Cosmological Parameters from the Atacama Cosmology Telescope DR4 CMB Power Spectra

Steve Choi
(Cornell University)

for the ACT Collaboration

Aug 6th 2020 – act.princeton.edu

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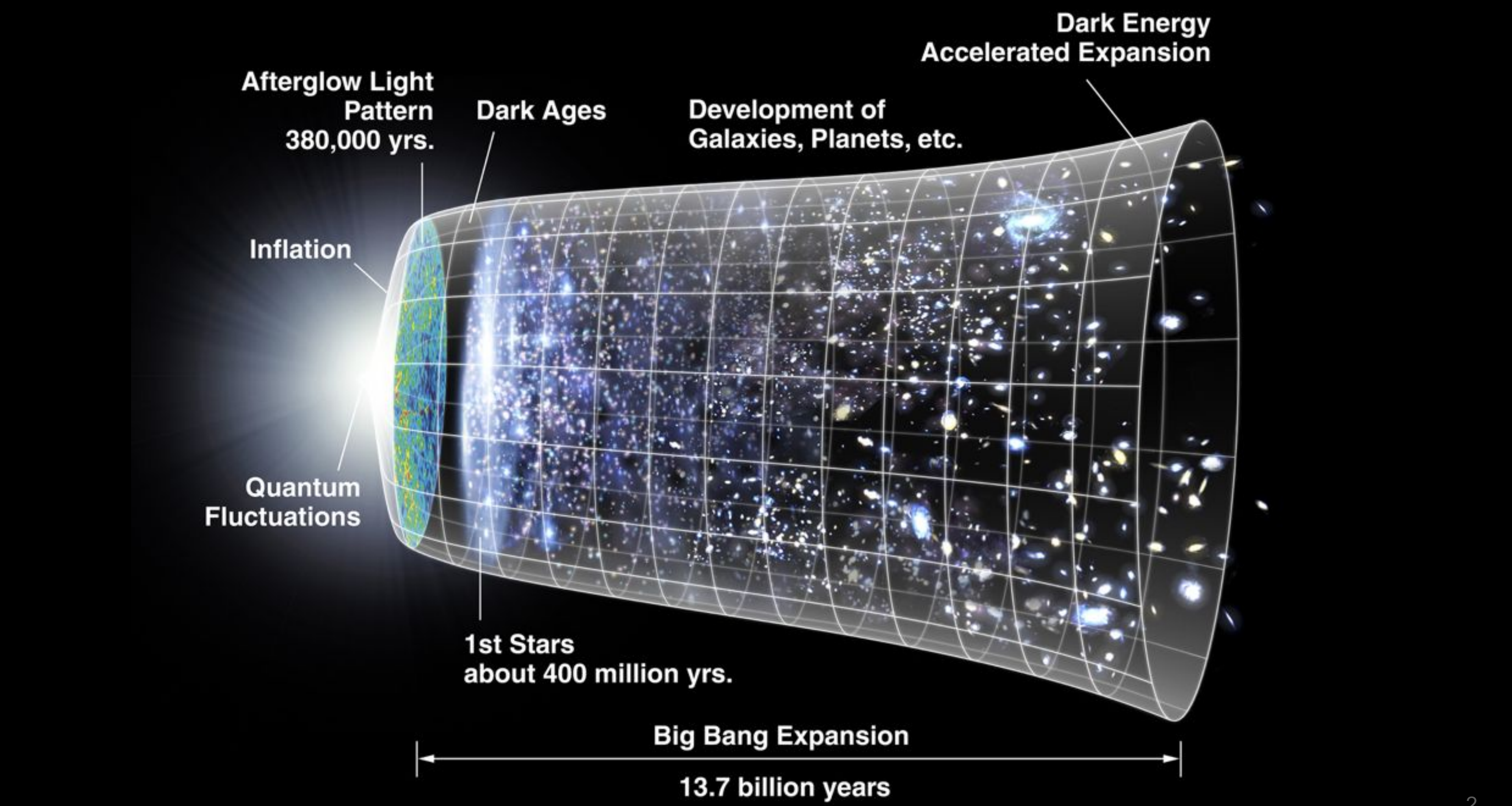
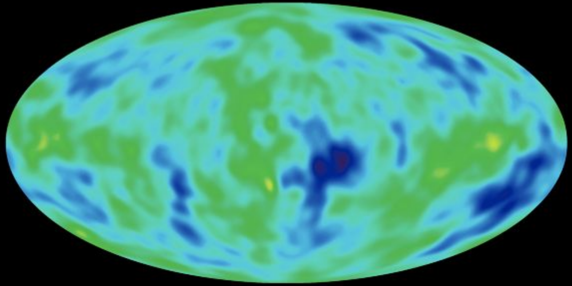
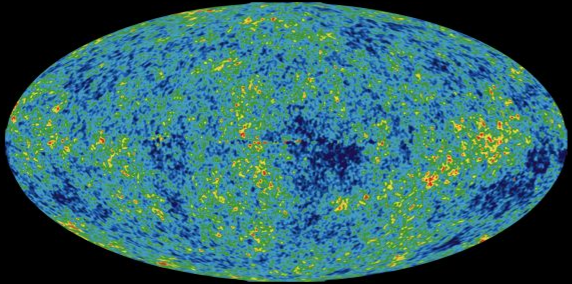


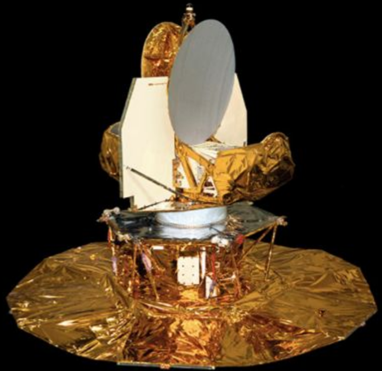
Image: WMAP Science Team

COBE
(1989-1993)

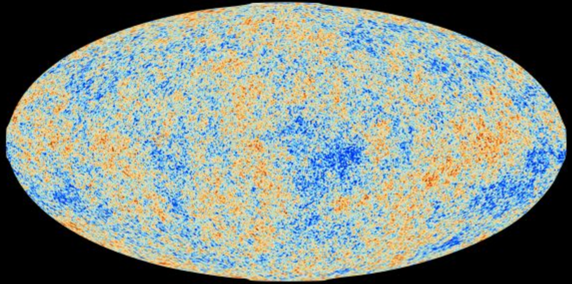


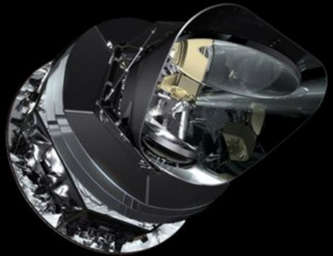
WMAP
(2001-2010)



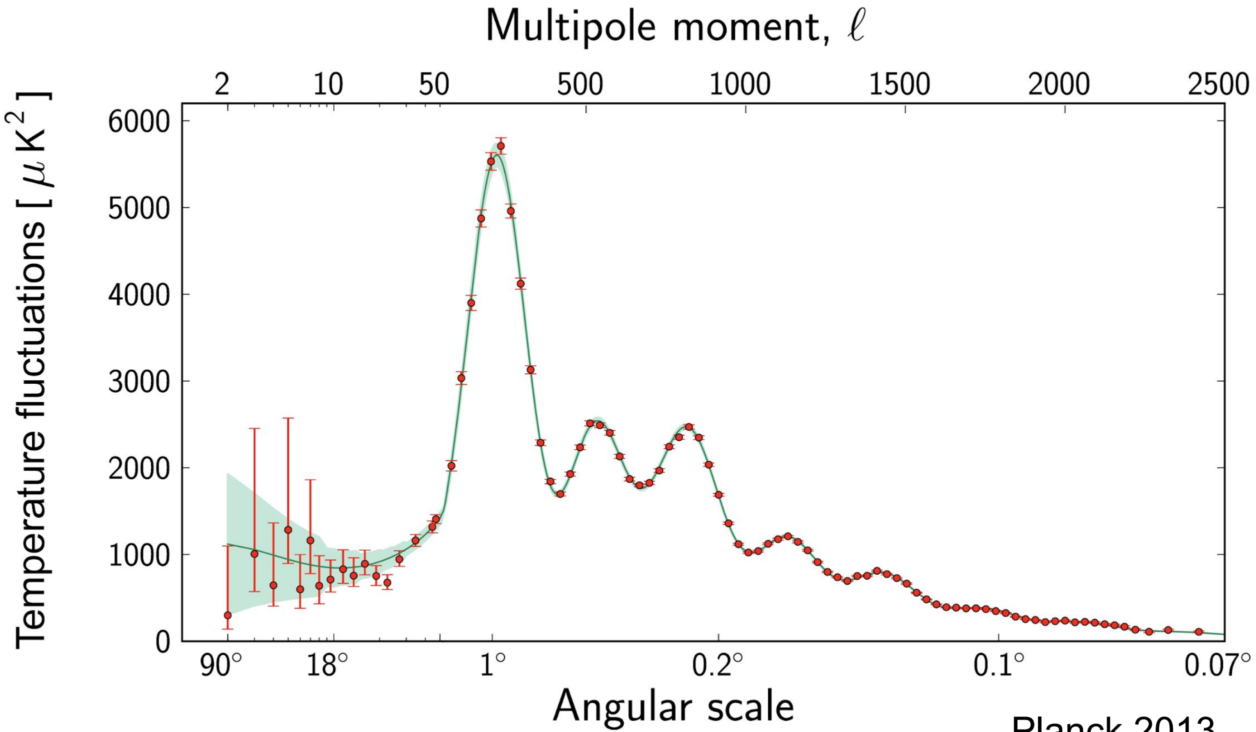


Planck
(2009-2013)





CMB power spectrum

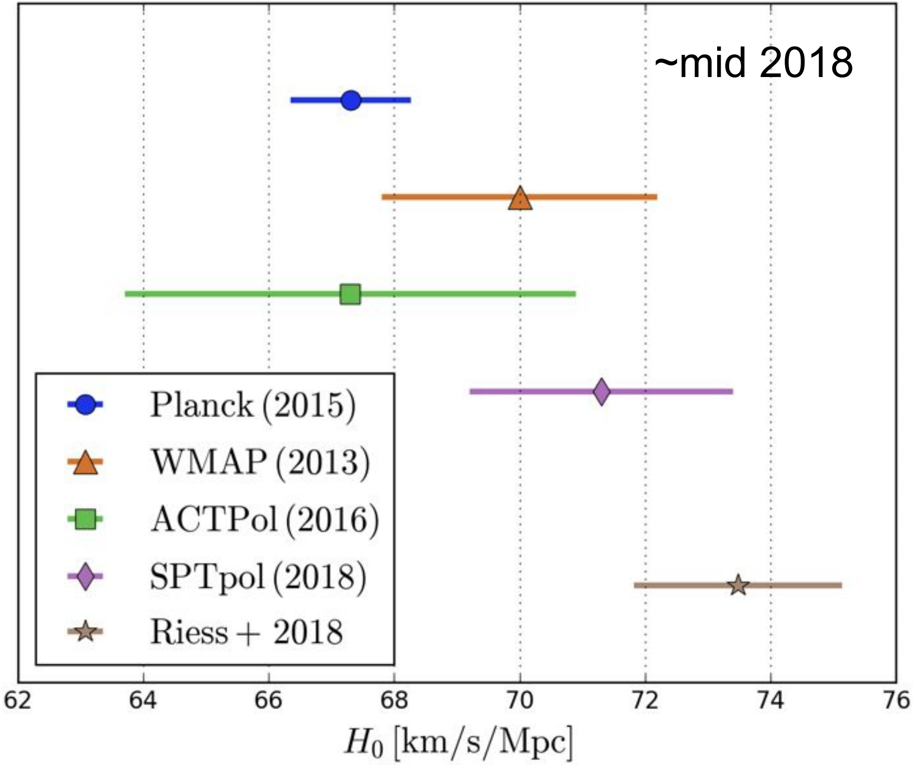


Planck 2013

Hubble constant

CMB:
Measuring (angular diameter) distance to surface of last scattering from the angle and size of the horizon determined from the power spectra.

Bigger distance means the light took longer to get to us (older Universe) and smaller expansion rate as the Universe had more time to grow to the size we have today.



Distance ladder:
Measuring distance and redshift to nearby galaxies.

Hubble cons

CMB:
Measuring (angular diameter) distance to surface of last scattering from the angle and size of the horizon determined from the power spectra.

Bigger distance means the light took longer to get to us (older Universe) and smaller expansion rate as the Universe had more time to grow to the size we have today.

Distance ladder:
Measuring distance and redshift to nearby galaxies.

ACT Collaboration

Argonne CITA ICAT CARDIFF UNIVERSITY HAVERFORD NIST RUTGERS SLAC Stony Brook University UBC Penn WCU WEST CHESTER UNIVERSITY

Atacama Cosmology Telescope

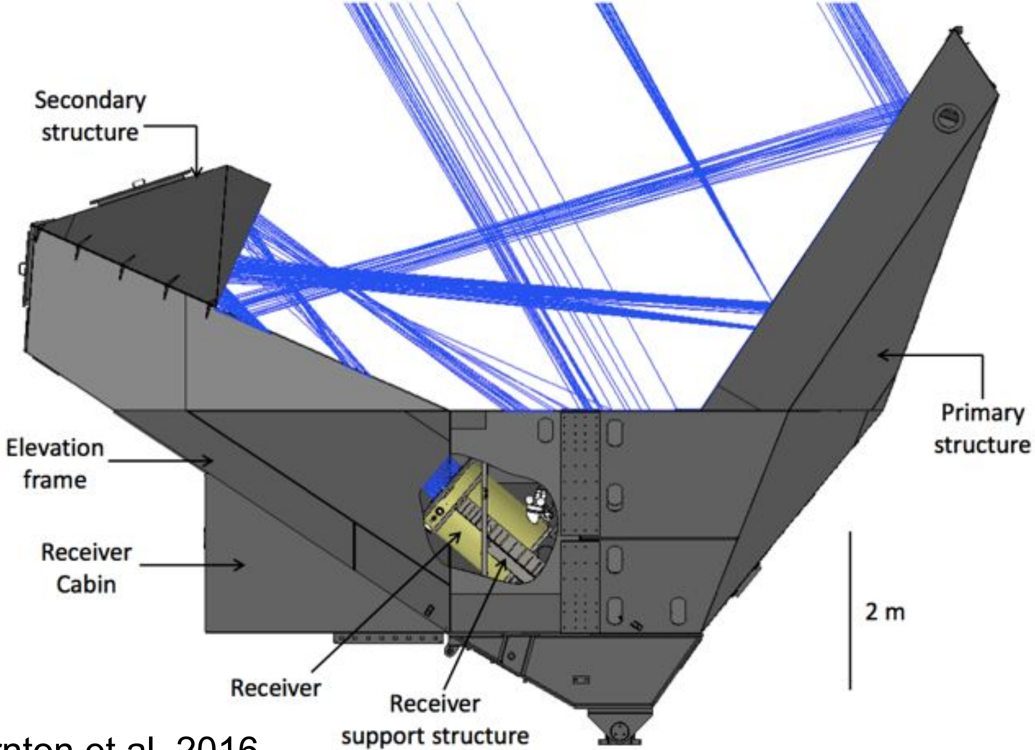
ACT Site

ACT, Polarbear, CLASS, Simons Observatory (~5200 m)

CCAT-prime (~5600 m)

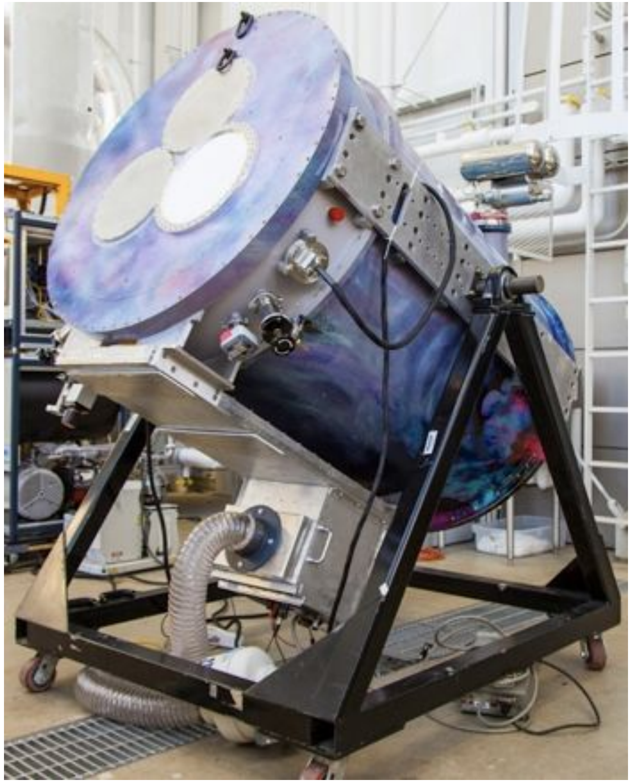
ACT Instrument

6 m off-axis Gregorian telescope
(1.4 arcmin beam at 150 GHz)



Thornton et al. 2016

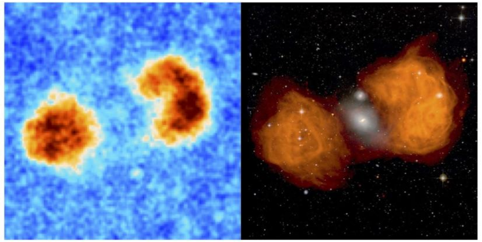
3 instrument modules (optics tubes)
TES arrays (98 and 150 GHz) at 100 mK



ACT DR4 Papers

- Aiola et al. 2020 – Maps, data products, and baseline parameters
- Choi et al. 2020 – Power spectra, consistency tests, and parameters
- Naess et al. 2020 – 17,000deg^2 high-resolution maps with ACT+Planck
- Darwish et al. 2020 – Lensing maps over 2,000 deg^2 and cross-correlation with BOSS
- Namikawa et al. 2020 – Birefringence constraints
- Madhavacheril et al. 2019 – Component-separated maps: CMB and tSZ
- … and a lot more!

