Map-Making and Beams for the Atacama Cosmology Telescope

Emilie Storer

Princeton University

Photo credit: Debra Kellner

ACT: Atacama Cosmology Telescope

- 6 m off-axis Gregorian telescope in Northern Chile (5200 m elevation)
- operating since 2007
- arcminute resolution
- now on our 3rd generation of detectors
- observe at 30, 40, 98, 150, 230 GHz

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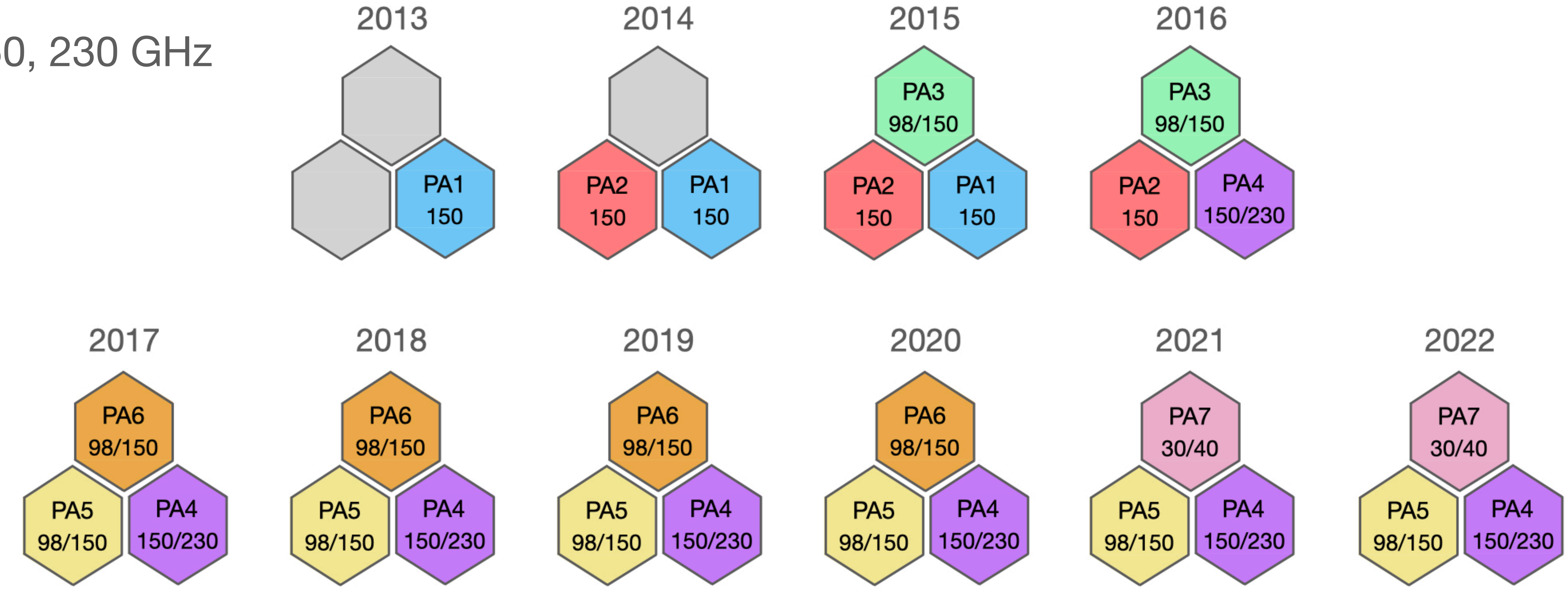
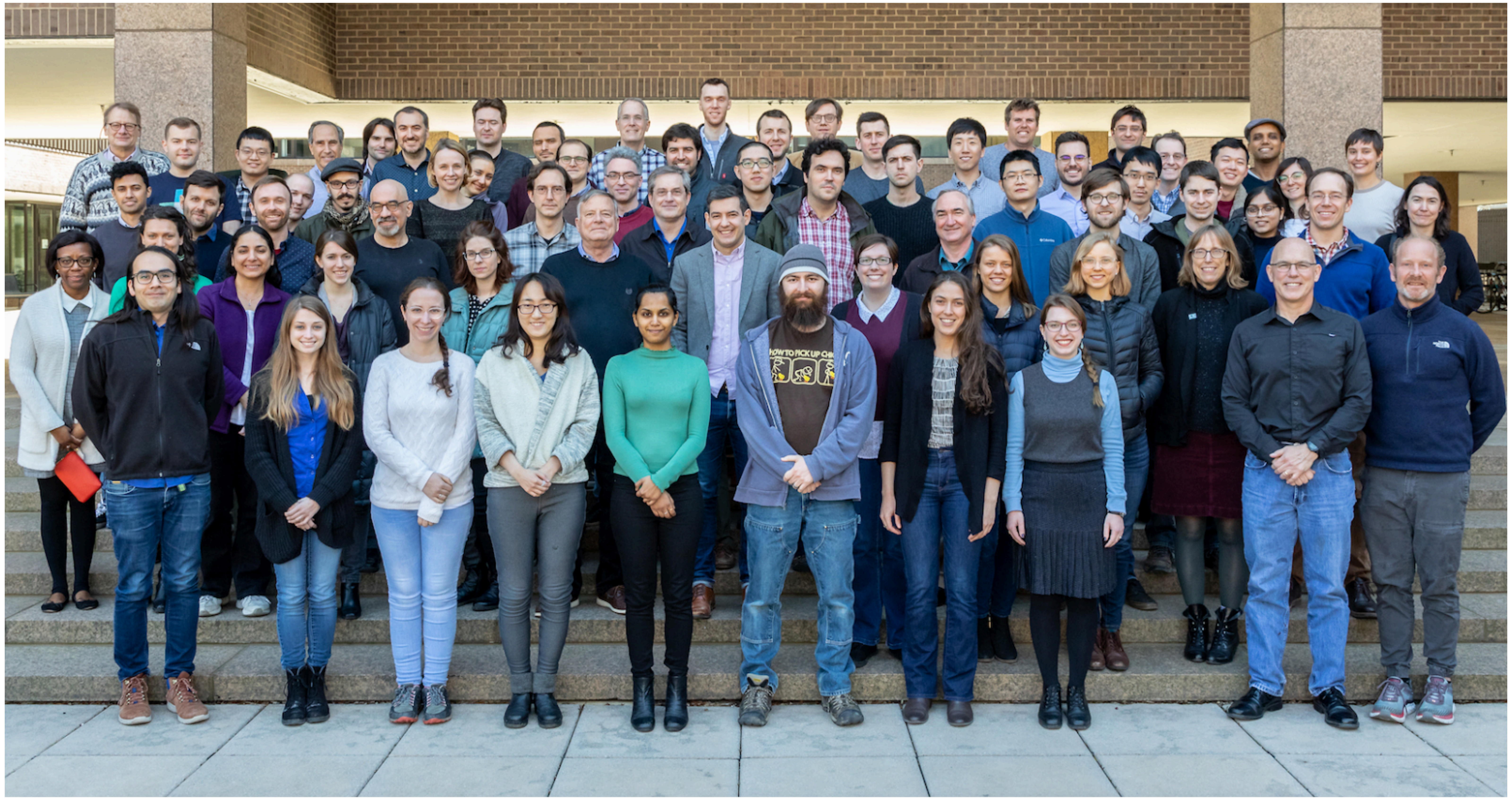


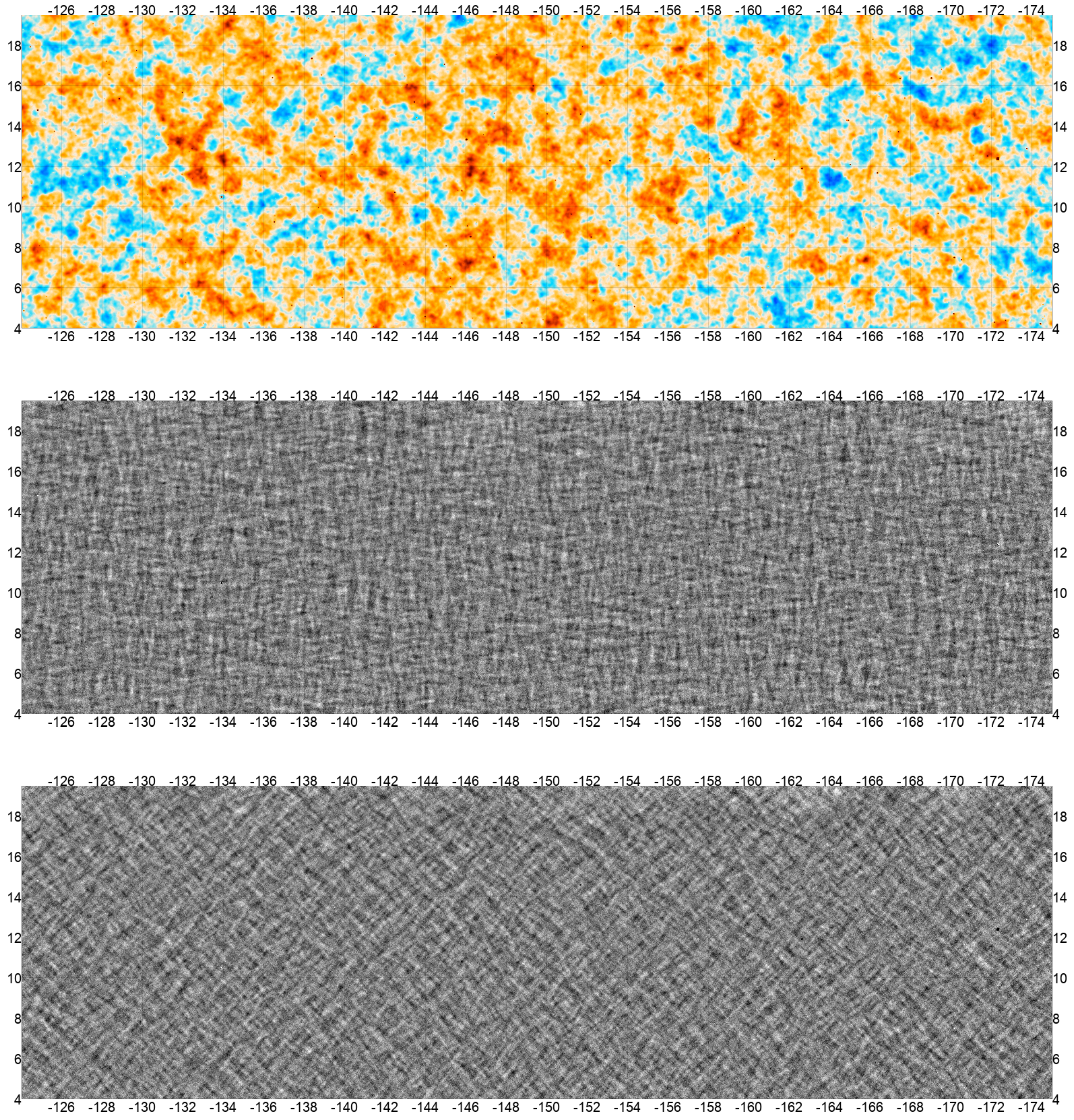
ACT Collaboration



PI: Suzanne Staggs
Deputy director: Mark Devlin

Map-Making

- Maximum-likelihood mapmaking
- Computationally intensive
- Solve for best-fit sky map given measured data and noise (I, Q, U simultaneously)
- Use a preconditioned conjugate gradient algorithm



Naess et al. 2020 (arXiv: 2007.07290)

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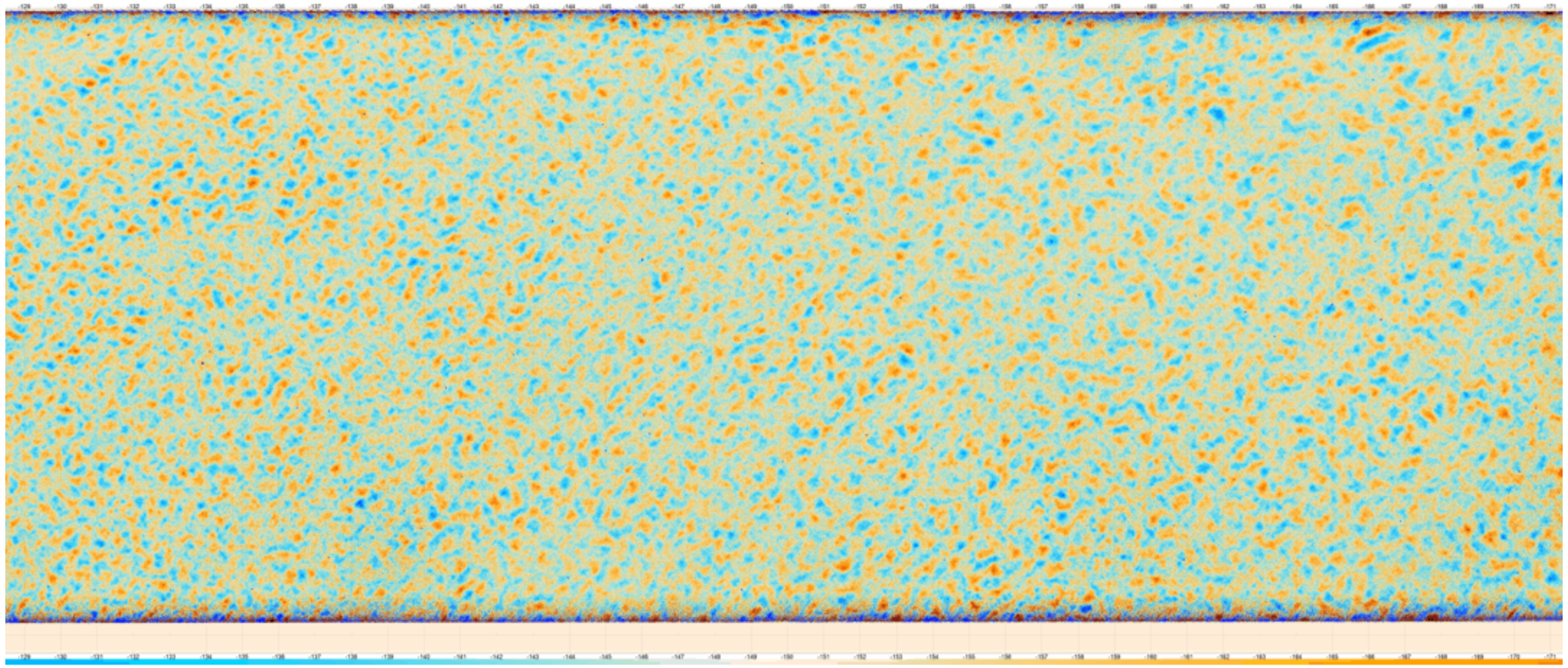
CG steps: 50



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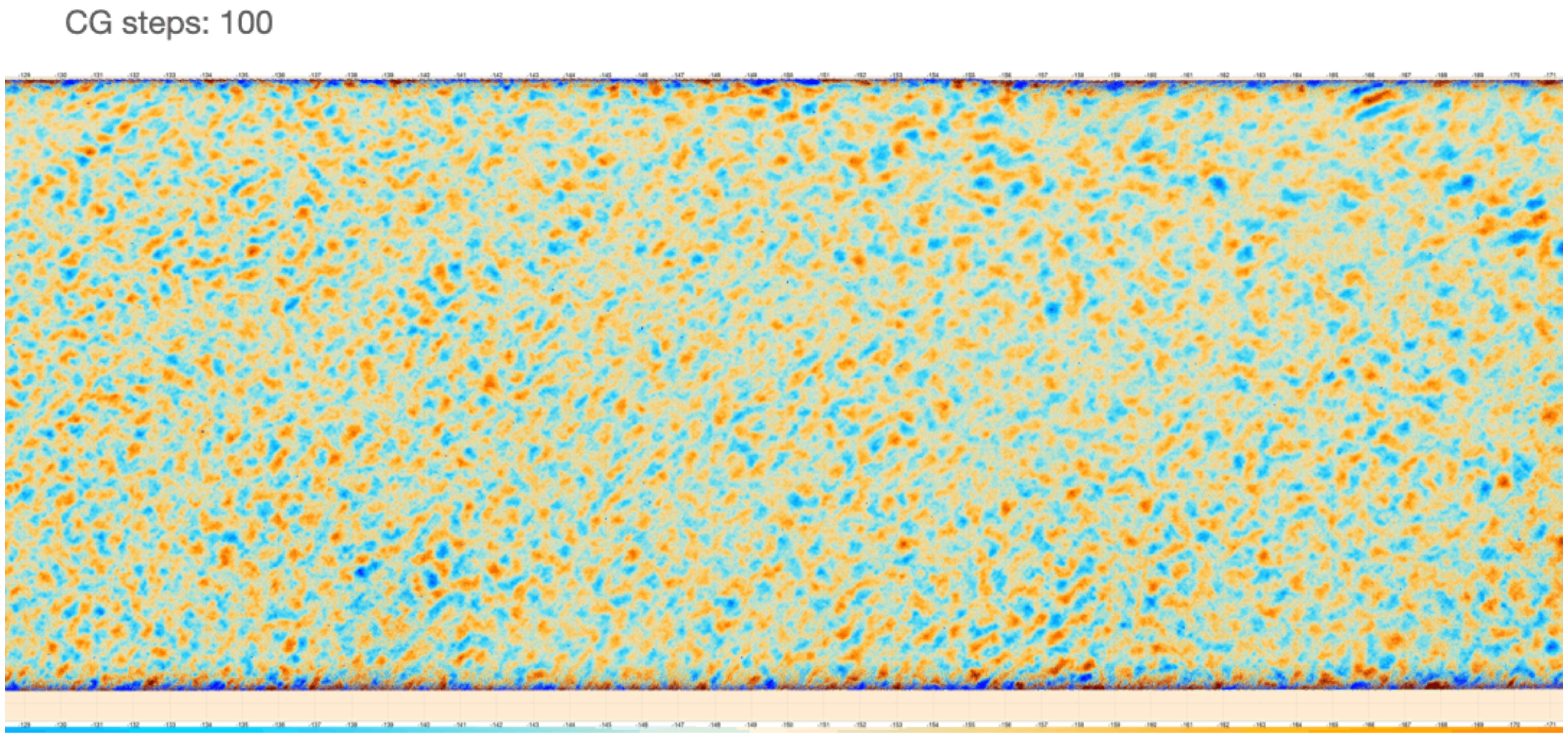

Map-Making

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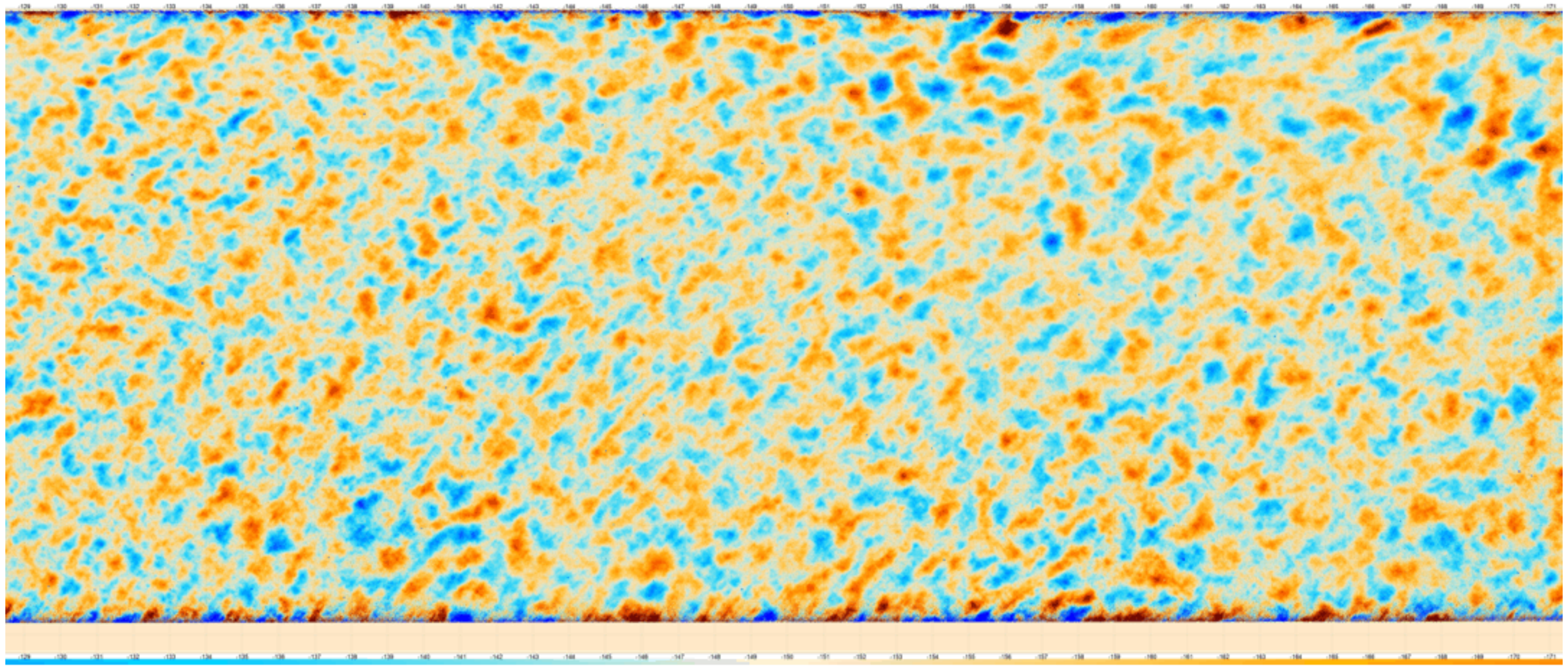
CG steps: 300



Map-Making

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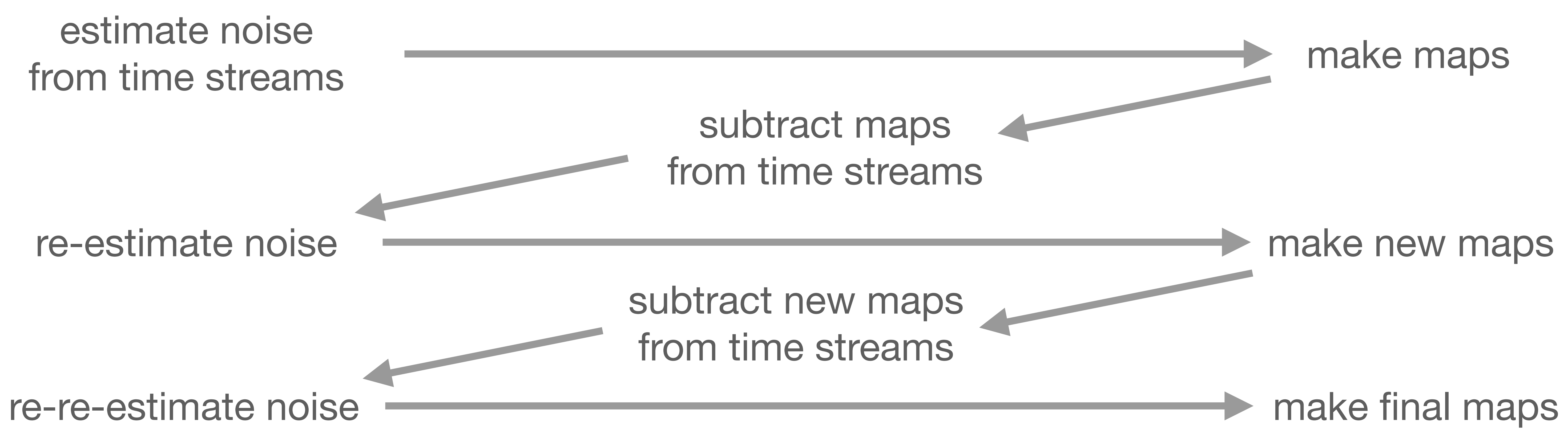
- Solve for best-fit sky map given measured data and noise (I, Q, U simultaneously)
- Use a preconditioned conjugate gradient algorithm
- To avoid signal-induced bias, subtract estimate of sky signal from data before estimating noise
- Run through 3 passes of the map-maker:



