Unveiling cosmic structure formation with galaxy imaging and redshift surveys

Chiaki Hikage (KMI)

References

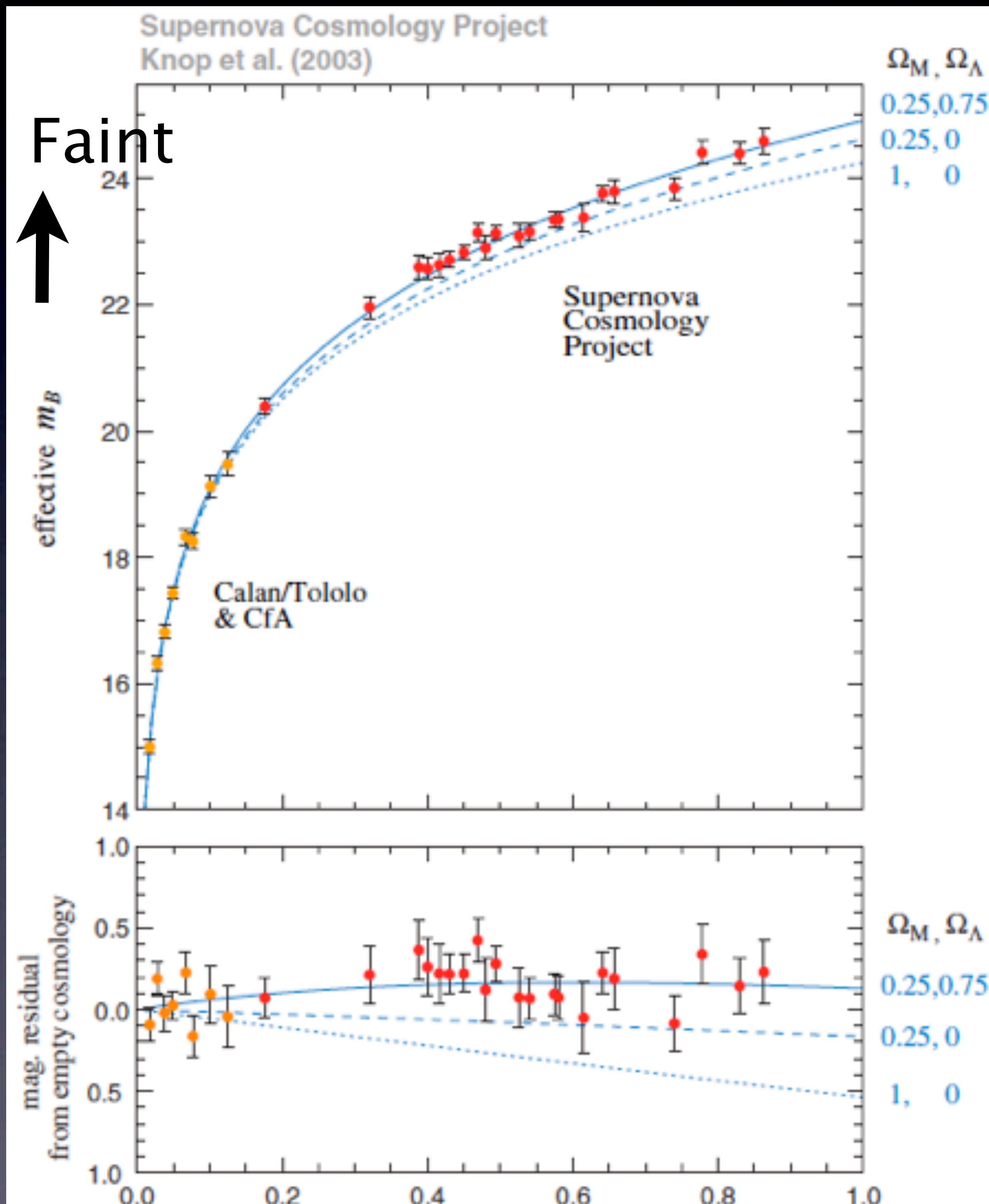
“Impacts of satellite galaxies in measuring the redshift distortions”
C. Hikage, K. Yamamoto
J. Cosmol. Astropart. Phys., 8 (2013), 19 (arXiv:1303.3380)

“Where are the Luminous Red Galaxies? Using correlation measurements and lensing to relate LRGs to dark matter”
C. Hikage, R. Mandelbaum, M. Takada, D. N. Spergel
Mon. Not. Royal Astron. Soc, 435 (2013), 2345-2370 (arXiv:1211.1009)

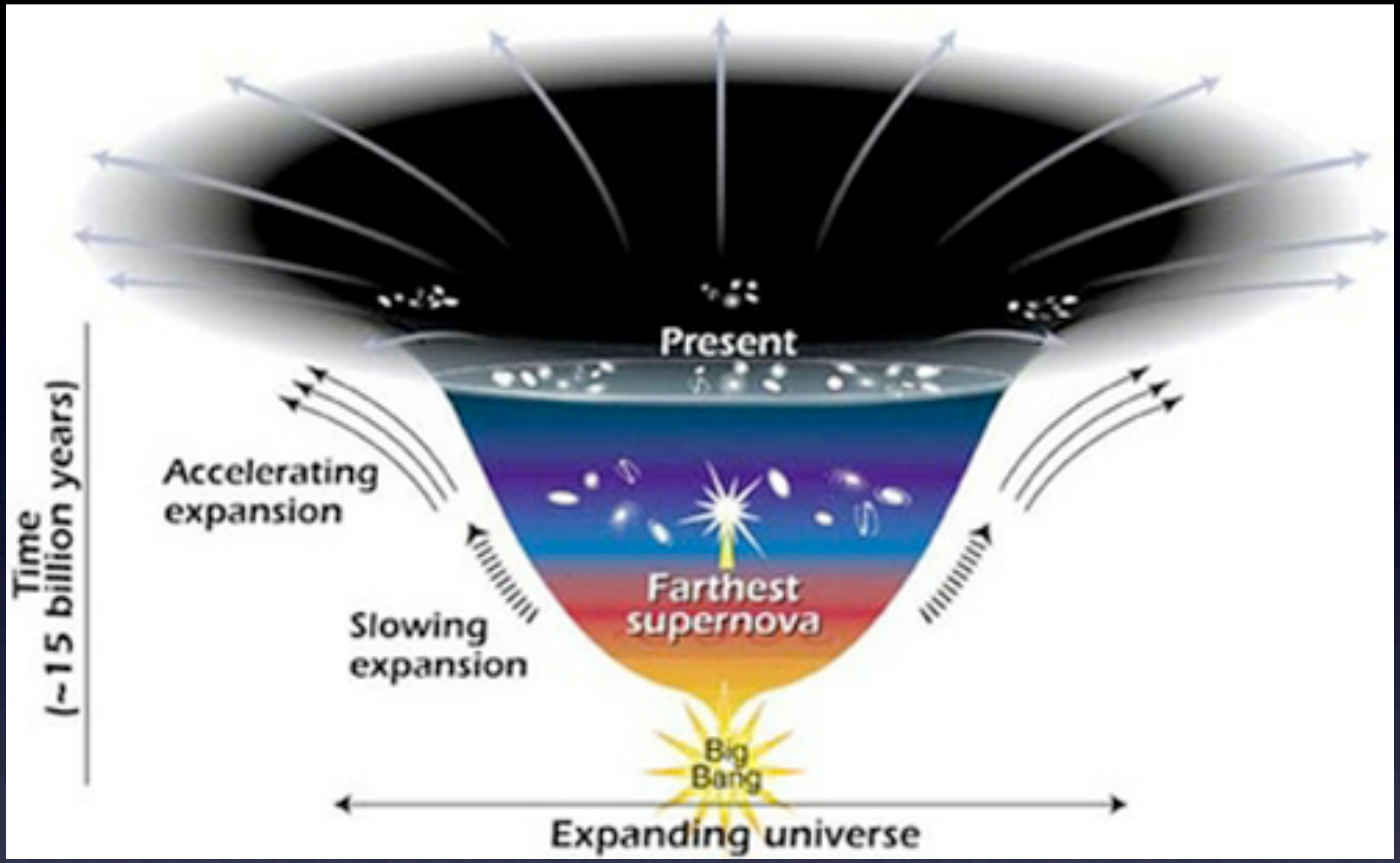
“Understanding the nature of luminous red galaxies: Connecting LRGs to central and satellite subhalos”
S. Masaki, C. Hikage, M. Takada, D. N. Spergel, N. Sugiyama
Mon. Noy. Roy. Astron. Soc., 433 (2013), 3506-3522 (arXiv:1211.7077)

“Galaxy-Galaxy Weak Lensing as a Tool to Correct Finger-of-God”
C. Hikage, M. Takada, D. N. Spergel
Mon. Not. Roy. Astron. Soc, 419 (2012), 3457-3481

What is the origin of cosmic acceleration ?



Perlmutter et al. 1998



Dark Energy or Modified Gravity ?

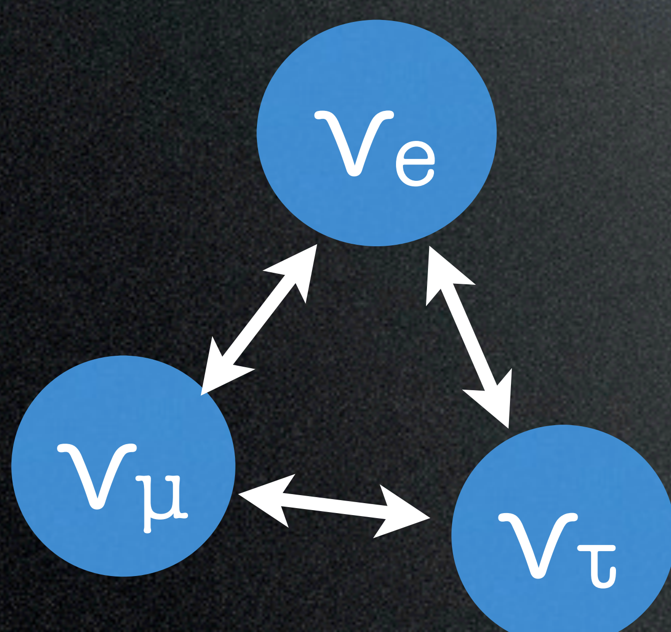
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \stackrel{?}{=} \frac{8\pi G}{c^4} T_{\mu\nu}$$

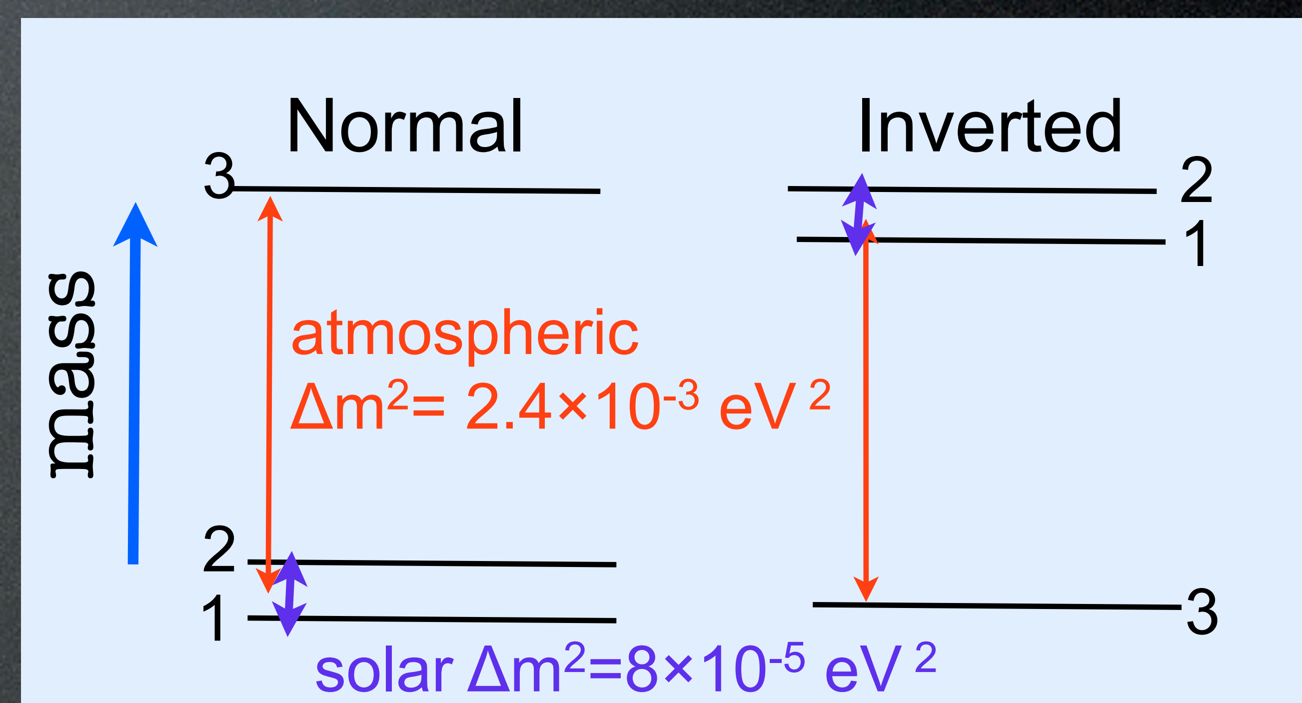
Nature of Neutrinos

What is the absolute mass of neutrino ?

Mass hierarchy is normal or inverted ?

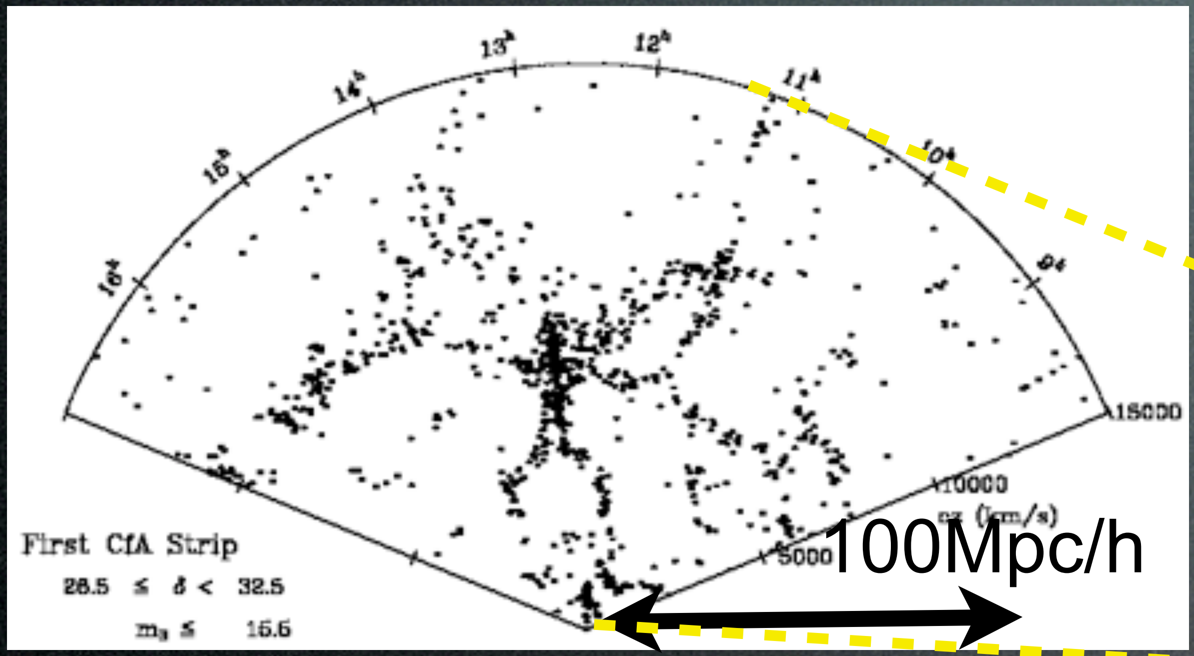
Neutrino is Majorana or Dirac fermions ?





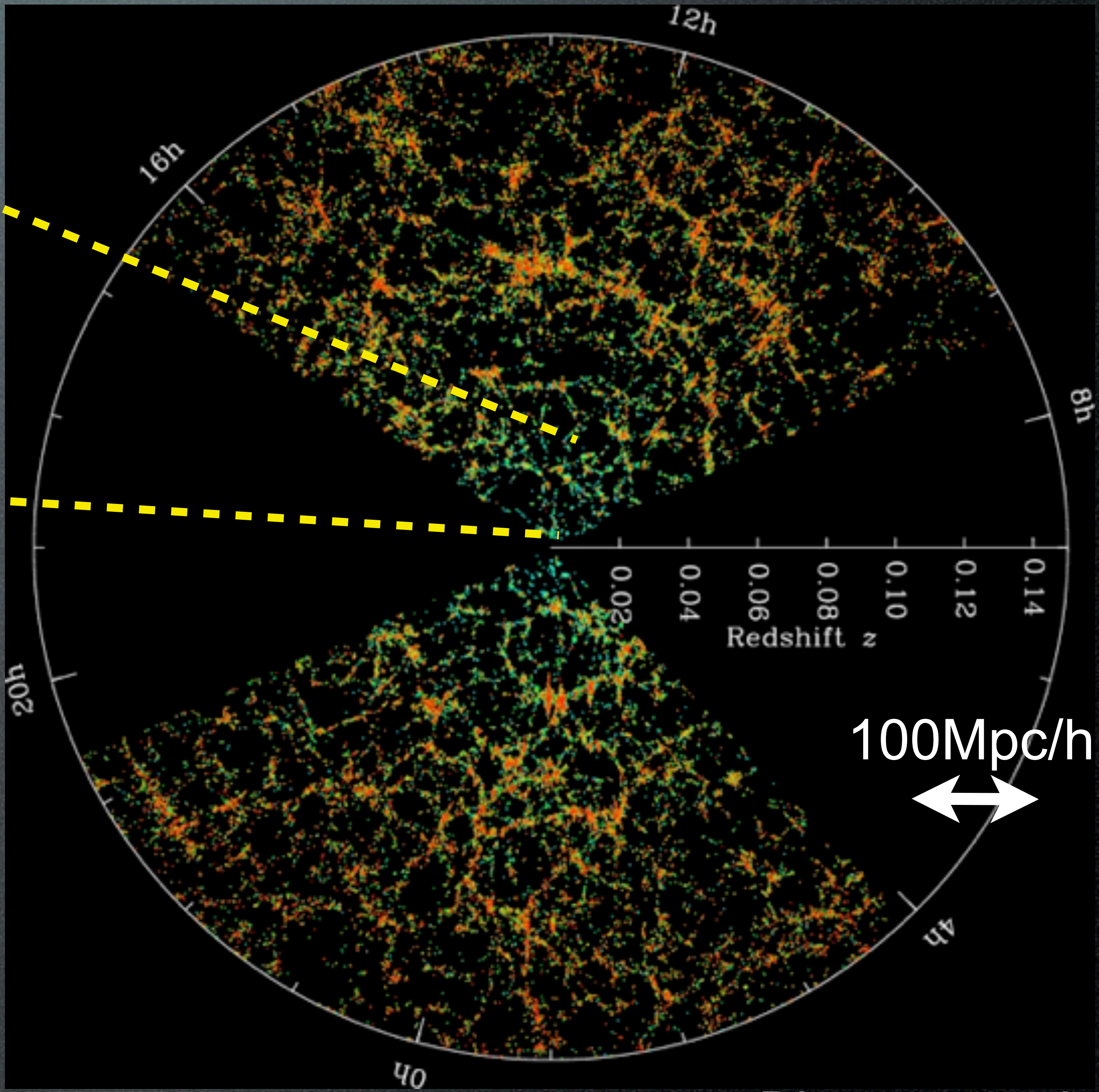
Large-Scale Structure (LSS)

CfA galaxy redshift survey (1100 galaxies)



de Lapparent, Geller, Huchra, 1986

Sloan Digital Sky Survey(SDSS) 10^6 galaxies



Blanton et al.

