ATACAMA COSMOLOGY TELESCOPE

Adri Duivenvoorden
Center for Computational Astrophysics

FLATIRON INSTITUTE

CMB-S4 summer 2024 meeting
07-31-2024

ATACAMA COSMOLOGY TELESCOPE

2007–2022

CONICYT
Ministerio de Educación
Gobierno de Chile

image credit: Mark Devlin

ATACAMA COSMOLOGY TELESCOPE

2022 collaboration meeting, Princeton

NSF

CONICYT
Ministerio de Educación
Gobierno de Chile

Argonne CITA ICAT HAVERFORD NIST RUTGERS SLAC Penn WCU

ATACAMA COSMOLOGY TELESCOPE

Altitude of 5200 m in the Atacama desert in northern Chile

- Access to ~70% of the sky (ACT maps ~40%)

6 m telescope

- ~5 times *Planck* resolution

PI: Suzanne Staggs, Co-Director: Mark Devlin

image credit: Debra Kellner

ATACAMA COSMOLOGY TELESCOPE

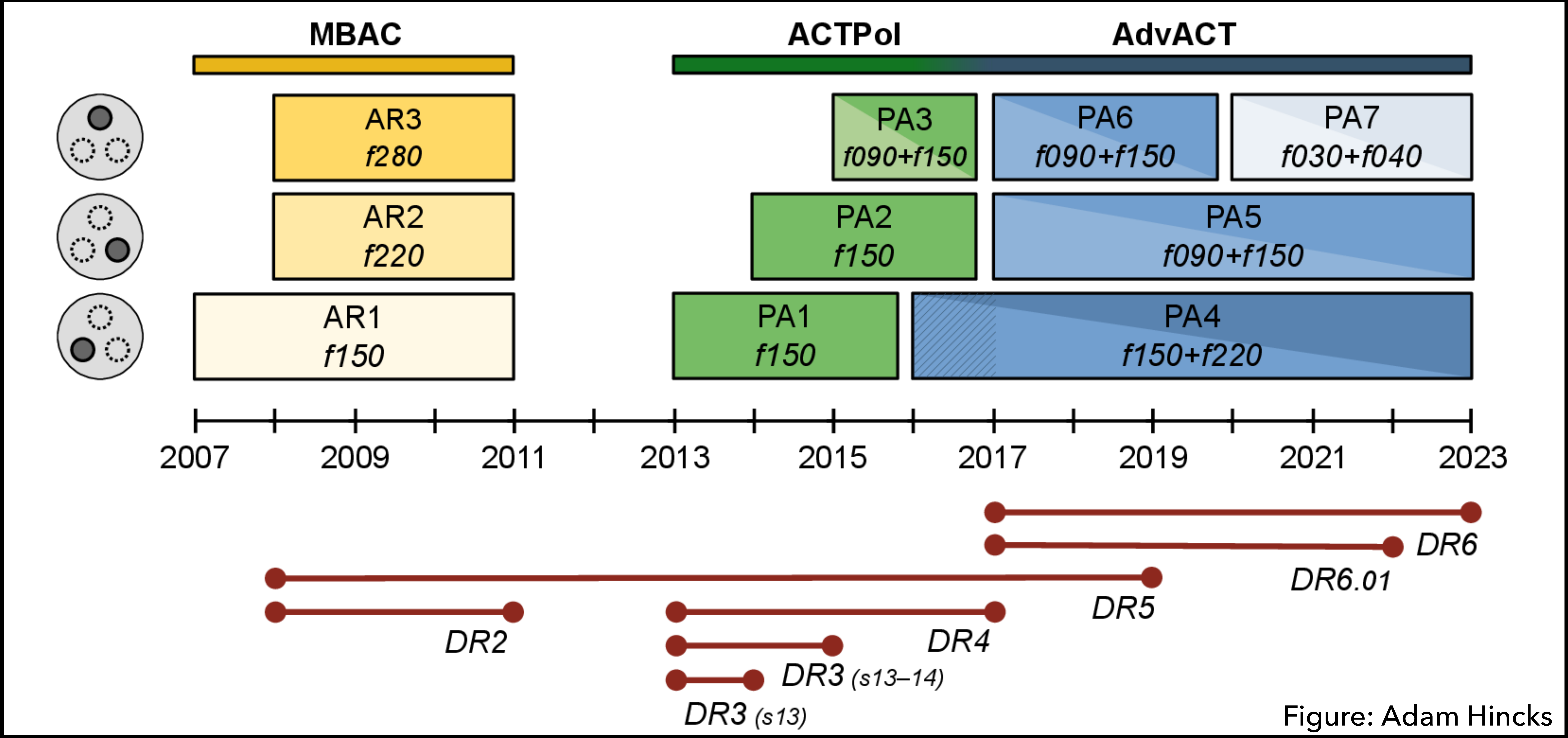


Figure: Adam Hincks

ATACAMA COSMOLOGY TELESCOPE

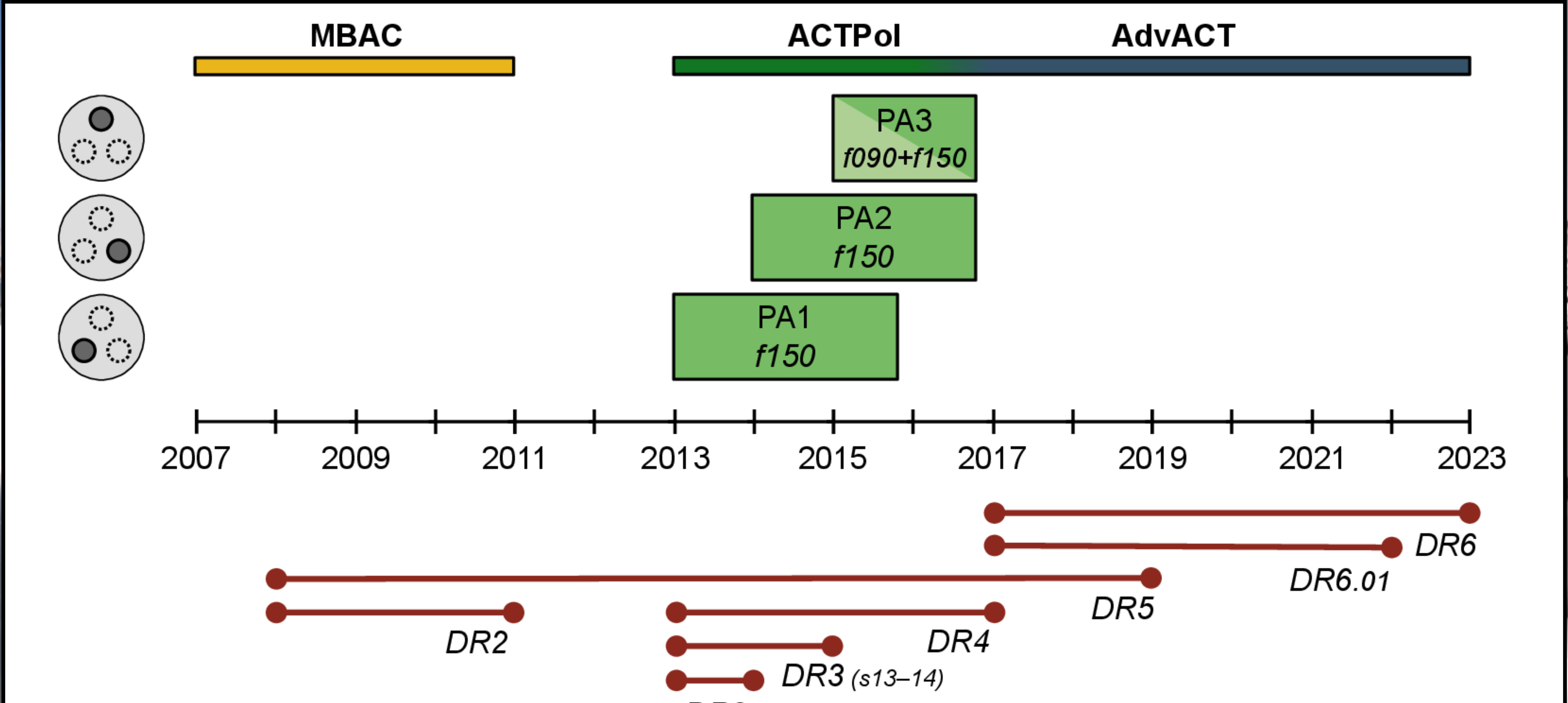
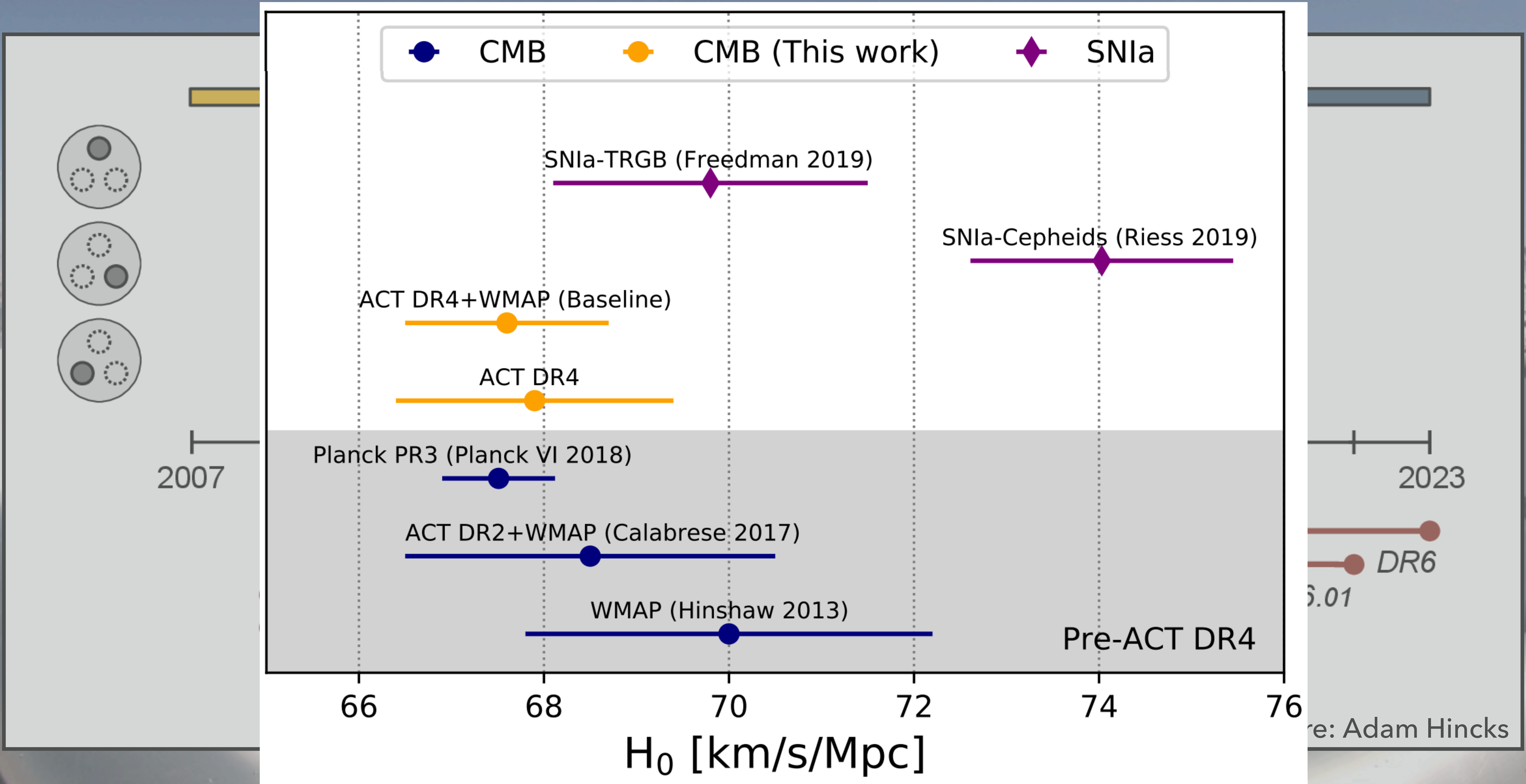


