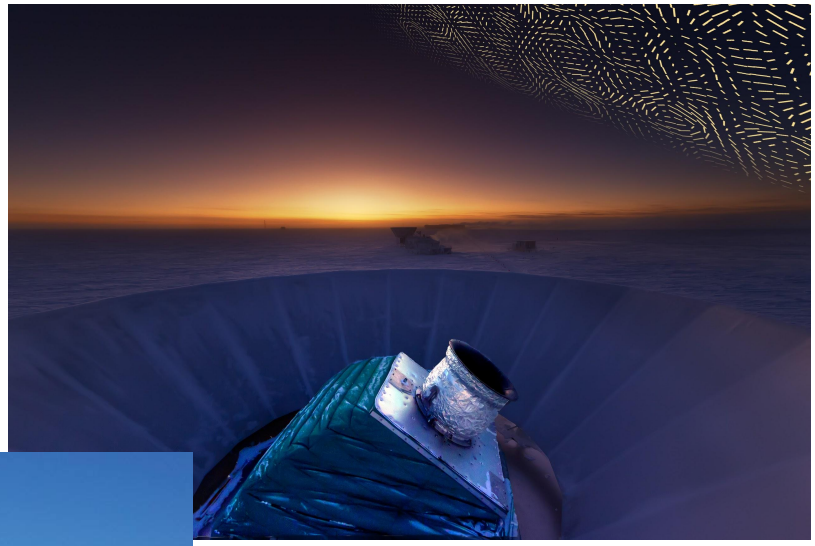
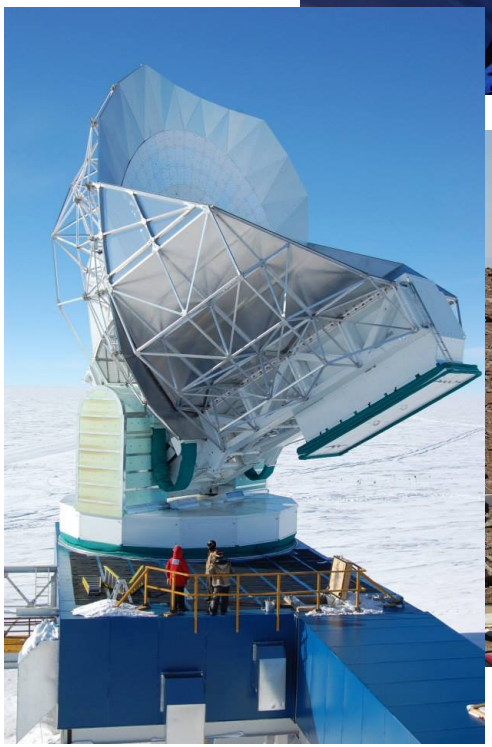
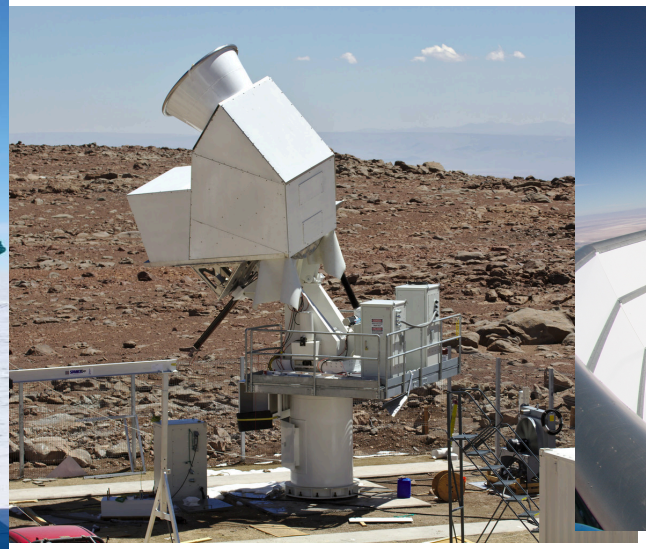
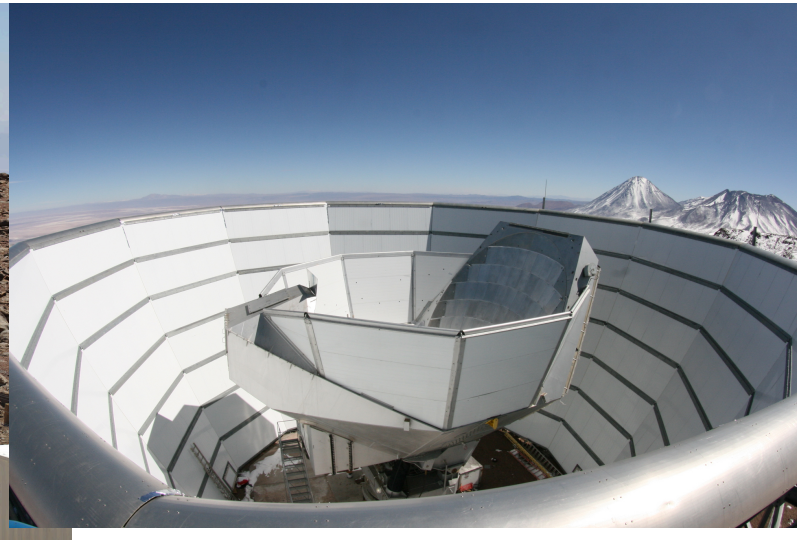
The CMB-S3 Landscape (US ground based)





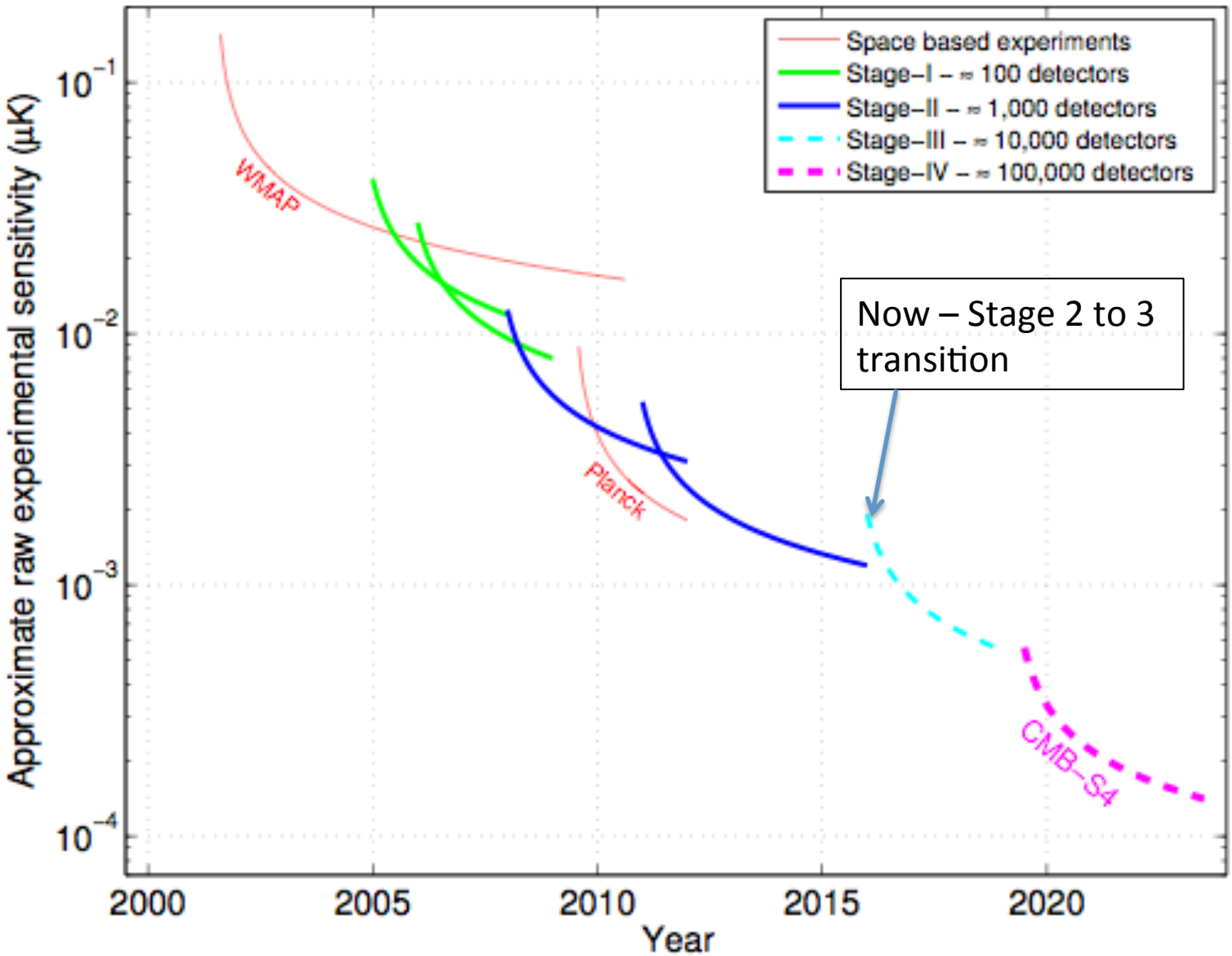




Clem Pryke from The BICEP2/Keck Collaborations

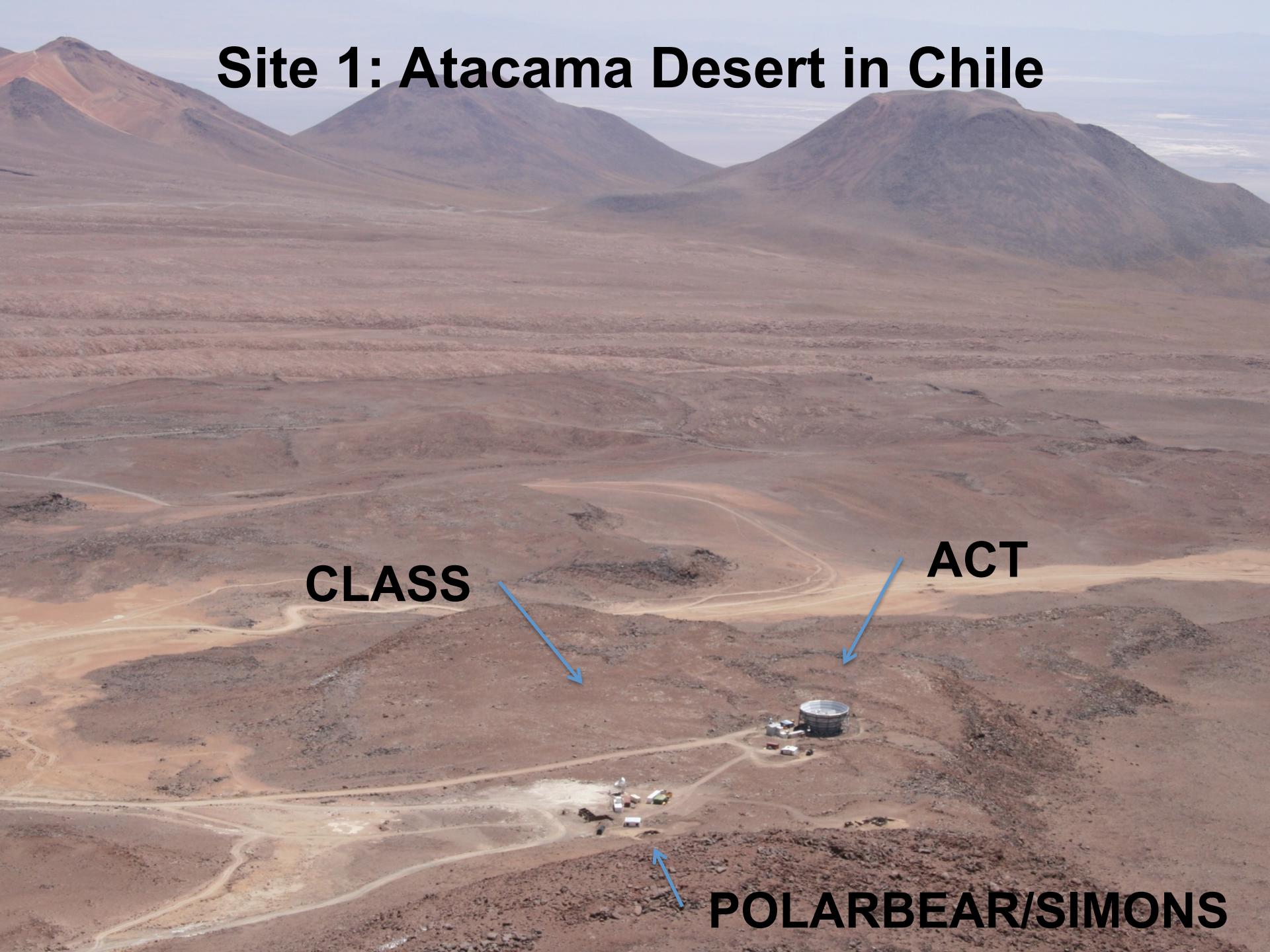
IHEP – May 23 2016

Generations of suborbital pol experiments

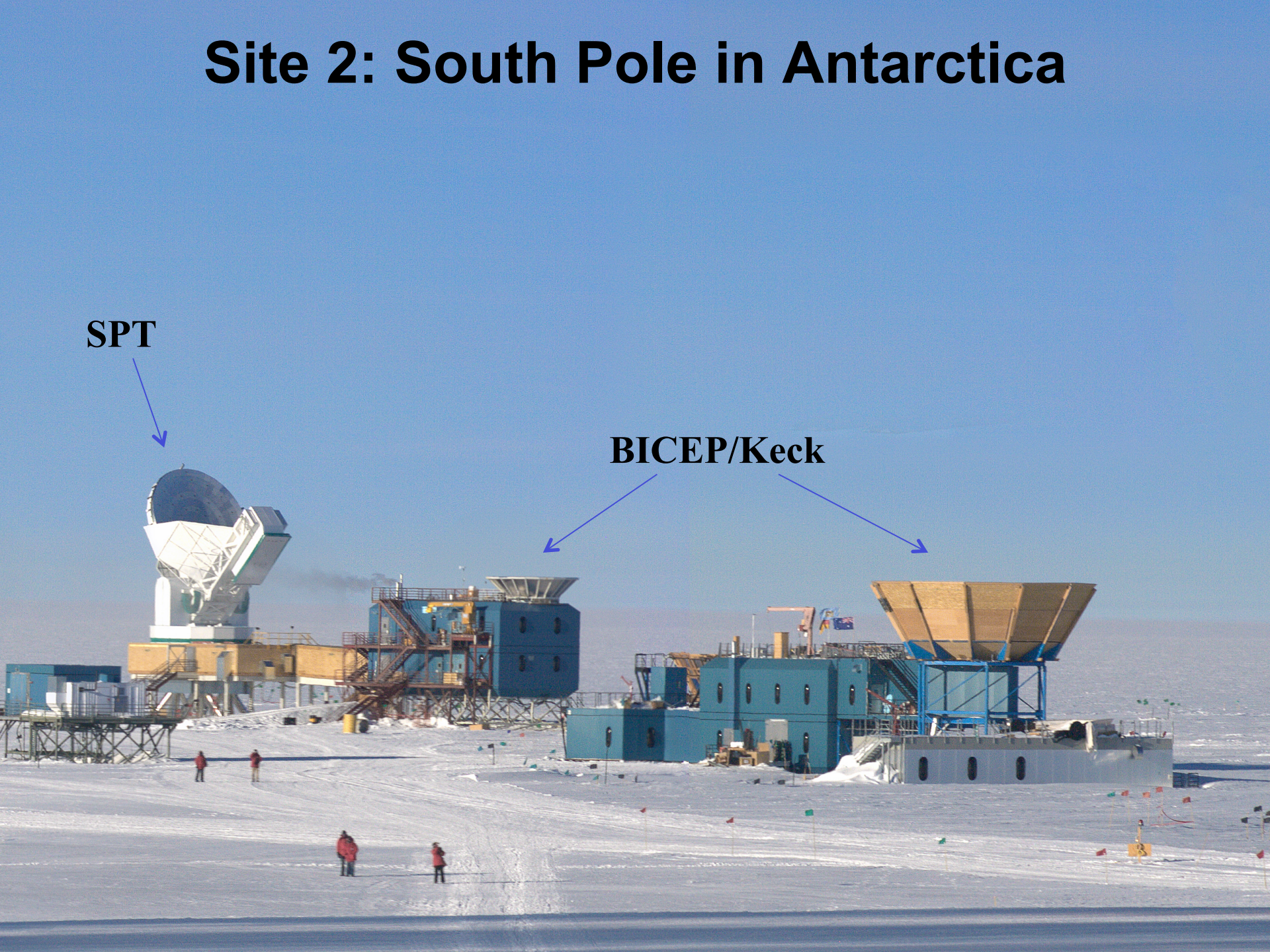


(Figure made summer 2013 for Snowmass process)

