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

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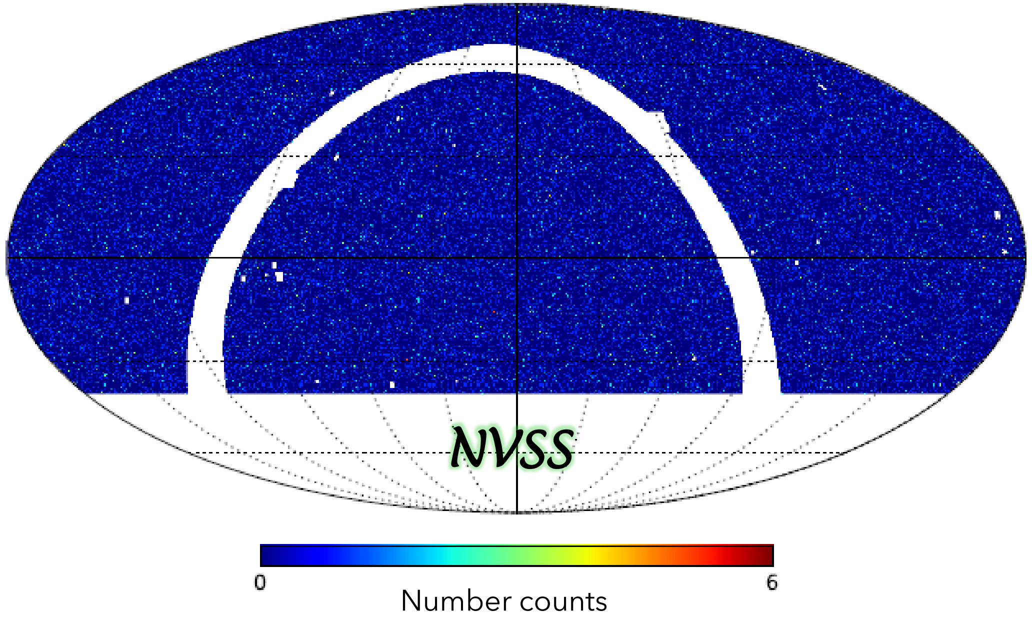
Overview

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

Extragalactic radio sources catalogues

- Less affected by galactic obscuration → wide sky coverage
- Very powerful sources where electrons are accelerated to relativistic velocities and produce synchrotron radiation
- Active galactic nuclei or sites of intensive star formation → probe the LSS out to high redshifts



- We analyzed two of the wideset catalogues to date
  i. the NRAO VLA Sky Survey (NVSS) at 1.4 GHz
  ii. the TIFR GMRT Sky Survey (TGSS) at 150 MHz

Extragalactic radio sources catalogues

BUT

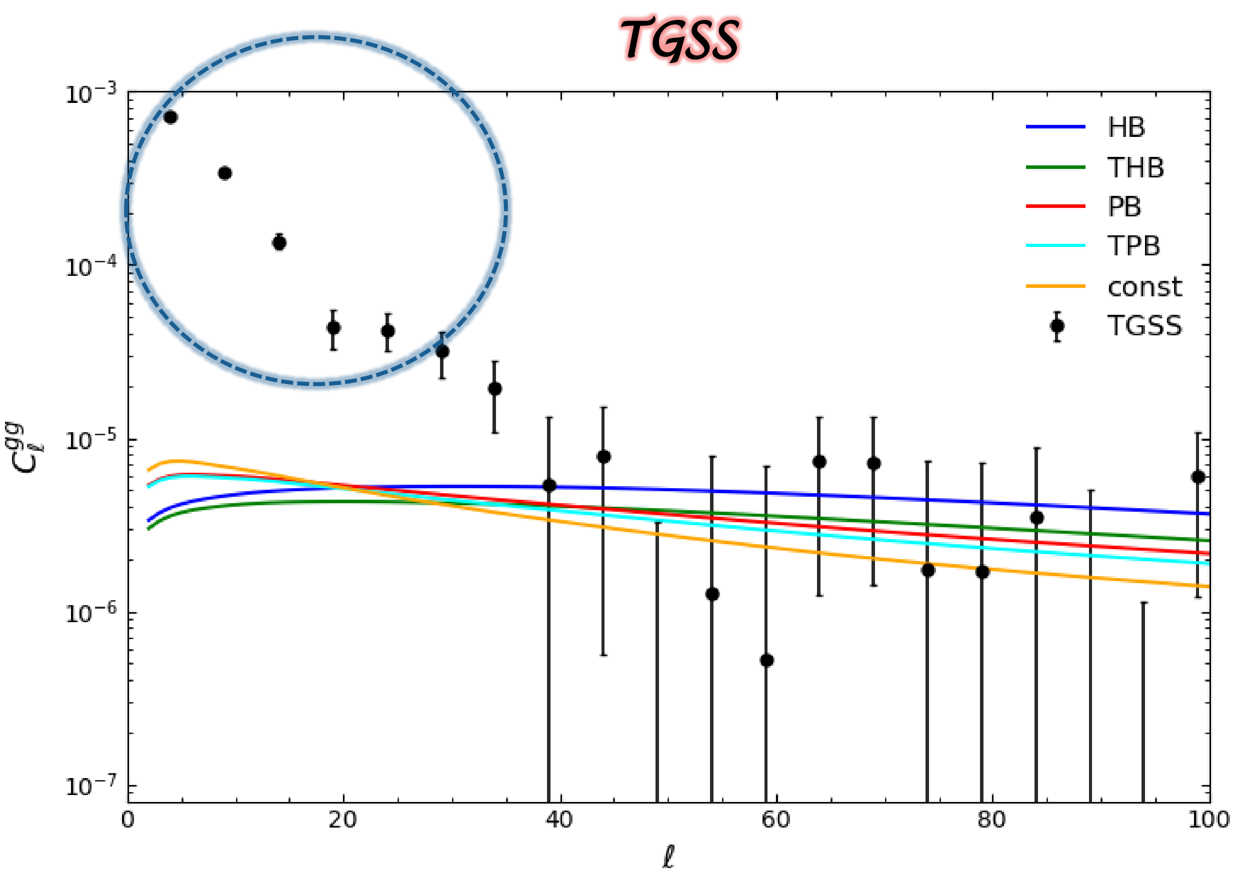
- Difficulties in obtaining information about luminosity distance allow only a 2D analysis