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- Brightest point sources receive special treatment (added degrees of freedom) to avoid propagation of model errors (bias) along scanning direction for one noise correlation length

Maps

DR4

- publicly available (LAMBDA)
- data through 2016
- several maps (splits with uncorrelated noise, simulations, lensing, CMB+kSZ, Compton-y)
- cosmological likelihood for CMB power spectra

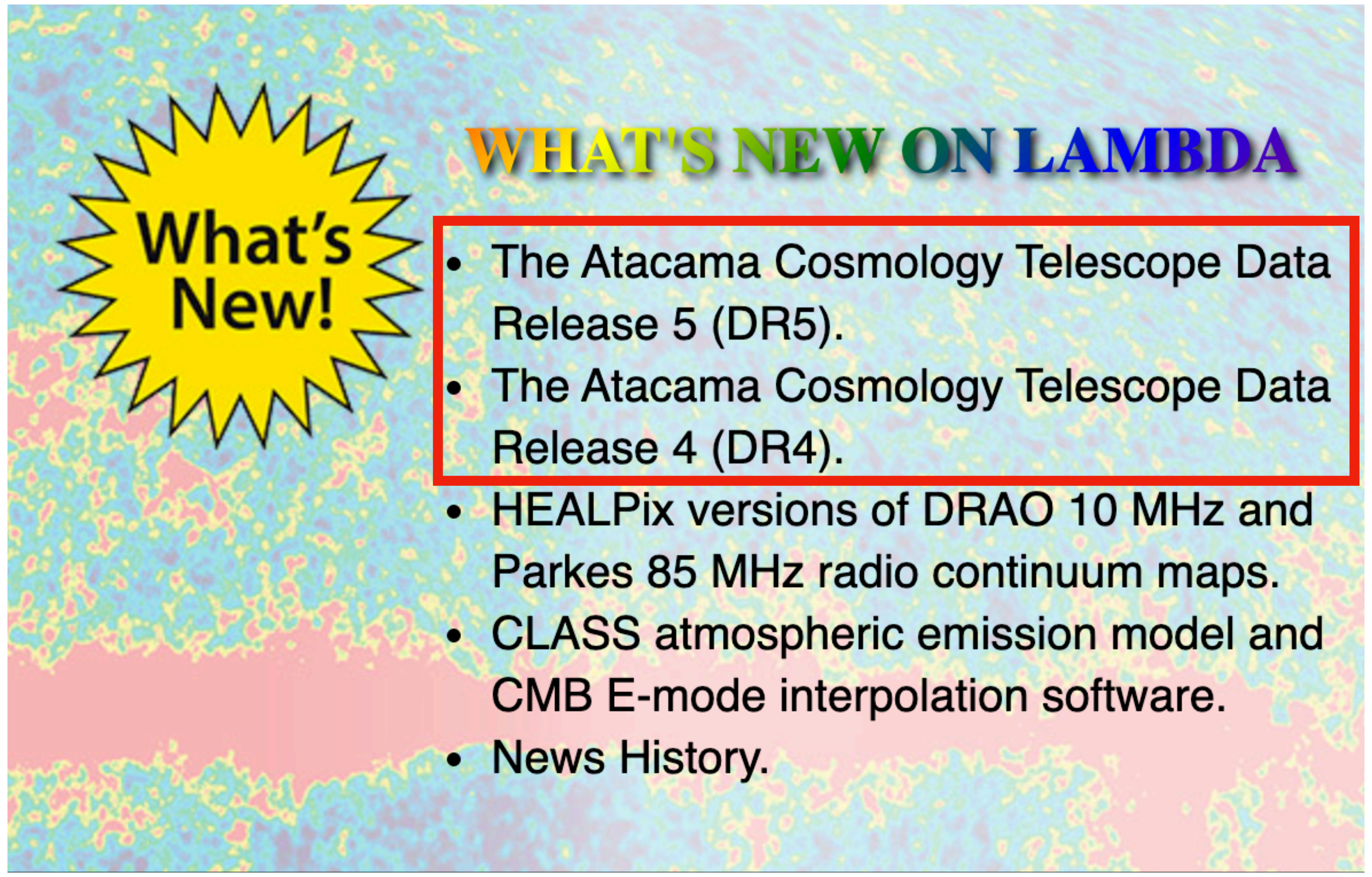
DR5

- publicly available (LAMBDA)
- data through 2018
- single co-added map at each frequency
- catalog of ~4000 SZ clusters
- not for precision cosmology

DR6

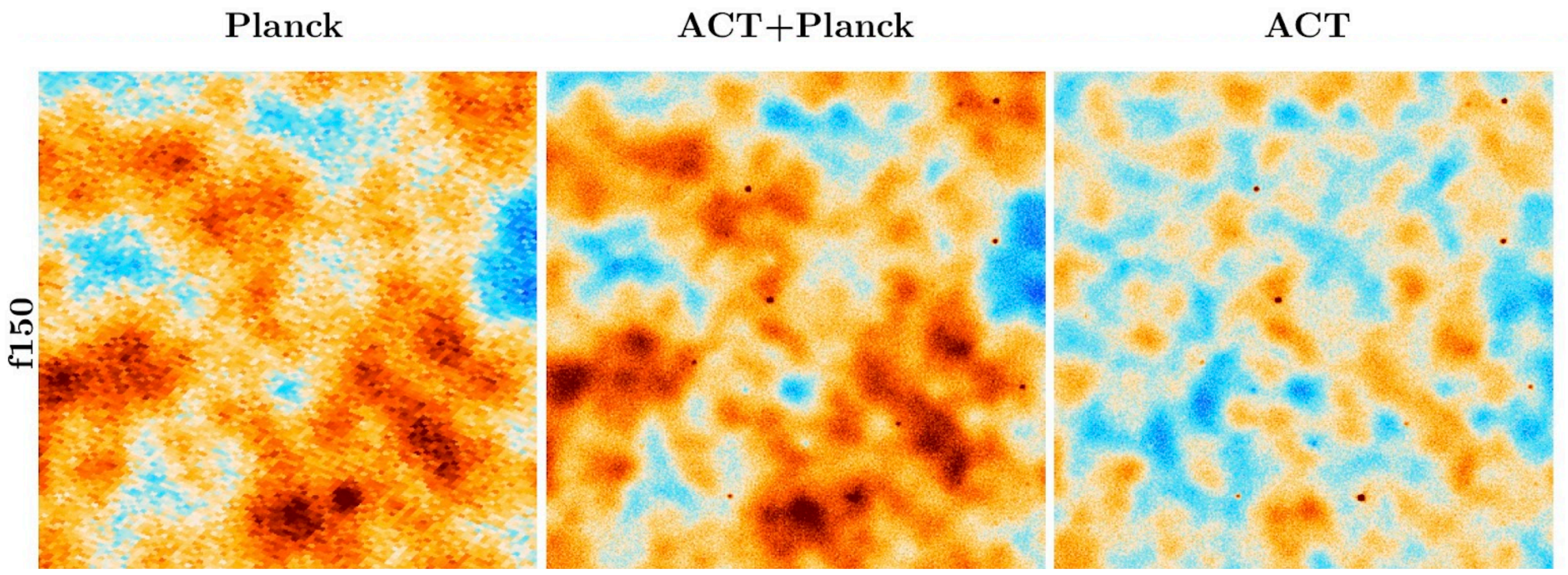
- work in progress
- data from 2017 - 2021

Legacy Archive for Microwave Background Data Analysis

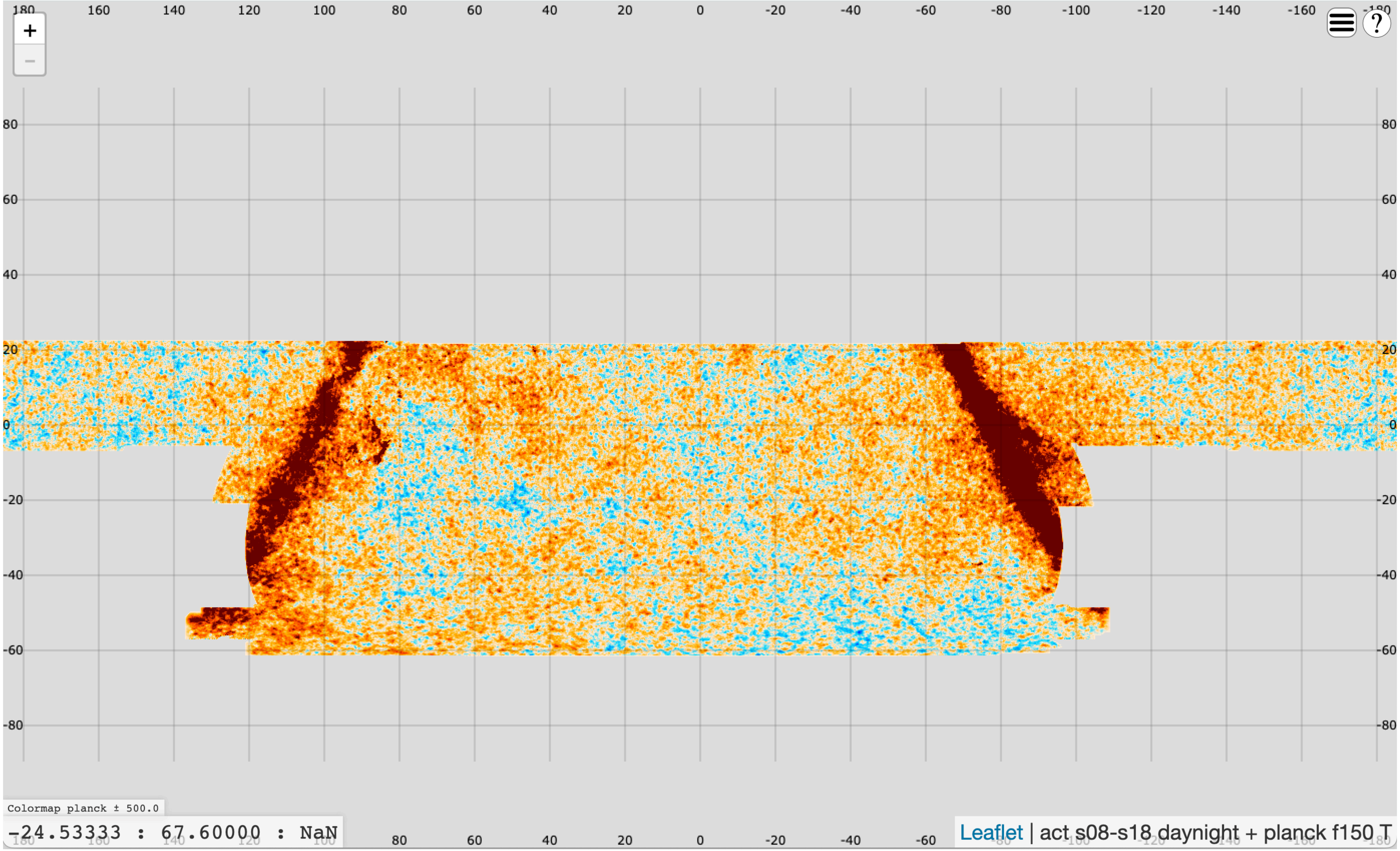


DR5 Maps

- publicly available (LAMBDA)
- data through 2018
- single co-added map at each frequency
- catalog of ~4000 SZ clusters
- not for precision cosmology
- data on ~ 18,000 deg^2
- co-added maps of ACT + Planck
- viewable in ACT web atlas (link on LAMBDA)



Naess et al. 2020 (arXiv: 2007.07290)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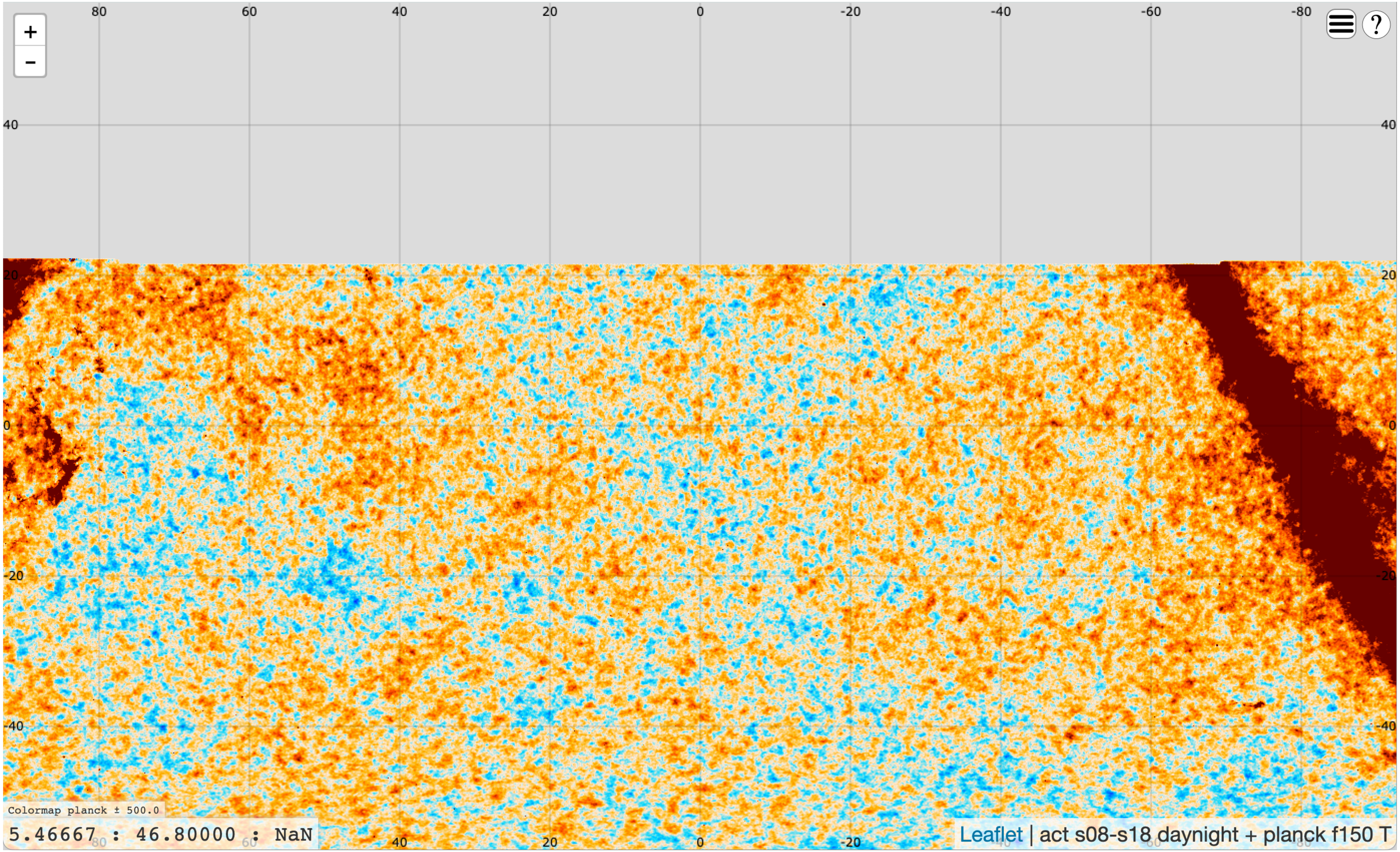
-24.53333 : 67.60000 : NaN
Leaflet | act s08-s18 daynight + planck f150 T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Colormap planck ± 500.0
5.46667 : 46.80000 : NaN
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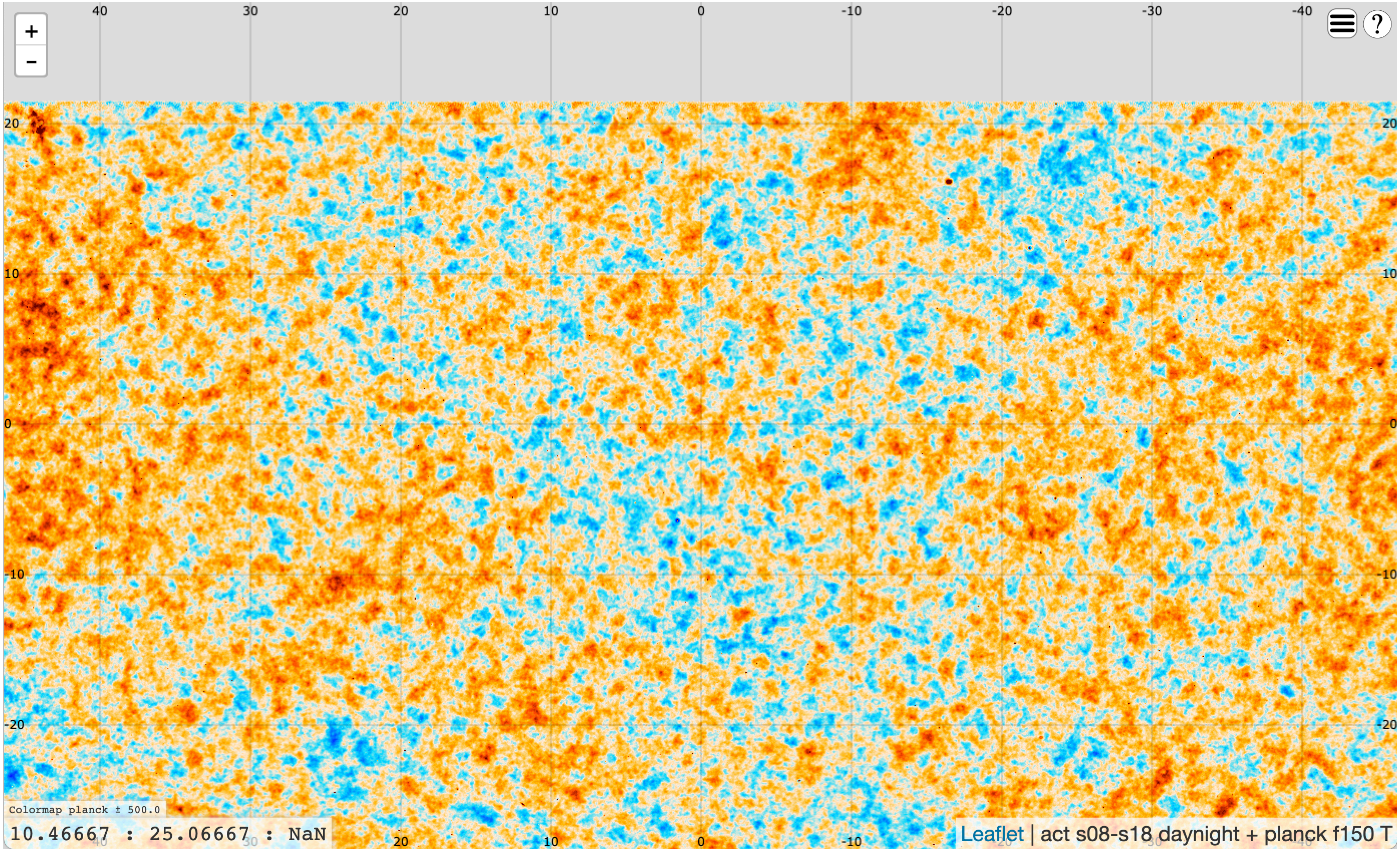
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10.46667 : 25.06667 : NaN
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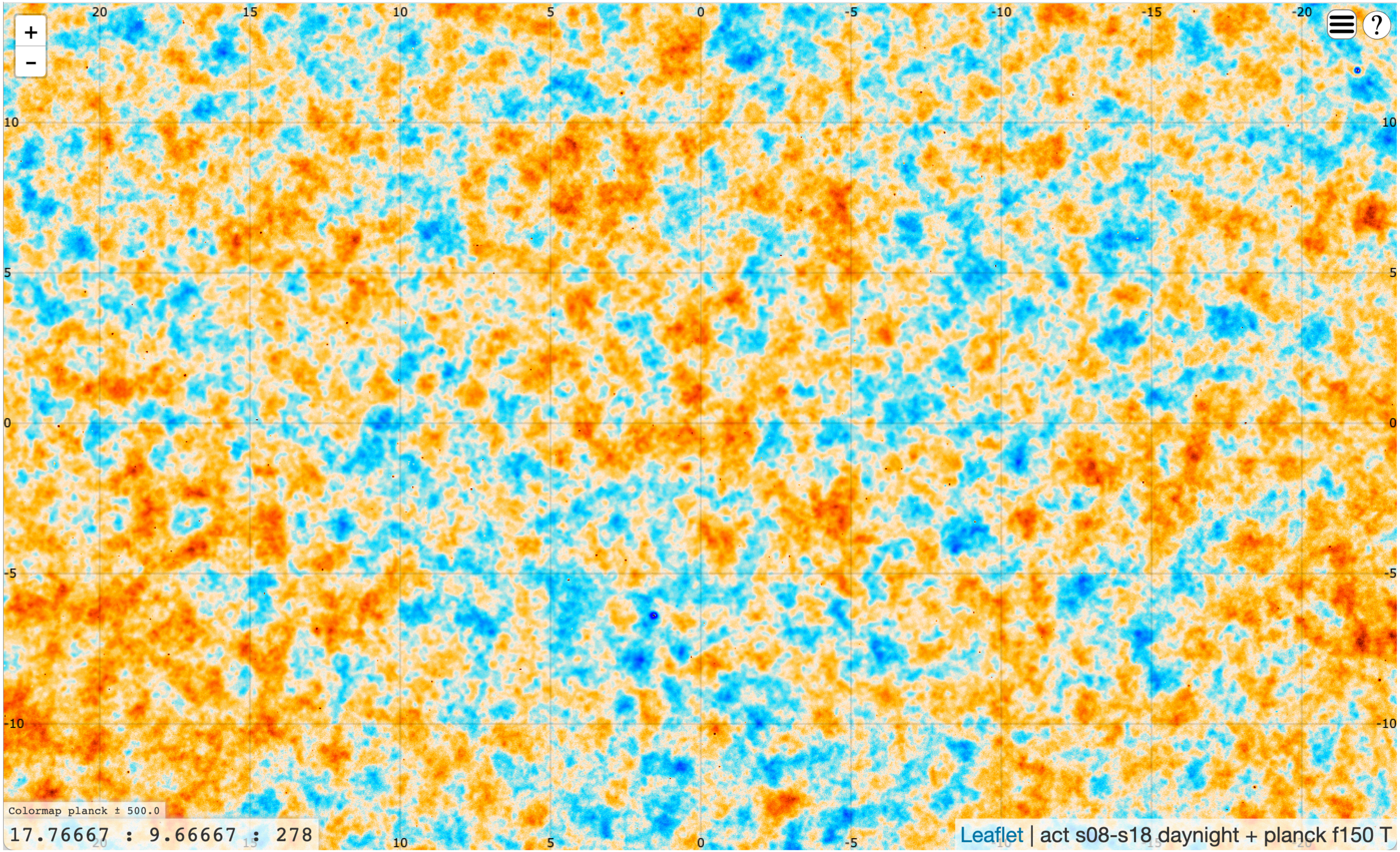

