2016年11月15-17日

東京大学大学院理学系研究科物理学専攻

物理学特別講義 B XVI

宇宙大規模構造と観測的宇宙論

Observational cosmology with large-scale structure

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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)

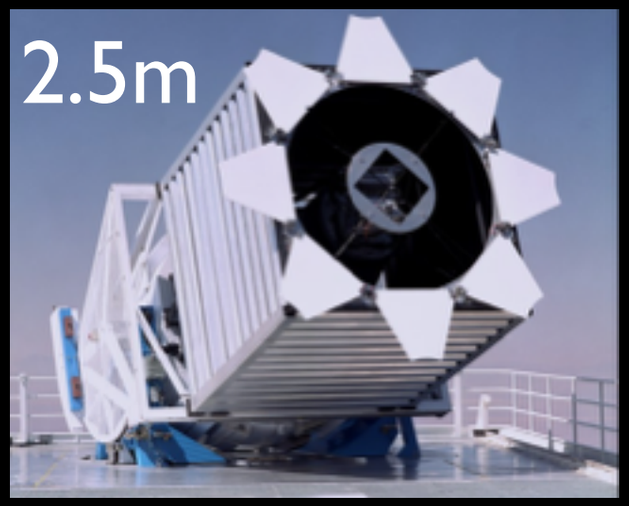
Observing large-scale structure

Intensive use of telescope is necessary

Very Large Telescope (Chile)

Subaru Telescope (Hawaii)

Canada-France-Hawaii Telescope (Hawaii)



Sloan Digital Sky Survey @ APO (New Mexico)

Blanco telescope @ CTIO (Chile)

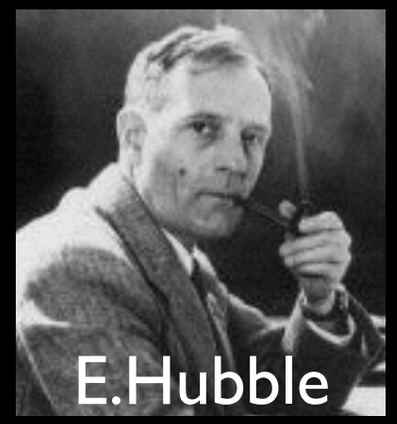
https://en.wikipedia.org/wiki/Very_Large_Telescope
http://www.sdss.org/instruments/
http://subarutelescope.org/Information/Download/DImage/index.html
http://www.cfht.hawaii.edu/en/news/CFHT30/#wallpaper
http://www.darkenergysurvey.org/DECam/index.shtml