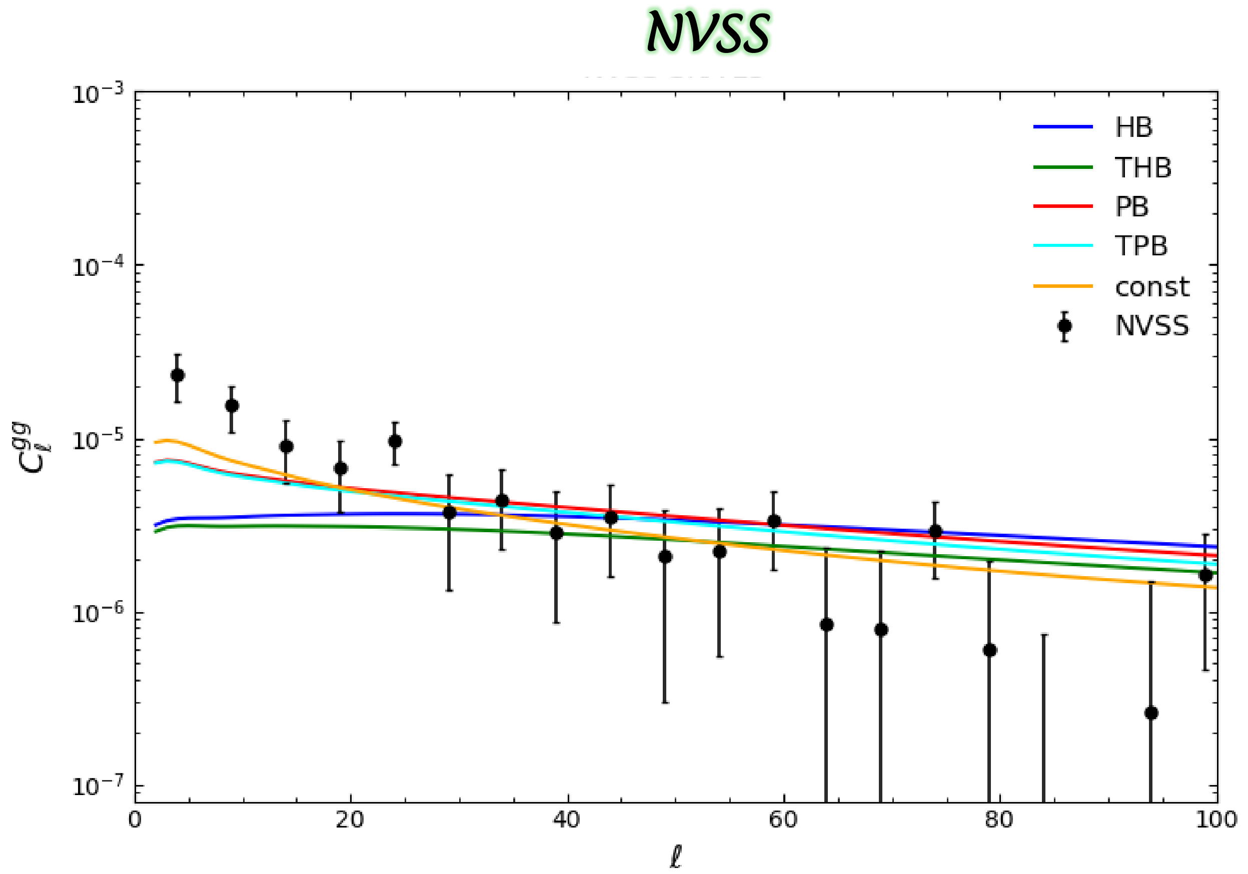
- Cosmological information is extracted from the 2D angular power spectrum

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

Galaxy window function $W^G(z) = b(z)N(z)$

Radio sources





- Radio catalogues show a power excess at large scales consistent with previous studies (*see e.g. Dolfi et al. 2019*)
- The excess could be due to systematic effects 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 for addressing some of these issues:

- Different catalogues or maps are typically affected by uncorrelated systematic errors. A cross-correlation analysis is not sensitive to uncorrelated spurious signals and provides robust estimates of cosmological quantities

- Can potentially break degeneracies between number counts and bias models if the tracer have different window functions

- An independent observable is needed

The CMB lensing map satisfies both requirements as it is an unbiased tracer of LSS

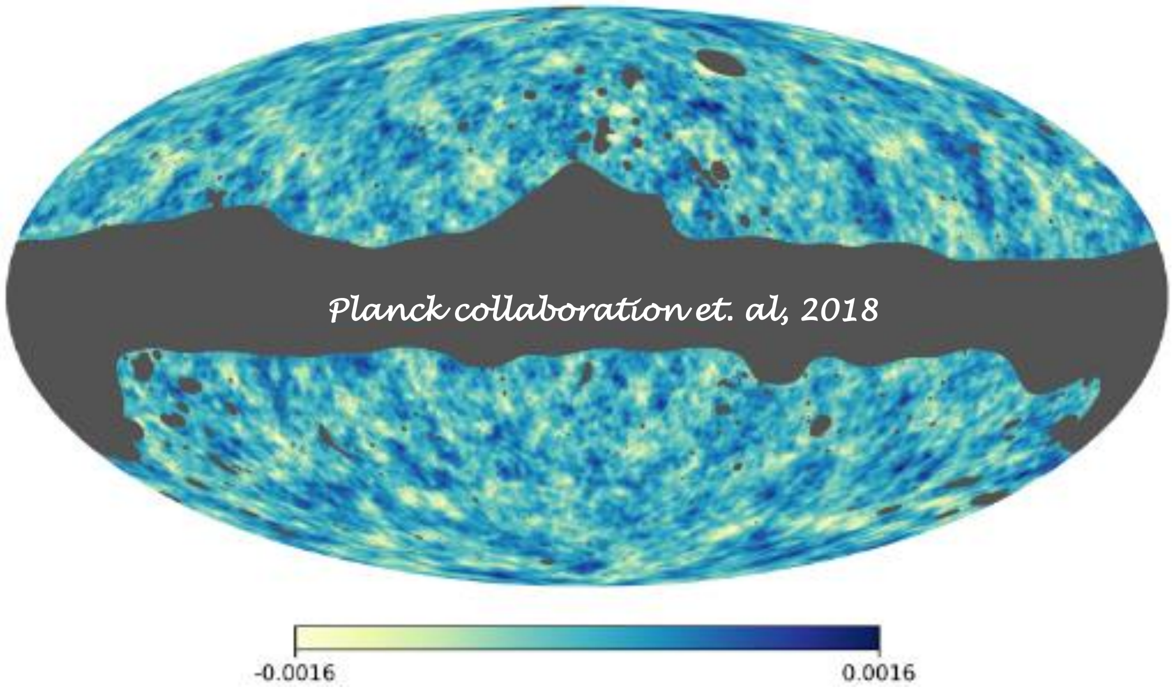
Cosmic Microwave Background lensing

- Gravitational lensing refers to the deflection of the light trajectory induced by a gravitational field

