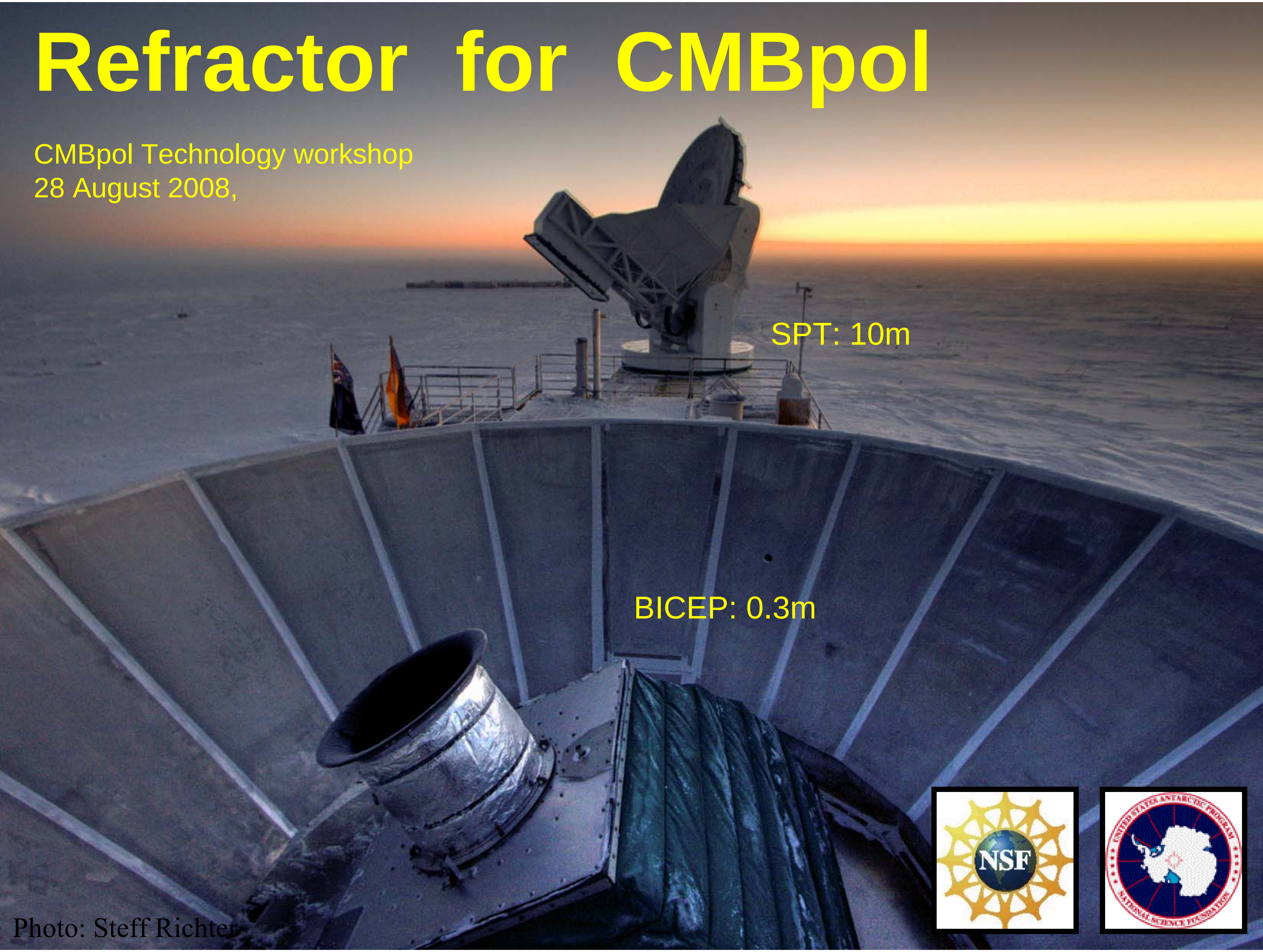
Refractor for CMBpol

CMBpol Technology workshop
28 August 2008,

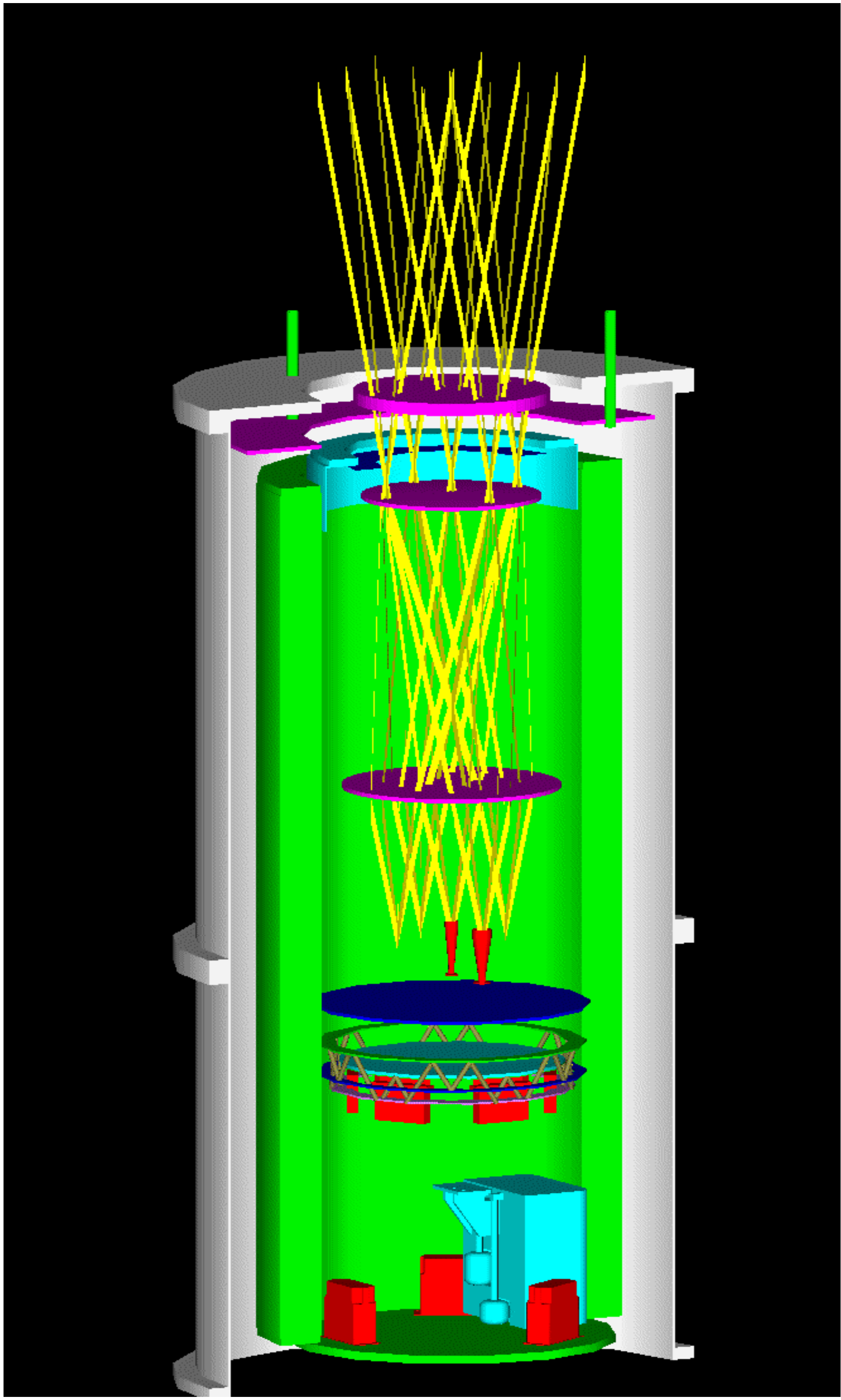


BICEP optics

- Wide-field refractor:
  - Cold Optics: 2 lenses + filters
    - HDPE lenses (Darren Dowell)
    - Teflon AR coat (Chao-Lin Kuo)
  - 30cm -> 0.9°, 0.6° FWHMs
  - High throughput, 17° FOV
  - Instr-pol< 1%, Cross-pol< 0.01%
  - Flat, telecentric focal plane
  - Ready for lithographed arrays!

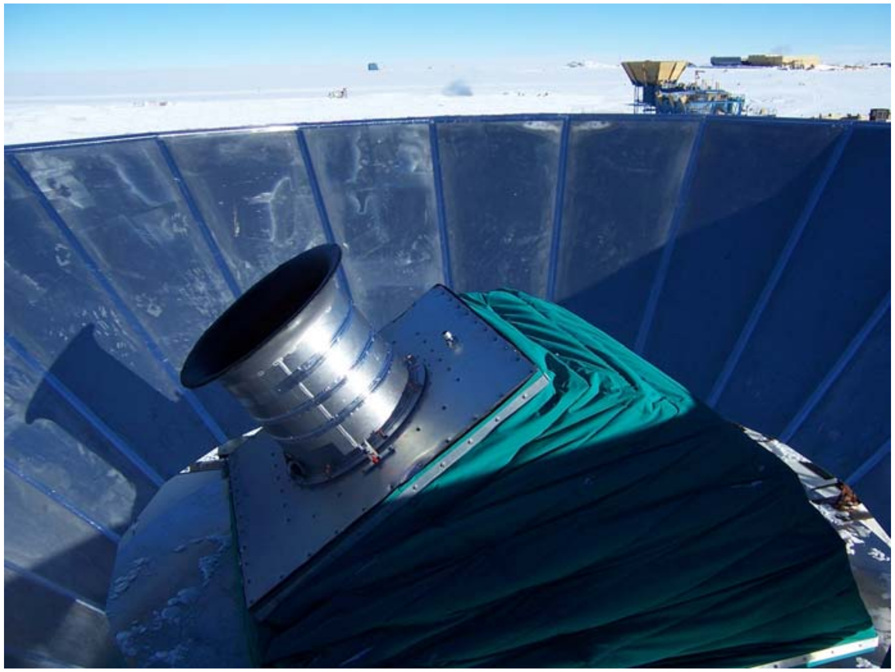
  -> BICEP2/Keck, Spider

  ->CMBpol?



Why did we choose a small refractor?

- High throughput in smallest possible package
- Efficient ($) to integrate / deploy
- Stability of 4K telescope &beams
- Ease of optical characterization (~100m range)
- Aperture filling calibrators
- Aperture filling waveplate (BICEP2/Keck)
- Superior sidelobe suppression

