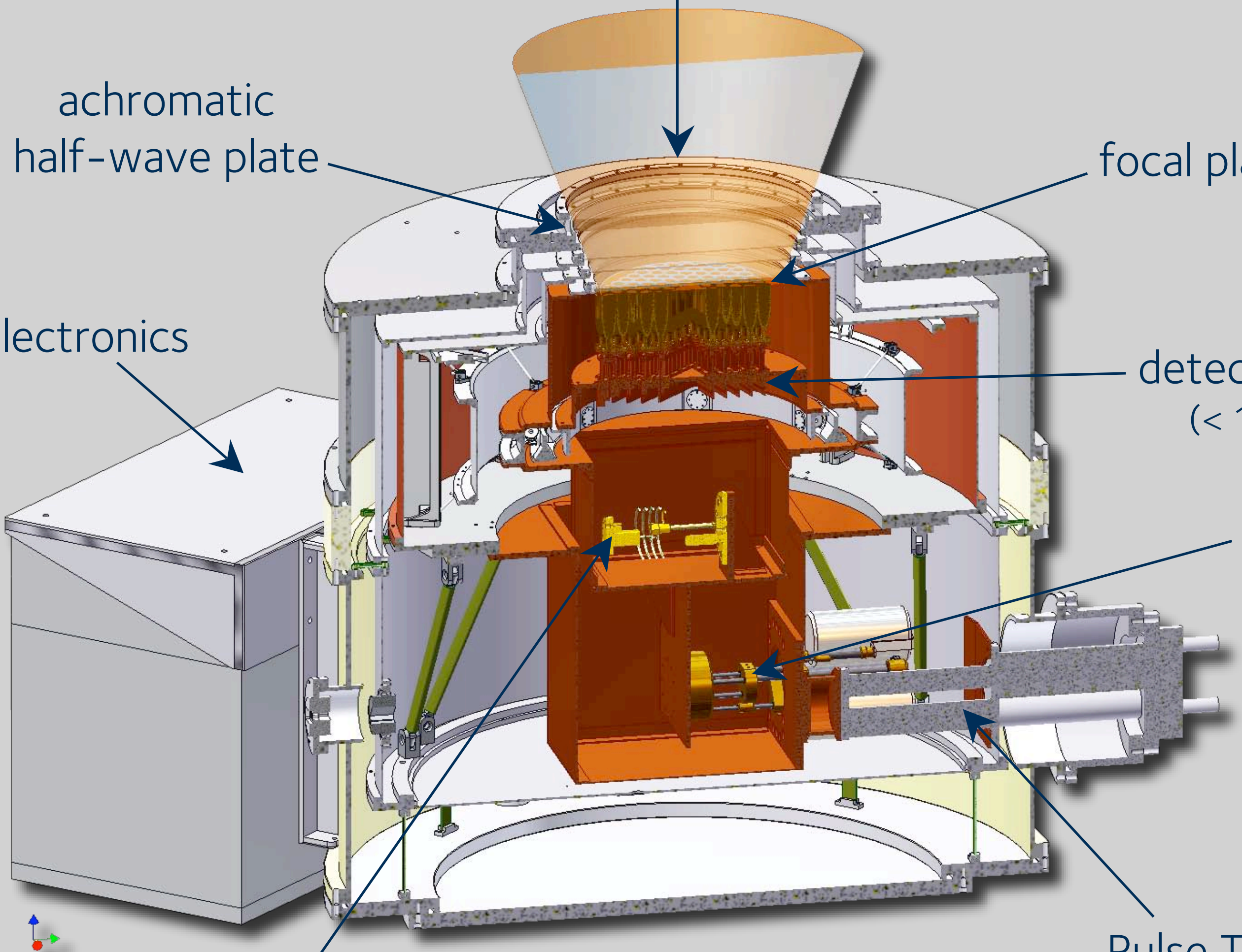
- moves signals away from $1/f$ noise
- modulation allows strong rejection of systematic errors
- each detector simultaneously measures T, Q and U

Achromatic Half-Wave Plate Design

Frequency [GHz]	97	150/225
material	sapphire	
number of crystals	3	5
modulation efficiency [%]	99	99/99
rotation frequency	both stepped operation and continuous rotation speeds up to ~5 Hz are being considered	
operating temperature [K]	300	60 (100)
rotation mechanism	air bearing	superconducting magnetic bearing

✓ multi-layer cryogenic anti-reflection coating technology in hand

97 GHz Receiver



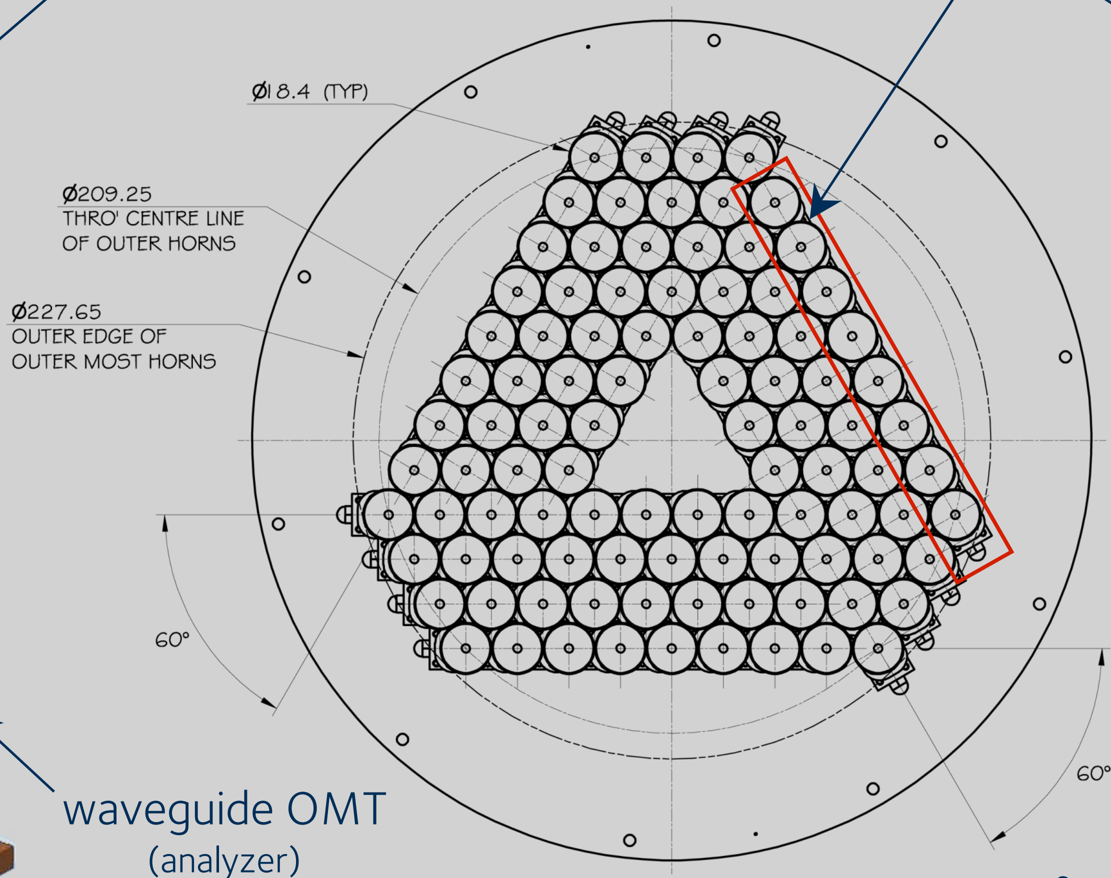
150/225 GHz receiver has a similar layout

97 GHz Focal Plane

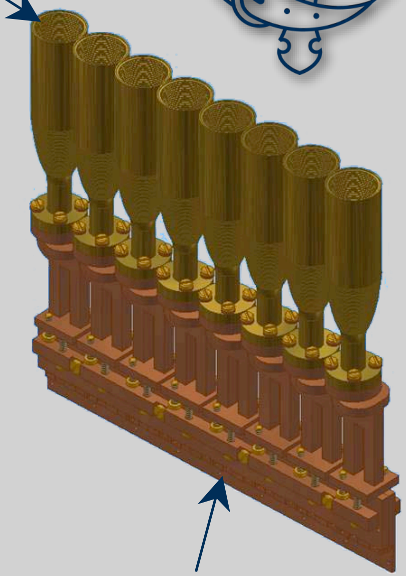
profiled corrugated horn

waveguide OMT
(analyzer)

waveguide outputs to detectors



focal plane module



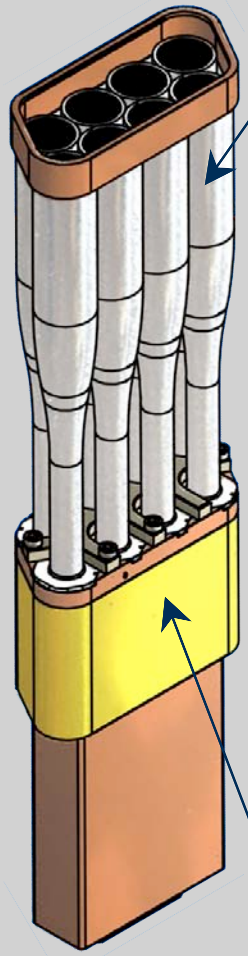
detector block

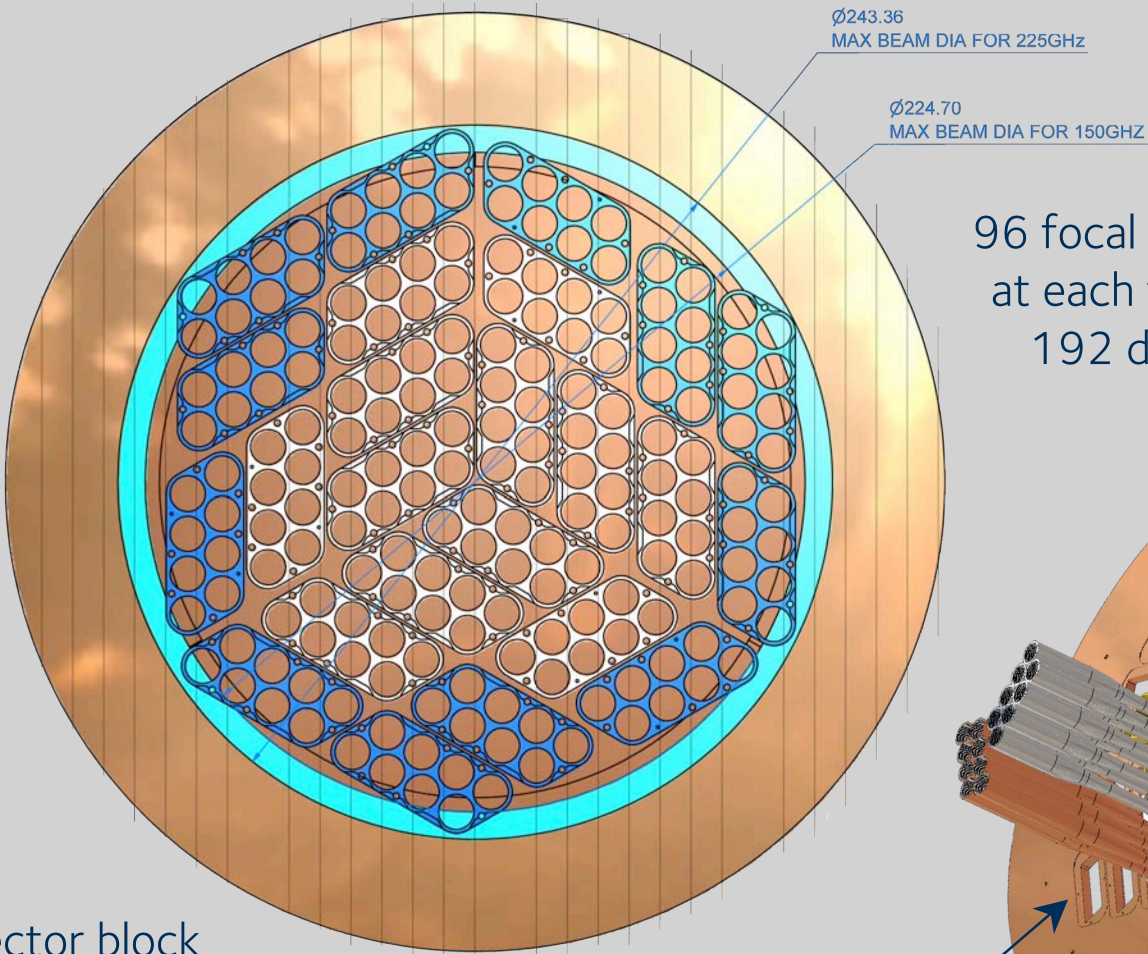
96 focal plane pixels
192 single polarization detectors

