The 4th International Workshop on
Dark Matter, Dark Energy and Matter-Antimatter Asymmetry
(非) 不對稱 2016

CAN WE USE MULTIPOLES DATA TO PROVE COSMOLOGY

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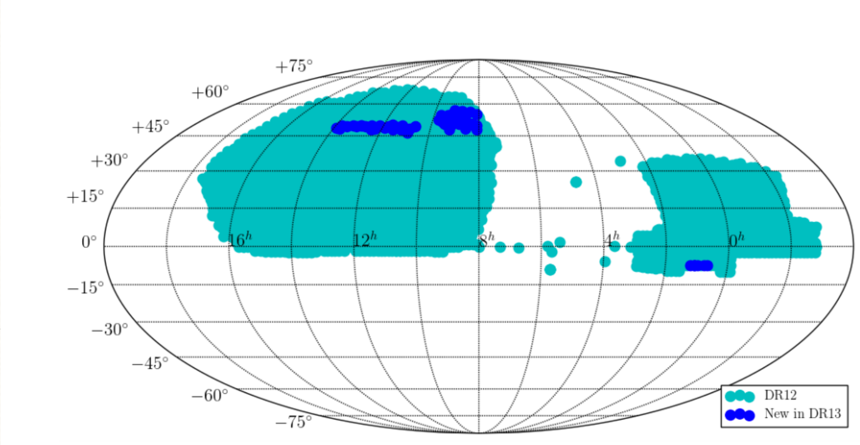
OUTLINE

- OBSERVATION : BOSS DR 12
  - DR12
  - Multipoles
- THEORY
  - Peculiar velocity of galaxies
  - Redshift Space Distortions : Kaiser effect + Fingers of God
- COMPARISON BETWEEN OBSERVATION & THEORY
  - Linear prediction vs Quasi-linear results
- CONCLUSIONS

GOAL

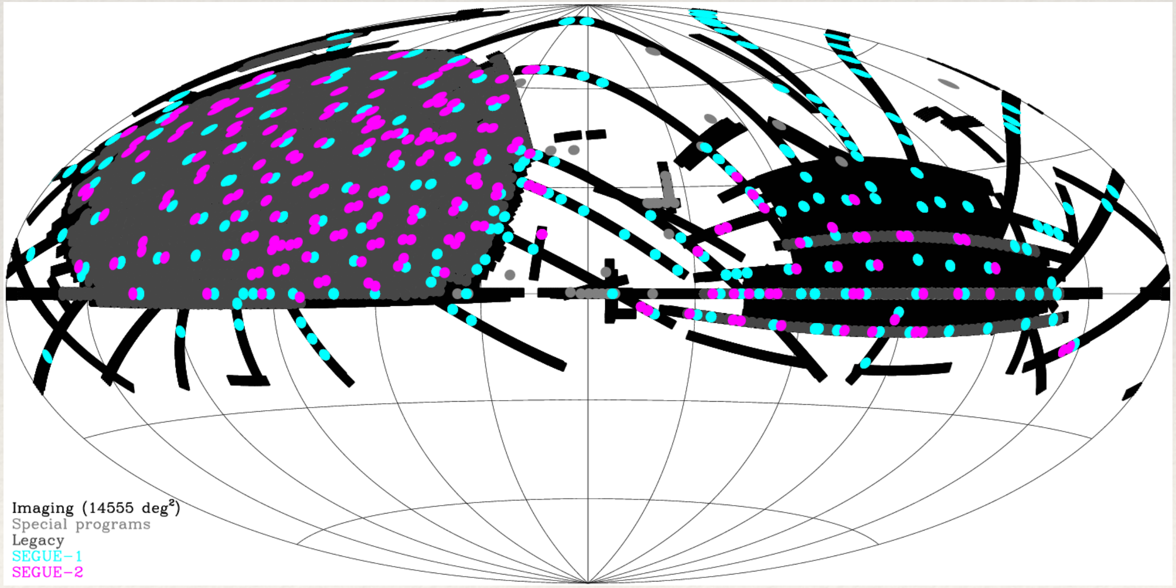
- Use multipoles data to reconstruct power spectrum (PS) : observation
- PS can be calculated up to the 3rd order perturbations exactly (reduce systematic) : theory
- One can constrain cosmological parameters from the fiducial PS with the better systematic

BOSS DR12



- Baryon Oscillation Spectroscopic Survery (BOSS) Data Release (DR) 12 : 1.5M galaxies
- BOSS : 3rd project (2008-2014) of Sloan Digital Sky Survey (SDSS)

- SDSS : The spectroscopic redshift survey using a 2.5m wide angle optical telescope at Apache Point Observatory in New Mexico.



http://www.sdss.org/dr12/

DATA

Quick Look tool: SkyServer

skyserver.sdss.org/dr9/en/tools/quicklook/quickobj.asp

앱 Bookmarks 학회 LSS arXiv 책 KIAS Wiki CMB 우주론일반 컴퓨터 Inflation

DR9 SDSS

- Summary
- Explore
- Search by
  - ObjId
  - Ra,dec
  - 5-part SDSS
  - Plate-MJD-Fiber
- Notes
  - Add to Notes
  - Show Notes
- Finding Chart
- Print
- Help
  - Tutorial
  - Examples

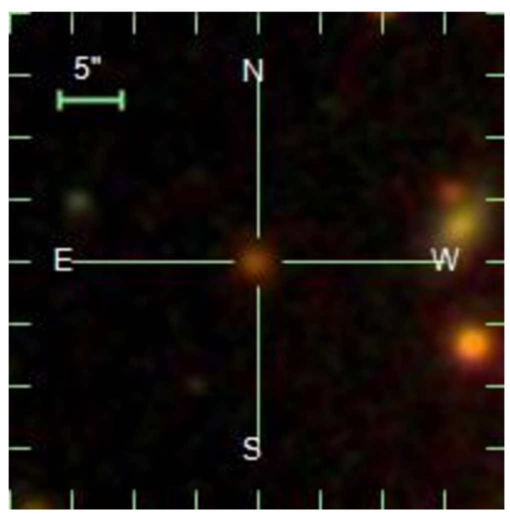
Summary data for: SDSS J082749.75+445208.5

Position Data (How do I find it?)

Object ID (objID):	Right ascension (ra):	Declination (dec):
1237654386268439267	126.95733174	44.86903116

Image Data (What does it look like?)

