Consistent modified gravity analysis of anisotropic galaxy clustering using BOSS DR11

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Implication of cosmic acceleration

- Breaking down our knowledge of particle physics: we have limited knowledge of particle physics bounded by testable high energy, and our efforts to explain the cosmic acceleration turn out in vain.
    - Alternative mechanism to generate fine tuned vacuum energy
    - New unknown energy component
    - Unification or coupling between dark sectors
- Breaking down our knowledge of gravitational physics: gravitational physics has been tested in solar system scales, and it is yet confirmed at horizon size,
    - Presence of extra dimension
    - Non-linear interaction to Einstein equation
- Failure of standard cosmology model: our understanding of the universe is still standing on assumptions:
    - Inhomogeneous models: LTB, back reaction

Theoretical models to explain acceleration

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Dynamical Dark Energy: modifying matter

$$G_{\mu\nu} = 4\pi G_N T_{\mu\nu} + \Delta T_{\mu\nu}$$

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Geometrical Dark Energy: modifying gravity

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Key observables in cosmological science

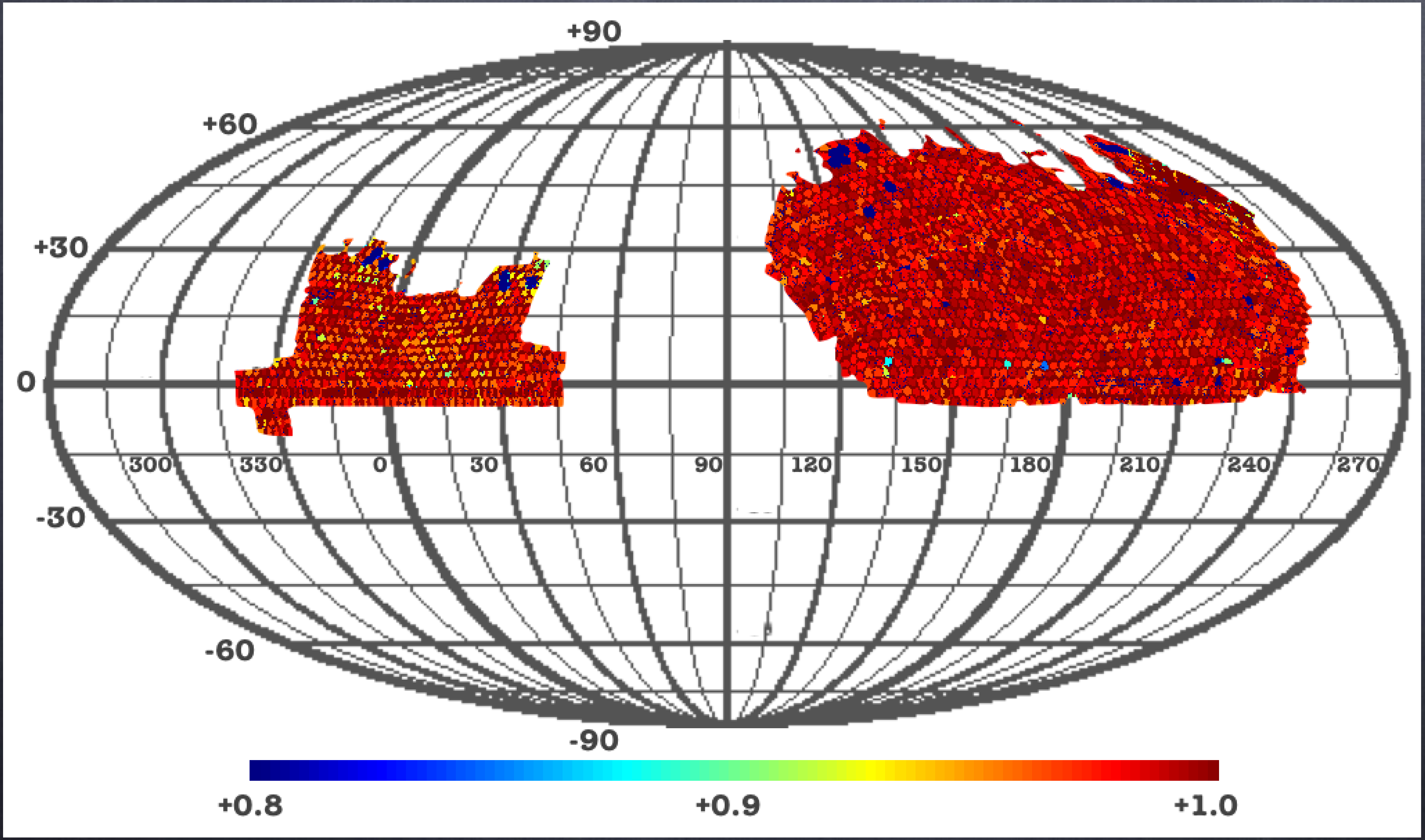
Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H^{-1}: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

Coherent motion G_θ: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

Spectroscopy wide deep field survey

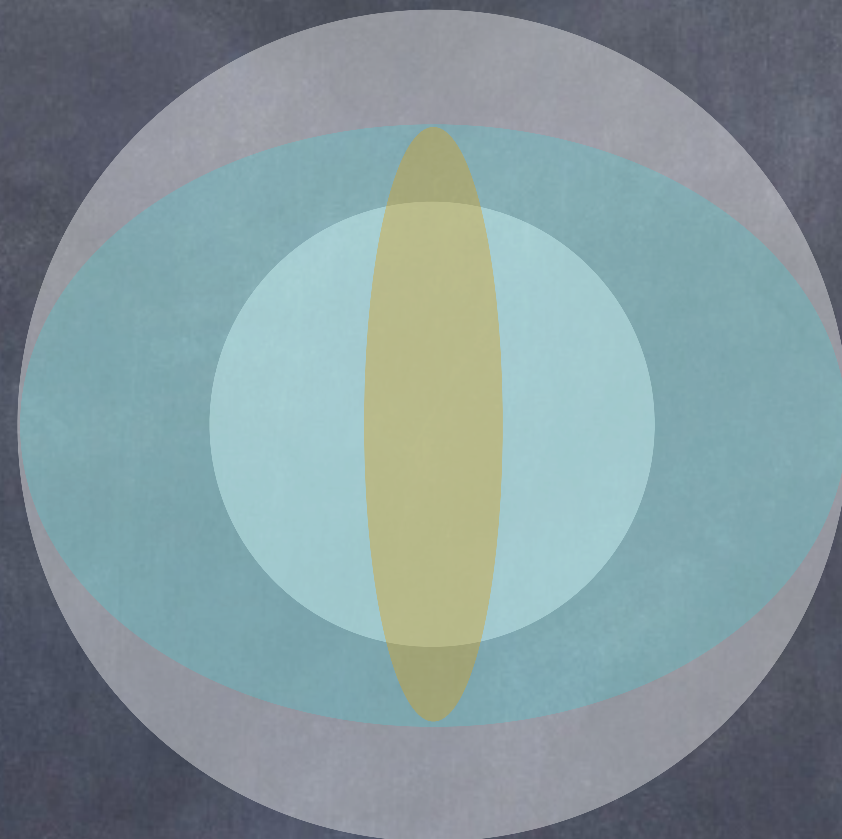
BOSS DR11 catalogue



Structure formation

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$

$$\downarrow$$

$$P_s(k,\mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta} + \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + \dots] \exp[-(k\mu\sigma_p)^2]$$

Taruya, Nishimichi, Saito 2010; Taruya, Hiramatsu 2008; Taruya, Bernardeau, Nishimichi 2012

Theoretical model in configuration space

$$P_s(k,\mu) = [Q_0(k) + \mu^2 Q_2(k) + \mu^4 Q_4(k) + \mu^6 Q_6(k)] \exp[-(k\mu\sigma_p)^2]$$

$$\xi(\sigma,\pi) = \int d^3k\, P(k,\mu) e^{ikx} = \Sigma\, \xi_\ell(s)\, \mathcal{P}_\ell(\nu)$$

$$\xi_\ell(s) = i^\ell \int k^2 dk\, P_\ell(k)\, j_\ell(ks)$$

$$P_0(k) = p_0(k)$$

$$P_2(k) = 5/2\, [3p_1(k) - p_0(k)]$$

$$P_4(k) = 9/8\, [35p_2(k) - 30p_1(k) + 3p_0(k)]$$

$$P_6(k) = 13/16\, [231p_3(k) - 315p_2(k) - 105p_1(k) + 5p_0(k)]$$

$$\vdots$$

$$p_n(k) = 1/2\, [\, \gamma(n+1/2,\kappa)/\kappa^{n+1/2} Q_0(k) + \gamma(n+3/2,\kappa)/\kappa^{n+3/2} Q_2(k)$$

$$+ \gamma(n+5/2,\kappa)/\kappa^{n+5/2} Q_4(k) + \gamma(n+7/2,\kappa)/\kappa^{n+7/2} Q_6(k)$$

