Review of Ground-Based CMB Experiments

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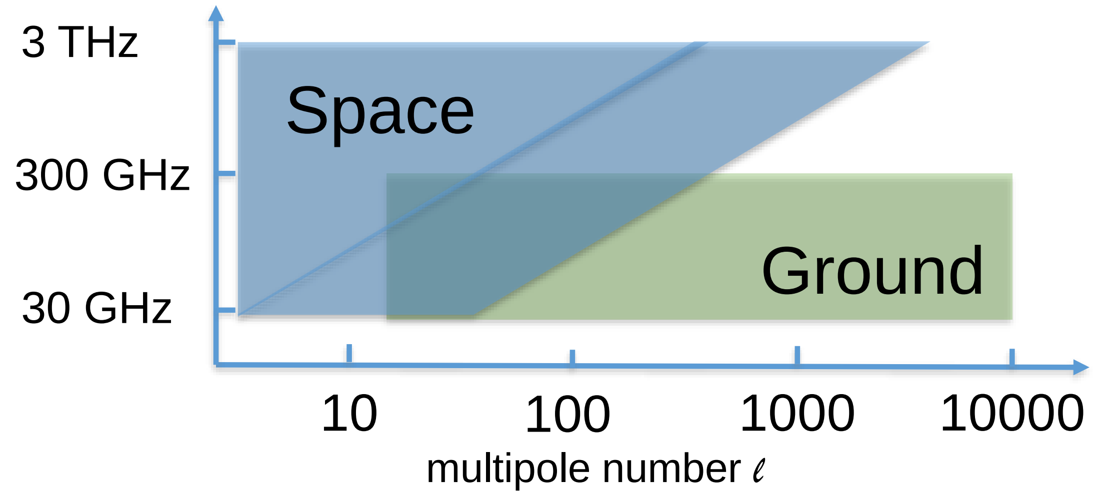
2015-12-12

B-modes from Space

Outline

- Ground & Space: platform strengths
- 2010s: current & near future capabilities of ground-based experiments: what will be done before LiteBIRD launches?
- 2020s: observations at approximately the same time as LiteBIRD
- Conclusion

Platform Strengths



Space-based

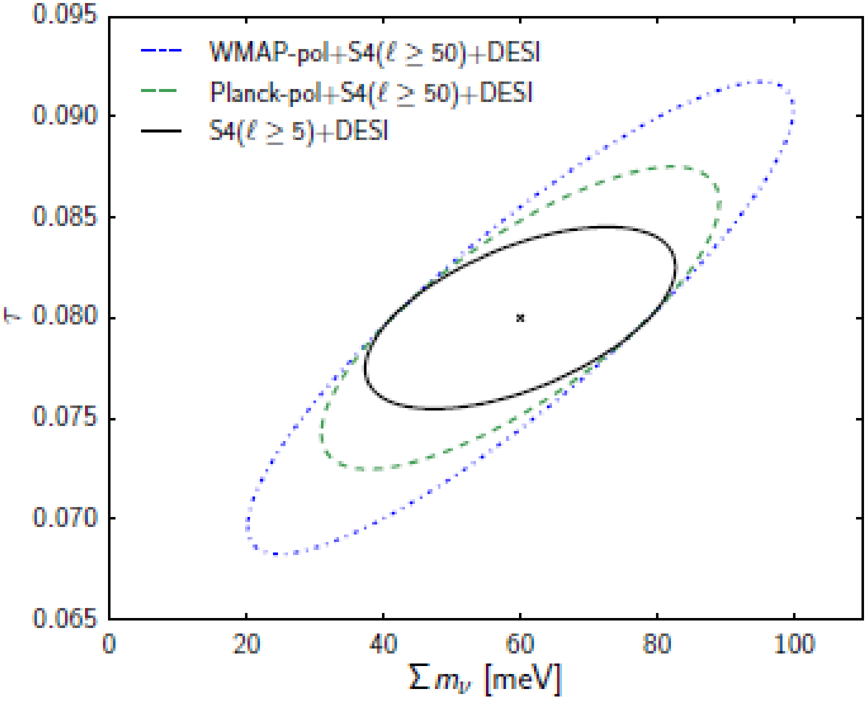
- High frequency
  - Atmosphere
  - Can achieve necessary resolution with modest aperture
- Low ℓ
  - Several ground-based experiments are trying to achieve low ell, but $\ell < 20$ hasn't been demonstrated from the ground.

Ground-based

- Low frequency
- High resolution
  - Neutrino mass Σm_ν from measurements of large scale structure
  - Number of early relativistic species N_{eff}
  - De-lensing to optimally search for the inflationary signal
  - Galaxy cluster counts & dynamics as a probe of structure formation, dark energy, and gravity

Achieving low ℓ is important for "high resolution" science goals

- Low ell allows us to break degeneracy between τ and Σm_ν.



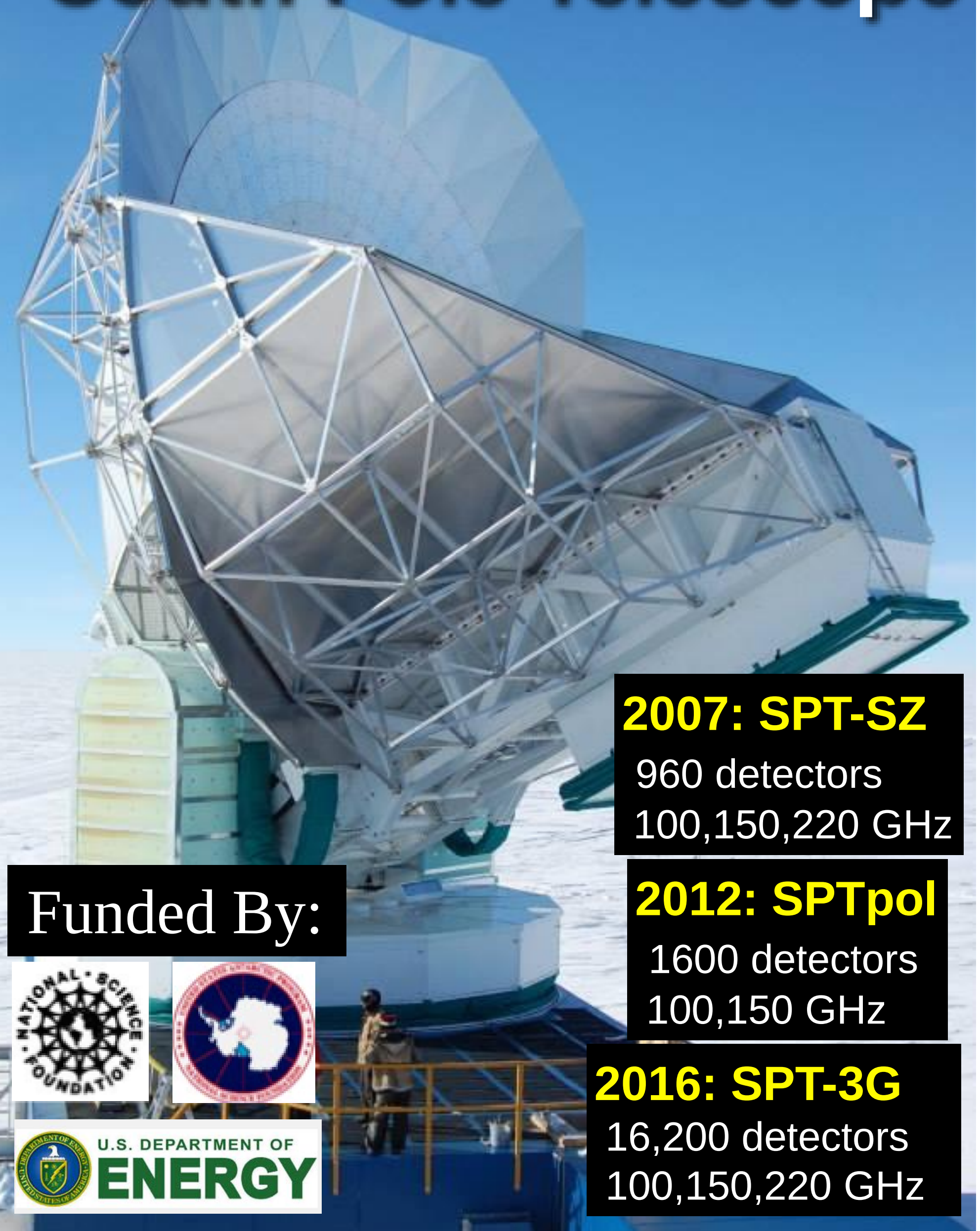
High resolution is important for "low-ℓ" science goals

- Larger-aperture ground-based instruments:
  - Can provide low-frequency information at the resolution of the CMB bands in LiteBIRD
  - Can use high-resolution CMB data to de-lens LiteBIRD's CMB data
- Neither of these require that the ground-based instrument be able to measure the smallest ℓ

2010s: what has been done recently, and what will be done before LiteBIRD launches?

- SPT
- ACT
- POLARBEAR / Simons Array
- BICEP/Keck
- ABS
- CLASS
- QUIJOTE

SPT: The 10-m South Pole Telescope



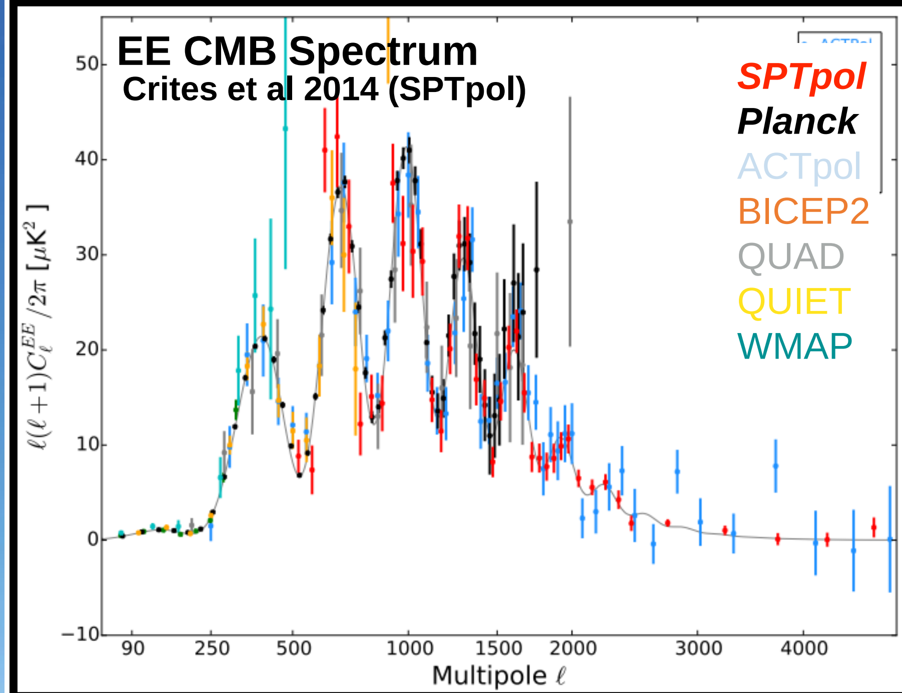
2007: SPT-SZ
960 detectors
100,150,220 GHz

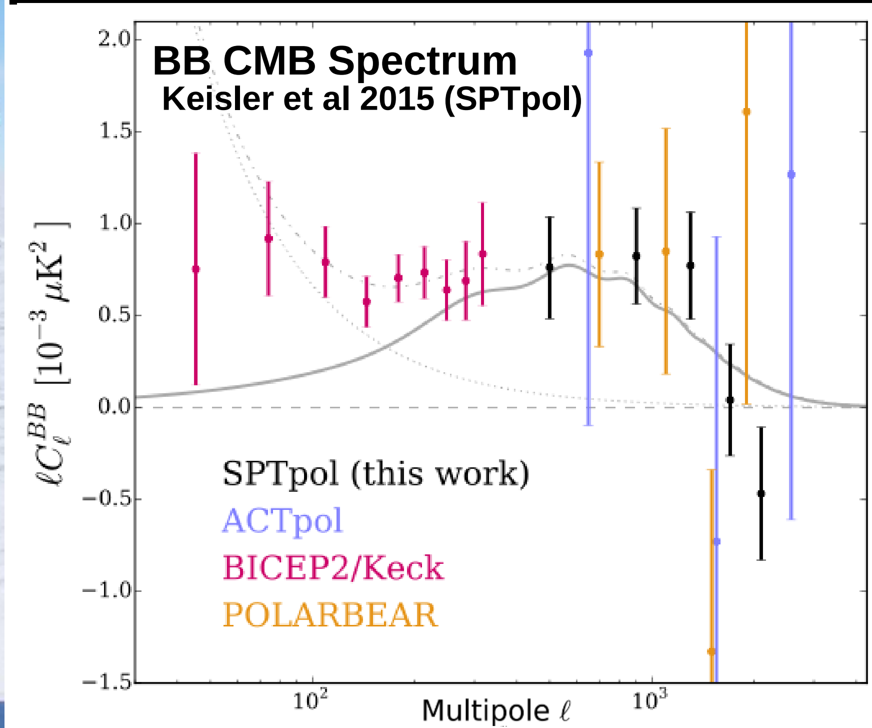
2012: SPTpol
1600 detectors
100,150 GHz

2016: SPT-3G
16,200 detectors
100,150,220 GHz

Funded By:

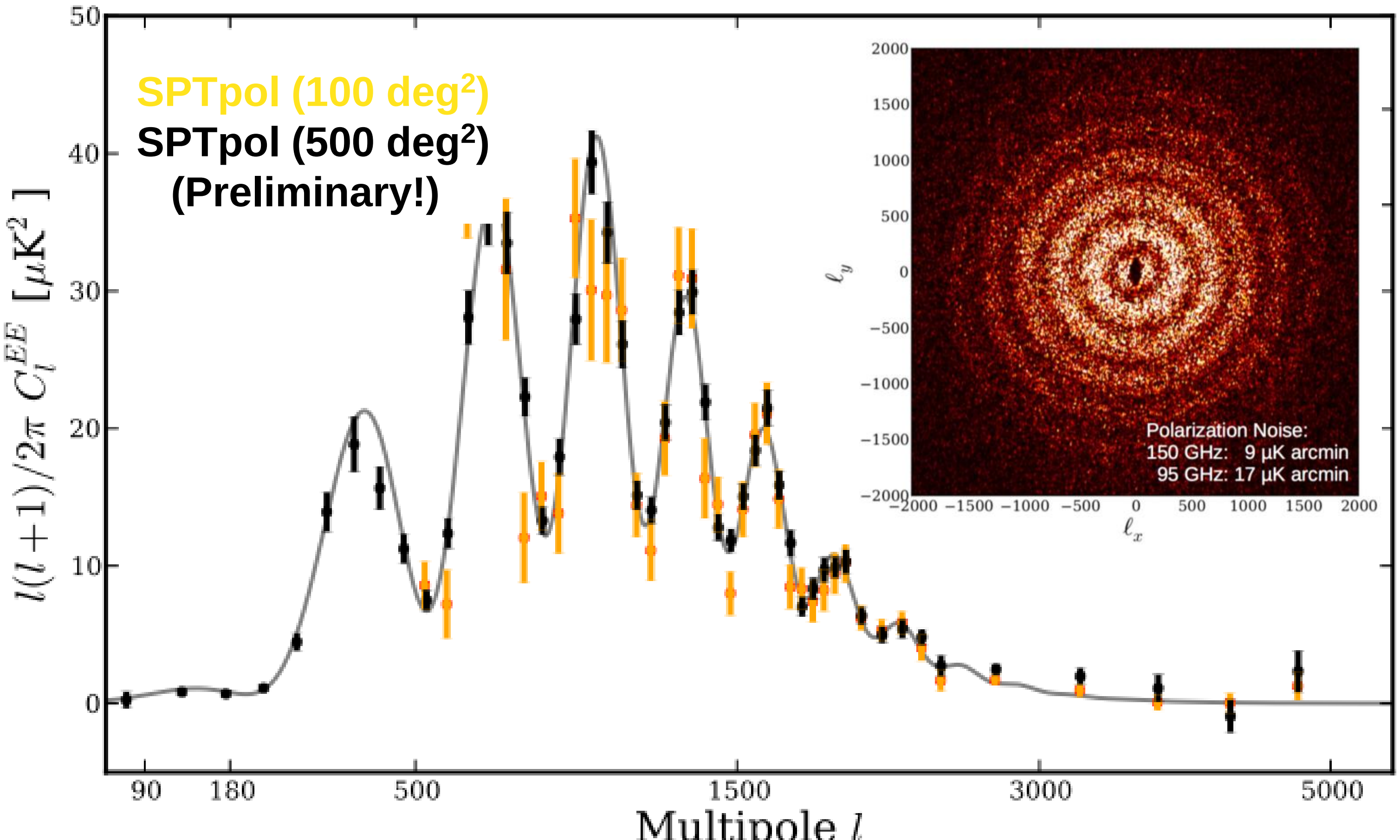
U.S. DEPARTMENT OF ENERGY



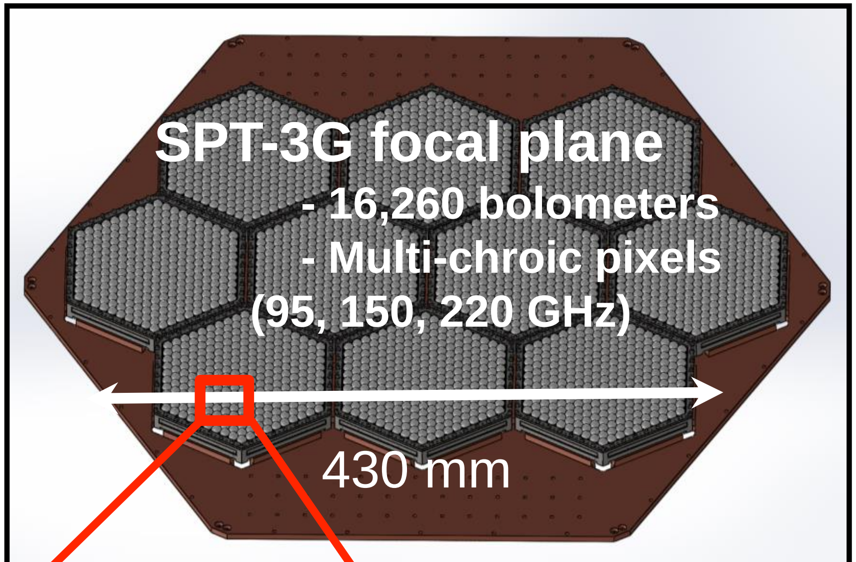


SPTpol 500 deg^2 Survey: EE Spectrum

- Published SPTpol results based on first 100 deg^2 of survey
- 3-years of observations on 500 deg^2 field (6 uK-arcmin depth)
  - Preliminary EE-spectrum below.
    - Additional science from CMB lensing; BB-spectrum; DES cross-correlation, clusters; etc.
  - Overlap with BICEP2/Keck survey:
    - B-mode de-lensing analysis underway with SPTpol; forecast σ(r) = 0.02

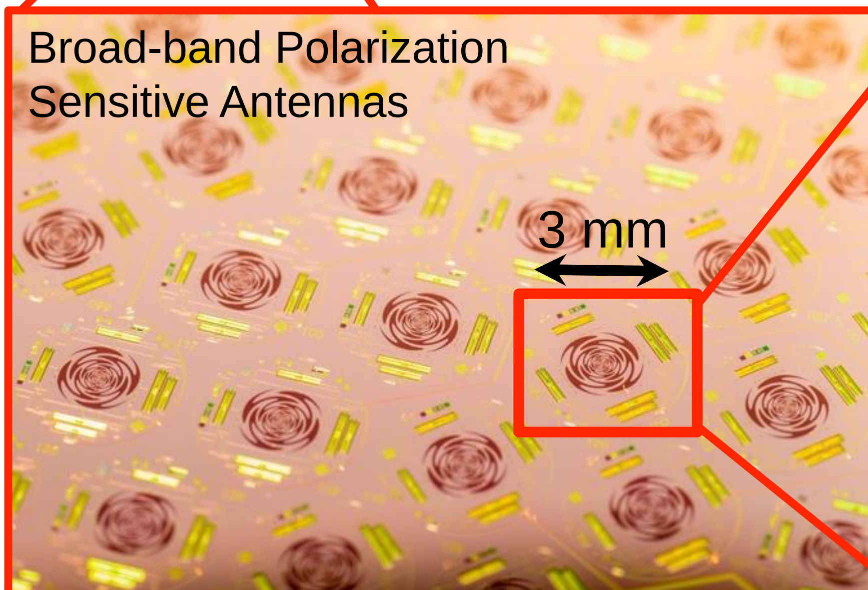


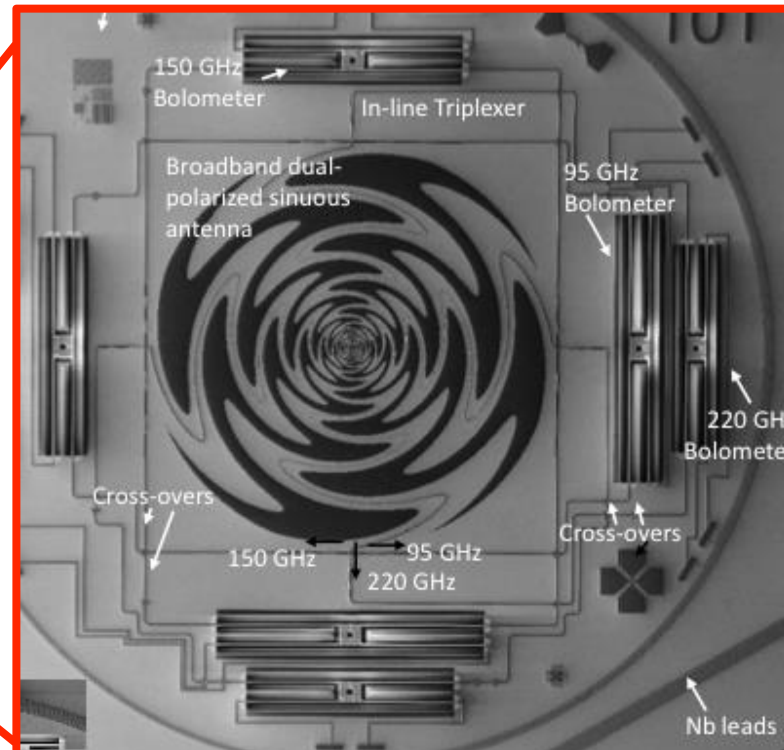
SPT-3G: Detector Development



Collaboration with many from US LiteBIRD team – triplexed sinuous detectors are a very similar design.

DOE Labs (ANL, FNAL, LBNL, SLAC) building up fabrication capabilities & infrastructure.

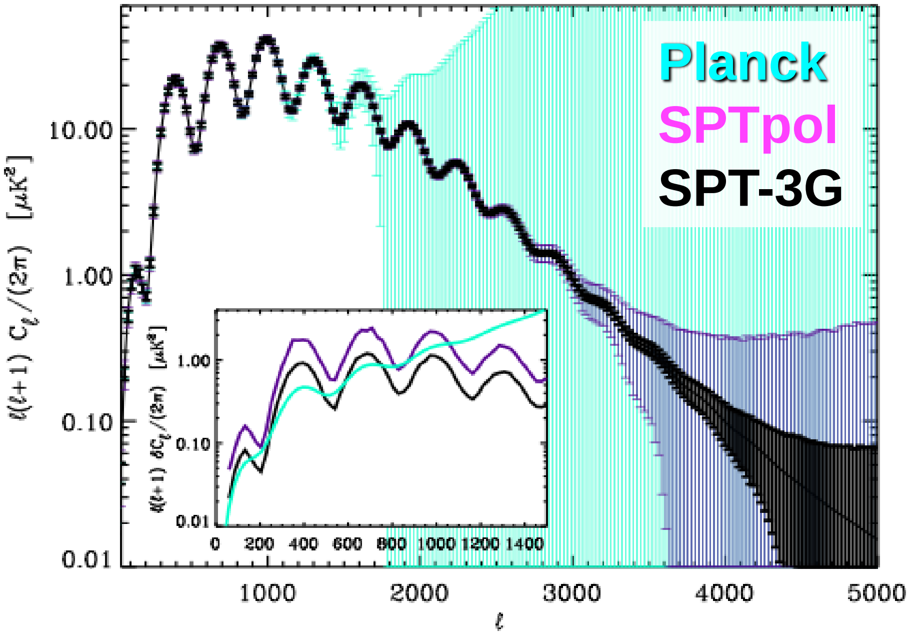




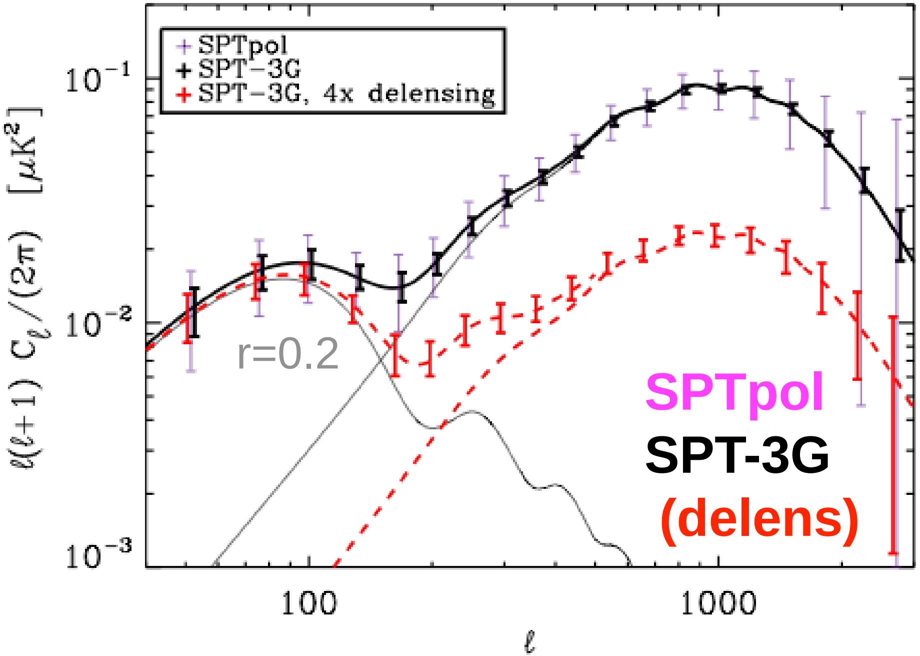
Fabricated at Argonne National Lab (ANL)

SPT-3G Survey (2016-2020)

EE-Spectrum



BB-Spectrum



SPT-3G Survey:

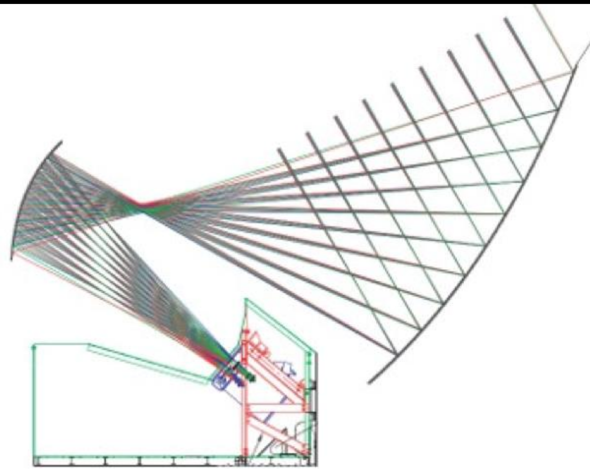
- 4-year survey, over 2500 deg^2 sky area:
- 150-σ detection of CMB lensing,
- Detect 10,000 clusters via the Sunyaev-Zel'dovich (SZ) effect,
- Constrain cosmology using the CMB power spectra (see table).

