DES Galaxy Clusters x Planck SZ Map
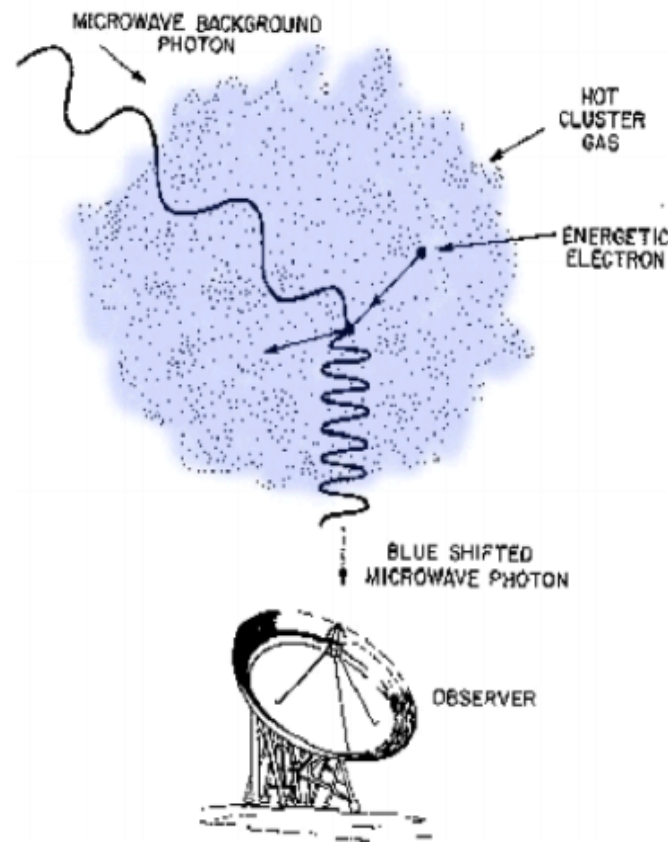
ASTR 448
Kuang Wei
Nov 27

Origin of Thermal Sunyaev-Zel'dovich (tSZ) Effect

Inverse Compton Scattering

Figure Courtesy to J. Carlstrom

Observables of tSZ Effect

Decrease in CMB intensity <= ~218 GHz

- Inverse Compton scattering boosts the energy of CMB photons

- TSZ effects lead to spectral distortion
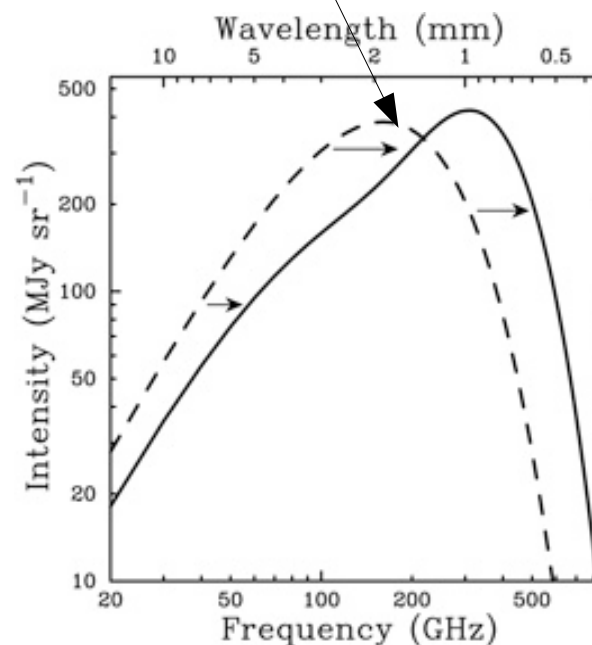
- Spectral distortion can be described by

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\ y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$

frequency dependence x = (hν) / ($k_B T_{CMB}$)

$$f(x) = \left(x \frac{e^x + 1}{e^x - 1} - 4 \right)(1 + \delta_{SZE}(x, T_e)),$$

Relativistic correction

tSZ distortion for a hypothetical 10^{18} solar mass cluster

Carlstrom, J. E. et al. Annual Review of Astronomy and Astrophysics, 40(1), 643-680.

Compton y-parameter

The intensity of the tSZ effect is proportional to Compton-y parameter

Thomson cross-section

Electron number density

Integrated along line of sight

$$y \equiv \frac{k_B \sigma_T}{m_e c^2} \int n_e T_e \, d\ell$$

Electron temperature

Electron rest mass energy

Integrating SZ effect over an area of the sky gives you the total thermal energy of the cluster, which is a good proxy for the cluster mass

$$\int \Delta T_{SZE} \, d\Omega \propto \frac{N_e \langle T_e \rangle}{D_A^2} \propto \frac{M \langle T_e \rangle}{D_A^2}$$

We can Use tSZ Effect to Find Clusters

$$\int \Delta T_{SZE}\, d\Omega \propto \frac{N_e\, \langle T_e \rangle}{D_A^2} \propto \frac{M\, \langle T_e \rangle}{D_A^2}$$

- Cluster of given mass will be denser and hotter at high redshift because the universal matter density scales as $(1+z)^3$

- Angular diameter distance is roughly flat at high redshift

- So SZE can detect all clusters above some mass threshold with little dependence on redshift

Carlstrom, J. E. et al. Annual Review of Astronomy and Astrophysics, 40(1), 643-680.
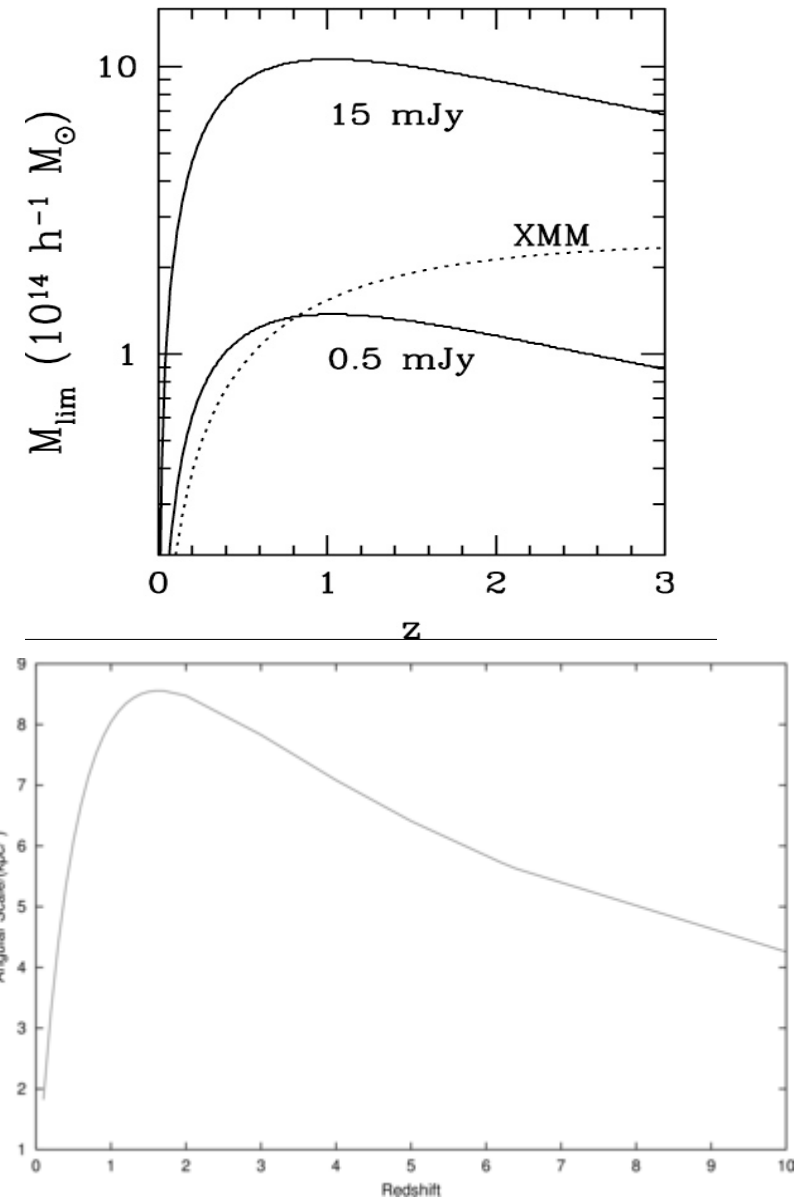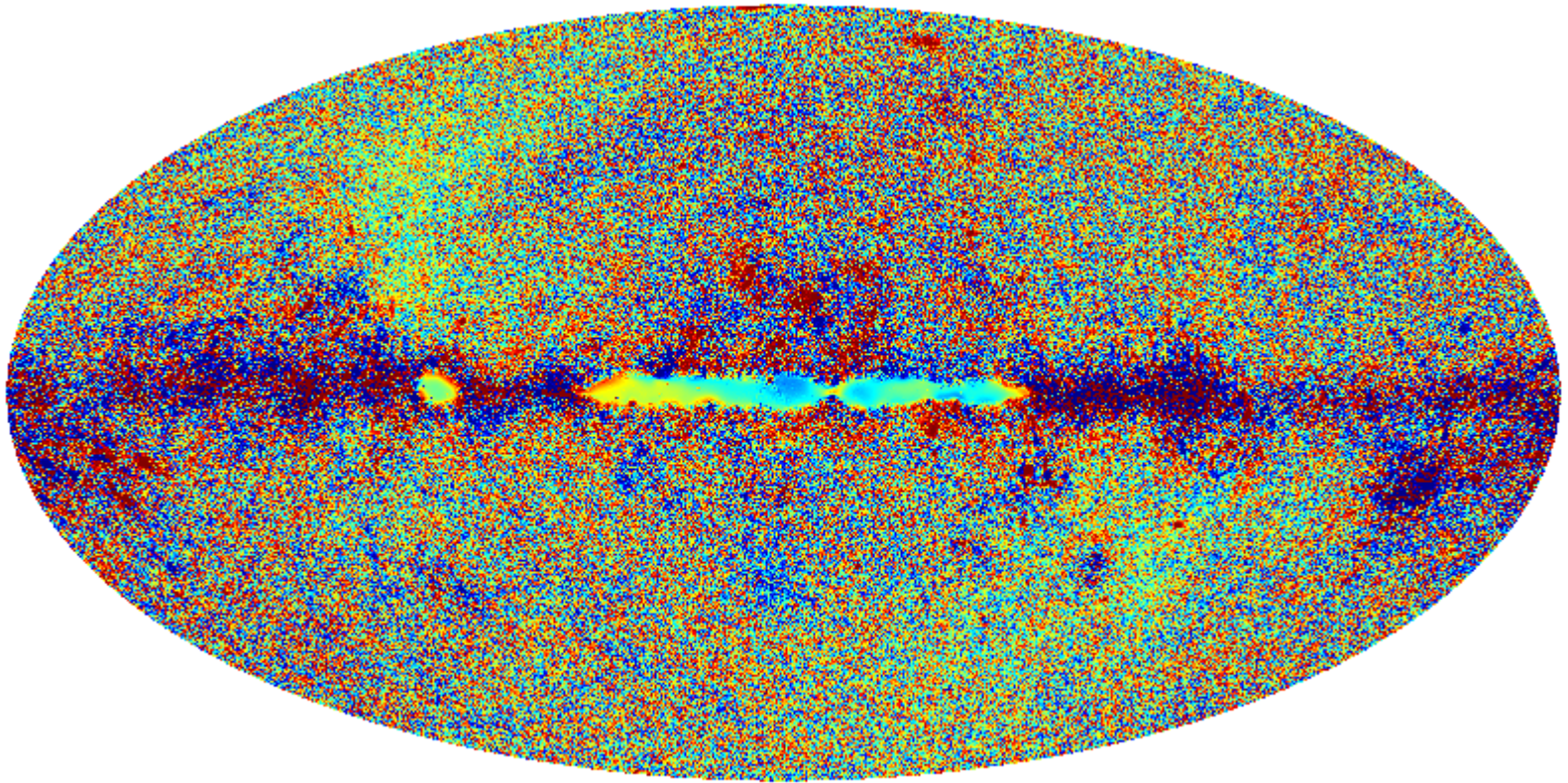
Summary of tSZ

