2017年6月26-28日

名古屋大学大学院理学研究科素粒子・宇宙物理学専攻

物理学特別講義 B XVI

暗黒物質宇宙における構造形成

Structure formation in the dark matter dominated universe

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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 $\subset$ group / cluster $\subset$ 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)

Observing large-scale structure

Intensive use of telescope is necessary

8.2m

Very Large Telescope (Chile)

8.2m

Subaru Telescope (Hawaii)

3.6m

Canada-France-Hawaii
Telescope (Hawaii)

2.5m

Sloan Digital Sky Survey
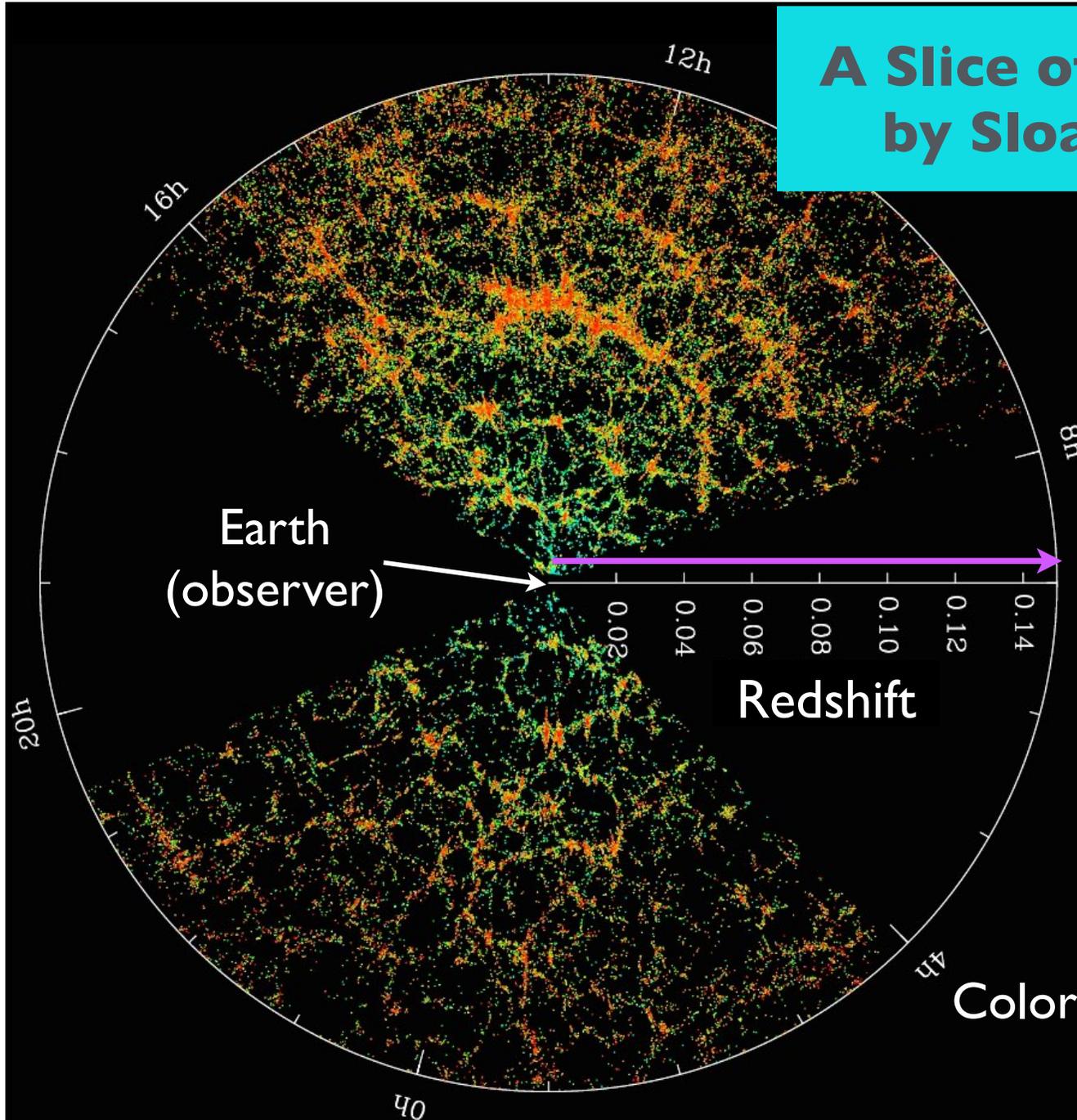@ APO (New Mexico)