(with Planck priors)	SPT-3G (2019)
$\sigma(r)$	**0.011**
$\sigma(N_{eff})$	**0.058**
$\sigma(\Sigma m_\nu)$	**0.061 eV***

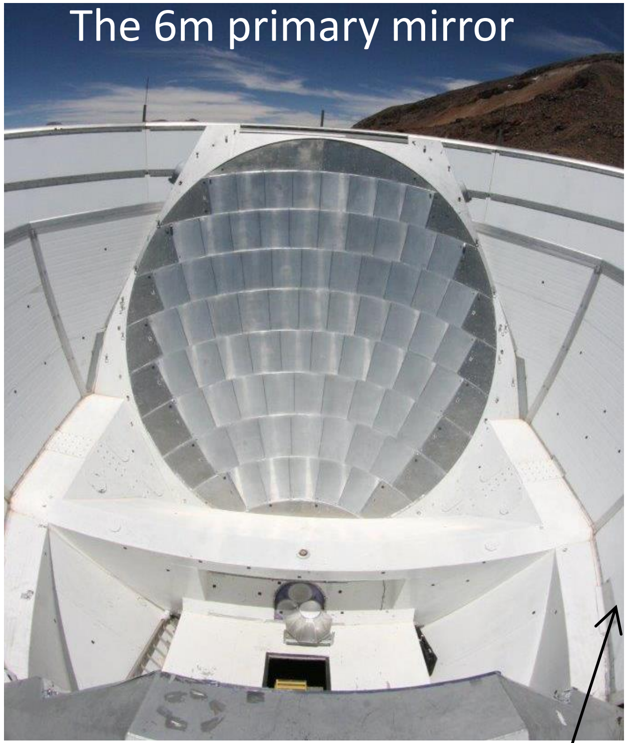
Benson et al 2014

* Includes BOSS prior

The Atacama Cosmology Telescope



- 6m off-axis telescope
- Arcminute resolution



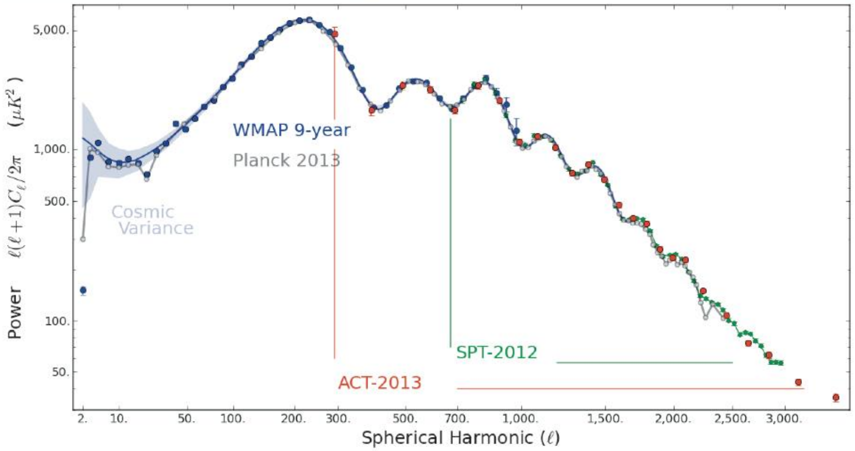
- 5200 m (high)
- Desert (dry)
- Latitude -23°

- 12 m groundscreen
- Large co-moving screen
- 100 mK dilution fridge
- 3 polarimeter arrays ~ 3000 TES bolometers

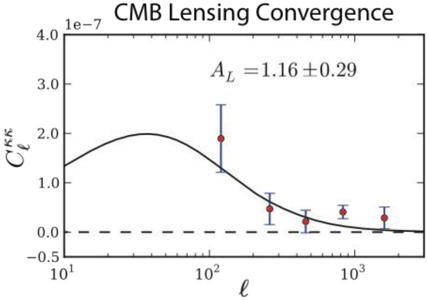
ACT
Discovery Highlights

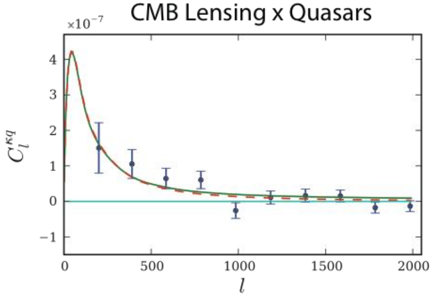
ACT RESULTS
from the first camera, MBAC (unpolarized)

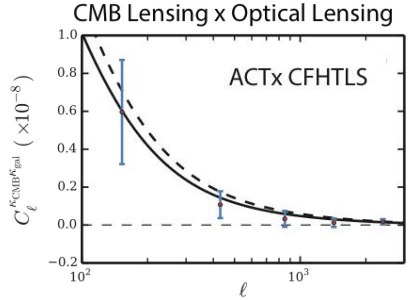
Standard Cosmological Model



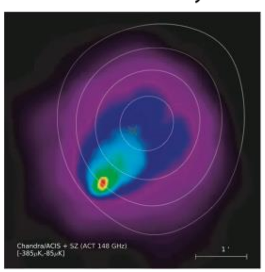
Gravitational Lensing

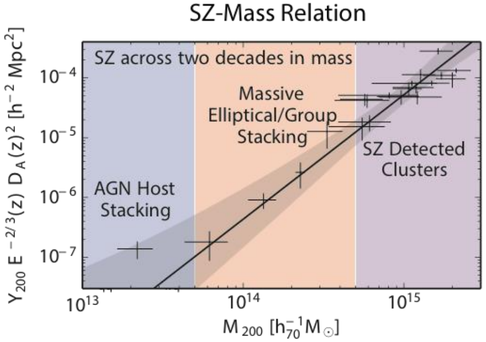


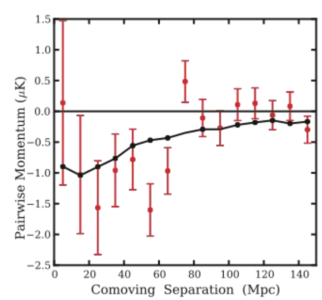




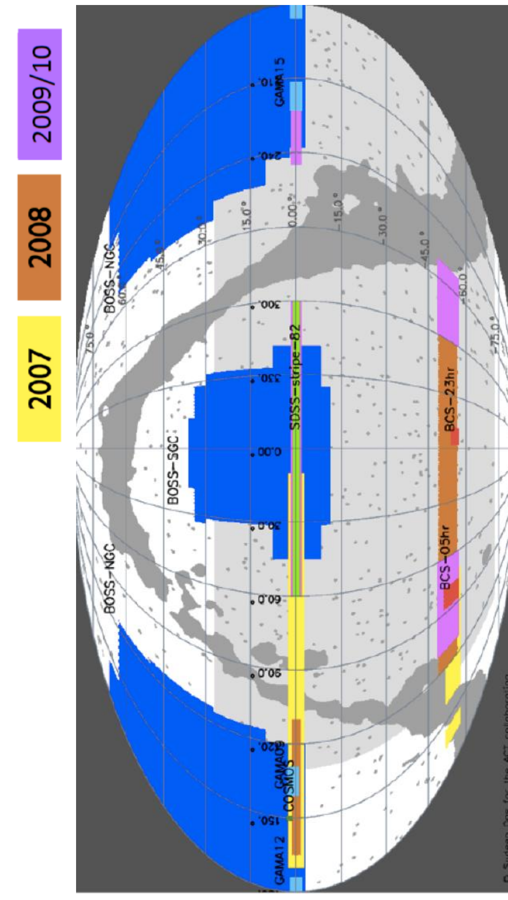
Sunyaev-Zel'dovich Effect

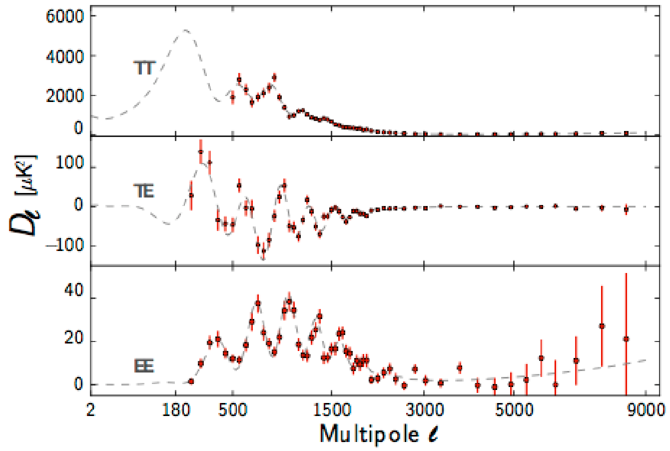






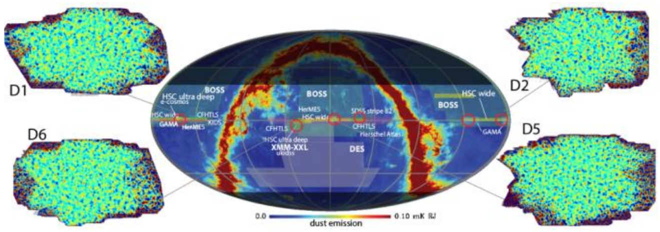
91 optically confirmed clusters; multiple stacking analyses





First ACTPol Specta

Naess et al, 2014, JCAP 10, 7.

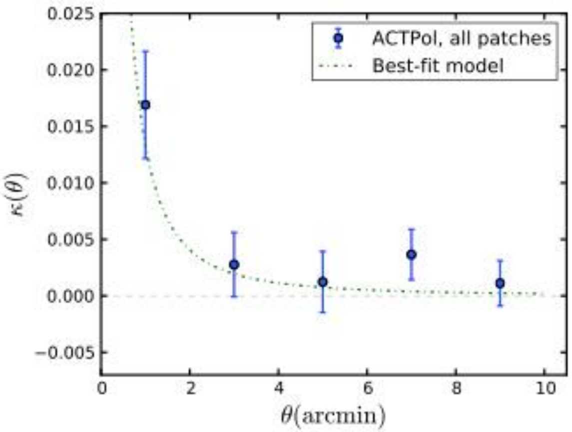


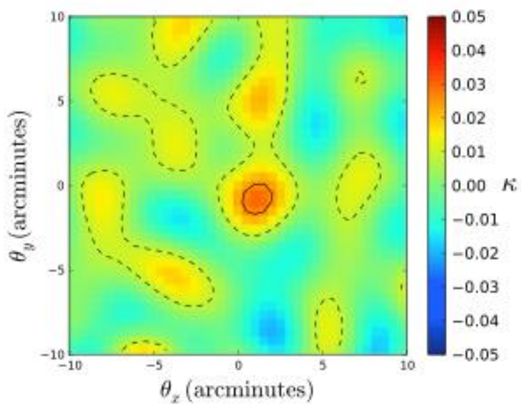
ACT RESULTS

from the second camera, ACTPol

CMB Lensing by DM Halos

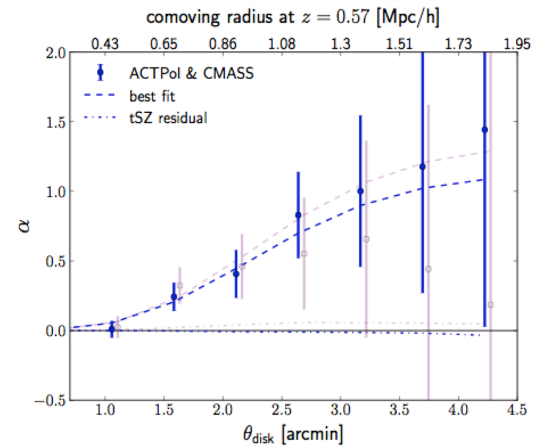
Madhavacheril et al, 2015 PRL 114, 151302.





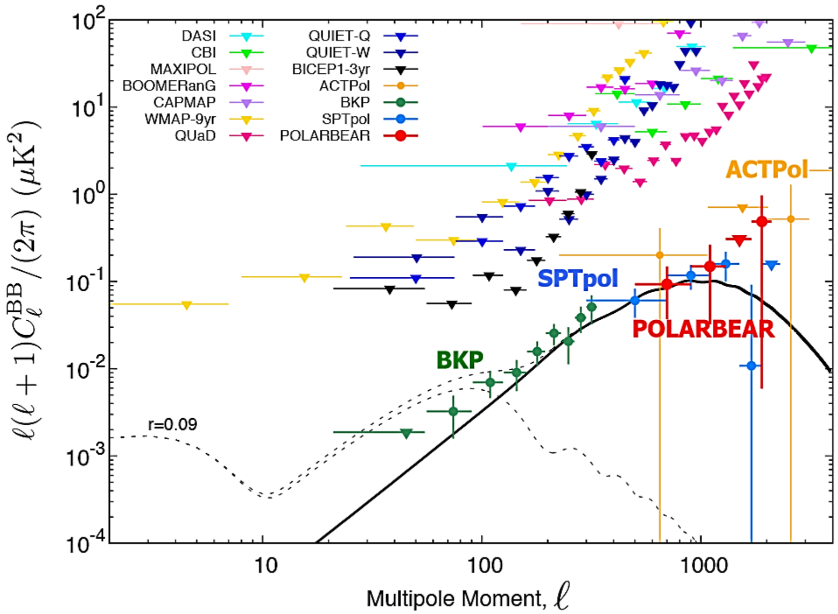
3σ kSZ detection with BOSS velocities

Schaan et al, 2015, arXiV:1510.06442



4.5σ radio bias detection with ACT+ACTPol lensing x FIRST Allison et al, 2015, arXiV:1502.06456	**9σ lensing detection** via ACTxCIB (B-mode lensing, 3σ) Van Engelen et al, 2015 ApJ 808, 7.

The POLARBEAR Project

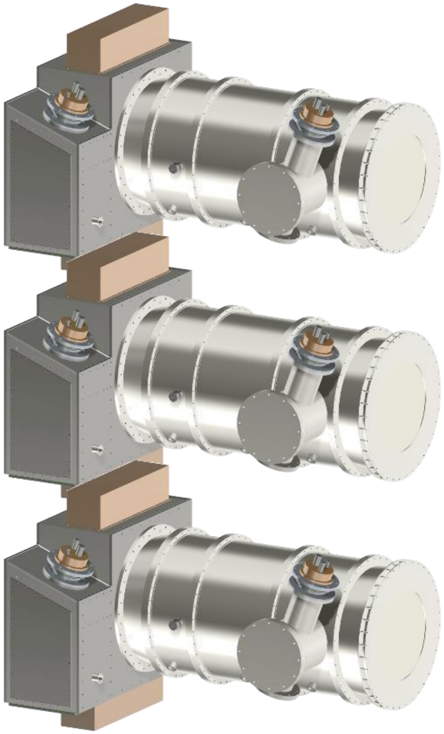


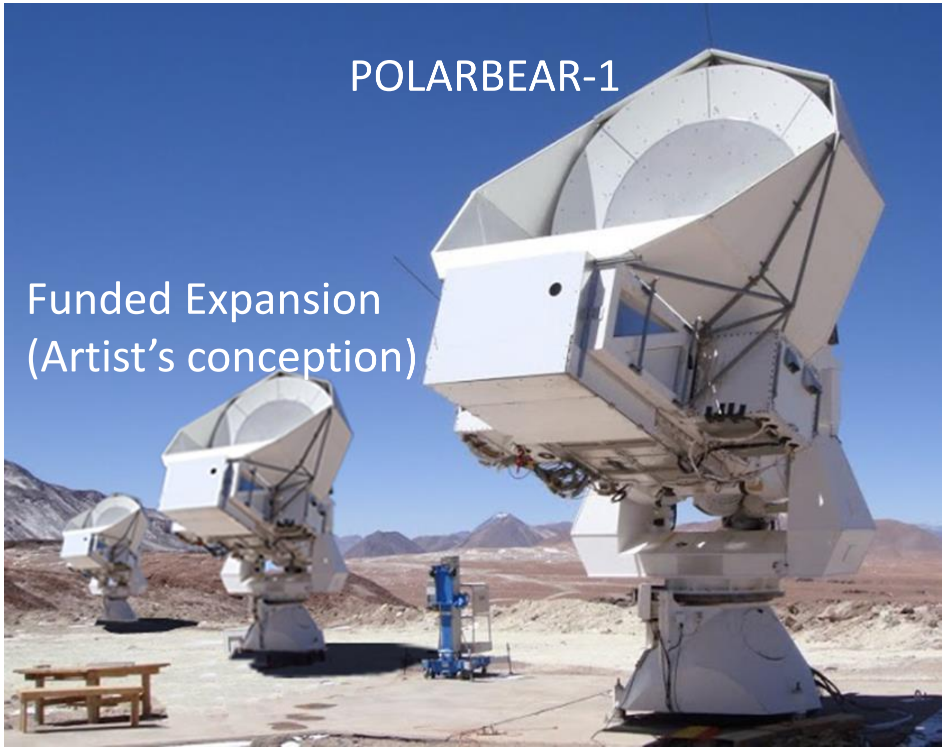
POLARBEAR-1 on Huan Tran Telescope

- **Cosmic Microwave Background (CMB) polarimetry experiment**
  - Inflationary and lensing B-modes
  - Primordial magnetic field and cosmic birefringence