Colormap planck ± 500.0
17.76667 : 9.66667 : 278
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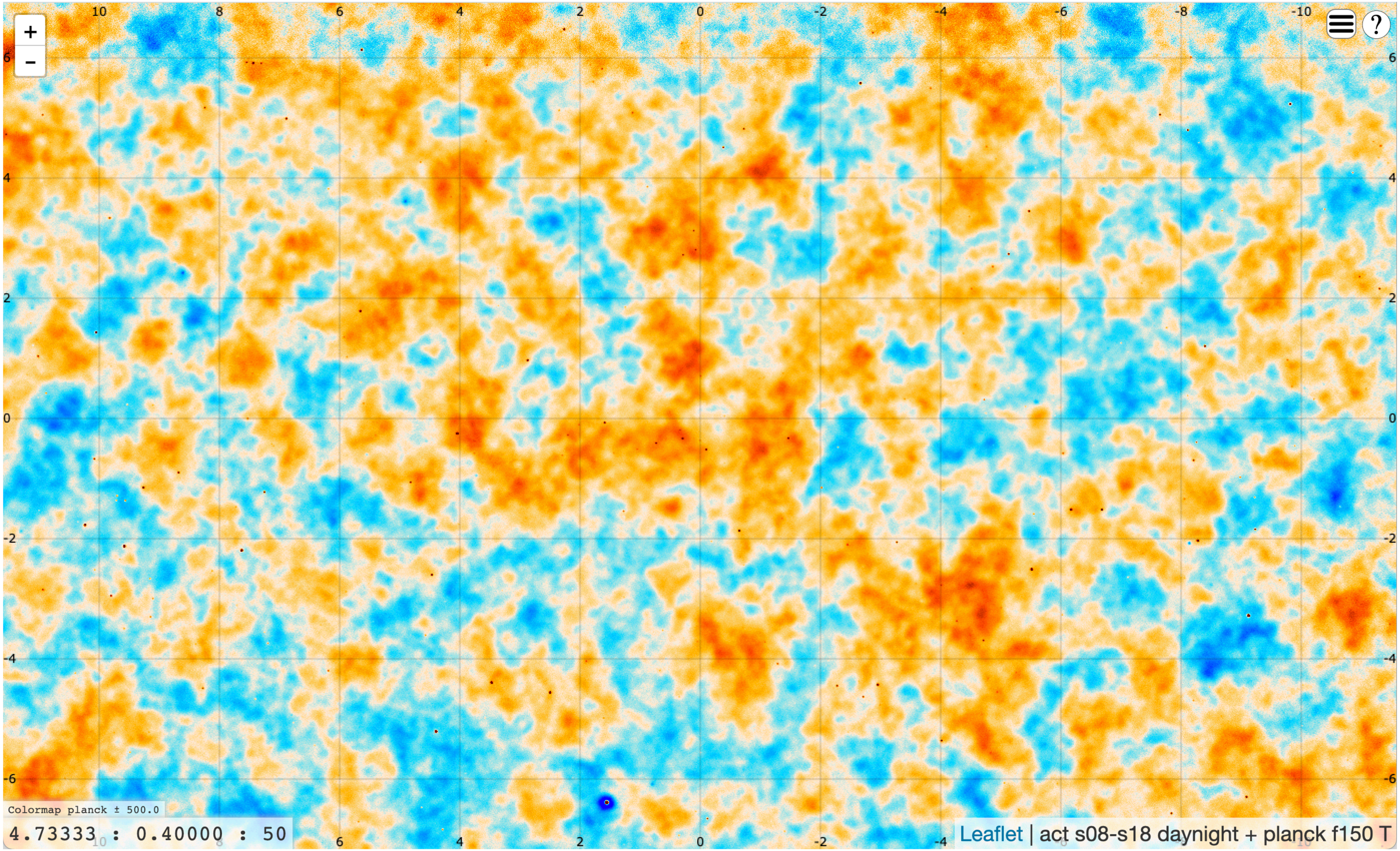

Colormap planck ± 500.0
4.73333 : 0.40000 : 50
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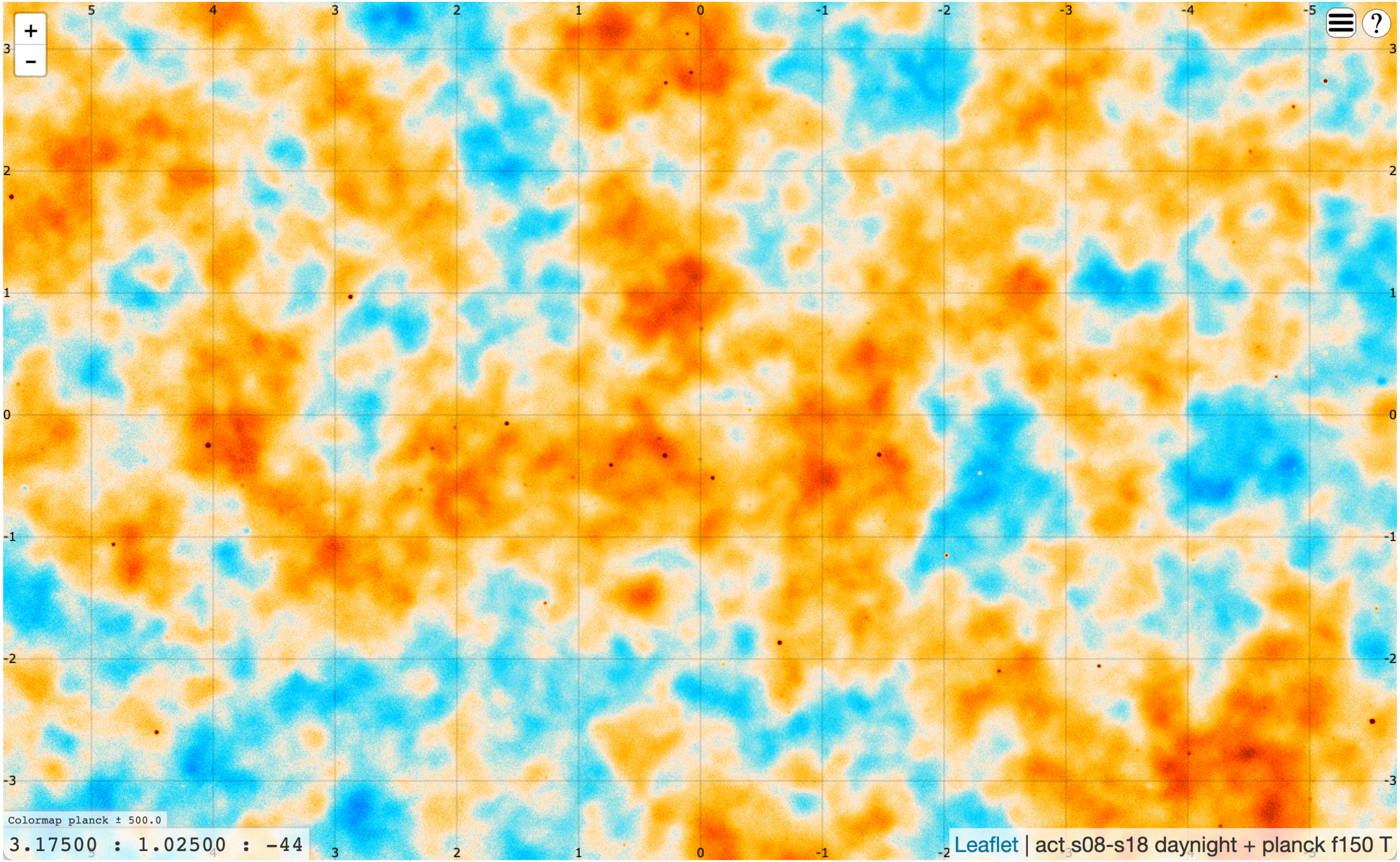
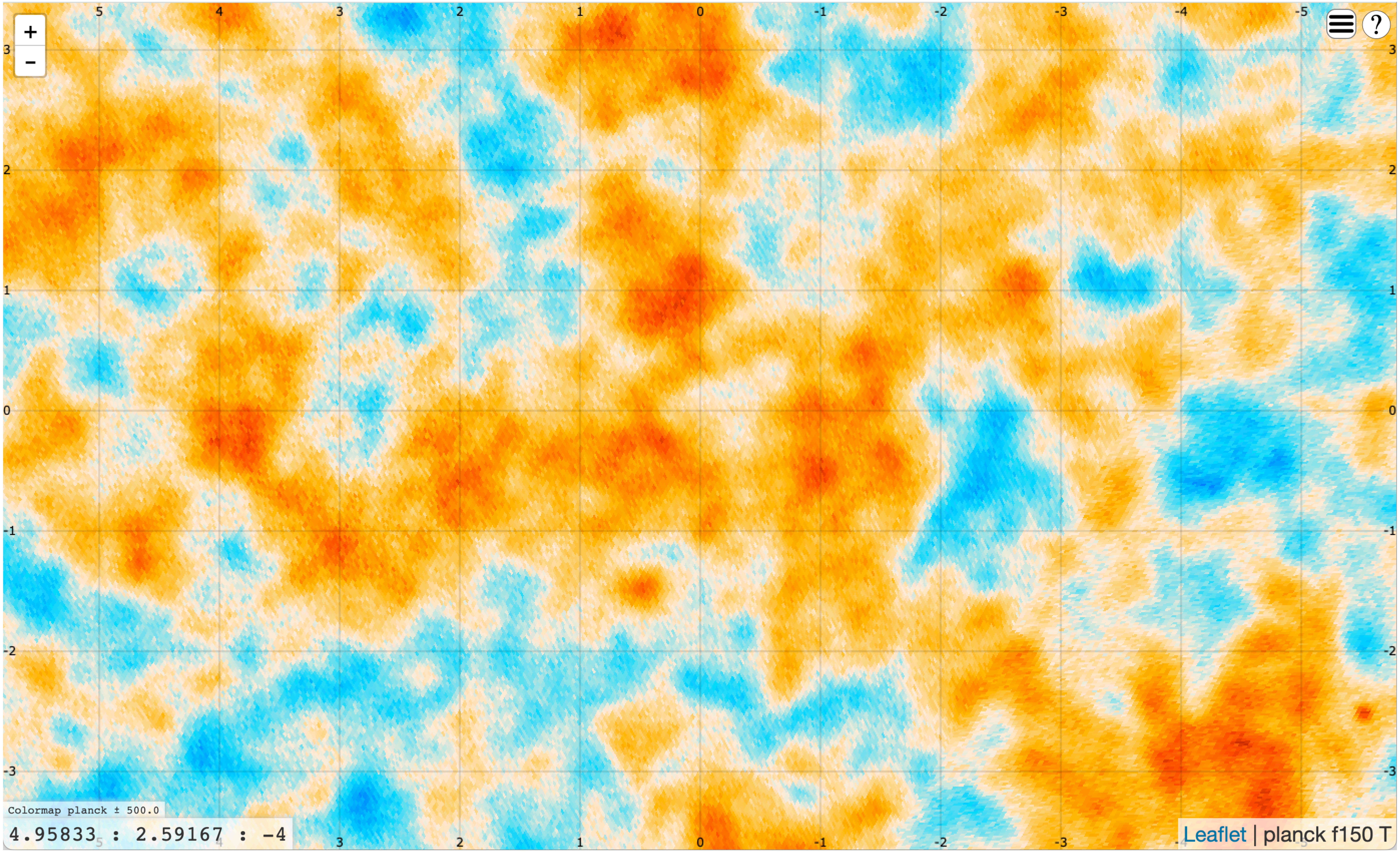
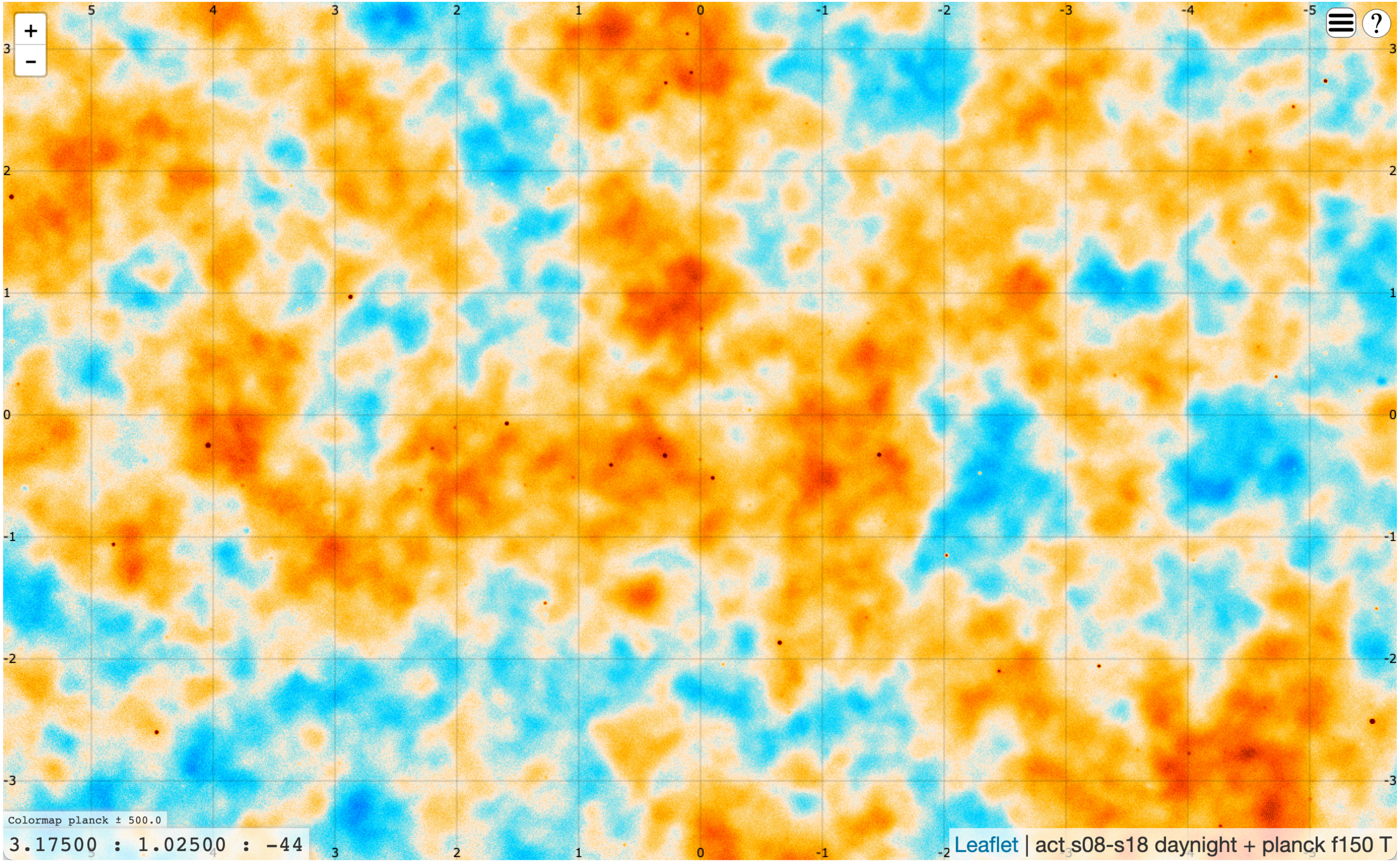
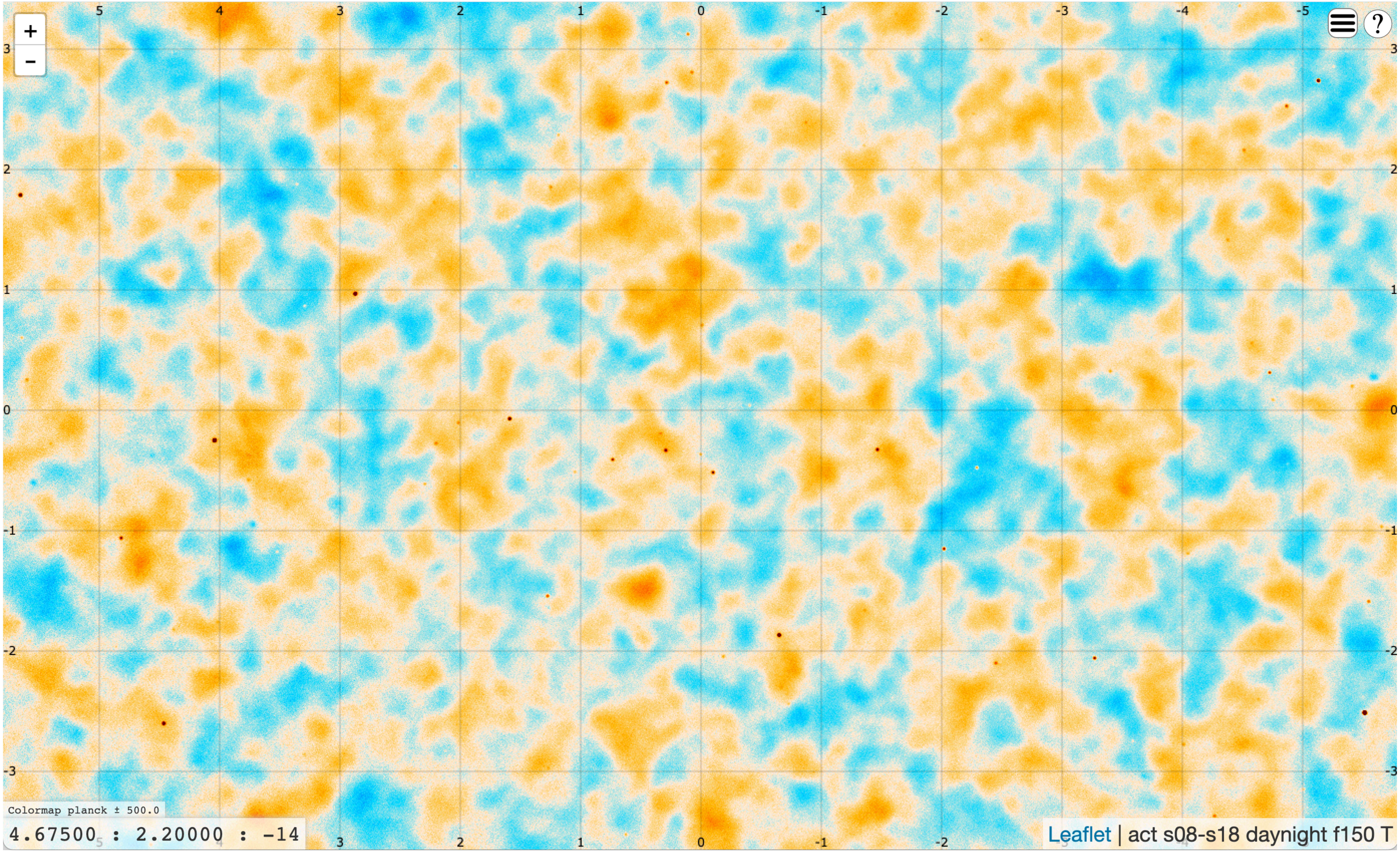


Colormap planck ± 500.0
3.17500 : 1.02500 : -44
Leaflet | act s08-s18 daynight + planck f150 T


Colormap planck ± 500.0
4.95833 : 2.59167 : -4
Leaflet | planck f150 T



Colormap planck ± 500.0
3.17500 : 1.02500 : -44
Leaflet | act s08-s18 daynight + planck f150 T


