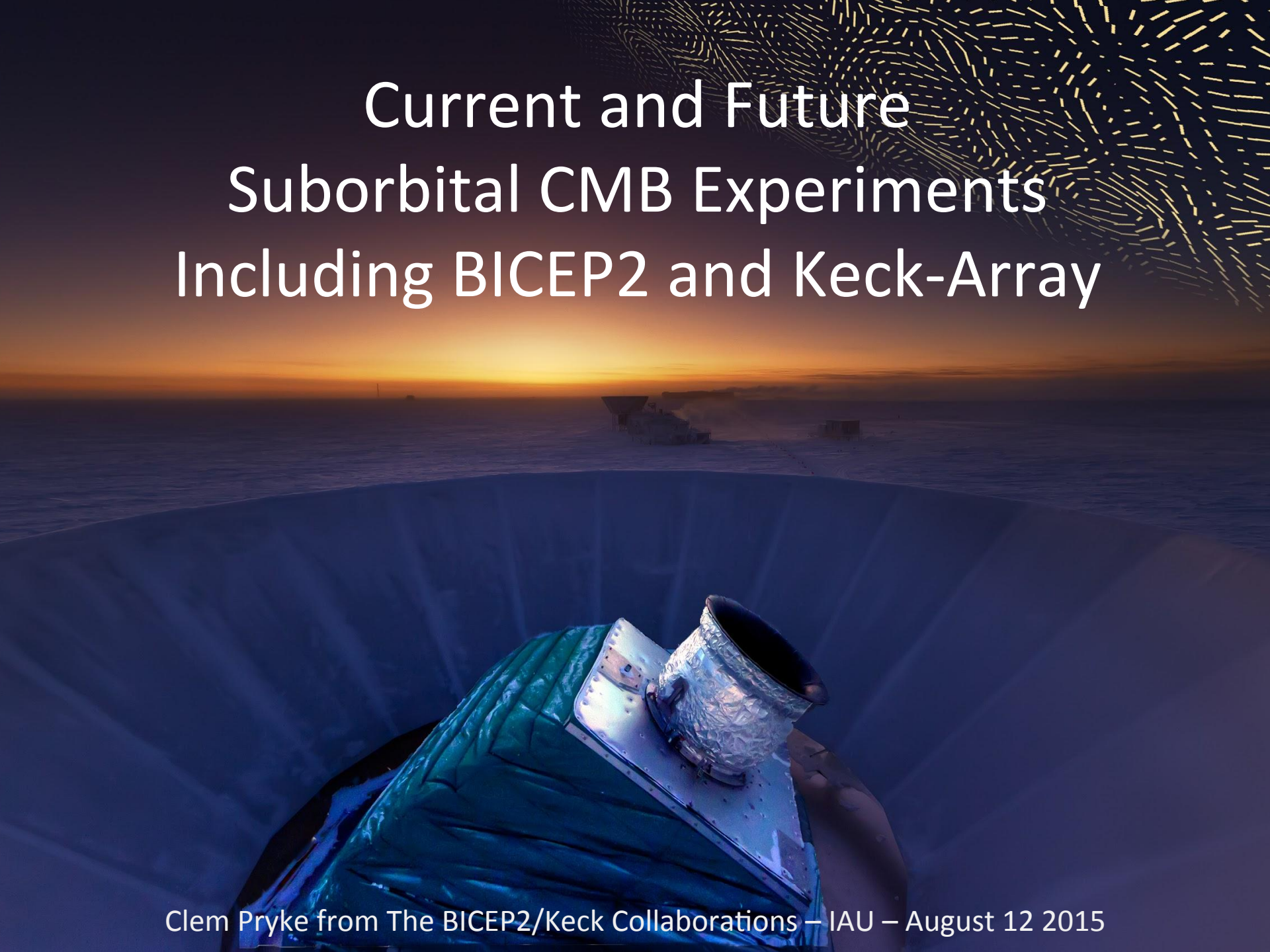
# Current and Future Suborbital CMB Experiments Including BICEP2 and Keck-Array

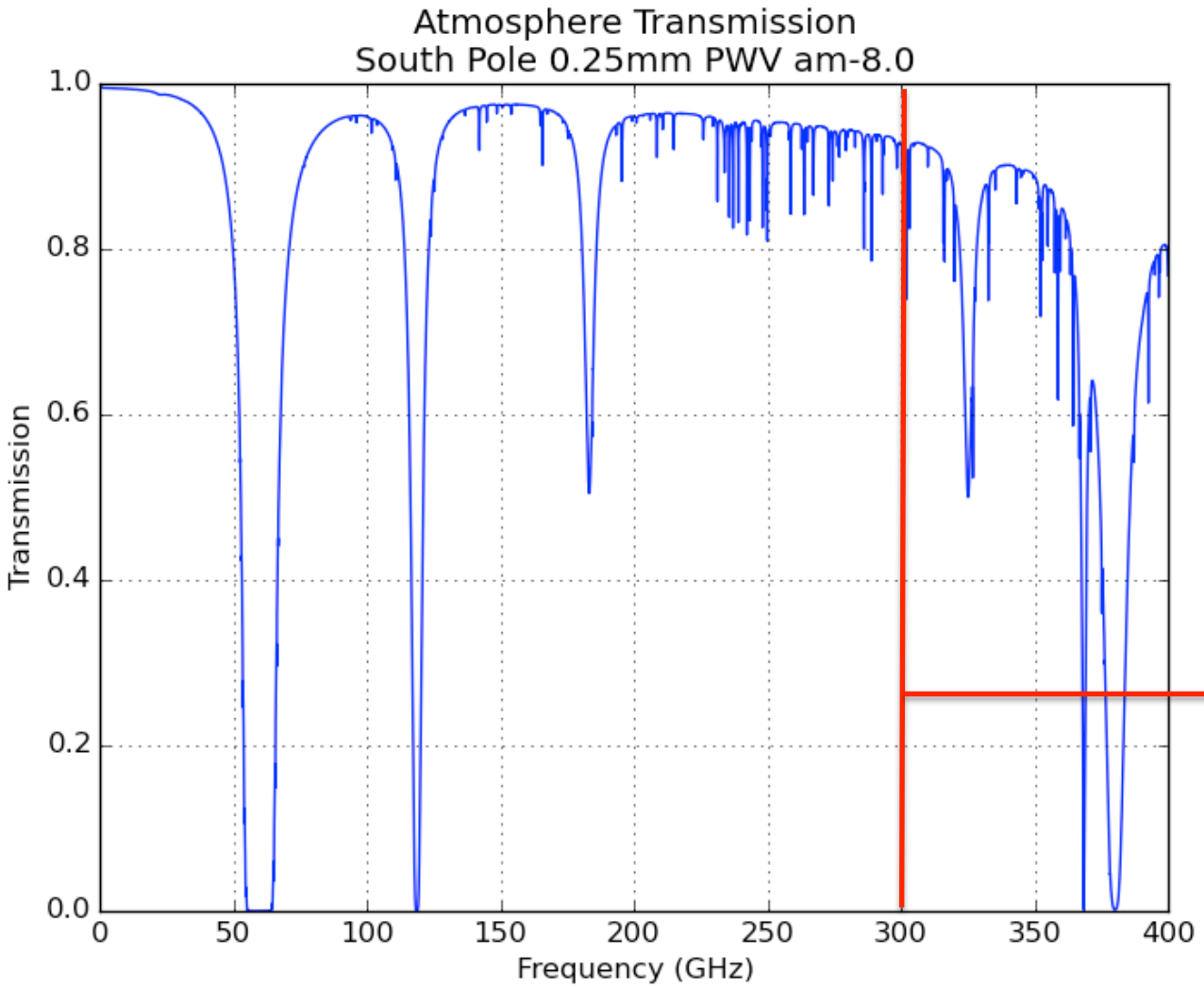


Clem Pryke from The BICEP2/Keck Collaborations – IAU – August 12 2015

# Given that Planck maps exist why make further suborbital measurements?

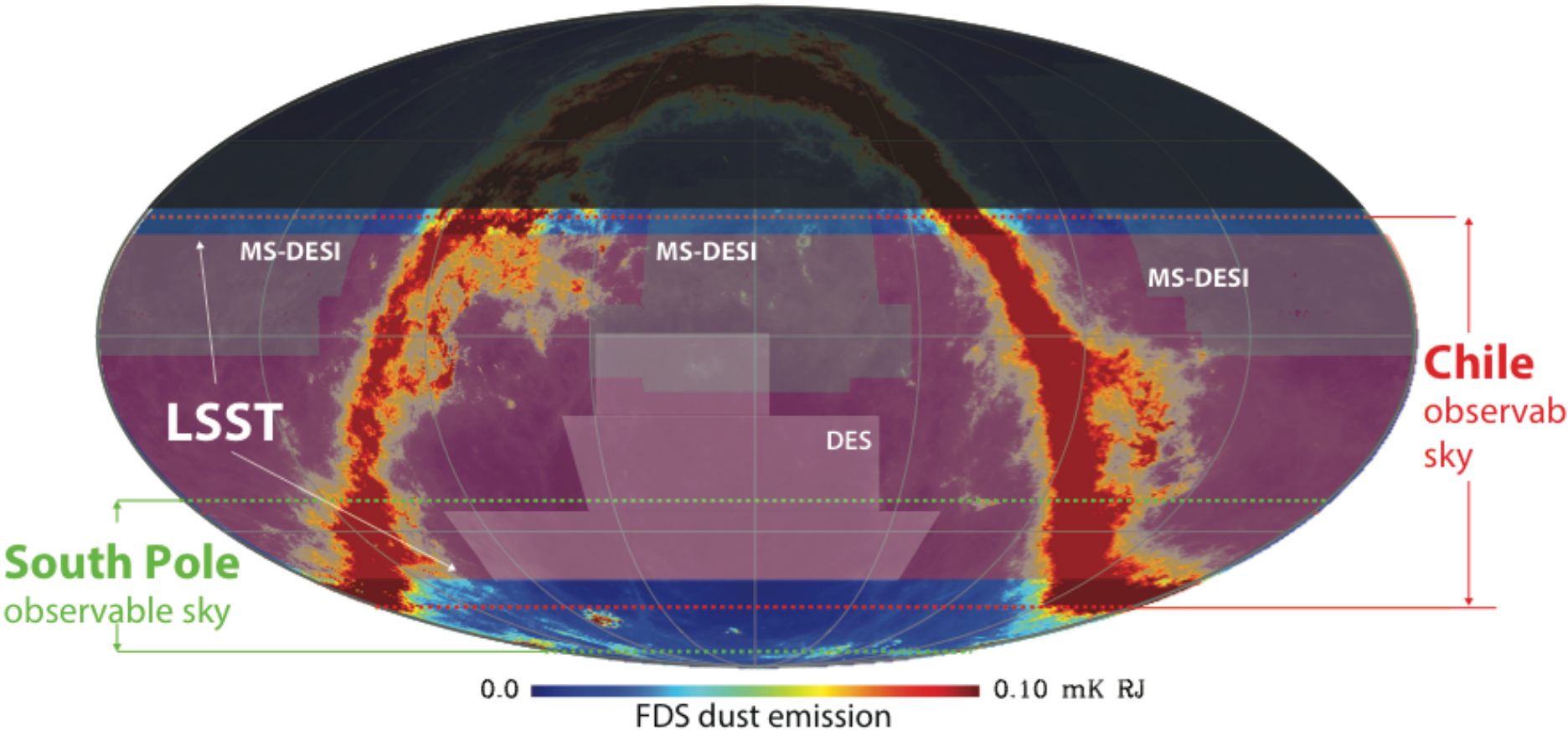
- Can achieve higher sensitivity – quite easily on small patches of the full sky
- Can have higher angular resolution – particularly with ground based experiments