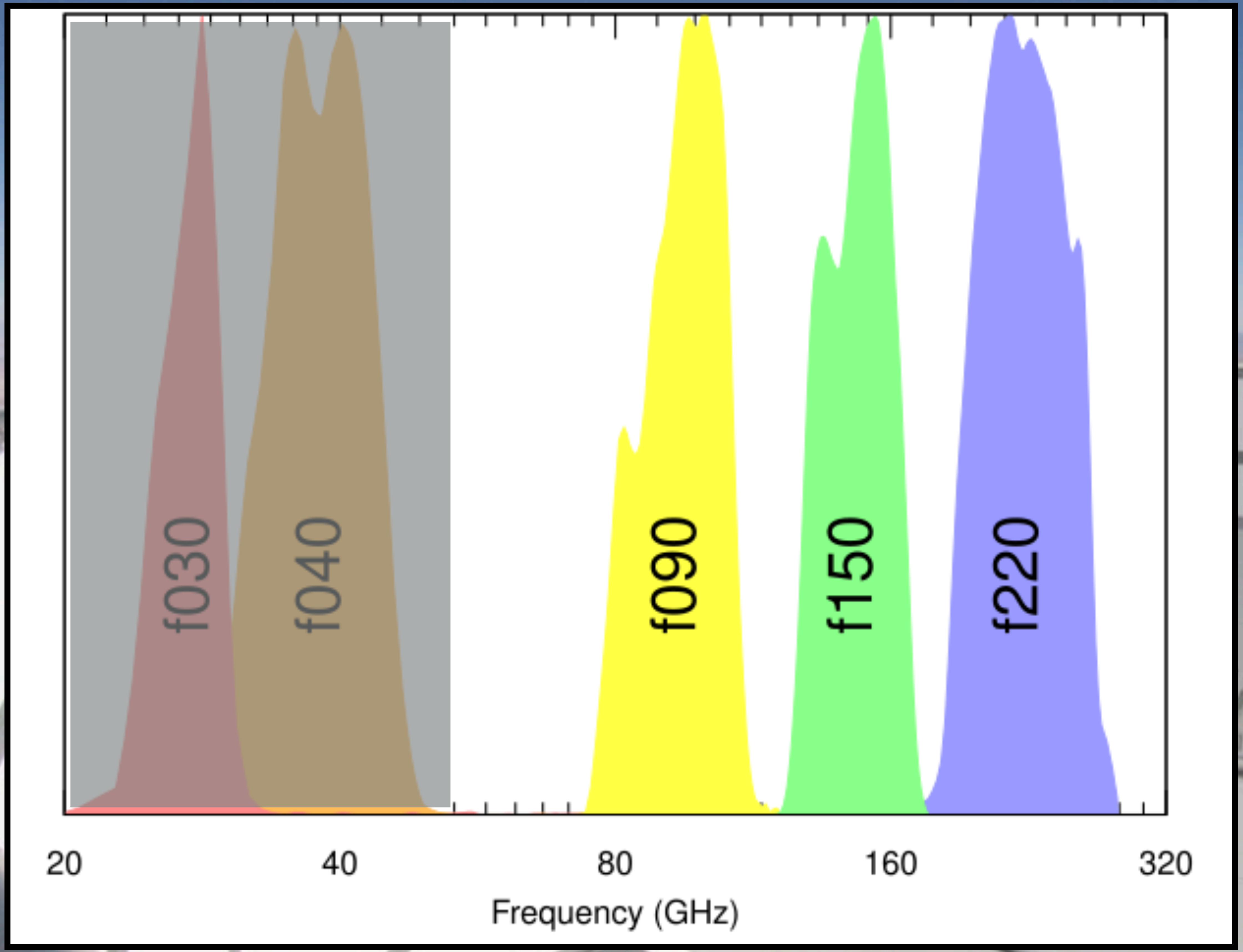
Figure: Adam Hincks

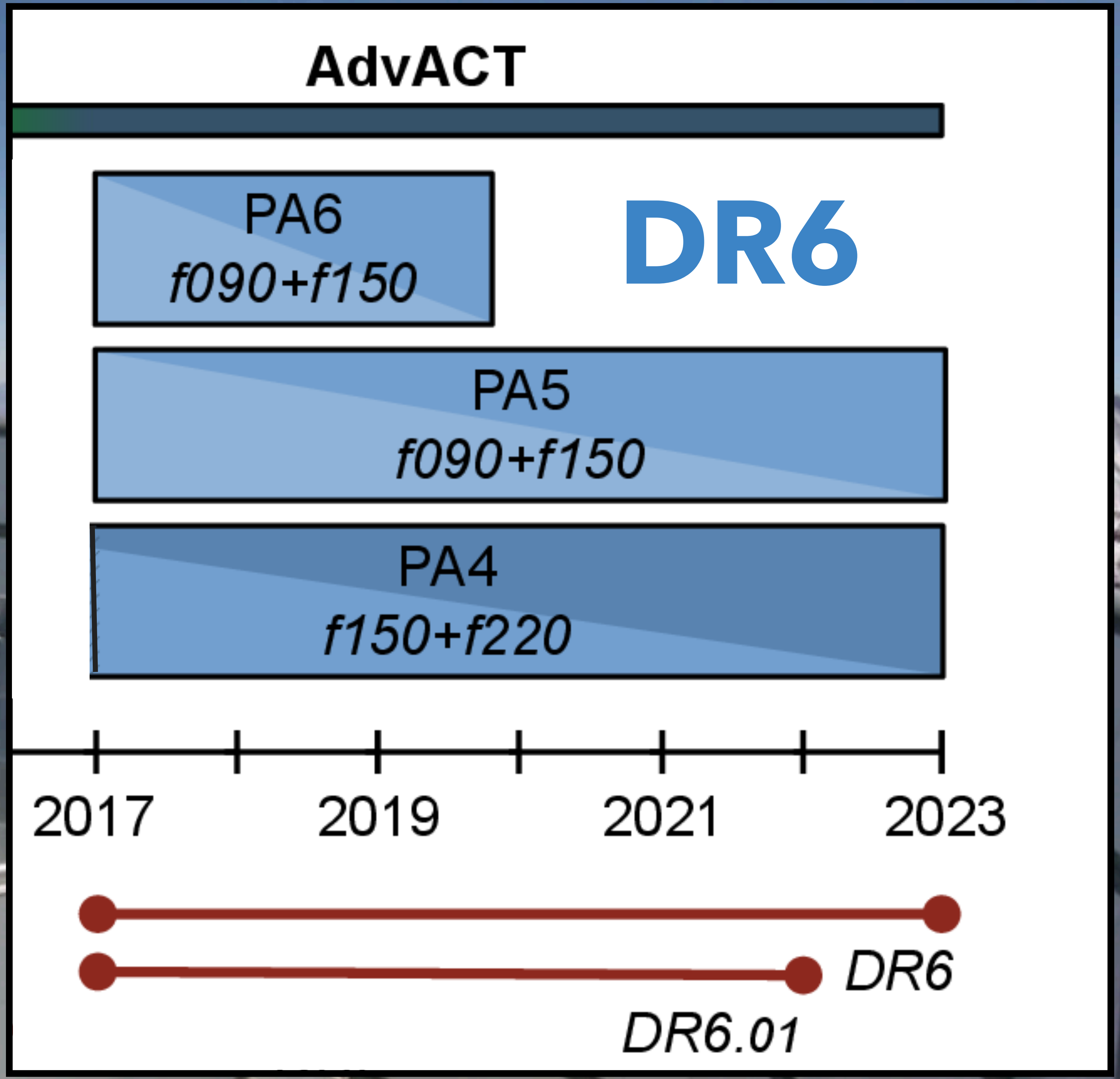
ATACAMA COSMOLOGY TELESCOPE



Aiola et al., 2020, Choi et al., 2020

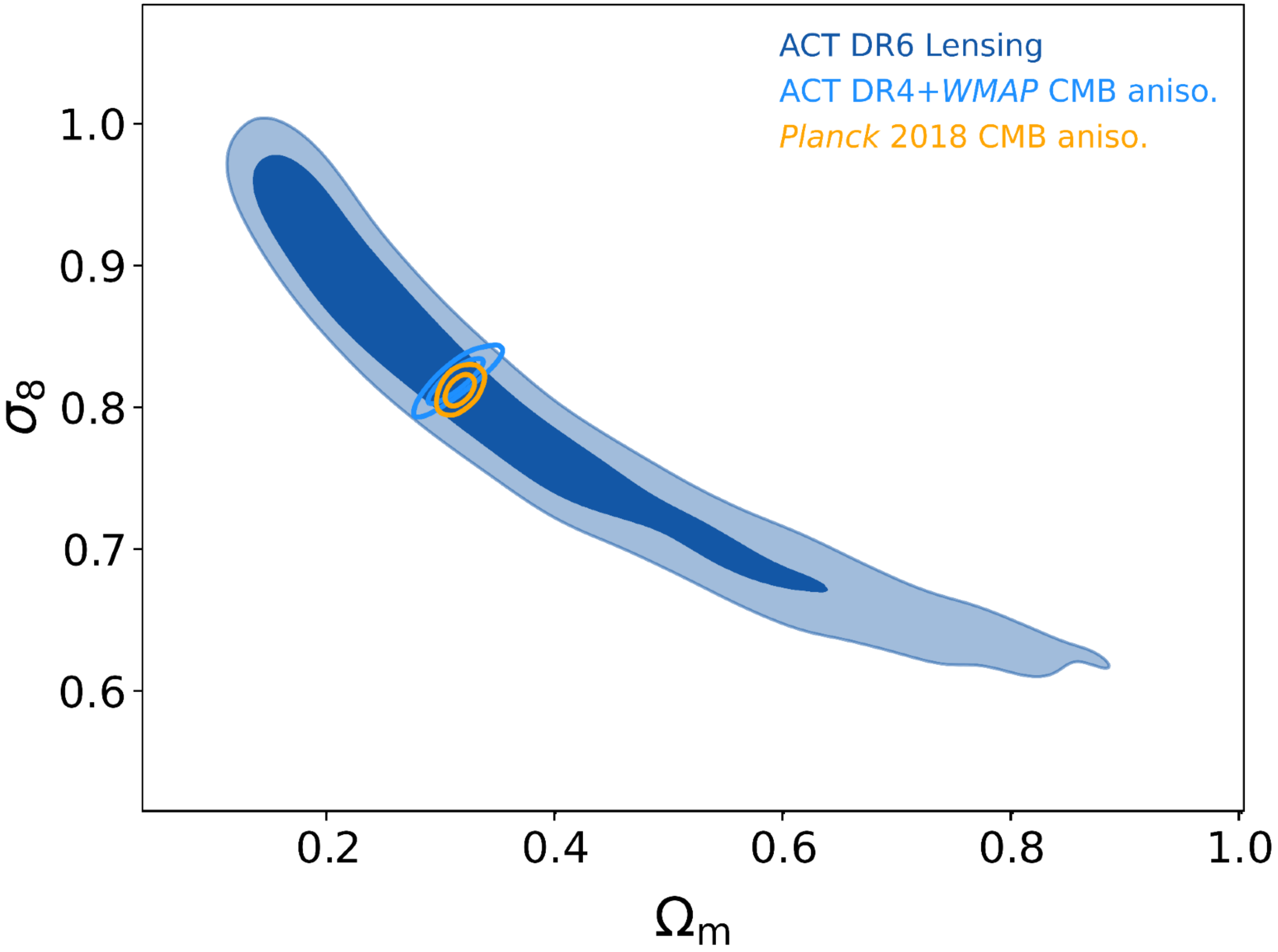
ATACAMA COSMOLOGY TELESCOPE, DR6

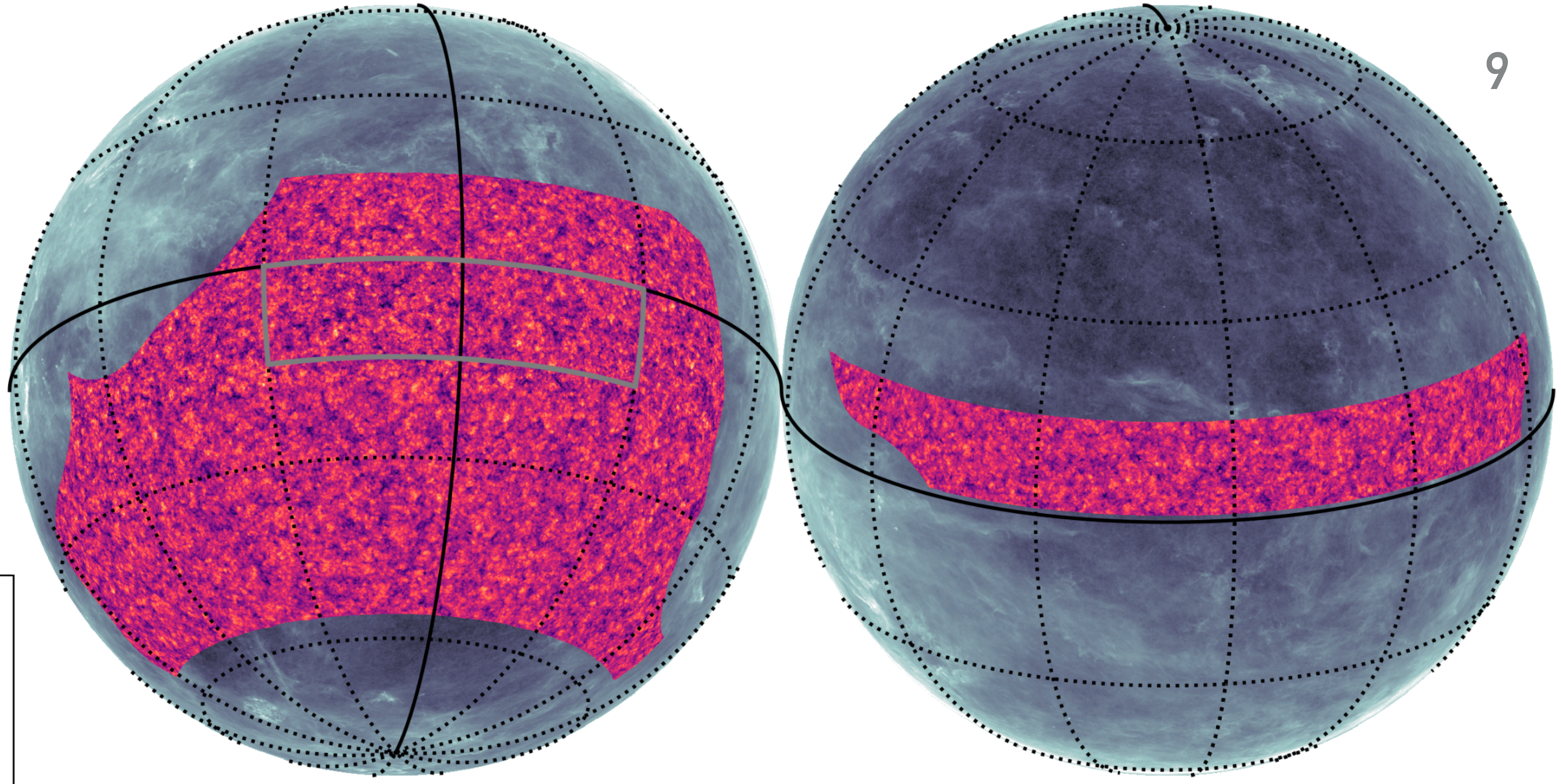




DR6 LENSING RESULTS

Late time structure formation as measured by ACT CMB lensing agrees with extrapolation from early universe



