Anisotropies and Anomalies in Low Frequency radio Surveys

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University Roma Tre

BAM 2018 &
3rd Anisotropic Universe
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OUTLINE OF THE TALK

- LF Radio Surveys: An overview.
- LF Radio Surveys: Anisotropies.
- The NVSS Dipole Anomaly.
- Large Scale Anisotropies: Recent results and open issues.

LOW FREQUENCY RADIO SURVEYS. ADVANTAGES

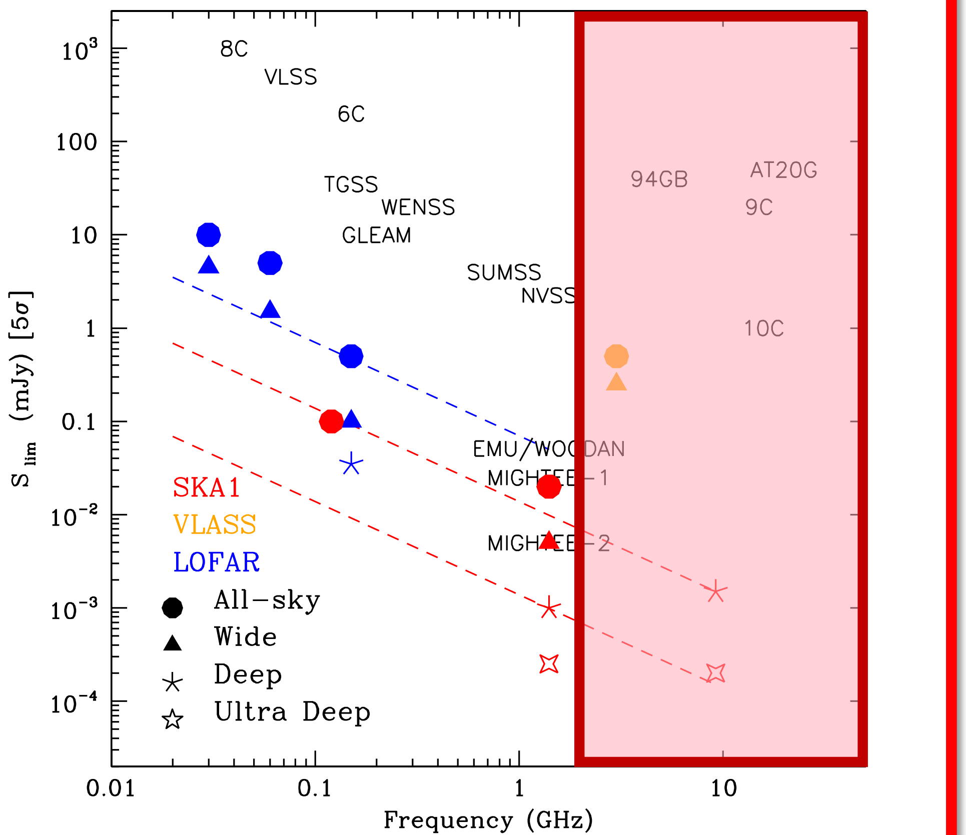
- Probe large volumes of the Universe.
- Unaffected by dust extinction.
- Unbiased sampling of cosmological volumes.
- Complementary to optical and IR surveys.

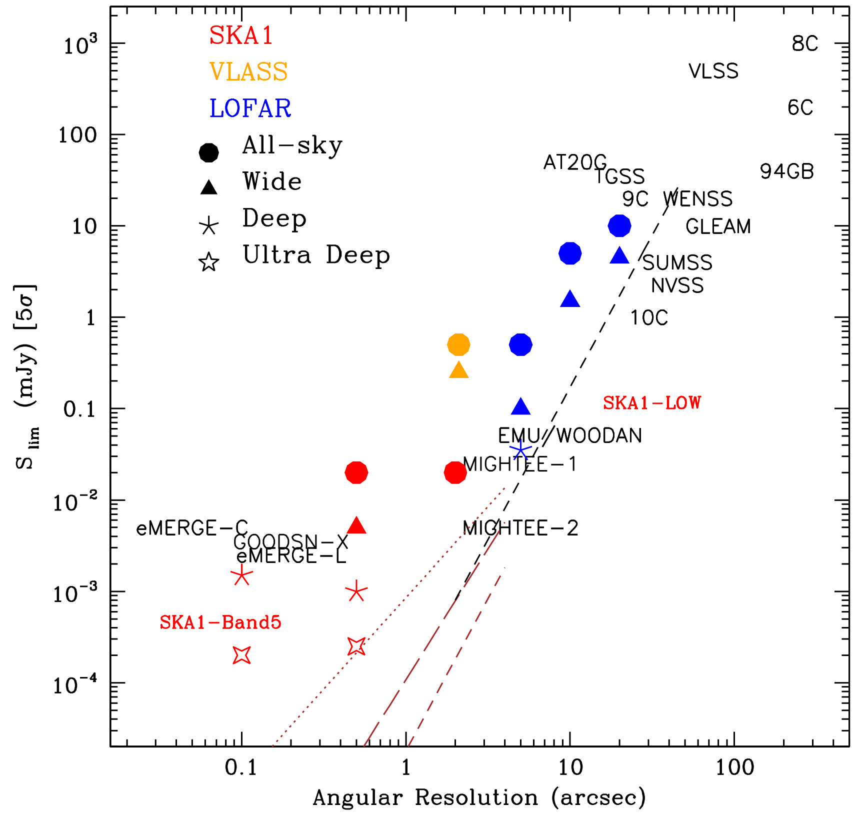
Low Frequency Radio Surveys: disadvantages.

- Faint optical/IR counterparts (w.r.t. high frequency radio surveys).
- 3D structures probed locally.
- 2D analysis only (assumptions about source types, redshift distribution and bias required).
- Complex structures (multi-components).
- Prone to systematics.

