The Challenge of the Largest Structures in the Universe to Cosmology

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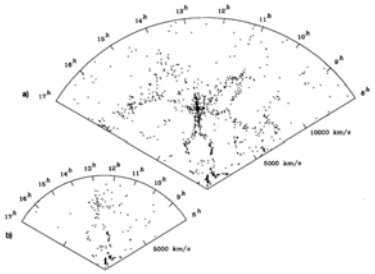
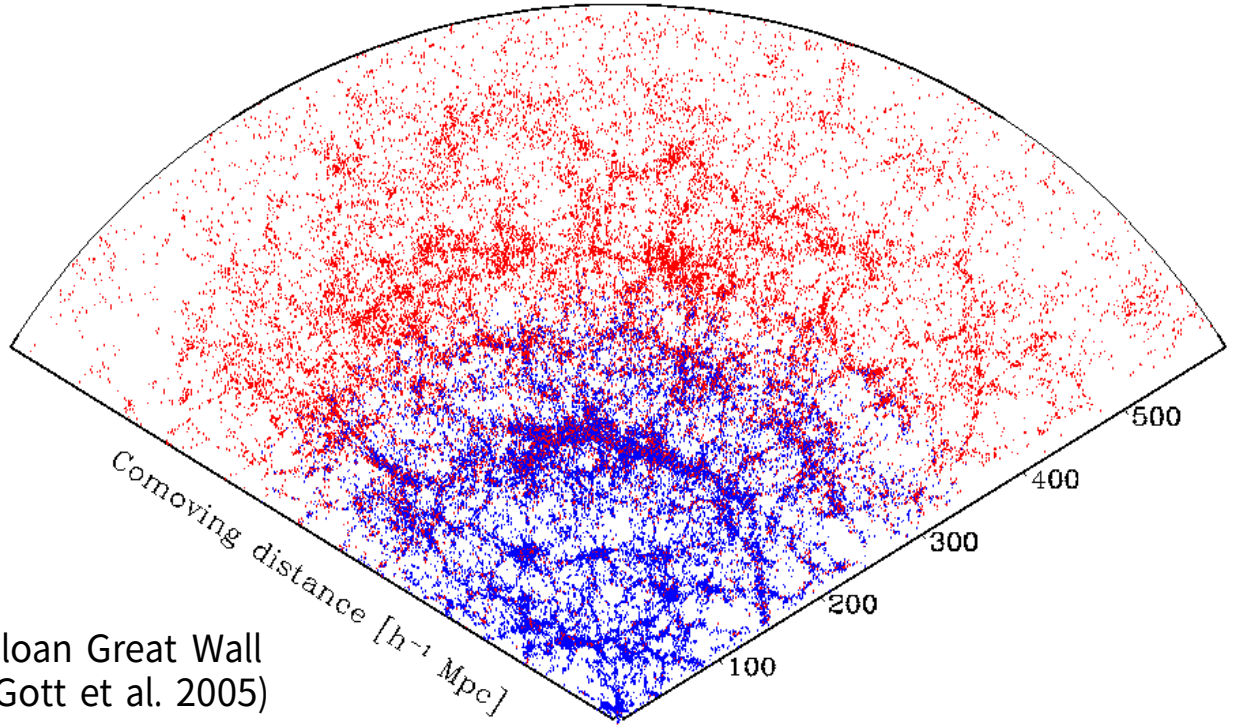
Are the largest-scale structures in the universe consistent with the ΛCDM model ?

(initially homogeneous, isotropic & Gaussian fluctuations growing according to GR)

Increasing size of the largest structure for increasing survey volume!



CfA Great Wall
(de Lapparent et al. 1986)



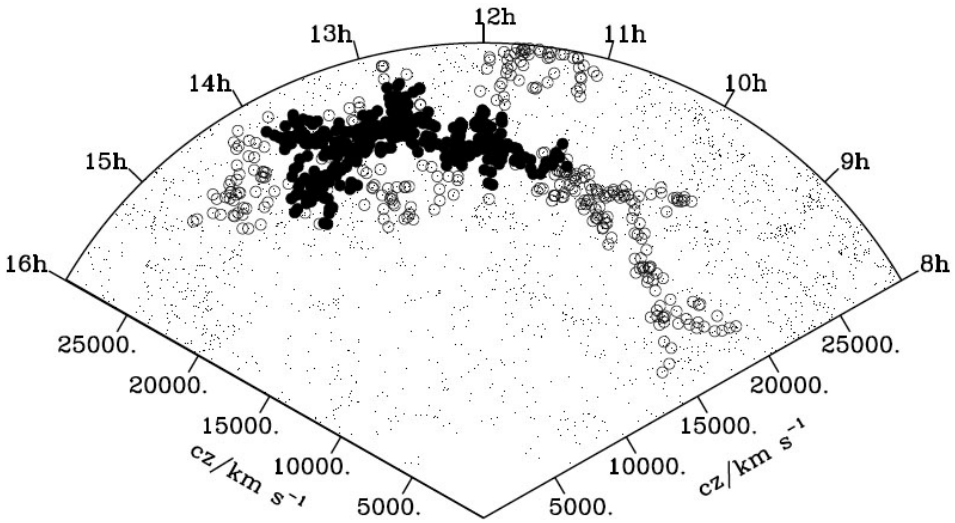
Sloan Great Wall
(Gott et al. 2005)

The largest LSS observed and its cosmological implications

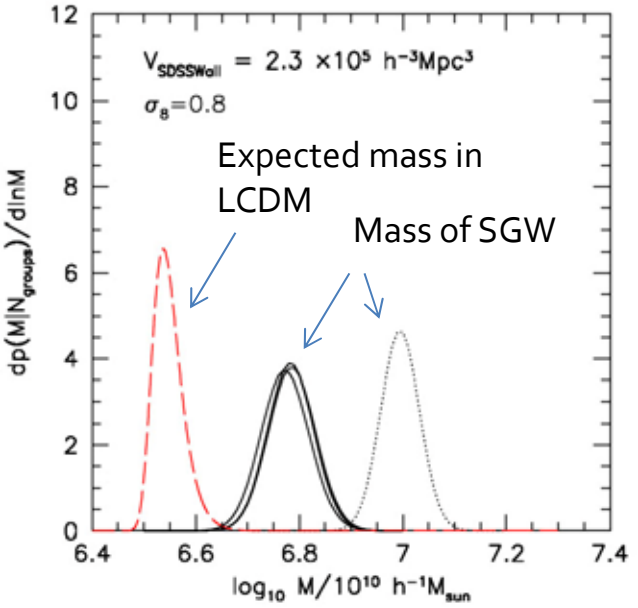
Sheth and Diaferio (2011)

How unusual are the Shapley Supercluster and Sloan Great Wall?
: 335 groups containing 2180 galaxies with M_r <-19.9 from percolation analysis
Total mass of the SGW ~ $1.2 \times 10^{17}\ h^{-1} M_\odot$

Extreme value statistics tells that
existence of SGW is difficult (4 sigma!) to reconcile with a model with Gaussian initial conditions and σ_8 =0.8.



SGW for $d_c = 8h^{-1}$Mpc (filled) & $12h^{-1}$Mpc (open)



Prob. that a spherical cell of size V having N clusters, contain mass M
: estimated vs expected masses

This work (Park et al. 2012, ApJL, 759, 7)

To compare the observed LSSs with those of the ΛCDM model

1. Catalog of LSSs
   Identification of both high-density and low-density LSSs
2. Mock SDSS surveys in the simulated ΛCDM universe
   Horizon Run 2
3. Statistical comparison of properties of LSSs
   Galaxy assignment scheme
   Cosmological model

Large-Scale Structures: Identification

LSS (high-density)
as concentrations of bright galaxies or luminosity density enhancements

1. Tracer: point distribution of galaxies or clusters

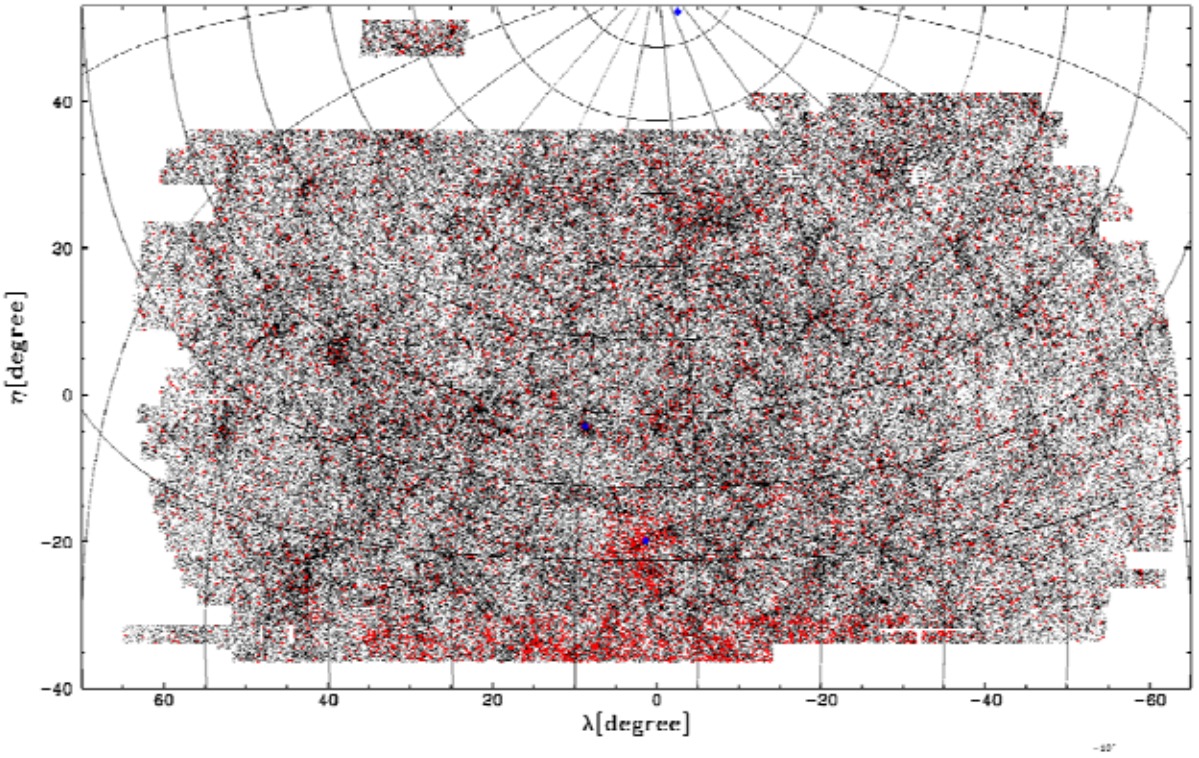
2. Identification method and thresholds
- Point distribution of galaxies
  : FoF method (free-p) linking length
- Smoothed number/luminosity density
  : (free-p) smoothing kernel, length, overdensity threshold

