A joint Planck and SPT-SZ measurement of CMB lensing cluster masses

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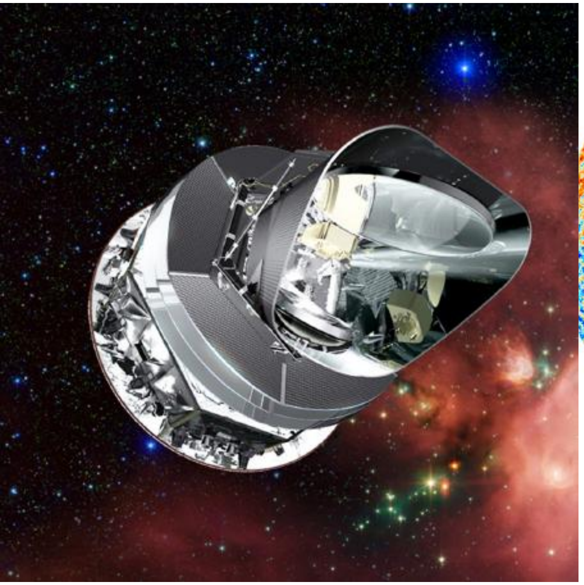

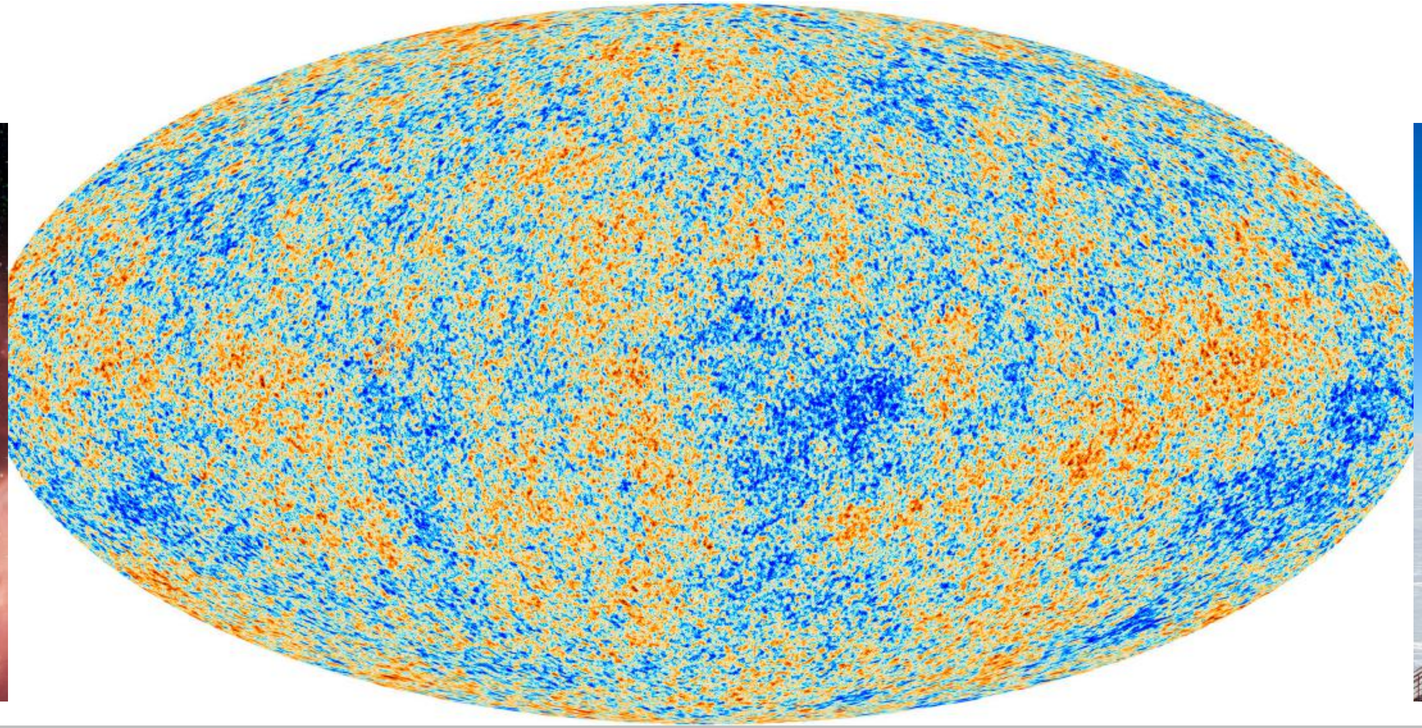

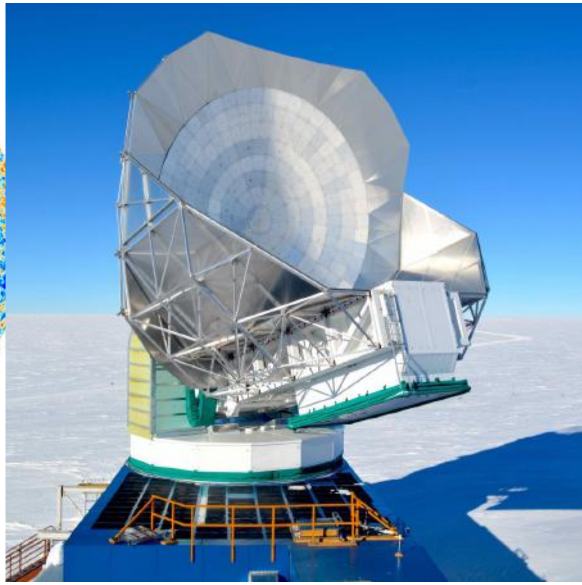

A joint Planck and SPT-SZ measurement of CMB lensing cluster masses

A quick introduction/reminder

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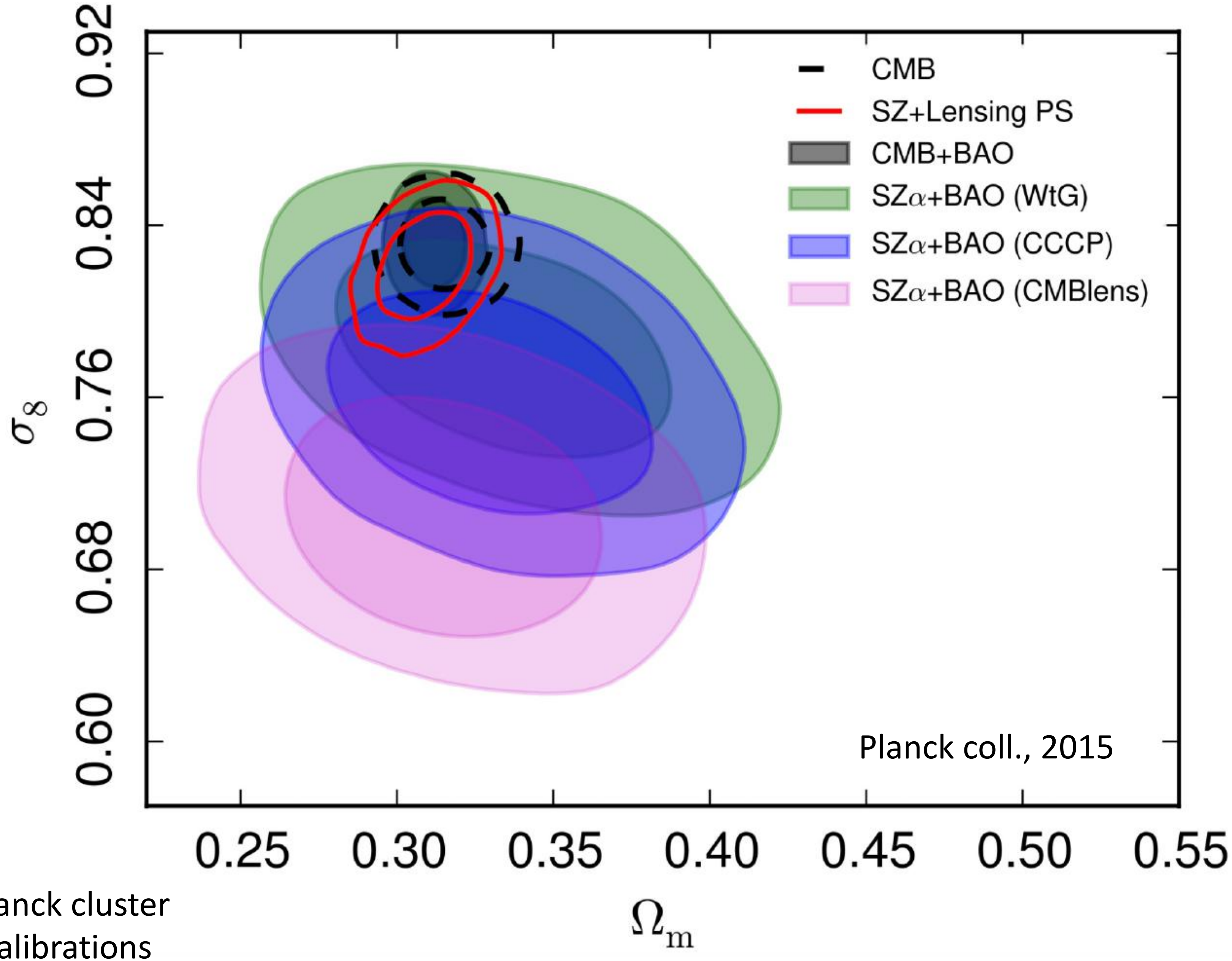
Cosmology with clusters

Mass function:

z, M <---> cosmo

- Redshift from optical survey
- Mass from?



Constraints on σ_8 and Ωm from Planck cluster count, based on different mass calibrations

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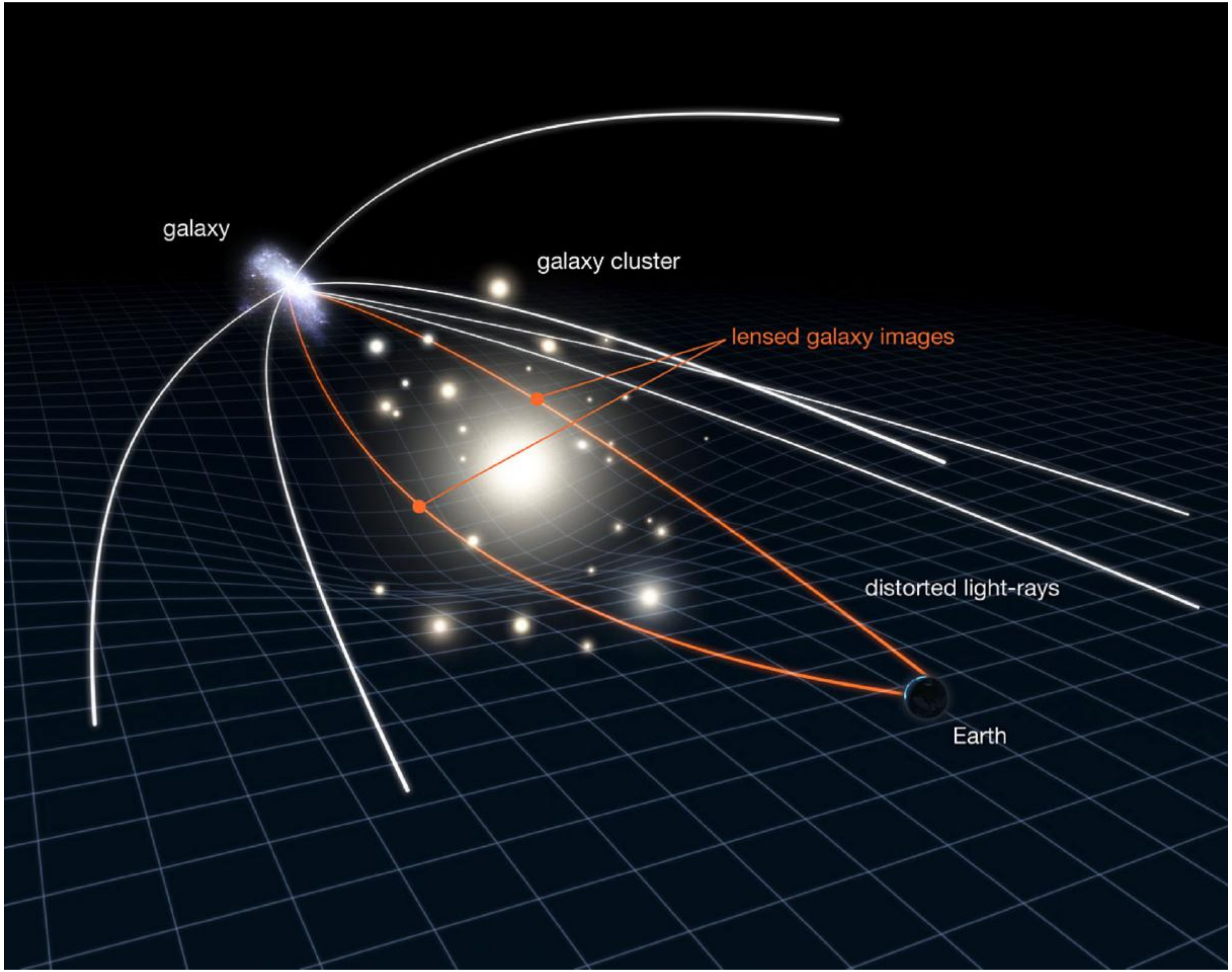
A quick introduction/reminder

Gravitational lensing

- **Visible light**: galaxies, 3% of total mass
- **X-rays**: hot intracluster gas, 12% of total mass

- **Gravitational lensing**: the above + dark matter (85%)

= 100% of total mass

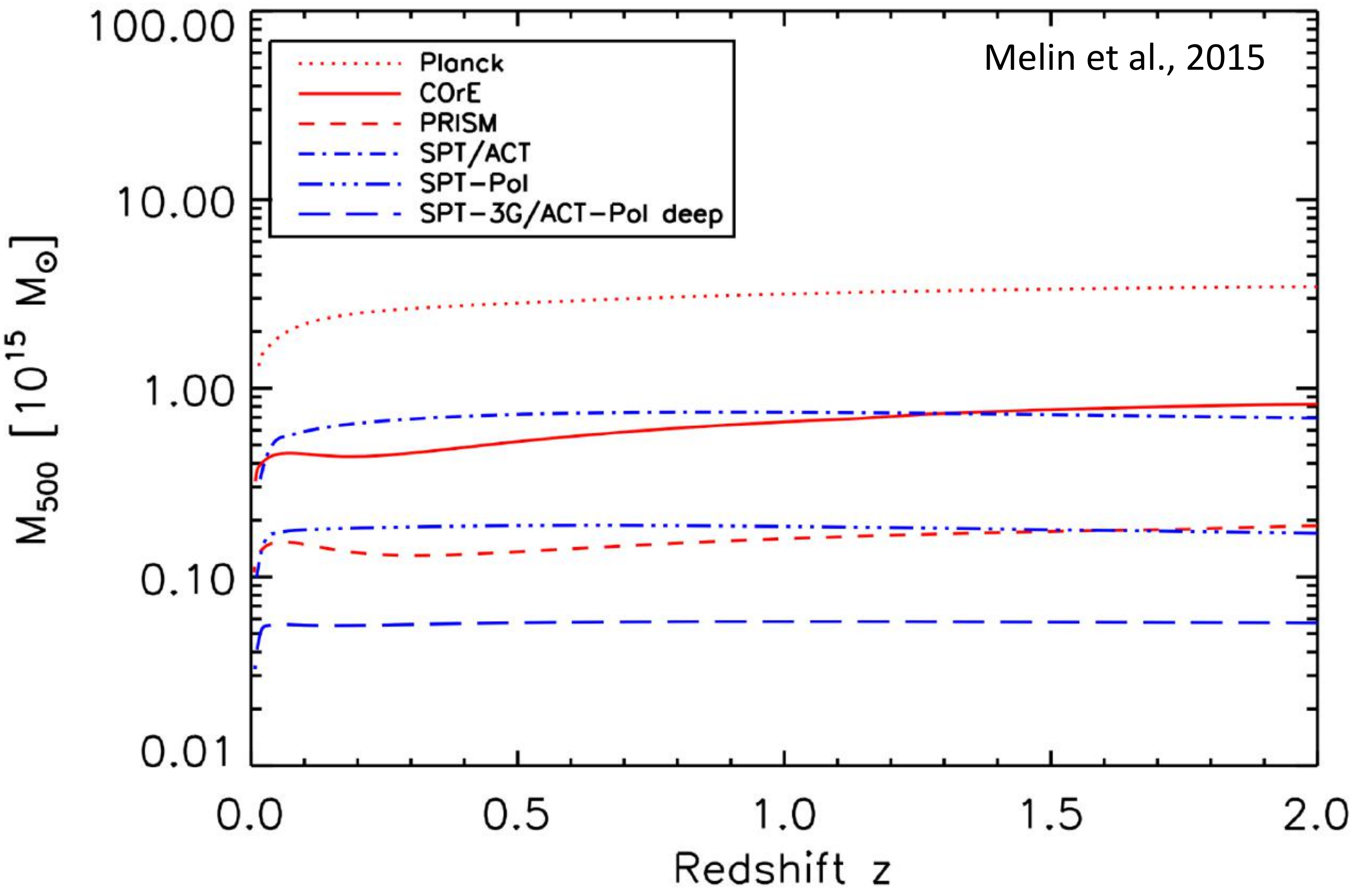


Lensing induced by a cluster on a background galaxy

Which source?

Two different types of sources:

- **Background galaxies**: need to find background galaxies, i.e. up to z~1
- **CMB**: the CMB is the source, i.e. up to z~1100



Mass measured with a signal to noise ratio of 1 as a function of redshift for CMB lensing

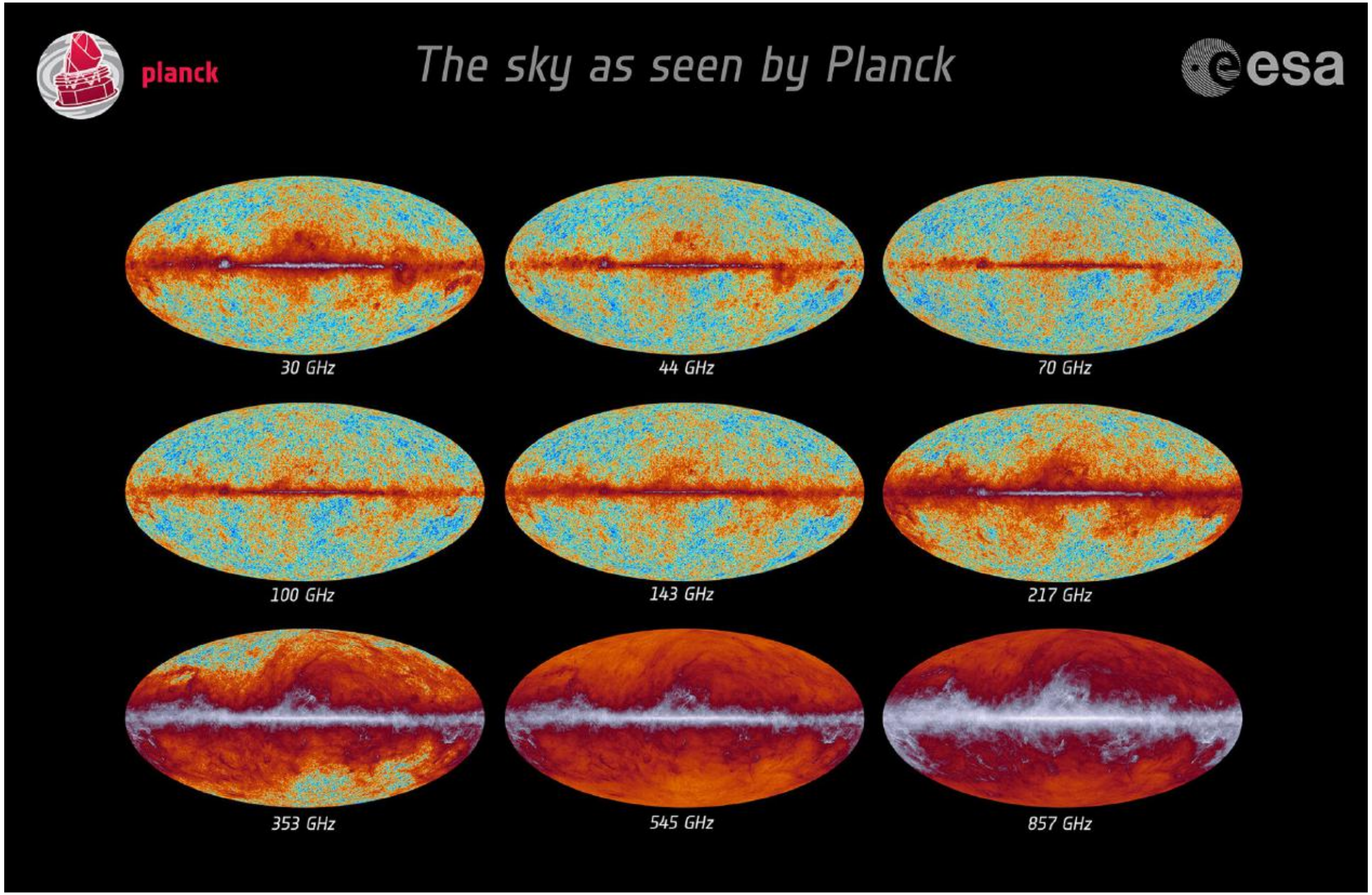
A joint Planck and SPT-SZ measurement of CMB lensing cluster masses

A quick introduction/reminder

Two surveys

- **Planck** survey:
  - All-sky (42000 deg²)
  - 5 arcmin beam
  - 6 frequencies (100, 143, 217, 353, 545, 857 GHz)
  - In space