Galaxy surveys:
1990~ Las Campanas
2000~ 2dF, SDSS
2010~ Wiggle Z, BOSS,
VVDS, Subaru (FastSound, PFS),
HETDEX, BigBOSS
2020~ Euclid, WFIRST

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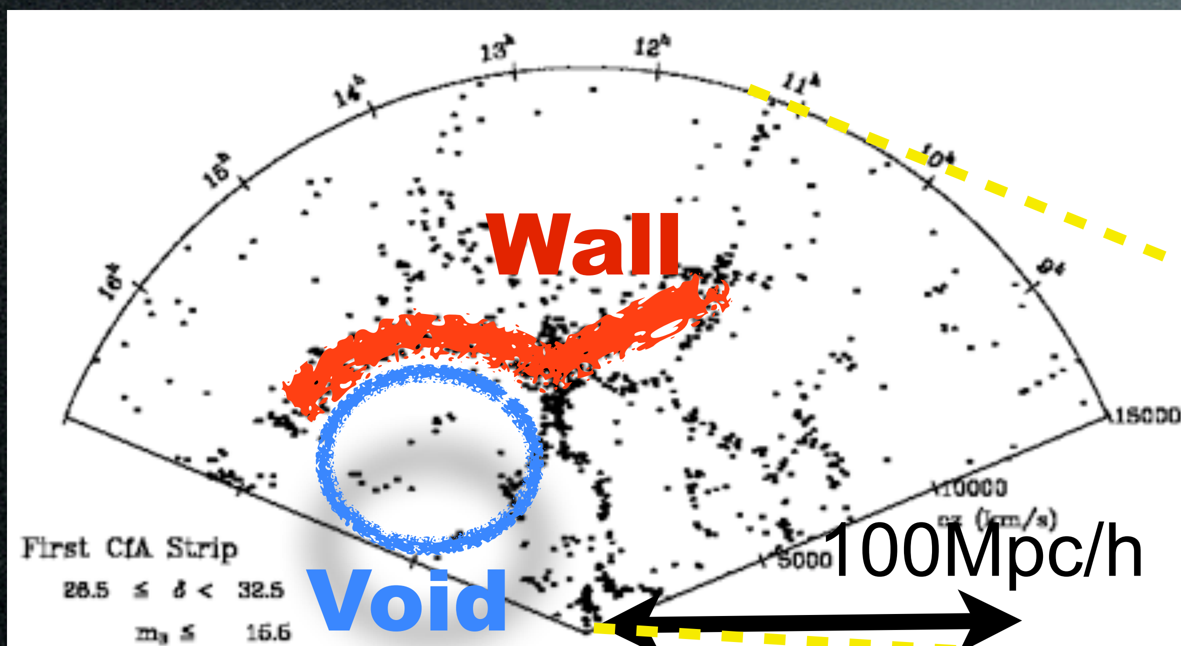

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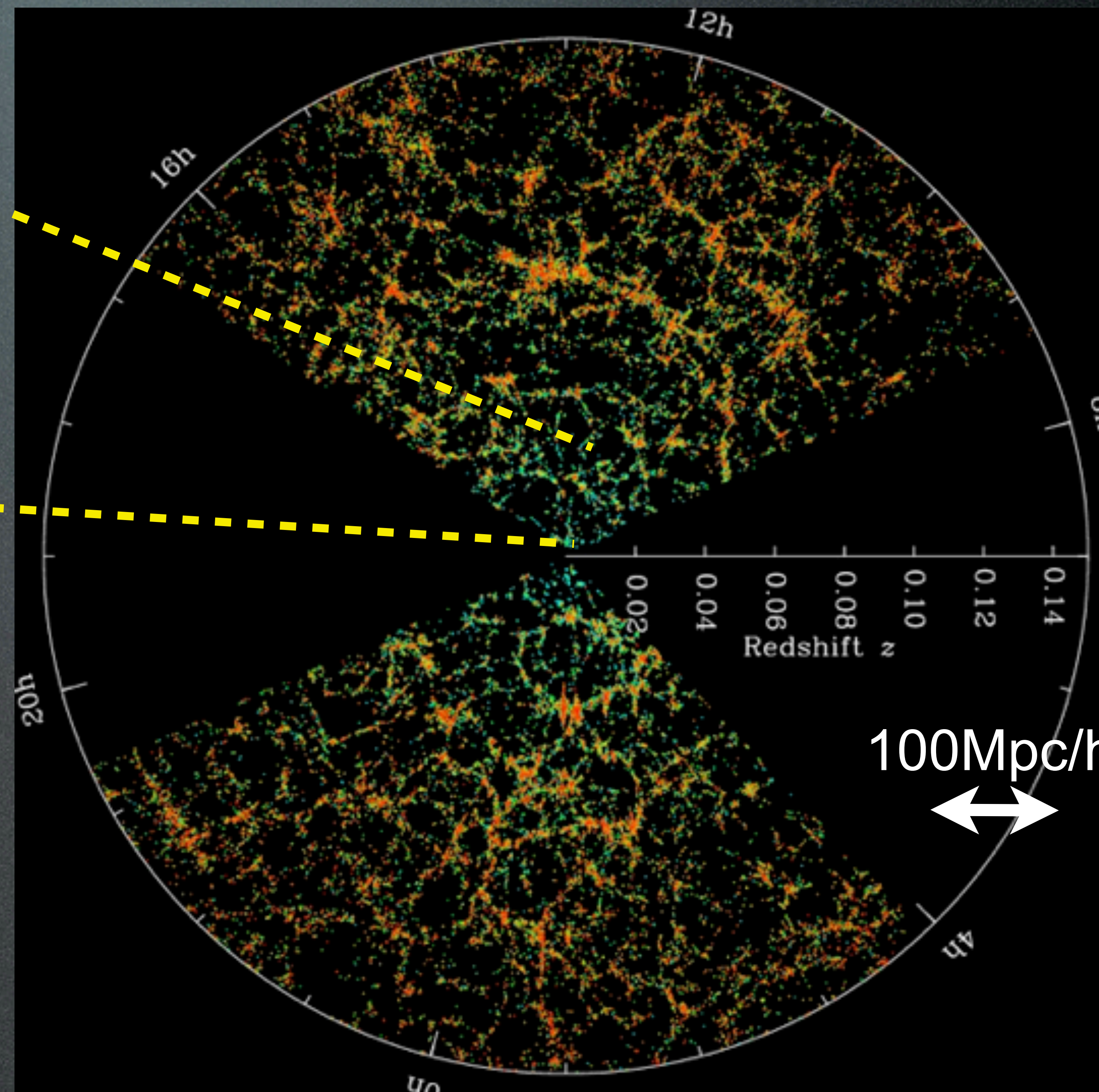

Blanton et al.

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1990~ Las Campanas

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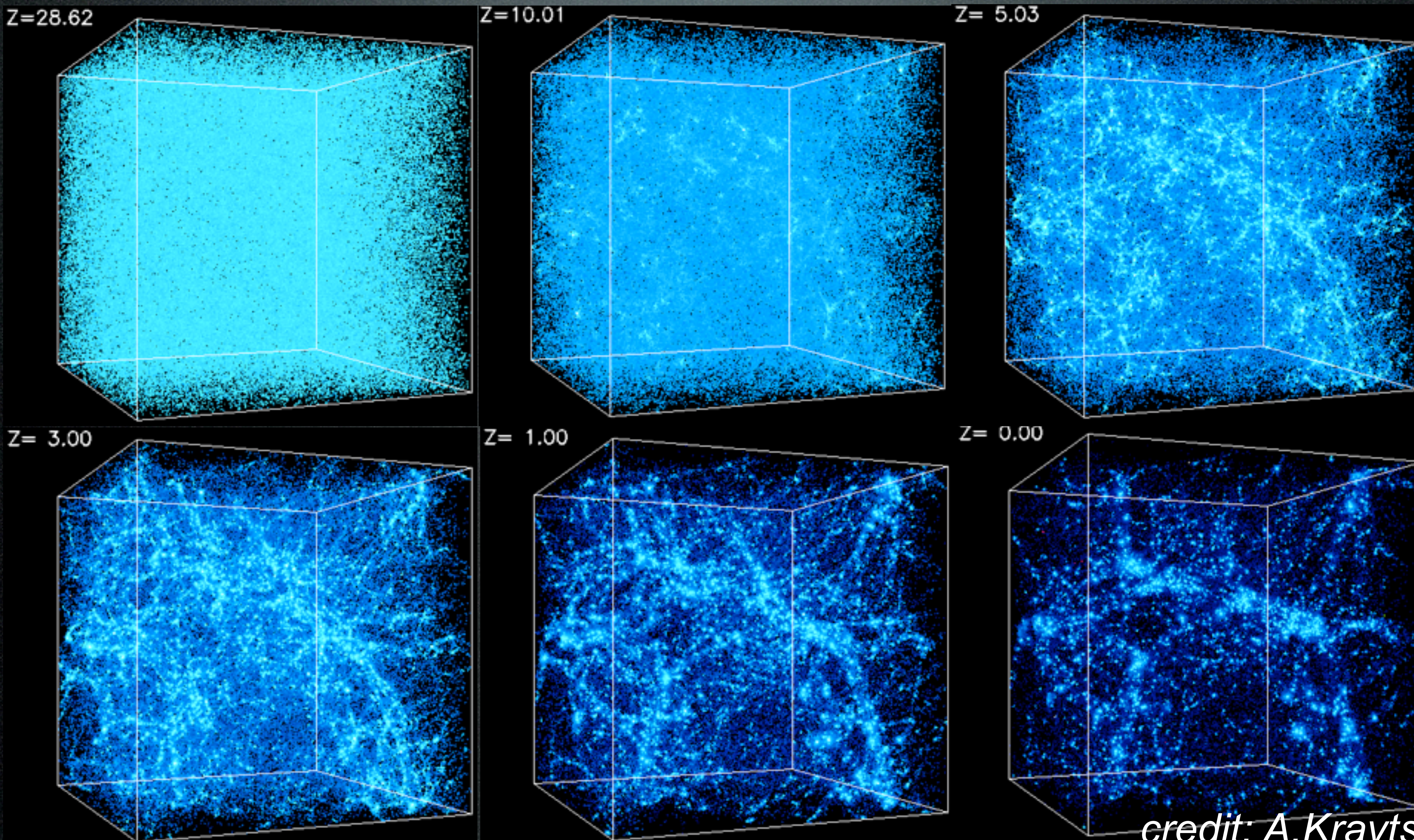
2020~ Euclid, WFIRST

Structure Formation induced by gravitational instability

Initial tiny fluctuation grows up by gravity and form large-scale structure



credit: A.Kravtsov

Cosmic Growth Rate

Linear matter evolution equation

$$\ddot{\delta} + 2\underline{H}\dot{\delta} - 4\pi G\bar{\rho}_m a^2 \delta = 0$$

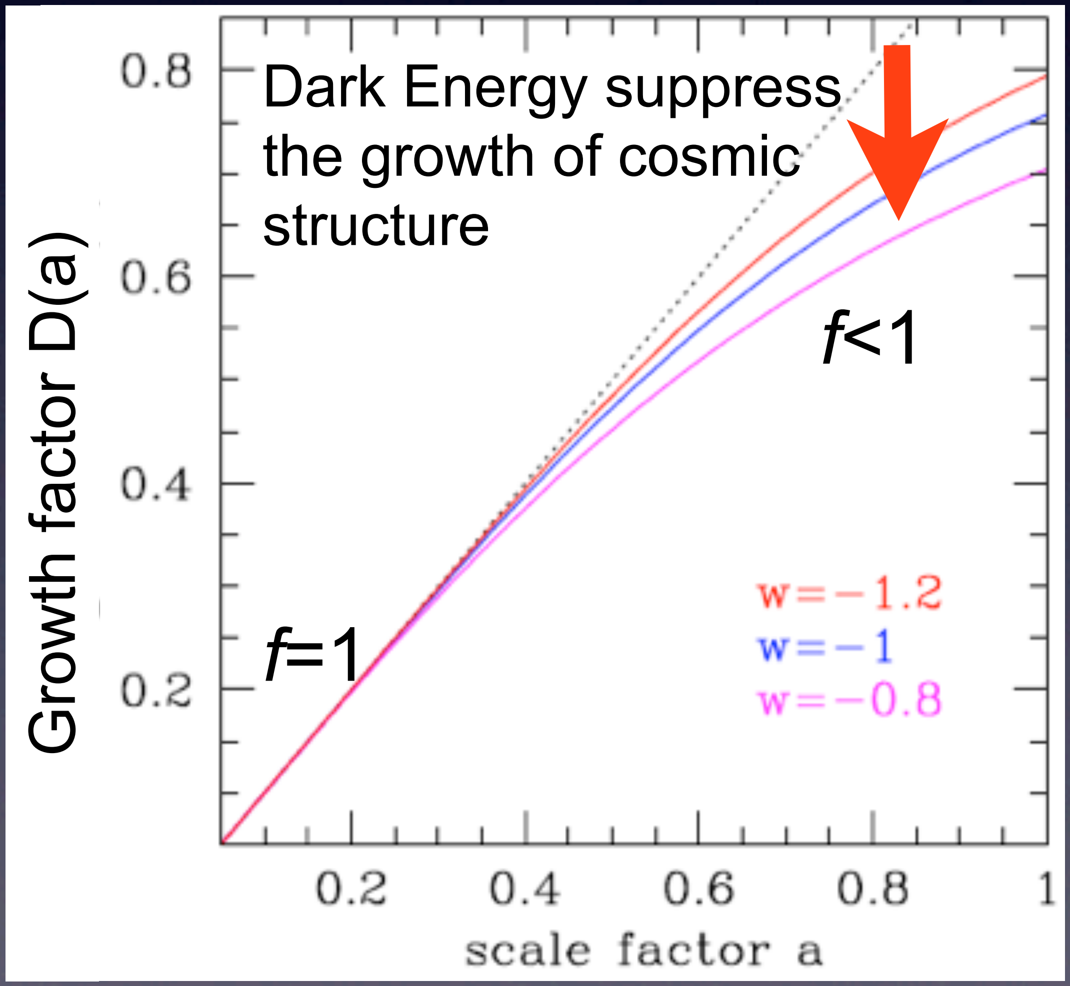
Hubble expansion rate

Growth rate

$$f \equiv \frac{d \ln D}{d \ln a} \simeq \Omega_m(z)^\gamma$$

Growth rate index

(Peebles 1976, Lahav et al. 1991)



Cosmic Growth Rate

Linear matter evolution equation

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Hubble expansion rate

In modified gravity, gravitational constant can be time- and scale-dependent

$G_{eff}(k,t)$

Growth rate

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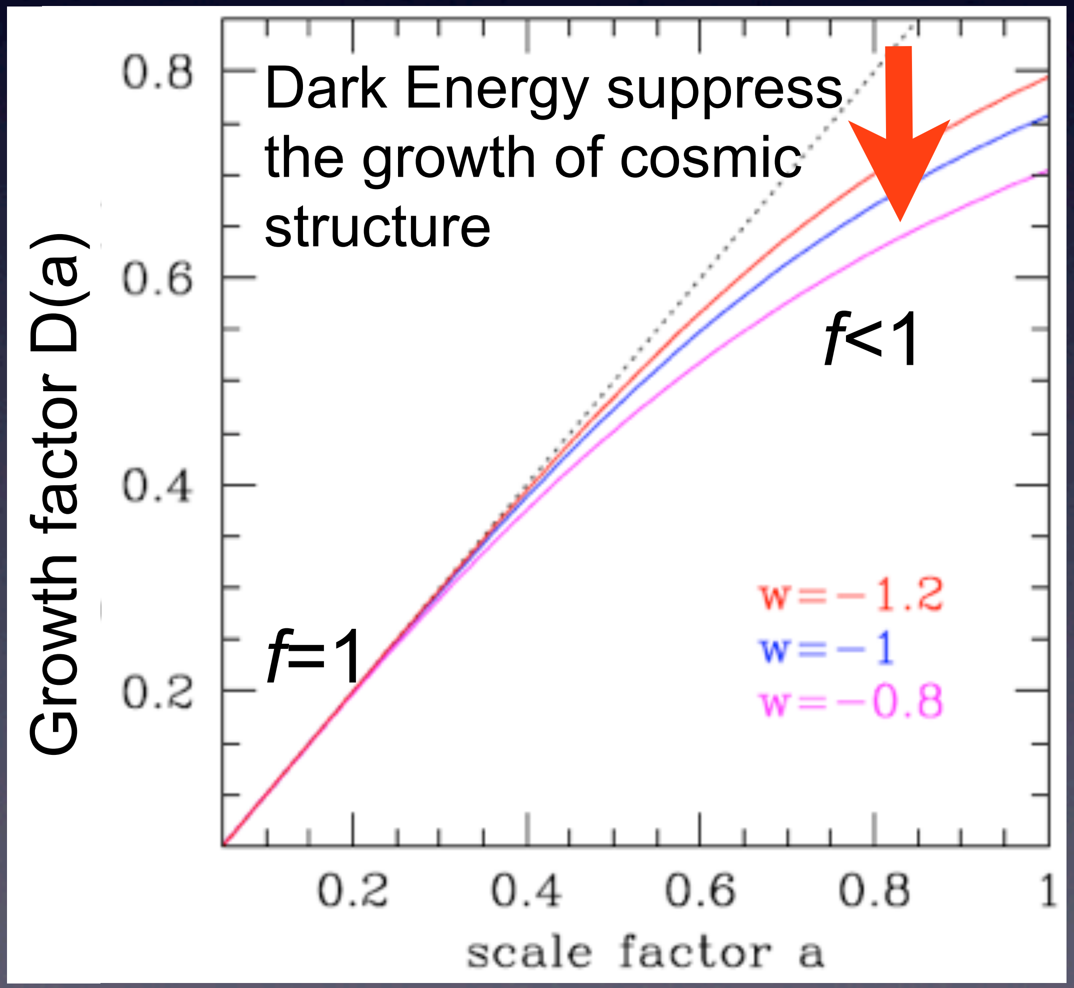

