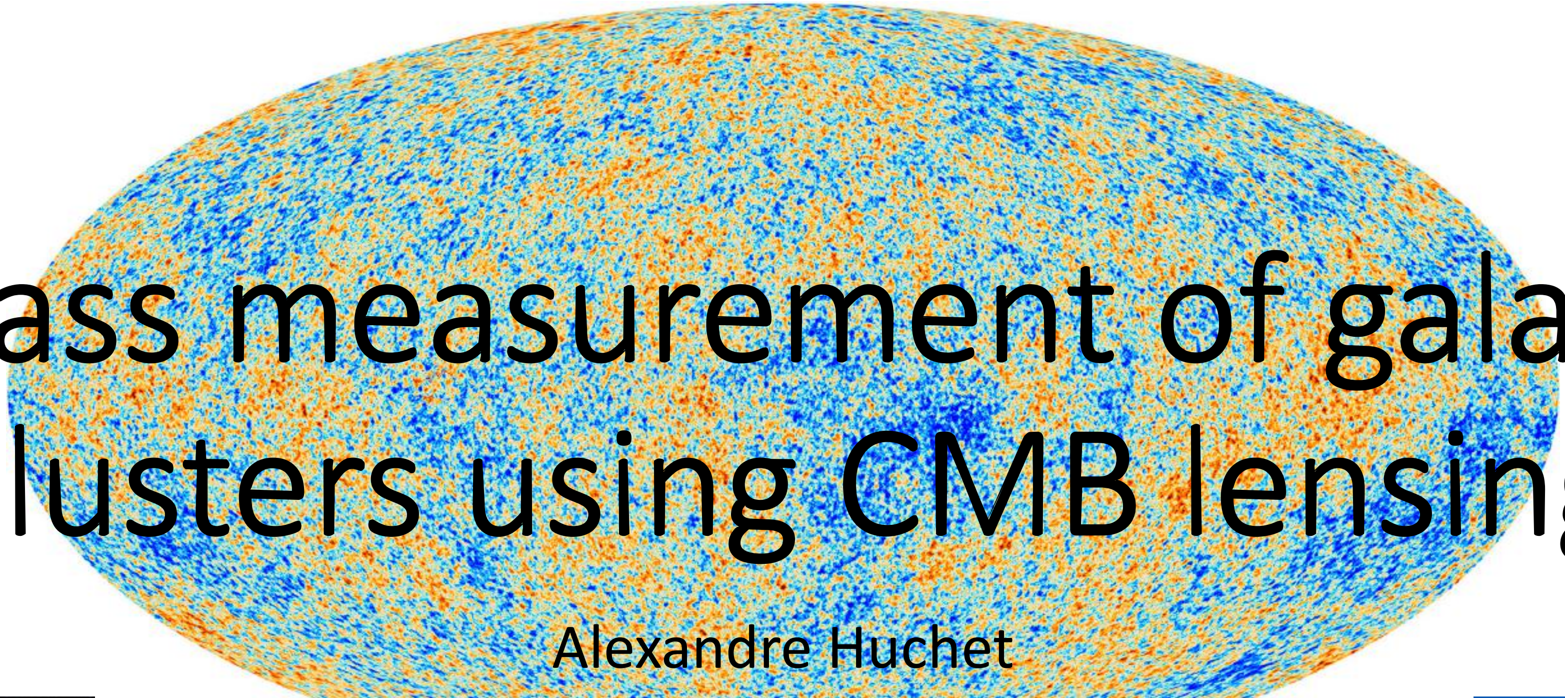
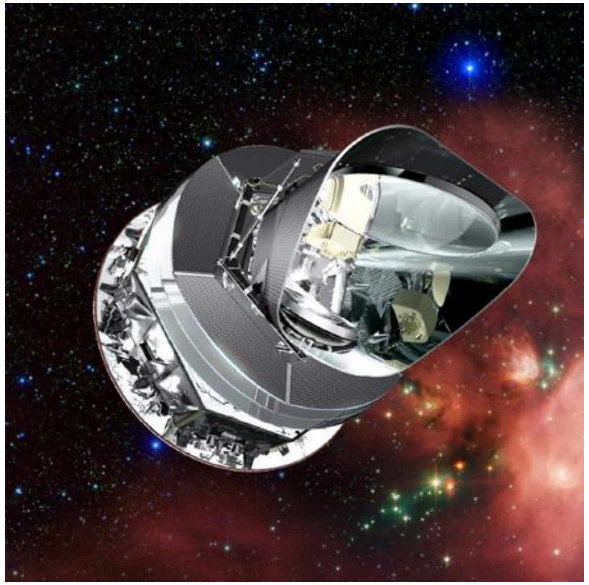
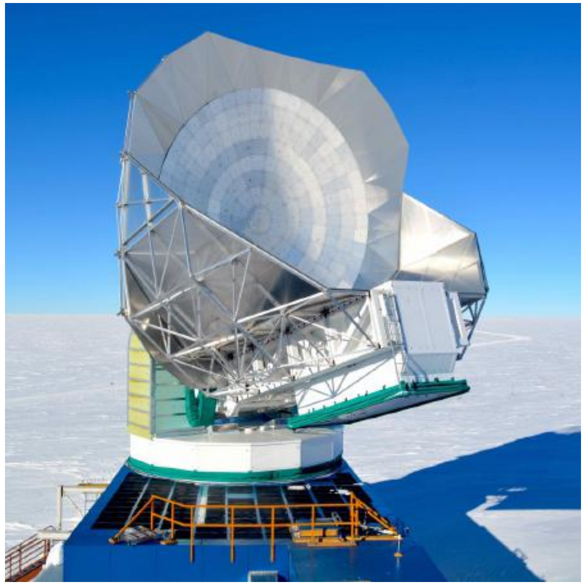


Mass measurement of galaxy clusters using CMB lensing

Alexandre Huchet

Tutor: Jean-Baptiste Melin, CEA/Irfu/DPhP





Mass measurement of galaxy clusters using CMB lensing

A quick introduction/reminder

Mass measurement of galaxy clusters using CMB lensing

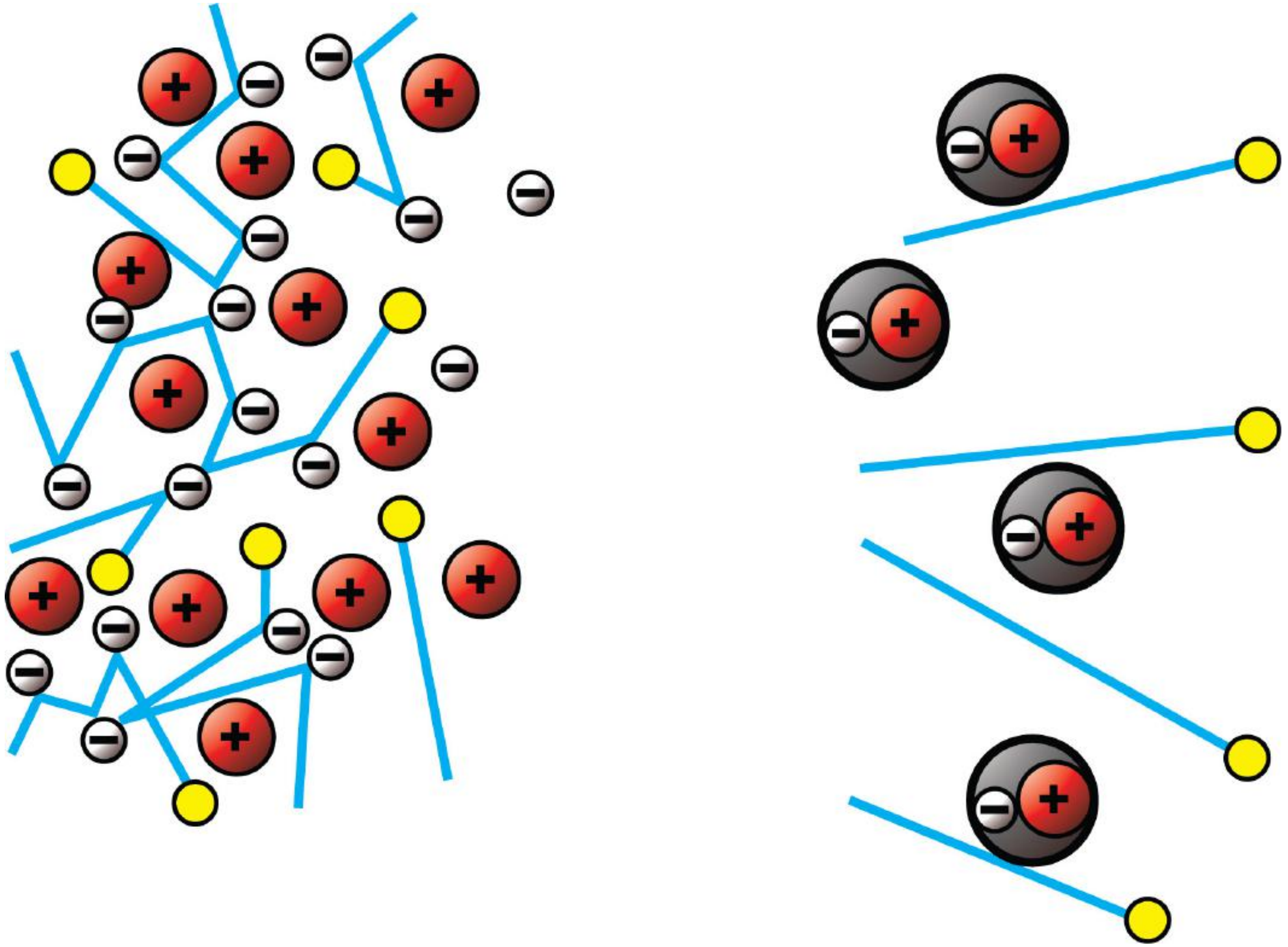
A quick introduction/reminder

The CMB

- The Cosmic Microwave Background (CMB) was emitted about 13.4 billion years ago
- It got cooler because of the expansion of the Universe:

3000 K --> 2.7 K

Credit: Write Science



Before (re)combination, the photons are **scattered** by free electrons. After, they travel freely.

Mass measurement of galaxy clusters using CMB lensing

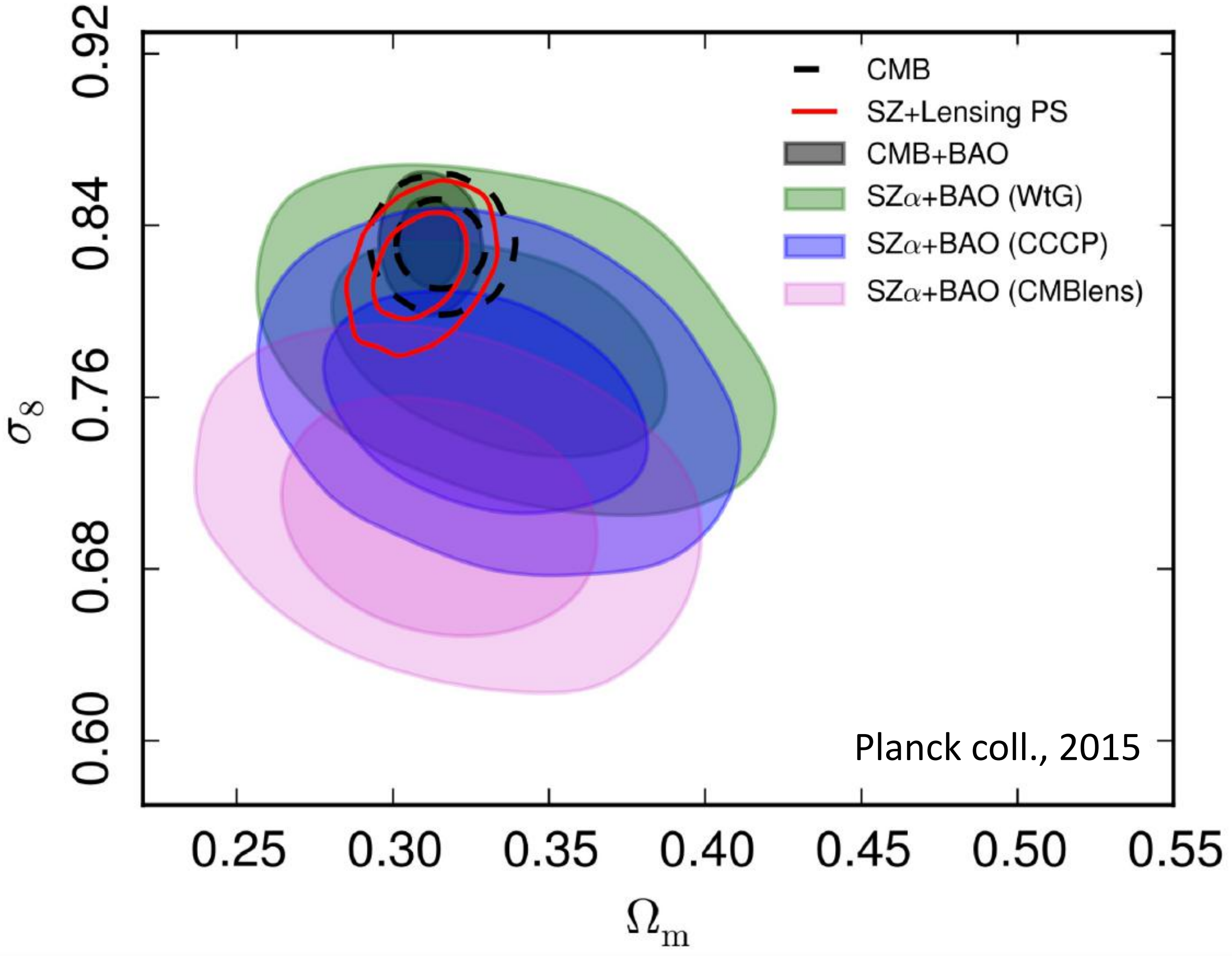
A quick introduction/reminder

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

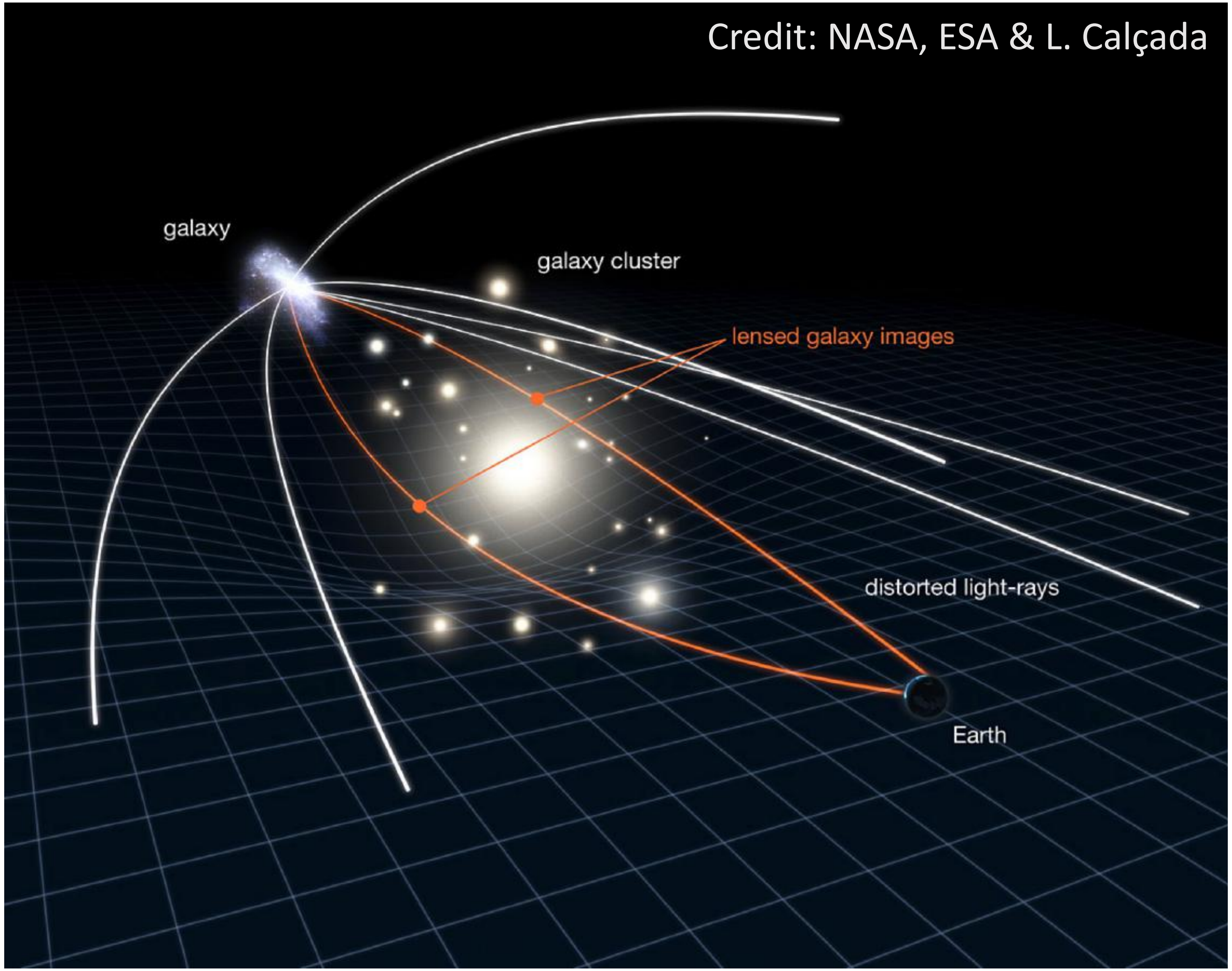
Mass measurement of galaxy clusters using CMB lensing

