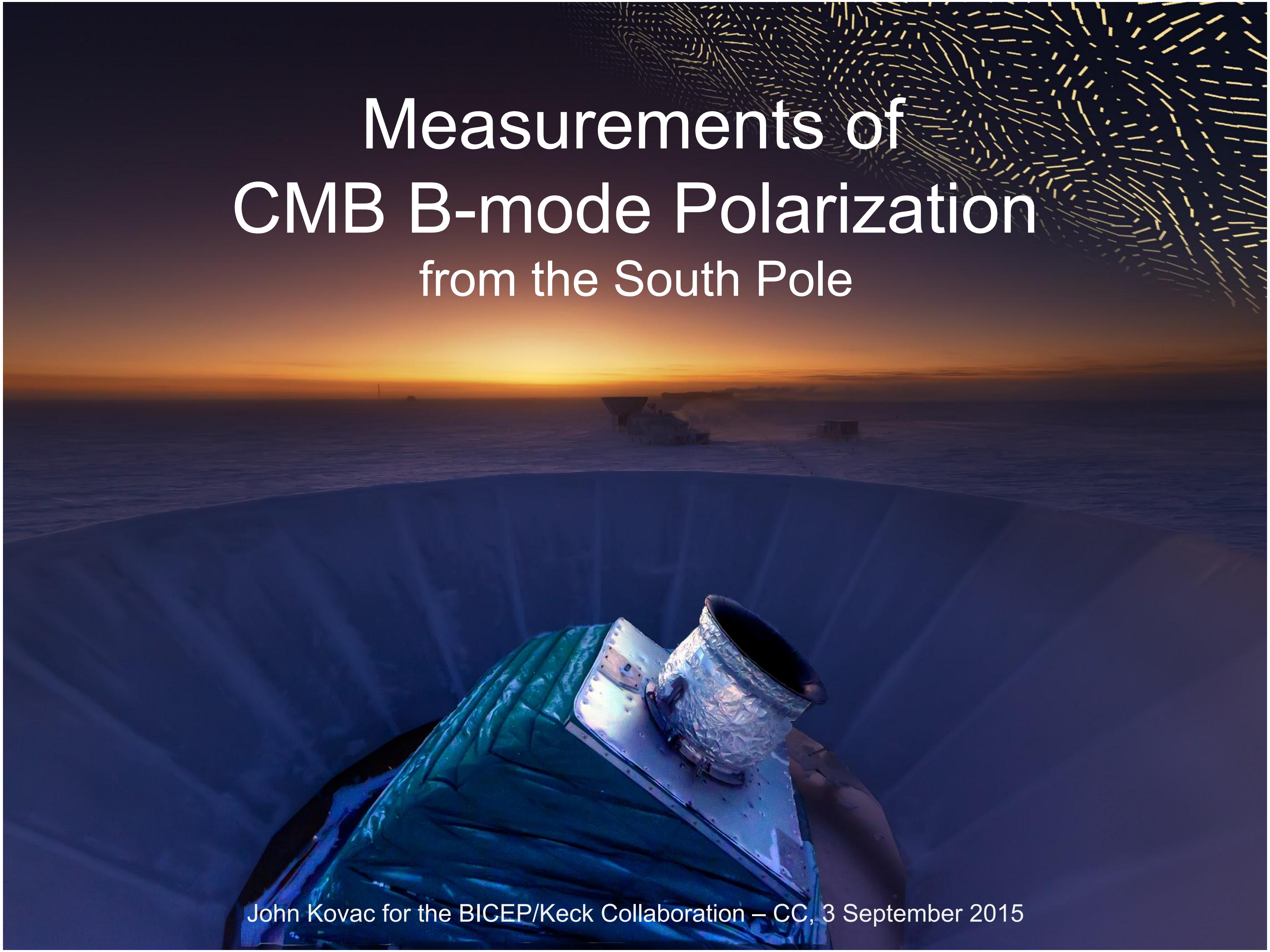
Measurements of CMB B-mode Polarization

from the South Pole

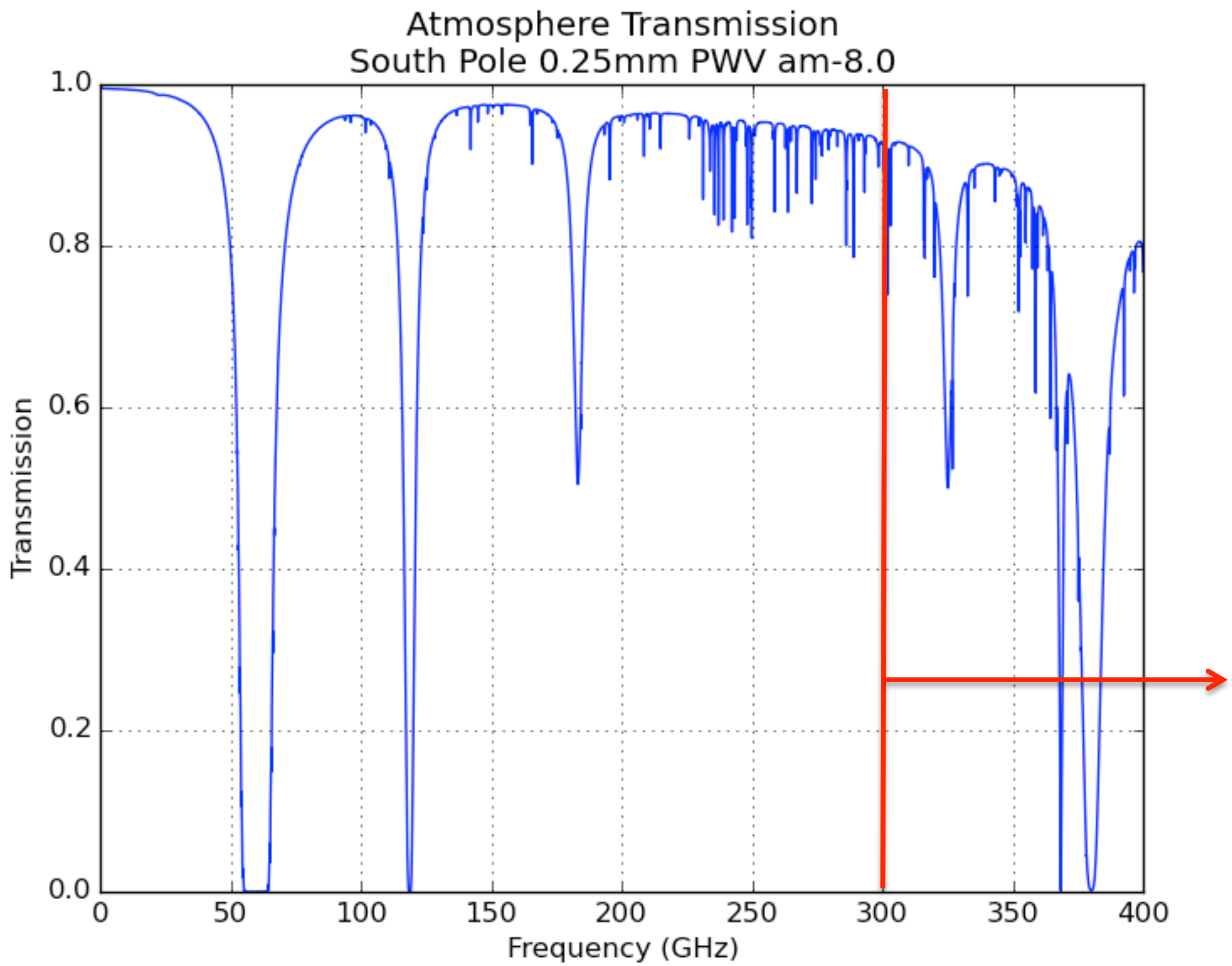


John Kovac for the BICEP/Keck Collaboration – CC, 3 September 2015

Given that beautiful Planck maps exist, why make further suborbital measurements?

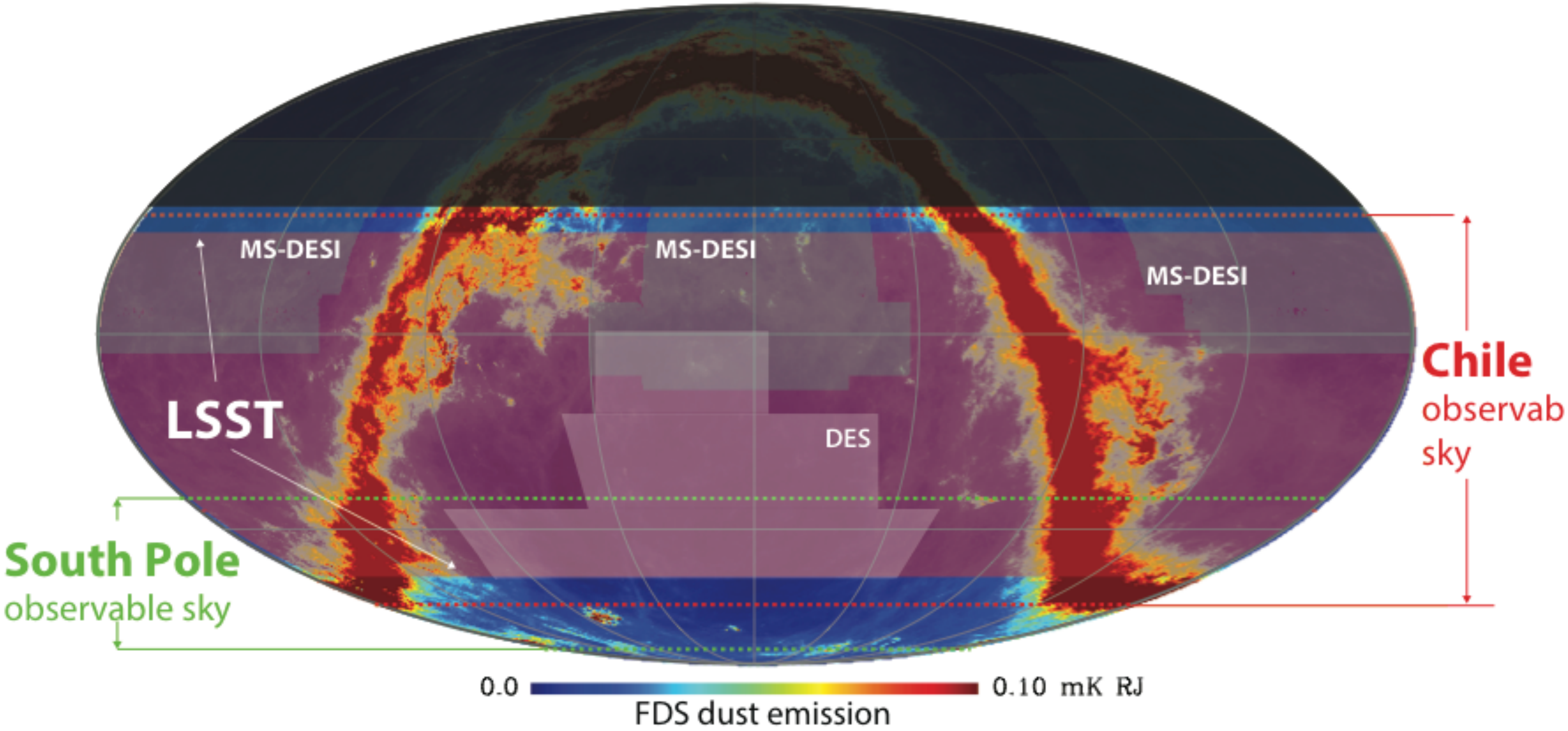
- Can achieve higher sensitivity – quite quickly now on small patches of the full sky
- Can have higher angular resolution – particularly with ground based experiments

Ground based limitation: Can’t do high frequencies



Even from the best sites can’t go above 300GHz

Suborbital Limitation: Can't do full sky from a single site (or flight)

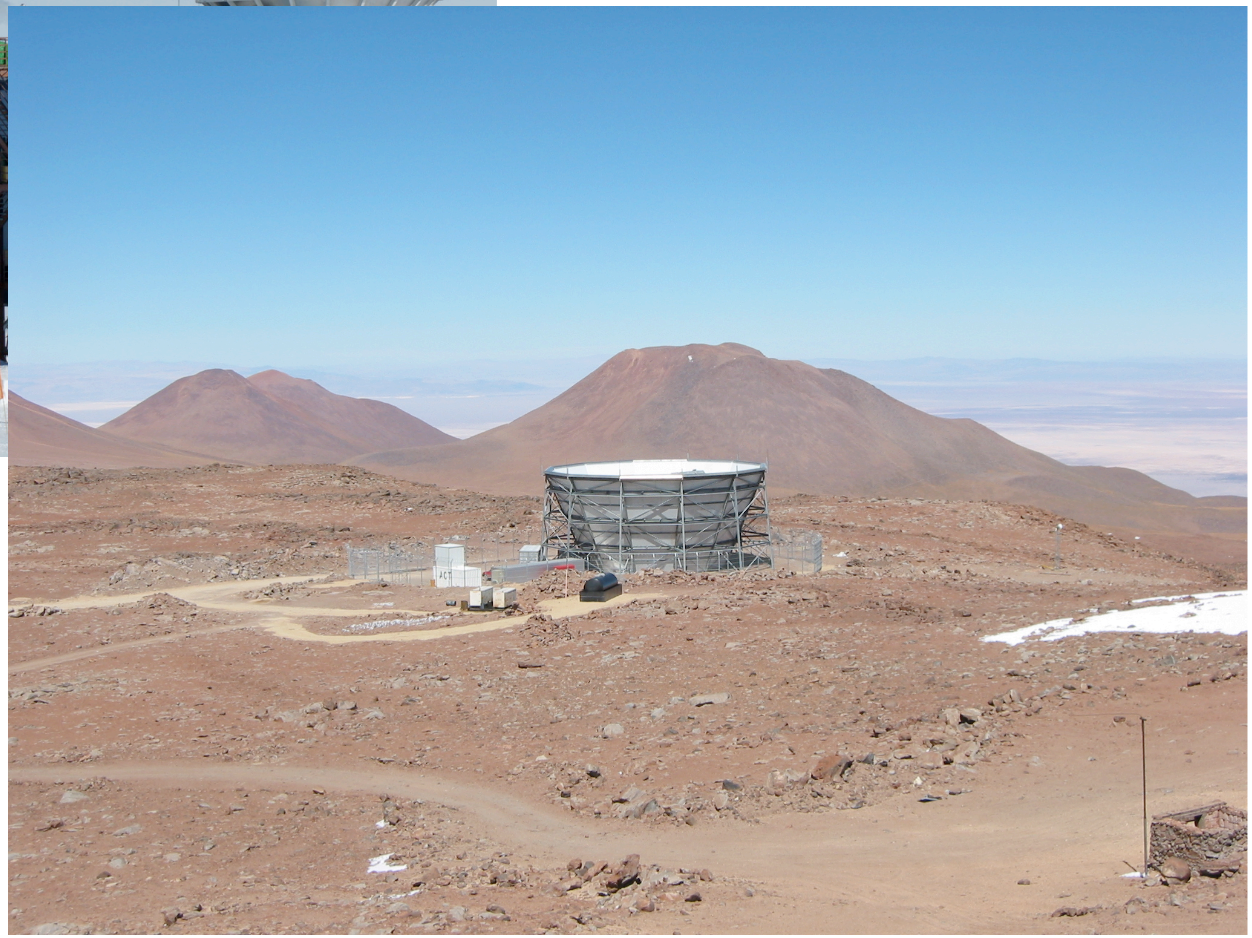


- But full sky maps have been made from the ground (e.g. Haslam 408MHz)

High Angular Resolution Experiments

South Pole
Telescope (SPT)
10 meter diameter

Atacama Cosmology
Telescope (ACT)
6 meter diameter



SPT Temperature Results

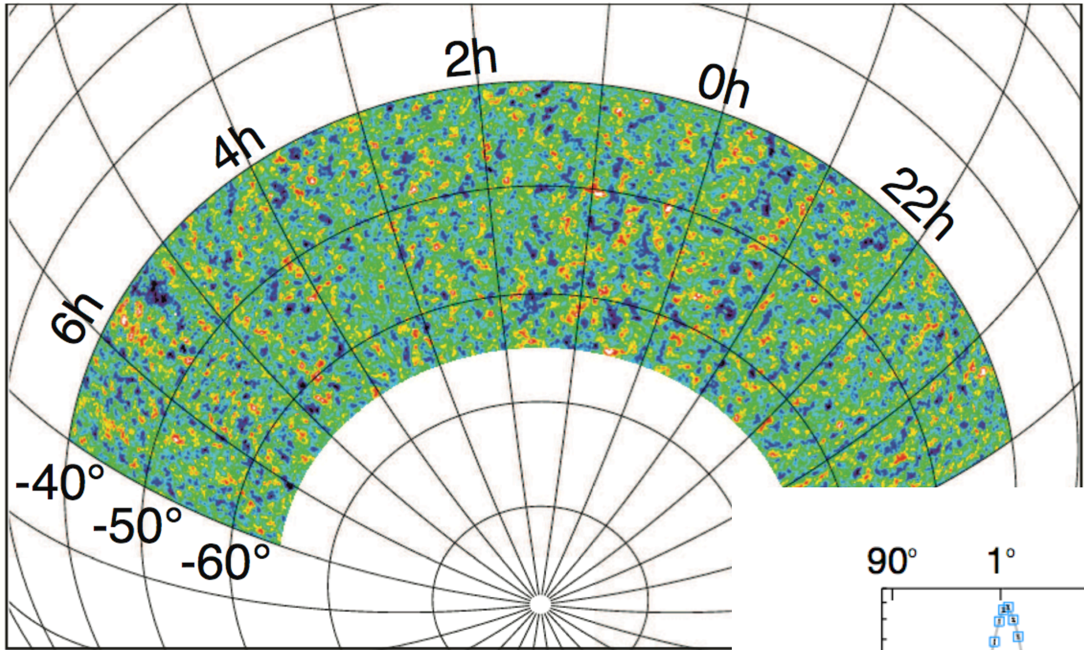


Fig1 of arxiv:1210.7231

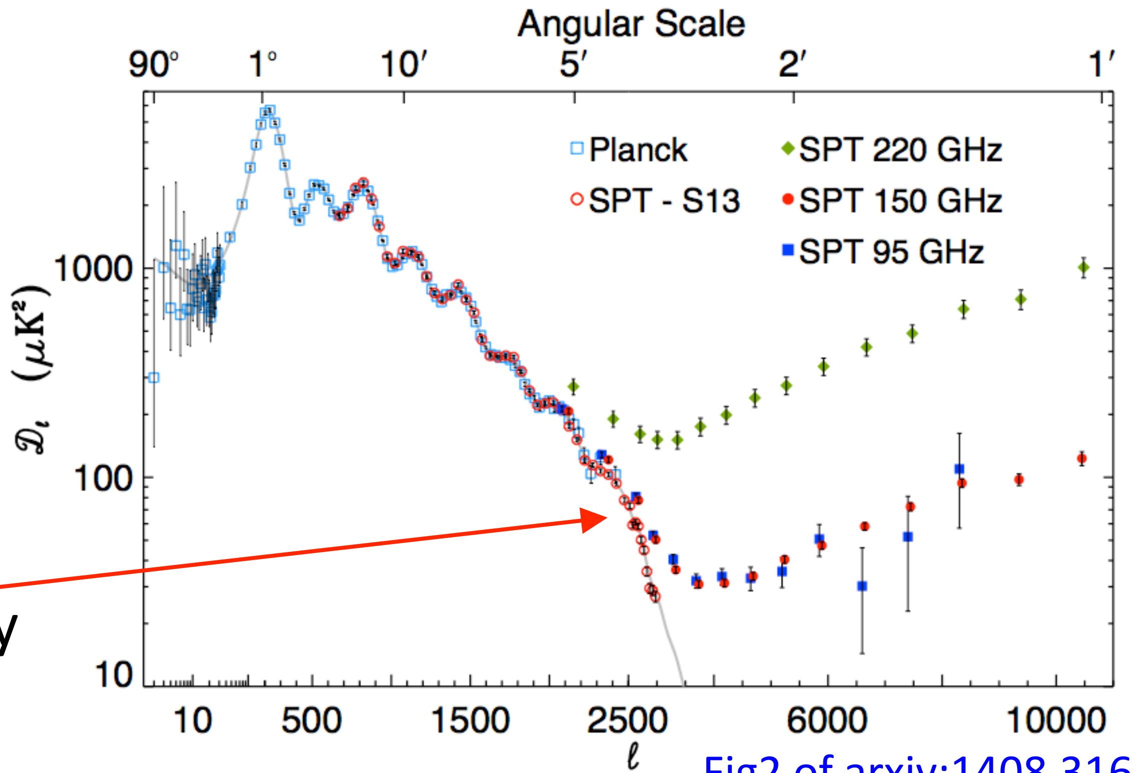
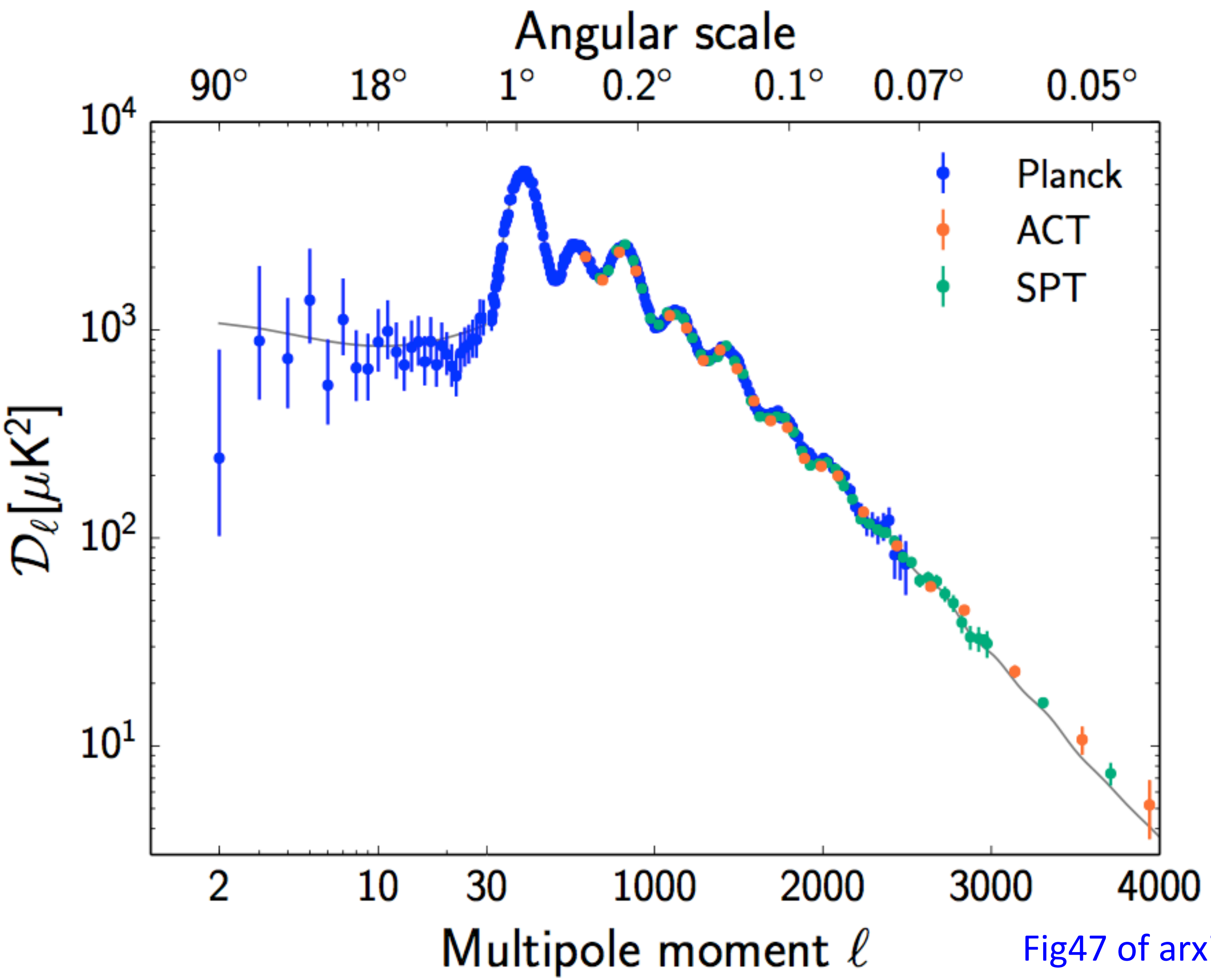


Fig2 of arxiv:1408.3161

Measurements of TT damping tail hampered by foregrounds

High ell TT in conjunction with Planck



At the moment, doesn't add much to basic LCDM fits.

