2017年大学院後期授業

宇宙論特論

暗黒物質優勢宇宙における構造形成

樽家篤史
Atsushi Taruya

（京都大学 基礎物理学研究所）
(Kyoto Univ. Yukawa Institute for Theoretical Physics)

Overview

Large-scale structure

Spatial matter inhomogeneities over Mpc ~10^3 Mpc

Mpc=10^6 parsec ~3・10^6 light years
(c.f., 40kpc for size of Milky Way)

- Hierarchical clustering of matter distribution:

  galaxy ⊂ group / cluster ⊂ supercluster

- Contain rich cosmological information

  primordial fluctuations,

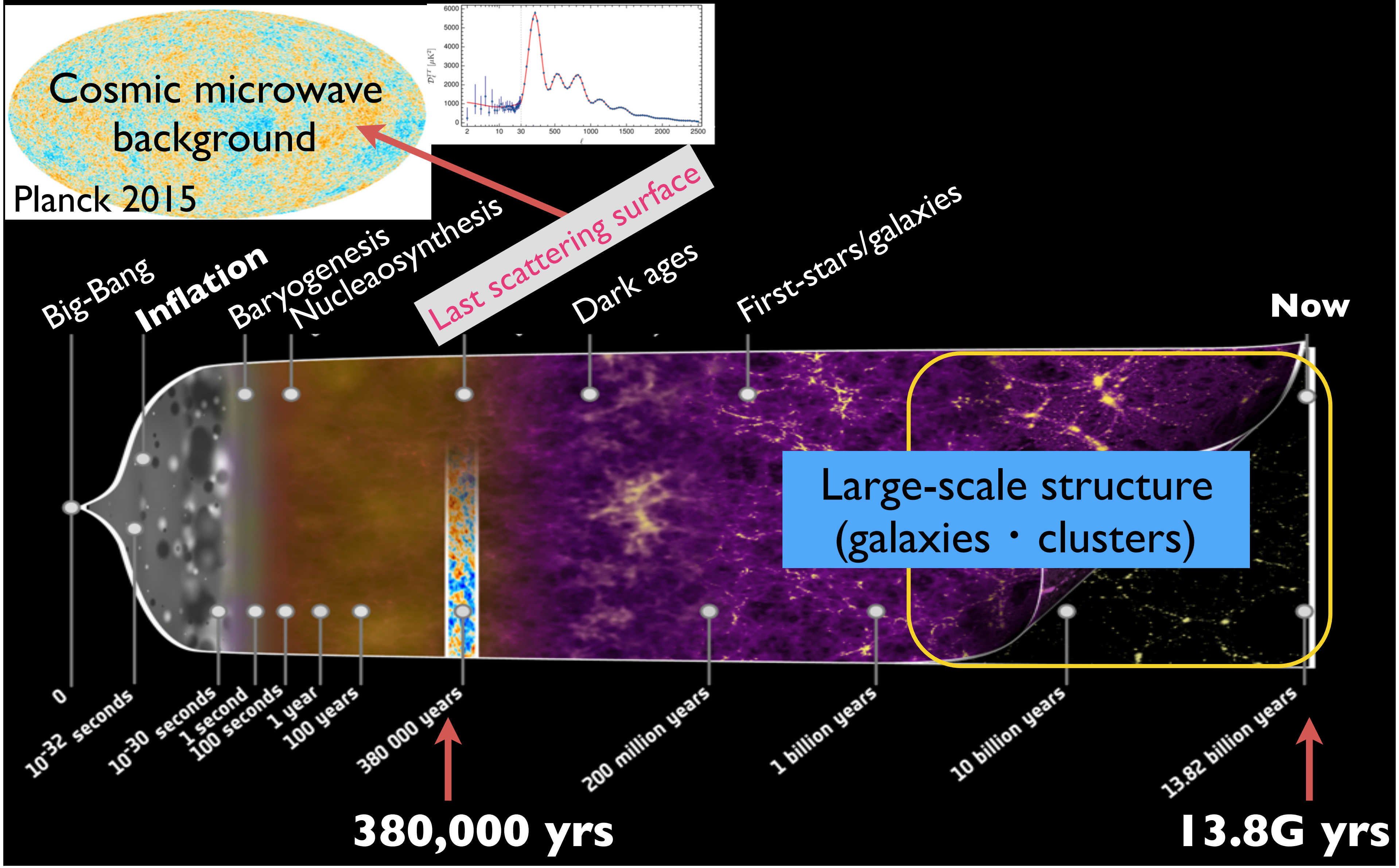
  structure formation

  dynamics of cosmic expansion

- Traditionally traced by galaxy redshift surveys

  (other LSS probes are gravitational lensing, Lyman-alpha forest)

Timeline of the Universe



Observing large-scale structure

Intensive use of telescope is necessary

Very Large Telescope (Chile)

Subaru Telescope (Hawaii)

Canada-France-Hawaii Telescope (Hawaii)

Sloan Digital Sky Survey @ APO (New Mexico)

Blanco telescope @ CTIO (Chile)

https://en.wikipedia.org/wiki/Very_Large_Telescope
http://www.sdss.org/instruments/
http://subarutelescope.org/Information/Download/DImage/index.html
http://www.cfht.hawaii.edu/en/news/CFHT30/#wallpaper
http://www.darkenergysurvey.org/DECam/index.shtml

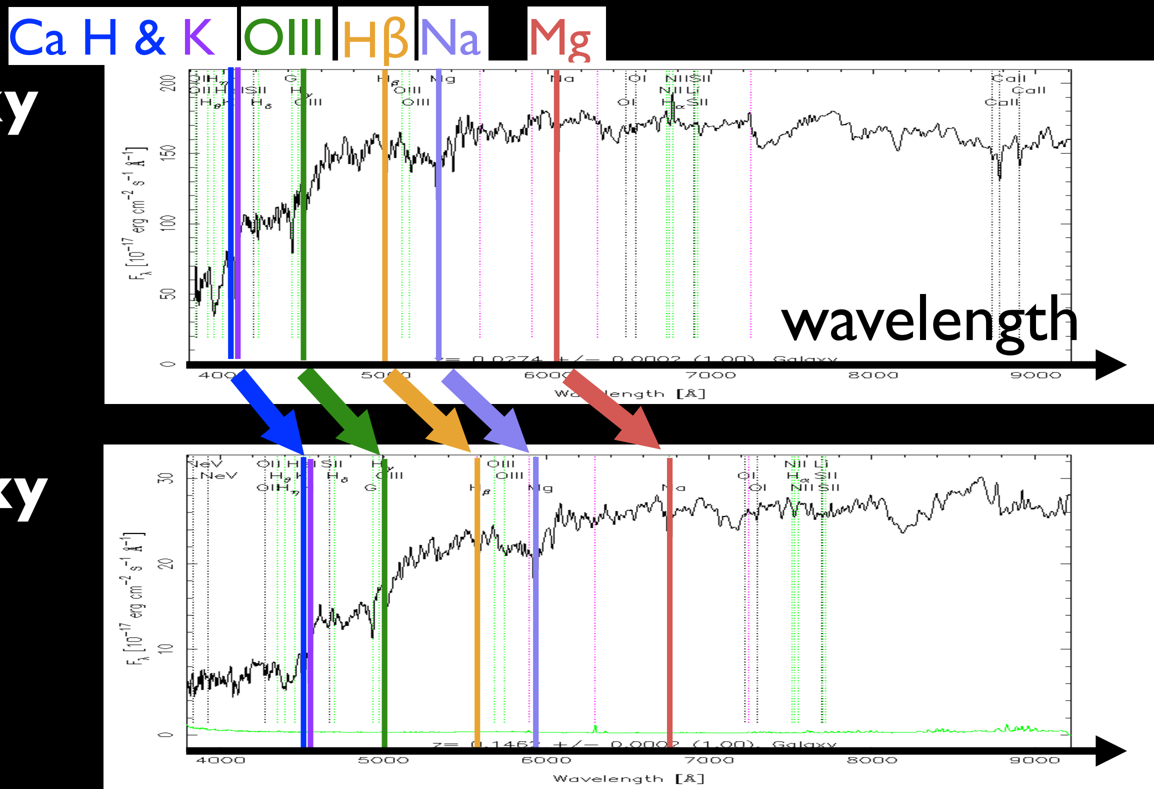
Redshift

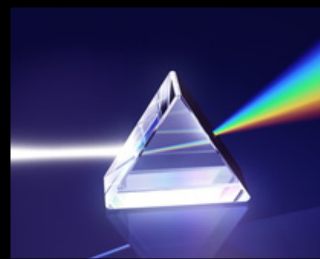
A key measurement to probe 3D view of large-scale structure

Distant galaxies looks ***redder*** than nearby galaxies
due to cosmic expansion

Nearby galaxy

Distant galaxy





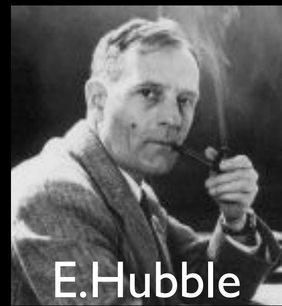
SDSS SkyServer

Redshift

A key measurement to probe 3D view of large-scale structure

Distant galaxies looks ***redder*** than nearby galaxies due to cosmic expansion

Redshift parameter $z = \Delta\lambda / \lambda$

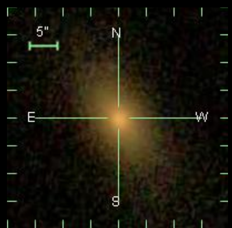


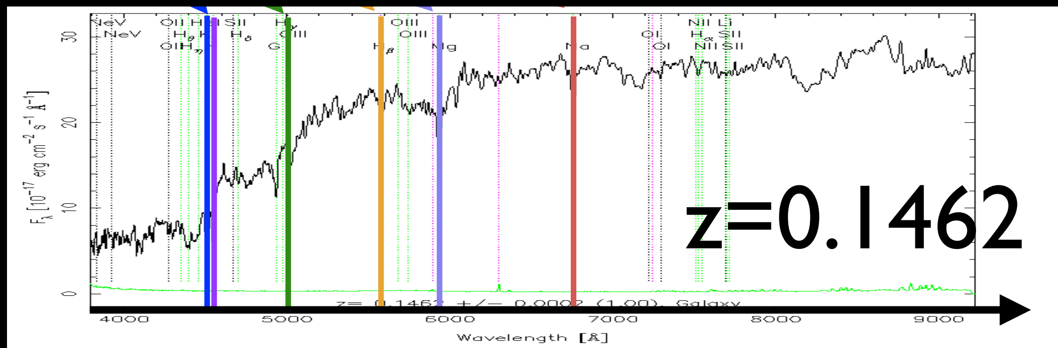
Hubble law

recession 'velocity' (= c z) $v = \underline{\underline{H}}\, d$ distance to galaxy