Blanco telescope
@ CTIO (Chile)

4m

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

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

Hubble law

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

E.Hubble

G. Lemaitre

Distant galaxy

z=0.146

SDSS SkyServer

A Slice of galaxy catalog by Sloan Digital Sky

12h

16h

8h

Earth (observer)

Redshift

0.02 0.04 0.06 0.08 0.10 0.12 0.14

20h

4h

0h

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

12h

16h

20h

0h

4h

8h

Earth (observer)

6 G yrs
(look back time)

0.2   0.4   0.6

Redshift

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

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

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A section of 3D map

redshift

120,000 galaxies
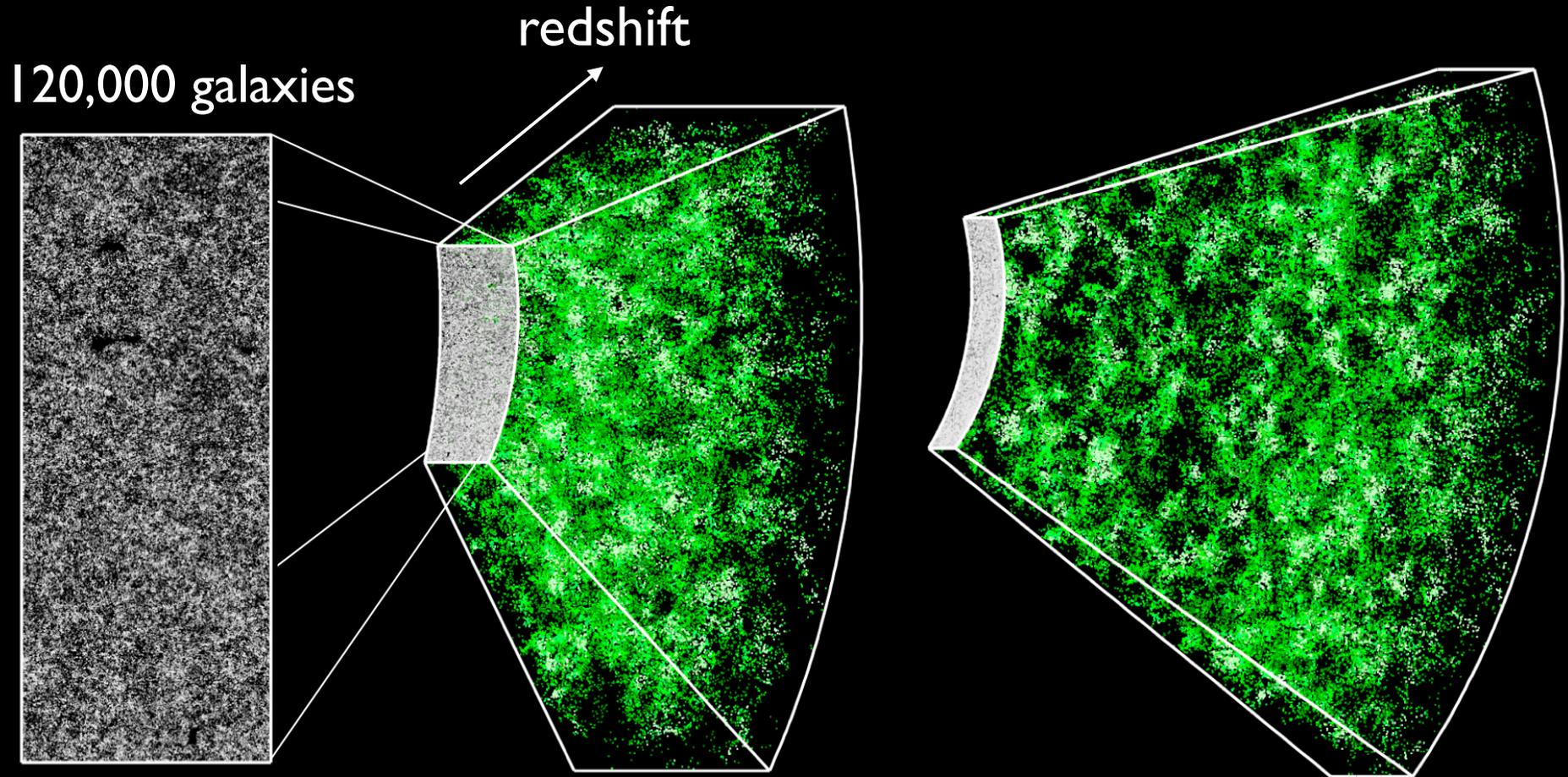
3D Map of galaxies

Sloan Digital Sky Survey

Miguel A Aragon (JHU), Mark Subbarao (Adler P.), Alex Szalay (JHU)

