Large Scale Structure of the Universe as a Cosmic Ruler

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This Study

: Large-scale structure as a cosmic ruler

Motivation: To introduce a new measure of geometry of the universe complementary to the BAO

Key Idea: In the comoving space the topology of LSS do not change in time, and can serve as a standard ruler.

Equivalent to using the overall shape of the PS or CF (Gaussian)

Strategy: Intrinsic topology statistics at large scales (insensitive to various non-linear effects)

Shape of the PS or CF at linear scales

Phenomena in the Universe
for cosmological parameter estimation

1. primordial fluctuations (~initial conditions)

CMB (+neutrino, gravitational wave), LSS

=> geometry of space, matter contents, matter P(k), non-Gaussianity

2. Expansion history of space

standard candle	$D_L(z) = (1+z)\, r(z)$	SN Ia	HST Legacy, Essence, DES, SNAP
standard ruler	$D_A(z) = (1+z)^{-1}\, r(z)$ $dV/dz d\Omega = r^2(z)/H(z)$	AP effects, BAO Topology	redshift surveys (CMB BAO helped)

=> H(z) or $r(z) = \int_0^z \frac{dz'}{H(z')}$

Phenomena

3. Growth of structures

ISW	l<30 CMB; CCF btw CMB & LSS	CMB, LSS	WMAP-Planck * SNAP-LSST-SDSS
Population density	# counts; comoving V * # density ~> dn/dz	clusters (SZ, Xray), galaxies, etc.	SDSS, ACT, APEX, DES, SPT
Weak lensing	shear field; path length on r(z) & shear pattern on matter distribution	imaging, photo-z	CFHTLS, SNAP, DES, LSST
Non-linear structures	properties of NL structures	galaxies, AGNs, clusters, globular clusters	various surveys

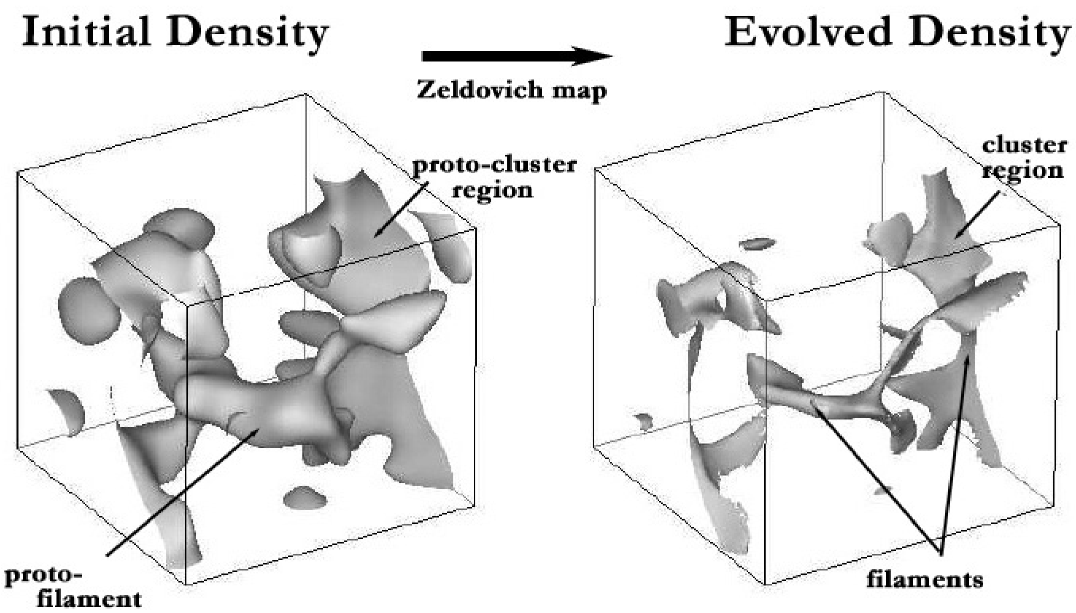
=> depends on both expansion of space H(z) & matter power spectrum P(k)

& non-linear physics (last case)

LSS as a standard ruler

Filament-dominated Cosmic Web

Bond et al. (1996) : Final-state web is present in embryonic form in the overdensity pattern of the initial fluctuations with NL dynamics just sharpening the image.

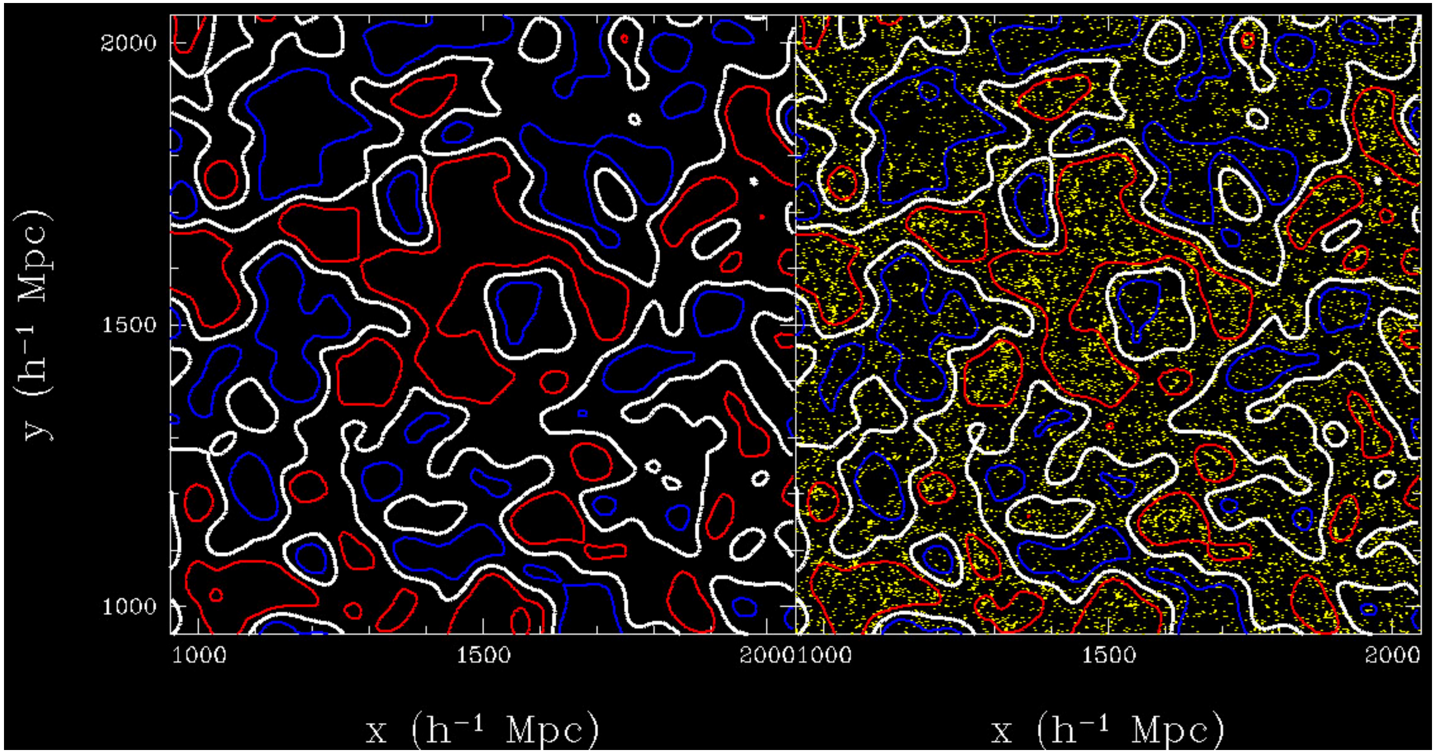


Cosmic Web Theory

Cosmic Sponge Theory

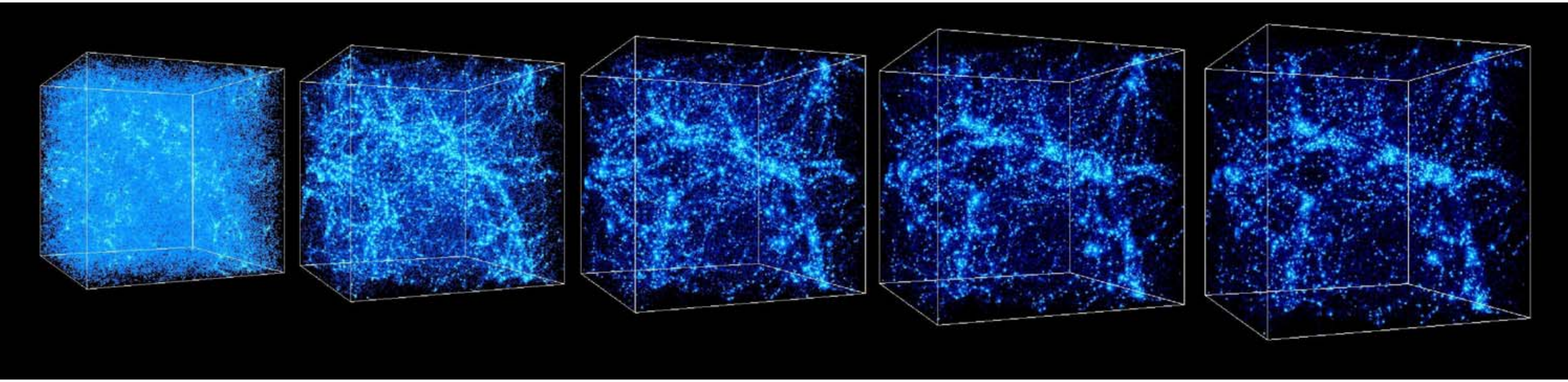
Not just overdensity patterns but all kinds of LSS including voids maintain their initial topology (sponge) till the present.

[Initial density field] **[Matter density field at z=0]**



flat LCDM

R_G=25h^{-1}Mpc



(courtesy: A. Kravtsov).

The LSSs are in the (quasi-)linear regime,

& maintain the primordial sponge topology at all redshifts!

(= the original idea of using topology for the test for the Gaussianity
of the primordial density field by Gott et al. in 1986)

The topology of LSS is conserved in time and

the LSS can be used as a standard ruler

(as its topology depends on scale)

Measures of intrinsic topology - Minkowski Functionals

3D

1. 3d genus (Euler characteristic) 2. mean curvature
3. contour surface area 4. volume fraction

→ 3d galaxy redshift survey data

2D

1. 2d genus (Euler characteristic) 2. contour length
3. area fraction

→ CMB temperature/polarization fluctuations, 2d galaxy surveys

1D

1. level crossings 2. length fraction

→ Lyα clouds, deep HI surveys, pencil beam galaxy surveys

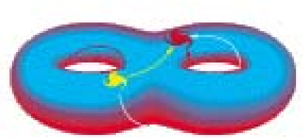
The 3D Genus

Definition

G = # of holes - # of isolated regions in iso-density contour surfaces

= 1/4π· $\int_S \kappa \, dA$ (Gauss-Bonnet Theorem)

[ex. G(sphere)=-1, G(torus)=0, G(two tori)=+1]



: 2 holes – 1 body = +1

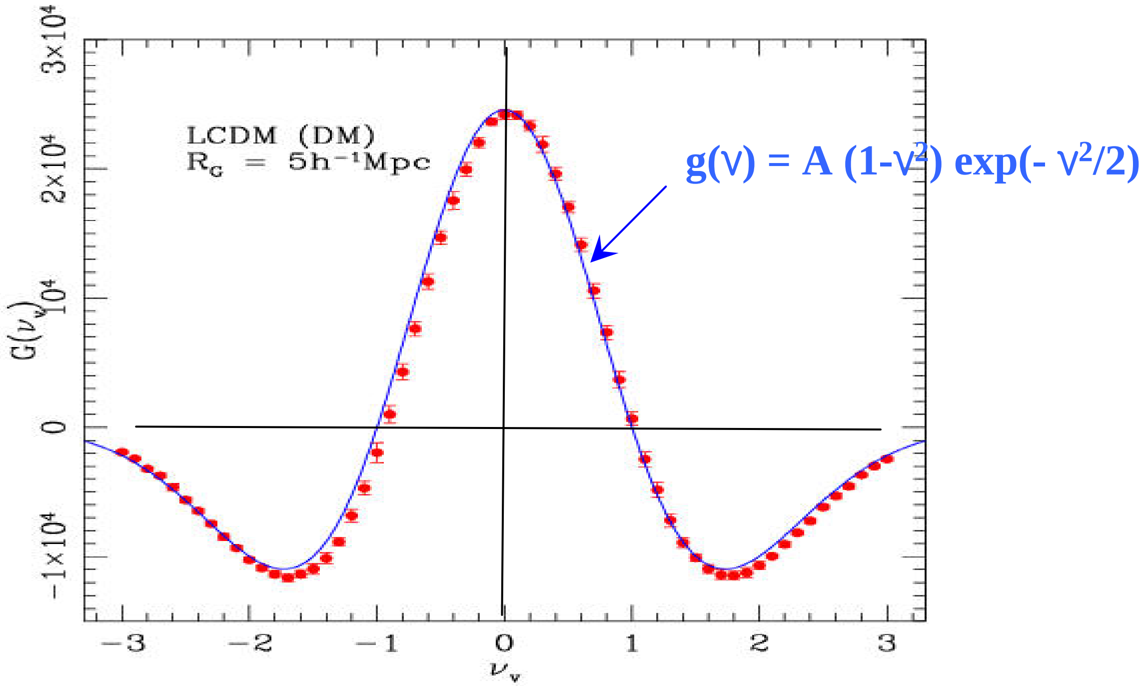
Gaussian Field

Genus/unit volume $g(\nu) = A\,(1-\nu^2)\exp(-\nu^2/2)$

where $\nu = (\rho - \rho_b)/\rho_b\sigma$

$A = 1/(2\pi)^2 \langle k^2/3\rangle^{3/2}$

$\langle k^2\rangle = \int k^2 P(k) W(k;R) d^3k = \int P(k) W(k;R) d^3k$



LSS as a Cosmic Ruler

In the case of a Gaussian field (very likely!)
the amplitude of the genus depends only on the shape of PS.
The overall shape of PS measured from the LSS being the standard ruler.