- Small spectral distortion of CMB proportional to the cluster pressure integrated along the line of sight

- Independent of redshift

- Unique signature in CMB intensity

- Integrated SZ flux is proportional to the total thermal energy of the cluster → mass threshold nearly independent of redshift
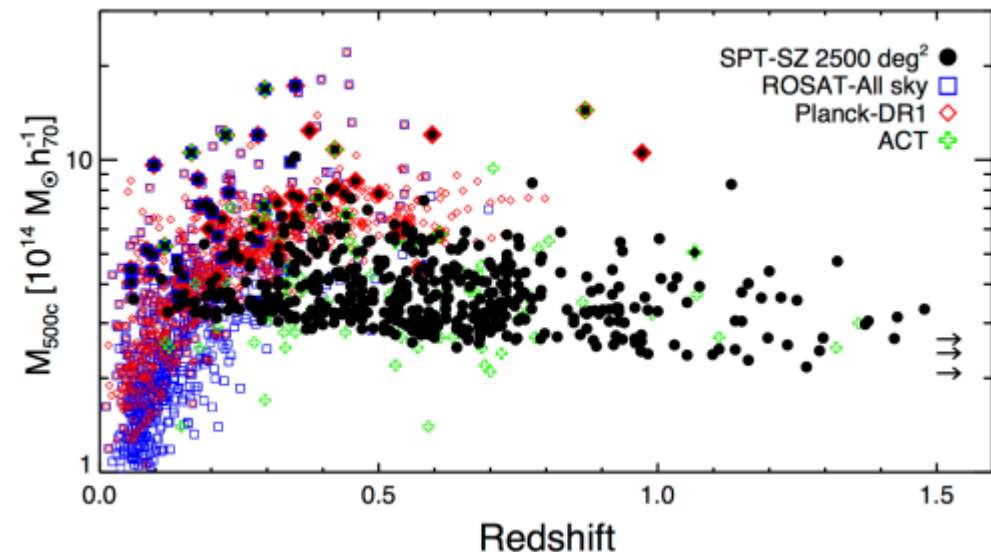
Planck y-Map

arXiv:1502.01596

Planck Data Overview

- 5 High Frequency Instrument (HFI) and 8 Low Frequency Instrument (LFI) full-sky data

- Noise map for each channel map obtained from the half difference of maps made from the first and second half of each stable pointing period

- In the half difference maps the astrophysical emission cancels out, leaving only the instrumental noise

Reconstruction Method

- tSZ effect from galaxy clusters is spatially localized and therefore a *highly non-Gaussian* signal

- Therefore typical CMB component separation algorithms don't work for tSZ

- Need tailored component separations algorithms that rely on the spatial localization of different astrophysical components and on their spectral diversity to separate them

Reconstruction Method – NILC

- Needlet Independent Linear Combination (NILC) searches the input maps that minimizes the variance of the final reconstructed map under the constraint of offering unit gain to the component of interest

- The 857 GHz map which traces the thermal dust emission on large angular scales is only used for multipoles l<300 to minimize residuals from IR point sources and clustered Cosmic Infrared Background emission in the final y-maps

Reconstruction Method – NILC

- Needlet Independent Linear Combination (NILC)

  - Provides localization of independent linear combination filters in both pixel and multipole space

  - Localization in multipole space achieved by using ten Gaussian window functions (needlet bands) as bandpass filters

  - Performs a weighted linear combination of the bandpass filtered Planck maps for each needlet scale independently

  - Spatial localization is achieved by defining scale-dependent zones over the sky on which the covariance matrices and ILC weights are computed
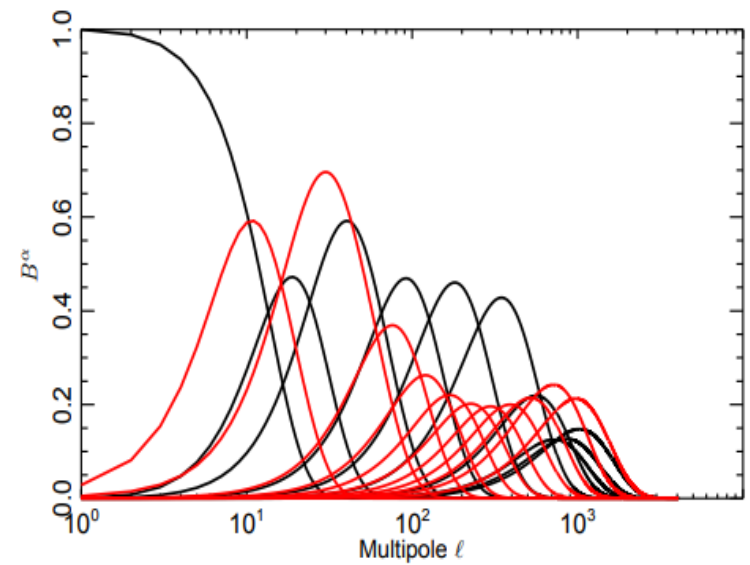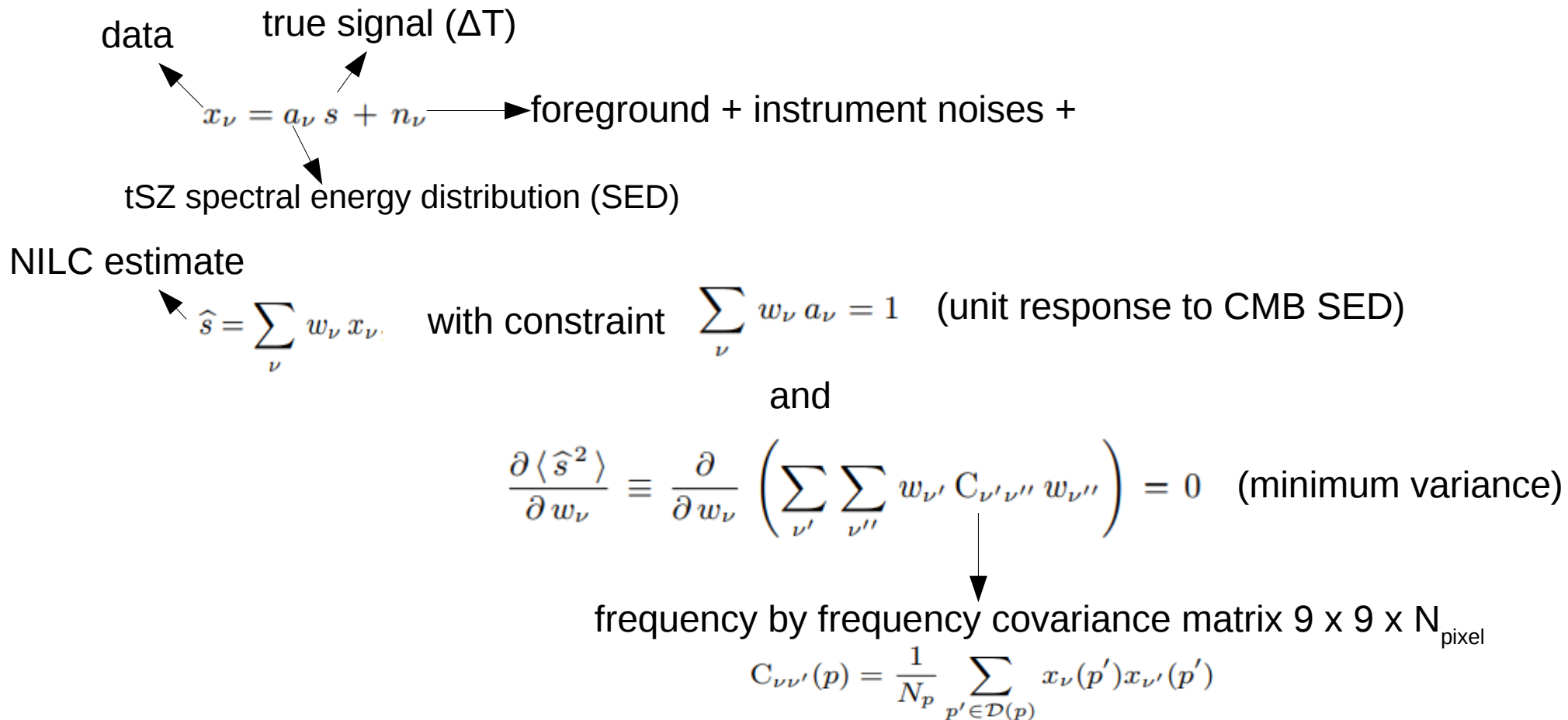