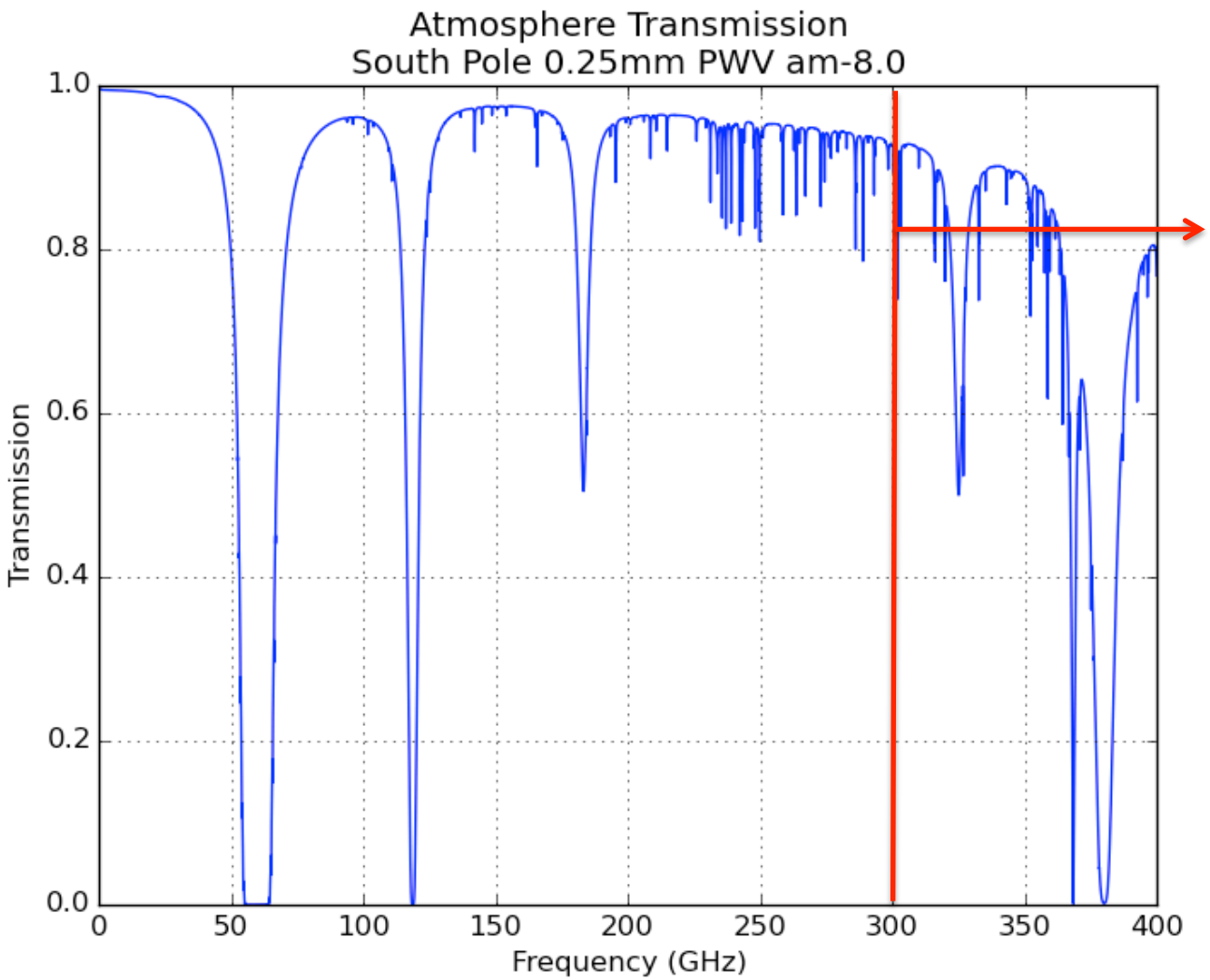
Site 1: Atacama Desert in Chile



Site 2: South Pole in Antarctica



Ground based limitation: Can't do high frequencies

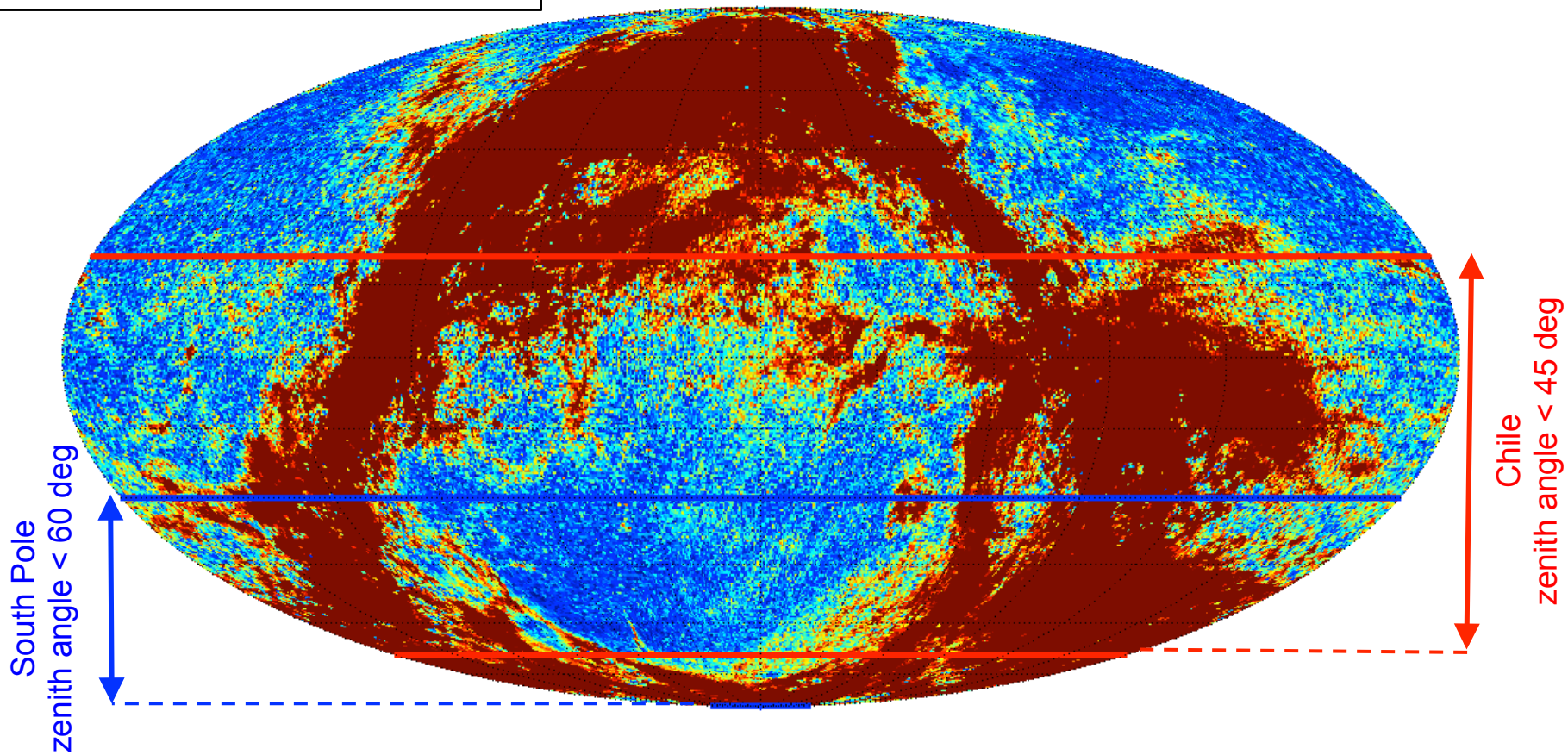


Even from the best sites can't go above 300GHz

4 windows: <45, 95, 150 & 200-300

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

Planck 353GHz polarized intensity map in celestial coordinates (color scale 0-100uK)

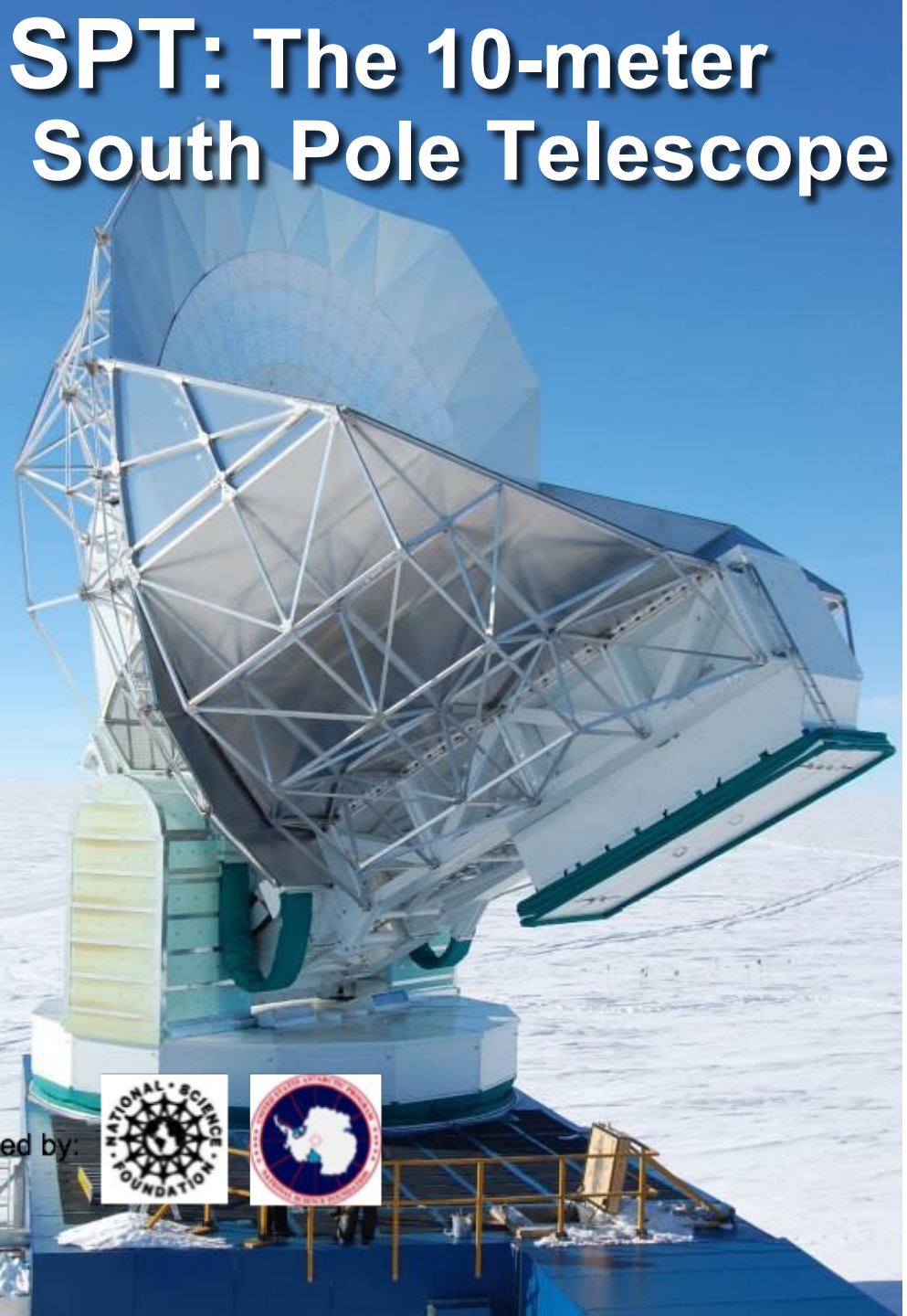


More sky is available from Chile - but it is not really better sky from the point of view of dust contamination

5 distinct programs:

- SPT – South Pole – 10 meter reflector
- ACT – Chile – 6 meter reflector
- POLARBEAR / Simons – Chile – 3 meter reflector(s)
- CLASS – Chile – 0.6 meter reflectors
- BICEP2/Keck Array – South Pole – 0.25 meter refractors