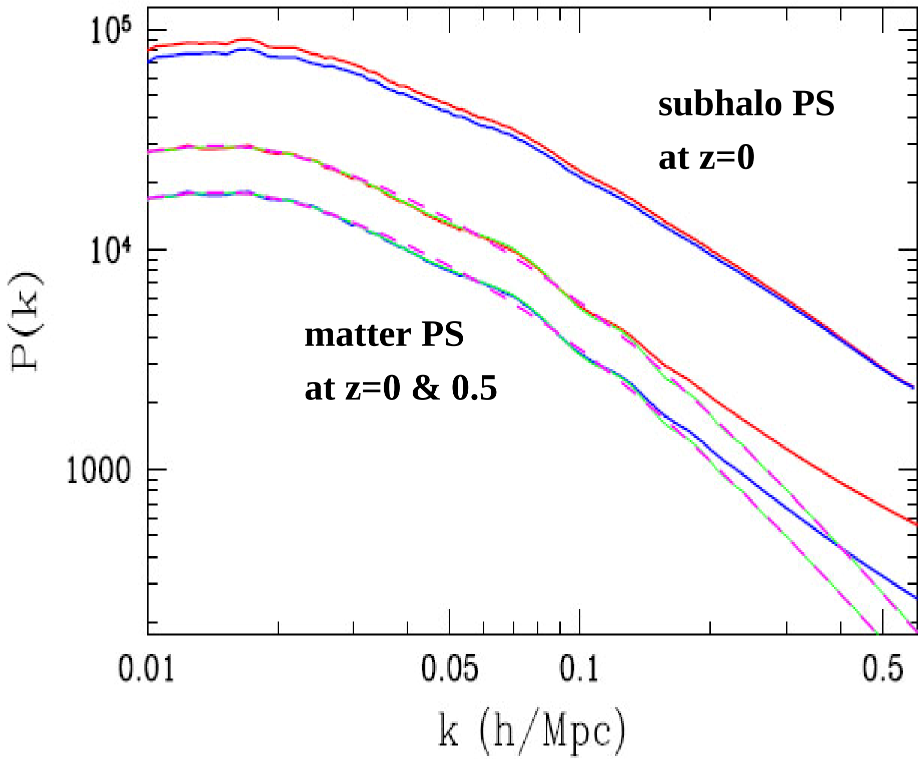
When the large-scale distribution of matter/galaxies is not Gaussian,
the amplitude of the genus does not exactly mean the slope of the PS.
But the topology of LSS is still a conserved property.
It remains true that the LSS can serve as the standard ruler.

Scale dependence of PS encoded in the LSS

The PS of each model universe has a specific scale dependence.

The whole shape of PS, not just the tiny wiggle (BAO) on top of the smooth PS, can be used as a cosmic ruler.

The genus measures the slope of the PS near the smoothing scale.

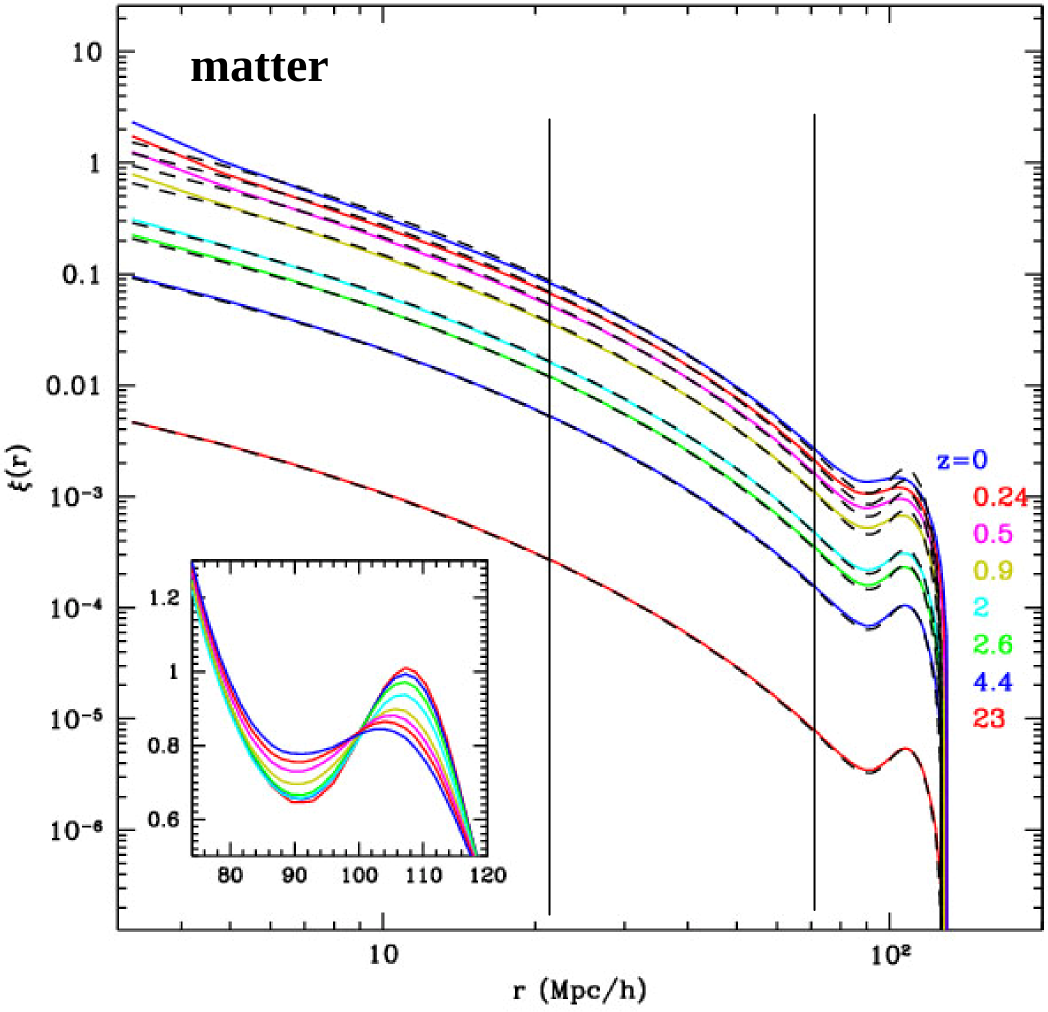


Kim, Park & Gott (2008)

The Horizon Run

Rapid evolution of the BAO peak. But

Little evolution of CF between ~20 & 70 h^{-1}Mpc



BAO peak positions (z=0, 0.5)

Linear theory = 107.6 h^{-1}Mpc

[In real space]

Matter = 103.2, 105.0 h^{-1}Mpc

Subhalos = 103.6, 104.7 h^{-1}Mpc

2.6~4.4% difference from the LT

~0.5% uncertainty in simulation

[past light cone; z-space]

Subhalos (SDSS-III) = 102.9 h^{-1}Mpc

4.7% difference from the LT

Kim, Park & Gott (2008)

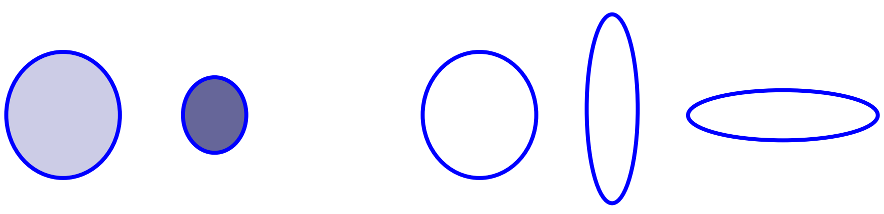
The Horizon Run

[LSS as a Cosmic Ruler]

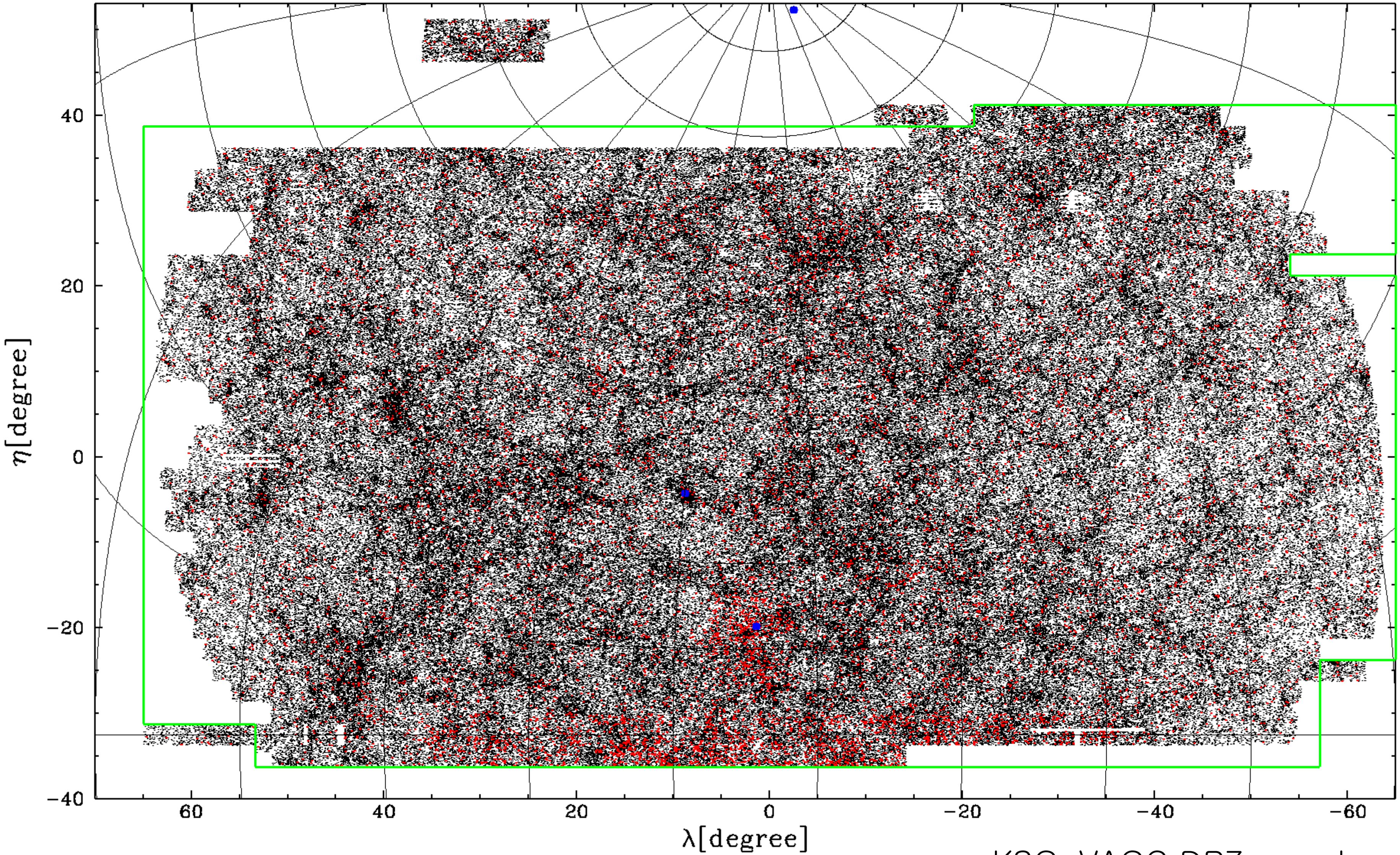
∴ The overall shapes of the PS and CF are conserved properties of LSS good for mapping the expansion history of the universe