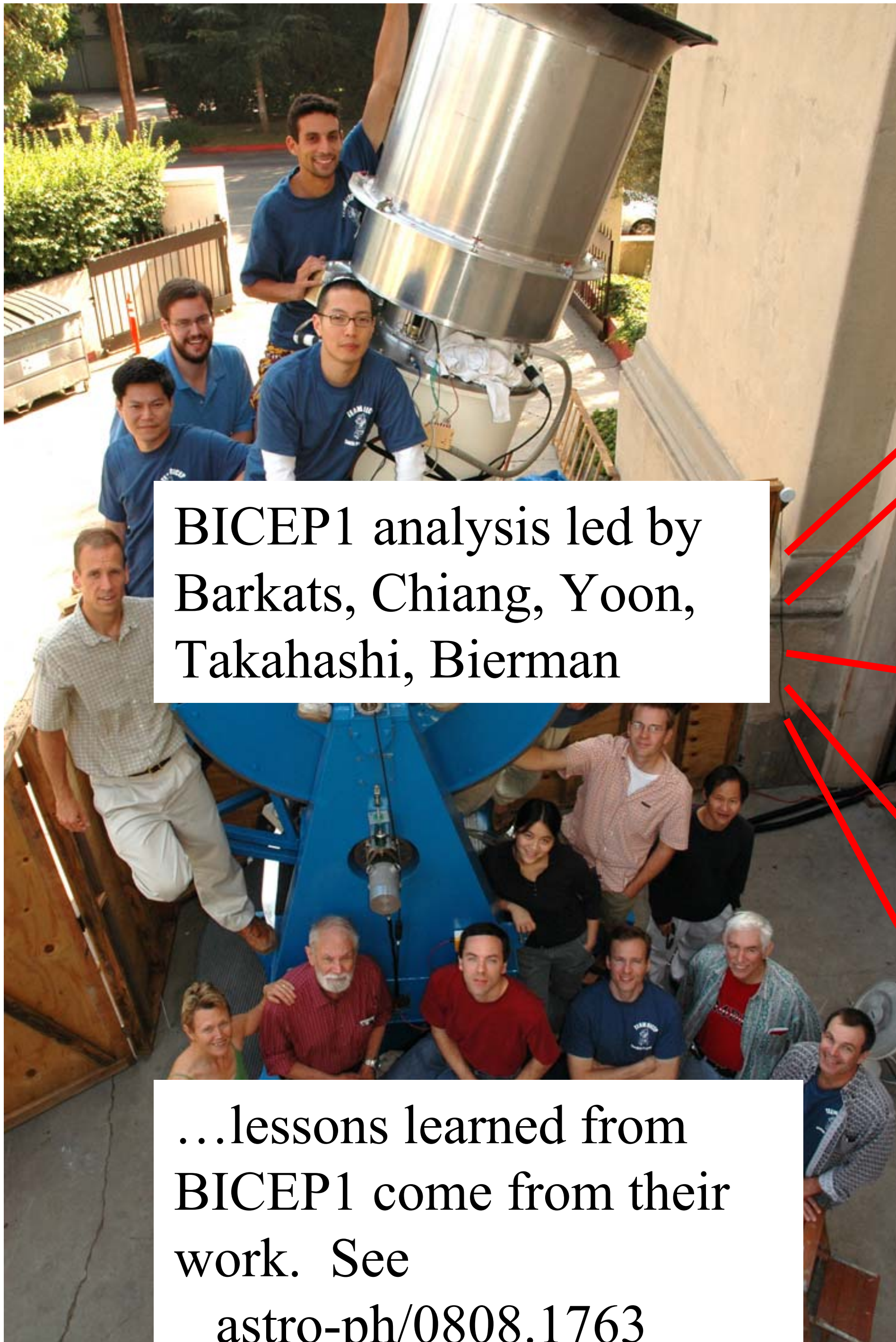


Why might CMBpol choose a small refractor?

- High throughput in smallest possible package (?)
- Efficient ($) to integrate / deploy
- Stability of 2K telescope &beams
- Ease of optical characterization (~100m range)
- Aperture filling calibrators(?)
- Aperture filling waveplate
- Superior sidelobesuppression
- Monochromatic optics – higher TRL
- easier to shield ?
- Proven heritage: BICEP1, BICEP2, Keck, Spider…

BICEP1 refractor:
lessons learned…

TEAM BICEP



BICEP1 analysis led by Barkats, Chiang, Yoon, Takahashi, Bierman

…lessons learned from BICEP1 come from their work. See astro-ph/0808.1763

Caltech
Andrew Lange
John Kovac
Denis Barkats
Cynthia Chiang
Greg Griffin
Steffen Richter

NIST, Boulder
Ki Won Yoon

UC Berkeley:
Bill Holzapfel
Yuki Takahashi

UC San Diego:
Brian Keating
Evan Bierman

Cardiff U.:
Peter Ade

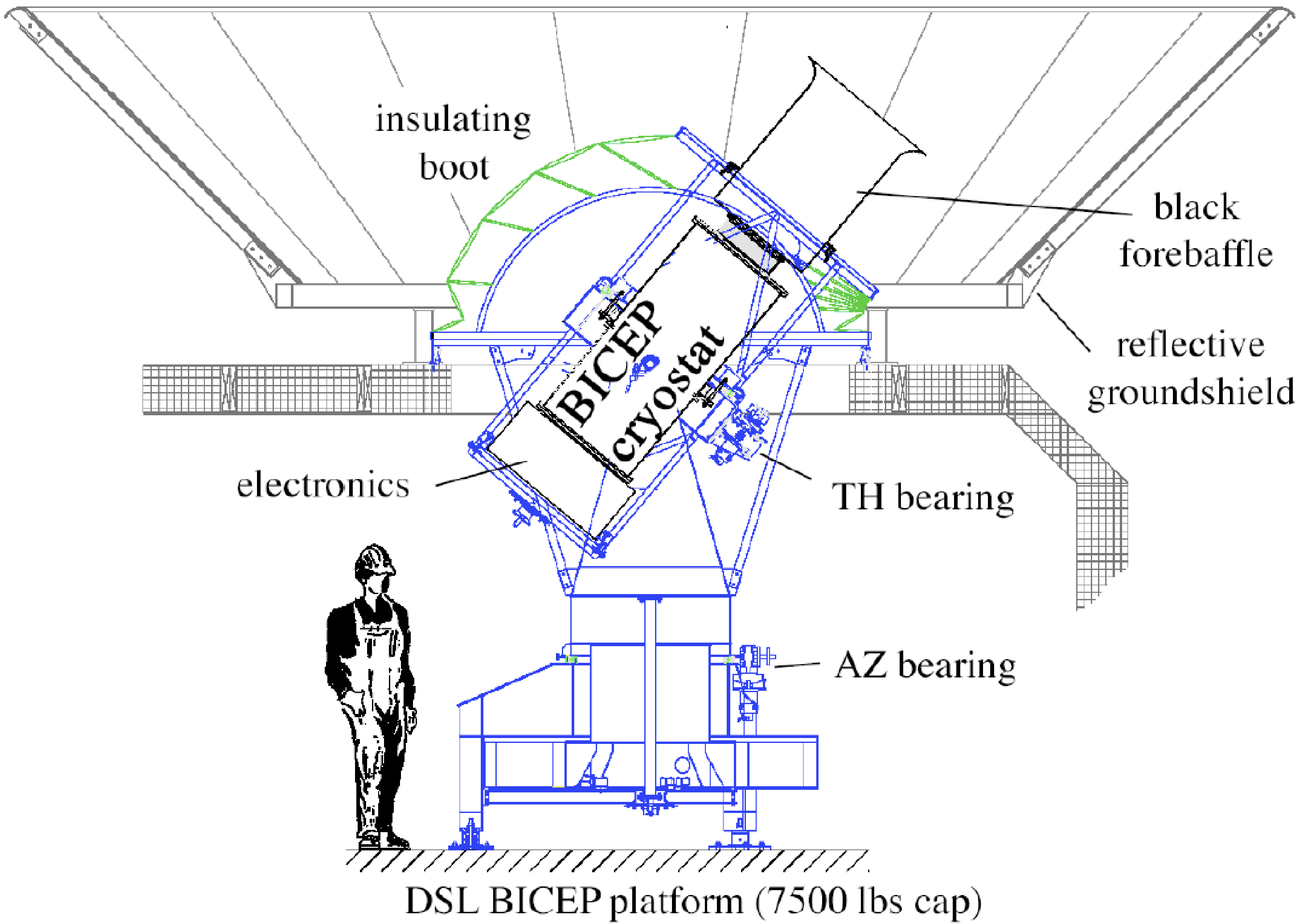
JPL
Jamie Bock
Darren Dowell
Hien Nguyen
Peter Mason
Erik Leitch
Viktor Hristov
John Battle