Identification of LSS's

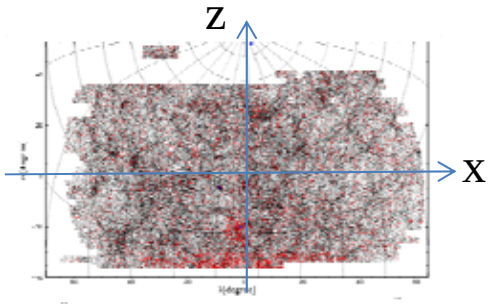
1. Point distribution of bright galaxies (∵ agrees with visual identification)

A volume-limited sample of SDSS Main galaxies

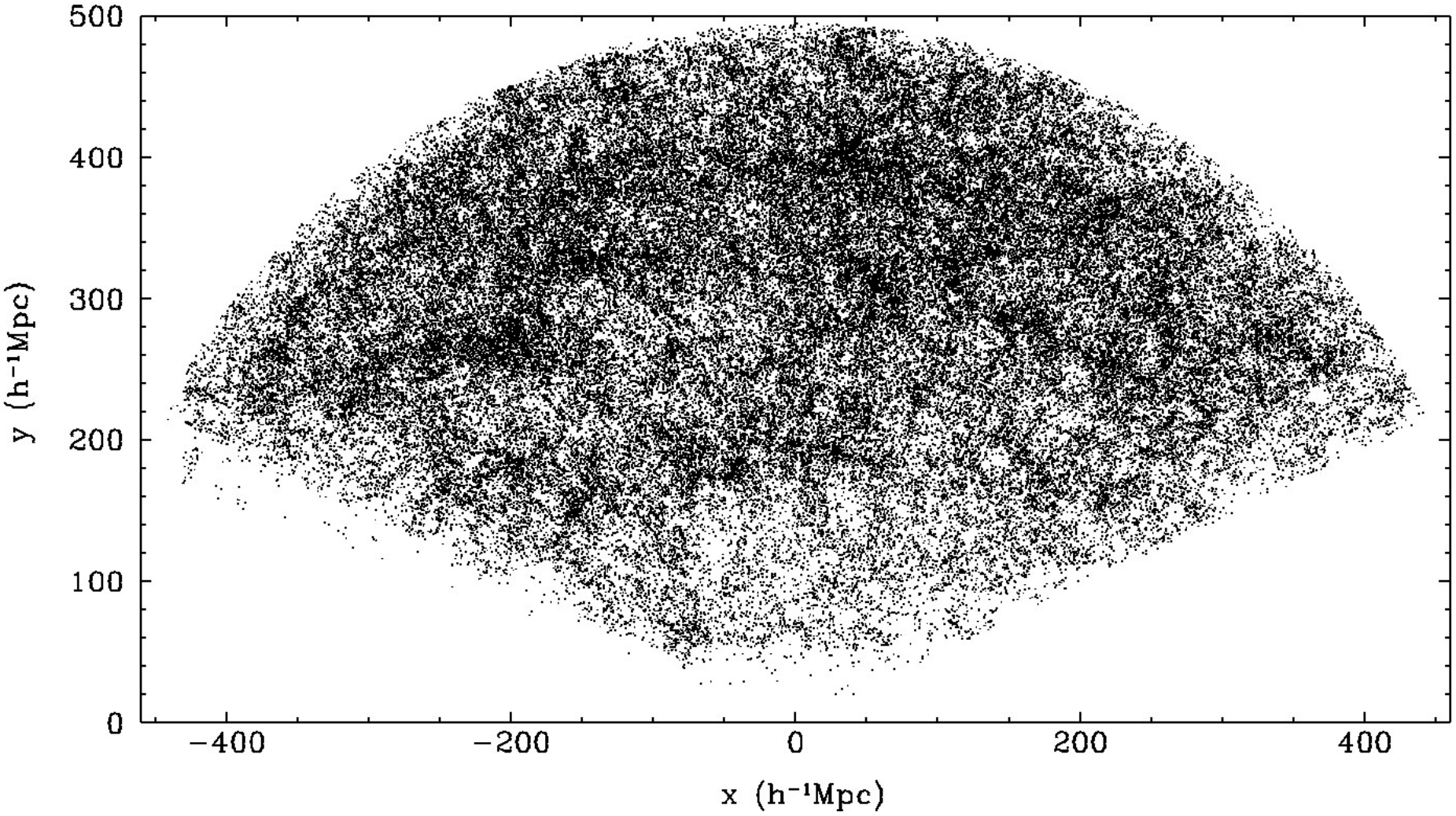
with $M_r < -20.92+5\log h$, $d=9h^{-1}$Mpc, $r < 496h^{-1}$Mpc



SDSS DR7:
KIAS-VAGC
(Choi et al. 2010)



LSS tracer galaxies in the x-y plane

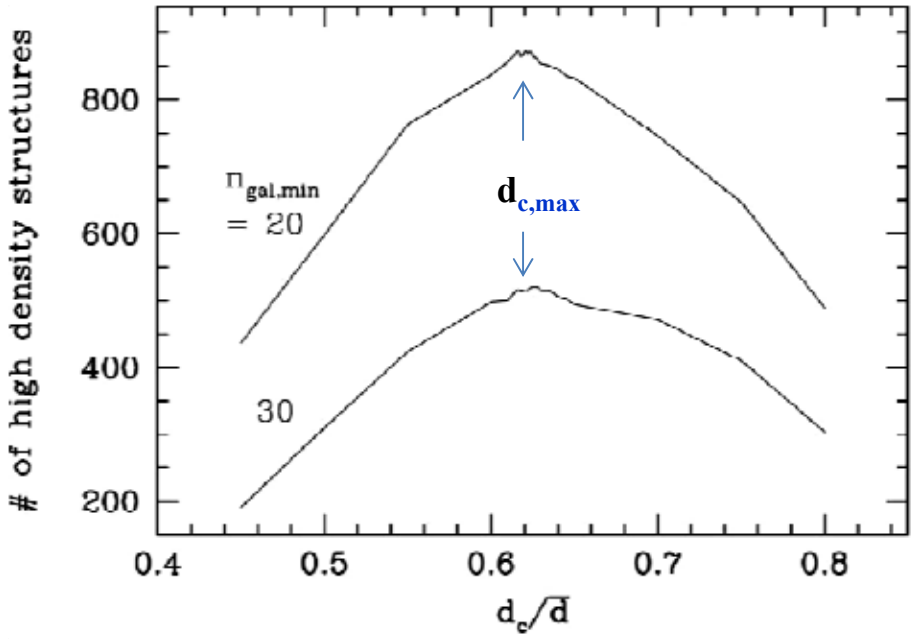


2. FoG contraction

Find FoF groups with $d_c=3h^{-1}$Mpc. Make $\sigma_{//} = \sigma_{\perp}$ if $\sigma_{//} > \sigma_{\perp}$.

3. High-density LSS identification

FoF grouping using the d_c resulting in the max. # of groups (for a given min. # of group members)



