Cosmological Implication of Large Scale Structure of the Universe

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CosPA 2015

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CosKASI

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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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.

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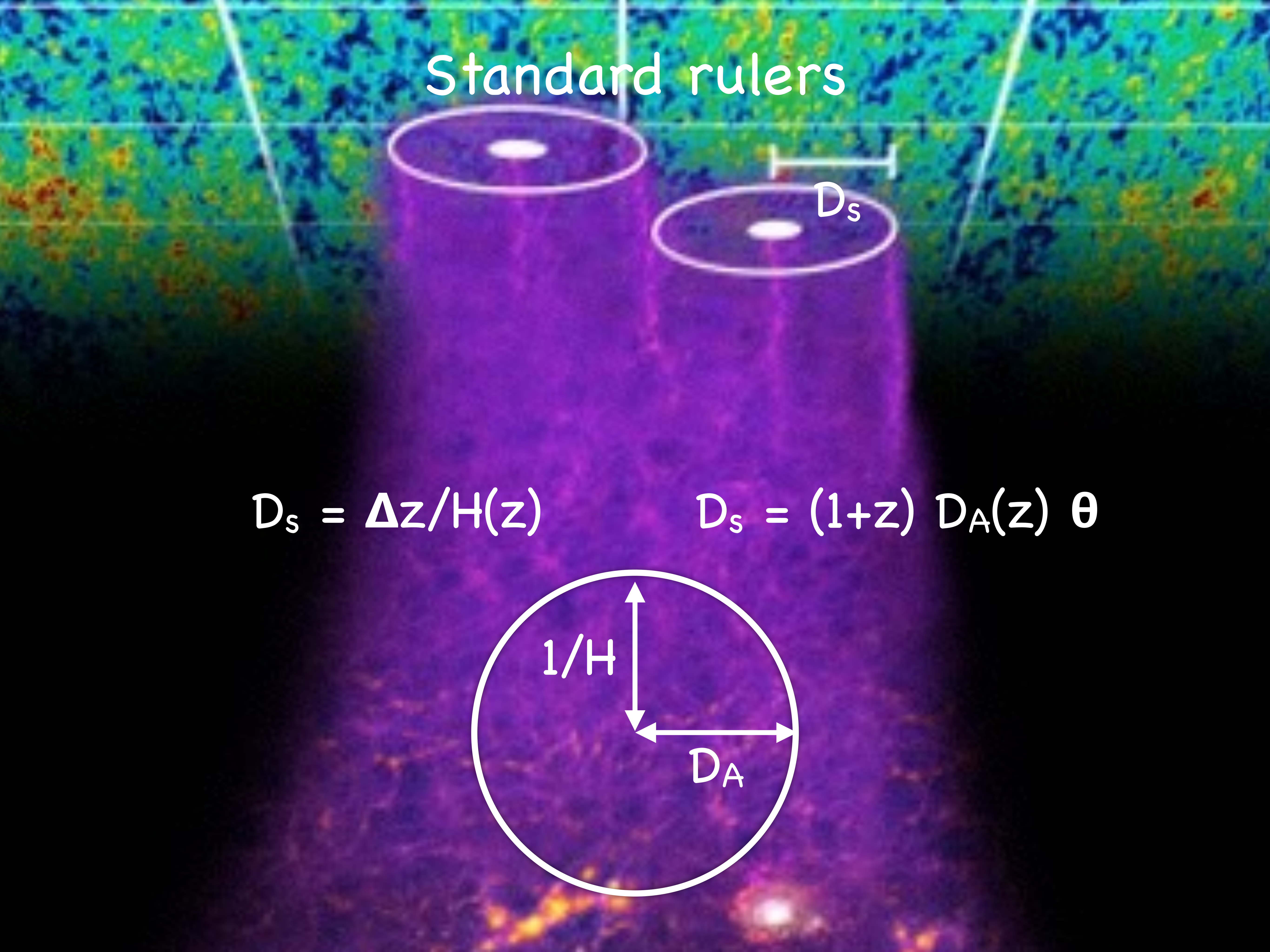
Standard rulers



$$D_s = \Delta z / H(z) \qquad D_s = (1+z)\, D_A(z)\, \theta$$

Key observables in cosmological science

Angular diameter distance D
which measure the angular diameter distance and expansion rate as a function of redshift.

Radial distance H
anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

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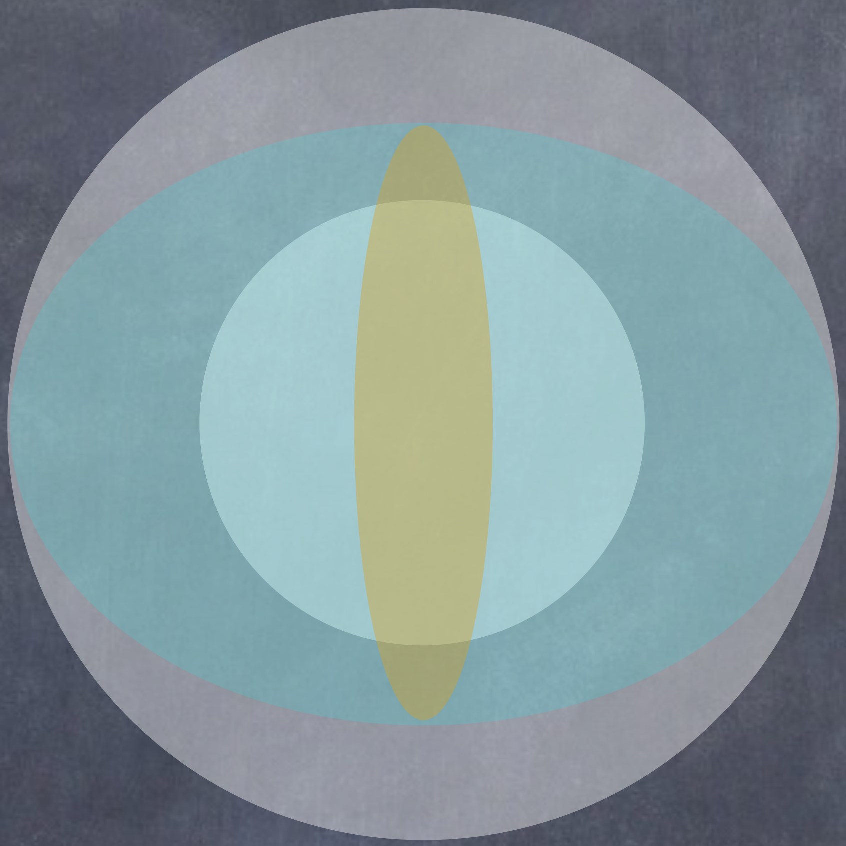
Redshift Space Distortion - Cons and Pros

Squeezing effect at large scales

(Kaiser 1987)



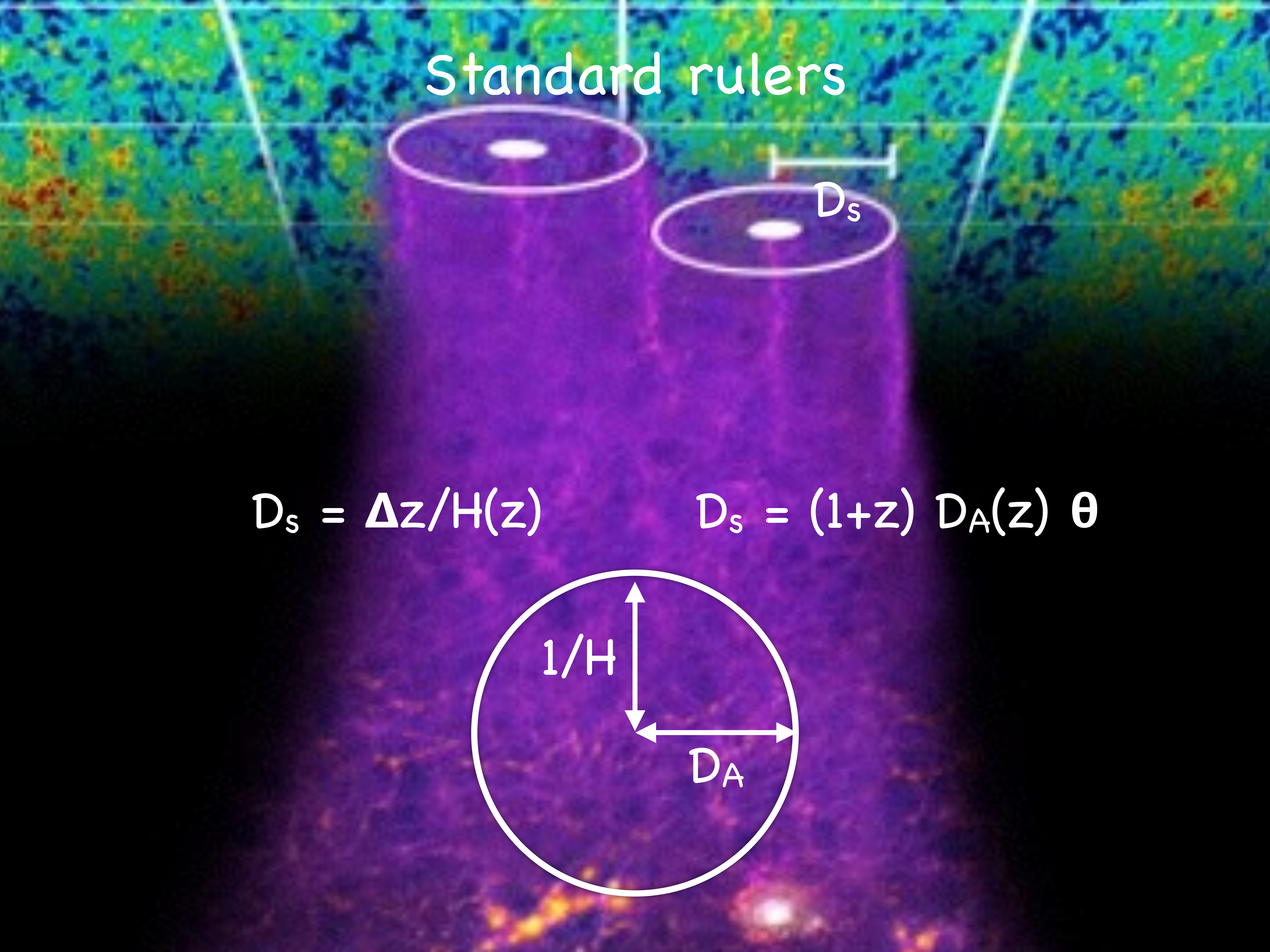
Finger of God effect at small scales

(Jackson 1972)

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

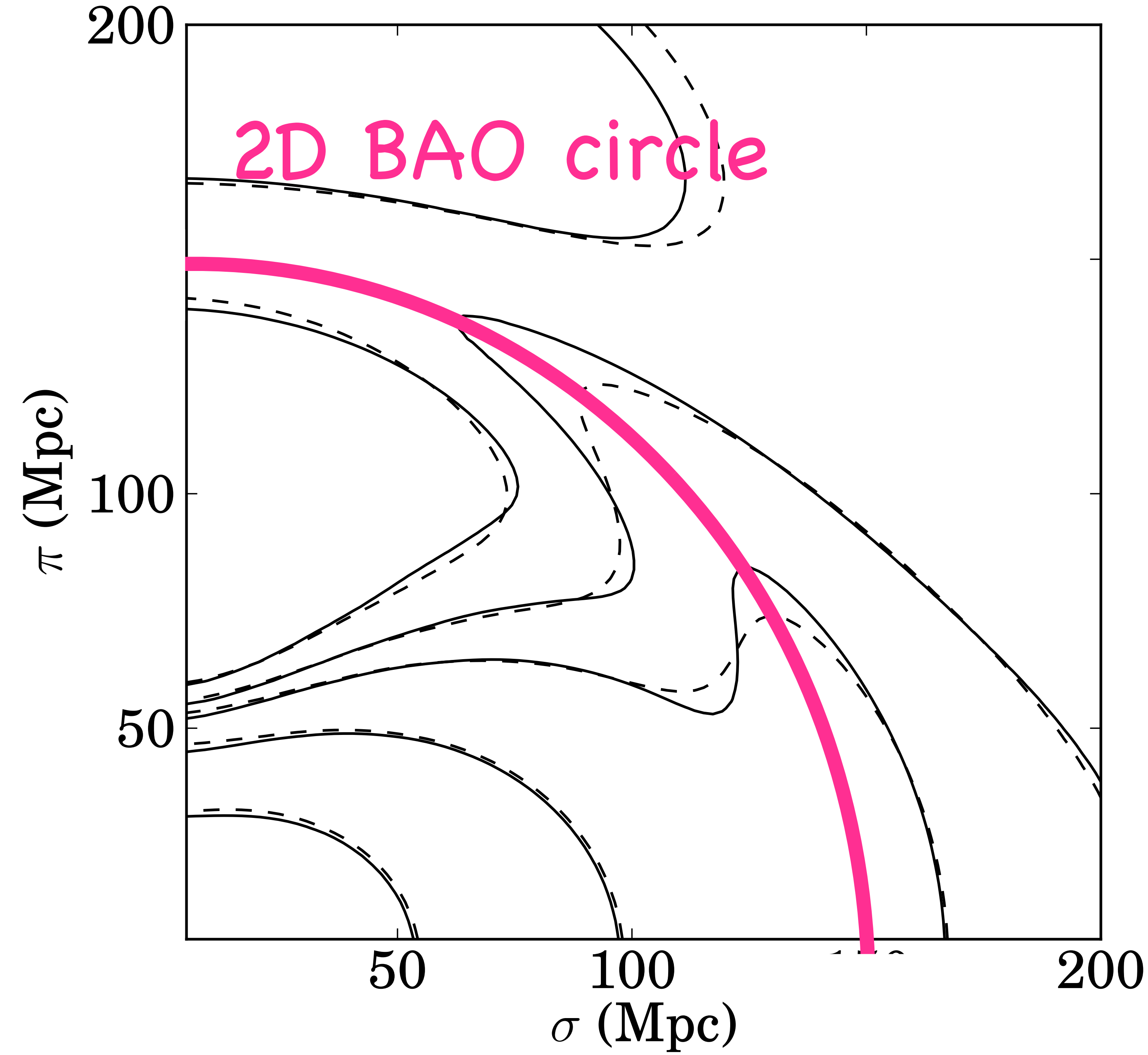
Against: The location of galaxy is shifted by the peculiar velocity of galaxy, and this transformation is stochastic. Therefore it generates non-trivial non-Gaussianity.

