Cosmology from CMB small scales

ACT DR6 results and SO goals

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Image: the Atacama Cosmology Telescope

erc European Research Council
UK SPACE AGENCY
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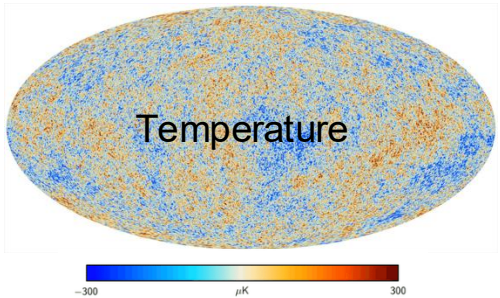
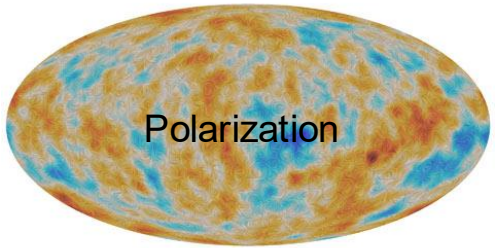
UKRI UK Research and Innovation

Exploring the Universe with the CMB



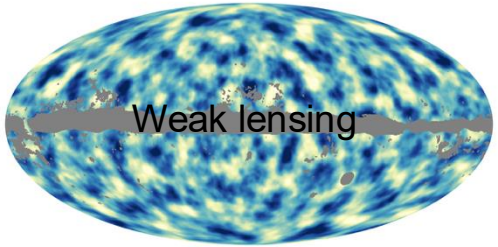
Cold light, 2.7K
Variations in the sky of
1 part in 100000

→ Initial seeds of cosmic structures
Gravitational fields
Make up of the Universe



Polarized light at the 10% level
Variations in the sky of less
than 1 part in 1000000(00)

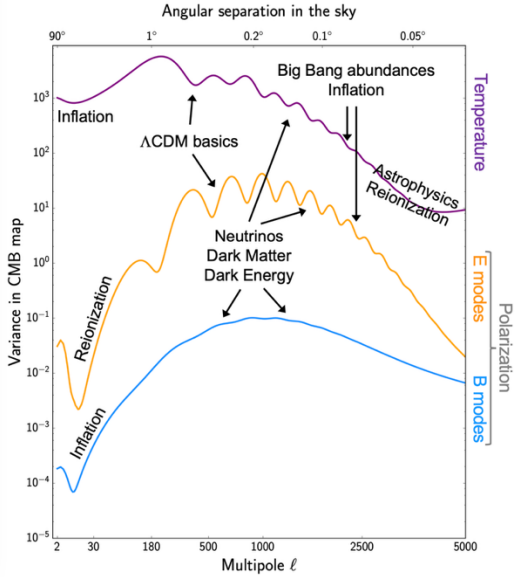
→ Where and how
atoms/molecules/stars are forming
First second of Universe existence

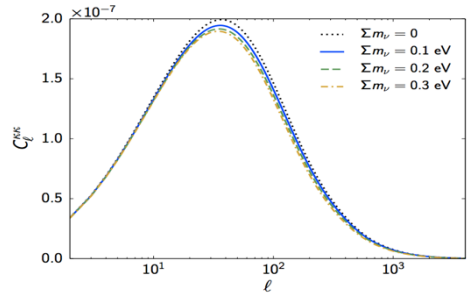


2 arcminute (~1/15 of the Moon)
total deflection over a 13.3
billion-year journey

→ Geometry and matter distribution
from early Universe to today

ESA/Planck Collaboration



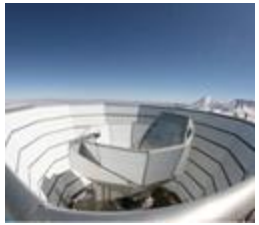


Exploring the Universe with the CMB

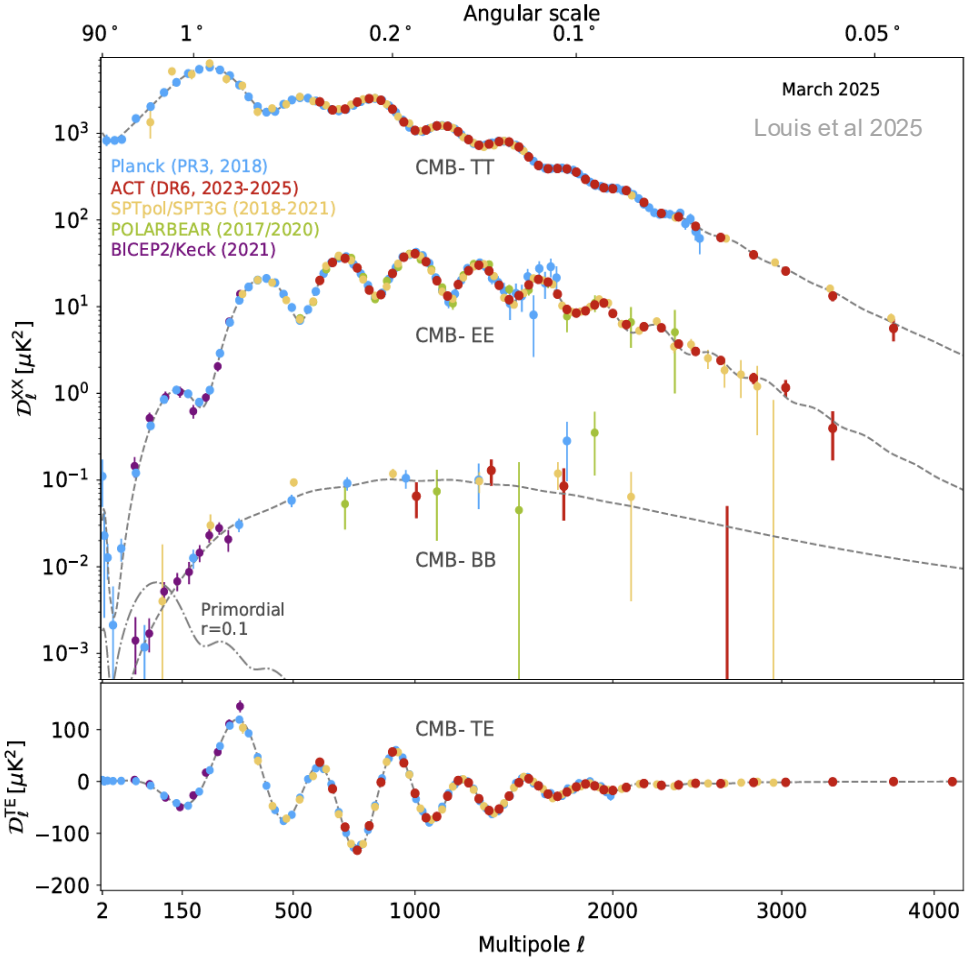
Three decades of increasingly accurate observations from space and ground

Planck

ACT



SPT



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Three decades of increasingly accurate observations from space and ground

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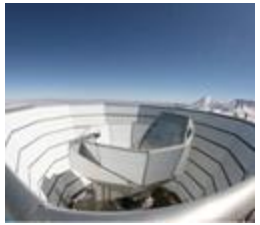
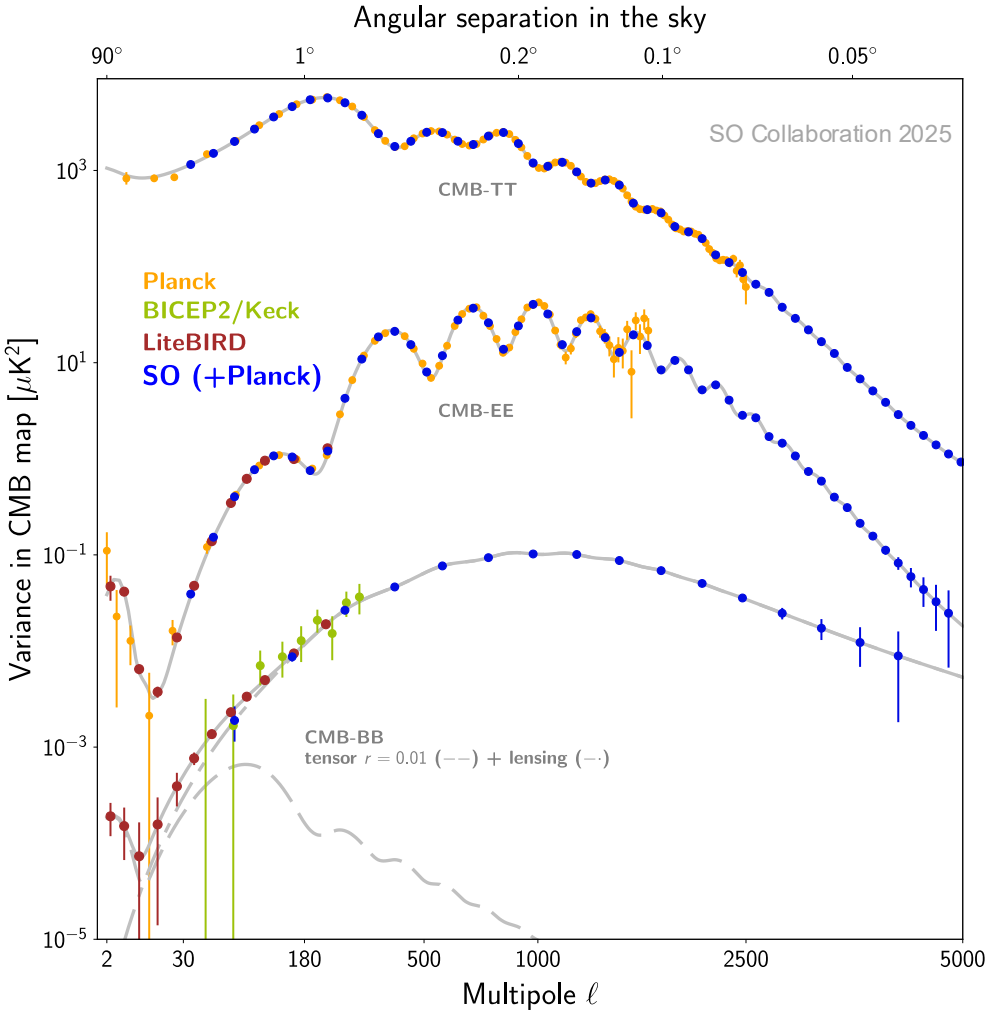


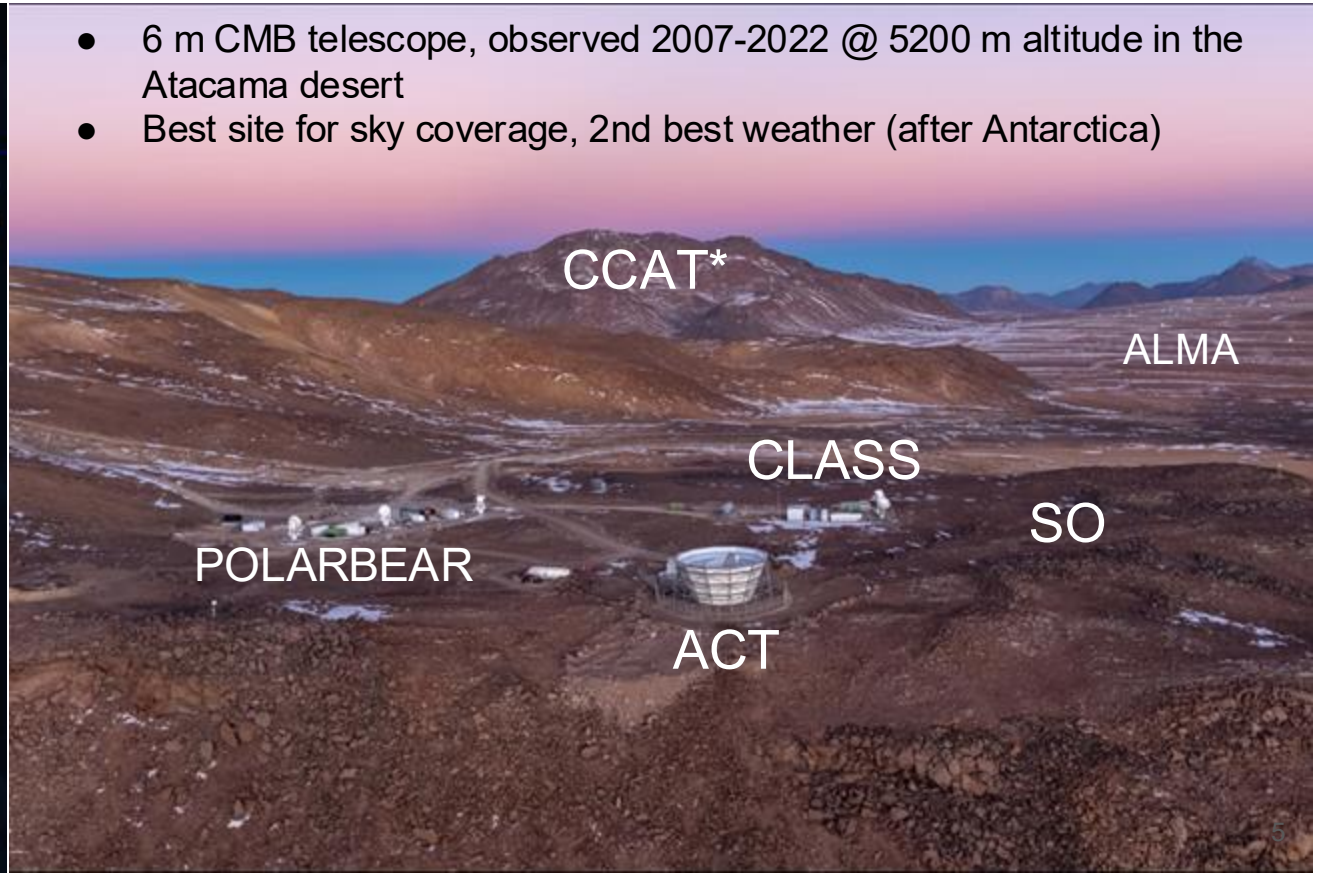
SPT

Two more decades ahead of us to map all the scales



The Atacama Cosmology Telescope

- 6 m CMB telescope, observed 2007-2022 @ 5200 m altitude in the Atacama desert
- Best site for sky coverage, 2nd best weather (after Antarctica)

