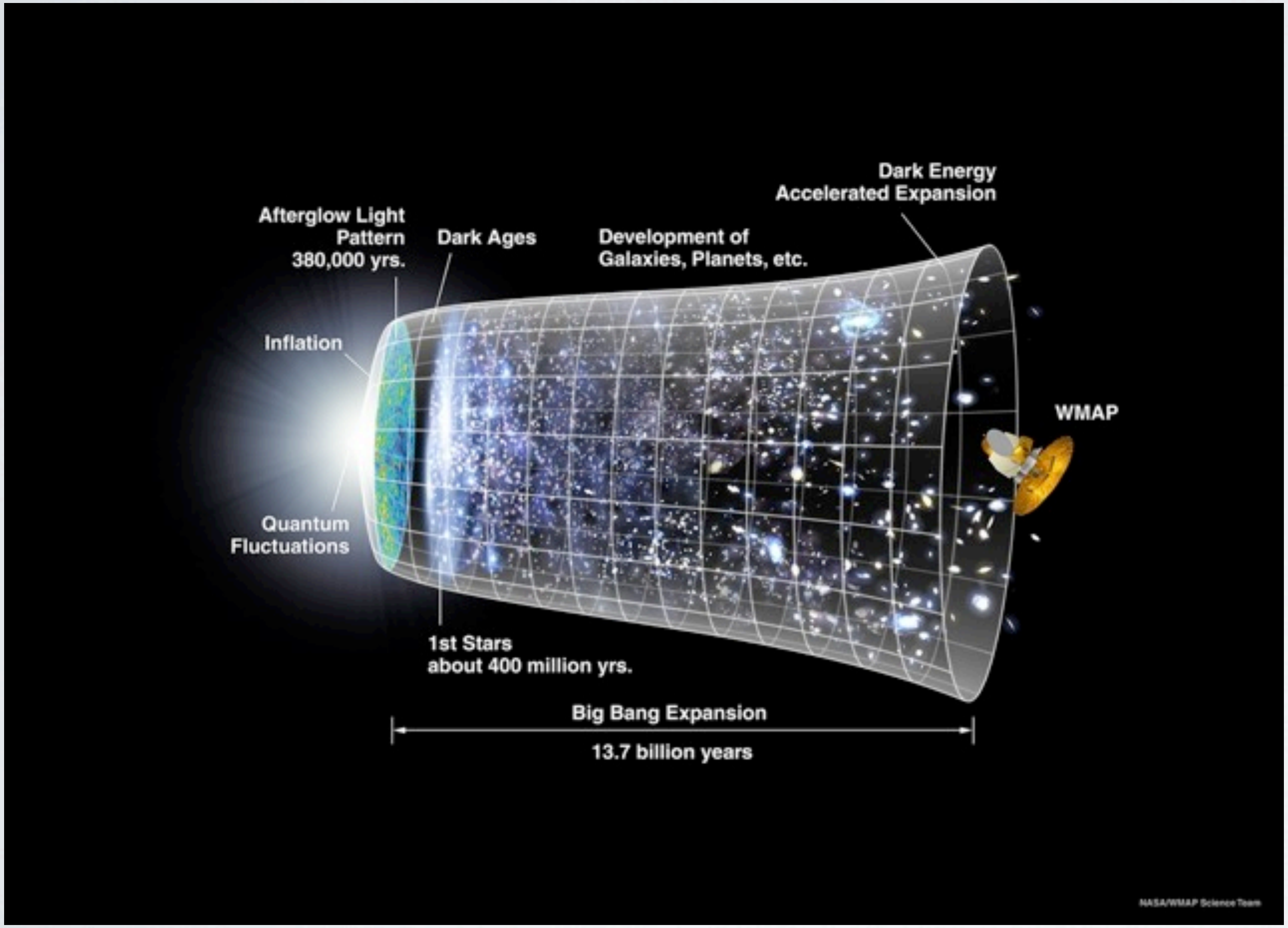
WiggleZ Dark Energy Survey

Baryon Acoustic Oscillations (BAOs) @ z=0.6
and
Redshift Distortion (RSD) since z=0.9

Blake *et. al.* 2010, MNRAS **406** 803
Blake *et. al.* 2011, arXiv:1104.2948
Blake *et. al.* 2011, arXiv:1105.2862

@ 第110回雑誌会 June 3rd, 2011

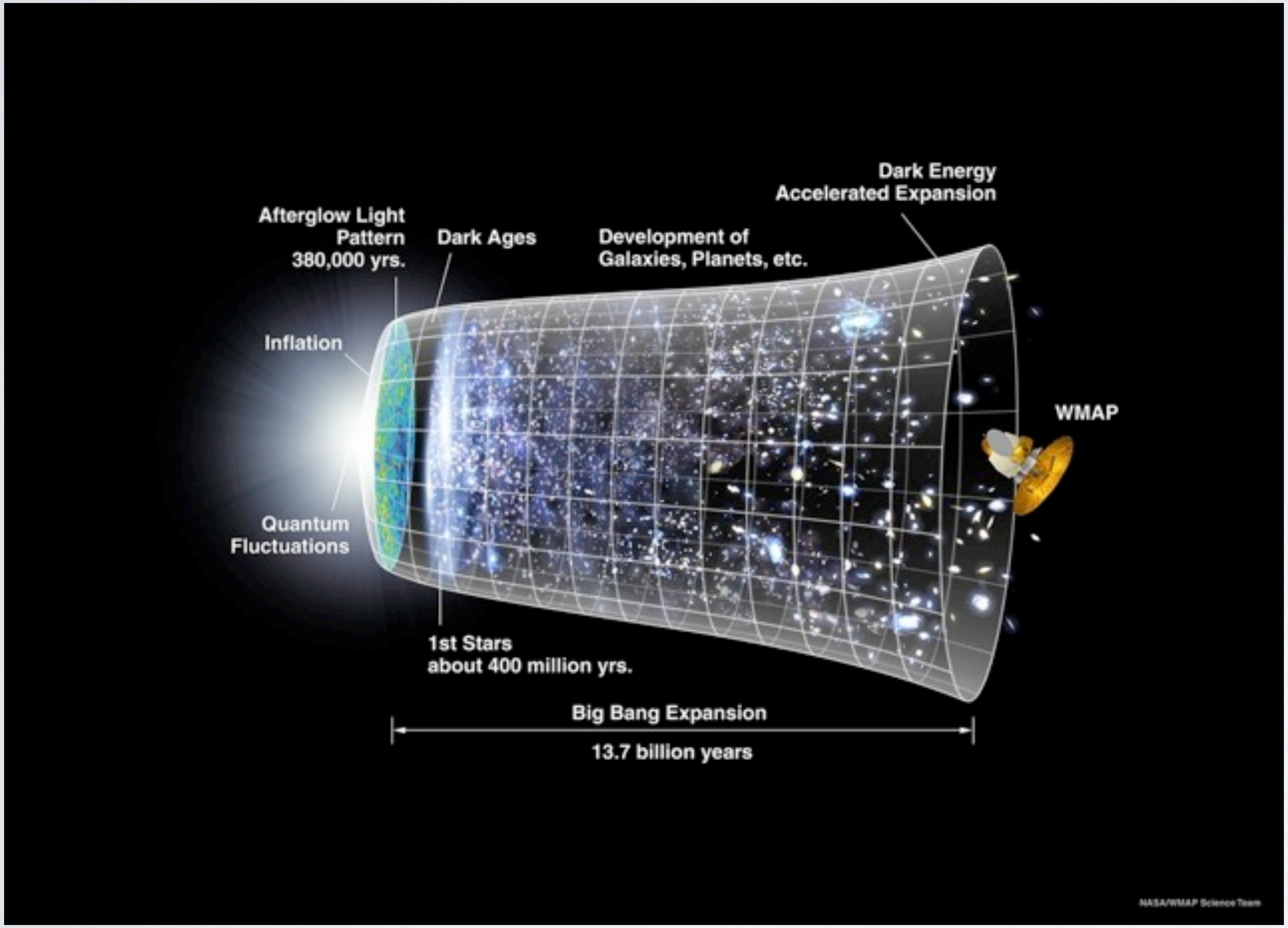
A review of last week
~ Naonori's talk ~



http://map.gsfc.nasa.gov/

- At the beginning of the universe, *inflation* expands the universe rapidly.
- Inflation also generate the primordial curvature perturbations.

Today's talk



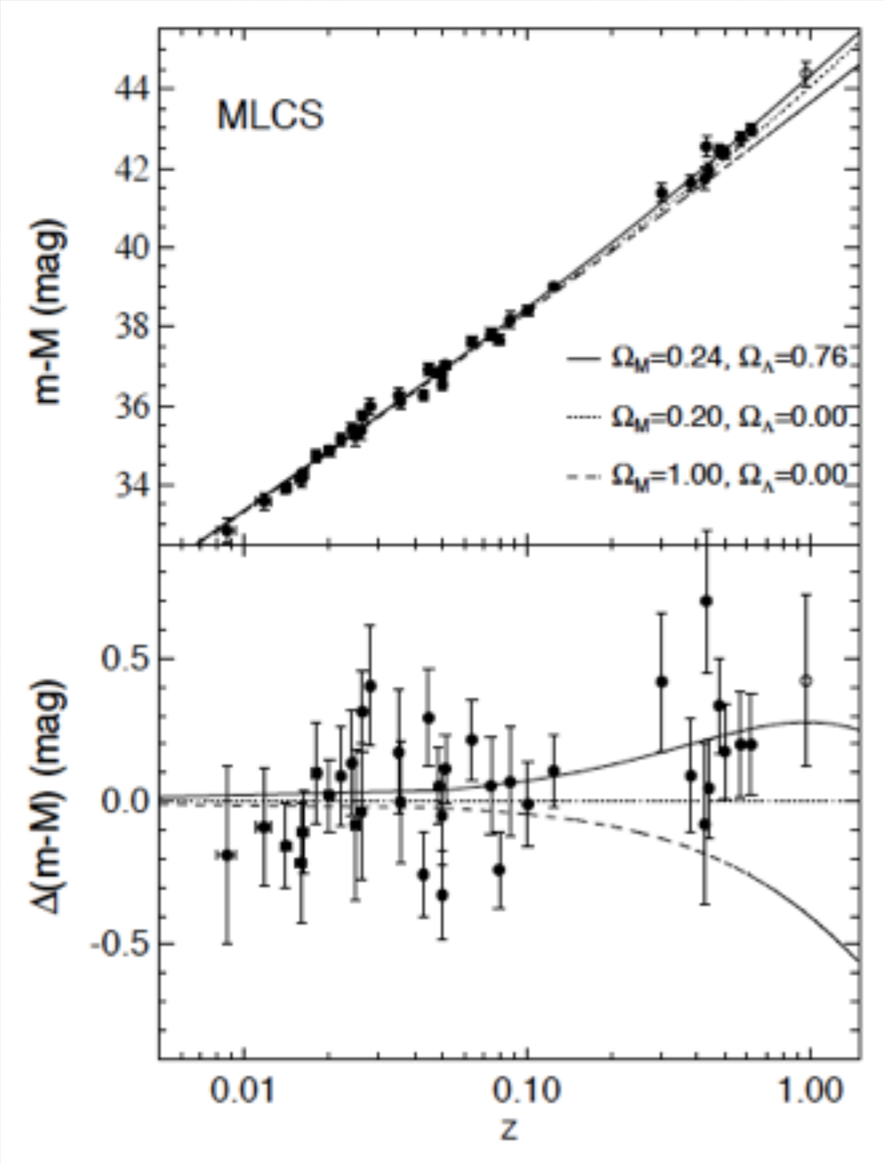
- After the inflation, how evolve the universe and the perturbations.
- How can we investigate the status of the universe.
- WiggleZ results as an example.