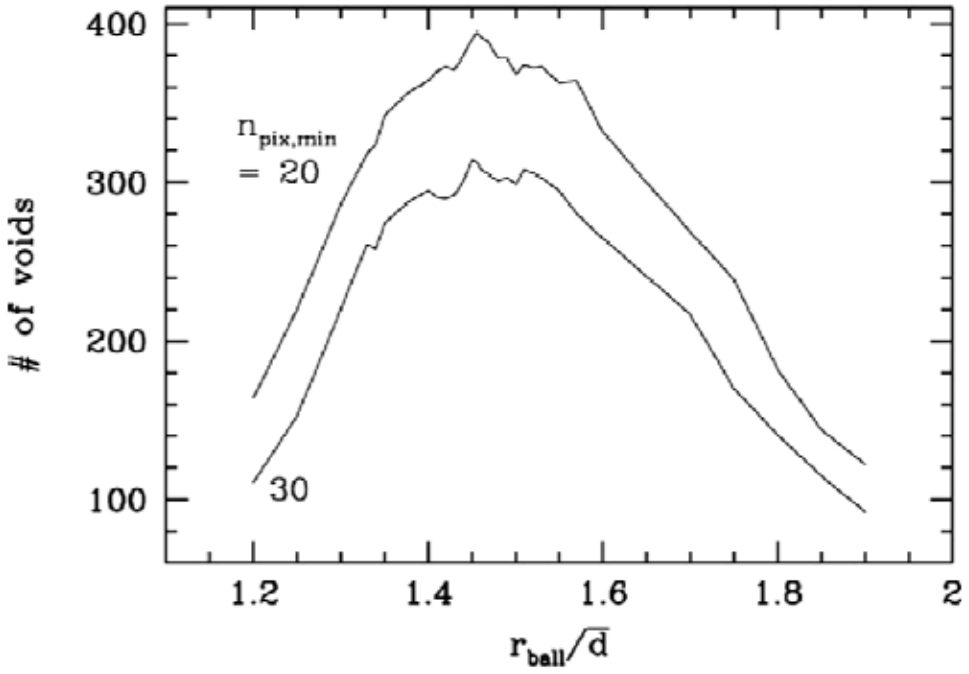
$\rightarrow d_{c,max} = 0.62\ d_{bar}$

or $\delta_{th} = n_{th}/n_{bar}-1 = 0.99$

4. Low-density LSS identification

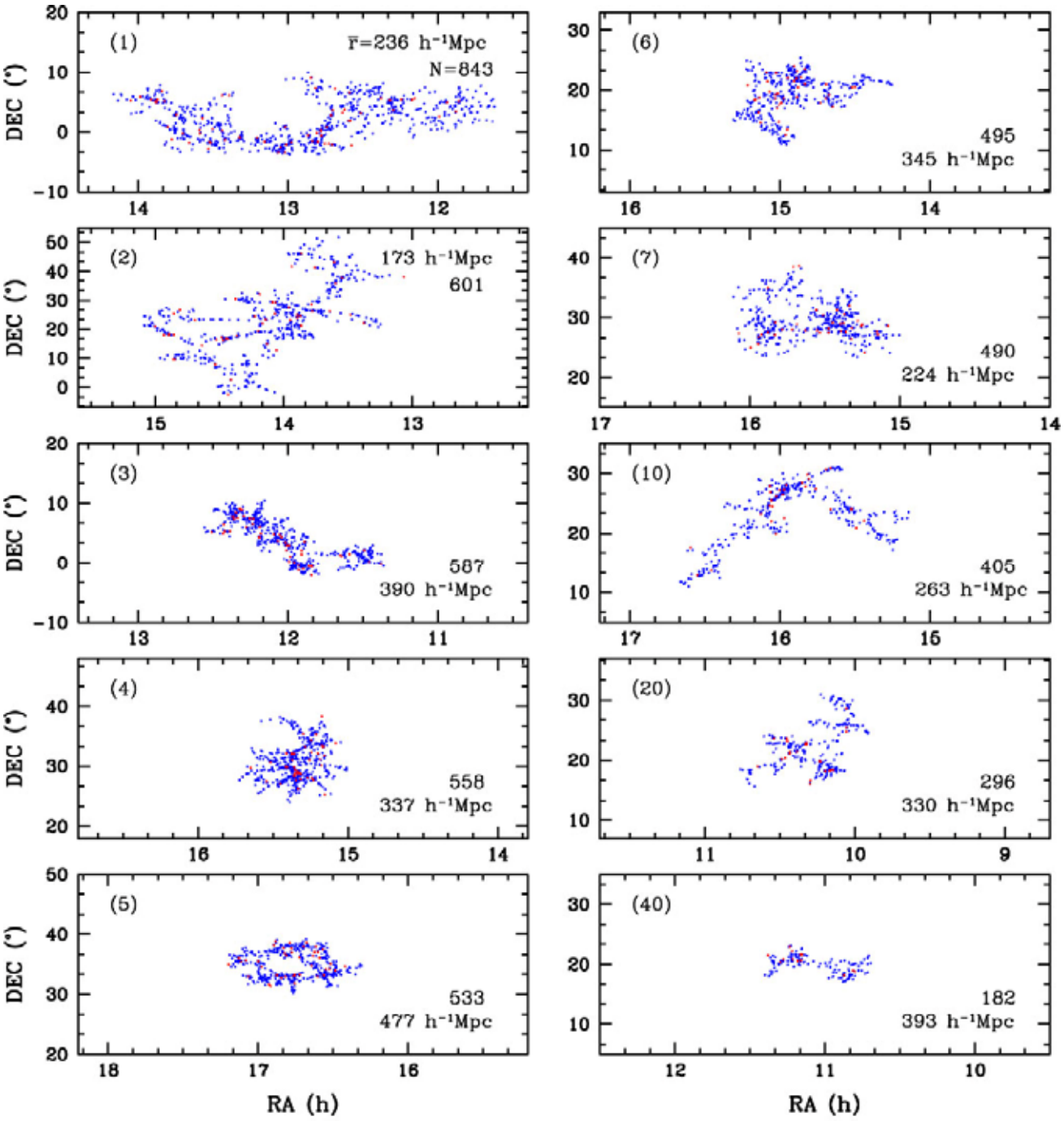
Look for void pixels that have one or no galaxy within r_{ball}

Find $r_{ball,max}$ resulting in the max. # of connected low-density regions

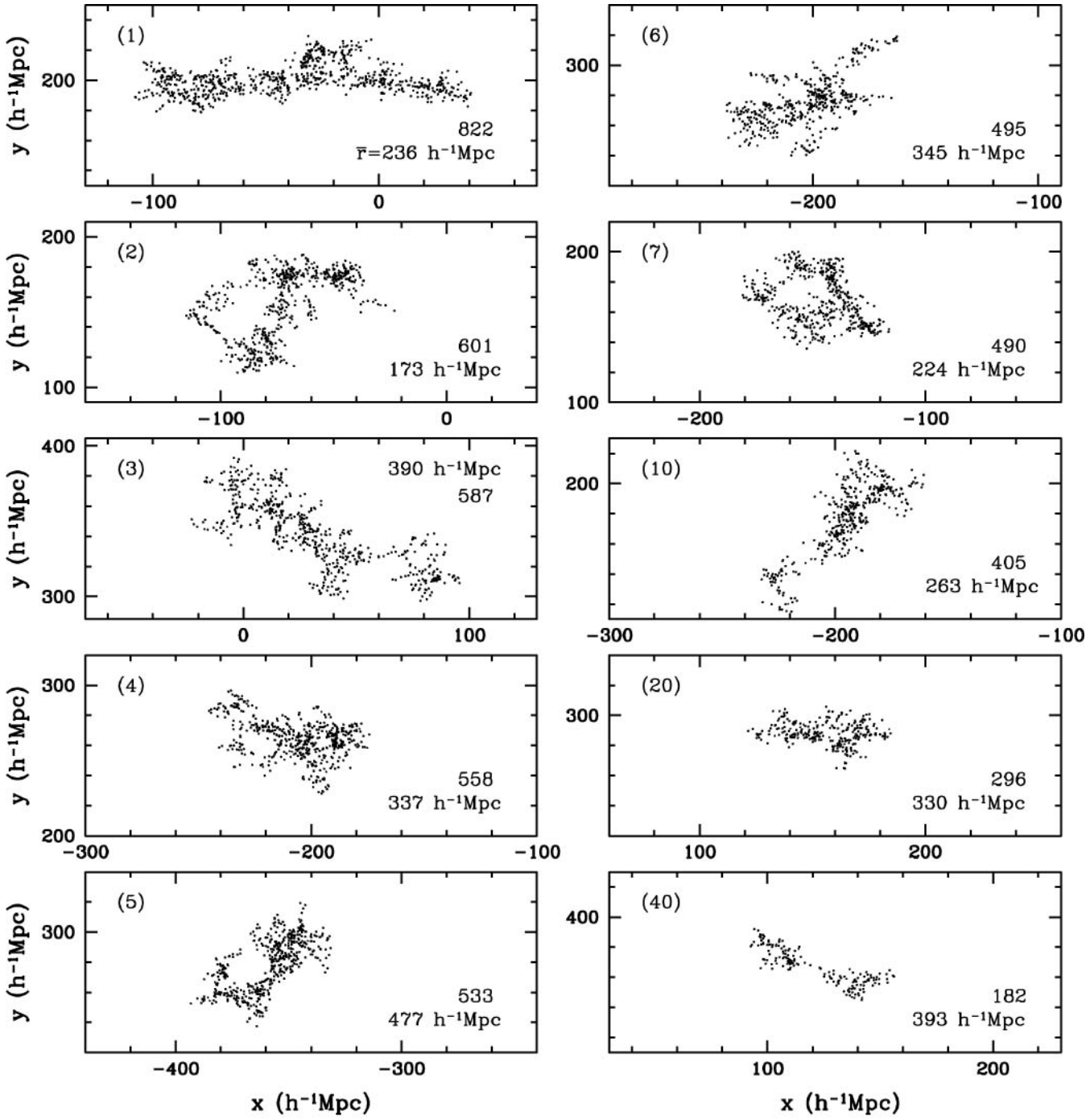


→ $r_{ball,max} = 1.45\ d_{bar}$

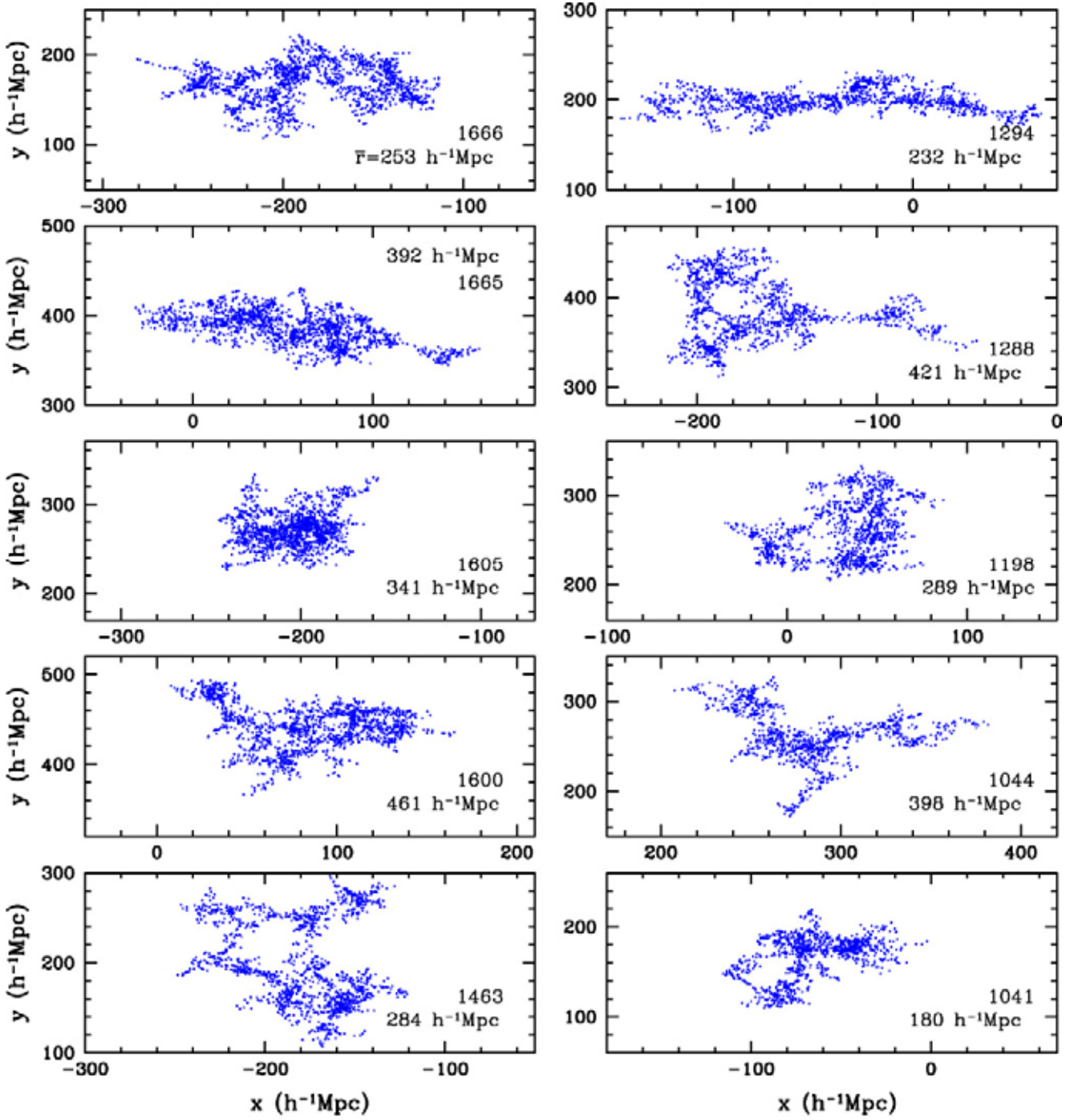
Minimum 30 pixels:
$V_{min}=(12h^{-1}Mpc)^3$