# Ground based limitation: Can't do high frequencies




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

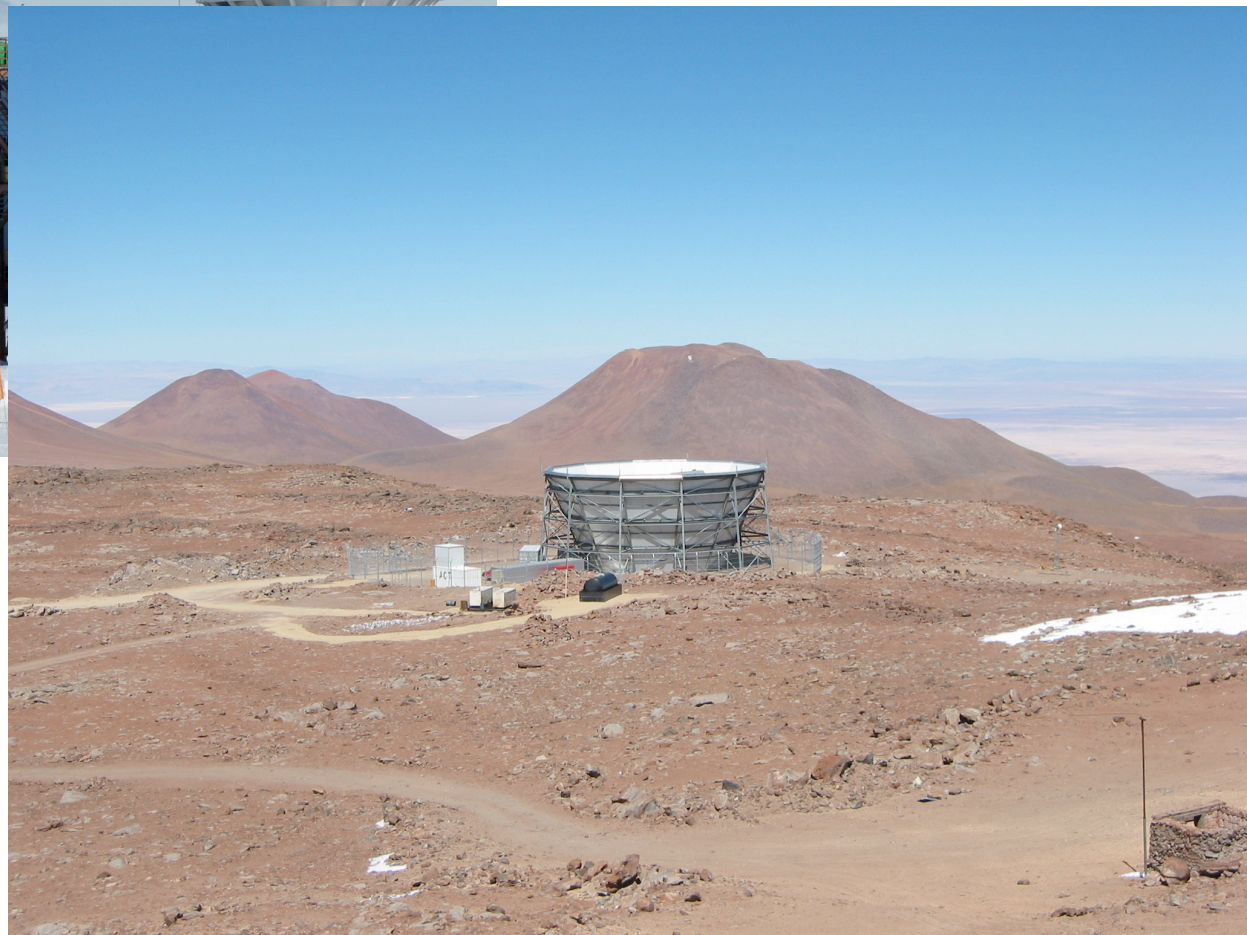
# Suborbital Limitation: Can't do full sky from a single site (or flight)




But full sky maps have been made from the ground
(e.g. Haslam 408MHz using 2 sites)

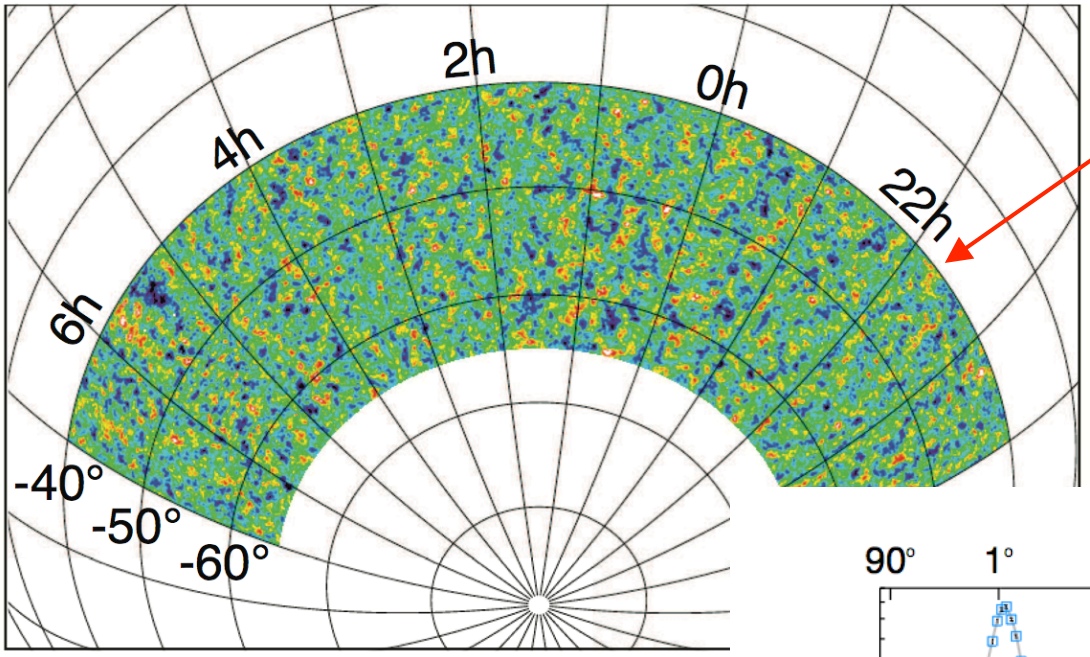
# High Angular Resolution Experiments

South Pole
Telescope (SPT)
10 meter diameter



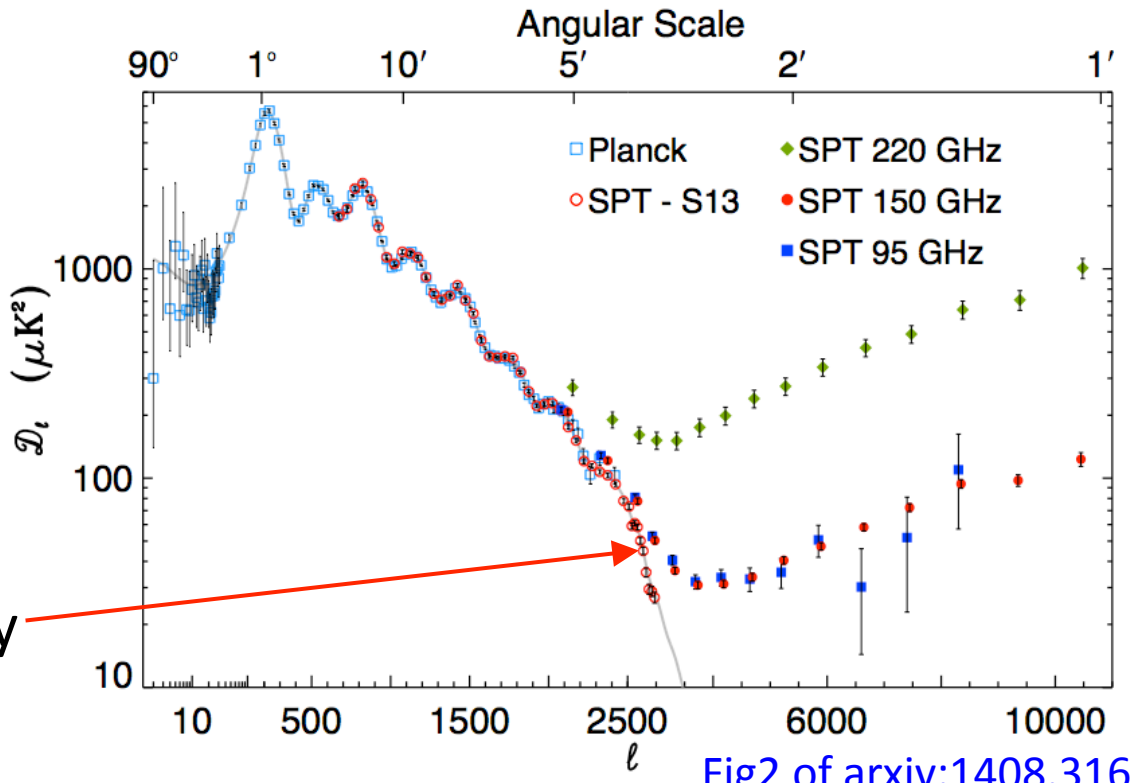
Atacama Cosmology
Telescope (ACT)
6 meter diameter