Hubble parameter

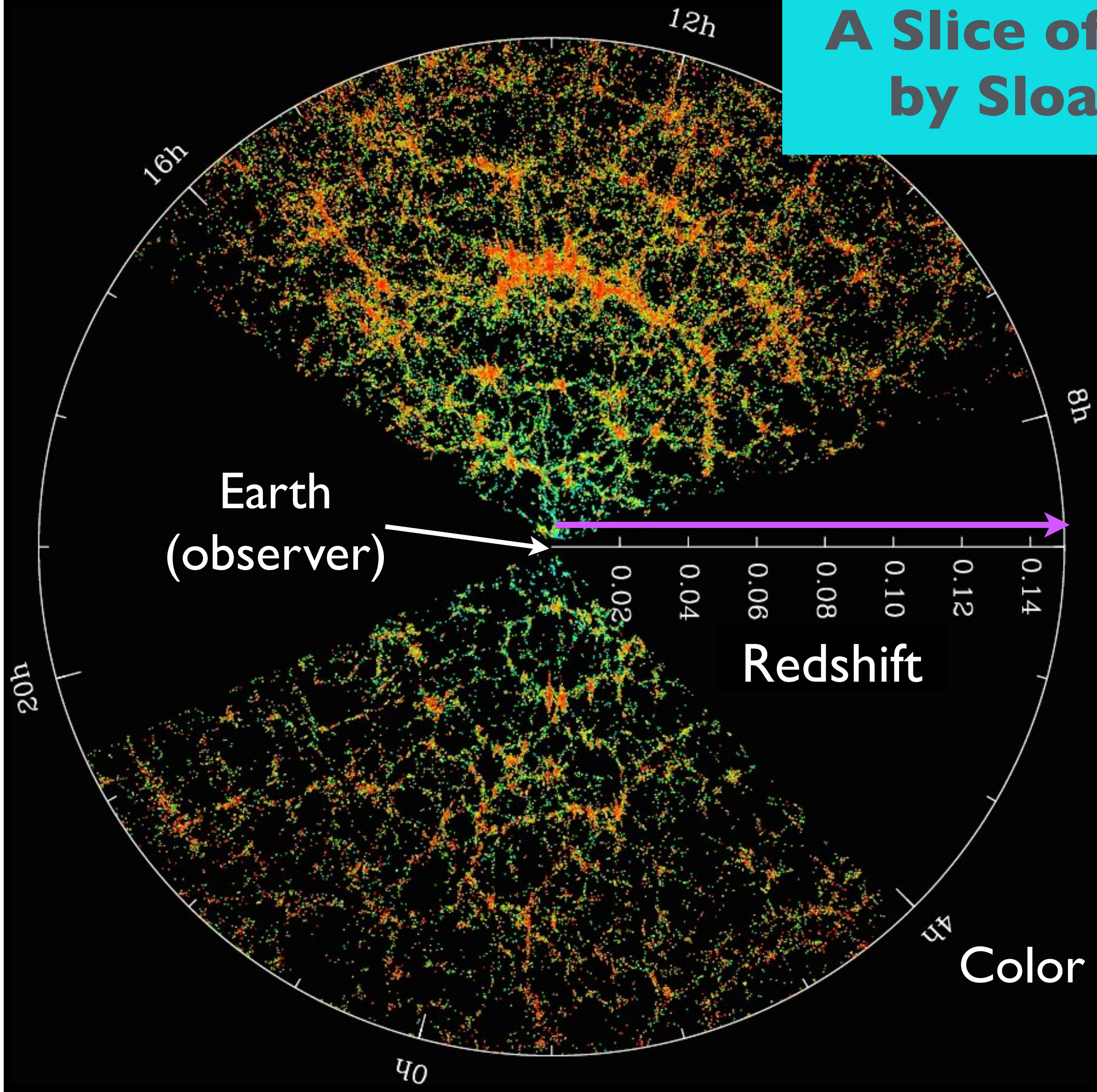
Distant galaxy





SDSS SkyServer

A Slice of galaxy catalog by Sloan Digital Sky



finished in 2008

2 G yrs

(look back time)

Color indicates age of galaxy

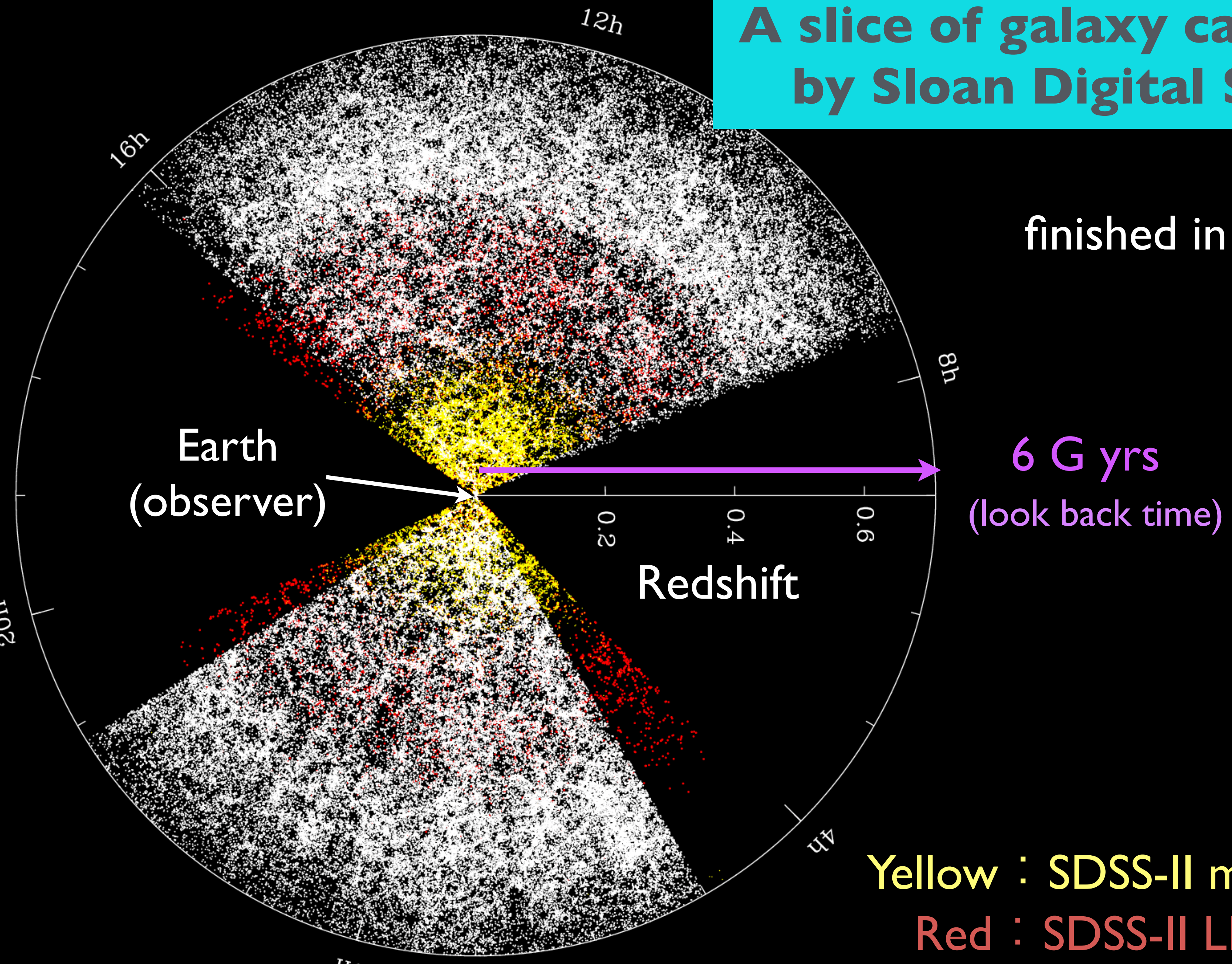
Blue : young

Red : old

http://www.sdss.org/science/#Cosmology

A slice of galaxy catalog by Sloan Digital Sky

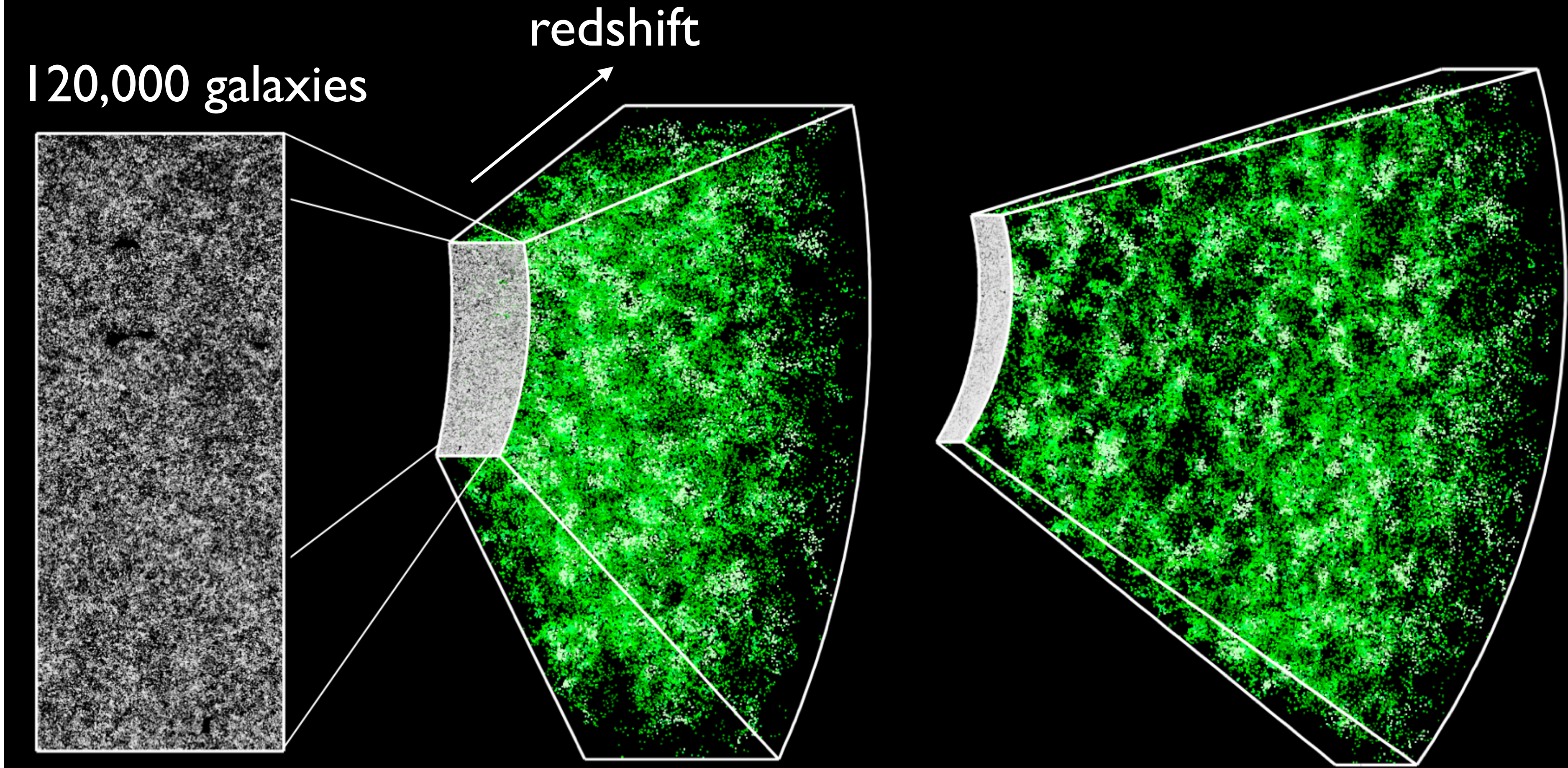
finished in 2014



Yellow：SDSS-II main
Red：SDSS-II LRG
White：SDSS-III CMASS

http://www.mpa-garching.mpg.de/131601/hl201506

A section of 3D map



http://www.sdss.org/press-releases/astronomers-map-a-record-breaking-1-2-million-galaxies-to-study-the-properties-of-dark-energy/

3D Map of galaxies

Sloan Digital Sky Survey III
Baryon Oscillation Spectroscopic Survey

https://www.sdss3.org/press/dr9.php

3D Map of galaxies

Sloan Digital Sky Survey III
Baryon Oscillation Spectroscopic Survey

https://www.sdss3.org/press/dr9.php

Cosmology with galaxy 3D map

Statistical properties

- Initial conditions for primordial fluctuations (cosmic inflation)
- Growth of structure
- Matter contents of the Universe