Colormap planck ± 500.0
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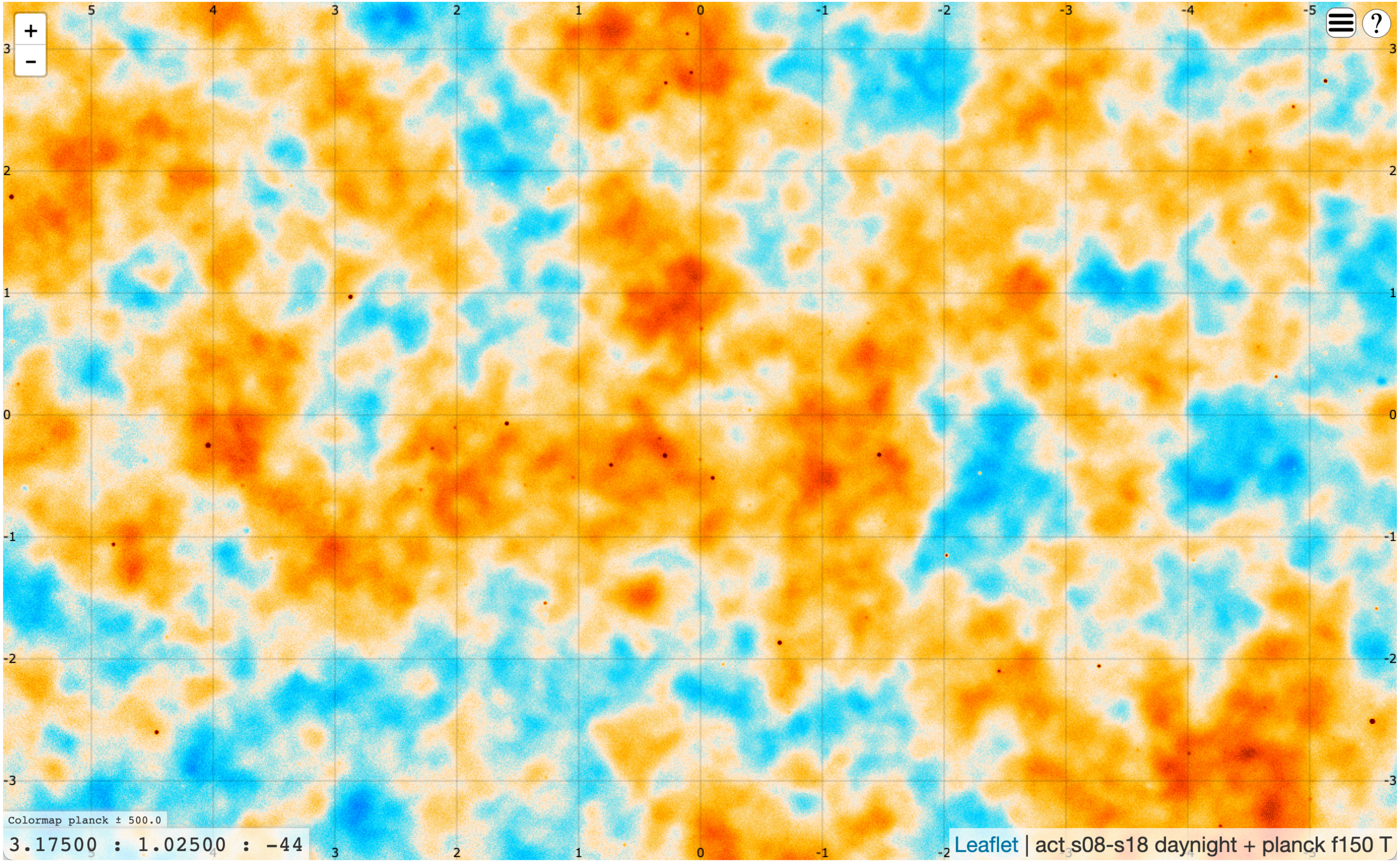
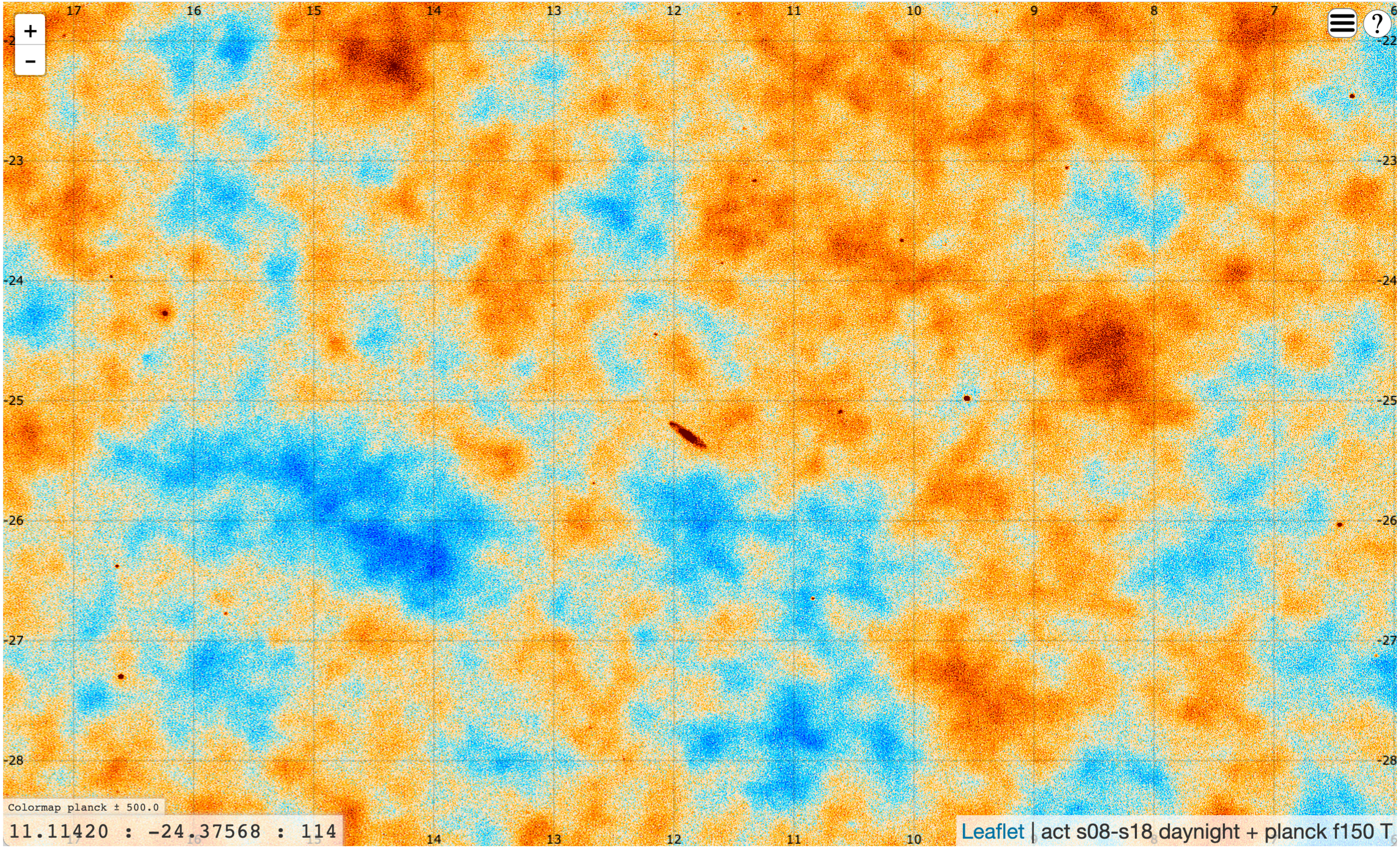

Colormap planck ± 500.0
3.17500 : 1.02500 : -44
Leaflet | act s08-s18 daynight + planck f150 T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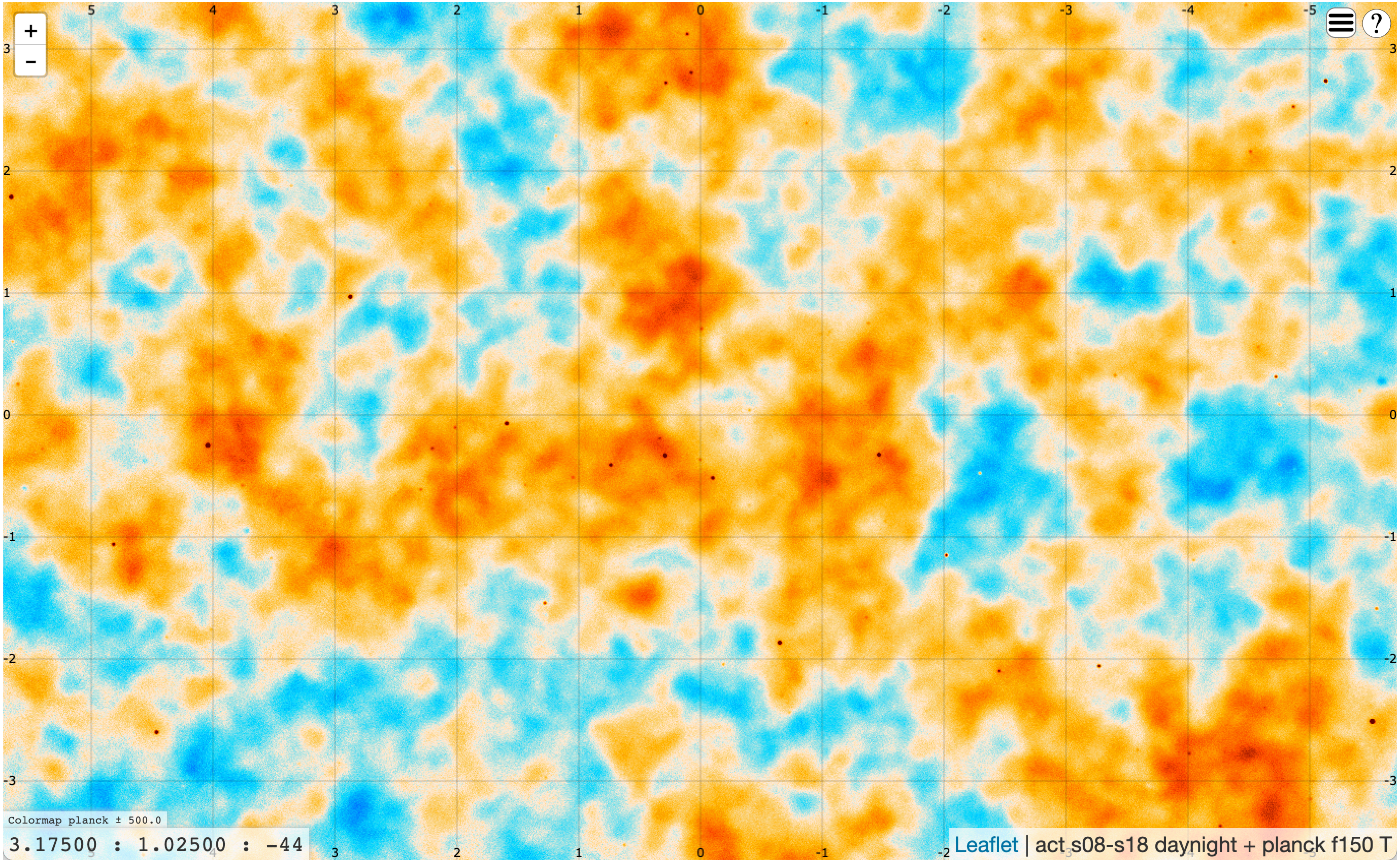
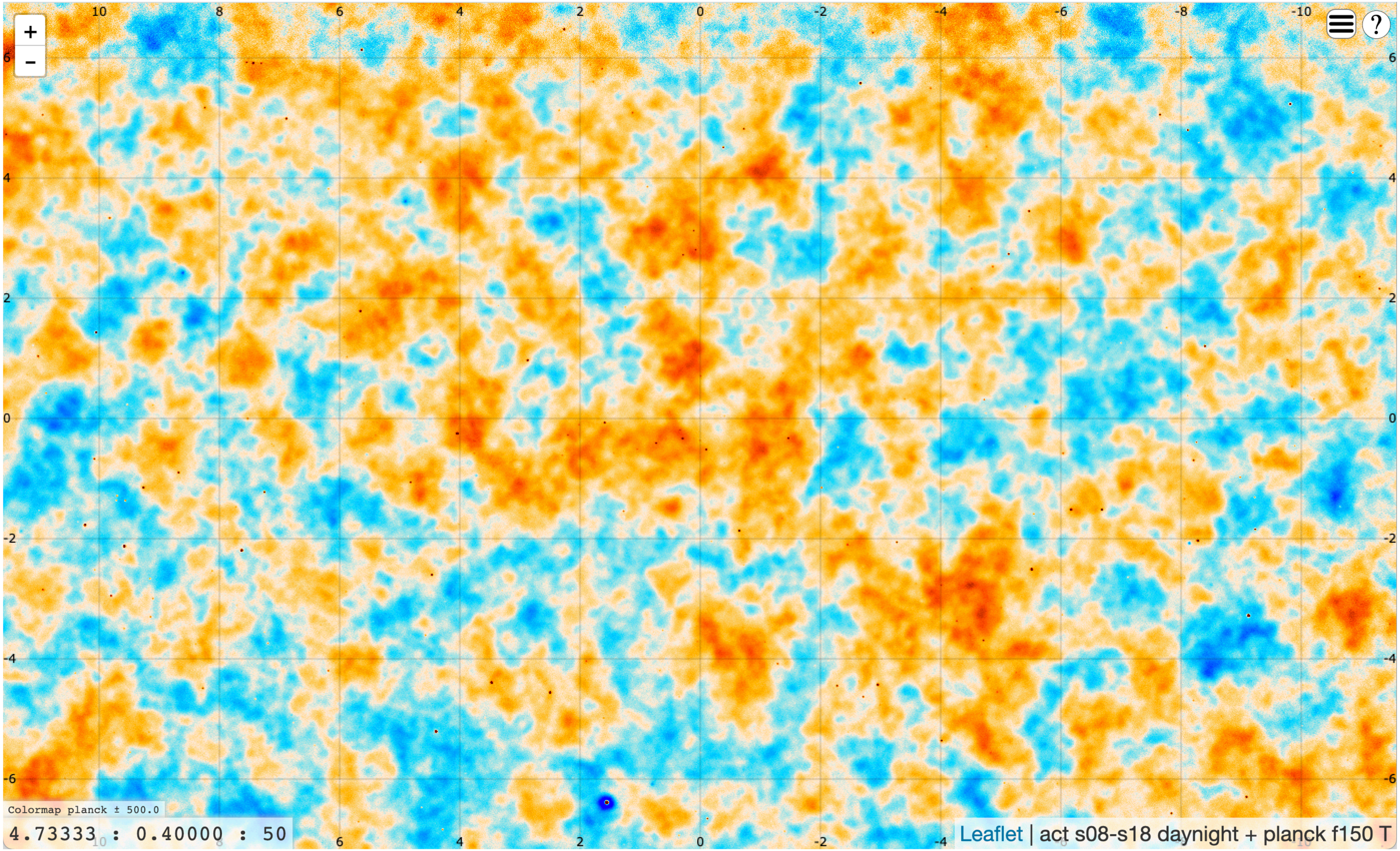
-28
Colormap planck ± 500.0
11.11420 : -24.37568 : 114
Leaflet | act s08-s18 daynight + planck f150 T


Colormap planck ± 500.0
3.17500 : 1.02500 : -44
Leaflet | act s08-s18 daynight + planck f150 T


10
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-8
-10
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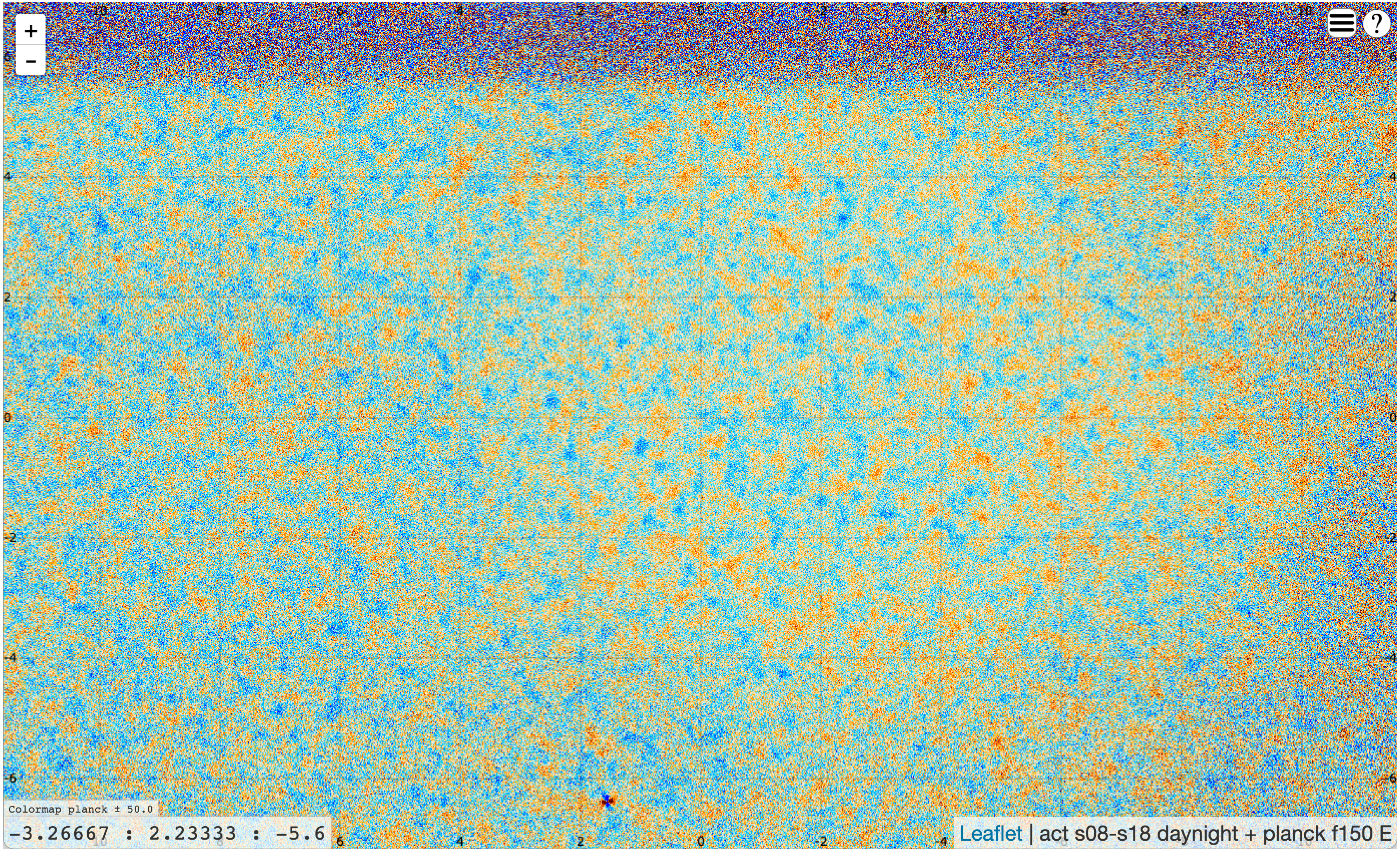
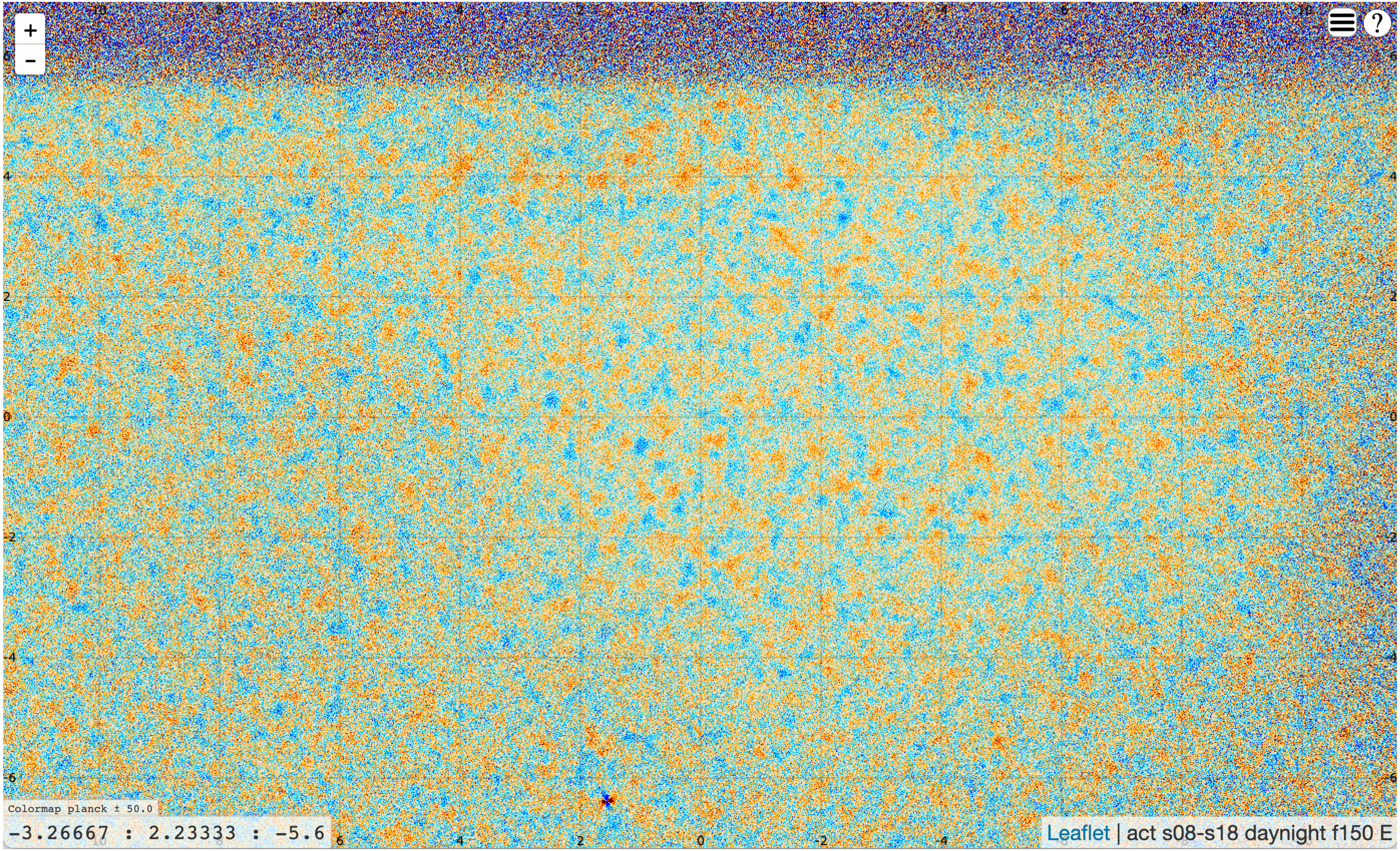
-2
-4
-6
Colormap planck ± 500.0
4.73333 : 0.40000 : 50
Leaflet | act s08-s18 daynight + planck f150 T