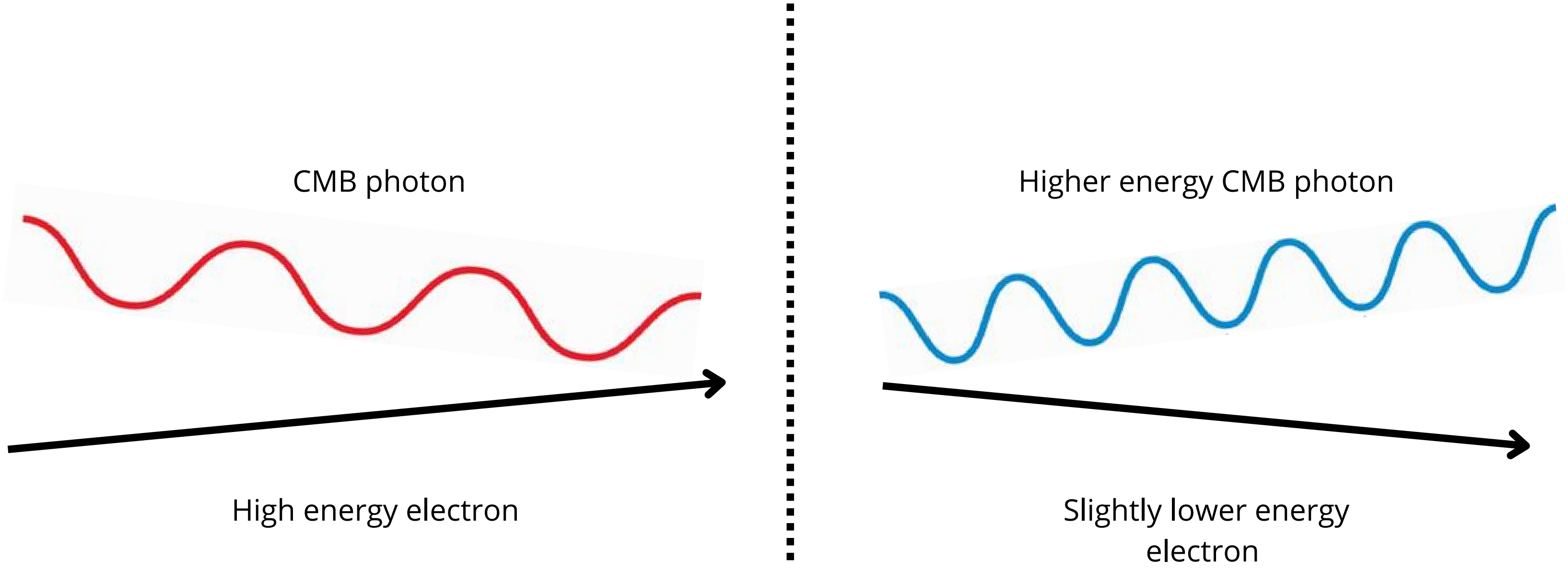
- **SPT-SZ** survey:
  - 2500 deg²
  - 1.75 arcmin beam
  - 3 frequencies (95, 150, 220 GHz)
  - Ground based



SZ effect

Sunyaev Zel’dovich effect:

- Inverse Compton **scattering** of CMB photons by hot intracluster gas electrons
- The CMB blackbody spectrum is shifted
- The detection of this shift is a hint to the presence of a cluster



Inverse Compton scattering

SZ effect

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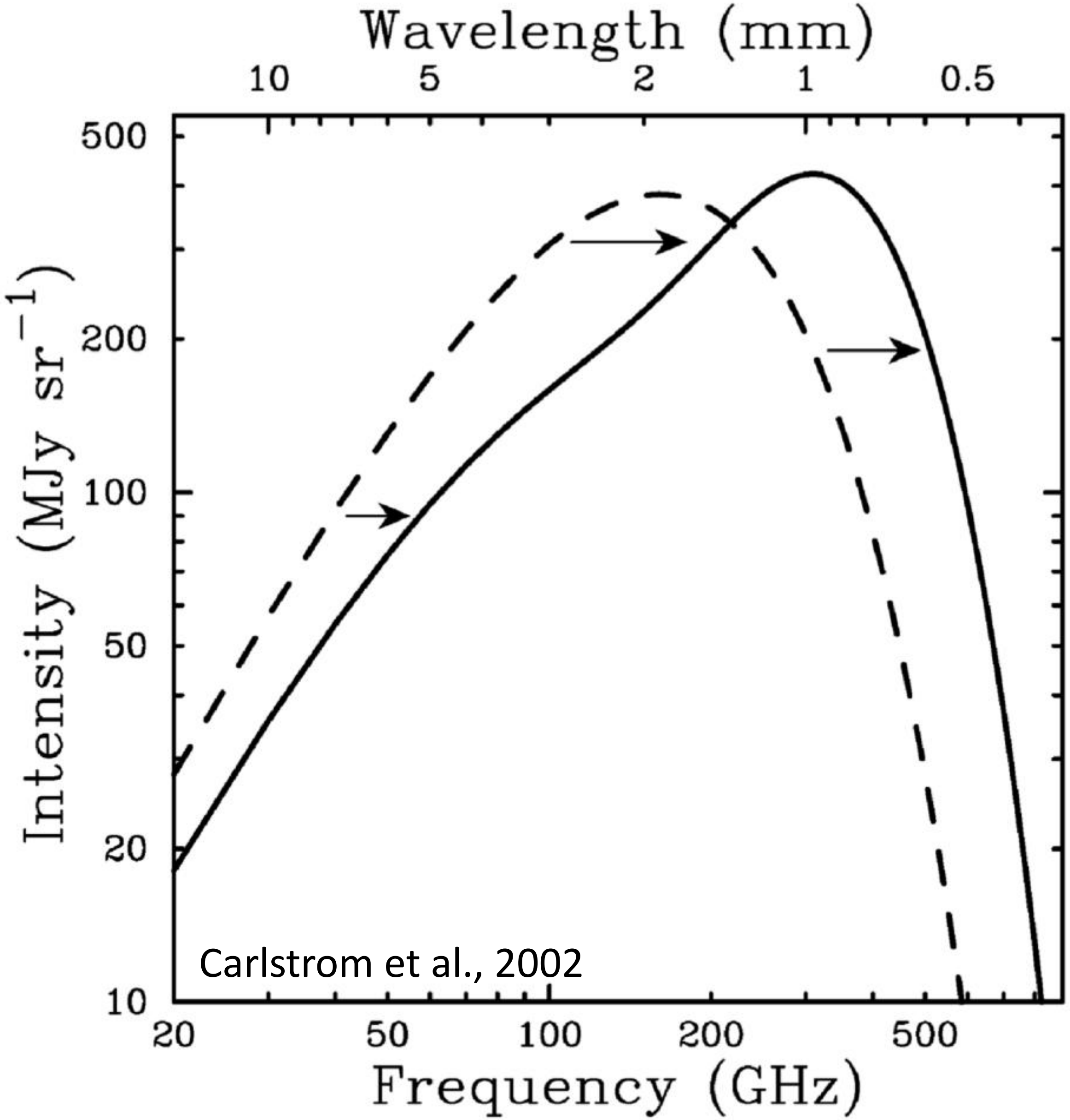

Sunyaev-Zel’dovich intensity **shift** with respect to frequency

SZ effect

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- Inverse Compton **scattering** of CMB photons by hot intracluster gas electrons
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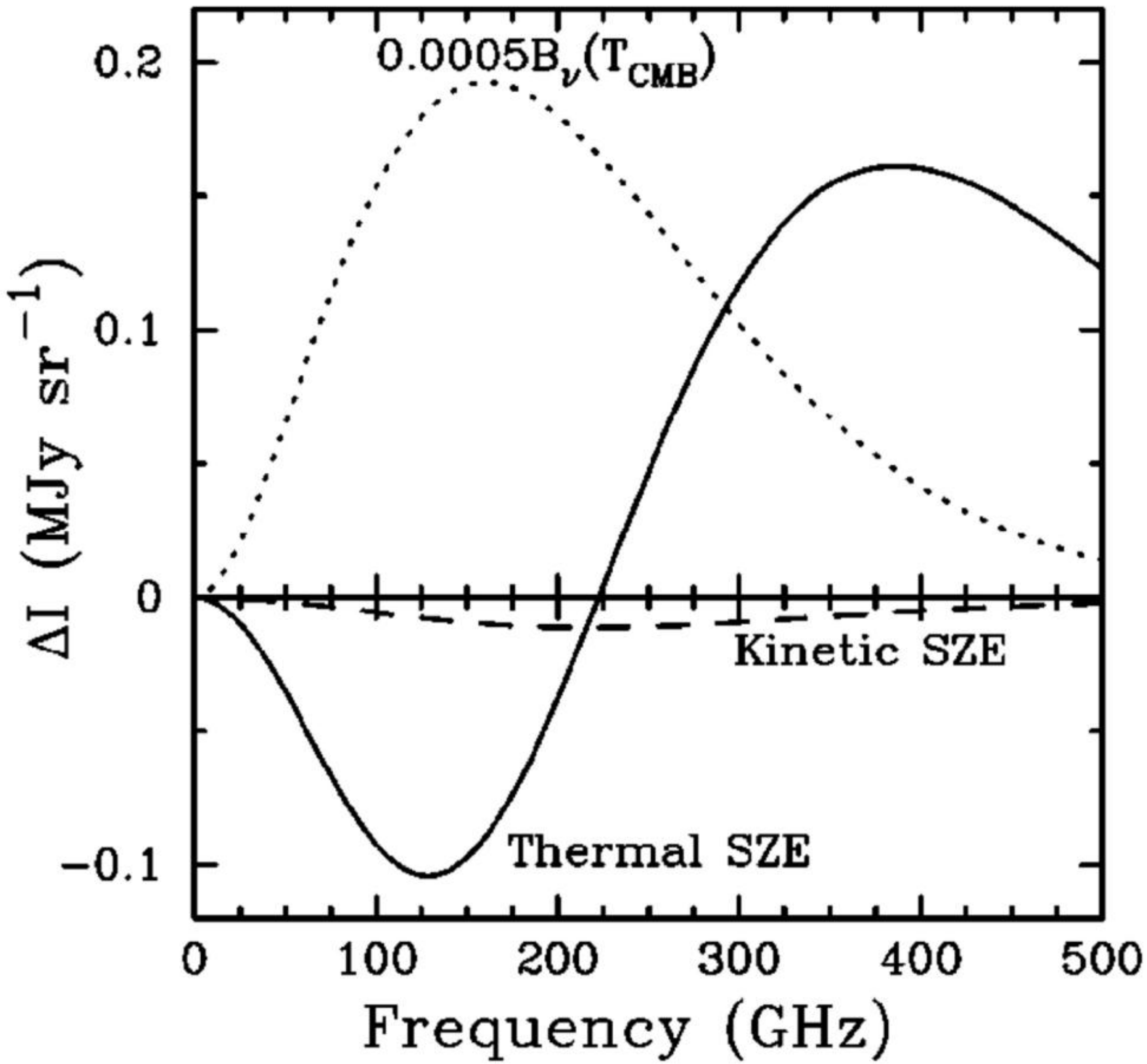
Carlstrom et al., 2002



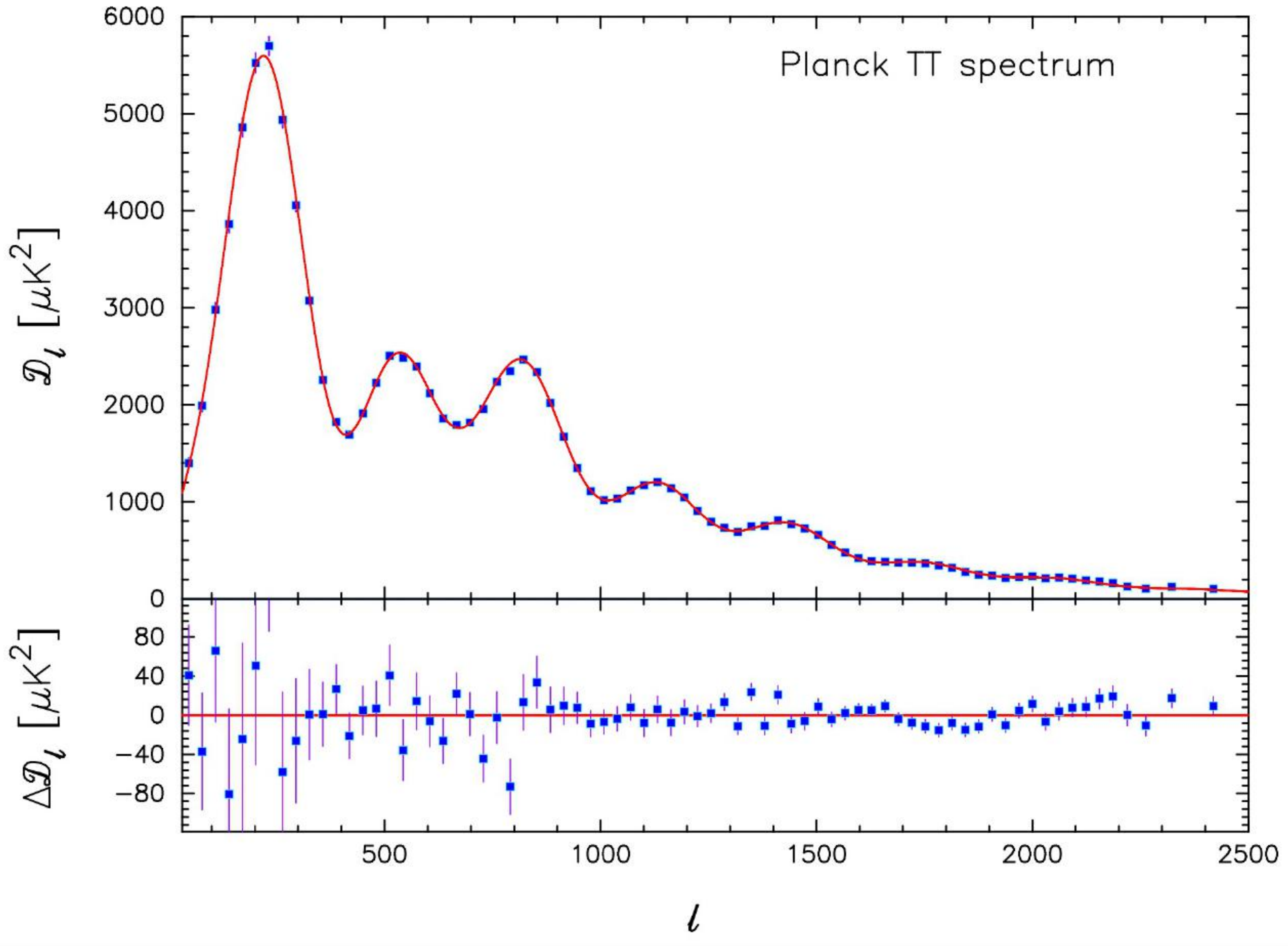
Intensity of the CMB with respect to frequency before and after the scattering

What to do then?

- We use **Planck** et **SPT-SZ**, two complementary data sets
- First steps: **separated** analysis for each data set
  - Analysis on simulated maps
  - Apply the method to real data
- We then **combine** the Planck and SPT-SZ data sets
  - First simulation
  - Then real data

Map simulation

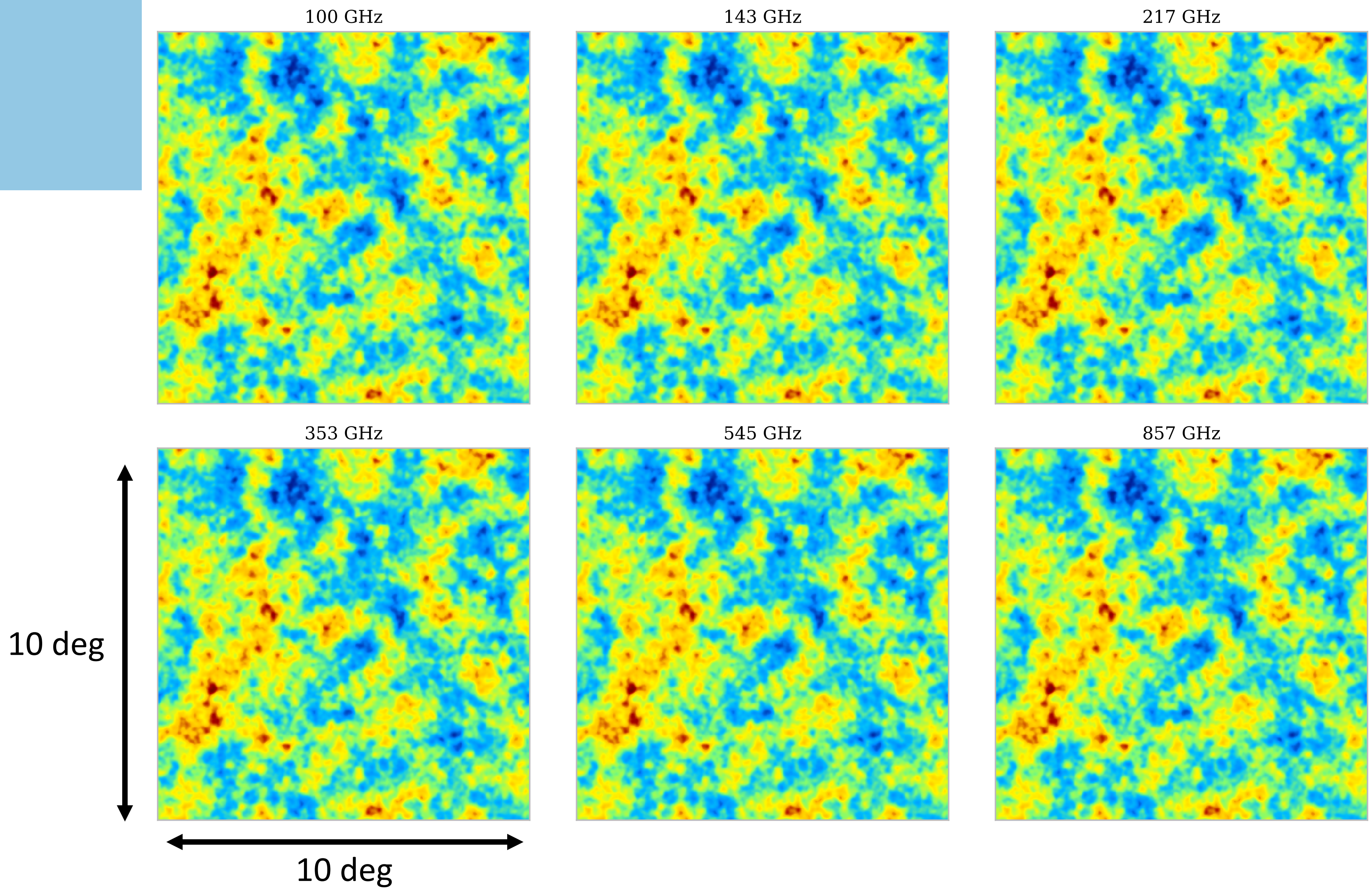
- **CMB**: Gaussian random field from Planck CMB power spectrum
- **Cluster lens**: Navarro-Frenk-White (NFW) density profile
- **SZ effect**: generalized NFW (GNFW) profile (Arnaud et al. 2010)
- **Instrumental point spread function** (PSF)
- **Instrumental noise**