- **POLARBEAR-1**
  - Observing in Atacama, Chile since January, 2012 with 1274 bolometers @ 150 GHz
  - Published two measurements of lensing B-mode with CMB polarization data alone
    - Auto-correlation
    - Lensing power spectrum
  - Published evidence of lensing B-mode from cross-correlation with CIB
  - Season 1 release: Combined 4.7 σ for lensing B-mode measurement
  - Season 2 and season 3 data are being analyzed

POLARBEAR-2 & The Simons Array

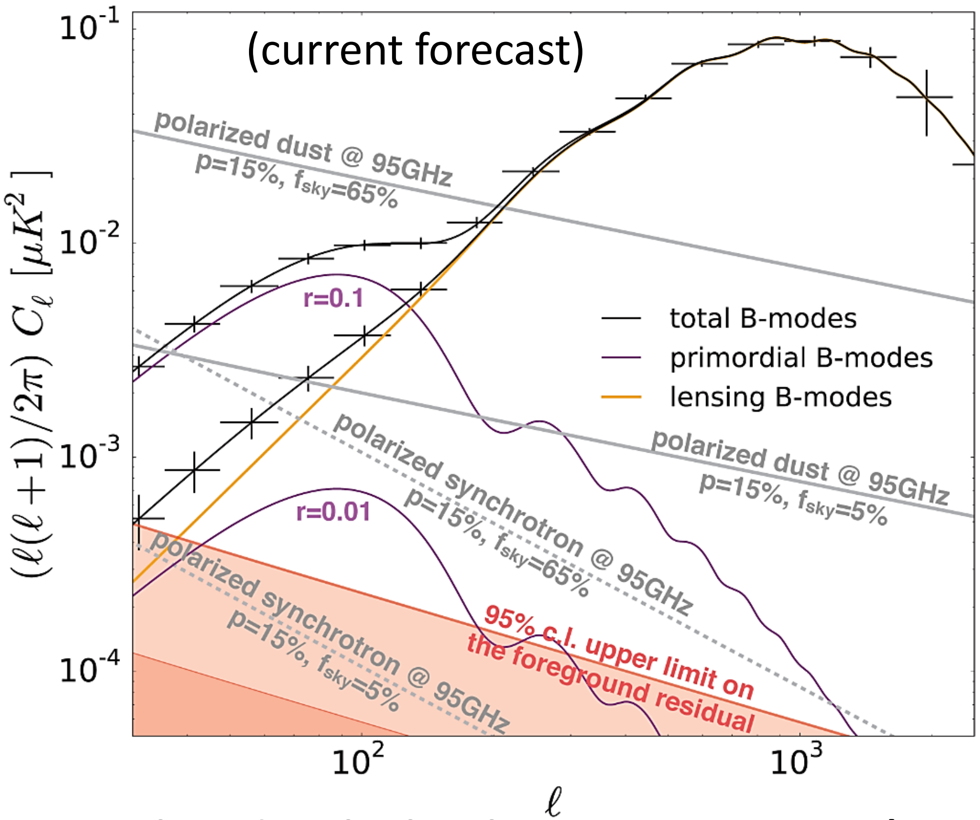




Simons Array Receiver Frequency Plan
Detector technology is 'diplexer' version of SPT and LiteBIRD design

- Increase number of detectors for higher sensitivity
- Expand frequency coverage for foreground removal
- Three telescopes (two new telescopes on ship to site now)
- 7,588 bolometers per receiver, factor of 6 increase from POLARBEAR-1 receiver
- Deploy first POLARBEAR-2 receiver (PB2A) in 2016
- Deploy two more POLARBEAR-2 receivers (PB2B, PB2C) in 2017

Simons Array Forecast



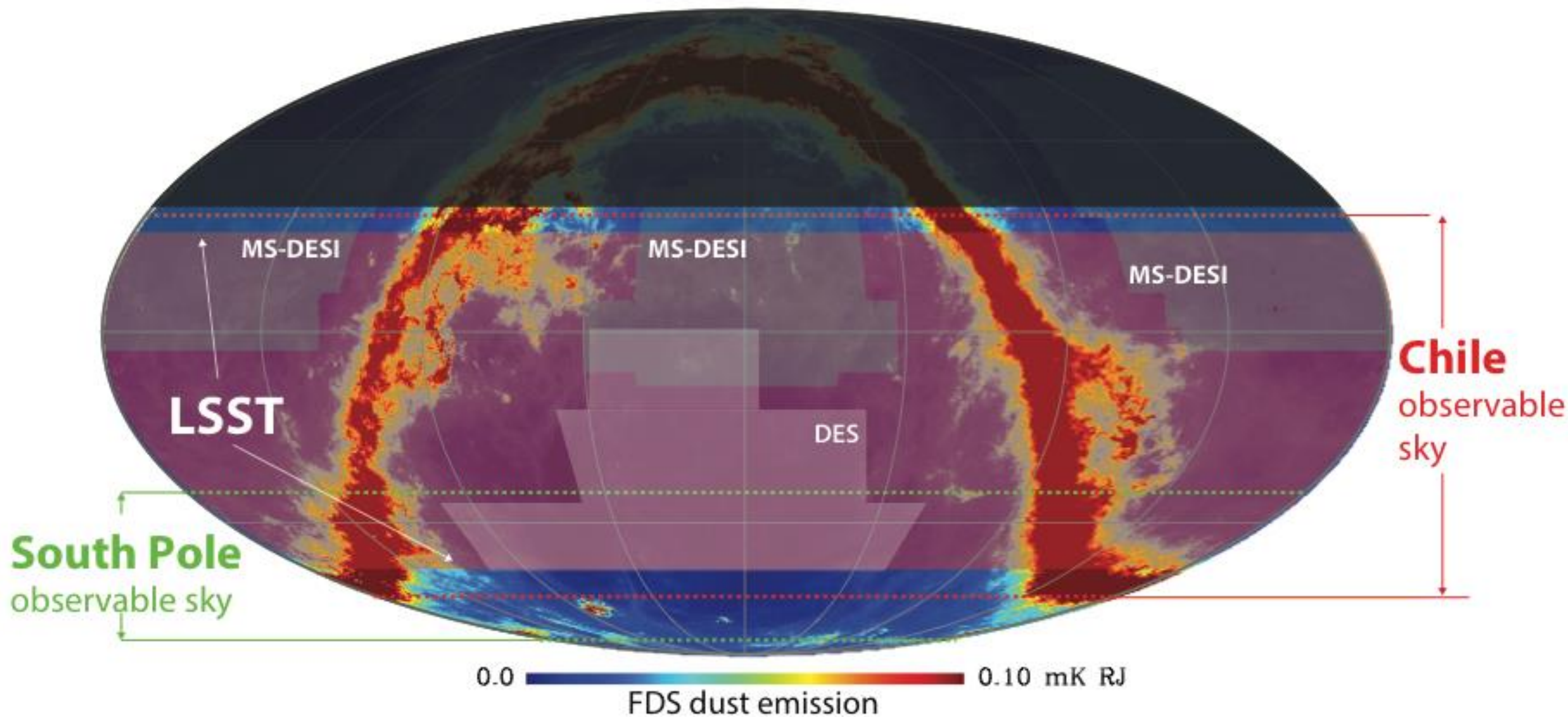
Simons Array combined with Planck, C-Bass, DESI BAO (3-years)

- Inflation: $\sigma(r = 0.1) = 4 \cdot 10^{-3}$(stat), $6 \cdot 10^{-3}$(stat + foreground cleaning)
- Sum of neutrino mass: $\sigma(\Sigma m_\nu) =$ 19 meV (stat), 40 meV (stat + FC)
- Neff constrain to +/- 0.04
- Scalar tilt: $\sigma(n_s) = 6 \cdot 10^{-3}$
- Primordial magnetic field to μ-gauss scale

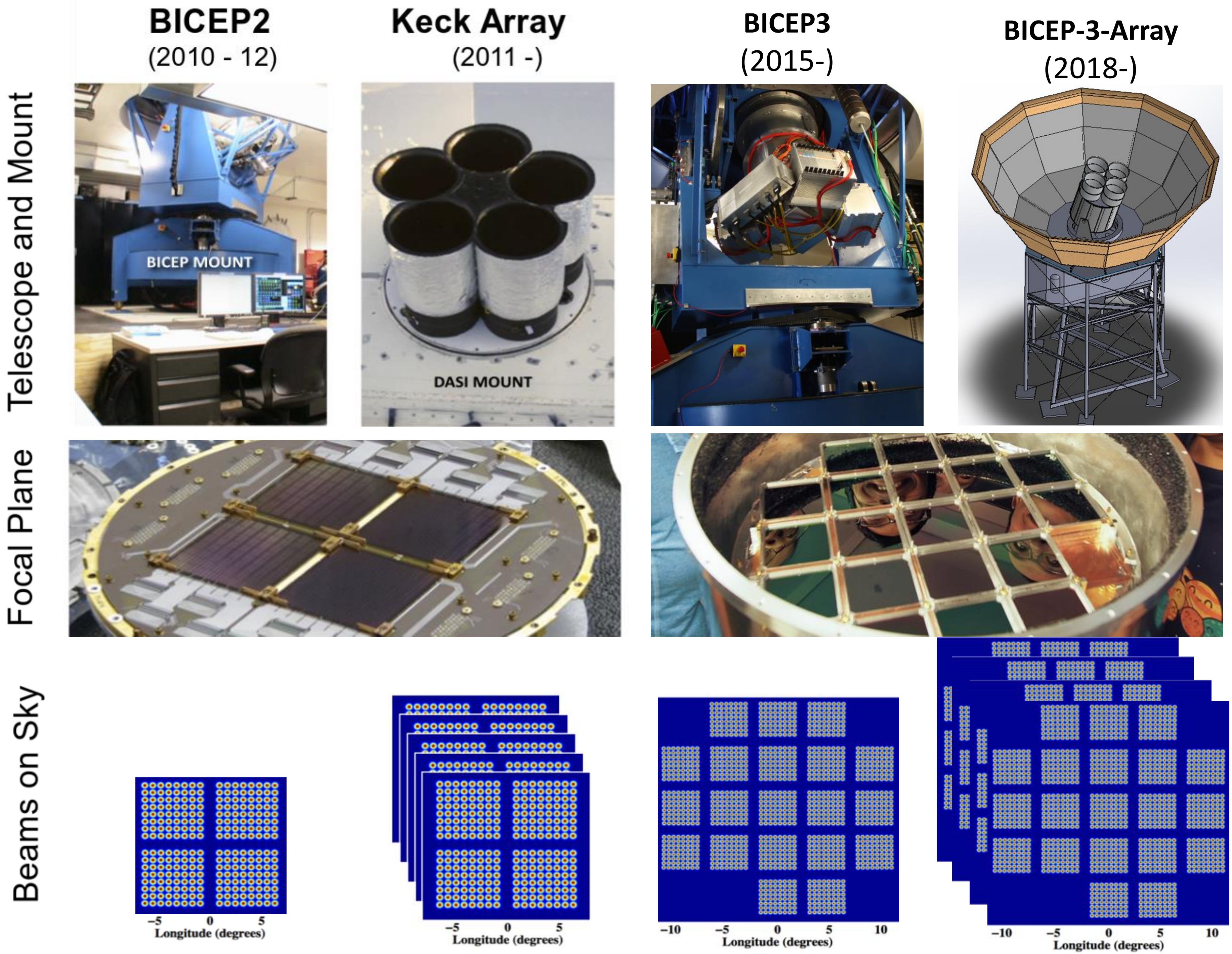
Coverage from Chile and South Pole

70% of the sky, overlapping the large optical surveys

Greatly enhance DES, DESI and LSST science by overlapping sky



BICEP2 and Keck-Array


BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2015-)
BICEP-3-Array
(2018-)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
Focal Plane
Beams on Sky
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)

BICEP/Keck first 95 GHz results

BICEP/Keck 150 GHz + Keck Array 2014 95 GHz

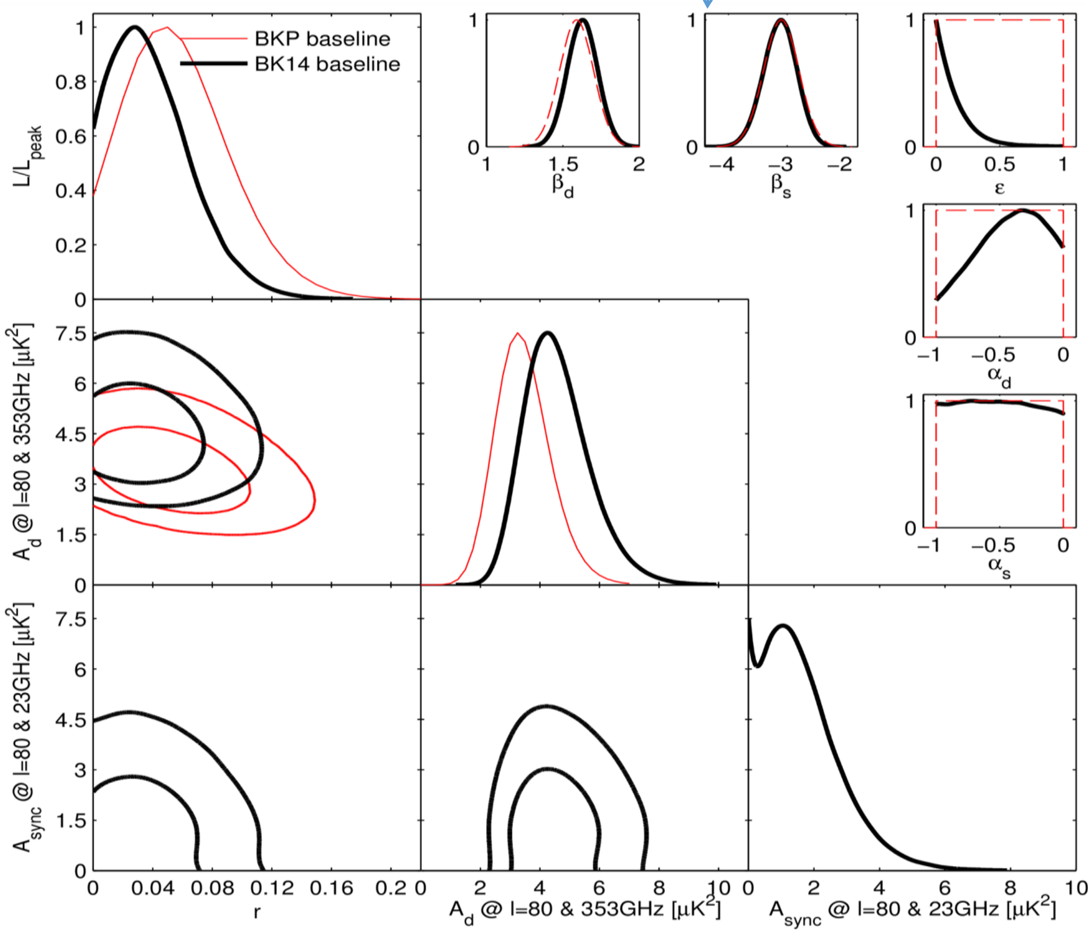
arXiv:1510.09217 [astro-ph.CO]

