Testing the Standard Model of Cosmology with Large-scale Structures in the Real and Simulated Universe

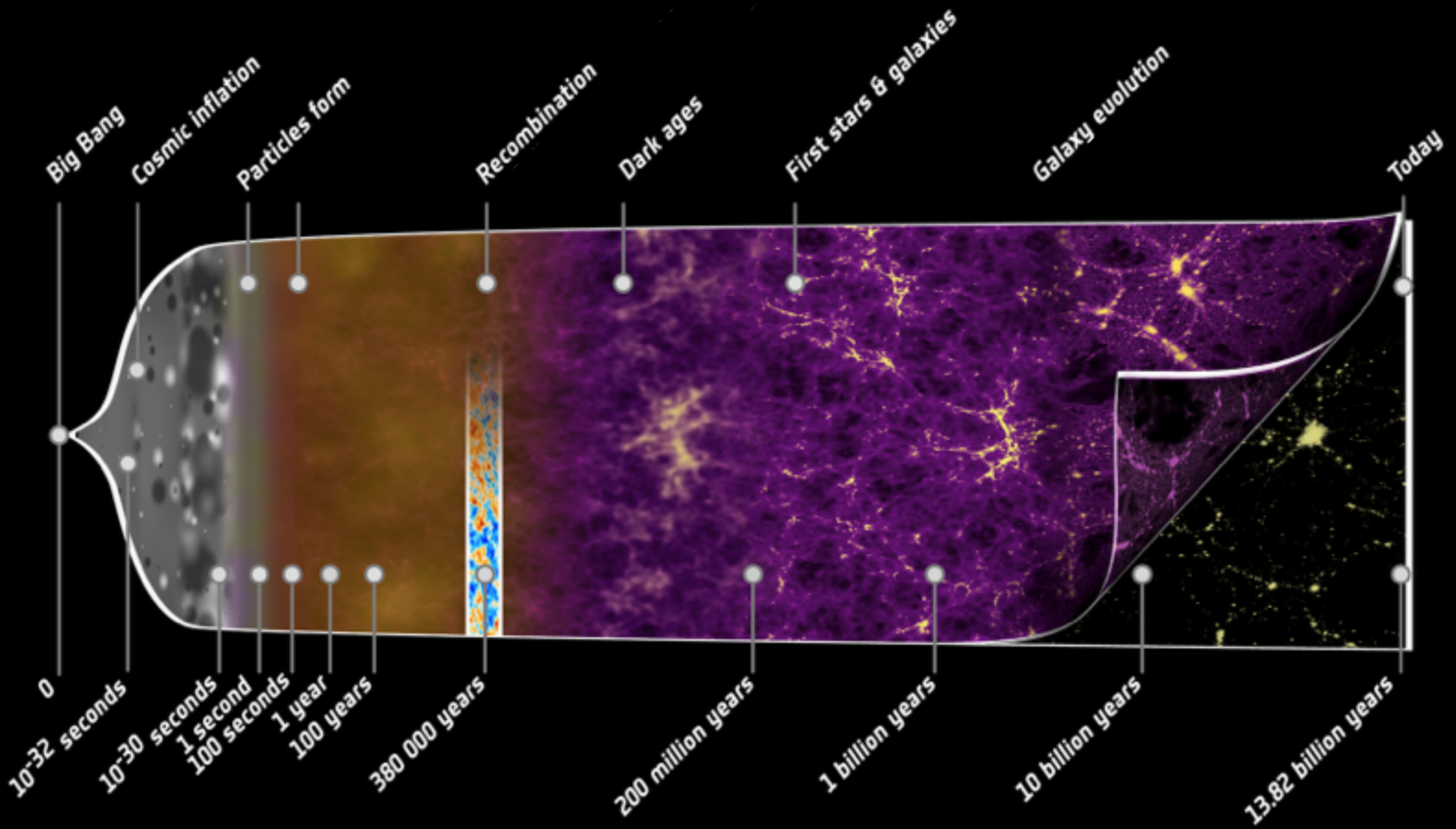
Hwang, Ho Seong (KIAS)

September 20, 2017

KIAS-YITP Joint Workshop 2017 @ YITP

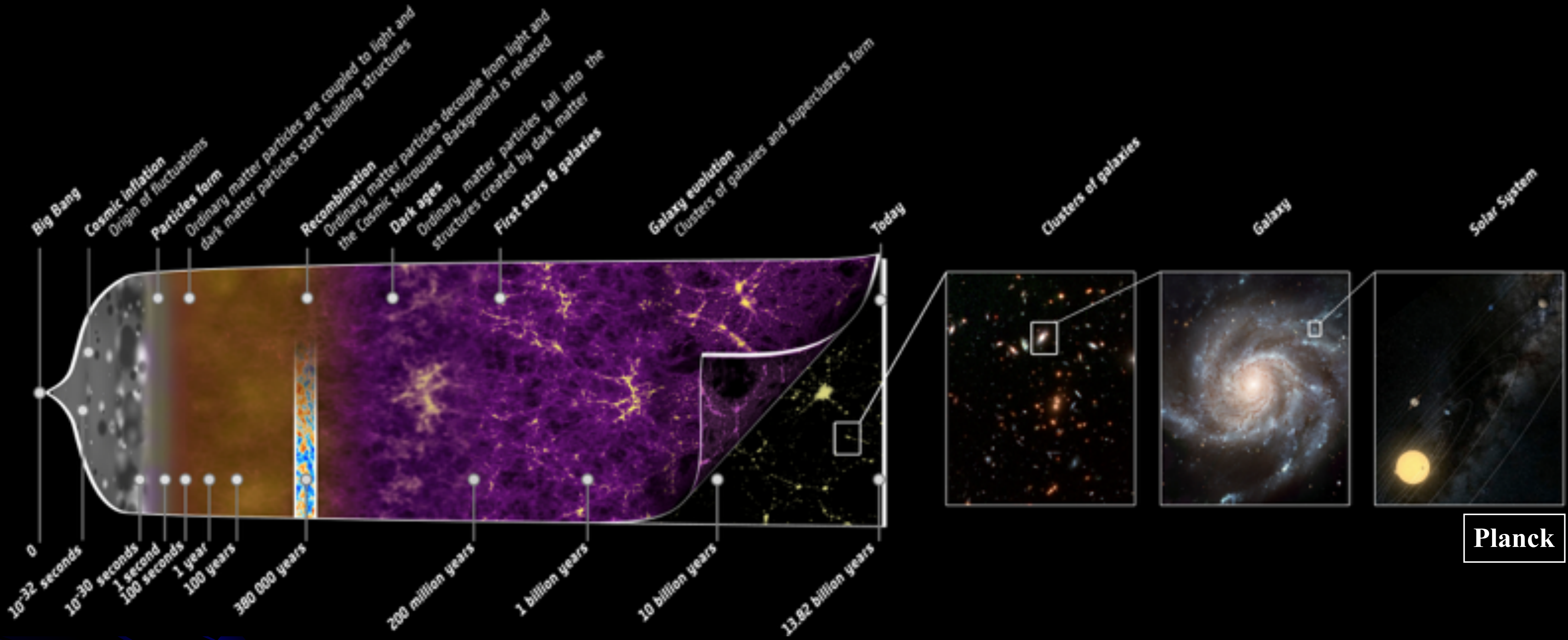
A Road to Reality (YITP)

History of the Universe

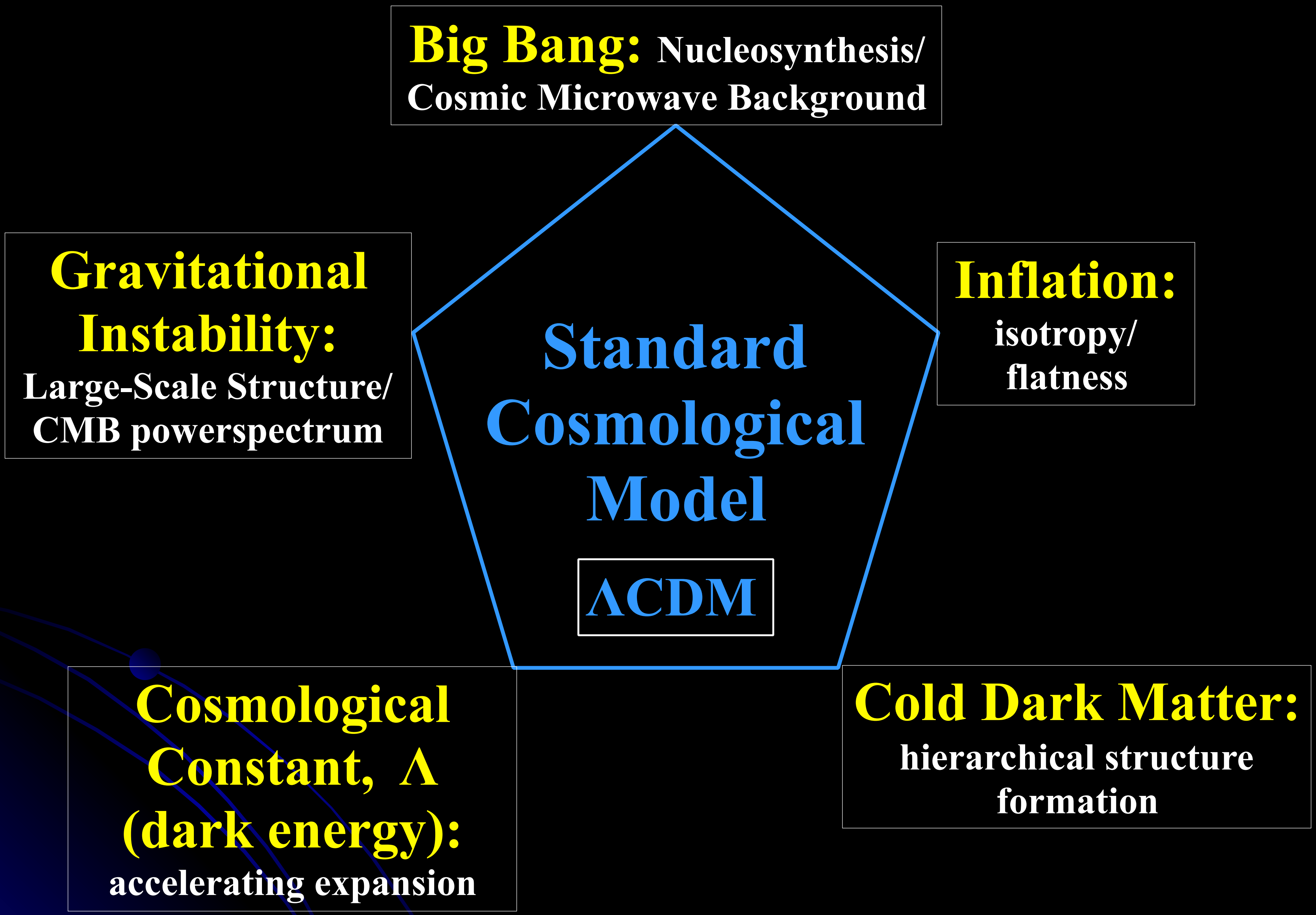


Planck

History of the Universe



We think we live in the Universe that can be described by a standard cosmological model.



Based on General Relativity

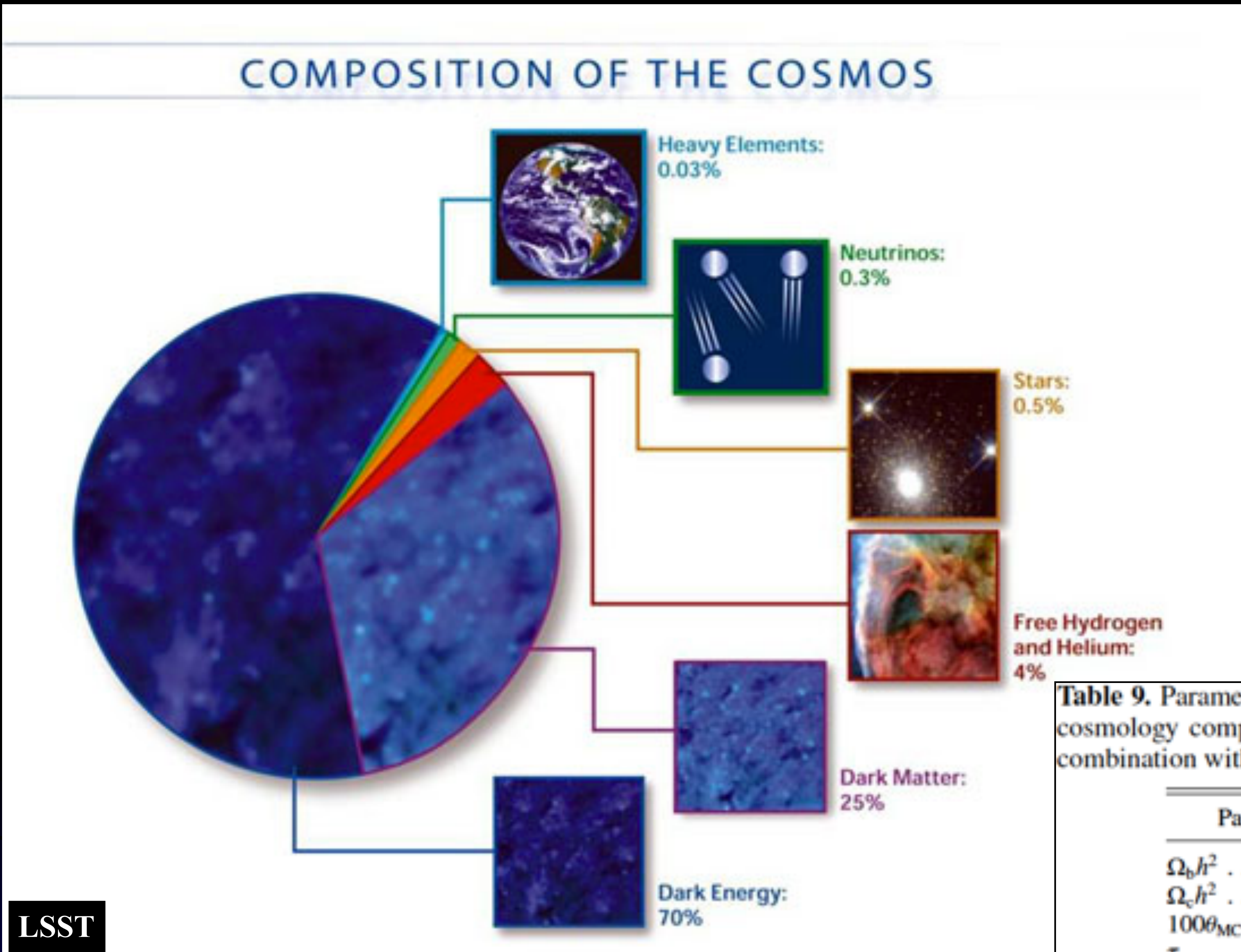


Table 9. Parameter 68 % confidence levels for the base ΛCDM cosmology computed from the *Planck* CMB power spectra, in combination with the CMB lensing likelihood ("lensing").

Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

Planck

Issues in the Standard Cosmological Model

Space:
Is the Universe really homogenous and isotropic?

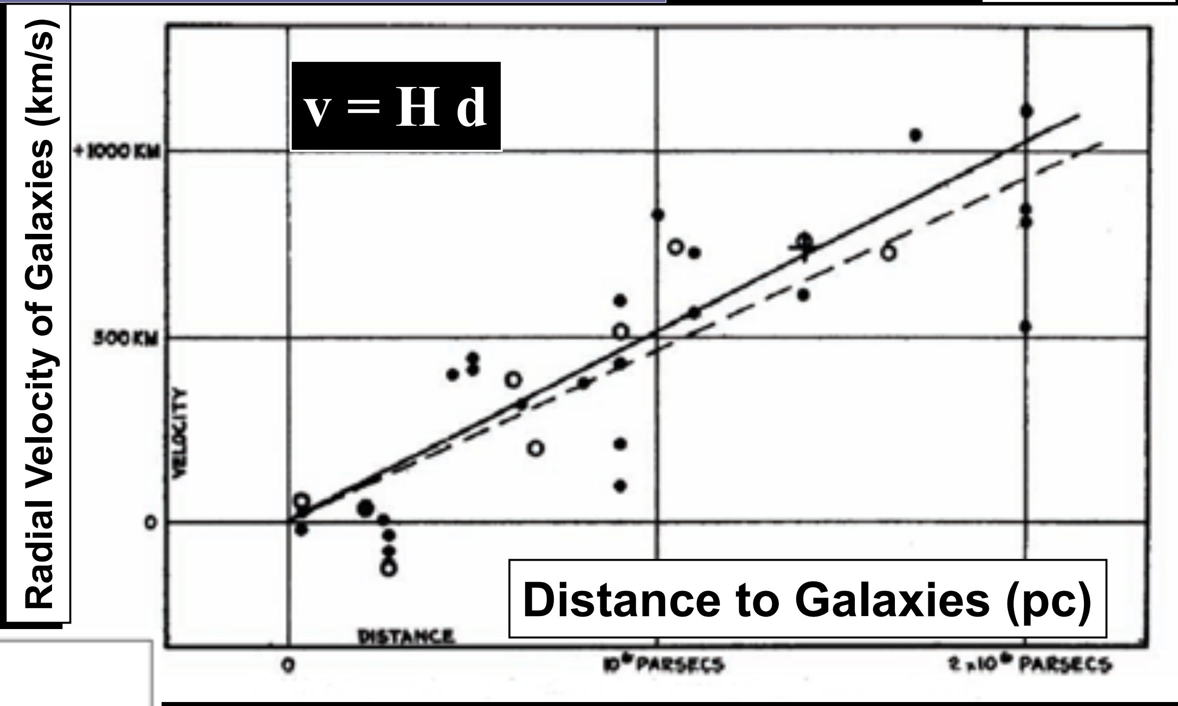
Contents:
What is the nature of dark matter and dark energy?

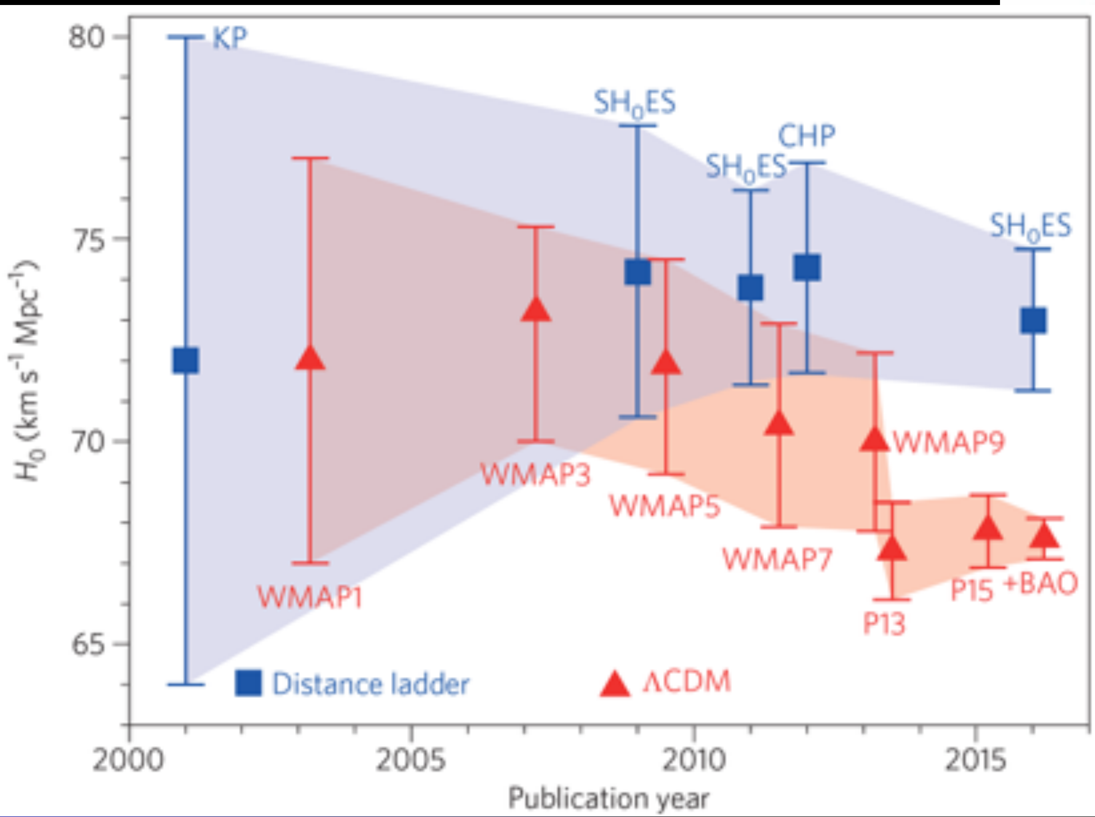
Phenomena/Laws:
New Physics instead of dark matter and dark energy?