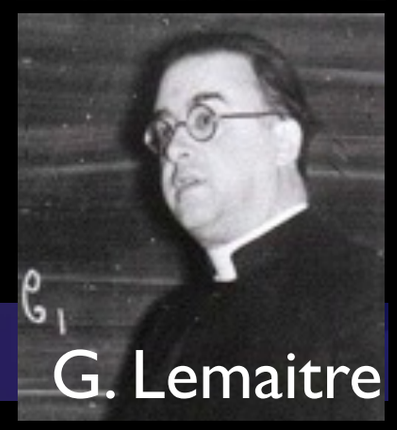
Redshift

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

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

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


E.Hubble

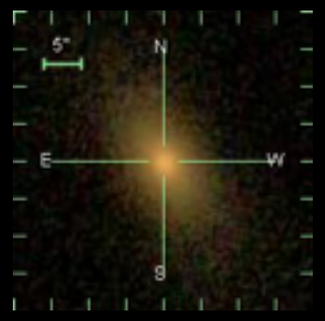

G. Lemaitre

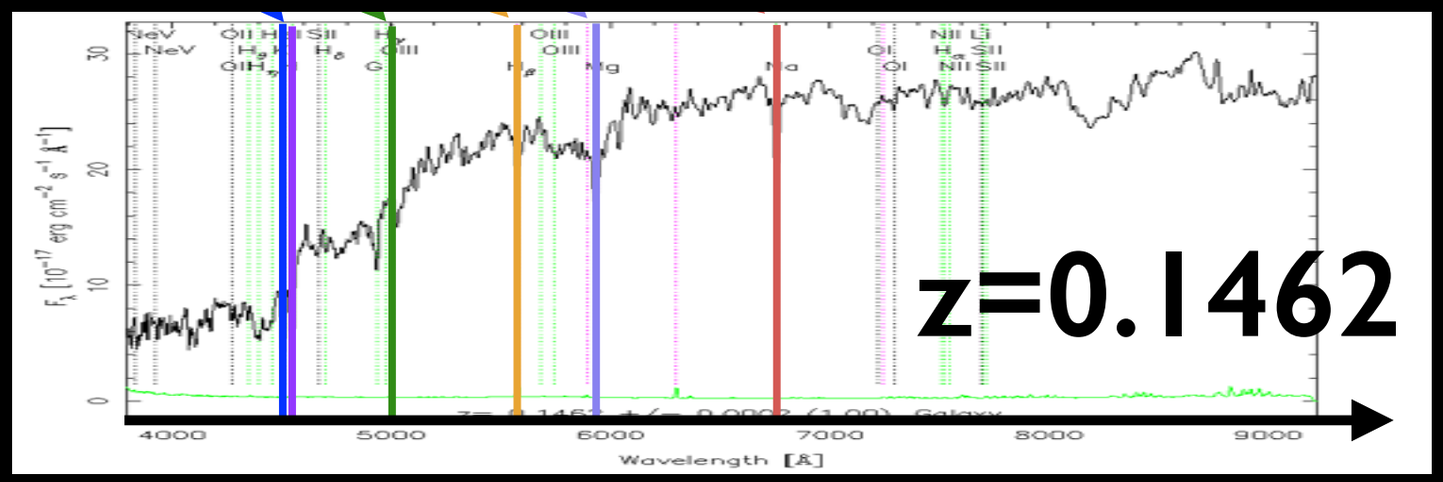
Hubble law

recession 'velocity' $v = H\,d$ distance to galaxy

(= c z) Hubble parameter

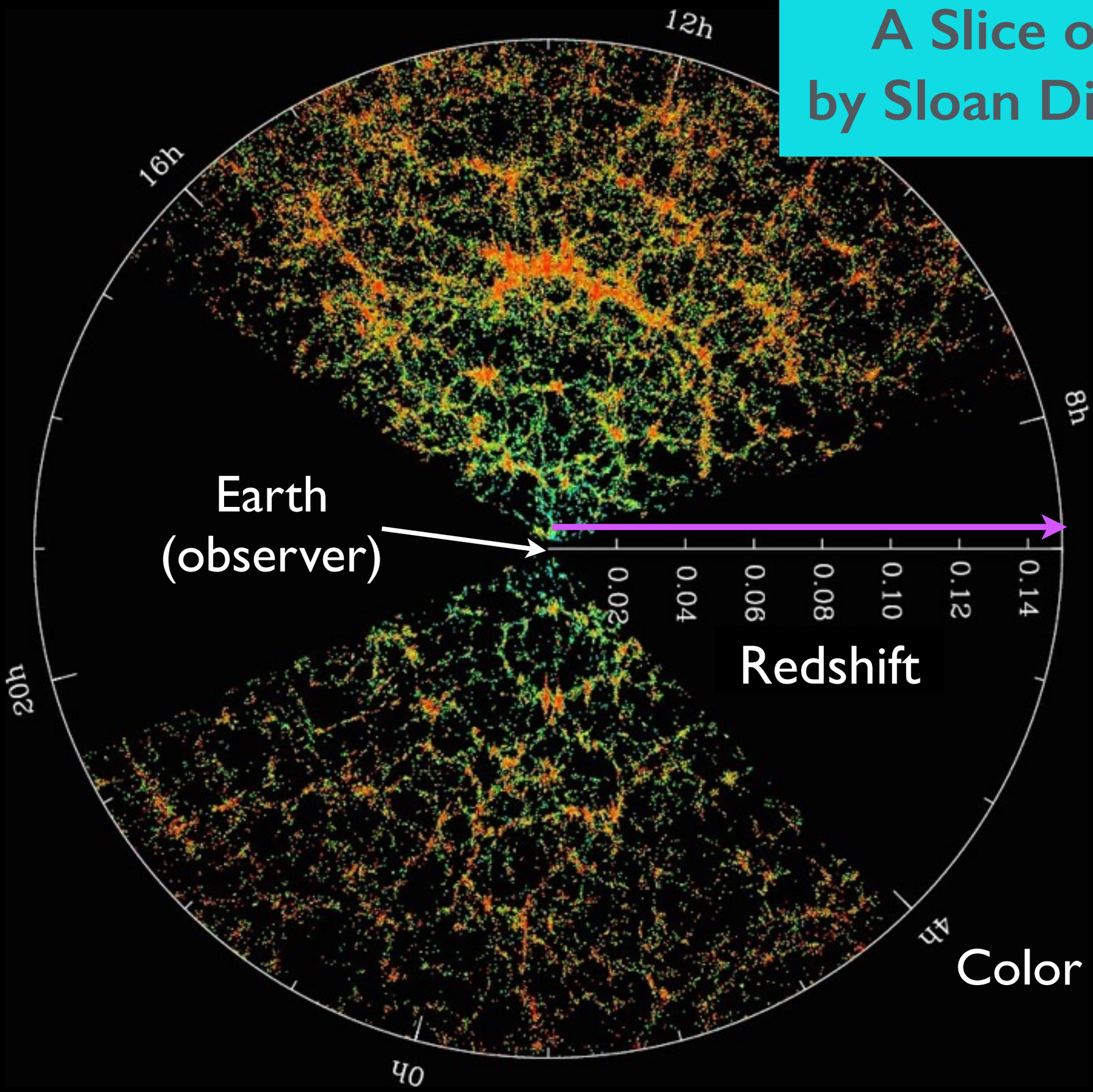
Distant galaxy





SDSS SkyServer

A Slice of galaxy catalog by Sloan Digital Sky Survey II



finished in 2008

2 G yrs

(look back time)