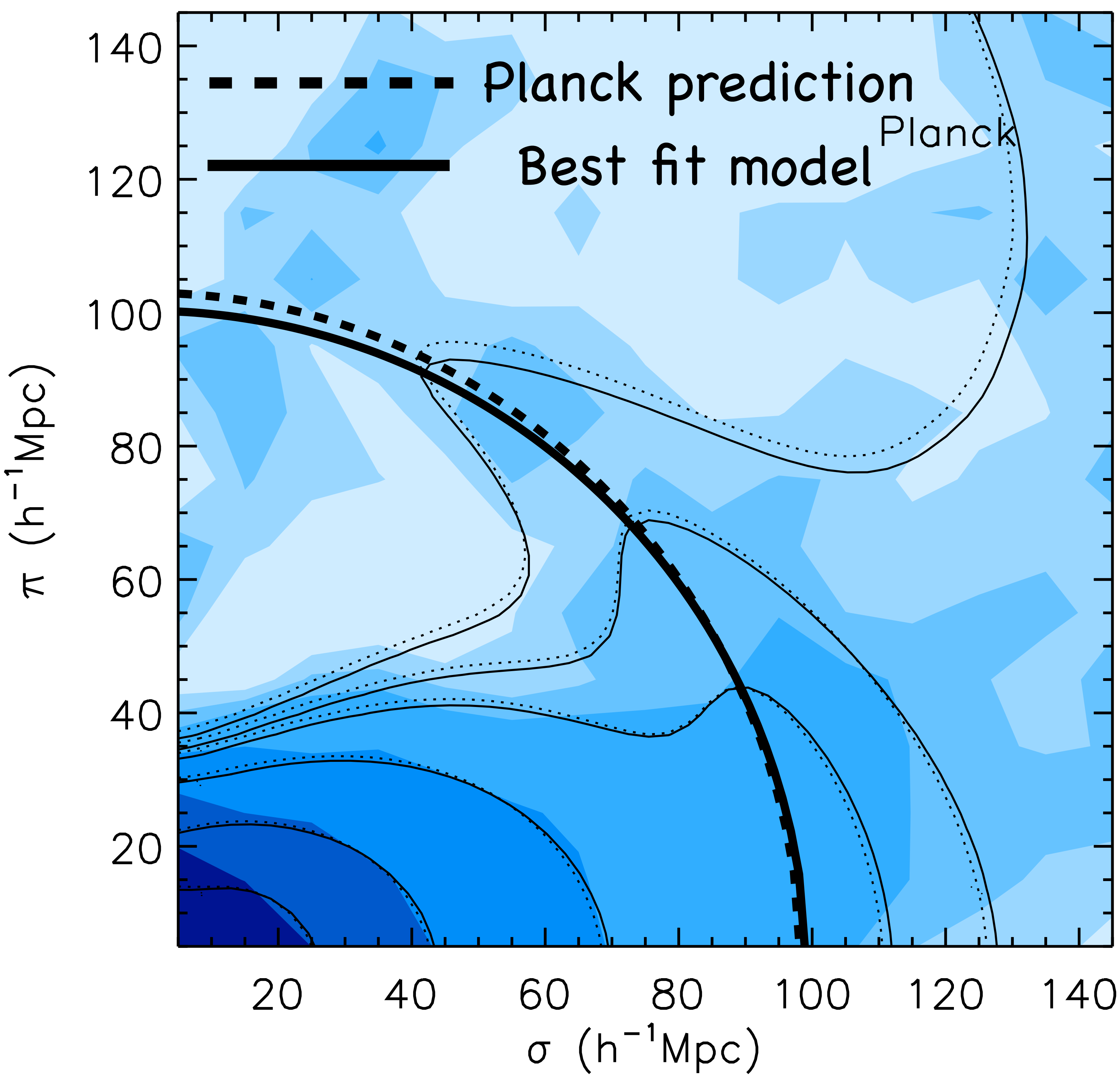
$$\kappa = k^2 \sigma^2_p$$

YSS, Okumura, Taruya 2014   Taruya, Nichimishi, Saito 2010

YSS, Sabiu, Okumura, Oh, Linder2014

Measured correlation functions using DR11

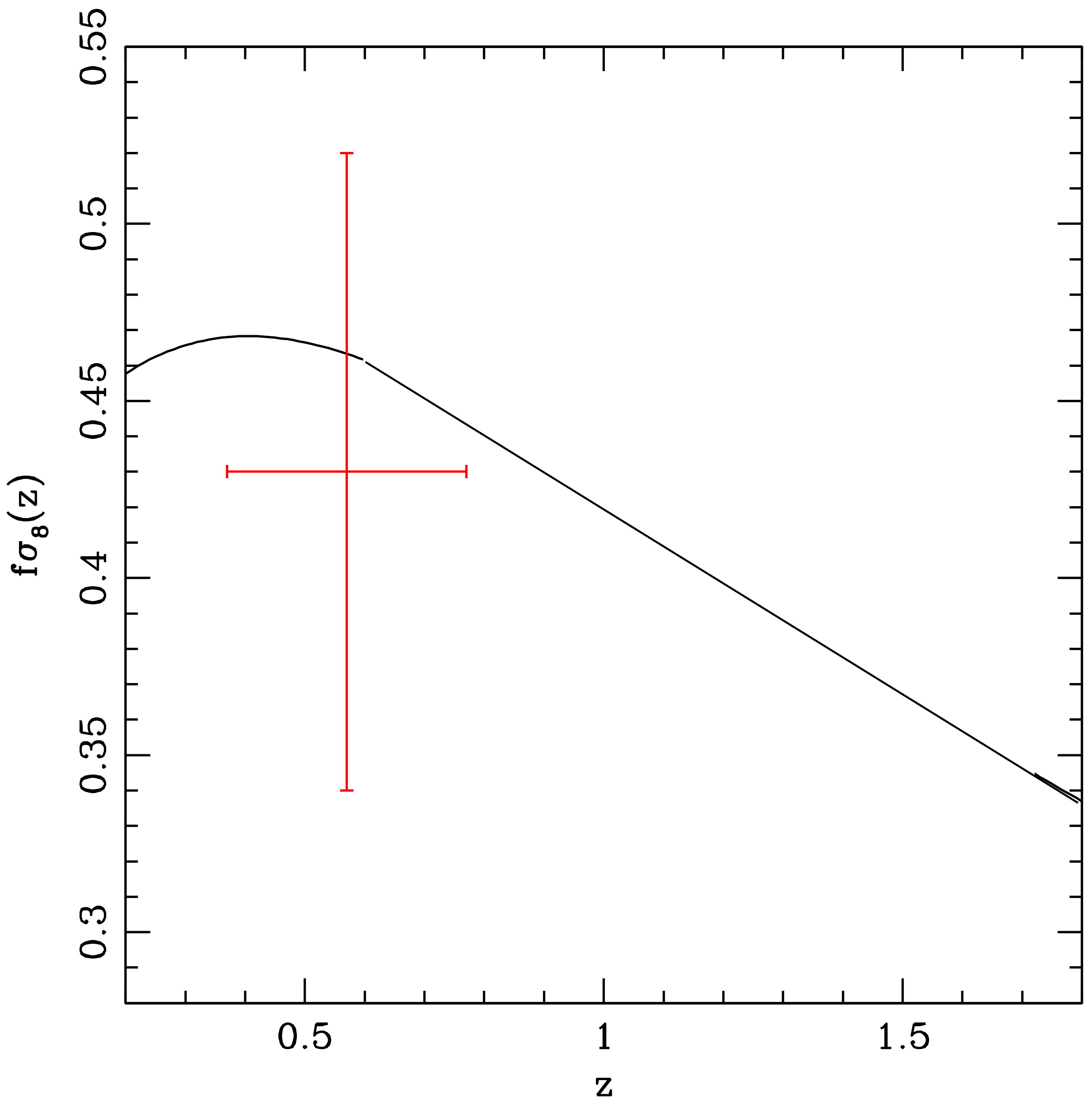
Parameter space is (D_A, H^{-1}, G_δ, G_Θ, FoG)



YSS, Sabiu, Okumura, Oh, Linder2014

Measured coherent motion

Results from BOSS maps



f(R) gravity

Corrections are introduced in the Einstein-Hilbert Lagrangian to modify the general relativity, which gets influential only low curvature, e.g. late time & not dense region. The corrections can be adjusted to generate the cosmic acceleration, Carroll, Duvvuri, Trodden, Turner (2004:CDTT)

$$S = \int d^4x \sqrt{-g} \left[\frac{R + f(R)}{2\mu^2} + \mathcal{L}_m \right]$$

cosmic acceleration was discovered with $f(R) = -a/R$. Ruled out

Two distinct branches of f(R) gravity was found depending on the sign of second order derivative of f(R) in terms of R,

$f_{RR} = d^2f/dR^2 < 0$ Unstable

$f_{RR} = d^2f/dR^2 > 0$ Stable

The original proposal of CDTT is ruled out due to instability.

YSS, Hu, Sawicki (2007)

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The f(R) gravity model in this talk is given by,

$$f(R) = -2\, \kappa^2 \rho_\Lambda + |f_{R0}|\, R_0^2/R^2$$

Measured coherent motion

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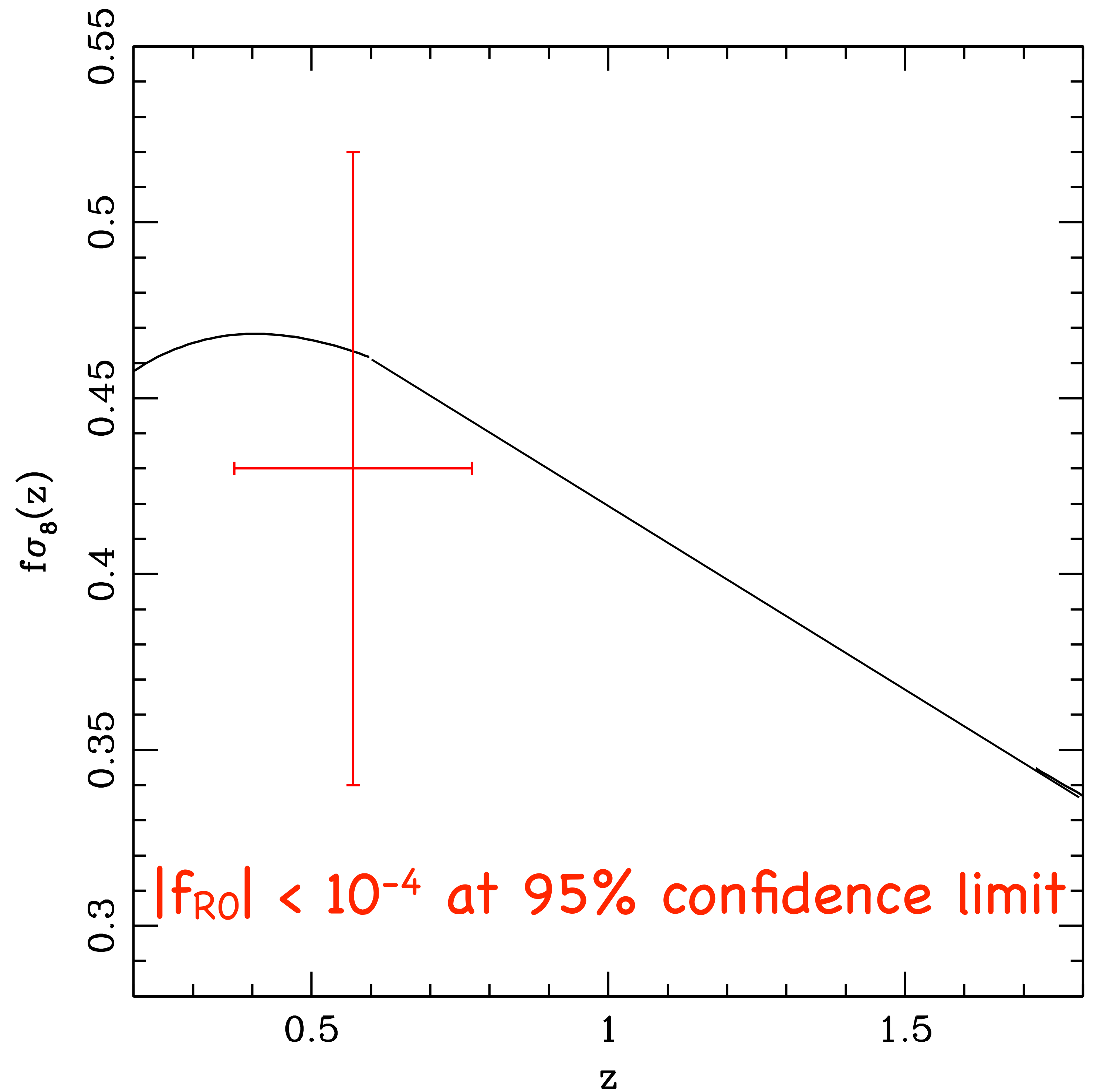

LSS of f(R) gravity

Dynamic equations of perturbations

$$d\delta_m/dt + \theta_m/a = 0$$

$$d\theta_m/dt + H\theta_m = k^2\psi/a$$

$$k^2\phi = 3/2\ H_0^2\Omega_m\ \delta_m/a\ F(\epsilon)$$

$$k^2\psi = -3/2\ H_0^2\Omega_m\ \delta_m/a\ G(\epsilon)$$

which are not closed without knowing ϵ evolution

For the case of DGP, dynamics equations with extra variable are closed with a constraint equation, but for the case of f(R) gravity, it is closed with an extra dynamic equation of ϵ.

$$\epsilon'' + \left(\frac{7}{2} + 4p_B\right)\epsilon' + \frac{2}{B}\epsilon = \frac{1}{B}F(\Phi_-, S, Hq)$$

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which are not closed without knowing ϵ evolution

Mass screening effect:

$$k^2\phi_{fR} = \phi_{GR}\ F(\epsilon)$$

Geometrical anisotropy:

$$k^2\phi_{fR} + k^2\psi_{fR} = -3H_0{}^2\Omega_m\ \delta_m/a\ [F(\epsilon) - G(\epsilon)]$$

Change on photon trajectory:

$$\phi_{fR} - \psi_{fR} = (\phi_{GR} - \psi_{GR})$$

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$$k^2 \psi = -3/2\, H_0{}^2\Omega_m\, \delta_m/a\, G(\epsilon)$$

Introducing the Brans-Dicke parameter φ

$$\phi_{fR} - \psi_{fR} = \varphi$$

$$k^2 \psi = -3/2\, H_0{}^2\Omega_m\, \delta_m/a - 1/2\, k^2\varphi$$

$$(1+w_{BD})\, k^2/a^2\, \varphi = 3H_0{}^2\Omega_m\, \delta_m/a - I(\varphi)$$

where $I(\varphi)$ is given by

$$I(\varphi) = M_1(k)\varphi(k) + 1/2 \int\cdots\int d^3k_1\cdots d^3k_n\, M_1(k)\cdots M_n(k)\, \varphi(k_1)\cdots\varphi(k_n)$$

LSS of f(R) gravity

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Later time growth functions are given by,

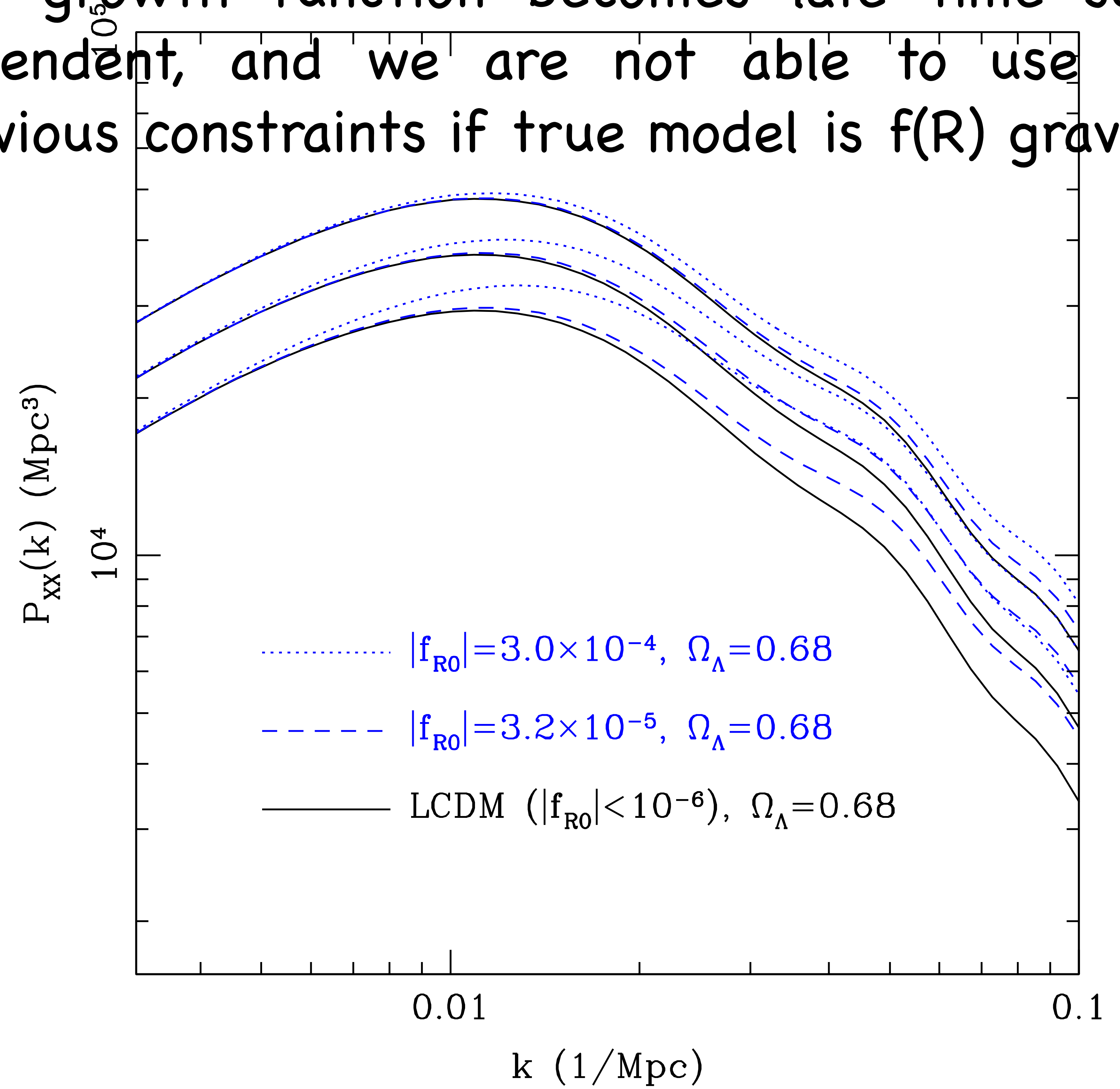
$$D^{\delta}(k,t) = G_{\delta}(t)\ F_{\delta}(k,t;M_1)$$