# SPT Temperature Results




Beautiful contiguous 2500 sq deg high resolution survey

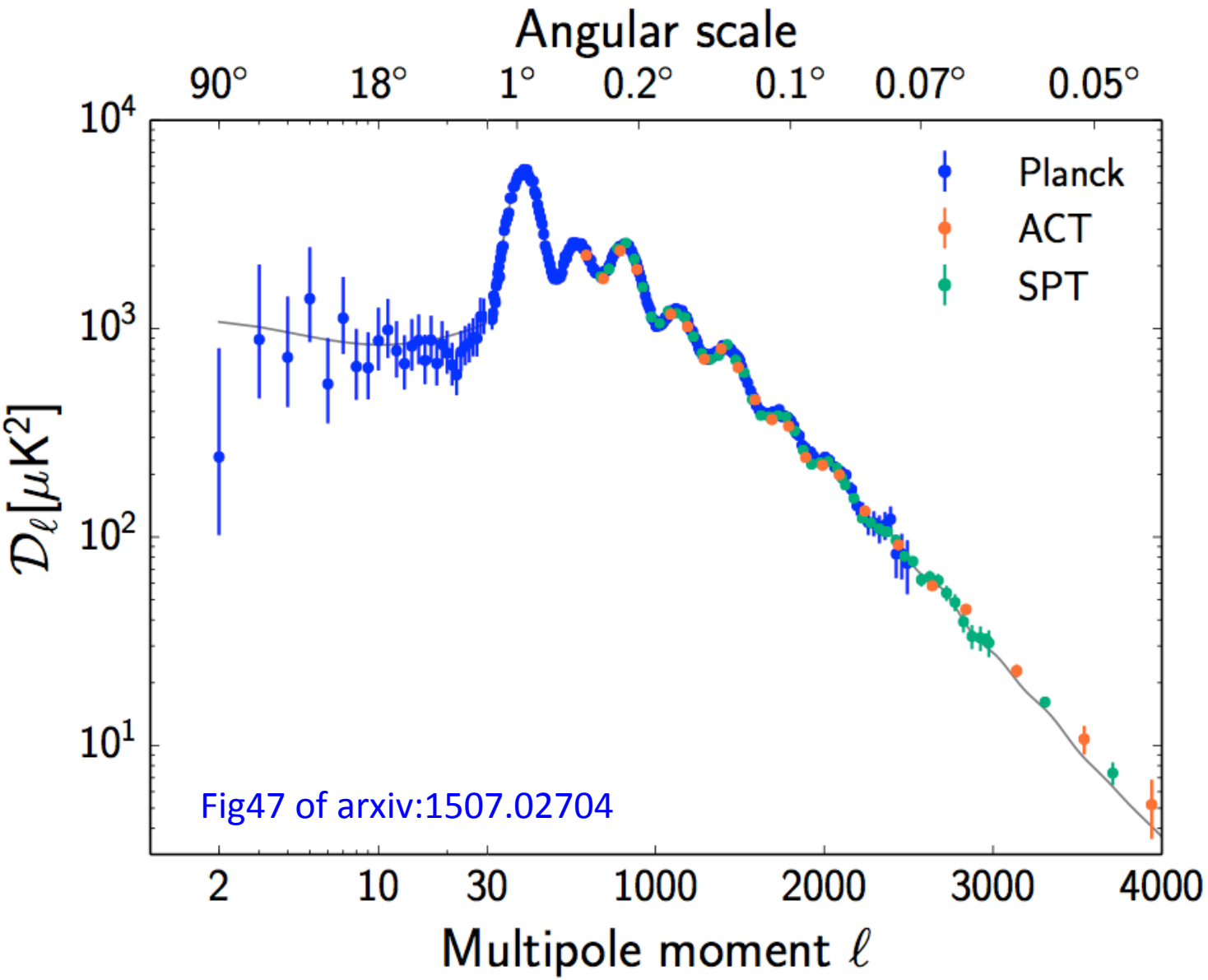
Fig1 of arxiv:1210.7231




Measurements of TT damping tail hampered by foregrounds

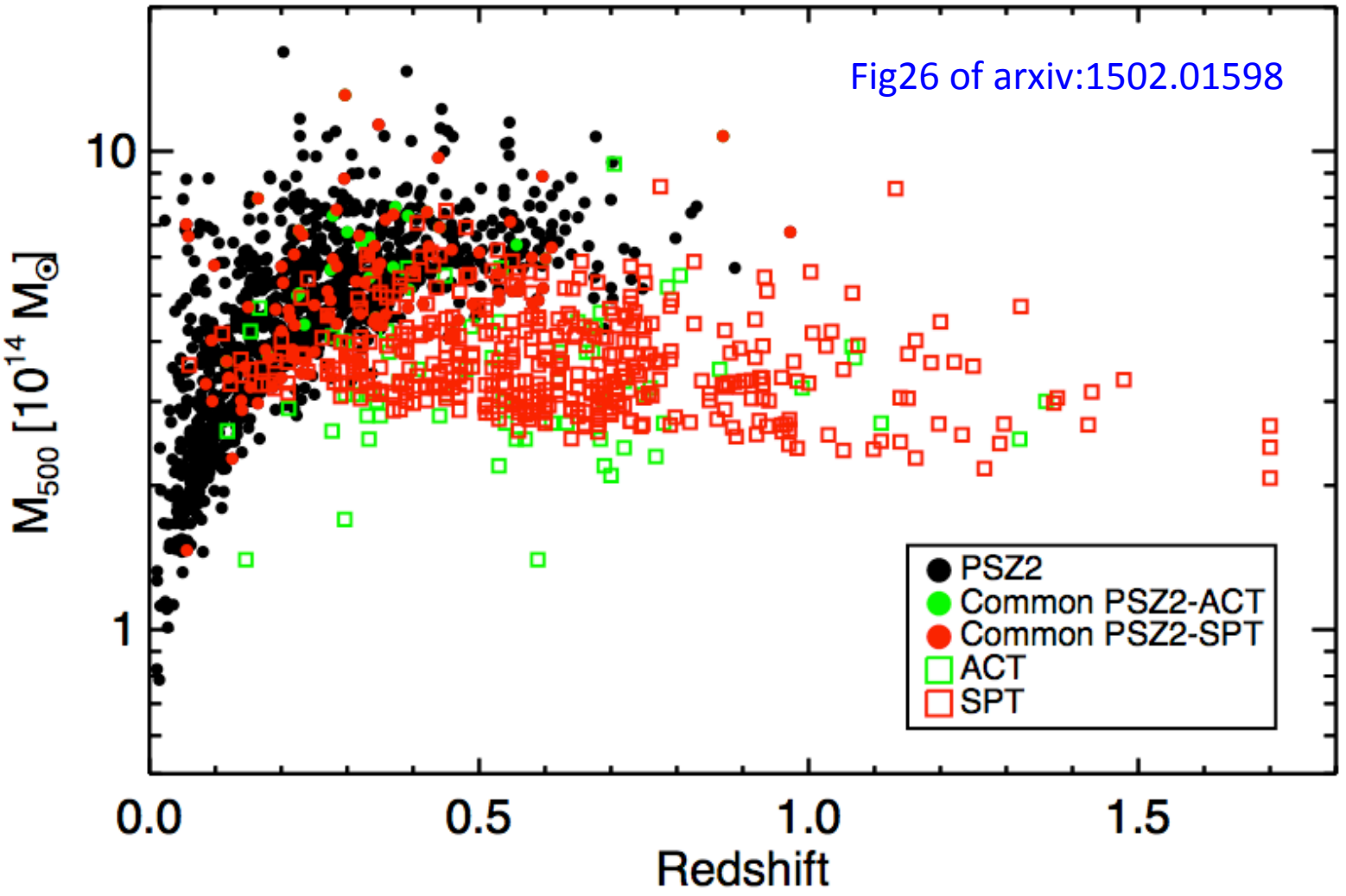
Fig2 of arxiv:1408.3161

# High ell TT in conjunction with Planck



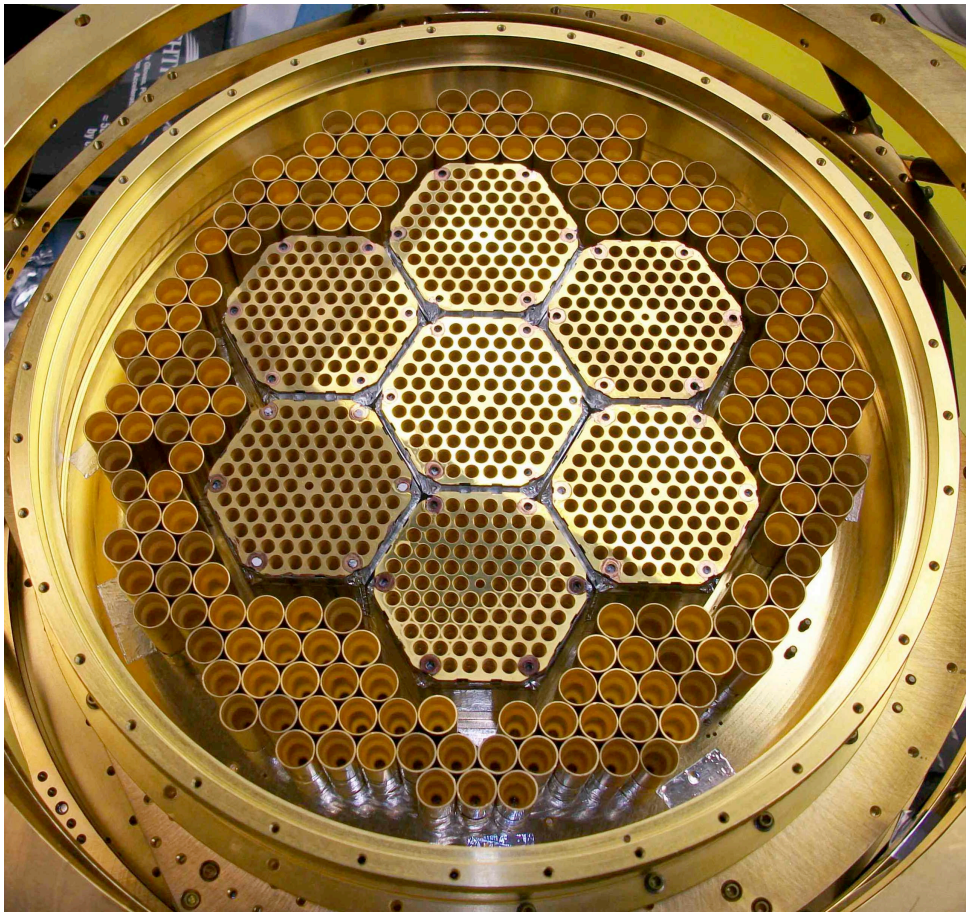

At the moment doesn't add much in basic LCDM fits

# SPT/ACT SZ Clusters in conjunction with Planck



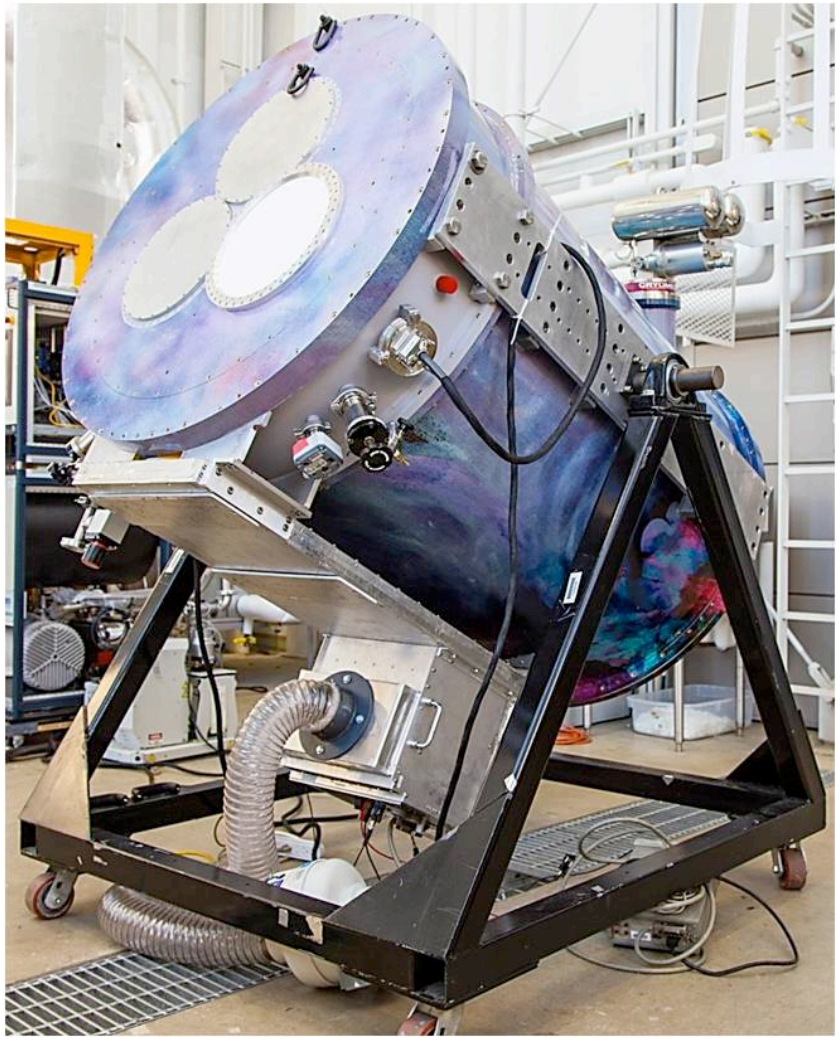

Planck provides lower redshift cluster sample – will be a major legacy going forward