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



Credit: NASA, ESA & L. Calçada

Lensing induced by a cluster on a background galaxy

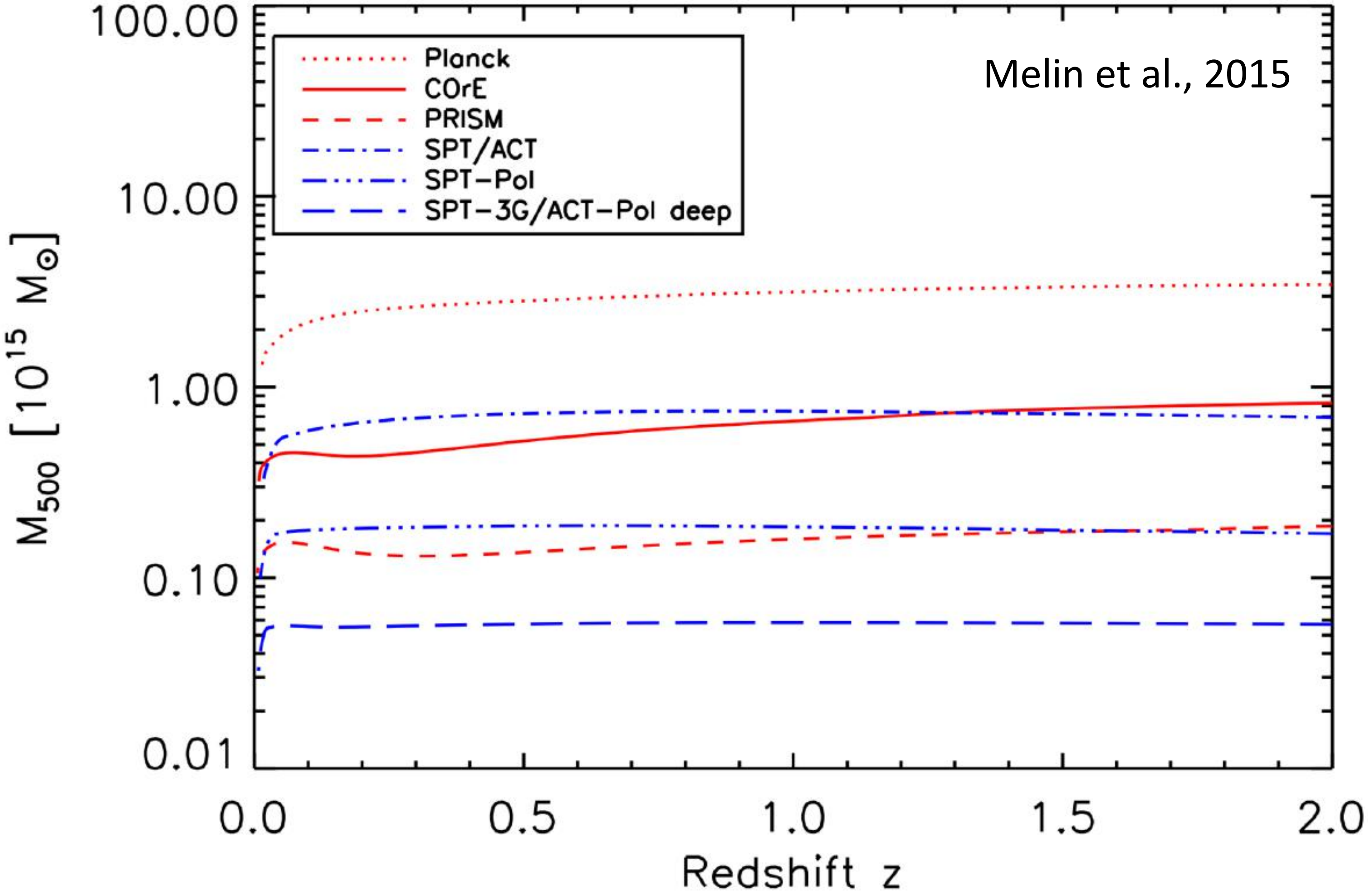
Mass measurement of galaxy clusters using CMB lensing

A quick introduction/reminder

Clusters as lenses

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



Melin et al., 2015

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

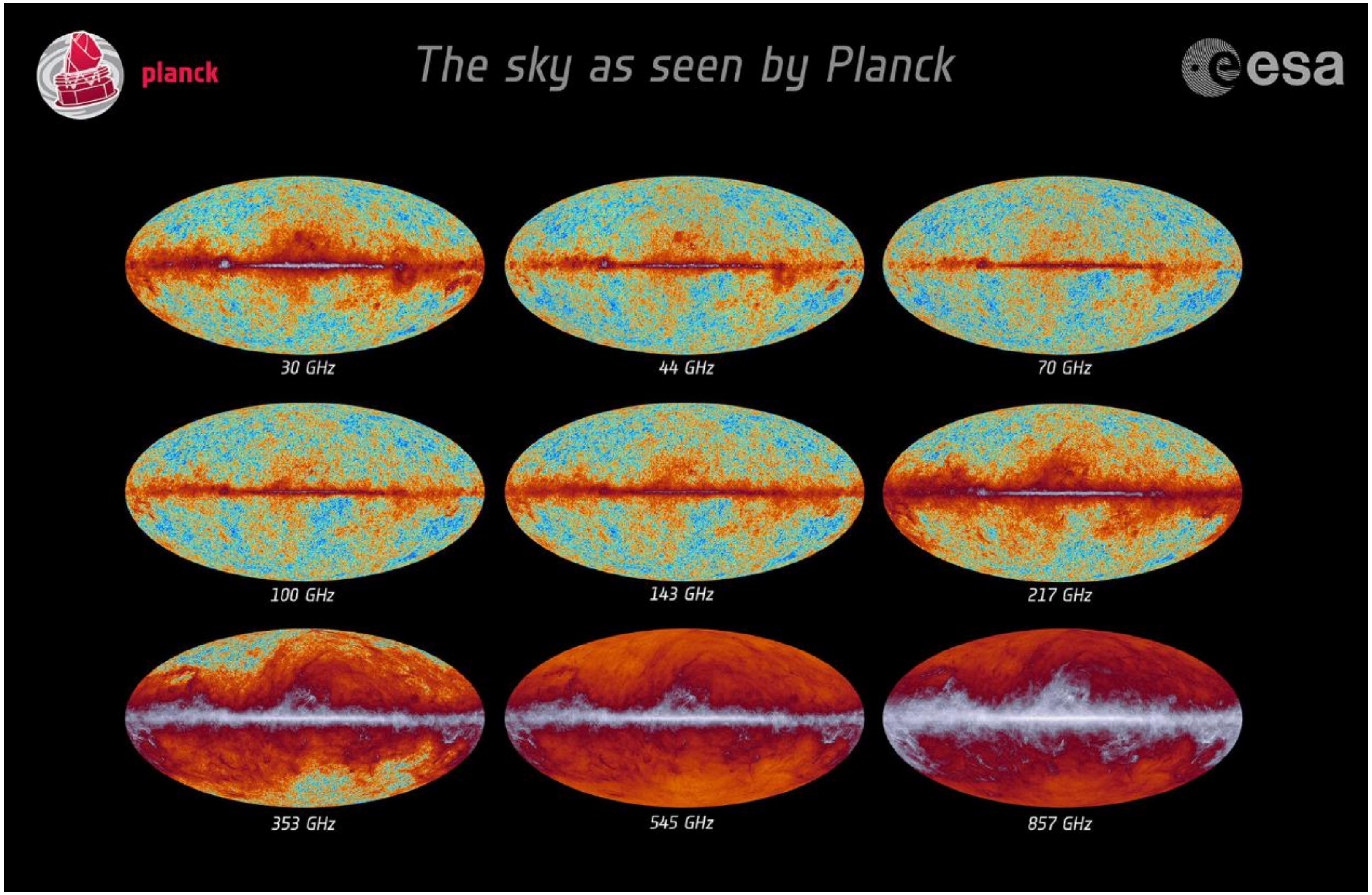
What to do then?

- 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

Two surveys

- Planck survey:
  - All-sky (42000 deg^2)
  - 5 arcmin beam
  - 6 frequencies used
  - In space

- SPT-SZ survey:
  - 2500 deg^2
  - 1.75 arcmin beam
  - 3 frequencies (95, 150, 220 GHz)
  - Ground based

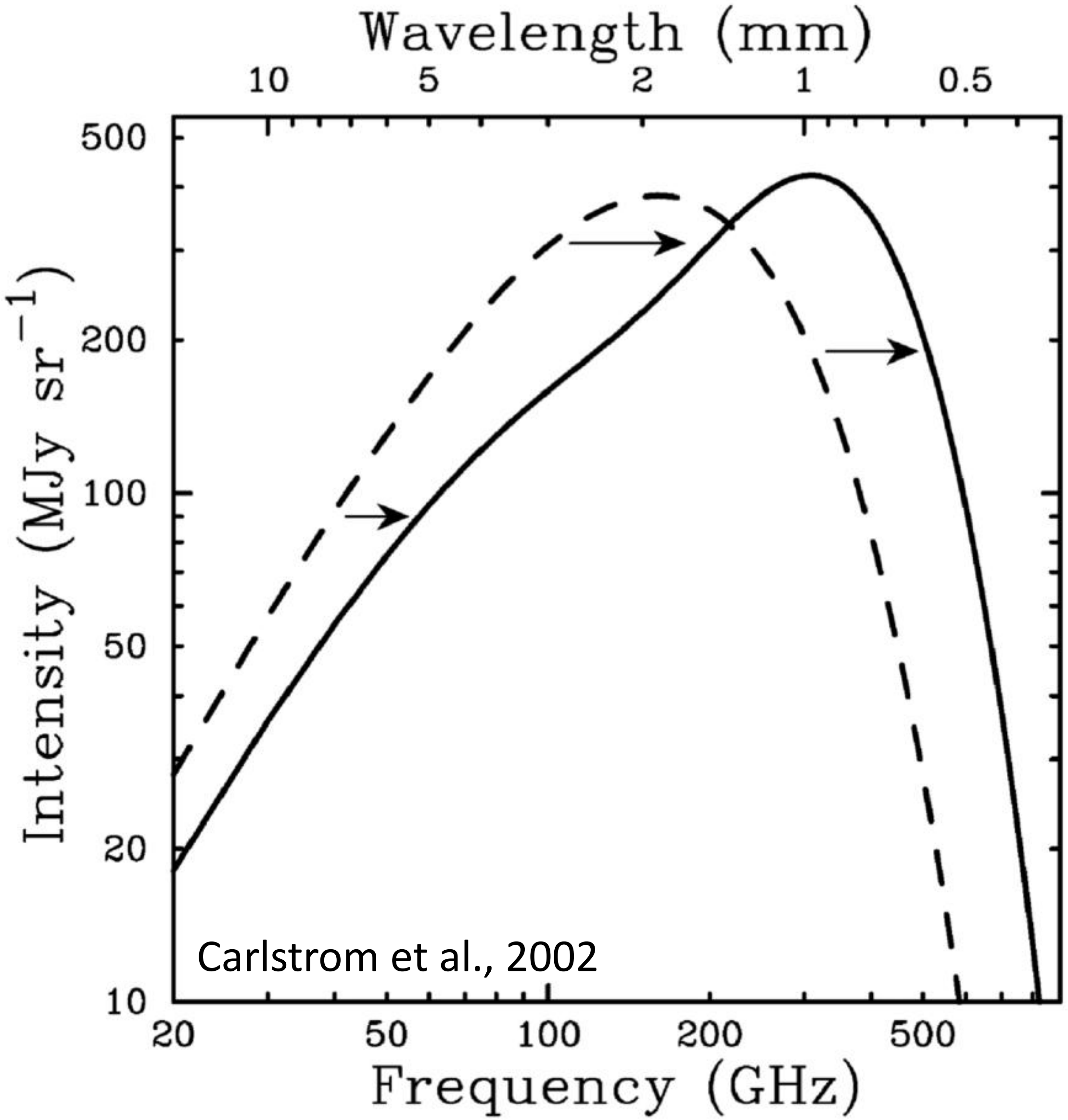


Planck maps of the sky for its 9 frequencies

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



Carlstrom et al., 2002

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

SZ effect

Sunyaev Zel’dovich effect:

- Inverse Compton **scattering** of CMB photons by hot intracluster gas electrons
- The CMB blackbody spectrum is shifted
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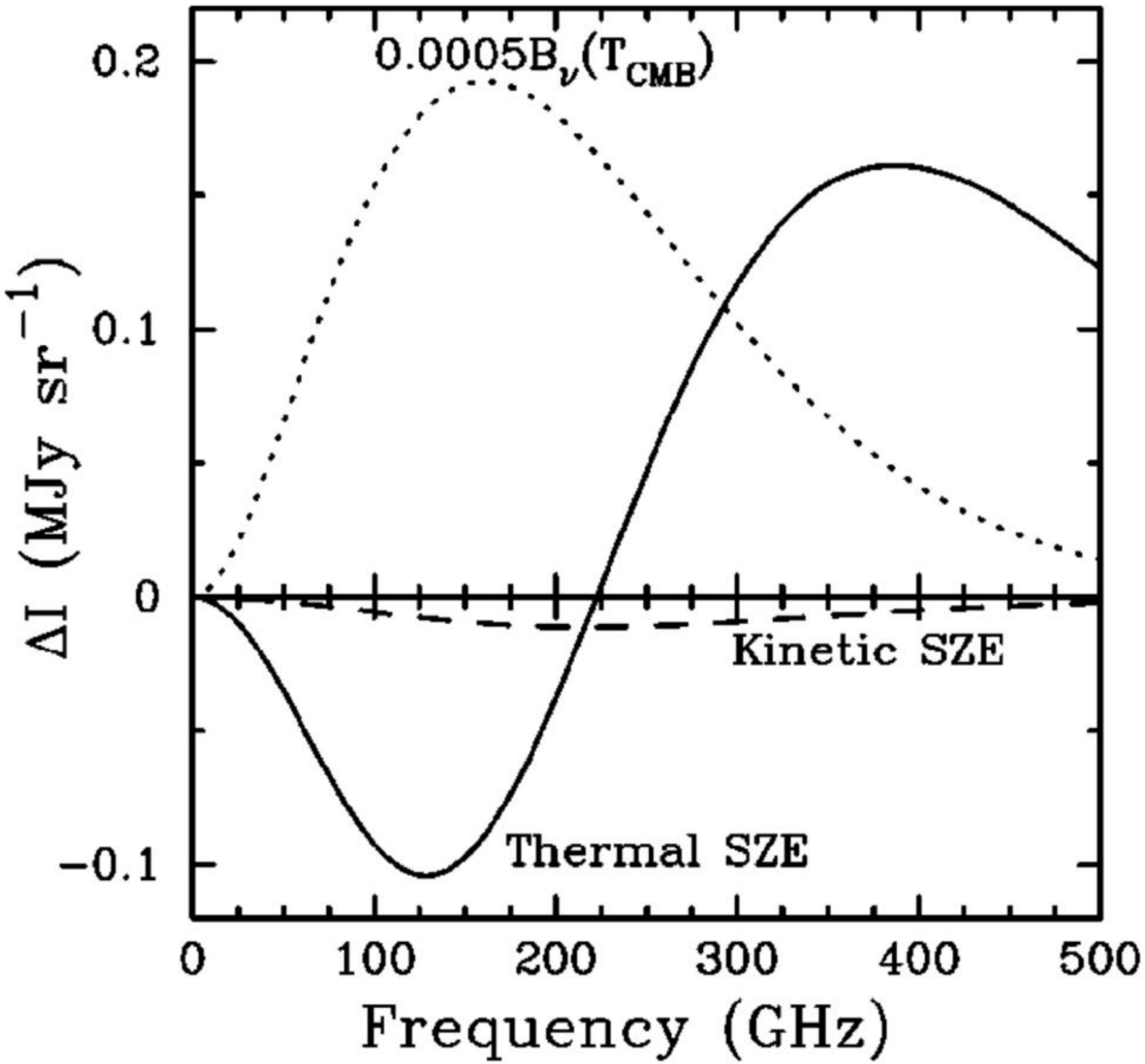
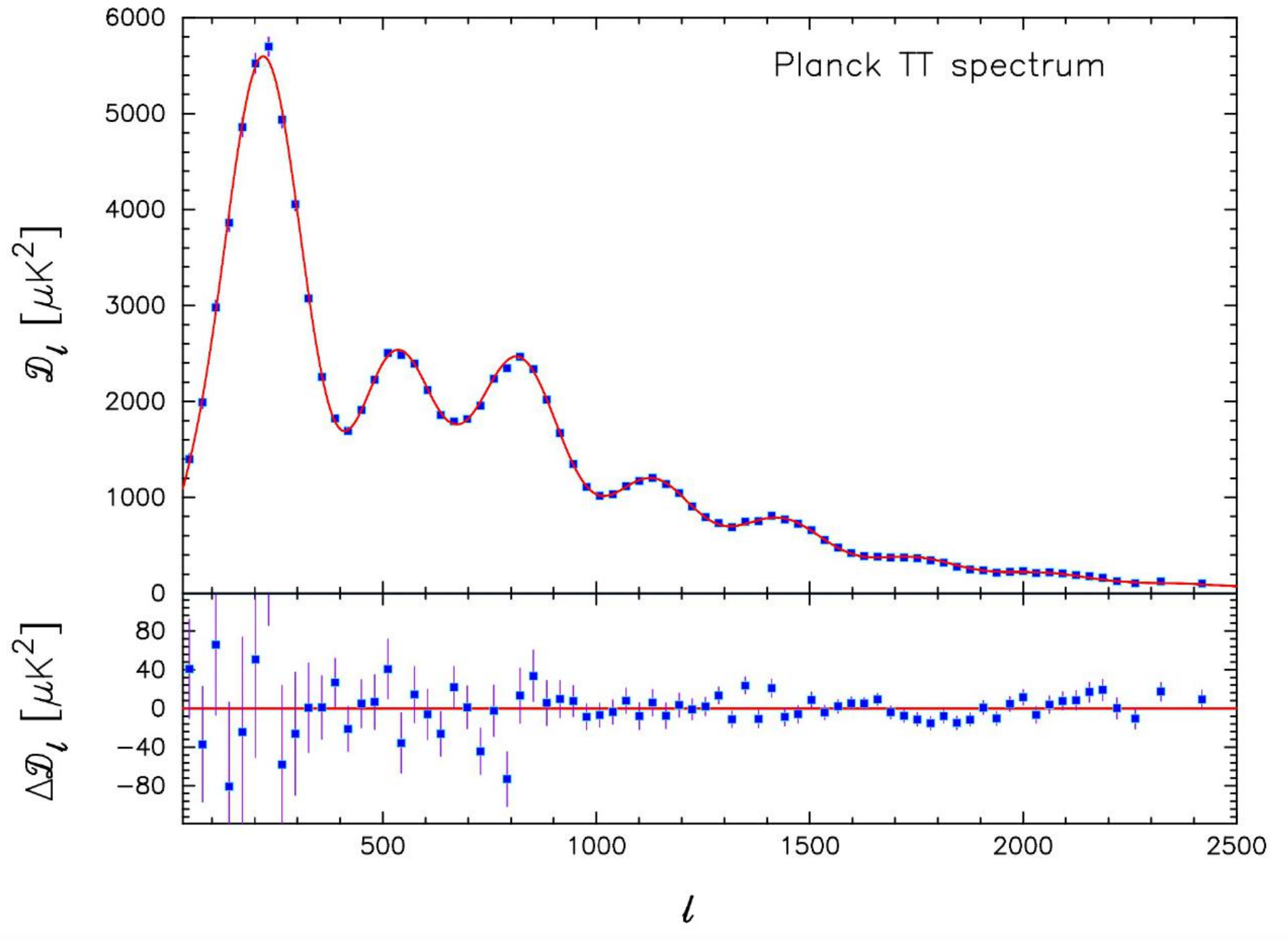
Carlstrom et al., 2002



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

Map simulation

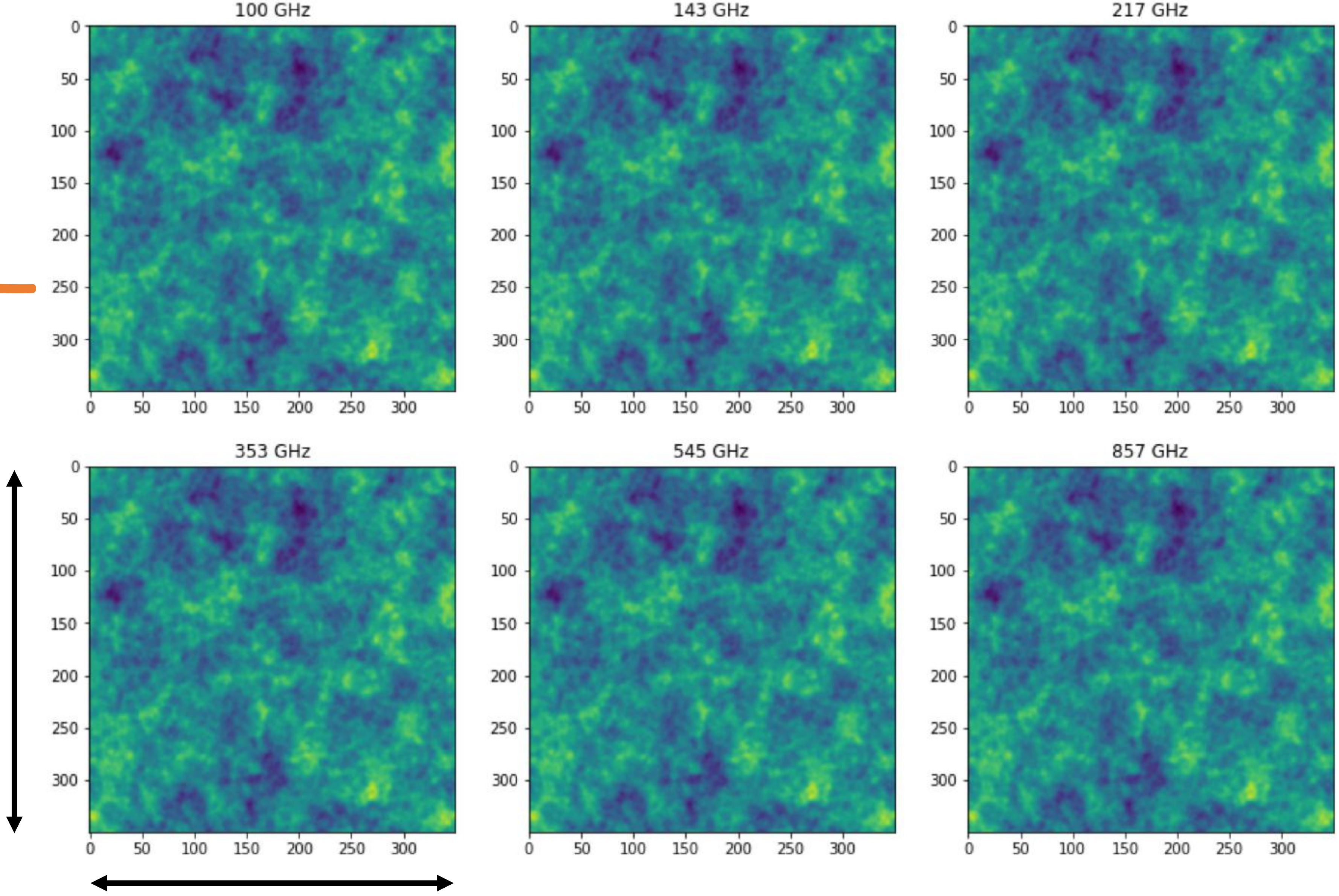
- **CMB**: built from Planck CMB power spectrum
- **Cluster lens**: Navarro-Frenk-White (NFW) density profile
- **SZ effect**: generalized NFW (GNFW) profile
- **Instrumental point spread function** (PSF)
- **Instrumental noise**