Colormap planck ± 50.0
-3.26667 : 2.23333 : -5.6
Leaflet | act s08-s18 daynight + planck f150 E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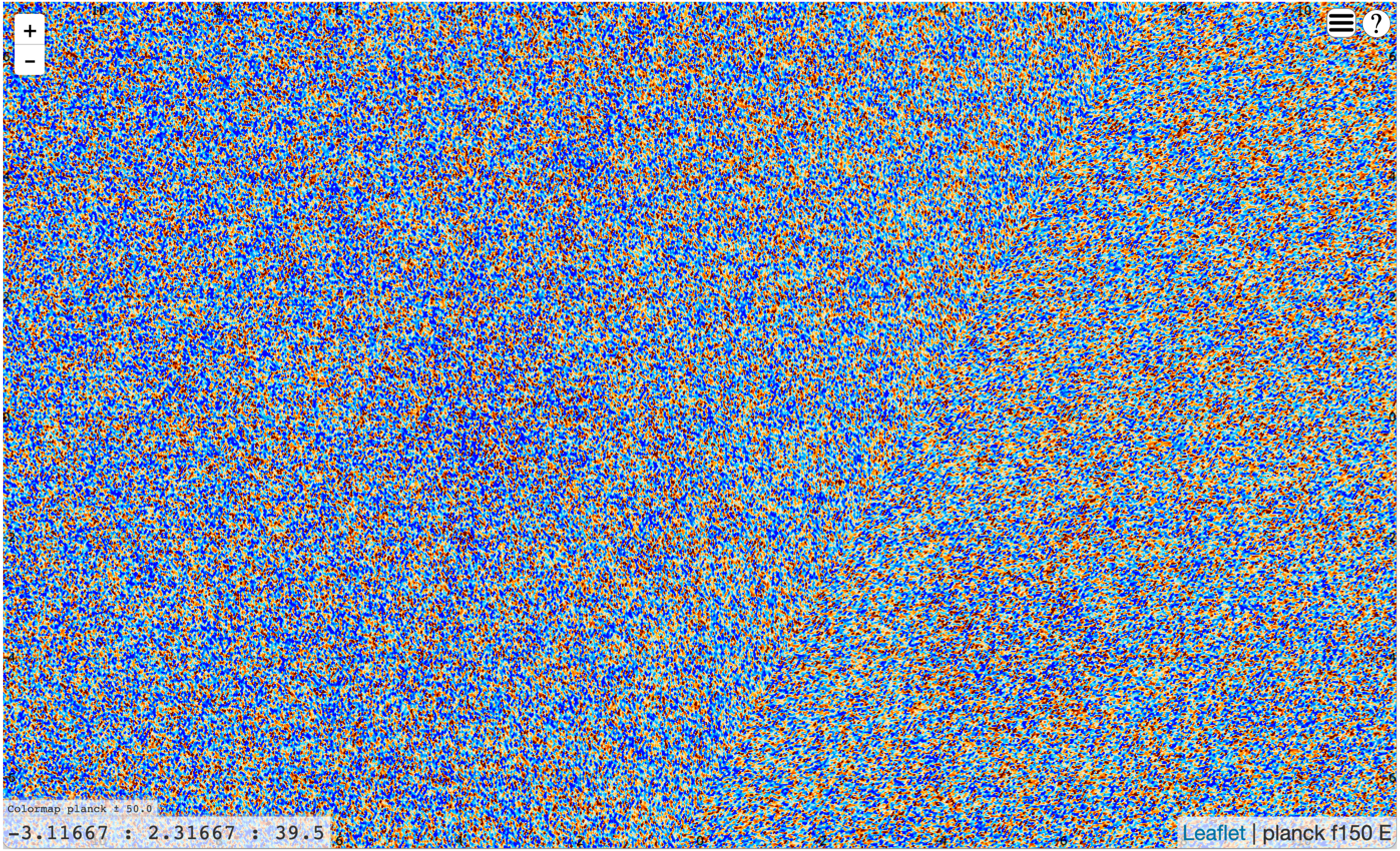
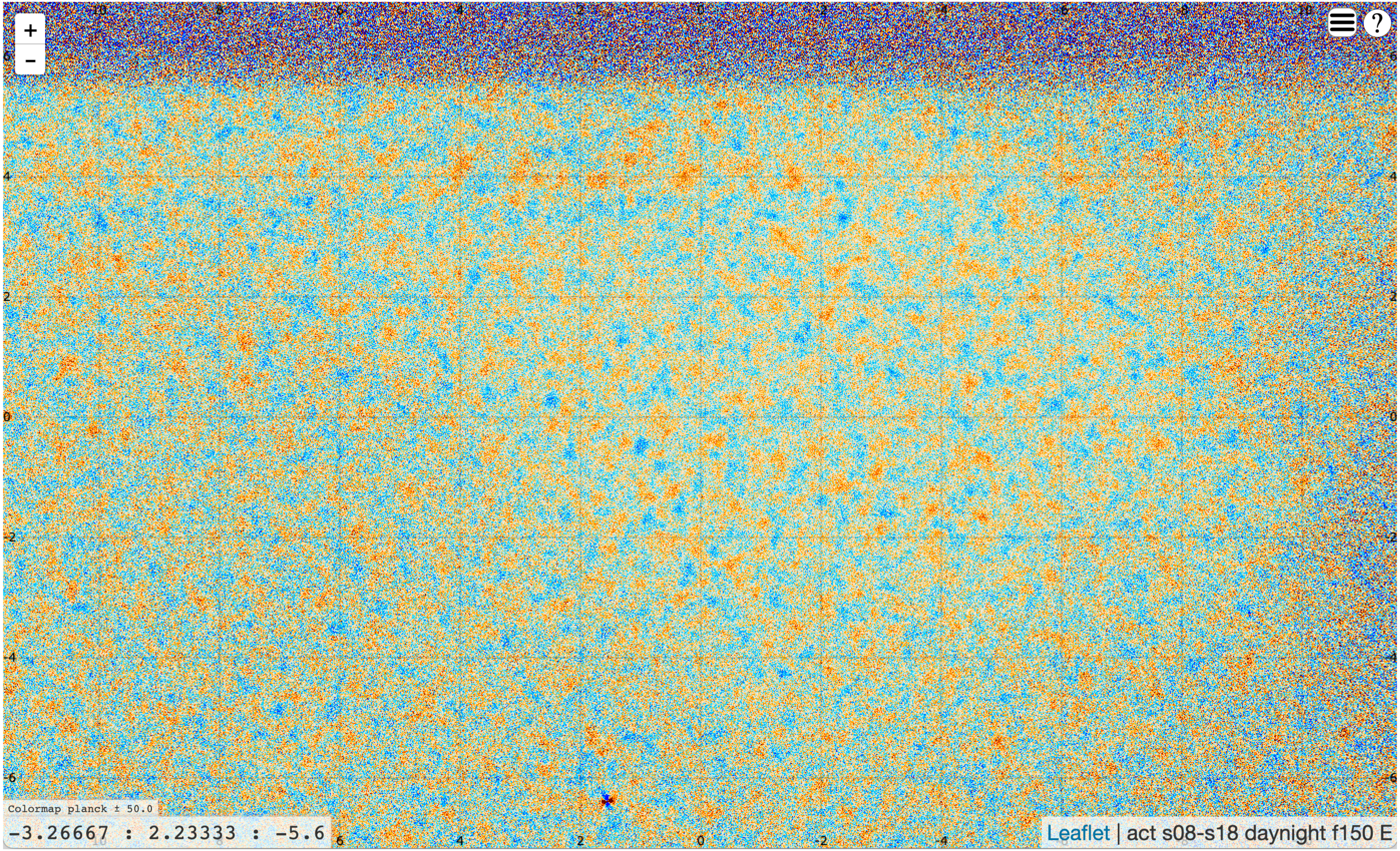
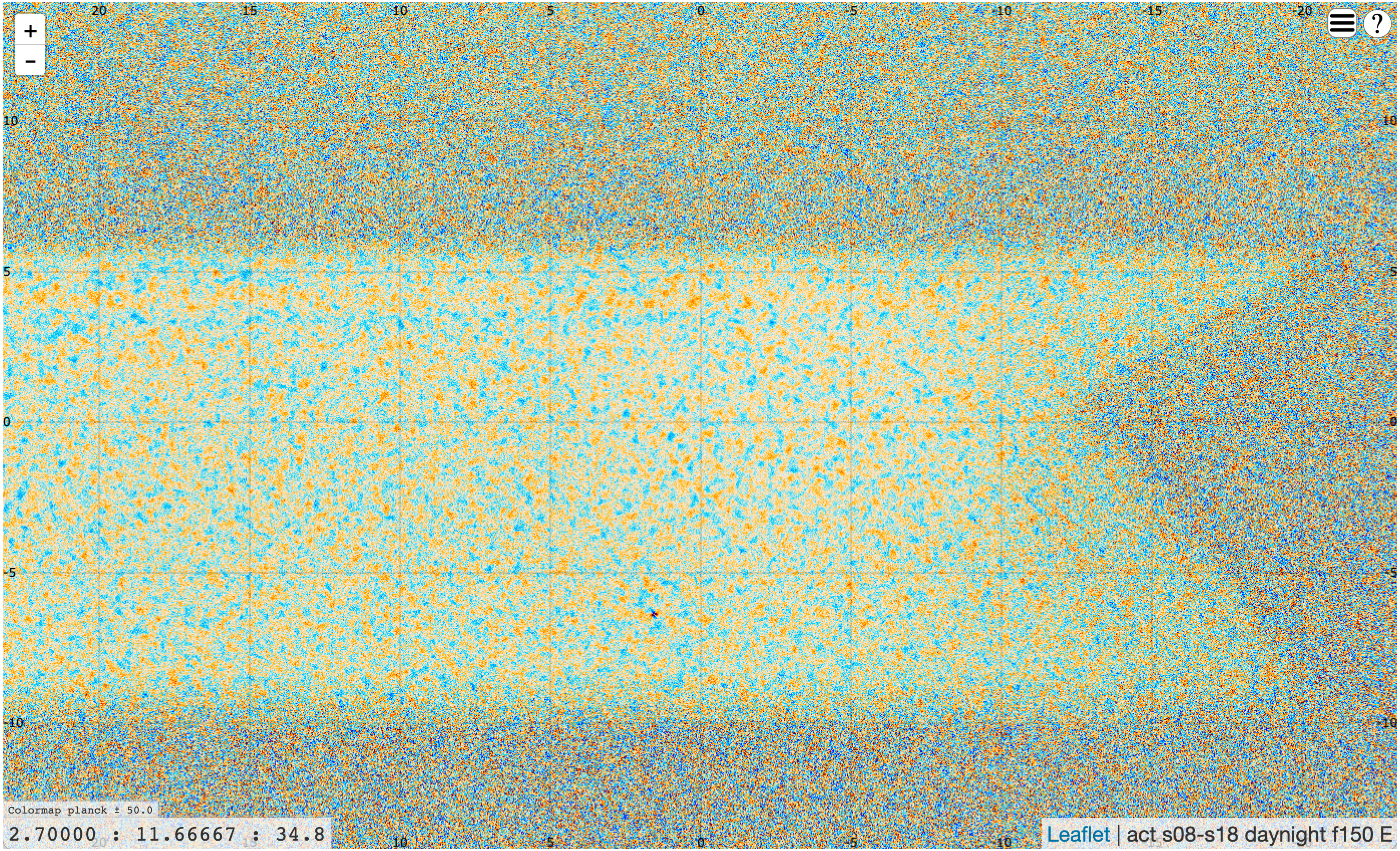
Leaflet | act s08-s18 daynight f150 E


+
−
Colormap planck ± 50.0
-3.11667 : 2.31667 : 39.5
Leaflet | planck f150 E


Colormap planck ± 50.0
-3.26667 : 2.23333 : -5.6
Leaflet | act s08-s18 daynight f150 E



Colormap planck ± 50.0
2.70000 : 11.66667 : 34.8
Leaflet | act s08-s18 daynight f150 E

Maps

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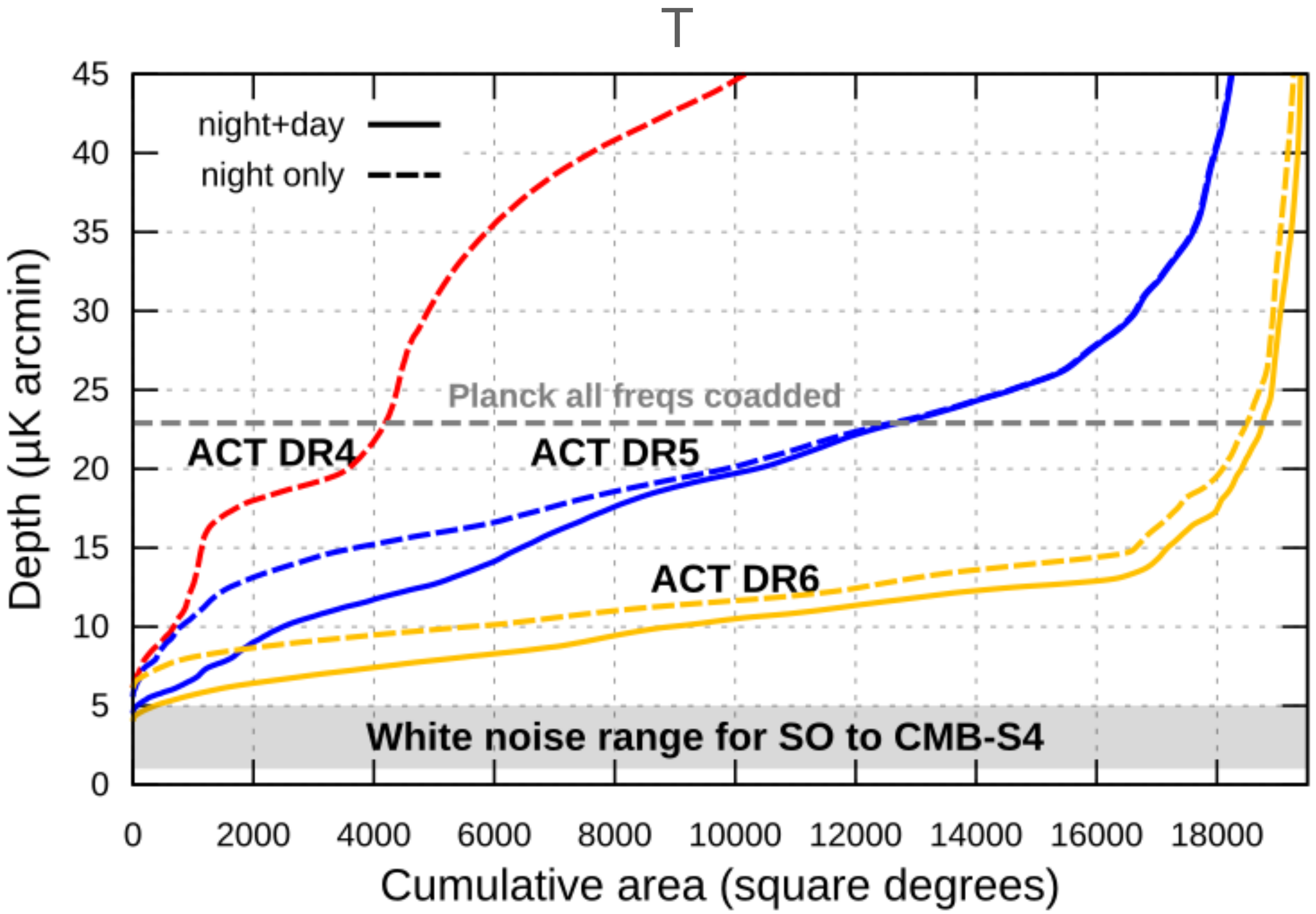
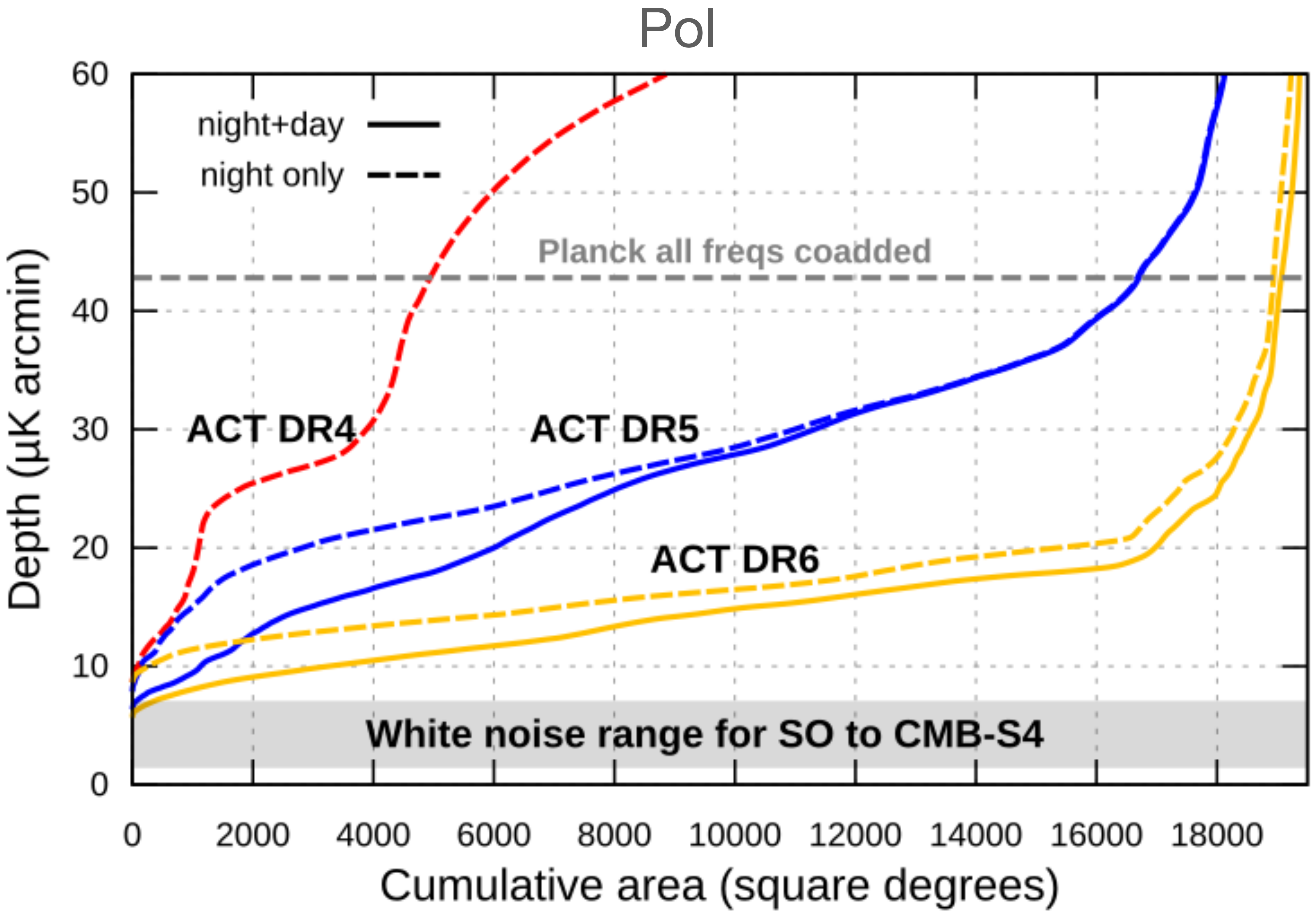
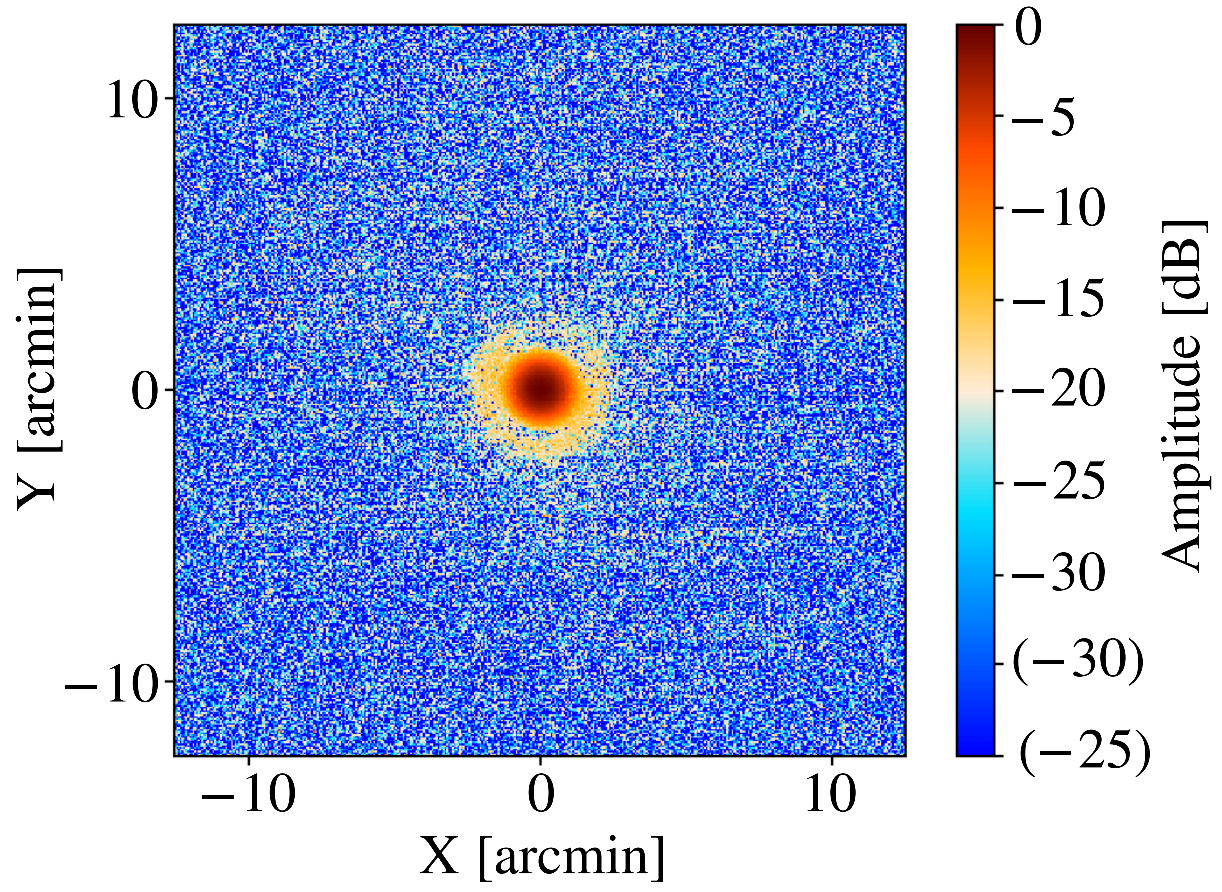
- data from 2017 - 2021