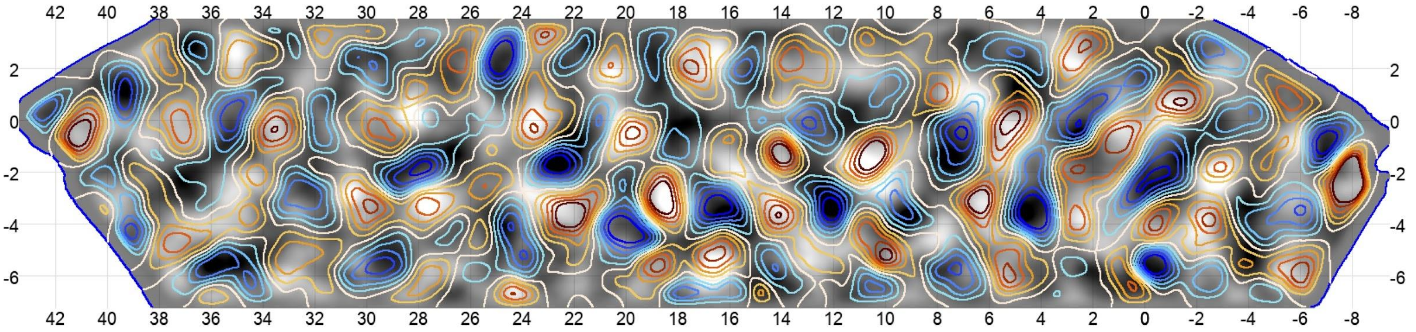
Fornax A



ACT+Planck f090 - f150 Radio+Optical

Naess et al. 2020

CMB Lensing Map; contours CIB from Planck



Darwish et al. 2020

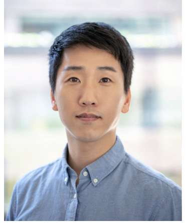
ACT DR4 Papers

Material in these slides is presented in two connected papers

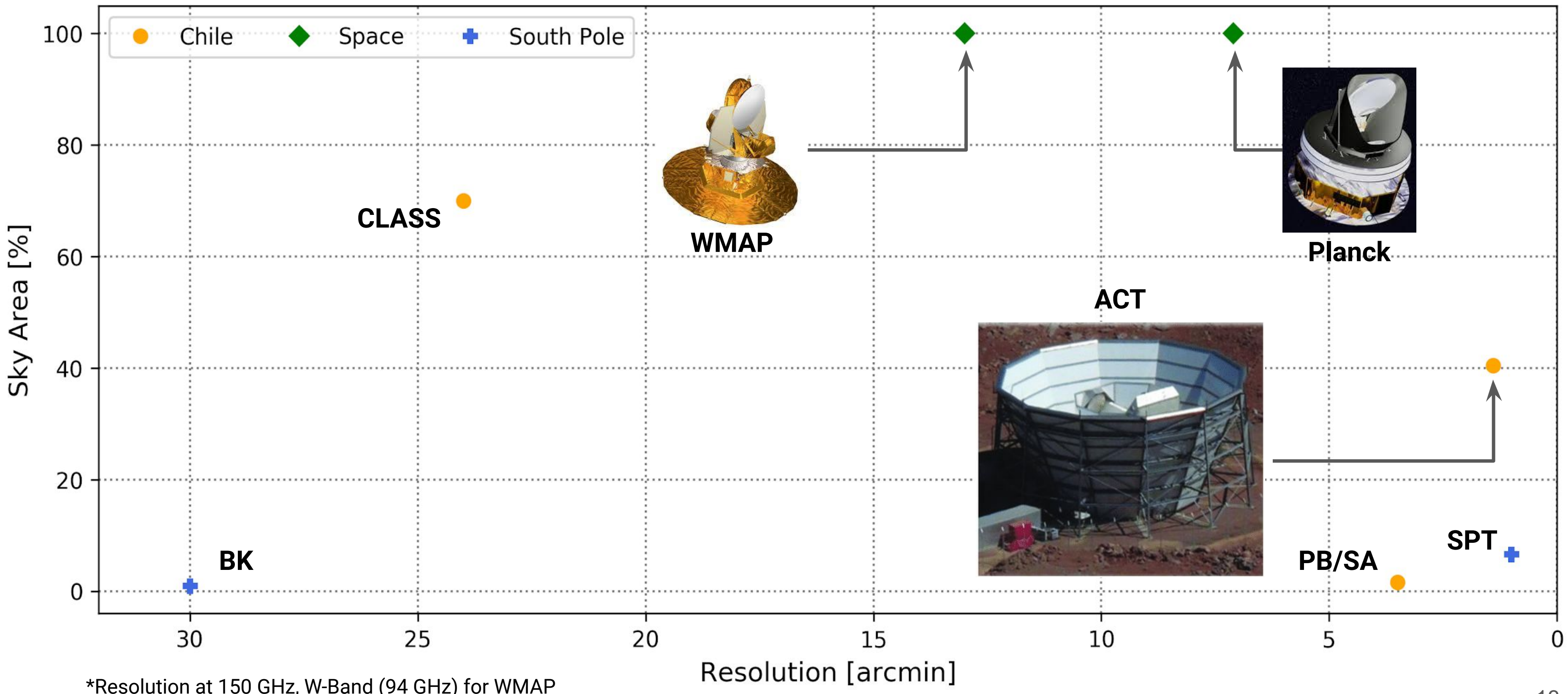
- Aiola, Calabrese, Maurin, Naess, Schmitt **+ ACT** **(arXiv: 2007.07288)**