Content

1. Introduction (accelerating universe, dark energy and modified gravity)
2. BAO in WiggleZ (physics of BAO, result from WiggleZ)
3. RSD in WiggleZ (physics of RSD, result from WiggleZ)
4. Summary

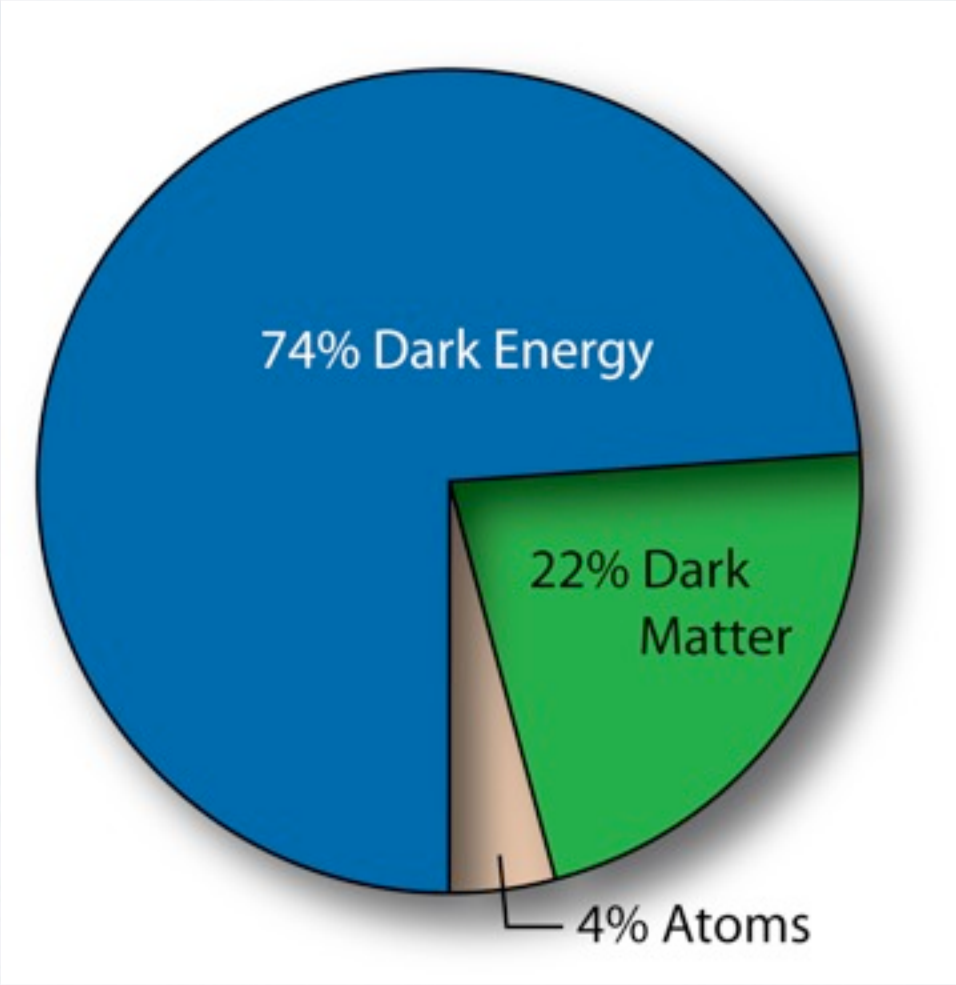
Accelerating universe

Riess *et. al.* 1998



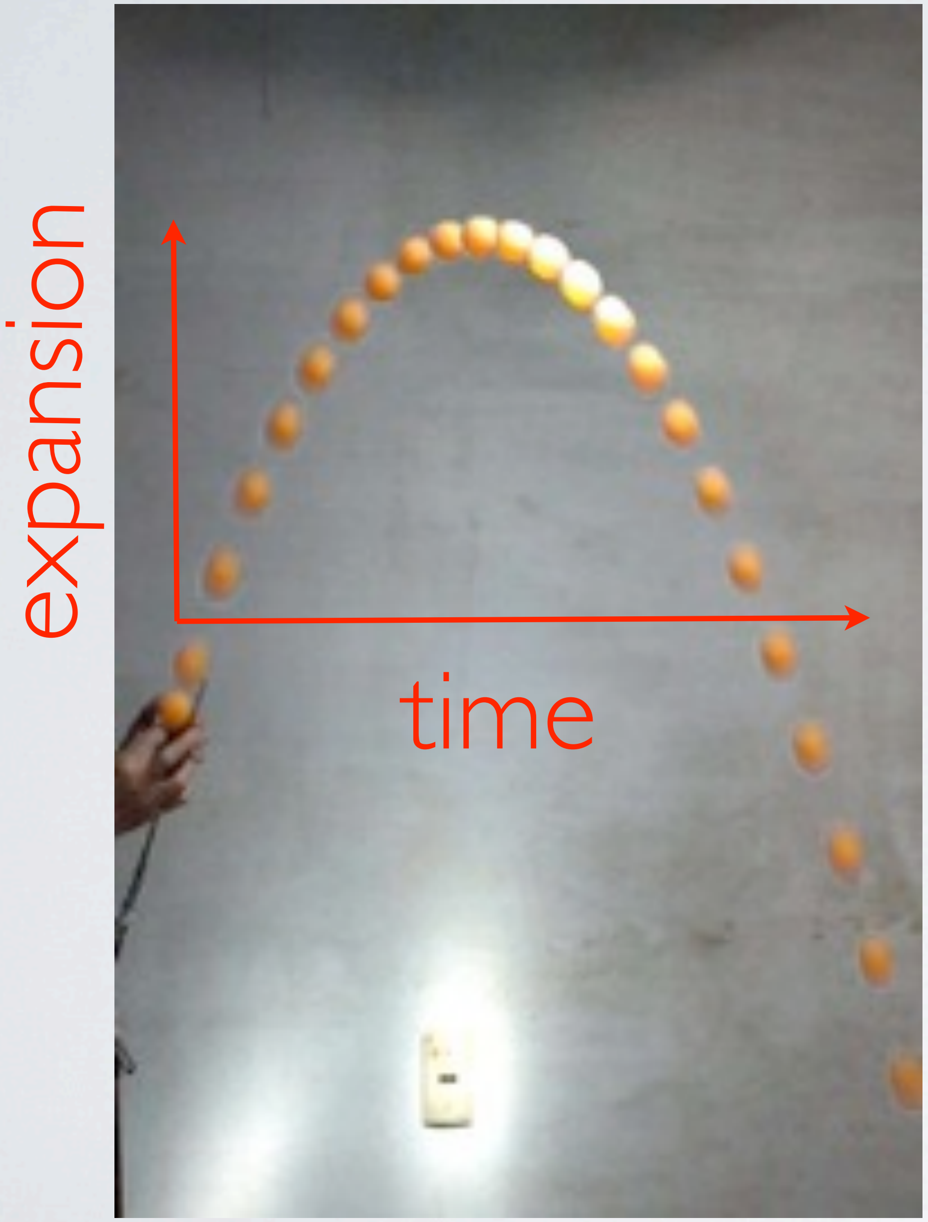
The present universe is accelerating, which was confirmed by SNIa, CMB, galaxy clustering, weak gravitational lensing...

http://map.gsfc.nasa.gov/



If we attribute this acceleration to the dark energy, it dominates the current universe.

Why the cosmic acceleration is bad (or exciting)



- Cosmic expansion is determined by energy(matter) content of universe through the Einstein equation

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

- Normal matter can only act as attractive force, so that the cosmic expansion always decreases

- We can not explain the current observation with well-known physics = *bad*

- This fact imply that the cosmic acceleration is caused by the new physics = *exciting*

Simple solution: cosmological constant Λ

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

- Cosmological constant is proposed by Einstein originally, in order to make the universe static
- Λ has negative pressure and can cause the accelerating expansion
- strong point : simple, link with vacuum energy of QFT
- weak point : $\rho_{vac}=10^{74}$GeV, $\rho_{\Lambda}=10^{-47}$GeV

⇒ some researchers try to consider the *alternative* solution

How accelerate the universe ?

Dark Energy: DE

vs

Modified Gravity: MG

Expansion of Universe is governed by the Theory of Gravity, i.e., General Relativity

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

In order to accelerate the universe, one have to weaken the gravitational force

1. change the RHS : ***dark energy (DE)*** which has a negative pressure $p/\rho = w < -1/3$
   quintessence, k-essence, phantoms, coupled dark energy, ...
2. change the LHS : ***modified gravity (MD)***
   f(R) gravity, scalar-tensor theories, blaneworld, ...

Similar to Inflation,
the number of DE/MG model = the number of researcher who research DE/MG.

Expansion of Universe
vs
Growth of (cosmological) structure

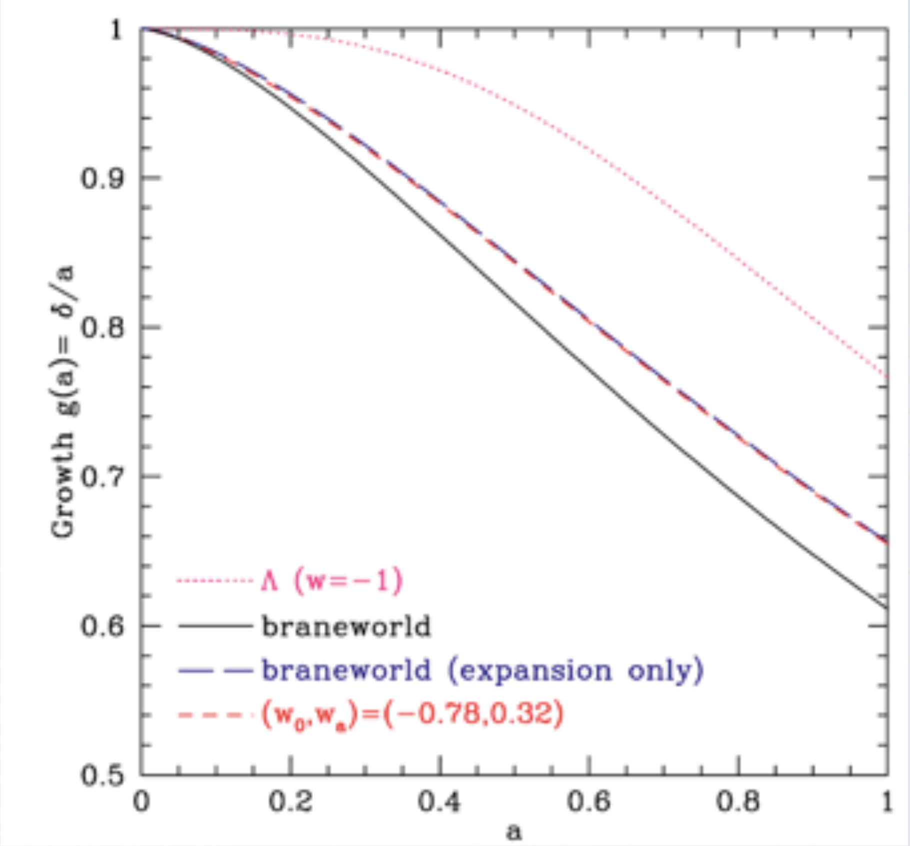
expansion

$$H(z) = H_0 \left[\Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\mathrm{de},0} a^{-3(1+w)}\right]^{1/2}$$

growth

$$f(z) = \frac{d\ln D(z)}{d\ln a} = \frac{d}{d\ln a}\ln\left(\frac{\delta(z)}{\delta(z=0)}\right) = [\Omega_{\mathrm{m}}(z)]^{\gamma}$$

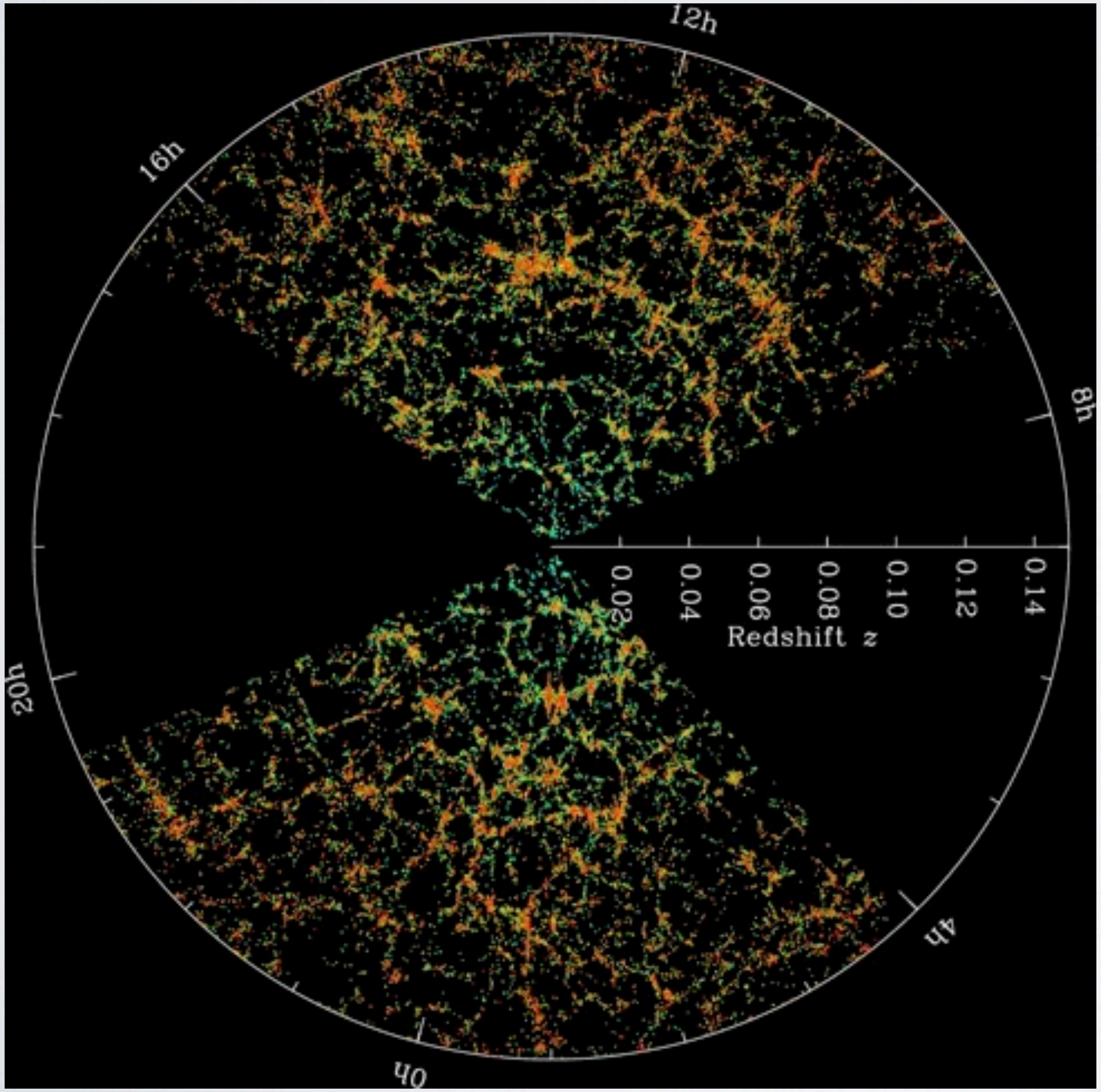
- γ=0.55 & w=-1 ➞ cosmological constant
- γ=0.55 & w≠-1 ➞ dark energy
- γ≠0.55 ➞ modified gravity



linder 04

Galaxy redshift survey

Sloan Digital Sky Survey(SDSS)