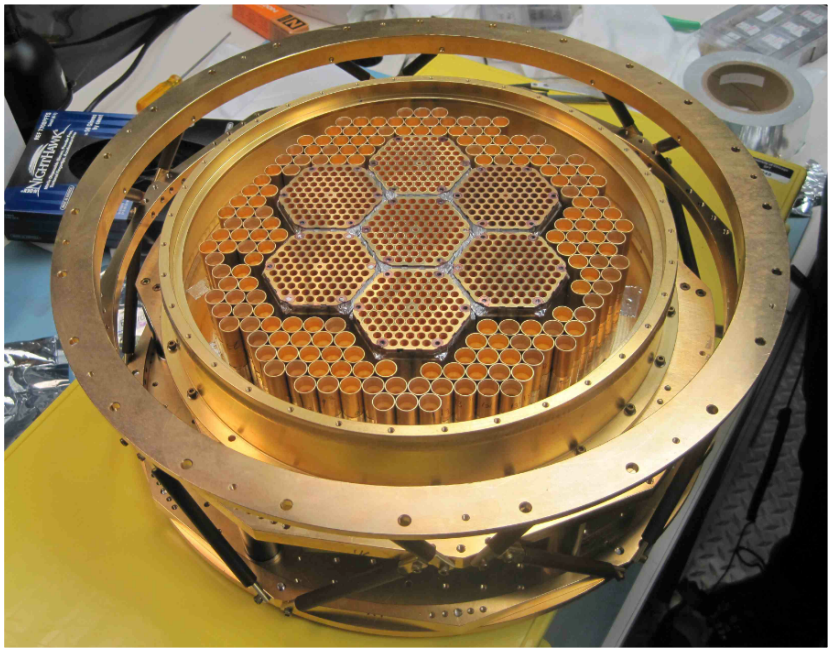
SPT: The 10-meter South Pole Telescope



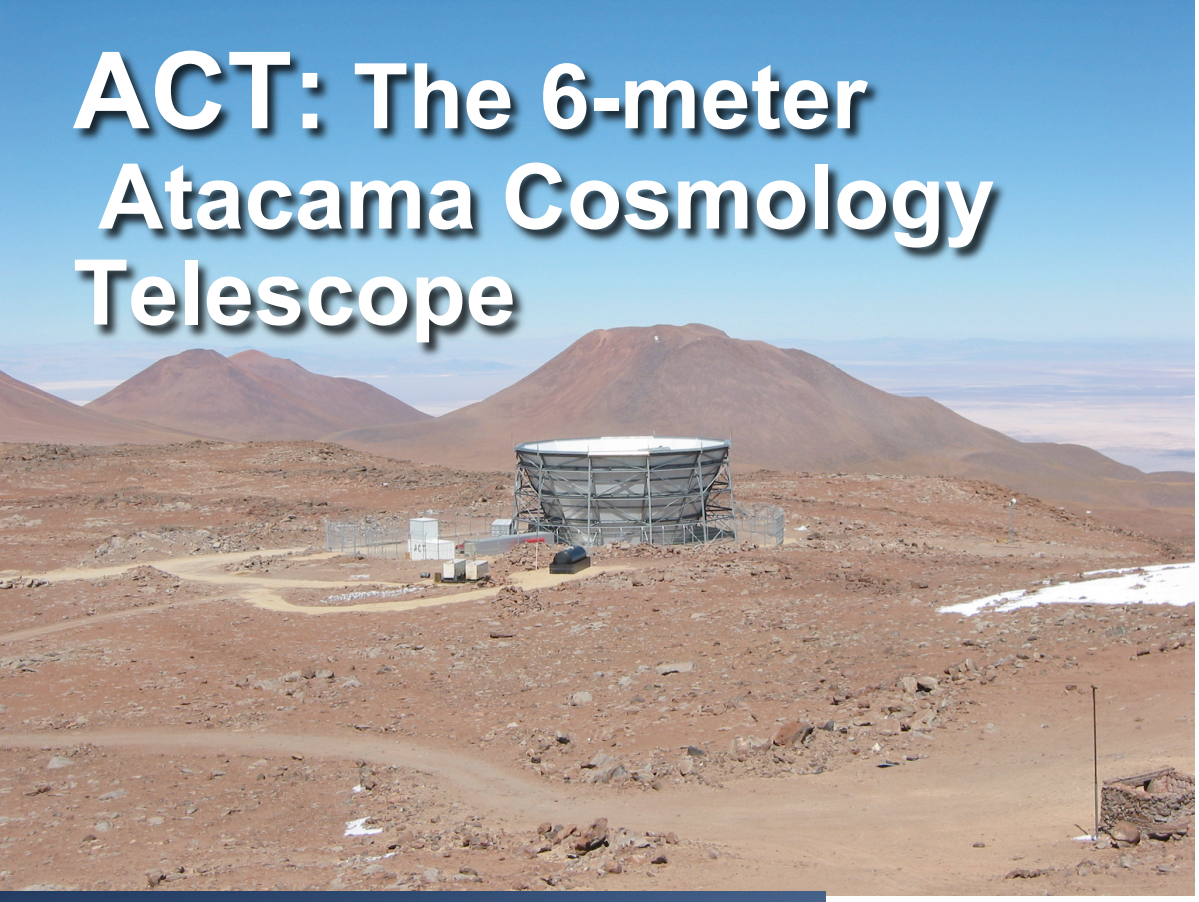
Current camera: SPTpol

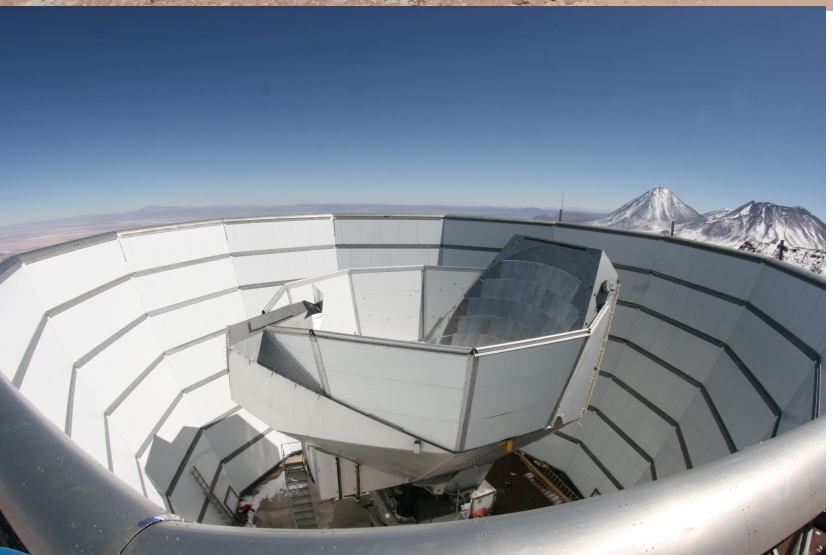
1600 detectors

100 &150 GHz



ACT: The 6-meter Atacama Cosmology Telescope

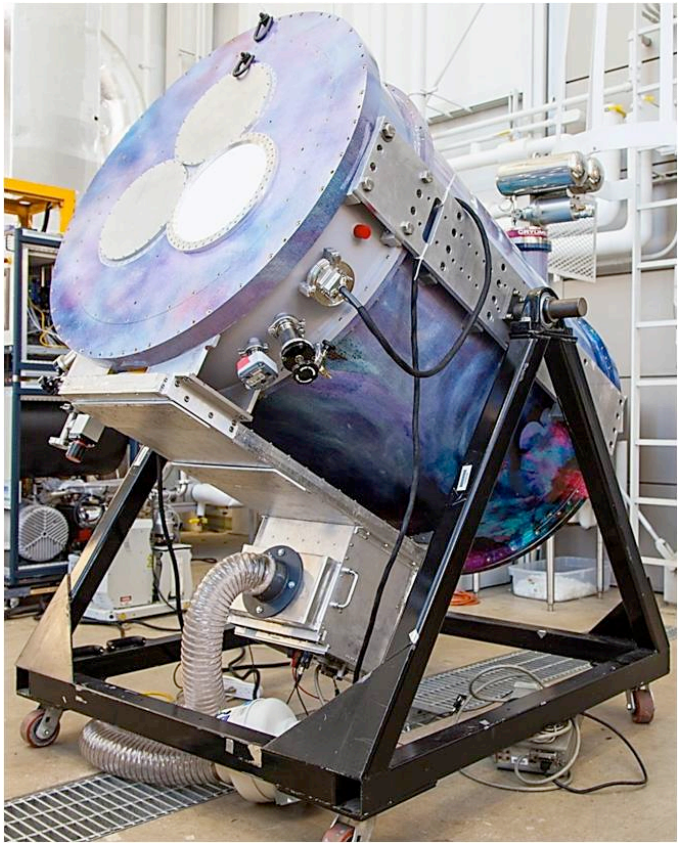




Current camera: ACTpol

3000 detectors (full strength)

100 &150 GHz

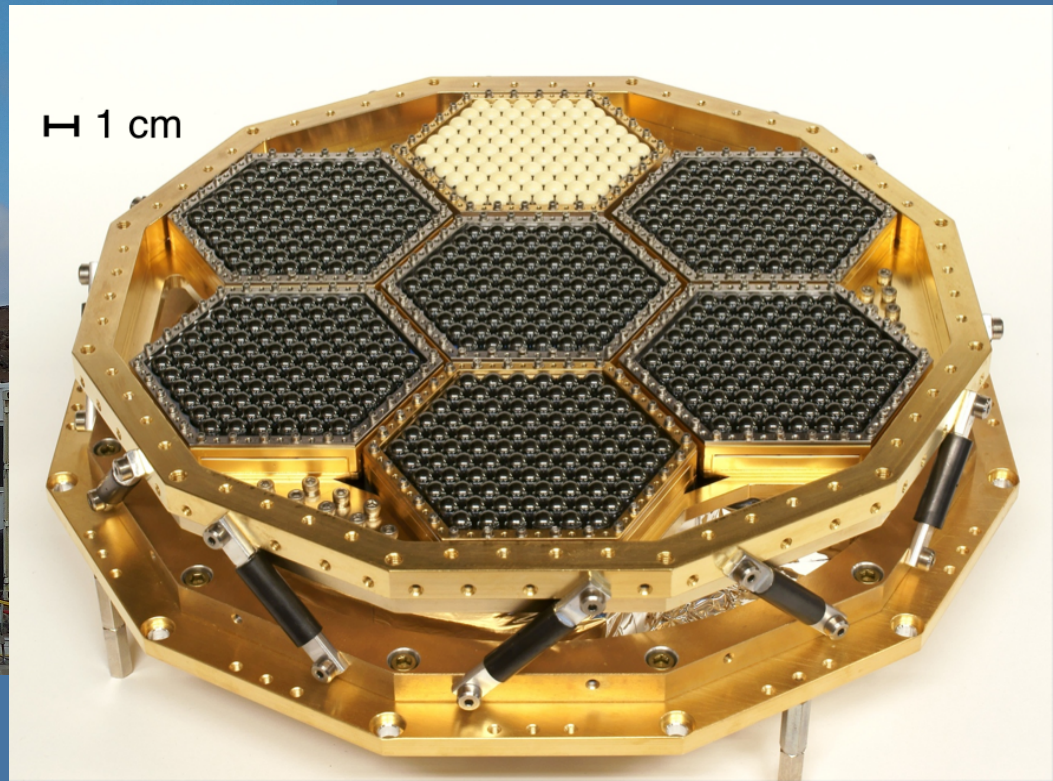


POLARBEAR: 3.5-meter Telescope in Atacama

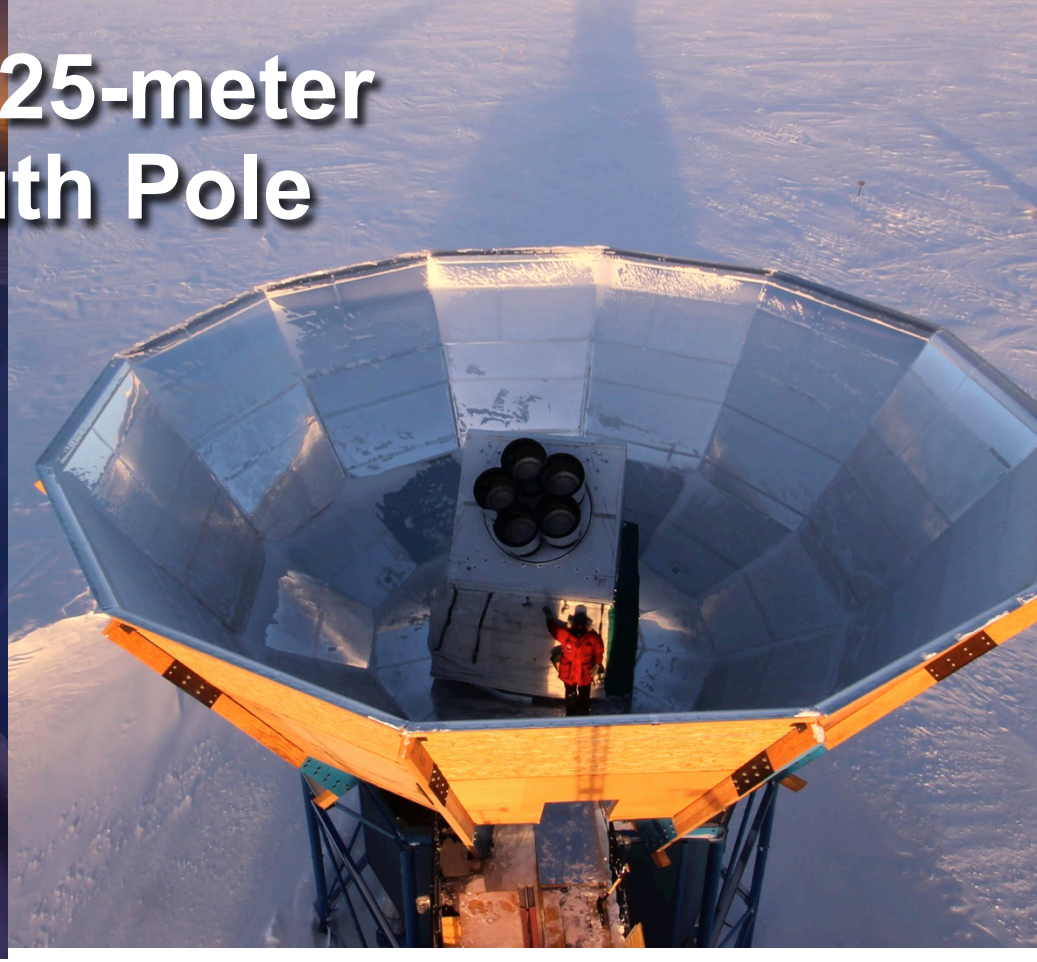
Current camera: POLARBEAR 1

1300 detectors

150 GHz



BICEP2/Keck: 0.25-meter Telescopes at South Pole



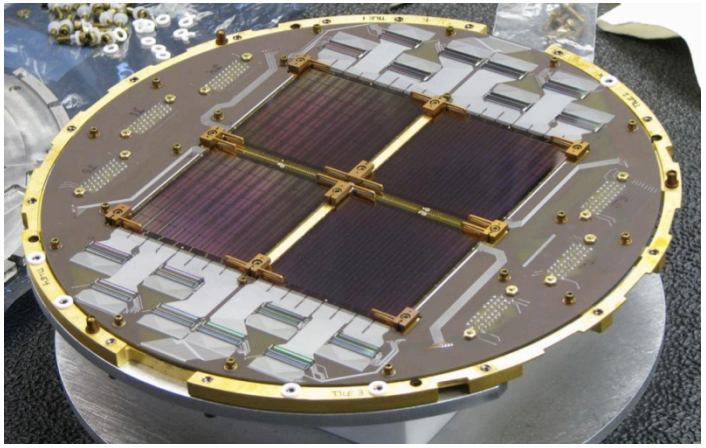
Focal planes:

500 detectors each, approx 2500 total

100,150, & 220 GHz

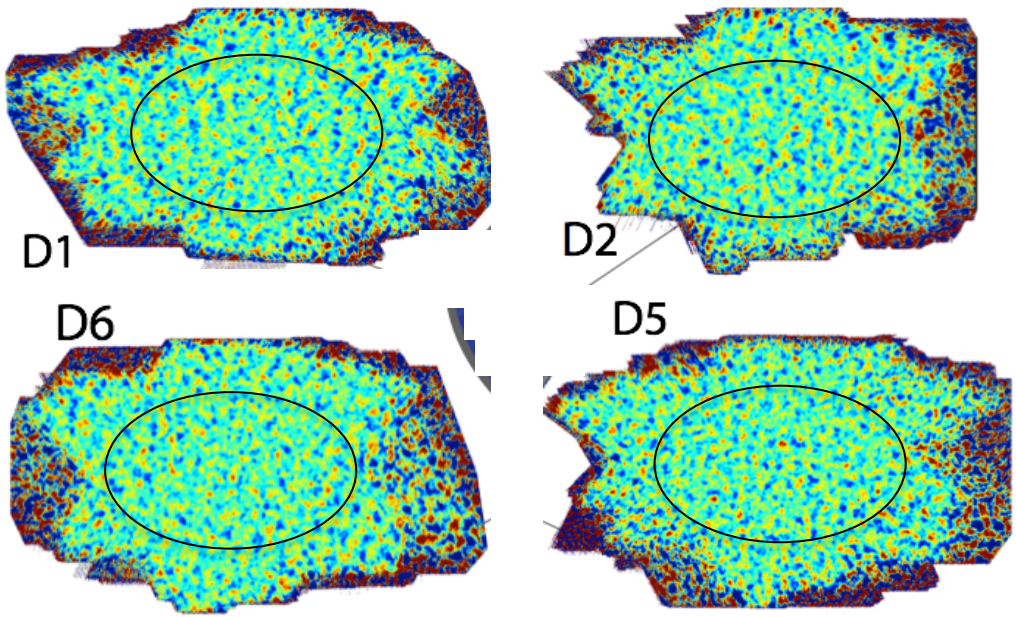
Specifically optimized for large scales:

Boresight rotation and absorptive forebaffles

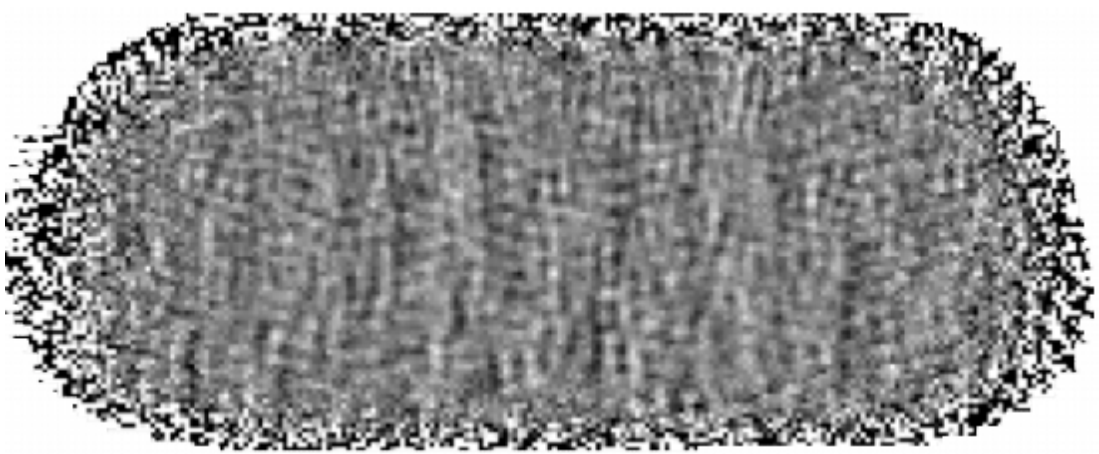


Published Stage 2 Results

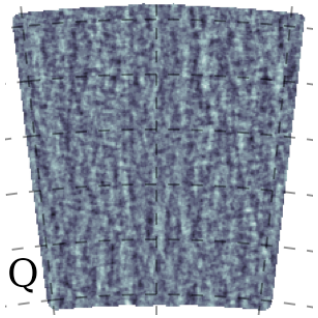
Published Deep Suborbital Polarization Maps To Date



ACTpol 275 sq deg arxiv:1405.5524

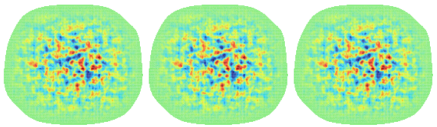


BICEP2/Keck 400 sq deg arxiv:1403.3985, 1502.00643, 1510.09217



SPTpol 100 sq deg arxiv: 1411.1042 and 1503.02315

Roughly scaled to indicate relative map sky coverage



POLARBEAR 25 sq deg arxiv:1403.2369

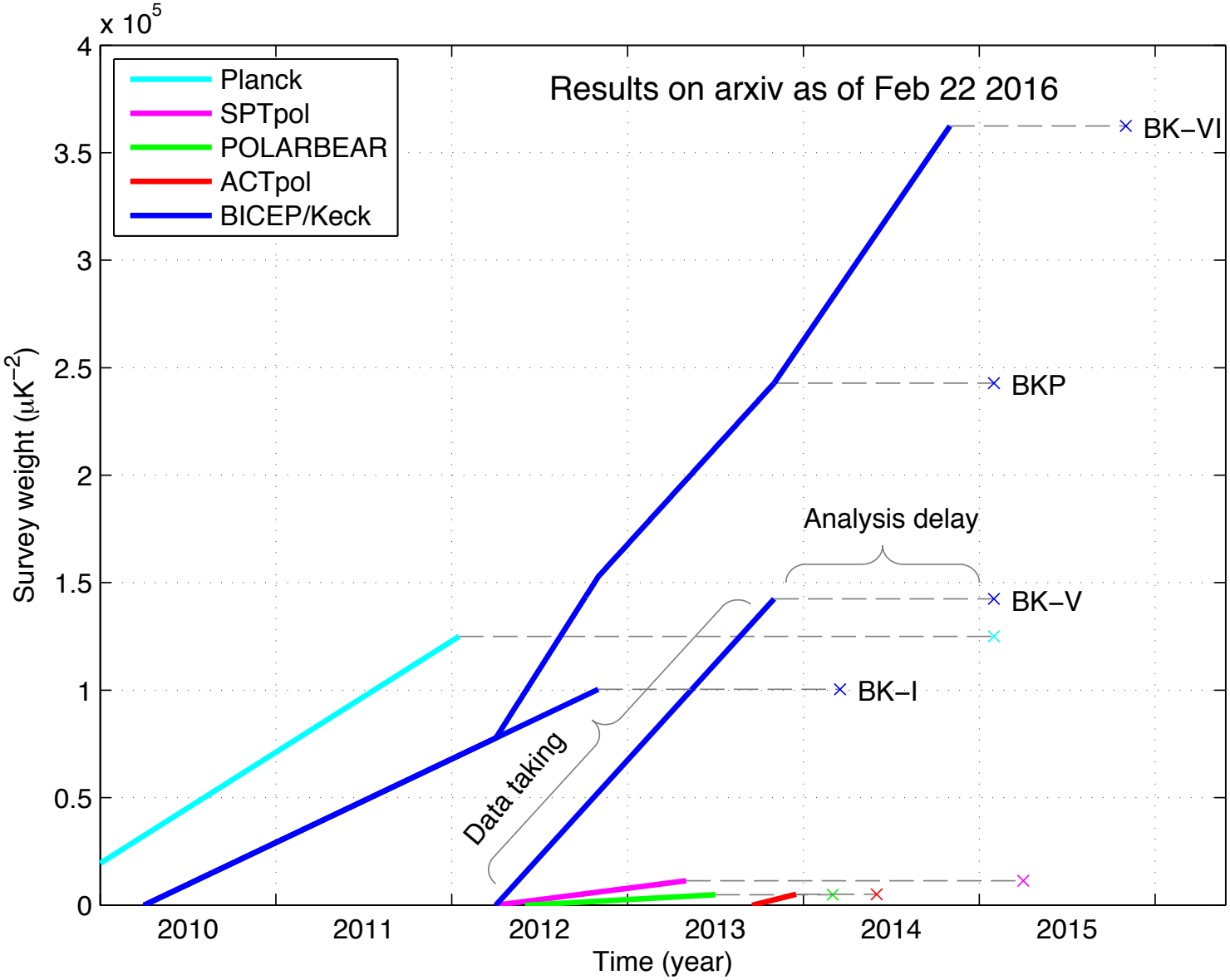
Published Deep Suborbital Polarization Maps To Date

	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 (100d)	17@95 & 9@150	100	**11,000**	arxiv:1503.02315
BICEP2+Keck (BK14)	3.0	400	**300,000**	arxiv:1510.09217
Planck 143 GHz (for reference)	70	41,000	**60,000**	arxiv:1502.01582

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

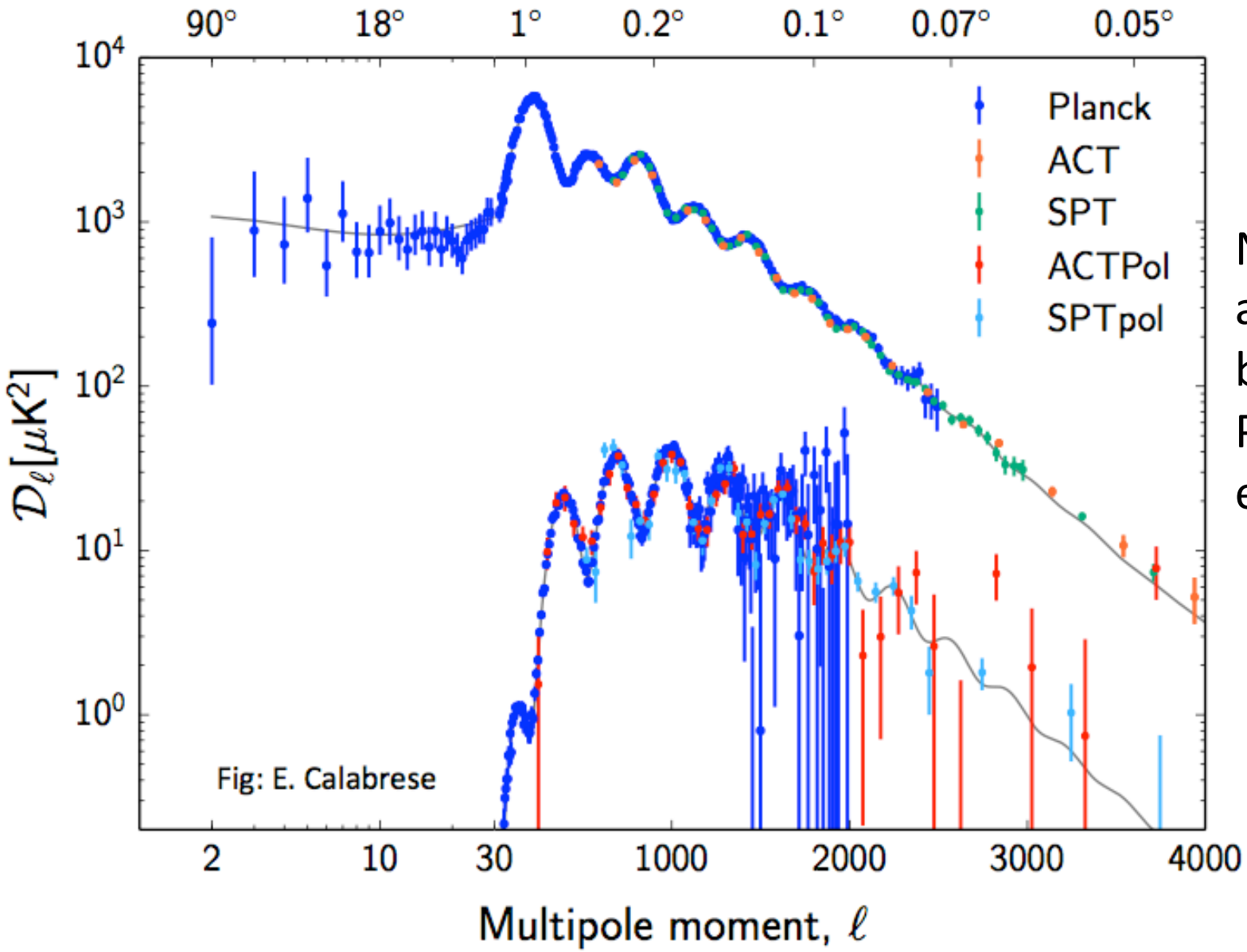
Survey weight: A quantity which is linear in number of detectors and integration time – i.e. difficulty of achieving
Also linear in power spectrum noise error bar size

