
The ATACAMA COSMOLOGY TELESCOPE: two decades of precision cosmology

*Elia Battistelli on behalf of Lyman Page
for the ACT collaboration*



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ATACAMA COSMOLOGY TELESCOPE



ACT Founding director: Lyman Page
ACT PI: Suzanne Staggs

ACT deputy PI: Mark Devlin
ACT analysis leader: Jo Dunkley

Lyman Page
(in the lab)

Jo Dunkley

Mark Devlin



The ACT collaboration
160 collaborators from 60 institutions

Acknowledgements for the images



ATACAMA COSMOLOGY TELESCOPE

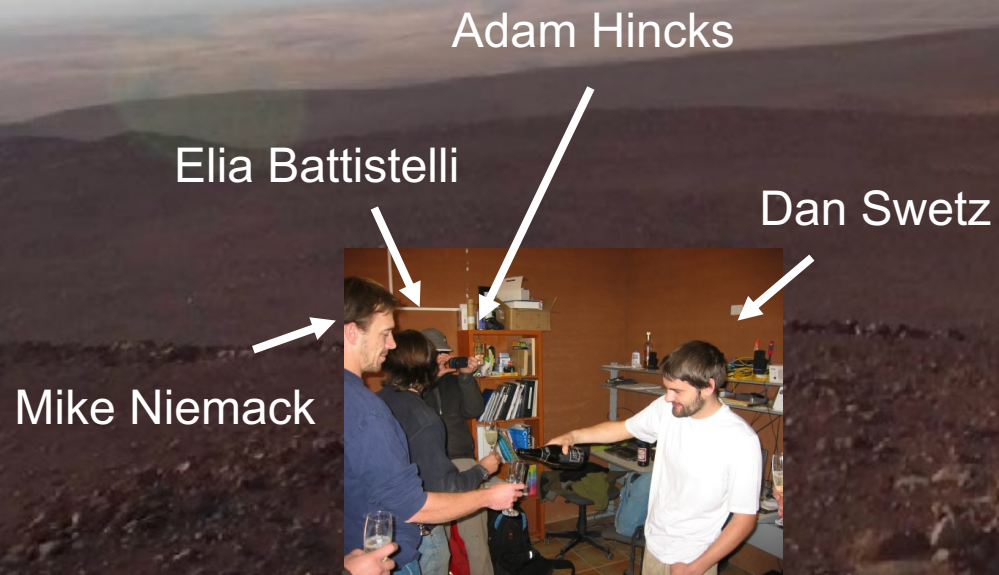
ACT in a nutshell:

- 6m telescope → 1.4' FWHM at 150GHz
- Operated 2007-2022 from 5200m
- Mid latitude (and dry) site
- TES bolometers (polarization sensitive)
- 30, 40, 90, 150, 220 GHz (and 280 GHz)
- Complement to Planck (5 time its resolution)
- Several scientific goals
- Last Data Release: DR6 2017-2022

First light in 2007



ATACAMA COSMOLOGY TELESCOPE



First light in 2007: "young" folks "at work"

Campaign recorded in a blog by Adam Hincks
https://adh-sj.info/chile_journal/chile2.php





ACT TIMELINES

2003



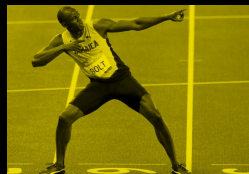
- 2003: proposal for a 6m Telescope for CMB science
- The goal: measure intensity and polarization of the mm sky

2006



- 2004: NSF funding for ACT
- 2007 first camera and first light of ACT

2009



- 2010: Funding for ACTPol camera
- 2011: First CMB lensing (Das et al)

2012



- 2011: Λ detected with only CMB (Sherwin et al)
- 2012: First kSZ detection (Hand et al)

2019



- 2014: Funding for Advanced ACTPol camera
- 2022: Last season of ACT observations

2022



- 2024: ACT donated to Ckairama Observatory
- 2025: ACT DR6 Lensing Maps, Spectra, Parameters

2024



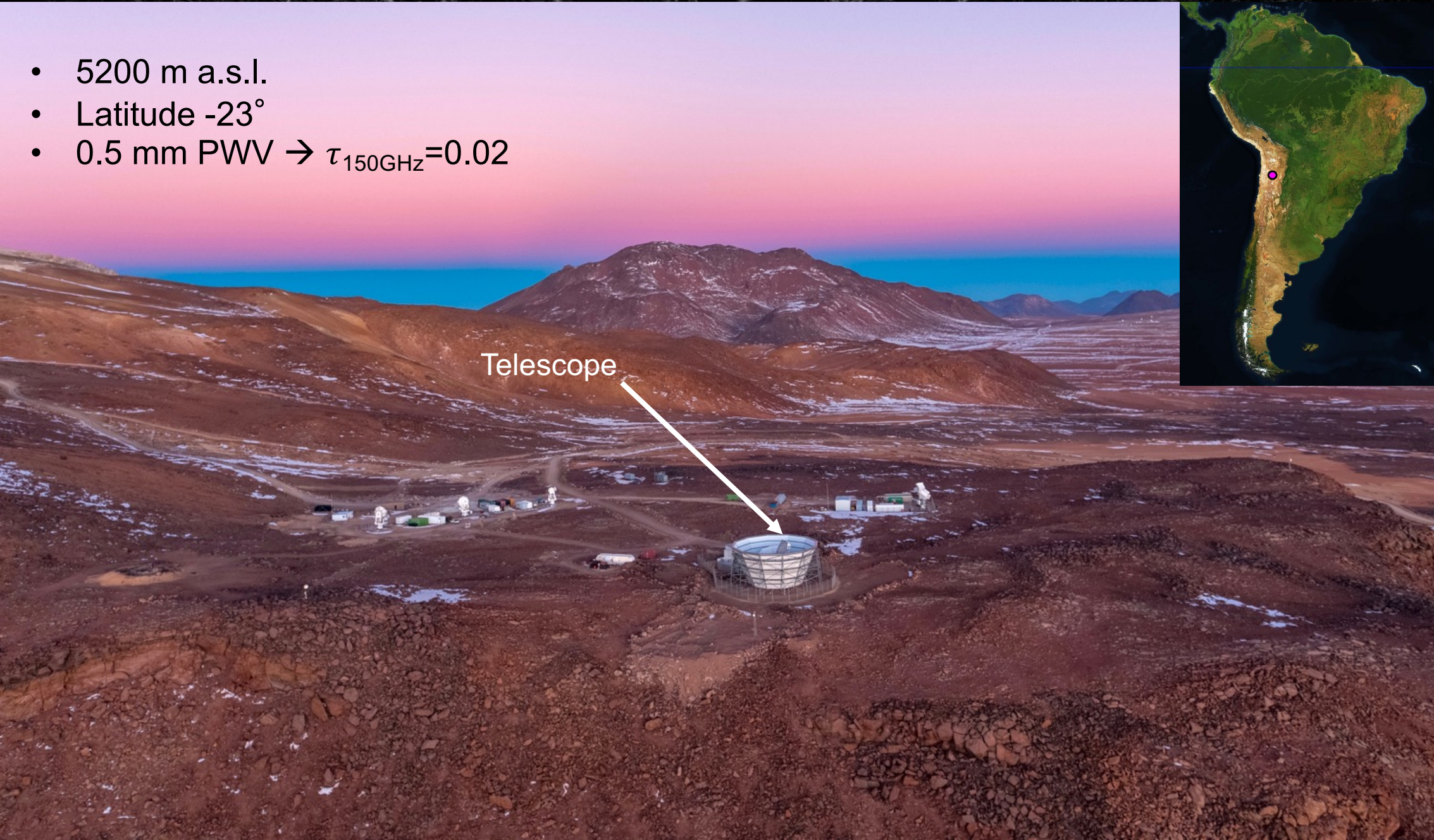
- 2026: ACT Collaboration writing papers still (and focused on SO)

Credit: S. Staggs

ACT SITE

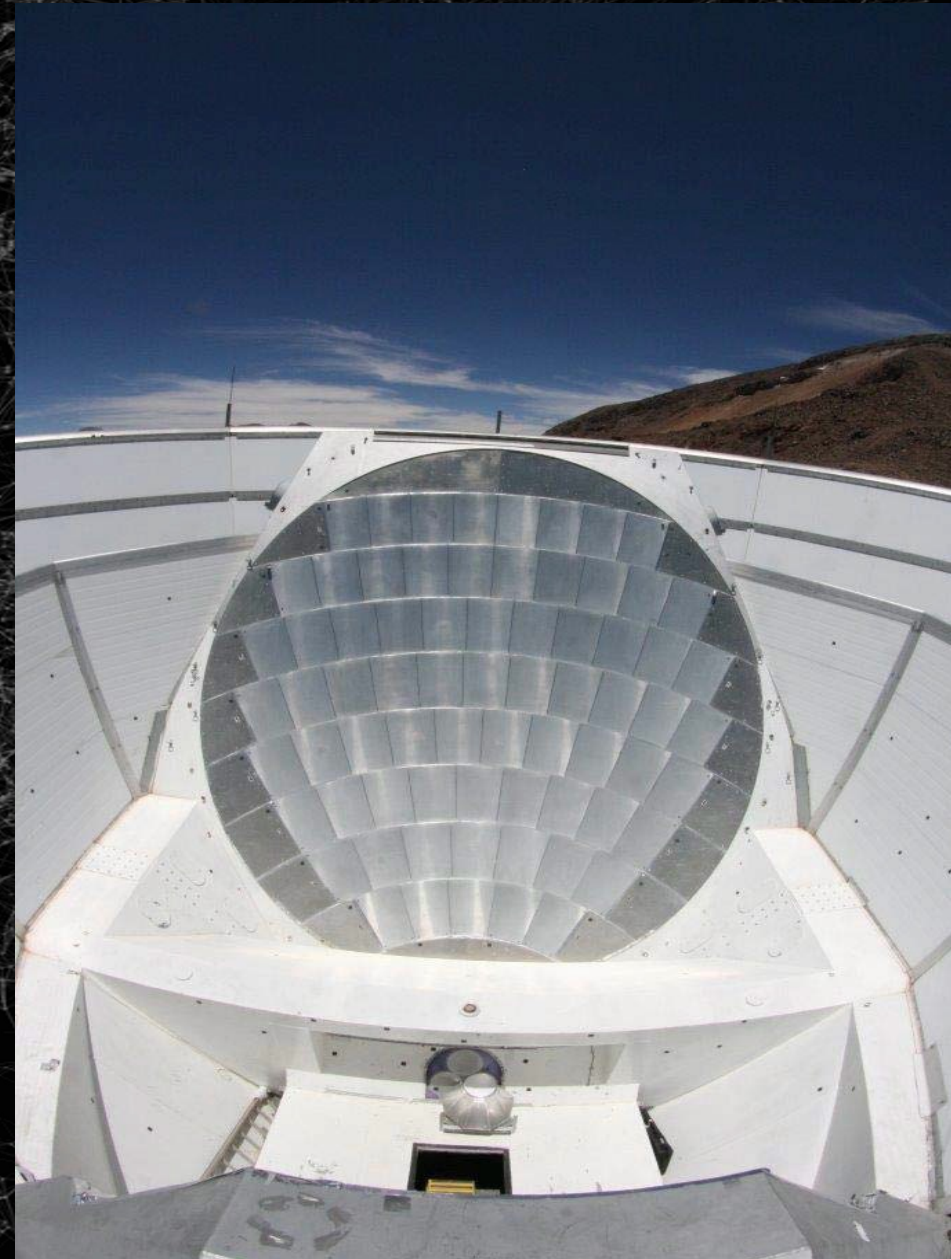
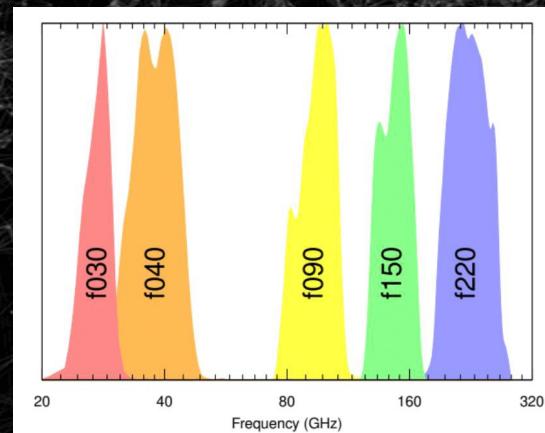
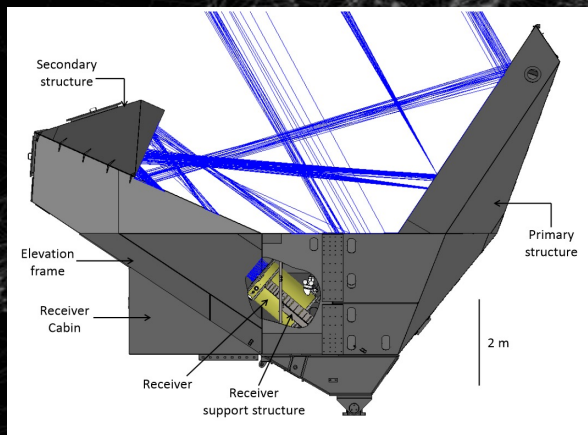
- 5200 m a.s.l.
- Latitude -23°
- 0.5 mm PWV $\rightarrow \tau_{150\text{GHz}}=0.02$

Telescope



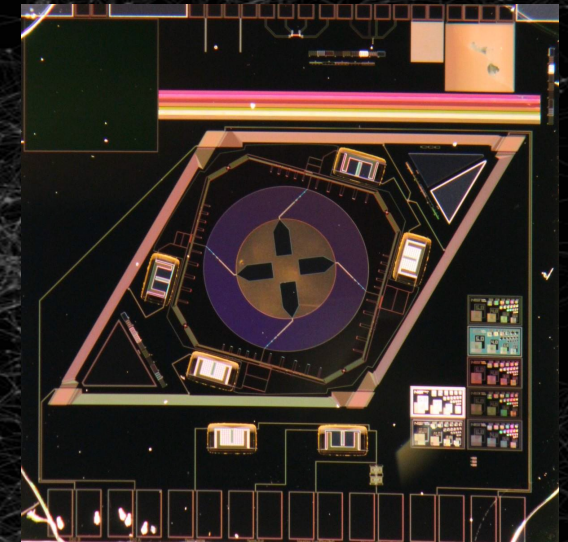
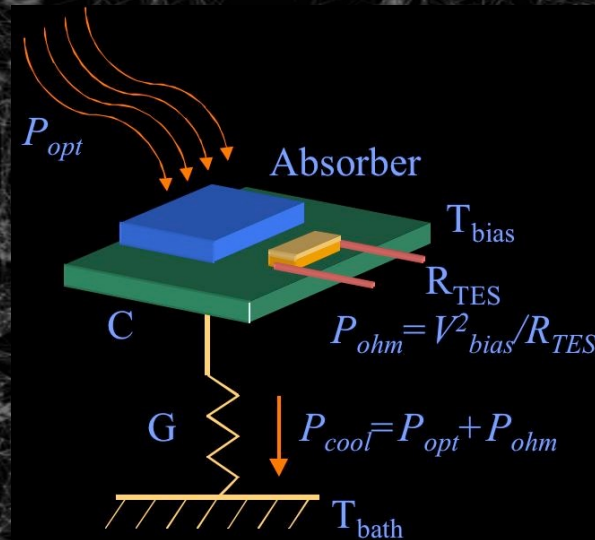
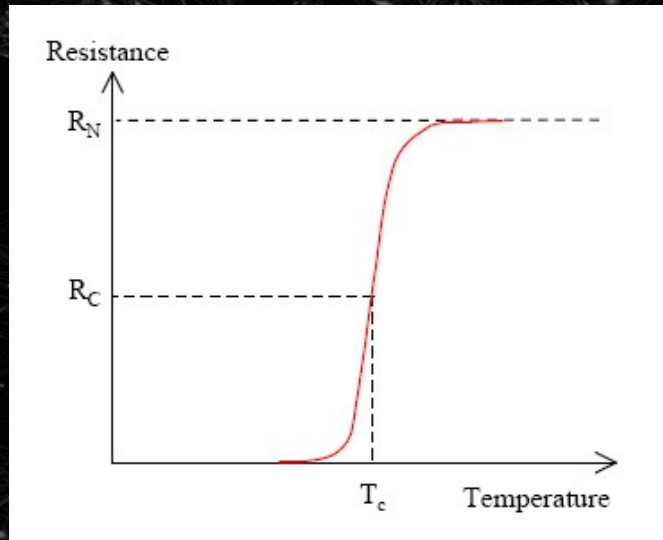
ACT OPTICS

- 6-m primary $\rightarrow$ @ 150GHz 1.4' FWHM (great for GC)
- Off-axis telescope $\rightarrow$ no obstruction
- Cross-dragone $\rightarrow$ polarization accurate
- Ground shield $\rightarrow$ low ground pick up
- Large f.o.v. $\sim 1\text{deg}^2$
- Cold silicon Lenses and Lyot stop
- Frequency bands: 30, 40, 90, 150, 220 GHz (and 280 GHz)

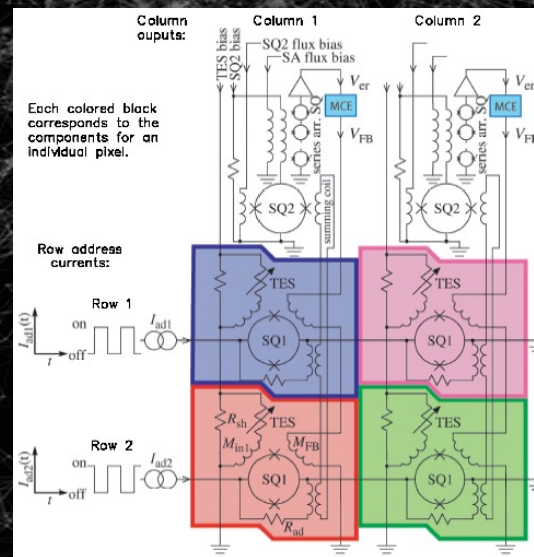


Credit: S. Staggs

ACT DETECTORS AND READ-OUT



Credit: NIST



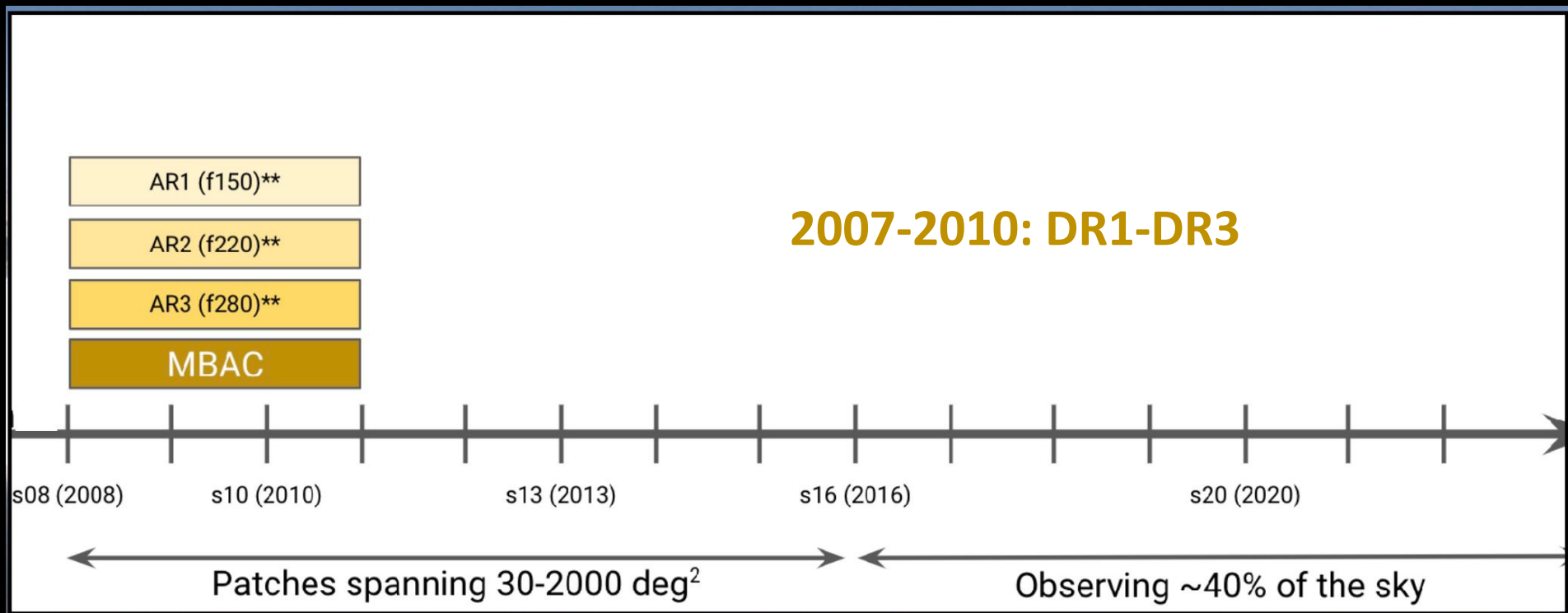
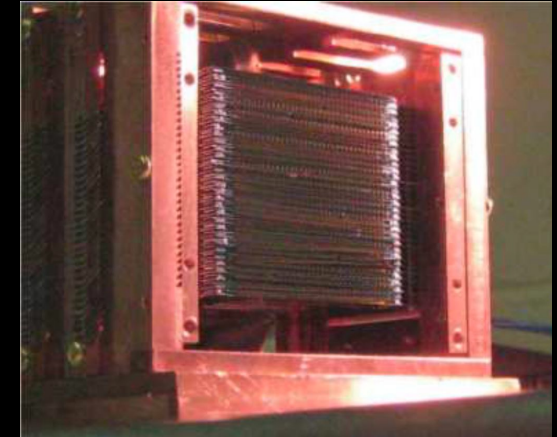
Credit: M. Halpern