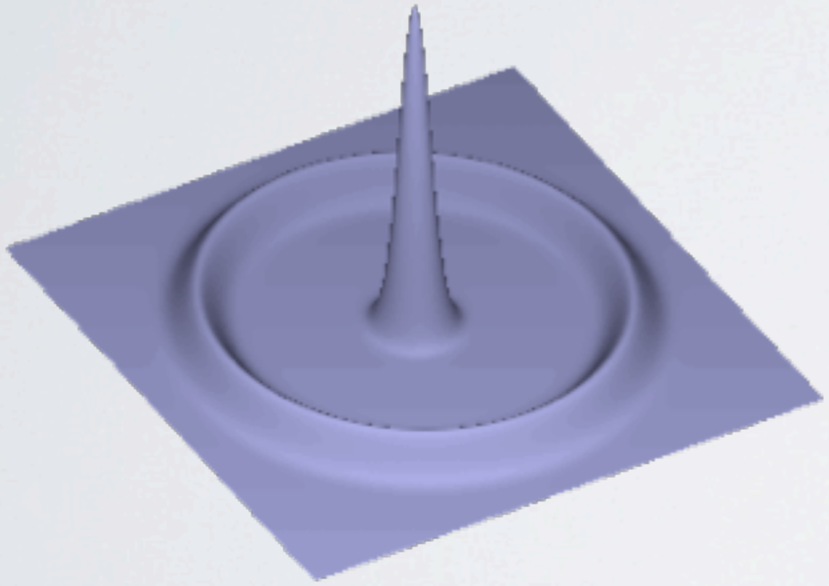


- Galaxy redshift survey measure the angular position and redshift of galaxies, and clarify the clustering pattern of galaxies.

http://www.sdss.org/

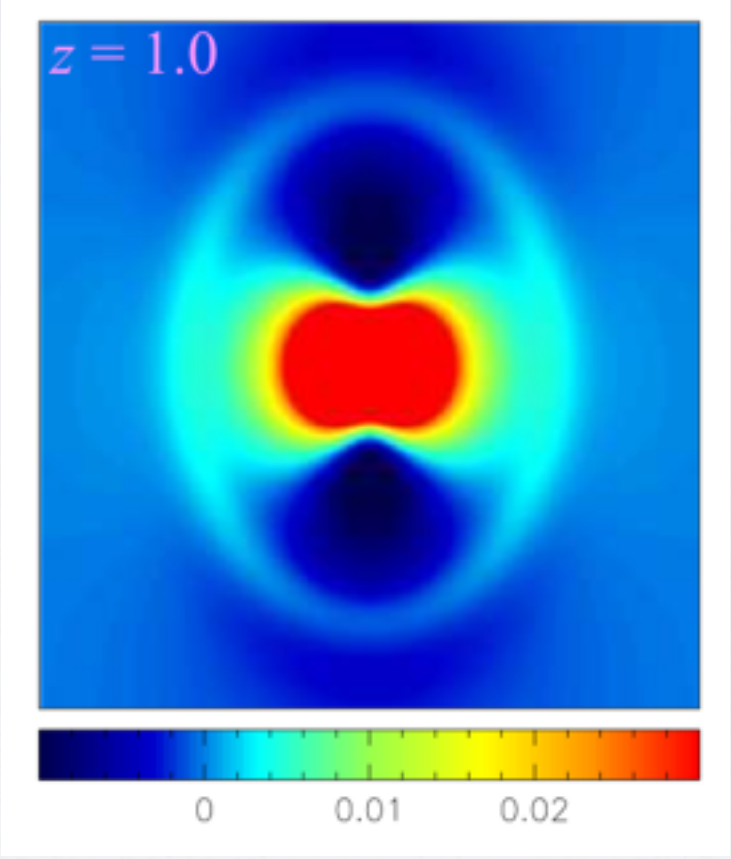
The 3 sacred treasures for attacking the dark energy / Modified gravity from galaxy clustering pattern

- BAO



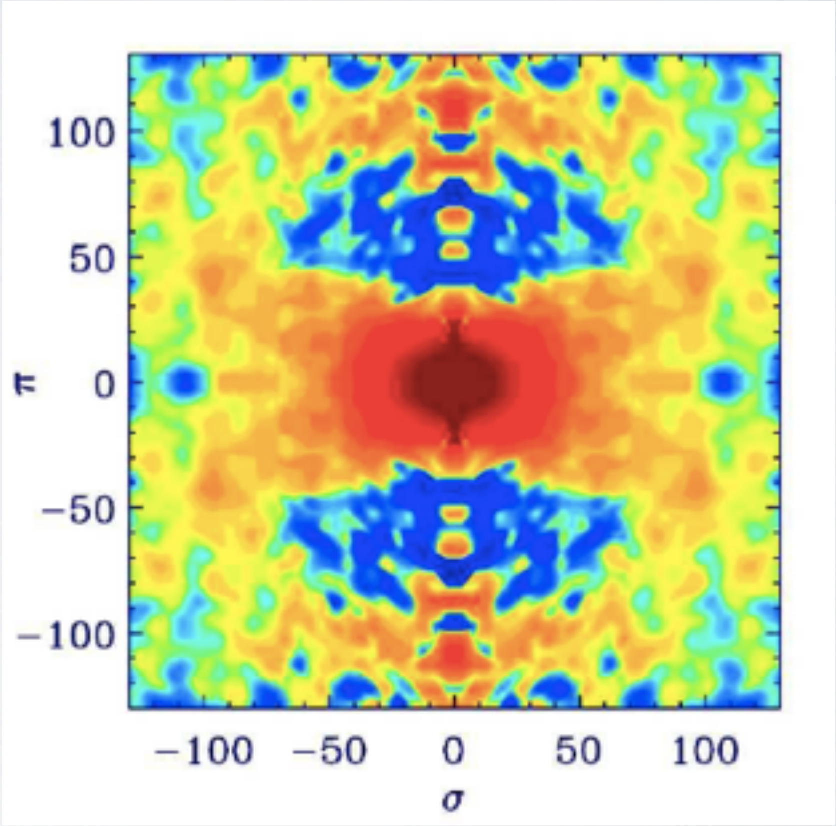
expansion

- AP effect



expansion

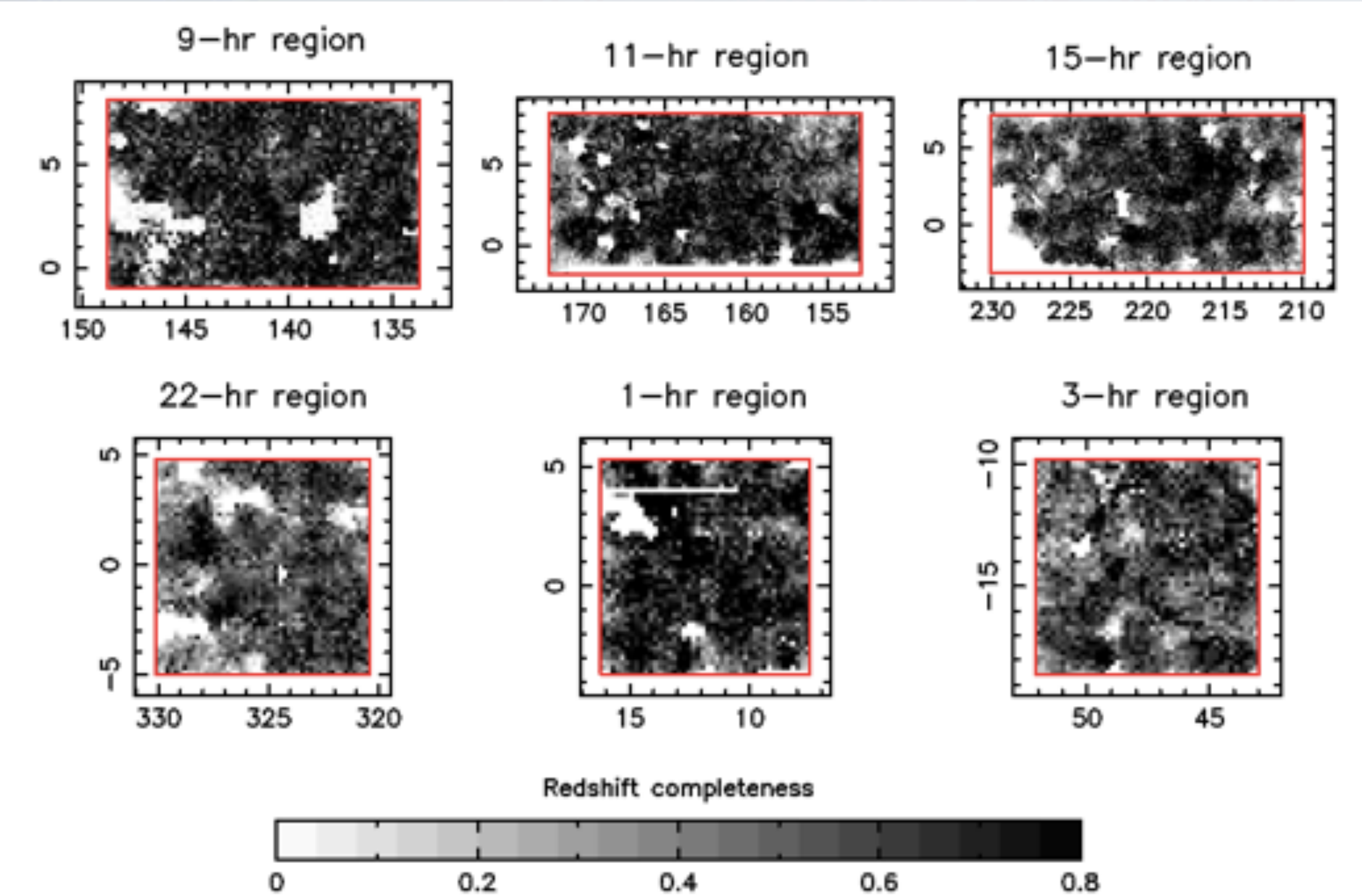
- RSD

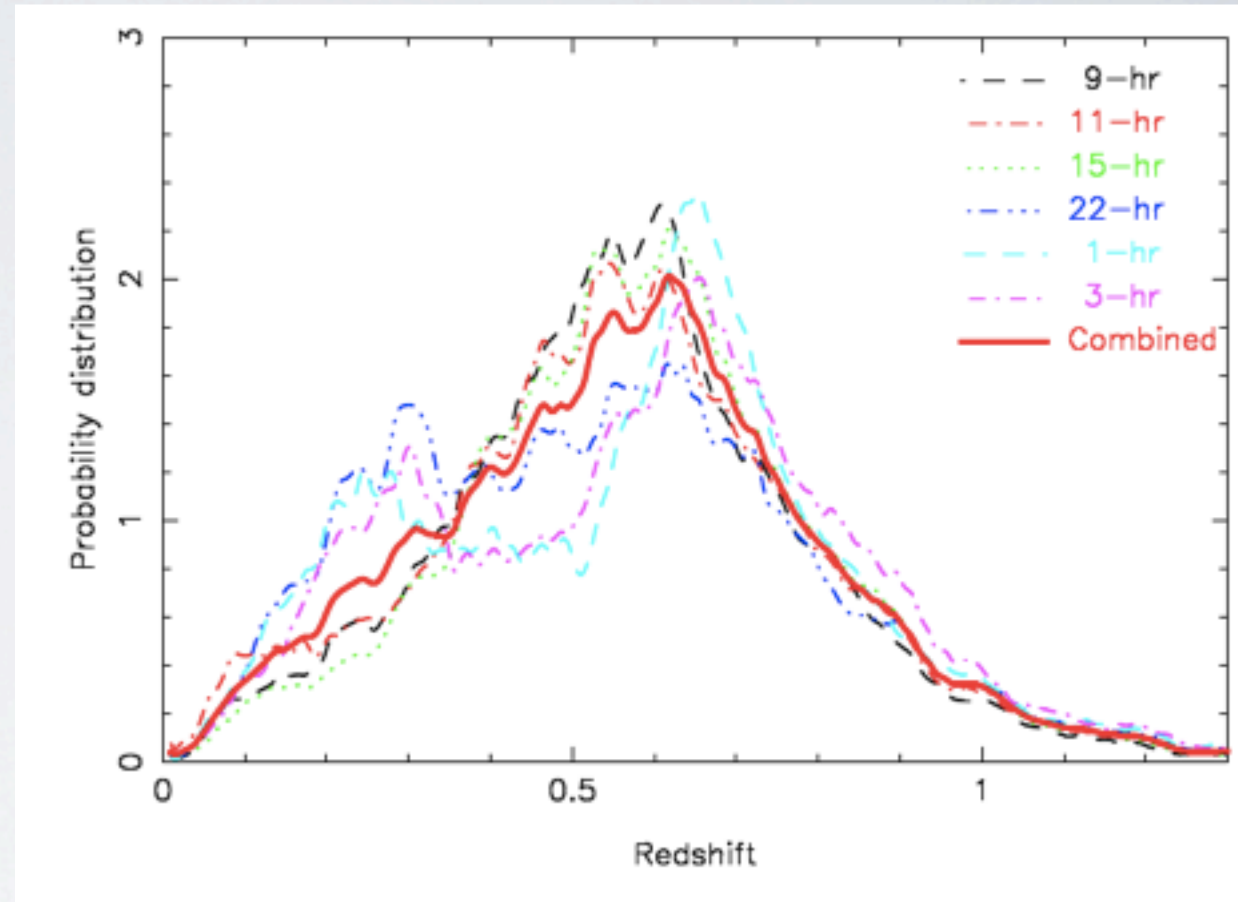


growth

※ AP effect has somewhat degeneracy with RSD, but one can break this degeneracy.