Sloan Digital Sky Survey III
Baryon Oscillation Spectroscopic Survey

Cosmology with galaxy 3D map

Statistical properties

- Initial conditions for primordial fluctuations (cosmic inflation)
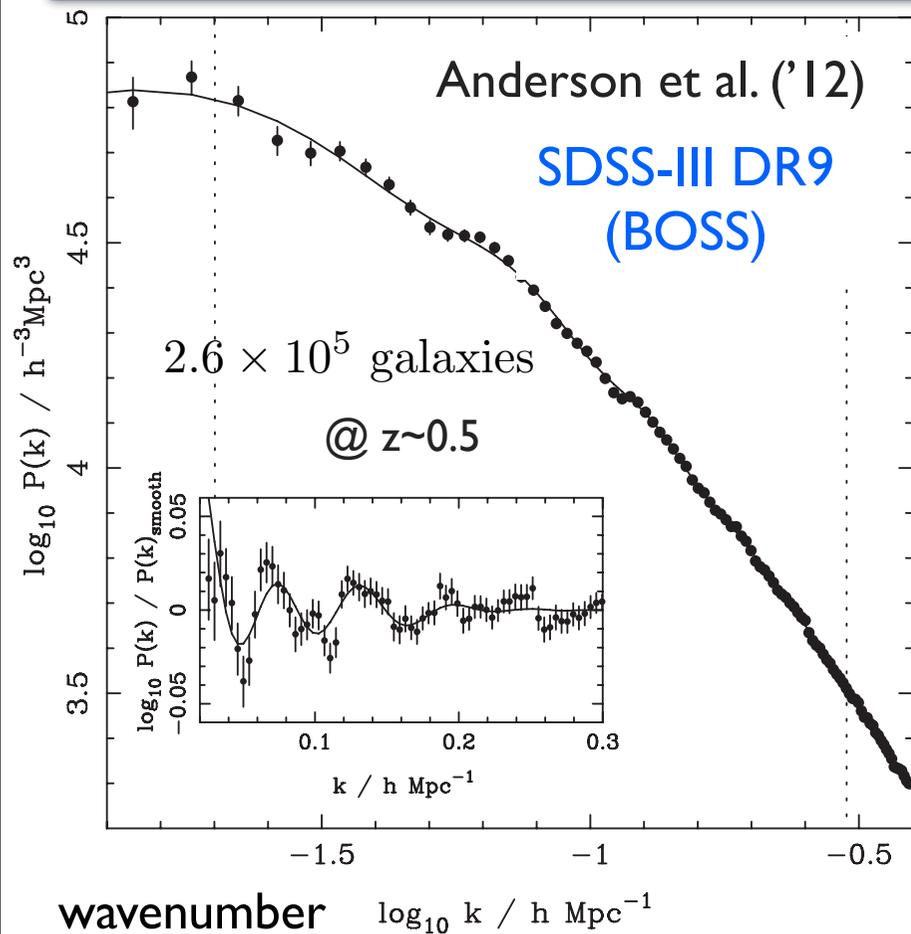
- Growth of structure

- Matter contents of the Universe

Gauging the scales of large-scale structure

$$(\vec{\theta}, z) \longleftarrow \boxed{\text{cosmology}} \longrightarrow \vec{r}$$

