ICTP 050531~0604

# Theoretical and Observational Studies of
# Topology of Large Scale Structure
## Study of Space and Structure through Shapes of Large S cale Structures

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# Why is topology study useful?

1. Gaussianity of the linear (primordial) density field pr edicted by simple inflationary scenarios

2. Topology of galaxy distribution at NL scales sensitive to cosmological parameters & t o galaxy formation mechanism

3. Direct Intuitive meaning

| Large Scales | Small Scales |
| --- | --- |
| Primordial Gaussianity | Galaxy Formation |
| | Cosmological Parameters |

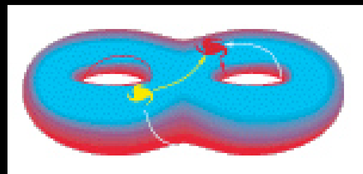
# Genus – A Measure of Topology

- **Definition**

G = # of holes - # of isolated regions

in iso-density contour surfaces

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

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

: 2 holes – 1 body = +1

- **Gaussian Field**

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

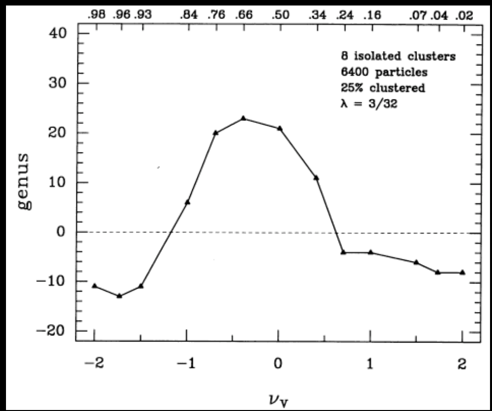
where $\_ = (\_ - \_{b})/ \_{b}\_$ &

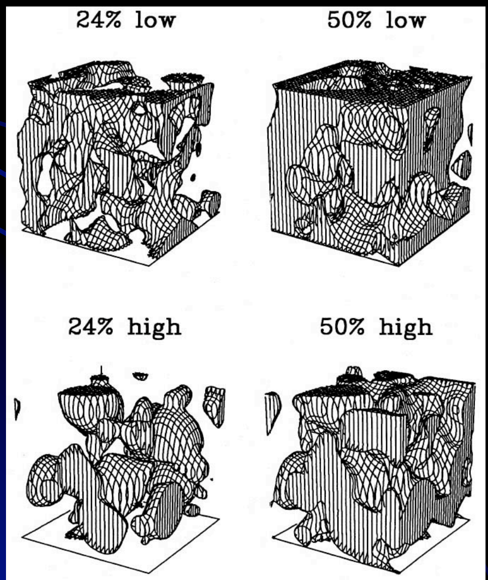
$A = 1/(2\pi)^2 \langle k^2/3 \rangle^{3/2}$

if $P(k) \sim k^n$, $A\,R_G^3 = [8\sqrt{2}\pi^2]^{-1} * [(n+3)/3]^{3/2}$

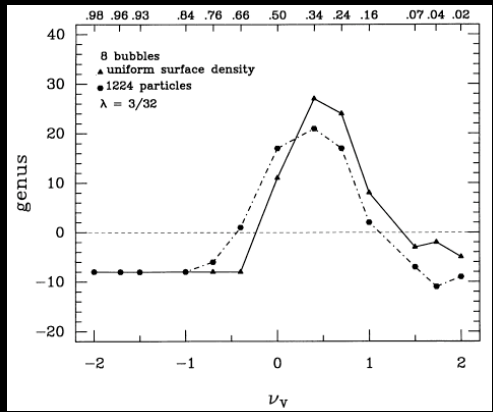
## ● Non-Gaussian Field (Toy models)

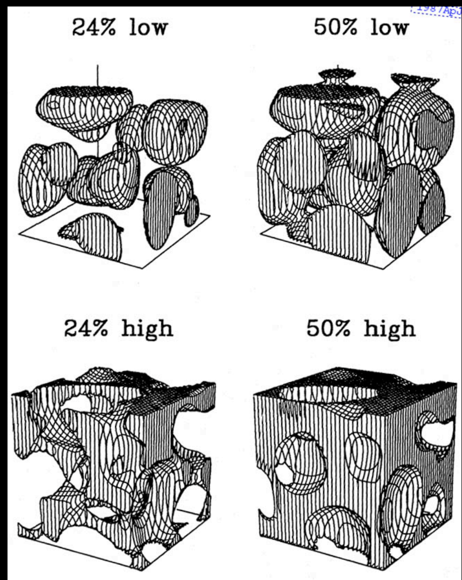
### Clusters



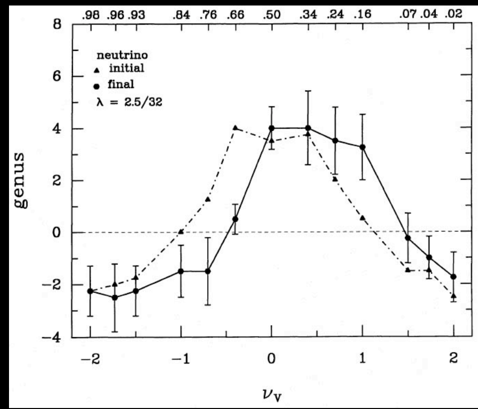



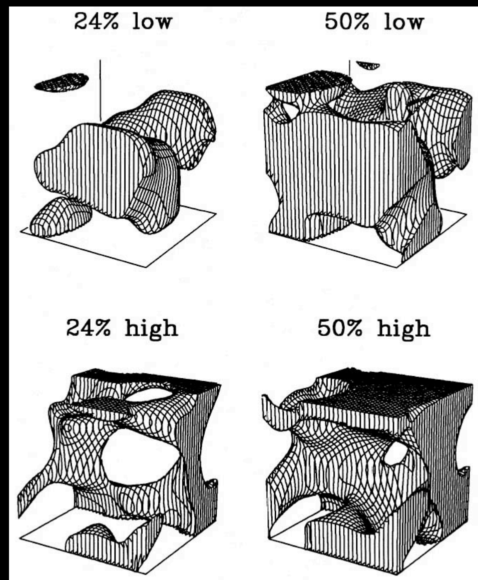

### Bubbles




### HDM




(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 – gravitational & biasing effects
- 1992: Weinberg, Cole – PS, initial skewness, biasing effects
- 1994: Matsubara – 2nd order perturbation in weakly NL regime
- 1996: Matsubara – redshift space distortion in L regime
- 1996: Matsubara, Suto – gravitational & z-space distortion
- Etc….

## II. Recent Works

- **2000: Colley et al.** – Simulation of SDSS
- **2001, 2003: Hikage, Taruya & Suto** – dark halos (analytic & numerical)
- **2003: Matsubara** – 2nd orber perturbation theory
- [ Minkowski functionals (Mecke, Buchert & Wagner 1994; Schmalzing & Buchert 1997 etc.)]

## III. 3D genus analysis of observational data

| | |
|---|---|
| 1989: Gott et al. | - CfA 1 etc. |
| 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 |

# IV. 2D Genus (LSS)

- 2D genus before SDSS
  - Suggested by Melott (1987)
  - Coles & Plionis (1991): Lick Galaxy Catalogue
  - Plionins, Valdarnini, & Coles (1992): Abell and ACO cluster catalogue
  - Park et al. (1992): CfA Slice
  - Colley (2000): Simulated SDSS
  - Park, Gott, & Choi (2001): HDF
  - Hoyle, Vogeley & Gott (2002): 2dFGRS

- 2D genus with SDSS
  - Hoyle, Vogeley & Gott (2002): weak evidence for variation in the genus with galaxy type

# Current status of LSS topology study

1. **Large scales** (>> 10 $h^{-1}$Mpc)

   Small survey size → No strong constraints on primordial Gaussianity

2. **Small scales** (< 10 $h^{-1}$Mpc)

   Little study so far

   Effects of gravitational evolution,
   galaxy biasing & internal physical properties of galaxies,
   redshift-space distortion …

# Effects of Gravitational Evolution, Biasing, & Redshift Space Distortion on Topology

- ÀCDM Simulations (Kim & Park 2004. 7)

TreePM code GOTPM (Dubinski, Kim, Park 2003)

$2048^3$ mesh (initial condition)

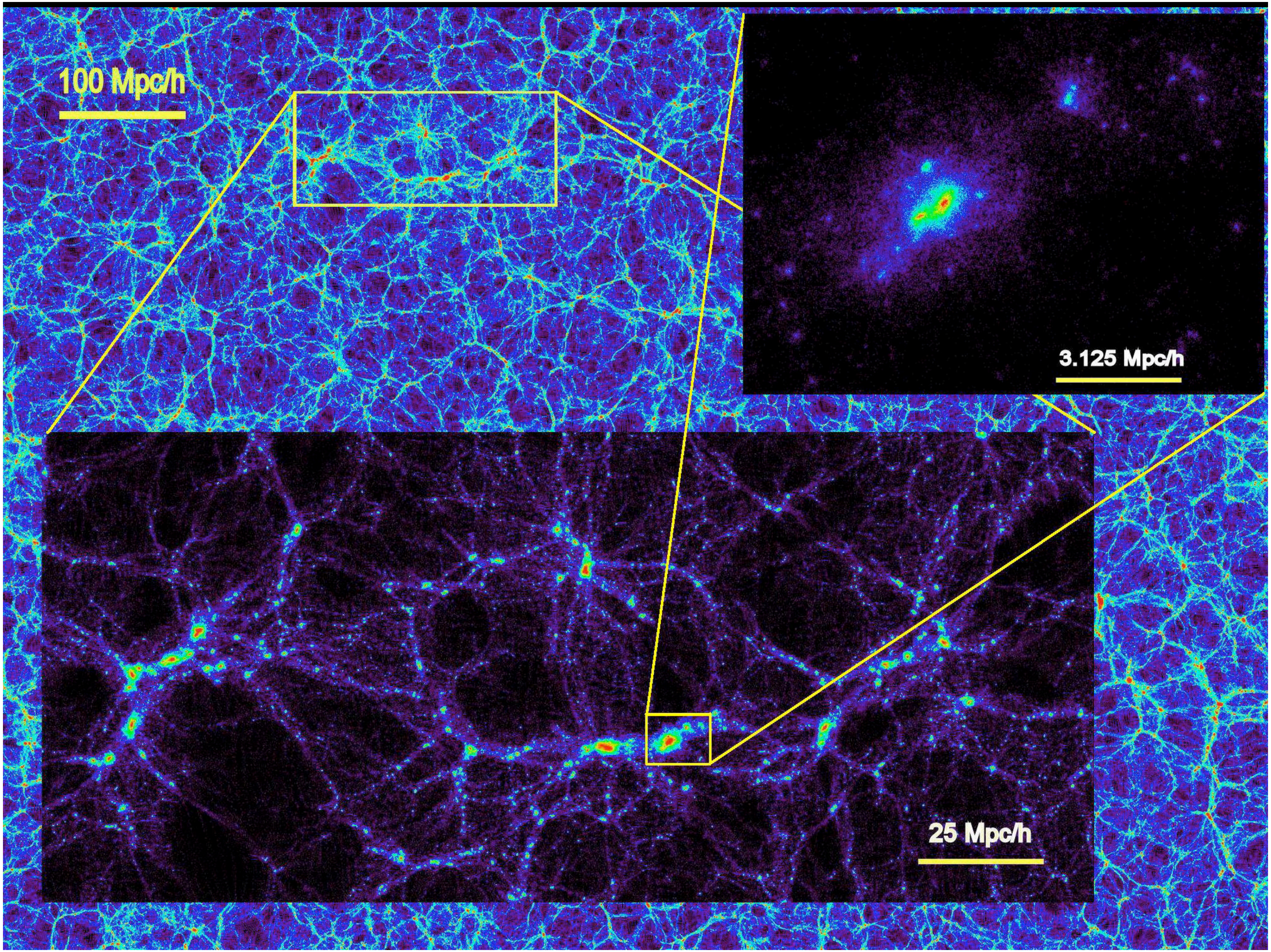
$2048^3$ CDM particles

1024 & 5632 $h^{-1}$Mpc size boxes (>30 max$R_G$)

50 & 275 $h^{-1}$kpc force resolutions

**FOR PRECISION COMPARISON**

**between cosmological models with the real universe**


100 Mpc/h
3.125 Mpc/h
25 Mpc/h

# Dark Halo Identification

(Kim& Park 2004:

•ΛCDM 1024 $h^{-1}$Mpc)

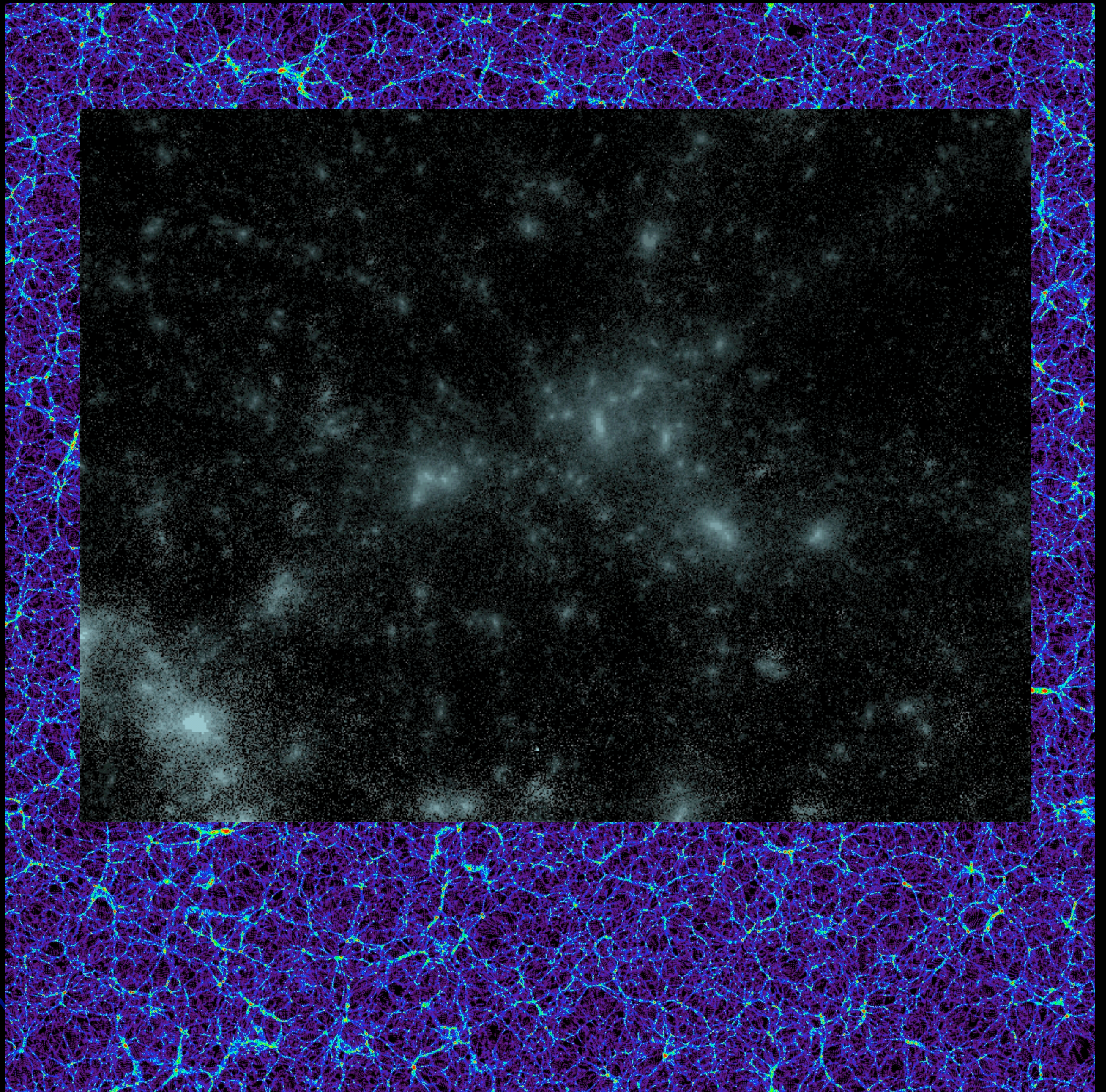
**Physically Self-Bound**

Halo centers
- local density peaks

Binding E wrt local halo centers

Tidal radii of subhalos wrt bigger halos

Halos with >=53 particles ($5x10^{11}$ M_)



[Kim & Park 2004 : 5632 & 1024 $h^{-1}$Mpc]

# N-body simulation parameters

Table 1: Simulation Characteristics

| | model | $\Omega_m$ | $\Omega_\Lambda$ | $h$ | $b$ | $N_m$ [a] | $N_p$ | $L(h^{-1}\mathrm{Mpc})$ | $z_i$ | $N_{step}$ | code |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a) | ΛCDM | 0.27 | 0.73 | 0.71 | 1.11 | $2048^3$ | $2048^3$ | 1024 | 17 | 680 | PMTree |
| a) | ΛCDM | 0.27 | 0.73 | 0.71 | 1.11 | $2048^3$ | $2048^3$ | 5632 | 17 | 170 | PMTree |
| b) | ΛCDM | 0.3 | 0.7 | 0.7 | 1.11 | $512^3$ | $512^3$ | 128 | 23 | 980 | PMTree |
| c) | ΛCDM | 0.3 | 0.7 | 0.7 | 1.11 | $2048^3$ | $1024^3$ | 409.6 | 47 | 470 | PM |
| c) | SCDM | 1.00 | 0.00 | 0.5 | 1.5 | $2048^3$ | $1024^3$ | 1024 | 23 | 230 | PM |
| c) | SCDM | 1.00 | 0.00 | 0.5 | 1.5 | $2048^3$ | $1024^3$ | 409.6 | 47 | 470 | PM |

[a] Size of mesh on which initial conditions are defined.