Color indicates age of galaxy

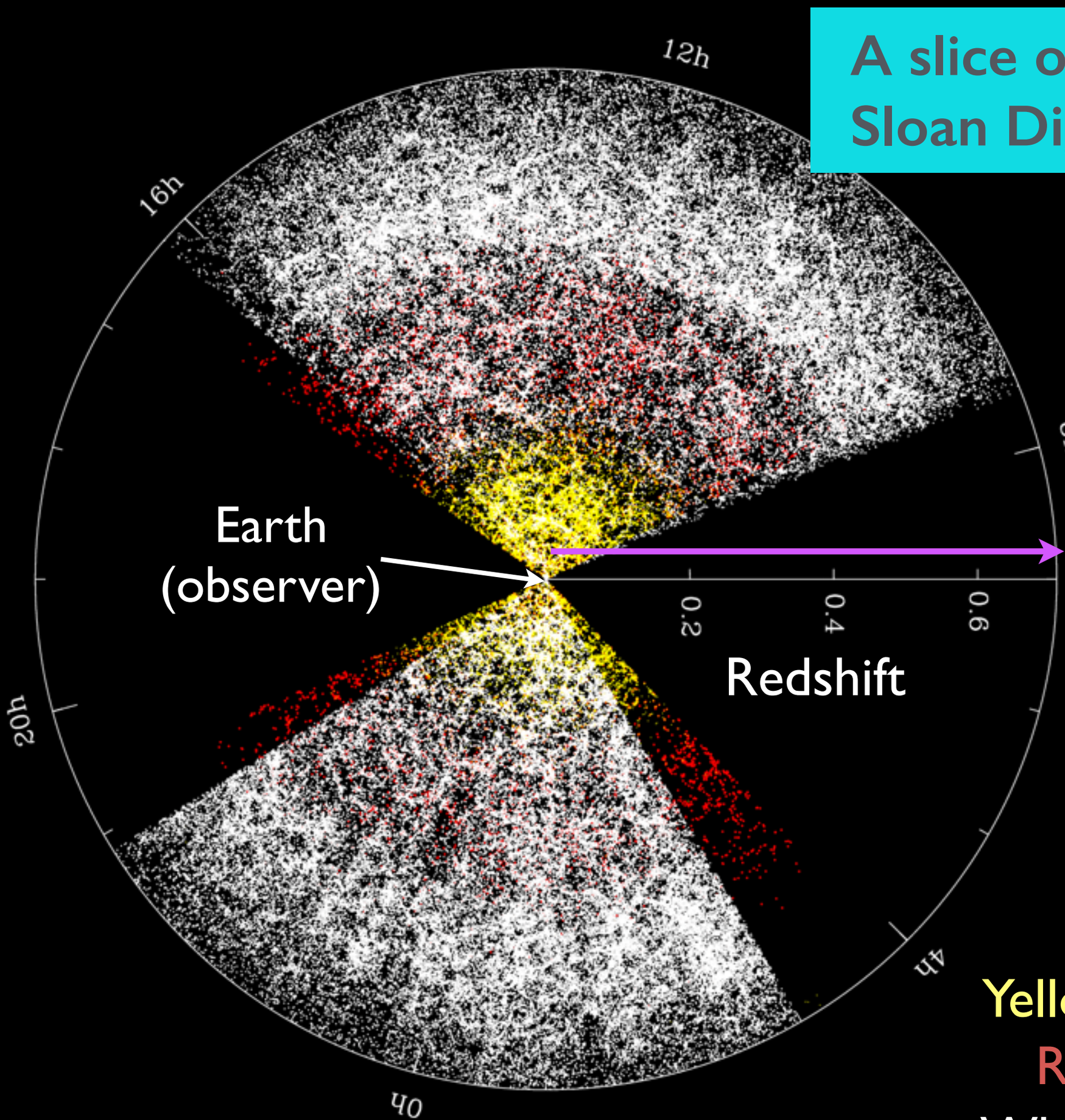
Blue : young

Red : old

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

A slice of galaxy catalog by Sloan Digital Sky Survey III

finished in 2014



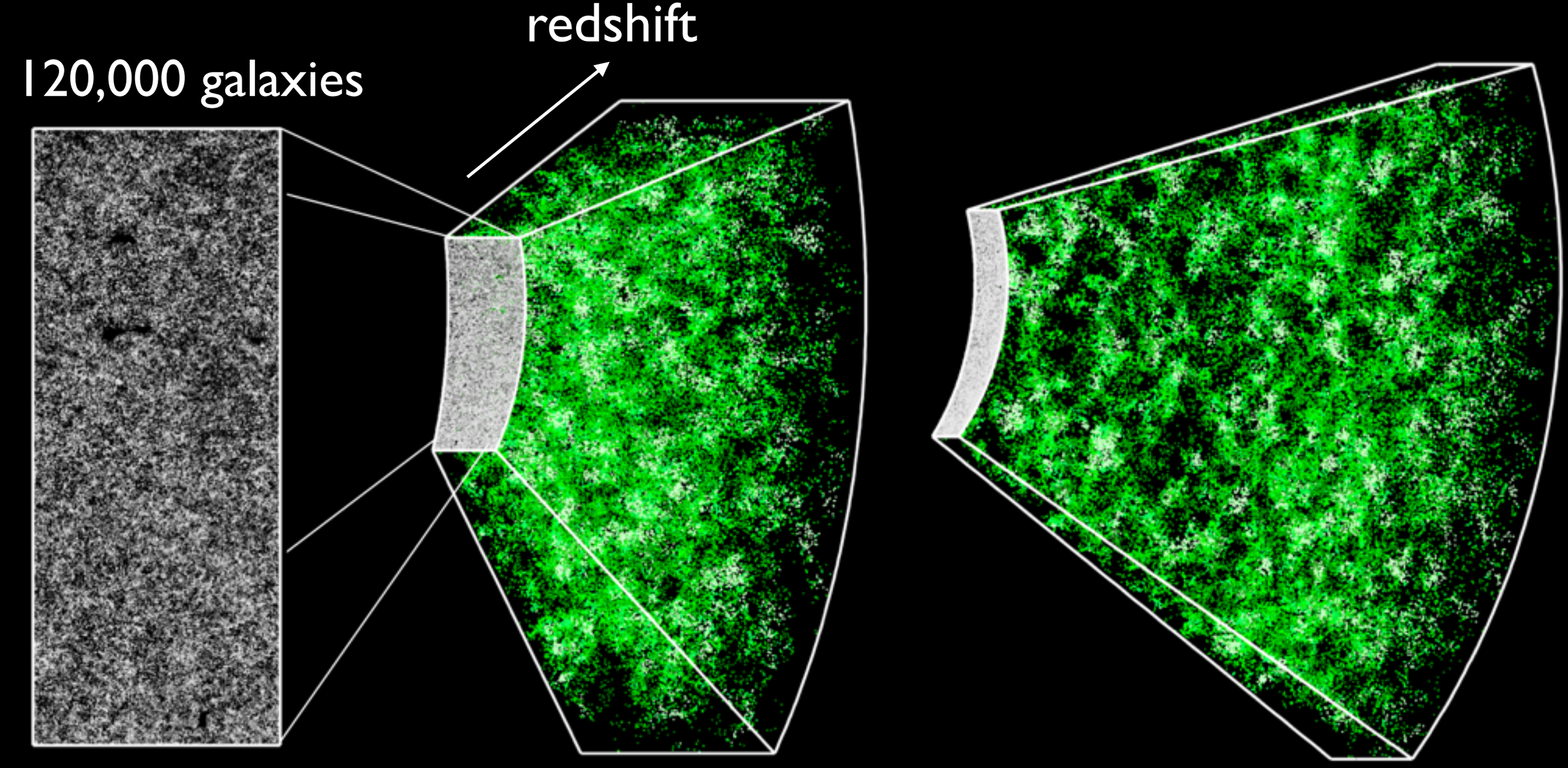