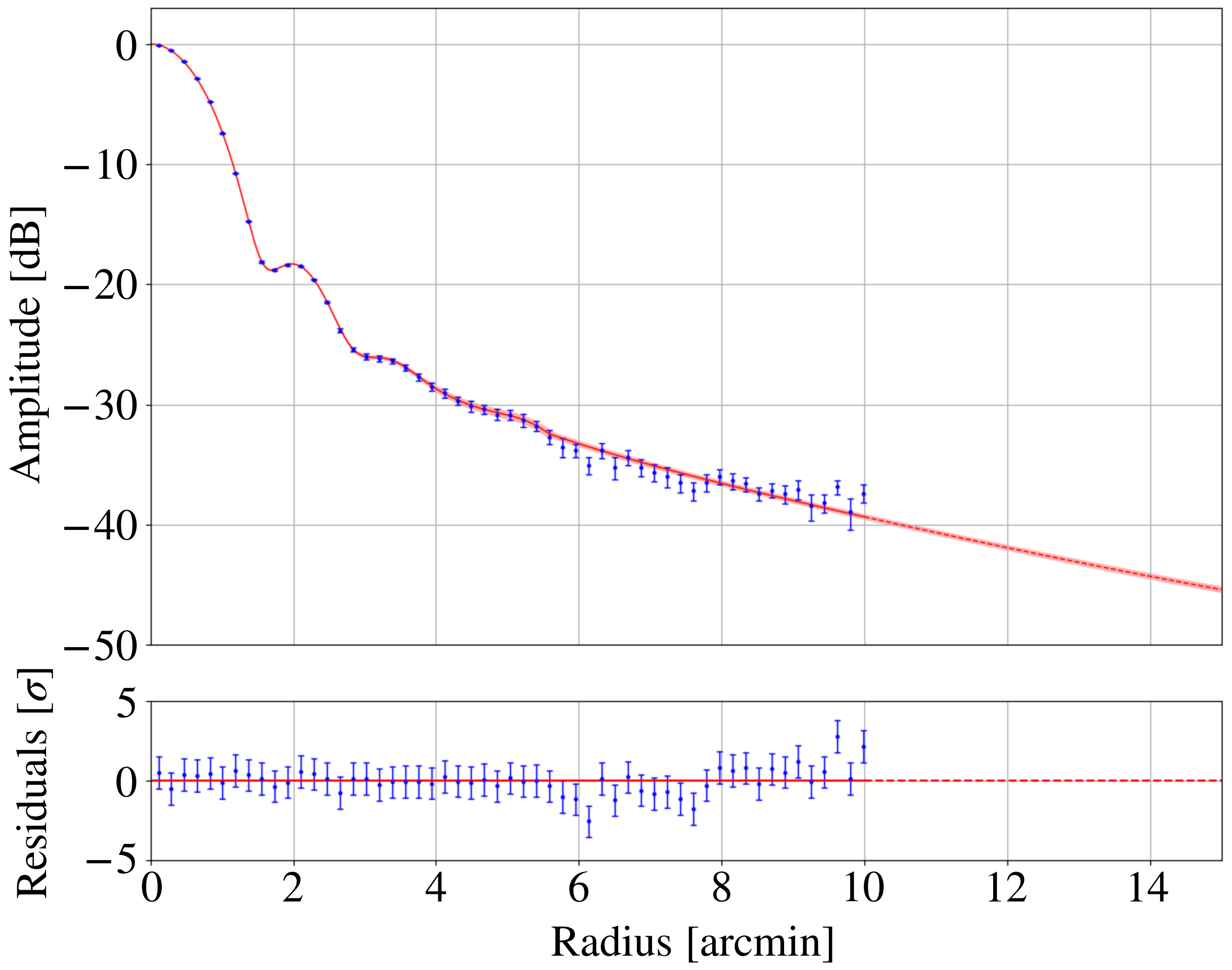


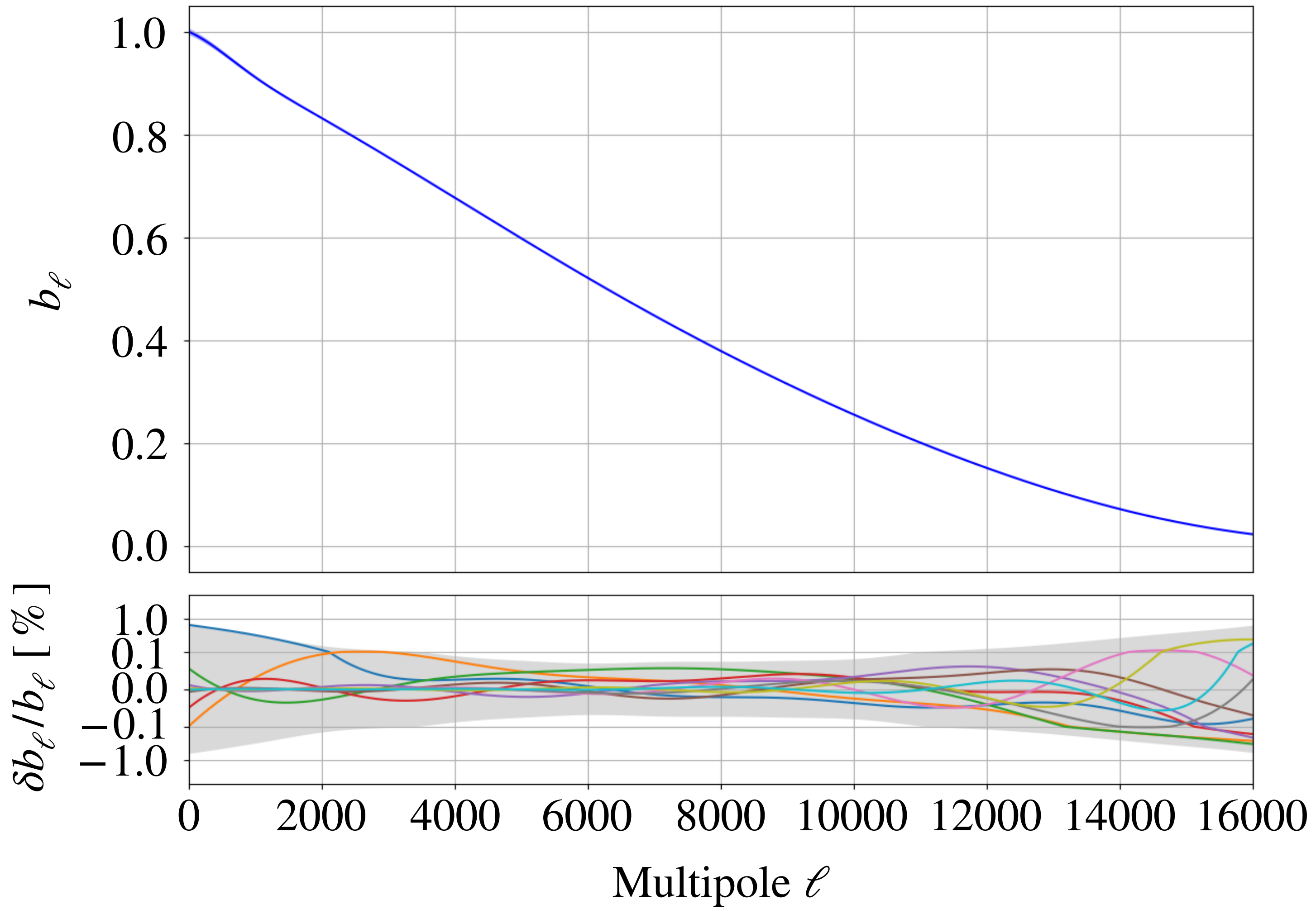


Beams

use multiple observations of Uranus → construct an average radial profile & fit a physically motivated model → compute the transform & its covariance matrix







$$B(\theta) = \begin{cases} \sum_{n=0}^{n_{\rm mode}-1} a_n f_n(\theta \ell_{\rm max}) & \text{for } \theta \leq \theta_1 \\ \alpha/\theta^3 + S(\theta) & \text{for } \theta_1 < \theta \end{cases}$$

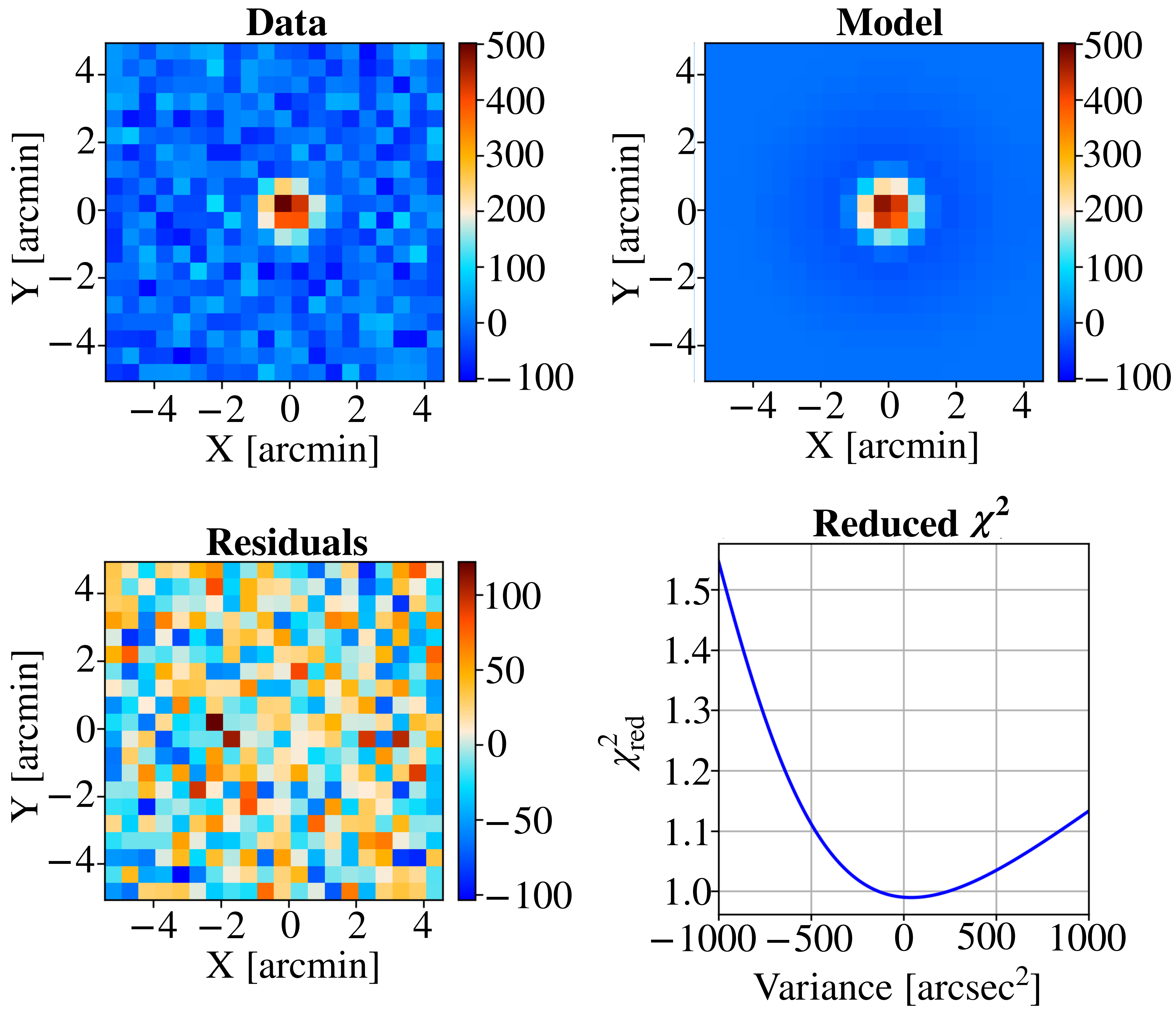
Lungu, Storer et al. 2022 (arXiv: 2112.12226)

Jitter Beam

- In the maps, each pixel contains data collected on several different nights
- Resulting effective beam for each map is not as sharp as the beam inferred from carefully re-centered planet maps
- Parametrize effective beam as instantaneous beam with Gaussian correction term :

$$B_\ell^{eff} = B_\ell \times e^{-\ell(\ell+1)V/2}$$

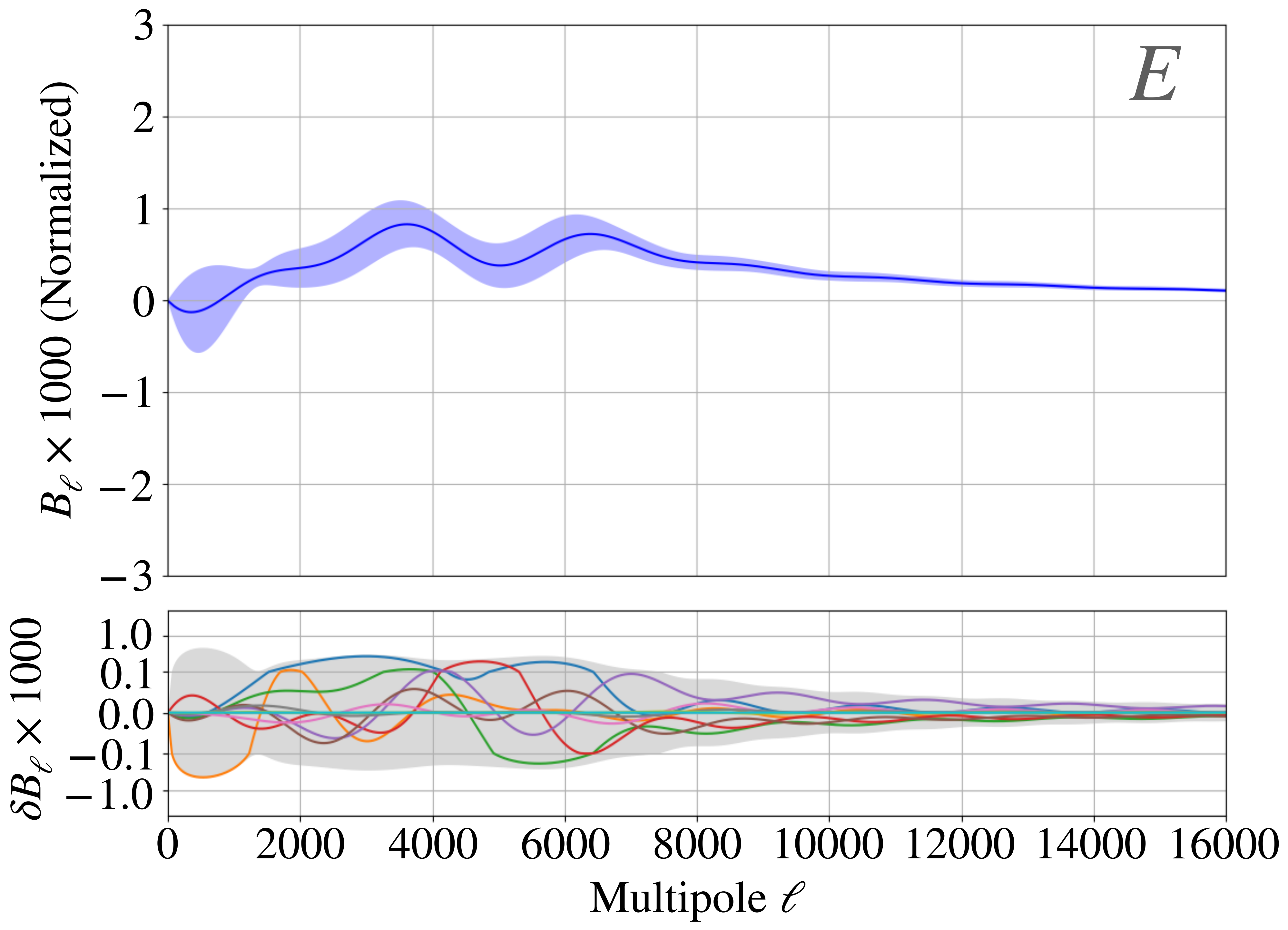
- Fit to brightest point sources in each map

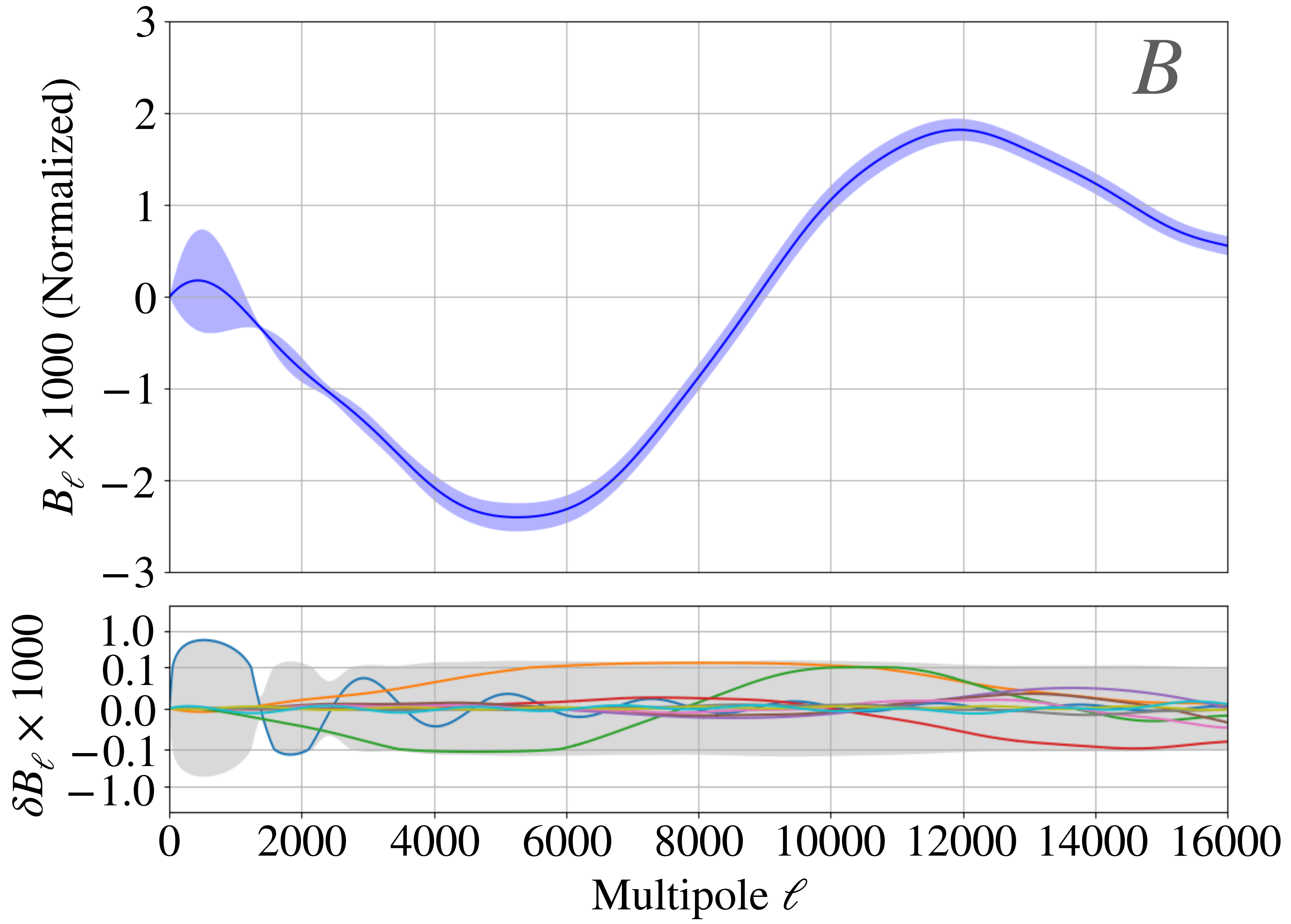


Lungu, Storer et al. 2022 (arXiv: 2112.12226)

Leakage Beam

- In our bands Uranus should not be significantly polarized
- Interpret any polarization seen from Uranus as temperature-to-polarization leakage
- Use a radial polarization basis
- Leakage beams are measured in the exact same way as the main beam and then included in our final likelihood

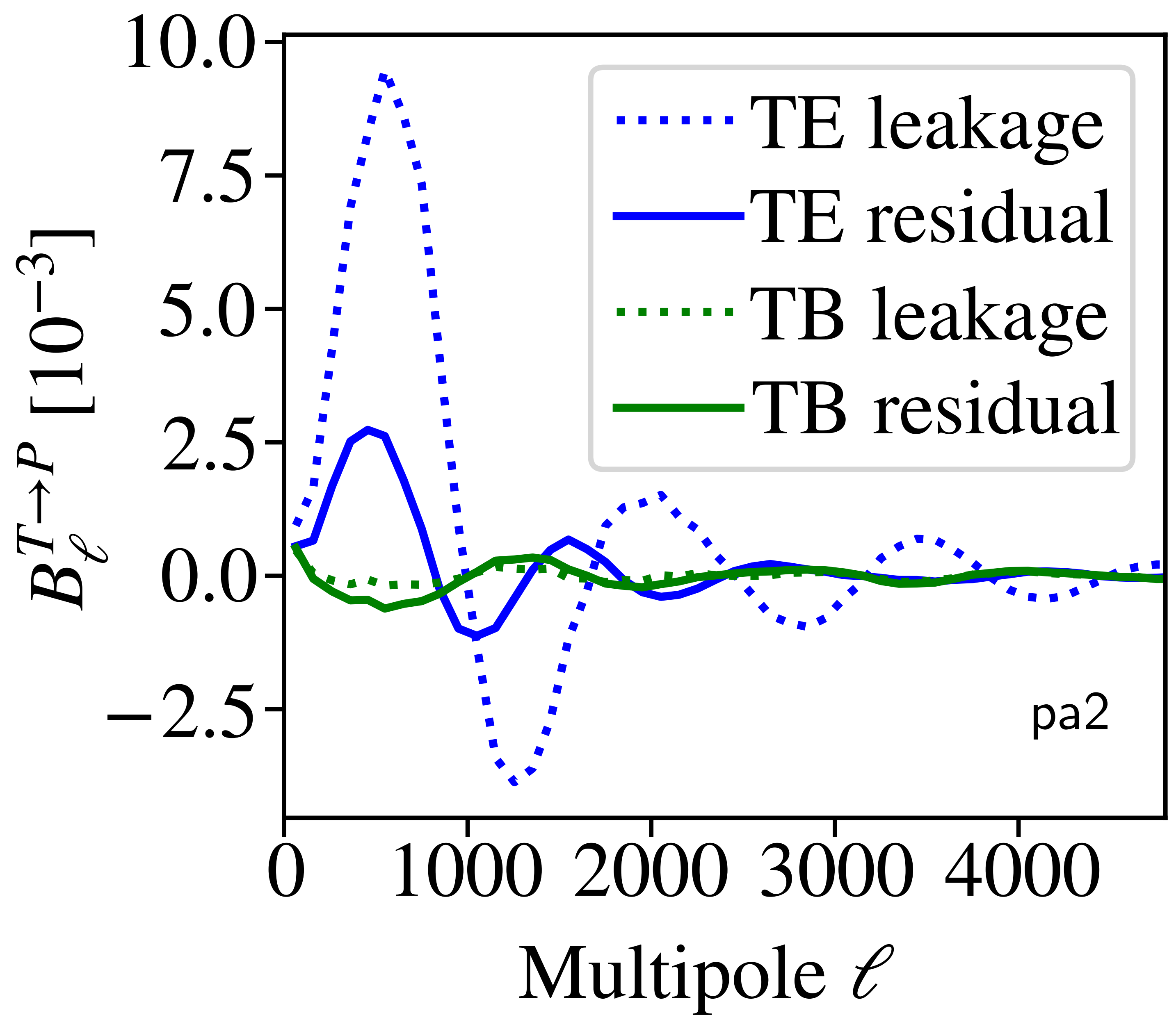


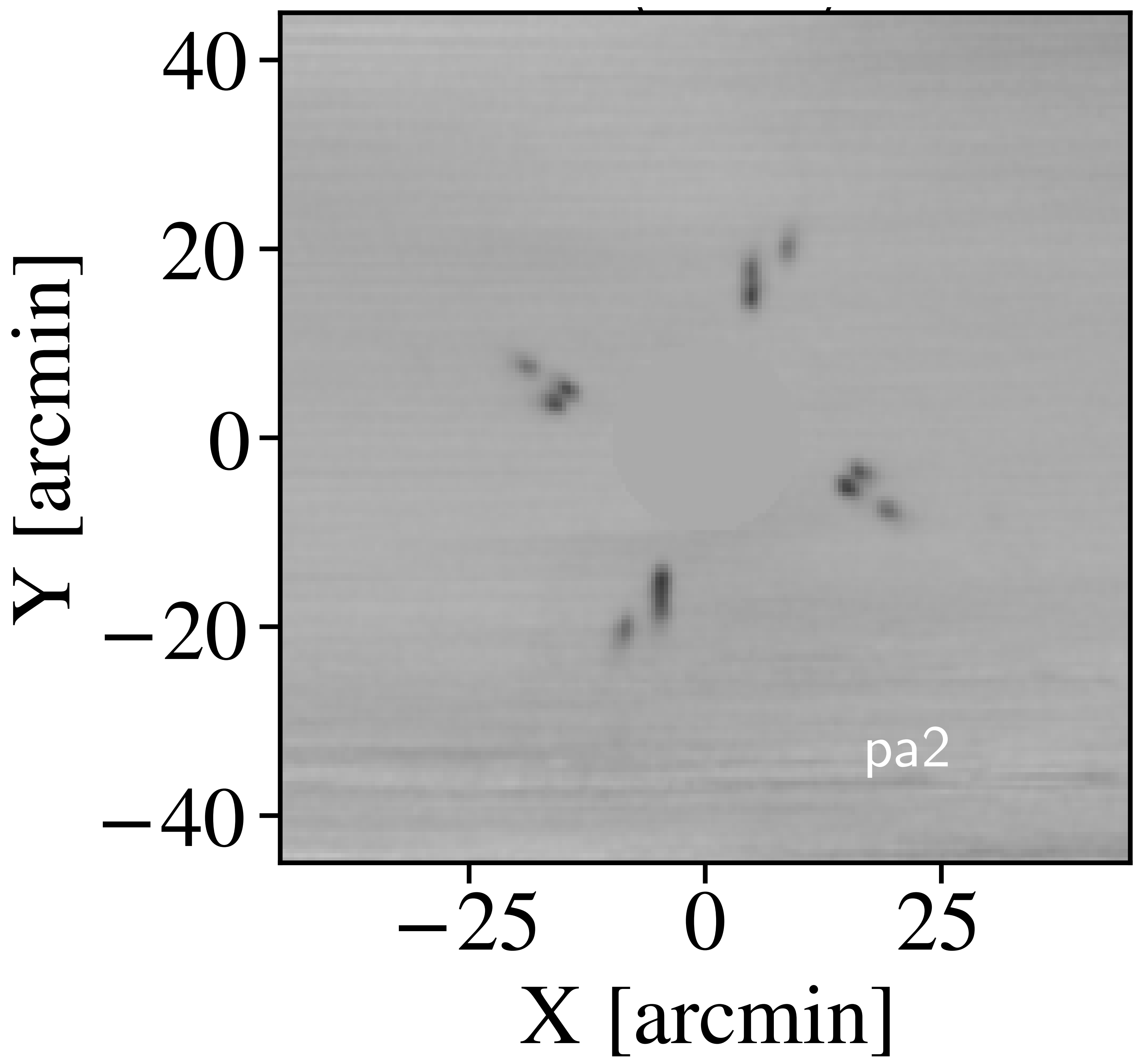


Lungu, Storer et al. 2022 (arXiv: 2112.12226)