Preview image (click to go to Navigate tool)



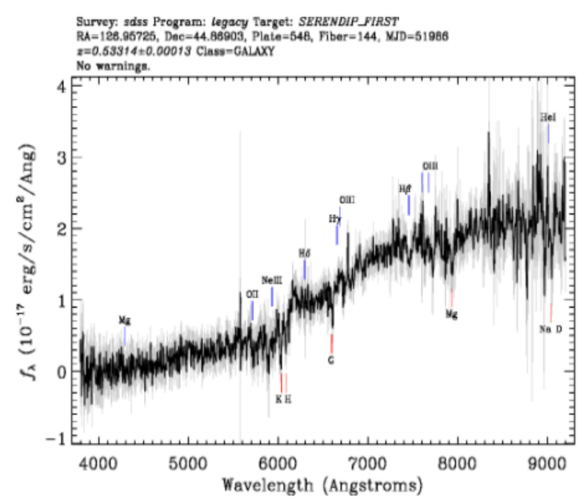
Object Type (type): GALAXY

Magnitudes:

Ultraviolet (u):	26.10 ± 0.53
Green (g):	22.50 ± 0.19
Red (r):	20.52 ± 0.04
Infrared - 7600 Å (i):	19.55 ± 0.03
Infrared - 9100 Å (z):	19.07 ± 0.07

Spectrum Data (What does its spectrum look like?)

Preview spectrum (click for a larger version)



[Interactive spectrum]

Spectral classification (Class): GALAXY

Redshift Data:

Redshift (z):	0.533137

[Get spectrum as CSV]

Beutler et.al arXiv:1607.03150

BOSS DR12 MULTIPOLES DATA

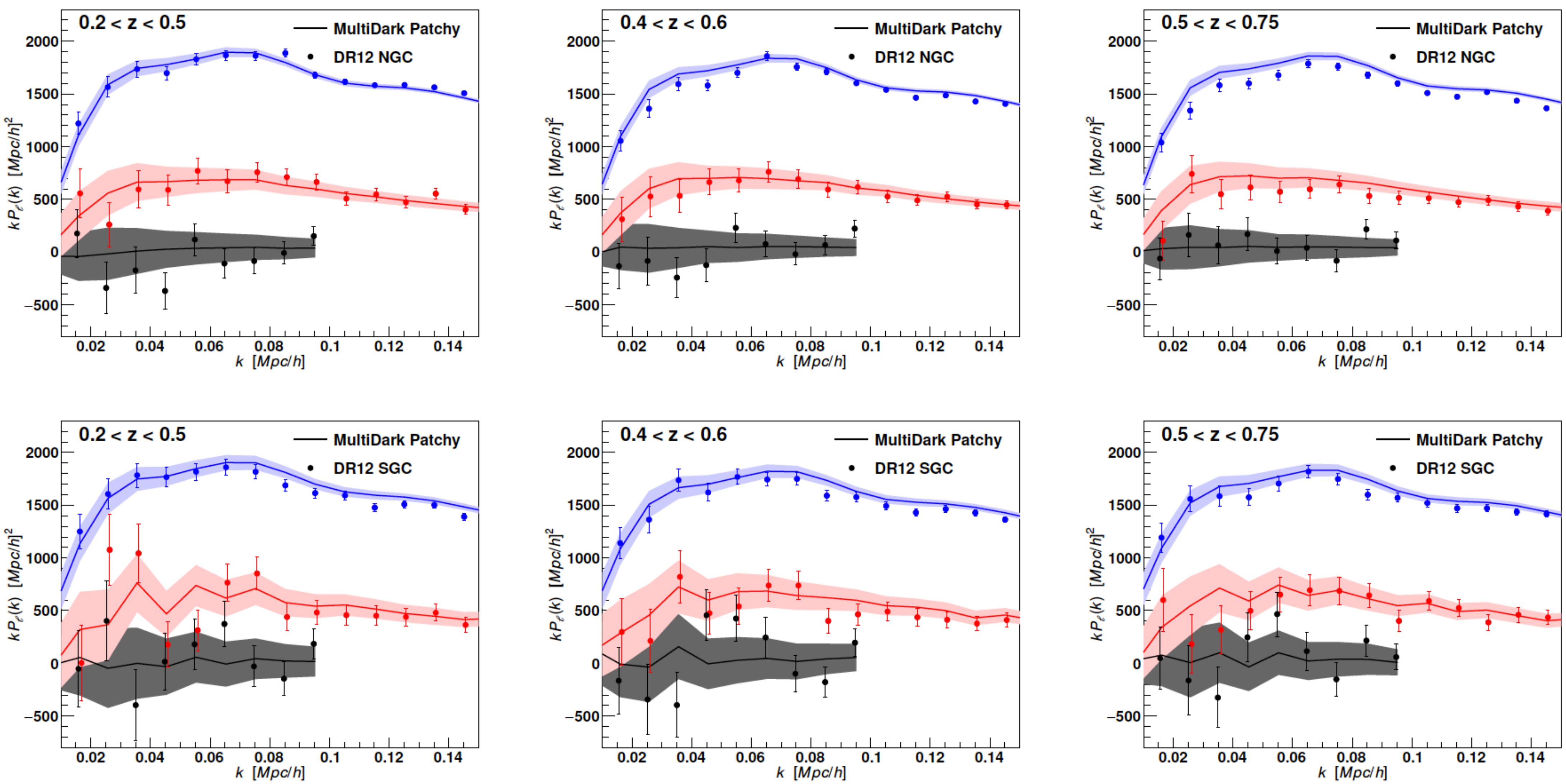
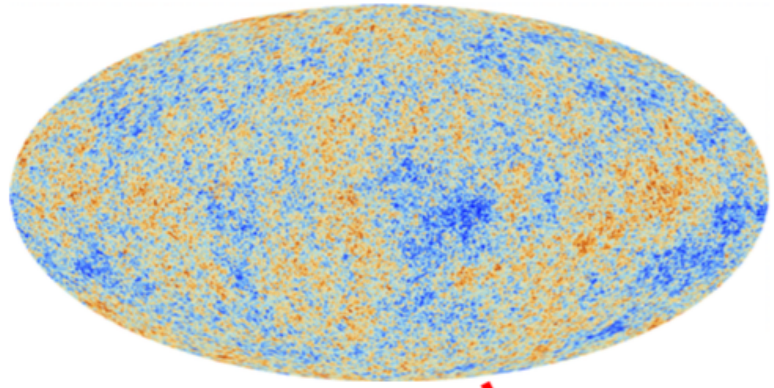
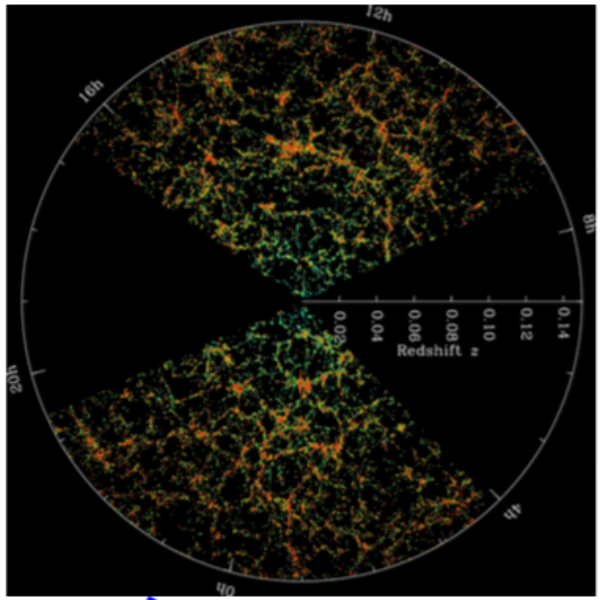