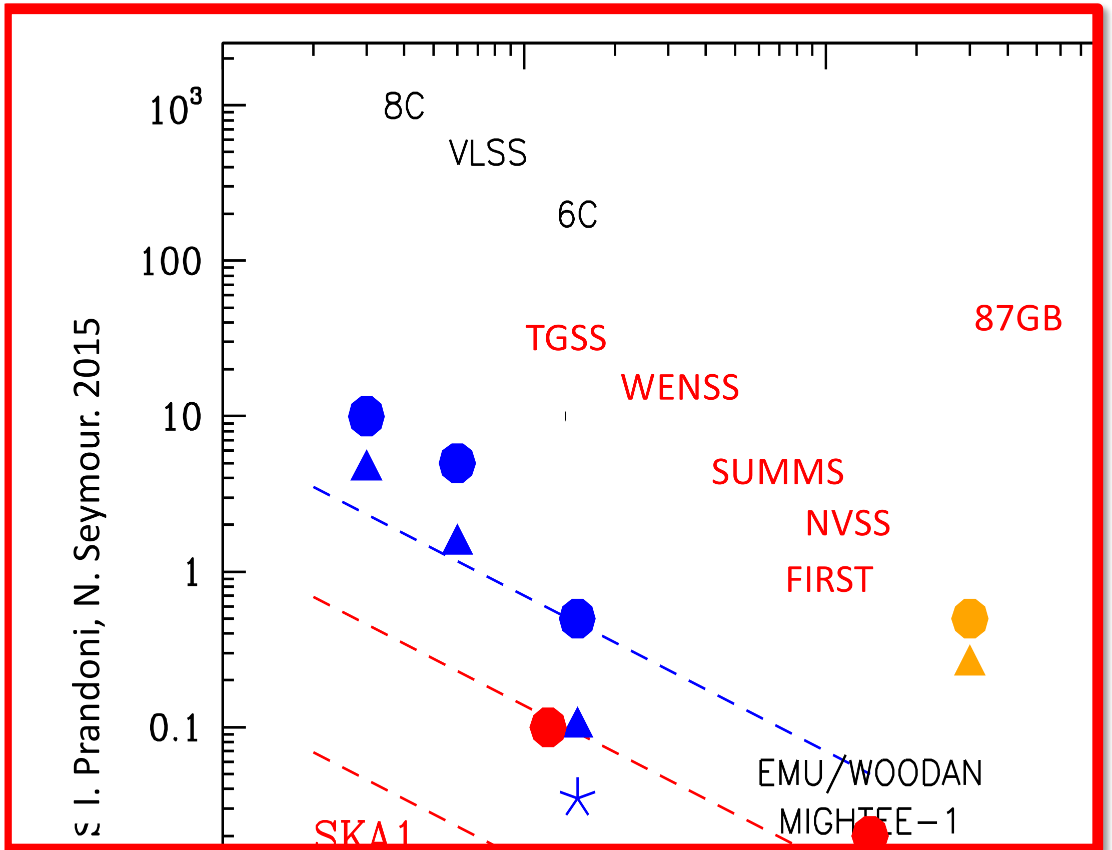
Anisotropies and Anomalies in Low-Frequency Radio Surveys

I. Prandoni, N. Seymour. 2015



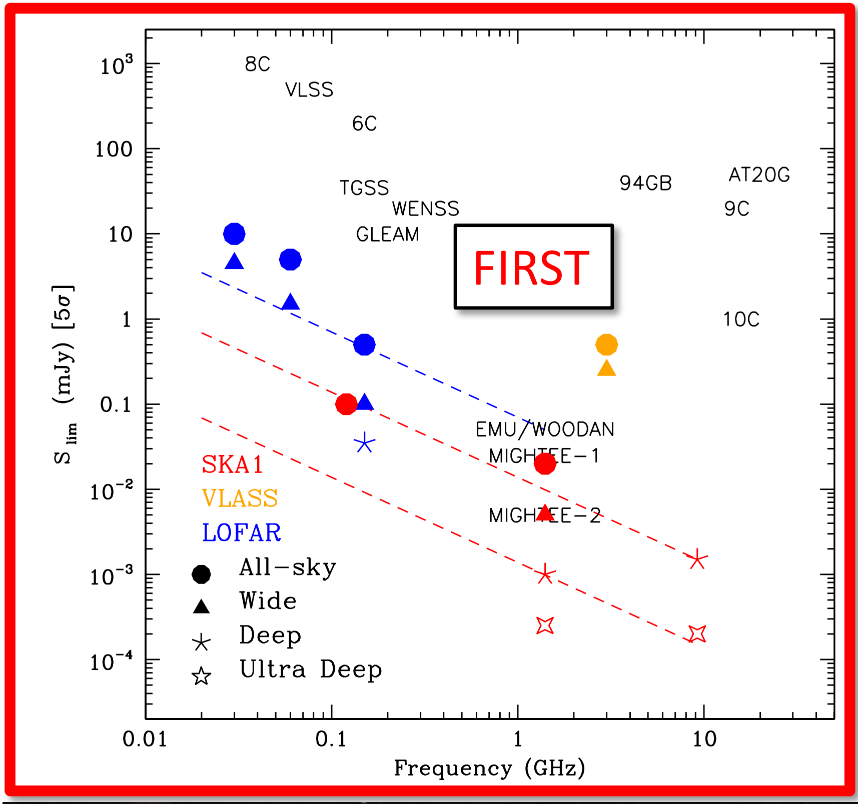


Anisotropies and Anomalies in Low-Frequency Radio Surveys

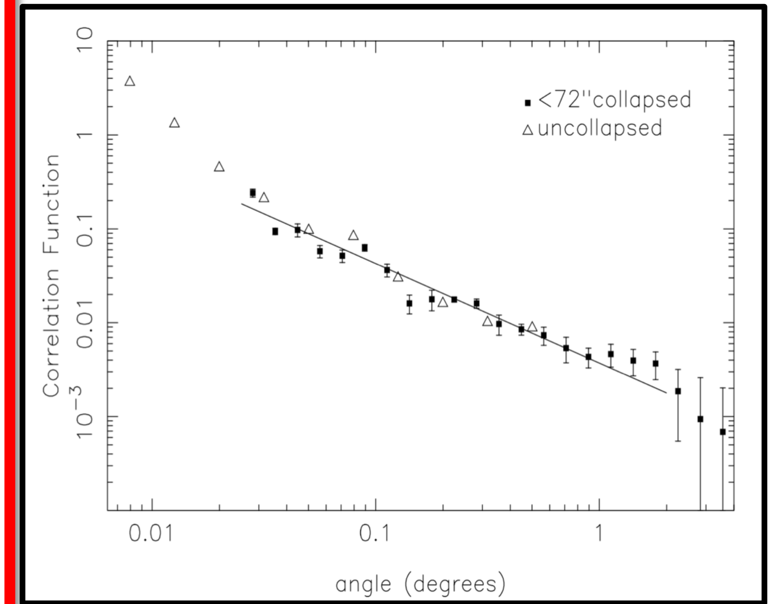


- Only some LF wide survey used to investigate anisotropies.
- Probe Large Volumes.
- Shot Noise Main source of random errors.
- Small or known large scale gradients from flux calibration uncertainties, observational strategies / techniques.

