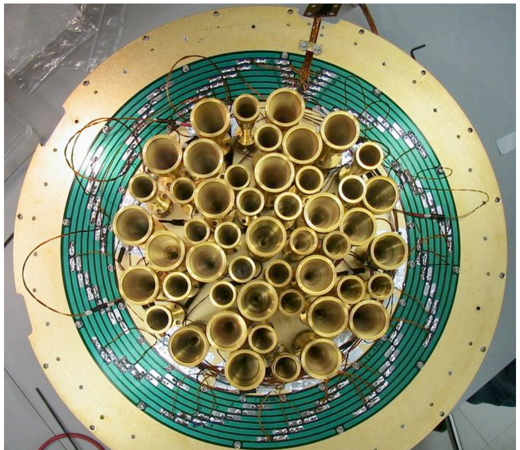
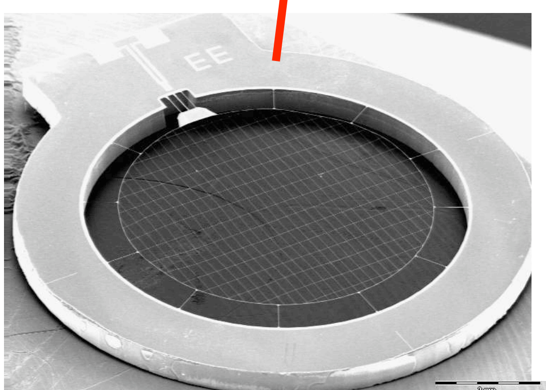

From BICEP1 to BICEP2 & KECK
SPT: 10m
BICEP/Keck: 0.3m
John Kovac, Caltech / Harvard
July 2, 2009 CMPpol workshop
Photo: Steff Richter

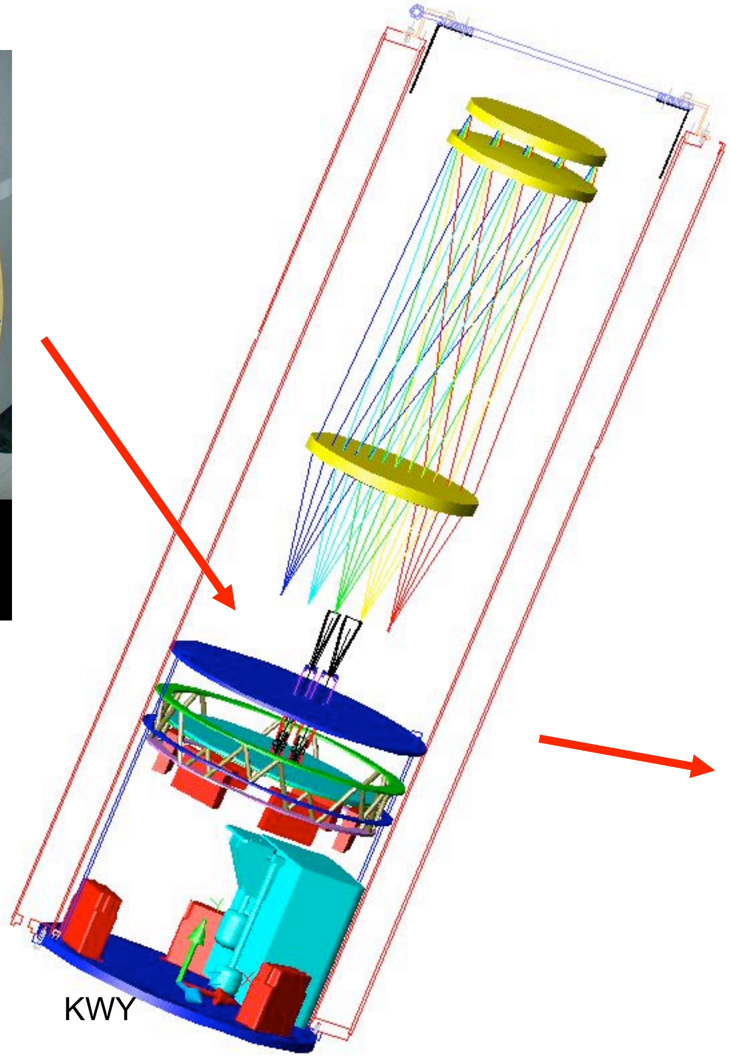
BICEP1: a hard-working B-mode machine!



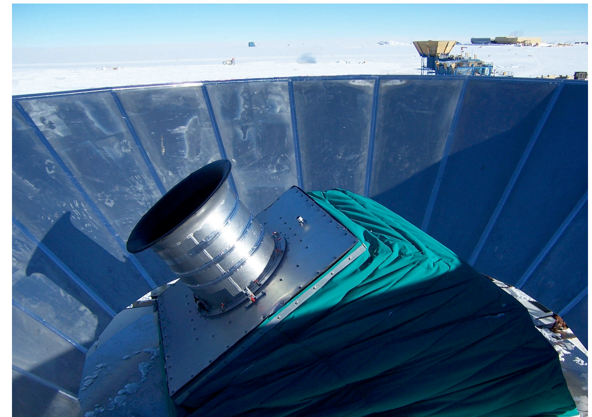
98 Detector Focal Plane
(100 GHz and 150 GHz)



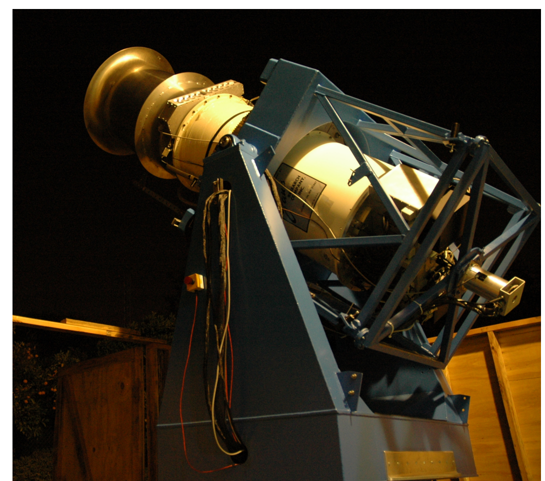
Polarization-Selective
Bolometers (JPL)



Telescope: 30 cm wide-field
refractor, all optics at 4 K

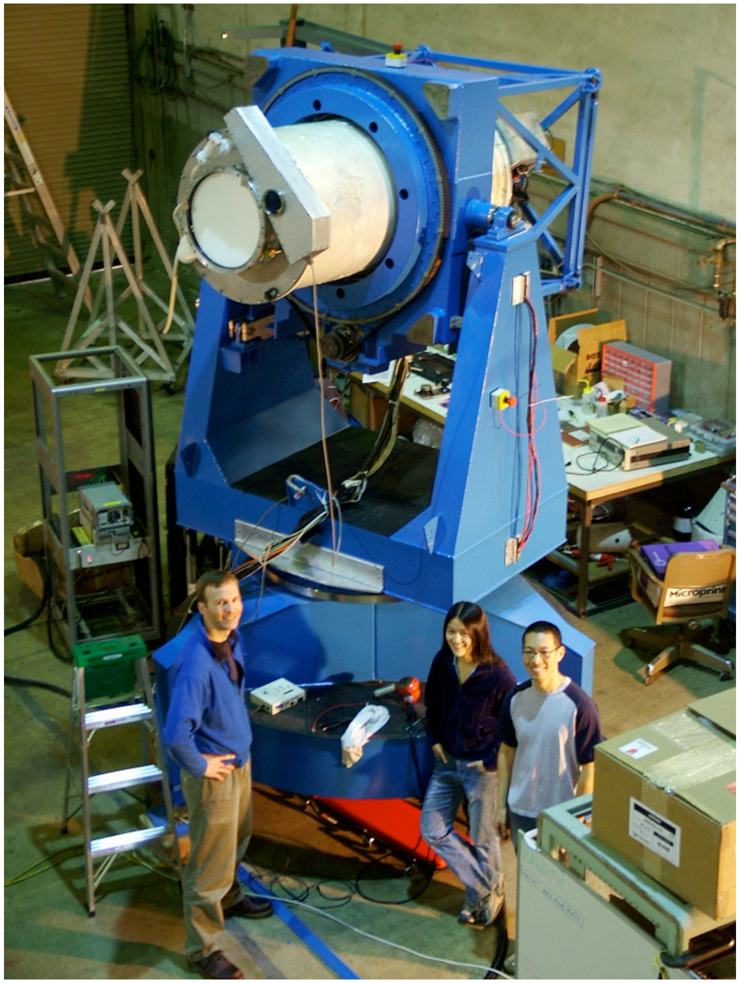


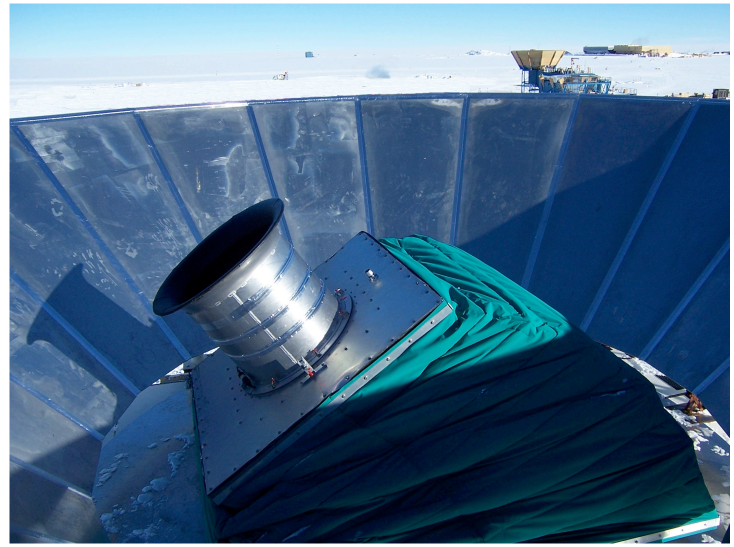
Feb 2006: working at Pole!