WiggleZ data



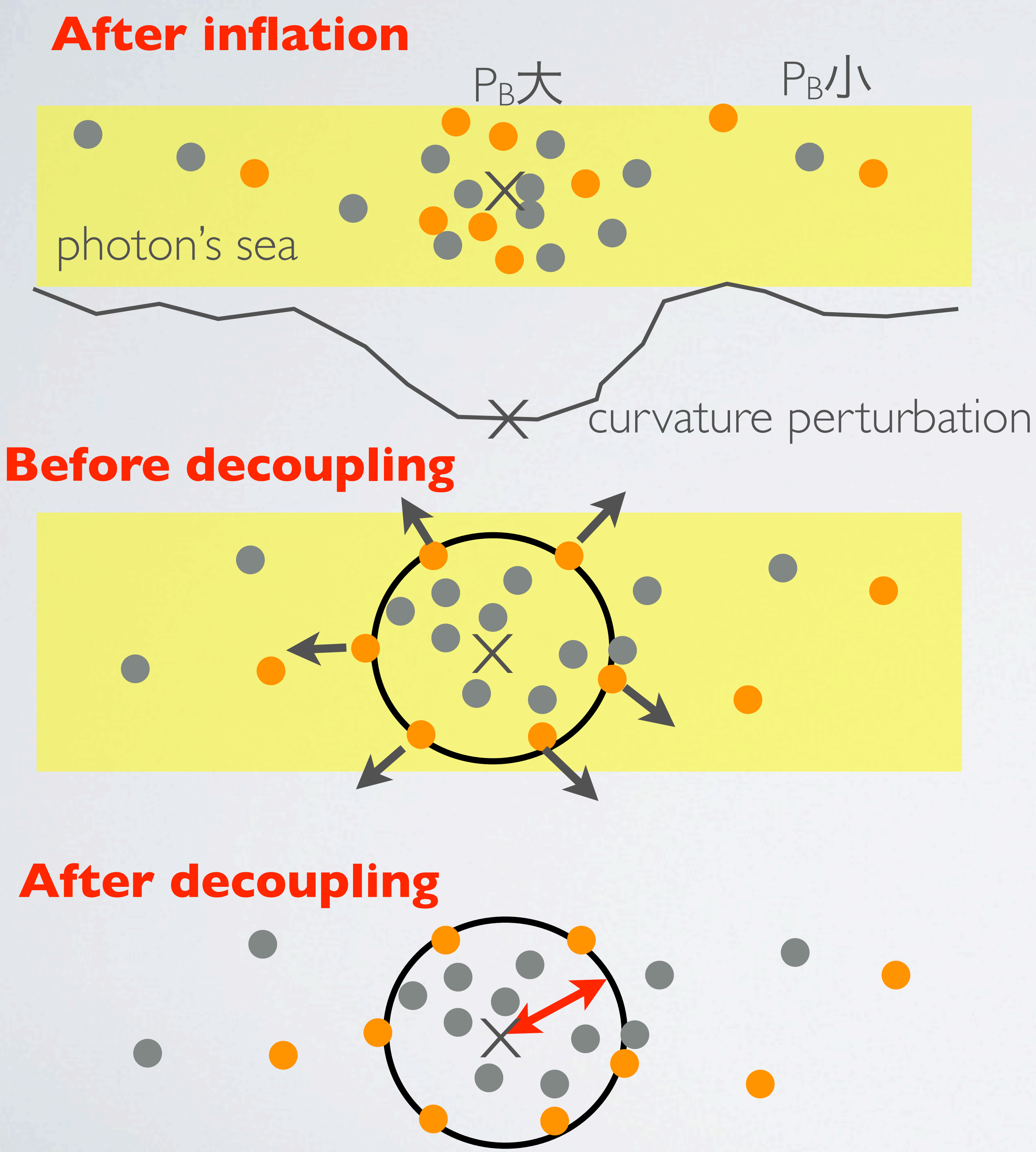


- taken by Australian Astronomical Telescope / AAOmega spectrograph during Aug. 2006- Jan. 2011
- 132,509 / 152,117 emission-line galaxies selected from GALEX (UV) & SDSS / RCS 2 (optical) for BAO / RSD(c.f. 200,000)

- Area : 1,000 deg^2 x redshift range: $0 < z < 1$ = 1 Gpc^3

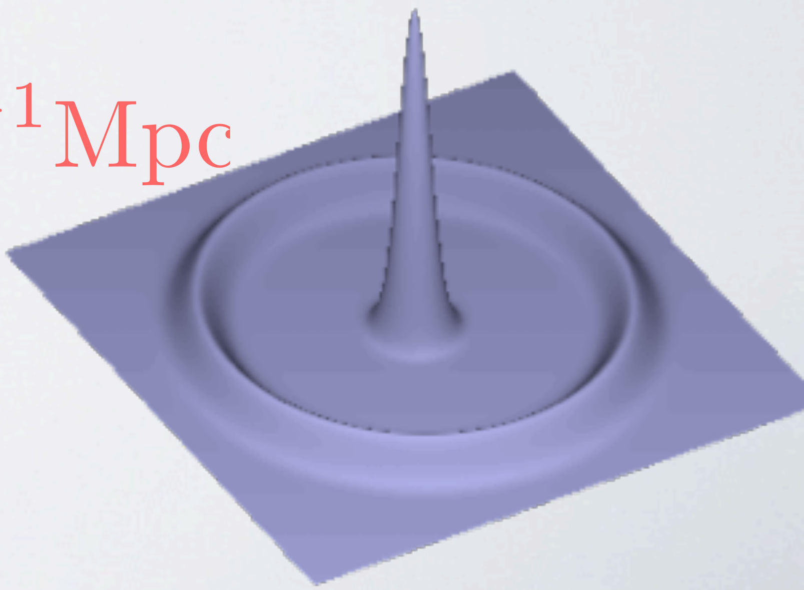
Baryon Acoustic Oscillations (BAOs) @ $z = 0.6$

Physics of BAO



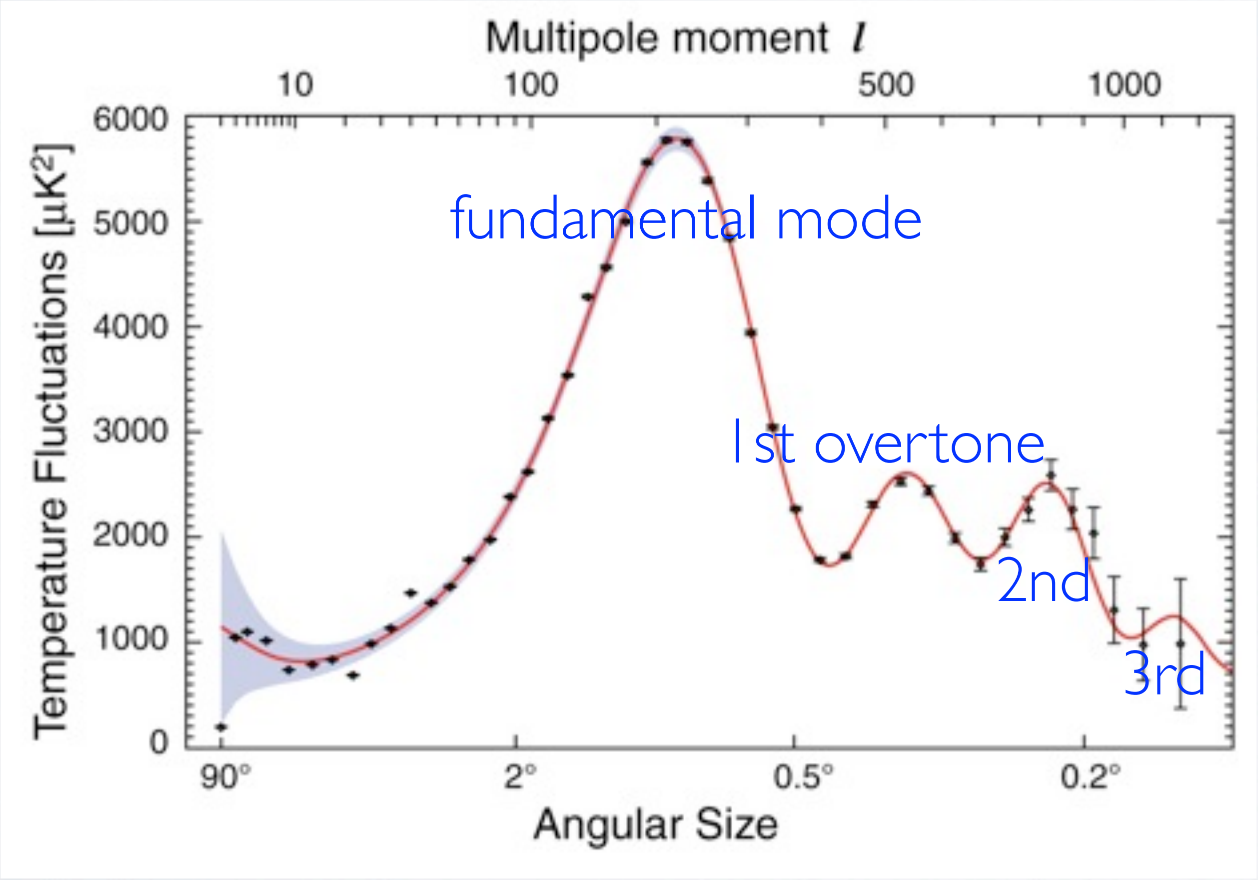
- Curvature perturbation generated by Inflation makes the density perturbation of DM and baryon.
- Baryon which is tightly-coupled with photons through the Tomson scattering has pressure and try to escape from the overdensity with sound velocity Cs
- After decoupling, sound velocity becomes 0, and the runaway distance is called as "*sound horizon*", Sh.

$$s_h = 103h^{-1}\mathrm{Mpc}$$

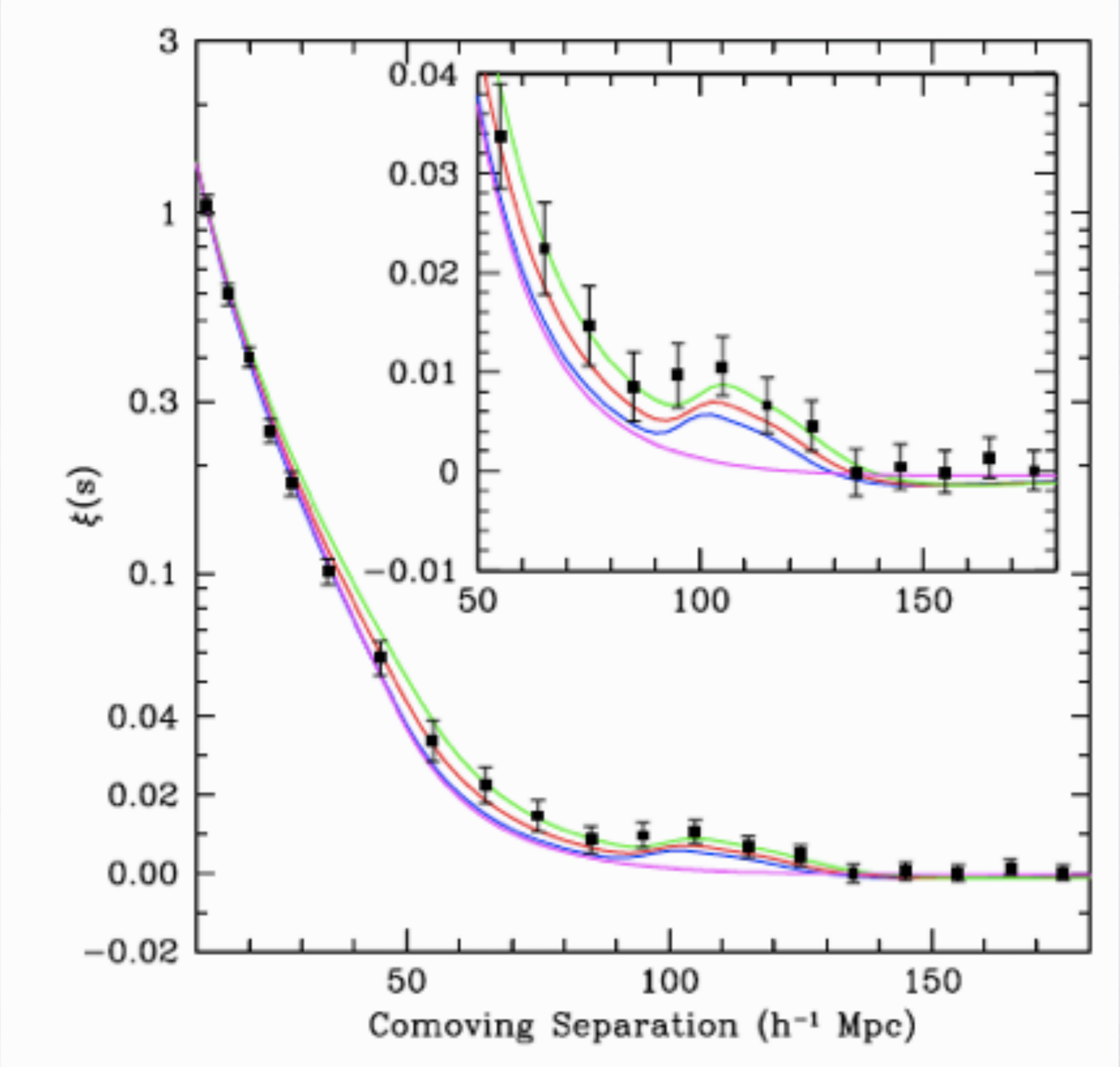


BAO in clustering pattern

BAO in CMB (z=1,100)