For: It provides information of coherent motion unbiased probe of structure formation


Standard rulers
D_s
$D_s = \Delta z / H(z)$
$D_s = (1+z)\, D_A(z)\, \theta$
1/H
D_A

Validating BAO standard ruler

2D BAO circle is observed with known shape of spectra



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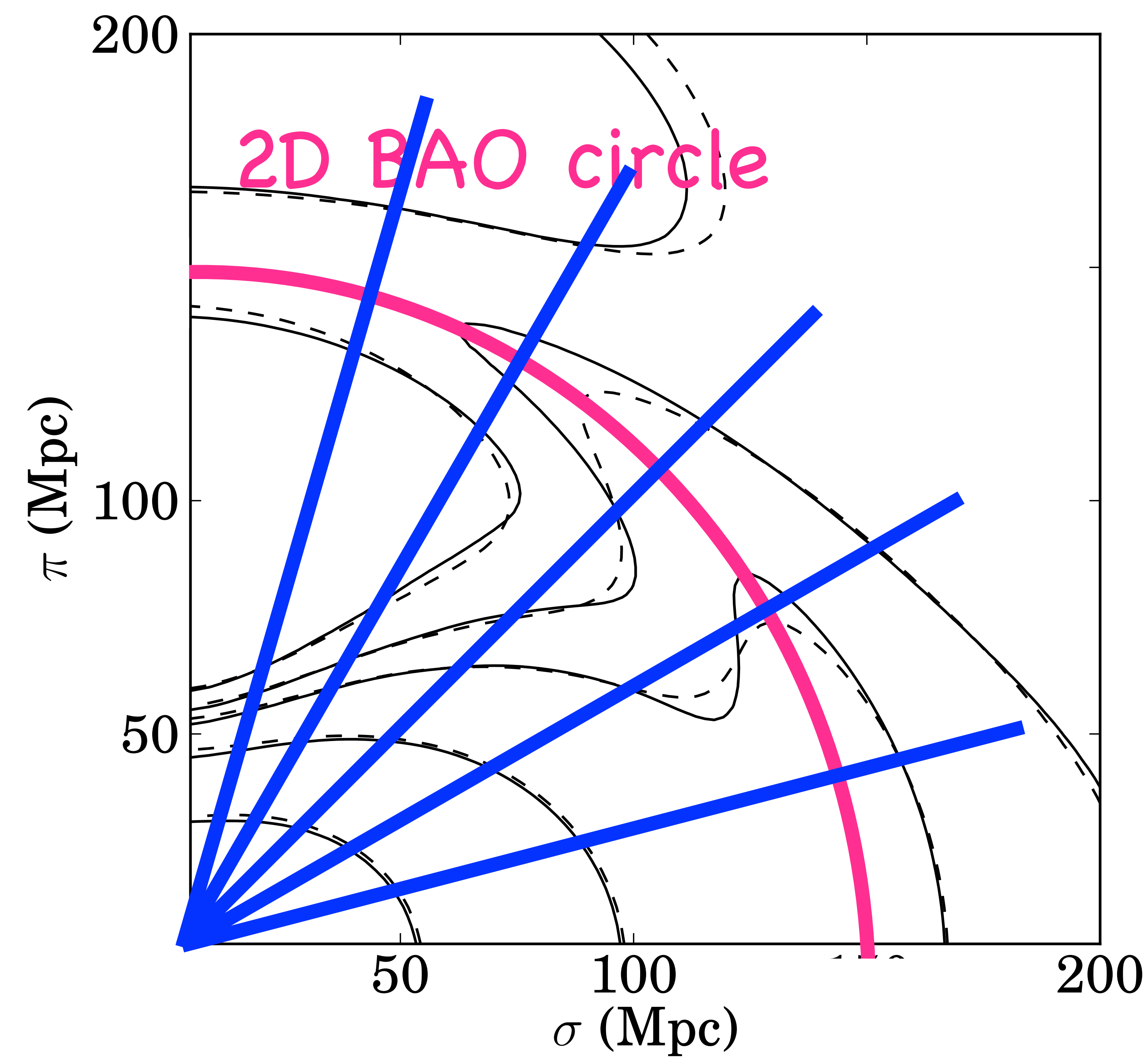

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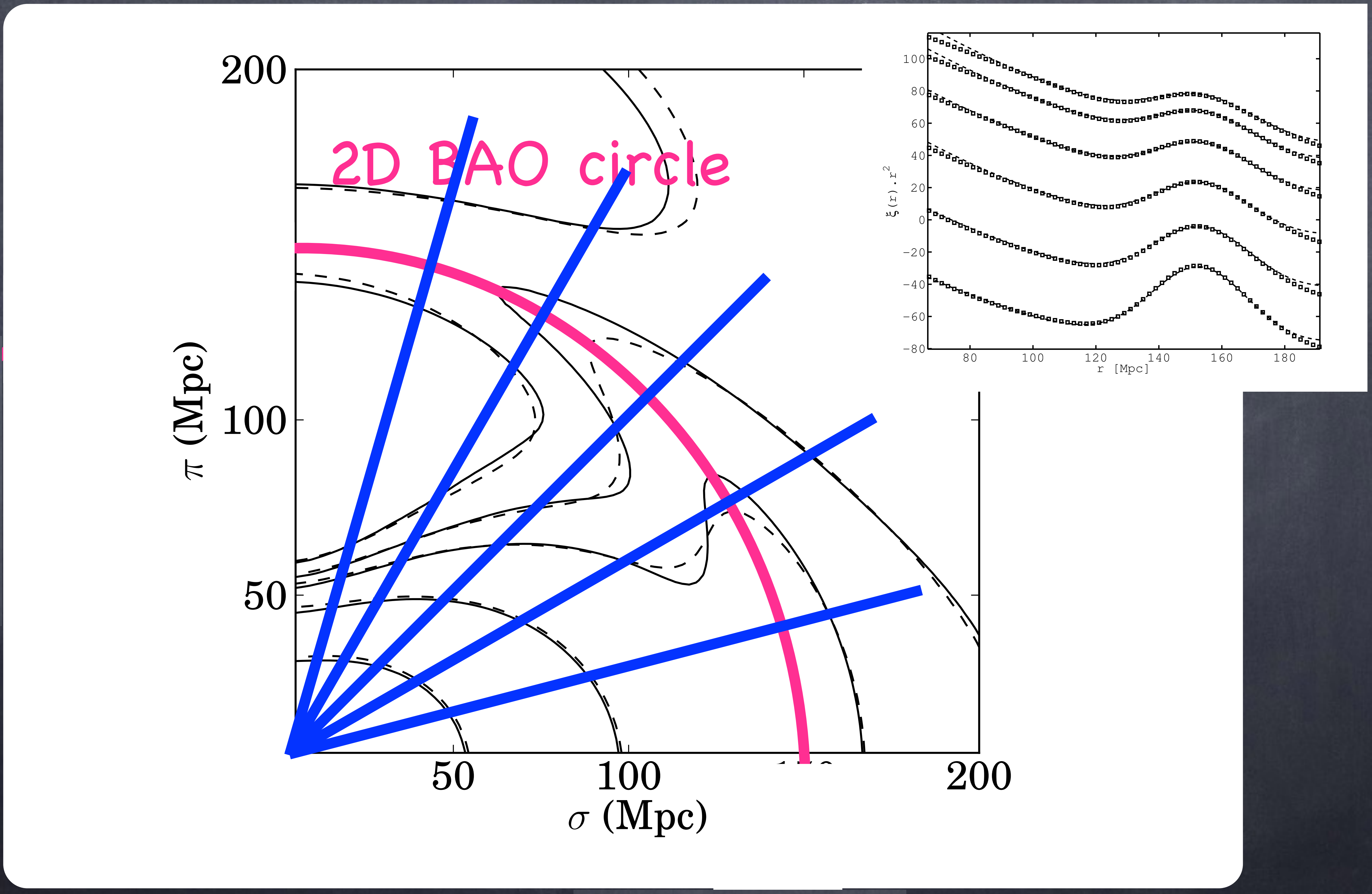
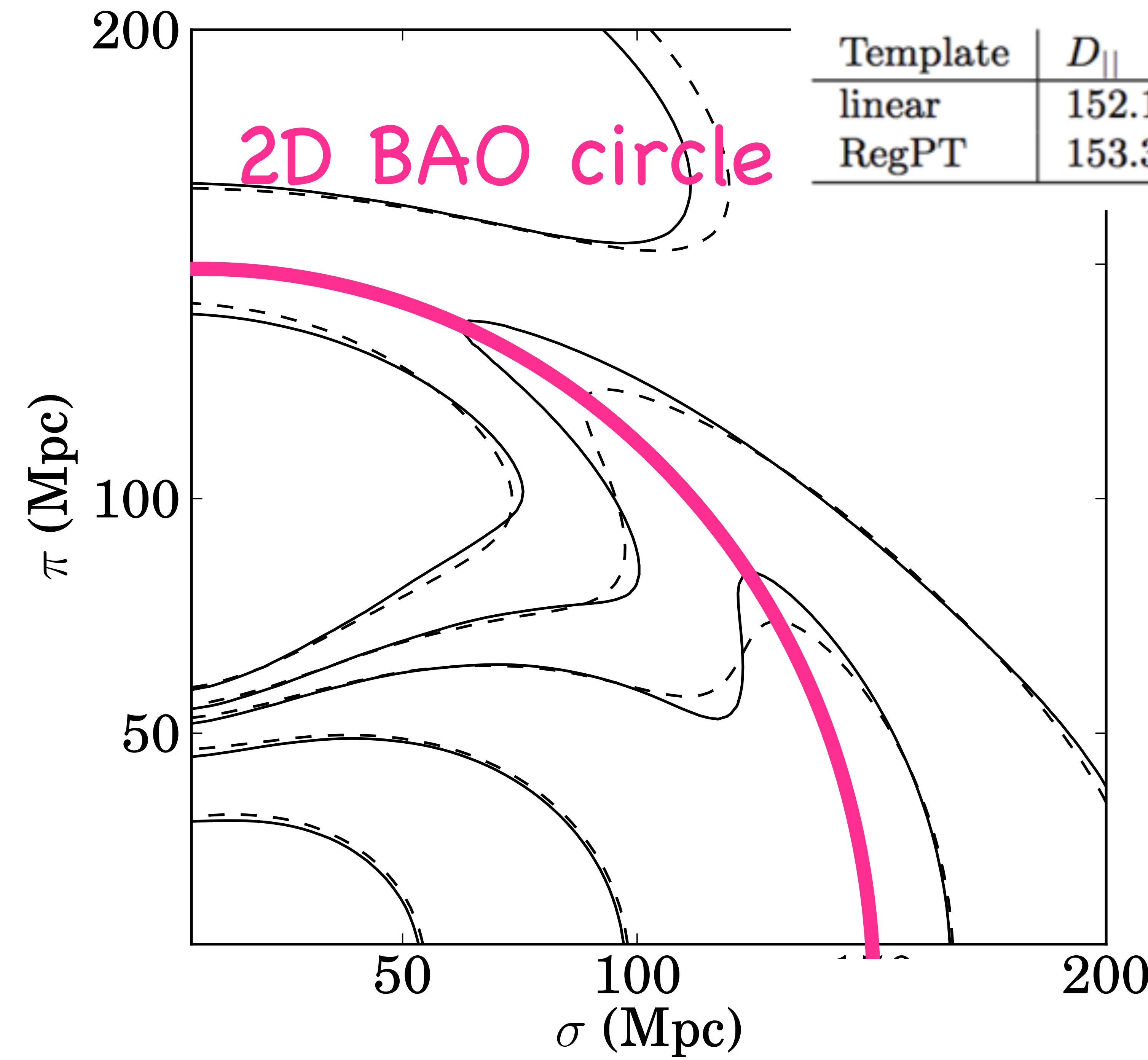