Fast-scan mount (5 d/s)

Why a small aperture?

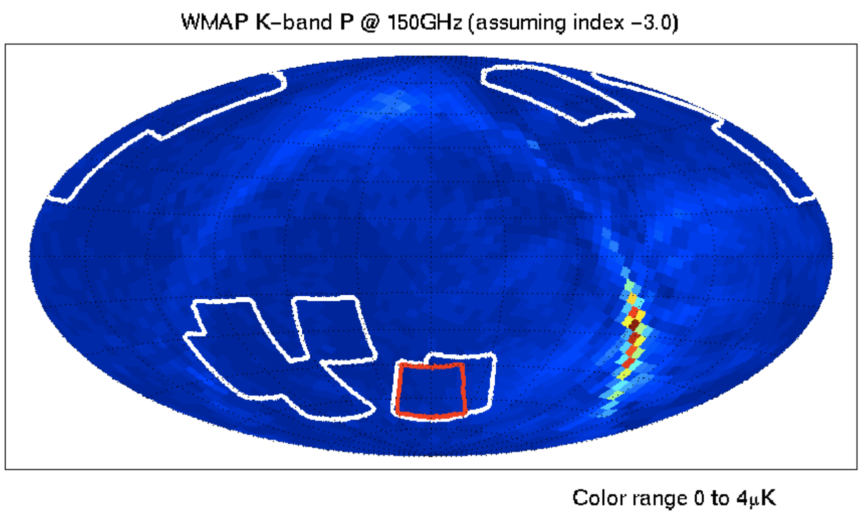


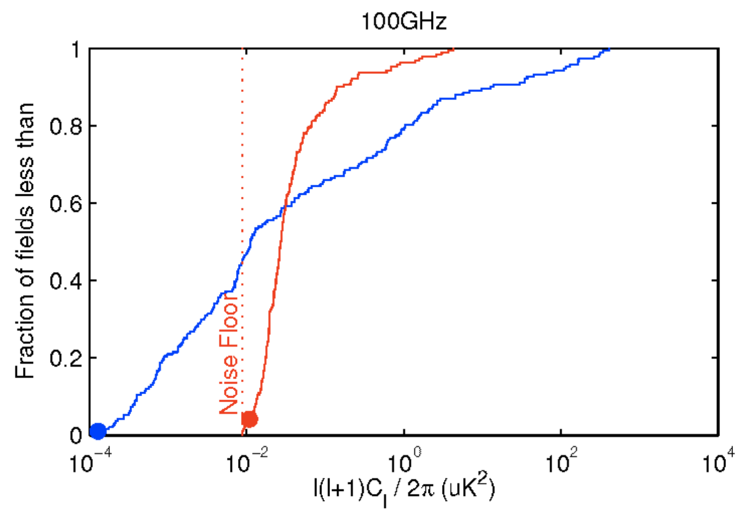


- Efficient ($) to integrate / test / deploy
- Stability of (4K) telescope & beams
- Aperture filling calibrators
- Aperture filling waveplate (BICEP2)
- Superior sidelobe suppression

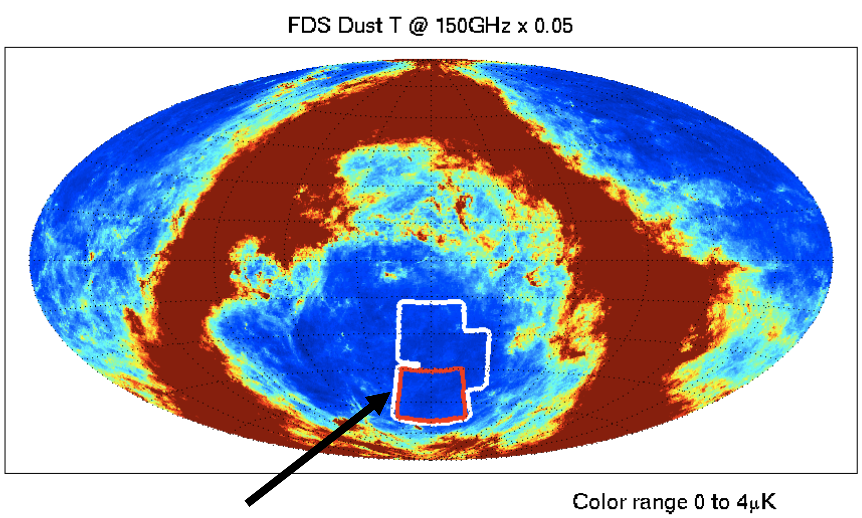
Why 100 & 150 GHz?

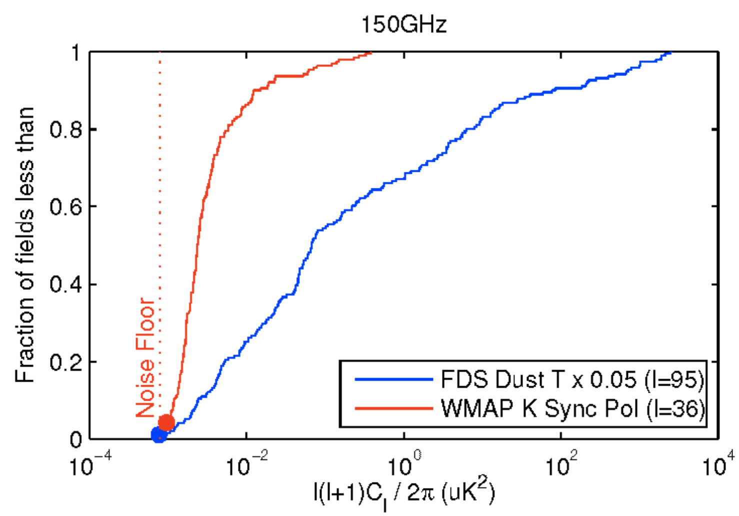
sync





dust





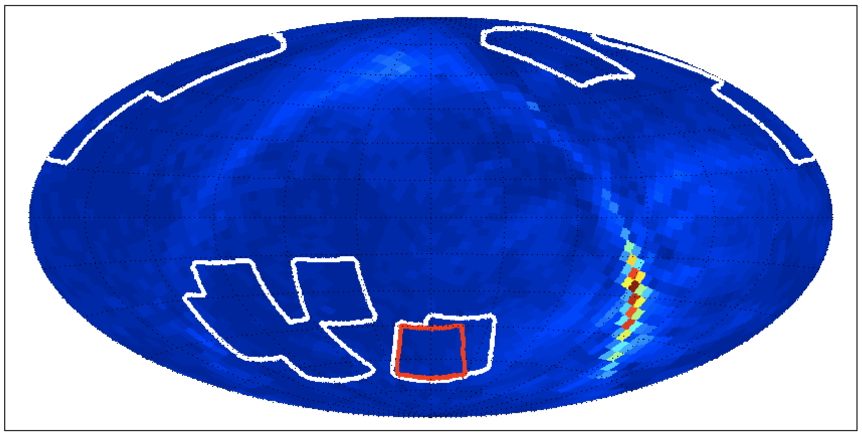
"Southern Hole"

Clem Pryke & JK

Why 100 & 150 GHz?

sync

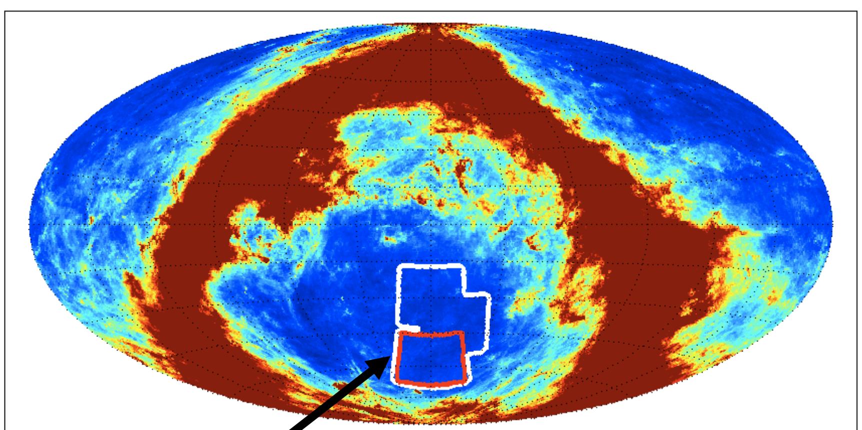
WMAP K-band P @ 150GHz (assuming index −3.0)