Fig. 1: Window functions corresponding to the spectral localisation of the NILC and MILCA algorithms. For NILC (black) there are 10 Gaussian window functions defining 10 needlet scales. MILCA (red) uses 11 Gaussian overlapping windows.

Aghanim, N., et al. "Planck 2015 results-XXII. A map of the thermal Sunyaev-Zeldovich effect." Astronomy & Astrophysics 594 (2016): A22.

NILC Details

data   true signal (ΔT)

$$x_\nu = a_\nu\, s + n_\nu$$ →foreground + instrument noises +

tSZ spectral energy distribution (SED)

NILC estimate

$$\hat{s} = \sum_\nu w_\nu\, x_\nu$$ with constraint $\sum_\nu w_\nu\, a_\nu = 1$ (unit response to CMB SED)

and

$$\frac{\partial \langle \hat{s}^2 \rangle}{\partial w_\nu} \equiv \frac{\partial}{\partial w_\nu}\left(\sum_{\nu'} \sum_{\nu''} w_{\nu'}\, \mathrm{C}_{\nu'\nu''}\, w_{\nu''} \right) = 0 \quad \text{(minimum variance)}$$

frequency by frequency covariance matrix 9 x 9 x N$_{pixel}$

$$\mathrm{C}_{\nu\nu'}(p) = \frac{1}{N_p} \sum_{p' \in \mathcal{D}(p)} x_\nu(p')x_{\nu'}(p')$$

With Lagrange multiplier, the solution of the NILC weights is $w^t = \dfrac{a^t\, \mathrm{C}^{-1}}{a^t\, \mathrm{C}^{-1}\, a}$

Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252

NILC Details

With $\quad w^t = \dfrac{a^t C^{-1}}{a^t\, C^{-1}\, a}\quad$ We get $\quad \widehat{s} = s + \displaystyle\sum_{\nu} w_\nu\, n_\nu$
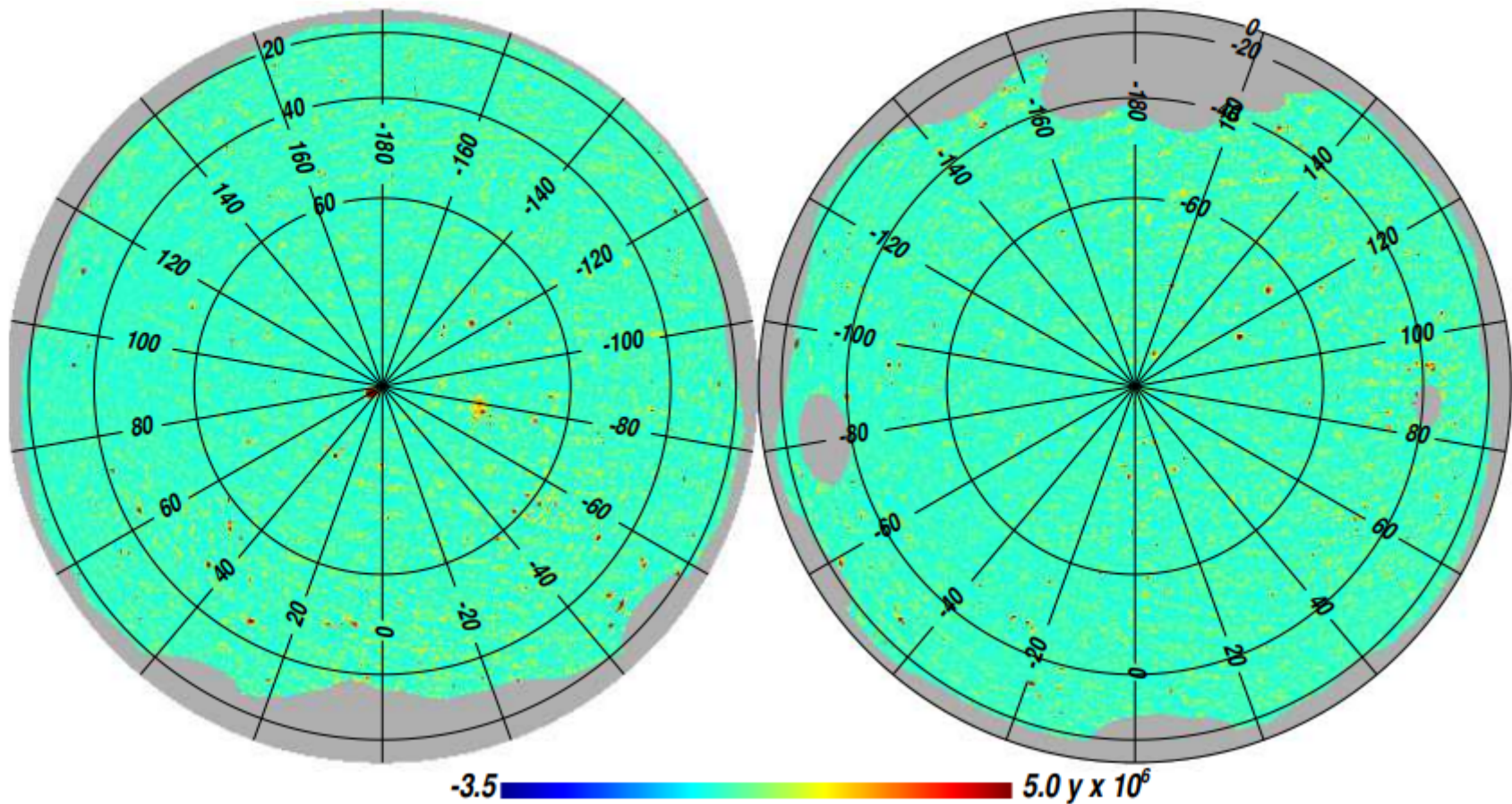
Here we get an unbiased estimate of the tSZ signal because of constraint $\quad \displaystyle\sum_{\nu} w_\nu\, a_\nu = 1$

