A cross-correlation analysis of CMB lensing and radio galaxy maps

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Overview

- Radio sources as probe of Large-Scale Structure (LSS) of the Universe
- The case for a cross-correlation analysis
- Cosmic Microwave Background lensing
- Results from cross-correlation analysis
- Conclusions

Extragalactic radio source catalogs

Why radio catalogs are so important for cosmological research?

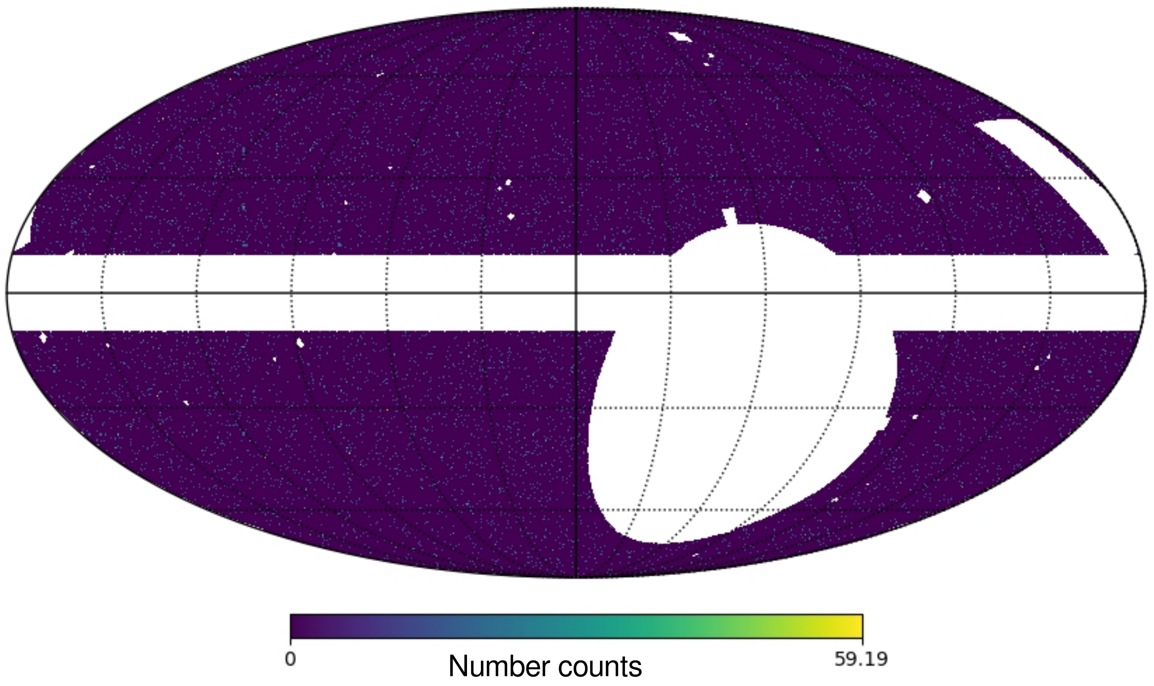
- They can be used to trace the spatial distribution of matter on large cosmological volumes

- They are less affected by galactic obscuration → wide sky coverage

- Very bright sources which allow us to trace the mass up to high redshifts

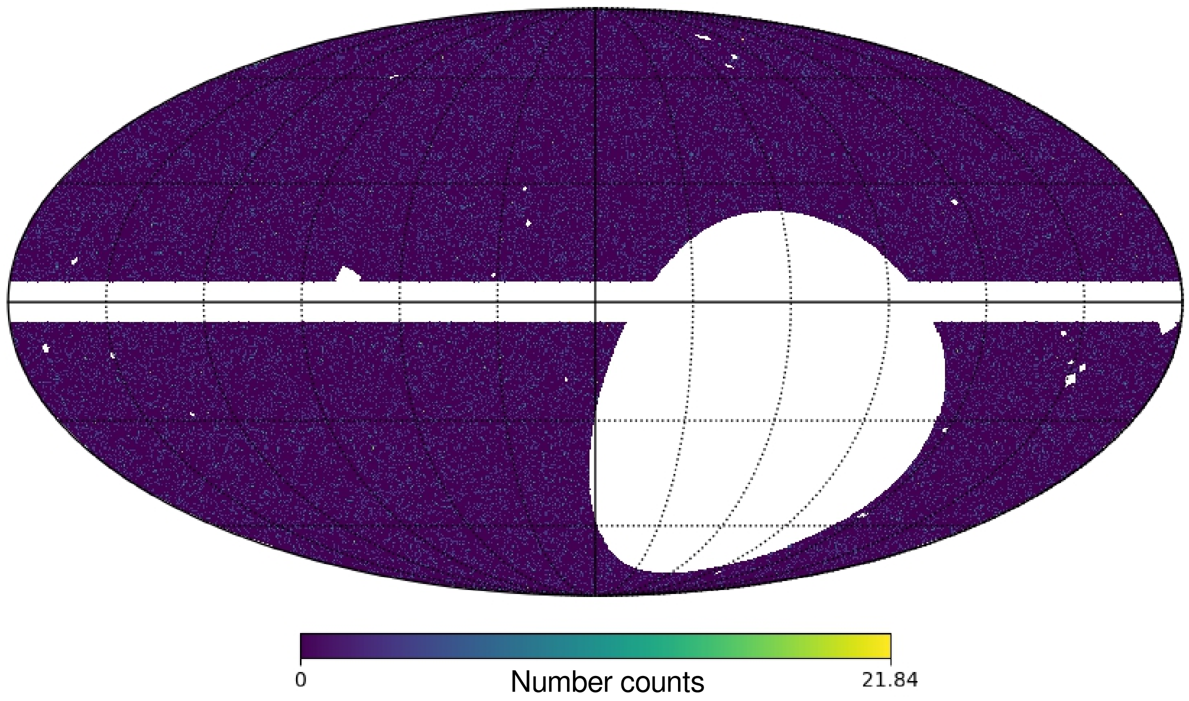
Extragalactic radio source catalogs

TIFR GMRT SKY SURVEY (TGSS)



- Radio survey at 150 MHz
- Giant Metrewave Radio Telescope
- Flux = [200, 1000] mJy
- 109 940 radio sources
- $f_{sky} = 0.70$

NRAO VLA SKY SURVEY (NVSS)



- Radio survey at 1.4 GHz
- Very Large Array observatory
- Flux = [10,1000] mJy
- 518 894 radio sources
- $f_{sky} = 0.75$

Extragalactic radio source catalogs

BUT

- The catalogs contain various types of radio objects

- For this two catalogs, the fraction of objects with measured redshift is small ⟶ is not possible to obtain a 3D distribution

- Cosmological information is extracted through the 2D angular power spectrum

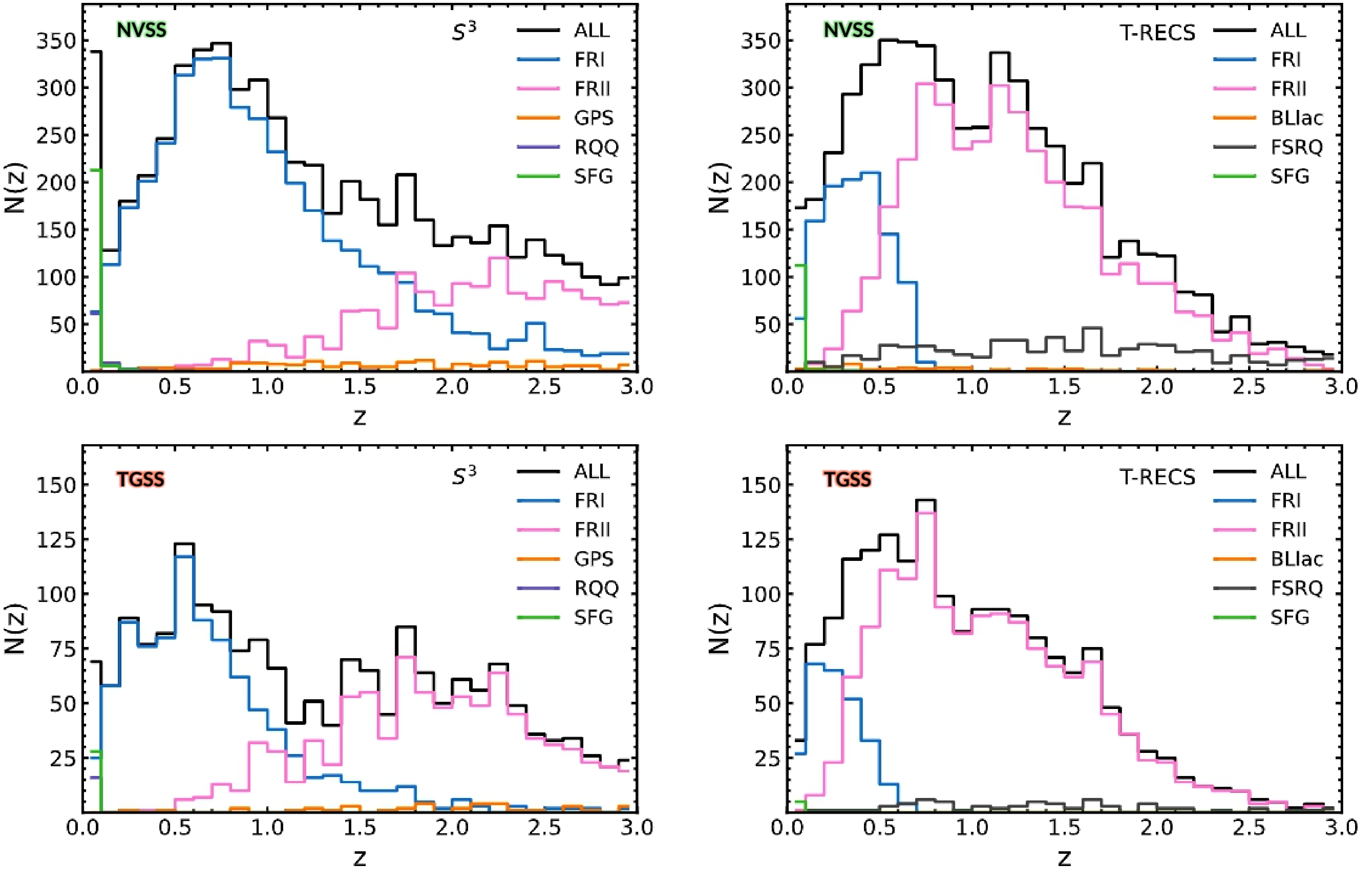
$$C_\ell^{gg} = \frac{2}{\pi} \int_0^\infty dz \, [W^g(z)]^2 \int_0^\infty dk \, k^2 \, j_\ell^2[k\chi(z)] \, P(k,z)$$