Planck CMB TT angular power spectrum

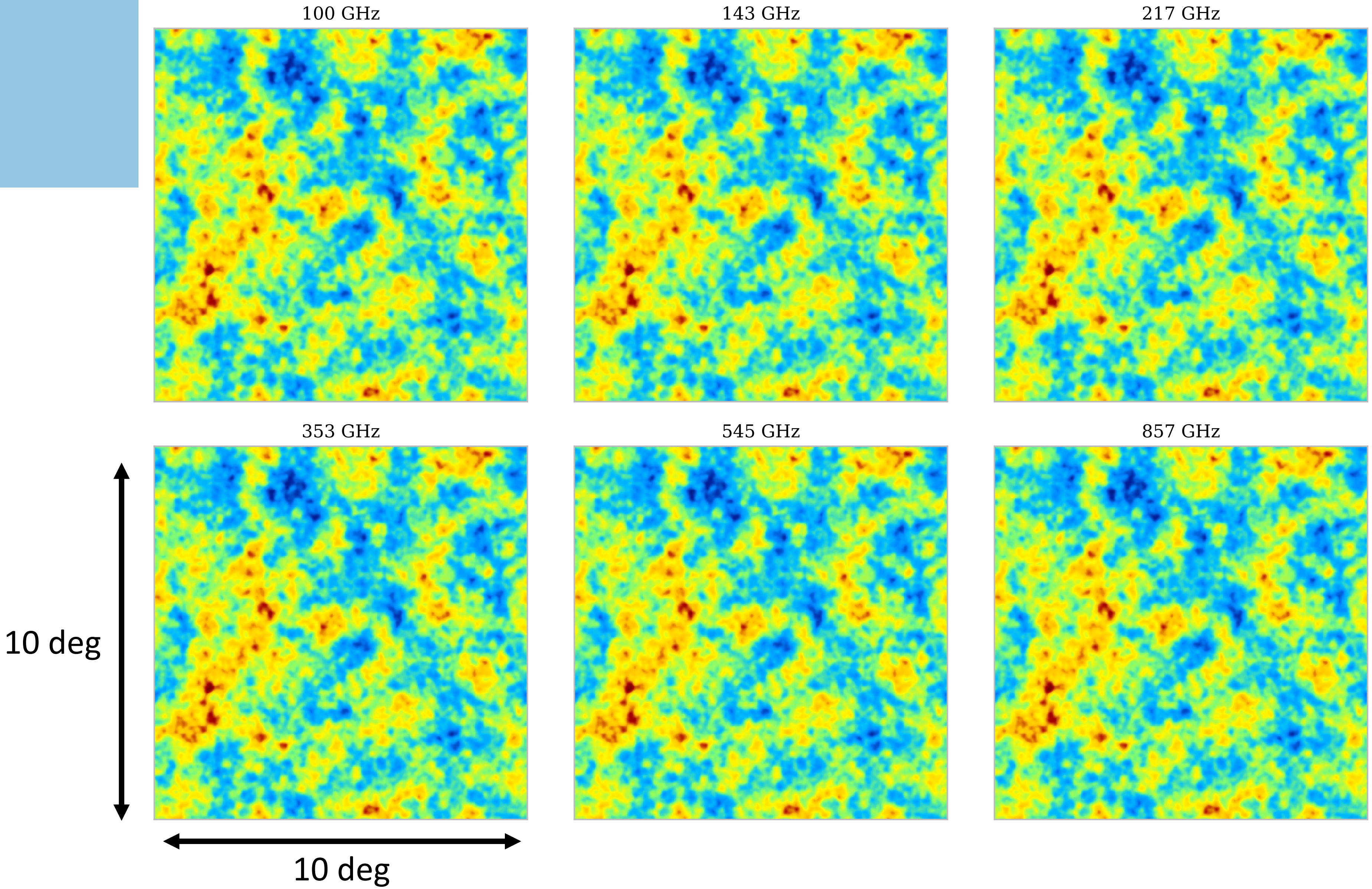
Planck simulation

- CMB



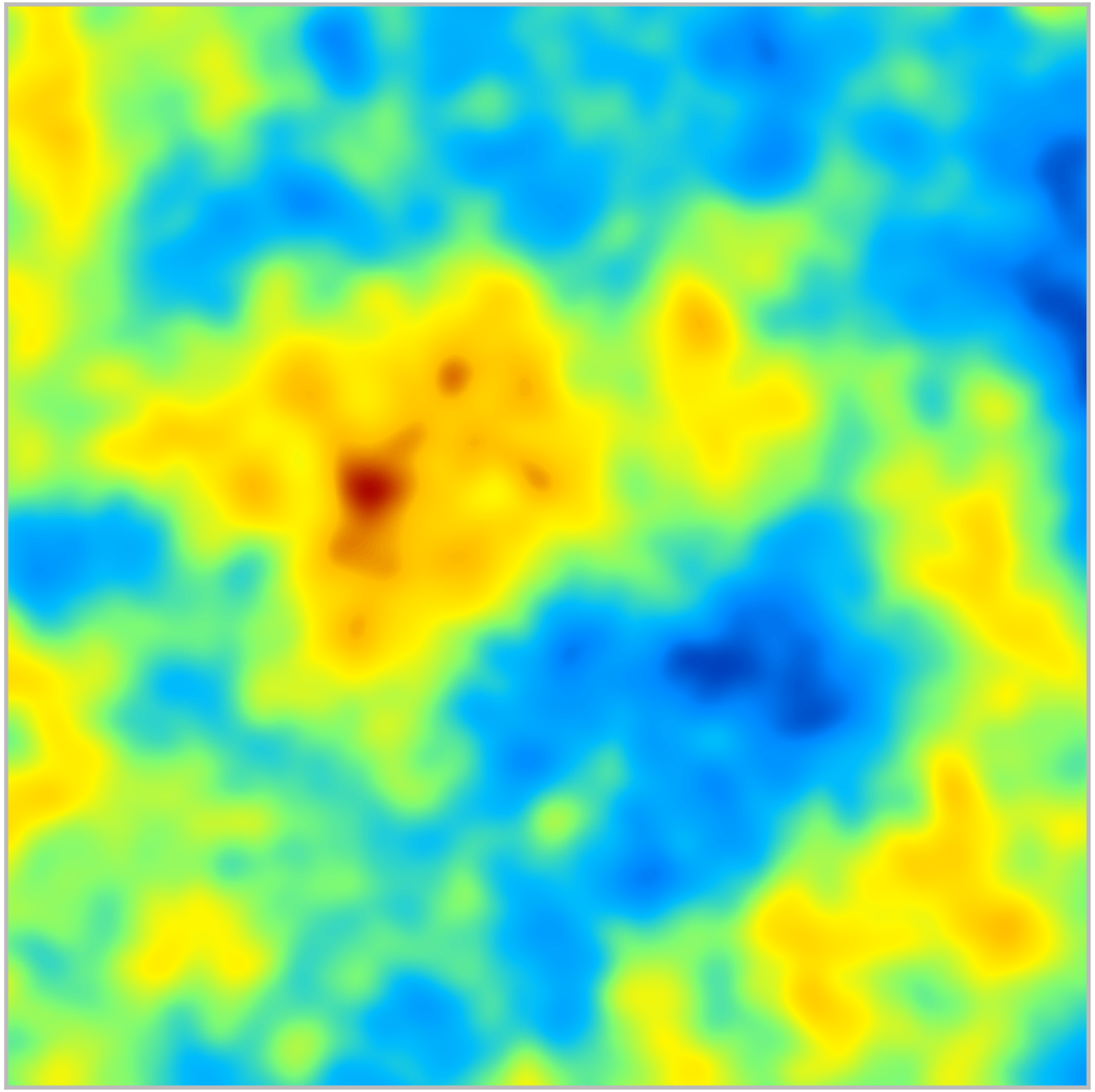
Planck simulation

- CMB
- Cluster lens



Planck simulation

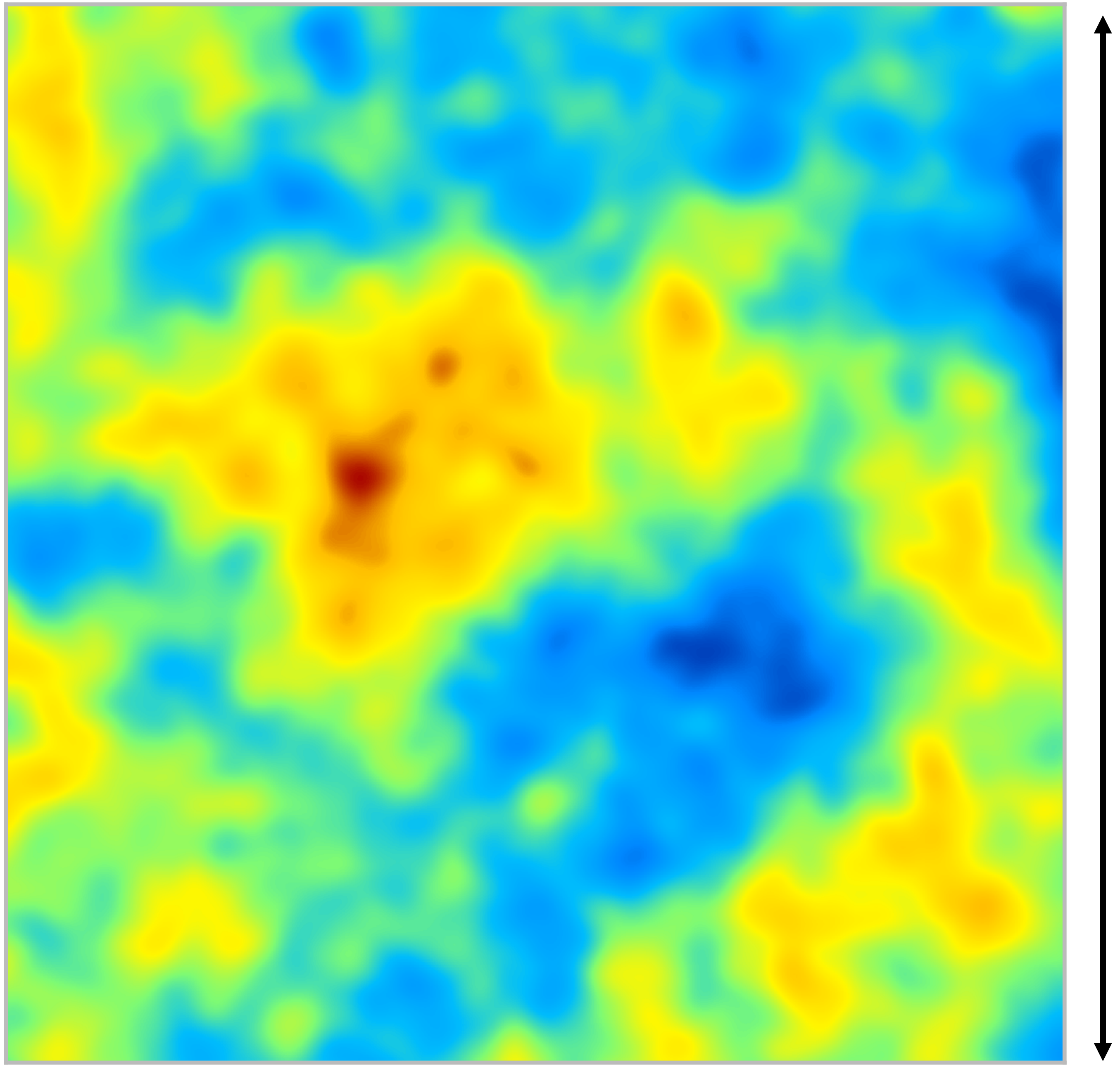
- CMB
- No lensing



2.9 deg

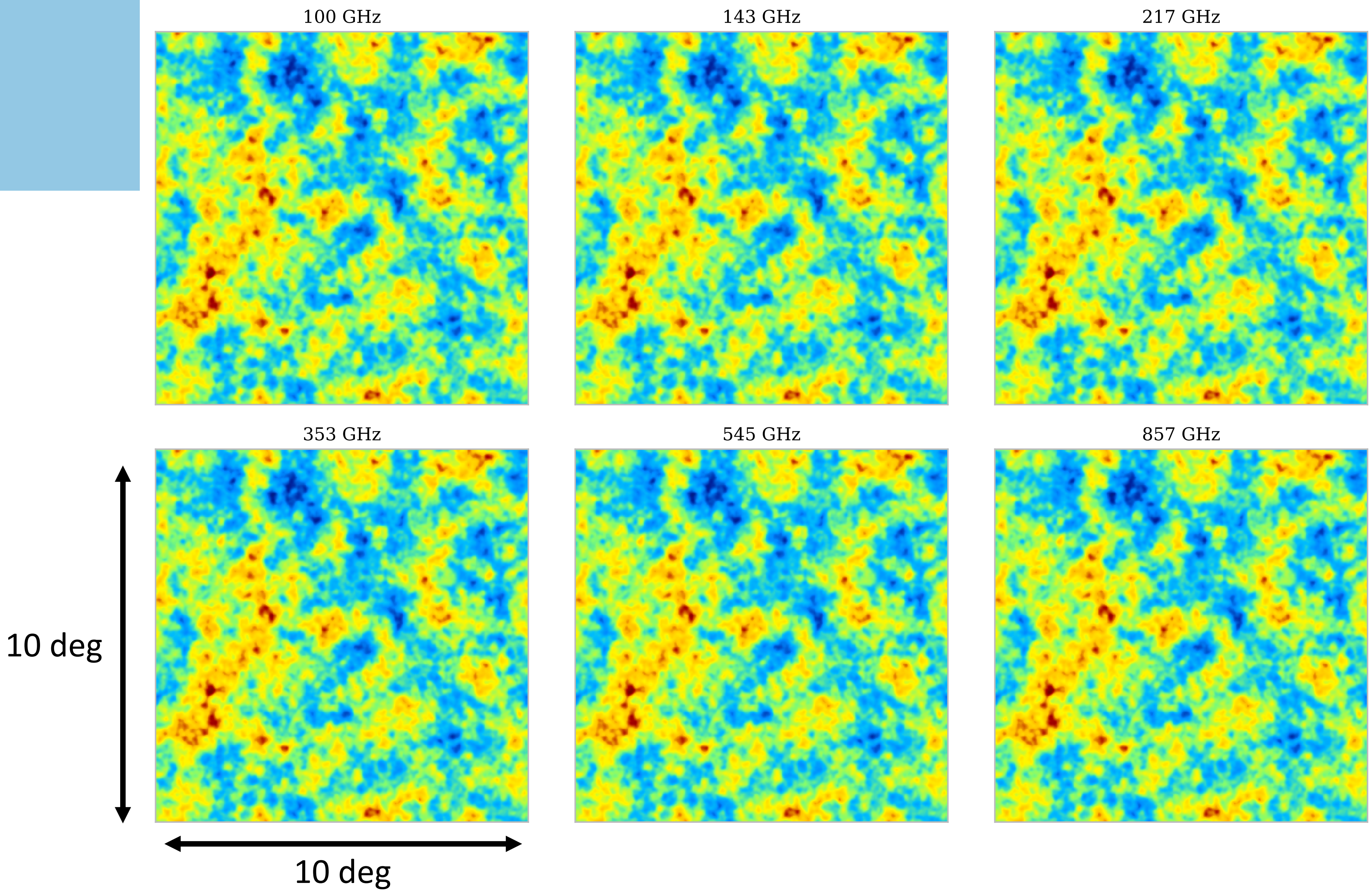
Planck simulation

- CMB
- Lensing



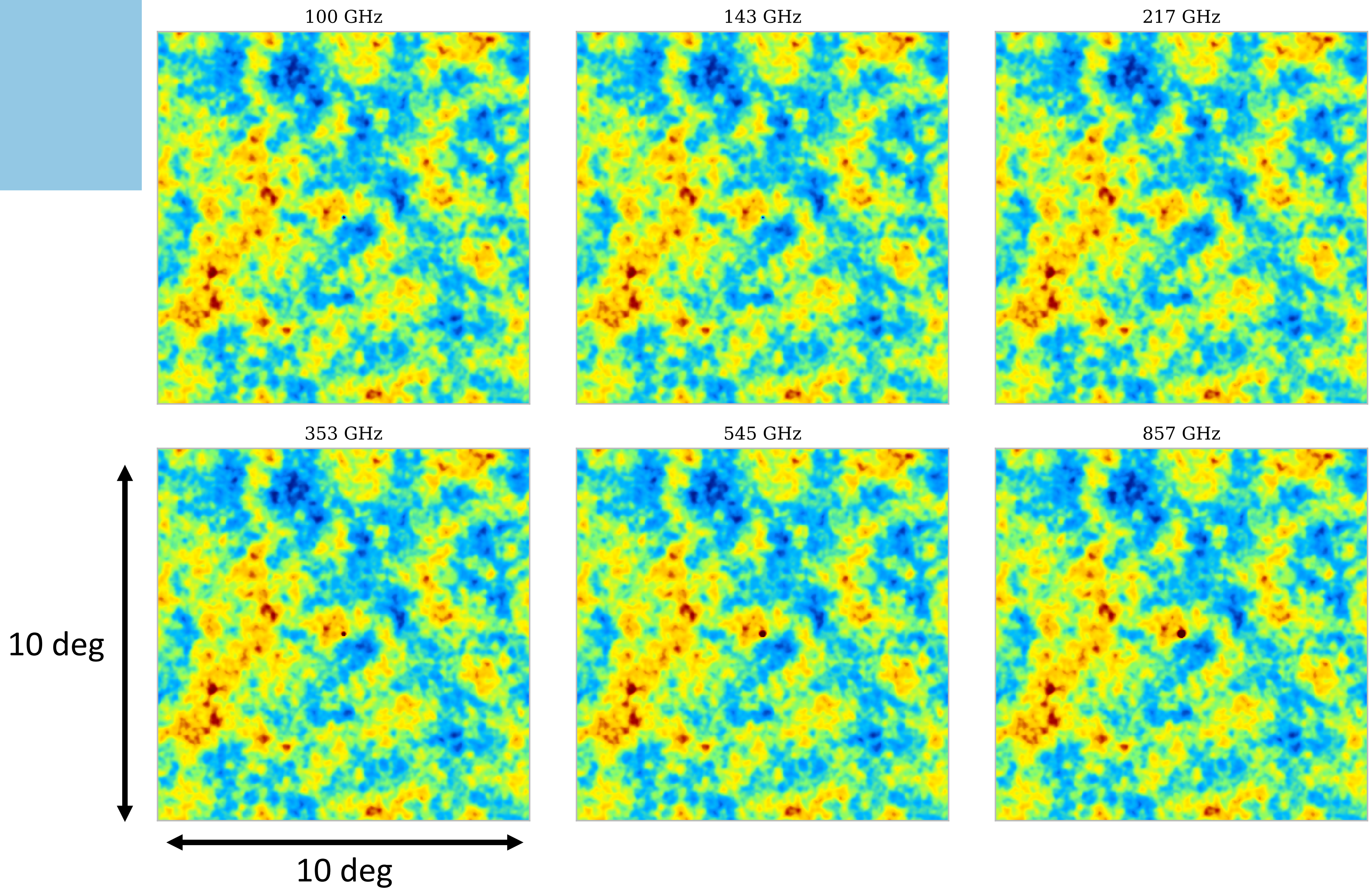
Planck simulation

- CMB
- Cluster lens



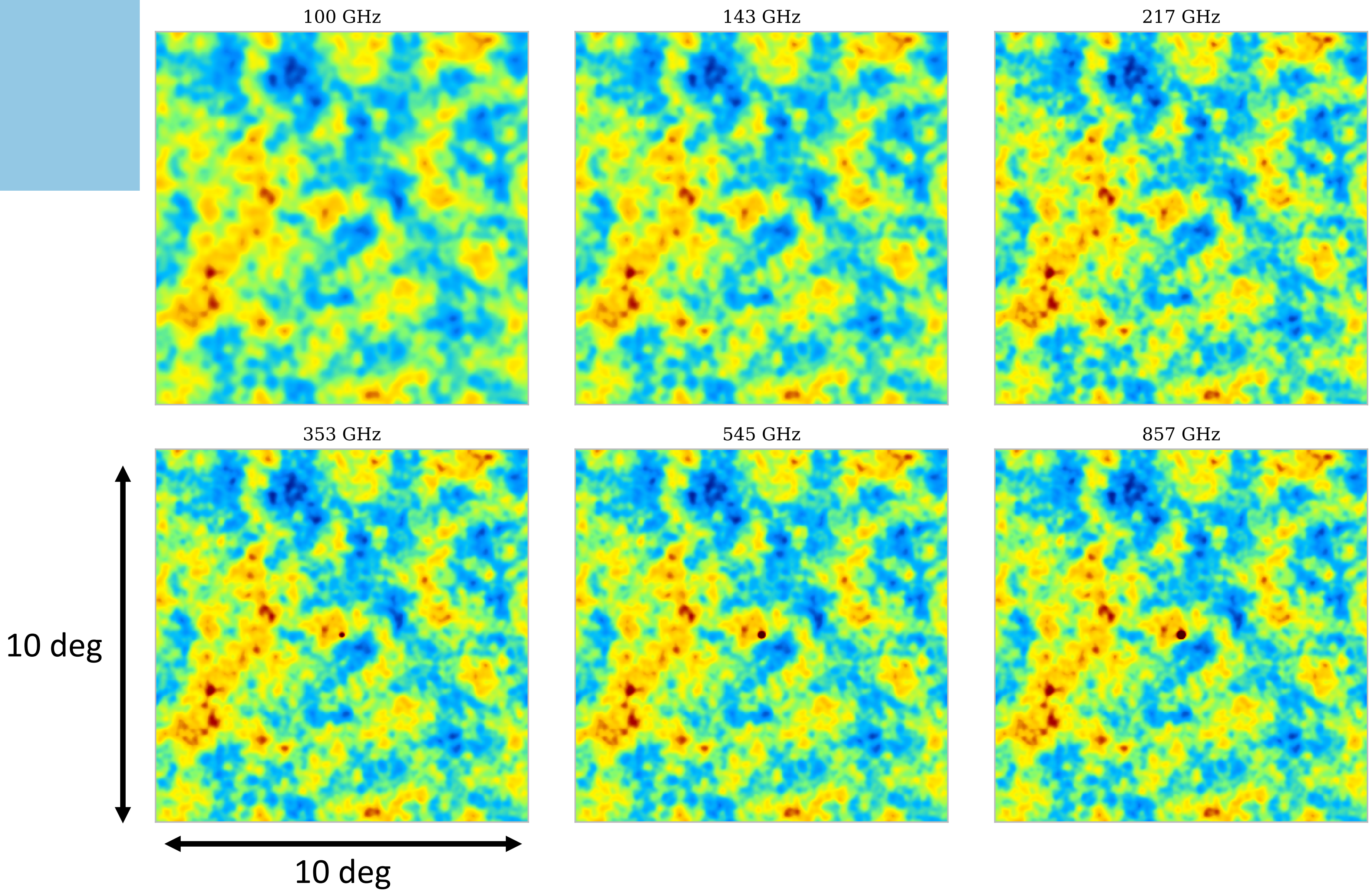
Planck simulation

- CMB
- Cluster lens
- SZ effect



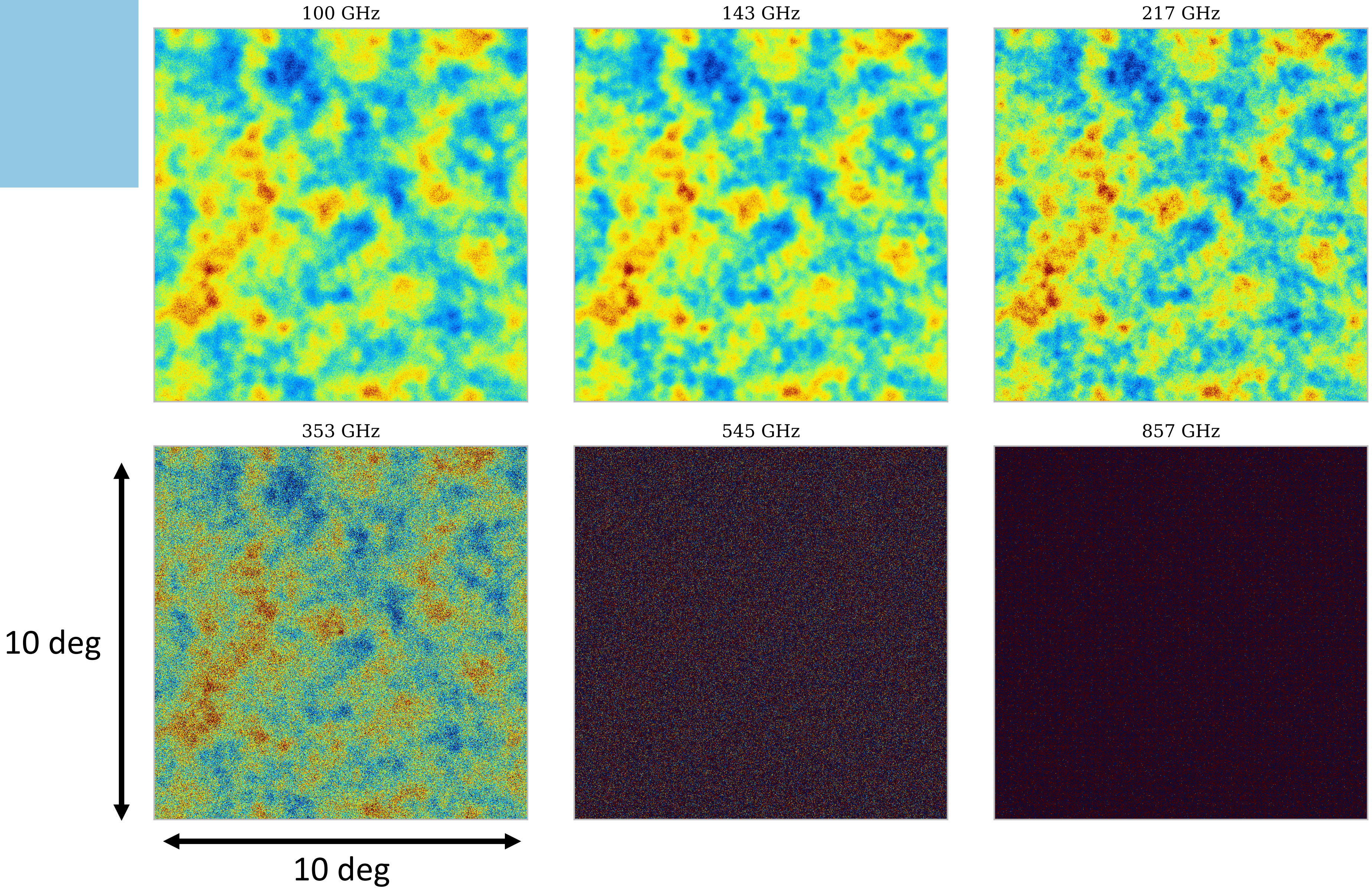
Planck simulation

- CMB
- Cluster lens
- SZ effect
- Instrumental PSF



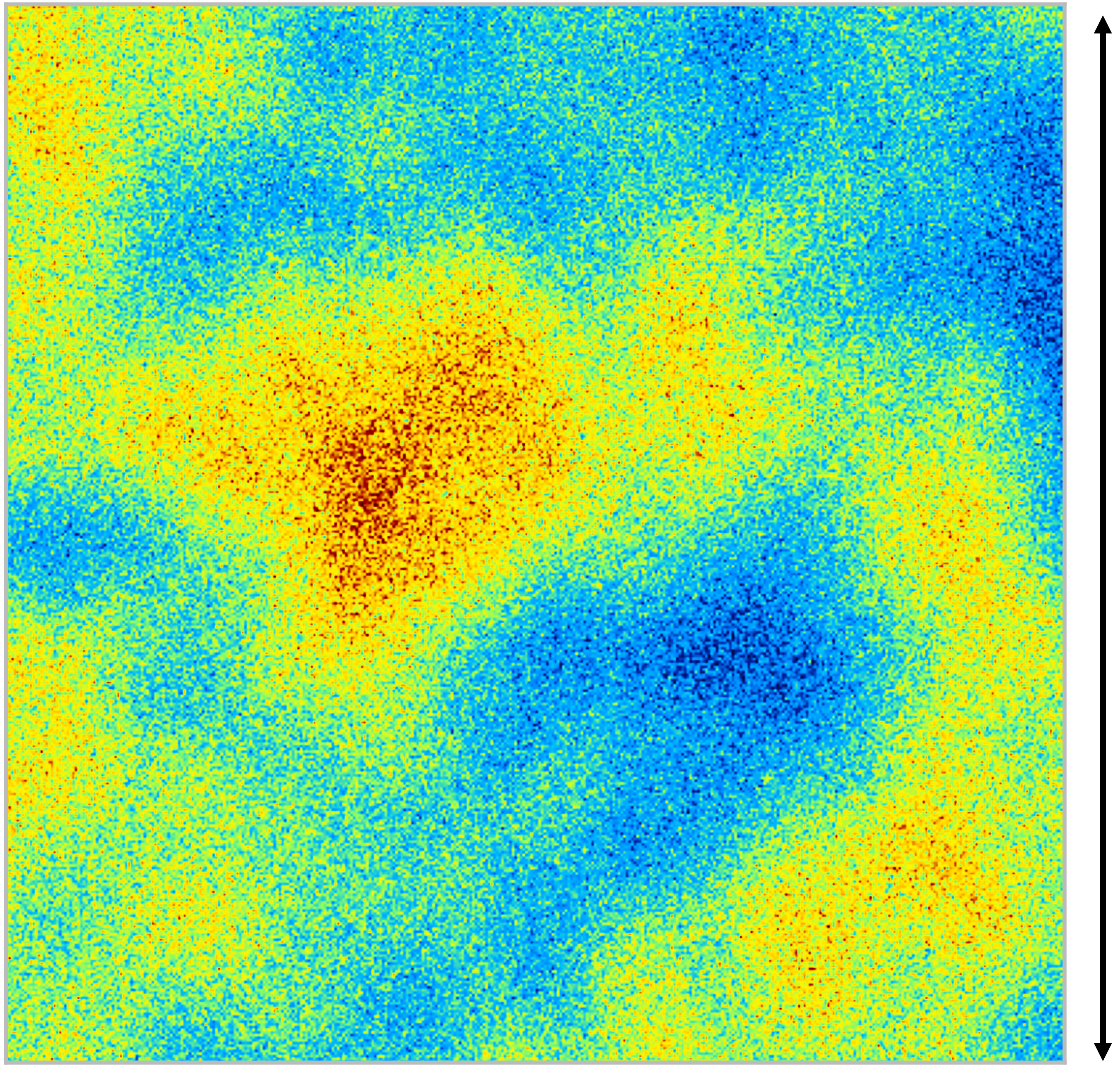
Planck simulation

- CMB
- Cluster lens
- SZ effect
- Instrumental PSF
- Instrumental noise



Planck simulation

- 100 GHz map
- No SZ effect
- No lensing



Planck simulation

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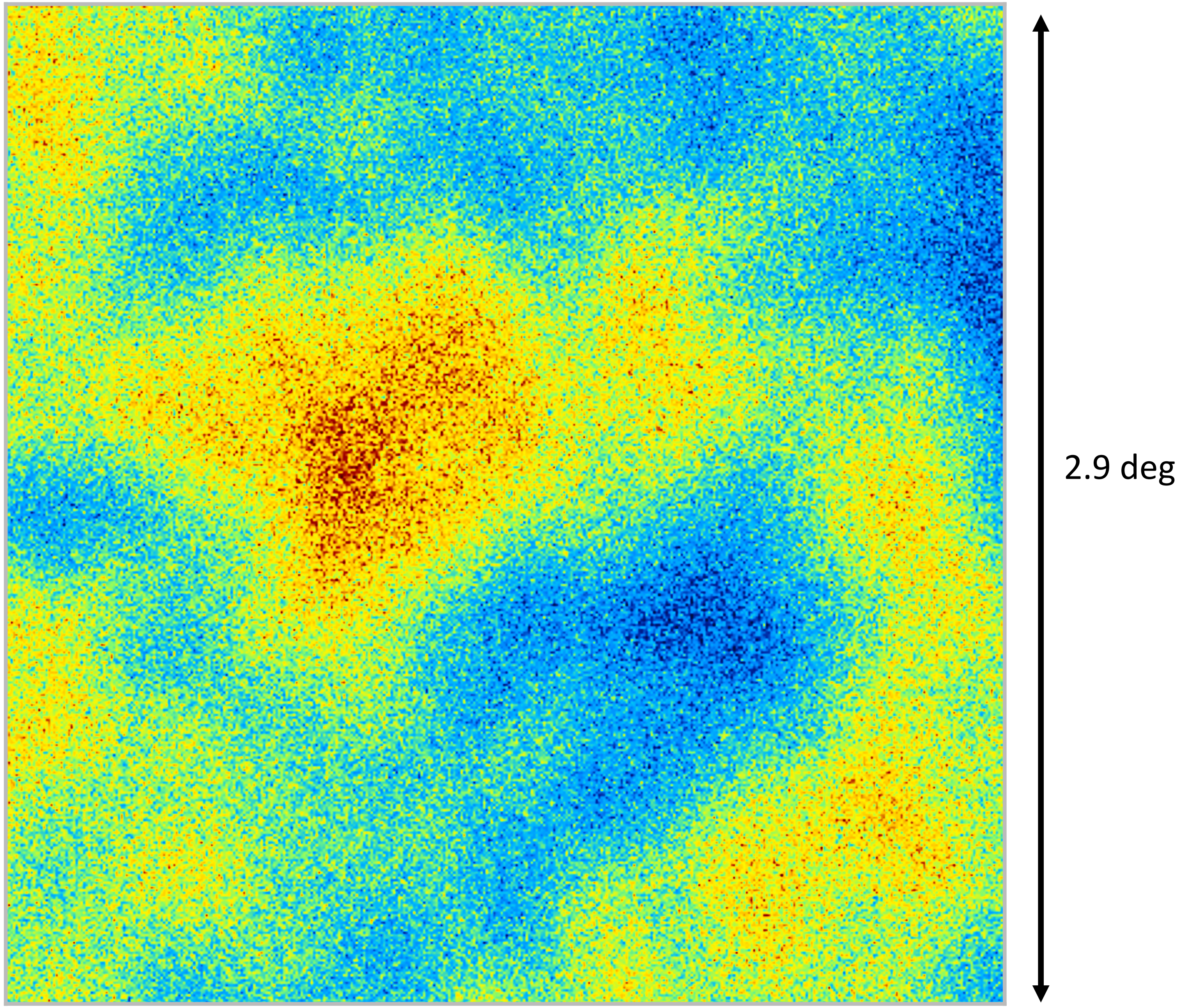
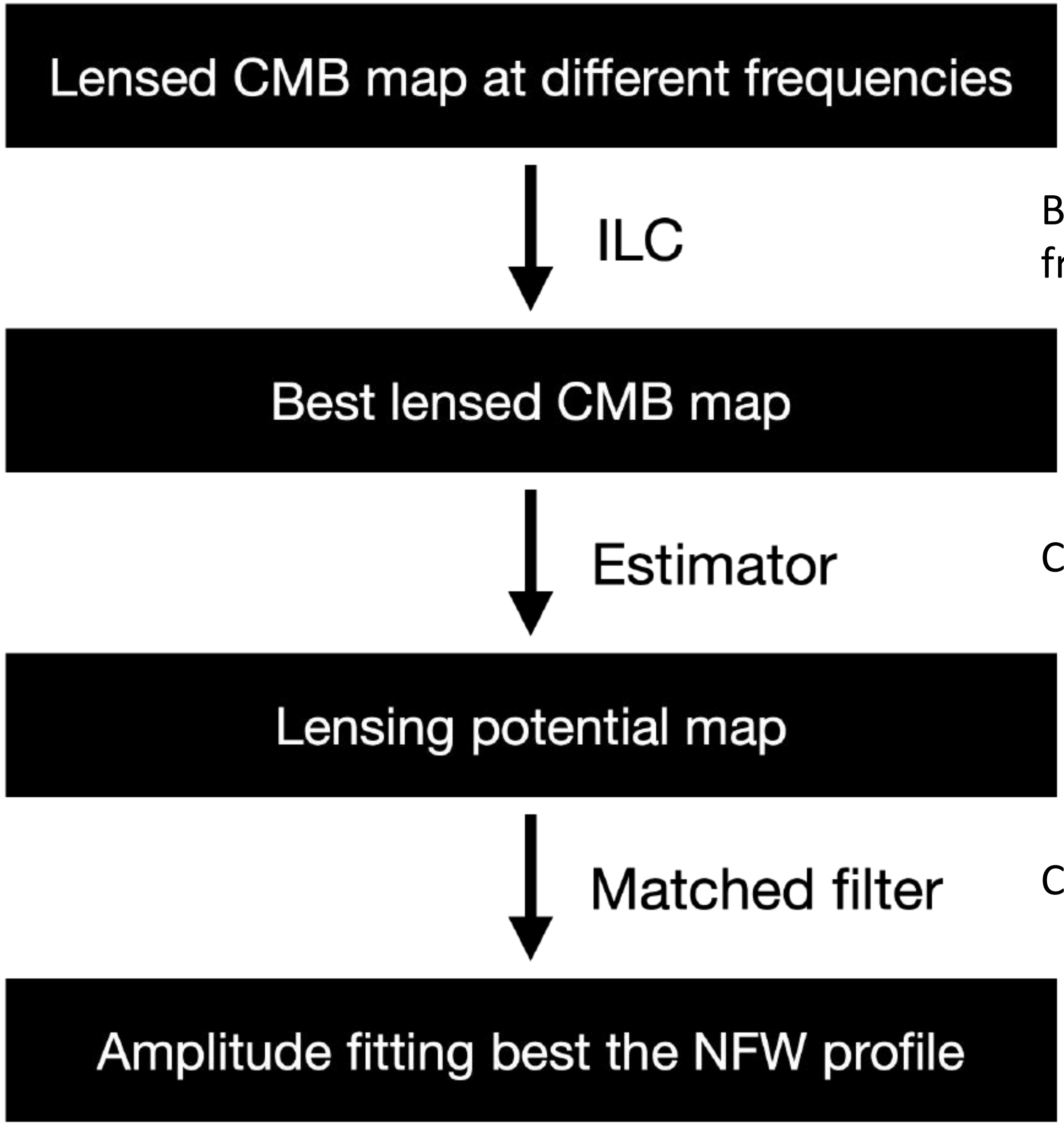