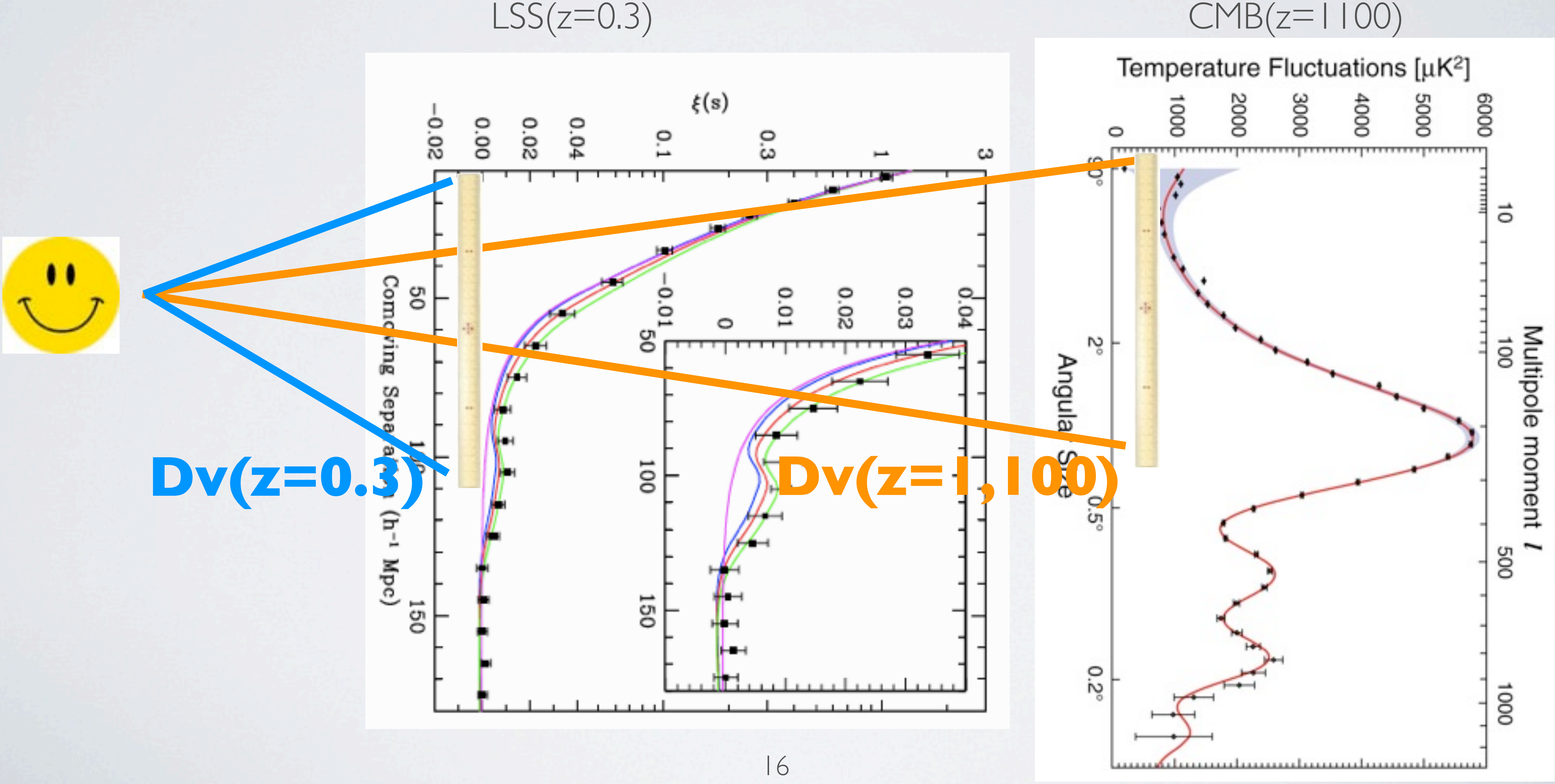
BAO in LSS (z=0.3)



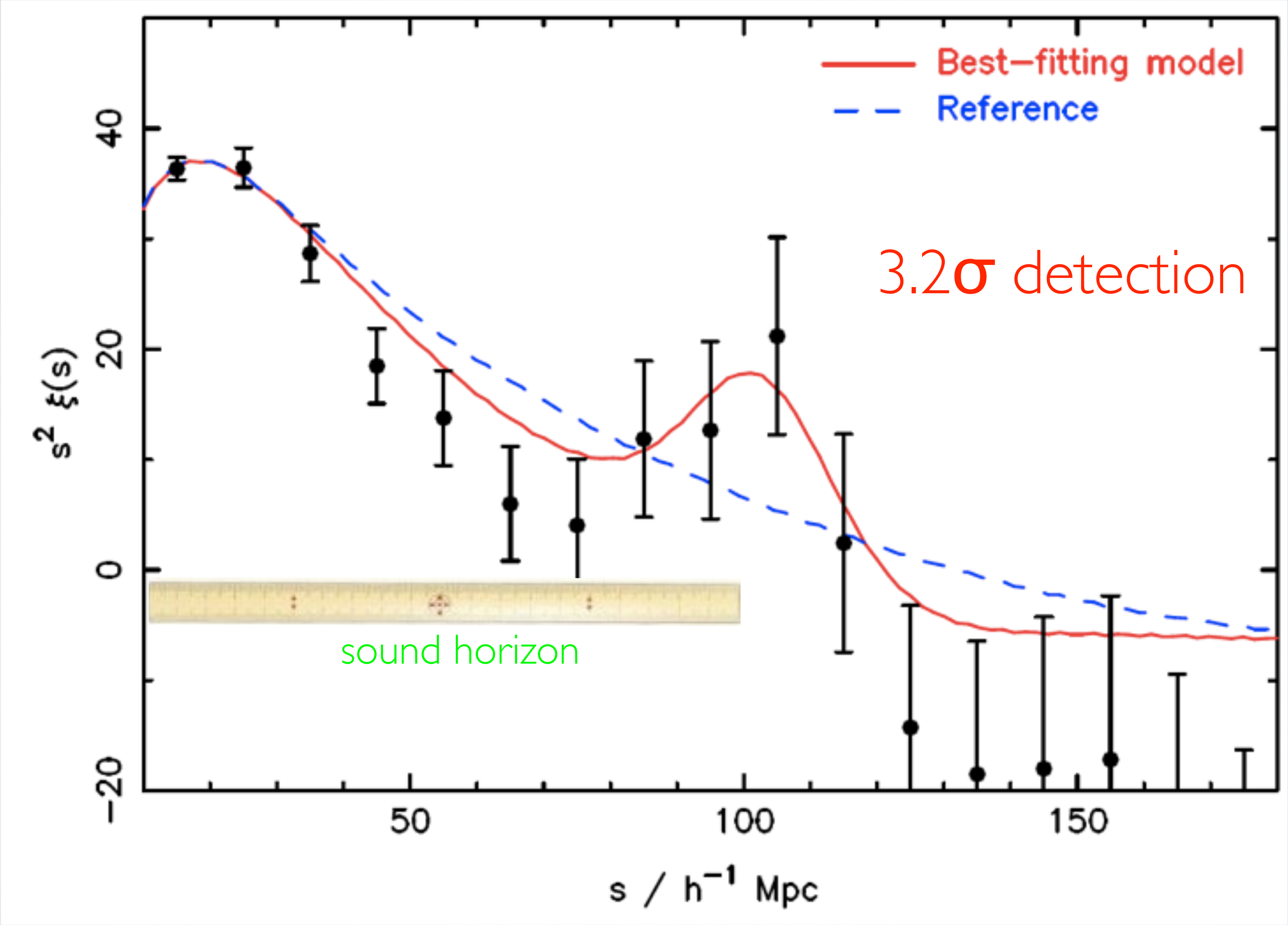
BAO as a standard ruler

$$\theta_p(z) = s_h / D_{\mathrm{v}}(z)$$

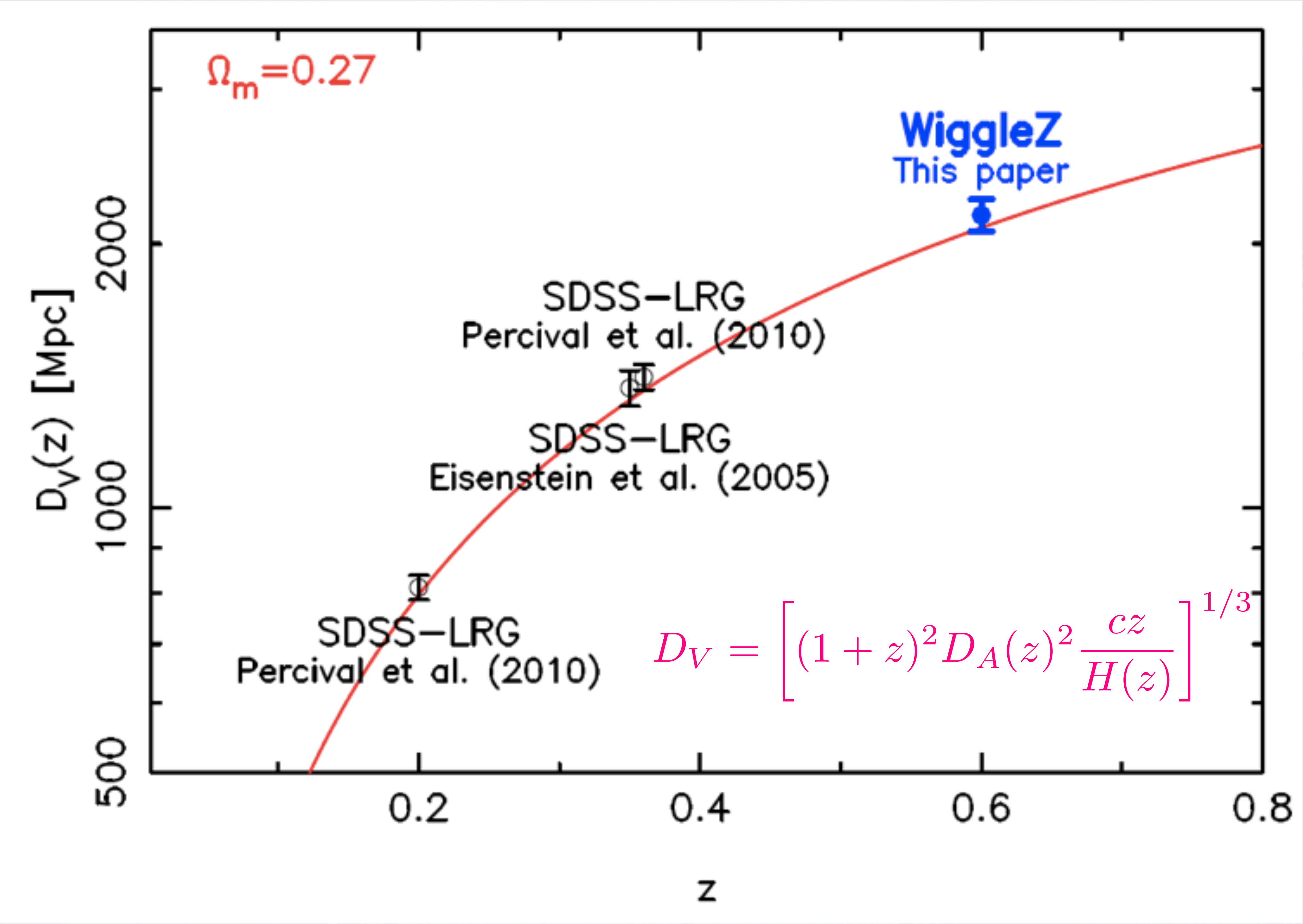
Measurement of the angular scale of BAOs enable us to estimate the distance in expansion universe, and expansion rate!!!



