Topology of Large Scale Structure as a Cosmic Ruler

Extended Workshop on DM, LHC and Cosmology
The KIAS-KAIST-YITP Joint Workshop
27 Aug. - 4 Sept. 2009

Changbom Park
(Korea Institute for Advanced Study)

Why is the topology study useful?

1. Direct intuitive meanings

2. At large/linear scales

Gaussianity of the primordial density field (Gott et al. 1986)

3. At small non-linear scales

Galaxy distribution at non-linear scales sensitive to cosmological parameters & galaxy formation mechanism

(Park, Kim & Gott 2005)

Measures of 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

⟶ 2d galaxy surveys, CMB temperature/polarization fluctuations

1D

1. level crossings
2. length fraction

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

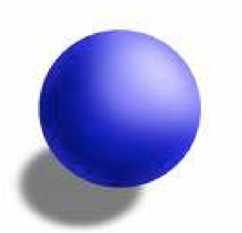
The 3D Genus

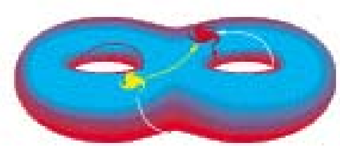
- **Definition**

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

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

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





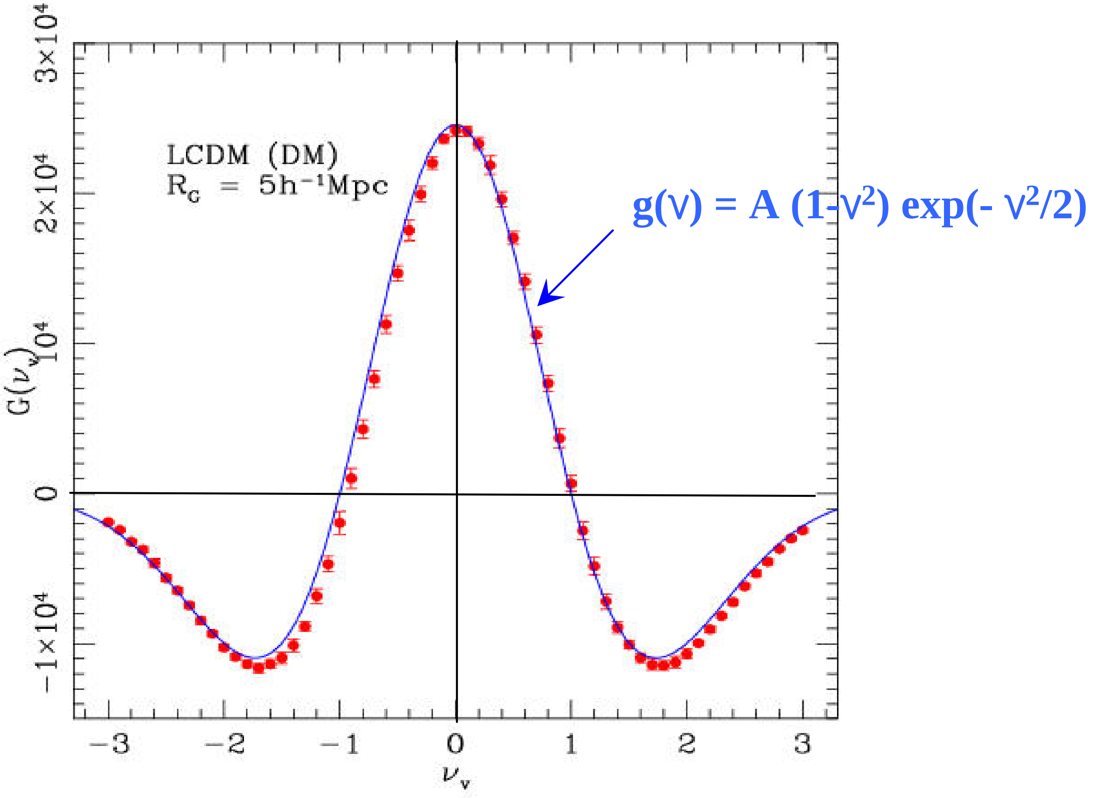
: 2 holes – 1 body = +1

- **Gaussian Field**

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

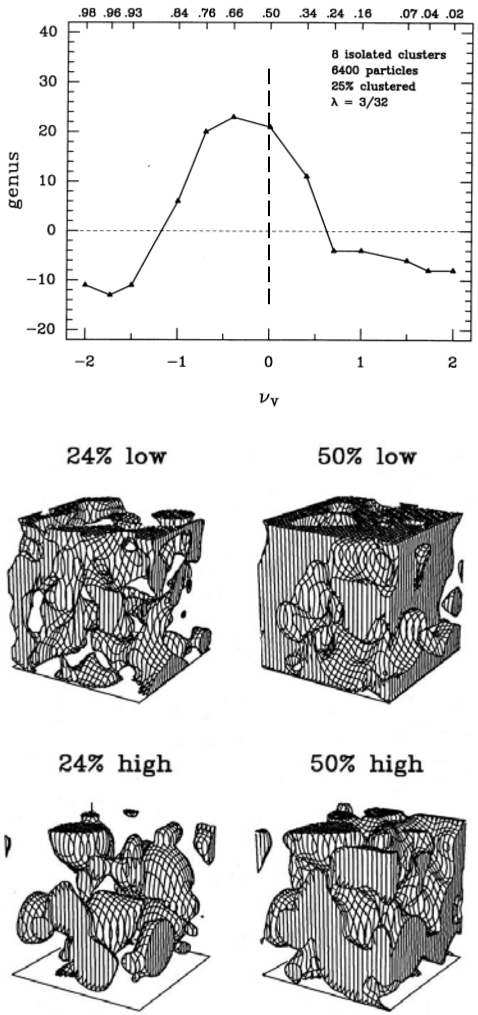
where $A = 1/(2\pi)^2 \langle k^2/3 \rangle^{3/2}$

does not depend on the amplitude of power spectrum

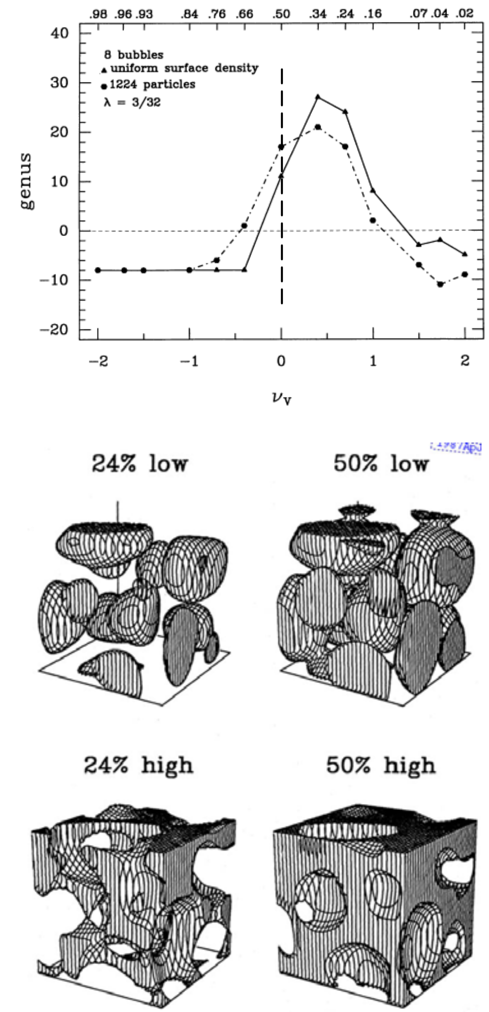


■ Non-Gaussian Field (Toy models)

Clusters



Voids



(Weinberg, Gott & Melott 1987)

History of LSS Topology Study

I. Early Works

- 1986: Hamilton, Gott, Weinberg; Gott, Melott, Dickinson
  – smooth small-scale NL clustering to recover initial topology
- 1987-8: GWM, WGM, MWG, Gott et al.
  – cosmological & toy models. $R_G > 3r_c$ to recover initial topology
- 1989: Gott et al. – observed galaxies, dwarfs, clusters
- 1991: Park & Gott – NL gravitational evolution& biasing effects
- 1992: Weinberg, Cole – PS, initial skewness, biasing effects
- 1994: Matsubara – 2^{nd} order perturbation in weakly NL regime
- 1996: Matsubara – redshift space distortion in L regime
  Matsubara & Suto – NL gravitational evolution & z-space distortion
  Matsubara & Yokoyama - non-Gaussian fields

II. Recent Works

- 2000: Colley et al. – Simulation of SDSS
- 2001, 2003: Hikage, Taruya & Suto – dark halos (analytic & numerical)
- *2003: Matsubara – 2^{nd} order perturbation theory*
- Minkowski functionals

  Gott et al. (1990) - CMB

  Mecke, Buchert & Wagner (1994); Schmalzing & Buchert (1997)