Galaxy window function: $W^g(z) = \frac{b(z)N(z)}{\int dz' \, N(z')}$

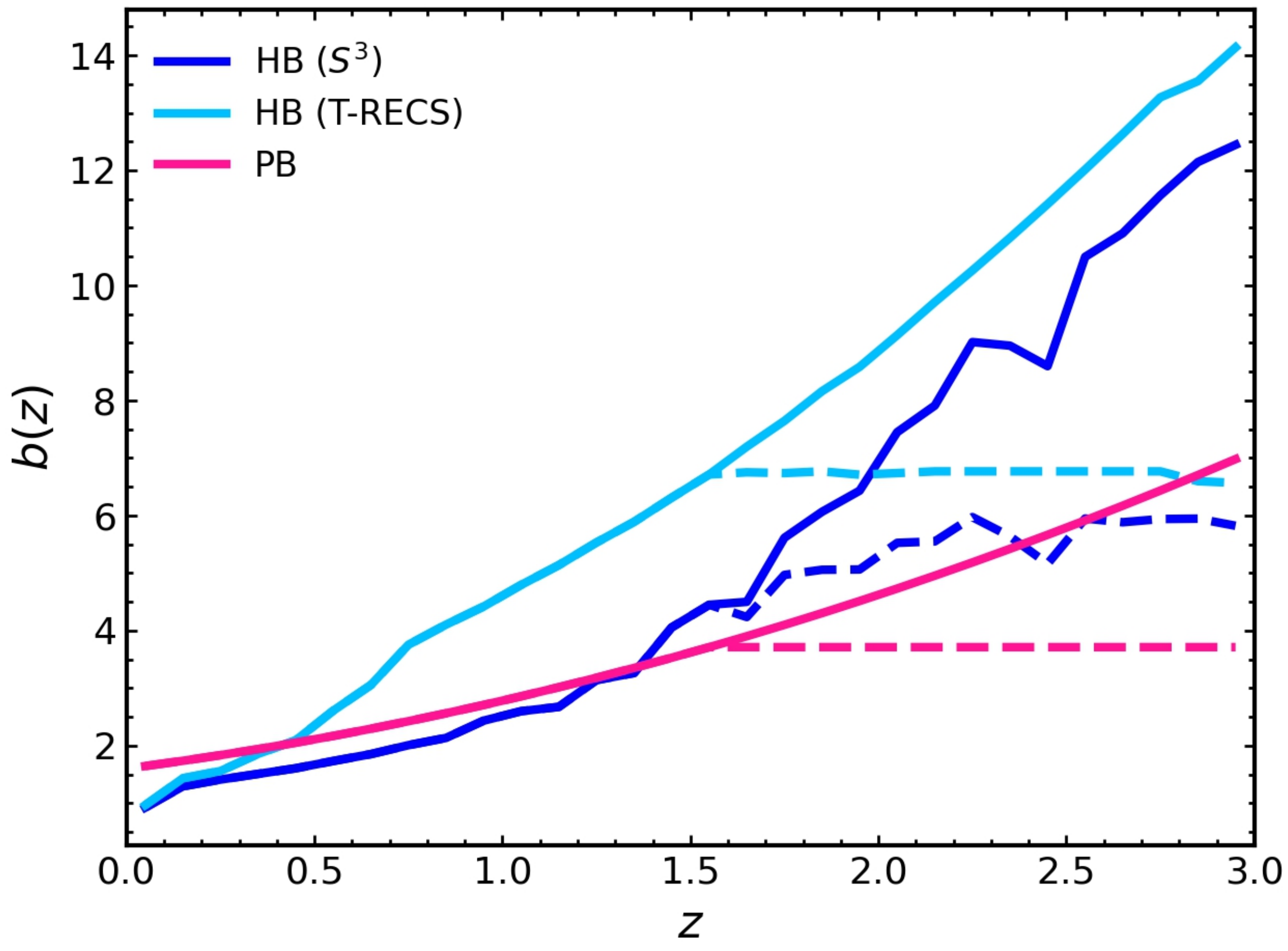
Radio sources N(z)

S^3 by Wilman+, 2008

T-RECS by Bonaldi+, 2019



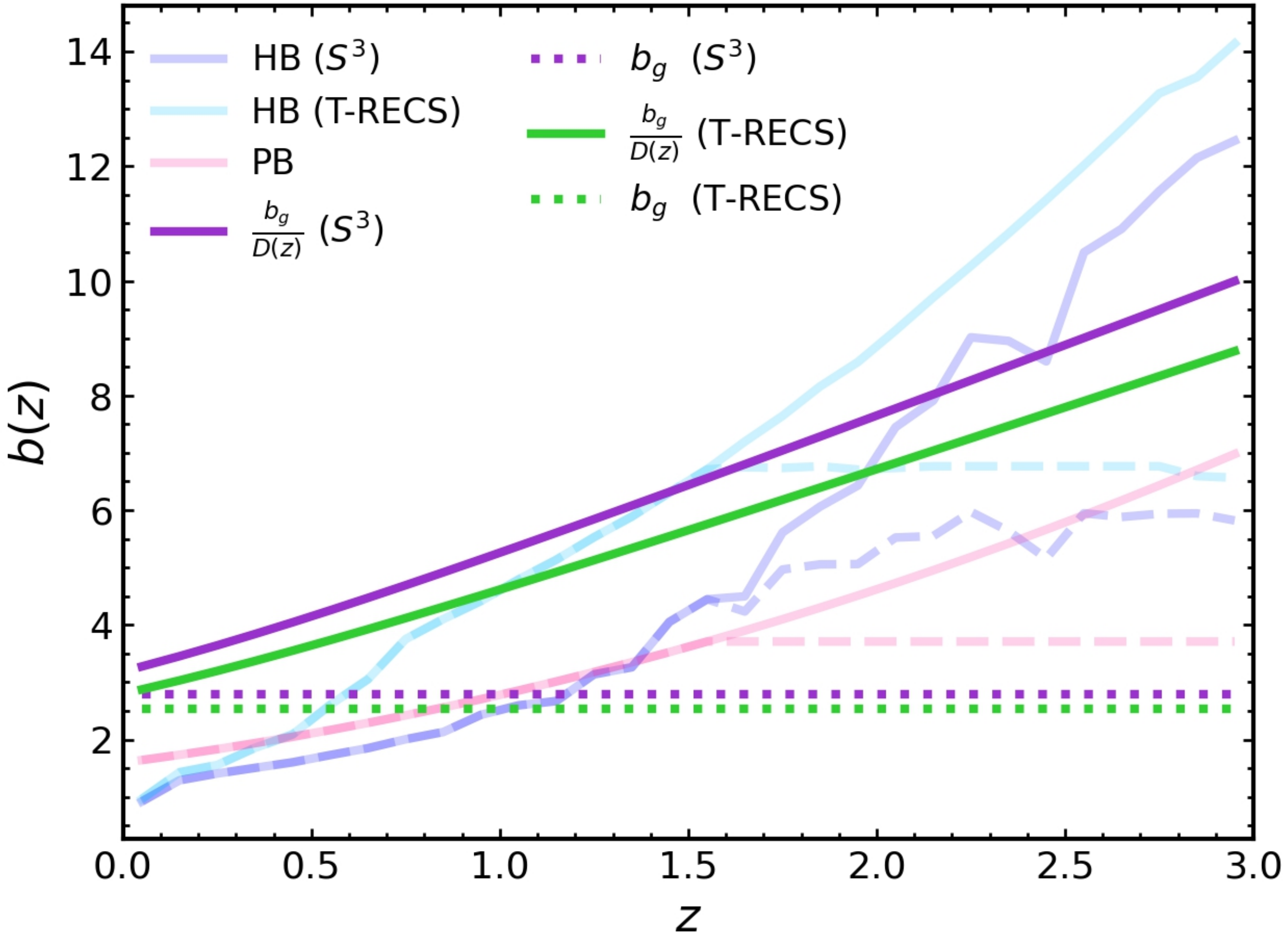
Radio sources b(z)