$$D^{\Theta}(k,t) = G_{\Theta}(t)\ F_{\Theta}(k,t;M_1)$$

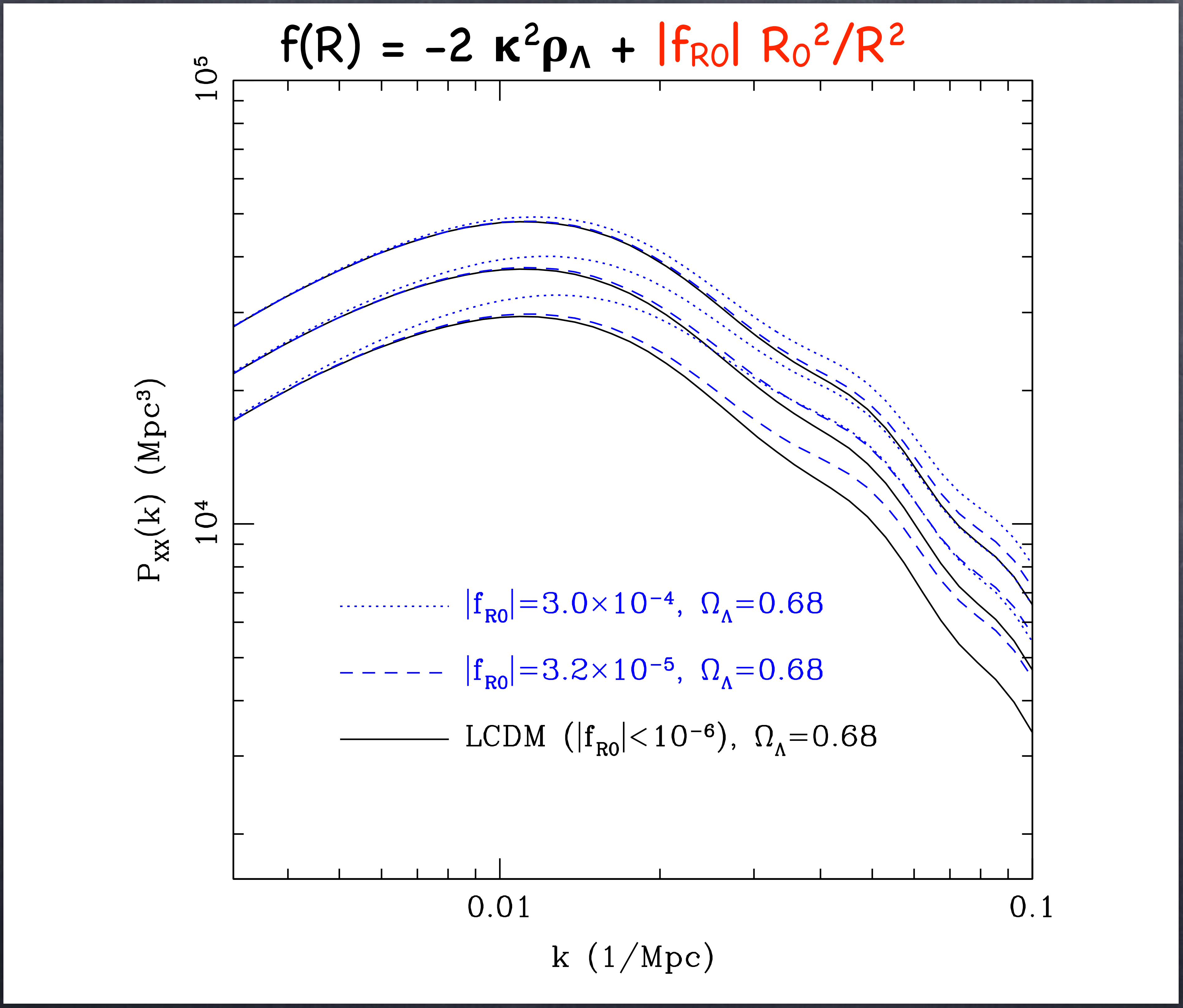
We are not able to constrain f(R) gravity models using measured growth functions with the assumption of coherent growing after last scattering surface.

Linear power spectra with running f(R)

The growth function becomes late time scale dependent, and we are not able to use the previous constraints if true model is f(R) gravity



Parameterisation of f(R) gravity model



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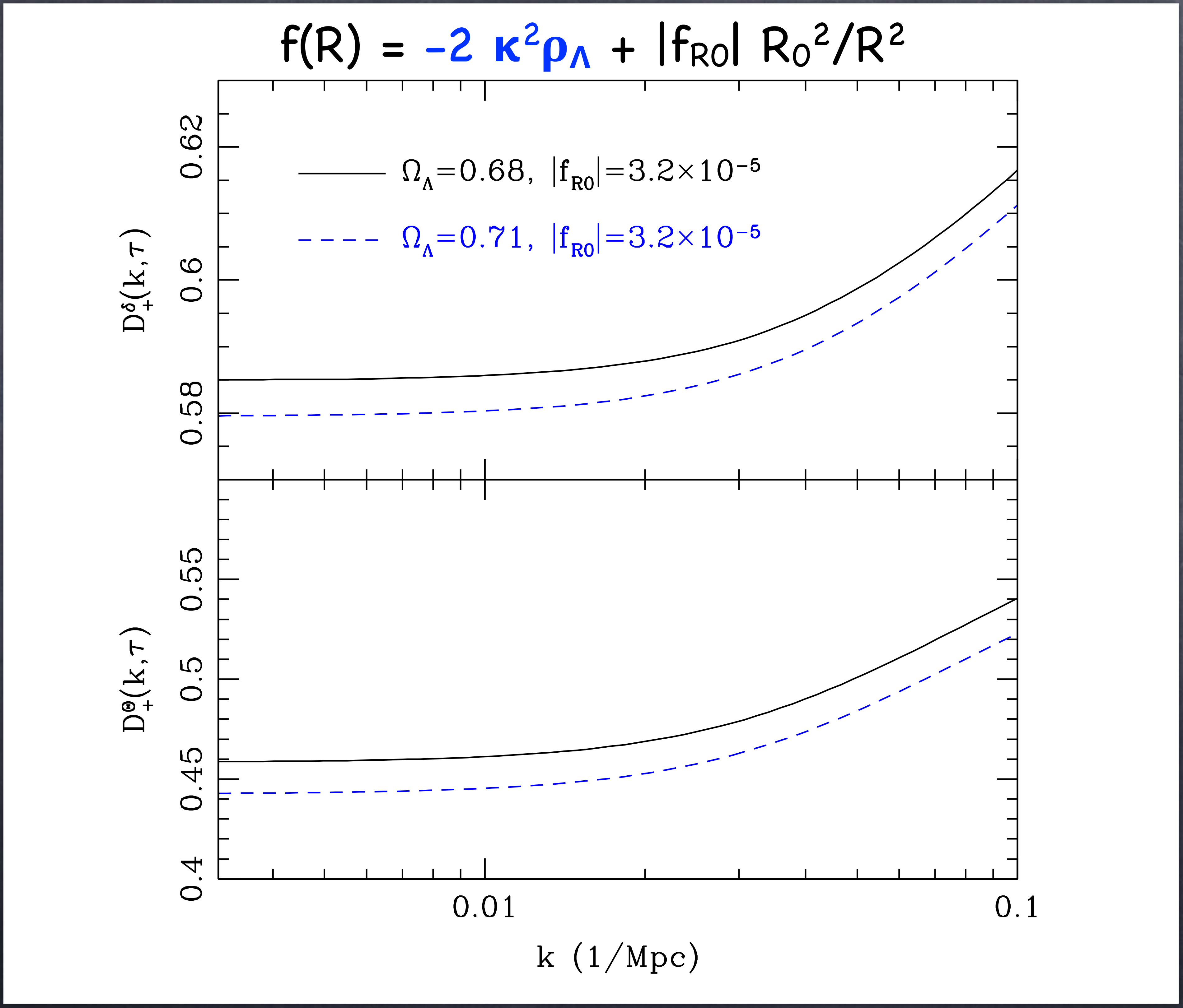


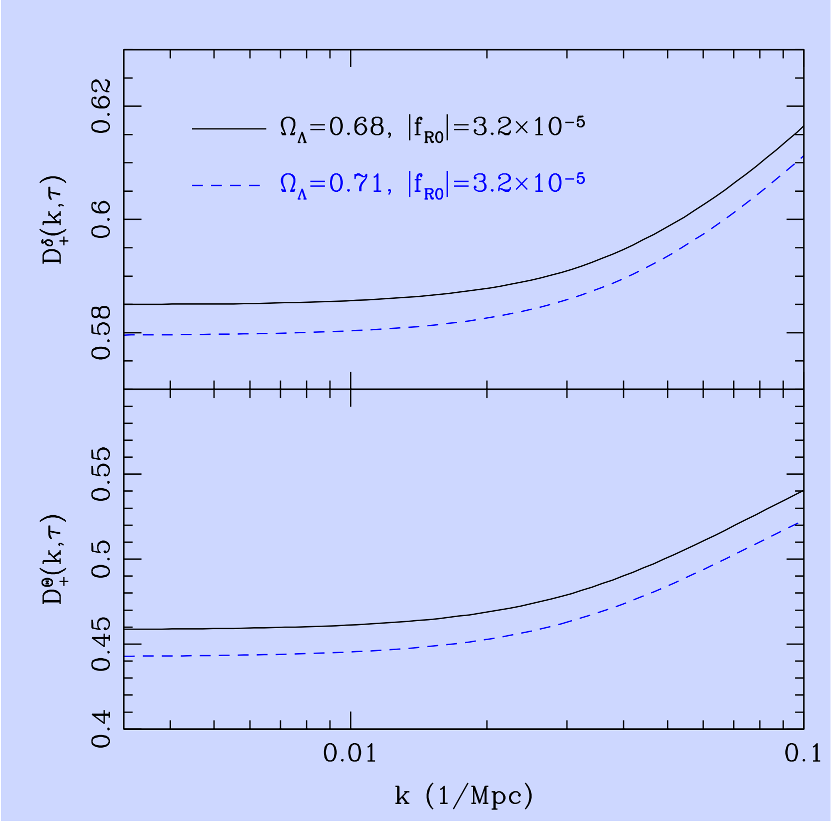
Parameterisation of f(R) gravity model

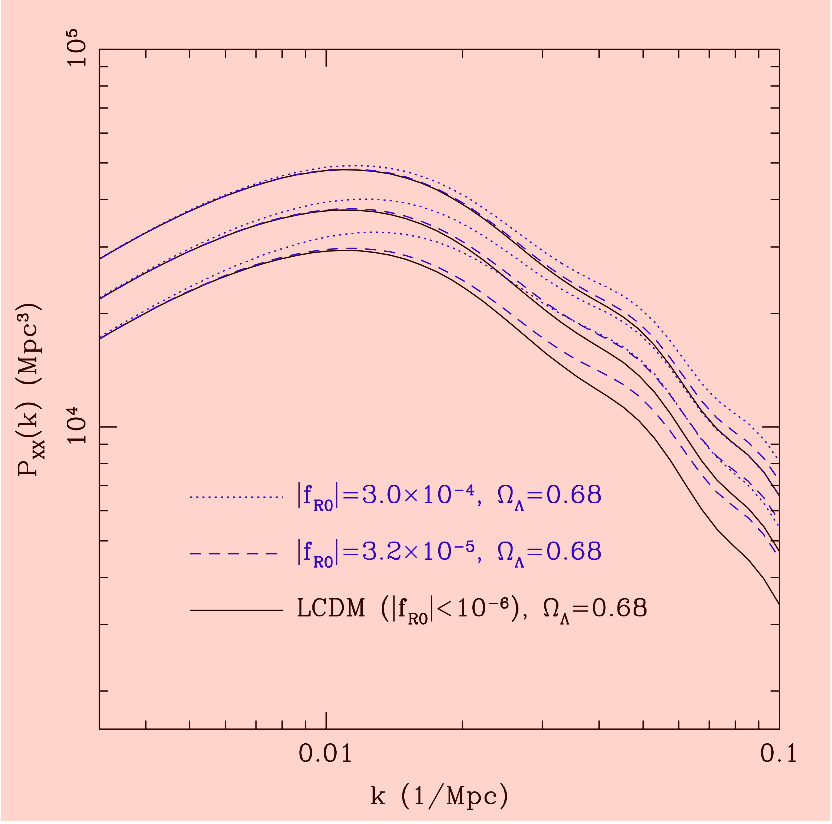
$$f(R) = -2\,\kappa^2\rho_\Lambda + |f_{R0}|\,R_0^2/R^2$$