Systematic #1 - non-linearity

There is no much difference between 1 loop and 2 loop

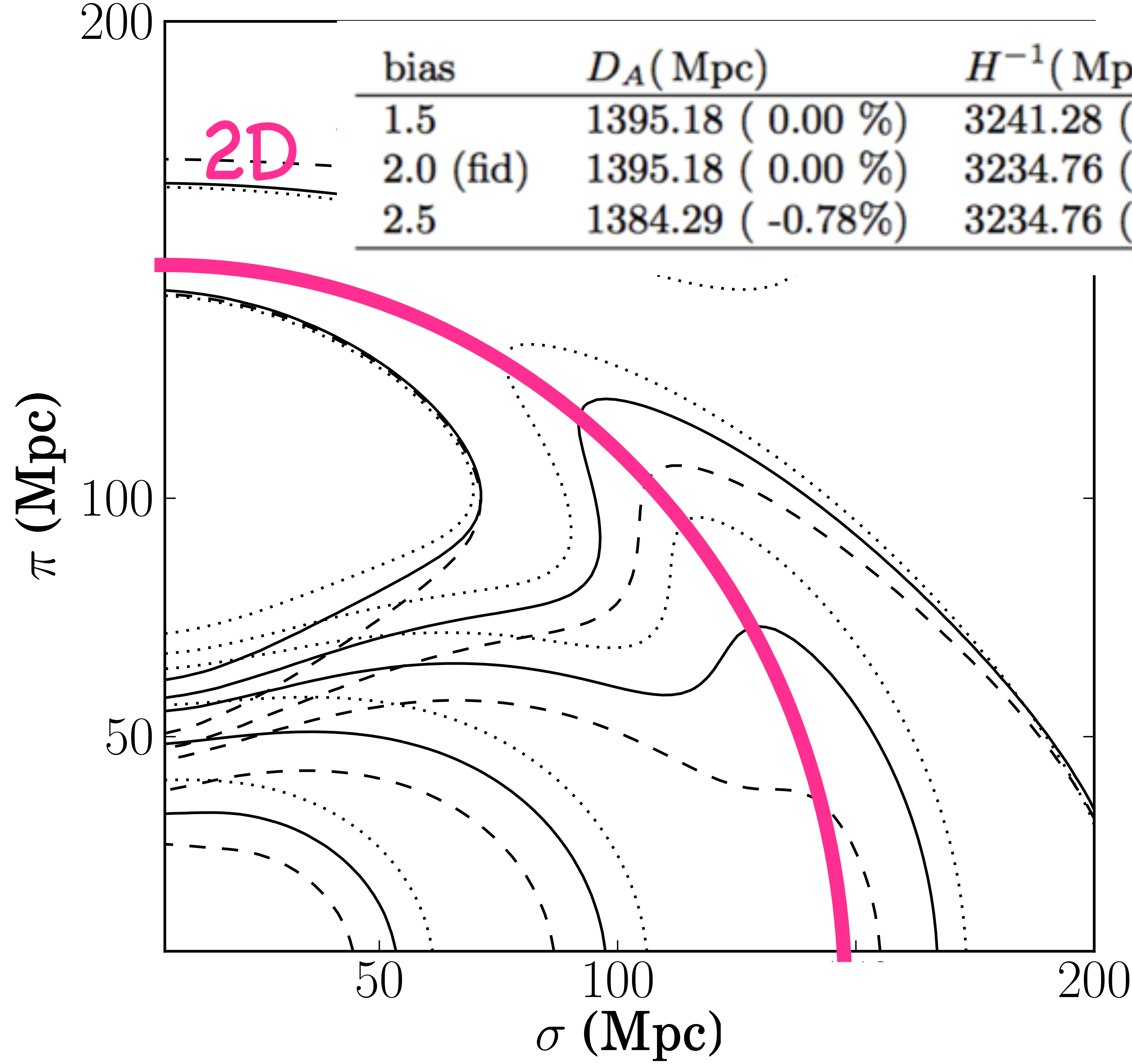


Template	$D_{\|\|}$	$D_{\perp}$
linear	152.12	153.33
RegPT	153.33	154.54

Systematic #2 - bias

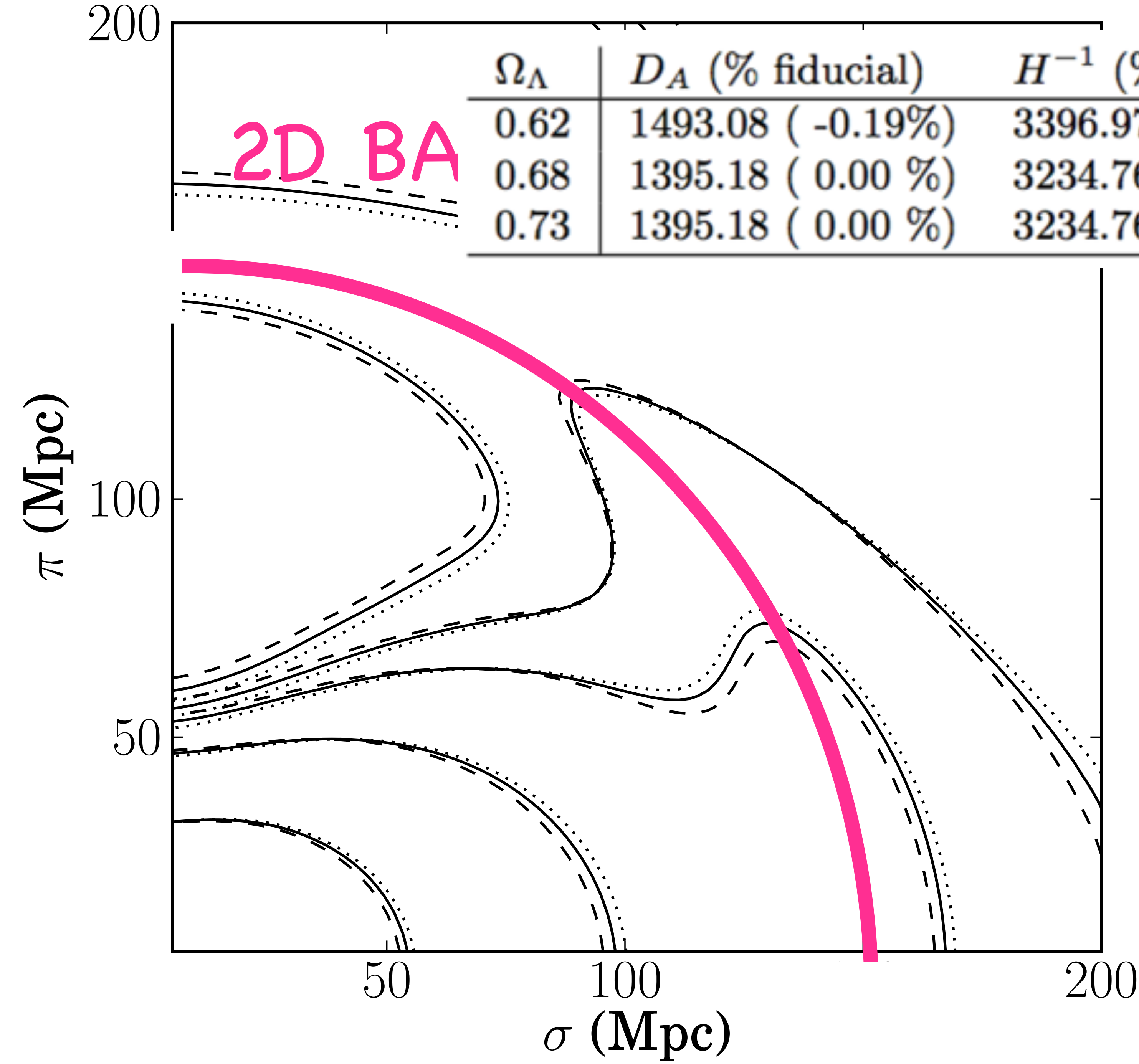
Little difference from scale dependent bias

bias	D_A(Mpc)	H^{-1}(Mpc)
1.5	1395.18 (0.00 %)	3241.28 (0.20%)
2.0 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
2.5	1384.29 (-0.78%)	3234.76 (0.00%)



Systematic #3 - wrong fiducial

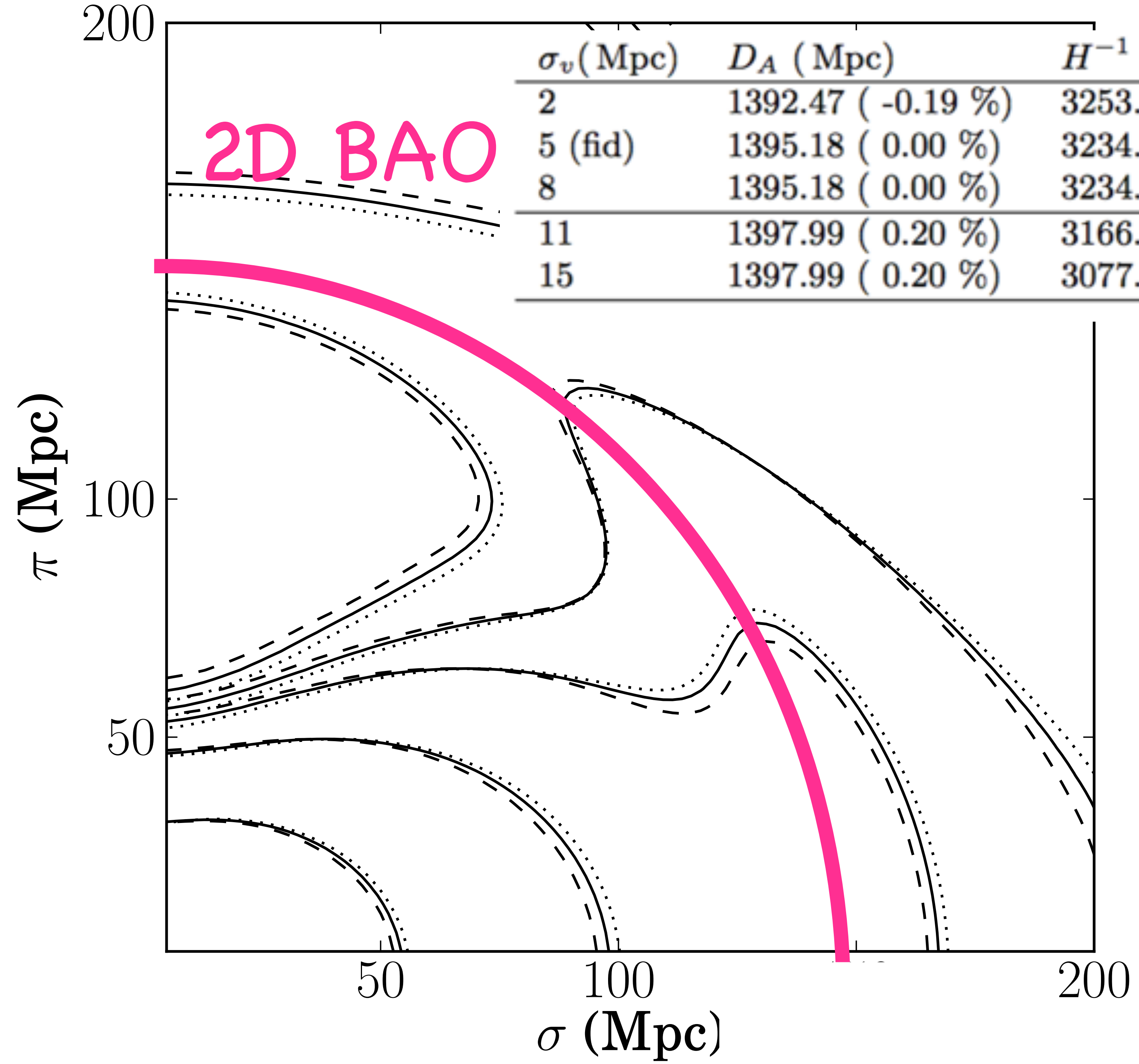
We assume that RA Dec is wrongly transformed



Ω_Λ	D_A (% fiducial)	H^{-1} (% fiducial)
0.62	1493.08 (-0.19%)	3396.97 (0.20%)
0.68	1395.18 (0.00 %)	3234.76 (0.00%)
0.73	1395.18 (0.00 %)	3234.76 (0.00%)

Systematic #4 - FoG

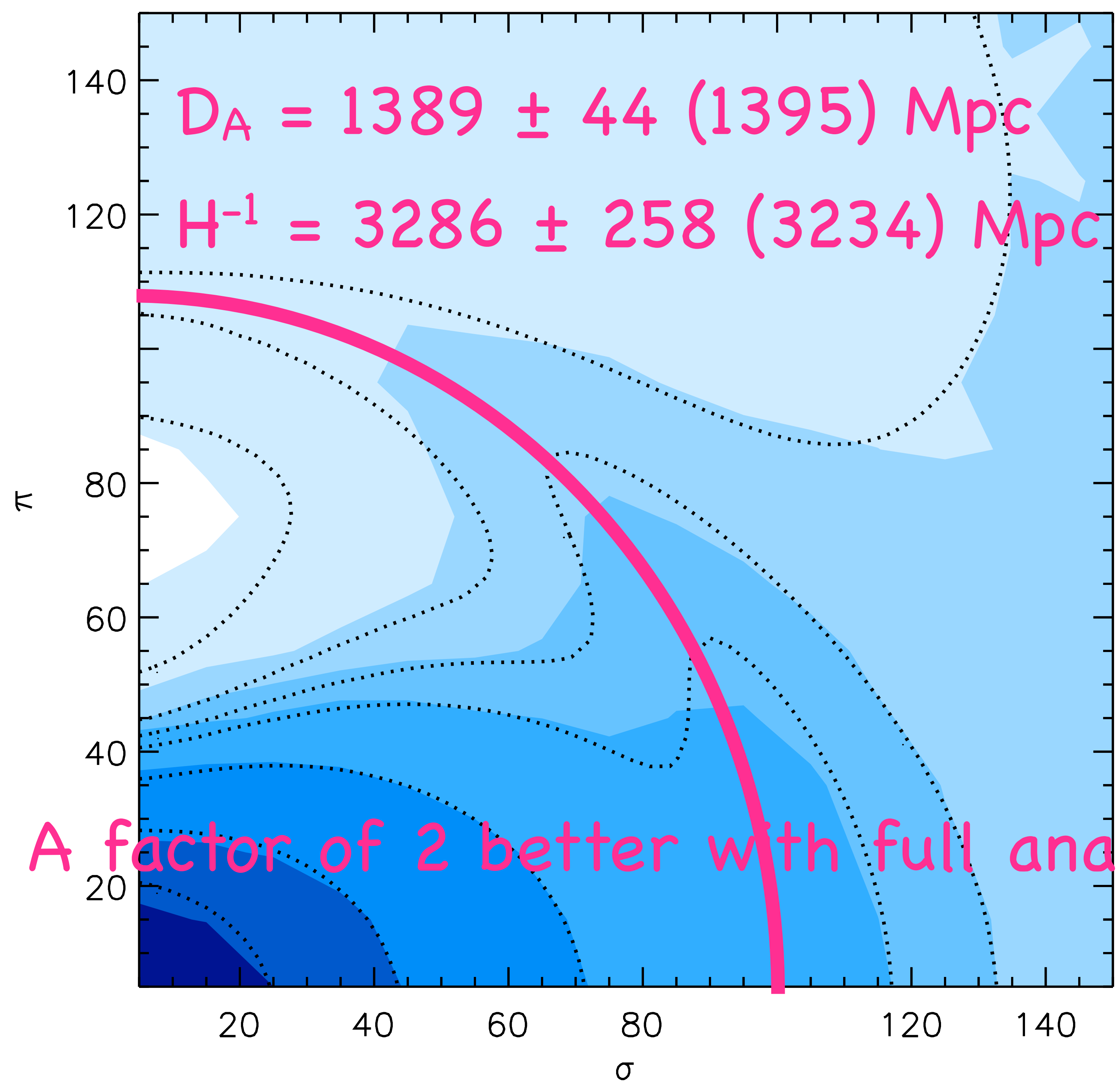
There might be subtle issue with unknown FoG



σ_v (Mpc)	D_A (Mpc)	H^{-1} (Mpc)
2	1392.47 (-0.19 %)	3253.96 (0.59%)
5 (fid)	1395.18 (0.00 %)	3234.76 (0.00 %)
8	1395.18 (0.00 %)	3234.76 (0.00 %)
11	1397.99 (0.20 %)	3166.40 (-2.11%)
15	1397.99 (0.20 %)	3077.53 (-4.86%)

Application for BOSS mock

We compare the result with full RSD analysis



D_A = 1389 ± 44 (1395) Mpc

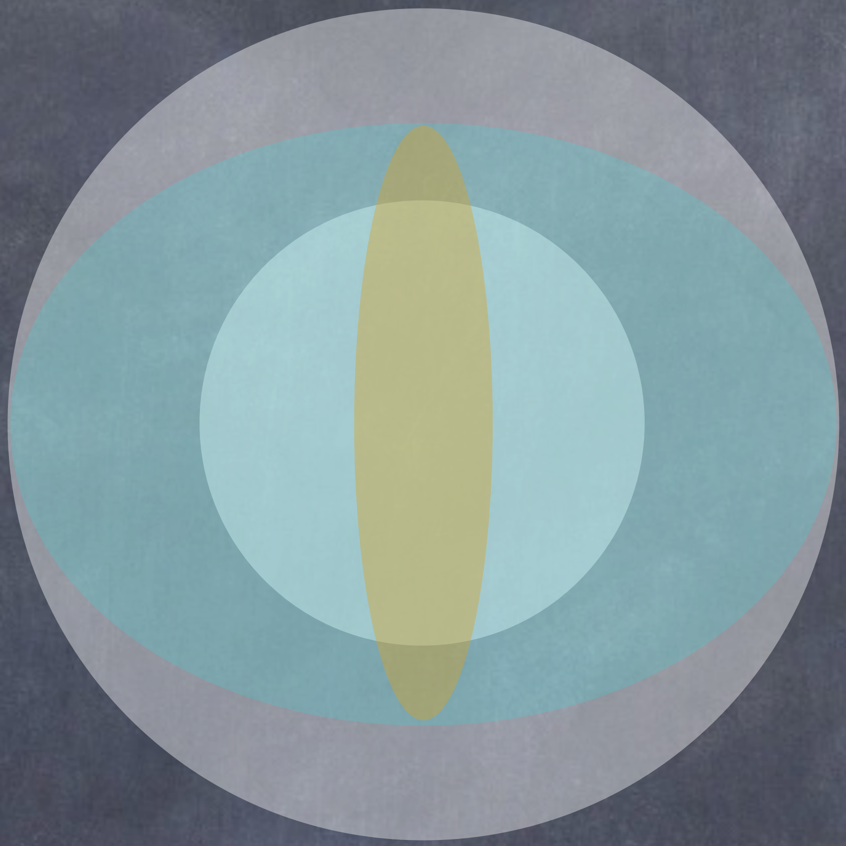
H^{-1} = 3286 ± 258 (3234) Mpc

A factor of 2 better with full analysis

Redshift Space Distortion

Squeezing effect at large scales

(Kaiser 1987)



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Separable non-perturbative effect

The RSD spectrum is fully expressed as,

$$P_s(k,\mu) = \int d^3x\ e^{ikx} \langle e^{j1\ A1}\ A_2 A_3 \rangle$$

$$j_1 = -ik\mu f,\ A_1 = u_z(r) - u_z(r'),\ A_2 = \delta(r) + f\nabla_z u_z(r),\ A_3 = \delta(r') + f\nabla_z u_z(r')$$

It can be rearranged as,

$$P_s(k,\mu) = \int d^3x\ e^{ikx} \exp\{\langle e^{j1\ A1} \rangle_c\}\ [\langle e^{j1\ A1}\ A_2 A_3 \rangle_c + \langle e^{j1\ A1}\ A_2 \rangle_c \langle e^{j1\ A1}\ A_3 \rangle_c]$$

The ensemble averages over the quantities A_2 and A_3 responsible for the Kaiser effect all includes the exponential factor, which can produce a non negligible correlation between density and velocity.