Bradley R Johnson

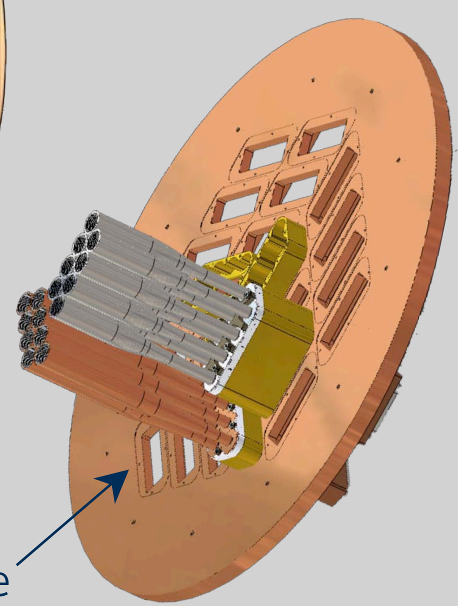
January 29, 2008

150/225 GHz Focal Plane





96 focal plane pixels
at each frequency,
192 detectors



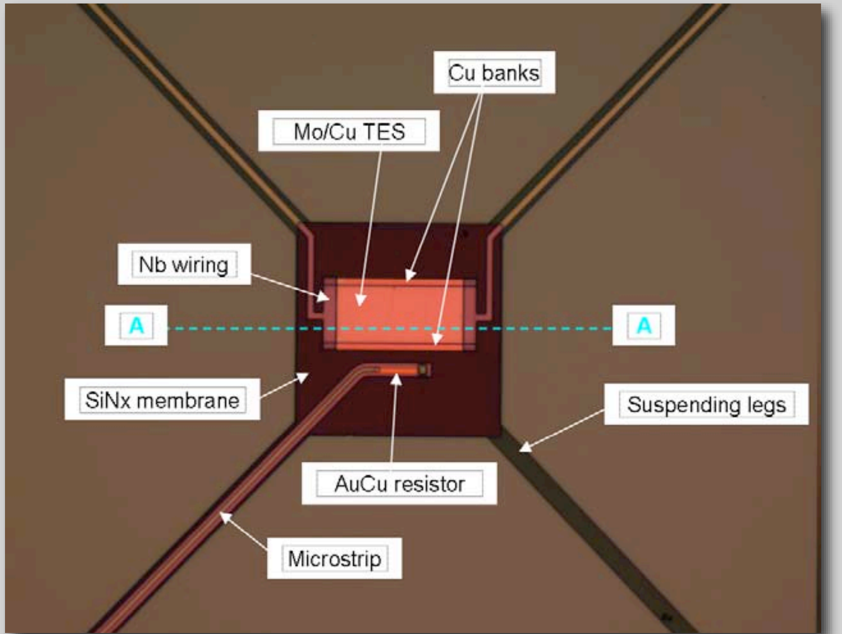
Bradley R Johnson

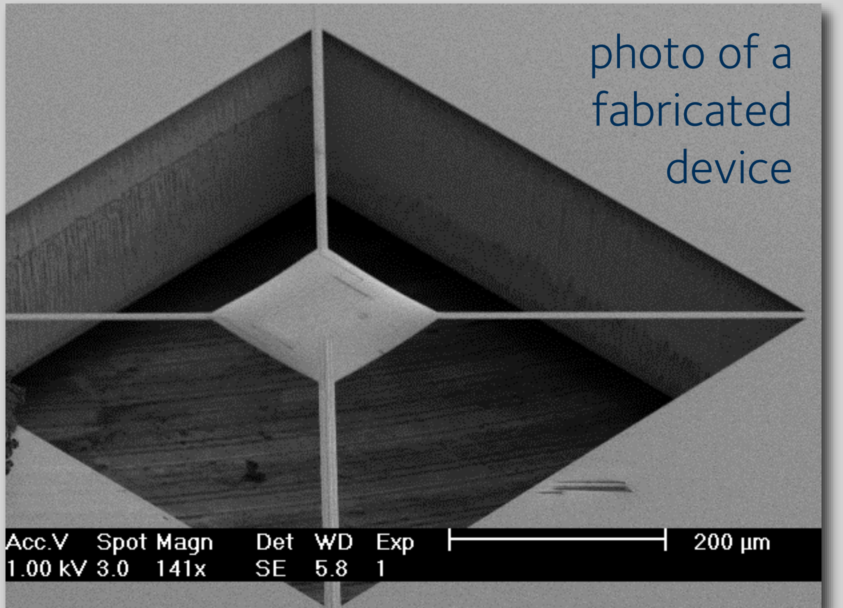
January 29, 2008

Microstrip-Coupled TES

Detector and Optical Physics Group at the Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE





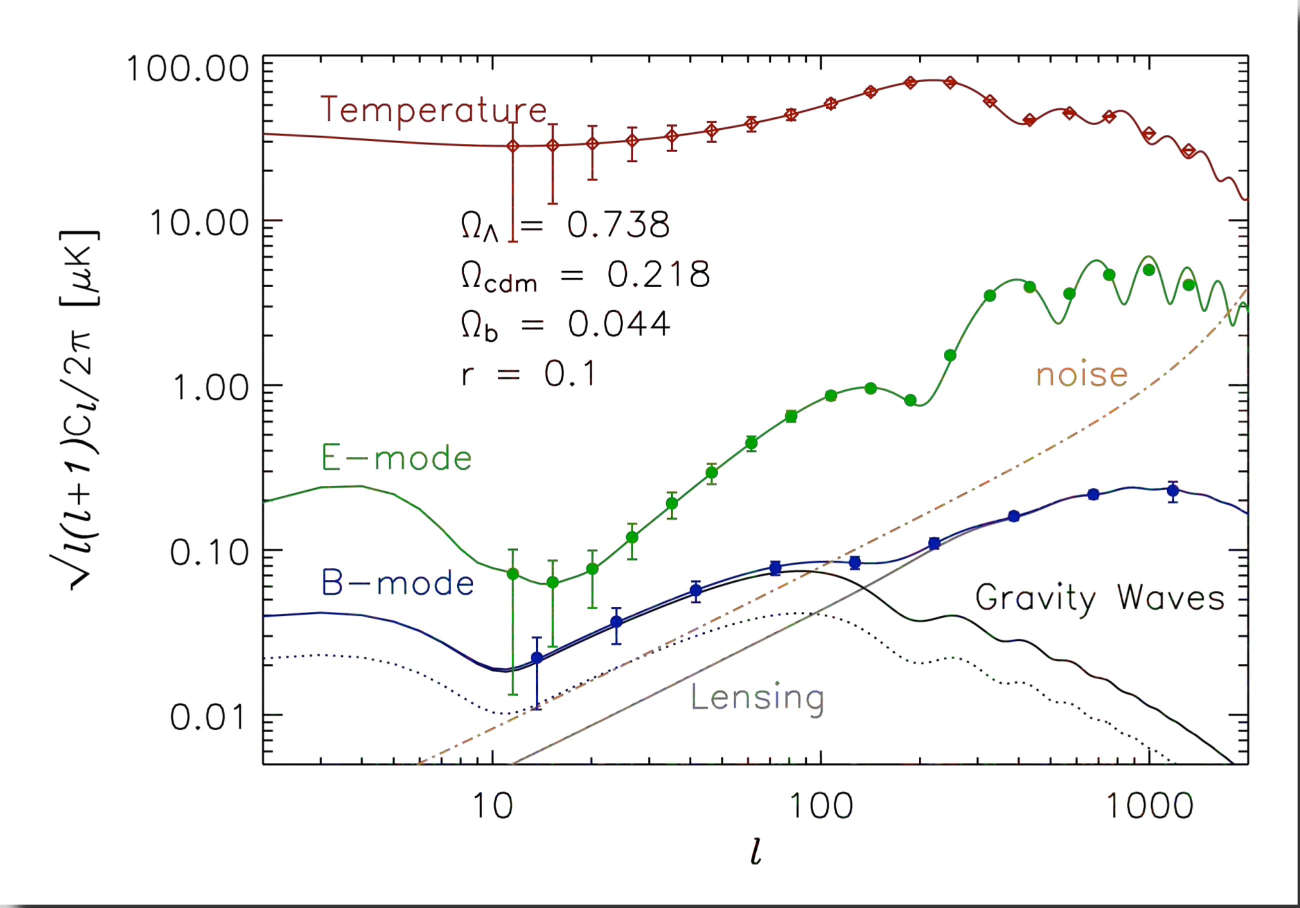
G = 215, 375, 260 [pW/K]

NEP = 2.2, 3.7, 6.7 [x 10^{-17} W/$Hz^{1/2}$]

τ = 100 to 1000 [µsec]

T_{bath} = 100 mK

Expected Performance



Control of Systematic Errors in Polarbear

Adrian Lee
U.C. Berkeley/LBNL

Inflation Probe Systematics Workshop
Annapolis, MD July 28-30

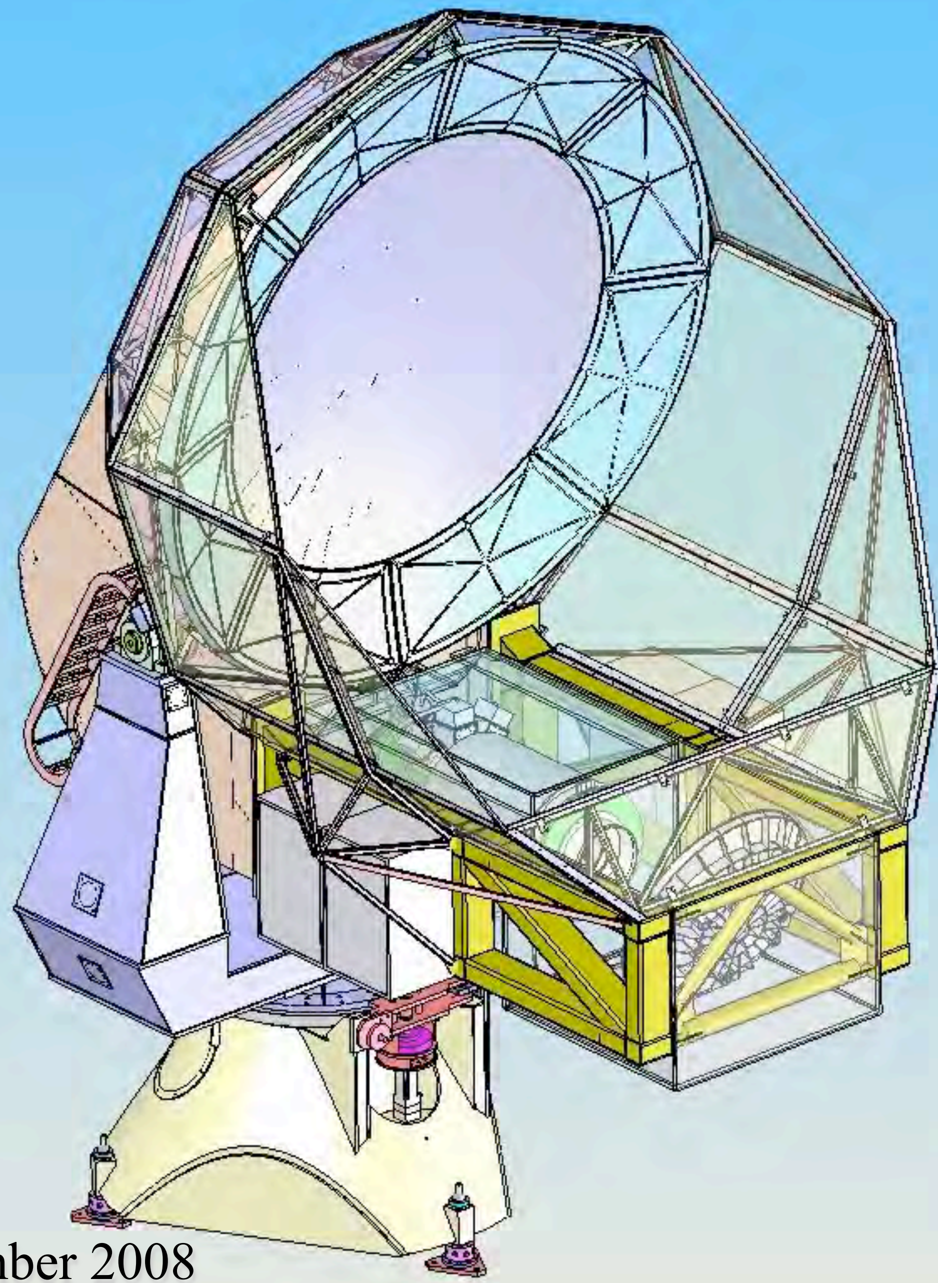
PolarBear Collaboration

U.C. Berkeley/LBNL, APC, Cardiff U., U. Colorado, Imperial, McGill, U.C. San Diego

Peter Ade (Cardiff)
Kam Arnold (UCB)
Julian Borrill (CRD-LBNL)
Matt Dobbs (McGill/LBNL)
Josquin Errard (UBC/APC)
Jacob Howard (UCB)
Andrew Jaffe (Imperial)
George Fuller (UCSD)
Nils Halverson (Colorado)
William Holzapfel (UCB)
Brian Keating (UCSD)
Zigmund Kermish (UCB)
Adrian Lee (UCB/LBNL)
Eric Linder (LBNL)
Nathan Miller (UCSD)
Michael Myers (UCB)
Anastasia Niarchou (Imperial)
Roger O’brient (UCB)
Erin Quealy (UCB)
Hans Paar (UCSD)
Christian Reichardt (UCB)
Paul Richards (UCB)
Meir Shimon (UCSD)
Helmuth Spieler (LBNL)
Radek Stompor (APC)
Huan Tran (UCB)
Carole Tucker (Cardiff)
Oliver Zahn (UCB/LBNL)