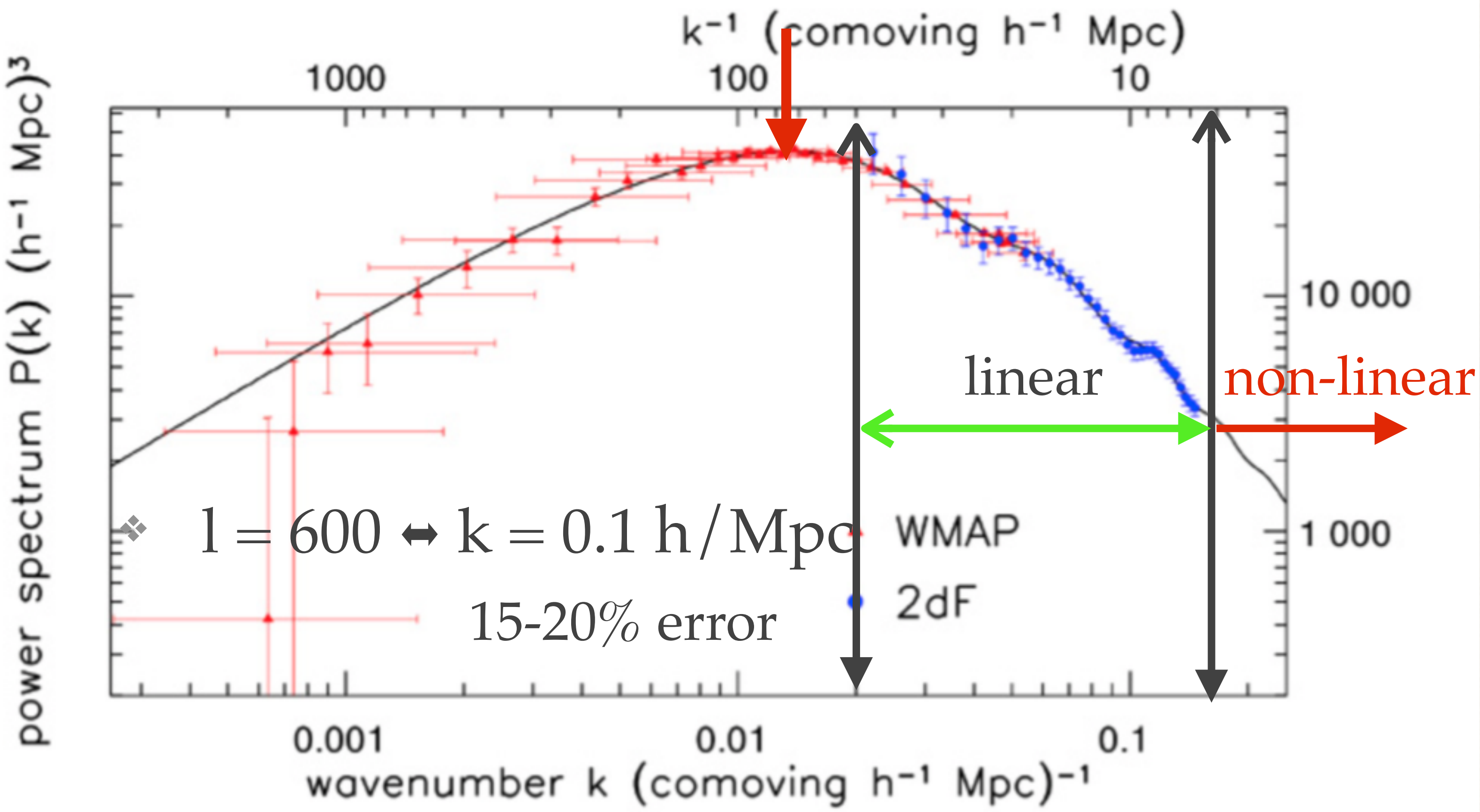
Figure 6. Comparison of the BOSS DR12 power spectrum multipoles (coloured data points) and the mean of the MultiDark-Patchy mock catalogues (coloured solid lines) with the same selection function as the data. The top panels show the power spectrum multipoles for the three redshift bins in the North Galactic Cap (NGC) and the bottom panels are the same measurements for South Galactic Cap (SGC). The different multipoles are colour coded, where blue represents the monopole, red represents the quadrupole and black shows the hexadecapole. The shaded area is the variance between all mock catalogues and is identical to the extent of the error bars on the data points. For SGC (bottom panels), the mock catalogues show some correlated fluctuations at small k, which is most prominent in the higher order multipoles. This feature is a discreteness effect, due to the finite number of modes at large scales. This effect is present in the data as well, and we discuss how to account for this effect in our power spectrum model in section 5.1.





CMB 宇宙微波背景射

LSS 宇宙大尺度



Matter PS from CMB and LSS observations, $k \sim \frac{l}{d_A^c} \sim \frac{H_0}{2c} l \sim \frac{l}{6000}$ **h/Mpc**

OBSERVABLES

"the devil is in the detail"

$$\underbrace{\mathcal{O}_k^X(\tau)}_{\text{link to Measurement}} = T_{\mathcal{O}}^X(k,\tau,\tau_*)\underbrace{\mathcal{R}_k(\tau_*)}_{\text{Curvature perturbation}} \xrightarrow{inflaton} T_{\mathcal{O}}^X(k,\tau,\tau_*)\underbrace{\frac{\mathcal{H}}{\bar{\phi}'}\delta\phi_k}_{\text{no evolution}}$$

perturbed quantities

$$\langle \mathcal{O}_k^X \rangle = 0 \ : \text{Quantum fluctuation} \rightarrow \text{random distribution}$$

$$P_k^X \equiv \langle \mathcal{O}_k^X \mathcal{O}_k^X \rangle \ : \text{measurements, X : CMB (T, E, B), LSS 測量}$$

$$B_k^X \equiv \langle \mathcal{O}_{k_1}^X \mathcal{O}_{k_2}^X \mathcal{O}_{k_3}^X \rangle = 0 \ : \text{Gaussianity}$$