Models appear to be in contradiction with observations:
Missing Satellite Problem
Central Density Profile of Dark Matter Halos (core vs. cusp)

Issues in the Standard Cosmological Model

Hubble 29

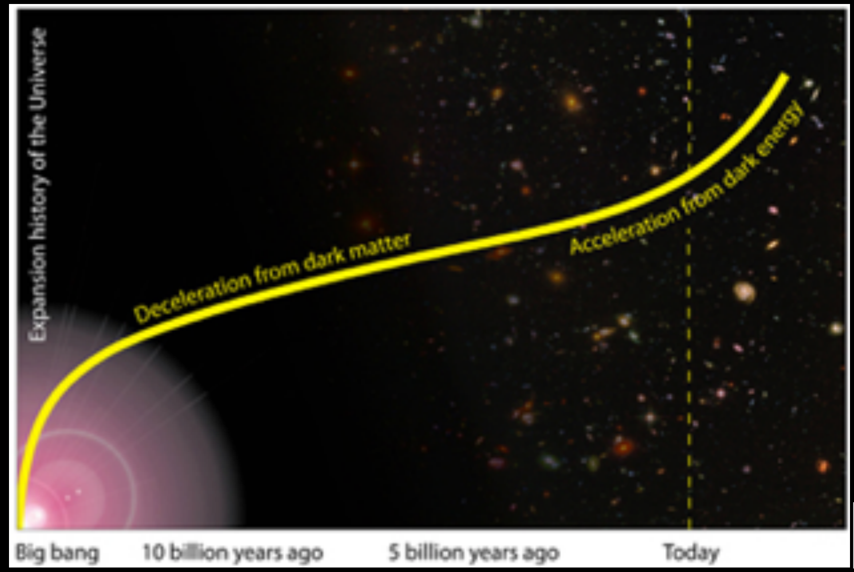




Freedman 17

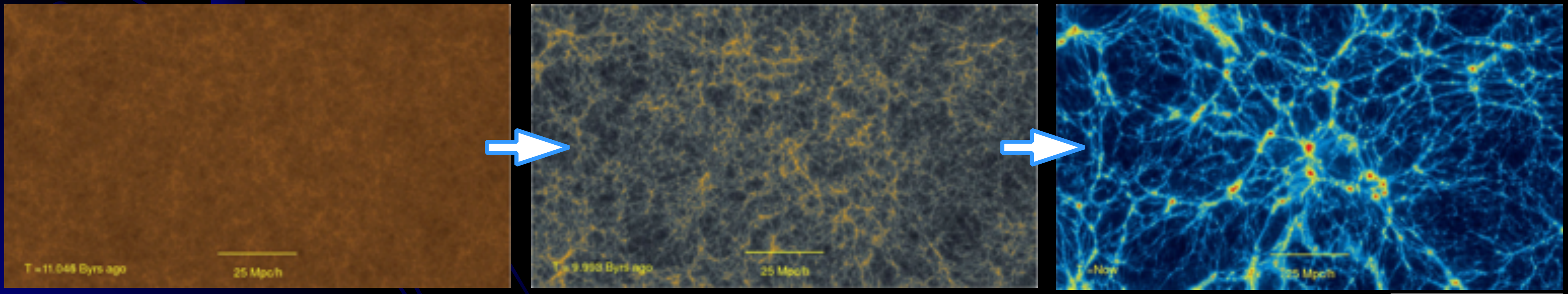
Effects of Dark Matter/Energy

➢ Expansion History of the Universe



Euclid

➢ Growth History of Structures



Kim & Park

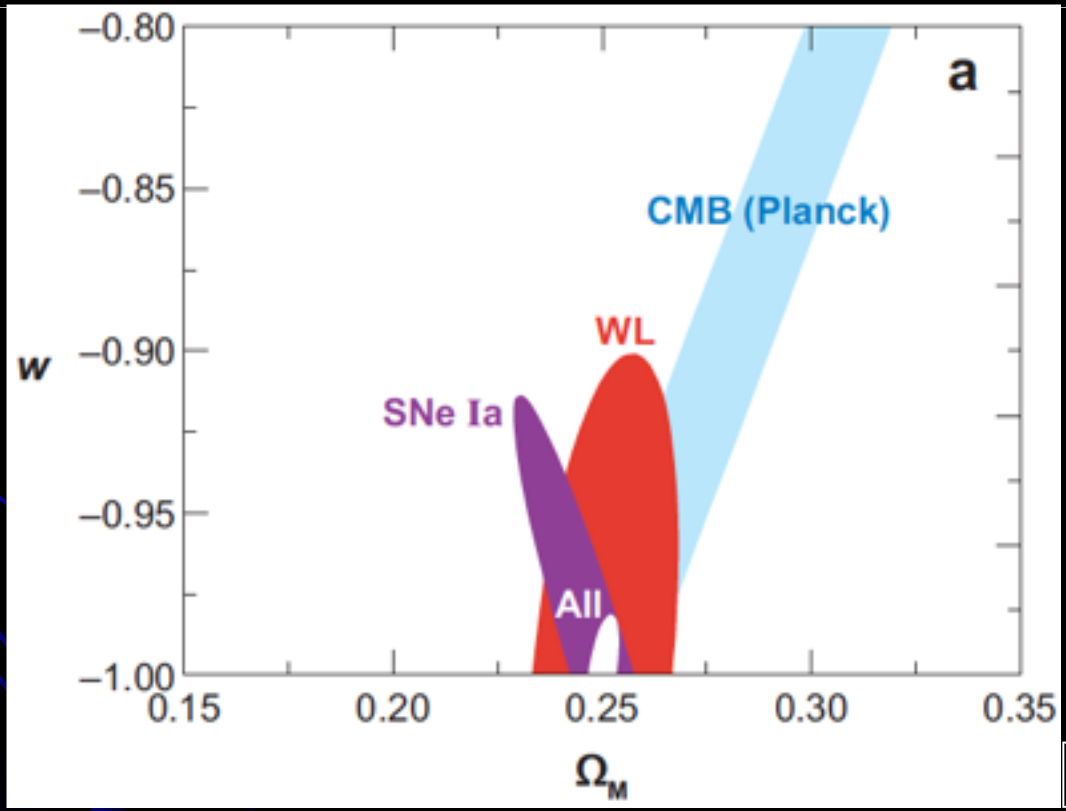
Effects of Dark Matter/Energy

Type Ia Supernovae: accelerating universe

Cosmic Microwave Background: WMAP, Planck

Large-scale Structure: SDSS, DESI

Weak Gravitational Lensing: LSST



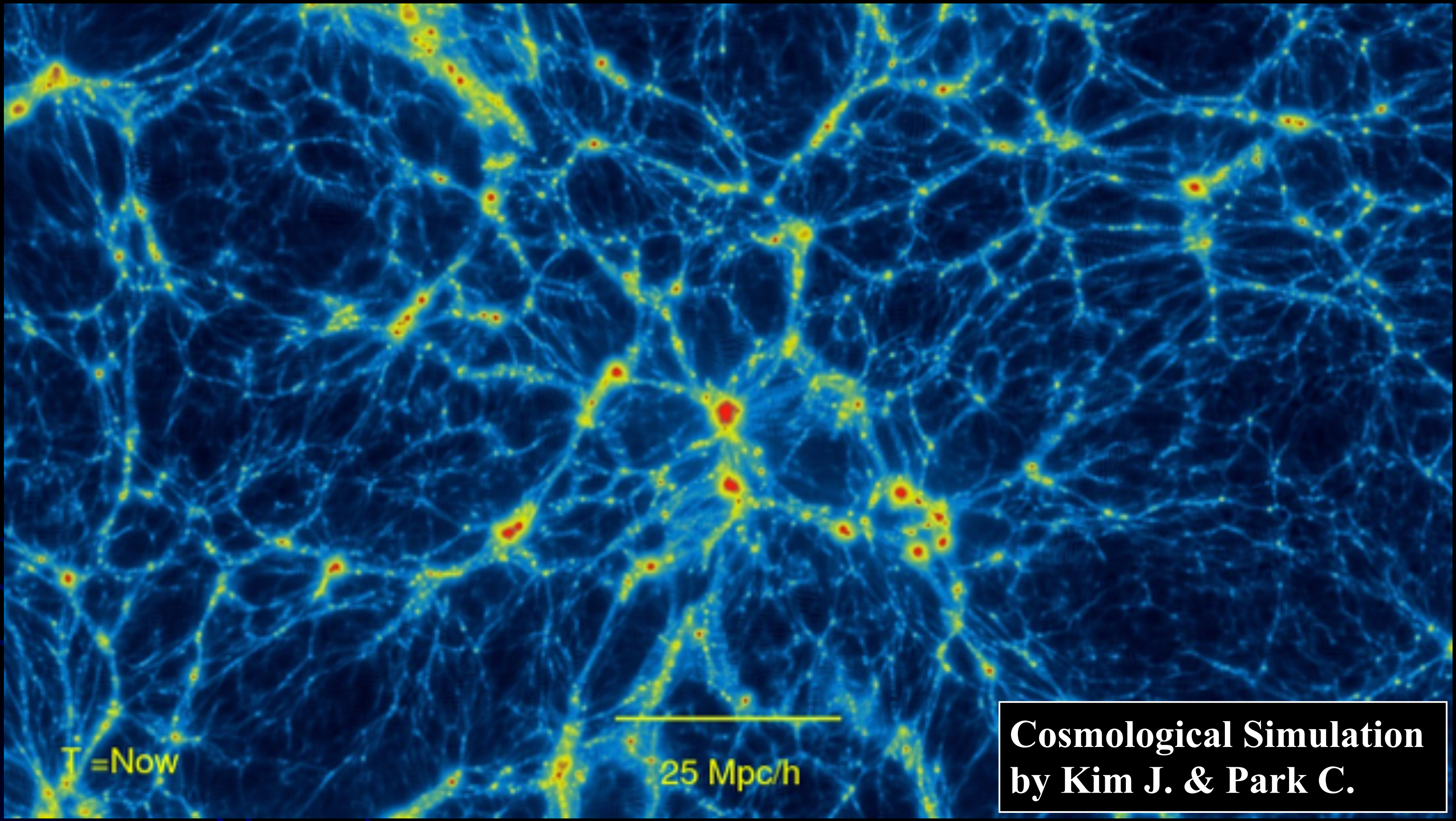
Frieman+08

➢ Test the Standard Cosmological Model with Large-scale Structure of the Universe

LSS: Any structure of galaxy distribution larger than galaxy clusters (>~10 Mpc)

- Over-density Structure
  - Filament, Chain
  - Wall, Pancake, Sheet

- Under-density Structure
  - Tunnel
  - Void, Cell, Bubble



- **In Short, we call it "Cosmic Web"**

Why Large-Scale Structure of the Universe?

- ➢ Large Structures :
  grew from small initial fluctuations after the inflation
  (might tell us how early universe looks like)

- ➢ Smaller structures form first, larger structures form later:
  we can study the formation of structure in action

- ➢ Physical properties of large-scale structure depend on
  - ➢ cosmological parameters
  - ➢ physics of galaxy formation

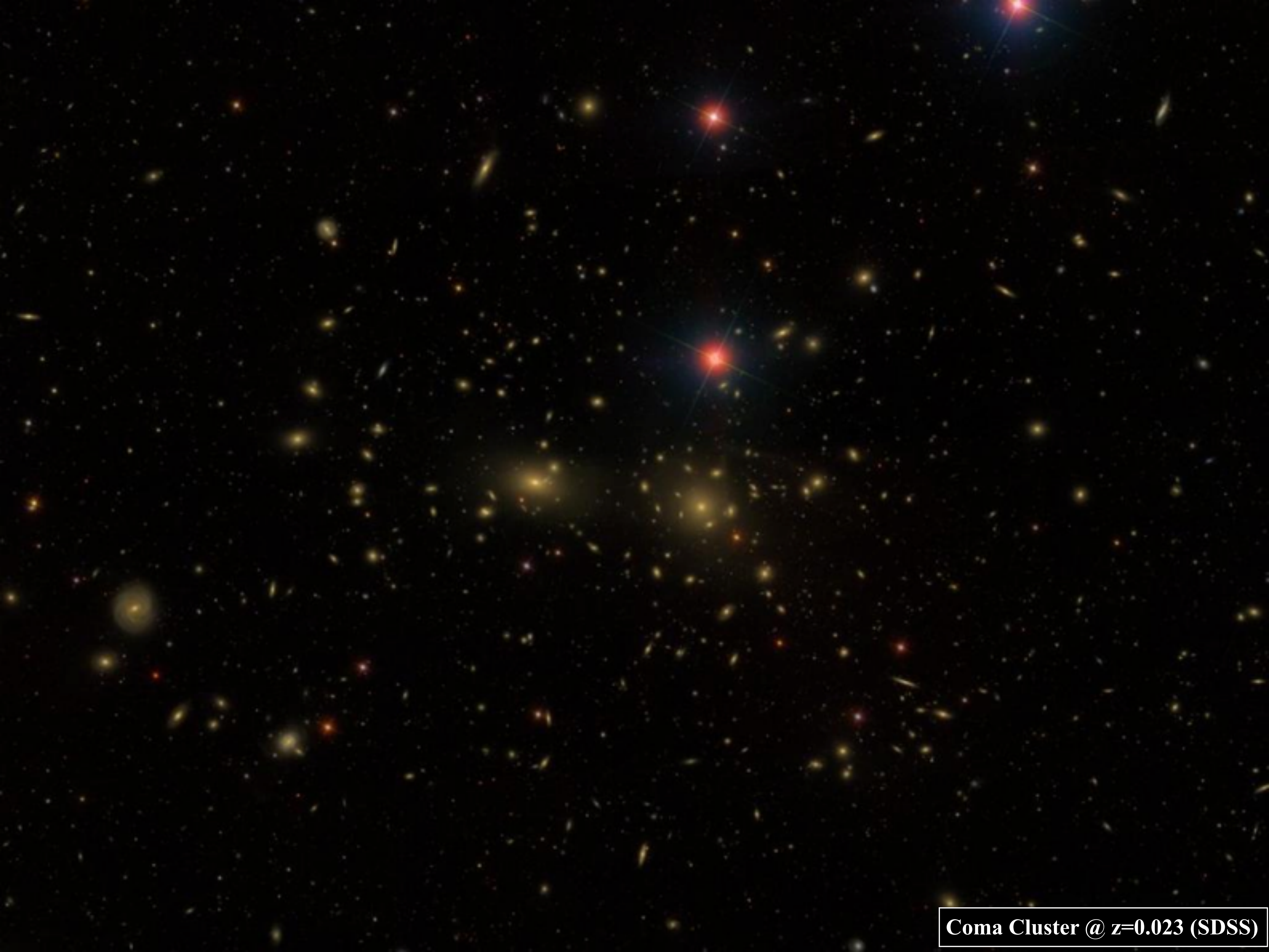
←Strong Constraints

In this Talk,

- ➢ Test of Standard Cosmological Model with the large-scale structure
- ➢ There were many such tests in nearby Universe
- ➢ Need to study the evolution of large-scale structure (structure is still forming)
- ➢ Good theoretical input from cosmological simulations (C. Park & J. Kim)

Q: Is the large-scale structure in cosmological simulations consistent with that in observations?

Goal: To better understand Cosmology and Structure Formation



Coma Cluster @ z=0.023 (SDSS)

THE ASTROPHYSICAL JOURNAL, 222:784–799, 1978 June 15

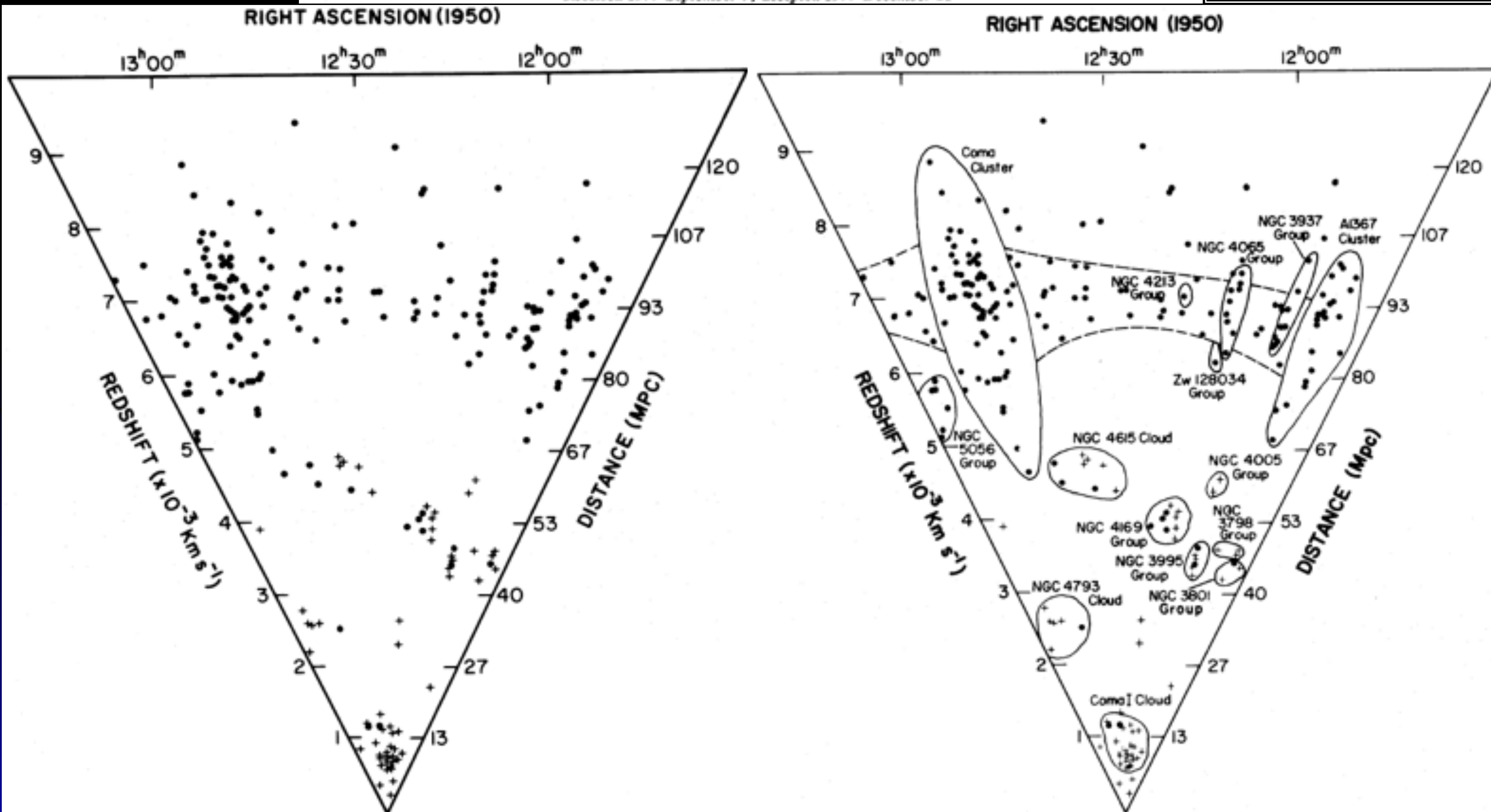
THE COMA/A1367 SUPERCLUSTER AND ITS ENVIRONS

STEPHEN A. GREGORY*
Department of Earth Sciences, State University of New York College at Oswego; and Physics Department, Bowling Green State University

AND

LAIRD A. THOMPSON
Kitt Peak National Observatory;† and Department of Physics and Astronomy, University of Nebraska
Received 1977 September 7; accepted 1977 December 21

Supercluster and Voids (see also Joeveer+78; Kirshner+78,+81)

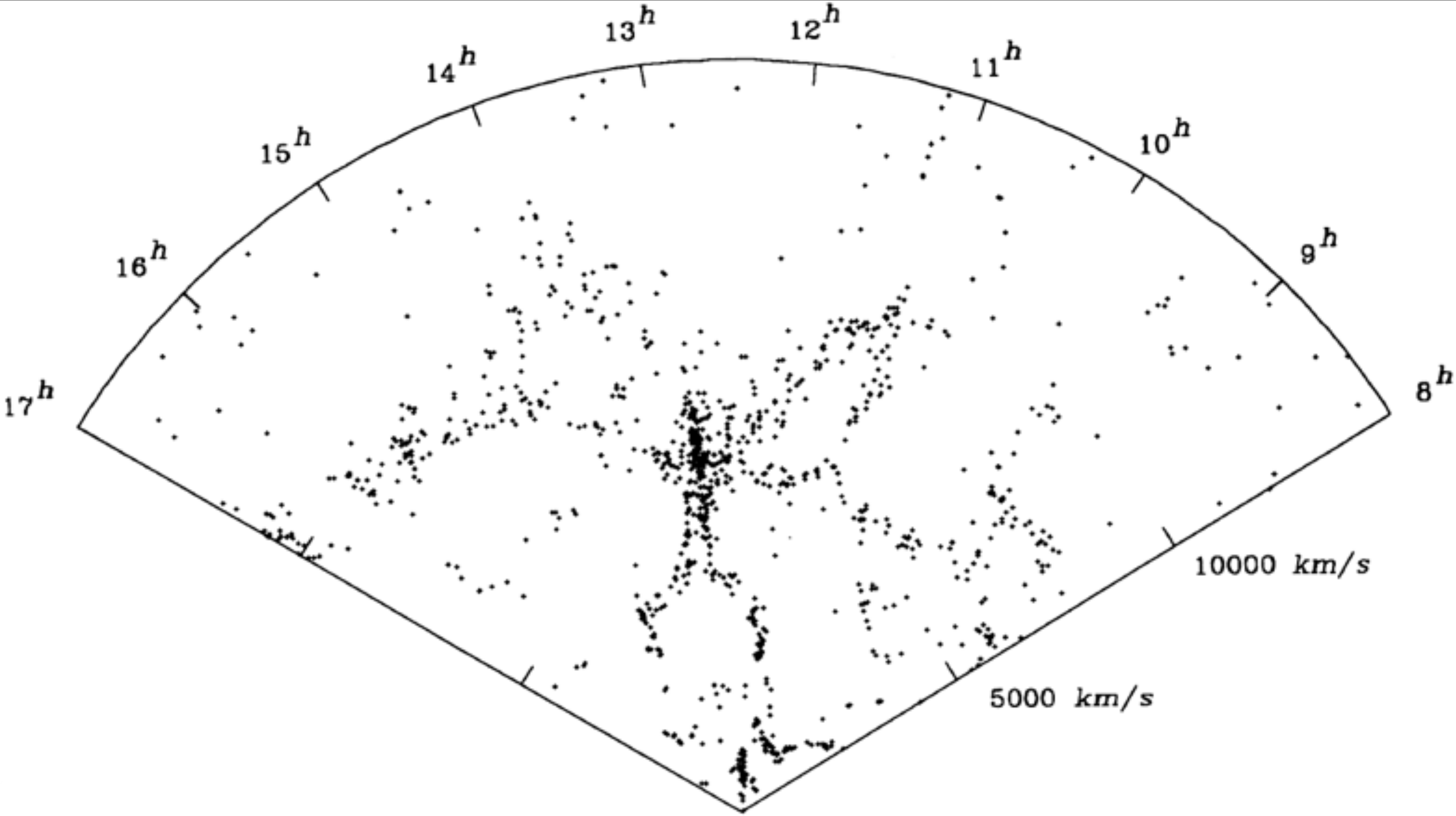


THE ASTROPHYSICAL JOURNAL, 302:L1–L5, 1986 March 1

A SLICE OF THE UNIVERSE[1]

VALÉRIE DE LAPPARENT,[2,3] MARGARET J. GELLER,[2] AND JOHN P. HUCHRA[2]
Received 1985 November 12; accepted 1985 December 5

CfA Stick Man (Running Man)