Fig47 of arxiv:1507.02704

SPT/ACT SZ Clusters in conjunction with Planck

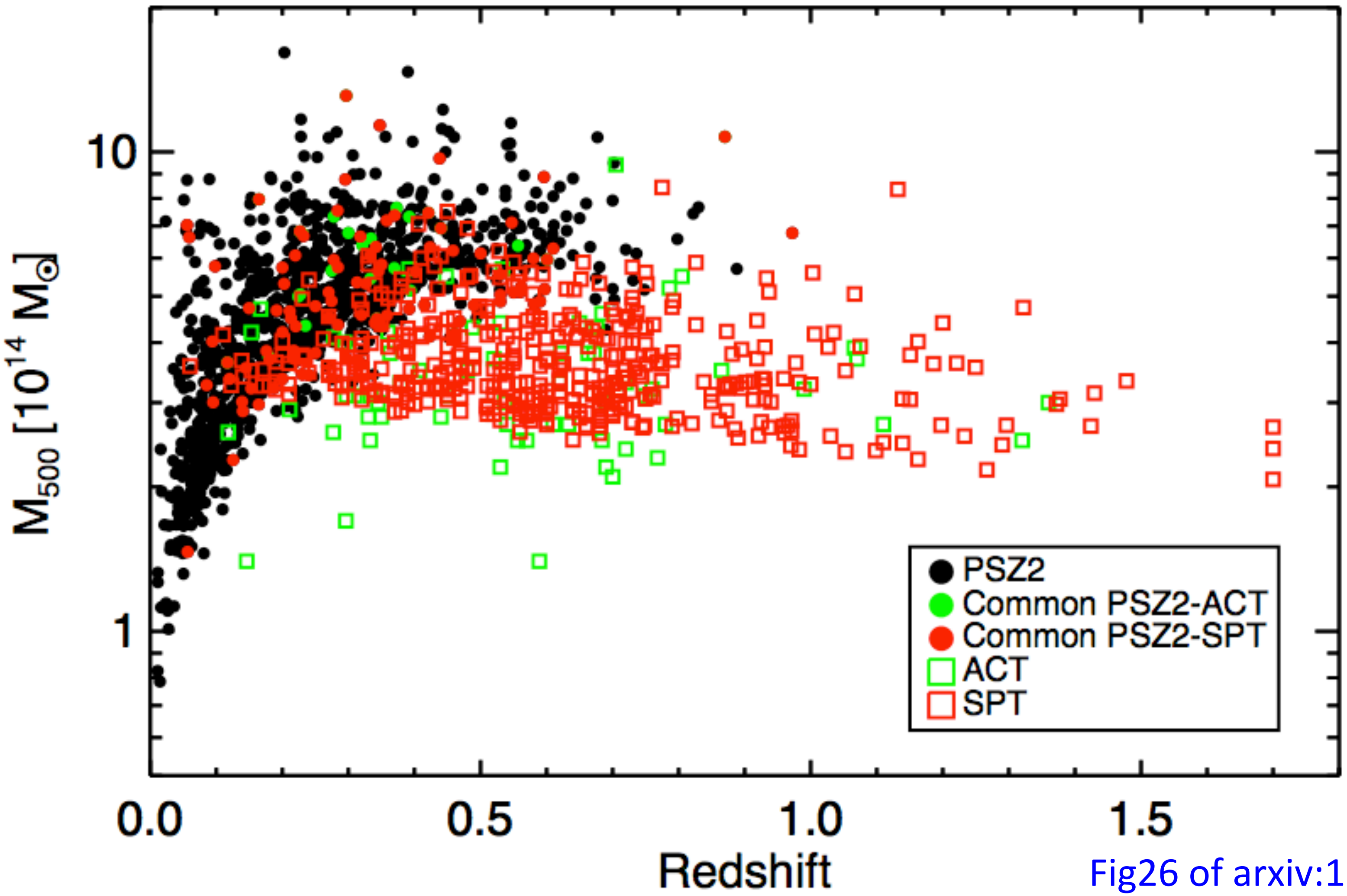
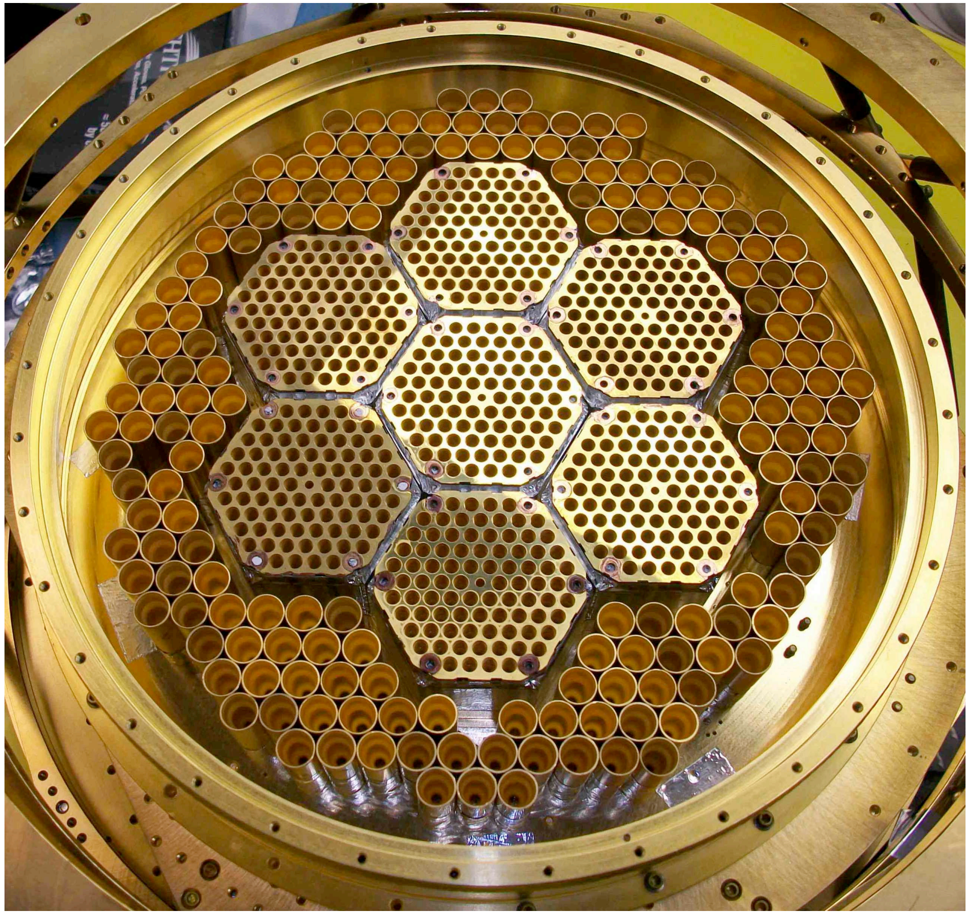


Fig26 of arxiv:1502.01598

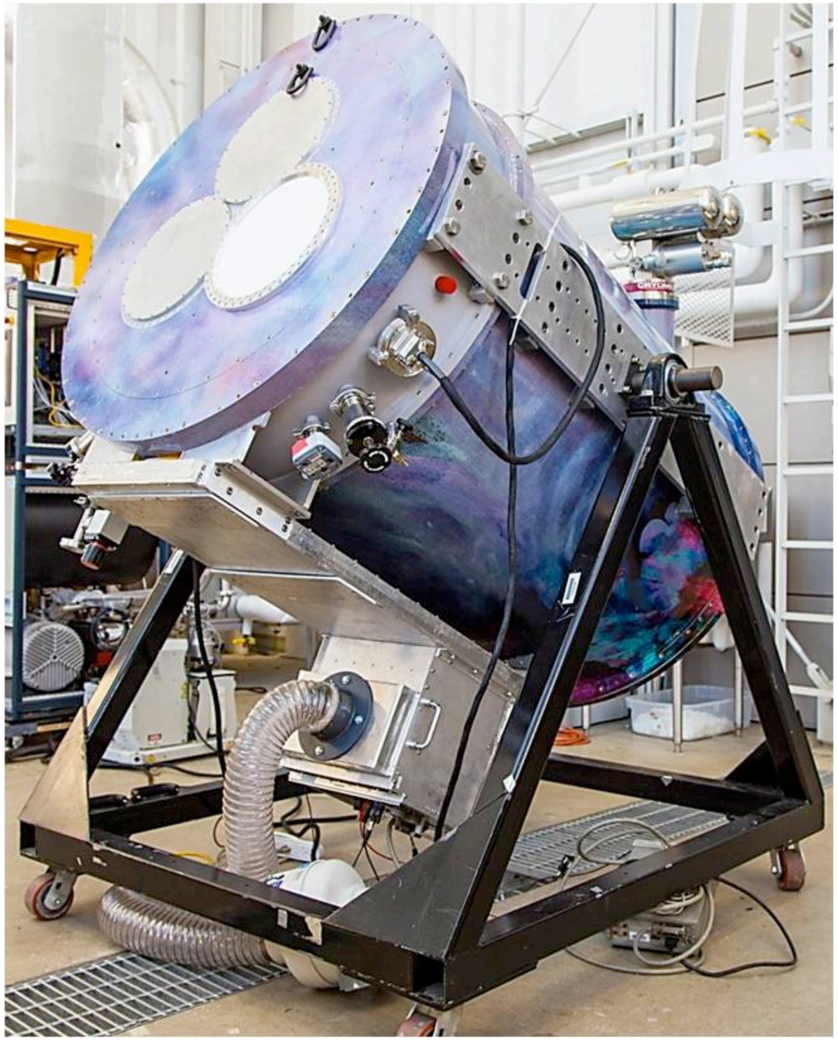
Planck provides lower redshift cluster sample –
will be a major legacy going forward

High Angular Res Pol Experiments (2G)

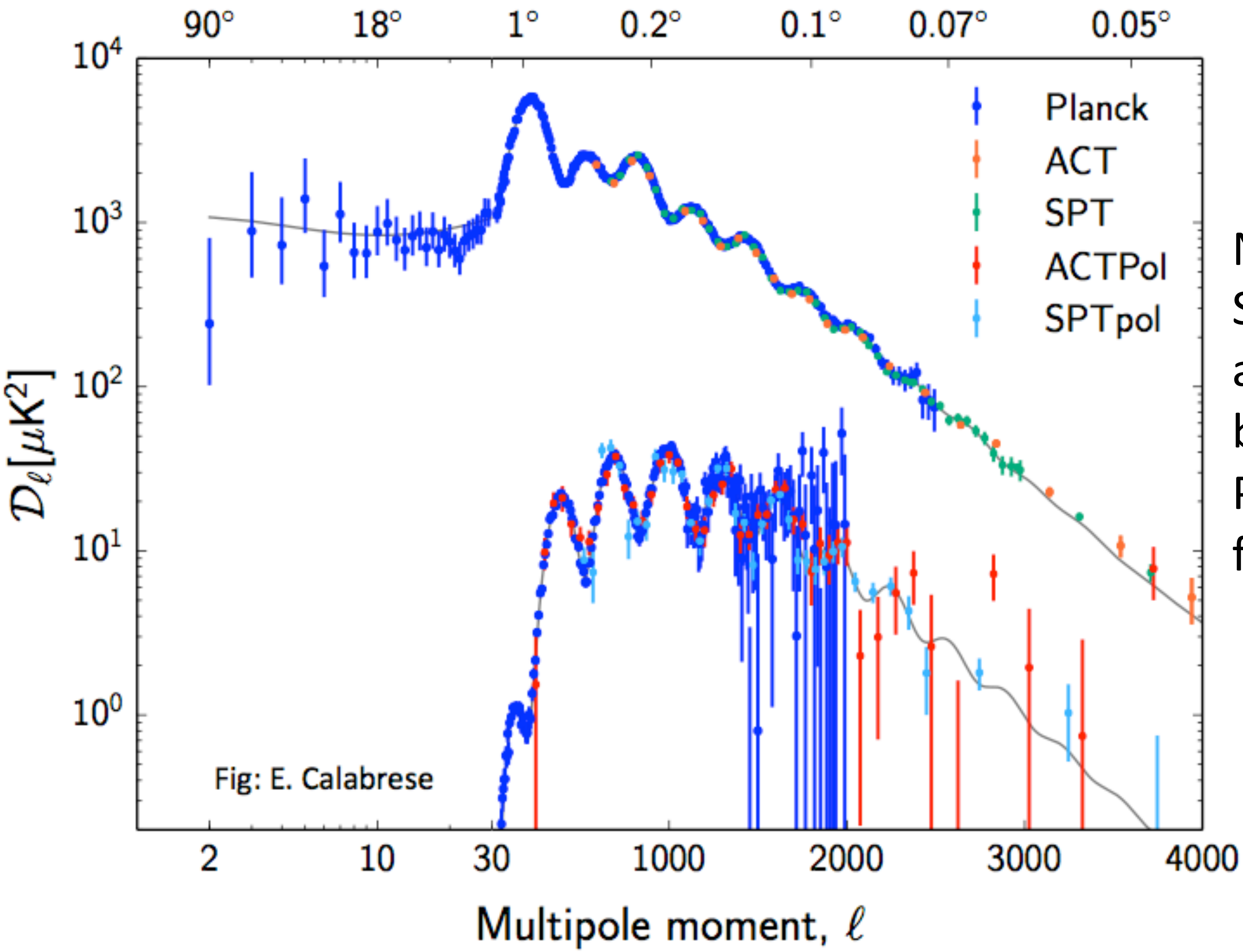


The SPTpol camera

The ACTpol receiver

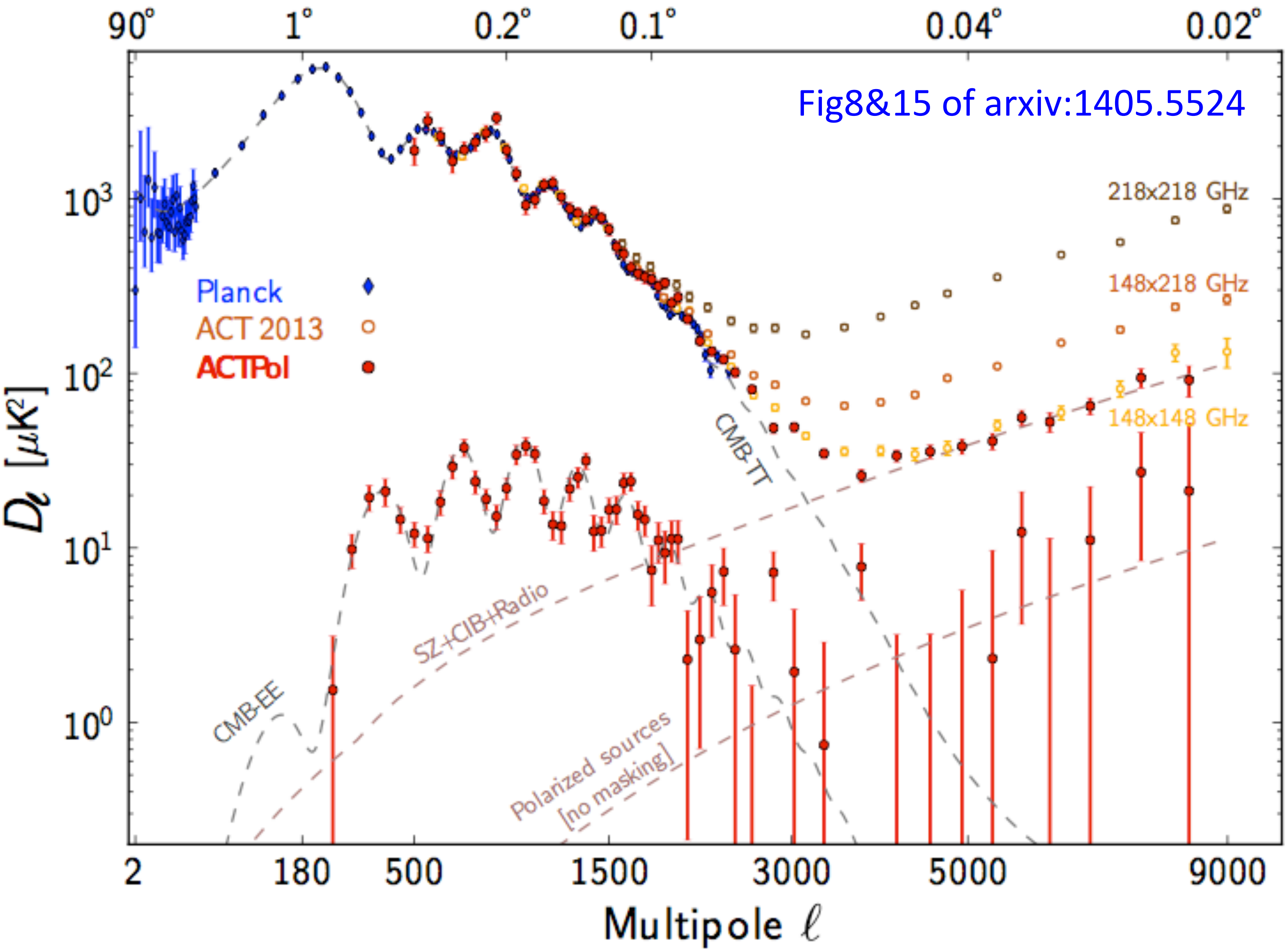


High Res Experiments can measure EE damping tail



Note that SPT/ACTpol already better than Planck EE for ell>1500

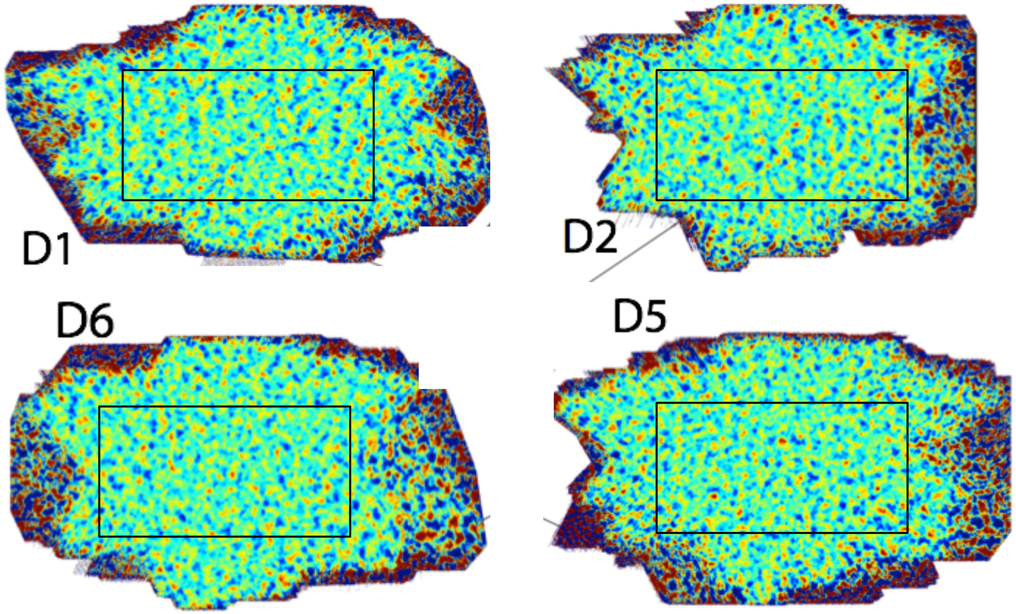
High Res Experiments can measure EE damping tail



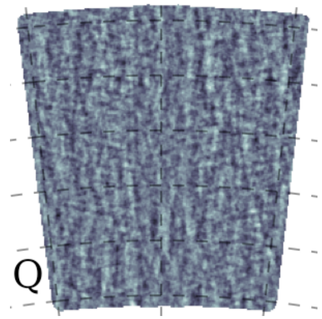
Note that SPT/ACTpol already better than Planck EE for ell>1500

CMB has higher fractional polarization than point sources – can push further down the damping tail in EE

Published Deep Suborbital Polarization Maps To Date

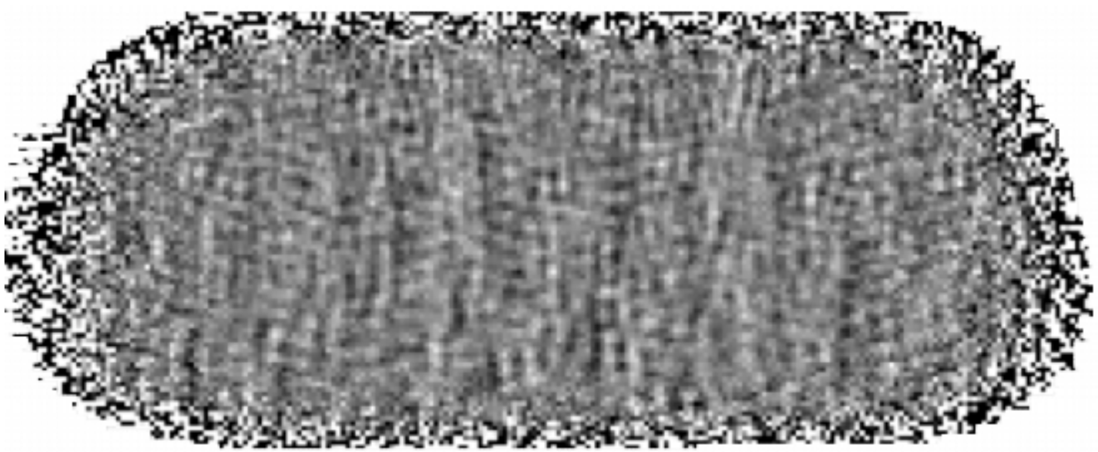


ACTpol 275 sq deg arxiv:1405.5524

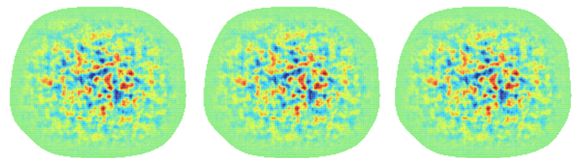


SPTpol 100 sq deg arxiv: 1411.1042 and 1503.02315

Roughly scaled to indicate relative map sky coverage



BICEP/Keck 400 sq deg arxiv:1403.3985 and 1502.00643



POLARBEAR 25 sq deg arxiv:1403.2369

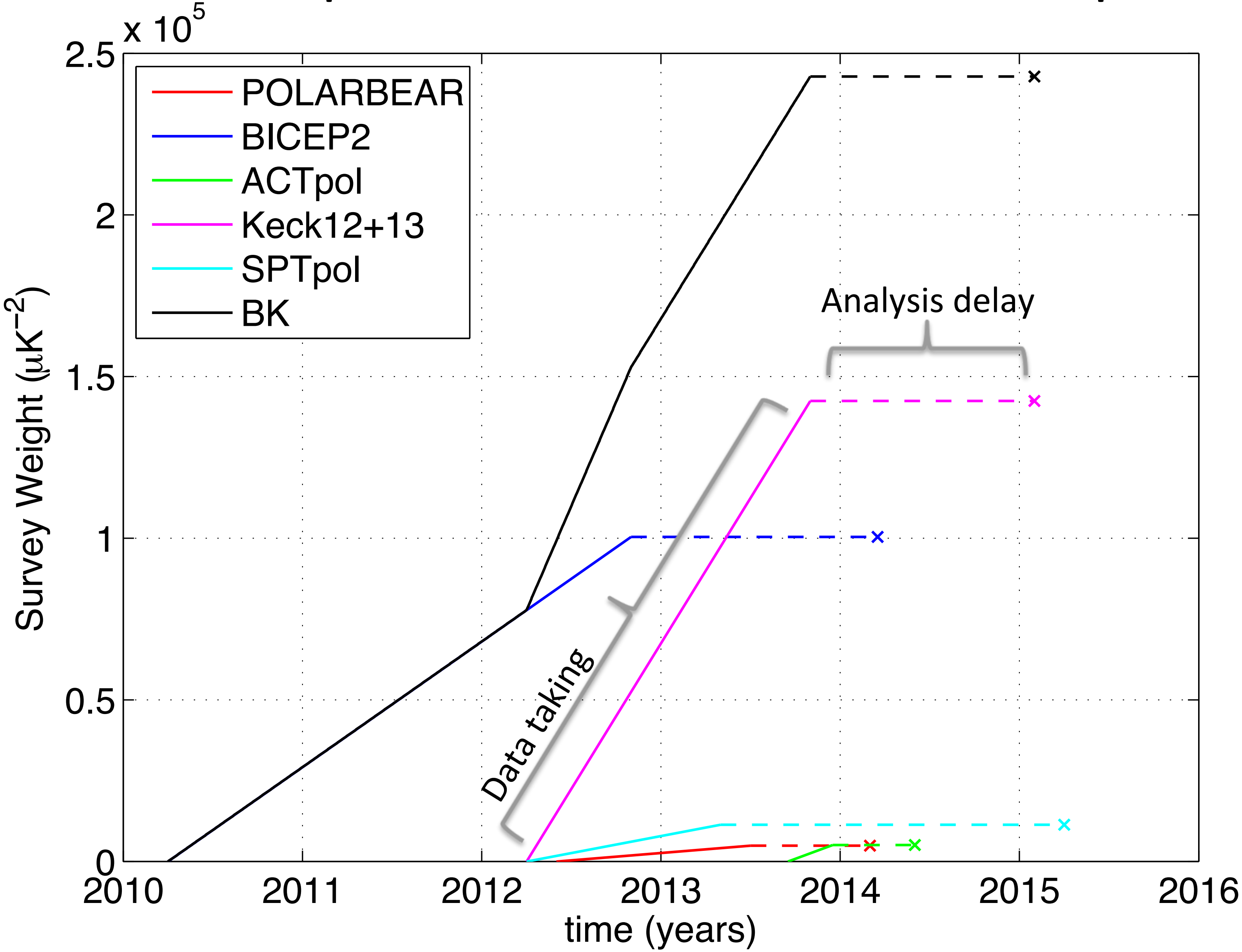
Published Deep Suborbital Polarization Maps To Date

	Q,U Map rms noise N [uK-arcmin]	Survey effective area A [deg^2]	**Total** Q+U **Survey Weight** $W=2A/N^2$ [uK^{-2}]	Reference
POLARBEAR	6	24.5	**5,000**	arxiv:1403.2369
BICEP2	5.2	380	**100,000**	arxiv:1403.3985
ACTpol	15.8 to 24	276	**5,000**	arxiv:1405.5524
SPTpol	17@95 & 9@150	100	**11,000**	arxiv:1503.02315
BICEP2+Keck	3.4	400	**250,000**	arxiv:1502.00643
Planck 143 GHz (for reference)	70	41,000	**60,000**	

Caution: gauging relative performance of experiments using nominal detector counts can be misleading – also projections are often optimistic!

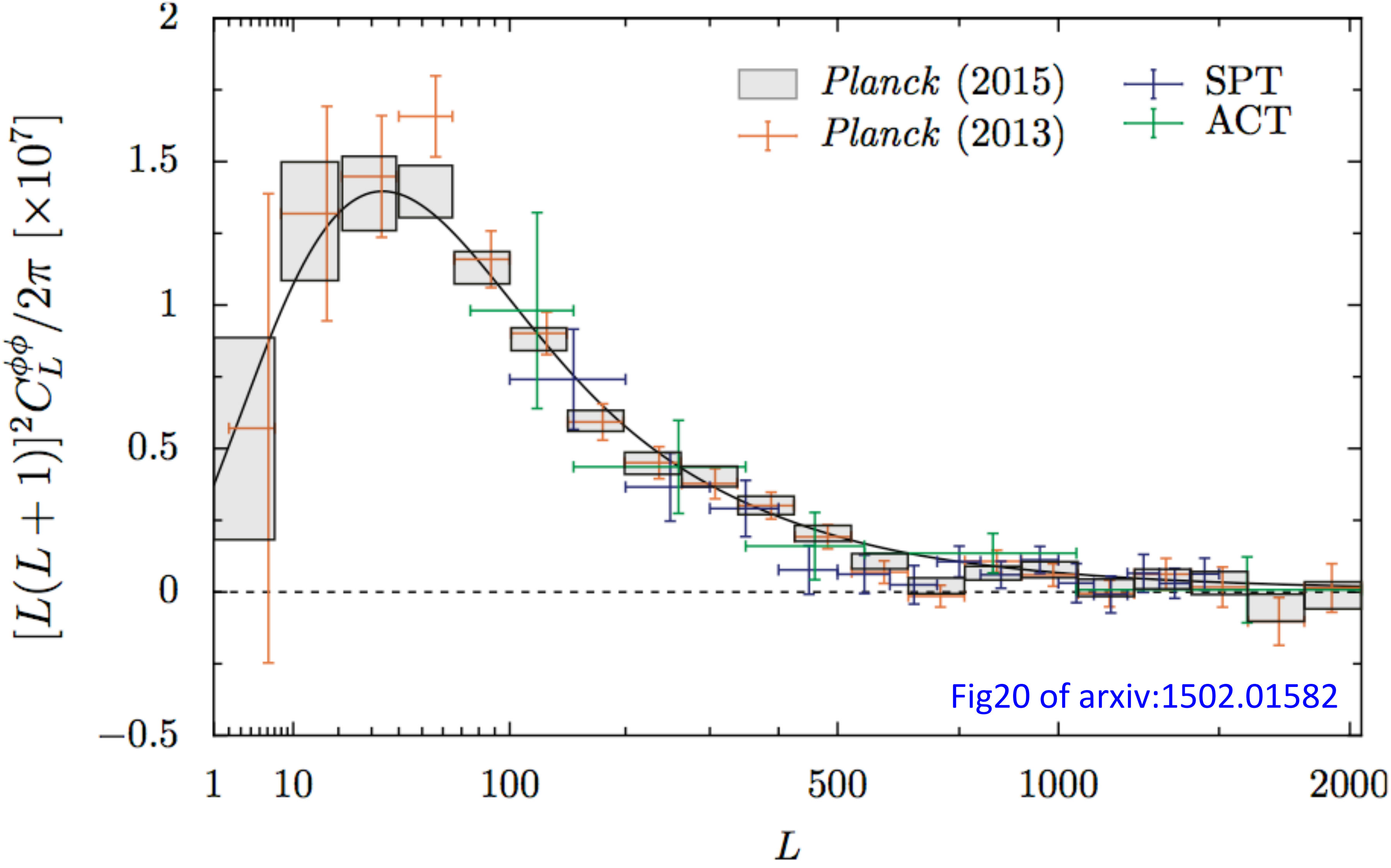
Survey weight: A quantity which is linear in number of detectors and integration time – i.e. difficulty of achieving
Also linear in power spectrum noise error bar size

Published Deep Suborbital Polarization Maps To Date



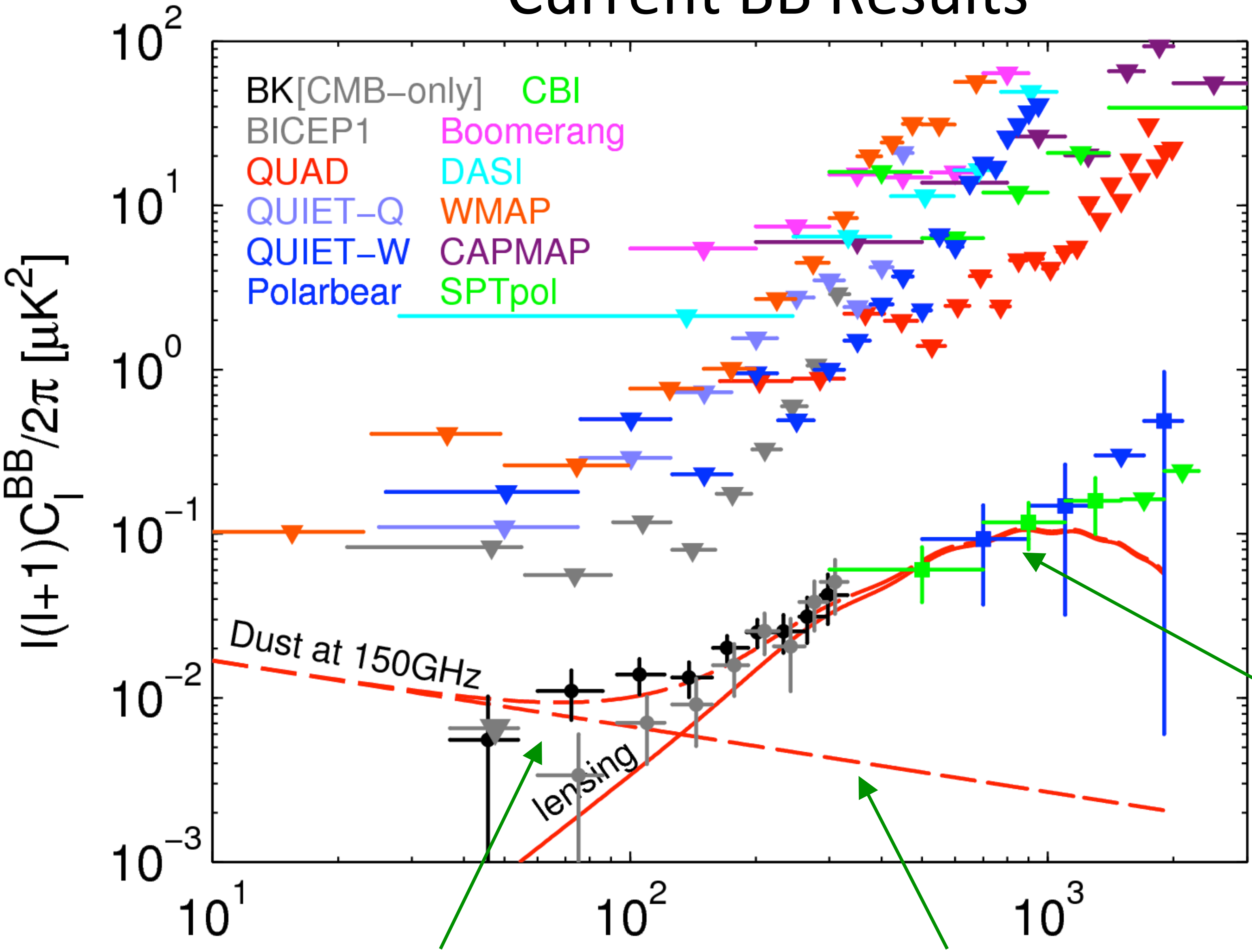
NB: Published results only – no projections!