Anisotropies and Anomalies in Low-Frequency Radio Surveys



Angular correlation detected in the FIRST survey (Cress+ 1996)

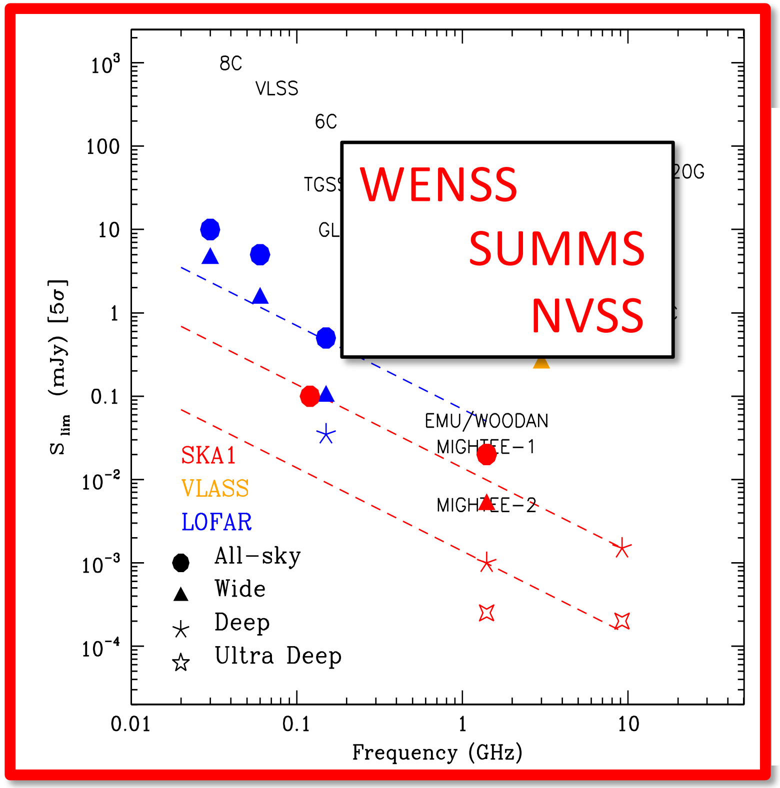


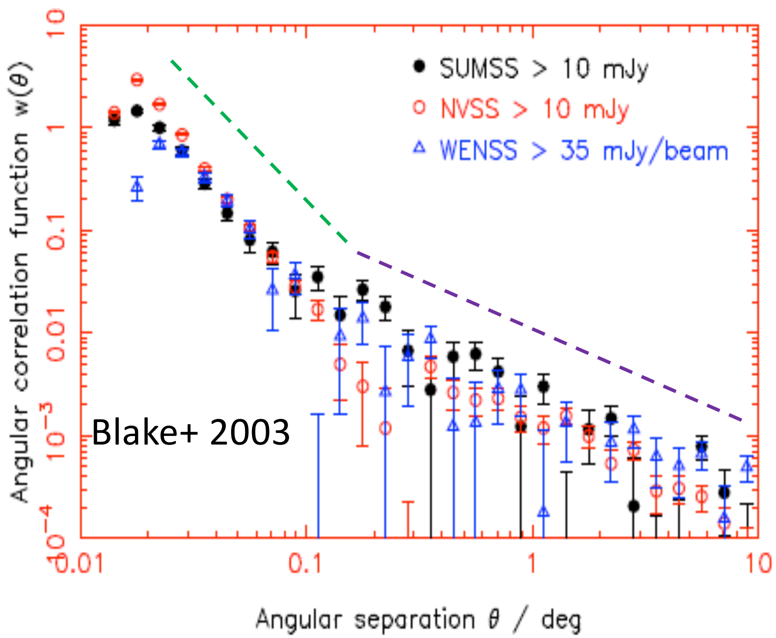
- 15% of the catalog
- ~140,000 sources
- ~ 1500 deg^2
- 1.4 GHz
- S> 1 mJy
- Res. 1”

Multiple components have a characteristic signature in w(θ)

Anisotropies and Anomalies in Low-Frequency Radio Surveys

Angular correlation detected in several radio surveys



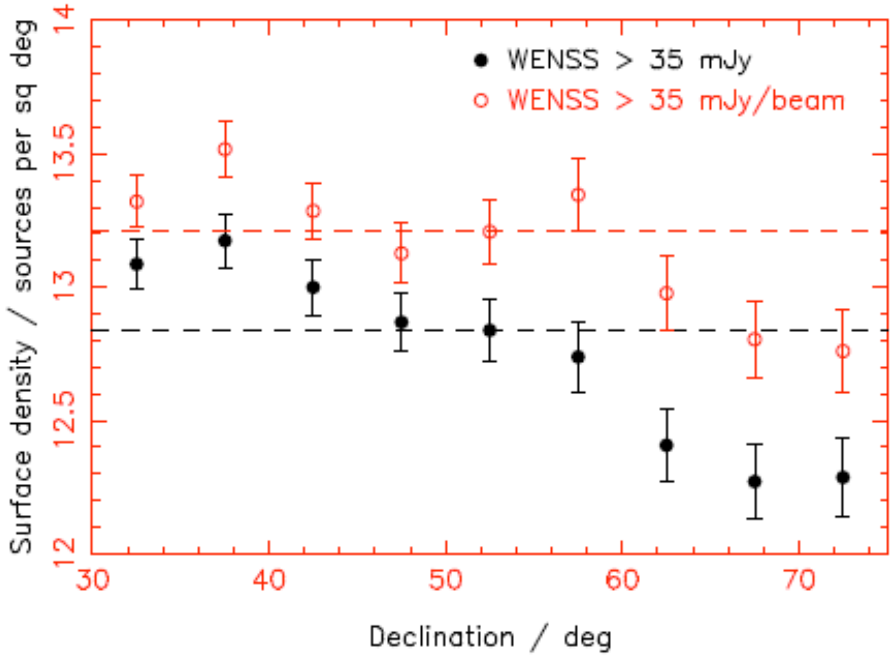


- NRAO VLA Sky Survey
- Sydney University Molonglo Sky Survey
- Westerbork Northern Sky Survey
- 87Green Bank + Parkes MIT-NRAO surveys

Characteristic double power-law $w(\theta)$ clearly detected.