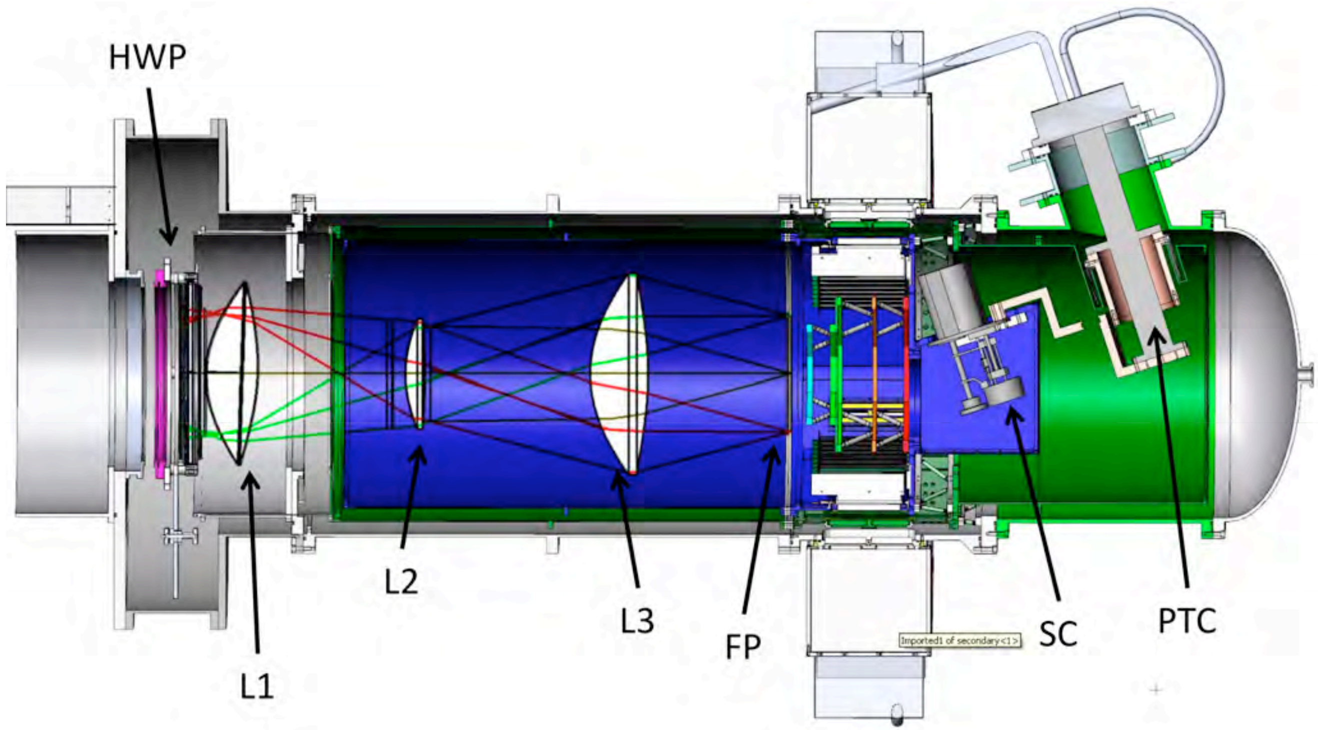
Experiment Details

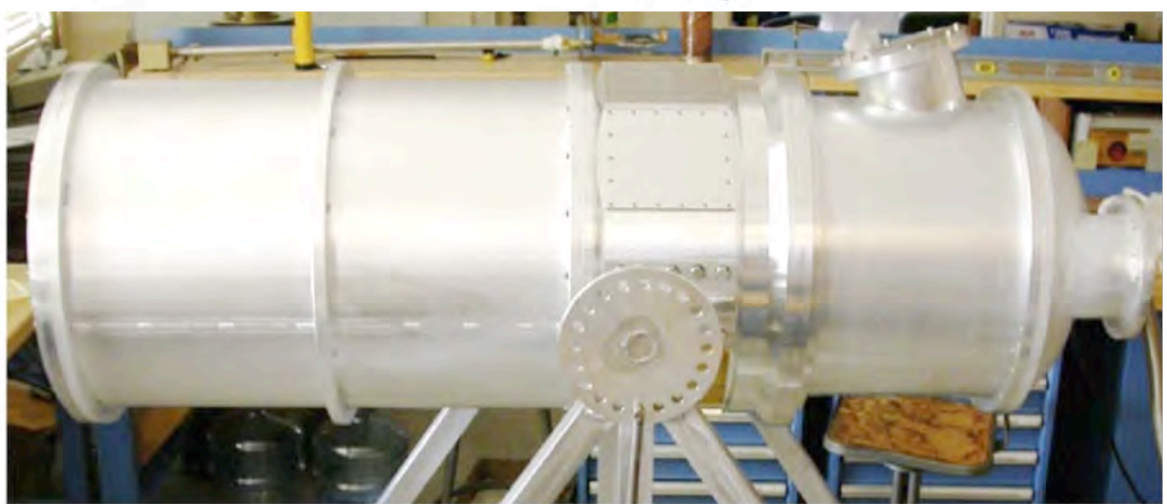
Angular resolution	4'/2.7'@150/220 GHz	Arcminutes
Frequency Coverage	150 and 220	GHz
Sky Coverage	1000 (~2% sky)	Square Degrees
Multipole Coverage	~20-3000	-
Polarization Modulation?	HWP	-
Types of Detectors	Ant-coupled TES/MUX	-
Location	Chile	(Balloon/Ground/Space)
Instrument NET	360/sqrt(1288) =10	μK_CMB $s^{1/2}$
Expected/Current limit on *r*	0.025 (95% C.L.)	mid-lat dust model subtracted w/220 GHz
Status	Funded	Spring 2009 Test Obs



Delivery: December 2008
Test Phase: Spring 2009 @ CARMA

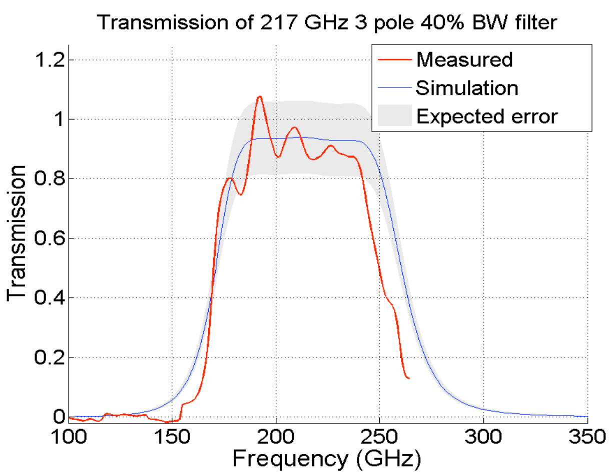
POLARBeaR Receiver

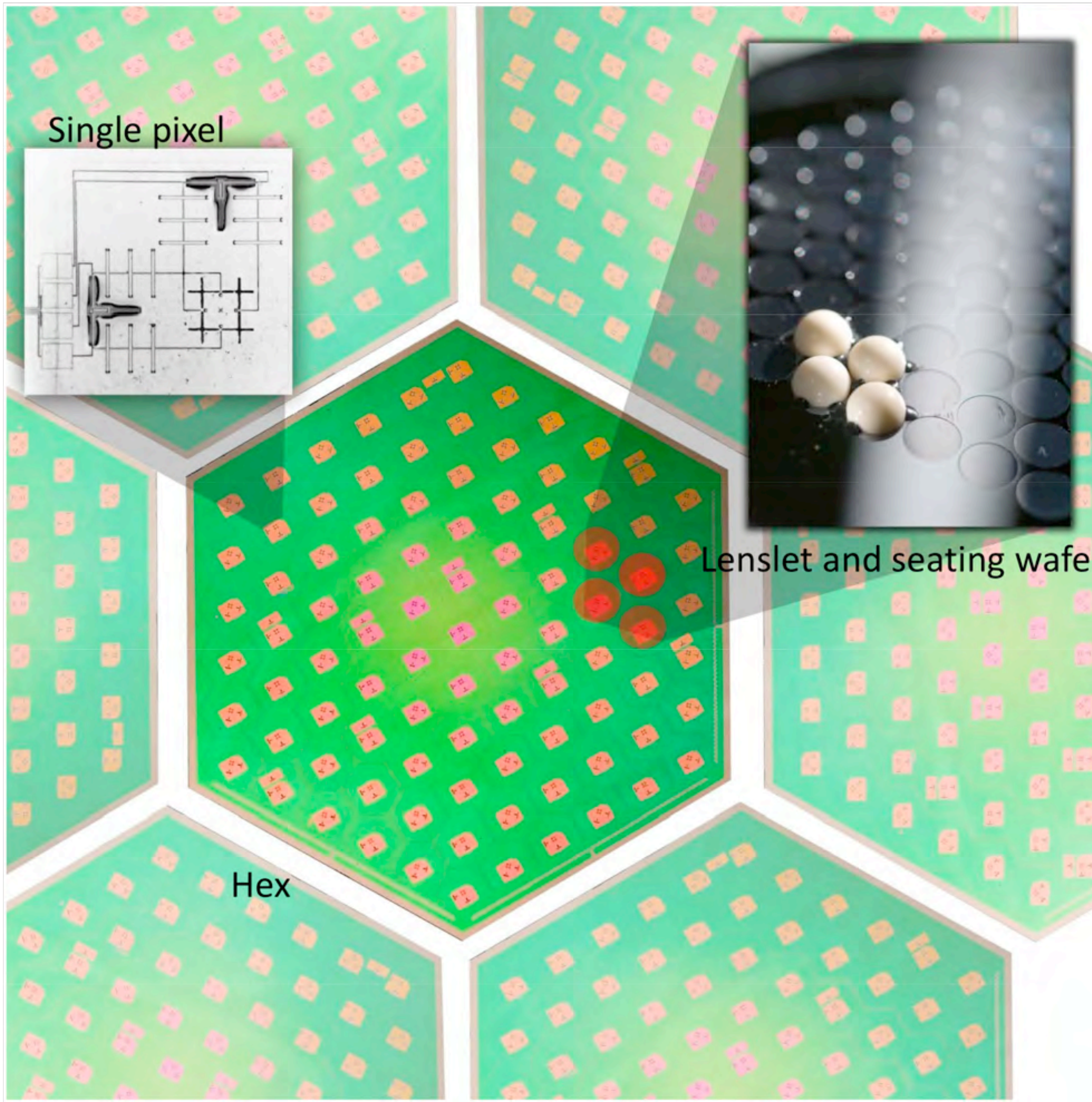




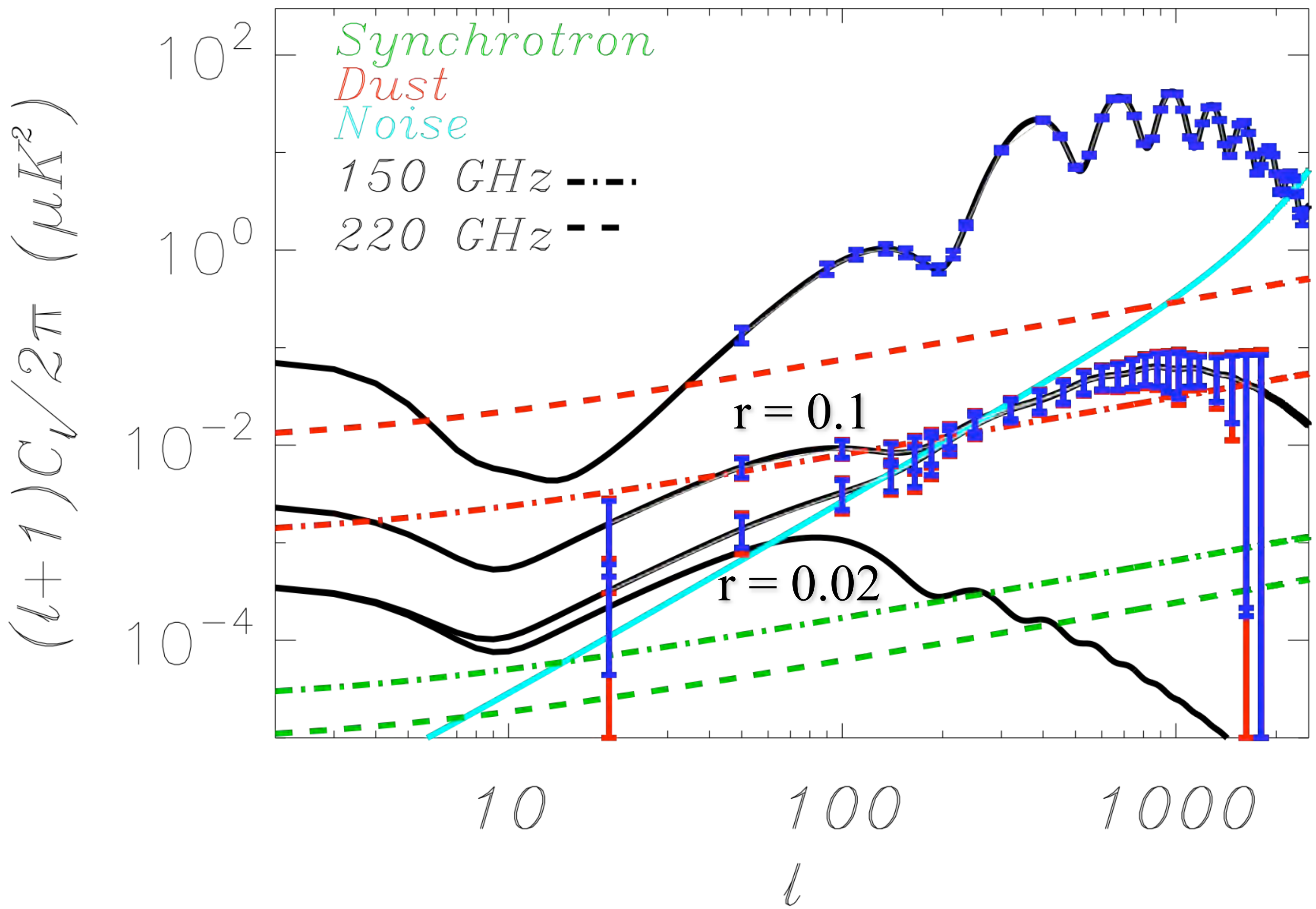
Polarbear Array

- 7 wafers = 1288 bolos
  - fMUX (simple shielding)
- Single-color, dual-pol
  - CARMA, 2 wafers
  - Chile yr1 = 150 GHz
  - Chile yr2 = 220 GHz
- Myers et al. 2005
- Myers et al. 2008 (LTD)