High Res Experiments Can Do Lensing



Planck currently better – High res ground based can eventually do much better – see later…

Current BB Results



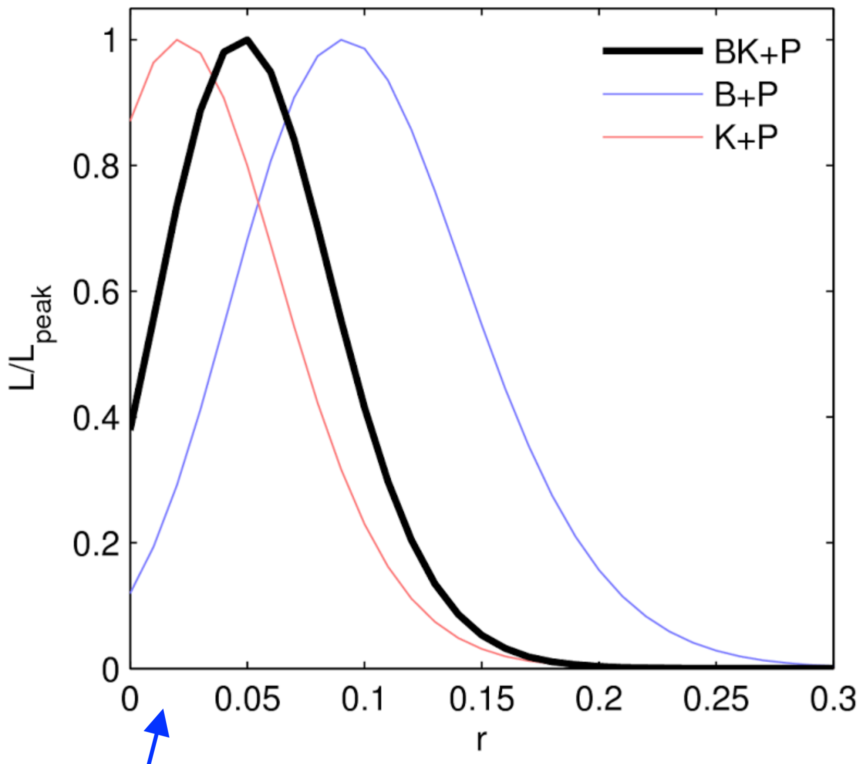
At higher ell lensing signal starting to be seen

At mid ell a signal is detected – but at least half is dust!

Planck 353 GHz data constrains dust contribution

BICEP/Keck/Planck limits on Inflation

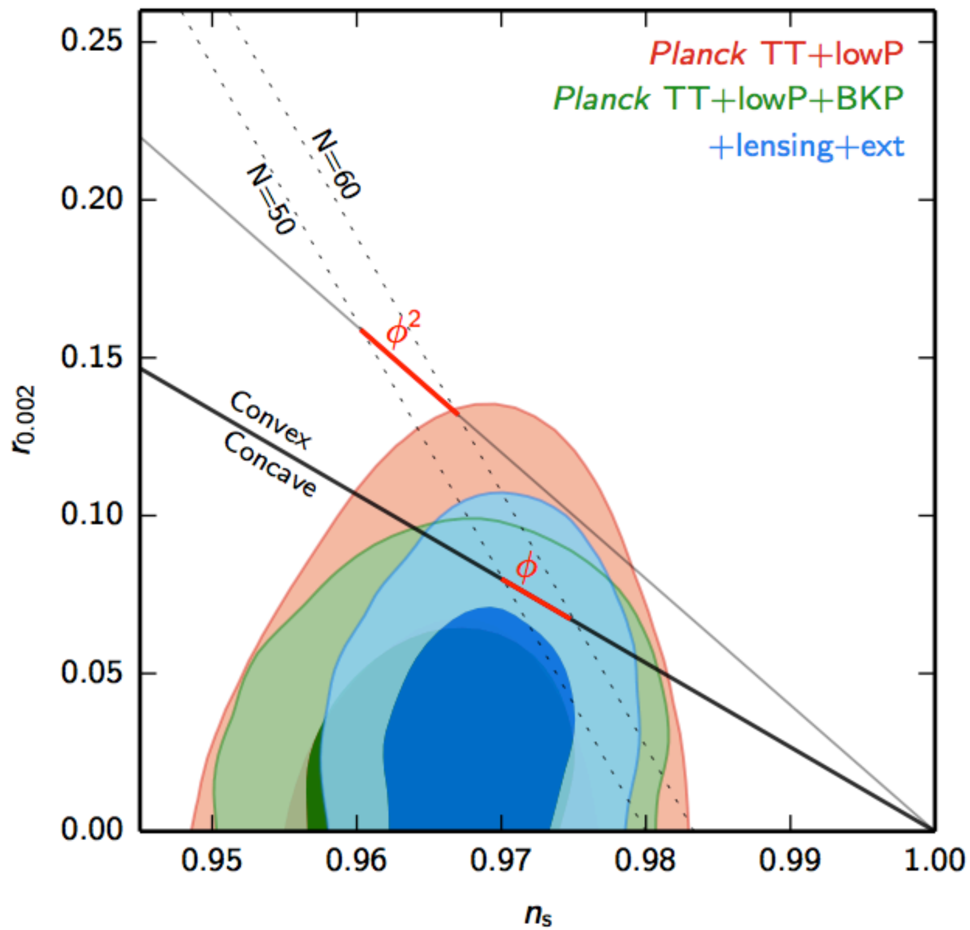
From joint BK/Planck paper



r constraint consistent with zero (For BK+P L_0/ L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

σ(r)≈0.035 (limited by Planck 353 GHz)

Inflationary constraint finally starts to tighten due to B-mode information

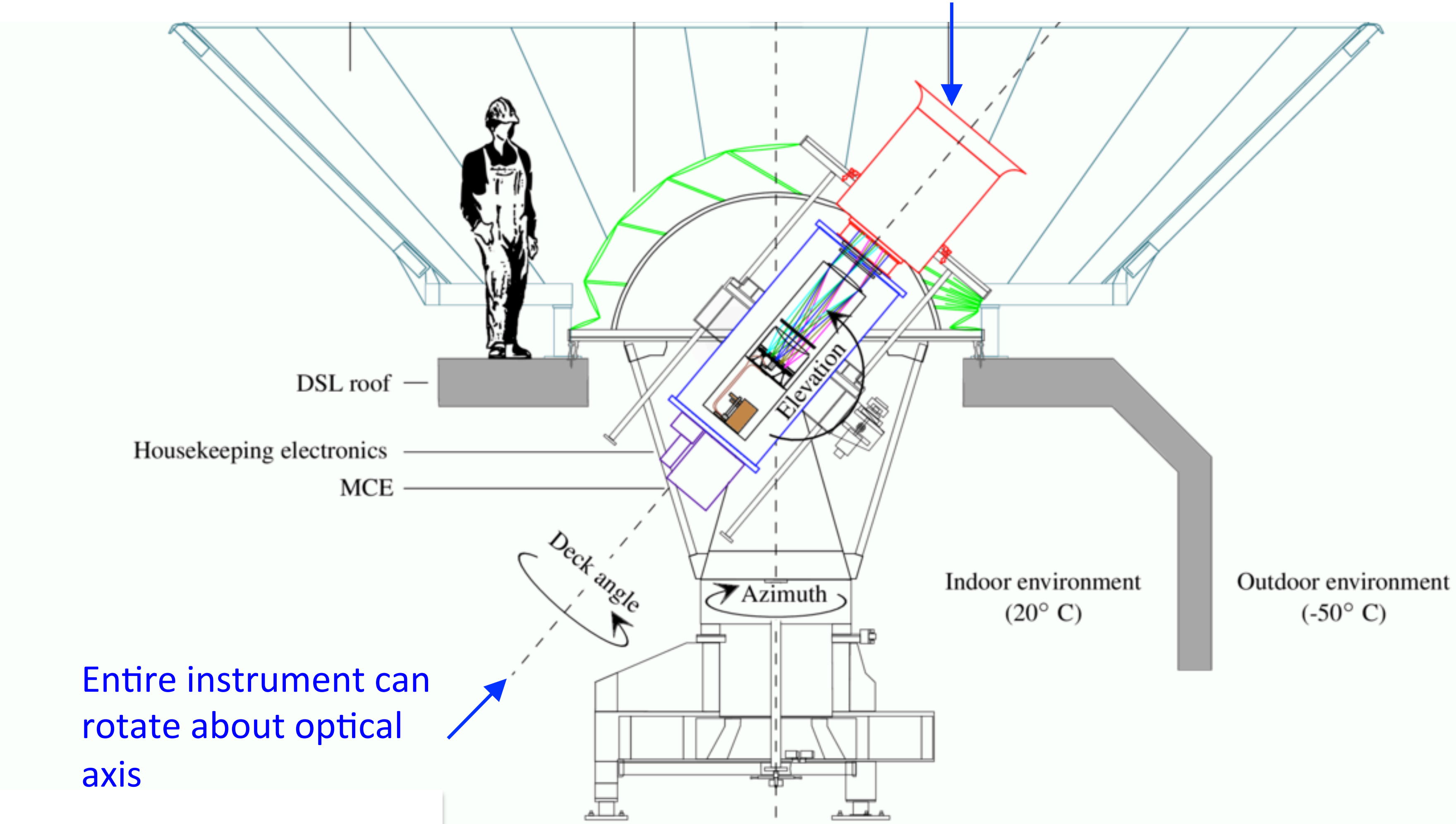


From Planck 2015 parameters paper

BICEP/Keck – targeted on gravity waves

- Single issue "physics experiment"
- Small aperture – low resolution – optimized for ell<200
- All cold (4K) refracting telescopes
- Single frequency at a time
- Best achieved sensitivity to date…

Co-moving absorptive forebaffle – ultra low sidelobes



Entire instrument can rotate about optical axis


VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION
NSF
UCSD
JPL
NIST
CARDIFF UNIVERSITY
cea
UNIVERSITY OF TORONTO
UBC

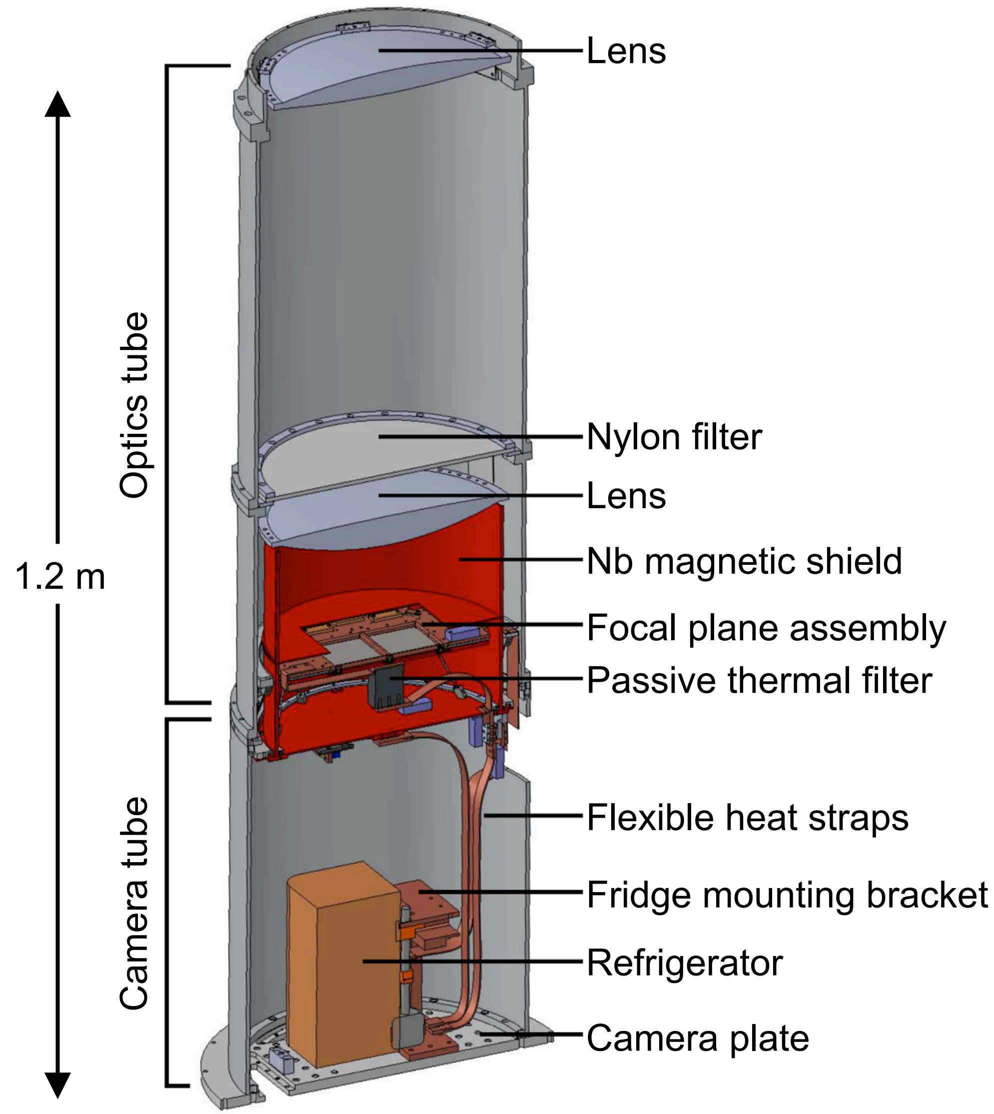
The BICEP2/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

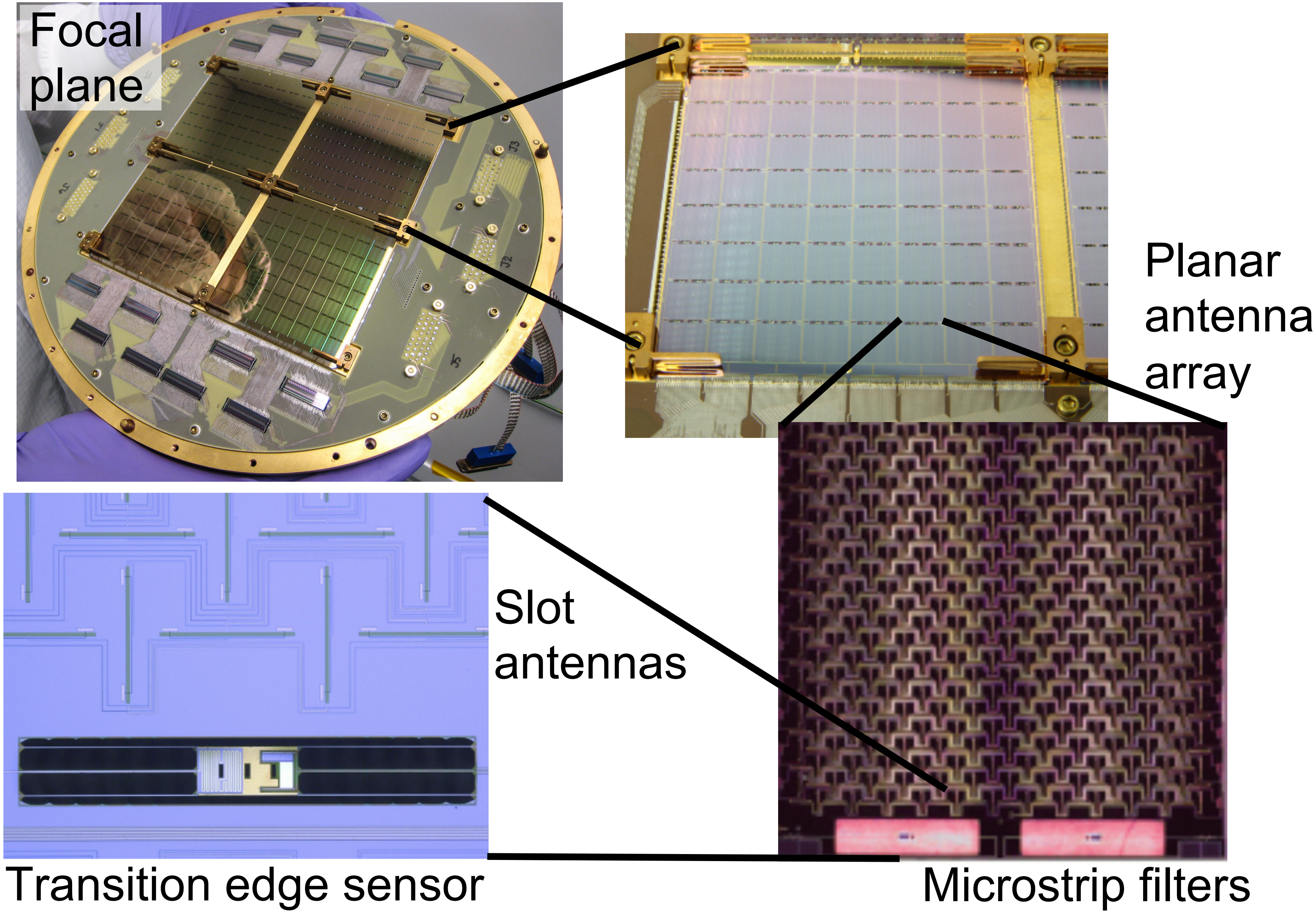
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

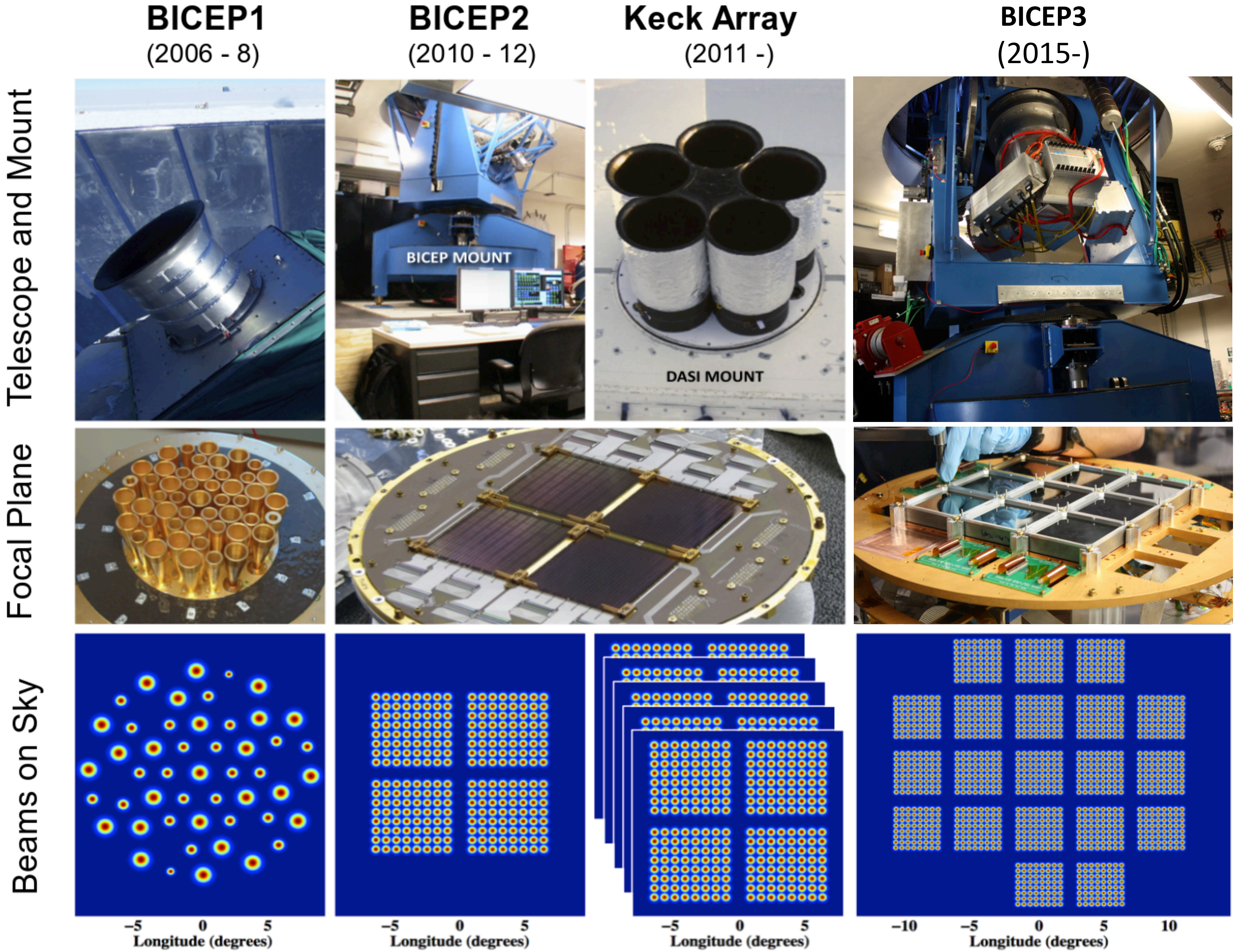
Liquid helium (or PT cooler) cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



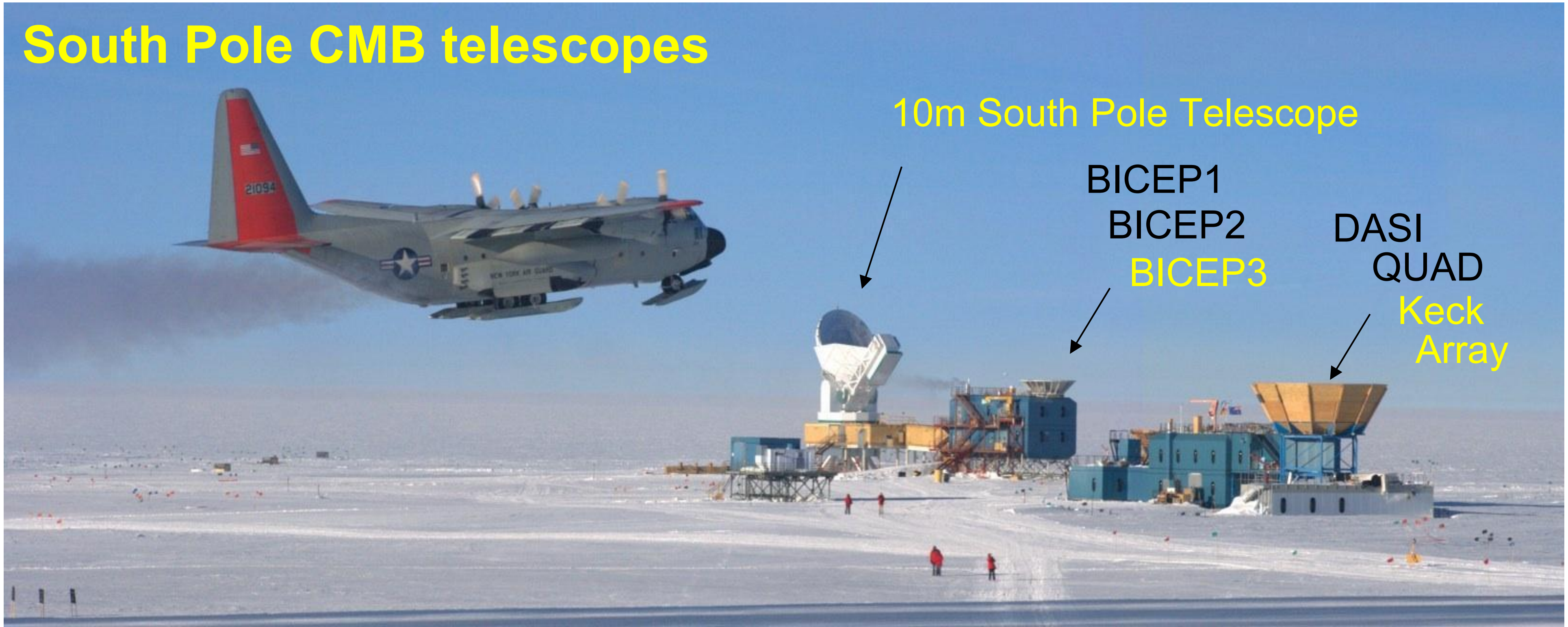
Mass-produced superconducting detectors from JPL





BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2015-)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
Focal Plane
Beams on Sky
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)

South Pole CMB telescopes



~~MSC's~~ NSF's South Pole Station:

Chartered cruises for CMB Experimentalists!