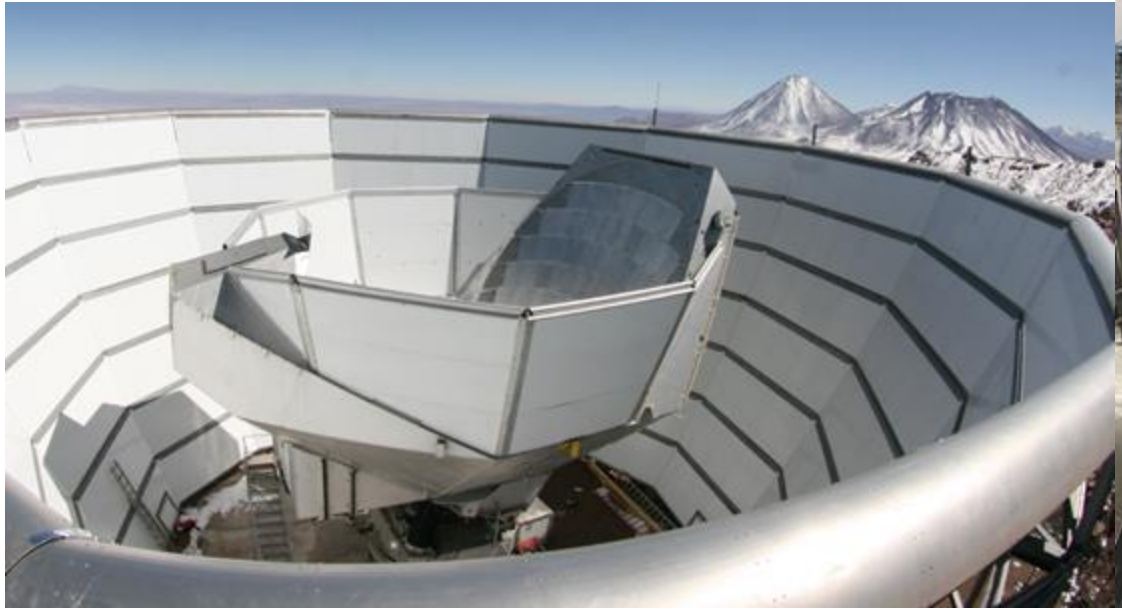


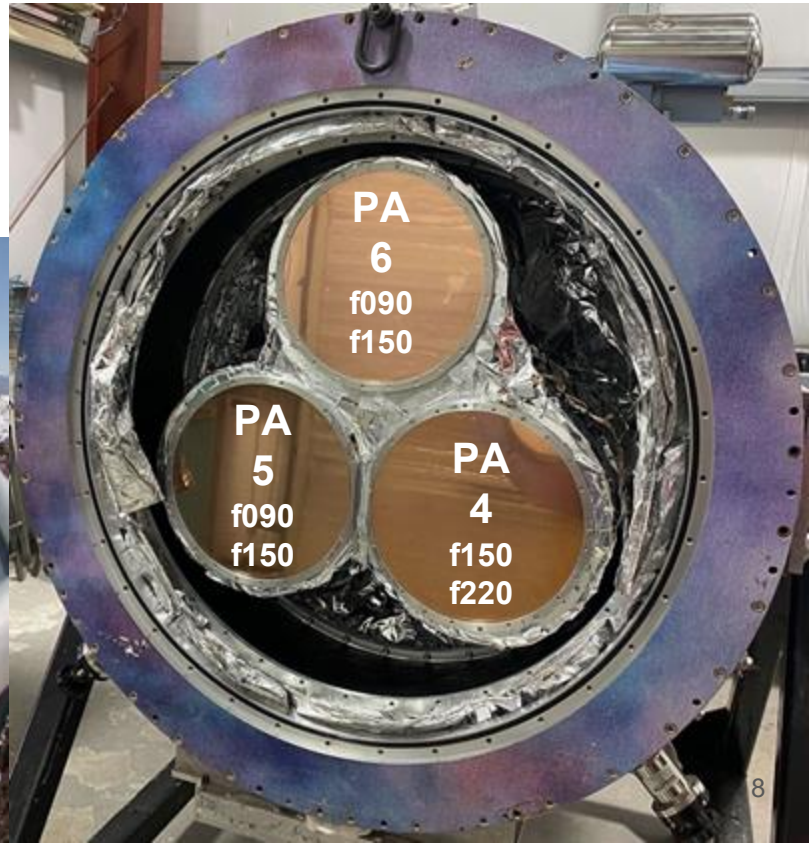
The ACT Collaboration

160 collaborators at 60 institutions

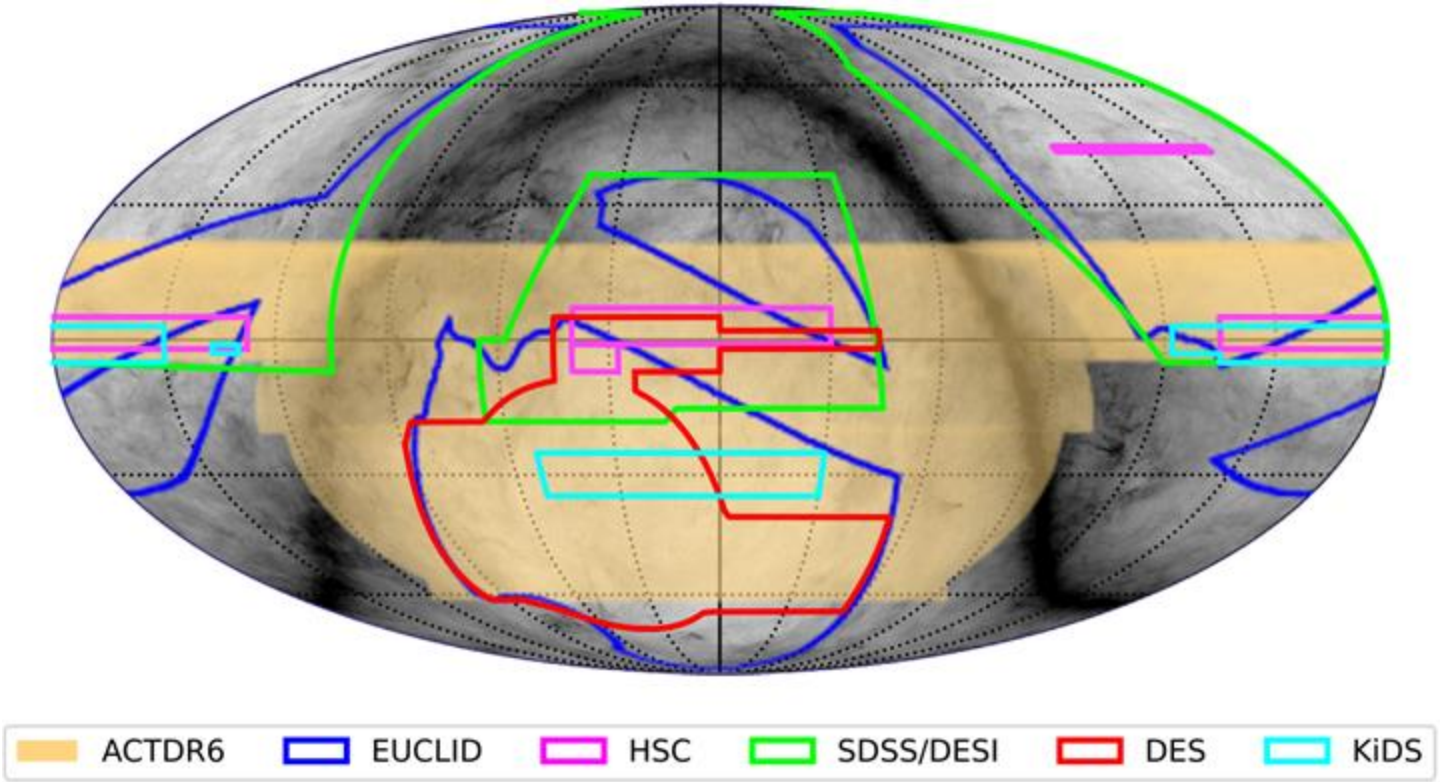
A closer look

- 3 dichroic detector arrays: PA4, PA5 and PA6
- 3 broad bands: f090 (77 – 112 GHz), f150 (124 – 172 GHz) and f220 (182 – 277 GHz)
- Combined sensitivity of 6.2 μK√s, and 1.4’ FWHM @ f150



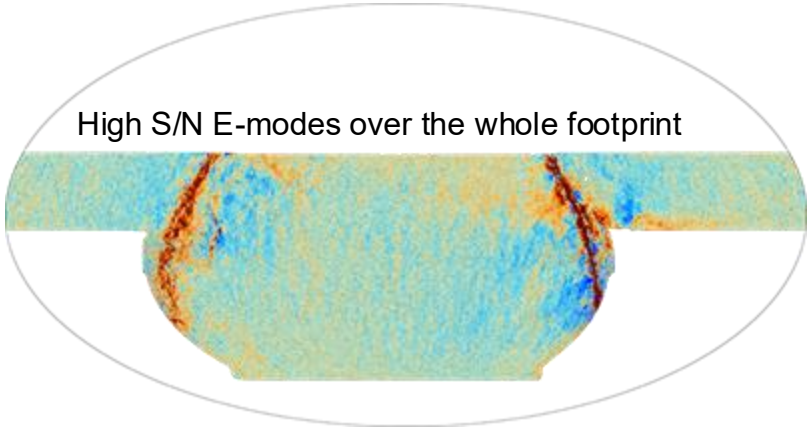


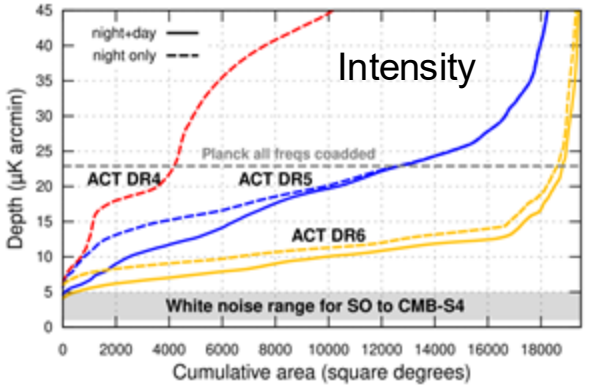
45% sky coverage and large overlap with other surveys

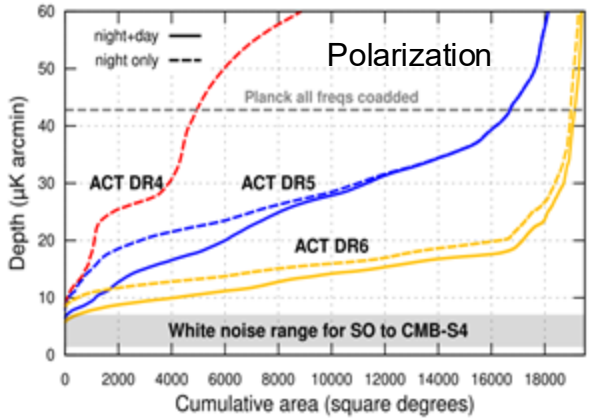


ACT Data Release 6

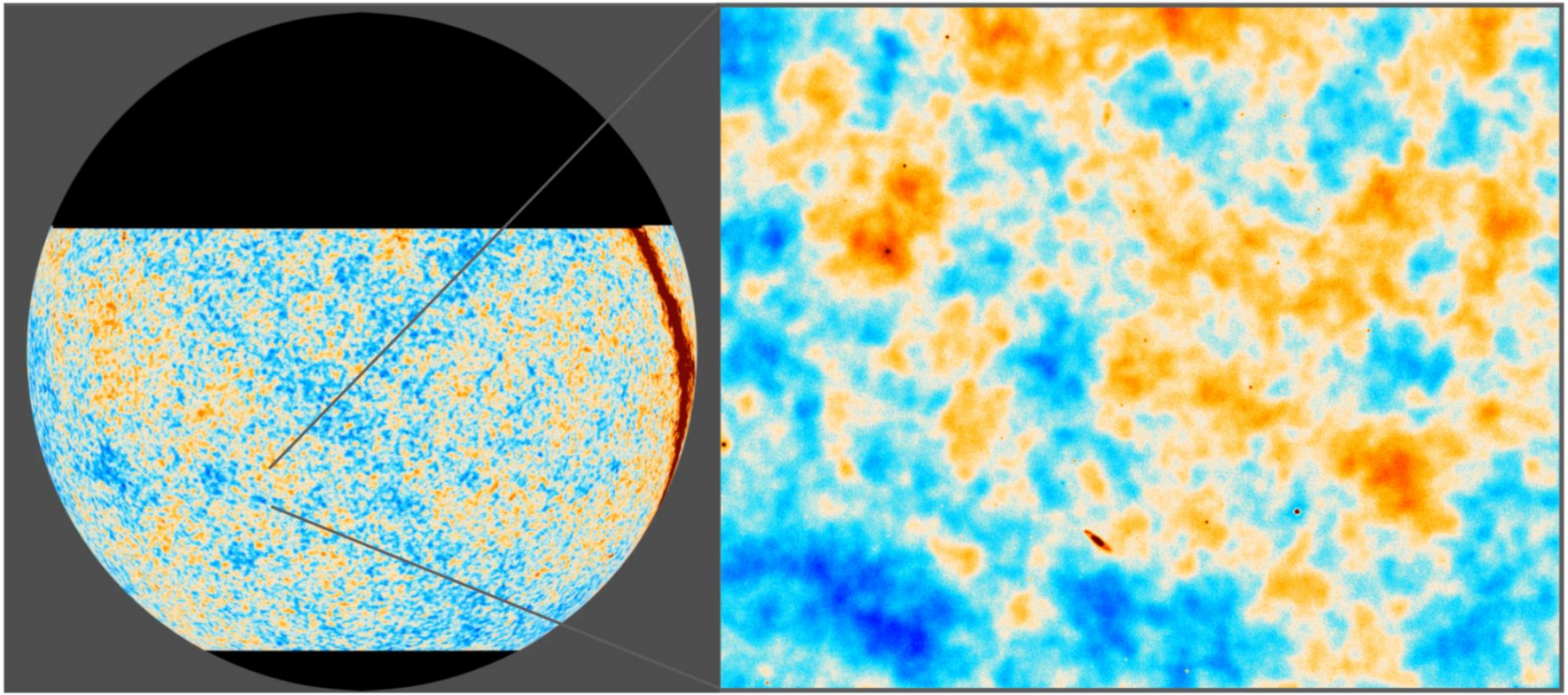
- DR6 = 2017-2022, 828 full days of CMB observations
- Night-time half primary data set
- Large improvement in depth compared to previous full data release (DR4) and interim release (DR5)
- Deeper than Planck over 19000 square degrees (on small scales)
- On average ⅓ the white noise RMS of Planck