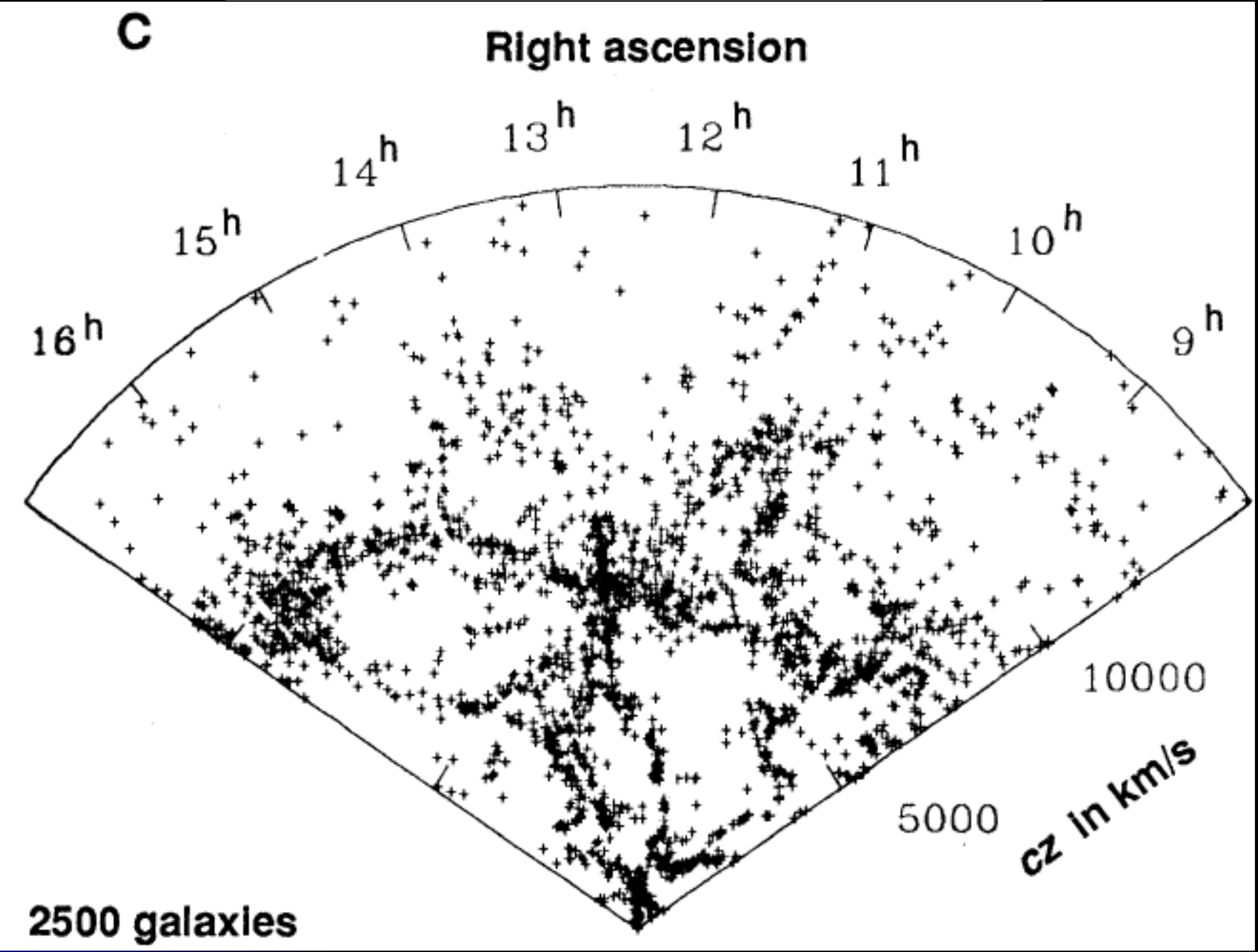


Source: *Science*, New Series, Vol. 246, No. 4932 (Nov. 17, 1989), pp. 897-903

Mapping the Universe

MARGARET J. GELLER AND JOHN P. HUCHRA

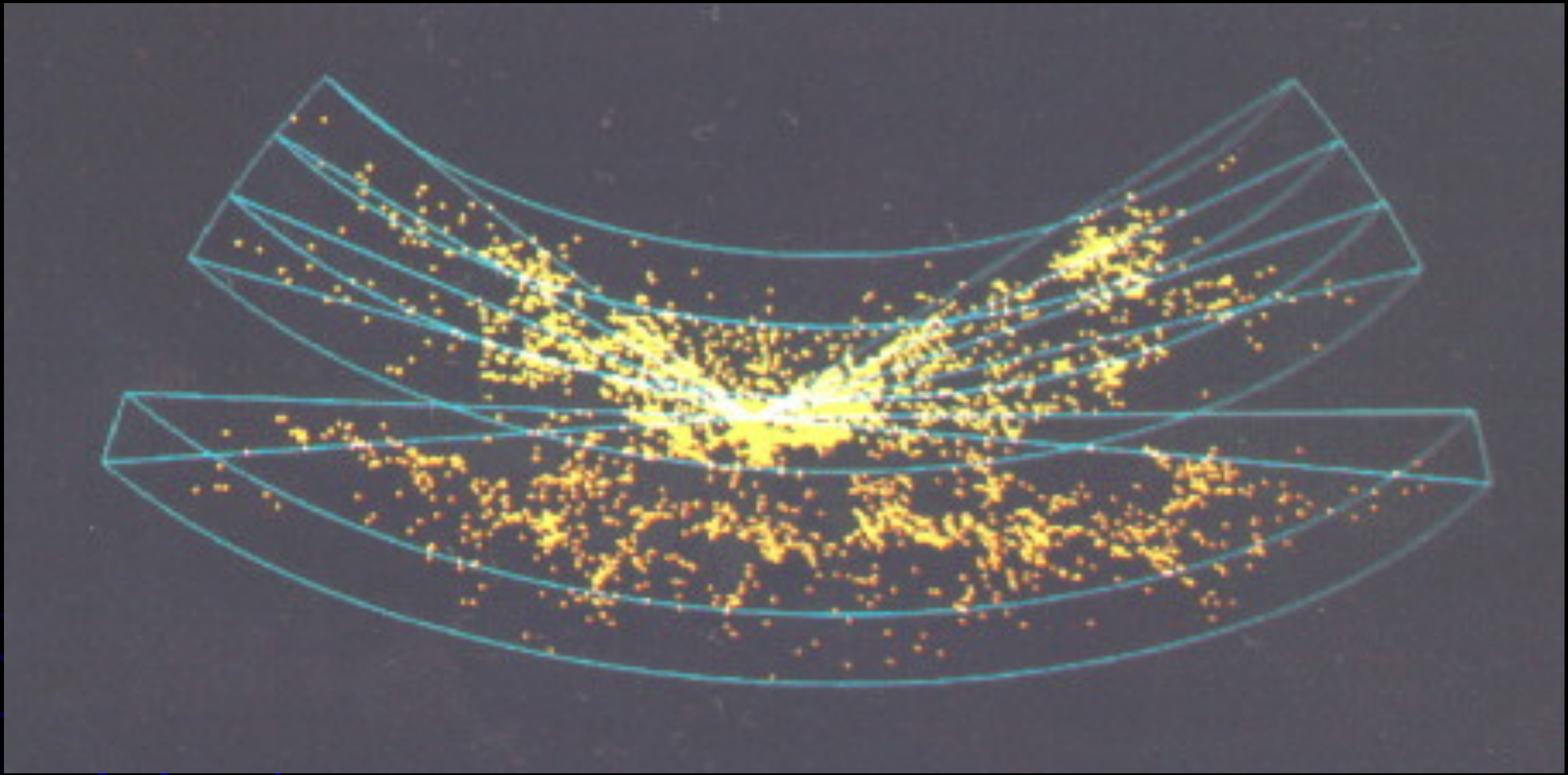
CfA Great Wall



Source: *Science*, New Series, Vol. 246, No. 4932 (Nov. 17, 1989), pp. 897-903

Mapping the Universe

Margaret J. Geller and John P. Huchra

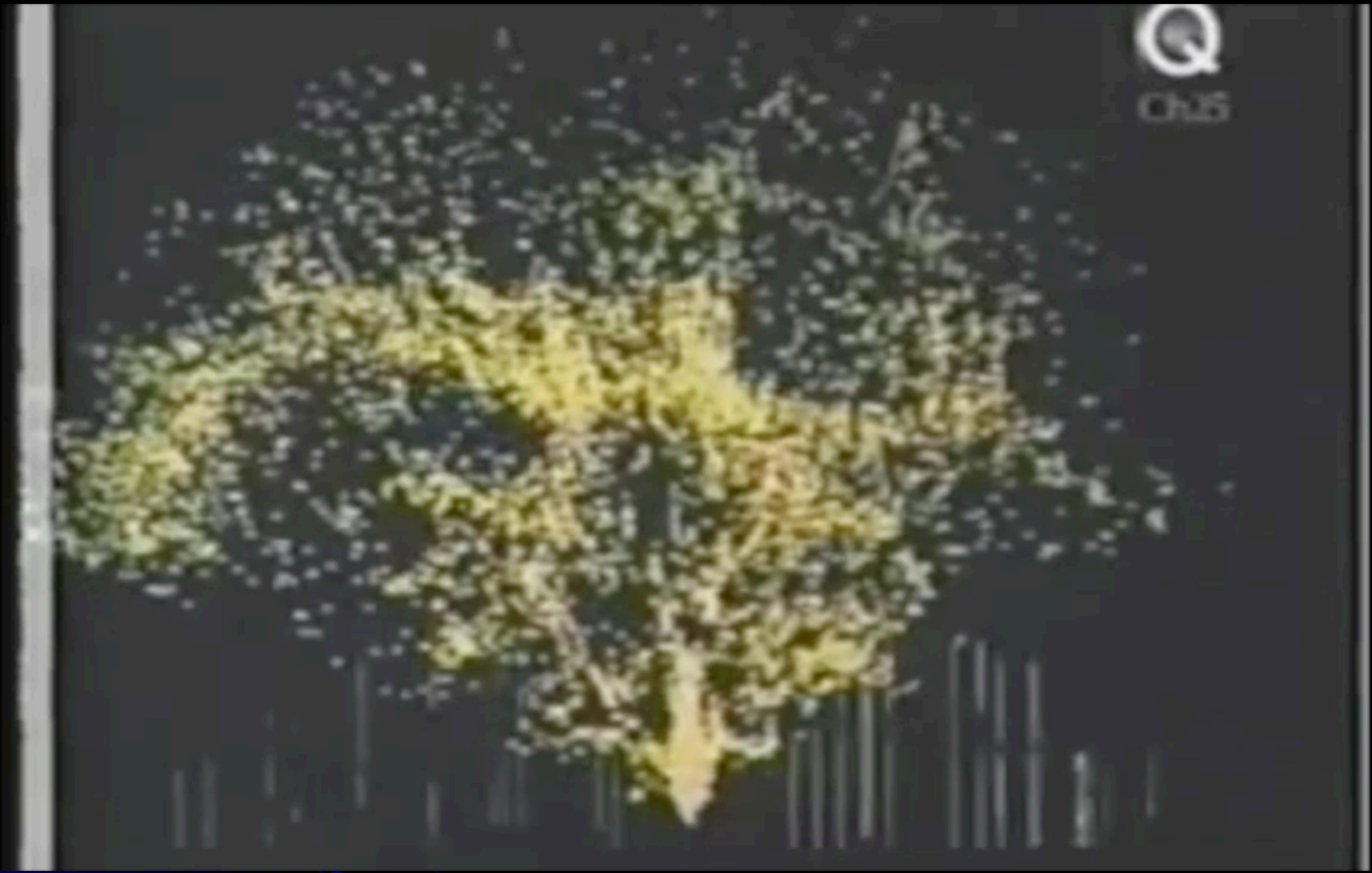


3D plot

Source: *Science*, New Series, Vol. 246, No. 4932 (Nov. 17, 1989), pp. 897-903

Mapping the Universe

Margaret J. Geller and John P. Huchra

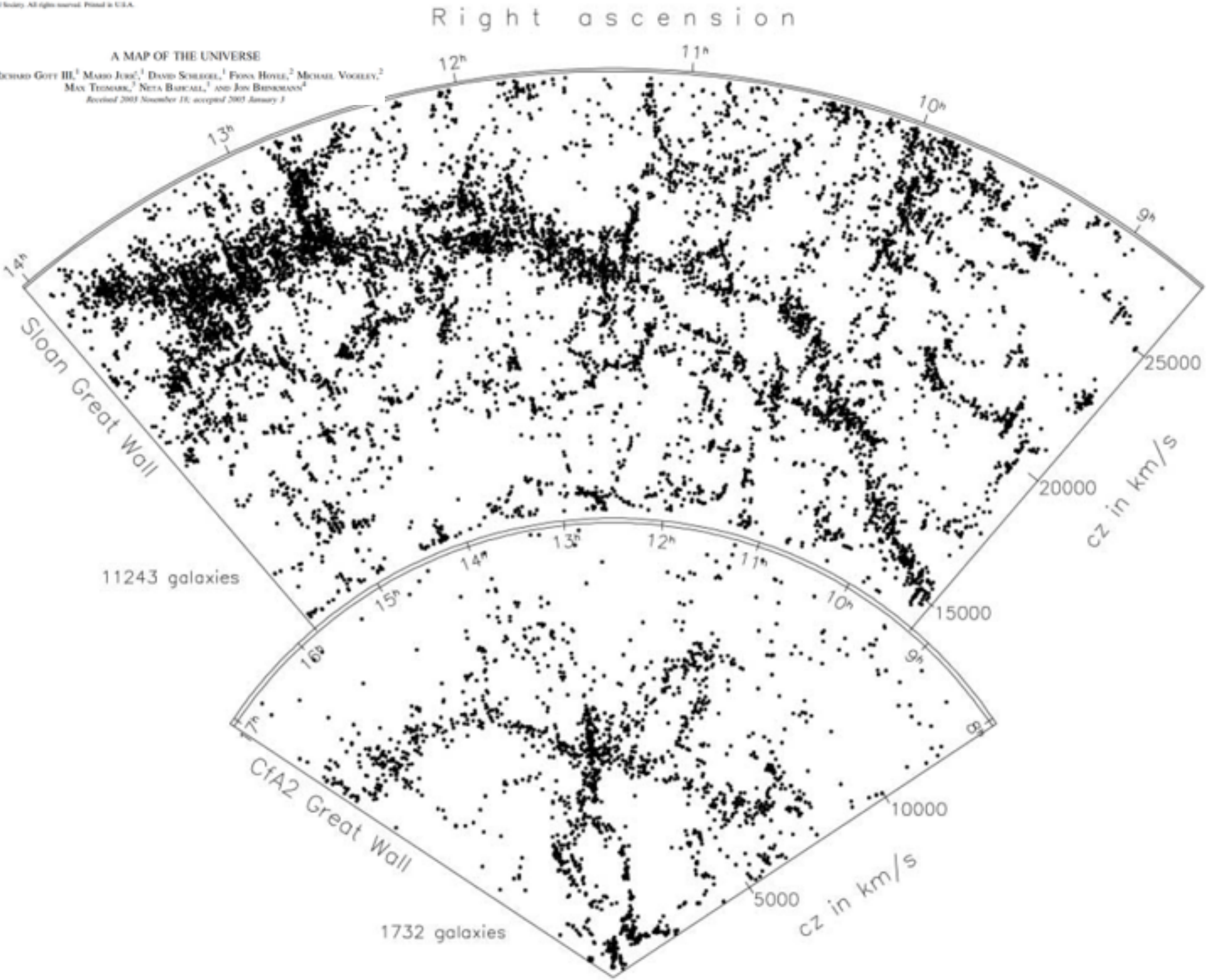


3D plot

The Astrophysical Journal, 624:463–484, 2005 May 10

A MAP OF THE UNIVERSE

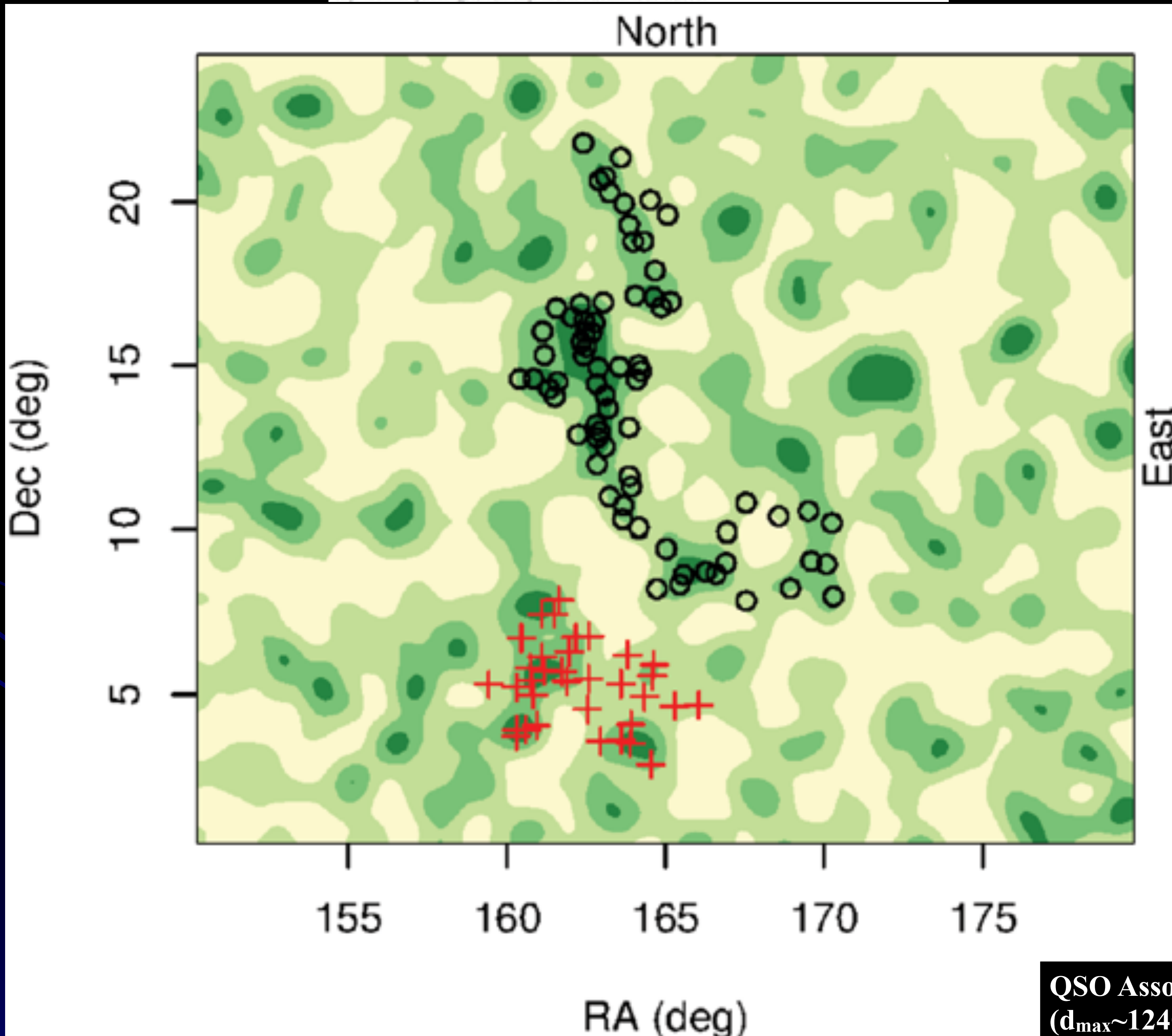
J. Richard Gott III,[1] Mario Jurić,[1] David Schlegel,[1] Fiona Hoyle,[2] Michael Vogeley,[2] Max Tegmark,[3] Neta Bahcall,[1] and Jon Brinkmann[4]
Received 2003 November 18; accepted 2005 January 3



MNRAS 429, 2910–2916 (2013)

A structure in the early Universe at $z \sim 1.3$ that exceeds the homogeneity scale of the R-W concordance cosmology

Roger G. Clowes,[1*] Kathryn A. Harris,[1] Srinivasan Raghunathan,[1,2]† Luis E. Campusano,[2] Ilona K. Söchting[3] and Matthew J. Graham[4]
[1]Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE
[2]Observatorio Astronómico Cerro Calán, Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
[3]Astrophysics, Denys Wilkinson Building, Keble Road, University of Oxford, Oxford OX1 3RH
[4]California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA



QSO Association
(d_{max}~1240 Mpc, Clowes+13)