Gauging the scales of large-scale structure

$(\vec{\theta}, z)$ ⟵ cosmology ⟶ $\vec{r}$

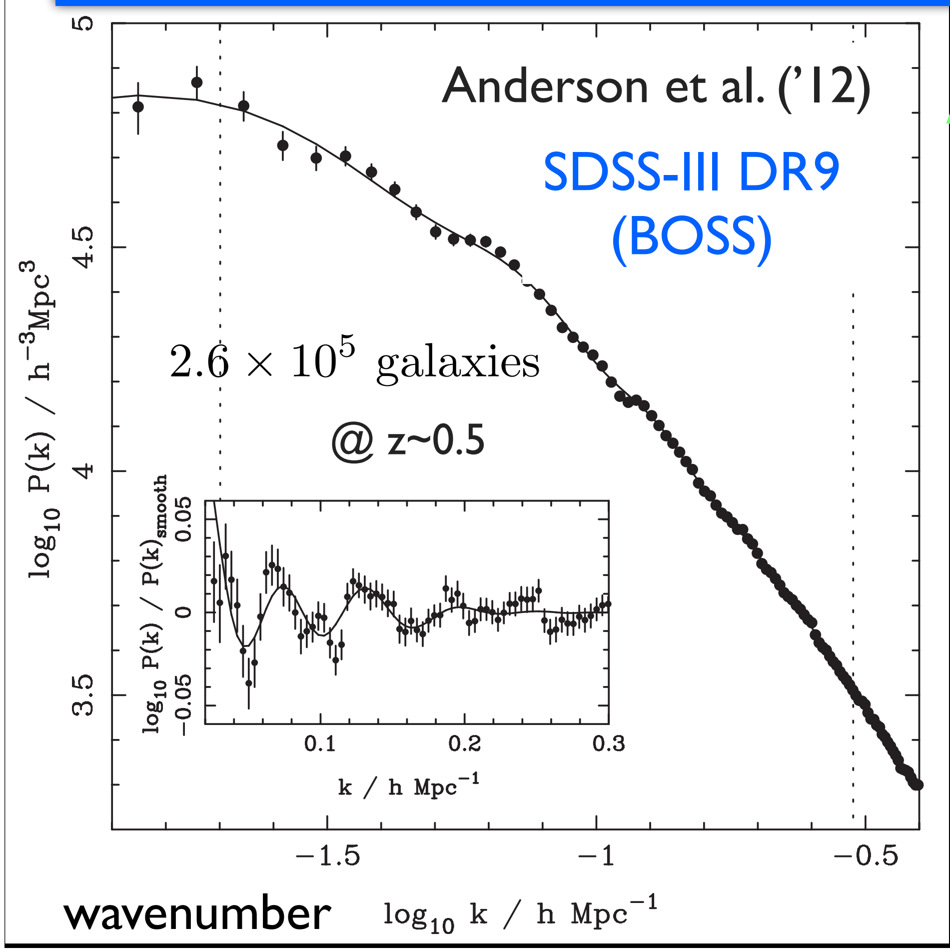
Angular position & redshift — (comoving) distance

Power spectrum of matter fluctuations

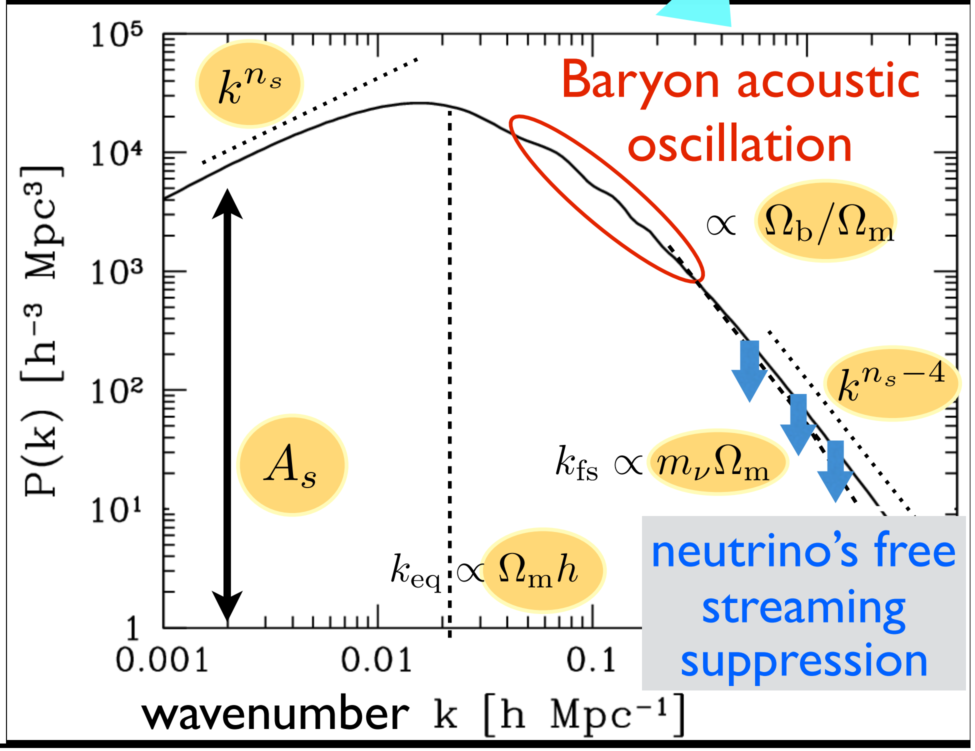
$$\delta(\vec{x}) \equiv \frac{\delta\rho_{\rm m}(\vec{x})}{\bar{\rho}_{\rm m}} = \frac{1}{\sqrt{V}} \sum_{\vec{k}} \delta(\vec{k})\, e^{i\vec{k}\cdot\vec{x}}$$

$$P(k) = \frac{1}{N_k} \sum_{|\vec{k}|=k} |\delta(\vec{k})|^2$$

Observation

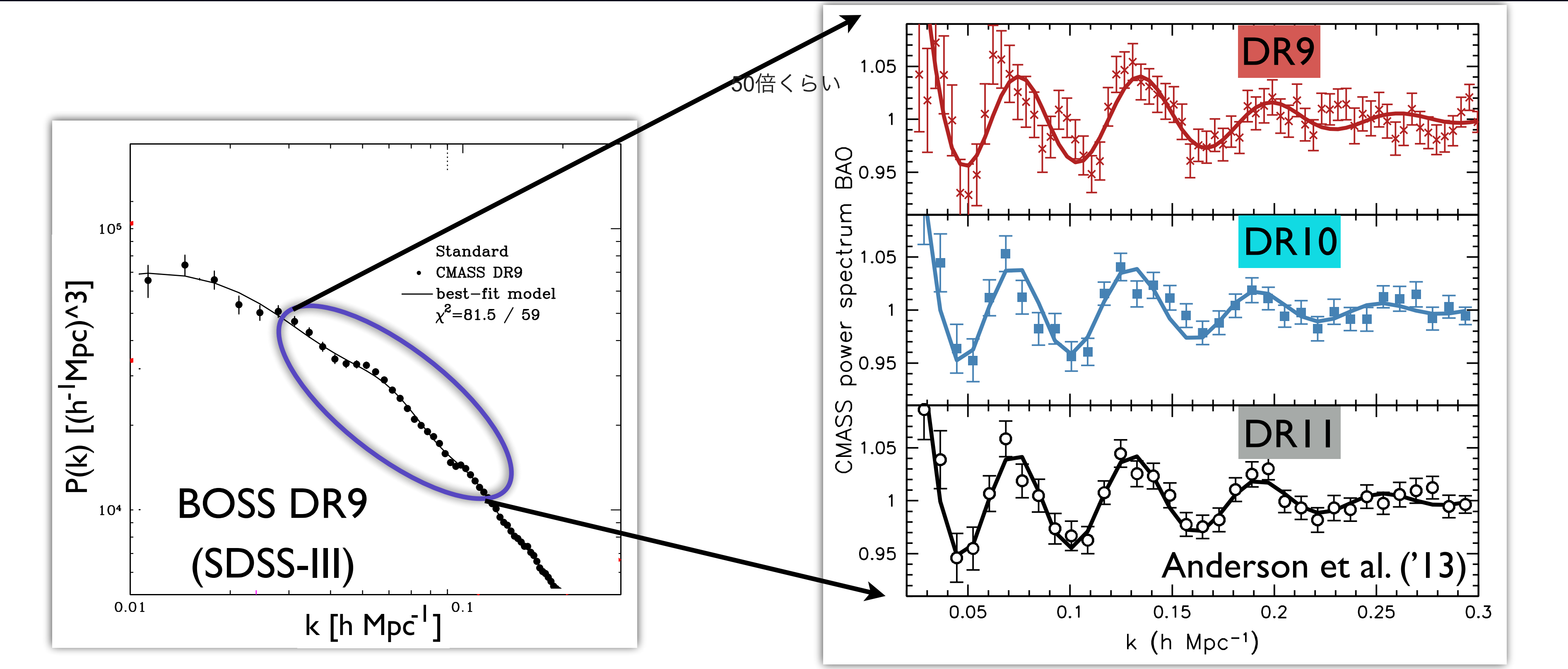


Linear theory



Baryon acoustic oscillations (BAO)

- Characteristic scale of primeval baryon-photon fluid (~150Mpc)
  (⇔ acoustic signal in CMB anisotropies)
- Can be used as standard ruler to measure cosmic expansion
  (theoretical prior)

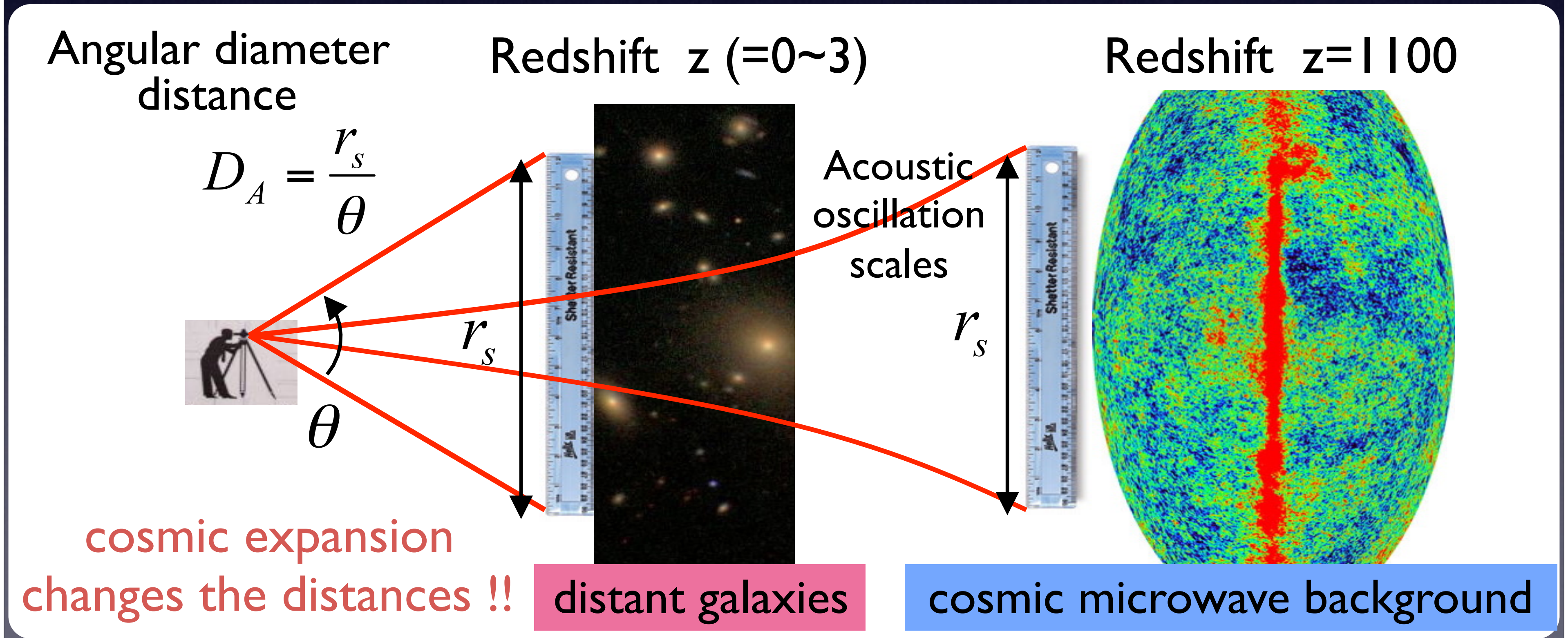


Baryon acoustic oscillations (BAO)

- Characteristic scale of primeval baryon-photon fluid (~150Mpc)

  (⇔ acoustic signal in CMB anisotropies)
- Can be used as <u>standard ruler</u> to measure cosmic expansion