Advantage of the topology method over the direct PS or CF methods

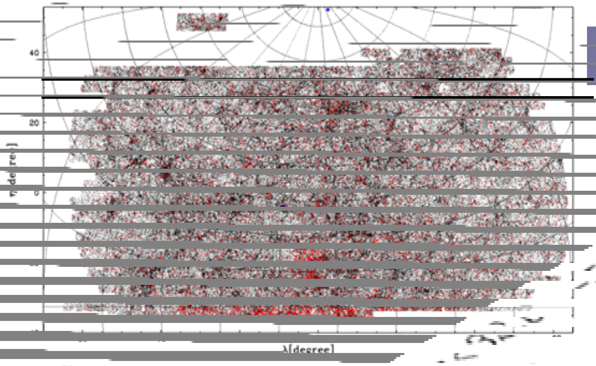
The genus, as an intrinsic topology, is
independent of all non-linear effects at least to the 1st order
because it is indep. of simple deformation and amplitude changes of LSS
[gravitational evolution - 2nd order (Matsubara 1994),
monotonic biasing, linear redshift-space distortion]

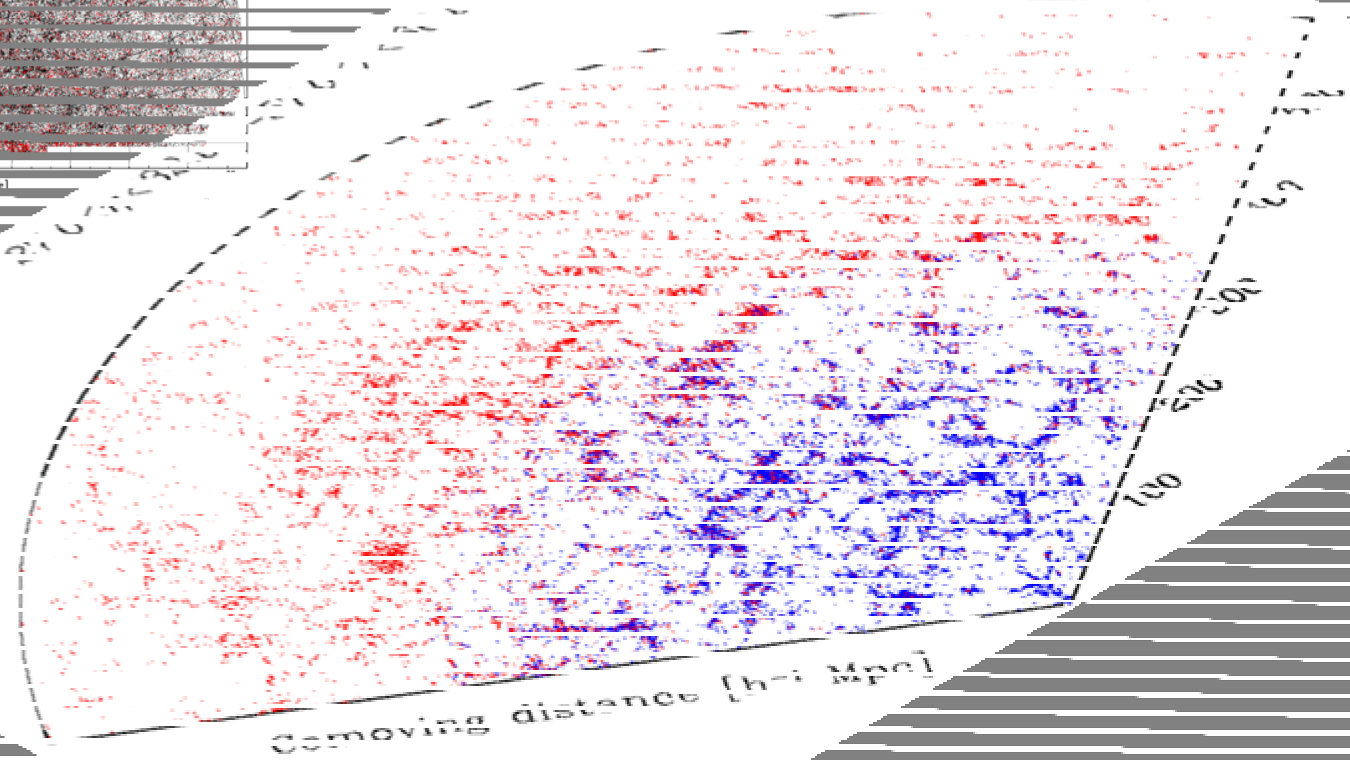


A tour of the real universe and genus measurements: SDSS galaxies

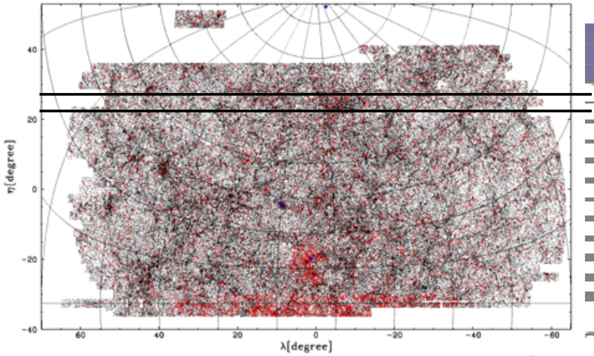


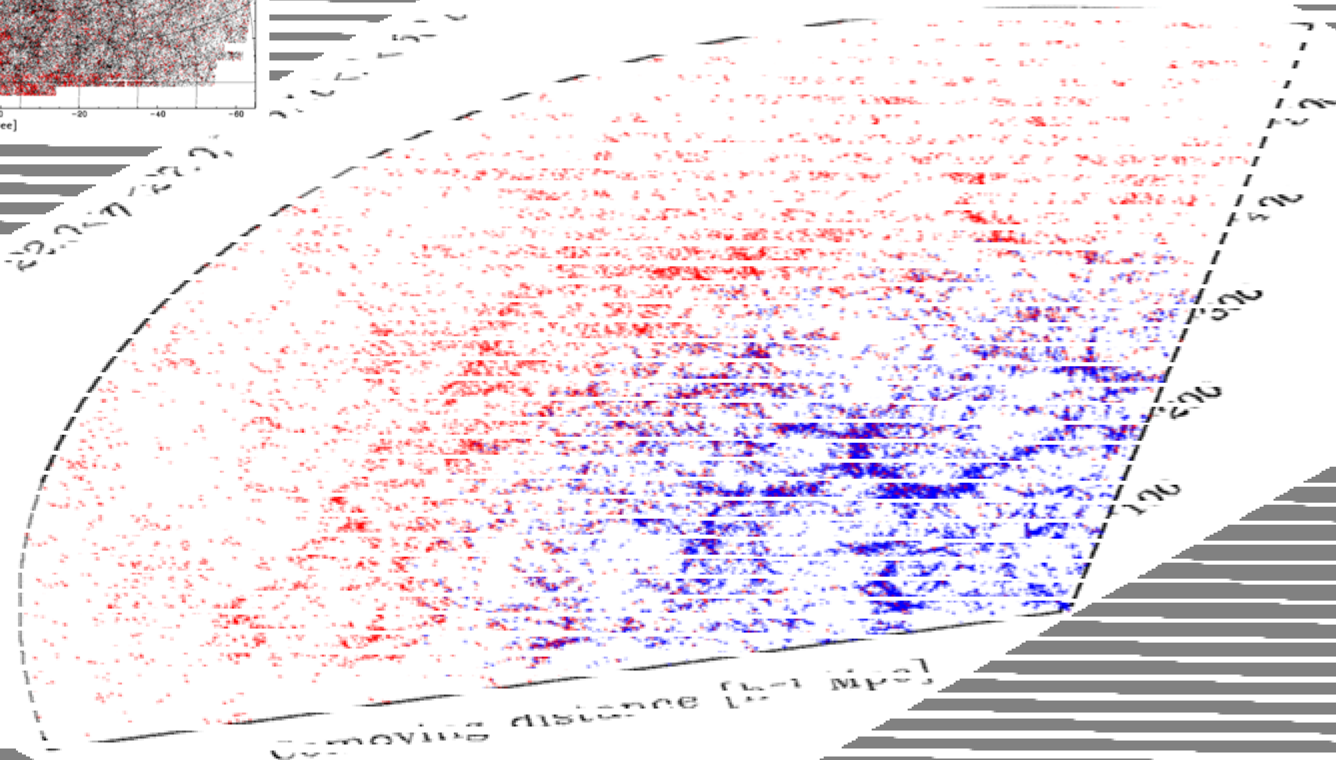
KSG-VAGC DR7 sample



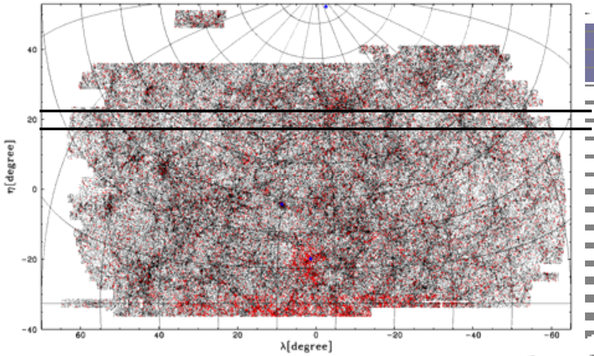


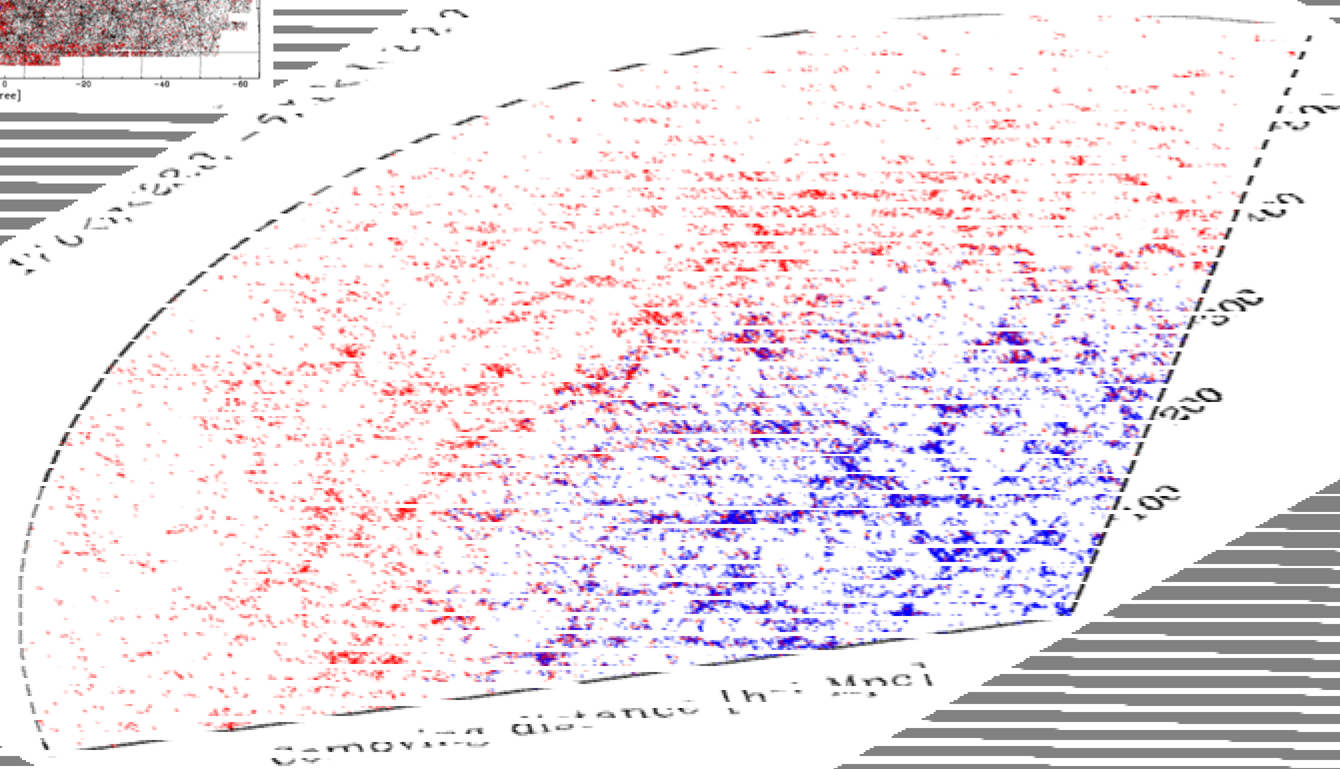
Large Scale Distribution

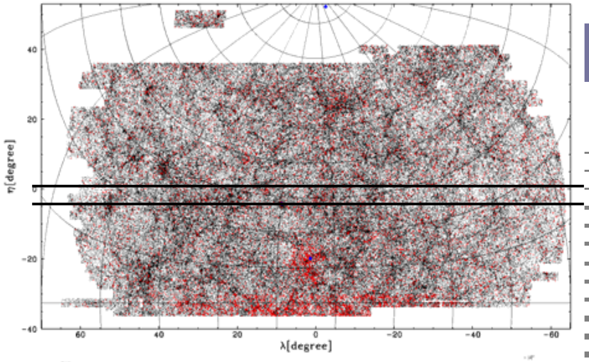


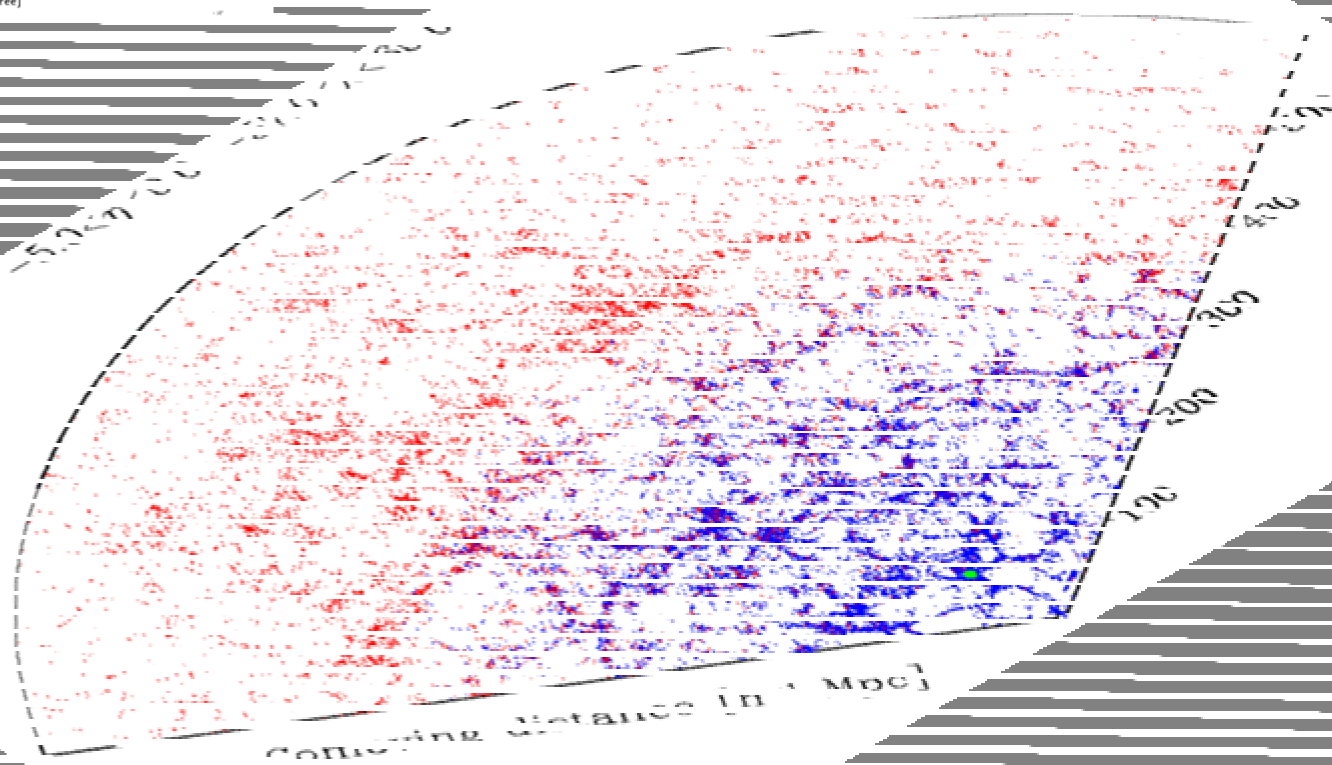


A Cosmic Runner (Park et al. 2005)

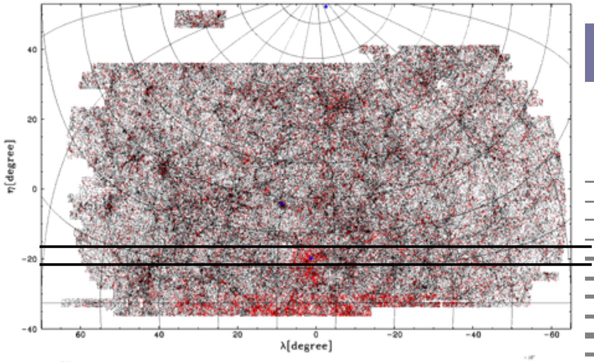

η[degree]
λ[degree]