- a) → IBM SP3 at KISTI, 128 CPUs, 900 Gbytes,
- b) → IBM SP3 at SNU, 16 CPUs,
- c) → QUEST at KIAS, 128 CPUs, 256 Gbytes,

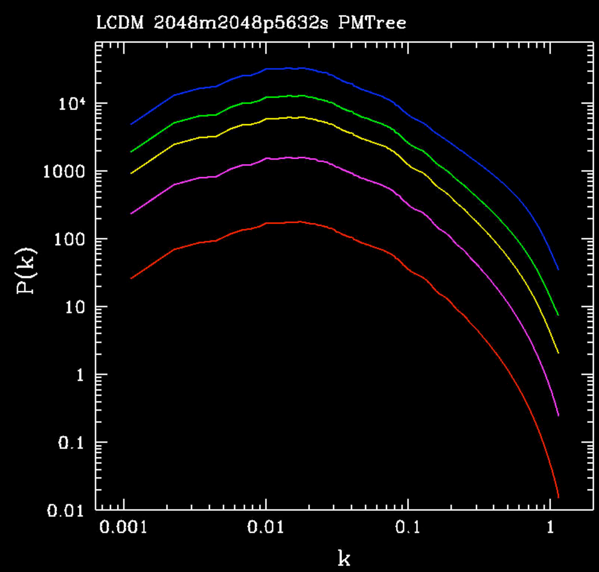
**Gravitational Evolution**

**Initial conditions**

**→Growth by gravitational instability**

**→ weakly interacting & cold matter**

**→ Present epoch at $_{8m}$=0.9**



# Dependence of Genus on …

(Park, Kim & Gott 2005)

1. Smoothing Scales

   $R_G$ = 1.5 ~ 150 $h^{-1}$ Mpc

2. Tracers

   Matter, Peaks in initial density field,

   Dark halos, HOD 'galaxies'

3. Redshift space distortion

4. Cosmogony : LCDM vs SCDM

# Genus-Related Statistics

- **Amplitude drop $R_A$**

  $R_A = A_{obs} / A_{PS}$

- **Shift parameter __**

  By fitting $G_{obs}$(_) over –1<_<1

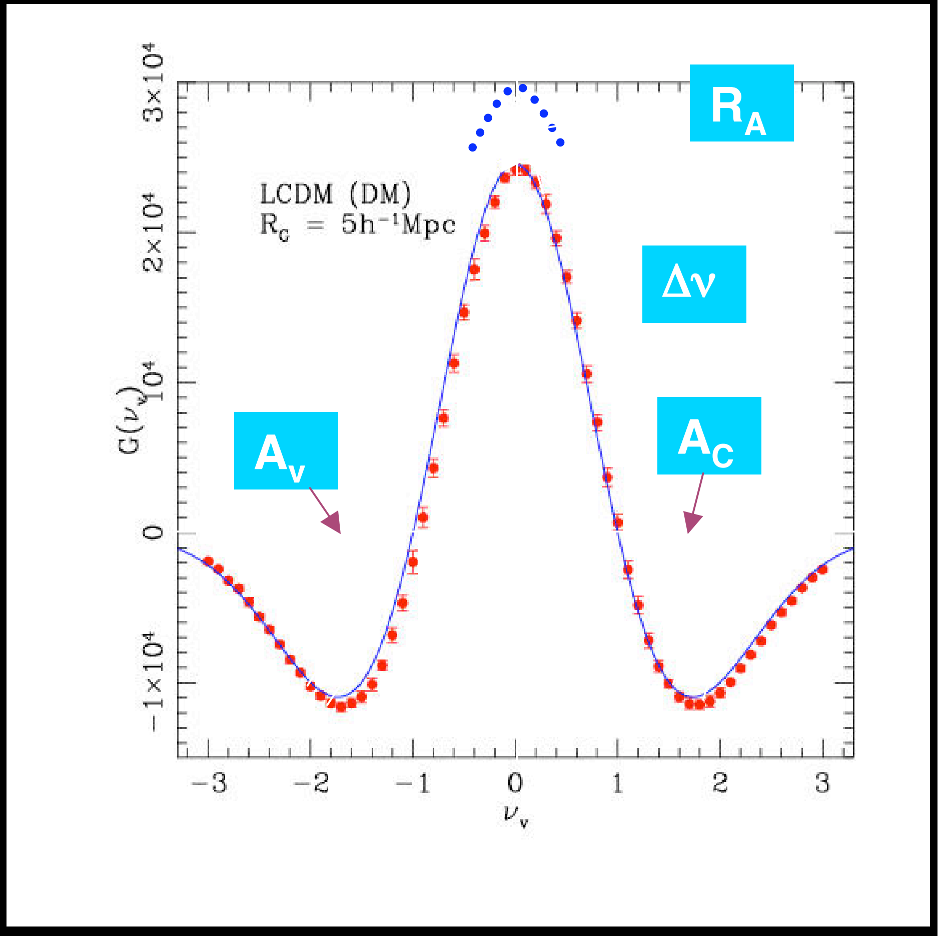
- **Asymmetry parameters**

  $A_V$ & $A_C$

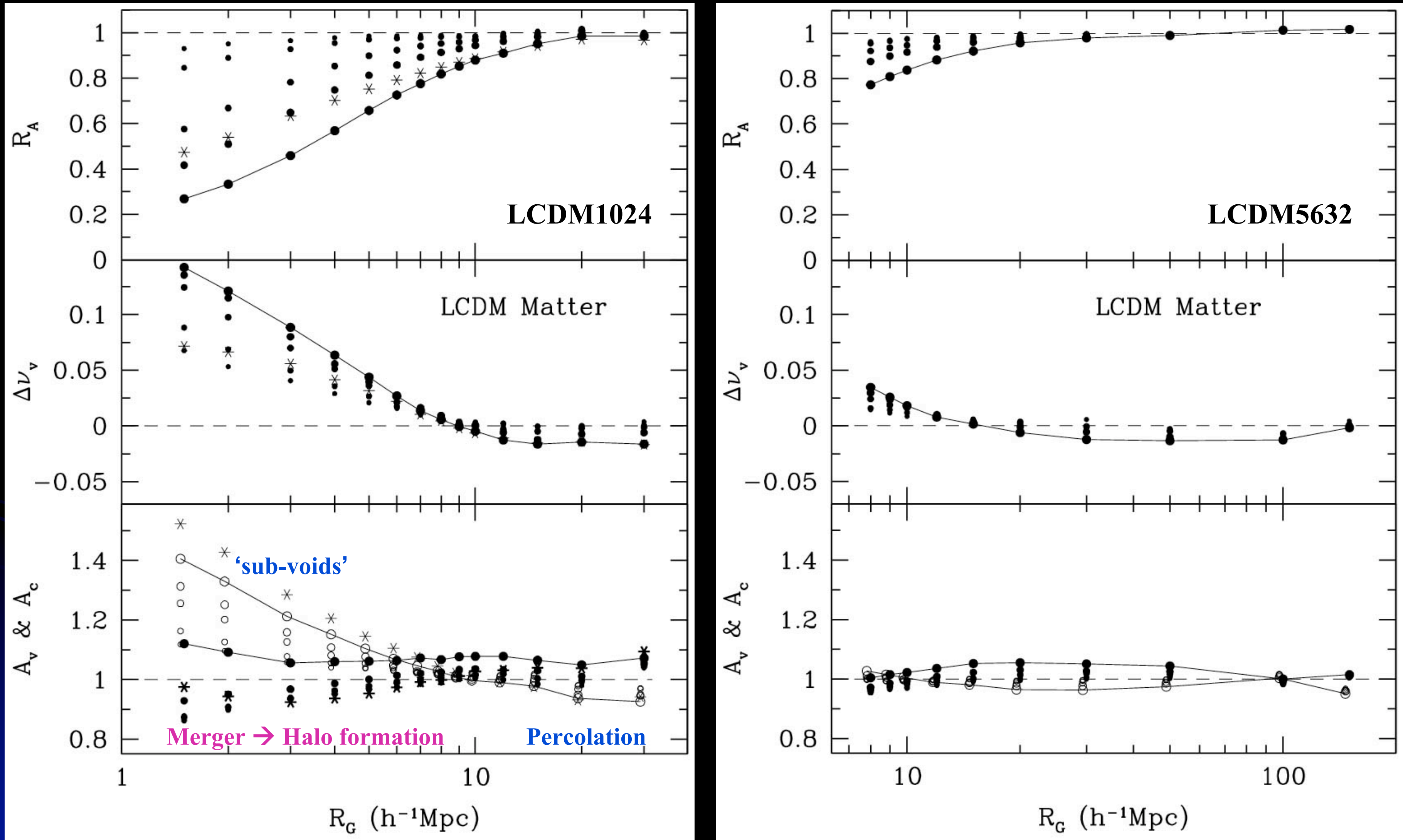
  A = ∫ $G_{obs}$(_) d _/∫ $G_{fit}$(_) d _

  where intervals are

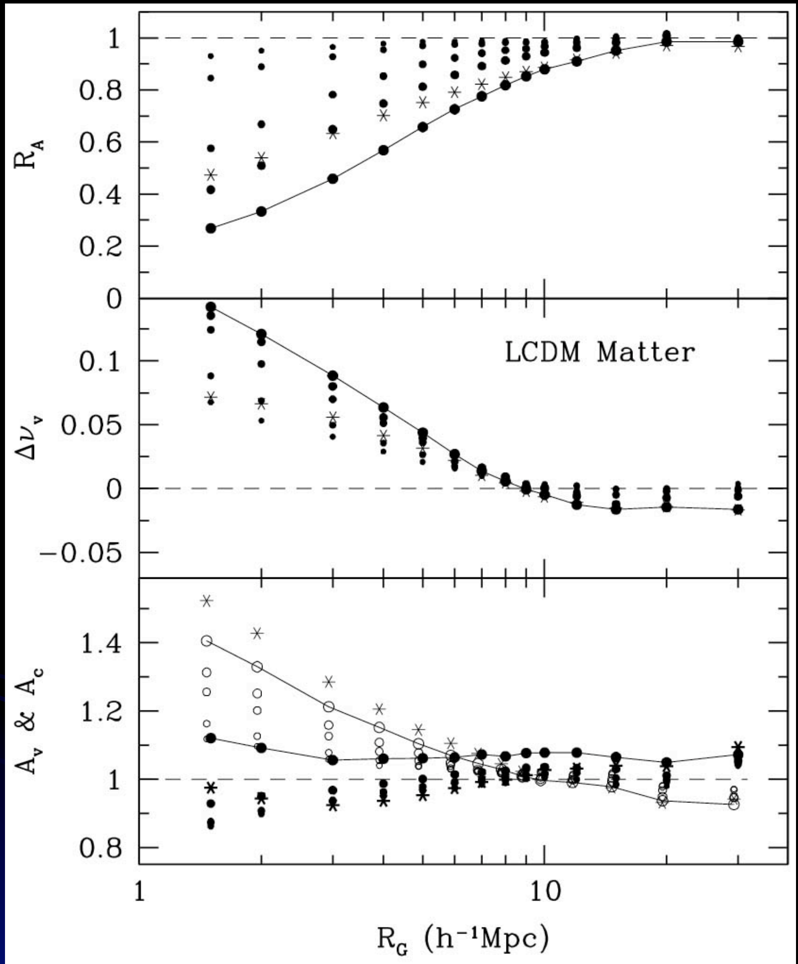
  -1.2~-2.2 ($A_V$), 1.2~2.2 ($A_C$)

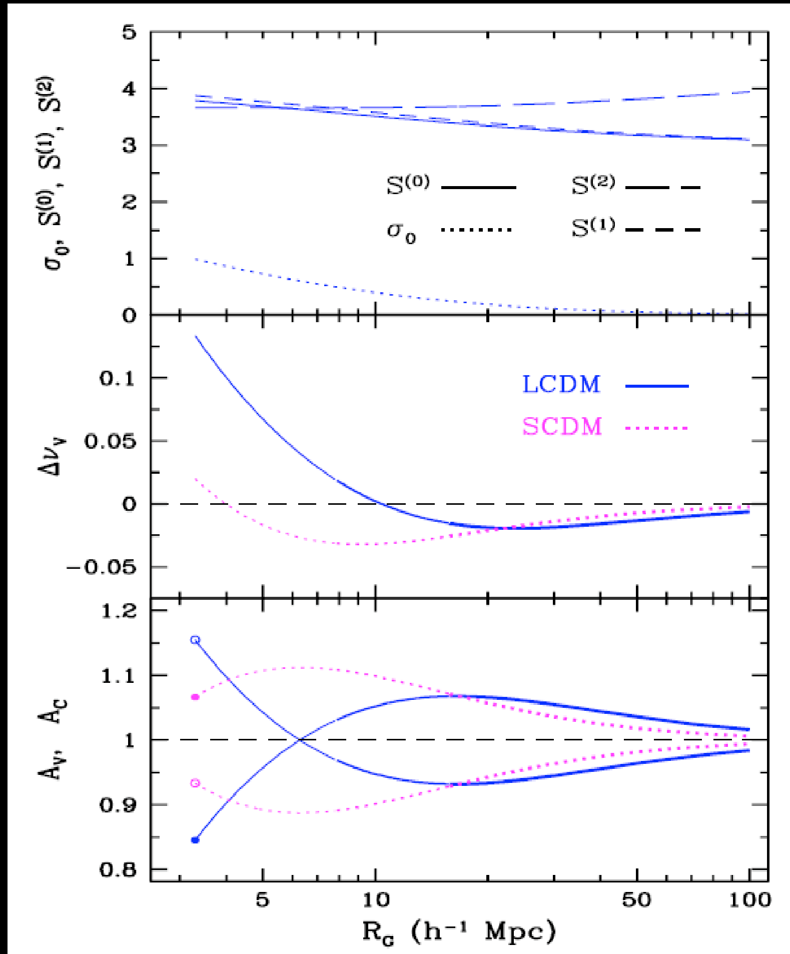


# Dependence of genus on smoothing scale



# Perturbation theory (Matsubara 2003)



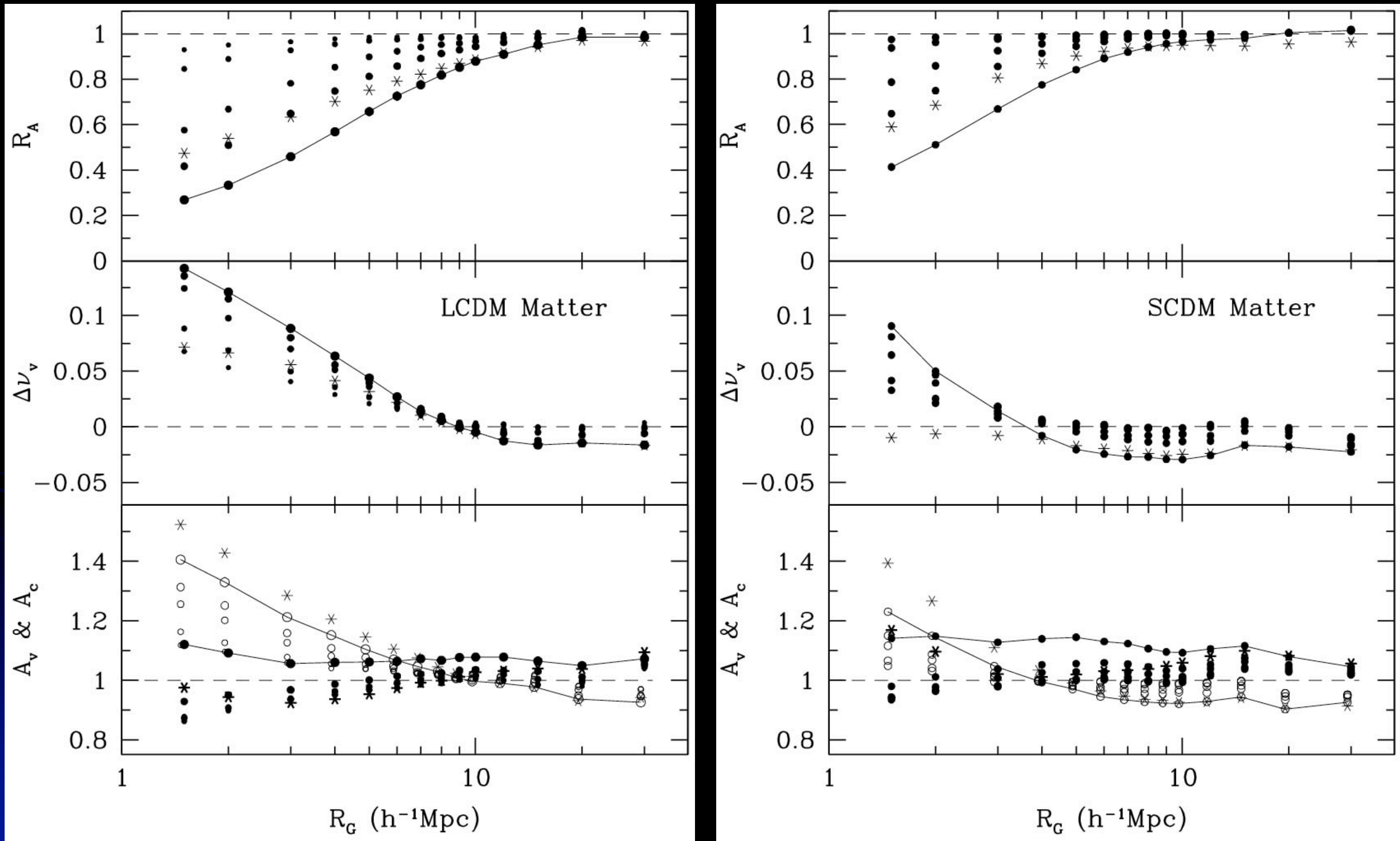

$$G(\nu_f) = \frac{1}{(2\pi)^2}\left(\frac{\sigma_1}{\sqrt{3}\sigma_0}\right)^3 e^{-\nu_f^2/2}\left(1-\nu_f^2-[(S^{(1)}-S^{(0)})(\nu_f^3-3\nu_f)+(S^{(2)}-S^{(0)})\nu_f]\sigma_0\right)$$

$$S^{(0)} = \langle\delta^3\rangle/\sigma_0^4 = \frac{1}{\sigma_0^4}\int\frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}B(k_1,k_2,k_{12}),$$