The factor of $\exp\{\langle e^{j1\ A1} \rangle_c\}$ is most likely affected by the virialized random motion of the mass around halos, and seems difficult to treat it perturbatively. ⟶ See the detailed test at Yi's talk

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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)

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

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

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

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

LSS of f(R) gravity

Dynamic equations of perturbations

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

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

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

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

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

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

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

Later time growth functions are given by,

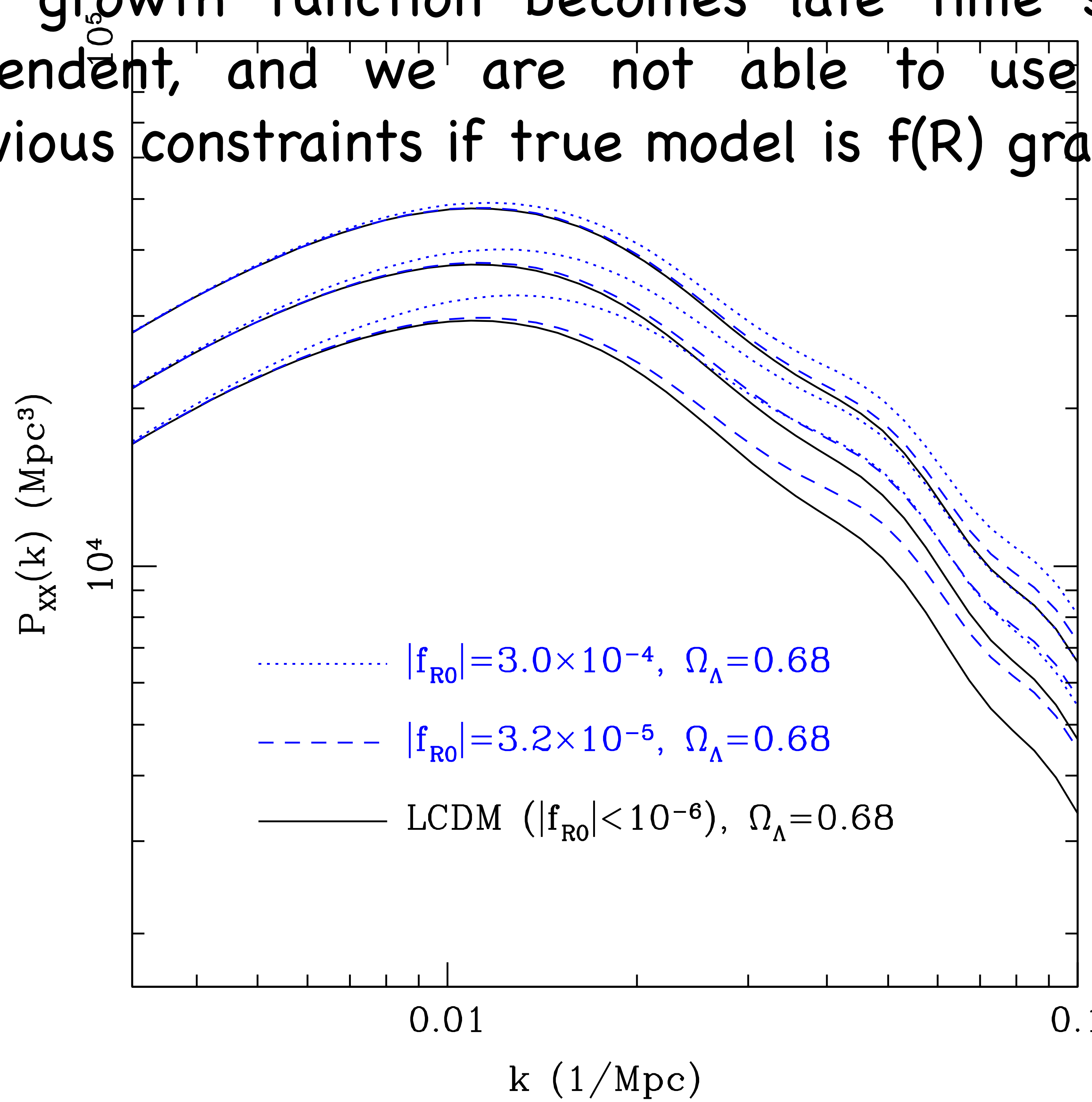
$$D^\delta(k,t) = G_\delta(t)\, F_\delta(k,t;M_1)$$

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

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



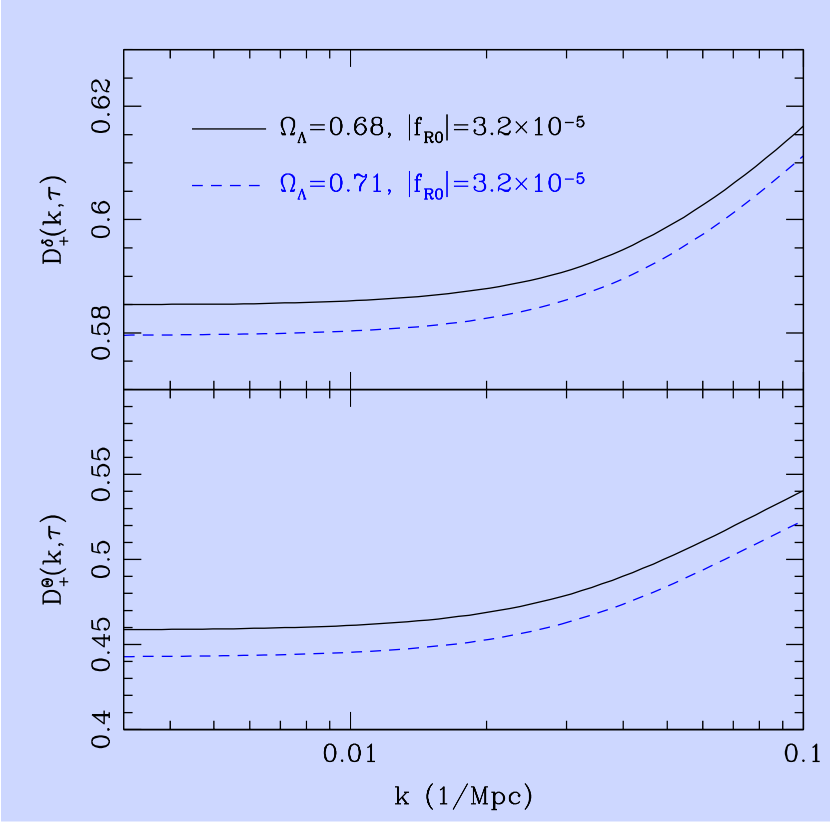
Parameterisation of f(R) gravity model

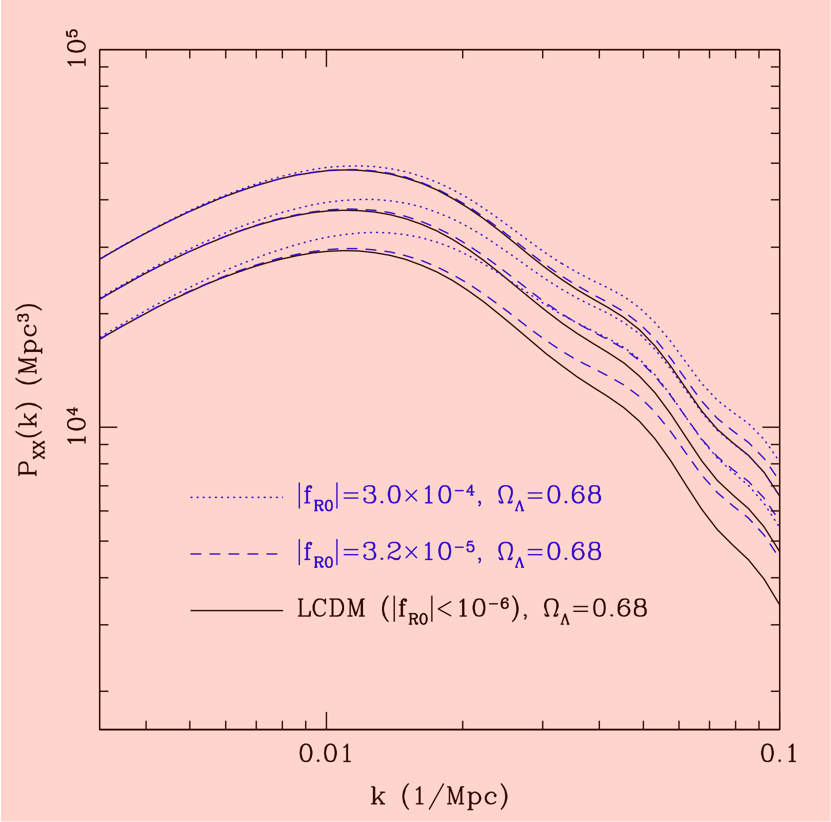
$$f(R) = -2\,\kappa^2\rho_\Lambda + |f_{R0}|\,R_0^2/R^2$$

Parameter space is (D_A, H^{-1}, G_δ, G_Θ, FoG, $|f_{R0}|$)

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

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

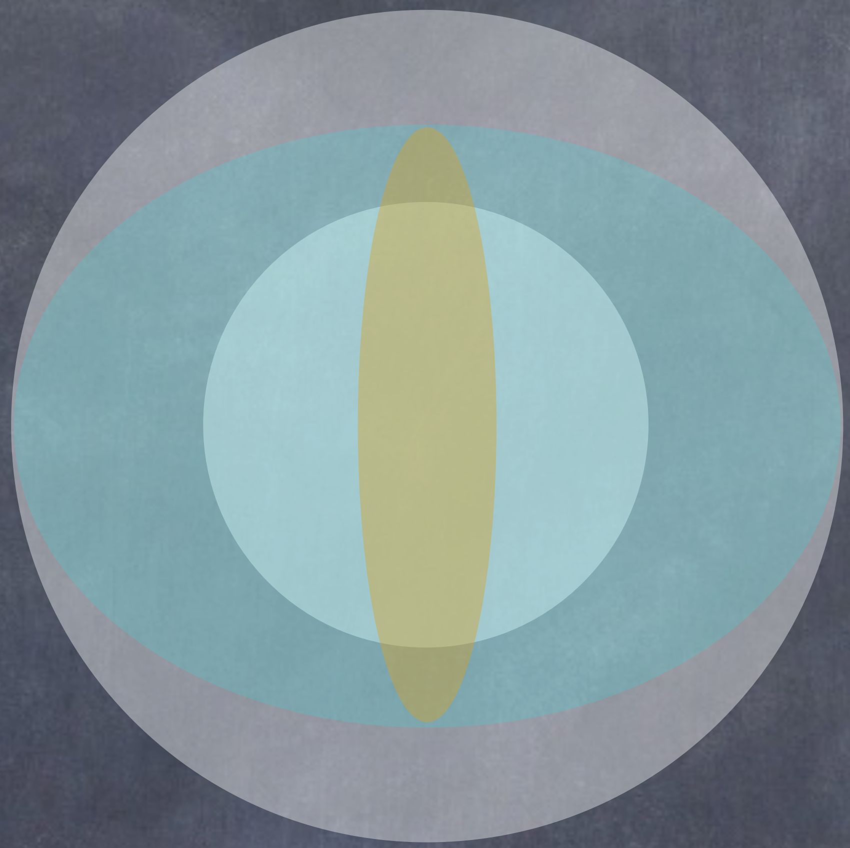




Structure formation of RSD

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

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

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

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

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

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

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

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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 higher order polynomials are given by,