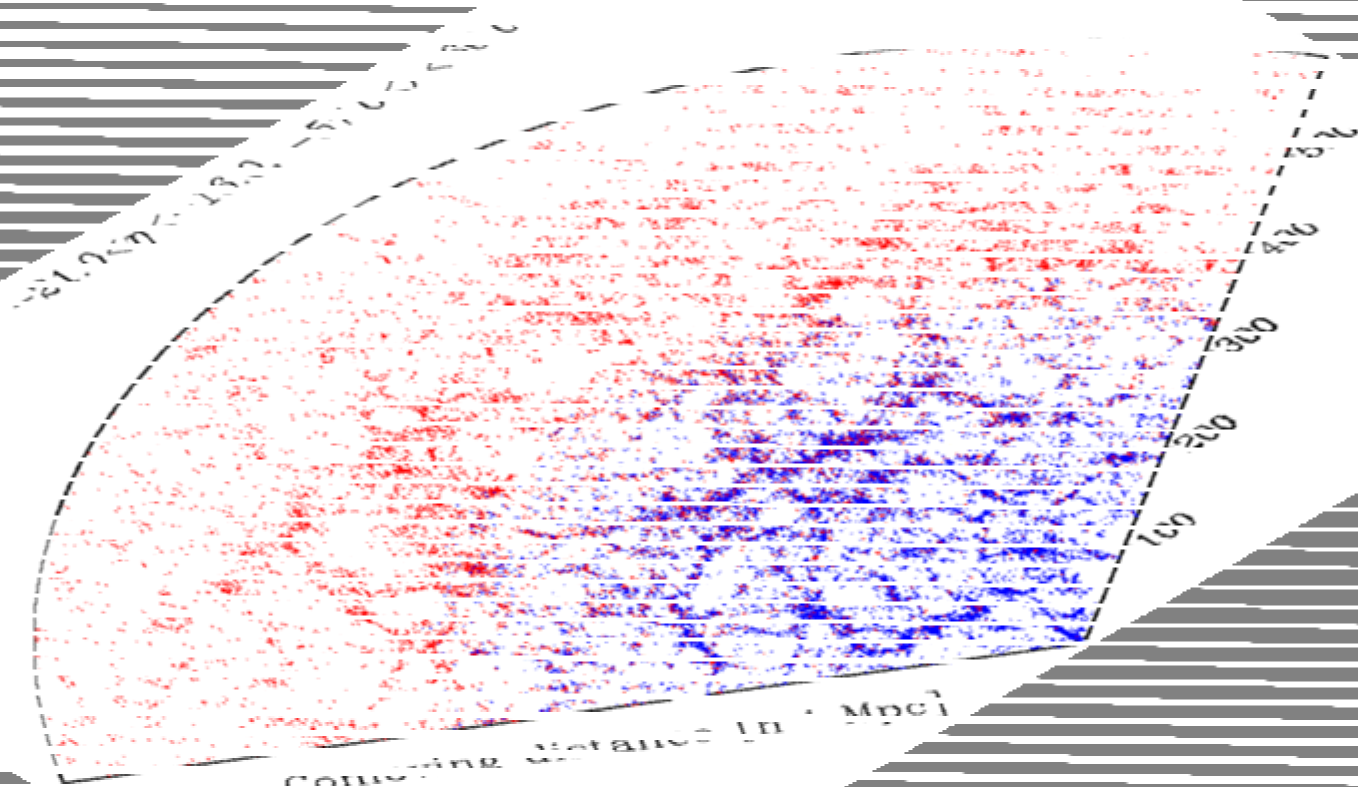

100
200
300
400





In DR7, CfA **homunculus shows up.**


η[degree]
λ[degree]
40
20
0
-20
-40
60
40
20
0
-20
-40
-60


100
200
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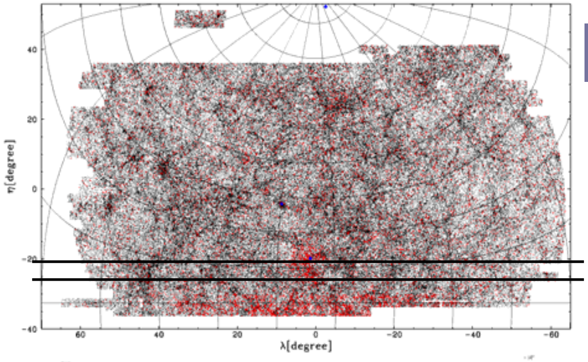
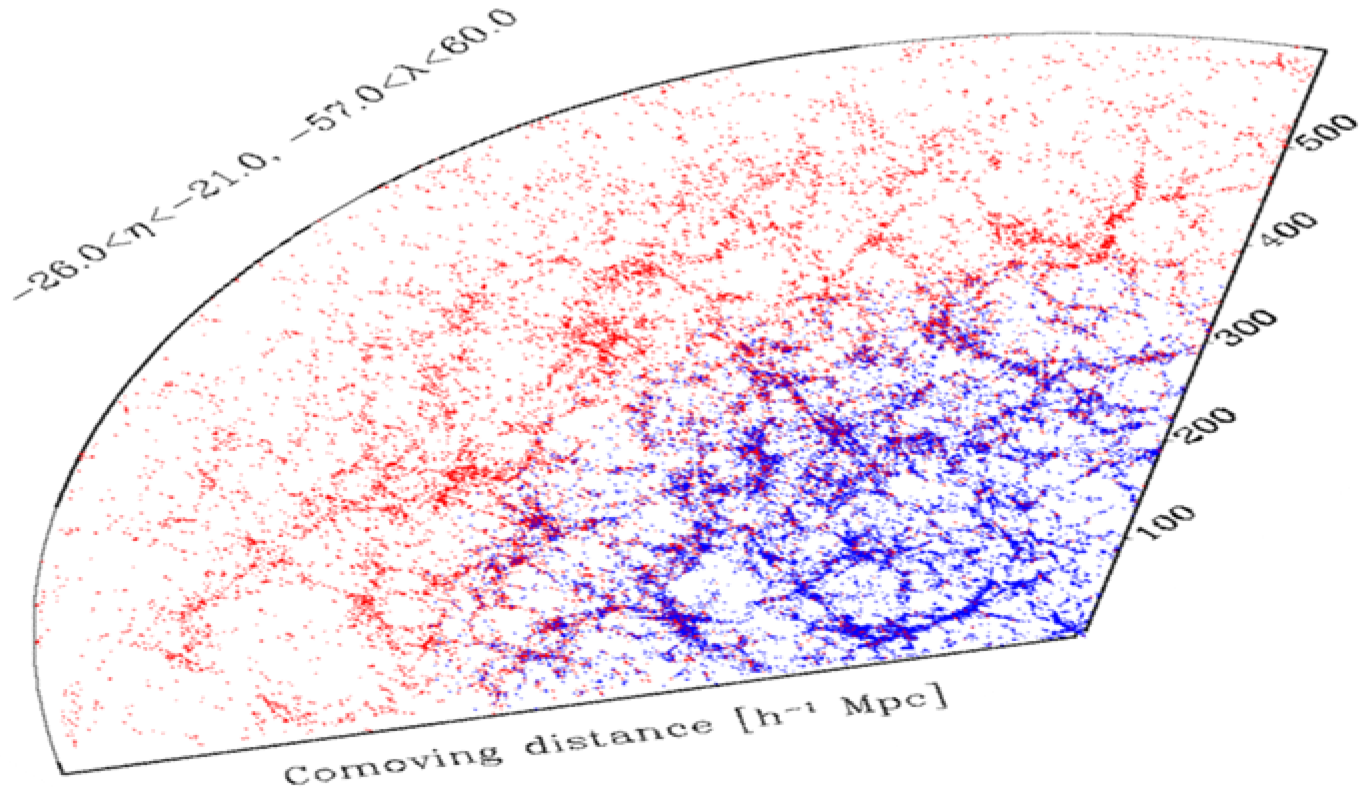
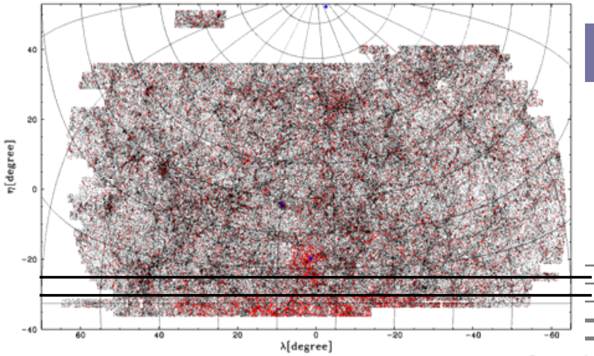