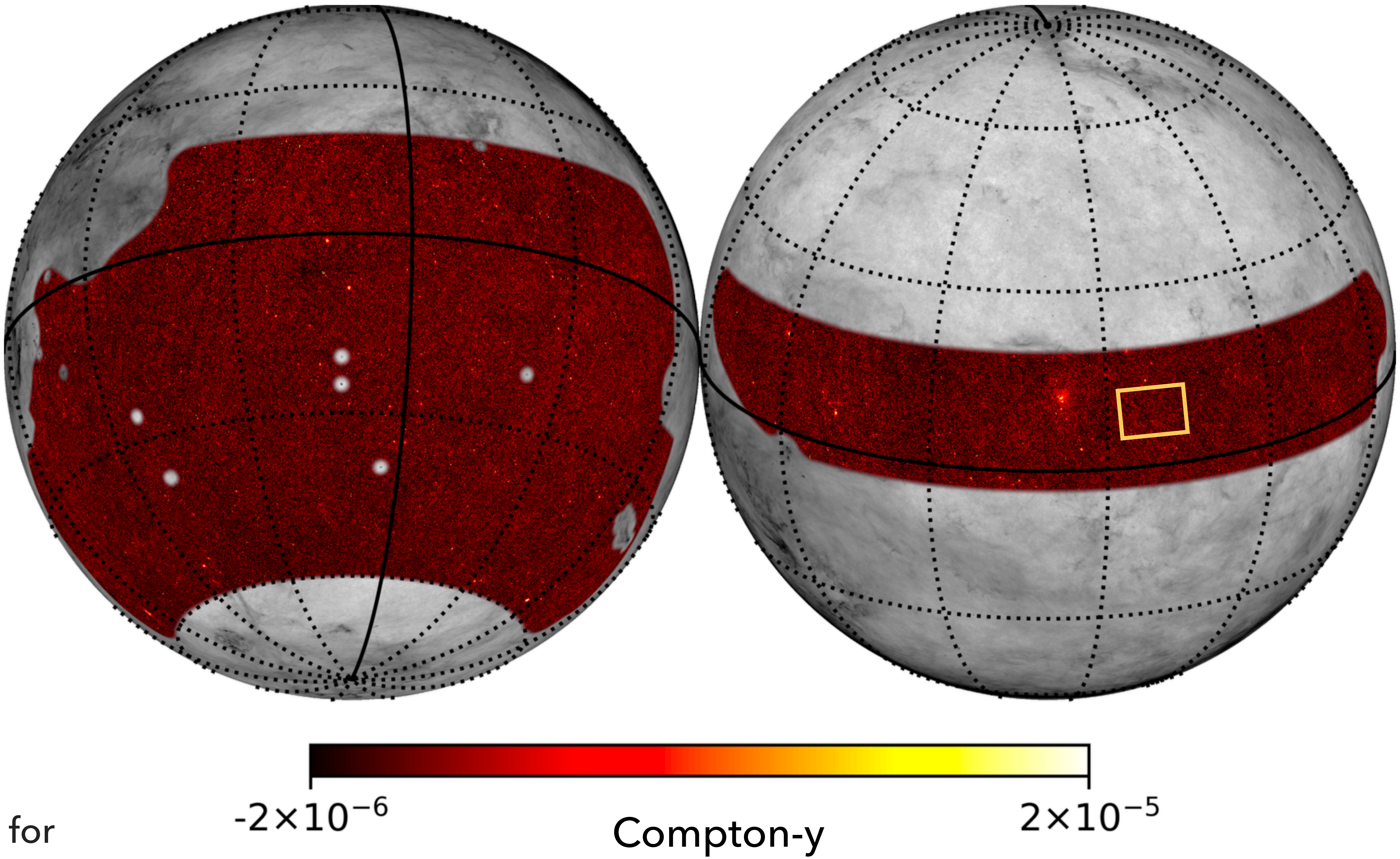


Described in [Qu++, 2023], [Madhavacheril++, 2023] and [MacCrann++, 2023] ACT lensing papers. Maps and likelihood available on Lambda

More recently: [Farren++, 2023] (ACT x UNWISE): structure formation at $z \sim 0.6$ and $z \sim 1.1$ also agrees with early universe

ACT + PLANCK MAP OF THE THERMAL SUNYAEV ZEL'DOVICH EFFECT

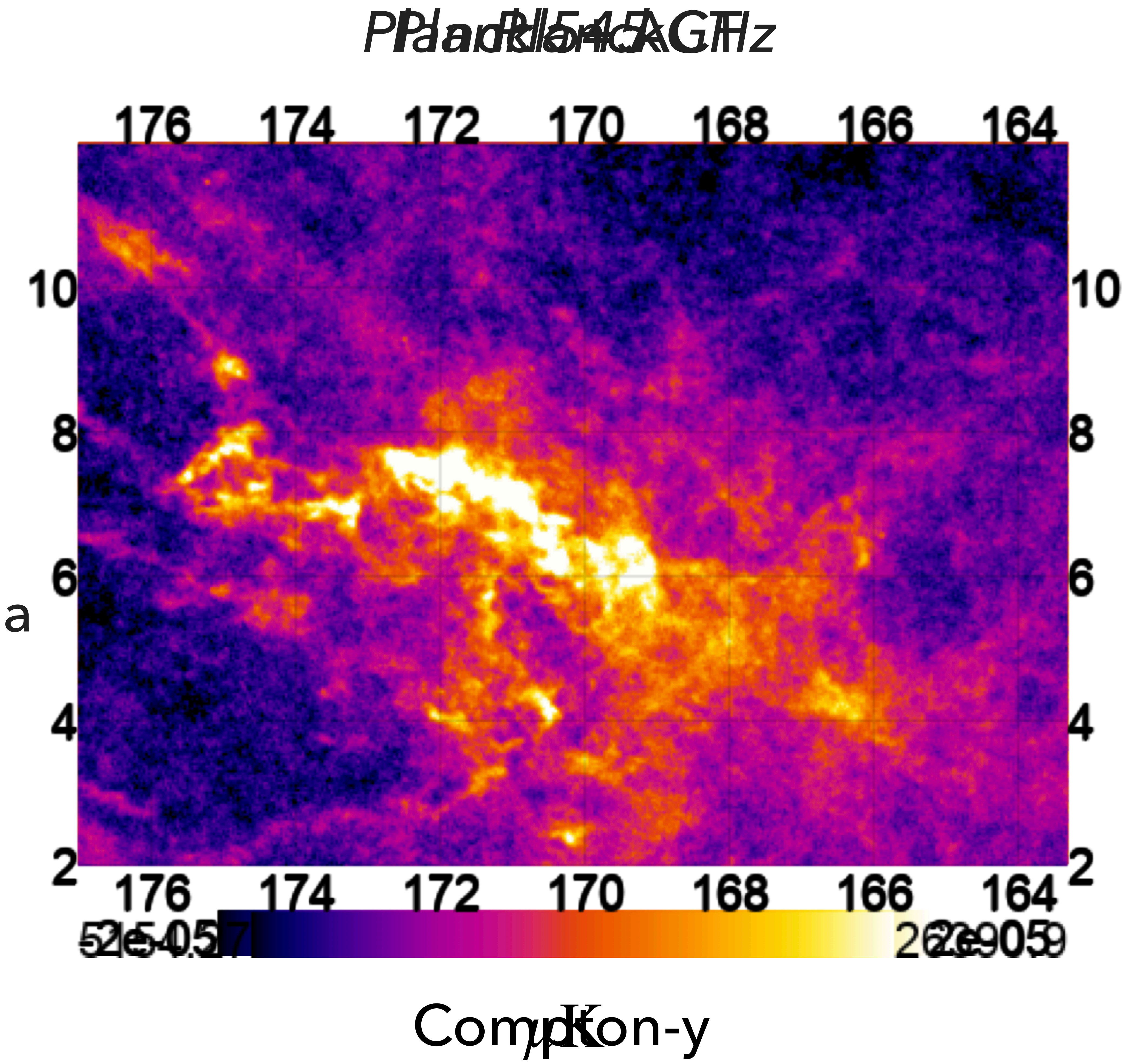
- Combine the 90, 150 and 220 GHz ACT bands with Planck NPIPE to form a map of the **total thermal SZ signal**
- A map of the integrated electron pressure in our universe



Coulton++, 2024
See also Hilton++, 2020 for cluster catalog

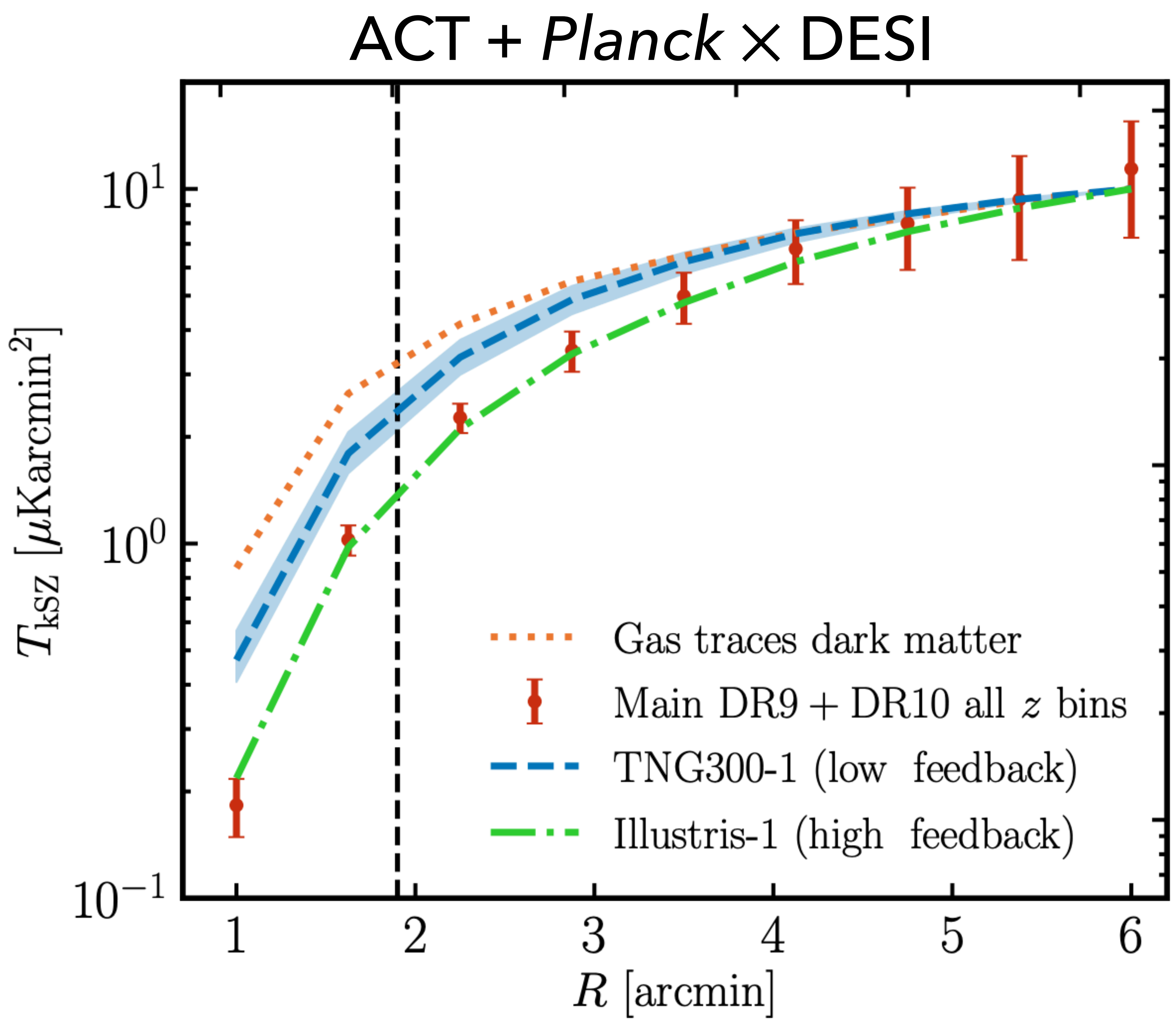
ACT + PLANCK MAP OF THE THERMAL SUNYAEV ZEL'DOVICH EFFECT

- High-res ACT data helps with foreground contamination
- Several "deprojection" options available that explicitly remove contamination
- Maps available on Lambda