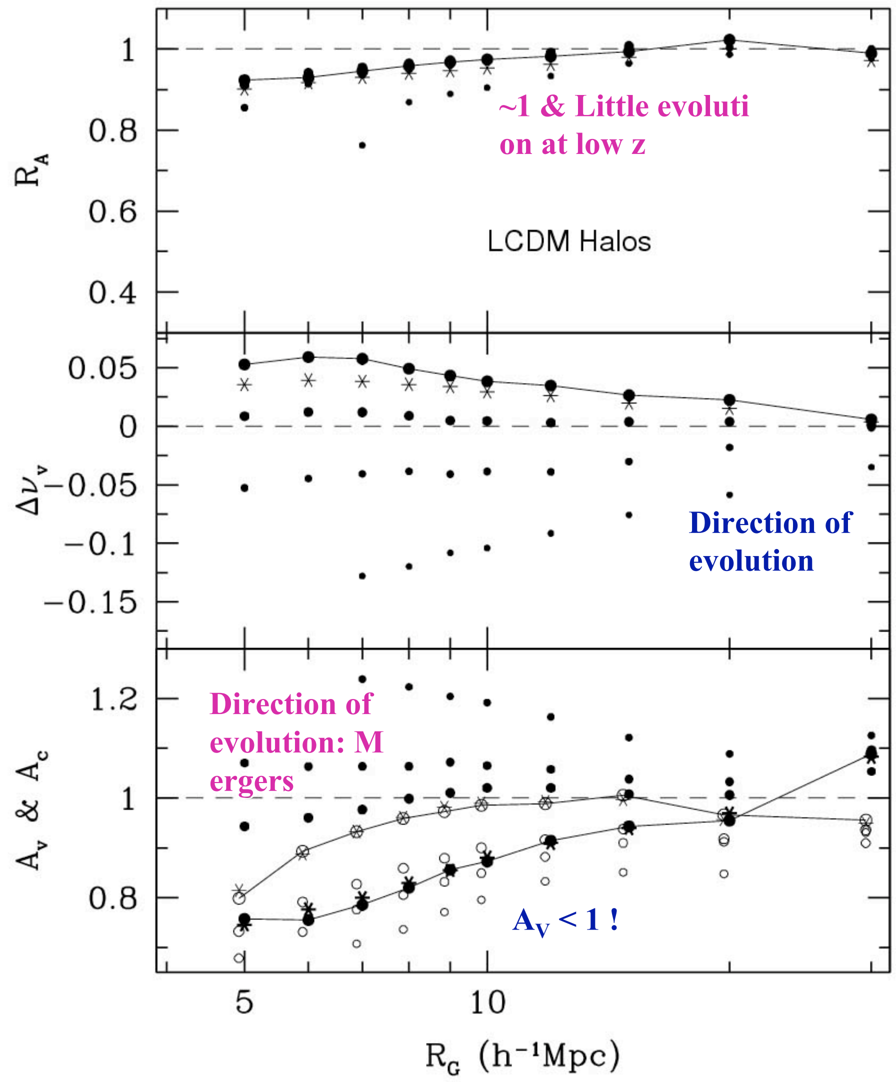
$$S^{(1)} = -\frac{3}{4}\langle\delta^2\nabla^2\delta\rangle/\sigma_0^2\sigma_1^2 = \frac{3}{4\sigma_0^2\sigma_1^2}\int\frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}k_{12}^2 B(k_1,k_2,k_{12}),$$

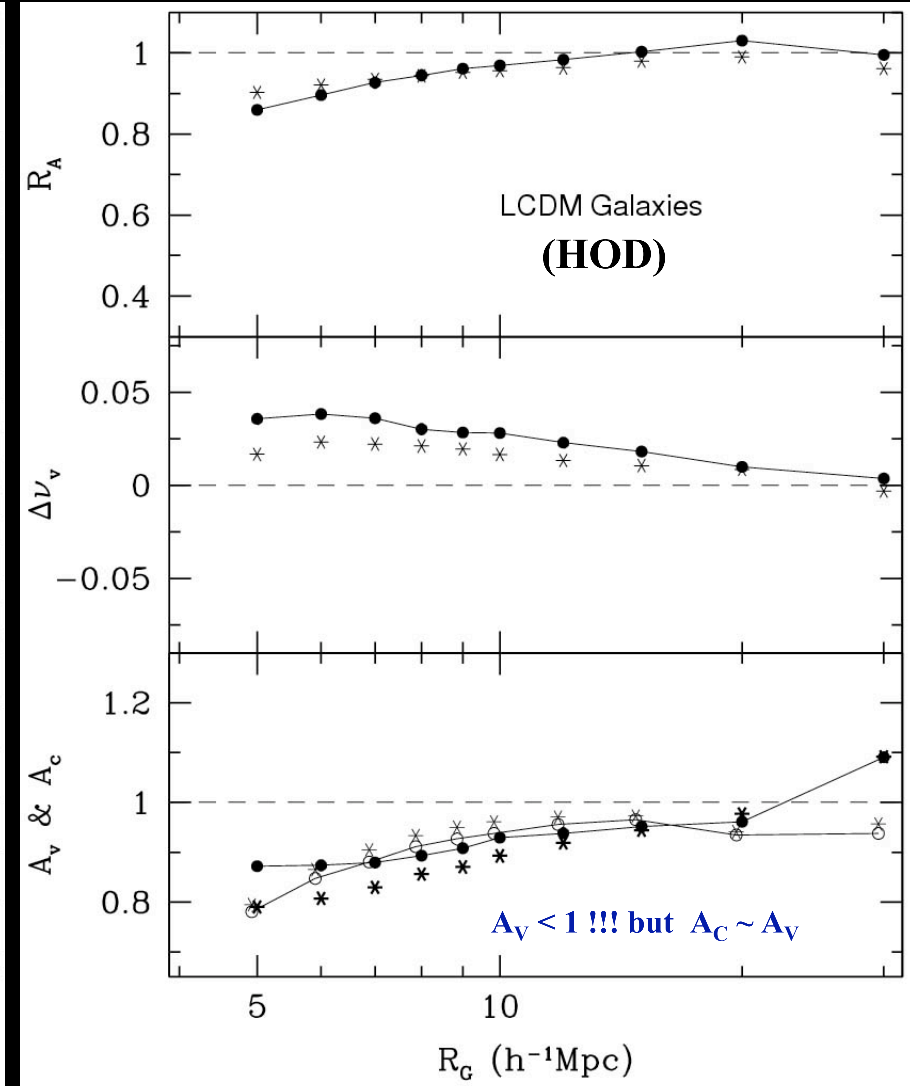
$$S^{(2)} = -\frac{9}{4}\langle(\nabla\delta\cdot\nabla\delta)\nabla^2\delta\rangle/\sigma_1^4 = \frac{9}{4\sigma_1^4}\int\frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\mathbf{k_1}\cdot\mathbf{k_2}k_{12}^2 B(k_1,k_2,k_{12})$$

# Dependence of genus on cosmogony



# Dependence of genus on LSS tracers




$<N_{sat}> = (M/M_1)$_ for $M>M_{min}$ where $\log M_{min}=11.76$, $\log M_1=13.15$, _=1.13

# Findings …

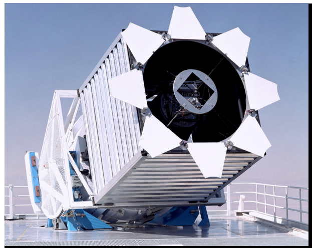
(Park, Kim & Gott 2005)

1. Strong dependences on scale, time & tracers
2. $R_A$ freezes at z ~< 3 (insensitivity of amplitude of G to time)
3. Gravitation evolution makes $A_V$ increase & Observed $A_V$< 1

   → proper **biasing mechanism** needed

(4. Problem with HOD: $A_C \sim A_V$?)

Voids are not the places where there is nothing, but pl aces where history of the universe is better kept.



# Sloan Digital Sky Survey

## 1. Imaging of North Galactic Cap

**2.5m APO telescope with a mosaic CCD camera**

**u, g, r, i, z photometric bandpasses → objects for spectroscopy**

## 2. Spectroscopy

**~ $10^6$ galaxies & $10^5$ quasars with rms z-error ~ 30 & 300 km/s**

## 3. Samples

**Main Galaxies: $r_{Pet} < 17.77$ → Recent Samples 14 & 15 (~DR3 & DR4)**

**Quasars**

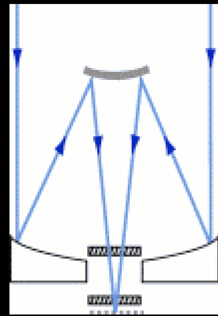
**Luminous Red Galaxies (LRG): $z<0.4$ & $>0.4$ samples**

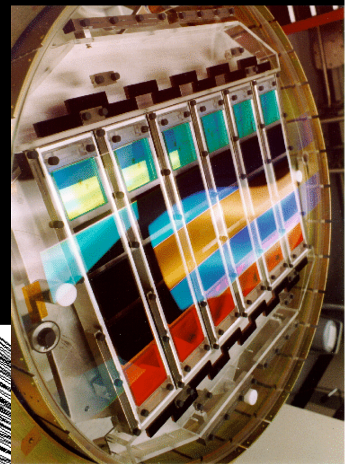
# Survey characteristics

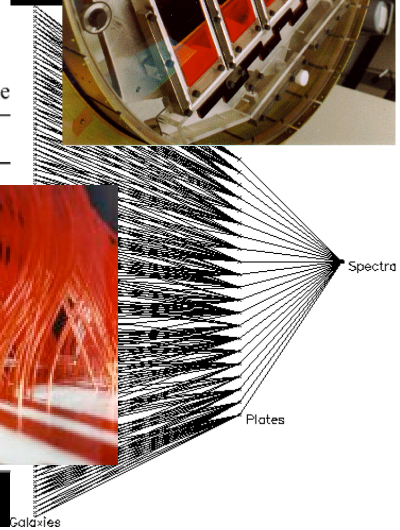
TABLE 1

SDSS Equipment Summary

| Parameter | Value |
|---|---|
| **Telescope and Site: Apache Point Observatory** | |
| Latitude and longitude | N32°46′49″.3, W105°49′13″.5 |
| Elevation | 2788 m |
| Survey telescope | 2.5 m diameter, modified Ritchey-Chrétien design; 27% central obscuration |
| Survey area | North Galactic cap, 10,000 deg$^2$, minimal Galactic extinction, plus three stripes in south Galactic cap |
| Instruments | Imaging camera and two double spectrographs |
| Photometric telescope | 20 inch (0.5 m), with one CCD camera, filter wheel, and shutter |
| **Imaging Camera** | |
| Photometric CCDs | 30, 2048 × 2048, SITe/Tektronix, 49.2 mm square |
| CCD read noise | $<5\ e^-$ pixel$^{-1}$ (overall system is sky limited) |
| Image frame size | 2048 × 1361 pixels (13′.52 × 8′.98) |
| Image column separation | 25′.17 |
| Detector separation along column | 17′.98 |
| Focal-plane image scale | 3.616 mm arcmin$^{-1}$ |
| Detector image scale | 3.636 mm arcmin$^{-1}$ |
| Pixel size and scale | 24 $\mu$m; 0″.396 pixel$^{-1}$ |
| Filters | *riuzg* scanned in that order, 71.7 s apart |
| Integration time | 54 s |
| Operating mode | Time-delay and integrate (“ drift scan ”) |
| Field distortion | <0″.1 over entire field |
| Field size | 2°.5 |
| Flux calibration | Standard-star fields at 15° intervals along scans, tied to BD + 17°4708, atmospheric extinction determined by PT |
| Astrometric CCDs | 22, 0.25 × 2 inches, above and below CCD columns; *r* filter plus 3 mag neutral density filter, 10.5 s integration time |
| **Spectrographs** | |
| Channels | One red, one blue for each spectrograph |
| CCDs | SITe/Tektronix (as for imager) |
| Coverage | 3800–6150 Å (blue), 5800–9200 Å (red), $\lambda/\Delta\lambda \approx 1800$ |
| Number of fibers | 320 × 2 |
| Fiber diameter | 3″ |
| Flux calibration | Standard stars in each field, tied to colors observed with camera |
| Integration time | 45 minutes, in three exposures [nominal (S/N)$^2$ > 15 pixel$^{-1}$ at $g^* = 20.2$] |
| Pixel size | 69 km s$^{-1}$ |
| Wavelength calibration | Hg, Cd, and Ne arc lamps, rms error of 0.07 pixels (10 km s$^{-1}$) |
| Flat field | Quartz lamps |