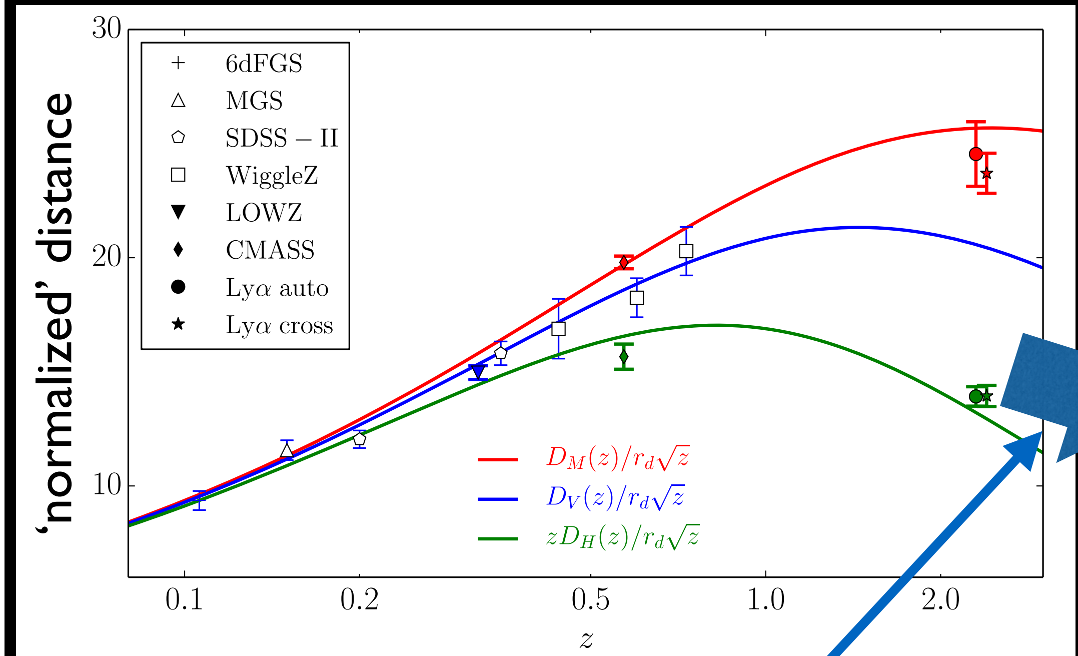
  (theoretical prior)

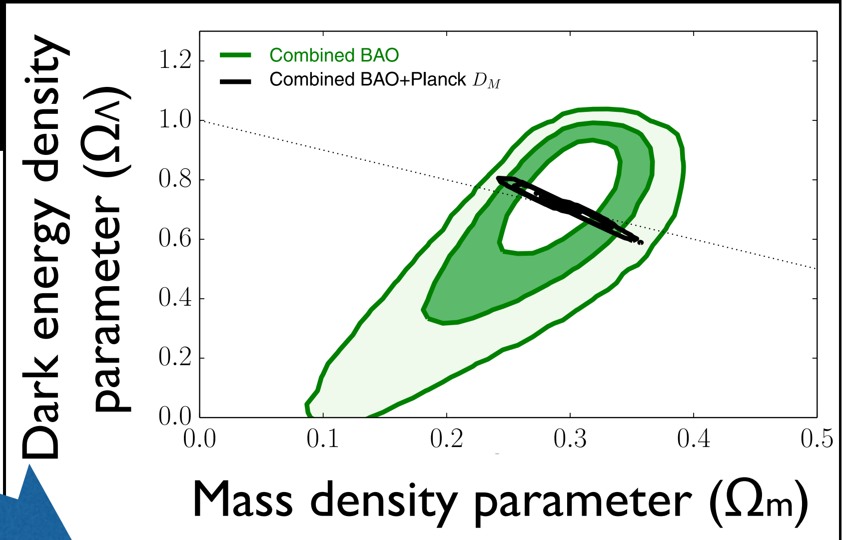


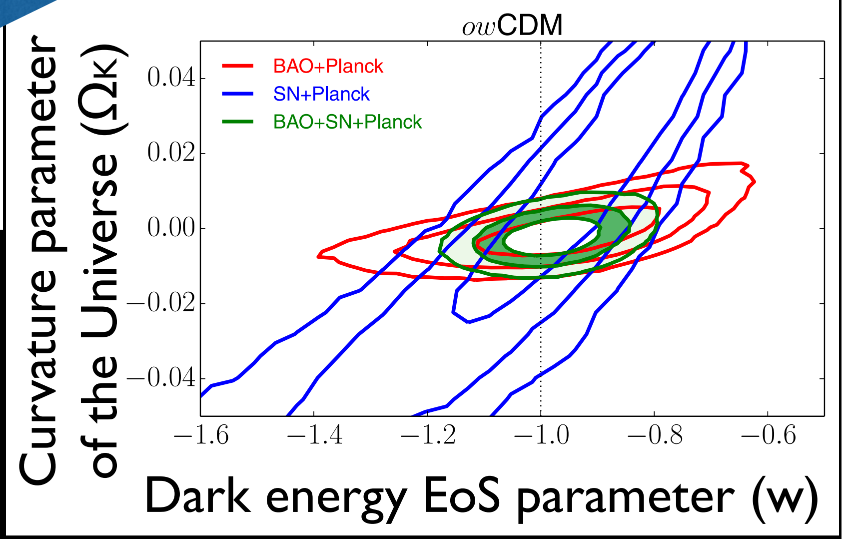
Cosmological constraints from BAO

Aubourg et al. '15

Distance-redshift relation from BAO measurement





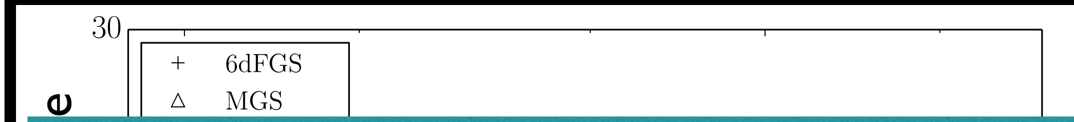


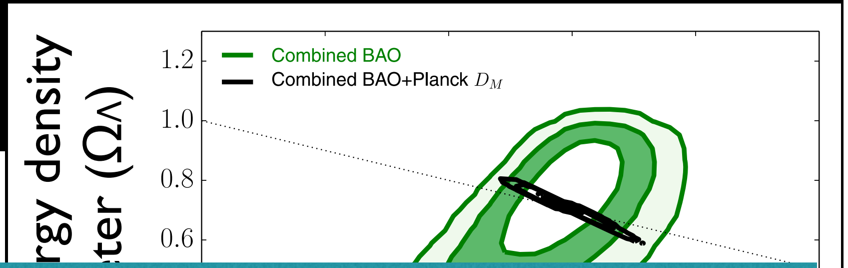
Combining CMB measurement by Planck

Cosmological constraints from BAO

Aubourg et al.'15

Distance-redshift relation from BAO measurement





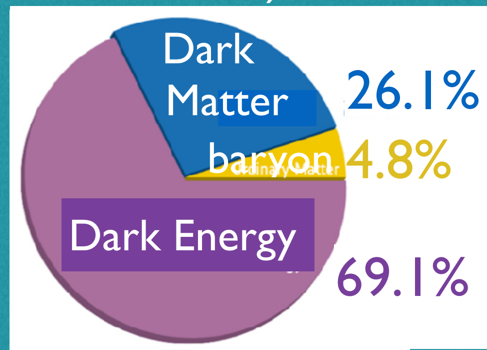
ΛCDM model (standard cosmological model)

flat universe filled with mysterious energy/matter components :

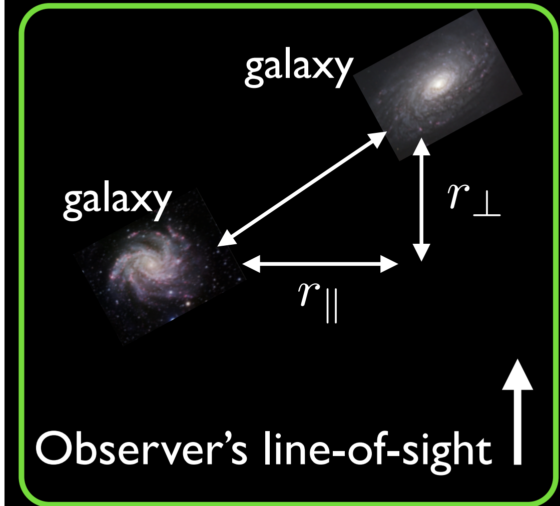
- dark matter → structure formation
- dark energy → late-time cosmic acceleration

(In ΛCDM model, dark energy=cosmological constant, Λ)

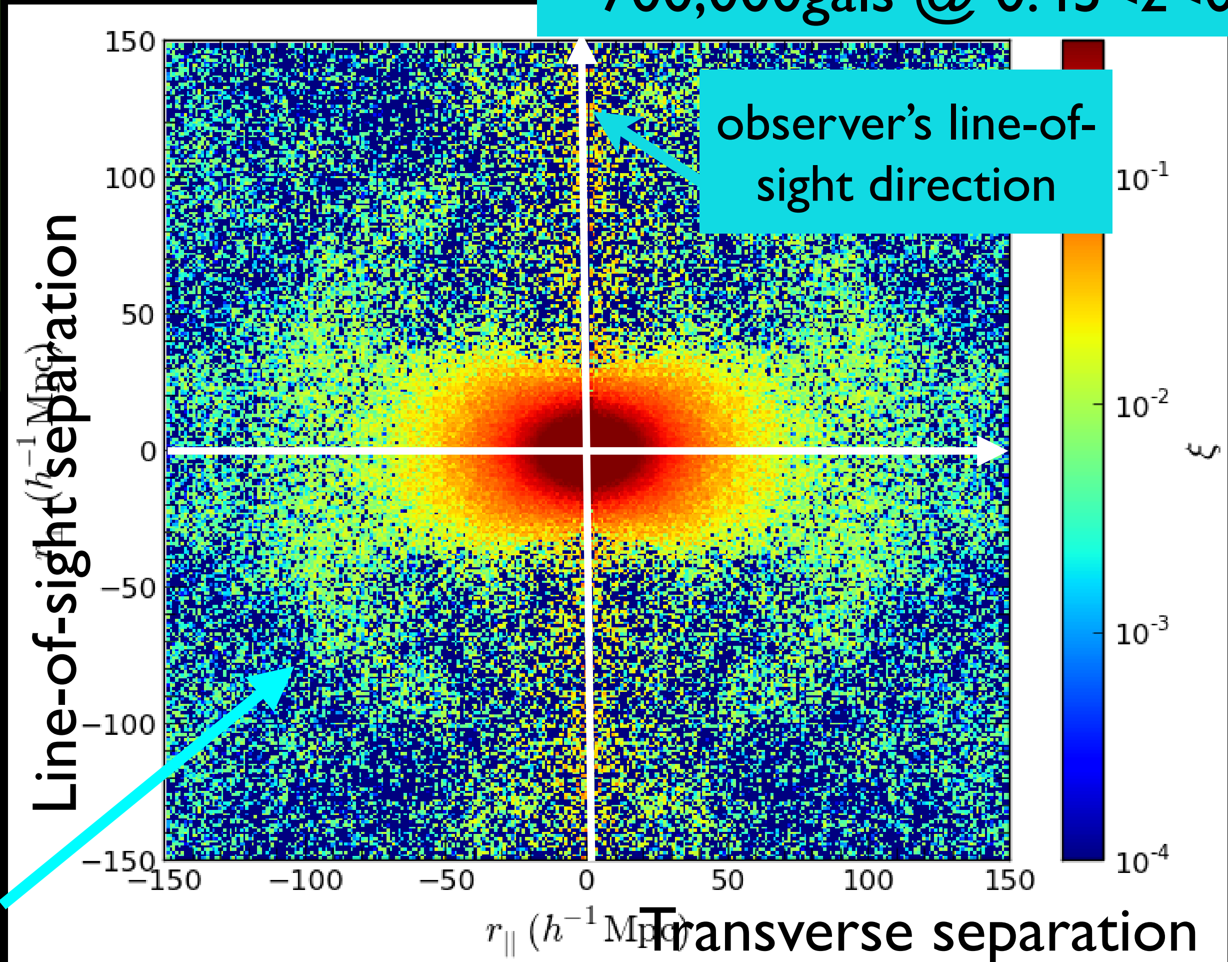
Origin & nature of these components are largely unknown. Need further observations !!