- Dry, stable atmosphere and 24h coverage of "Southern Hole"
- "Excursion office" to book heavy equipment support, etc.
- Bingo night, all-you-can-eat buffet

South Pole: "Relentless Observing"

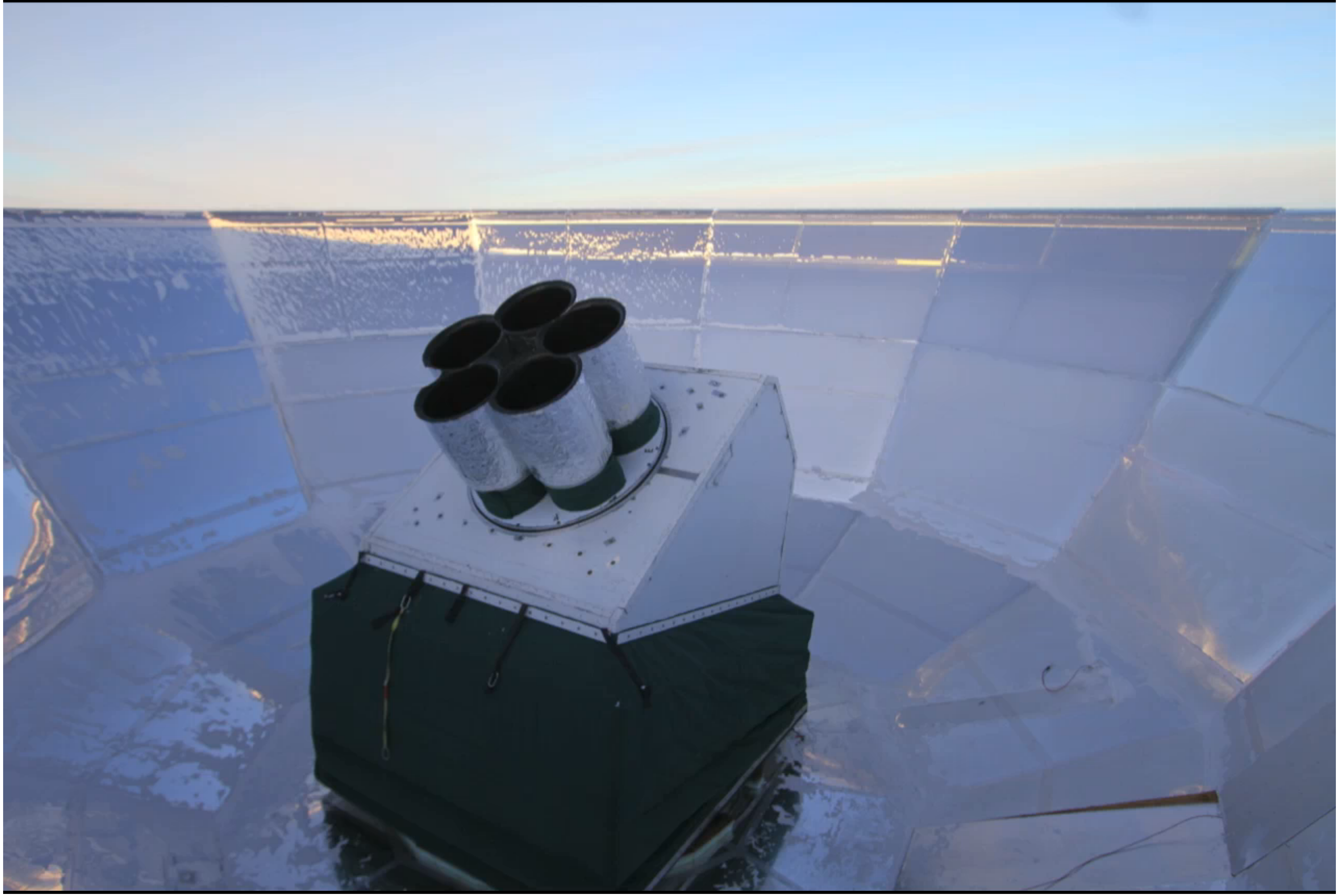
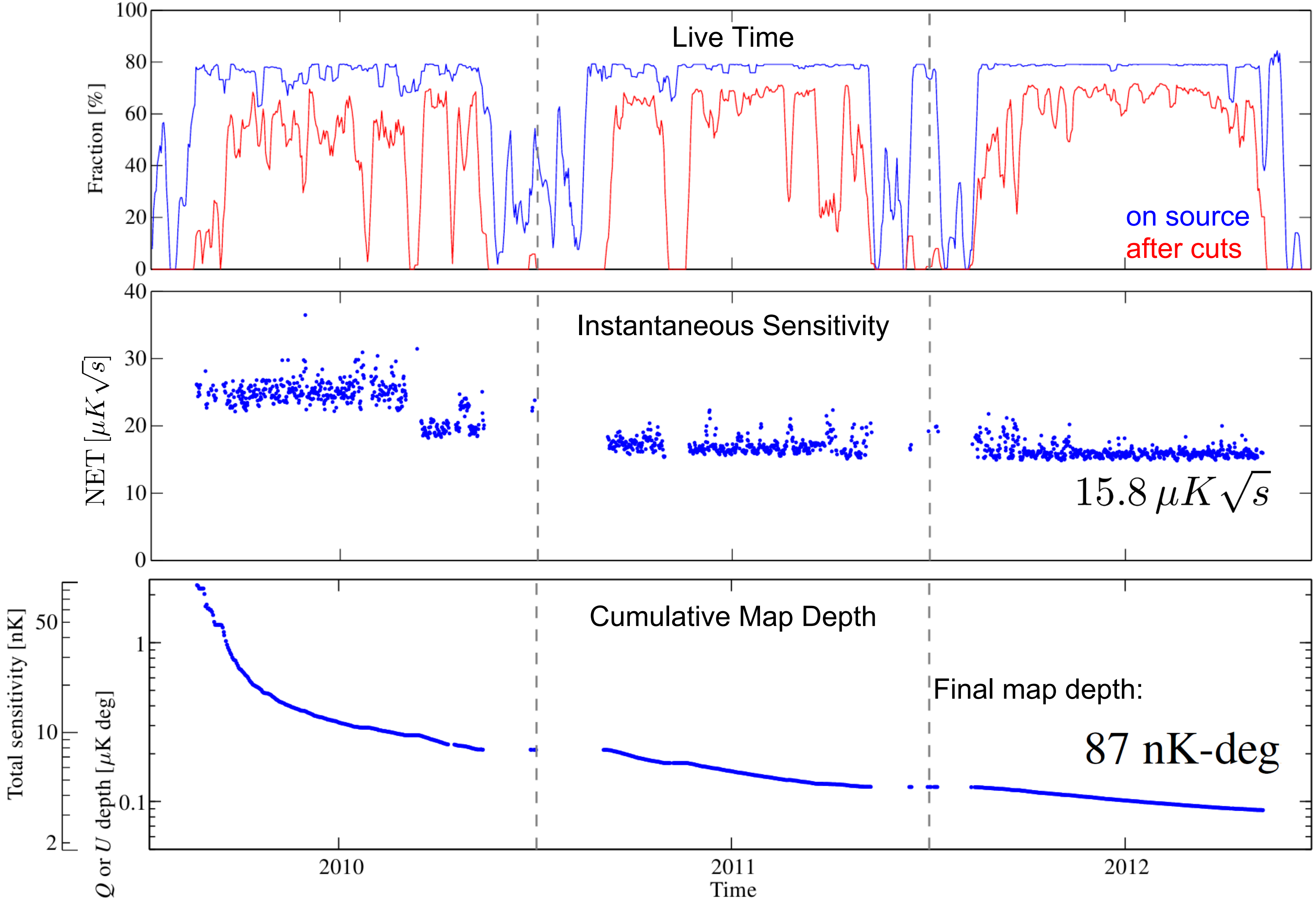
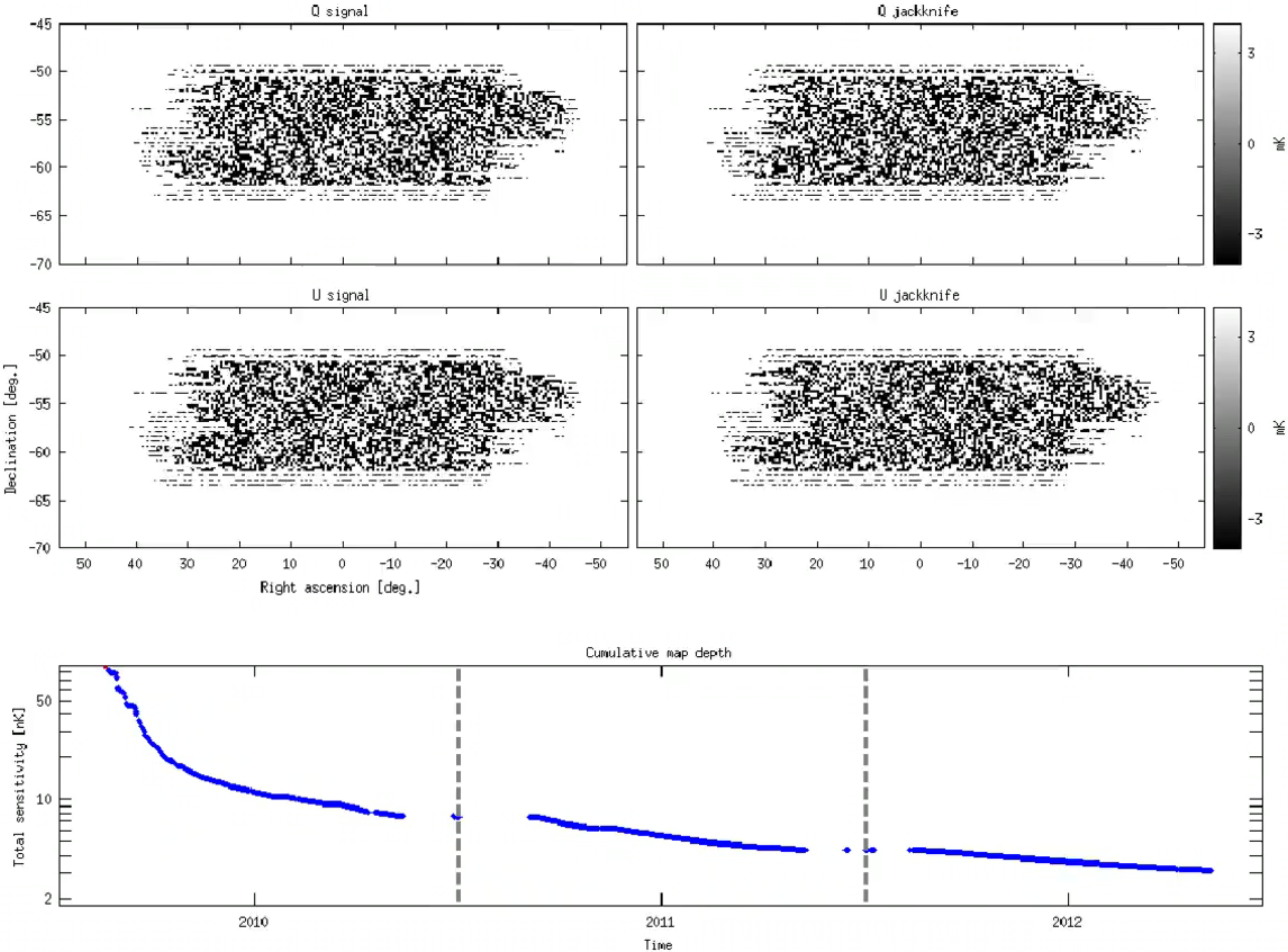


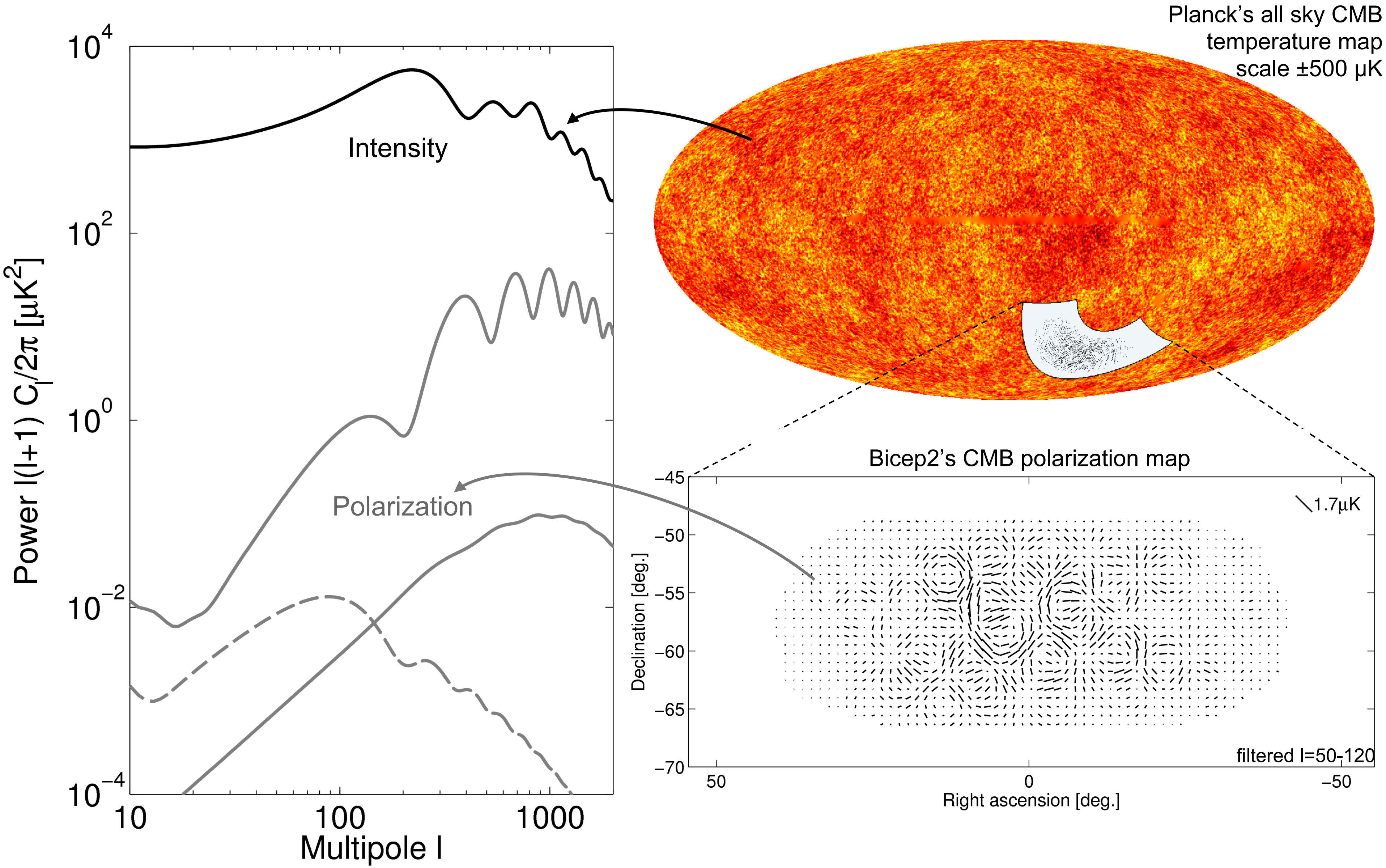

photo: Keith Vanderlinde

BICEP2 3-year Data Set



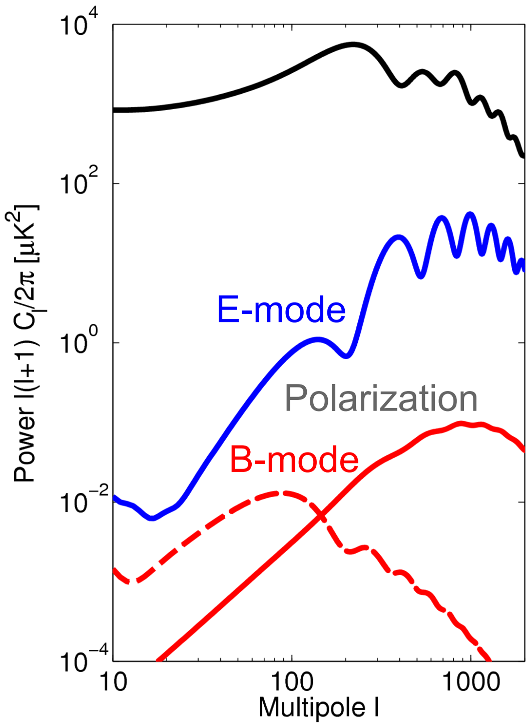

Q signal
Q jackknife
U signal
U jackknife
mK
Declination [deg.]
Right ascension [deg.]
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012

Cosmic Microwave Background

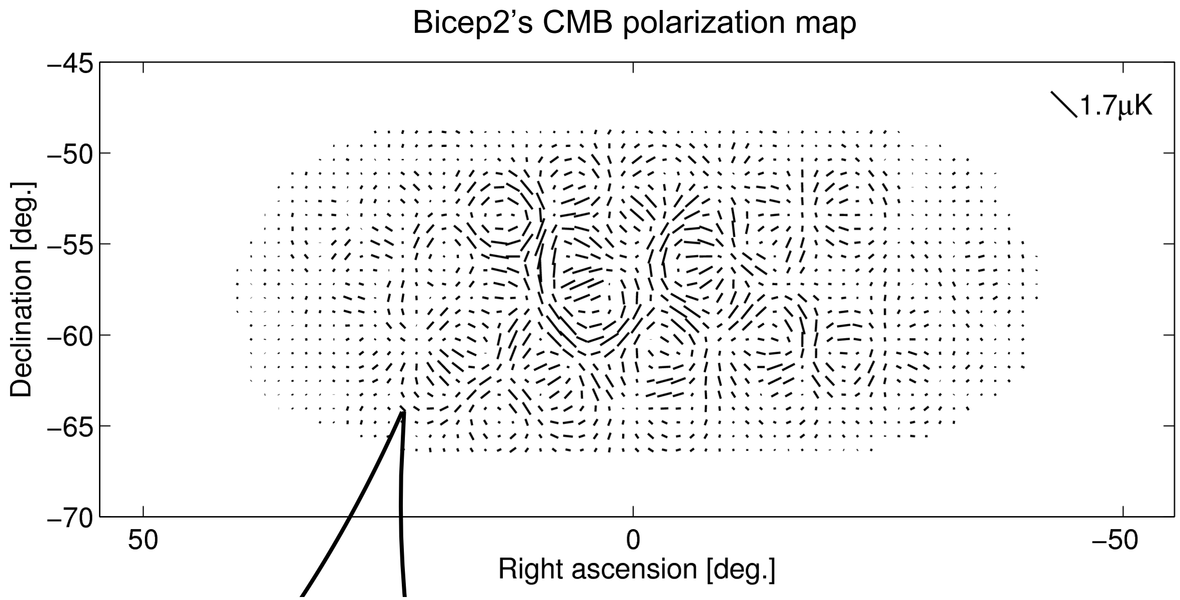


The Bicep2 Collaboration

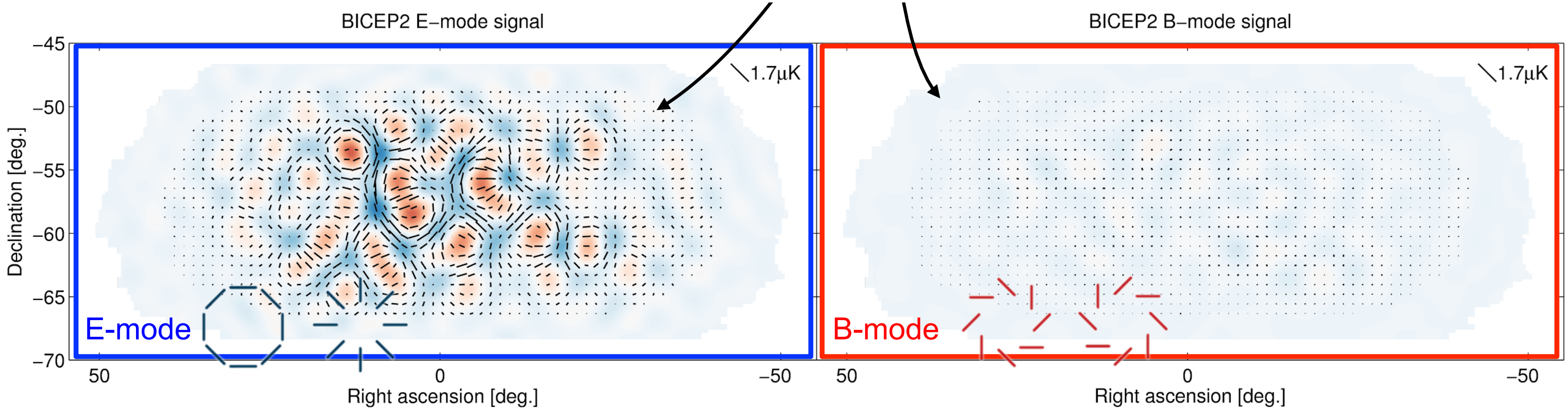
CMB Polarization



Need 2D basis to describe polarization map...

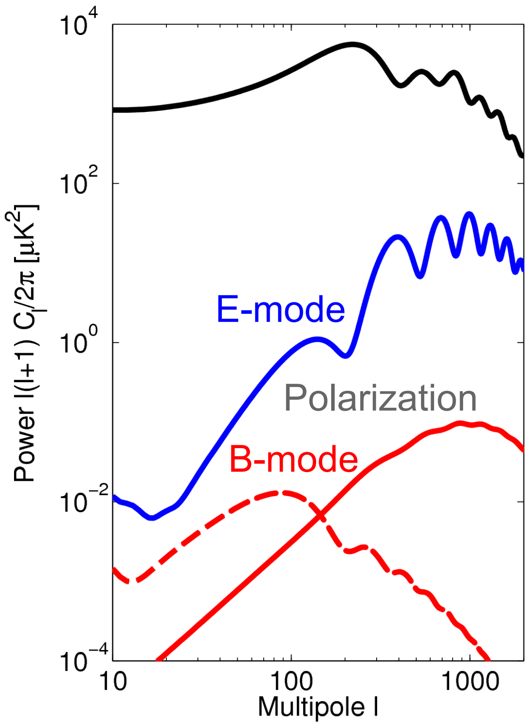


...clever choice in this case: E&B-modes



The Bicep2 Collaboration

CMB Polarization



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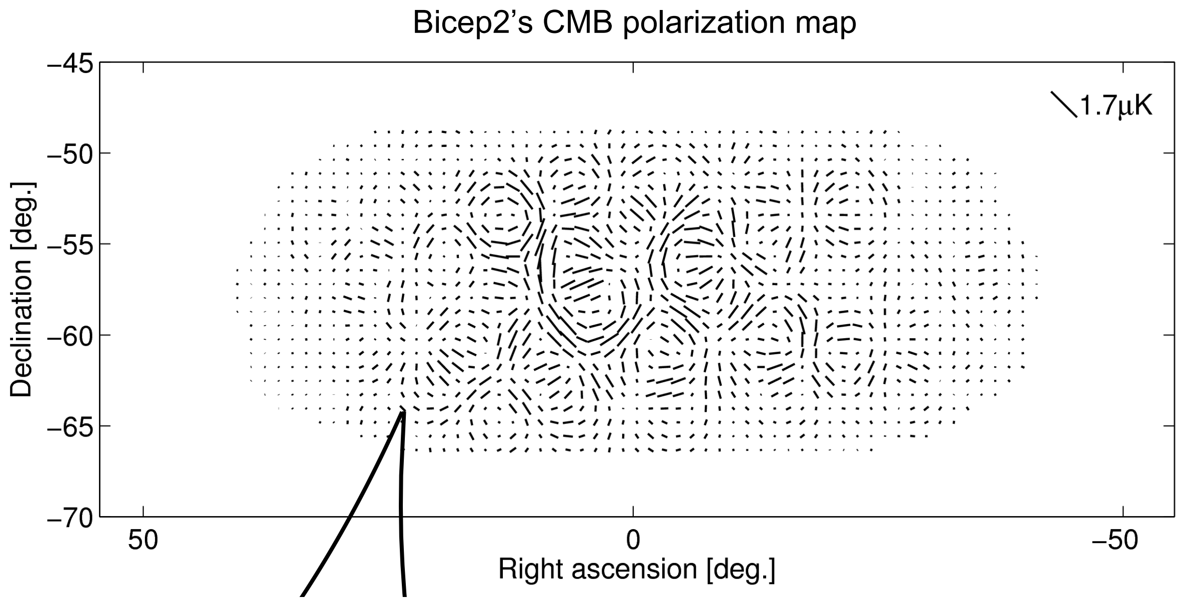

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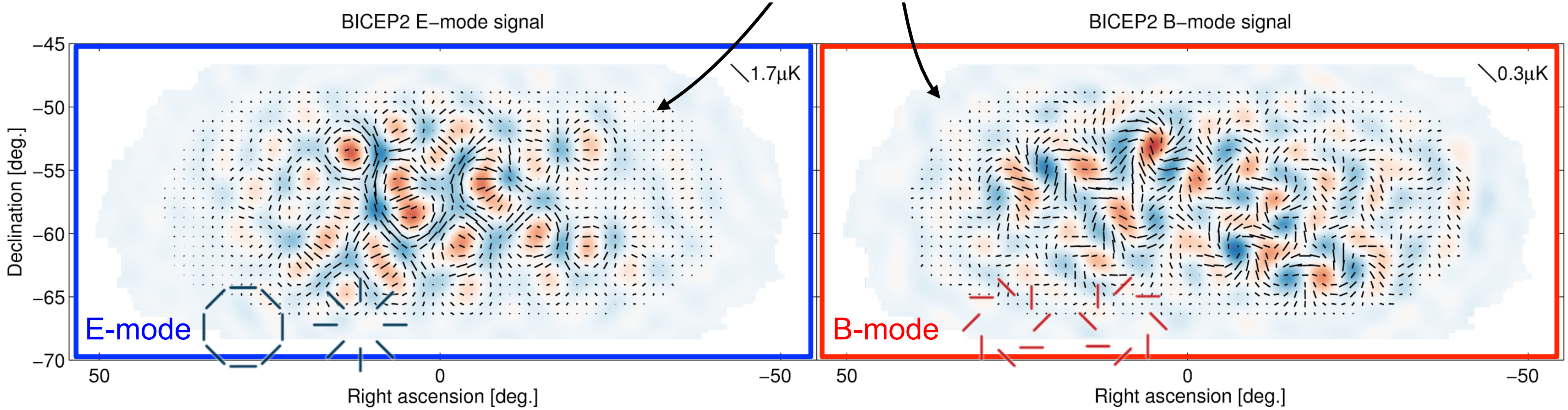
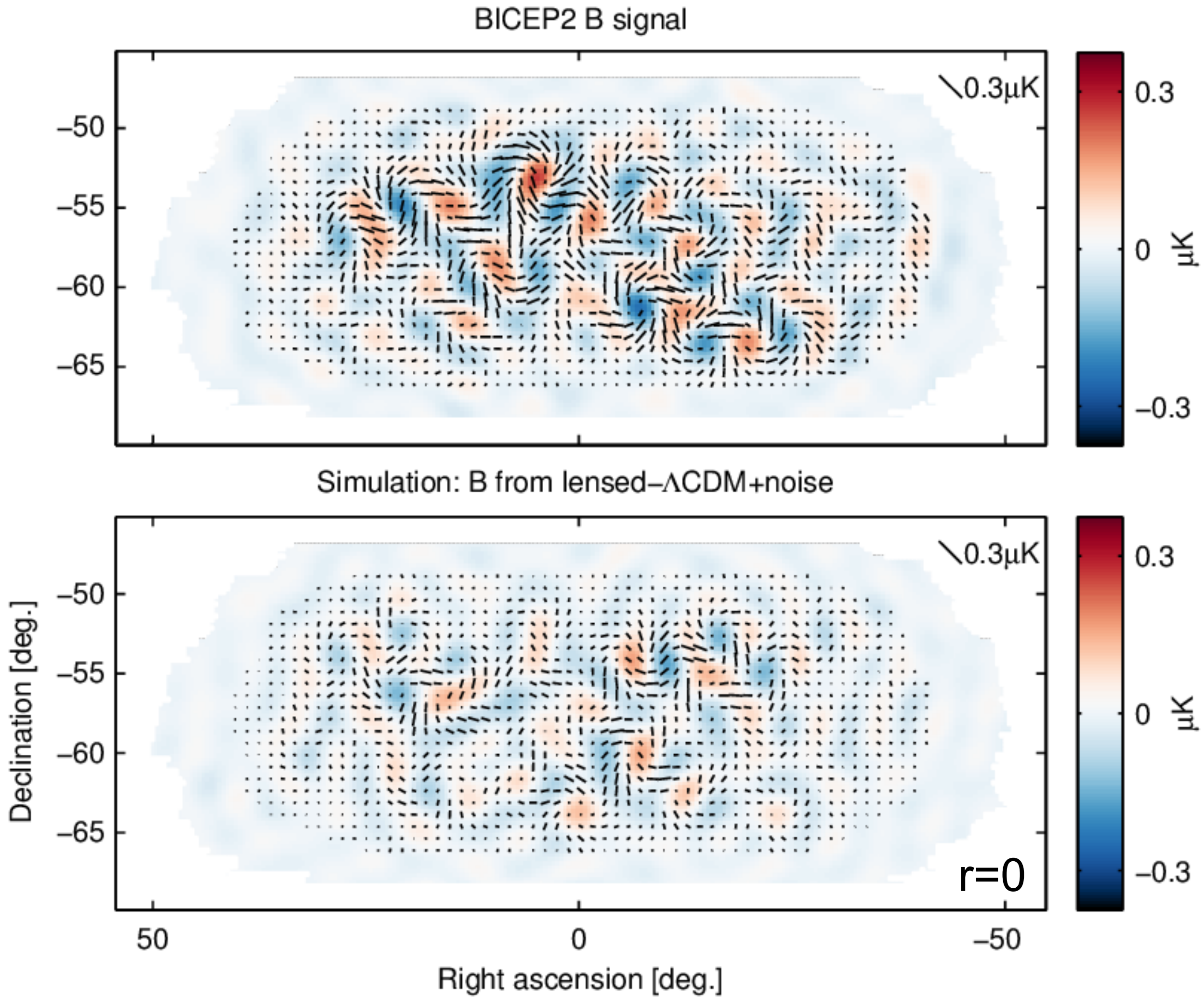


The Bicep2 Collaboration

B-mode Map vs. Simulation



Analysis “calibrated” using lensed-ΛCDM+noise simulations.