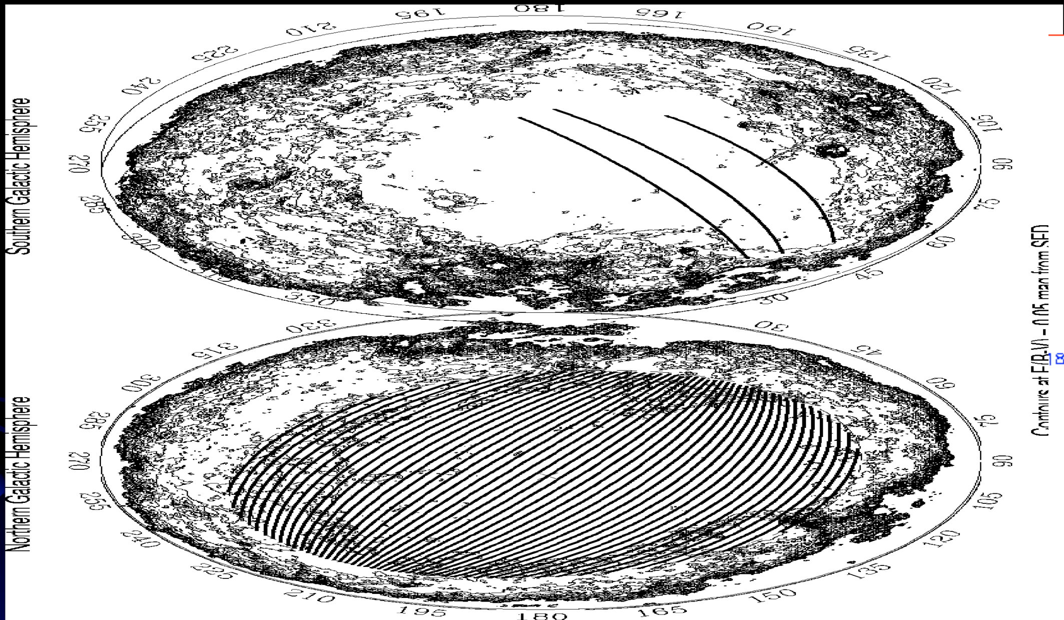




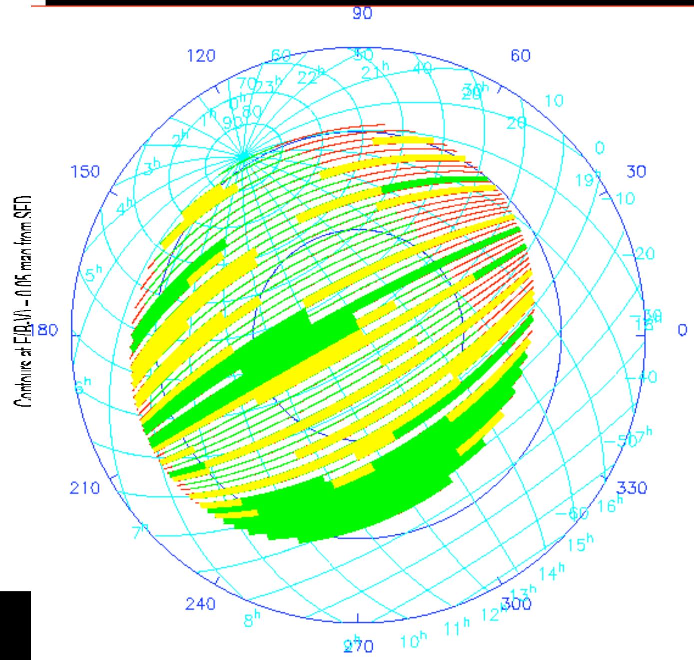


# Sky Coverage

- Minimize Galactic foreground extinction

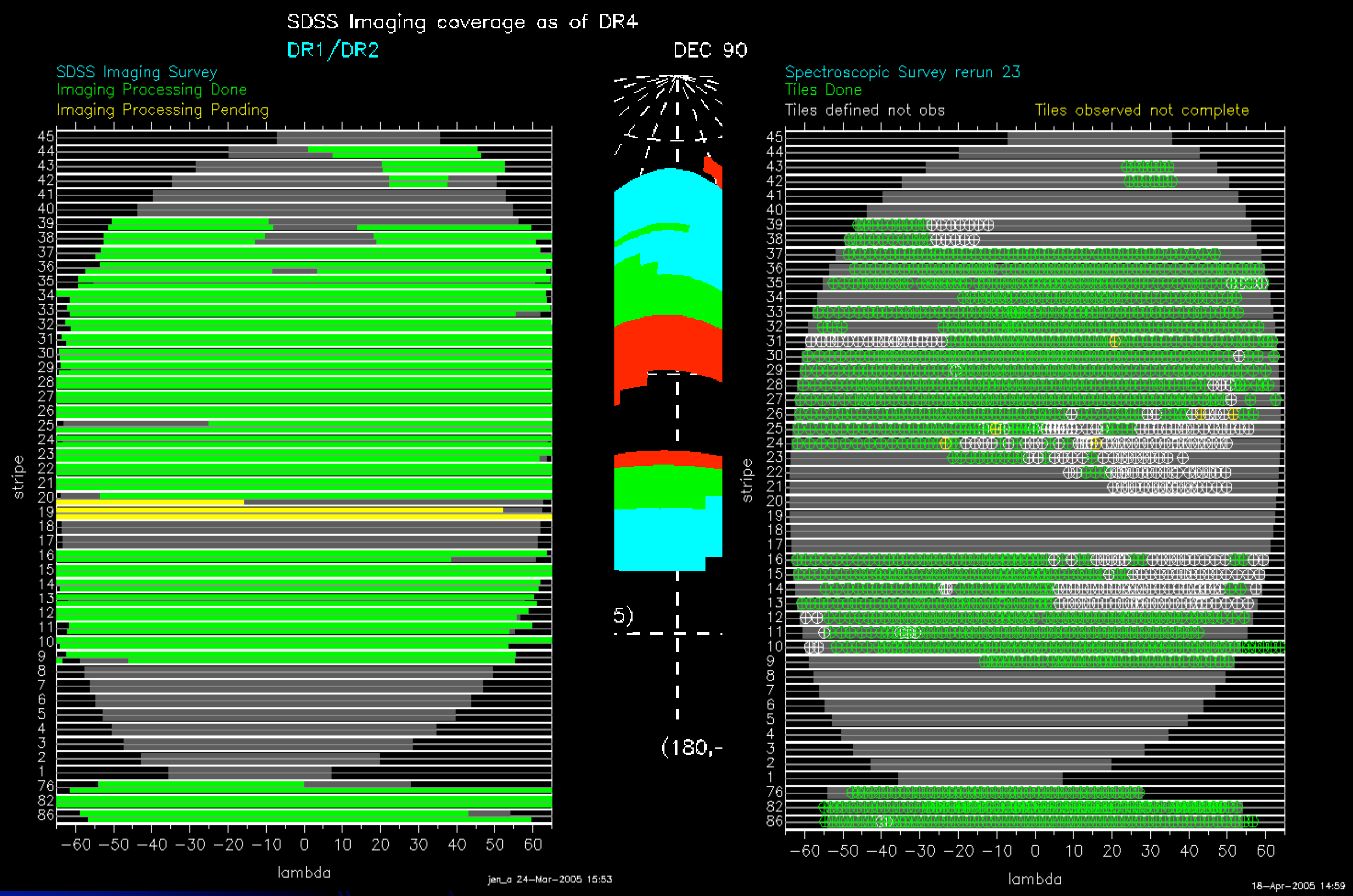


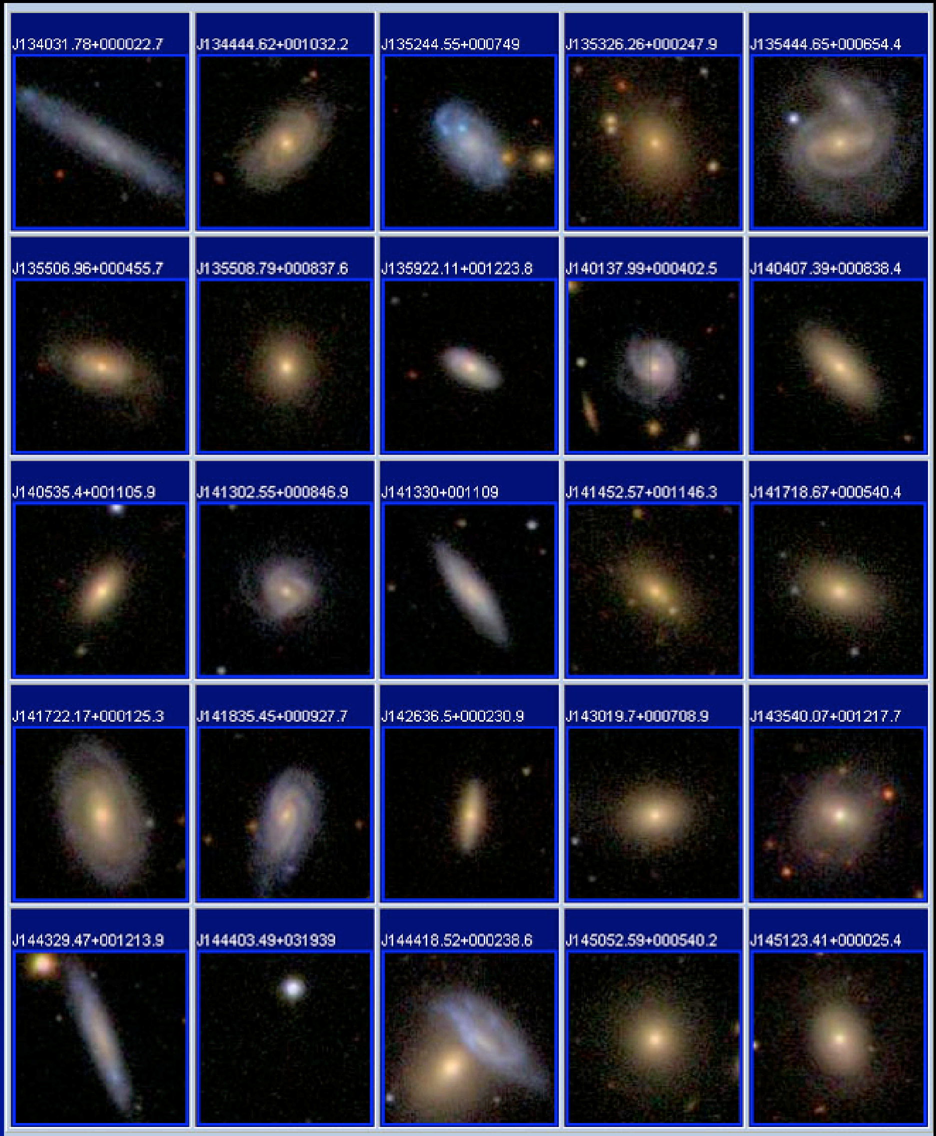

Projection on the sky (Galactic coordinates) of the Northern and Southern SDSS surveys. The lines show the individual stripes to be scanned by the imaging camera. These are overlaid on the extinction contours of Schlegel, Finkbeiner and Davis (1998). The Survey pole is marked by the `X‘ (Fig 2. York et al. 2000)



Both equatorial and galactic coordinates are plotted.

# SDSS Sky Coverage




J134031.78+000022.7
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J135244.55+000749
J135326.26+000247.9
J135444.65+000654.4
J135506.96+000455.7
J135508.79+000837.6
J135922.11+001223.8
J140137.99+000402.5
J140407.39+000838.4
J140535.4+001105.9
J141302.55+000846.9
J141330+001109
J141452.57+001146.3
J141718.67+000540.4
J141722.17+000125.3
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J142636.5+000230.9
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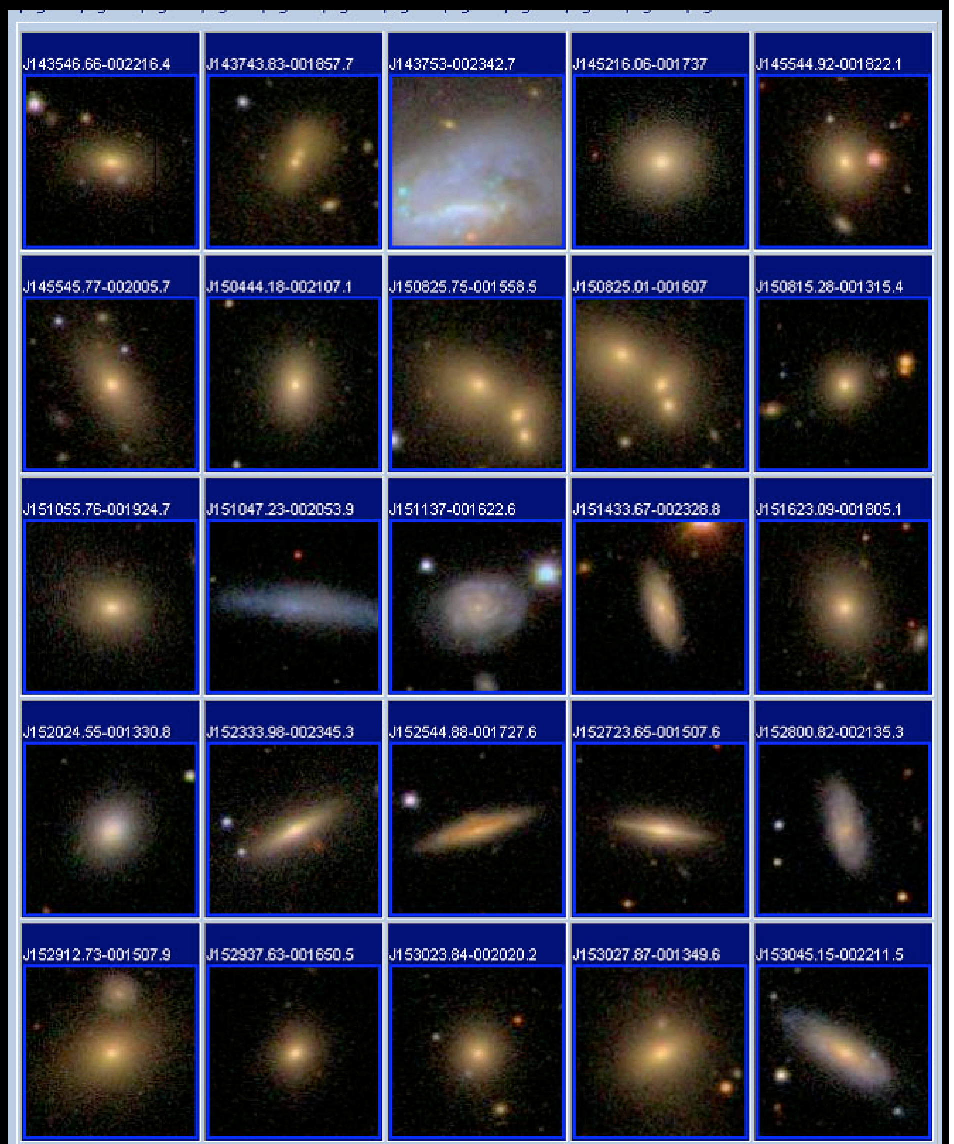
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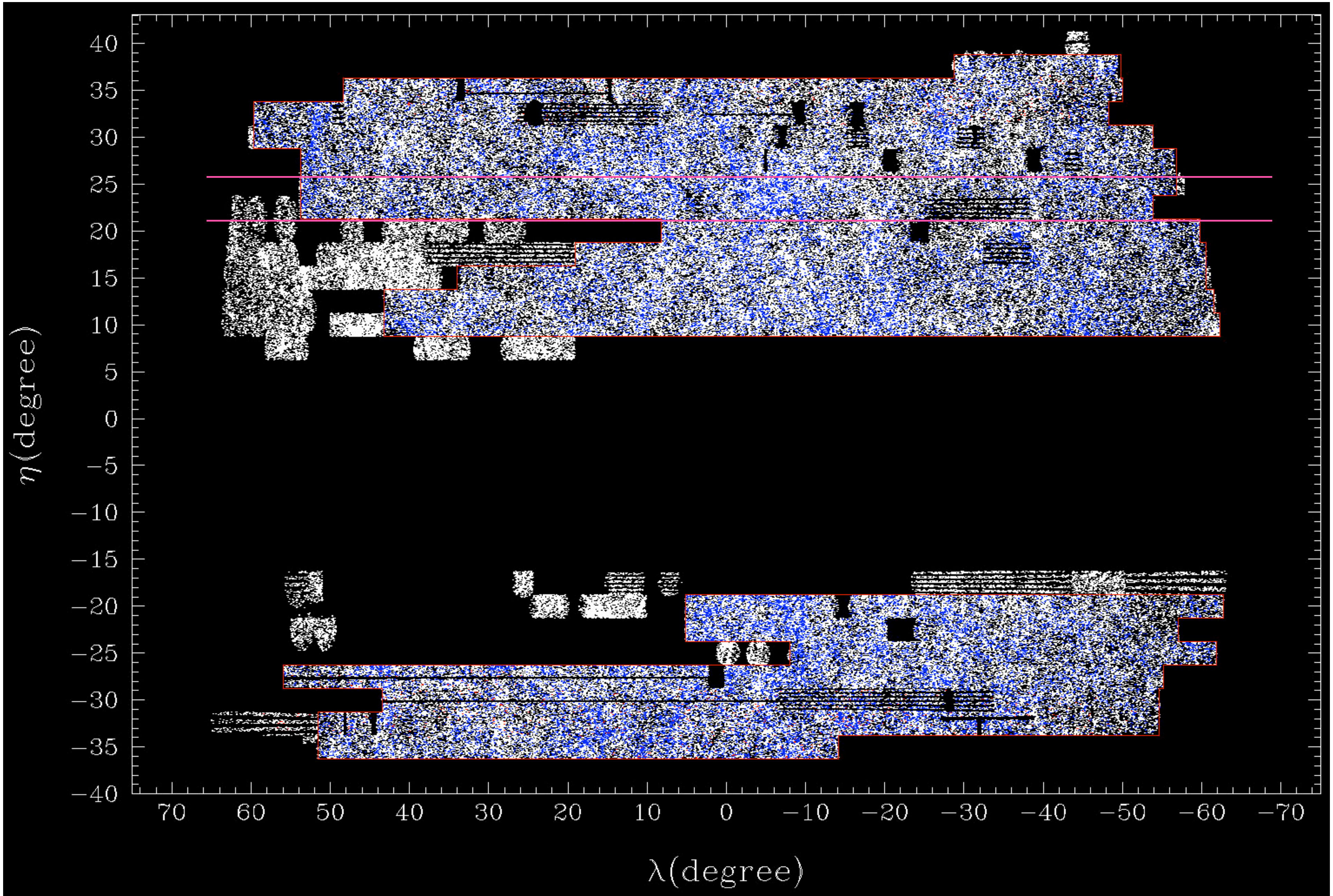



Sample 15 SDSS galaxies on Survey coordinate plane

blue: BEST, red: bright galaxies (14.0−15.0)