We find that both coherent growth factors and scale dependent growth factors are separable in the following sense,

$$D^\delta(k,t) = G_\delta(t)\,F_\delta(k,t;M_1)$$

$$D^\Theta(k,t) = G_\Theta(t)\,F_\Theta(k,t;M_1)$$





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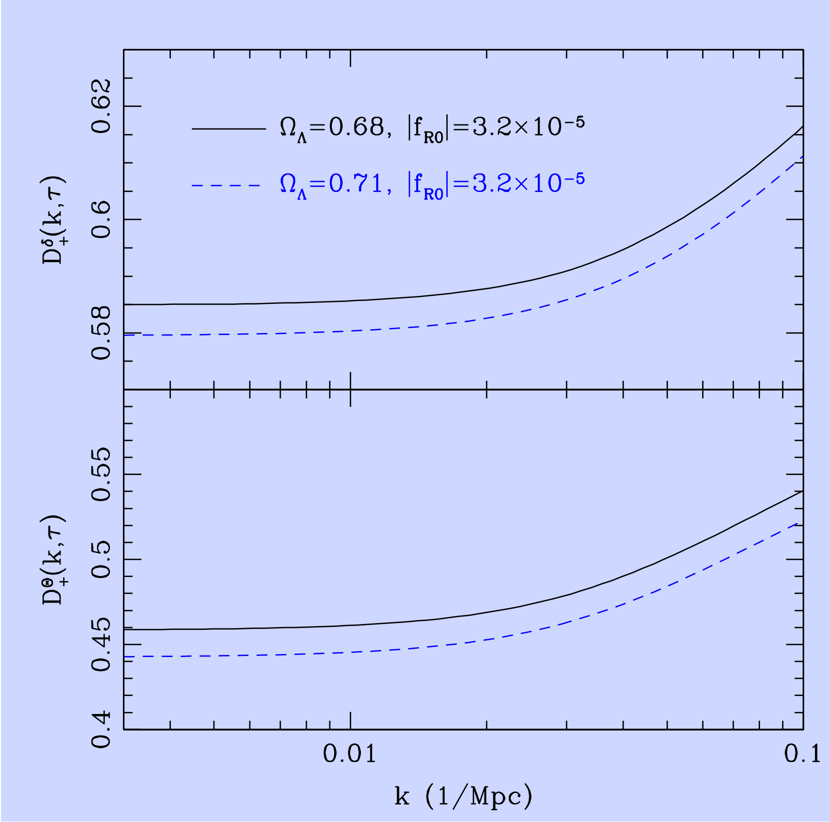
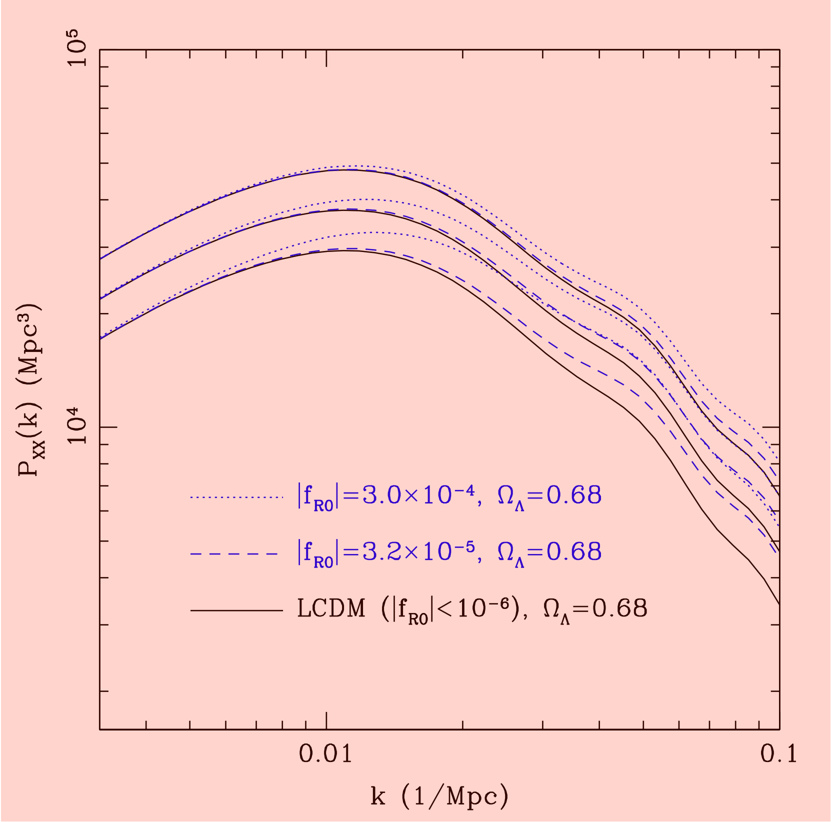
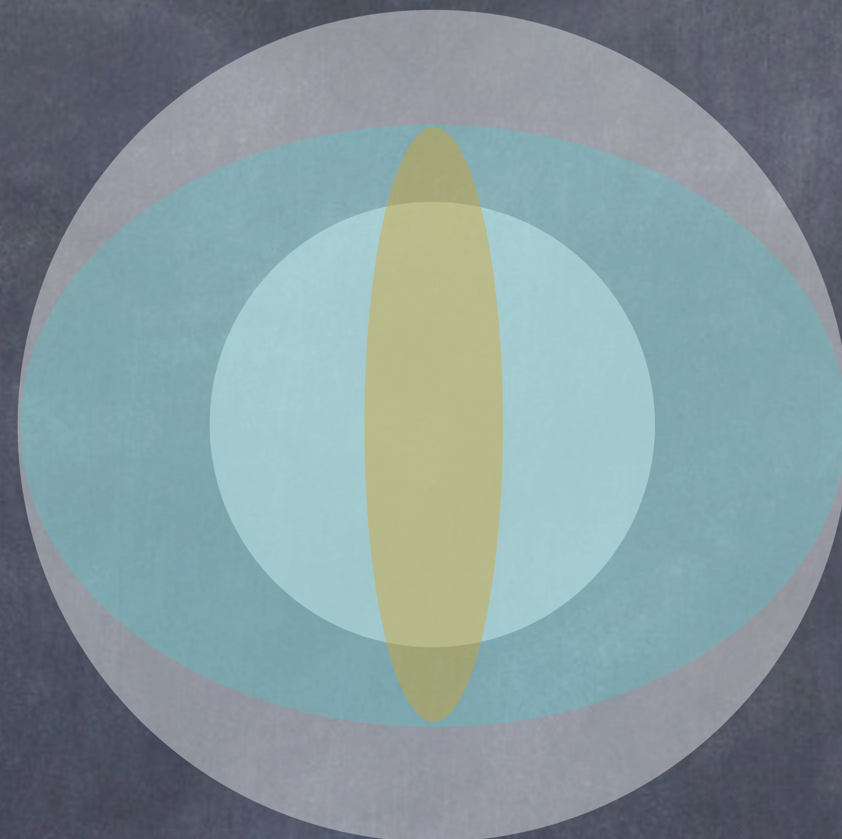




Structure formation of RSD

Squeezing effect at large scales

(Kaiser 1987)



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$$P_s(k,\mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\Theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta} + \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + \dots] \exp[-(k\mu\sigma_p)^2]$$

Structure formation of RSD

The non-linear solution is derived from

$$d\delta_m/dt + \nabla[(1+\delta_m)v_m]/a = 0$$

$$dv_m/dt + Hv_m + (v_m\nabla)v_m/a = -\nabla\psi/a$$

$$\phi_{fR} - \psi_{fR} = \varphi$$

$$k^2\,\psi = -3/2\, H_0{}^2\Omega_m\, \delta_m/a - 1/2\, k^2\varphi$$

$$(1+w_{BD})\, k^2/a^2\, \varphi = 3H_0{}^2\Omega_m\, \delta_m/a - I(\varphi)$$

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Structure formation of RSD

The higher order polynomials are given by,

$$A(k,t) = b^3\, \Sigma_n\, \Sigma_{a,b}\, \mu^{2n}(G_\Theta/b)^{2a+b-1} \int d^3k \int dr \int dx$$

$$\times\, [A^n{}_{ab}(r,x)B_{2ab}(p,k-p,-k) + A^n{}_{ab}(r,x)B_{2ab}(k-p,p,-k)$$

$$B(k,t) = b^4\, \Sigma_n\, \Sigma_{a,b}\, \mu^{2n}(-G_\Theta/b)^{2a+b-1} \int d^3k \int dr \int dx$$

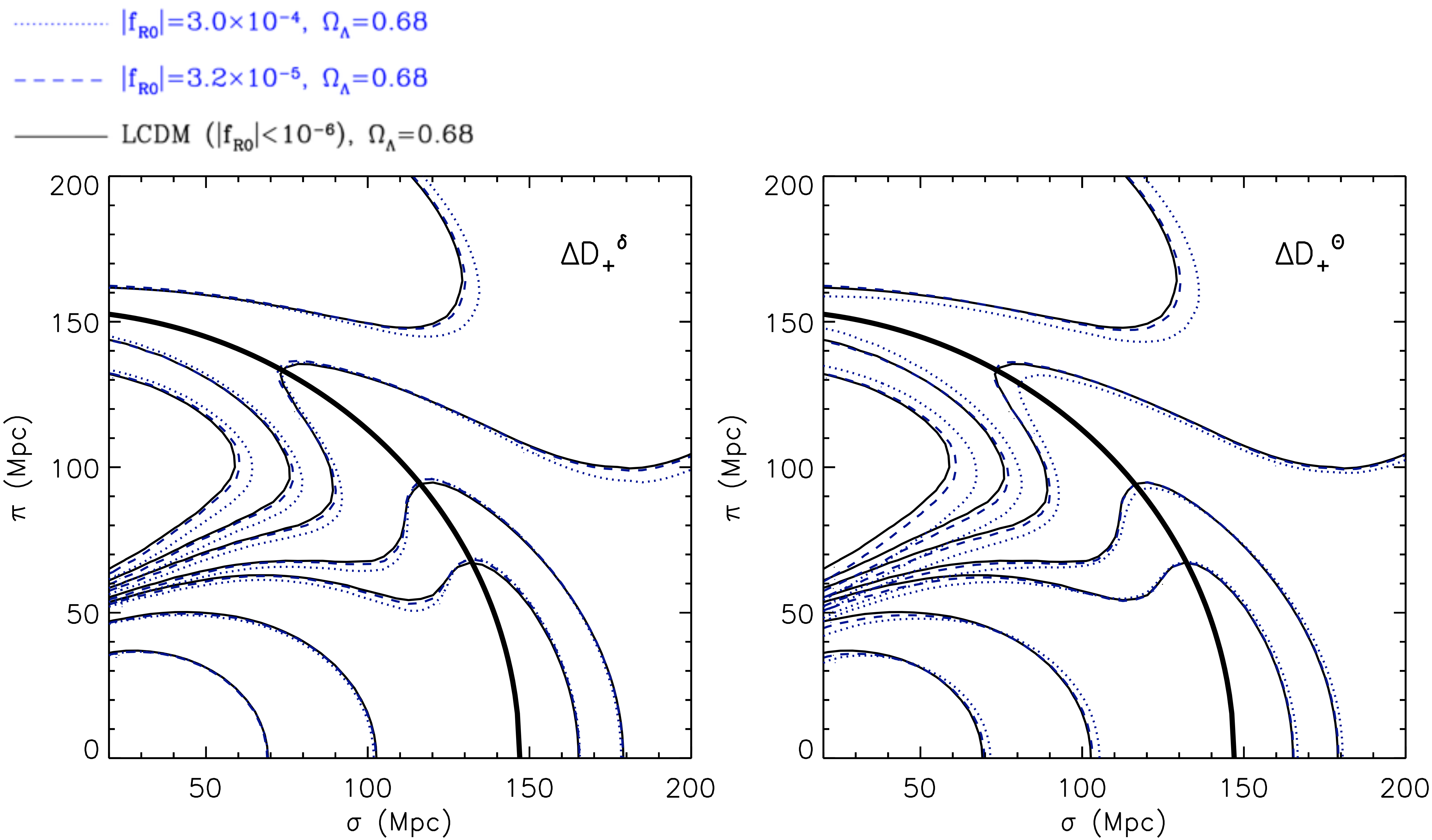
$$\times\, B^n{}_{ab}(r,x)P_{a2}(k\sqrt{1+r^2-2rx})P_{b2}(kr)/(1+r^2-2rx)^a$$

$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)$$

$$\Downarrow$$

$$P_s(k,\mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta}$$
$$+ \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + \dots]\, \exp[-(k\mu\sigma_p)^2]$$

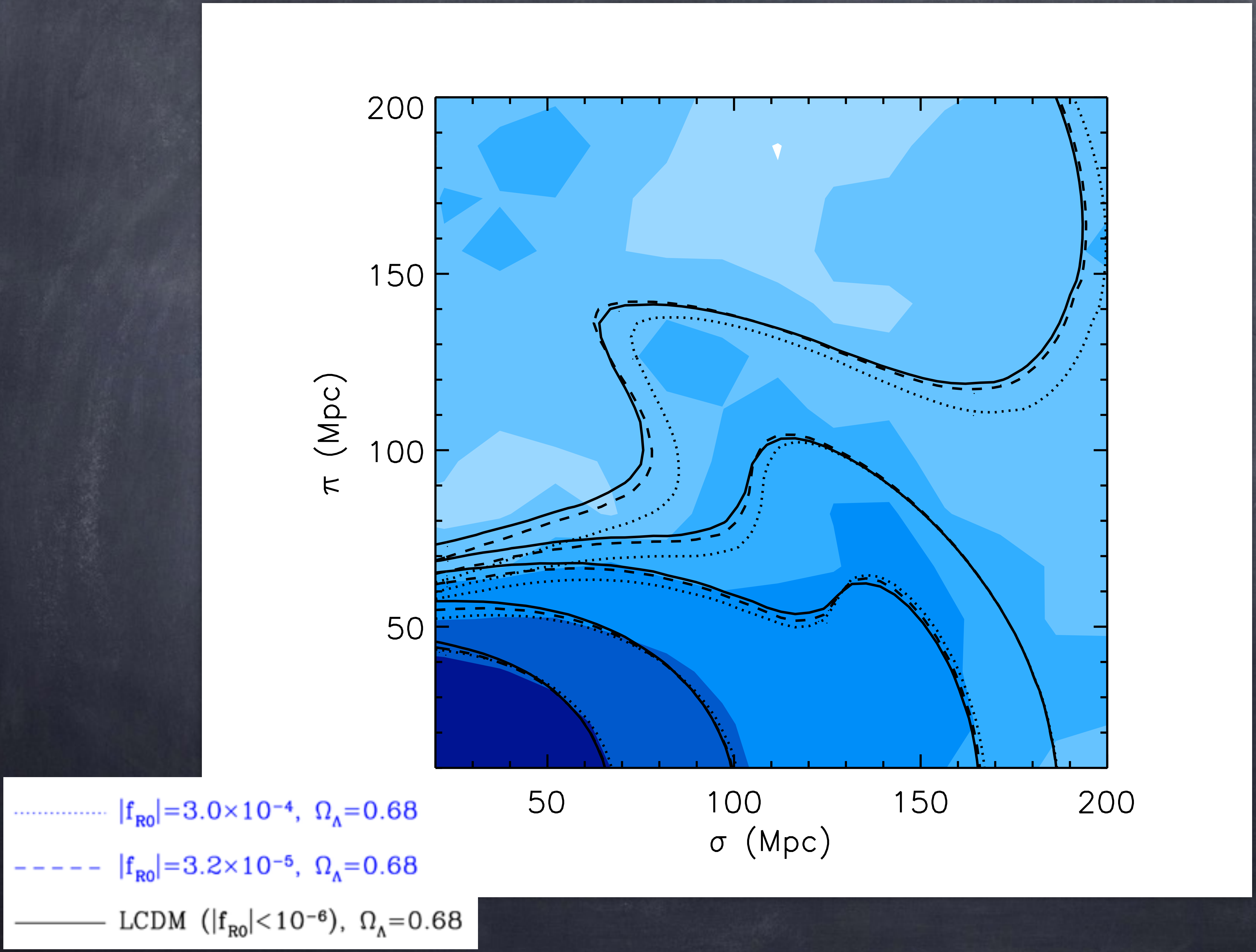
Correlation function of f(R) gravity model



