# THE CLUSTERING OF RADIO GALAXIES: BIASING AND EVOLUTION

**Prabhakar Tiwari**
**in collaboration with Adi Nusser**

Physics Department
Asher Space Science Institute-Technion
Haifa 32000, Israel

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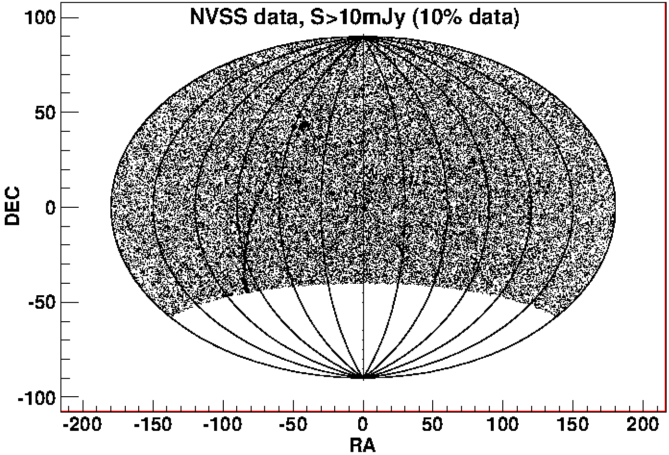
# Introduction

We study the clustering of radio galaxies and extract biasing, large scale correlations and some other important results.

- NVSS data
  $\sim 6 \times 10^5$ sources with $S_{1.4\mathrm{GHz}} > 10$ mJy
- **Assumptions:**
  **redshift distribution from Hercules and CENSORS survey**
  **ratio of stellar to dark halo mass**
- model the angular clustering of NVSS galaxies,
  ....
- biasing factor, dipole, angular correlations ...

# NRAO VLA Sky Survey (NVSS)

$\sim$1.7 billion sources at 1.4 GHz, $S > 2.5\mathrm{mJy}$, FWHM resolution is 45 arcsec.



# NVSS data

- angular position at 1.4Ghz, FWHM resolution 45 arcsec, partial sky, 80% of the sky
- $|b| < 5^\circ$ to avoid Galactic contamination
- 22 bright extended local radio galaxies (Blake & Wall 2002)
- lower intensity cut to avoid systematic gradients in surface density (Blake & Wall 2002), $10 < S < 1000 mJy$
- 574466 sources.

# NVSS data: Dipole?

**Cosmological Principle?**

**Velocity dipole: we are moving with** $369 \pm 0.9$ **Km/sec in RA=**$167.9^o$**, Dec=**$-6.93^o$ **(Hinshaw et al. 2009)**

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# Velocity Dipole in NVSS
## Doppler Effect and aberration effect

An observer moving with a velocity $\vec{v}$ ($v << c$), sees the sky brighter in forward direction due to Doppler boosting and aberration effect.
$S \propto \nu^{-\alpha}$, with $\alpha \approx 0.75$, Ellis & Baldwin 1984 .

Doppler effect
$\nu_{obs} = \nu_{rest}\delta$, where $\delta \approx 1 + (v/c)\cos\theta \Rightarrow S_{obs} = S_{rest}\delta^{1+\alpha}$

Aberration effect changes the solid angle in the direction of motion

$$d\Omega_{obs} = d\Omega_{rest}\delta^{-2}$$

# Velocity Dipole in NVSS ...

Assume a power law form for the differential number count per unit solid angle per unit flux density $n_{rest}(\theta, \phi, S_{rest})$.

$$n_{rest}(\theta, \phi, S_{rest}) \equiv \frac{d^2 N_{rest}}{d\Omega_{rest} dS_{rest}} = kx\left(S_{rest}\right)^{-1-x} \quad (1)$$

