Probing homogeneity of the Cosmos using Quasars

Atul Kedia

University of Notre Dame, USA

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Overview

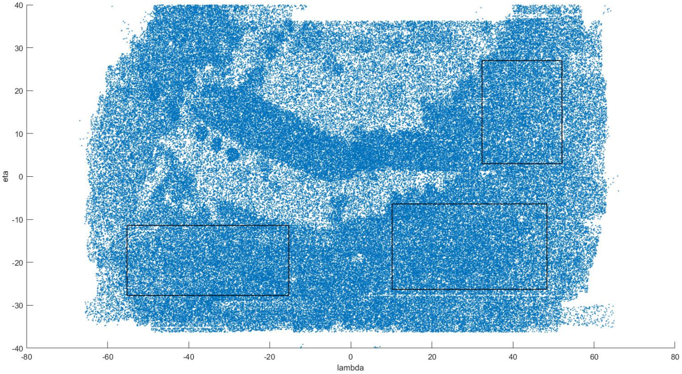
The Cosmological Principle

The Cosmological Principle states that the universe is **homogeneous** and **isotropic**. The cosmological principle implies that, at a large enough length scales, observers at different points in space would observe the universe to be the same and all directions would be indistinguishable for the observers.

Current understanding:
Some works have calculated and found homogeneity to be achieved at length scales of $70h^{-1}\,\mathrm{Mpc} - 80h^{-1}\,\mathrm{Mpc}$.
Other works suggest a **fractal like structured** universe. (Pietronero, 1987 and Coleman & Pietronero 1992)

SDSS III: Data Release 10

The SDSS data



Three subsamples in survey coordinates (λ, η) ranges.

Comoving Distance calculation

Comoving Distance[1] (D_C) is defined as the distance between two objects that remains constant if the two move along with the **Hubble flow**. This gives us their position in cartesian coordinates.

$$D_C = D_H \int_0^\infty \frac{dz'}{E(z')} \tag{1}$$

where z is the redshift, D_H the **Hubble distance**

$$D_H = \frac{c}{H_0} \tag{2}$$

and $E(z')$ given by

$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda} \tag{3}$$

[1] Hogg D. W., 2000, arXiv

Absolute Magnitude

Absolute magnitude(M) is calculated using the Apparent Magnitude(m), the comoving distance(D_C) and a K-correction term.
Hogg D.W., 2000 described Luminosity distance(DL) and Distance Modulus(DM) which lead to the Absolute magnitude (M).

$$D_L = (1+z) D_H \frac{1}{\sqrt{|\Omega_K|}} sin\left[\sqrt{|\Omega_K|}\frac{D_C}{D_H}\right] \tag{4}$$

$$DM = 5\log\left(\frac{D_L}{10pc}\right) \tag{5}$$

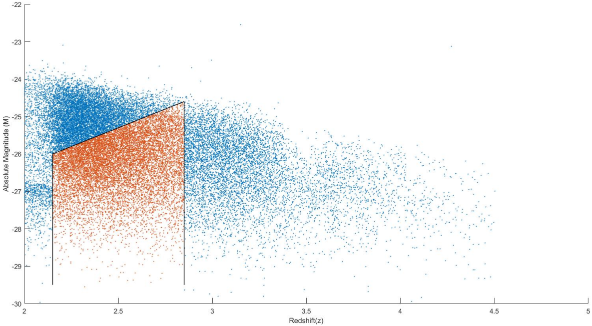
$$M = m - DM - K \tag{6}$$

Where K is the **k-correction** of magnitude.

Volume Limited Sample

Quasars, due to their brightness, can be observed at large distances easily. The presence of low brightness quasars at small distances (redshift) suggests the **presence of low brightness quasars** at larger redshifts though not detected.

A Volume Limited Sampling technique is employed to correct for these, so that the **density** of quasars remains unchanged with increasing radius.



Scaled Number Counts

Count-in-spheres $n_i(< R)$ - No. of quasars within a distance of R from i^{th} quasar.

Averaged count-in-spheres $N_A(< R)$ - Average of $n_i(< R)$), for all i.

Scaled Number Count $\mathcal{N}(< R) = \frac{\sum_{i=1}^{N_c} {\rho_i}^2 \left(\frac{N_A(<R)}{{N_R}_i(<R)} \right)}{\sum_{i=1}^{N_c} {\rho_i}^2}$,

At homogeneity,

$$N_A(< R) \propto R^D$$
$$\mathcal{N}(< R) \sim 1$$

Minkowski-Bouligand Dimension

Correlation Integral[2]:-

$$C_q(R) = \frac{1}{MN} \sum_{i=1}^{M} [n_i(< R)]^{(q-1)} \tag{7}$$

where, N is the total number of quasars and M is the number of quasars used for this particular value of R. q represents different moments of the quasar counts.