# High Angular Res Pol Experiments (2G)

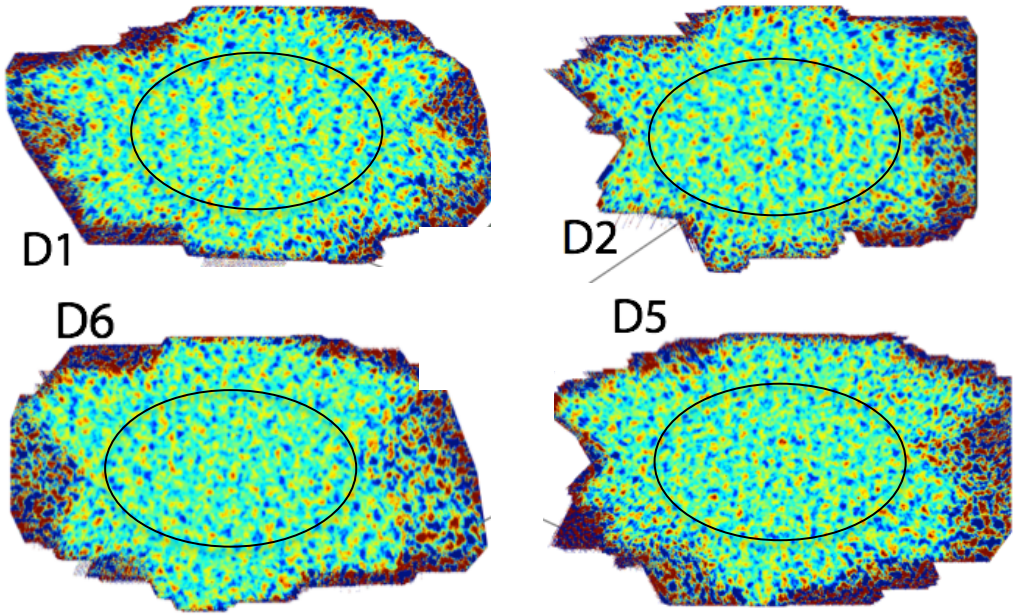


The SPTpol camera

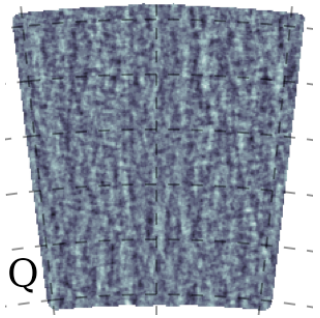
The ACTpol receiver



# *Published* Deep Suborbital Polarization Maps To Date

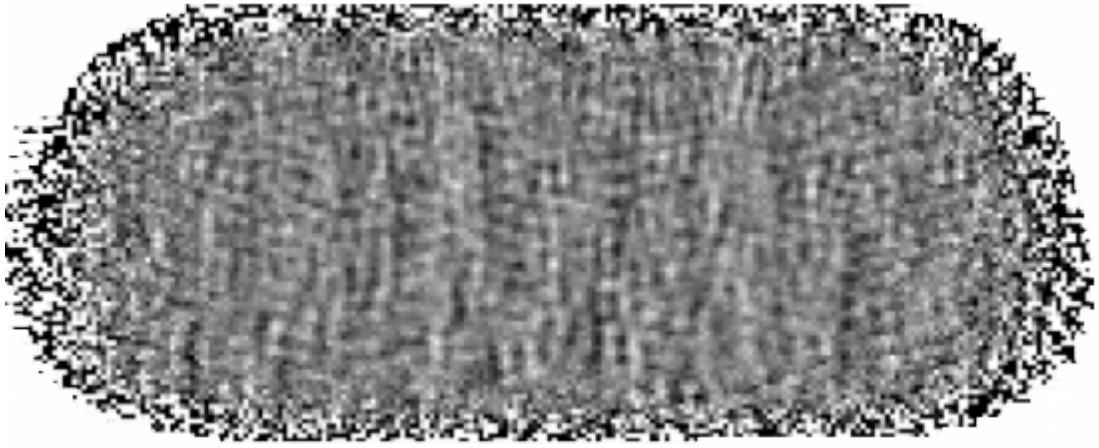



ACTpol 275 sq deg arxiv:1405.5524

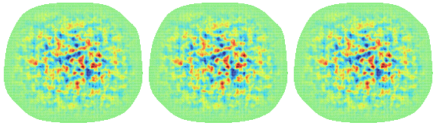



SPTpol 100 sq deg arxiv:
1411.1042 and 1503.02315

Roughly scaled to indicate relative map sky coverage



BICEP2/Keck 400 sq deg arxiv:1403.3985 and 1502.00643



POLARBEAR 25 sq deg
arxiv:1403.2369

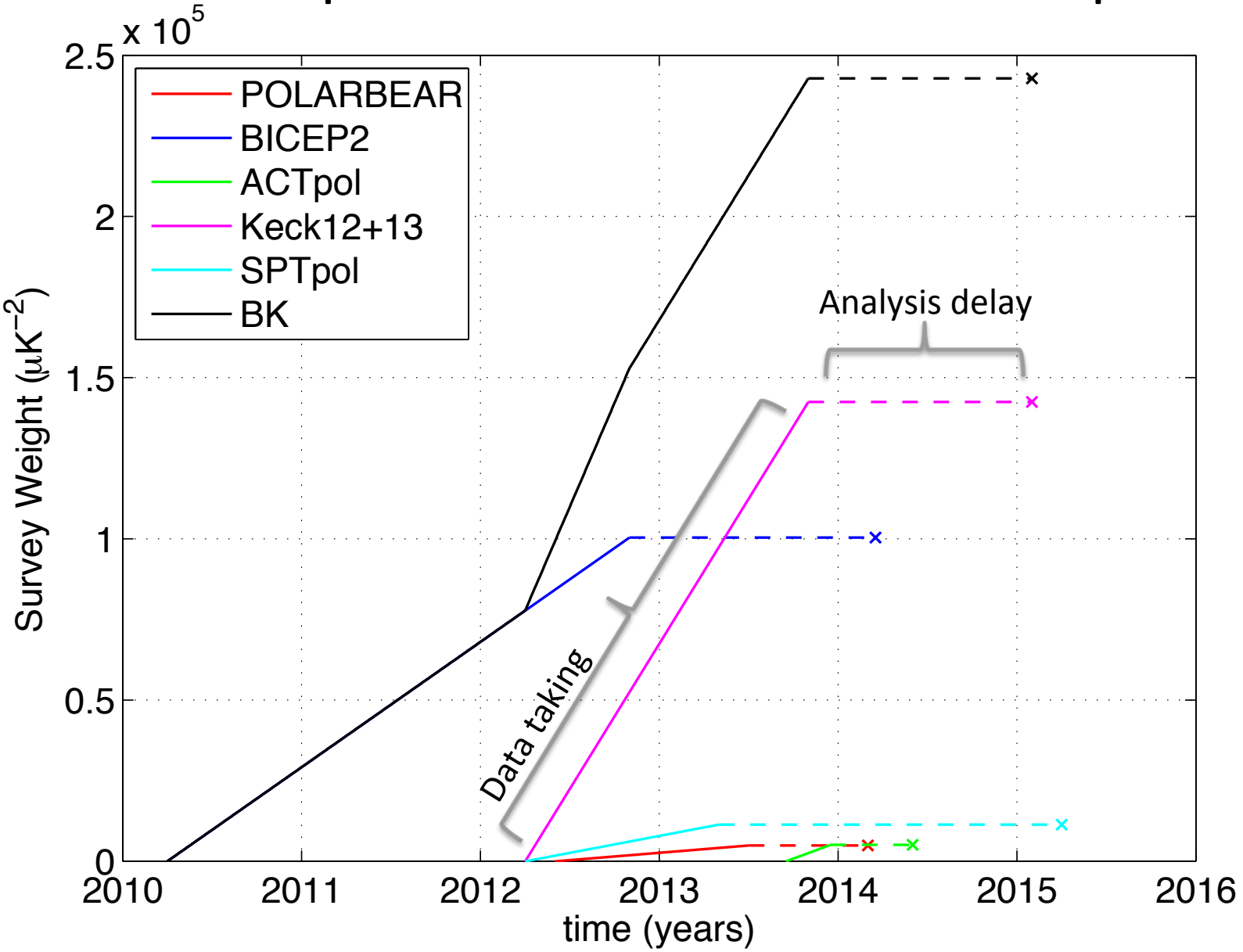
# *Published* Deep Suborbital Polarization Maps To Date

| | 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!

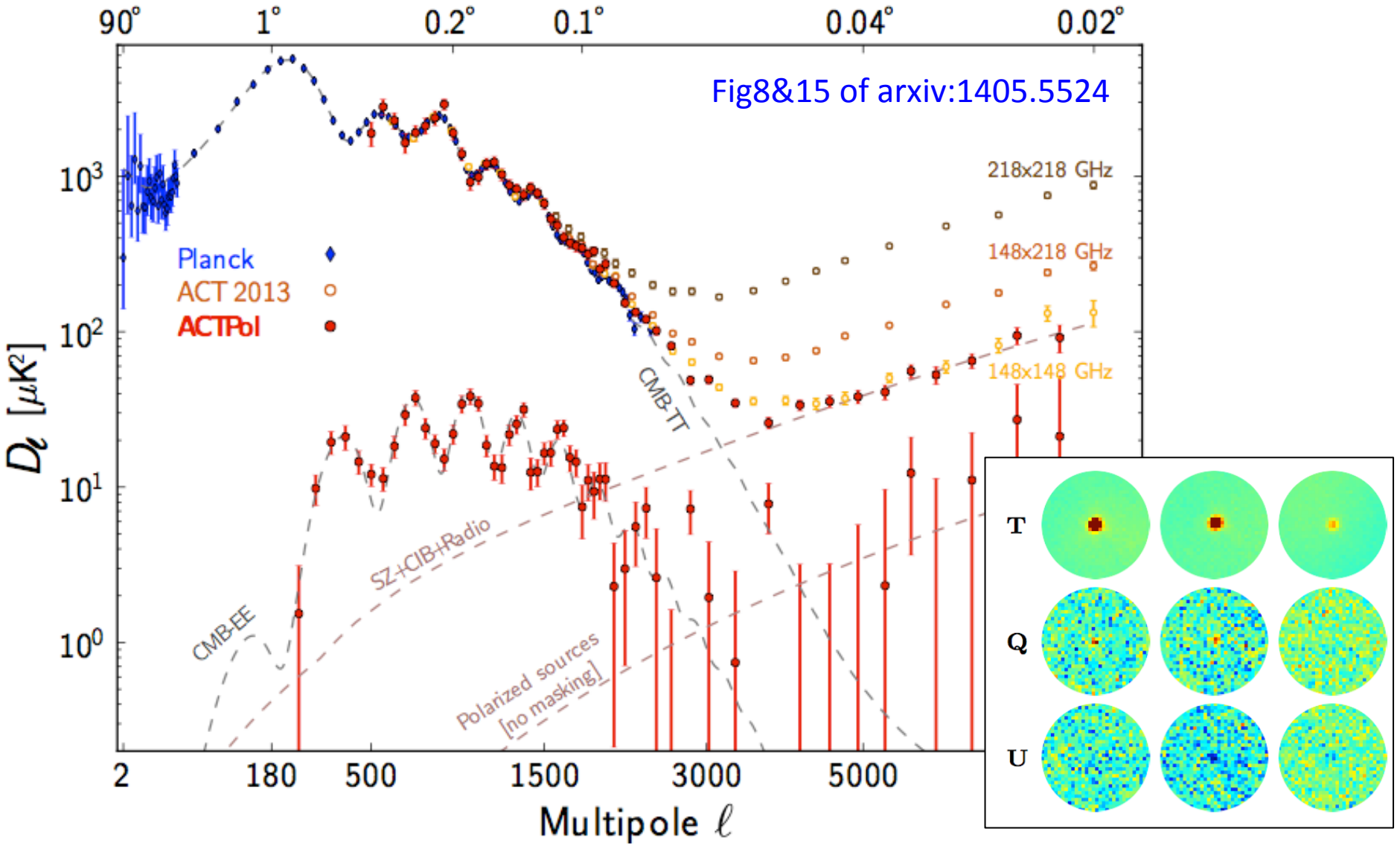
Survey weight: A quantity which is linear in number of detectors and integration time – i.e. difficulty of achieving
Also linear in power spectrum noise error bar size

# *Published* Deep Suborbital Polarization Maps To Date



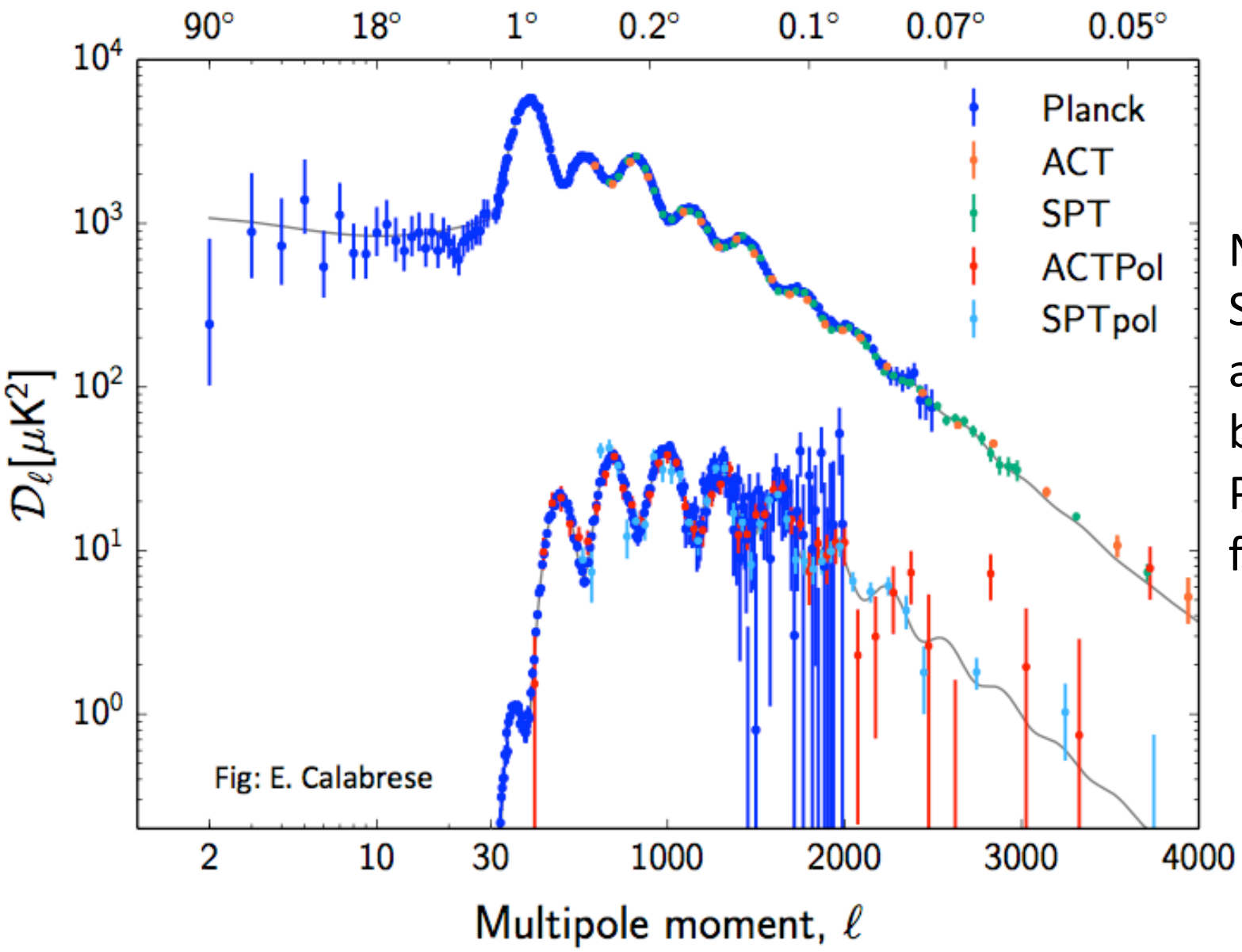

NB: Published results only – no projections!