And the other residual foreground signals are minimized because of the following constraint

$$\frac{\partial \langle \widehat{s}^2 \rangle}{\partial\, w_\nu} \equiv \frac{\partial}{\partial\, w_\nu} \left(\sum_{\nu'} \sum_{\nu''} w_{\nu'}\, C_{\nu'\nu''}\, w_{\nu''} \right) = 0$$
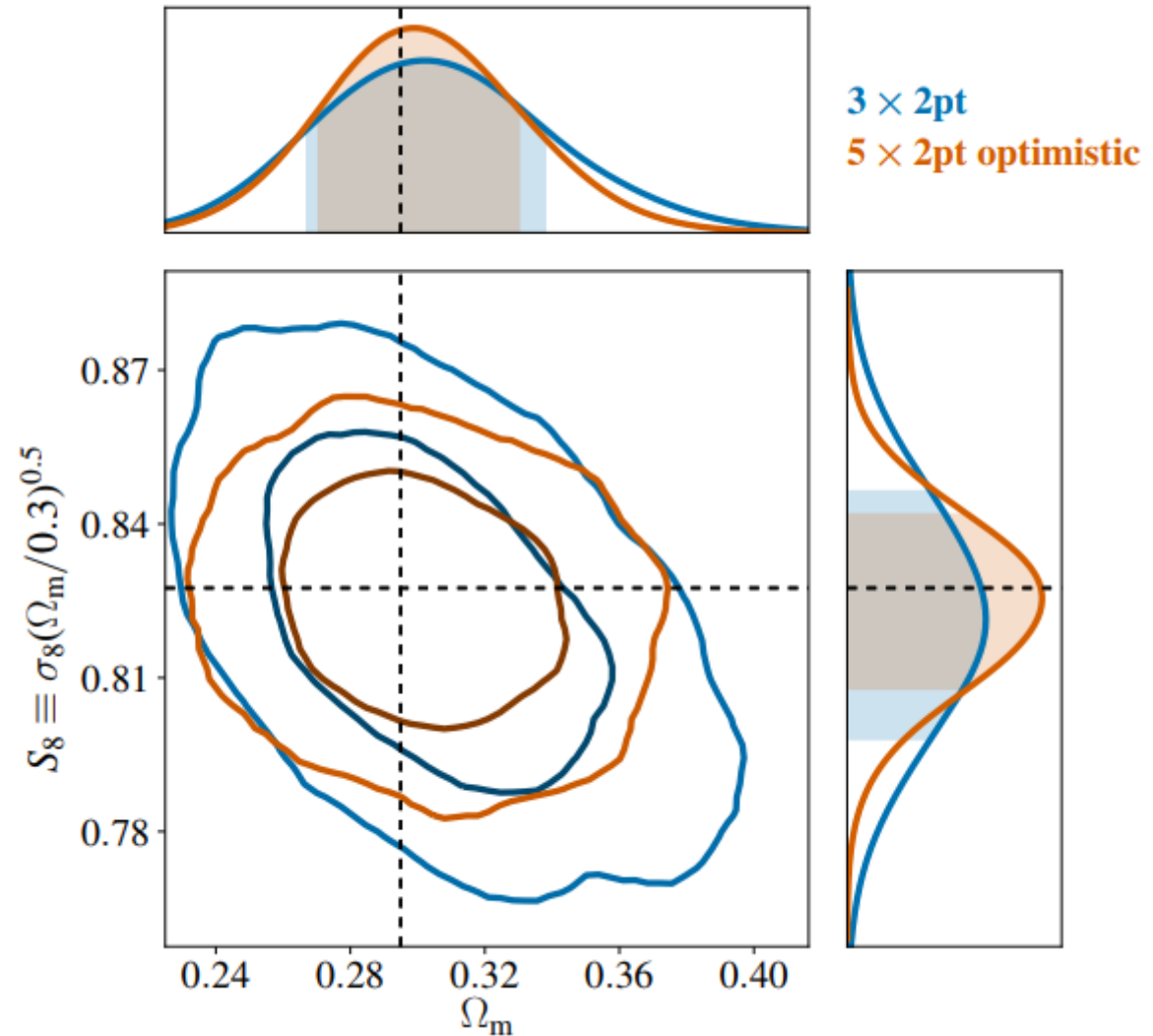
Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252

NILC Result of y-Map

NILC tSZ map

Clusters appear as positive sources (galactic plane is masked)

Aghanim, N., et al. "Planck 2015 results-XXII. A map of the thermal Sunyaev-Zeldovich effect." Astronomy & Astrophysics 594 (2016): A22.

CMB x Large Scale Structure Cross-Correlations

- CMB and galaxy surveys offer indirect and direct tracers of matter distributions, respectively

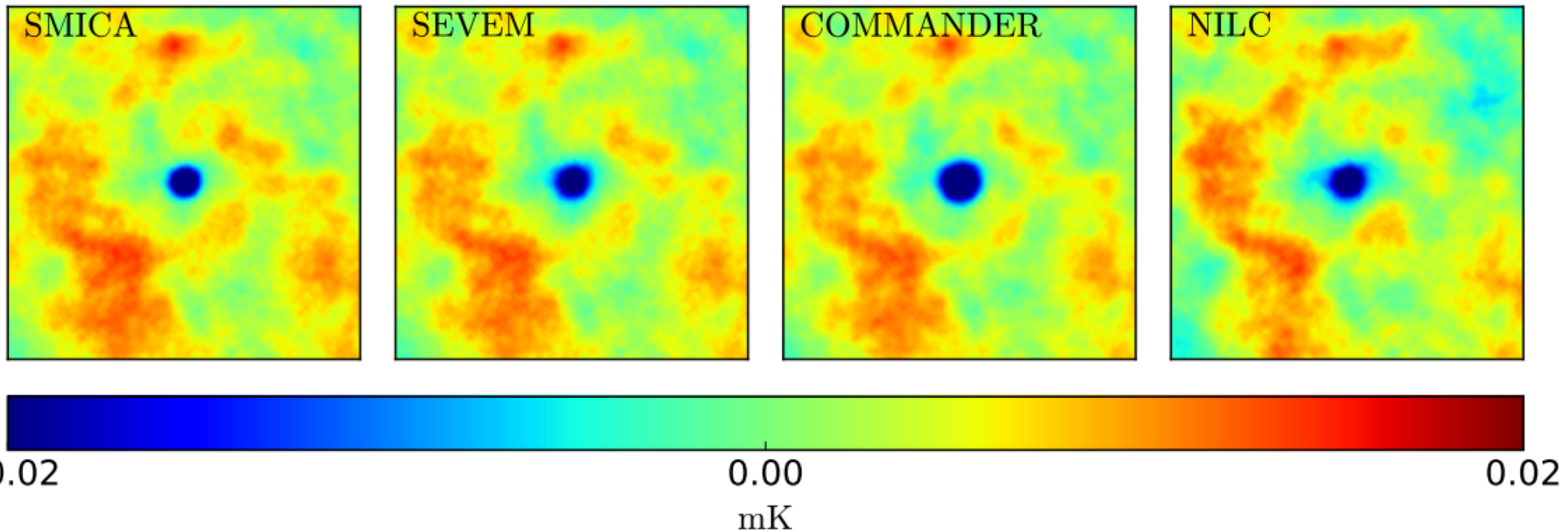- Cross correlating CMB maps (i.e. lensing map) with large scale structure surveys can provide strong constraints

Baxter, E. J. et al. "Dark Energy Survey Year 1 Results: Methodology and Projections for Joint Analysis of Galaxy Clustering, Galaxy Lensing, and CMB Lensing Two-point Functions." arXiv preprint arXiv:1802.05257

tSZ as a Systematic Errors Source for CMB x LSS

- Planck removes various foreground contaminations from the CMB map

- But there could still be tSZ residuals in the final map

- This can lead to spurious biases

tSZ Residuals in CMB Map

- tSZ residuals appear as negative temperature fluctuations in CMB maps

- Most of the ω_ν for CMB reconstruction comes from the 100-143 GHz frequency channels

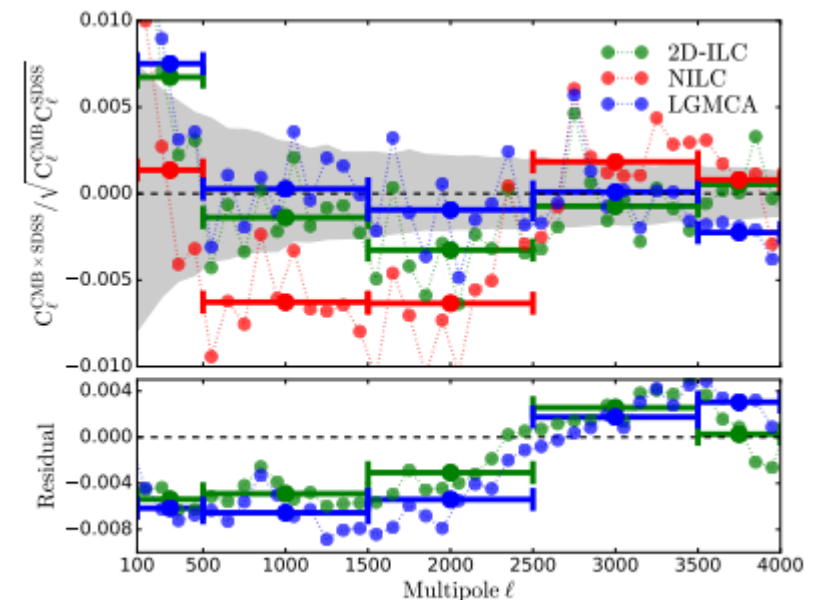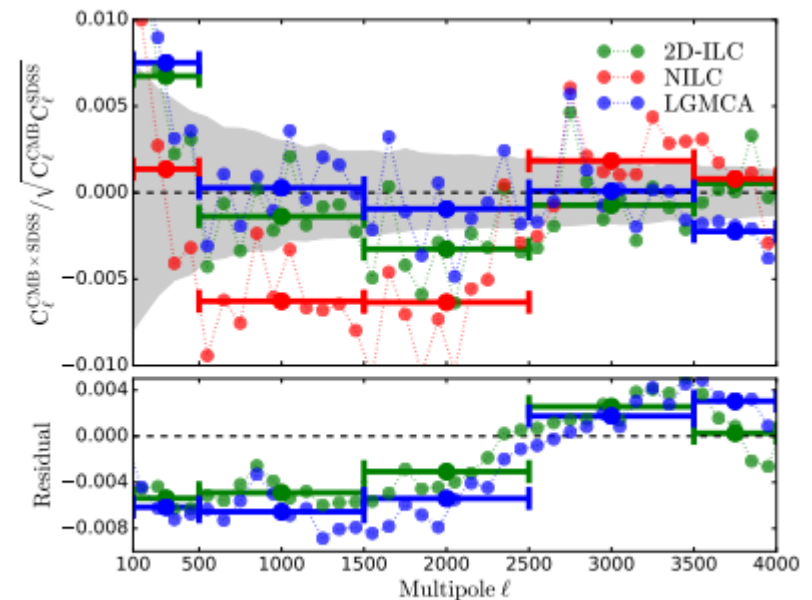- tSZ spectral energy distribution is negative relative to CMB in this range

Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252

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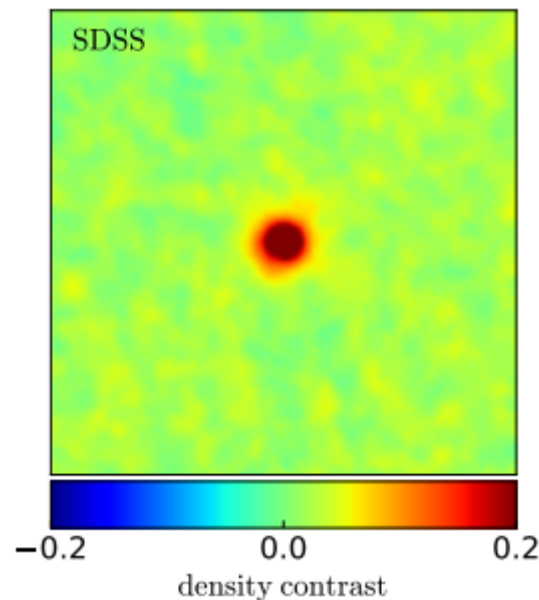
Cross Correlating SDSS Density Map with CMB Map

- One way to test if the residual contamination is present is to cross correlate large scale structure (LSS) as measured by galaxy surveys with CMB map

- If negative residuals are present, we should get a deficit of power on small scales in the matter cross-power spectrum

- T. Chen, et al. 2018 demonstrates that is indeed the case

Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252

Cross Correlating SDSS Density Map with CMB Map

- Due to ISW, CMB temperature fluctuations should positively correlate with LSS for l<=~200, and uncorrelated for l>~500

- Cnen, et al. 2018 demonstrated the negative correlation >1σ for 500<l<2500

- The negative correlation is due to the negative thermal SZ residual contaminations from galaxy clusters

Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252

Nullify tSZ Signals in CMB Map

frequency dependent SED of tSZ effect

Decompose tSZ as $\sum_{\nu} w_{\nu}\, b_{\nu}\, y$

Impose constraint $\sum_{\nu} w_{\nu}\, b_{\nu} = 0.$

tSZ free solution $w^{t} = \dfrac{\left(b^{t}\mathbf{C}^{-1}b\right) a^{t}\mathbf{C}^{-1} - \left(a^{t}\mathbf{C}^{-1}b\right) b^{t}\mathbf{C}^{-1}}{\left(a^{t}\mathbf{C}^{-1}a\right)\left(b^{t}\mathbf{C}^{-1}b\right) - \left(a^{t}\mathbf{C}^{-1}b\right)^{2}}$

Chen, T., Remazeilles, M., & Dickinson, C. (2018). Impact of SZ cluster residuals in CMB maps and CMB–LSS cross-correlations. MNRS, 479(3), 4239-4252
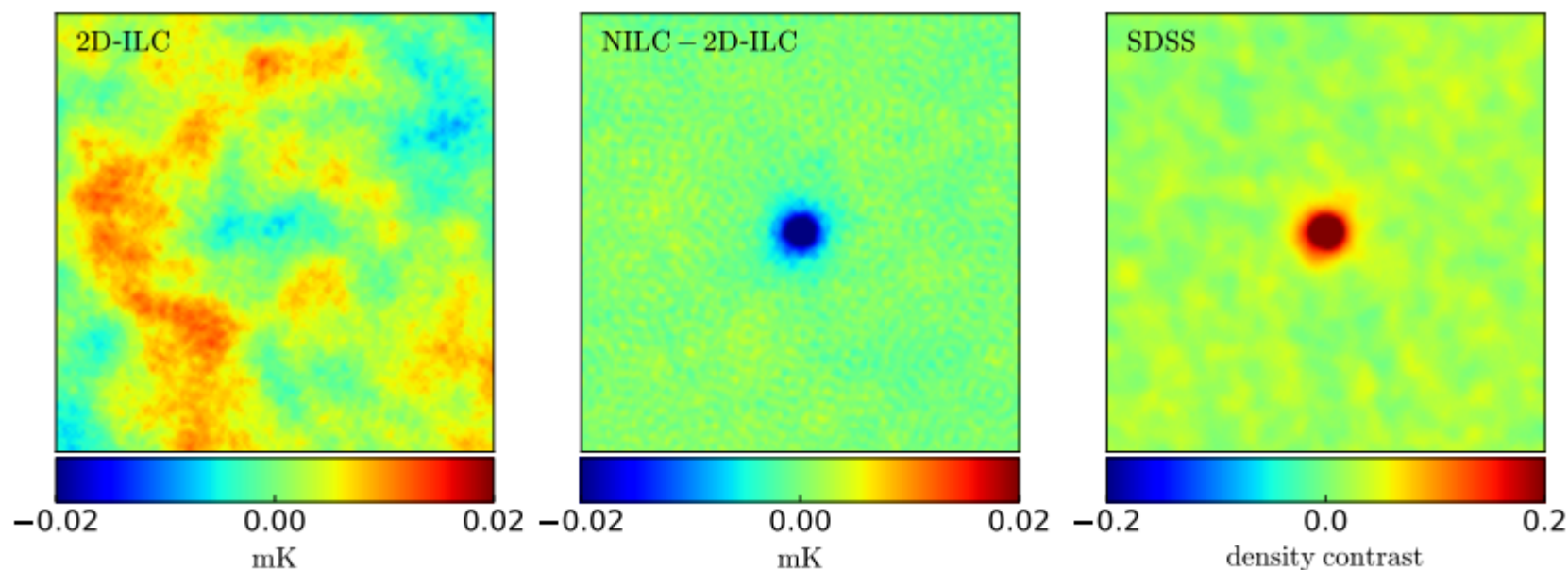
DES RedMaPPer Galaxies

- A way to select galaxies that are in clusters to probe LSS

- We know that galaxies in clusters are roughly red

- Red galaxies follow a certain color-magnitude relation – red sequence

- Have other cuts in photo-z, etc
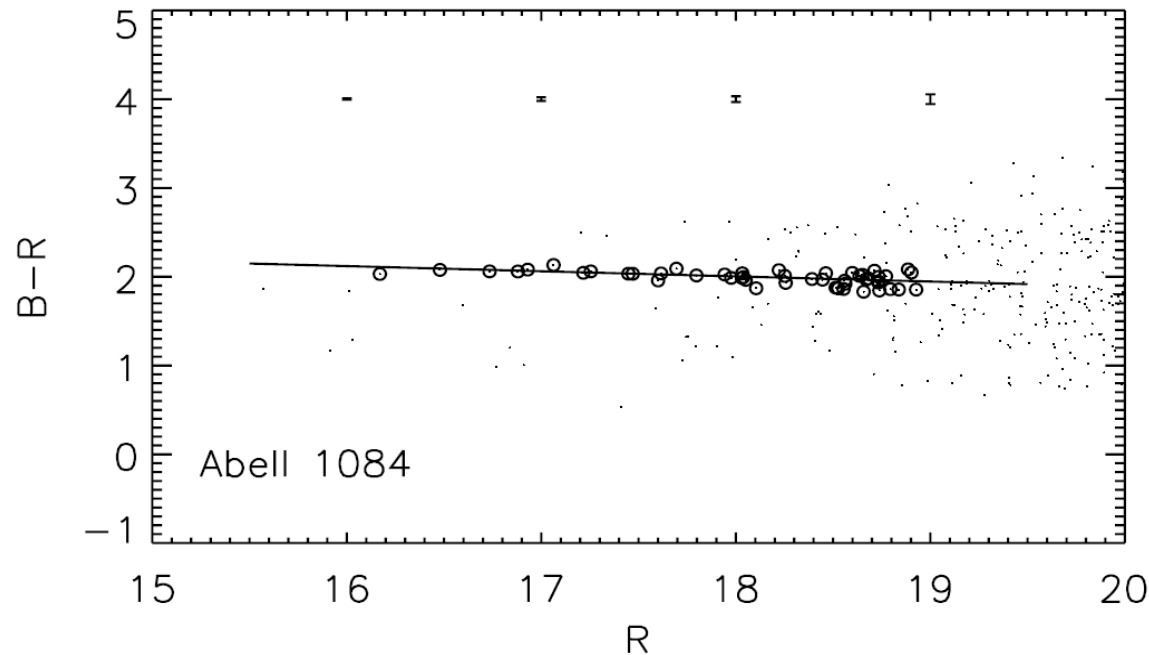
DES RedMaPPer Galaxies