(1)
r̄=236 h⁻¹Mpc
N=843
(2)
173 h⁻¹Mpc
601
(3)
587
390 h⁻¹Mpc
(4)
558
337 h⁻¹Mpc
(5)
533
477 h⁻¹Mpc
(6)
495
345 h⁻¹Mpc
(7)
490
224 h⁻¹Mpc
(10)
405
263 h⁻¹Mpc
(20)
296
330 h⁻¹Mpc
(40)
182
393 h⁻¹Mpc
DEC (°)
RA (h)

$d_{c,}=d_{c,max} = 0.62\ d_{bar}$

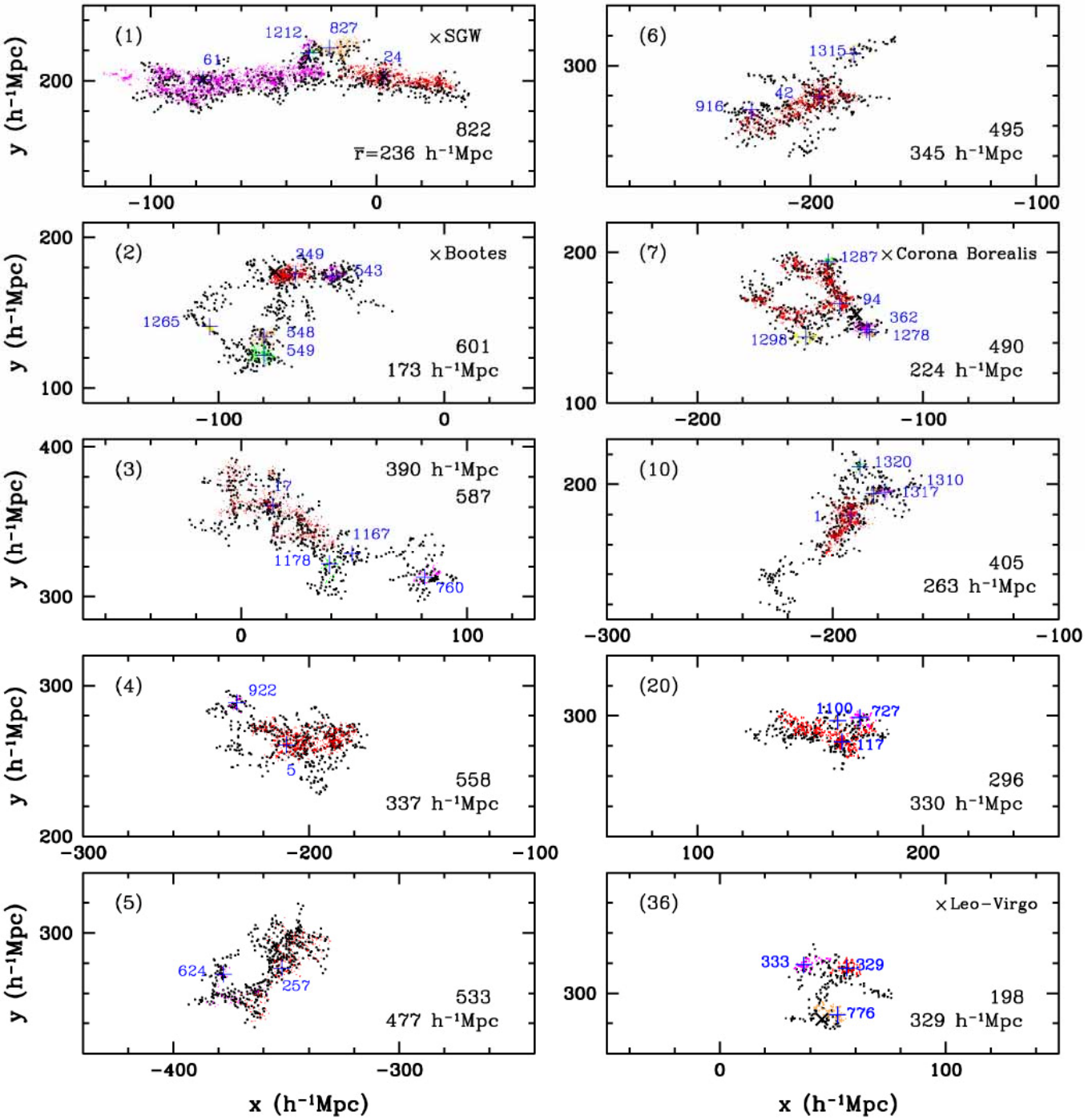


$d_c = 0.71\ d_{bar}$

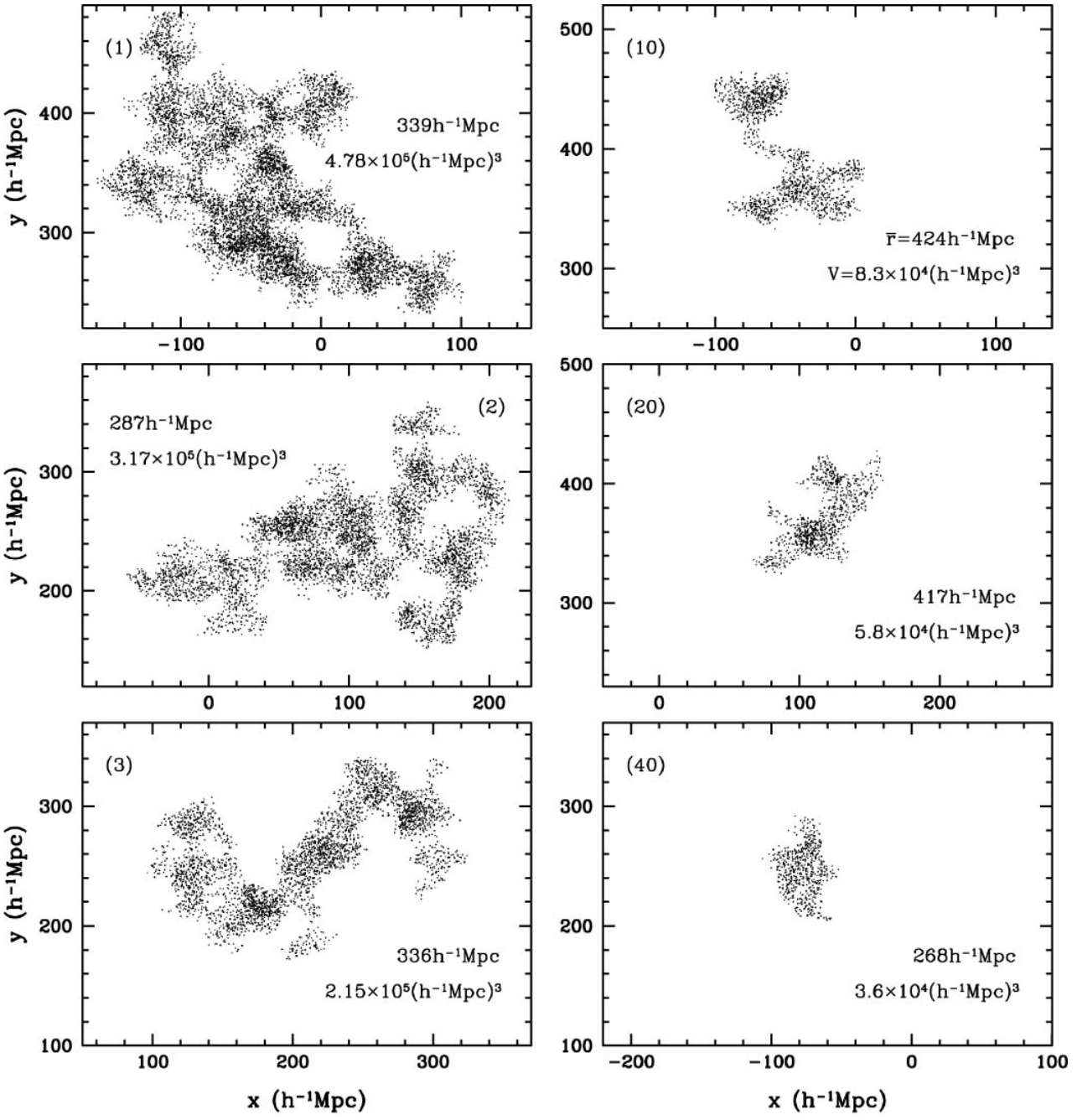

1666
r̄=253 h⁻¹Mpc
1294
232 h⁻¹Mpc
392 h⁻¹Mpc
1665
1288
421 h⁻¹Mpc
1605
341 h⁻¹Mpc
1198
289 h⁻¹Mpc
1600
461 h⁻¹Mpc
1044
398 h⁻¹Mpc
1463
284 h⁻¹Mpc
1041
180 h⁻¹Mpc
y (h⁻¹Mpc)
x (h⁻¹Mpc)