We assume a local, deterministic, evolving bias and explore two scenarios:

1. b(z) models from literature that are designed to match NVSS or TGSS auto-correlation (*Dolfi+, 2019*):
   Halo Bias (HB), Parametric Bias (PB)
   and their truncated versions

Radio sources b(z)

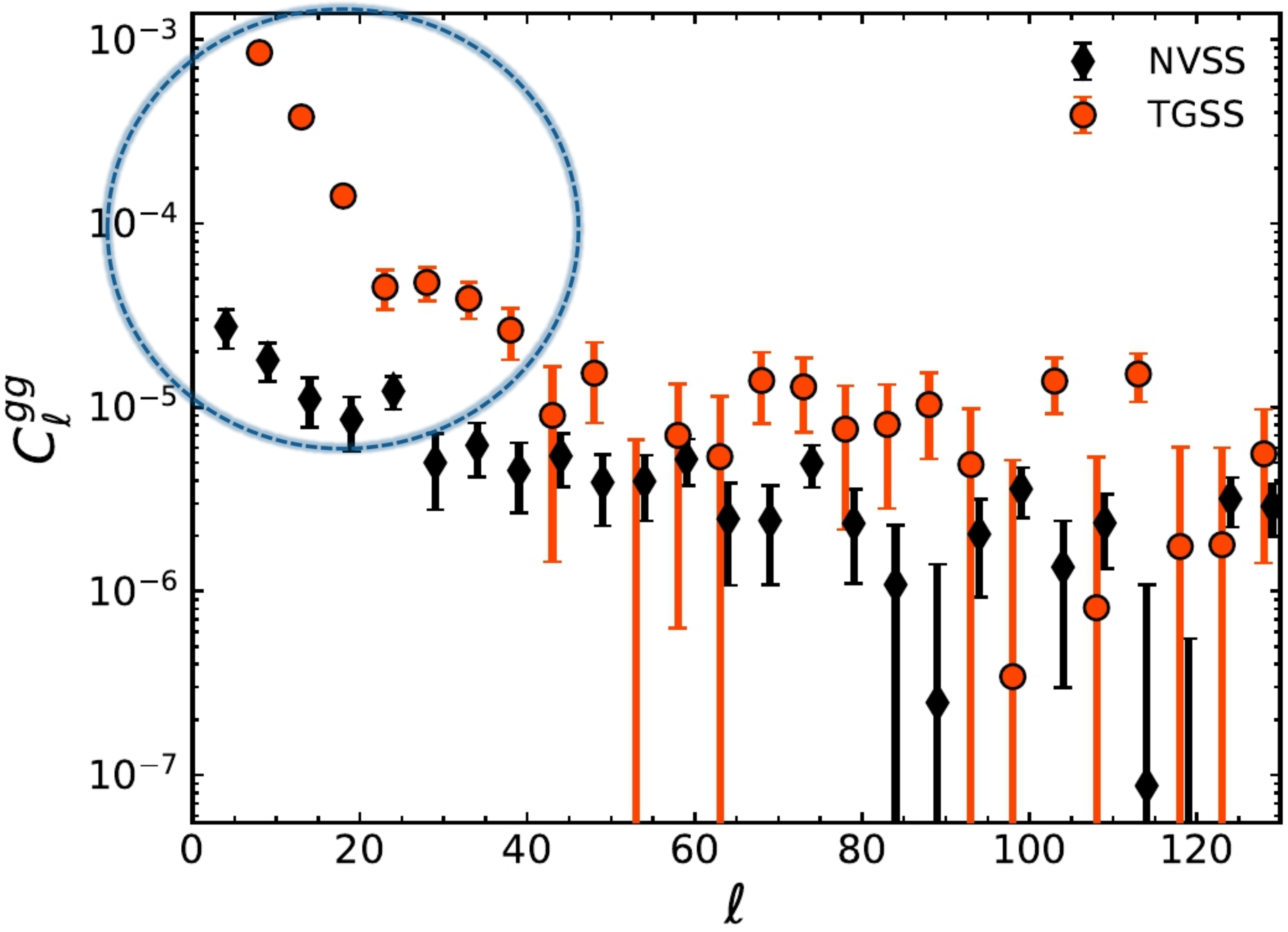


We assume a local, deterministic, evolving bias and explore two scenarios:

1. b(z) models from literature that are designed to match NVSS or TGSS auto-correlation (*Dolfi+, 2019*):
   Halo Bias (HB), Parametric Bias (PB) and their truncated versions

2. b(z) is free to vary in the analysis. We considered two ansatz (*Alonso+, 2020*):
   constant amplitude ($b(z) = b_g/\mathrm{D}(z)$) and constant bias ($b(z) = b_g$)

Radio sources auto power spectra



- The power excess at large scales is already discussed in previous studies (*see e.g. Dolfi+, 2019*) but is still an open issue

- The excess could be due to systematic effects (*Tiwari+,2019*) in the observations. This prevents us from using the auto-correlation analysis to investigate radio sources properties

The case for a cross-correlation analysis

Cross-correlation analysis between different tracers of the LSS of the Universe is a precious tool to tackle this issue:

- Different catalogs or maps are typically affected by various systematic errors. If the catalogs are properly chosen, these systematics are not correlated and then the cross-correlation analysis will not be affected by either of them. Its results will be suitable for cosmological study

- When performed jointly with auto-correlation analysis, it can potentially break N(z)-b(z) degeneracy, allowing us to investigate the nature of the different radio sources in the catalog

We need an independent tracer to correlate radio catalogs with → The CMB lensing map satisfies both requirements as it is an unbiased tracer of LSS

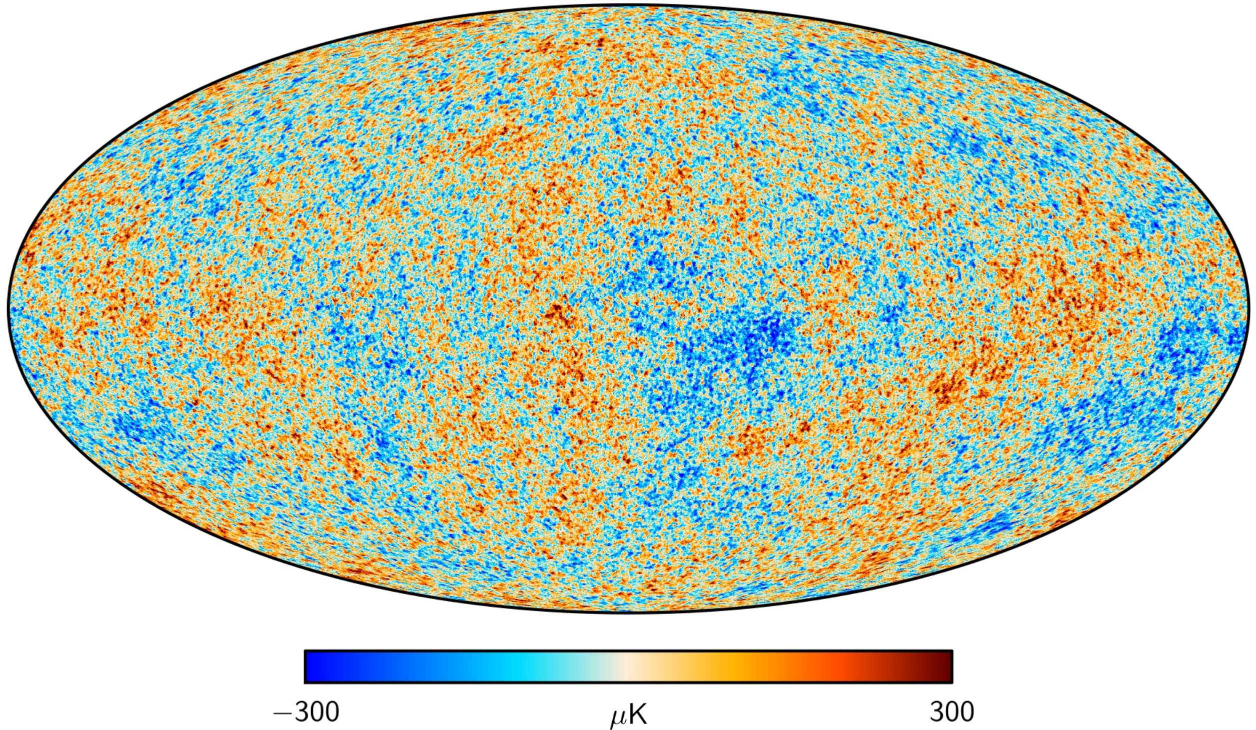
Cosmic Microwave Background (CMB)