# High Res Experiments can measure EE damping tail



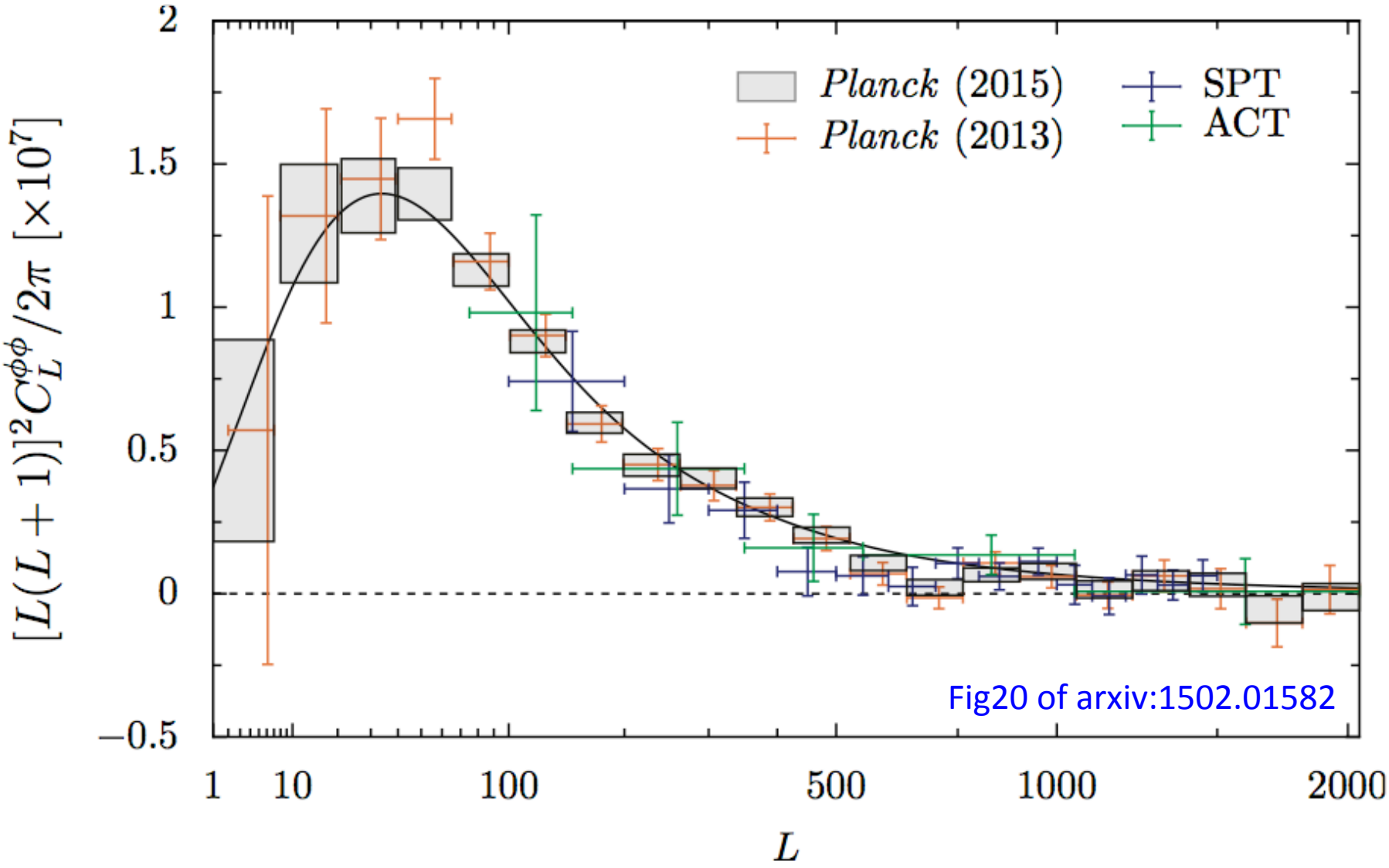

CMB has higher fractional polarization than point source foregrounds – can push further down the damping tail in EE

# High Res Experiments can measure EE damping tail



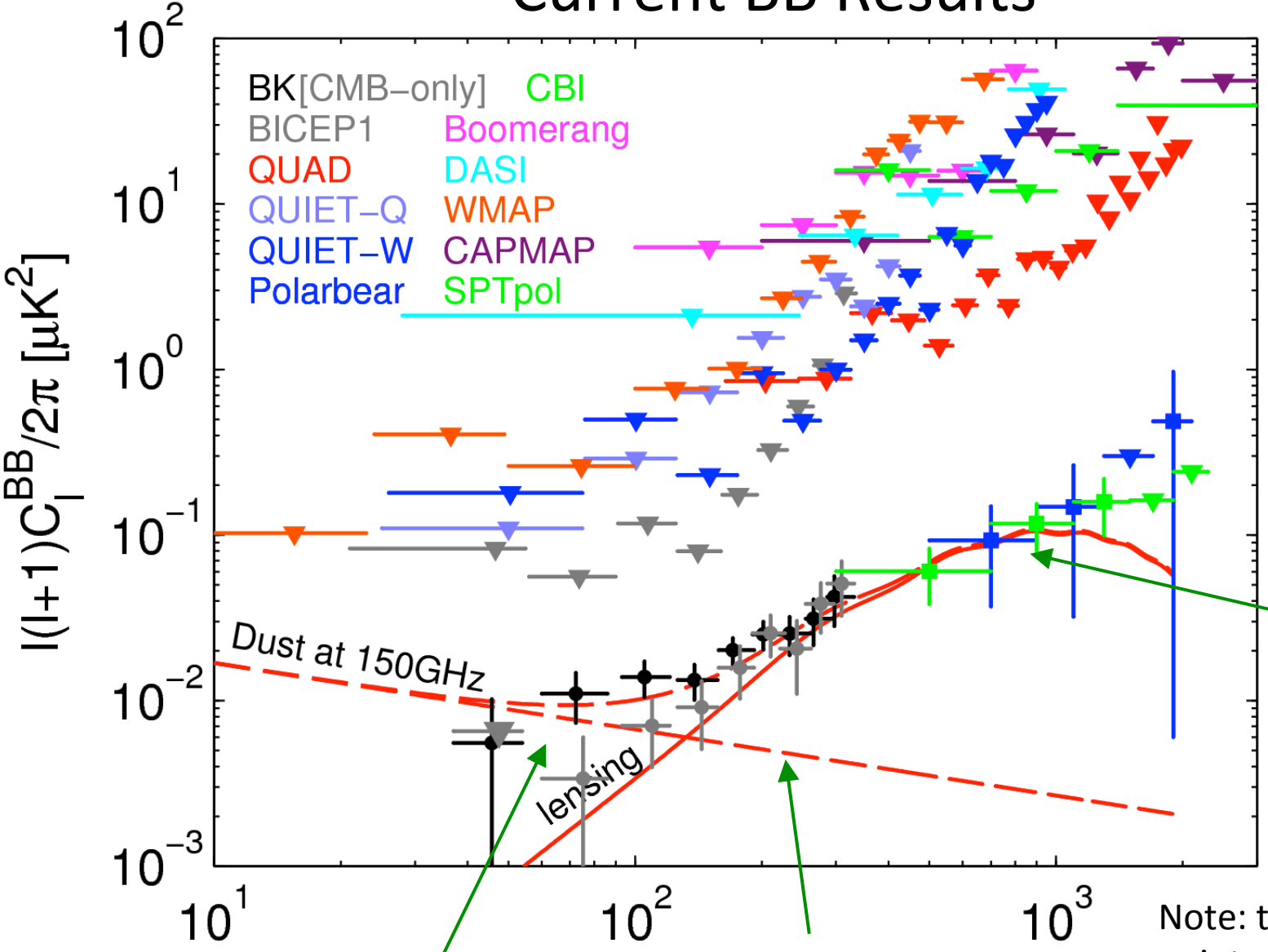

Note that SPT/ACTpol already better than Planck EE for ell>1500

# 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

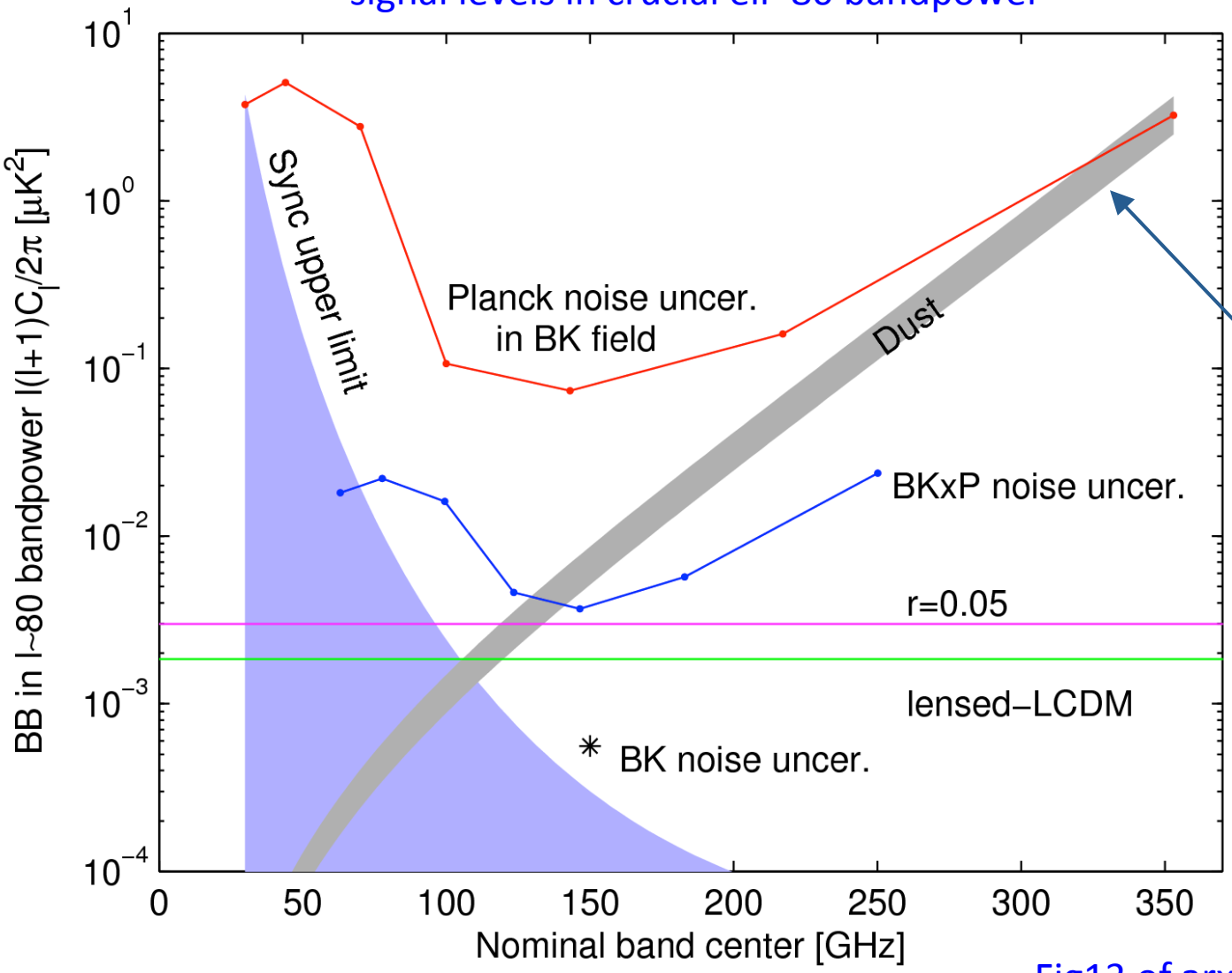
At mid ell a signal is detected – but at least half is dust!