Here $d^2 N_{rest}$ is the number of sources in a small bin, $d\Omega_{rest} dS_{rest}$ in solid angle and flux density.
$d^2 N_{obs} = d^2 N_{rest}$
$n_{rest} d\Omega_{rest} dS_{rest} = kx\left(S_{rest}\right)^{-1-x} d\Omega_{obs}\delta^2 dS_{rest}$

we obtain

$\vec{D}_N(v) = [2 + x(1+\alpha)](\vec{v}/c)$.
and similarly $\vec{D}_S(v) = [2 + x(1+\alpha)](\vec{v}/c)$

- Blake & Wall 2002, Singal 2011, Gibelyou & Huterer 2012, Rubart & Schwarz 2013, Tiwari et al 2014, Tiwari & Jain 2015 ...
- **Inconsistent with CMBR predicted velocity dipole: Singal 2011 , Tiwari et al 2014, Tiwari & Jain 2015**.

| data | *speed* (Km/s) | RA (deg) | DEC (deg) |
|---|---|---|---|
| CMBR (Hinshaw et al. 2009) | $369 \pm 0.9$ | 167.9 | $-6.93$ |
| NVSS Source count ($S > 30$mJy) | $1320 \pm 310$ | $149 \pm 22$ | $-21 \pm 22$ |
| NVSS Source count ($S > 30$mJy) | $1960 \pm 530$ | $135 \pm 16$ | $20 \pm 14$ |
| NVSS polarization ($S > 30$mJy) | $2880 \pm 670$ | $136 \pm 13$ | $-16 \pm 13$ |

all directions are in J2000.

# Simulating NVSS

- angular correlations
- redshift distribution
- bias,luminosity function ...

# Formulation

- Numeber density: $\Delta(\hat{\boldsymbol{r}}) = \frac{\mathcal{N}(\hat{\boldsymbol{r}})}{\bar{\mathcal{N}}} - 1$
  $\mathcal{N}(\hat{\boldsymbol{r}})$ is projected number density (per steradian) in the direction $\hat{\boldsymbol{r}}$,
  $\bar{\mathcal{N}}$ is the mean of $\mathcal{N}$ over the sky.
  ($\mathcal{N}(\hat{\boldsymbol{r}})$ is obtained by using HEALPix Gorski et al. 2005)

- decompose $\Delta(\hat{\boldsymbol{r}})$ in spherical harmonics $Y_{lm}$:
  $d_{lm} = \int_{\mathrm{survey}} d\Omega \Delta(\hat{\boldsymbol{r}}) Y_{lm}(\hat{\boldsymbol{r}})$

- $< |d_{lm}|^2 >_{\mathrm{ens}} = \left(C_l + \frac{1}{\bar{\mathcal{N}}}\right) J_{lm}$,
  where $J_{lm} = \int_{\mathrm{survey}} |Y_{lm}|^2 \mathrm{d}\Omega$ (Peebles 1980)

$$C_l^{\mathrm{obs}} = \frac{1}{2l+1} \sum_m \frac{|d_{lm}|^2}{J_{lm}} - \frac{1}{\bar{\mathcal{N}}}$$

# Cosmology Prediction

- The theoretical counterpart of $\Delta(\hat{\boldsymbol{r}})$: $\tilde{\Delta}(\hat{\boldsymbol{r}}) = \int_0^\infty \delta(\hat{\boldsymbol{r}}r, z(r))p(r)\mathrm{d}r$ where $\delta$ is the density contrast in $3D$, $\boldsymbol{r}$ is comoving and $p(r)\mathrm{d}r$ is the probability of observing a galaxy between $r$ and $(r + \mathrm{d}r)$.

- linear biasing $\delta(\boldsymbol{r}, z) = b(z)\delta^m(\boldsymbol{r}, z)$.
  $\delta^{\mathrm{m}}(\boldsymbol{r}, z) = \delta_0^m(\boldsymbol{r})D(z)$, where $D$ is linear growth factor of linear fluctuations normalized to unity at $z = 0$

- Therefore,

$$\tilde{a}_{lm} = \int d\Omega \tilde{\Delta} Y_{lm}(\hat{\boldsymbol{r}}) = \int d\Omega Y_{lm}(\hat{\boldsymbol{r}}) \int_0^\infty W(r)\delta_0(\hat{\boldsymbol{r}}r)dr$$

where $W = D(z)b(z)p(r)$ with $z = z(r)$.