The variation of D^{δ}

The variation of D^{Θ}

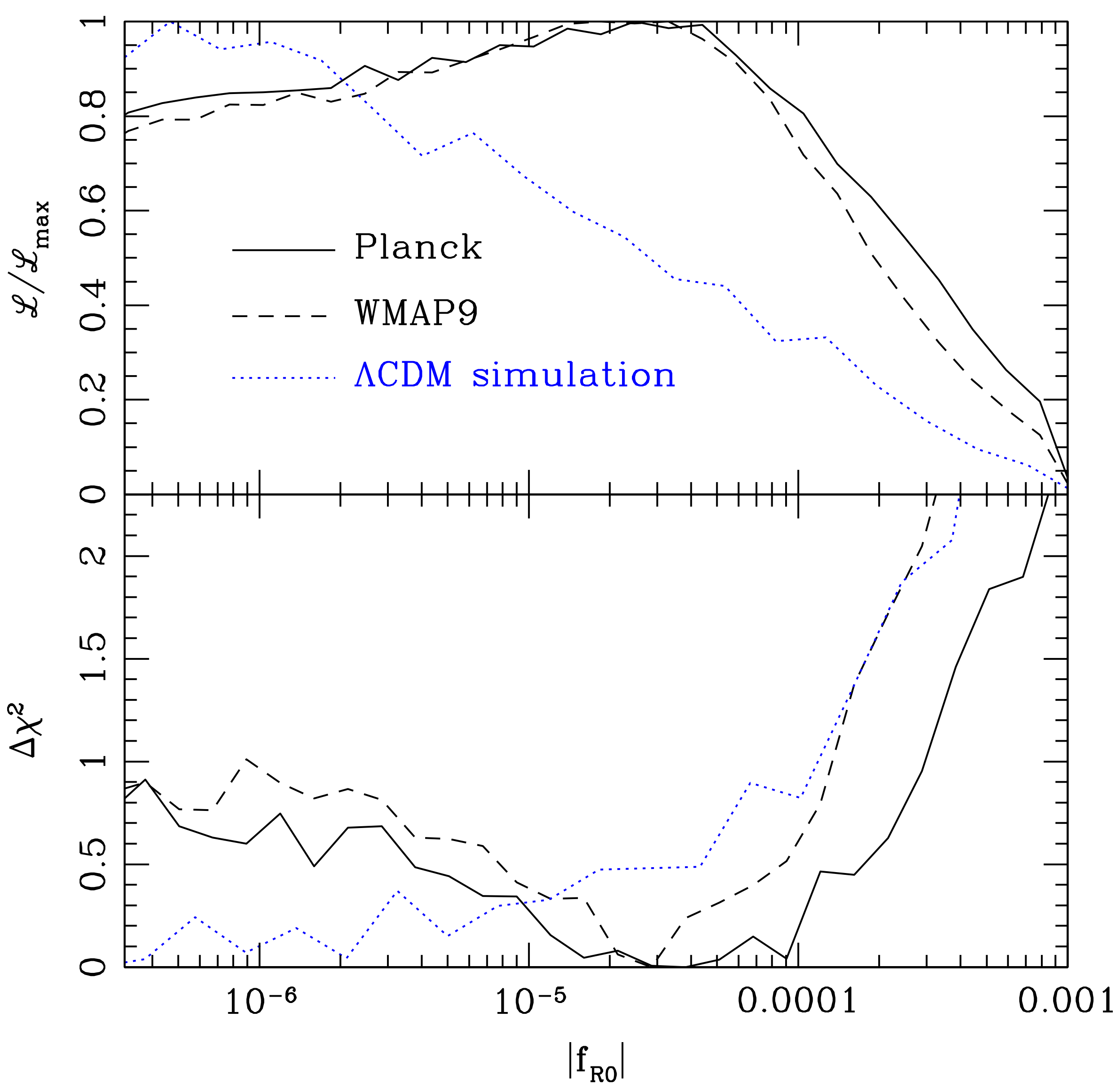
The measurement and best fit models



Constraints on f(R) gravity model

We find new constraints on f(R) gravity models using BOSS DR11

$|f_{R0}| < 8\times10^{-4}$ at 95% confidence limit



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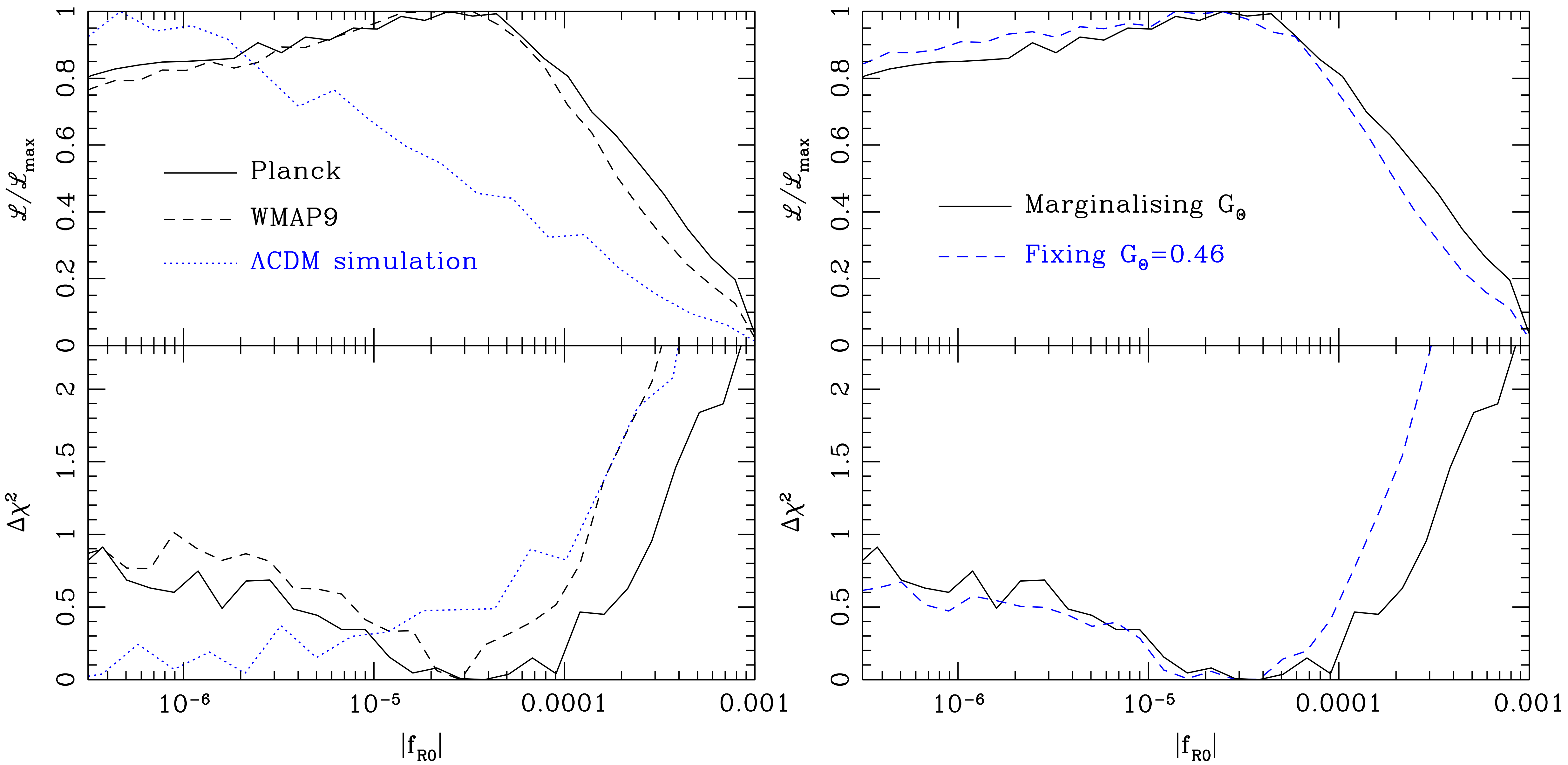
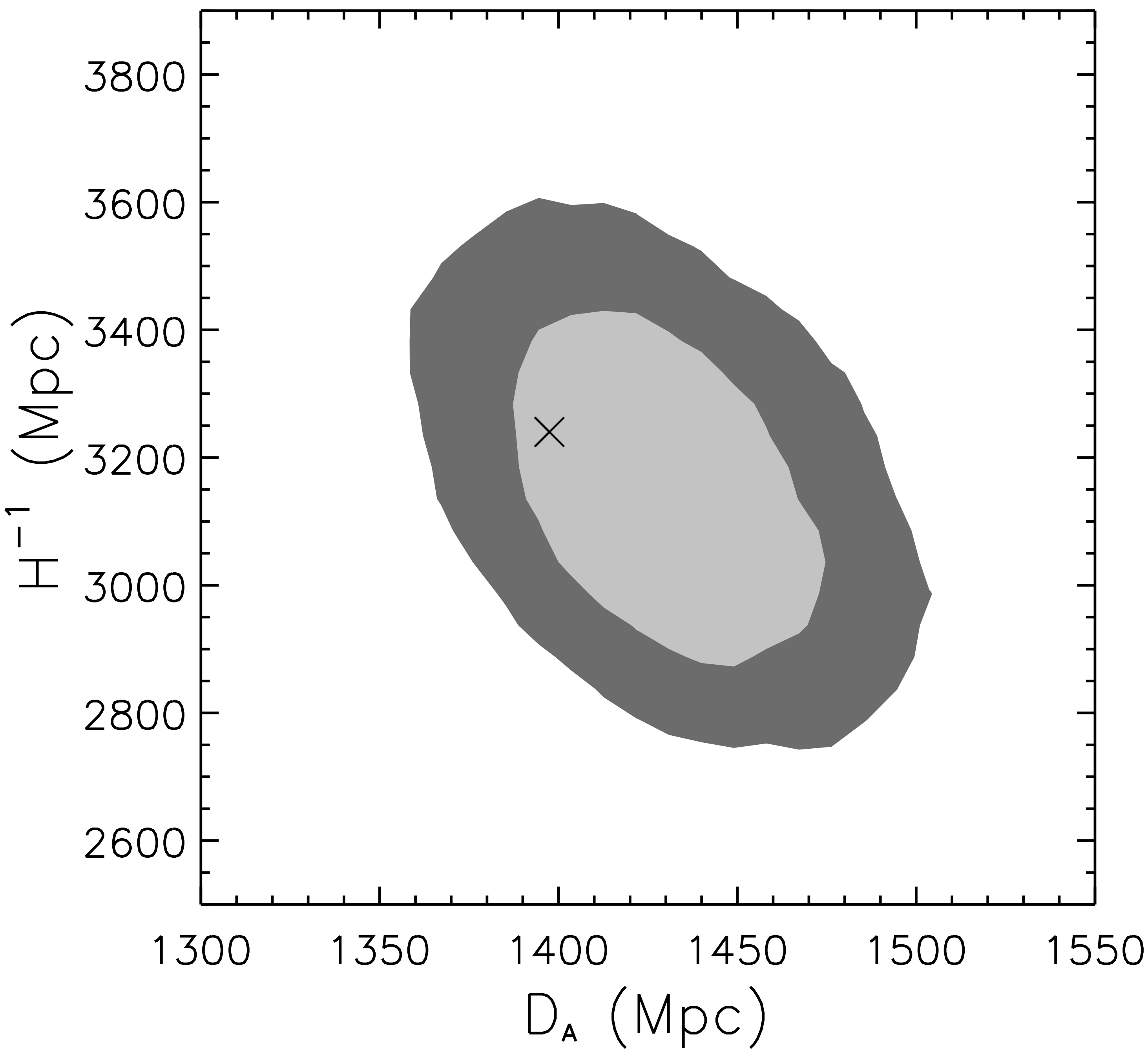


