3rd Korea-Japan Workshop on Dark Energy

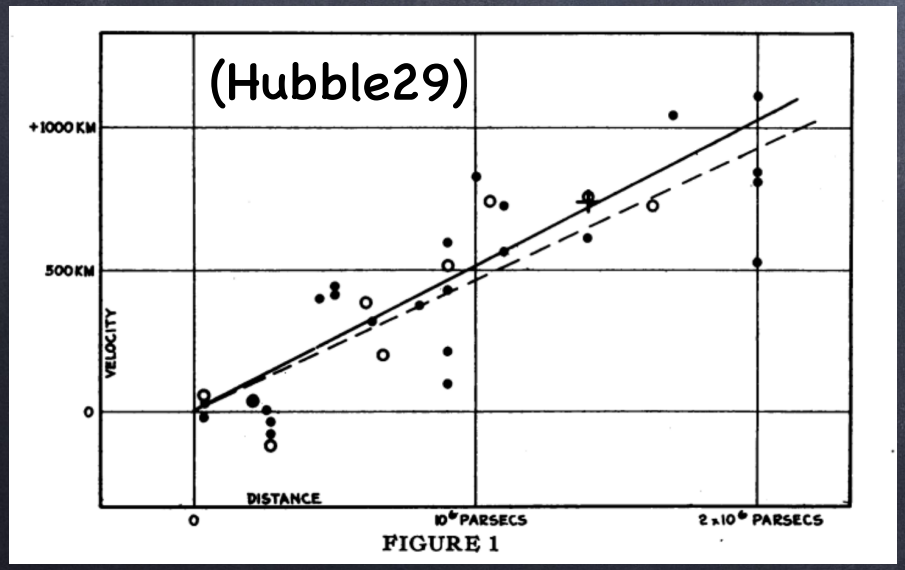
Varying supercluster shape in different cosmology

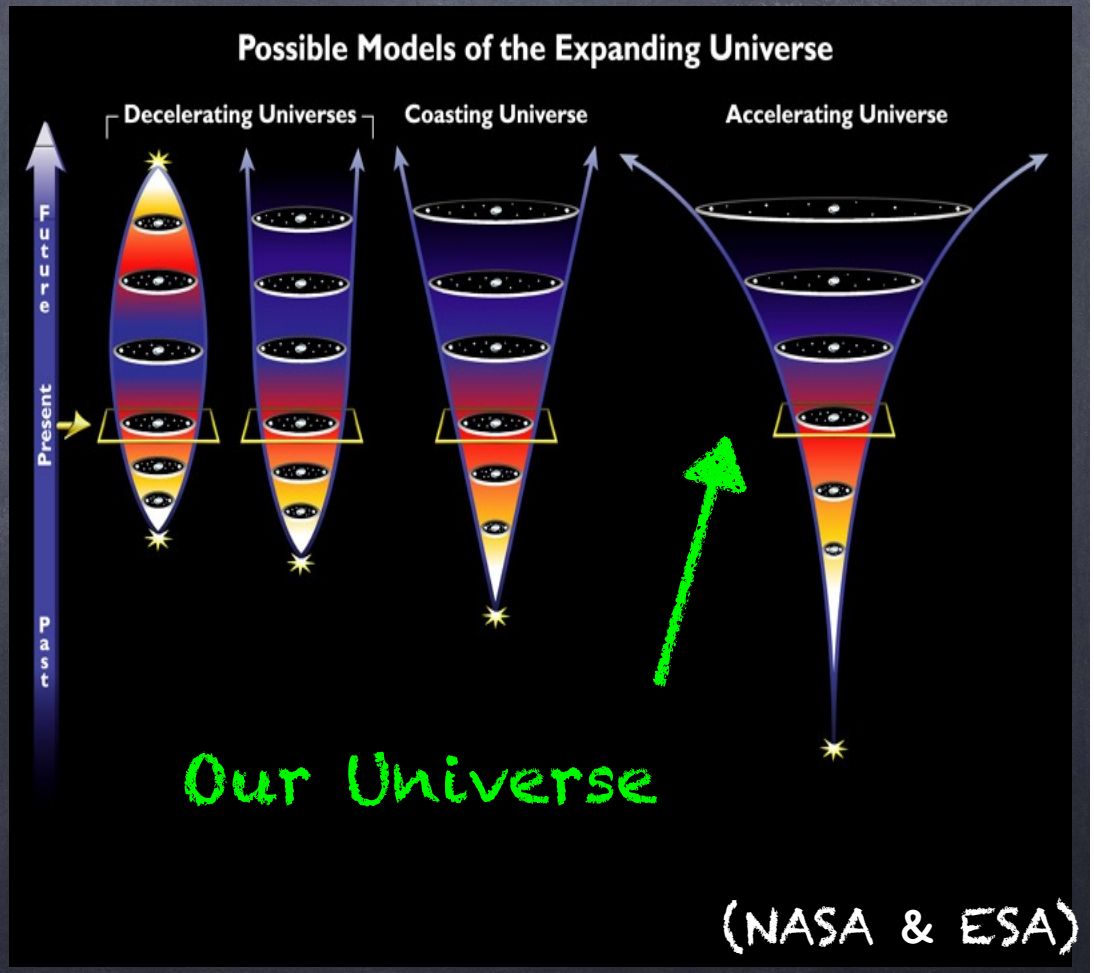
Junsup Shim[1], Jounghun Lee[1], Baojiu Li[2], Marco Baldi[3]

[1] Seoul National Univ., Korea
[2] Durham Univ., UK
[3] Bologna Univ., INAF, INFN, Italy

Expanding Universe

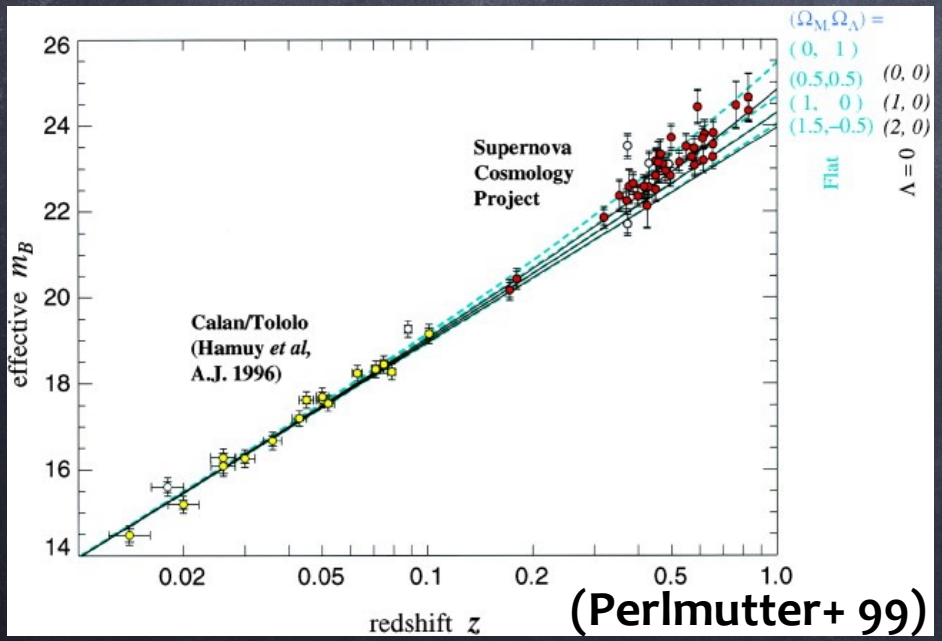
- Our Universe is known to be expanding faster and faster.