- We use data from Planck satellite which measured the temperature fluctuations of the CMB with exquisite precision

- Ultimate map: in the next future, no experiment will be able to perform better in probing the CMB temperature anisotropies

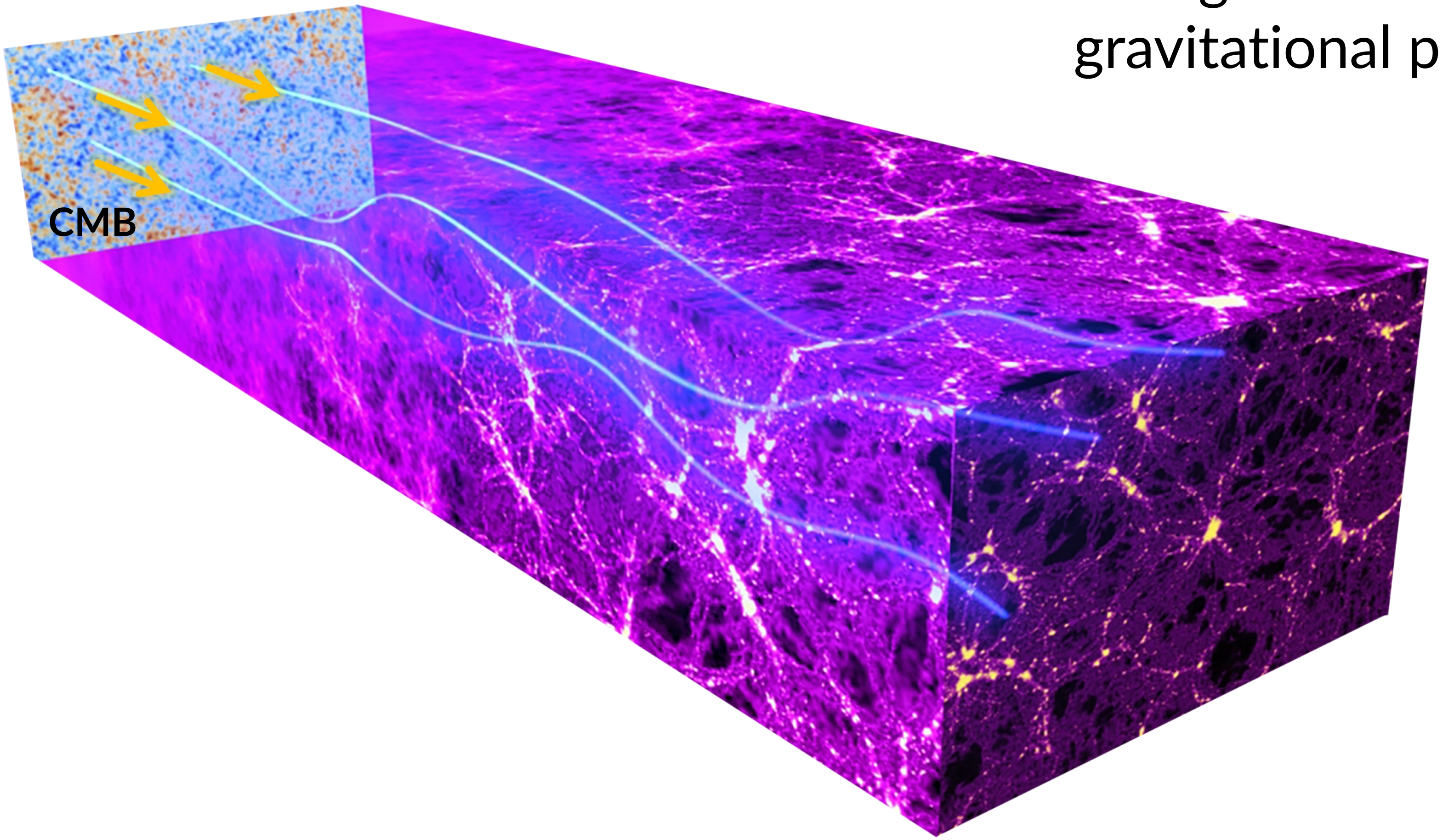
- Planck experiment also sets the stage for new studies which involve the lensing phenomenon

Planck collaboration+, 2018



CMB gravitational lensing

Gravitational lensing indicates the deflection of the light trajectory induced by a gravitational field

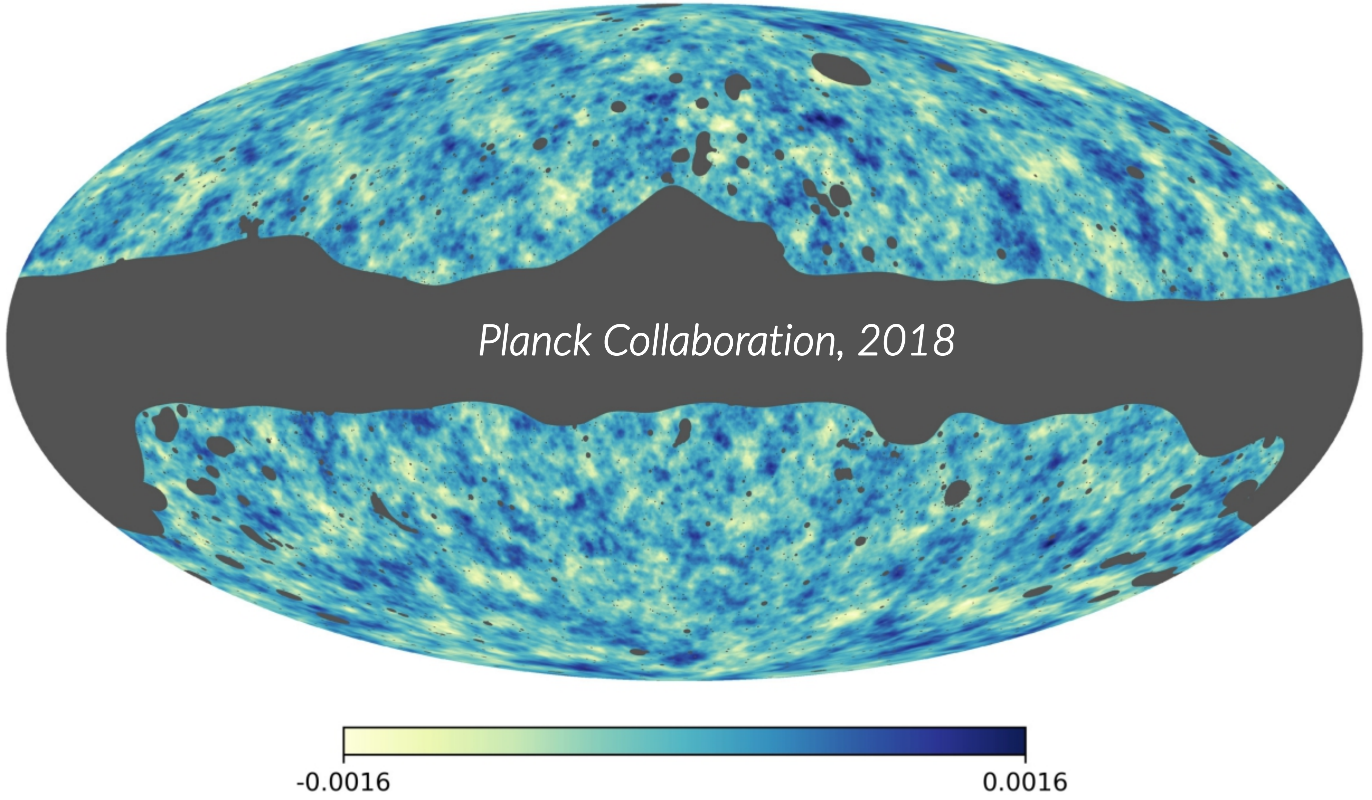


Background anisotropies are re-mapped by the gravitational potential of the LSS of the Universe

$$\tilde{\Theta} = \Theta(\hat{n} + \nabla\phi(\hat{n}))$$

CMB gravitational lensing

- The re-mapping process has a non-negligible impact on most of the CMB observables
- By studying the variation in temperature and polarization is possible to construct the lensing deflection angle map
- This is therefore a proxy of the gravitational potential generated by the LSS integrated along the line of sight