     ++

- Choi, Hasselfield, Ho, Koopman, Lungu **+ ACT** **(arXiv: 2007.07289)**

     ++

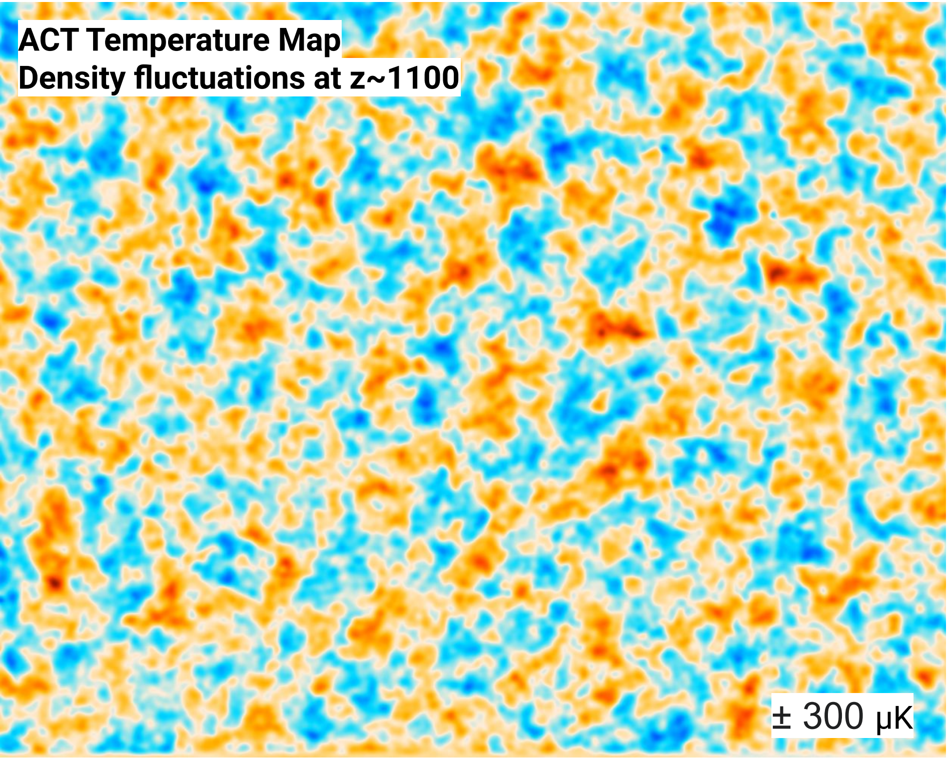
CMB Experiments

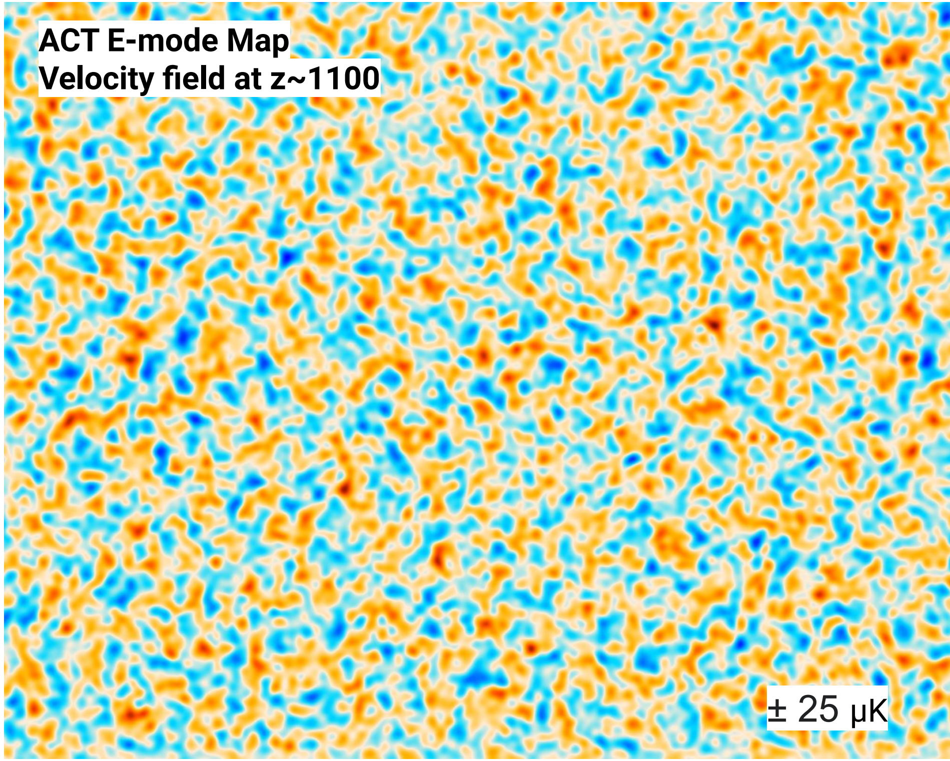


*Resolution at 150 GHz, W-Band (94 GHz) for WMAP

ACT DR4 Measurement

Wiener filtered 150 GHz maps

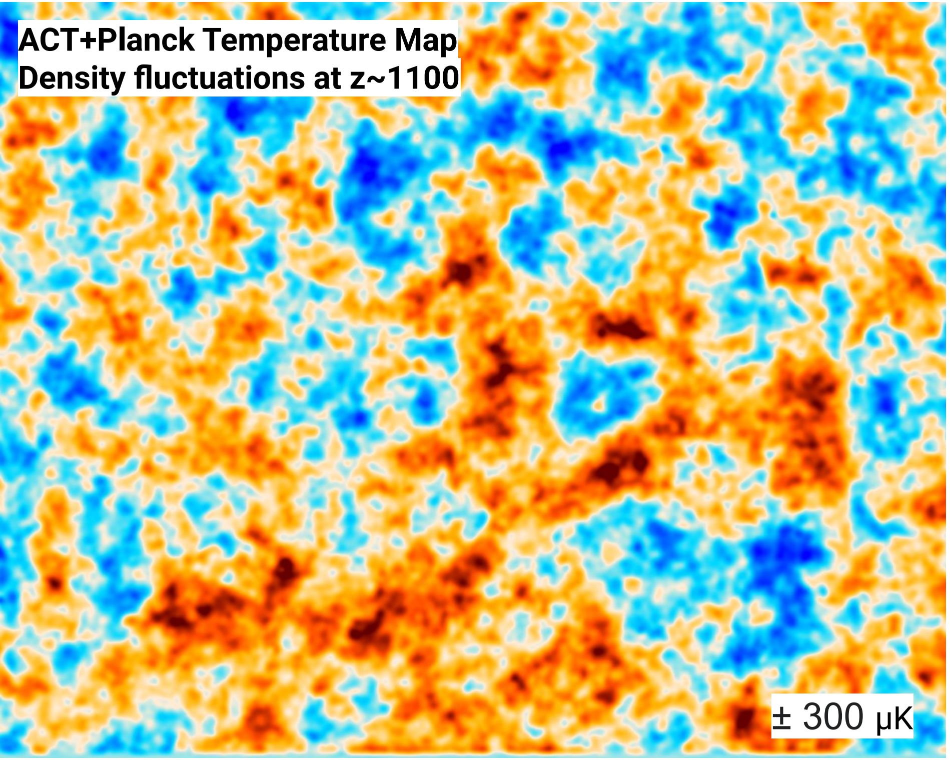


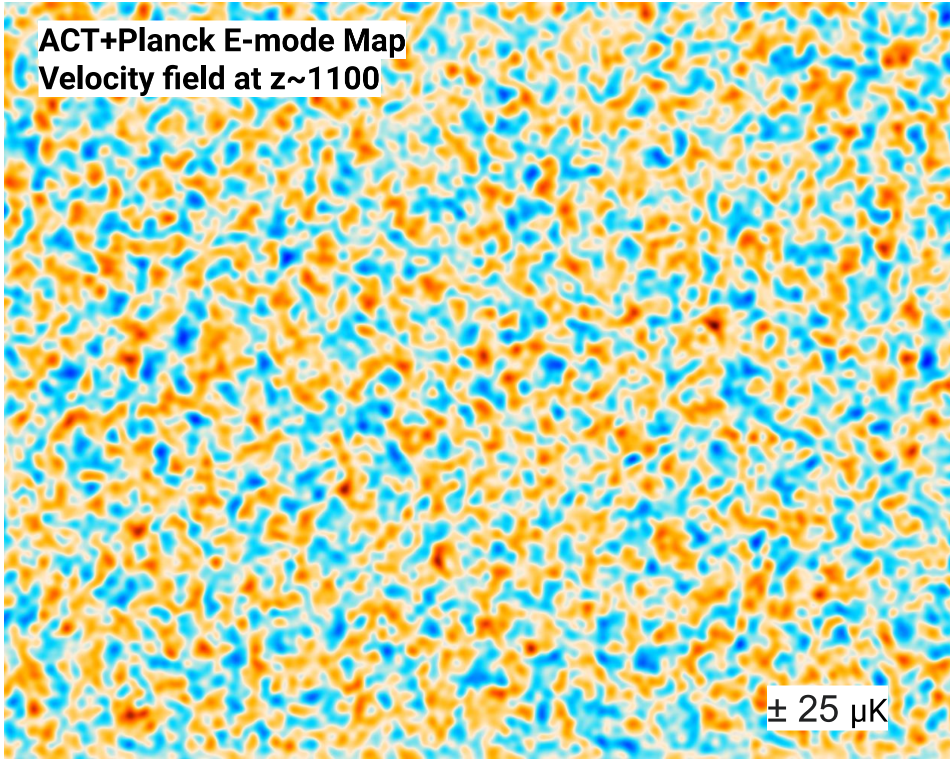


*Only showing 150 deg^2

ACT DR4 Measurement

Wiener filtered 150 GHz maps





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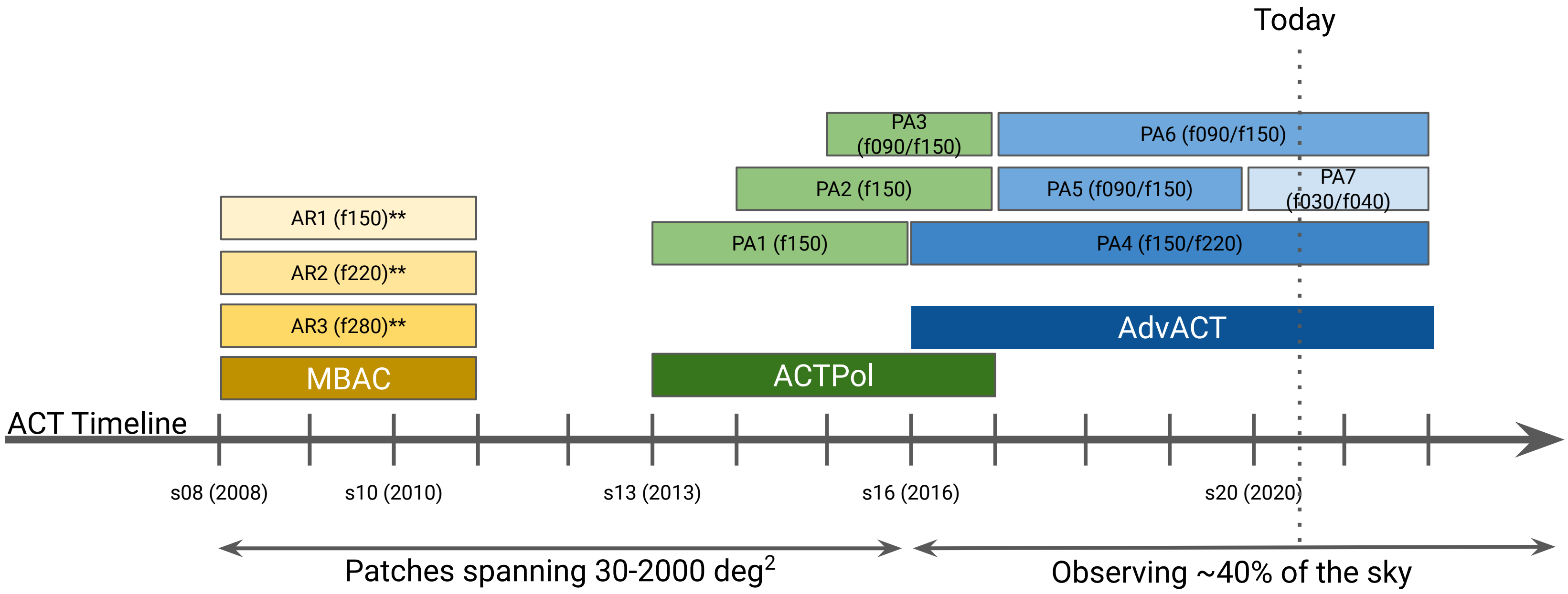
ACT Datasets

A brief overview of past, current, and future ACT datasets



*timeline is just indicative, observations do not start on Jan
**no polarization

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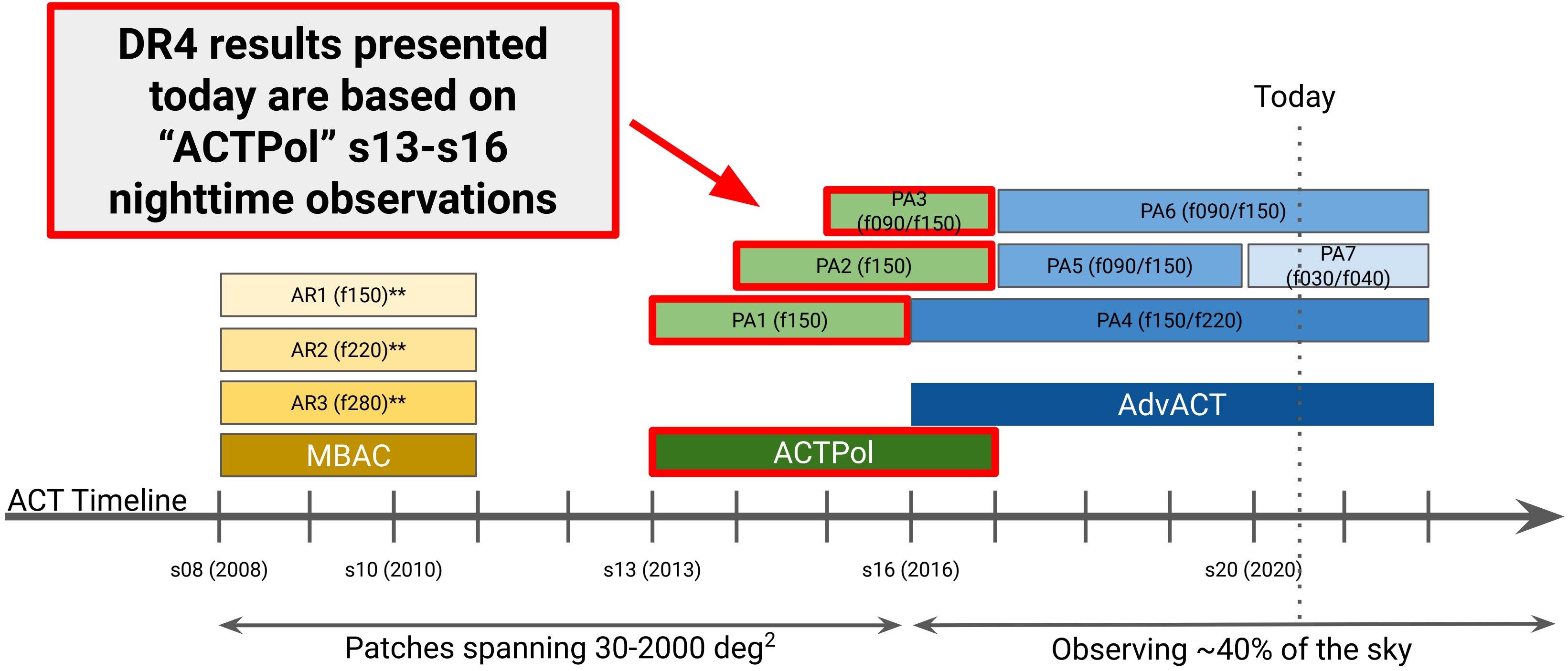

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ACT DR4 Publicly Released

Roughly 0.5TB of data products and 4.5TB of simulations made available to the community at **lambda.gsfc.nasa.gov**

DR4 2013-2016 Maps

Product Download Page	Description
Season 13 Maps	Frequency Maps at 98 and 150 GHz for Season 13 More...
Season 14 Maps	Frequency Maps at 98 and 150 GHz for Season 14 More...
Season 15 Maps	Frequency Maps at 98 and 150 GHz for Season 15 More...
Season 16 Maps	Frequency Maps at 98 and 150 GHz for Season 16 More...

DR4 2013-2016 Derived Maps

Product Download Page	Description
Coadd Maps	s08-s16 Coadd Maps presented in Naess et al. 2020 More...
Component Separated Maps	TILe-C Component Separated Maps presented in Madhavacheril et al. 2019 More...
Lensing Maps	Lensing Maps presented in Darwish et al. 2019 More...

DR4 2013-2016 Ancillary Products

Product Download Page	Description
Masks	Data Analysis Masks More...
Window Functions	Data Analysis Window Functions More...

DR4 2013-2016 Derived Spectra

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Multifrequency Spectra	Multifrequency Spectra presented in Choi et al. 2020 More...
CMB-only Spectra	CMB-only Spectra presented in Choi et al. 2020 More...
Birefringence Spectra	Cosmic-Birefringence Spectrum presented in Namikawa et al. 2020 More...

DR4 2013-2016 Likelihoods

Product Download Page	Description
Multifrequency Likelihood Software	Baseline Multi-frquency Likelihood presented in Choi et al. 2020 More...
CMB-only Likelihood Software	Baseline CMB-only Likelihood presented in Aiola et al. 2020 More...

DR4 2013-2016 Cosmological Results

Product Download Page	Description
Likelihood Products	Baseline CMB-only Likelihood Products presented in Aiola et al. 2020 More...

DR4 2013-2016 Simulations

Product Download Page	Description
	Simulations associated to the DR4 products will be available on NERSC.

DR4 2013-2016 Notebooks

Product Download Page	Description
Data Notebooks	Jupiter Notebook tutorials associated with ACT DR4 available on the ACT GitHub.

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DR4 2013-2016 Notebooks

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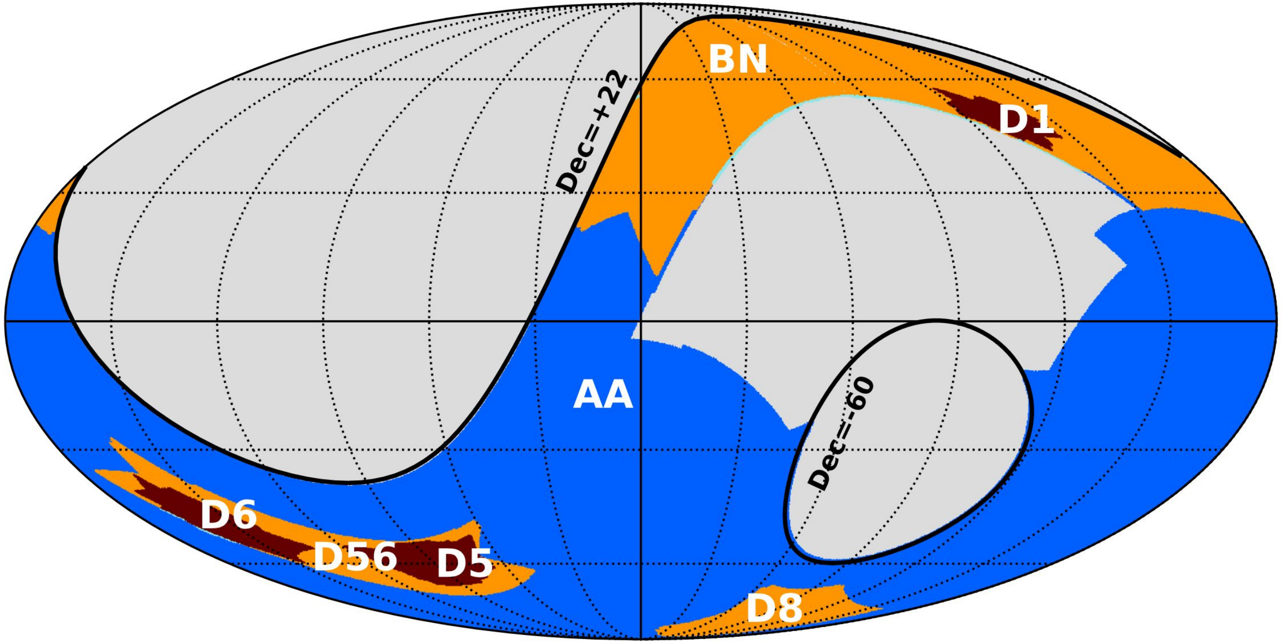
Webinar on Aug 10th 10am ET:
https://simonsfoundation.zoom.us/webinar/register/WN_-NzIyvosRj2hXhwvzG_p9w

ACT DR4 Survey

A variety of patches were observed over the course of multiple seasons:



Layered "wedding cake" survey

ACT DR4 Survey

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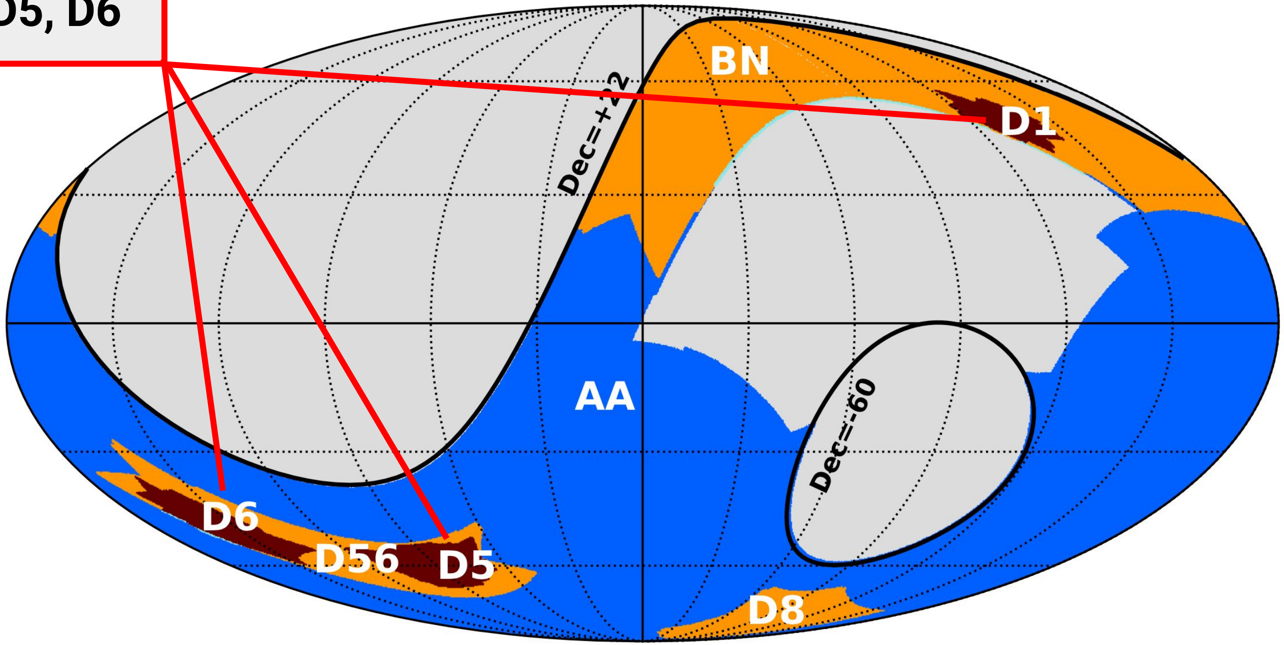
s13: D5, D5, D6