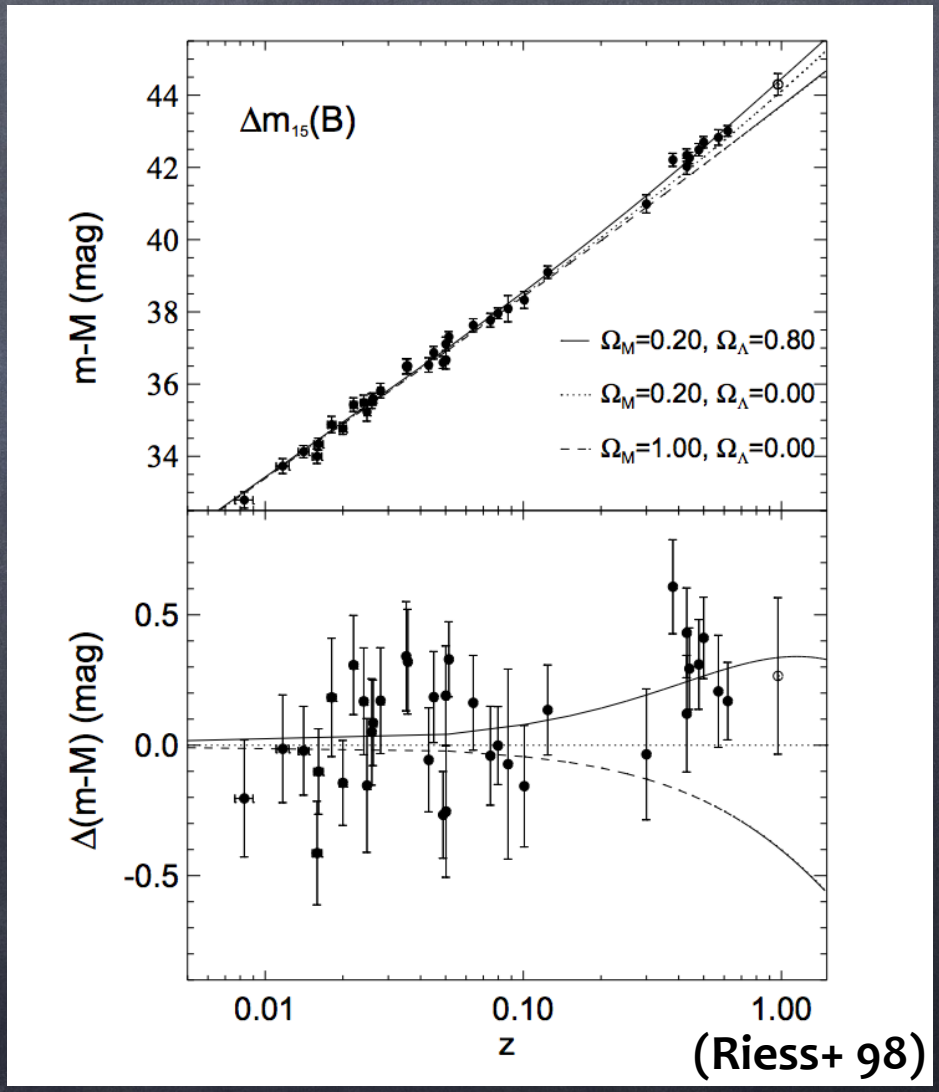


Accelerated expansion

- Physical origin of this acceleration is a hot issue in cosmology.



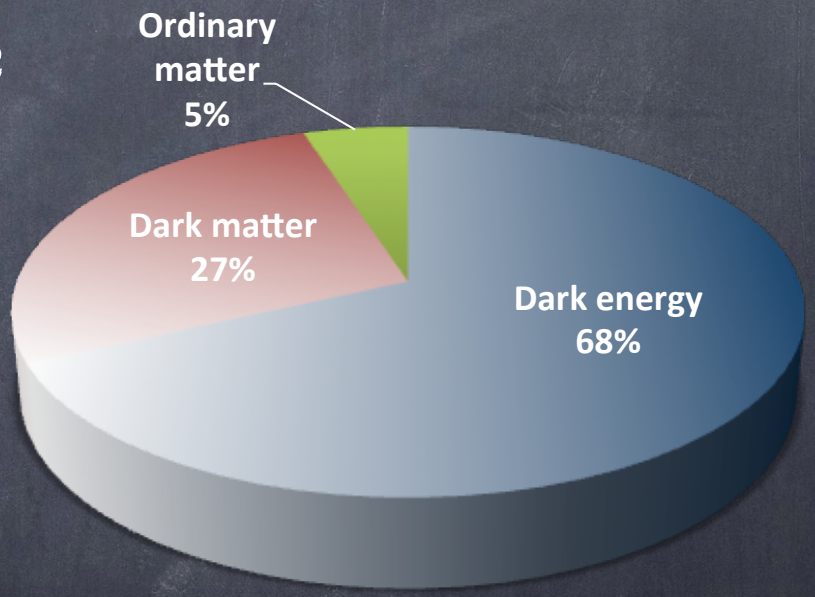
(Perlmutter+ 99)



(Riess+ 98)

'Λ'CDM cosmology

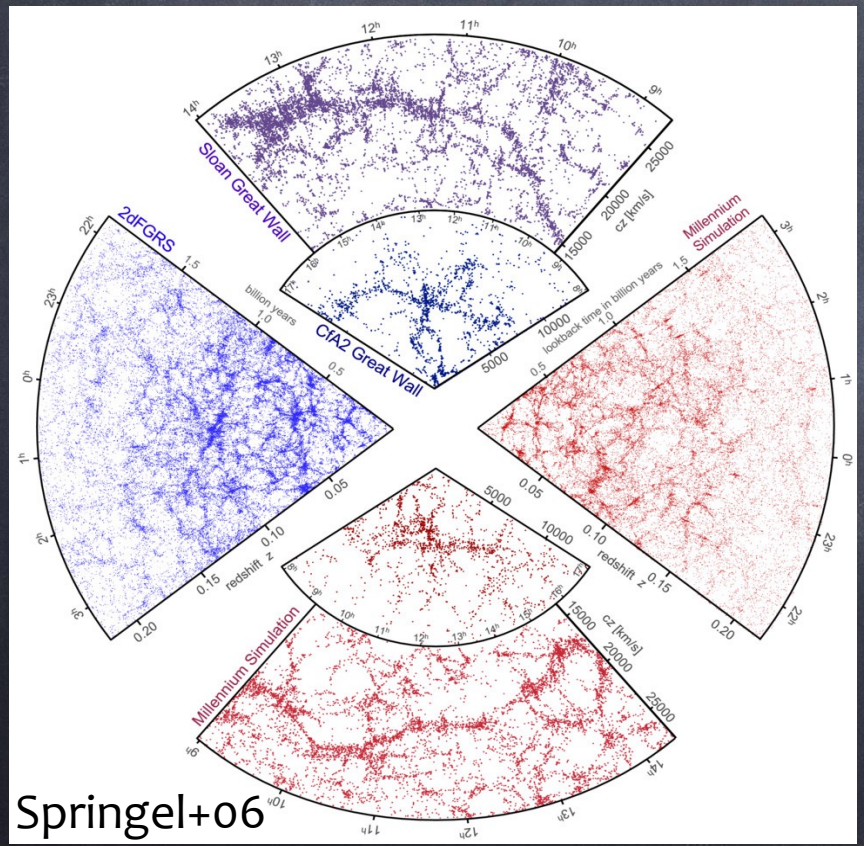
- Accelerated expansion is attributed to 'Λ'. (Riess +98, Perlmutter+99)
- Our Universe is mainly (~95%) dominated by dark components.



Cosmic energy budget

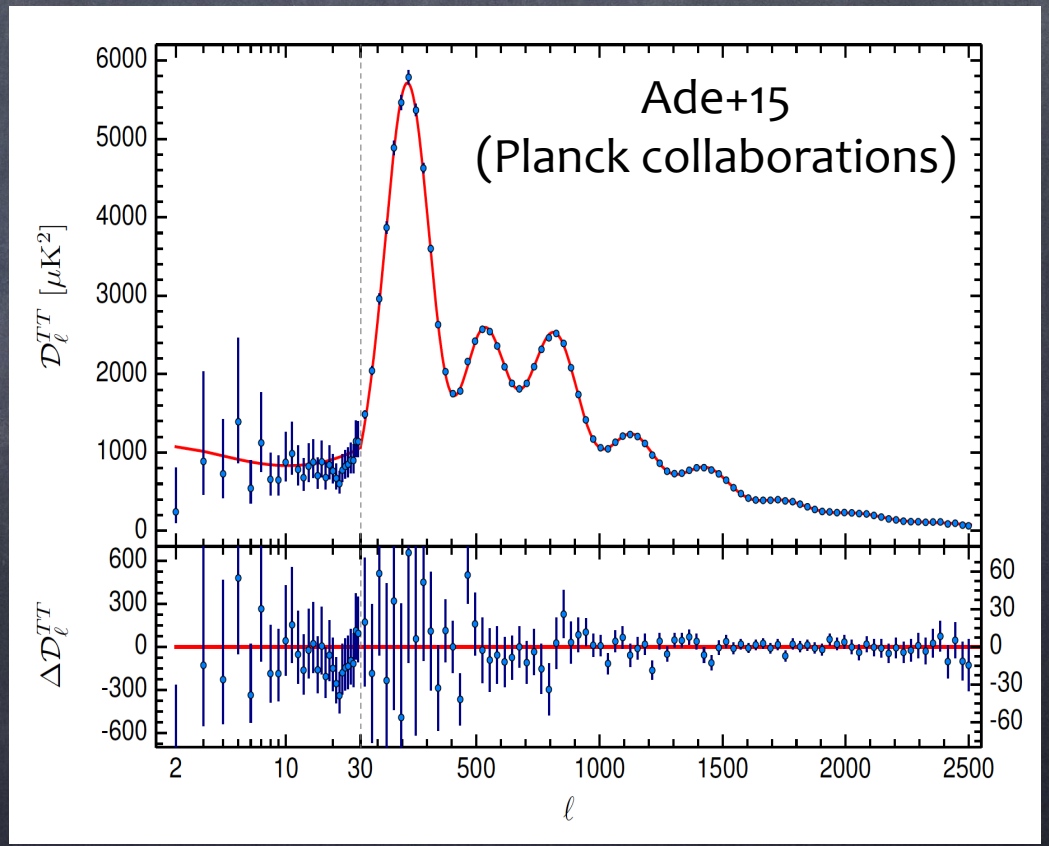
Features of Cosmos

- "Concordance cosmology"



Springel+06

Large scale structure



CMB power spectrum

Fine tuning of Λ

- ΛCDM suffers from fine tuning problem ($\rho_{vaccum}/\rho_{\Lambda} \sim 10^{120}$) of cosmological constant Λ.
- Alternative theories to explain the accelerating expansion, at the same time, to avoid/alleviate the fine tuning have been suggested.