Polarbear Sensitivity



Red error bars: Includes noise increase from subtracting 220 GHz to remove mid lat dust

KICP

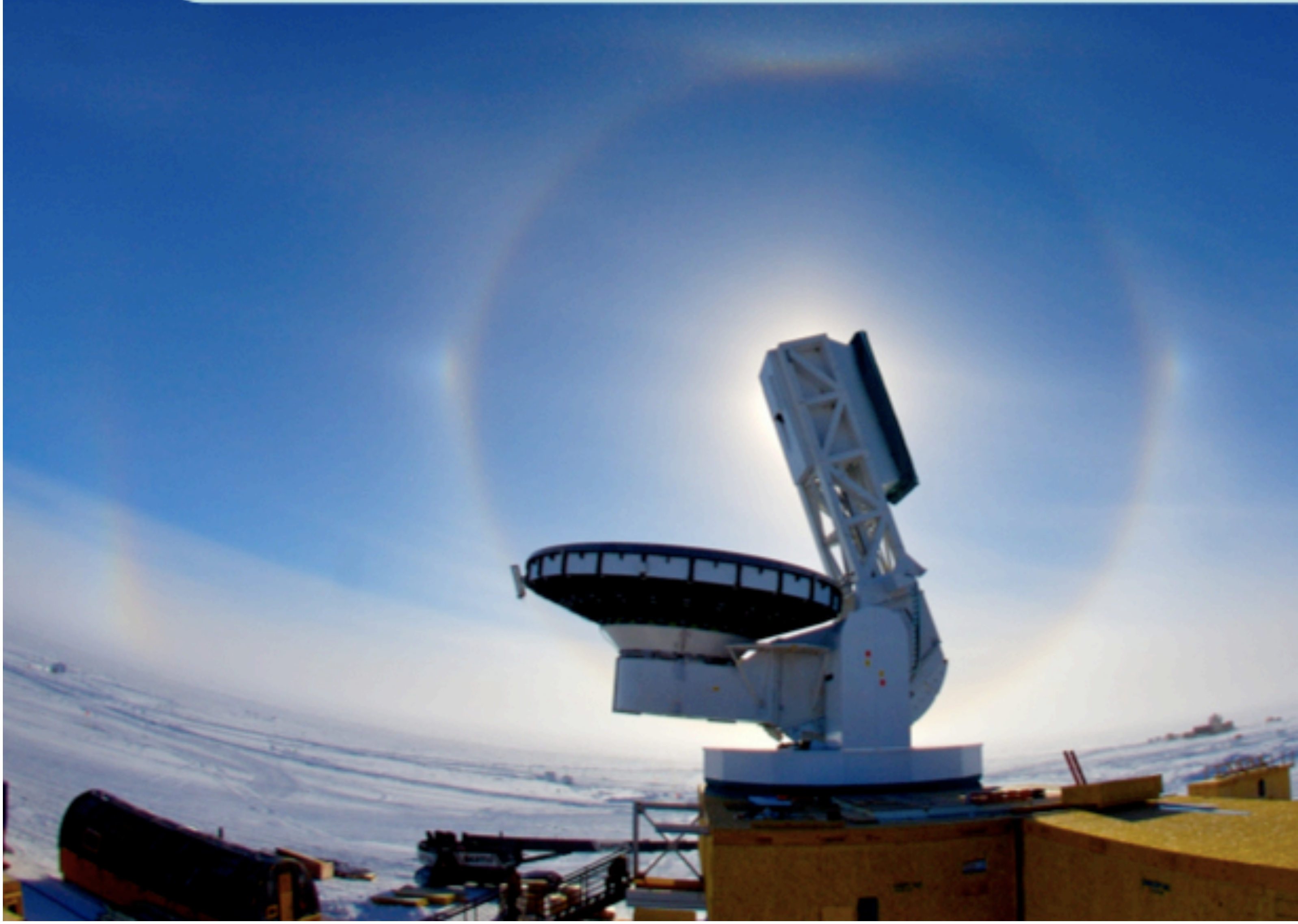
THE UNIVERSITY OF CHICAGO

SPTpol Systematics

Jeff McMahon (for the SPT collaboration)

Inflation Probe Systematics Workshop

Annapolis, MD, July 28-30



SPT collaboration

Chicago
Carlstrom
Hu
Kravtsov
Meyer
Pryke
Aird
Leitch
Padin
Chang
Crawford
McMahon
Miknaitis
Keisler
Bleem
Crites
Vieira

Case
Ruhl
Staniszewski

Berkeley/LBNL
Holzapfel
Lee
White
Spieler
Benson
Reichardt
Lueker
Plagge
Shirokoff
Zahn

McGill
Dobbs
Holder
Shaw

SAO
Stark

Illino
Mohr

Card
Filters
Ade

Boul
Halver

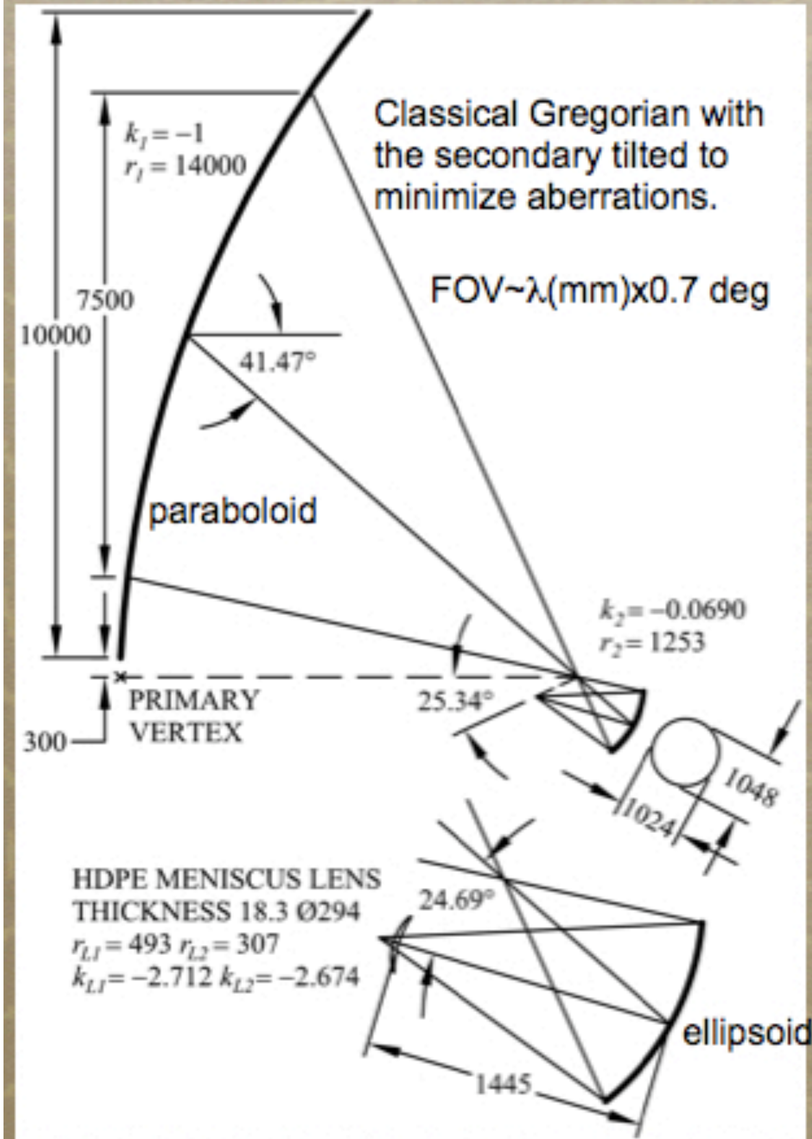
Davi
Knox

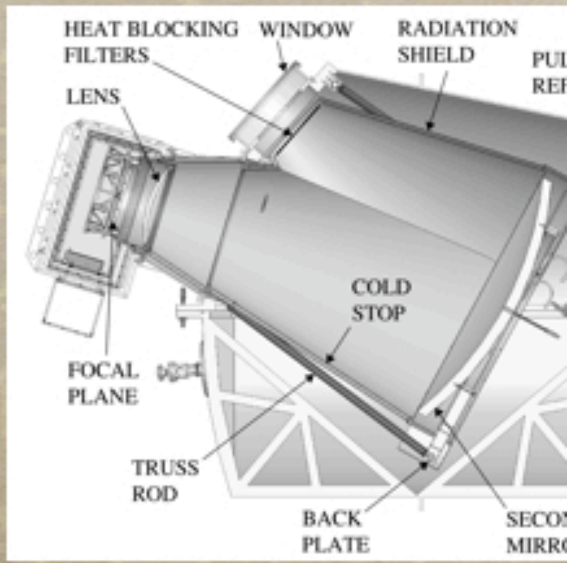
MSF
Joy

SPTpol Summary Table

Angular resolution	1.6, 1.0, 0.8	Arcminu
Frequency Coverage	90, 150, 220	GHz
Sky Coverage	600	Square De
Multipole Coverage	50-10000	-
Polarization Modulation?	HWP?	-
Types of Detectors	Bolometer, differencing	-
Location	Ground, South Pole	(Balloon/Grour
Instrument NEQ	14	$\mu K\ s^{1}$
Expected/Current limit on *r*	0.01 ($\sigma(r) = 0.004$)	-
Status	Funded	(Funded/Pro Future

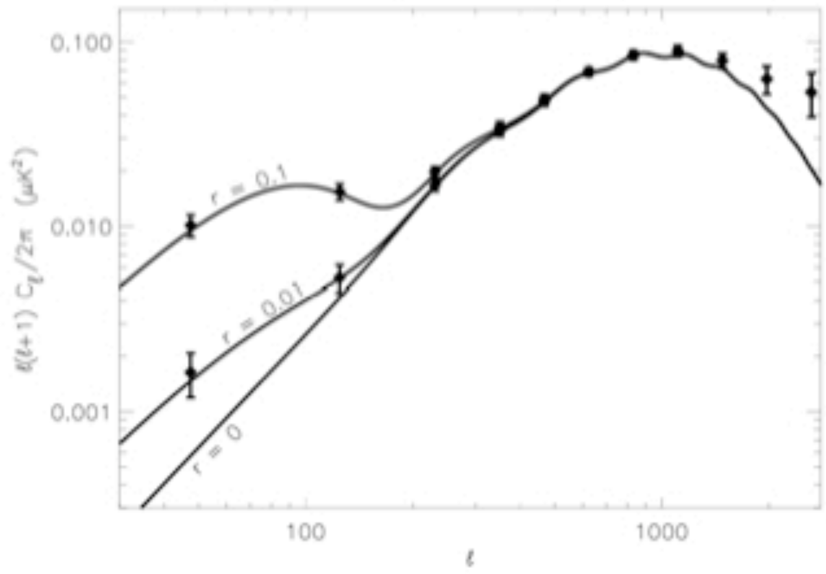
SPT optics





- Low background, low side
- Cooled secondary
- Accommodates 1000 elem
- Introduction of a wave pla

B-mode Projection



$\sigma(r) = 0.004$

Simulation i

- *1000 bolon*
- *3 years / 50*

Simulation i

- *1/f noise*
- *point sourc*
- *foreground*
- *E/B separa*
- *projection*
- *removal of I*

EBEX

Michele Limon
Columbia University

Inflation Probe Systematics Workshop

Annapolis, MD July 28-30

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
Daniel Chapman
Will Grainger
Seth Hillbrand
Michele Limon
Amber Miller
Britt Reichborn-Kjennerud