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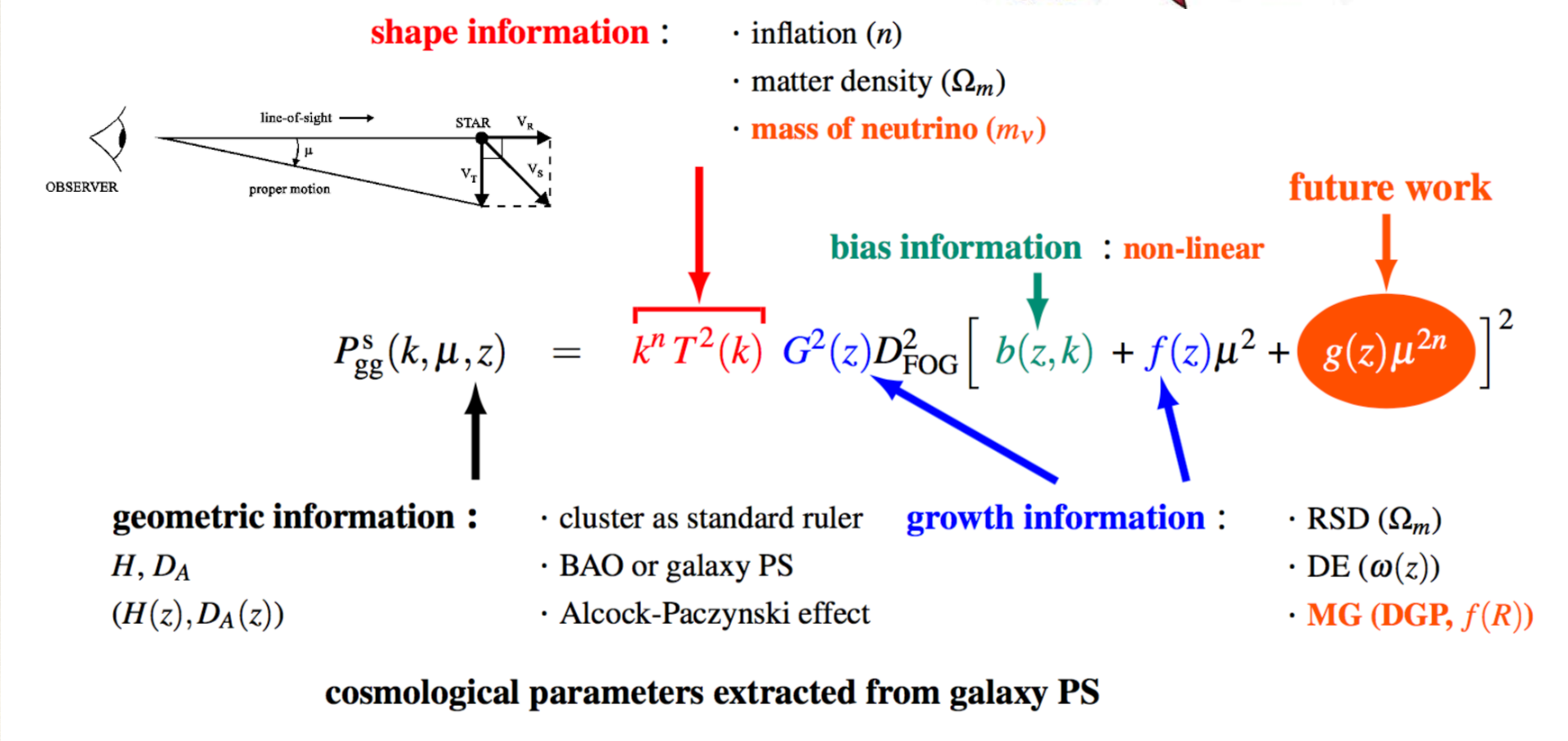
REPOSITORY 寶庫

- (Devil or Angel)



THEORY : PECULIAR VELOCITY

- Redshift space vs Real space

$$\begin{aligned}\vec{r}(t,x) &= a(t)\vec{x}(t)\,, \vec{r}\,:\ \text{physical distance}\,, \vec{x}\ :\text{comoving distance}\\ \vec{v}_{\rm obs} &= \dot{a}\vec{x} + a\dot{\vec{x}} \equiv H\vec{r} + \vec{v}_{\rm pec} \equiv \vec{v}_{\rm true} + \vec{v}_{\rm pec}\\ \frac{\vec{v}_{\rm obs}}{c} &\simeq \frac{\vec{v}_{\rm true}}{c} + \frac{\vec{v}_{\rm pec}}{c} \rightarrow \vec{s} \simeq \vec{r} + v_z(\vec{r})\hat{z}\end{aligned}$$

where $\vec{s}$: redshift space position, $\vec{r}$: real space position,
$v_z(\vec{r}) = \vec{v}_{\rm pec}/(aH)$: l.o.s component of galaxy velocity

$$(1+\delta_g^s) = (1+\delta_g)\frac{d^3r}{d^3s} \simeq (1+\delta_g)\left(1+\frac{dv_z}{dz}\right)^{-1}$$

$$\delta_g^s(k) = \delta_g(k) + \mu^2\theta(k) \qquad \theta(k) = f\delta_{\rm m}(k)$$