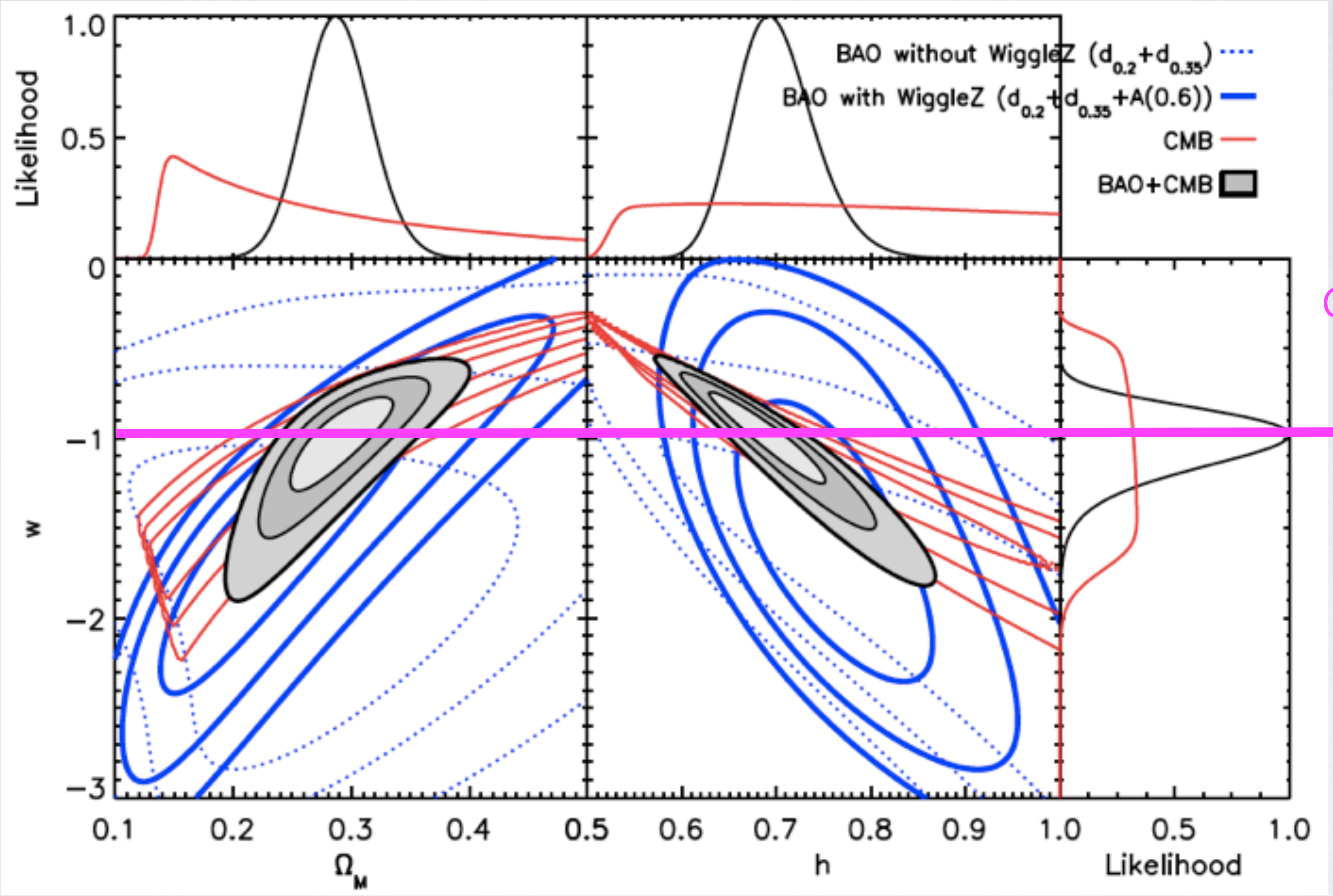
BAO in WiggleZ



Distance from BAO



Constraints on cosmological parameter



cosmological constant

EoS of DE w=p/ρ

energy density
from matter component

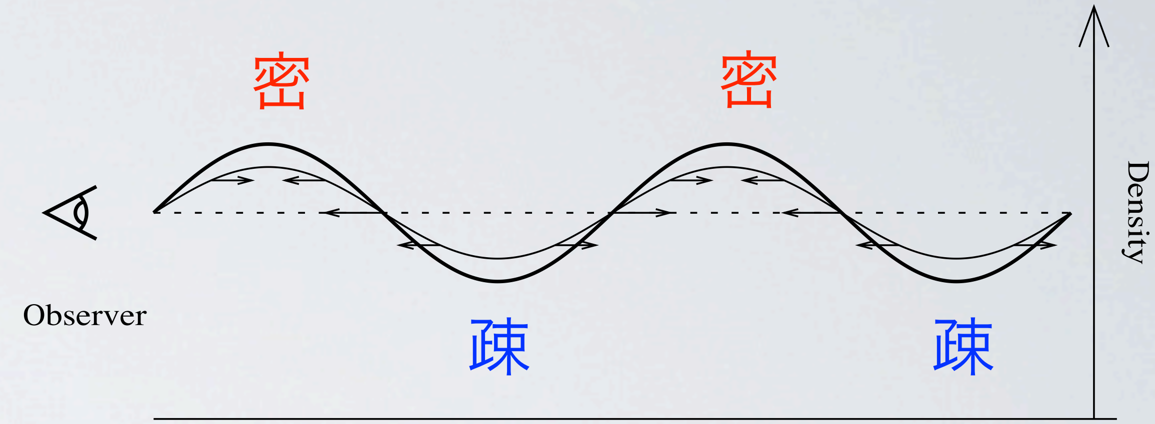
Summary (I)

- The intermediate sample of WiggleZ Dark Energy Survey detects the BAOs at the *highest redshift* achieved to date z= 0.6 .
- They measured the cosmological distance *Dv(z=0.6) with an accuracy of about 5 %* .
- The measured Dv(z=0.6) is *consistent with flat-ΛCDM model*.
- Combined with SDSS-LRG results, BAO enable us to detect the acceleration of the universe *without any prior,* i.e., CMB
- Combined with CMB and SNIa, they find the best fit values $\Omega m = 0.284 \pm 0.016$, $w = -1.026 \pm 0.081$

Redshift distortion (RSD) since z = 0.9

Redshift Distortion: RSD

Hamilton 98



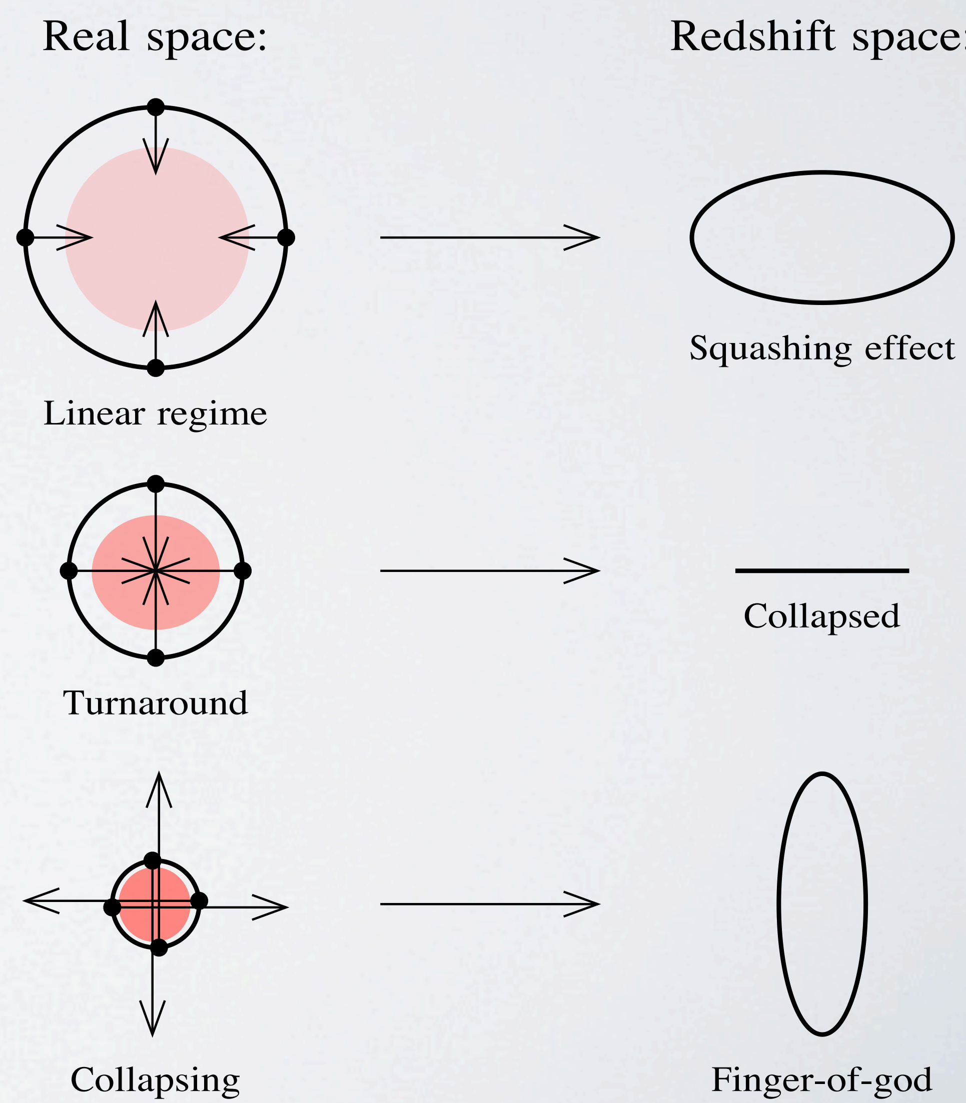
- Basically, we can only know the redshift of galaxies, not the radial distance.

- In the presence of peculiar velocity, observable position of galaxies is modified as (doppler effect)

$$\vec{s} = \vec{x} + \frac{v_z}{aH}\hat{z}$$

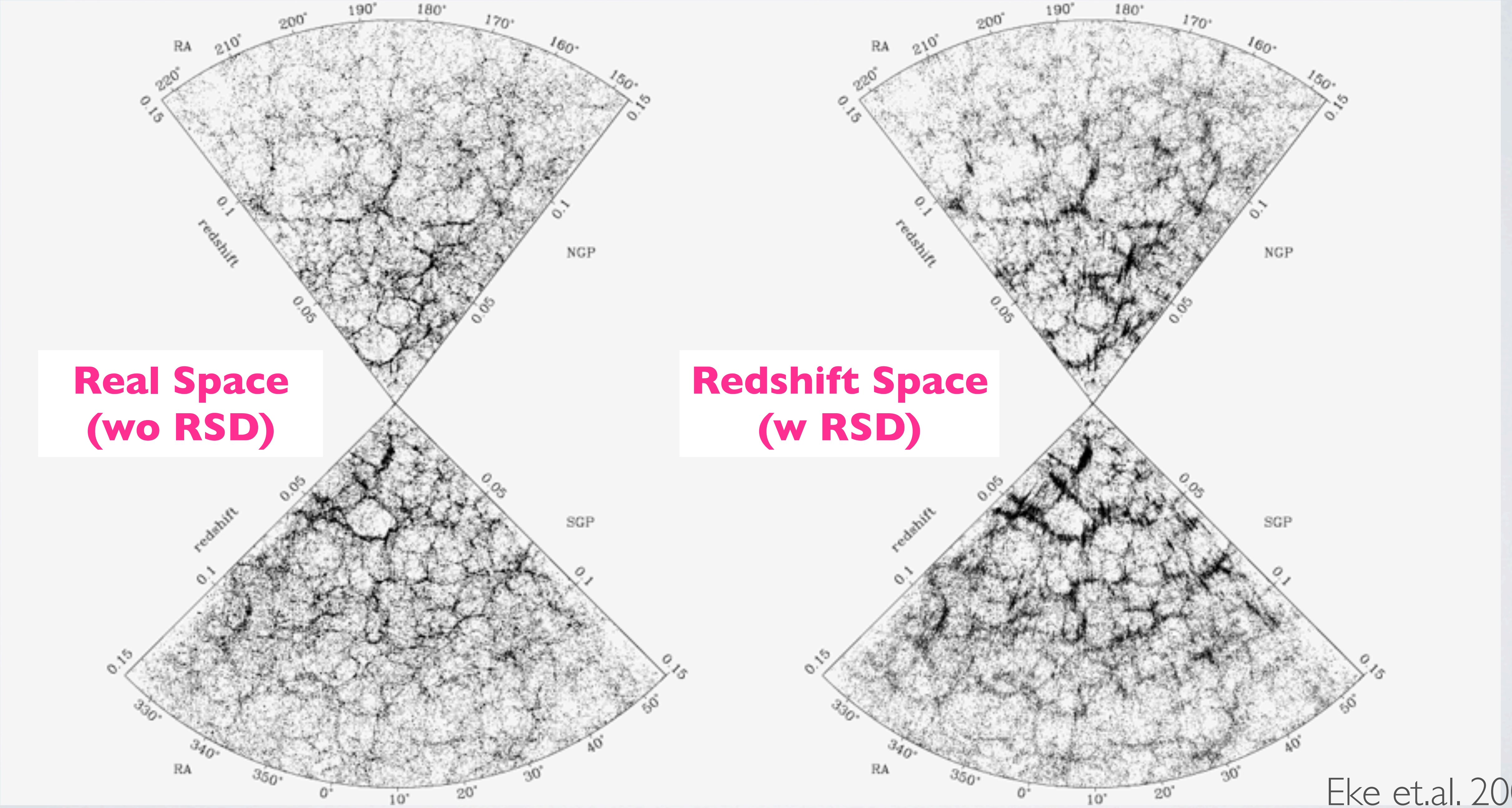
and the radial direction becomes the special direction.