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

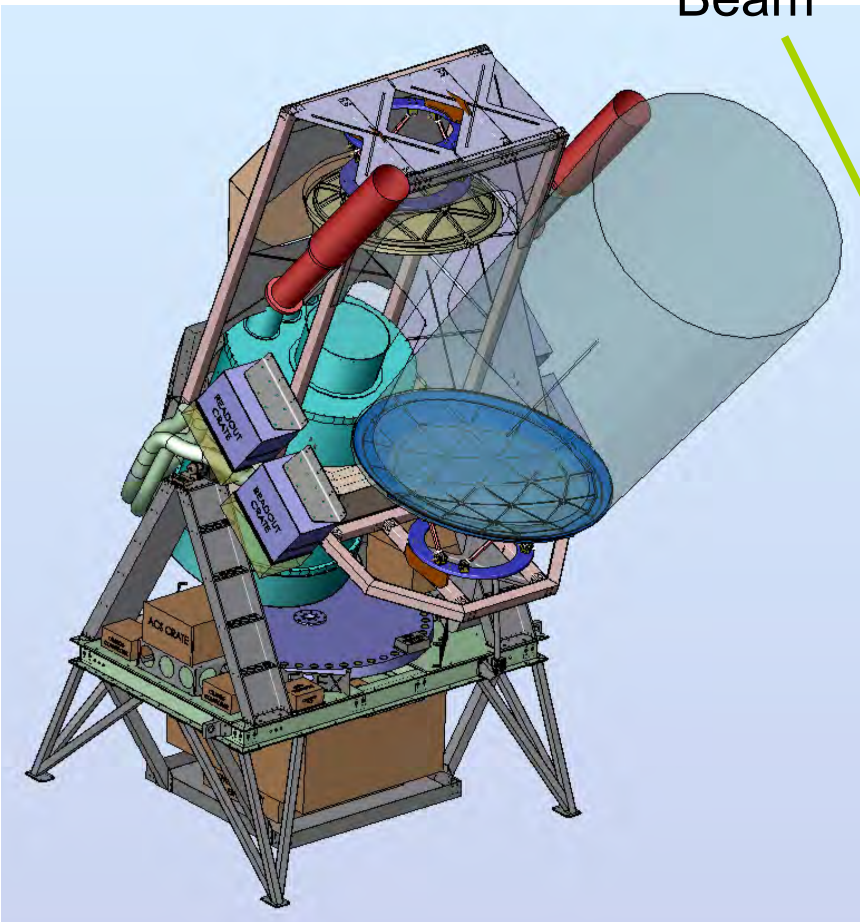
University of Minnesota/Twin Cities
Asad Aboobaker
Shaul Hanany
Hannes Hubmayr
Terry Jones
Jeff Klein
Michael Milligan
Dan Polsgrove
Ilan Sagiv
Kyle Zilic

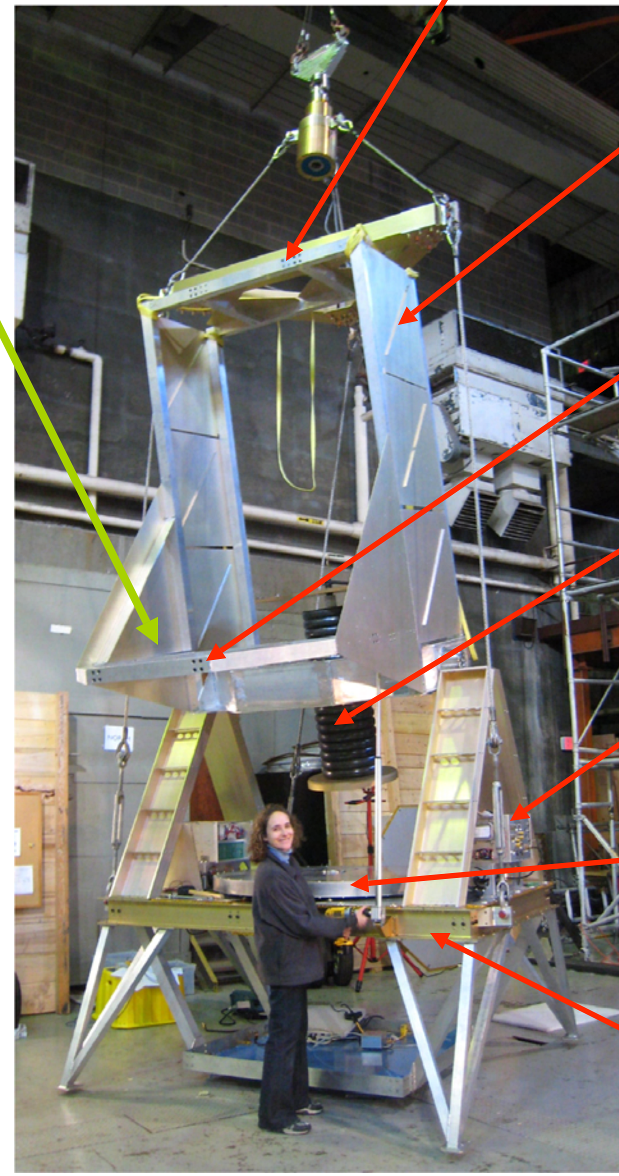
Weizmann Institute of Science
Lorne Levinson

Experiment Details

Angular resolution	8	Arcminutes
Frequency Coverage	150, 250, 410	GHz
Sky Coverage	420	Square Degrees
Multipole Coverage	20 - 1500	-
Polarization Modulation?	Half-Wave Plate	-
Types of Detectors	TES Bolometers	-
Location	Balloon	Balloon/Ground/Space
Instrument NEQ	5.0 at 150 GHz	$\mu K\ s^{1/2}$
Expected/Current limit on *r*	= .1 at 5σ < .02 at 2σ	-
Status	Funded	Funded

Gondola Design

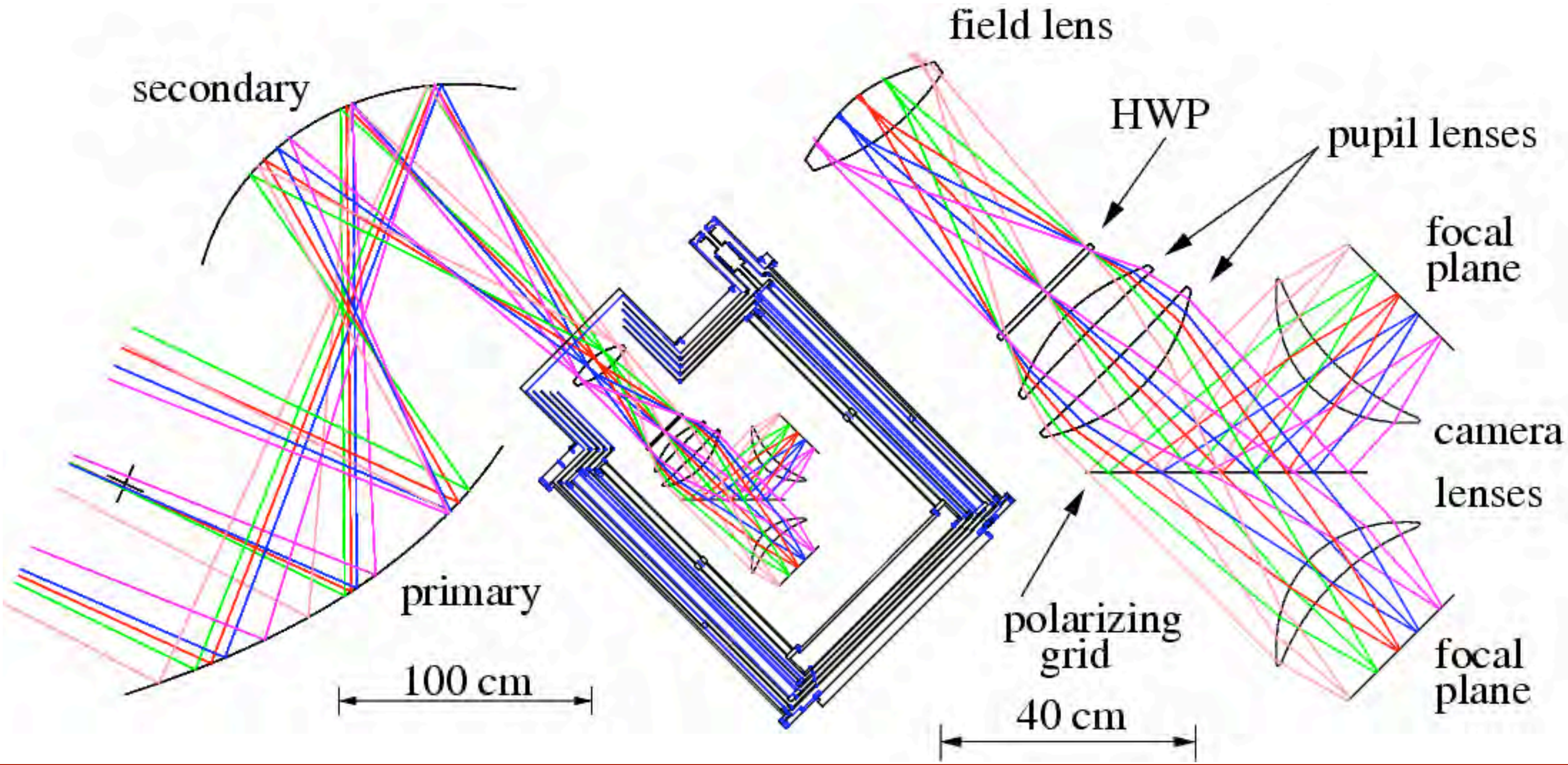




- Cable Suspension
- Designed at SSL (Berkeley)
- Integration at Nevis Lab at Columbia

Optics

- 1.5 m Aperture Gregorian Dragone telescope—allows for sensitivity to lensing B-mode scales
- Cold aperture stop -- control of sidelobes
- Achromatic Half Wave Plate on magnetic bearing -- strong rejection of polarimetric systematics
- Wire Grid Analyzer -- Detection of two orthogonal states

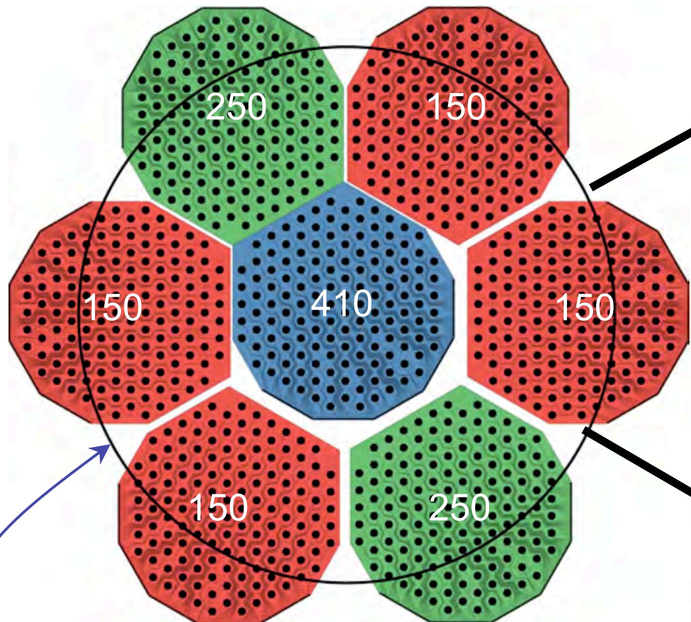


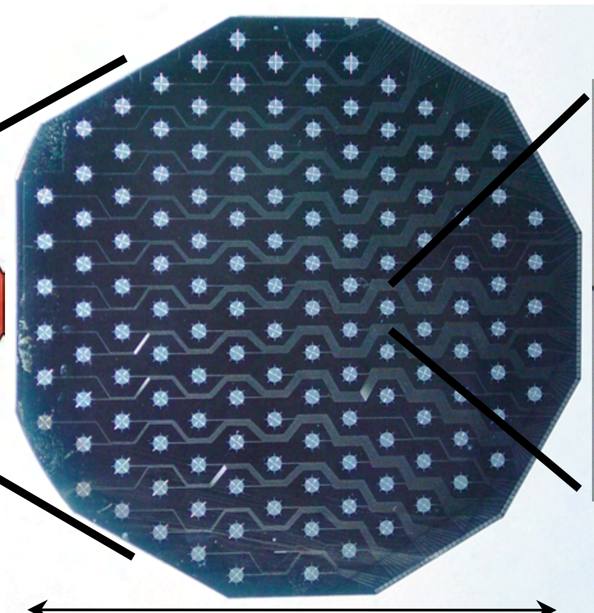
Focal Plane

738 element array

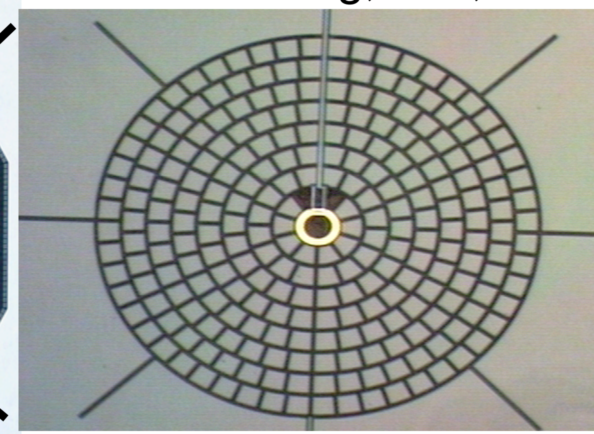
139 element decagon

Single TES





Meng, Lee, UCB



30 cm

8.6 cm

2.1 mm

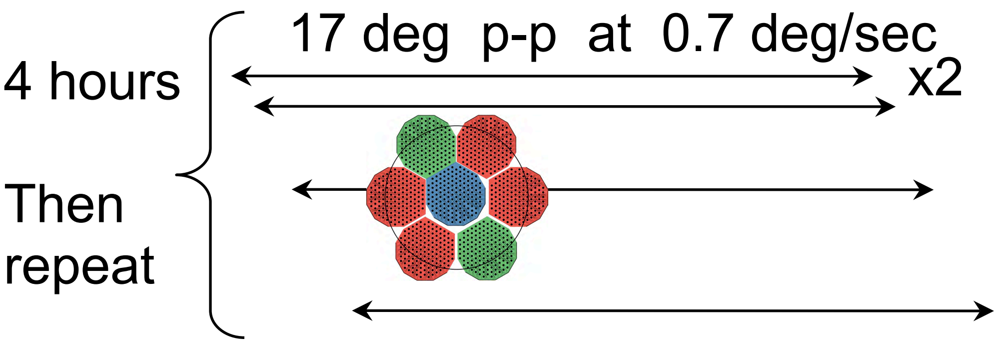
Strehl>0.85 at 250 GHz

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

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

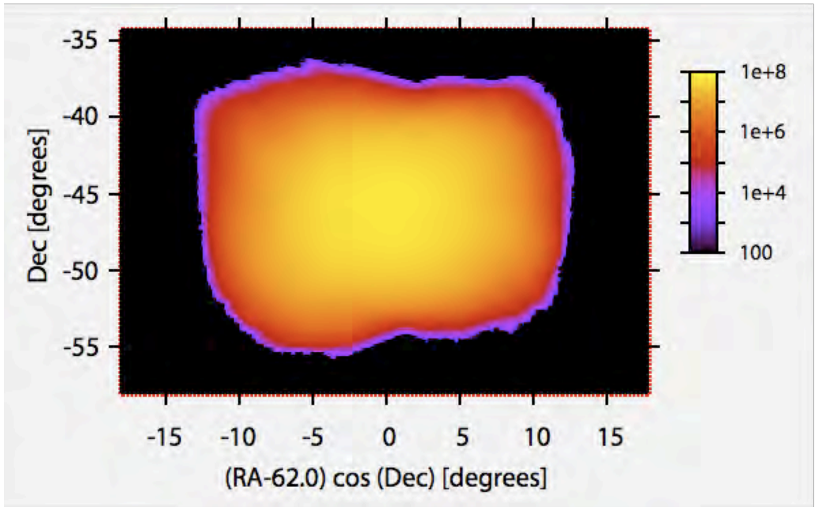
Scan + Coverage

Scan Profile:
- Constant elevation
- Speed: ~5 x (Q,U) per full beam
- Multiple visitations per pixel