Angular position & redshift   (comoving) distance

Power spectrum of matter fluctuations

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

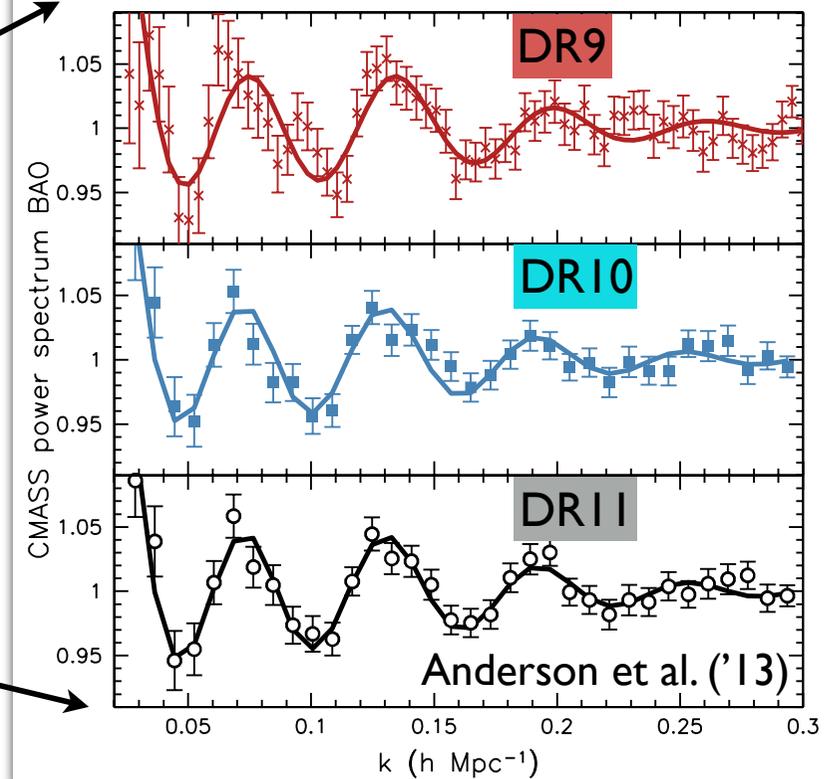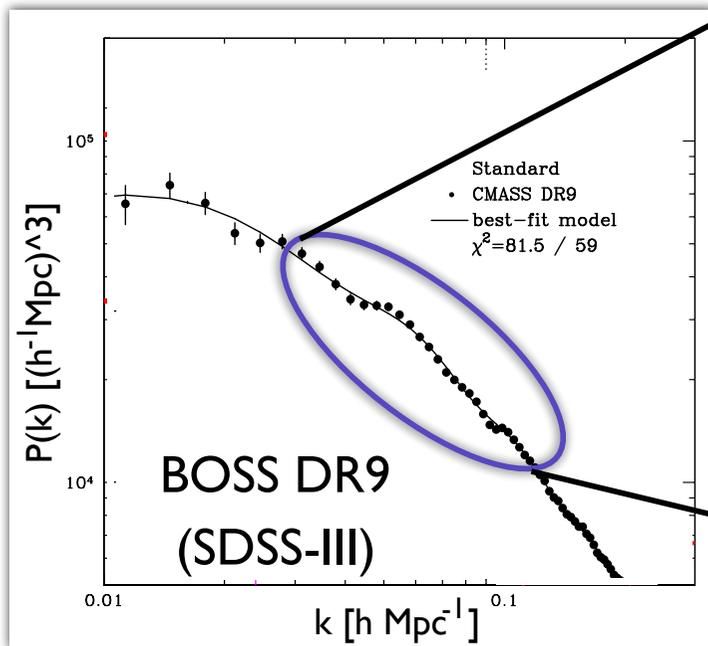$$P(k) = \frac{1}{N_k} \sum_{|\vec{k}|=k} |\delta(\vec{k})|^2$$
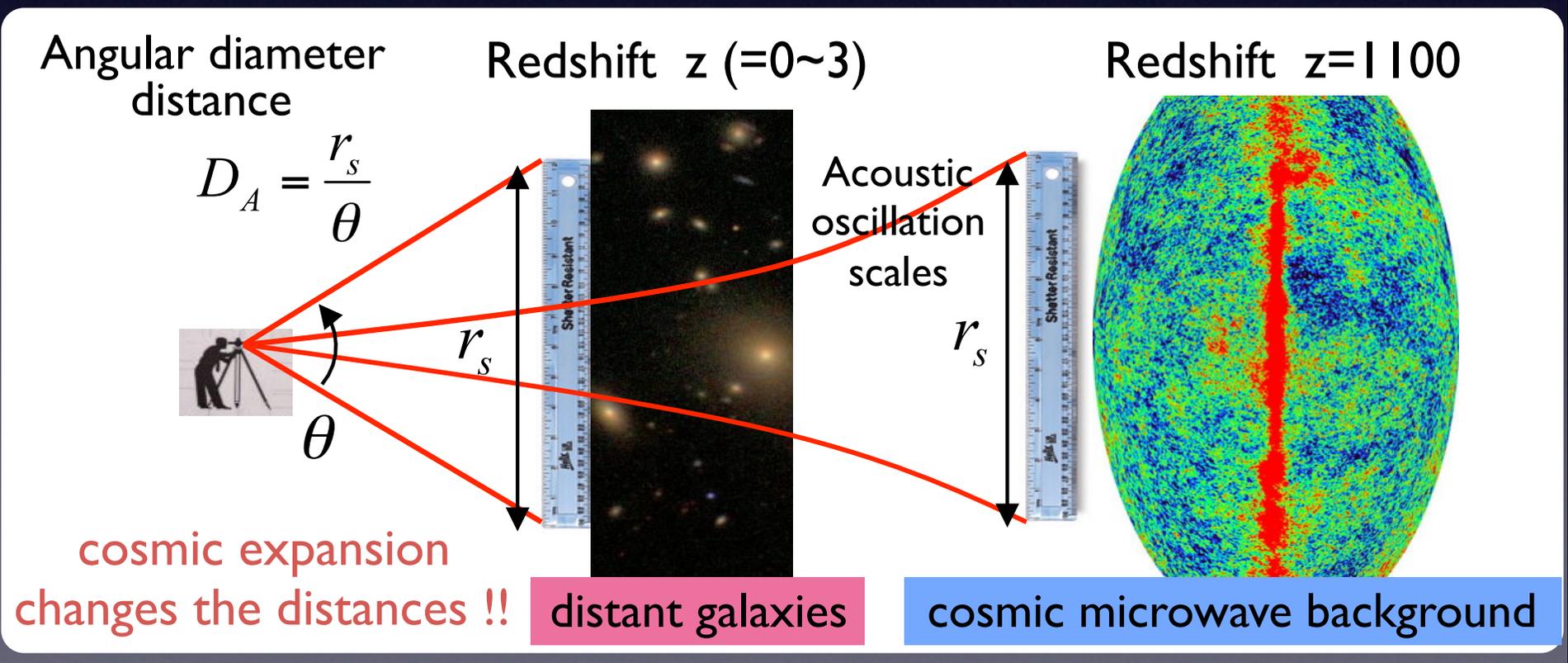
Observation