Minkowski-Bouligand Dimension:-

$$D_q(R) = \frac{1}{(q-1)} \frac{\mathrm{d}\, log\, C_q(R)}{\mathrm{d}\, log\, r} \tag{8}$$

[2] Prakash Sarkar, et al. 2009

Fractal dimensions calculated

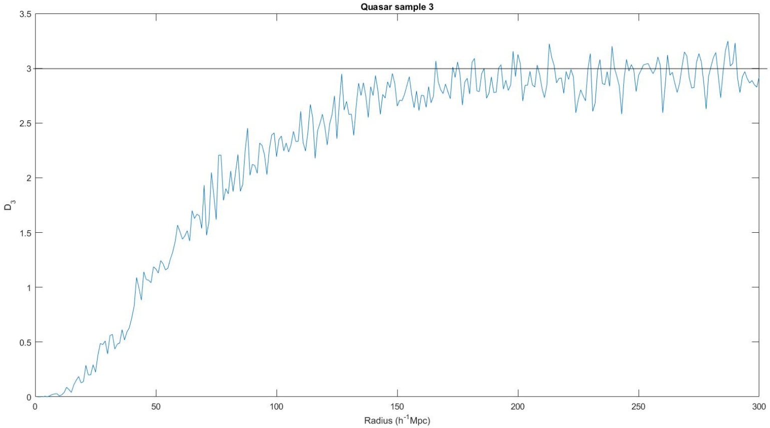


Figure 1: D_3 calculated for Quasar sample 3.

Bootstrap resampling technique

We employ bootstrap resampling technique to estimate the standard deviation in the calculated D_qs.

1. Ten bootstrap resamples were generated randomly.
2. The aforementioned calculations for correlation integral($C_q(R)$) and fractal dimension($D_q(R)$) was performed.
3. Standard deviation among the $D_q(R)$ was evaluated.

Averaged D_q

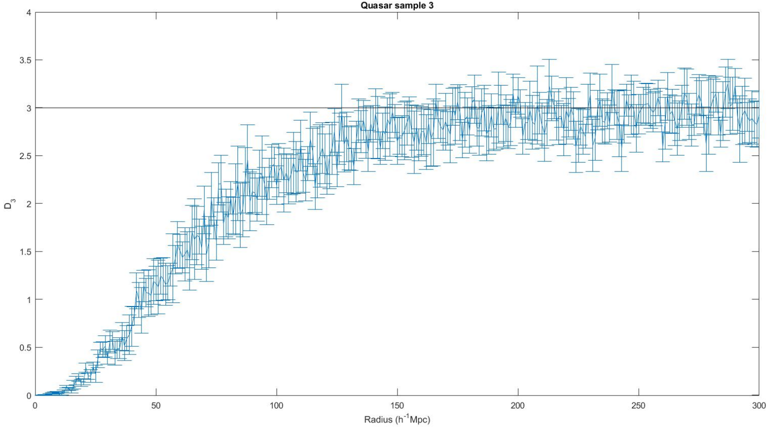


Figure 2: D_3 calculated for Quasar sample 3

Averaged D_q

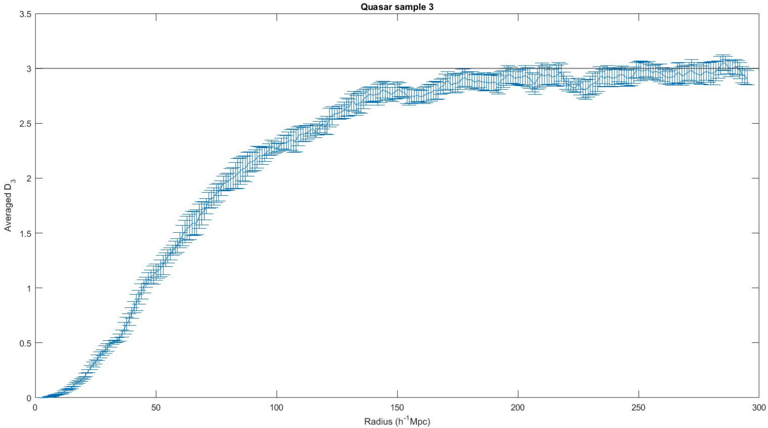


Figure 3: Averaged D_3 calculated for Quasar sample 3.

Averaged D_q

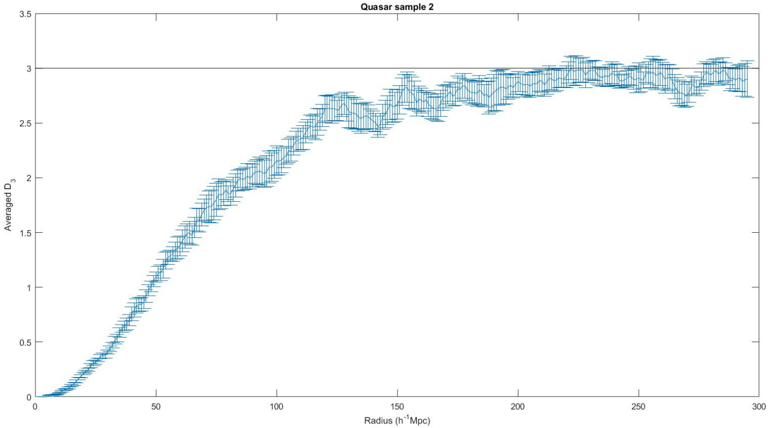


Figure 4: Averaged D_3 calculated for Quasar sample 2.