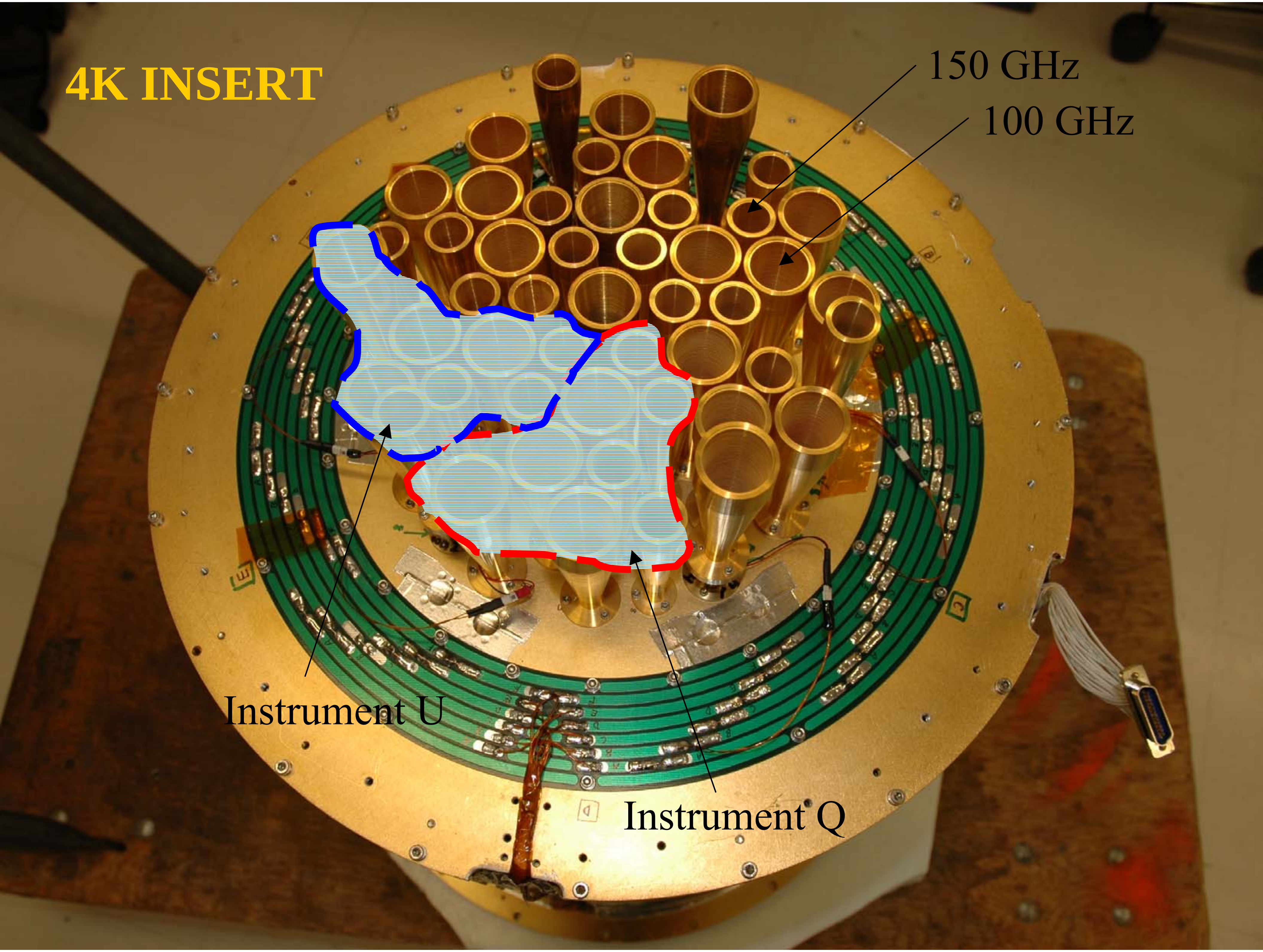
Stanford
Chao-Lin Kuo

Chicago
Clem Pryke
Chris Sheehy

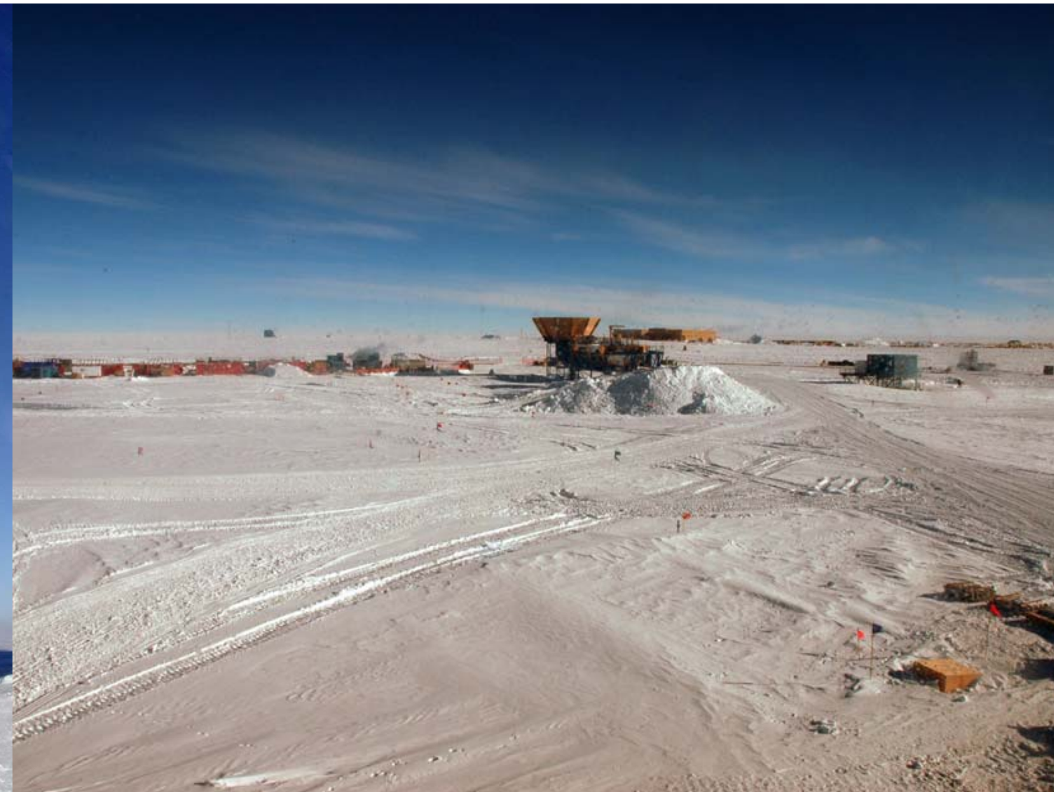
CEA, Grenoble:
Lionel Duband

IAS, Paris:
Eric Hivon
Nicolas Ponthieu

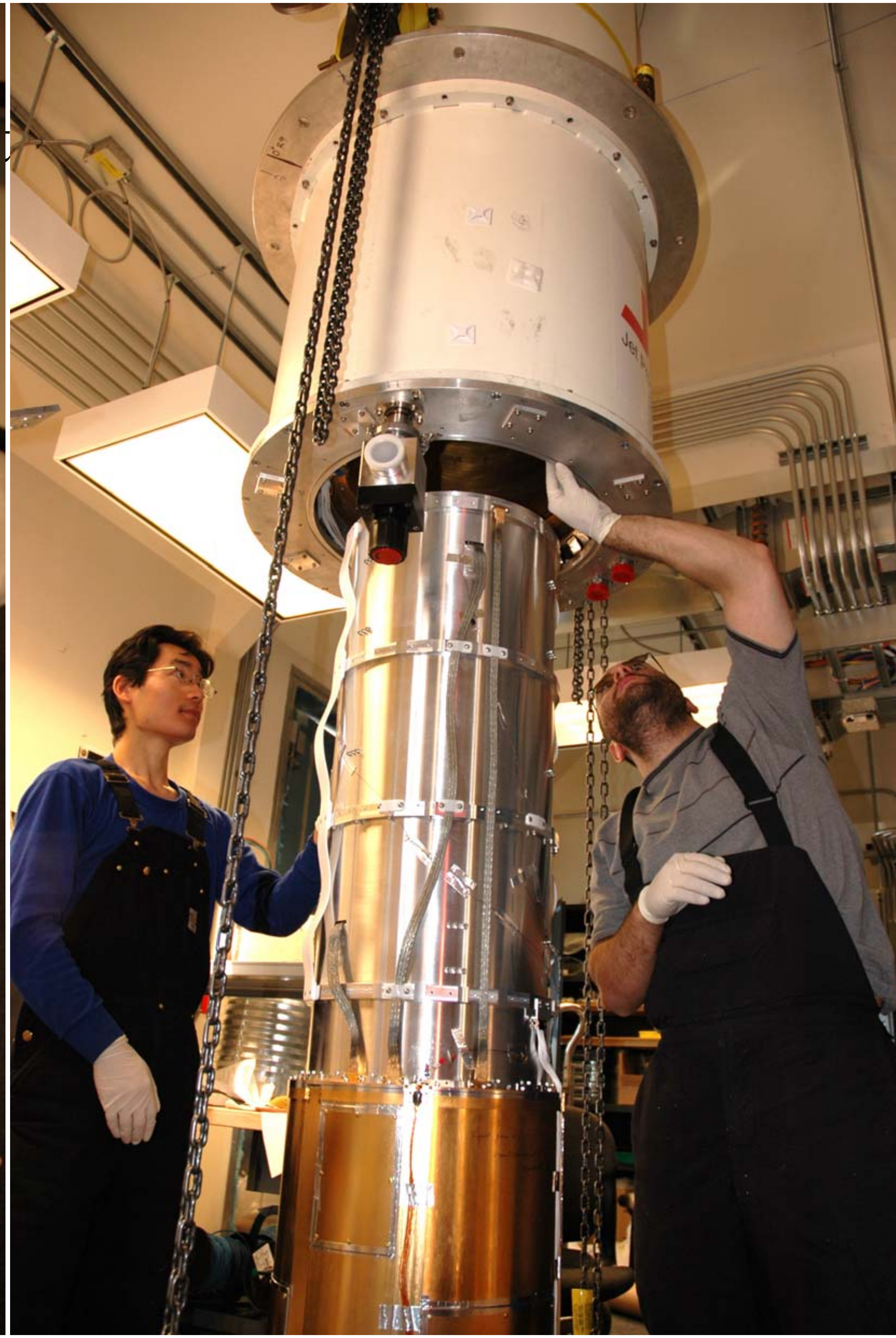

insulating
boot
black
forebaffle
reflective
groundshield
BICEP
cryostat
electronics
TH bearing
AZ bearing
DSL BICEP platform (7500 lbs cap)

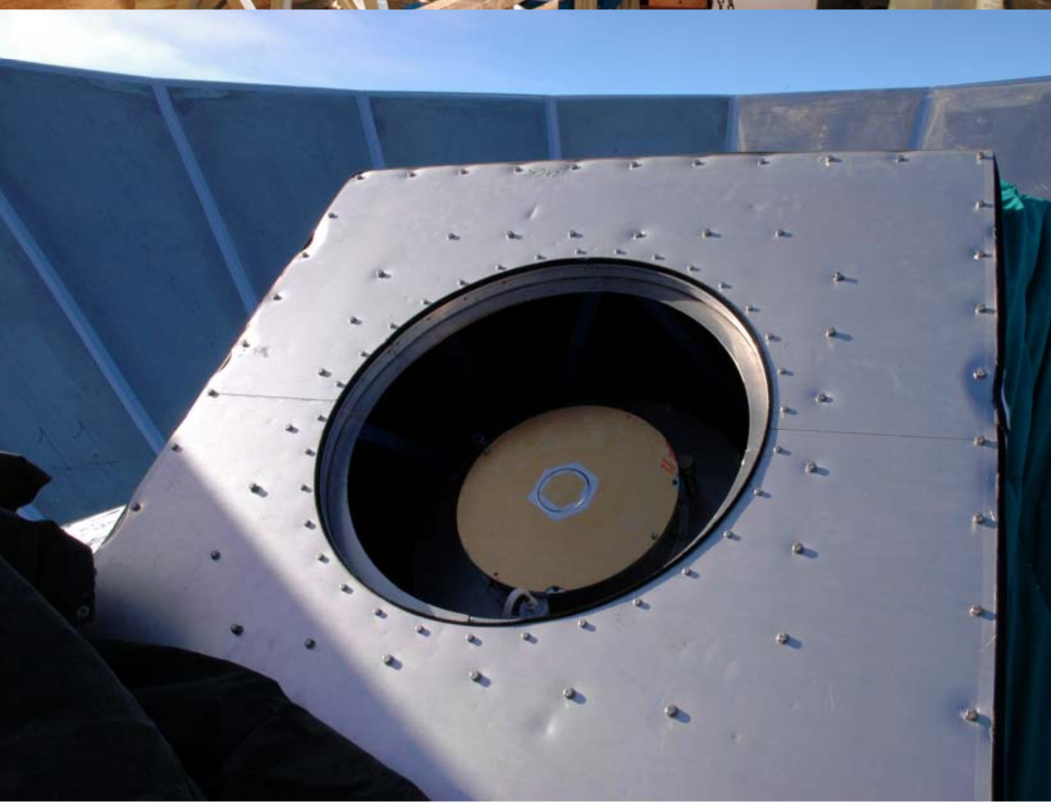

4K INSERT
150 GHz
100 GHz
Instrument U
Instrument Q


Dark Sector Laboratory




November 2005...





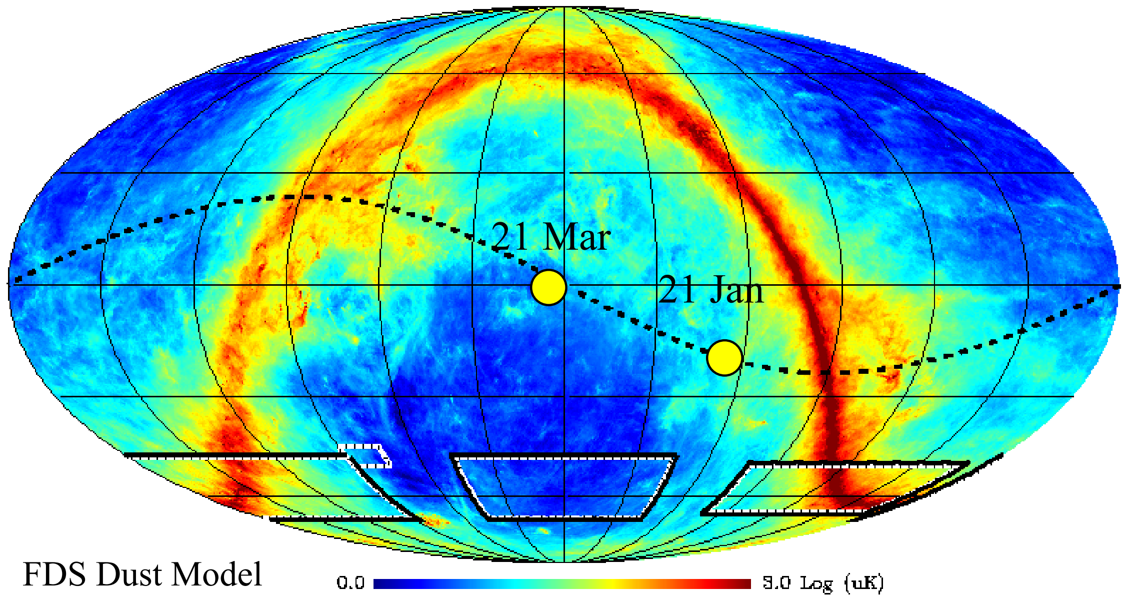
Early January 2006:
a working instrument!