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

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

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

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

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

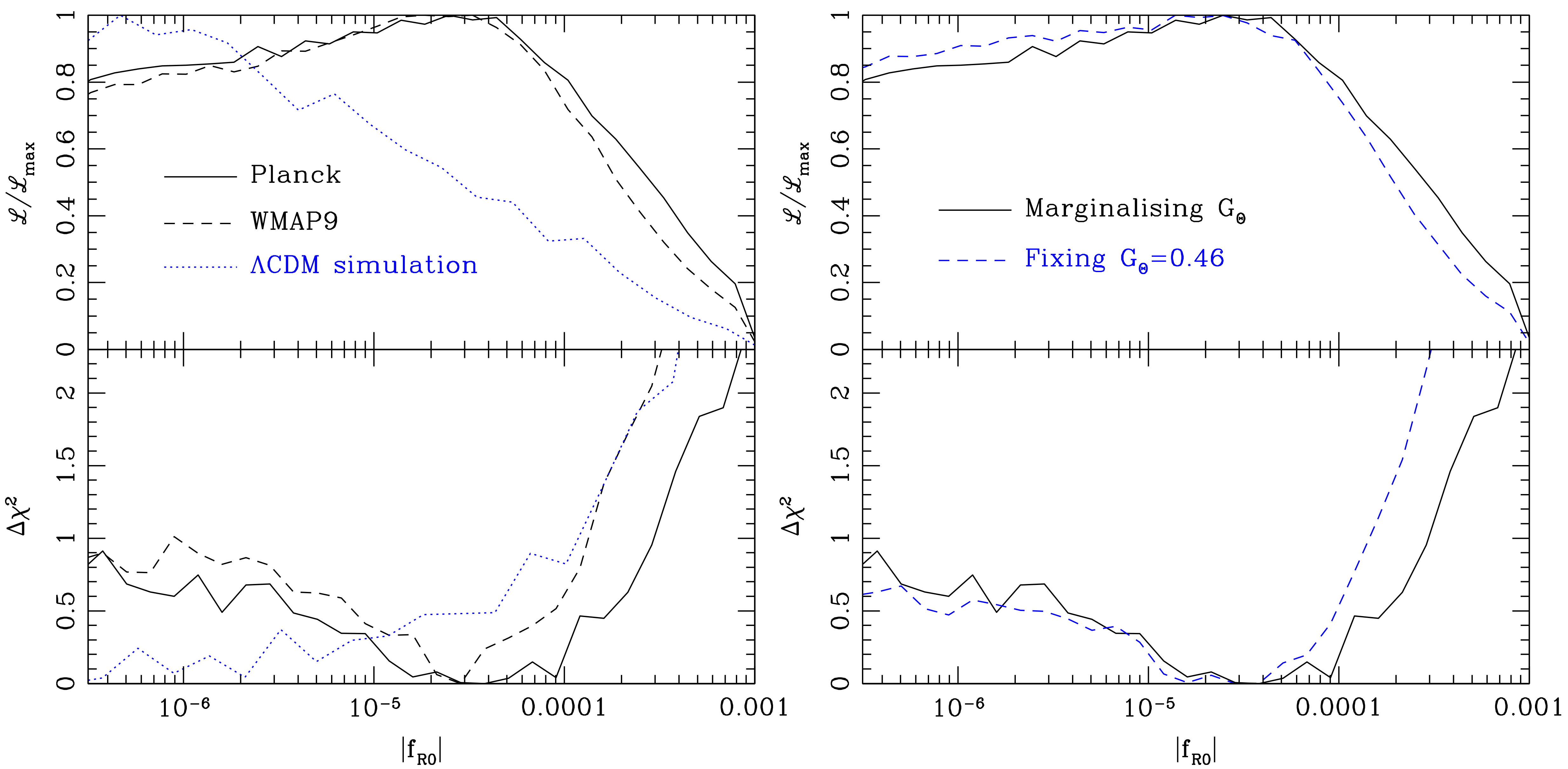
↓

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

Constraints on f(R) gravity model

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

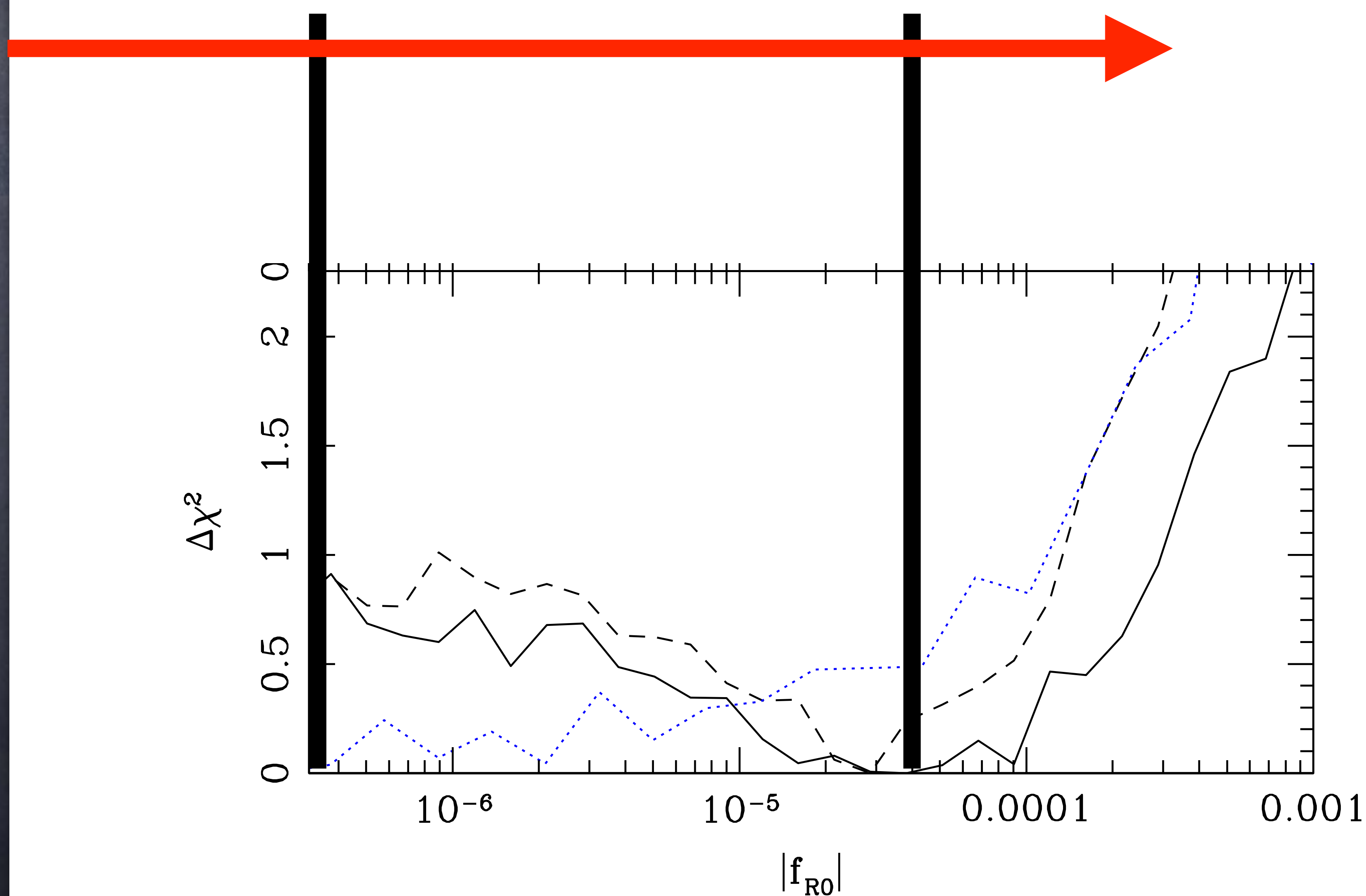
$|f_{R0}| < 8\times10^{-4}$ at 95% confidence limit