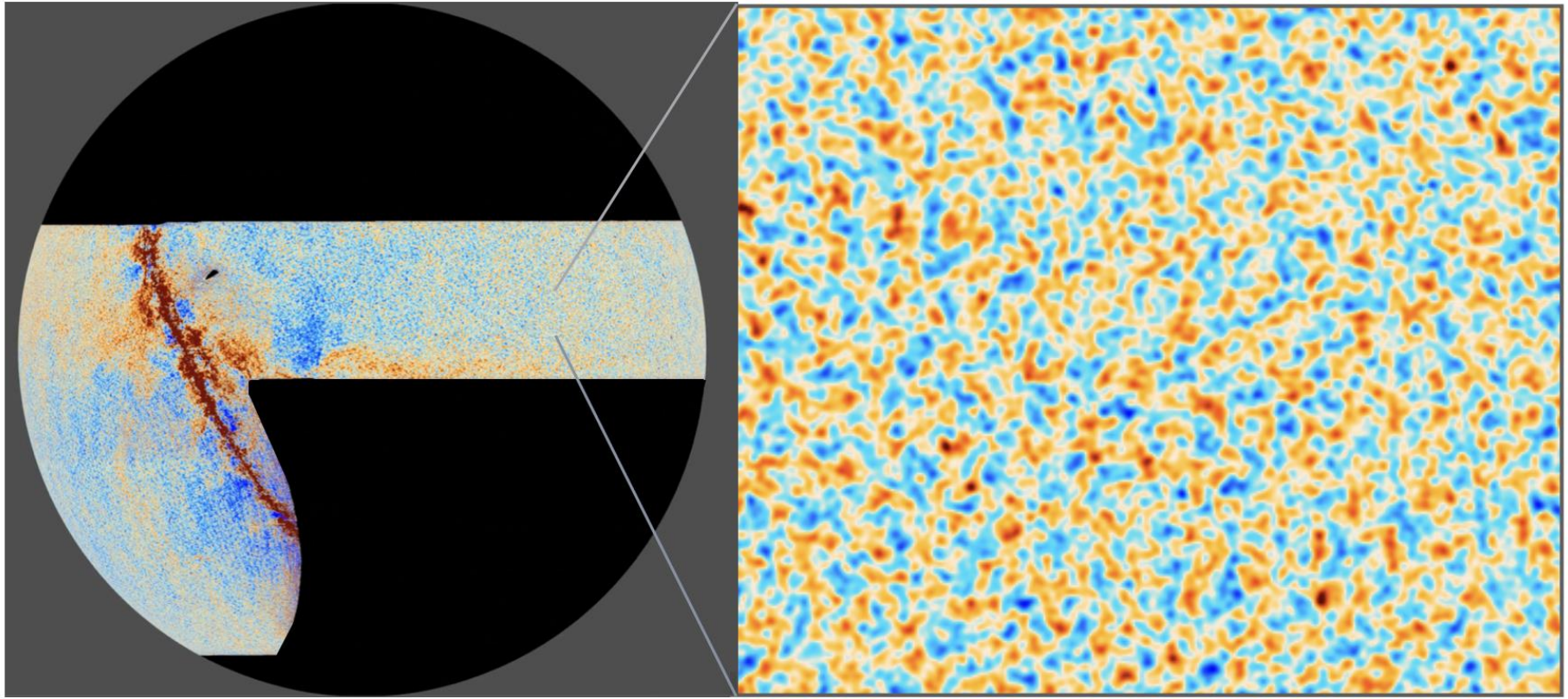




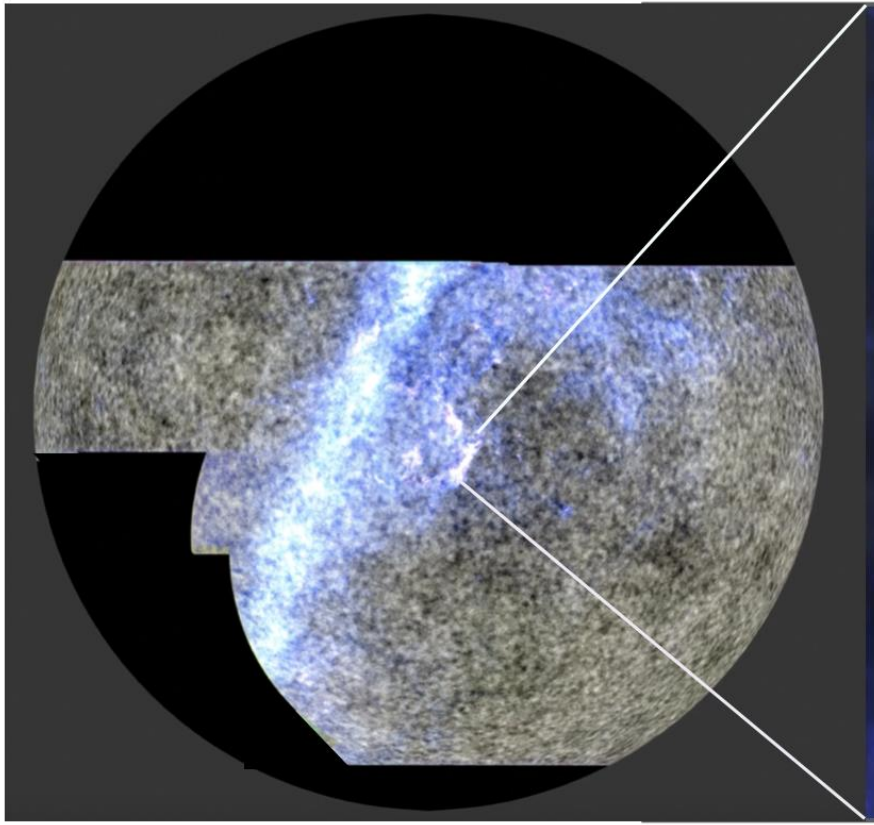
Naess, Guan, Duivenvoorden, Hasselfield, Wang et al: *DR6 Maps – arXiv:2503.14451*
Louis, La Posta, Atkins, Jense et al: *DR6 Spectra, Likelihoods & ΛCDM Parameters – arXiv:2503.14452*
Calabrese, Hill, Jense, La Posta et al: *DR6 Constraints on Extended Cosmological Models – arXiv:2503.14454*



A new image of the cosmic microwave background temperature, adding high definition from ACT to existing measurements from Planck. The zoom-in is 10 degrees across. The image includes closer-by objects: the red band is the Milky Way, the red dots in the zoom-in are galaxies, the blue dots are galaxy clusters, and the spiral Sculptor Galaxy is visible.



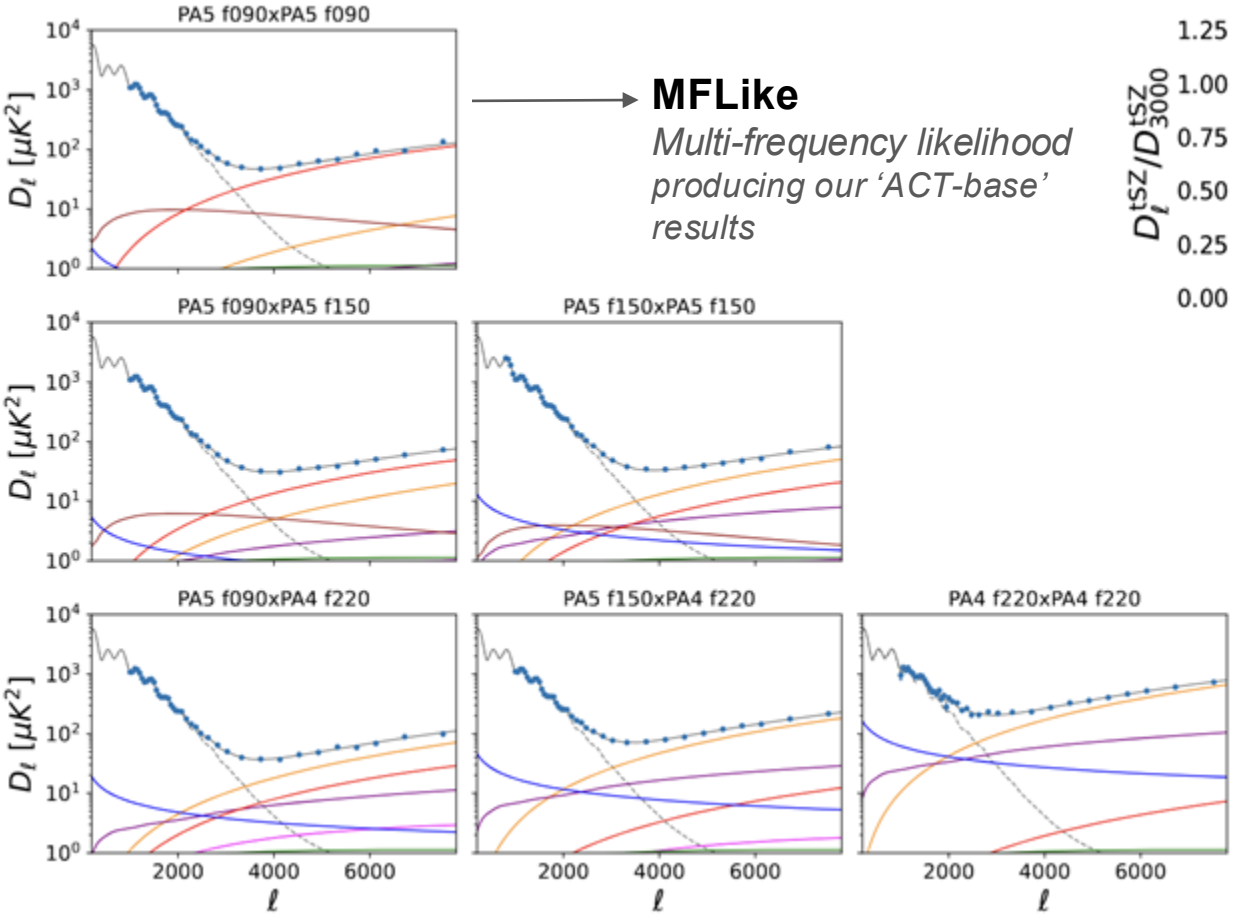
Same for CMB polarization. Polarized light vibrates in a particular direction; blue shows where the surrounding light's vibration directions are angled towards it; orange shows places where the vibration directions circle around it. The Milky Way is also polarized.



Three wavelengths of light have been combined together to highlight the Milky Way in purple, and the cosmic microwave background in grey

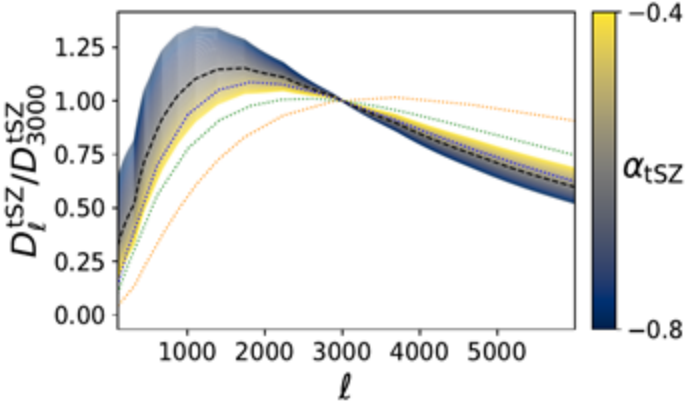
The Orion Nebula, shown in a 5-degree-high zoom-in

Multi-frequency modeling



MFLike

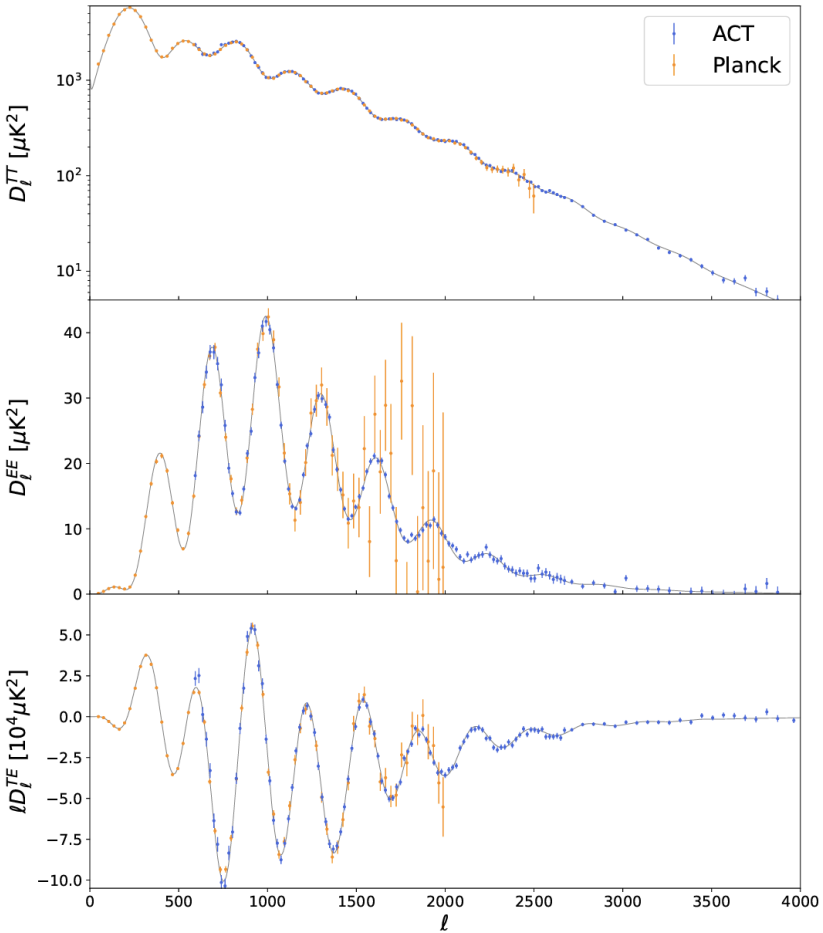
Multi-frequency likelihood producing our 'ACT-base' results



Finding evidence for steeper shape of thermal SZ spectrum

Louis et al 2025

CMB Spectra



ACT data

- extend Planck measurements to small angular scales
- are very consistent with Planck data on overlapping angular scales
- ACT DR6 EE is more sensitive than Planck for multipoles $\ell > 600$

Louis et al 2025

ACT DR6 Constraining Power on New Physics

ACT DR6 probes new information

- in TT for multipoles > 1700,
- in TE for multipoles > 1000,
- in EE for multipoles > 600.

Select models that are well within allowed Planck bounds, but strongly excluded by the addition of the new ACT DR6 power spectra:

Free-streaming dark radiation

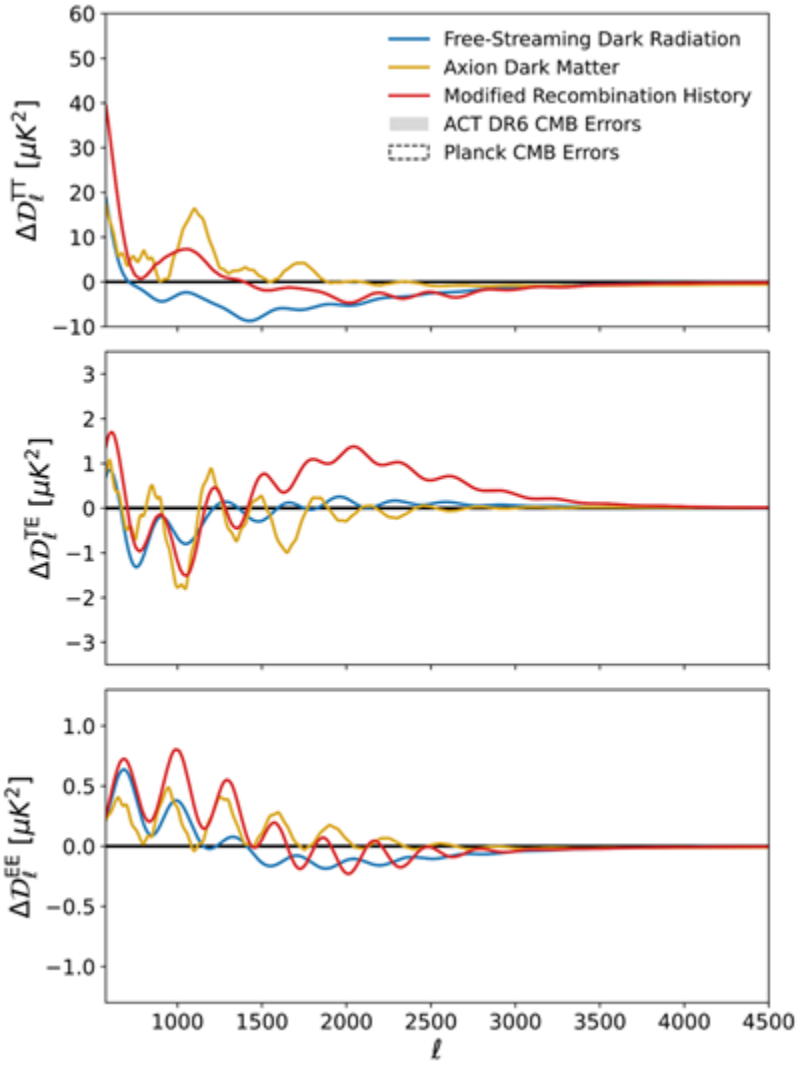
$N_{\rm eff} = 3.4$

Axion-like particles contributing to Dark Matter

$\Omega_{\rm ax}/(\Omega_{\rm ax} + \Omega_{\rm c}) = 5\% \quad (m_{\rm ax} = 10^{-26}\ {\rm eV})$

Modified recombination history

$\Delta X_e/X_e = -20\% \quad {\rm at} \quad z \sim 1470$



Calabrese et al 2025

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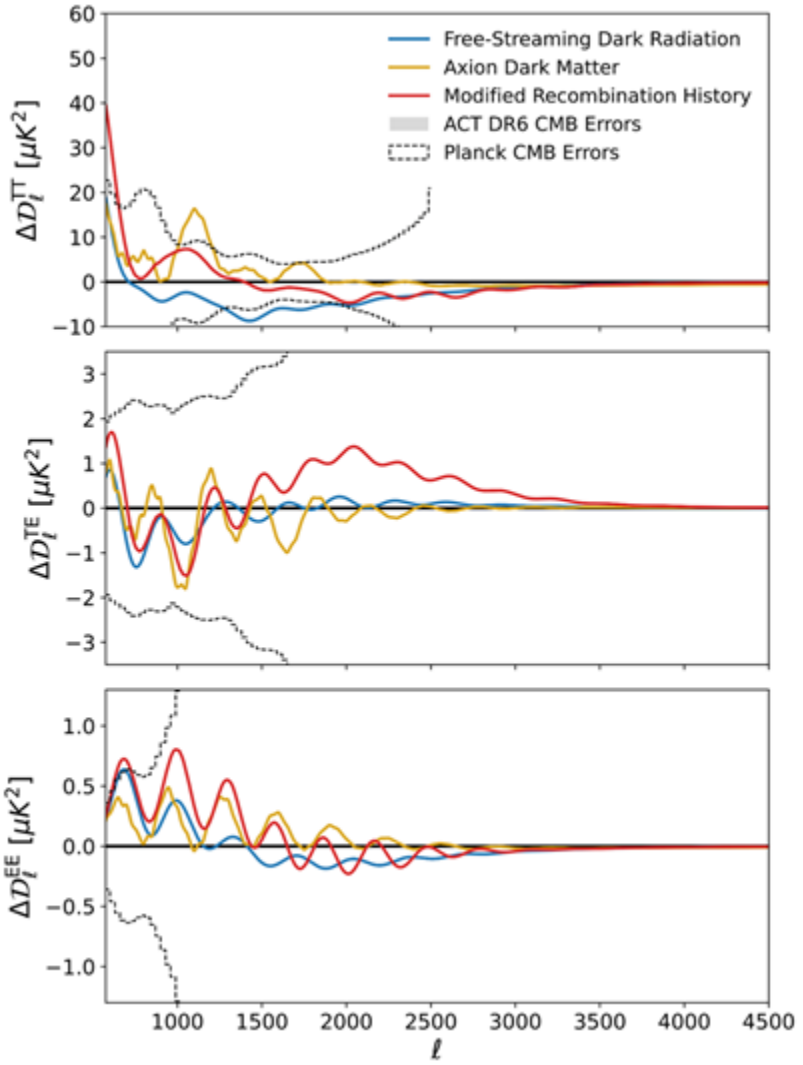