- CMB is the most distant observable light source

- It is an integrated measure of the intervening matter in the Universe back to the last scattering surface

- CMB lensing phenomenon is useful to study the matter distribution of the Universe at intermediate redshifts



lensing deflection angle map

Cross-correlation analysis

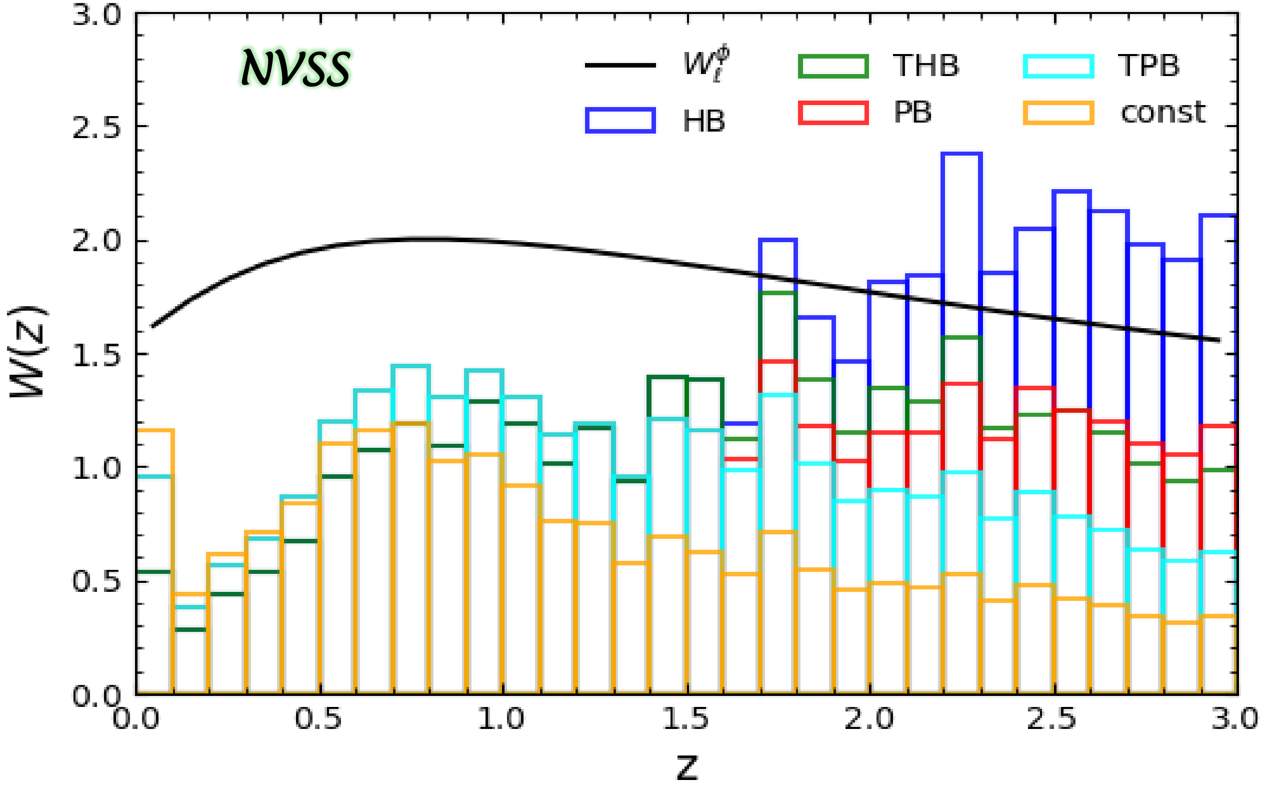
- The cross correlation angular power spectrum is computed as:

Lensing window function $\propto \frac{(1+z)}{H(z)}\chi(z)\left(\frac{\chi(z_\star)-\chi(z)}{\chi(z_\star)\chi(z)}\right)$

Galaxy window function: $b(z)N(z)$

$$C_\ell^{\phi G} = \frac{2}{\pi}\int_0^\infty dz\, W^G(z) \int_0^\infty dz' W^\phi(z') \times$$