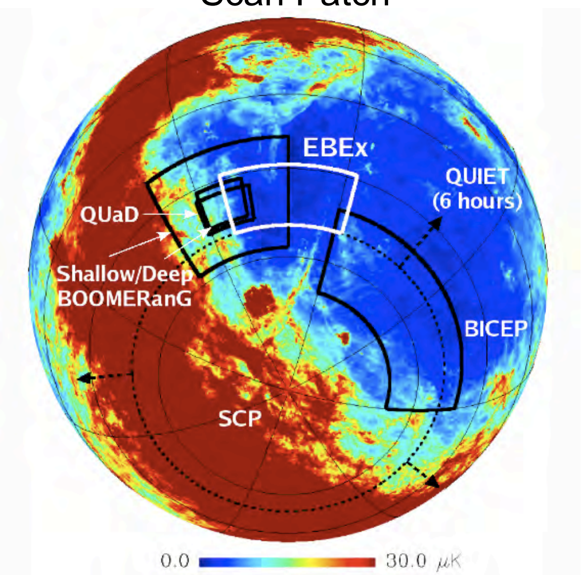


Coverage and Scan Area:
- Relatively uniform coverage
- Up to 10^8 samples/beam
- Scan area 420 deg^2
- Low dust contrast (4μK rms)

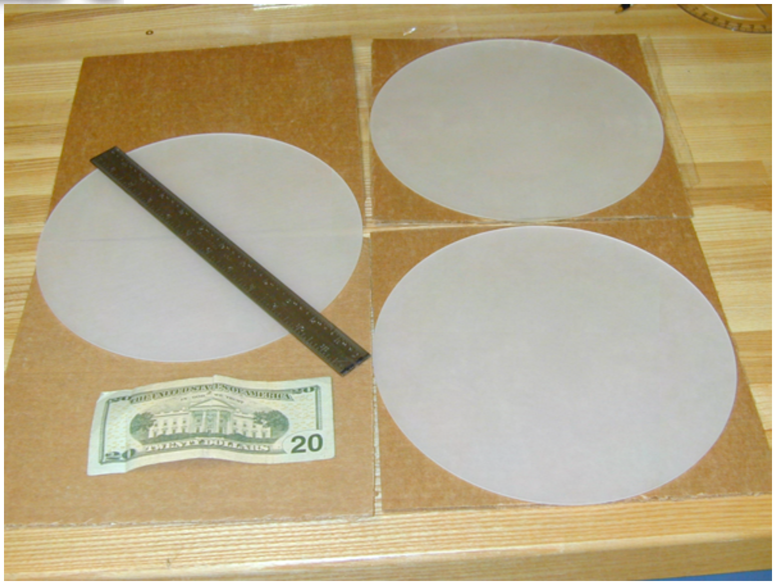
Scan Map for all (796) 150 GHz, 14 Days
(sample/beam in color scale)

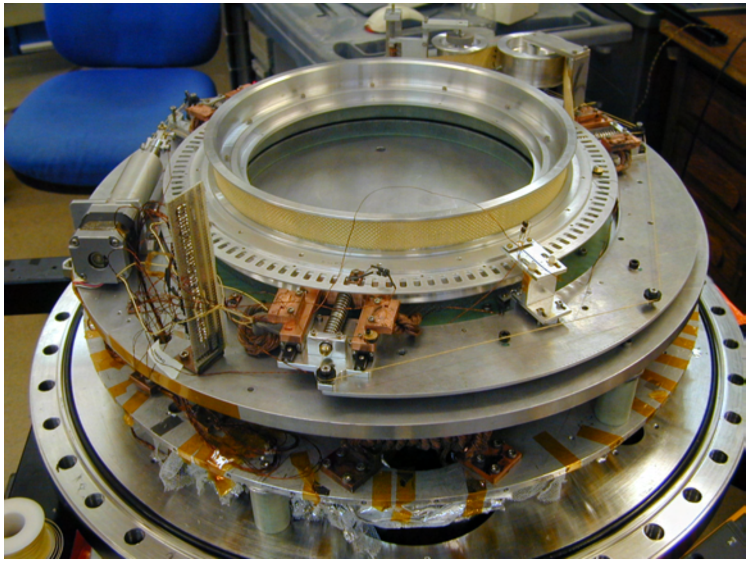


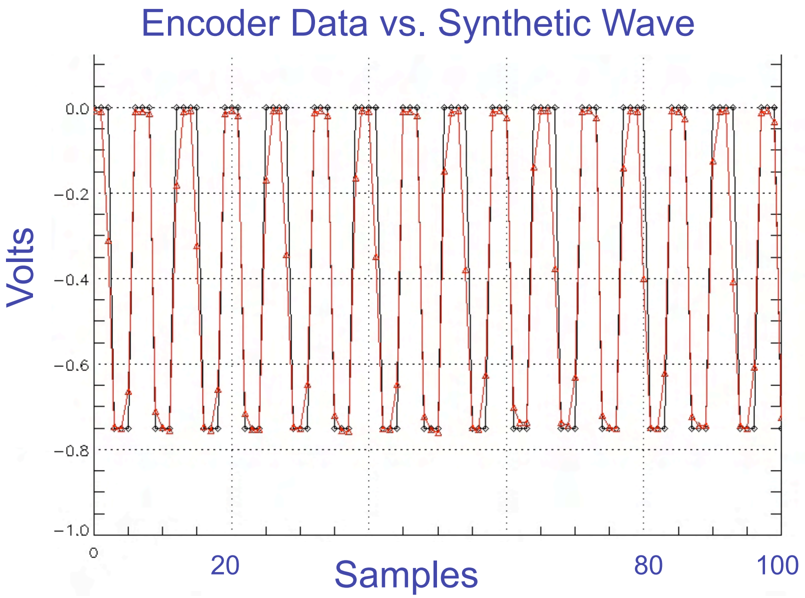
Scan Patch



Half Wave Plate Polarimetry







- HWP prototype bonded + thermally cycled
- ARC prototype bonded + thermally cycled
- AHWP now being bonded @ Cardiff
- Magnetic bearing tested end-to-end
- 0.25 degree angular encoding limited by sampling (0.3 deg required)

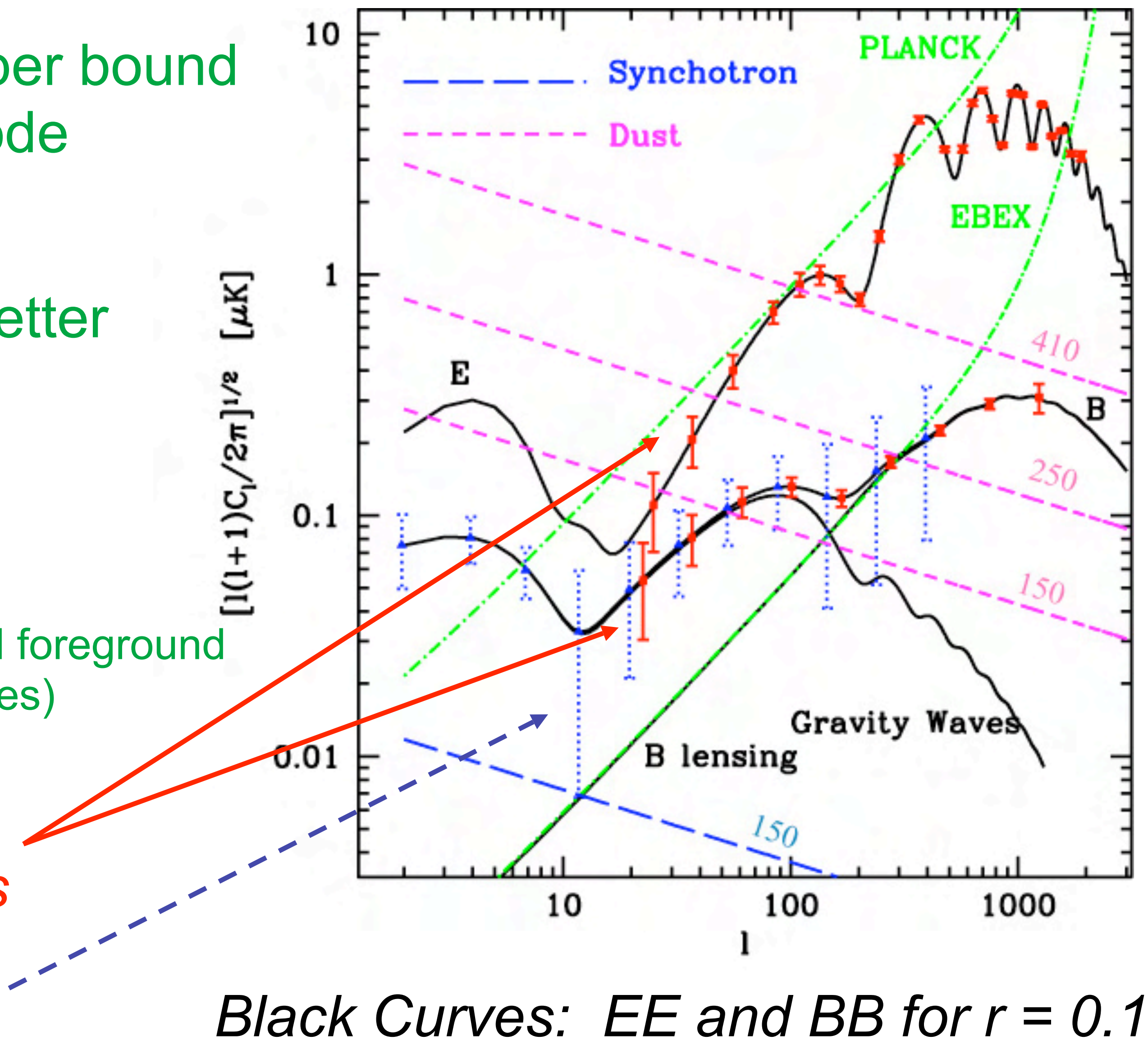
Science Goals I

1. Detect or set upper bound on inflation B-mode

If r = 0.1, S/N>5
Restrict r to ~x10 better than now:

$r < 0.02$ at 2σ

(excluding systematic and foreground subtraction uncertainties)



Black Curves: EE and BB for r = 0.1

SPIDER

2008

Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization

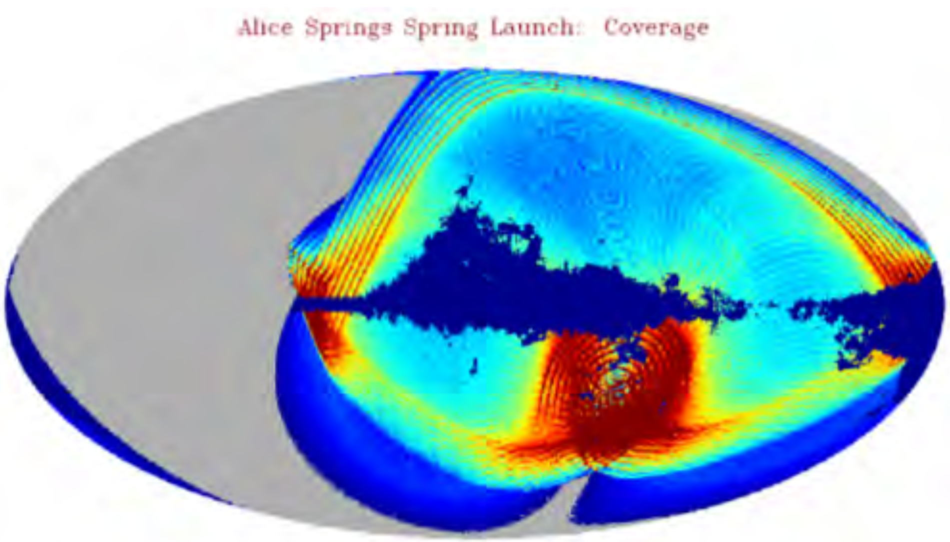
William Jones
Princeton University
for the
Spider Collaboration