The simulations repeat the full observation at the timestream level - including all filtering operations.

We perform various filtering operations: Use the sims to correct for these

Also use the sims to derive the final uncertainties (error bars)

John Kovac for The Bicep2 Collaboration

Check Systematics: Jackknifes

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

3 years of analysis :

14 jackknife tests applied to 3 spectra, 4 statistics

Splits the 4 boresight rotations

Amplifies differential pointing in comparison to fully added data. Important check of deprojection. See later slides.

Splits by time

Checks for contamination on long ("Temporal Split") and short ("Scan Dir") timescales. Short timescales probe detector transfer functions.

Splits by channel selection

Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

Splits by possible external contamination

Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

Splits to check intrinsic detector properties

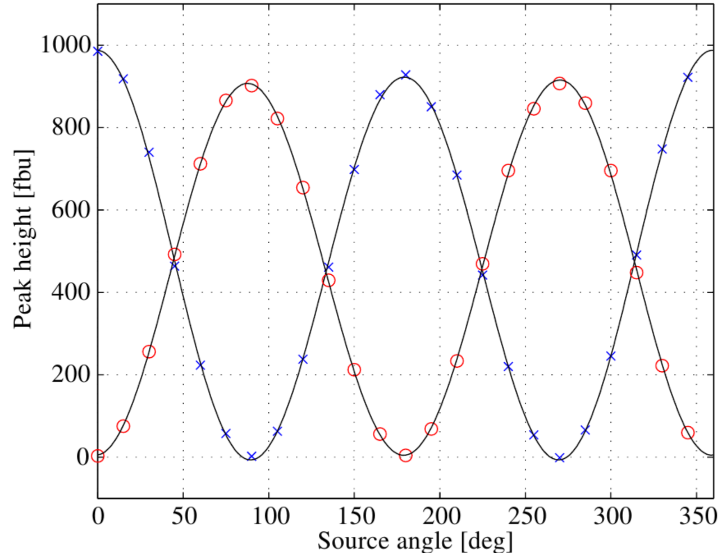
Checks for contamination from detectors with best/ worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

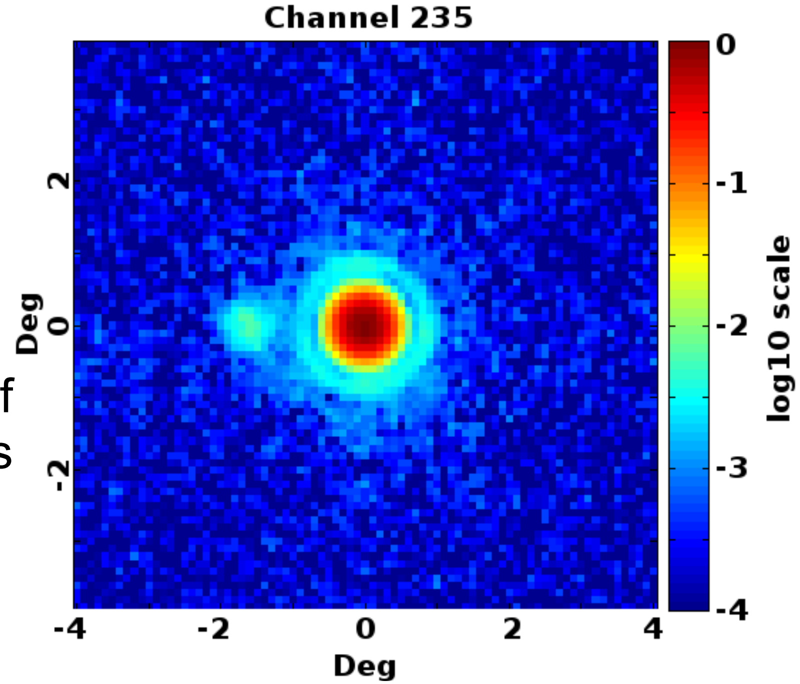
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration





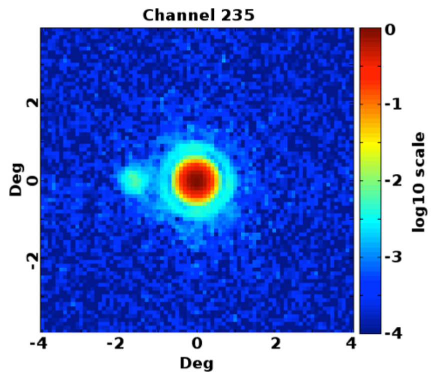
Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

We know our Beam Shapes

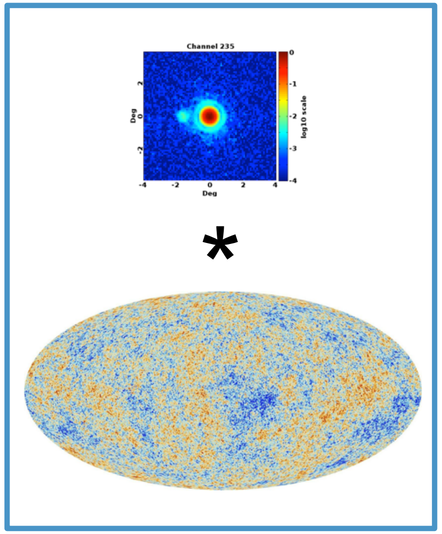
Because contamination from beam shape mismatch is entirely deterministic, we can both filter the affected modes (deprojection) **and** predict it in simulation using calibration + Planck T data as input.

Calibration data for each channel

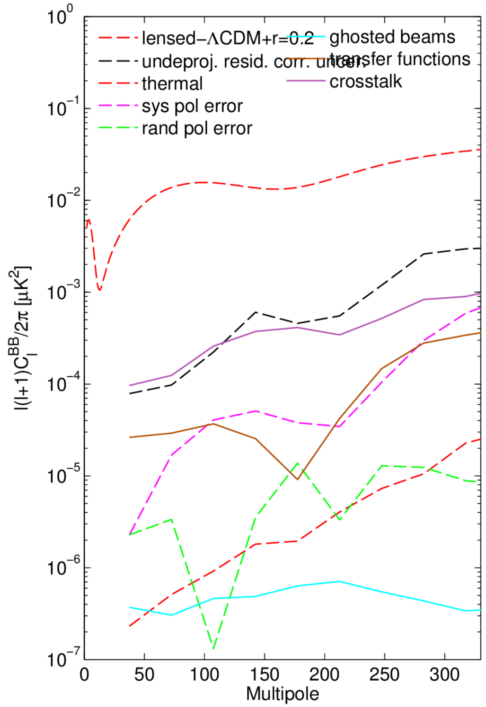


Simulation

(explicit convolution with Planck T map)

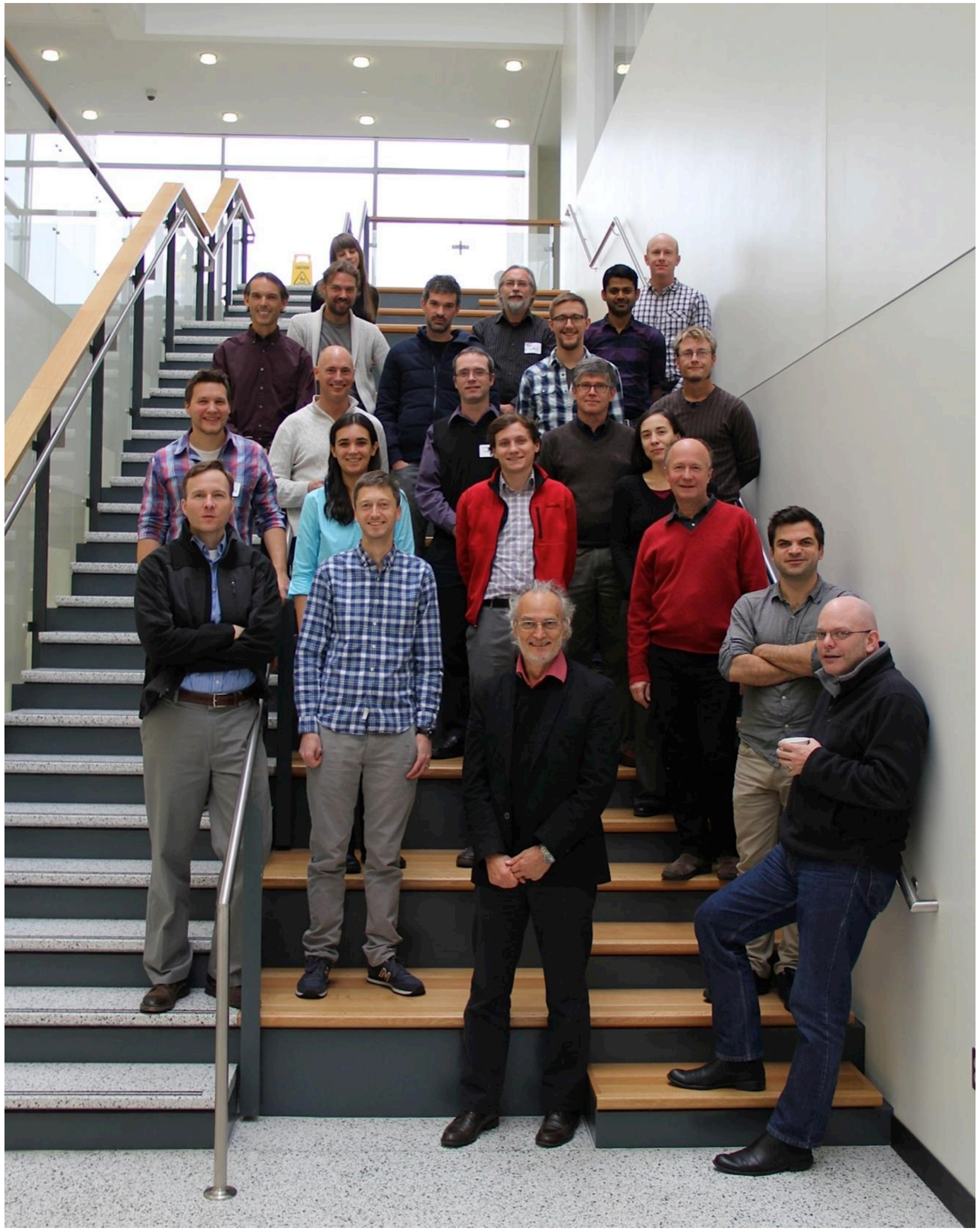


Predictions of contamination



analysis by Chris Sheehy, Chin Lin Wong

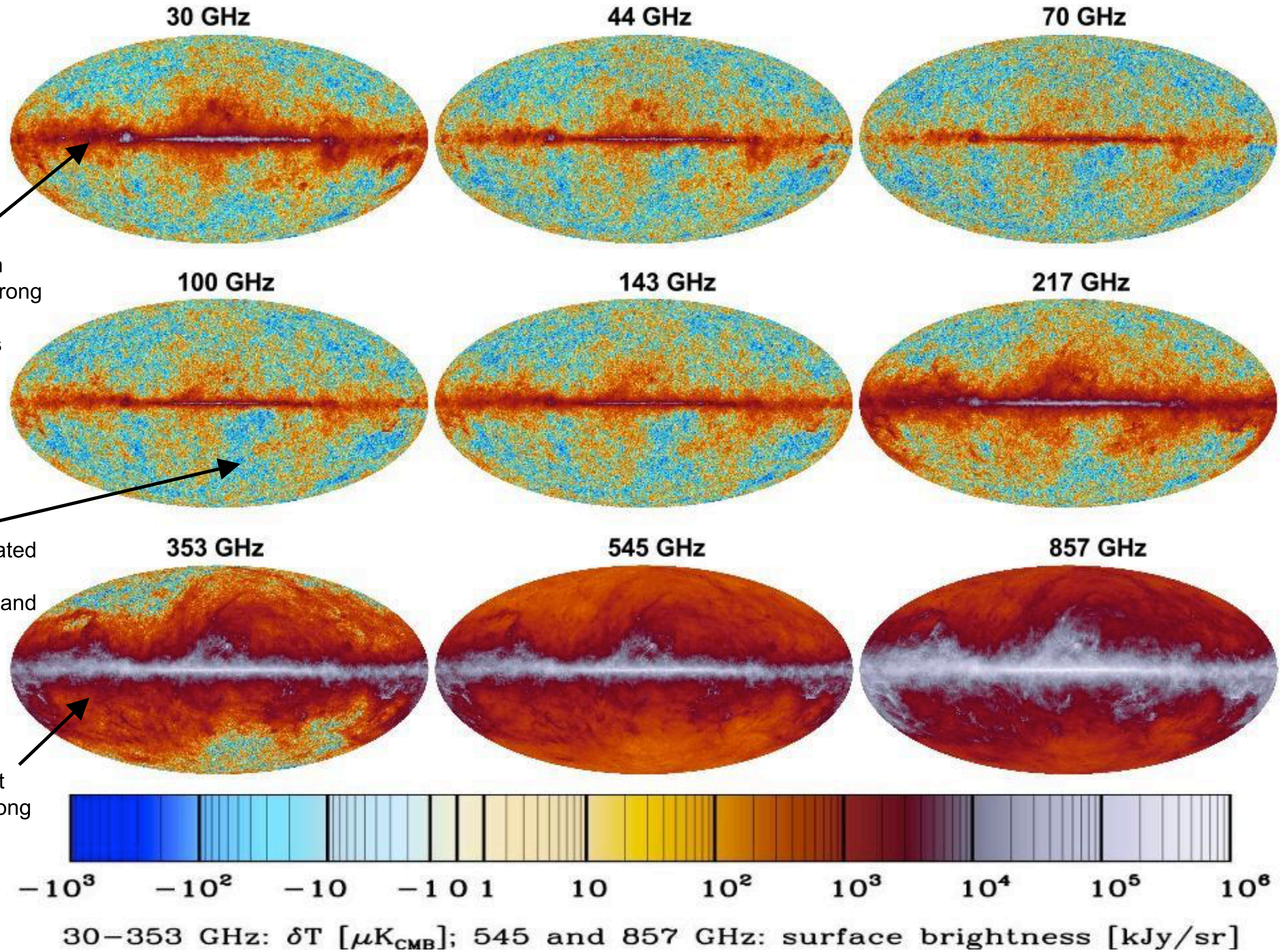
Joint analysis of BICEP2/Keck and Planck data



- In summer 2014 BICEP2/ Keck and Planck collaborations signed MOU to do a joint analysis
- Data exchanged in late July
- Results of this analysis published last January, arxiv:1502.00612 (and PRL)

BICEP2/Keck/Planck meeting at University of Minnesota 5 Nov 2014

Planck full sky maps at 9 frequencies



Galactic synchrotron emission strong at low frequencies

CMB most uncontaminated at mid frequencies and high latitude

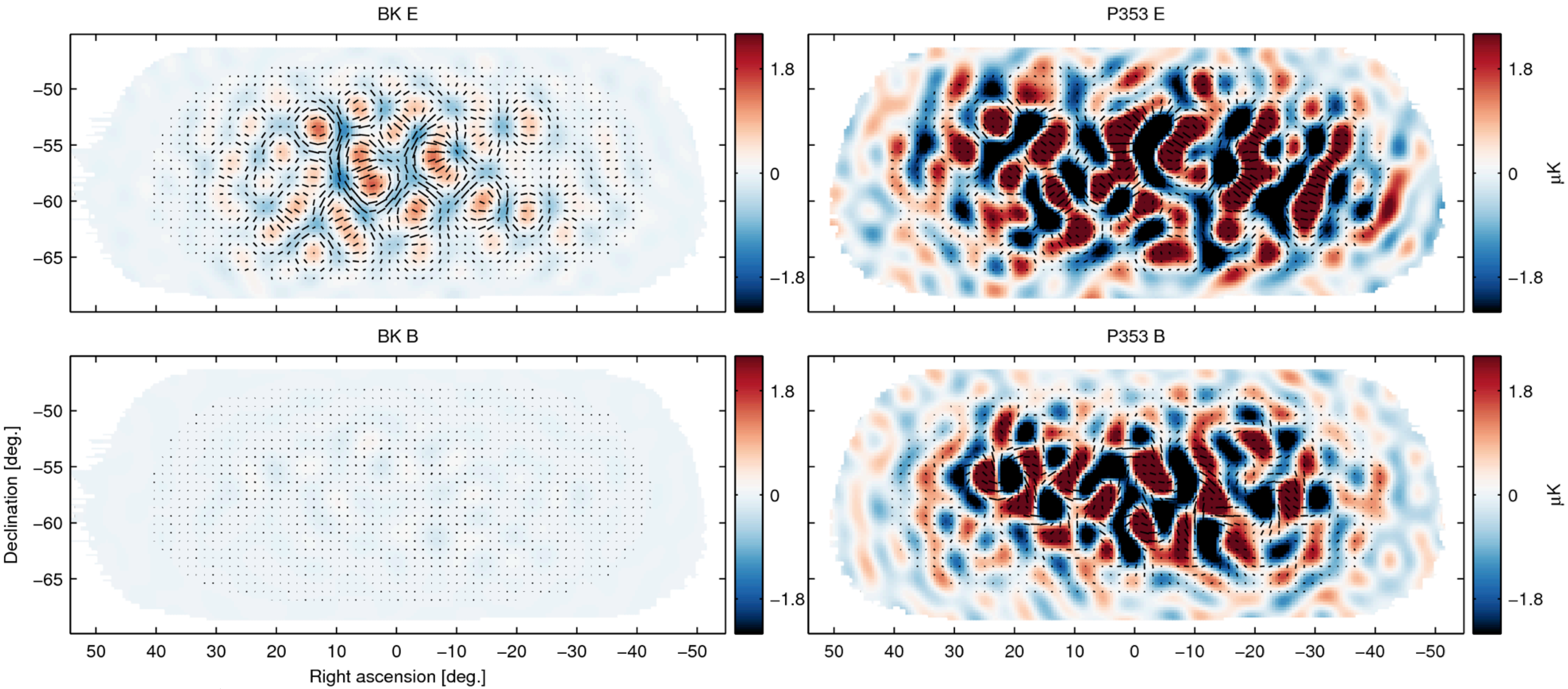
Galactic dust emission strong at high frequencies

Full sky coverage and 9 frequencies - but not as deep as BICEP2/Keck in any given region of the sky

Bicep2, Keck Array and Planck Collaboration

BICEP2/Keck 150 GHz

Planck 353 GHz

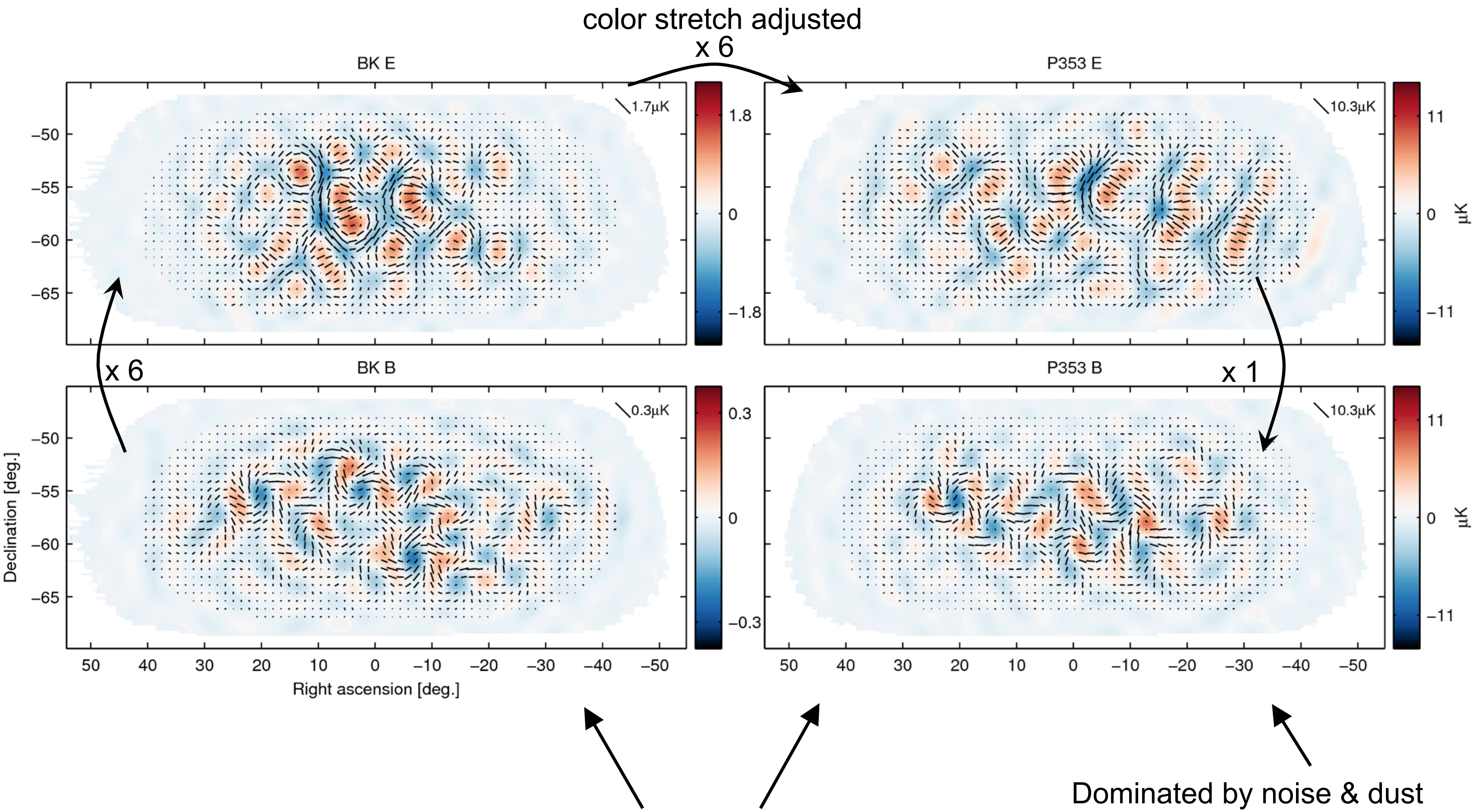


Dominated by E-modes

Dominated by noise & dust

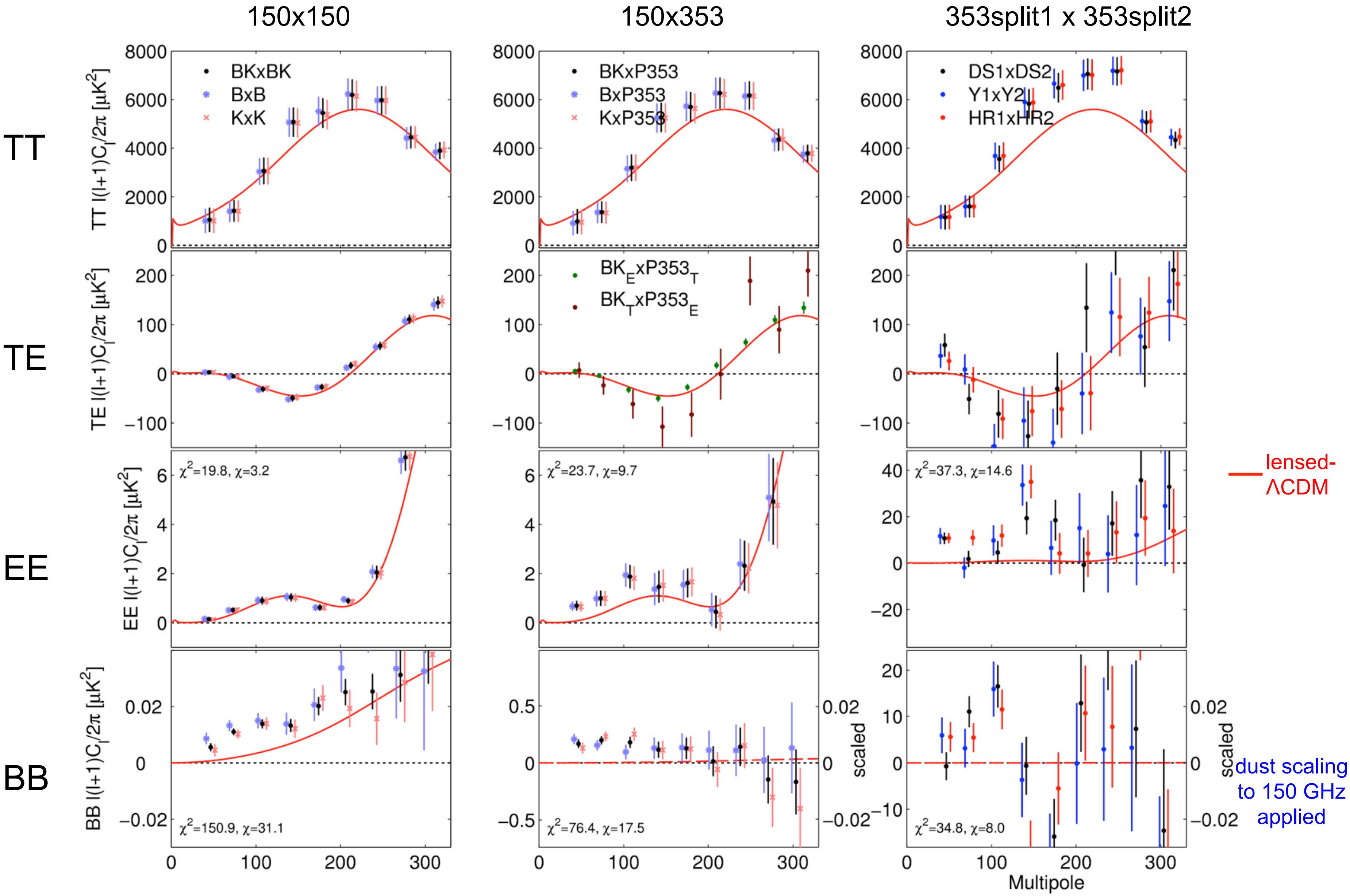
BICEP2/Keck 150 GHz

Planck 353 GHz

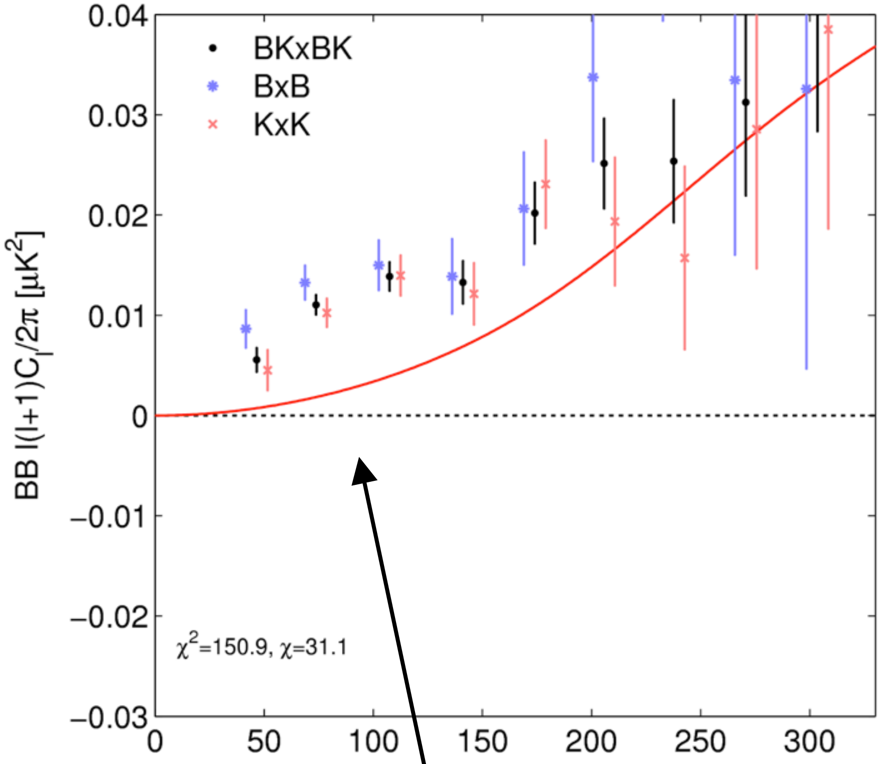


How much B-mode signal is common? (Dust!)