Liivamägi, Tempel, Saar (2012)'s Super Clusters

D=5.0 ρ_bar



Voids: points are empty pixels

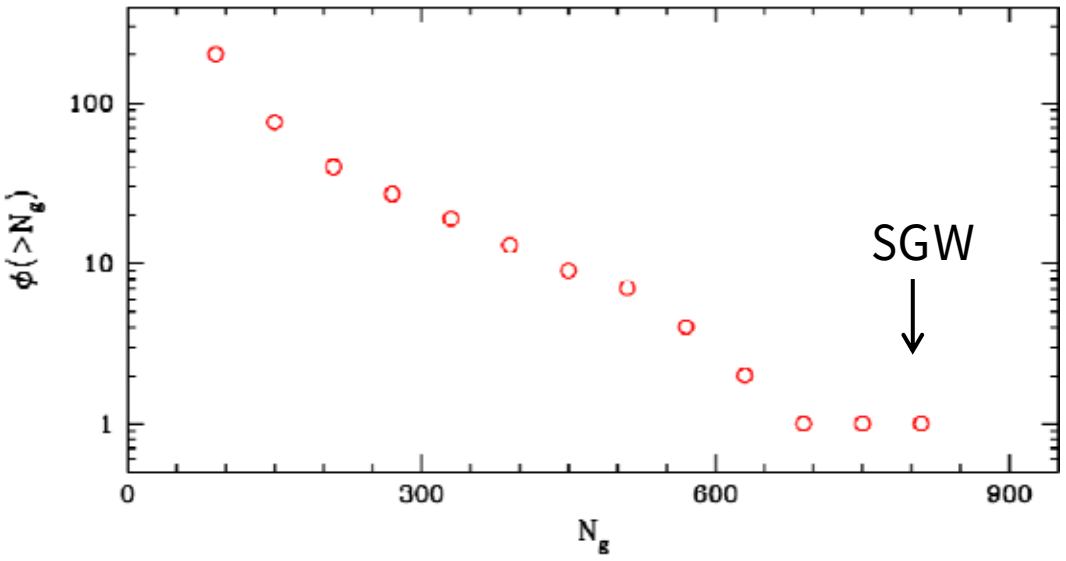


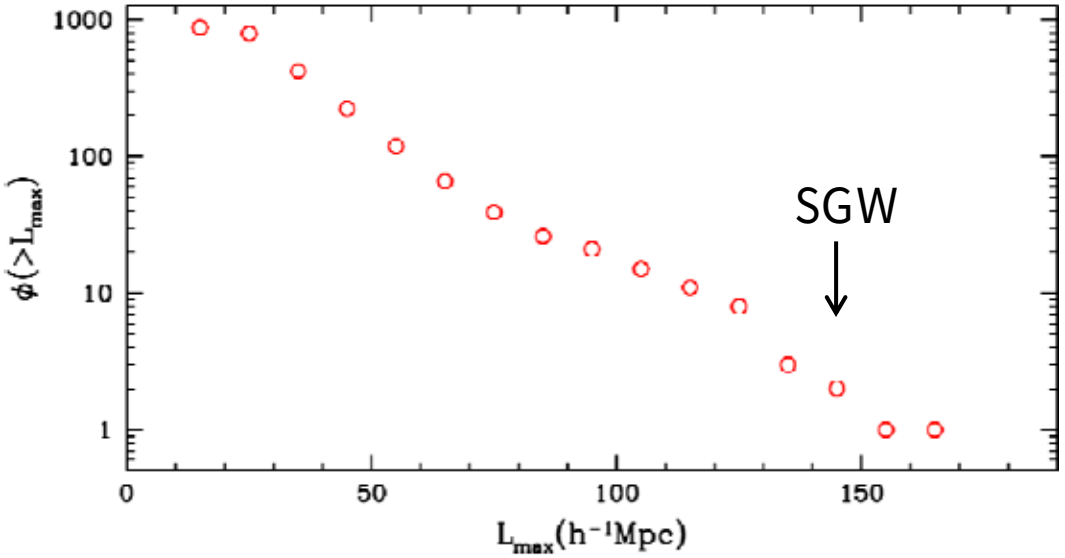
Cumulative distribution functions

Richness: # of member galaxies > N_g

Size: the maximum extent > L_{max}

: $\mathbf{d_{c,max} = 0.62\ d_{bar}}$ **case**





Dependence of the distribution functions on

1. **Cosmological model**
   SCDM (Ω_m=1, h=0.5, Ω_Λ=0)
   OCDM (Ω_m=0.26, h=0.72, Ω_Λ=0)
   LCDM (Ω_m=0.26, h=0.72, Ω_Λ=0.74)

2. **Galaxy Assignment scheme**
   Halo-Galaxy 1-1 correspondence (HGC)
   Halo-Occupation distribution (HOD)
   Semi-Analytic Models (SAM)

3. **LSS identification method**
   Linking length

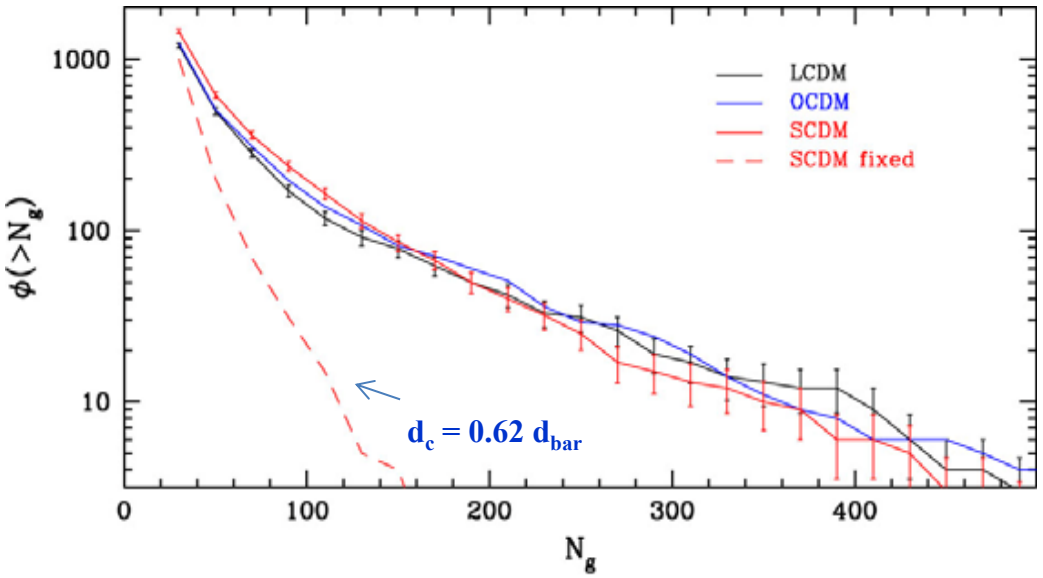
Dependence on Cosmology

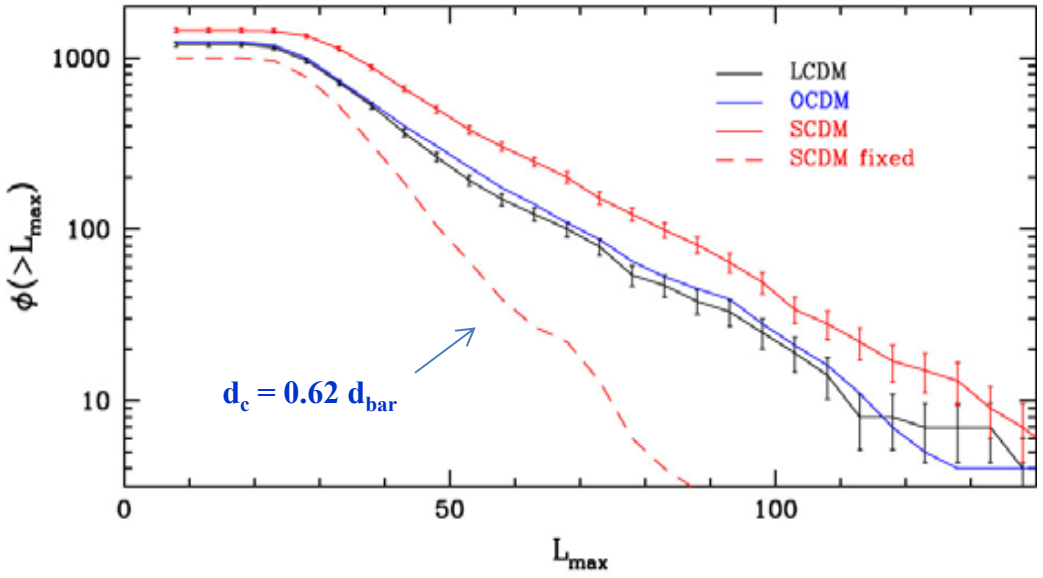
- N-body simulations with 512^3 particles and $500h^{-1}$Mpc box size

  SCDM (Ω_m=1, h=0.5, Ω_Λ=0)
  OCDM (Ω_m=0.26, h=0.72, Ω_Λ=0)
  LCDM (Ω_m=0.26, h=0.72, Ω_Λ=0.74)

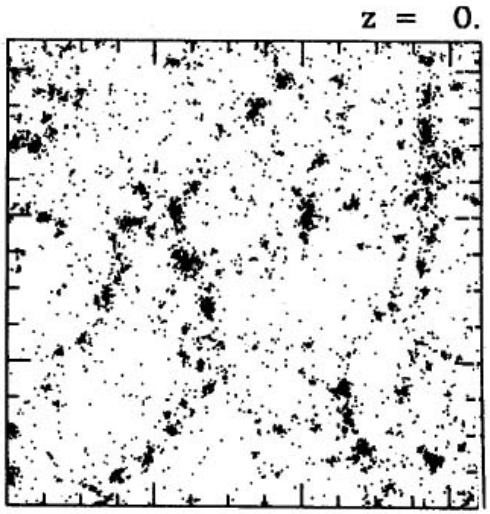
- Subhalo finding
- Halo-Galaxy correspondence
- Abundance matching (mass cut)
- LSS finding with d_c maximizing the # of LSS's in real space