Two-point correlation function



BOSS DR11, CMASS samples
700,000gals @ 0.43<z<0.7



Baryon acoustic oscillation (ridge)

Samushia et al.('14)

RSD as a probe of gravity

Kaiser formula

(Kaiser '87)

$$\delta^{(\mathrm{S})}(\boldsymbol{k}) = (1 + f\,\mu_k^2)\,\delta(\boldsymbol{k}) \; ; \quad f \equiv \frac{d\ln D_+}{d\ln a}$$

Linear growth factor

scale factor

This parameter tells us

how the nature of gravity affects the growth of structure

Importantly,

This Kaiser formula holds <u>irrespective of gravity theory</u>

→ probe of gravity (general relativity) on cosmological scales

- Untested hypothesis in ΛCDM model
- Hint for cosmic acceleration

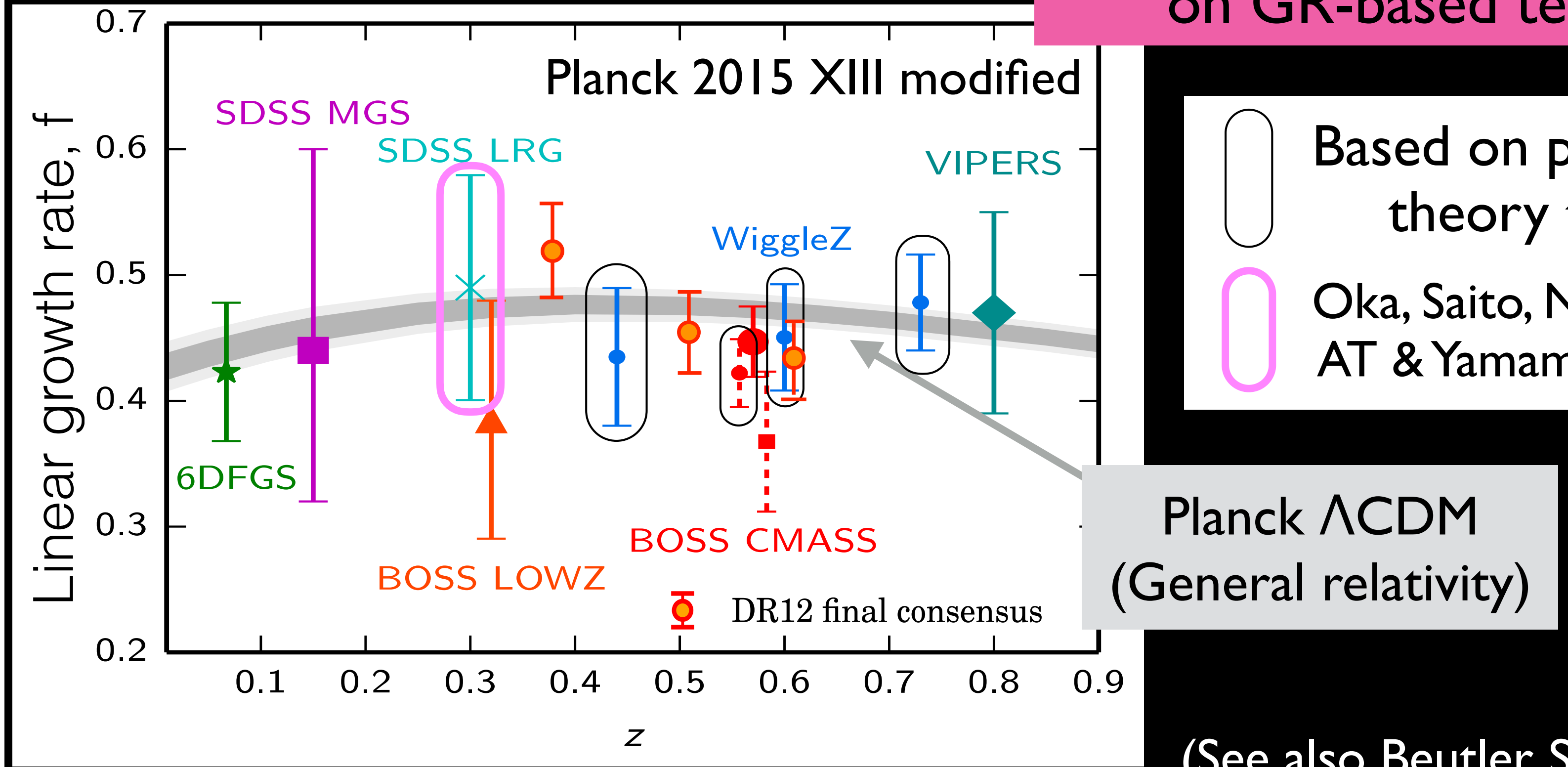
e.g., Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Percival & White ('09)

Consistency test of GR

In practice

Testing gravity needs a nonlinear RSD model assuming underlying theory of gravity

A blind fit of growth rate based on GR-based template

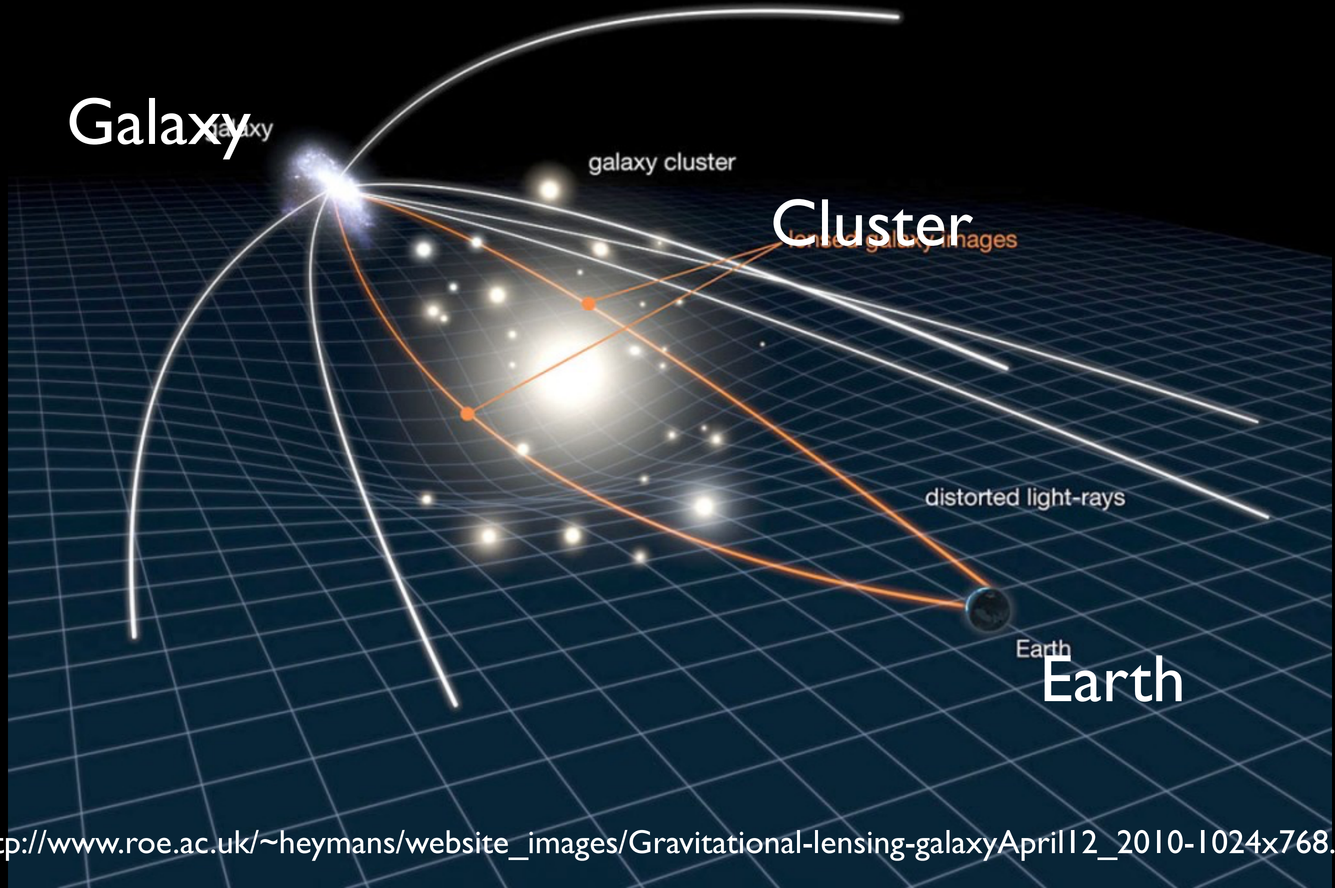


No strong evidence of deviation from GR

(See also Beutler, Seo, Saito et al. '16 for latest BOSS DR12)

Gravitational lensing effect

Light bending phenomena caused by gravity induced by massive objects such as galaxy and star

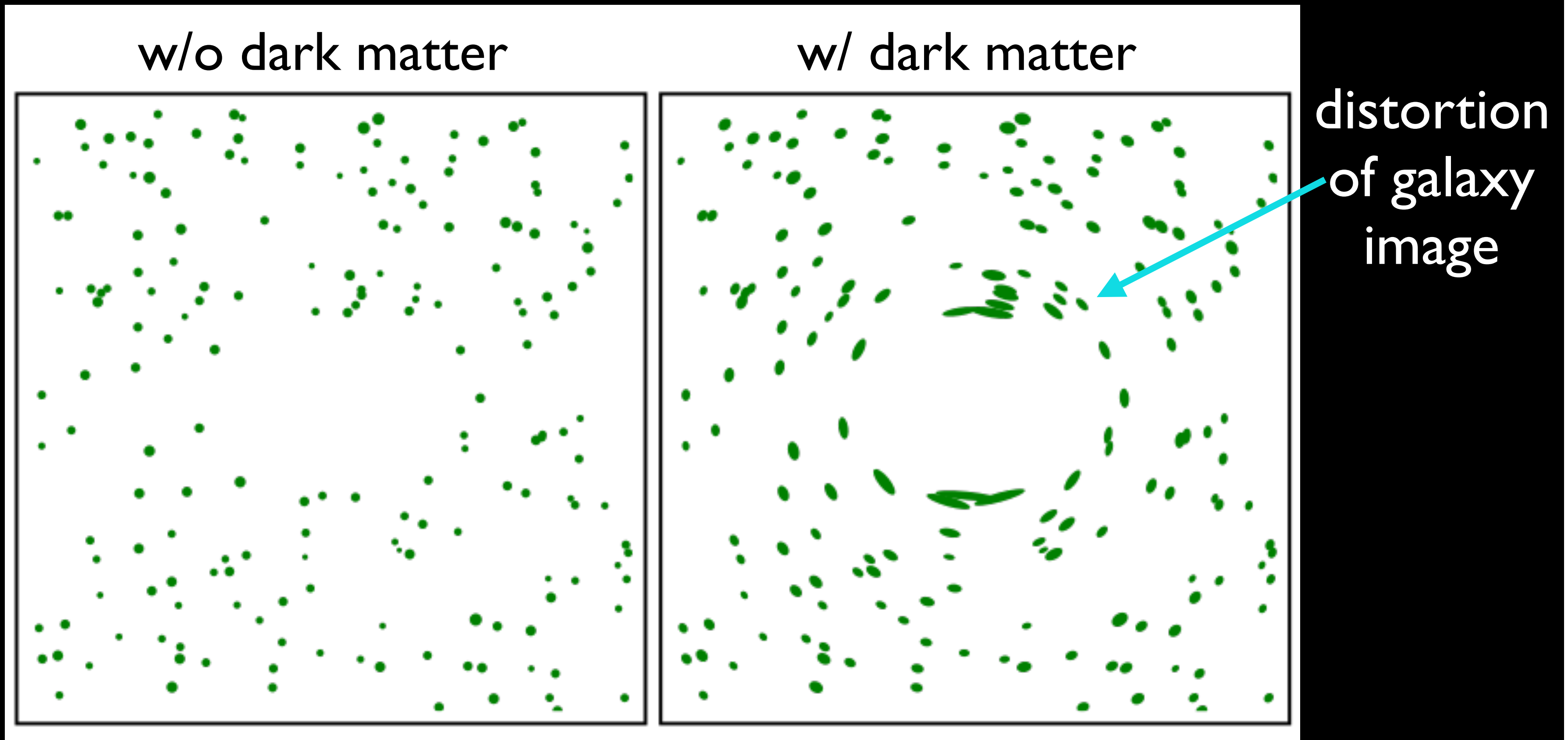


http://www.roe.ac.uk/~heymans/website_images/Gravitational-lensing-galaxyApril12_2010-1024x768.jpg