Color range 0 to 4μK

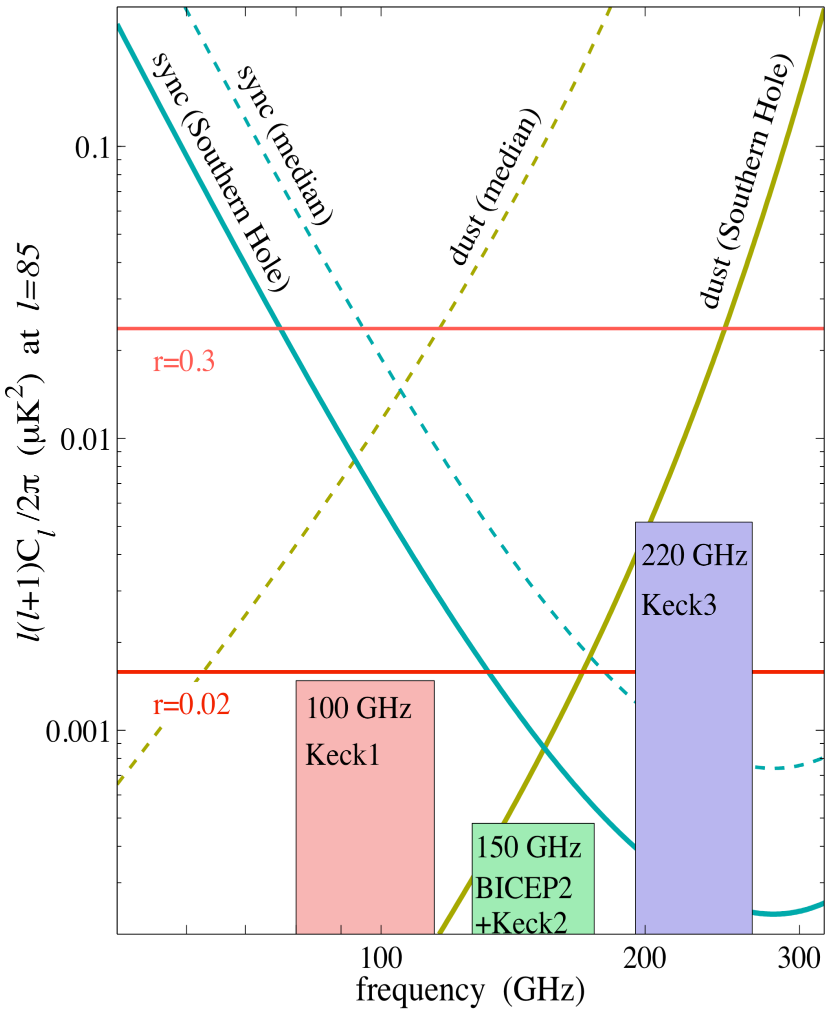
dust

FDS Dust T @ 150GHz x 0.05



Color range 0 to 4μK

“Southern Hole”



Clem Pryke & JK

BICEP1 initial results

CMB result: **Chiang et al. 0906.1181**
Characterization: **Takahashi et al. 0906.4069**

- **This is doable.**
  - Instrument worked as designed
  - No exotic polarization modulators – just careful optical design and azimuth scanning.
  - Systematics controllable down to at least r = 0.01
  - First high S/N measurement of CMB (E) polarization at l = 100

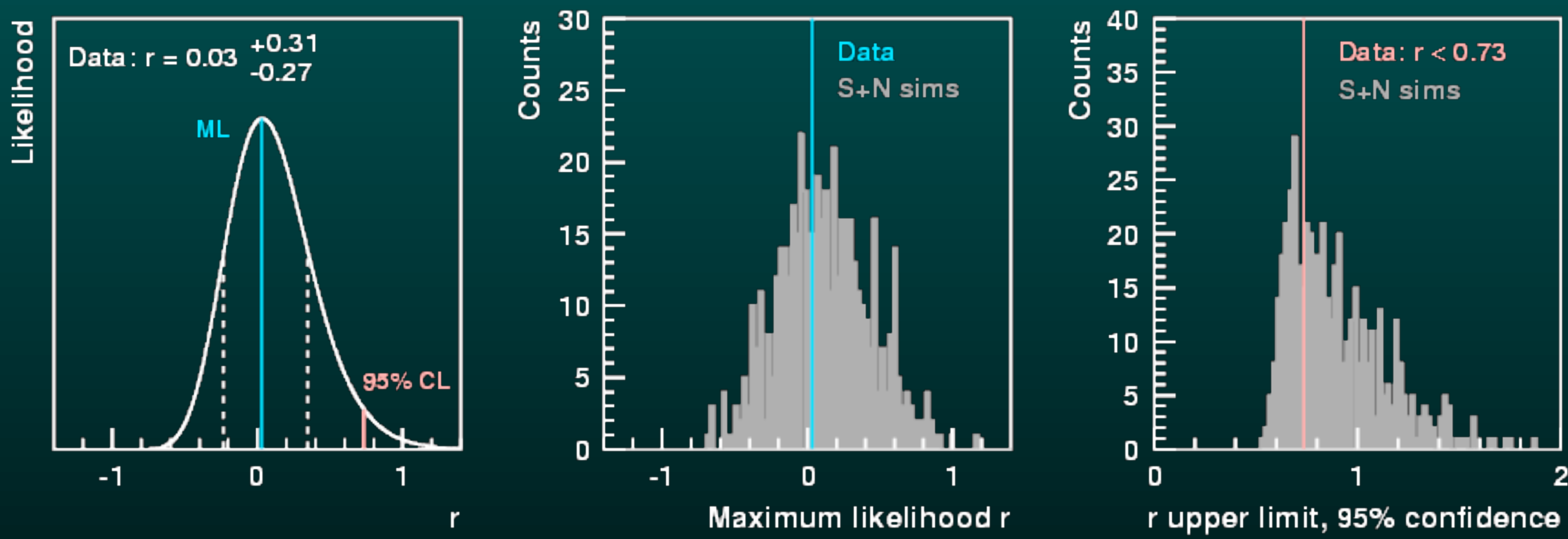
- **This is hard.**
  - Initial result from first 2 seasons after massive analysis effort:
    r = 0.03, +0.31, -0.27, or upper limit r < 0.73 at 95% confidence

This is doable.

	Measured	max false B, equiv. r
1. Relative gain uncertainty: $\Delta(g_1/g_2)/(g_1/g_2)$	$< 1.1\%$	< 0.15
2. Differential pointing: $(\mathbf{r_1} - \mathbf{r_2})/\sigma$	1.3%	0.05
3. Focal plane temperature stability: ΔT_{FP}	1 nK	0.011
4. Polarization orientation uncertainty: $\Delta\psi$	$< 0.7^\circ$	< 0.009
5. Optics temperature stability: ΔT_{RJ}	0.7 μK	0.003
6. Differential ellipticity: $(e_1 - e_2)/2$	$< 0.2\%$	< 0.002
7. Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$	$< 0.3\%$	< 0.0007
8. Polarized sidelobes (100, 150 GHz)	-26, -17 dBi	0.0002
9. Telescope pointing uncertainty: $\Delta\mathbf{b}$	$0.2'$	0.0002

This is hard.