  Matsubara(2008) - perturbation theory of halo bias & redshift-space distortion

III. 3D genus analysis of observational data

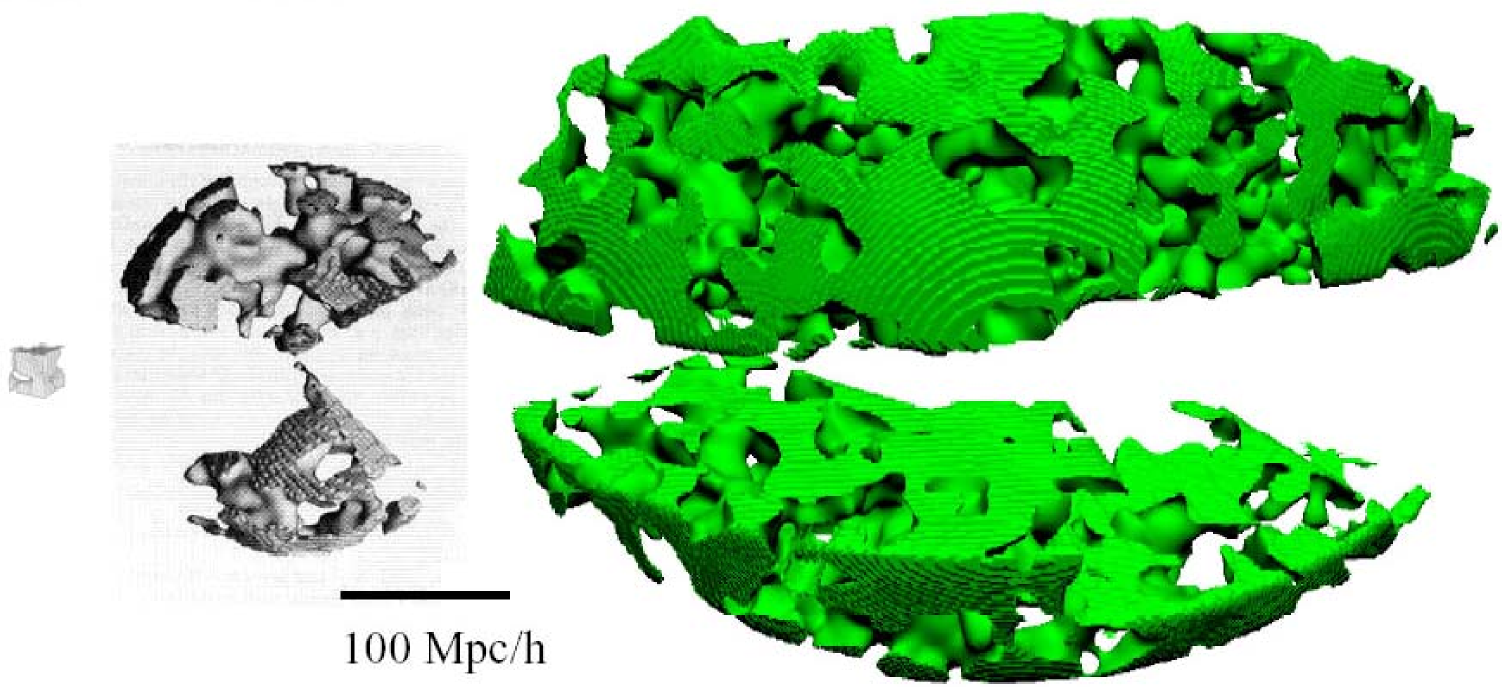
1989: Gott et al.	- CfA 1 etc.	→ consistent with Gaussian
1992: Park, Gott, & da Costa	- SSRS 1	
1992: Moore et al.	- IRAS QDOT	
1994: Rhoads et al.	- Abell Clusters	
1994: Vogeley et al.	- CfA 1+2	
1997: Protogeros & Weinbergs	- IRAS 1.2Jy	
1998: Springel et al.	- IRAS 1.2Jy	"
1998: Canavezes et al.	- IRAS PSCz	
2002: Hikage et al.	- SDSS EDR	
2003: Hikage et al.	- SDSS LSS Sample 12	
2004: Canavezes & Efstathious	- 2dFRGS	
2005: Park et al.	- SDSS LSS Sample 14	→Luminosity bias in topology
2008: Gott et al.	- SDSS DR4plus	