Yellow：SDSS-II main

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/

Cosmology with galaxy 3D map

Statistical properties

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

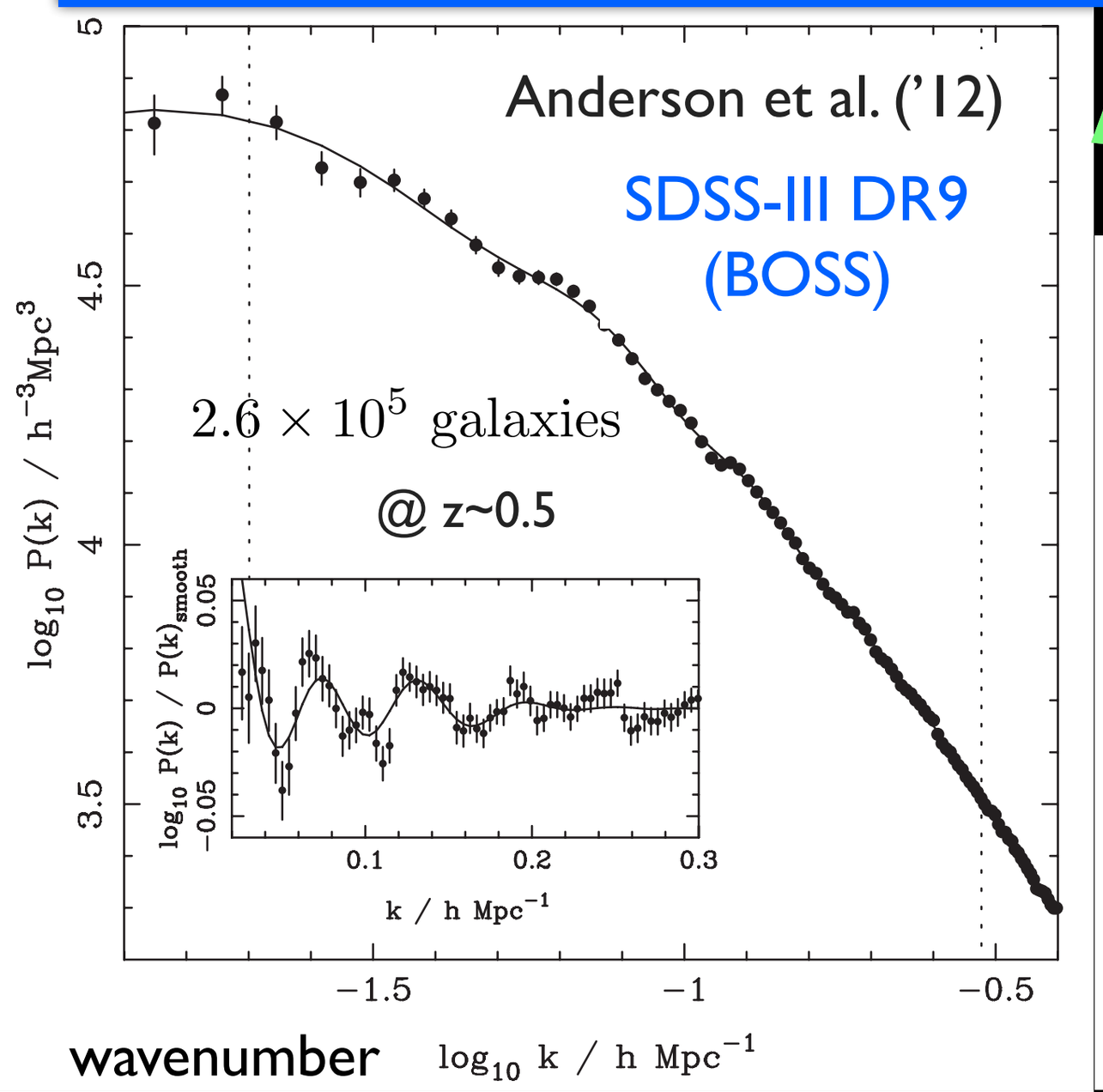
Gauging the scales of large-scale structure