Planck CMB TT angular power spectrum

Planck simulation

- CMB



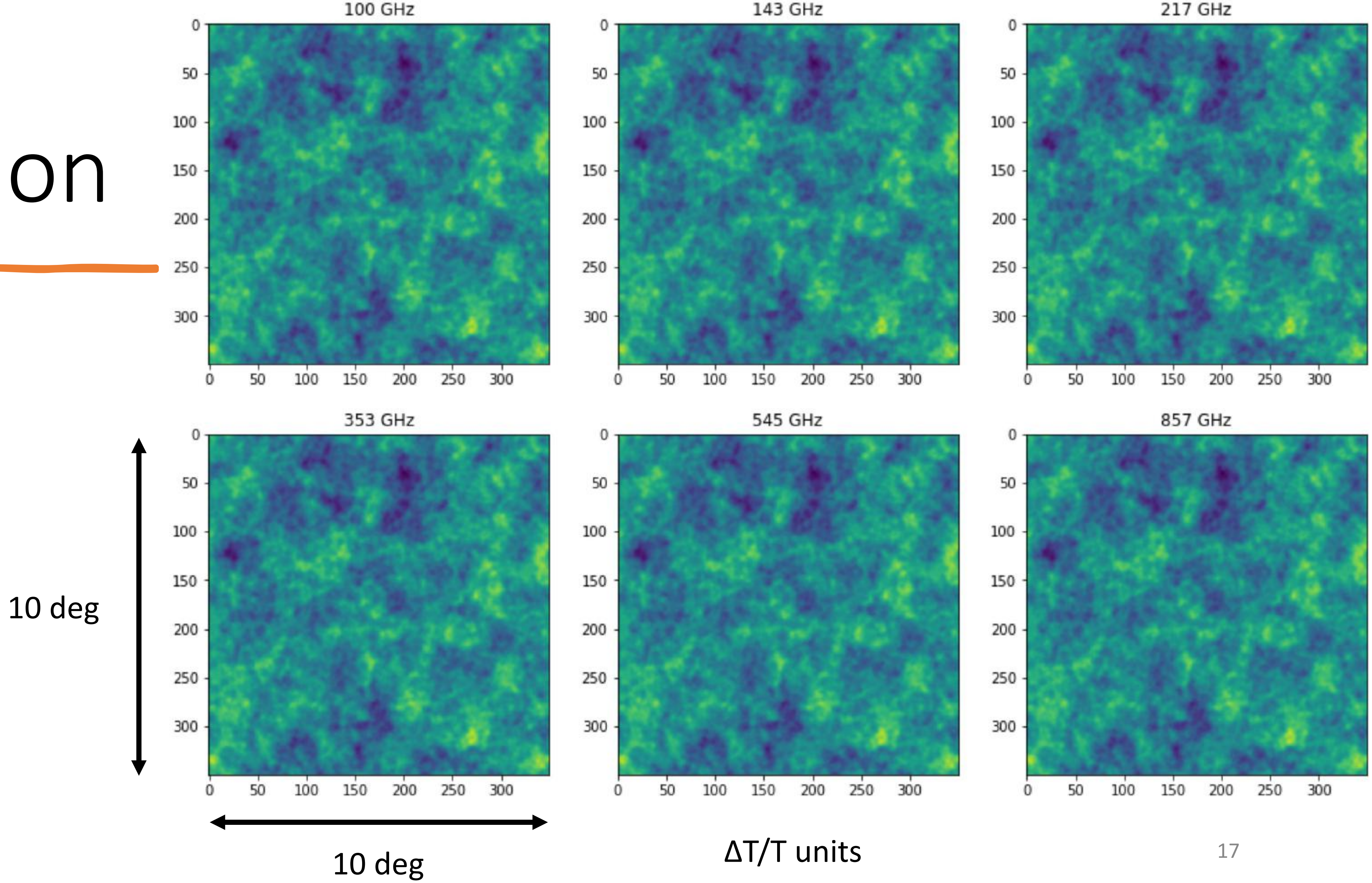
10 deg

10 deg

ΔT/T units

Planck simulation

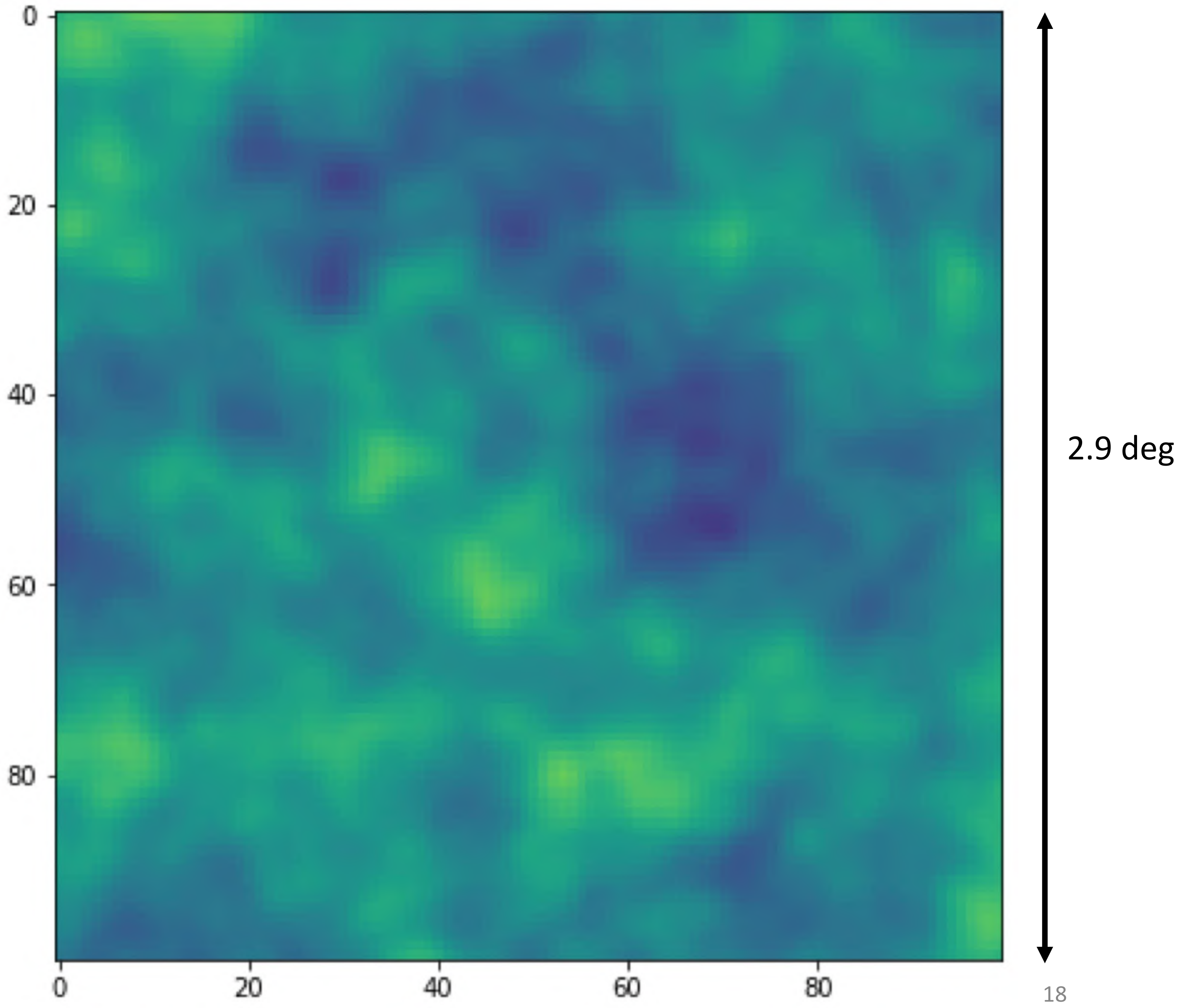
- CMB
- Cluster lens



ΔT/T units

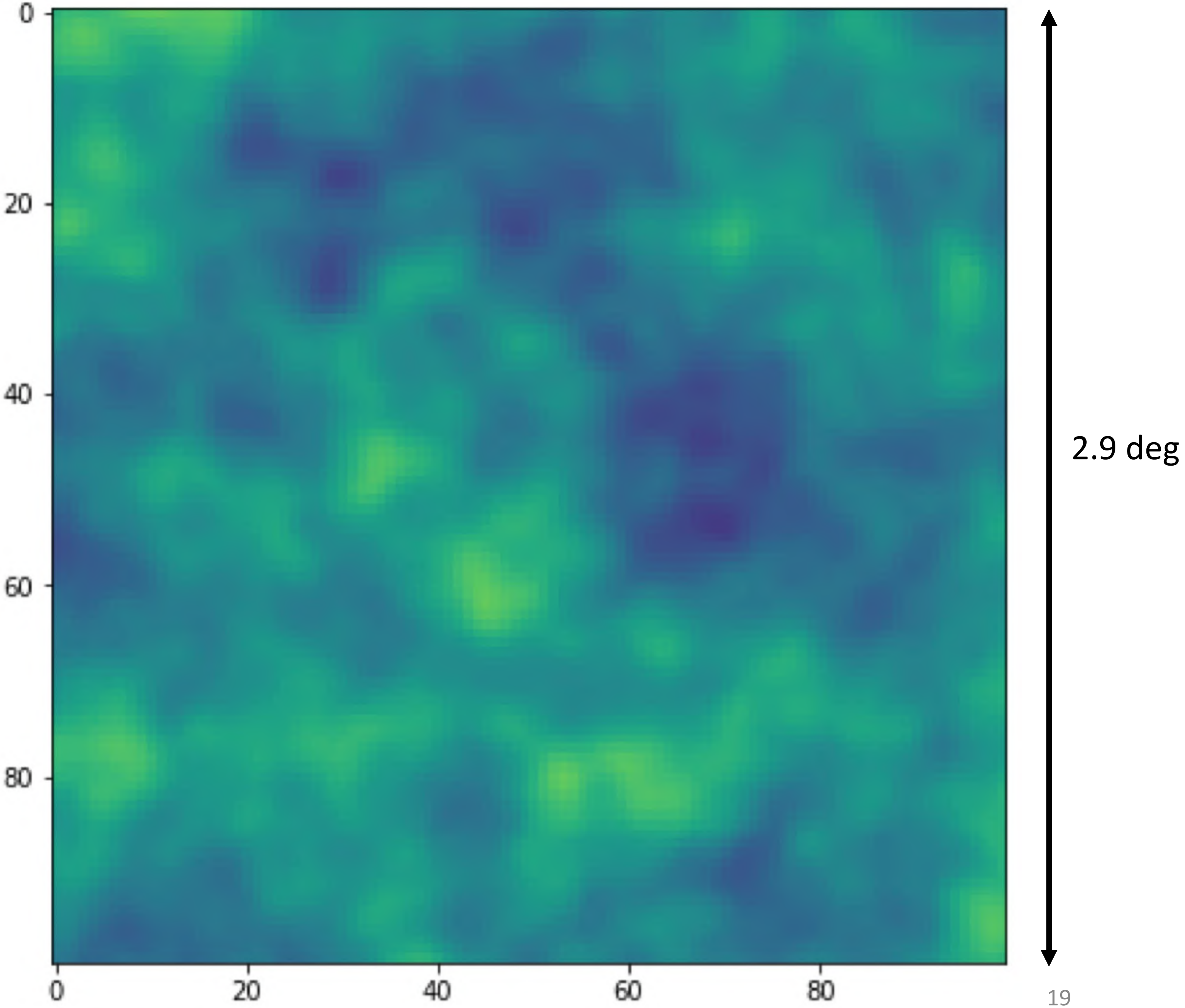
Planck simulation

- CMB



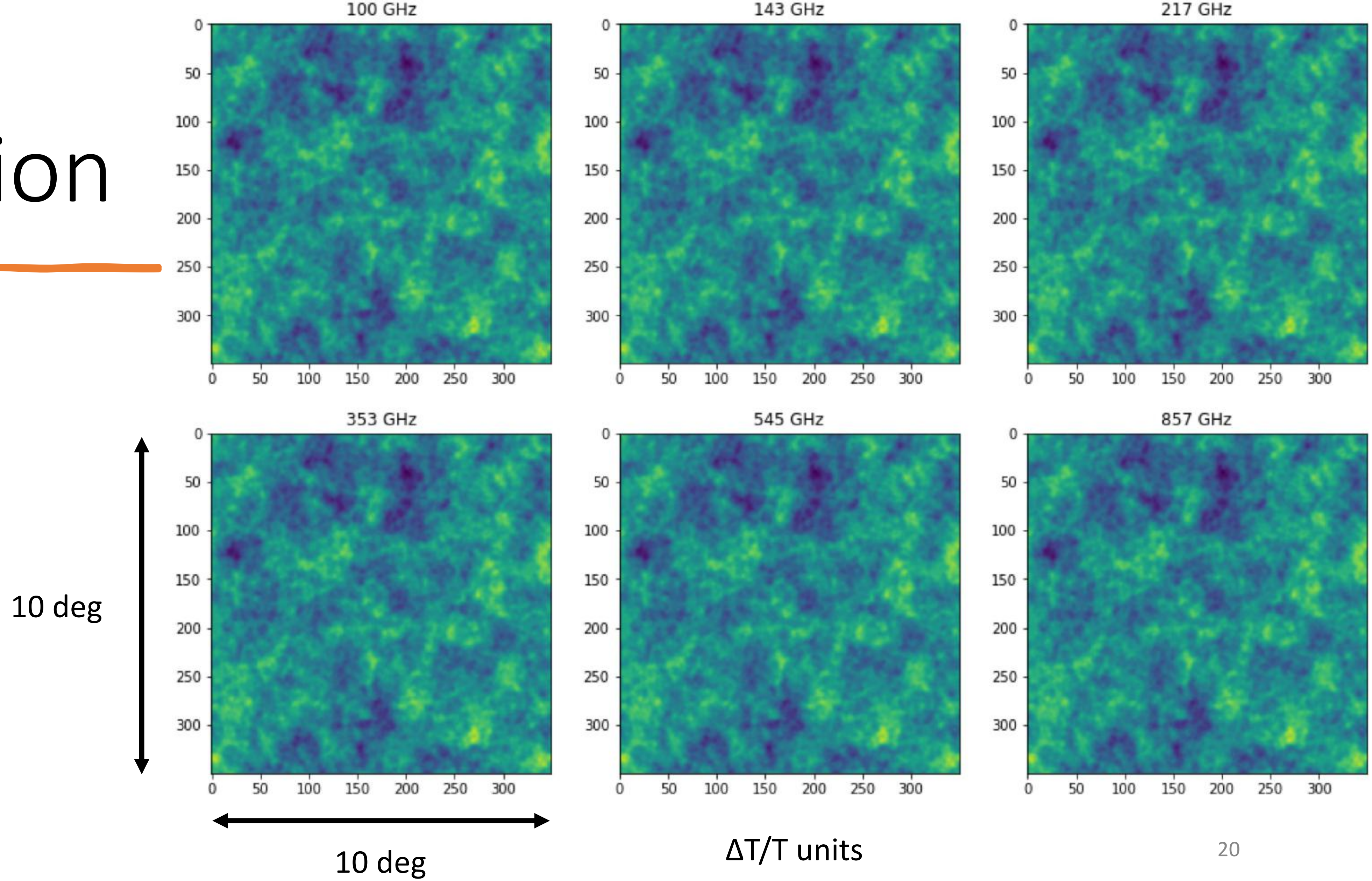
Planck simulation

- CMB
- Cluster lens



Planck simulation

- CMB
- Cluster lens



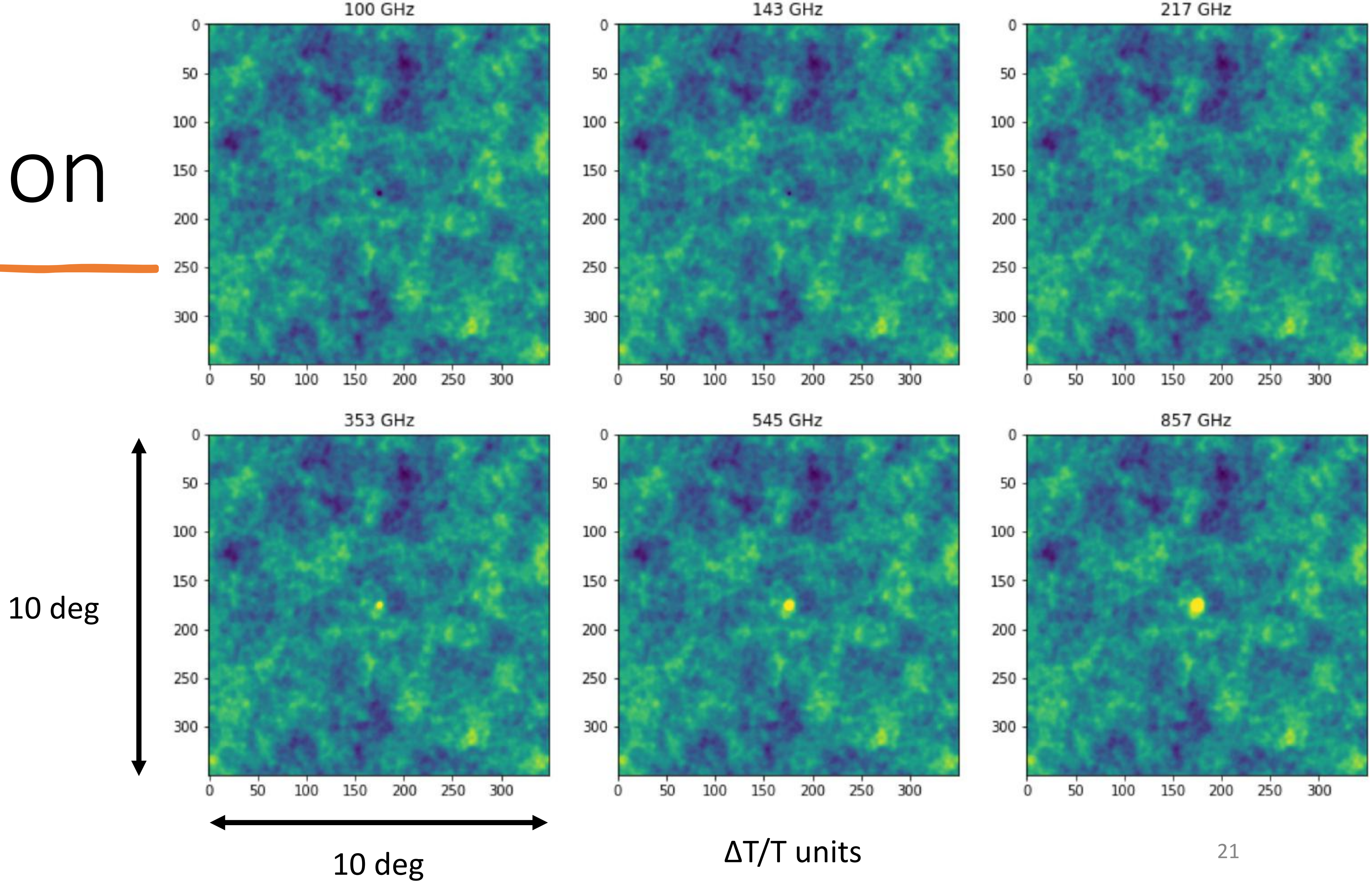
10 deg

10 deg

ΔT/T units

Planck simulation