DES RedMaPPer cluster visualization

Mollweide view
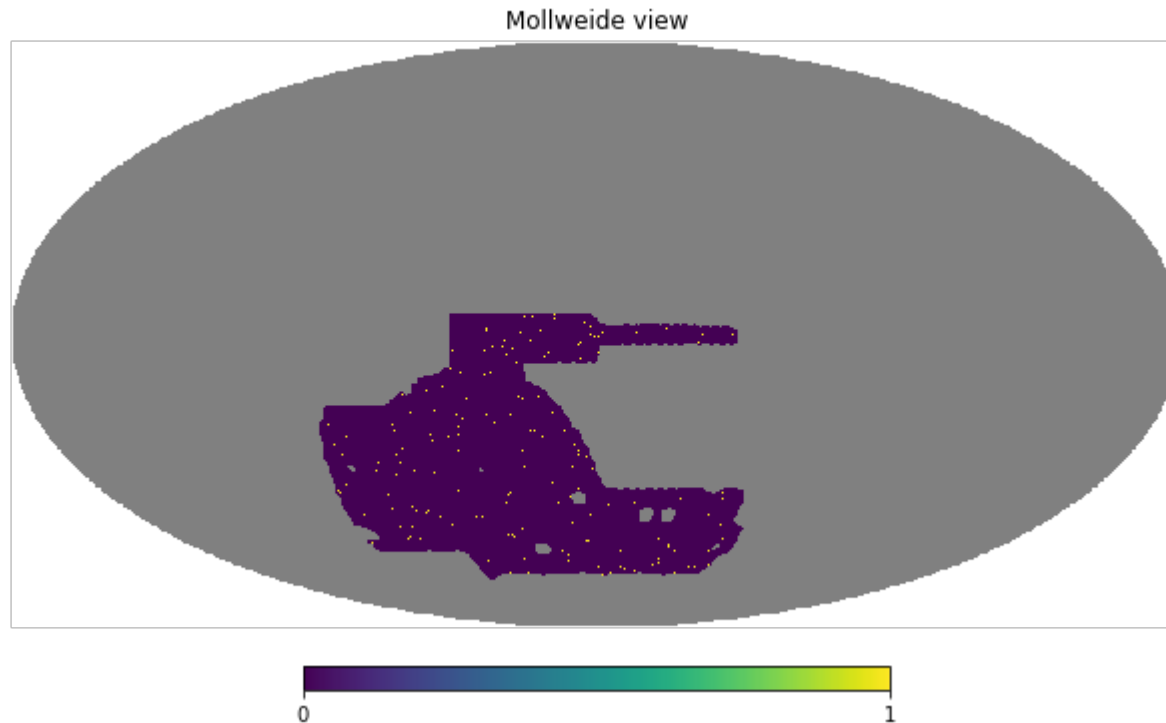
Healpix and Coordinate Transformations

- Planck data is given in healpix format with NSIDE=2048 and in Galactic Coordinates format

- Healpix is simply a way to pixalize a spherical projection into patches of roughly the same size
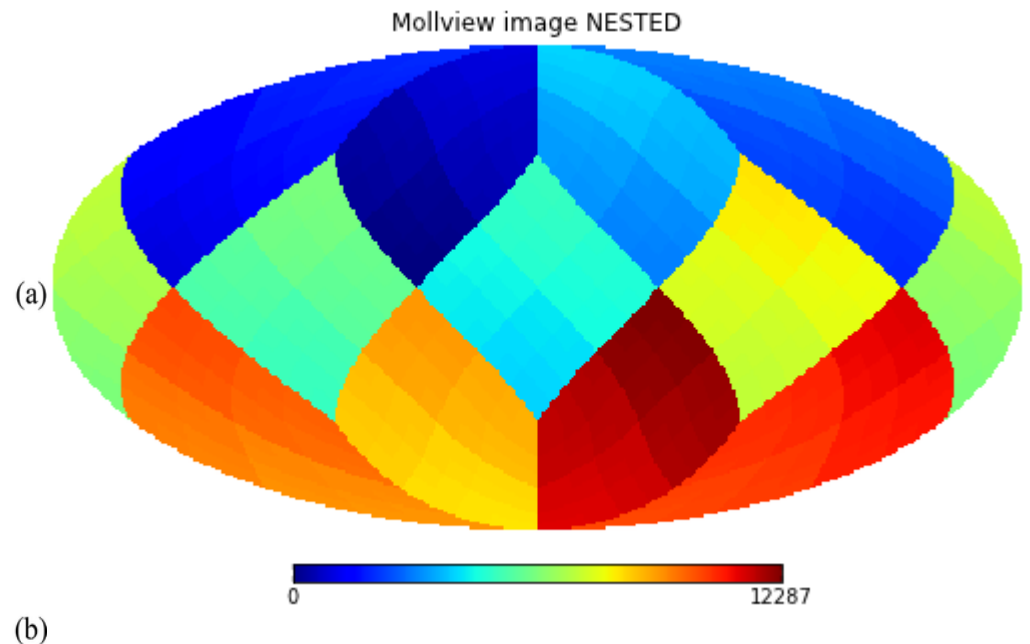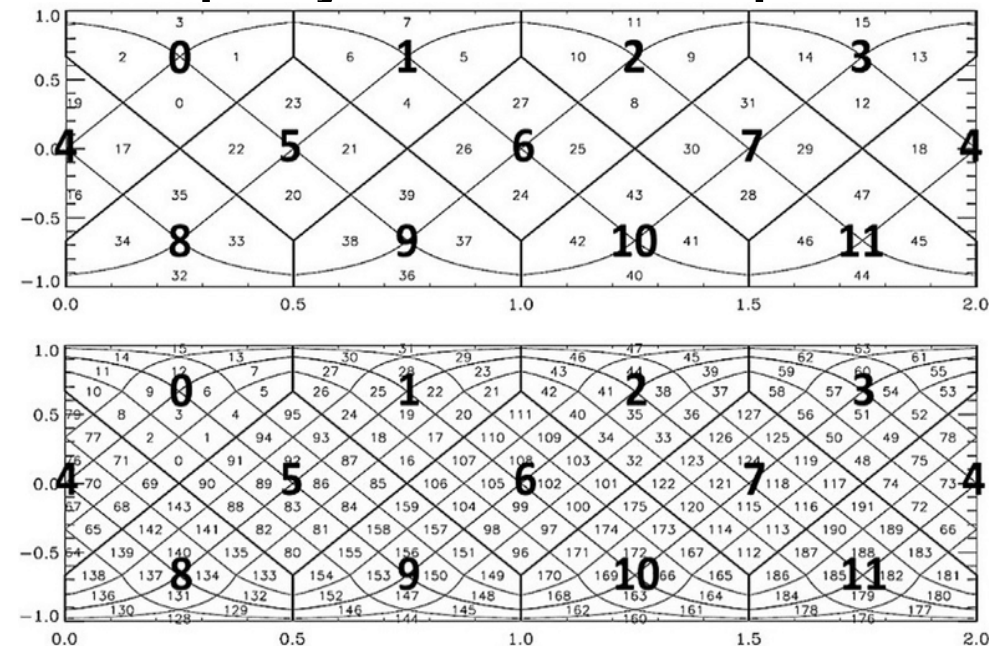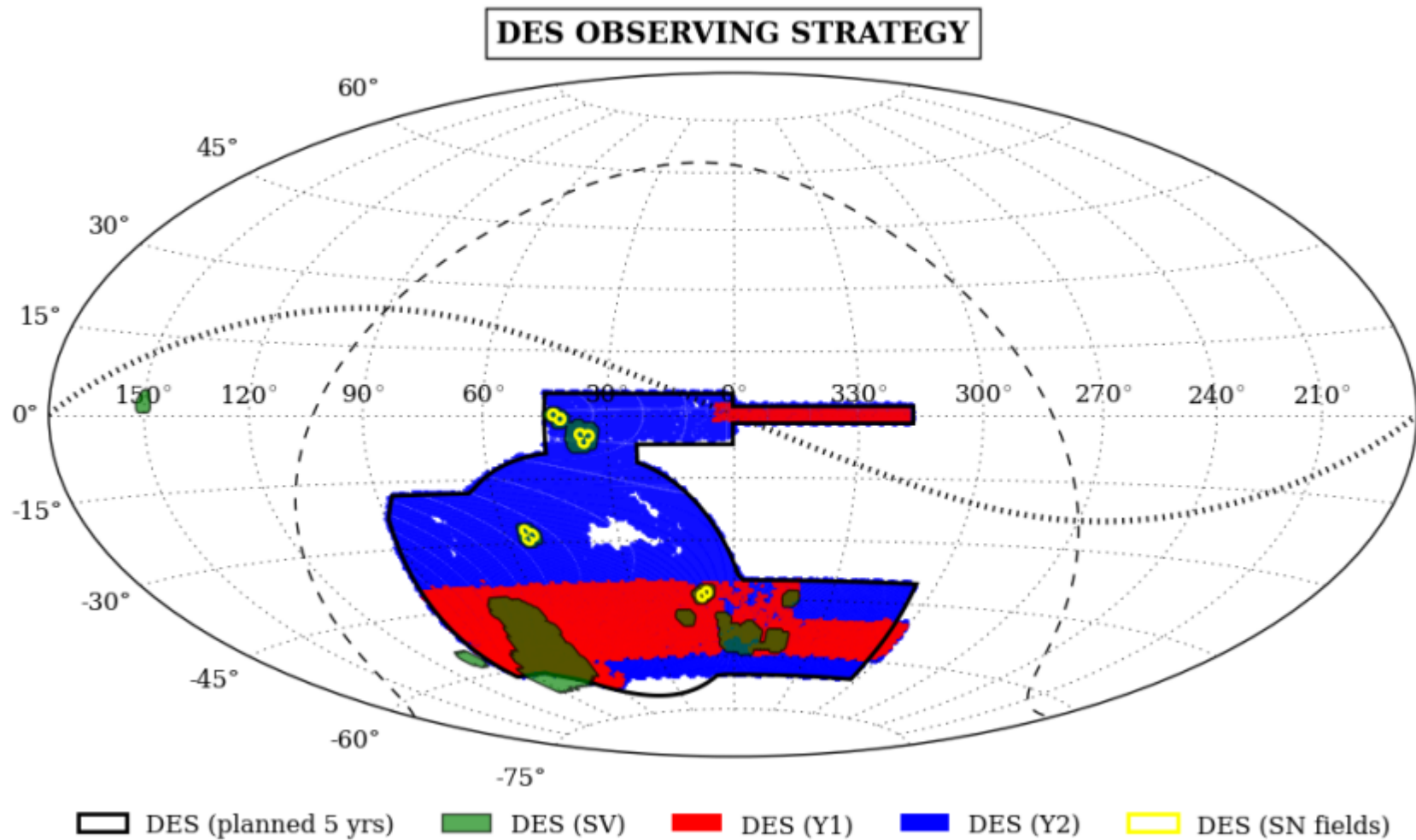
Select y Map data with DES Footprint