- If we want to go beat the photon noise, we have to increase the number of detectors
- **TES** are very sensitive and multiplexable detectors through dedicated electronics
- We developed **Multi Channel Electronics** for Time Domain Multiplexing managing of TES and SQUIDS



THREE GENERATION OF CAMERAS

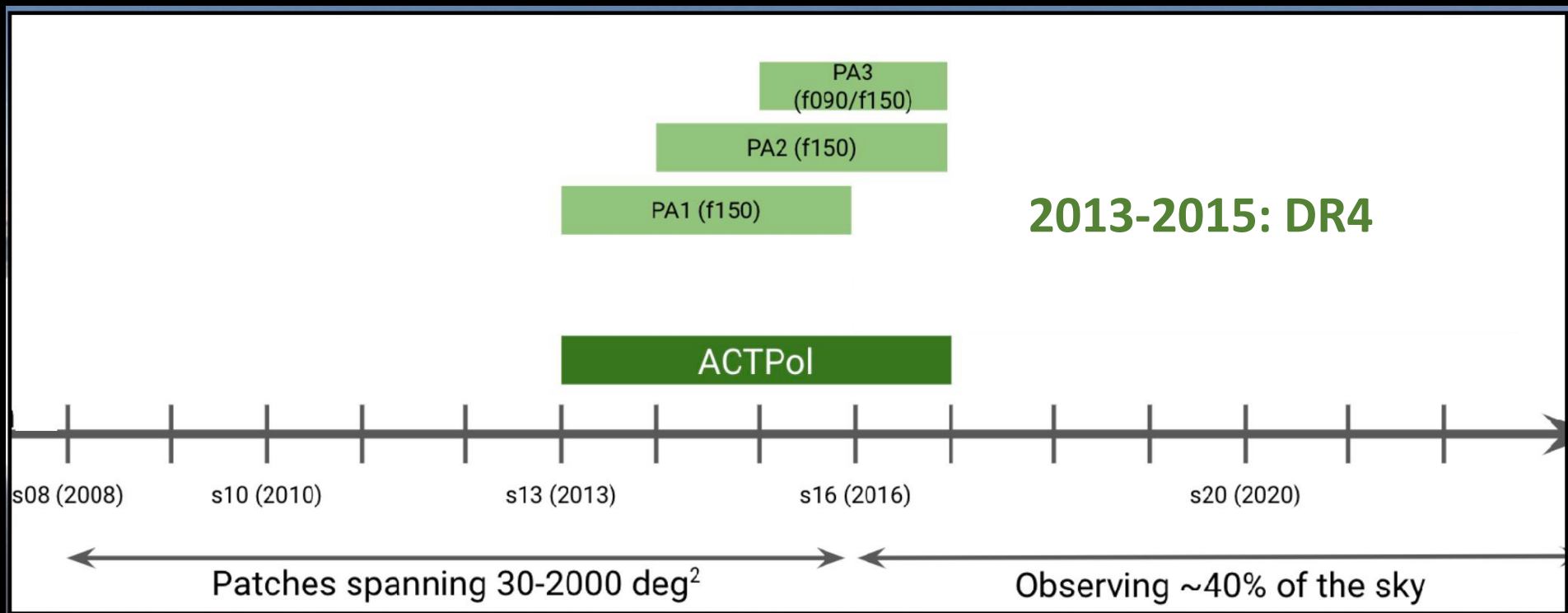
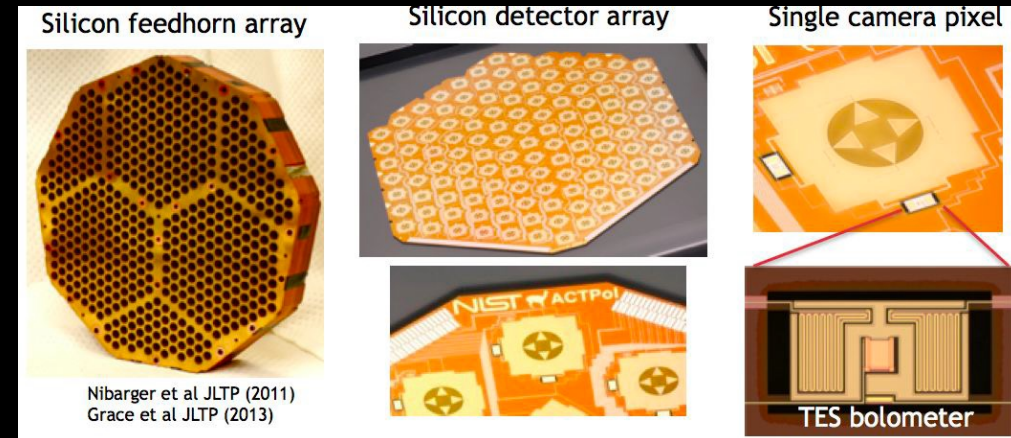
- **Three generations of cameras**, each based on TES bolometers
- 2007-2010: Millimeter Bolometric Array Camera (**MBAC**)
- Each unpolarized MBAC array is a filled array comprised 32x32 1-mm² absorbers cooled down at 300mK with a 3-He refrigerator
- For the first time 3000 TES on the sky (include a 280GHz array)





THREE GENERATION OF CAMERAS

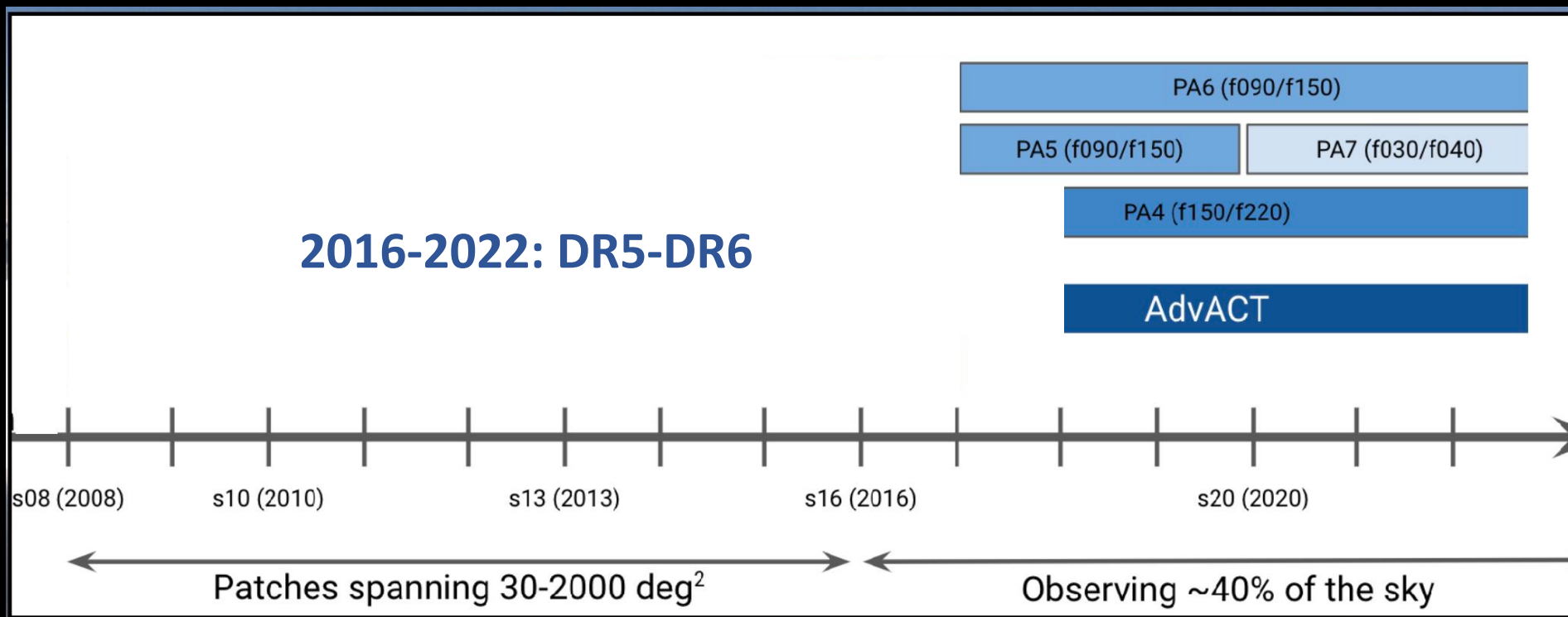
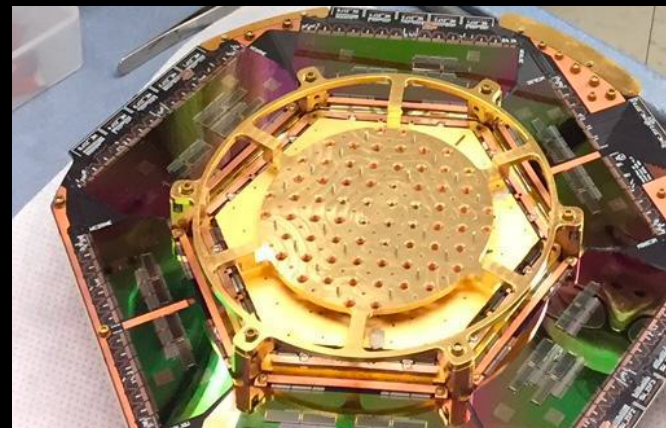
- The second was **ACTPol**, polarization-sensitive and made observations from 2013-2015
- Horn-coupled polarimeters with coupling on the wafer (OMTs, transmission lines, filters)
- Cooled at 100 mK with a Dilution Refrigerator





THREE GENERATION OF CAMERAS

- The final camera is **AdvACT**, which stands for Advanced ACTPol
- Horn-coupled polarimeters at 100 mK
- Four dichroic arrays: 10000 TES observing 40% of the sky (30/40 GHz part time)

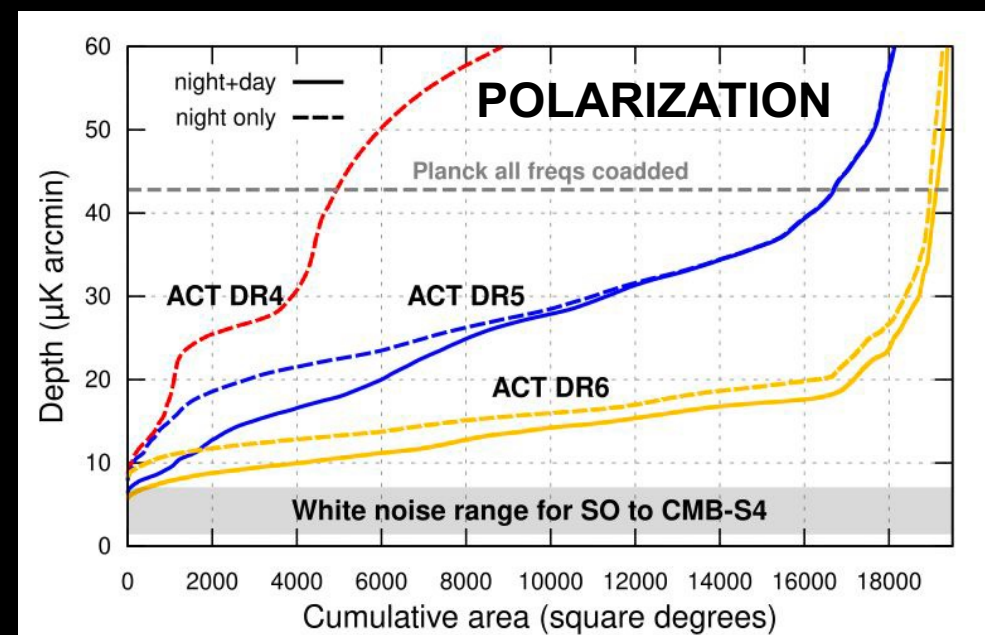
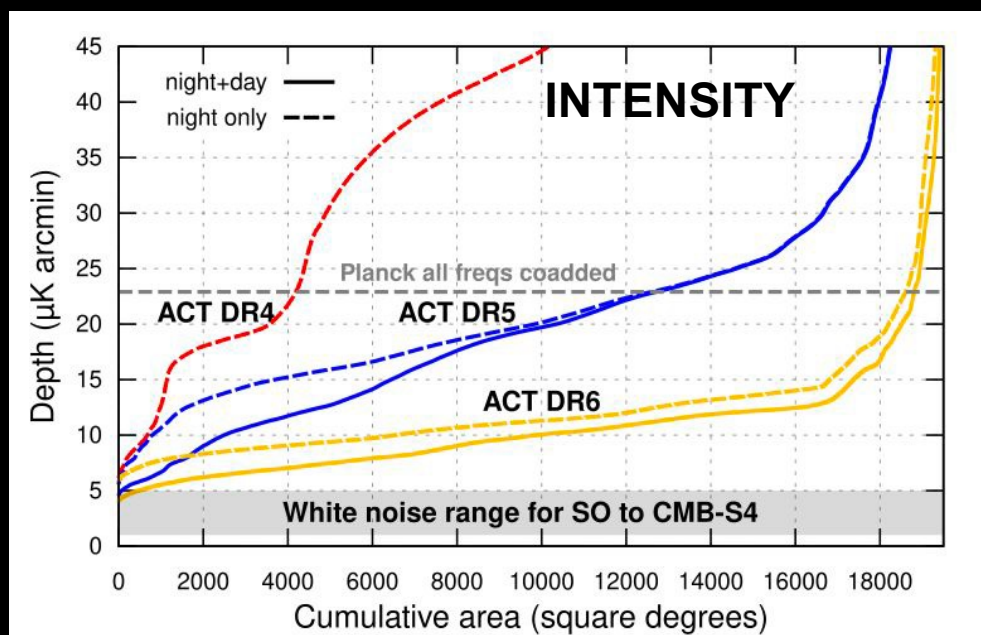
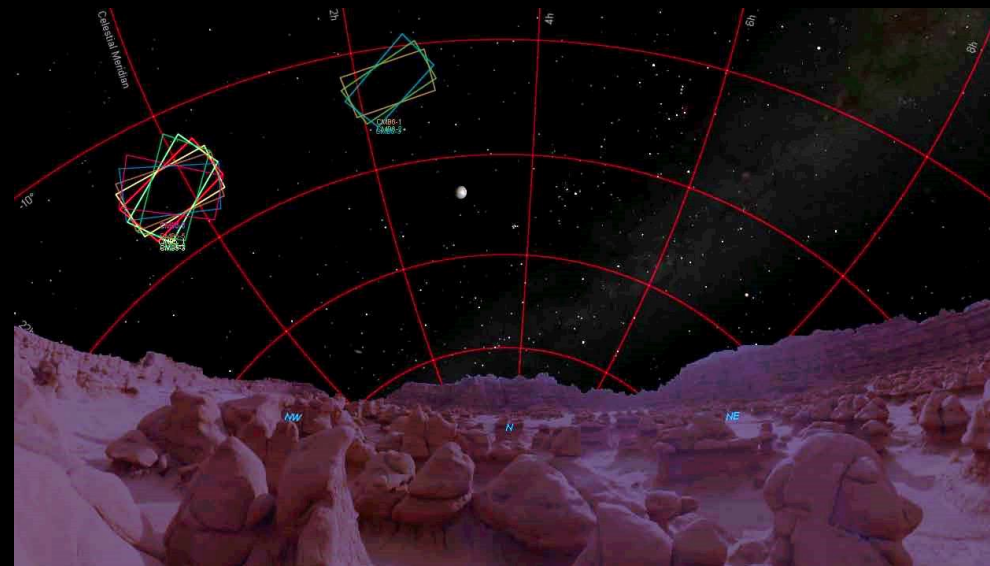




DATA



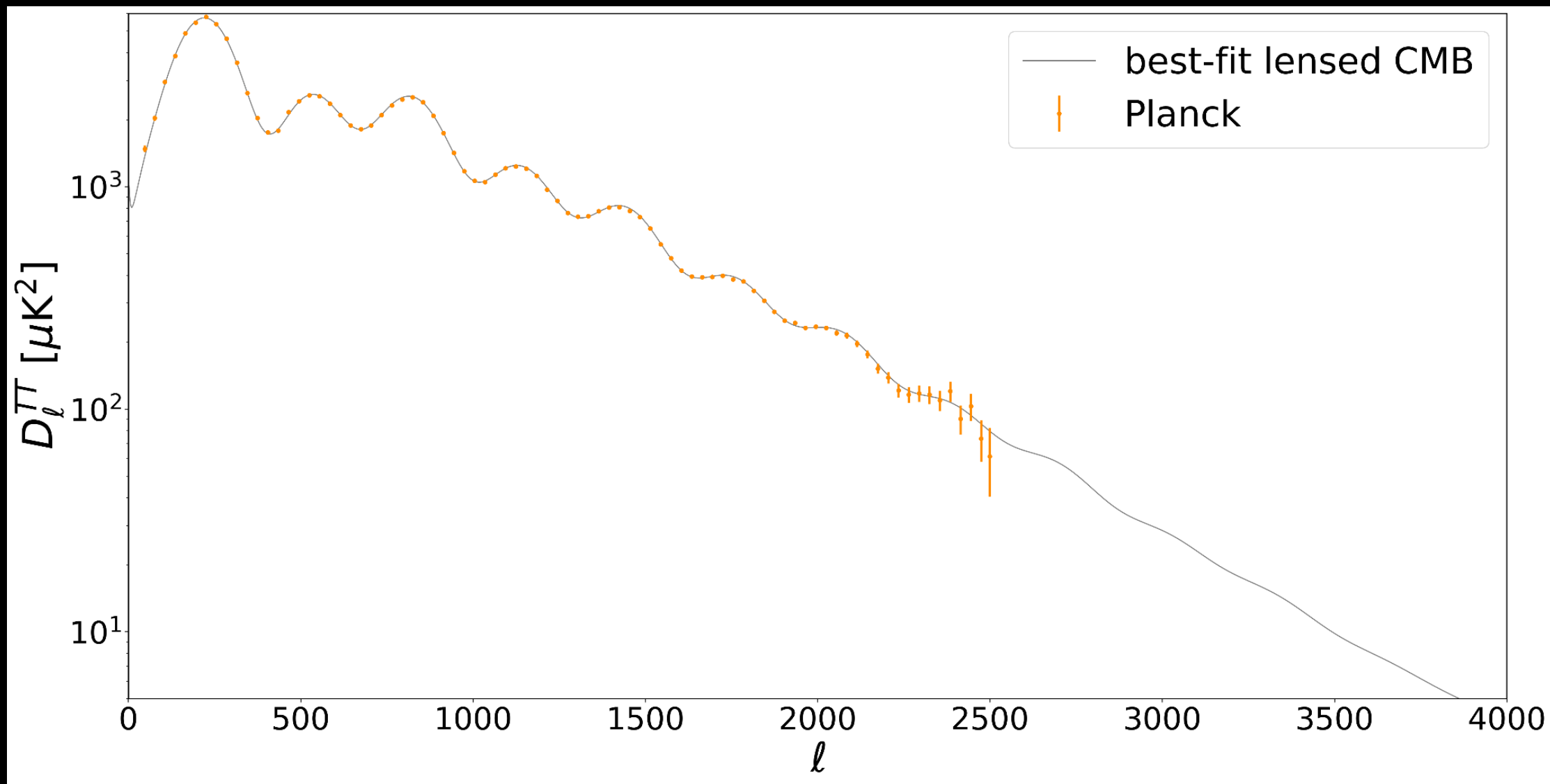
- 40% of the sky mapped: 19000 deg²
- Constant elevation scans: cross linking is key for map making to remove atmosphere
- All data and likelihood available in LAMBDA
- Several cross-correlation activities
- Null test and blind analysis performed