# Cosmology Prediction ...

- Fourier spacae:

$$\delta_0(\boldsymbol{r}) = \frac{1}{(2\pi)^3}\int d^3k\delta_{\boldsymbol{k}}\mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}}$$

- substituting $\mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}} = 4\pi\sum_l \mathrm{i}^l j_l(kr)Y^*_{lm}(\hat{\boldsymbol{n}})Y_{lm}(\hat{\boldsymbol{k}})$

$$\tilde{a}_{lm} = \frac{\mathrm{i}^l}{2\pi^2}\int drW\int d^3k\delta_{\boldsymbol{k}}j_l(kr)Y^*_{lm}(\hat{\boldsymbol{k}})$$

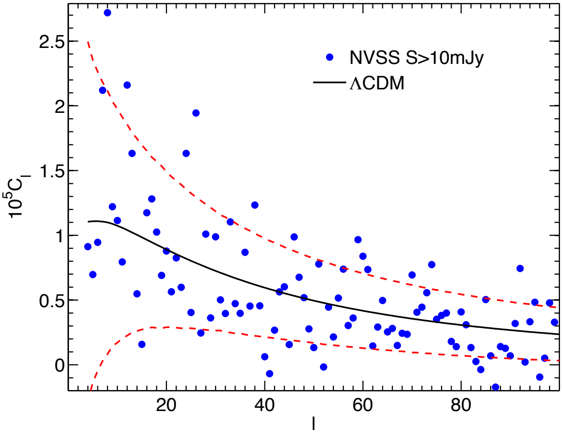
- Thefore (using $<\delta_{\boldsymbol{k}}\delta_{\boldsymbol{k}'}>=(2\pi)^3\delta^{\mathrm{D}}(\boldsymbol{k}-\boldsymbol{k}')P(k)$),

$$\tilde{C}_l =<|\tilde{a}_{lm}|^2>=\frac{2}{\pi}\int dkk^2P(k)\left|\int_0^\infty drWj_l(kr)\right|^2$$

- **radial distribution $p(r)$ and the biasing $b(z)$ ?**

# Angular power spectrum

Angular power spectrum ($C_l^{\rm obs}$) estimated from the NVSS data for $S > 10{\rm mJy}$. The solid curve is the theoretical $\tilde{C}_l$ in the ΛCDM, dashed red curves are $1\sigma$ limits due to shot-noise and cosmic variance scatter.



# The radial distribution
## modeling of $p(r)$

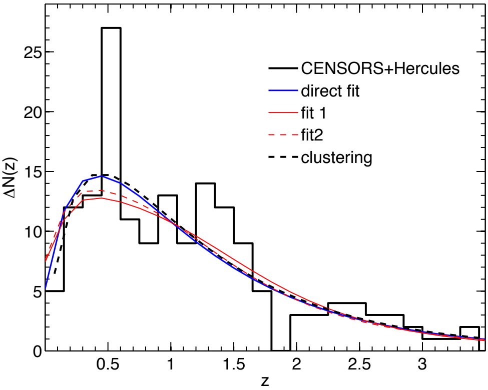
- Combined EIS-NVSS Survey(CENSORS) (Best 2003, Rigby 2011) and Hercules (Waddington 2001)
- CENSORS: redshifts and 1.4GHz fluxes, 135 radio sources over $6\mathrm{deg}^2$ complete down to 7.2 $\mathrm{mJy}$ 73% spectroscopic redshifts, remaining $I - z$ or $K - z$ magnitude-redshift relations.
- Hercules: 64 objects 1.2 $\mathrm{deg}^2$ with $S > 2\ \mathrm{mJy}$.