2005.5.9 quest ~/yychoi/Sam15/Type/145150/survey.i

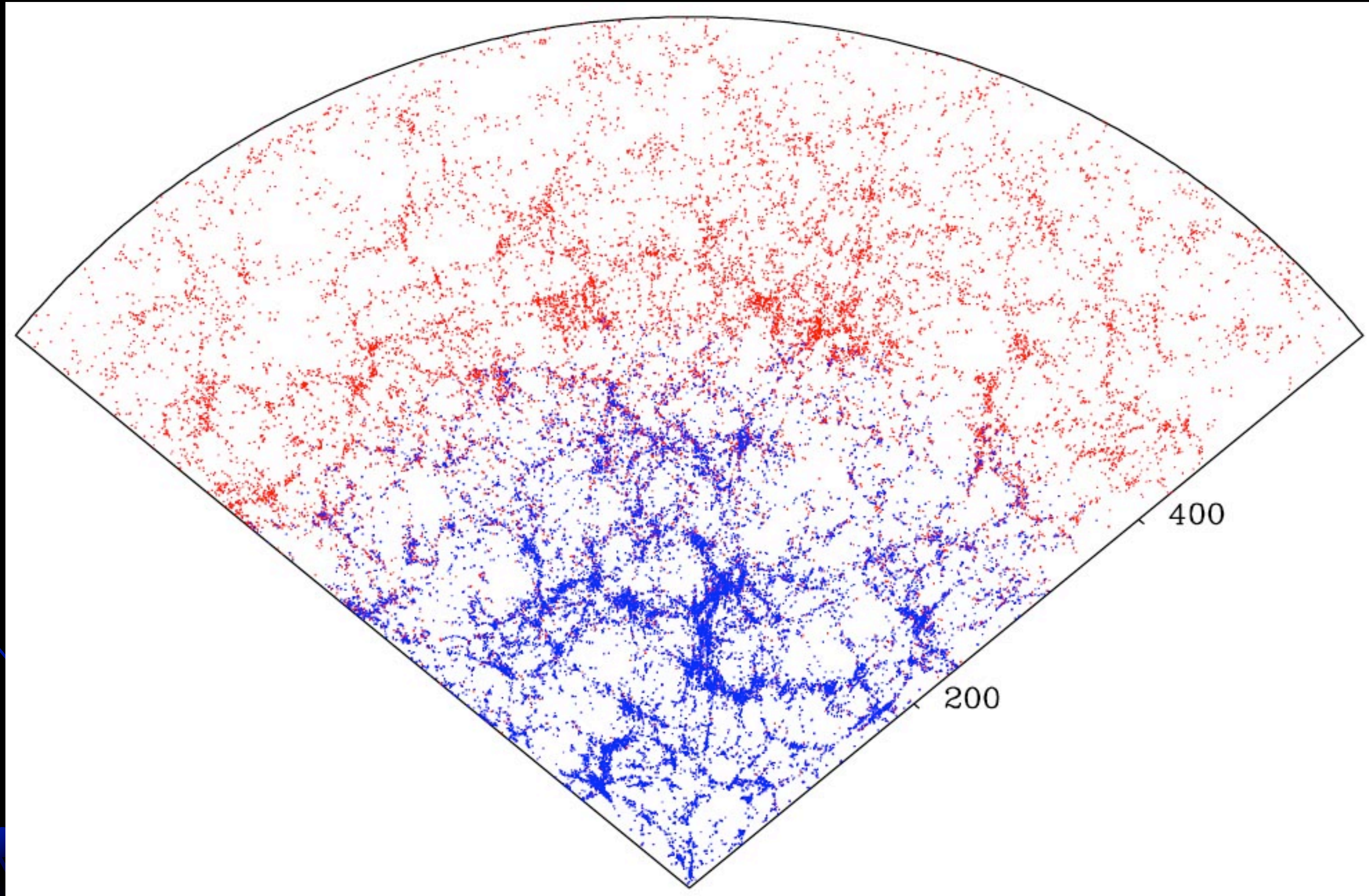
# SDSS LSS Sample 15 in survey coor. (410K galaxies)

# Horizon of human knowledge is expanding

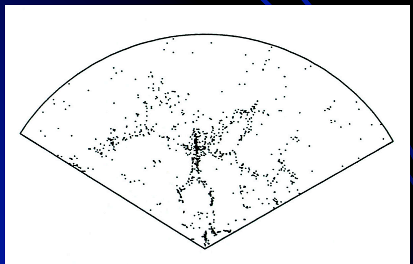
**SDSS V~ $10^2$ CfA V ~ 1/5000 Horizon V**

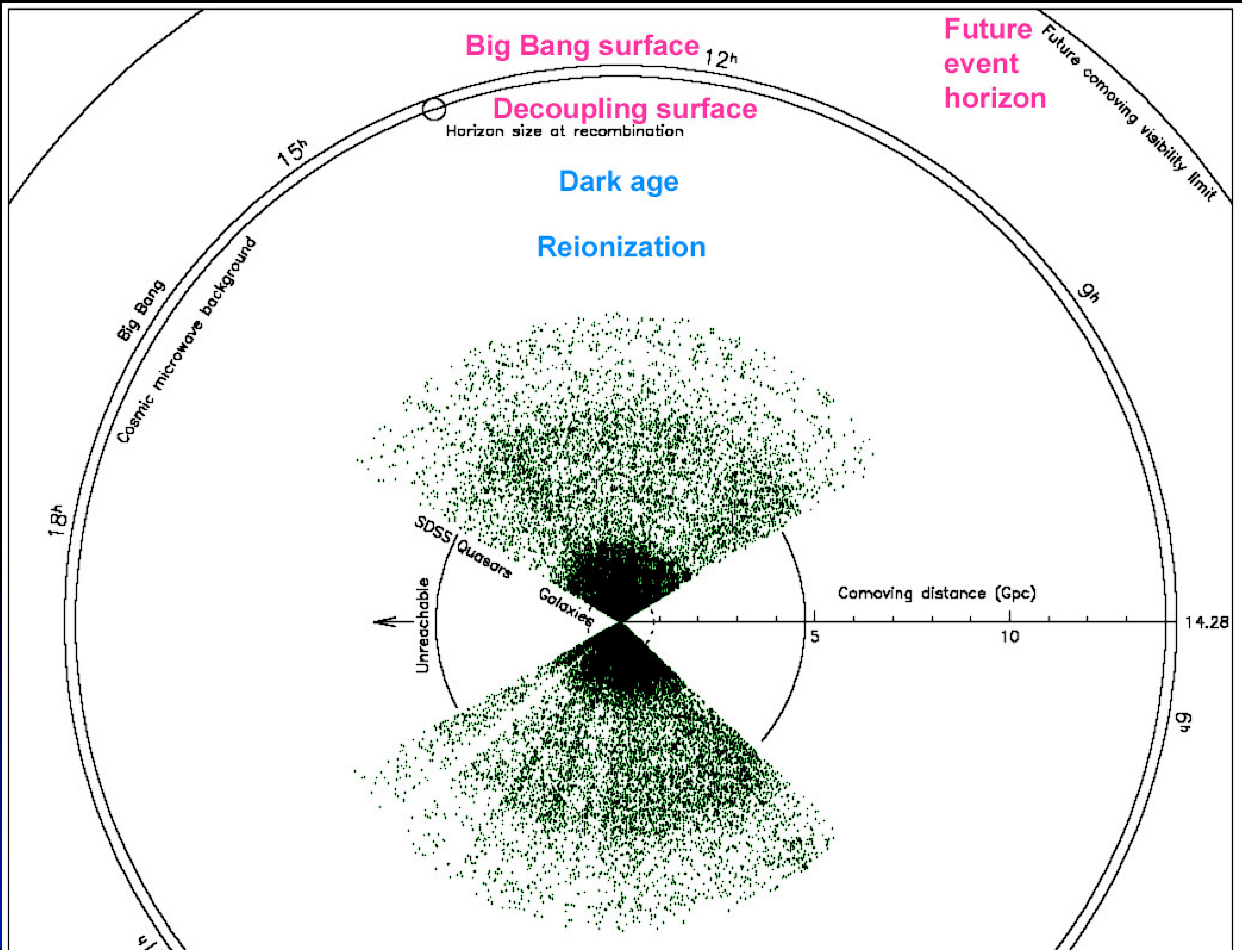
**Italy A ~ 1/1700 Earth Surface**

**2005 SDSS**

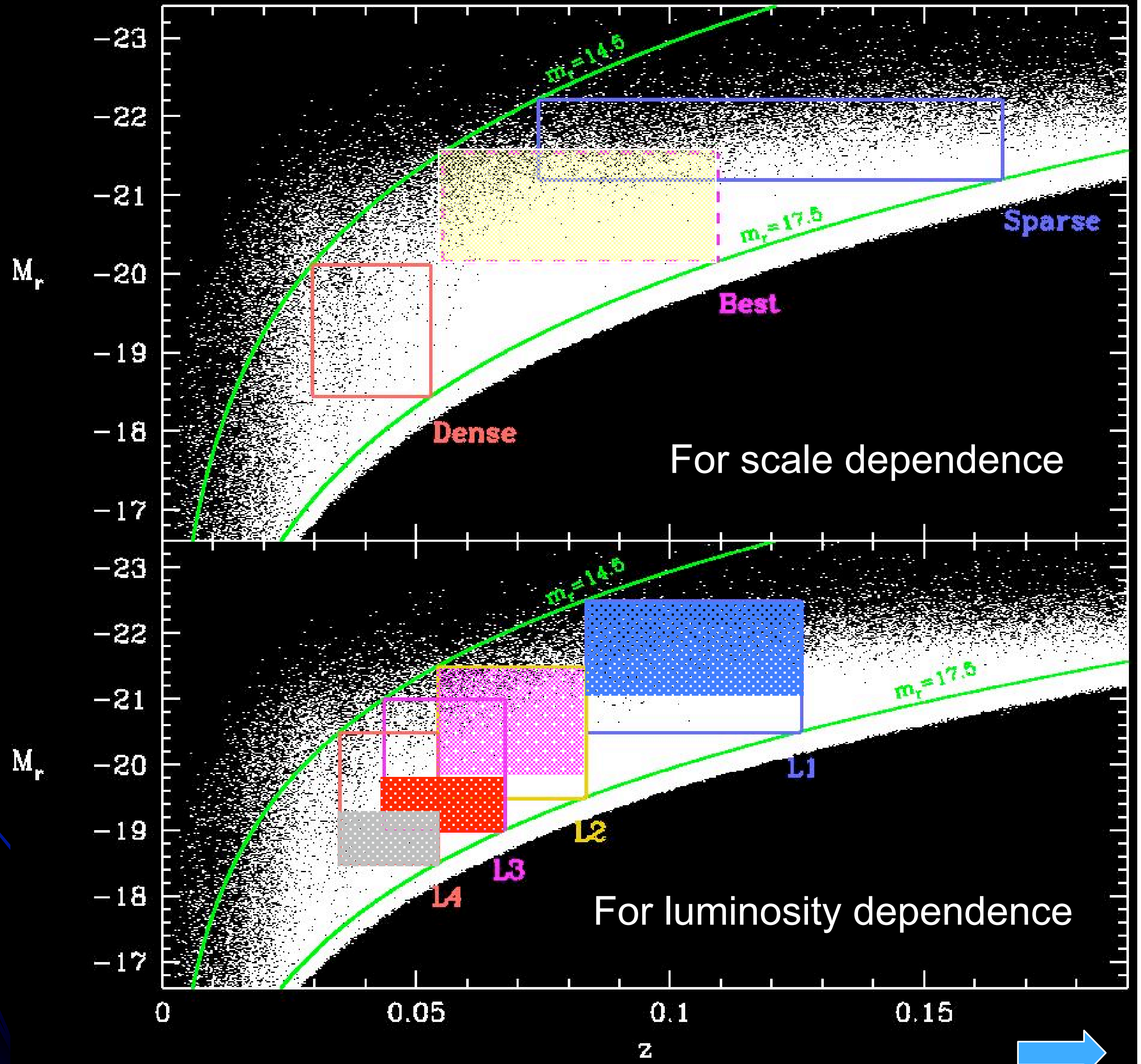



**1986 CfA**

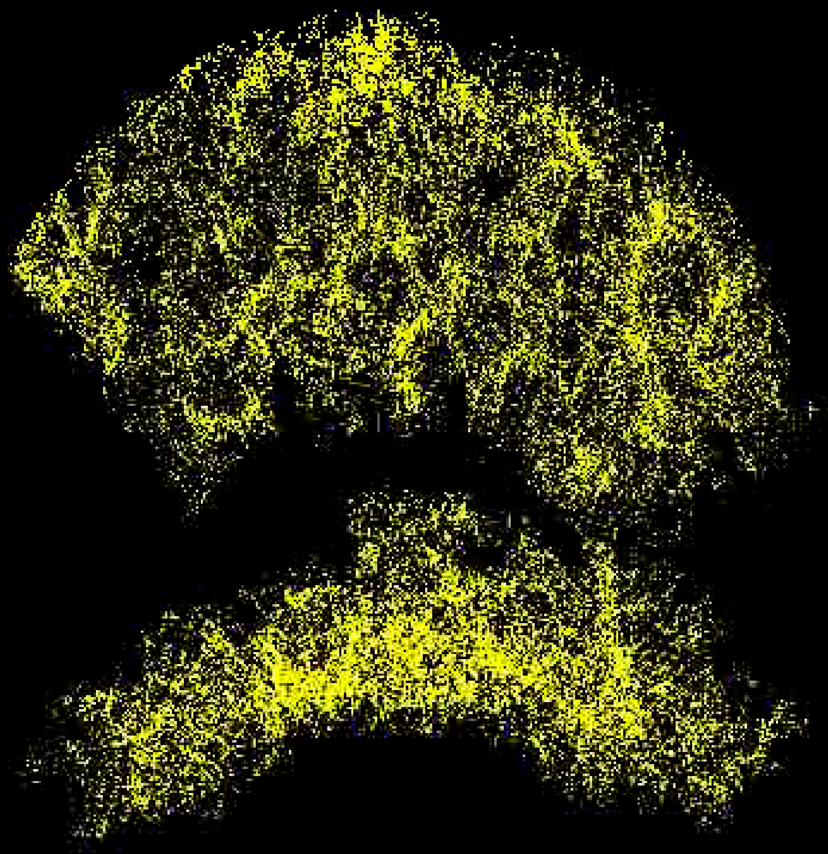



Big Bang surface
Decoupling surface
Horizon size at recombination
Future event horizon
Future comoving visibility limit
Dark age
Reionization
12h
15h
9h
18h
6h
Big Bang
Cosmic microwave background
SDSS
Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28

# Sample Definition for Genus Analysis



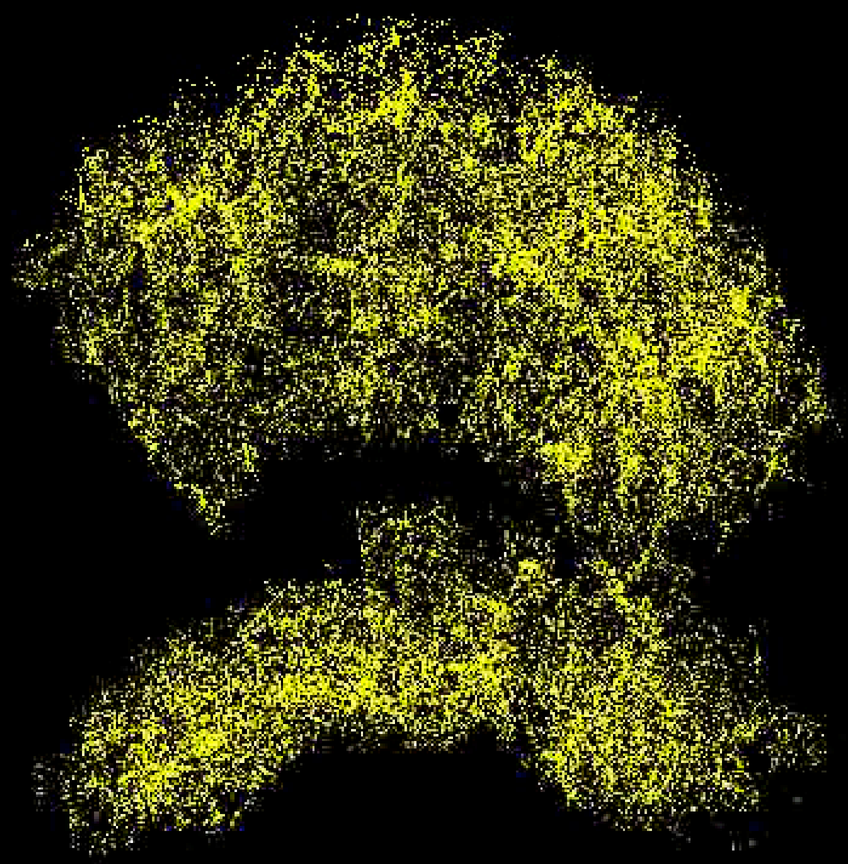

BEST Sample
-20.15 < Mr <-21.53
162.9 < r < 319.0 $h^{-1}$Mpc
0.0550 < z < 0.1091
36,000 galaxies
d = 6.14 $h^{-1}$Mpc