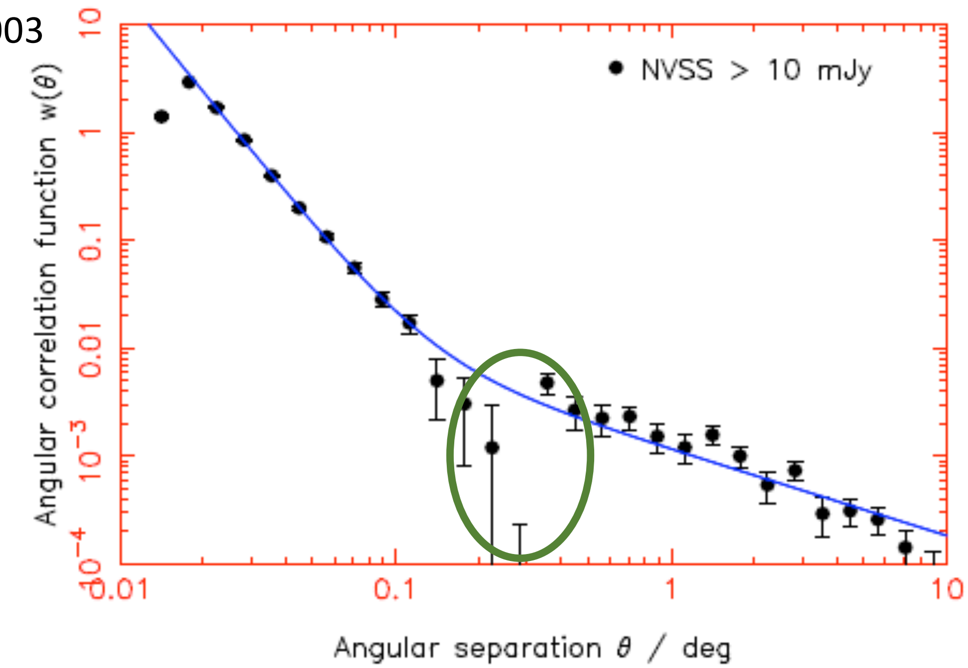
Observational systematic errors in radio surveys can be nontrivial.

- Declination-dependent completeness.



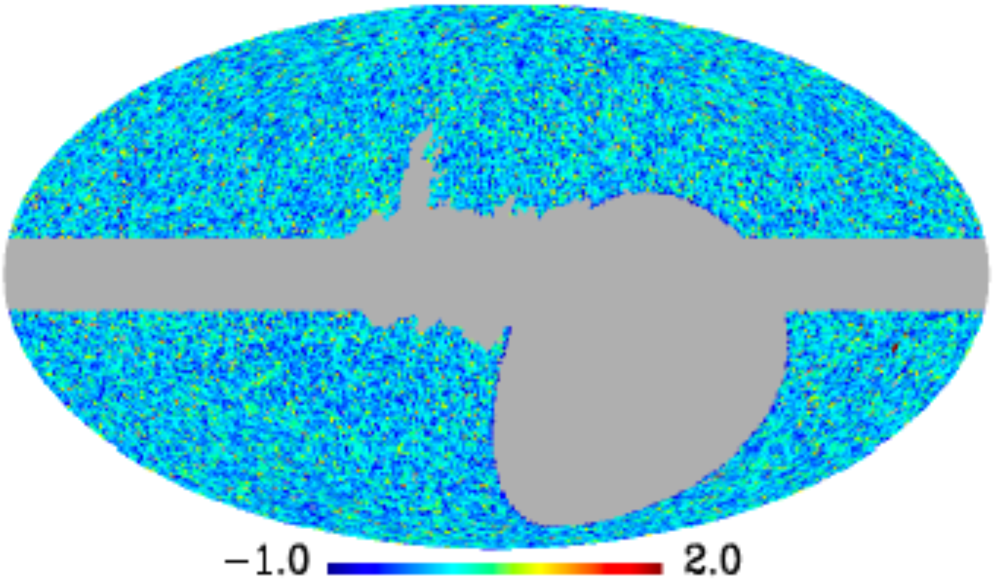
Blake+ 2003

- Overcleaning pairs at $\Delta\theta \sim 0.2^{o}$ (NVSS).



Anisotropies and Anomalies in Low-Frequency Radio Surveys

NVSS (Condon+ 1998)



Bengaly+ 2018

- 1.4 GHz
- 82% sky (δ>-40º)
- 99% complete @ S>3.5 mJy
- Resolution: 45”
- 1.8×10^6 sources
- Anisotropies: w(θ), Dipole, Angular Spectrum, Counts in Cells (and their PDF), x-correlation analyses.

THE NVSS DIPOLE ISSUE

Cosmological Dipoles have two components:

- **Kinematic**: Doppler effects and relativistic aberration of angles from Earth's motion produce an almost dipole-like anisotropy in a uniform field (e.g. CMB). Kinematic dipole dominates the LSS one at large distances.
- **Large scale structure**: [LSS] local anisotropies in the mass density field have an Intrinsic dipole component that dominant at small distances.

At large distance the dipole in the counts' distribution should converge to the CMB one. **If not then**:

1. The CMB frame and the LSS frames do not coincide.
2. There are very large scale (global) anisotropies.

$$\Delta(\hat{\mathbf{r}}) = \sum_{l=1}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\hat{\mathbf{r}}) \qquad l=1$$

$$\vec{D} = [2 + x(1+\alpha)](\vec{v}/c)$$

$$S \propto \nu^{-\alpha}, \quad n(>S) \propto S^{-x} \quad C_1 = \frac{4\pi}{9} D^2.$$

$$\begin{aligned} \tilde{C}_l &= <|\tilde{a}_{lm}|^2> \\ &= \frac{2}{\pi} \int dk k^2 P(k) W^2(k) , \end{aligned}$$

$$W(k) = \int_0^{\infty} D(z) b(z) p(r) dr j_l(kr)$$

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- **NVSS dipole first detected by Blake & Wall 2002.**
- **Since then many re-analyses with different techniques.**
- **Direction consistent with CMB**
- **But larger amplitude.**
- **Discrepancy (2.5-5)-σ**

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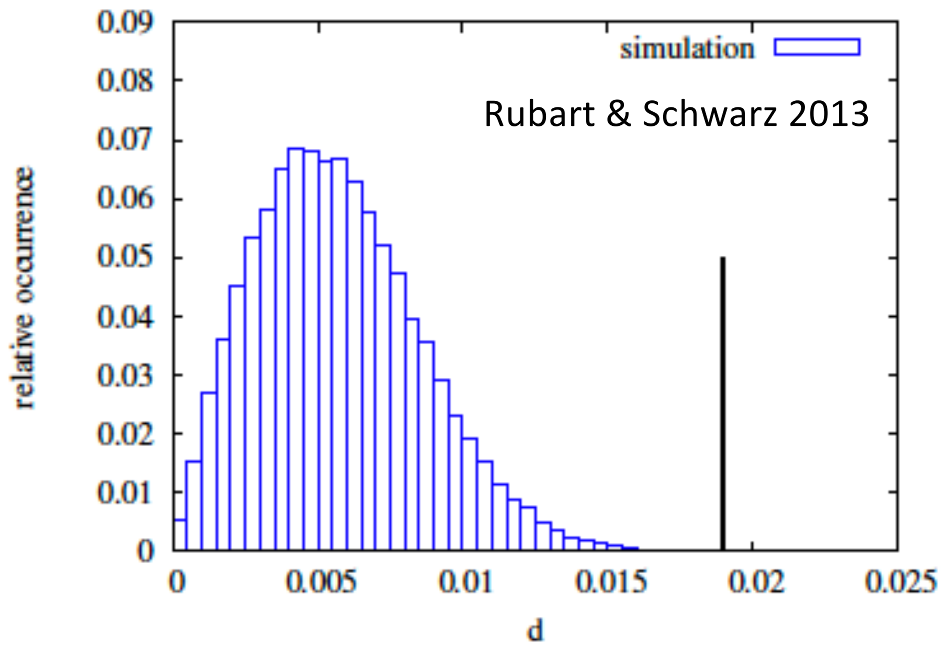