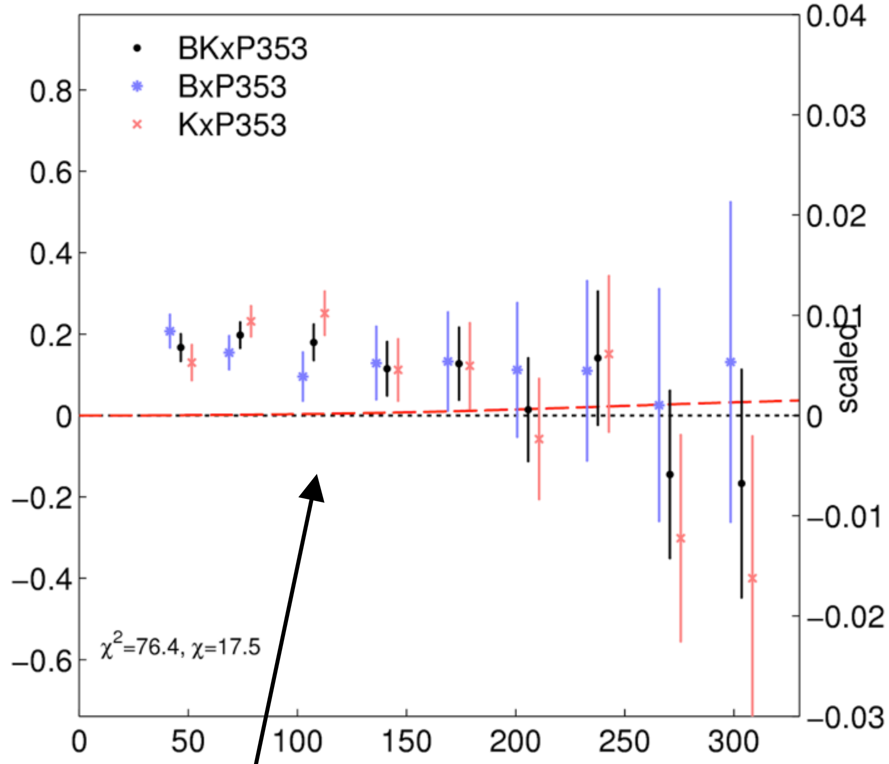
Single- and Cross-Frequency Spectra



BICEP2/Keck 150 GHz



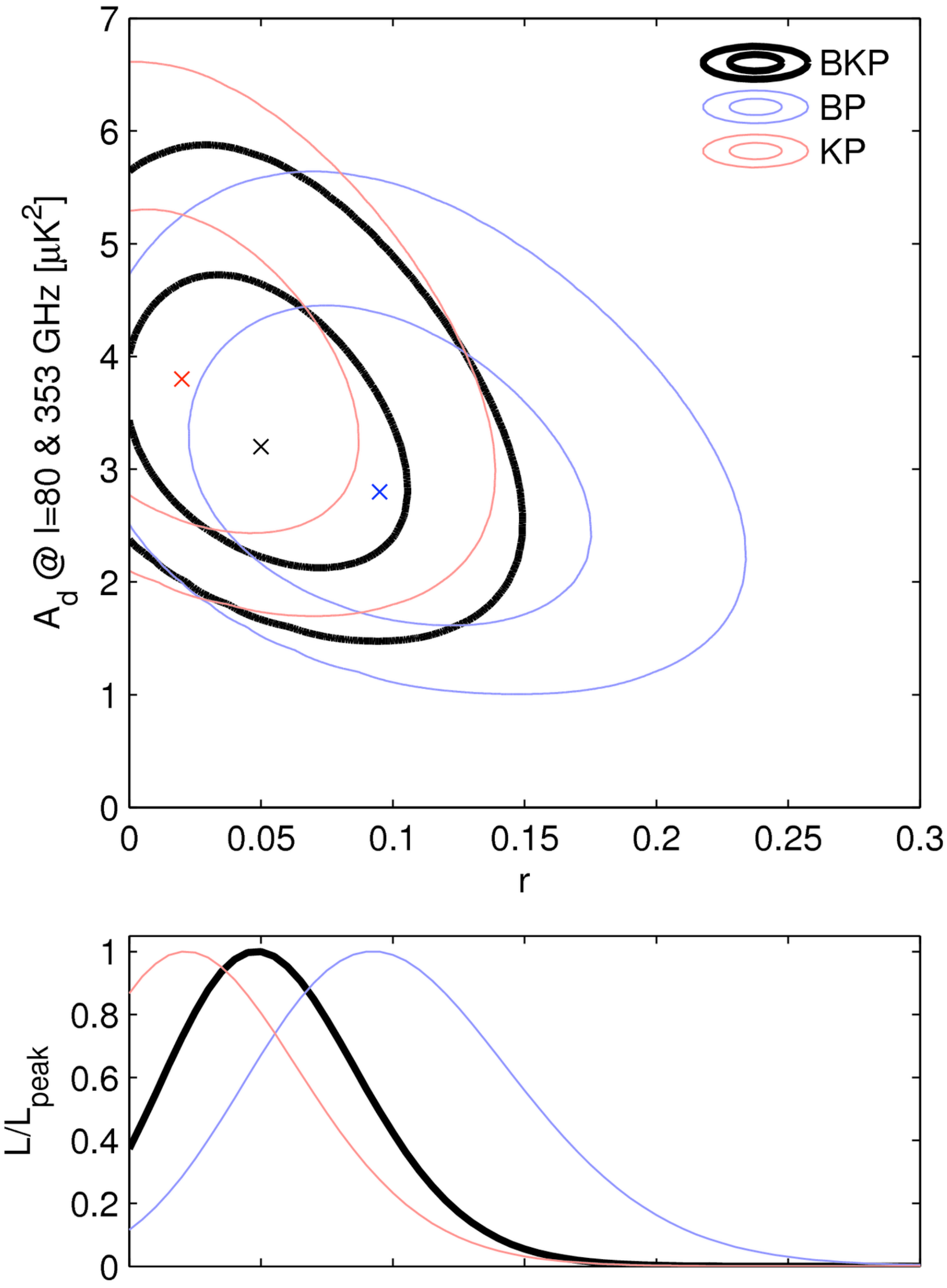
BICEP2/Keck 150 GHz X Planck 353 GHz



Correlation detected with high signal-to-noise!

Consistent with expected "slope" for dust

Applying expected dust scaling (25x), level comparable to BICEP2/Keck B-mode excess



Jan 2015

BICEP2+Keck (150 GHz)
Planck (30-353 GHz)

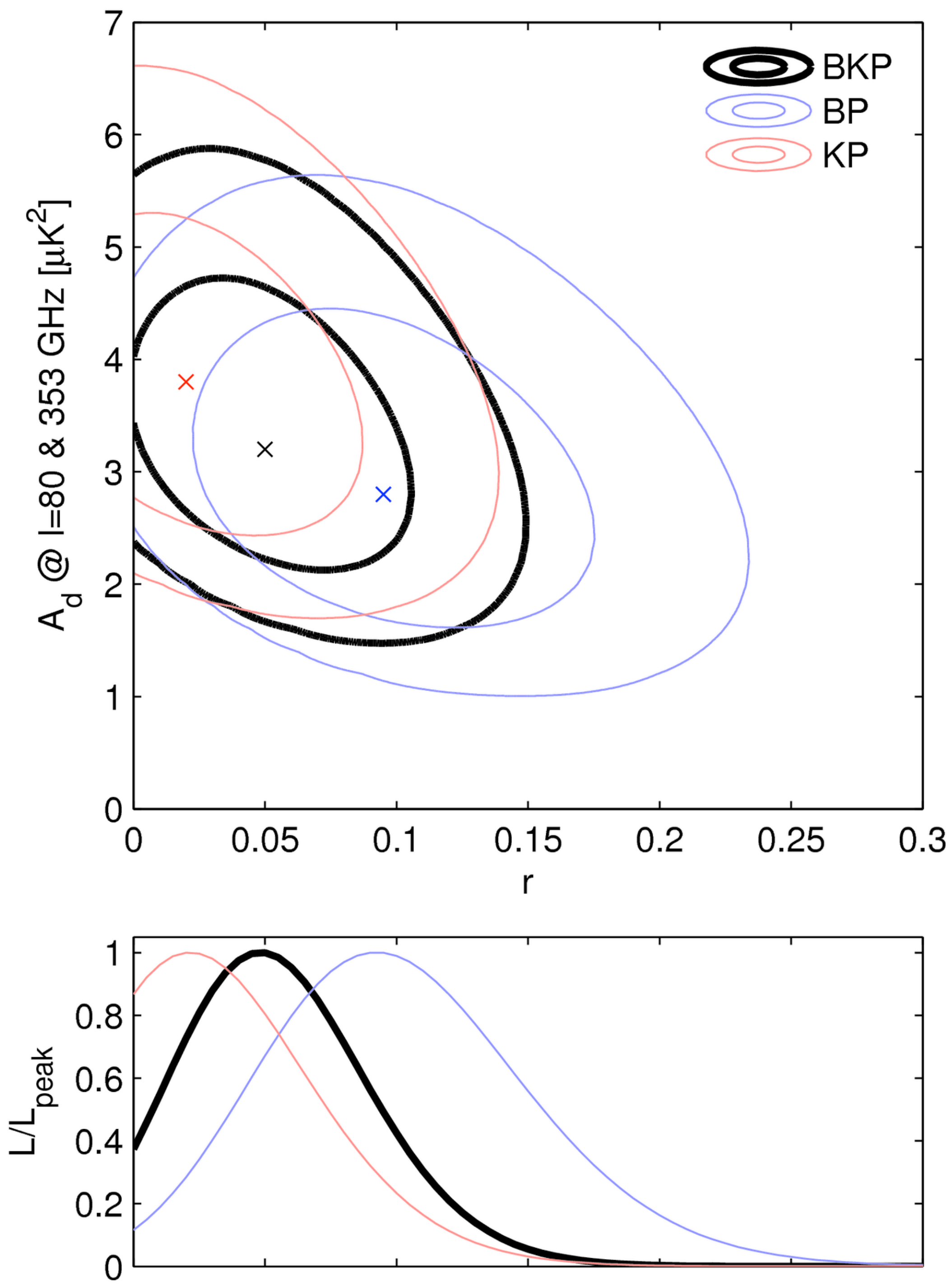
Multi-component model allows simultaneous constraints for

r, $A_{lensing}$, A_{dust}, A_{sync}

Can also marginalize over priors for
- frequency spectral indices of FGs
- spatial indices of FG's
- dust/sync correlation
- FG E/B ratio, etc.

Analysis approach developed at Harvard: Colin Bischoff, Victor Buza, Kate Alexander, Immanuel Buder, and Cora Dvorkin

(thanks also to ITC / FAS Odyssey computing!)



Jan 2015

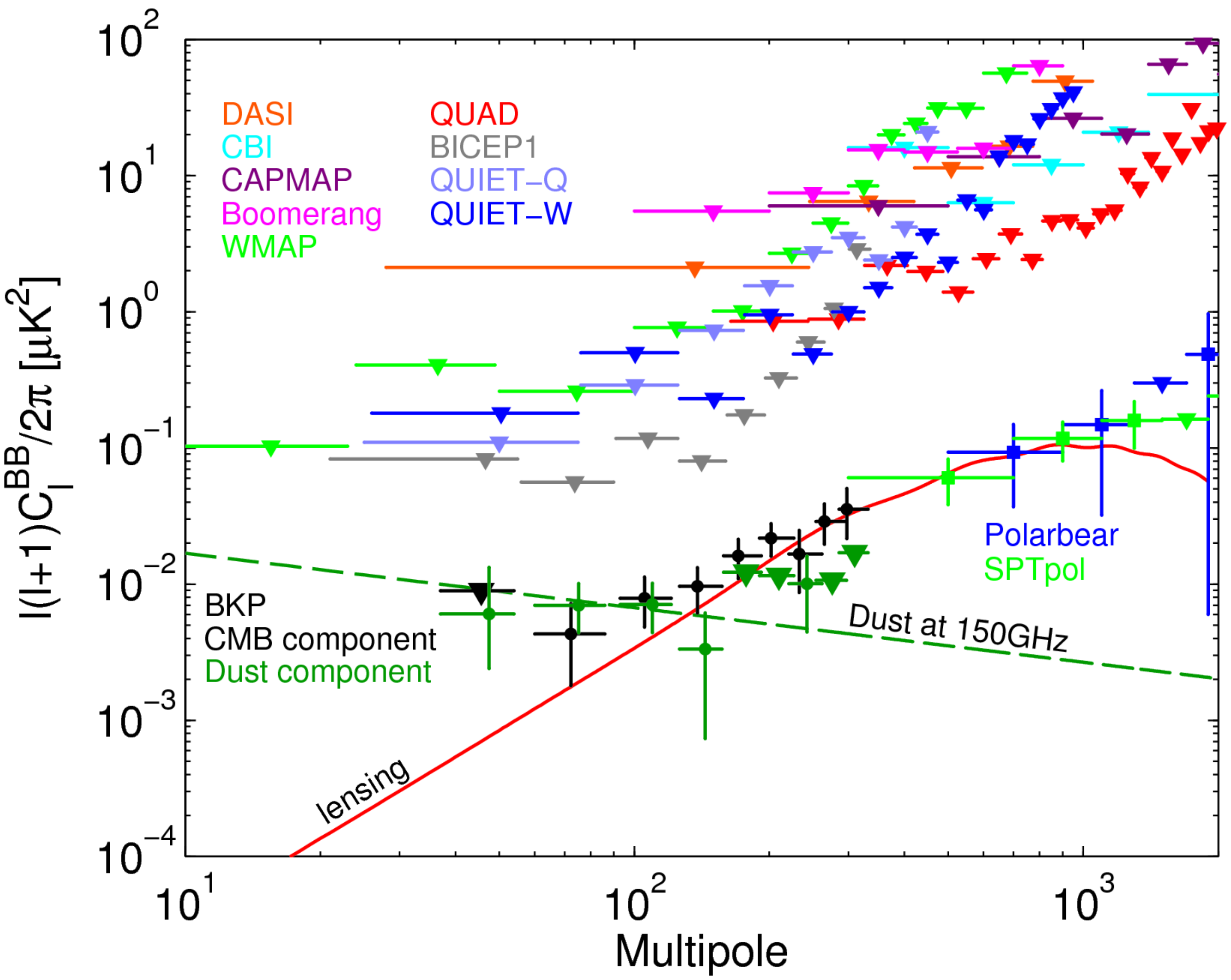
BICEP2+Keck (150 GHz)
Planck (30-353 GHz)

BKP Results:

- **Dust clearly detected (5.1 σ), ≥ 40% of full signal.**
- **No significant evidence for r > 0**
- **From B-modes alone:**
  r < 0.12 (95%), σ(r) ~ 0.035
- **r = 0 and r = 0.1 currently at equal likelihood in this analysis.**

(STILL NEED BETTER DATA!)

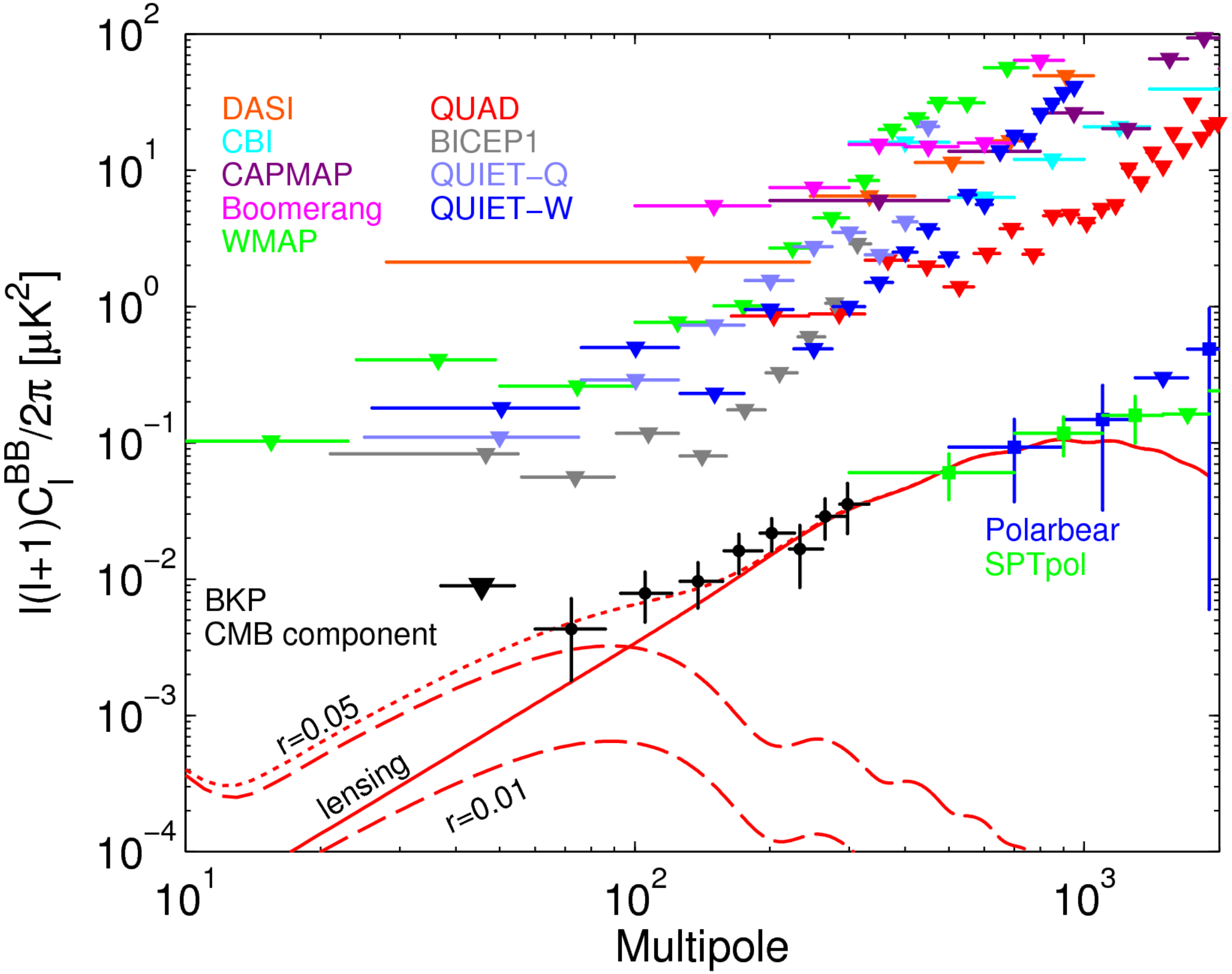
Separating B-mode components



BKP Results

Uncertainties will be reduced with new higher S/N multi-frequency data

Separating B-mode components



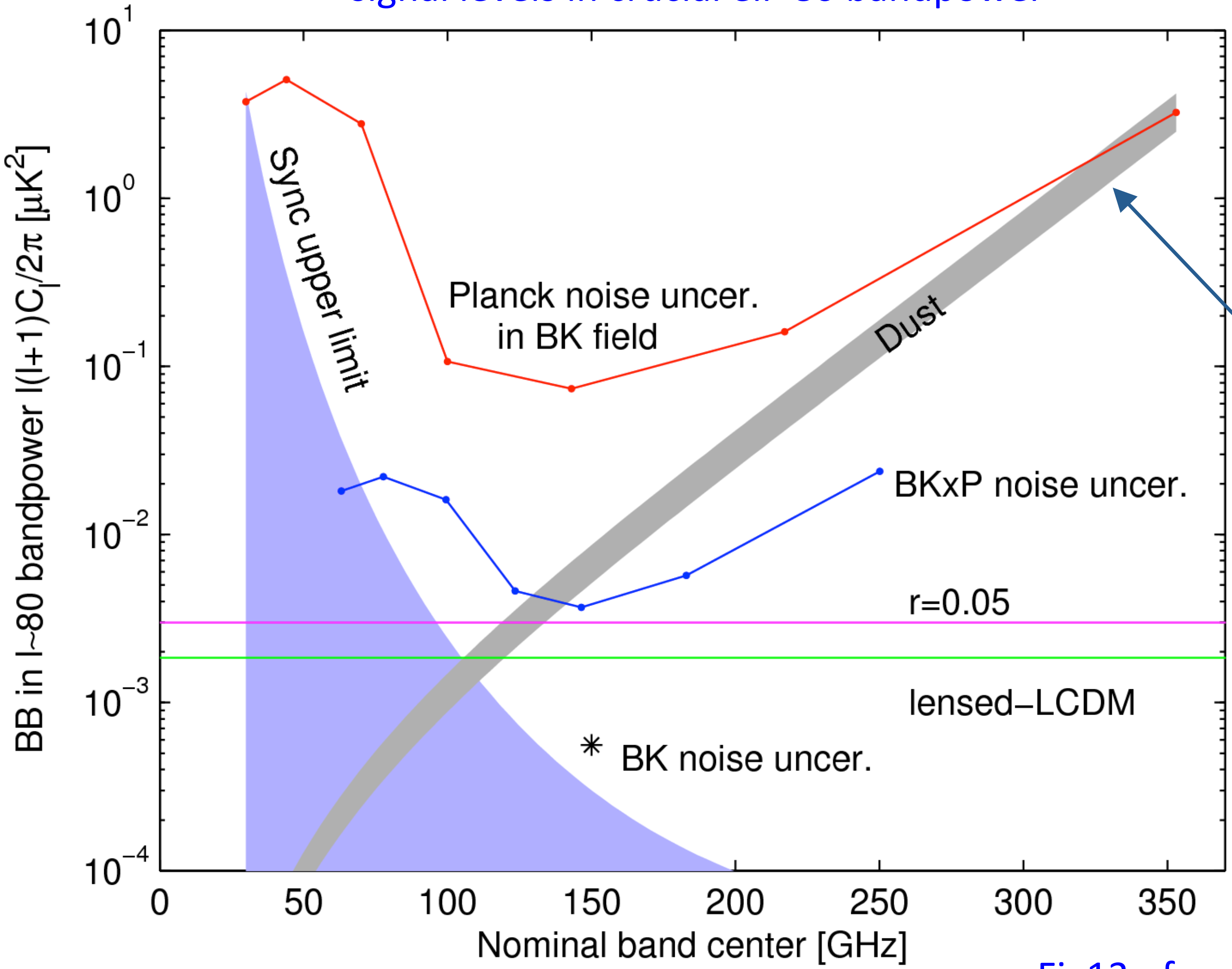
BKP Results

Uncertainties will be reduced with new higher S/N multi-frequency data

Also de-lensing!