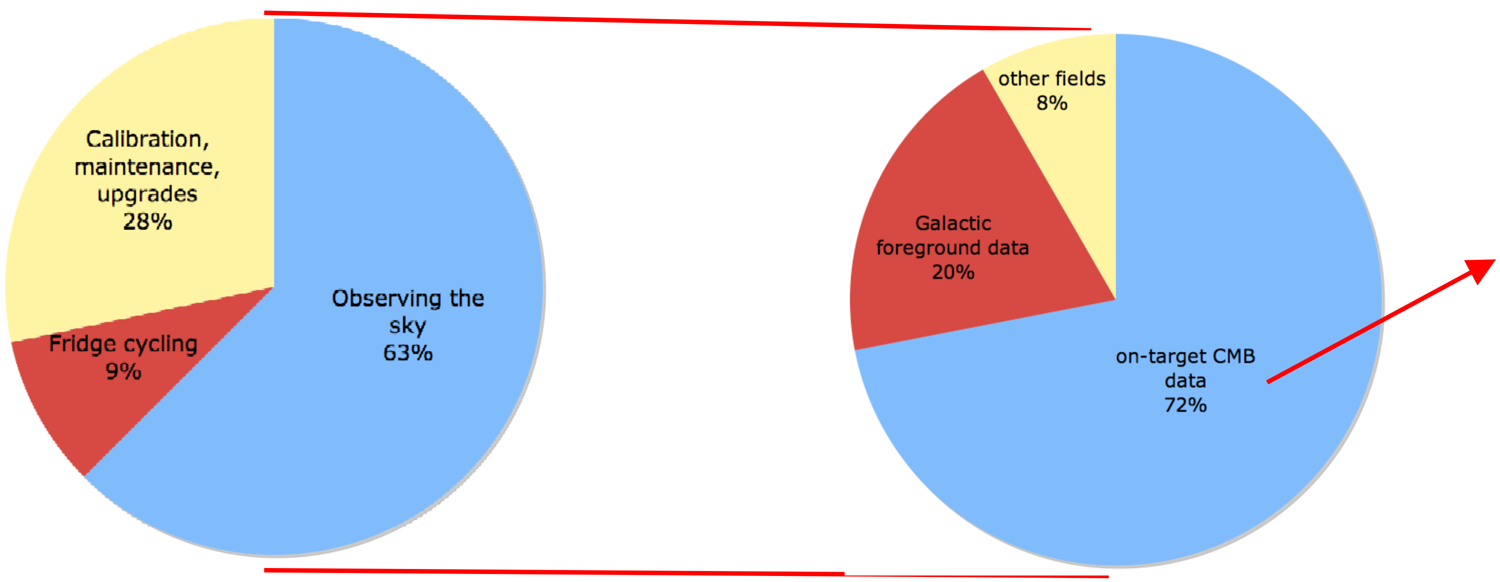
March 2006 – March 2008: Observations to-date

CMB obs started March 4th 2006

24 months (17500 hours) since then:

	HOURS
Observing the sky	10900
Fridge cycling, Cryo ops	1640
Calibration, maintenance, upgrades	4950

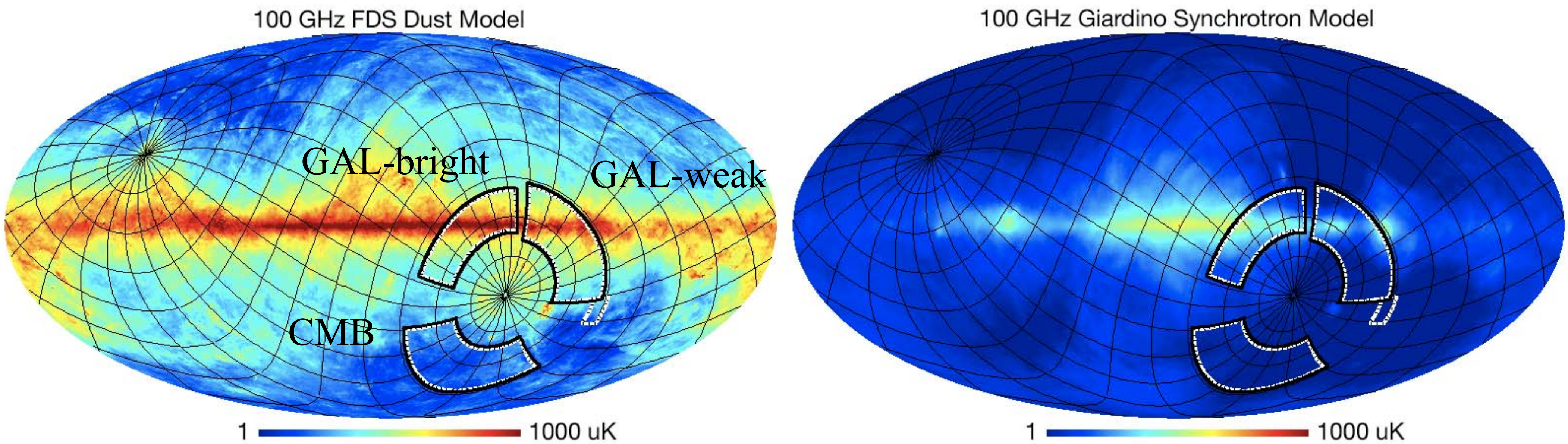




Good CMB-field data, afterweather and othercuts = 5700 hours

Greatobservingef ficiency!

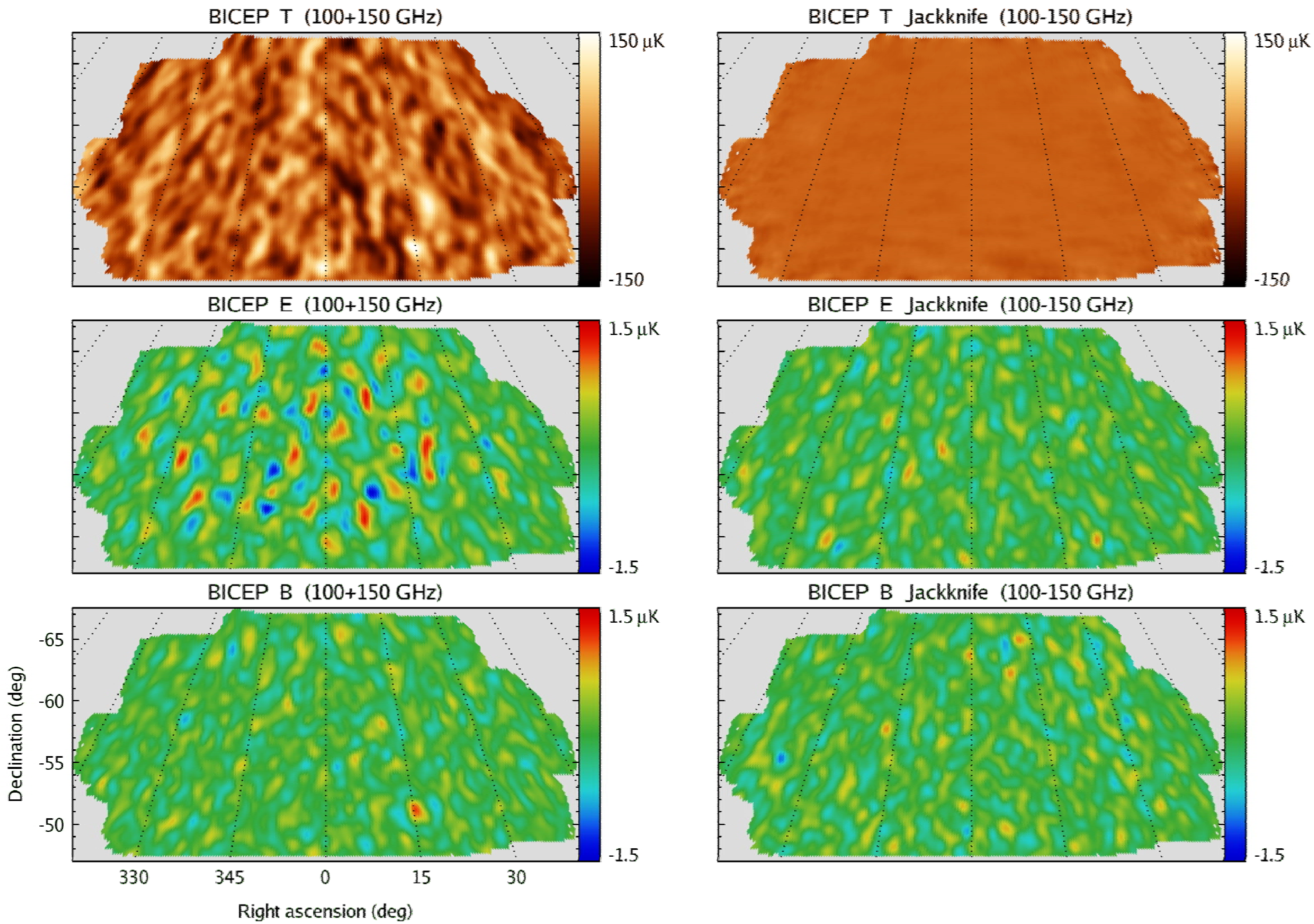
Observed Fields



Observations in 48-hour cycles:

[day 1]		[day 2]	
6 hrs:	A. cycle fridge	6 hrs:	D. GAL-weak
9 hrs:	B. CMB (lower half)	9 hrs:	E. CMB (upper half)
9 Hrs:	C. CMB (upper half)	9 hrs:	F. CMB (lower half)

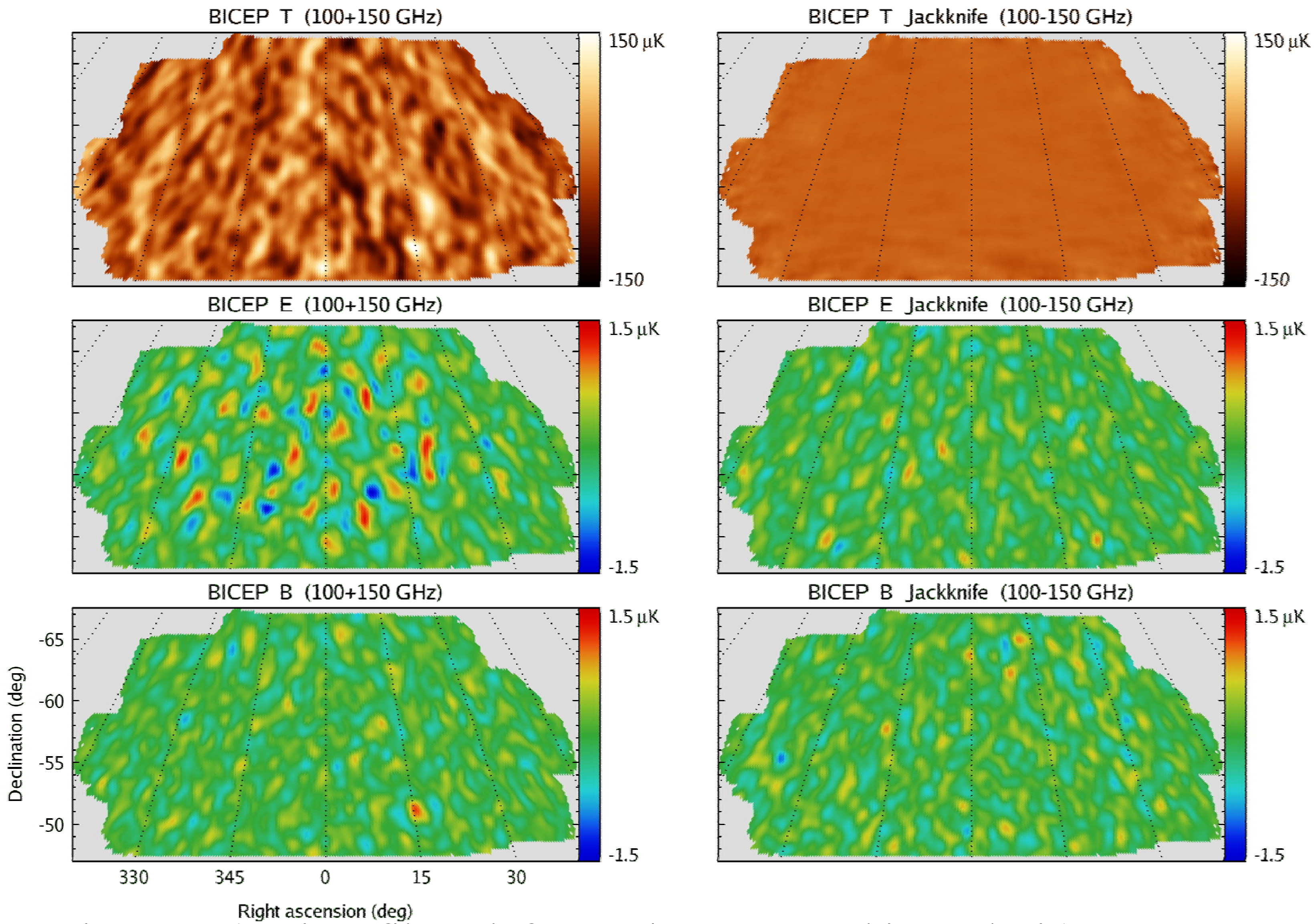
Preliminary T/E/B Maps



-Data from first 2 years (2006 March through 2007 October).

