Spatial galaxy correlations in real and redshift space in the Local Universe

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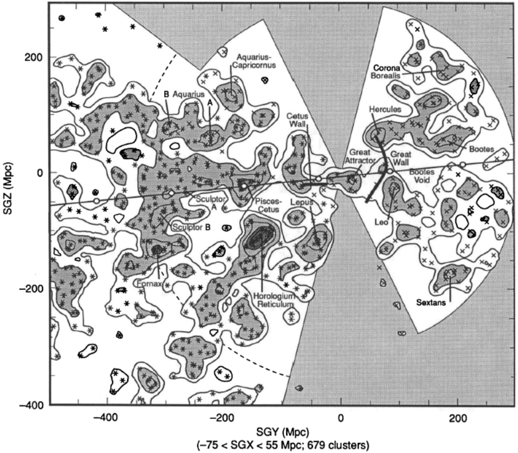
SPbD SAO RAS, SPbSU, INASAN, INFN

2 october 2019

History of LU LSS

R. Brent Tully, *Possible geometric patterns in 0.1c scale structure*, ApJ, 1992, 388(1):9-16, DOI: 10.1086/171124



679 ACO & Abell clusters,

130 h^{-1} Mpc a slab thickness,

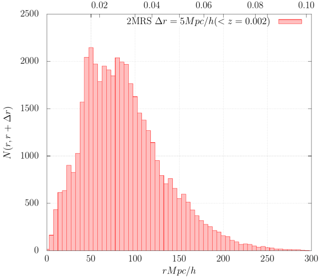
the contours shade steps: $1, 2$ and 4×10^{-3} clusters Mpc^{-2}

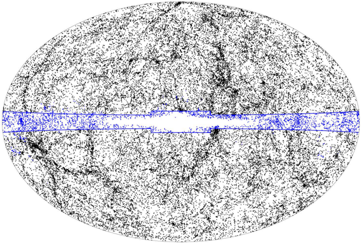
"..the previously announced concentration of rich clusters to the supergalactic equator extends across a domain of ∼450 h^{-1} Mpc.."

Modern state of LU LSS

Spectroscopic survey of 2MASS XSC galaxies (2MRS)

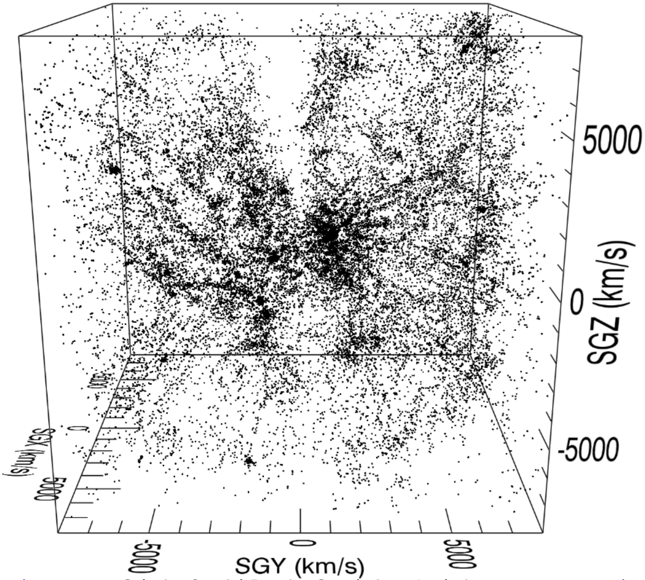
- only 44599 spectral redshifts
- $K_s < 11.75$ mag (IR)
- $|b| > 5$ deg; $|b| > 8$ deg (bulge)
- the redshift mean $z = 0.03$
- completeness $\sim 90\%$
- Huchra J. et al., 2012, ApJS, 199, 26