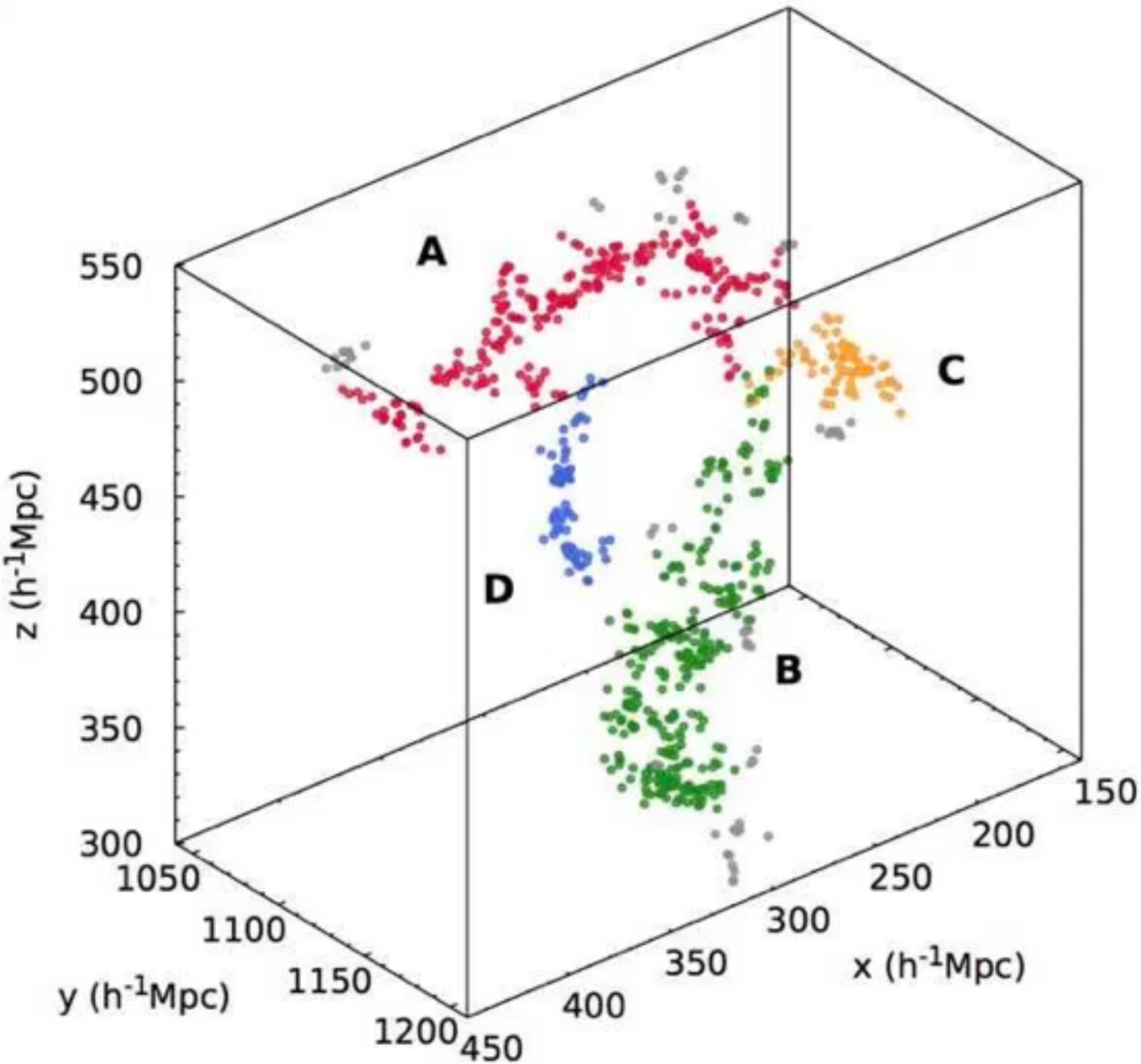


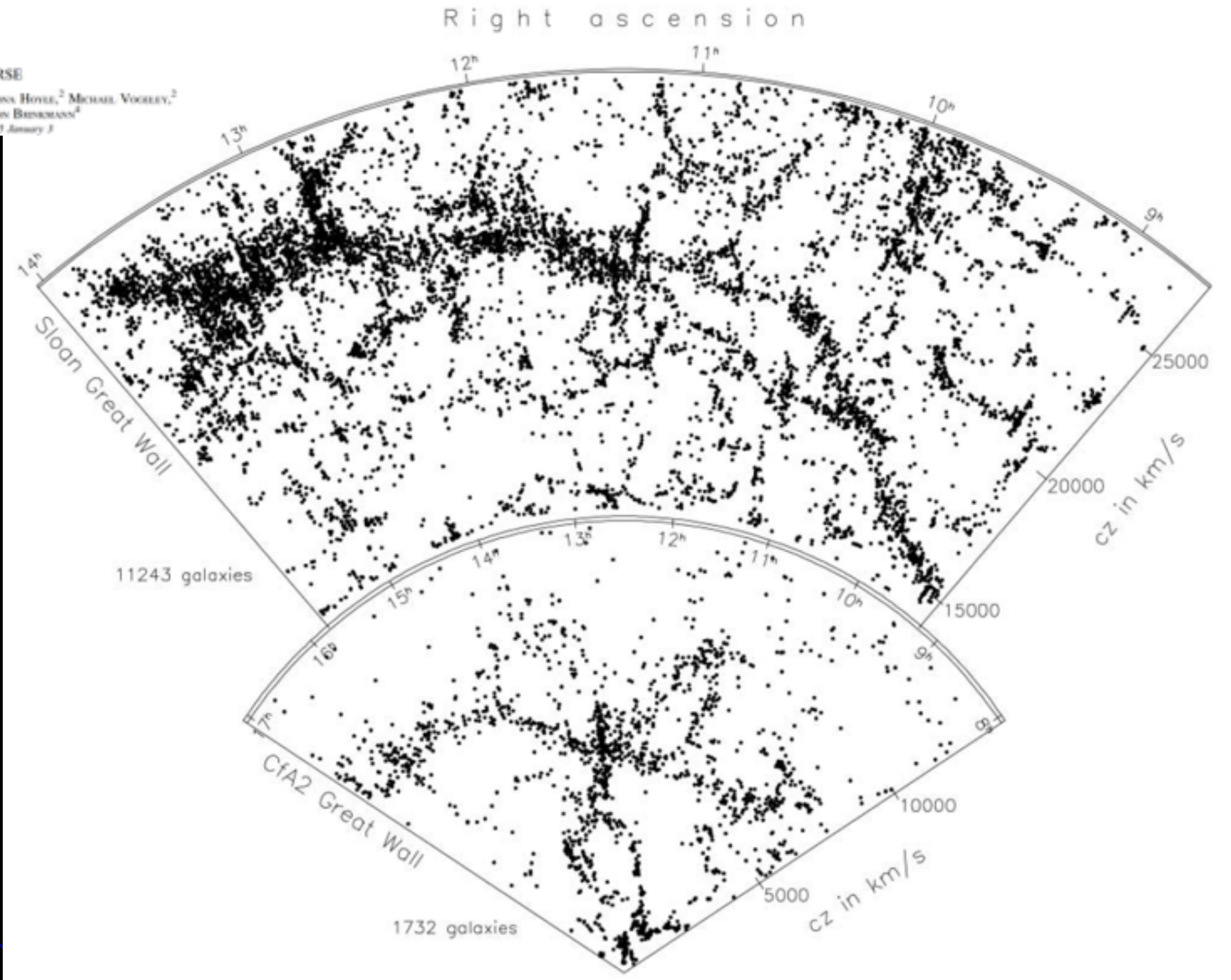
Fig. 4. Galaxies in the BGW superclusters in Cartesian coordinates. Different colors show the individual superclusters in the BGW system.

BOSS Great Wall (Lietzen+16)

The Astrophysical Journal, 624:463–484, 2005 May 10

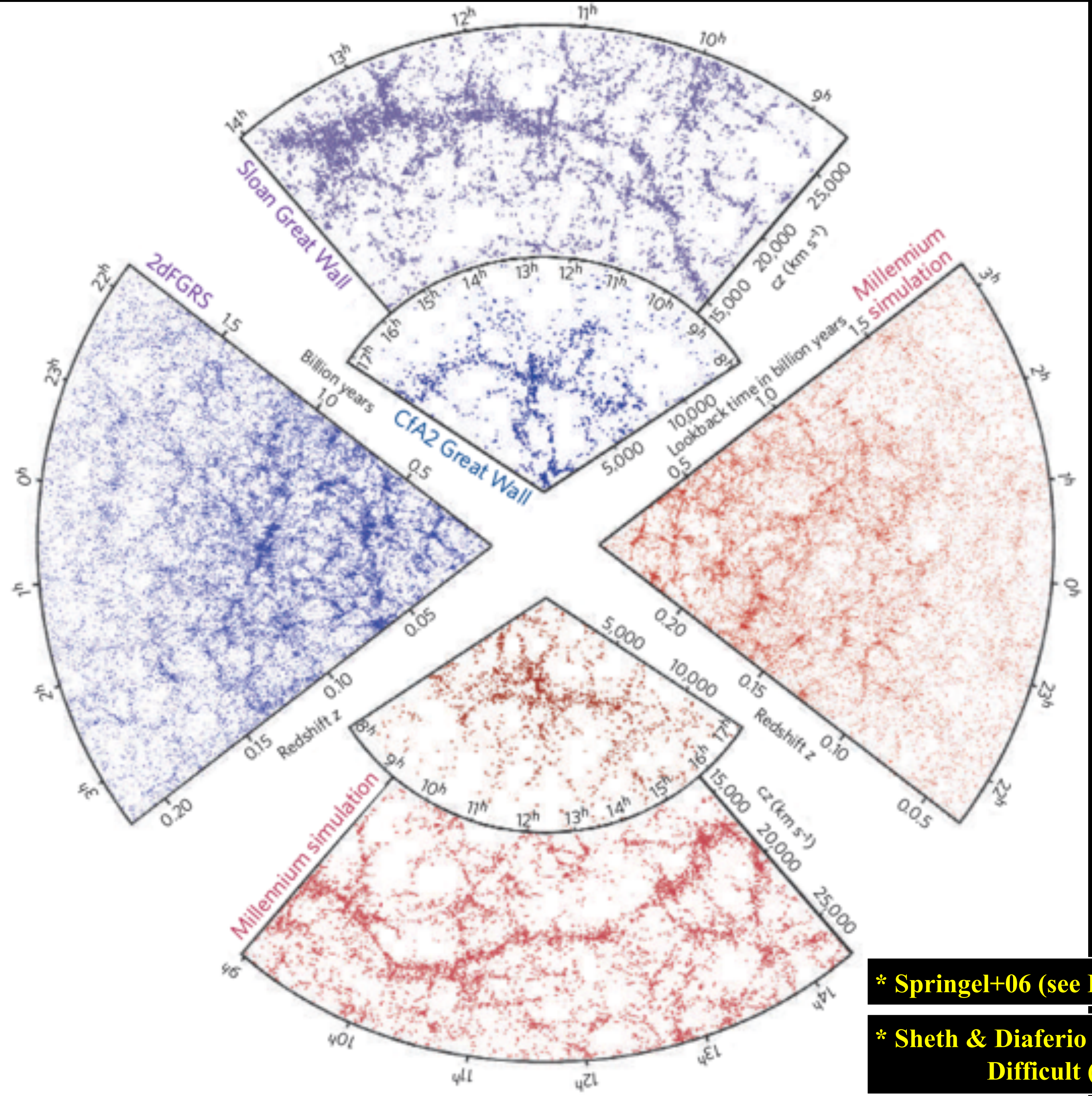
A MAP OF THE UNIVERSE

J. Richard Gott III,[1] Mario Jurić,[1] David Schlegel,[1] Fiona Hoyle,[2] Michael Vogeley,[2]
Max Tegmark,[3] Neta Bahcall,[1] and Jon Brinkmann[4]
Received 2003 November 18; accepted 2005 January 3



Q: Do we expect this kinds of largest-scale structures in our standard ΛCDM cosmology?
(~ physically meaningful structure?)

Largest Structures: Cosmological Tests

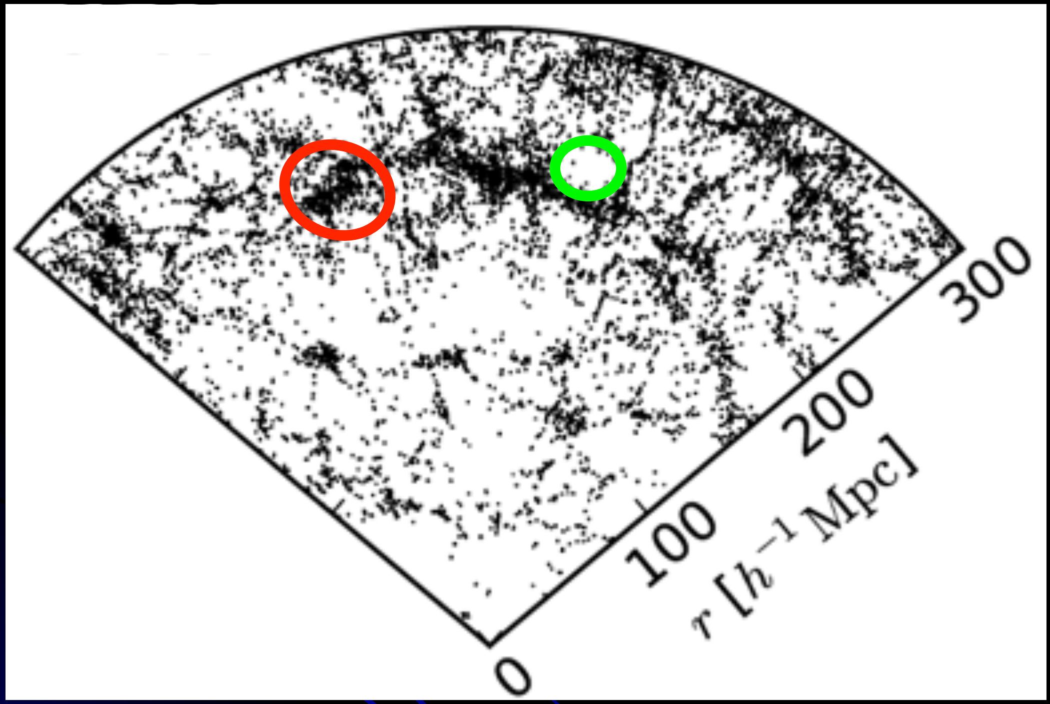


* Springel+06 (see Park+90;+12;+15): Ok.

* Sheth & Diaferio 11: The Sloan Great Wall is very unusual; Difficult (4 sigma) to reconcile with the ΛCDM model

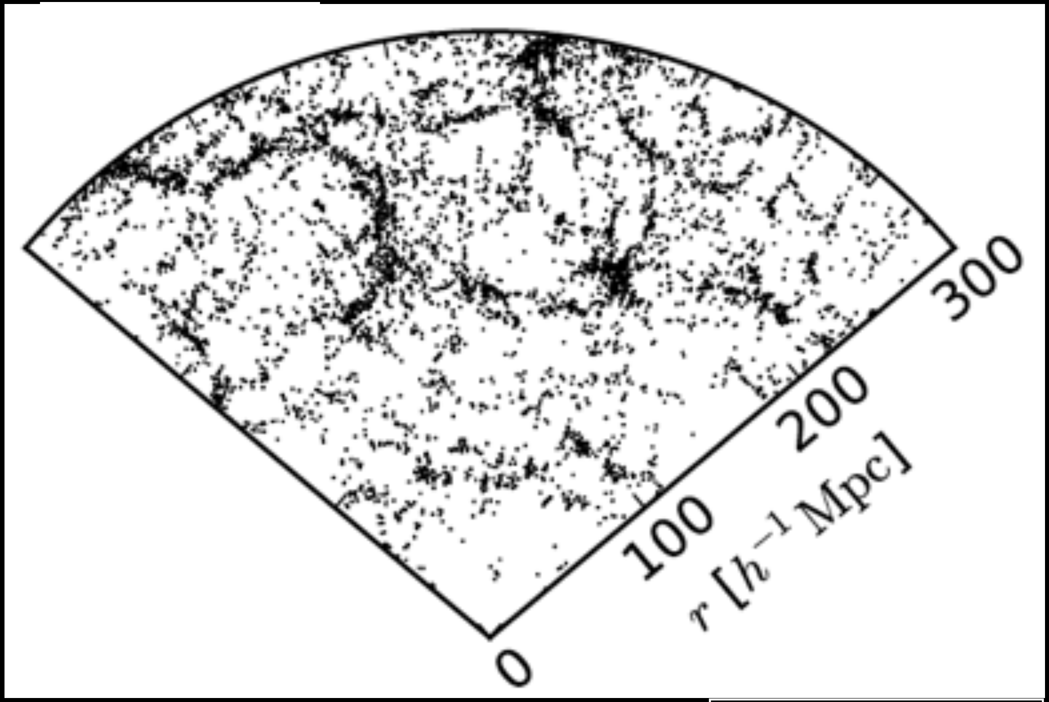
The Challenge of the Largest Structures in the Universe to Cosmology