Planck 353 GHz data constrains dust contribution

Note: there are no points at lower ell on this plot from high res experiments

# BKP Result: Dust is at least 50% of observed excess

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

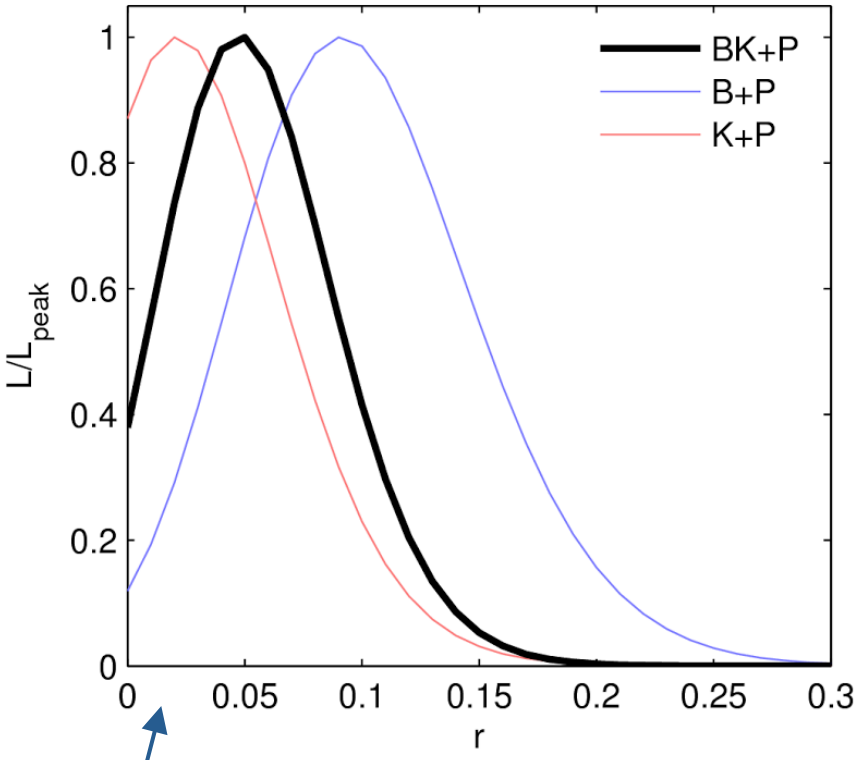



Dust is detected with 5 sigma significance – amplitude quite well constrained

See Brendan Crill talk for more

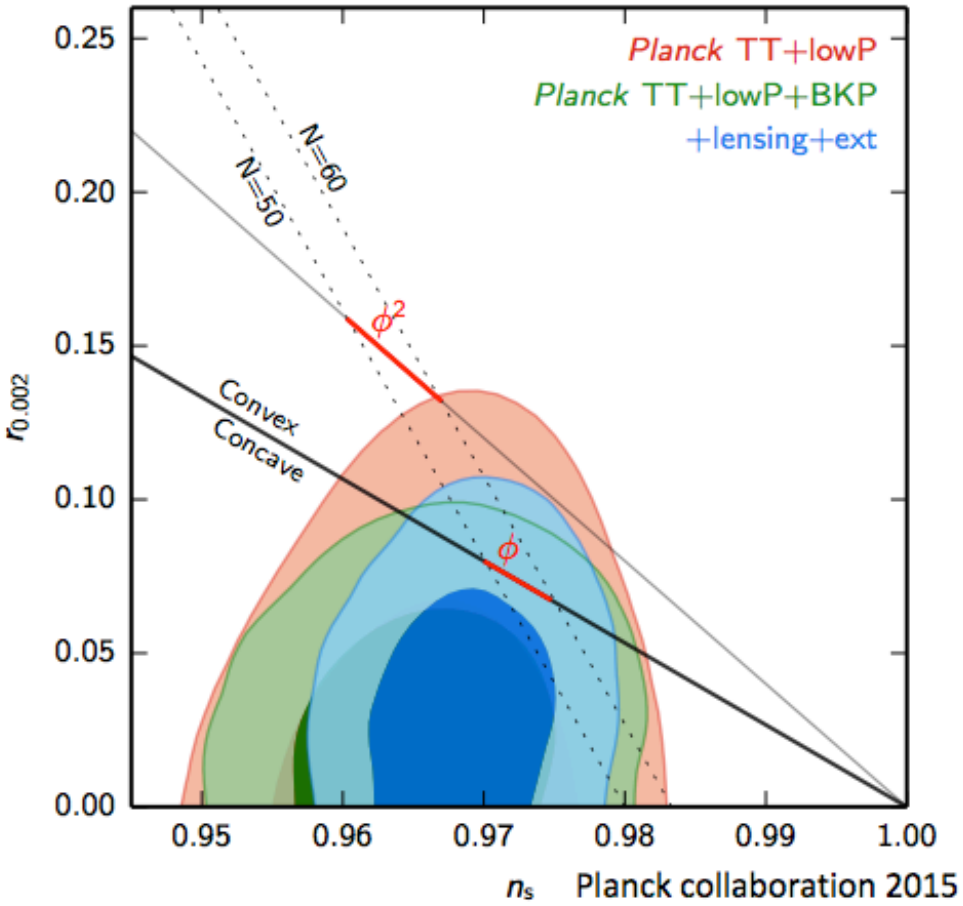
Fig13 of arxiv:1502.00612

# Current Constraints on Inflation




*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.)

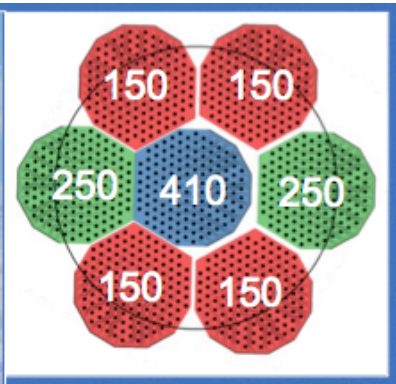
Inflationary constraint finally starts to tighten due to B-mode information

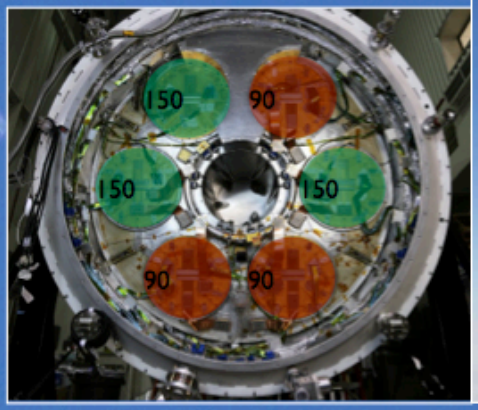


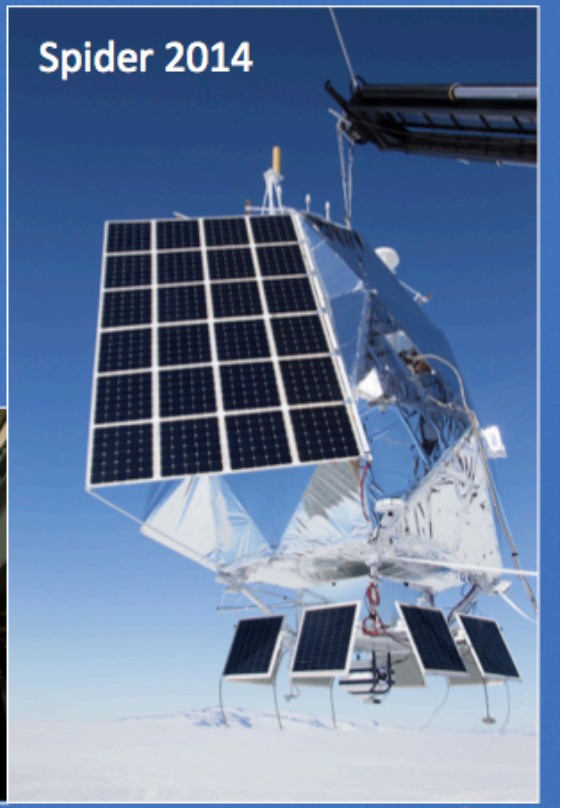
# Removal of beam systematics using Planck templates

- Not just about resolution and sensitivity…
- Systematics can also be a major headache (as Planck well knows…)
- BICEP/Keck relies on "deprojection" to clean out beam systematics using Planck temperature maps as templates
  - The Planck maps have more than sufficient sensitivity for this purpose and similar uses will be a Legacy of Planck going forward.

# 2G Balloons which have already flown: EBEX and SPIDER


Antarctic balloons

SPIDER will fly again in 2016

# Additional 2G ground based data under analysis and/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 observing 250 sq deg
- Keck 95GHz in 2014/15 and 220GHz in 2015 plus BICEP3 coming on line
- CLASS coming online (at 40GHz)

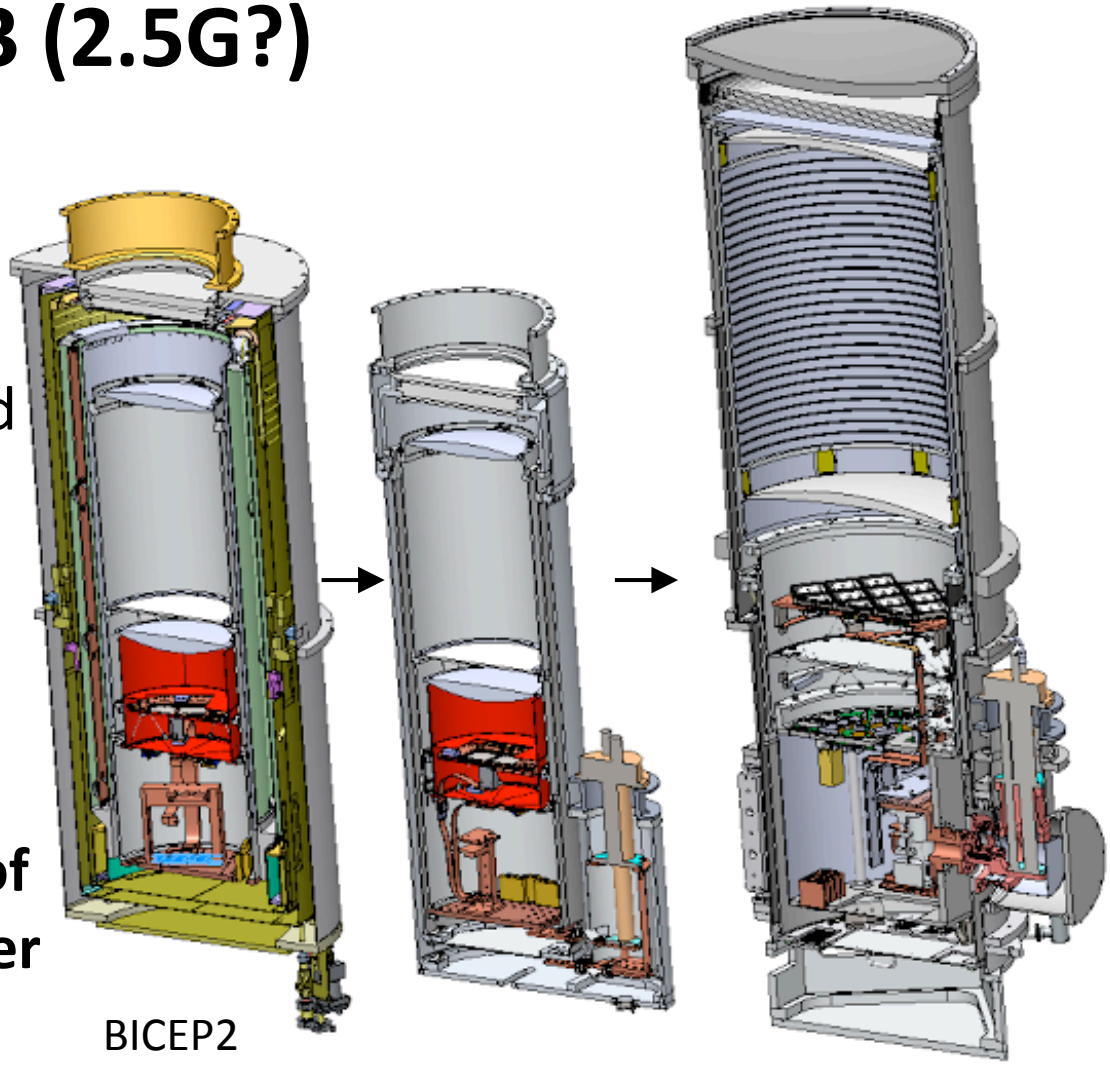
# New in 2015 BICEP3 (2.5G?)