REDSHIFT SPACE DISTORTIONS

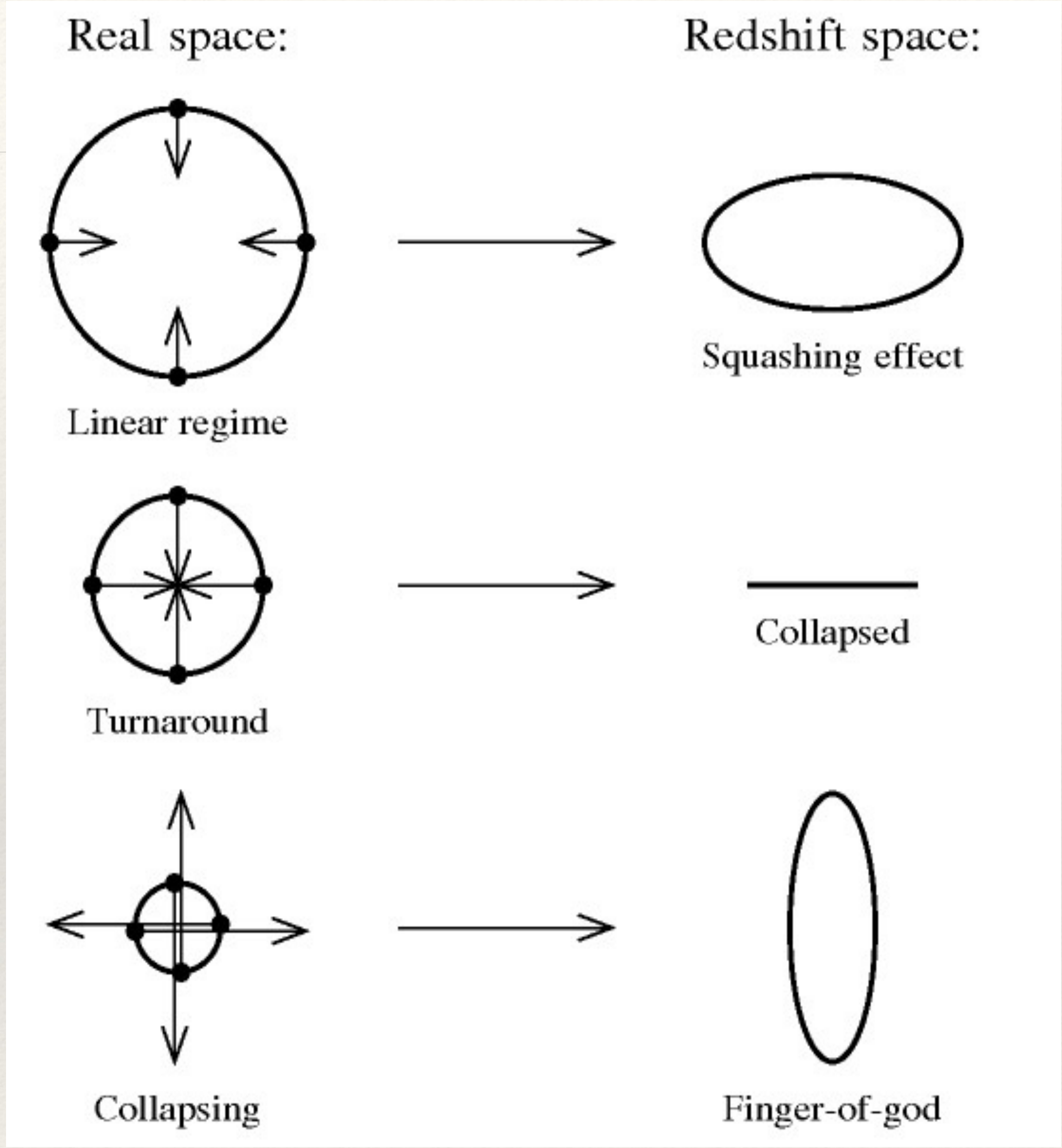
: KAISER EFFECT VS FINGERS OF GOD EFFECT

- Kaiser effect : spherical distribution of galaxies to look flattened along the line of sight due to its coherent infall
- Fingers of God effect : random peculiar velocities of galaxies bound in clusters through the virial theorem cause a Doppler shift to make galaxy distribution elongated toward the observer

$$\mathrm{P}_g(f,b,\mu,k,z) = \left(b(k,z) + f(z)\mu^2\right)^2 \mathrm{P}_{\delta\delta}(k,z) \simeq b(z)^2\left(1+\beta(z)\mu^2\right)^2 \mathrm{P}_{\delta\delta}(k,z),$$

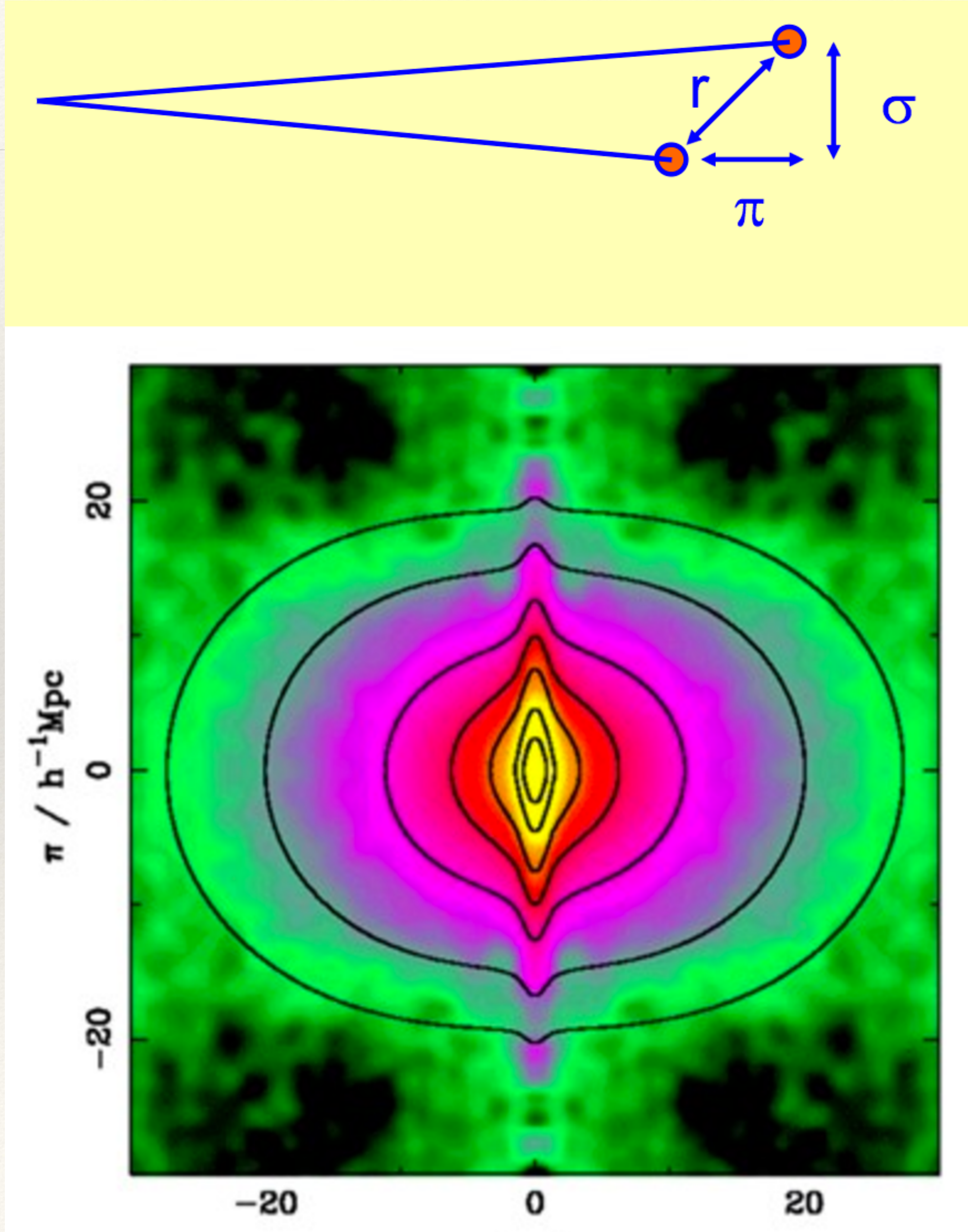
$$\mathrm{P}_\mathrm{s}(f,b,\sigma,\mu,k,z) \rightarrow \mathrm{D}^2_{\mathrm{FoG}}(f,\sigma,\mu,k,z)\mathrm{P}_\mathrm{s}(f,b,\mu,k,z)$$