Linear theory
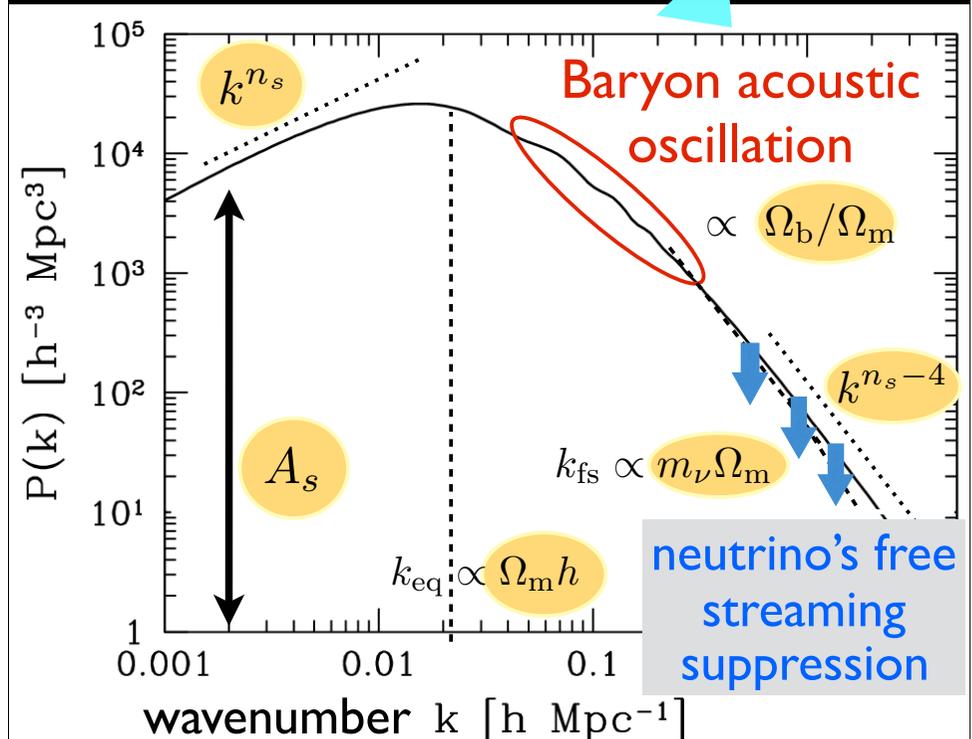
Anderson et al. ('12)