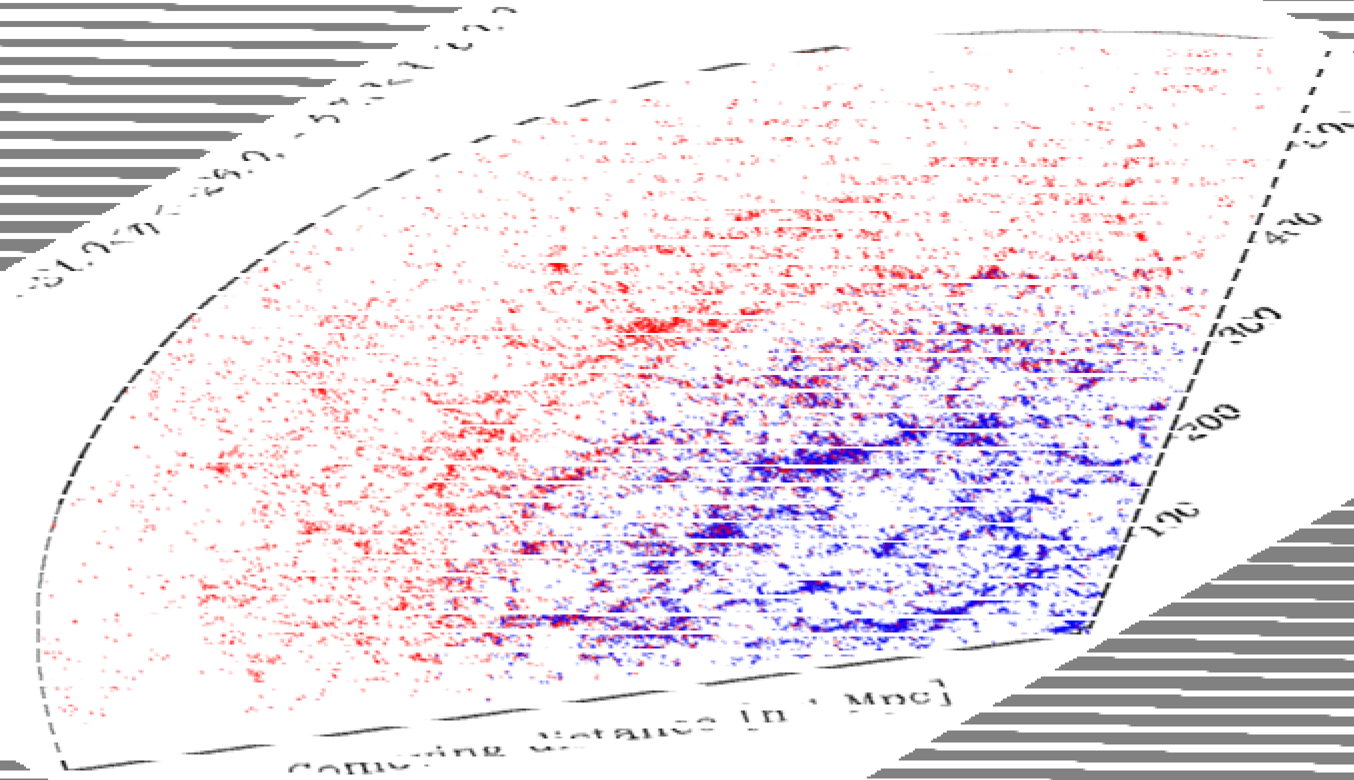


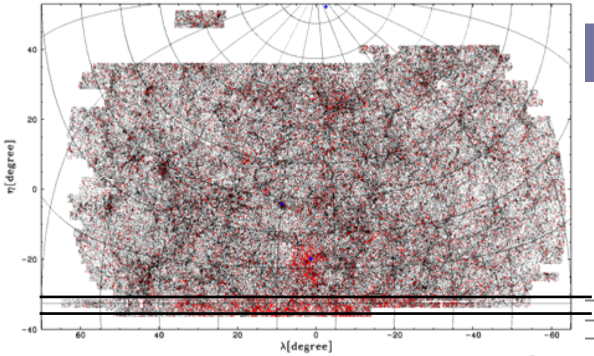
η[degree]
λ[degree]

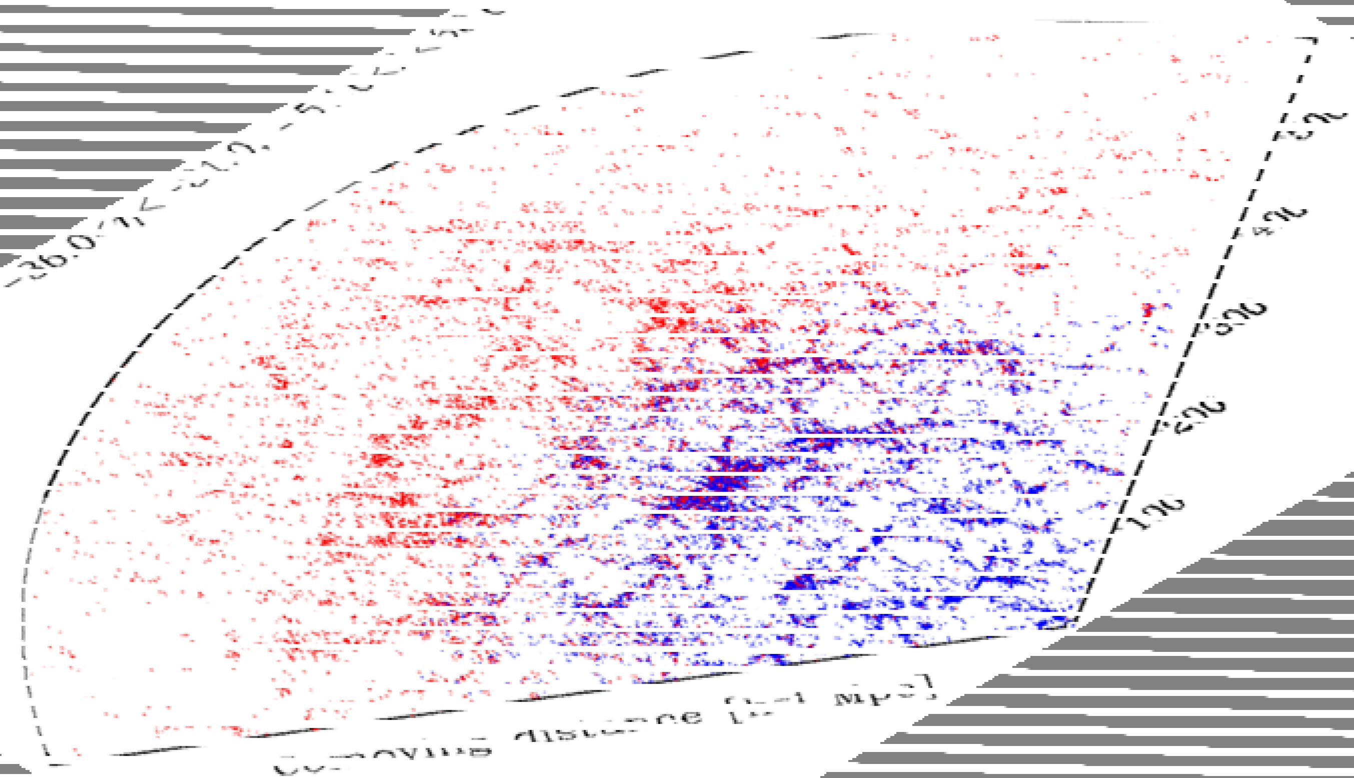


−26.0<η<−21.0, −57.0<λ<60.0
100
200
300
400
500
Comoving distance [h^{-1} Mpc]

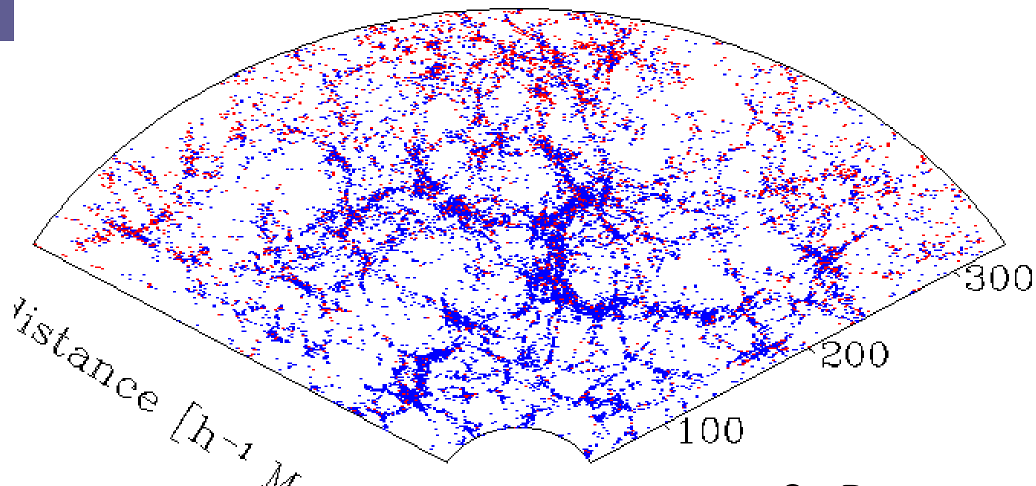

η[degree]
λ[degree]



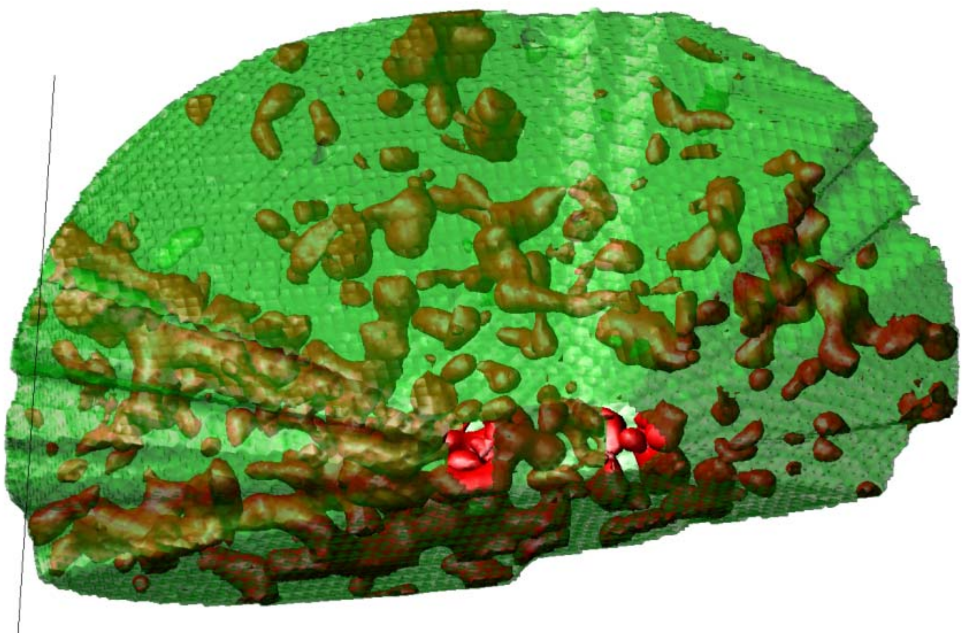




The Sloan Great Wall (Gott et al. 2005)