Credit: M. Devlin -S. Staggs

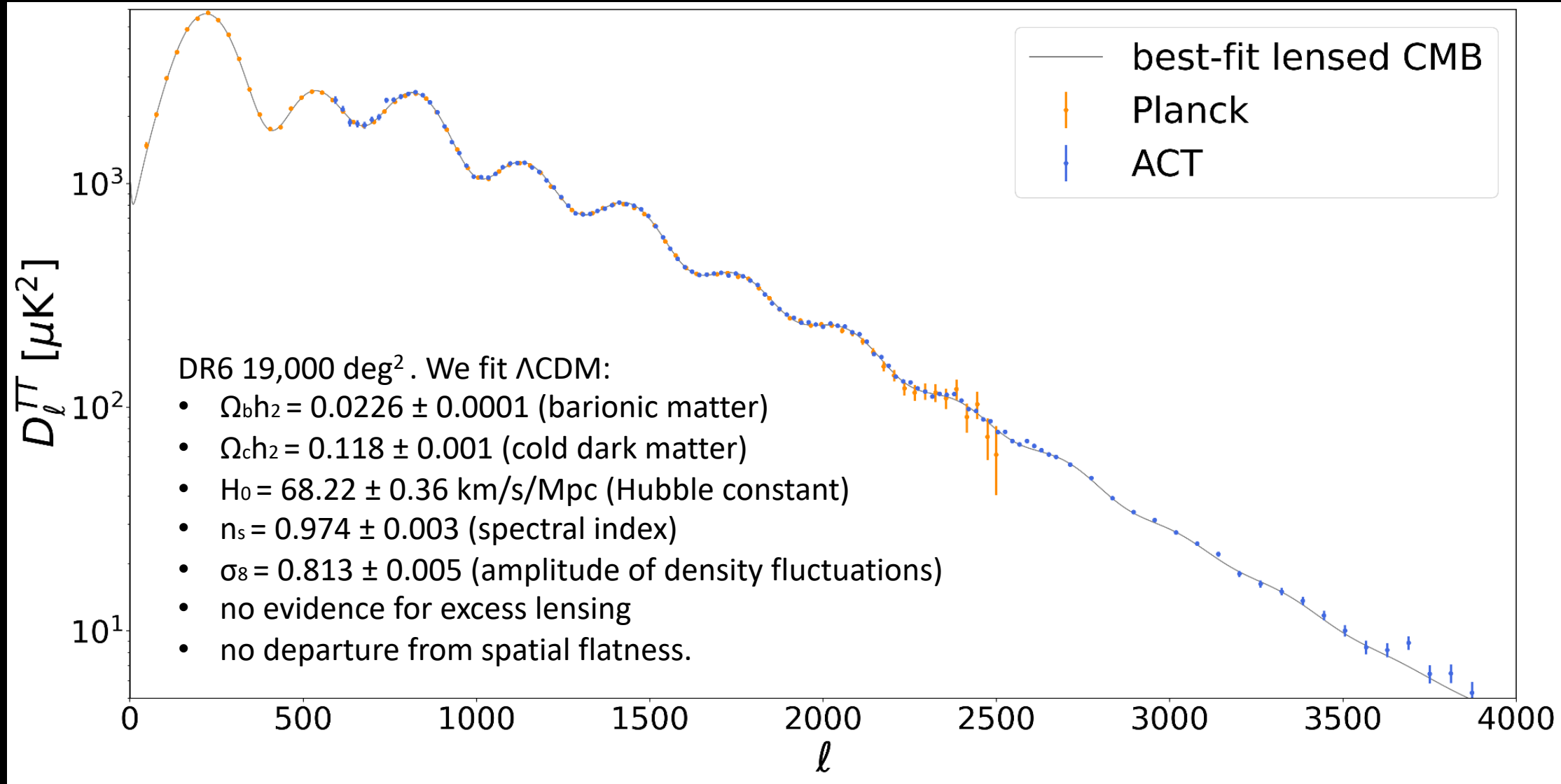


POWER SPECTRA



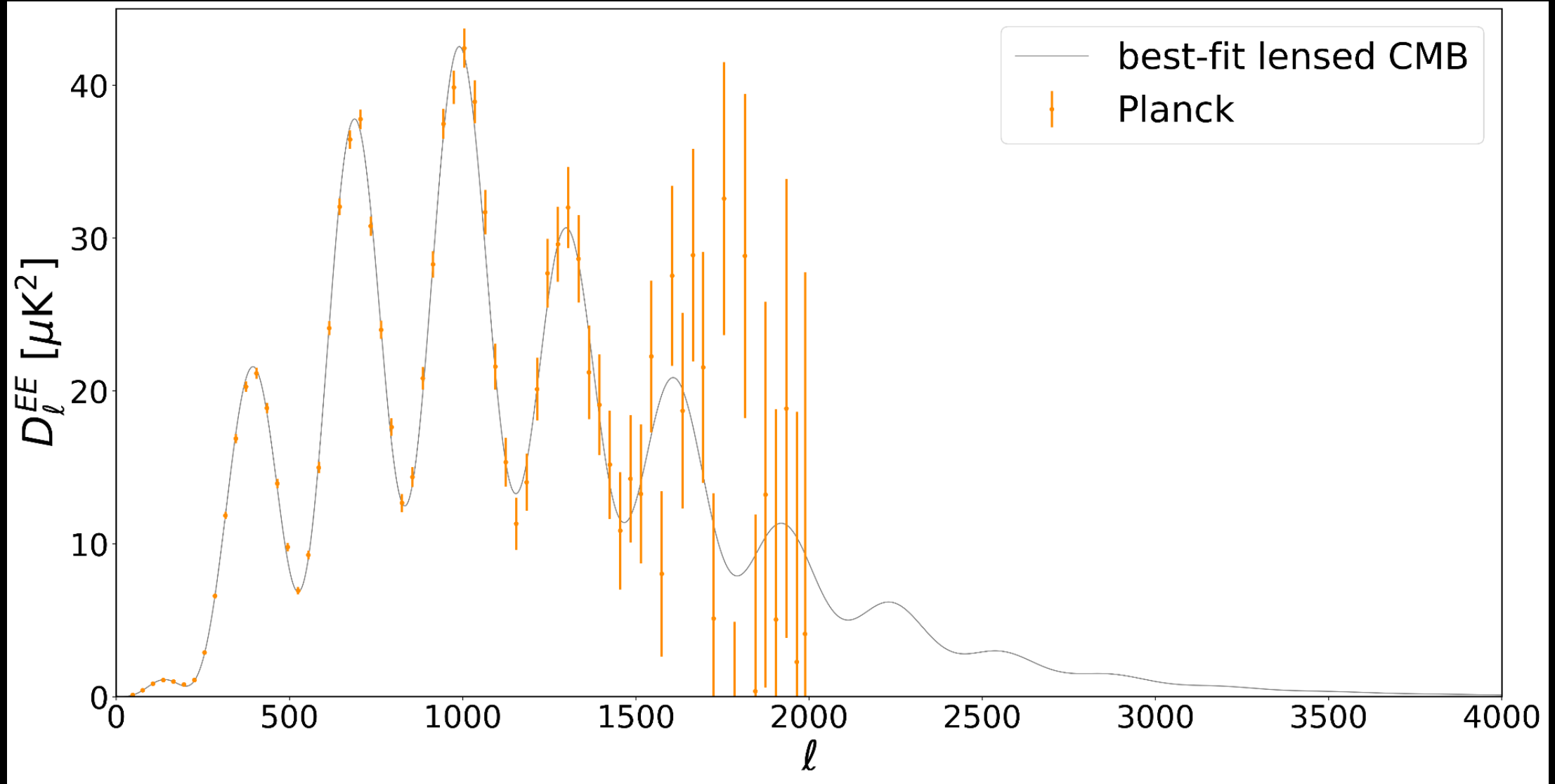


POWER SPECTRA



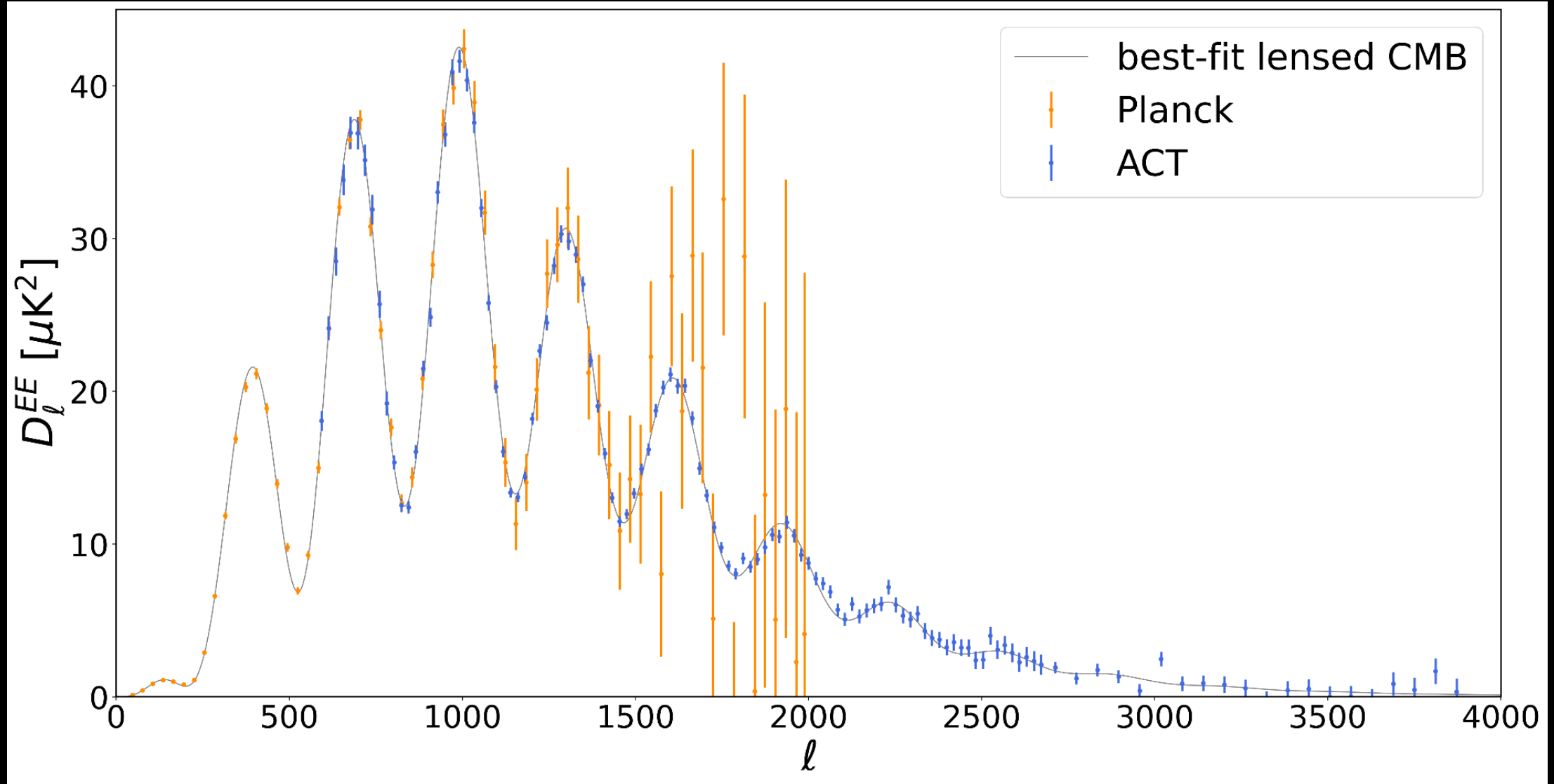


POWER SPECTRA





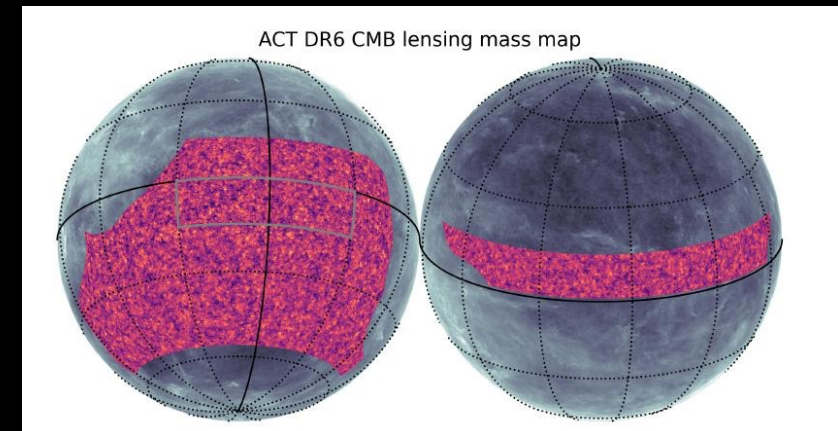
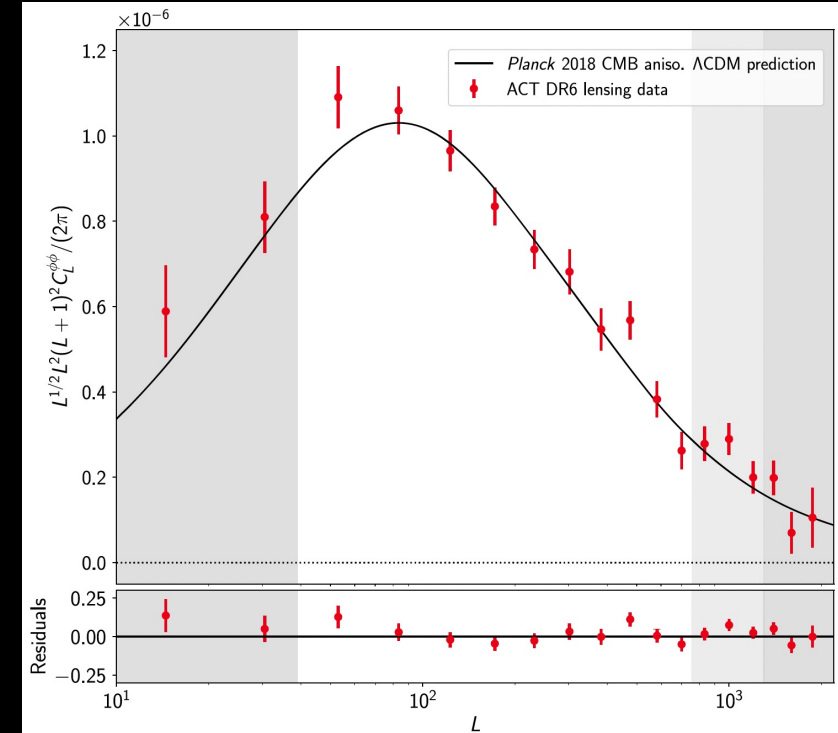
POWER SPECTRA





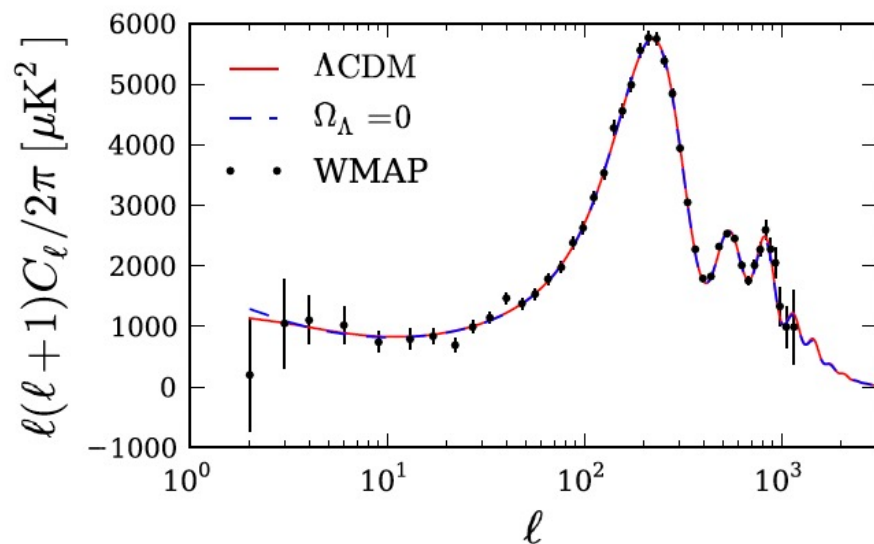
CMB lensing

- CMB lensing detection (Das et al. 2011 – Darwish et al. 2021 – Qu et al. 2024) from temperature and polarization
- CMB is the furthest light we can see so there is a big potential for lensing detection
- Not only high-resolution maps but also covering half of the sky: we use **small scale to constraint large scale** lenses $600 < l < 3000$
- We measured the lensing power spectrum and extract the Dark Matter potential
- DR6 maps (9400 deg²): blind analysis, cross correlation
- $A_{\text{lens}} = 1.013 \pm 0.023$ (43σ) compatible with Λ CDM

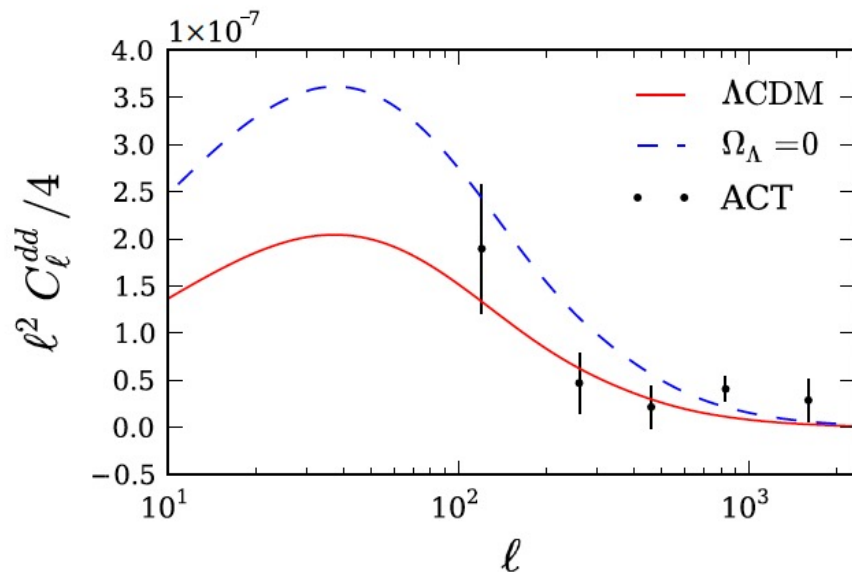




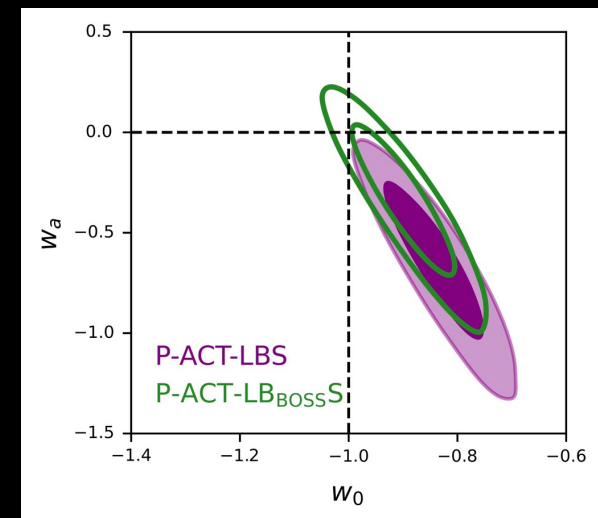
CMB (only) Dark Energy evidence



- Sherwin et al. 2011 found the first **CMB only evidence of Dark Energy**
- This, again, with the lensing power spectrum
- From DR6 primary CMB data, we find no evidence for non-standard (dynamic) dark energy; hints of non-standard evolution are driven by low-redshift data