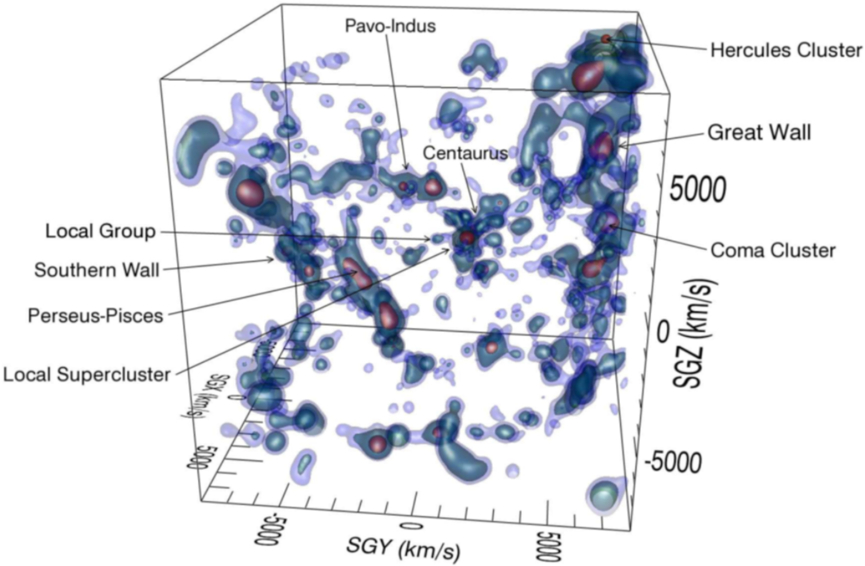
V8k LU catalog 30124 galaxies

Courtois H. et al., AJ, 146 (2013) 69: LSS Discreetness



V8k LU catalog 30124 galaxies

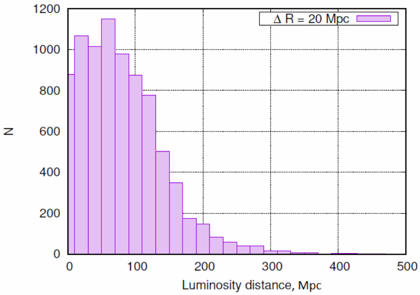
Courtois H. et al., AJ, 146 (2013) 69: LSS Isodensities



Modern state of LU LSS

The Cosmicflows-2 work catalogue

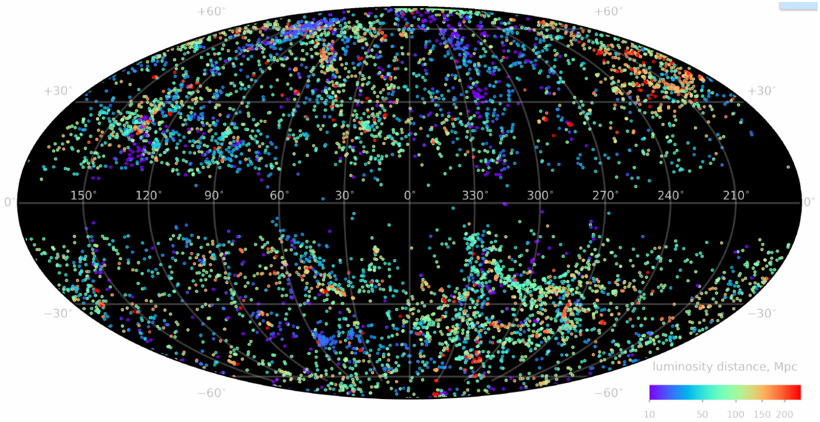
- 8 188 luminosity distances and spectral redshifts (independent from 2MRS sample)
- $K_s < 11.75$ mag
- $|b| > 5$ deg; $|b| > 8$ deg (bulge)
- The luminosity distances $R_{lum} < 300$ Mpc
- Tully B. et al., AJ, 146, 86 (2013)



The data on redshift space indicate separated structures and the data on real space allows to reconstruct the galaxy flows.

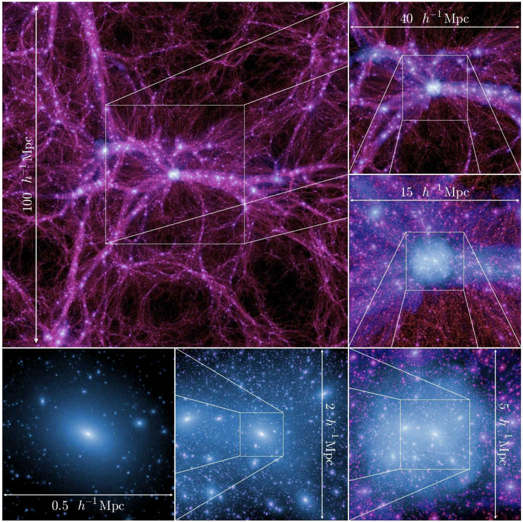
Modern state of LU LSS

The Cosmicflows-2 catalogue



Modern state of LU LSS

The Millennium-II simulations



N-body simulation of dark matter evolution in the concordance ΛCDM model cosmology.