$D_q(150)$ v. q

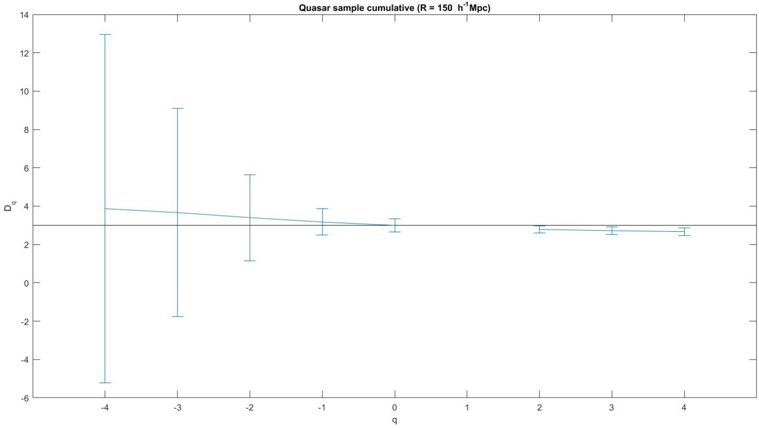


Figure 5: D_q v. q for $R = 150h^{-1}\,\mathrm{Mpc}$

$D_q(200)$ v. q

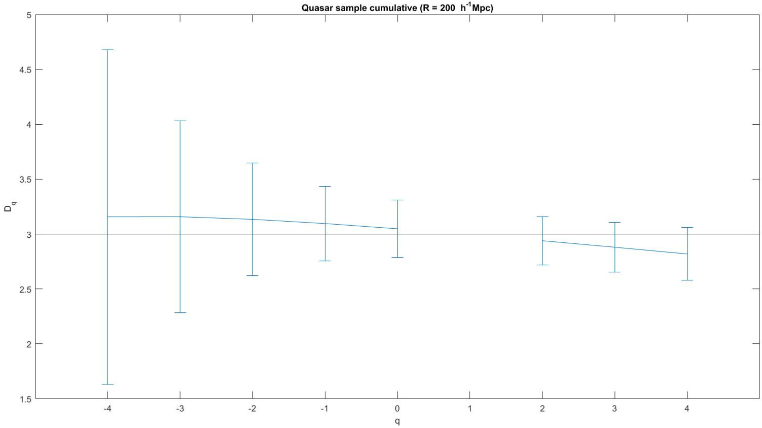


Figure 6: D_q v. q for $R = 200h^{-1}\,\mathrm{Mpc}$

Quasar data and Random sample

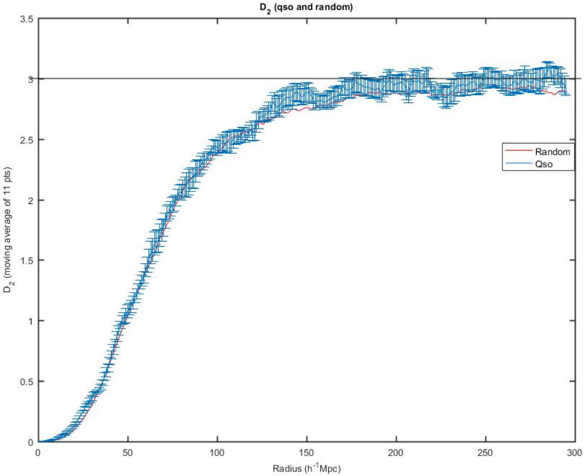


Figure 7: D_2 for quasar data and random sample

Quasar data and Random sample

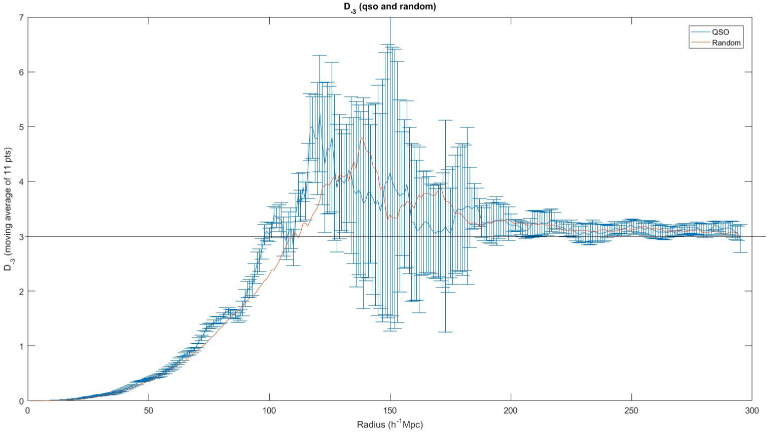


Figure 8: D_{-3} for quasar data and random sample

Acknowledgment

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Reference: Sarkar, Prakash, et al. "The many scales to cosmic homogeneity: Use of multiple tracers from the SDSS." arXiv preprint arXiv:1611.07915 (2016).