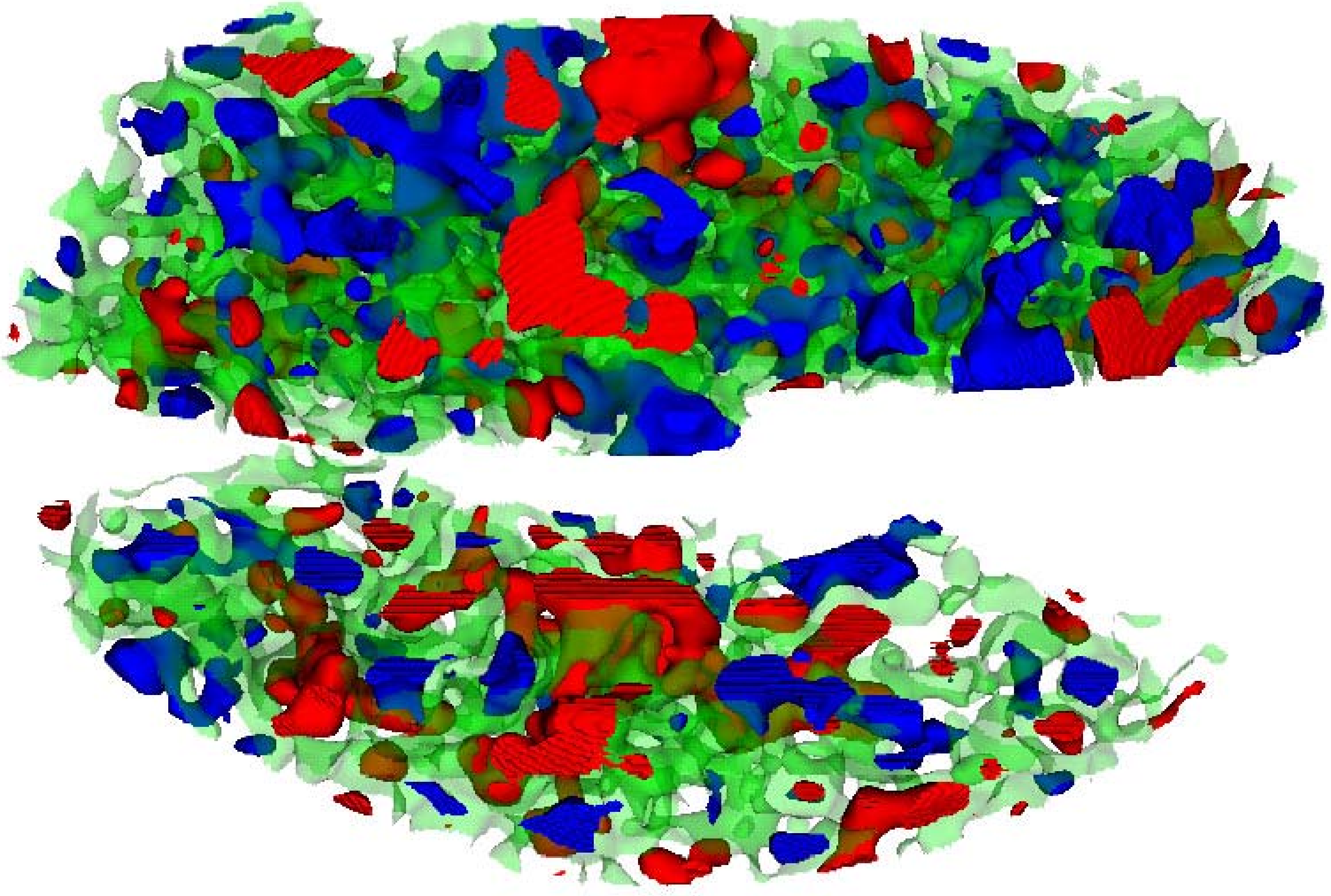
Observational samples

Gott et al. (1986): CfA1

Vogeley et al. (1994): CfA2

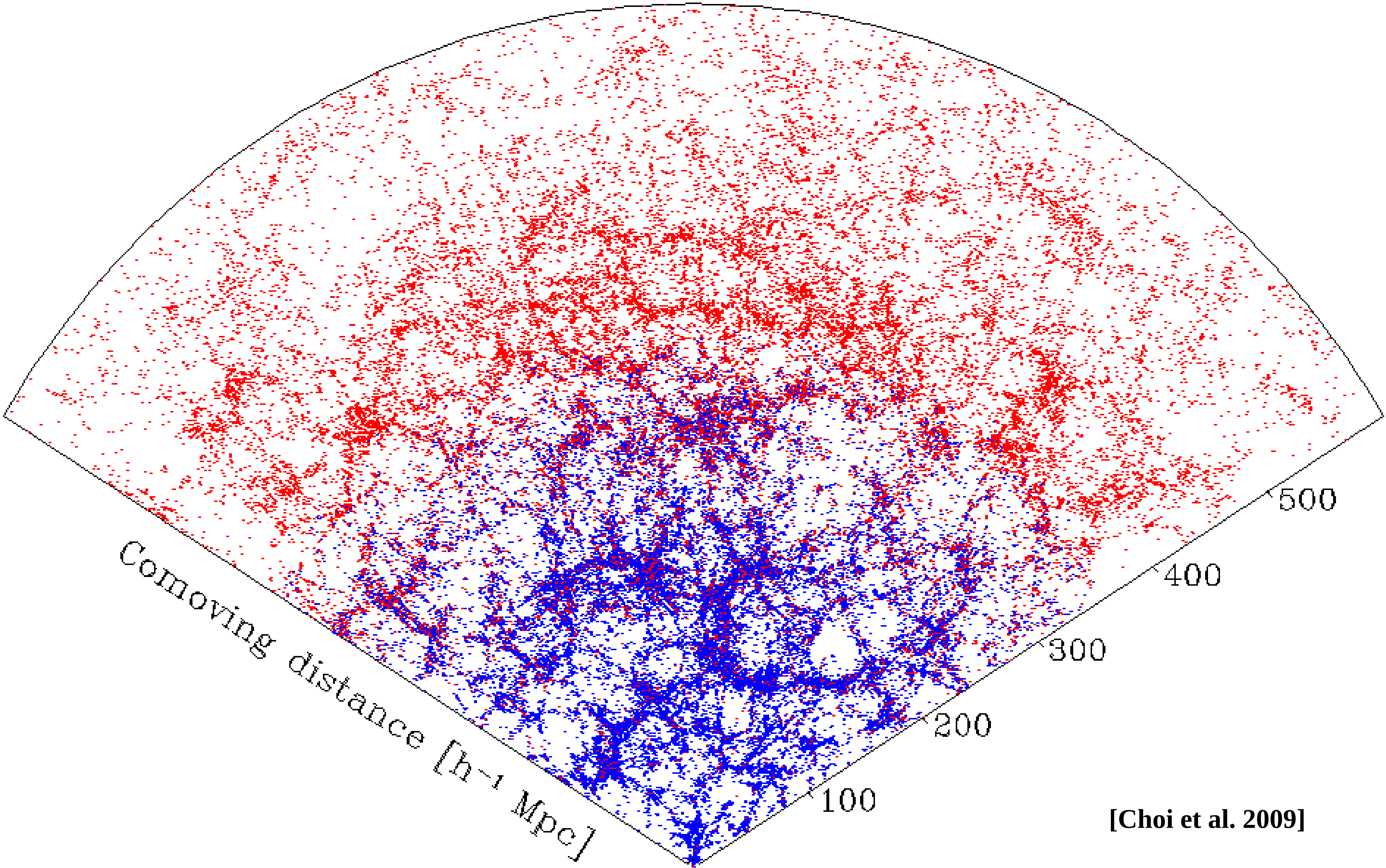
Gott et al. (2006) : SDSS DR4plus





Voids (blue - 7% low), filaments/clusters (red - 7% high) => Sponge !! (Gott et al. 2008)

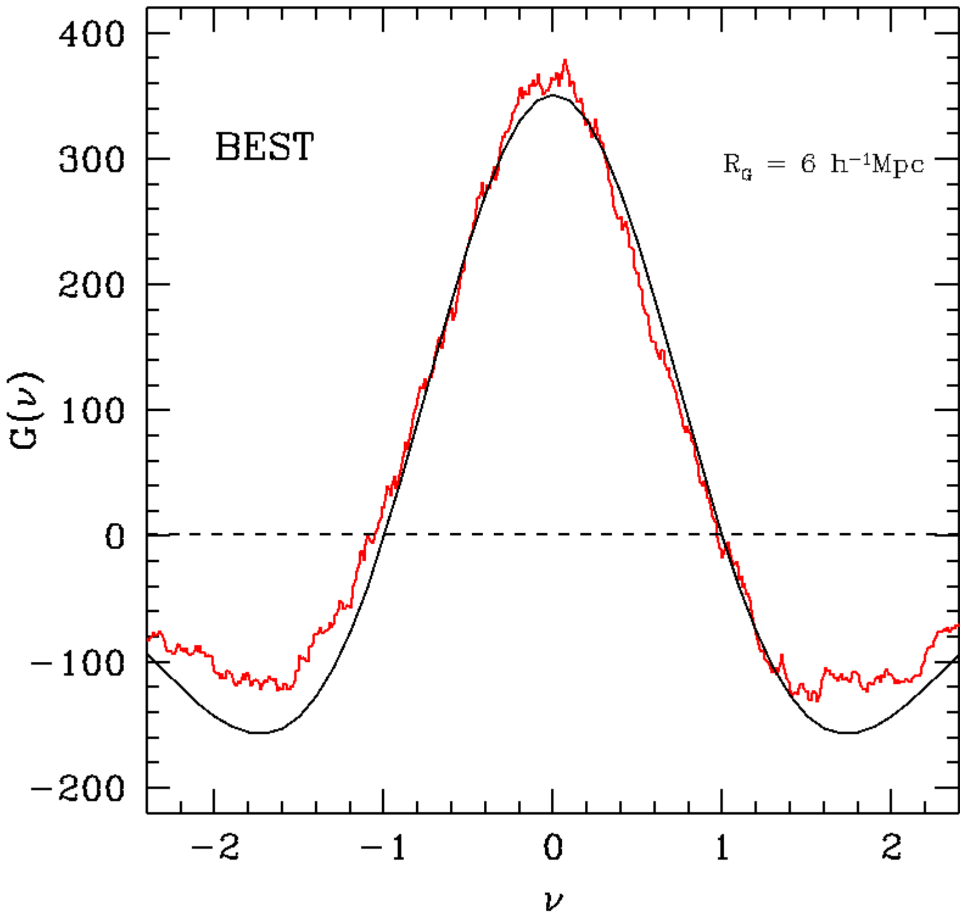
Final SDSS DR7 Main Galaxy Sample (2008)



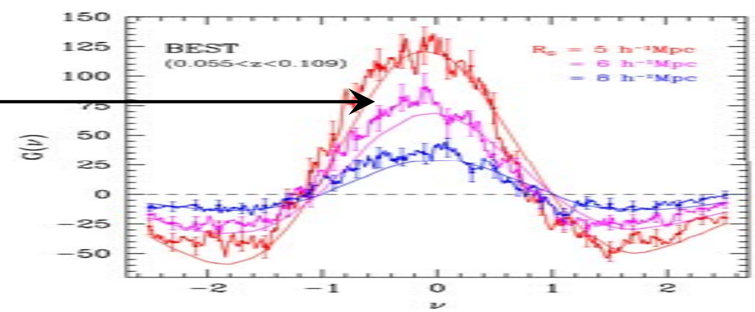
[Choi et al. 2009]

3-D genus curve

[Sample DR7: Choi et al. 2009]



[Sample 14: Park et al. 2005]



Large-scale structure

as a cosmic ruler

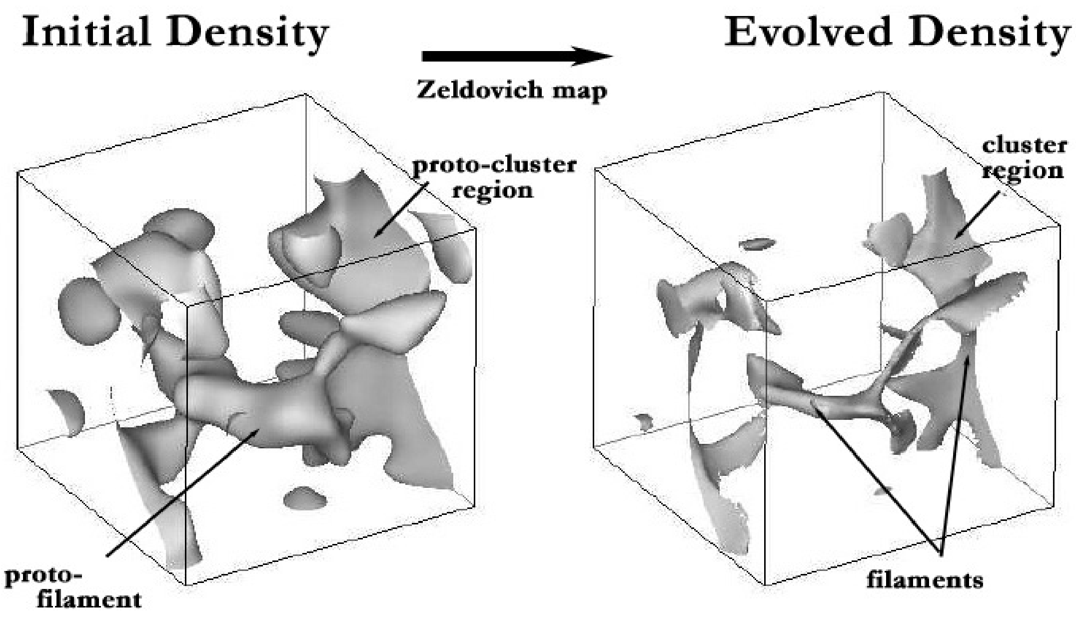
Use the sponge topology of LSS or the overall shape of P(k) at large scales as a standard ruler to measure the expansion history of the universe

→ cosmological parameters like $\Omega_m h$, w, etc.