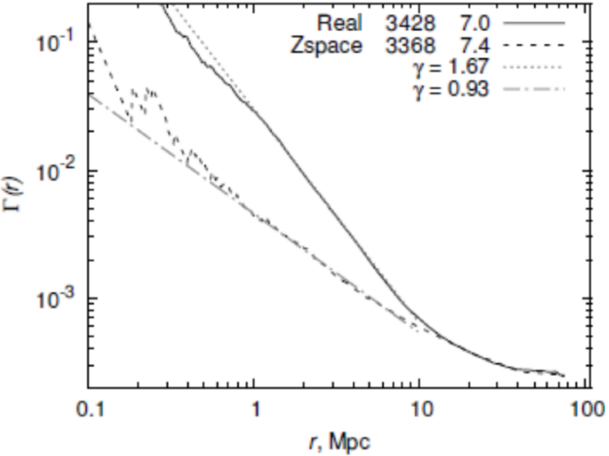
the size 100 Mpc/h, spatial resolution 1 kpc/h

and mass resolution 6.89×10^6 $\mathrm{M_{sun}}$/h.

https://wwwmpa.mpa-garching.mpg.de/galform/millennium-II

Modern state of LU LSS

The Millennium-II simulations (ΛCDM)



D. I. Tekhanovich and Yu. V. Baryshev, Astroph. Bull., **71**, 2 (2016), the catalogue: D. J. Croton et al., MNRAS, 365, 11 (2006)

A New Observational Test

The Power-Law Conditional Density Has Different Slopes for Redshift Space and Real Space

According to the N-body simulations of the ΛCDM model, conditional density has a power-law form $\Gamma(r) \sim r^{-\gamma}$ in the scale interval $0.1 < r < 20$ Mpc and becomes uniform starting from 20 Mpc. Note that slope γ has two significantly different values:
$\gamma = 1.67$ (fractal dimension $D = 1.33$) for real-space and
$\gamma = 0.93$ (fractal dimension $D = 2.07$) for redshift-space.

This is due to the Peculiar Velocities of galaxies.

Definitions of correlation functions

The **complete two-point correlation function** of a stationary isotropic process

$$R_{\mu\mu}(r) = \langle \mu(\vec{r_1})\mu(\vec{r_2})\rangle, \quad r = |\vec{r}| = |\vec{r_1} - \vec{r_2}|$$

The **reduced (centered) two-point correlation function**

$$C_2(r) = \langle (\mu(\vec{r}_1) - \mu_0)(\mu(\vec{r_2}) - \mu_0)\rangle = R_{\mu\mu}(r) - \mu_0^2$$

$$\mu_0 = \langle \mu(\vec{r})\rangle$$

Discrete stochastic process

$$\rho(\vec{r}) = \sum_{i=1}^{N} m_i \delta(\vec{r} - \vec{r_i})$$

$$\rho_0 = \langle \rho(\vec{r})\rangle$$

Definitions of correlation functions

The **normalized reduced two-point correlation function**. For a distribution with a well defined positive average density $\rho_0 > 0$, we can use dimensionless form of CF as:

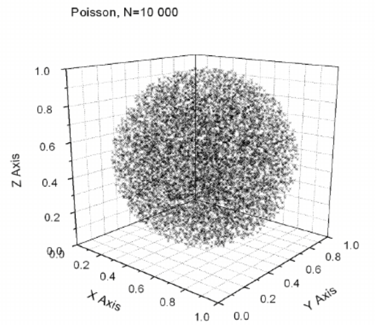
$$\xi(r) = \frac{C_2(r)}{\rho_0^2} = \frac{\langle \Delta\rho(\vec{r_1})\Delta\rho(\vec{r_2})\rangle}{\rho_0^2} = \frac{\langle \rho(\vec{r_1})\rho(\vec{r_2})\rangle - \rho_0^2}{\rho_0^2}$$

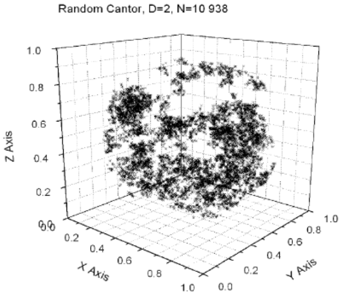
In the case of a mass field $\rho(\vec{r})$ is a non-negative quantity; therefore $\xi(r) \geq -1$ at any r (Peebles, 1980), and must change sing in any sample.