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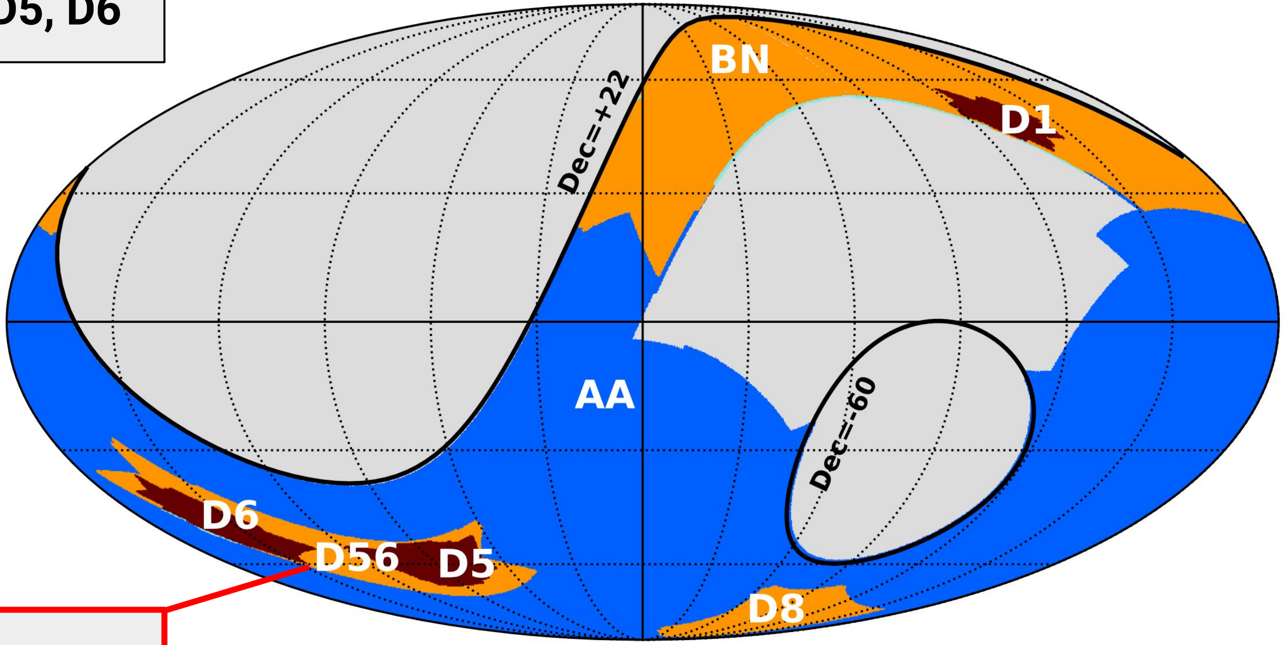


s14: D56

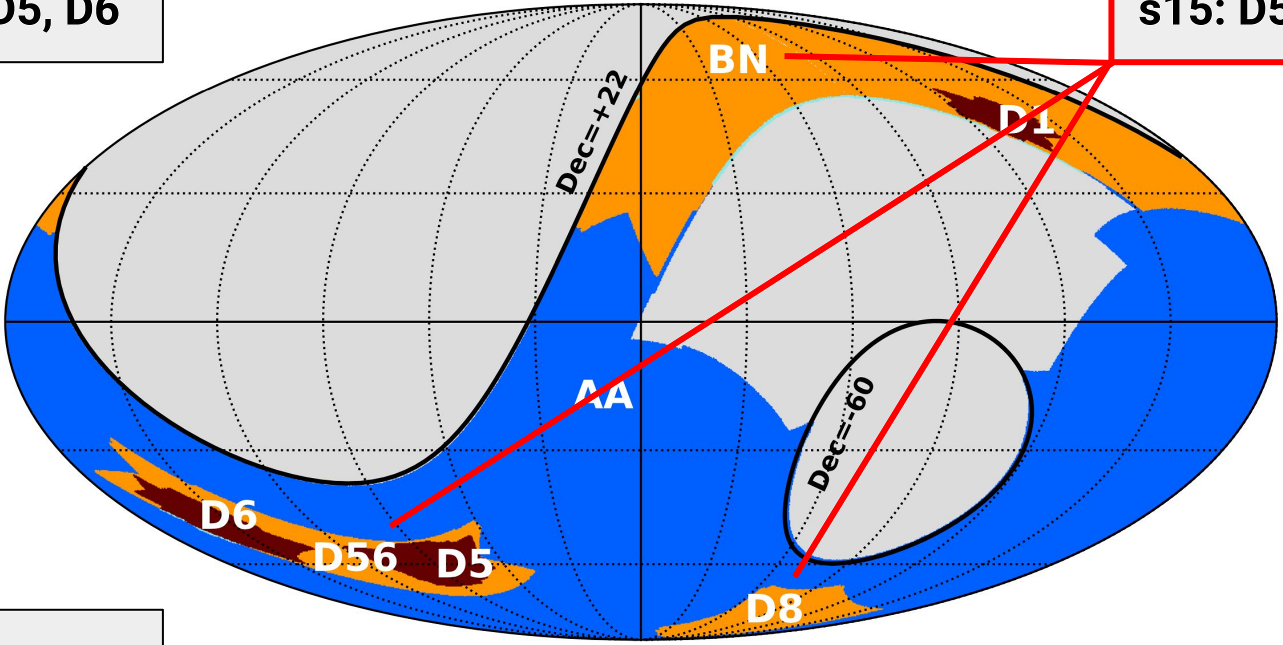
Layered "wedding cake" survey

ACT DR4 Survey

A variety of patches were observed over the course of multiple seasons:

s13: D5, D5, D6

s15: D56, BN, D8



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A variety of patches were observed over the course of multiple seasons:

s13: D5, D5, D6

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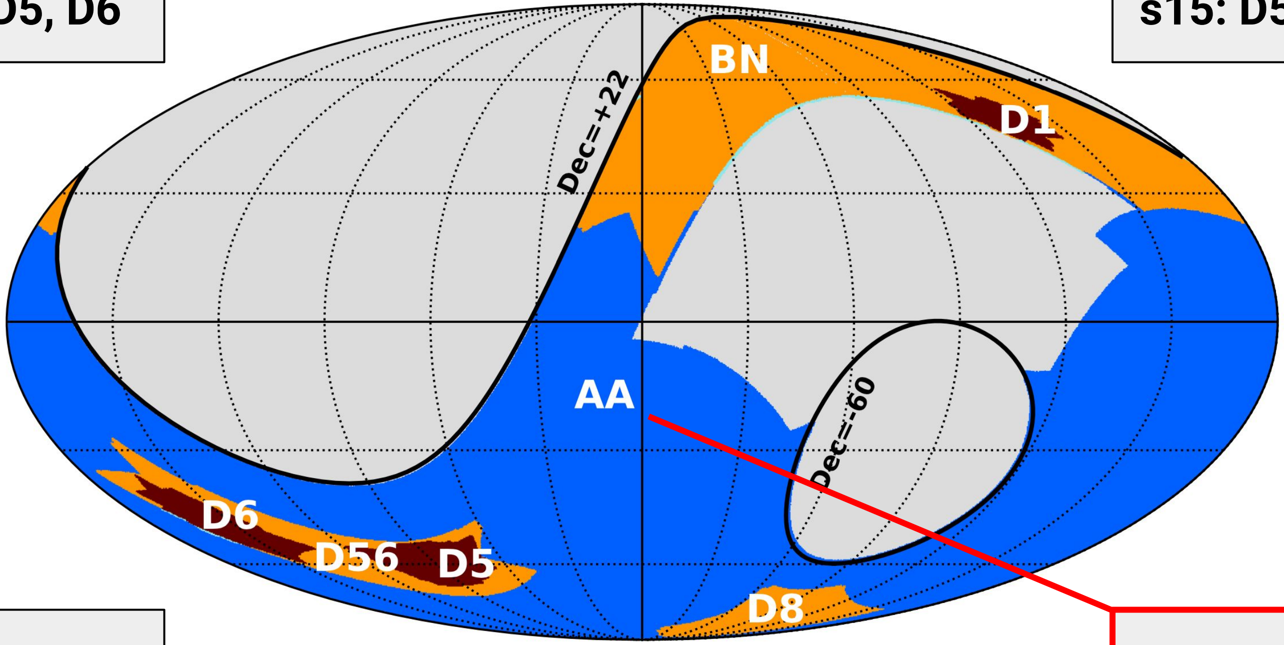


s14: D56

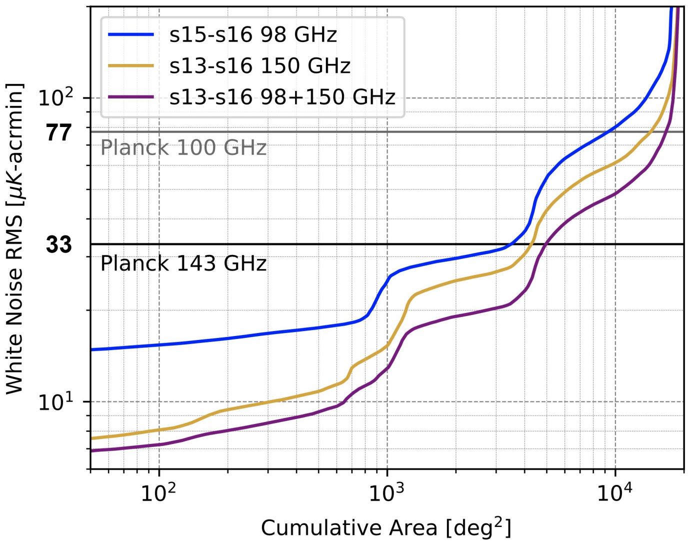
Layered "wedding cake" survey

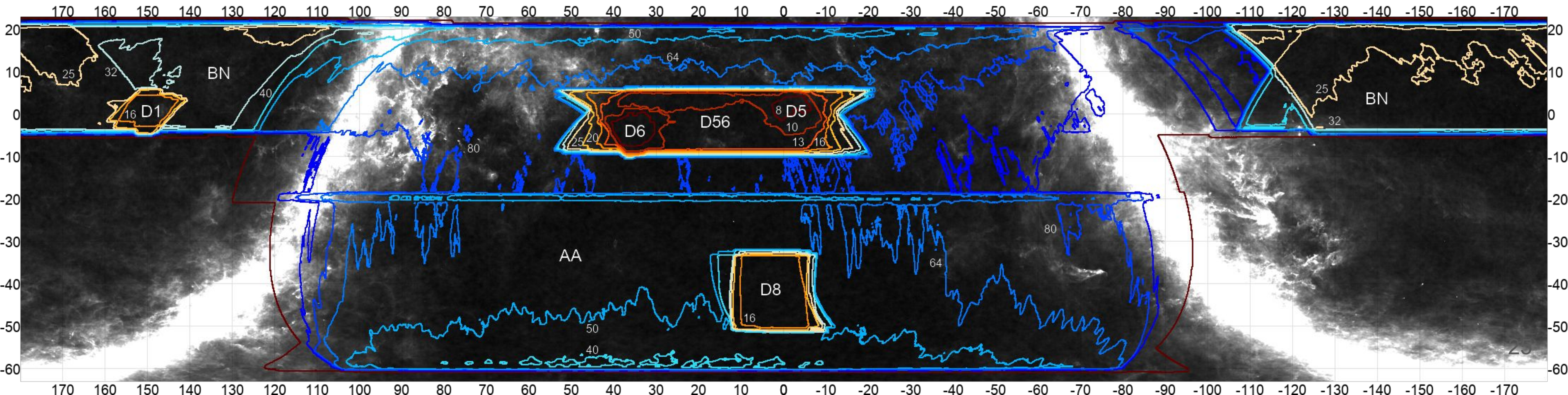
s16: AA

ACT DR4 Survey

Total map-depth varies across the sky:

- At 150 GHz: ~**4,000 deg²** with noise < Planck's 143 GHz full-sky





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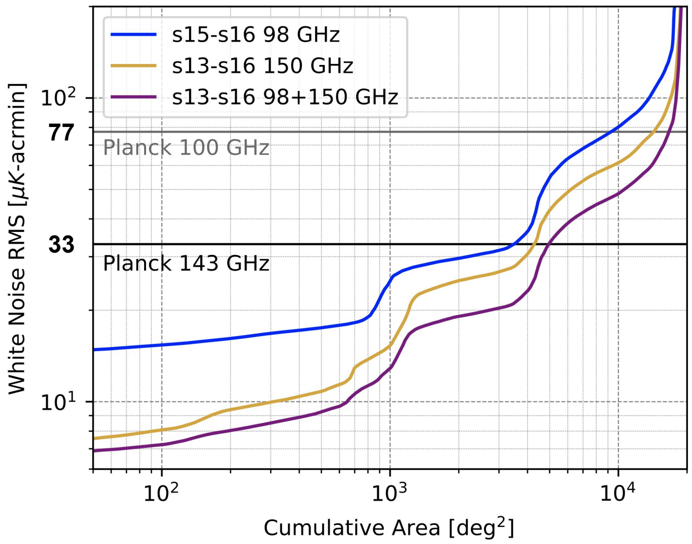
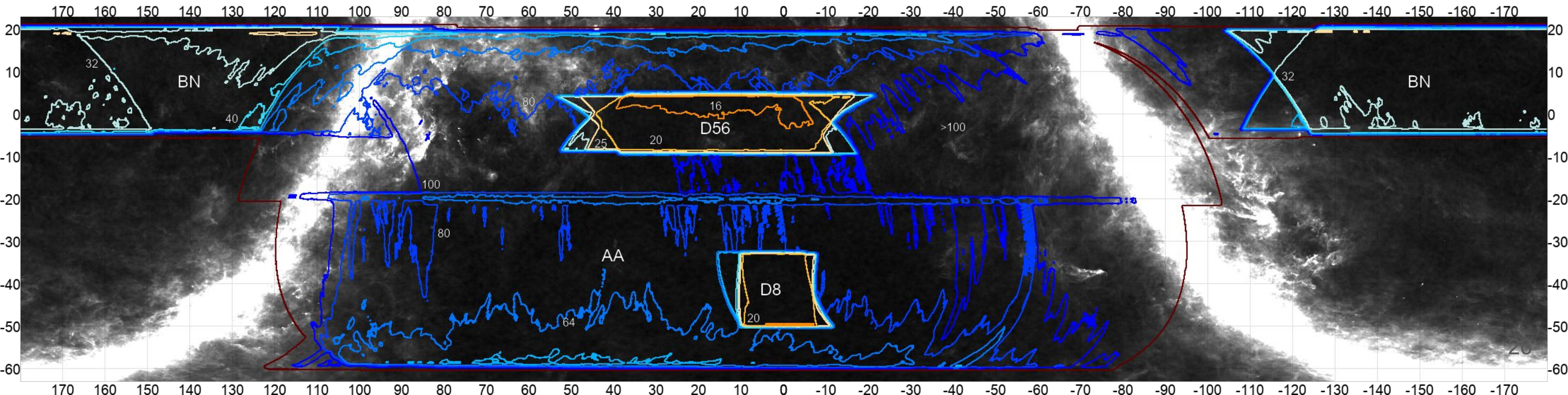
- At 150 GHz: ~**4,000 deg^2** with noise < Planck's 143 GHz full-sky
- At 98 GHz: ~**9,000 deg^2** with noise < Planck's 100 GHz full-sky



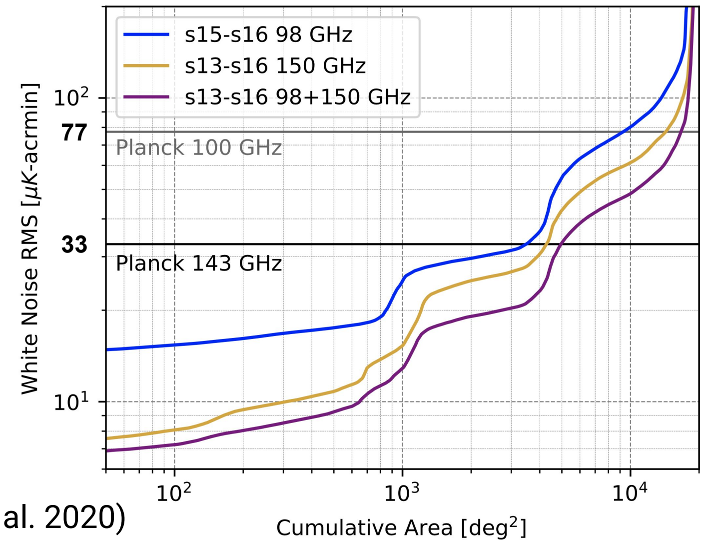


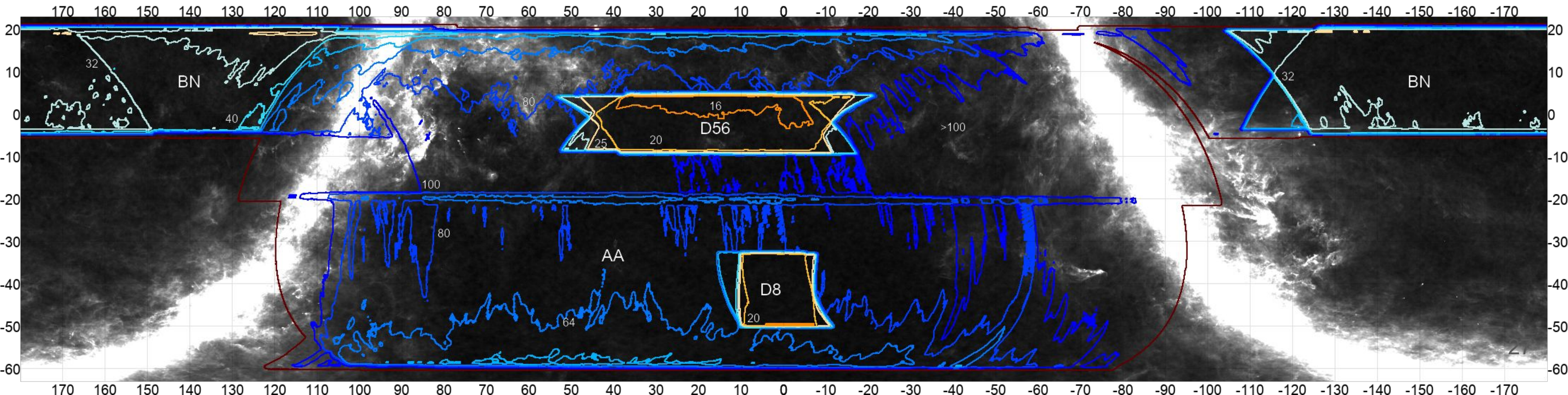
ACT DR4 Survey

Total map-depth varies across the sky:

- At 150 GHz: ~**4,000 deg²** with noise < Planck's 143 GHz full-sky
- At 98 GHz: ~**9,000 deg²** with noise < Planck's 100 GHz full-sky
- 98 + 150 GHz: ~**600 deg²** with noise < 10 μK-arcmin

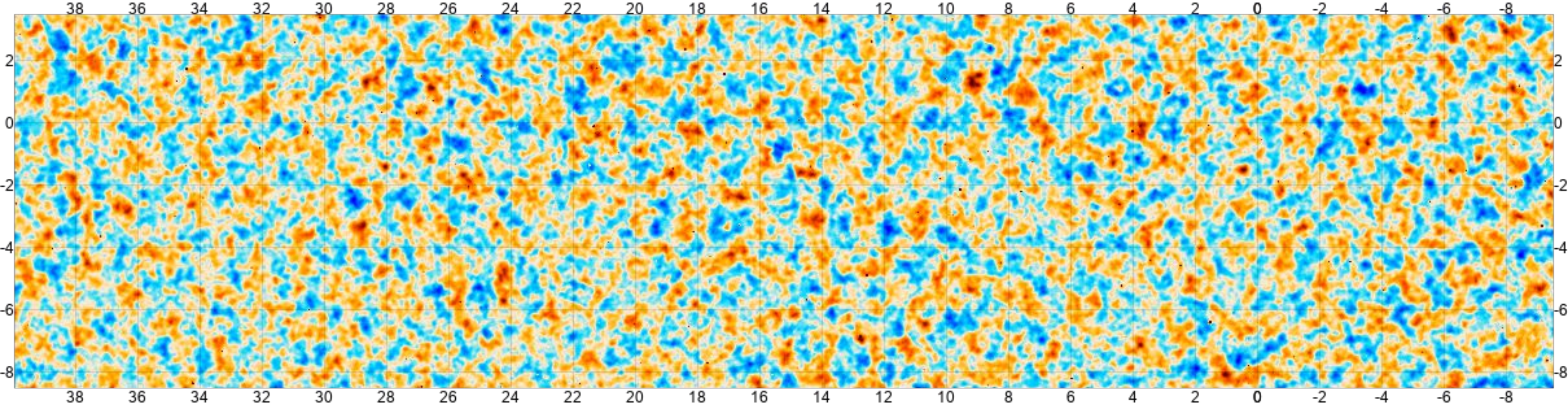
~2500 deg² when adding AdvACT data (Naess et al. 2020)





ACT DR4 Maps

Temperature (T)



D56: 630 deg^2 at 150 GHz

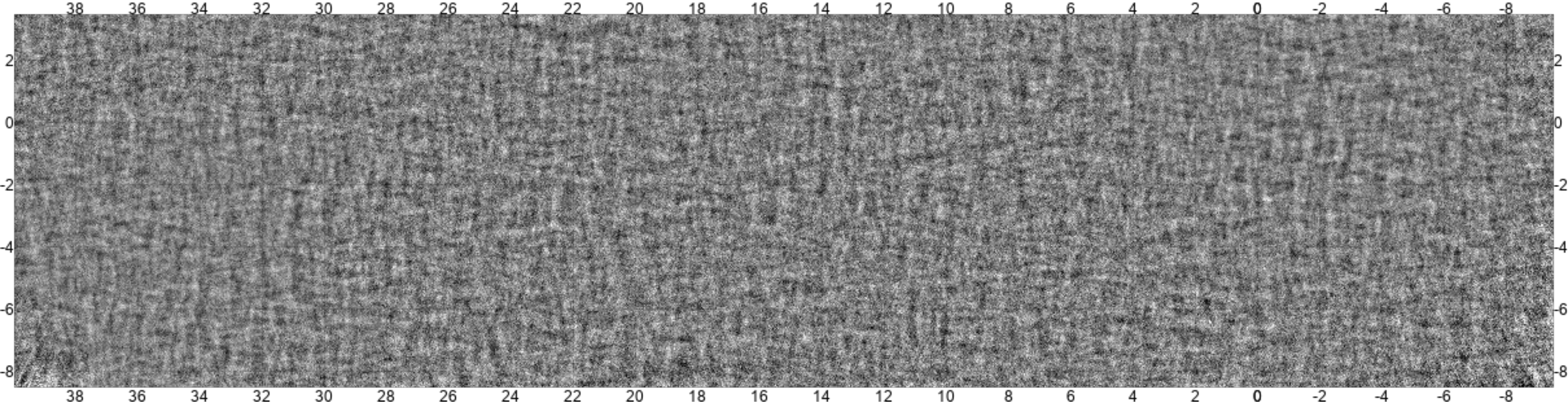
Map Depth ~ 11.5 μK-arcmin

Color scale ± 250 μK

Providing high-resolution measurements over ~40% of the sky

ACT DR4 Maps

Polarization (Q)



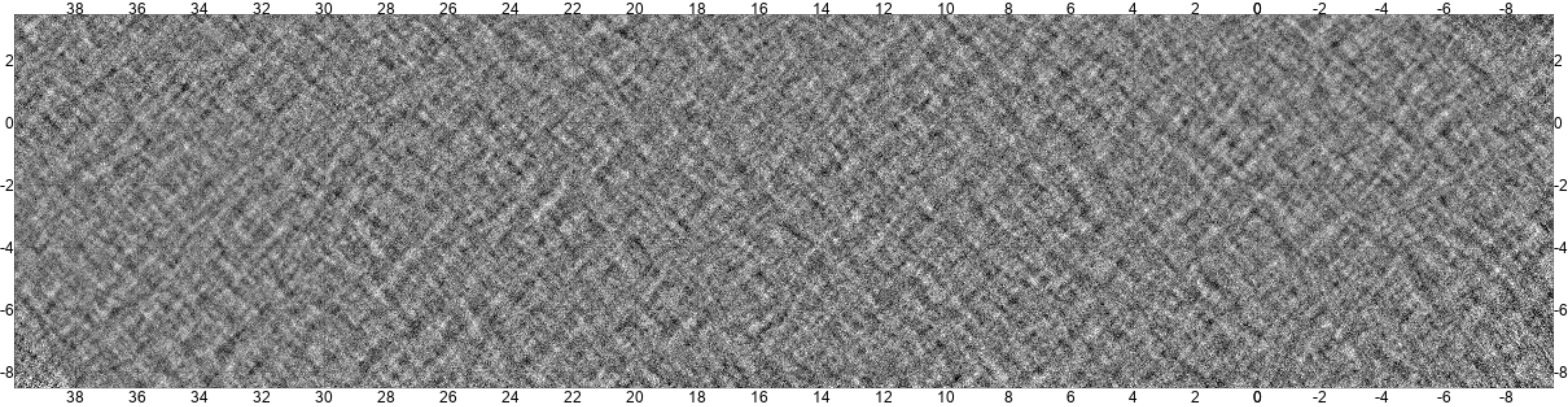
D56: 630 deg^2 at 150 GHz

Map Depth ~ 16.3 μK-arcmin

Color scale ± 30 μK

ACT DR4 Maps

Polarization (U)



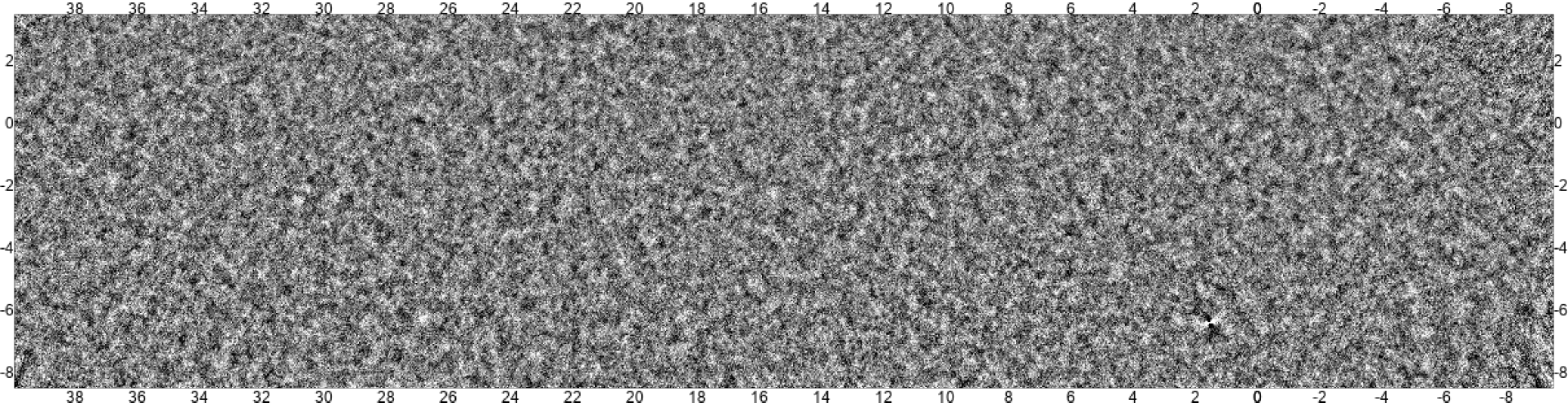
D56: 630 deg^2 at 150 GHz

Map Depth ~ 16.3 μK-arcmin

Color scale ± 30 μK

ACT DR4 Maps

Polarization (E)



D56: 630 deg^2 at 150 GHz

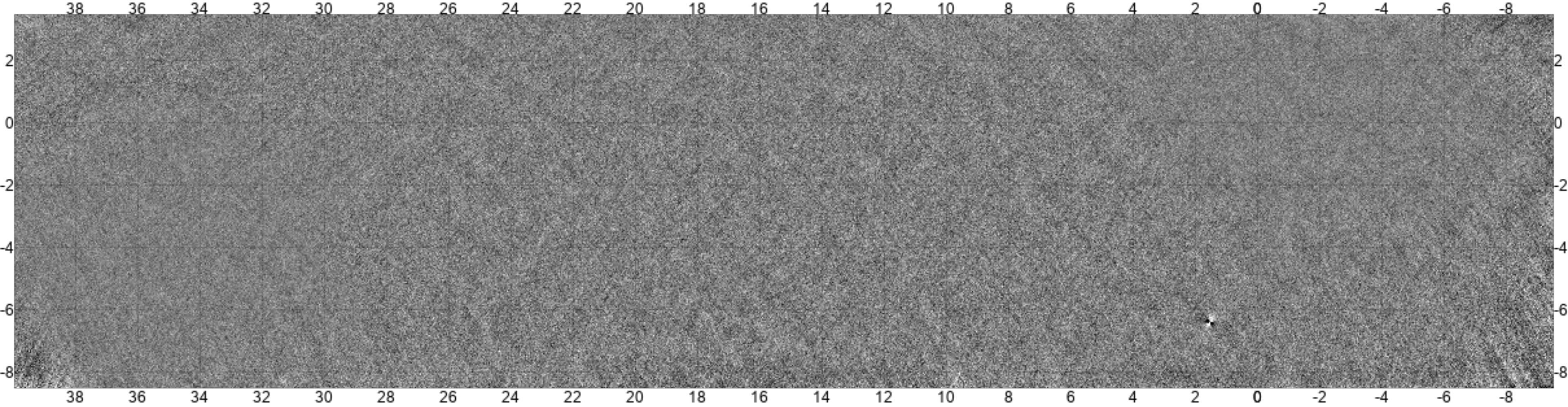
Map Depth ~ 16.3 μK-arcmin

Color scale ± 30 μK

Providing a signal-dominated E map over ~4,000 deg^2

ACT DR4 Maps

Polarization (B)



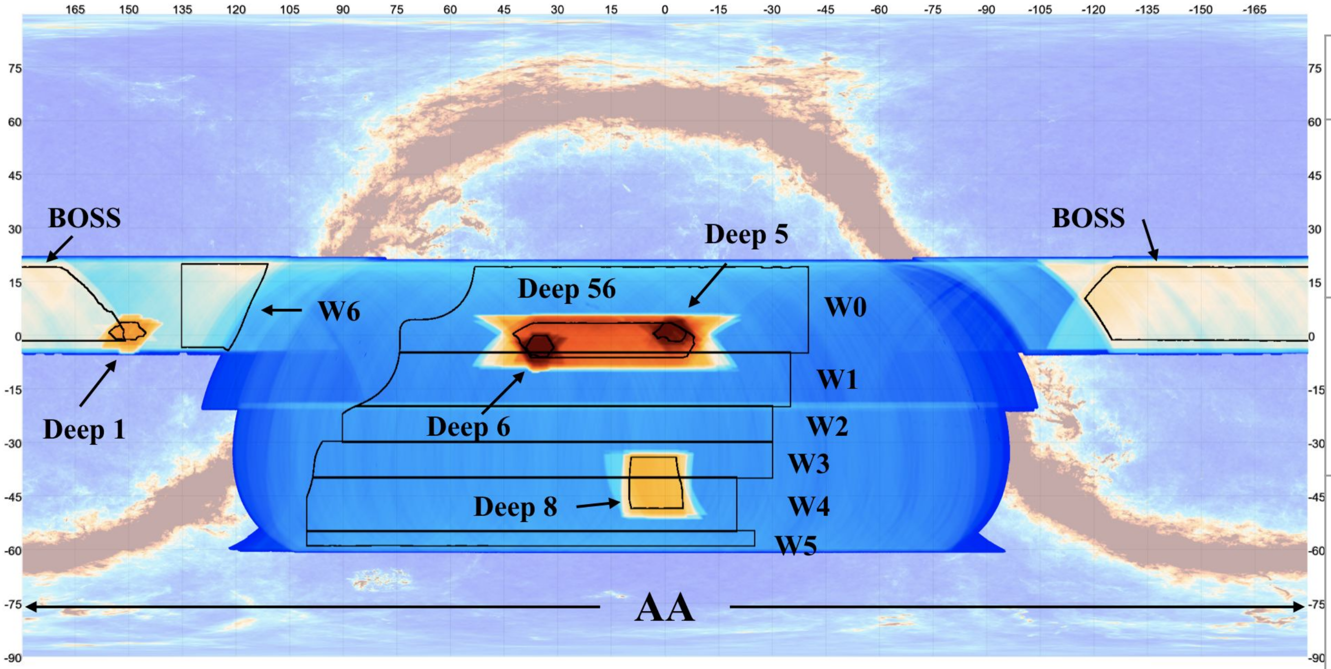
D56: 630 deg^2 at 150 GHz

Map Depth ~ 16.3 μK-arcmin

Color scale ± 30 μK

Regions for power spectra

5,400 sq deg (effective area) used for PS;
~17,000 sq deg observed

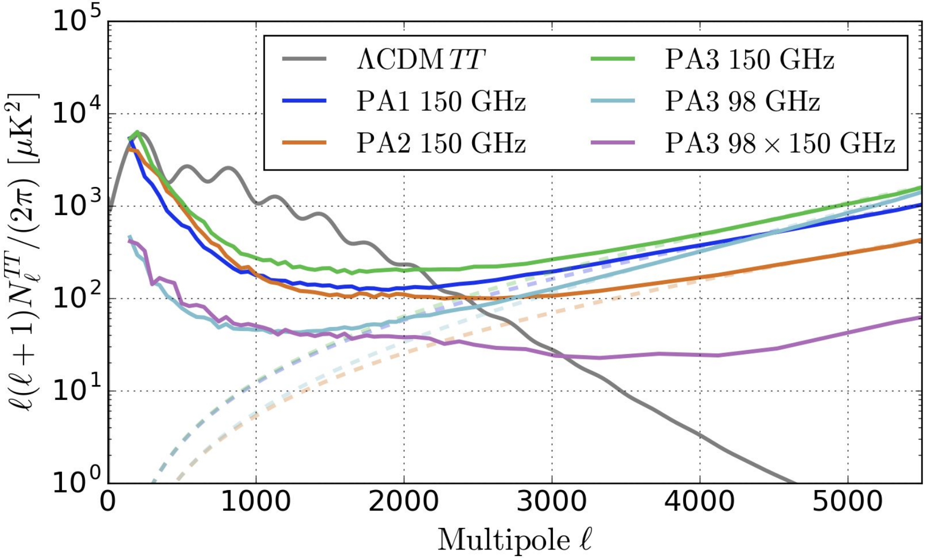


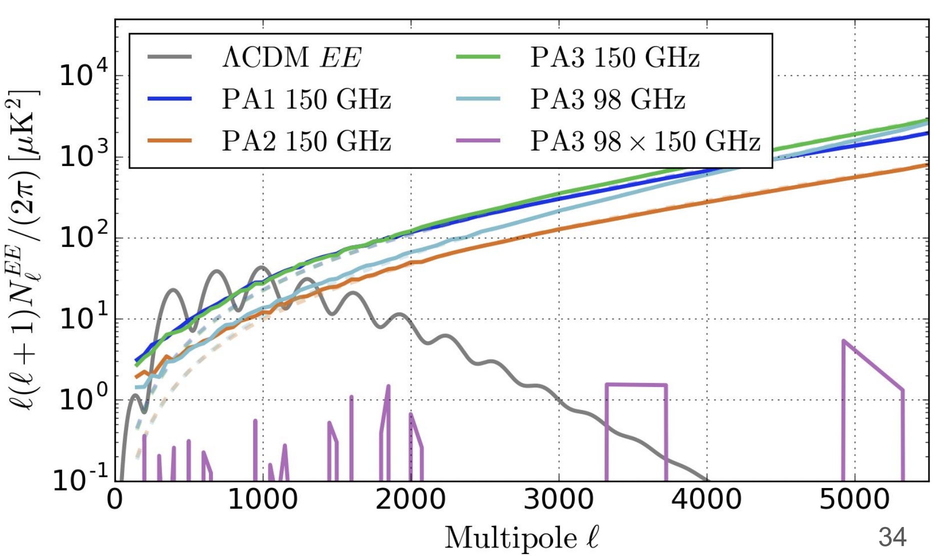
Regions observed in 4 seasons (2013–2016) with different arrays

	s13	s14	s15	s16
PA1 150 GHz	D1 D5 D6	D56	D56 BN D8	
PA2 150 GHz		D56	D56 BN D8	AA
PA3 98/ 150 GHz			D56 BN D8	AA

Noise power spectra

Noise power spectra in D56 region for different arrays.
Measured noise in solid, white noise fit in dashed.
TT low ℓ noise due to atmosphere, EE low ℓ noise is not.
Many modes signal dominated: more sky area to add information.