SDSS-III DR9
(BOSS)

2.6×10^5 galaxies

@ z~0.5

wavenumber $\quad \log_{10} \mathrm{k} \;/\; \mathrm{h\; Mpc^{-1}}$

k^{n_s}

Baryon acoustic
oscillation

$\propto\; \Omega_{\mathrm{b}}/\Omega_{\mathrm{m}}$

$k^{n_s - 4}$

A_s

$k_{\mathrm{fs}} \propto m_\nu \Omega_{\mathrm{m}}$

$k_{\mathrm{eq}} \propto \Omega_{\mathrm{m}} h$

neutrino's free
streaming
suppression

wavenumber $\mathrm{k}\;[\mathrm{h\; Mpc^{-1}}]$

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)

BOSS DR9 (SDSS-III)

Standard
· CMASS DR9
— best-fit model
$\chi^2 = 81.5 / 59$

DR9

DR10

DR11

Anderson et al. ('13)

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)

Angular diameter distance

Redshift z (=0~3)

Redshift z=1100

$$D_A = \frac{r_s}{\theta}$$

Acoustic oscillation scales

r_s

r_s

θ

cosmic expansion changes the distances !!

distant galaxies

cosmic microwave background

Upcoming/on-going projects

Multi-purpose ground- & space-based experiments

DES (2013~)

HETDEX (2016+)

DESI (2018+)
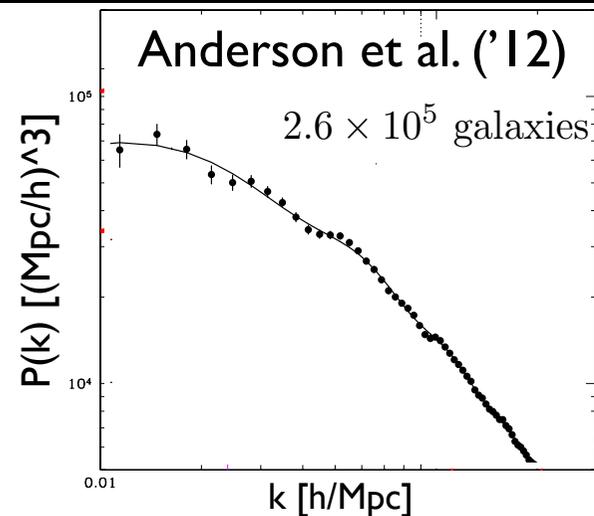
WFIRST (2024++)

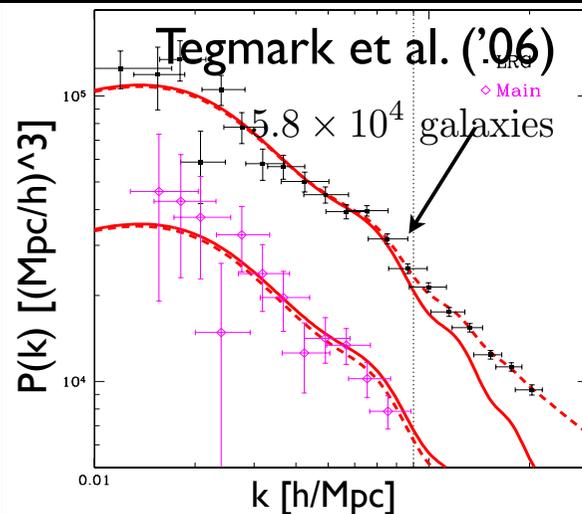space
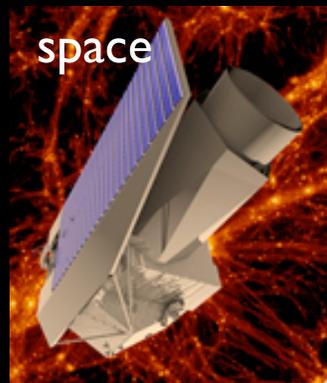
eBOSS (2014~)