To study the large-scale distribution of galaxies fractal analysis is more resistant to distorting effects.

The Fractal Approach Analysis

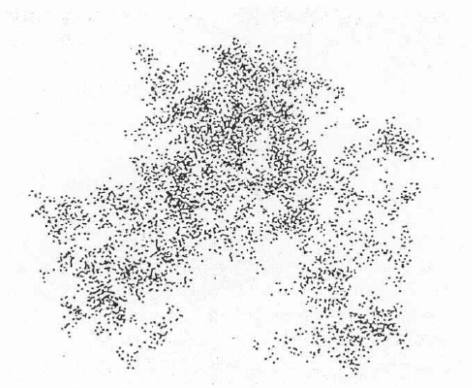
B. Mandelbrot *The Fractal Geometry of Nature*,
W. H. Freeman and Co. (1982)
A. Gabrielli, F. Sylos Labini, M. Joice, L. Pietronero,
Statistical physics for cosmic structures, Springer (2005)
Yu. V. Baryshev and P. Teerikorpi,
Fundamental questions of practical cosmology, Springer (2012)





Stochastic fractal structure

hierarchy + randomness



$$\rho(\vec{r}) = \sum_i \delta(\vec{r} - \vec{r_i})$$

If mass M scales as:

$$\lim_{R\to\infty} M(R) \sim R^D$$

then D is called the *mass-radius dimension*.

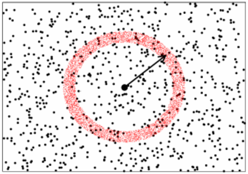
$$\Gamma(r) = Ar^{-\gamma}$$

with $\gamma = d - D$

- Conditional density (within shells)

$$\Gamma(r) = \langle \rho(r) \rangle_p$$

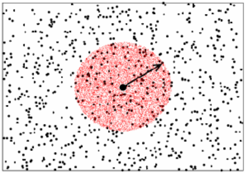
$$\Gamma_E(r) = \frac{1}{N_c(r+\Delta r)} \sum_{i=1}^{N_c(r+\Delta)} \frac{N_i(r,\Delta r)}{V(r,\Delta r)}$$



- Integrated conditional density (within spheres)

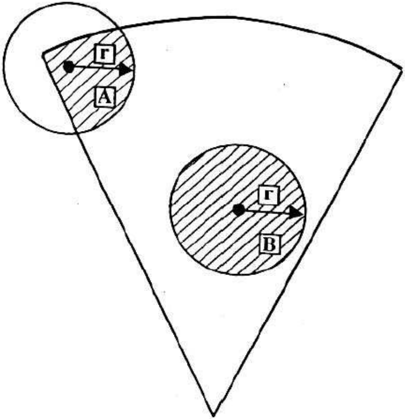
$$\Gamma^*(r) = \langle \rho(r' < r) \rangle_p$$

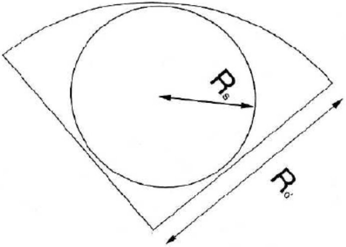
$$\Gamma^*_E(r) = \frac{1}{N_c(r)} \sum_{i=1}^{N_c(r)} \frac{N_i(r)}{V(r)}$$