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Joint likelihood of all spectra vs. lensing+dust+sync+r model:

dust vs. r degeneracy lifted



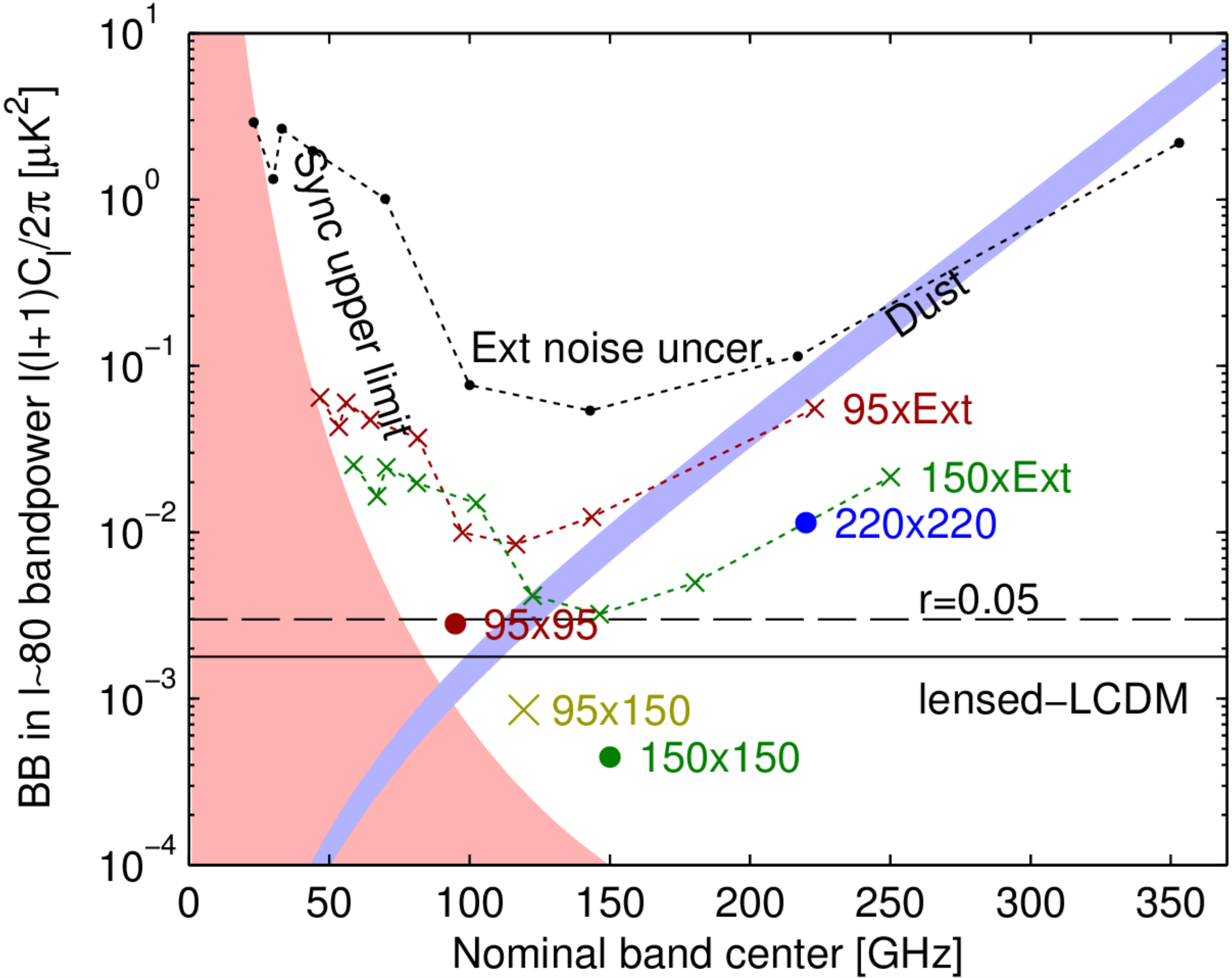
Marginalize over generous ranges in spatial spectral indices

r < 0.09 (95% CL)

from polarization only;

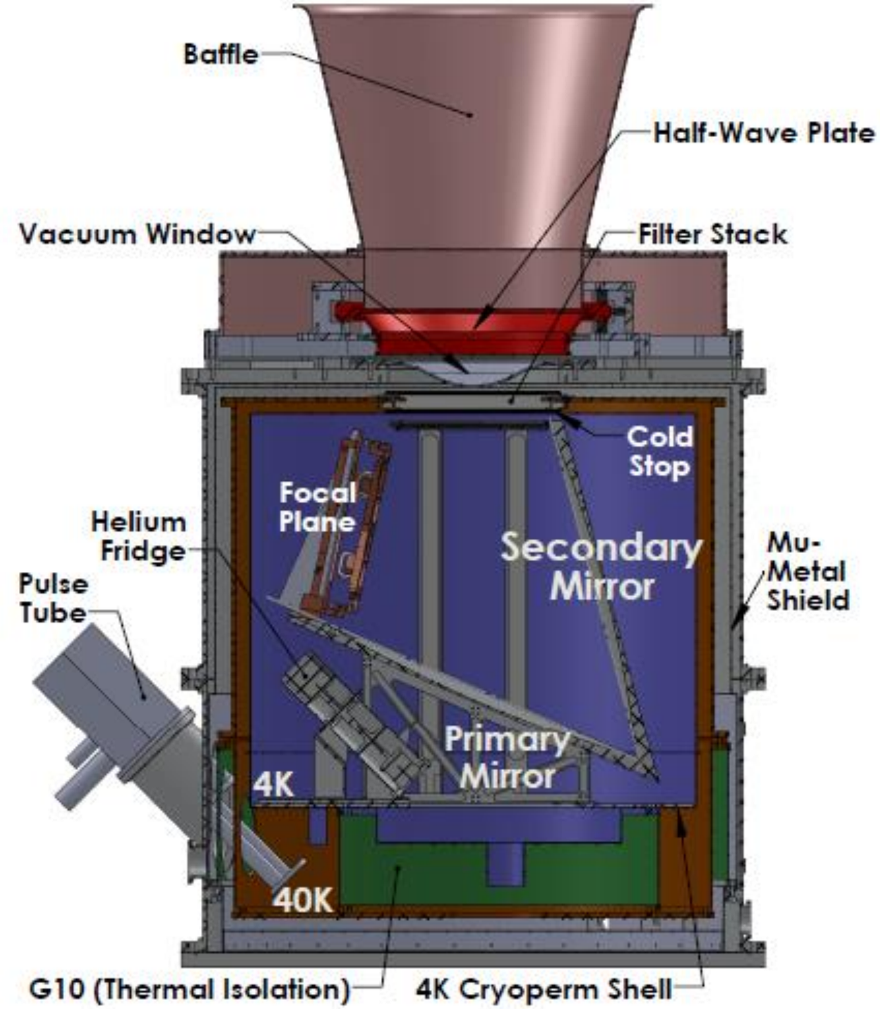
Now stronger than constraints from CMB temperature!

BICEP/Keck program map depths



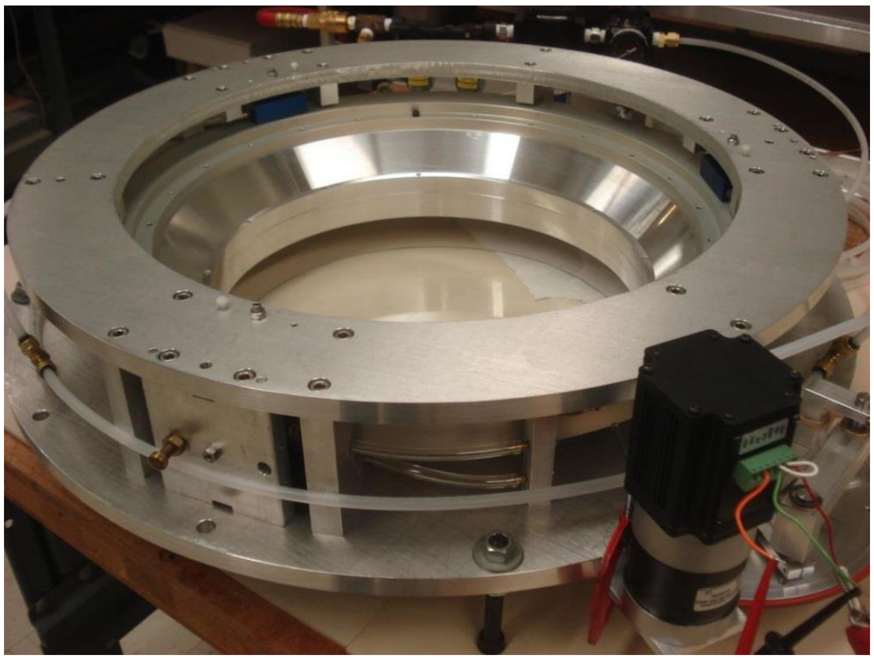
Atacama B-mode Search (ABS)

- 240 feeds / 480 TES
  - @ 300 mK, 150 GHz
- Warm rapid rot. HWP
  - 2.5 Hz continuous
  - Close to aperture
- 4-K cross Dragone
  - D~60 cm mirrors
  - D=25 cm aperture
  - 4-K enclosure
- Obs.: 2012 – 2014

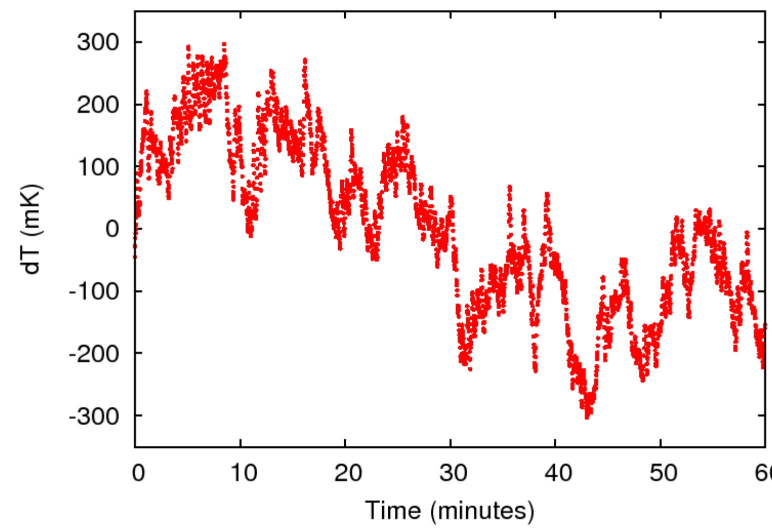


Atacama B-mode Search (ABS)