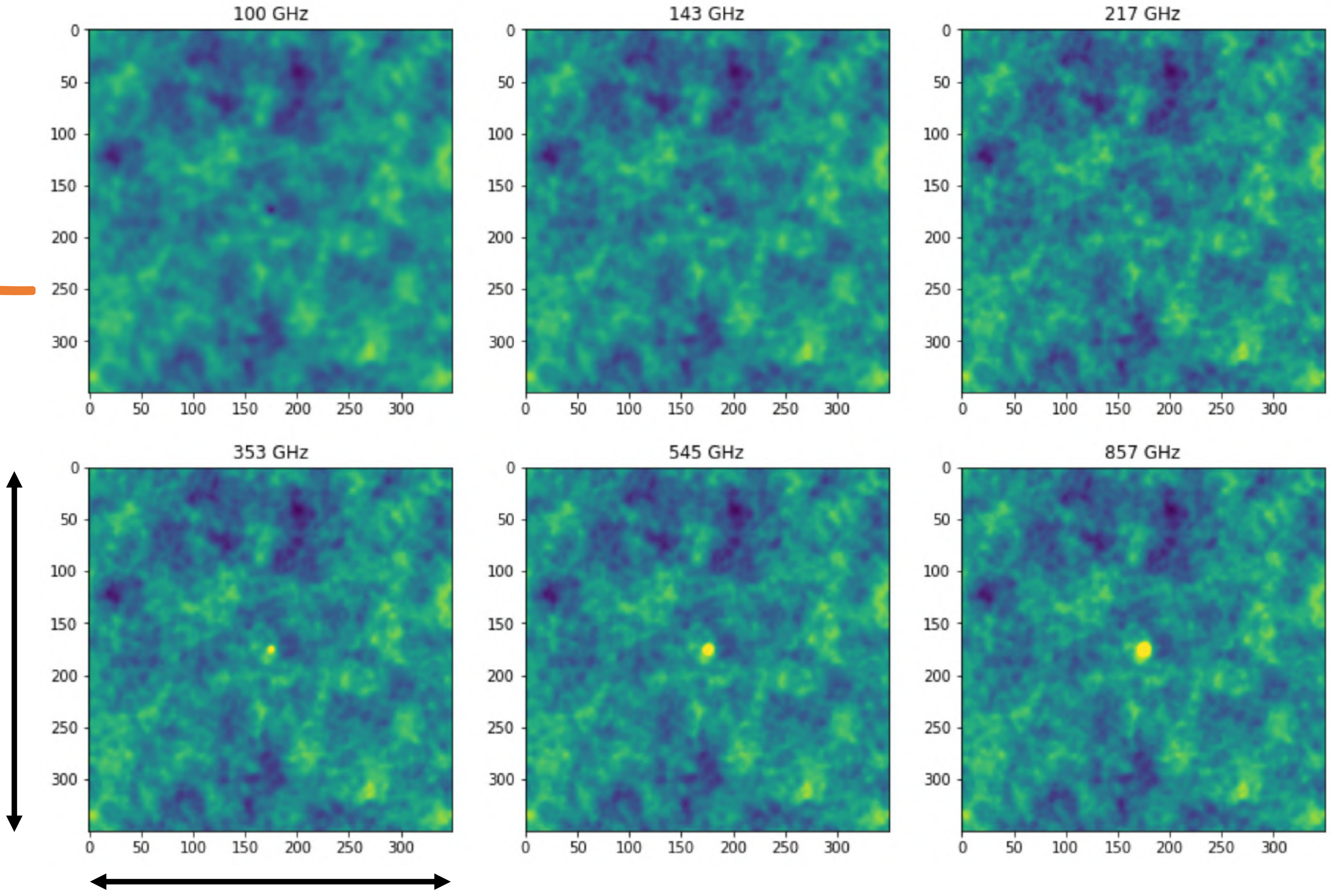
- CMB
- Cluster lens
- SZ effect



ΔT/T units

Planck simulation

- CMB
- Cluster lens
- SZ effect
- Instrumental PSF



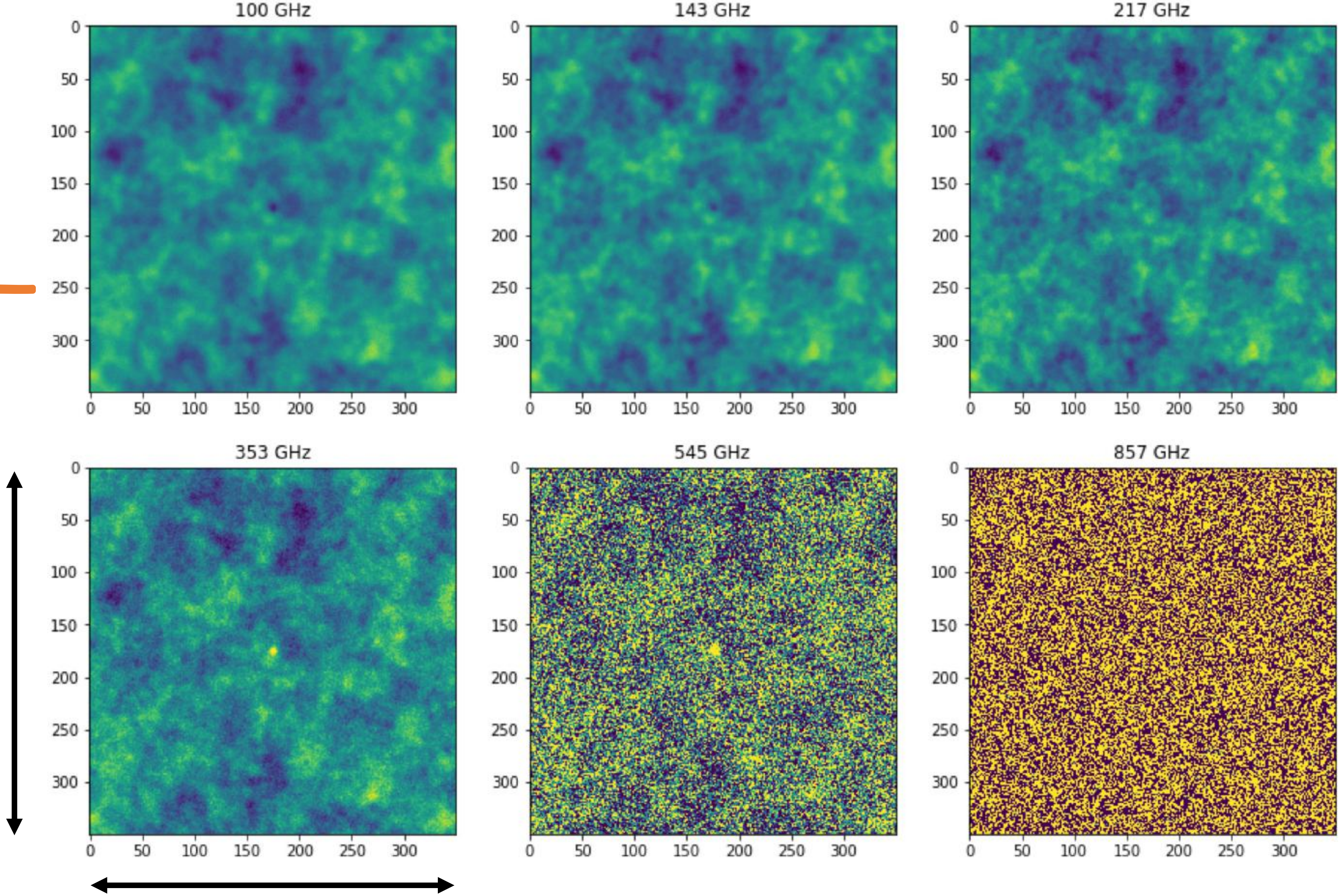
10 deg

10 deg

ΔT/T units

Planck simulation

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



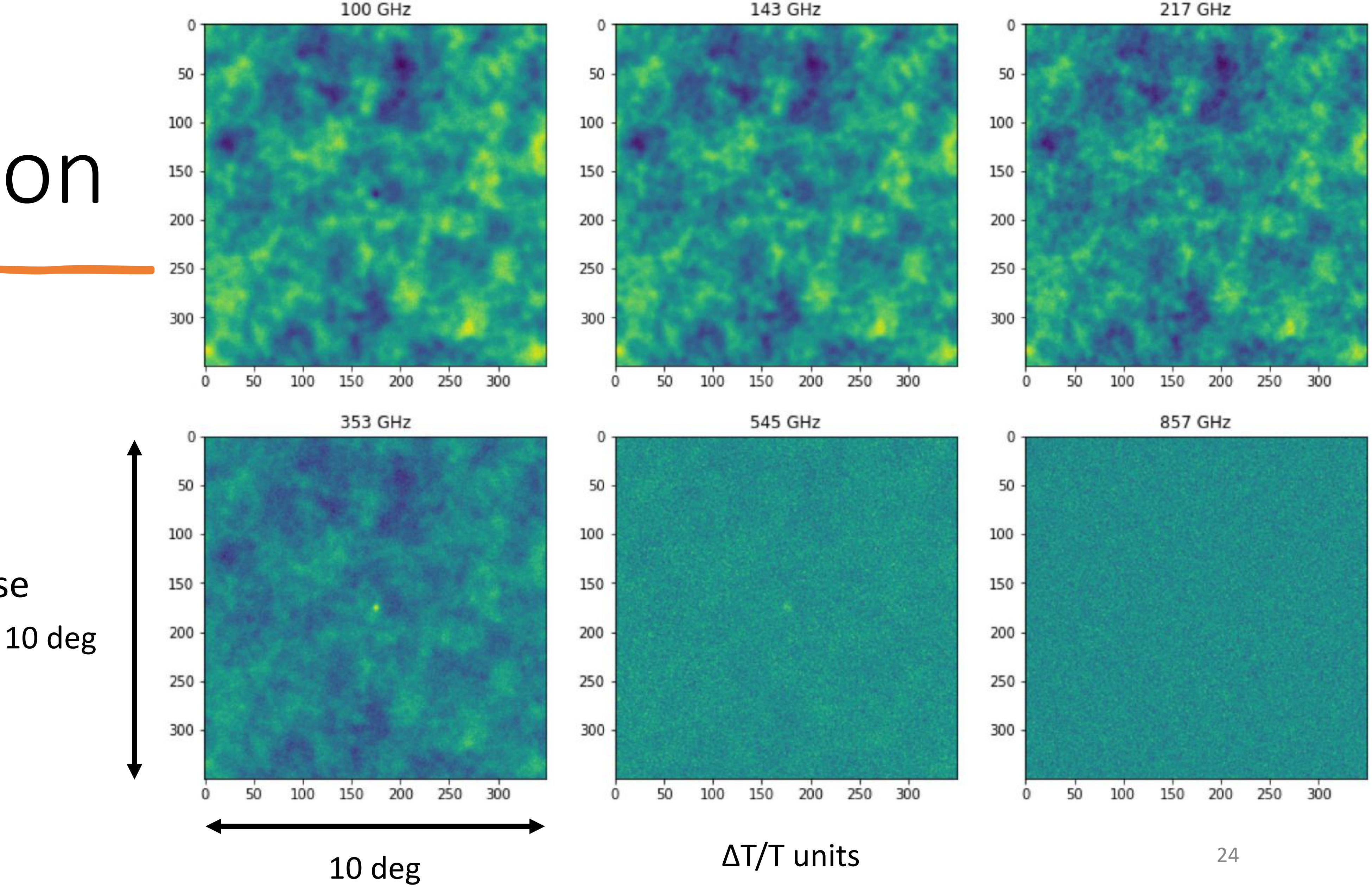
10 deg

10 deg

ΔT/T units

Planck simulation

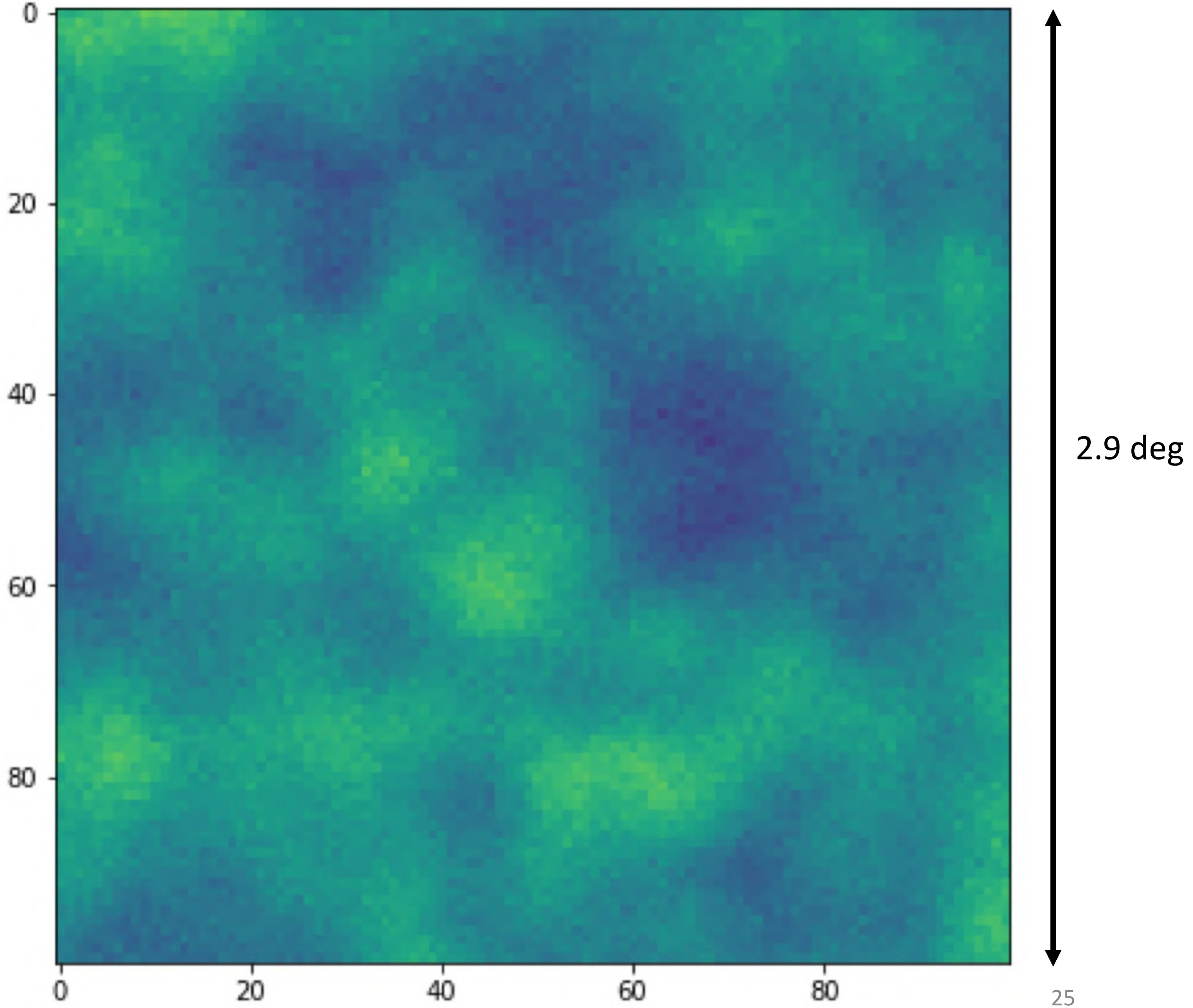
- CMB
- Cluster lens
- SZ effect
- Instrumental PSF
- Instrumental noise