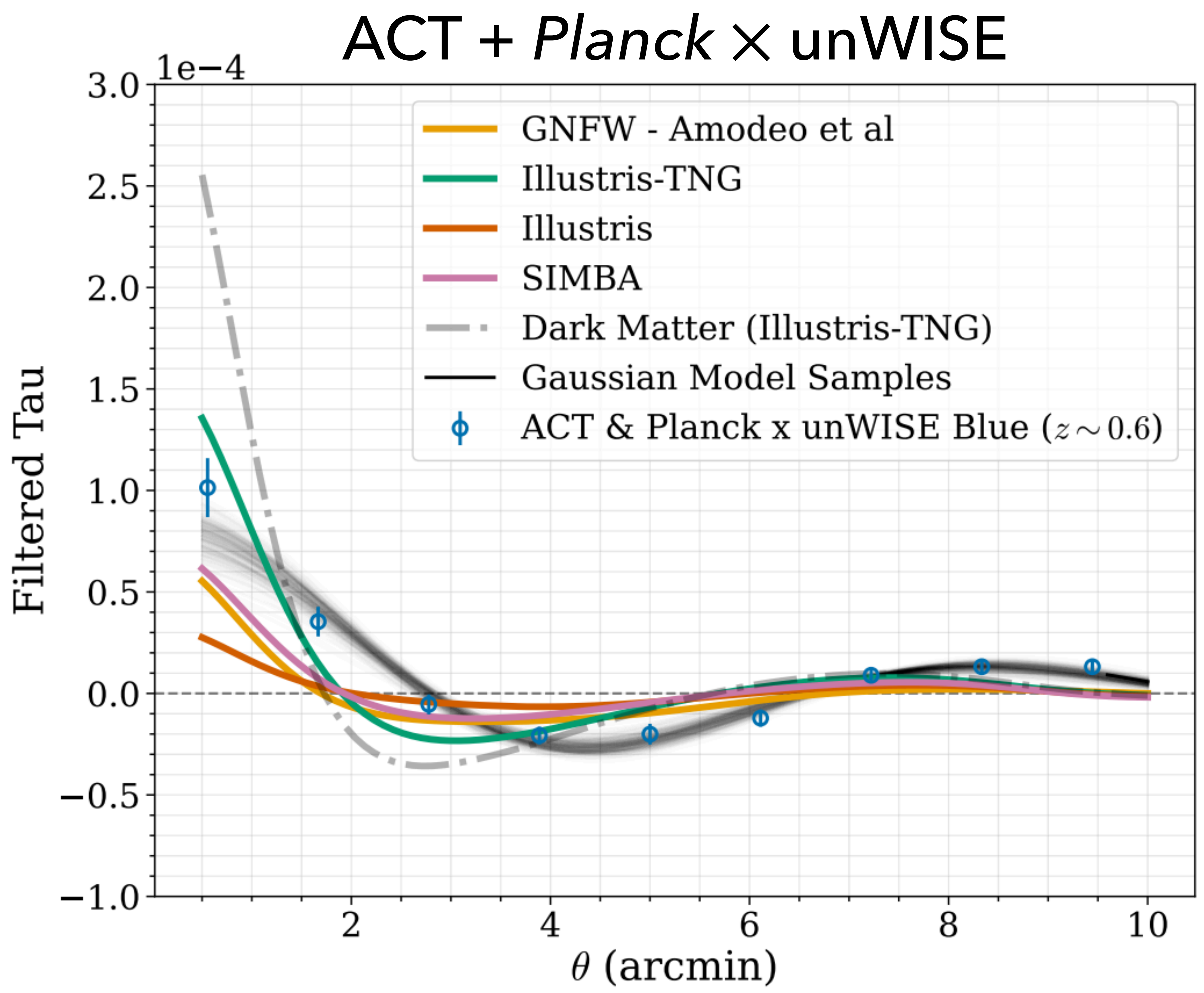


DR6 SECONDARIES II

- Kinetic SZ effect starts to seriously constrain cosmology
- First detection of patchy screening



Hadzhiyska++, 2024



Coulton++, 2024

DR6 – SMALL SCALE CMB

Power spectrum analysis Internal null tests are passing. Final analysis of the data in progress

- CMB power spectrum results are significantly more sensitive than *Planck*

- Temperature-polarization correlation (TE) becomes most sensitive channel

S/N in polarization (EE)