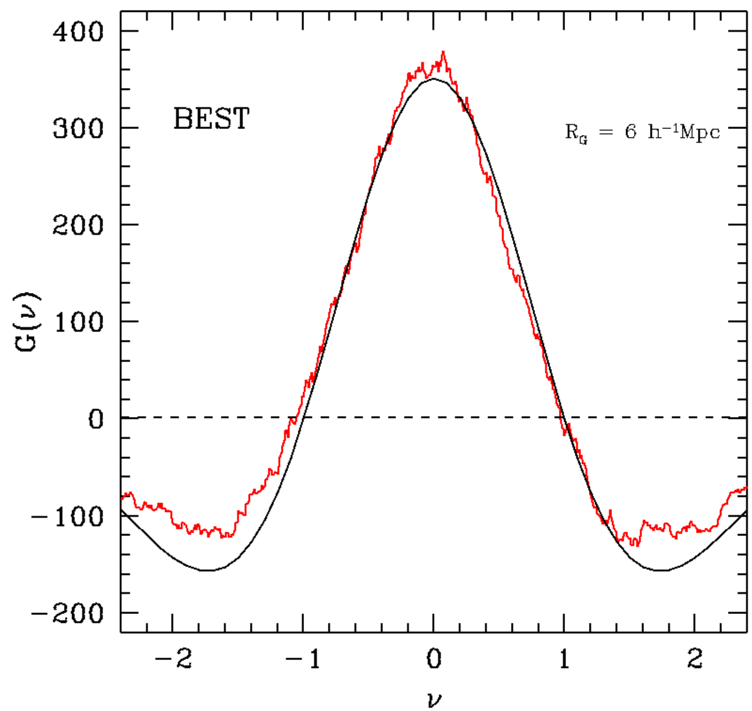


3-D galaxy number density field



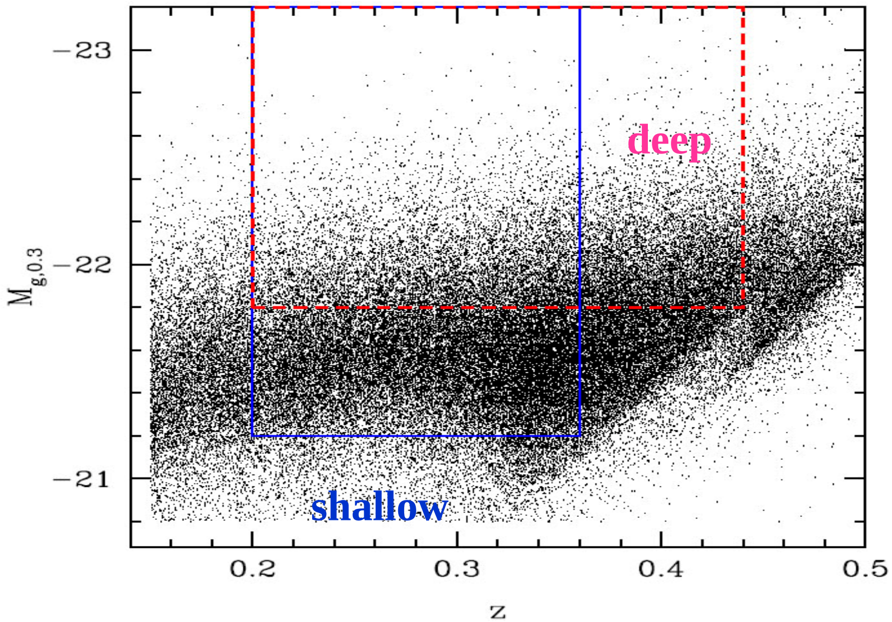
3-D genus curve:

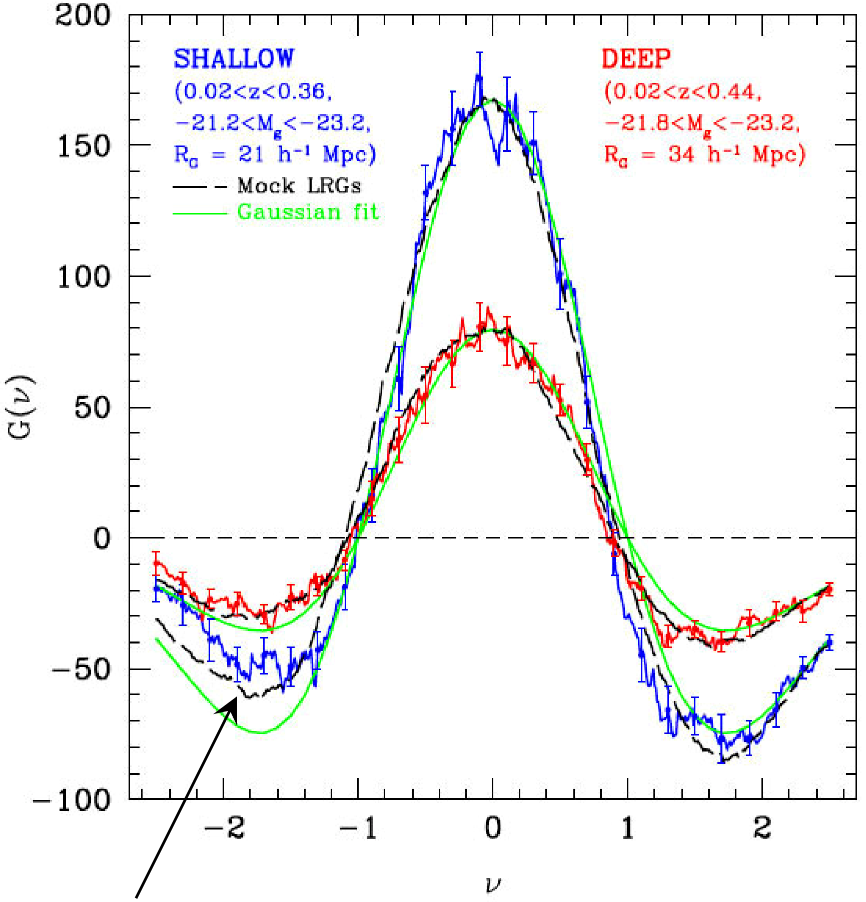
DR7 Main Galaxies at 6 h^{-1}Mpc



Luminous Red Galaxies:
SDSS DR4plus

[Gott et al. 2008]



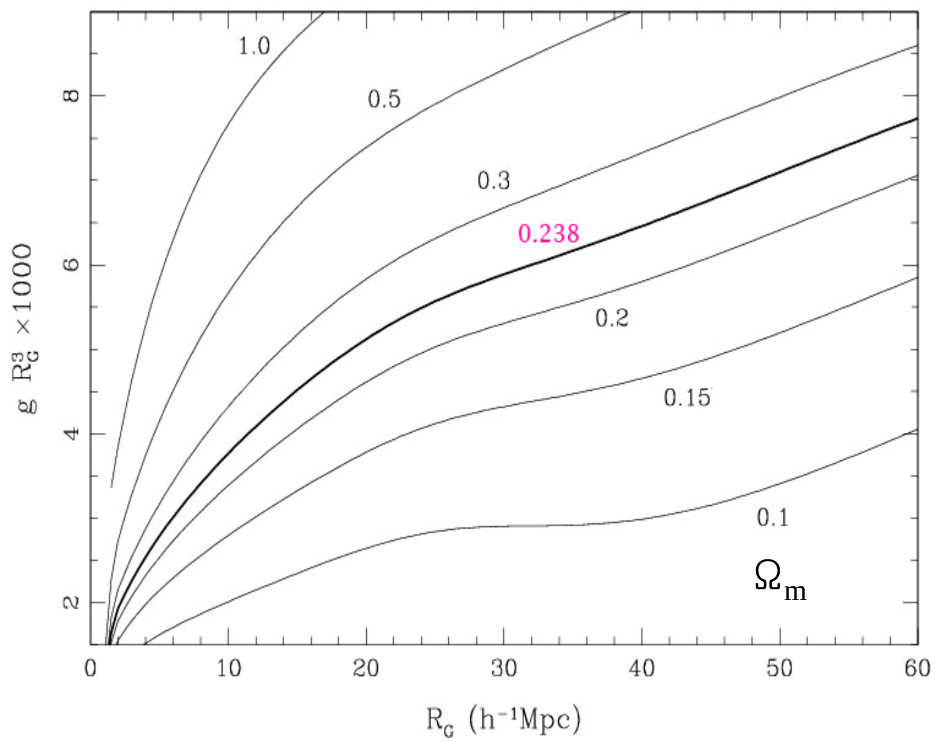


dark subhalos
from LCDM

Amplitude of the genus curve : CDM models

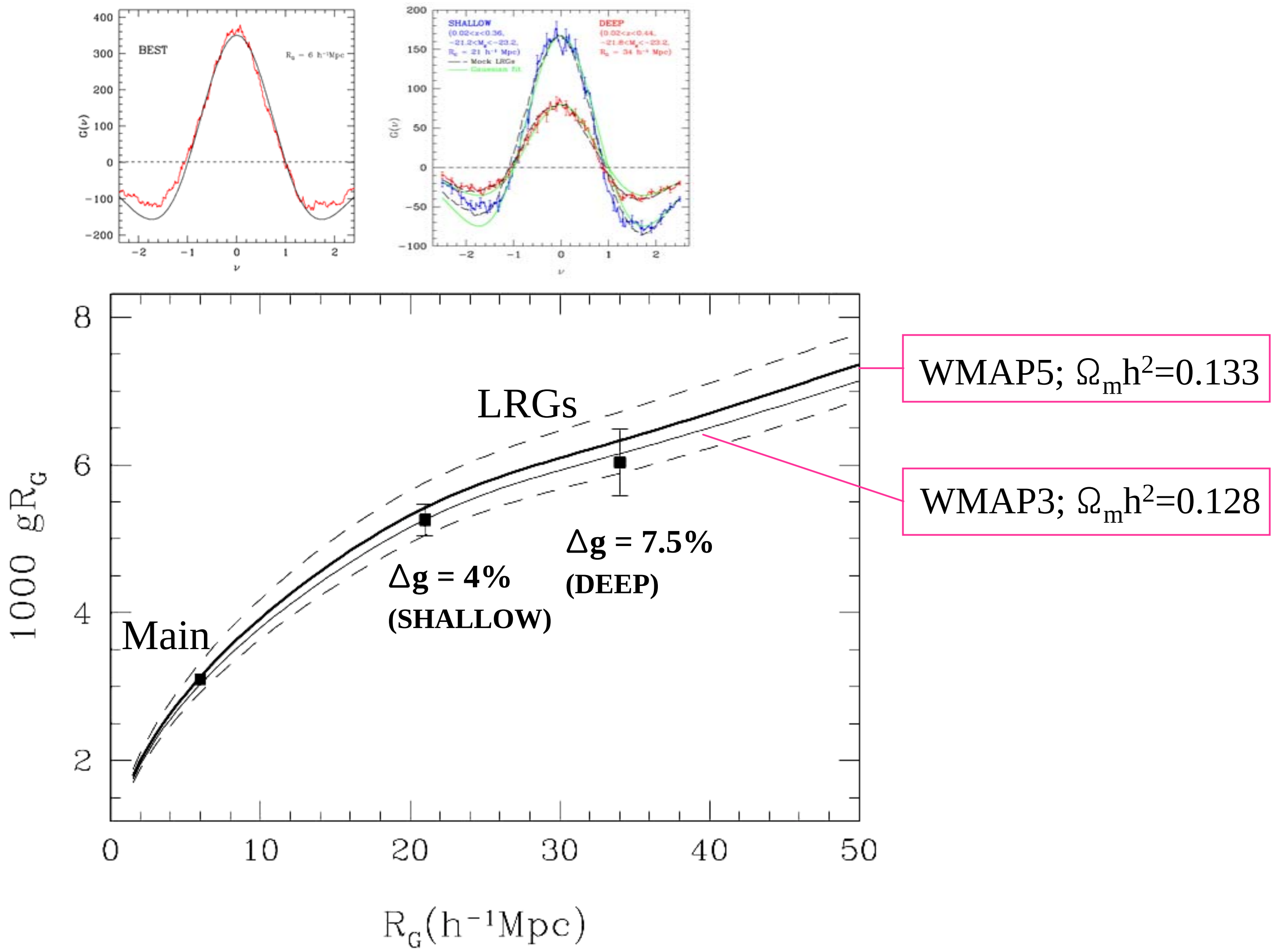
: sensitive to the shape of the PS (i.e. $\Omega_m h$)