$(\vec{\theta}, z)$ ← cosmology → $\vec{r}$

Angular position & redshift (comoving) distance

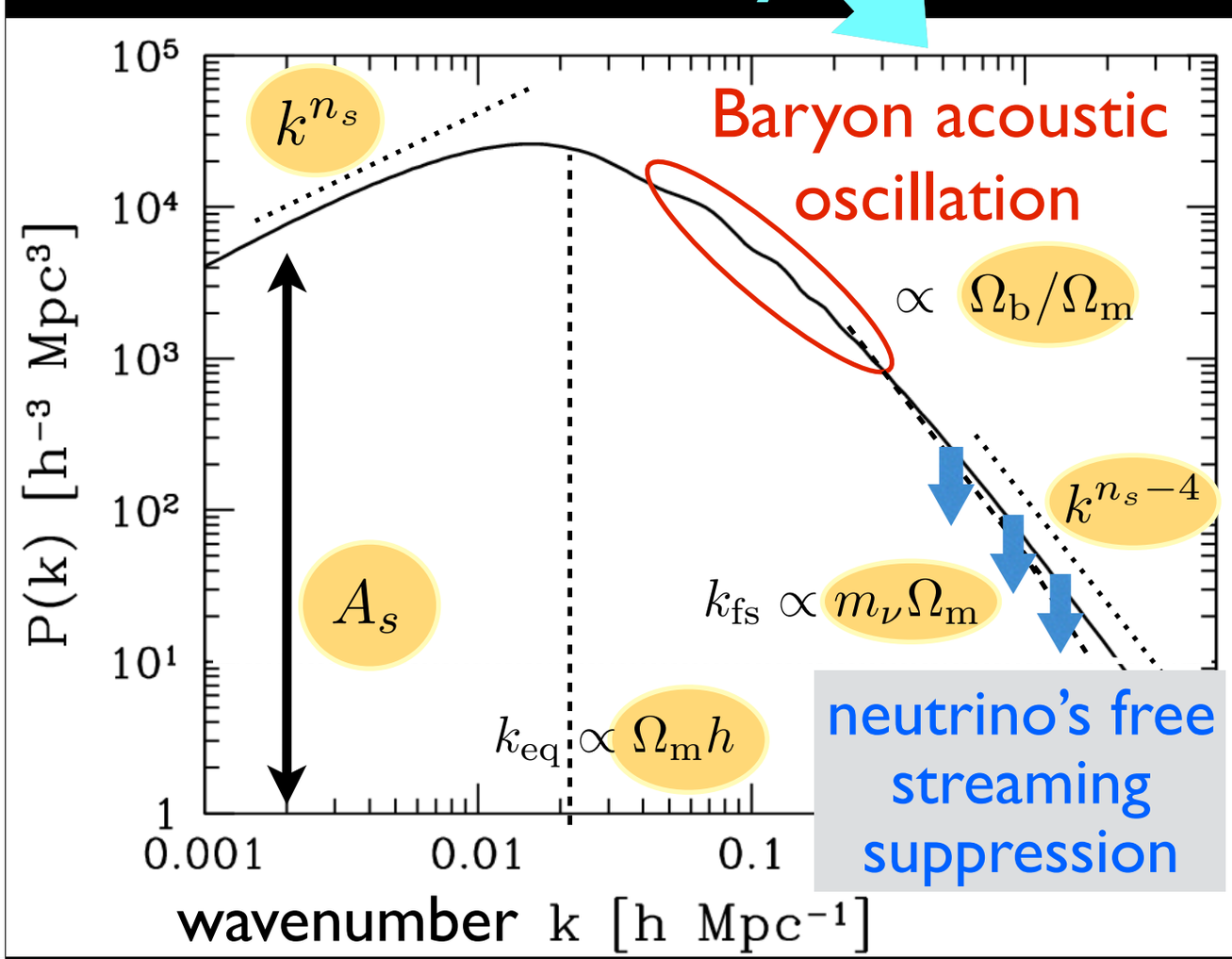
Power spectrum of matter fluctuations

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