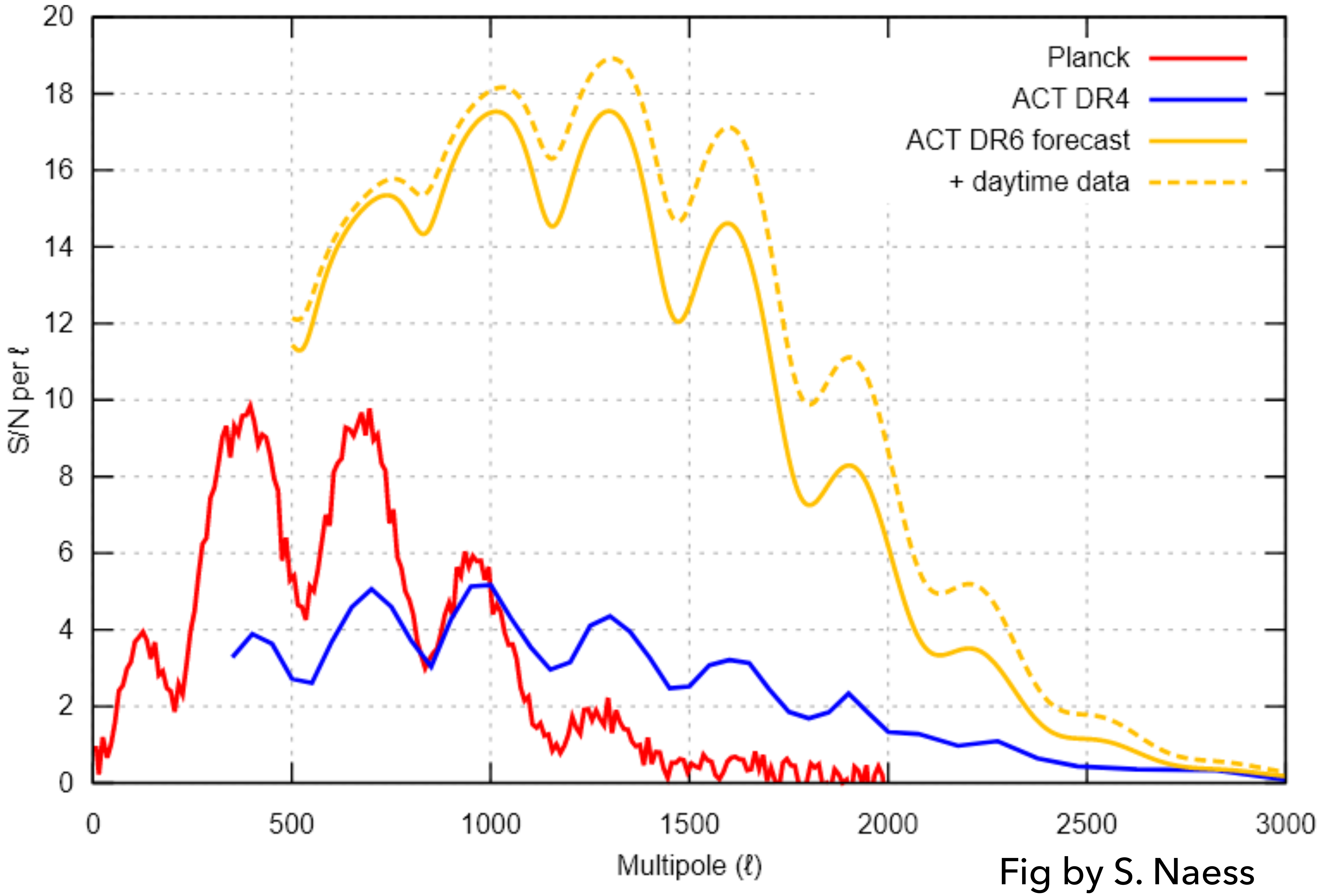


Fig by S. Naess

DR6 – SMALL SCALE CMB

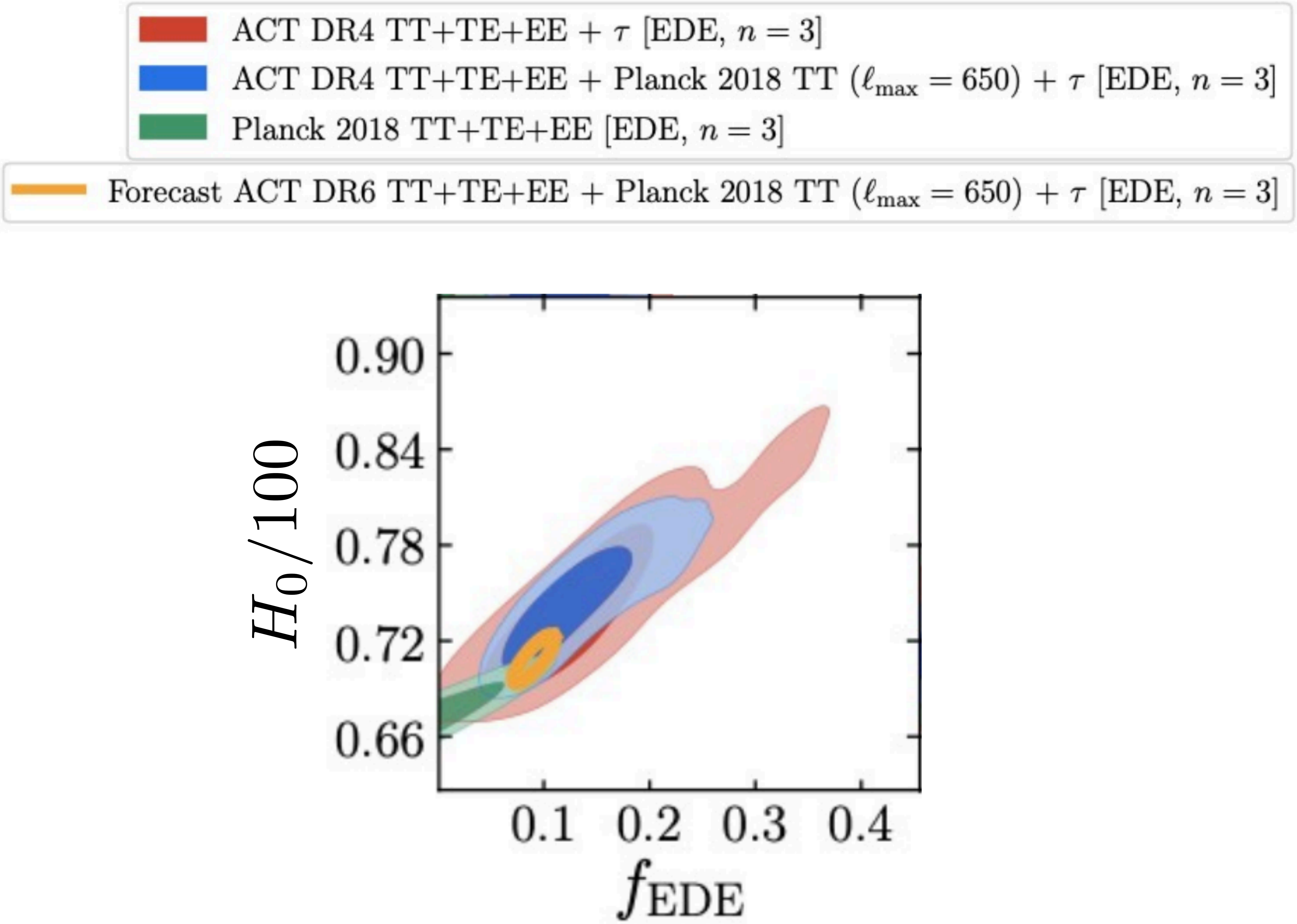
- Addition of small scale and polarization data enables testing of a range of extensions to ΛCDM
  - 2x more sensitive to extra relativistic species ($N_{\rm eff}$) compared to *Planck* alone

Forecast

	DR4 + WMAP	Planck	DR6 + Planck
$\sigma(H_0)$	1.1	0.5	**0.4**
$\sigma(n_s)$	0.006	0.004	**0.003**
→ $\sigma(N_{\rm eff})$	0.3	0.2	**0.1**

DR6 – SMALL SCALE CMB

- Addition of small scale and polarization data enables testing of a range of extensions to ΛCDM
  - Early dark energy" (EDE) solution to the "Hubble tension"