Genus per smoothing volume in a flat ΛCDM universe



smoothing length

Observational constraints on the PS shape



Using the LSS as a Cosmic Ruler

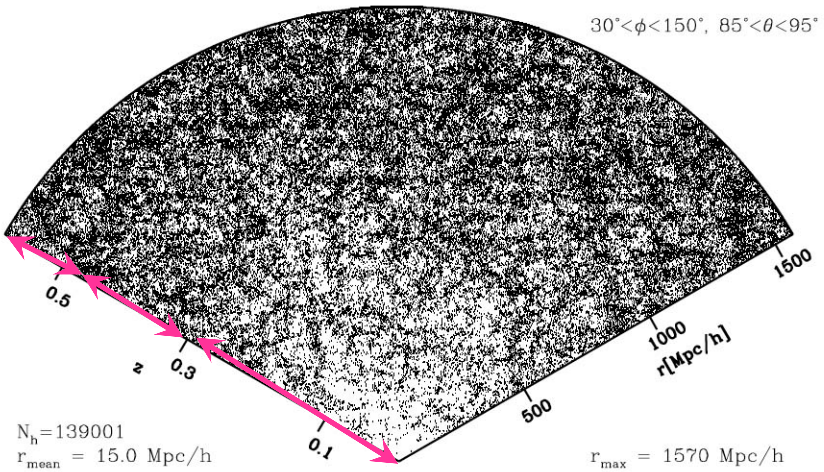
LSS at different redshift shells

→ Measure the topology statistic

→ Require the topology be the same in each comoving shell

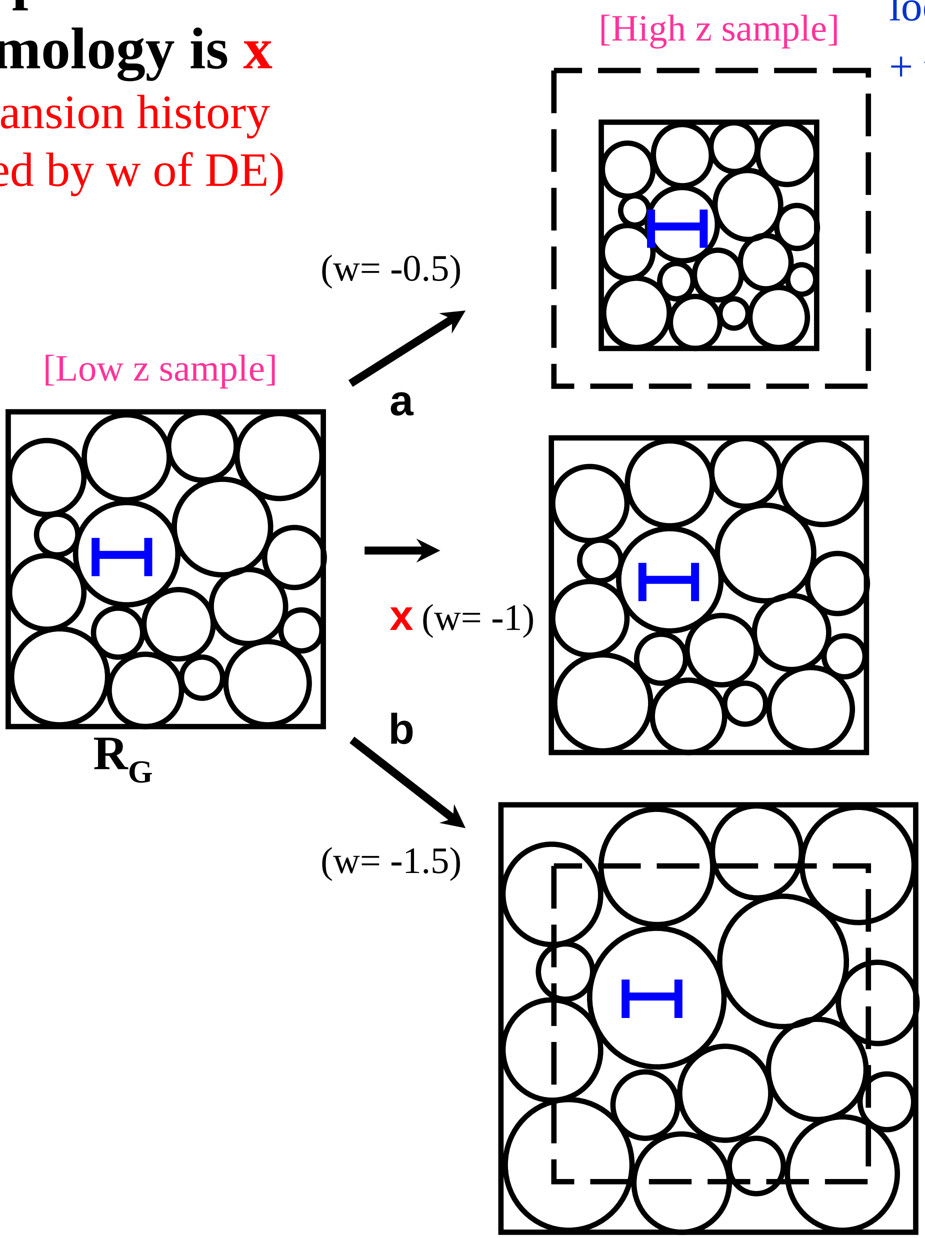
→ Expansion history of the universe

→ Cosmological parameter estimation



Suppose the true cosmology is x

(expansion history varied by w of DE)



looking at a larger smoothing scale
+ taking a larger unit volume

genus per unit volume in a wrong cosmology

= genus of true cosmology at scaled smoothing length

X volume factor of true cosmology

/ volume factor of wrong cosmology

(Park & YR Kim 2009)

Measured genus density when a wrong cosmology 'a' is adopted

= genus of true cosmology at scaled R_G

× (volume factor of true cosmology / volume factor of wrong cosmology)

= $g(R_G') \times D_V(\text{cosmology x}) / D_V(\text{cosmology a})$

where $D_V = d_A{}^2/H(z)$, $R_G' = R_G \times [D_V(x)/D_V(a)]^{1/3}$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_X \exp\left[3 \int_0^z \frac{1+w(z)}{1+z} dz\right]}$$

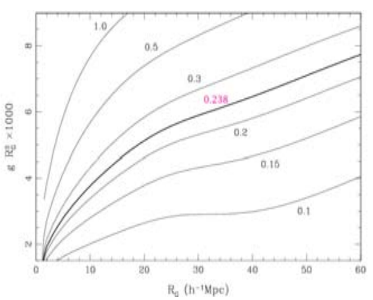
$d_A(z) = (1+z)^{-1}\, r(z)$ and $r(z) = \int_0^z \frac{dz'}{H(z')}$

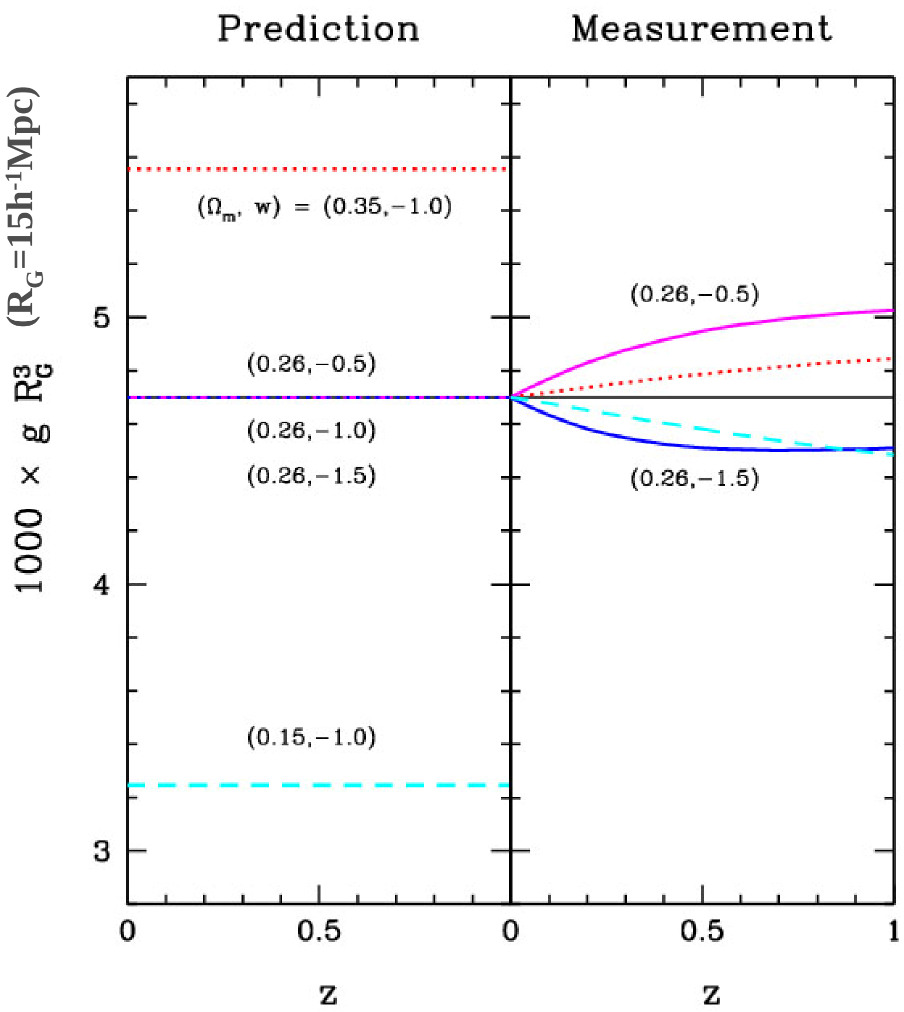
LSS Genus & Constraining Dark Energy

Suppose we live in a universe with $(\Omega_m, w) = (0.26, -1.0)$.

Let's choose a wrong w when z is converted to r(z).

Difference between the predicted and measured genus as z changes.
(the w-dependence originates from different expansion history of space)





(Park & YR Kim 2009)

Preliminary

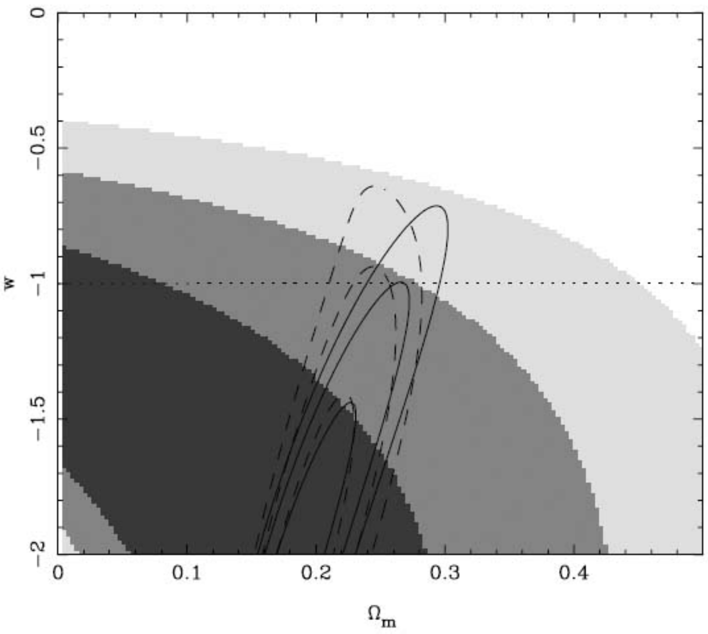
Constraint on 'w' using the genus statistic only :

LRGs in SDSS DR4plus

: $\triangle g$ = 4% (shallow, R_G=21h^{-1}Mpc) & 7.5% (deep, R_G=34h^{-1}Mpc)

→ $\Delta w \sim 0.4$

Likelihood contours from the BAO scale measurement for flat LCDM models with constant w. $D_V(z=0.35)/D_V(0.2)$ is used. [Percival et al. 2007]