Possible origin of accelerated expansion

- Cosmological constant Λ (Concordance cosmology)
- Dynamic dark energy
- Modification of gravity

Conventional probes

- Conventional LSS statistics mainly focused on the strength of clustering. (Sutter+08, Lombriser+12, Bel+15, Munshi +16)
- To survive as viable from the stringent tests (Bean+08, Reyes+10, Wojtak+11, Wei+13), their behavior should mimic concordance cosmology.

Complimentary probe

- In this work, we concentrate on the pattern of clustering in particular at the largest scale through the superclusters.

The Largest scale clustering

Cosmic web= func(Gravity, Repulsion)

Gravitational law ?
Nature of dark energy ?

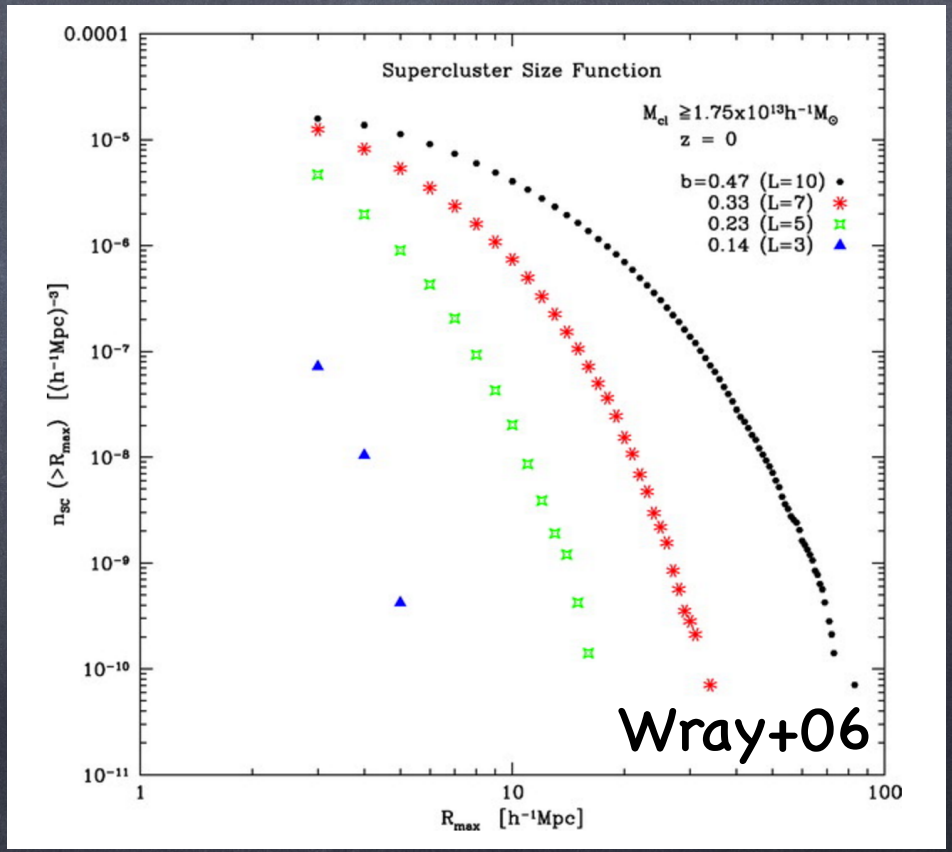
→ Strength of clustering

→ Pattern of clustering

Superclusters are located at the densest part of the cosmic web.

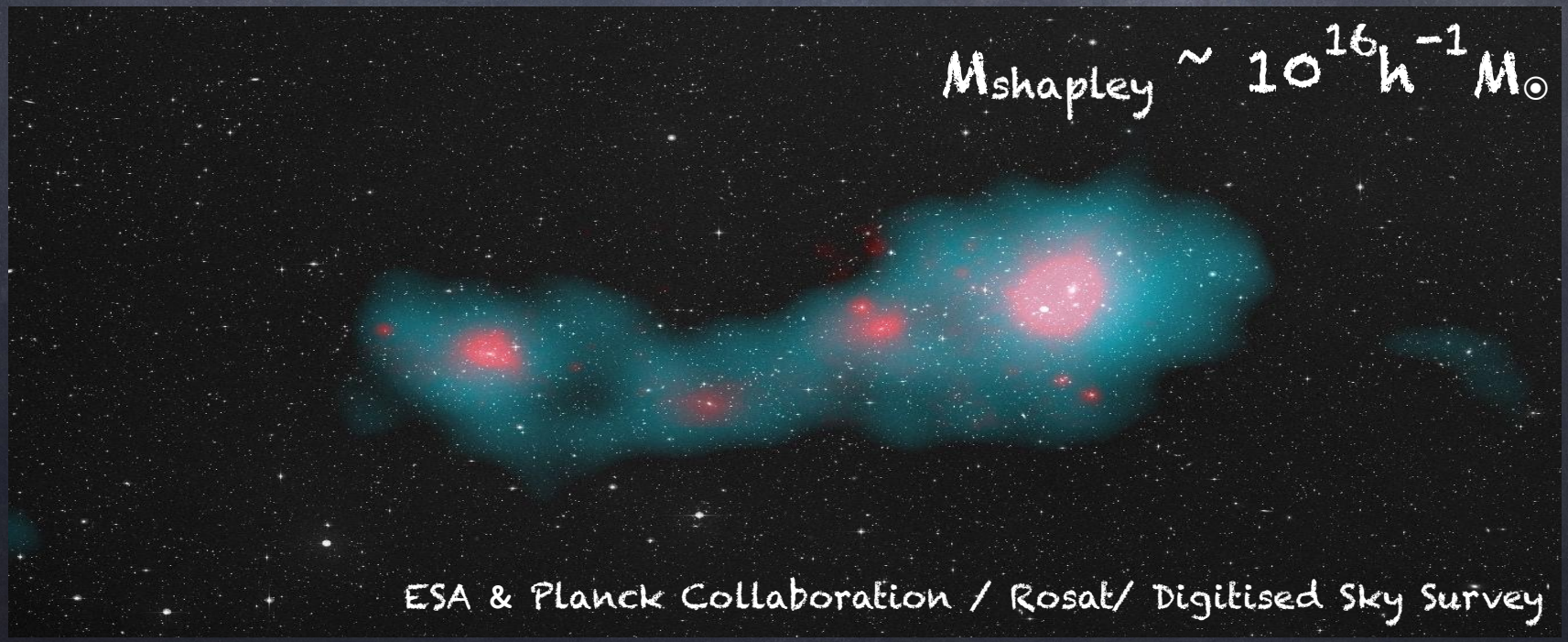
Supercluster

- 2nd order clusters, Cluster of clusters (Abell 58)
- The largest structure known in the cosmos.



Filamentary supercluster

- Superclusters have elongated filamentary structures. (Dekel+84, Wray+06, Einasto+11)



Superclusters in different Universe?