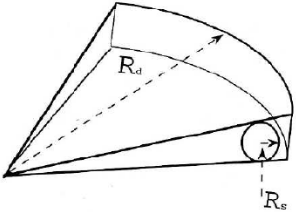


Finite volume effects

Sylos Labini et al., Phys.Rep., 293, 66, 1998

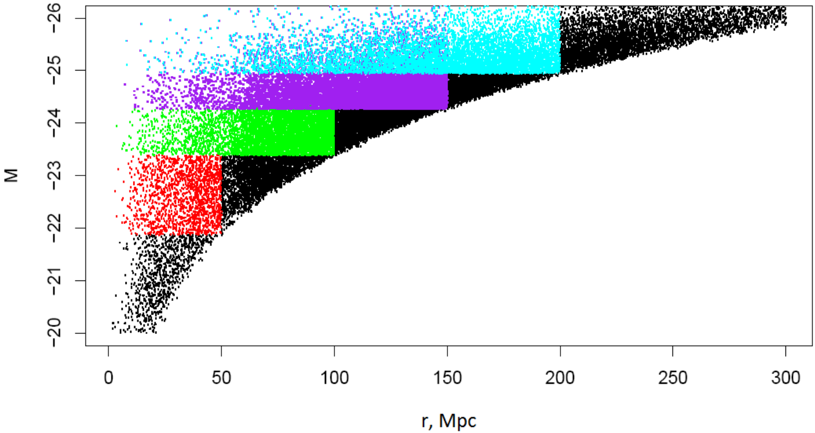






Preparation for the LSS analysis

The 2MRS Volume Limited Samples



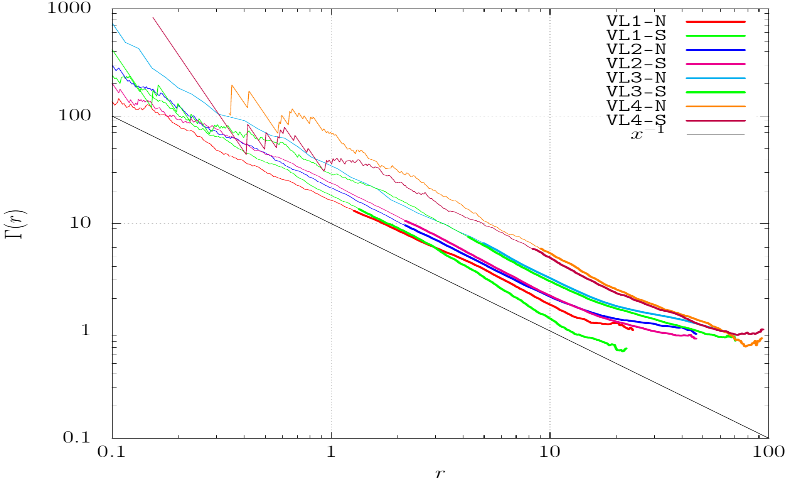
Preparation for the LSS analysis

The 2MRS Volume Limited Samples

subsamples	R_{max}, Mpc	M_{k}	N	R_{nn}, Mpc
VL1-N	50	-21.87	1845	1.51
VL2-N	100	-23.39	4768	2.27
VL3-N	150	-24.27	6133	3.26
VL4-N	200	-24.95	3741	5.64
VL1-S	50	-21.87	936	1.93
VL2-S	100	-23.39	4925	2.23
VL3-S	150	-24.27	5923	3.28
VL4-S	200	-24.95	4015	5.38

The Fractal Approach Analysis

The 2MRS Conditional Density (Redshift Space)



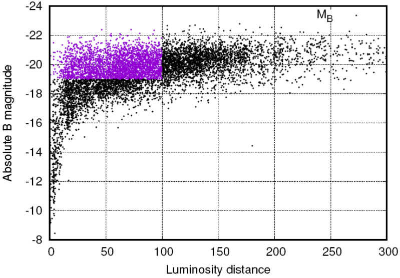
$\gamma^{Z}_{\text{average}} = 1.03 \pm 0.05$, $D^{Z}_{\text{average}} = 1.97 \pm 0.05$ on scales from 1 to 20 Mpc