LSS as a cosmic ruler

Filament-dominated Cosmic Web

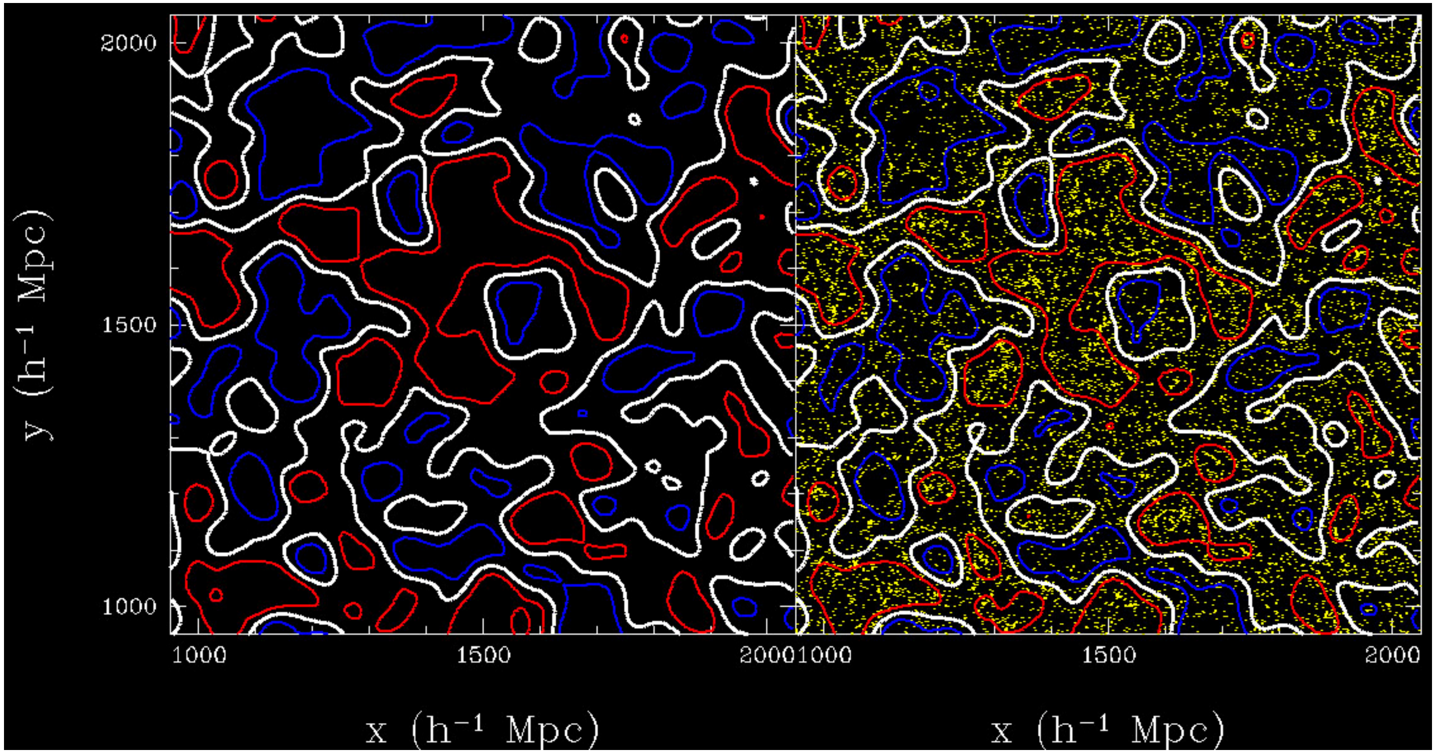
Bond et al. (1996) : Final-state web is present in embryonic form in the overdensity pattern of the initial fluctuations with NL dynamics just sharpening the image.



Cosmic sponge theory

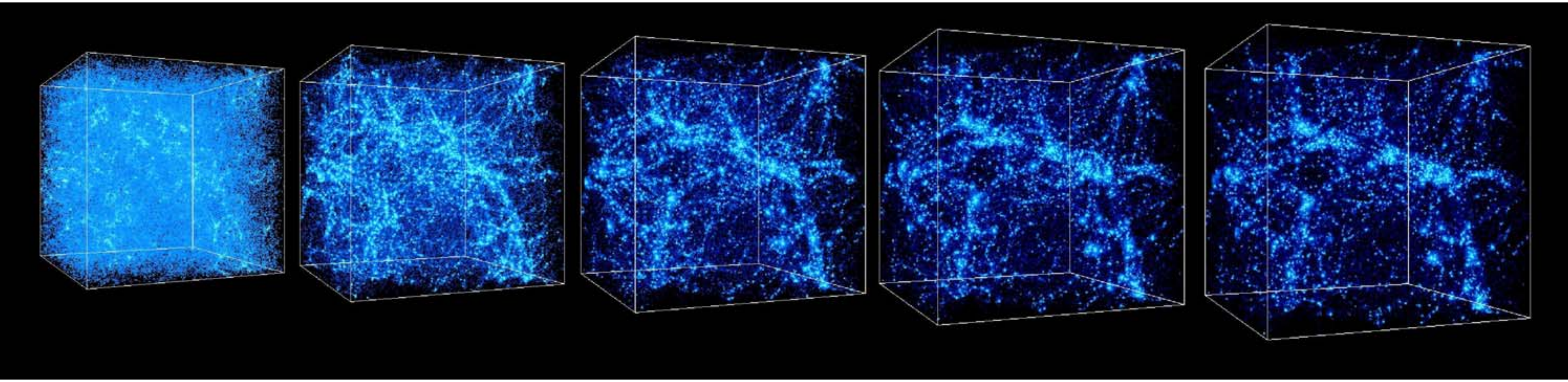
Not just overdensity patterns but all large-scale structures including voids maintain their initial topology (sponge) till the present

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



flat LCDM

R_G=25h^{-1}Mpc



(courtesy: A. Kravtsov).

The LSS 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)

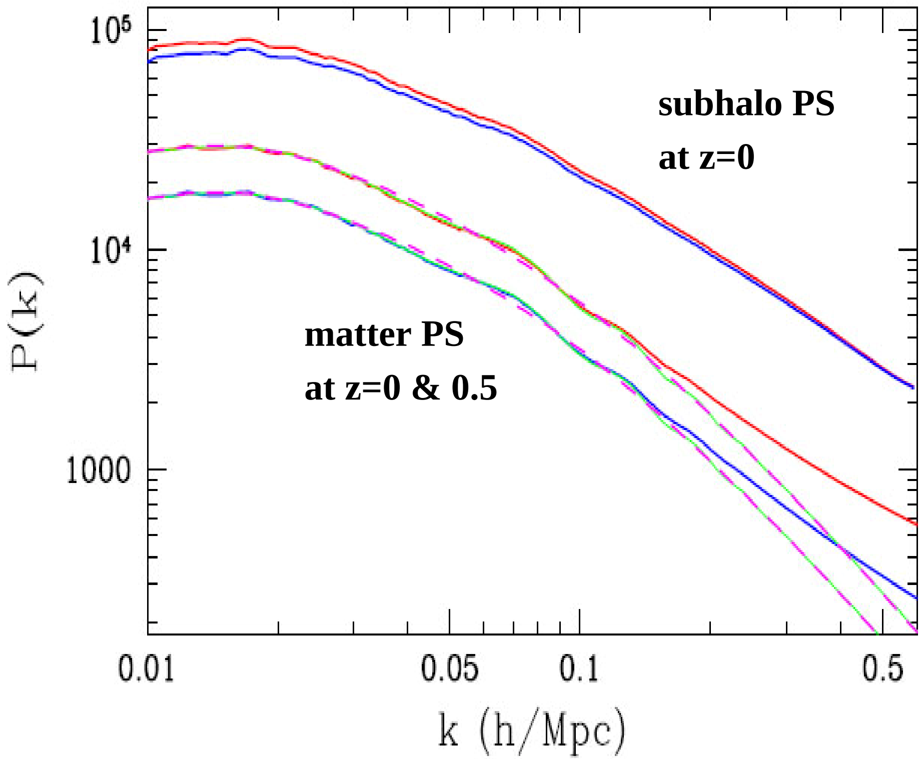
Now, the LSS can be used as a cosmic ruler for cosmological parameter estimation!