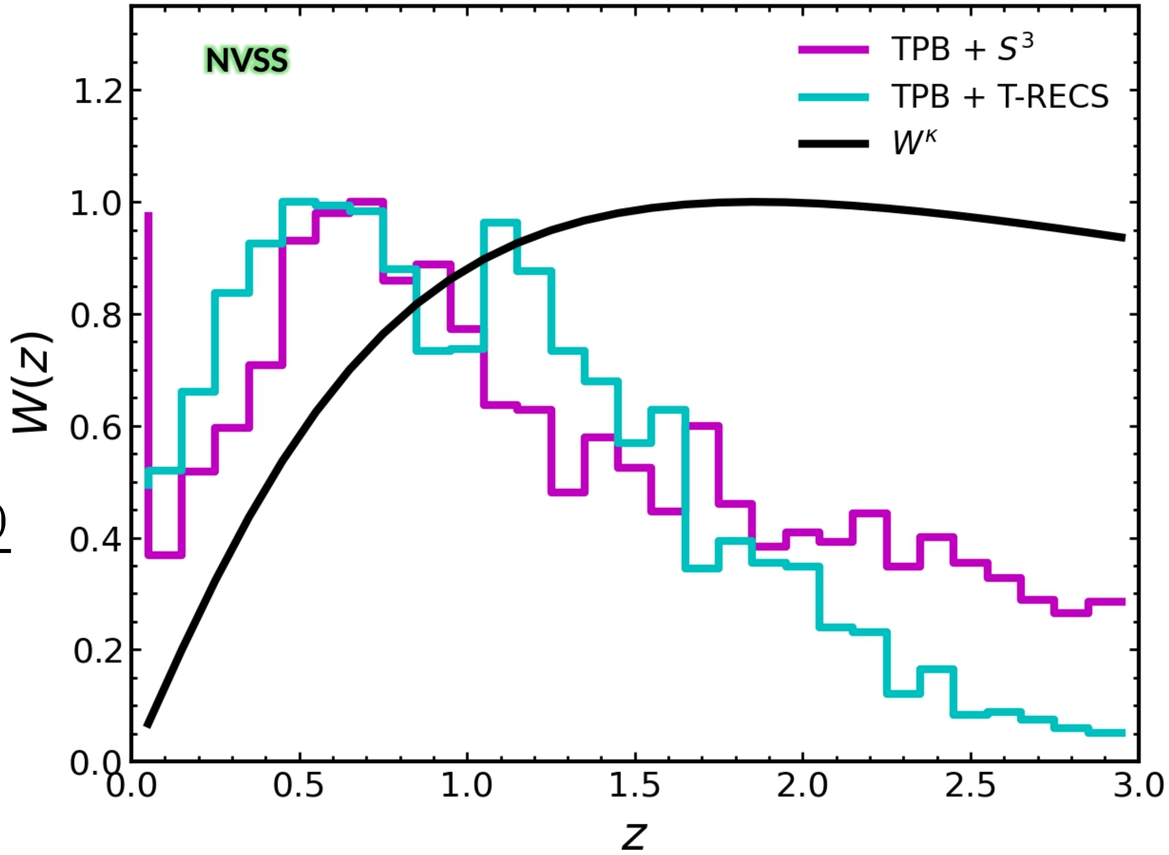
Cross-correlation analysis

- The cross-correlation angular power spectrum is estimated as:

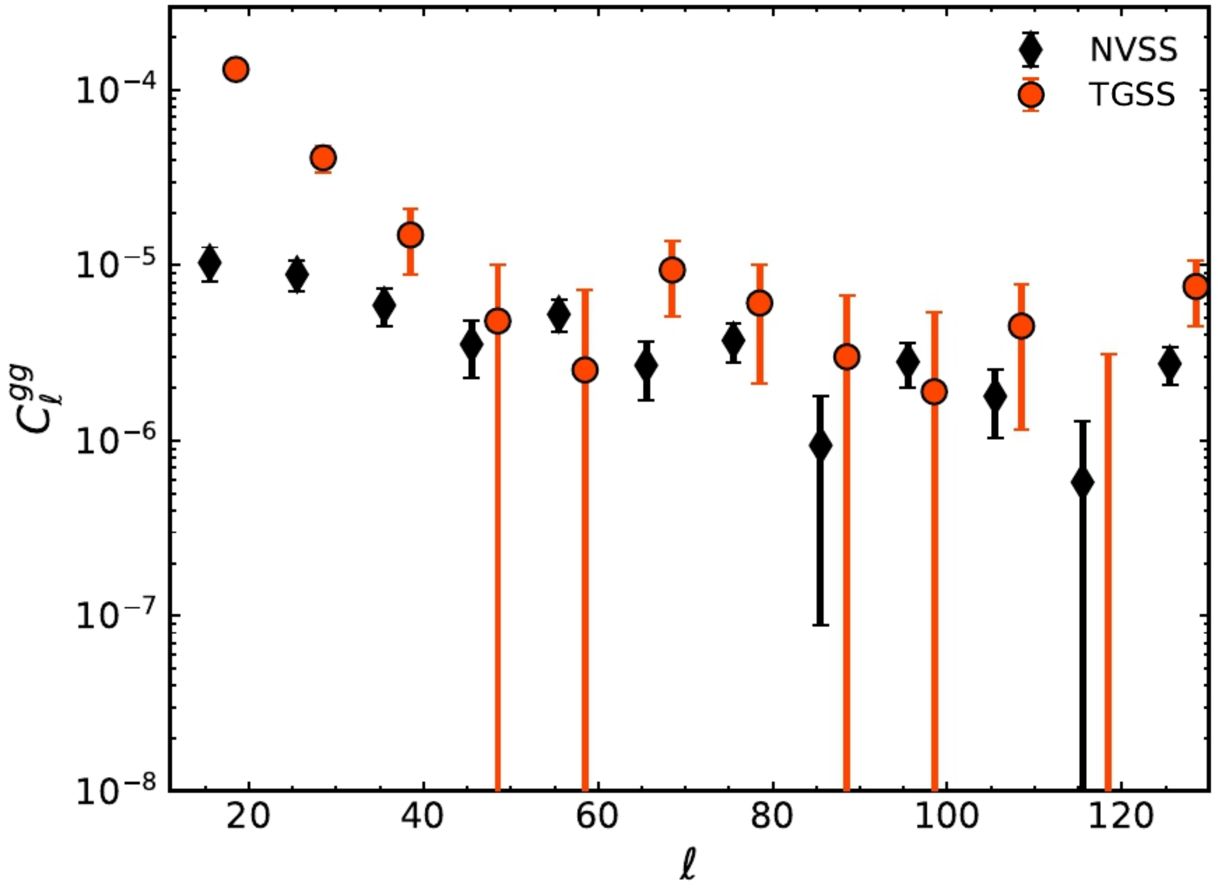
$$C_\ell^{\kappa g} = \frac{2}{\pi}\int_0^\infty dz\; W^g(z)\int_0^\infty dz' W^\kappa(z')\; x\; \int_0^\infty dk\; k^2 P(k,z,z') j_\ell[k\chi(z)] j_\ell[k\chi(z')]$$

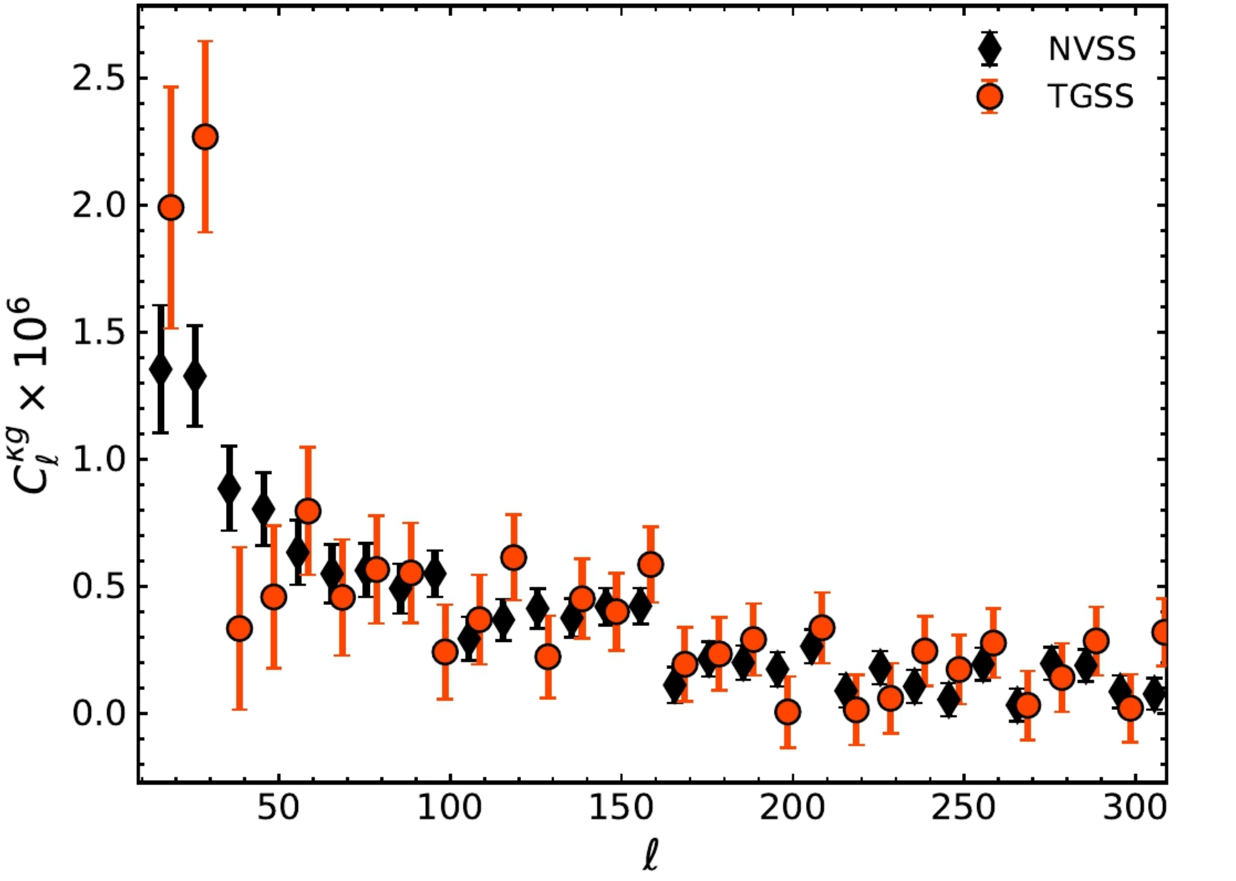
Galaxy window function: $W^g(z) = \frac{b(z)N(z)}{\int dz'\; N(z')}$