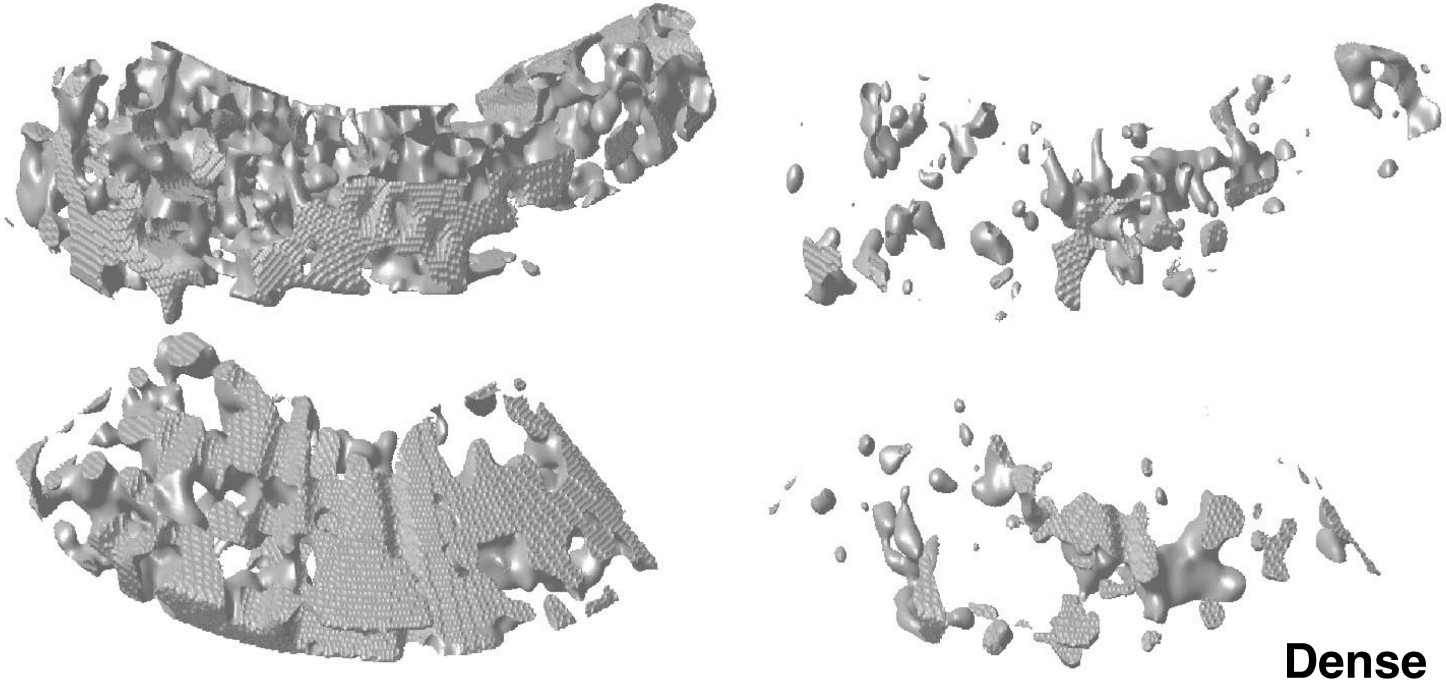
# 3D View of SDSS

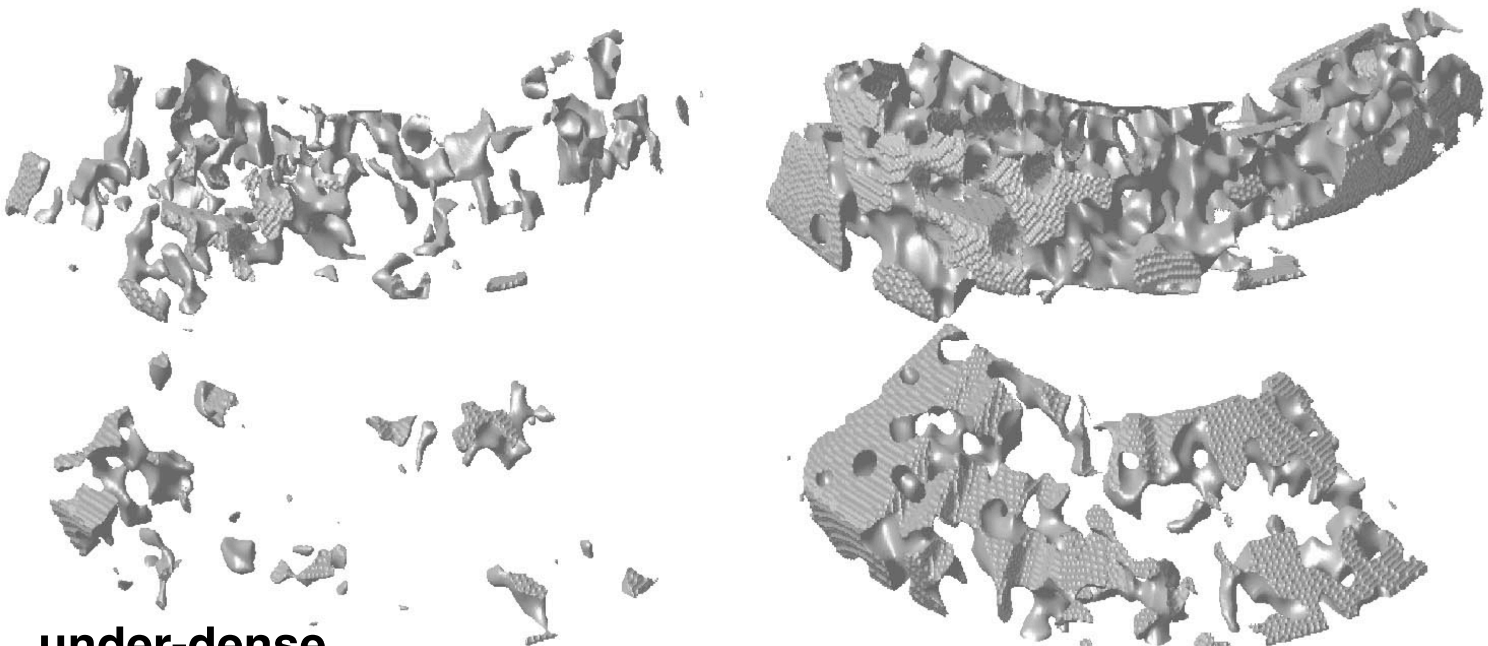
# 3D Vie
# w of a
# mock
# SDSS

HOD galaxy for
mation prescript
ion

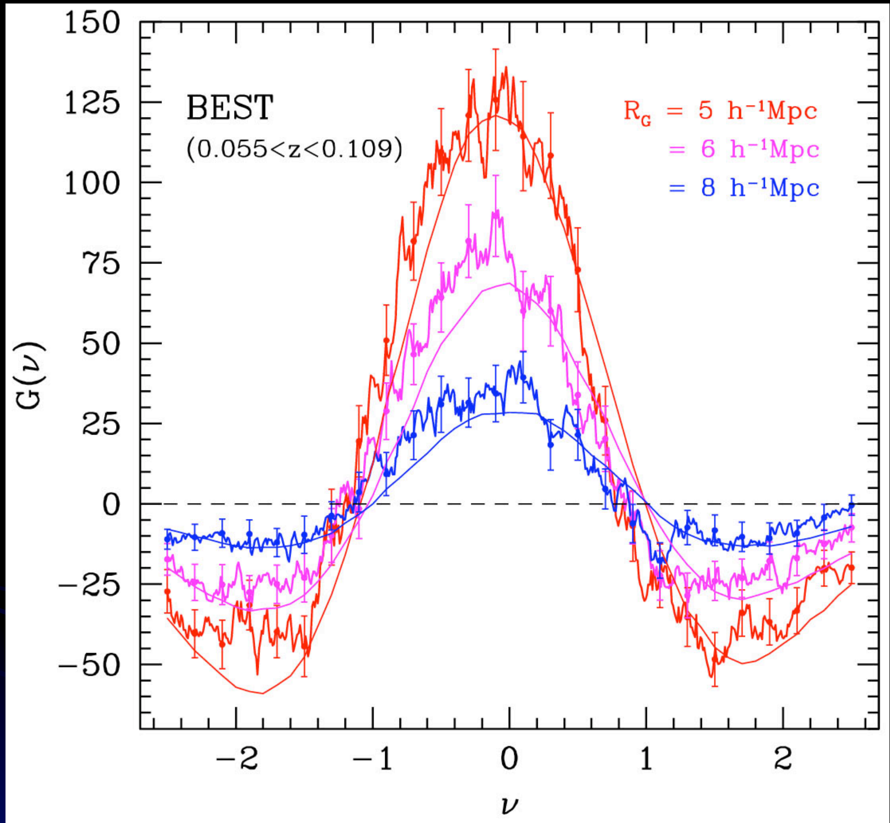


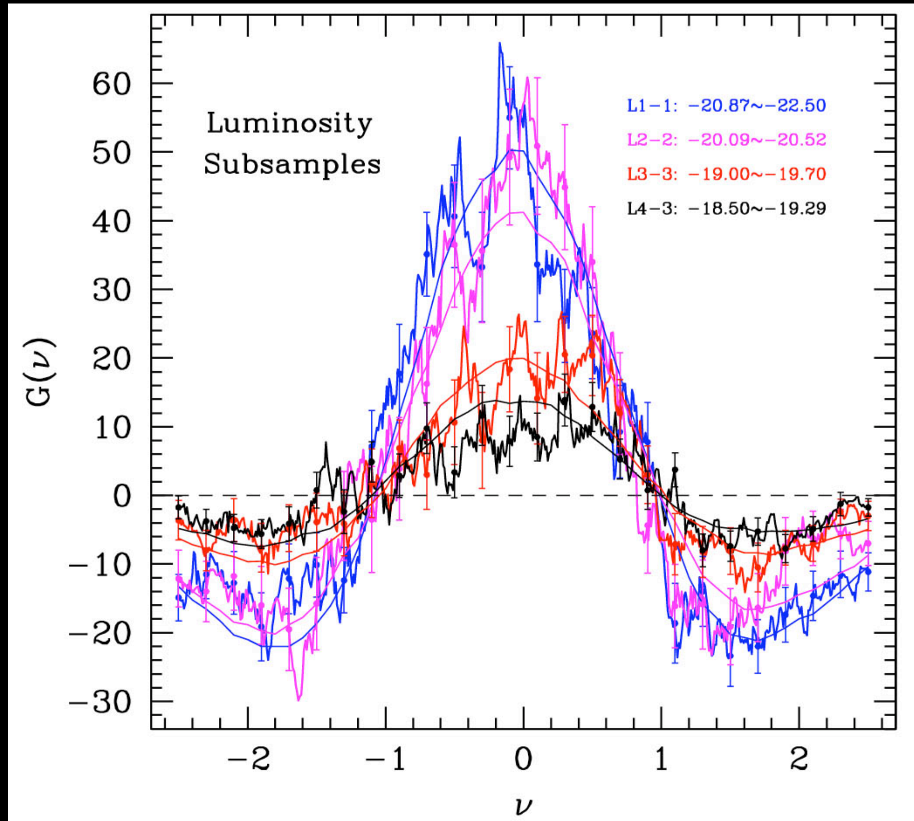
# Galaxy Density Field

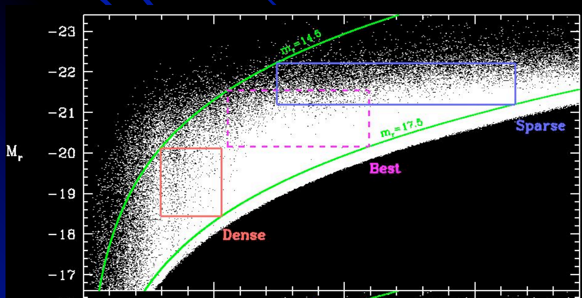


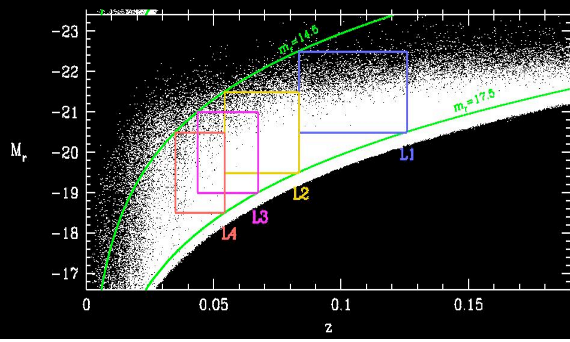



# SDSS Sample 14: Genus Analysis (Park, Choi, Vogeley, Gott, Kim, Suto, et al. 2005)

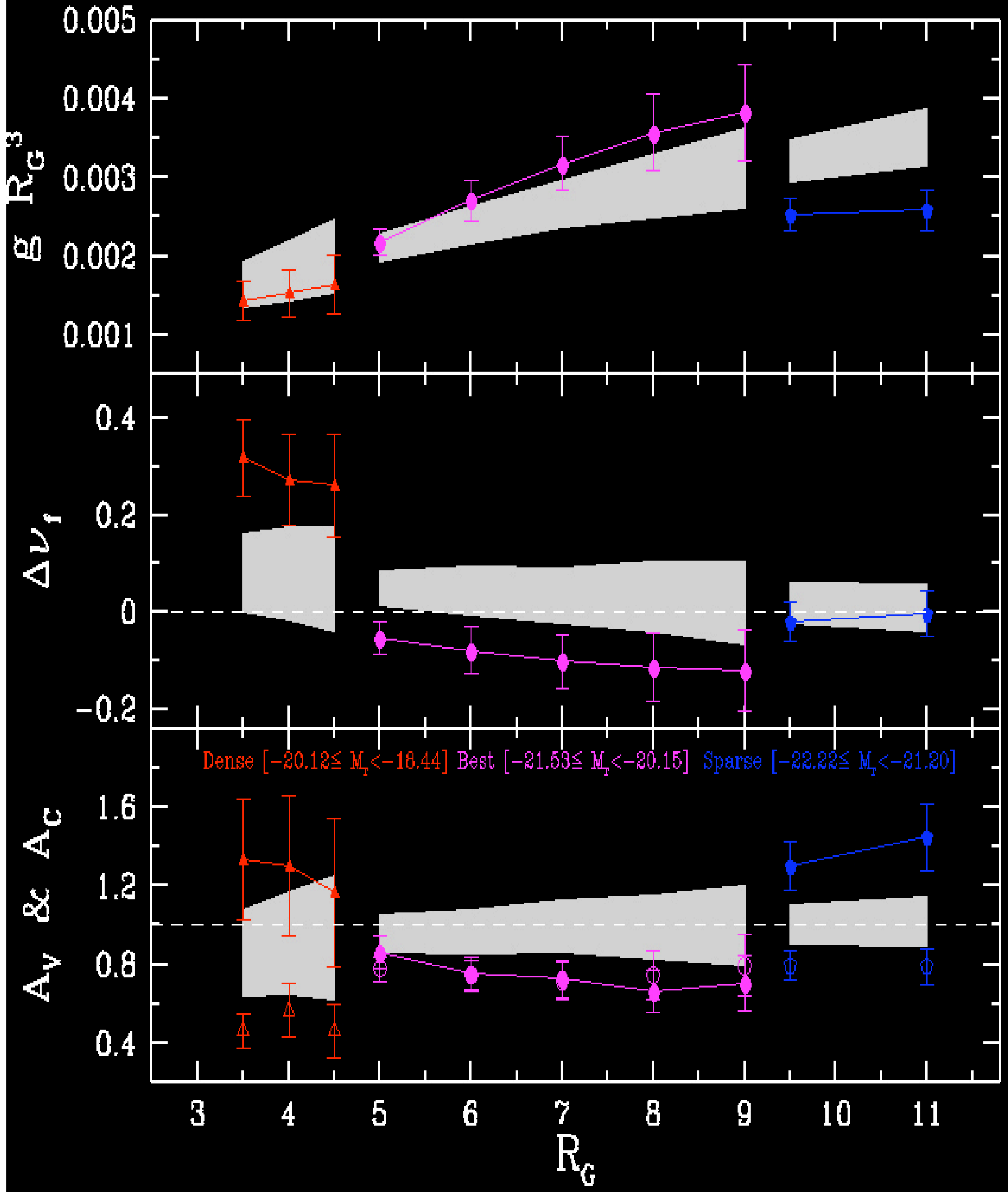


# Scale dependence



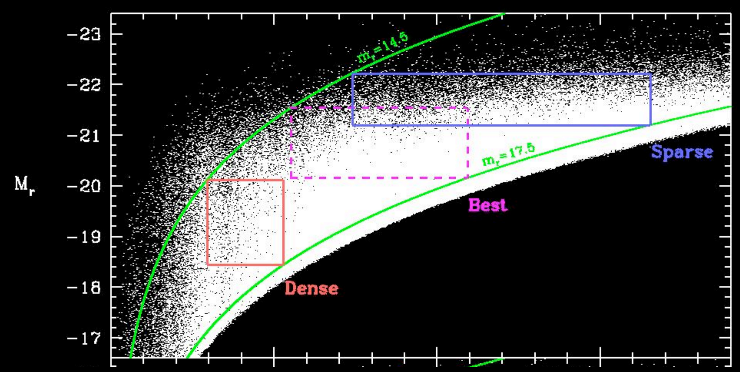

$gR_G^3$ – genus density per smoothing volume

•ƒ•Ì Shift

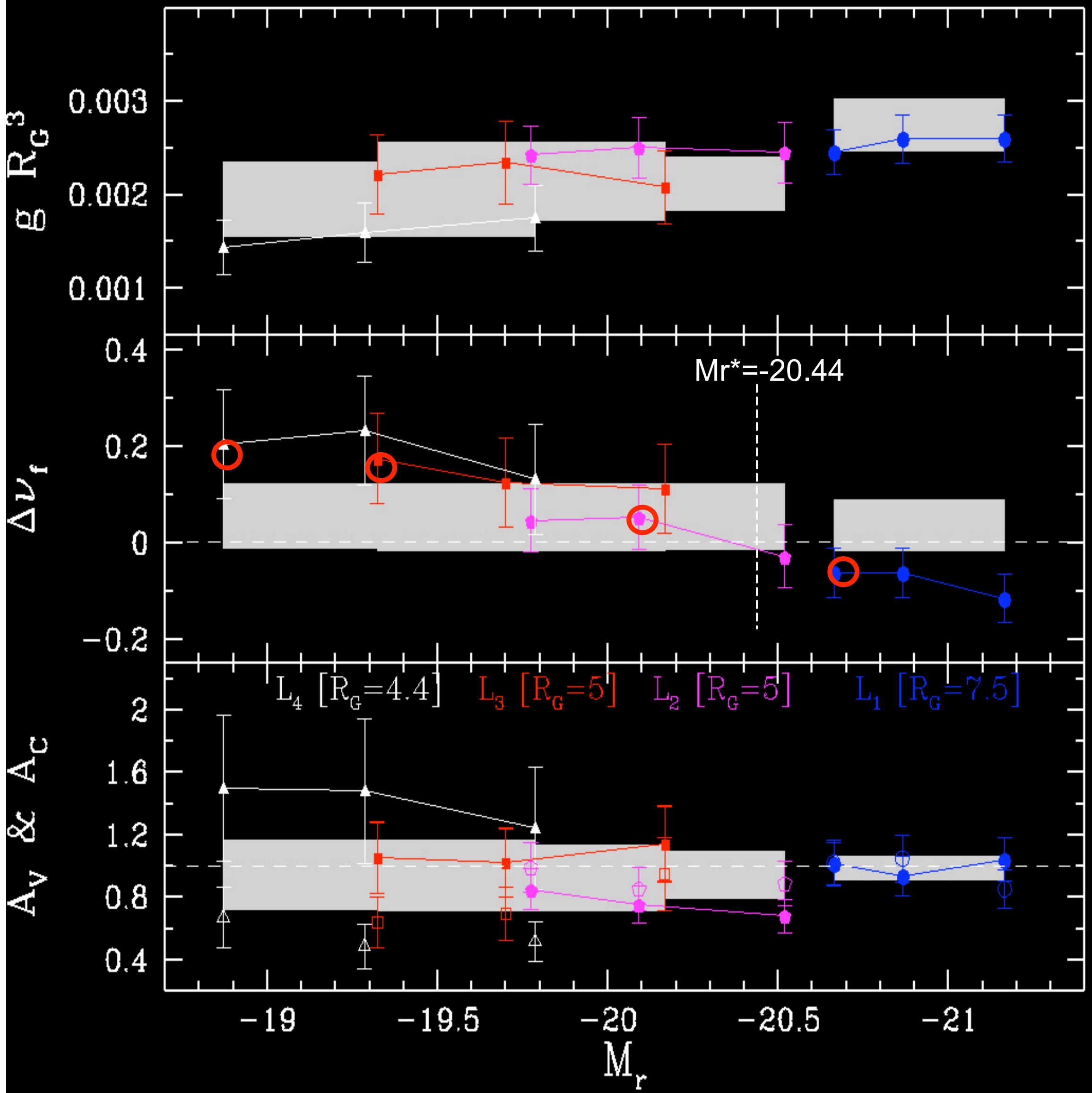
$A_C$ & $A_V$ – clusters & voids multiplicity

Shaded area - 1σ limits from 100 Mock surveys

- Strong evidence for biased gala
xy formation in low density envir
onments (Av <1)
- Effects of the Sloan Great Wall



# Luminosity dependence




$gR_G^3$ – genus density / smoothing volume

•ƒ•Ì Shift