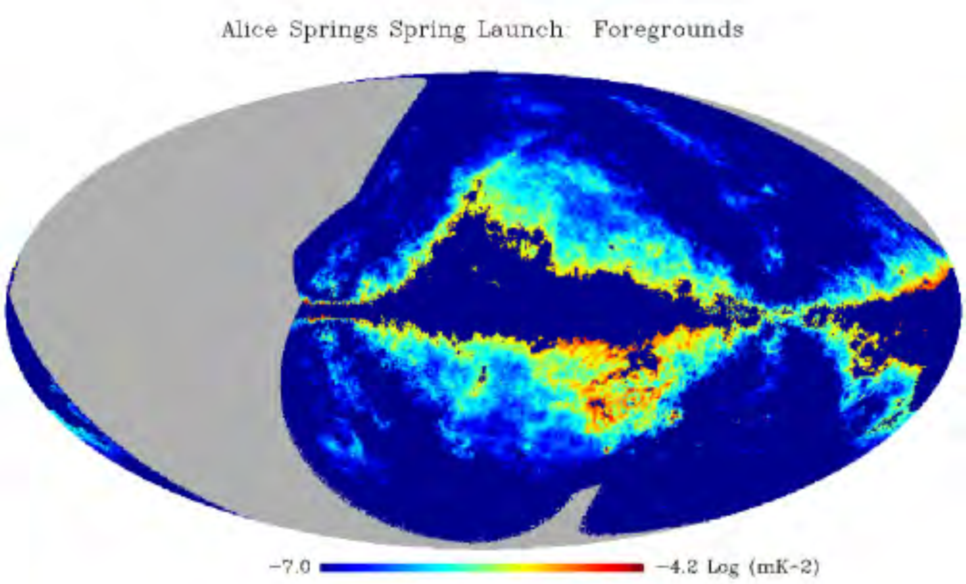
Inflation Probe Systematics Workshop
Annapolis, MD July 28-30

NASA · CSA ASC · C.S.B.F. Palestine, Texas · NSERC CRSNG · JPL · California Institute of Technology · University of Toronto · Case Western Reserve University · 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's Flight Schedule:

- April 2010: Alice Springs ~5-day turnaround flight
  - Achieve E-mode science goals
  - Establish competitive limits on scalar to tensor ratio
- 20+ day ULDB flight the following season
  - Characterize the B-mode spectrum
  - Map the Galactic polarized emission





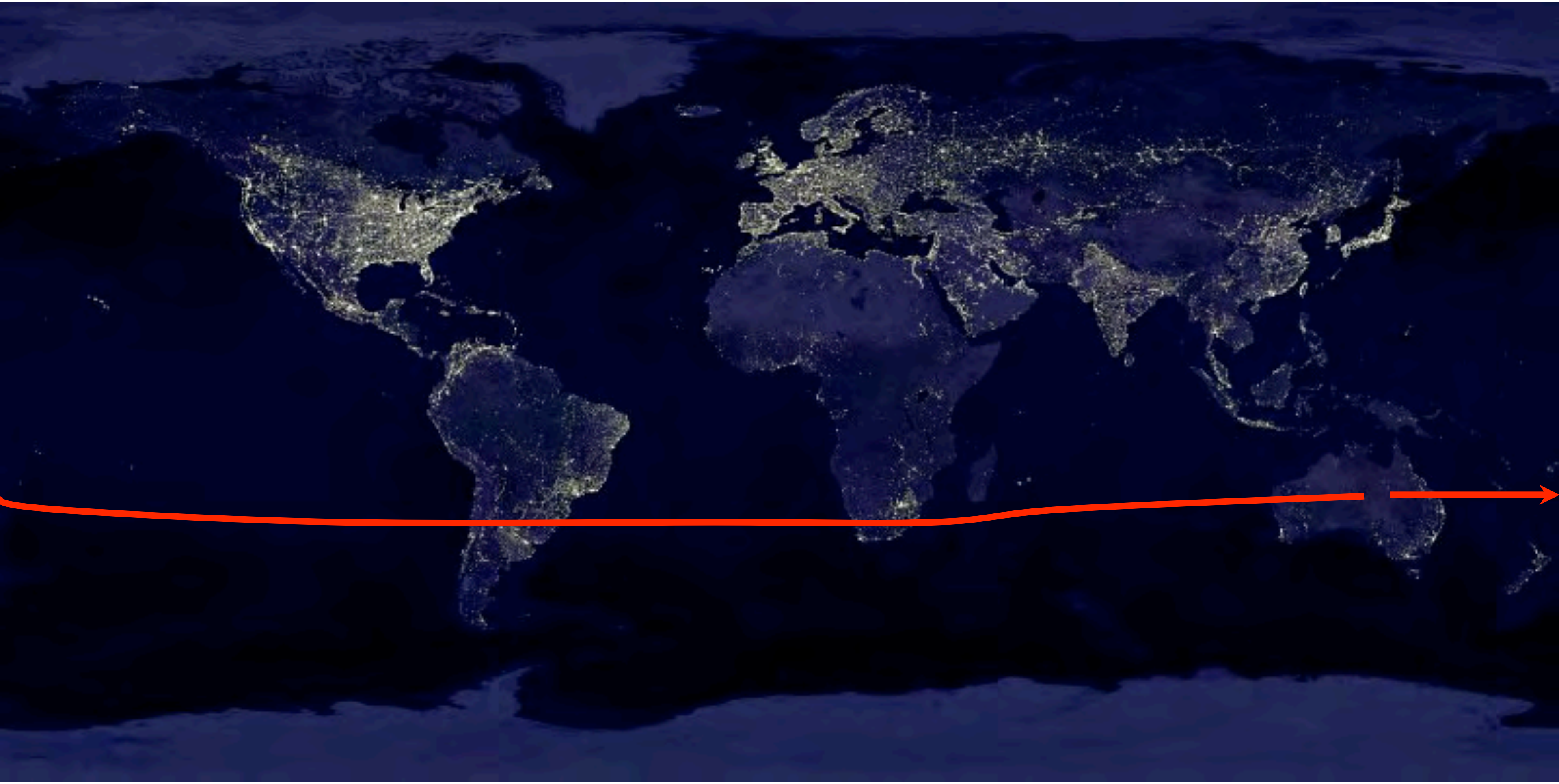
Spider Turnaround Flight: Experiment Details

Angular resolution	60 / 42	Arcminutes
Frequency Coverage	96 / 145	GHz
Sky Coverage	60%	24800 deg^2
Multipole Coverage	8 - 300	-
Polarization Modulation?	Stepped HWP	-
Types of Detectors	Antenna coupled TES	-
Location	Balloon	-
Instrument NET	4 / 3	$\mu K\ s^{1/2}$
Limit on *r*	< 0.15	$3\ \sigma$
Status	April 2010	-

Spider LDB Flight: Experiment Details

Angular resolution	60 / 40 / 30	Arcminutes
Frequency Coverage	96 / 145 / 220	GHz
Sky Coverage	60%	24800 deg^2
Multipole Coverage	8 - 300	-
Polarization Modulation?	Stepped HWP	-
Types of Detectors	Antenna coupled TES	-
Location	Balloon	-
Instrument NET	4 / 3 / 9	$\mu K\ s^{1/2}$
Limit on *r*	< 0.04	3 σ
Status	April 2010	-

Spider Long Duration Balloon Flight

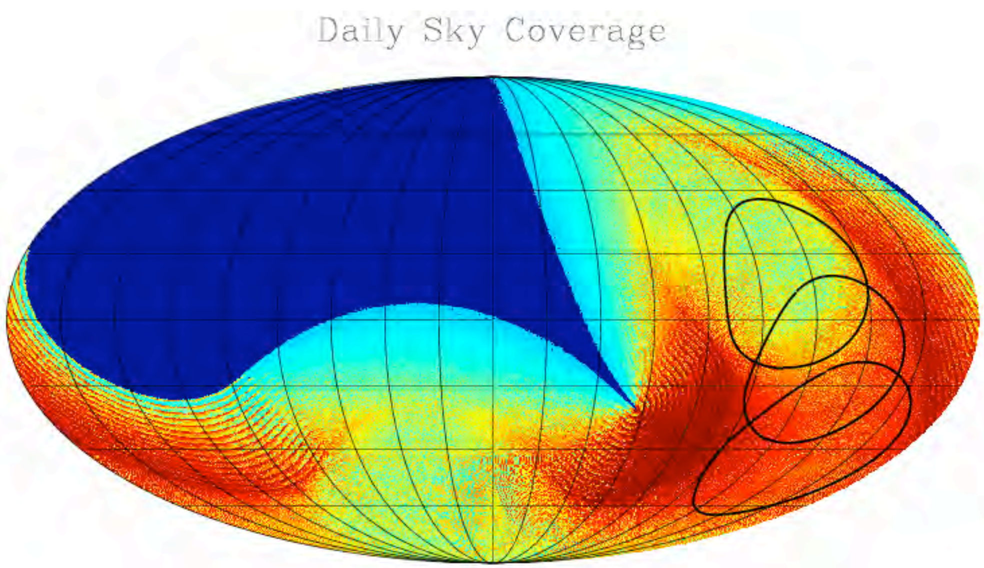


Flight test of the 34H: 8000 lbs suspended mass

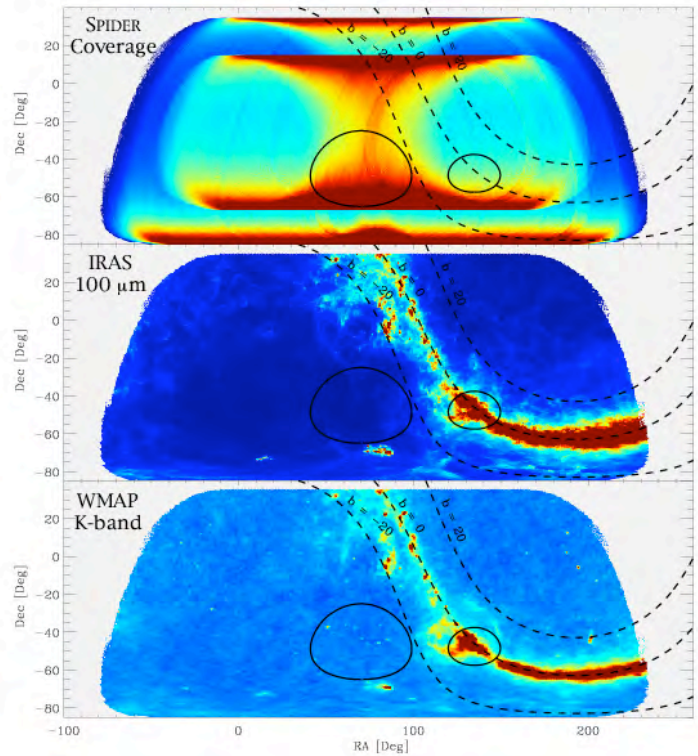
May 31

Spider's Scan Strategy

- 36 deg/s gondola spin rate at night
- HWP stepped 22.5 degrees once per day
- paired telescopes clocked by 45 deg
- pointed sinusoidal scanning during the day

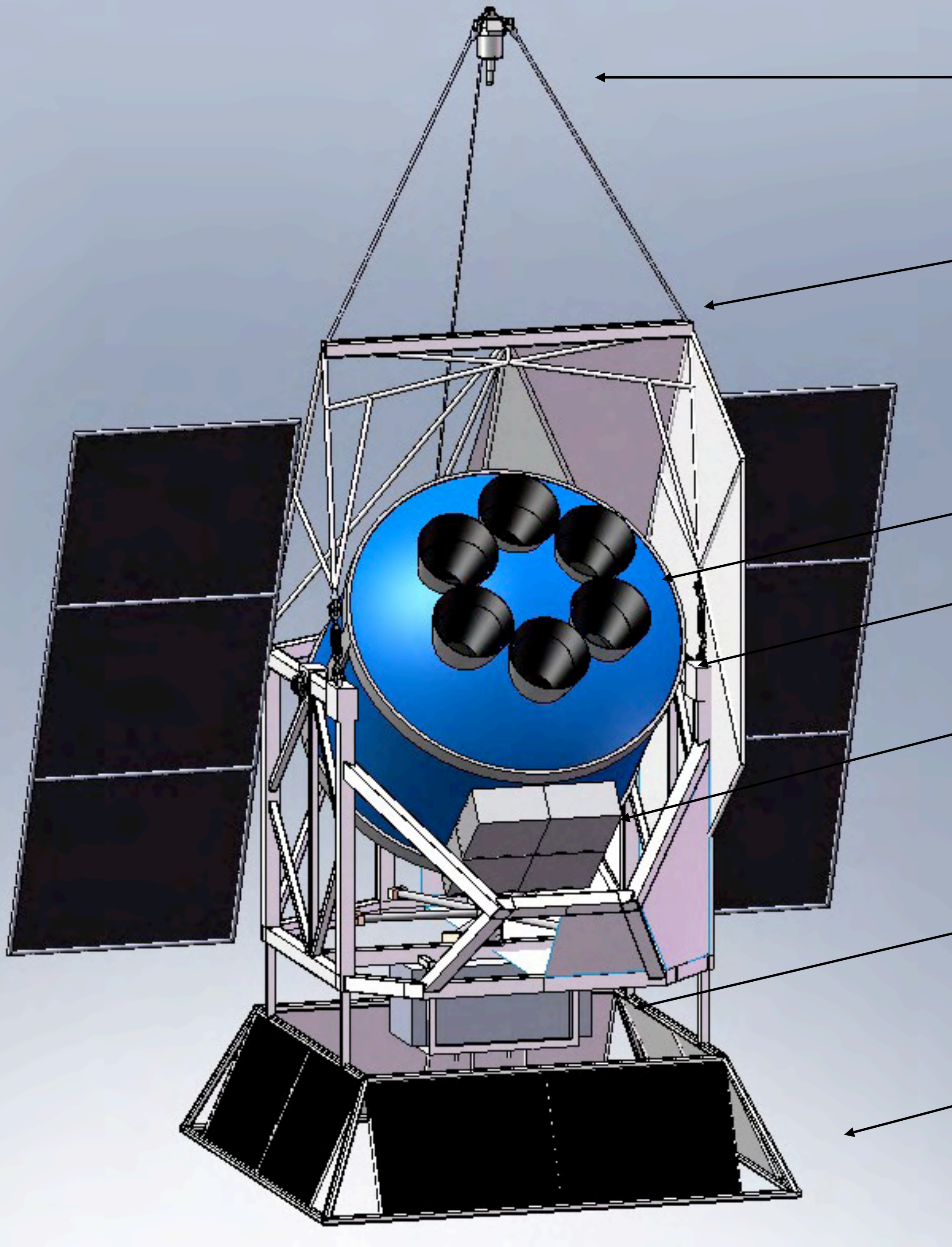


Galactic Coordinates



Celestial Coordinates

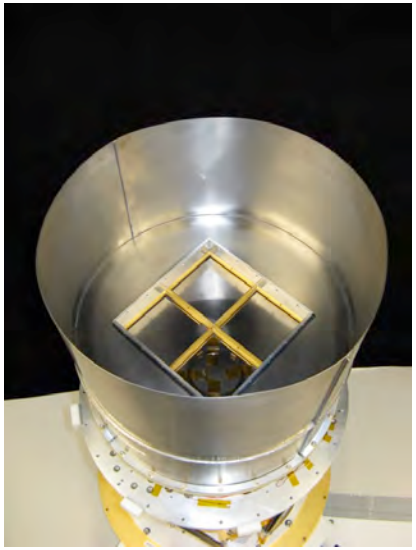
Note: coverage shown for Austral Summer launch