Scale dependence of PS encoded in the LSS

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

The whole shape of PS, not just the BAO wiggle 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 et al. (2009)

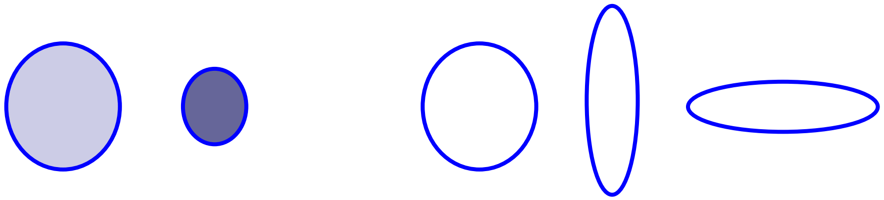
The Horizon Run

[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]



Using the LSS topology to measure the expansion history

Strategy

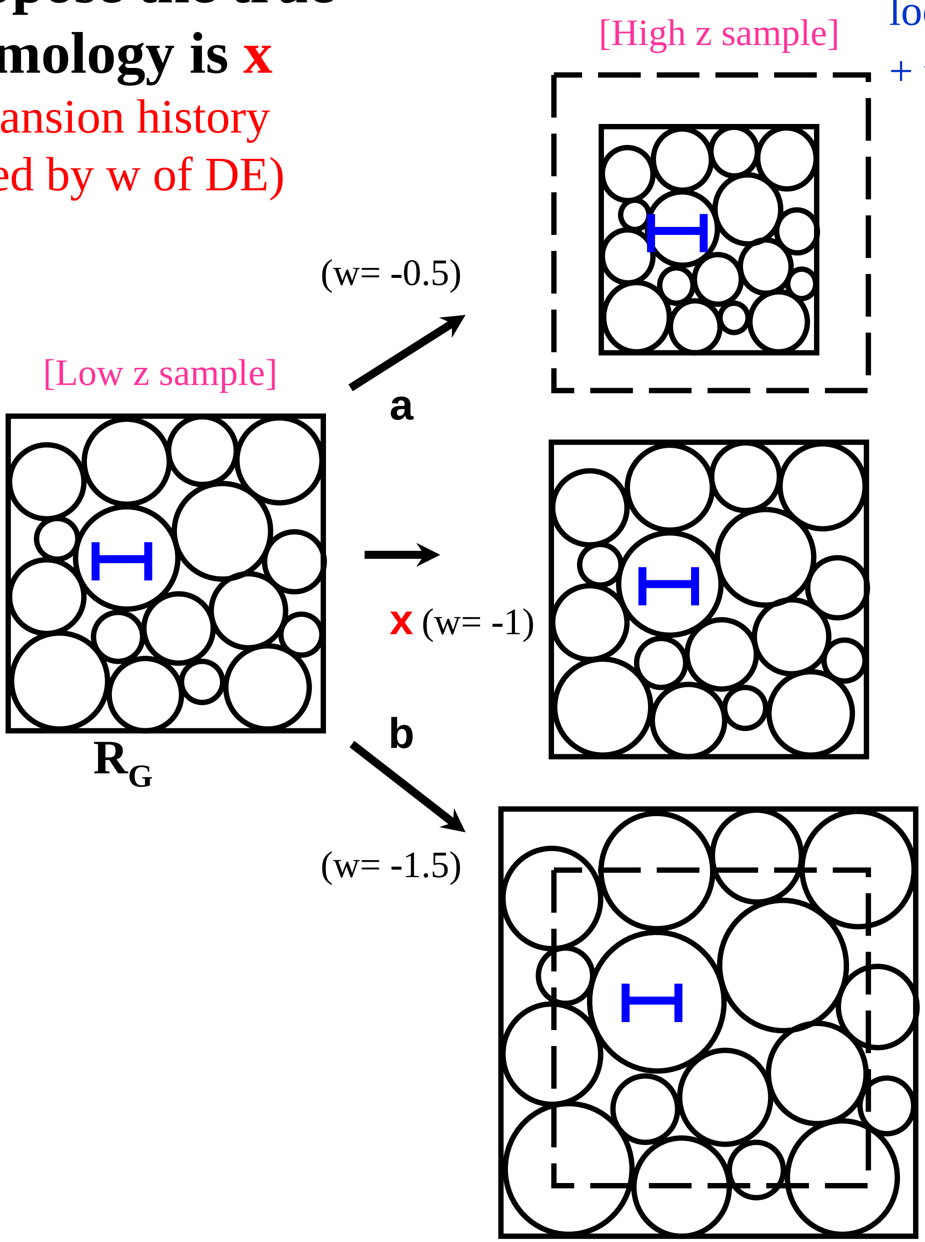
- choose a reference cosmology with a certain $w = P/\rho$
- convert z of galaxies into r(z) assuming the reference cosmology
- calculate the genus
- compare the measured genus with the predicted genus in the reference cosmology

(the w-dependence originated from the different expansion history of space)

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

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

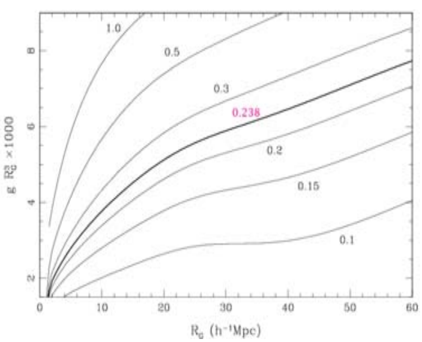
$d_A(z) = (1+z)^{-1}\, r(z)$ and $r(z) = \int_0^z \frac{dz'}{H(z')}$

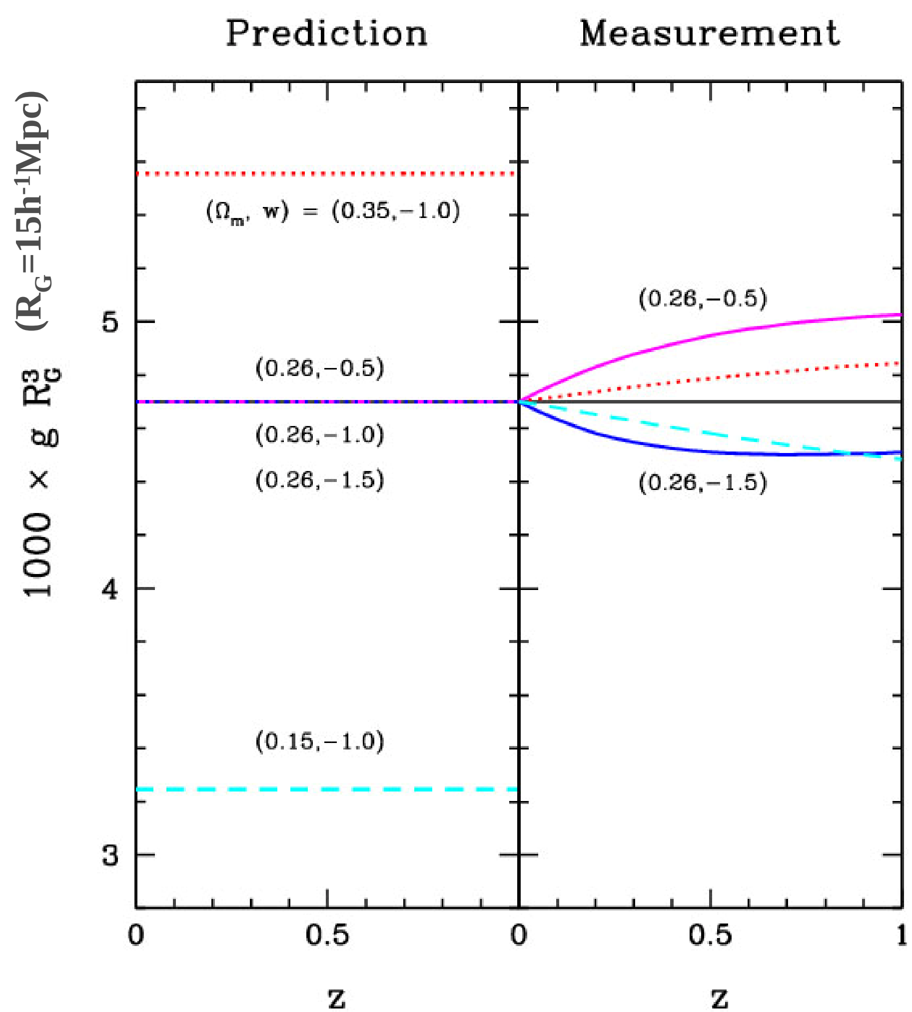
LSS Genus & Constraining Dark Energy

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).

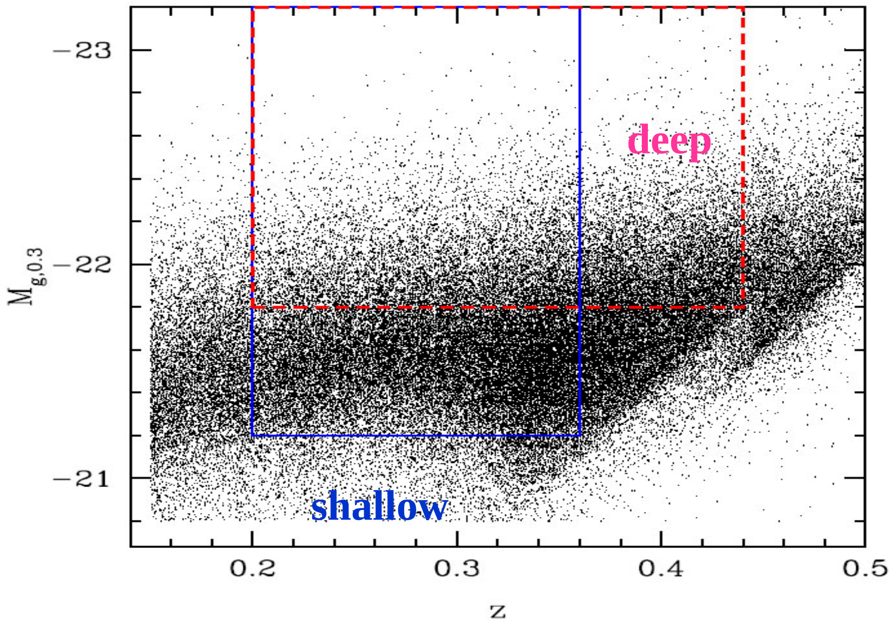
Difference between the predicted and measured genus as z changes.
(the w-dependence originates from different expansion history of space)