Observation

Linear theory



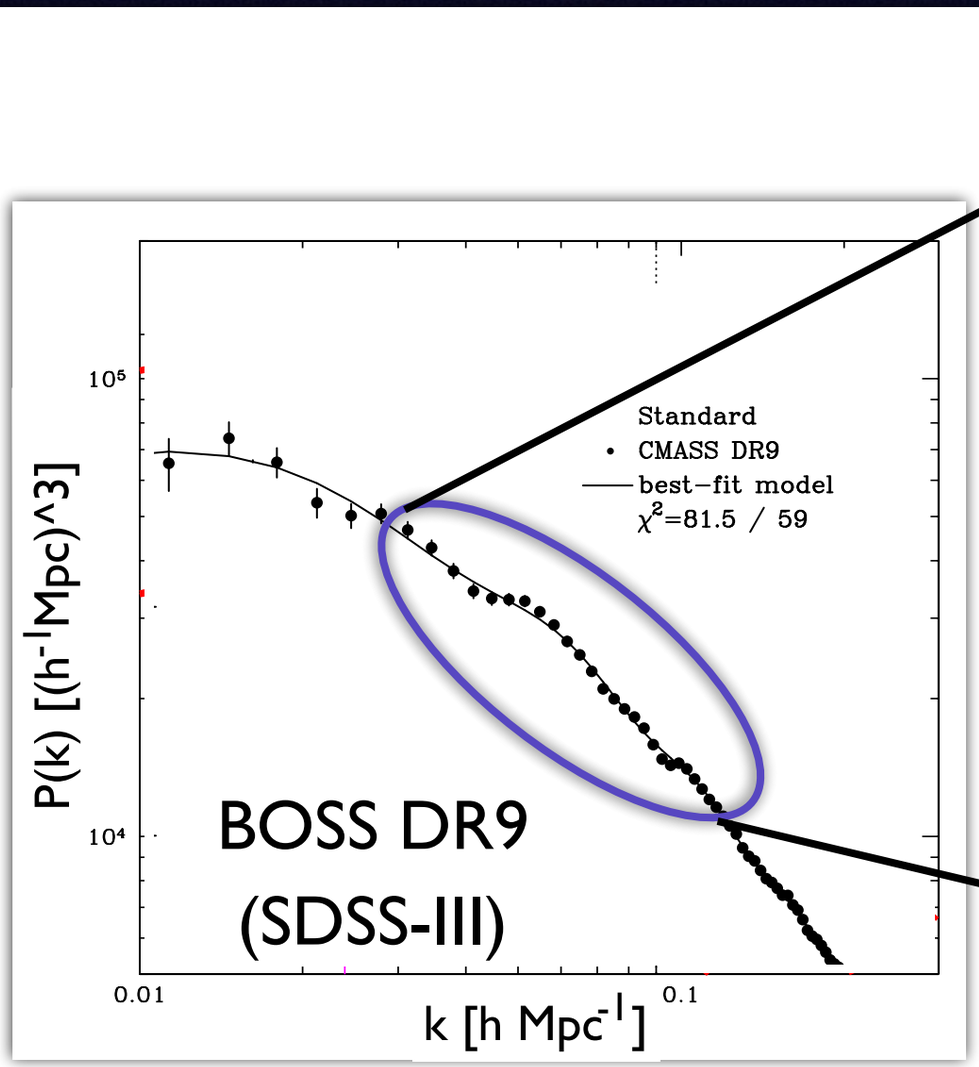
Baryon acoustic oscillations (BAO)

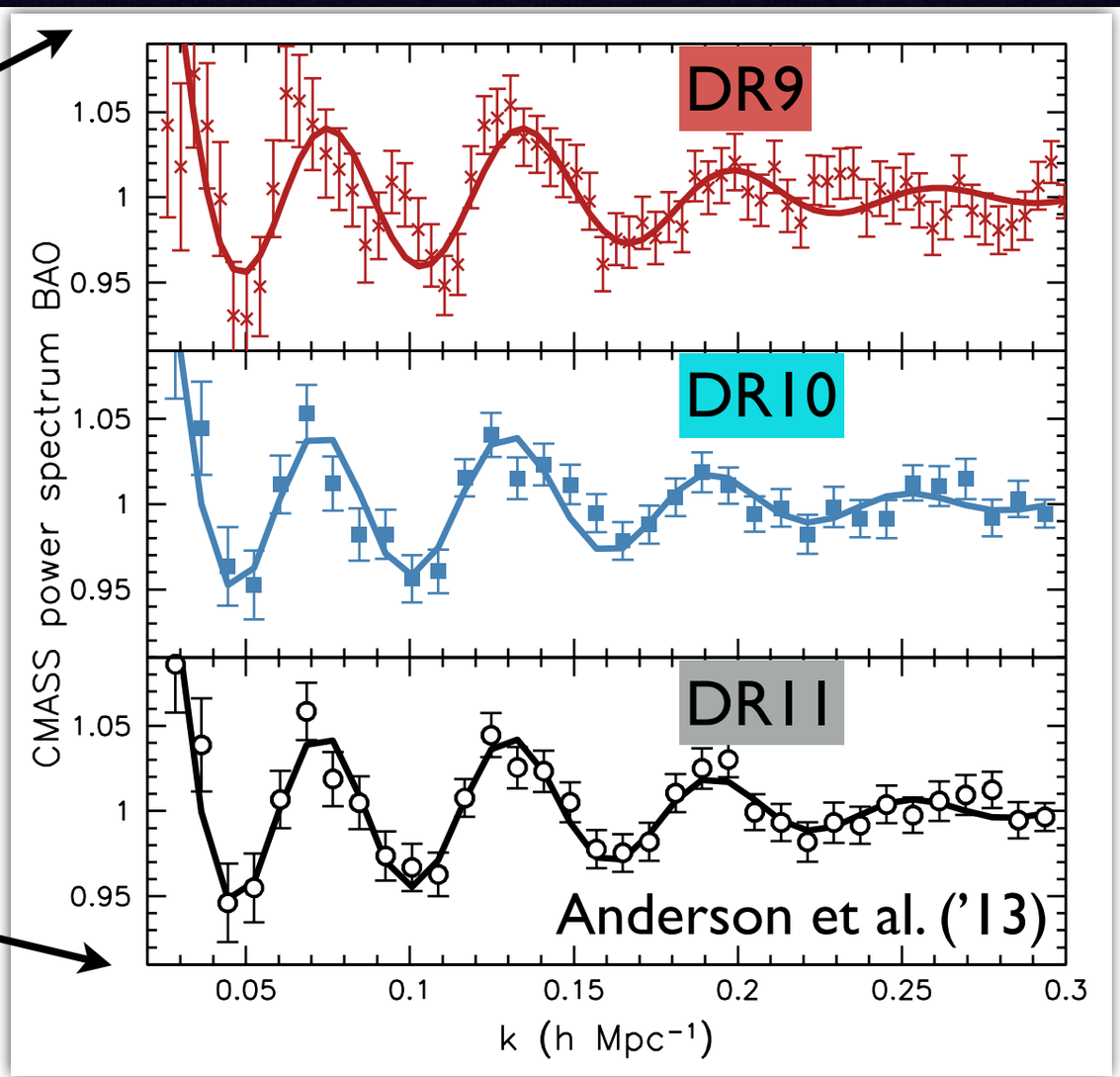
- Characteristic scale of primeval baryon-photon fluid (~150Mpc)