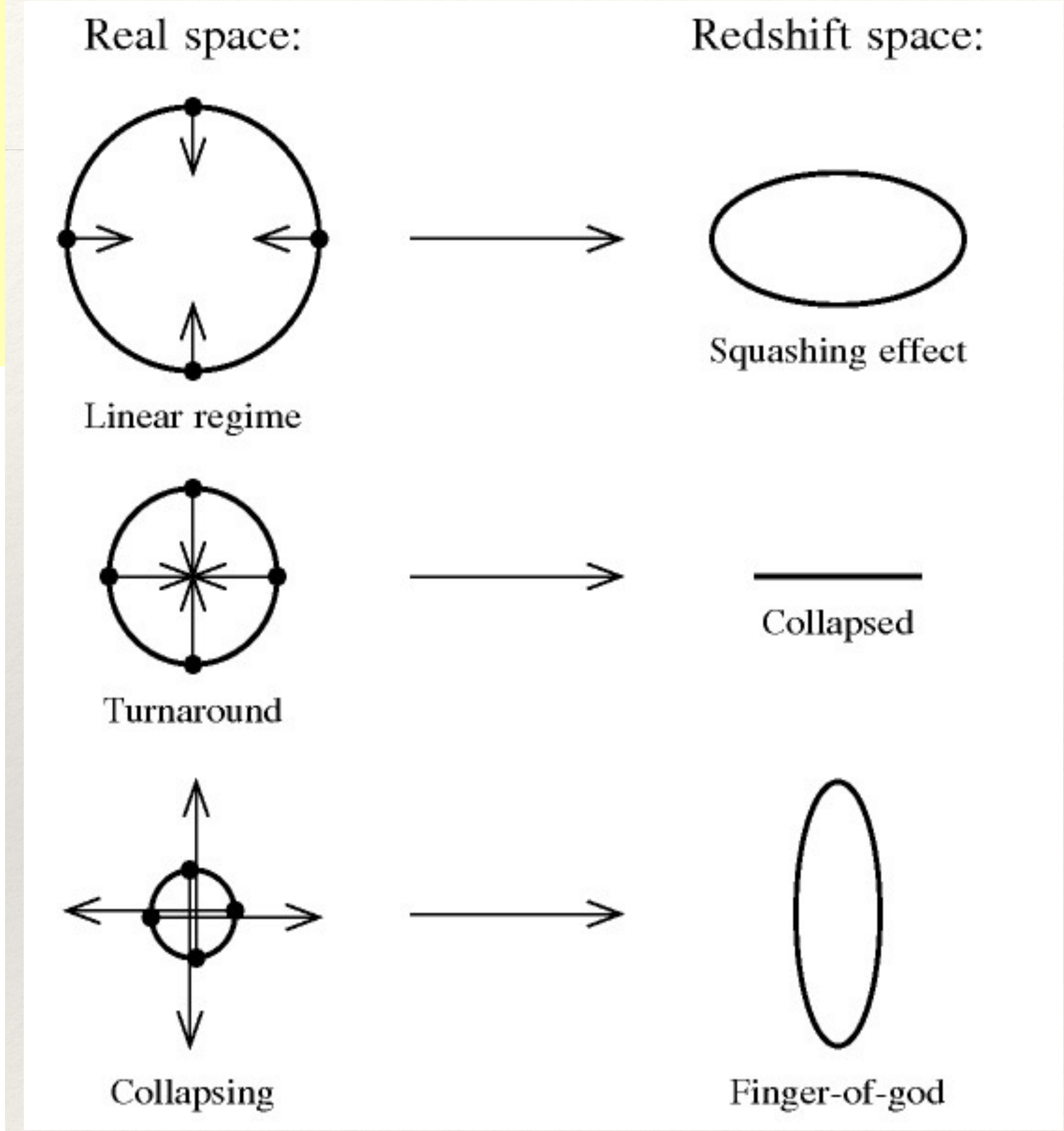
$$\mathrm{D}^{\mathrm{Gau}}_{\mathrm{FoG}}(f,\sigma,\mu,k,z) = \exp\left[-\frac{\sigma^2(z)f^2(z)k^2\mu^2}{2H^2(z)}\right]$$



REDSHIFT SPACE DISTORTIONS

: KAISER EFFECT VS FINGERS OF GOD EFFECT





MULTIPOLES

- One can average these anisotropic effect by integrating over distributions of μ to obtain the multipoles

$$\mathrm{P_s}(k,f,\mu,z)=\sum_{l=0,2,4,\cdots}\mathrm{P}_l(k,f,z)\mathcal{L}_l(\mu)$$

, where $$\mathrm{P}_l(k,f,z)=\frac{2l+1}{2}\int_{-1}^{1}d\mu\mathrm{P_s}(k,f,\mu,z)\mathcal{L}_l(\mu)$$

$$\mathcal{L}_0=1,\ \mathcal{L}_2(\mu)=\tfrac{1}{2}(3\mu^2-1),\ \text{and}\ \mathcal{L}_4(\mu)=\tfrac{1}{8}\left(35\mu^4-30\mu^2+3\right).$$

- One can obtain analytic solutions for multipoles when one applies either Gaussian FoG factor (can be applied for linear, quasi-linear theory, and non-linear theory) ***SL arXiv:1610.07785***

$$\mathrm{P}_0^{\mathrm{lin}} = \frac{e^{-x^2}\left(-6f^2x-4f(2b+f)x^3+e^{x^2}\sqrt{\pi}\left(3f^2+4bfx^2+4b^2x^4\right)\mathrm{Erf}[x]\right)\mathrm{P}_{\delta\delta}}{8x^5}$$

$$\mathrm{P}_2^{\mathrm{lin}} = -\frac{5e^{-x^2}\left(12b^2x^4+4bfx^2\left(9+4x^2\right)+f^2\left(45+24x^2+8x^4\right)\right)\mathrm{P}_{\delta\delta}}{16x^6} - \frac{5\sqrt{\pi}\left(-45f^2+6f(-6b+f)x^2+4b(-3b+2f)x^4+8b^2x^6\right)\mathrm{Erf}[x]\mathrm{P}_{\delta\delta}}{32x^7}$$

$$\mathrm{P}_4^{\mathrm{lin}} = -\frac{9e^{-x^2}\left(20b^2x^4\left(21+2x^2\right)+4bfx^2\left(525+170x^2+32x^4\right)+f^2\left(3675+1550x^2+416x^4+64x^6\right)\right)\mathrm{P}_{\delta\delta}}{128x^8} + \frac{27\sqrt{\pi}\left(4bfx^2\left(175-60x^2+4x^4\right)+4b^2x^4\left(35-20x^2+4x^4\right)+f^2\left(1225-300x^2+12x^4\right)\right)\mathrm{Erf}[x]\mathrm{P}_{\delta\delta}}{256x^9}$$

$$\frac{x}{k}\equiv\frac{\sigma(z)f(z)}{H(z)}=\frac{\sigma_0}{D_0H_0}\frac{D(z)f(z)}{E(z)}=\frac{\sigma_0 f_0}{H_0}\frac{D'(z)}{D'(z_0)}\frac{(1+z)}{E(z)}$$

$$\mathrm{Erf}(x)=\frac{2}{\sqrt{\pi}}\sum_{n=0}^{\infty}\frac{(-1)^n x^{2n+1}}{n!(2n+1)}$$