- Therefore, observed galaxy clustering has anisotropic pattern depending on the strength of peculiar velocity.



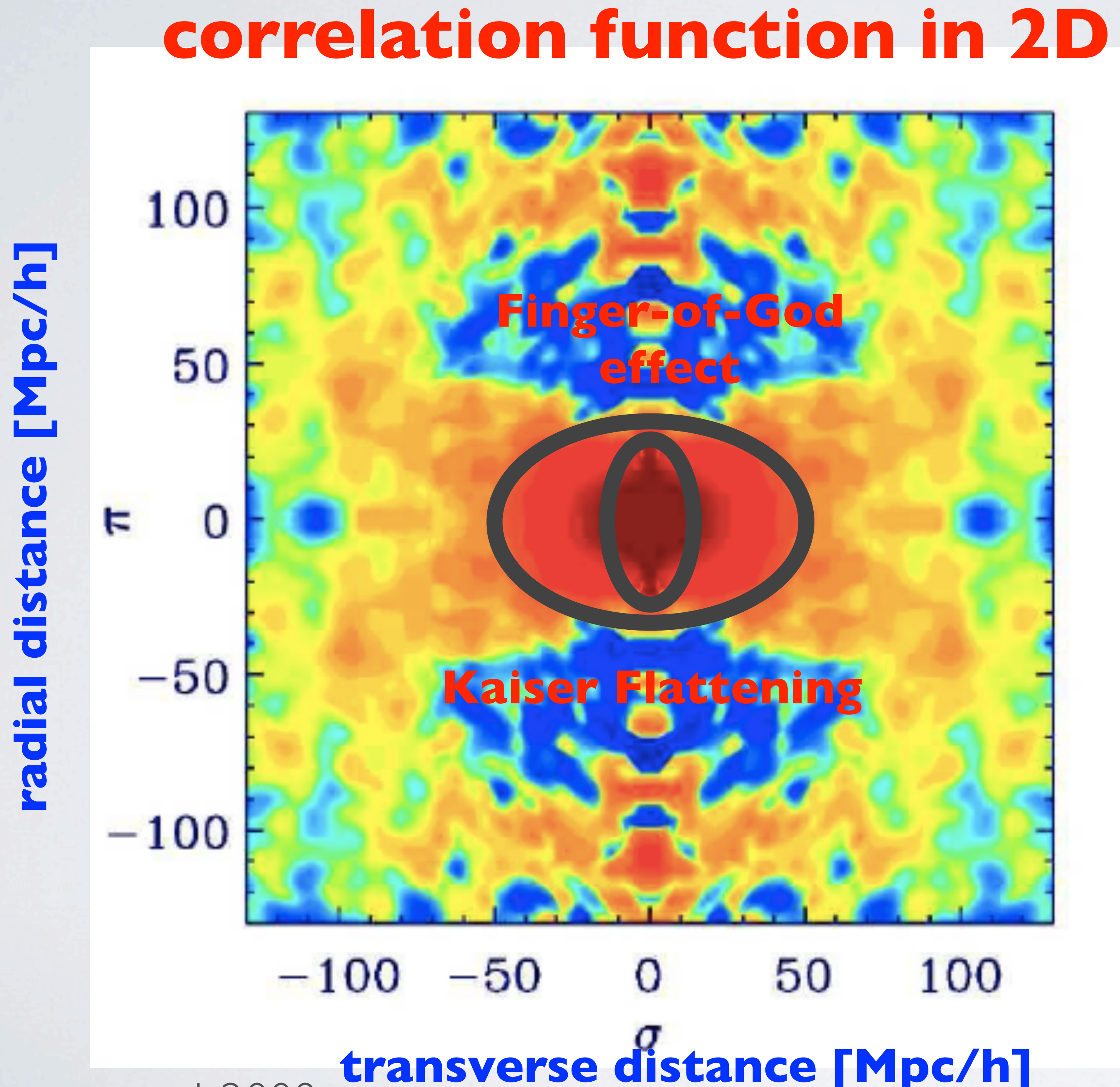
RSD at a glance

2dF mock galaxy catalog from Hubble volume simulation



Eke et.al. 2003

Example: Redshift space clustering from SDSS



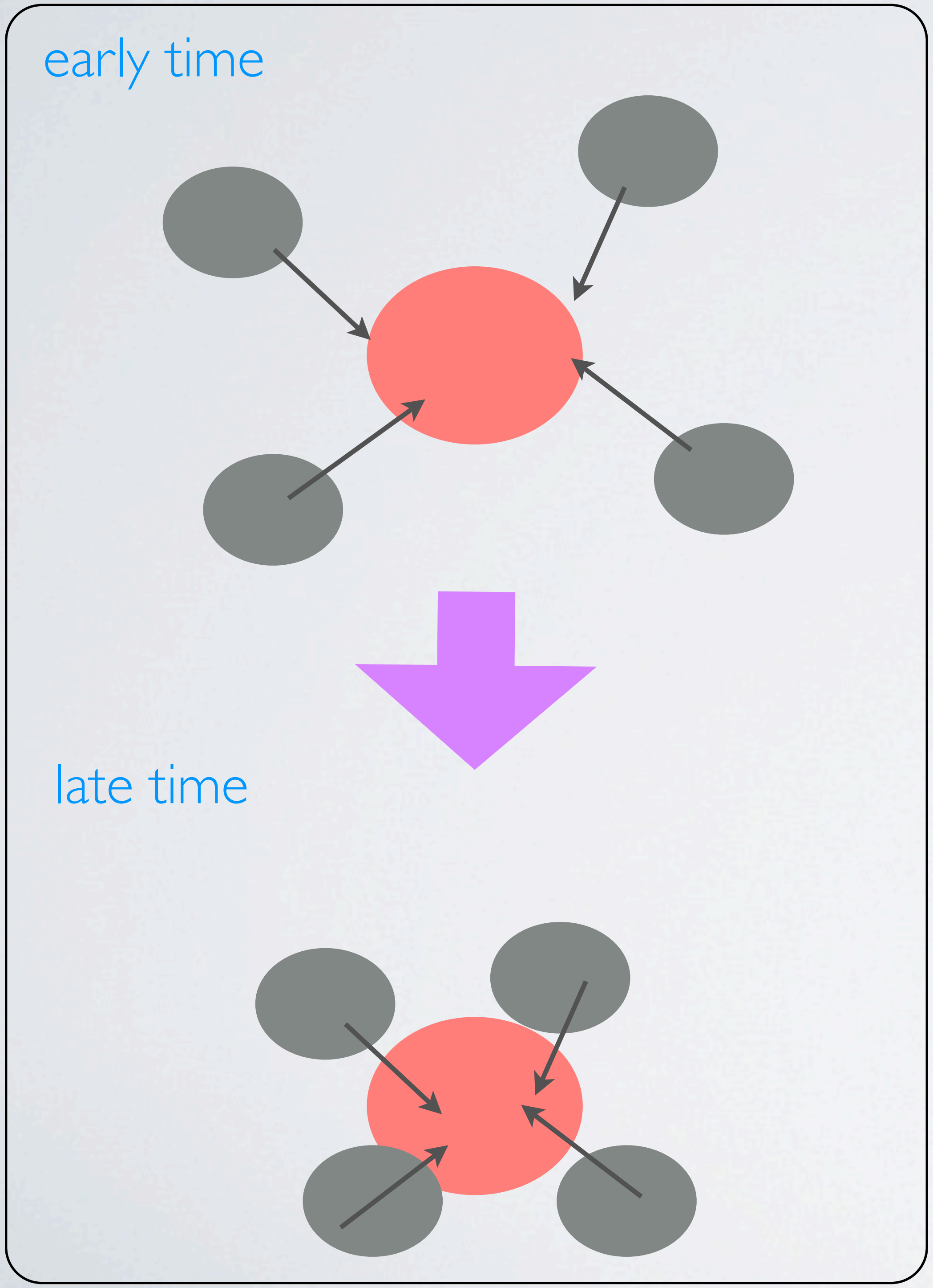
gaztanaga et.al. 2008

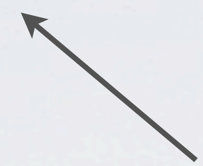
We can see the various anisotropy at different scale

- very small scale: Finger-of-God
- 10~40 Mpc/h: Kaiser flattening
- 100 Mpc/h: BAO

※ AP effect is also seen

What can we know from RSD




= gravitational force

= growth rate of the density perturbation

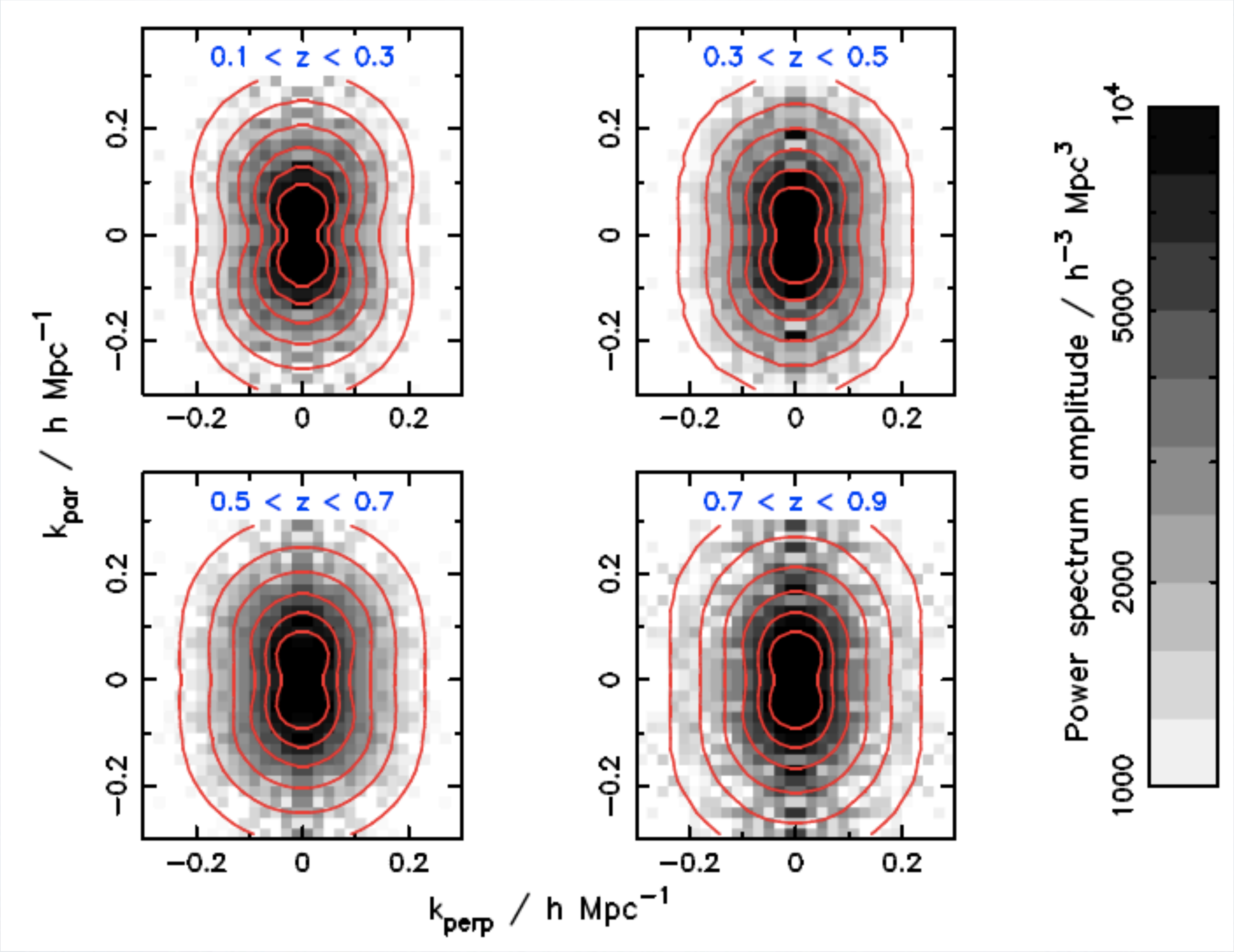
= peculiar velocity $\quad v \propto f = \dfrac{d\ln D}{d\ln a}$