Euclid (2020)

space
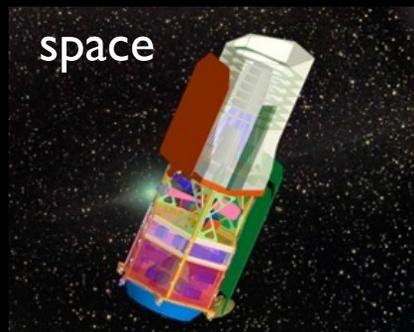
LSST (2022++)

SuMIRe (2014~)

subaru

LLS as precision cosmological tools

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

Tegmark et al. ('06)

5.8×10^4 galaxies

Anderson et al. ('12)

2.6×10^5 galaxies
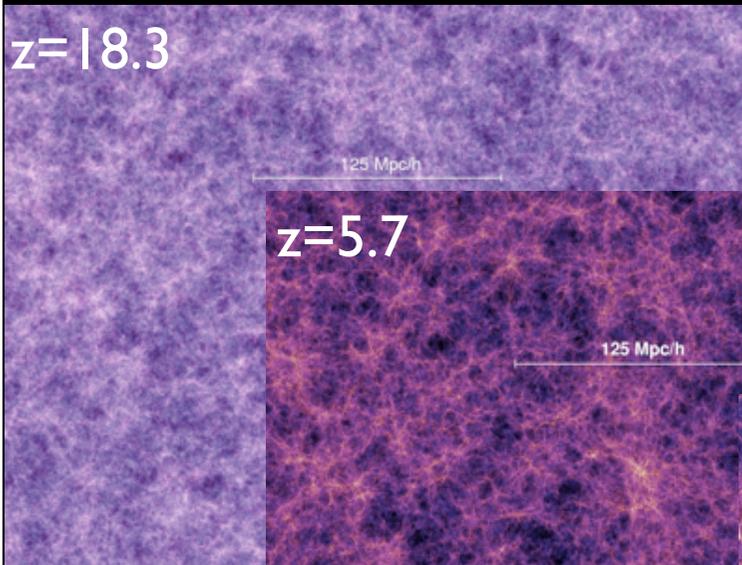
$10^7 \sim 10^9$ galaxies

~1% precision

New opportunity & scientific synergy :

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

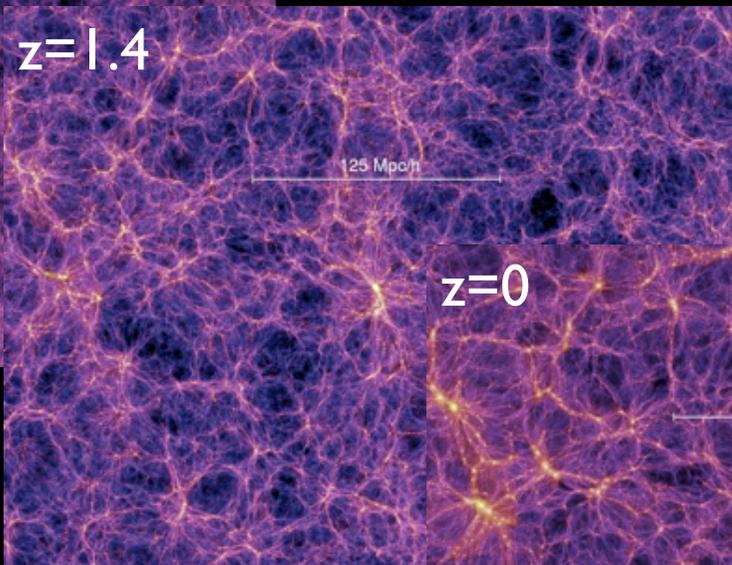Accurate theoretical description for LSS needs to be developed