- We compare straightness of superclusters in

- Coupled dark energy (cDE) : a branch of dynamic DE

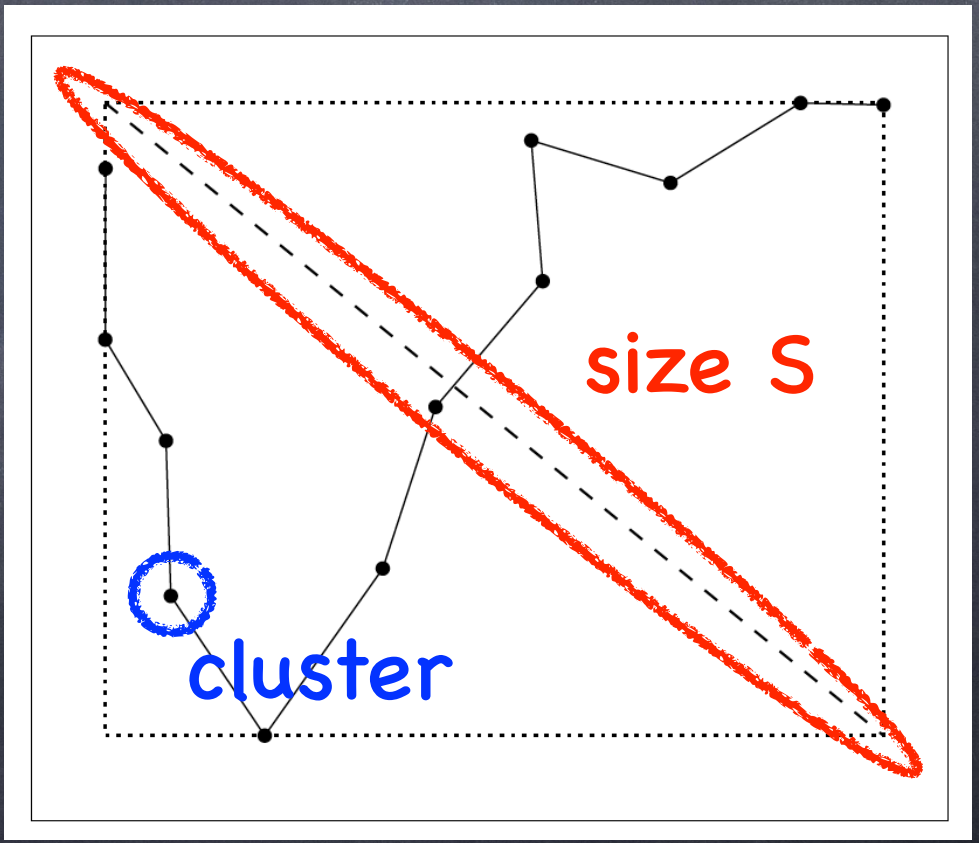
- f(R) gravity : a branch of modified gravity

by analyzing halo catalogs from cosmological simulations of respective cosmologies.

Supercluster Size & specific size

$$\tilde{S} \equiv \frac{S}{N_{cluster}}$$

- The degree of how much straight the supercluster is.



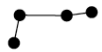
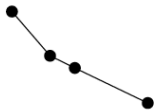
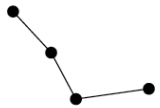
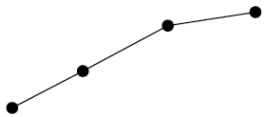
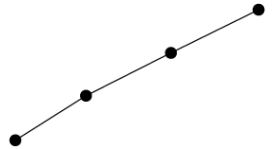
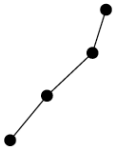
(Shim & Lee 13)

Supercluster straightness

(Shim & Lee 13)

- The larger the value of $\tilde{S}$, the straighter the supercluster is.

straighter

xy plane	yz plane	xz plane
		
$\tilde{S} = 0.92h^{-1}Mpc$		
		
$\tilde{S} = 1.95h^{-1}Mpc$		
		
$\tilde{S} = 3.07h^{-1}Mpc$		

Coupled dark energy

- Coupled dark energy (CDE) : Interaction exists between scalar field dark energy ϕ and CDM.

Model	$U(\phi)$	α	$\beta(\phi)$
ΛCDM	Const	...	...
EXP002	$e^{-\alpha\phi}$	0.08	0.1
EXP003	$e^{-\alpha\phi}$	0.08	0.15
EXP003e3	$e^{-\alpha\phi}$	0.08	$0.4e^{3\phi}$
SUGRA003	$\phi^{-\alpha}e^{\phi^2/2}$	2.15	-0.15

Coupling function

$$\beta(\phi) \equiv -\frac{d\ln m_{\rm CDM}}{d\phi}$$

=> additional fifth force

f(R) gravity

- f(R) gravity : Modified gravity model which generalizes Ricci scalar R in Einstein-Hilbert action to f(R).

$$f(R) = -m^2 \frac{c_1(-R/m^2)^n}{c_2(-R/m^2)^n + 1}$$ (Hu & Sawicki 07)

General Relativity

$f_{R0} = 0, f(R) = \Lambda$ where $f_R \equiv \frac{df}{dR}$ => additional fifth force