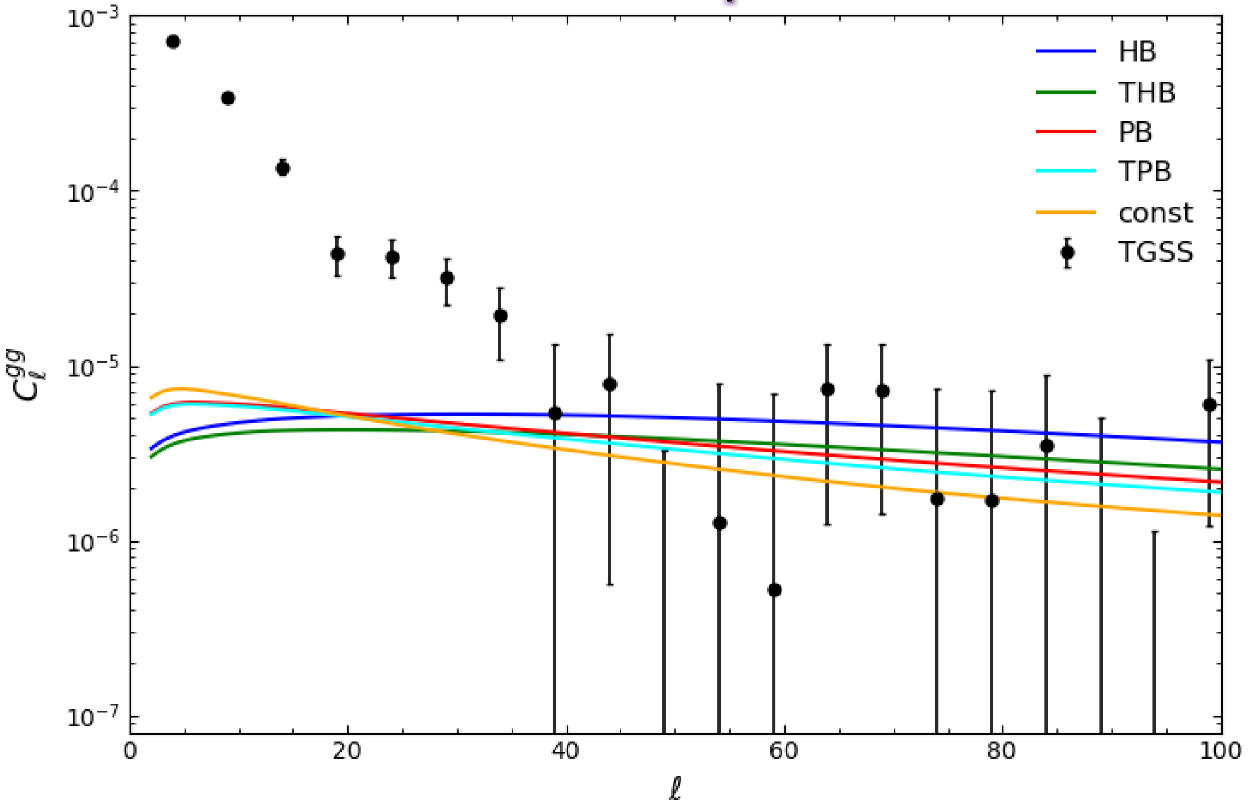
$$\int_0^\infty dk\, k^2 P(k,z,z') j_\ell[k\chi(z)] j_\ell[k\chi(z')]$$