Lensing window function: $W^\kappa(z) \propto \frac{(1+z)\chi(z)}{H(z)}\frac{\chi^* - \chi(z)}{\chi^*}$



Results 1: measured cross power spectra





- First measure of TGSS and Plank CMB convergence cross-correlation signal with a 12σ significance
- Reduced power excess at large scales in the cross correlation

Results 2: Testing b(z) and N(z) models

- To quantify the agreement between data and theoretical predictions, we estimated the χ^2 and p-value

$$\boxed{\chi^2 = \sum_{\ell,\ \ell'} (C_\ell^{th} - C_\ell^{obs})\mathbf{Cov}^{-1}_{\ell,\ \ell'}\ (C_{\ell'}^{th} - C_{\ell'}^{obs})}$$

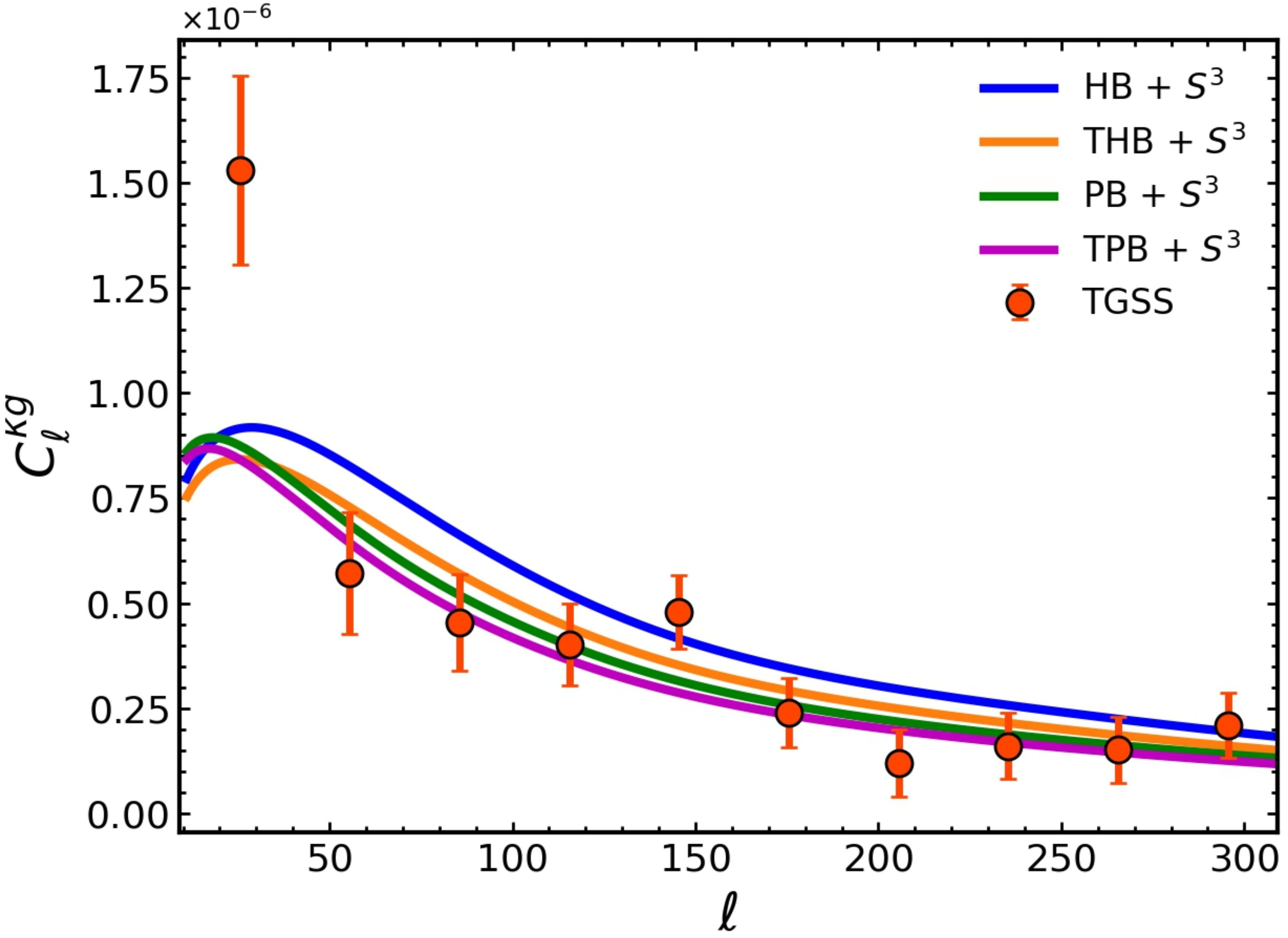
1. Cross power spectrum $C_\ell^{\kappa g}$ alone (CA):

$$Cov_{\ell\ell'}^{\kappa g,\kappa g} = \frac{\delta_{\ell\ell'}}{(2\ell+1) f_{sky}^{kg,kg}} \left[(C_\ell^{\kappa g})^2 + (C_\ell^{gg} + N_\ell^{gg})(C_\ell^{\kappa\kappa} + N_\ell^{\kappa\kappa})\right]$$

2. Joint analysis (JA) considering both cross $C_\ell^{\kappa g}$ and auto C_ℓ^{gg} spectra:

$$\mathrm{Cov}^{joint} = \begin{bmatrix} Cov^{\kappa g,\kappa g} & (Cov^{\kappa g,\ gg})^T \\ Cov^{\kappa g,\ gg} & Cov^{gg,gg} \end{bmatrix}$$