Published Deep Suborbital Polarization Maps To Date



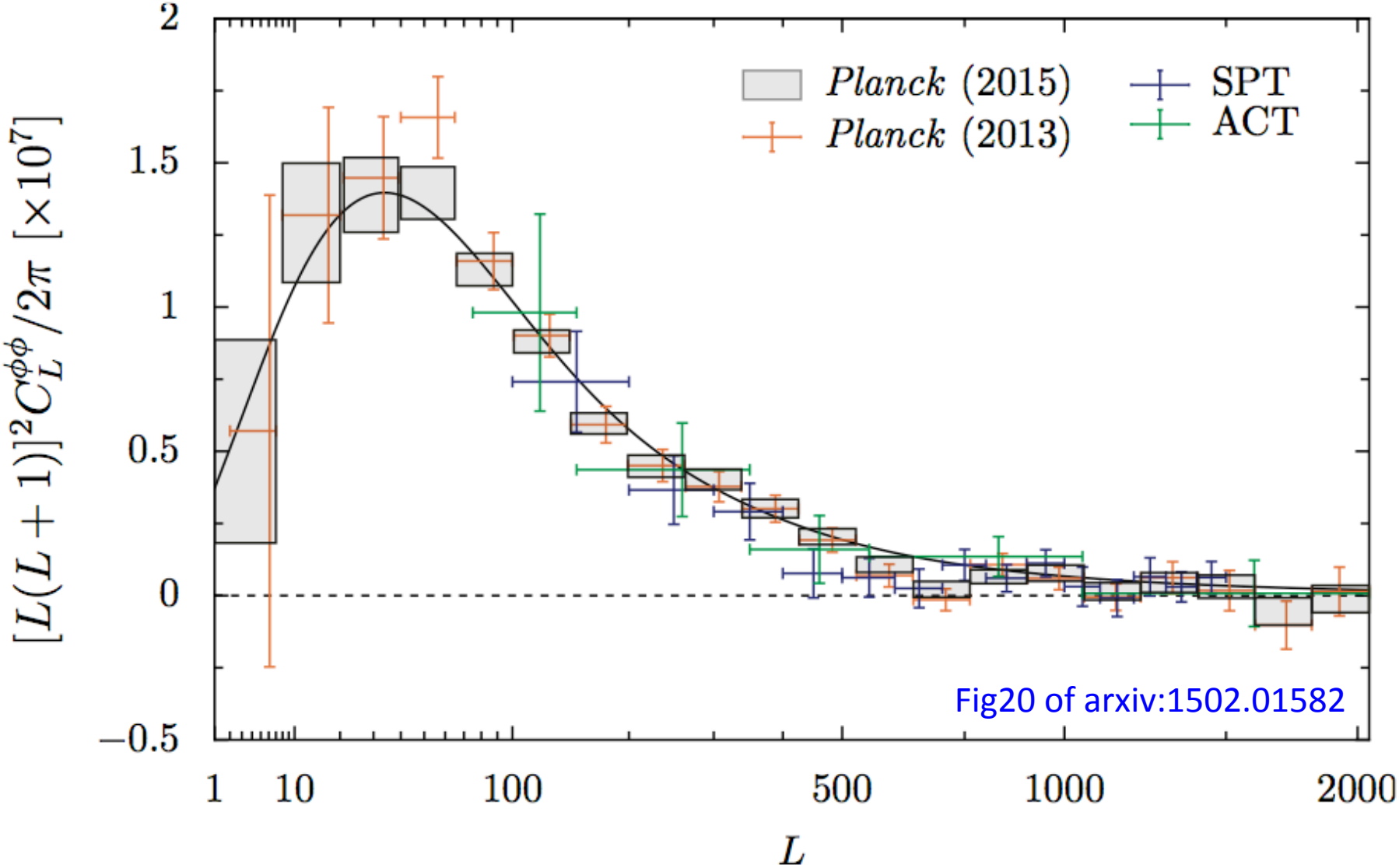
NB: Published results only – no projections! – (much) more data in the can

Published SPTpol/ACTpol EE Measurements



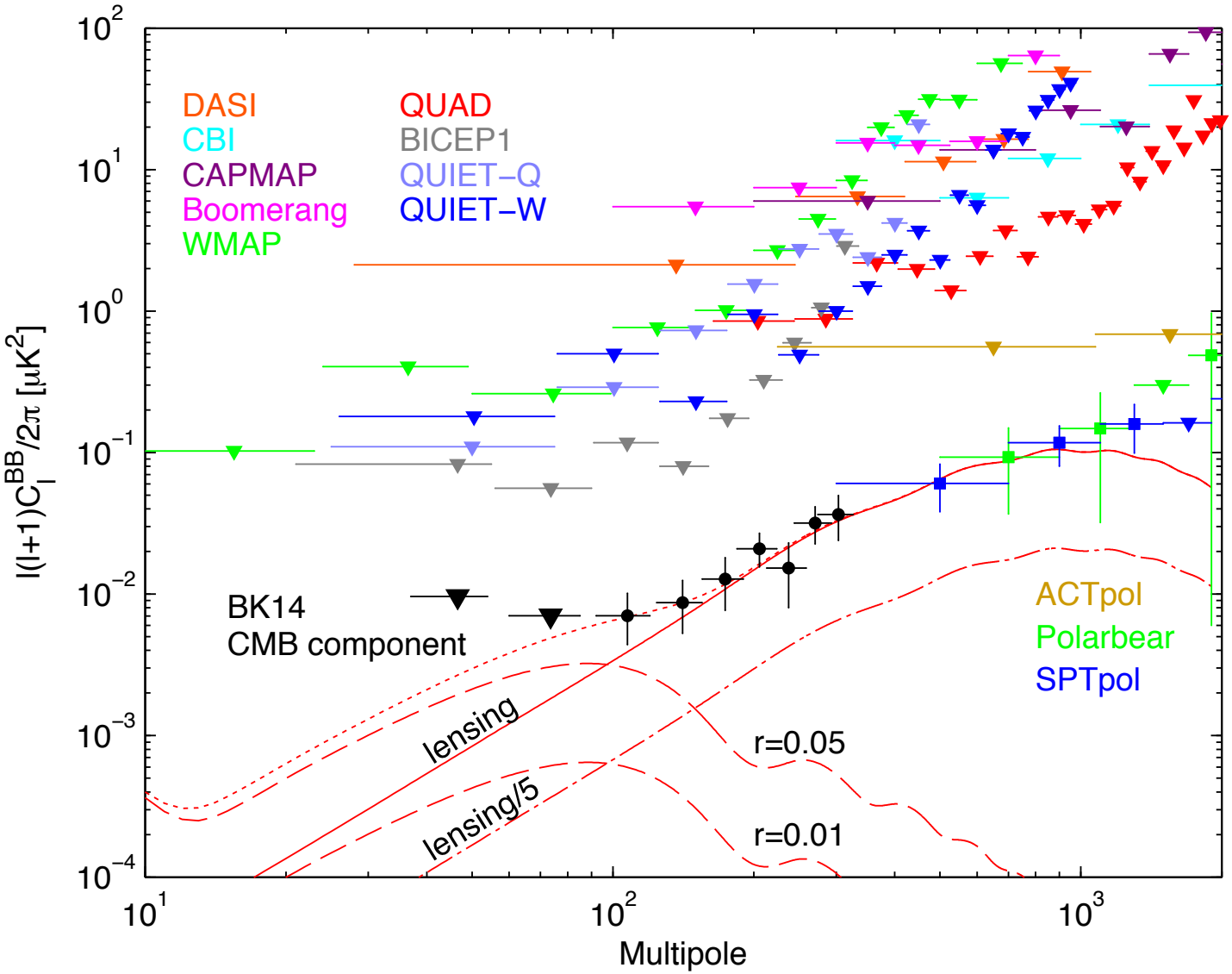
Note that already better than Planck for ell>1500

Published Lensing Measurements



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

Published BB Measurements



BK14 = All BICEP2/ Keck data up to and including 2014 season 150 and 95 GHz arXiv:1510.09217

ACTPOL = arXiv: 1405.5524

POLARBEAR = arXiv: 1403.2369

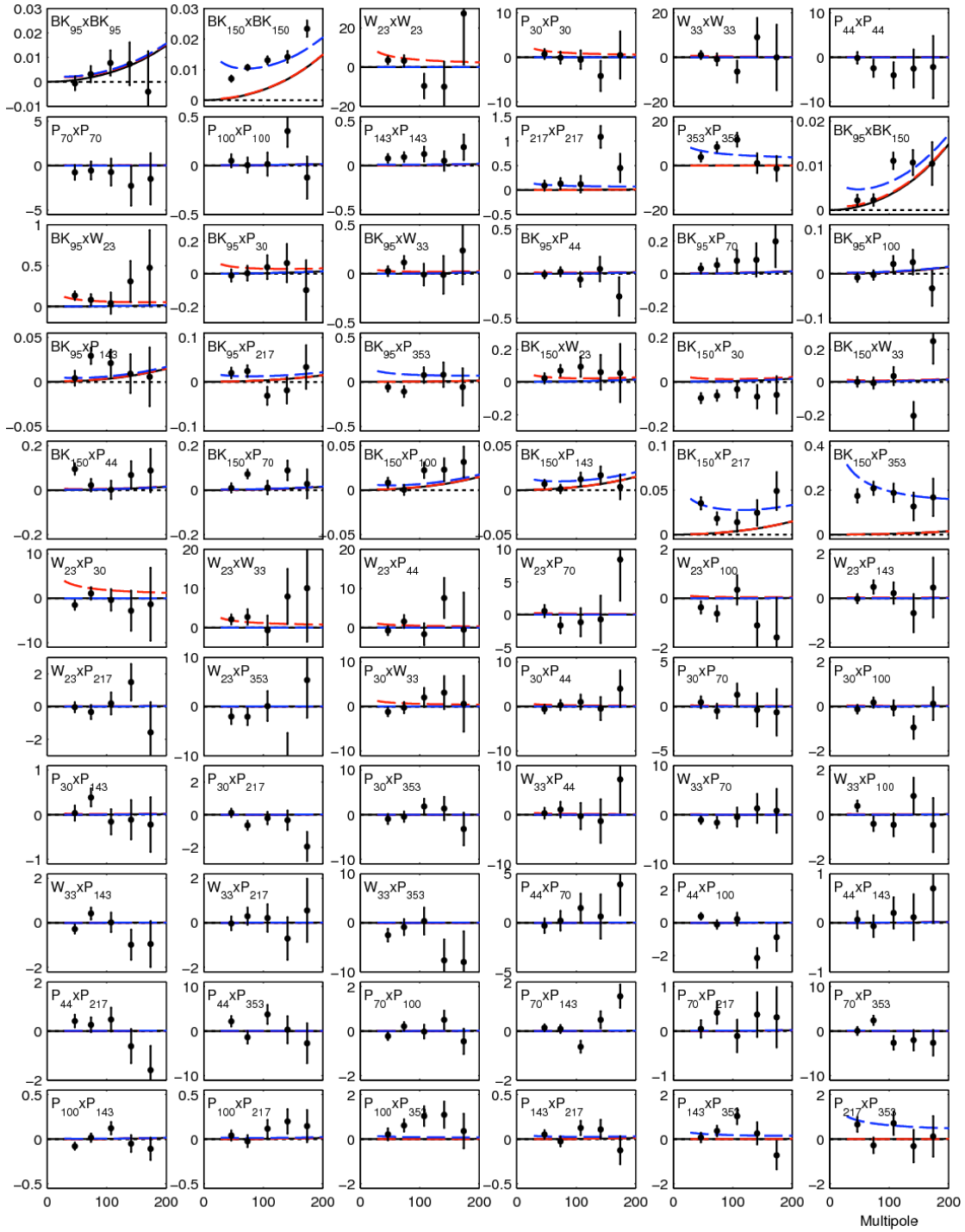
SPTpol = arXiv: 1503.02315

To date no results from high res experiments at ell<200

BICEP/Keck Analysis Technique:

Take all possible auto- and cross-spectra between BICEP/Keck, WMAP, and Planck bands (66 of them)

Not map based cleaning



BICEP/Keck Multicomponent likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the ΛCDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron

A_{dust} — amplitudes @ l=80

A_{synch} — amplitudes @ l=80

β_{dust} — frequency spectral indices

β_{synch} — frequency spectral indices

α_{dust} — spatial spectral indices

α_{synch} — spatial spectral indices

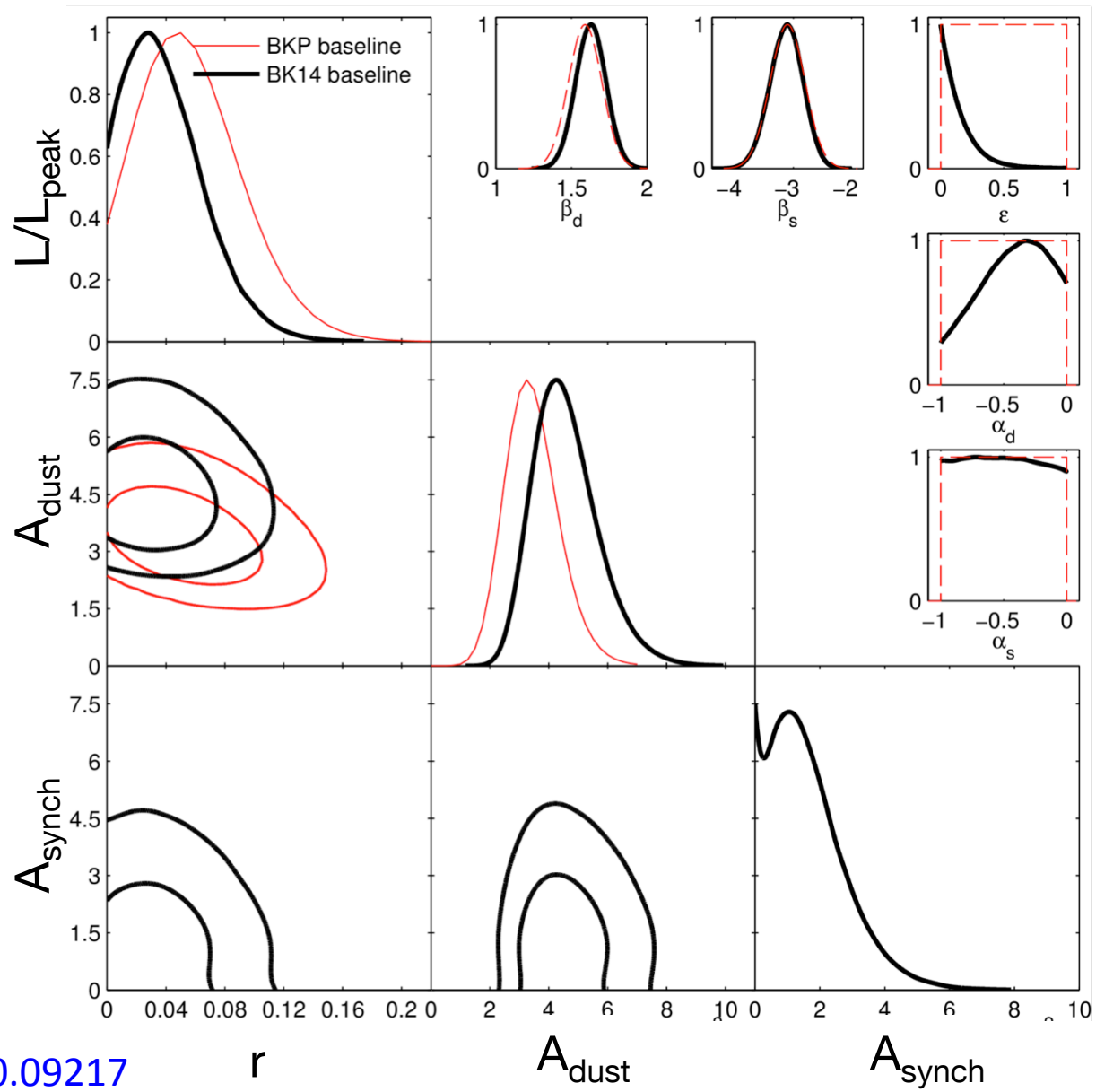
ε — dust/synch spatial correlation

BK14 Results:

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

dust vs. r degeneracy lifted



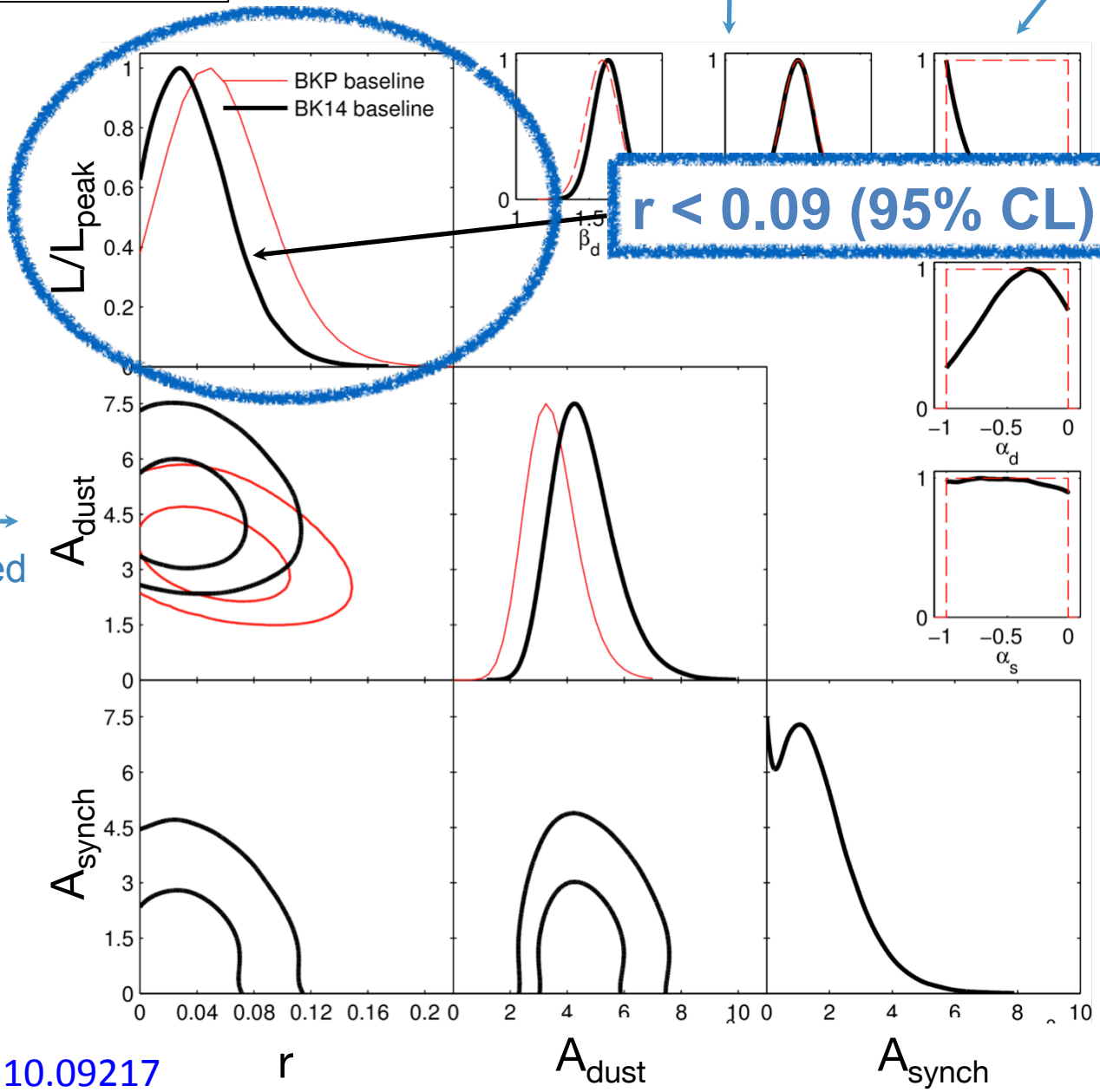
Marginalize over generous ranges in spatial spectral indices

Fig4 of arXiv:1510.09217

BK14 Results:

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation



r < 0.09 (95% CL)

dust vs. r degeneracy lifted

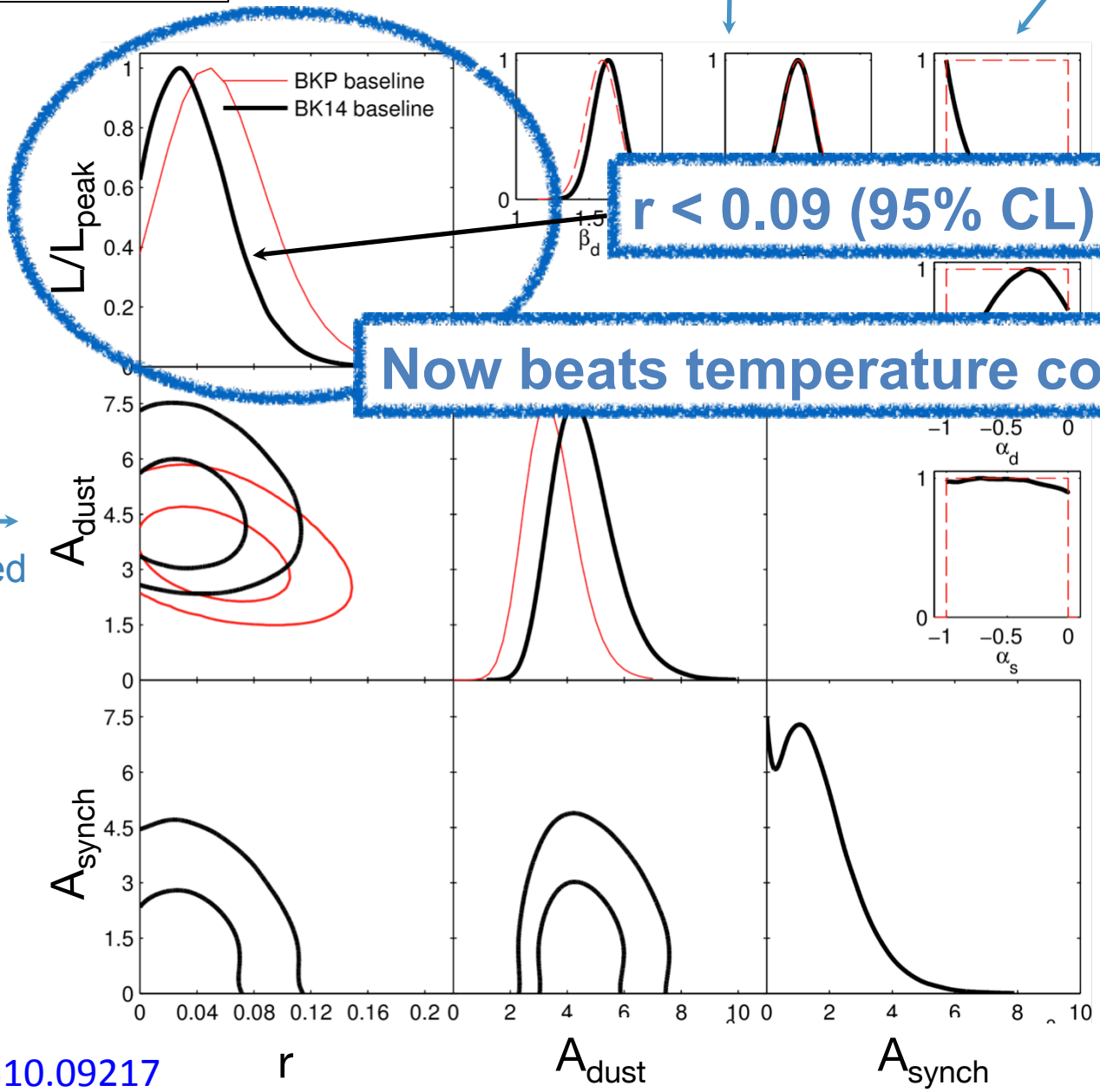
Marginalize over generous ranges in spatial spectral indices

Fig4 of arXiv:1510.09217

BK14 Results:

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation



r < 0.09 (95% CL)