Observation: Sloan Digital Sky Survey

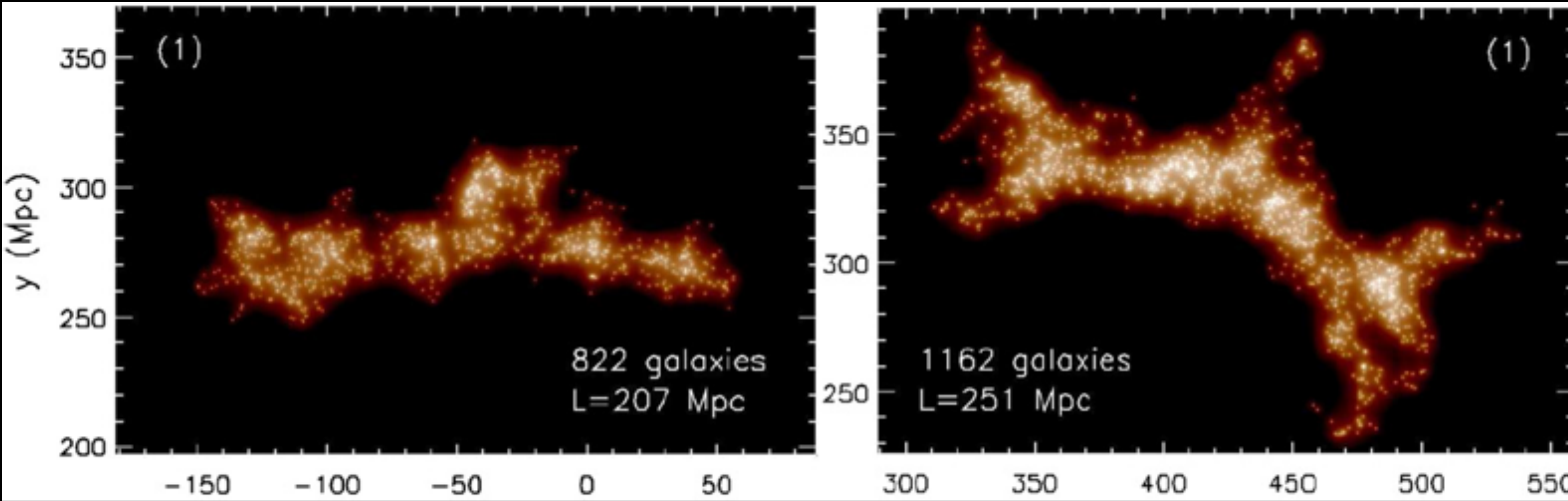


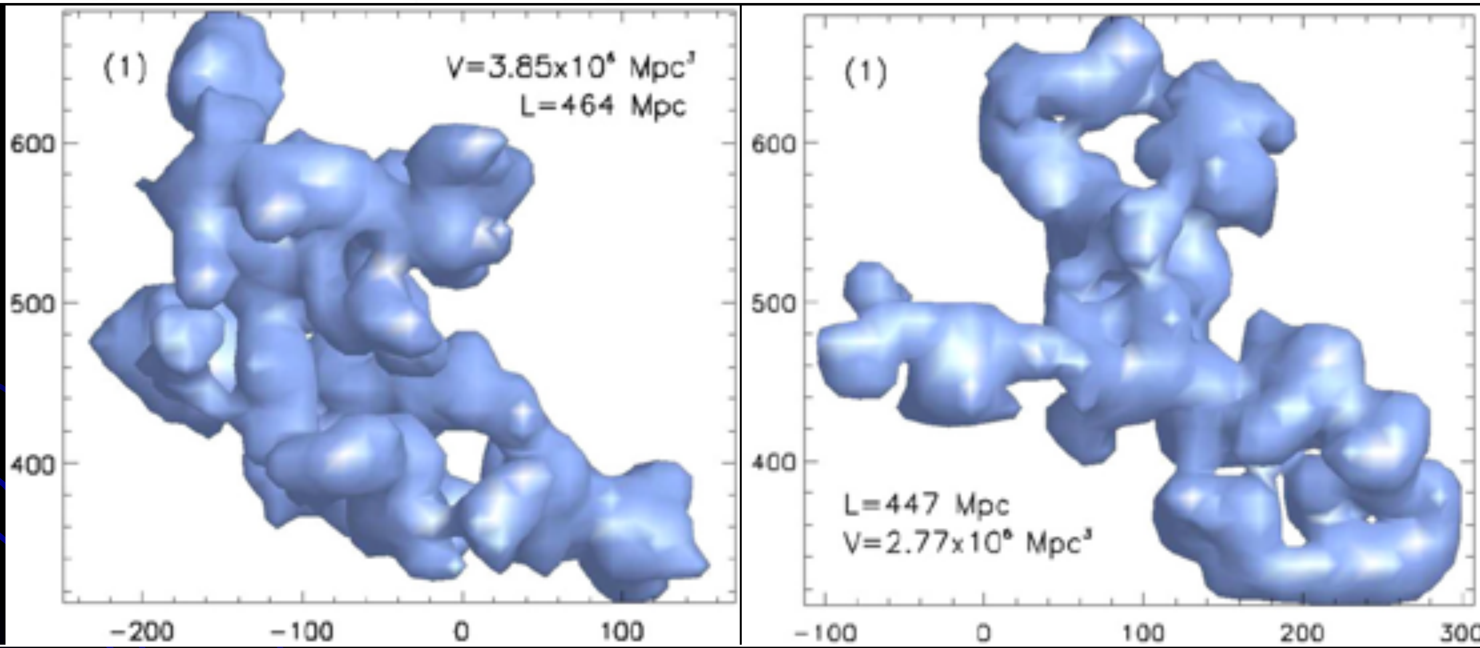
ΛCDM based
Simulation: Horizon Run 2

Kim+11



Park+12;Hong+15

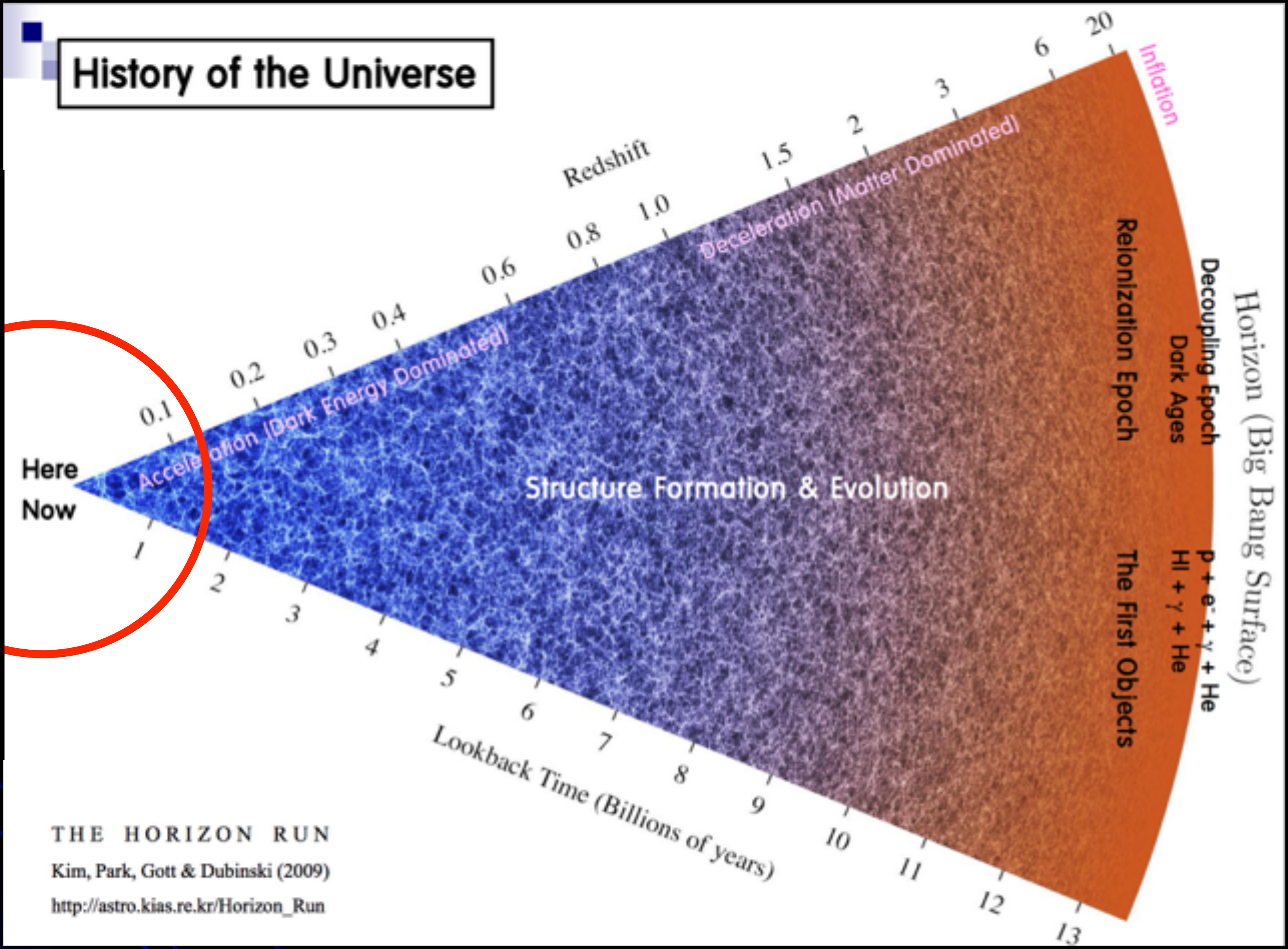




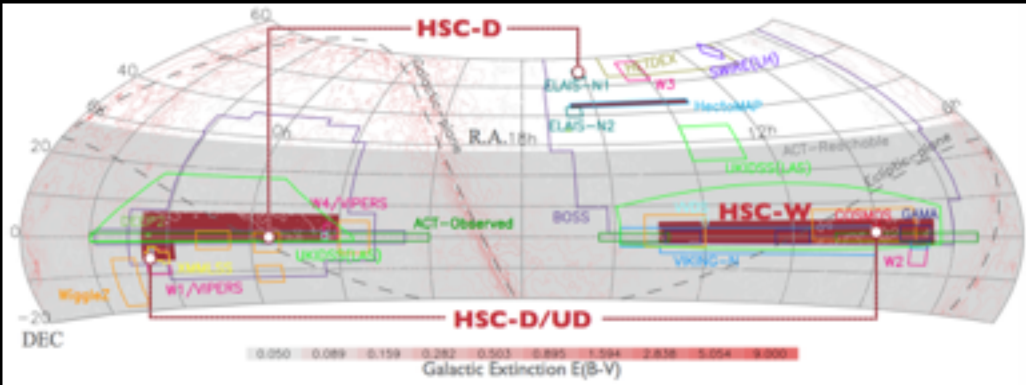
Park+12

Q: Do we expect this kinds of largest-scale structures in our standard ΛCDM cosmology?

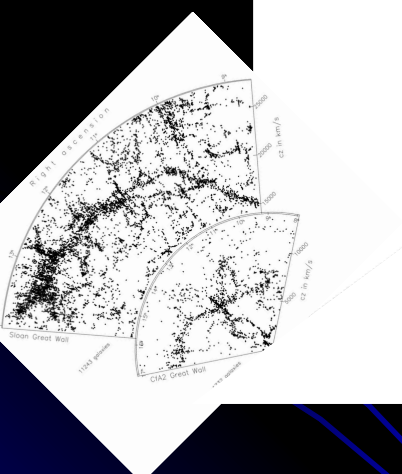
A: Yes, for nearby universe (~1.3 Gyrs ago, quantitative analysis in Park+12)



- **Only for nearby universe where structure formation is almost complete.**
- **To fully understand how structure forms in the universe, it is important to study the *evolution of large-scale structure*, sensitive to dark matter and dark energy.**



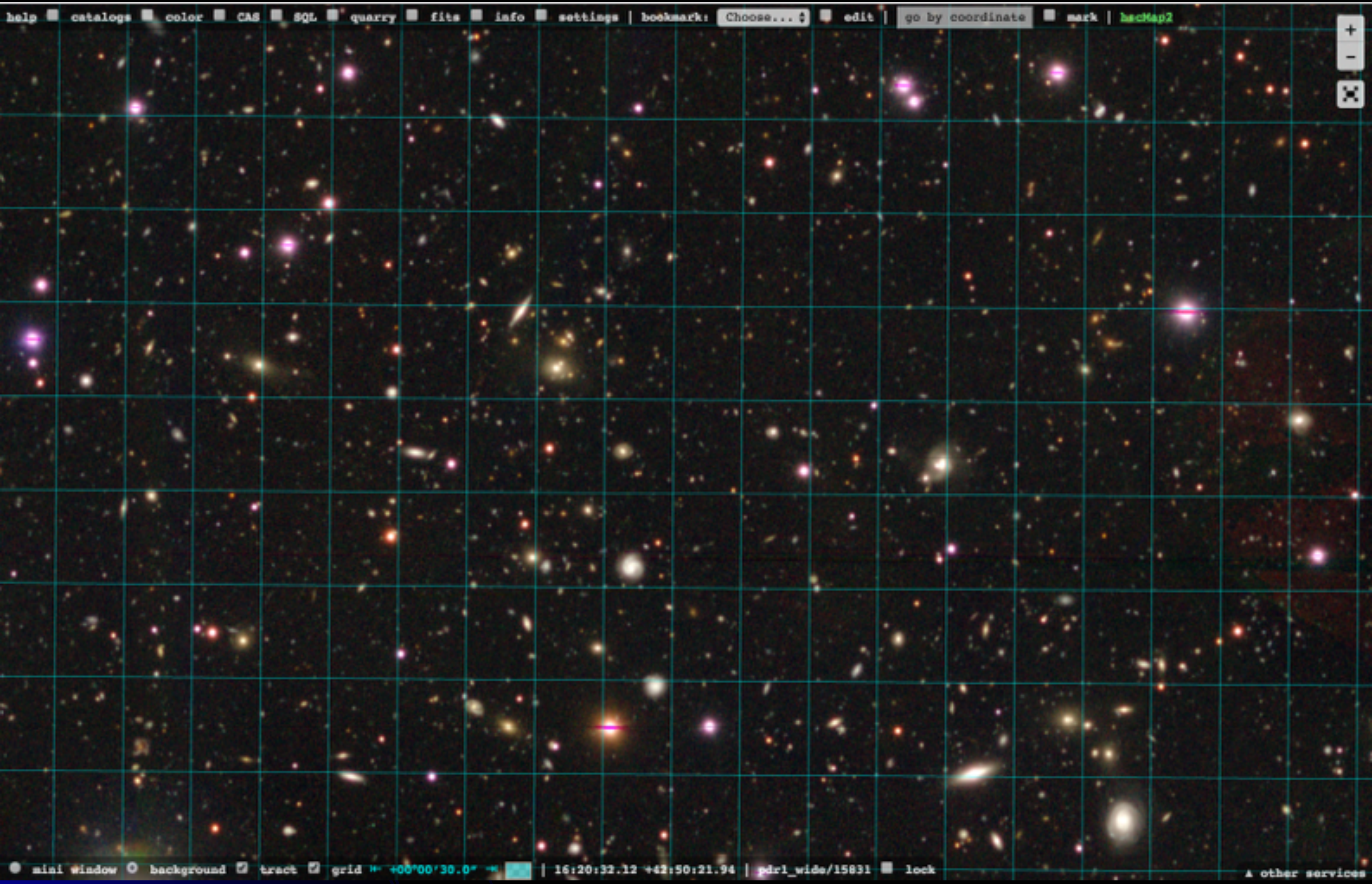
Subaru/HSC SSP



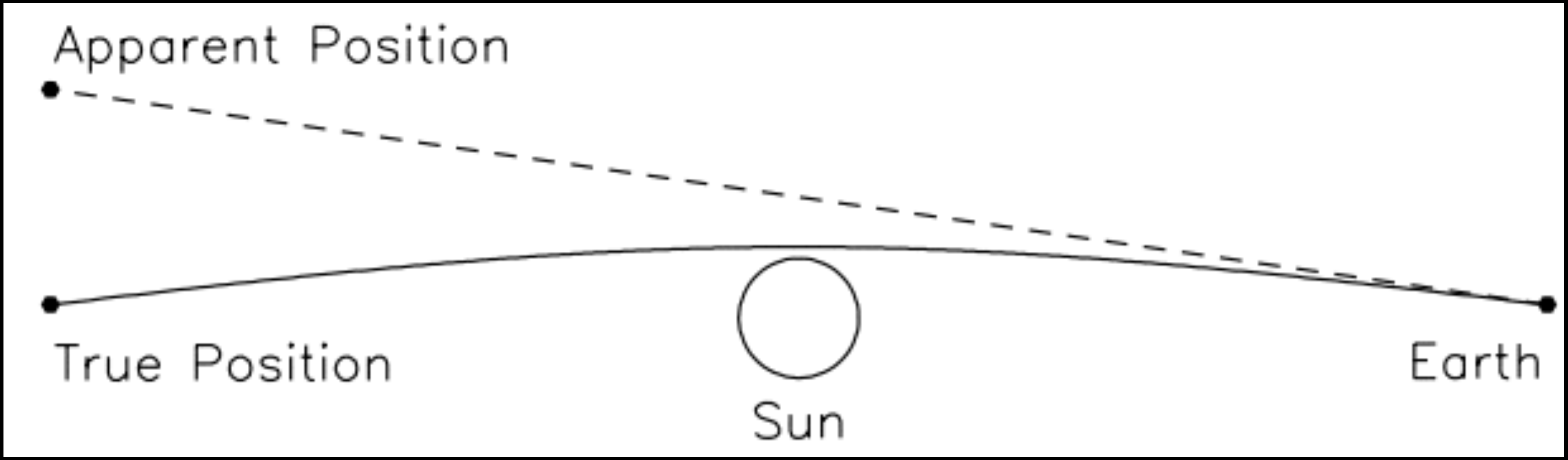
HectoMAP (Geller, Hwang, Sohn+)

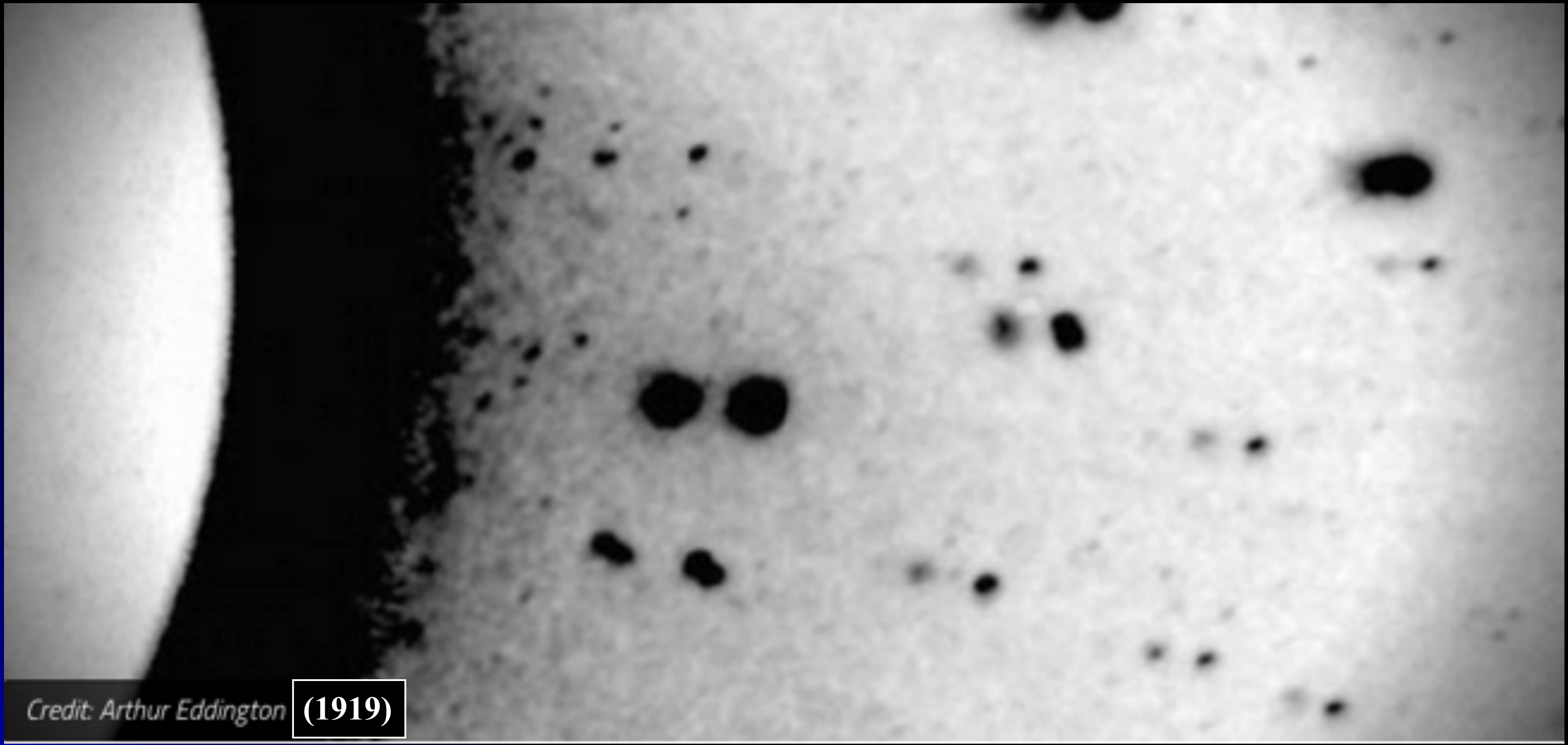
- HectoMAP (50 deg^2, Geller+11, Geller & Hwang 15, Hwang+16)
  - ~70,000 redshifts: One of densest and complete survey of red galaxies at r<21.3
  - HectoMAP: ~1250 gals/deg^2, SDSS/BOSS: ~150 gals/deg^2

Weak Lensing Analysis of Subaru/HSC images in the HectoMAP region



Gravitational Lensing

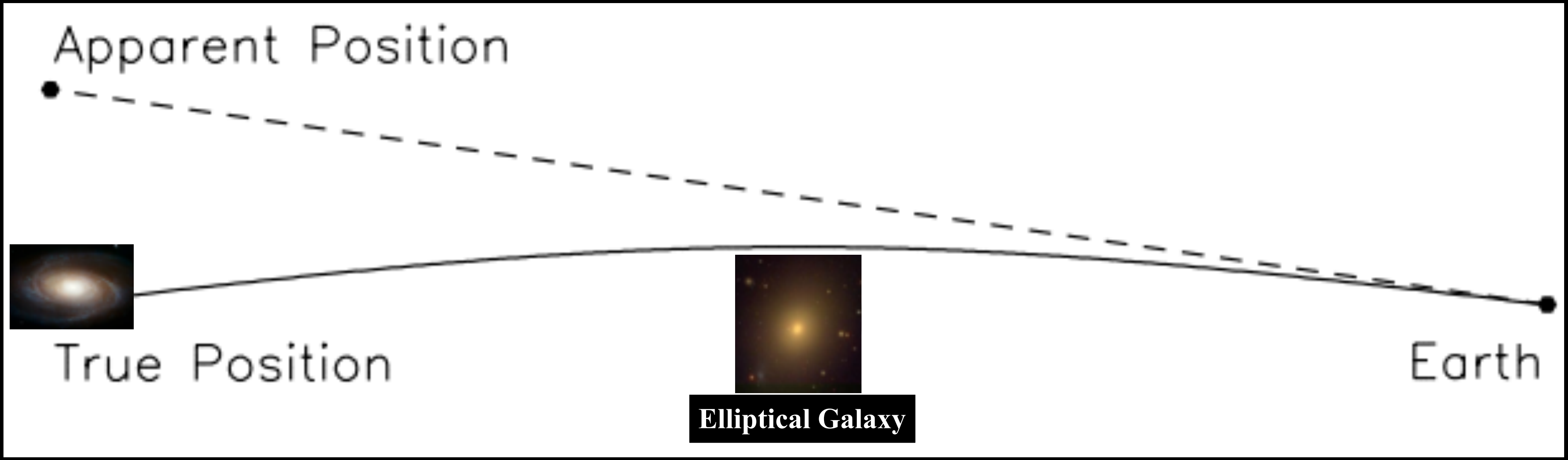


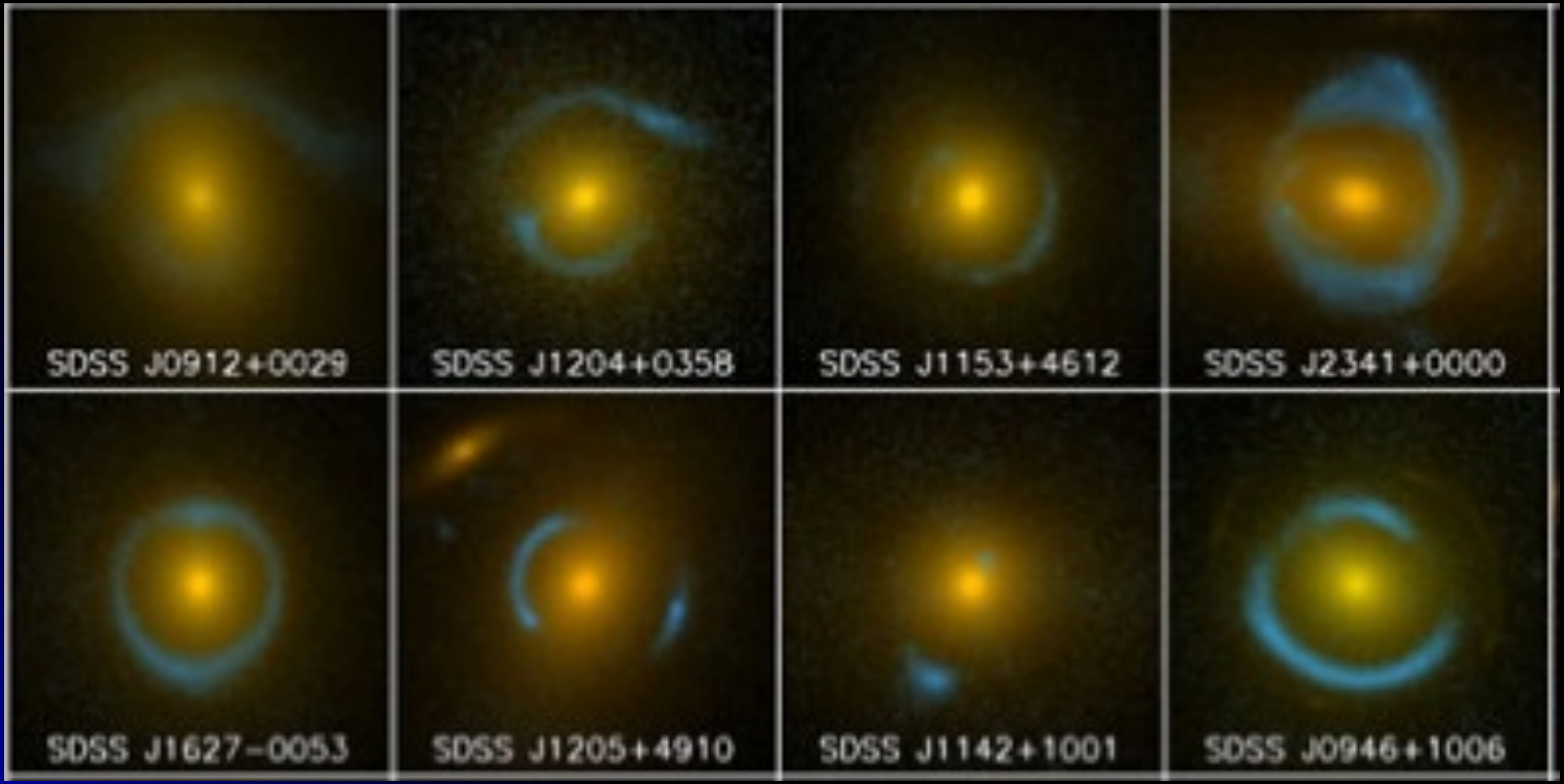


(1919)

Narayan & Bartelmann (2008)