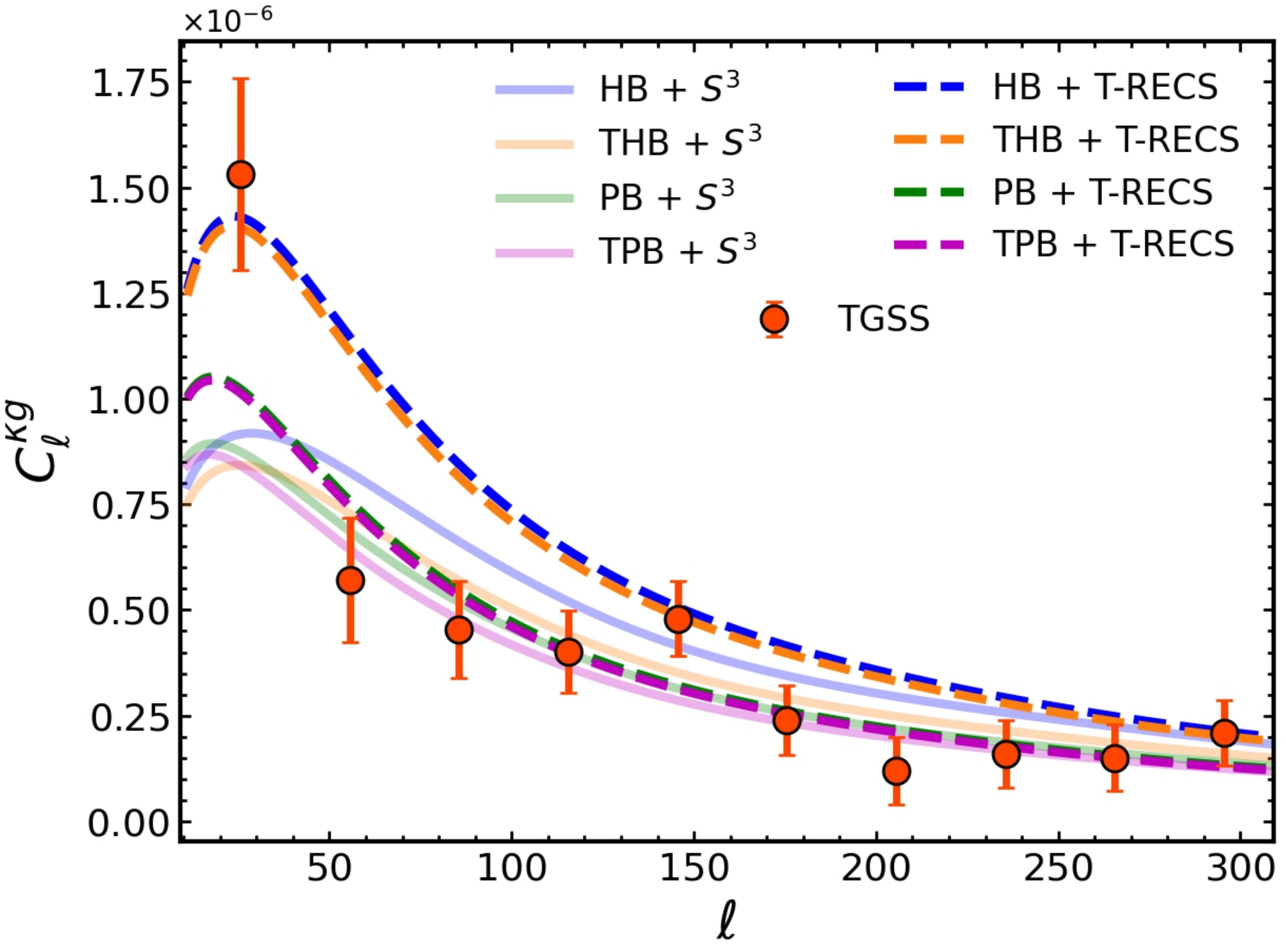
Results 2: TGSS χ^2 analysis



Once we estimate the cross power spectrum, we compute theoretical predictions for different combinations of N(z) and b(z) models

1. solid lines (S^3): theoretical models match the angular spectra everywhere but in the first bin → difficulties in reproducing the radio sources clustering at large scales

Results 2: TGSS χ^2 analysis



Once we estimate the cross power spectrum, we compute theoretical predictions for different combinations of N(z) and b(z) models

1. solid lines (S^3): theoretical models match the angular spectra everywhere but in the first bin → difficulties in reproducing the radio sources clustering at large scales

2. dashed lines (T-RECS): in this case, some of the models fit the first bin but then they fail to match data in most of other bins

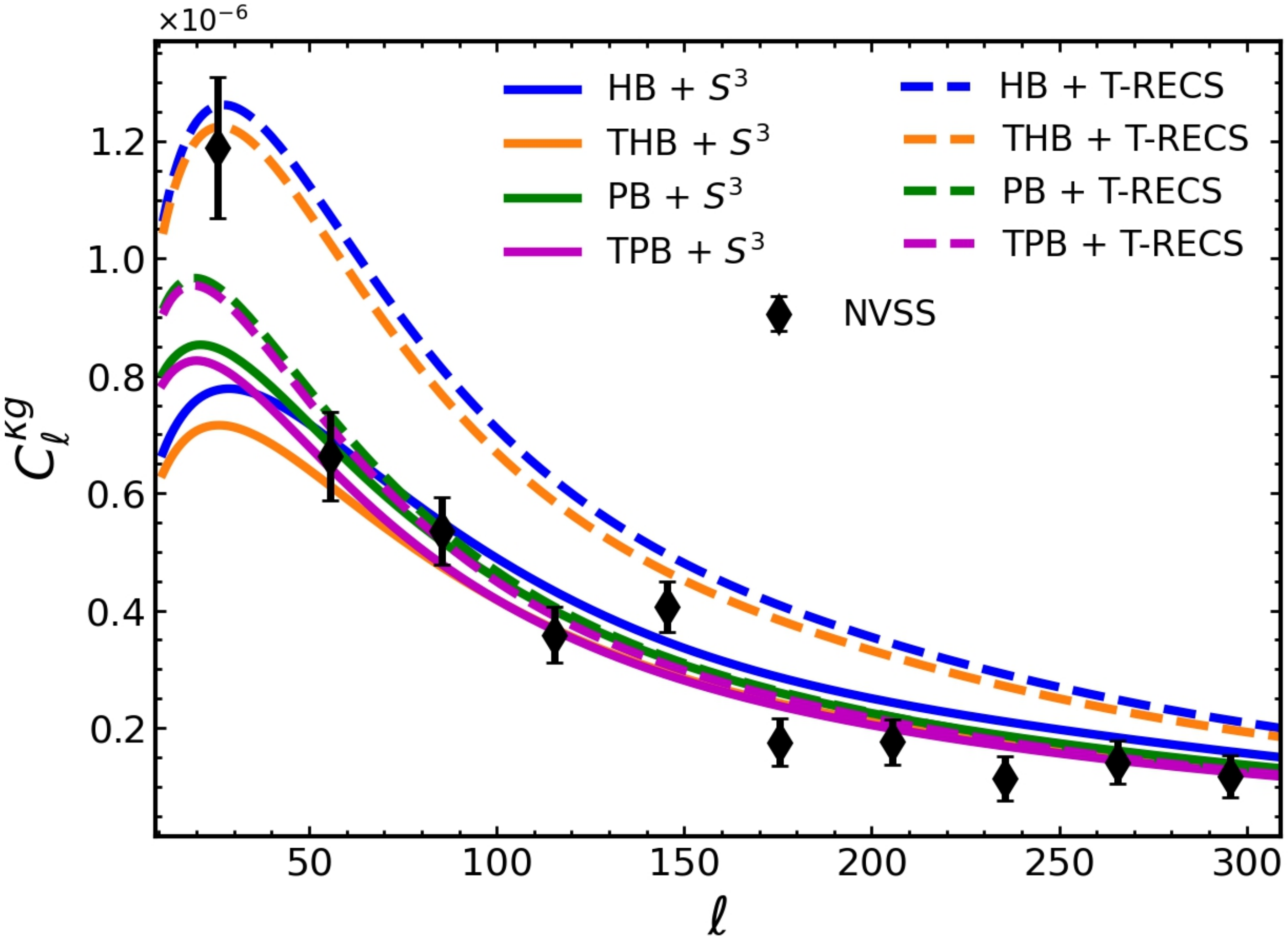
Results 2: TGSS χ^2 analysis

Lesson learned ❗

1. Theoretical prescriptions, which fit the first ℓ –bin, are generally ruled out by data (χ^2= 4.88 and pte = 4.3×10^{-7})

2. The other models perform similarly in describing the behaviour of data (χ^2= 1.59 and pte = 1.0×10^{-1})

Results 2: NVSS χ^2 analysis



- For NVSS catalogs, results are in agreement with the TGSS ones

- Also the joint analysis (cross + auto-correlation), confirms these outcomes

Results 2: recap

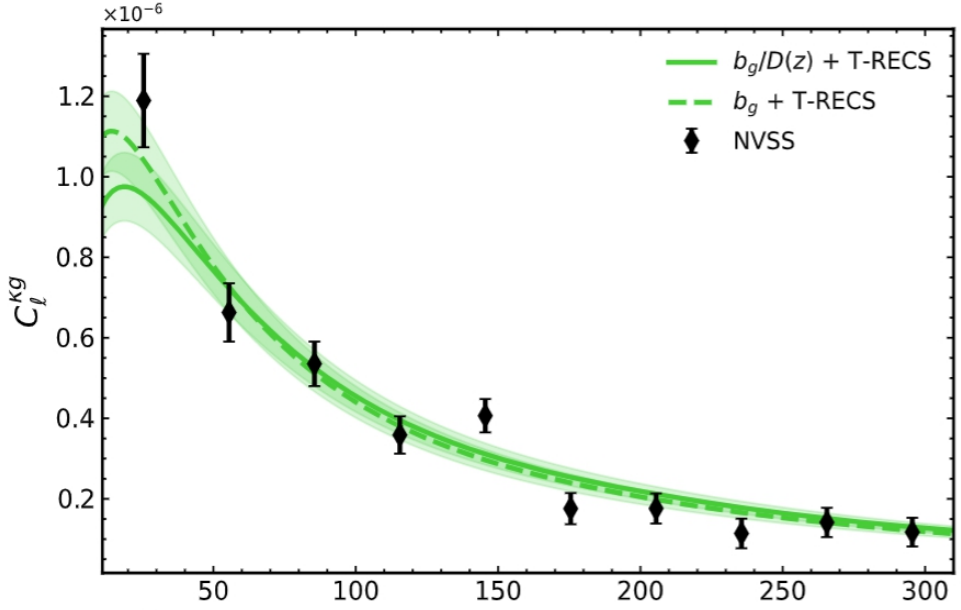
- Models proposed in the literature to match NVSS and TGSS auto-spectra do not provide a good fit to the cross-spectra. They fail to match the large power on large angular scales