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$\rightarrow G_{eff}(k,t)$

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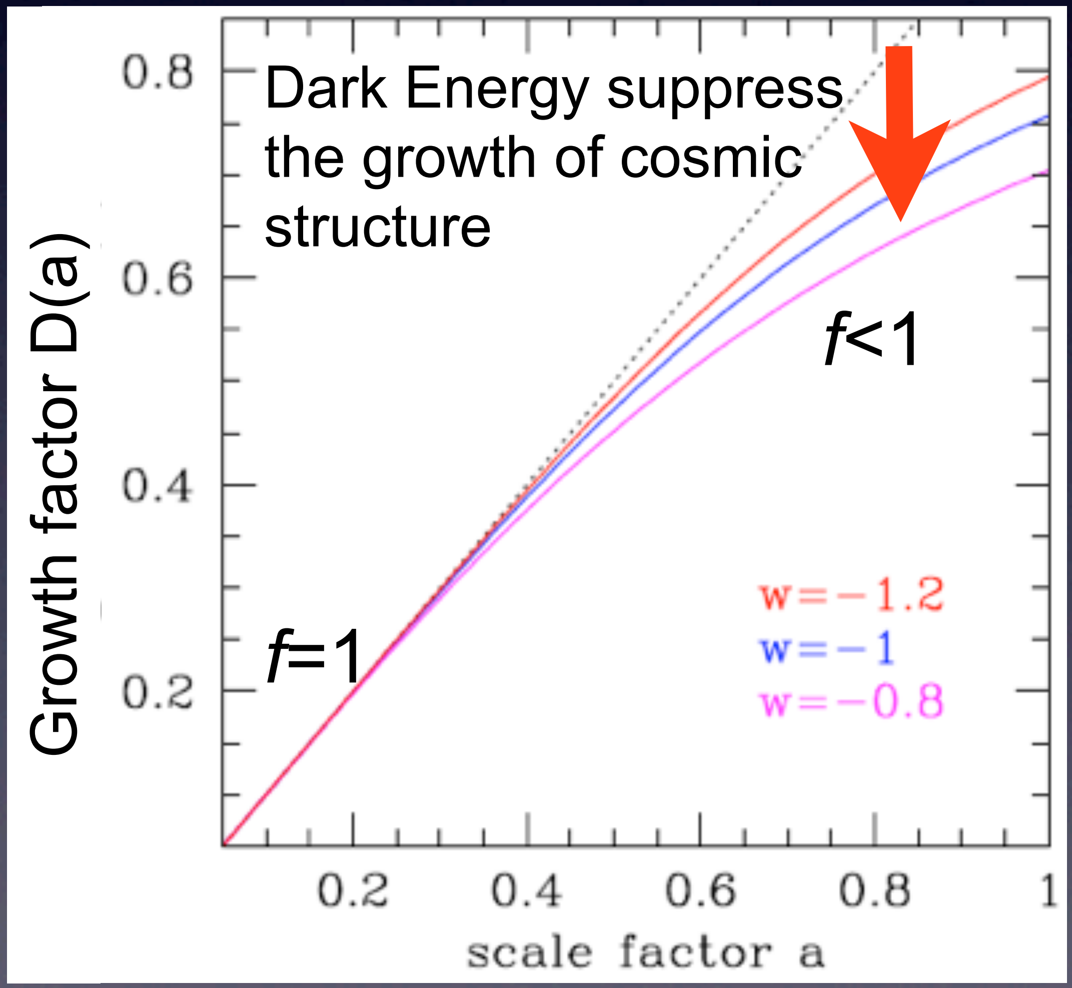


Growth rate index is a key probe to differentiate gravity models

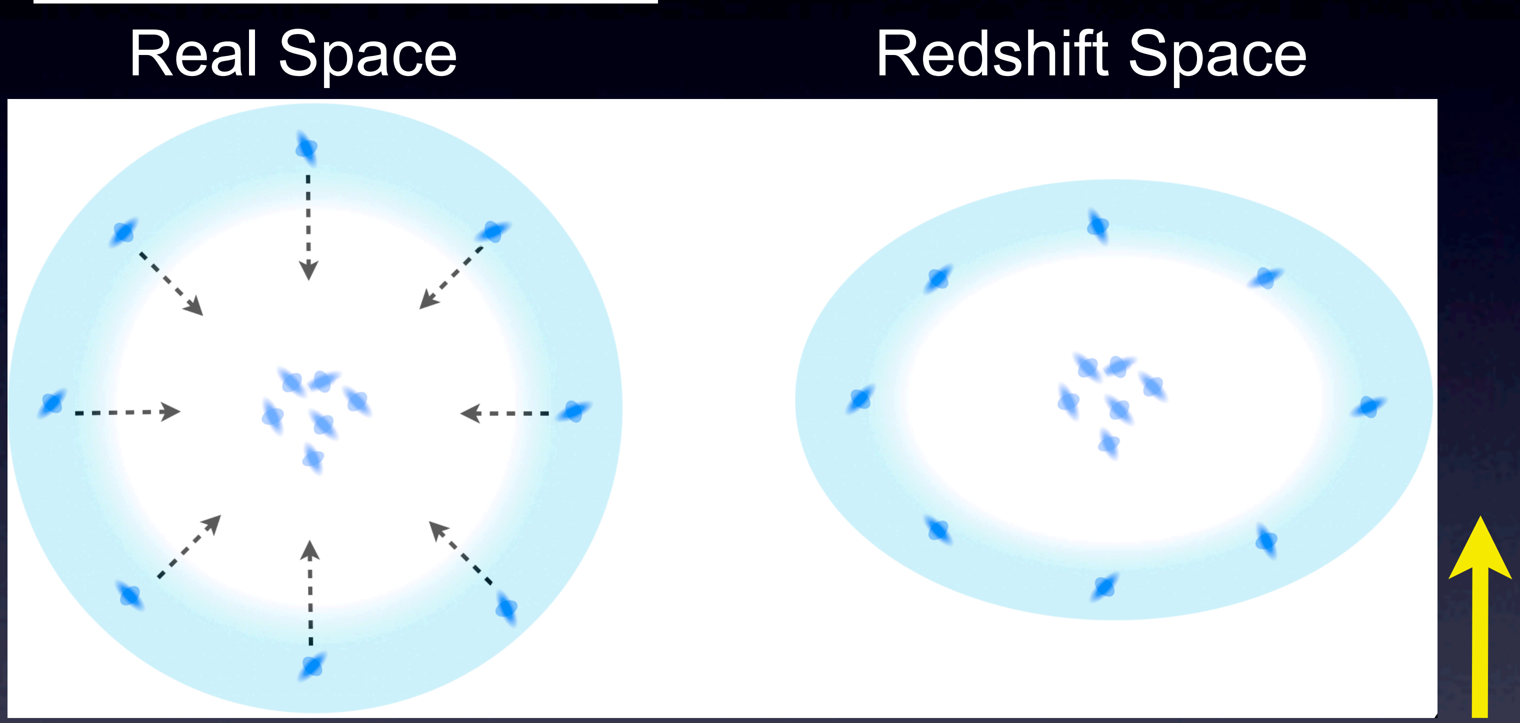
γ ~ 0.55 for GR

γ ~ 0.43 for f(R) (e.g., Hu & Sawicki 2007)

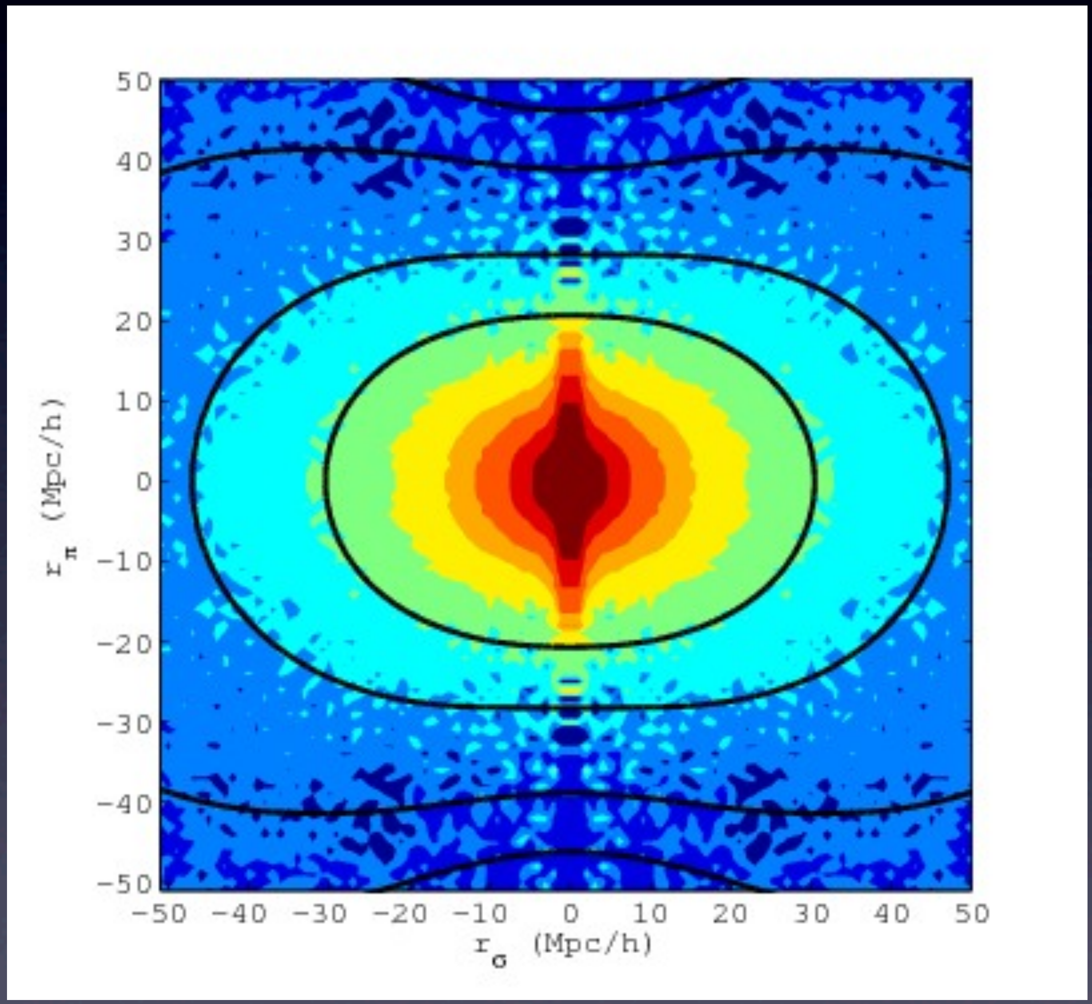
γ ~ 0.68 for flat DGP (e.g., Linder & Cahn 2007)

Redshift-space distortion (RSD)

$z_{obs} = z_{true} + \delta v/c$



2-point correlation functions $\xi(r_p, r_\pi)$ of BOSS CMASS galaxy samples

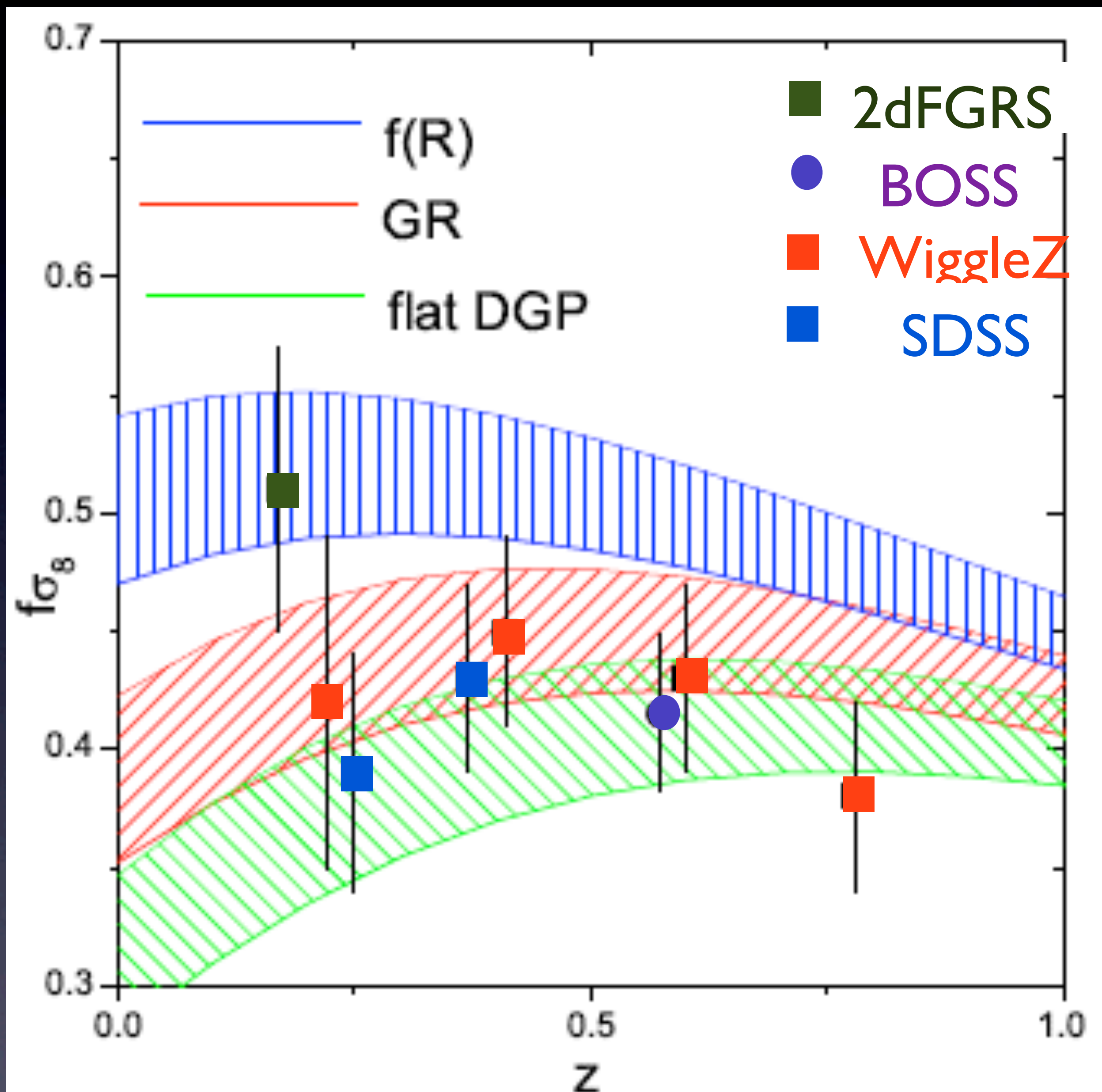


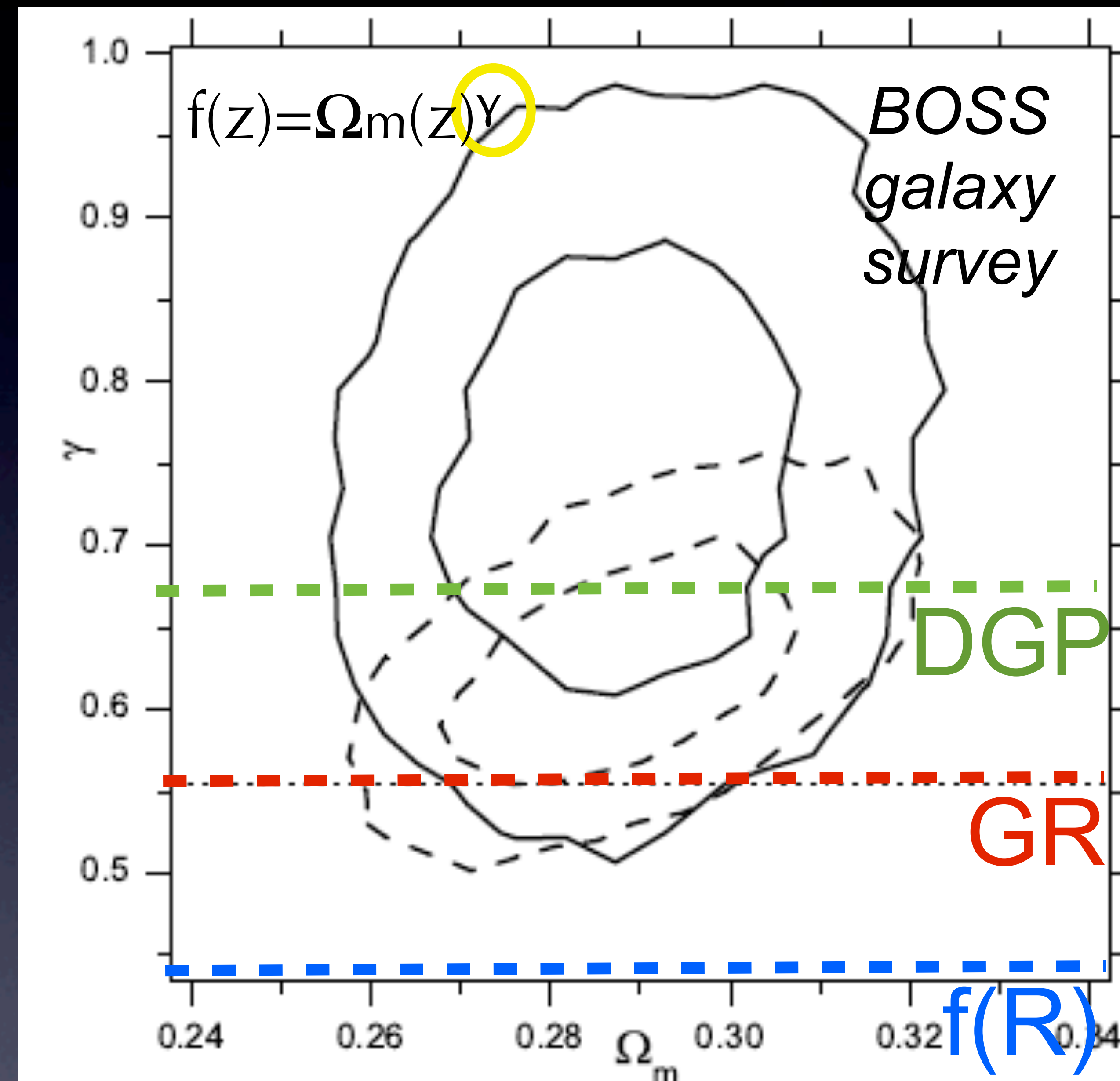
Reid et al. 2010

Galaxy distribution becomes anisotropic due to the peculiar motion of galaxies
➡ observational probe of growth rate

$$\dot{\delta}(z) = -(1+z)\nabla \cdot \mathbf{v}$$

Current constraints on growth rate and modified Gravity

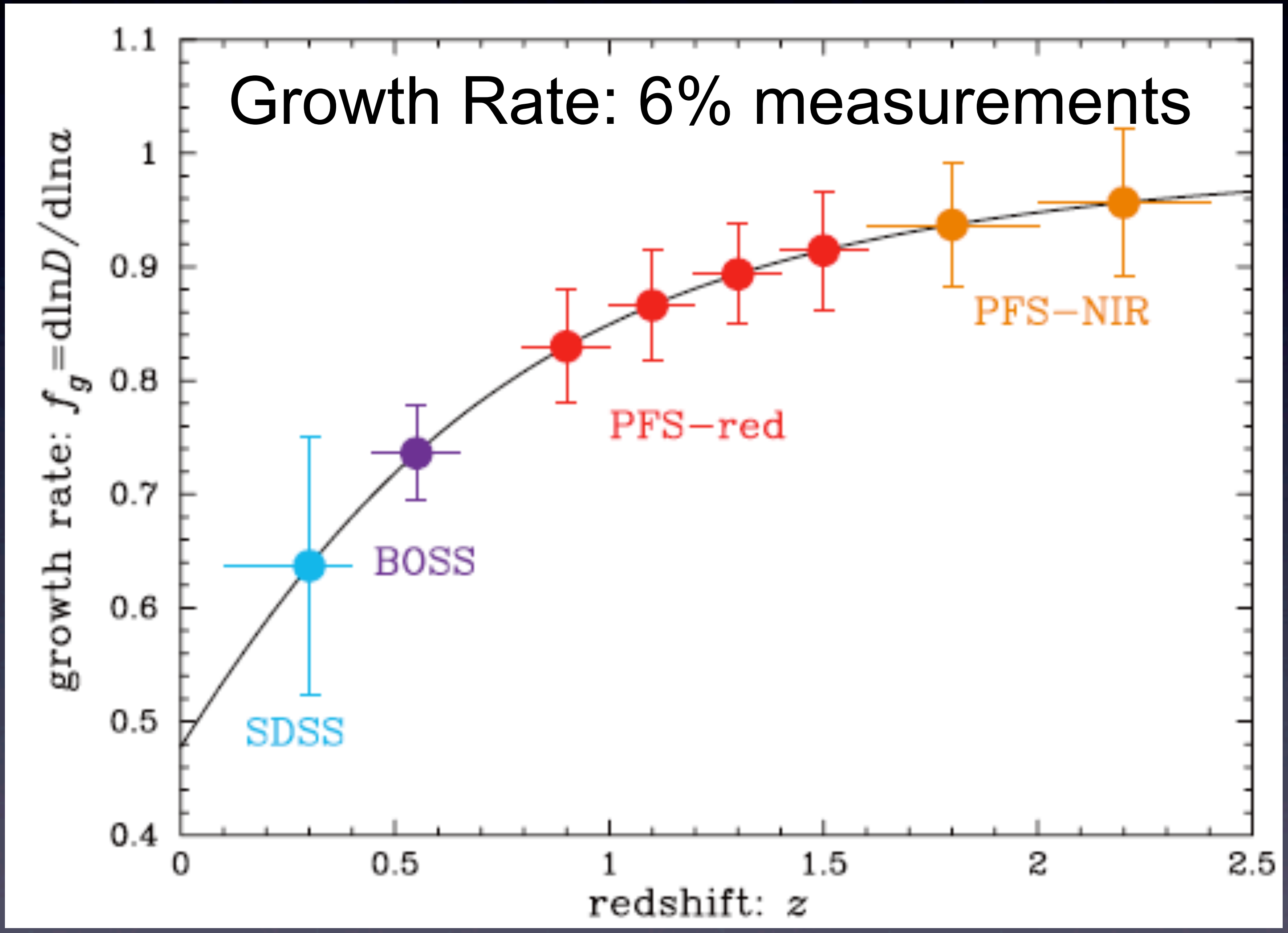




Samshia et al. 2012

Current observations are consistent with GR, but the measured values of growth rate are slightly smaller (γ is larger) than GR prediction