Simulations have the same mean galaxy number density

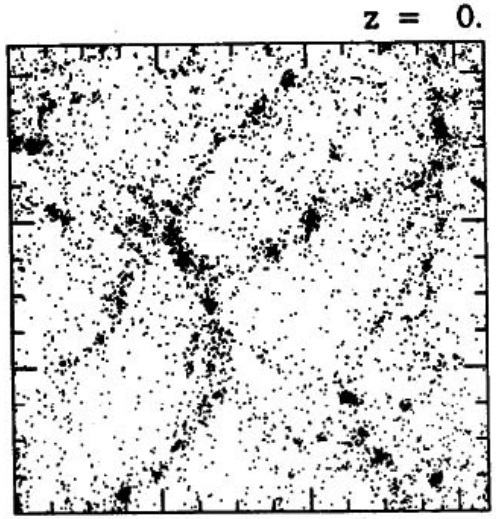




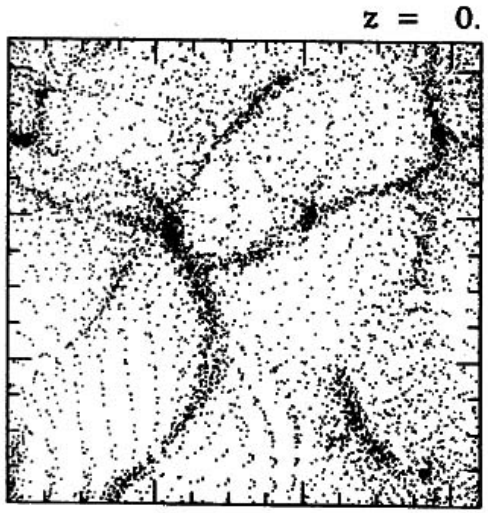
White noise



SCDM



HDM



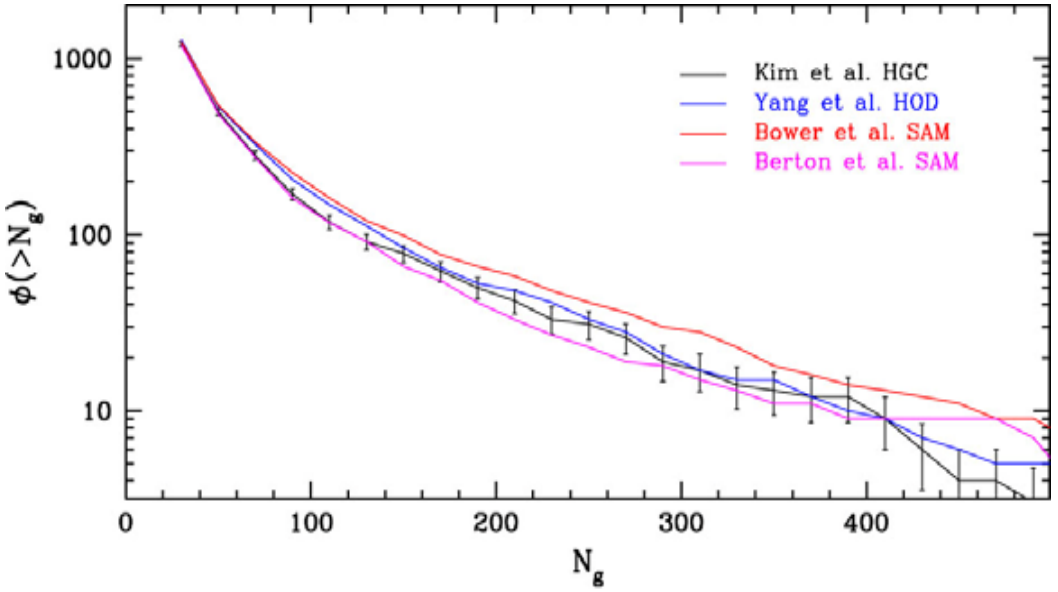
Weinberg & Gunn (1990)

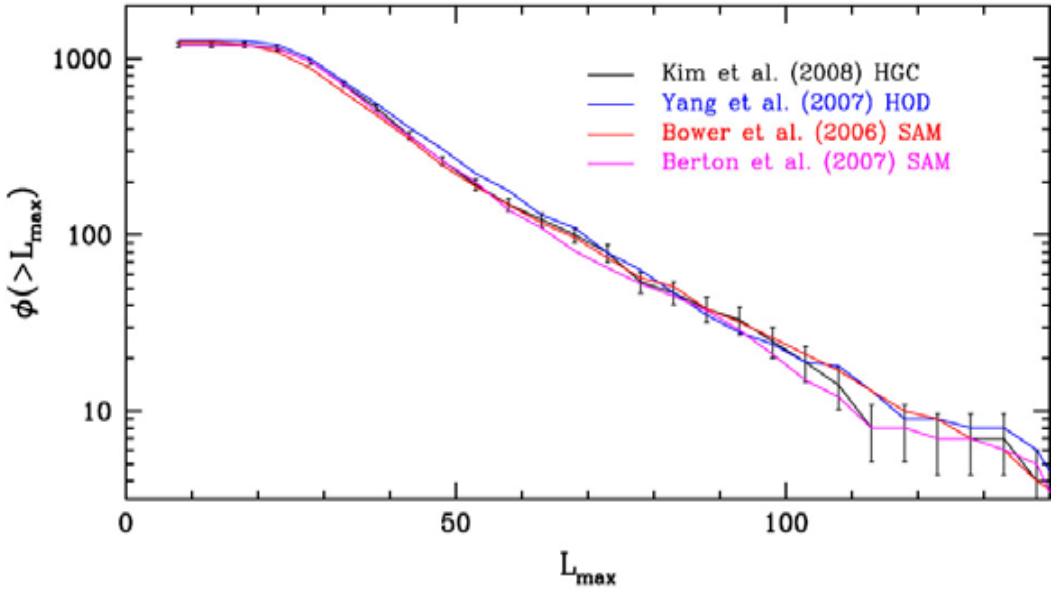
Dependence on galaxy assignment scheme

- HGC: subhalo-galaxy 1-1 correspondence above a mass cut (LCDM, 512^3 particles, $500h^{-1}$Mpc)

- HOD: Yang et al. (2007), MR
- SAM: Bower et al. (2006), MR
- SAM: Berton et al. (2007), MR

Simulations have the same mean galaxy number density



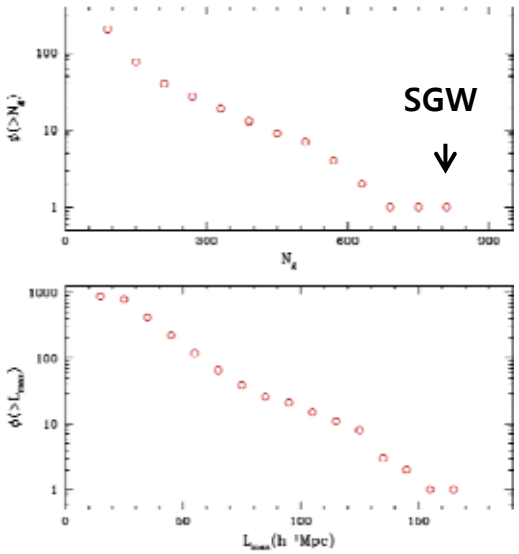


QUESTION !

Are structures like the Sloan Great Wall typical & expected for SDSS-like surveys in the LCDM universe?

Need large cosmological simulations that can properly take into account the occurrence of such large structures

Horizon Run simulation!

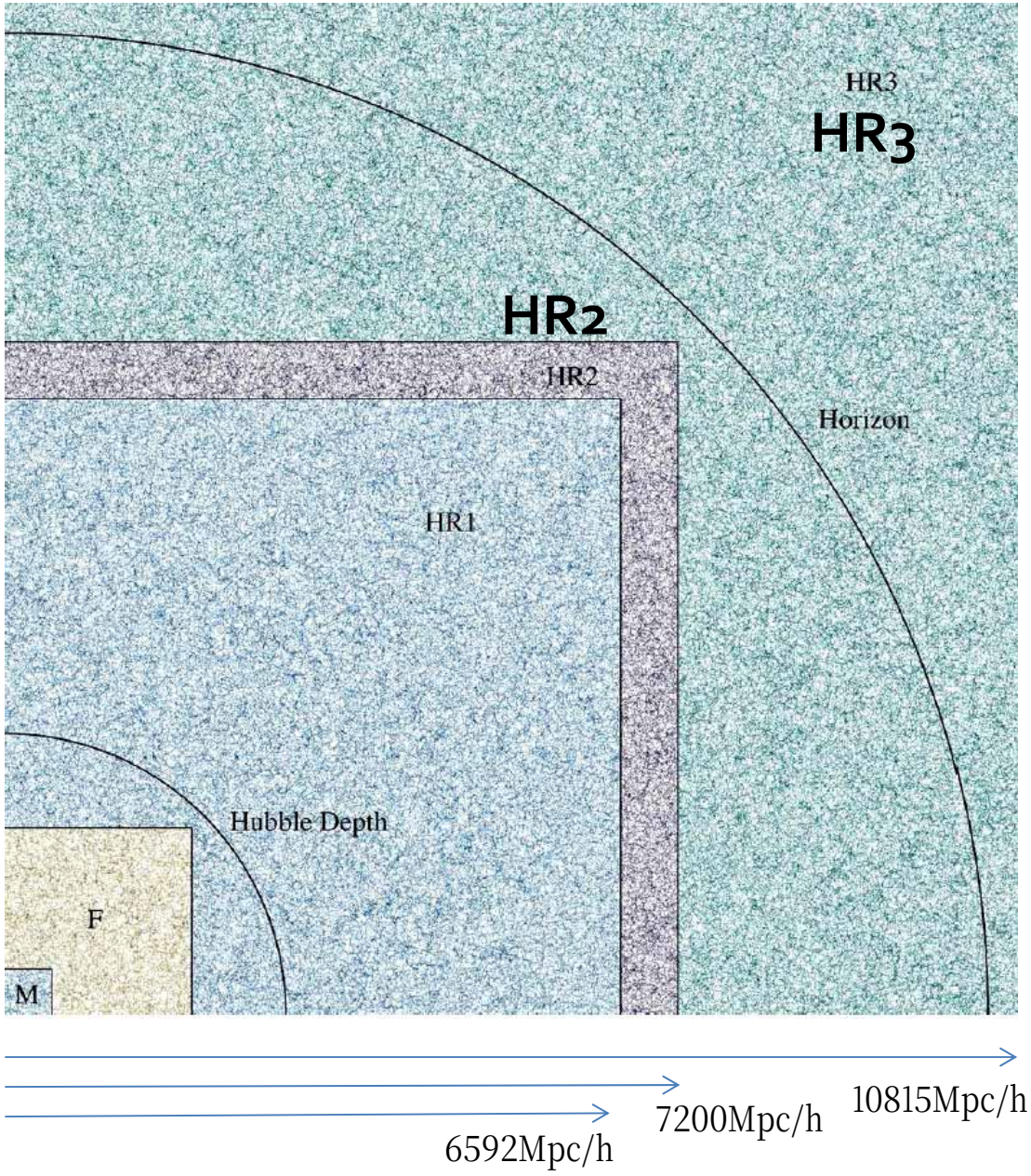


The Horizon Run N-Body Simulations

(J. Kim et al. 2009;
J. Kim et al. 2011;
http://astro.kias.re.kr/Horizon-Run23/)