- Temperature anisotropy measured with very high S/N
    - precise absolute calibration vs. WMAP on 2-day timescales.
    - faint striping due to ATM noise, removed by PSB differencing

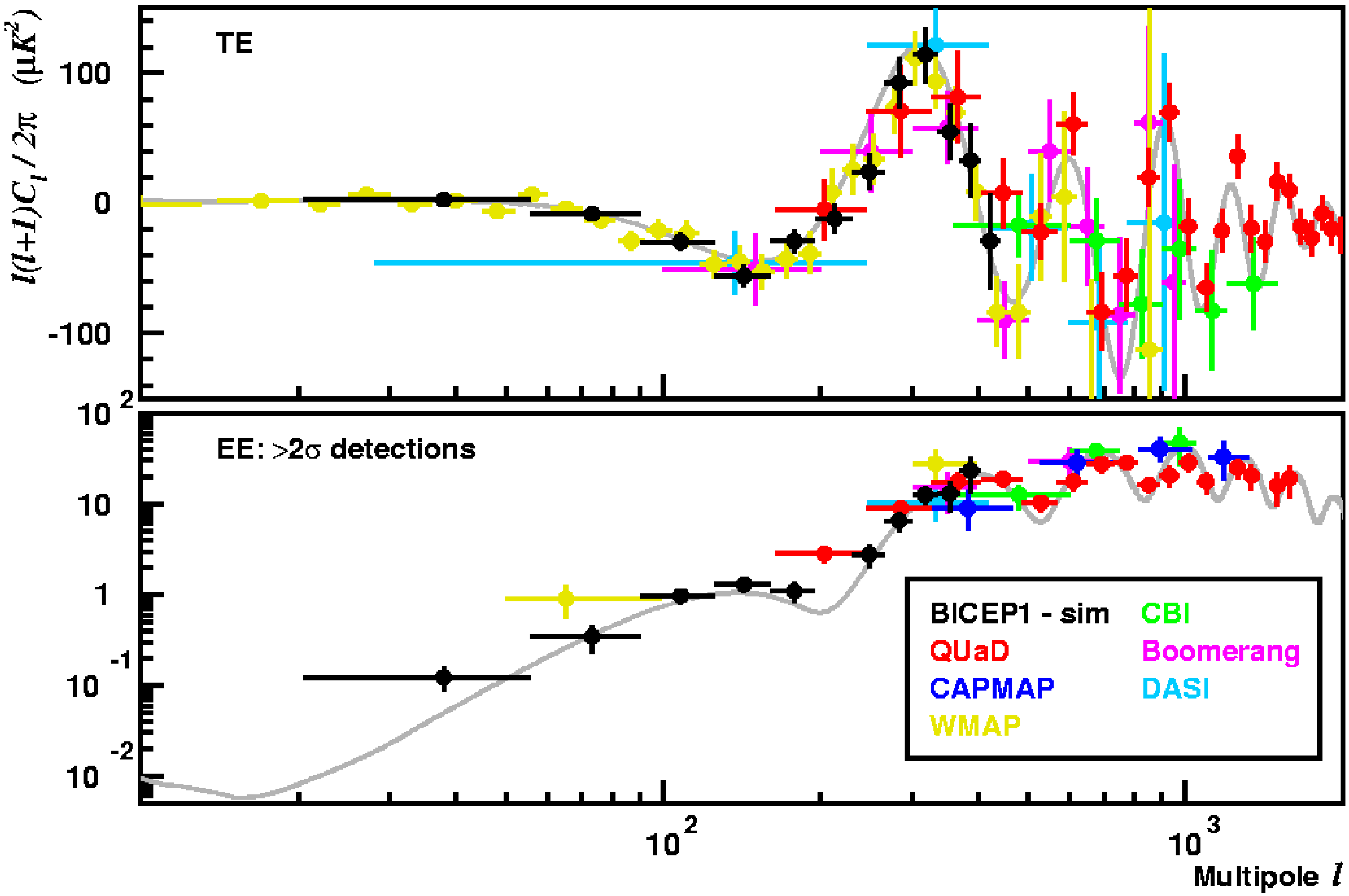
Preliminary T/E/B Maps



- E/B maps (Weiner filtered, from Q/U maps used in analysis)
- Frequency jacknife maps of E/B are consistent with noise, as is the B signal map --> No evidence of foreground contamination.
- Q/U jackknife map-derived 1-deg^2 noise in line with expectation:

100 GHz: 0.78 uK   150 GHz: 0.62 uK

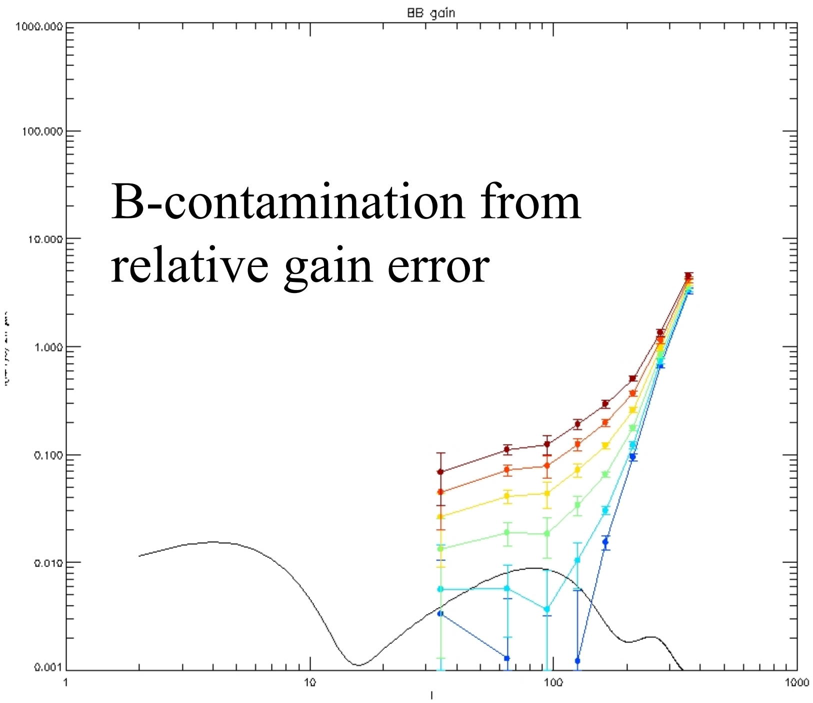
Where are we?
Preliminary analysis is maturing…



H.C. Chiang

- black points: simulation based on 2-yr data used in current initial analysis
- TE and EE spectra are already sample-variance dominated
    - First high S/N pol measurements around $l \sim 100$
- Level of initial BB limits will depend strongly on cuts
    - these are likely to be conservative in first round

Instrument Systematics



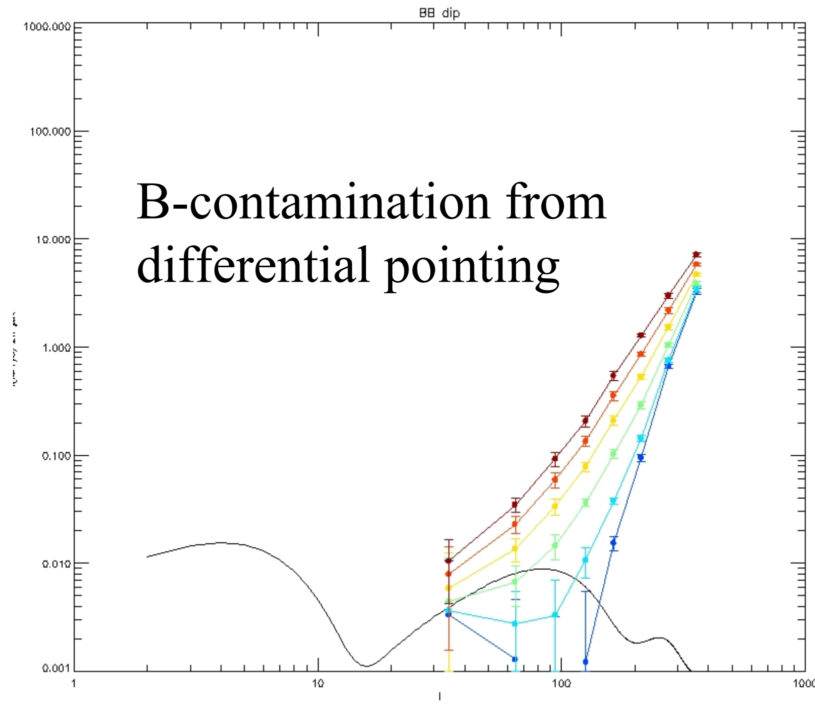


Table 1. Potential Systematic Errors for BICEP.

Instrument properties	Benchmark (r=0.1)	Measured
Relative gain error: $\Delta(s_1 - s_2)/s$	1.0%	0.4%
Differential beam size[a]: $(\sigma_1 - \sigma_2)/\bar{\sigma}$	4.0%	< 0.2%
Differential pointing[a]: $\lvert\vec{r_1} - \vec{r_2}\rvert/\bar{\sigma}$	1.5%	1.3%[b]
Differential ellipticity: $(e_1 - e_2)/2$	9.0%	< 0.1%
Polarization orientation error: $\Delta\psi$	8°	0.7°
Polarized sidelobes to Galaxy[c]	- 8 dBi	< -38 dBi
Polarized sidelobes to ground[c]	-19 dBi	< -38 dBi
Cold-stage temperature stability[d]: ΔT	1.3 nK	< 0.5 nK
Optics temperature stability[d]: ΔT_{RJ}	10 μK	< 0.7 μK

[a] $\bar{\sigma} = FWHM/\sqrt{8\ln(2)}$.

[b] A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

[c] At 30° from the beam center, based on the measured upper limit of 20% (-7 dB) polarized response in the sidelobes.

[d] Scan-synchronous, over $\ell = 30 - 300$.

Beam shape effects

Table 1. Potential Systematic Errors for BICEP.

Instrument properties	Benchmark (r=0.1)	Measured
Relative gain error: $\Delta(s_1 - s_2)/s$	1.0%	0.4%
Differential beam size[a]: $(\sigma_1 - \sigma_2)/\bar{\sigma}$	4.0%	$<$ 0.2%
Differential pointing[a]: $\lvert\vec{r_1} - \vec{r_2}\rvert/\bar{\sigma}$	1.5%	1.3%[b]
Differential ellipticity: $(e_1 - e_2)/2$	9.0%	$<$ 0.1%
Polarization orientation error: $\Delta\psi$	8°	0.7°
Polarized sidelobes to Galaxy[c]	- 8 dBi	$<$ -38 dBi
Polarized sidelobes to ground[c]	-19 dBi	$<$ -38 dBi
Cold-stage temperature stability[d]: ΔT	1.3 nK	$<$ 0.5 nK
Optics temperature stability[d]: ΔT_{RJ}	10 μK	$<$ 0.7 μK

[a] $\bar{\sigma} = FWHM/\sqrt{8\ln(2)}$.

[b] A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

[c] At 30° from the beam center, based on the measured upper limit of 20% (-7 dB) polarized response in the sidelobes.

[d] Scan-synchronous, over $\ell = 30 - 300$.

- Upper limits on differential beam size and ellipticity easily meet specs for r=0.1 (and r=0.01)!

- Differential pointing was the surprise…measured to be significant even for r=0.1.