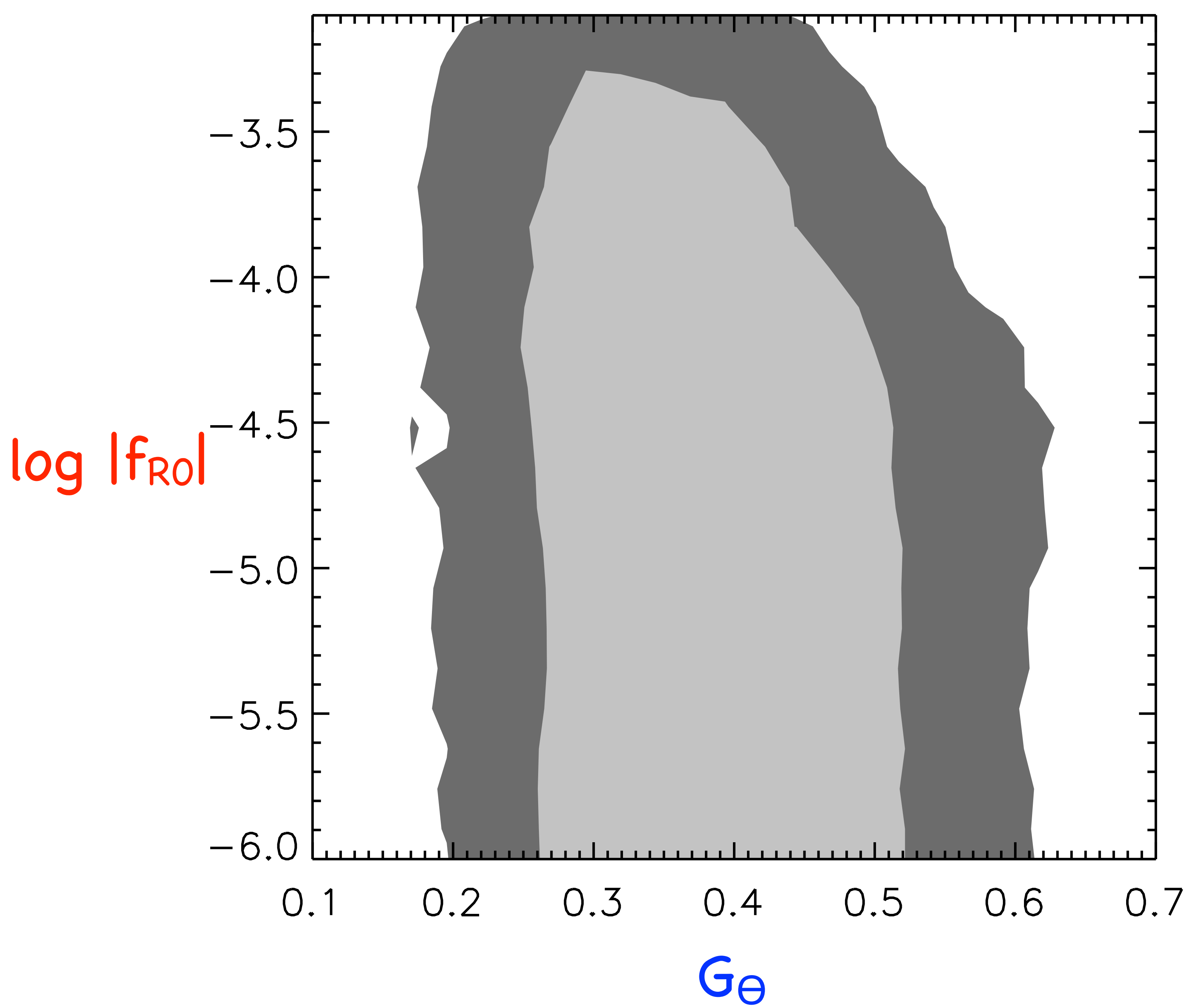
Constraints on distance measures

Measured distances are consistent with LCDM model



Constraints on growth functions

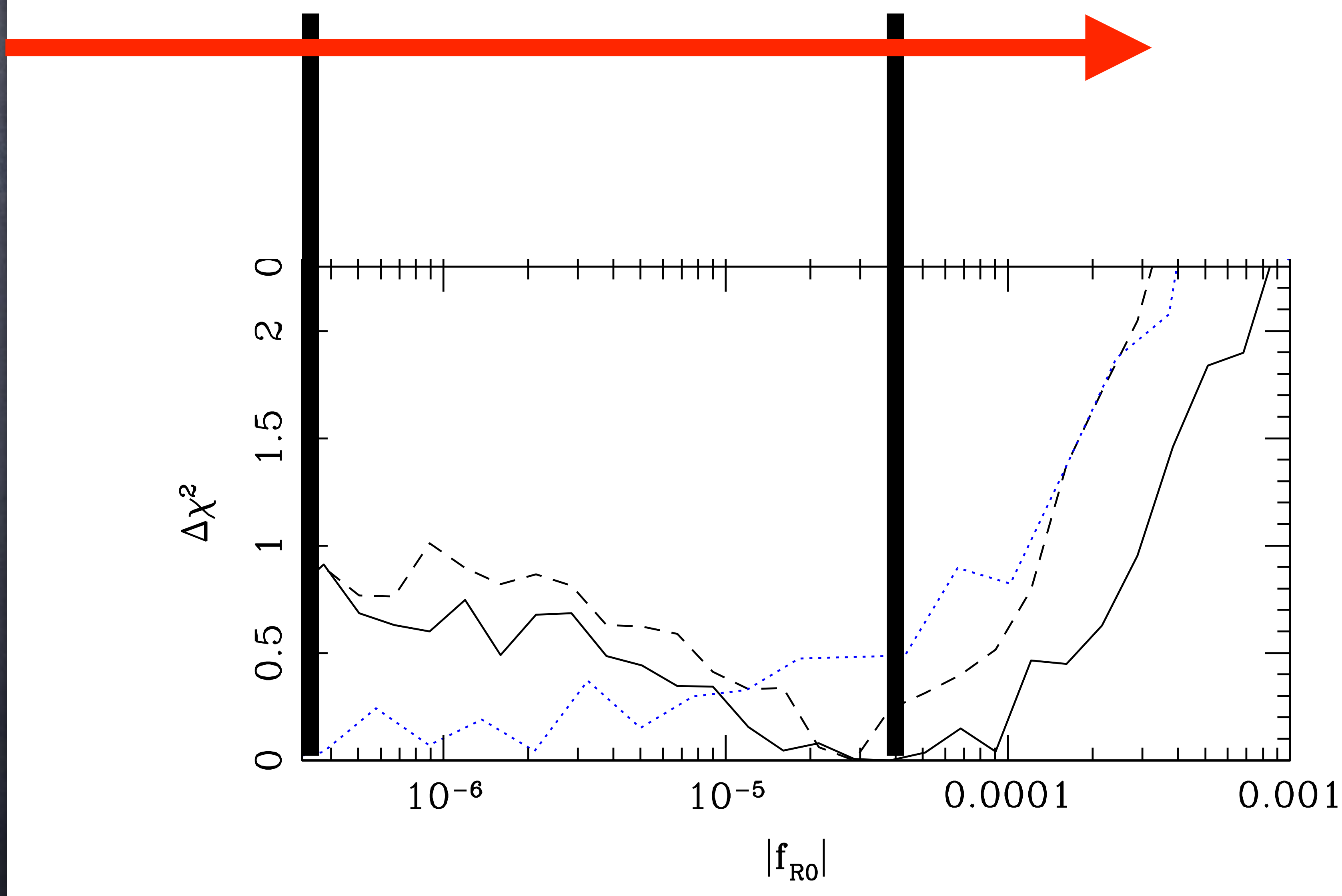
$$D^{\Theta}(k,t) = G_{\Theta}(t)\, F_{\Theta}(k,t;M_1)$$



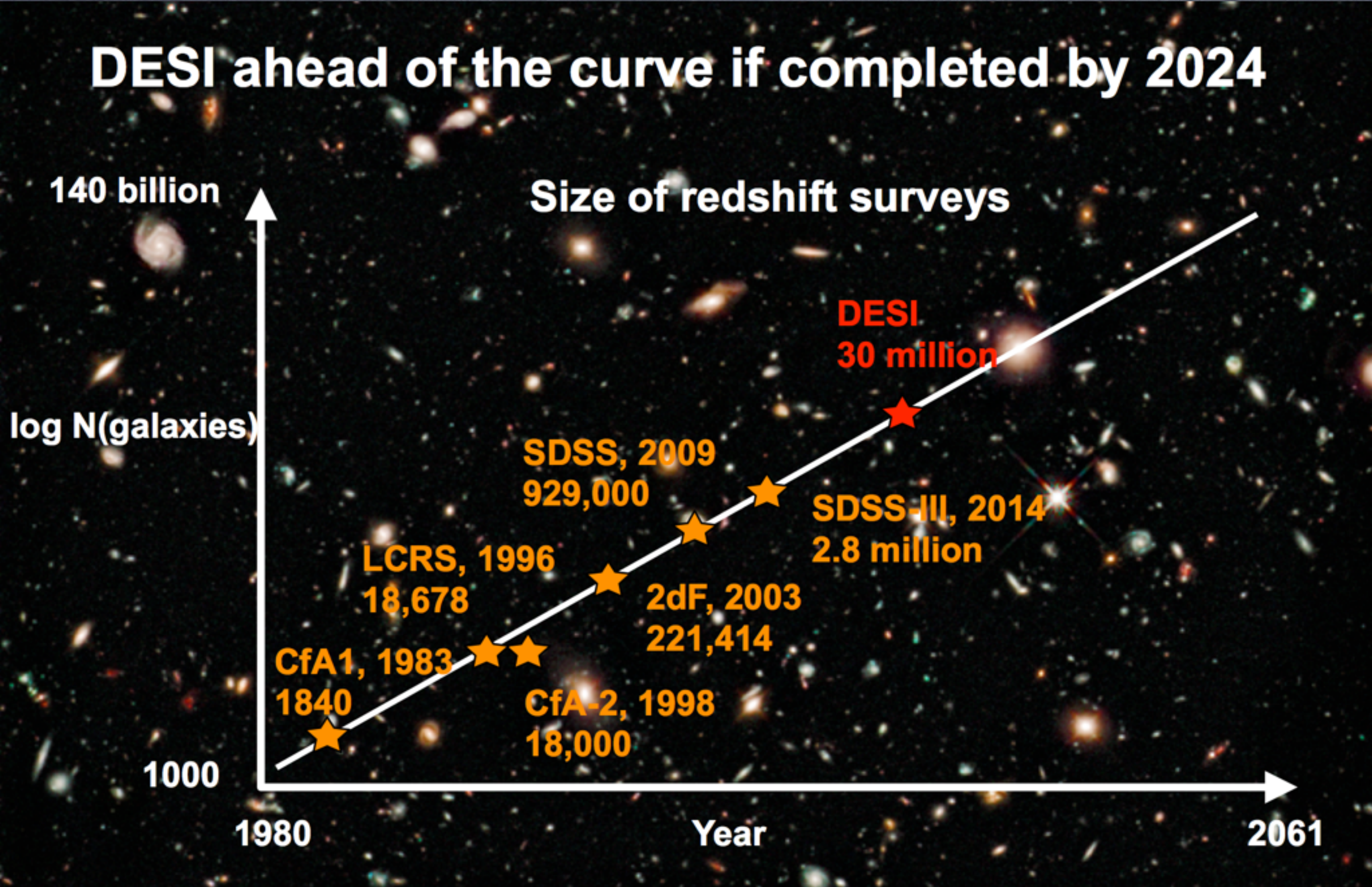
Constraints on f(R) now and future

Invisible difference from LCDM model using BOSS

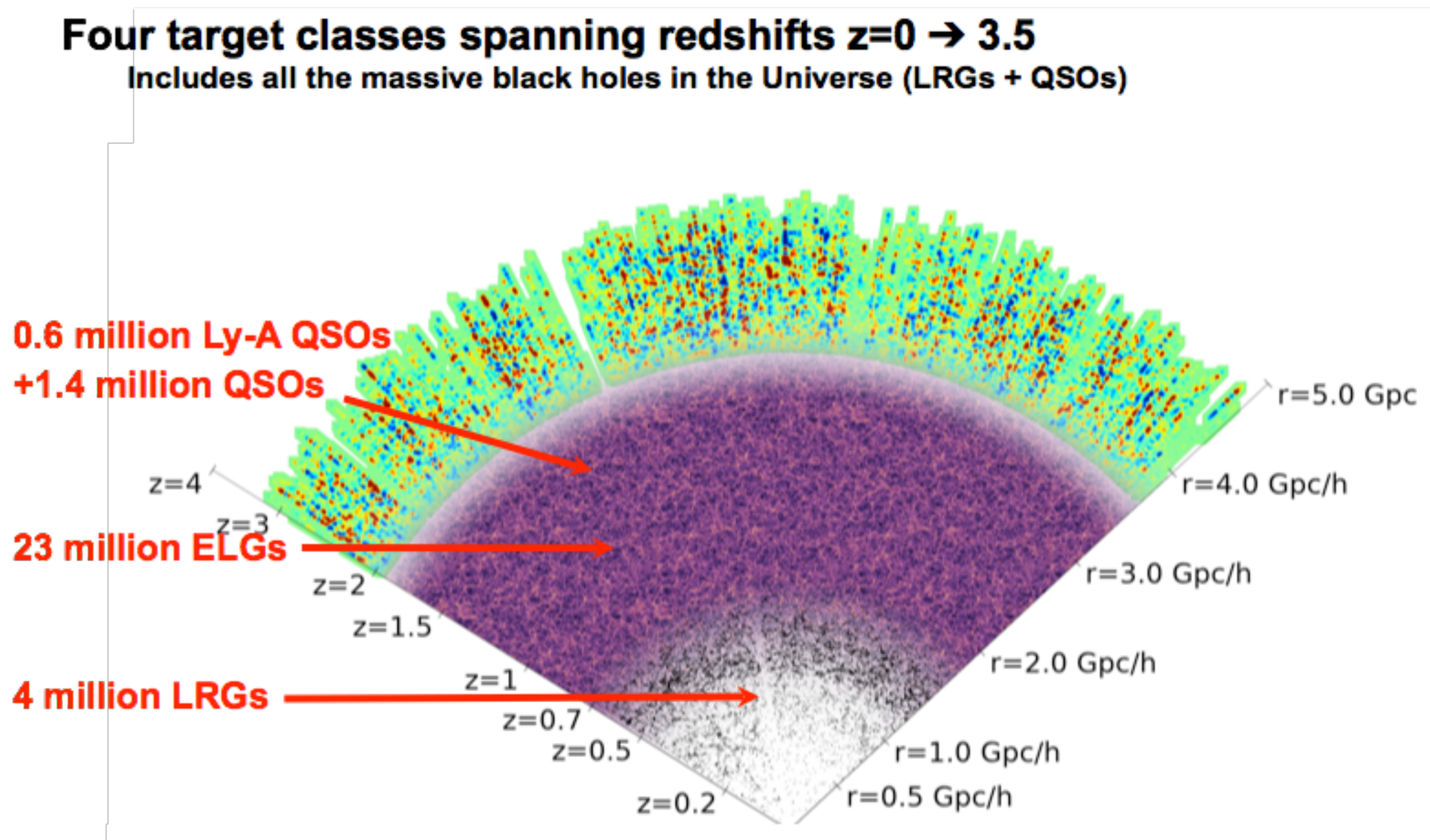
Need a factor of 10 improvement



Where we are, and where will we go?