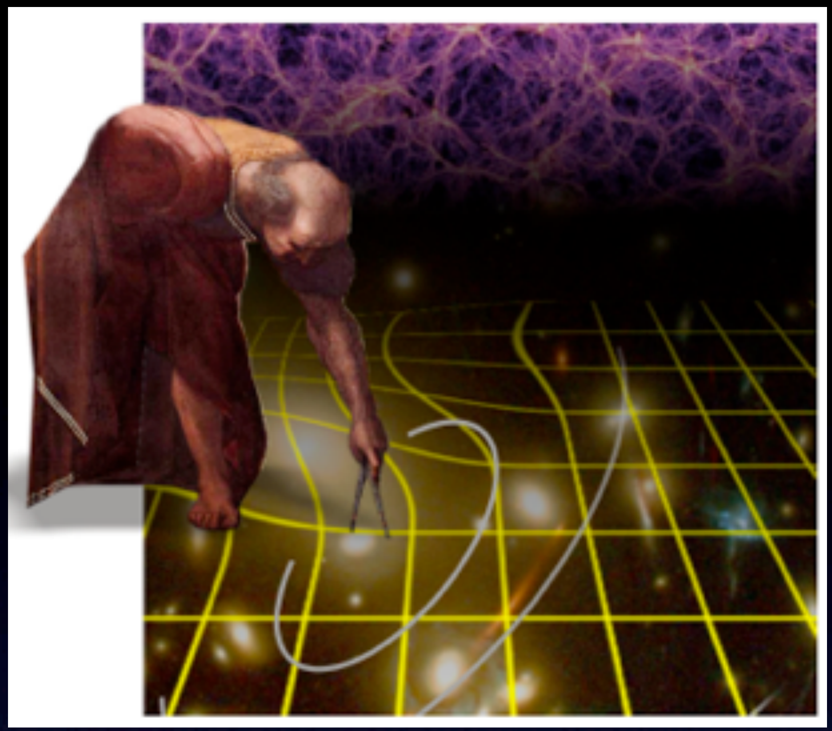
Prime Focus Spectrograph (PFS)



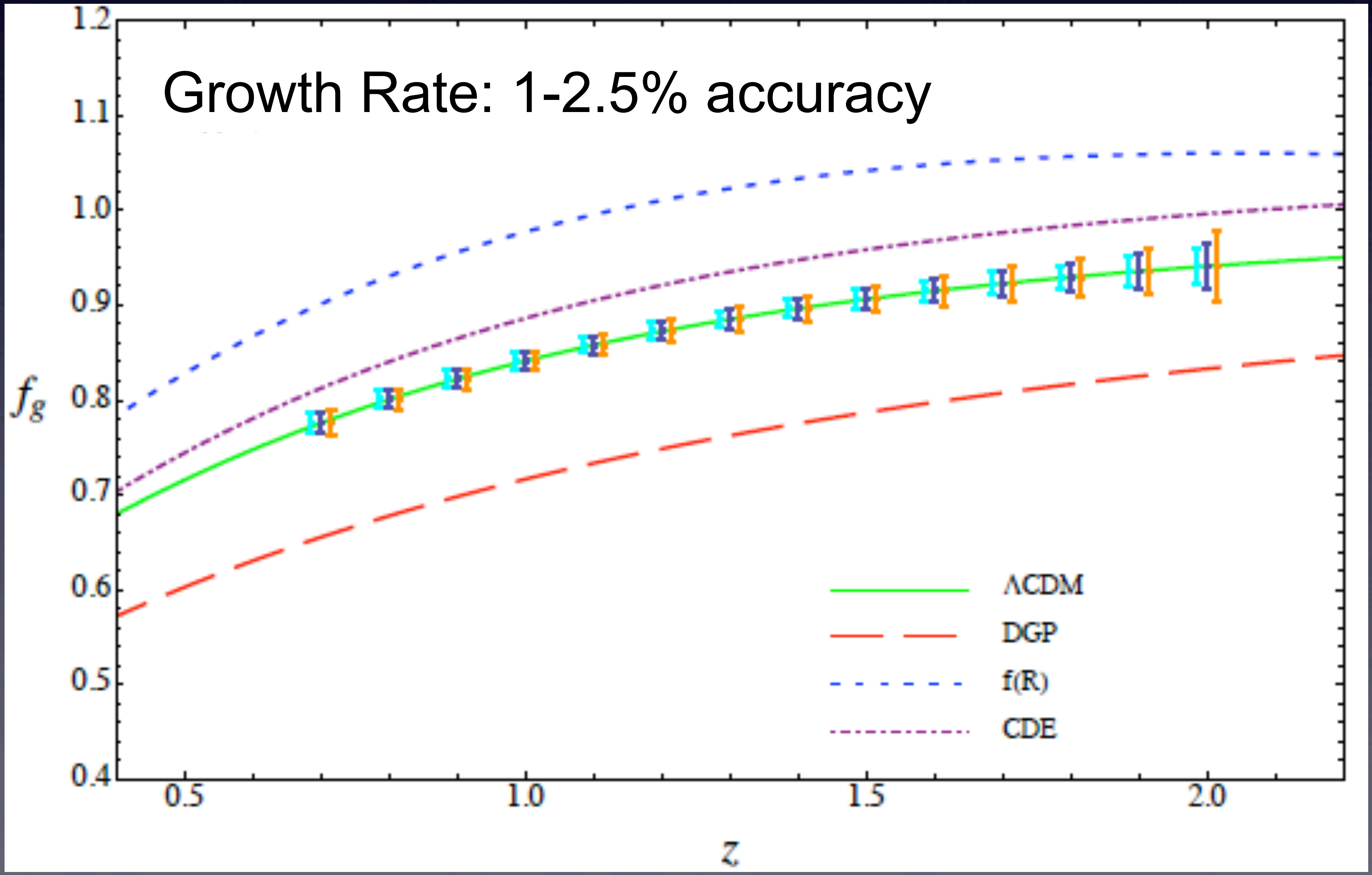
Takada et al. 2013

- Redshift survey of the same sky as HSC
- Main target: LRGs, OII emitters
- $0.8<z<2.4$ (9.3 Gpc/h^3)
- 2400 fibers, 380nm~1300nm
- 2019-2023 (planed)

Euclid



- Imaging 15,000 deg^2 sky, 40gals/arcmin^2
- Spectrum of 70M Hα emitters at 0.5<z<2
- 1.2m telescope
- FoV 0.5deg^2, rizYJH(550nm~1800nm)
- 0.2-0.3" pixel size
- 2023-2028 (planed)



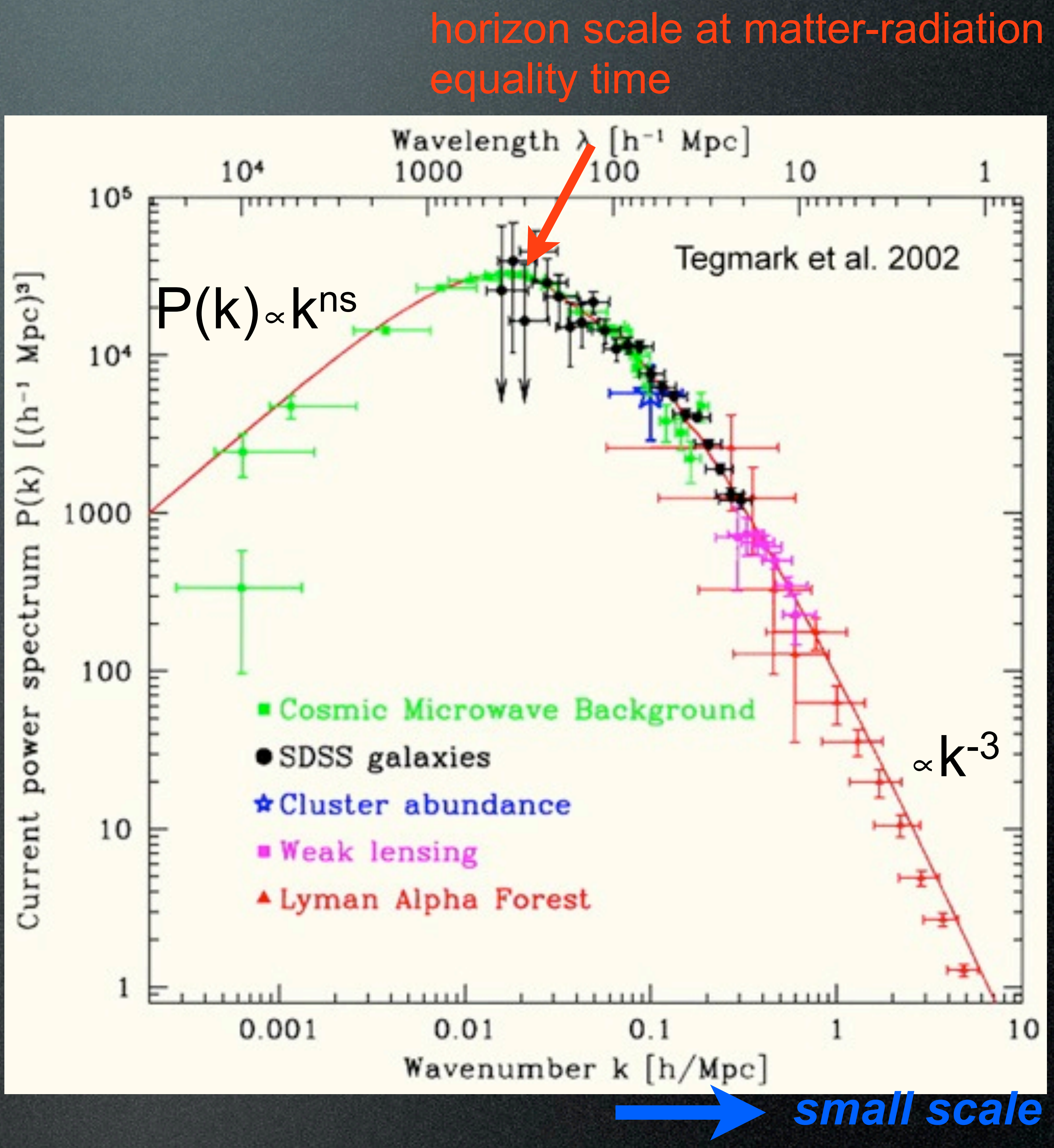
Euclid White Pape
(arXiv:1206.1225)

Power spectrum of Large-Scale Structure

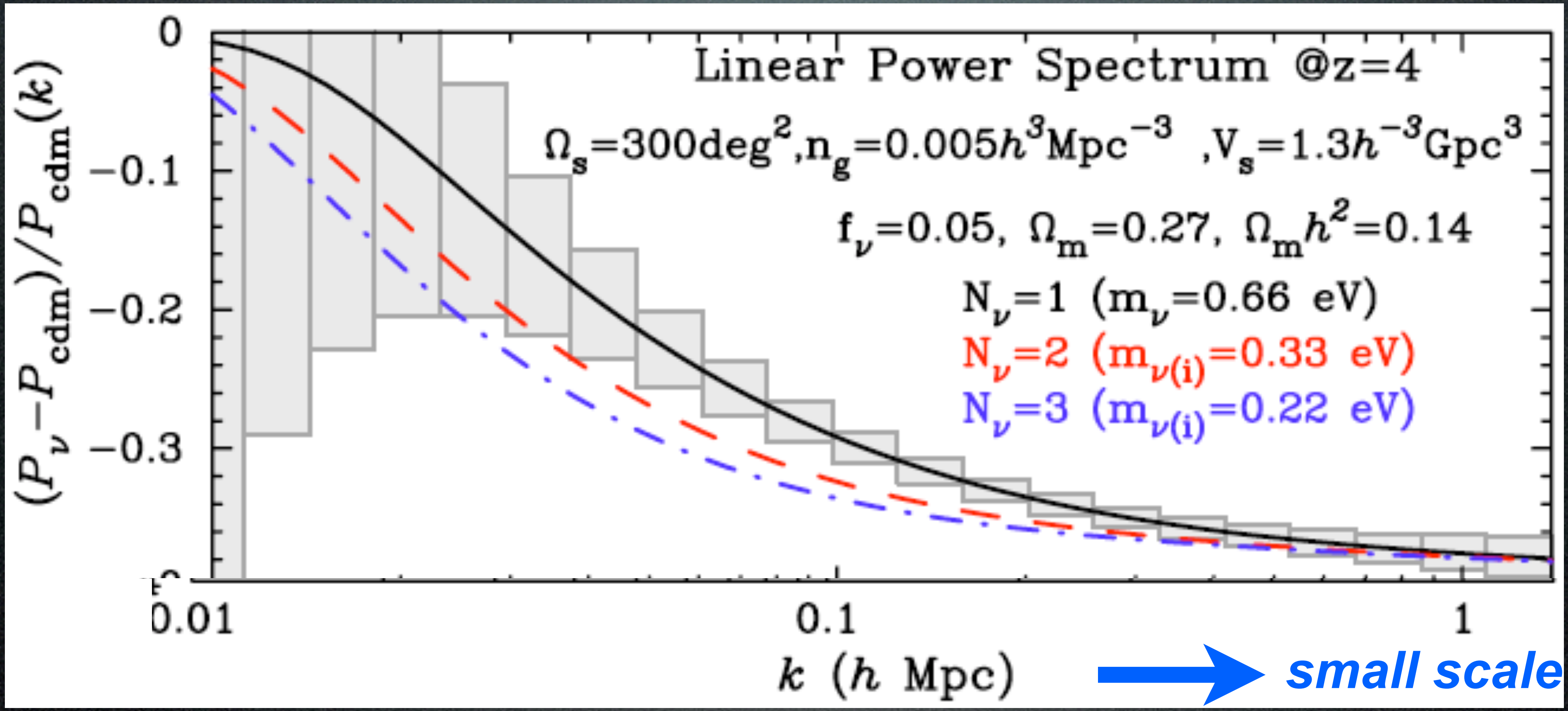
$P(k)=<|\delta_k|^2>$

Amplitude of the fluctuation at the wavenumber of k

Power spectrum of LSS has been measured from different observations at wide range of scales



Free-streaming damping of the LSS power spectrum



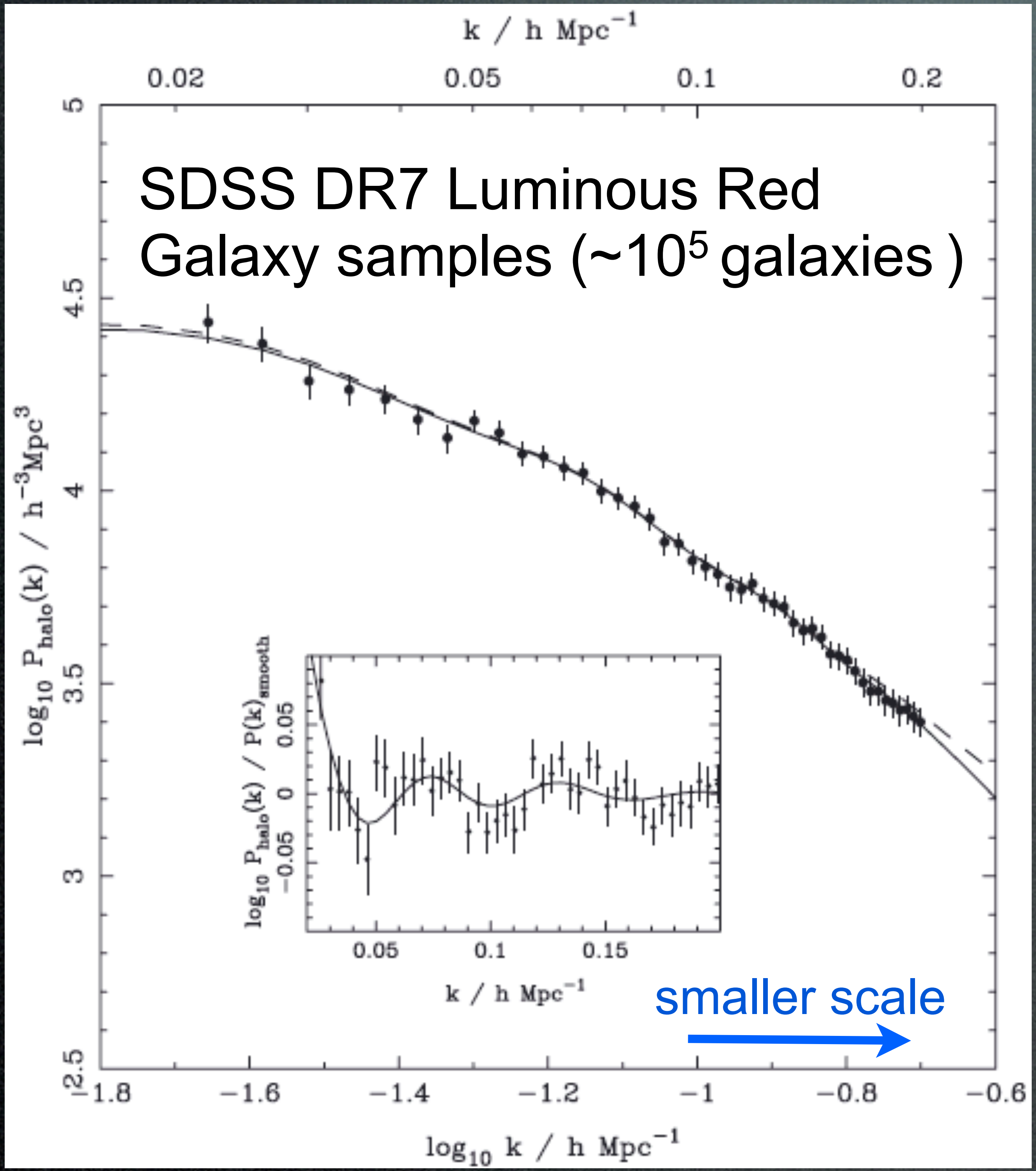
Takada, Komatsu, Futamase 2006

Small-scale suppression of the matter power spectrum is sensitive to the neutrino mass

$$\frac{\Delta P}{P} \sim 8 f_\nu$$

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_m} = 0.05\left(\frac{N_\nu^{nr} m_\nu}{0.658\ \text{eV}}\right)\left(\frac{0.14}{\Omega_m h^2}\right)$$