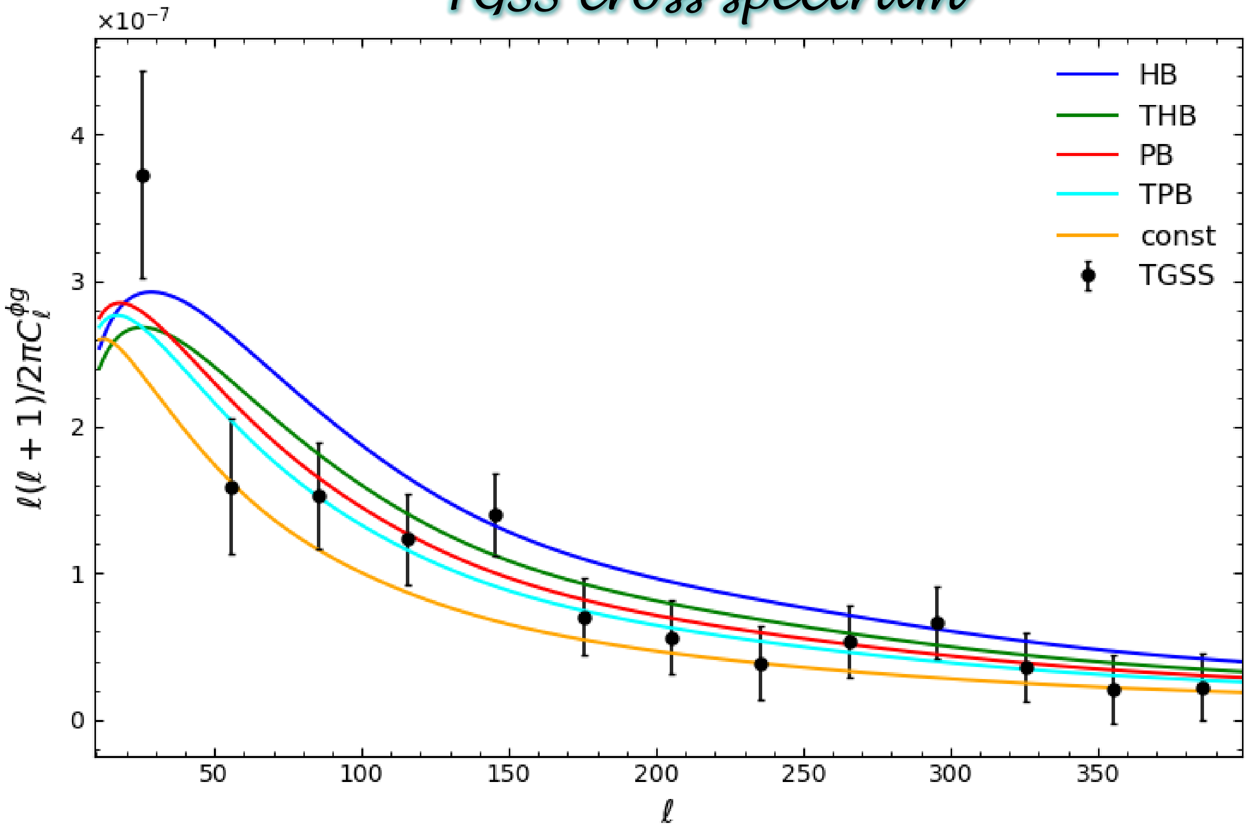
Results: TGSS power excess

- In the cross-power spectrum the excess is significatively reduced

TGSS auto spectrum



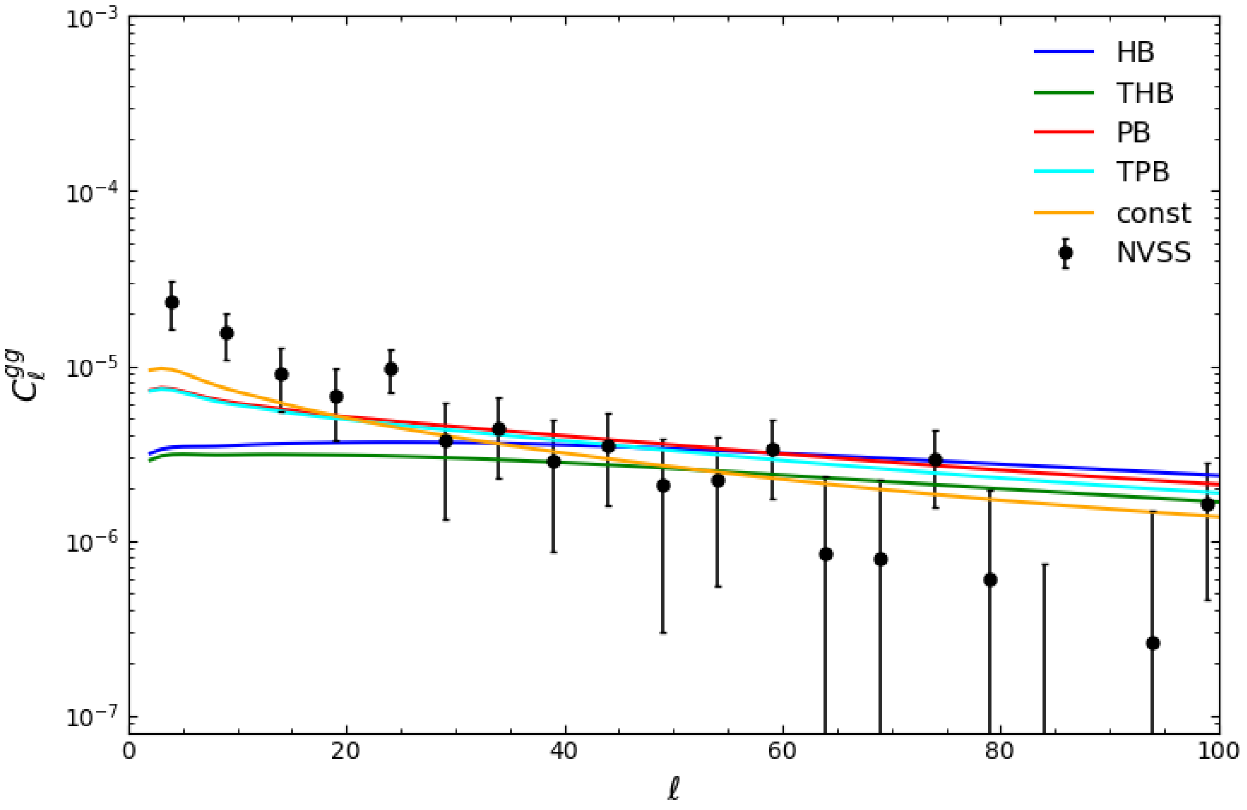
TGSS cross spectrum



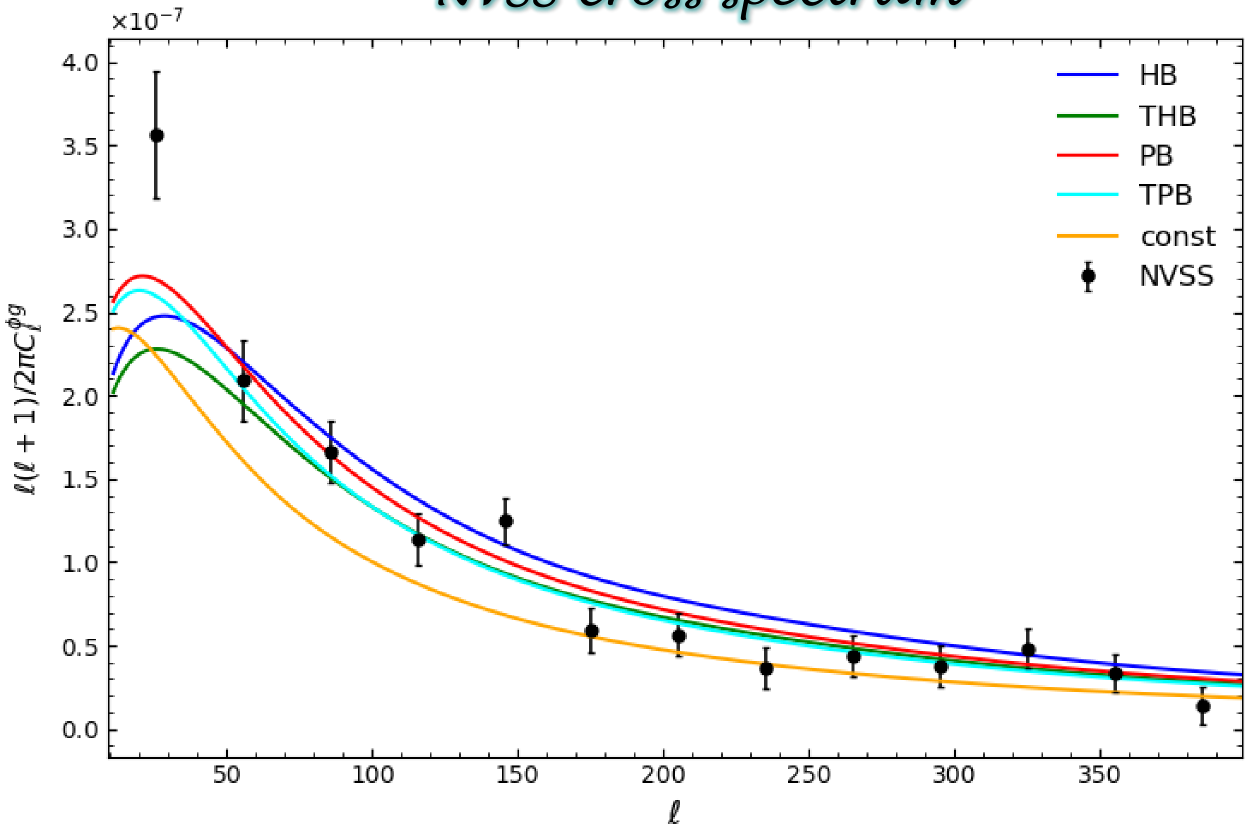
Results: NVSS catalogues

- From now on, the analysis is focused on NVSS
- NVSS is a larger statistical sample with respect to TGSS

NVSS auto spectrum



NVSS cross spectrum



Results: NVSS

- Theoretical models are obtained considering:

    i. Different models of galaxy bias b(z) present in literature(*e.g. Nusser and Tiwari, 2015 and Sheth et al., 2001*) which describe the evolution of the bias factor for radio sources

    ii. Redshift distribution N(z) from previous studies (*Wilman et al, 2008 and Bonaldi et al, 2018*) obtained from simulations and observational constraints