Data consistency test

52 ℓ bins for 350 < ℓ < 7525.

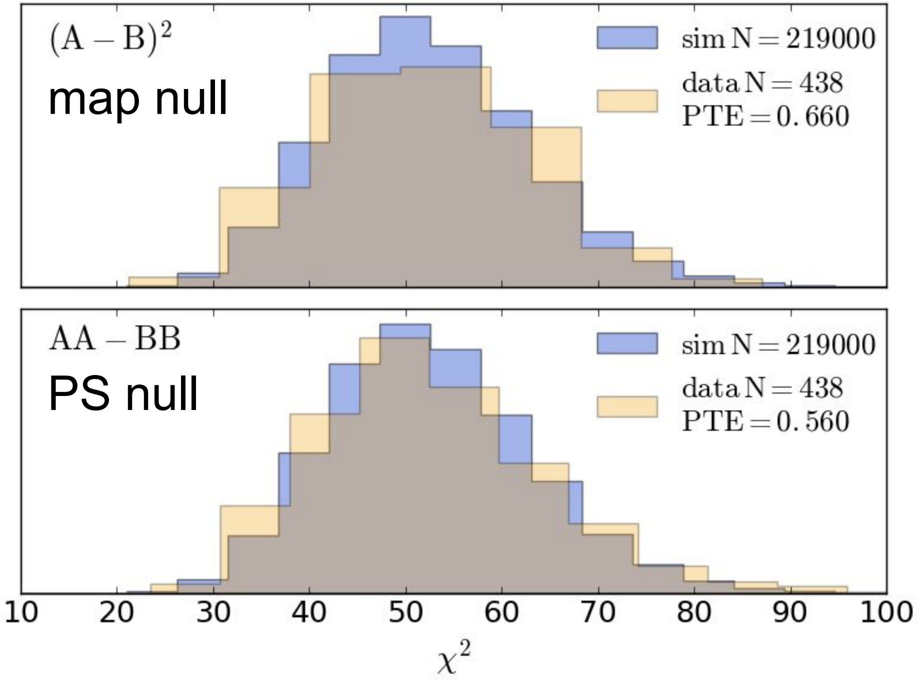
Null tests among multiple arrays and seasons of observation in each region.

Two null power spectra checked for every pair of maps (power spectra of map difference, and power spectra difference). For maps A and B:

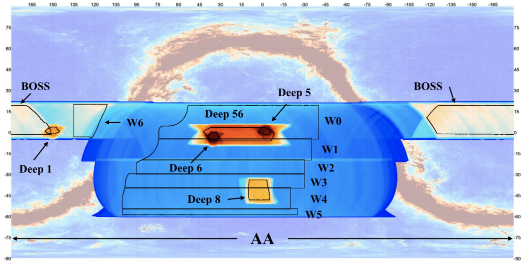
1. $PS(A-B) = C_\ell^{AA} + C_\ell^{BB} - 2C_\ell^{AB}$
2. $PS(A)-PS(B) = C_\ell^{AA} - C_\ell^{BB}$

438 total pairs, 500 simulations each.

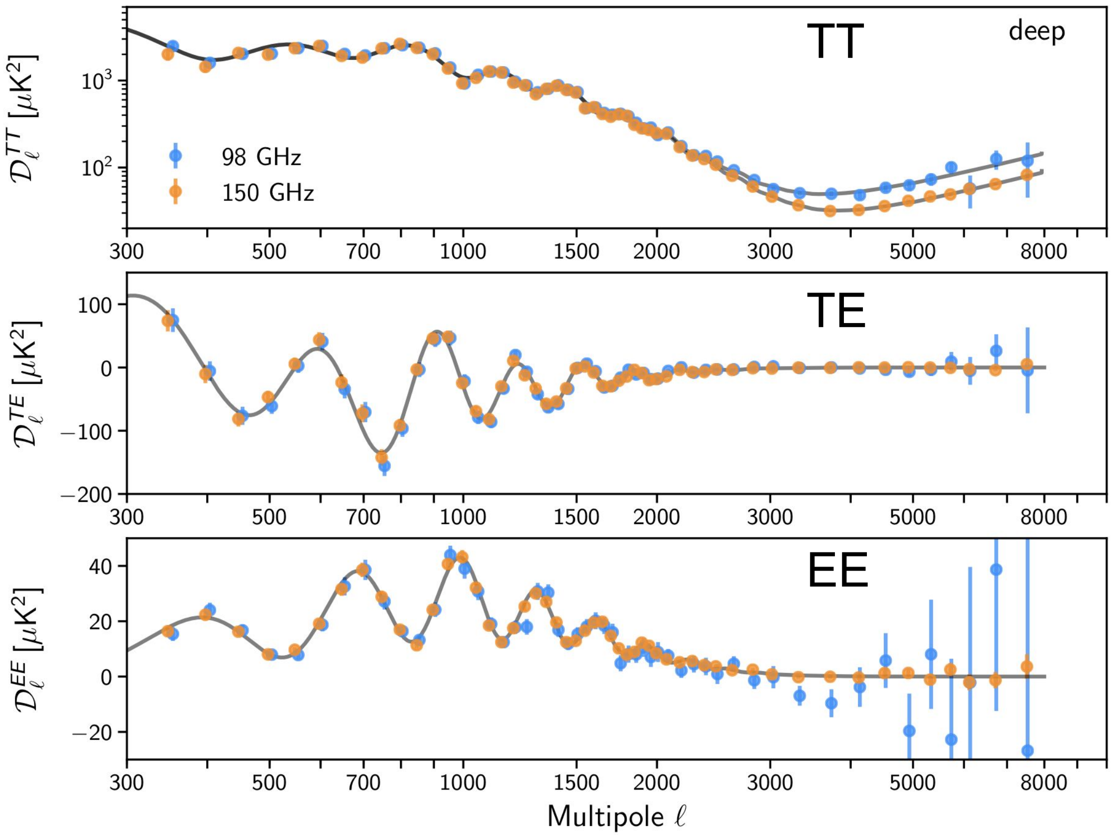
Normalized χ^2 distribution



Power spectra at 98 & 150 GHz



	s13	s14	s15	s16
PA1 150	**D1** **D5** **D6**	**D56**	**D56** BN D8	
PA2 150		**D56**	**D56** BN D8	AA
PA3 98/1 50			**D56** BN D8	AA



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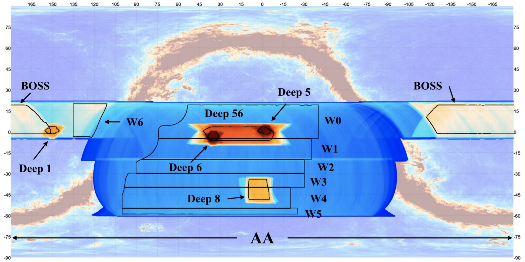
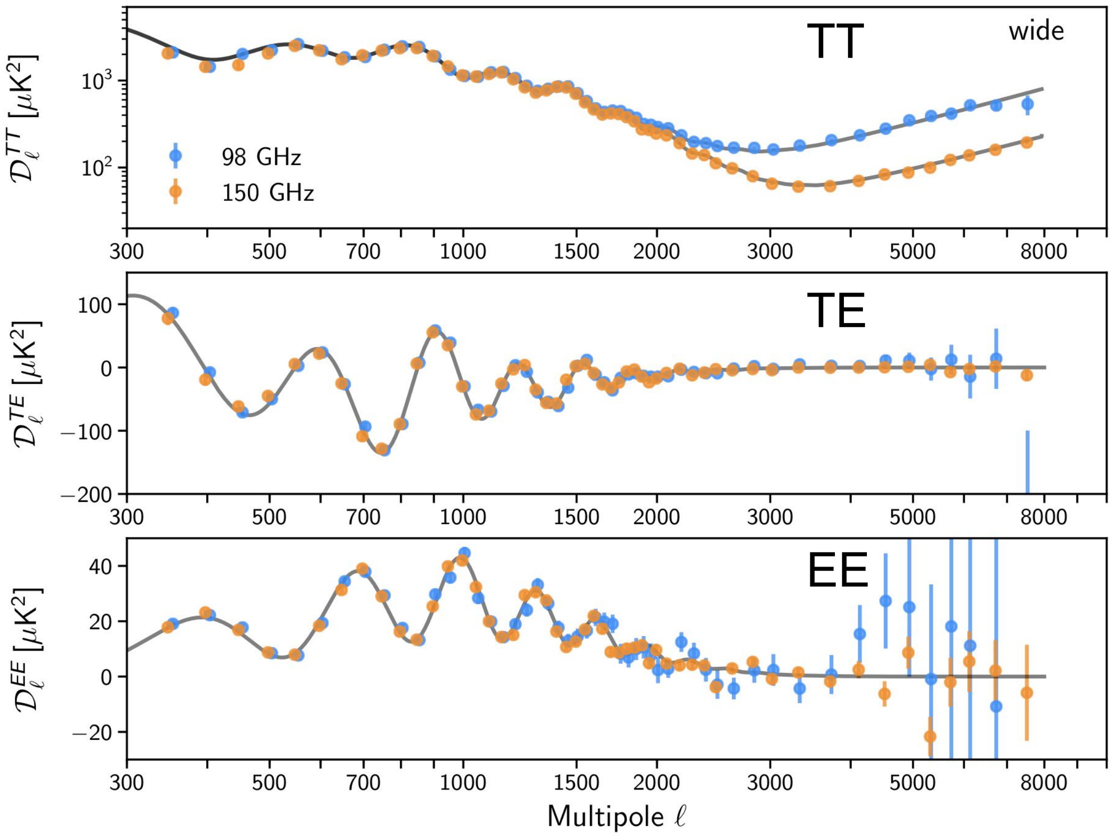
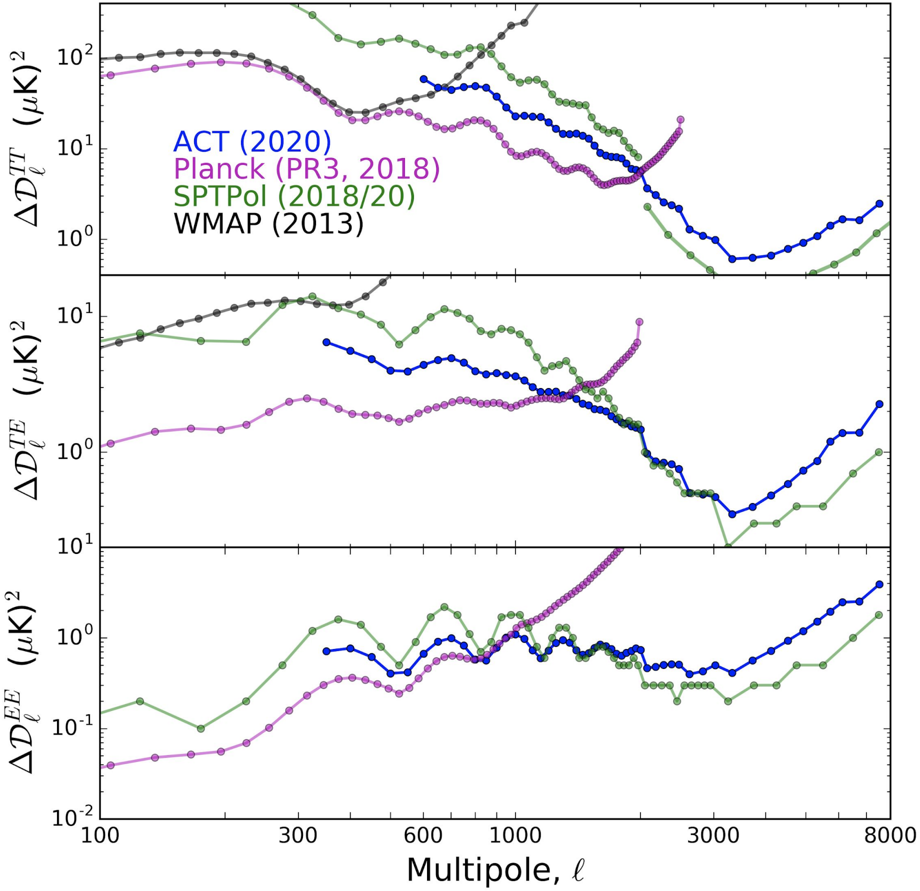


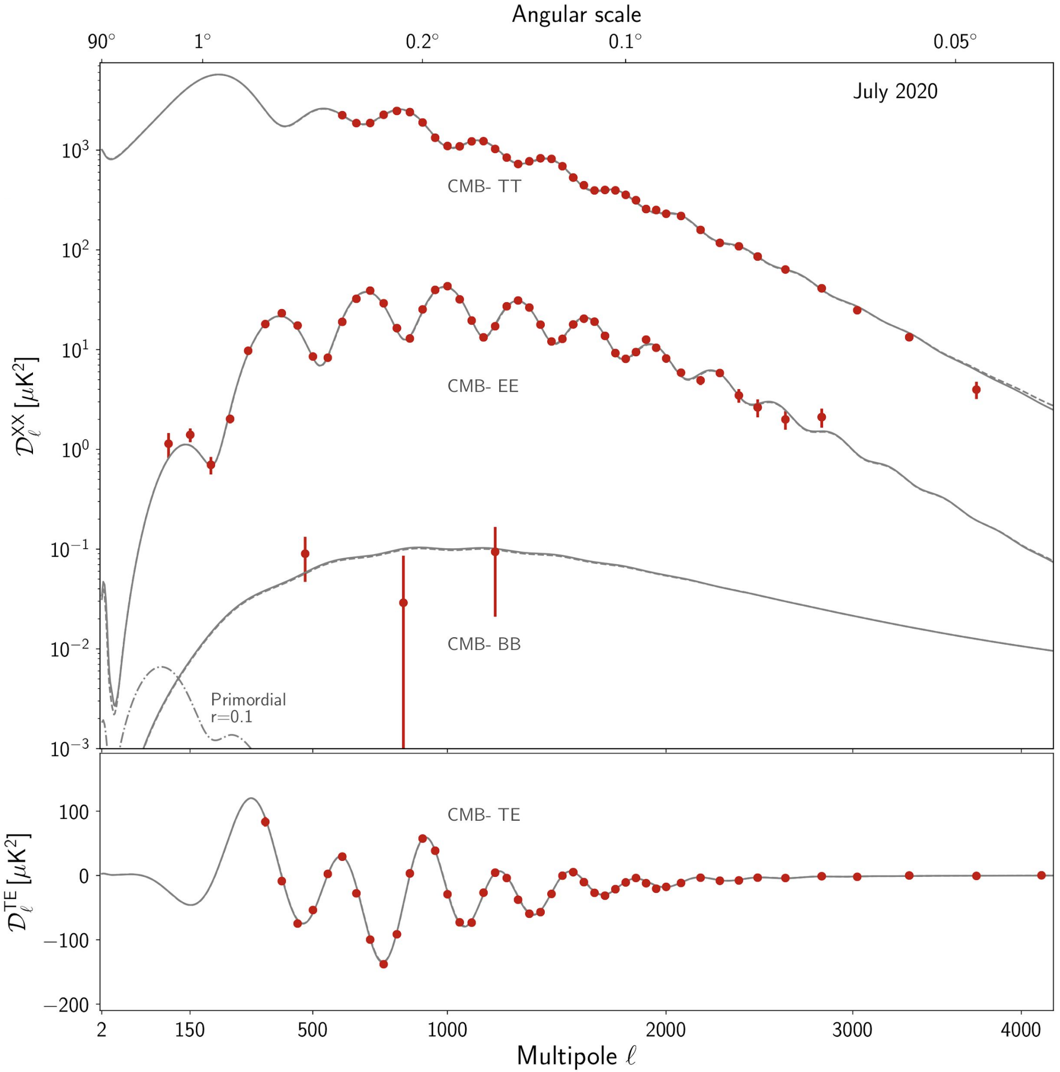
	s13	s14	s15	s16
PA1 150	D1 D5 D6	D56	D56 **BN** D8	
PA2 150		D56	D56 **BN** D8	**AA**
PA3 98/1 50			D56 **BN** D8	**AA**