Constraints on total neutrino mass



Reid et al. 2010

Current constraints

SDSS/BOSS CMASS

$m_{\nu,tot}$<0.34eV

(Gong-Bo et al. 2012)

Future prospects

Subaru PFS: $\Delta m_{\nu,tot}$=0.13eV

Euclid: $\Delta m_{\nu,tot}$=0.02eV

Systematic uncertainty

In order to achieve these goals, we have to control systematic uncertainties at percent-level accuracy:

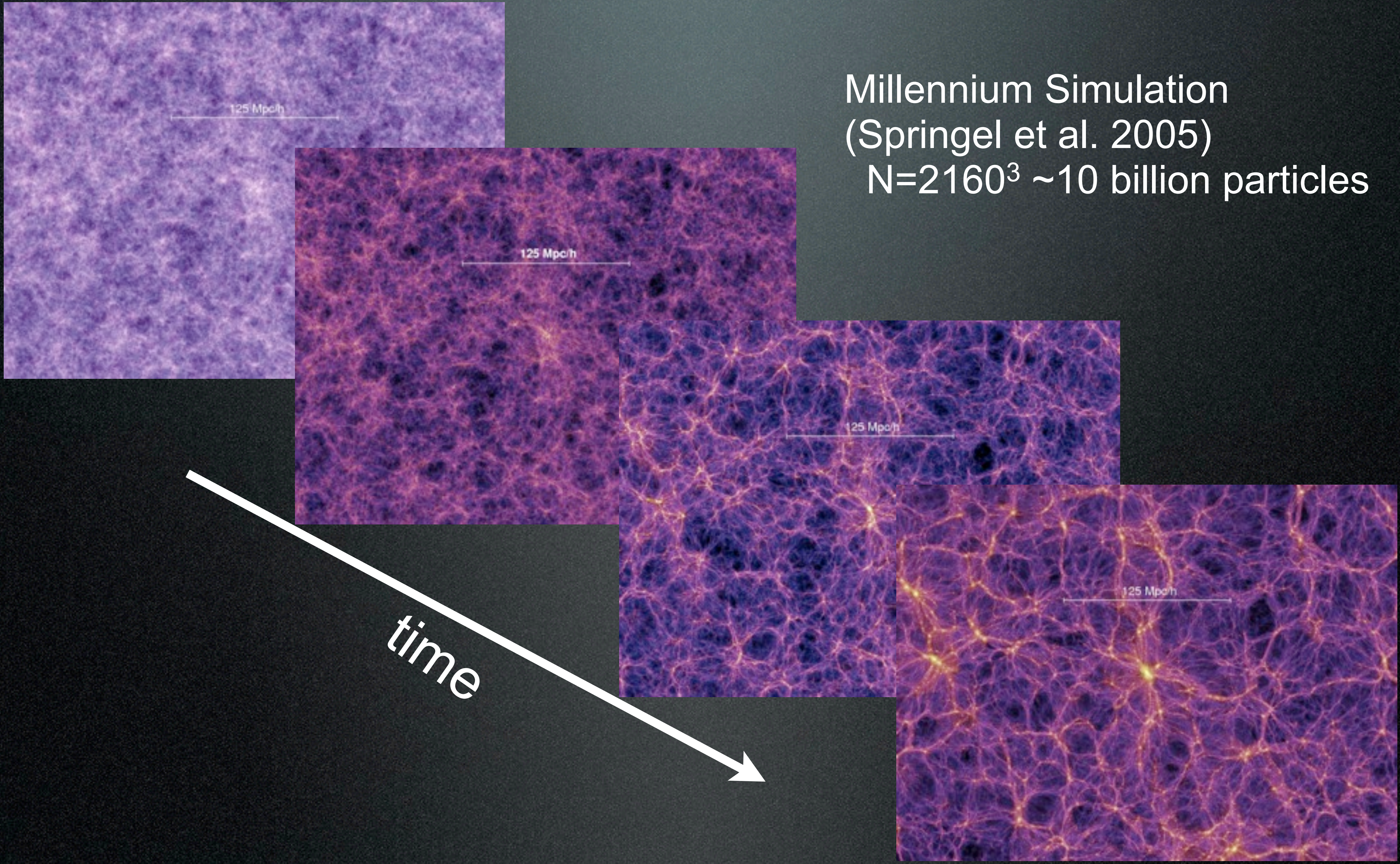
1. Nonlinear Gravity

2. Uncertainty between galaxy redshift and matter distribution

   a) Galaxy biasing

   b) Fingers-of-God: nonlinear redshift distortion due to the random motion of galaxies

1. N-body simulations



Millennium Simulation
(Springel et al. 2005)
$N=2160^3$ ~10 billion particles

Lagrangian Perturbation theory

$$\boldsymbol{x}(\boldsymbol{q}, t) = \boldsymbol{q} + \boldsymbol{\Psi}(\boldsymbol{q}, t).$$

displacement field

Equation of motion

$$\frac{d^2\boldsymbol{\Psi}}{dt^2} + 2H\frac{d\boldsymbol{\Psi}}{dt} = -\nabla_x \phi[\boldsymbol{q} + \boldsymbol{\Psi}(\boldsymbol{q})],$$

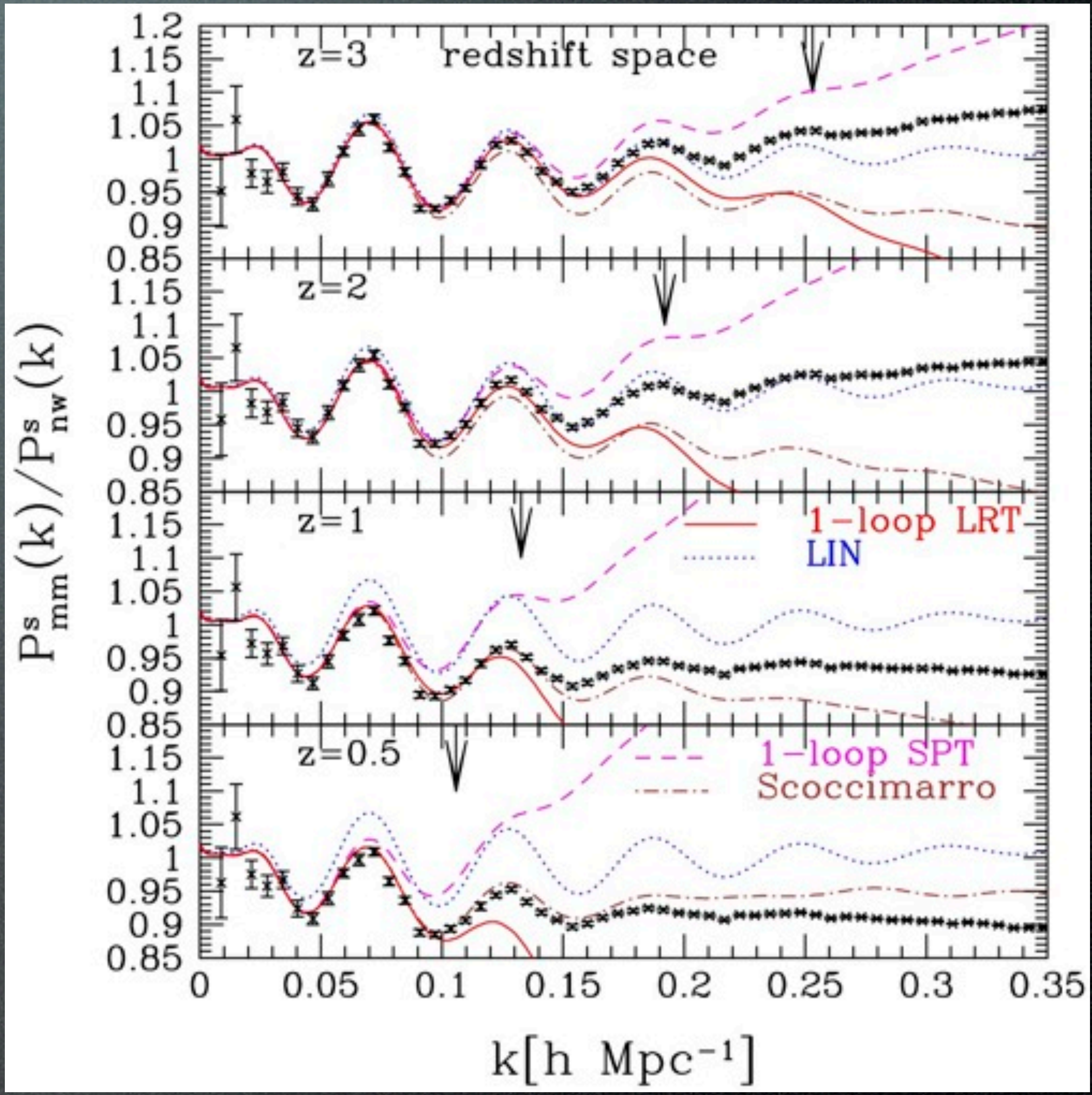
gravitational potential

Poisson equation

$$\nabla_x^2 \phi(\boldsymbol{x}) = 4\pi G\bar{\rho}a^2\delta(\boldsymbol{x}),$$

$$\boldsymbol{\Psi} = \boldsymbol{\Psi}^{(1)} + \boldsymbol{\Psi}^{(2)} + \boldsymbol{\Psi}^{(3)} + \cdots,$$

Matsubara 2008



Sato & Matsubara 2011

The perturbation agree with simulation results upto k=0.1~0.2h/Mpc in a percent-level accuracy

2a. Galaxy Biasing

Relationship between galaxy number density δ_g and mass density δ_m

<u>Linear Biasing</u>

$\delta_g = b\delta_m$ (Kaiser 1984)

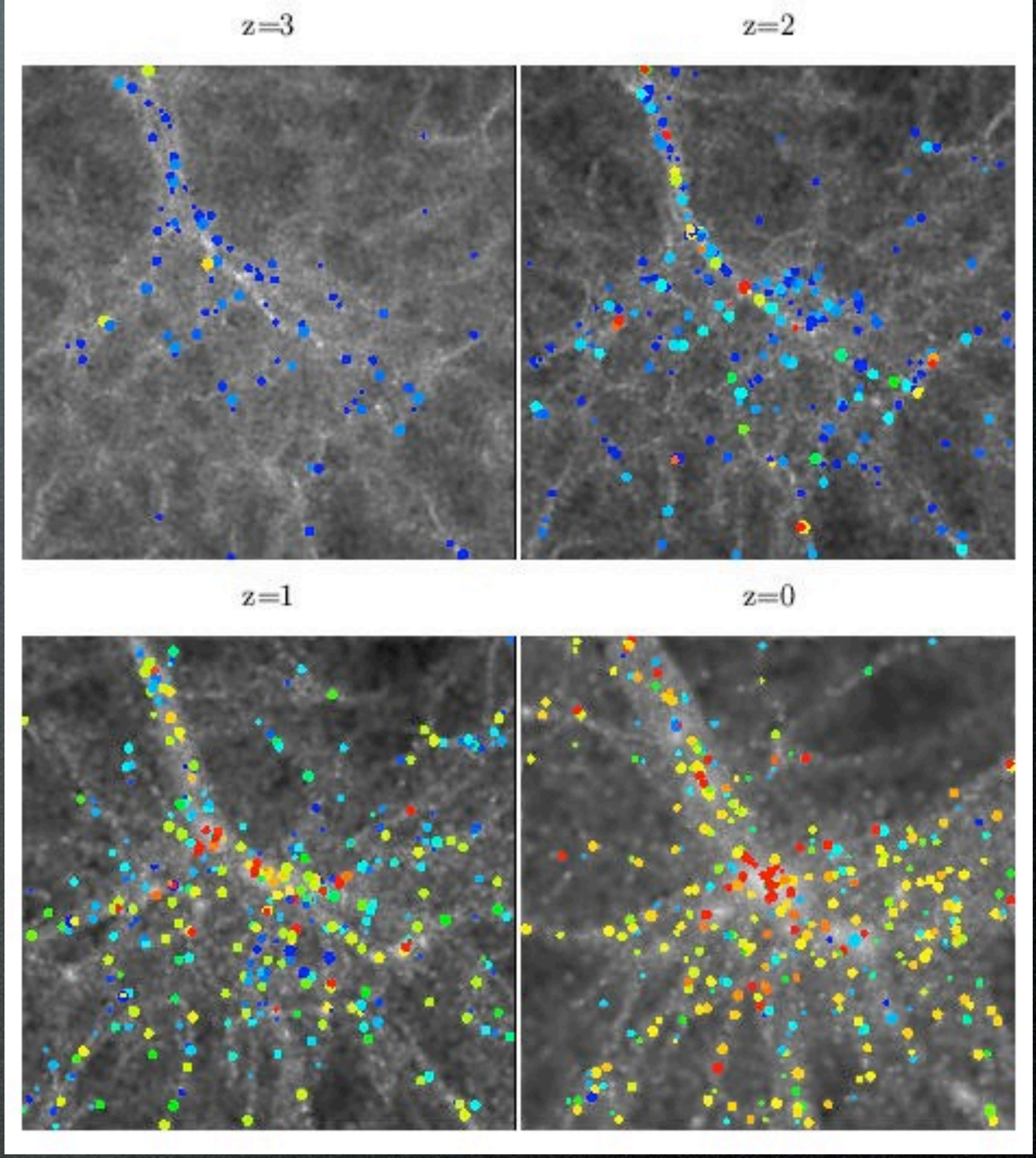
<u>Nonlinear Biasing</u>

$\delta_g = b_1\delta_m + b_2\delta_m^2 + \cdot\cdot$

(Fry & Gaztanaga 1993)

<u>Nonlinear Stochastic Biasing</u>

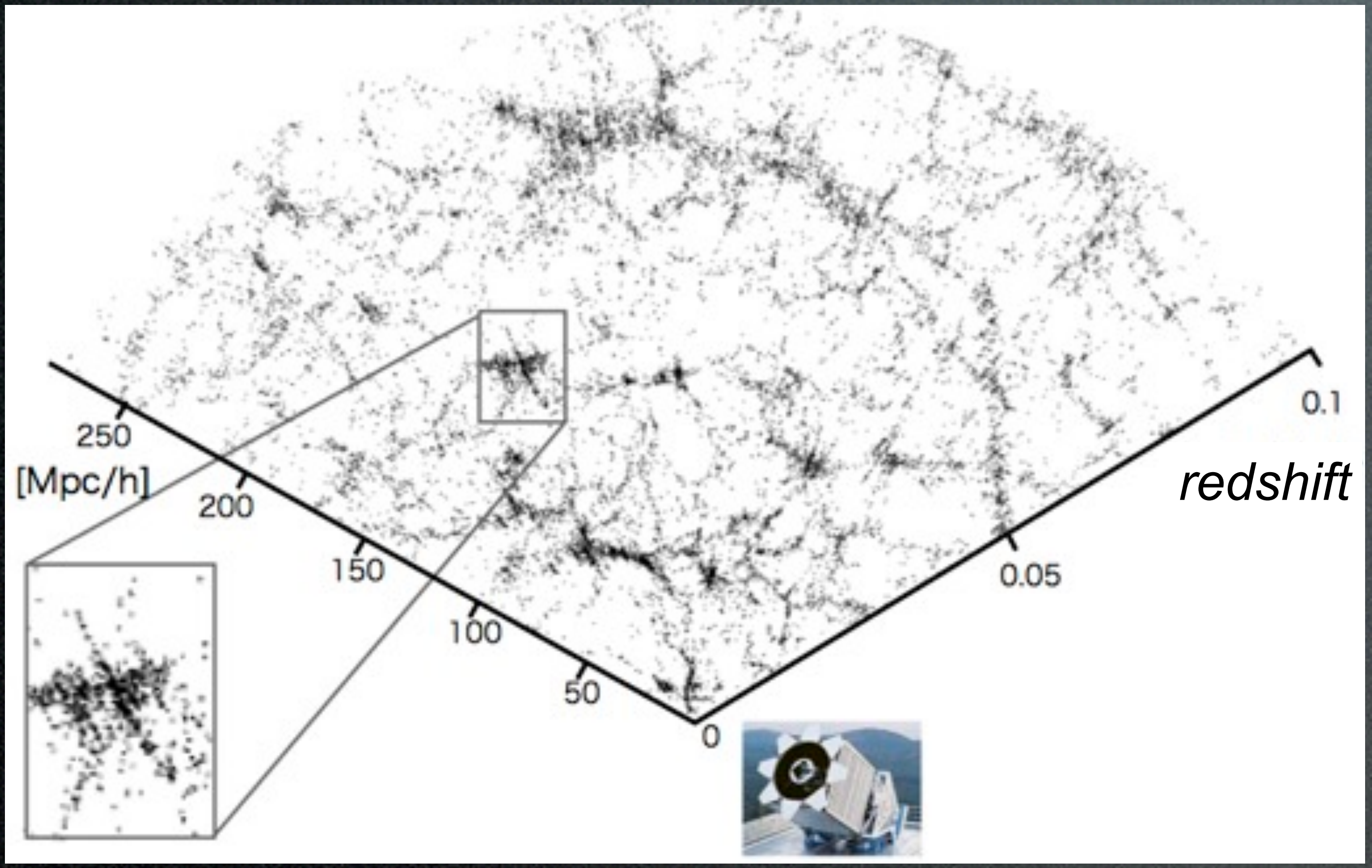
$P(\delta_g|\delta_m)$
(Dekel & Lahav 1999)



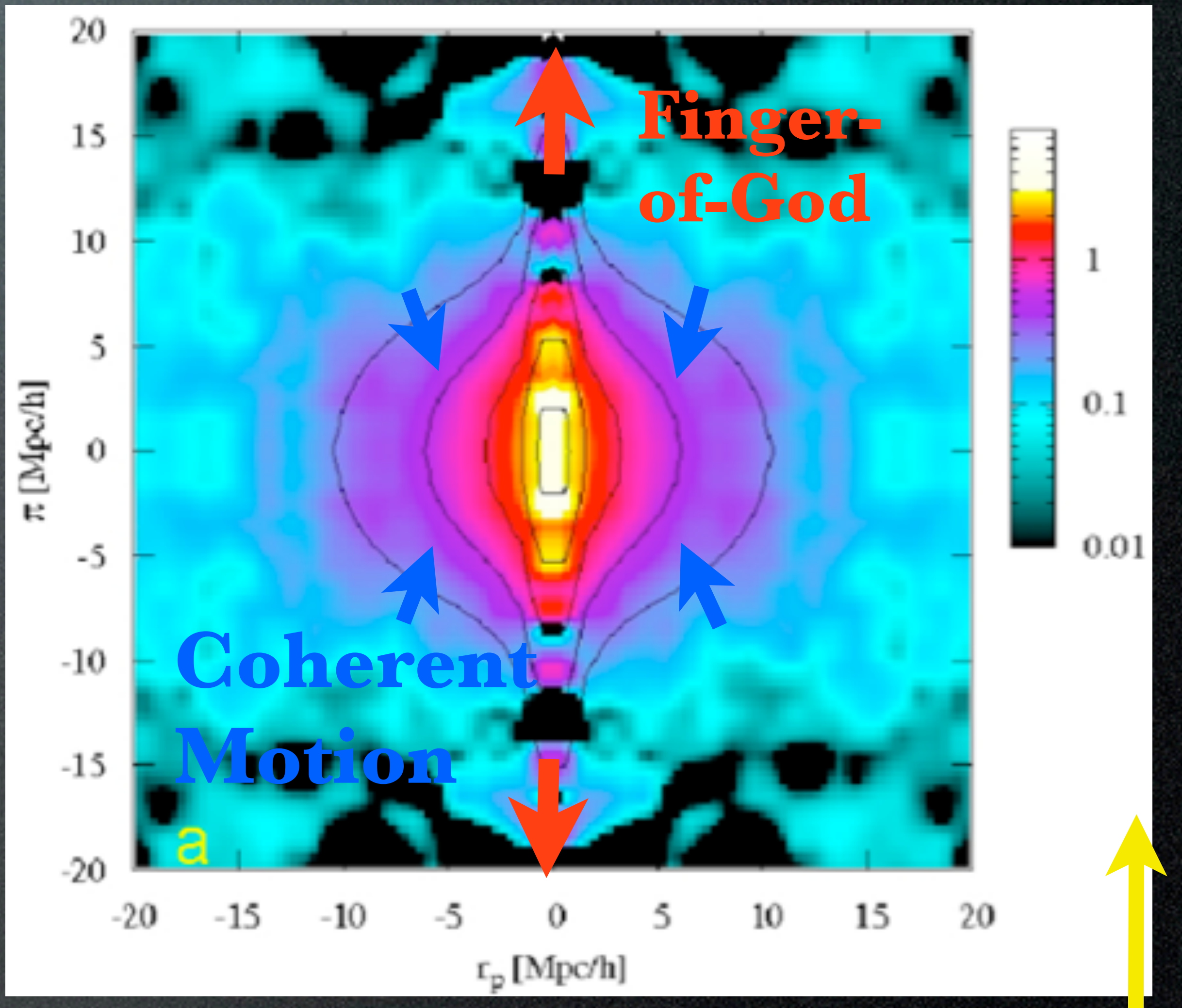
Colberg et al.