HR2

216 Billion (6000^3) particles
WMAP 5yr cosmology
Box size 7200Mpc/h
Min. halo mass $3.74 \times 10^{12} M$
Mean particle d= 1.2 Mpc/h
Mean halo d=9.01 Mpc/h



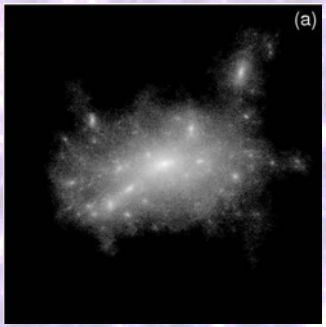
Galaxy assignment - Halo-Galaxy Correspondence (HGC) model [Kim & Park 2006; Kim et al. 2008; Gott et al. 2009; Kim et al. 2009; Park et al. 2010; Choi et al. 2010; Jee et al. 2011; Choi et al. 2012]

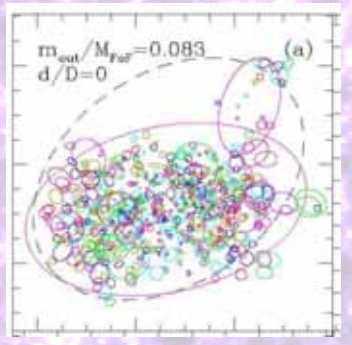
Each Isolated, central or satellite subhalo above a mass cut contains one galaxy (1-1 or scatter).

Assignment of L is done using the abundance matching
using halo mass function $\phi[M_h(z),z]$ and luminosity function $\phi[L(z),z]$.

matter – dark halos -- galaxies

- $d_{bar}=9h^{-1}$Mpc for dark halos with > 3.7×10^{12}Mo and galaxies with Mr < -20.9.

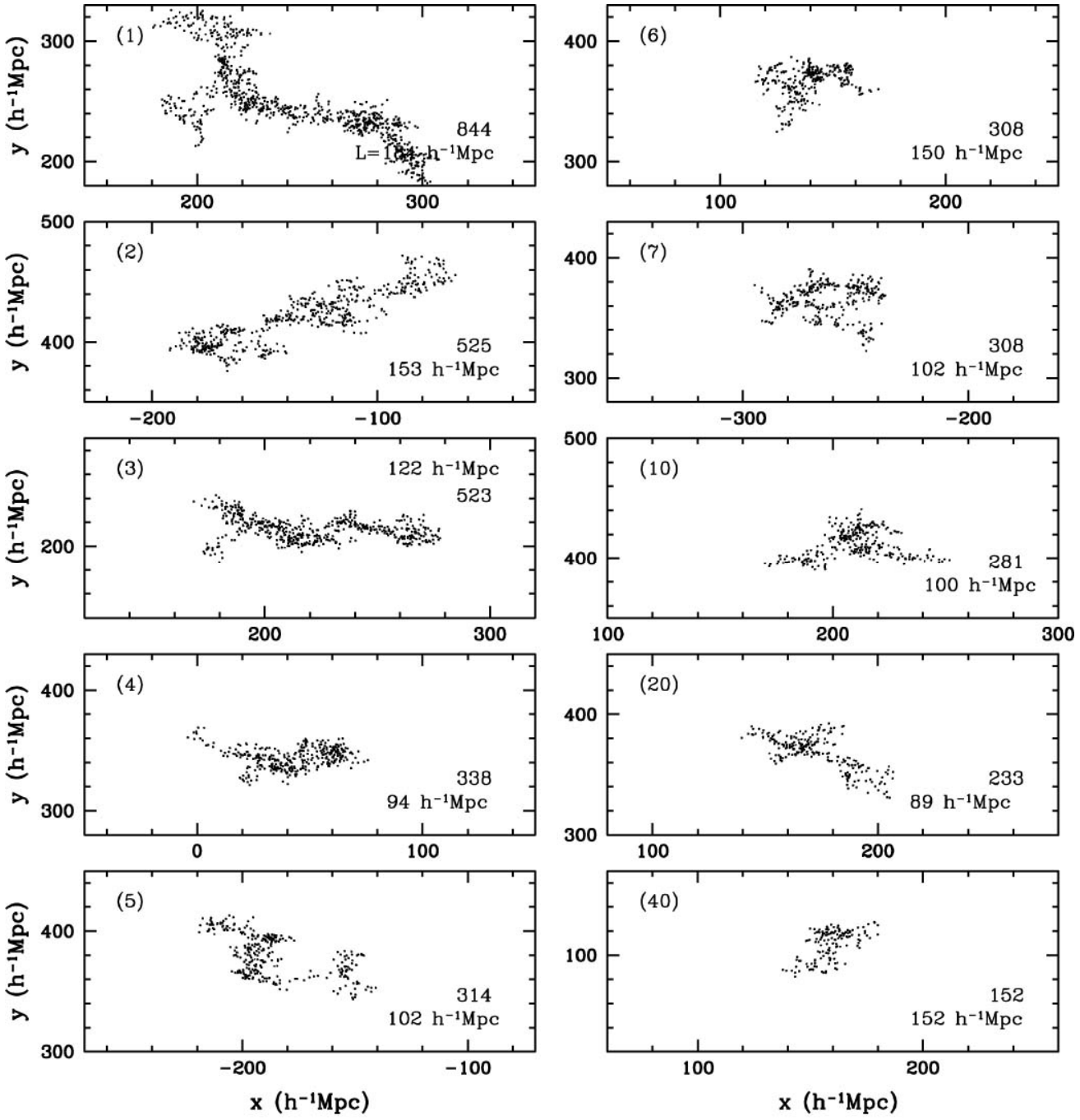


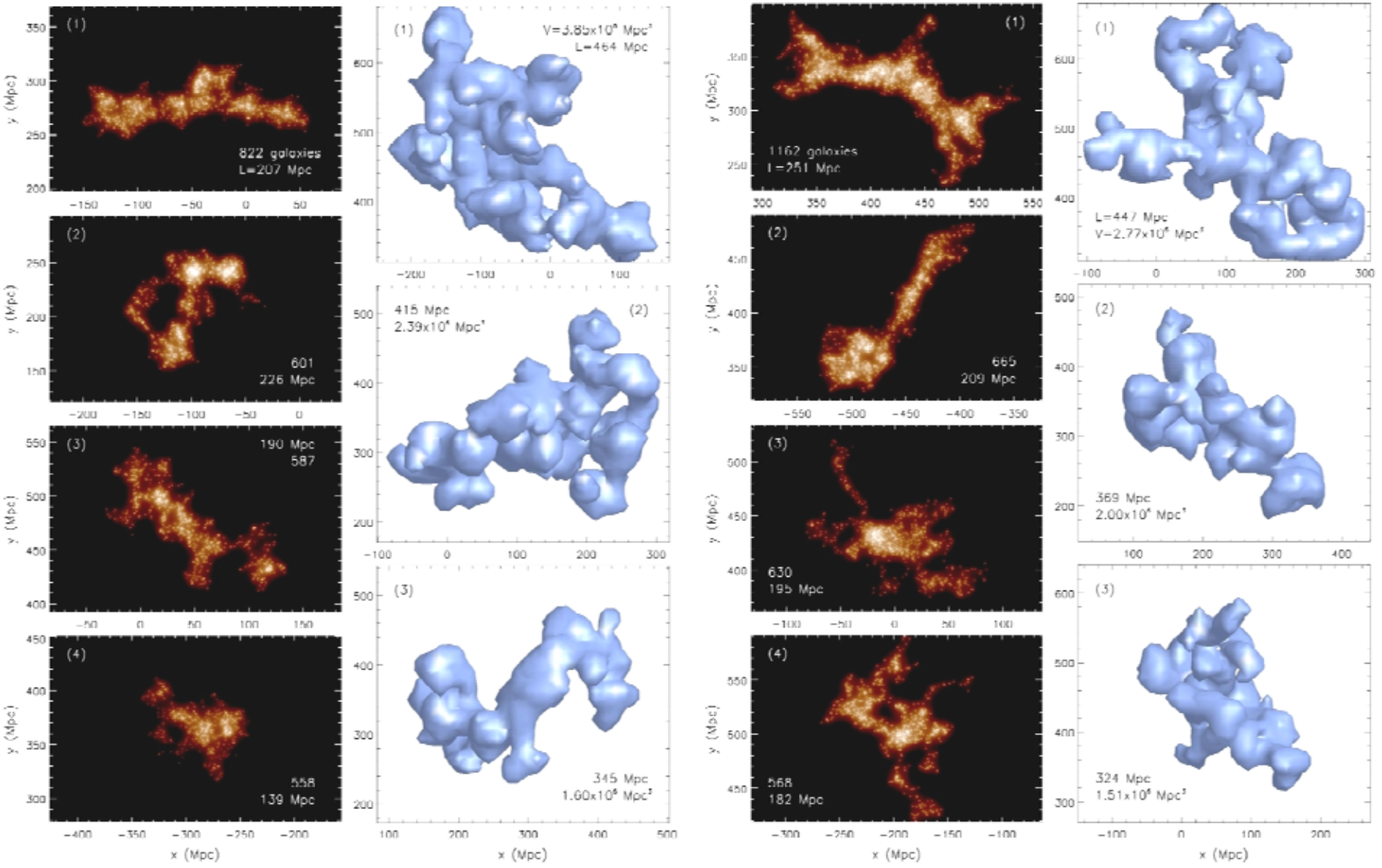


(FoF with l=0.2)

LSS from mock samples

- $d_{c,max} = 0.616 \pm 0.014\ d_{bar}$ for 200 mock surveys
($d_{c,max} = 0.621\ d_{bar}$ for obs.)