ΔT/T units

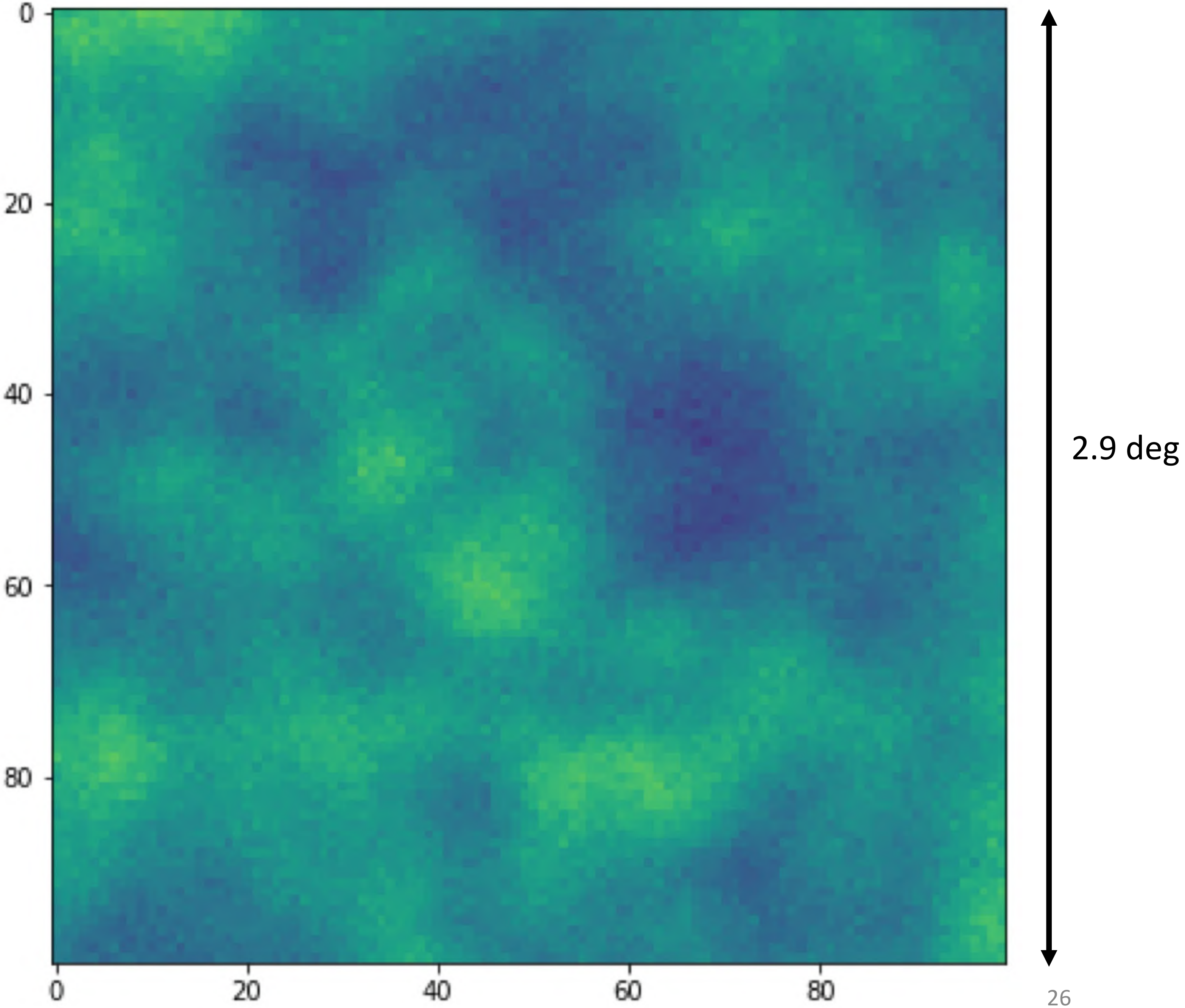
Planck simulation

- 100 GHz map
- No SZ
- No lens



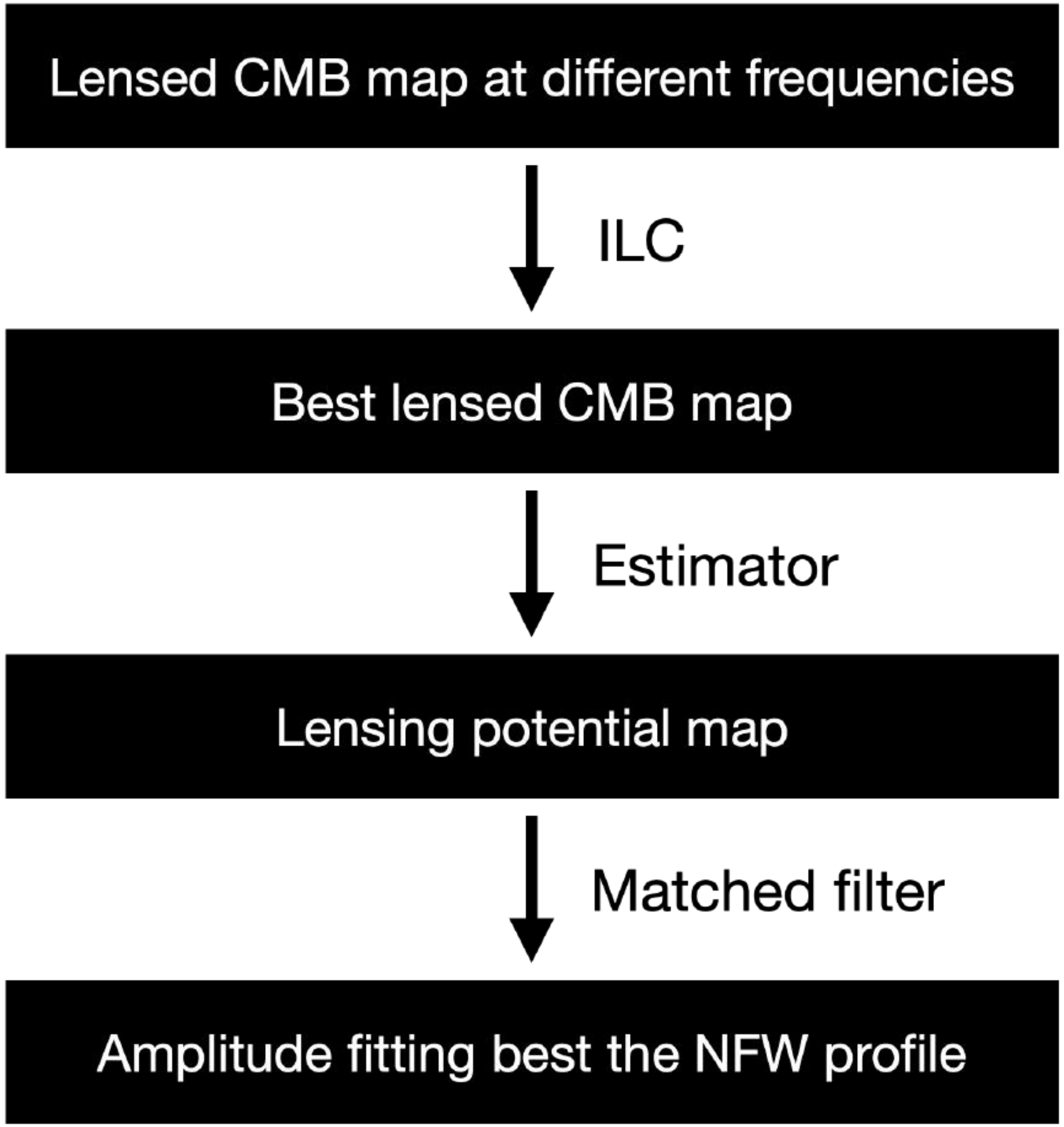
Planck simulation

- 100 GHz map
- No SZ
- Cluster lens



Data analysis

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



Lensed CMB map at different frequencies

ILC

Best lensed CMB map

Estimator

Lensing potential map

Matched filter

Amplitude fitting best the NFW profile

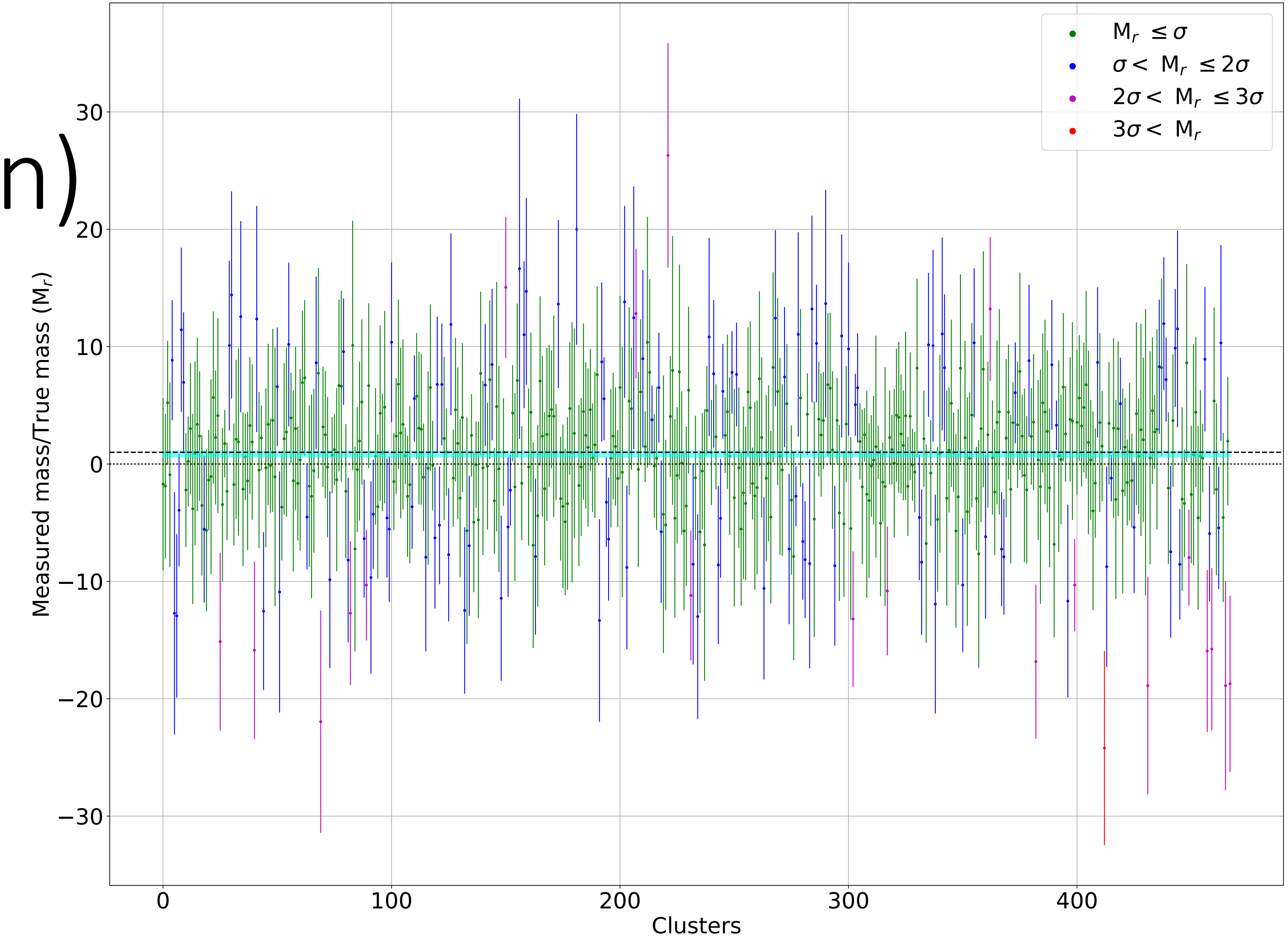
Planck results (one realization)

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



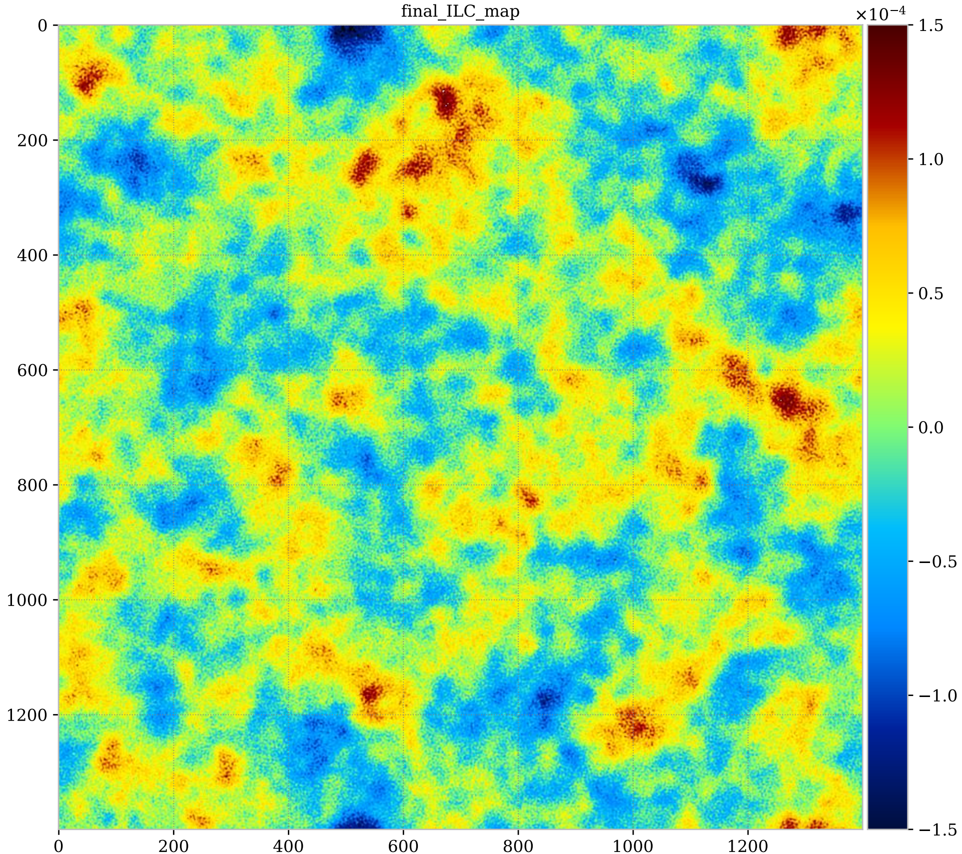
Comparison between Planck and SPT results…

Planck ILC maps: large scales

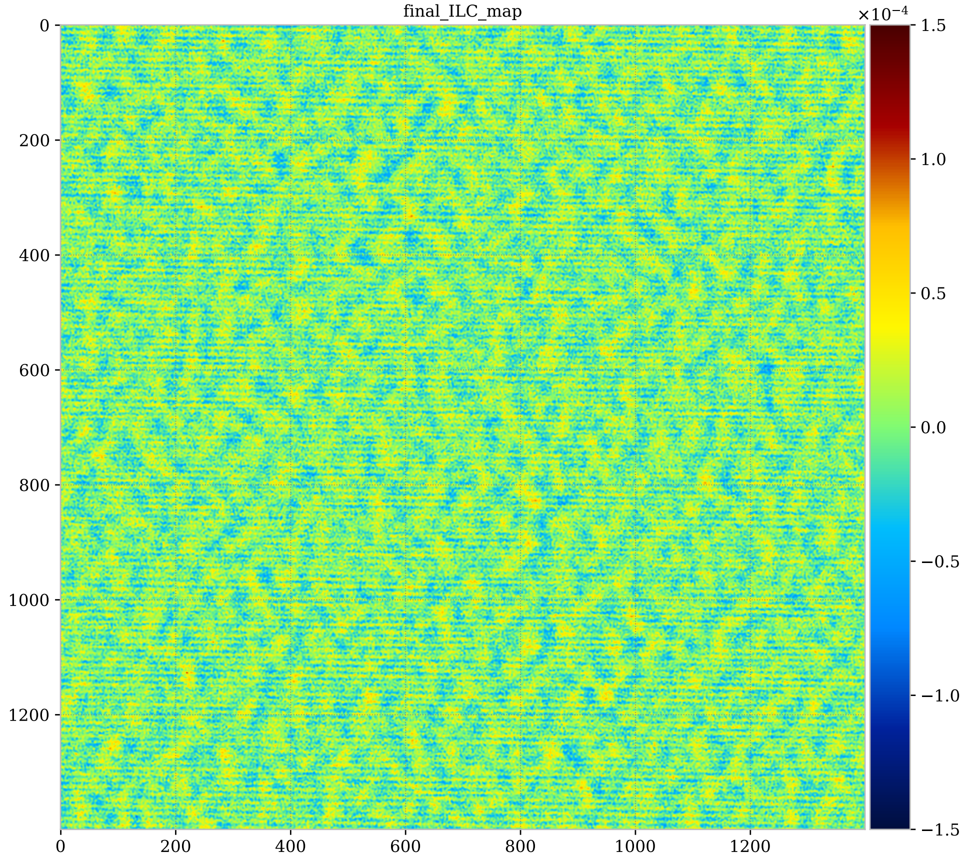
<Mr> = 0.84 ± 0.25 (one realization)

SPT ILC maps: small scales

<Mr> = 0.91 ± 0.22 (one realization)



Planck ILC map



SPT ILC map

Final ILC maps for the same location

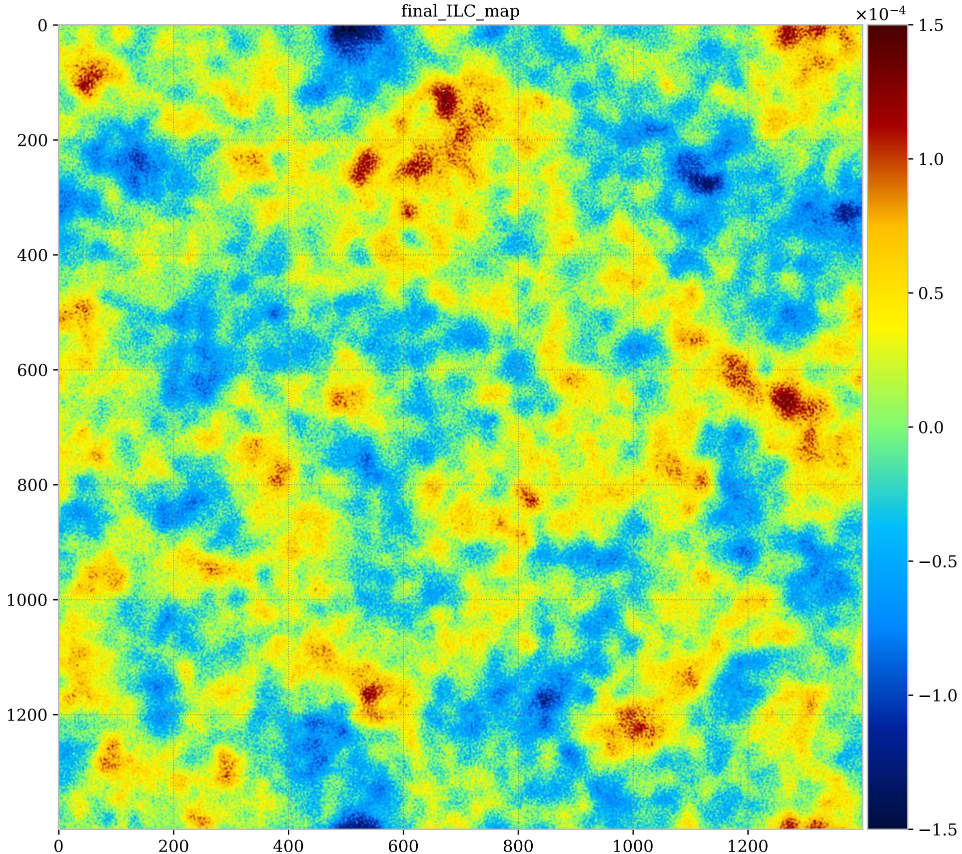
… and the combination of both

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

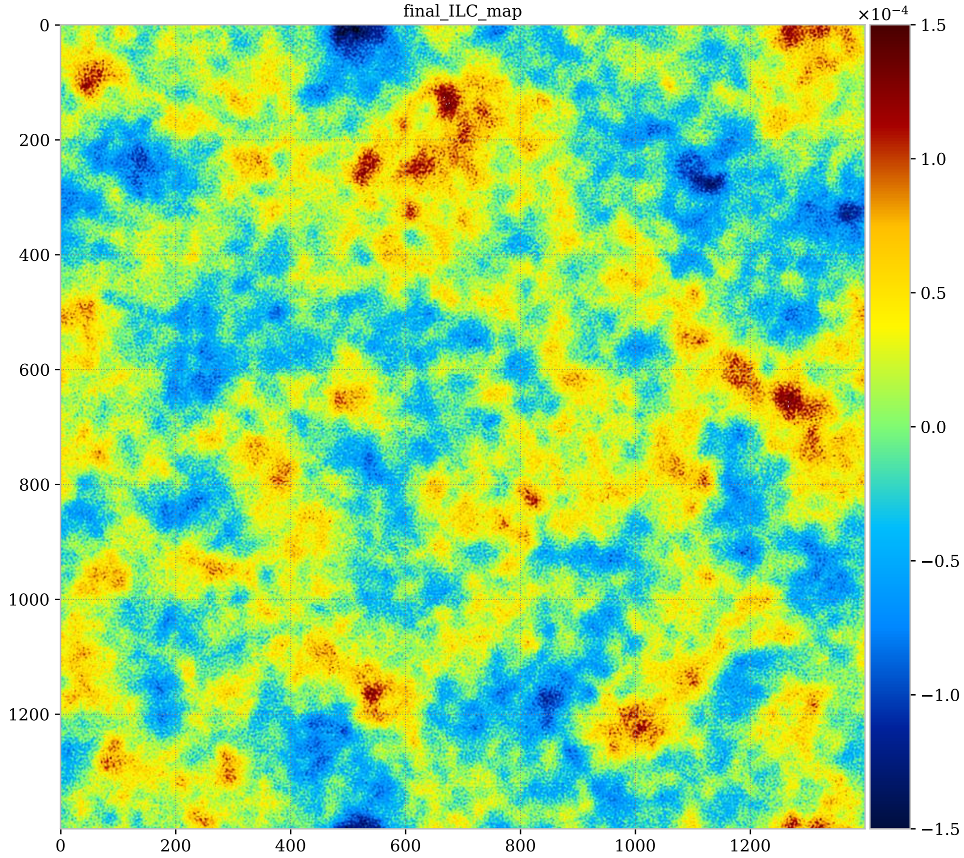
SPT: <Mr> = 0.91 ± 0.22

Combination:

<Mr> = 0.88 ± 0.17



Planck ILC map

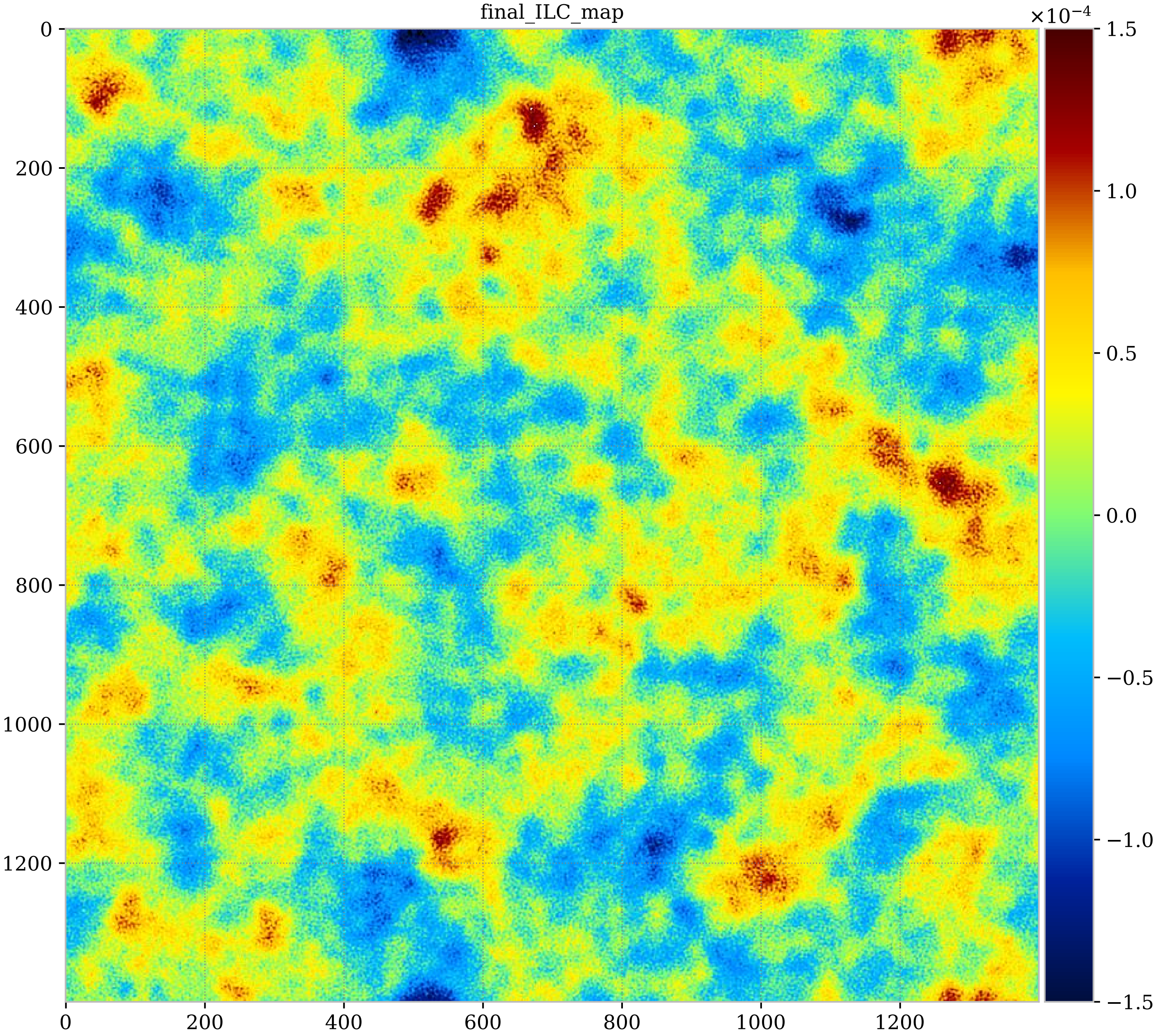


Combi ILC map

Final ILC maps for the same location

Planck ILC map

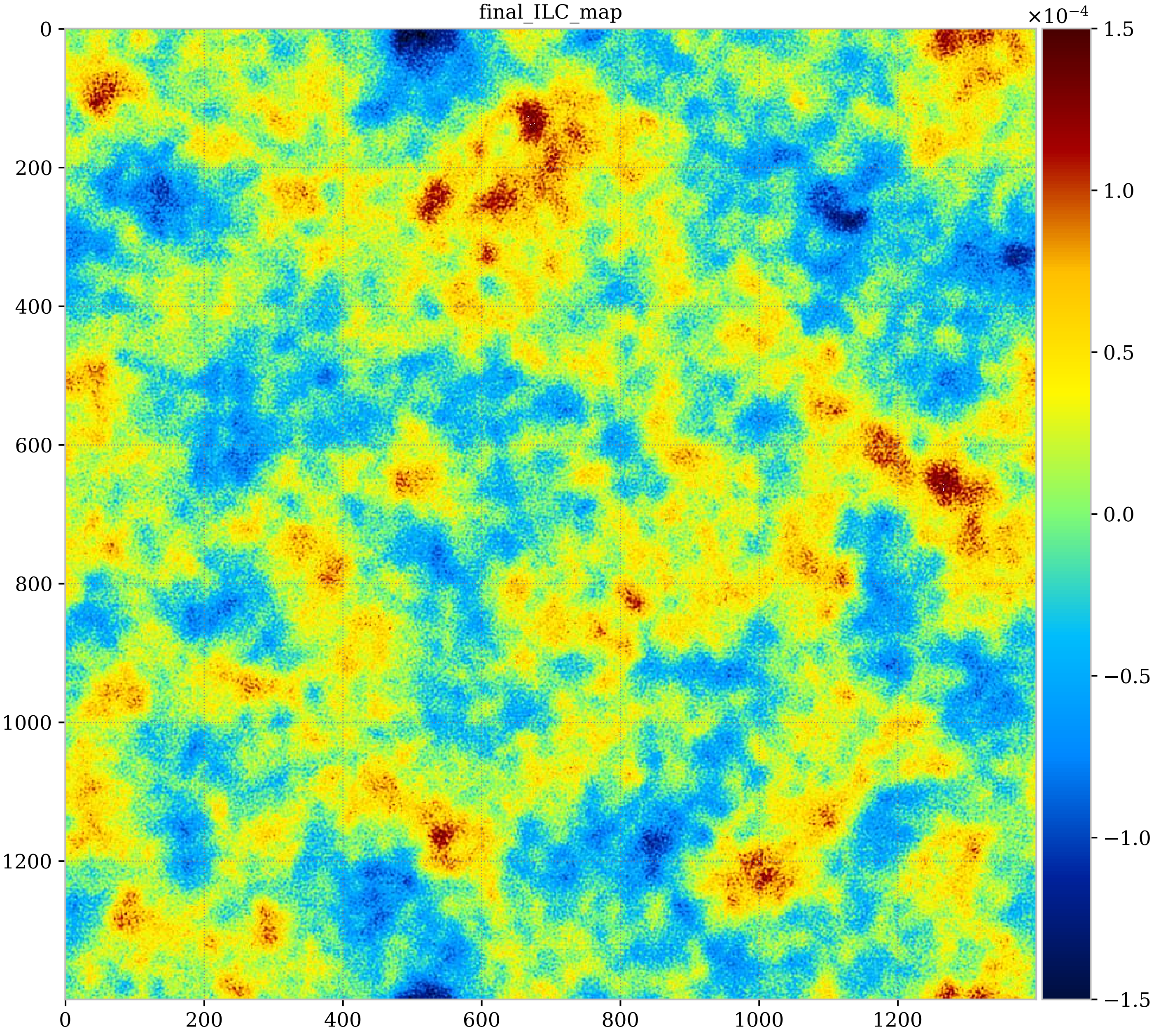
- For one simulated cluster
- No foreground simulated
- The map is periodic



Combined ILC map

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

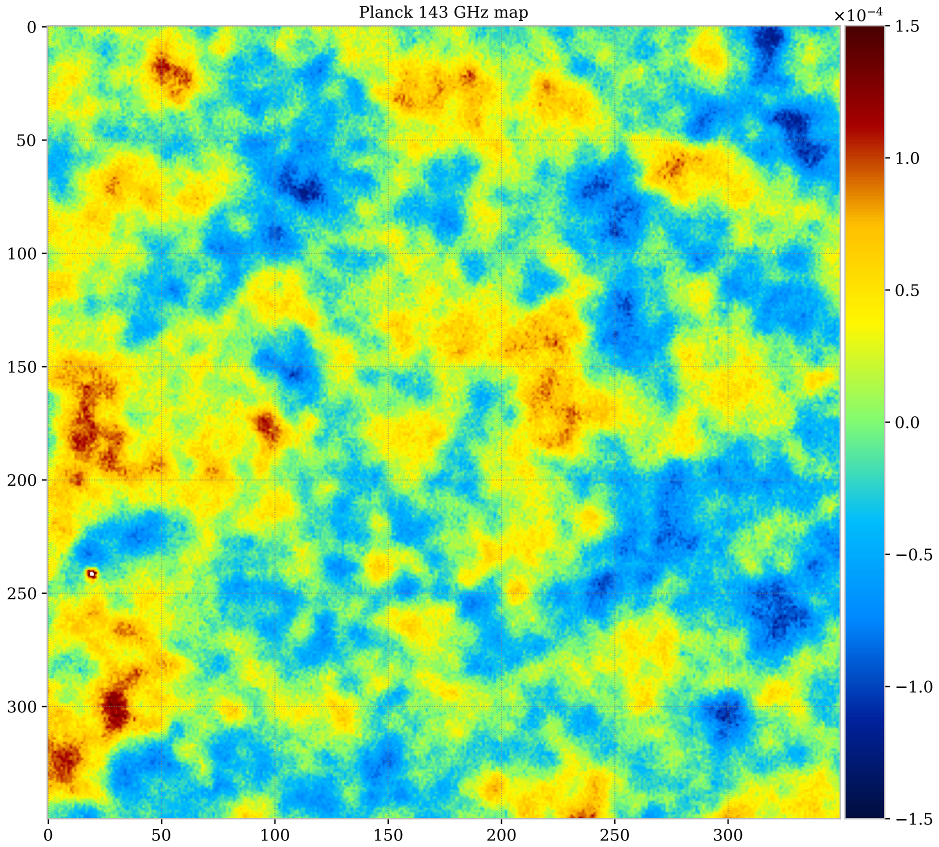
$$\frac{1}{\sigma^2_{combi}} = \frac{1}{\sigma^2_{planck}} + \frac{1}{\sigma^2_{SPT}}$$