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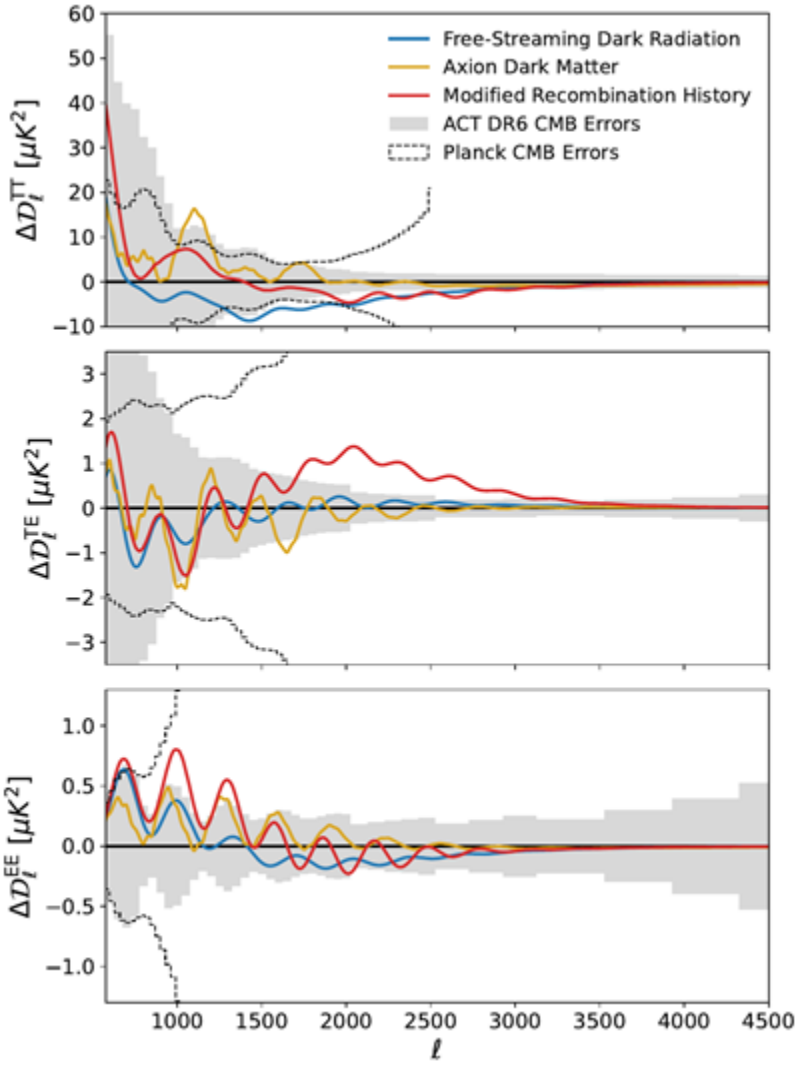
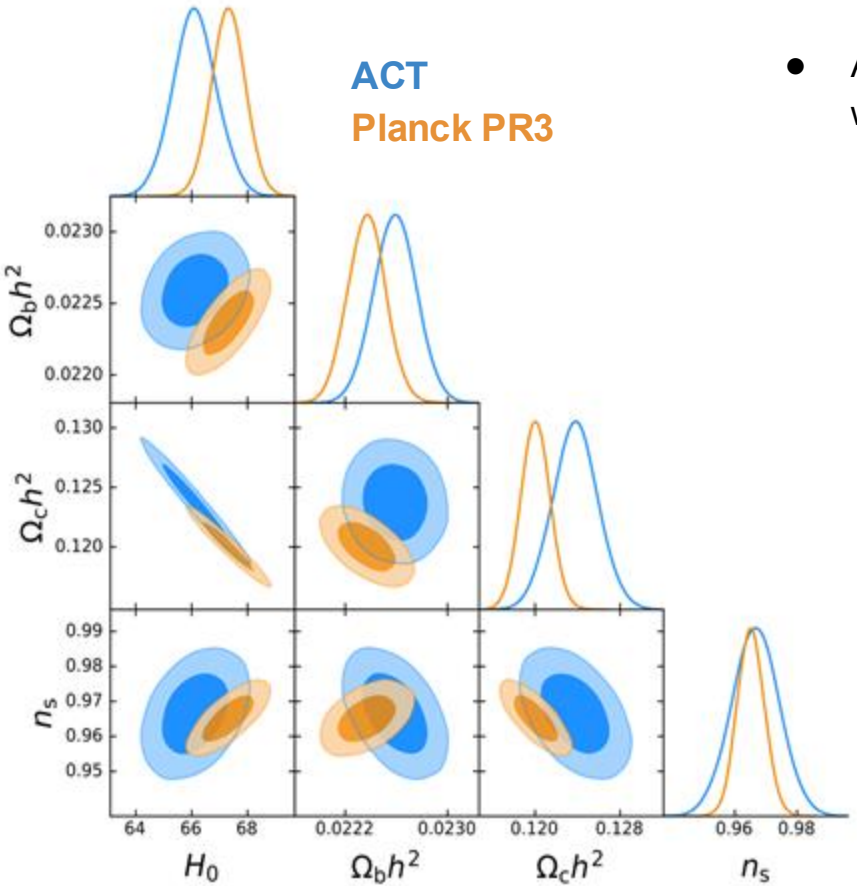
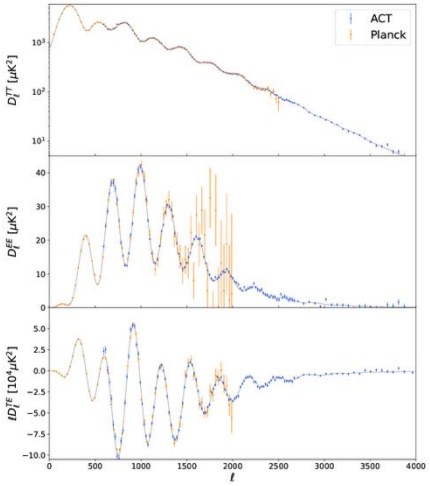


Calabrese et al 2025

Constraints on ΛCDM



- ACT DR6 and Planck are consistent within ΛCDM (1.6σ)



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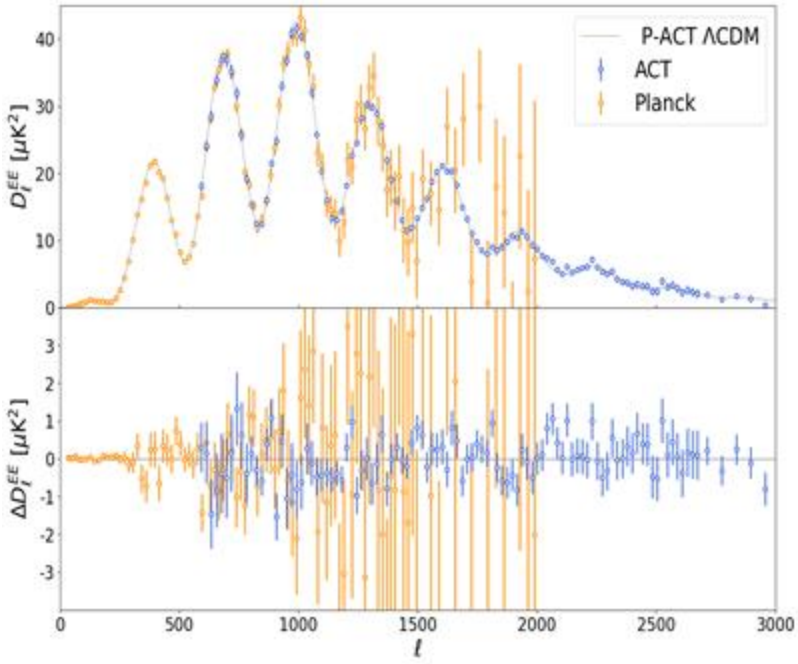
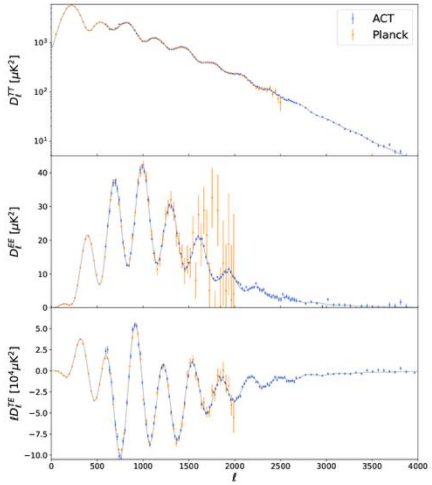


- ACT DR6 and Planck are consistent within ΛCDM (1.6σ)
- ΛCDM provides an excellent fit to both Planck and ACT



χ^2(ACT) = 1598/1617 (63%)
χ^2(P-ACT) = 1842/1897 (81%)

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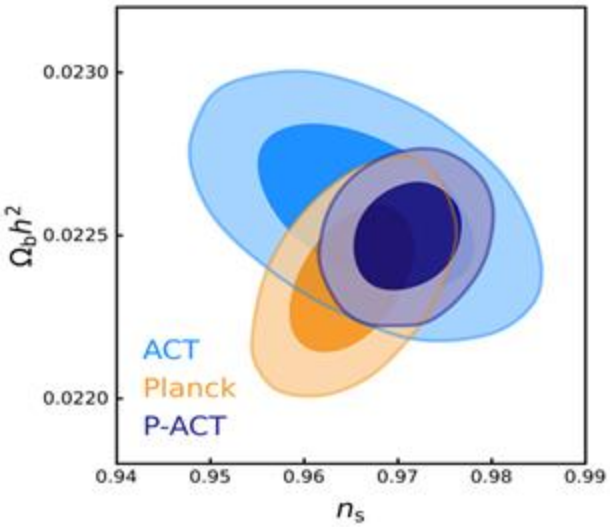
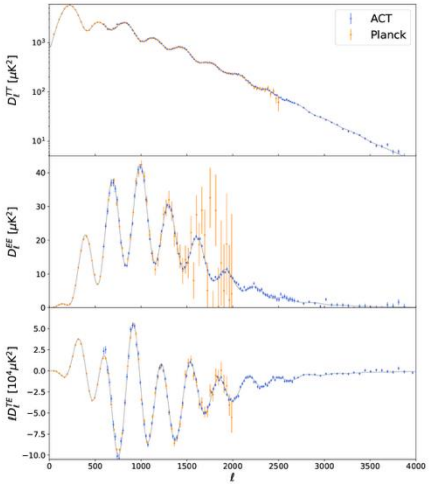
Constraints on ΛCDM



With larger scale information from Planck these parameters are positively correlated; at smaller scales from ACT they both act to damp the spectrum so are anti-correlated.

- ACT DR6 and Planck are consistent within ΛCDM (1.6σ)
- ΛCDM provides an excellent fit to both Planck and ACT
- Limits from joint fit improve on Planck alone



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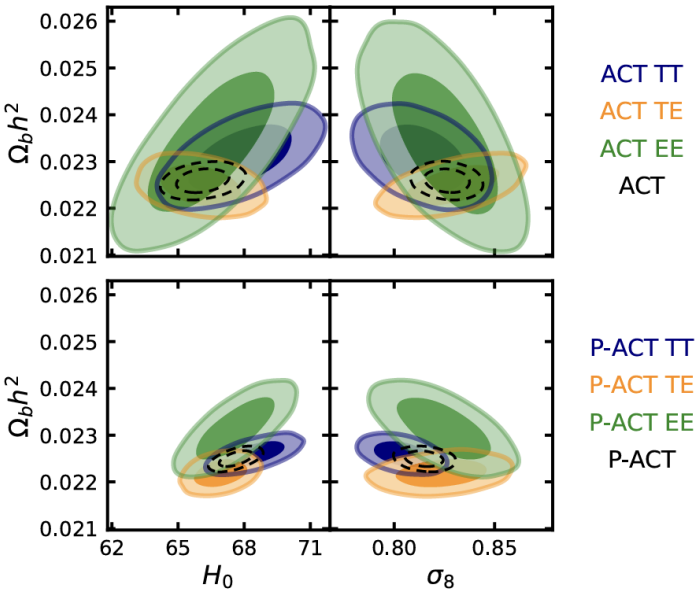
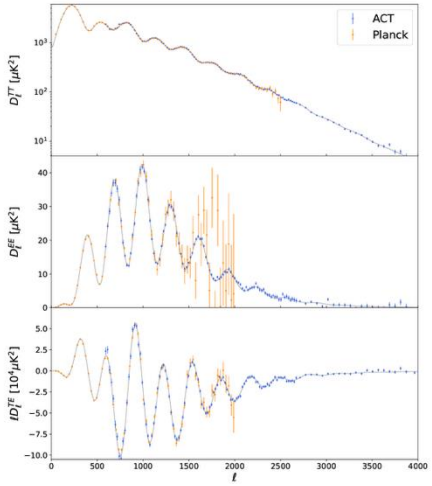
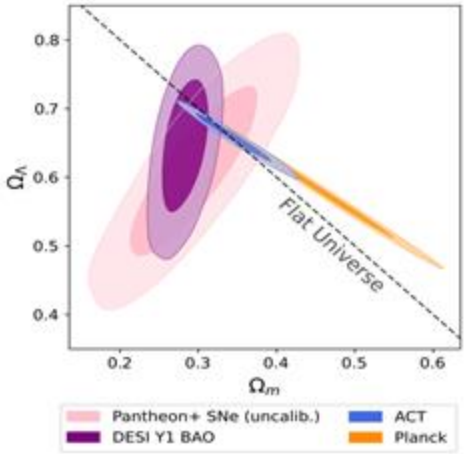


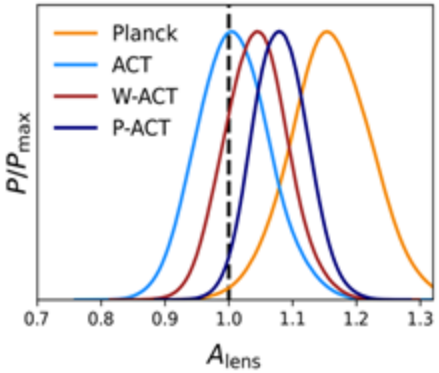


- ACT DR6 and Planck are consistent within ΛCDM (1.6σ)
- ΛCDM provides an excellent fit to both Planck and ACT
- Limits from joint fit improve on Planck alone
- Parameters from different channels are consistent and with distinct degeneracies
- Parameters estimated from polarization are now competitive with those from temperature

Louis et al 2025

Constraints on ΛCDM





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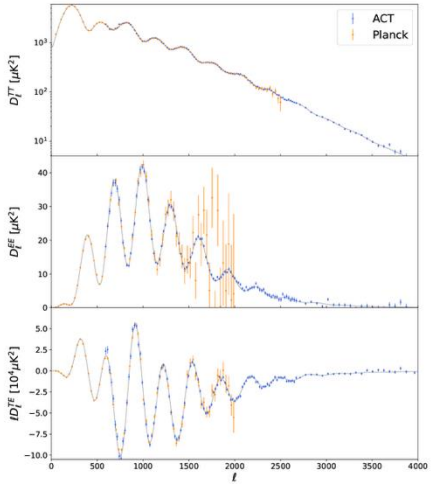
- Consistent with flat Universe and no excess lensing



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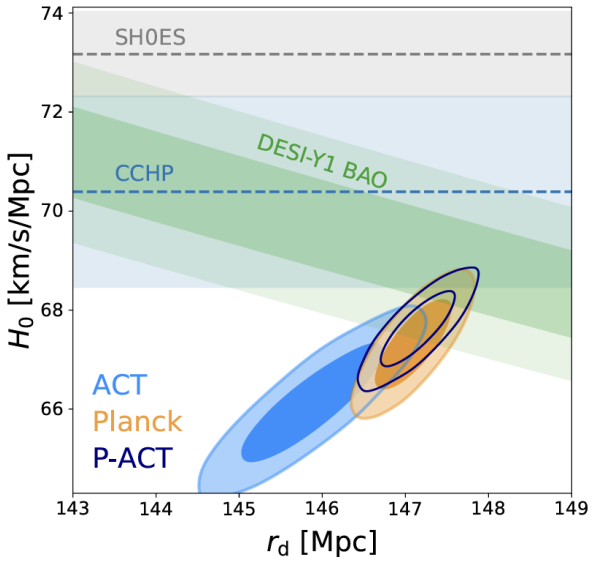
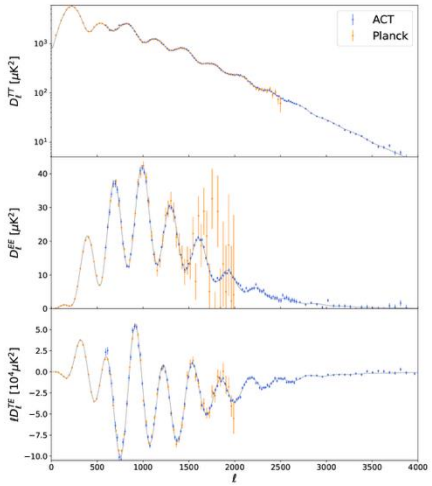


The P-ACT polarization data alone (EE) now independently rule out a ΛCDM model with a higher Hubble constant of 73km/s/Mpc at >4σ.