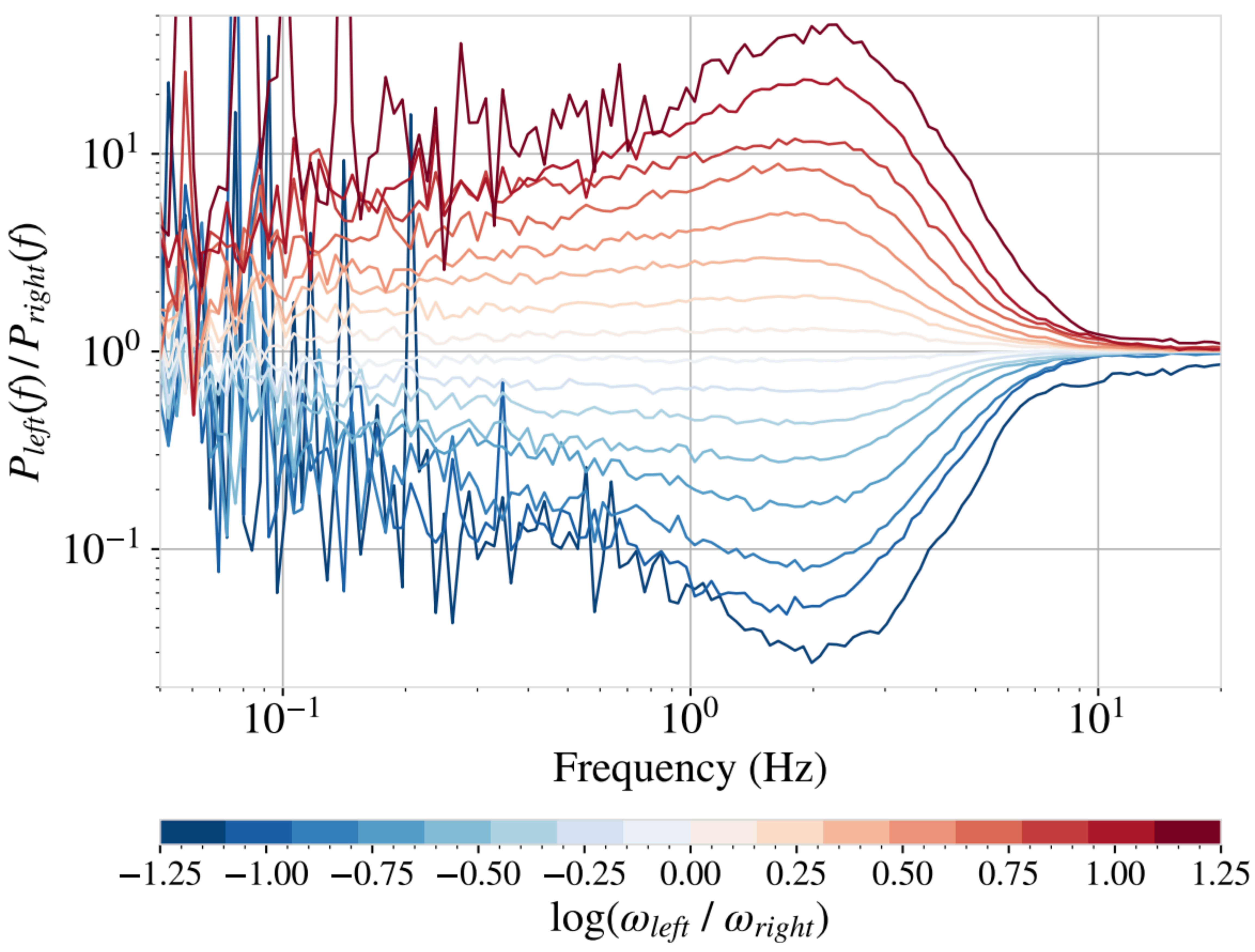


See e.g. V. Poulin, T. L. Smith, T. Karwal and M. Kamionkowski Phys. Rev. Lett. 122 (2019) 221301

Forecast by C. Hill

LESSONS LEARNED: MAXIMUM LIKELIHOOD MAPS

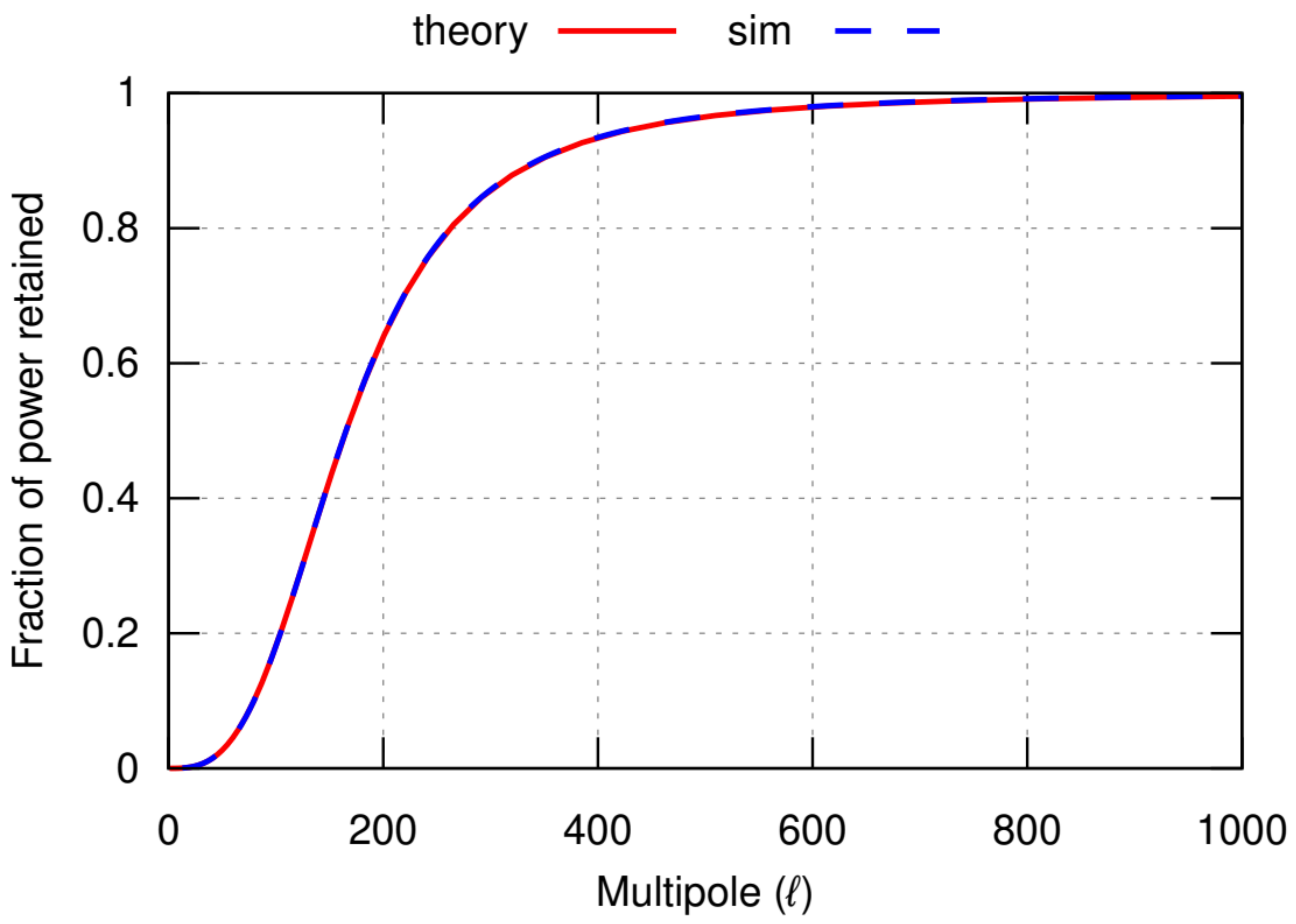
- ML maps, very expensive but (approximately) unbiased
  - Downsides: complicated noise properties and limited ability to produce time-ordered end-to-end simulations
- Atmosphere modeled as stationary in time-domain. Crucial to include correlations between detectors in noise model
  - Example of possible improvement from [Morris++, 2022]: take wind direction into account