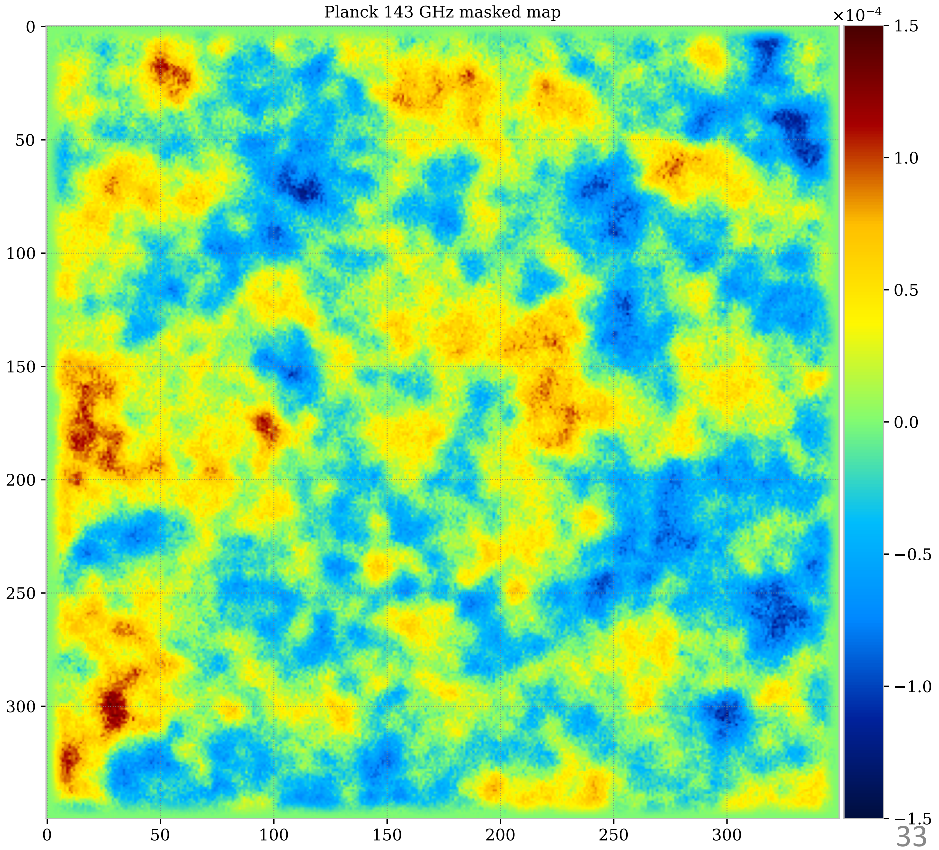


Real maps need to be cleaned

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

Maps not periodic: apodisation of the maps





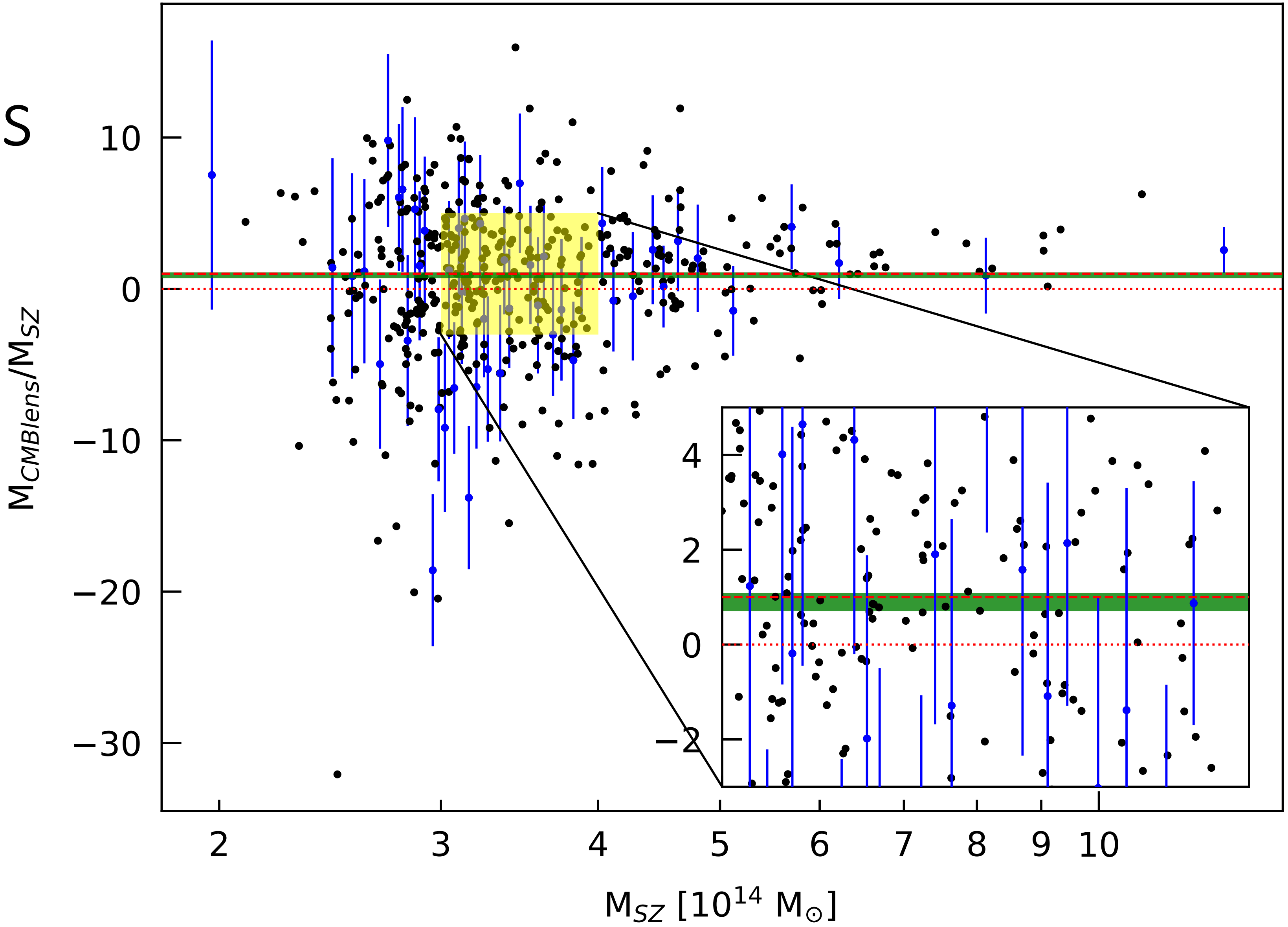
Combined results (real maps)

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

Averaging these measurements provides

<Mr> = 0.90 ± 0.19,

compatible with one



To be continued

Thank you for your attention

Alexandre Huchet

Tutor: Jean-Baptiste Melin, CEA/Irfu/DPhP

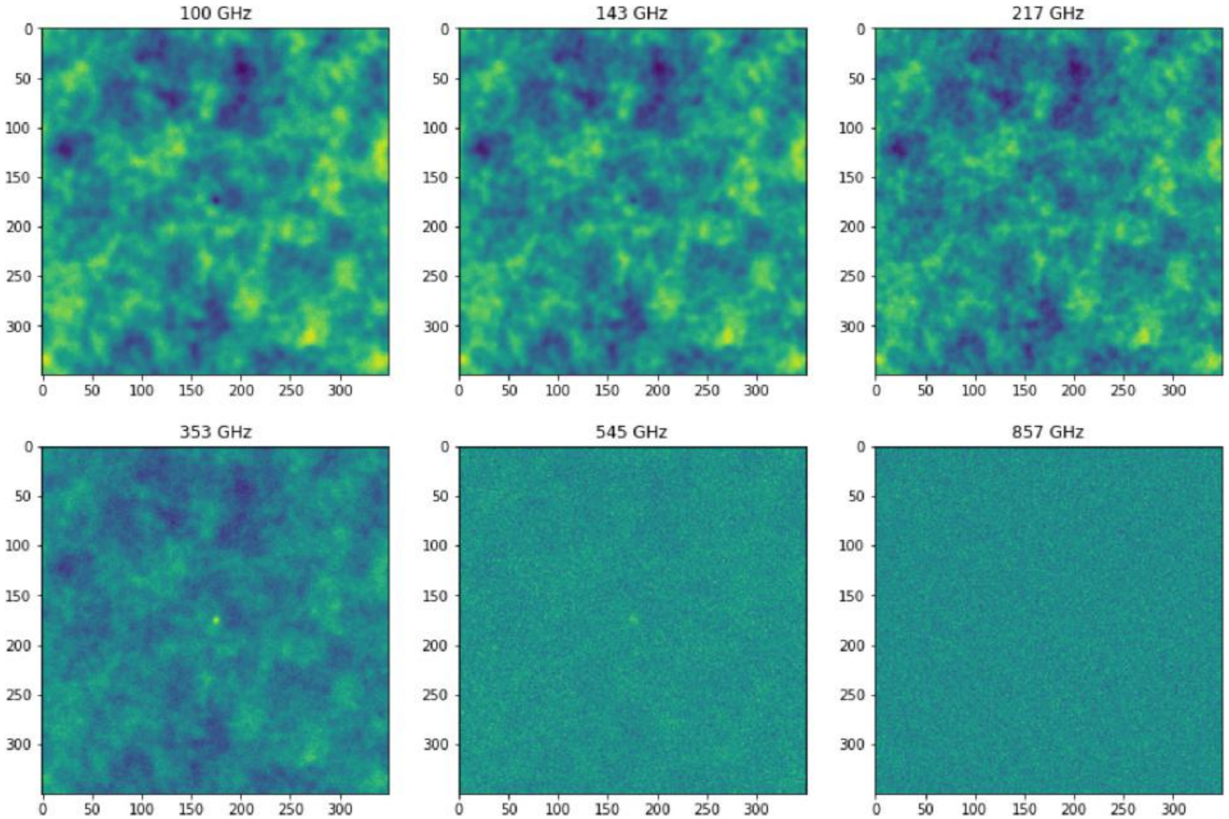
Backup slides

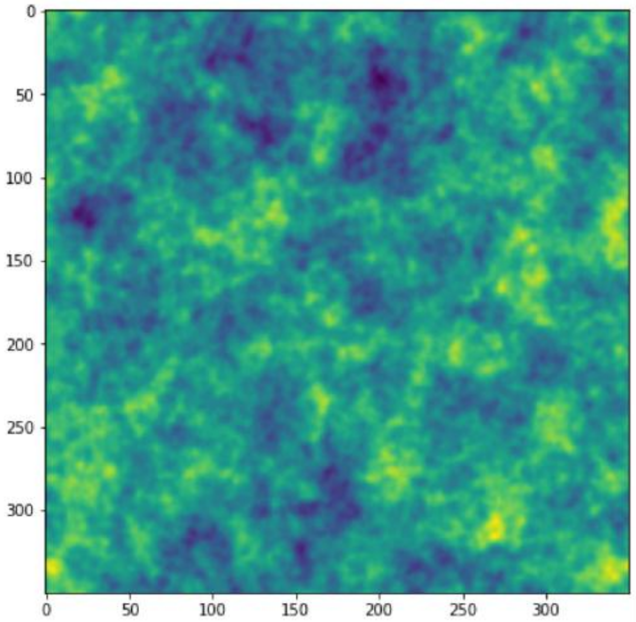
Internal Linear Combinations

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

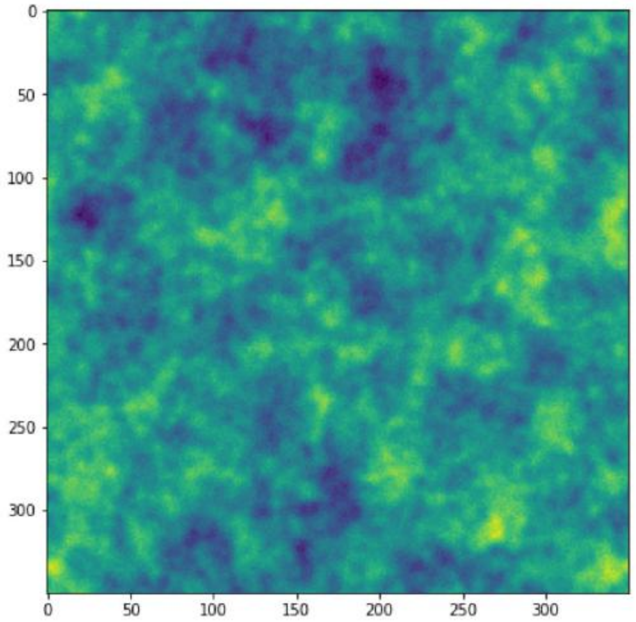
Combine the maps at different frequencies to remove contaminants, easier when we know the recipe

→ **Best lensed CMB map**





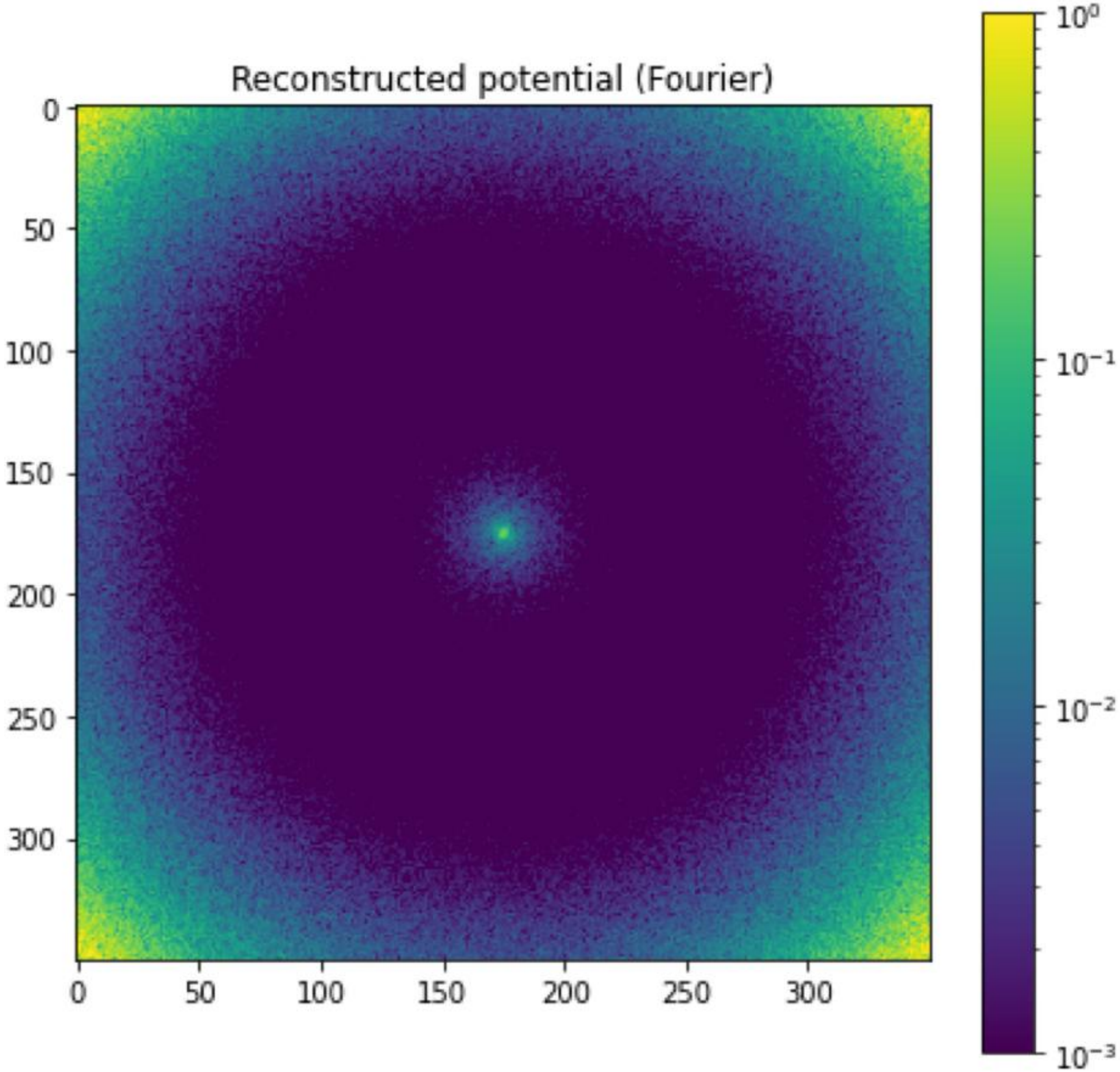
Input lensed CMB



Reconstructed ILC map

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

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

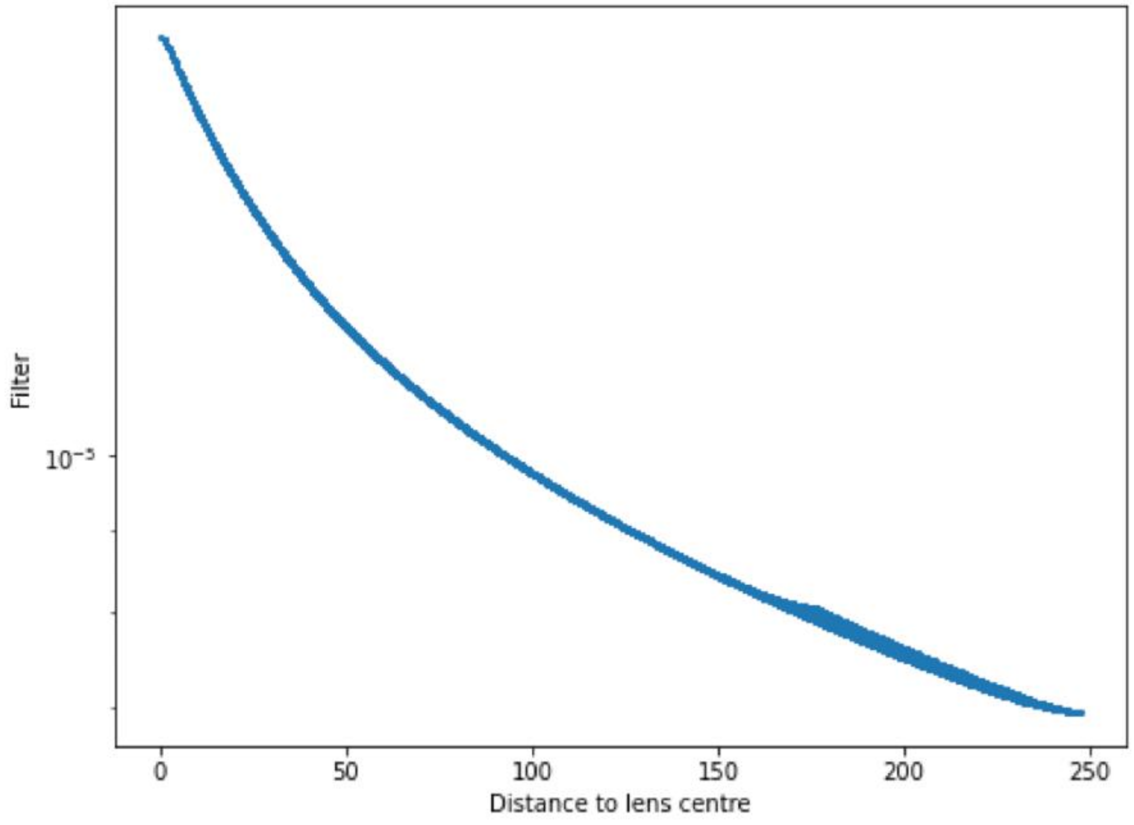
NFW lensing potential

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