We use the redshift distribution above $S > 7.2\mathrm{mJy}$ where the two surveys are fairly complete. Adding two we have 165 and 131 sources, respectively for $S >\ 7.2\mathrm{mJy}$ and 10 $\mathrm{mJy}$.

# The radial distribution ...

$$N^{\mathrm{model}} \propto z^{a_1} \exp\left[-\left(\frac{z}{a_2}\right)^{a_3}\right]$$

$a_1$, $a_2$ and $a_3$ are determined by $N(z)$ and from the observed angular power spectrum, $C_l/(C_l^{\mathrm{obs}})$.




sources with $S > 7.2\ \mathrm{mJy}$ per redshift bin $\Delta z = 0.15$.

# Bias estimation

- We write the fraction of radio loud AGNs with radio luminosity brighter than $P$ as,

$$f_{\rm RL} = F(M_*, z)\tilde{\Phi}(P, z)$$

We take

$$F(M_*, z) = \left(\frac{M_*}{10^{11} M_\odot}\right)^{\alpha_0 + \alpha_1 z}$$

where $\alpha_0 = 2.5 \pm 0.2$ (Best et al. 2005).

$$b(z) = \frac{\int_{M_{\rm d}}^{M_{\rm u}} {\rm d}M n(M, z) b_{\rm h}(M, z) F(M_*, z)}{\int_{M_{\rm d}}^{M_{\rm u}} {\rm d}M n(M, z) F(M_*, z)}$$

$M_d$ and $M_u$ are minimum and maximum halo mass to host a radio galaxy
$M_d = 4 \times 10^{11} M_\odot$ which corresponds to $M_* = 10^{10} M_\odot$ (Moster 2013)
$M_u = 10^{15} M_\odot$, the mass scale of rich galaxy clusters.
$n(M, z)$ is number density and $b(M, z)$ is biasing of halos of mass $M$.
(Sheth 2001)

# Fitting the Model

constraints on the 5 parameters $\alpha_0$, $\alpha_1$, $a_1$, $a_2$ and $a_3$ by maximizing the probability, $P_{\rm tot}$, for observing ${C_l}^{\rm d}$ (from NVSS) and $N(z)$ (from the joint CENSORS and Hercules catalogs).

we denote these parameters by $\theta_i$ $(i = 1 \cdots 5)$ and by $\theta_i^{\rm ML}$ the corresponding ML values.

$$P(\tilde{d}_{lm}) \propto \frac{1}{(C_l + 1/\bar{\mathcal{N}})^{1/2}} \exp\left[-\frac{1}{2}\frac{\tilde{d}_{lm}^2}{C_l + 1/\bar{\mathcal{N}}}\right]$$

$$P_l \propto \frac{1}{(C_l + 1/\bar{\mathcal{N}})^{(2l+1)/2}} \exp\left(-\frac{2l+1}{2}\frac{{C_l}^{\rm d}}{C_l + 1/\bar{\mathcal{N}}}\right)$$

where ${C_l}^{\rm d} = (\sum_m d_{lm}^2)/(2l+1)$. Maximizing this probability with respect to $C_l$ yields $C_l = {C_l}^{\rm d} - \bar{\mathcal{N}}^{-1} = {C_l}^{\rm obs}$. $1\sigma$ error on this $C_l$ is $\sigma_{C_l}^2 = (-{\rm d}^2 {\rm ln} P/{\rm d}{C_l}^2)^{-1} = 2(C_l + \bar{\mathcal{N}}^{-1})^2/(2l+1)$.

# Fitting the Model...

Using the power spectrum of the ΛCDM we maximize for $C_l$

$$P_{\rm tot}(\{\theta_i\}; N, {C_l}^{\rm d}) = P_{\alpha_0} \prod_{z_i} P_{\rm N_i} \prod_{l=l_{min}}^{l_{max}} P_l$$

$P(k)$ parametrized form from (Eisenstein & Hu 1998)
$H_0 = 67.8 \rm{kms^{-1}Mpc^{-1}}$, $\Omega_m = 0.308$, $\Omega_b = 0.0486$, $\sigma_8 = 0.815$, $n_s = 0.9667$ from Planck results 2015.