$A_C$ & $A_V$ – clusters & voids multiplicity S

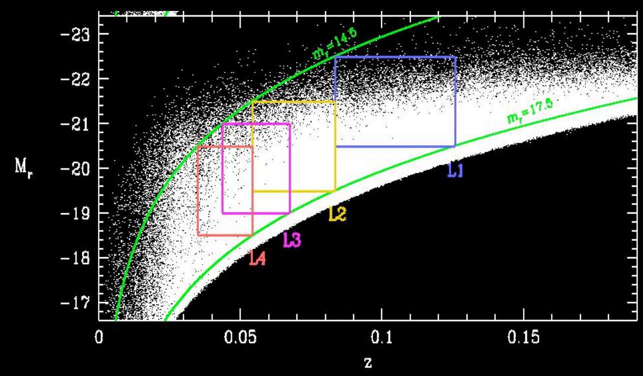
haded area - 1σ from 100 Mock surveys

**L-dependnce of topology !!!**

**Faint galaxies**

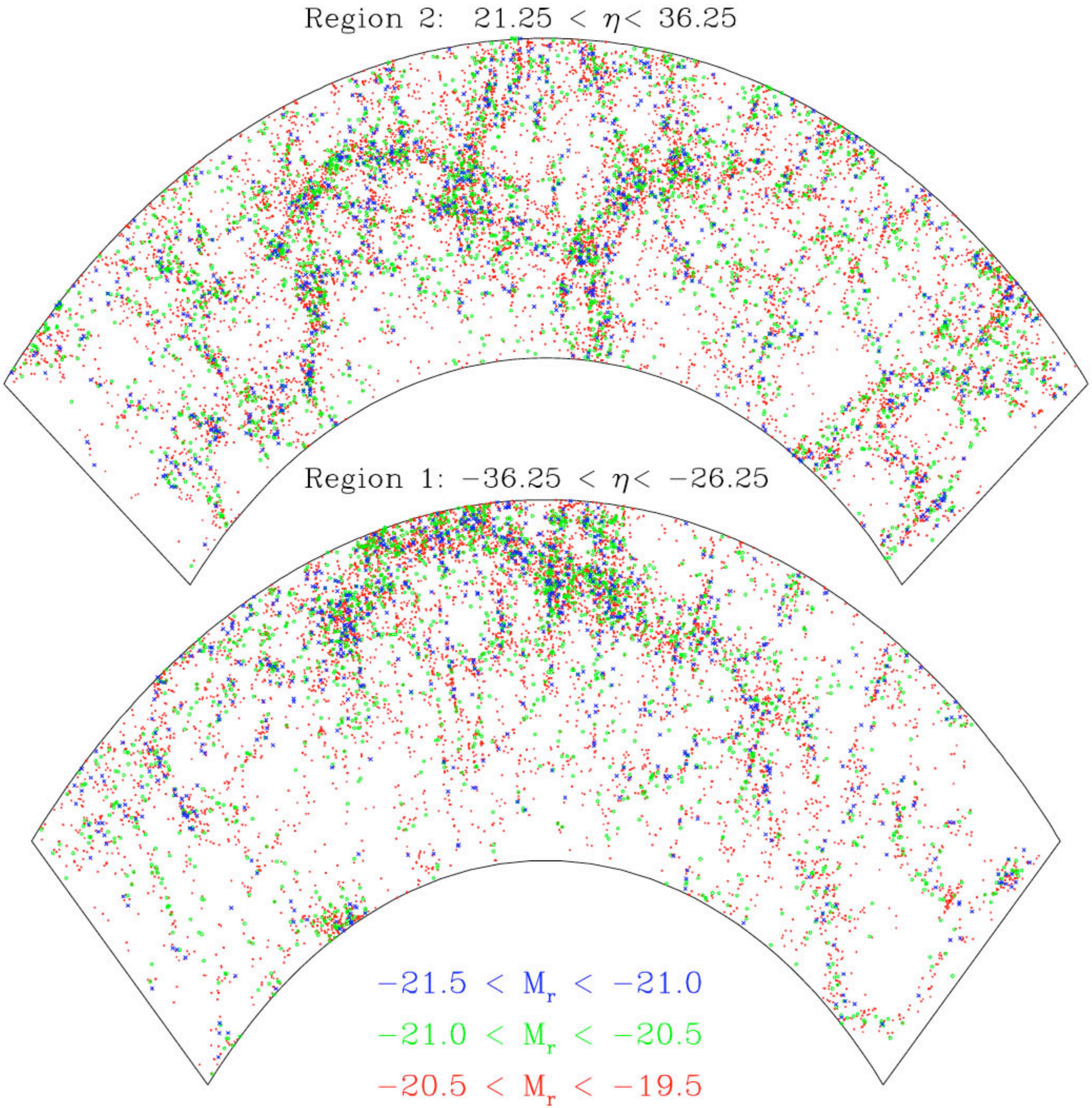
**- more positive shift**

**- lower void multiplicity**



# Biased Formation of Galaxies

**1 & 2 point distribution, but also topology !**

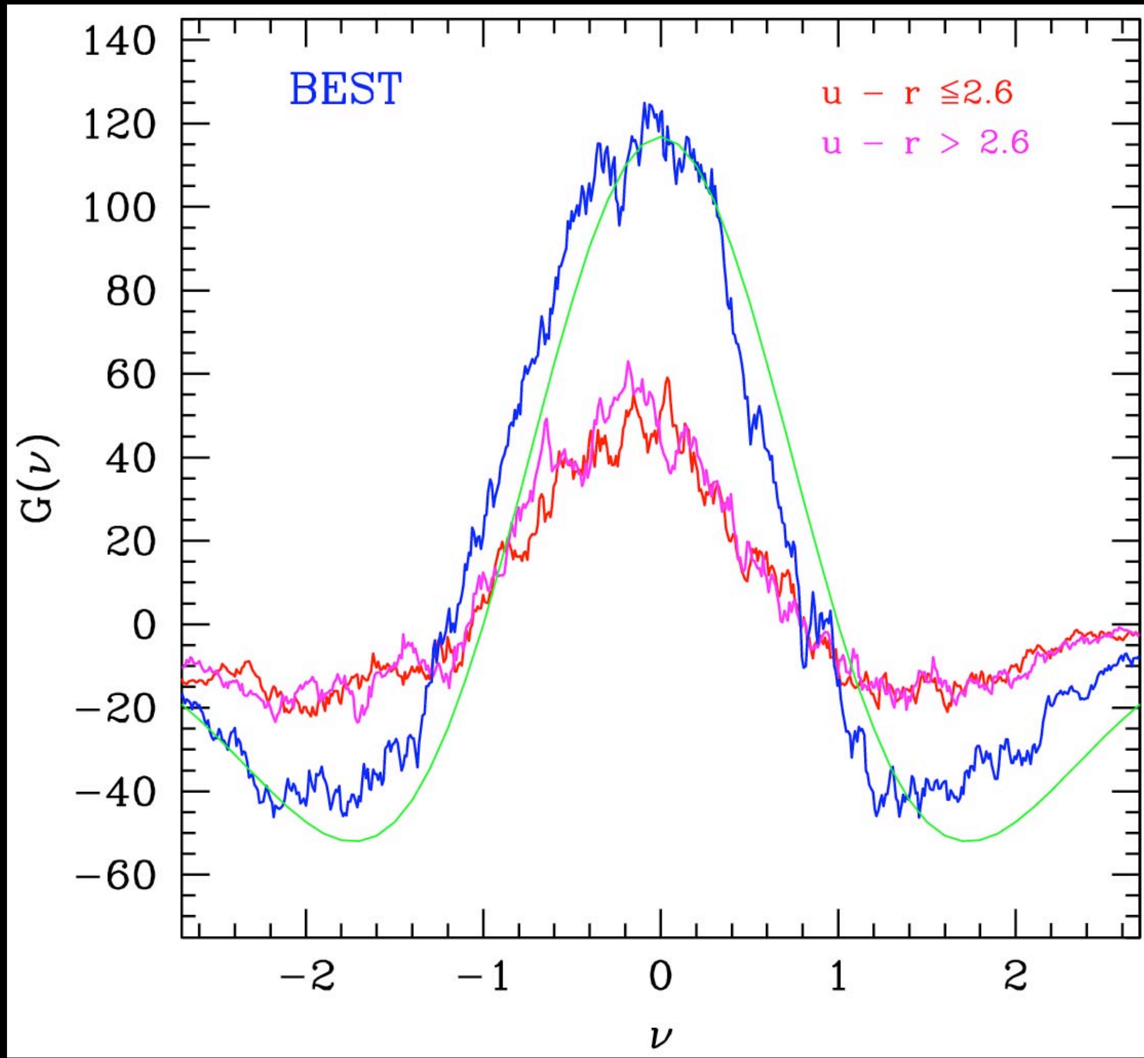


# On going works

(Choi, Gott, Kim, Park, Suto, Vogeley, Yahata 2005)

1. Color & Morphology Dependence
2. $R_A$ parameter
3. LRG, quasars, clusters
4. Comparison with Cosmological & galaxy form ation models
5. Minkowski functionals

# Dependence on color




(Vogeley, Choi, Park, et al. 2005)

# Dependence on Morphology of Galaxies

## Existing Morphology Classifier

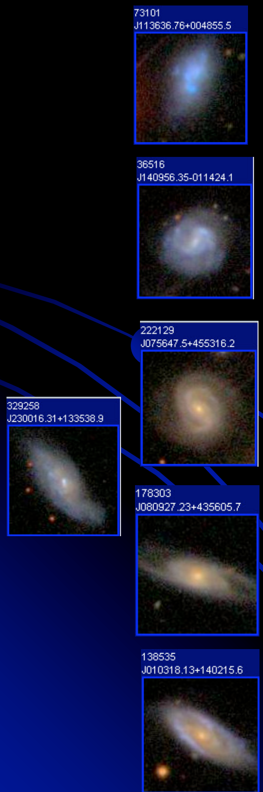
1. Structure Parameter : Sersic index n, concentration index C, profile likelihoods
2. Star formation : u-r color, emission/absorption lines, PCA of spectra