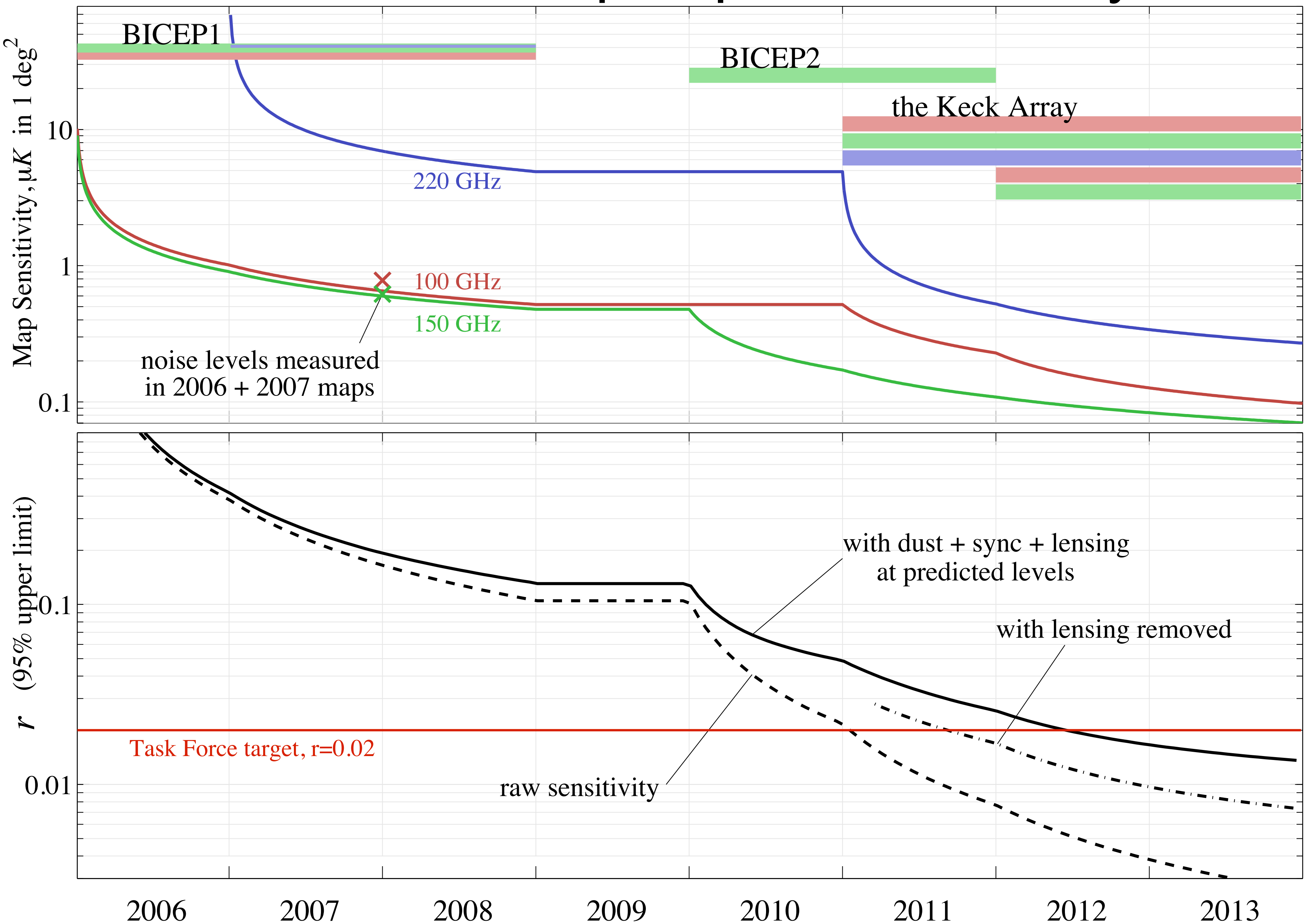
Constraint on r from BICEP BB



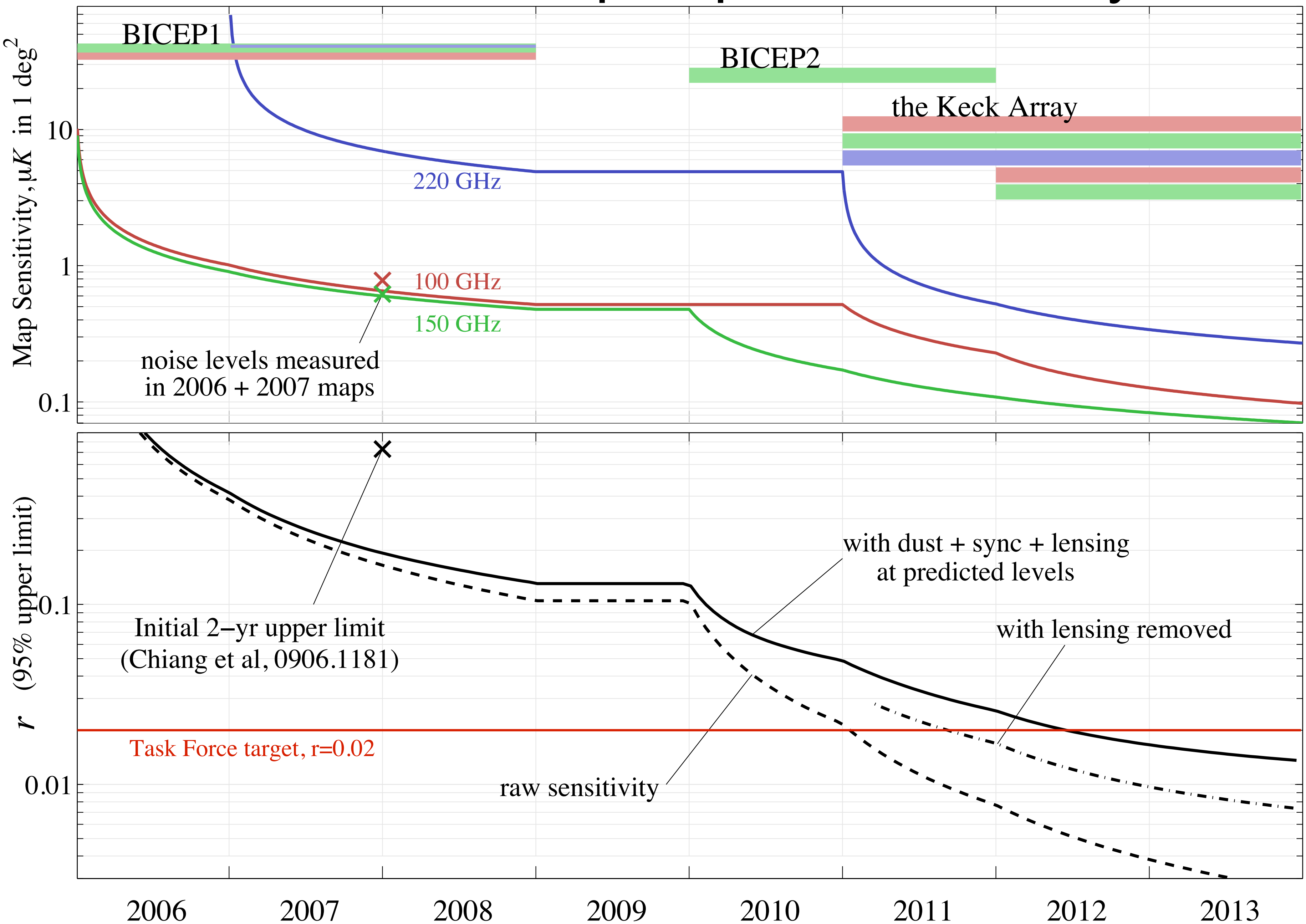
- Assume fixed LCDM parameters, calculate template BB, vary *r*
- Calculate chi-squared and likelihood as function of *r*
- BICEP BB: *r* = 0.03, +0.31, -0.27, upper limit is *r* < 0.73 at 95% confidence

H. C. Chiang

BICEP / Keck : map depth & sensitivity to *r*



BICEP / Keck : map depth & sensitivity to *r*



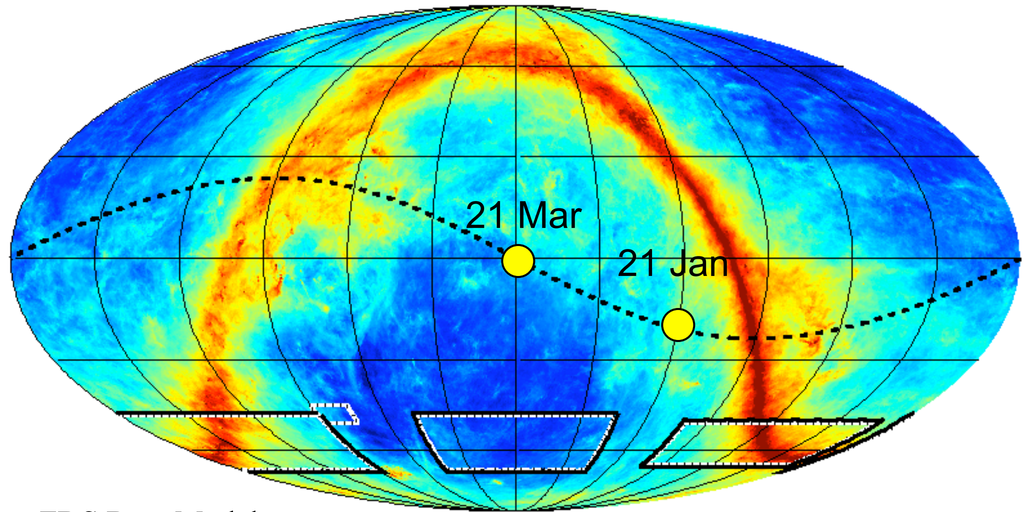
Where did the factor of 4 go?

- **NOT:**
  - Time on target.   > 3000 hours / season on Southern Hole, better than projected
  - Foreground removal
  - 1/f noise. Very small in pair difference across science band
  - E/B separation
  - Chance fluctuation… sims show 95% limit could have been $r < 0.5$ or $r < 1.3$

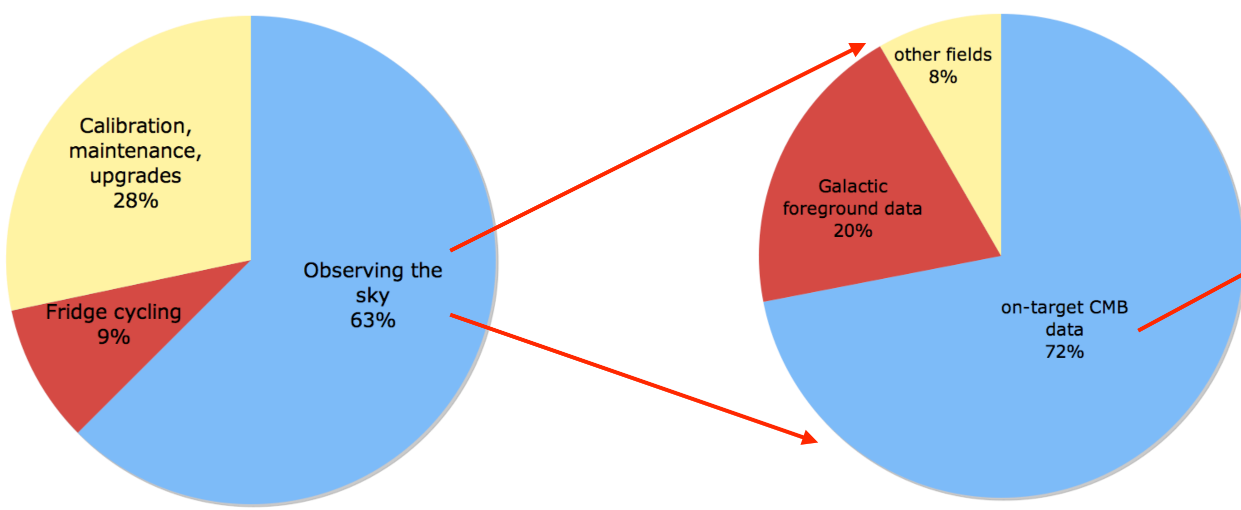
BICEP1 Observing efficiency

CMB obs started Mar 4th 2006
ended Dec 3rd 2008
33 months (24,000 hours) since then:

	HOURS
Observing the sky	15,100
Fridge cycling, Cryo ops	2200
Calibration, maintenance, upgrades	6700



FDS Dust Model



Good CMB data after weather and other cuts = 10,090 hours!

Chiang et al.: 6174 hours from 2006+2007

Where did the factor of 4 go?