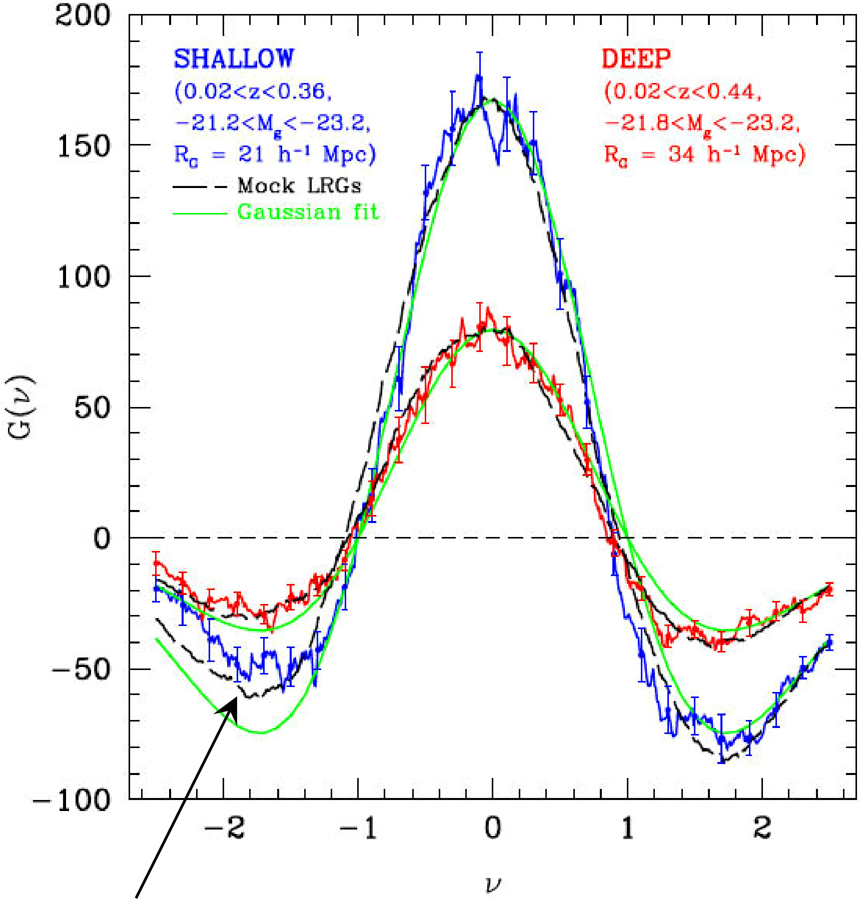


(Park & YR Kim 2009)

Luminous Red Galaxies:
SDSS DR4plus

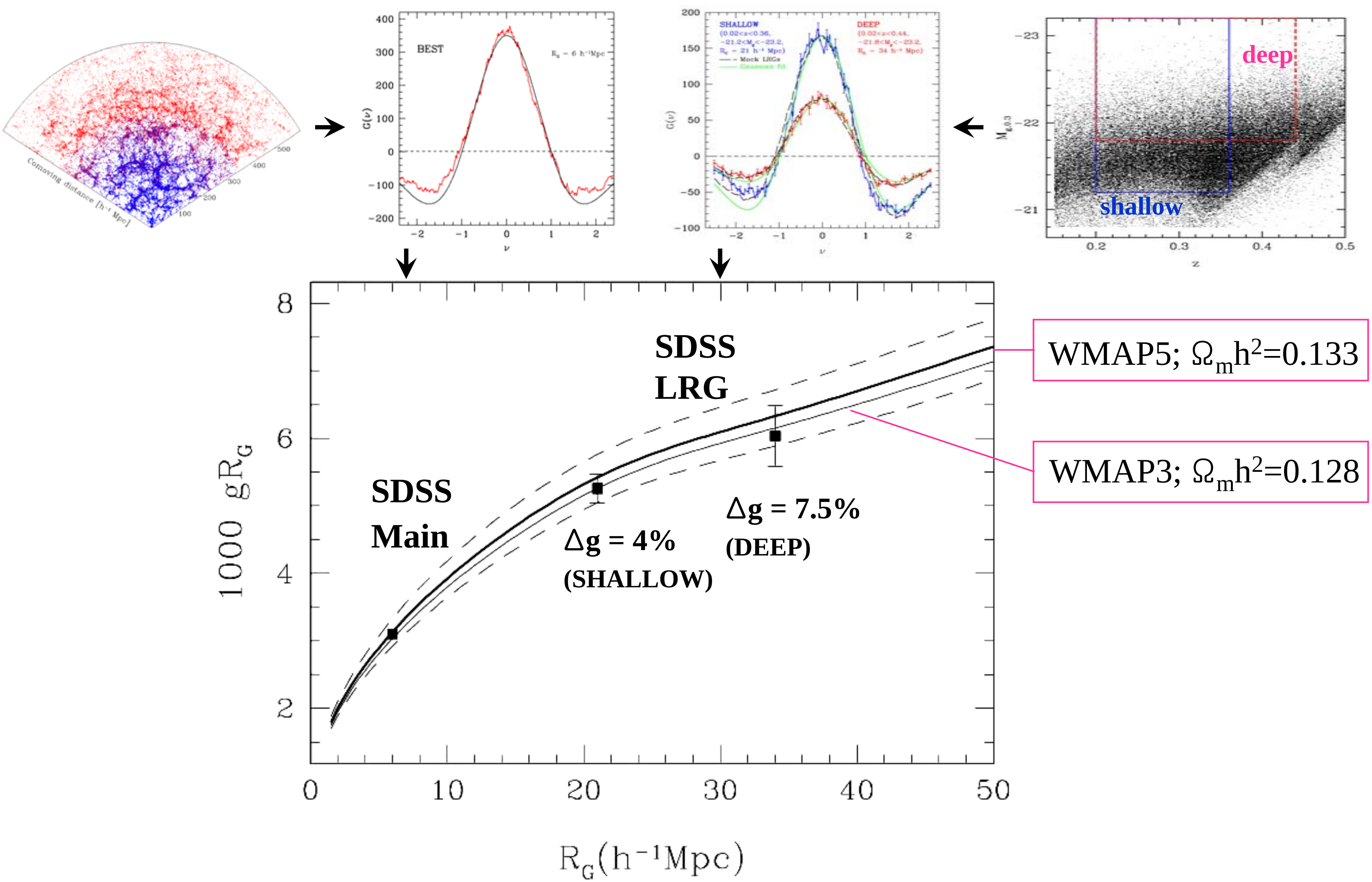


[Gott et al. 2008]



dark subhalos
from LCDM

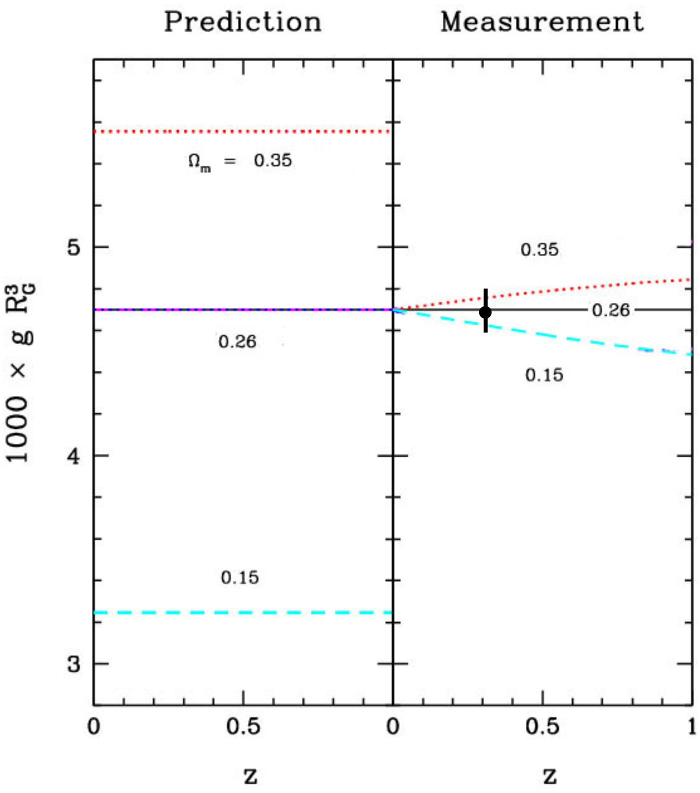
Observational constraints on the PS shape



LRGs in SDSS DR4plus

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

$\Omega_m = 0.241 \pm 0.014$ (if flat LCDM & h=0.72)