BKP Result: Dust is ≥ 40% of observed excess

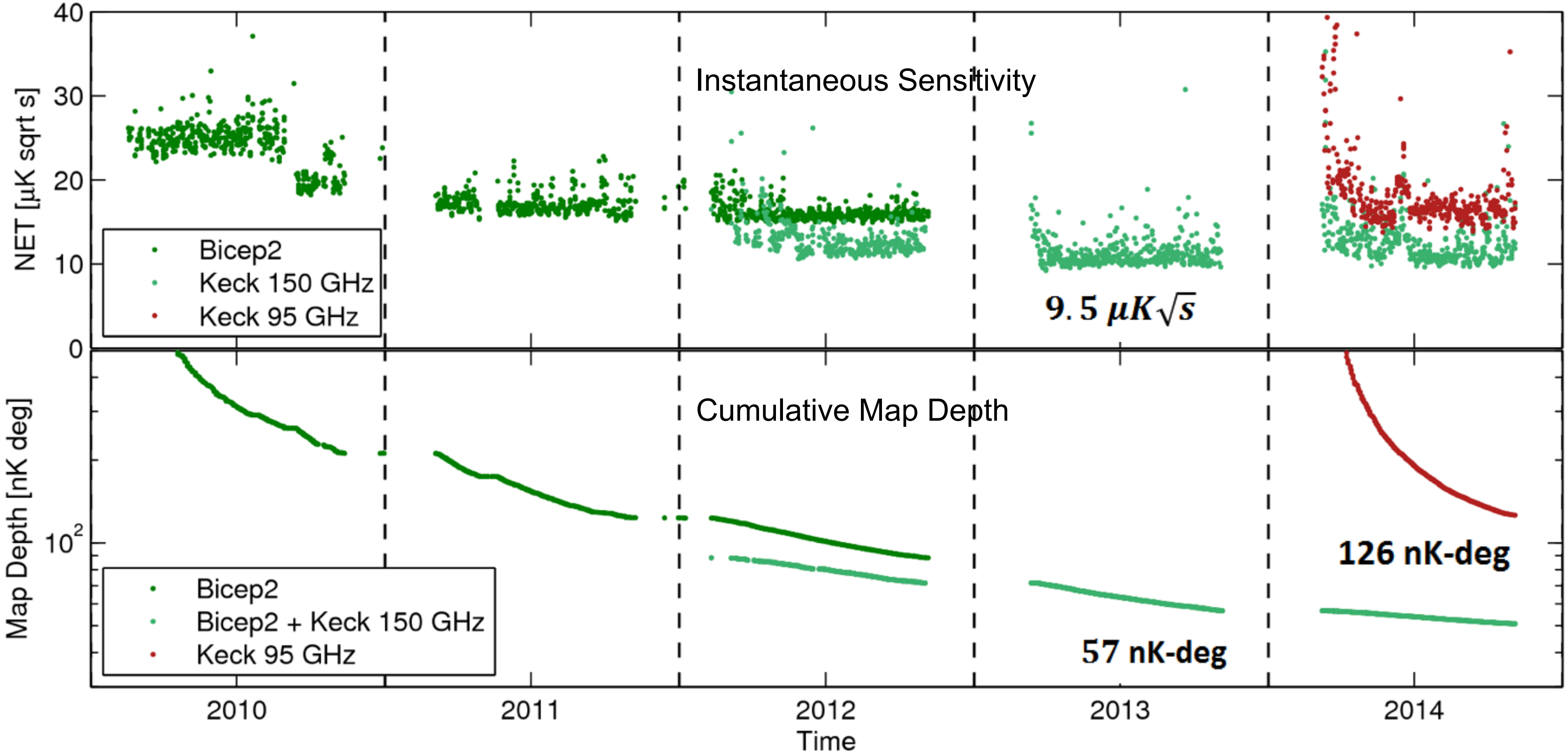
This plot shows noise uncertainty and signal levels in crucial ell=80 bandpower



Dust is detected with 5 sigma significance – amplitude fairly well constrained

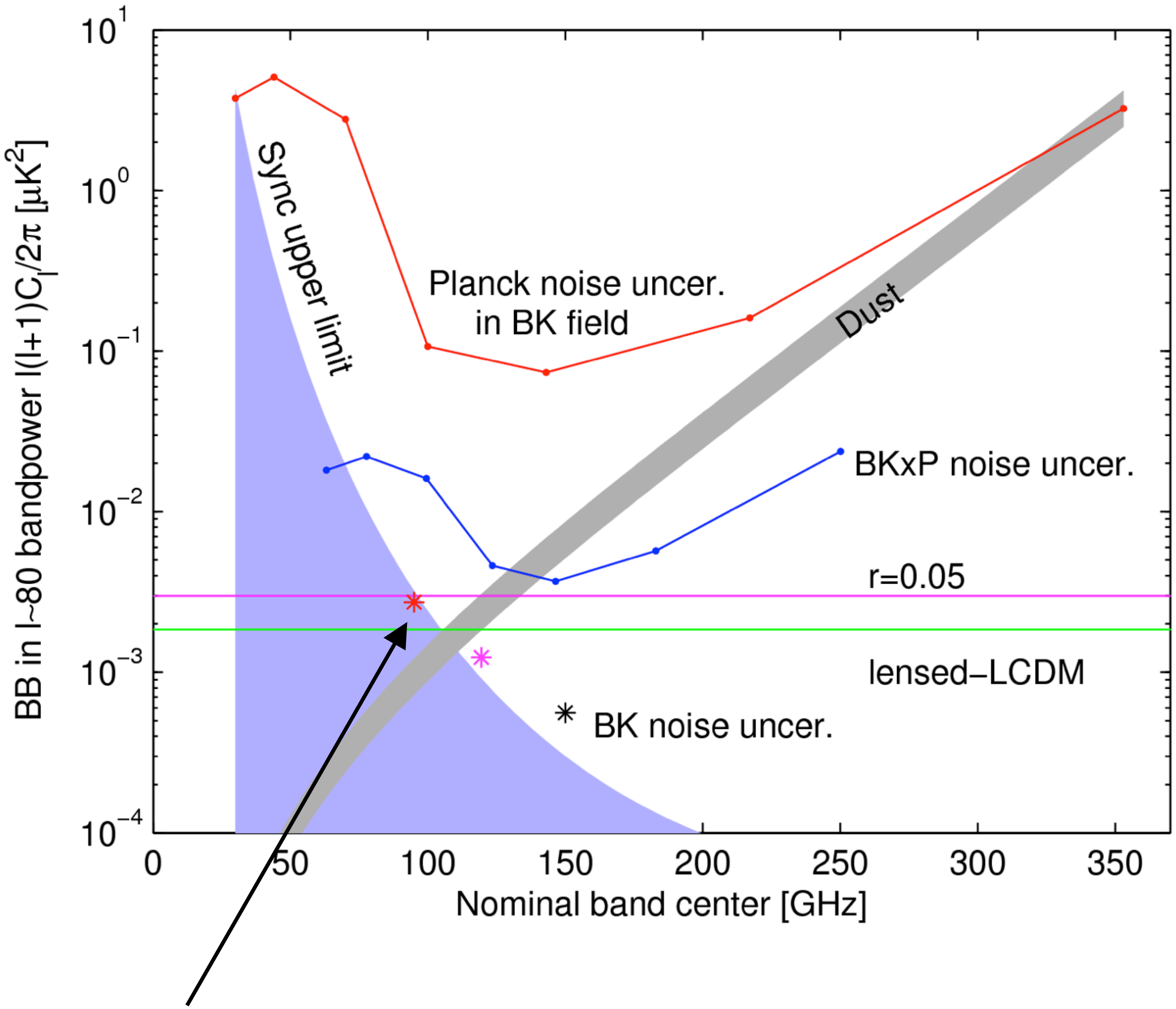
Fig13 of arxiv:1502.00612

Coming soon - Keck 2014 95 GHz

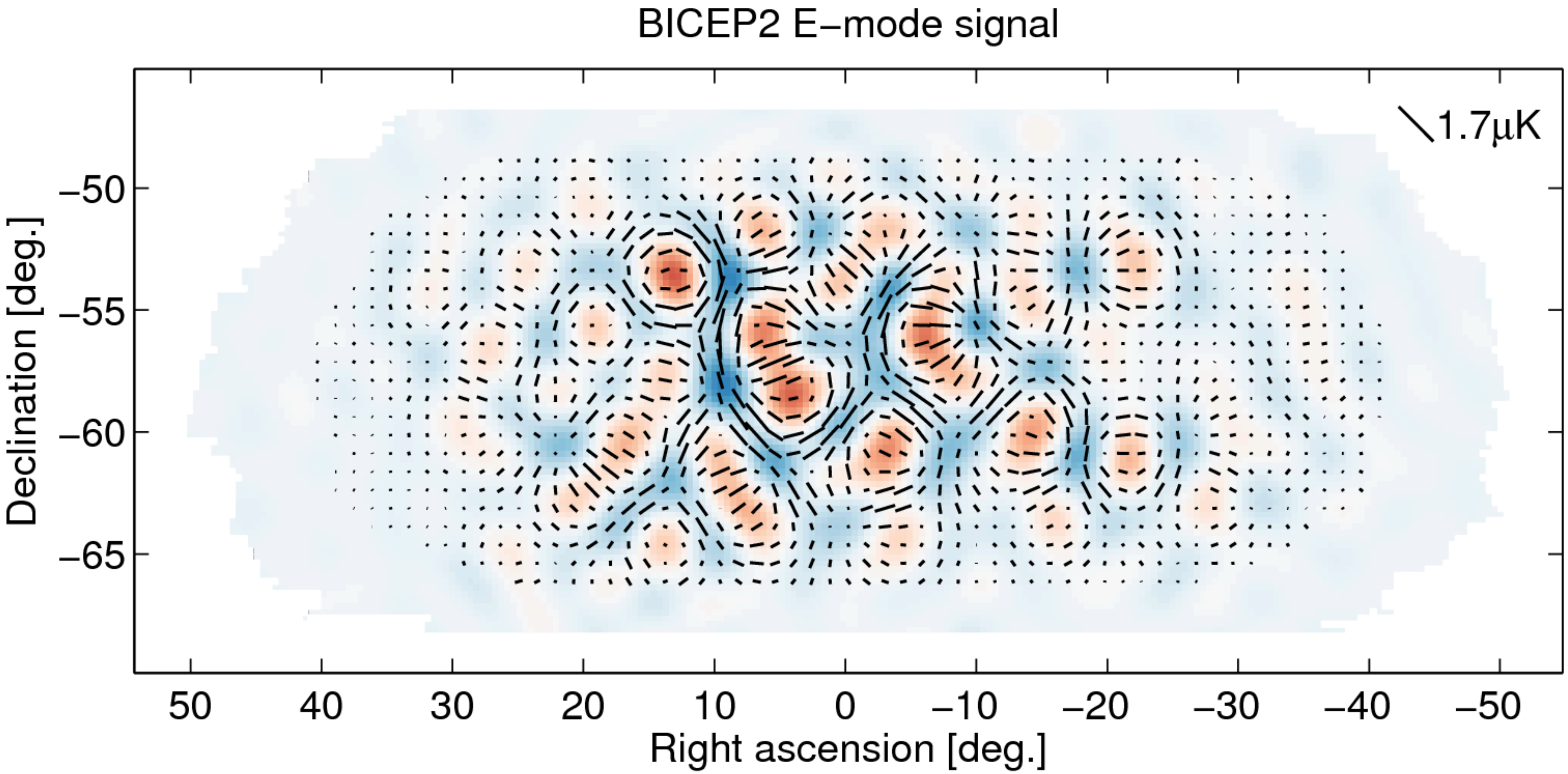


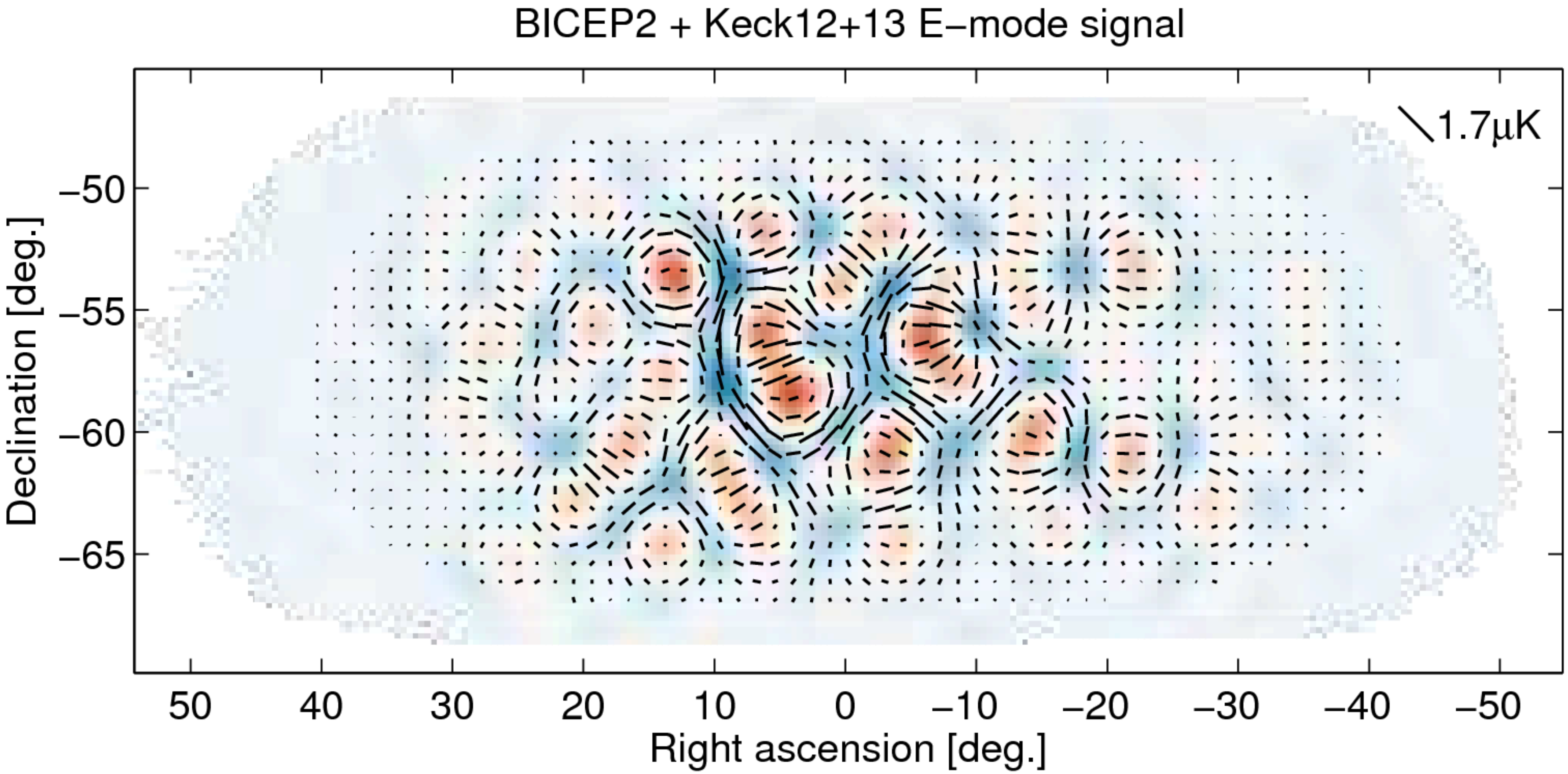
For 2014 season two of the Keck array receivers switched out for 95 GHz

Comparison of signal and noise levels



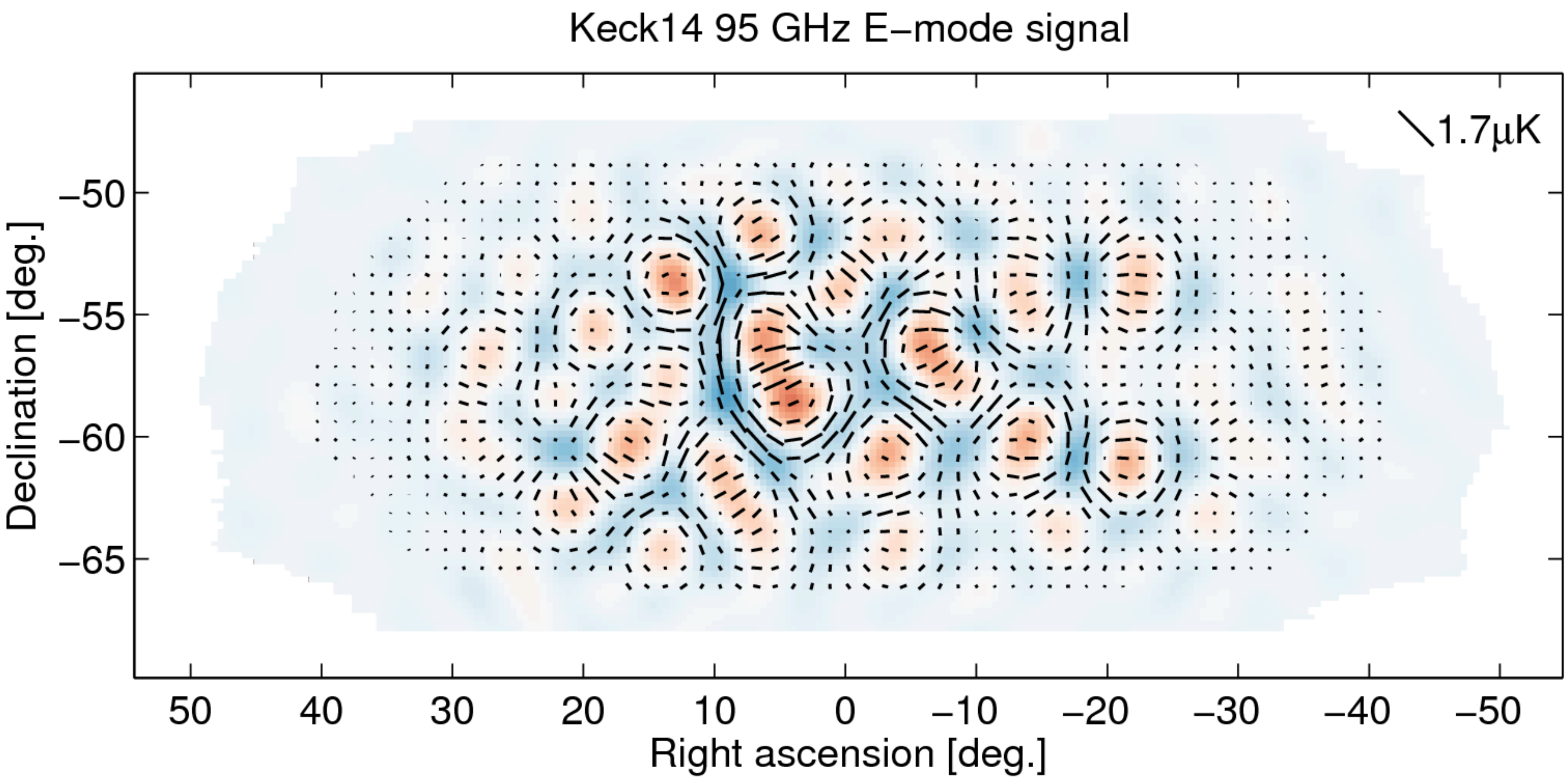
Keck 2014 95 GHz achieved noise level


BICEP2 E−mode signal
1.7μK
−50
−55
−60
−65
Declination [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50
Right ascension [deg.]



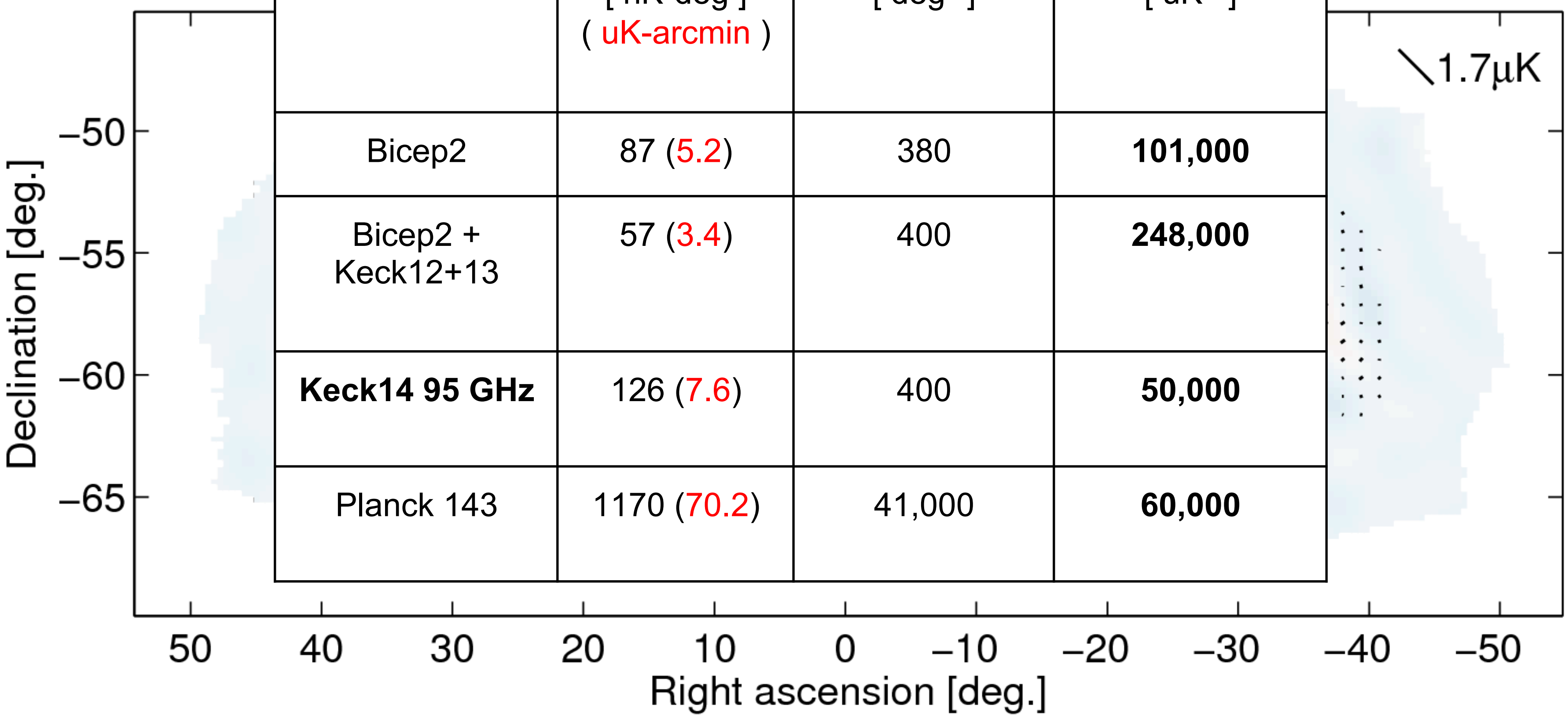
BICEP2 + Keck12+13 E−mode signal
1.7μK
−50
−55
−60
−65
Declination [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50
Right ascension [deg.]

Keck Array 2014 at 95 GHz



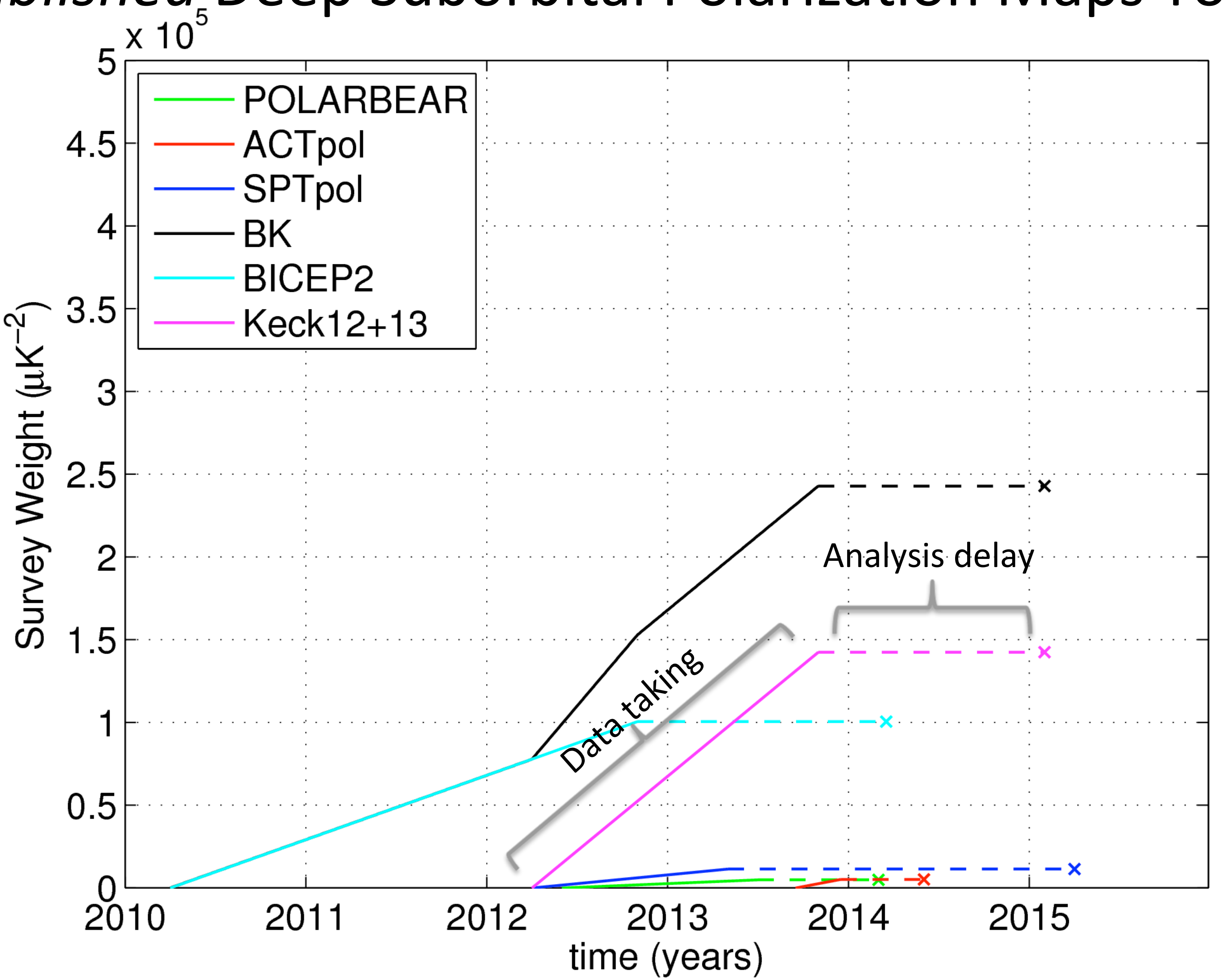
Keck Array 2014 at 95 GHz

	Q,U Map Depth [nK-deg] (uK-arcmin)	Survey effective area [deg^2]	**Total** Q+U **Survey Weight** [uK^{-2}]
Bicep2	87 (5.2)	380	**101,000**
Bicep2 + Keck12+13	57 (3.4)	400	**248,000**
Keck14 95 GHz	126 (7.6)	400	**50,000**
Planck 143	1170 (70.2)	41,000	**60,000**



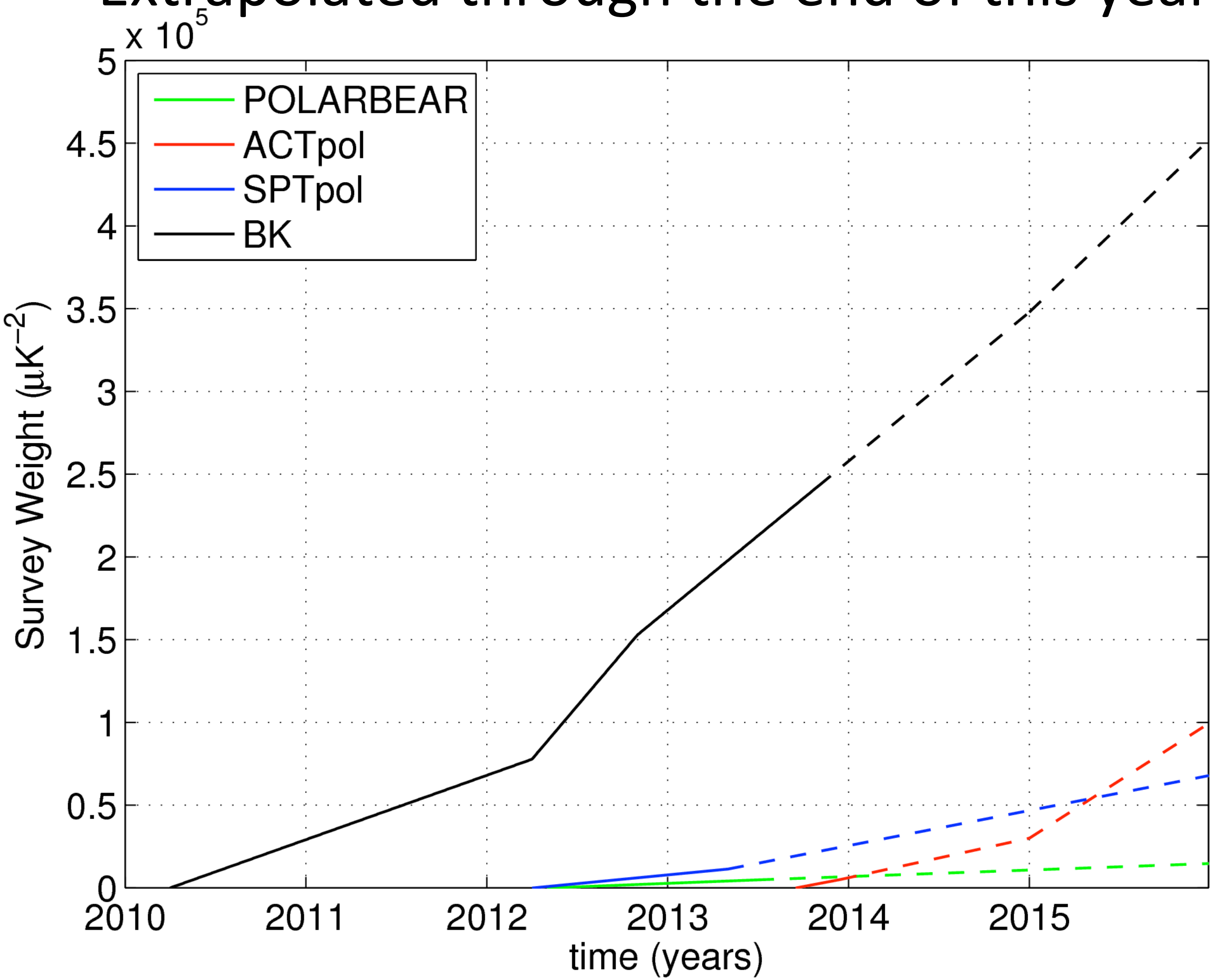
Dust BB expected ~5x fainter at 95 GHz vs 150 GHz