Noise power spectrum changes significantly as one scans with or against the wind direction

LESSONS LEARNED: MODEL ERRORS

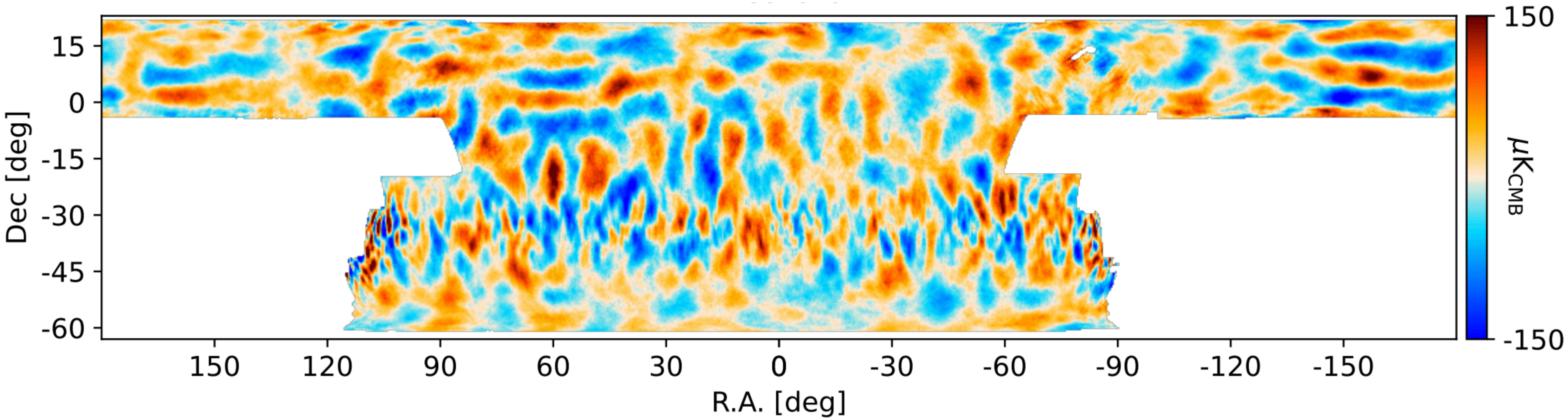
- As dynamic range in noise covariance increases, seemingly benign model errors start to cause large biases during mapmaking
  - Examples: pixelization and relative gain errors between the detectors
- For ACT, the lack of hardware calibrator leaves planet- or atmosphere-based gain calibration
  - Planet sensitive to per-detector beams
  - Atmosphere sensitive to passband differences between detectors
- Having overlapping angular scales with Planck is important. Accurate gain calibration should be very high priority for upcoming experiments



Toy model from Naess, Louis, 2023 showing the bias due to detector gain errors

LESSONS LEARNED: NOISE SIMULATIONS

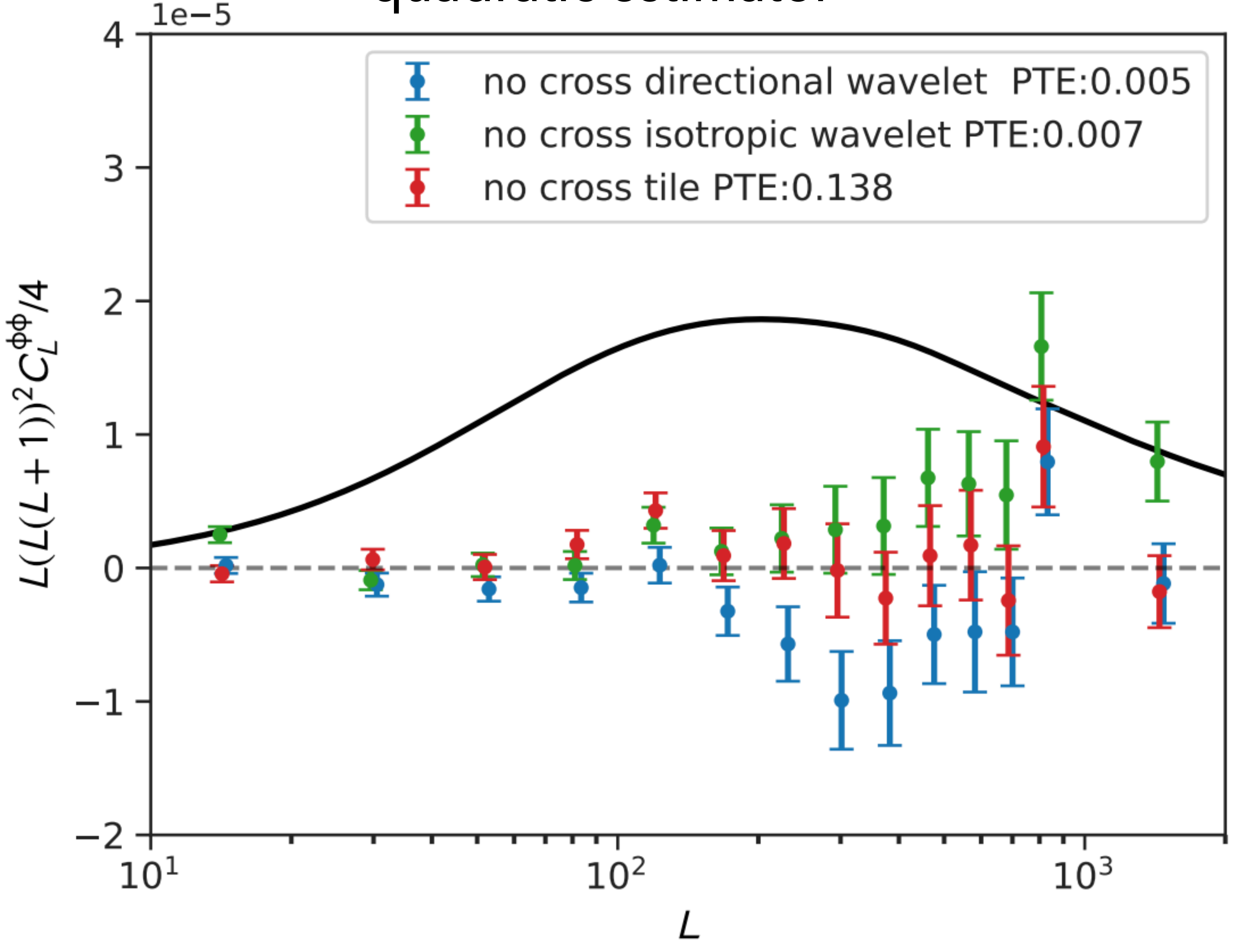
- Time-domain noise simulations are too expensive for ACT (and unclear how accurate they would be)
- Developed wavelet-based method to efficiently draw accurate noise simulations [Atkins++, 2023] from model estimated directly from map differences
- Crucial for recent ACT CMB lensing results and other upcoming cosmological results