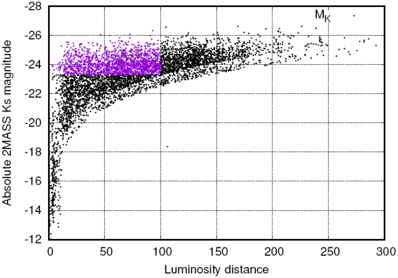
Preparation for the LSS analysis

The Cosmicflows 2 Volume Limited Samples

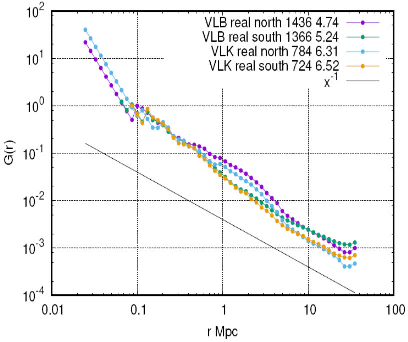
CF-2 catalog gives the unique opportunity for direct observational construction of the two spatial LSS maps based on the real-space and redshift-space data, and thus compare theirs conditional densities $\Gamma^R = \Gamma_{lum}(r_{lum})$ and $\Gamma^Z = \Gamma_z(r_z)$ (up to internal selection effects).

VL samples

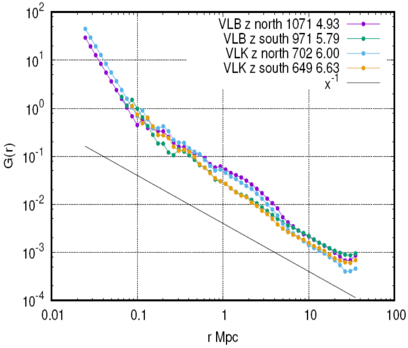




The conditional density results



real space



redshift space

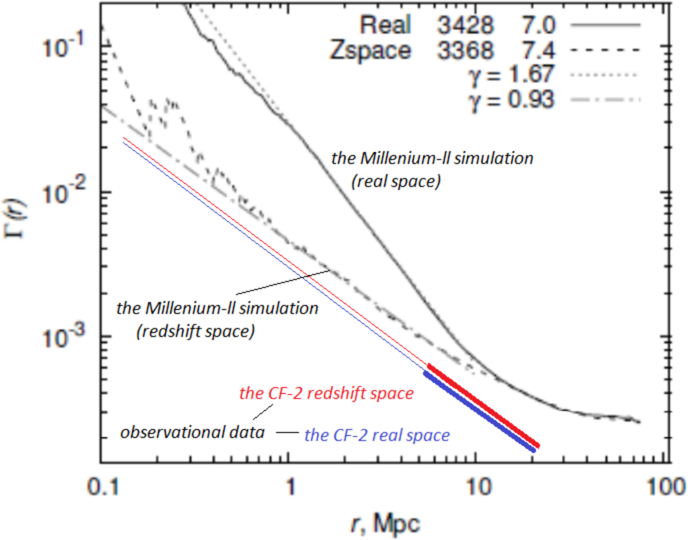
The conditional density results

space	north	south	north	south
	VL B-band		VL K-band	
	$r \in [6, 20]$			
γ^R γ^Z	1.1 1.1	0.8 1.0	1.2 1.2	0.9 0.9

$$\gamma^R_{\text{average}} = 1.00 \pm 0.14$$
$$\gamma^Z_{\text{average}} = 1.06 \pm 0.09$$

The Fractal Approach Analysis

The Cosmicflows 2 samples



Conclusion

- According to our analysis, the conditional density slopes are $\gamma^R = 1.67$ and $\gamma^Z = 0.93$ in the Millenium-II simulations sample (in ΛCDM framework)
- Our preliminary analysis shows no difference between real space and redshift space with $\gamma^R = 1.00 \pm 0.14$ and $\gamma^Z = 1.06 \pm 0.09$.

References

- B. Mandelbrot *The Fractal Geometry of Nature*, W. H. Freeman and Co. (1982)
- P.J.E. Peebles *Principles of Physical Cosmology*, Princeton Univ.Press (1993)
- P. J. E. Peebles, *The Galaxy and Mass N-Point Correlation Functions: a Blast from the Past*, arXiv:astro-ph/0103040 (2001)
- A. Gabrielli, F. Sylos Labini, M. Joice, L. Pietronero, *Statistical physics for cosmic structures*, Springer (2005)
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- D. I. Tekhanovich and Yu. V. Baryshev, *Global structure of the Local Universe according to 2MRS survey*, Astroph. Bull. **71**, 2 (2016)