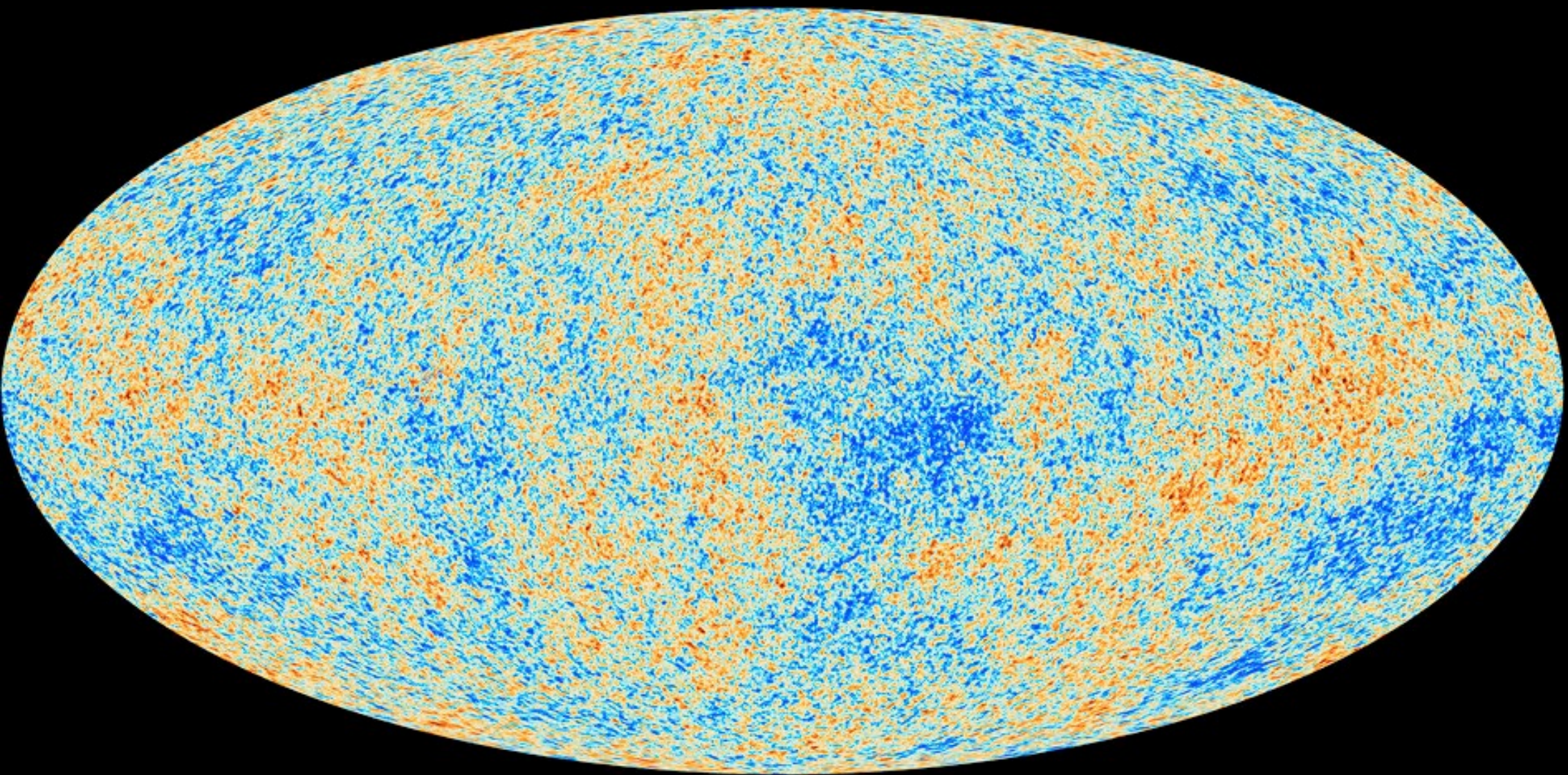


- With DR6 we also measured the growth of structures: $S_8 = 0.818 \pm 0.022$ consistent with a standard one



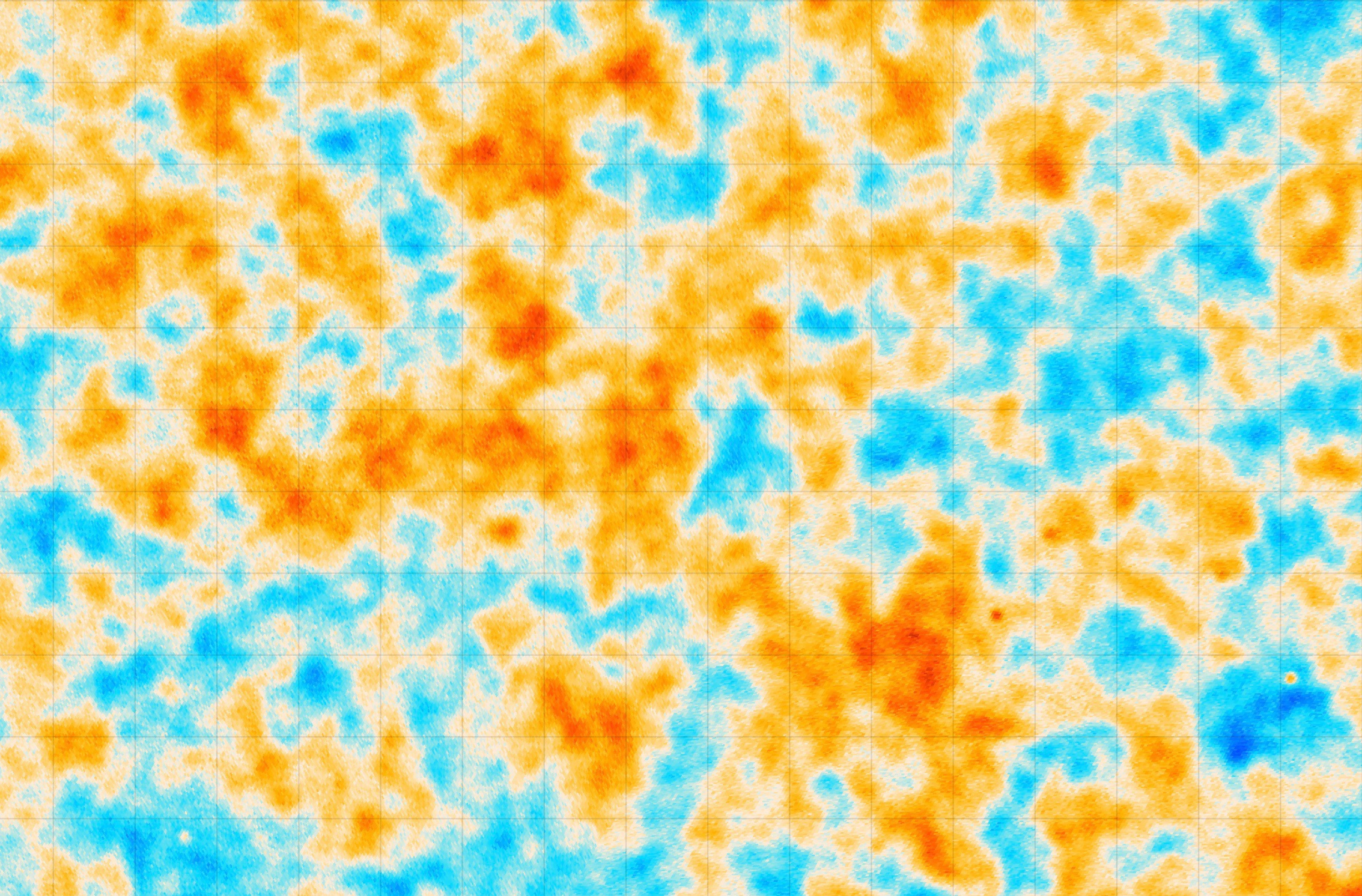


COSMIC MICROWAVE BACKGROUND



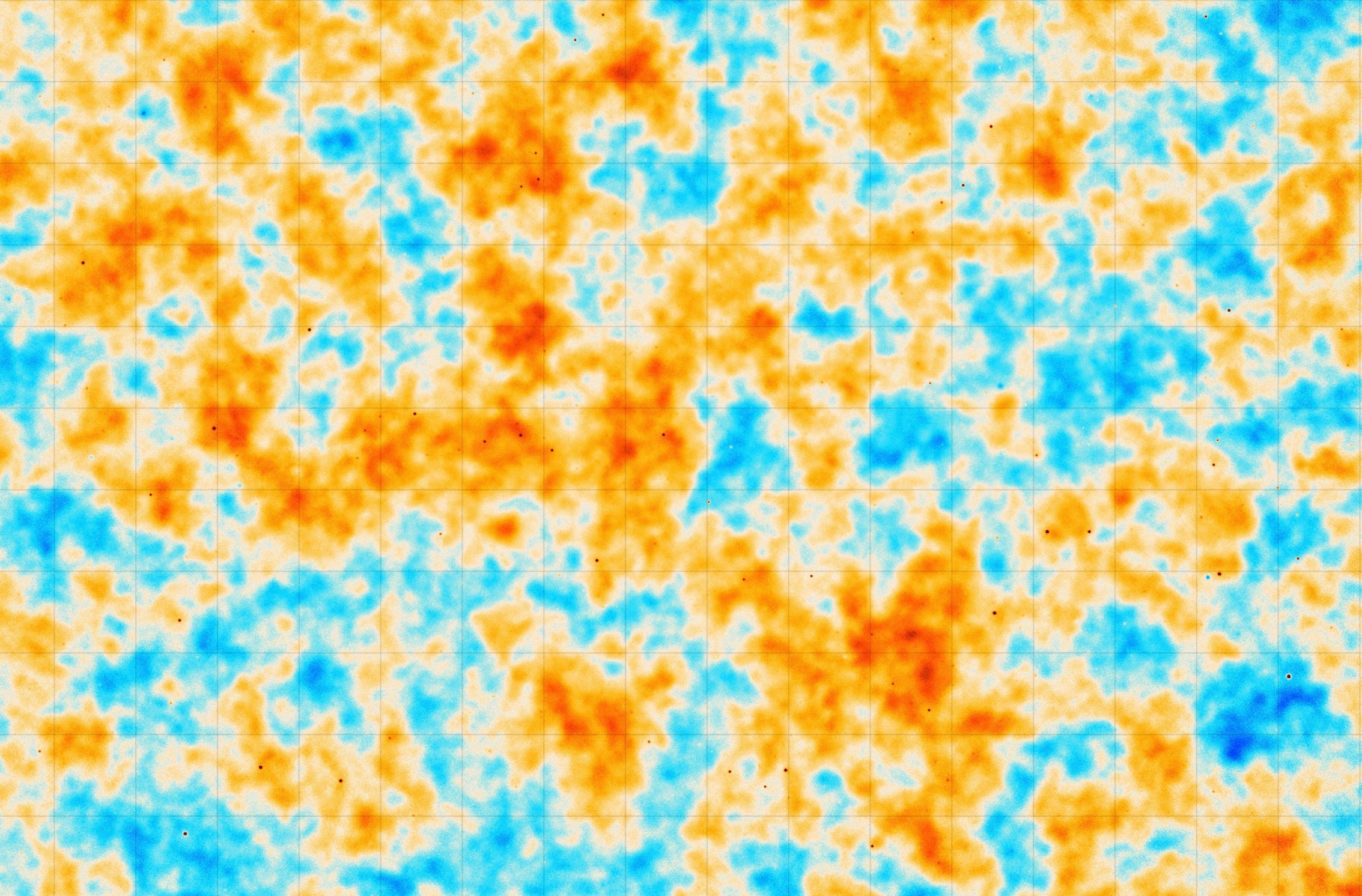
PLANCK

ESA/Planck Collaboration



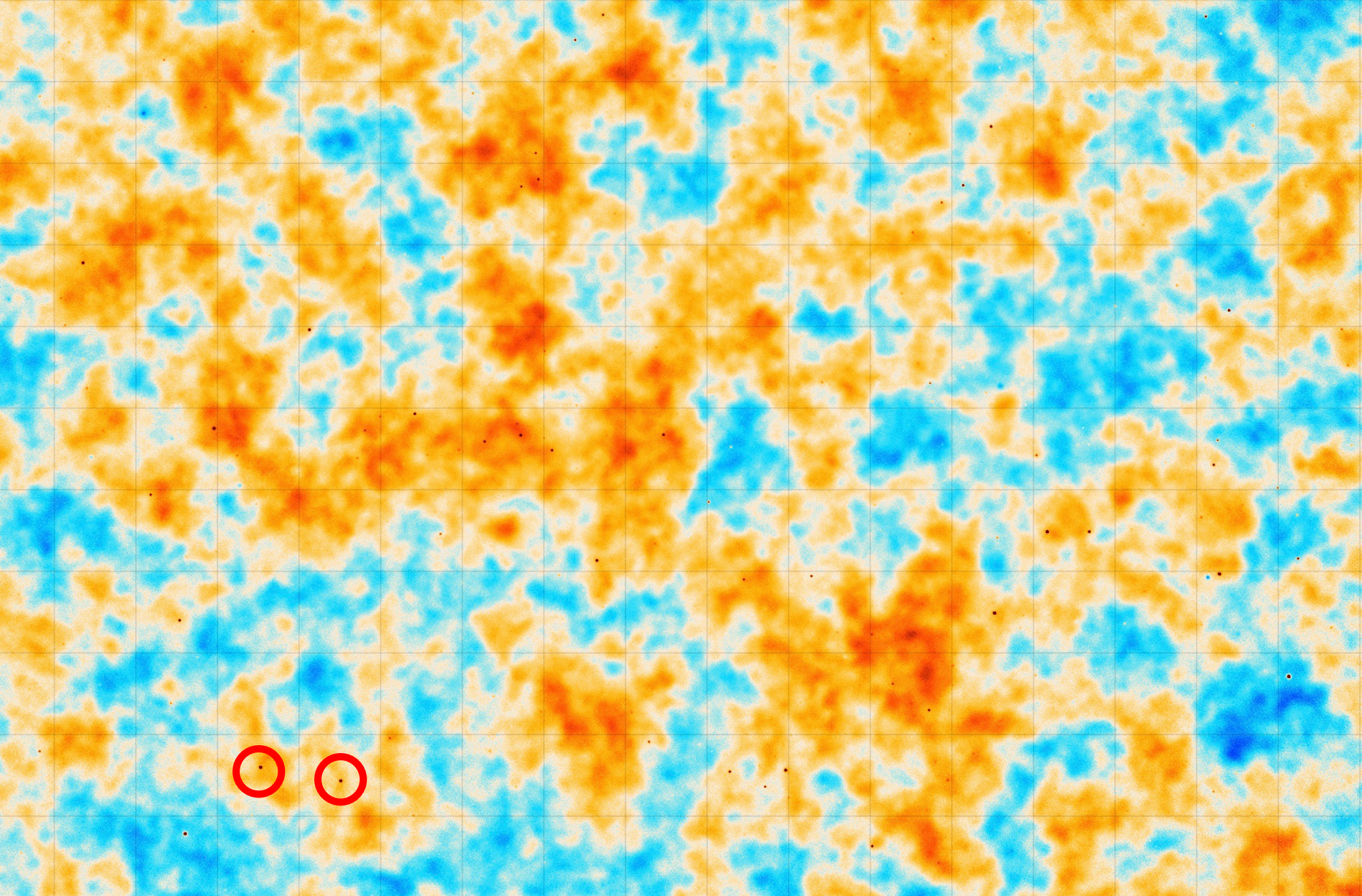
30x22 deg² CMB map as seen from Planck (150GHz)

Naess et al. 2020



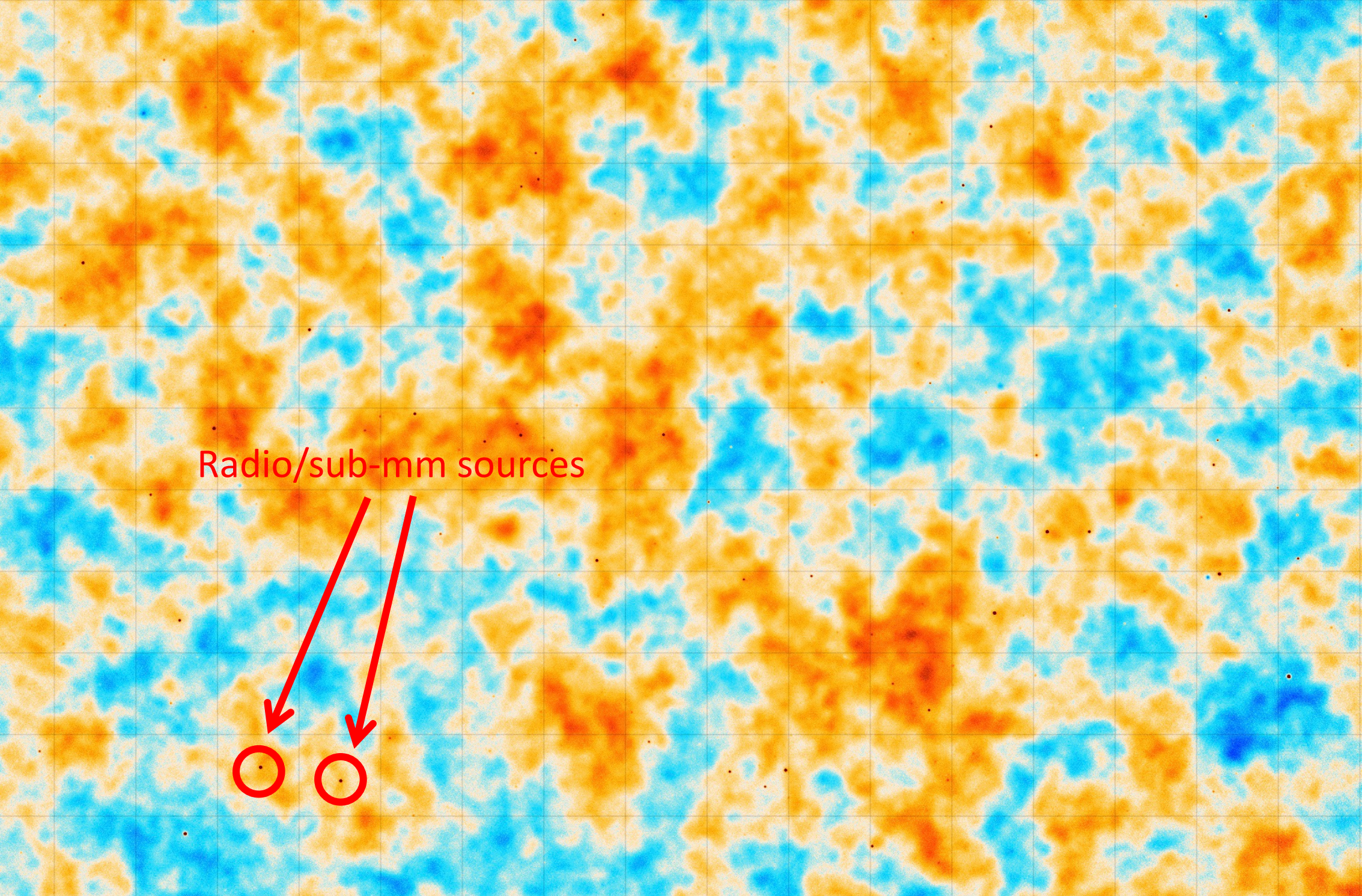
30x22 deg² CMB map as seen from Planck+ACT-DR4 (150GHz)