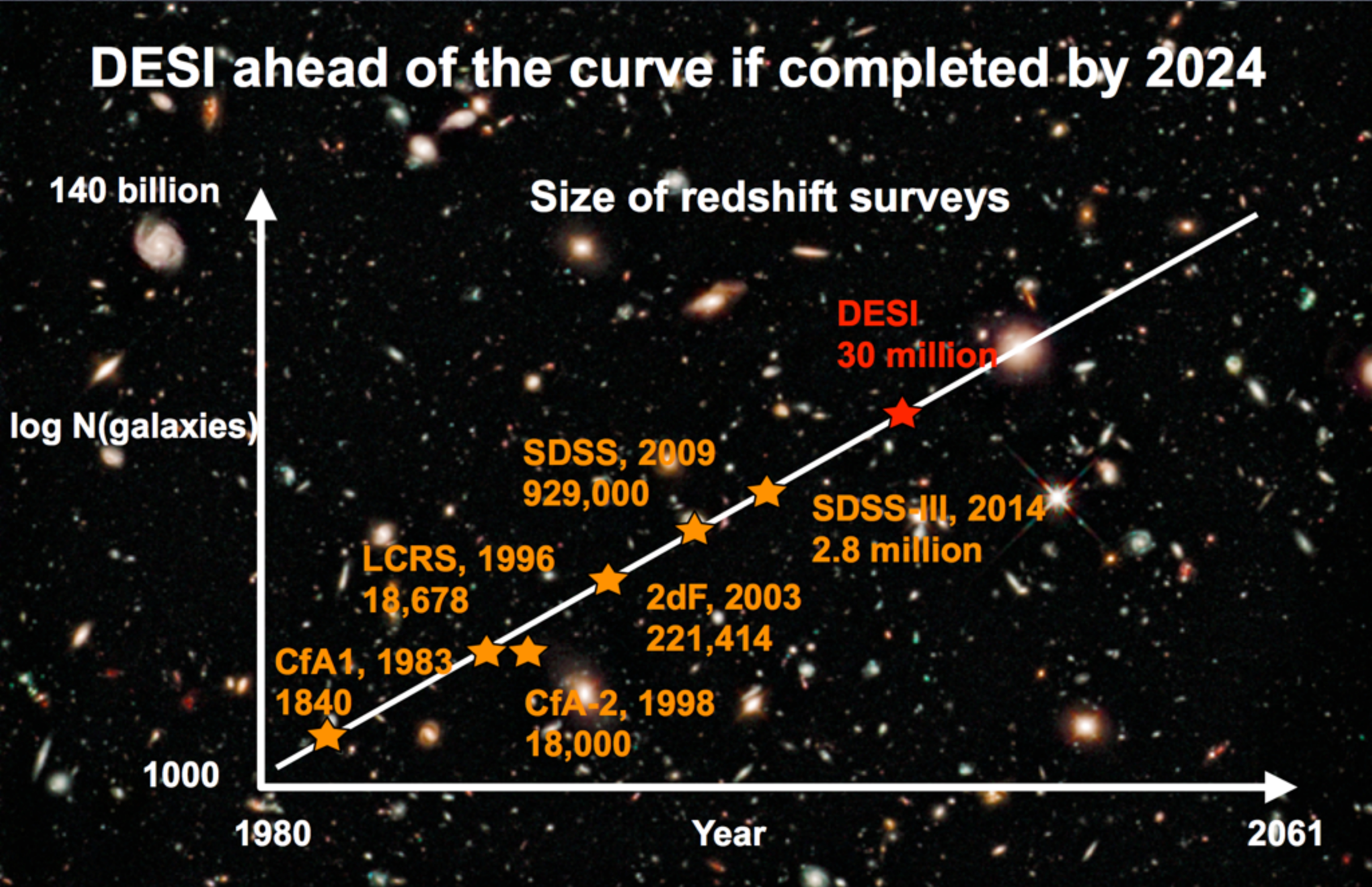
Constraints on f(R) now and future

Invisible difference from LCDM model using BOSS

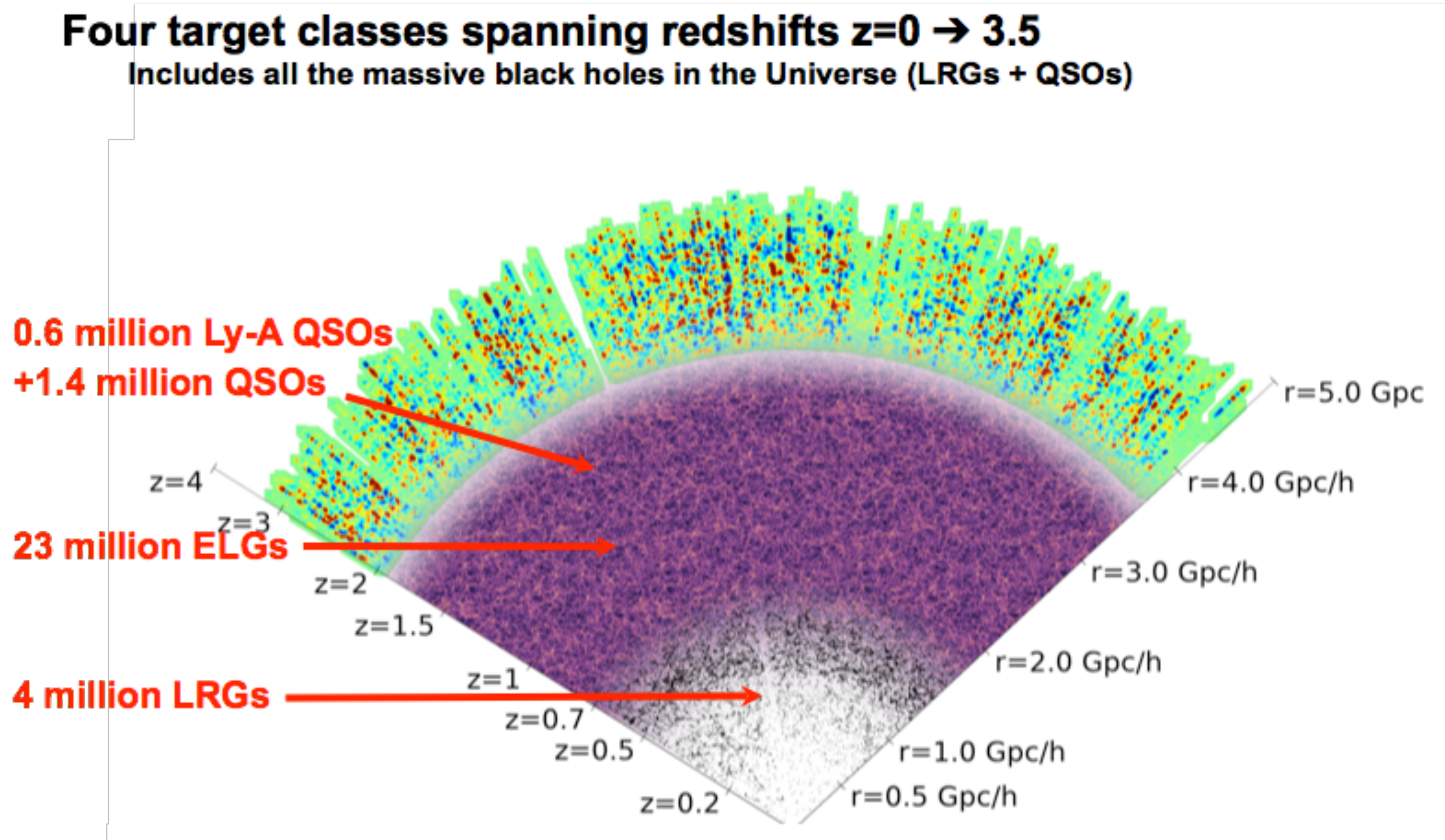
Need a factor of 10 improvement



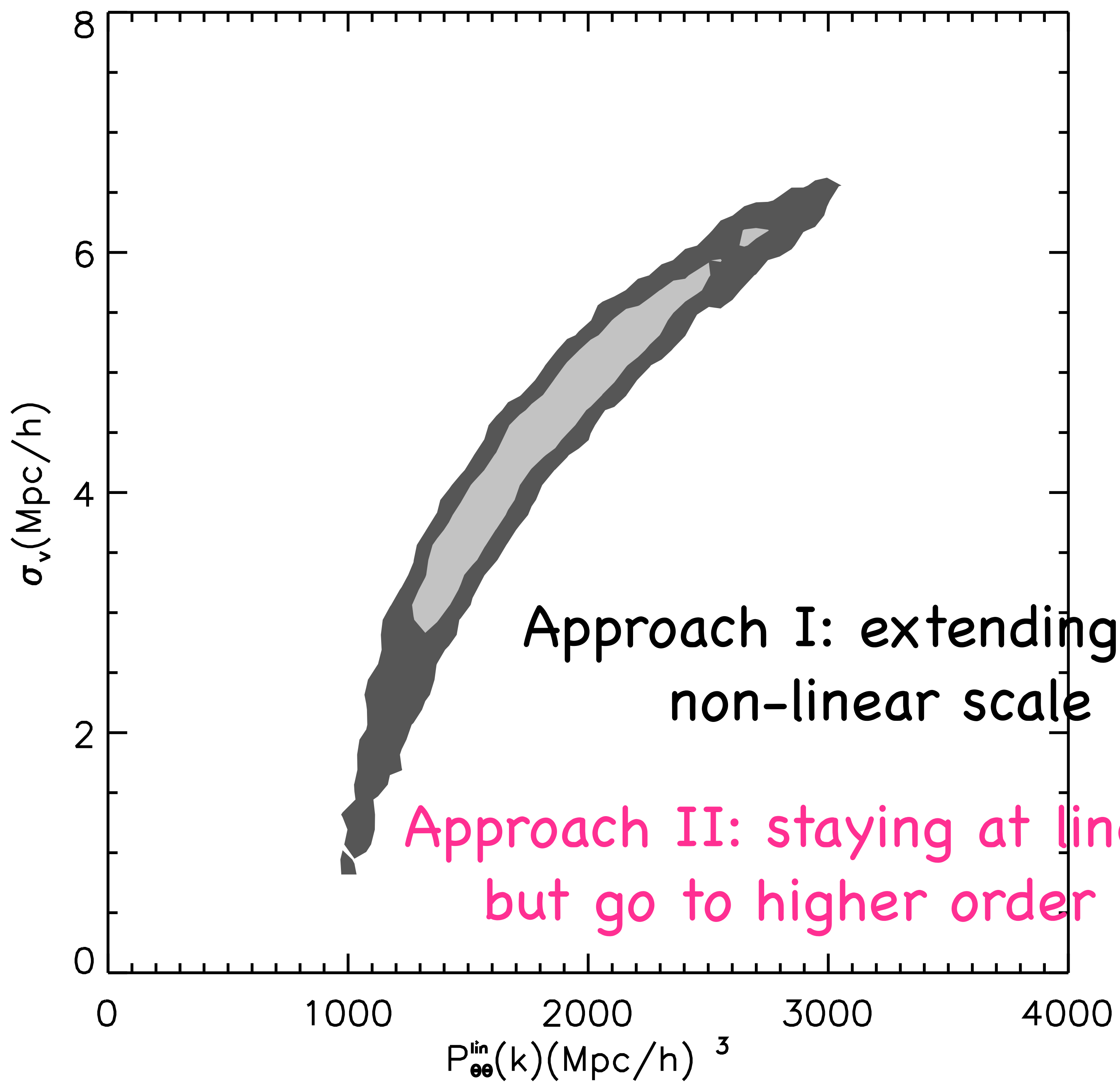
Where we are, and where will we go?



The targeted galaxies in next generation



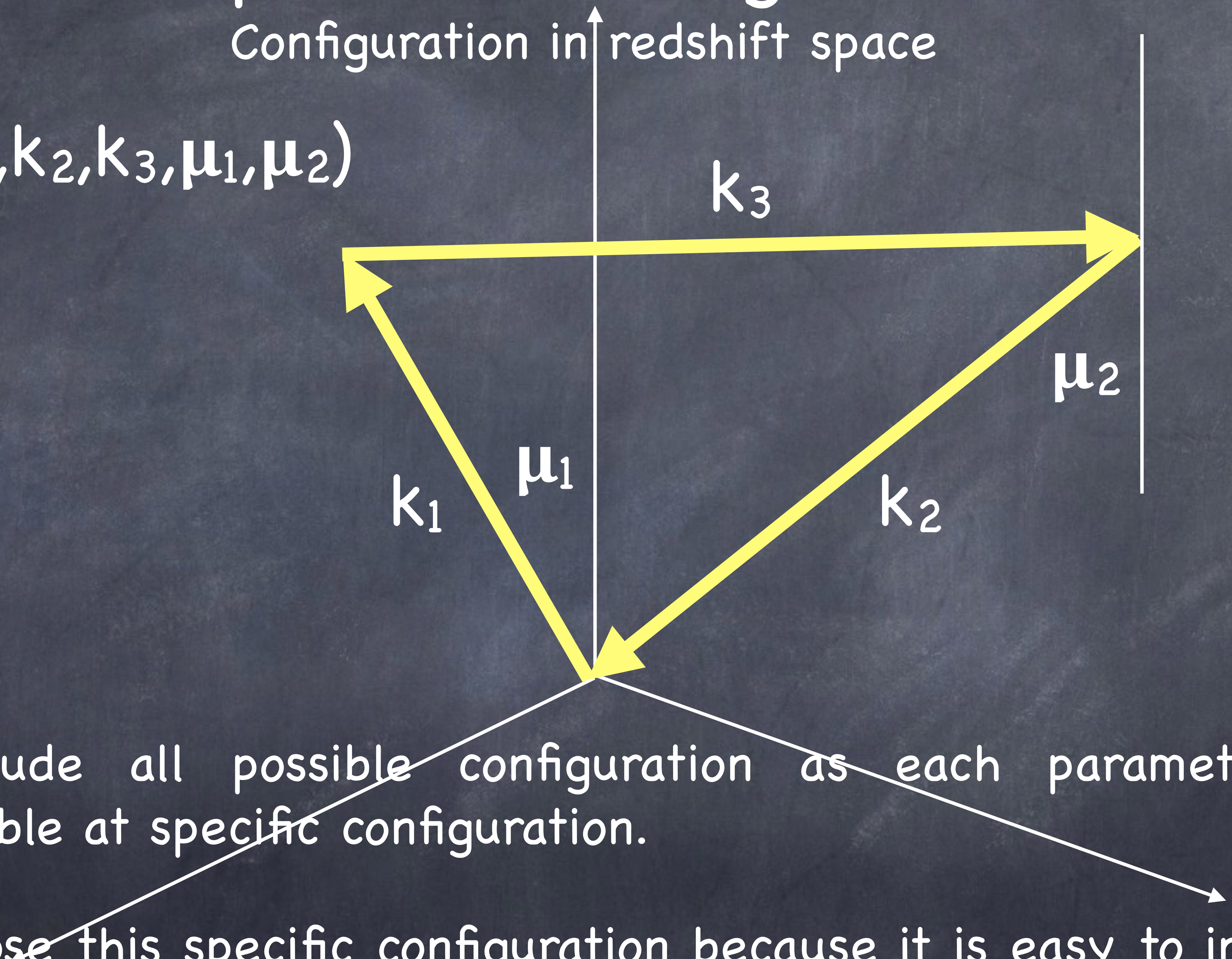
Degeneracy for coherent motions



Approach I: extending into non-linear scale

Approach II: staying at linear scale but go to higher order points

Bispectrum configuration



We include all possible configuration as each parameter is extractable at specific configuration.

We choose this specific configuration because it is easy to include FoG effect and to handle AP projection.

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The assumption on FoG effect

In contrast to the redshift space power spectrum, the influence of nonlinear RSD on bispectrum is not yet fully understood and studied in detail. Although it deserves further investigation, we can make the best guess on the possible damping effect due to the random motion of galaxy. The FoG effect in the bispectrum is assumed to be Gaussian as,

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

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

YSS, Taruya, Oka 2015

Bispectrum in redshift space

While the initial condition for perturbations is assumed to be Gaussian, gravitational evolution naturally induces mode-mode coupling, giving rise to the non vanishing bispectrum. We are able to write it in full redshift space form as,

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

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

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

$$Z_2(k_1,k_2) = b_2/2 + bF_2 + f\mu_{12}G_2 + fk_{12}\mu_{12}/2[\mu_1/k_1Z_2(k_2)+\mu_1/k_1Z_2(k_2)]$$

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Bispectrum Alcock-Paczynski effect

The observed galaxy clustering also exhibits anisotropies through the AP effect. This can happen if the background expansion of the real universe differs from fiducial cosmology used to convert the redshift and angular position to comoving coordinates, given by,

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

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

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

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

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

YSS, Taruya, Oka 2015

Forecast based upon full covariance approach

Fisher matrix is given by

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

where the vector field S is given by

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

The full covariance matrix is given by, $M = (C_{pp} - C_{PB} C_{BB}^{-1} C_{BP})^{-1}$

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

This full covariance calculation is performed for DESI forecast.

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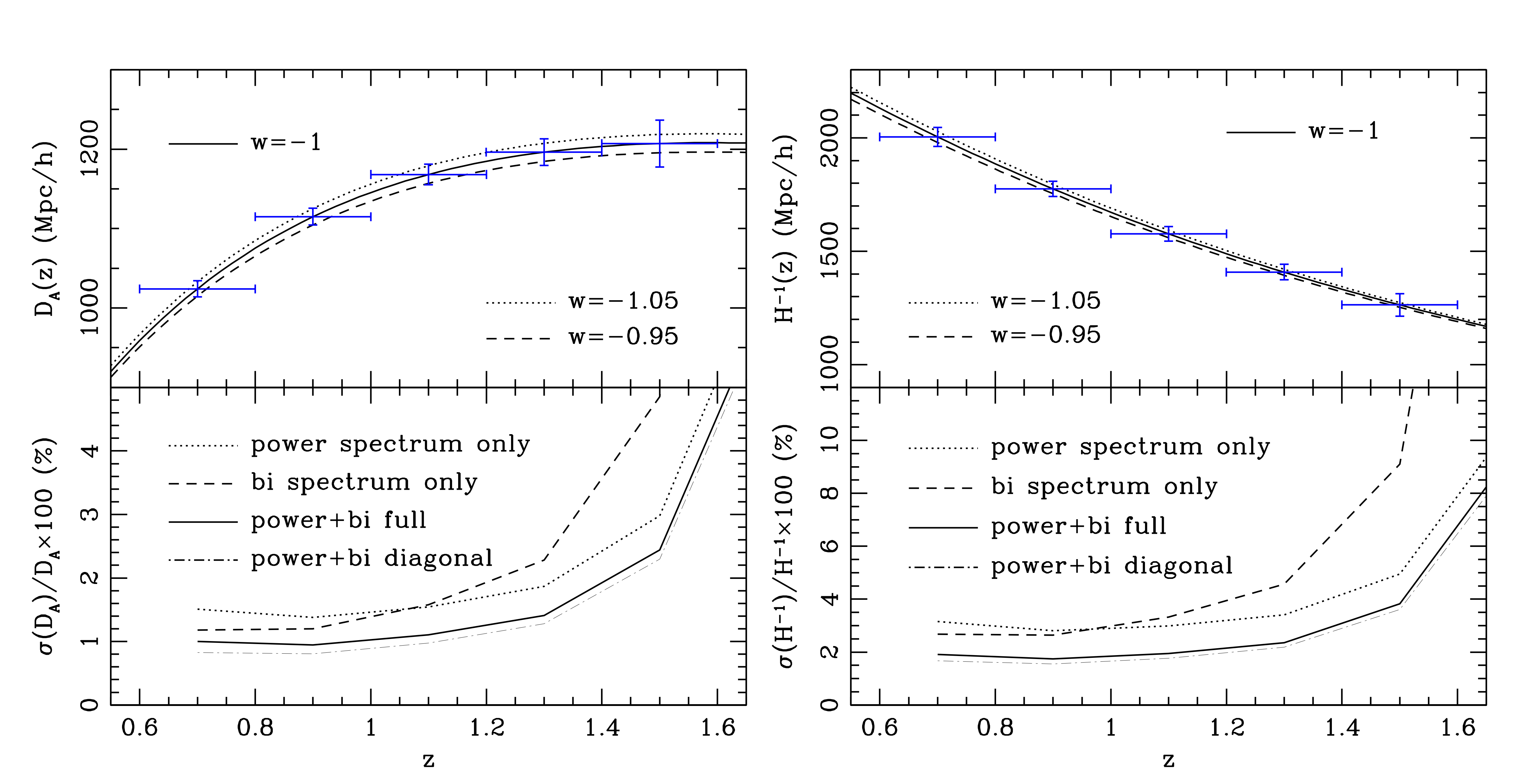
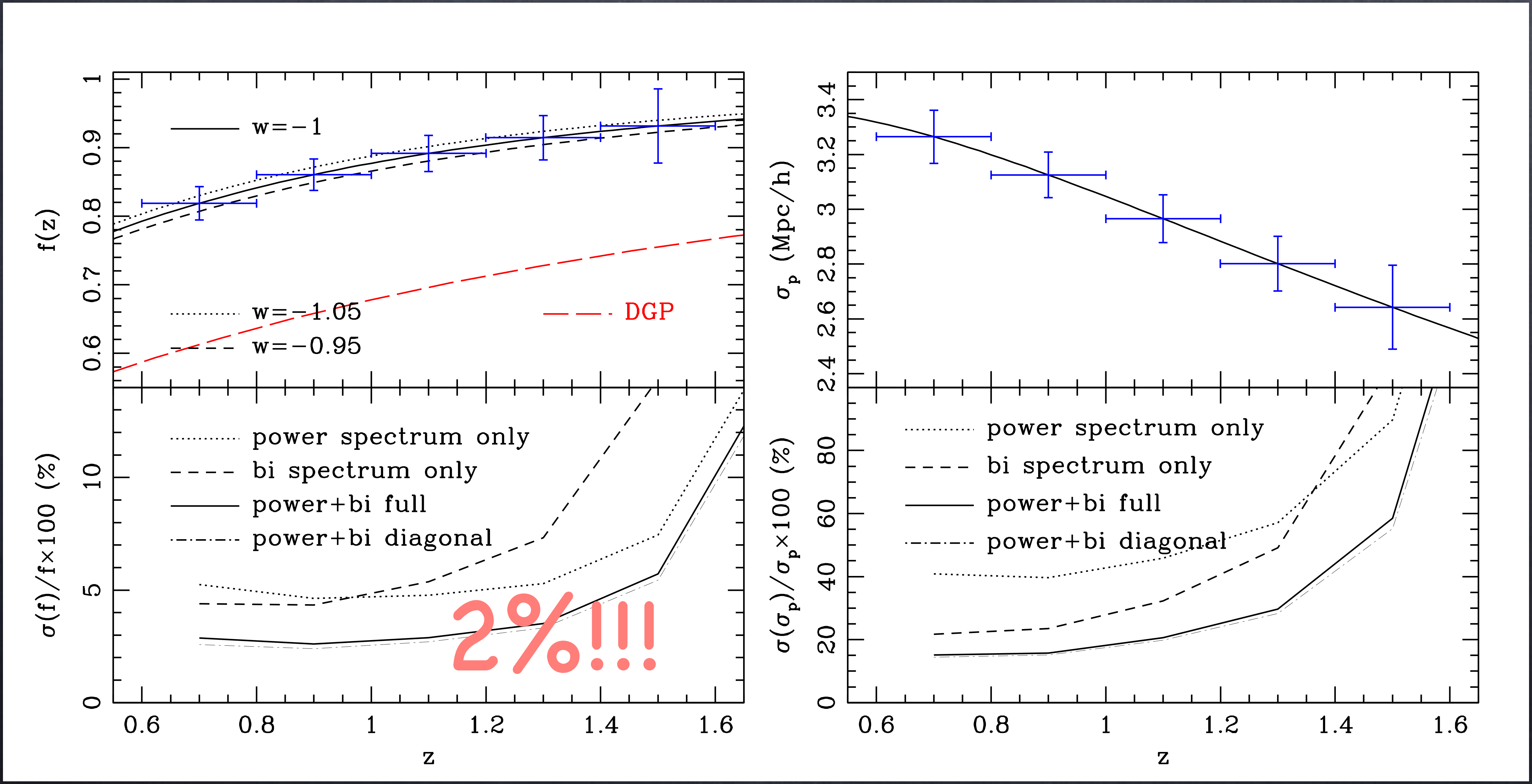
Forecast on distances