Preliminary

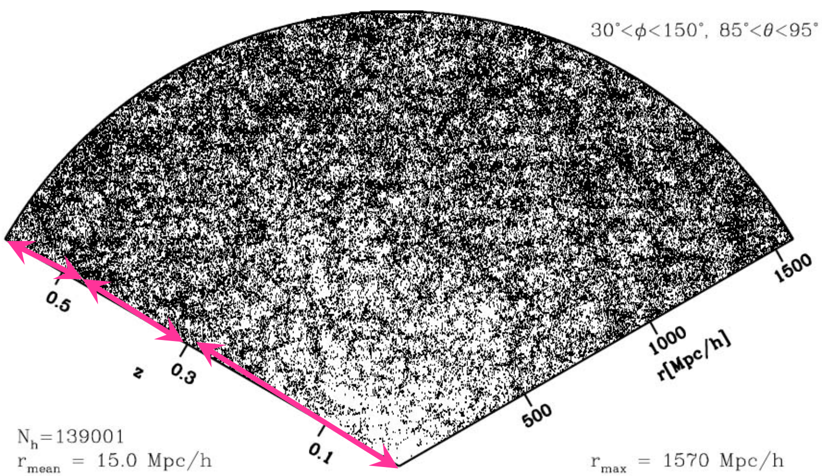
Future surveys

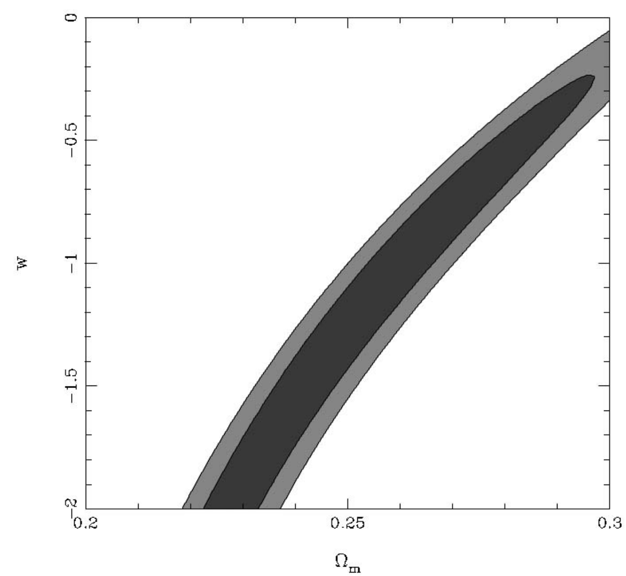
Constraint on 'w' using the genus statistic only :

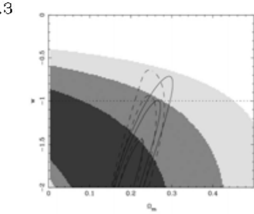
LRGs in SDSS-III : # of LRGs ~ 1.5M

$\triangle$g = ~1.0% in each of 3 z-bins $\rightarrow$ $\triangle$w ~ 0.05

(uncertainty in the BAO peak scale ~ 4% in such shells - JH Kim et al. 2008)





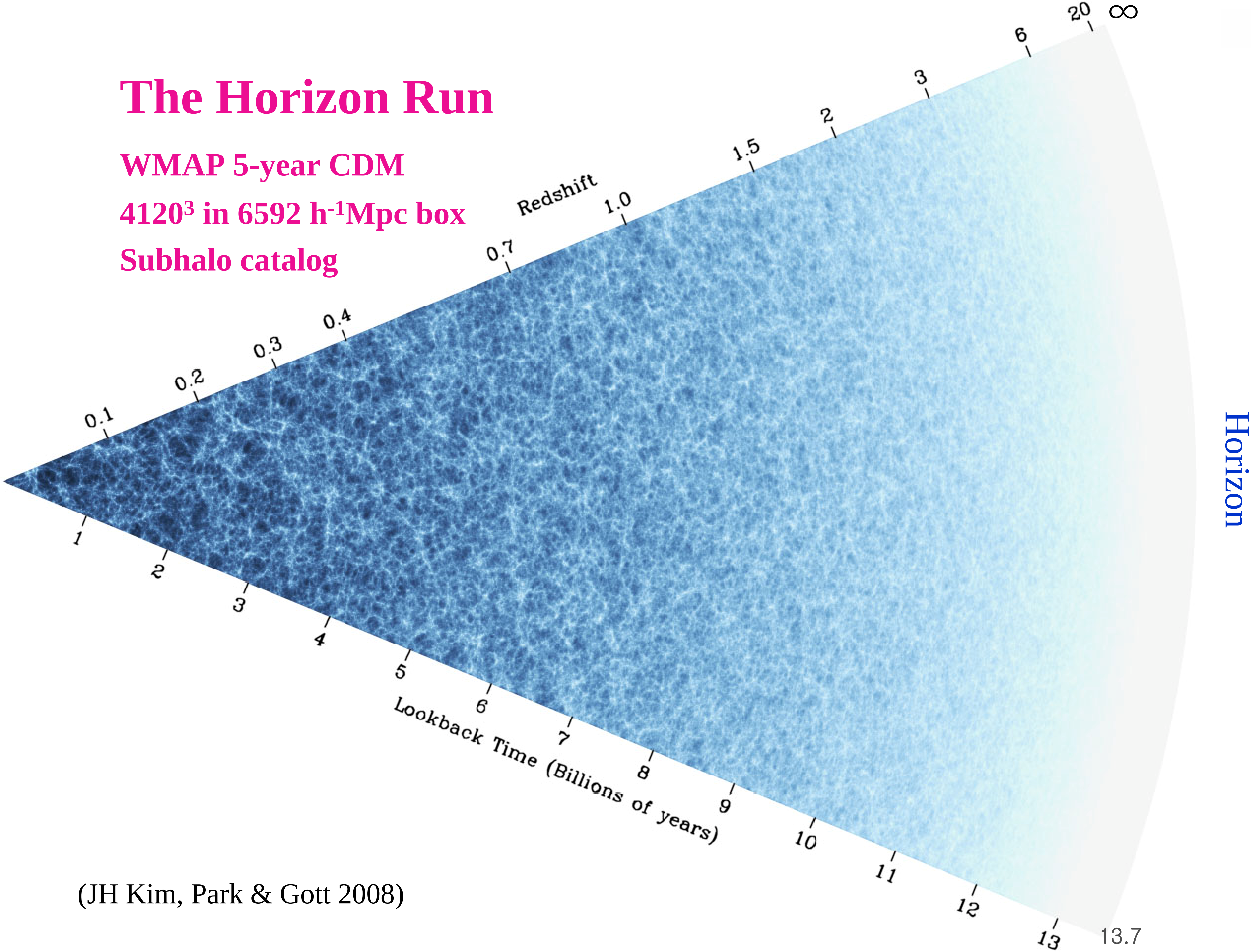


The Horizon Run

WMAP 5-year CDM

4120^3 in 6592 h^{-1}Mpc box

Subhalo catalog



(JH Kim, Park & Gott 2008)

Now small effects of

NL gravitational evolution, biasing, redshift-space distortion
(also discreteness & finite pixel size effects)

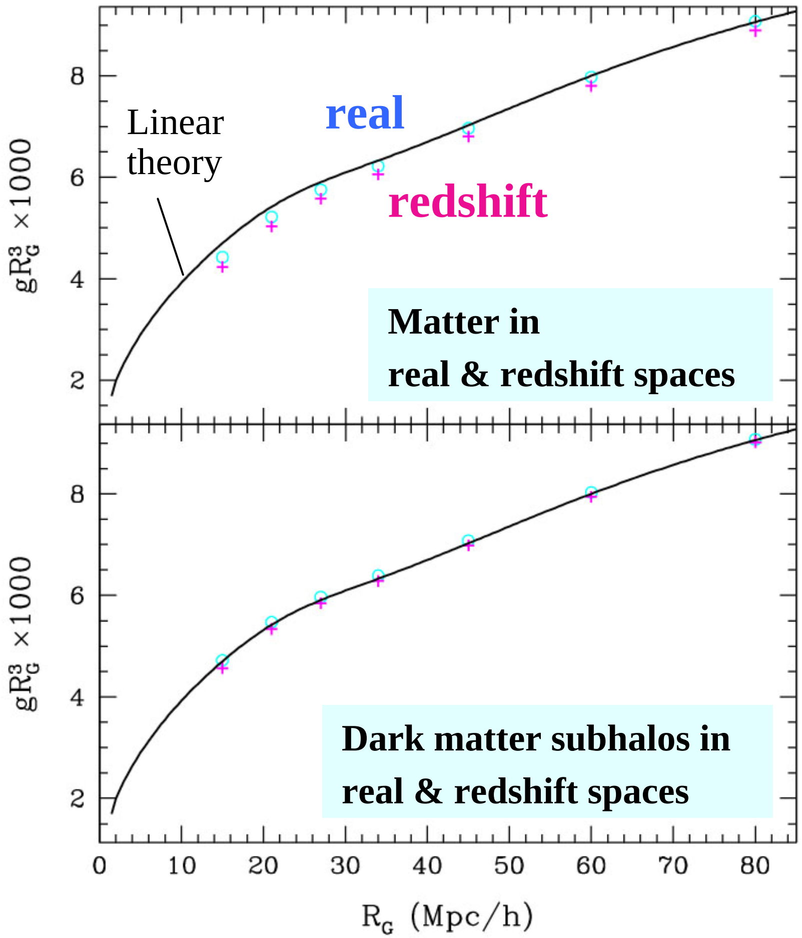
A ΛCDM N-body simulation with Ω_m=0.26

1. gravitationally evolved matter field

2. distribution of dark subhalos (d=15h^{-1}Mpc)

Genus in real and redshift spaces

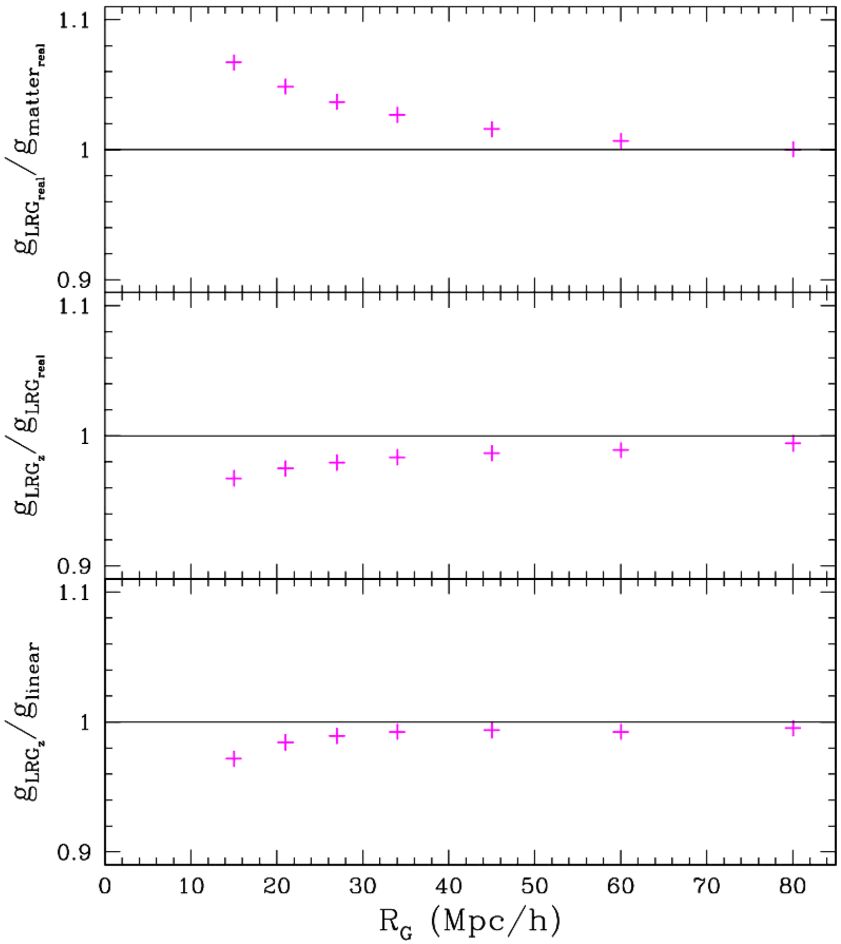
[Kim, Park & Gott (2008)'s Horizon Run]



[biasing]

[redshift space distortion]

[gravitational evolution]
[biasing]
[redshift space distortion]
[discreteness]



space / R_G	LRGz vs linear theory
redshift / 15	-2.8%
redshift / 20	-1.7%
redshift / 30	-0.85%

Summary

1. **Topology of LSS has been used to examine the Gaussianity of galaxy distribution at large scales.**

This was used to test for the Gaussianity of the primordial density field,

which is one of the major predictions of the simple inflationary scenarios.

2. **Topology of galaxy distribution at non-linear scales is being used to constrain the galaxy formation mechanisms.**

3. **Here we propose to use the LSS as a standard ruler, and use the sponge topology of LSS or the overall shape of P(k) to measure the expansion history of the universe**

4. **2D and 1D LSS topology studies too!**

Redshift slices from the deep imaging surveys - 2d topology

Line-of-sight level crossings of Ly-a forest clouds, HI gas distribution - 1d topology