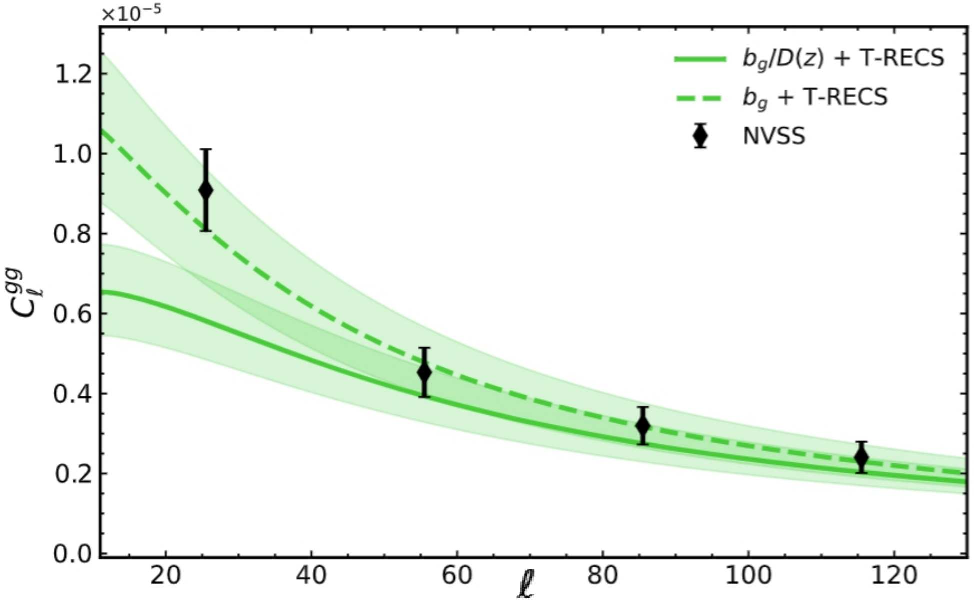
- This conclusions are robust against the choice of N(z) models

- Next step: fix the N(z) prescription and let b(z) vary

- Given the constraining power of our datasets, we consider simple b(z) models with one free parameter b_g only

Results 3: Galaxy bias estimation





- Results are shown for T-RECS based N(z) model. S^3 model provides similar results
- The constant model fits better the auto- and cross-power spectrum also in the first bin
- It increases the relative weight of the local LSS clustering signal, that dominated at low multipoles, with respect to the high-z one
- The best fit value (2.53-3.2, depending on the model) is close to that QSOs (*Devereux+,2019*) but much higher than FRI and SFG that are expected to dominate the composition of catalogs at low-z

Results 3: Galaxy bias estimation

- Possible explanation

1. The N(z) prescriptions are not accurate ⟶ need a clustered population of radio objects at small redshift but there are no observational evidence for this

2. The bias of these NVSS low-z sources, decreases with the increasing of z (*Negrello+, 2006; Raccanelli+, 2008*) ⟶ more weight for sources at $z \lesssim 1$

3. The ΛCDM cosmological model is wrong

4. Observational systematics are unlikely the explanation since cross-correlation is designed to minimize their impact

Conclusions

- Wide, almost full-sky coverage radio surveys are useful for cosmological research and we can perform 2D studies

- The angular auto spectrum has an excess at large scale which is still an open issue. Cross-correlation with CMB lensing can be the key to solve this problem

- Our cross-correlation analysis confirms that the large scale excess detected in the auto angular power spectrum is due to systematics effects in the radio observations

- The cross-correlation analysis is able to discern between physical plausible theoretical models of N(z) and b(z)

- Next step: forecast the ability of cross-correlation analysis of future observations of CMB lensing (*S0*, *CMB-S4*, *LiteBIRD*) and radio surveys (*e.g. SKA*, *ASKAP*) to unveil the composite nature and clustering properties of radio sources and to constrain relevant cosmological parameters

Thank you for your attention

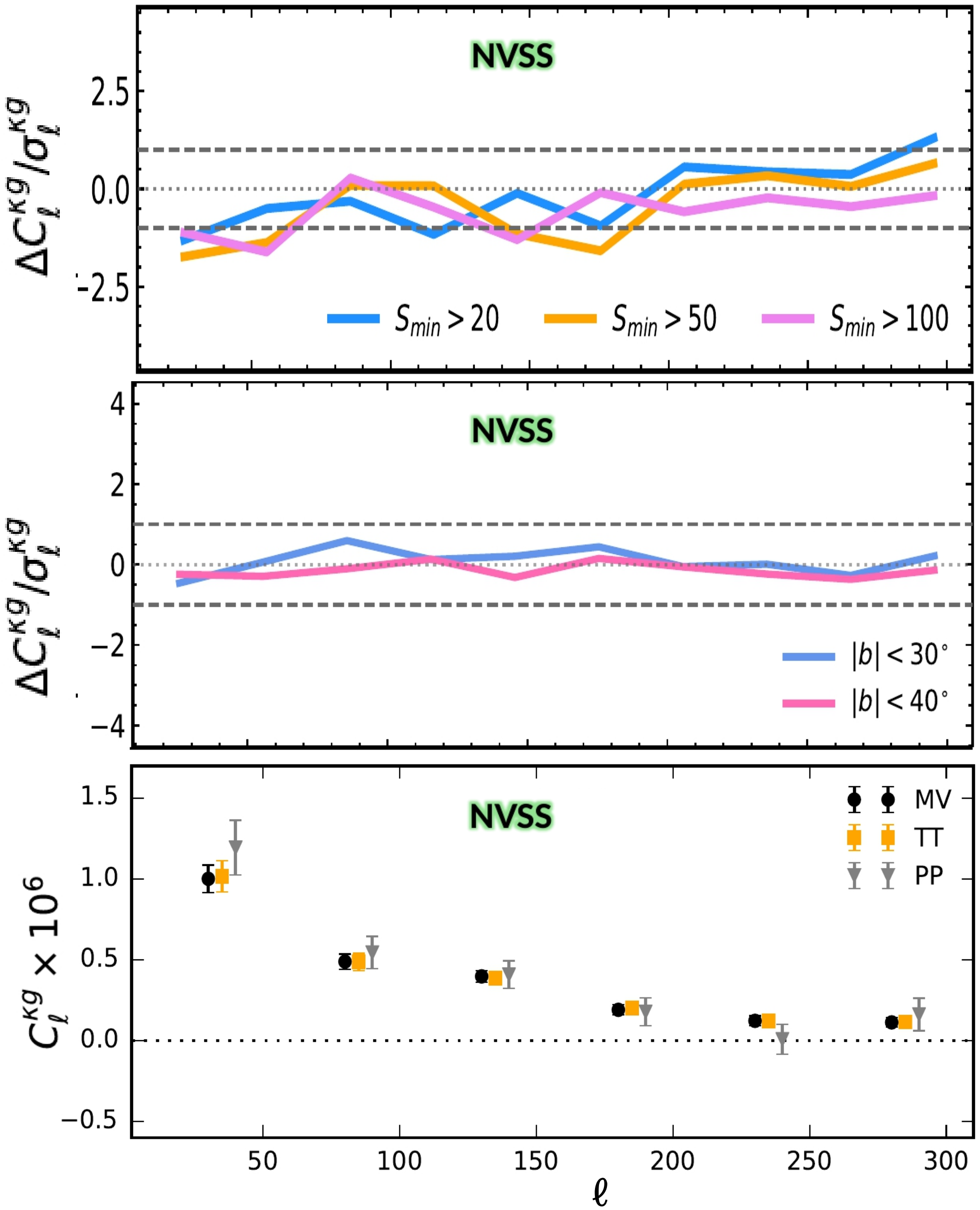
Robustness tests: NVSS case

The cross correlation analysis is robust against observational systematic effects

- Radio catalog flux threshold [mJy]: differences are computed wrt the baseline analysis in which S_{min} = 10 mJy

- Galactic latitude cuts: differences are computed wrt the baseline analysis in which |b| < 5°

- Different reconstruction of CMB convergence: temperature (TT) or polarization (PP) only and their minimum variance (MV) combination



CMB gravitational lensing

- Gravitational lensing refers to the deflection of the light trajectory induced by a gravitational field
- The total deflection angle $\boldsymbol{\alpha}$, due to lensing by all the potential gradients along the line of sight, is defined for a flat Universe:

$$\boldsymbol{\alpha}(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} d\chi\, \frac{(\chi_* - \chi)}{\chi_*\chi} \nabla_\perp \Psi(\chi\hat{\boldsymbol{n}};\eta_0 - \chi)$$

$$\alpha \propto \nabla\Psi$$

$$\phi(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} d\chi\, \frac{(\chi_* - \chi)}{\chi_*\chi} \Psi(\chi\hat{\boldsymbol{n}};\eta_0 - \chi)$$

Lensing potential