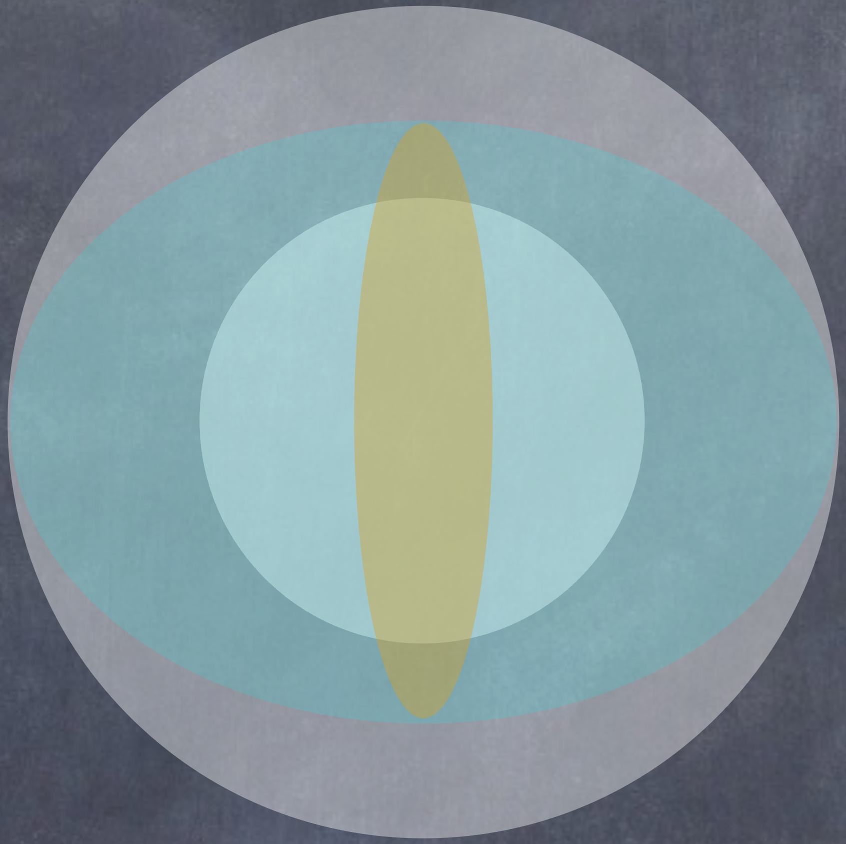
The targeted galaxies in next generation



Degeneracy for coherent motions

Squeezing effect at large scales

(Kaiser 1987)



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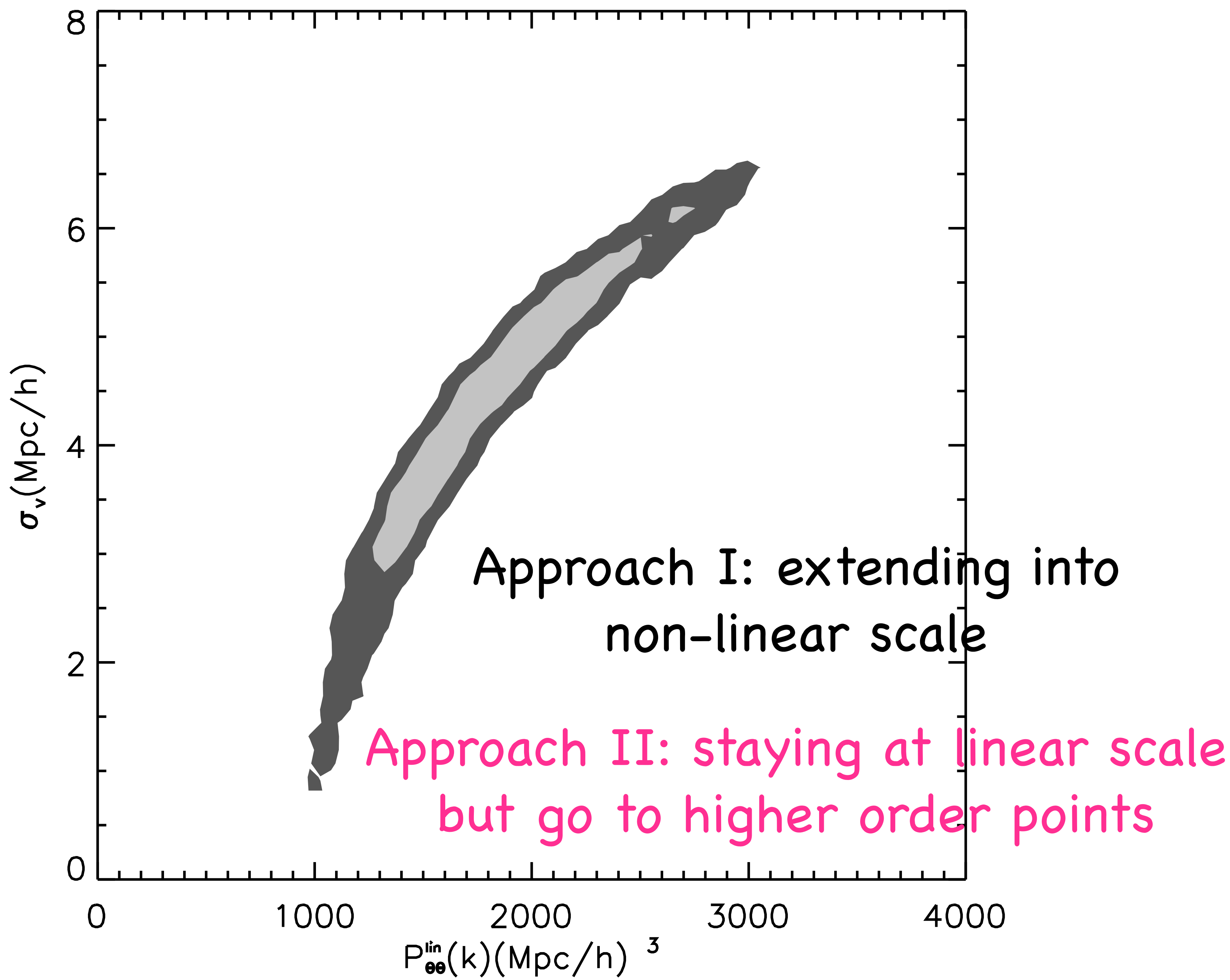
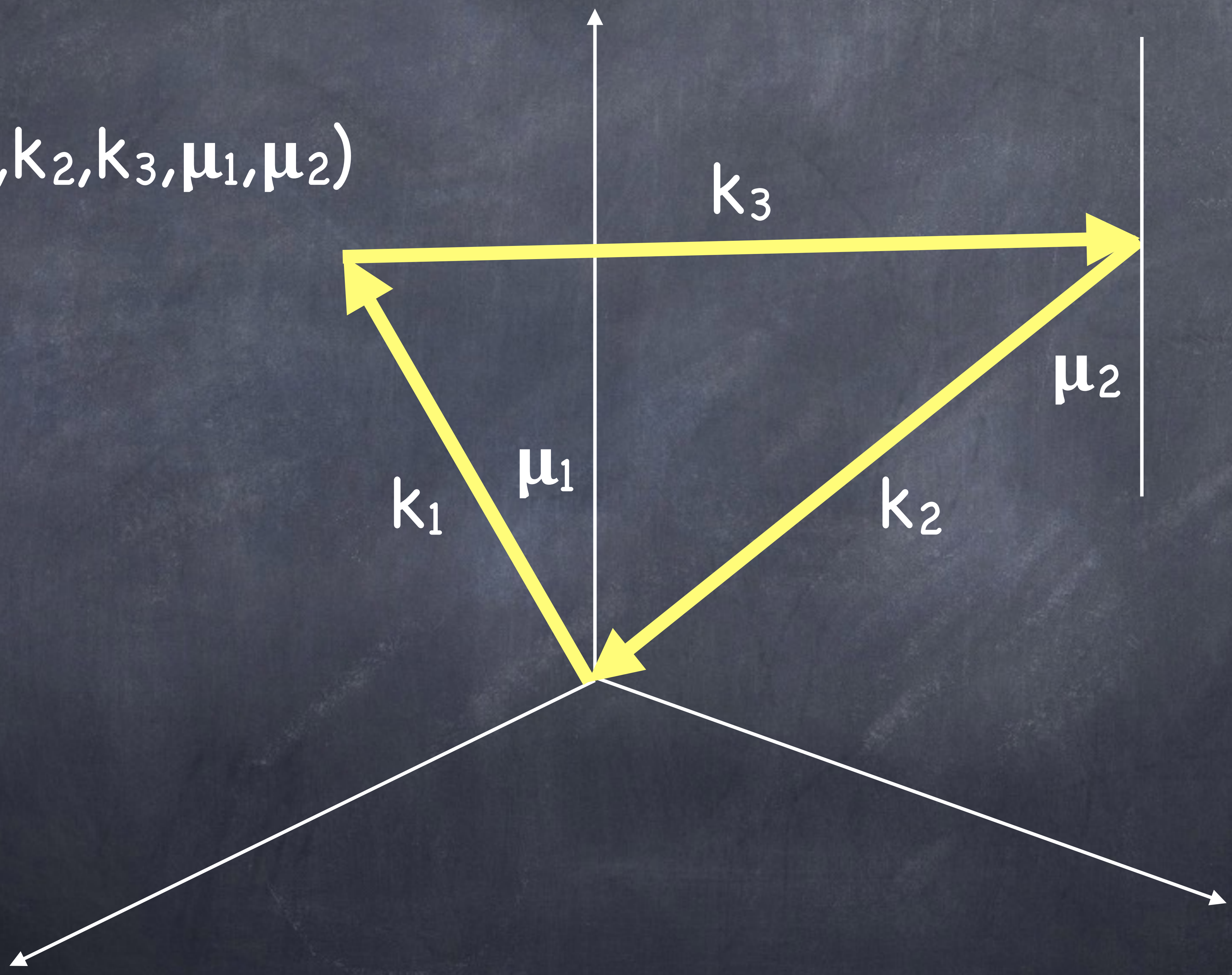


Bispectrum Alcock-Paczynski effect

Configuration in redshift space

$B(k_1, k_2, k_3, \mu_1, \mu_2)$



YSS, Taruya, Oka 2015

Bispectrum Alcock-Paczynski effect

Definition of FoG effect

$$B(k_1,k_2,k_3,\mu_1,\mu_2) = D^B{}_{FoG}\, B^{PT}(k_1,k_2,k_3,\mu_1,\mu_2)$$

$$D^B{}_{FoG} = \exp[-(k_1{}^2\mu_1{}^2+k_2{}^2\mu_2{}^2+k_3{}^2\mu_3{}^2)\sigma_p{}^2]$$

YSS, Taruya, Oka 2015

Bispectrum Alcock-Paczynski effect

B^{PT} in redshift space

$$B(k_1,k_2,k_3,\mu_1,\mu_2) = D^B{}_{FoG}\, B^{PT}(k_1,k_2,k_3,\mu_1,\mu_2)$$

$$B^{PT}(k_1,k_2,k_3,\mu_1,\mu_2) = 2[Z_2(k_1,k_2)Z_1(k_1)Z_2(k_2)P(k_1)P(k_2) + \text{cyclic}\ ]$$

$$Z_1(k_1) = b+f\mu_1{}^2$$

$$Z_2(k_1,k_2) = b_2/2 + bF_2 + f\mu_{12}G_2 + fk_{12}\mu_{12}/2[\mu_1/k_1 Z_2(k_2)+\mu_1/k_1 Z_2(k_2)]$$

YSS, Taruya, Oka 2015

Bispectrum Alcock-Paczynski effect

AP projection

$$B^{obs}(k_1,k_2,k_3,\mu_1,\mu_2) = (\Delta H^{-1})^2 (\Delta D_A)^4 B(q_1,q_2,q_3,\nu_1,\nu_2)$$

$$\Delta H^{-1}=H^{-1}_{fid}/H^{-1}_{true} \quad \Delta D_A=D_{A\ fid}/D_{A\ true}$$

$$q_i=\alpha(\mu_i)k_i \quad \nu_i=\mu_i\Delta H^{-1}/\alpha(\mu_i)$$

$$\alpha(\mu_i)=\{(\Delta D_A)^2 + [(\Delta H^{-1})^2-(\Delta D_A)^2]\mu_i{}^2\}^{1/2}$$

$$\nu_{ij}=(\Delta D_A)^2\ \eta_{ij}/\alpha(\mu_i)\alpha(\mu_j)+[(\Delta H^{-1})^2-(\Delta D_A)^2]\mu_i\mu_j/\alpha(\mu_i)\alpha(\mu_j)$$

YSS, Taruya, Oka 2015

Error forecast using power and bi combination

$$F_{\alpha\beta} = \Sigma_k \Sigma_{k1k2k3} (\partial S/\partial p_\alpha)\, C^{-1}\, (\partial S/\partial p_\beta)$$

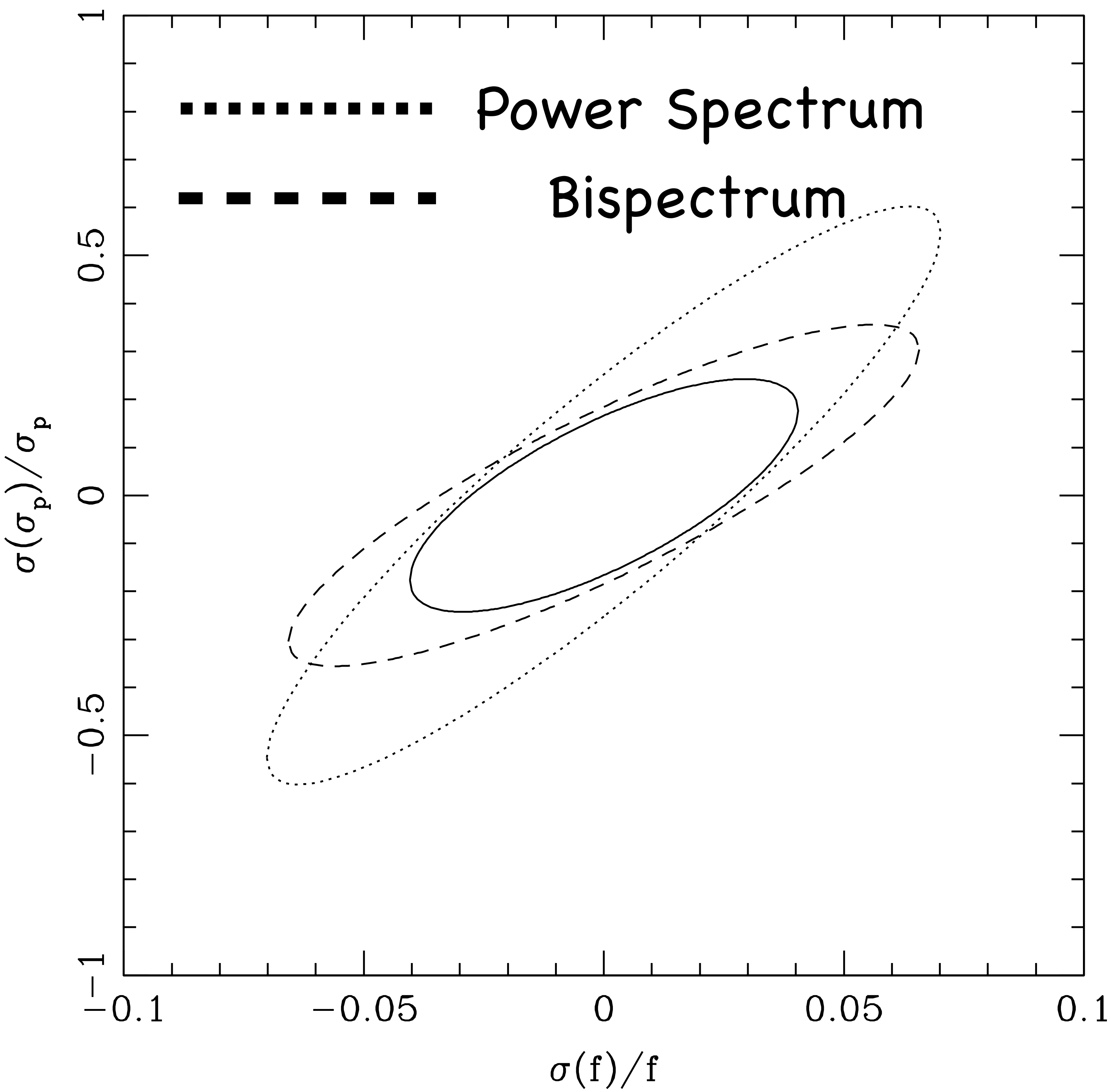
$$S = \begin{pmatrix} P(k,\mu) \\ B(k_1,k_2,k_3,\mu_1,\mu_2) \end{pmatrix}$$