Thanks for your attention

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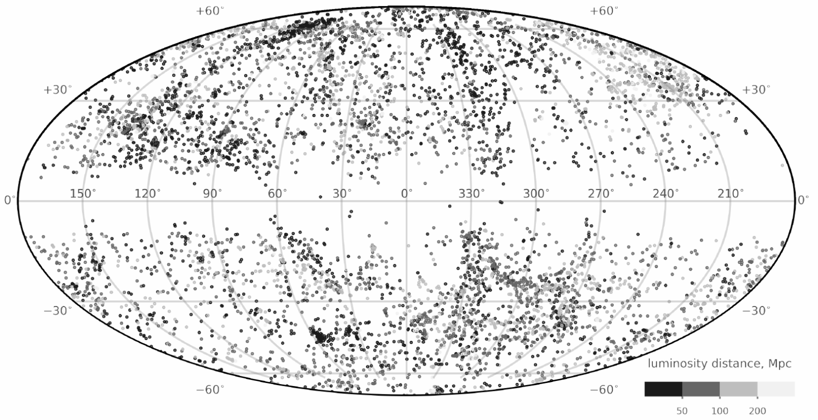
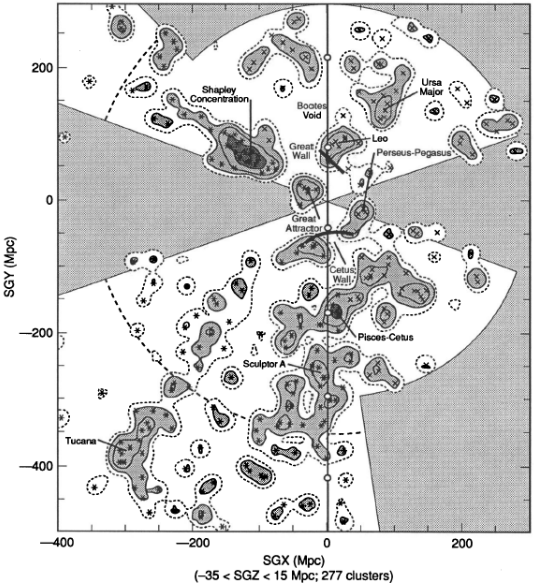
Attachment