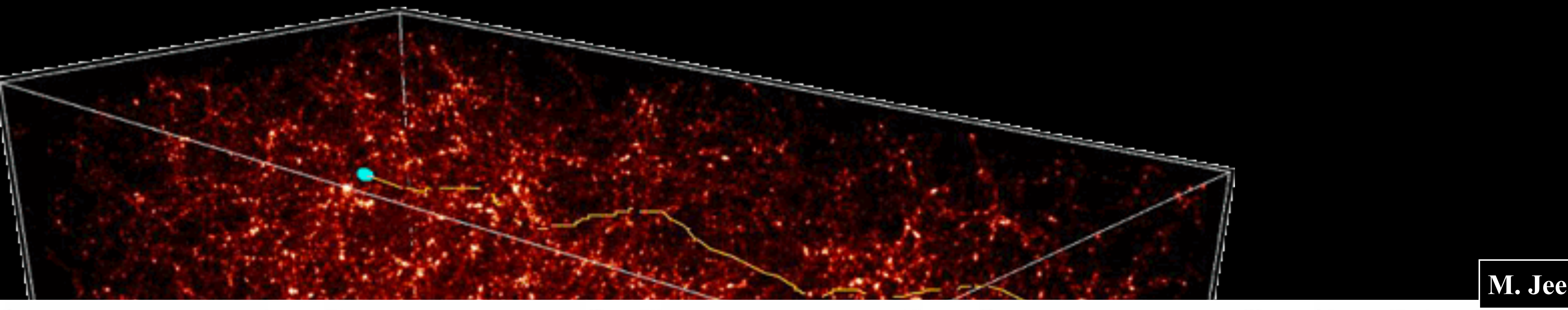
Gravitational Lensing

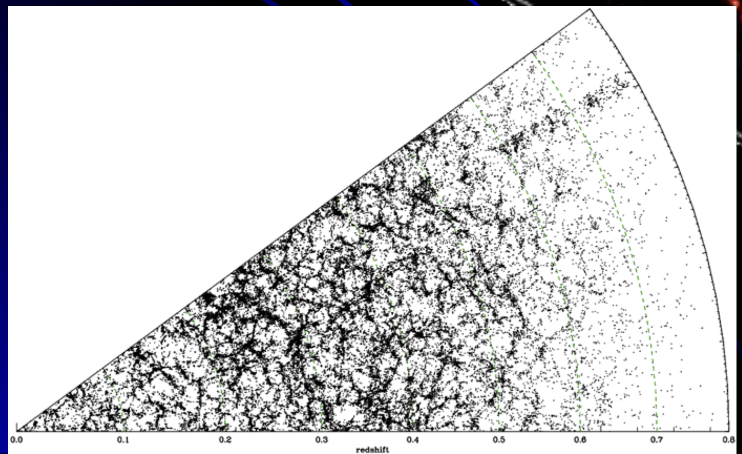


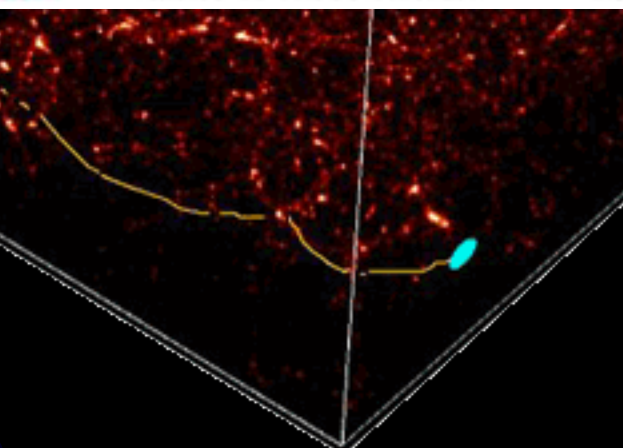


SLACS (Bolton+)

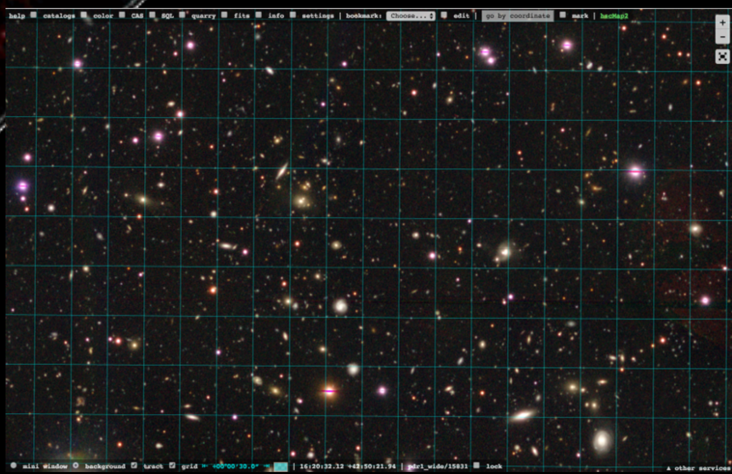
Gravitational Lensing => Dark Matter Distribution







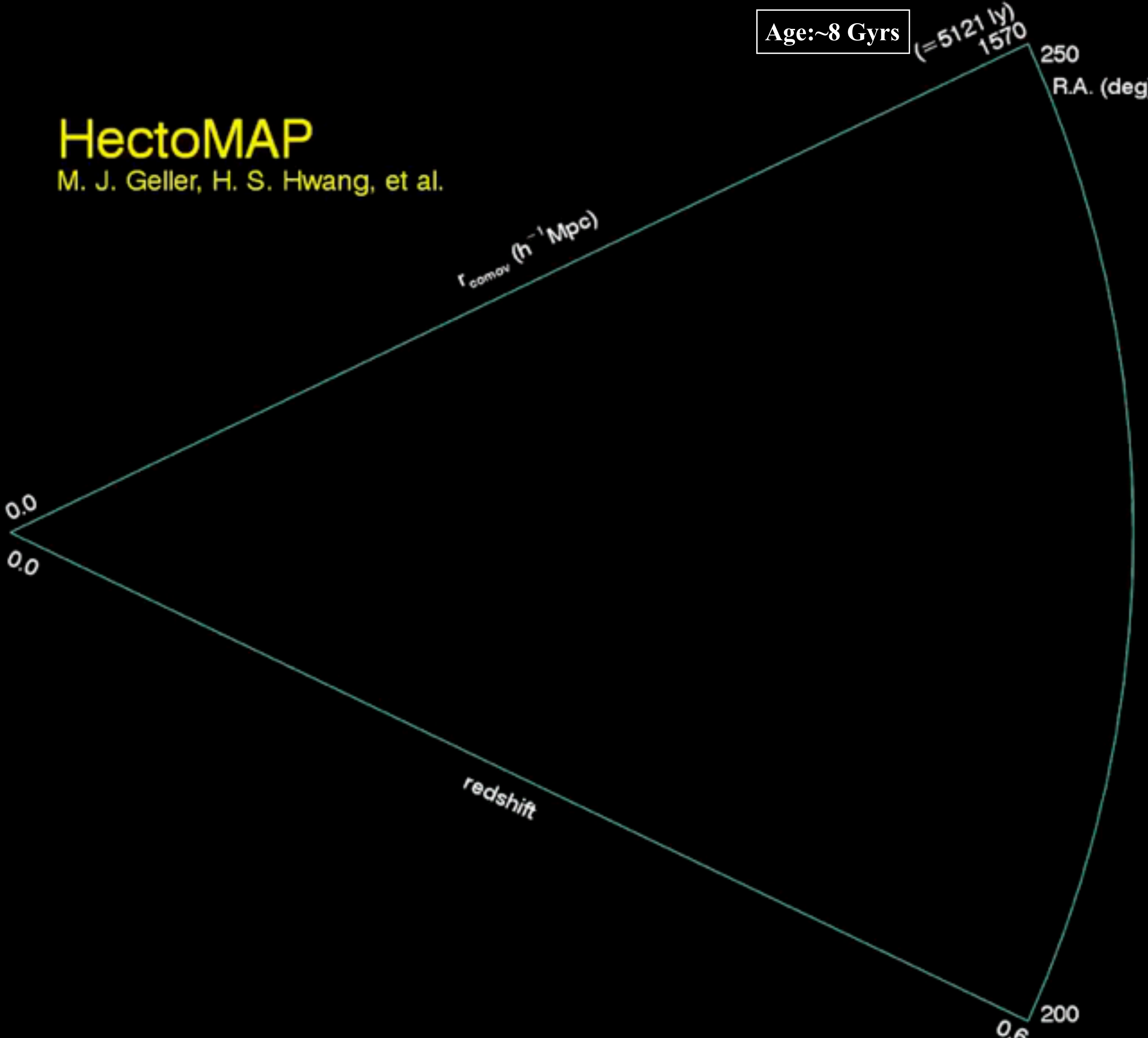
S. Colombi (IAP), CFHT team



Age:~8 Gyrs

HectoMAP

M. J. Geller, H. S. Hwang, et al.

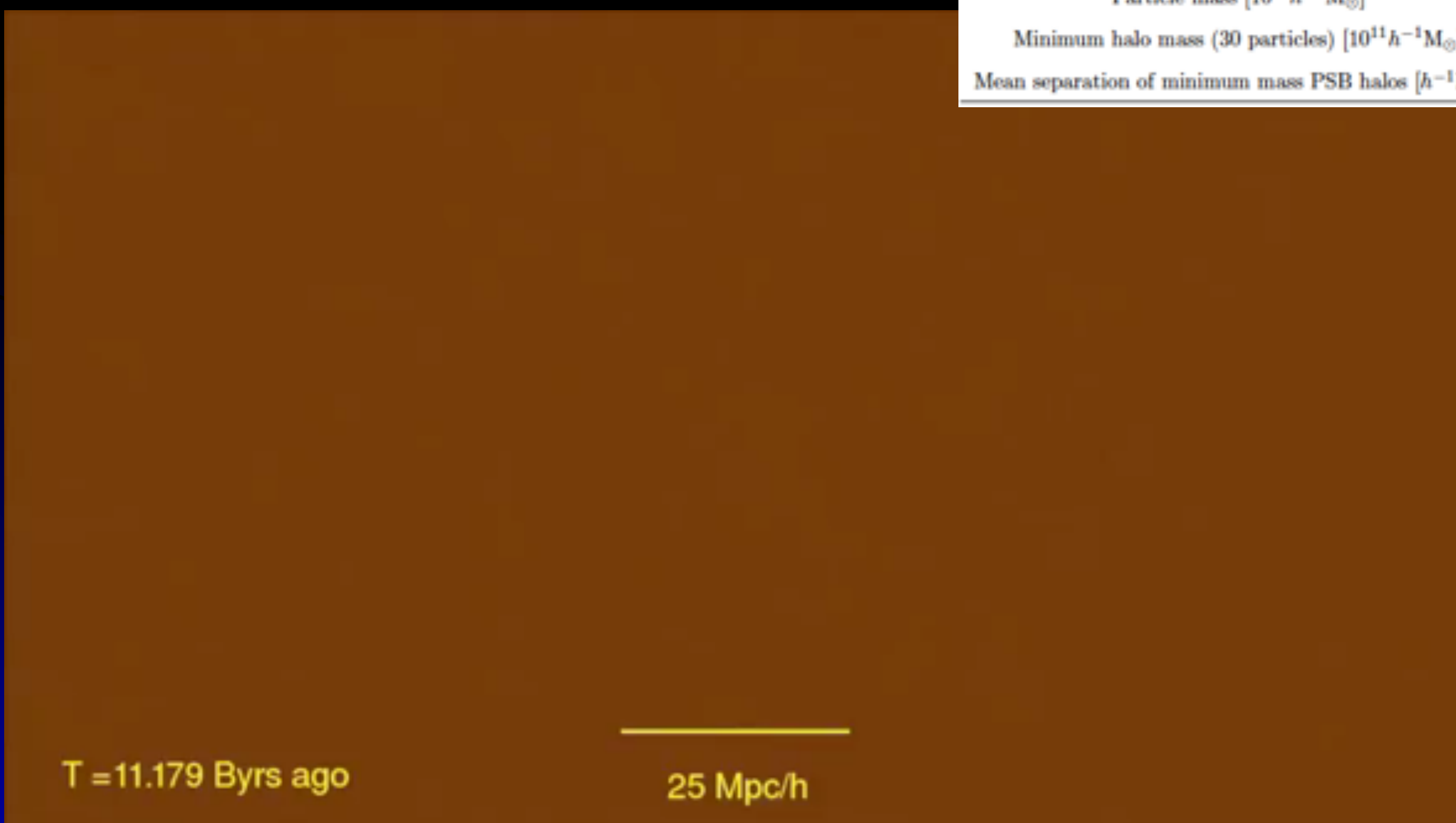


Horizon Runs @ KIAS

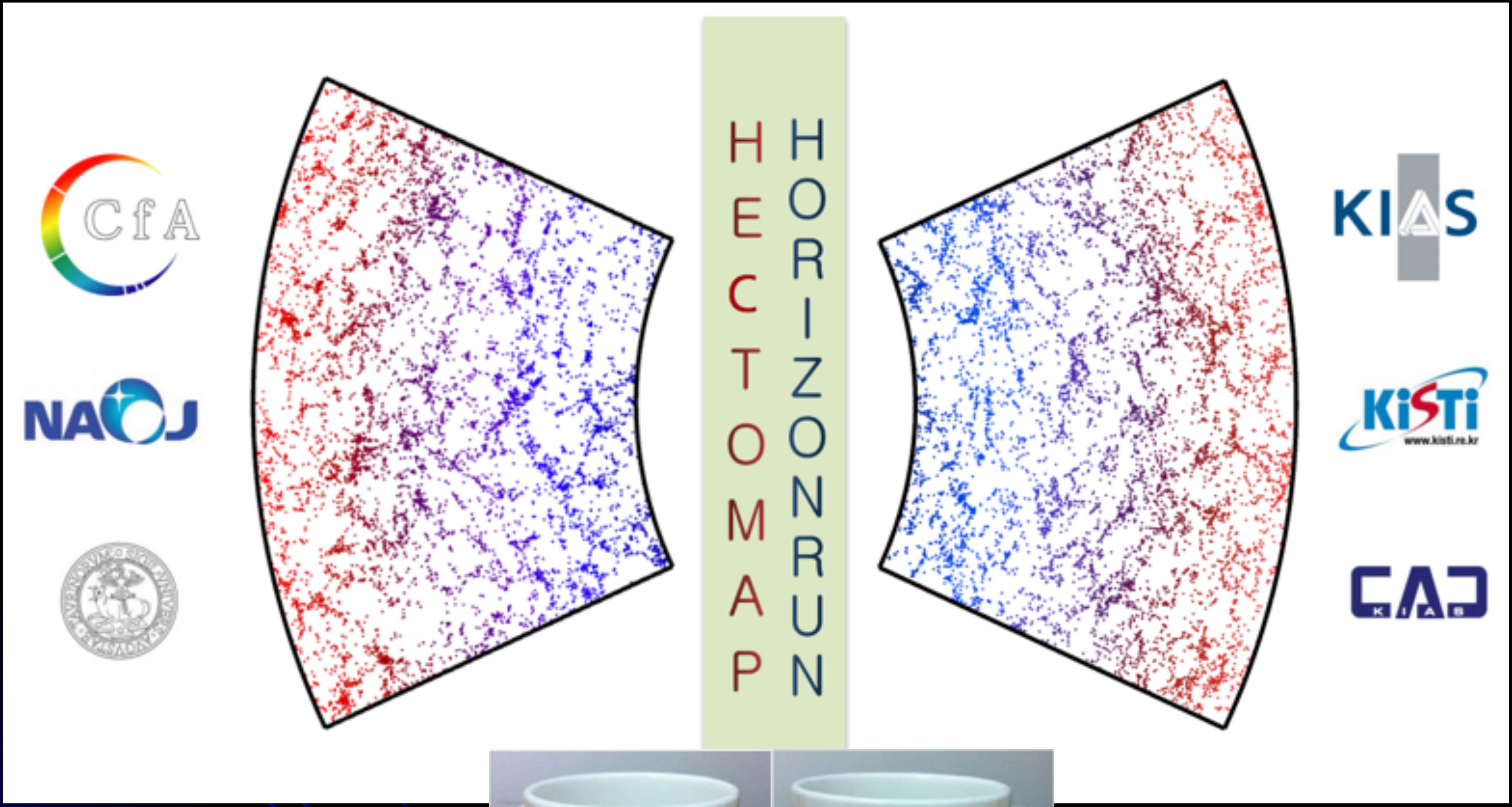
- One of densest and largest cosmological simulations

	HR1	HR2	HR3	HR4
Model	WMAP5	WMAP5	WMAP5	WMAP5
Ω_M	0.26	0.26	0.26	0.26
Ω_b	0.044	0.044	0.044	0.044
Ω_Λ	0.74	0.74	0.74	0.74
Spectral index	0.96	0.96	0.96	0.96
H_0 [100 km $s^{-1}Mpc^{-1}$]	72	72	72	72
σ_8	0.794	0.794	0.794	0.794
Box size [h^{-1}Mpc]	6592	7200	10815	3150
No. of grids for initial conditions	4120^3	6000^3	7210^3	6300^3
No. of CDM particles	4120^3	6000^3	7210^3	6300^3
Starting redshift	23	32	27	100
No. of global time steps	400	800	600	2000
Mean particle separation [h^{-1}Mpc]	1.6	1.2	1.5	0.5
Particle mass [$10^{11}h^{-1}M_\odot$]	2.96	1.25	2.44	0.0902
Minimum halo mass (30 particles) [$10^{11}h^{-1}M_\odot$]	88.8	37.5	73.2	2.706
Mean separation of minimum mass PSB halos [h^{-1}Mpc]	13.08	9.01	11.97	4.08

Kim J., Park C. +15



Large-scale Structures in the HectoMAP and Horizon Runs



HectoMAP: Science Goals

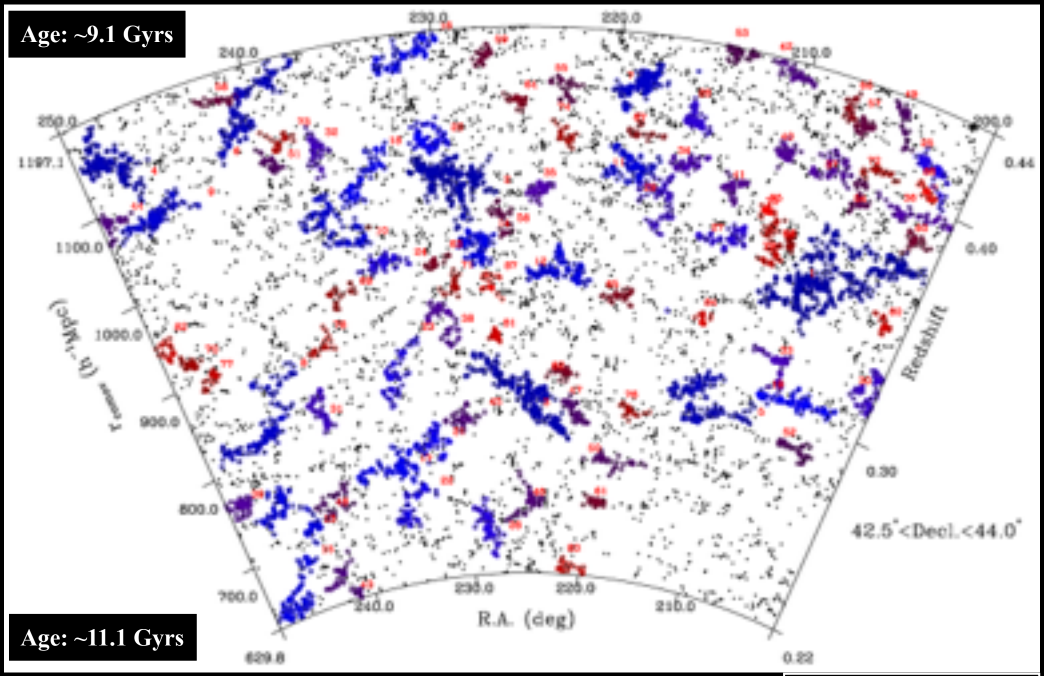
- ➢ Compare the mass distribution with that in weak lensing maps
- ➢ Directly measure the mass accretion rate of galaxy clusters
- ➢ Cosmological test with the largest structures

In this Talk,

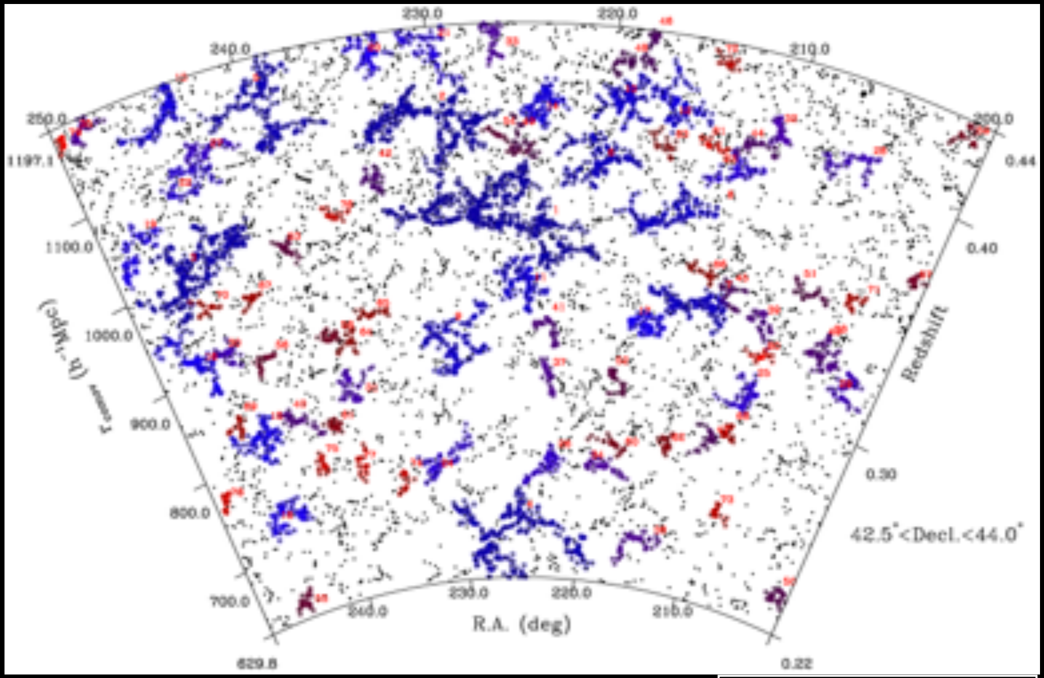
By applying the same criteria to the observations and simulations
to identify over- and under-dense large-scale features of the galaxy distribution,

- ➢ 1) Compare the Physical Properties of over- and under-dense large scale-structures in HectoMAP and Horizon Run 4, and
- ➢ 2) Examine the Probability to find observed largest structures in the simulation.