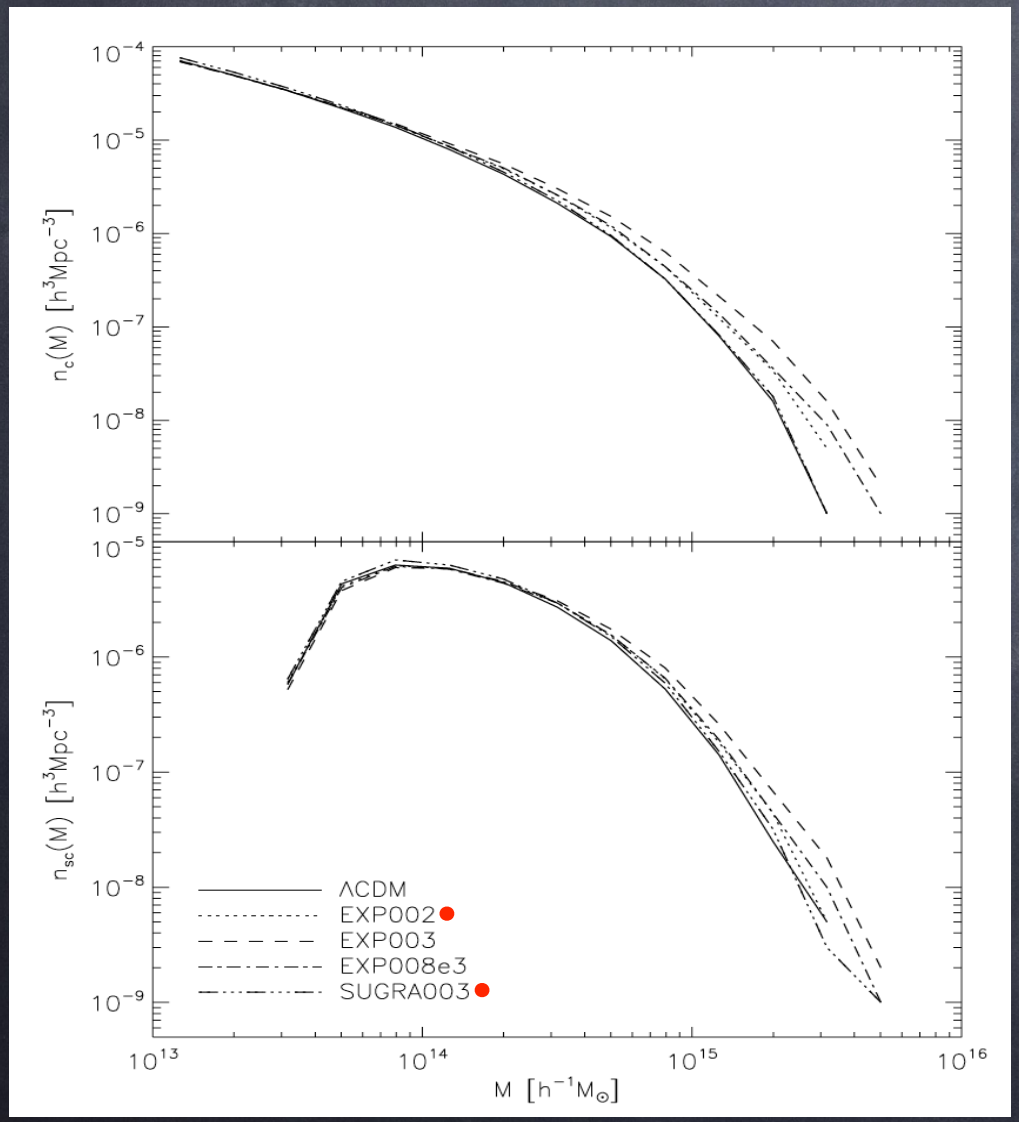
Simulation setup

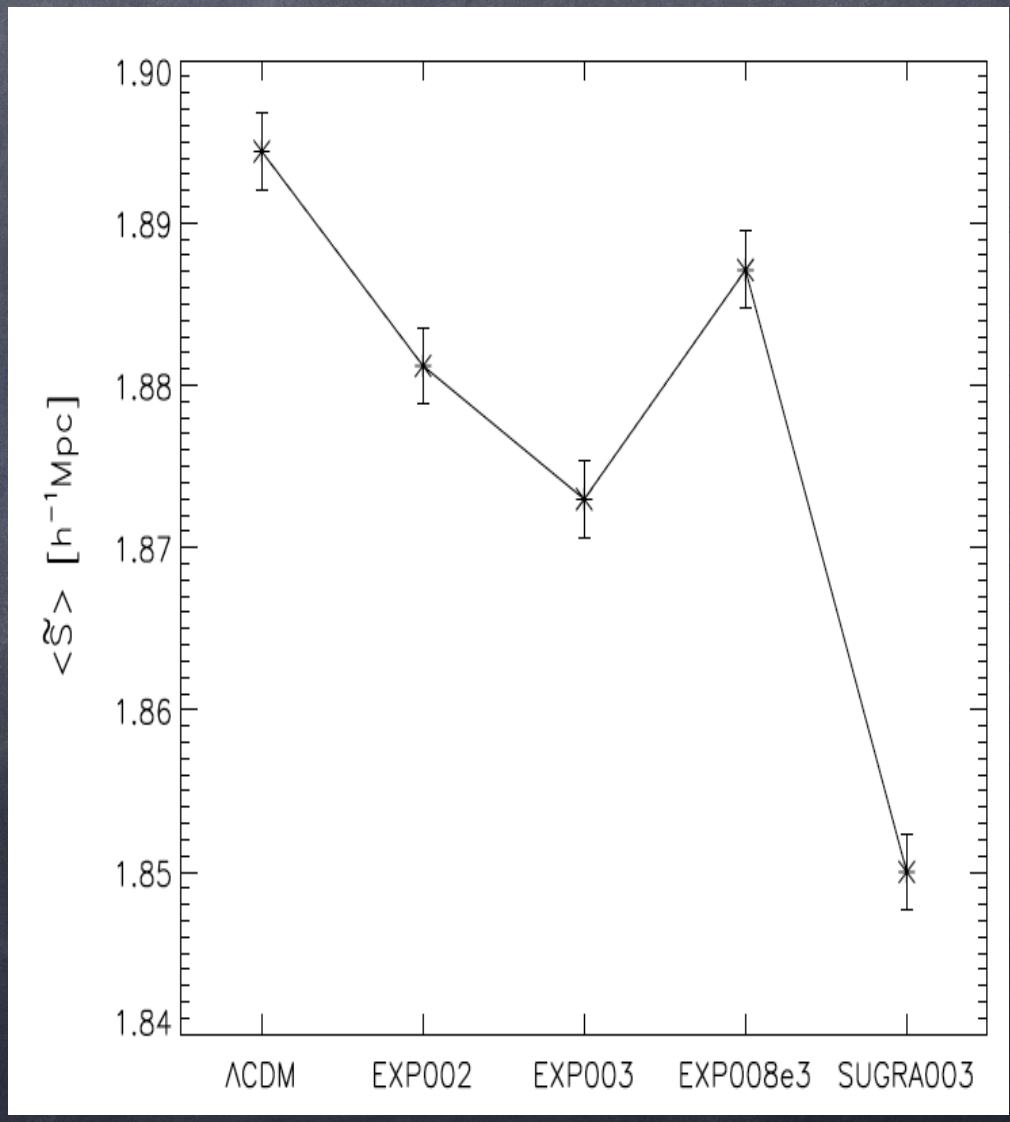
	cDE	f(R) gravity
Data	CoDECS (Baldi12)	ECOSMOG (Li+12)
# particles	1024^3	1024^3
Box size	$1h^{-1}$Gpc	$1h^{-1}$Gpc
$(\Omega_m, \Omega_\Lambda, \Omega_b)$	(0.27, 0.73, 0.045)	(0.24, 0.76, 0.045)
(h, σ_8, n_s)	(0.703, 0.809, 0.966)	(0.73, 0.8, 0.96)

Construction of supercluster

- We apply Friends-of-Friends group finder to halos of mass $M \geqq 10^{13} h^{-1} M_{\odot}$ and regard clusters within the linking length as member of supercluster.
- Then we also apply minimal spanning tree method to identify filamentary structure.