Data analysis

- **Internal Linear Combinations** (ILC), Remazeilles et al., 2011
- **Lensing estimator**, Hu & Okamoto, 2002
- **Matched filter**, Melin et al., 2015



Needed information

Beams, transfer functions, frequency-band responses

Cluster positions

Cluster masses and redshifts

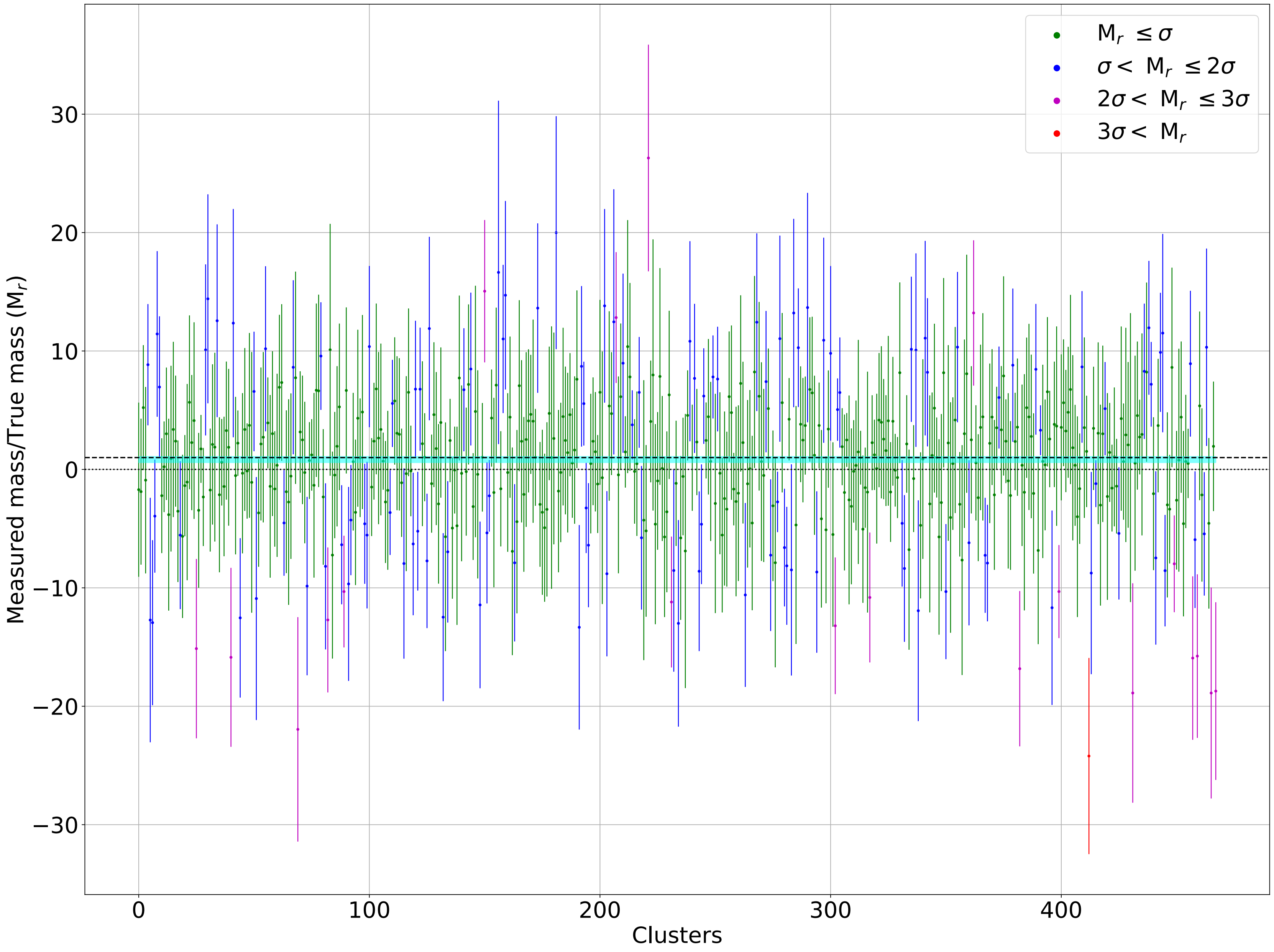
One Planck simulation

Each point and associated error bar correspond to an **individual cluster mass measurement**, for a total of 468.

Averaging these measurements provides

<Mr> = 0.84 ± 0.25,

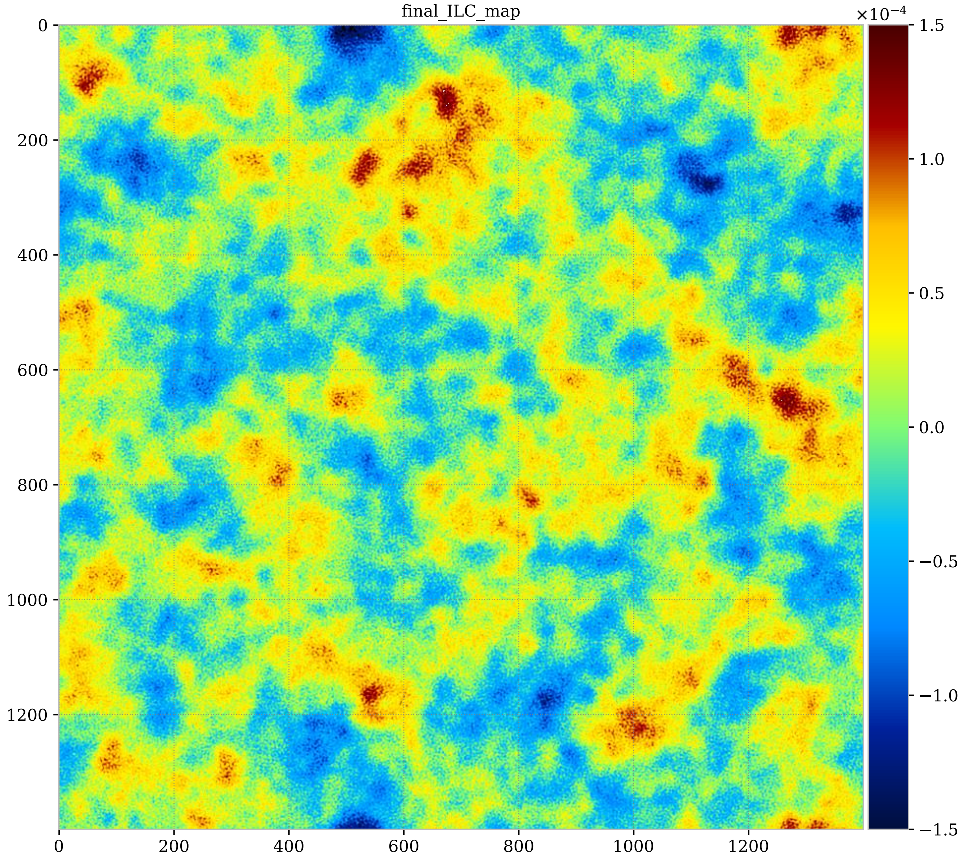
compatible with one



Comparison between Planck and SPT results…

Planck ILC maps: large scales

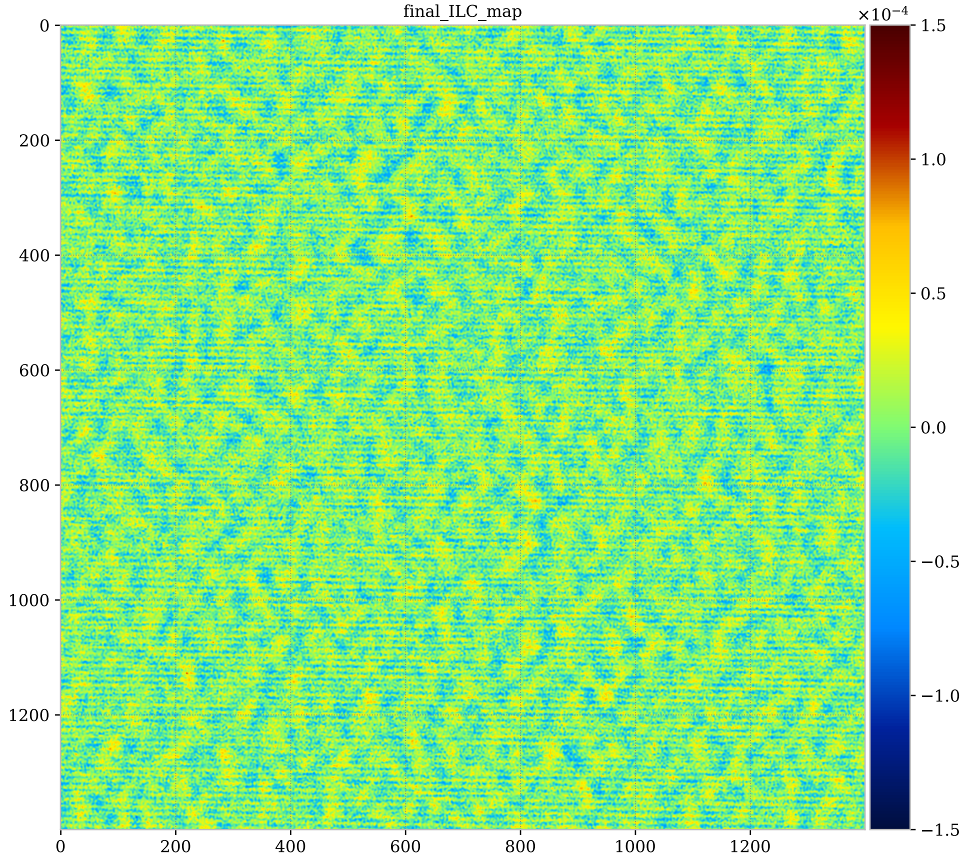
<Mr> = 0.84 ± 0.25 (one simulation)



Planck ILC map

SPT ILC maps: small scales

<Mr> = 0.91 ± 0.22 (one simulation)



SPT ILC map

Final ILC maps for the same location

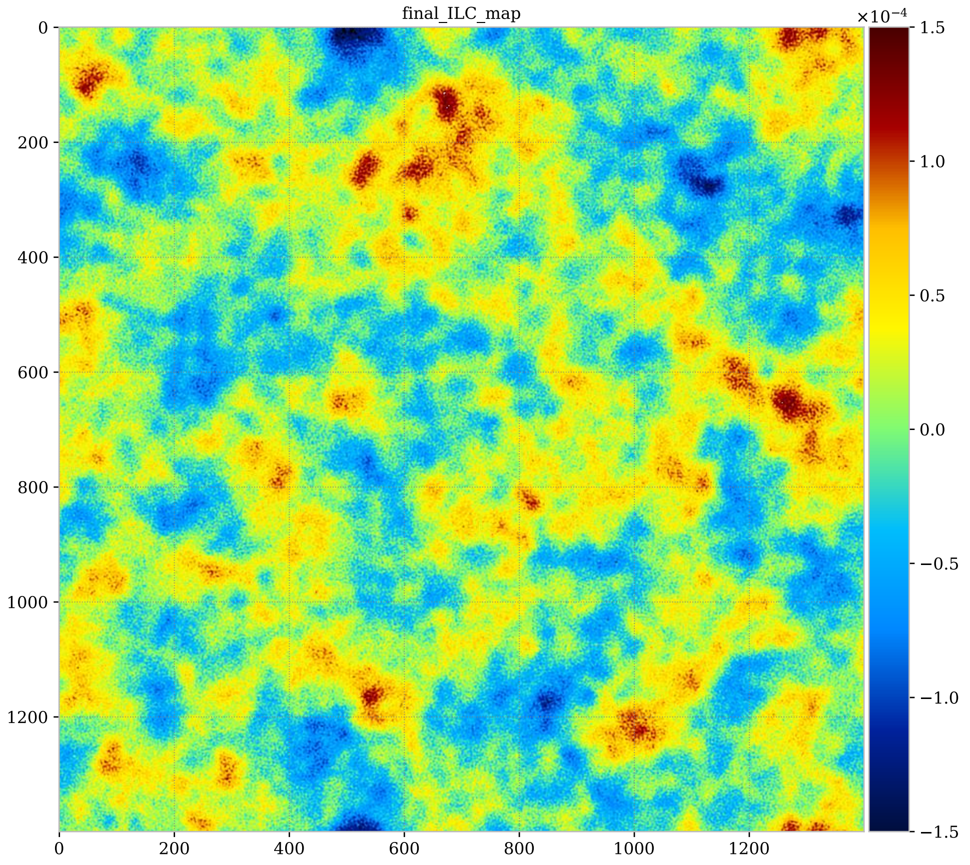
… and the combination of both

Planck: <Mr> = 0.84 ± 0.25 (one simulation)