2b. Fingers-of-God (FoG)

Nonlinear redshift distortion due to the internal motion of satellite galaxies in their hosted dark matter halo



Fingers-of-God effect



Guzzo et al. 2008

2-Point Correlation Function VVDS-Wide Survey (6000 gals, 0.6<z<1.2, 4deg^2)

Impact of FoG on Growth Rate measurement

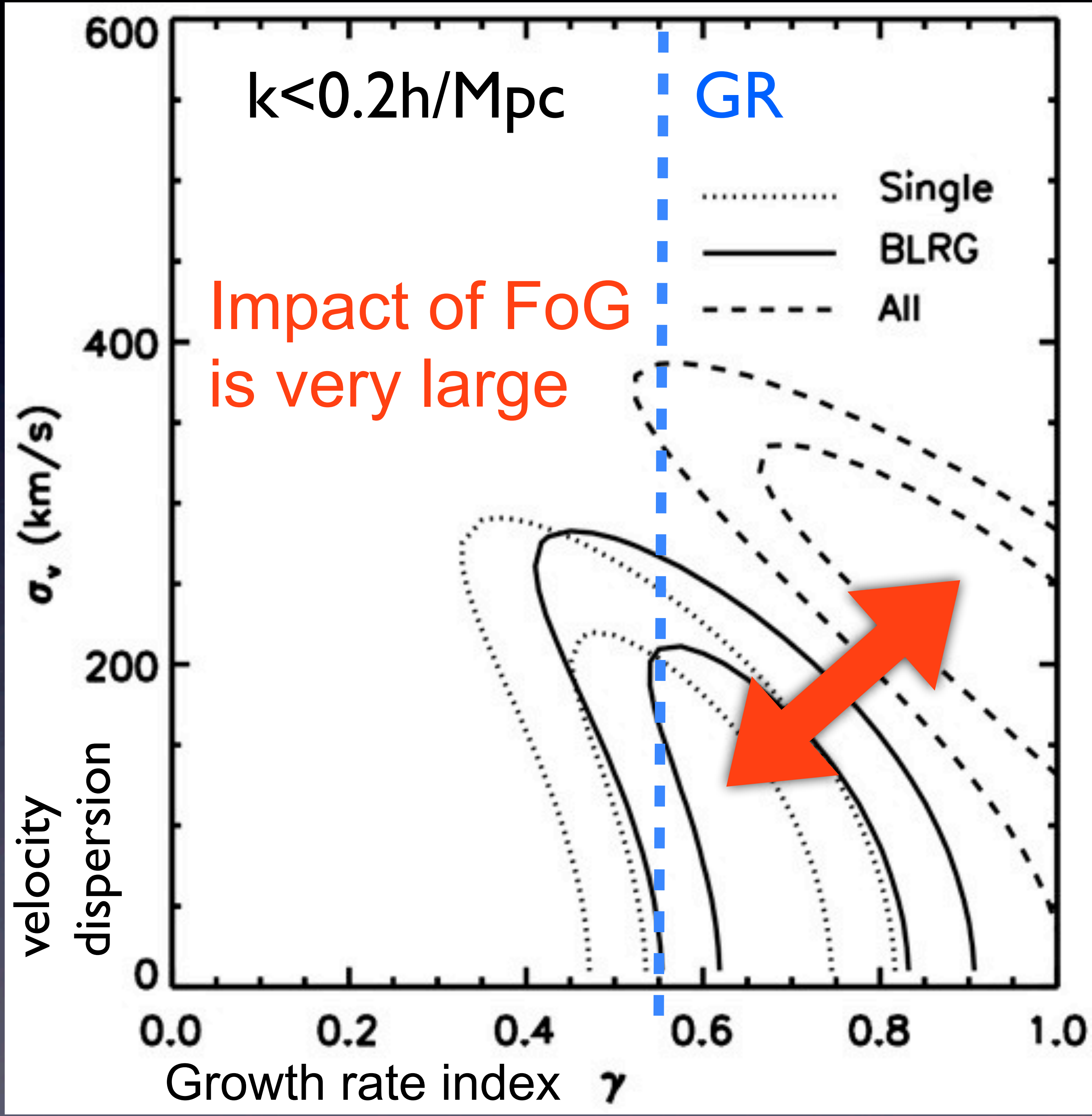
SDSS DR7 Luminous Red Galaxy (LRG) sample (0.16<z<0.47)

Grouping nearby LRGs using counts-in-cylinder method (Reid & Spergel 2010)

1) **ALL** : All LRGs (satellite galaxies are included)

2) **BLRG** : Brightest LRG in each LRG group

3) **Single** : Single LRG systems only (most of satellite galaxies are removed)

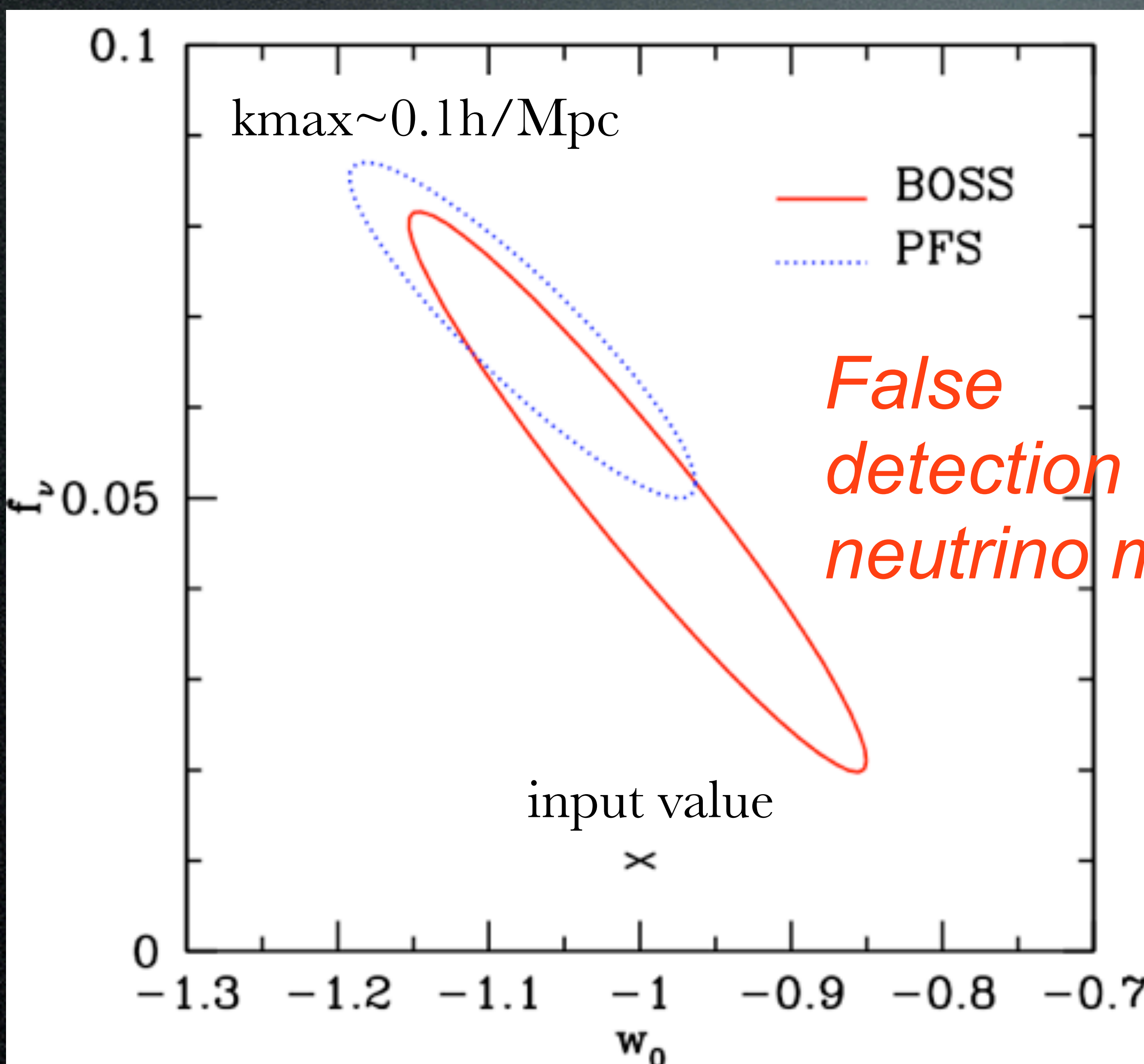


CH & Yamamoto (2013)

FoG damping assuming Lorentzian form (velocity dispersion σ_v is free parameter)

Difference among the samples is just ~5% satellite galaxies

Impact of FoG effect on neutrino mass measurement



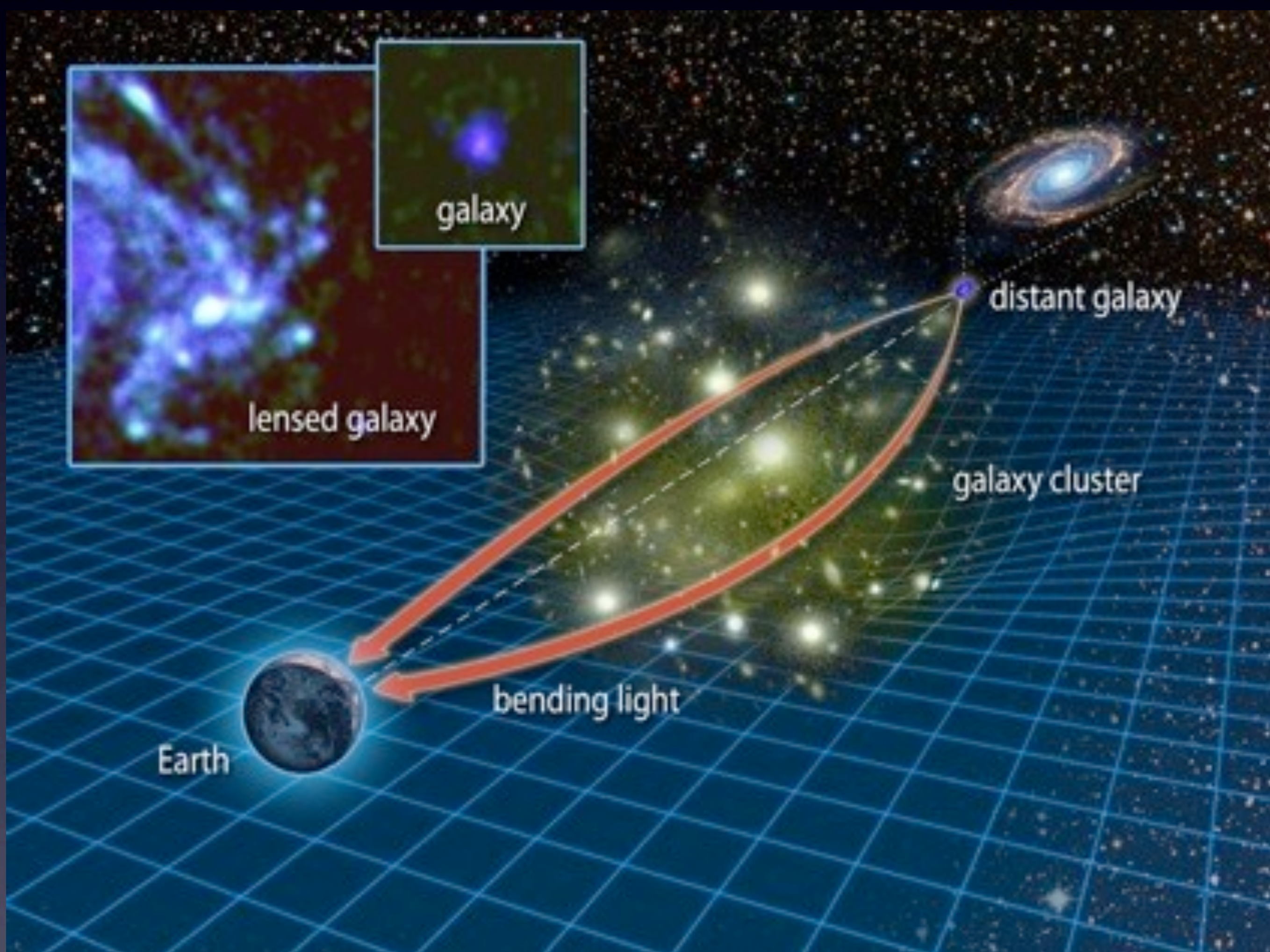
False detection of neutrino mass

CH, Takada, Spergel (2012)

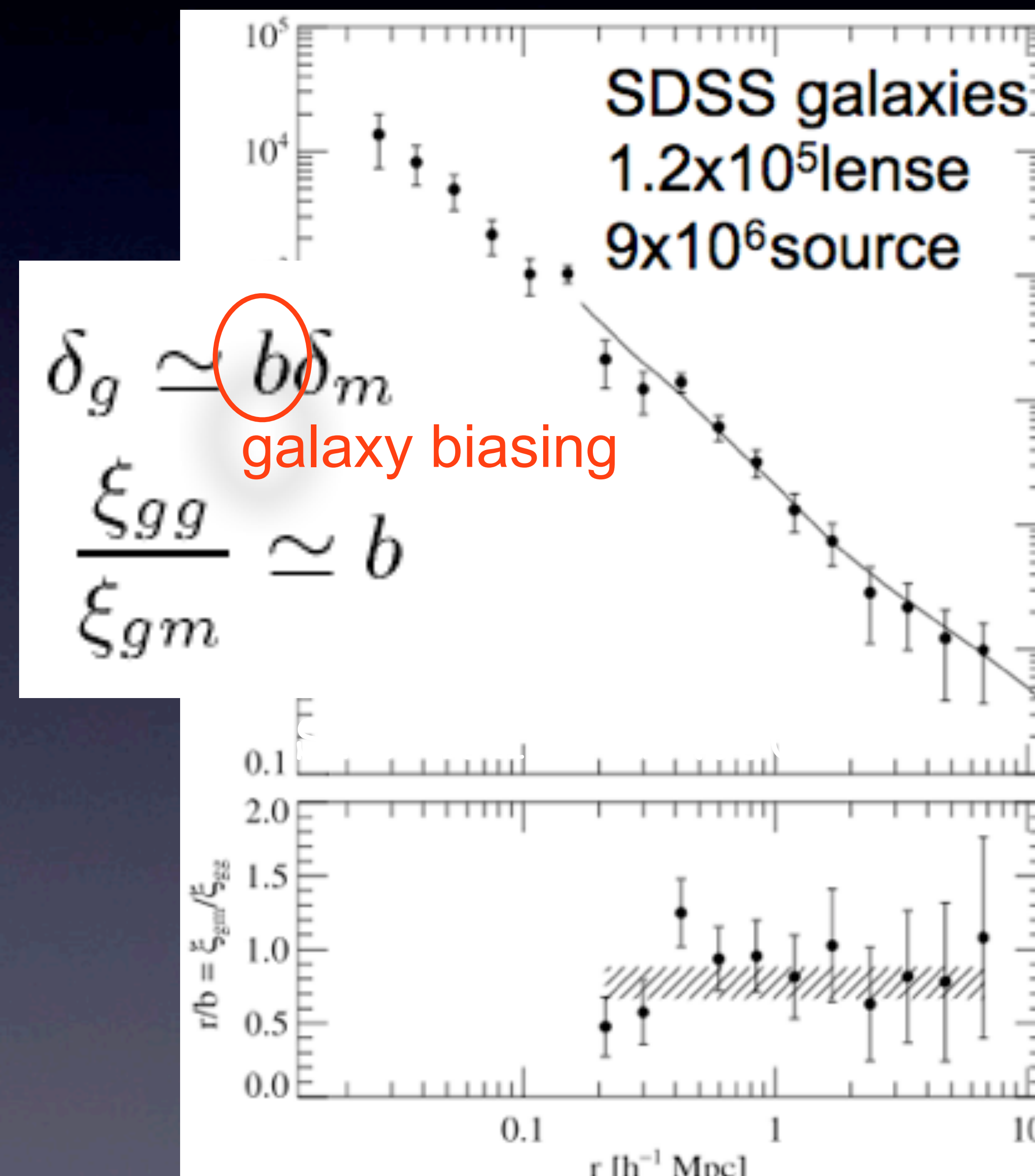
FoG damping mimics the free-streaming damping of neutrinos