**All 95 GHz**

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

Twice the aperture of BICEP2/Keck

**> 10x optical throughput of single BICEP2/Keck receiver**



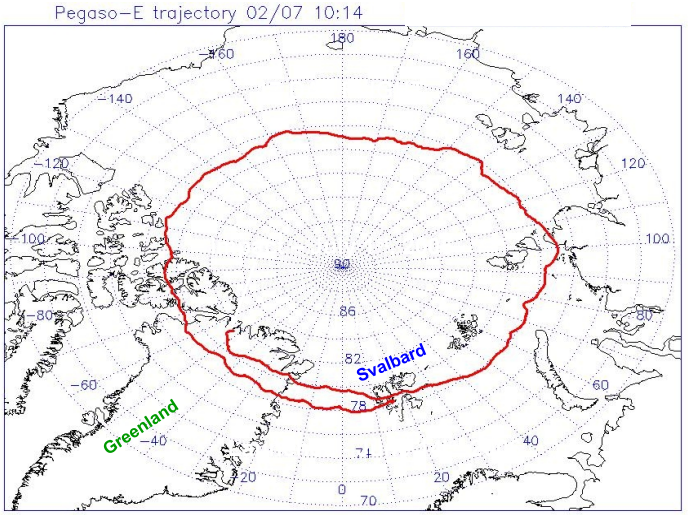
# Funded 3G Ground Based Experiments

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

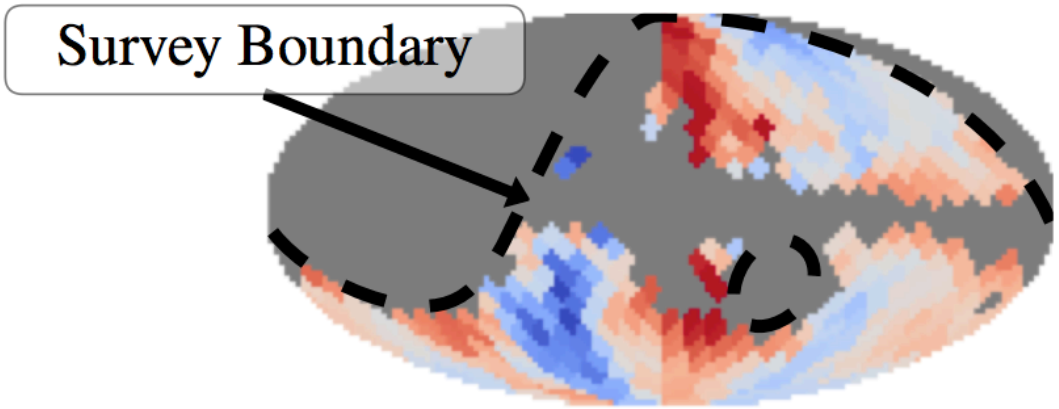
See Mike Niemack talk for more on ACTpol and Advanced ACTpol

# Do really large angular scales from suborbital?

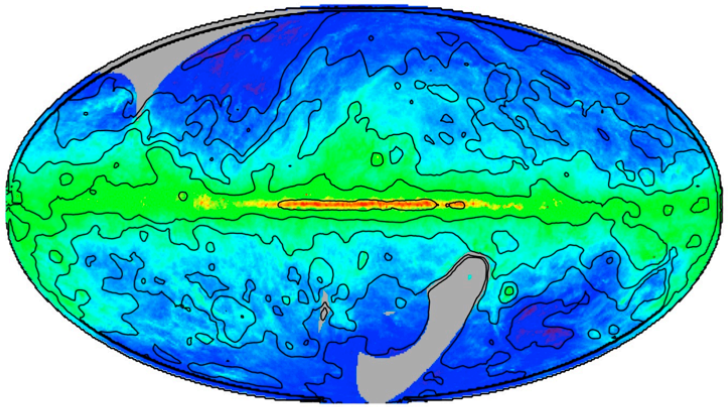
- Three low res experiments are targeting:
  - CLASS ground based (Chile)
  - PIPER balloon (multiple flights)
  - LSPE balloon (arctic night flight)




LSPE (140, 220, 240 GHz)




CLASS (40, 90, 150, 220 GHz)

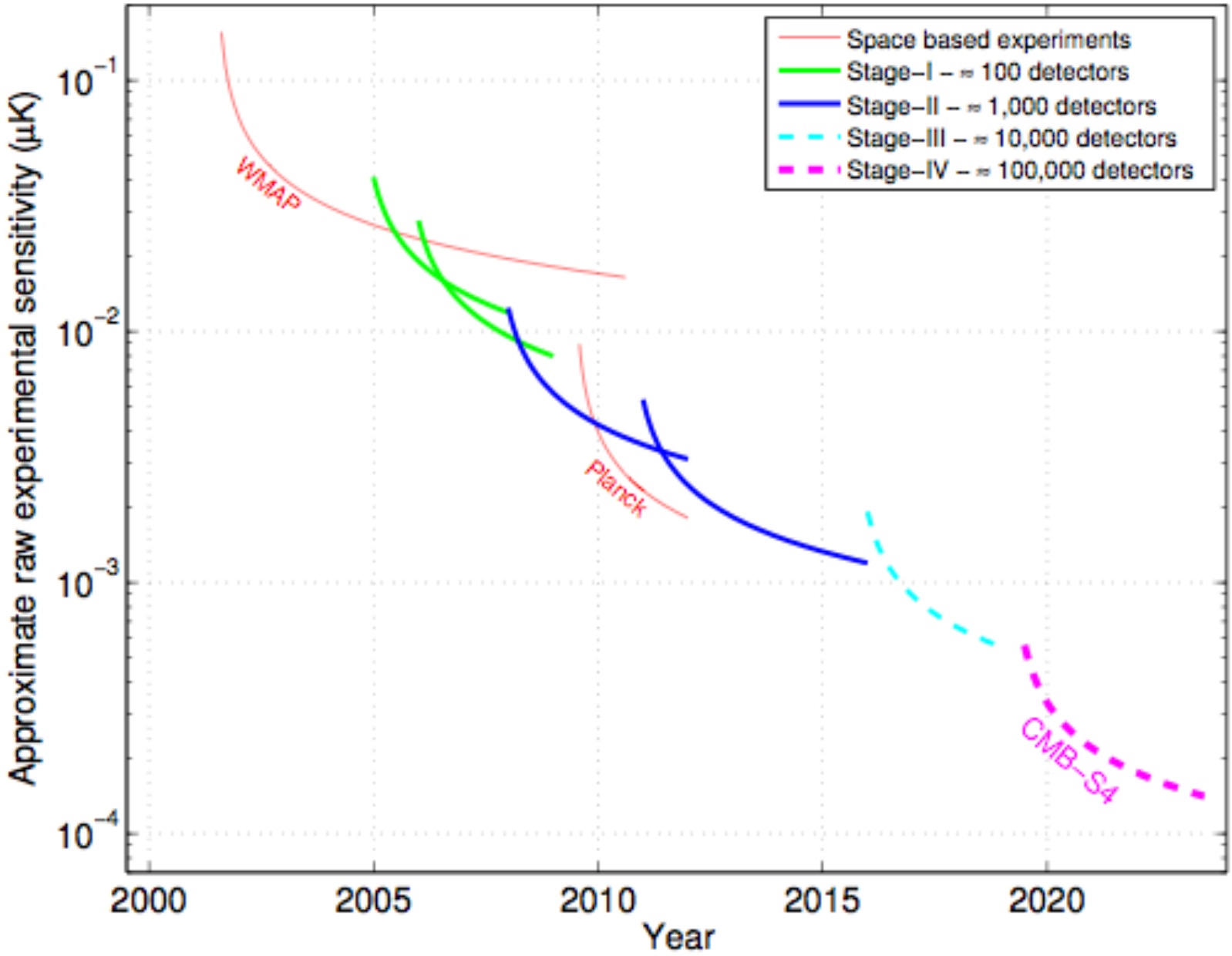


PIPER (200, 270, 350, 600 GHz)

# 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 info needed as well)
  - At ell=10 bump
    - Need >50% sky
    - Need super good foreground cleaning
    - Reionization from low ell E-modes will come as a bonus…
- Dark energy science via SZ clusters
    - Need >10,000 sq deg and high res
- Neutrino science etc via lensing plus cross correlations
    - Need >10,000 sq deg and medium res
- Further probe LCDM and recombination 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:**

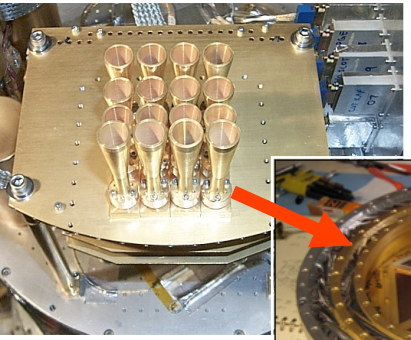
  - 200,000+ detectors on multiple platforms
  - spanning 40 - 240 GHz for foreground removal
  - ≲ **3 arcmin resolution** required for CMB lensing & neutrino science
  - ***higher resolution leads to amazing and complementary dark energy constraints, and gravity tests on large scales via the SZ effects***

See Snowmass planning document arxiv:1309.5383

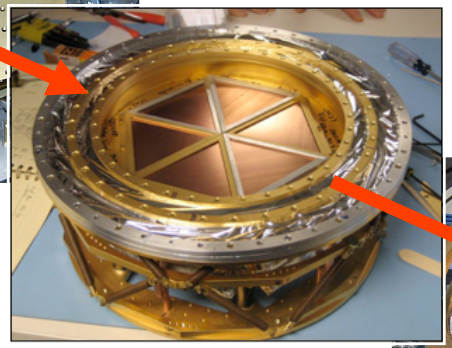
"Official" CMB-S4 Slide

**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**

**2001: ACBAR**
16 detectors

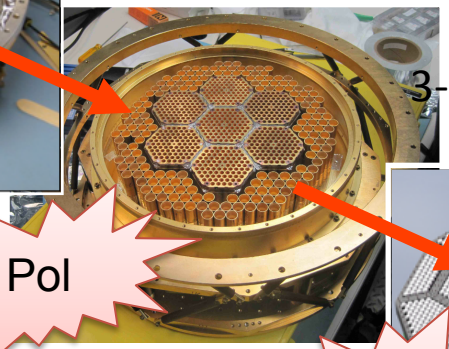


**2007: SPT**
960 detectors



Stage-2

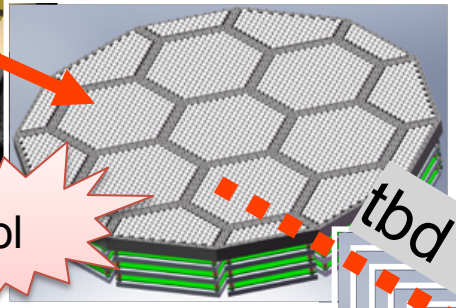
**2012: SPTpol**
~1600 detectors



Pol

Stage-3

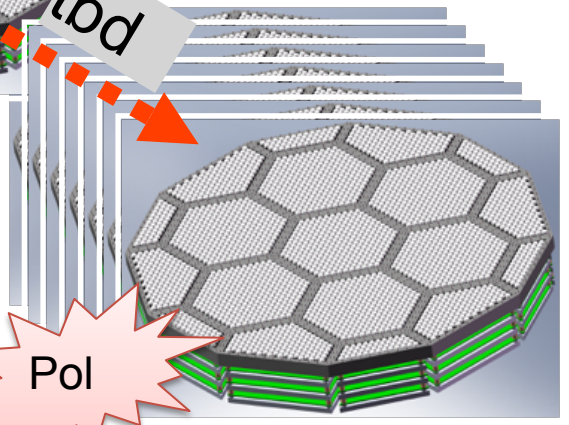
**2016: SPT-3G**
3-band multichroic pixels
~16,000 detectors



Pol

Stage-4

**~2022: CMB-S4**
200,000-500,000 detectors




Pol

Evolution of focal planes (an example)