Naess et al. 2020

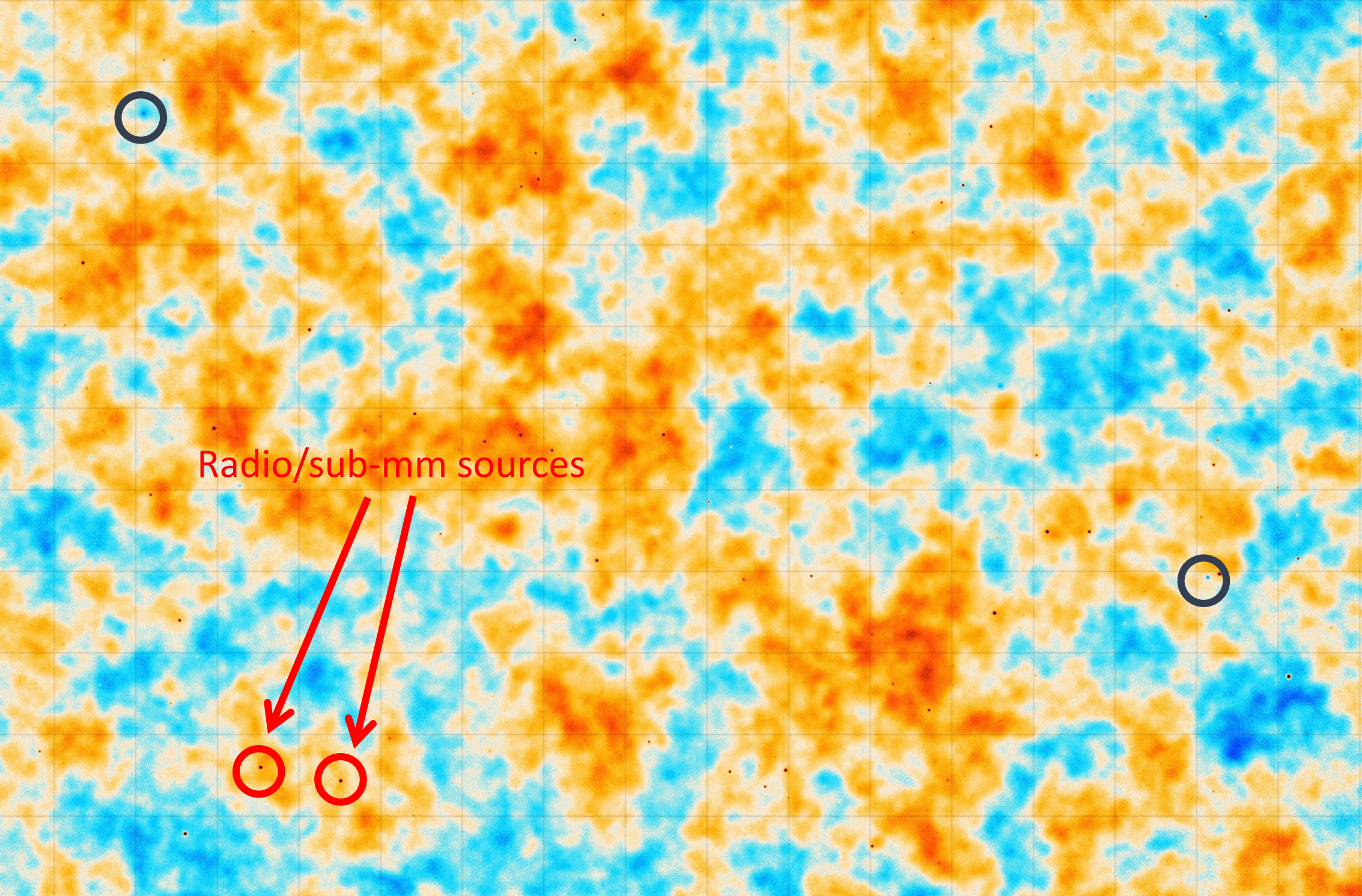


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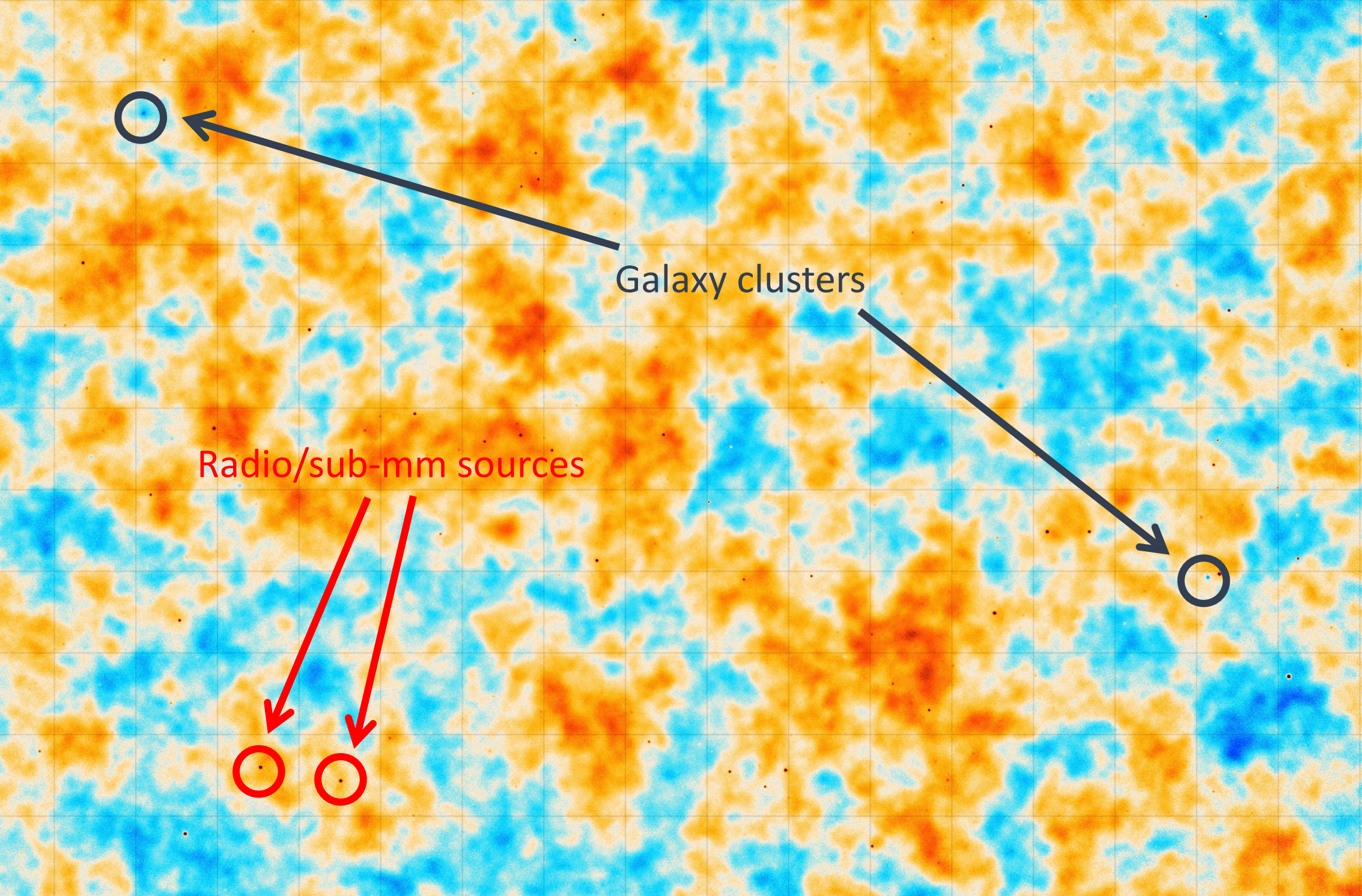
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Radio/sub-mm sources



Radio/sub-mm sources

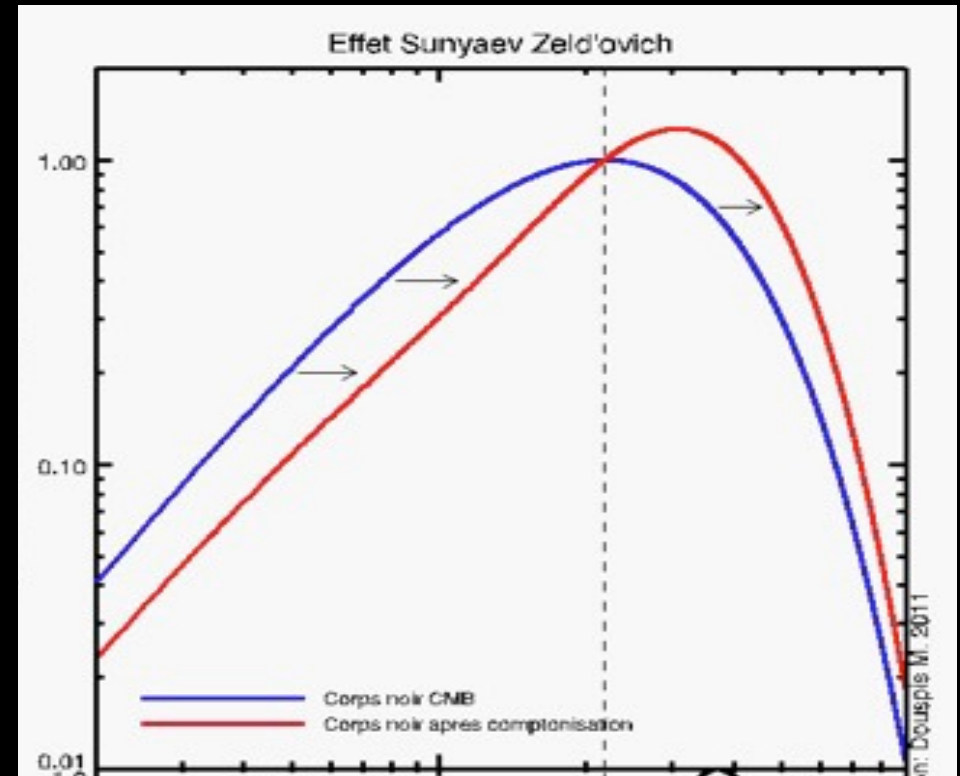




THE THERMAL EFFECT

- Inverse Compton scattering
- Spectral distortion of the CMB due to a burst by the hot ($T \sim 10^8 \text{K}$) electron gas. It can be quantified by:

$$y = \int n_e \sigma_T \frac{k_B T_e}{m_e c^2} dl = \tau \theta_e$$

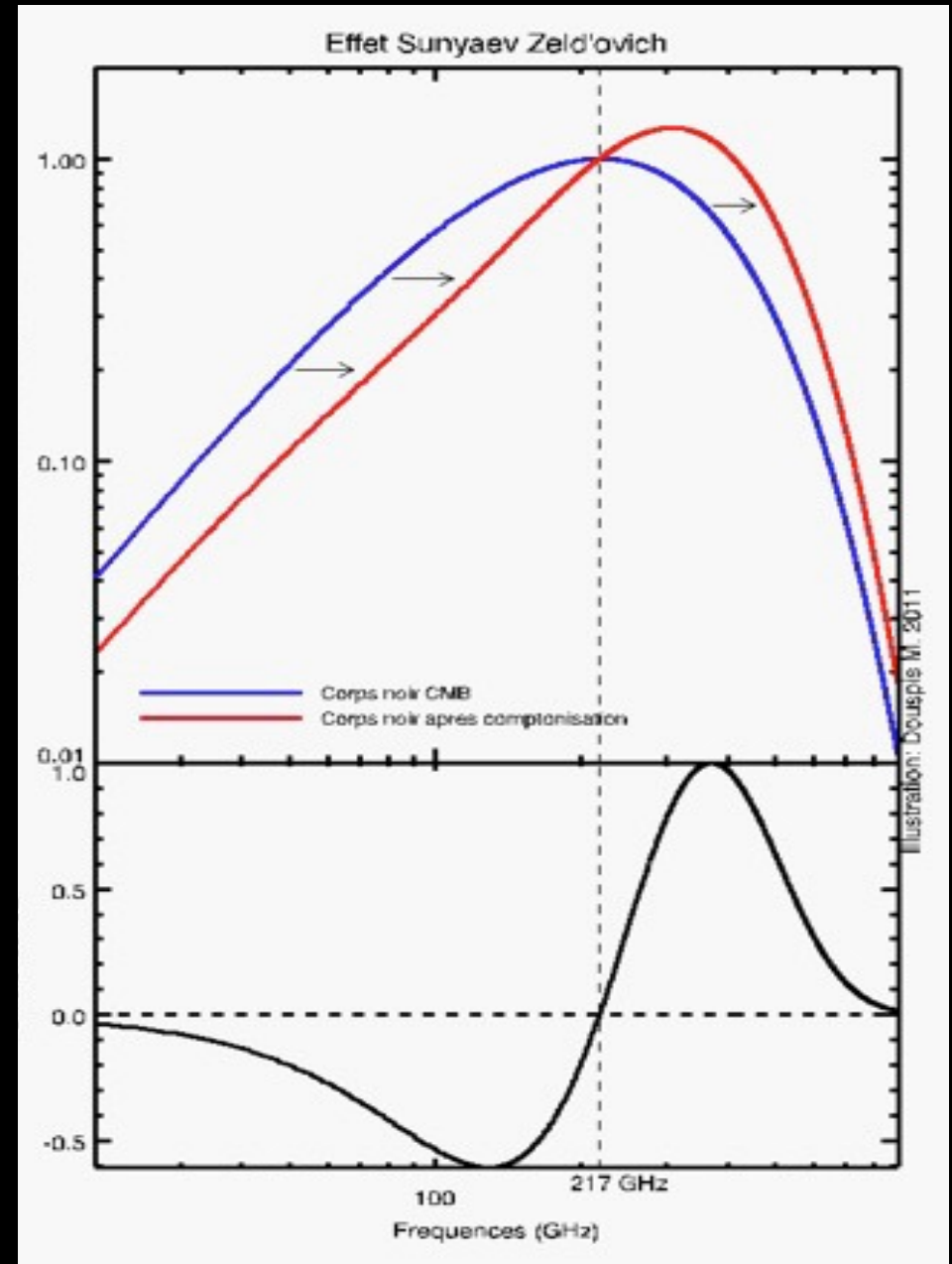




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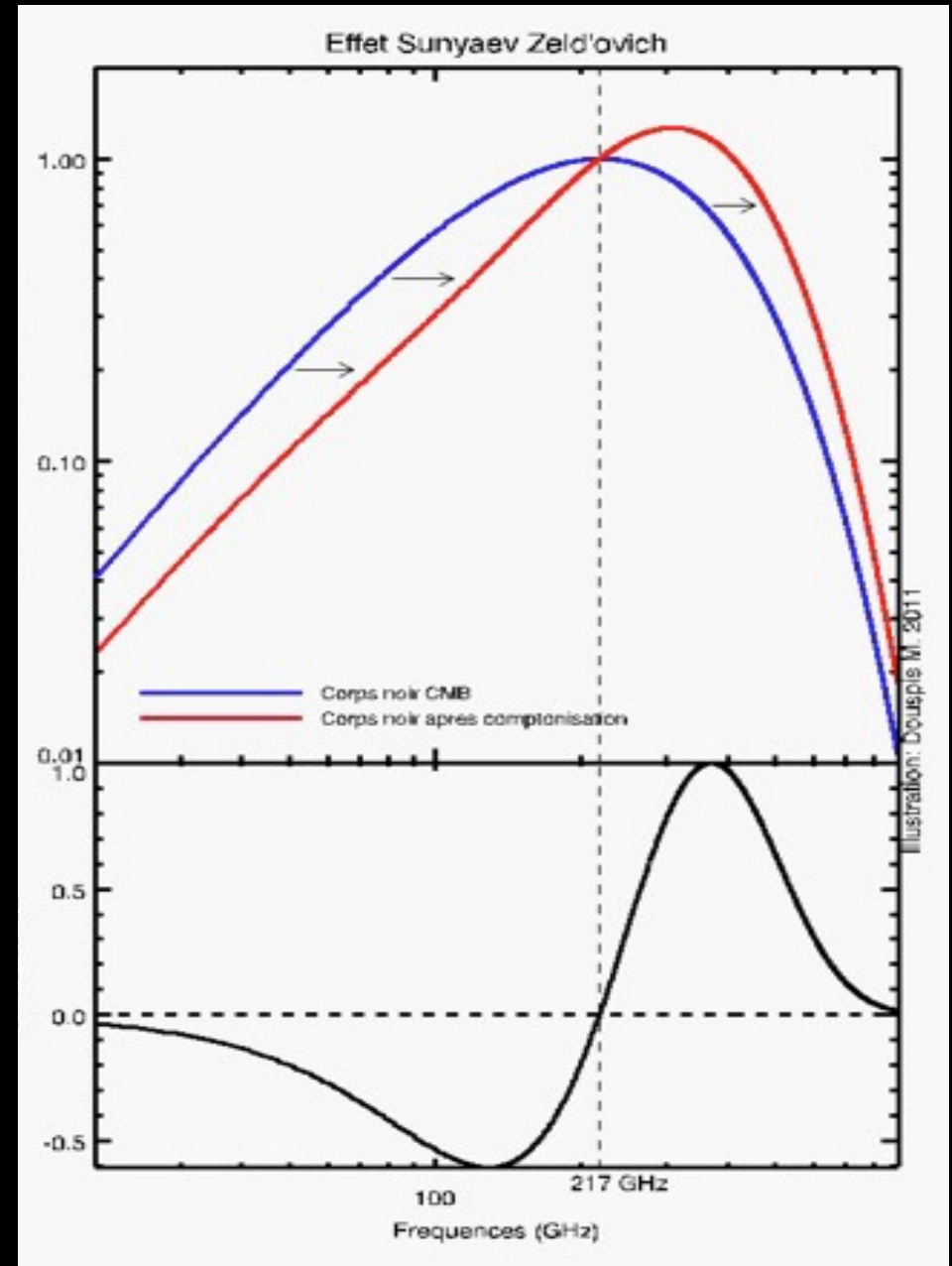
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- X-ray studies could see them but due to the different dependence wrt to n_e and T_e , SZ can provide more information for low densities environments

$$X_{br} \propto n_e^2 \cdot \sqrt{T_e} \cdot l$$





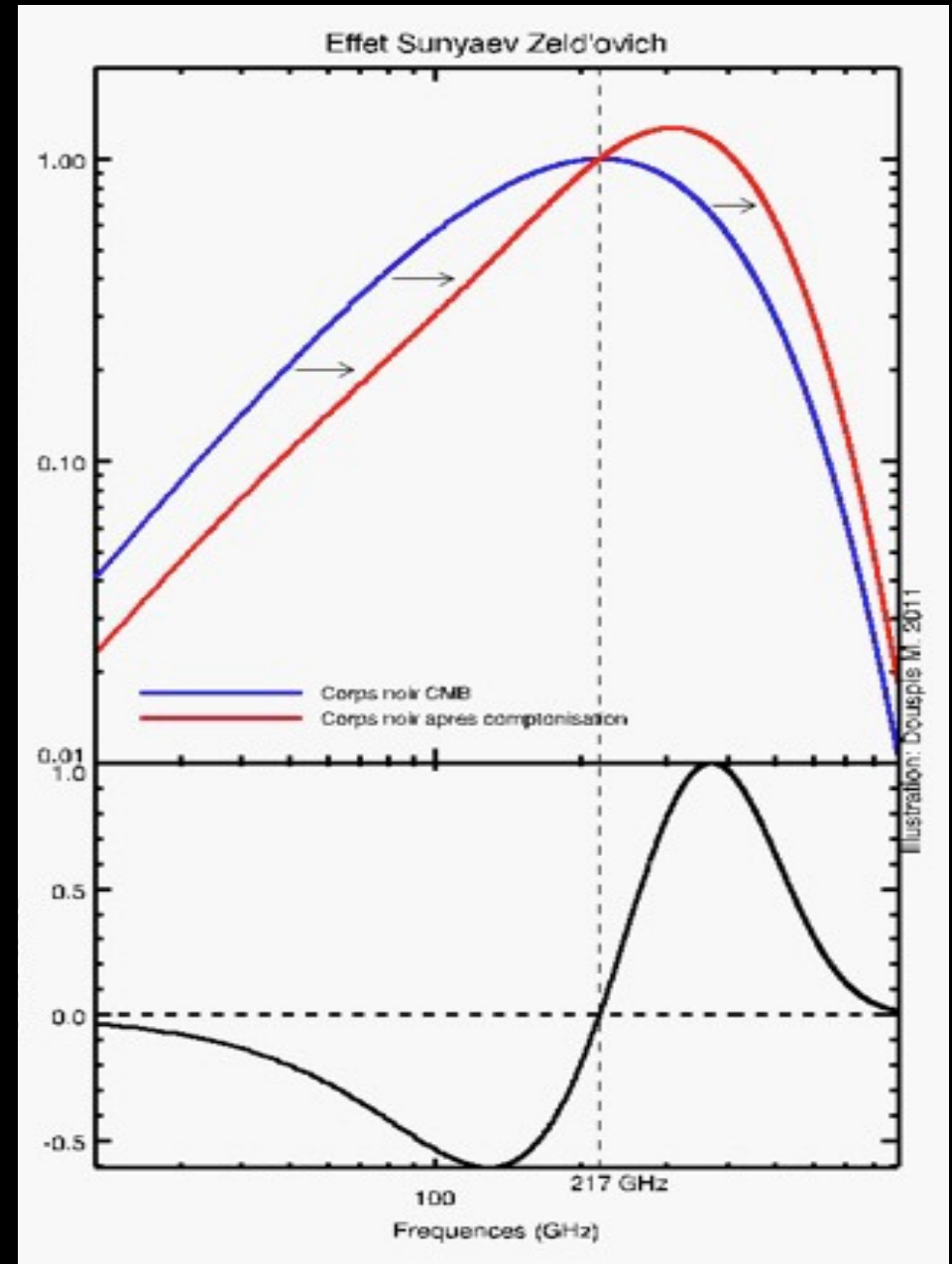
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MATTER DISTRIBUTION