Mollweide view

-839.34   563.15

Mollweide view

-86.6624   74.7609
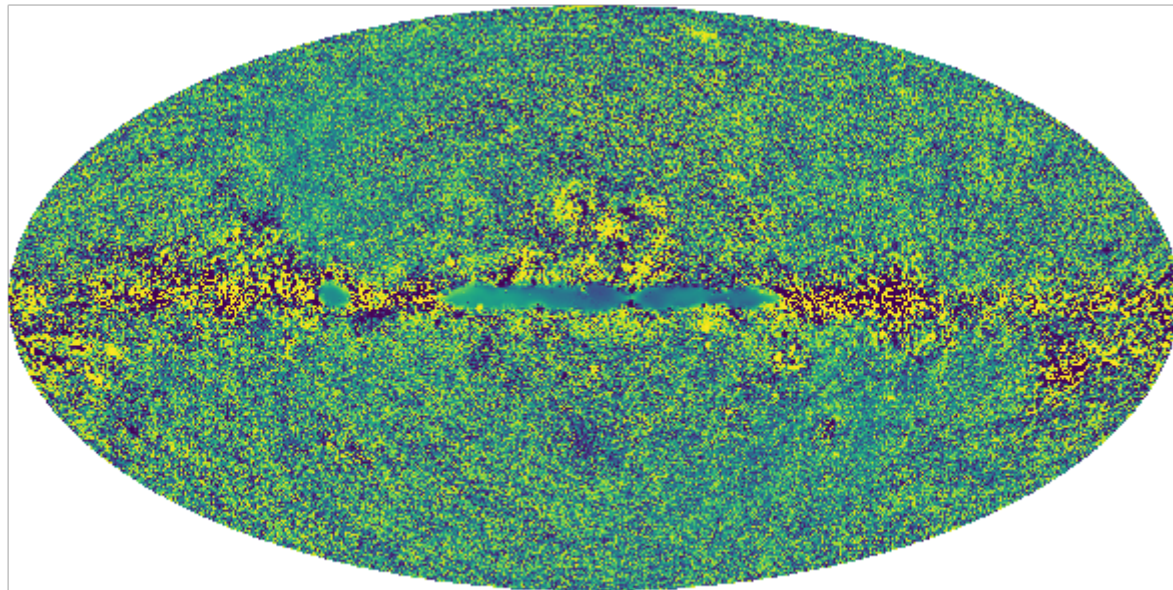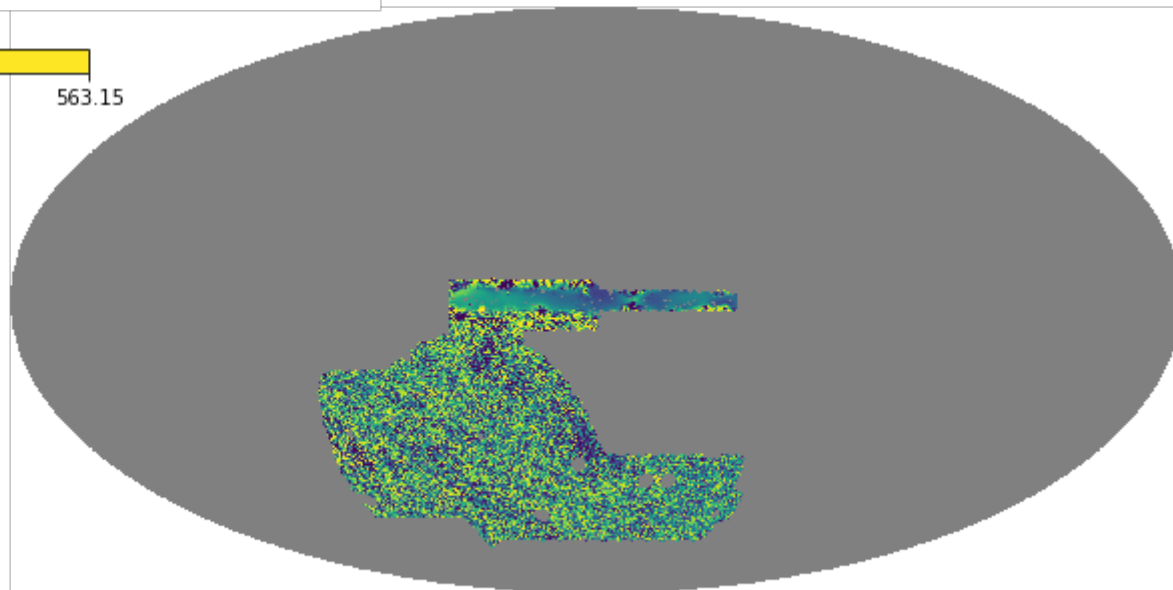
Select y Map data with DES Footprint

The DES S82 region shouldn't align with the galactic plane

# Transform DES Mask to Galactic Plane

- DES footprint mask is given in healpix with NSIDE=4096 and locations of clusters are given in Celestial Coordinates

- Process:
    - Transform healpix mask with NSIDE=4096 to RA/DEC in Celestial coordinates
    - Transform RA/DEC from Celestial coordinates to Galactic coordinates
    - Transform back to healpix with NSIDE=2048 based on the new Galactic coordinates