= RSD

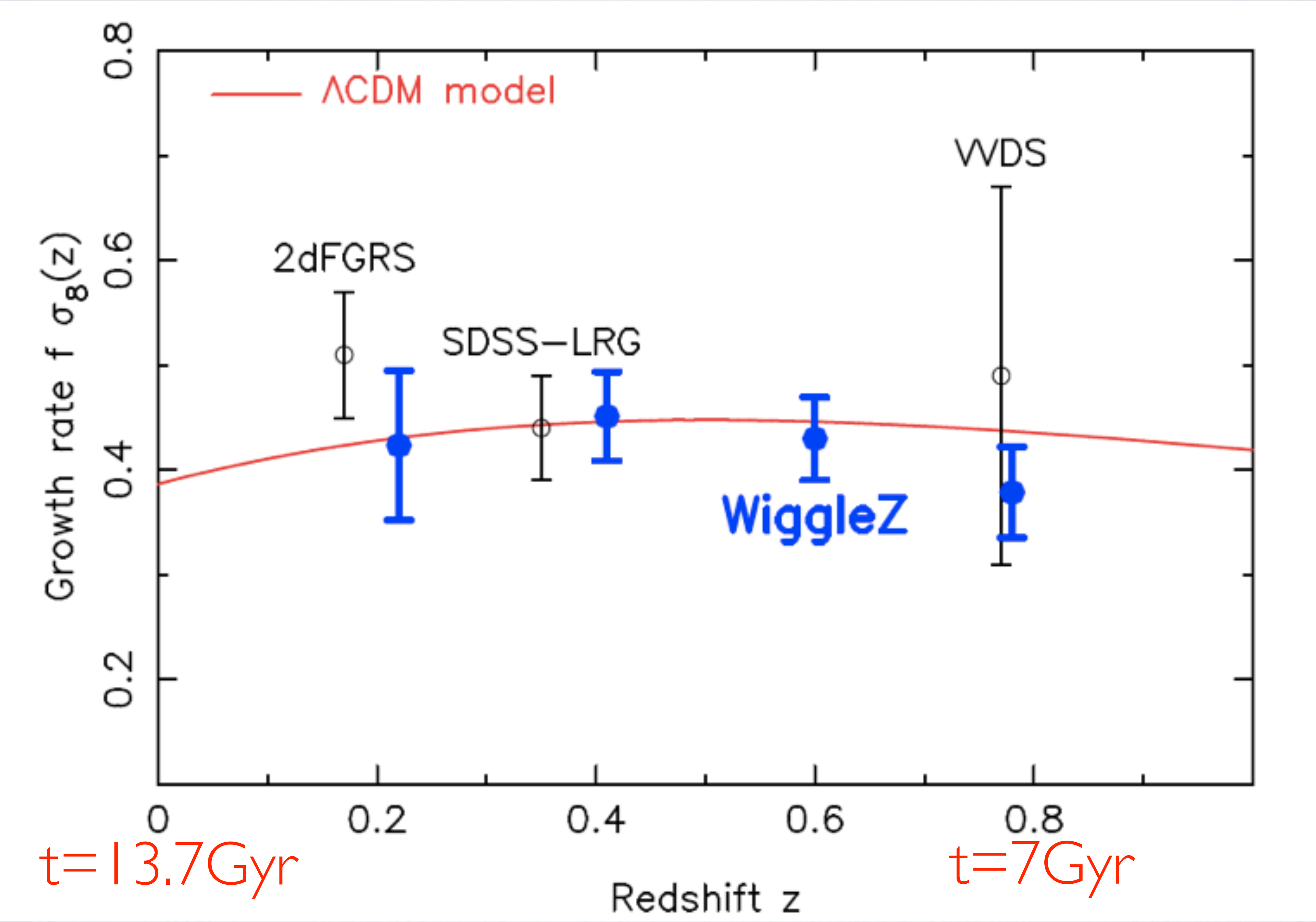
≠ density perturbation

RSD enables us to measure
the gravitational force directly
at observed redshift
and test the theory of gravity !!!

2D Power Spectrum in WiggleZ



Growth history since z=0.9



Summary (2)

- The intermediate sample of WiggleZ Dark Energy Survey measures the RSD at the various redshifts z= 0.22, 0.41, 0.6, and 0.78, which covers *the latter half of the cosmic history*.

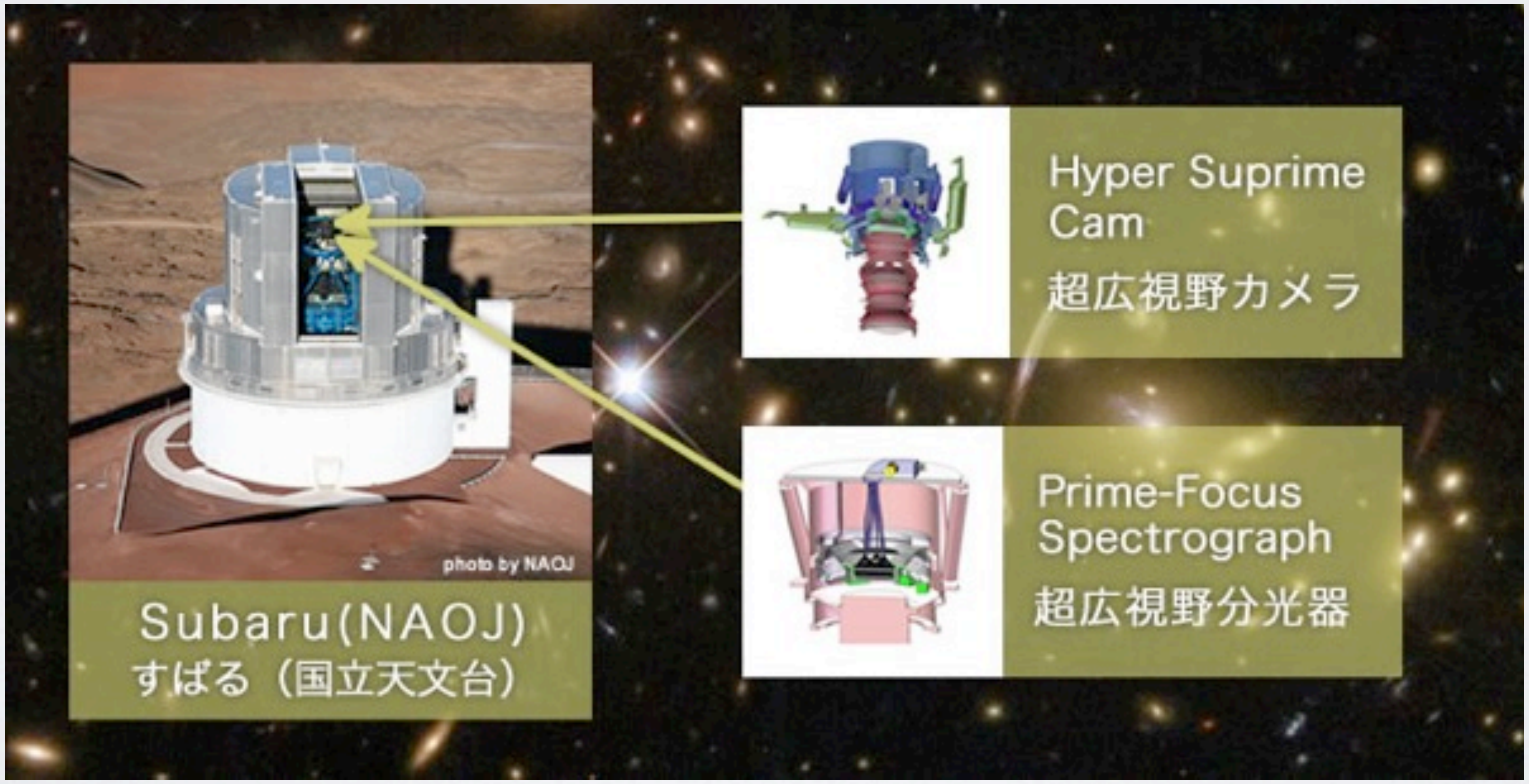
- They estimate the growth rate *f(z)=(0.60±0.10, 0.70±0.07, 0.73±0.07, 0.70±0.08) for z= (0.22,0.41, 0.6, 0.78)* .

- The measured f(z) is *consistent with flat-ΛCDM model, i.e., General Relativity*.

- The results of BAOs and RSD indicate that a flat-ΛCDM model provides a *self-consistent description* of the growth of cosmic structure formation and the homogeneous cosmic expansion.

Japanese (proposed) project

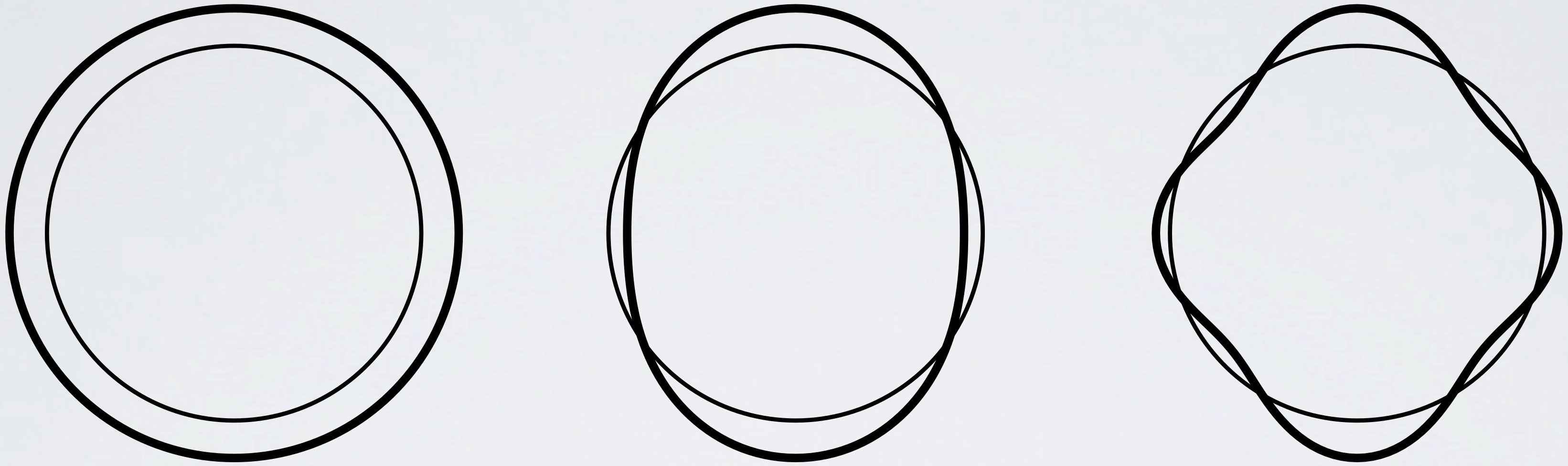
- FastSOUND: FMOS ankoku sindou tansa
- SuMIRe-PFS: Subaru Measurement of Image and Redshift - Prime-Focus Spectrograph, see http://sumire.ipmu.jp/



APPENDIX

Multipole moment expansion

Hamilton 98



Monopole Quadrupole Hexadecapole

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\, P(k,\mu)\mathcal{P}_\ell(\mu)$$

$$\xi_\ell(s) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\ \xi(s,\mu)\mathcal{P}_\ell(\mu)$$

where P_ℓ is Legendre polynomial of order ℓ

Model for BAO in Blake et.al. (2011)

2pcf is obtained by Fourier transform of power spectrum,

$$\xi(s) = \frac{1}{2\pi^2} \int dk\, k^2\, P(k) \left[\frac{\sin(ks)}{ks}\right]$$

To correct the non-linear smearing effect on the power spectrum,

$$P_{\rm damped}(k) = g(k)\, P_L(k) + [1 - g(k)]\, P_{\rm ref}(k)$$

where PL is linear matter power spectrum estimated by CAMB, and Pref is smoothed spectrum by Eisenstein & Hu 1998, and damping function is given by

$$g(k) = \exp\left(-k^2\sigma_v^2\right) \qquad \sigma_v^2 = \frac{1}{6\pi^2}\int P_L(k)\, dk.$$

They also correct the non-linear enhancement at small scale with *Halofit* model (Smith 04)

$$P_{\rm damped,NL}(k) = \left(\frac{P_{\rm ref,NL}(k)}{P_{\rm ref}(k)}\right) \times P_{\rm damped}(k)$$

Finally, the non-linear galaxy bias is modeled as

$$\xi_{\rm fid,galaxy}(s) = B(s)\, \xi_{\rm damped,NL}(s)$$

where the function B(s) is estimated by N-body simulation

$$B(s) = 1 + (s/s_0)^\gamma$$

Model for RSD in Blake et.al. 2011

- 18 model
- the model 17 is used for parameter estimation

	Model	Damping	Fitted parameters
1.	Empirical Lorentzian with linear $P_{\delta\delta}(k)$	Variable	f, b, σ_v
2.	Empirical Lorentzian with non-linear $P_{\delta\delta}(k)$	Variable	f, b, σ_v
3.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	None	f, b
4.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	Variable	f, b, σ_v
5.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop SPT	Linear	f, b
6.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop RPT	None	f, b
7.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 1-loop RPT	Linear	f, b
8.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	None	f, b
9.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	Variable	f, b
10.	$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ from 2-loop RPT	Linear	f, b
11.	$P(k,\mu)$ from 1-loop SPT	None	f, b
12.	$P(k,\mu)$ from 1-loop SPT	Linear	f, b
13.	$P(k,\mu)$ with additional corrections	None	f, b
14.	$P(k,\mu)$ with additional corrections	Variable	f, b, σ_v
15.	$P(k,\mu)$ with additional corrections	Linear	f, b
16.	Fitting formulae from N-body simulations	None	f, b
17.	Fitting formulae from N-body simulations	Variable	f, b, σ_v
18.	Fitting formulae from N-body simulations	Linear	f, b