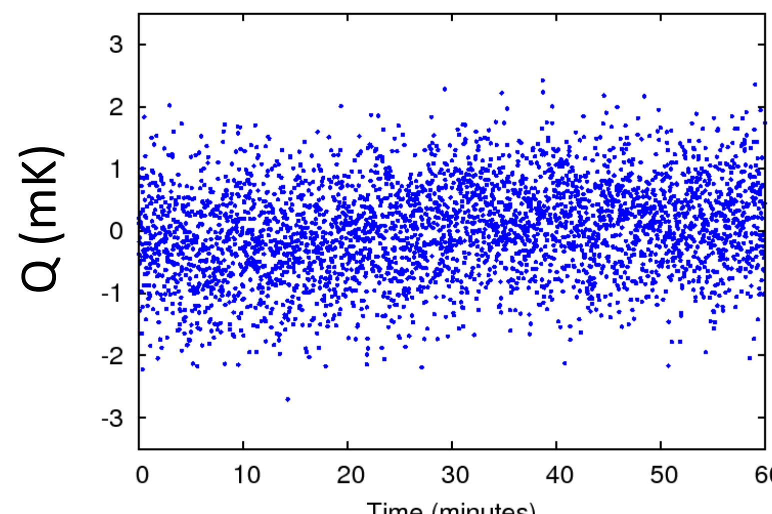
Rapidly rotating warm HWP

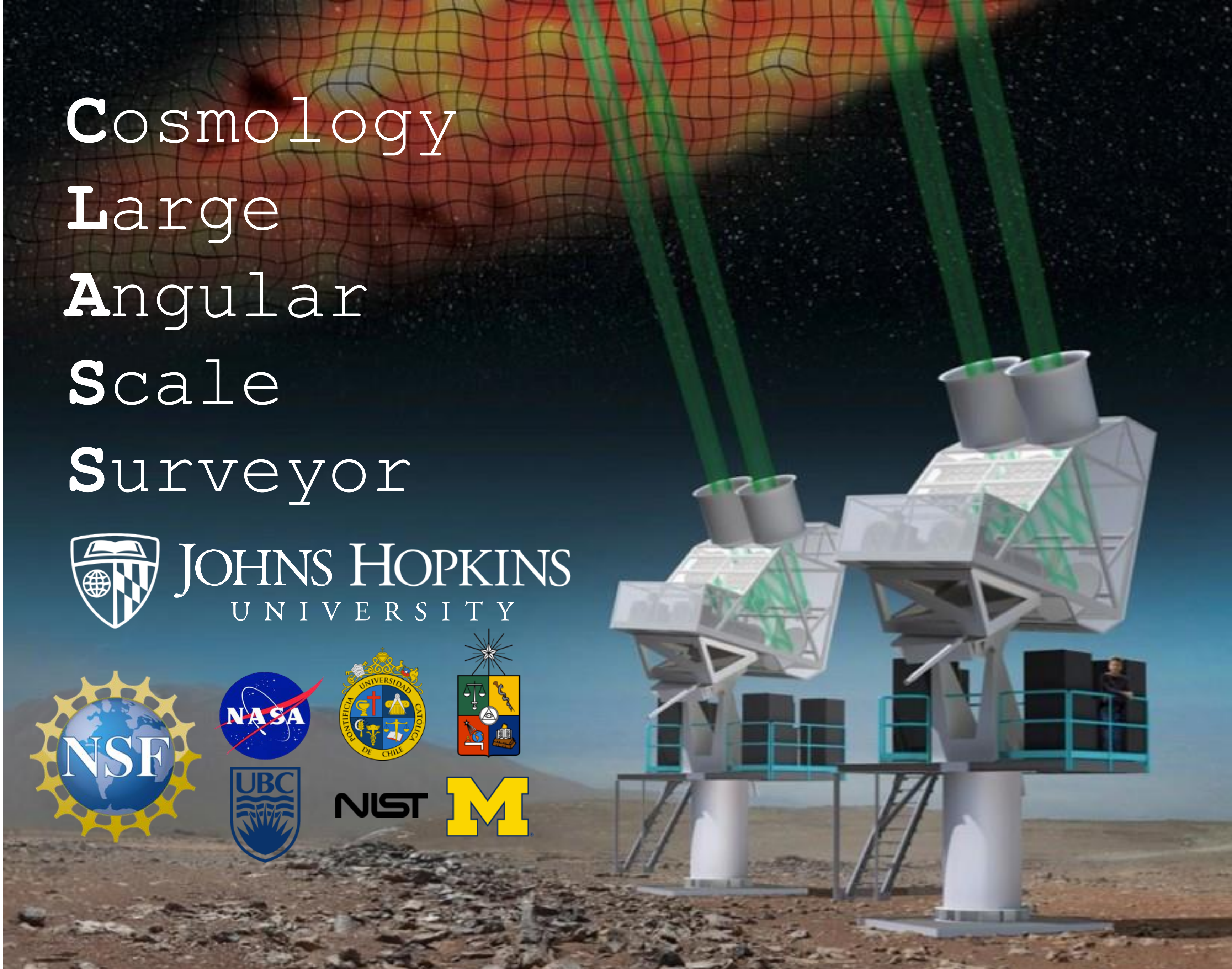


A-cut sapphire (D=330mm)
f~2.5Hz rotation
→ f~10Hz modulation
Air-baring → Stable rotation
No need for pair differencing



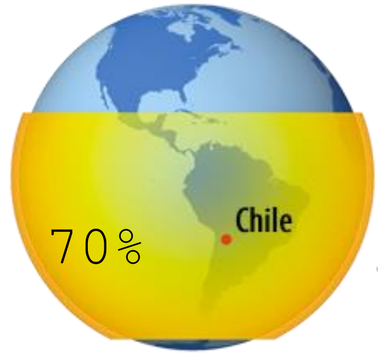
Demodulation

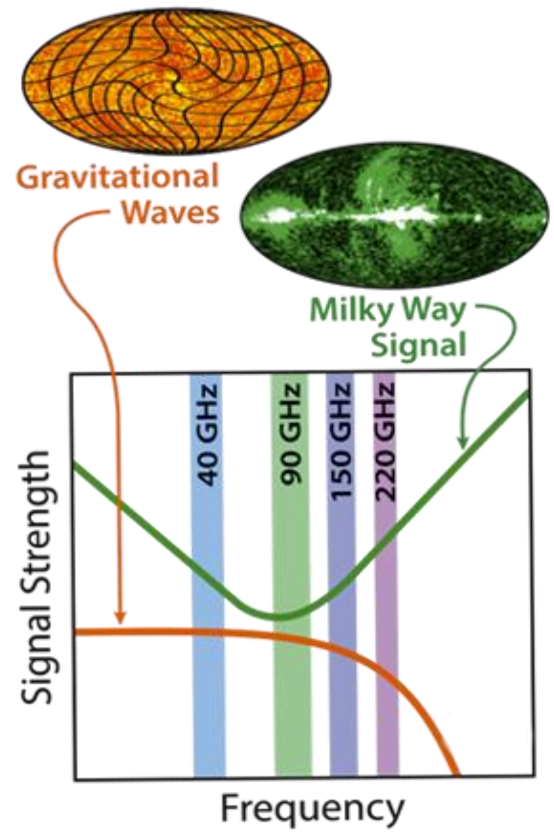


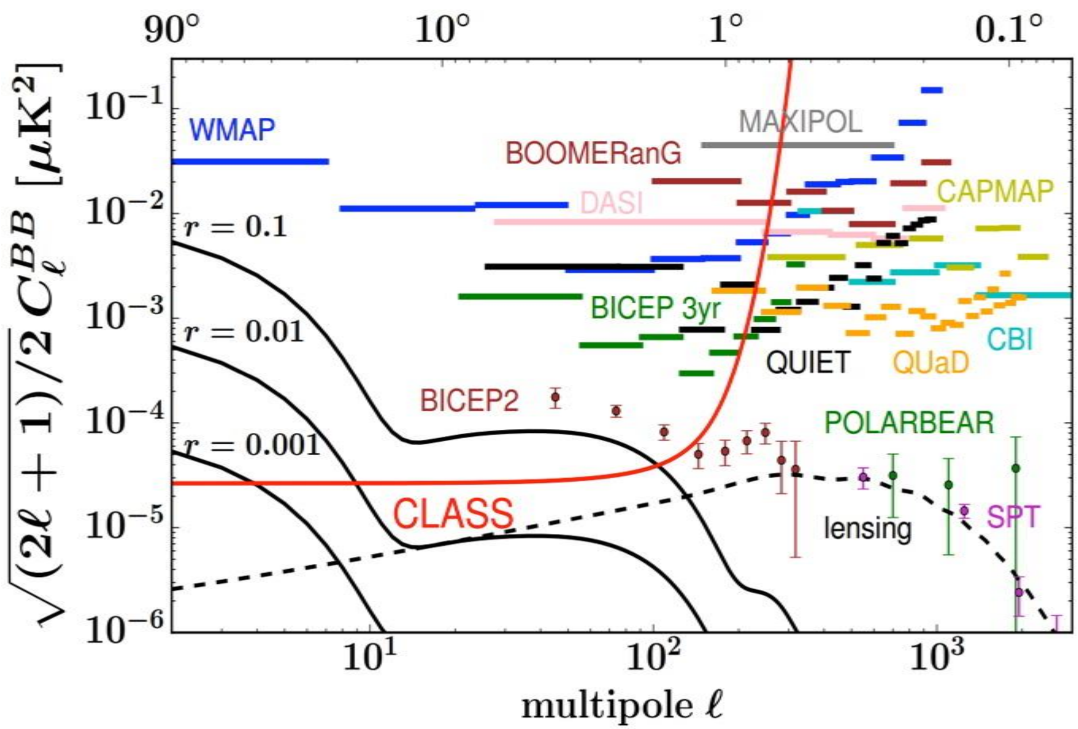

Cosmology
Large
Angular
Scale
Surveyor
JOHNS HOPKINS
UNIVERSITY
NSF
NASA
UBC
NIST
M

CLASS

- ✓ Inflation
- ✓ Reionization







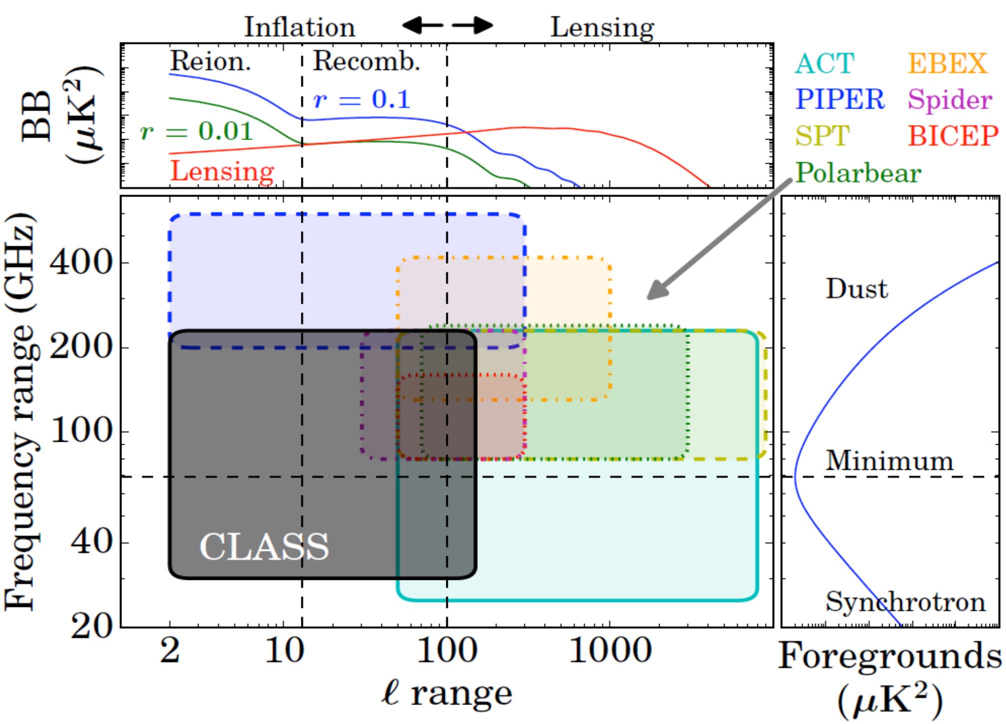
Deploying 2015

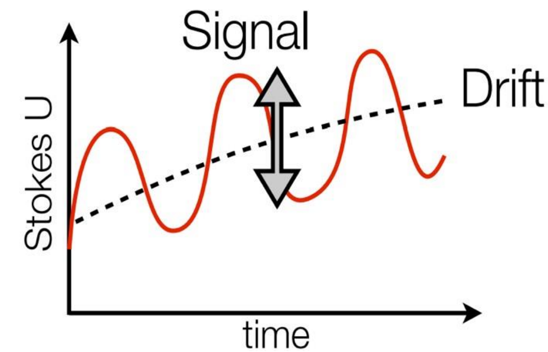
CLASS

✓ Inflation

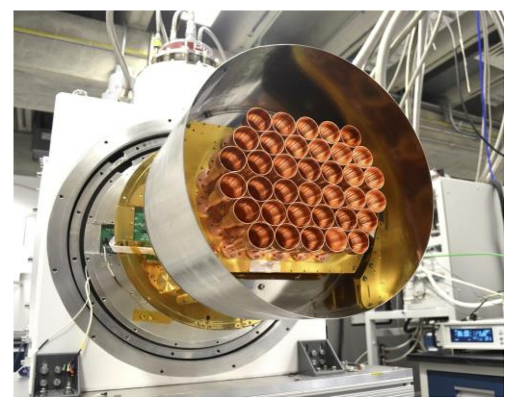
✓ Reionization

Rapid Front-end Modulation = DC-stable Large-scale Measurement





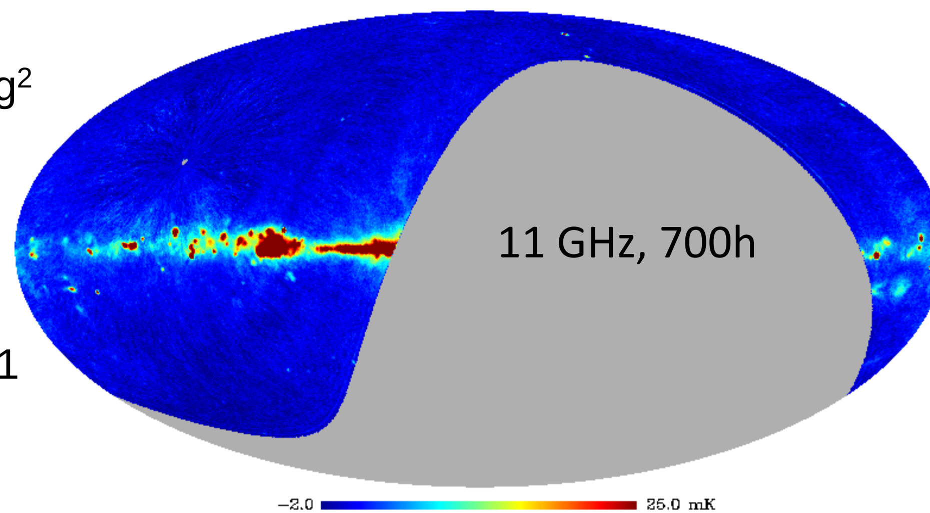
40 GHz Focal Plane



QUIJOTE

- **Q-U-I Joint Tenerife Experiment**
- Teide Observatory (Tenerife, Spain), 2.4km asl
- **Two telescopes** (both operative) and **three instruments**: MFI (10-20 GHz) -operative-, TGI (30 GHz) –commissioning Dec 2015- and FGI (40 GHz) -2016-
- 1-deg angular resolution.
- **Surveys**:
  - Wide survey: 20,000 deg^2, ≈15 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤3 μK/deg^2 @ 30, 40 GHz
  - Deep cosmological survey: 3×1,000 deg^2, ≈5 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤1 μK/deg^2 @ 30, 40 GHz (after 1 year)

- **Scientific goals**:
  - B-modes down to r=0.05 (after 5 years), r=0.1 (after 1 year).
  - Characterization of the synchrotron and AME polarization.

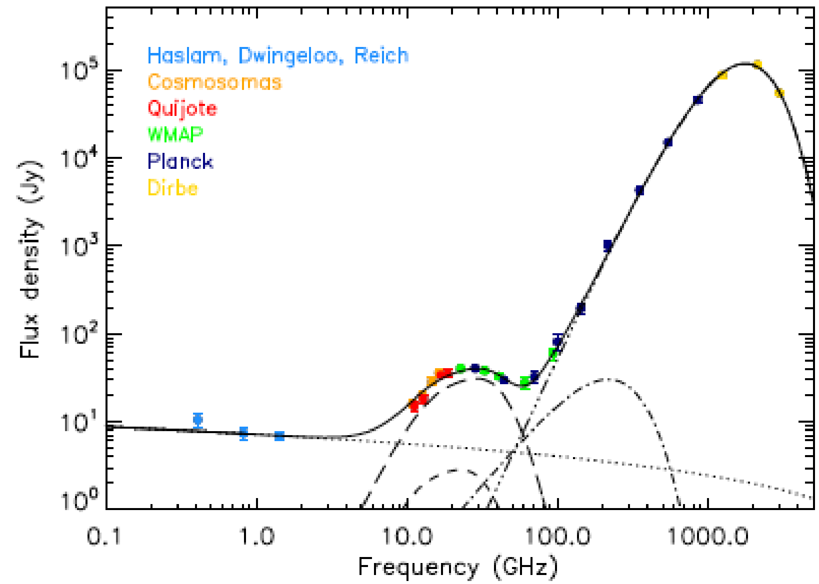


QUIJOTE

- **MFI Instrument (10-20 GHz).**
  - In operations since Nov. 2012.
  - 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
  - Sensitivities: ~400-600 μK $s^{1/2}$ per channel.