Sidelobes ("Buddies")

- Weakly polarized sidelobes
- Lead to T-to-P leakage
- Meaured using observations of Saturn
- Modeled as copies of the main beam
- Removed during the mapping process
- Residuals added to main beam leakage in likelihood

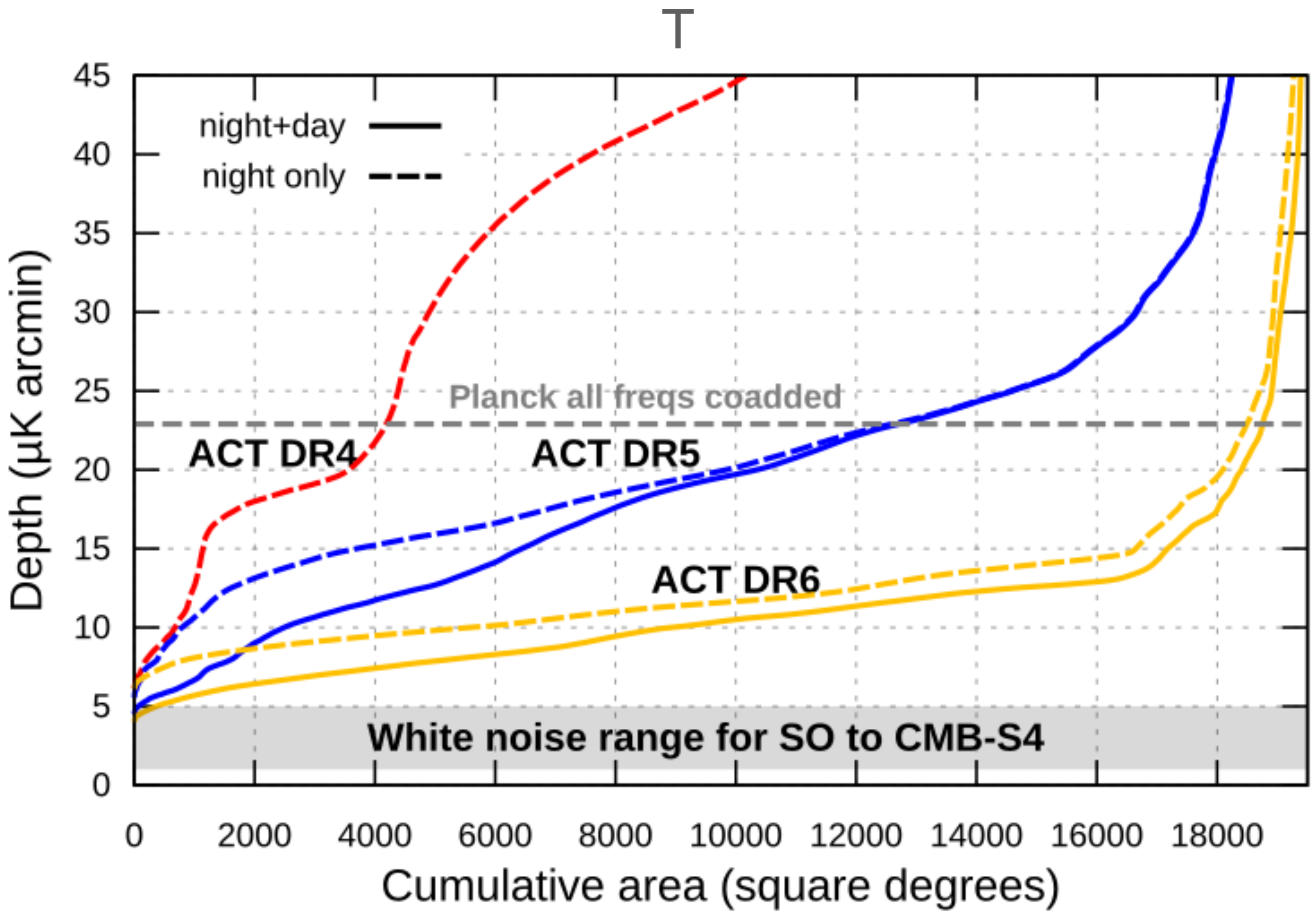


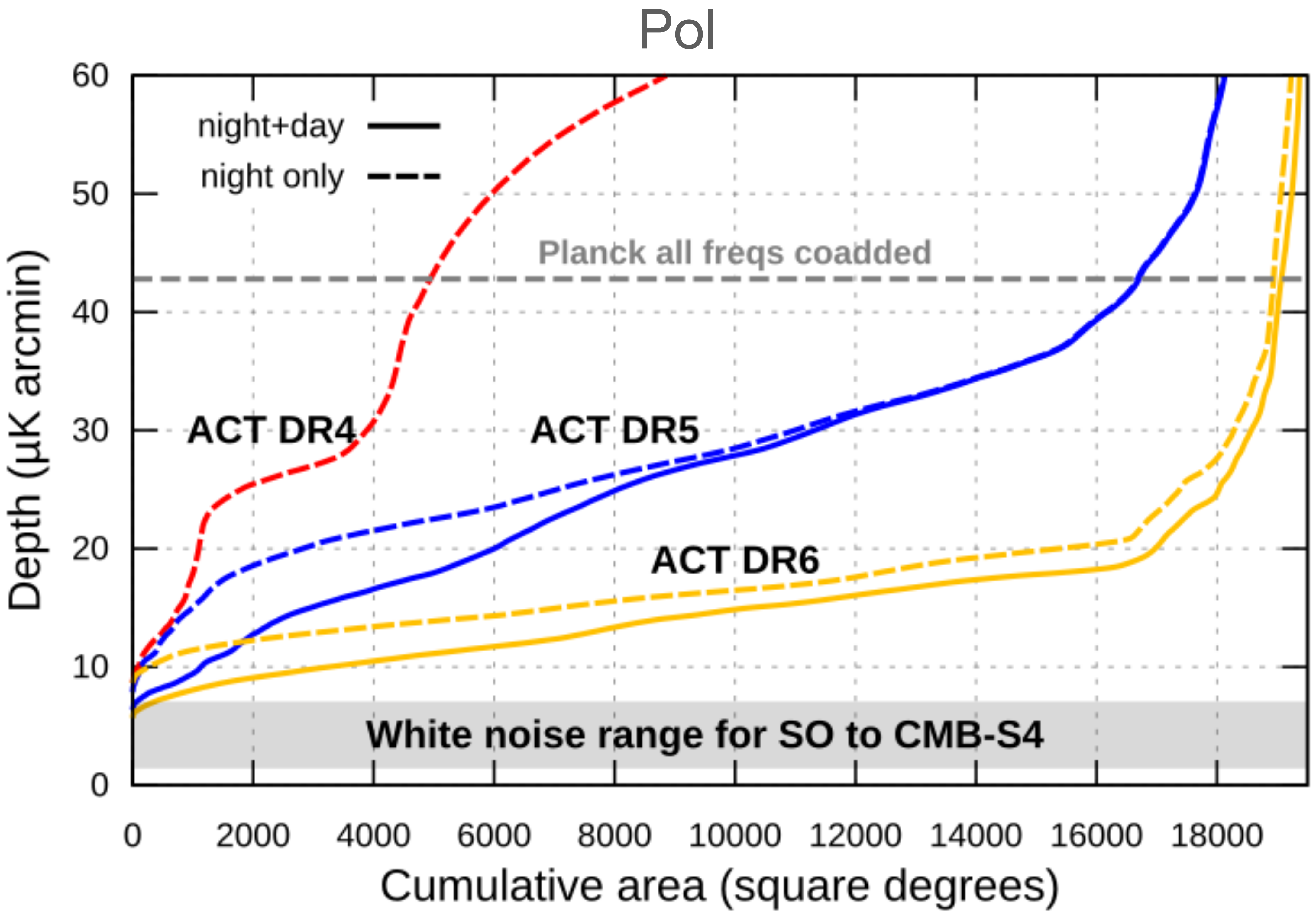


Lungu, Storer et al. 2022 (arXiv: 2112.12226)

Current Status - Working on DR6

- all the maps have been made
- working on the beams, using the same approach as DR4 (Adri Duivenvoorden)
- separately studying the daytime data





Extra Slides

Maximum-Likelihood Mapmaking

Model our data as $\mathbf{d} = A\mathbf{m} + \mathbf{n}$ where

$\mathbf{d} =$ time-ordered data

$A =$ pointing matrix (projects from map domain to time domain)

$\mathbf{m} =$ vector whose components are the sky map pixels (for which we want to solve)

$\mathbf{n} =$ noise contribution to the data, taken to be normally distributed with covariance $N = \langle \mathbf{n}\mathbf{n}^T \rangle$

Solve for best-fit sky map given measured data and noise: $\mathscr{L} = \exp\left[-\frac{1}{2}(\mathbf{d} - A\mathbf{m})^T N^{-1} (\mathbf{d} - A\mathbf{m}) \right]$

Linear least squares solution (mapmaking equation): $A^T N^{-1} A\mathbf{m} = A^T N^{-1} \mathbf{d}$

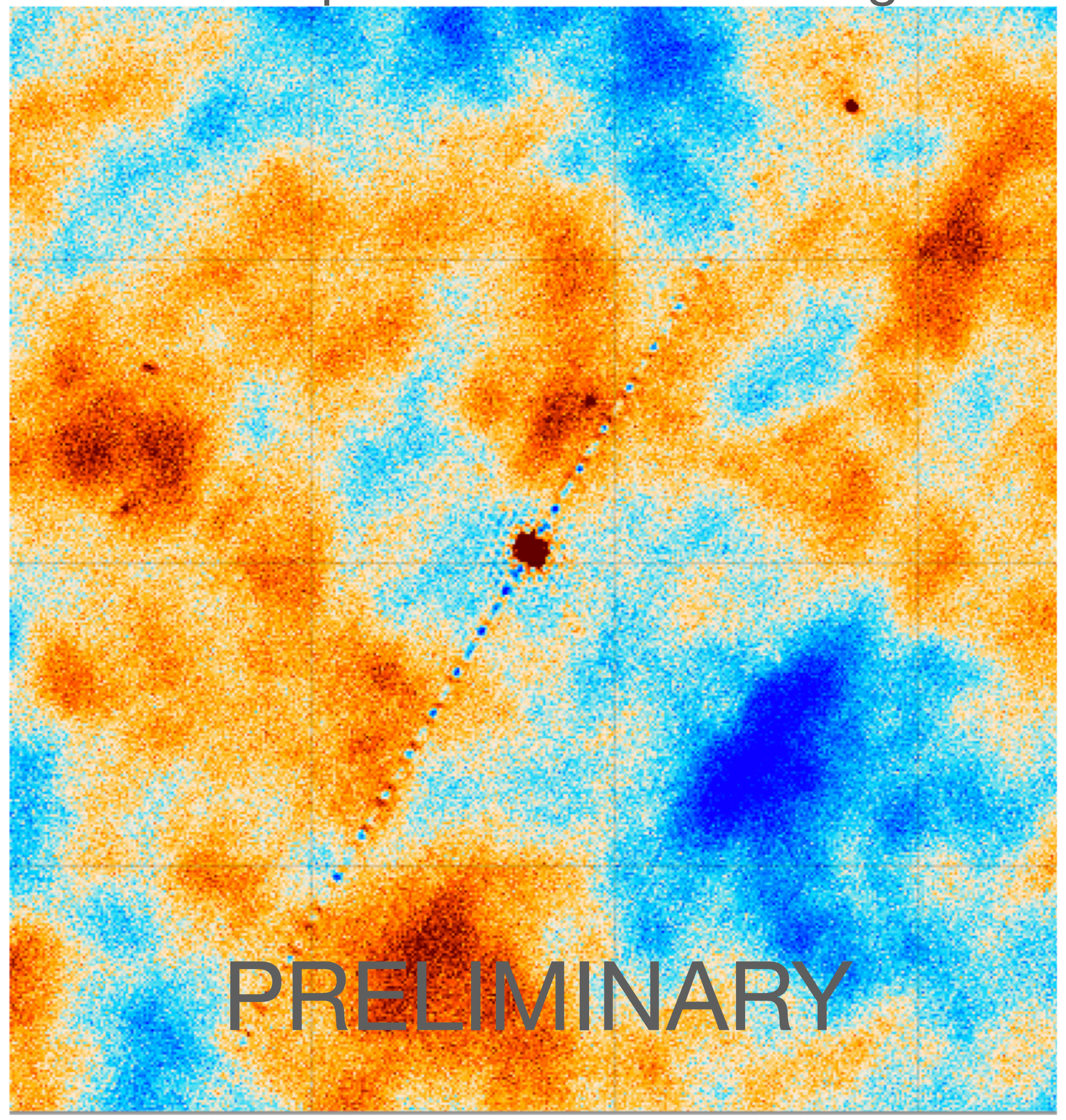
Solve for $\mathbf{m}$ iteratively using a preconditioned conjugate gradient algorithm

Choose a sufficient number of steps of the CG algorithm for the modes with $\ell \gtrsim 50$ to converge, roughly 300

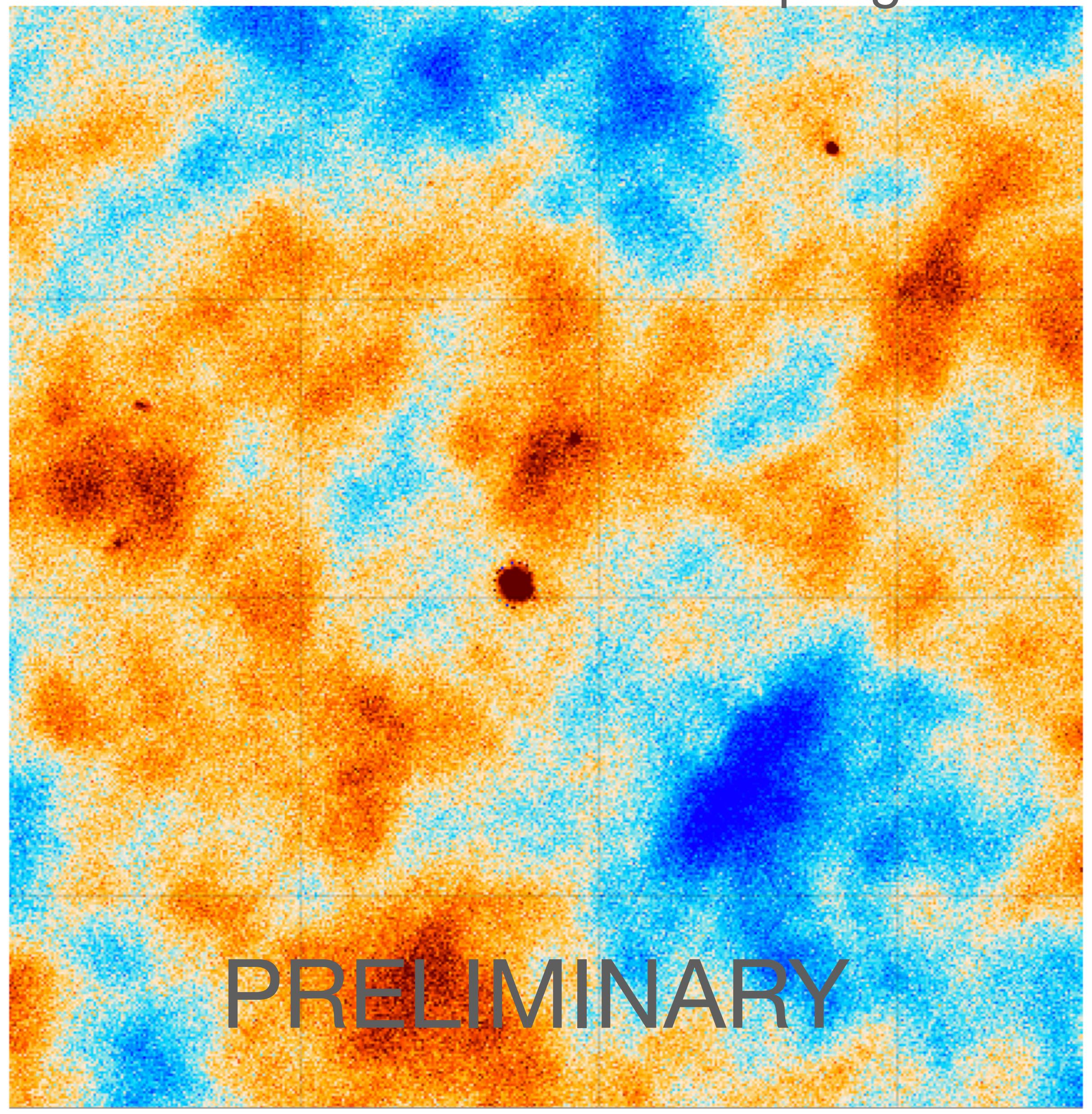
Point Sources

- Mapmaking equation only optimal and unbiased when the model is correct
- Model errors lead to bias, error in each pixel propagates along scanning direction for one noise correlation length
- Errors are several orders of magnitude fainter than signal in pixel that sourced them
- Not a problem for smooth, low-contrast signal like CMB, but concern with point sources
- To avoid model error, brightest point sources receive special treatment in mapmaker by adding a degree of freedom per sample in the map