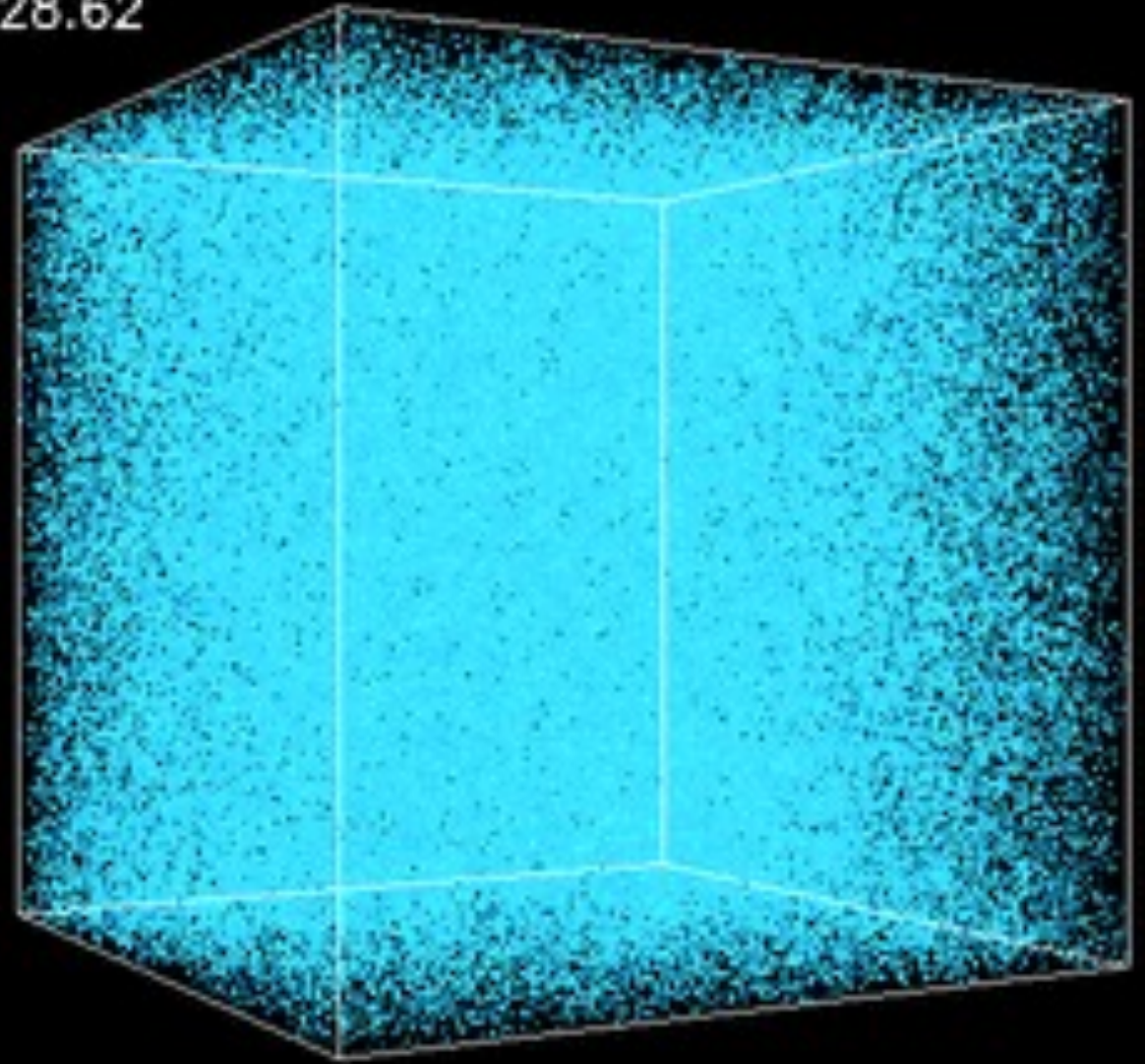
- Even if the **dark sectors** of our universe are still unknown, one may think we perfectly know the **baryonic matter distribution**
- Hydrodynamical simulations predict that baryonic matter is distributed in a so-called cosmic web distribution
- Filamentary structures between the knots of the Cosmic Web occupied by Galaxy Clusters
- Fast radio burst have demonstrated that the integrated baryon fraction along the l.o.s. is consistent with early-Universe (Macquart et al. Nature 2020)
- However, the actual distribution is still debated



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$z=28.62$



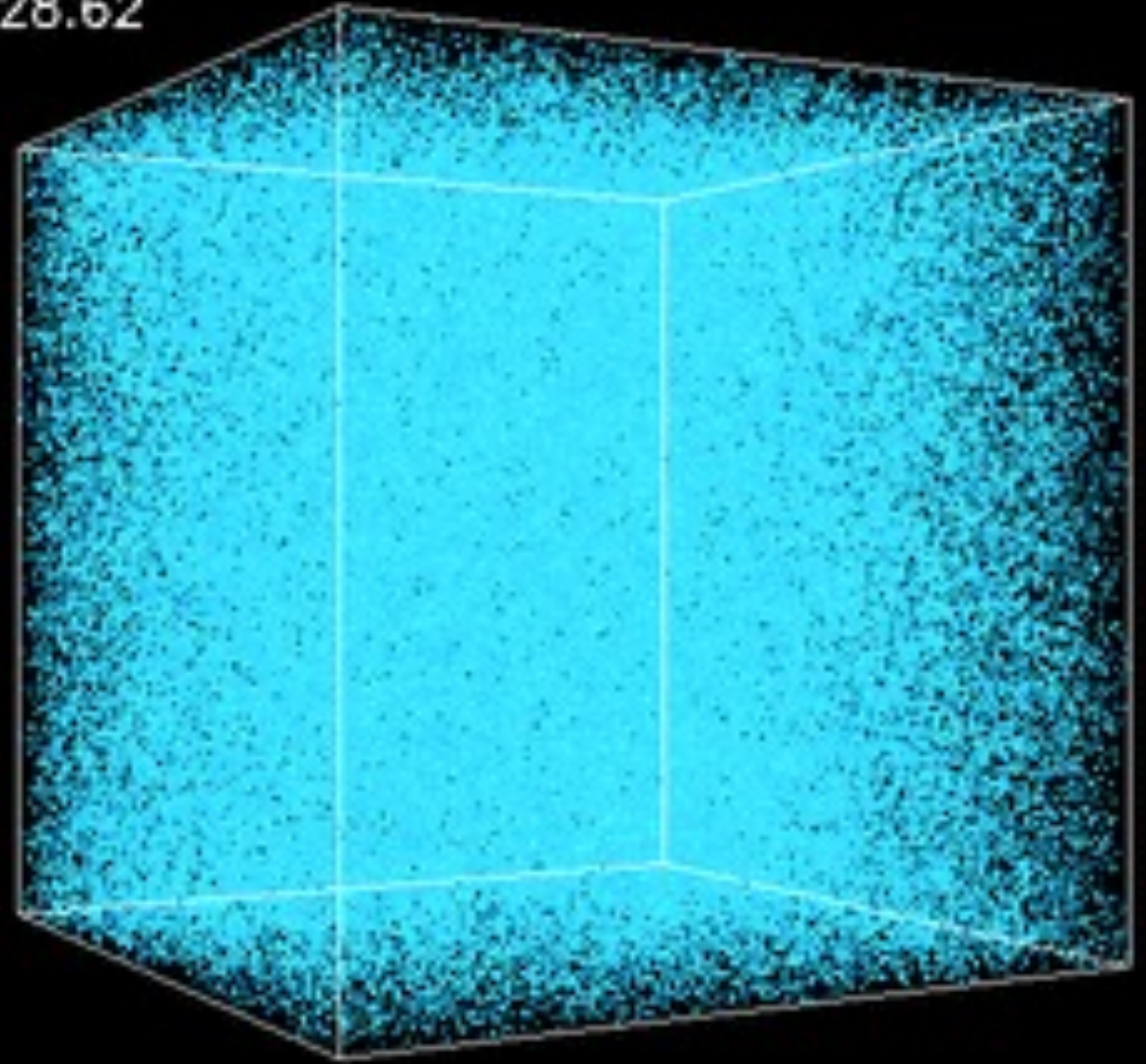
Acknowledgements: A. Kravstov, <http://cosmicweb.uchicago.edu/index.html>



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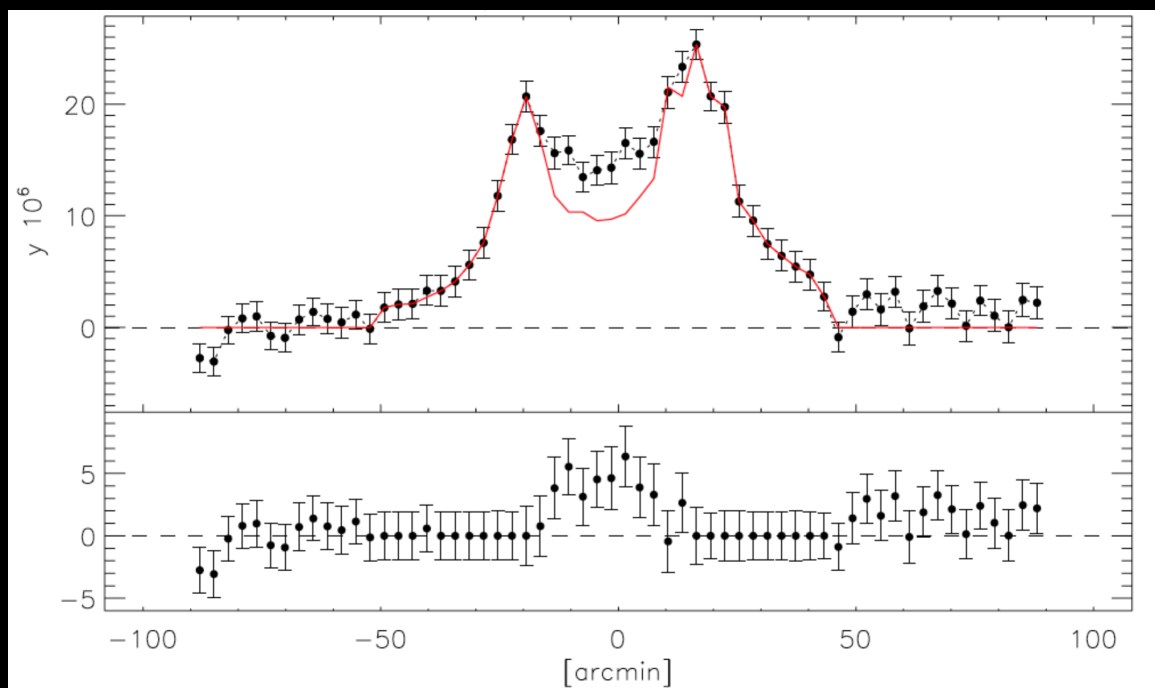
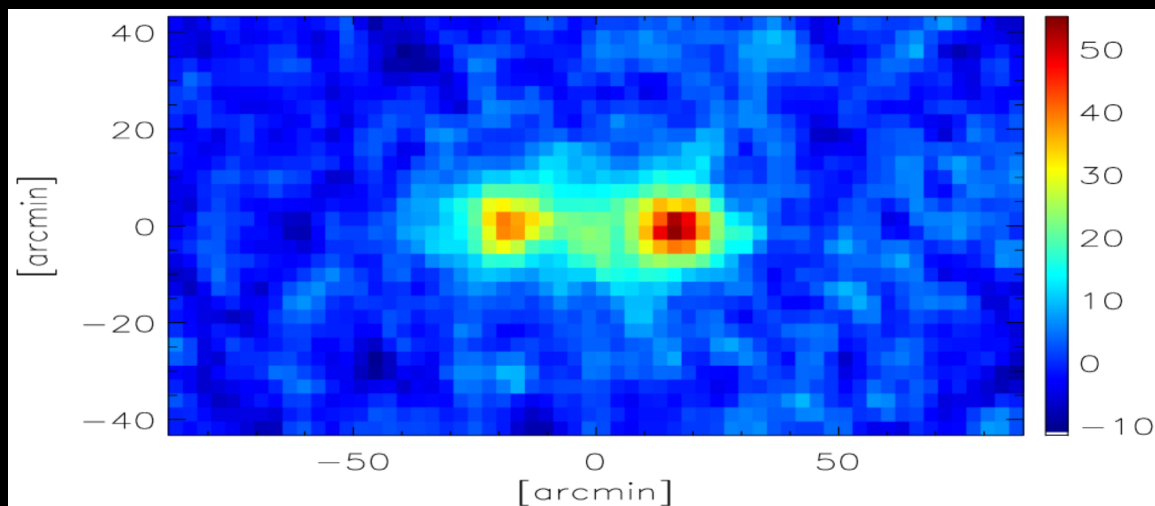
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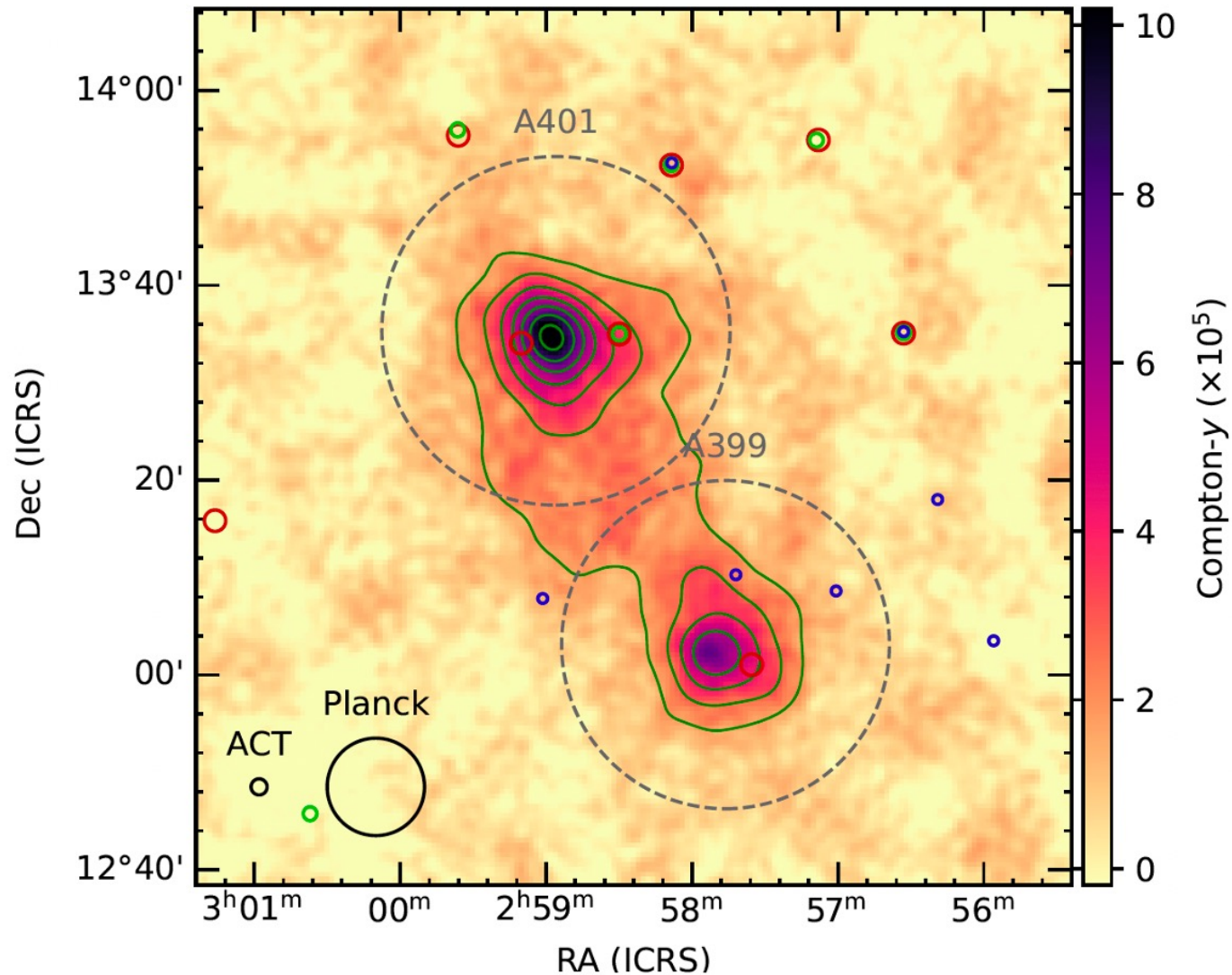
Abel 399 – Abel 401



- **A401-A399** (36'-3Mpc apart) studied with:
 - VLA, LOFAR in the radio (Murgia et al. 2010)
 - with XMM in the X-ray
 - with Planck in the mm
- Data foresee their **pre-merger state**, no cooling flow and nearly isothermal: relaxed cluster. Anything in between comes from the cosmic web
- **Planck tentatively** showed a bridge between them



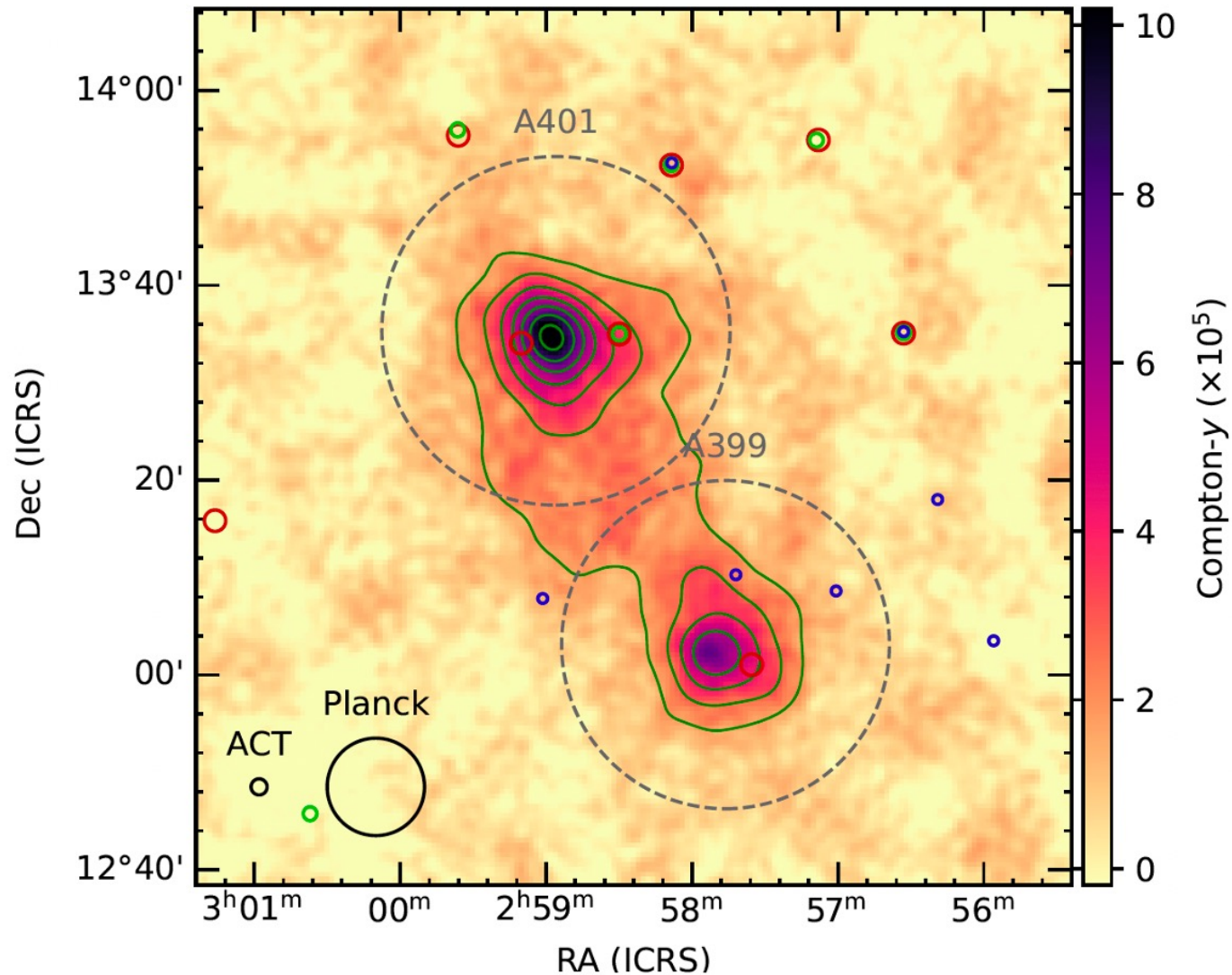
SHARPENING THE IMAGE: ACT



- Using ACT maps at 98, 150, and 220GHz
- 1.65' resolution
- → good fit with 5.5σ detection
- Total mass = $3.3 \pm 0.7 \cdot 10^{14} M_{\text{sun}}$
- Total separation = 12.1 ± 3.9 Mpc (vs 3.2Mpc in the sky)