Cosmological N-body simulation

z=18.3

z=5.7

z=1.4

z=0

Self-gravitating many-body system
in an expanding universe

$N \rightarrow \infty$

$$\frac{\vec{p}_i}{dt} = -\frac{Gm^2}{a} \sum_{j \neq i}^{N} \frac{\vec{x}_i - \vec{x}_j}{|\vec{x}_i - \vec{x}_j|^3} \quad \vec{p}_i = ma^2 \frac{d\vec{x}_i}{dt}$$
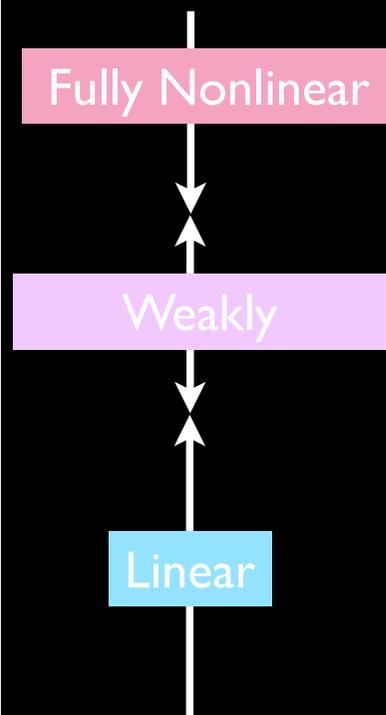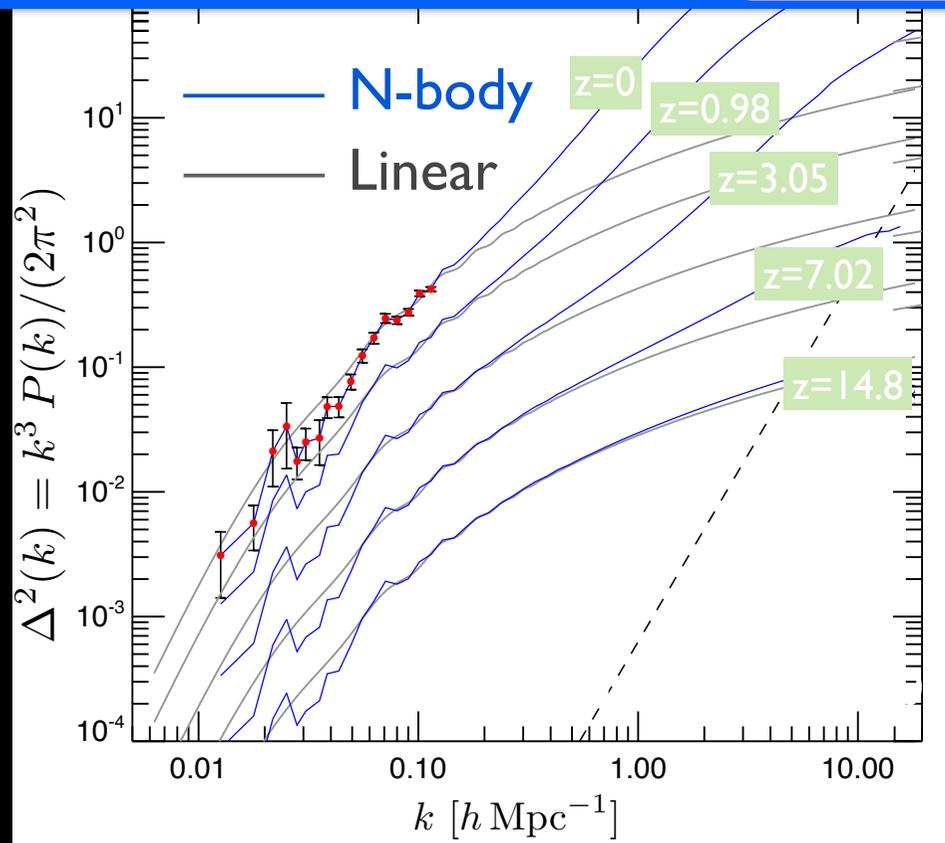
$$(i = 1, 2, \cdots, N)$$

125 Mpc/h

Formation of halos and
filamentary structure

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

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Nonlinear power spectrum

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

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

26th June

27th June

28th June

Note and supplements

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

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

物理学基礎論特別講義 5 「暗黒物質宇宙における構造形成」

Intensive course on "Structure formation in the dark matter dominated universe"

日時: 2017年 6月26日(月)~28日(水)

場所: 名古屋大学理学部物理学教室 ES656講義室

- Lecture note: PDF
- Supplemental materials
  - Overview: PDF
  - Linear theory of structure formation: PDF
  - Observational effects: PDF
  - Analytic approaches to nonlinear structure formation: PDF
  - Selected topics on dynamics and statistics of large-scale structure: PDF
- Assignment: PDF