No special source handling



With source sub-sampling

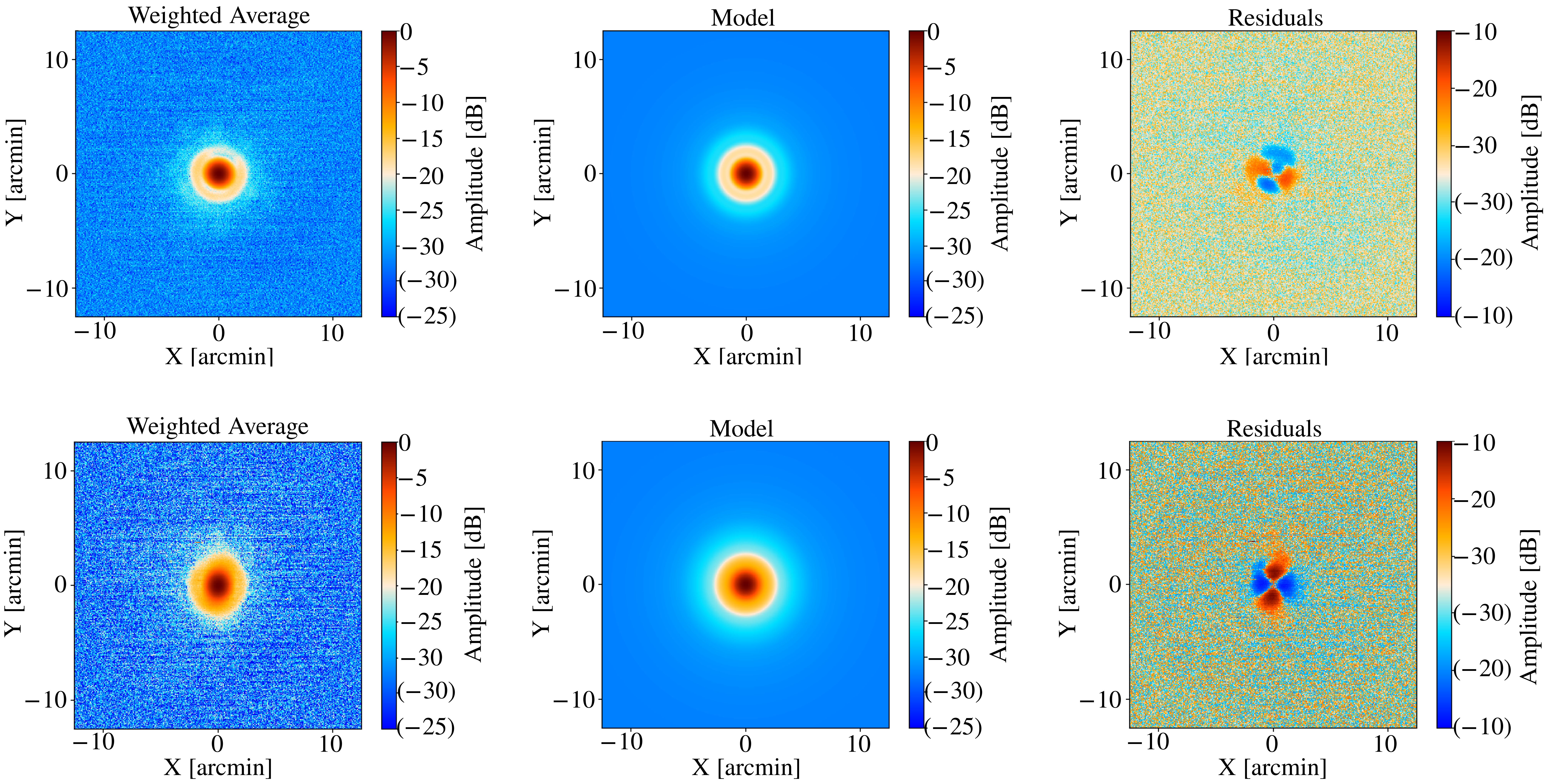


described in Naess 2019

Temperature Beam Maps

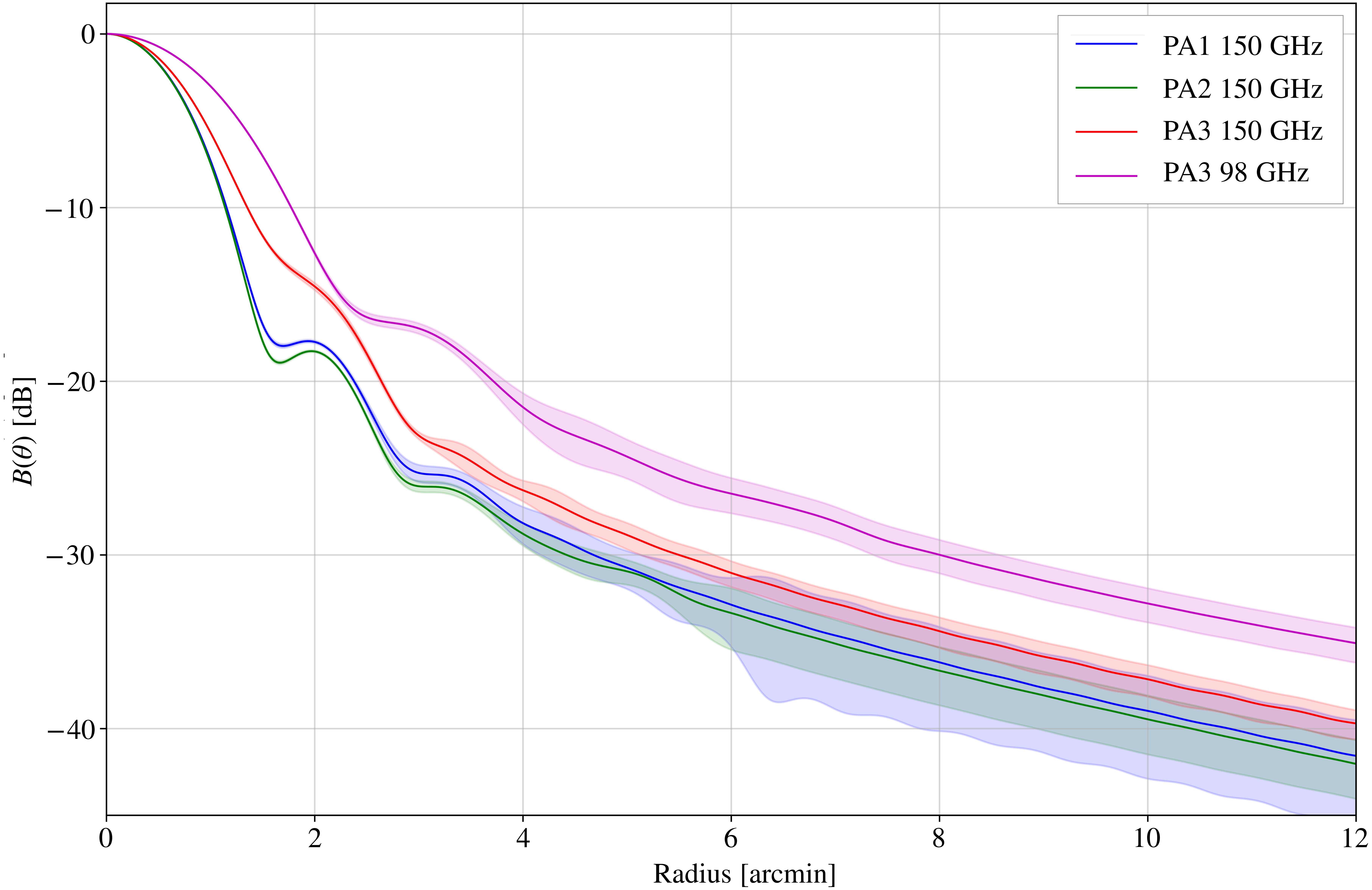
PA2
150 GHz

PA3
150 GHz



Lungu et al. 2022 (arXiv: 2112.12226)

Beam Profiles



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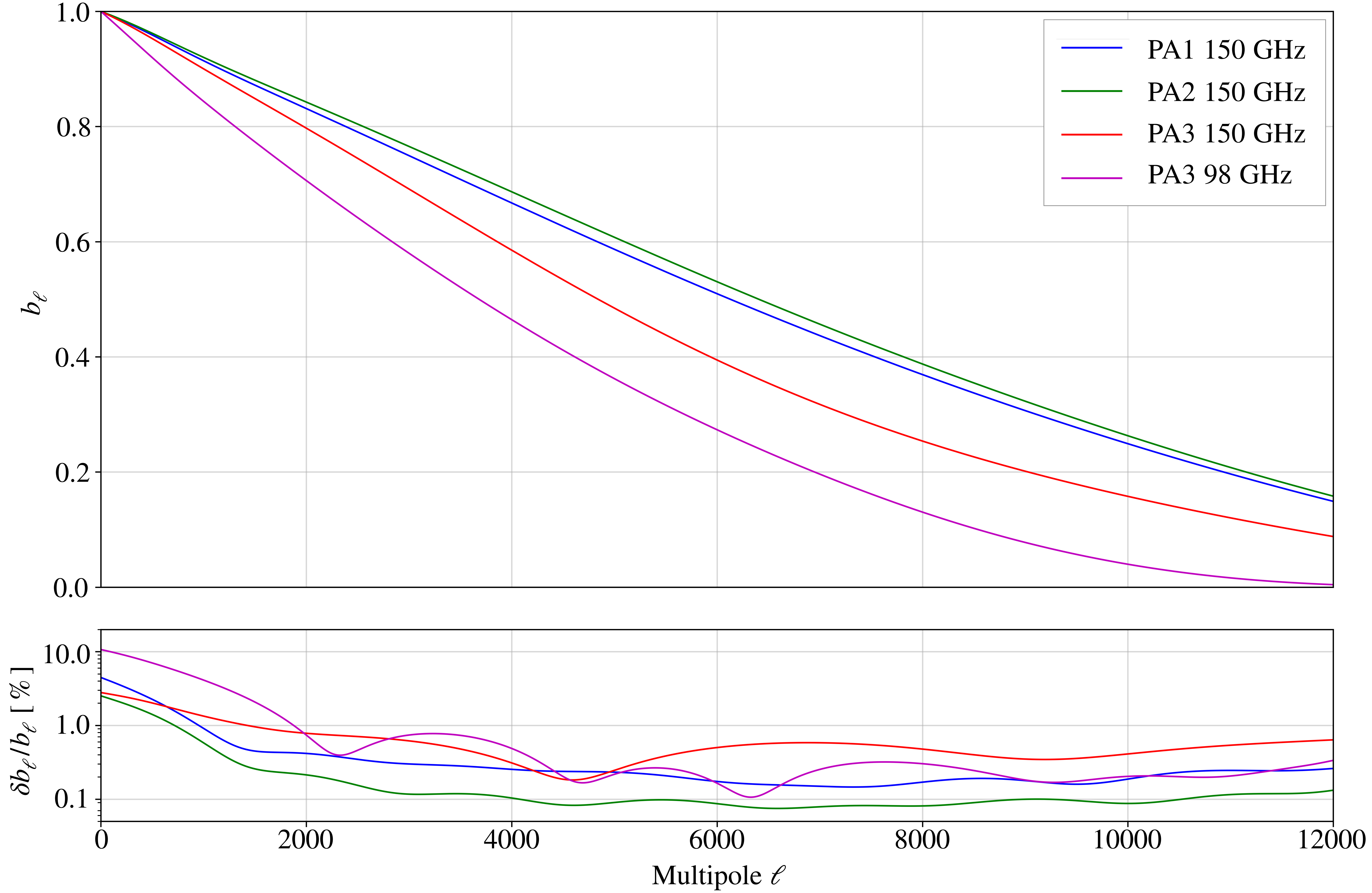
Beam Transforms



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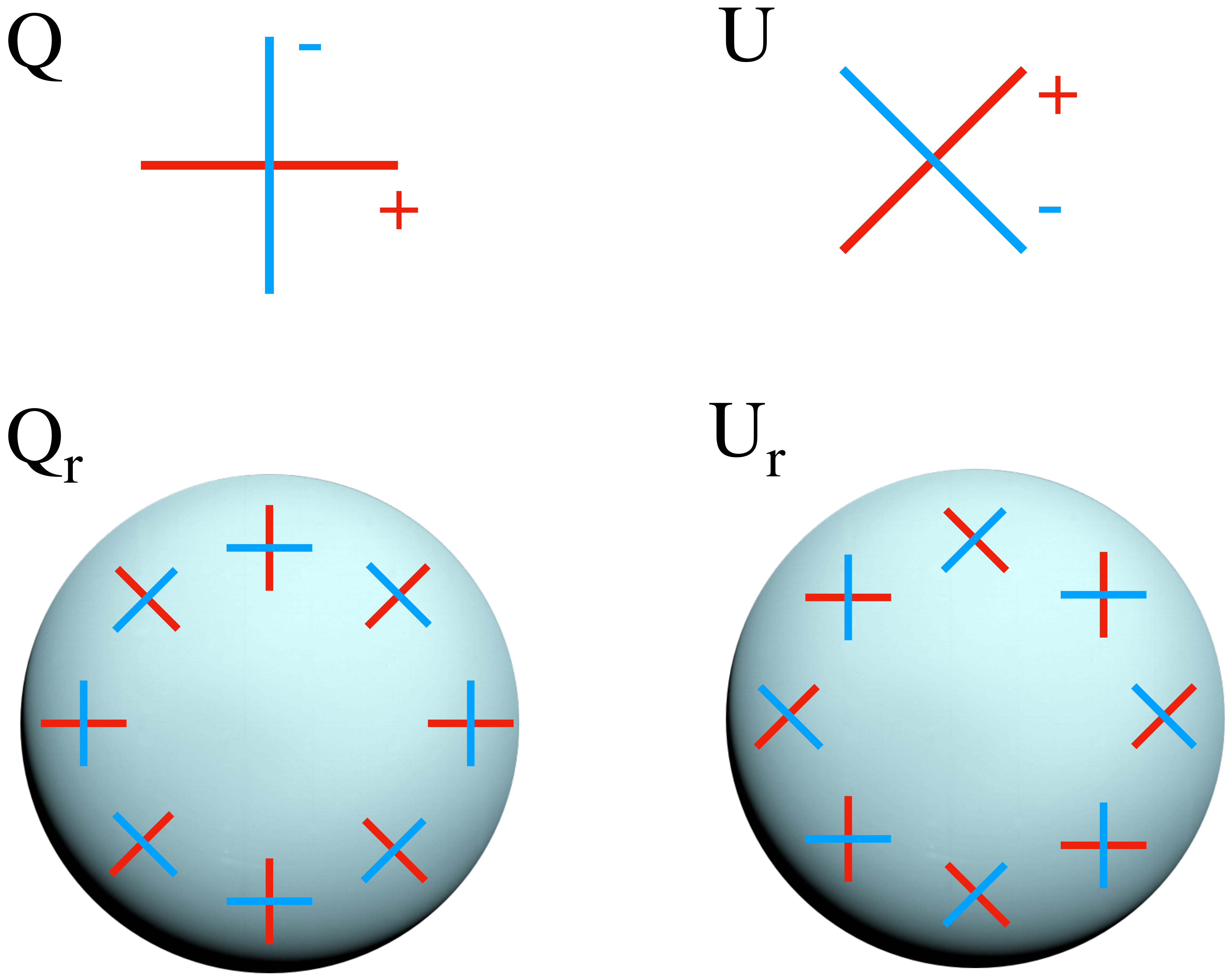
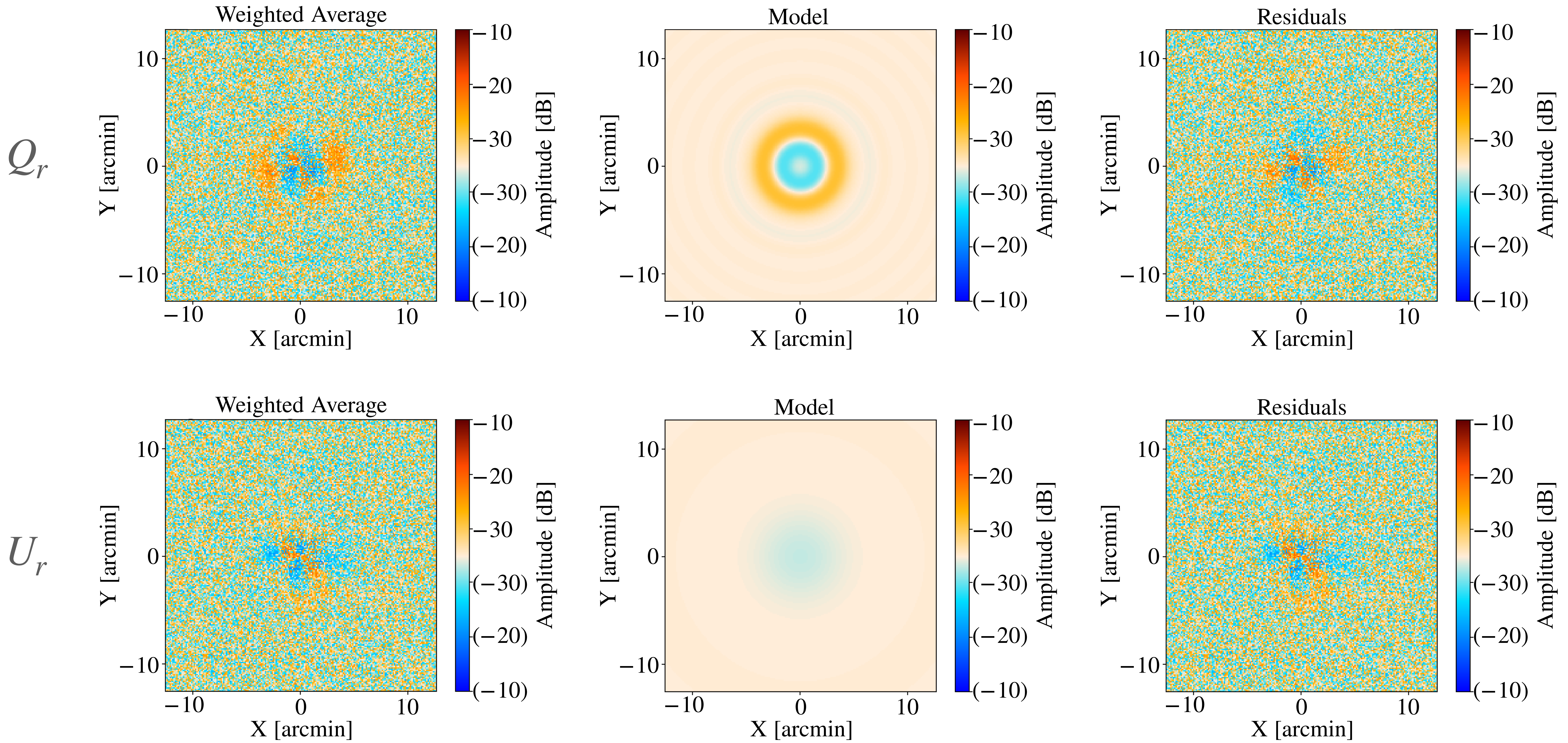
Stokes Parameters for Leakage Beam Measurements



Polarization Beam Maps



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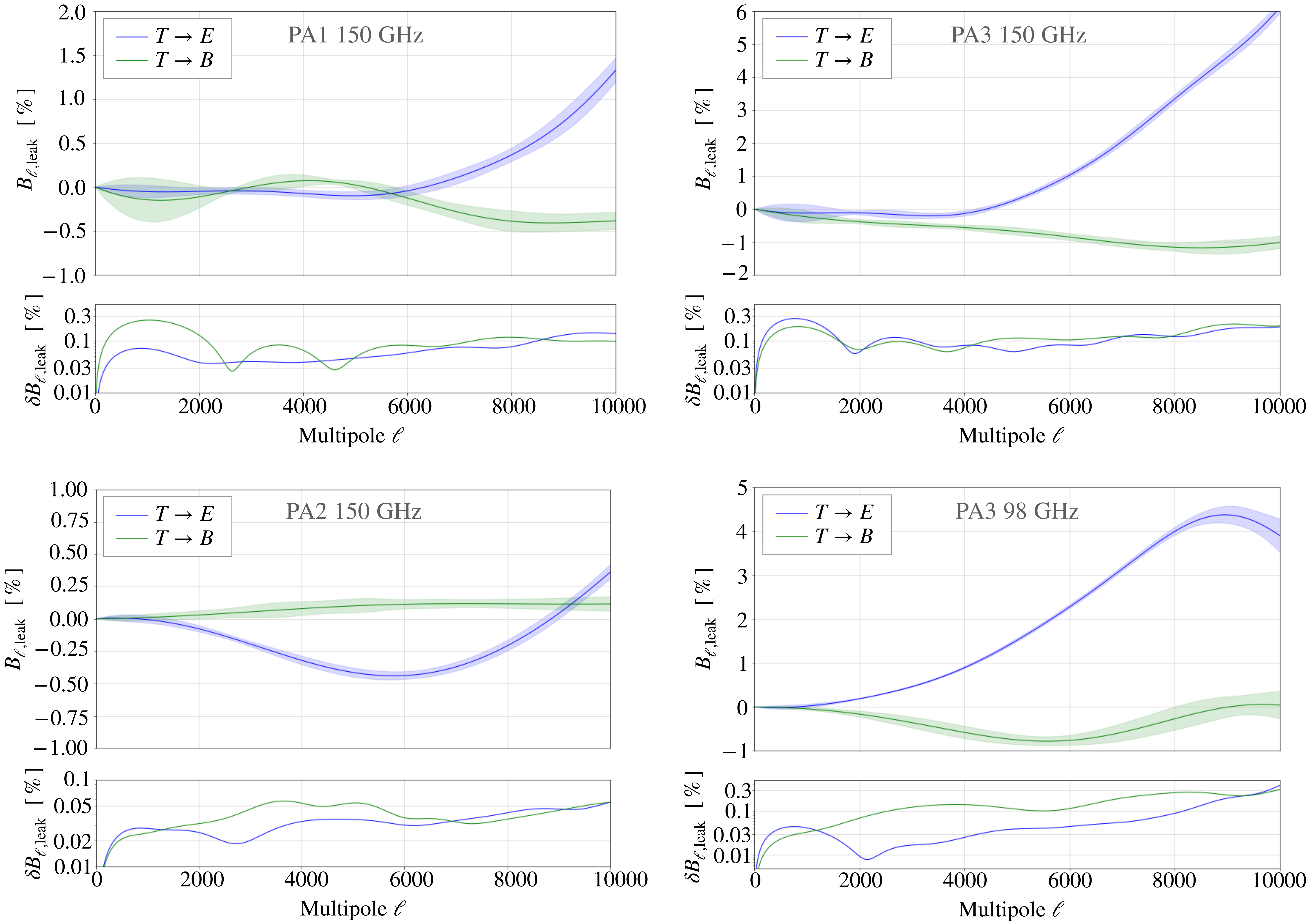
Main Beam Leakage



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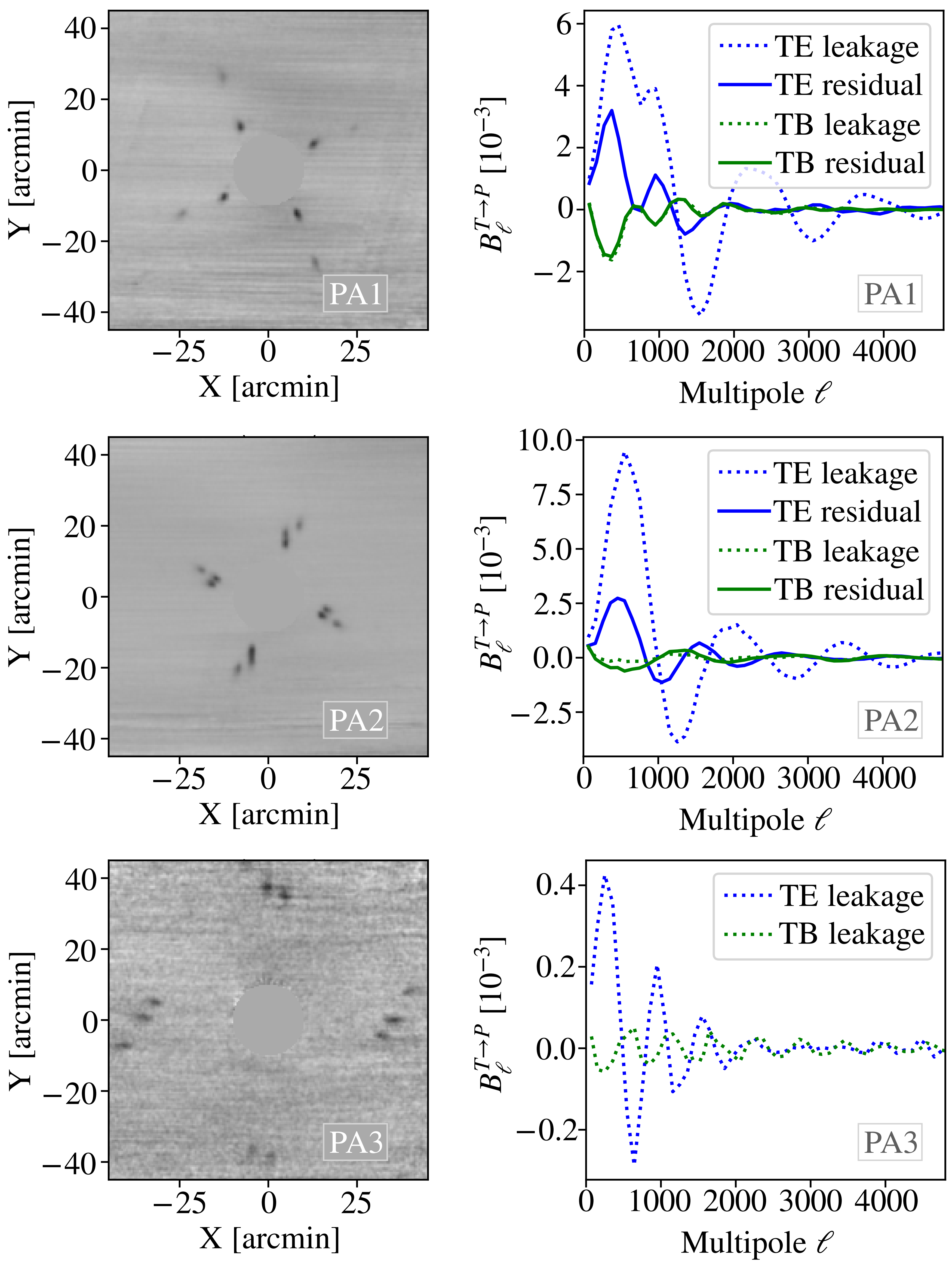
Sidelobes



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