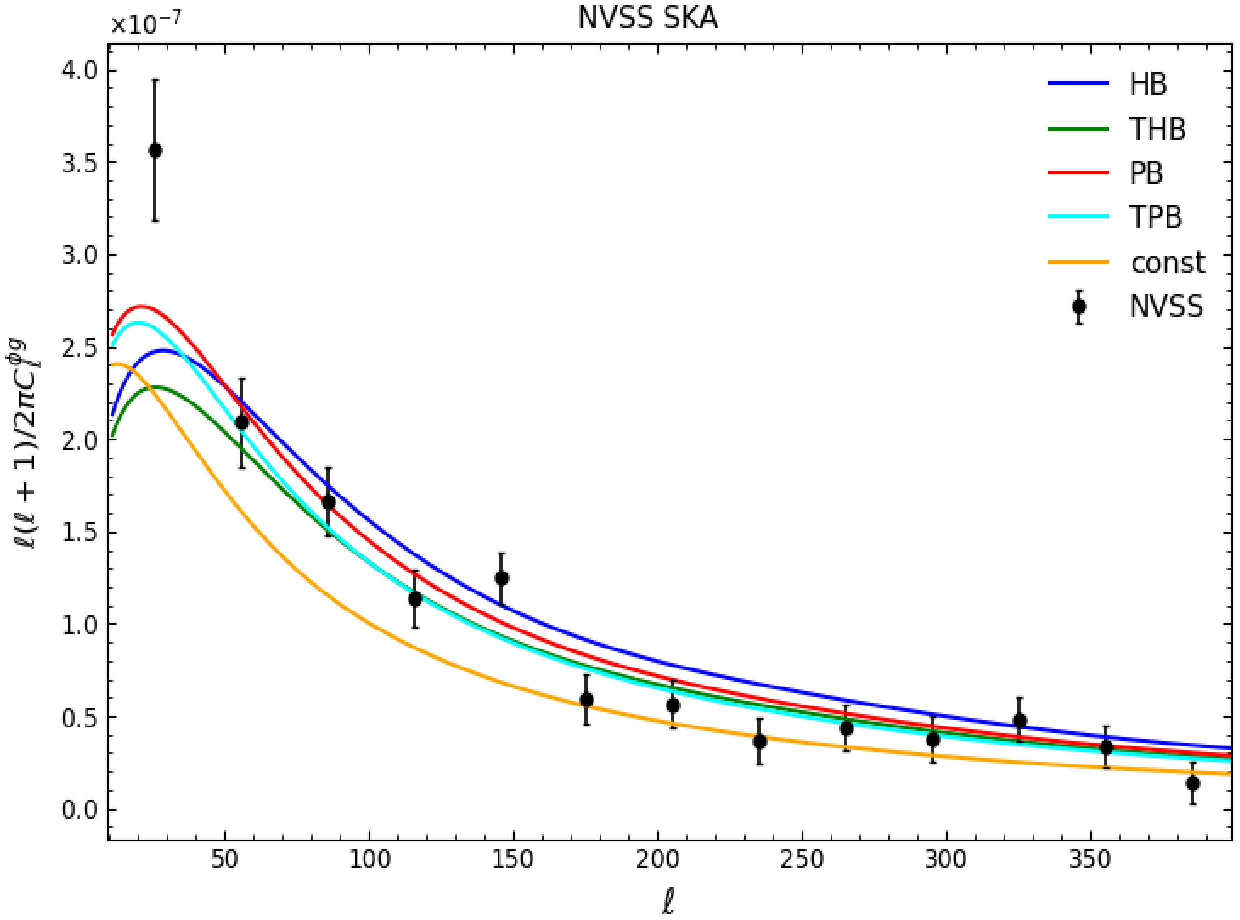
- To quantify the agreement between data and theoretical predictions, we estimated the χ^2 and p-value

$$\boxed{\chi^2 = \sum_{\ell_1,\ell_2} \left(C_{\ell_1}^{th} - C_{\ell_1}^{obs}\right) \mathbf{C}_{\ell_1,\ell_2}^{-1} \left(C_{\ell_2}^{th} - C_{\ell_2}^{obs}\right)}$$

from theory

Results: NVSS constrain on b(z)

- Considering cross-correlation between NVSS and Planck CMB lensing potential



Best fit

Model	χ^2/dof	pte
HB	34.28/13	1.1e-03
THB	27.27/13	1.1e-02
PB	20.58/13	8.2e-02
TPB	19.57/13	1.1e-01
const	50.60/13	2.4e-06

TPB :
- b(z) from *Nusser &Tiwari, 2015*
- N(z) from simulation of *Wilman et al. 2008*

Conclusions

- Wide, almost full-sky coverage radio surveys are useful for cosmological research. However, the lack of information about the distance of radio sources allows only for 2D studies

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

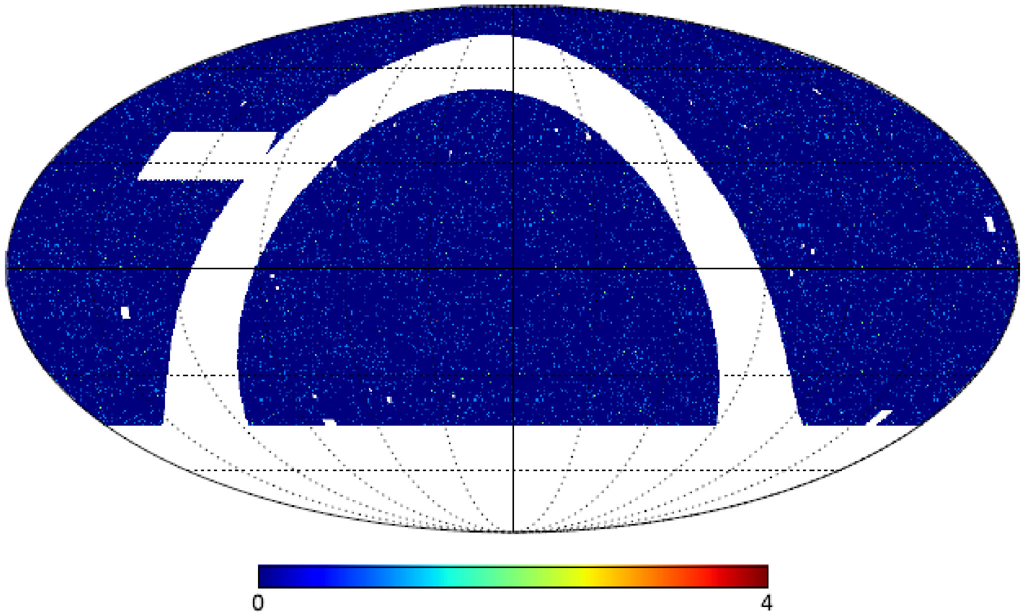
- As result, cross-correlation is
  i. successfully removing the power excess for TGSS
  ii. able to discern between physical plausible theoretical models of bias