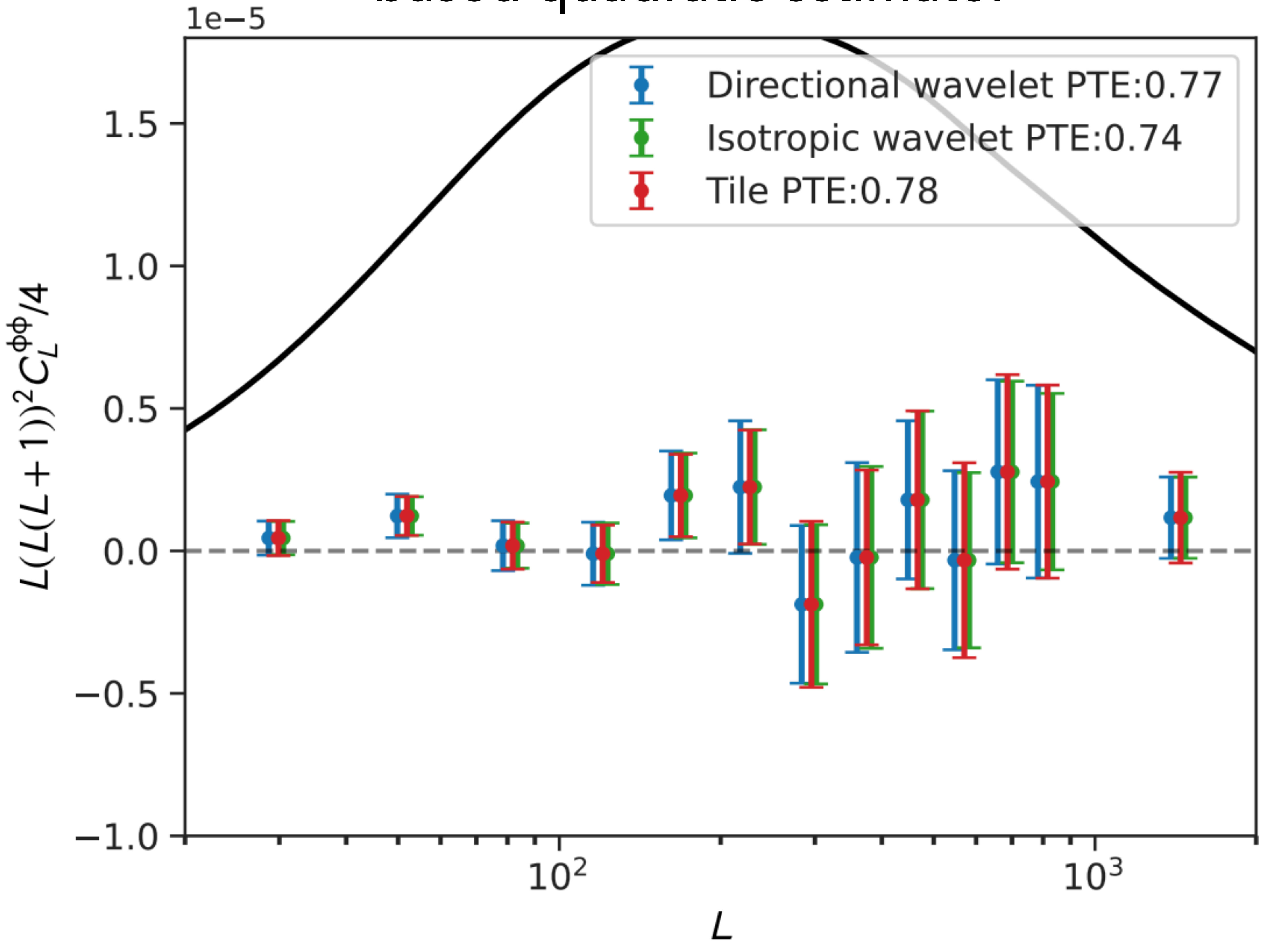
ACT noise simulation, Stokes Q

LESSONS LEARNED: SPLIT-BASED ESTIMATORS

Lensing null with normal quadratic estimator



Lensing null with cross-spectrum-based quadratic estimator

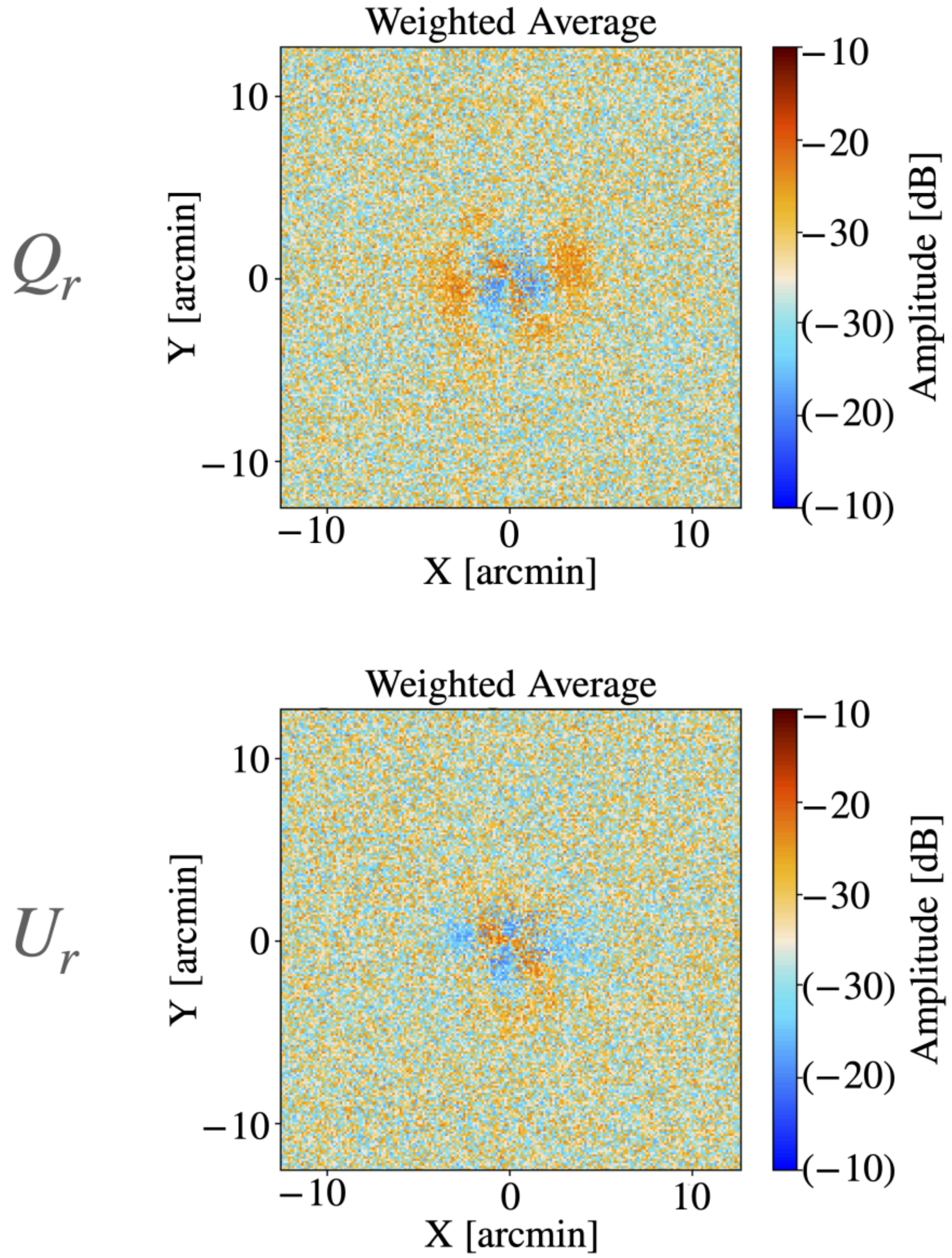


Plots from [Qu++, 2023]

See [Madhavacheril, Smith, Sherwin, Naess, 2020]

LESSONS LEARNED: BEAM LEAKAGE

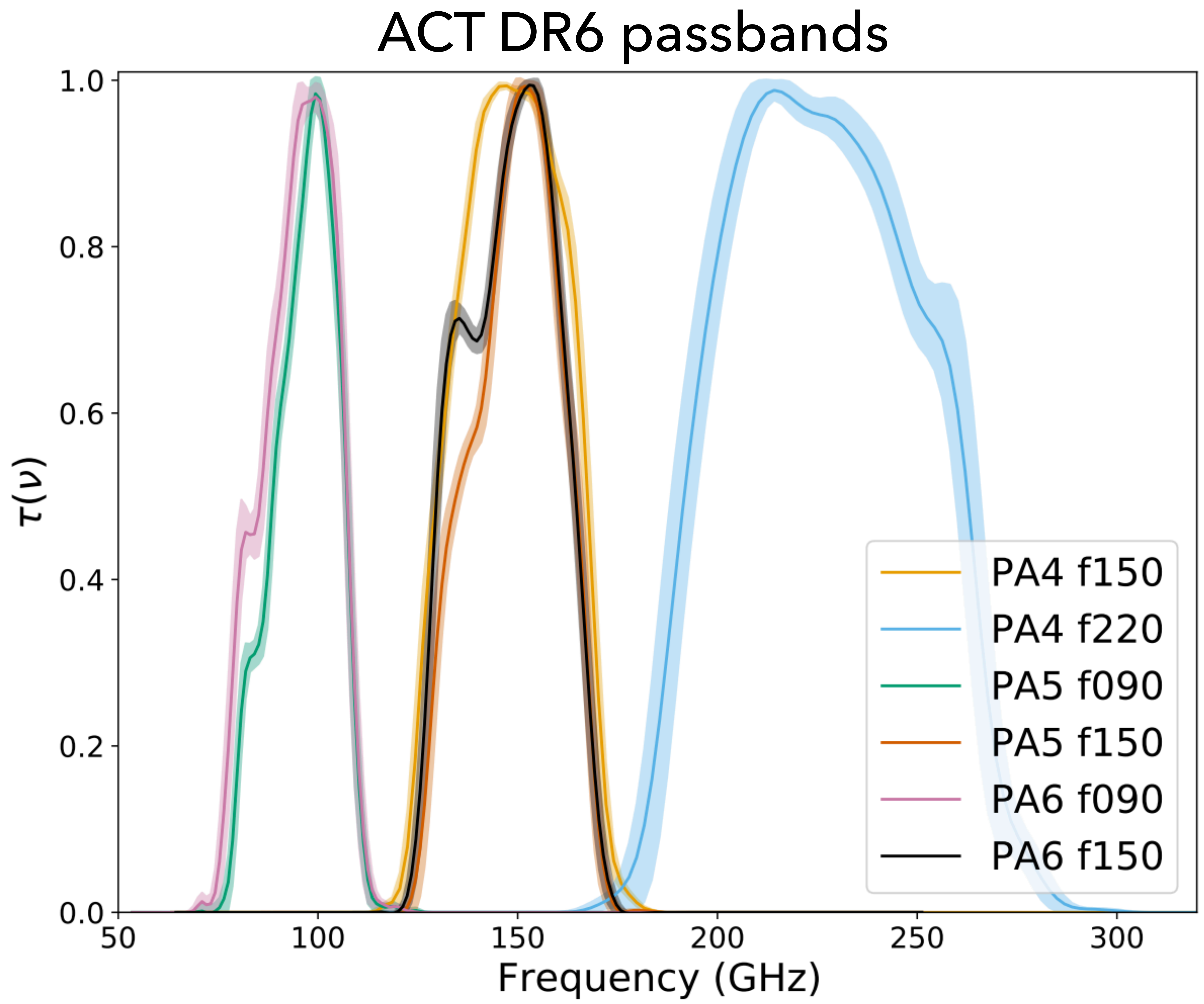
- The uncertainty in the estimates of temperature-to-polarization leakage starts to dominate the error budged at large scales
- One should be very generous with scheduling planet observations (and again, detector gain calibration!)



ACT DR4 leakage beams from Lungu++, 2022

LESSONS LEARNED: PASSBANDS

- Foreground modeling becomes sensitive to 1 GHz shifts in the central passbands
    - 1 GHz is comparable to the current systematic uncertainty
    - More accurate measurements of the passbands are vital to go beyond ACT sensitivity



Coulton++, 2024

CONCLUSION

- ACT DR6 is a quite dramatic improvement over ACT DR4
  - Power spectrum analysis in final stage. Many other analyses (updated lensing, bispectrum, cluster catalogs, cross-correlations) also in prep
  - We will release all of the DR6 maps
- Error budged starts to become systematics dominated, rethinking of calibration strategies will be vital for upcoming experiments
- We still have very sensitive 30 and 40 GHz data that has been mapped but not yet seriously analyzed