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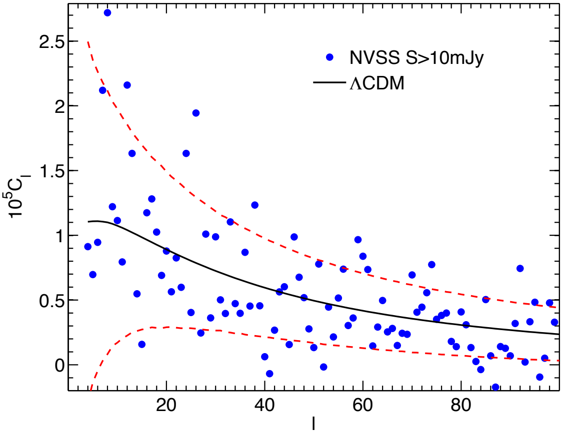
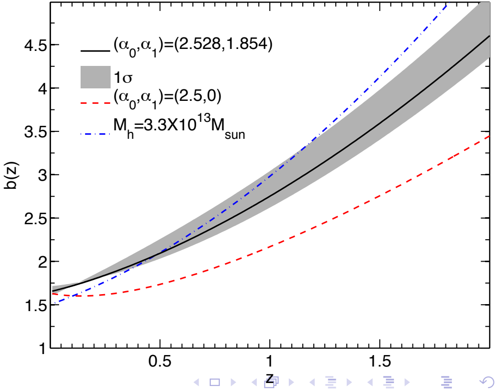


# Results

ML estimates of the model 5 parameters and the corresponding error estimates for $l_{max} = 100$.

| | $\alpha_0$ | $\alpha_1$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|---|
| | $2.529^{+0.184}_{-0.184}$ $\pm 0.197$ | $1.854^{+0.708}_{-0.761}$ $\pm 0.742$ | $0.739^{+1.077}_{-0.382}$ $\pm 0.572$ | $0.705^{+0.689}_{-0.649}$ $\pm 0.792$ | $1.057^{+0.550}_{-0.506}$ $\pm 0.531$ |

The biasing factor of radio galaxies as a function of redshift for $\alpha_1 = 2.216$ the shaded area represents $\pm 1\sigma$ deviation from the best fit $\alpha_1$. For reference, the red dashed and blue dash-dot lines show, respectively, the $b(z)$ for $\alpha_1 = 0$ and for halos of mass $3.3 \times 10^{13} M_\odot$.
$b(z) = 0.33z^2 + 0.85z + 1.6$.



# Results: NVSS Dipole

**Simulation for NVSS dipole:-**

- **Gaussian random density and velocity field assuming $P(k)$, the power spectrum in standard $\Lambda$CDM ( GRAFIC2, E. Bertschinger).**

- **$N(z)$ and $b(z)$ to get galaxy count in a bin (Poisson distribution!).**

- **Calculate angular correlation!**

# Results: NVSS Dipole (Realistic Modeling)

- $3D$ **modeling:** $N(z)$ **and** $b(z)$**.**
  lower the redshift higher the dipole

- **Velocity Constrain: The local 100 Mpc bulge is moving with 300 KM/sec.**
  indeed not zero but much less ($<$0.001) as compared to shot noise ($\sim$0.004)

- **Tuning dipole direction to match observation sky area.**

# Results: NVSS Dipole (Realistic Modeling)

- **Including all these we get the most convincing value (assuming $\Lambda$CDM) till data.**

- **NVSS observed dipole (0.085, local motion corrected) is at $\sim 2$ sigma probability assuming $\Lambda$CDM!**

# Thank You