The precision levels for D_A and H^{-1} are improved by 1% and 2% respectively. In particular, constraint on H^{-1} is improved by a factor of 2 by the combination

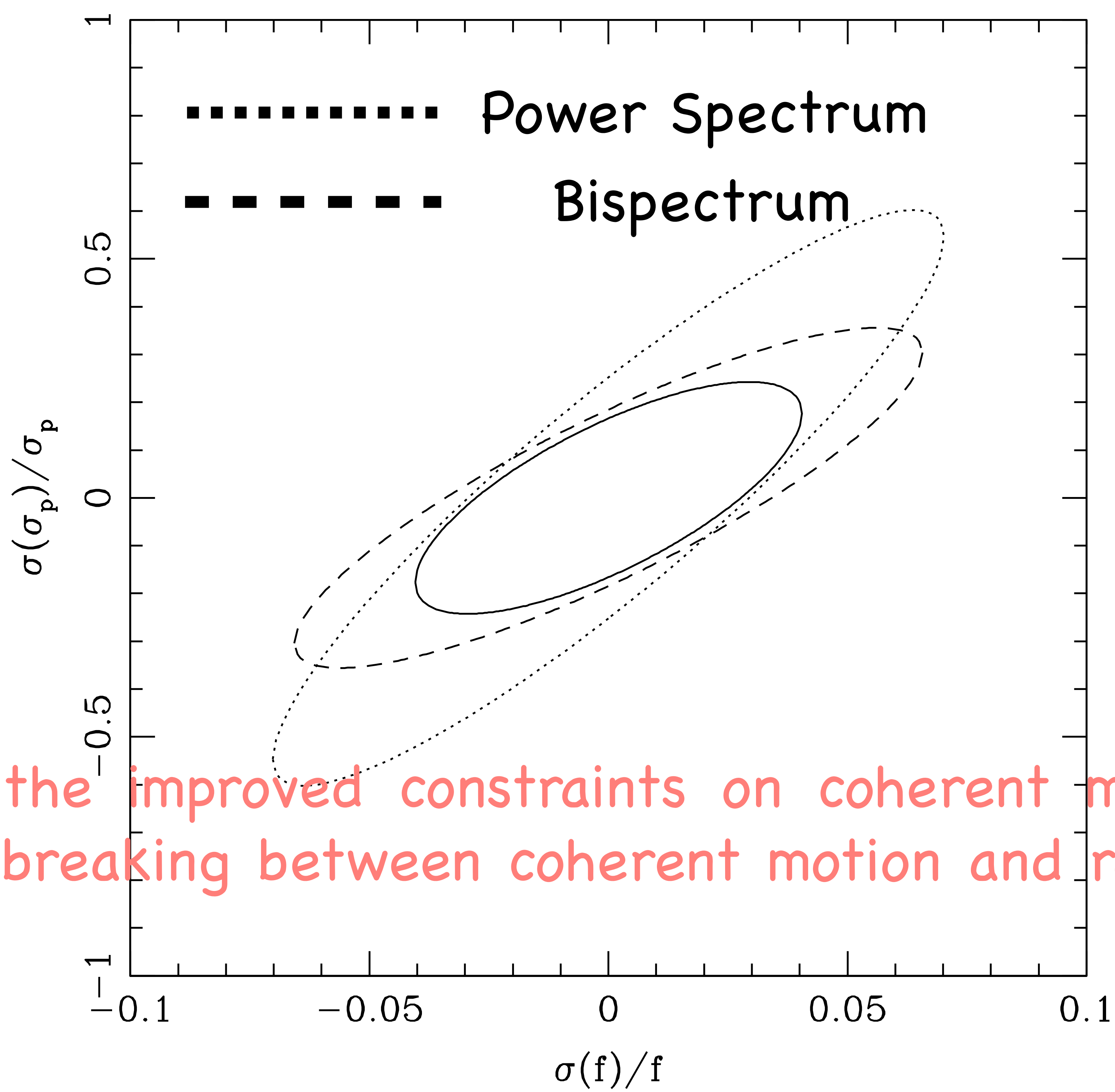


Forecast on coherent motion

Constraints on coherent motion is significantly improved by the combination. In particular, the improvement is significant at redshift z<1 due to high galaxy density.



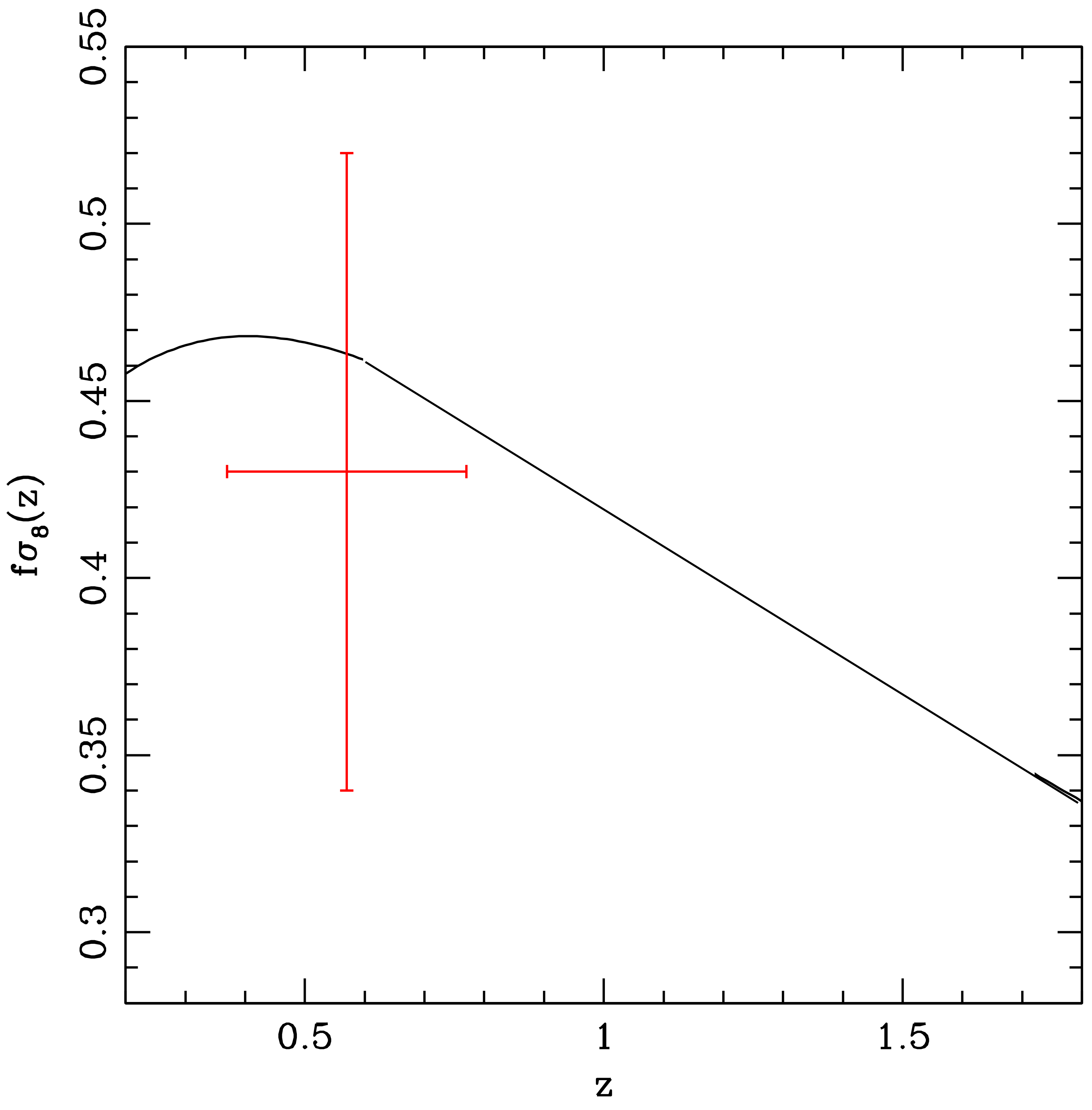
Degeneracy in coherent and random motions



We reason the improved constraints on coherent motion by the degeneracy breaking between coherent motion and random motion effects.