- **NOT:**
  - Time on target.   > 3000 hours / season on Southern Hole, better than projected
  - Foreground removal
  - 1/f noise. Very small in pair difference across science band
  - E/B separation
  - Chance fluctuation

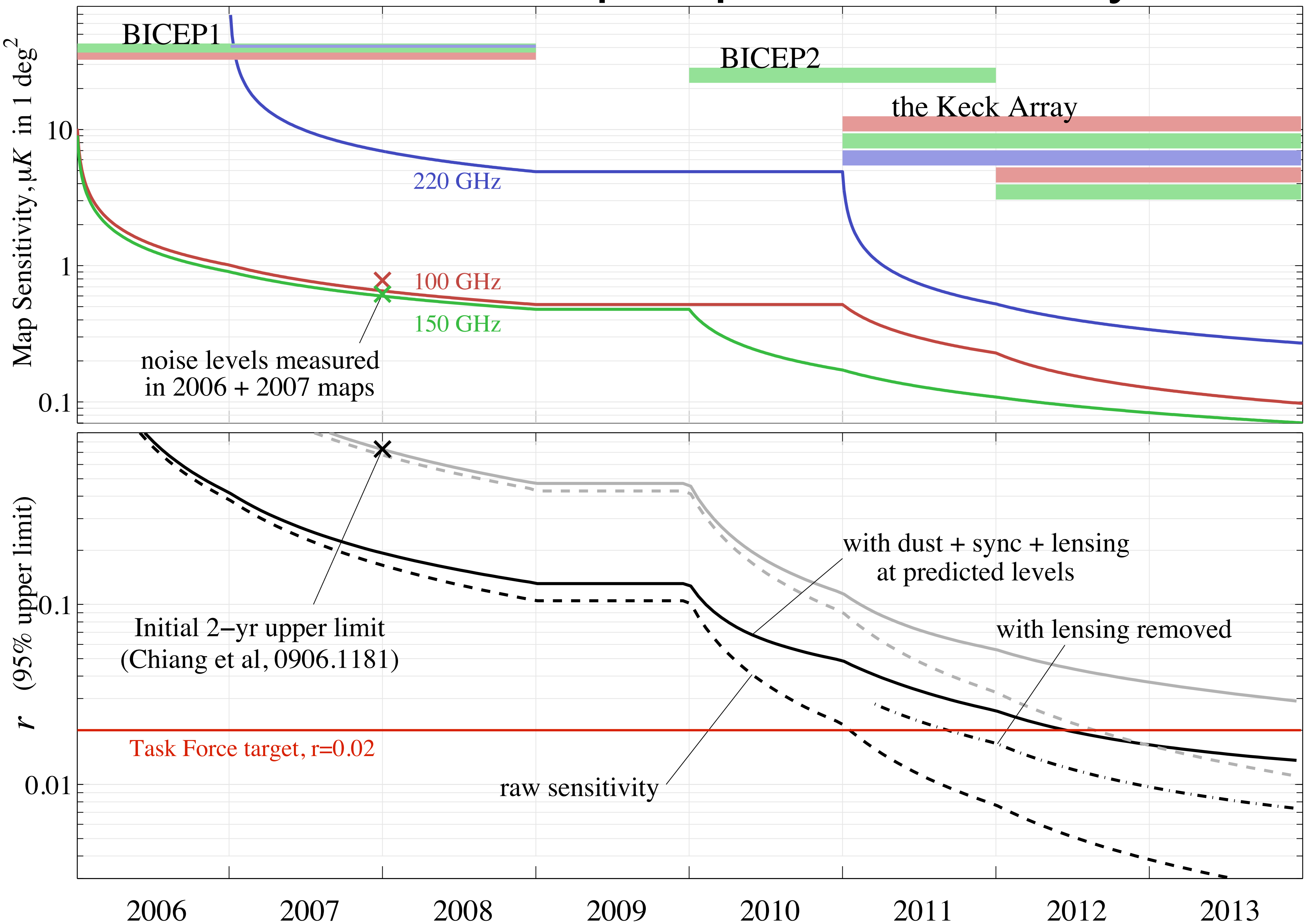
- **Small factors:**

– Final array-averaged NEQs in science band: 19%, 14% high	1.3
– Channels cut for unusual transfer functions	1.2
– Channels lost for other reasons	1.2
– Fraction of scanning time used: 60%	1.6
– Exclusion of partial scans	1.05
– Mode-loss due to aggressive filtering scheme	1.3 ?
– Sub-optimal B spectrum estimation?	1.2 ?
total:	4.9

So what factor can realistically be gained back with more work?

Guess: 1.5 - 3

BICEP / Keck : map depth & sensitivity to *r*



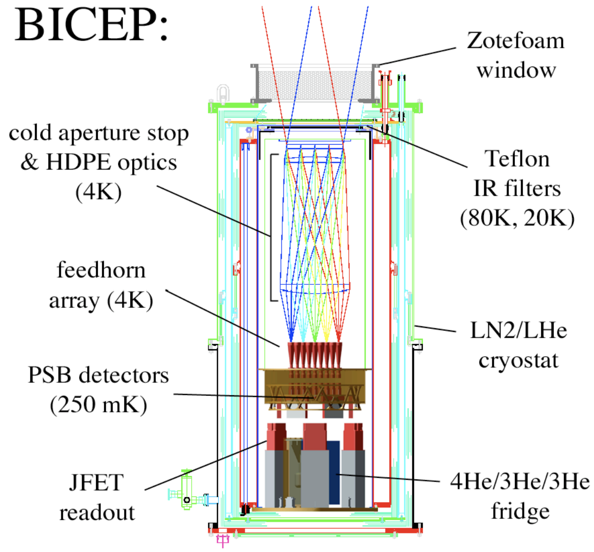
So if you want to measure $r = 0.02$…

1. You need to be as good as BICEP1 in every way (time on target, efficiency, foreground avoidance, etc)…

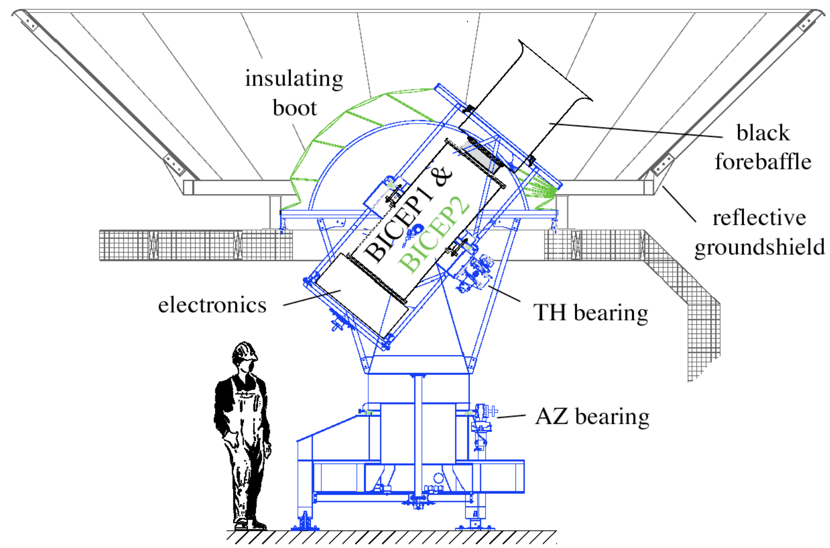
2. and you need 20x the sensitivity!

BICEP2/Keck Array: more detectors, more telescopes

BICEP:

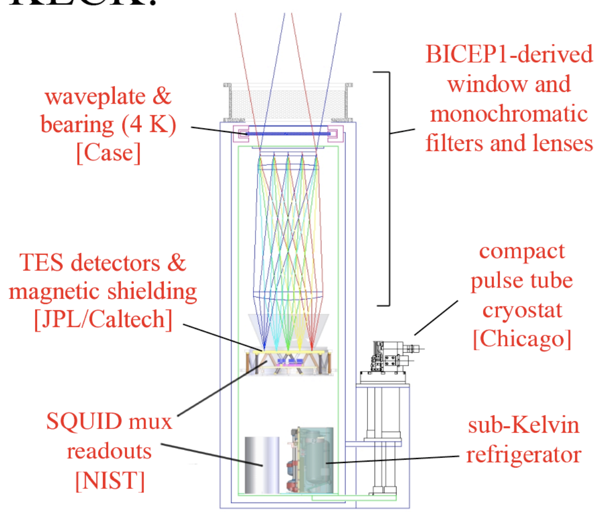


BICEP1

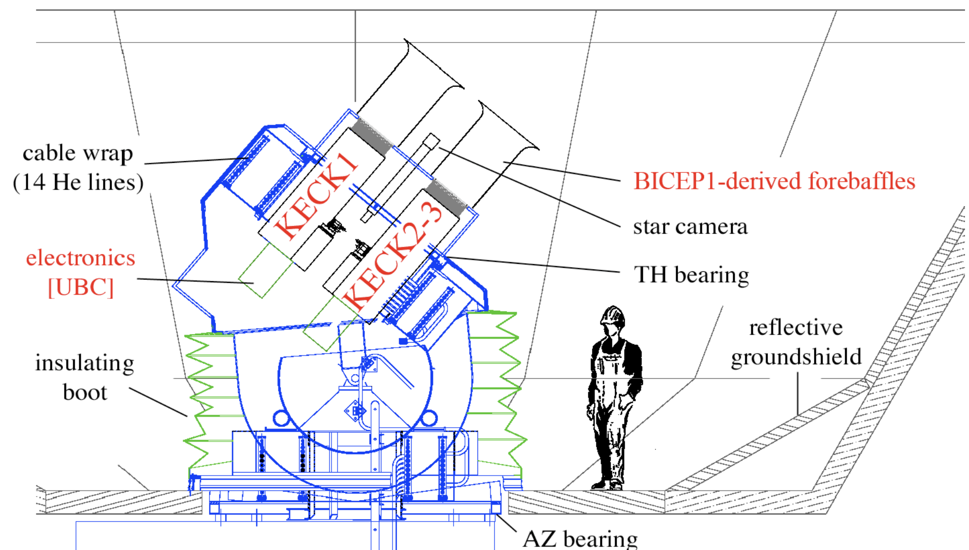


DSL BICEP platform (7500 lbs cap)

KECK:



KECK1,2,3



DASI tower (100,000 lbs cap)