Published Deep Suborbital Polarization Maps To Date



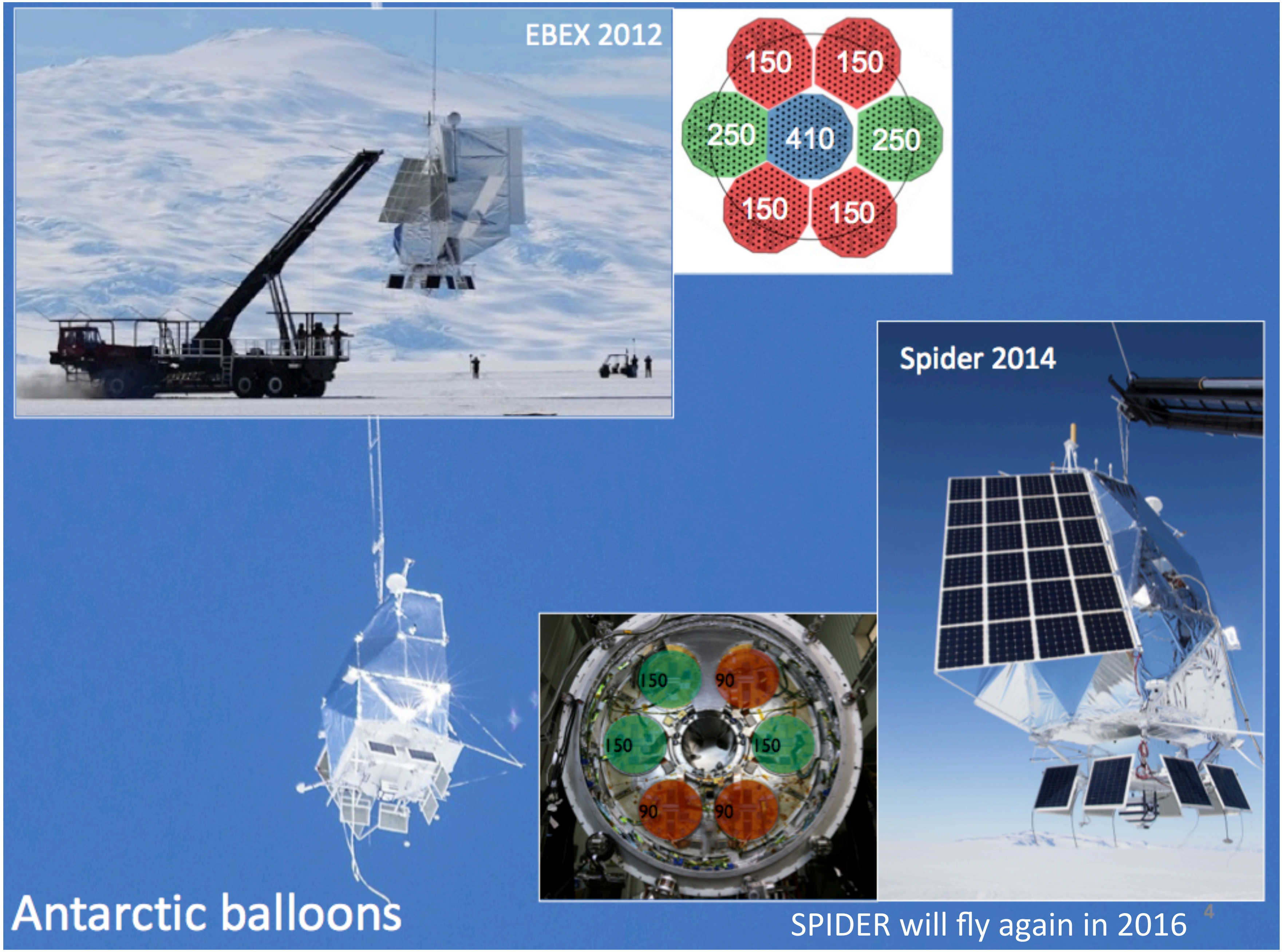
NB: Published results only – no projections!

Extrapolated through the end of this year



Solid projections based on proven performance

2G Balloons which have already flown: EBEX and SPIDER



Additional 2G ground based data under analysis or being taken right now

- SPTpol 2014/15 observing 500 sq deg
- ACTpol 2014/15 observing 2800 sq deg with 2x and 3x receivers
- POLARBEAR
- Keck 95GHz in 2014/15 and 220GHz in 2015 plus BICEP3 coming on line
- CLASS coming online (at 40GHz)

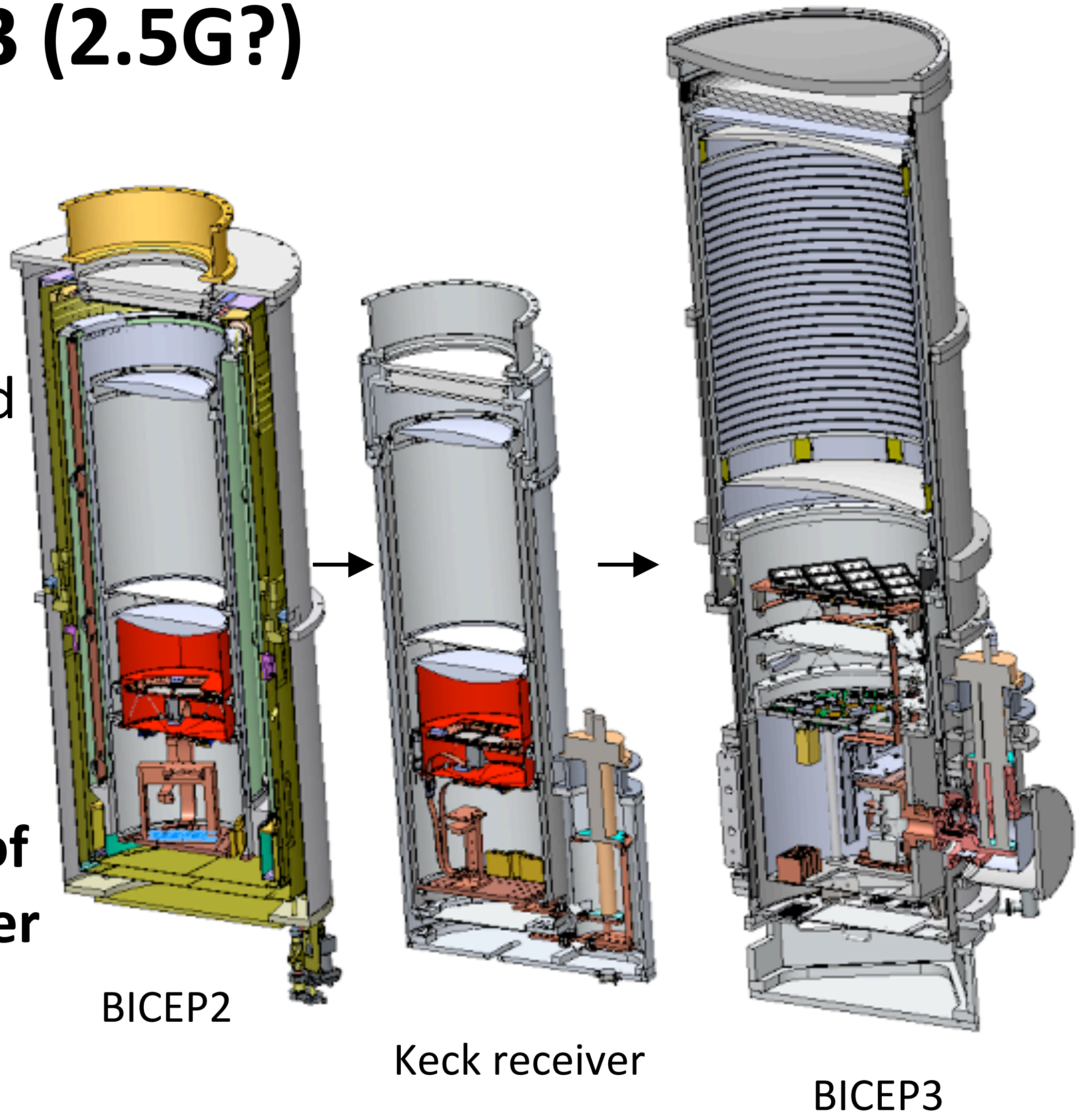
New in 2015 BICEP3 (2.5G?)

95 GHz focal plane

2560 detectors in modular focal plane (45% populated in 2015)

Twice the aperture of BICEP2/Keck

> 10x optical throughput of single BICEP2/Keck receiver

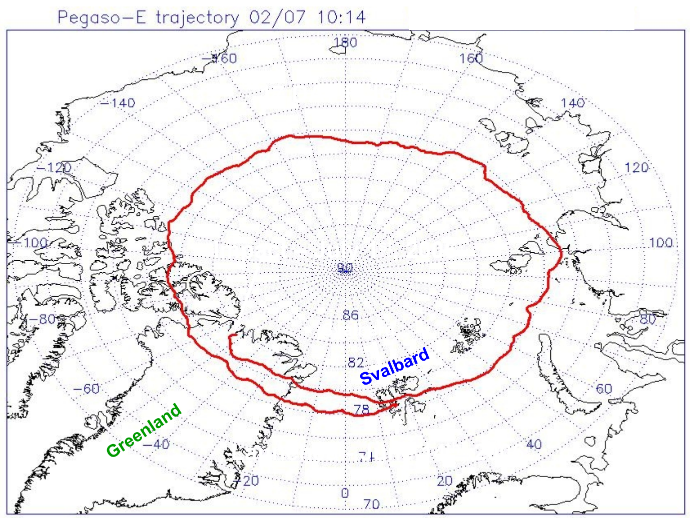


Funded 3G Ground Based Experiments

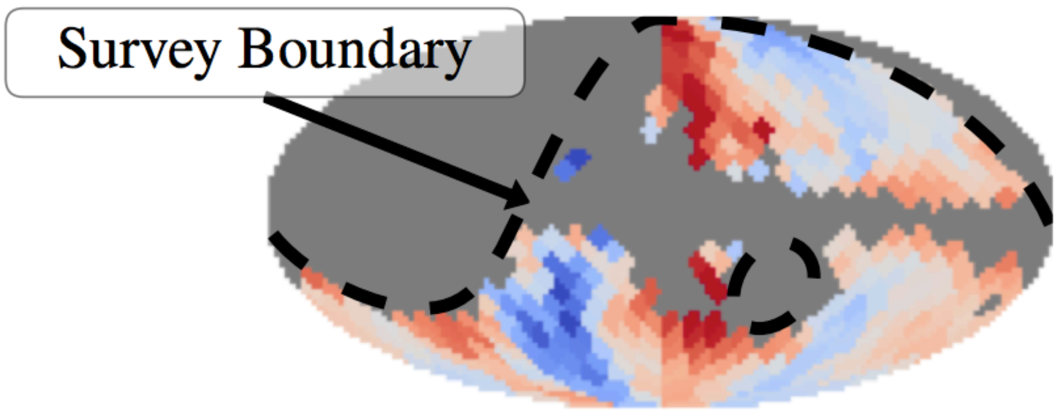
- SPT-3G receiver under construction and will deploy fall 2016
- ACTpol → Advanced ACTpol ($7.3M NSF MSIP funding)
- POLARBEAR → Simon's Array ($5M NSF MSIP funding)

Do really large angular scales from suborbital?

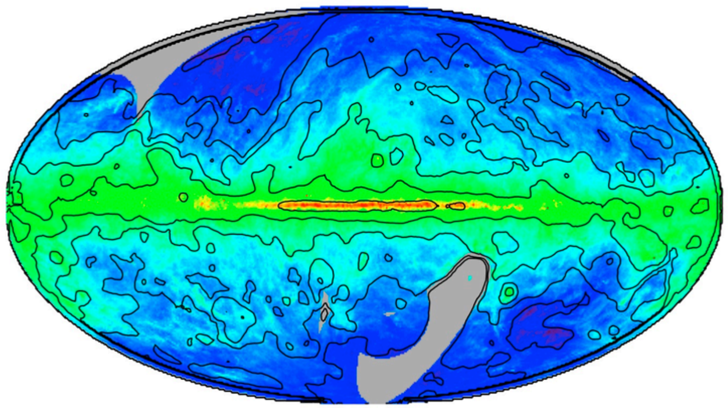
- At least three low res experiments will try:
  - CLASS ground based (Chile)
  - PIPER balloon (multiple flights)
  - LSPE balloon (arctic night flight)



LSPE (140, 220, 240 GHz)



CLASS (40, 90, 150, 220 GHz)

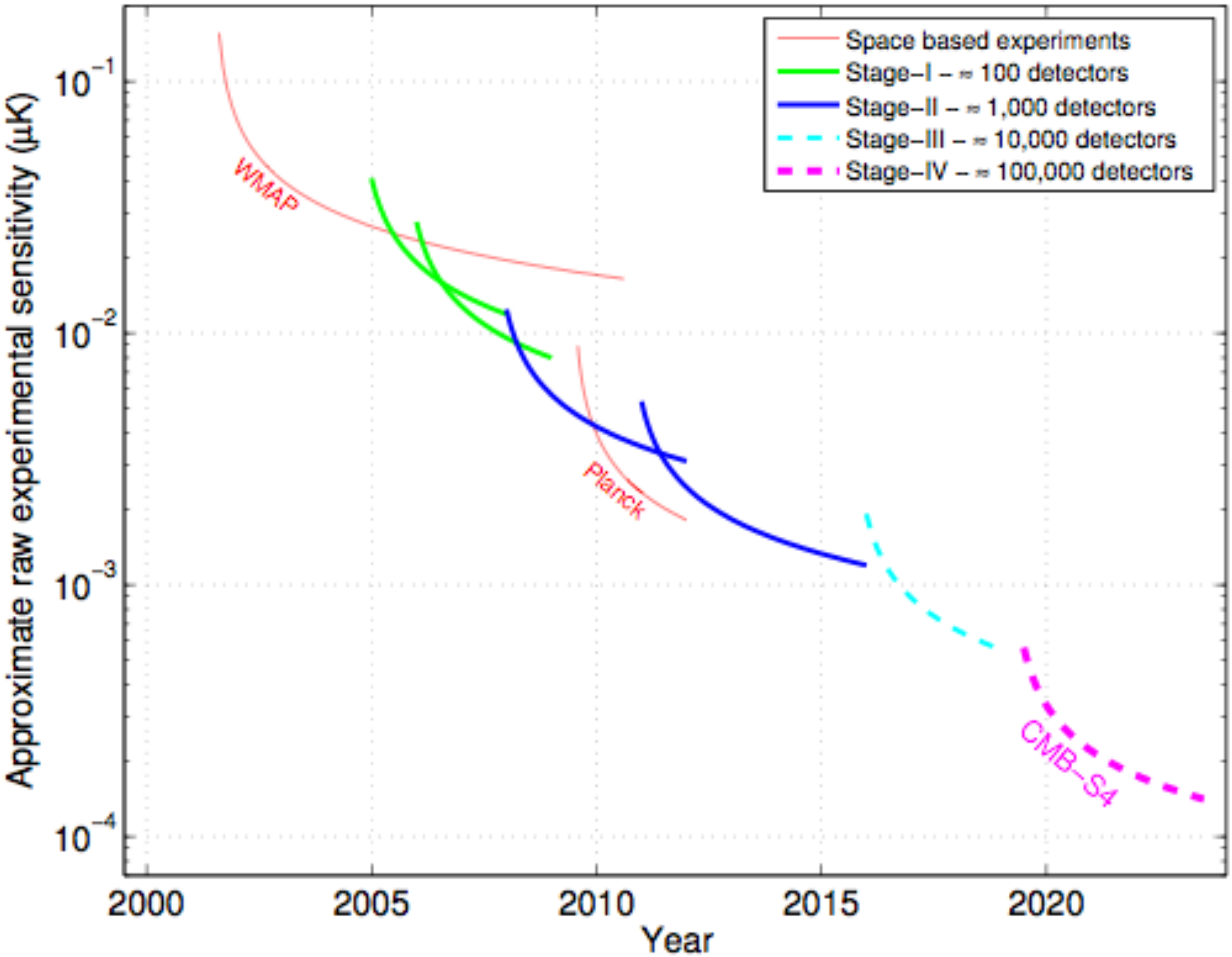


PIPER (200, 270, 350, 600 GHz)

What's left to do?

- Inflationary B-modes
  - At ell=80 bump
    - Need 1000 sq deg
    - Need foreground cleaning and delensing (so small angular scale polarization info needed as well)
  - At ell=10 bump
    - Need >50% sky
    - Need *extremely good* foreground cleaning
    - Reionization from low ell E-modes will come as a bonus…
- Dark energy science via SZ
    - Need >10,000 sq deg and high res
- Neutrino science via lensing
    - Need >10,000 sq deg and medium res
- Further refine LCDM via damping tail
    - Need >=10,000 sq deg and high res

Generations of suborbital pol experiments



"Official" CMB-S4 Slide

CMB-Stage 4 experiment

Because there is a lot more to learn from the CMB.

CMB-S4: a plan to build a coherent ground-based program working with, and building on, CMB stage II & III projects.

Participation includes, ***but is not limited to:***

- the ACT, BICEP/KECK, SPT, Polarbear,… CMB teams and their international partners
- Argonne, FNAL, LBNL, SLAC, NIST U.S. national labs and the high energy physics community.

“Official” CMB-S4 Slide

What it will require

- **Survey:**

  - Inflation, Neutrino, and Dark Energy science requires an optimized survey which includes a range of resolution and sky coverage from deep to wide.

- **Sensitivity of ~1 uK-arcmin over half the sky**

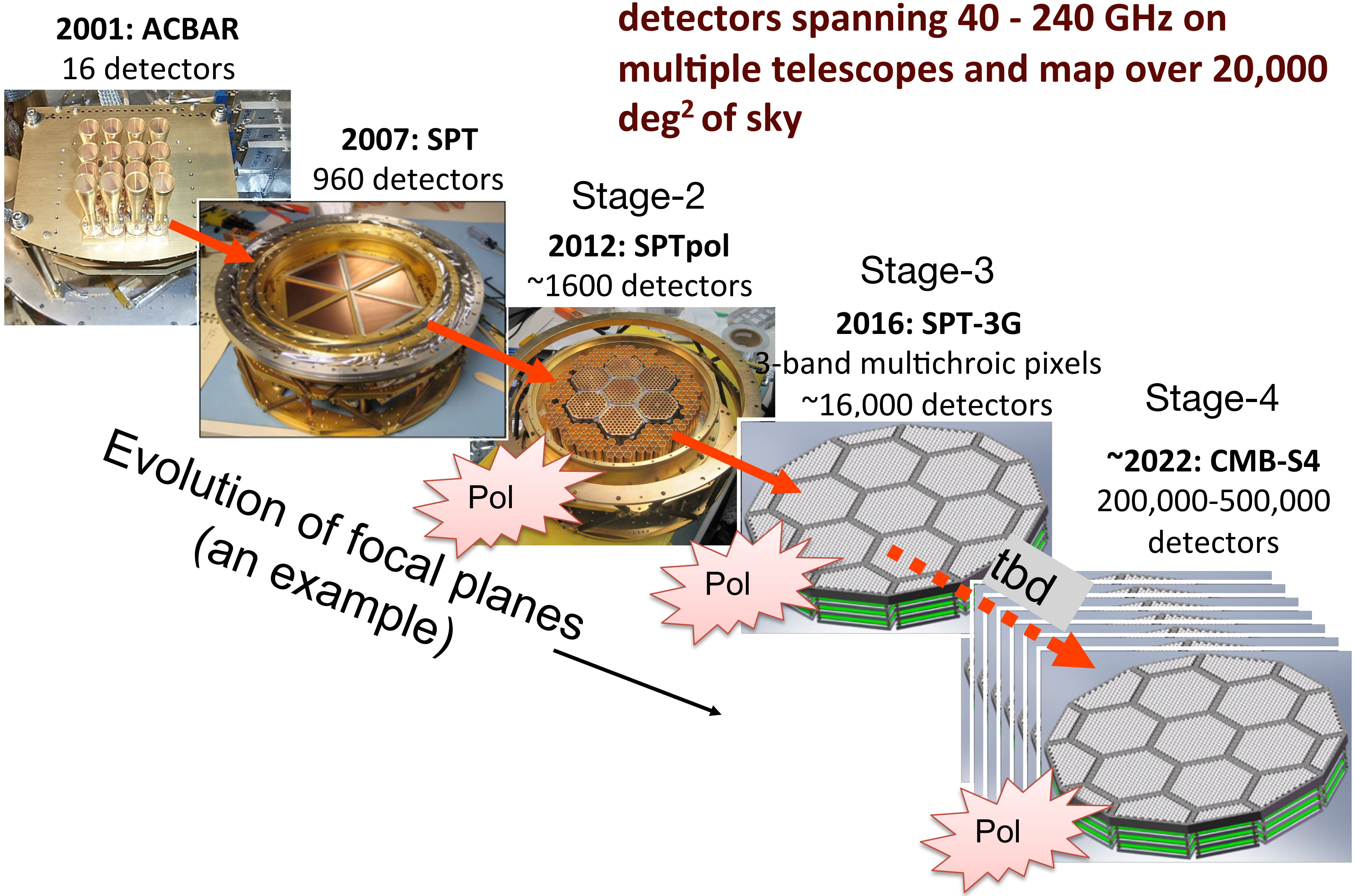
  - **Experimental Configuration:**

  - 200,000+ detectors on multiple platforms
  - spanning 40 - 240 GHz for foreground removal
  - $\lesssim$ **3 arcmin resolution** required for CMB lensing & neutrino science
  - ***higher resolution leads to amazing and complementary dark energy constraints, and gravity tests on large scales via the SZ effects***

See Snowmass planning document arxiv:1309.5383

“Official” CMB-S4 Slide

CMB-S4: A coordinated community wide program to put 200,000 to 500,000 detectors spanning 40 - 240 GHz on multiple telescopes and map over 20,000 deg^2 of sky



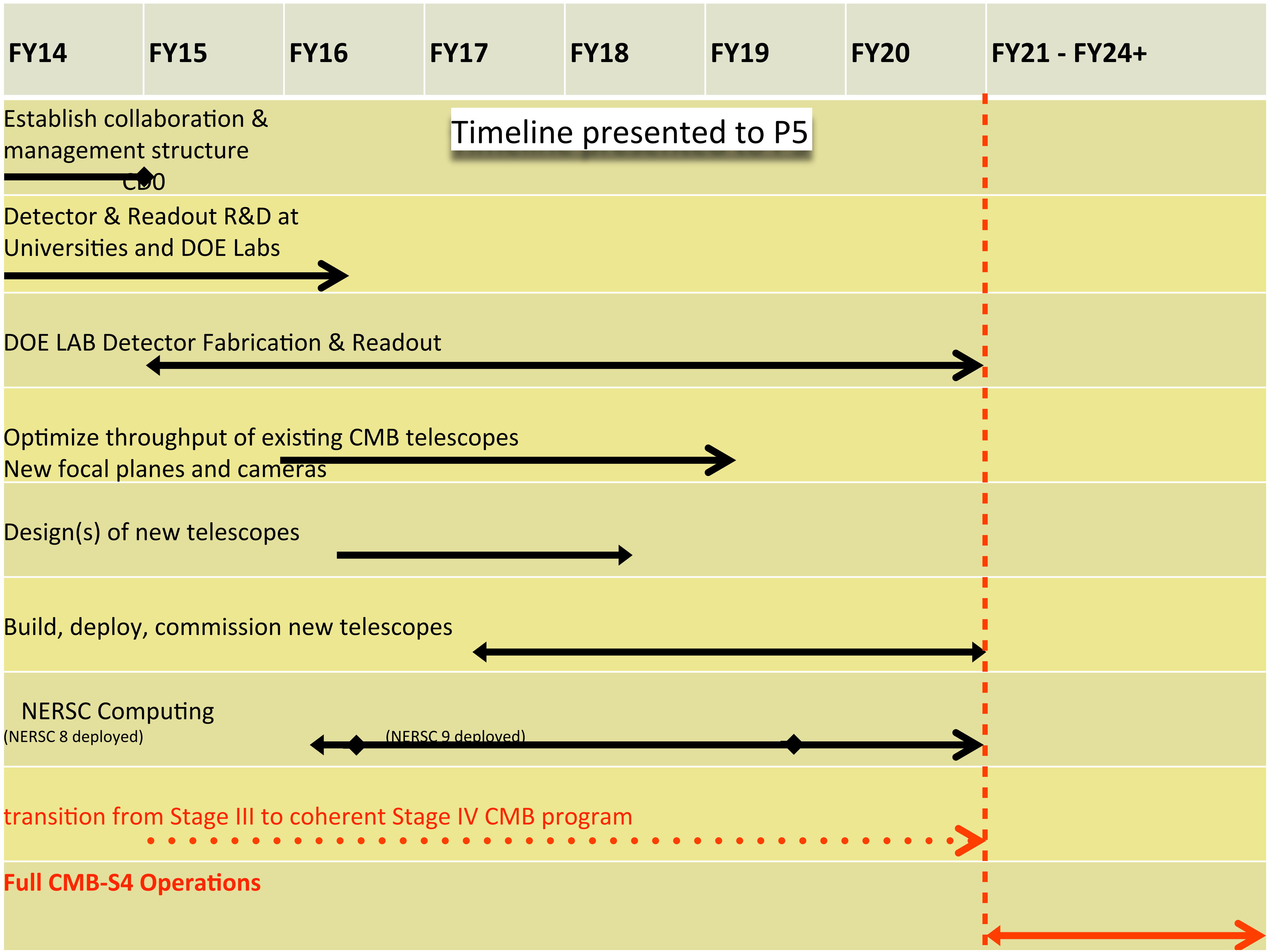
“Official” CMB-S4 Slide

US HEP P5 Panel recommended DoE support CMB-S4

recommended
under all funding scenarios

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenarios: Scenario B	Scenarios: Scenario C	Science Drivers: Higgs	Science Drivers: Neutrinos	Science Drivers: Dark Matter	Science Drivers: Cosm. Accel.	Science Drivers: The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I


FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21 - FY24+
Timeline presented to P5
Establish collaboration & management structure
CD0
Detector & Readout R&D at Universities and DOE Labs
DOE LAB Detector Fabrication & Readout
Optimize throughput of existing CMB telescopes
New focal planes and cameras
Design(s) of new telescopes
Build, deploy, commission new telescopes
NERSC Computing
(NERSC 8 deployed)
(NERSC 9 deployed)
transition from Stage III to coherent Stage IV CMB program
Full CMB-S4 Operations

Conclusions

- Suborbital experiments are pushing the CMB frontier
  – in many cases enabled by and in conjunction with Planck
- The small aperture BICEP/Keck experiments currently have by far the highest published sensitivity
  – Don't over focus on nominal detector count…
  – But 3G experiments are coming…
  – Value of joint analyses is obvious!
- BICEP/Keck also achieve systematic control at low ell
  – It remains to be seen: can large apertures deliver at lower ell?
- Big plans for the future:
  – CMB-S4 seeks to put 100,000's of detectors on the sky!


Thank you !