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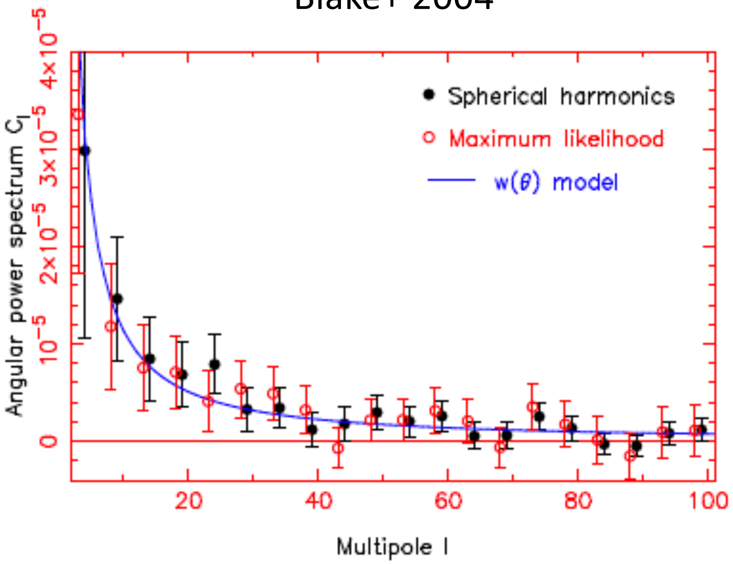
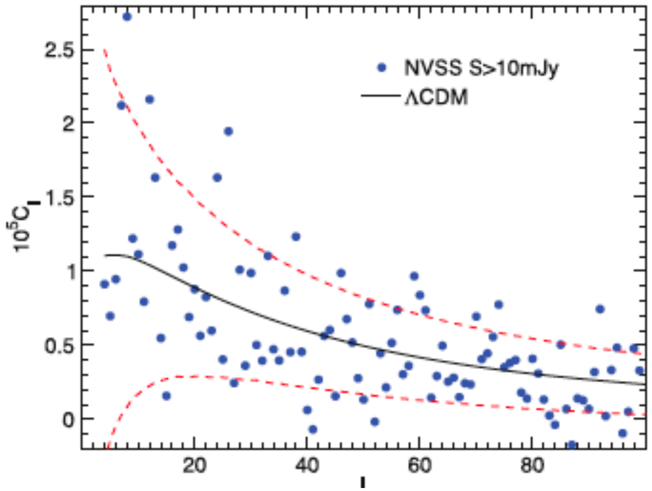
NVSS BEYOND DIPOLE: POWER SPECTRUM

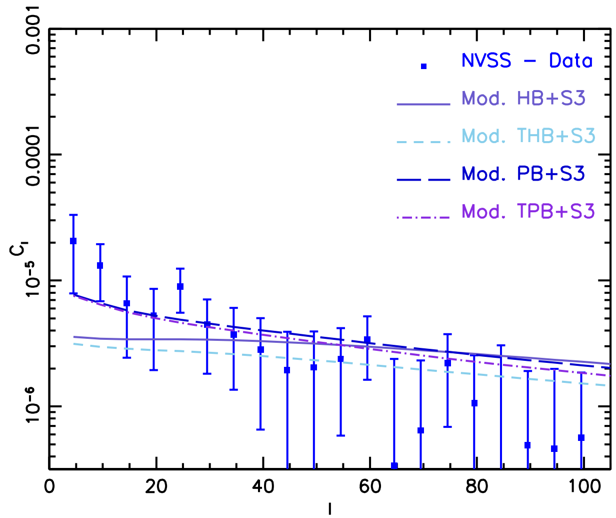
Blake+ 2004



Nusser & Tiwari 2015



Dolfi, EB, Bilicki + in prep.



Good fit for *l*>1

MODELING RADIO SOURCES' ANGULAR SPECTRA

Simple case: linear model model

$$\tilde{C}_l = \langle |\tilde{a}_{lm}|^2 \rangle = \frac{2}{\pi} \int dk k^2 P(k) \left| \int_0^\infty dr W j_l(kr) \right|^2 .$$

Mass Power Spectrum

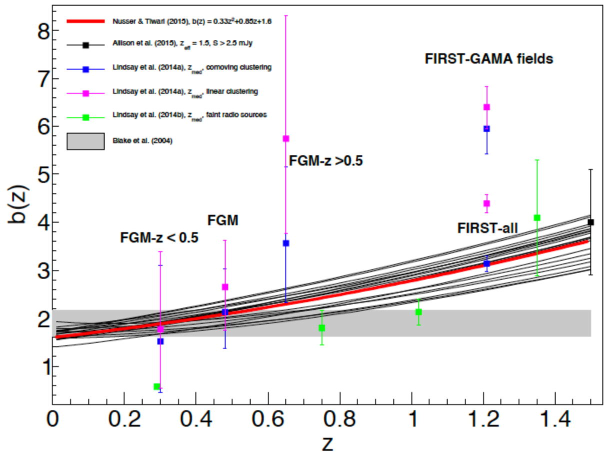
COSMOLOGY

Growth Factor

$$W = D(z)\, b(z)\, p(r)$$

Effective Linear Bias

Redshift Distribution



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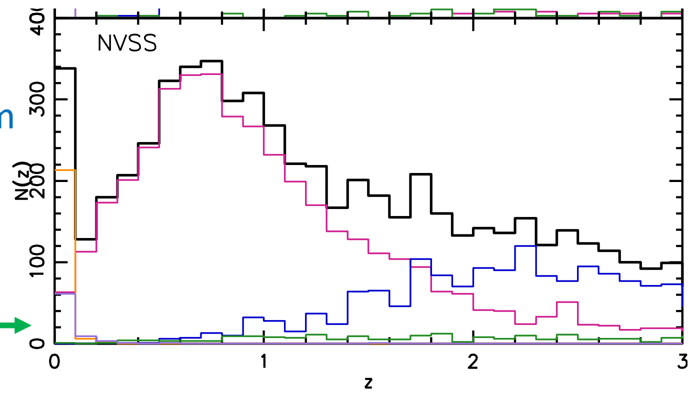