(⇔ acoustic signal in CMB anisotropies)

- Can be used as <u>standard ruler</u> to measure cosmic expansion

(theoretical prior)





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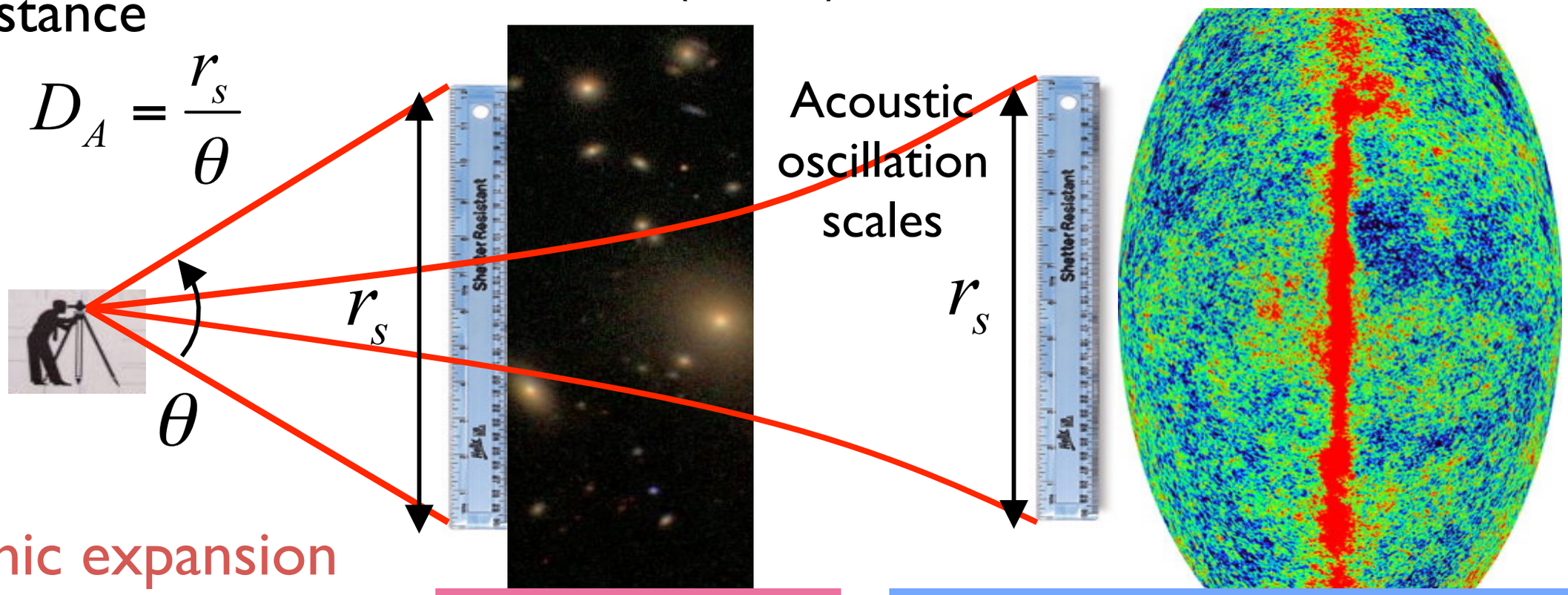
Angular diameter distance

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

Redshift z (=0~3)

Redshift z=1100



cosmic expansion changes the distances !!

distant galaxies

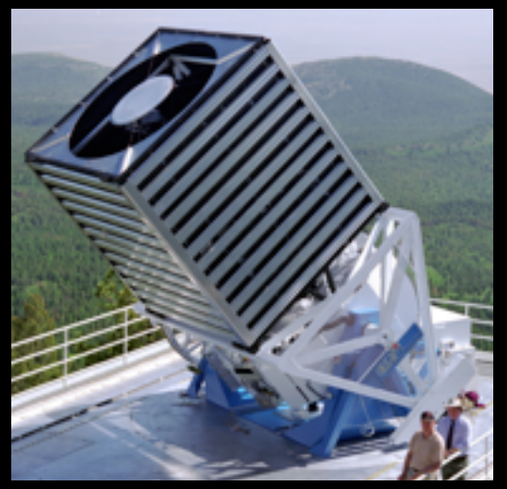
cosmic microwave background

Upcoming/on-going projects

Multi-purpose ground- & space-based experiments

DES (2013~)

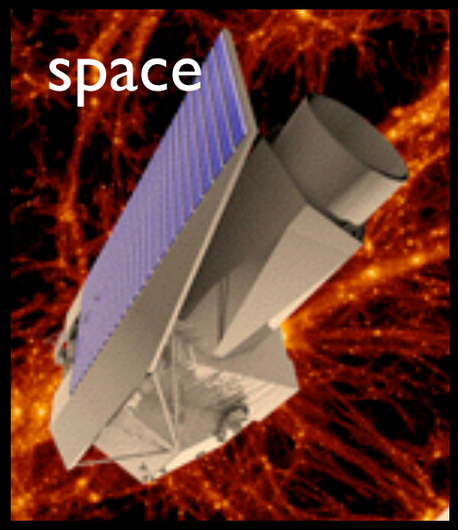
HETDEX (2016+)