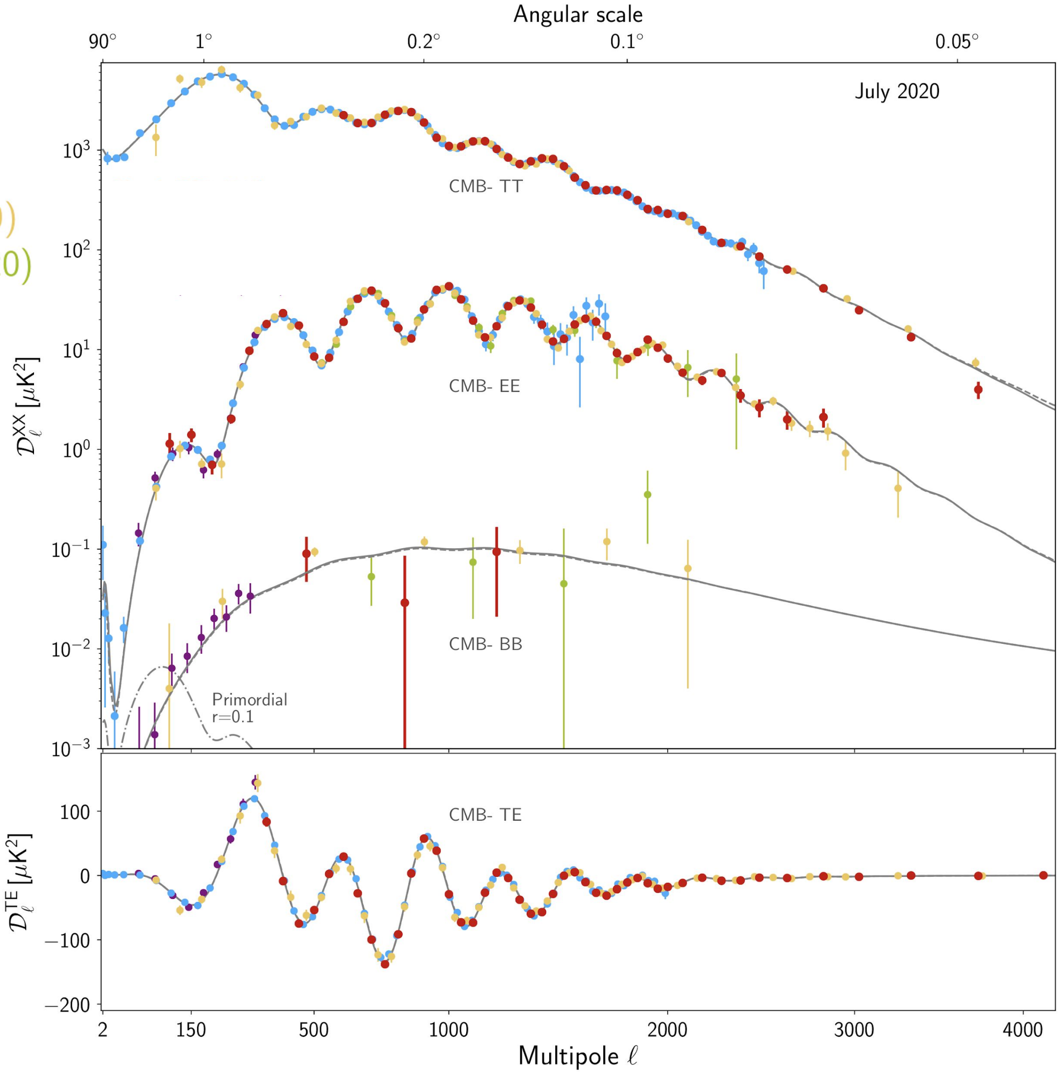
Power spectrum error bar comparison



ACT (DR4, 2020)


Angular scale
90°
1°
0.2°
0.1°
0.05°
July 2020
CMB- TT
CMB- EE
CMB- BB
Primordial
r=0.1
CMB- TE
$\mathcal{D}_\ell^{XX}\,[\mu K^2]$
$\mathcal{D}_\ell^{TE}\,[\mu K^2]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
100
0
−100
−200
2
150
500
1000
2000
3000
4000
Multipole ℓ

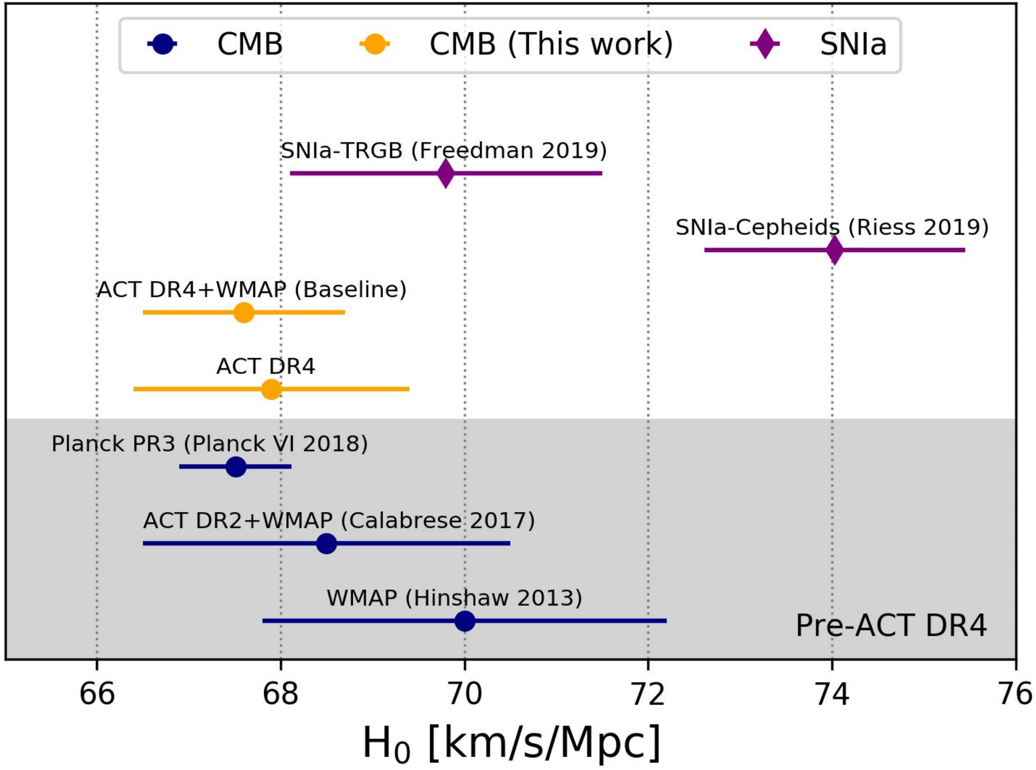
Planck (PR3, 2018)
ACT (DR4, 2020)
SPTpol (2018/2019/2020)
POLARBEAR (2017/2020)
BICEP2/Keck (2018)



ACT DR4 H_0 Estimate

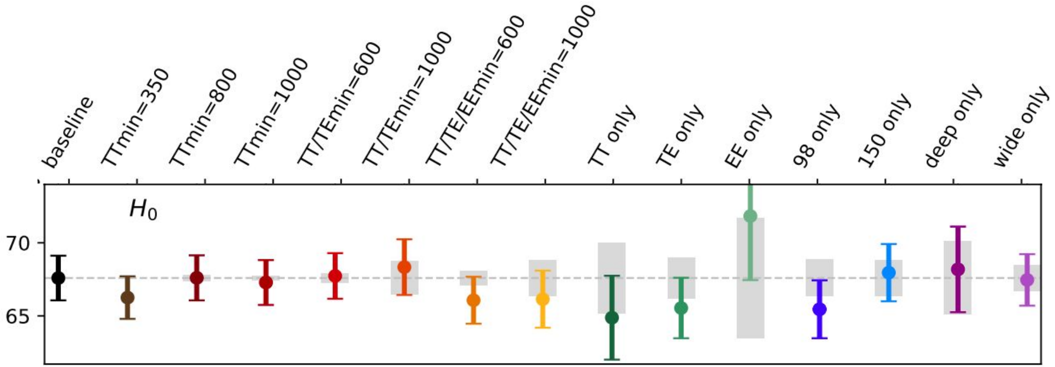
ACT DR4 + WMAP: $H_0 = 67.6 \pm 1.1$ km/s/Mpc

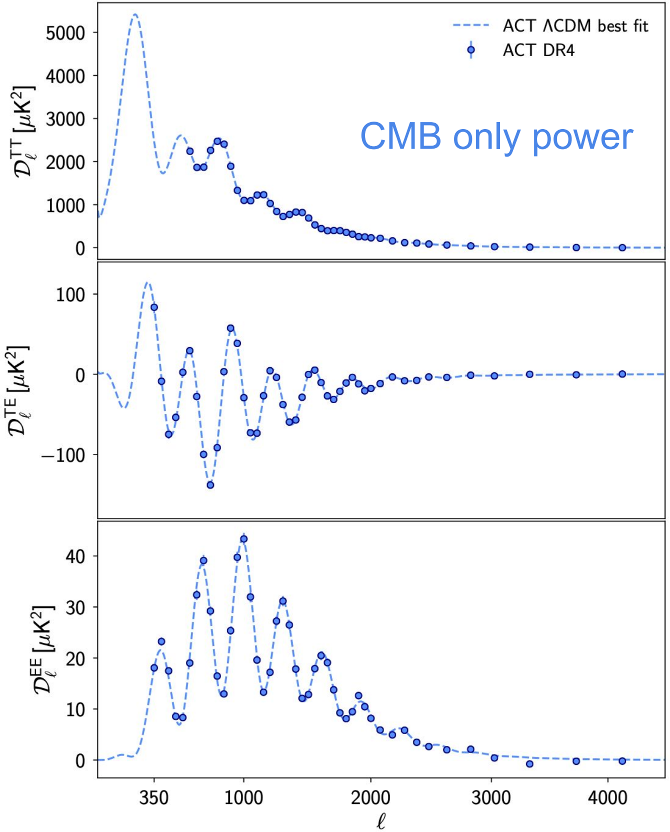
- agrees with Planck within 1σ
- agrees with SNIa-TRGB within 1σ
- $\sim 4\sigma$ tension with SNIa-Cepheids



ACT Likelihoods and modeling

Multi-frequency spectra modeled to include CMB emission plus additional Galactic and extragalactic source of emission, frequency-dependent polarization efficiency and beam leakage → actpolfull_dr4 likelihood

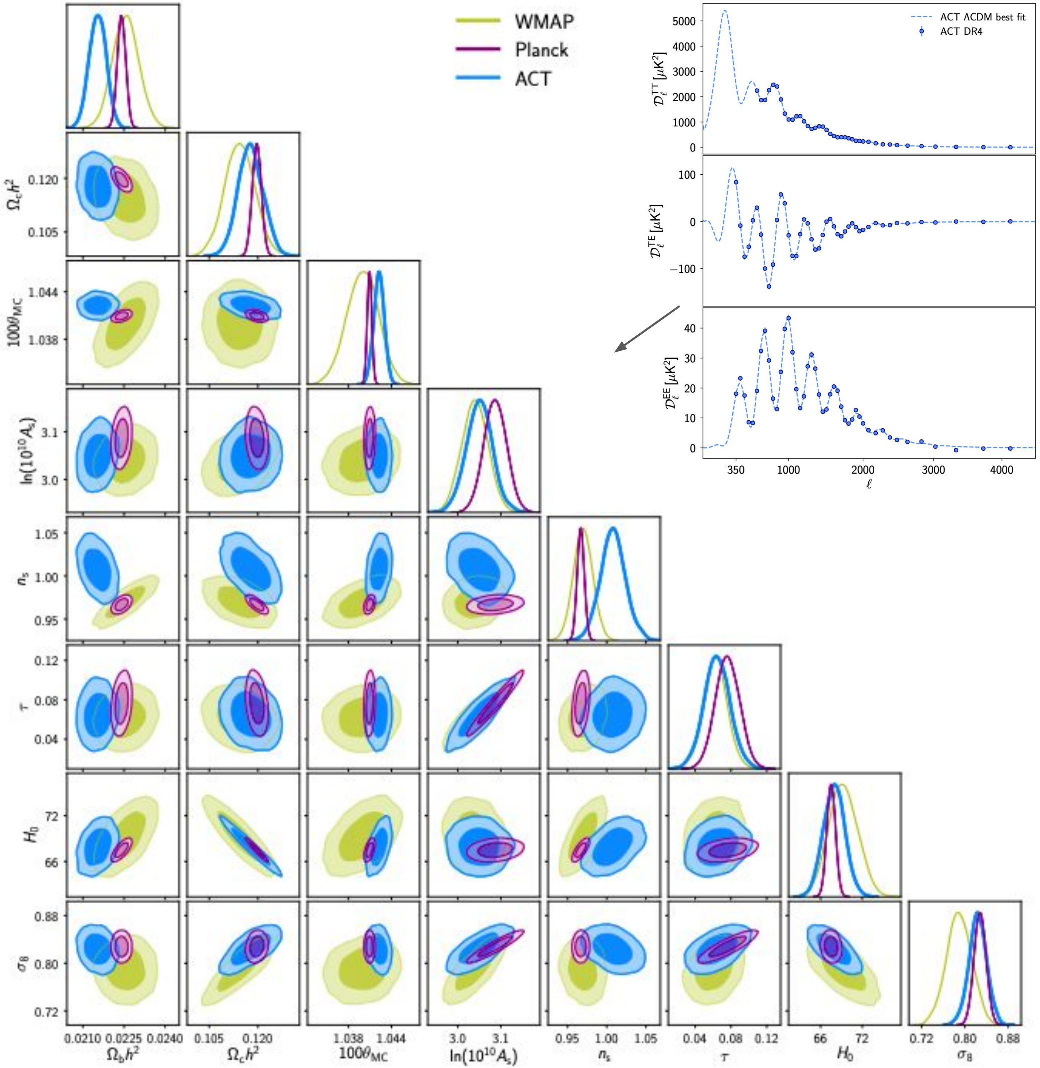




- Used for a wide range of cosmological parameters robustness tests
- Used, in combination with previous ACT DR2 data, to extract the CMB-only power in DR4
  → actpollite_dr4 likelihood

ACT DR4 Cosmology

- ΛCDM is a good fit to the ACT data (PTE=0.13)
  - τ prior included for this and all other runs
- Parameters consistent at 2.3-2.7**σ** with WMAP and Planck ΛCDM results
  - The main difference is in the $\Omega_b h^2$-n_s space which is affected by ACT lack of data on large scales