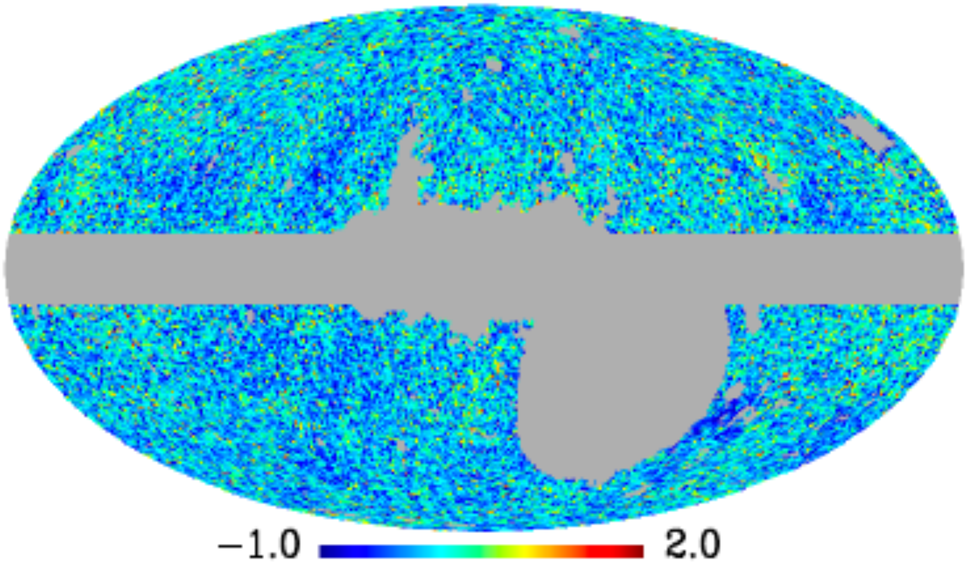
Dolfi, EB, Bilicki + in prep.

NVSS Anisotropy Studies: Some Results

- NVSS anomalous dipole origin unclear. Likely some residual systematic errors from observations.
- Different types of NVSS sources with different biases.
- Mass of the halo host (and thus the NVSS sources' bias) evolves with z.
- Fraction of radio activity vs. halo mass evolves with redshift.

Anisotropies and Anomalies in Low-Frequency Radio Surveys

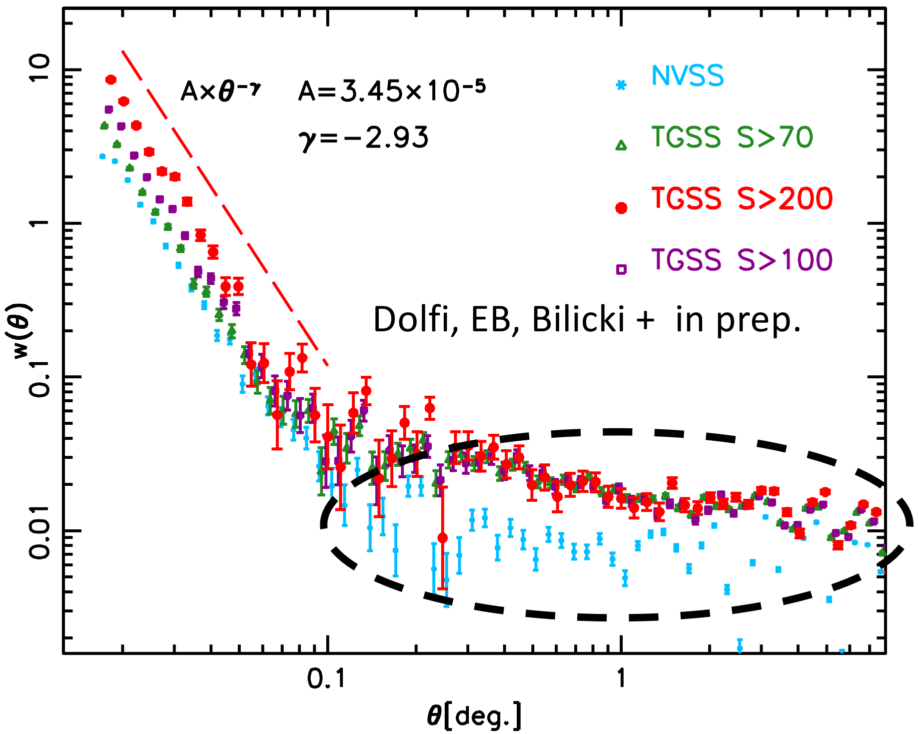
TGSS (Intema+ 2017)



Bengaly+ 2018

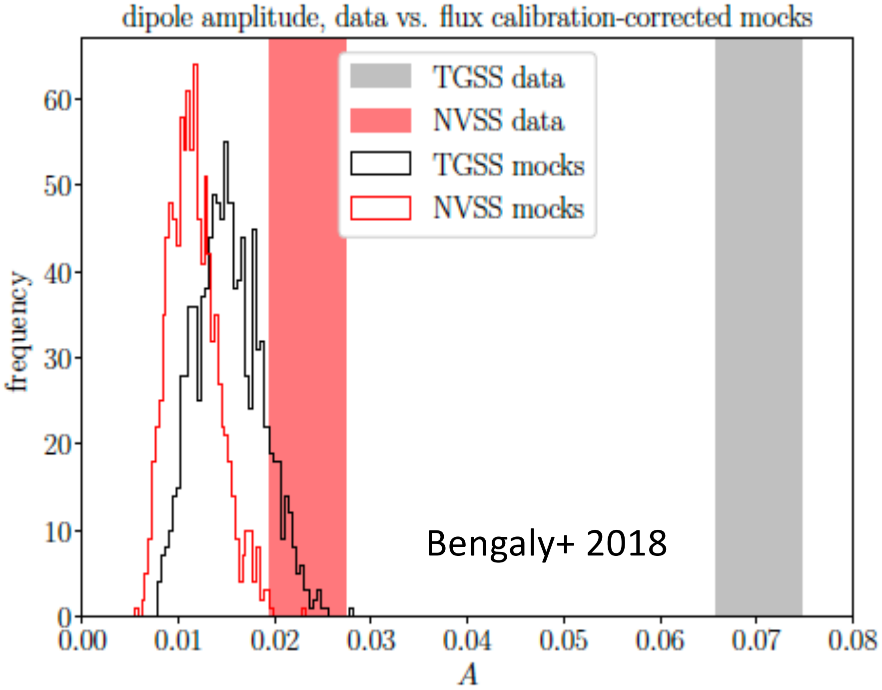
- 150 MHz
- 90% sky (δ>-53°)
- 50% complete @ S> 25mJy
- Resolution: 25”
- 6x10^5 sources
- Anisotropies: w(θ), Dipole, Angular Spectrum.
- Large overlap with NVSS footprint.