Future surveys

Constraint on PS shape using only the genus statistic

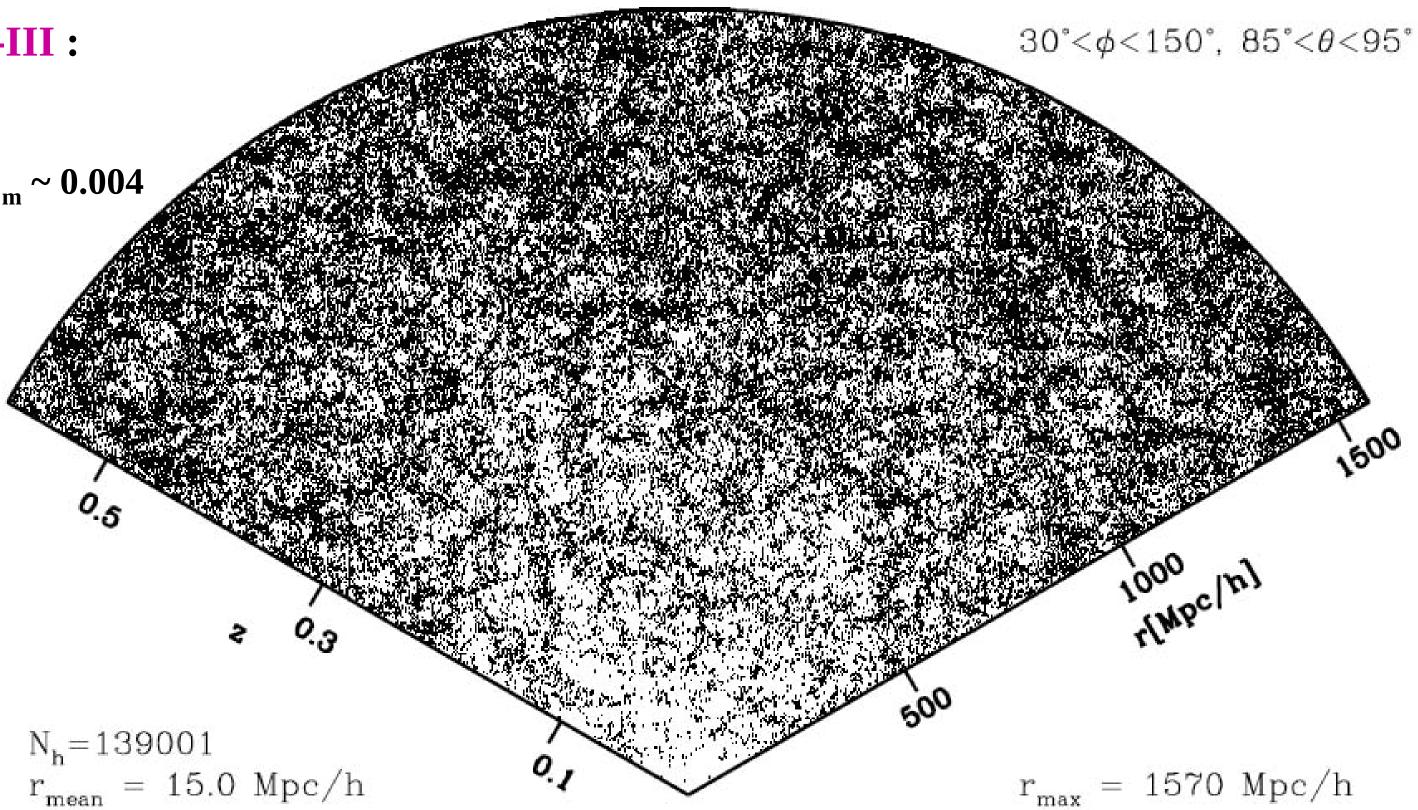
1. DR7 of SDSS I+II : # of LRGs ~ 100K

$\triangle g$ = ~3% & $\triangle \Omega_m$ = ~ 0.010

2. LRGs in SDSS-III :

# of LRGs ~ 1.5M

$\triangle g$ = ~0.8% & $\triangle \Omega_m$ ~ 0.004



Preliminary

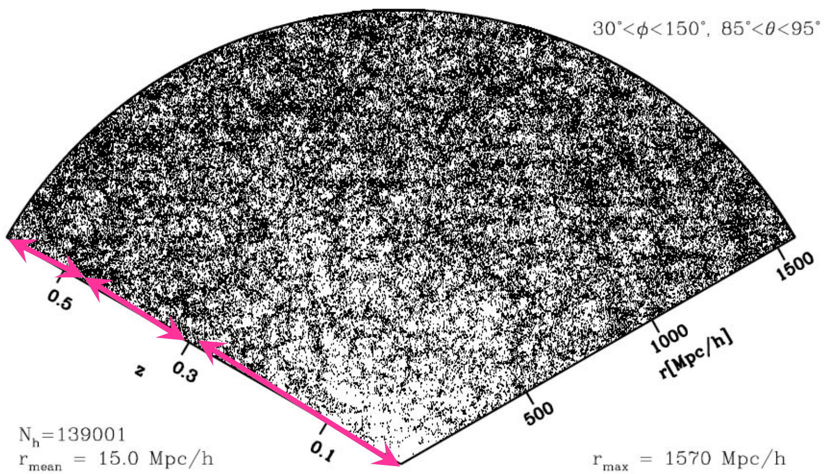
Constraint on 'w' using the genus statistic only :

LRGs in SDSS DR4plus

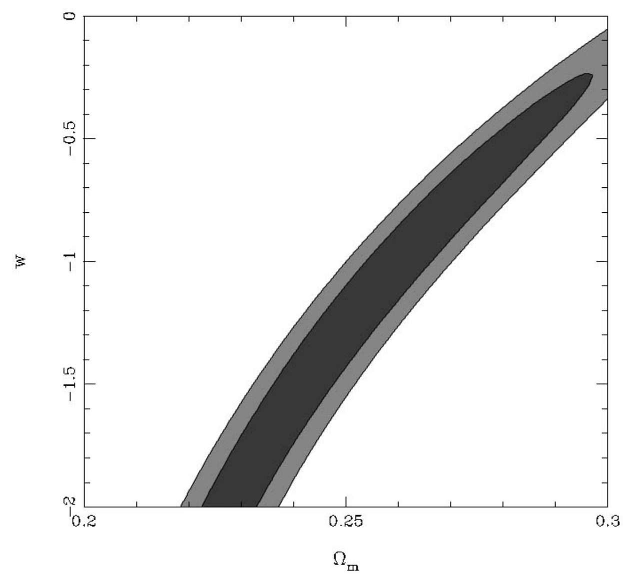
: △g = 4% (R_G=21h^{-1}Mpc) & 7.5% (R_G=34h^{-1}Mpc) → Δw ~ 0.4

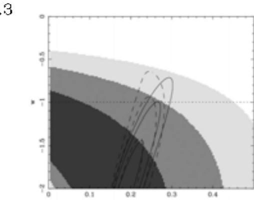
LRGs in SDSS-III : # of LRGs ~ 1.5M

△g = ~1.0% in each of 3 z-bins → △w ~ 0.08



The Horizon Run (Kim et al. 2009)

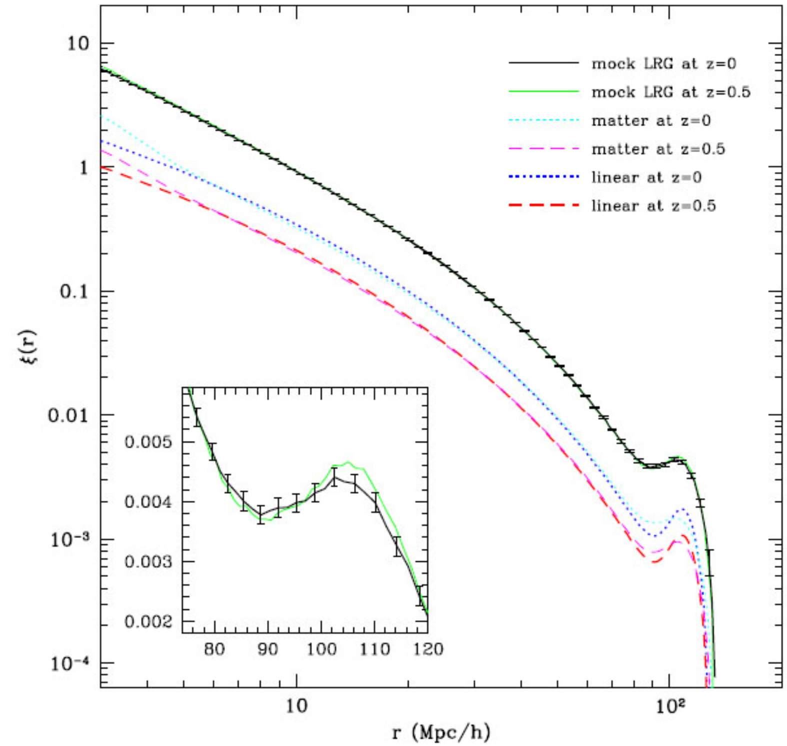


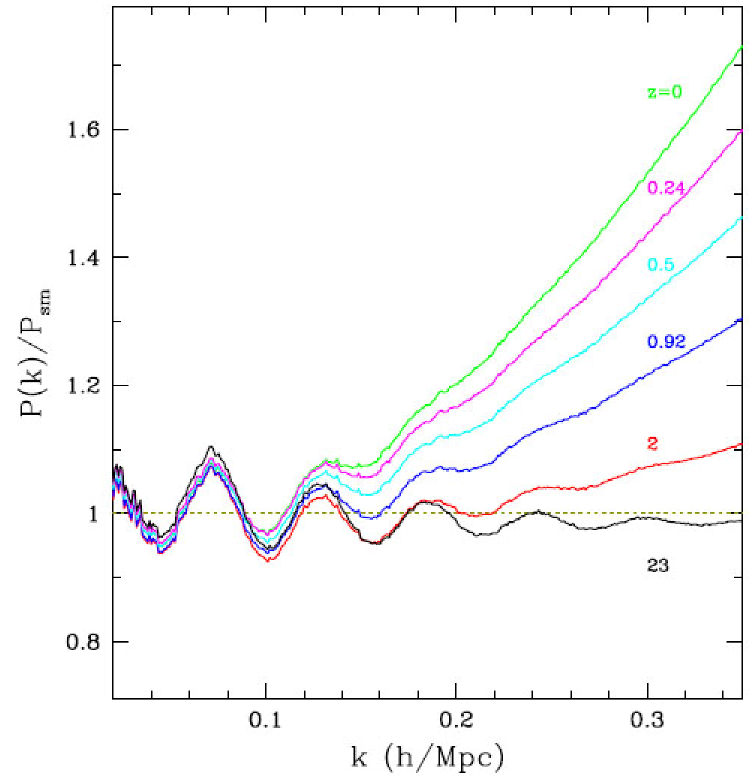


[Percival et al. 2007]