MULTIPOLES

What we want to obtain from observation

- Mutipoles and their ratios

3 Observables

3 independent unknowns

$$P_{g,\delta\delta} = \frac{N_{P_{\delta\delta}P_0} + N_{P_{\delta\delta}P_2} + N_{P_{\delta\delta}P_4}}{D_P}$$

Want to get P from P0,P2, P4

$$P_0 = \frac{e^{-x^2}\left(-6\mathcal{B}x - 4(\mathcal{A}+\mathcal{B})x^3 + e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(3\mathcal{B} + 2\mathcal{A}x^2 + 4x^4 P_{\delta\delta}\right)\right)}{8x^5}$$

$$P_2 = \frac{-10xe^{-x^2}\left(45\mathcal{B} + 6(3\mathcal{A}+4\mathcal{B})x^2 + 8(\mathcal{A}+\mathcal{B})x^4 + 12x^4 P_{\delta\delta}\right)}{32x^7} - \frac{5\sqrt{\pi}\mathrm{Erf}[x]\left(-45B + 6(-3A+B)x^2 + 4Ax^4 + 4x^4\left(-3+2x^2\right)P_{\delta\delta}\right)}{32x^7}$$

$$P_4 = \frac{-18xe^{-x^2}\left(3675\mathcal{B} + 50(21\mathcal{A}+31\mathcal{B})x^2 + 4(85\mathcal{A}+104\mathcal{B})x^4 + 64(A+B)x^6 + 20x^4\left(21+2x^2\right)P_{\delta\delta}\right)}{256x^9} + \frac{27\sqrt{\pi}\mathrm{Erf}[x]\left(1225B + 50(7A-6B)x^2 + 12(-10A+B)x^4 + 8Ax^6 + 4x^4\left(35+4x^2\left(-5+x^2\right)\right)P_{\delta\delta}\right)}{256x^9}$$

$$R_2 = \frac{5\left(-2x\left(45\mathcal{B} + 8x^4(\mathcal{A}+\mathcal{B}) + 6x^2(3\mathcal{A}+4\mathcal{B}) + 12x^4 P_{g,\delta\delta}\right) - e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(4x^4\mathcal{A} - 45\mathcal{B} + 6x^2(-3\mathcal{A}+\mathcal{B}) + 4x^4\left(-3+2x^2\right)P_{g,\delta\delta}\right)\right)}{4x^2\left(-2x\left(3\mathcal{B} + 2x^2(\mathcal{A}+\mathcal{B})\right) + e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(2x^2\mathcal{A} + 3\mathcal{B} + 4x^4 P_{g,\delta\delta}\right)\right)}$$

$$R_4 = \frac{9\left(-2\left(3675xY + 64x^7(X+Y) + 50x^3(21X+31Y) + 4x^5(85X+104Y)\right) - 40x^5\left(21+2x^2\right)P_{g,\delta\delta}\right)}{32x^4\left(-2x\left(3Y + 2x^2(X+Y)\right) + e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(2x^2X + 3Y + 4x^4 P_{g,\delta\delta}\right)\right)} + \frac{27e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(8x^6X + 50x^2(7X-6Y) + 1225Y + 12x^4(-10X+Y) + 4x^4\left(35+4x^2\left(-5+x^2\right)\right)P_{g,\delta\delta}\right)}{32x^4\left(-2x\left(3Y + 2x^2(X+Y)\right) + e^{x^2}\sqrt{\pi}\mathrm{Erf}[x]\left(2x^2X + 3Y + 4x^4 P_{g,\delta\delta}\right)\right)} \quad (45)$$

COMPARISON BETWEEN THEORY AND OBSERVATION

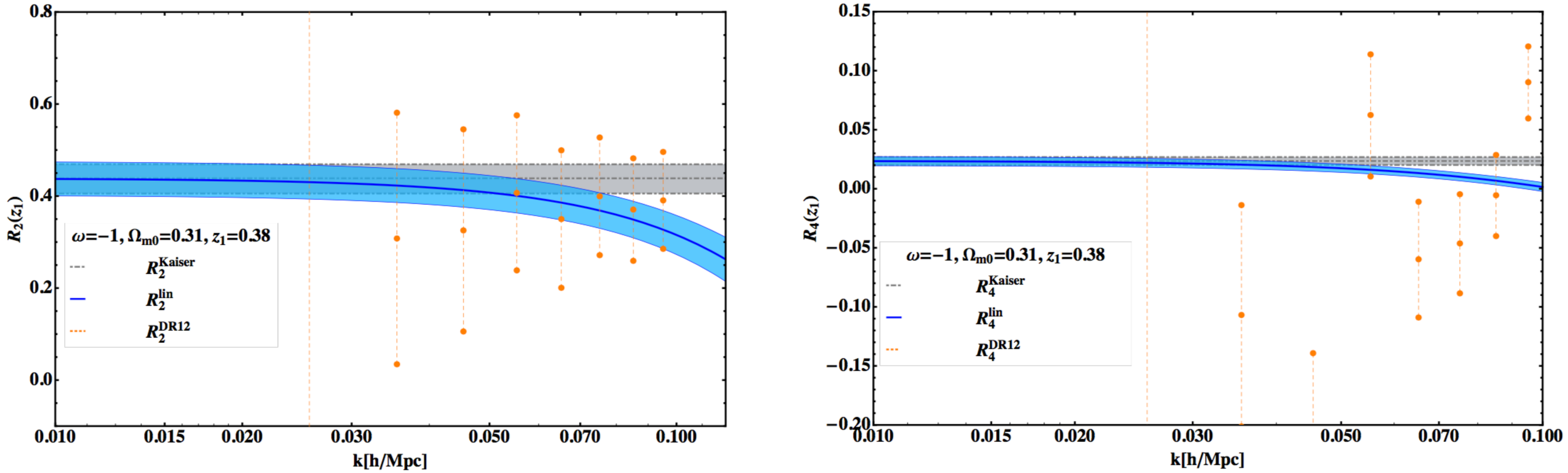


FIG. 2: The values of R_2 and R_4 at $z = 0.38$. a) The ratio of quadrupole to monopole, R_2. The dark shaded lines are the 1-σ regions of the Kaiser limit. The bright shaded lines are the 1-σ regions of the linear theory. The vertical dashed lines indicate the 1-σ results of the DR12. b) The ratio of hexadecapole to monopole, R_4 with the same notation as in the left panel.