Superclusters in cDE

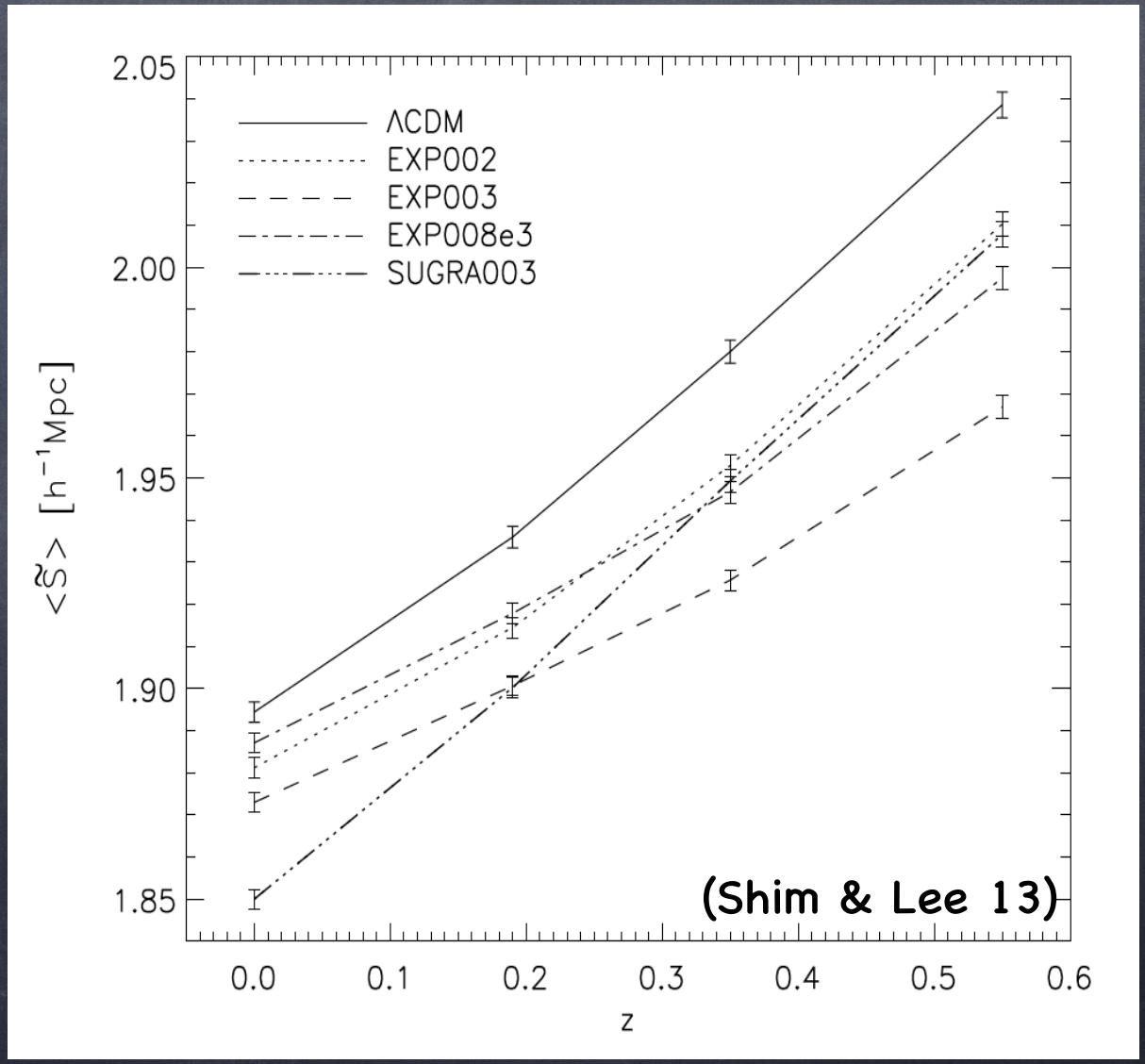




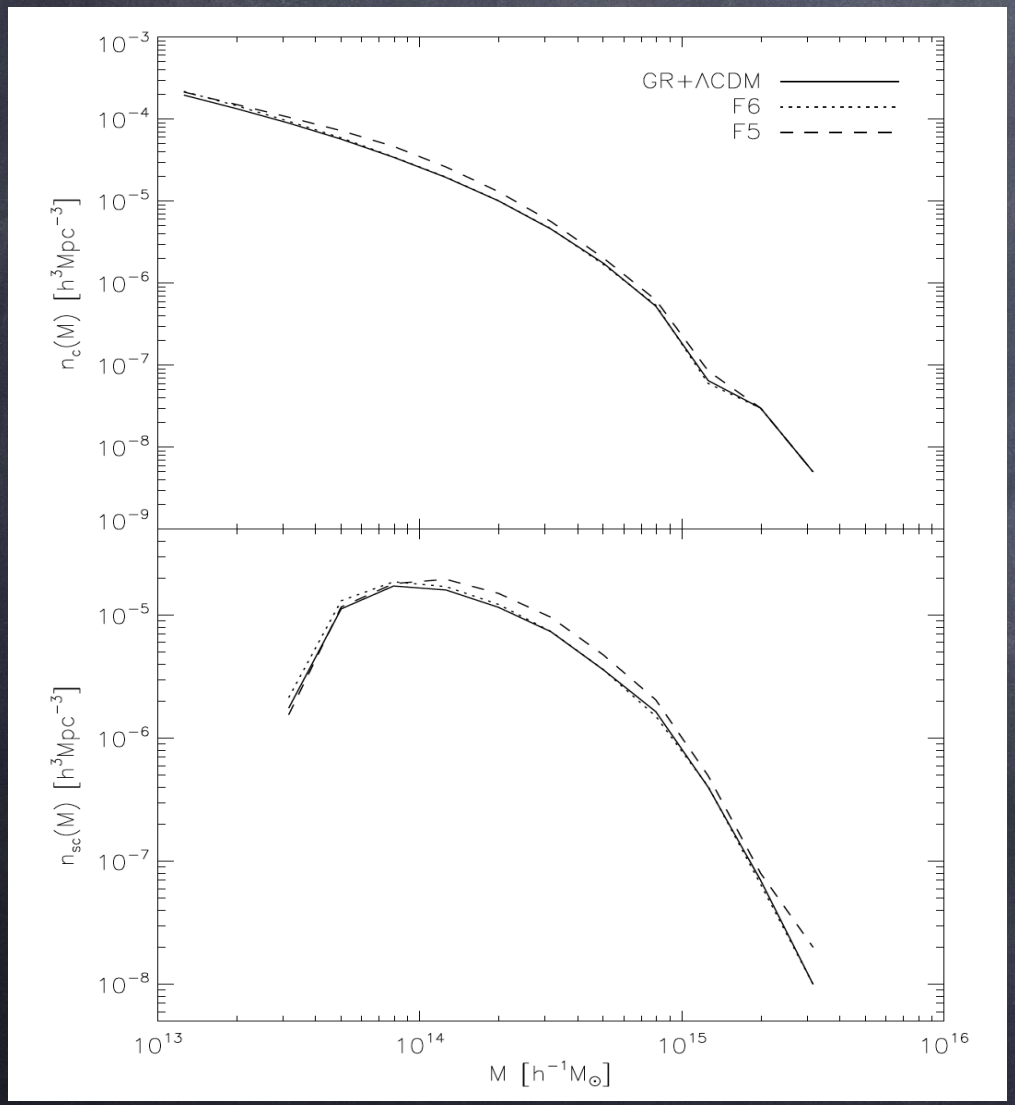
(Shim & Lee 13)

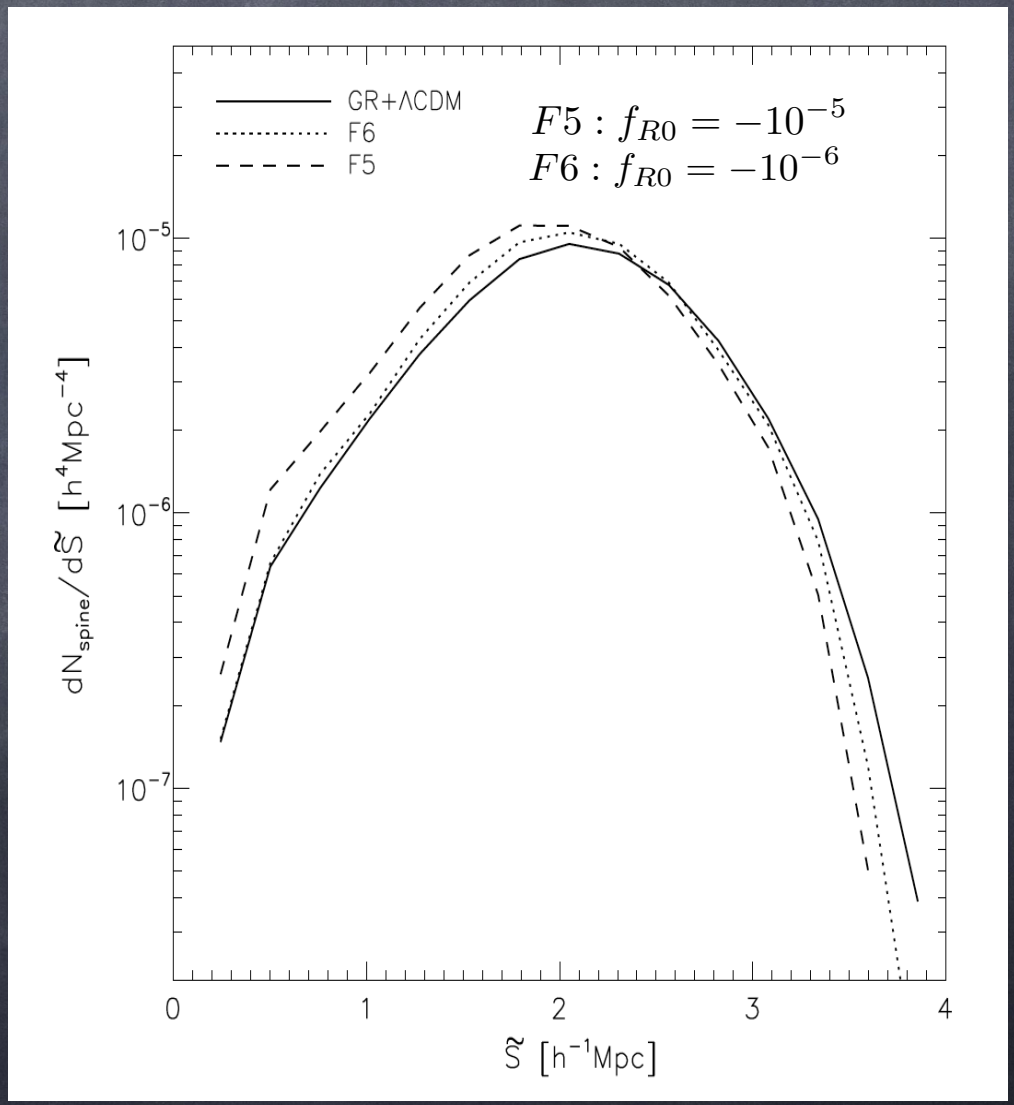
Superclusters in cDE

- Superclusters were straighter in the past.
- Straightness deviation from ΛCDM is growing in higher redshift.



Superclusters in f(R)