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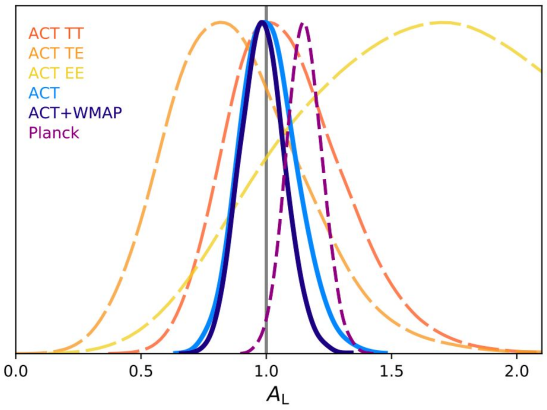
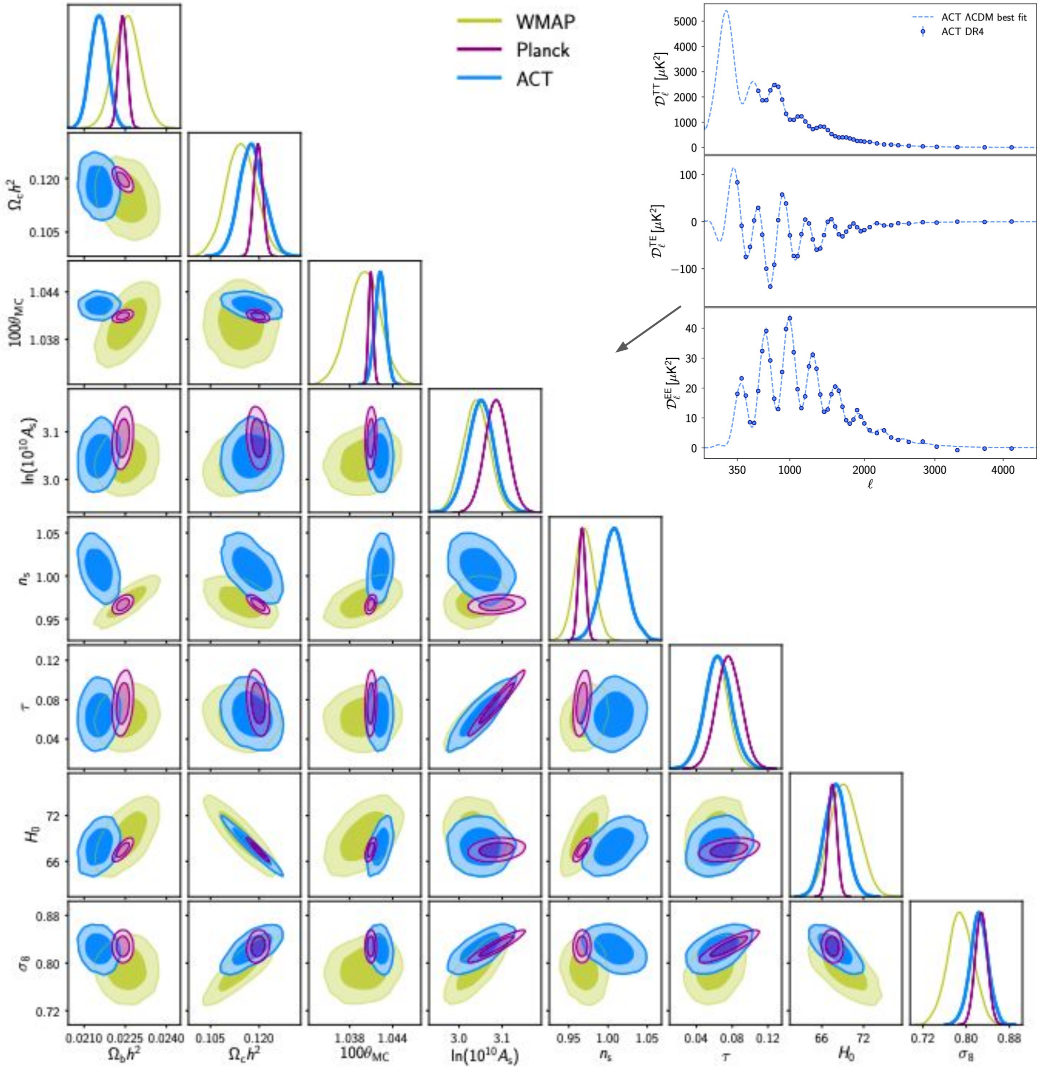
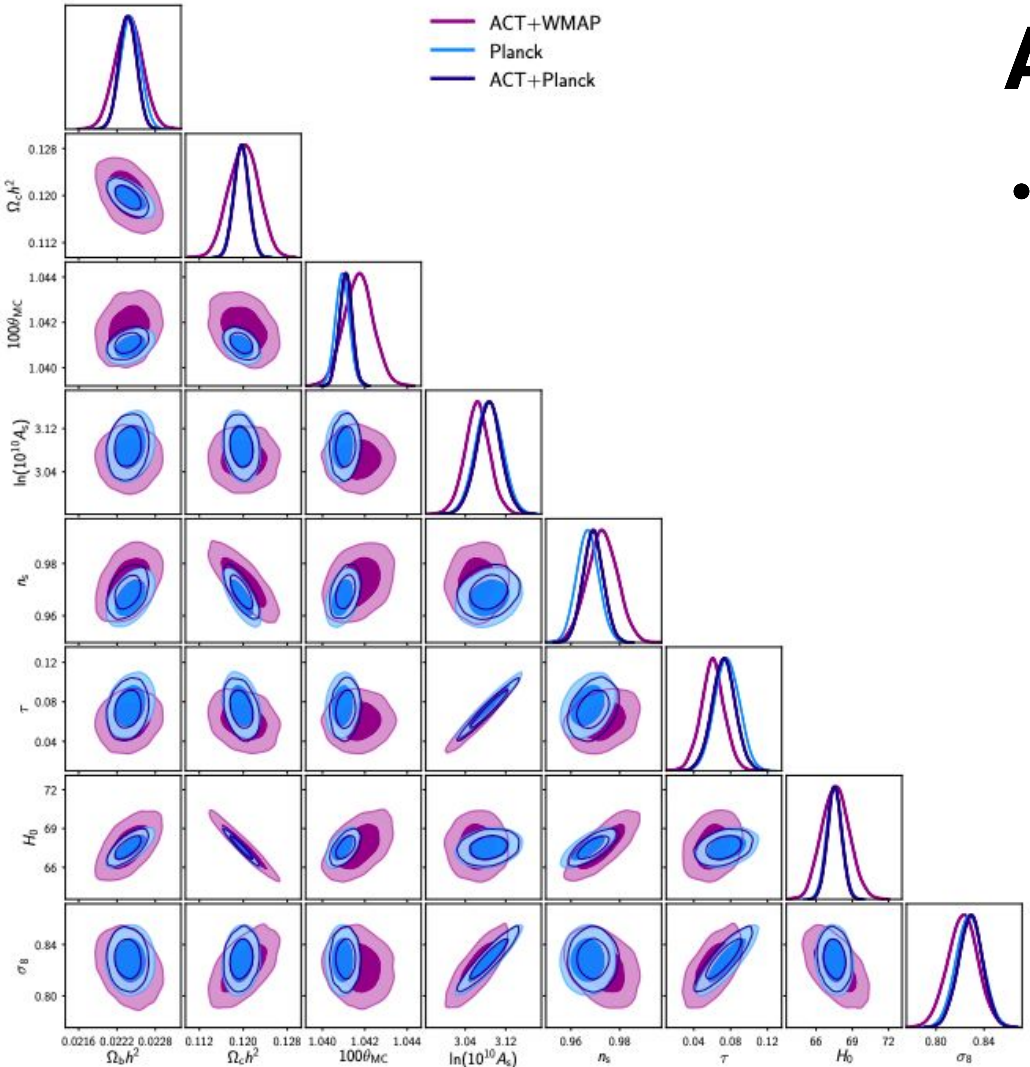
  - τ prior included for this and all other runs
- Parameters consistent at 2.3-2.7$\boldsymbol{\sigma}$ with WMAP and Planck ΛCDM results
  - The main difference is in the $\Omega_b h^2$-n_s space which is affected by ACT lack of data on large scales
- Lensing smoothing in ACT power spectra is consistent with ΛCDM expectations







ACT DR4 Cosmology

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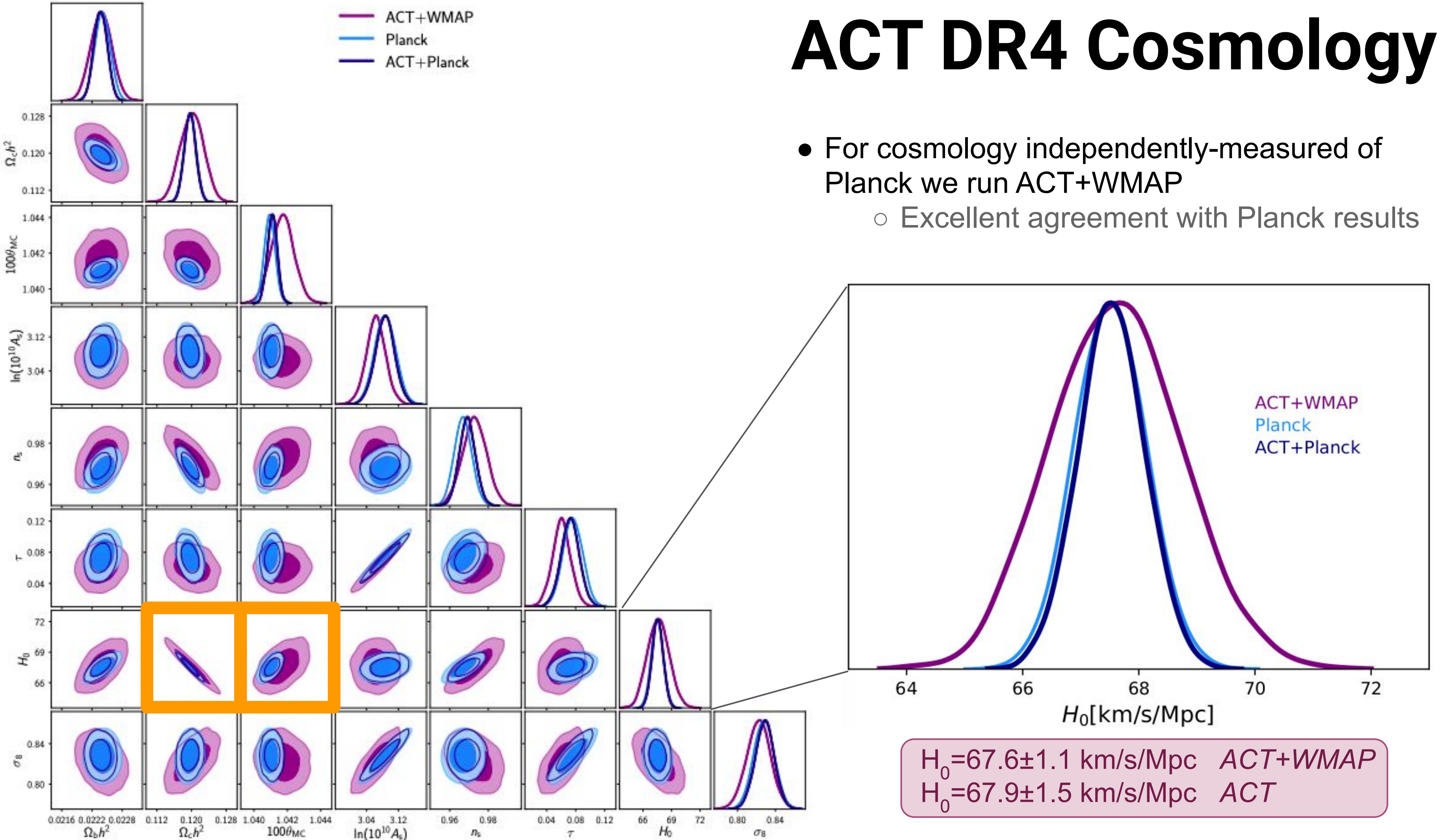
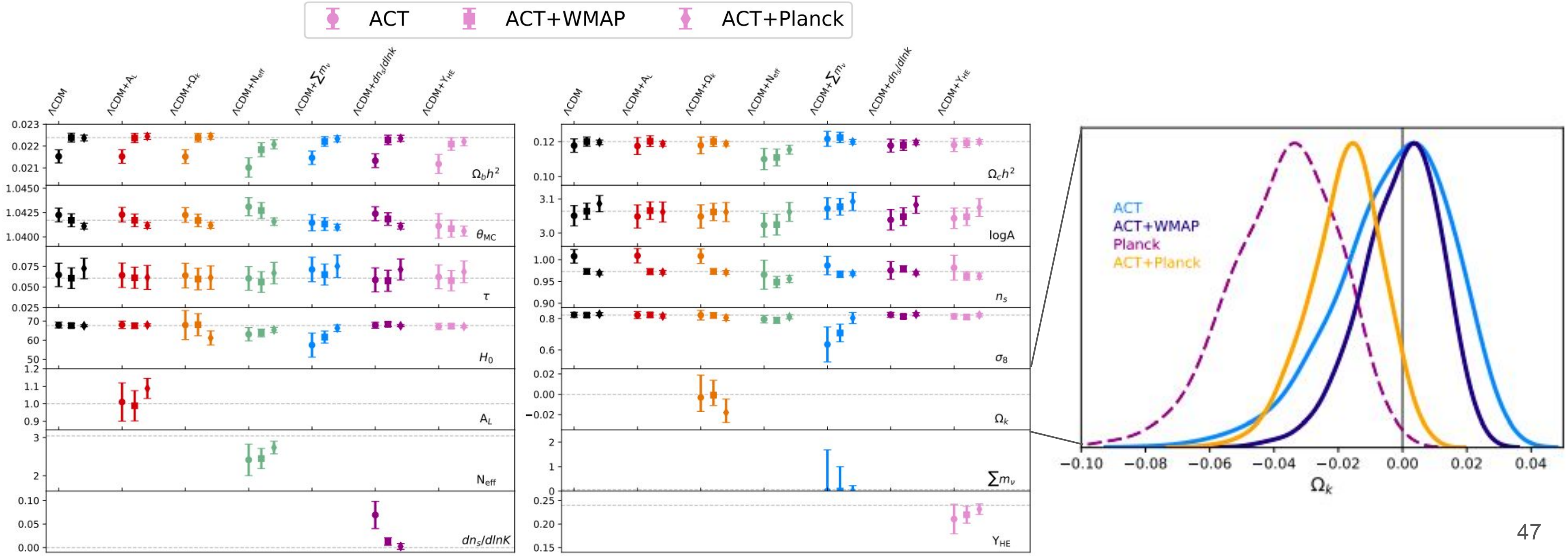


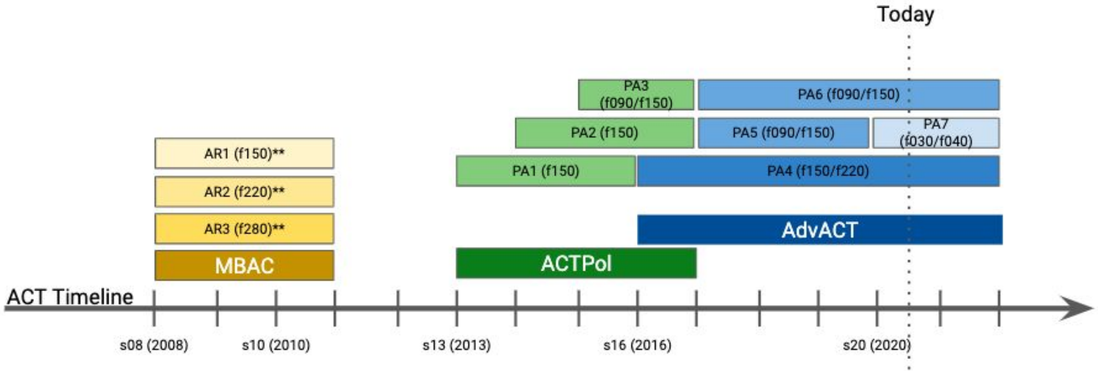
H_0=67.6±1.1 km/s/Mpc *ACT+WMAP*
H_0=67.9±1.5 km/s/Mpc *ACT*

ACT DR4 Cosmology beyond ΛCDM

- We tested a number of single-parameter extensions to ΛCDM
  - Constraints on primordial parameters (like N_{eff}, helium abundance and running of the spectral index)
  - Constraints on lensing parameters (neutrino mass and curvature)
- Results are within ΛCDM expectations at the 1.5-2.2**σ** level with ACT+WMAP
  - We note no deviation from flatness



Outlook



ACT is due to observe until 2021

- Over four times more data than DR4 already in hand and under analysis.
  - Hitting regime where polarization is more constraining than temperature.
- During 2020 observing with a low frequency array.
- Lots more to come in the coming months (e.g., lensing, cluster, kSZ analyses)

- ❏ Access data via lambda -- **lambda.gsfc.nasa.gov**
  - ❏ Tutorials/iPython notebooks to learn how to use our data and codes
- ❏ More webinars over the summer on other scientific results

We thank NSF for continuous support of ACT and CONICYT for hosting the telescope in Chile

CONICYT
Ministerio de Educación
Gobierno de Chile