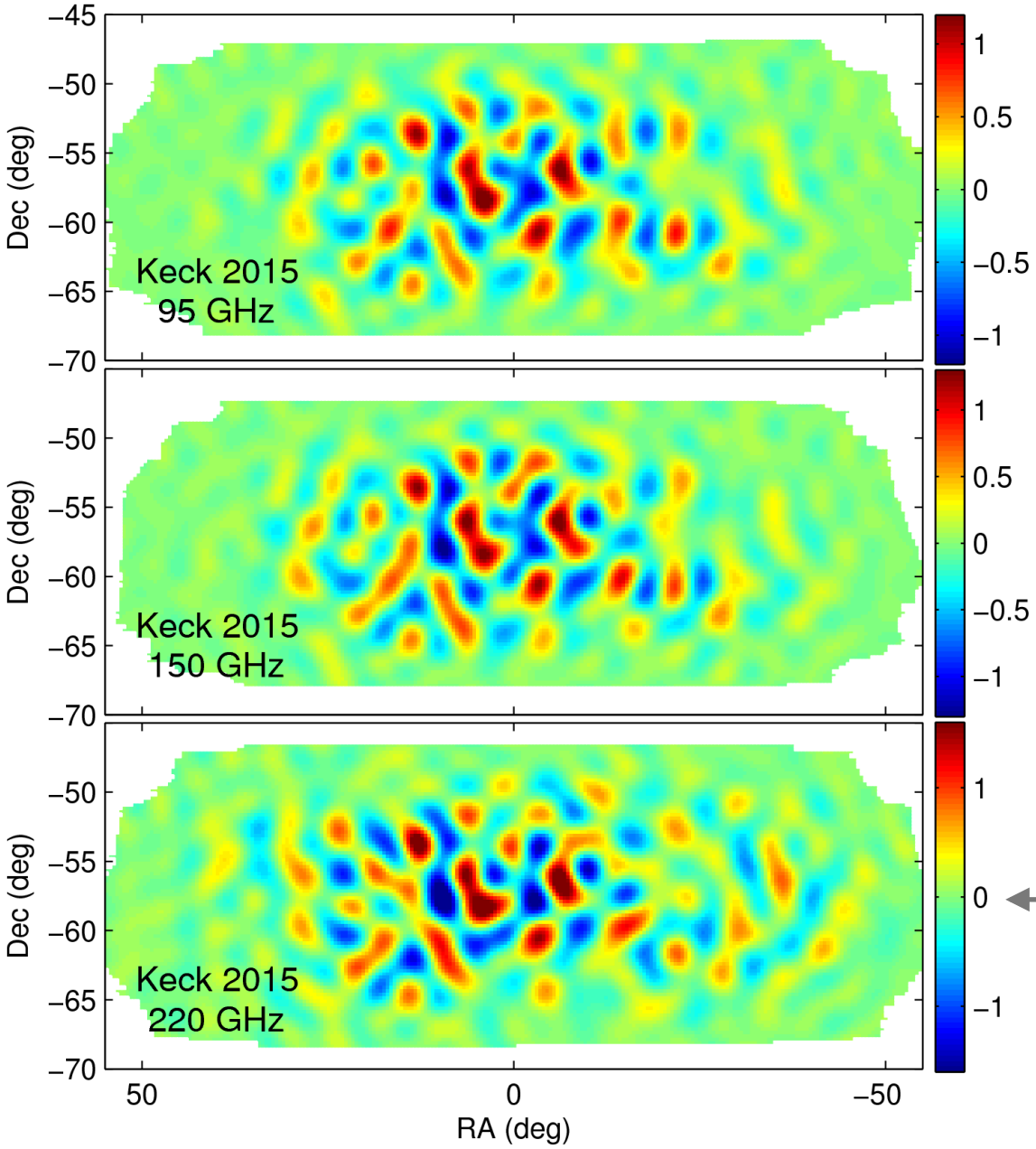
Now beats temperature constraints

dust vs. r degeneracy lifted

Marginalize over generous ranges in spatial spectral indices

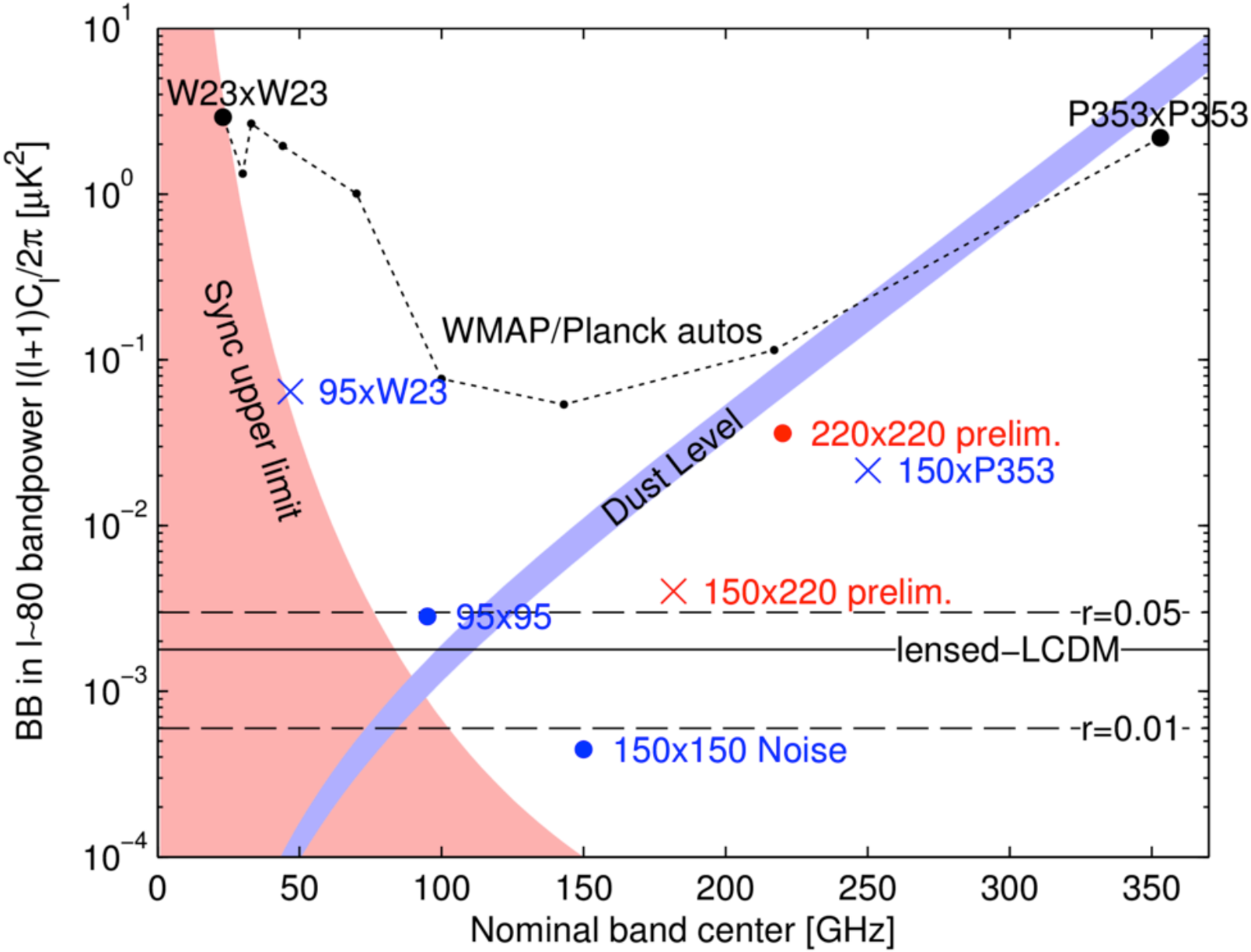
Fig4 of arXiv:1510.09217

Teaser for the future: Keck 2015 E-mode maps



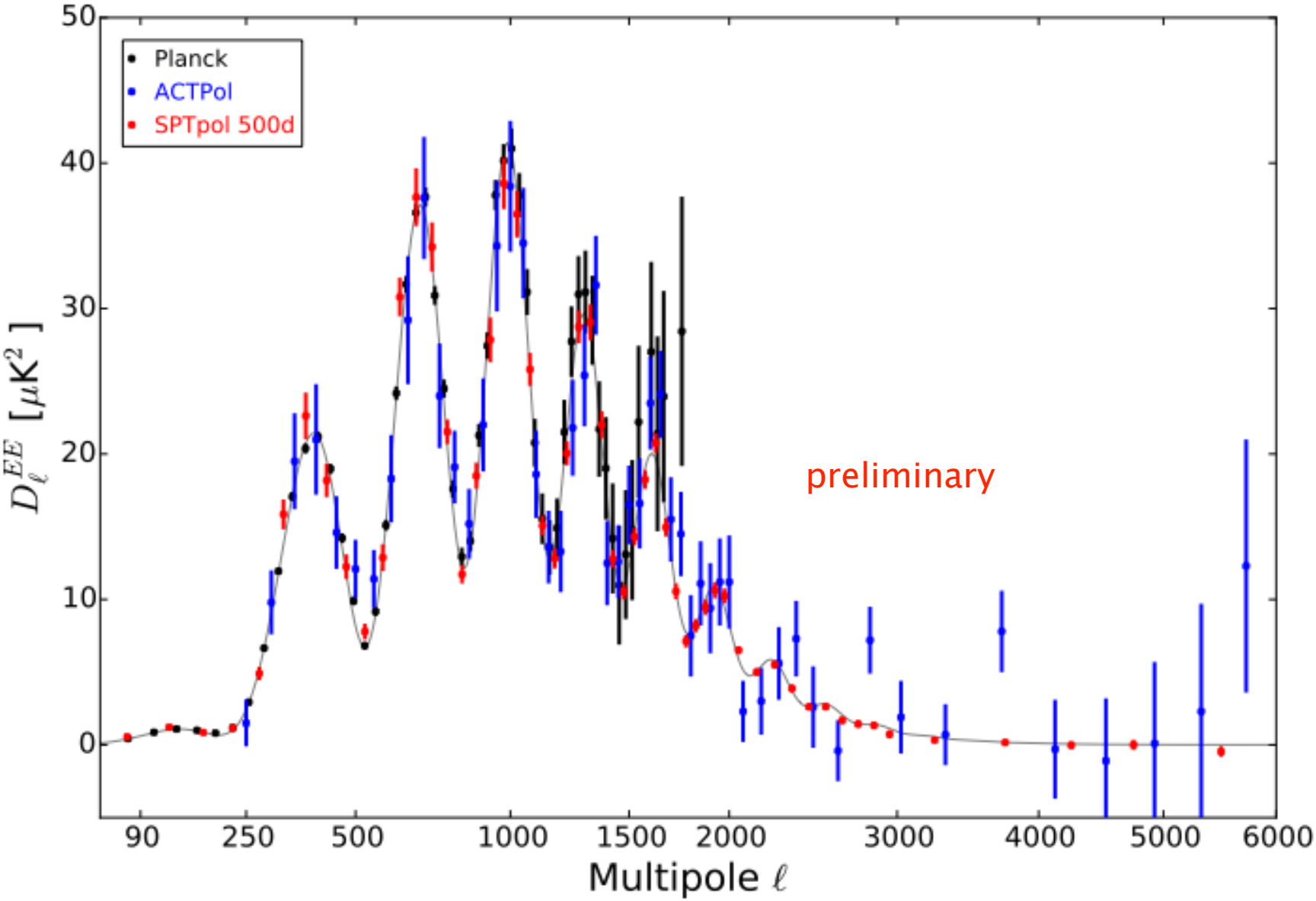
LCDM E-modes with high s/n at three frequencies in a single year!

Already deeper than Planck 217 GHz



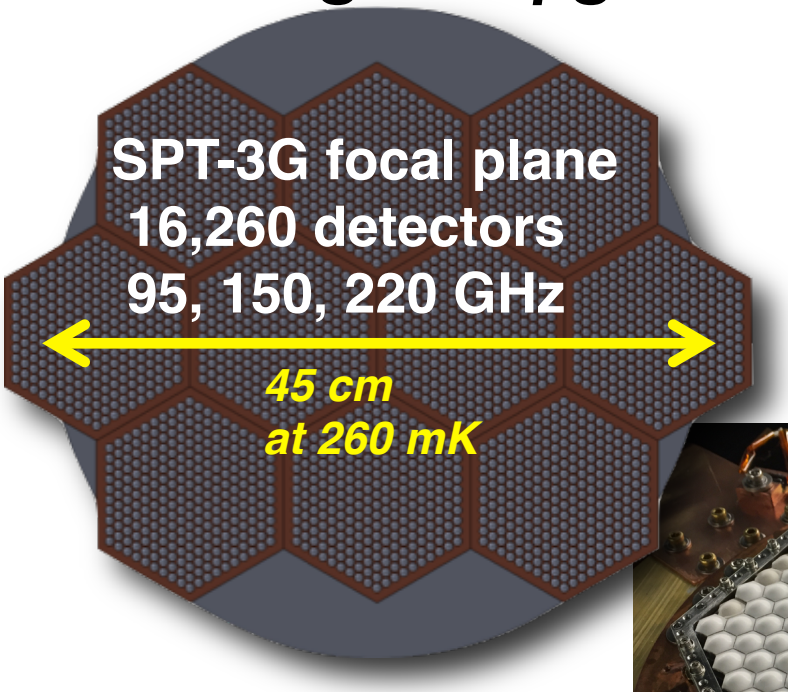
The current strength of the r-constraint is mostly dictated by the noise in the Planck 353GHz map – the result can get better quickly as the 220GHz measurements are brought to bear

Another teaser: SPTpol 500 deg^2 EE Spectrum

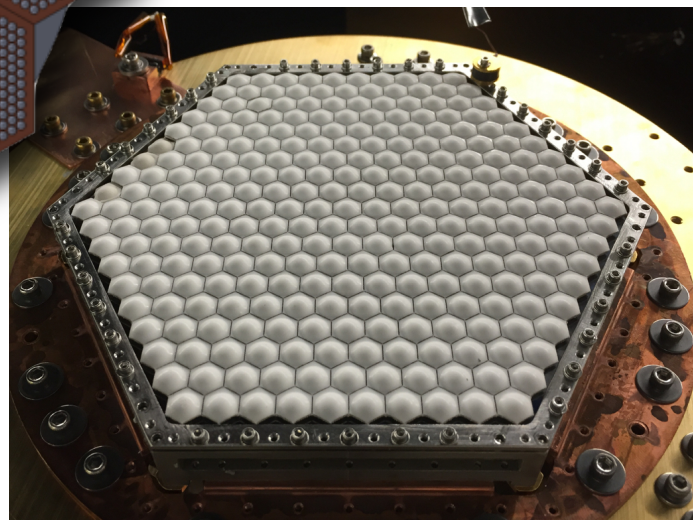


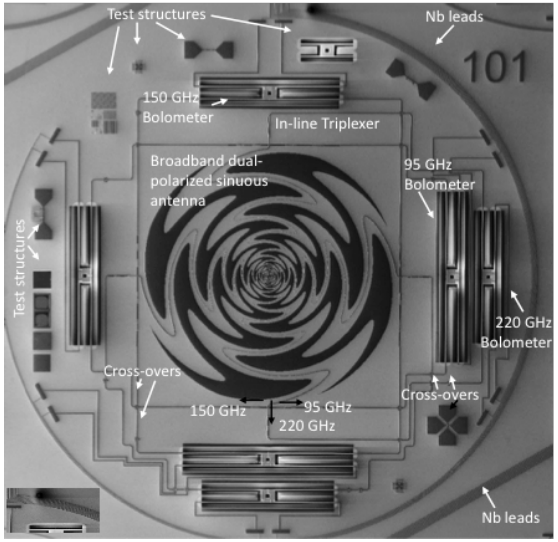
Stage 3 Instruments in Prep
(Deliberately with no projections)

SPT Stage 3 upgrade: SPT-3G to deploy Dec 2016



SPT-3G 2500 deg^2 survey
Overlap with BICEP/KECK
to provide de-lensing





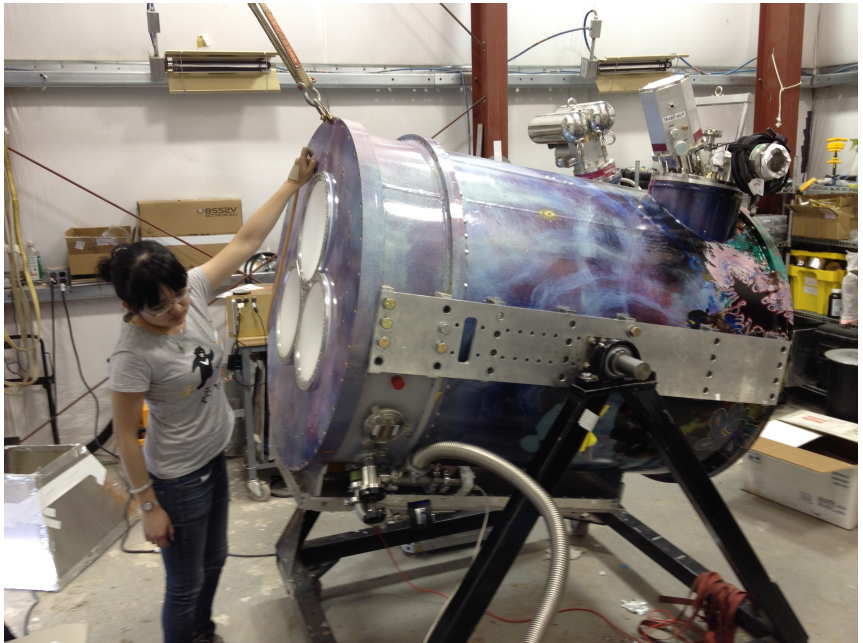
- *16,400 detectors*
- Detector fabrication at Argonne National Labs on 150mm silicon wafers
- Using lenslet coupled, 3-band sinuous antenna coupled TES detector design from UCB

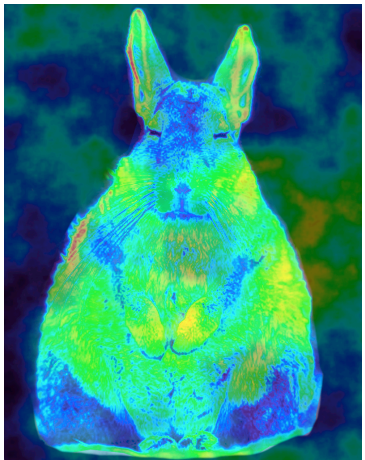
Advanced ACTPol

CMB Capabilities:

- Arcmin resolution, ~ 1/2 sky
- Upgrade all optics tubes to multichroic: 28 – 230 GHz coverage
- Rapid Polarization Modulation – waveplates as tested on ABS