TGSS w(θ)



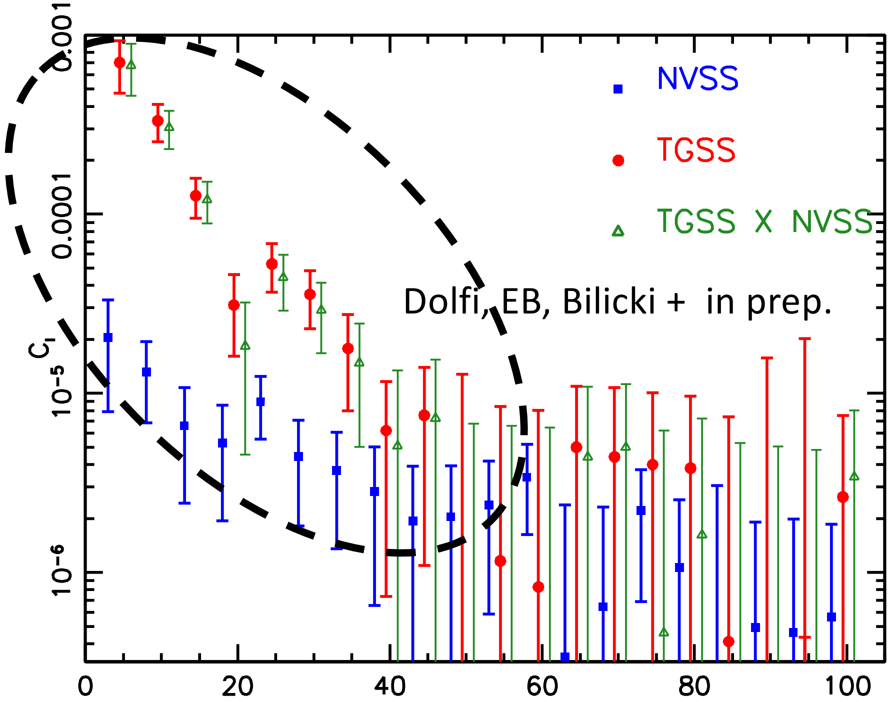
- Double power law with break @ $\Delta\theta=0.1^o$ (like NVSS).
- Flux-independent amplitude @ $\Delta\theta>0.1^o$ (like NVSS, but see Rana+ 2018).
- TGSS/NVSS amplitude mismatch for $\Delta\theta>0.1^o$.

TGSS Dipole



- TGSS dipole is ~2.5x larger than NVSS.
- TGSS dipole is 6x larger than predicted by ΛCDM.
- TGSS flux 5-10% flux calibration errors on the scale of the pointings (3°-30°;Hurley-Walker 2017) don't explain the mismatch.
- There are residual systematic errors in the TGSS data.

NVSS vs. TGSS SPECTRUM



- TGSS angular spectrum has more power on large scales than NVSS.
- TGSS objects that are also in NVSS show the same excess power.
- The power mismatch does neither depend on the flux cuts nor on the geometry/size of the TGSS subsample. It is a robust feature.

MODELING TGSS SPECTRUM: MATTER

To model the underlying mass power spectrum we have used the package *CLASSgal* (Di Dio+ 2013) considered all known effects and dropped commonly used approximations. That is we:

- **Assumed Planck 2016 cosmology.**
- **Included nonlinearities with *HALOFIT*.**

$$P(k,z) \neq P(k,z=0)\times D(z)$$

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- **Included redshift space distortions.**

$$P(\vec{k}) = P(k_{\parallel}, k_{\perp})$$
$$= P(k) \times F(\Omega_m^{\gamma})$$

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- **Add Lensing Magnification (using Willott 2011 radio luminosity functions).**

$$C_{nn}^{(ij)}(\ell) = C_{\rm gg}^{(ij)}(\ell) + \underbrace{C_{\rm gm}^{(ij)}(\ell) + C_{\rm gm}^{(ji)}(\ell) + C_{\rm mm}^{(ij)}(\ell)}_{\text{Depend on the lensing kernel and on the luminosity function slope at the limiting luminosity}}$$

Modeling TGSS spectrum: matter

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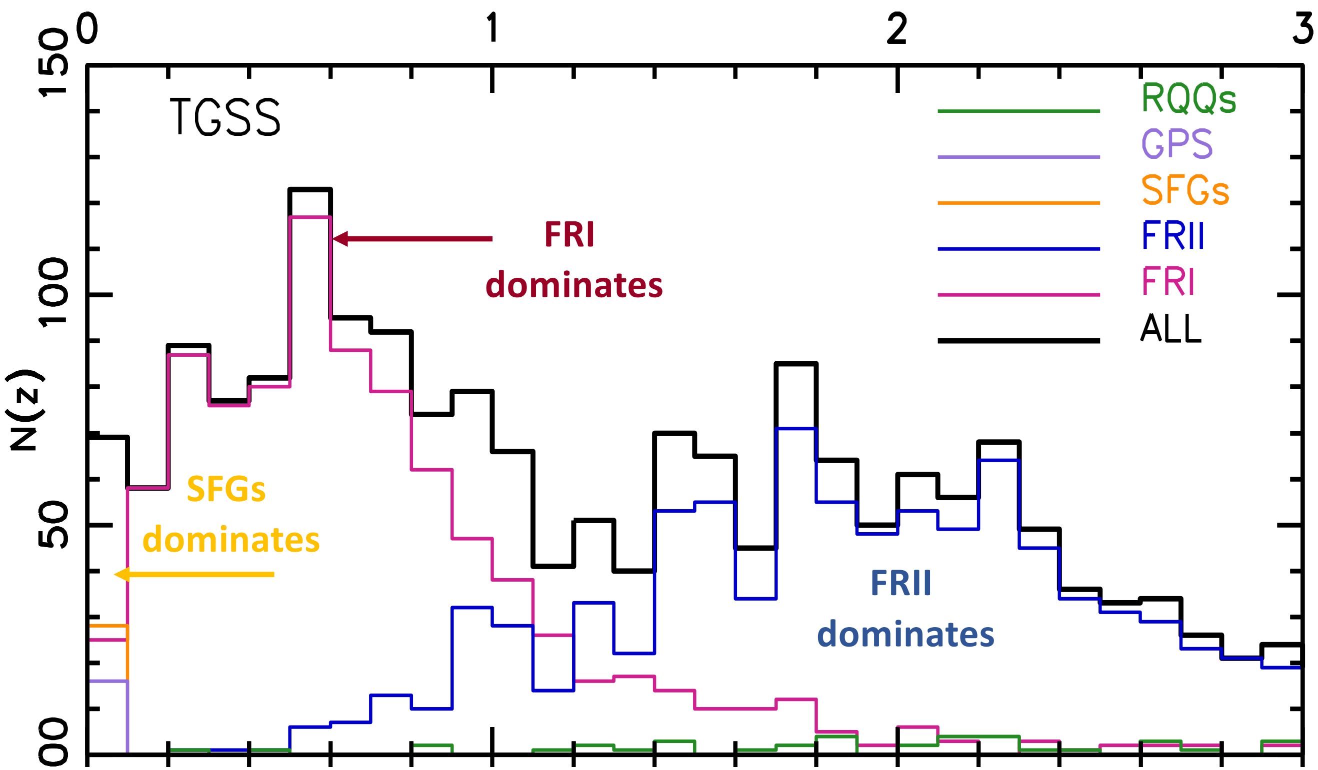
- **Assume Planck 2016 cosmology.**
- **Include nonlinearities with *HALOFIT*.**
- **Include redshift space distortions.**
- **Add Lensing Magnification (using Willott 2011 radio luminosity functions).**
- **Add relativistic corrections (Sachs-Wolfe and contributions from Ψ and Φ).**
- **Do not assume Limber approximation.**