Beam Shape Measurements

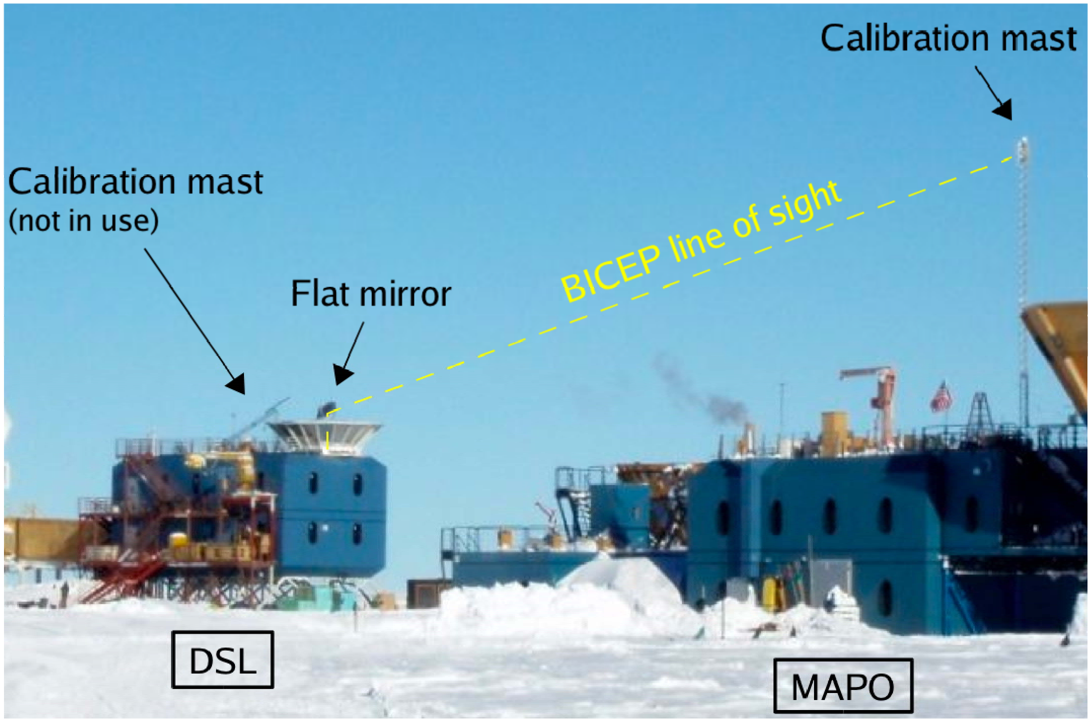


Figure 6. The beam mapping setup on site consisted of sources mounted on top of fold-over masts. When using the mast on the MAPO building (200 m from the Dark Sector Laboratory), a flat mirror is mounted to direct the beams over the ground screen.

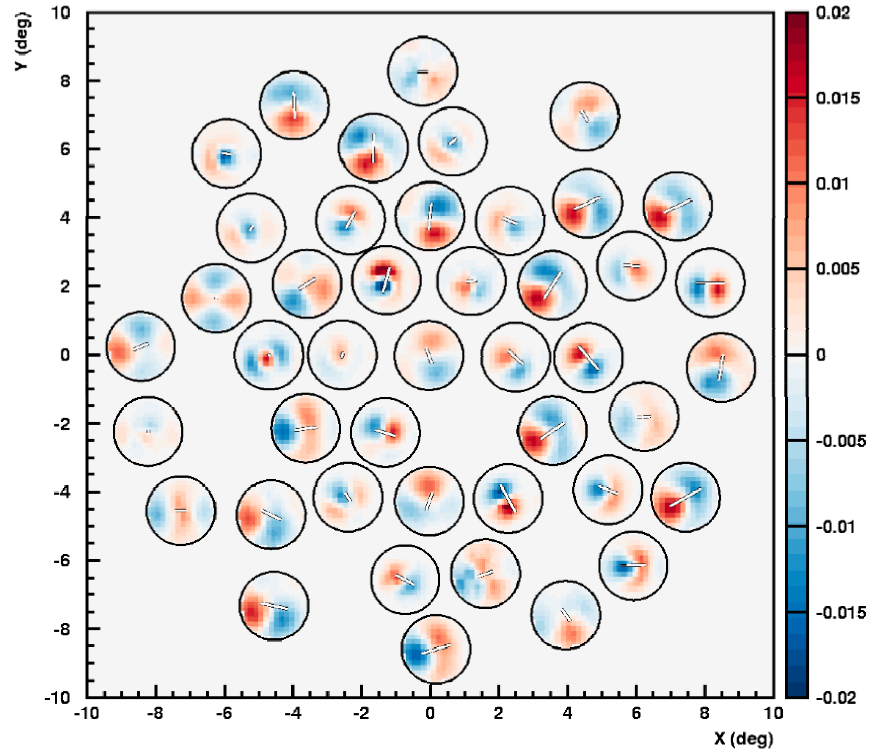


Figure 7. Beams for each PSB pair are normalized and differenced to produce this composite differential beam map. The overplotted lines show the fitted centroid offsets magnified by a factor of 100.

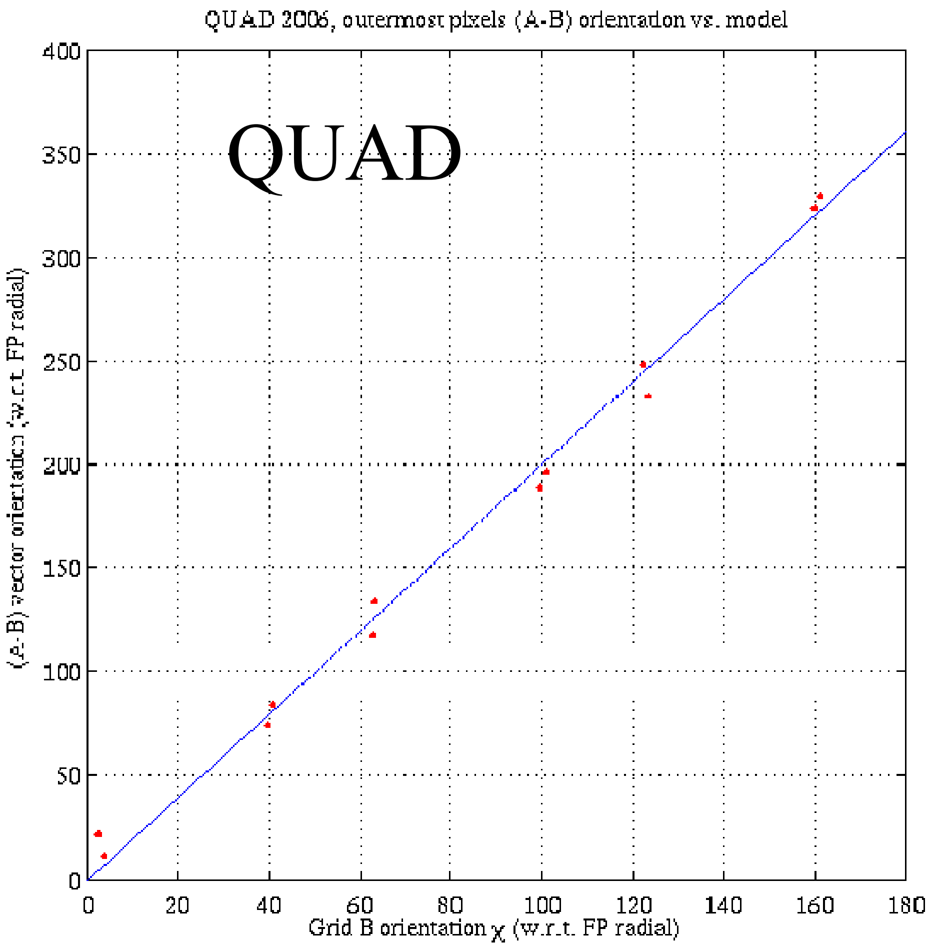
Beams were mapped in highbay prior to deployment (41 m)

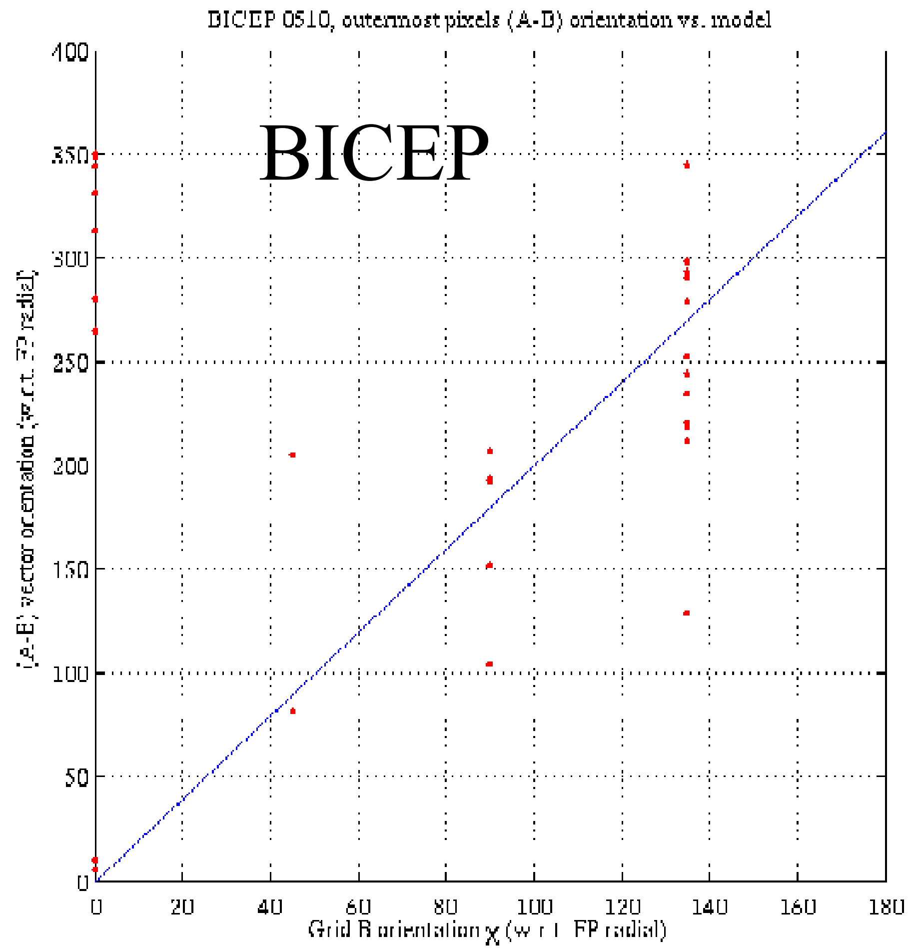
- Achieved sufficient precision to assure beam effects not dominant for r=0.1

Subsequently measured on site using a mast (200 m) and moon.

- Differential pointing is only measurable effect
- repeatable/stable to current measurement error (0.4%)

Pattern of A-B differential pointing offsets





Evidence for similar pattern of A-B beam offsets in QUAD and BICEP beams.

- c.f. Clem's talk
- effect is smaller in BICEP
- Follow-up lab measurements to understand origin of effect are ongoing…
- Stable to current measurement error (0.4%), which in principle allows removal to subdominant level for r=0.01

Polarization Orientation

Table 1. Potential Systematic Errors for BICEP.

Instrument properties	Benchmark (r=0.1)	Measured
Relative gain error: $\Delta(s_1 - s_2)/s$	1.0%	0.4%
Differential beam size[a]: $(\sigma_1 - \sigma_2)/\bar{\sigma}$	4.0%	$<$ 0.2%
Differential pointing[a]: $\lvert\vec{r_1} - \vec{r_2}\rvert/\bar{\sigma}$	1.5%	1.3%[b]
Differential ellipticity: $(e_1 - e_2)/2$	9.0%	$<$ 0.1%
Polarization orientation error: $\Delta\psi$	4°	0.7°
Polarized sidelobes to Galaxy[c]	- 8 dBi	$<$ -38 dBi
Polarized sidelobes to ground[c]	-19 dBi	$<$ -38 dBi
Cold-stage temperature stability[d]: ΔT	1.3 nK	$<$ 0.5 nK
Optics temperature stability[d]: ΔT_{RJ}	10 μK	$<$ 0.7 μK

[a] $\bar{\sigma} = FWHM/\sqrt{8\ln(2)}$.