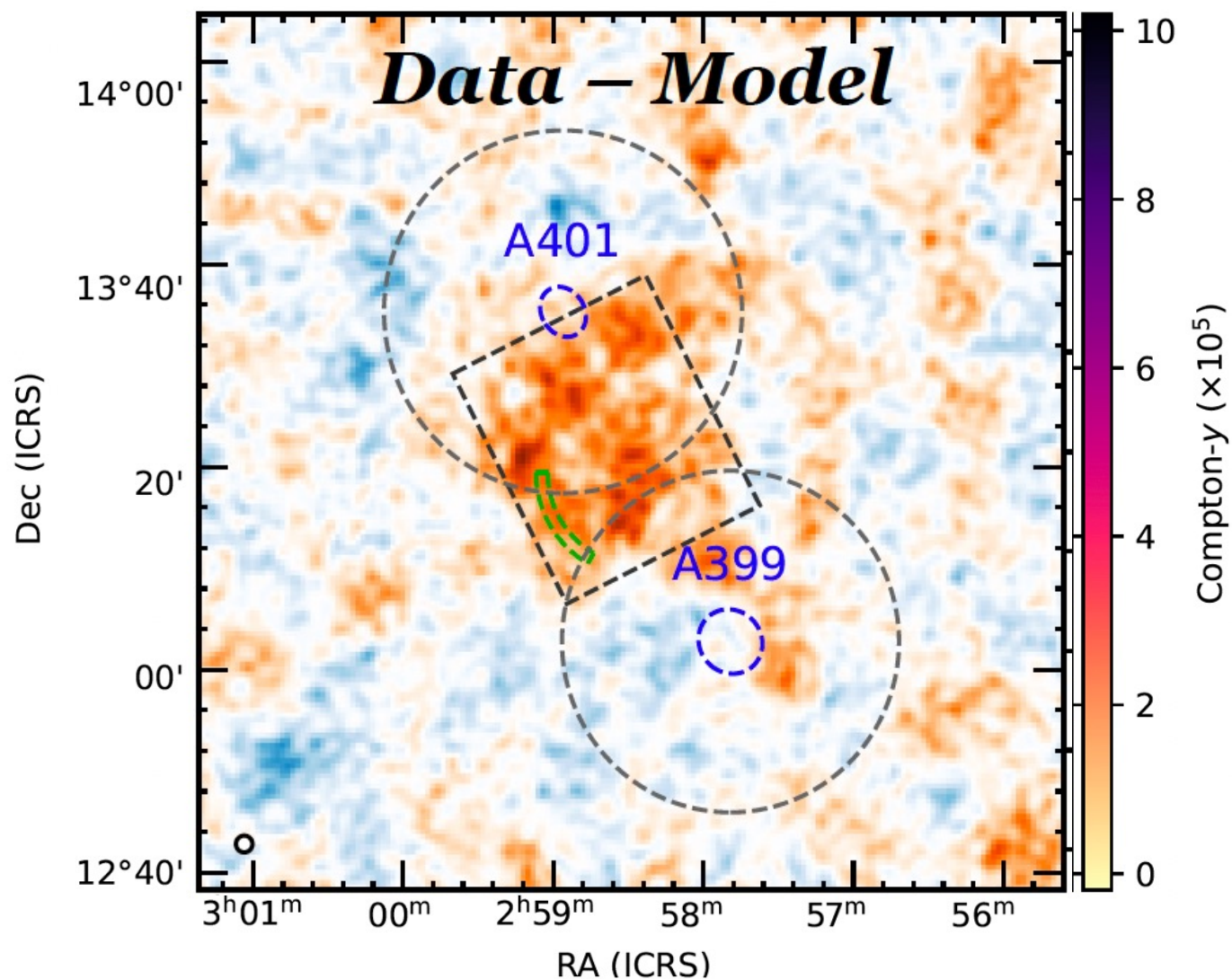
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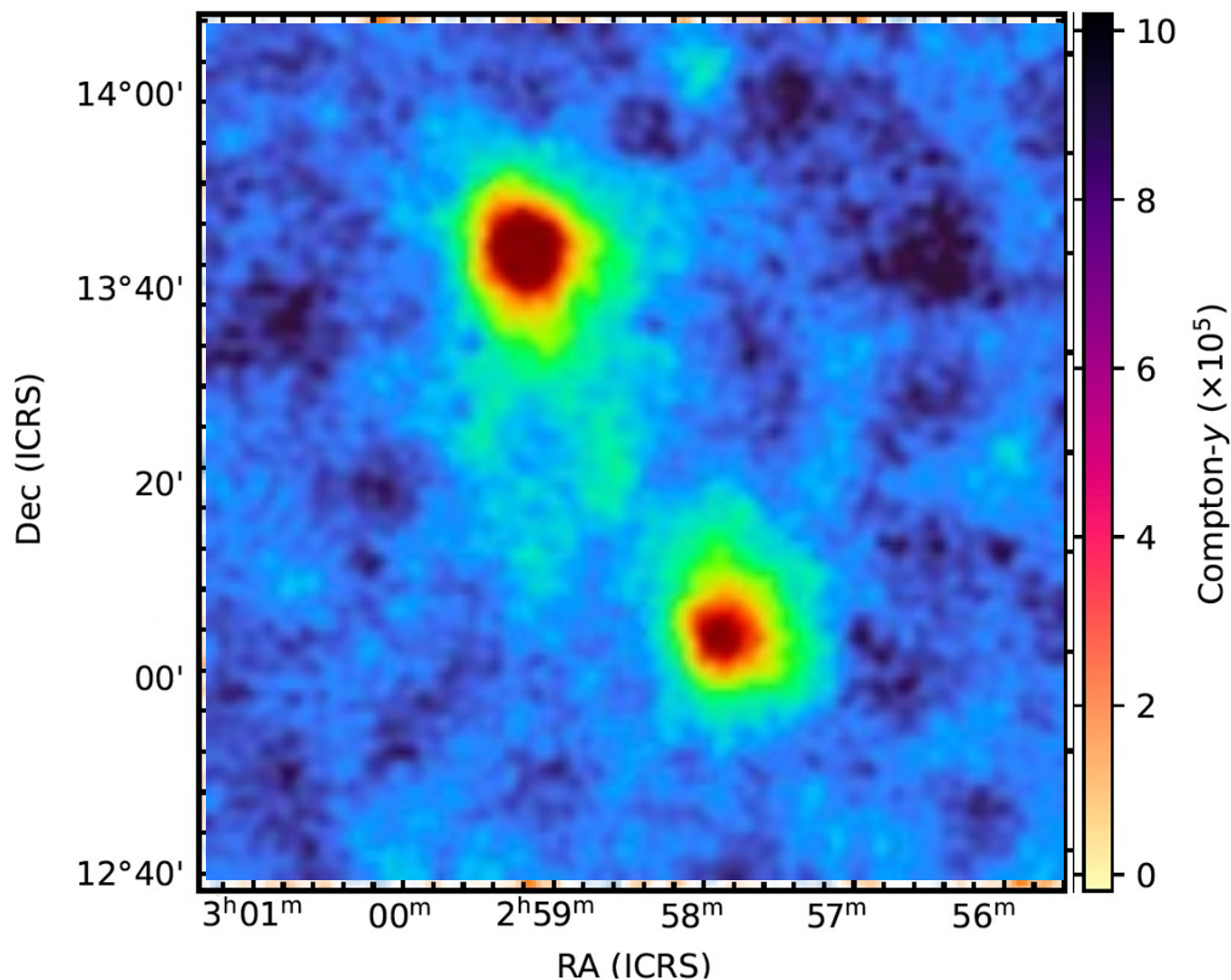
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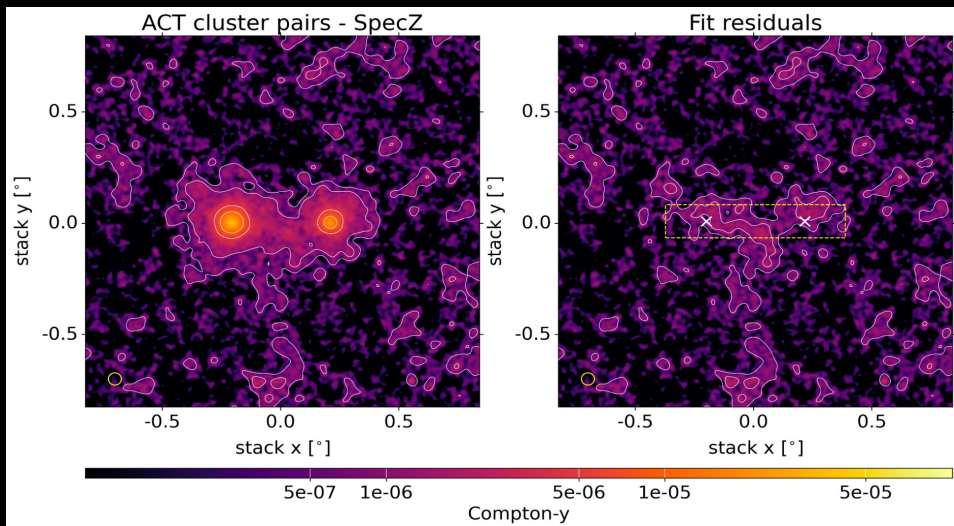
SHARPENING THE IMAGE: ACT



- **Re-observed** by Gill et al. 2026
- A new **multifrequency** approach enables simultaneous measurement of both the tSZ and kSZ and incorporates relativistic corrections
- 11 different frequencies from 30 GHz to 545 GHz. Our tSZ results are consistent with previous work
- We measure the line-of-sight peculiar velocities with uncertainties $\lesssim 600 \text{ km s}^{-1}$



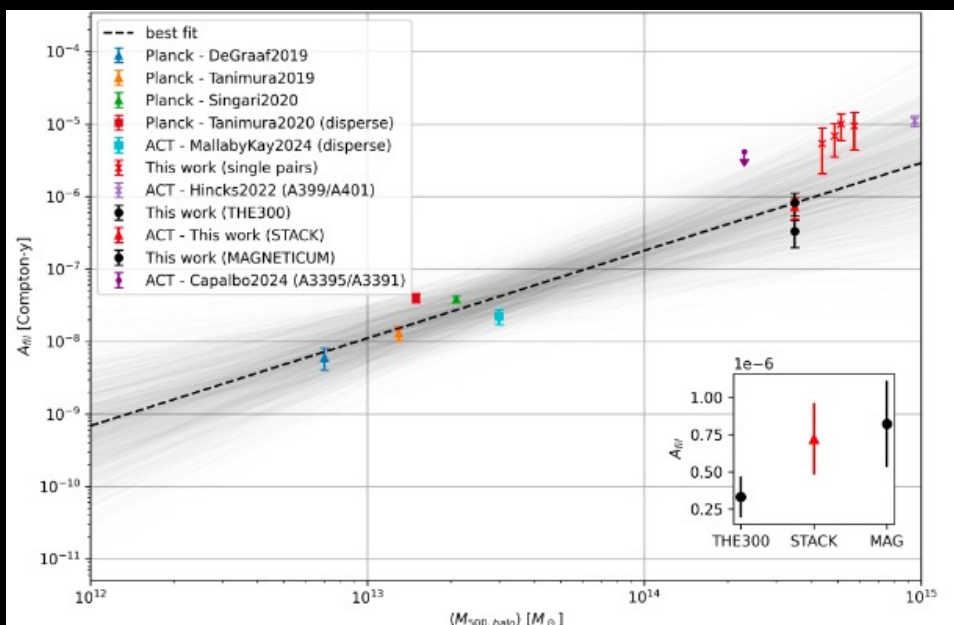
BRIDGE CENSUS



- We **stacked 86 pairs from the DR6** with spectroscopic redshift

- Images have been:

- Rotated
- Rescaled
- Aligned
- Averaged



- Result: **$y = (7.2^{+2.3}_{-2.5}) \times 10^{-7}$**

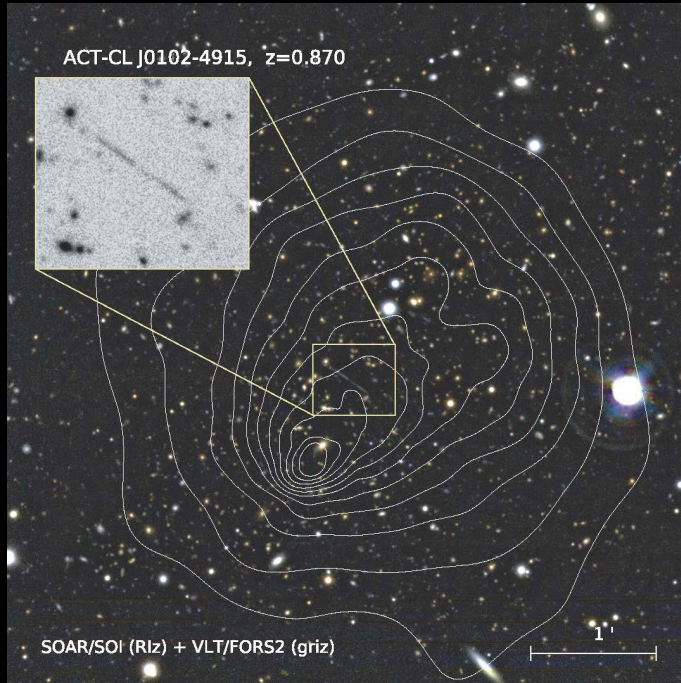
- Checked with THE300 simulation and with Magneticum Pathfinder

- It is the first measure through average mass clusters

$$\langle M_{500} \rangle \sim 3 \times 10^{14} M_{\odot}$$



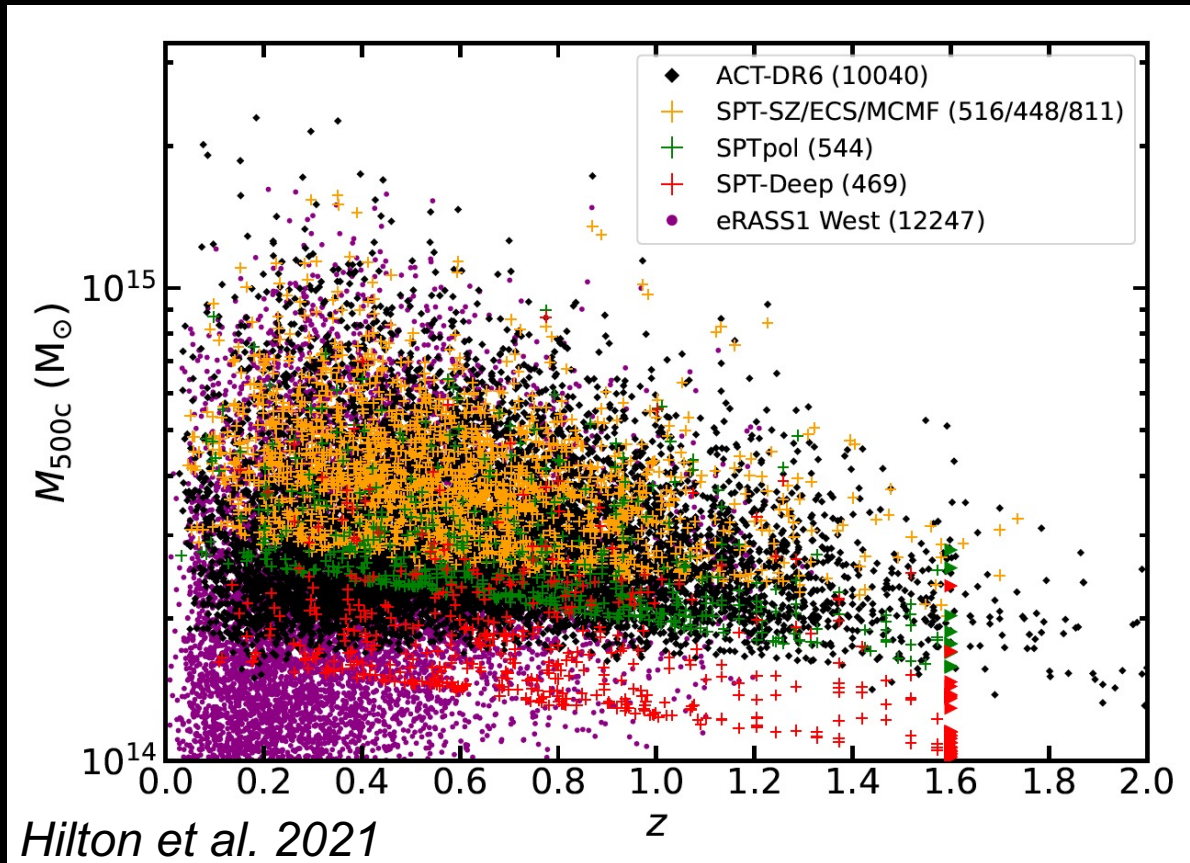
ACT-CL J0102-4915: **El Gordo**



- ACT discovered one of the **most extreme clusters** ever
- It is a high redshift $z = 0.87$ and very massive Cluster:
$$M_{200} \simeq 2.2 \times 10^{15} M_{\odot}$$
- A non relaxed one but two clusters interacting (a high redshift Bullet cluster)
- It was not found in X-ray or in optical but through the SZ
- In 2011 it was the most massive, hottest, and x-ray most luminous high redshift cluster challenging the structure formation
- $T_x \simeq 14.5$ keV with regions up to 22 keV
- **Even after DR6 no one similar to it**



SZ catalogues



- 2008-2012 tens of clusters on 755 deg² (Marriage et al. 2011)
- 2013: 68 cluster on 504 deg²
0.15 < z < 0.8
new cluster never observed before (Hasselfield et al. 2013)
- 2018: ACTPol 182 clusters on 988 deg² (Hilton et al. 2018)
- 2021: DR5, more than 4000 clusters in ~13000 deg² (Hilton et al. 2021)

- 2008-2022: 9977 clusters in 16293 deg² (ACT-DES-HSC Collaboration 2026)
 - 90% complete with mass $M_{500} > 5 \times 10^{14} M_{\odot}$
 - El Gordo remains unique