MODEL TGSS SPECTRUM: RADIO SOURCES

To predict the angular power of the radio sources and its theoretical error we modeled N(z) of different radio source types and their effective linear bias using halo models.

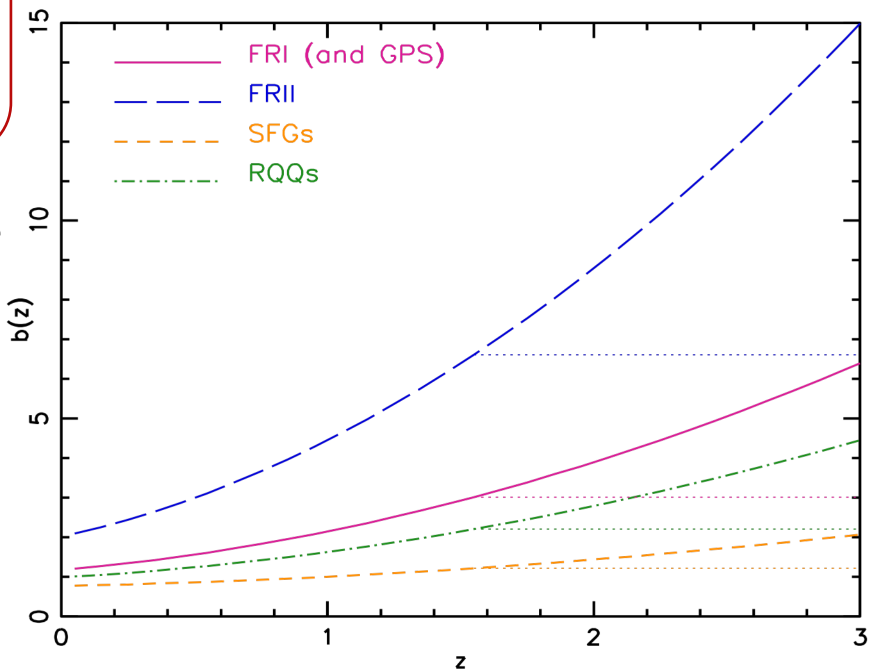
■ $N_i(z)$ from S^3 (Wilman+ 2008)



MODEL TGSS SPECTRUM: RADIO SOURCES

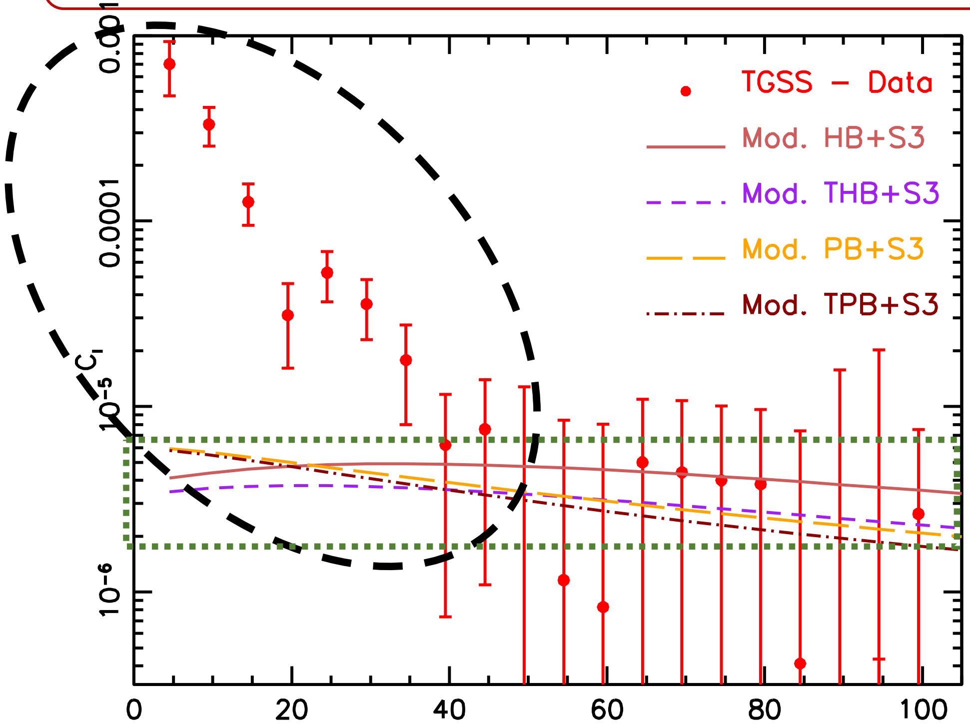
To predict the angular power of the radio sources and its theoretical error we modeled N(z) of different radio source types and their effective linear bias using halo models.

■ **$b_i(z)$ from halo model(s). Radio sources hosted in DM halos with typical mass.**



$$b_{eff}(z) = \frac{\sum N_i(z) b_i(z)}{\sum N_i(z)}$$

TGSS spectrum. Model vs. Data



- TGSS power at *l*<30 not matched by models.
- Discrepancy large w.r.t. data error (Gaussian, independent) and model uncertainties (scatter in model predictions).
- Excess power suggests residual systematics in the TGSS data.

LF RADIO SURVEYS: WHAT NEXT ?

- Dipole and excess large scale power open issues. Is it safe to use LF radio catalogs for anisotropy studies ?
- Next TGSS data release may clarify the origin of the problem.
- LOFAR projects and EMU/WOODAN (in progress) survey similar areas at similar frequencies and higher sensitivity.
- And then SKA.....