Transform DES Mask to Galactic Plane

Mollweide view

-20.5625   36.6678
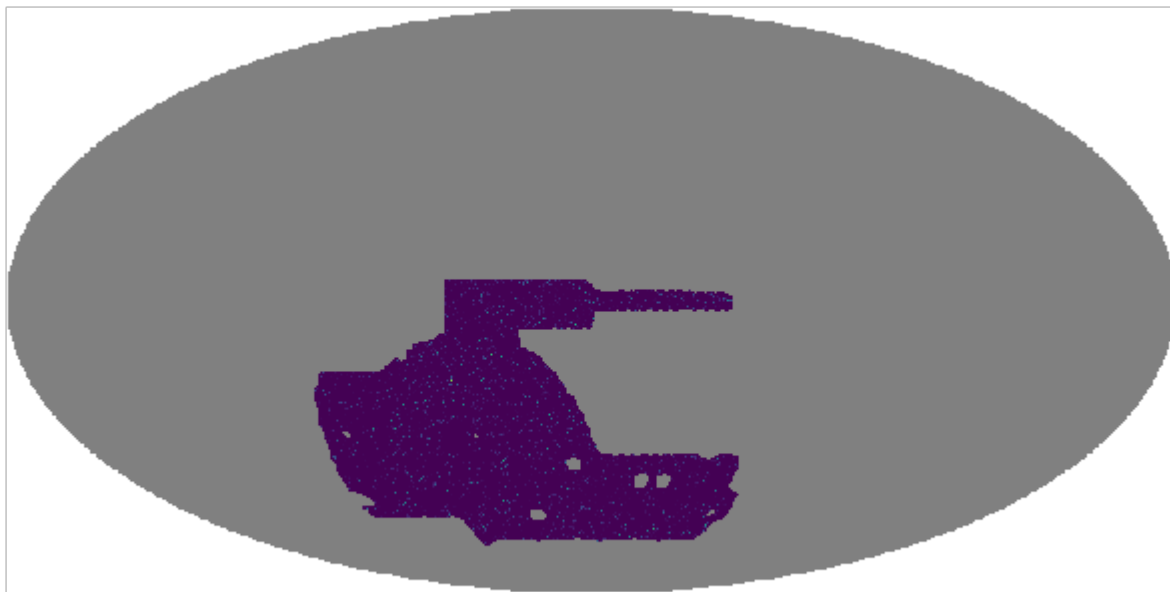
Selected Planck y map data
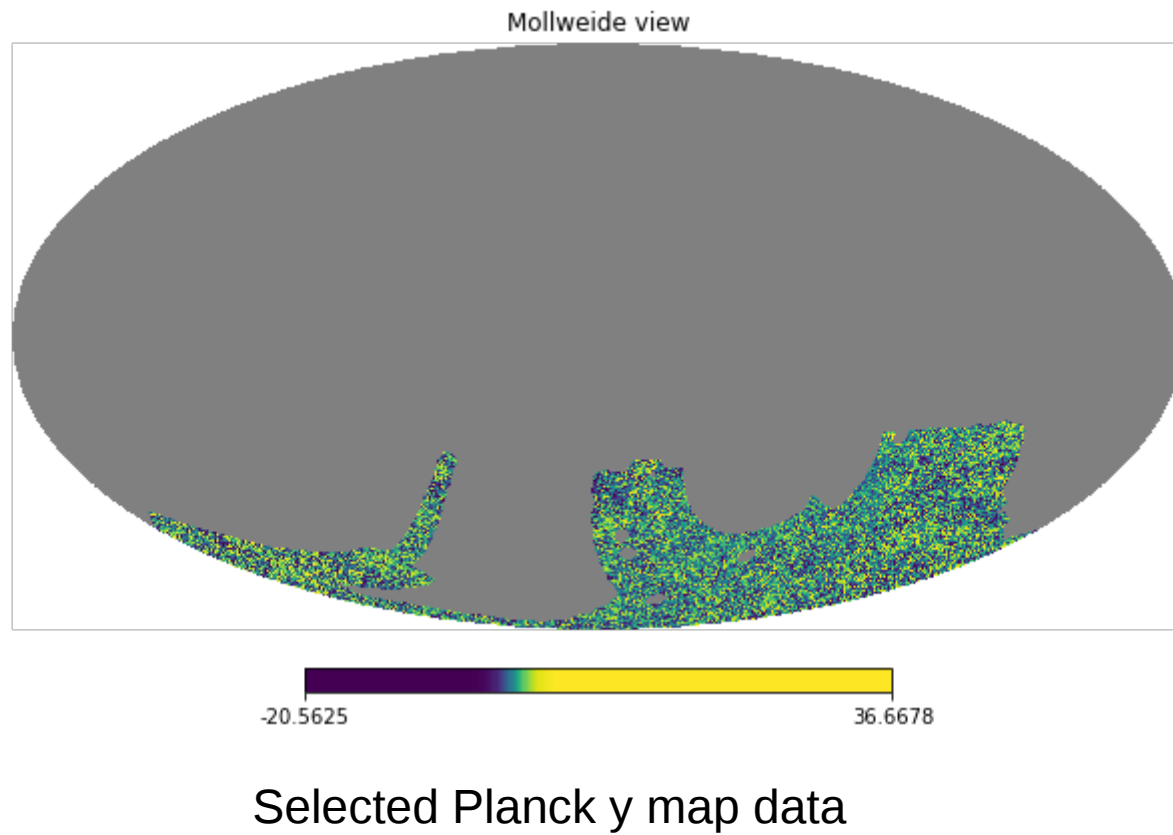
Transform RedMaPPer Catalog into Density Map

- Need to match cluster map spatial resolution to the Planck y-map beam resolution of 10'
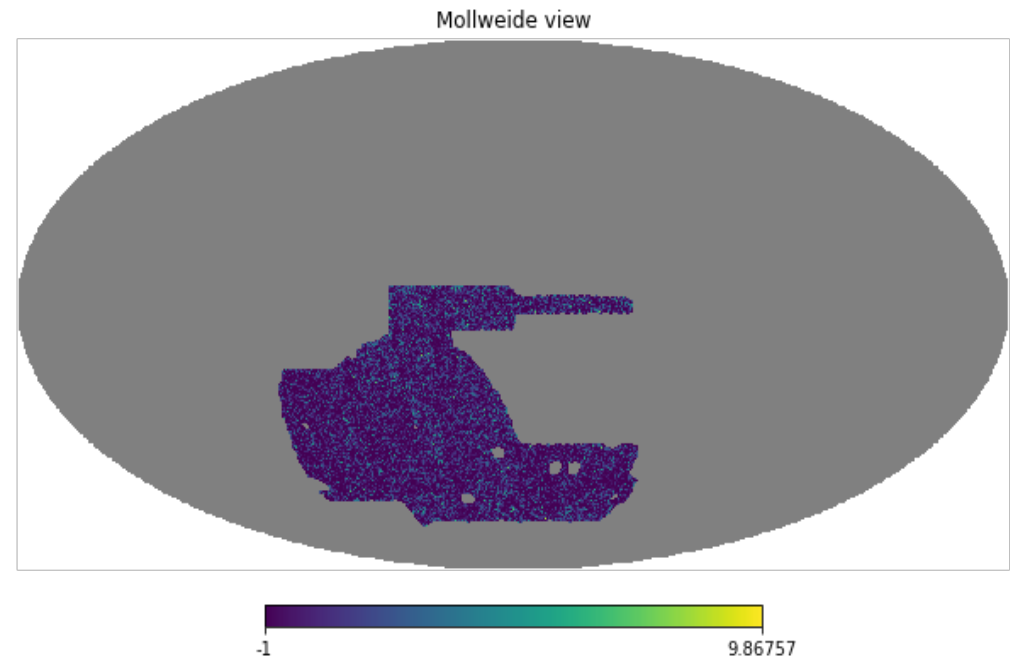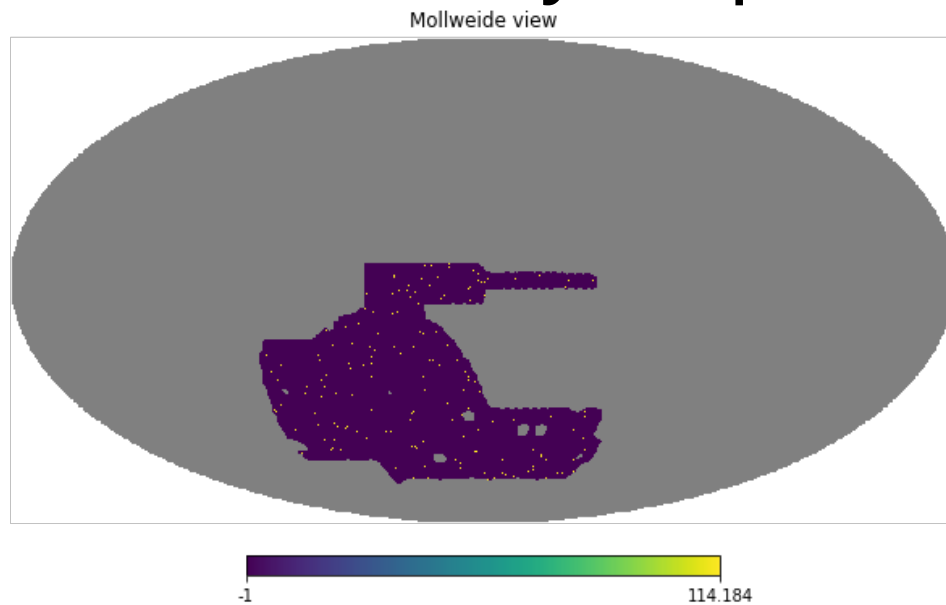
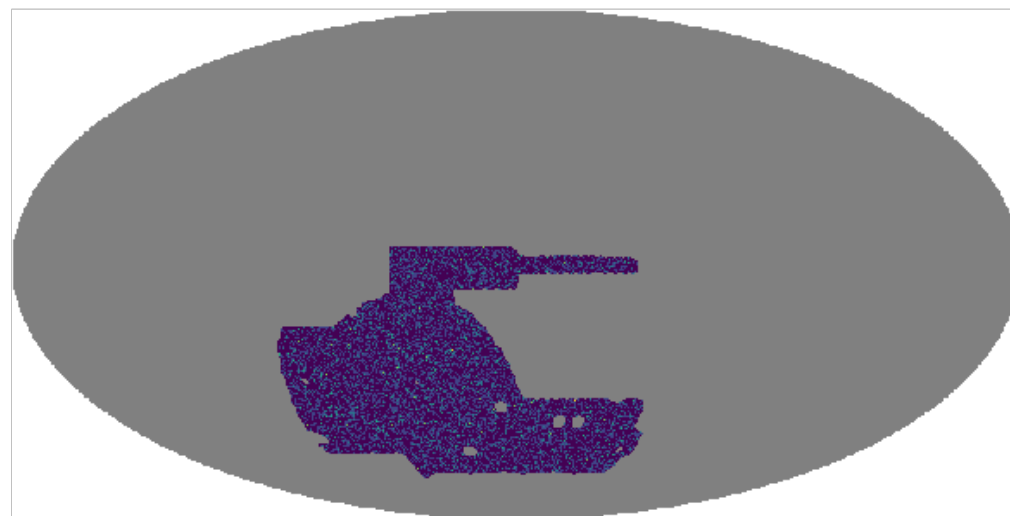# RedMaPPer Random Catalog as Null Test

Mollweide view

0   44

RedMaPPer galaxies with LSS

Mollweide view

0   5

RedMaPPer galaxies w/o LSS

Two Point Correlation Function Calculation

Planck y-map X DES RedMaPPer Cluster Galaxies