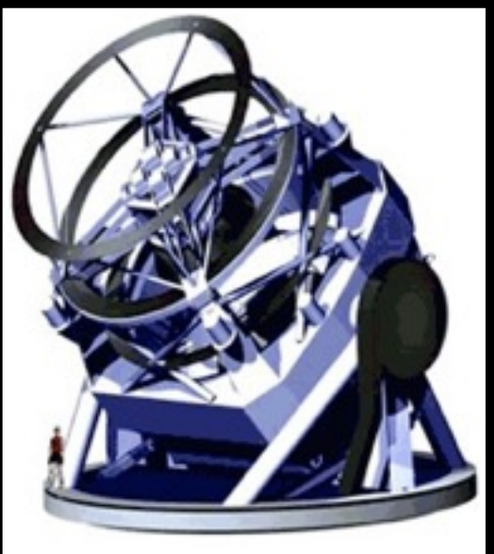


eBOSS (2014~)

DESI (2018+)

WFIRST (2024++)





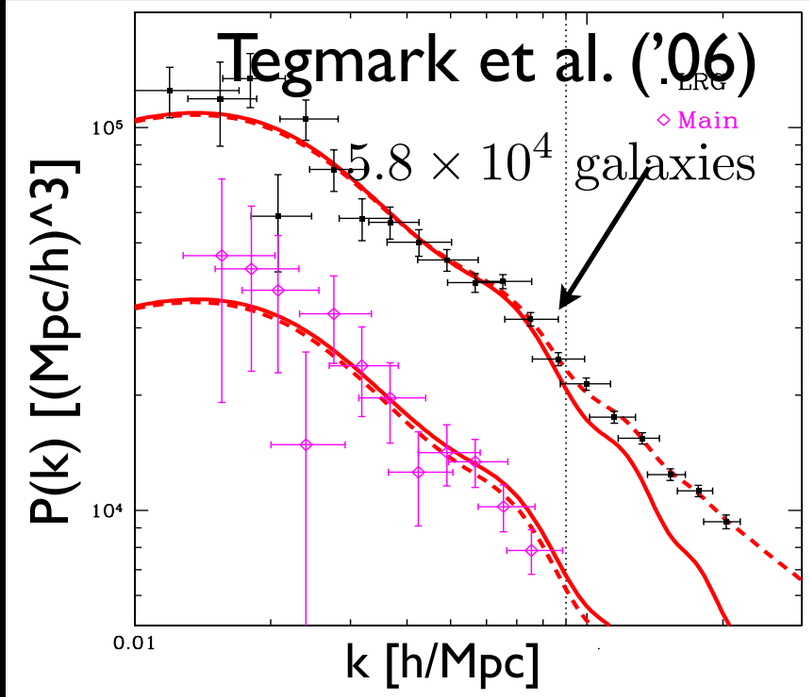
LSST (2022++)

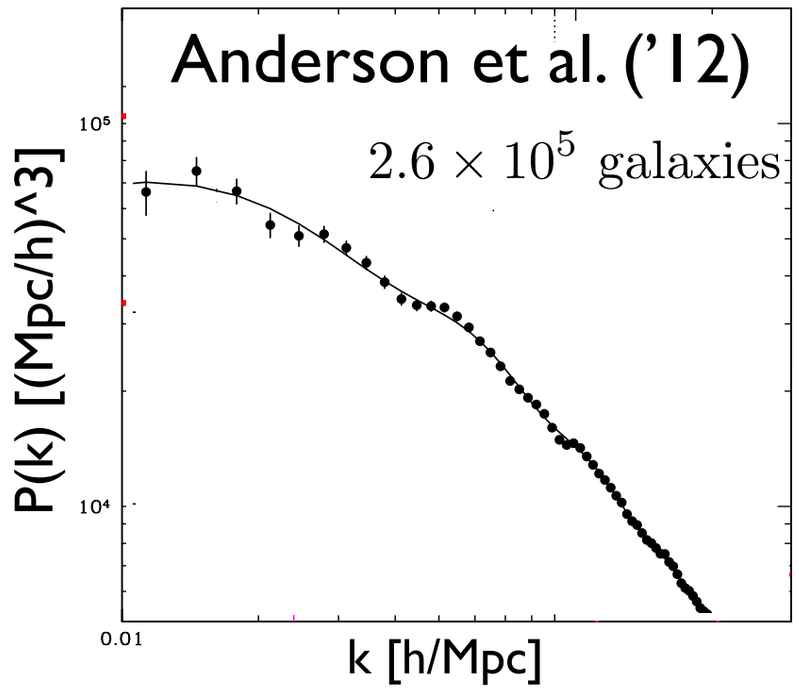
Euclid (2020)

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

Goal of this lecture

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

- Theoretical basis of formation & evolution of LSS
  - Standard model of structure formation: ΛCDM
  - Cosmological information imprinted on LSS
- Theoretical tools to confront with precision observations of LSS
  (mainly focusing on galaxy surveys)
  - precision theoretical calculations of LSS

Plan

- Friedmann cosmology

15th Nov.

- Linear theory of structure formation
- Observational effects:

  Redshift-space & geometric distortions

16th Nov.

17th Nov.

- Analytic approaches to nonlinear structure formation