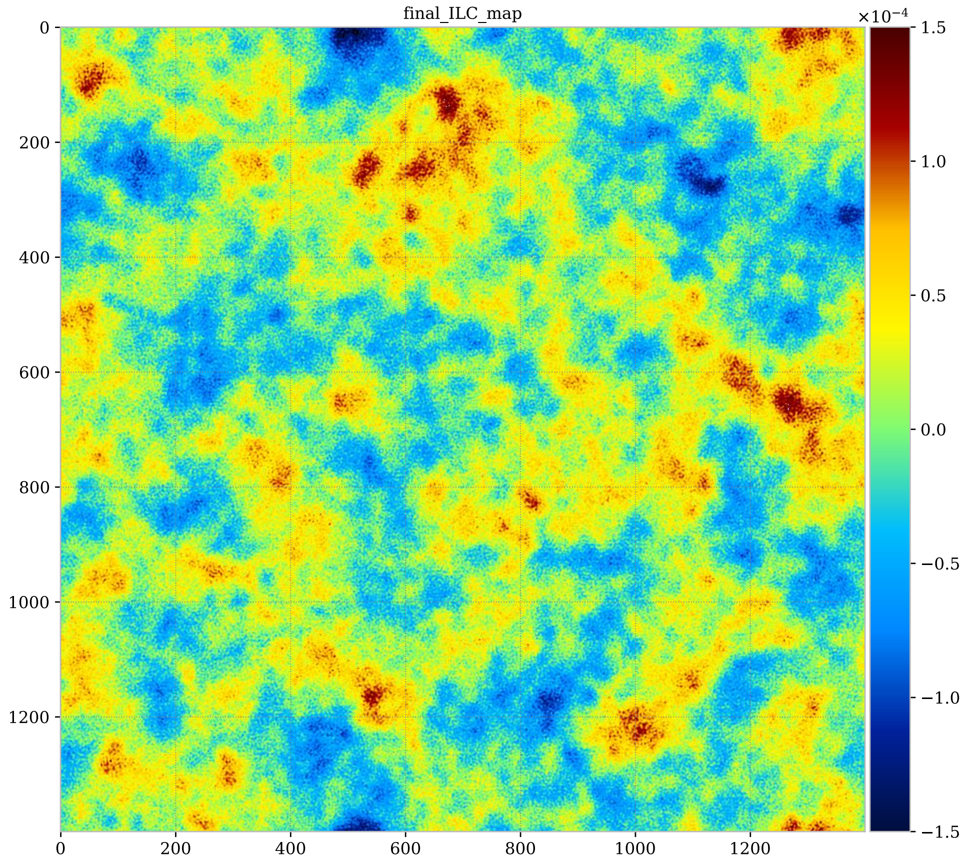
SPT: <Mr> = 0.91 ± 0.22

Combination:

<Mr> = 0.88 ± 0.17



Planck ILC map



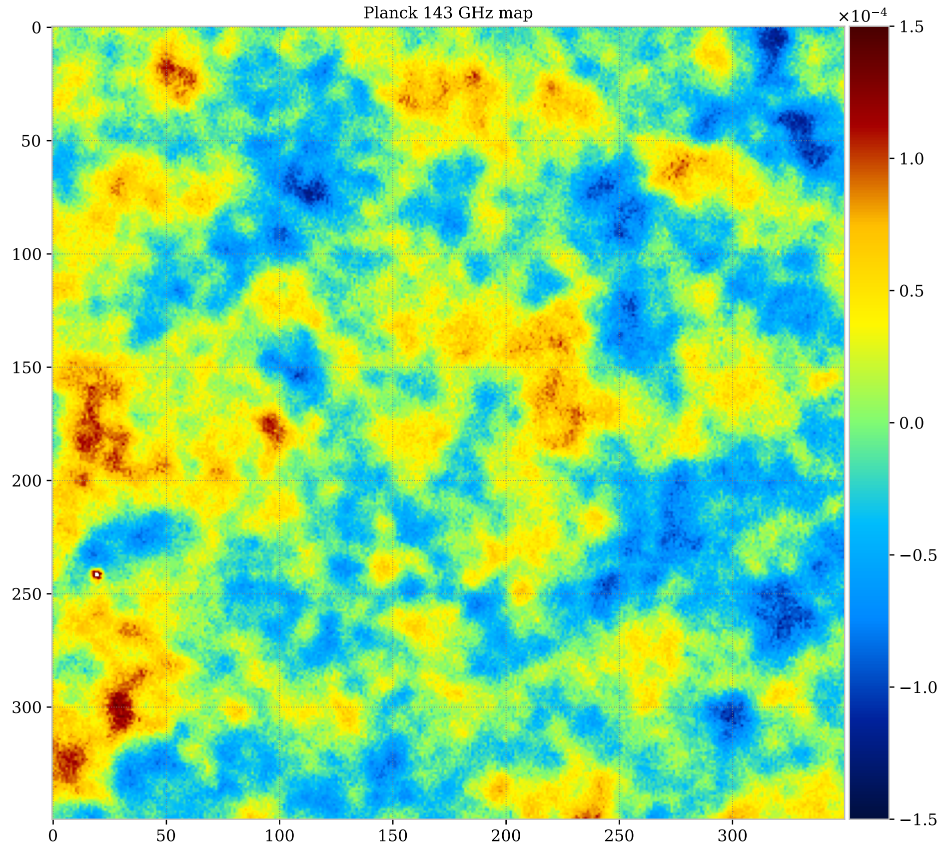
Combi ILC map

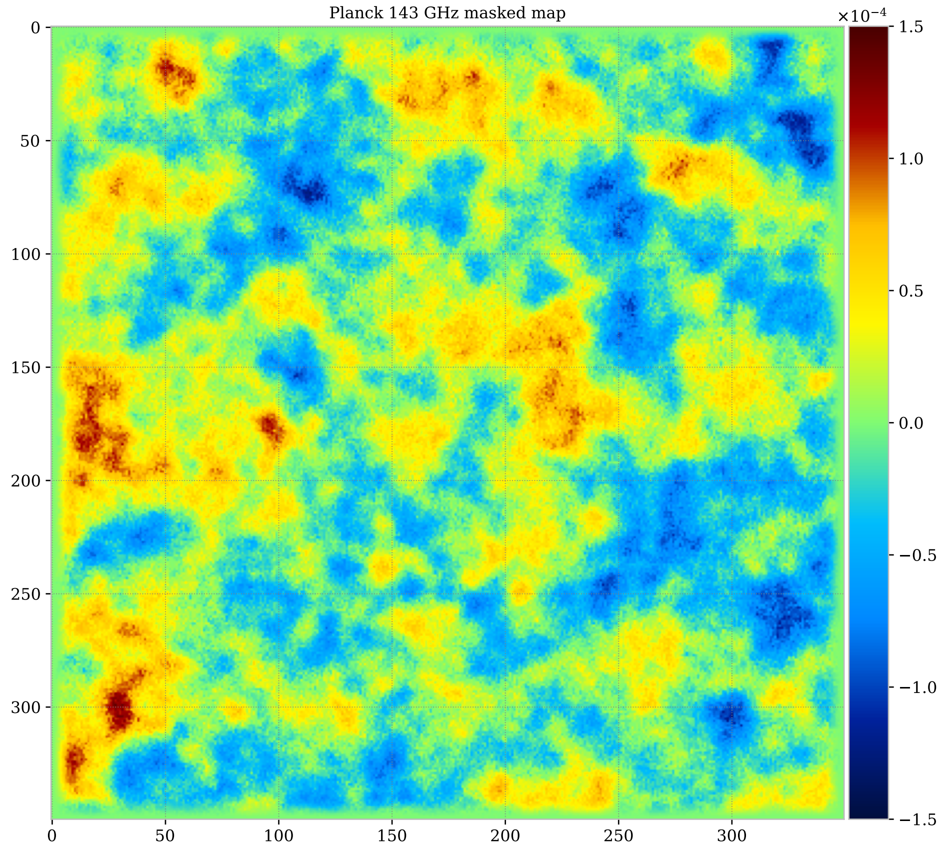
Final ILC maps for the same location

Real maps need to be cleaned

Points sources: replaced by gaussian field with CMB properties, continuity with vicinity

Maps not periodic: apodisation of the maps





Real maps need to be cleaned

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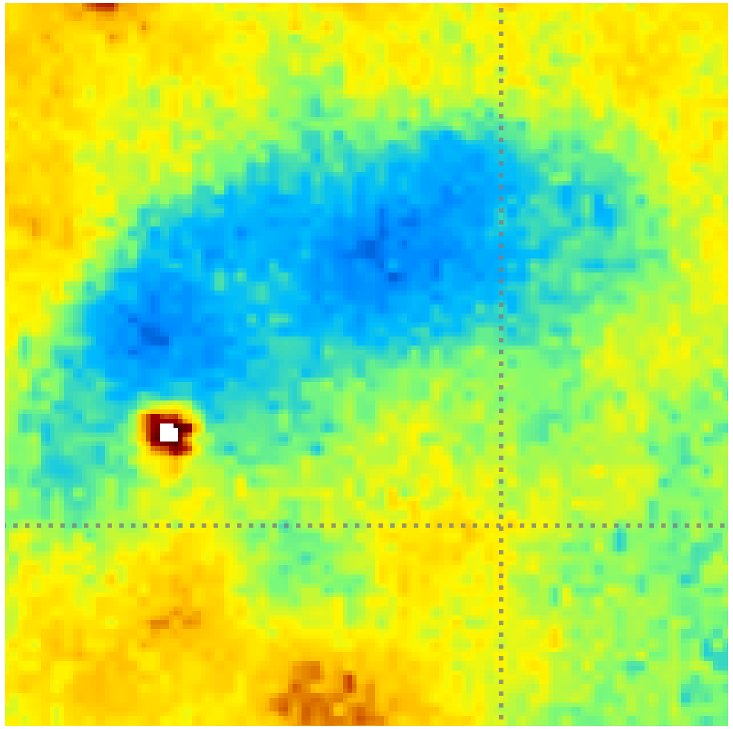
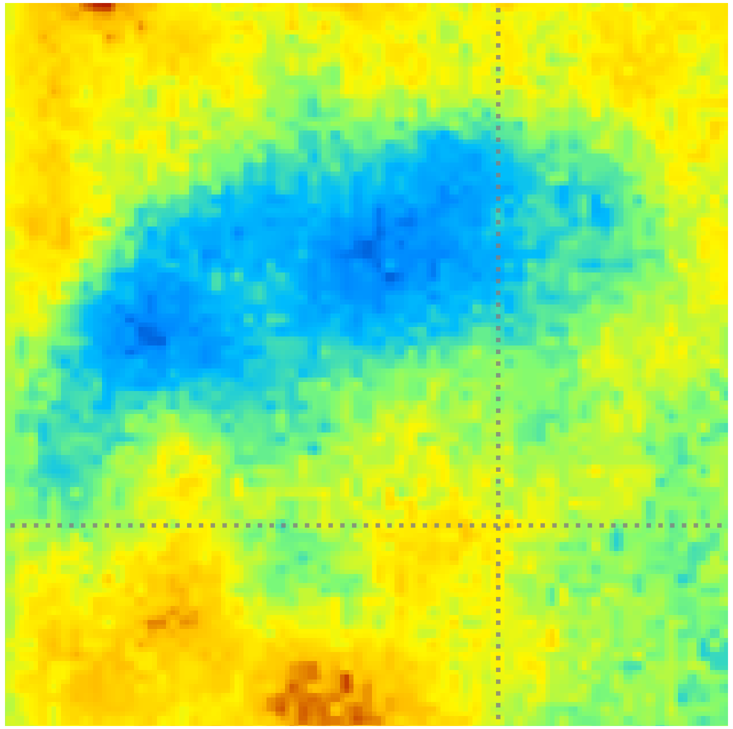
Maps not periodic: apodisation of the maps



Original map (zoom)



Masked map

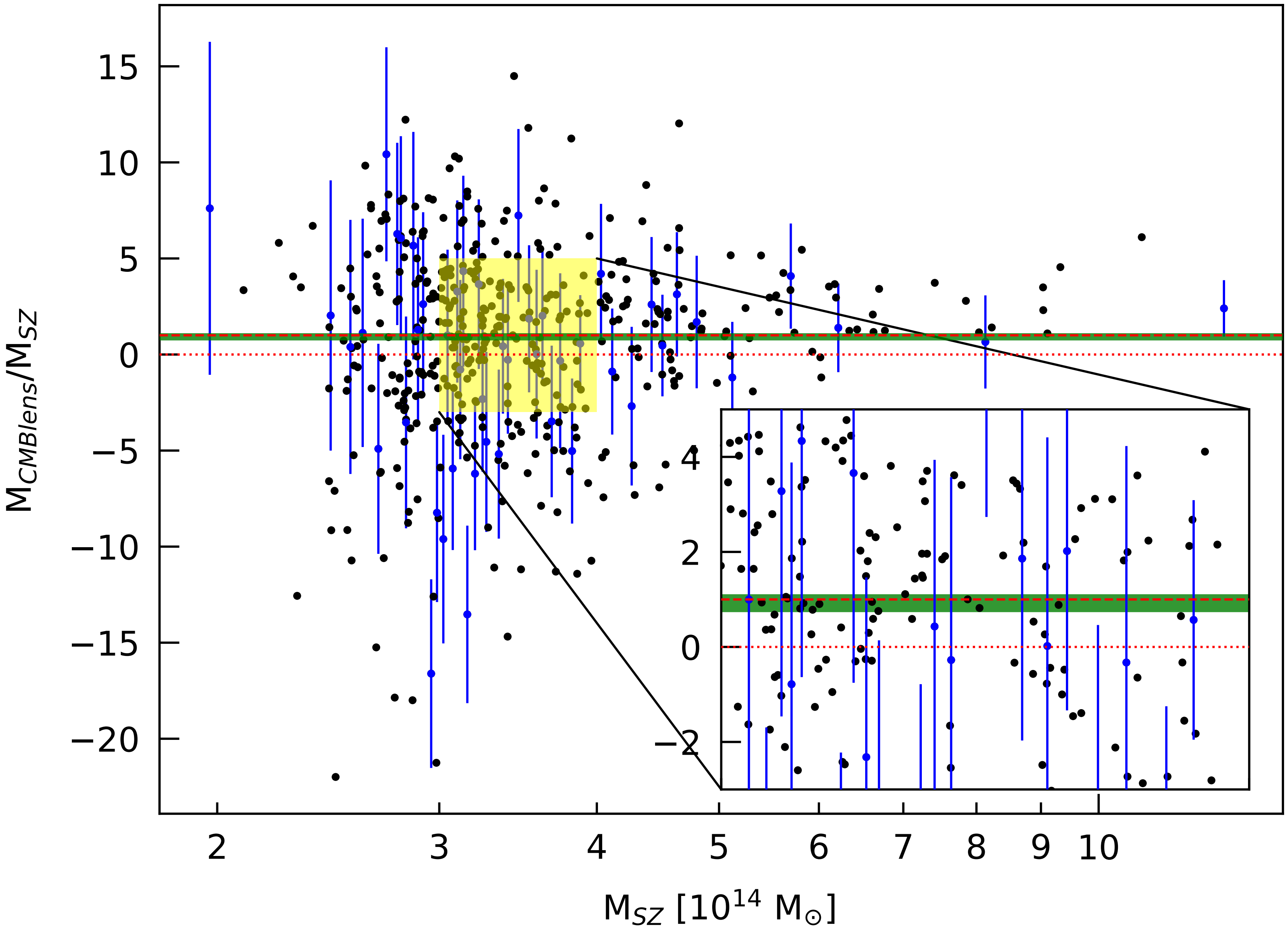
Combined results (real)

- The point sources are masked
- The lensing due to foregrounds is subtracted using “off” measurements

Averaging these measurements provides

<Mr> = 0.92 ± 0.19,

compatible with one



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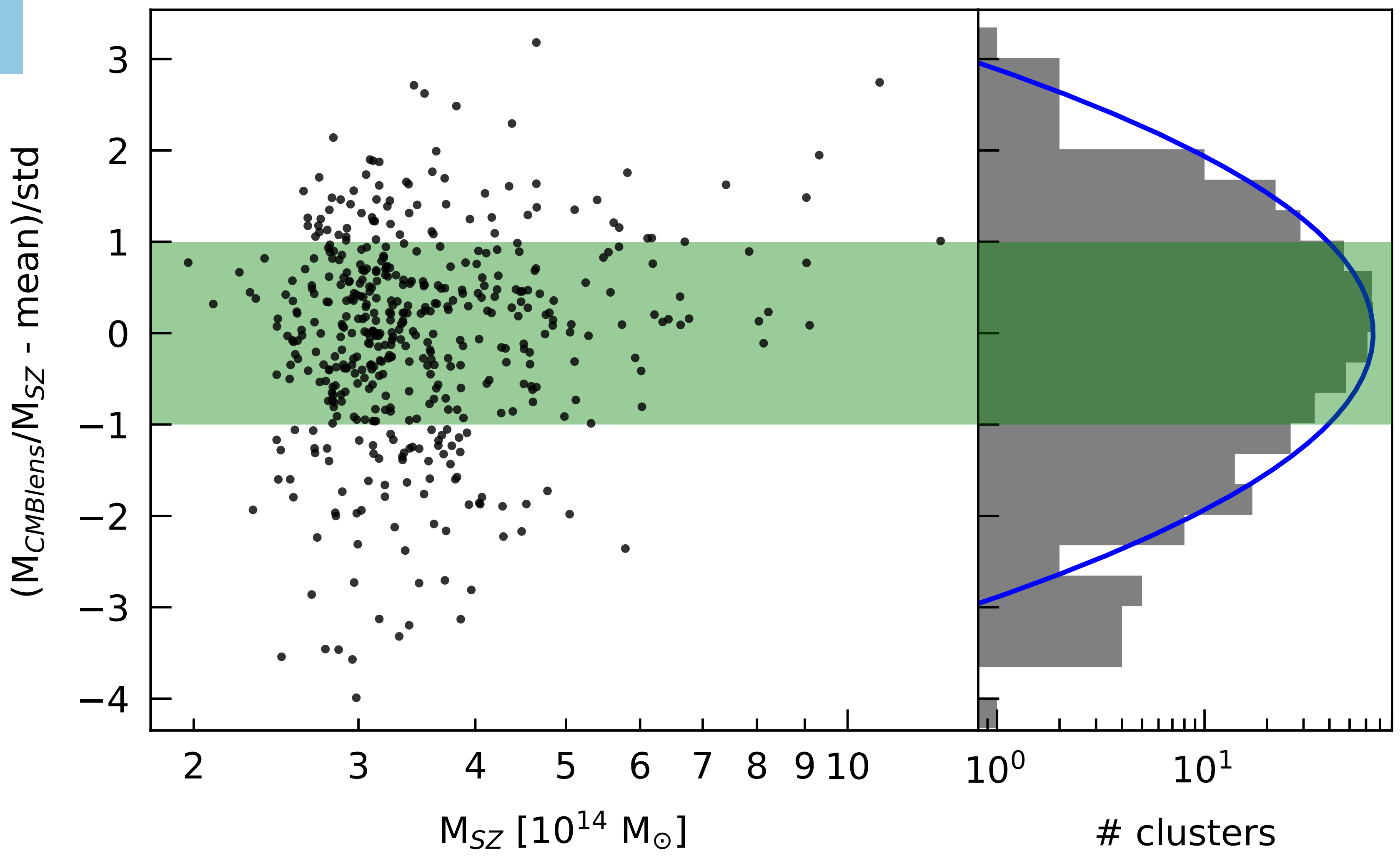