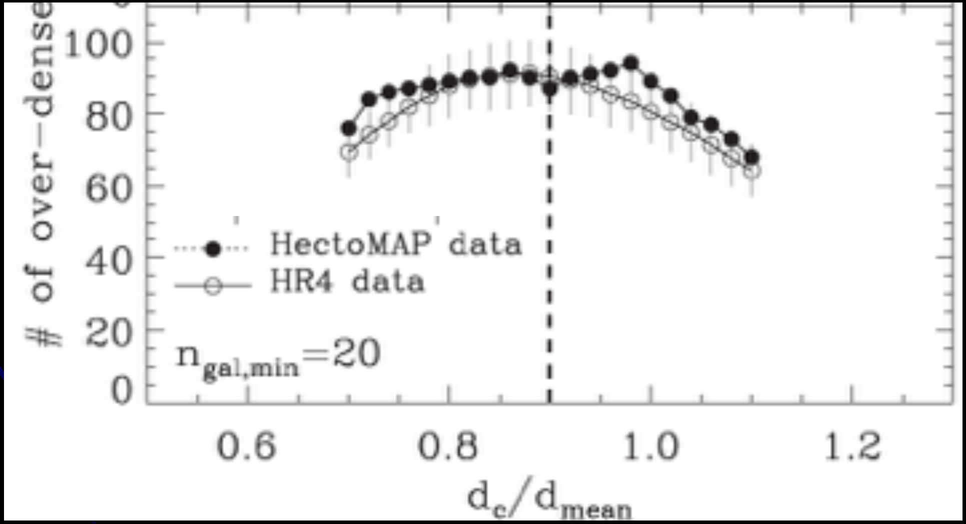
Identification of Over-dense Large-scale Structure



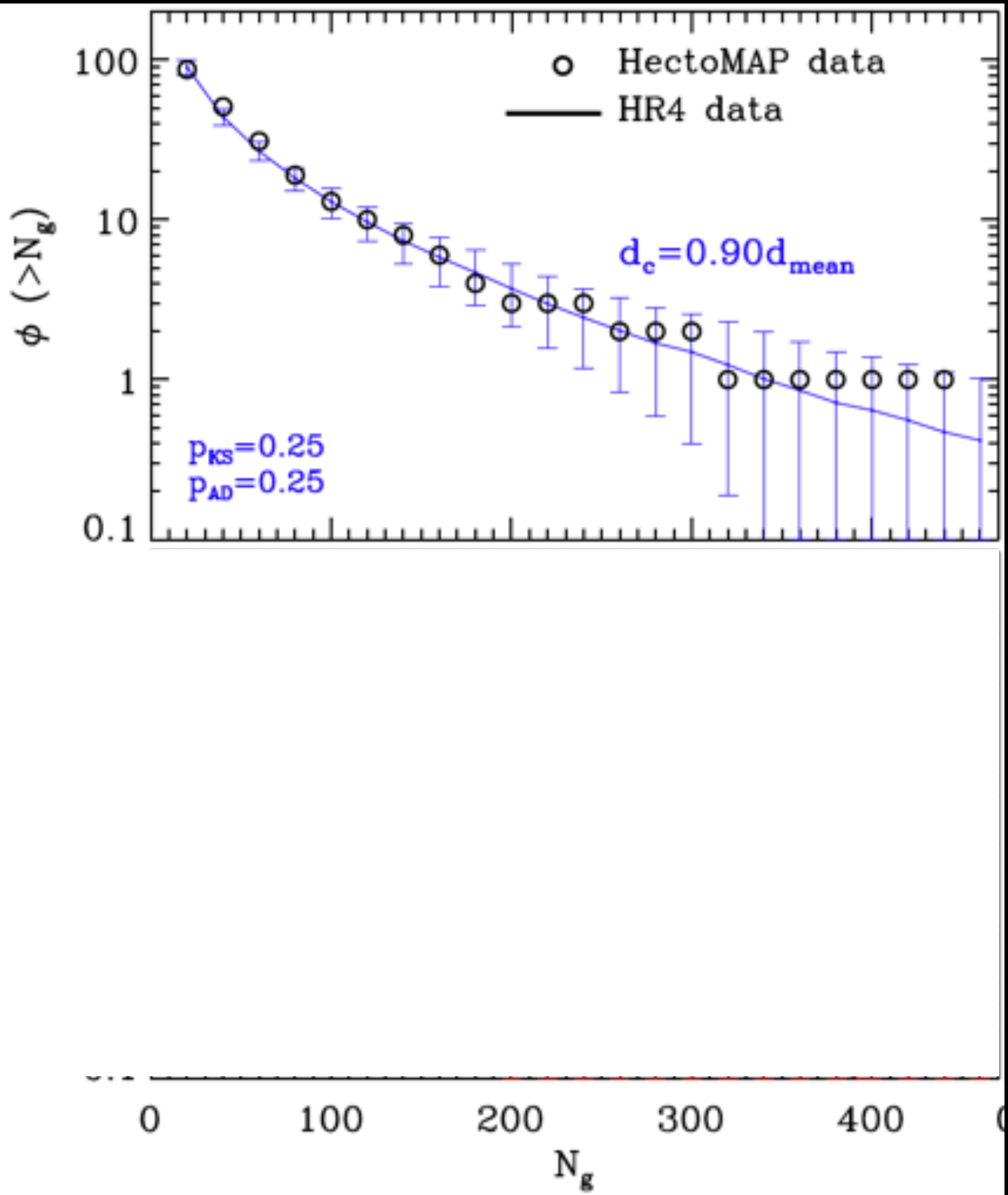
HectoMAP

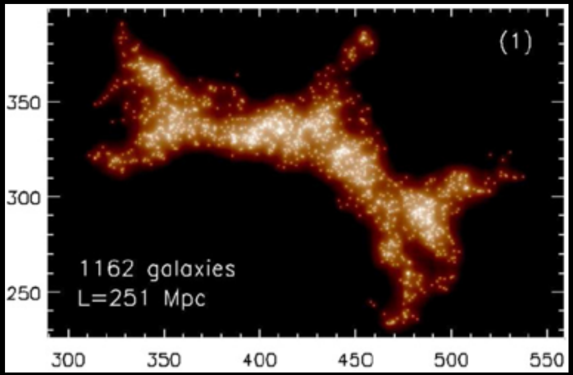


Horizon Run4

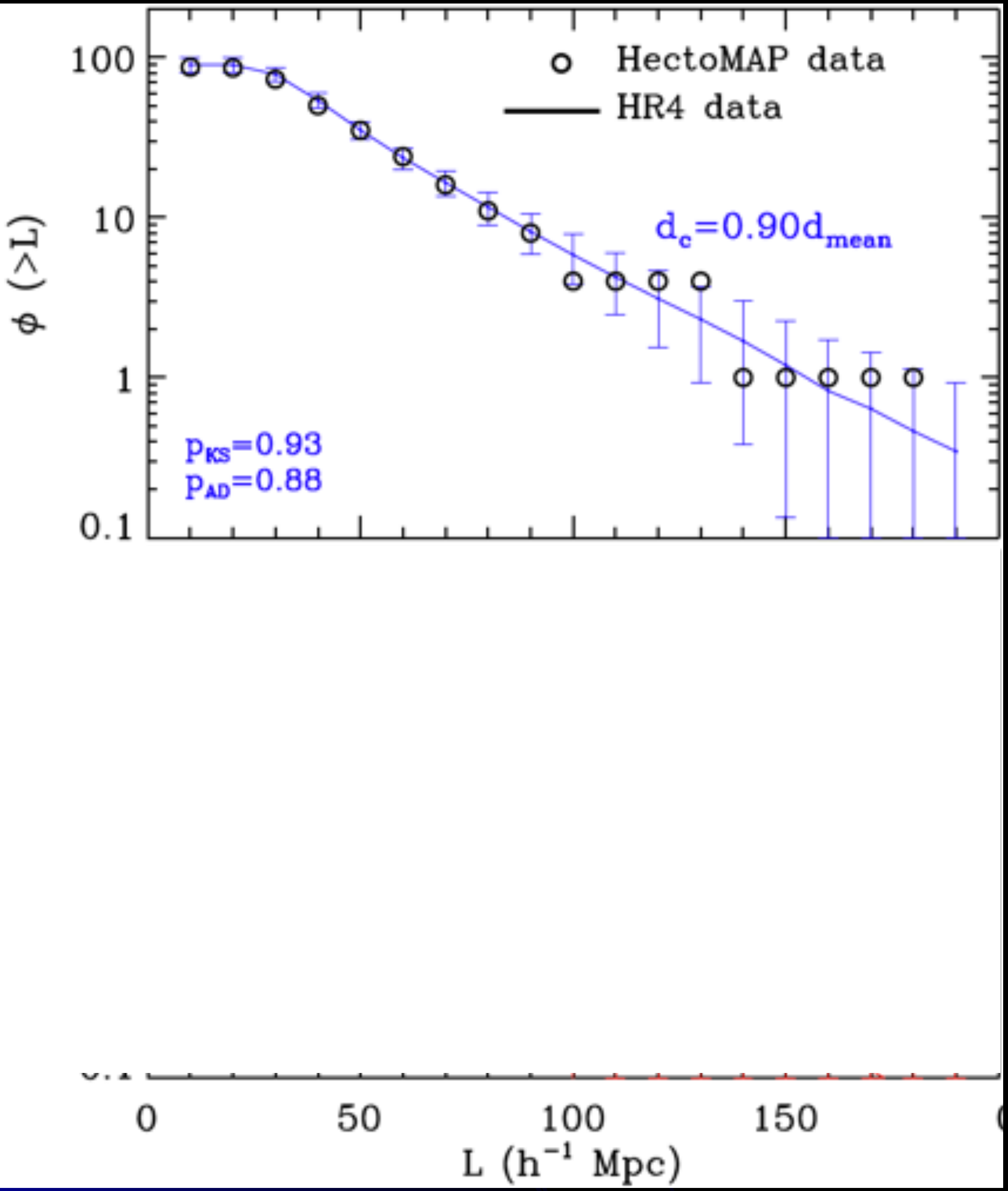


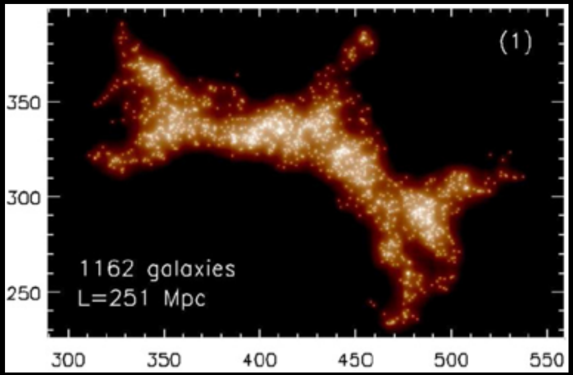
Richness Distribution of Over-dense LSS



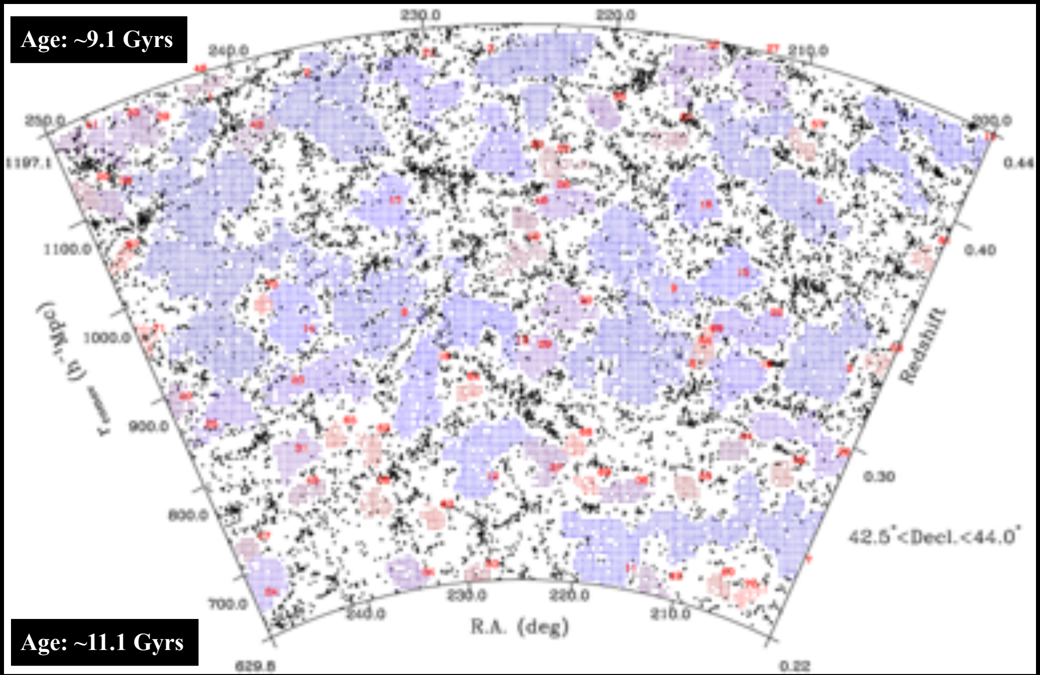


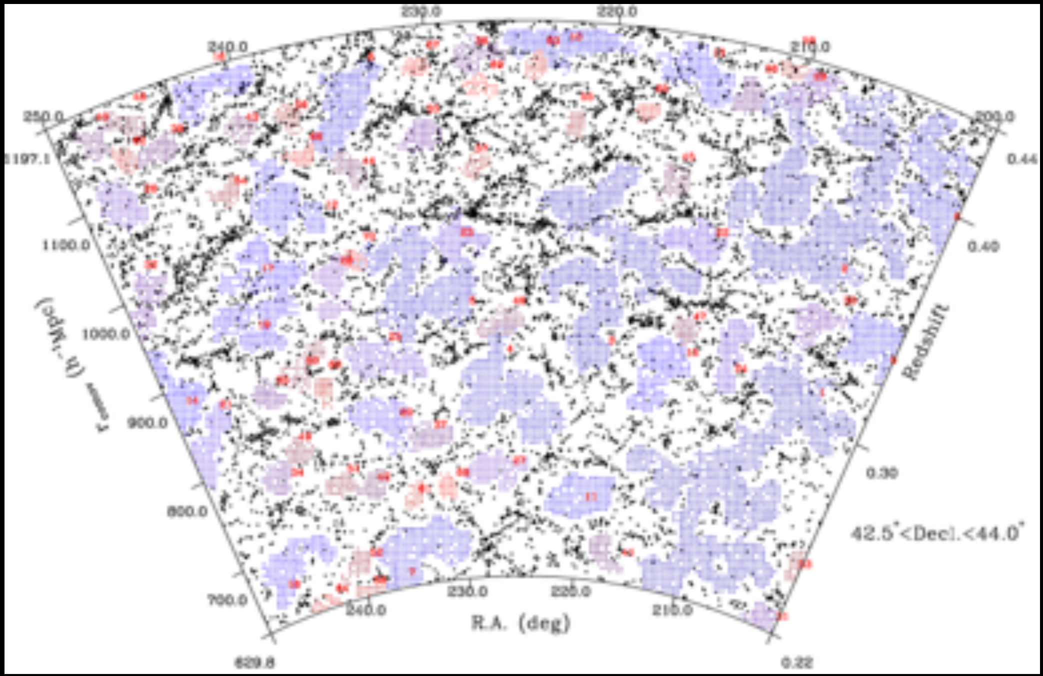
Size Distribution of Over-dense LSS





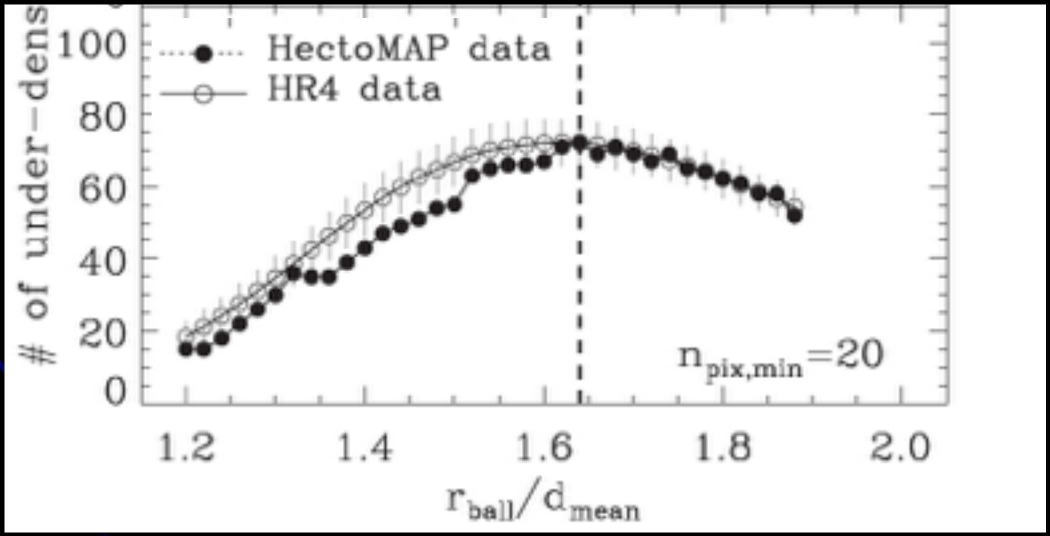
Identification of Under-dense LSS (Voids)