Needs to deal with non-linear effects

from NL gravitational evolution, galaxy biasing, redshift-space distortion
[Kim et al. 2009]





The Horizon Run (Kim et al. 2008): 4120^3 particles in $6592h^{-1}$Mpc box

All sky past light cone SDSS-III mock surveys - subhalos available on the web!

Effects of NL gravitational evolution, biasing, redshift-space distortion, discreteness, & finite pixel size

WMAP3

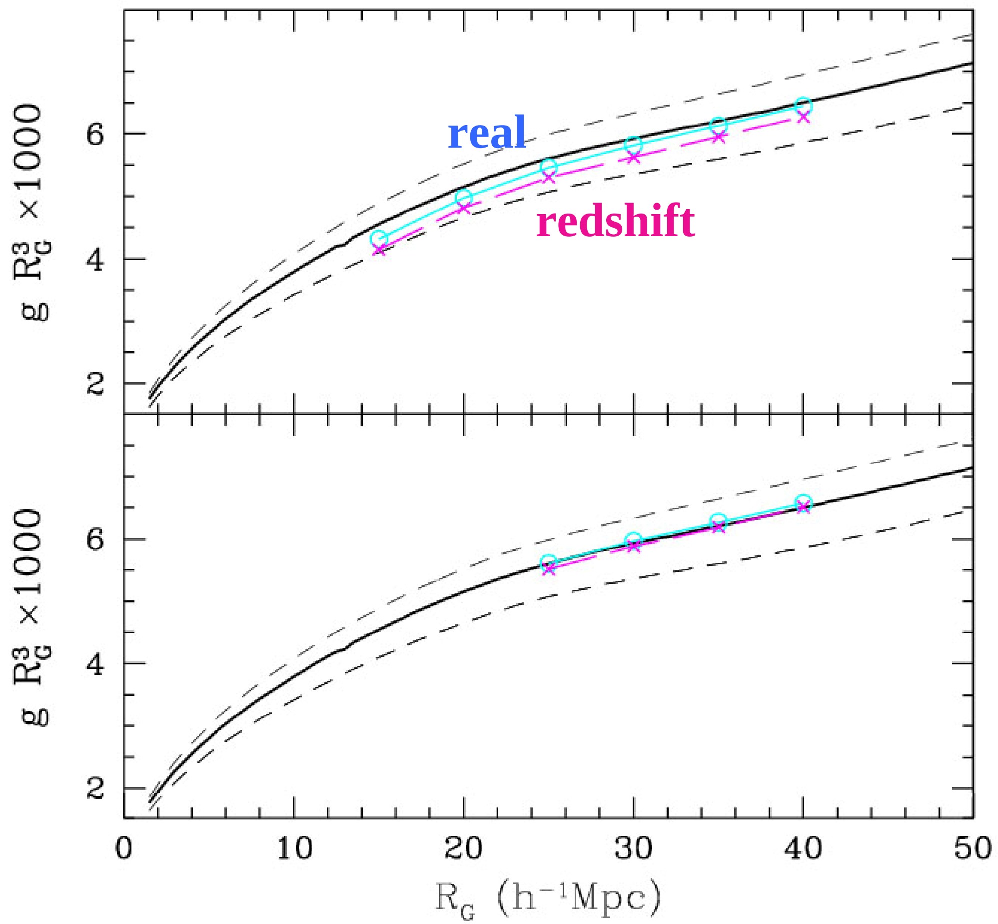
0.271

0.240

0.203

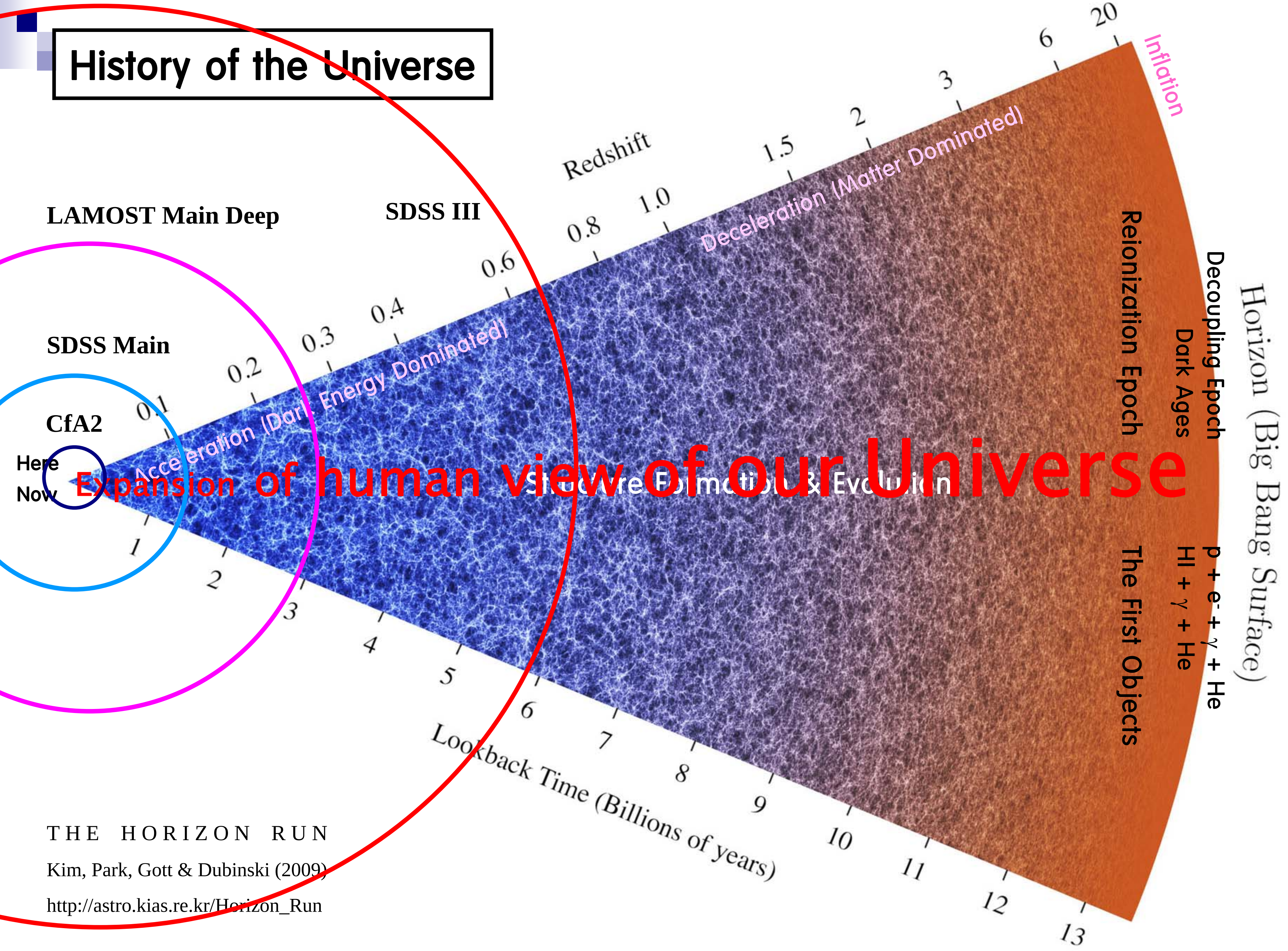
Matter in real & redshift spaces

Dark subhalos in real & redshift spaces



space / R_G	difference wrt linear g
real 25h^{-1}Mpc	-0.02%
redshift 25	-1.7%
real 35	+0.5%
redshift 35	-0.8%

History of the Universe



THE HORIZON RUN

Kim, Park, Gott & Dubinski (2009)

http://astro.kias.re.kr/Horizon_Run

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. Recently, topology of galaxy distribution at small non-linear scales is being used to constrain the galaxy formation mechanisms and cosmological parameters.

3. Here we propose to use the sponge topology of LSS to
measure the shape of power spectrum P(k) & the expansion history of space

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