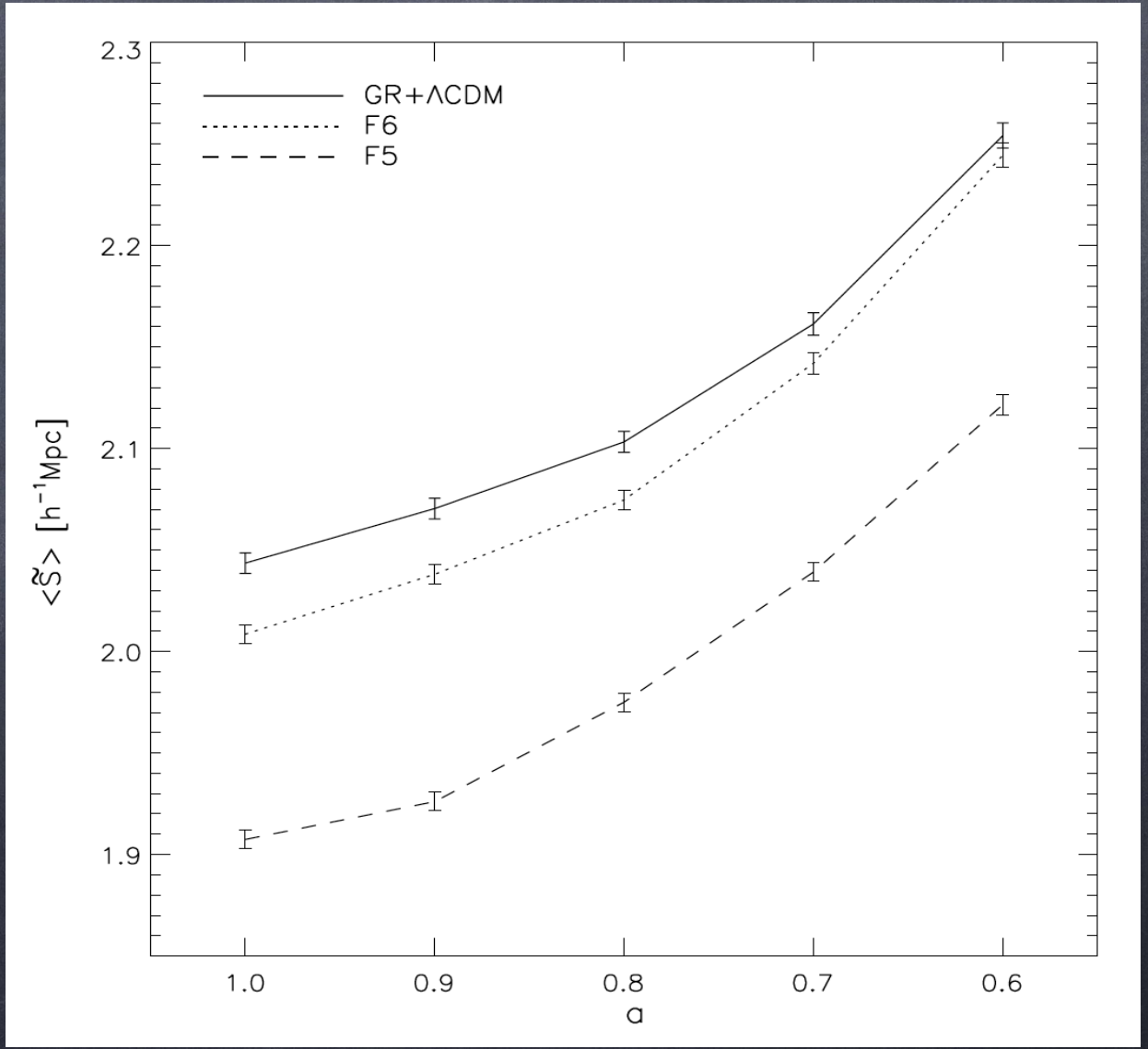


(Shim+14)

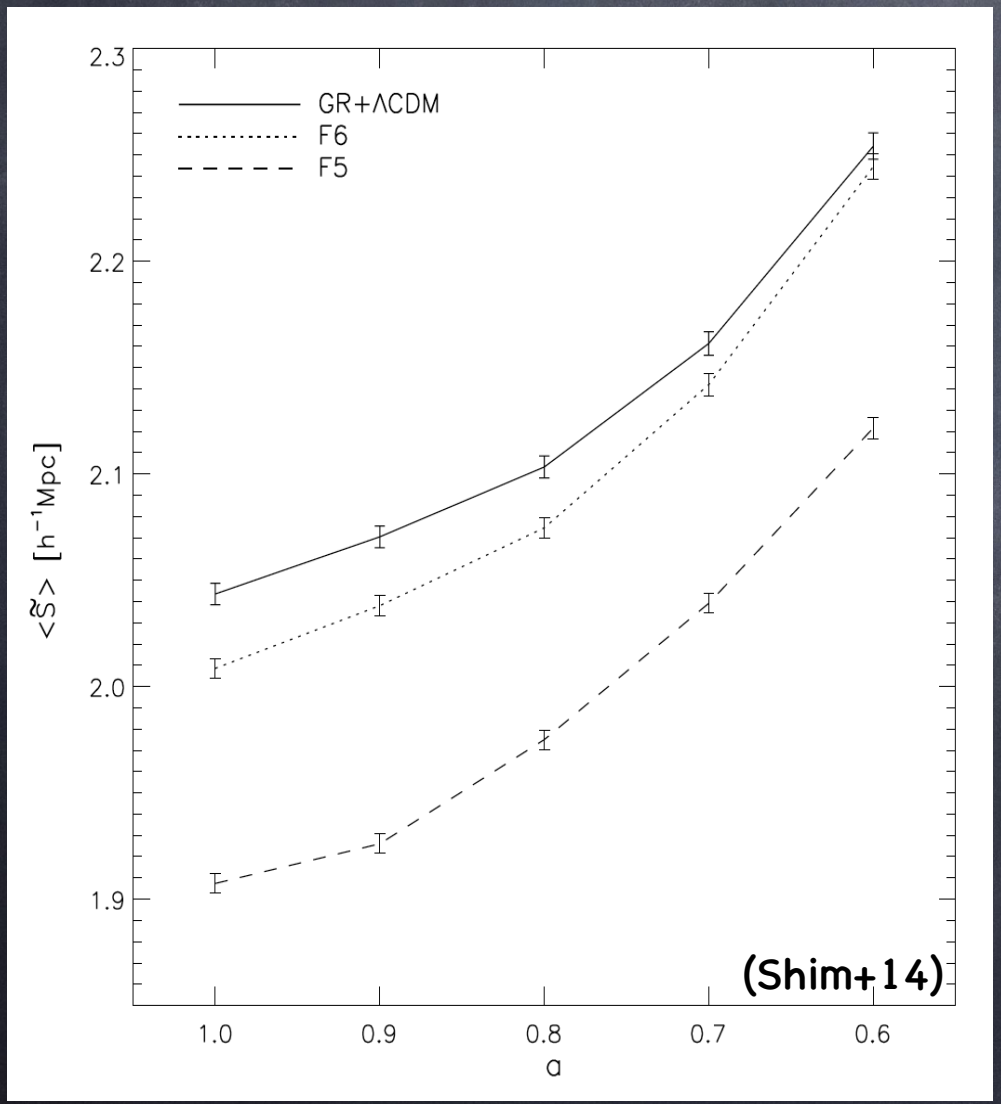
Superclusters in f(R)

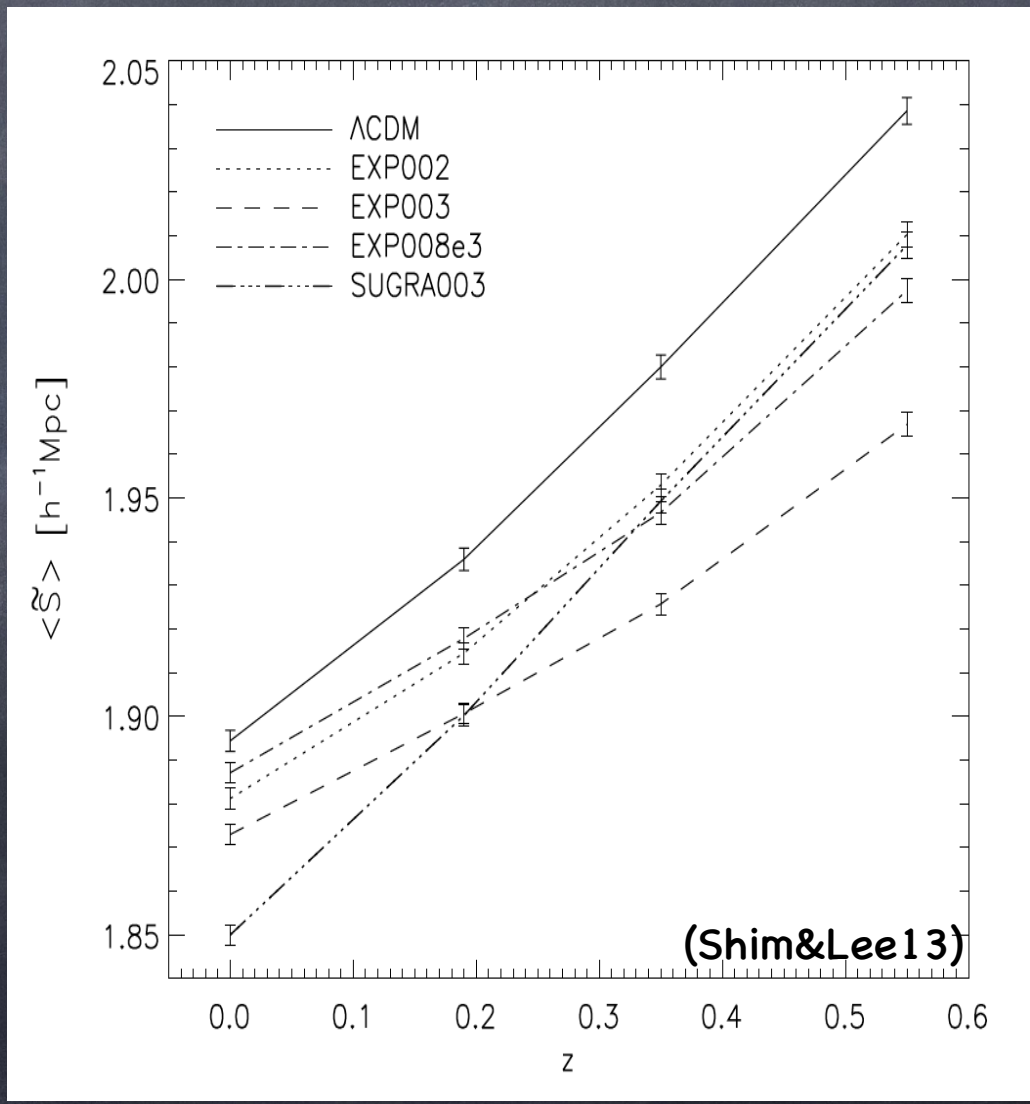
(Shim+14)