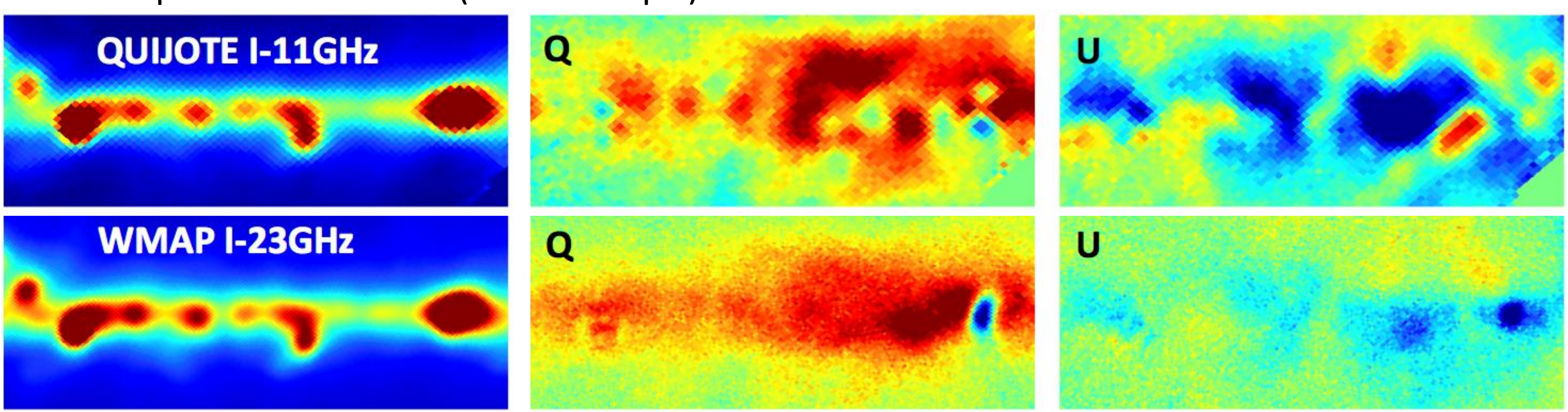
- **TGI (30 GHz) and FGI (40GHz) instruments**:
  - TGI: 31 pixels at 30GHz. Expected sensitivity: 50 μK $s^{1/2}$ for the full array.
  - FGI: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array.

Perseus molecular complex



Génova-Santos et al. (2015), arXiv:150104491

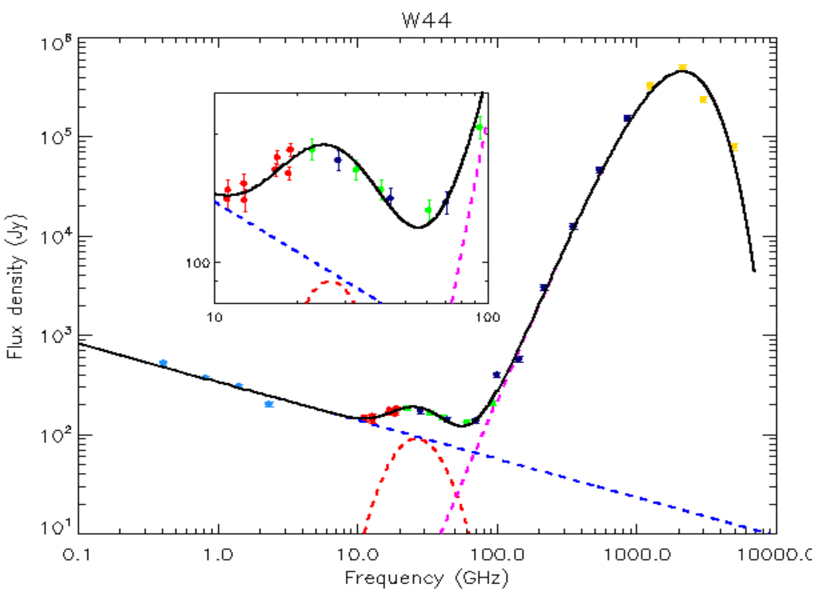
Galactic plane around l=8º (20ºx6º maps):

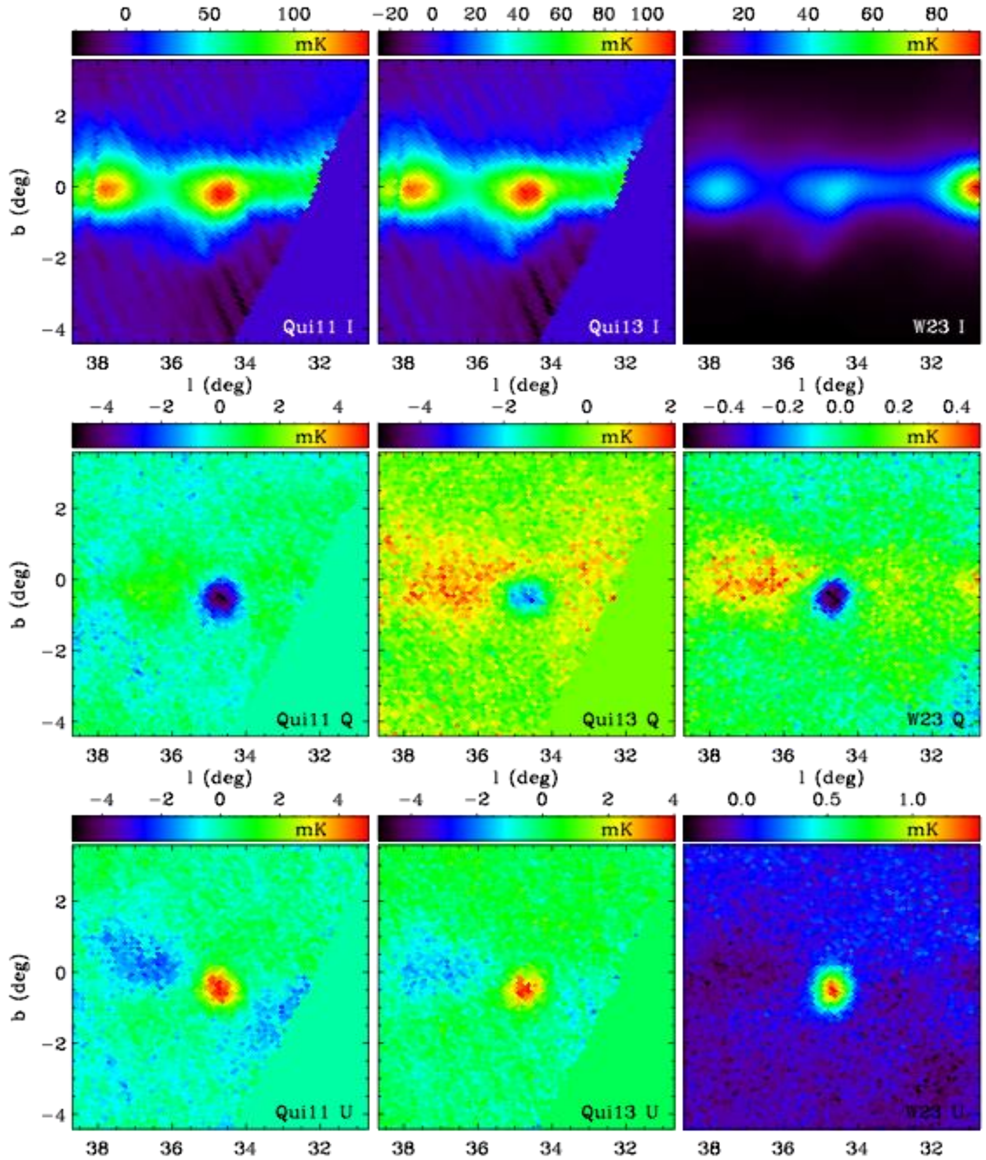


QUIJOTE

MFI results. W44

- Bright SNR on the Galactic plane showing AME (Planck collaboration et al. 2014)
- Confirmed with Quijote (50hrs)
- Possibility of getting tight polarization constraints on the AME, after subtracting out the polarized synchrotron component.

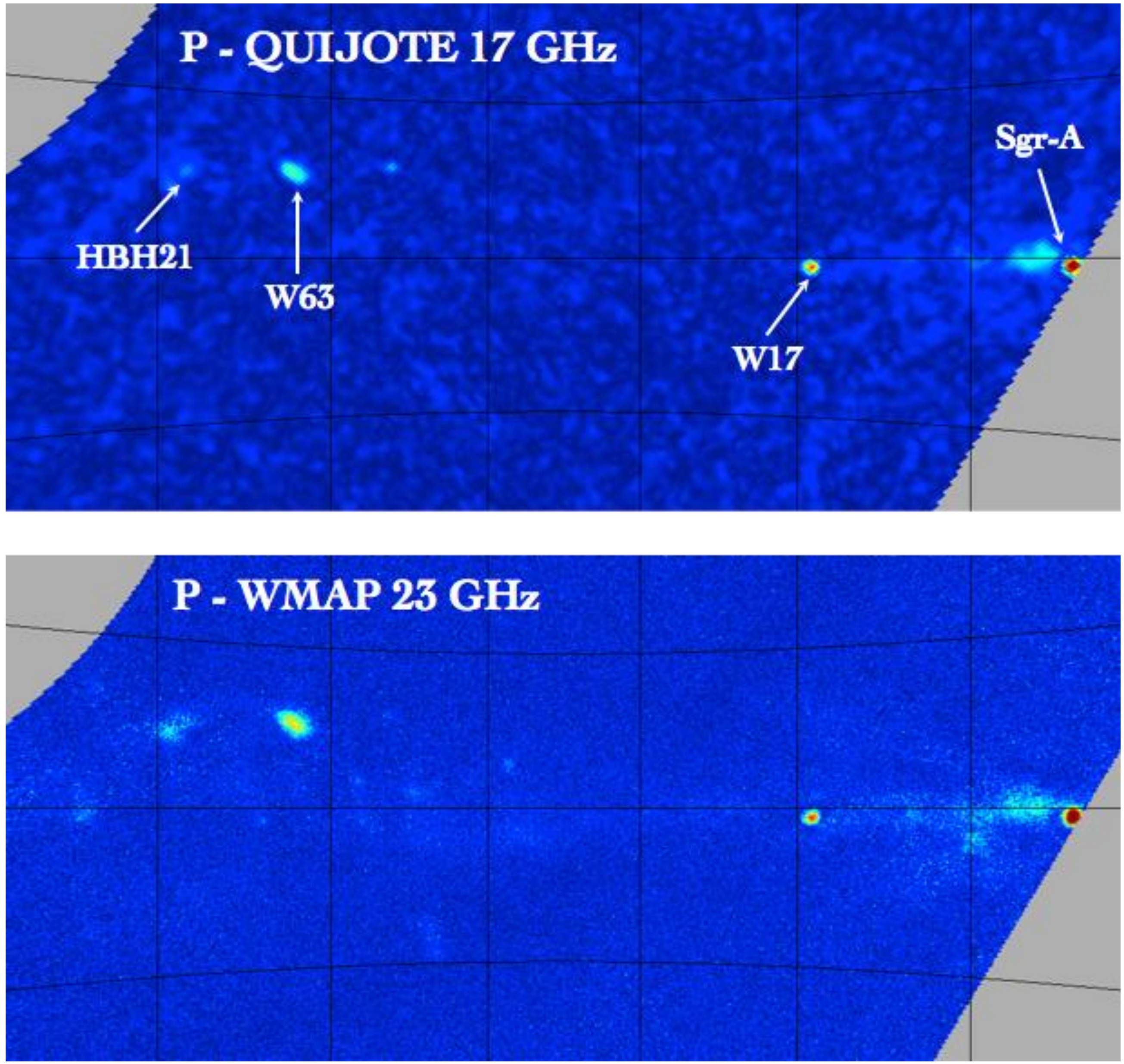




MFI results. Wide survey

○ Polarized intensity at 17GHz (wide survey, 700hr), compared to WMAP 23 GHz.

○ Even with a preliminary map-making, compact objects and u emission is starting to be seen.



Projections: by 2020

- $10^{-3} < \sigma(r) < 10^{-2}$ (Errard et al 2015)
- $\sigma(\Sigma m_\nu) \sim 0.04\ eV$
- $\sigma\left(N_{eff}\right) \sim 0.04$

A next generation (2020s) ground-based CMB experiment, CMB-S4

- What can we do with a larger-scale ground-based CMB experiment?
- How & when can we accomplish it?

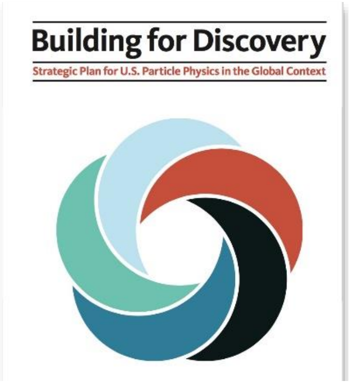
Sensitivity and Notional Timeline

Years	Stage	Sensitivity (μK^2)	$r_{u.lim}$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy FoM
2015–2016	Stage 2, 1000 detectors	$\gtrsim 10^{-5}$	$r \lesssim 0.1$	0.14	0.15eV (BOSS BAO prior)	~130 (Stage-3 DE (CMB+BAO+SN+WL))
2017–2020	Stage 3, 10,000 detectors	10^{-6}	$r \lesssim 0.01$	0.06	0.06eV (BOSS BAO prior)	~350 (Stage-3 DE +DESI-BAO)
2021–2024	Stage 4, CMB-S4, ~500,000 detectors	10^{-8}	$r \lesssim 0.001$	0.02	0.015eV (DESI BAO prior)	~1250 (Stage-4 DE (CMB+BAO+SN+WL+CL))

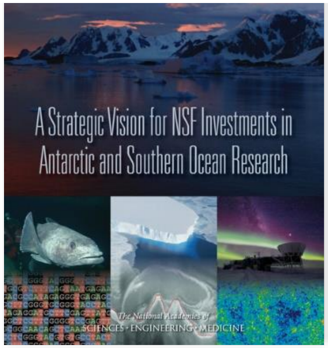
CMB-S4 achieves critical thresholds in r, N_{eff} and Σm_ν and a substantial increase in the dark energy figure of merit

Stage IV CMB experiment: CMB-S4

- Build on CMB stage II & III projects: inflation, neutrino properties and dark energy.
- Multiagency effort (US Department of Energy (DOE) and National Science Foundation (NSF)).
- To accomplish CMB-S4 we will need broad participation by the US CMB community, including the existing NSF-funded CMB groups, DOE National Labs and the High Energy Physics community.
- Complementary with balloon and space-based instruments.
- International partnerships expected.