Observer will see distorted or multiple images of distant objects

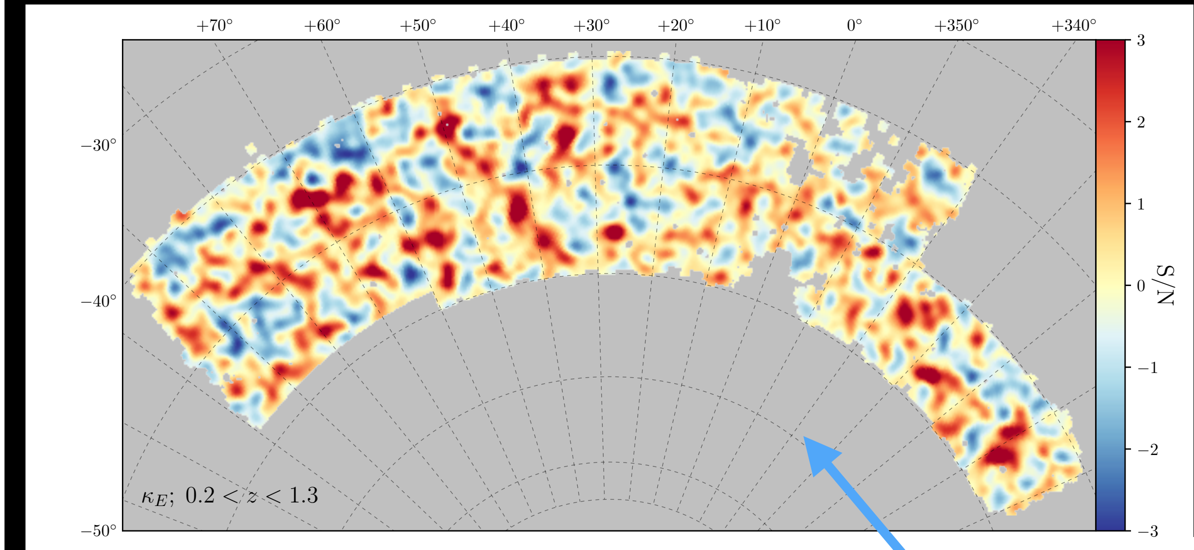
Mapping dark matter with weak lensing effect

Gravitational lensing effect can be powerful to probe invisible mass distribution (dark matter)



https://en.m.wikipedia.org/wiki/Weak_gravitational_lensing

Projected mass map

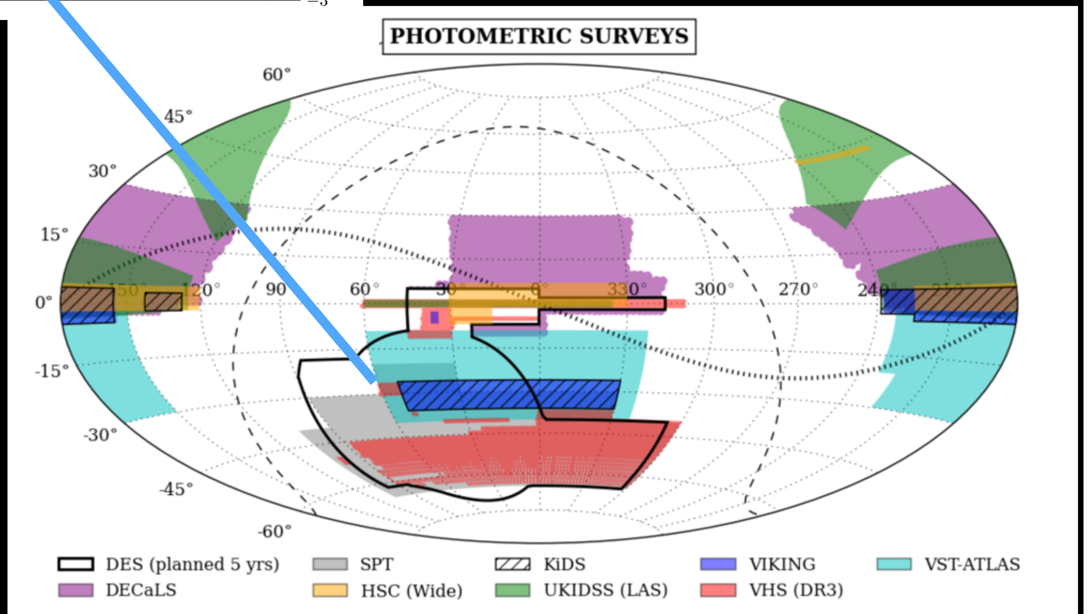


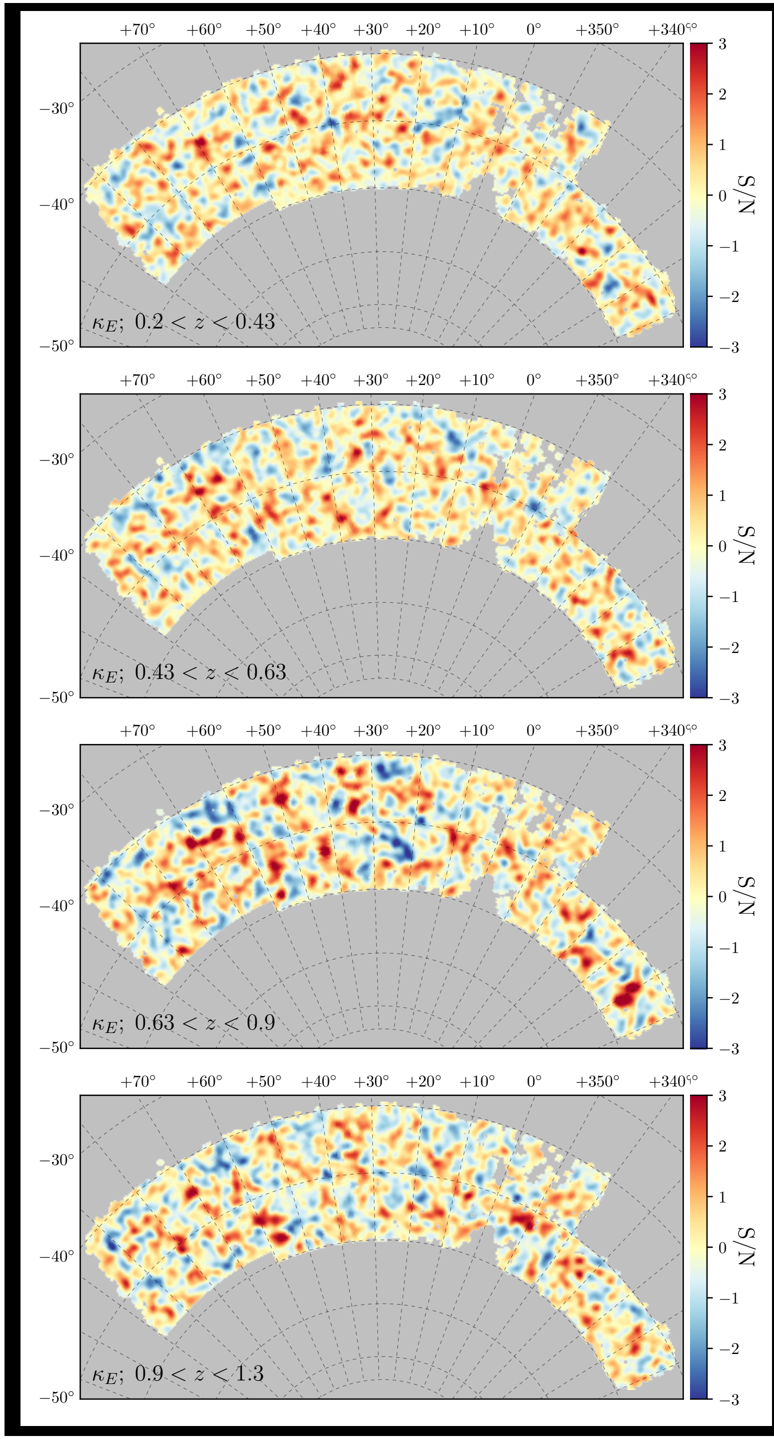
Dark Energy Survey

1st year result

~1,500 deg^2

(Chang et al. '17)



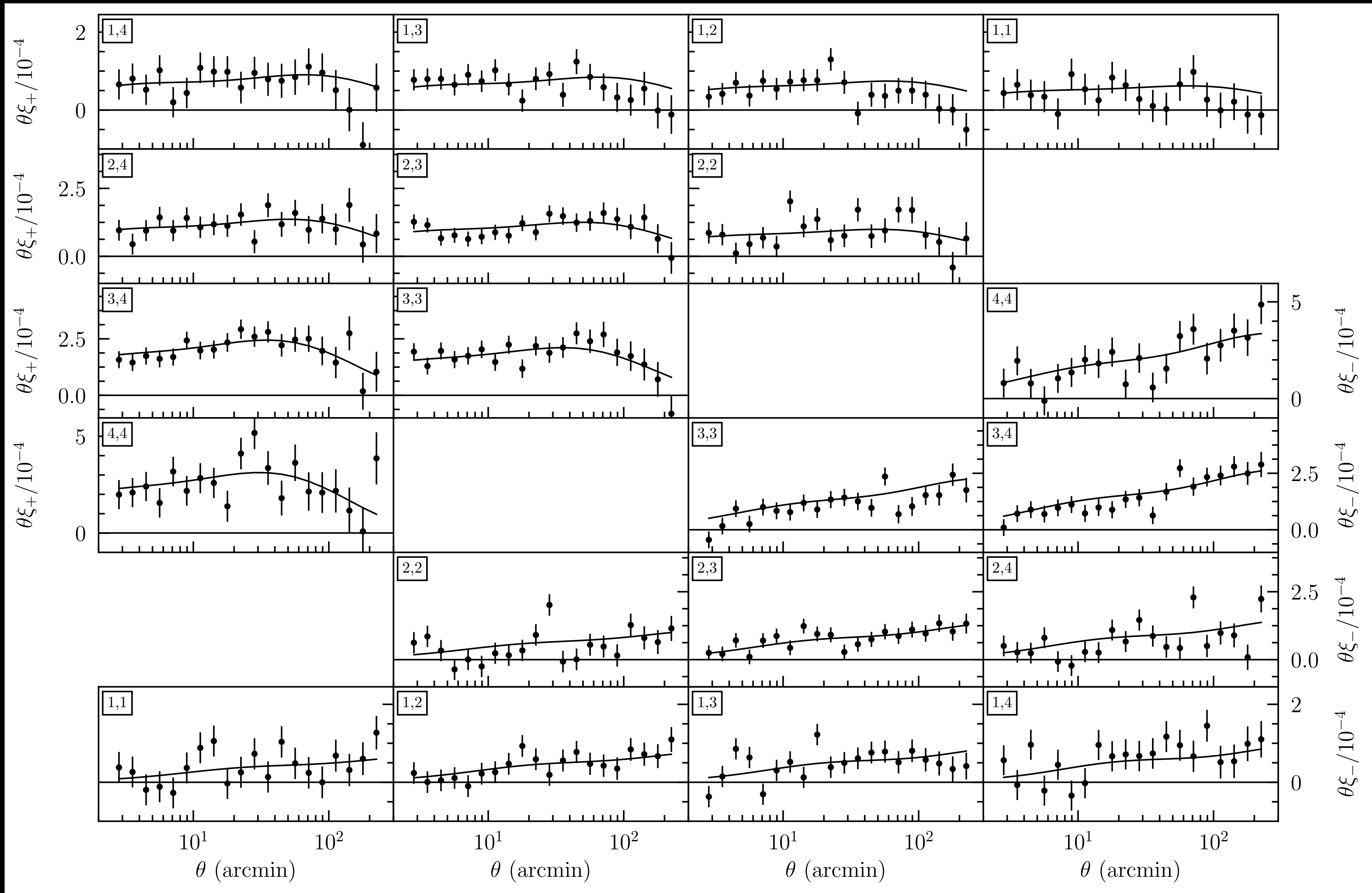


Tomographic maps

using photo-z information of source galaxies, projected mass maps are obtained from several redshift bins

(Chang et al. '17)