Black = already at South Pole
Green = deploying this year

Clem's mandatory

BICEP2 + Keck Experiment Summary

Frequencies	100	150	220	GHz
Angular resolutions	55	37	26	arcmin at each freq
Field centers and sizes	"Southern Hole" 0h, -55 ~800 sq deg.			Ra/Dec/Sq-Deg
Telescope type	Cryogenic refractor			Refractor, Gregorian, Compact-range etc
Polarization Modulations	3 deg/s azimuth scan. Stepped boresight + HWP rotation			Waveplate, boresight rot., sky rot., scan etc. – list all that apply
Detector type	576	1536	512	# of TES Bolometers
Location	South Pole			
Instrument NEQ/U	11.9	8.5	35.2	$\mu K\ s^{1/2}$
Observation start date	BICEP2 deploys Nov 2009 KECK(3) deploys Nov 2010			
Planned observing time	200 days/season			Elapsed/effective days
Projected limit on *r*	0.01 to 0.03 at 95%			By 2013

BICEP2 / Keck is:

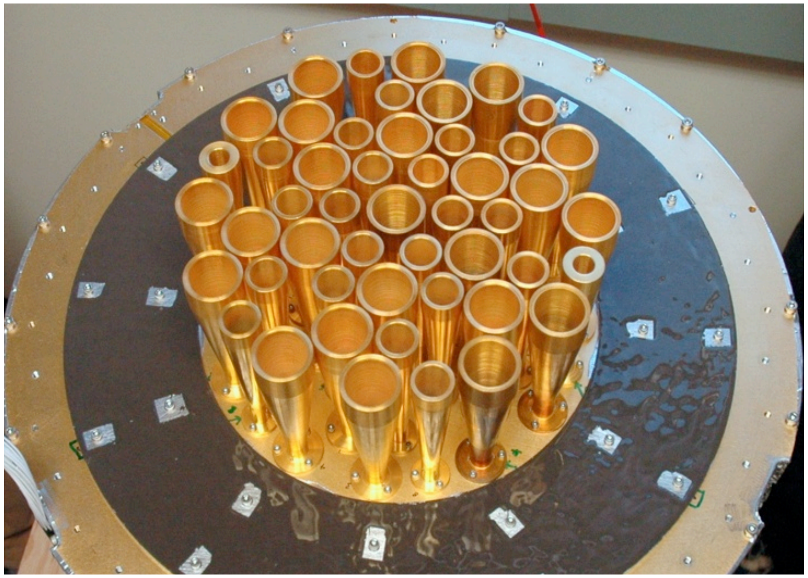
Caltech / JPL
Chicago
Stanford
Harvard
UCSD
NIST
UBC
Case Western
Toronto

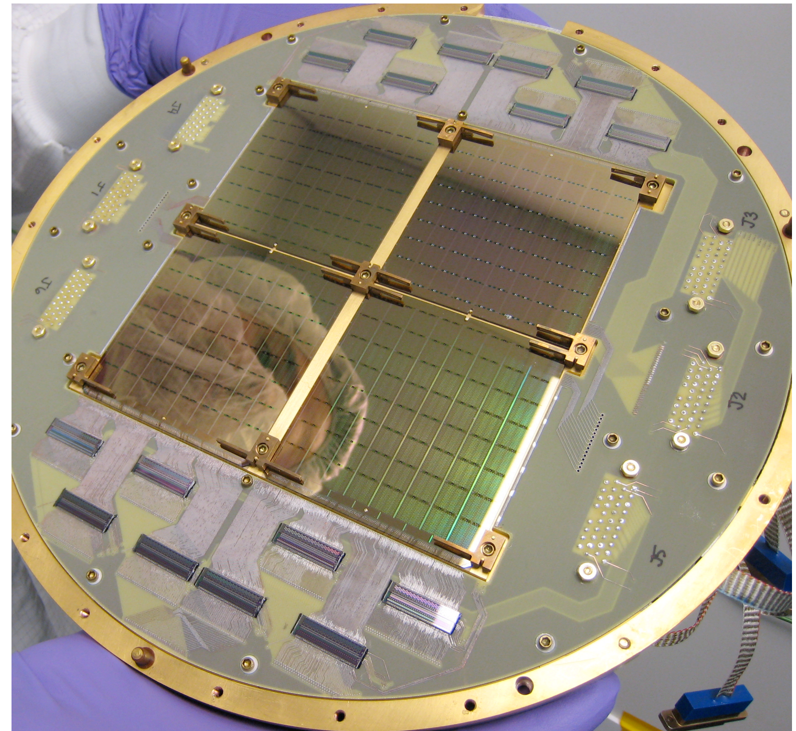
In collaboration with:

BICEP1
Spider

NSF - OPP

BICEP2: 10-fold increase in mapping speed:

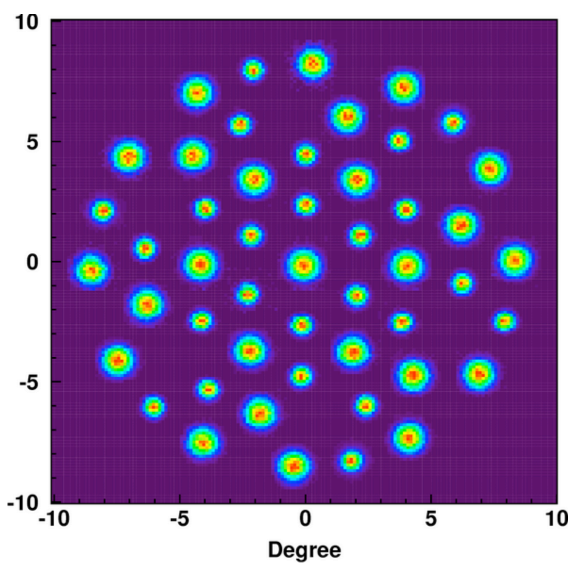


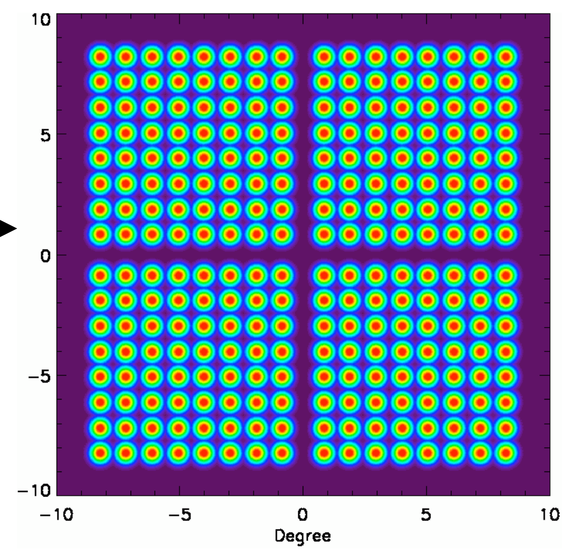


JPL : antenna-coupled TES arrays

BICEP1

48
150 GHz
detectors

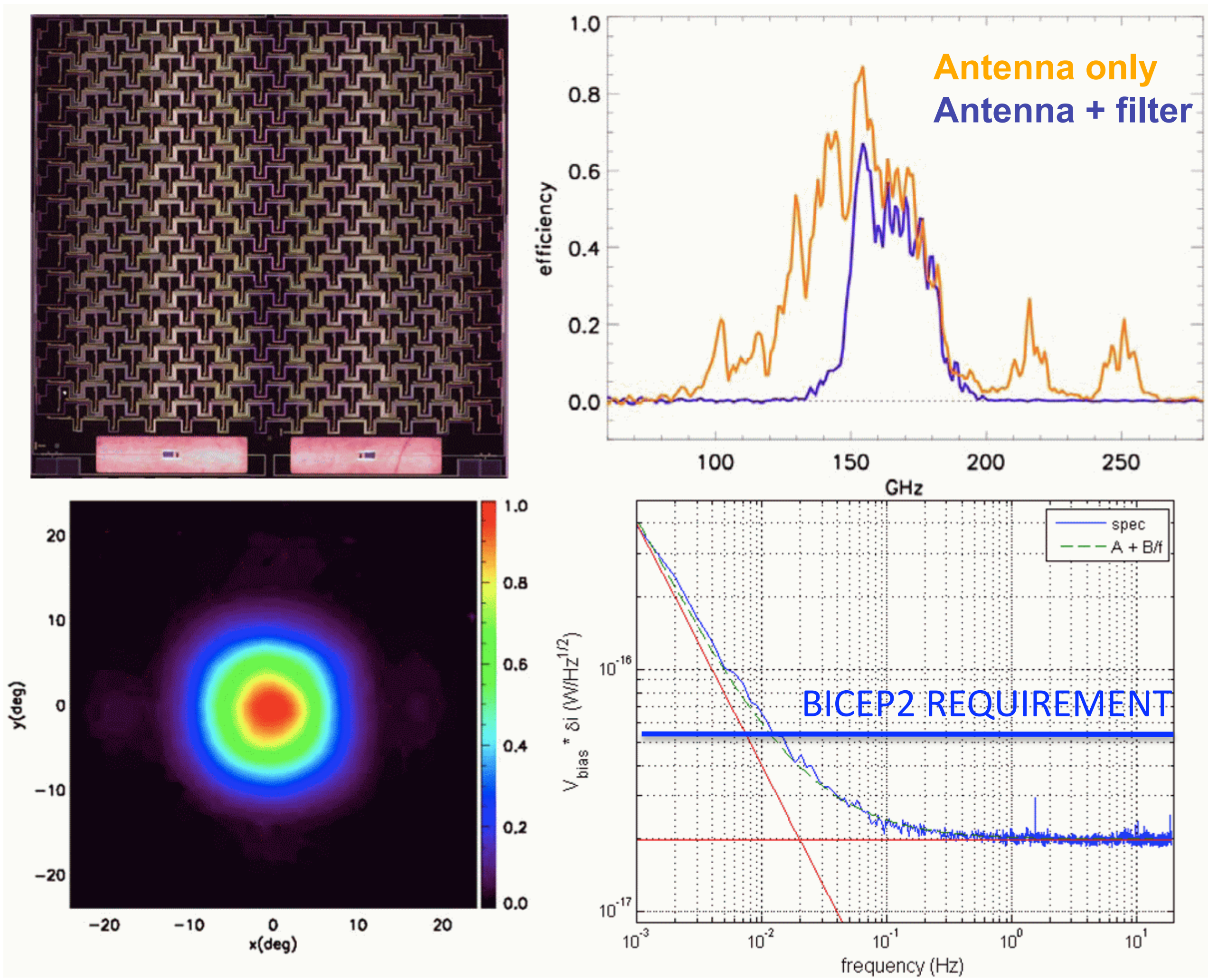




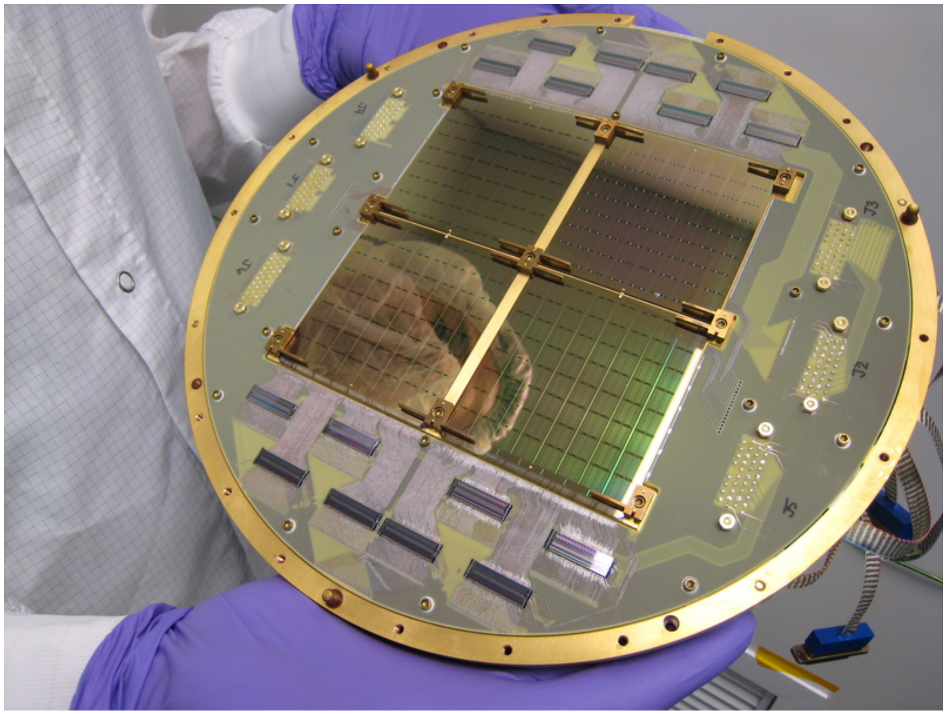
BICEP2

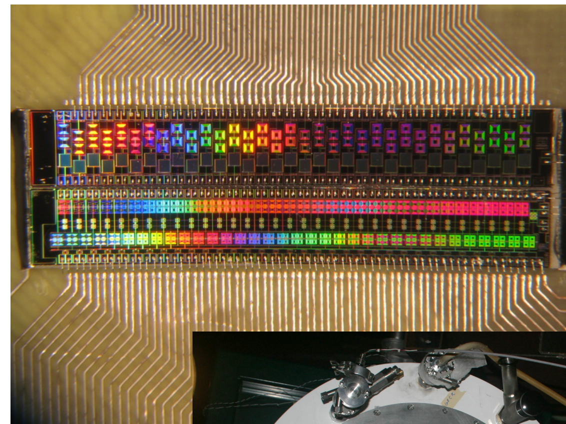
512
150 GHz
detectors

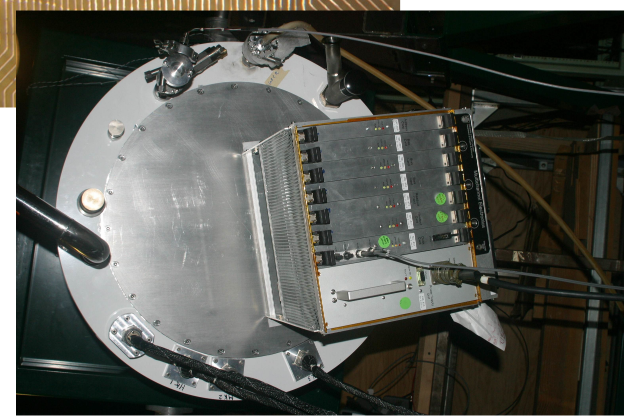
The TES Detectors



The TES Focal Plane for BICEP2







TES Antenna coupled Focal Plane Array
512 detectors (256 per polarization)
150 GHz

<u>READOUT</u>
32:1 TD SQUID Mux (NIST)
Multi Channel Electronics (UBC)

BICEP2/Keck Refractors: new features

- 2fλ antenna-coupled feeds increase edge illumination from

  BICEP1: -22 dB edge taper

  BICEP2: -12.4 dB edge taper, so…

- Lens design reoptimized using ZEMAX (Randol Aikin)

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

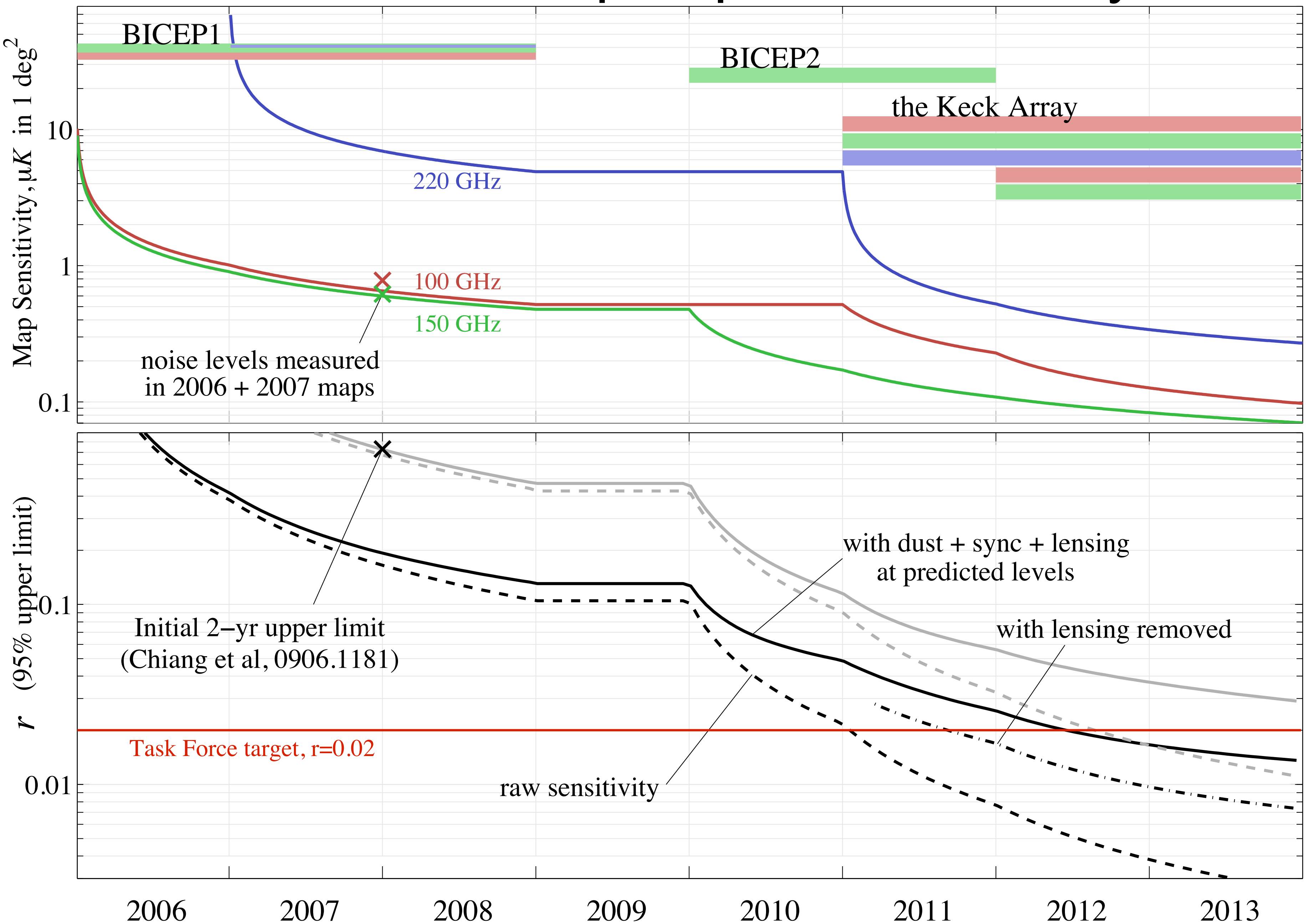
- Aperture stop refined (tapered HR10)
- AR coats still expanded PTFE, but optimized for monochromatic
- 4” Zotefoam window unlaminated, reducing scattering from 1.5% to 0.3%

BICEP2 status:

– starting 5th run with a full focal plane this week

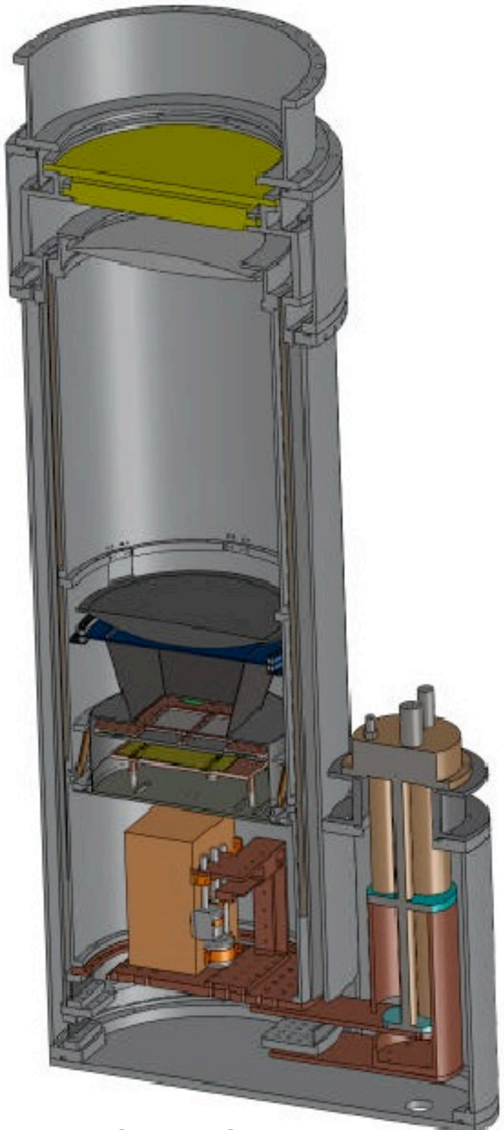
> 460 live detectors ready for beam mapping

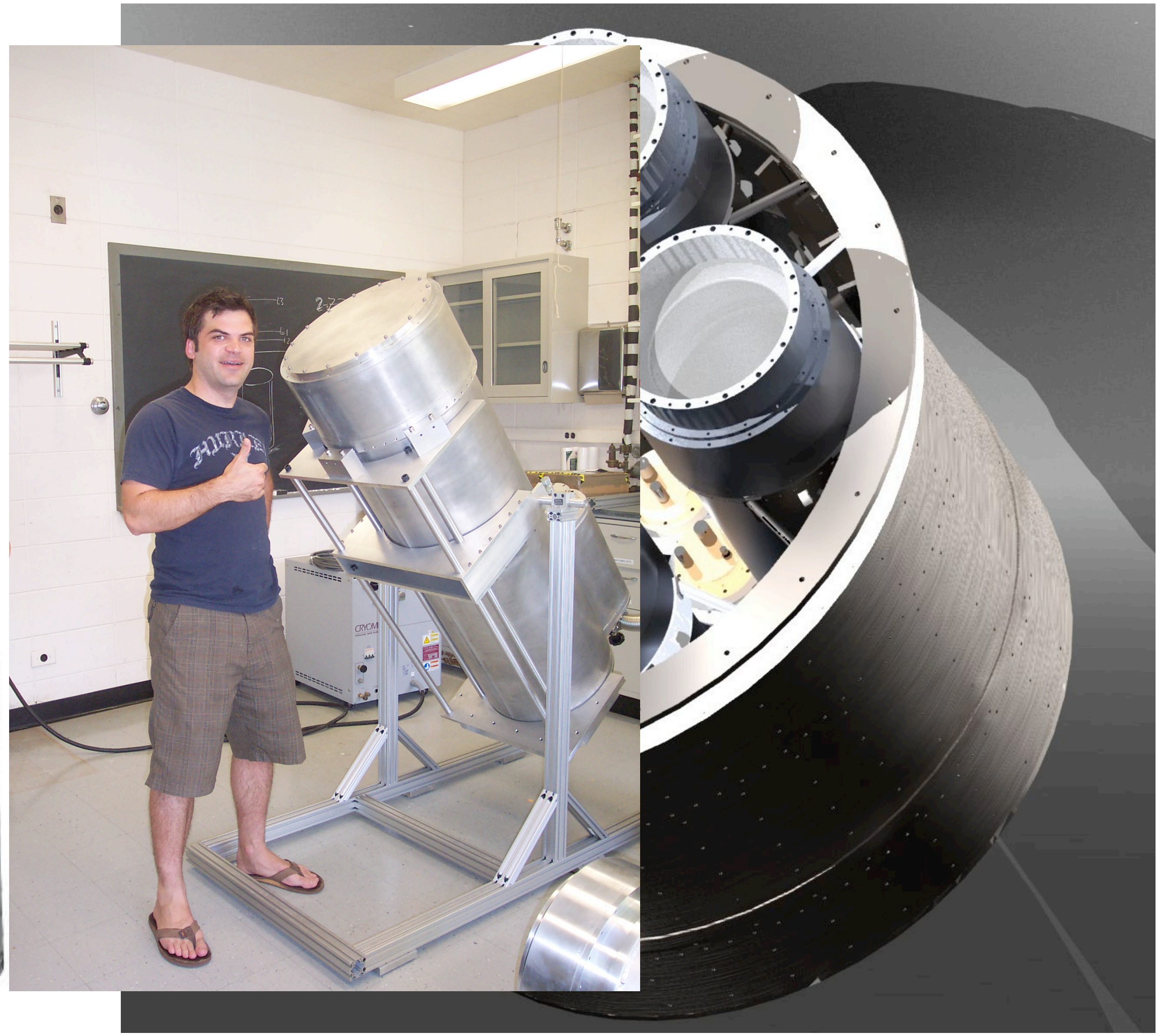
BICEP / Keck : map depth & sensitivity to *r*



Keck Array status:

– Cryostat and insert integration underway this summer





Design: Chris Sheehy

BICEP / Keck summary:

- **BICEP1** has shown merit of a targeted approach to *l* = 100 B-modes
  - Simple design emphasizes clean optics, high throughput, systematic control
  - Azimuth scan modulation, periodic boresight rotation
  - Systematics look controllable down to at least r=0.01

- **BICEP2** deploys to South Pole in November 2009
  - 512 detectors, 150 GHZ only, 10x mapping speed of BICEP1

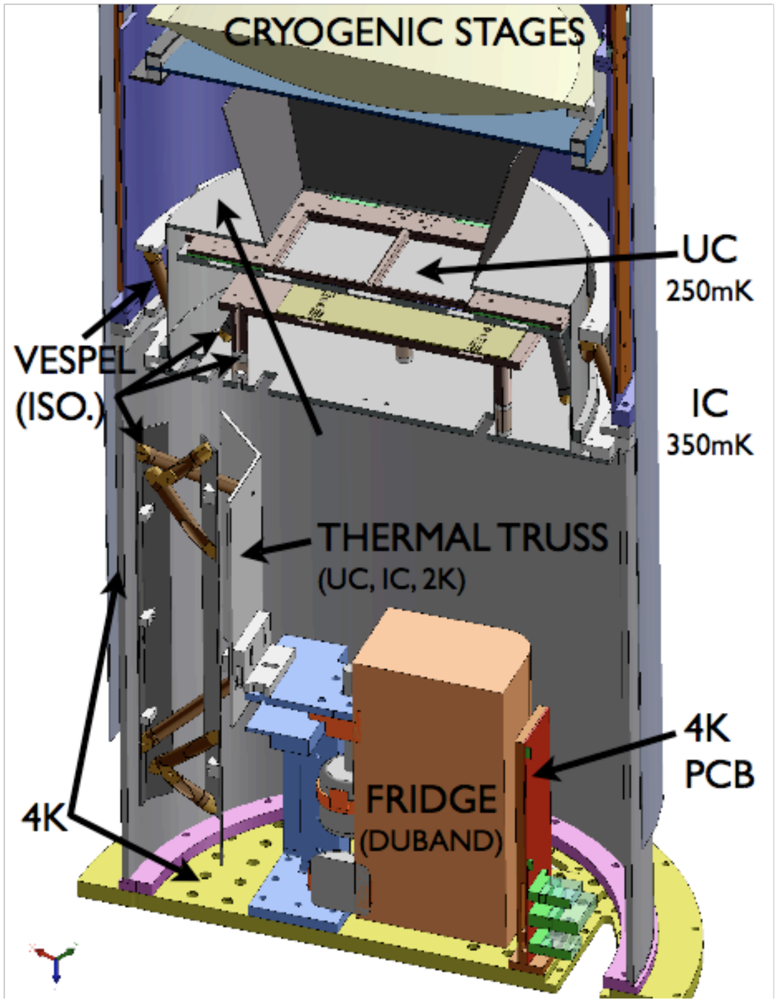
- **Keck Array** deploys at least 3 more telescopes in November 2010
  - Frequencies TBD, depending on whether we see a B-mode signal!
  - 5 telescopes (~2200 detectors) total by November 2011

In Southern Hole, hope to push to r < 0.02 and beyond…

Will continue to prove and improve technology for an orbital mission.

end

The Receiver



BICEP2 – only liquid Helium
(No Liquid Nitrogen)

Keck Cryostat – cryogen free

Cryoperm Shield

Stable thermal strap

BICEP and the Keck Array

A phased program of small-aperture CMB polarimeters at the South Pole
targeting the *l* = 100 Inflationary peak in the cleanest 2% of the sky

BICEP1, 2006-2008

- Has successfully proven the small aperture approach
- 50 detectors @100 GHz
- 44 detectors @150 GHz
- Final sensitivity: r ~ 0.1

BICEP2, 2009-2011

- New antenna-coupled TES focal plane (JPL)
- 512 detectors @150 GHz
- Superb systematic control
- Raw sensitivity: r ~ 0.02

Keck Array, 2010-2012

- 3 additional BICEP2-like receivers on DASI mount
- 100, 150, 220 GHz coverage (1824 detectors total)
- Sensitivity w/ foreground removal: r ~ 0.01