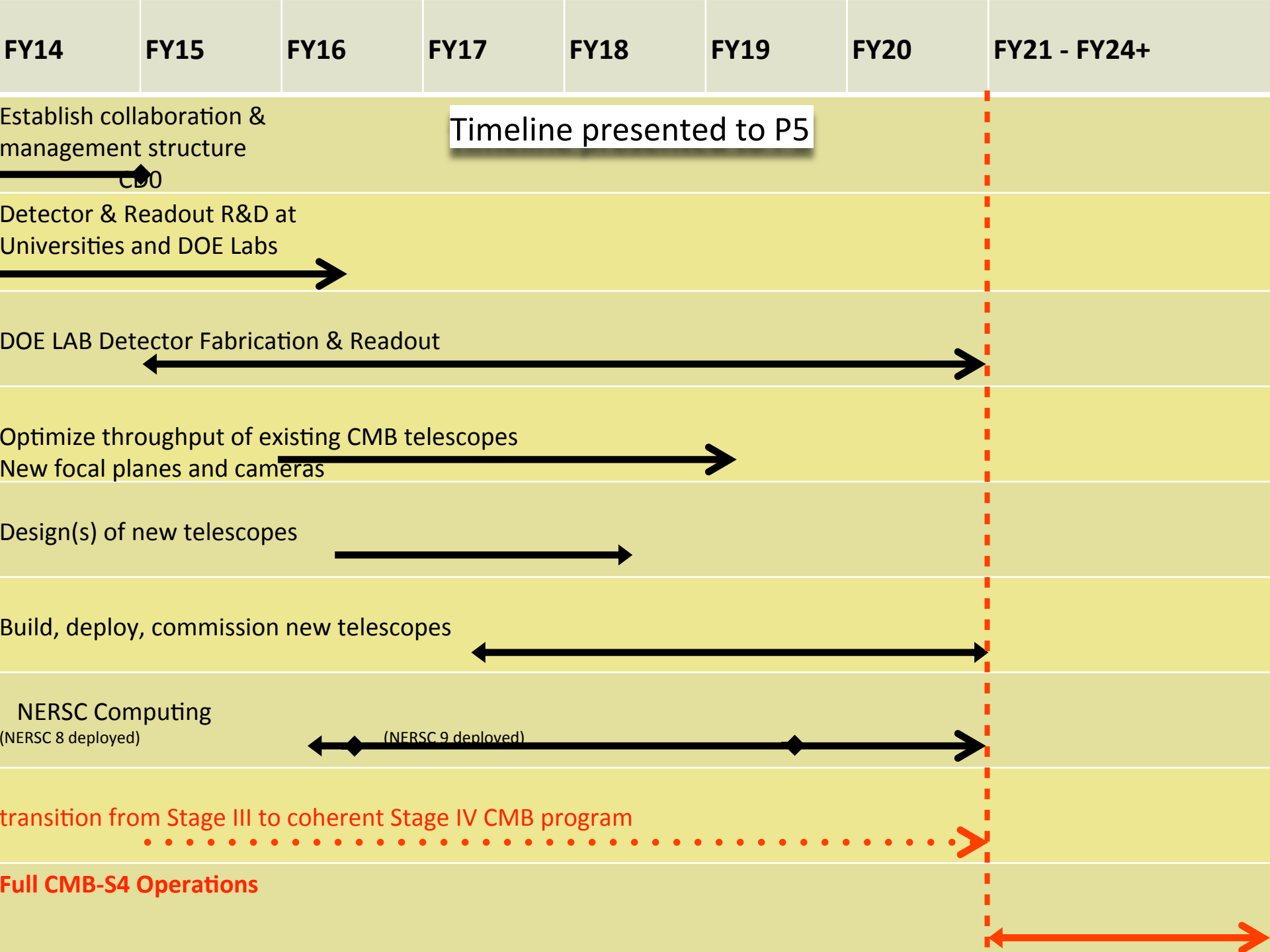
"Official" CMB-S4 Slide

# US HEP P5 Panel recommended DoE support CMB-S4

recommended
under all funding scenarios

## Table 1
## Summary of Scenarios

| Project/Activity | Scenarios | | | Science Drivers | | | | | Technique (Frontier) |
|---|---|---|---|---|---|---|---|---|---|
| | Scenario A | Scenario B | Scenario C | Higgs | Neutrinos | Dark Matter | Cosm. Accel. | The Unknown | |
| **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 doing important science
  - 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…
- BICEP/Keck also have the best systematic control at lower ell
  - It remains to be seen: can high res experiments deliver at lower ell?
- Big plans for the future:
  - CMB-S4 seeks to put 100,000's of detectors on the sky!

# Backup Slides

# Modulation is overrated – Pair differencing can work very well!

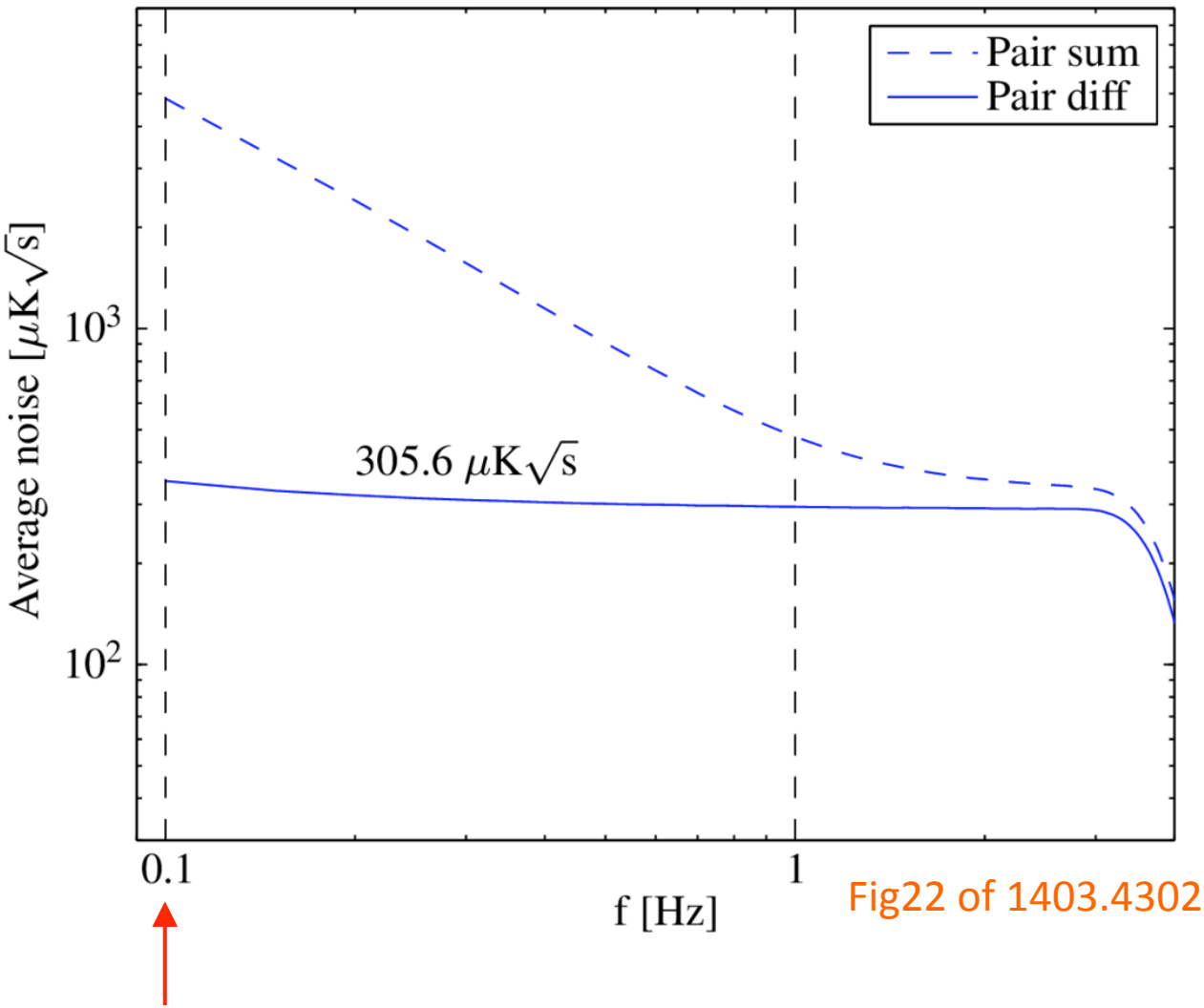


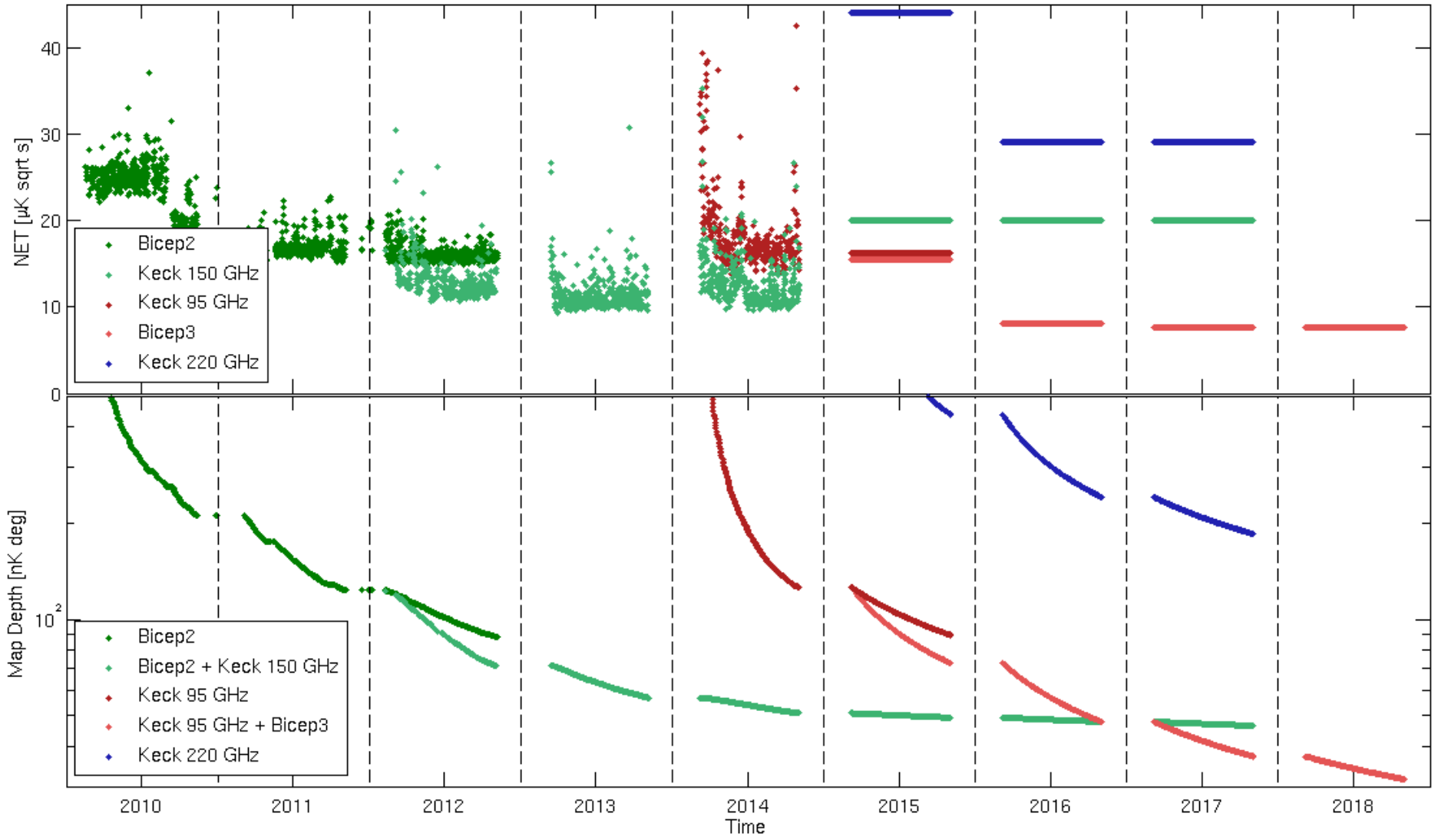

Fig22 of 1403.4302

0.1Hz = multipole 25

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)




The BICEP2/Keck/BICEP2 program is on-going – now with 3 frequency bands: 95/150/220 GHz