[b] A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

[c] At 30° from the beam center, based on the measured upper limit of 20% (-7 dB) polarized response in the sidelobes.

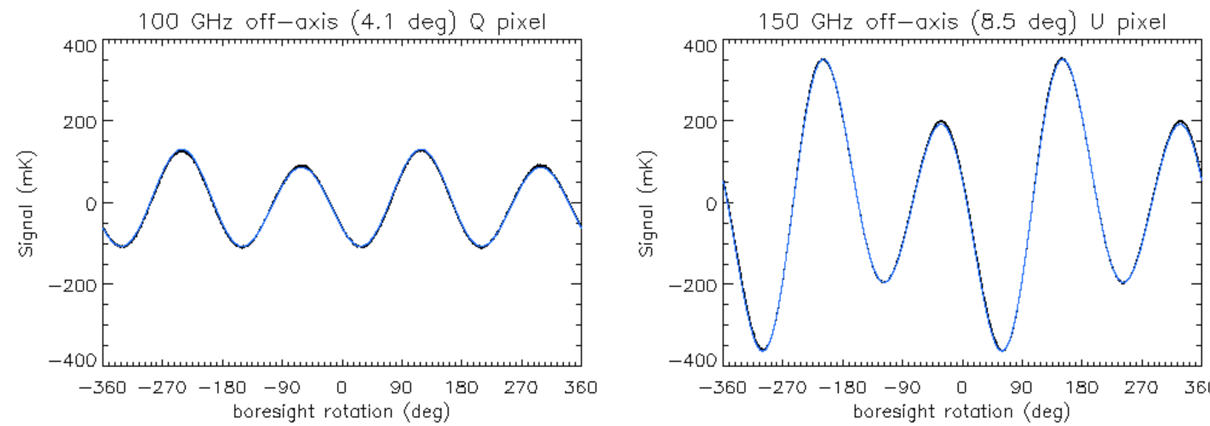
[d] Scan-synchronous, over $\ell = 30 - 300$.

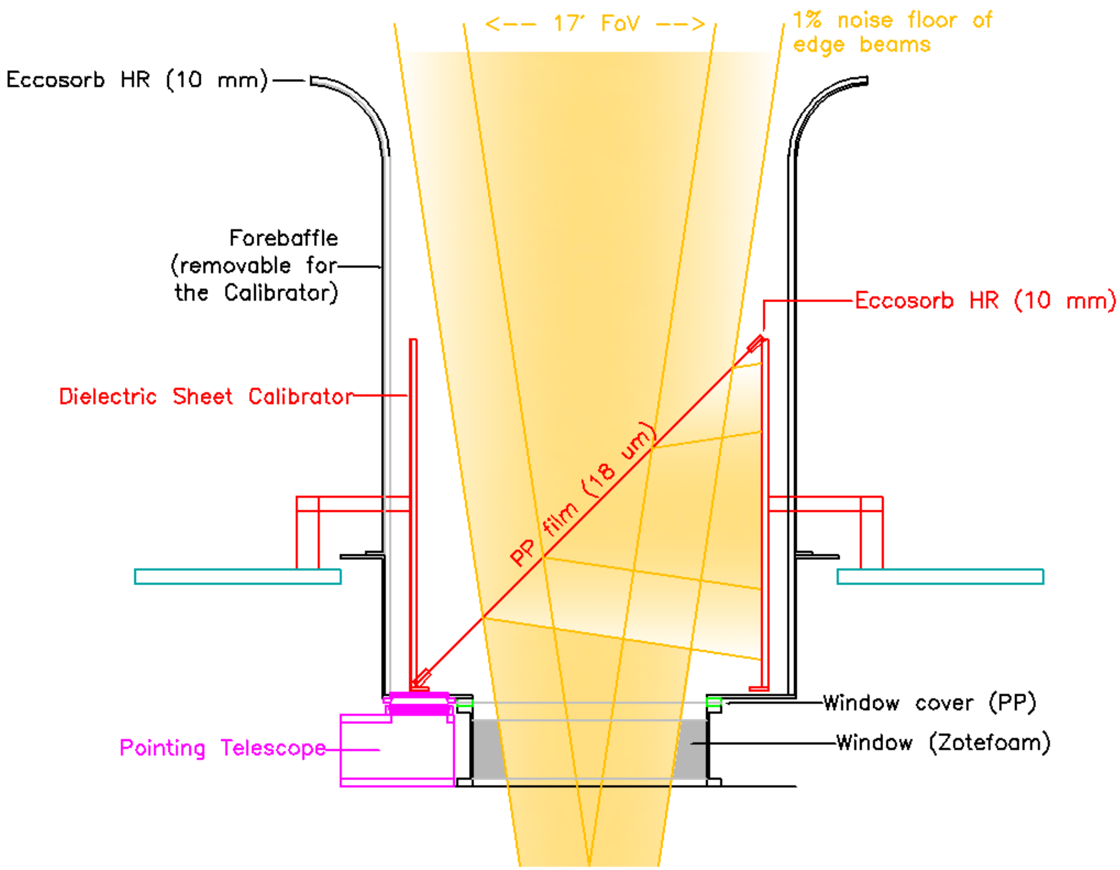
Quoted benchmark is (I believe) for random errors per feed. Benchmark (r=0.1) for error on global orientation is ~ 1.0 degree.

Measuring Polarization orientation: the Yukical

Polarization response angle is characterized using POLAR-style (O'Dell 2002) dielectric sheet calibrator.

(Y. Takahashi)





Provides polarization orientation to ~ 0.7 deg accuracy

Sidelobes

Table 1. Potential Systematic Errors for BICEP.

Instrument properties	Benchmark (r=0.1)	Measured
Relative gain error: $\Delta(s_1 - s_2)/s$	1.0%	0.4%
Differential beam size[a]: $(\sigma_1 - \sigma_2)/\bar{\sigma}$	4.0%	$<$ 0.2%
Differential pointing[a]: $\lvert\vec{r_1} - \vec{r_2}\rvert/\bar{\sigma}$	1.5%	1.3%[b]
Differential ellipticity: $(e_1 - e_2)/2$	9.0%	$<$ 0.1%
Polarization orientation error: $\Delta\psi$	4°	0.7°
Polarized sidelobes to Galaxy[c]	- 8 dBi	$<$ -38 dBi
Polarized sidelobes to ground[c]	-19 dBi	$<$ -38 dBi
Cold-stage temperature stability[d]: ΔT	1.3 nK	$<$ 0.5 nK
Optics temperature stability[d]: ΔT_{RJ}	10 μK	$<$ 0.7 μK

[a] $\bar{\sigma} = FWHM/\sqrt{8\ln(2)}$.

[b] A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

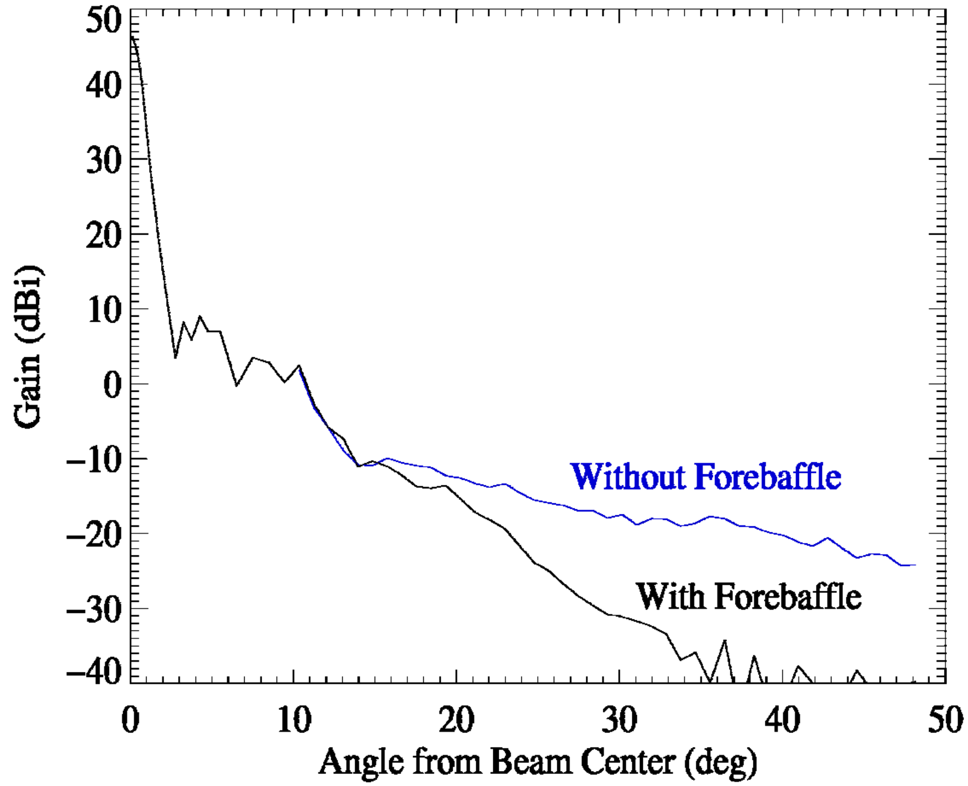
[c] At 30° from the beam center, based on the measured upper limit of 20% (-7 dB) polarized response in the sidelobes.

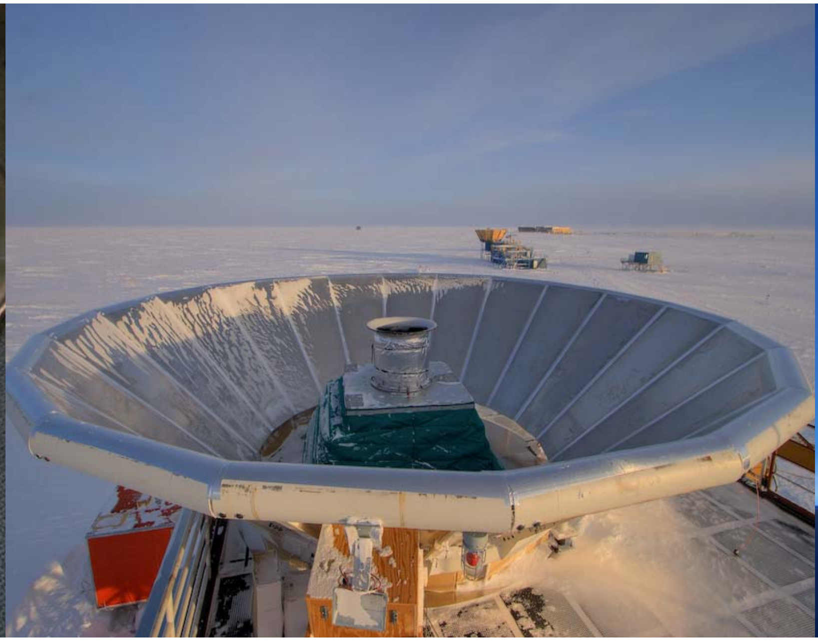
[d] Scan-synchronous, over $\ell = 30 - 300$.

Sidelobe characterization

- Extremely clean optical design:
  - Unobstructed aperture
  - Black forebaffle
  - Reflective groundshield
- Sidelobes mapped on-site using amplified sources on 30' mast
- Ground pickup reduced > 10^3 compared to QUAD…

  …no ground subtraction needed in analysis so far!





Thermal Stability

Table 1. Potential Systematic Errors for BICEP.