- Superclusters were straighter in the past.
- Straightness deviation from ΛCDM is diminishing in higher redshift.



cDE vs f(R)

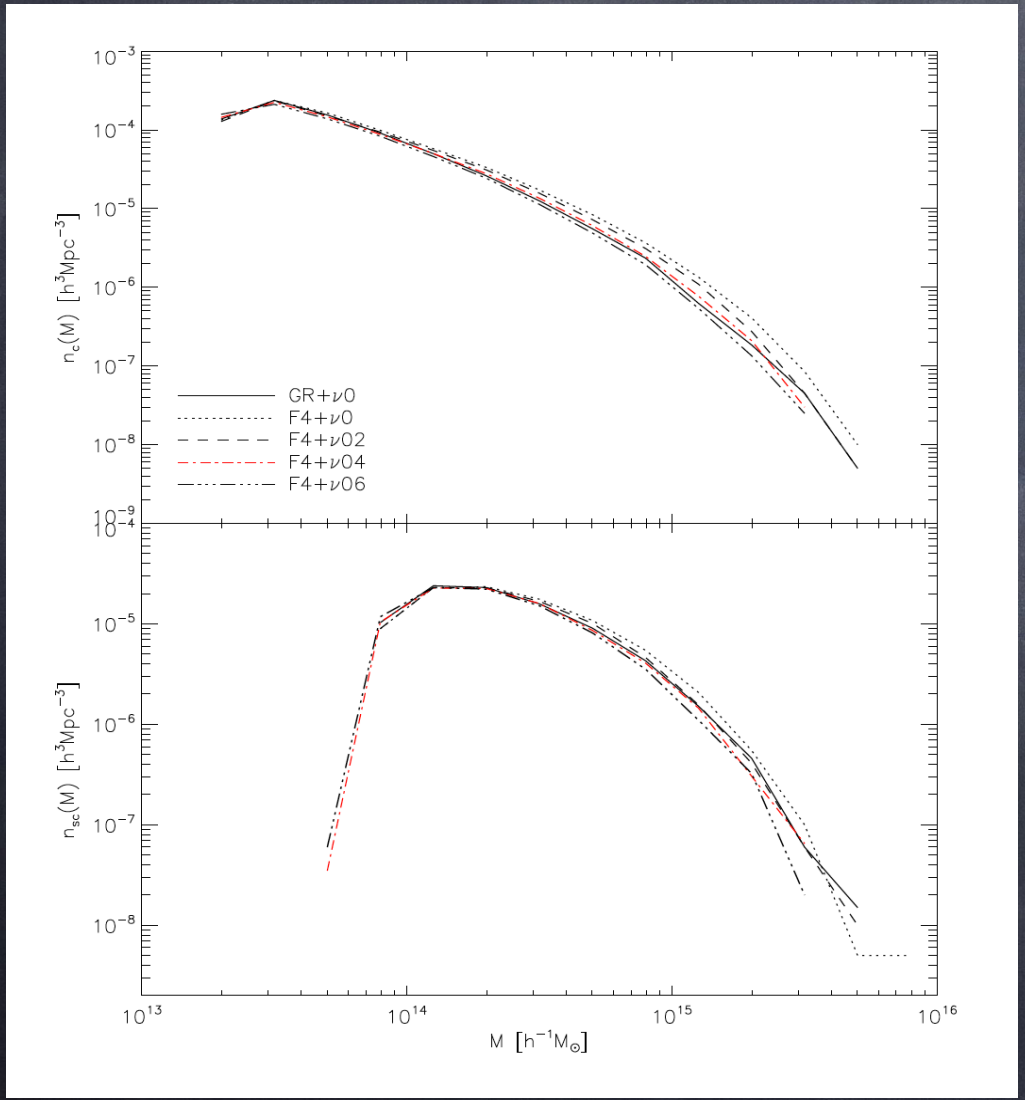

GR+ΛCDM
F6
F5
2.3
2.2
2.1
2.0
1.9
1.0
0.9
0.8
0.7
0.6
a
<S> [h⁻¹Mpc]
(Shim+14)

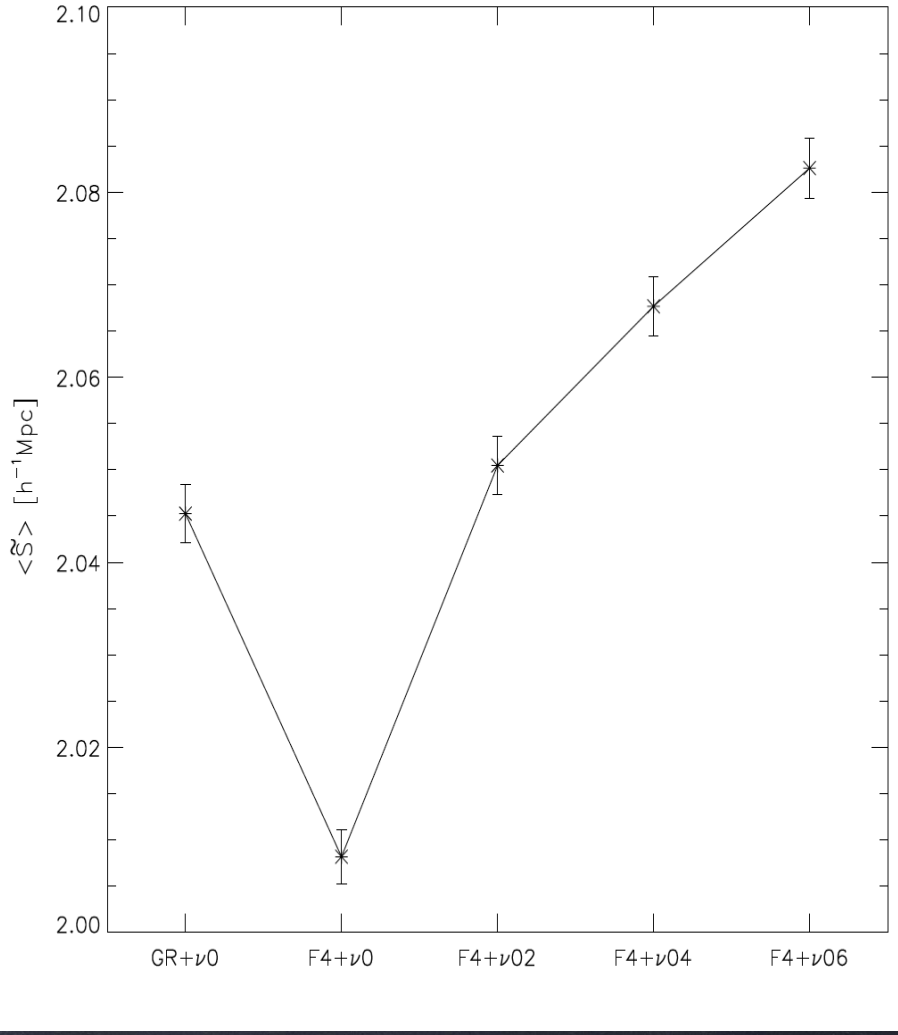

ΛCDM
EXP002
EXP003
EXP008e3
SUGRA003
2.05
2.00
1.95
1.90
1.85
0.0
0.1
0.2
0.3
0.4
0.5
0.6
z
<S> [h⁻¹Mpc]
(Shim&Lee13)

Summary

- We investigate how the clustering pattern at the largest scale changes in cDE/f(R) gravity through superclusters shape.
- It is found that superclusters in cDE/f(R) gravity are significantly less straight than those in ΛCDM.
- Straightness evolutions of cDE/f(R) gravity compared to that of ΛCDM are in the opposite direction.

Superclusters in f(R)+ν





Superclusters in f(R)+ν