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- Limits from joint fit improve on Planck alone
- Parameters from different channels are consistent and with distinct degeneracies
- Parameters estimated from polarization are now competitive with those from temperature
- Consistent with flat Universe and no excess lensing
- Confirming tension with Cepheids-based estimate of Hubble constant

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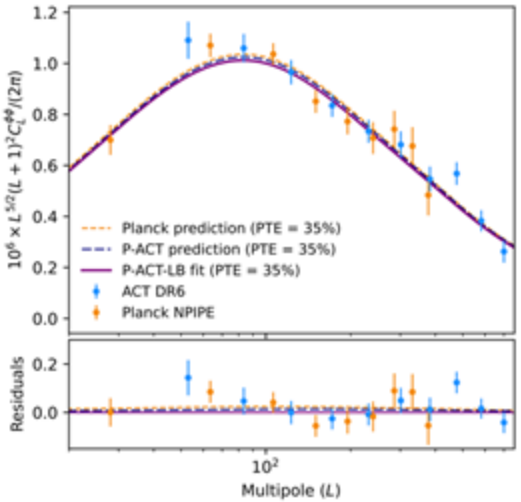
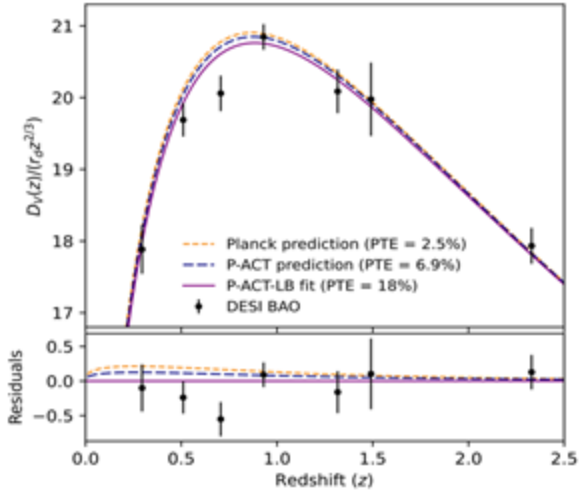
Cosmological concordance

- Predictions of the best-fit P-ACT ΛCDM model agree well with direct low-redshift measurements
- ΛCDM gives an excellent joint fit to these datasets

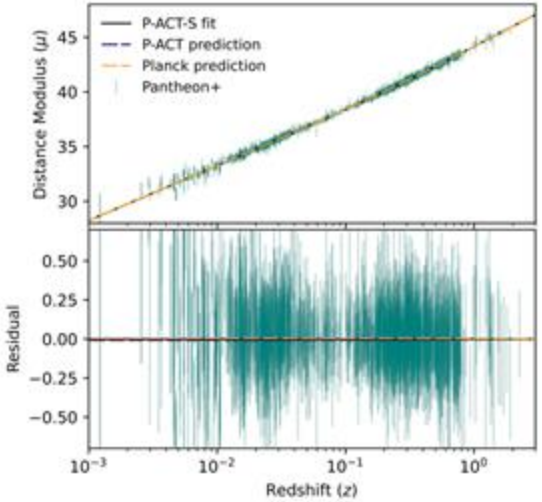
CMB Lensing (ACT DR6 + Planck PR4)



BAO (DESI Y-1)



SNIa (Pantheon+)



Low-redshift observations help the CMB by breaking geometric degeneracies, this is most effective in constraints on extensions to ΛCDM

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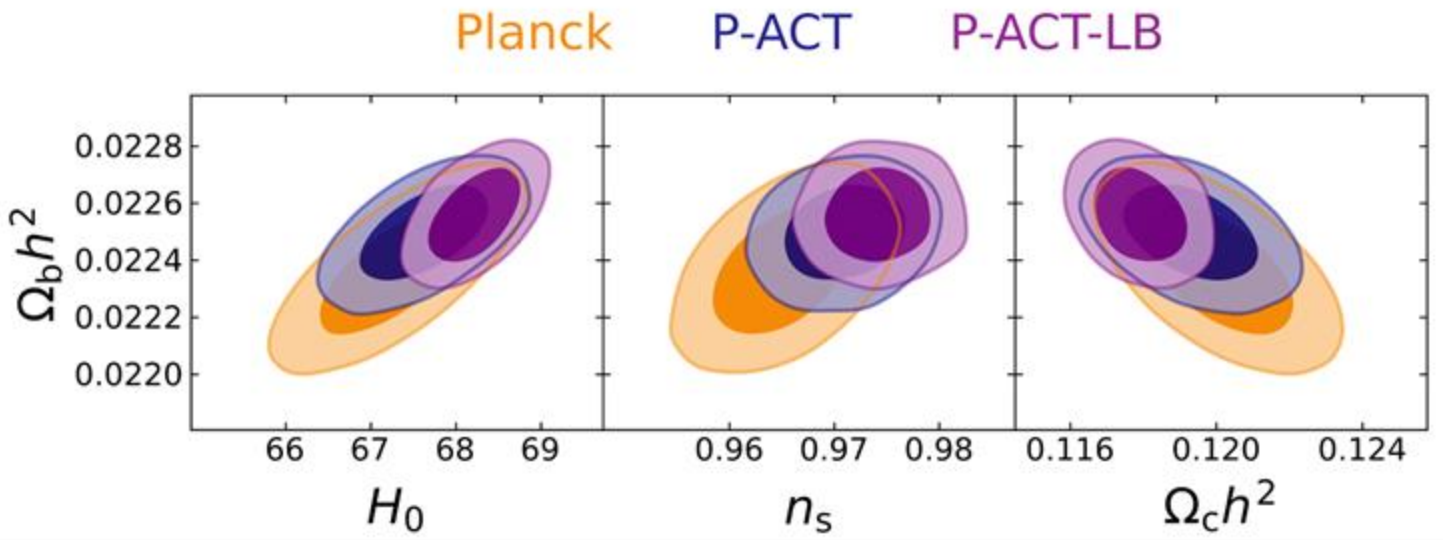
Combinations with the large scale structure

Combining with CMB lensing and DESI-Y1 BAO gives state-of-the art constraints on the ΛCDM model parameters

0.5% measurement of the expansion rate $H_0 = 68.22 \pm 0.36$ km/s/Mpc



Exploration of extended cosmological models

We investigated a large set of cosmological models, spanning energy scales from the inflationary epoch to the recombination epoch to the late-time universe

- **we do not find any statistically significant departure from ΛCDM**

Model	Section
Running of scalar spectral index	§4.1
$P_{\mathcal{R}}(k)$	§4.2
Isocurvature perturbations	§4.3
Tensor modes	§4.4
Early dark energy	§5.1
Varying electron mass	§5.2.1
Varying electron mass and curvature	§5.2.2
Varying fine-structure constant	§5.2.3
Varying fine-structure constant and curvature	§5.2.4
Primordial magnetic fields	§5.3
CMB temperature	§5.4
Modified recombination history	§5.5
Neutrino number, $N_{\rm eff}$	§6.1.1
Neutrino mass, $\sum m_\nu$	§6.1.1
$N_{\rm eff} + \sum m_\nu$	§6.1.1
Neutrino self-interactions	§6.1.2
Helium and deuterium	§6.2
Axion-like particles	§6.3
DM-baryon interactions	§6.4.1
DM annihilation	§6.4.2
Self-interacting DR	§6.5.1
Interacting DR-DM	§6.5.2
Spatial curvature	§7.1
Dark energy equation of state, w	§7.2
Dark energy equation of state, w_0/w_a	§7.2
Interacting DE-DM	§7.3
Modified gravity	§7.4

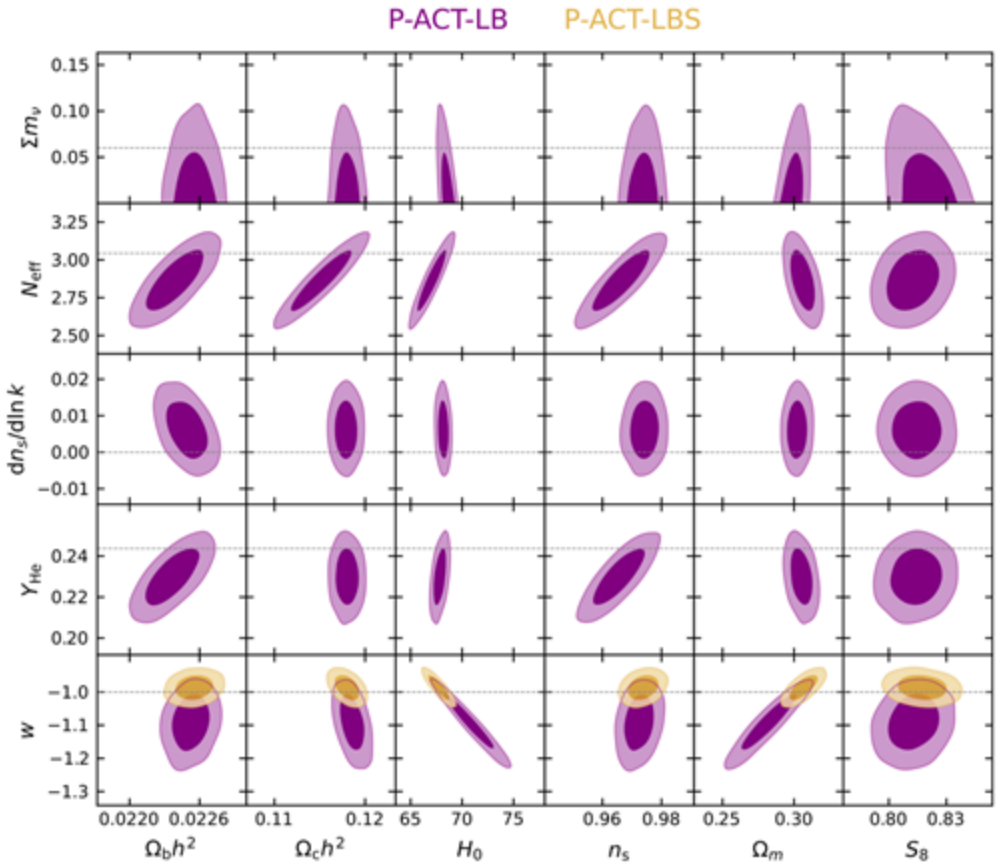
Calabrese et al 2025

Exploration of extended cosmological models

We investigated a large set of cosmological models, spanning energy scales from the inflationary epoch to the recombination epoch to the late-time universe

- **we do not find any statistically significant departure from ΛCDM**
- we find consistency with standard model predictions
- and accordingly set new leading constraints on fundamental physics parameters

Models constructed with the aim of increasing the value of the Hubble constant or decreasing the amplitude of late-time density fluctuations inferred from the primary CMB are not favoured by the data.

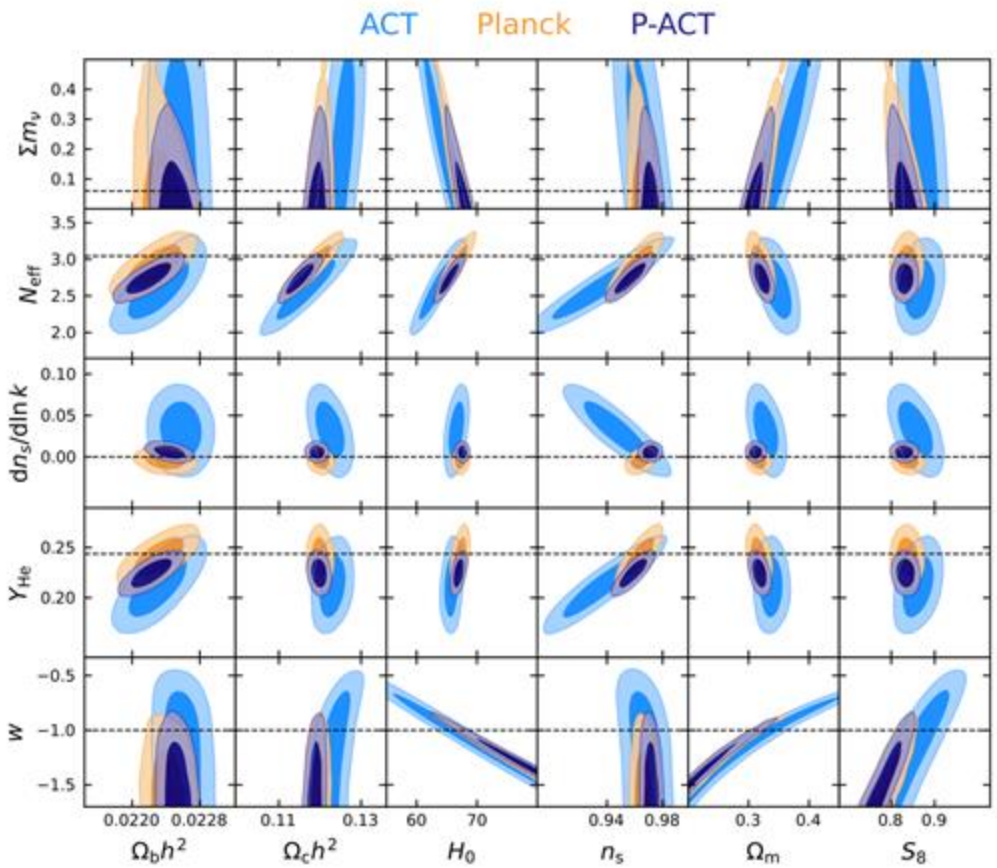


Calabrese et al 2025

Exploration of extended cosmological models

Highlighting consistency and complementarity between ACT and Planck CMB data and improvement achieved by their combination

In many cases the precision of the measurement is dominated by the primary CMB contribution