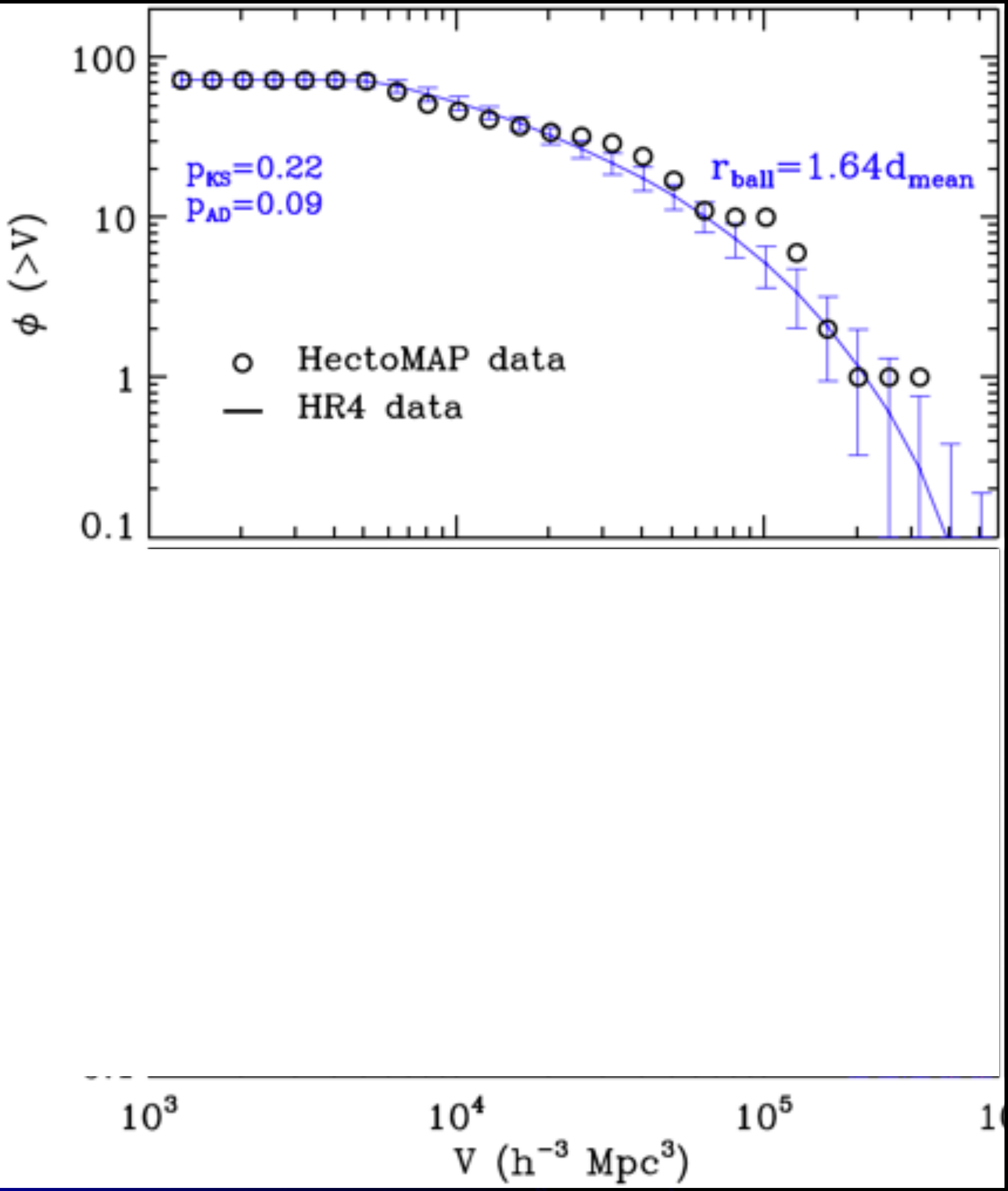


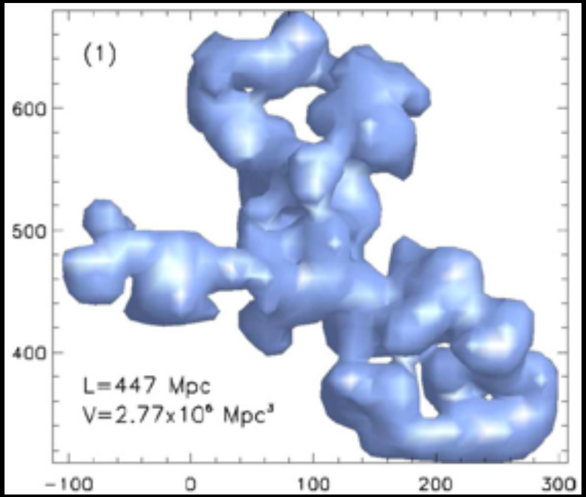
HectoMAP

Horizon Run4

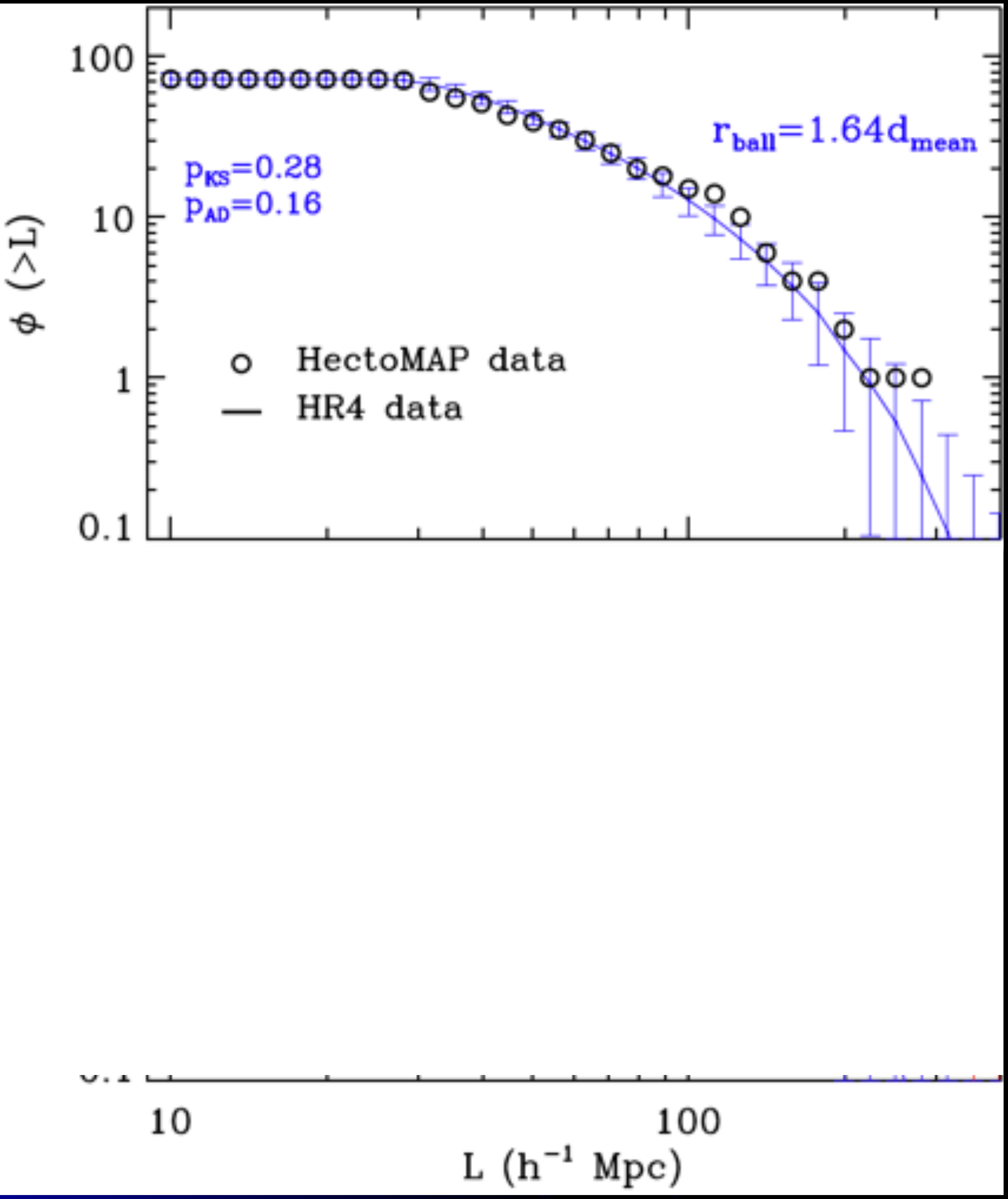


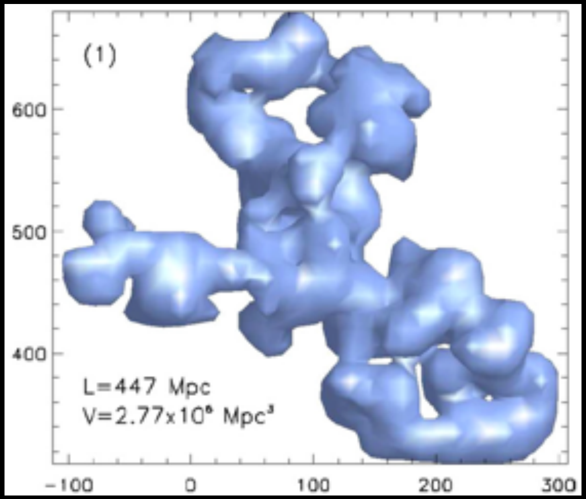
Volume Distribution of Voids





Size Distribution of Voids



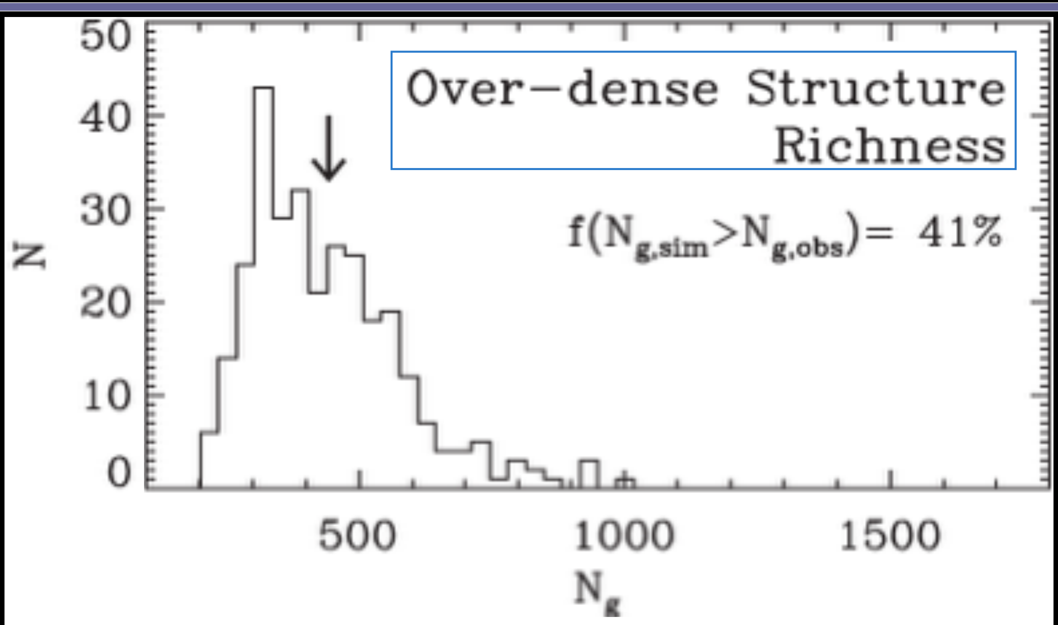


In this Talk,

➢ 1) Compare the Physical Properties of over- and under-dense large scale-structures in HectoMAP and Horizon Run 4, and

➢ The physical properties of observed large-scale structures at intermediate redshifts ($0.22<z<0.44$) are remarkably consistent with predictions of the standard ΛCDM model.

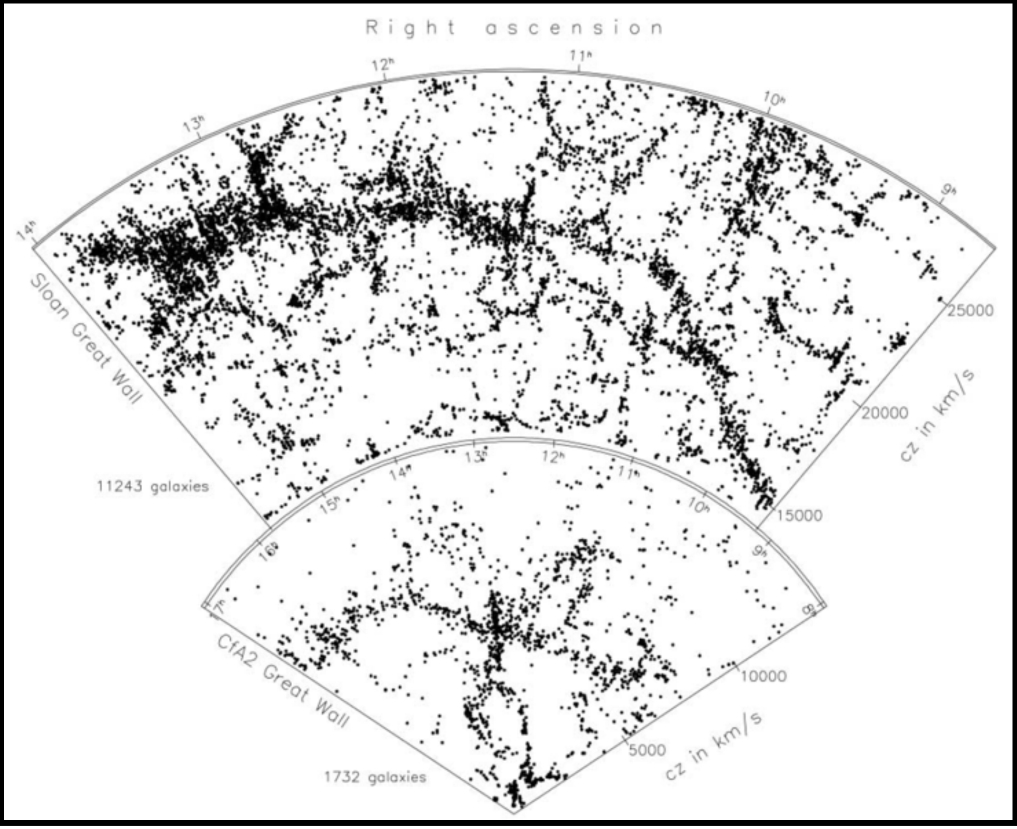
2) Largest Structures: HectoMAP vs. 300 Horizon Run 4 mock surveys



In this Talk,

- ➢ 2) Examine the Probability to find observed largest structures in the simulation.

- ➢ The properties of the largest over- and under-dense structures in HectoMAP are well within the distributions for the largest structures drawn from 300 Horizon Run 4 mock surveys.



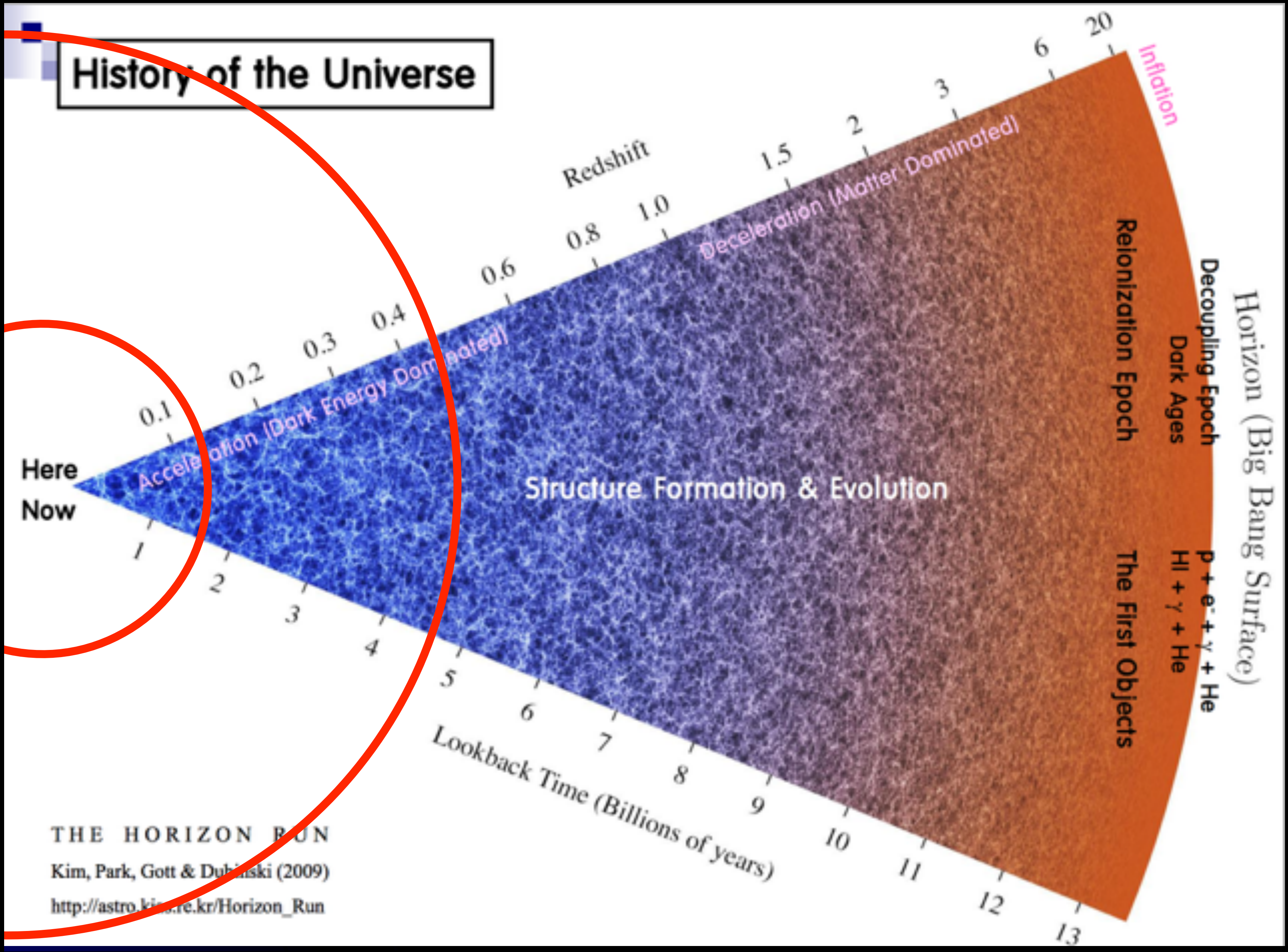
Gott+05

Q: Do we expect this kinds of largest-scale structures in our standard ΛCDM cosmology?

- **Yes, at 0.22<z<0.44. We would like to emphasize that**
  - **Many mock surveys for a robust test**
  - **The same criteria in identifying large-scale structures in the observations and simulations**
  - **Comparable samples of galaxies and halos with the matched number densities**

Summary I

- **Statistics for Largest-Scale Structure** (over- and under-density structures)
  - **ΛCDM model is still consistent with observations at 0.22<z<0.44 (~9-11 Gyrs old)**

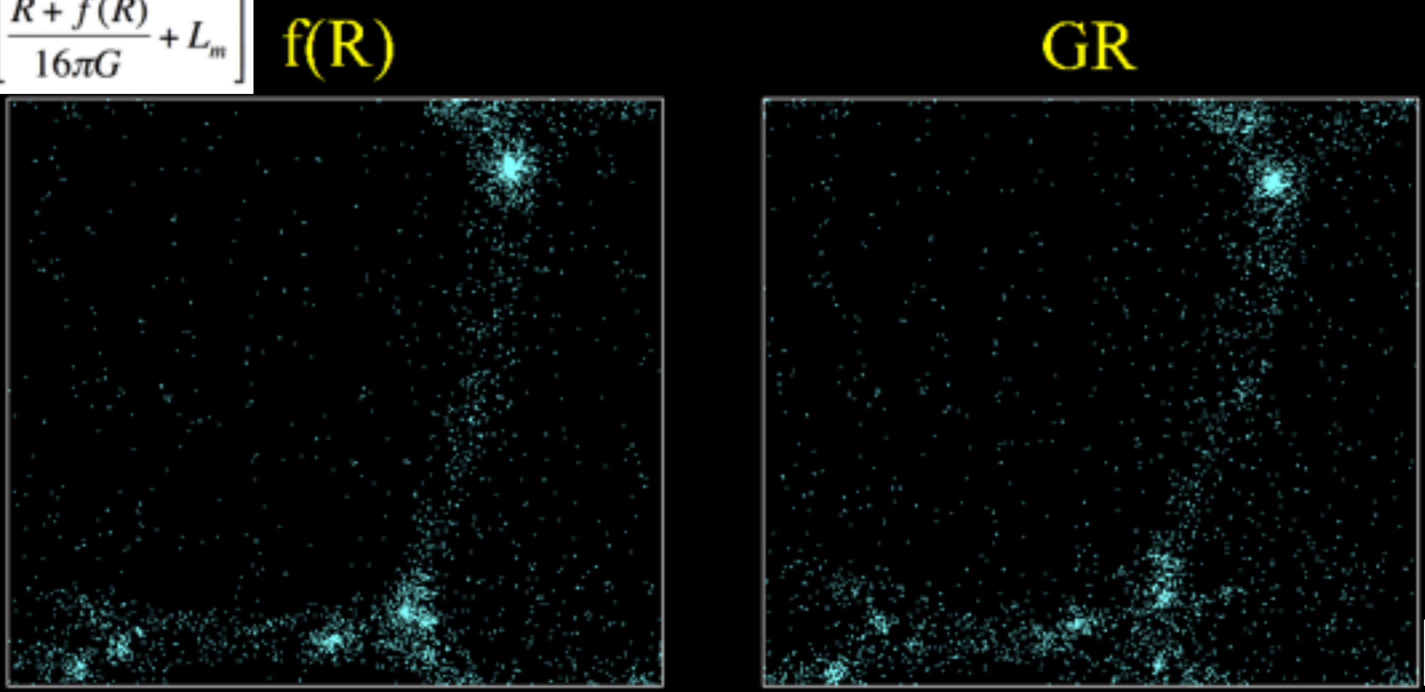


What's next?

- Scientific Issue?
  - Continue the cosmological test with large-scale structure
  - Focusing the **EVOLUTION** of large-scale structure: sensitive to **dark matter and dark energy**

- **Theory/Simulations**: using Modified Gravity models including f(R), dilaton, symmetron, general chameleon, DGP and Galileon

$$S = \int d^4x\sqrt{-g}\left[\frac{R+f(R)}{16\pi G}+L_m\right]$$



Gong-Bo Zhao

What's next?

- Scientific Issue?
  - Continue the cosmological test with large-scale structure
  - Focusing the **EVOLUTION** of large-scale structure: sensitive to **dark matter and dark energy**

- **Observations**: Current/Planned Wide-Field Spectroscopic Galaxy Surveys
  - SDSS eBOSS (2.5m, 2014 - 2020)
  - Taipan (1.2m, 2017-2020)
  - HETDEX (9.2m, 2017-)
  - DESI (4m) (2018-2022)
  - Subaru PFS SSP (8m, 2019-)
  - 4MOST (VISTA 4m, 2022-)
  - Euclid (1.3m in space, 2022-)
  - WFIRST (2.4m in space, mid-2020s)?
  - GMT (25m)?

Summary II

Cosmology → Structure Formation

Structure Formation:
- Large-scale Structure
- Galaxy

Test of Standard Model
* Large-Scale Structure
* Cosmic Microwave Background
* Type Ia Supernovae
* Weak Lensing

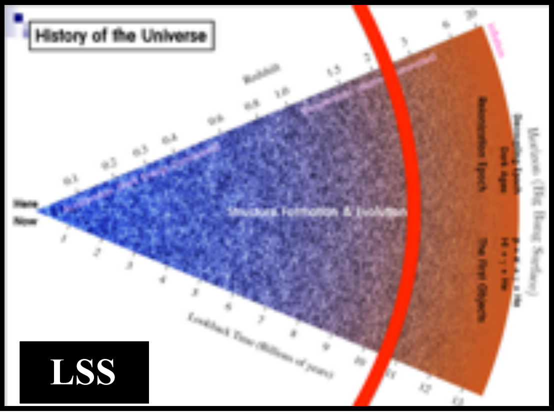
* Cosmological Simulations

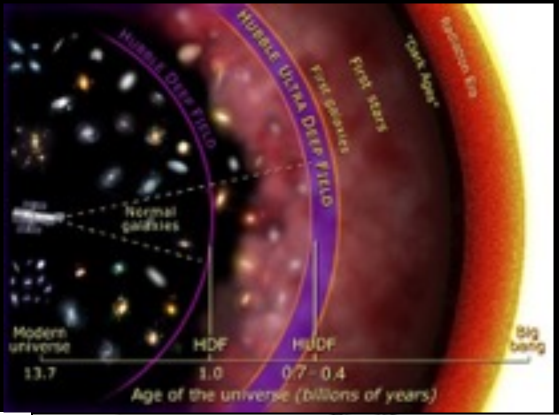
Strong Constraints on the model of structure growth
<= Effects of Dark Matter/Energy

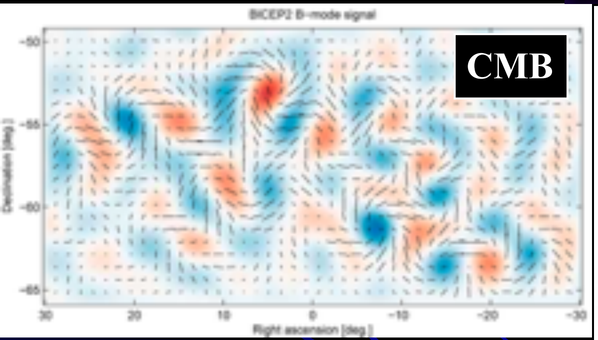
Concluding Remarks

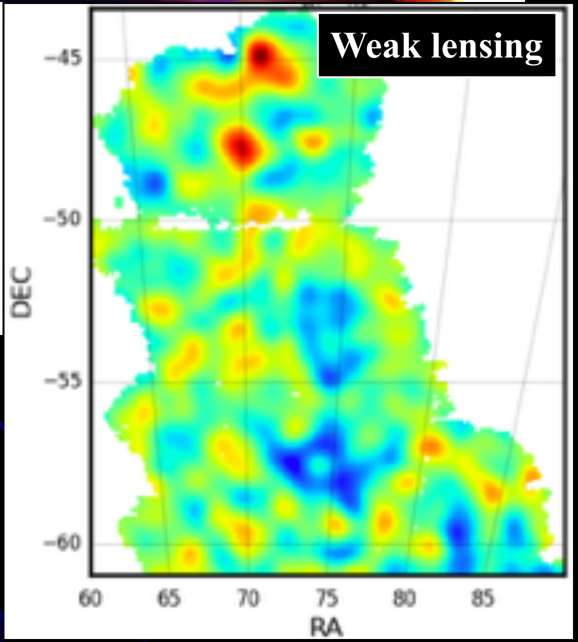
Cosmology and Structure Formation

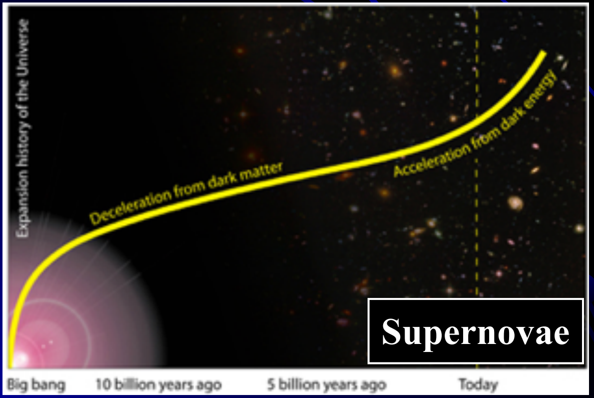
Observation ⟷ **Theory**











Nature of dark matter and dark energy?

New Physics instead of dark matter and dark energy?

Better Simulations including baryon physics

Goal: Keep Expanding our Horizons to better understand Cosmology & Structure Formation

Thank you!