$$C^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BB}^{-1}M & C_{BB}^{-1}+C_{BB}^{-1}C_{Bp}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

$$M = (C_{pp}-C_{PB}C_{BB}^{-1}C_{BP})^{-1}$$

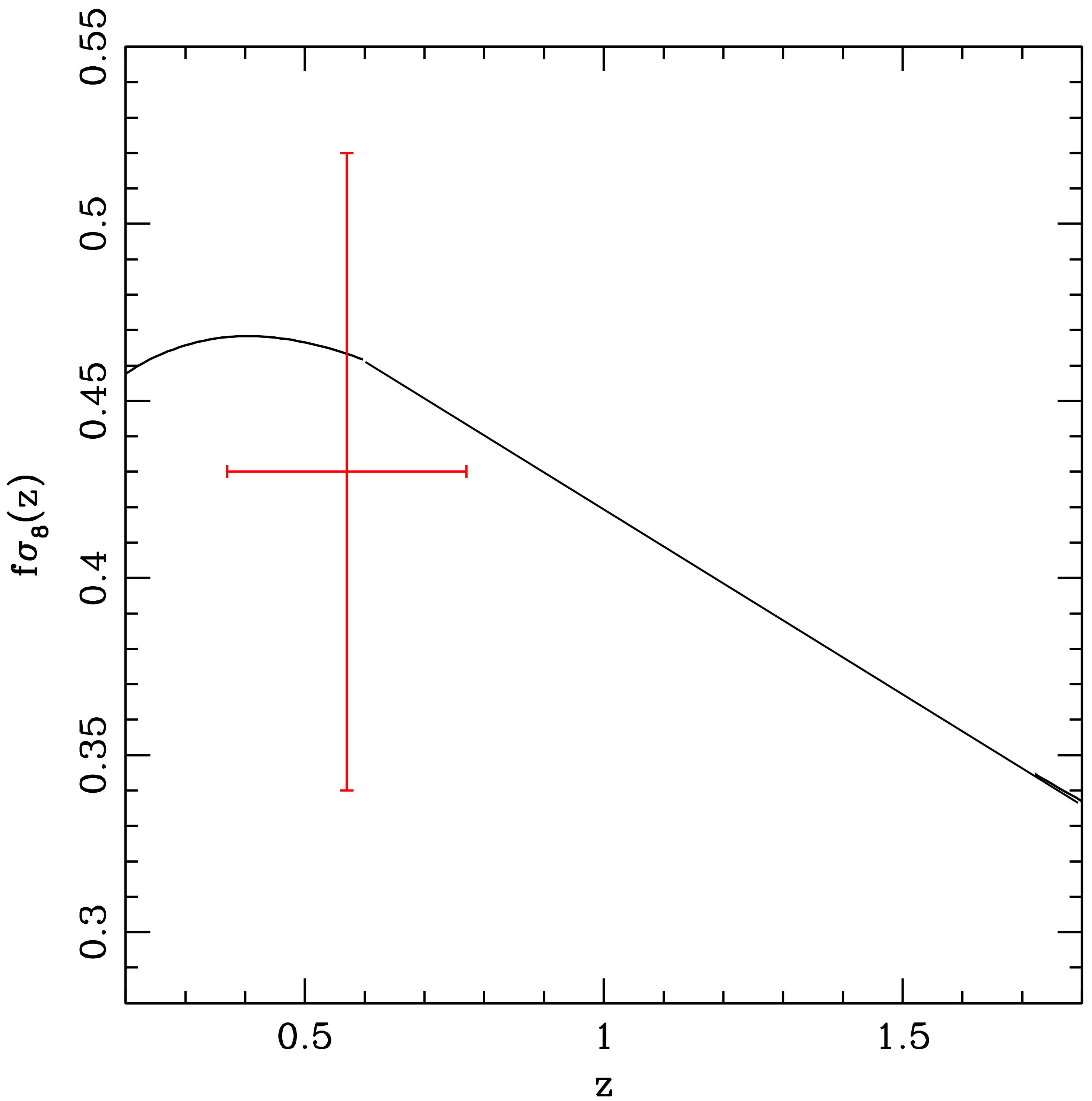
YSS, Taruya, Oka 2015

Degeneracy in coherent and random motions



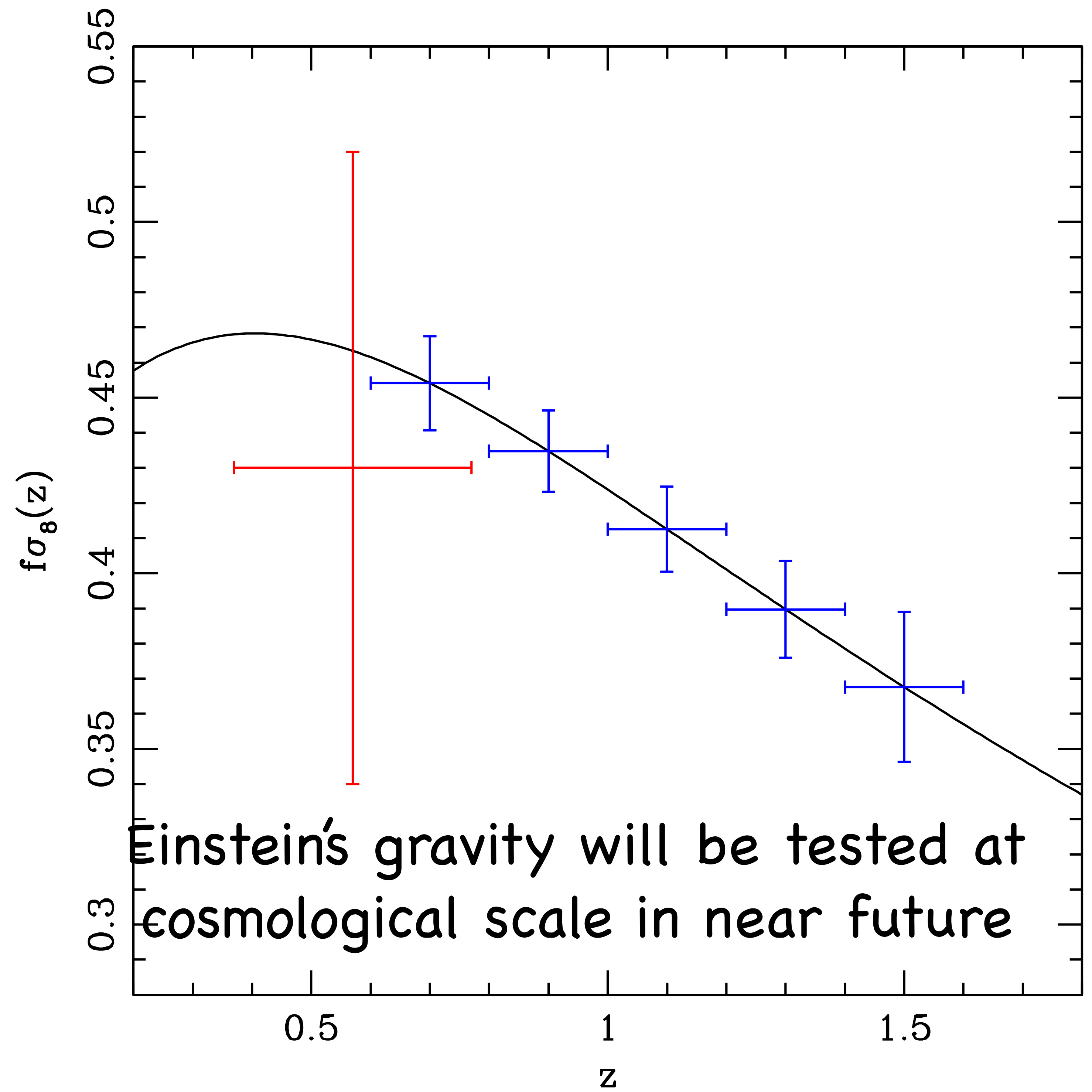
Measured coherent motion

Results from BOSS maps



Future constraints

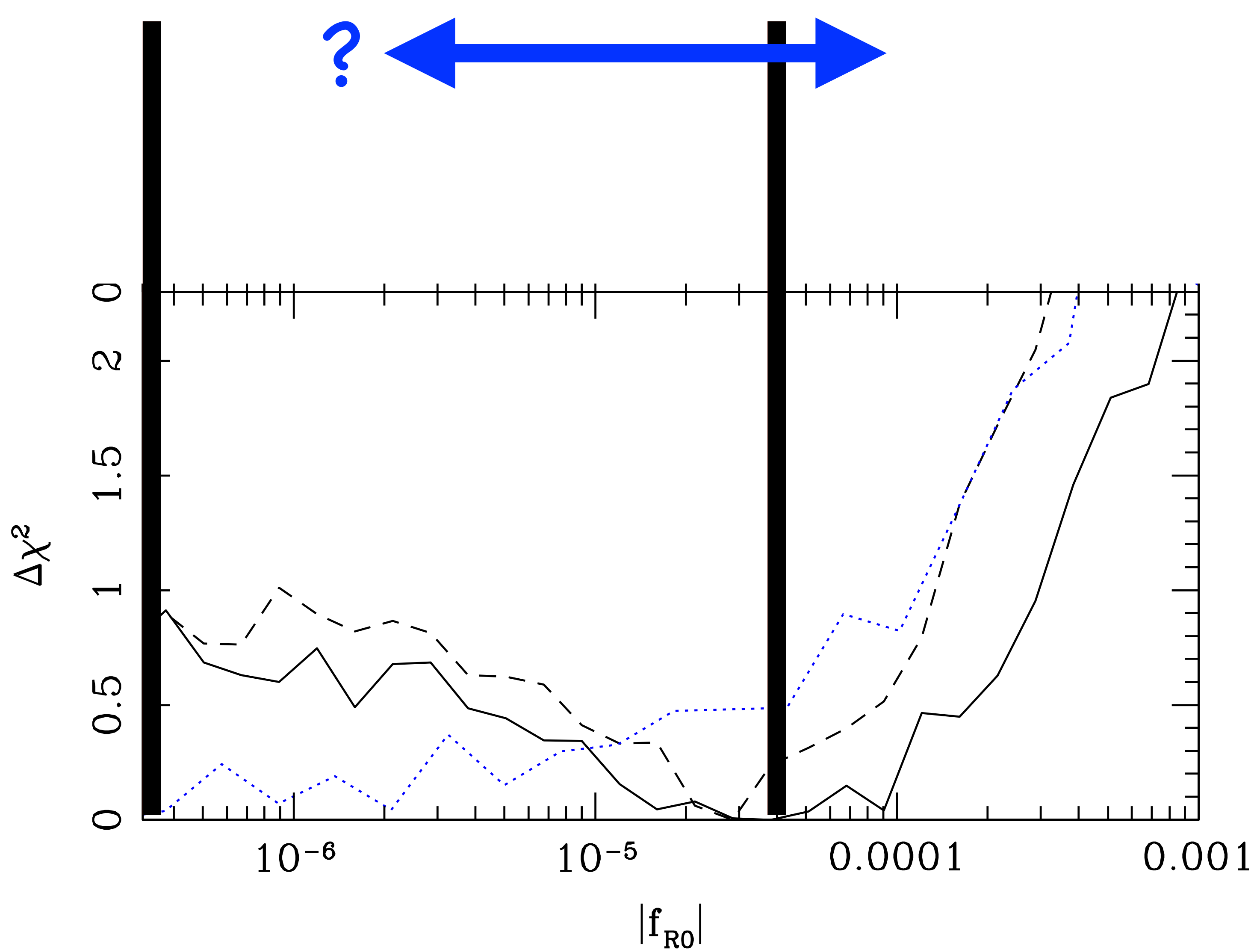
Expectation from DESI



Future work

Invisible difference from LCDM model using BOSS

then can we tell the difference in future?



Conclusion

- We succeed in measuring both distances and growth function simultaneously using RSD, and ready to test Einstein's gravity at cosmological scales through duality between distances and growth functions.

- We understand all systematics due to non-linear physics, and the perturbative description works fine the resolution of current experiment, at least two point correlation level.

- Now we face new challenge to meet the precision level of the high resolution experiment like DESI.

- We work out the Alcock-Paczynski effect on bispectra, and find that the combined constraint of power spectrum and bispectrum improves the detectability of growth function.

- We initiate new roadmap to accomplish this combination for the future experiment.