Calabrese et al 2025

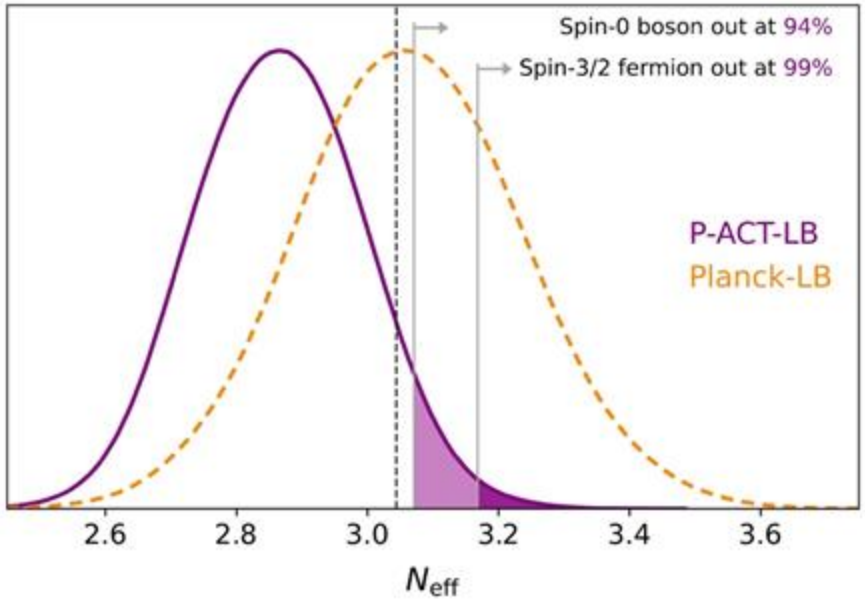
Particle cosmology

No evidence for new light, relativistic species

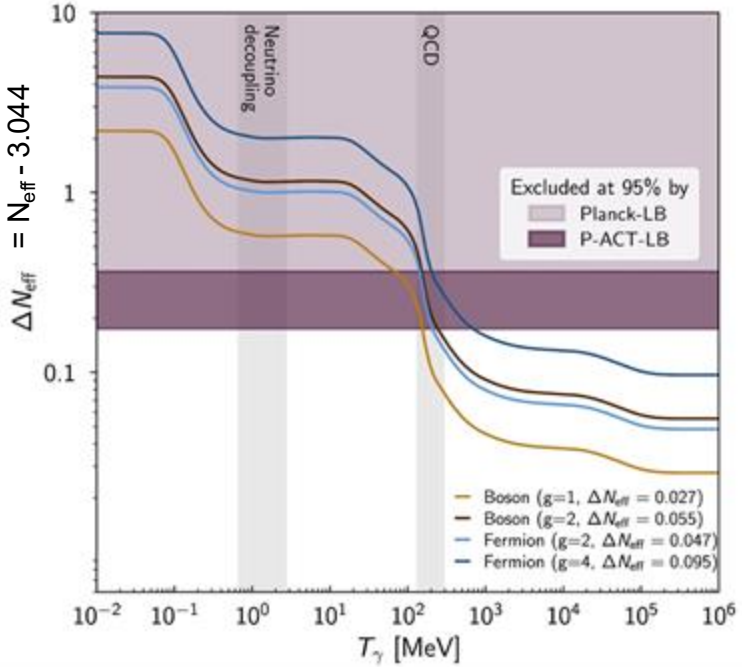
Free-streaming

$N_{eff} = 2.86 \pm 0.13$ (68%, P-ACT-LB)

$N_{eff} = 2.89 \pm 0.11$ (68%, P-ACT-LB-BBN)



Particles decoupling after QCD are excluded; light particles of spin 0 and1/2 must decouple at temperatures ≳200 MeV and all light particles of spin 3/2 must decouple at temperatures ≳1GeV.



Calabrese et al 2025

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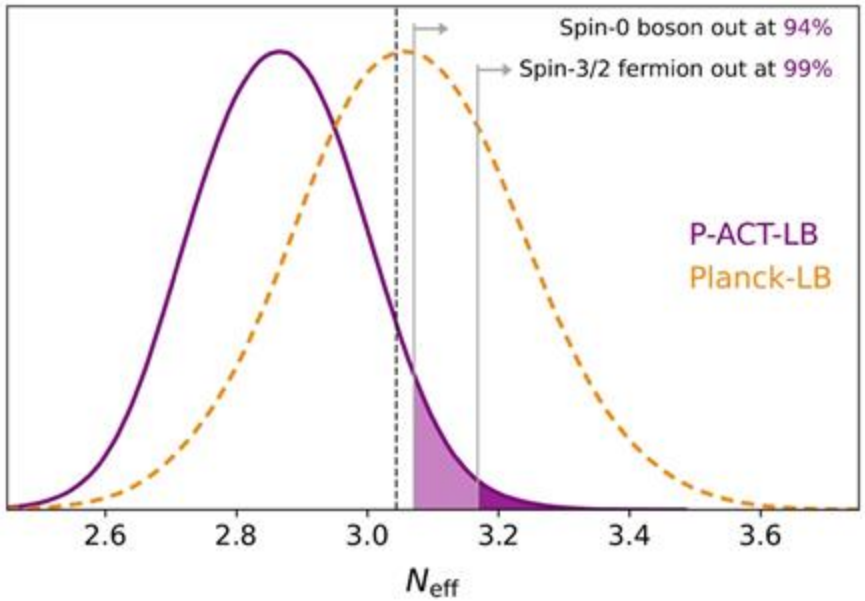


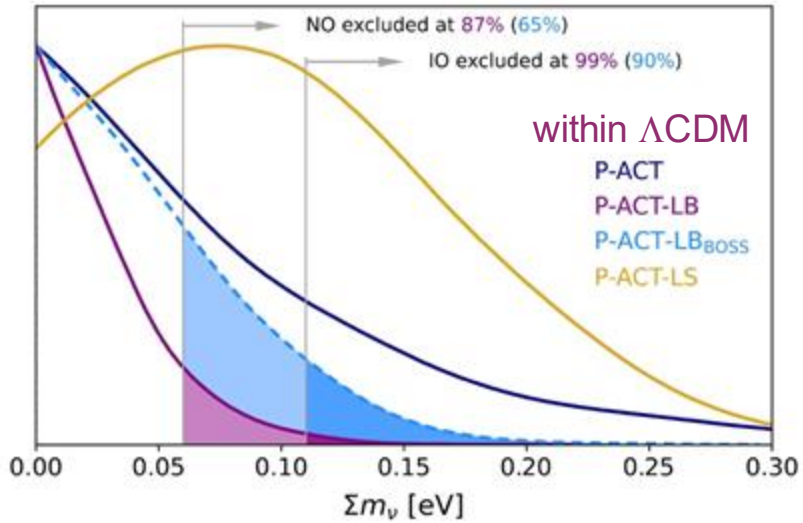
No evidence for non-zero neutrino masses

$\Sigma m_\nu < 0.082$ eV (95%, P-ACT-LB)

$\Sigma m_\nu < 0.083$ eV (95%, W-ACT-LB)

with significant contribution from DESI BAO

$\Sigma m_\nu < 0.13$ eV (95%, P-ACT-LB_{BOSS})



Calabrese et al 2025

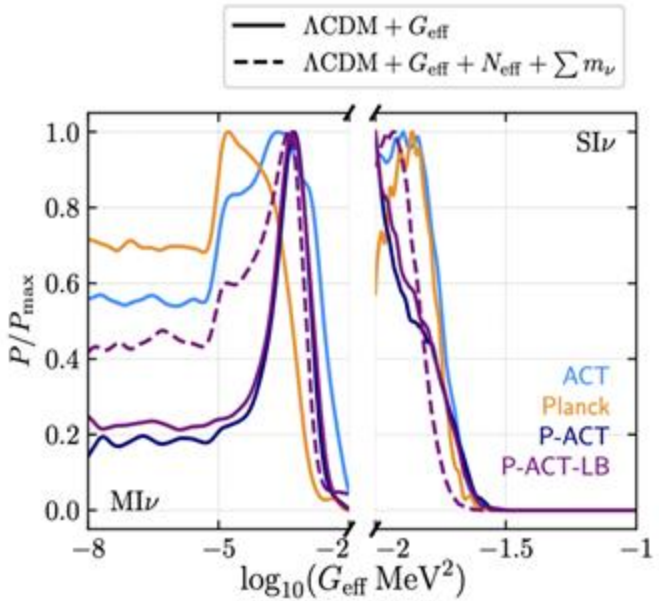
Particle cosmology

No evidence for new light, relativistic species

Self-interacting

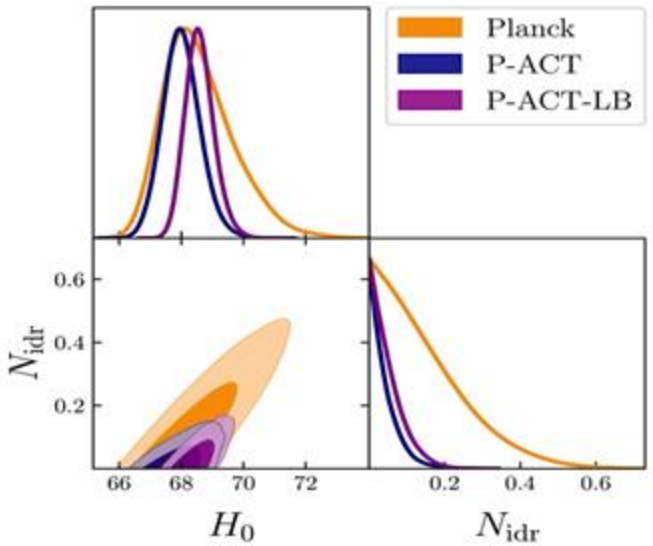
No evidence for neutrino self-interactions

MIν only at 1.8σ and no peak for SIν using for P-ACT-LB



No evidence for self-interacting dark radiation

$N_{\rm idr} < 0.134$ (95%, P-ACT-LB)

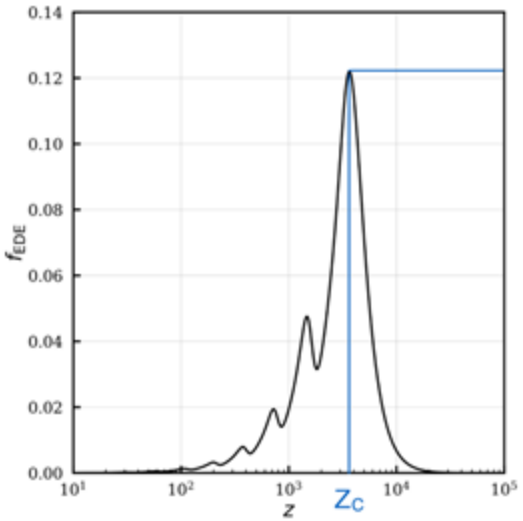


Calabrese et al 2025

Pre- and modified recombination physics

No evidence for an early dark energy (EDE) component

A mild hint (2-3σ) of EDE was seen in ACT DR4 (Hill+2022); the new ACT DR6 spectra show that this was a statistical fluctuation.



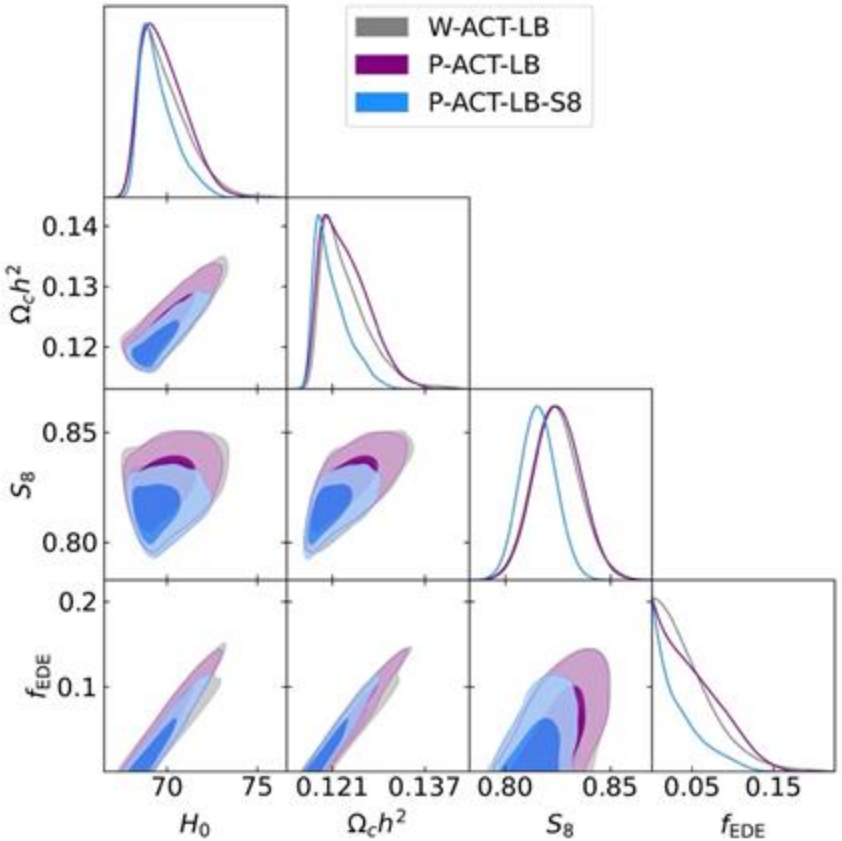
Maximal contribution:

$f_{\rm EDE}(z_c) \equiv (\rho_{\rm EDE}/3M_{pl}^2H^2)|_{z_c}$

which occurs at redshift z_c

Final parameter: $\theta_i = \phi_i/f$ (initial field displacement)

→ $\{f_{EDE}, z_c, \theta_i\}$



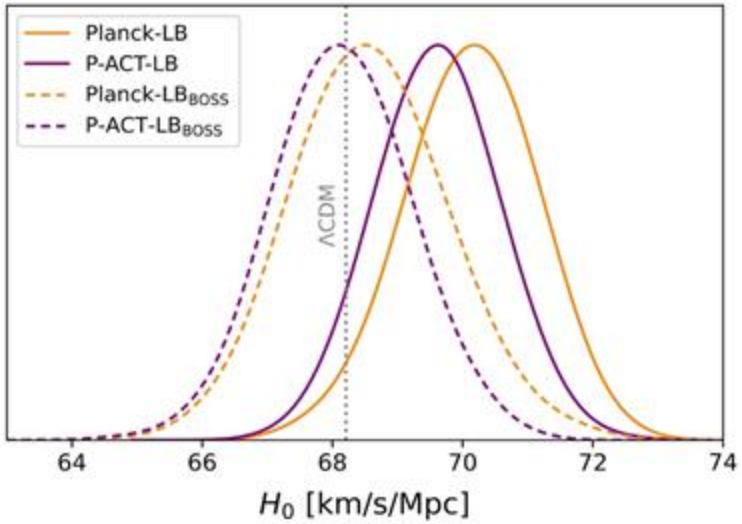
Max. preference: $\Delta\chi^2 = 6.6$ (1.7σ)

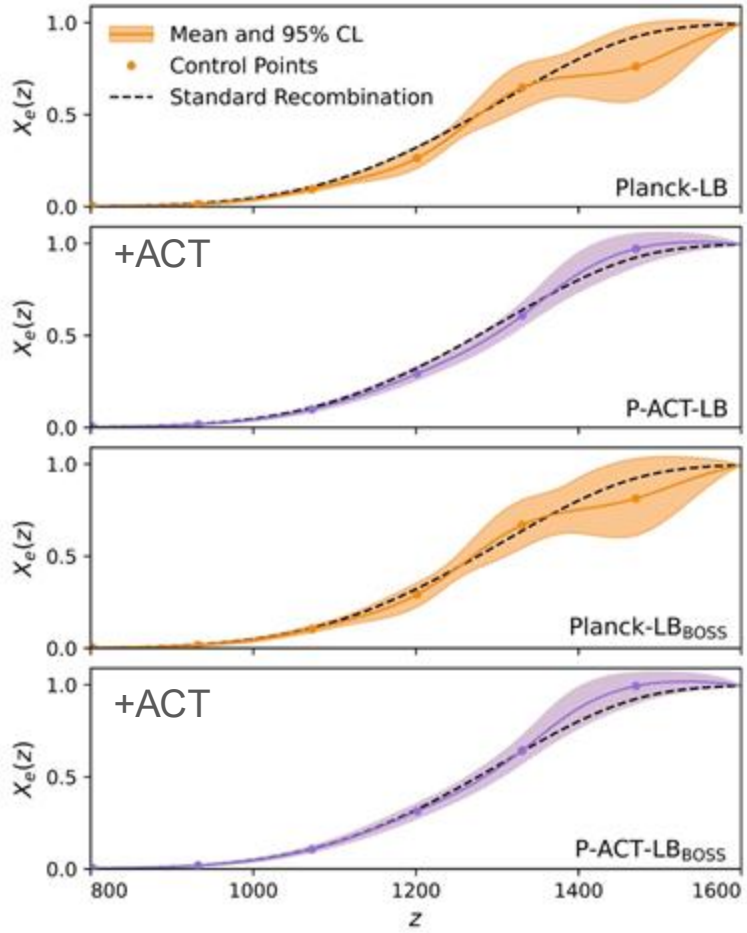
Calabrese et al 2025

Pre- and modified recombination physics

More generally, **we confirm a standard recombination history** using a non-parametric reconstruction.