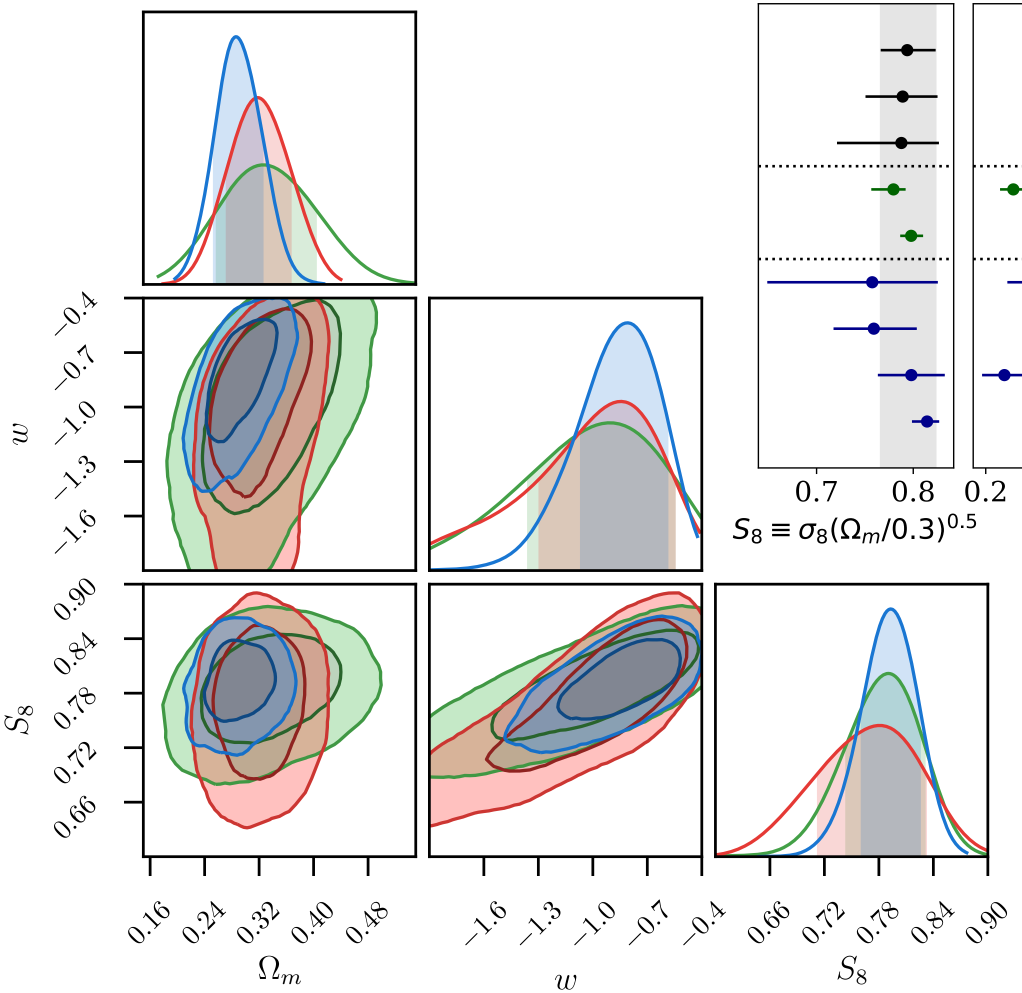
Shear correlation function

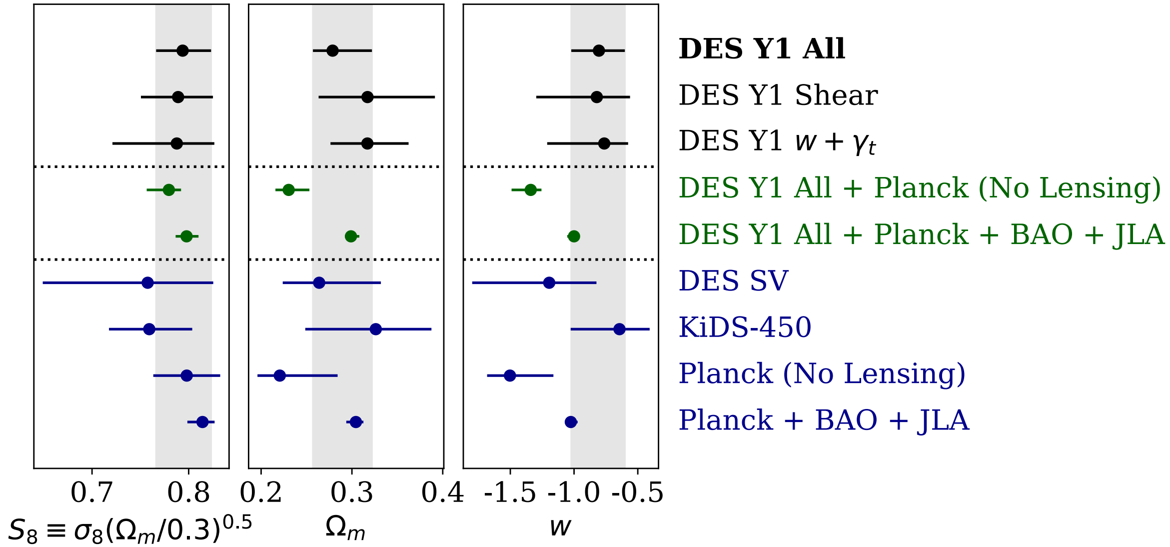


Troxel et al. ('17)

Cosmological results

DES 1yr (cosmic shear + galaxy clustering)





DES Y1
Planck
DES Y1 + Planck

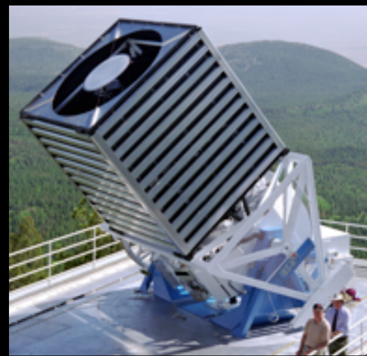
Abbott et al. ('17)

Upcoming/on-going projects

Multi-purpose ground- & space-based experiments

DES (2013~)

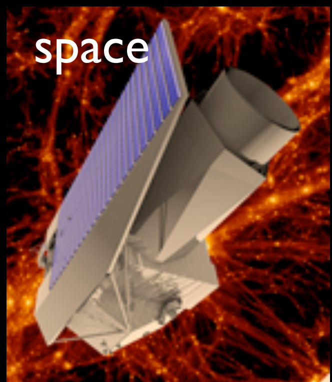
HETDEX (2016+)

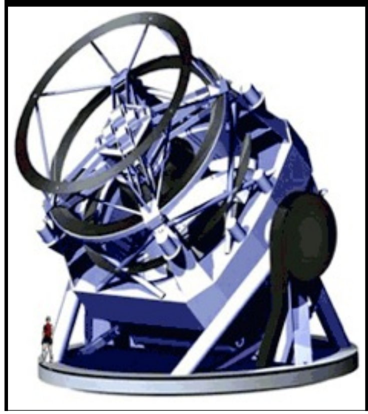


eBOSS (2014~)

DESI (2018+)

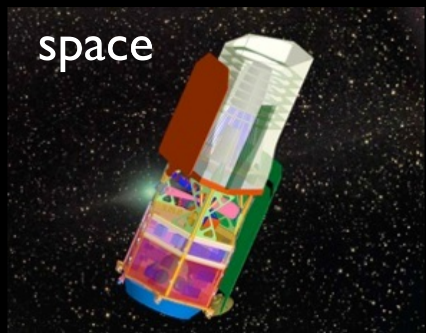
WFIRST (2024++)





LSST (2022++)

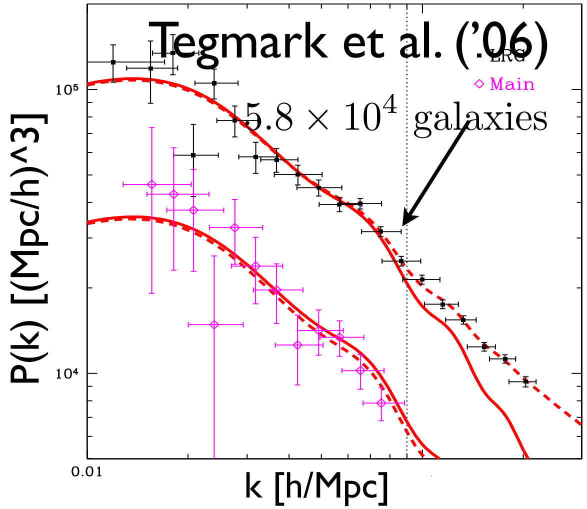
Euclid (2020)

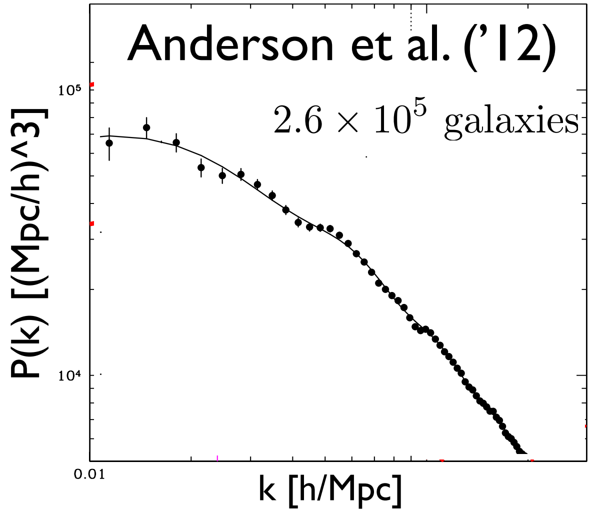


SuMIRe (2014~)

LLS as precision cosmological tools

Large data set will reveal statistical properties of LSS at an unprecedented precision level (→ precision cosmology)





$10^7 \sim 10^9$ galaxies

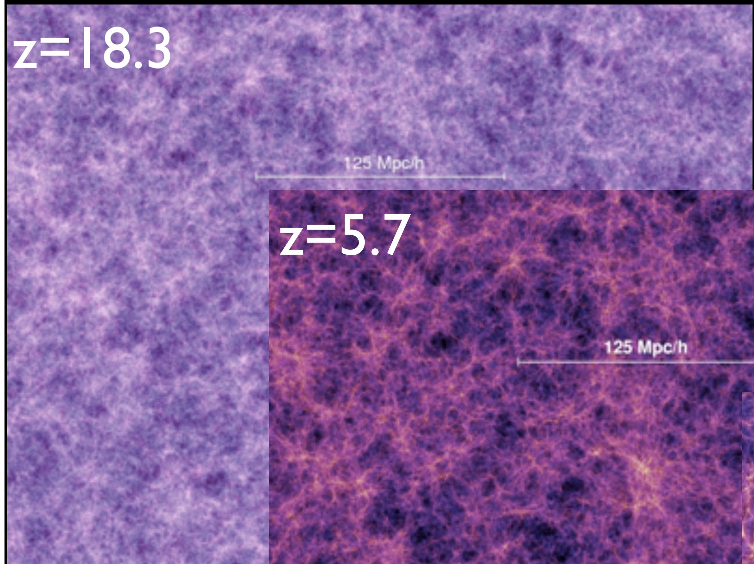
~1% precision

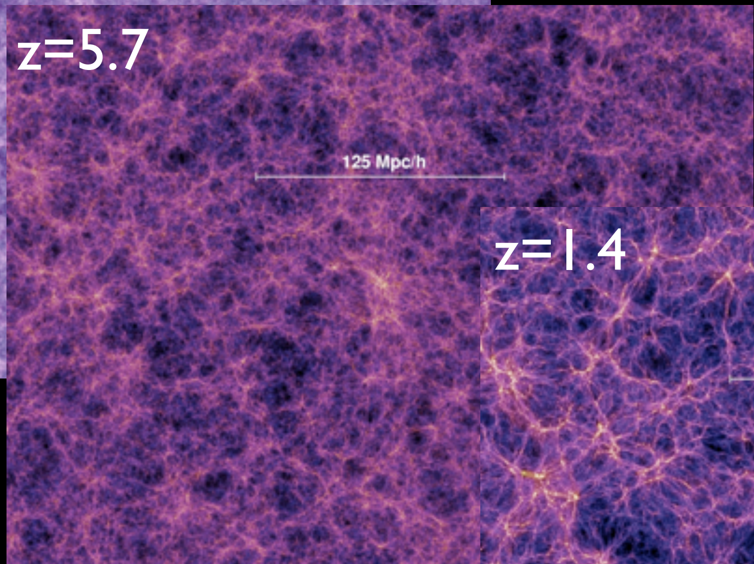
New opportunity & scientific synergy :