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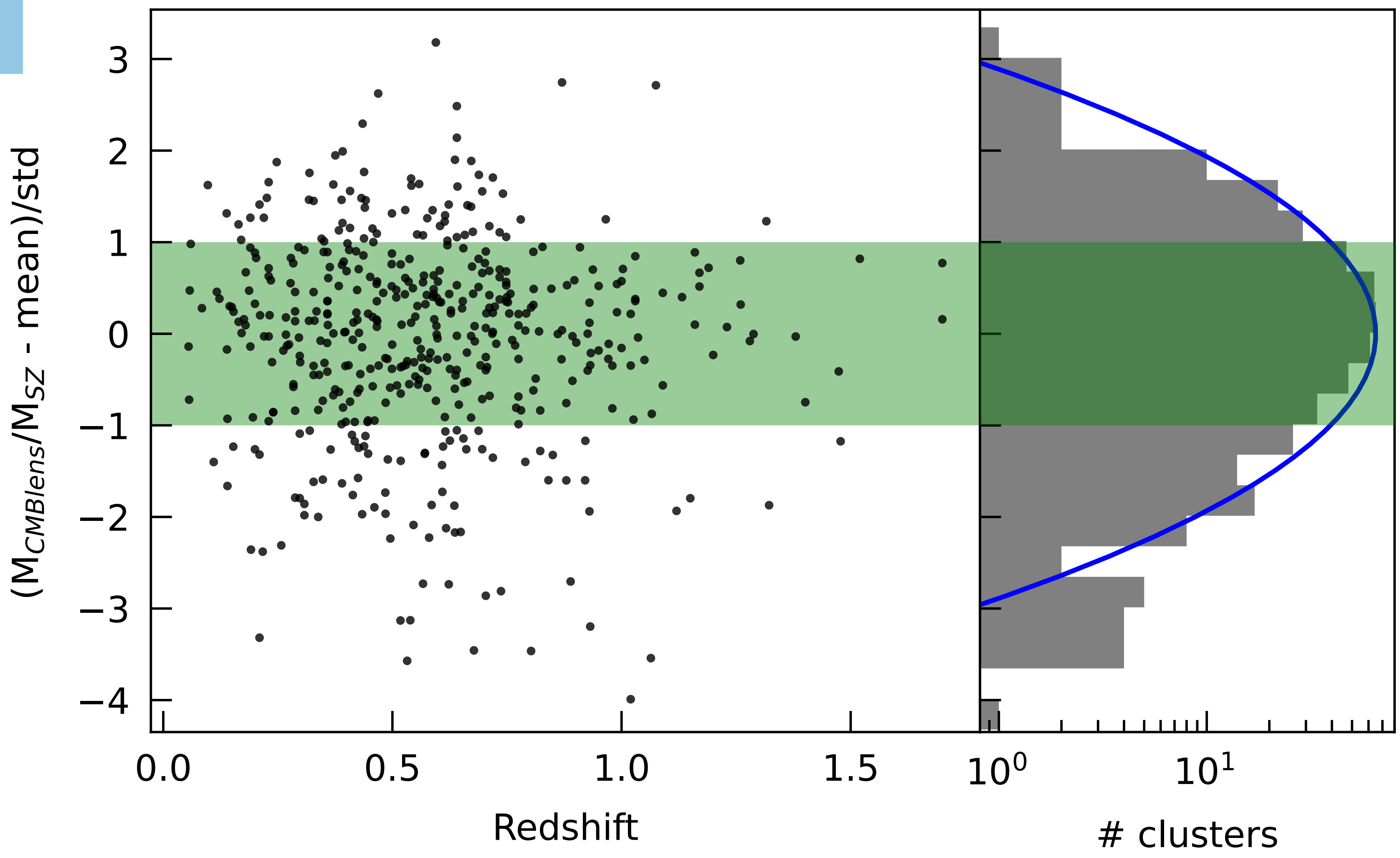
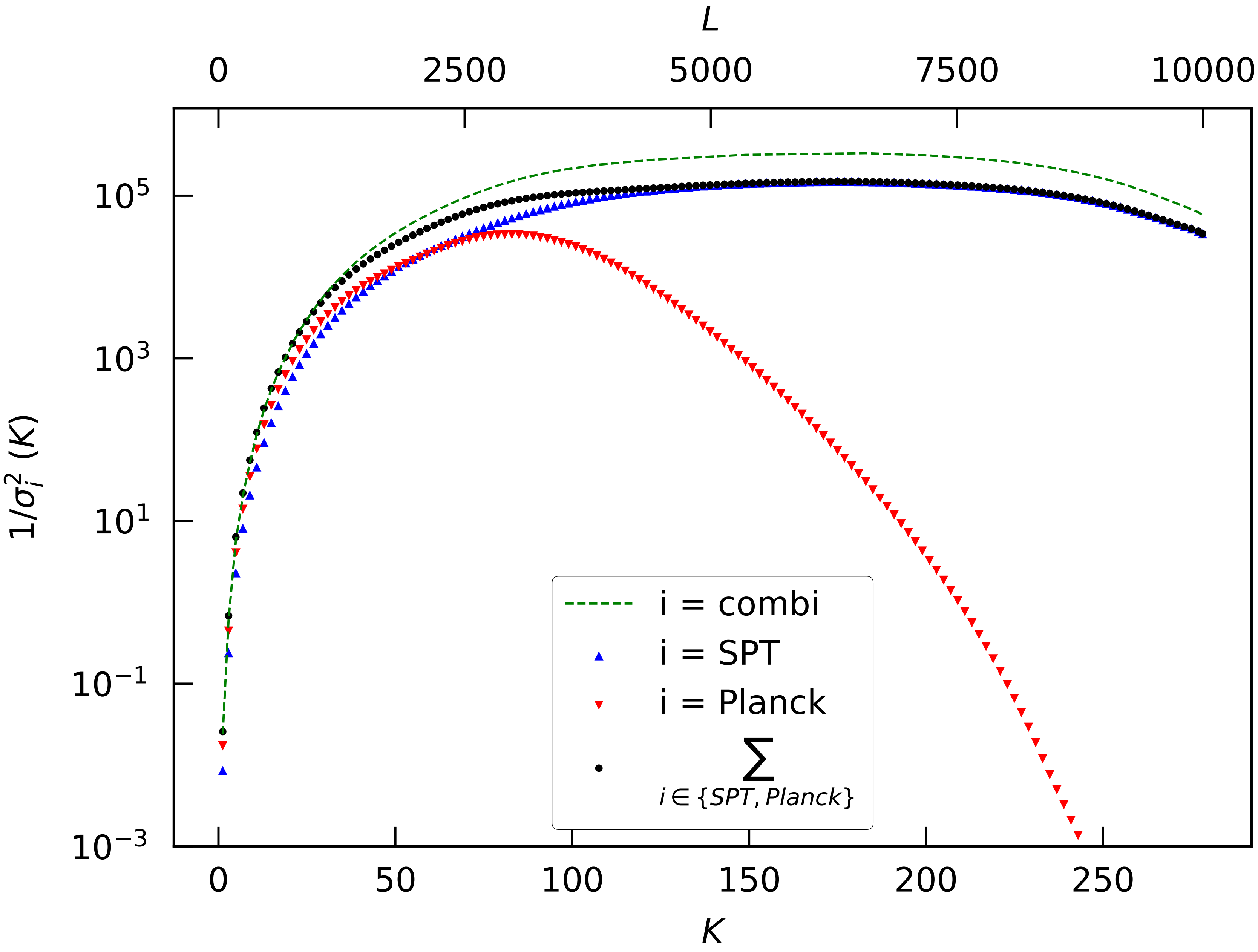


Combined ILC map

- Planck brings most of the information on large scales
- SPT on small scales
- We get a better precision at all scales, not only statistical precision

→ Complementarity

$$\Sigma = \frac{1}{\sigma^2_{planck}} + \frac{1}{\sigma^2_{SPT}} =? \frac{1}{\sigma^2_{combi}}$$



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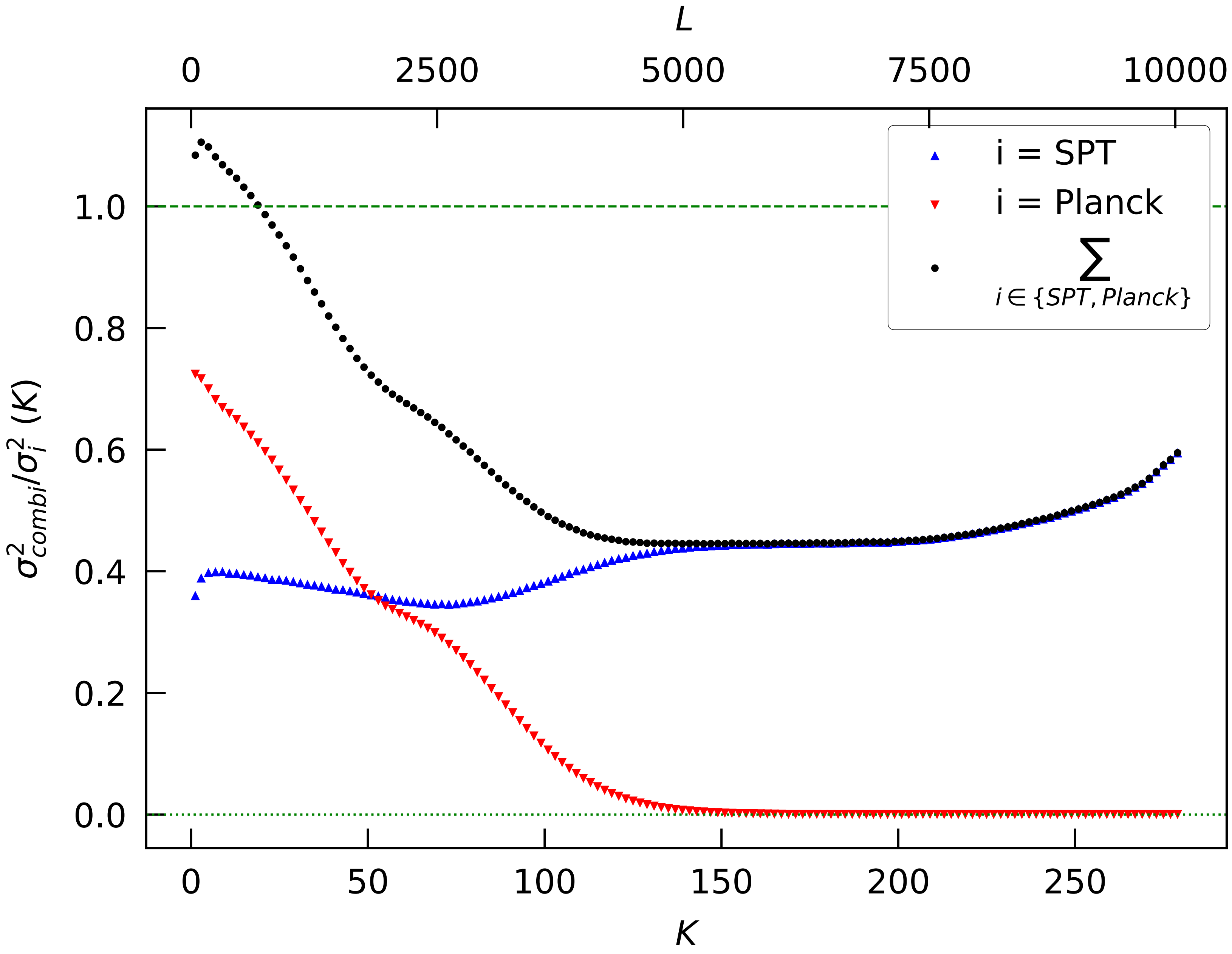


Summary

- **First** CMB-lensing galaxy cluster mass measurement using a **combination** of **ground** and **space**-based surveys
- Analysis tested on simulations and applied to actual SPT-SZ and Planck data
- We measure the signal at **4.8 sigma** on real data, a significant gain with respect to measurements performed on the two individual datasets
- Small increasing trend from $M_{CMBlens}$ with respect to M_{SZ} still to be understood
- **Correlations** between the scales observed by SPT-SZ and the scales observed by Planck **improve** the constraints on the lensing potential
- Planck data will remain a key element in CMB-lensing cluster studies for decades to come

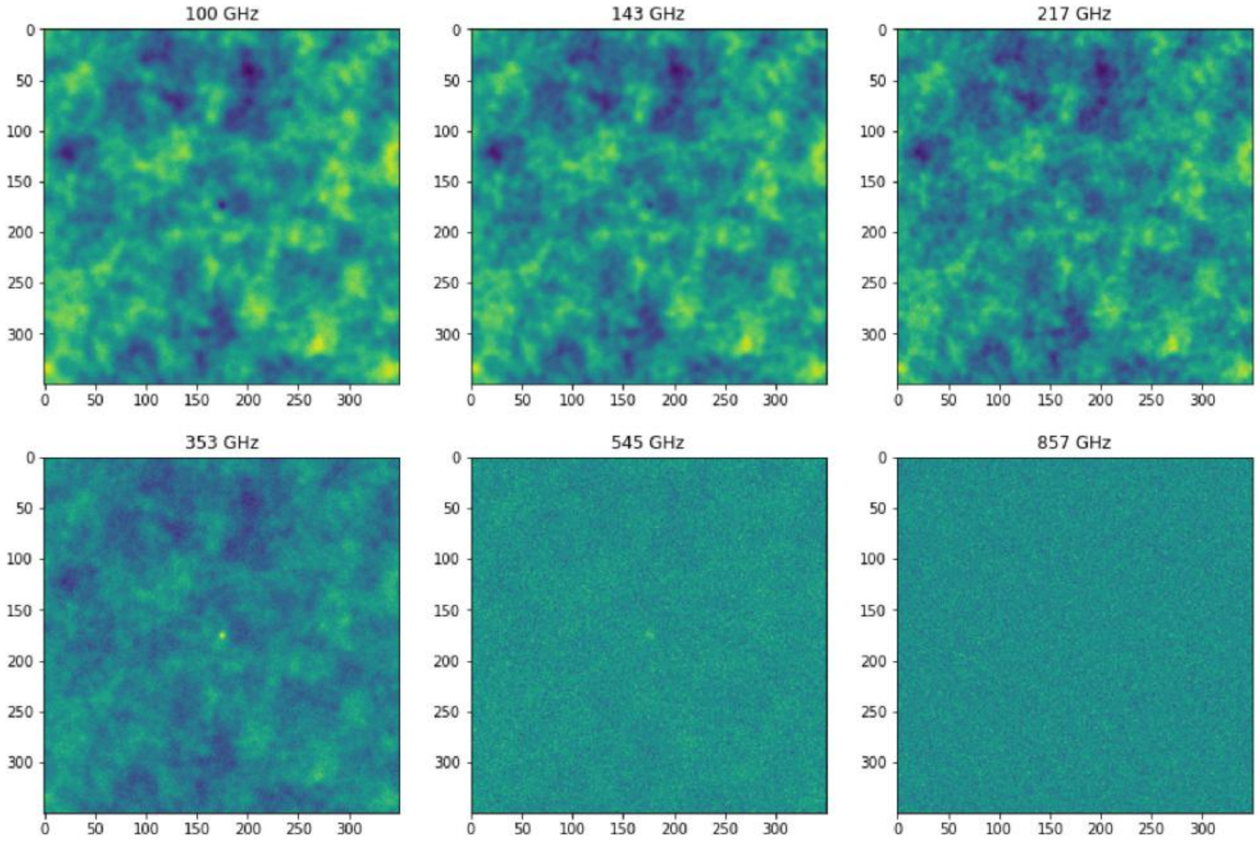
Backup slides

Internal Linear Combinations

- **Contaminants**: SZ effect, foreground
- **Instrumental characteristics**: PSF, noise

Combine the maps at different frequencies to remove contaminants, easier when we know the recipe

→ **Best lensed CMB map**



$$\begin{cases} m_{\nu_0}(\boldsymbol{k}) = \alpha_{\nu_0} s(\boldsymbol{k}) + \beta_{\nu_0} y_{\nu_0}(\boldsymbol{k}) + n_{\nu_0}(\boldsymbol{k}) \\ m_{\nu_1}(\boldsymbol{k}) = \alpha_{\nu_1} s(\boldsymbol{k}) + \beta_{\nu_1} y_{\nu_1}(\boldsymbol{k}) + n_{\nu_1}(\boldsymbol{k}) \\ \ldots \\ m_{\nu_5}(\boldsymbol{k}) = \alpha_{\nu_5} s(\boldsymbol{k}) + \beta_{\nu_5} y_{\nu_5}(\boldsymbol{k}) + n_{\nu_5}(\boldsymbol{k}) \end{cases}$$

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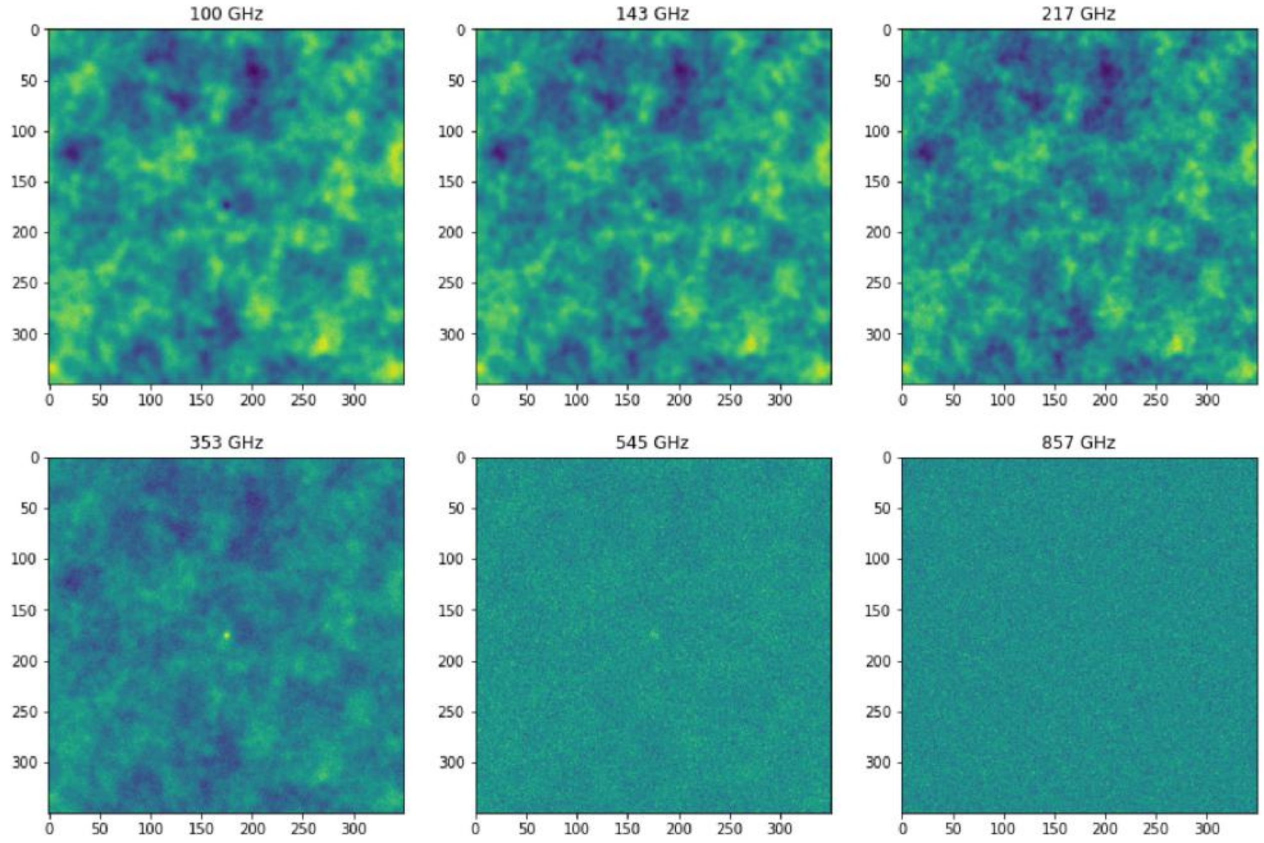
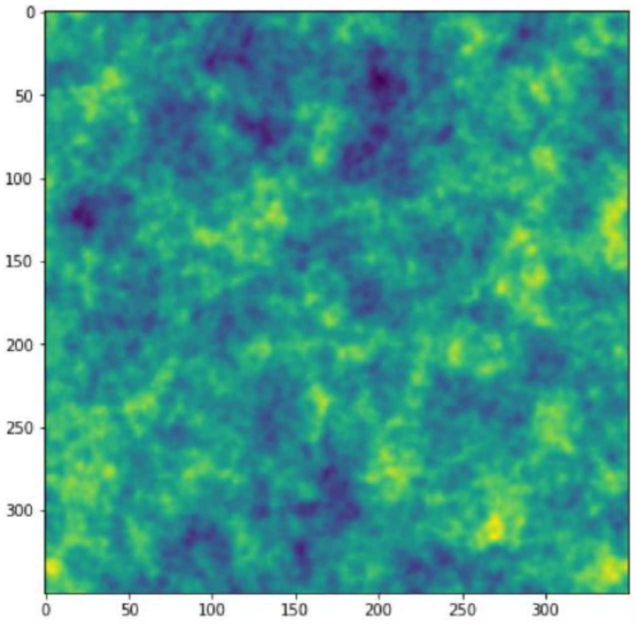
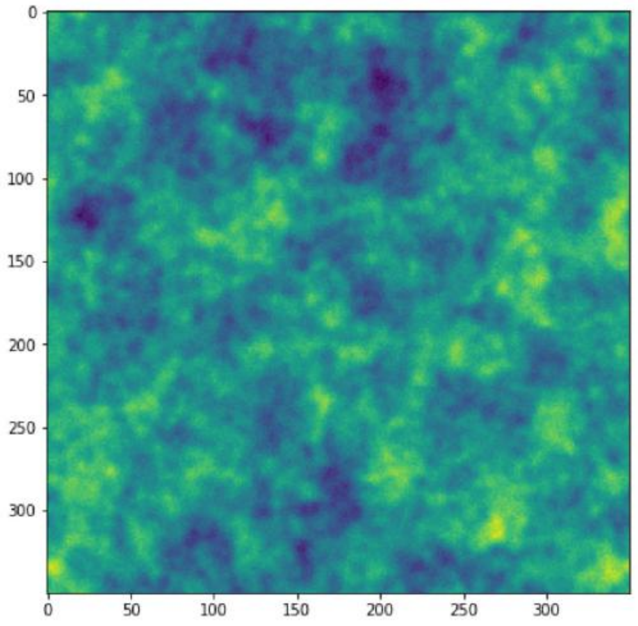
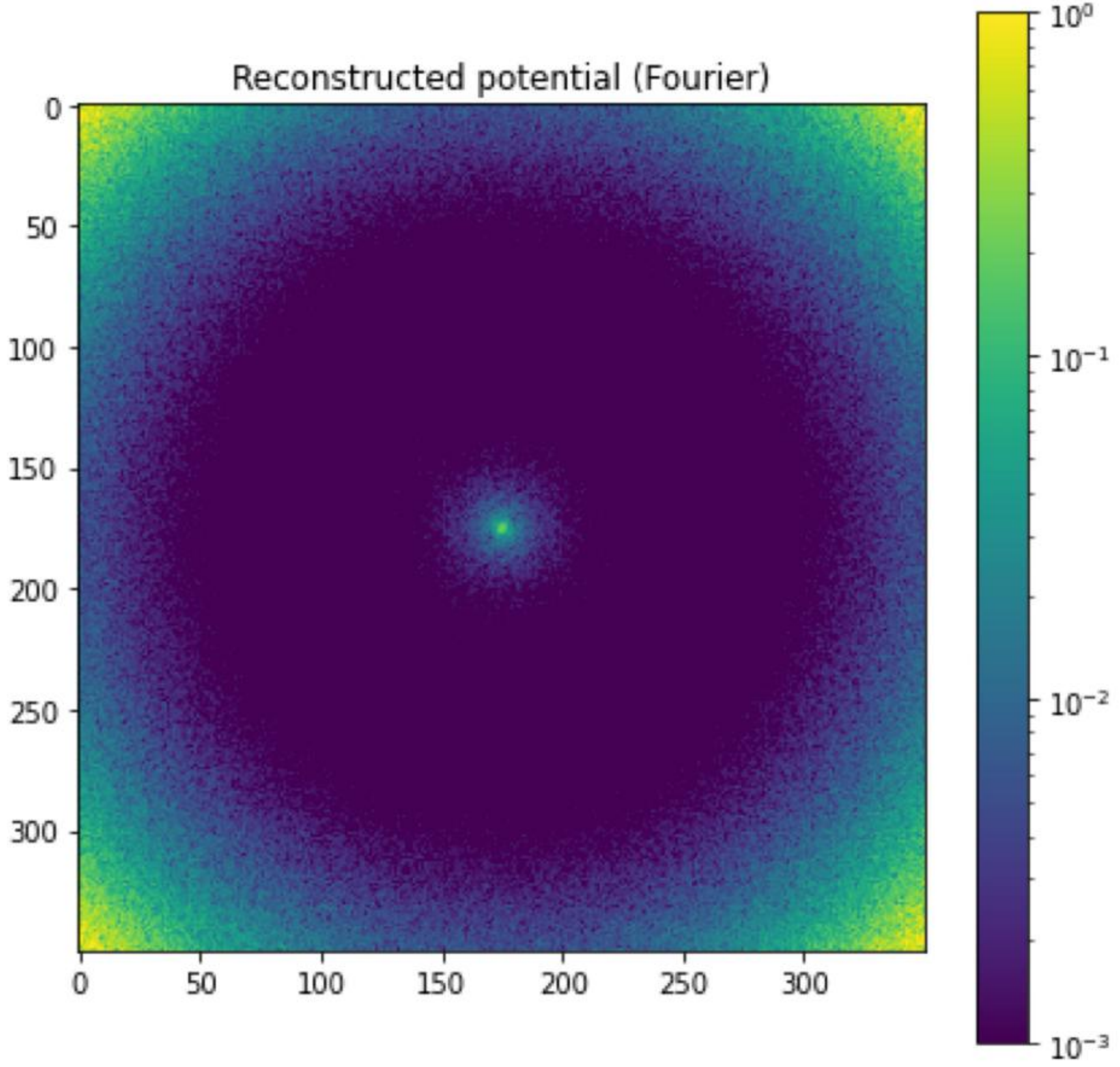