This significantly restricts the ability of such scenarios to increase the CMB-inferred Hubble constant.





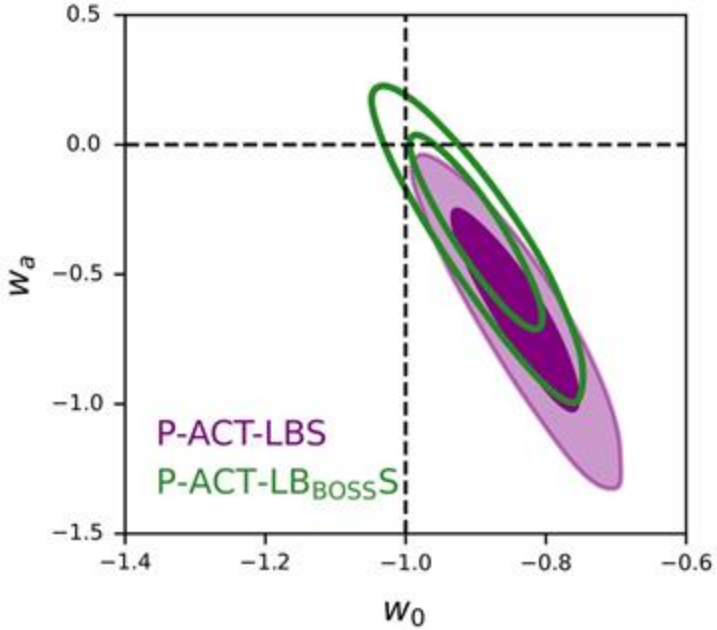
Calabrese et al 2025

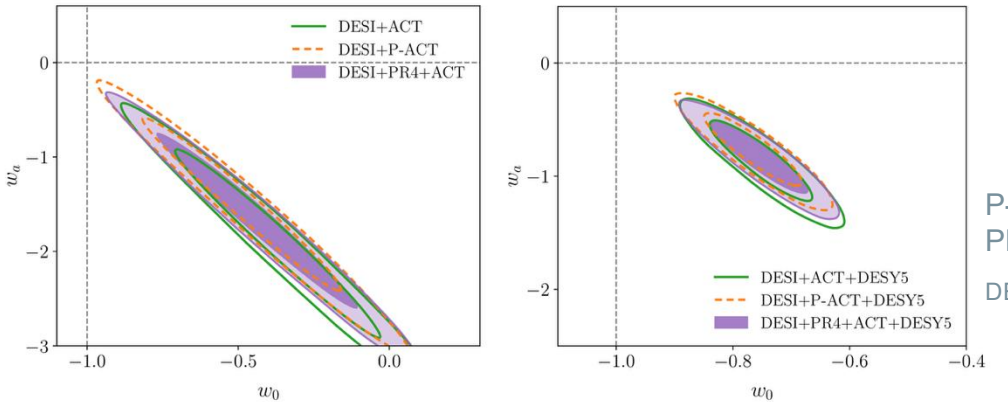
Late-time physics: dark energy

From primary CMB data, **we find no evidence for non-standard dark energy**
hints of non-standard evolution are driven by low-redshift data and consistent with previous analyses of DESI and SNIa data.

$$\left.\begin{aligned} w_0 &= -0.837 \pm 0.061 \\ w_a &= -0.66^{+0.27}_{-0.24} \end{aligned}\right\} \quad (68\%, \text{P-ACT-LBS})$$

P-ACT-LBS consistent with Λ at 2.2σ





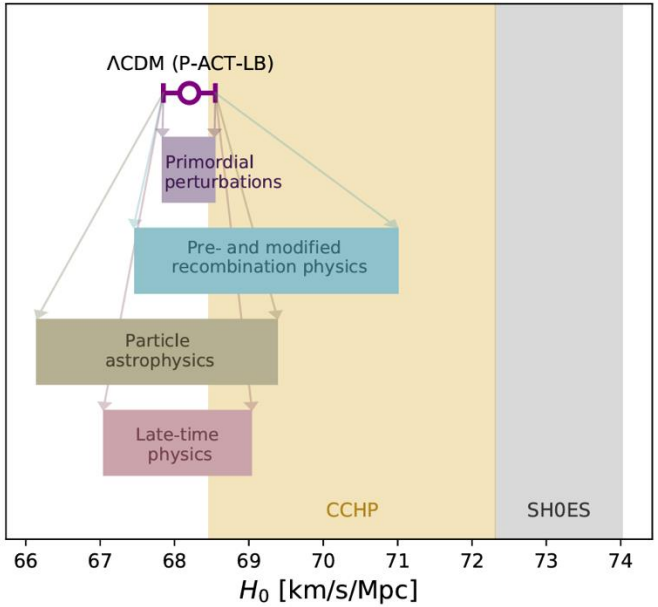
P-ACT+DESI 2.4σ
PR4+ACT+DESI 3.0σ

DESI Collaboration 2025

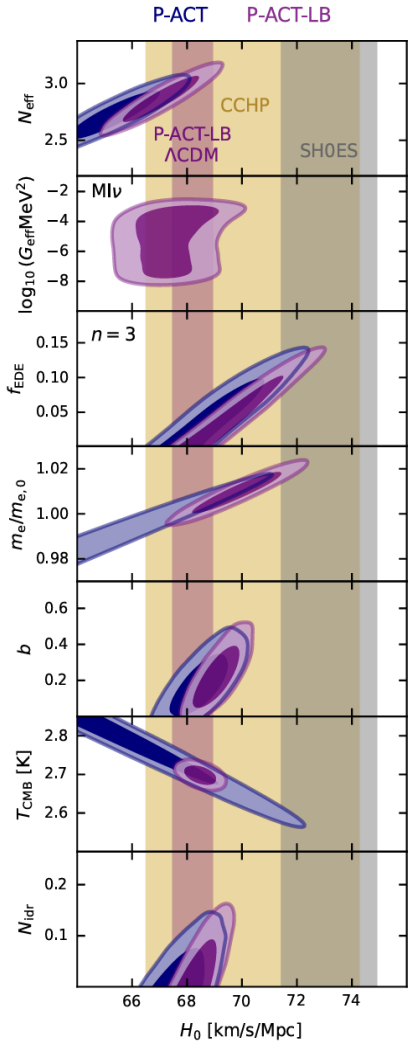
Calabrese et al 2025

Cosmological Con(dis)cordance

Tension between the CMB-inferred expansion rate and local measurements using Cepheids;
good agreement with Tip of Red Giant Branch



Models constructed with the aim of increasing the value of the Hubble constant or decreasing the amplitude of late-time density fluctuations inferred from the primary CMB are not favoured by CMB data.



Relativistic species

Neutrino self-interactions

Early Dark Energy

Variation in electron mass

Baryon clumping

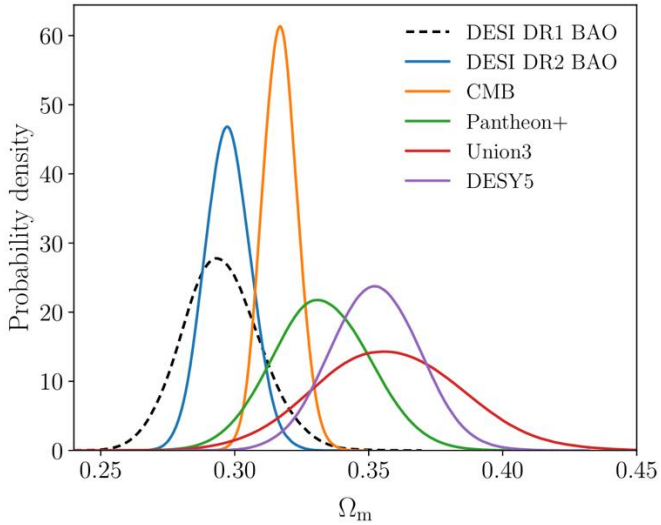
Temperature of the CMB

Interacting dark radiation

Calabrese et al 2025

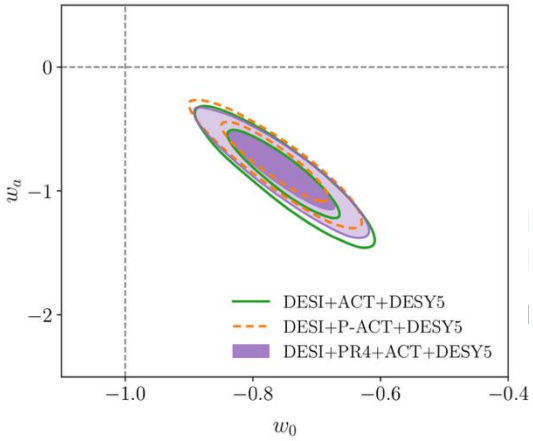
Cosmological Con(dis)cordance

Differences (not yet statistically significant) in matter densities



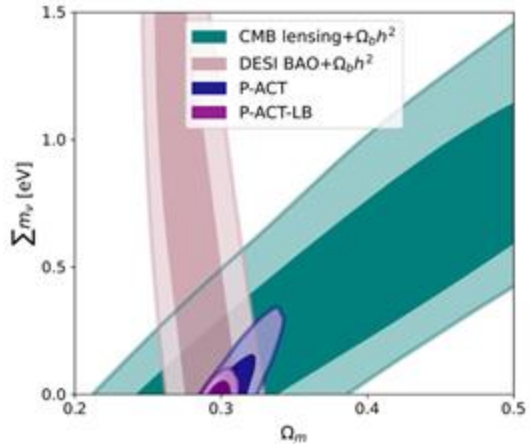
DESI Collaboration 2025

Evolving dark energy: other components of the model absorb the difference



DESI Collaboration 2025

Small (negative) neutrino mass: not much left for other matter densities



Calabrese et al 2025

Data release

LAMBDA legacy archive (lambda.gsfc.nasa.gov)

- 600 raw frequency maps including null test maps
- 94 processed maps including Needlet-ILC maps of the CMB blackbody signal and thermal Sunyaev- Zeldovich signal
- MCMC chains, power spectra

NERSC (/global/cfs/cdirs/cmb/data/act_dr6/dr6.02)

In addition to all products on LAMBDA

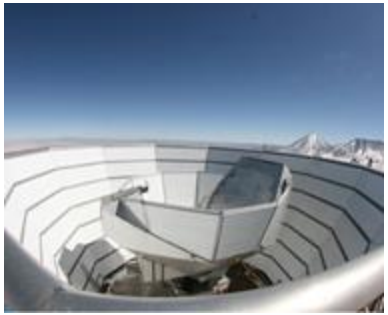
- 38 TB of short exposure maps used for time-domain analysis
- Noise models and noise simulations of the frequency maps
- All products needed to go from the maps to the power spectrum results

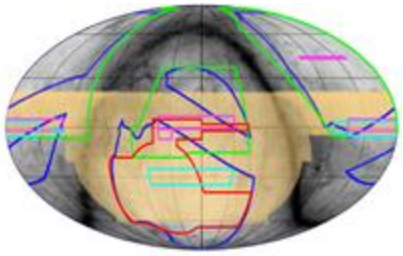
DR6_Notebooks Public

Python notebooks with DR6 tutorials:
github.com/ACTCollaboration/DR6_Notebooks

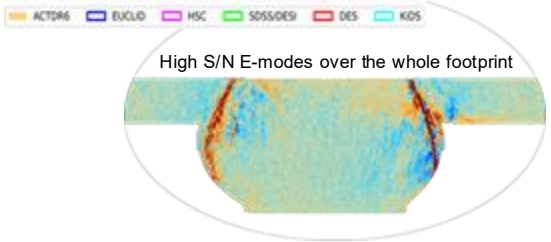
The (near) future

ACT DR6





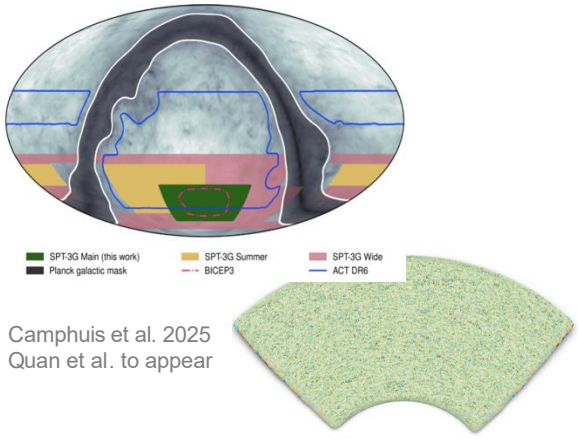
Naess et al. 2025



- 3 broad bands: 90, 150 and 220 GHz
- Combined sensitivity of 6.2 μK√s, and 1.4’ FWHM @ f150
- Deeper than Planck over 19000 square degrees (on small scales)
- On average ⅓ the white noise RMS of Planck

New lensing analysis, cross-correlations and sources

SPT 3G



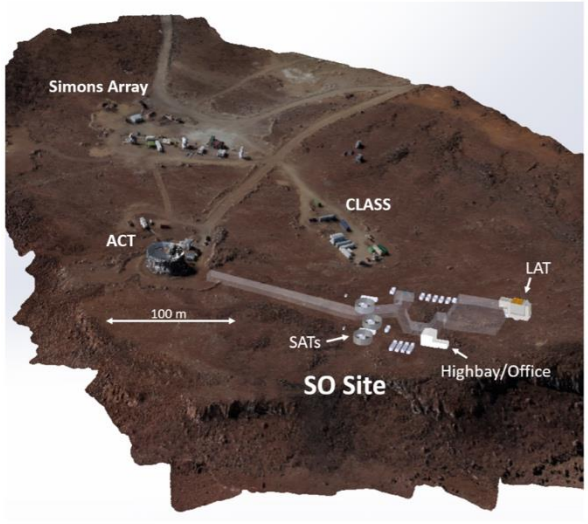
Camphuis et al. 2025
Quan et al. to appear

- D1 dataset from Main field 90, 150, 220 GHz during 2019-2020
- Combined sensitivity of 3.3 μk-arcmin in T and 5.1 in pol, over 4% of sky
- Summer and Wide fields bringing additional 2800/6000 deg2

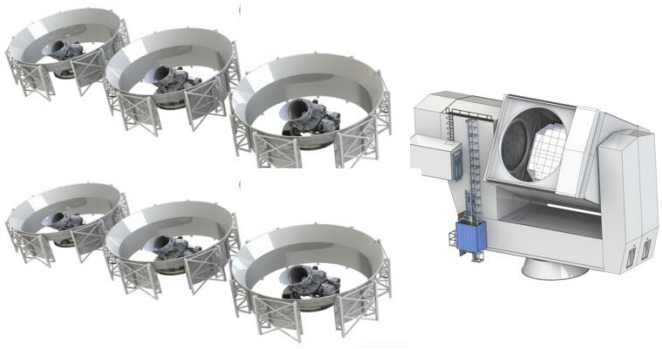
More D1 plus extra field analyses

** Also Simons Array, BICEP2/Keck*

The Simons Observatory



Six 0.5-m Small Aperture Telescopes
One 6-m Large Aperture Telescope fully populated with 13 tubes



a little over 123,000 detectors
6 frequency bands in the mm

Operations started!