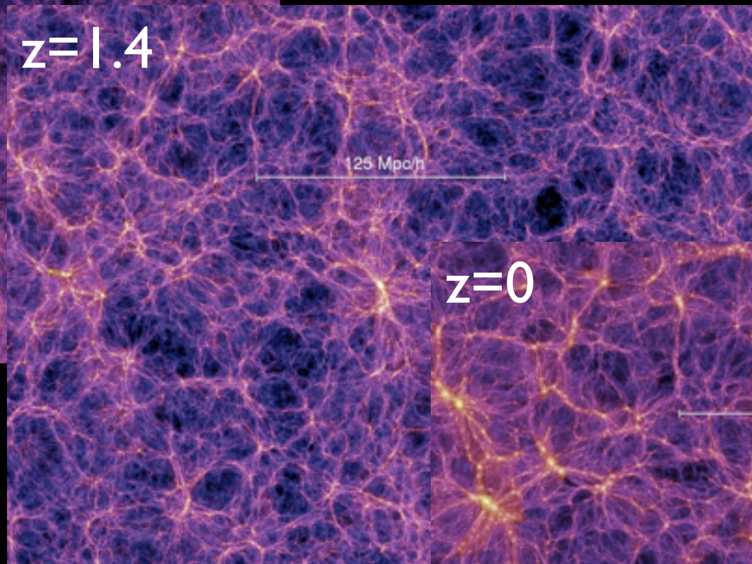
- Clarifying nature of dark energy (cosmic acceleration)
- Testing general relativity on cosmological scales
- Weighing total mass of neutrinos

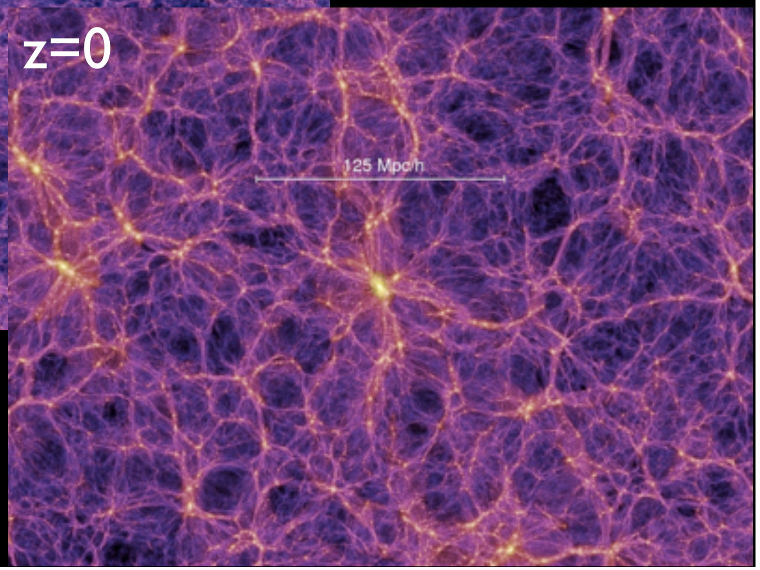
Accurate theoretical description for LSS needs to be developed

Cosmological N-body simulation









Self-gravitating many-body system
in an expanding universe

$N \to \infty$

$$\frac{\vec{p}_i}{dt} = -\frac{Gm^2}{a}\sum_{j\neq i}^{N}\frac{\vec{x}_i - \vec{x}_j}{|\vec{x}_i - \vec{x}_j|^3} \qquad \vec{p}_i = ma^2\frac{d\vec{x}_i}{dt}$$

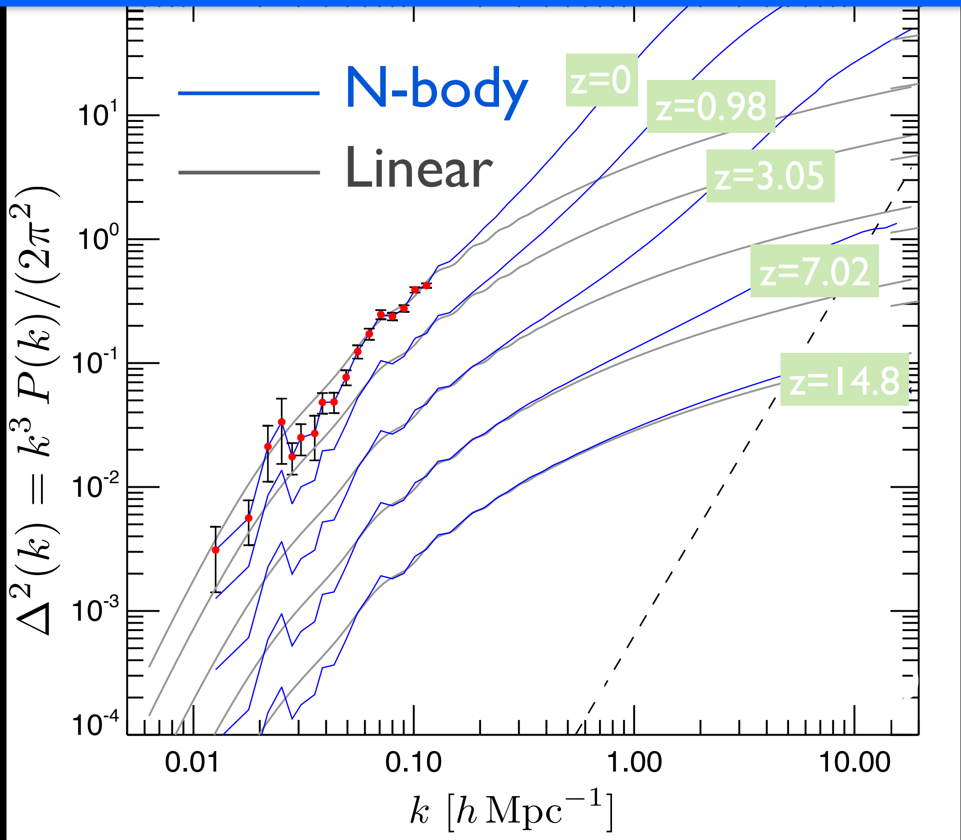
$$(i = 1, 2, \cdots, N)$$

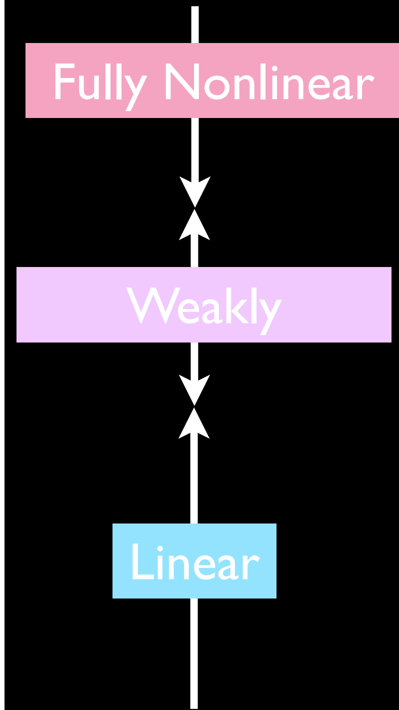
Formation of halos and
filamentary structure

http://www.mpa-garching.mpg.de/galform/millennium/

Nonlinear power spectrum

$$\delta(\vec{x}) \equiv \frac{\delta\rho_{\rm m}(\vec{x})}{\bar{\rho}_{\rm m}} = \frac{1}{\sqrt{V}}\sum_{\vec{k}} \delta(\vec{k})\, e^{i\vec{k}\cdot\vec{x}} \Rightarrow P(k) = \frac{1}{N_k}\sum_{|\vec{k}|=k} |\delta(\vec{k})|^2$$





To what extent we can quantitatively understand statistical properties of large-scale structure?

Goal of this lecture

Understanding of large-scale structure (LSS)
as cosmology probe

- Theoretical basis of formation & evolution of LSS
  - Structure formation Standard model (ΛCDM)
  - Cosmological information imprinted in LSS
- Theoretical tools to confront with precision observations of LSS
  (mainly focusing on galaxy surveys)
  - Perturbation theory of LSS

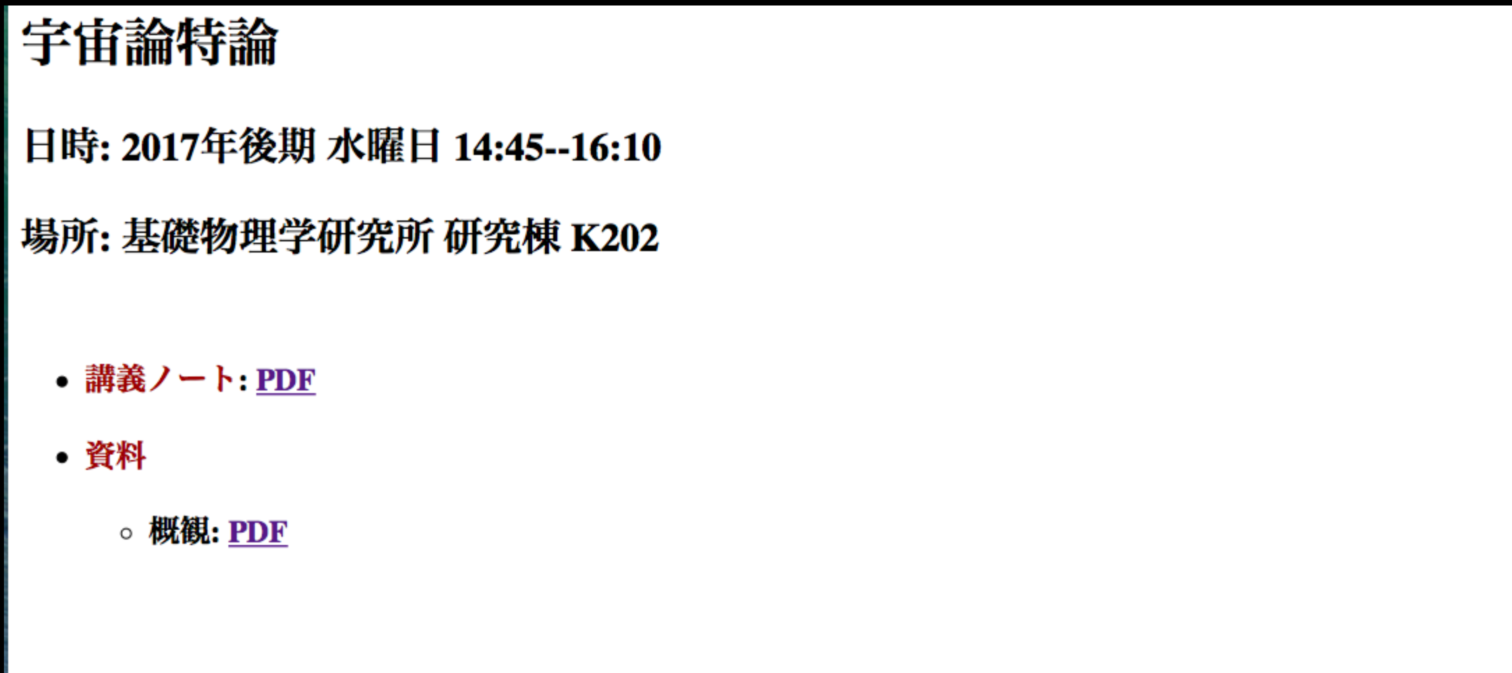
Plan

- Summary of background cosmology
- Linear theory of structure formation
- Observational effects:
  Redshift-space & geometric distortions
- Analytic approaches to nonlinear structure formation
- Selected topics on statistics and dynamics of large-scale structure

Note and supplements

Lecture note and supplemental materials (PDF files) are found in:

http://www2.yukawa.kyoto-u.ac.jp/~atsushi.taruya/lecture.html



宇宙論特論

日時: 2017年後期 水曜日 14:45--16:10

場所: 基礎物理学研究所 研究棟 K202

- **講義ノート: PDF**
- **資料**
  - **概観: PDF**