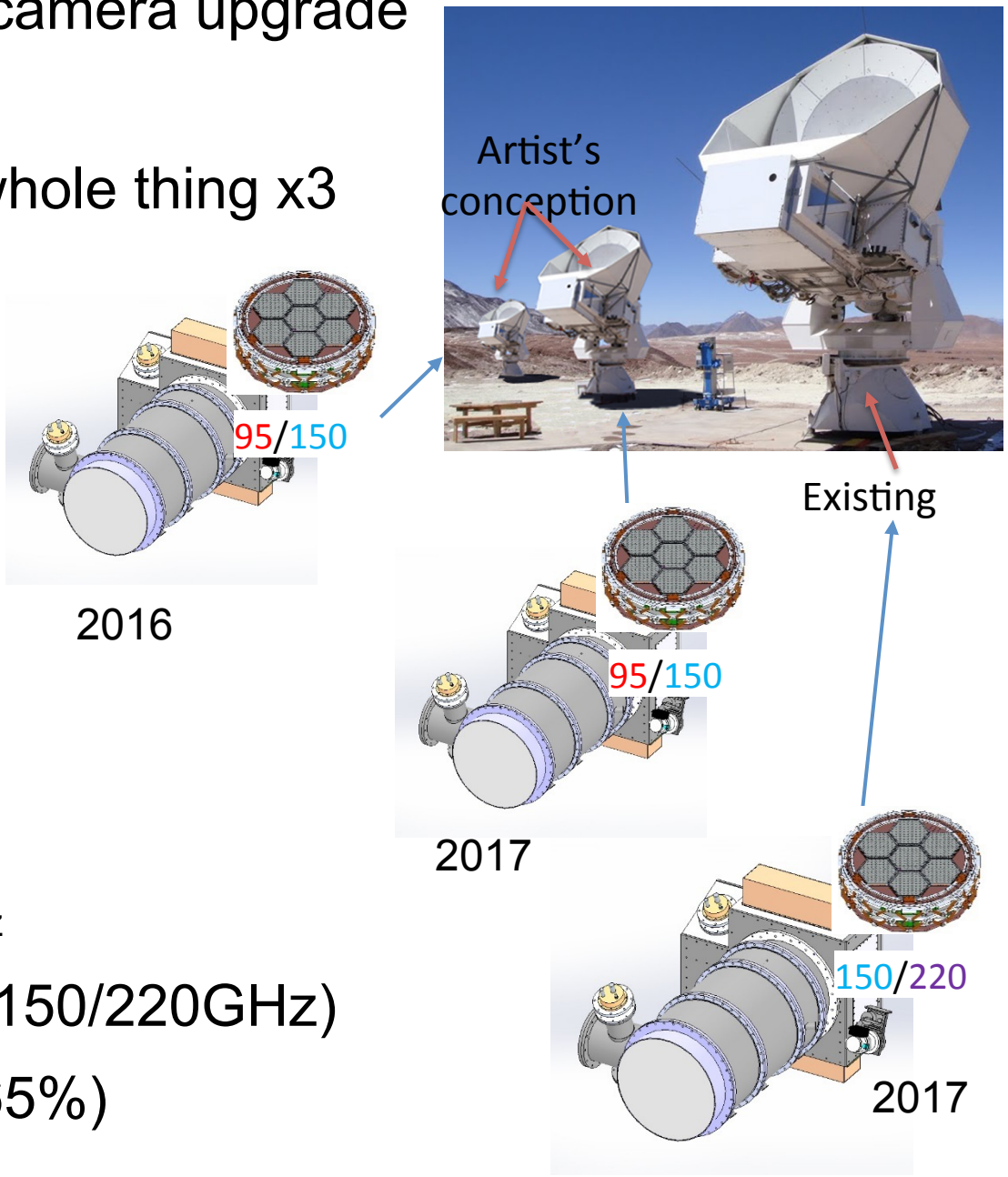
Staged Deployment starting 2016





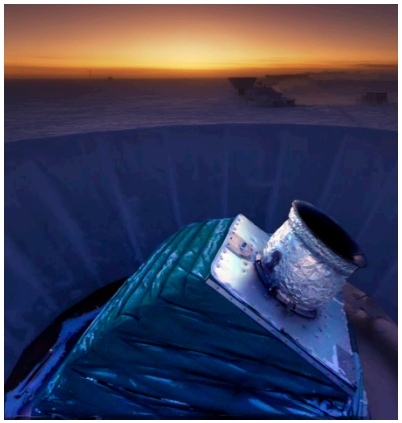
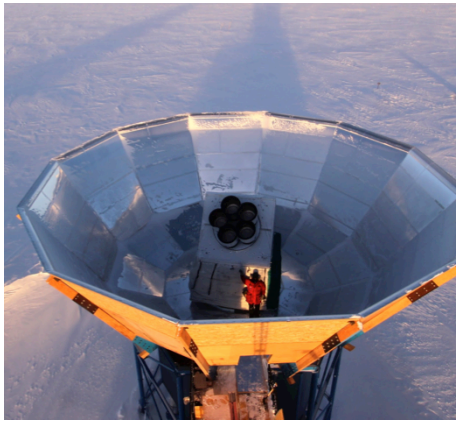
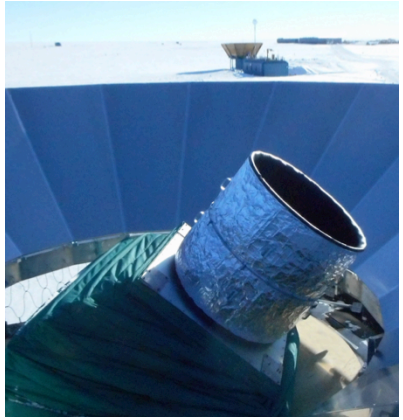
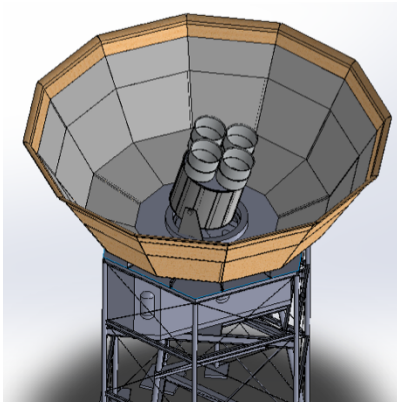
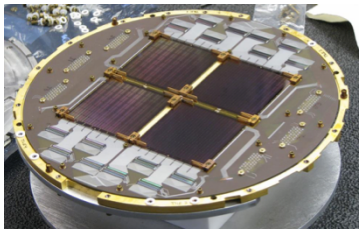
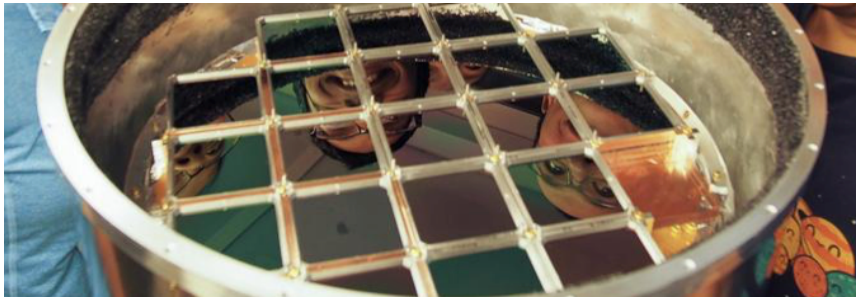
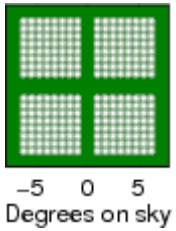
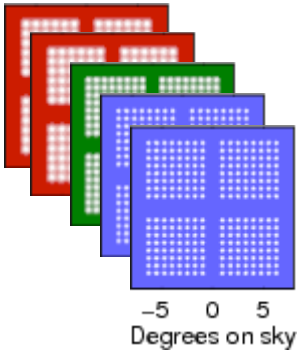
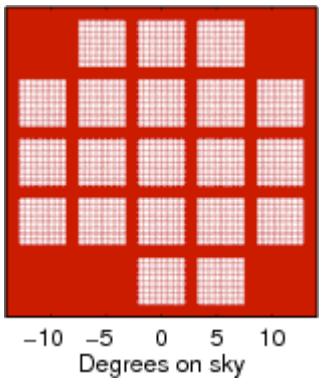
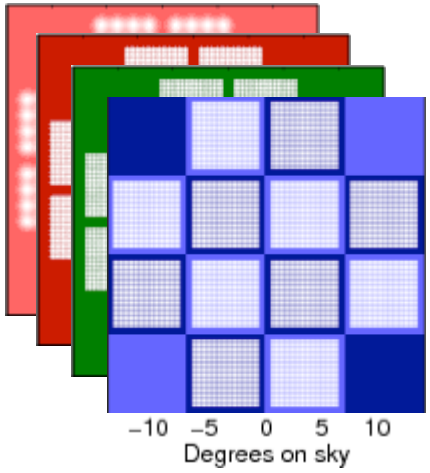
POLARBEAR2 = Massive camera upgrade

Simons Array = Copy the whole thing x3

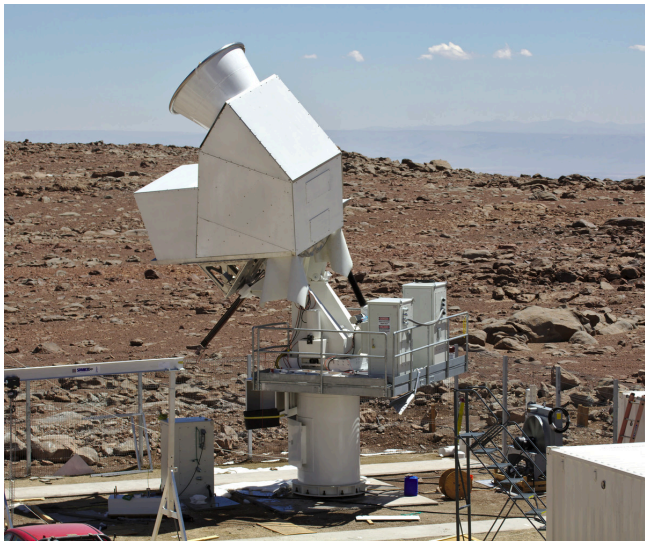


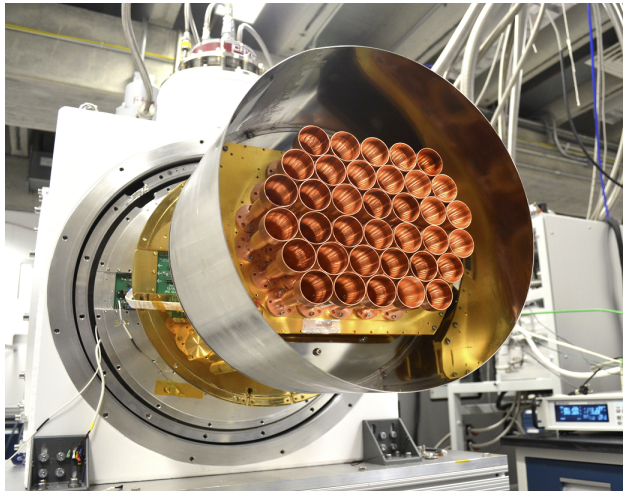
- 22,764 bolometers
- Resolution : 3.5' @150GHz
- 3 frequency bands (95/150/220GHz)
- Wide sky survey (f_{sky}=65%)

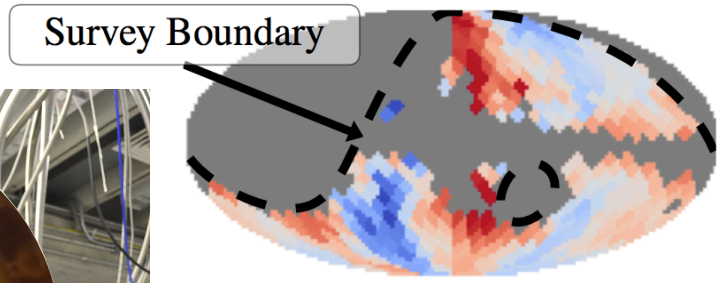
Stage 2 | **Stage 3**

	BICEP2 (2010-2012)	Keck Array (2012-2017)	BICEP3 (2015-)	BICEP Array (2018-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

Exciting Newcomer: CLASS







- Attempt to “do a space mission from the ground”
- Specifically optimized for large scales – mount spinning continuously in azimuth at 45 deg elevation, with front end pol. modulator (VPM), and boresight rotation
- Deploying now – initially 40GHz, later 90/150/220GHz
- Observing from Atacama cover 70% of the sky - claiming sensitivity to reionization bump at el<10

Breaking news: The Simons Observatory

- A five year $45M+ program to advance technology and infrastructure in preparation for CMB-S4.
- Merger of the ACT and POLARBEAR/Simons Array teams.
- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.

Ground based Stage 2➔3 Conclusions

- BICEP/Keck published limit is r<0.09 using B-mode polarization alone
  - currently limited by sensitivity of dust control channel (P353) but 220GHz data incoming
  - Systematics already controlled to r~0.01 level
- High-res experiments have some great results at higher ell
- All experiments pursuing aggressive upgrades and high-res projecting they will set limits on r soon also
- If r>0.01 then we should have evidence for it by the end of the decade. Biggest uncertainty is probably foreground complexity…

Backup Slides

Modulation is overrated – Pair differencing can work very well!

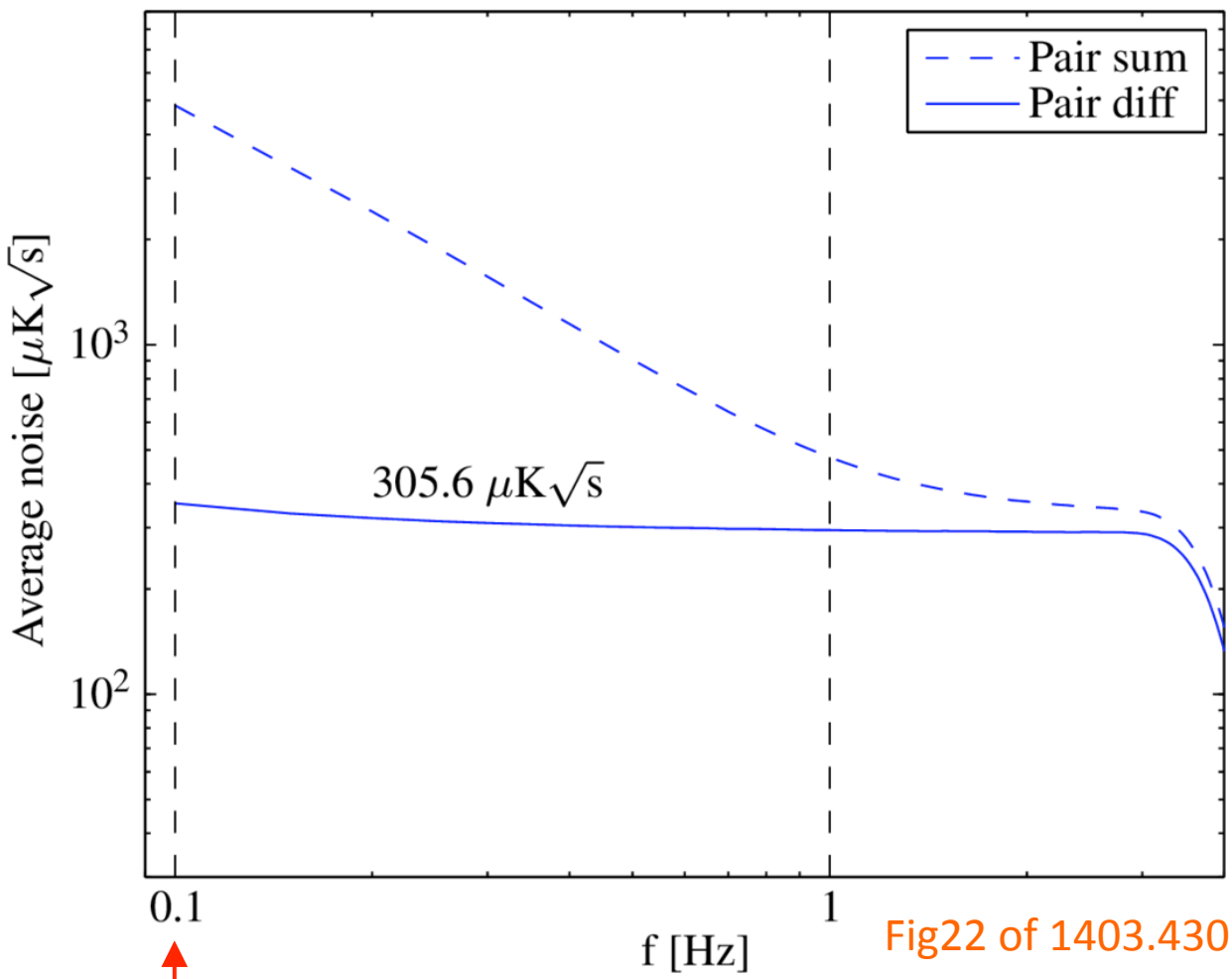


Fig22 of 1403.4302

This is PSD of BICEP2 timestream data with telescope scanning 30deg on the sky at 1.5deg/sec.

This plot shows that the combination of BICEP2 technology plus the South Pole atmosphere can do at least this well in terms of 1/f noise.

(A weighted average of the 2011+12 data as used in the final map)

0.1Hz = multipole 25