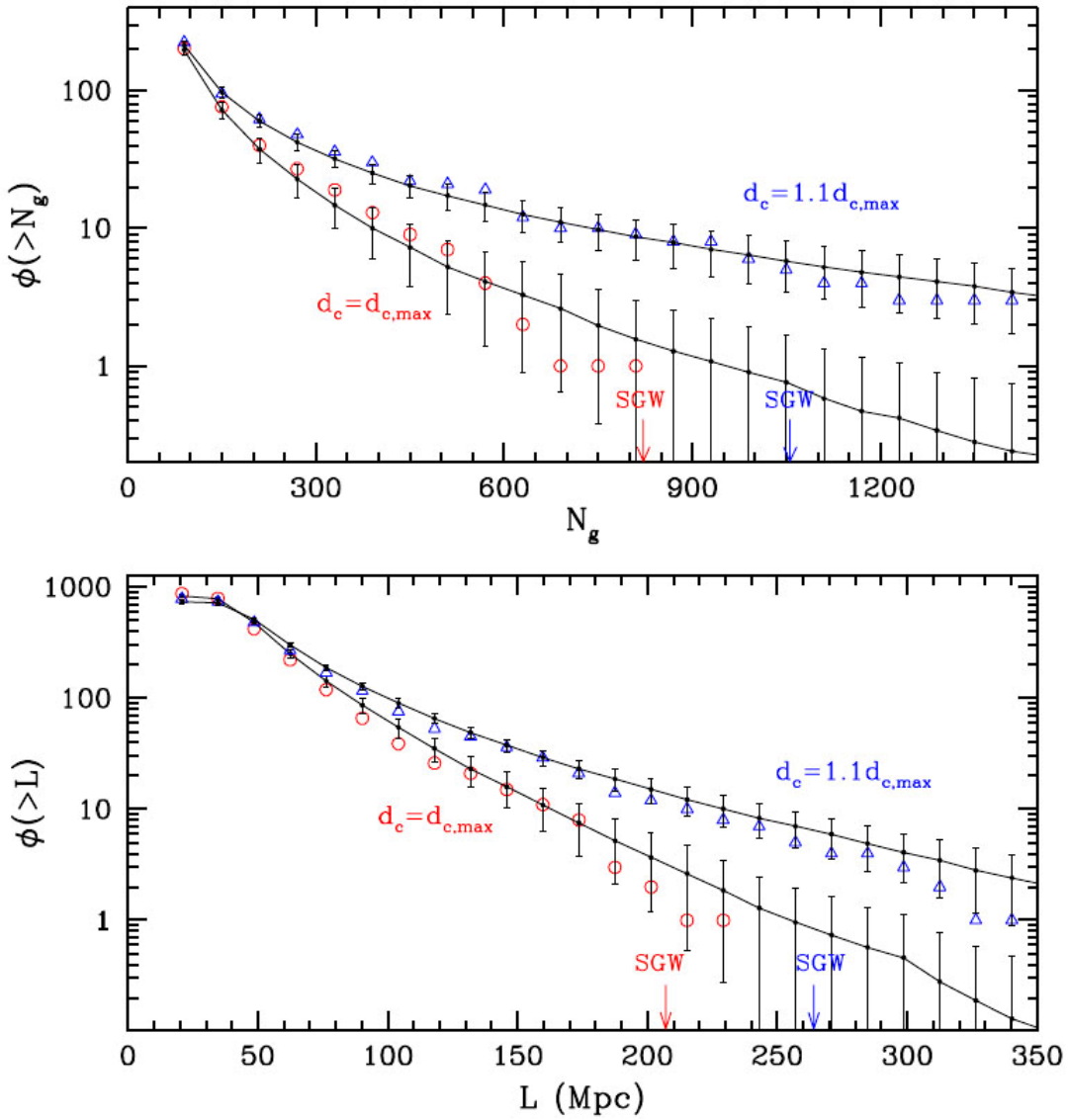



(1)
822 galaxies
L=207 Mpc
(2)
601
226 Mpc
(3)
190 Mpc
587
(4)
558
139 Mpc
y (Mpc)
x (Mpc)
(1)
V=3.85x10⁶ Mpc³
L=464 Mpc
(2)
415 Mpc
2.39x10⁶ Mpc³
(3)
345 Mpc
1.60x10⁶ Mpc³
(1)
1162 galaxies
L=251 Mpc
(2)
665
209 Mpc
(3)
630
195 Mpc
(4)
568
182 Mpc
(1)
L=447 Mpc
V=2.77x10⁶ Mpc³
(2)
369 Mpc
2.00x10⁶ Mpc³
(3)
324 Mpc
1.51x10⁶ Mpc³

Predictions of LCDM from mock surveys

- Consistents with ΛCDM for both $d_c = d_{c,max}$ and $1.1 * d_{c,max}$ cases

- $N_{mock}(N_g=844) = 137/200$
  $N_{mock}(L_{max}>149h^{-1}Mpc) = 155/200$



Predictions for future surveys

-27 non-overlapping mock surveys in HR2
- SDSS angular mask & galaxy number density
- 4 times deeper than SDSS: 1992 h^{-1}Mpc or z=0.8

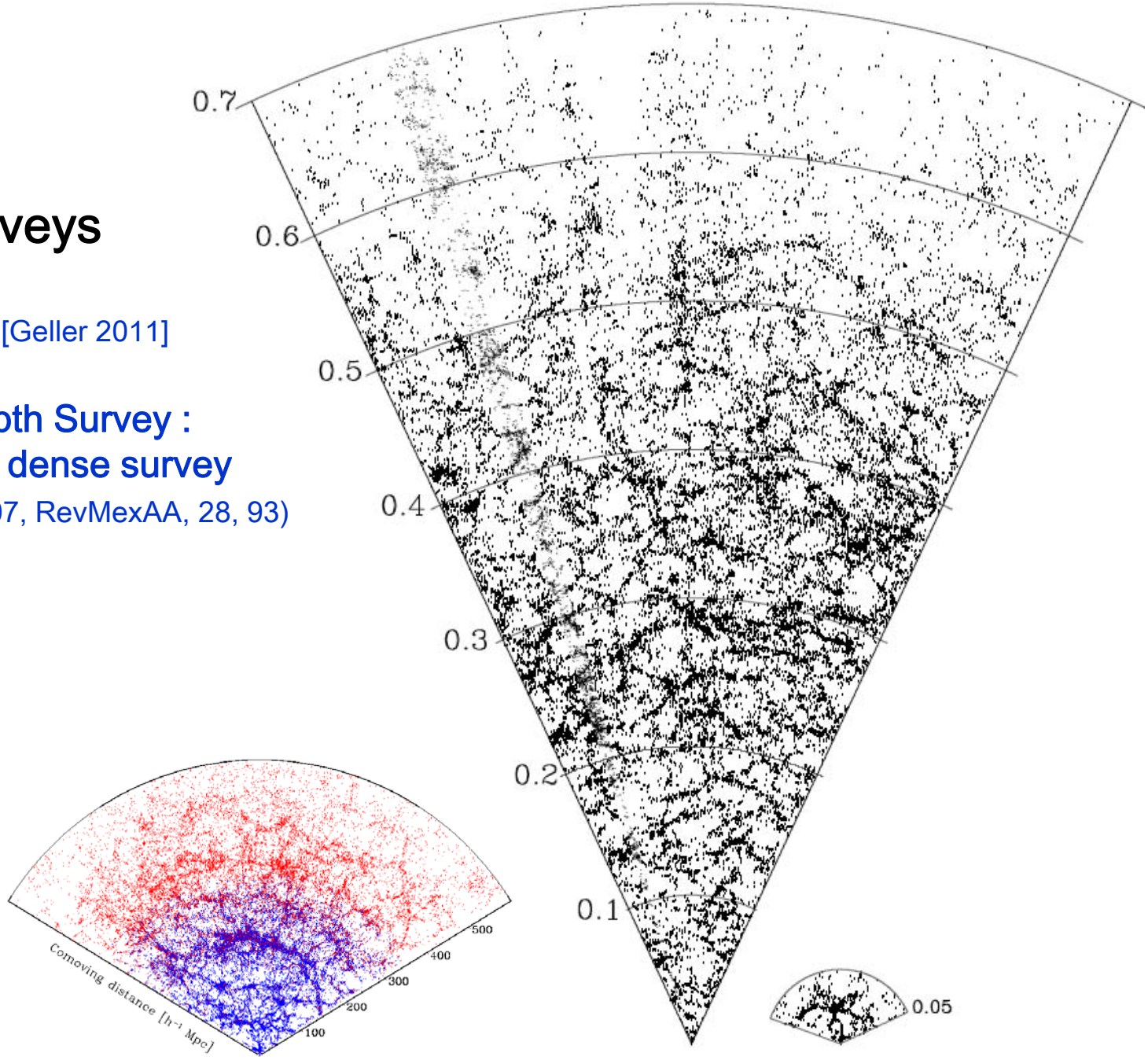
On average the largest structure has
Maximum extent of 310 h^{-1}Mpc : 1.7 times larger
Richness of 2480 galaxies: 3 times more

➔ **The universe will look more homogeneous over the scale of the survey size**

Future surveys

1. HectoMAP [Geller 2011]

2. Hubble-Depth Survey :
wide, deep, & dense survey
(Park & Kim 2007, RevMexAA, 28, 93)



Summary

1.If a structure like the SGW is consistent with the LCDM model that is homogeneous and isotropic on large scales with Gaussian initial conditions.

2. Catalogs of high-density LSSs and low-density LSSs made from SDSS DR7 Main galaxy sample.

The SGW is indeed the largest structure in the local universe when the threshold density is reasonably high .

3. A large Horizon Run cosmological N-body simulation with the WMAP 5yr cosmological parameters (HR2) that evolved $6000^3 = 2.16 \times 10^{11}$ particles, and spanned a volume of $(7.200\ h^{-1}\,\mathrm{Gpc})^3$, was made.

And its halo catalog is used to make 200 mock survey samples, which enabled us to confront the LCDM model with the observed LSSs statistically.

4. LCDM model predicts that within a SDSS-like survey there is on average 1 SGW-like object with the same mass and size.

A Hubble-Depth Survey (z~1, r<~21) will reveal a ~twice larger largest structure.

5. LSS as a tool constraining the galaxy assignment schemes and cosmological models