Galaxy-Galaxy lensing

Cross correlation of foreground galaxies and background galaxy images

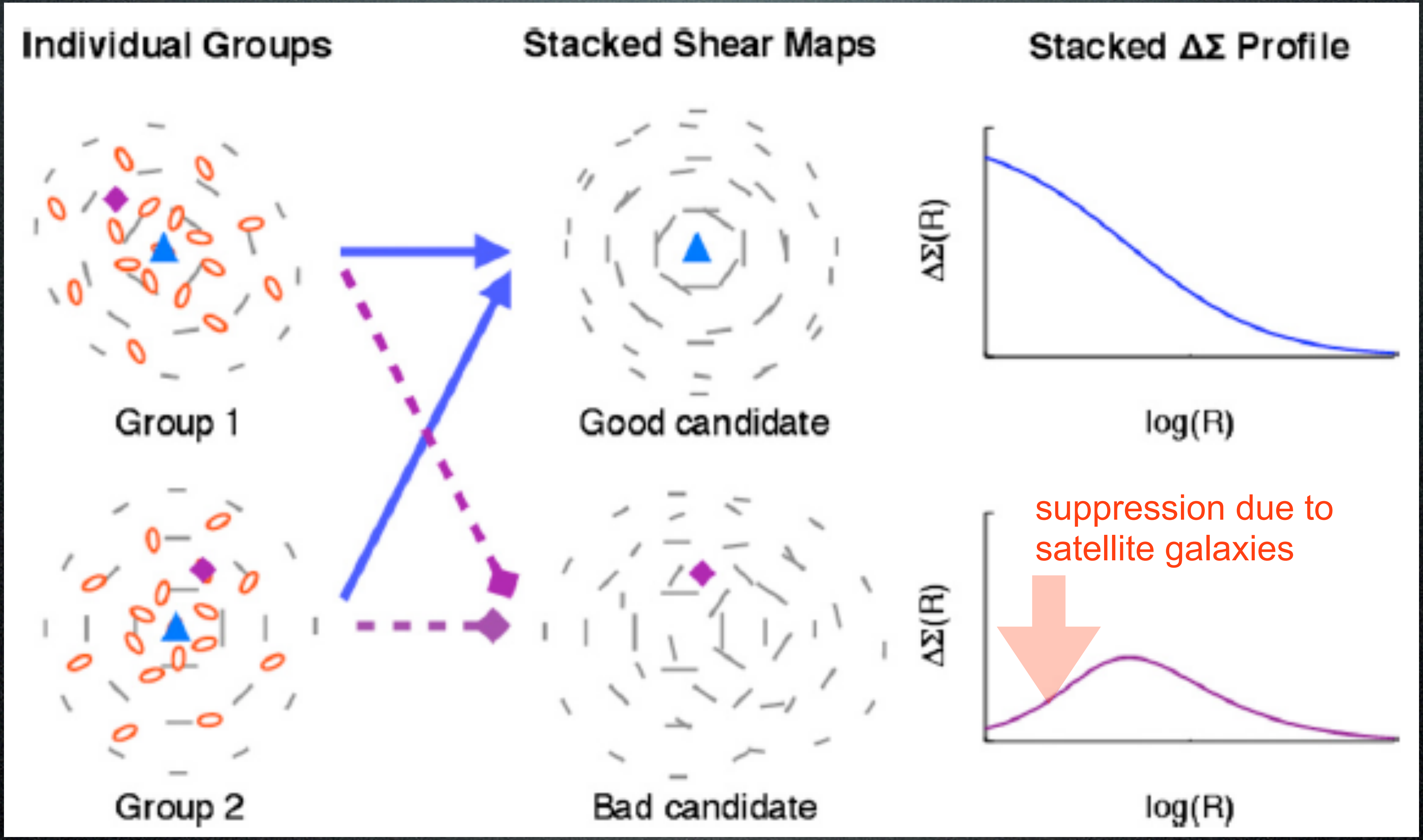


Credit: *Karen Teramura, U Hawai IfA*



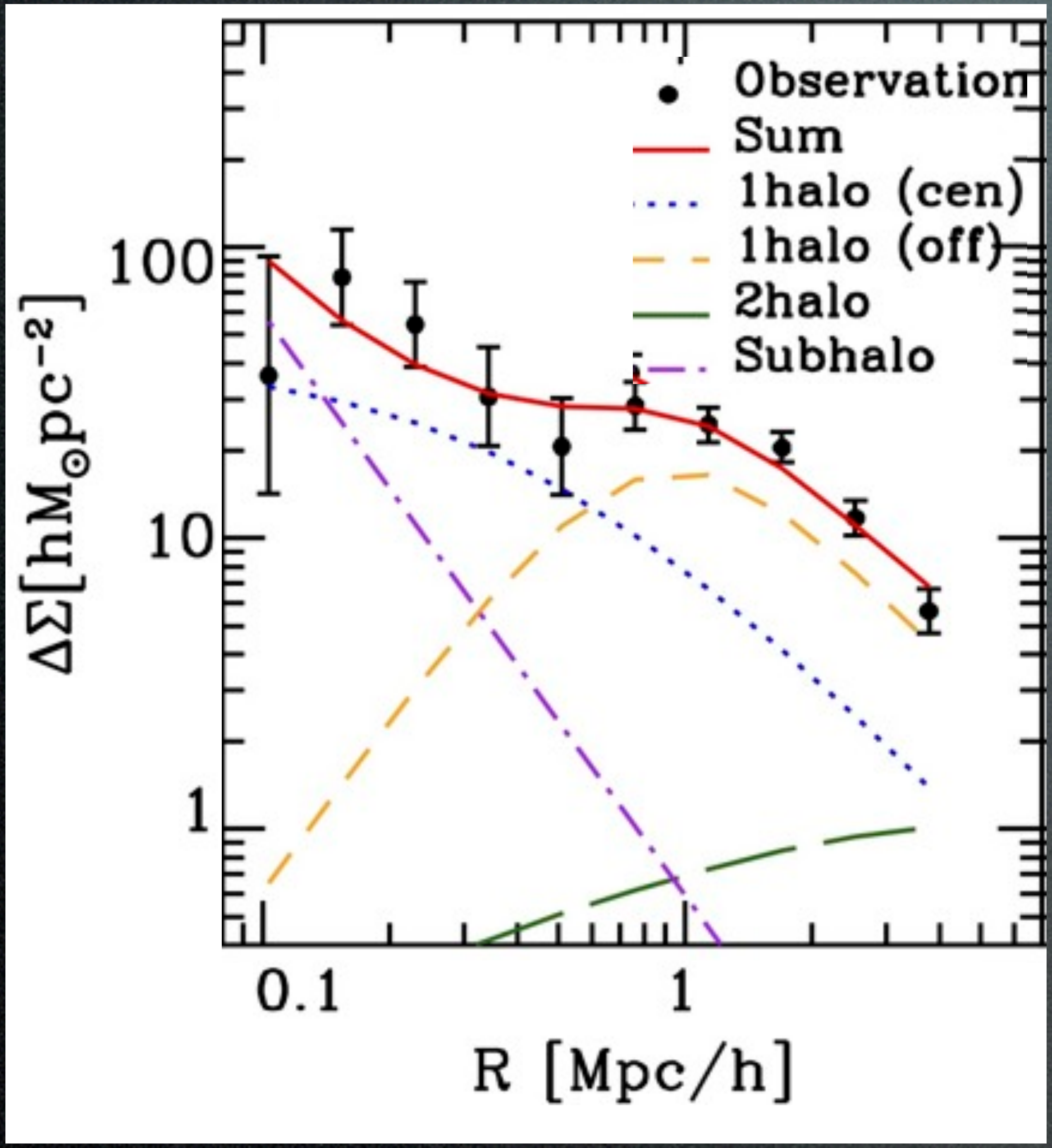
Galaxy-galaxy lensing clarify the relationship between galaxies and matter

Effect of satellite galaxies on stacked galaxy-galaxy lensing

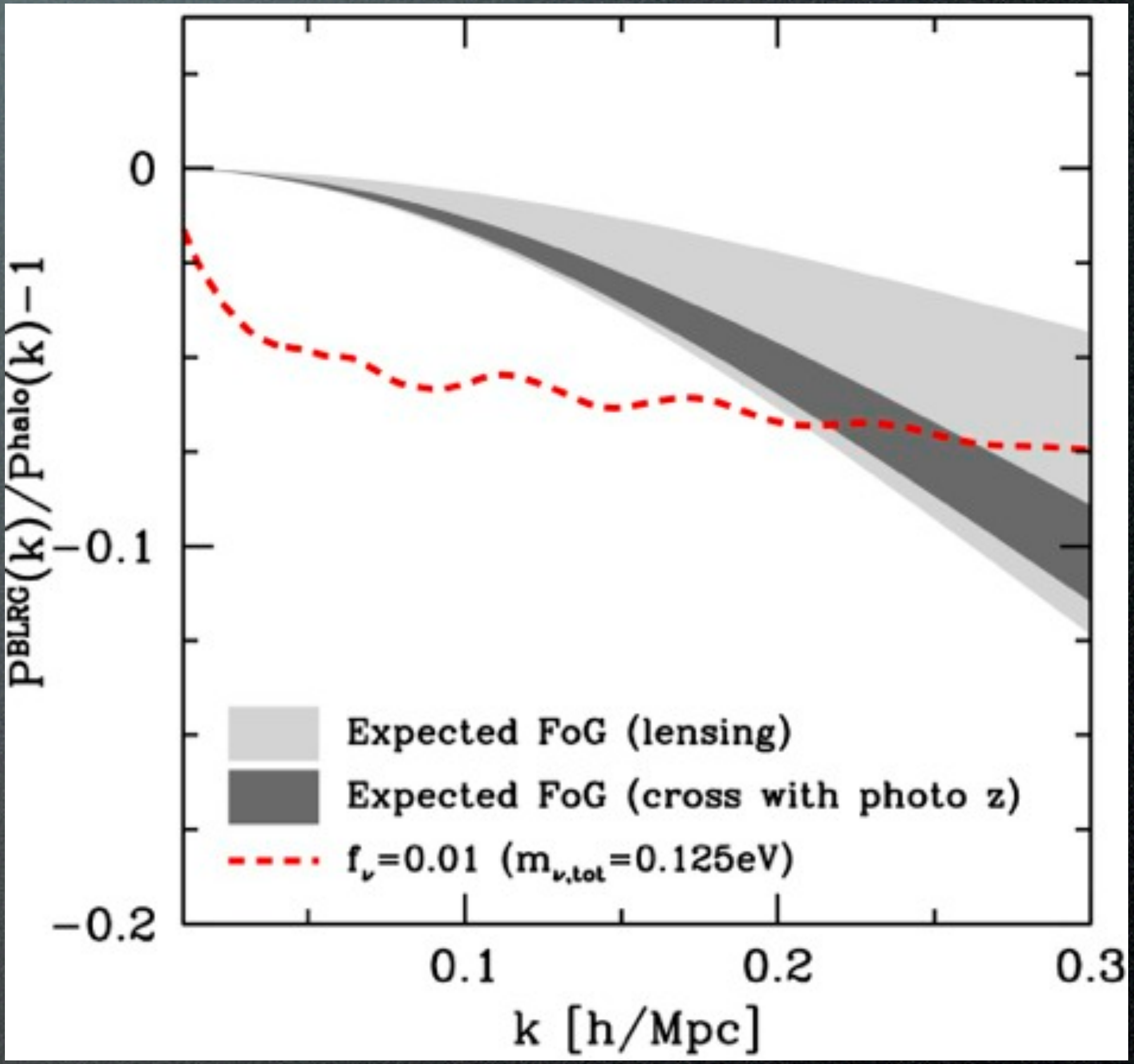


Galaxy-galaxy lensing/cross-correlation can be used to calibrate the satellite FoG effect

Constraints on satellite FoG effect



FoG damping ratio



CH, Mandelbaum, Takada, Spergel (2013)

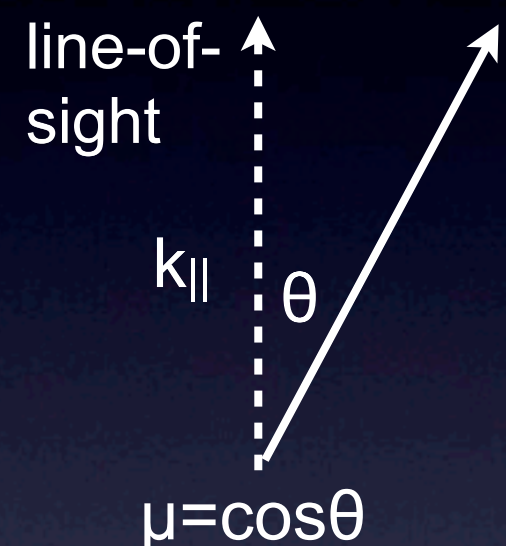
FoG suppression reaches 10% at k=0.2h/Mpc, which is comparable to the free-streaming damping due to neutrinos with $m_{\nu,tot}$=0.104eV

Anisotropy of Galaxy clustering

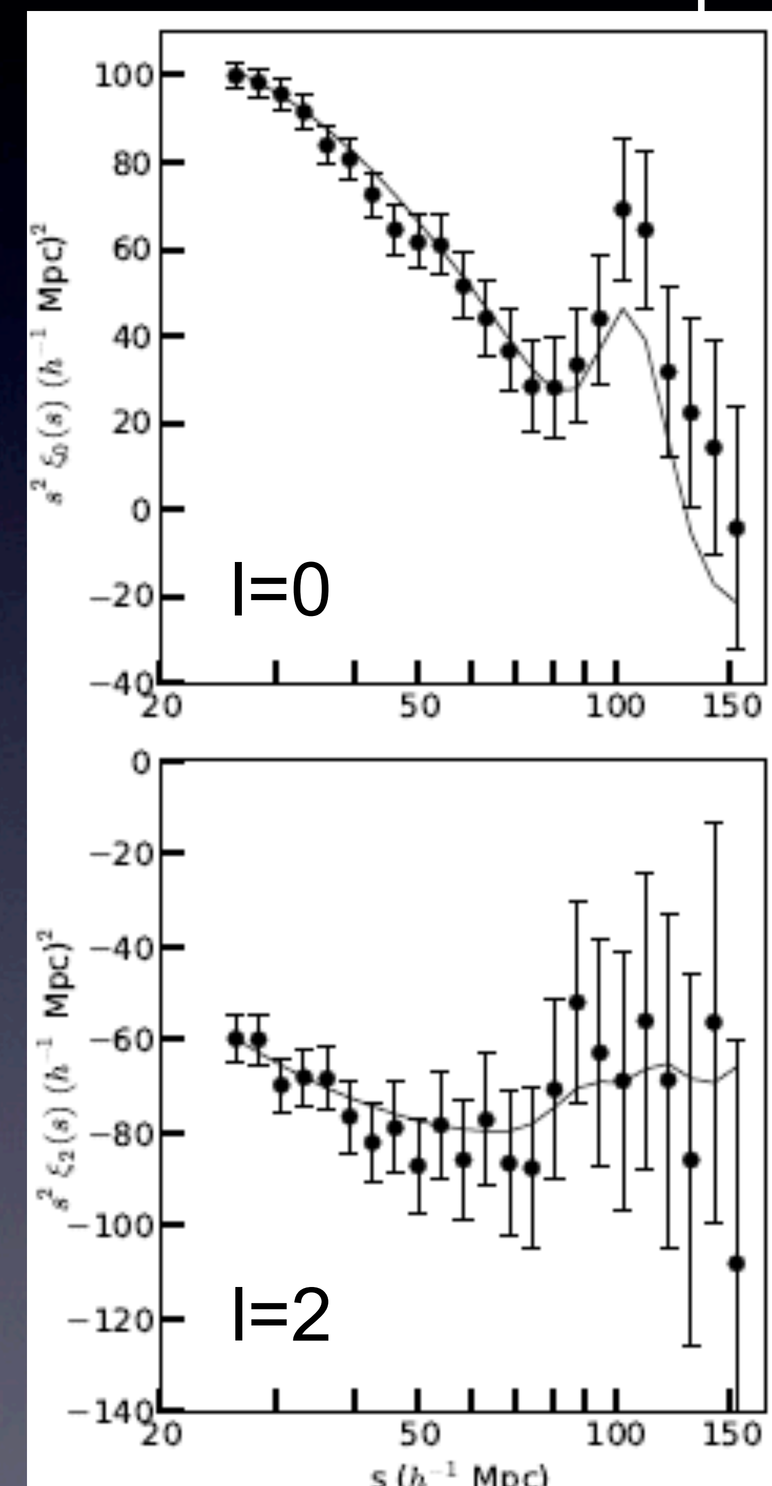
Multipole expansion of galaxy power spectra or correlation functions around the line-of-sight