Modern state of LU LSS

The Cosmicflows-2 catalogue



Modern state of LU LSS



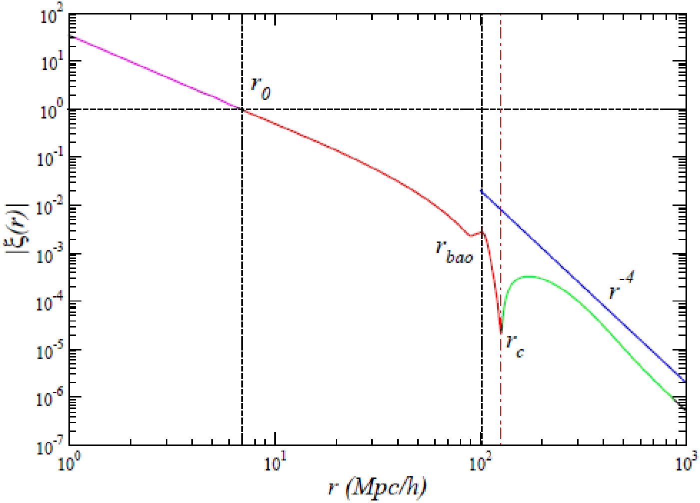
277 ACO & Abell clusters

50 h^{-1} Mpc a slab thickness,

the contours shade steps: $1 \div 3 \times 10^{-2}$ clusters Mpc^{-2}

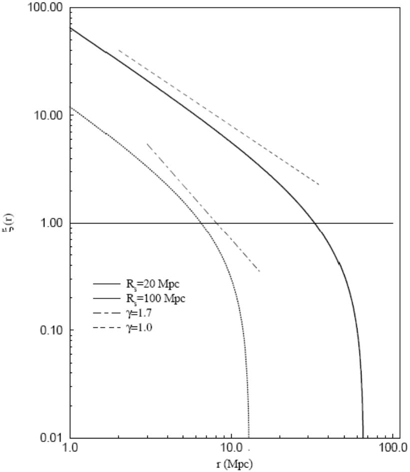
Correlation function in ΛCDM

F. Sylos Labini (2011)



Finite volume effects

Sylos Labini et al., Phys.Rep., 293, 66, 1998



$$\xi_E(r) = 2\left(\frac{r}{r_0}\right)^{\gamma} - 1$$

$$\gamma' = -\frac{\mathrm{d}[\log \xi(r)]}{\mathrm{d}\log r} =$$

$$= \frac{2\gamma(r/r_0)^{-\gamma}}{2(r/r_0)^{-\gamma} - 1}$$

$$\gamma_\xi(r_0) = 2\gamma$$

The Fractal Approach Analysis

The FDE Methods

The pairwise distances $f(l)$ are lengths of segments between two set points, with taking into account the set geometry, and has asymptotic for $l << L$:

$$f(l) \sim l^{D-1},$$

which also is retained for sets with a fractional dimensionality (Kendall & Moran, 1963).

The modified PD method:

$$f(l)dl = f(\log l)d\log l,$$

from which, taking into account

$$d\log l = \frac{d\ln l}{\ln 10} = \frac{1}{\ln 10}\frac{dl}{l},$$

follows that

$$f(\log l) = \ln 10 \cdot l f(l) \propto l \cdot l^{D-1} = l^D.$$

References

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- S. I. Shirokov, A. A. Raikov, Yu. V. Baryshev, *Spatial Distribution of Gamma-Ray Burst Sources*, Astrophysics, 60, 4 (2017), arXiv:1802.00953
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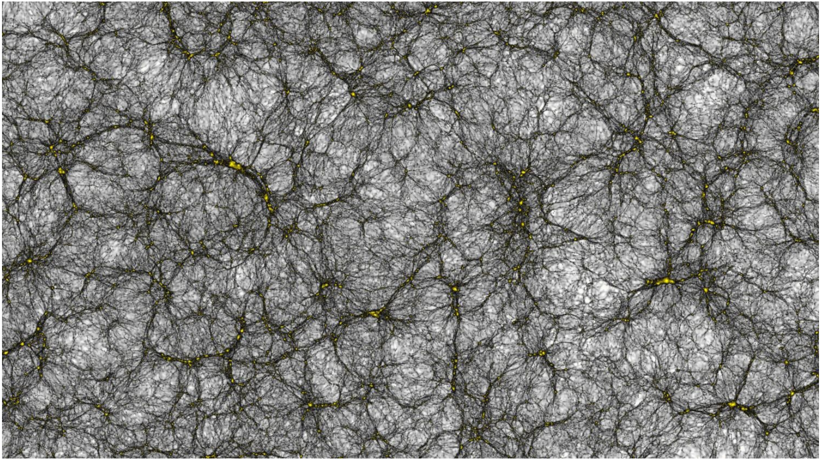
Thanks for your attention



Researchers from the University of Zurich have simulated the formation of our entire universe with a large supercomputer. A gigantic catalogue of about 25 billion virtual galaxies has been generated from 2 trillion digital particles. This catalogue is being used to calibrate the experiments on board the Euclid satellite, that will be launched in 2020 with the objective of investigating the nature of dark matter and dark energy.

Conditional Properties

Conditional average: average over observations from a point occupied by a particle:

$$\langle F(\rho(\vec{r_1}), \rho(\vec{r_2}), \dots) \rangle_p =$$

$$\lim_{V \to \infty} \frac{1}{N(V)} \sum_{i=1}^{N(V)} F(\vec{r_i} + \rho(\vec{r_1}), \rho(\vec{r_i} + \vec{r_2}), \dots)$$

where N(V) is the number of particles in the volume V.

The **conditional density**

Pietronero, 1987

The basic rule of conditional probability:

$$P(A|B) = P(A \cap B)/P(B)$$

conditional density:

$$\langle \rho(r) \rangle_p = \frac{\langle \rho(\vec{0}) \rho(\vec{r}) \rangle}{\rho_0} = \rho_0 [1 + \xi(r)]$$

and for statistically stationary and isotropic particle distribution it depends only on the scalar distance r, so

$$\Gamma(r) = \langle \rho(r) \rangle_p = \rho_0 [1 + \xi(r)]$$

r_c shifts due to depth of the survey

F. Sylos Labini (2011)