Lensing estimator

- The CMB k-modes (spatial frequencies, i.e. the different scales) are uncorrelated
- The CMB on our map is lensed, **inducing spatial correlations**
- Use these correlations to rebuild the lensing potential



2D-Fourier transform of the reconstructed gravitational potential (small k-modes – large scales in the middle)

Matched filter

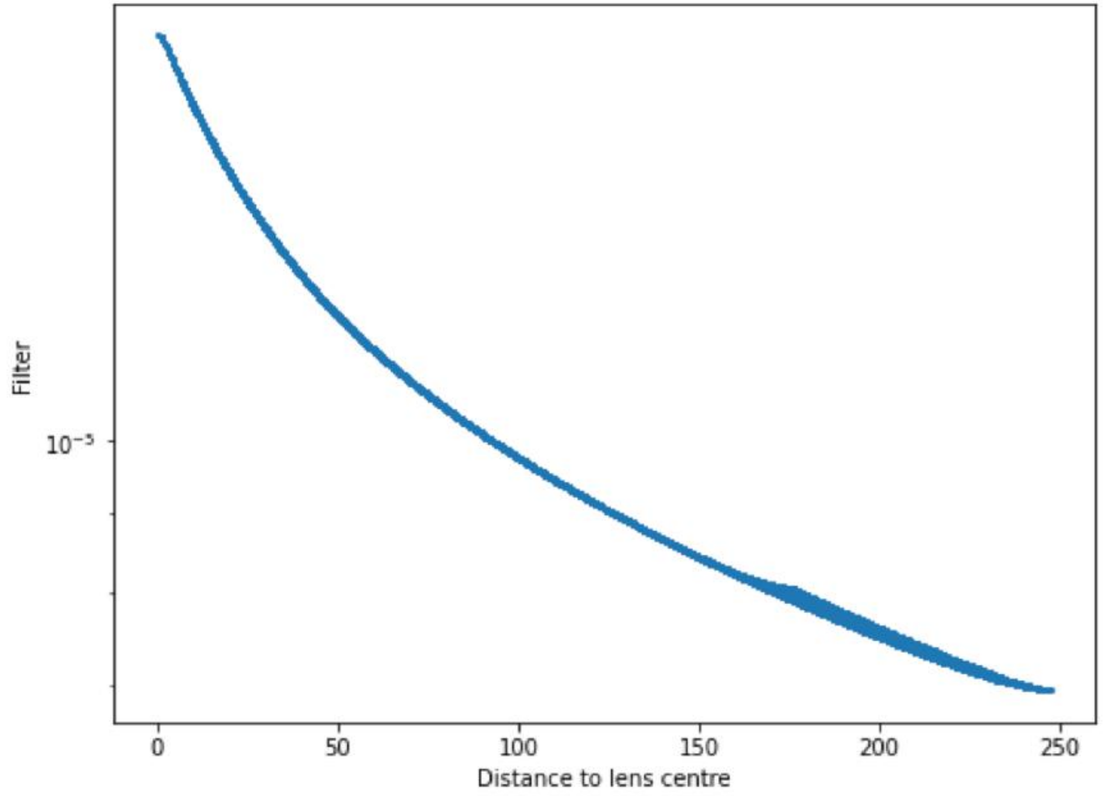
$$\hat{\phi}_0 = \left[\sum_{\boldsymbol{K}} \frac{|\Phi(\boldsymbol{K})|^2}{A(\boldsymbol{K})} \right]^{-1} \sum_{K} \frac{\Phi^*(\boldsymbol{K})}{A(\boldsymbol{K})} \hat{\phi}(\boldsymbol{K})$$

NFW lensing potential

Obtained lensing potential

Variance of measure obtained for **K**

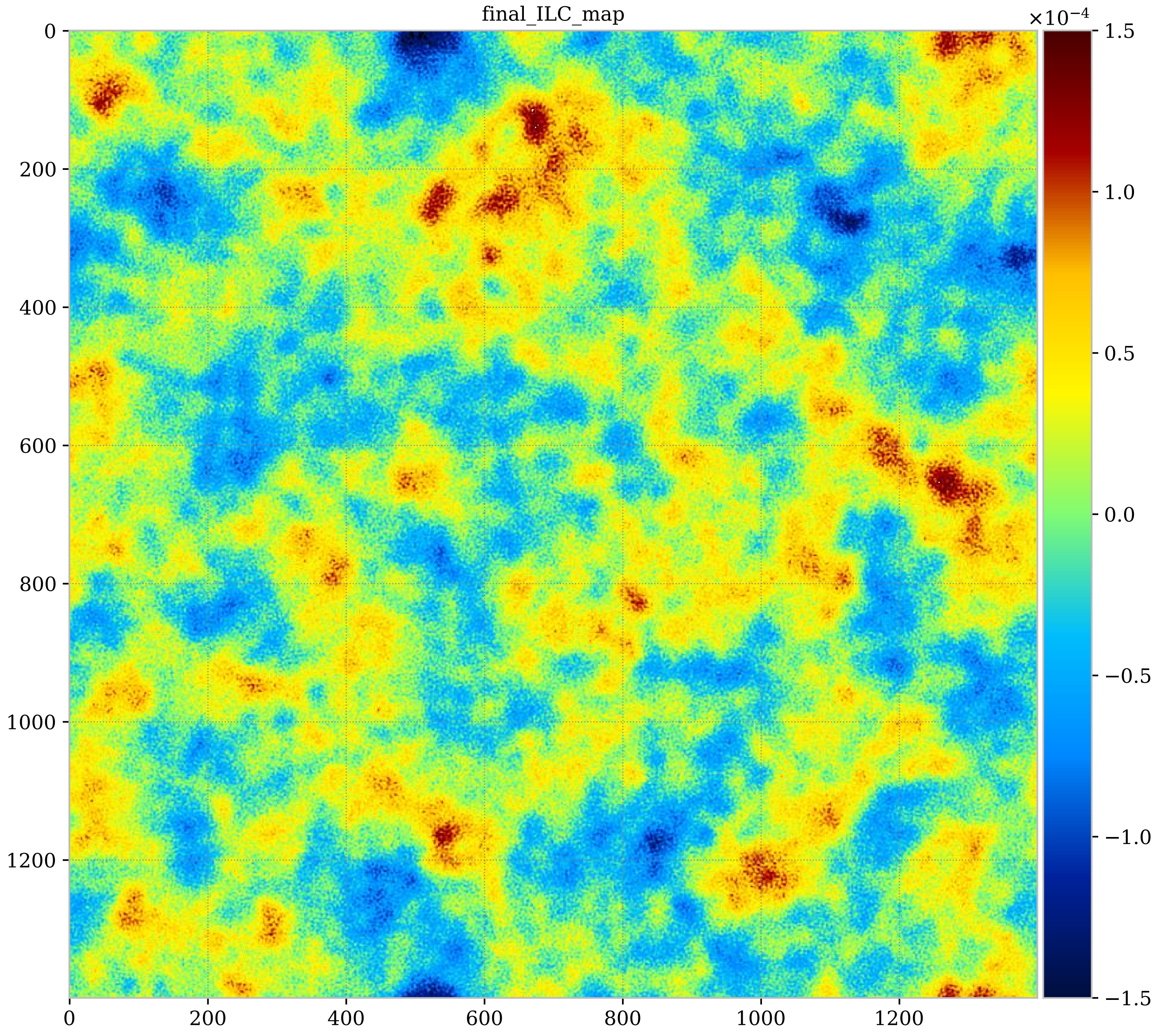
- Compares the obtained lensing potential to a NFW profile for a given mass
- We know the NFW profile used in the simulations
- Returns the estimation of the amplitude fitting best the NFW profile. For simulations, we expect to get, in average: $\frac{M_{measurement}}{M_{true}} = 1$



Filter NWF lensing profile

Planck ILC map

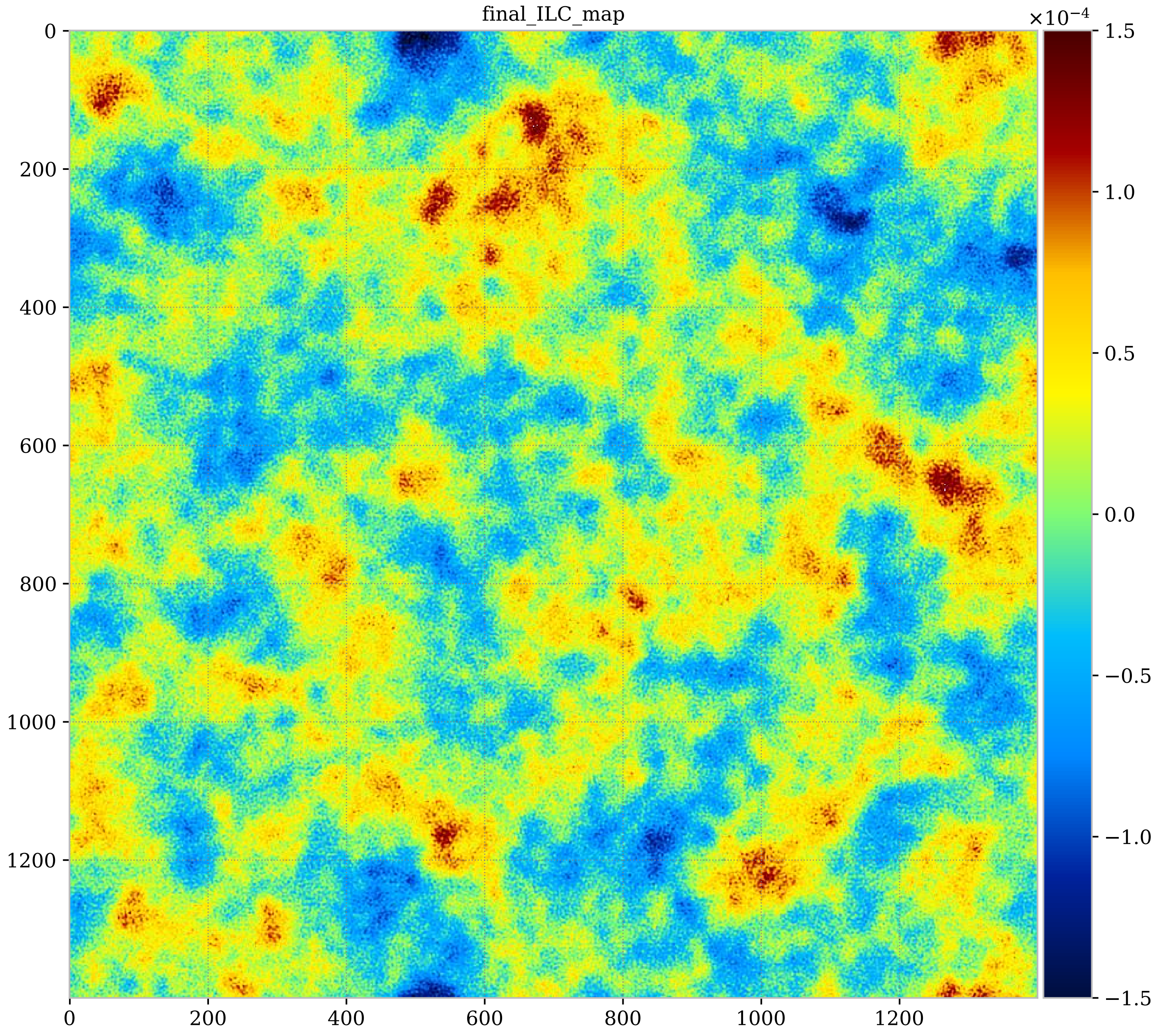
- For one simulated cluster
- No foreground simulated
- The map is periodic



Combined ILC map

- Better small scales than Planck only
- The surveys really are complementary

- $\frac{1}{\sigma^2_{combi}} = \frac{1}{\sigma^2_{planck}} + \frac{1}{\sigma^2_{SPT}}$



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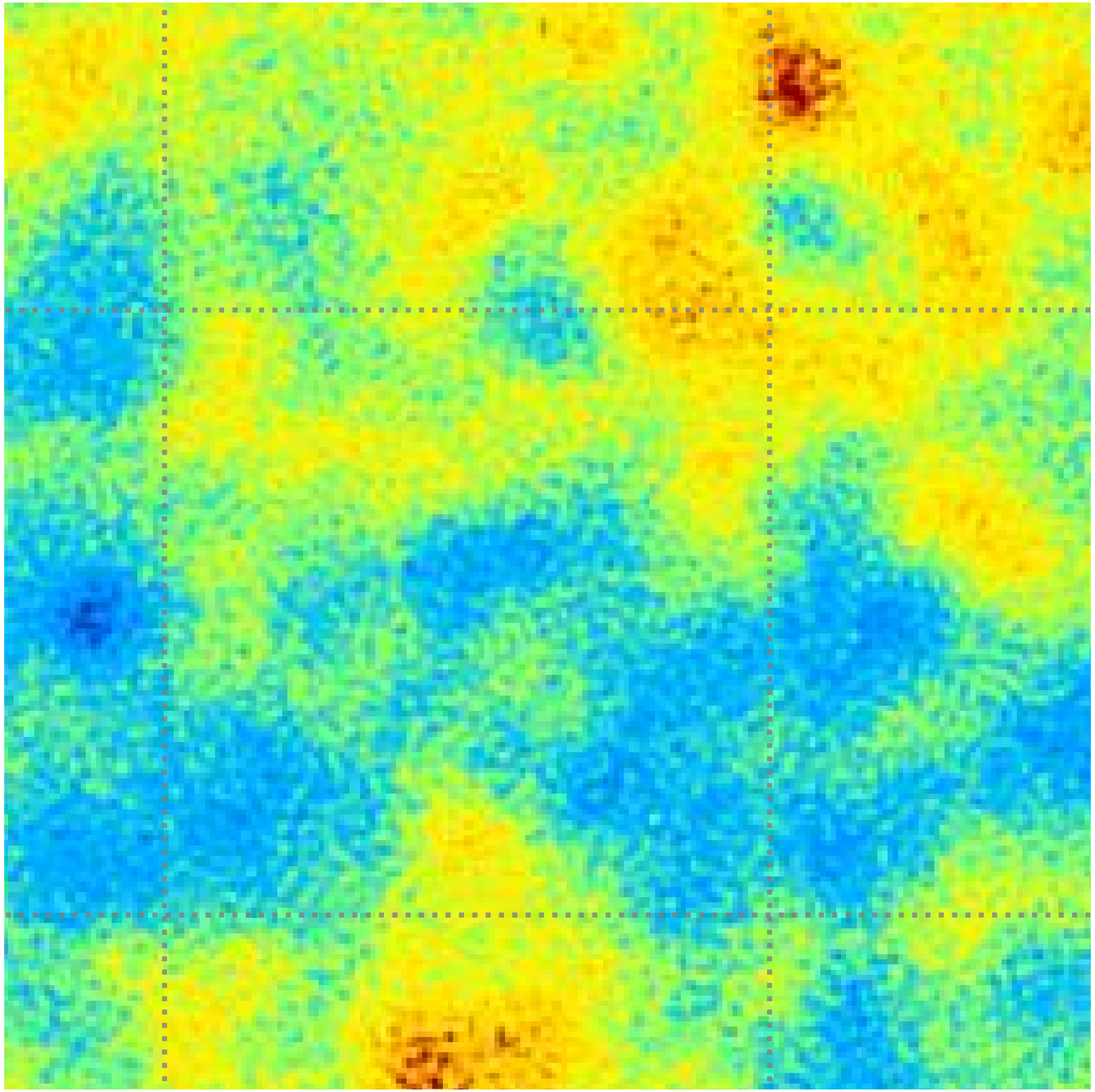

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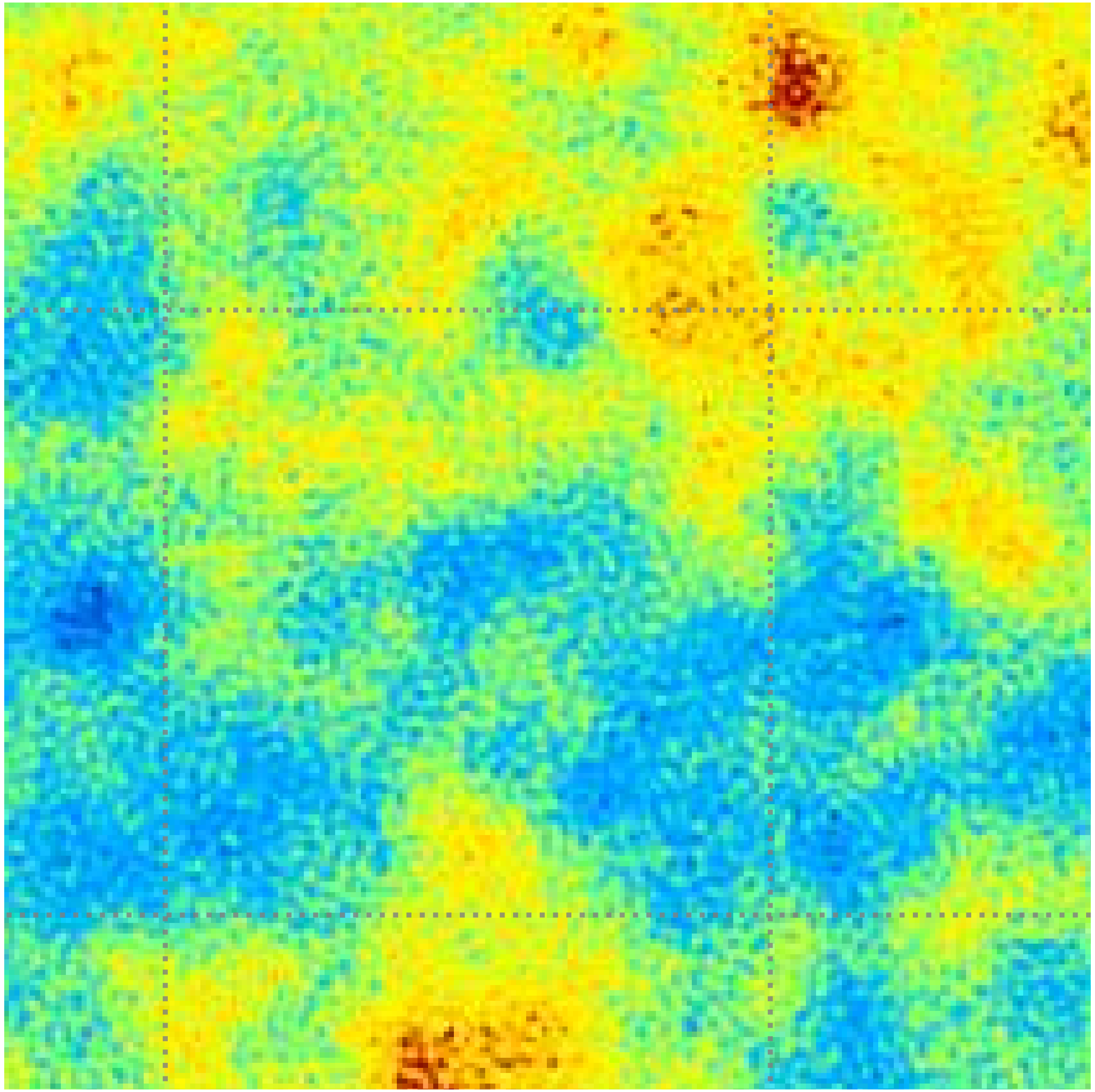
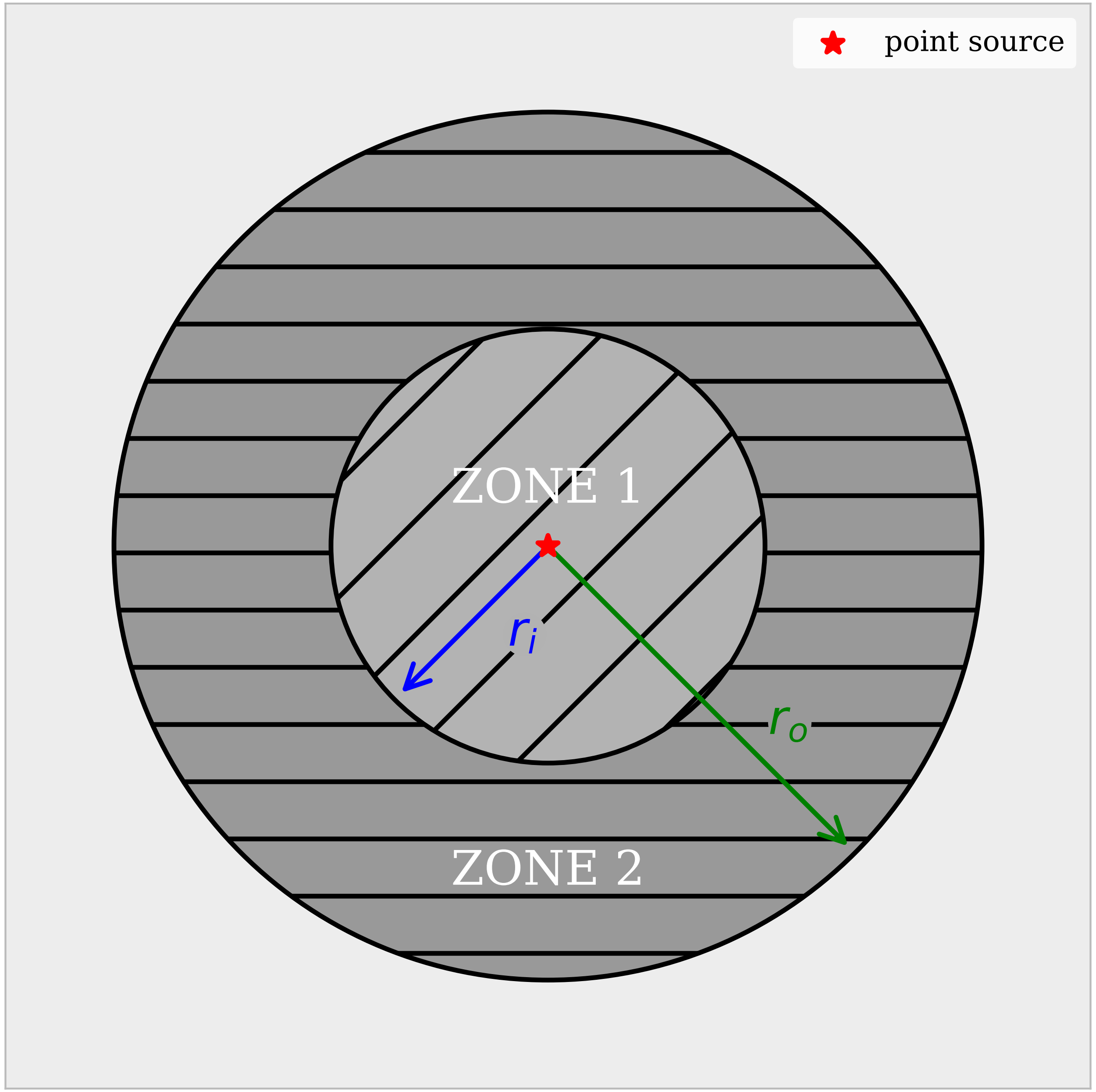