Recommended by the DOE Particle Physics Project Prioritization Panel (P5) report for funding under all budget scenarios considered, and by the National Resource Council's Antarctic Reports

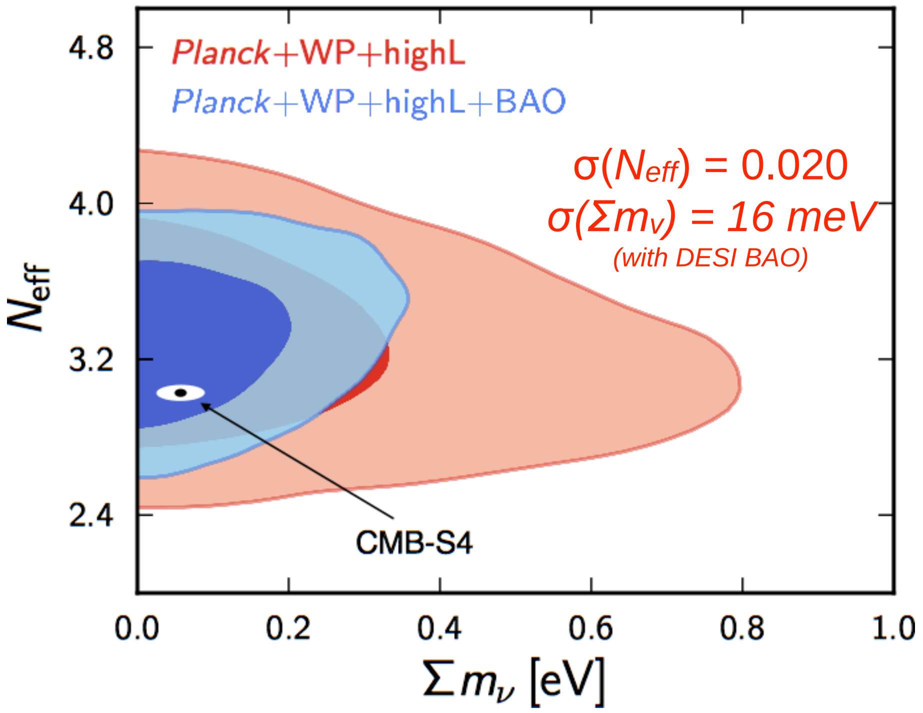


Cosmological constraints

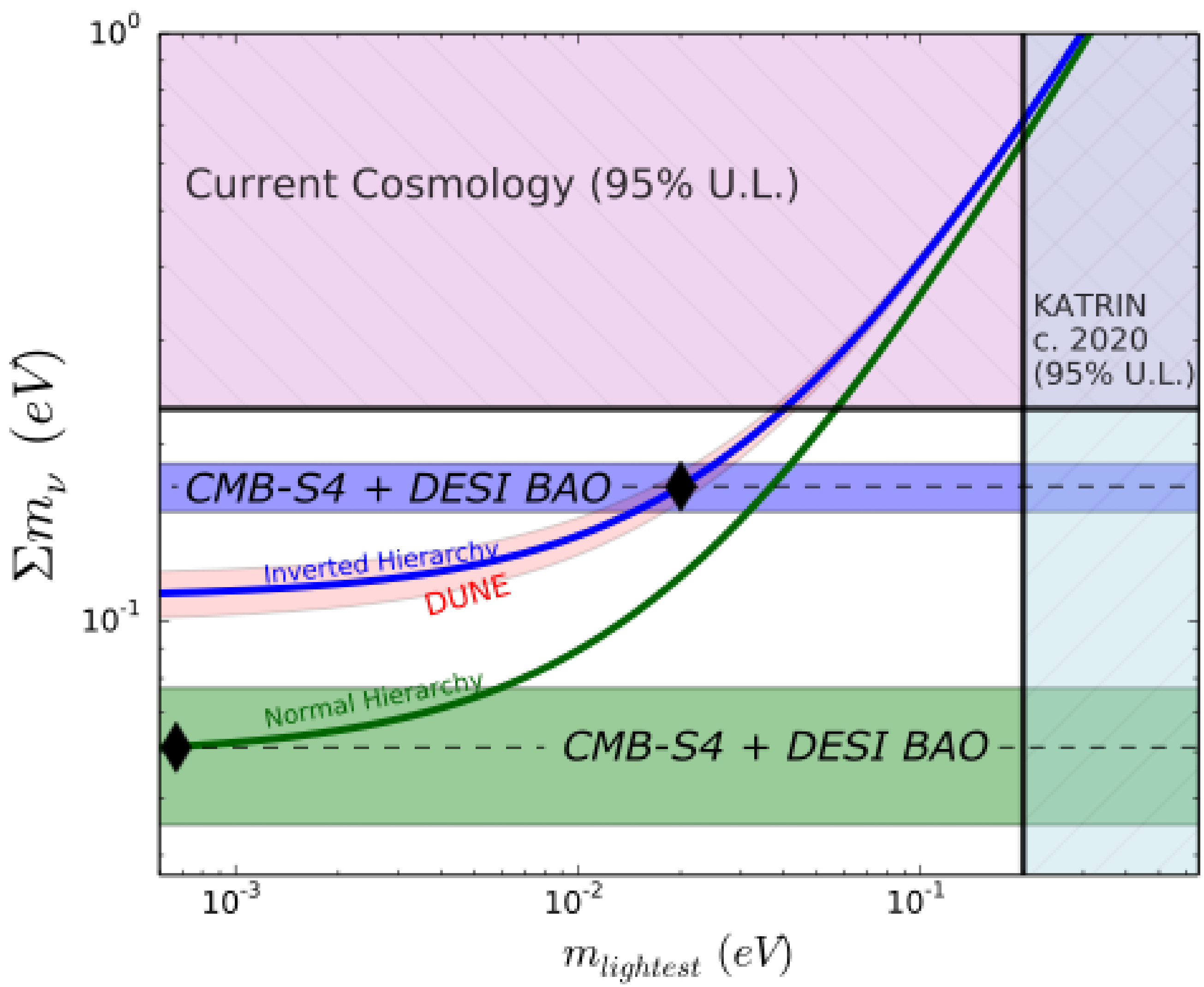
- $\sigma(r) < 2 \cdot 10^{-4}$ (Errard et al)
- $\sigma(N_{eff}) < 0.02$
- $\sigma(\Sigma m_{\nu}) < 0.02\ eV$
- Complements galaxy surveys with independent systematic errors.
- Complements neutrino oscillation experiments of the Intensity Frontier as well as Katrin mass limits.

Initial CMB-S4

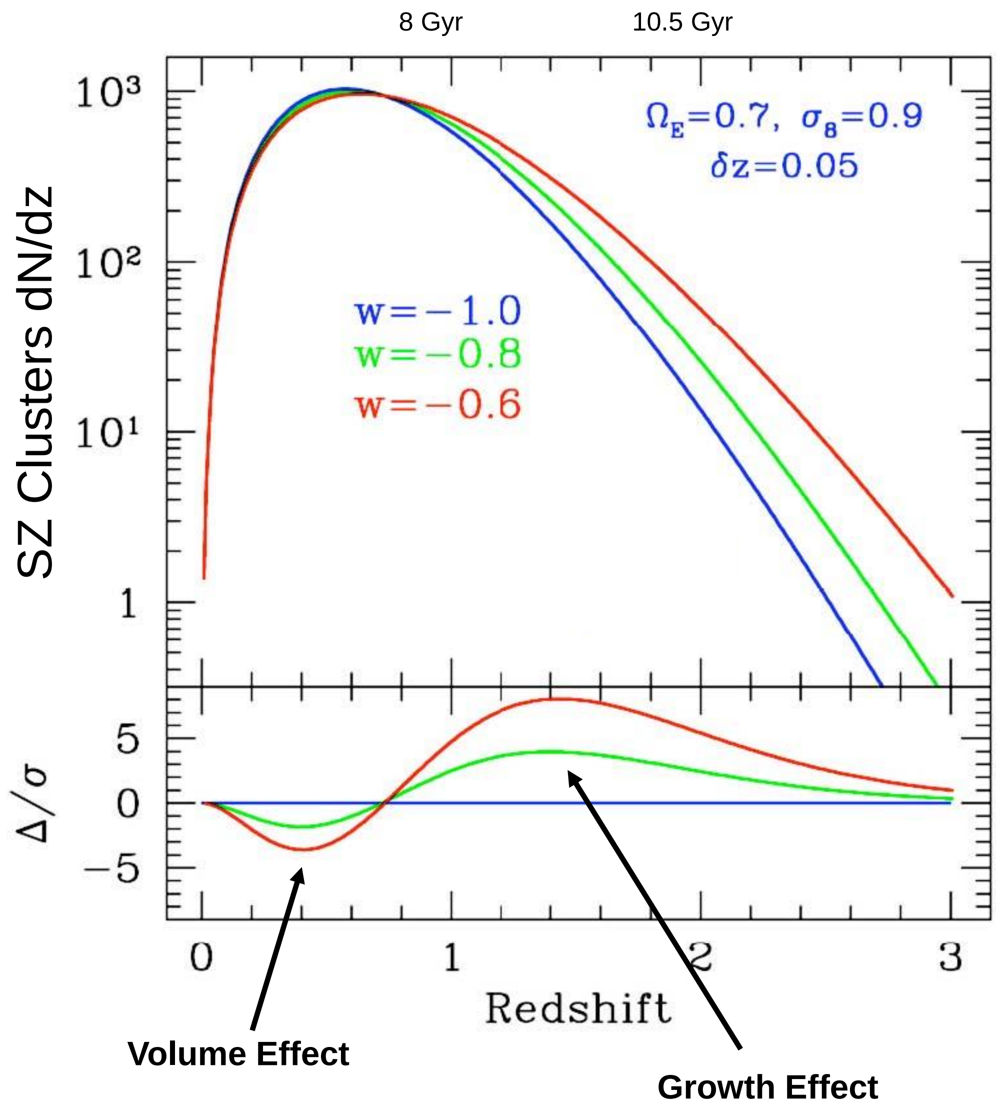
N_{eff} - Σm_{ν} projections



Snowmass combined Neutrino mass constraints

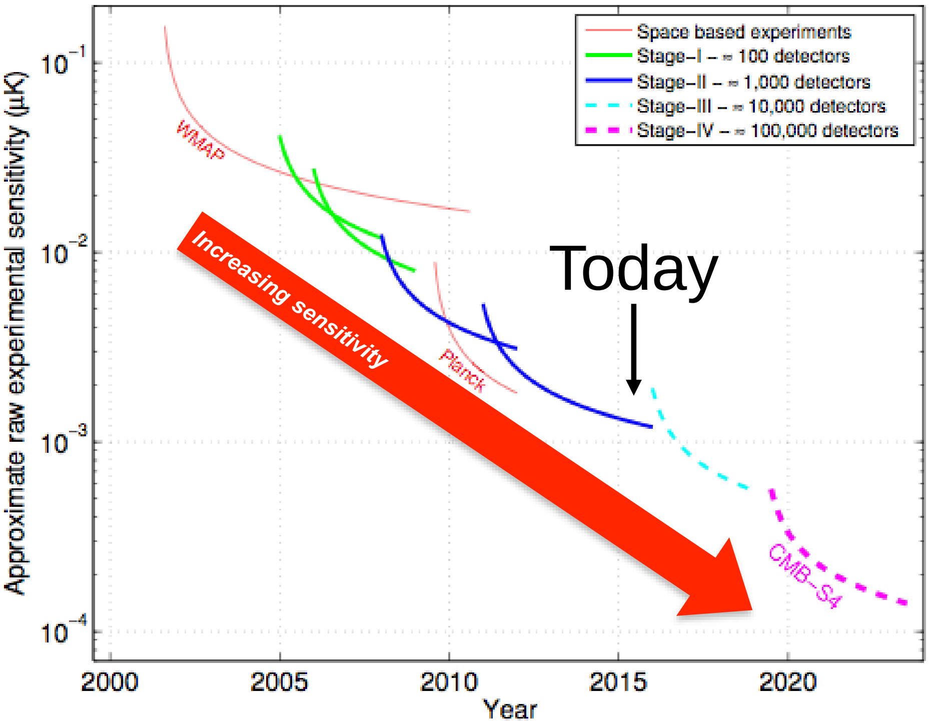


Dark Energy and Gravity



What's needed to realize CMB-S4

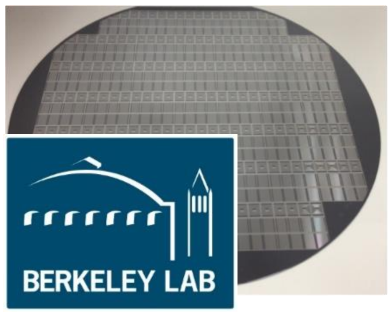
- **Scaling up:**
  - detectors, focal planes
  - multiple telescopes; new designs
  - sky area and frequency coverage
  - computation, data analysis, simulations
  - project management
- **Systematics:**
  - improved control, especially of foreground mitigation
- **Theory/phenomenology:**
  - Increased precision for analysis; new methods

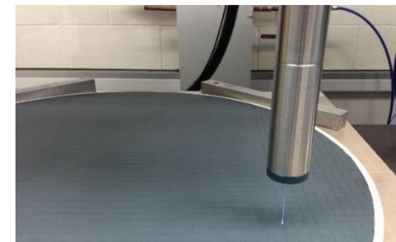


CMB-S4: A stage IV program to deploy <u>*O*(500,000) detectors</u> spanning 30 - 300 GHz using <u>multiple telescopes and sites</u> to map ≳70% of sky.

CMB-S4 requirements exceed capabilities of the traditional university-based CMB groups

→ DOE National Labs and HEP community working with the university-based CMB groups





- High Volume Fabrication of Detector Arrays
- Multiplexed Superconducting Readout Electronics
- High Volume Assembly and testing of Detector Modules
- Receiver Development (Optics, Polarization Modulators, …)
- High Performance Computing
- Project Management

Moving CMB-S4 forward

CMB-S4
Next Generation CMB Experiment

Community coming together to define the science goals and instrument definition, writing the CMB-S4 Science Book.

Next workshop March 7-8, 2016 at Berkeley LBNL

Conclusions

- There will be a race between space and ground for inflationary science – this is healthy
- The strengths and weaknesses of the two approaches are complementary
- Eventually, the combination of the two data sets will provide the lasting scientific reach.