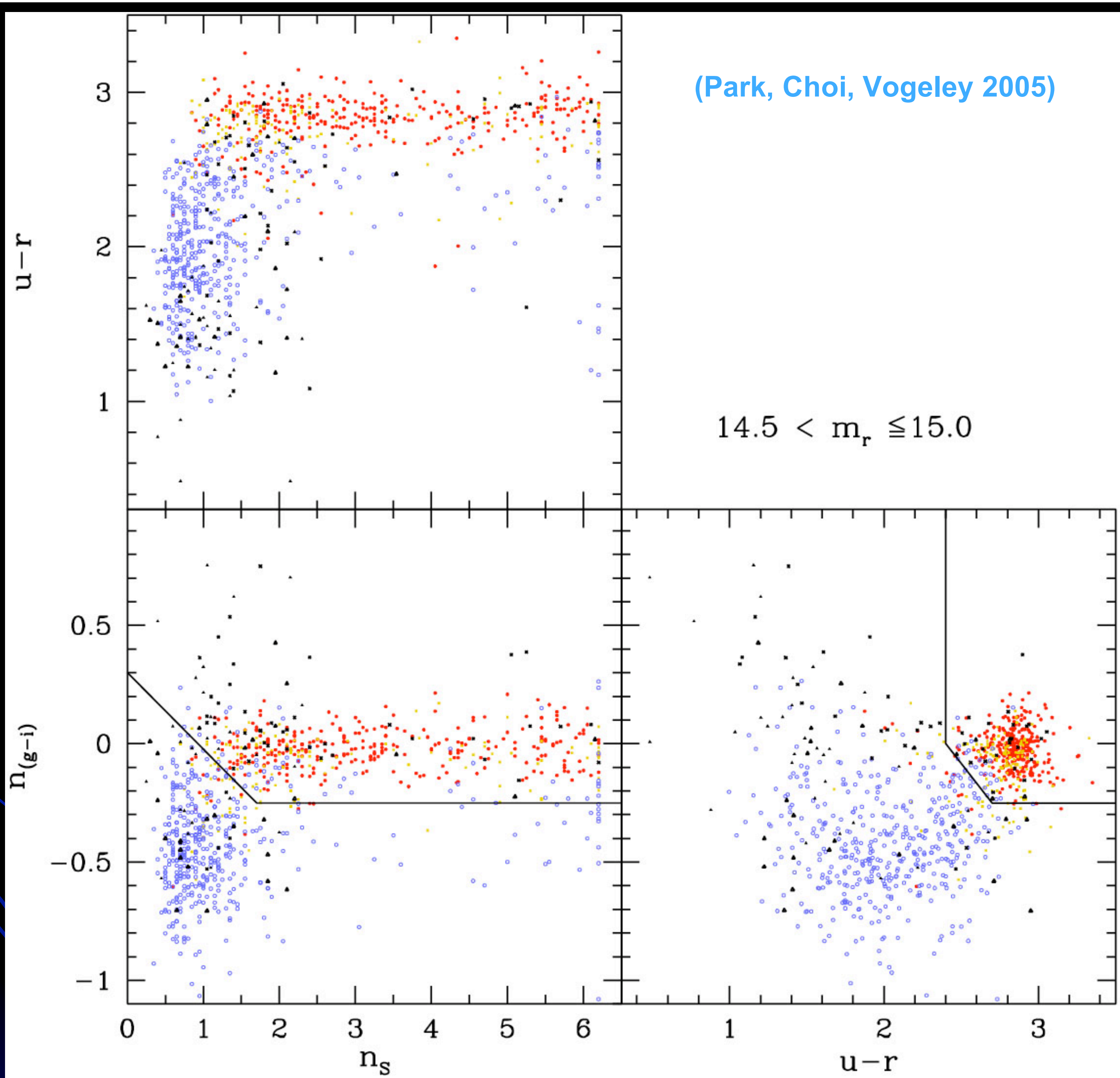
## Automated Morphology Classifier

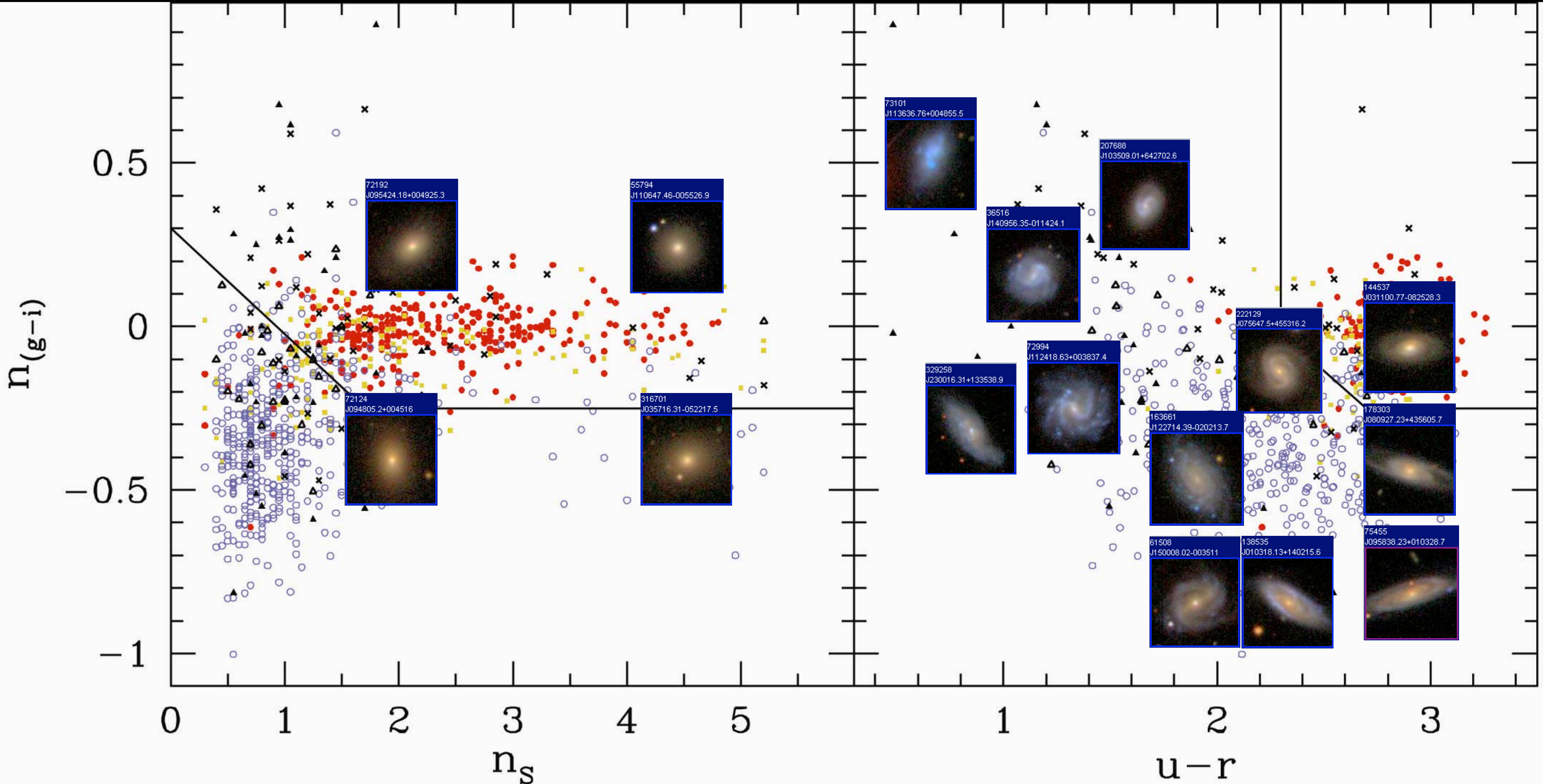
### Three Parameter Classification

1. Star formation history : u-r color
2. Structure +Star formation : color gradient °(g-i)
3. Structure Parameter : Sersic index n

# Morphology Classification of Galaxies





0.5
0
−0.5
−1
$n_{(g-i)}$
0
1
2
3
4
5
$n_s$
1
2
3
u−r
72192
J095424.18+004925.3
55794
J110647.46-005526.9
72124
J094805.2+004516
316701
J035716.31-052217.5
73101
J113636.76+004855.5
207688
J103509.01+642702.6
36516
J140956.35-011424.1
329258
J230016.31+133538.9
72994
J112418.63+003837.4
222129
J075647.5+455316.2
144537
J031100.77-082528.3
163661
J122714.39-020213.7
178303
J080927.23+435605.7
61508
J150008.02-003511
138535
J010318.13+140215.6
75455
J095838.23+010328.7

# 200 RC3 galaxies with $m_{pg}$<13.2

I

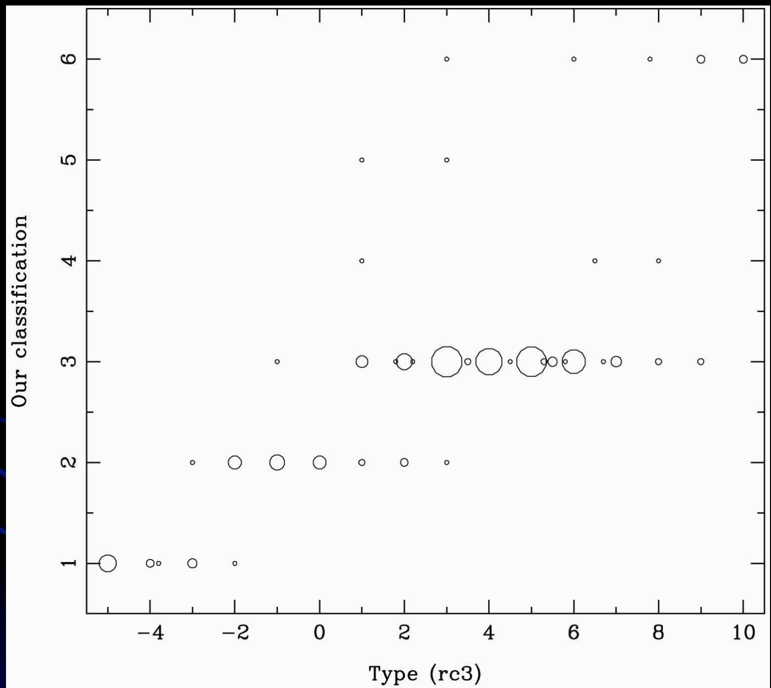
AS

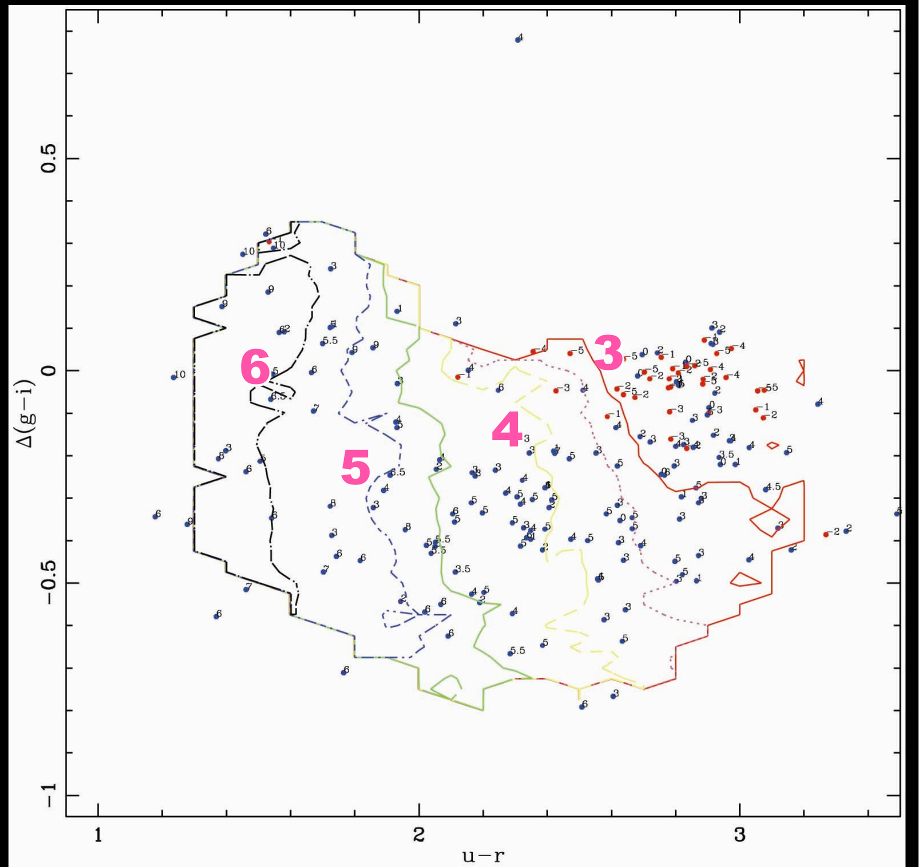
AE

S

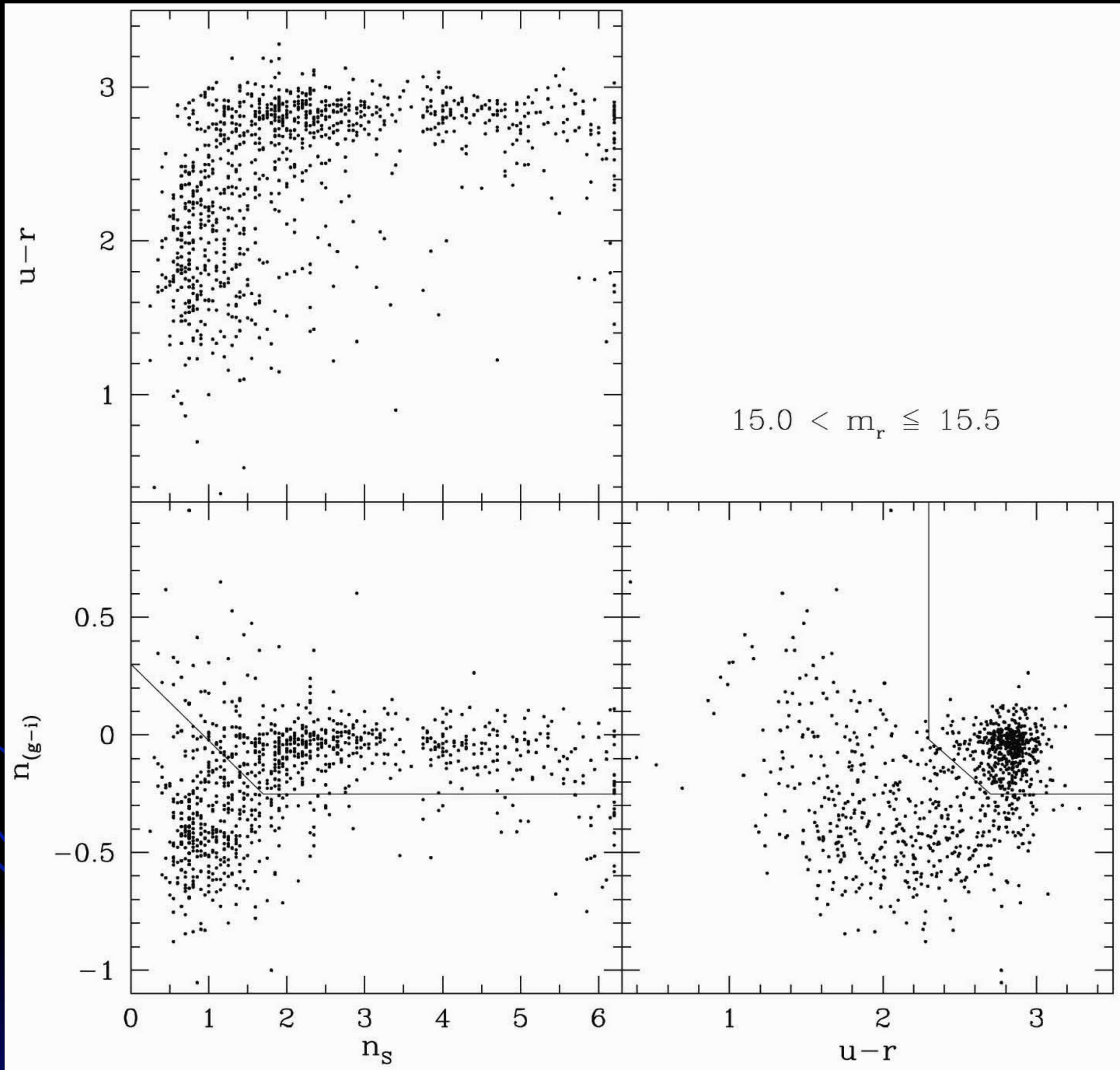
S0/Sa

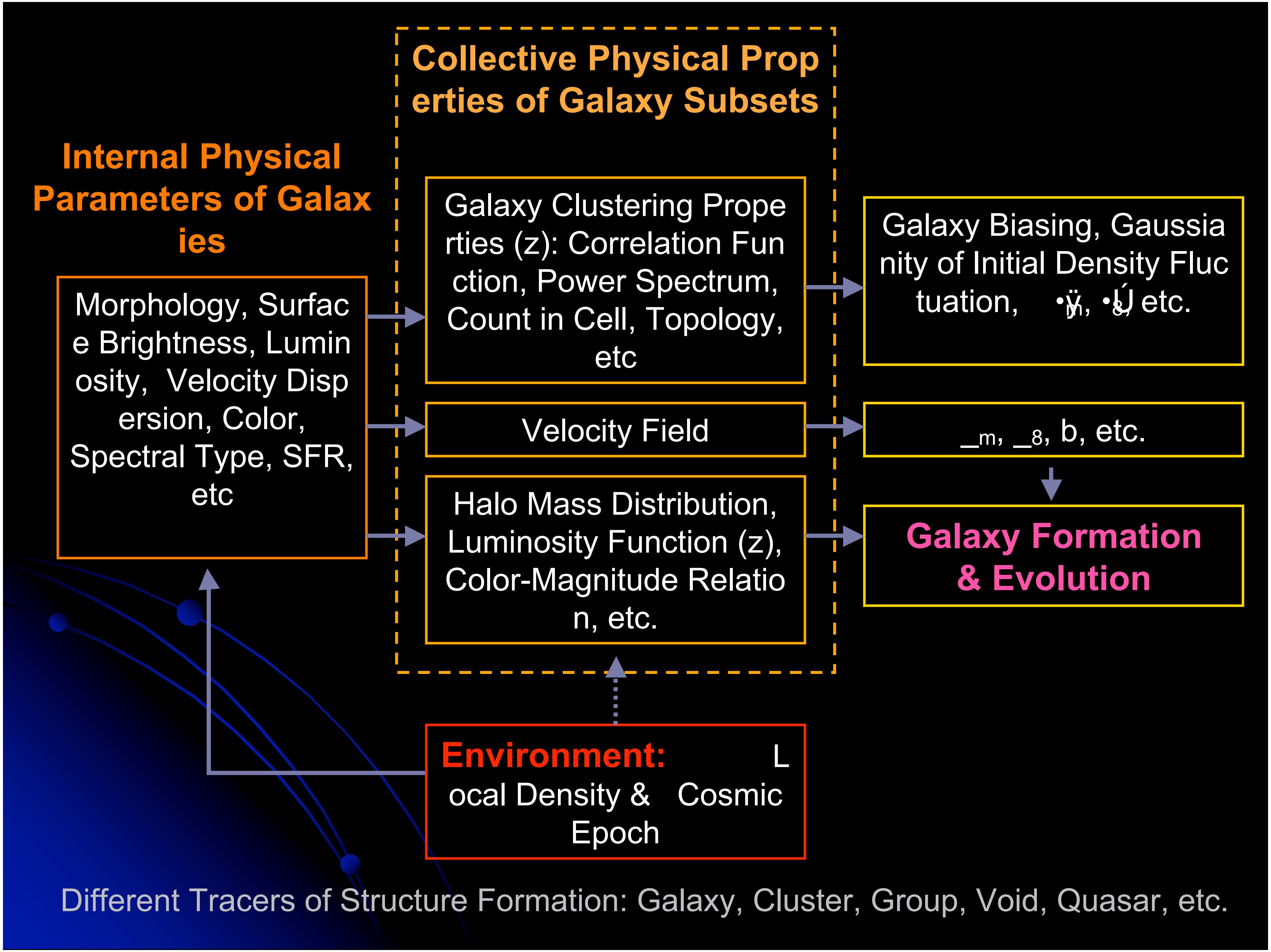
E/S0




(Park, Choi, Vogeley 2005)


u−r
15.0 < m_r ≦ 15.5
n_(g−i)
n_S
u−r
0
1
2
3
4
5
6
0.5
−0.5
−1


Collective Physical Properties of Galaxy Subsets
Internal Physical Parameters of Galaxies
Morphology, Surface Brightness, Luminosity, Velocity Dispersion, Color, Spectral Type, SFR, etc
Galaxy Clustering Properties (z): Correlation Function, Power Spectrum, Count in Cell, Topology, etc
Velocity Field
Halo Mass Distribution, Luminosity Function (z), Color-Magnitude Relation, etc.
Galaxy Biasing, Gaussianity of Initial Density Fluctuation, •ÿm, •Ú8 etc.
_m, _8, b, etc.
Galaxy Formation & Evolution
Environment: Local Density & Cosmic Epoch
Different Tracers of Structure Formation: Galaxy, Cluster, Group, Void, Quasar, etc.