Inpainting

To fill ZONE 1 with a realistic CMB compatible with ZONE 2:

- Compute the correlation function / power spectrum of the map
- Create a CMB map with it
- Adapt the new CMB map to ensure continuity



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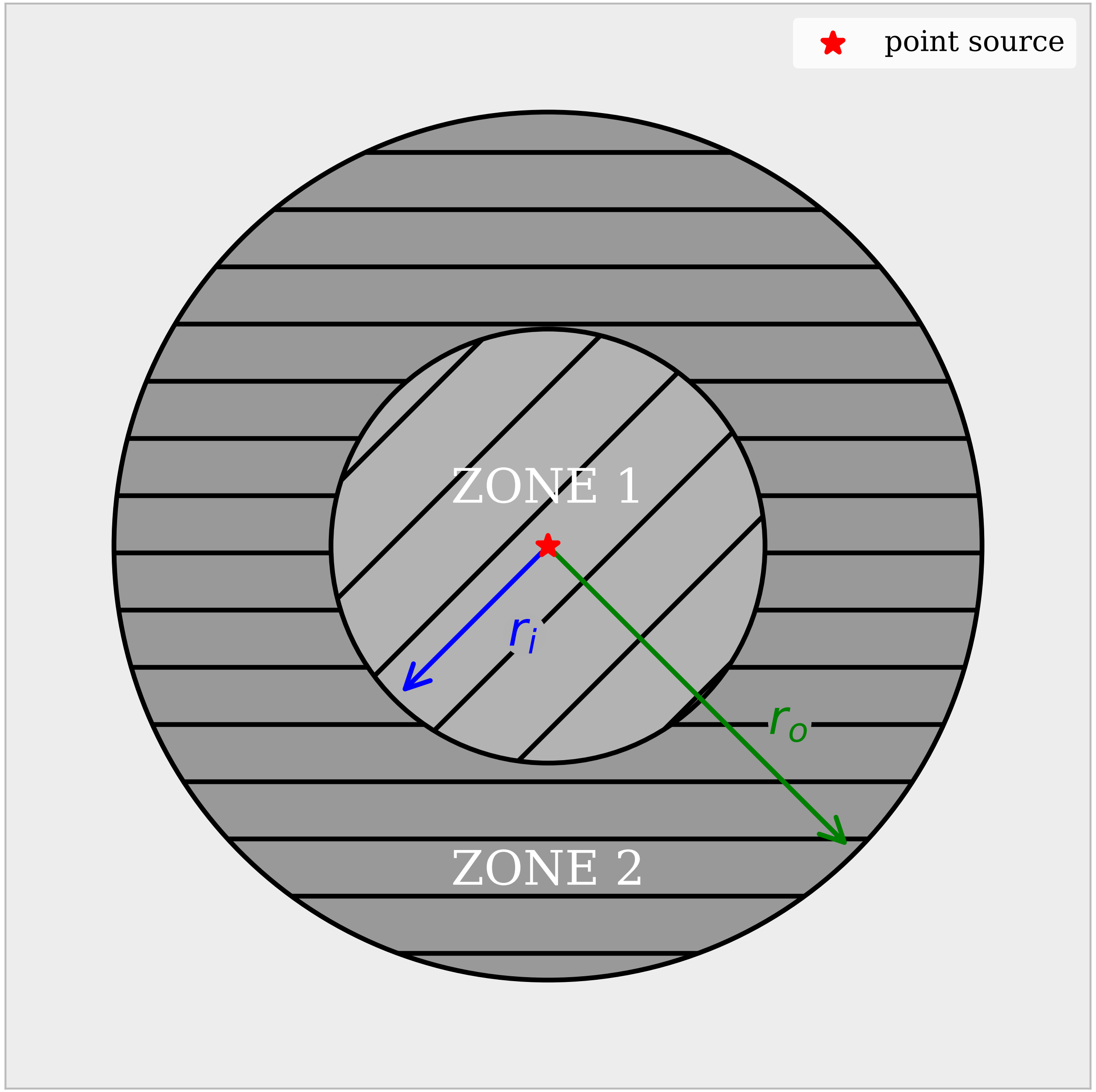
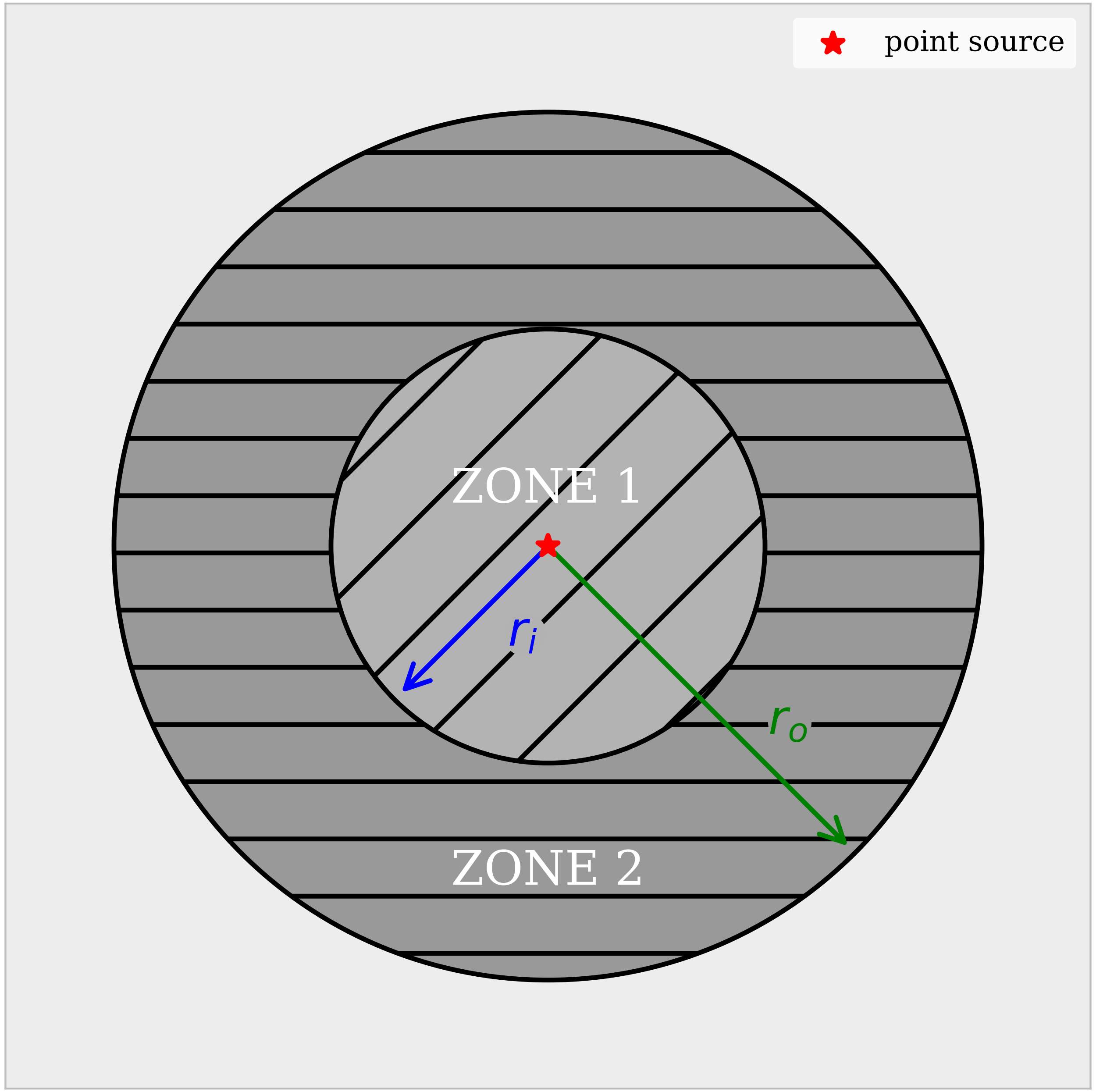


Inpainting

- We want to fill ZONE 1 with a realistic CMB, compatible with ZONE 2
- We compute the correlation function / power spectrum of the map
- We create a CMB map with it

→ We now have to adapt the new CMB map to ensure continuity

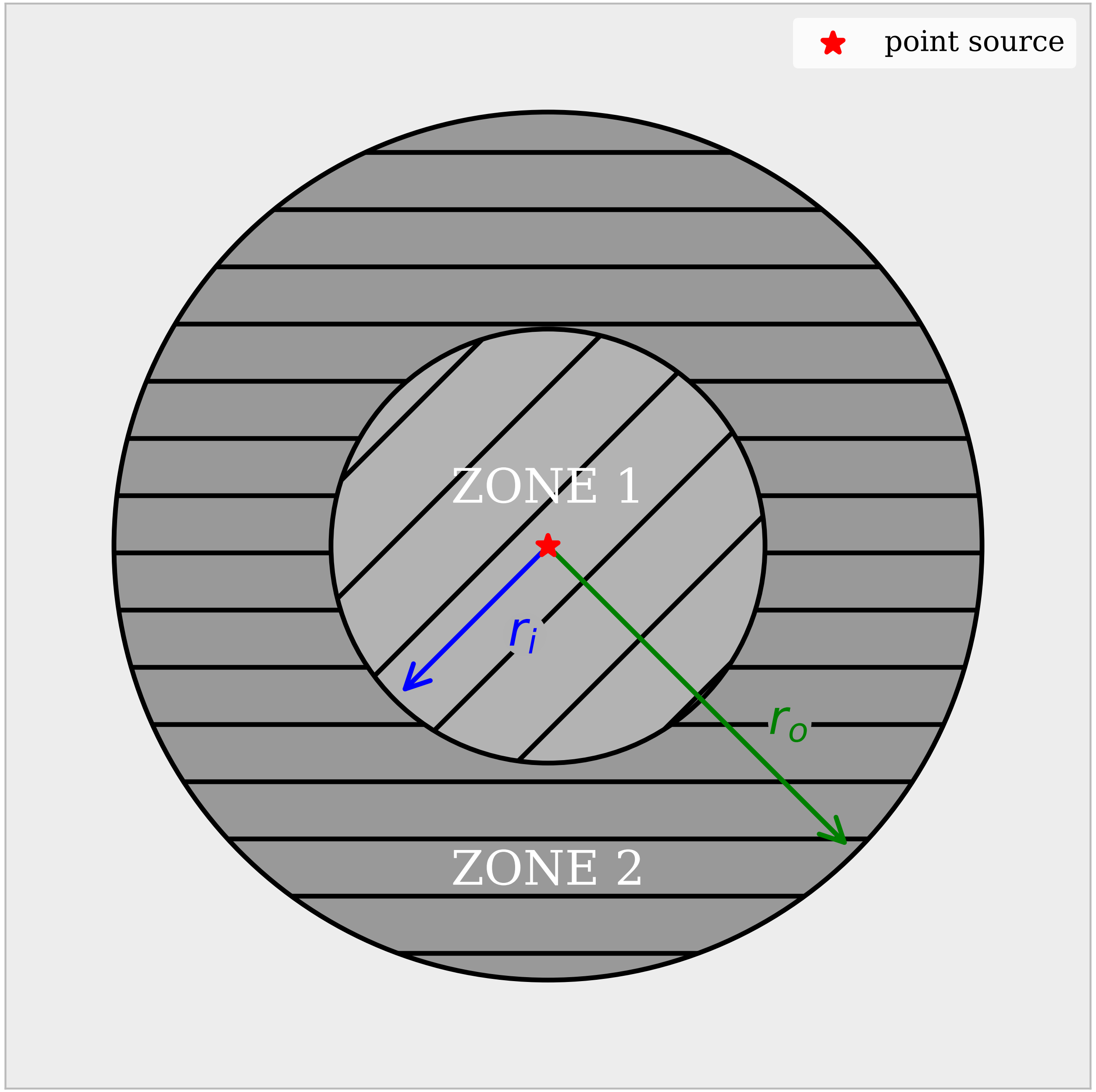


Inpainting

- The conditional probability distribution function of pixels in ZONE 1 constrained by pixels in ZONE 2 is a gaussian

$$\mathcal{P}(p_1|Z_2) = \frac{\mathcal{P}(Z_2|p_1)\mathcal{P}(p_1)}{\mathcal{P}(Z_2)}$$

- We keep the random deviations from the realization but use the mean of the PDF of the real map

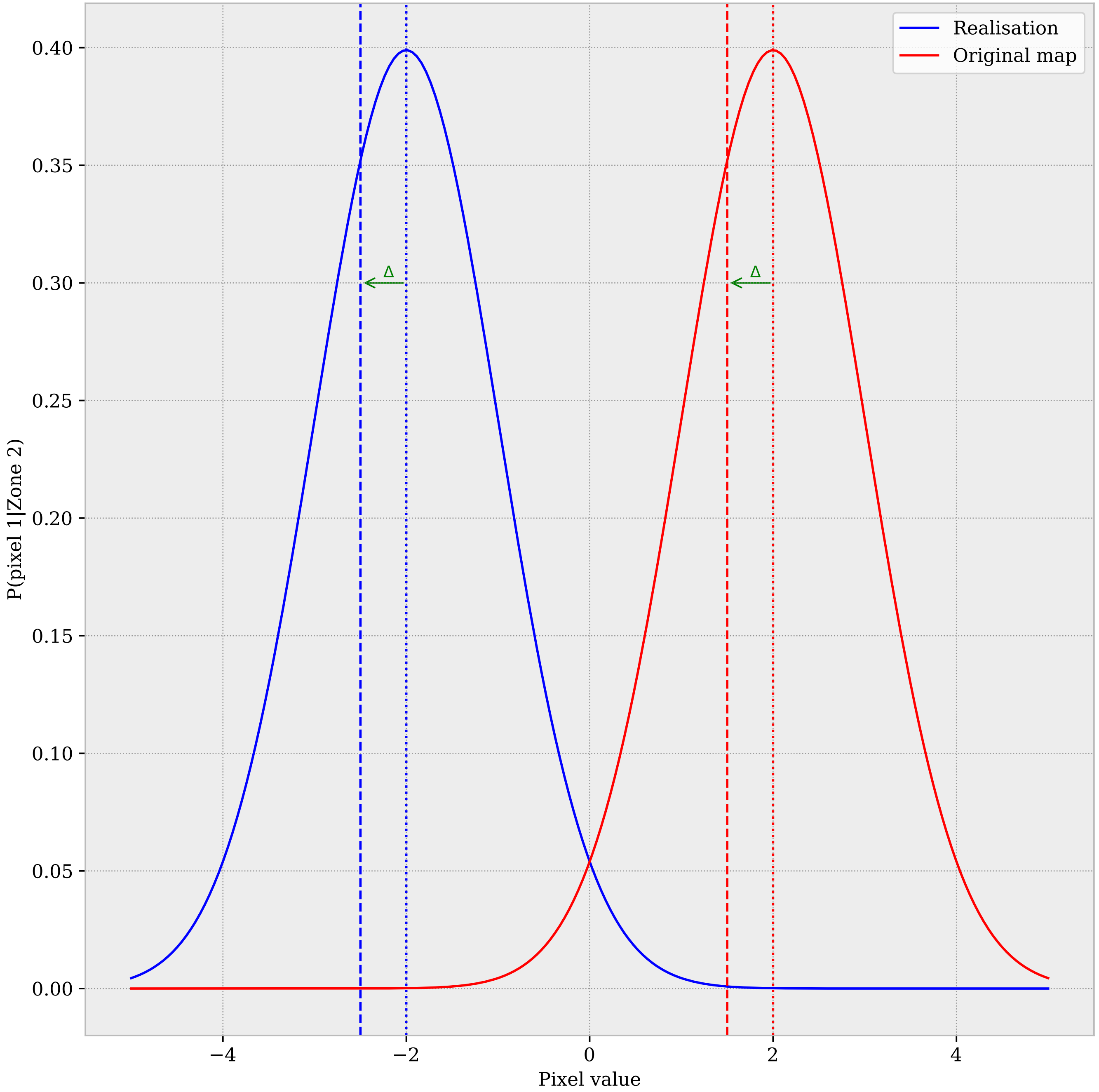


Inpainting

- The conditional probability distribution function of pixels in ZONE 1 constrained by pixels in ZONE 2 is a gaussian

$$\mathcal{P}(p_1|Z_2) = \frac{\mathcal{P}(Z_2|p_1)\mathcal{P}(p_1)}{\mathcal{P}(Z_2)}$$

- We keep the random deviations from the realization but use the mean of the PDF of the real map

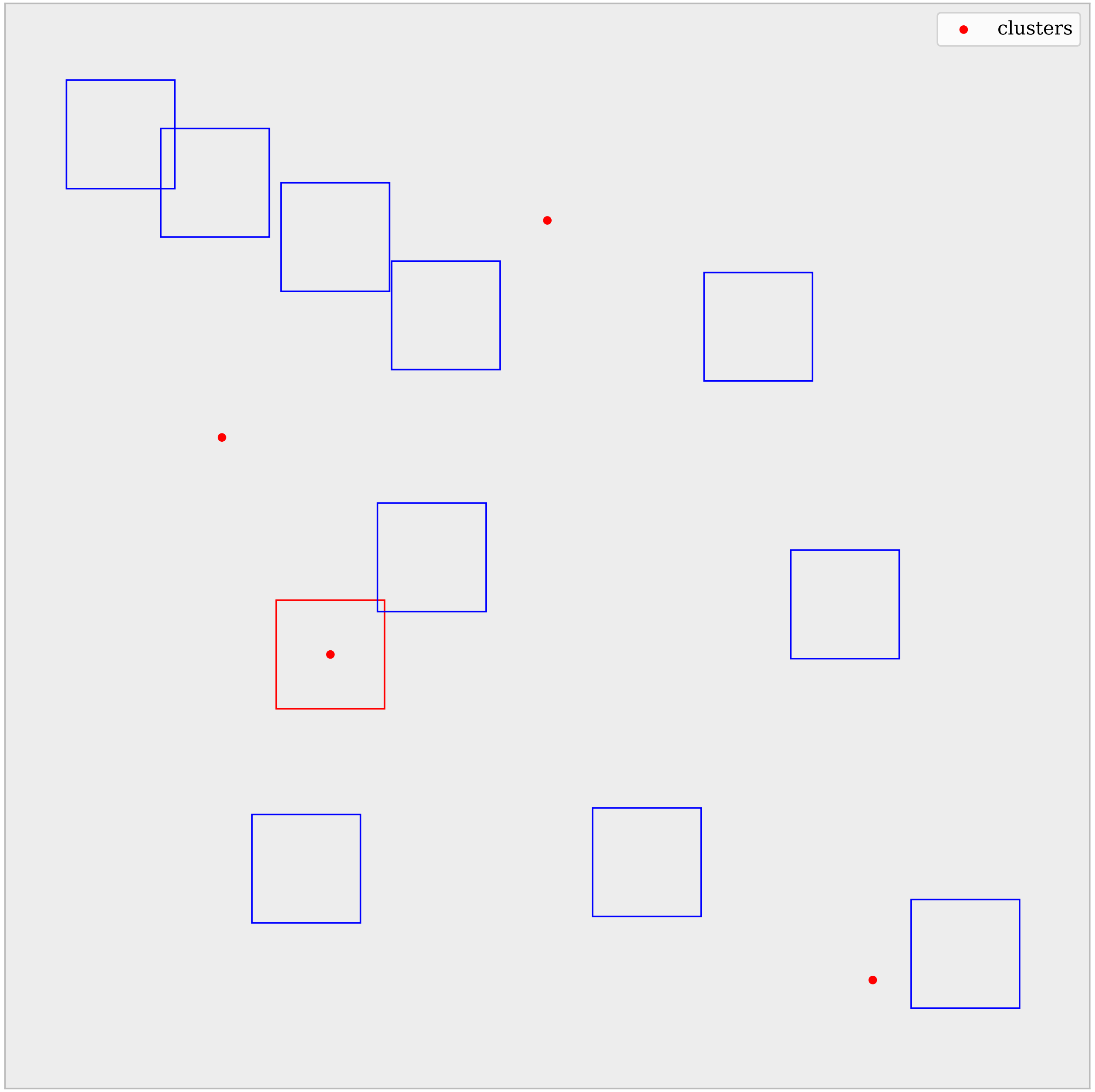


Bias in the lensing!

- Massive **foreground** objects have a lensing effect
- Having **non periodic** maps creates another bias
- These biases **can be corrected** by “off” measurements

→We draw 10 **random** “off” maps **not centered on a cluster** for each “on” map and run the analysis on them

→Final result is **on - off**



For one “on” map, we cut 10 “off” maps in the sky map

Systematic effect

- Different effects must be taken into account
- The baseline analysis uses a profile up to 3 x r500
- Relativistic SZ effect might integrate baseline

Effect	$\Delta \frac{M_{CMBlens}}{M_{SZ}}$
Profile up to $3\times r_{500}$	+0.020
Profile up to $7\times r_{500}$	−0.023
Relativistic SZ	+0.029
Misscentering	−0.0086
Error on z	±0.00083
Error on M_{500}	±0.0065