- Next step: joint analysis considering both auto and cross angular power spectra to constrain independently the bias model and the redshift distribution by fitting analytical functions with free parameters.

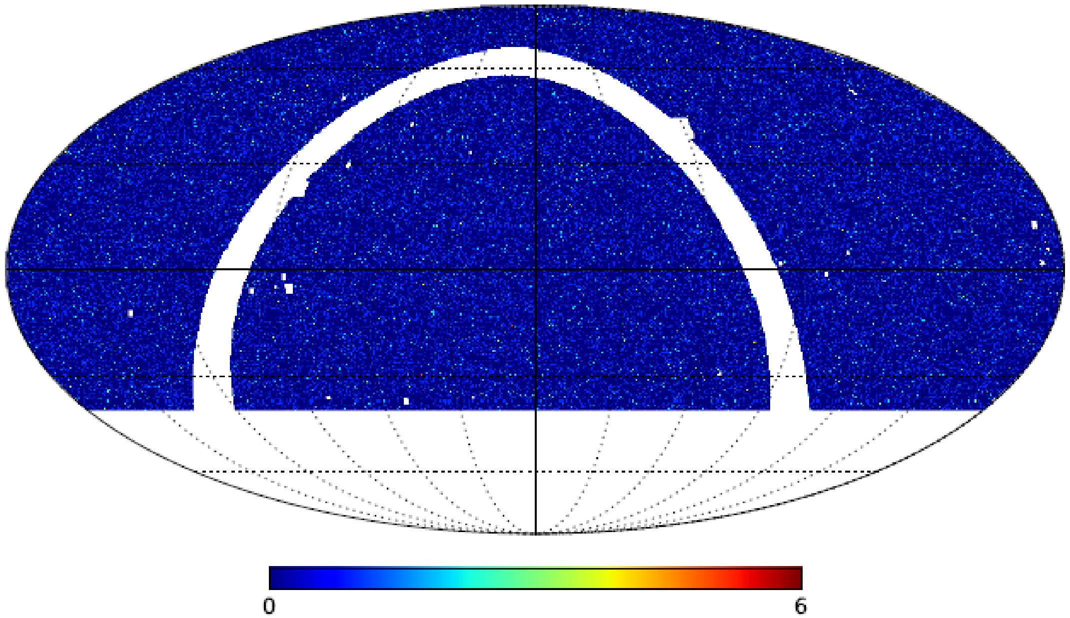

Thank you for your
attention

Catalogues: TGSS and NVSS

TGSS



NVSS

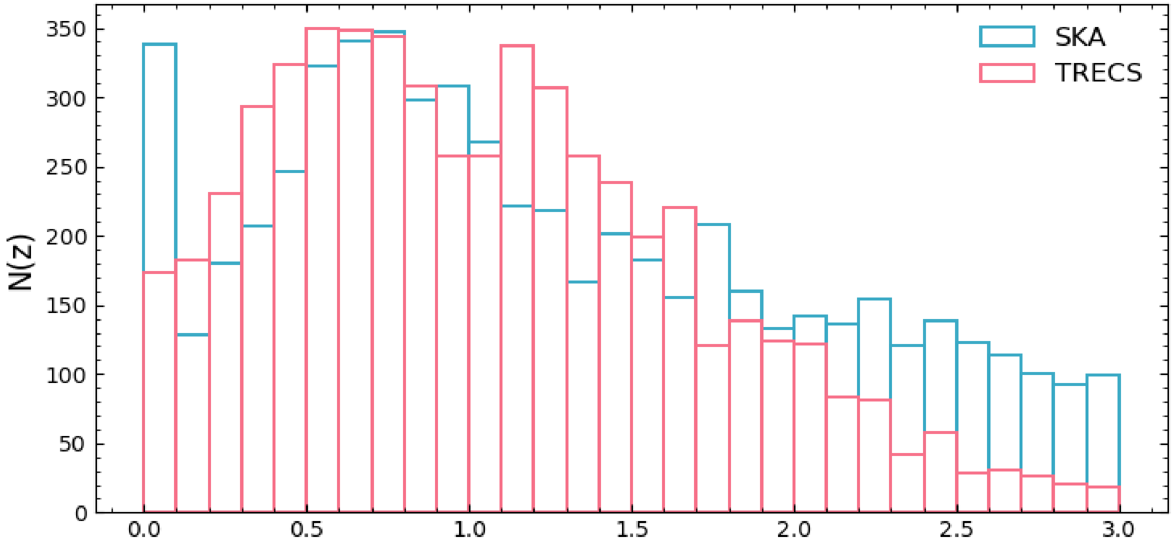


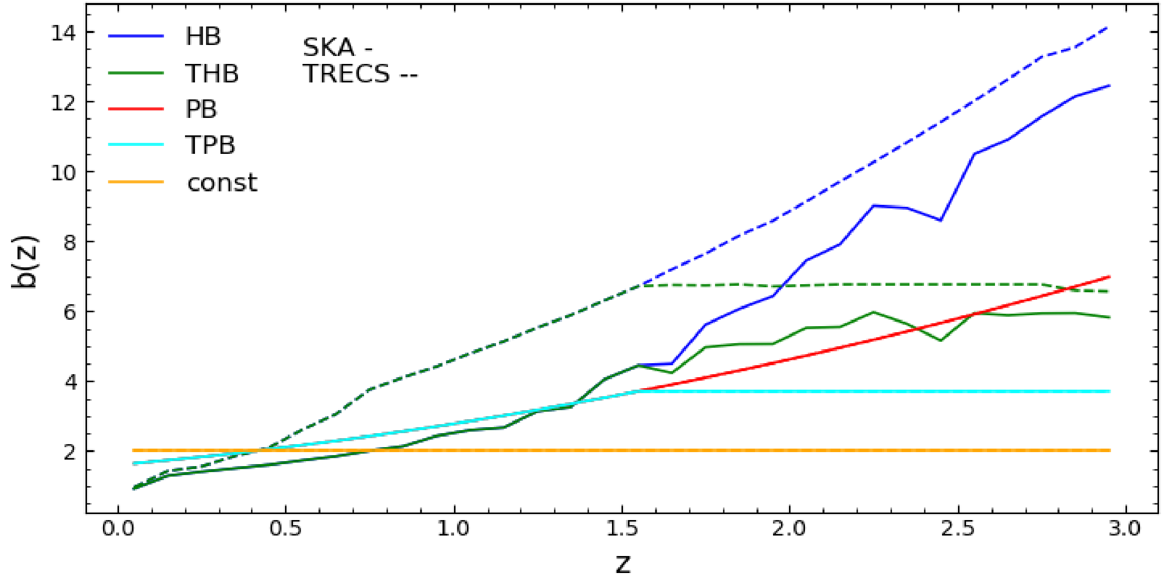
- Radio survey at $150\ MHz$
- 109940 radio sources
- Giant Metrewave Radio Telescope
- Flux = [200, 1000] mJy
- $f_{sky} = 0.70$

- Radio survey at $1.4\ \mathrm{GHz}$
- 518894 radio sources
- Very Large Array observatory
- Flux = [10,1000] mJy
- $f_{sky} = 0.75$

Radio sources

NVSS