Green Observatory, replacing 70% of the power at the site with Solar Energy

Large international collaboration
15+ countries, 60+ institutions
~375 collaborators

https://simonsobservatory.org/

Solar Power (2025)
(courtesy of NSF and UKRI)

SO Nominal

ASO (2028)
(fully populating
the LAT)

SO:JP – One SAT (2026)

SO:UK – Two SATs (2026)

Permissions request underway

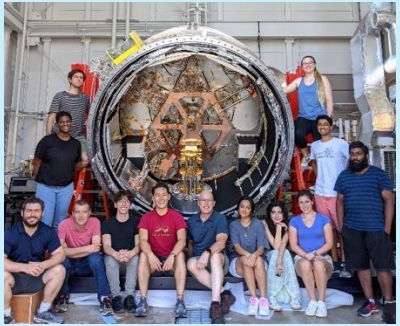
Time Domain Astrophysics

Tidal Disruption Events

Stellar Flares

Variable AGN

Training the Next Generation



Extragalactic Astronomy

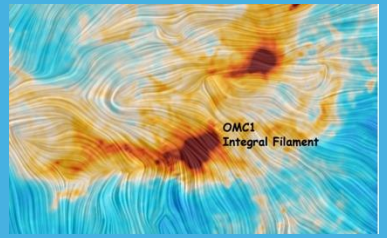
Missing Baryons

Sources

Galaxy Clusters

Galactic Astronomy

Interstellar Dust

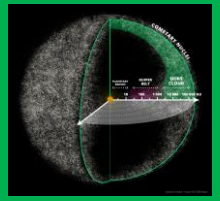


Star Formation, Magnetic Fields and Dust Turbulence

SIMONS OBSERVATORY

PARQUE ASTRONÓMICO ATACAMA, CHILE | ELEVATION: 5190m | 22° 57' 5, 67° 47' W | www.simonsobservatory.org

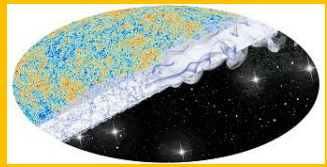
Planetary Science



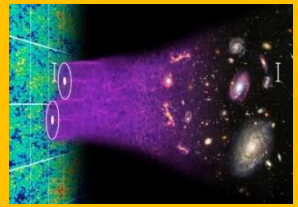
Exo-Oort Clouds

Planet 9

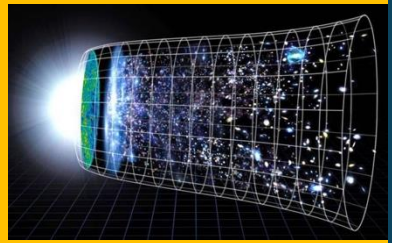
Cosmology and Particle Physics



H_0 Tension and New Physics

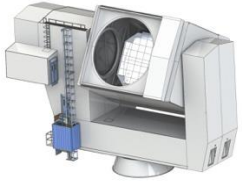


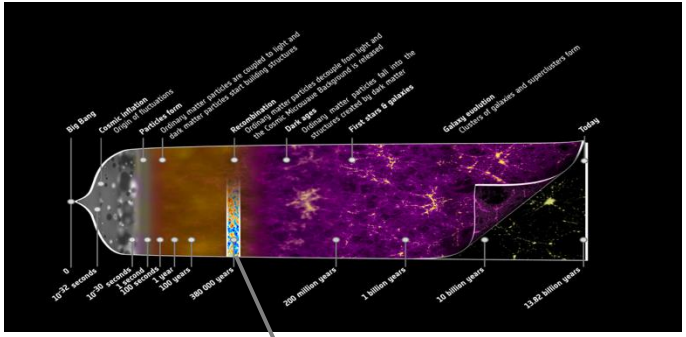
Light Relics and Neutrinos

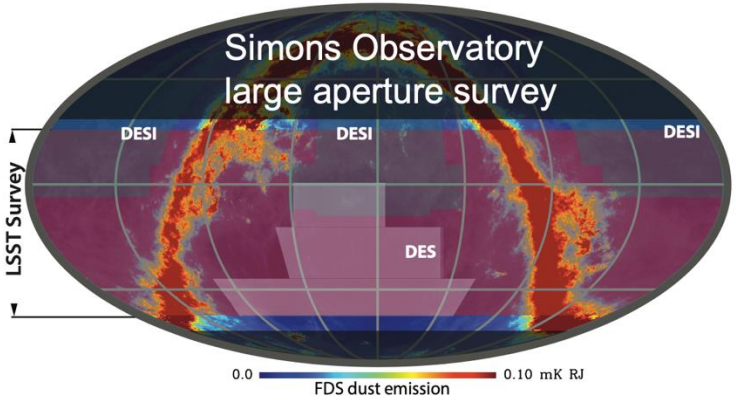


The Evolution of the Universe Over Cosmic Time

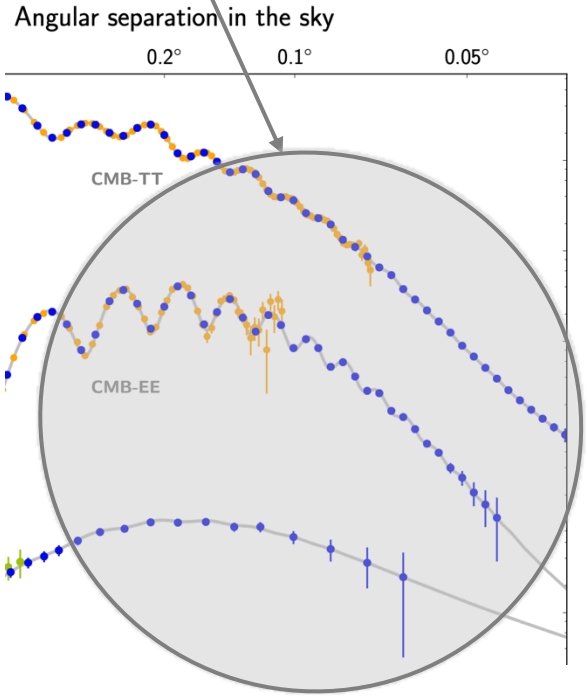
High precision tests of the cosmological model







First light Feb 2025!



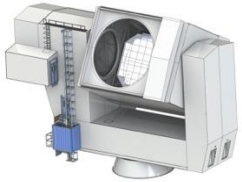
<u>Large Aperture Survey</u>

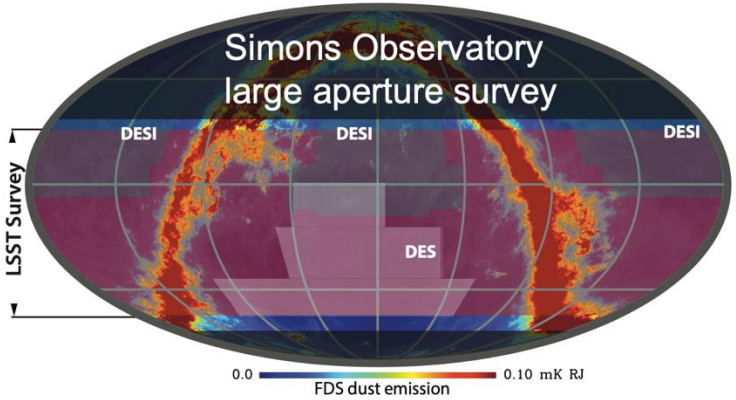
Wide (40-70% of sky), at high resolution (1.4' at 150 GHz) and high sensitivity (6 uK-arcmin in combined 90/150), over 6 frequencies (30-280 GHz)

New results on dark matter and matter distribution, neutrinos, expansion/age of the Universe and much more

The Simons Observatory Collaboration 2019, 2025

High precision tests of the cosmological model





Large Aperture Survey

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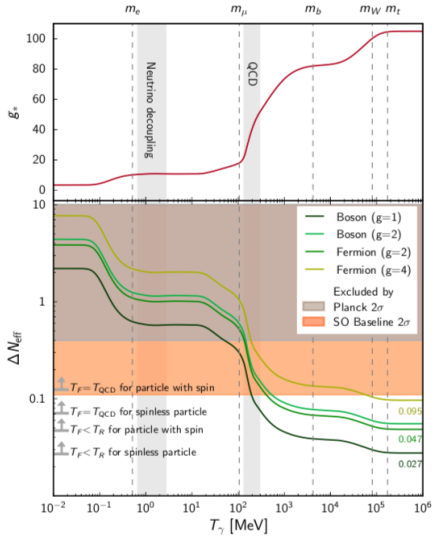
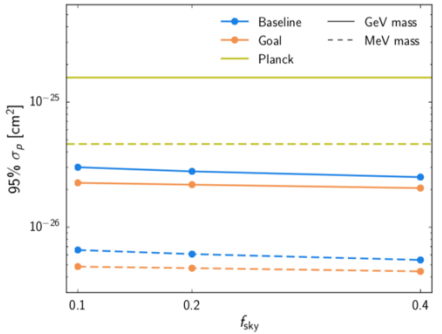
New results on dark matter and matter distribution, neutrinos, expansion/age of the Universe and much more

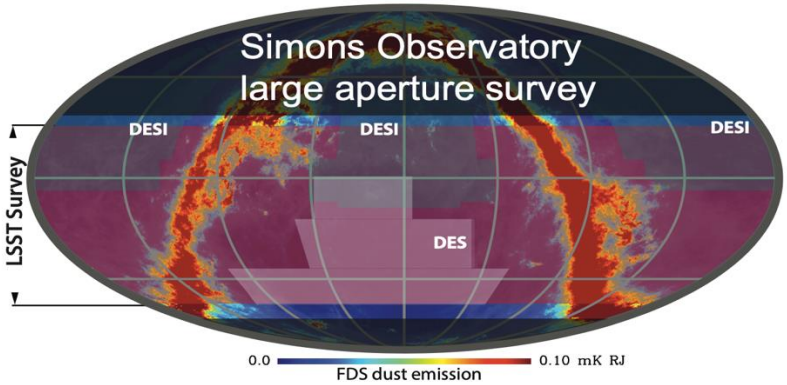
SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)



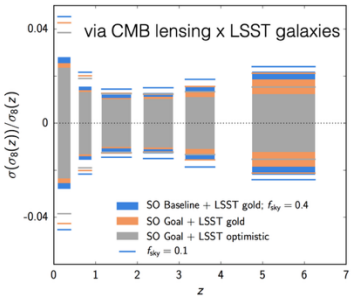
Strong limits on DM-proton elastic scattering;
Better limits and detection at intermediate mass scales of a DM axion fraction of 2%

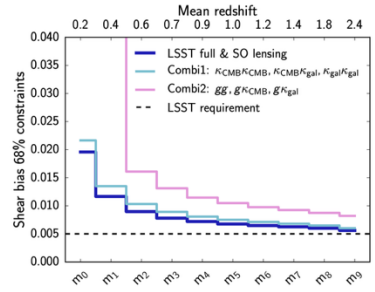


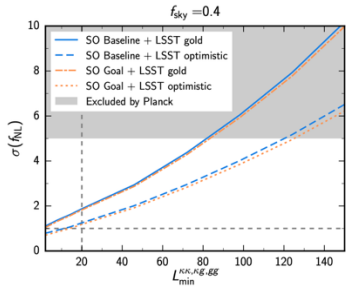
Multi-survey science

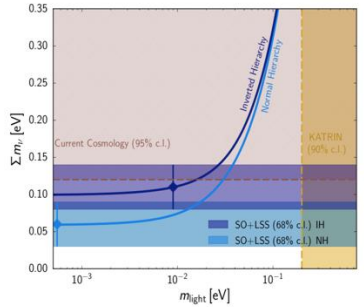


* with some post-pandemic and war updates









- *Enabling joint science from CMB lensing, tSZ, kSZ x Optical galaxy shear, clustering and clusters*
  - Neutrino mass
  - Structure growth: sigma8 at z>1
  - Non-Gaussianity: fnl
  - Cluster mass calibration
  - Shear bias calibration
  - Constraints on baryonic feedback

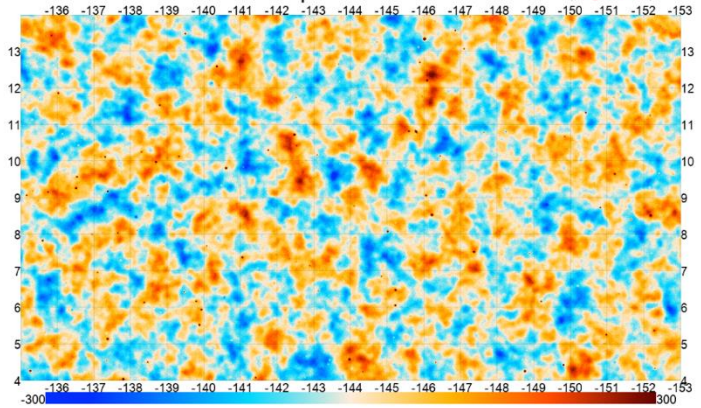
The Simons Observatory Collaboration 2019, 2025

Photo credit Felipe Carrero

Preliminary LAT Maps

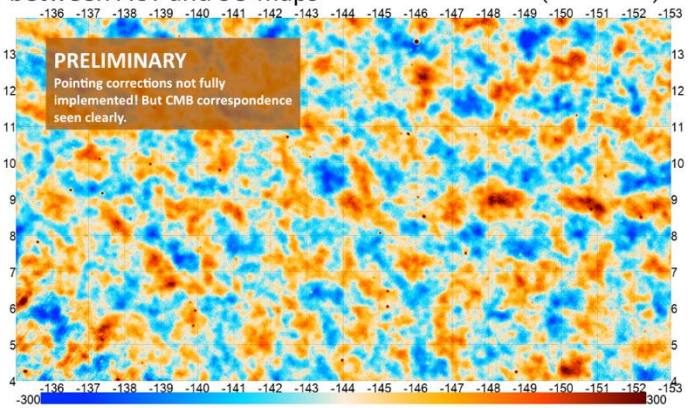
Flip between ACT and SO maps

ACT DR6 at 90 GHz (**5 years**)



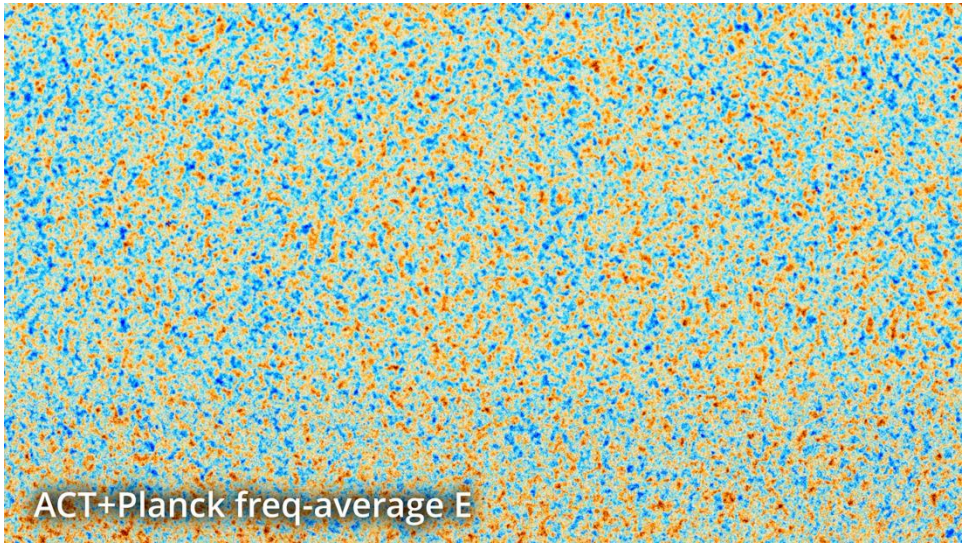
Flip between ACT and SO maps

SO LAT at 90 GHz (**144 hours**)



SO Collaboration

Outlook



ACT Collaboration

- The CMB is our main probe of the early Universe and is the leading dataset for constraining cosmological models
- New fundamental physics constraints starting to appear from polarization
- New experiments built to enable new breakthroughs
- Physical interpretation of the results now requires deeper connections between theory and data across experiments and fields