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

$\mathcal{L}_l$:Legendre polynomials

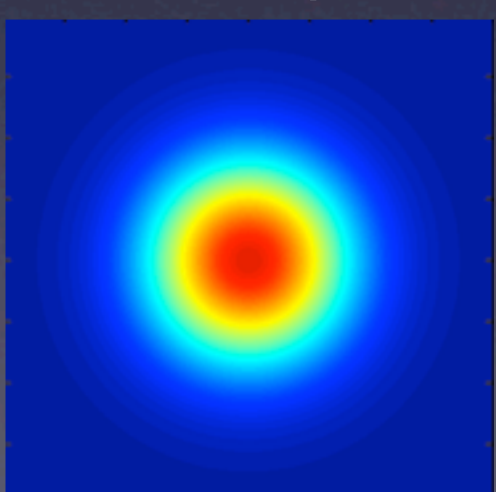


BOSS CMASS sample

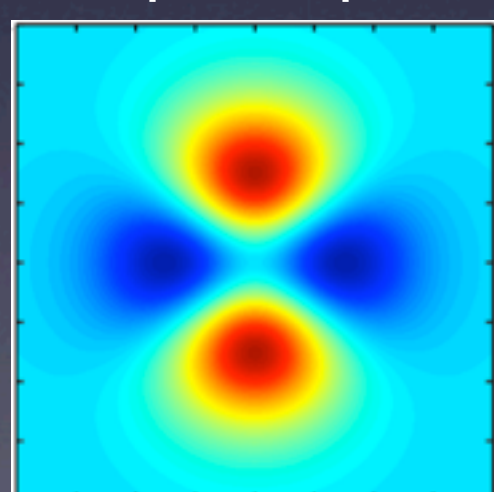


Reid et al. 2012

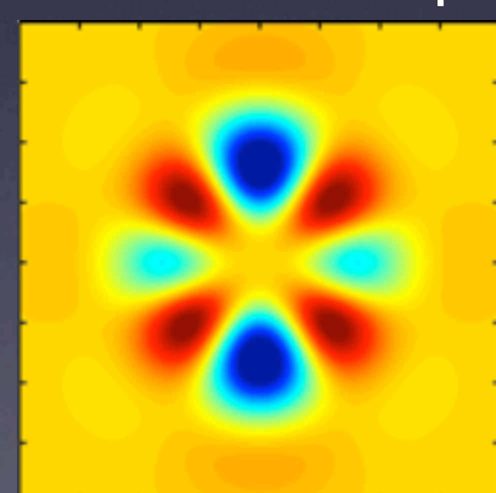
P_0: monopole



P_2: quadrupole



P_4: hexadecapole



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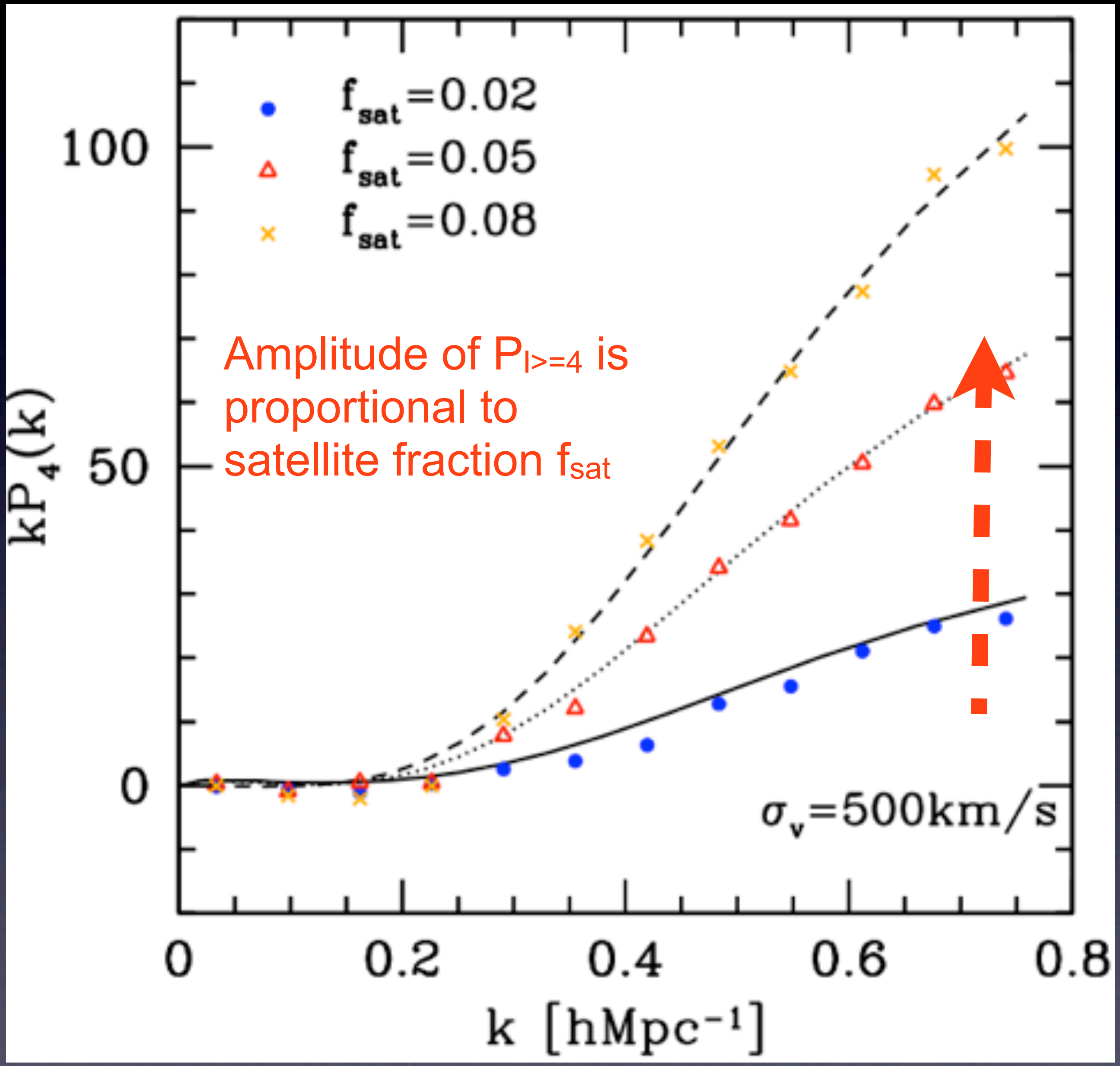
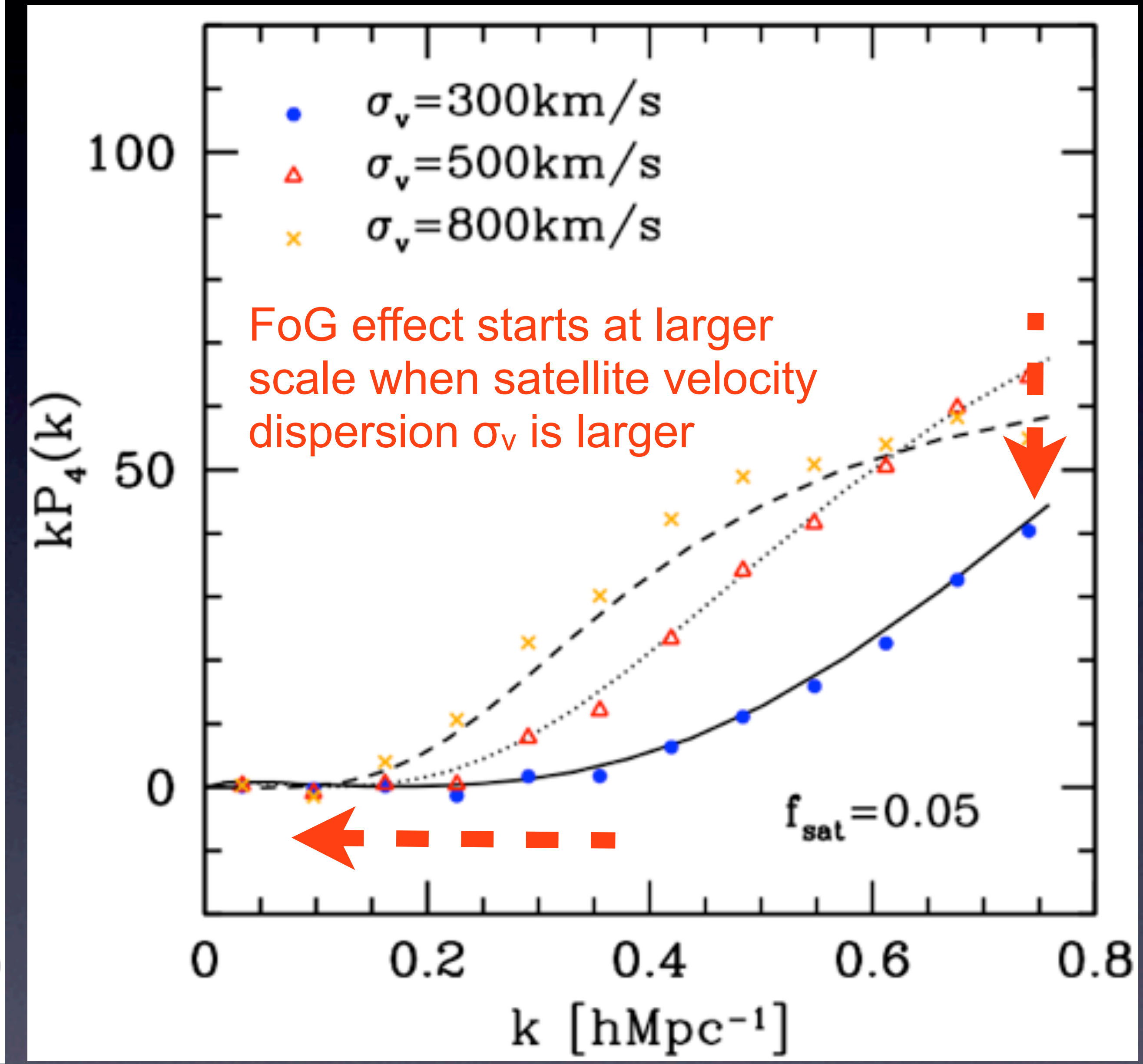
isotropic components

Anisotropic components

P_4 as a probe of satellite fraction

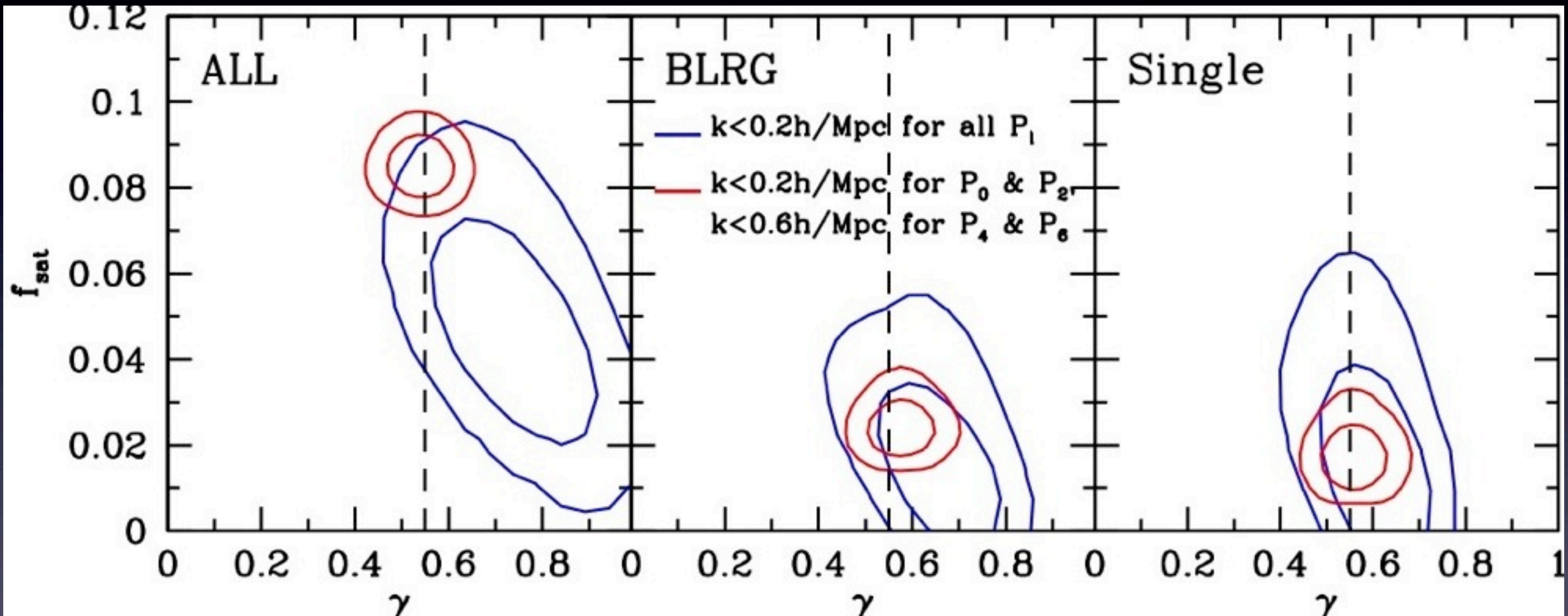




Multipole power spectra with l≧4 are good probes of satellite fraction and velocity dispersions

Improvement of growth rate measurement using P_4 & P_6

SDSS DR7 LRG samples



fitting parameter: γ, f_{sat}, $\sigma_{v,sat}$, b_0, b_1

C.H. & K.Yamamoto 2013

Multipole power spectra ($l \geqq 4$) breaks the degeneracy with satellite FoGs and improves the growth rate measurement by 3 times

SUbaru Measurement of Images and REdshift (SUMIRE)

Joint Mission of Imaging and Redshift surveys using 8.2m Subaru Telescope

Mauna Kea, Hawaii,
4139m alt., 0.6-0.7” seeing

Hyper-Suprime Cam (HSC)

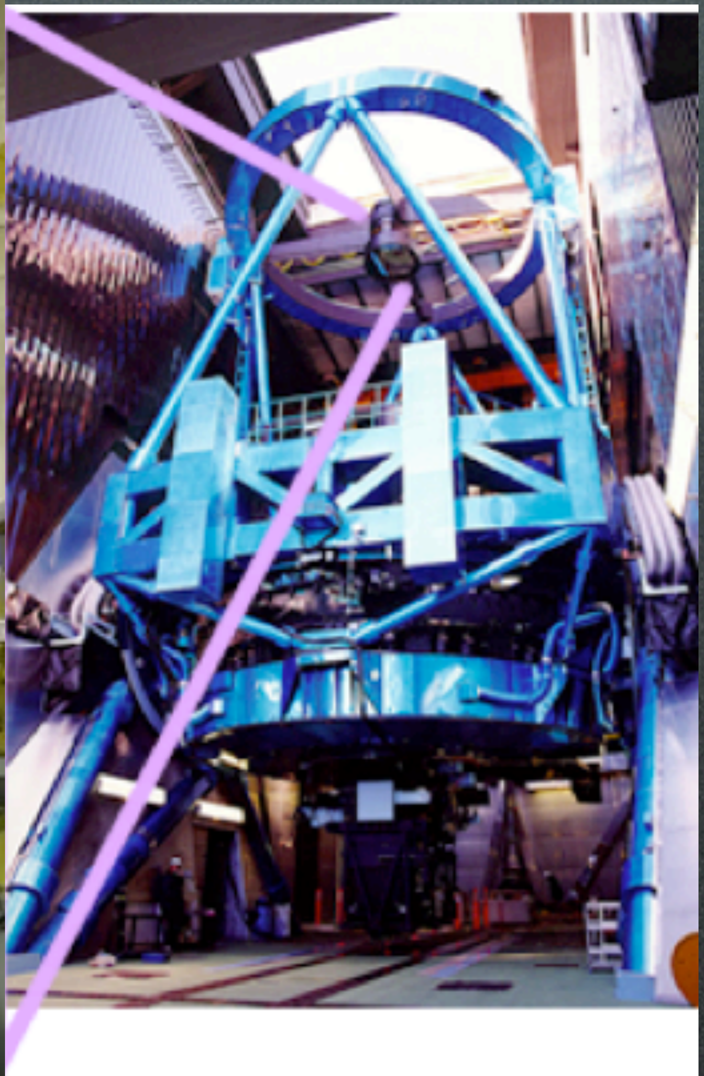
- 1400 deg^2 sky (overlap w ACT, BOSS)
- 30gals/$arcmin^2$, z_{mean}=1, i~26(5σ)
- 1.5 deg FoV, grizy band, 0.16"pix,
- 2014-2018

Prime Focus Spectrograph (PFS)

- 1400 deg^2 of sky (overlap with HSC)
- Redshift of LRGs + OII emitters at 0.8<z<2.4 (9.3 Gpc/h^3 comoving vol)
- 2400 fibers, 380~1300nm (R~3000)
- 2019-2023 (planed)

Hyper Suprime-Cam

height 3m, weight 3ton

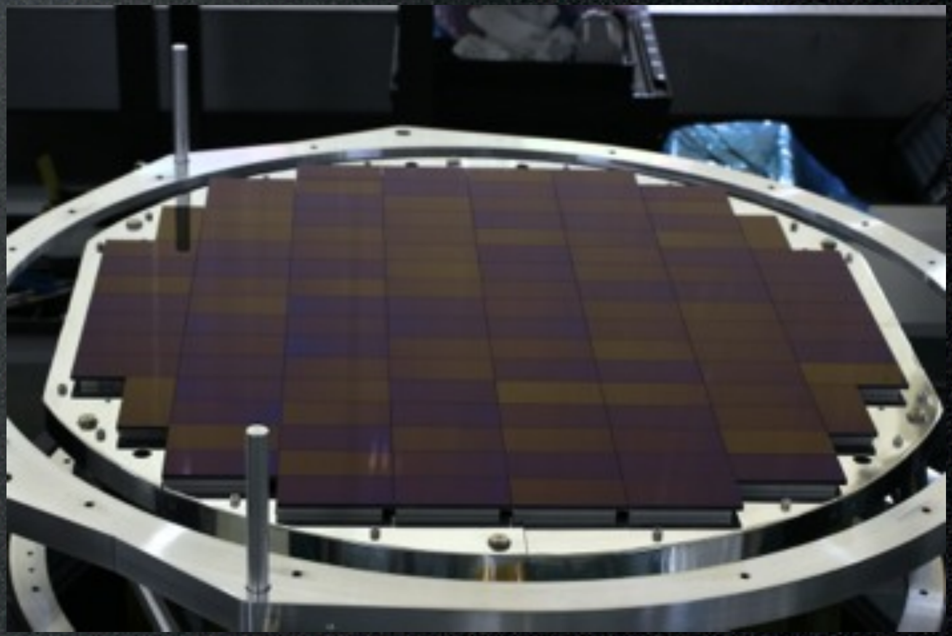


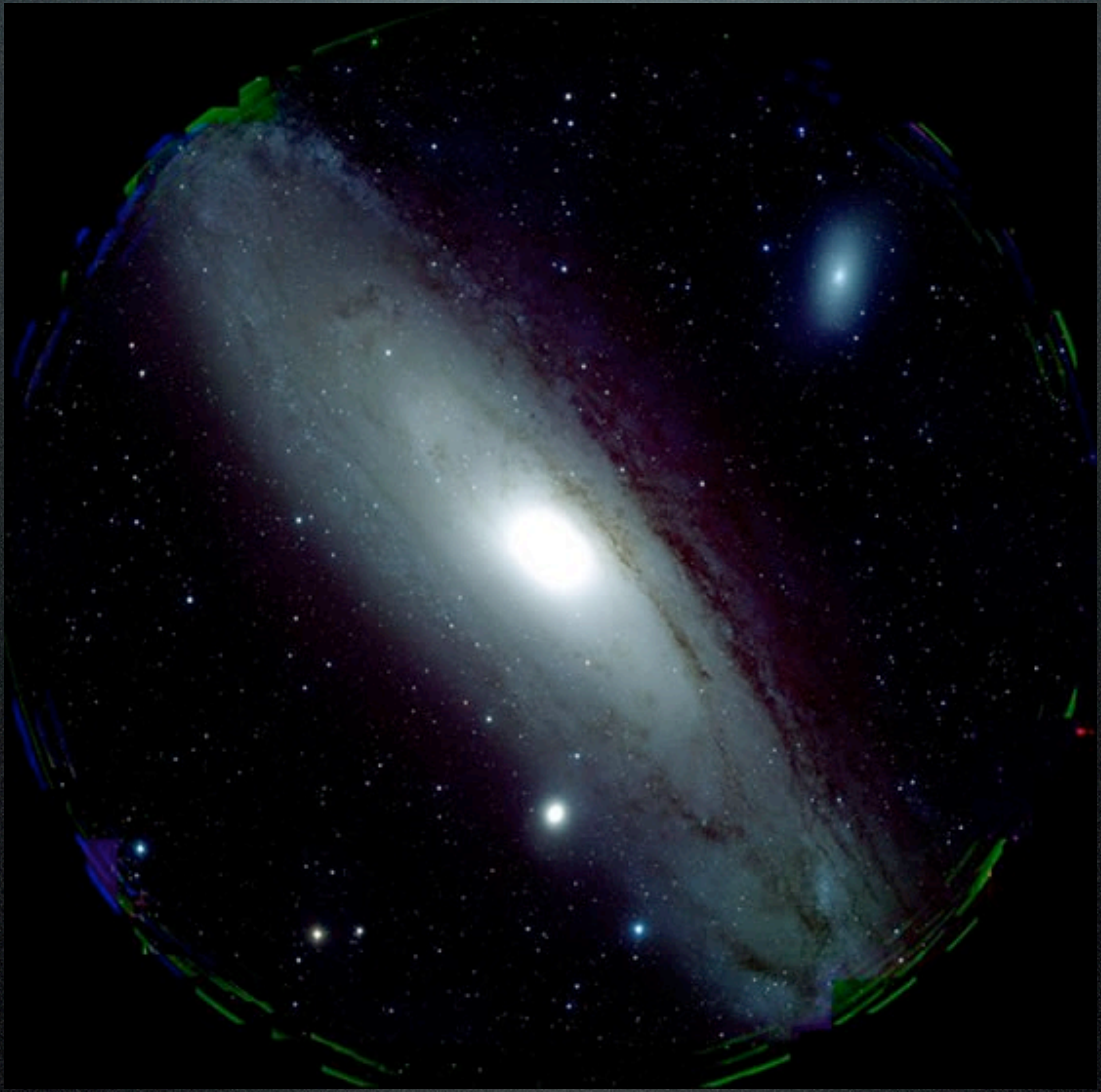
credit: NAOJ

Gigantic digital camera for Subaru 8.2m telescope

- Pixels: 870M (116CCDs)
- FOV: 1.5deg (9 full moons)
- Resolution: 0.2 arcsec

NAOJ, Hamamatsu Photonics, Canon, Mitsubishi





Andromeda galaxy credit: NAOJ

Summary

- Galaxy redshift surveys have a huge potential to provide a key insight on the nature of gravity and neutrino
- Major difficulty in this analysis comes from the systematic uncertainty in the relationship between galaxies and dark matter
    - Even when the fraction of satellite galaxies is small (~5%), their systematic effect is important
- We develop novel methods to eliminate the systematics:
    - galaxy-galaxy lensing: cross-correlation of galaxies with background galaxy image shape
    - High-l multipole power spectra $P_{l \geqq 4}$
- Near-future galaxy survey such as SuMIRe project significantly improves the accuracy of growth rate measurement and neutrino mass