Redshift distribution are obtained using:

- SKA Simulated Skies
- TRECS

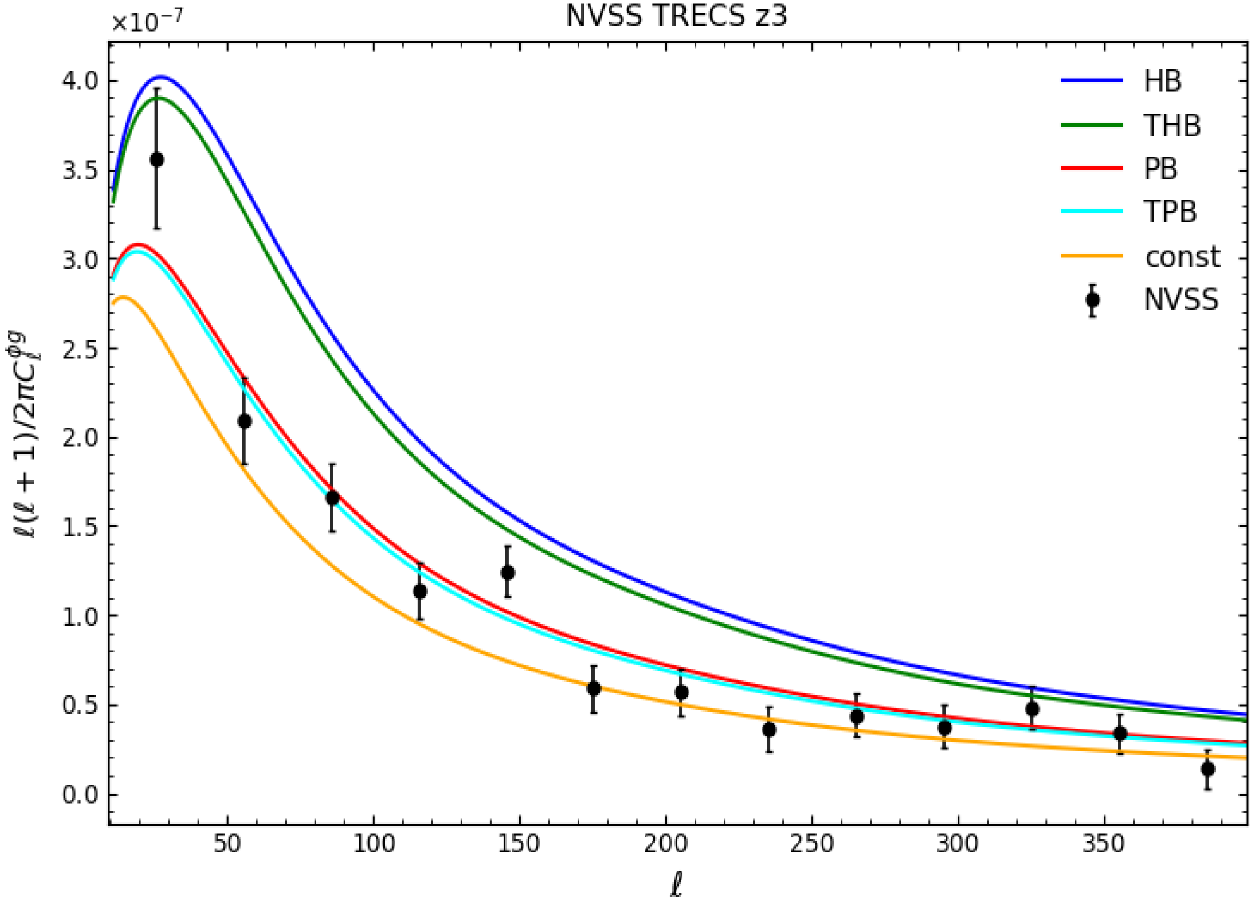
- Radio sources are biased tracers of the underlying matter distribution:

$$P_g(k,z) = b^2(z)P(k,z)$$

- Bias models rely on the Halo Model (*Cooray et al, 2002*) according to radio objects are hosted in dark matter halos with different masses

Results: NVSS constraint on b(z)

- Cross-correlation between CMB lensing potential from Planck and NVSS considering TRECS redshift distribution



Best fit

Model	χ^2/dof	pte
HB	163.40/13	0.0e+00
THB	123.25/13	0.0e+00
PB	17.92/13	1.6e-01
TPB	15.93/13	2.5e-01
const	32.17/13	2.3e-03

TPB :
- b(z) from *Nusser &Tiwari, 2015*
- N(z) from *Bonaldi et al, 2018*