Instrument properties	Benchmark (r=0.1)	Measured
Relative gain error: $\Delta(s_1 - s_2)/s$	1.0%	0.4%
Differential beam size[a]: $(\sigma_1 - \sigma_2)/\bar{\sigma}$	4.0%	$<$ 0.2%
Differential pointing[a]: $\|\vec{r_1} - \vec{r_2}\|/\bar{\sigma}$	1.5%	1.3%[b]
Differential ellipticity: $(e_1 - e_2)/2$	9.0%	$<$ 0.1%
Polarization orientation error: $\Delta\psi$	4°	0.7°
Polarized sidelobes to Galaxy[c]	- 8 dBi	$<$ -38 dBi
Polarized sidelobes to ground[c]	-19 dBi	$<$ -38 dBi
Cold-stage temperature stability[d]: ΔT	1.3 nK	$<$ 0.5 nK
Optics temperature stability[d]: ΔT_{RJ}	10 μK	$<$ 0.7 μK

[a] $\sigma = FWHM/\sqrt{8\ln(2)}$.

[b] A differential pointing which averages 1.3% has been repeatably characterized to 0.4% precision.

[c] At 30° from the beam center, based on the measured upper limit of 20% (-7 dB) polarized response in the sidelobes.

[d] Scan-synchronous, over $\ell = 30 - 300$.

Actually, we have evidence for scan-syncronous ~nK level thermal fluctuations in our thermistor maps, but only at certain scan rates and orientations.

These appear significant to polarization maps only for the largest scales (*l*< 50) but understanding which data and which detector pairs are affected has been a major focus in making cuts.

BICEP2/Keck refractors:
if it ain’t broke…

BICEP2 & Keck

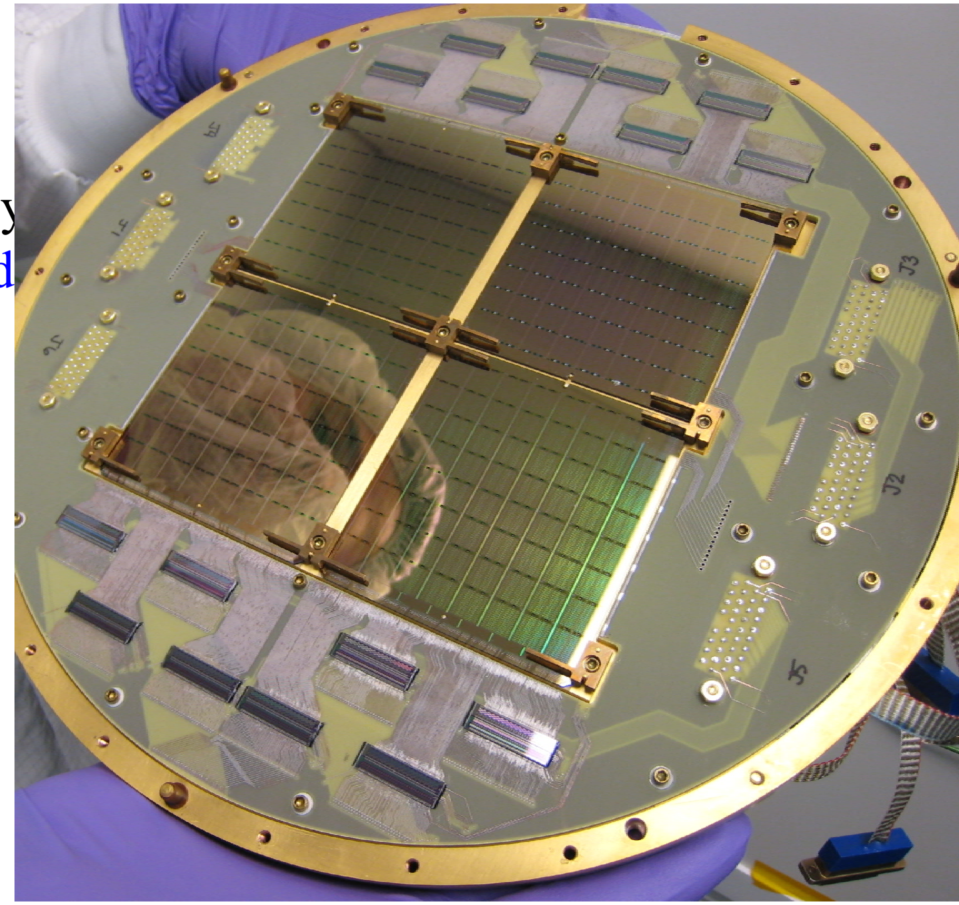
ExploitBICEP refractor methodology to aggressively push downto r=0.01 using antenna-coupled TES and SQUIDTmuxarrays.

BICEP2 (2009 - 2011):

- Upgrade BICEP1LHe receiver
- 512 detectors @ 150 GHz

Keck (2010 - 2012):

- Pulse-tube receivers
- Up to 6 such monochromatic receivers on the existing DASI mount (3 X 288 detectors at 100 GHz, 2 X 512 @ 150 GHz, 1 X 512 @ 220 GHz)



BICEP2 focal plane, May 2009

BICEP2/Keck Refractors: new features

- 2fλantenna-coupled feeds increase edge illumination from

  BICEP1: -22 dB edge taper

  BICEP2: -12.4 dB edge taper, so…

- Lens design reoptimized using ZEMAX (RandolAikin)

  BICEP2: < 1e-5 calculated diff. ellipticity; VERY symmetric illumination

- Aperture stop refined (tapered HR10)

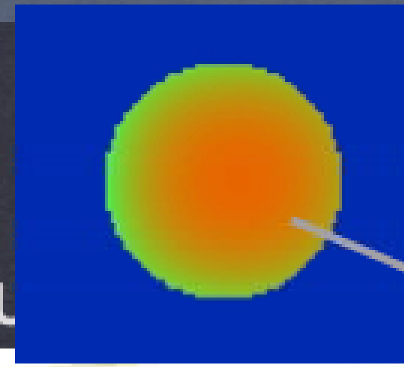
- AR coats still expanded PTFE, but optimized for monochromatic

- 4" Zotefoam window unlaminated, reducing scattering

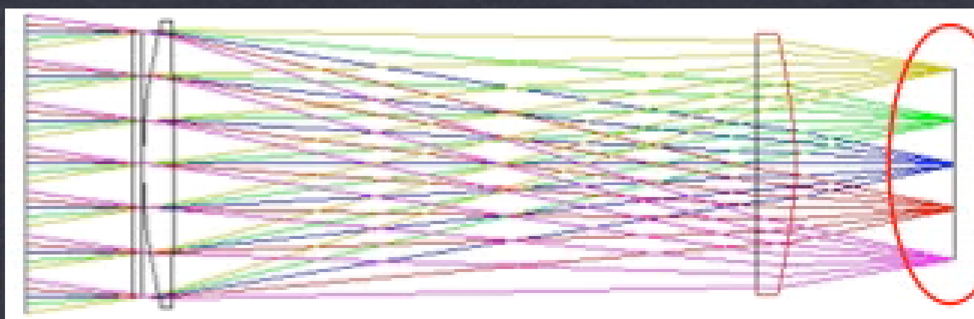
  BICEP1: 1.5% transmission loss at 150 GHz (0.5% onto forebaffle)

  BICEP2: 0.3% transmission loss at 150 GHz

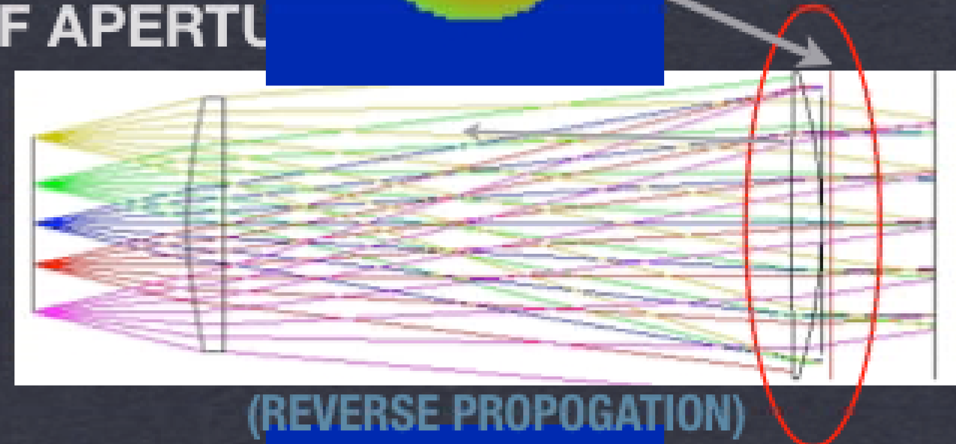
DETERMINING LENS CURVATURE:



OPTIMIZING W.R.T. ABERRATION:
+ SHARP FOCUS IN ARRAY
- ASYMMETRIC ILLUMINATION OF APERTU

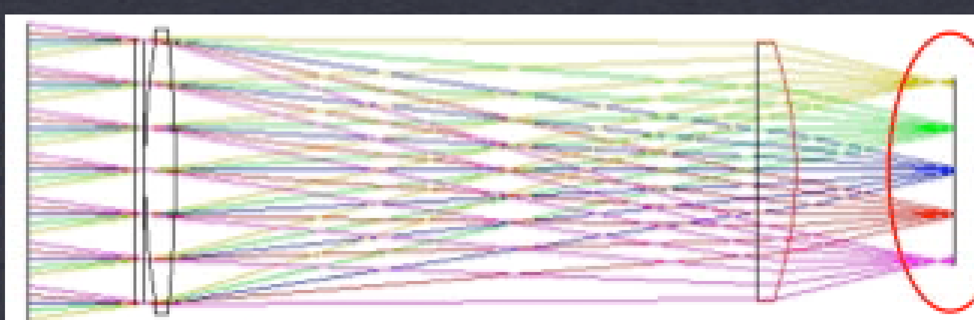


(FORWARD PROPOGATION)

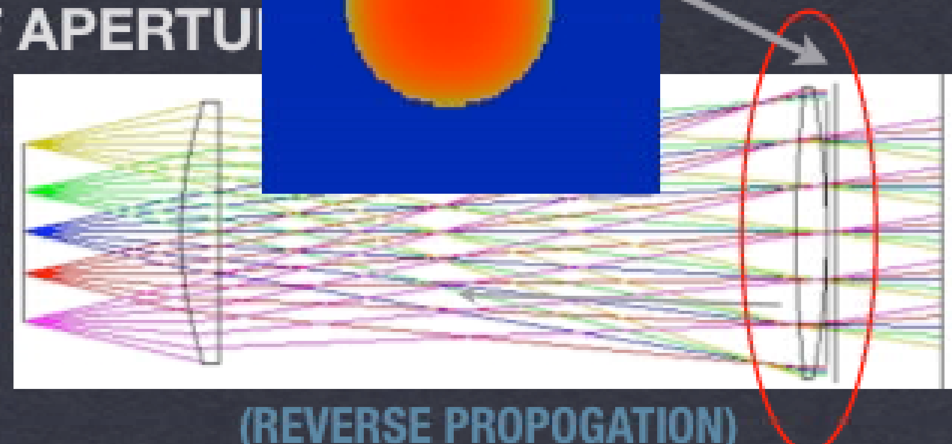


(REVERSE PROPOGATION)

OPTIMIZING W.R.T. TELECENTRICITY:
- ABERRATION IN THE FP
+ SYMMETRIC ILLUMINATION OF APERTU



(FORWARD PROPOGATION)



(REVERSE PROPOGATION)

BICEP2: optimized lens design,
monochromatic AR coat
HR10 aperture stop

Refractor Readiness…

• BICEP has demonstrated that a wide field refractor can make sensitive measurements of the CMB polarization at l = 50-100 using no polarization modulation, even from the ground.

• Optical systematics have been characterized to level needed for r=0.01

→ TRL 5 ? 4.99 ?

• Differential pointing still poorly understood. Stable, and "not likely to be a serious concern" (Hinshaw/systematics), nontheless

• need lab measurements to trace origin of effect (AR coats?)

• need better optics code

• Need verification that optics systematics remain under control with more aggressive detector coupling (BICEP2 will address, ~6 months)

•CMPpol: alternatives for high-throughput, compact systems?

1.5m crossed design?