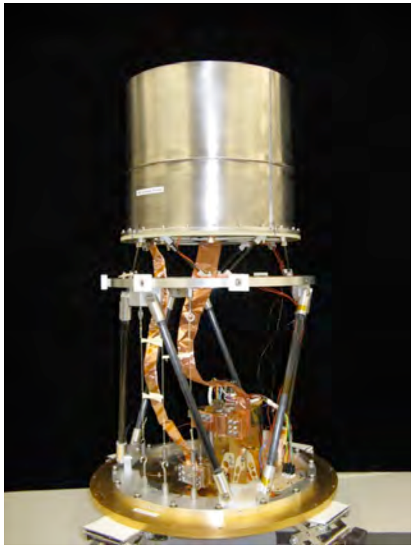


Pivot to flight train
Carbon Fiber Gondola
Science solar array
and Sun shields
Six single freq. telescopes
35 day, 1950 lb,
4K / 1.4 K cryostat
MCE arrays
Flight Computers/ACS
SIP and CSBF
Solar arrays

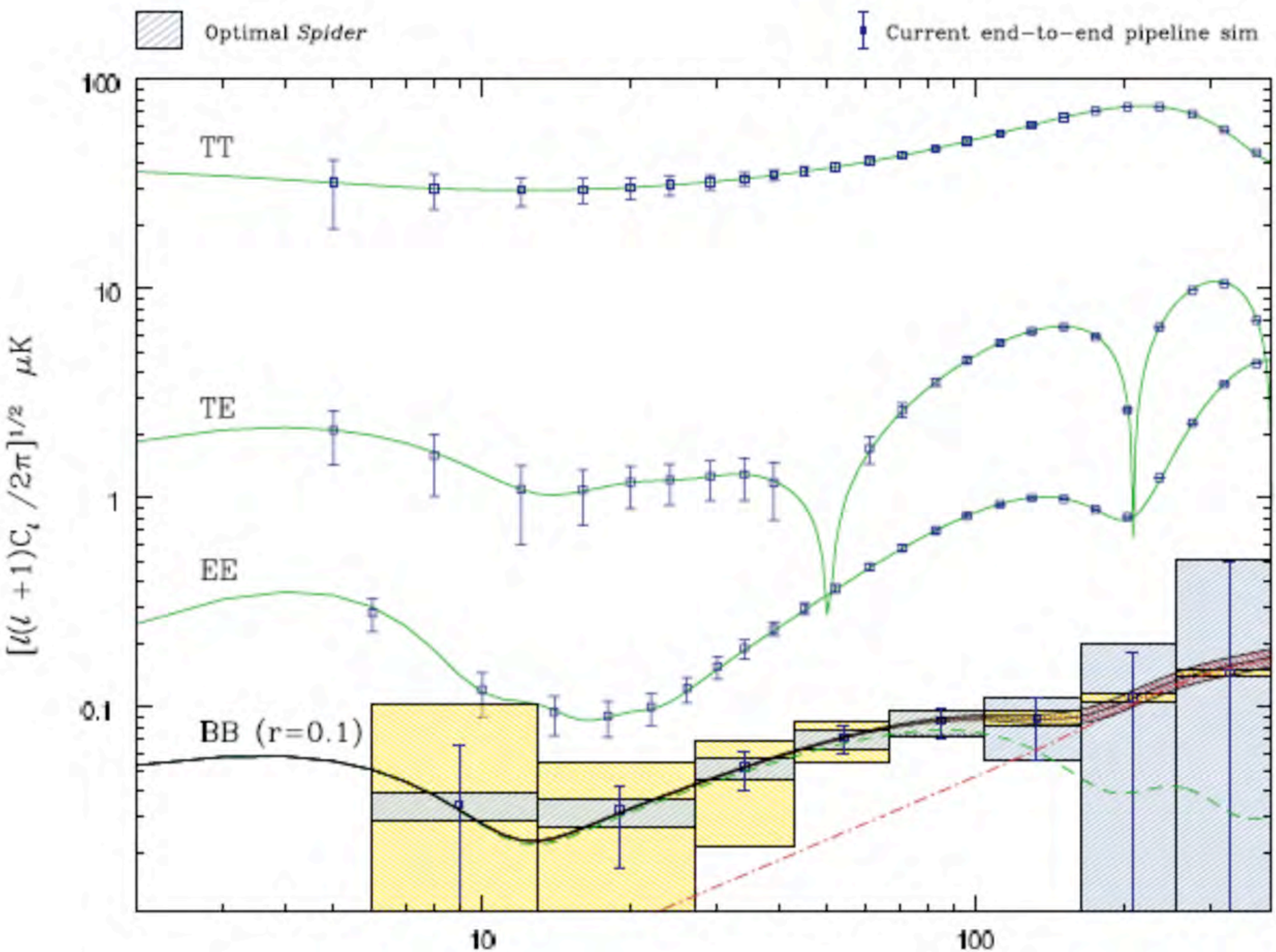
Spider Fabrication and Integration

- 4K optics and carbon fiber truss
- 1.4K superconducting shield / FPA enclosure
- Graphite standoffs to FPA
- Arrays fully enclosed in 300 mK box
- 4 days (and 180L LHe) from 300 K to 300 mK





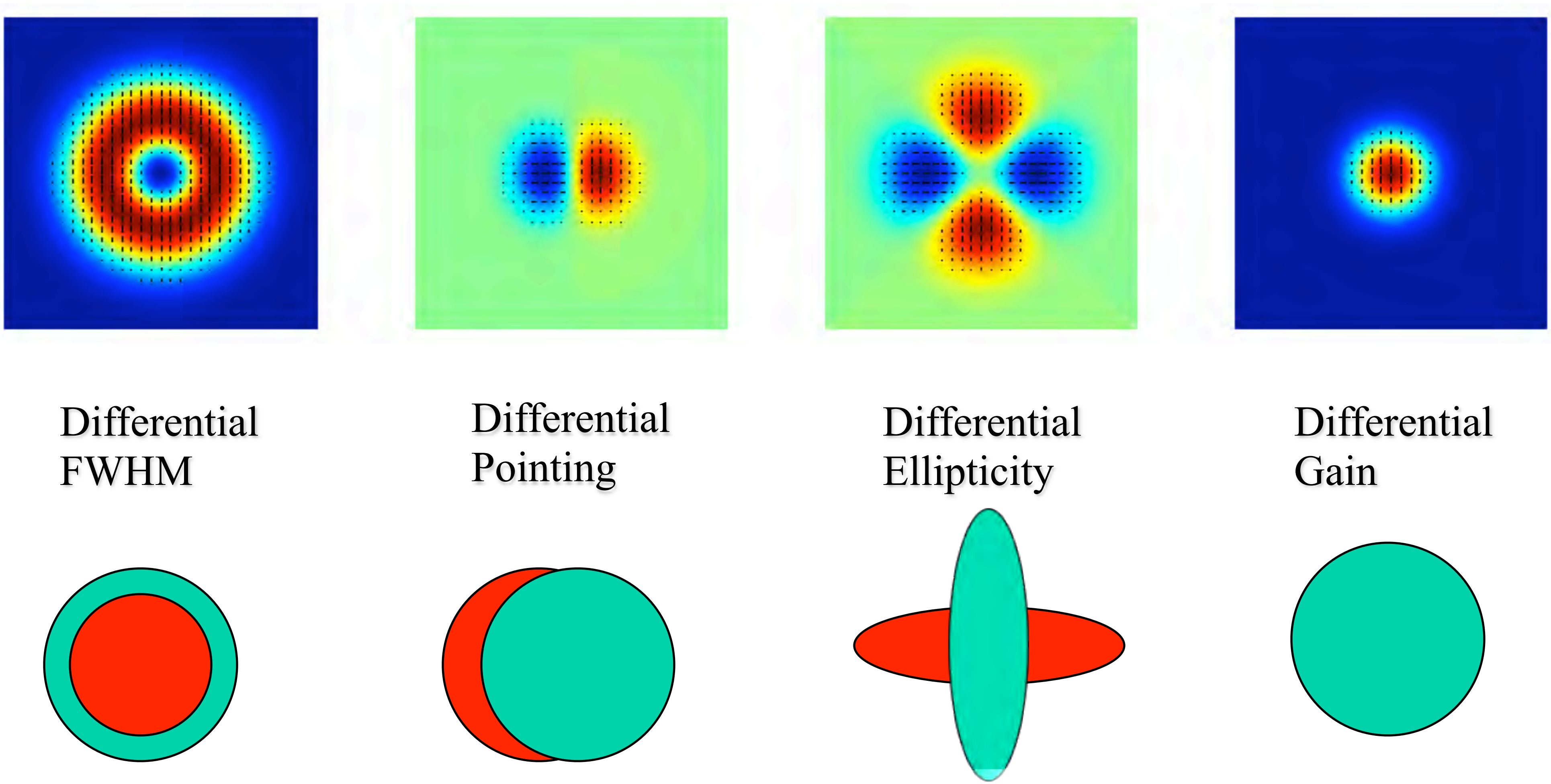
Turnaround Flight



Issues

- Can we separate E from B?
  - Yes - Kendrick & Zaldarriaga astro-ph/0610059
- Are clean patches as clean as we think?
  - Time will tell, but all expt are multi-freq anyway
- Can we de-lense?
  - In principle yes but realistic sims have not been done
- Is pol modulation needed?
  - Most experiments are including HWP, stepped or continuous.
- What are the experimental requirements on beams and detector stability?
  - A lot of confusion right now - depends on instrument type
    - Sufficiently realistic sims yet to be done...

Beam Effects



Weiss report table

Table 6.1: Instrument Performance Goals

Parameter	Effect	Goal	Me
Cross-Polar Beam response	E →B	< 0.003	Rotate Instrum
Main lobe ellipticity (0.5° beam)	dT → B	$< 10^{-4}$	Rotate Instrum
Polarized sidelobes (response at Galaxy)	dT → B	$< 10^{-6}$	Baffles/shieldi
Instrumental polarization	dT → B	$< 10^{-4}$	Rotate Instrum
Polarization angle	E → B	< 0.2 °	Measure
Relative pointing (of differenced samples)	dT → B	< 0.1″	Dual-polarizati
Relative calibration	dT → B	$< 10^{-5}$	Modulators
Relative calibration drift (scan synchronous)	T → B	$< 10^{-9}$	Modulators
Lyot Stop Temperature (10% spill, scan synch.)	dT_{opt} → B	$dT_{opt} < 30$ nK	Measure
Cold stage T drifts (scan synch.)	dT_{CS} → B	$dT_{CS} < 1$ nK	Improve unifor

TABLE 6.1 *Performance goals for a CMB* **B**-*mode measurement. The first eight para* *instrumental effects that transform various sky signals into false* **B**-*mode signals; here* *indicate intensity,* **E** *to indicate the* **E**-*mode polarization signal, and* **dT** *to indicate CM* *anisotropies. The listed "Goal" is the level at which an individual instrumental effect* *cause a 10% contamination (in units of temperature) of an* **r** = *0.01* **B**-*mode signal in t* *experimental design. Clever scan strategies and partial correction of known levels of c* *can relax these requirements. See the text for more details.*

Conclusions

- Detection of Gravity wave B-modes would be "smoking gun" for inflation
  - Everyone agrees this is extremely important/exciting science
- This has provoked many competitive experiments...
  - Most of them are targeting the l=70 bump via small ultra clean regions of sky
- Very high sensitivity will come online within 2 years from now
  - These experiments ought to be able to get close to r=0.01 with no (or simple) foreground removal
  - To go lower requires de-lensing which will be very hard...