$$\mathrm{P}_g(f, b, \sigma, \mu, k, z) \to \mathrm{D}^2_{\mathrm{FoG}}(f, \sigma, \mu, k, z) b(z)^2 \left(1 + \beta(z)\mu^2\right)^2 \mathrm{P}_{\delta\delta}(k, z)$$

COMPARISON BETWEEN THEORY AND OBSERVATION

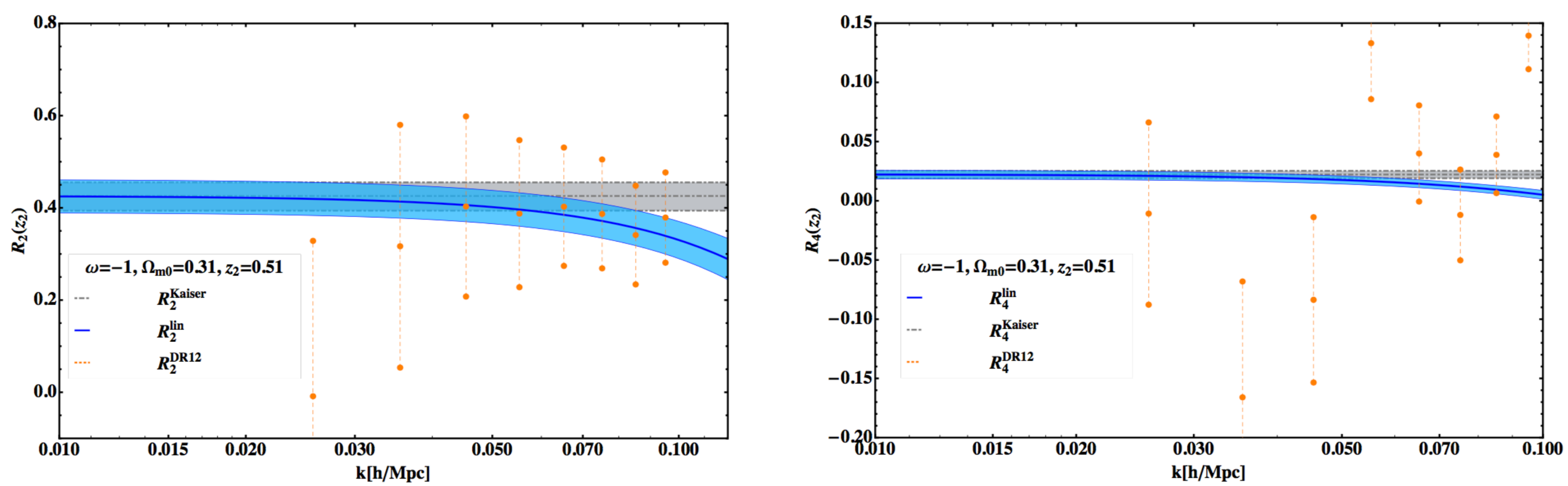


FIG. 3: The values of R_2 and R_4 at $z = 0.51$. a) R_2 with the same notations as those of Fig.2. b) R_4.

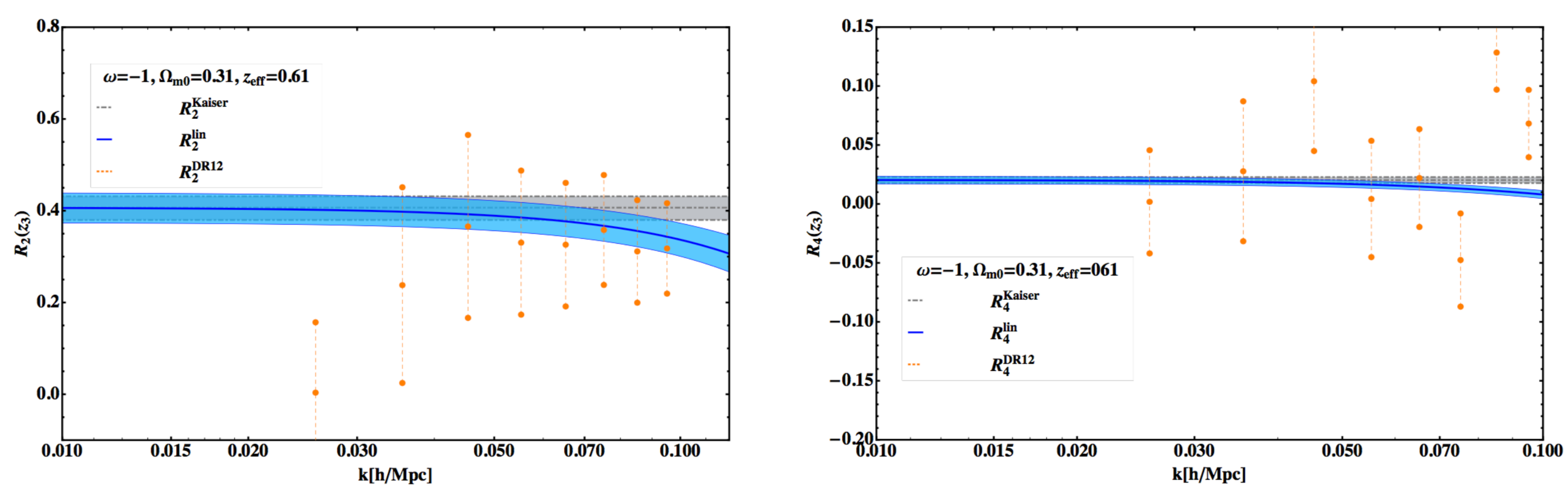


FIG. 4: The values of R_2 and R_4 at $z = 0.61$. a) R_2. b) R_4.

- R2 consistent with linear theory prediction but not for R4
- Current error is too large to distinguish FoG from Kaiser

CONCLUSIONS

- Current error is too large to distinguish the Kaiser effect (linear) from the FoG effect (non-linear)
- DR12 data is consistent with linear theory including FoG effect for monopole and quadrupole but not for hexadecapole
- One needs to obtain matter power spectrum to study theory
- Unfortunately, one cannot use DR12 data to reconstruct the galaxy (matter) power spectrum

Happy New Year!

新年快樂