*Bleem et al. 2026 just released
SPR3G 8000 GC catalogue*



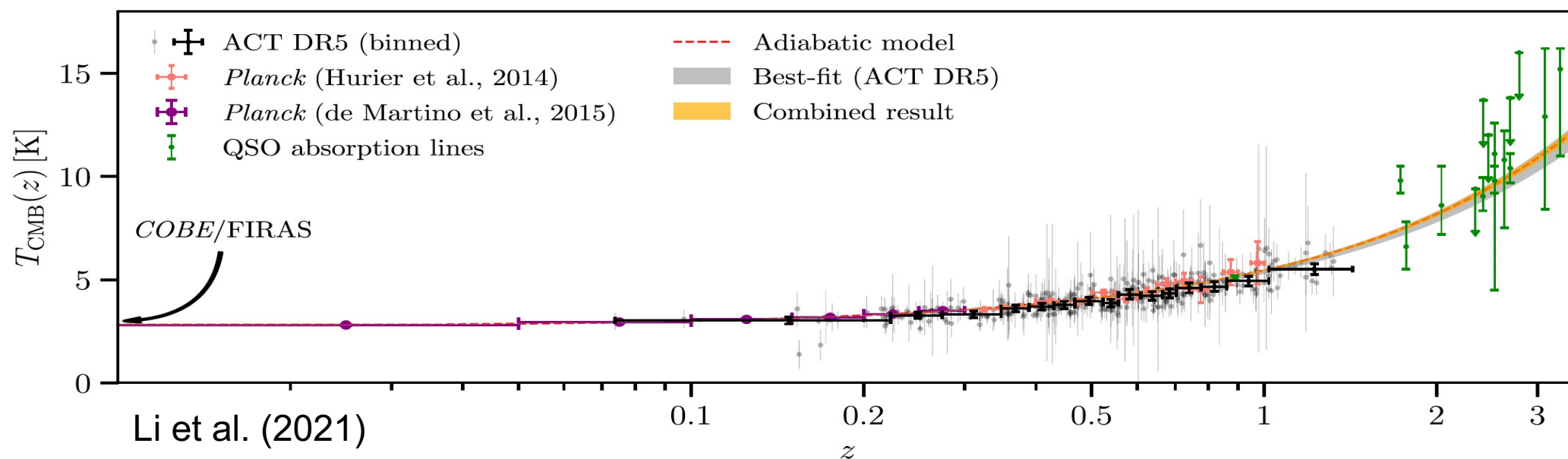
$T_{\text{CMB}}(z)$ vs z

- Battistelli et al. (2002) **first demonstration** of the possibility to measure $T_{\text{CMB}}(z)$ vs z from the SZ on Coma and A2163 from MITO and SuZie
- Luzzi et al. (2009), *ApJ*, first statistical constraint on parameter α .
- Li et al. (2021), with ACT set the best constraint on $\alpha=0.017-0.032+0.029$ (ACT+Planck $\alpha=-0.001\pm0.012$)**

Leverage on the z -dependence of the SZ spectrum

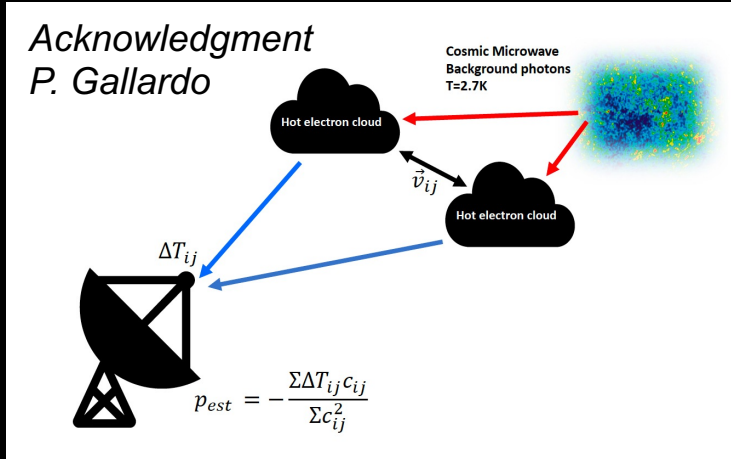
$$x = \frac{h\nu}{k_B T_{\text{CMB}}}$$

$$T_{\text{CMB}}(z) = T_0(1+z)^{1-\alpha}$$

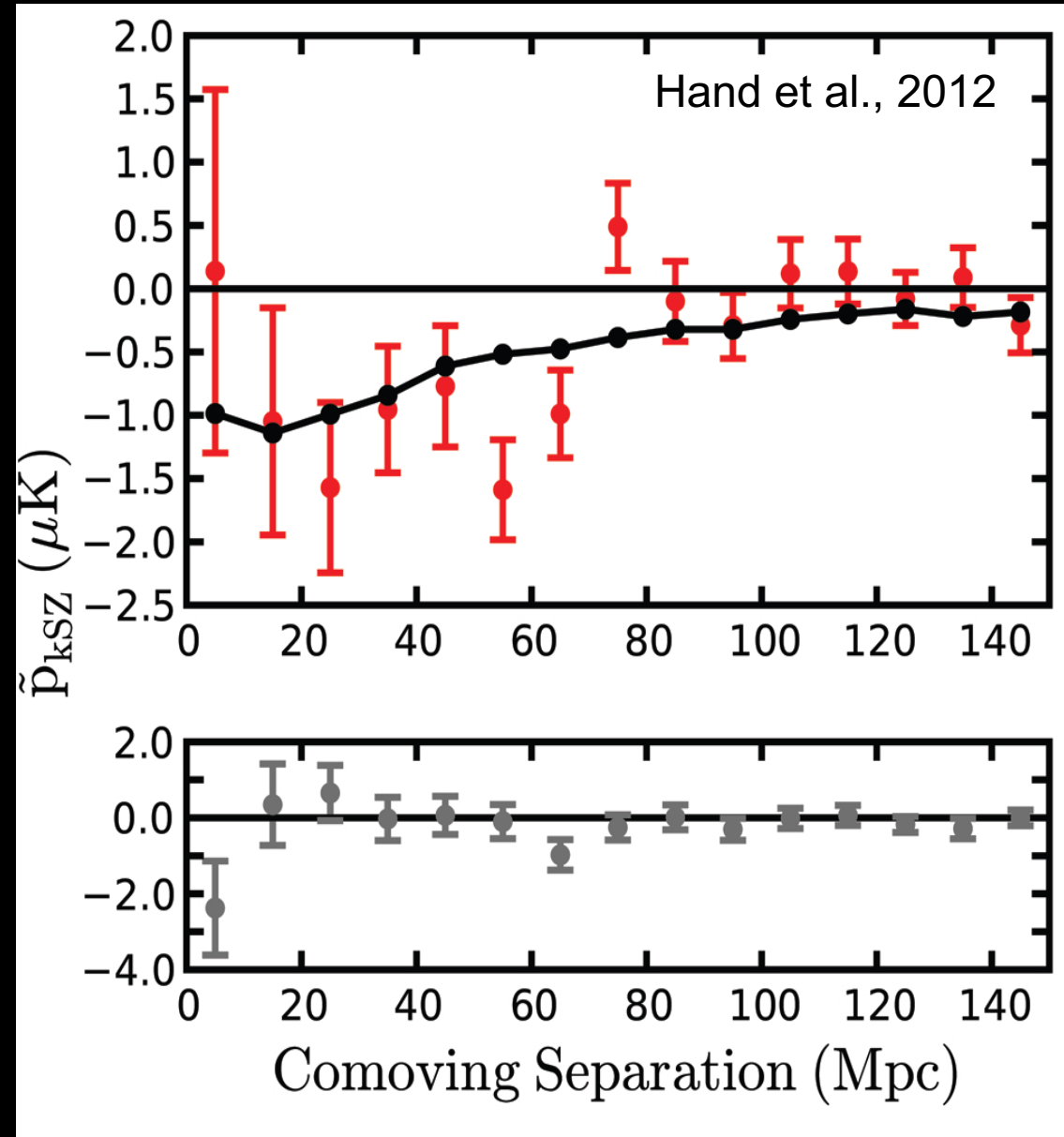




kSZ



- First pairwise detection of clusters motion
- 27000 Red Luminous galaxies from BOSS: 3σ detection of kSZ (Hand et al., 2012)
- Calafut et al. 2021 used DR5 with 343,647 galaxies from SDSS
- Gallardo et al. 2026 used to test gravitation...see Gallardo's talk!





FUTURE (PRESENT): SIMONS OBSERVATORY



- 3 SAT (nominal + 3 from UK and Japan) with large detector count (~60,000 detectors);
- 1 LAT with (~30,000 TES bolometers);
- Broad frequency coverage (27–280 GHz);
- Polarization optimized;
- Large overlap with Rubin, DESI, Euclid and Roman



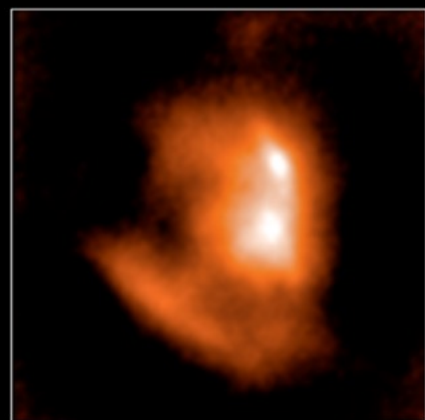
FUTURE (PRESENT): MISTRAL



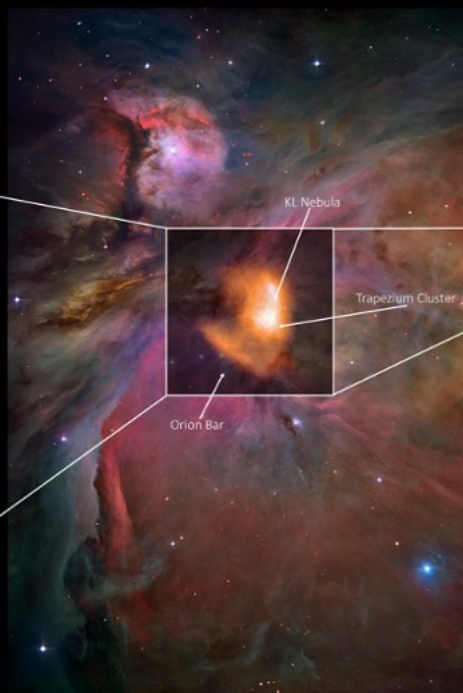
**MILLIMETER
SARDINIA RADIO
TELESCOPE
RECEIVER BASED ON
ARRAY OF
LUMPED ELEMENTS
KIDS**

- **Kinetic Inductance Detectors** developed in Rome
- **Dedicated Optics** with Silicon Lenses and Lyot stop (custom SRT)
- Careful designed **cryogenics** (can handle telescope movement)
- **First light** in 2025...more following including Galaxy Clusters!

The first light of MISTRAL
Millimeter Sardinia radio Telescope Receiver
based on Array of Lumped Elements KIDs



90 GHz image of the core of the Orion nebula as seen by MISTRAL



Combination of an optical image from the Hubble Space Telescope and MISTRAL



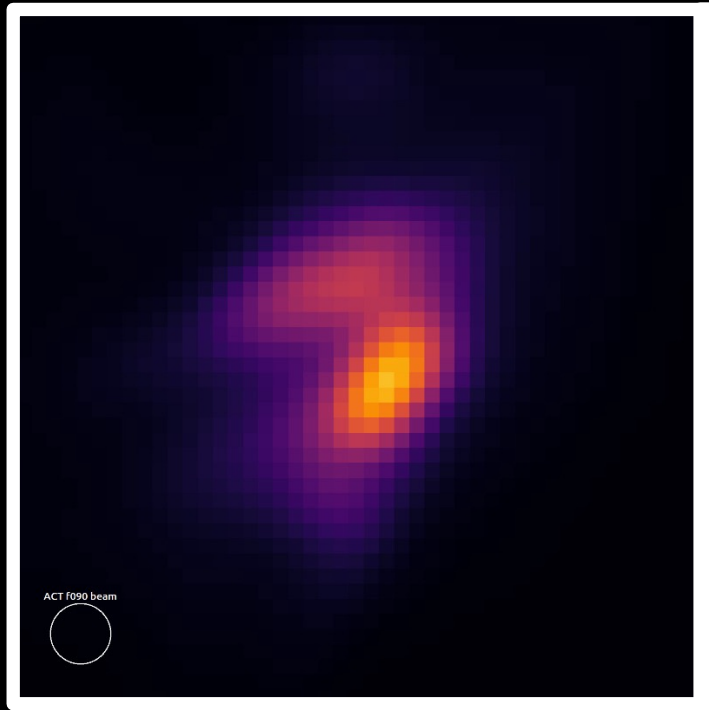
The Sardinia Radio Telescope while scanning the Orion Nebula



MISTRAL installed in the gregorian room of SRT and its detector array during fabrication



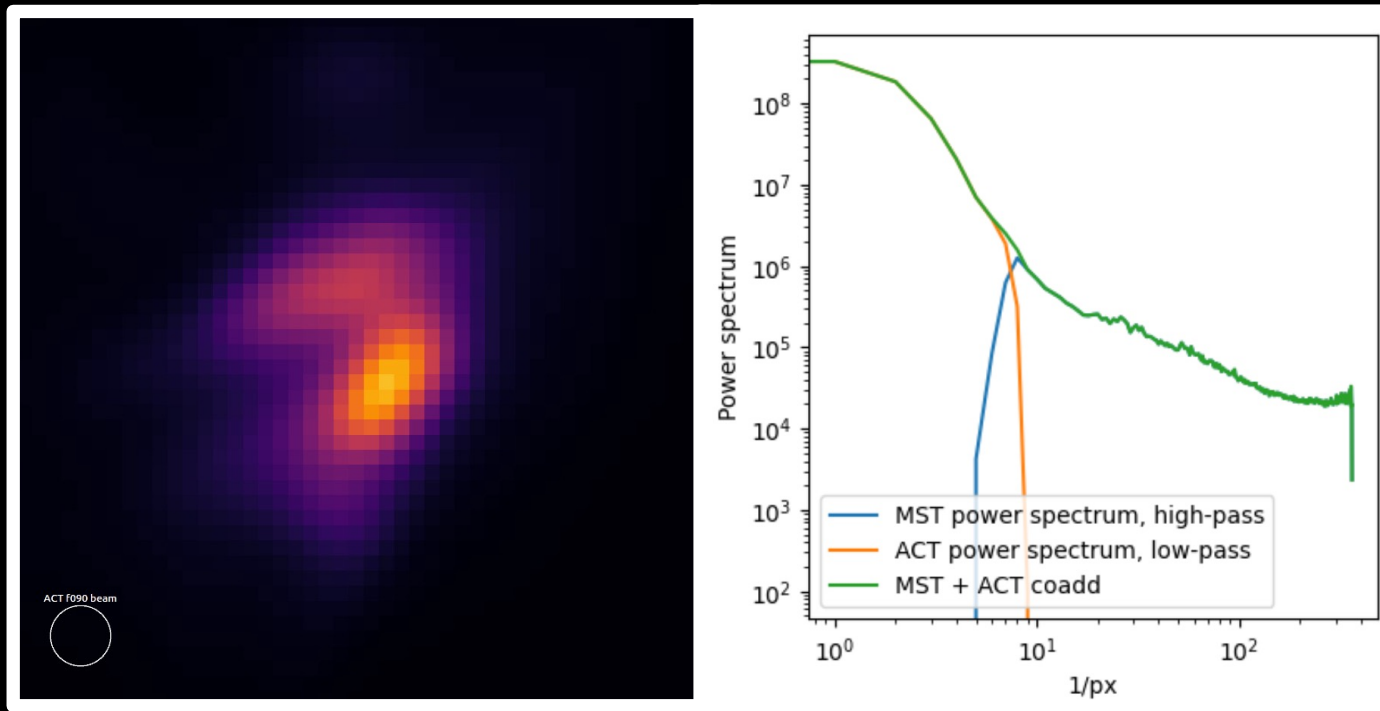
MISTRAL + ACT IN OMEGA NEBULA



ACT 90GHz



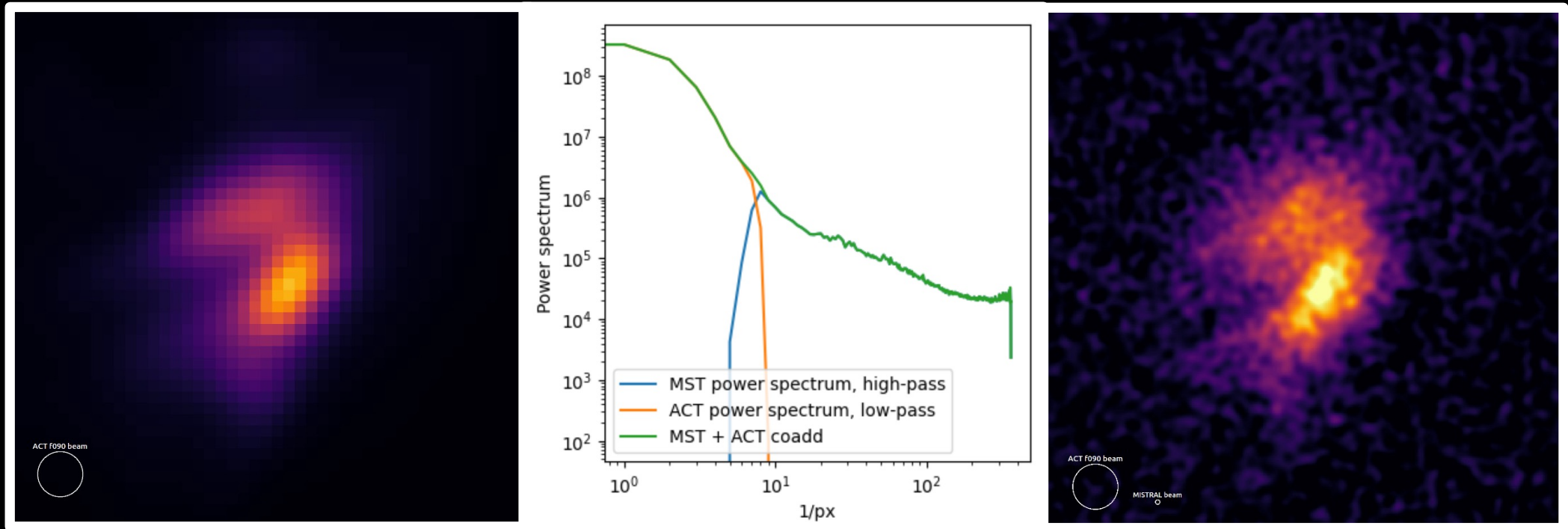
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MISTRAL + ACT IN OMEGA NEBULA

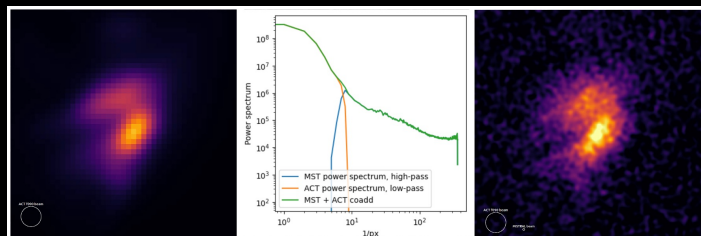
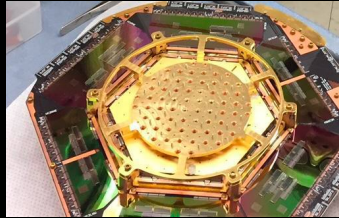
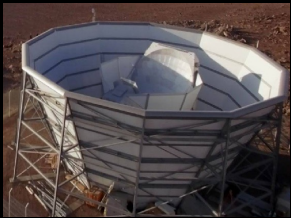
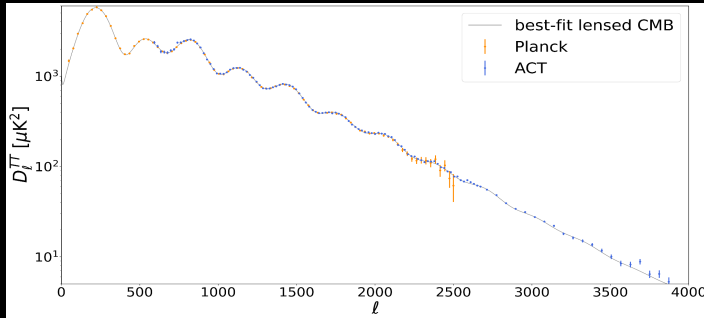


ACT 90GHz

MISTRAL+ACT 90GHz



CONCLUSIONS



- **ACT** was designed to map a large fraction of the sky deeply enough that the measurements become **limited by the sky itself** rather than by the instrument
- ACT measured cosmological parameters to the state of the art: its findings are largely **consistent** with **Λ CDM model**
- Furthermore, it has been a laboratory where **new techniques** were born and **young scientists** were formed, working on the heart of modern cosmology ...including SO
- **Simons Observatory** now collects this expertise and legacy extending sensitivity and sky coverage
- Furthermore, **MISTRAL** (and MUSTANG2) can go to the fine angular scales...a **unique possibility** that only for ground based telescopes can achieve



GENERATIONS

From the social/anthropological point of view...were born in:

- 1928-1945: Silent
- 1946-1964: Baby boomers
- 1965-1980: Gen X
- 1981-1996: Millennials
- 1997-2012: Gen Z
- 2013-2024: Gen alpha



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THANK YOU!