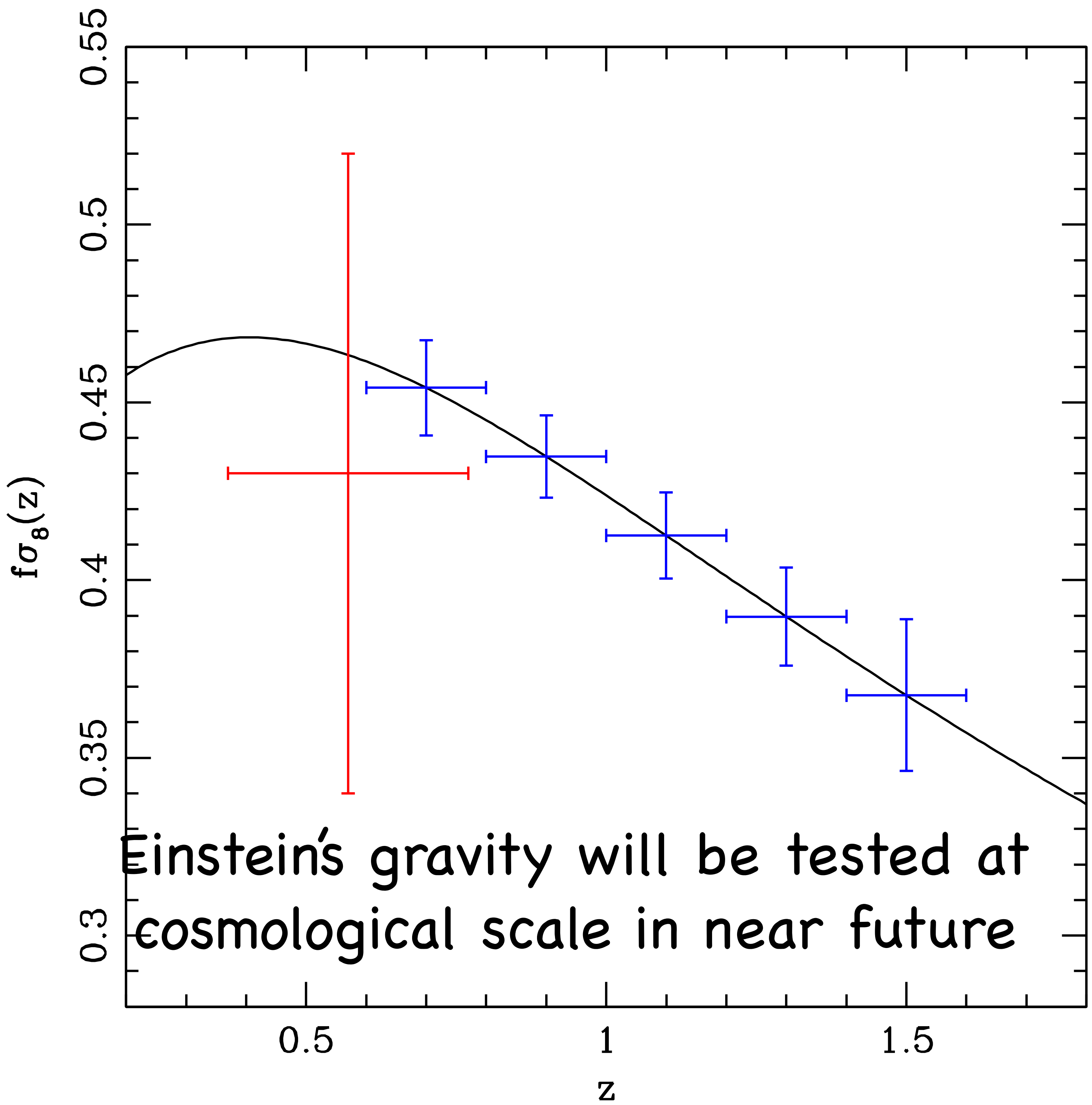
Measured coherent motion

Results from BOSS maps



Future constraints

Expectation from DESI

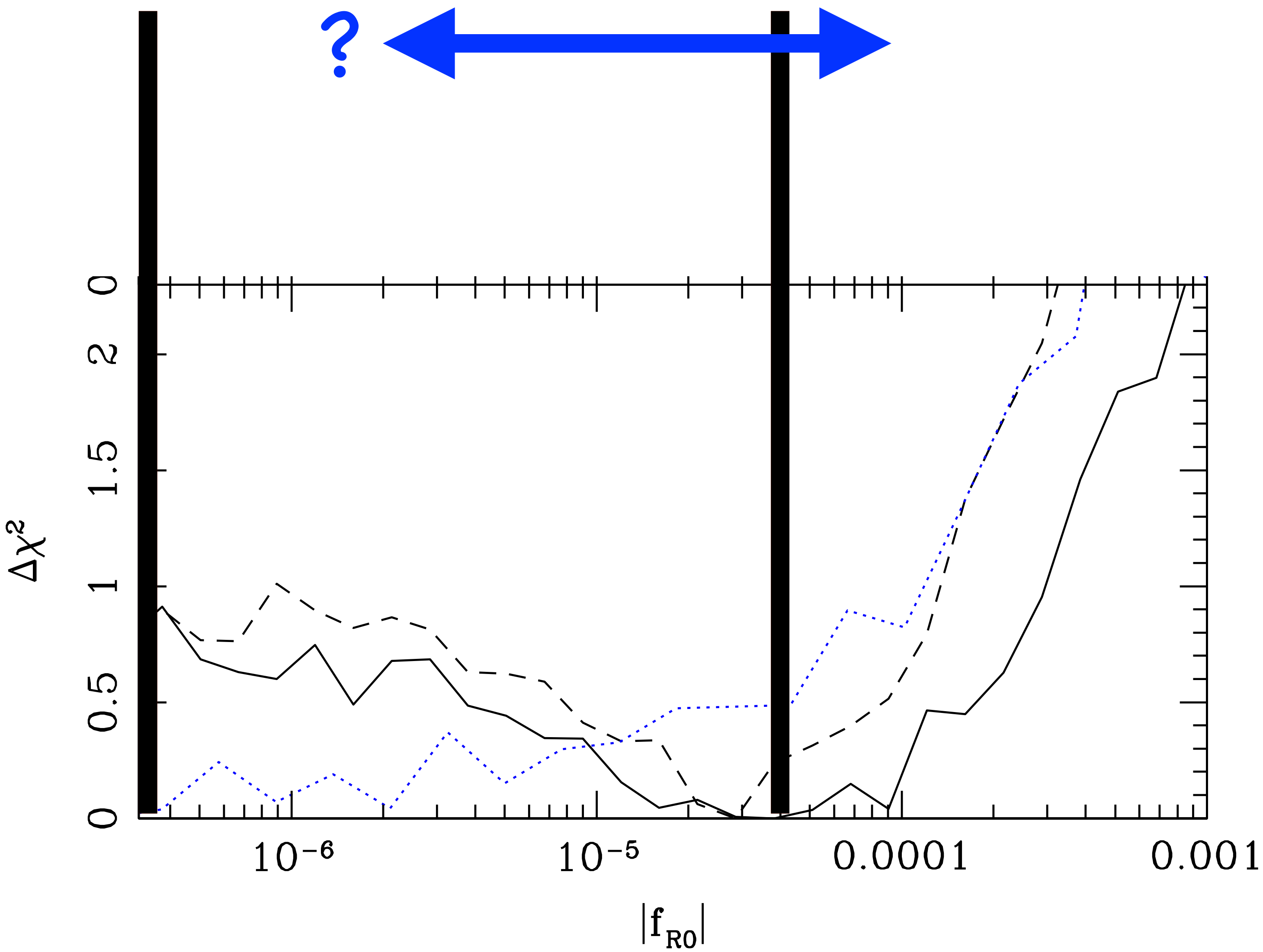


Einstein's gravity will be tested at cosmological scale in near future

Can we probe deviation from GR?

Invisible difference from LCDM model using BOSS

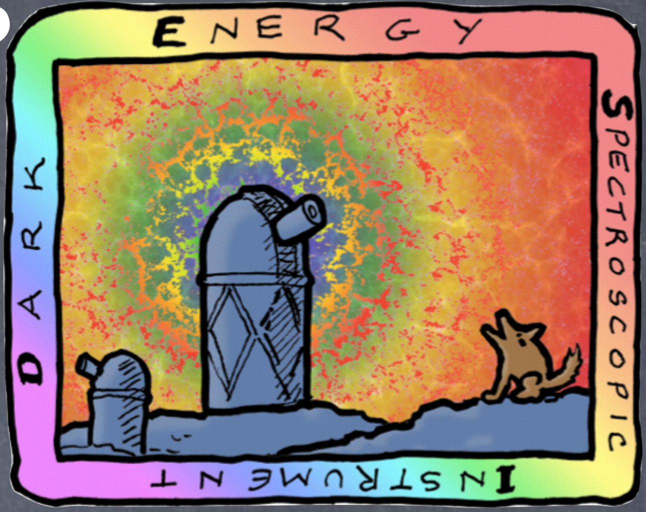
then can we tell the difference in future?



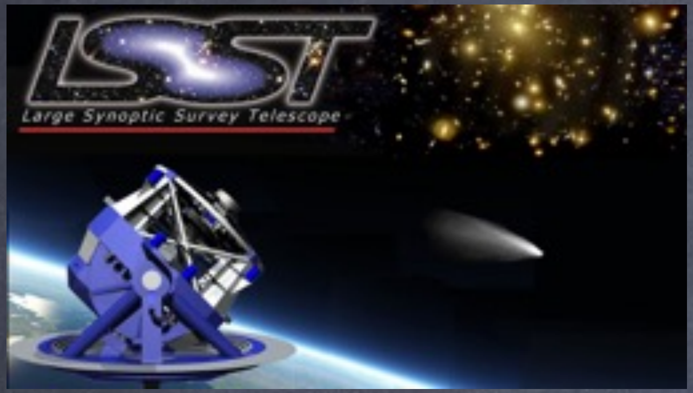
Cosmology group at KASI

Cosmology group at KASI initiates in 2014 under the project of "Research on Galaxy and Universe", and promoted to "FMRG" project in 2015 which award 9 years fund to develop the group by 2023.

Participating Projects

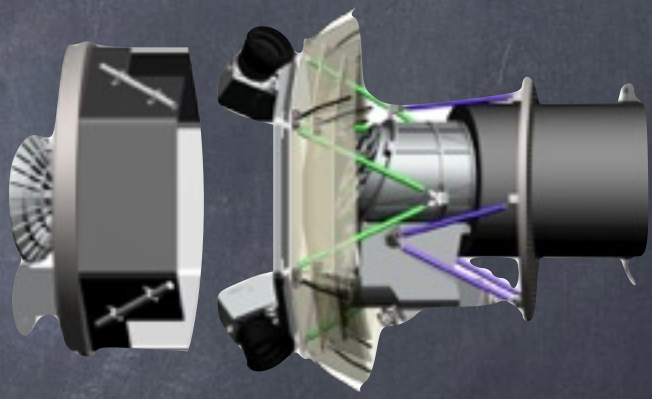


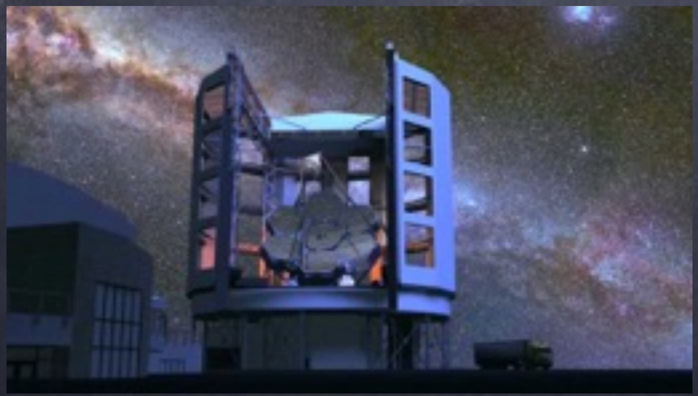
CosKASI is institutional member of DESI, the stage IV wide deep field spectroscopy survey



Two faculties at CosKASI are members of LSST, and joining Dark Energy working group

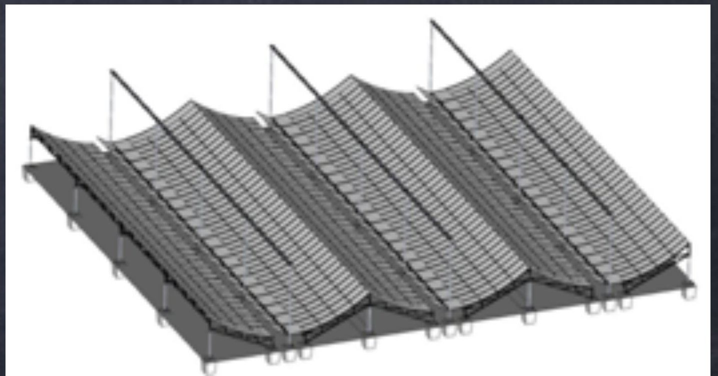
JPL and KASI submitted the SPHEREx project to NASA SMEX program





KASI is a key institutional member of GMT, 20m Giant Magellan Telescope

CosKASI is joining 21cm experiment of Tianlai organised by NAOC



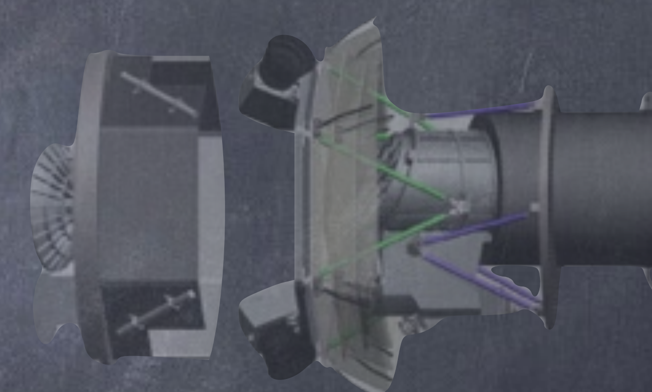
Participating Projects

CosKASI is institutional member of DESI, the stage IV wide deep field spectroscopy survey

Spectroscopy to Photometry

Two faculties at CosKASI are members of LSST, and joining Dark Energy working group

Ground to Space



JPL and CosKASI submitted the SPHEREx project to NASA SMEX program

80cm to 20m

Optic to radio

KASI is a key institutional member of GMT, 20m Giant Magellan Telescope

Initial condition to late time universe

CosKASI is joining 21cm experiment of Tianlai organised by NAOC

Conclusion

- We plan to launch new satellite instrument SPHEREx, and we expect that the observational landmark on non-Gaussianity is possible, and it provides us the new clue to understand the nature of initial condition

- 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.

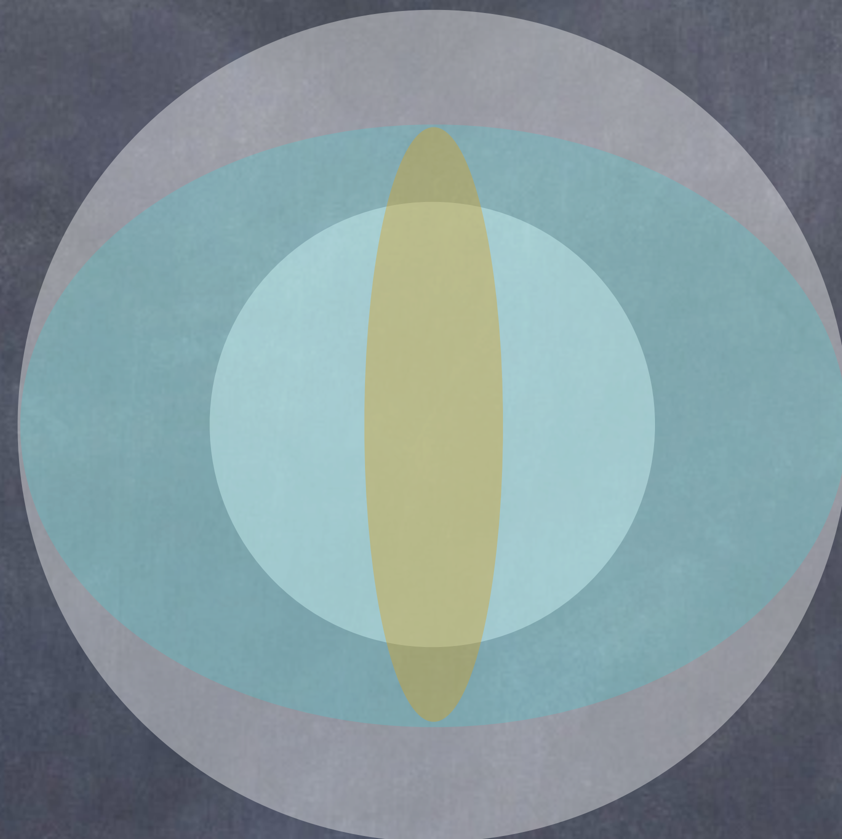
- We work out the Alcock-Paczynski effect on bispectra, and find that the combined constraint of power spectrum and bispectrum improves the detectability of growth function.

- We also prepare for the cross correlation between 21cm and galaxy clustering.

Redshift Space Distortion

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

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

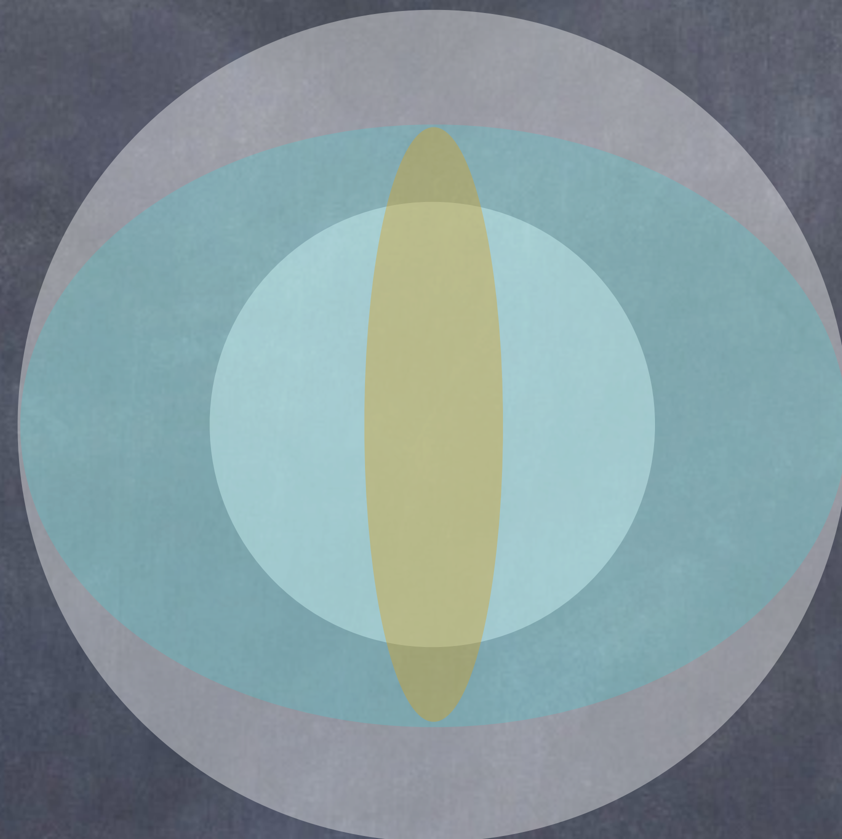
Perturbative method: separating disjoint non-perturbative effect, and formulating the rest as perturbative calculations

Streaming method: projecting probable distribution of random velocity, and estimating the non-linear smearing effect

Redshift Space Distortion

Squeezing effect at large scales

(Kaiser 1987)



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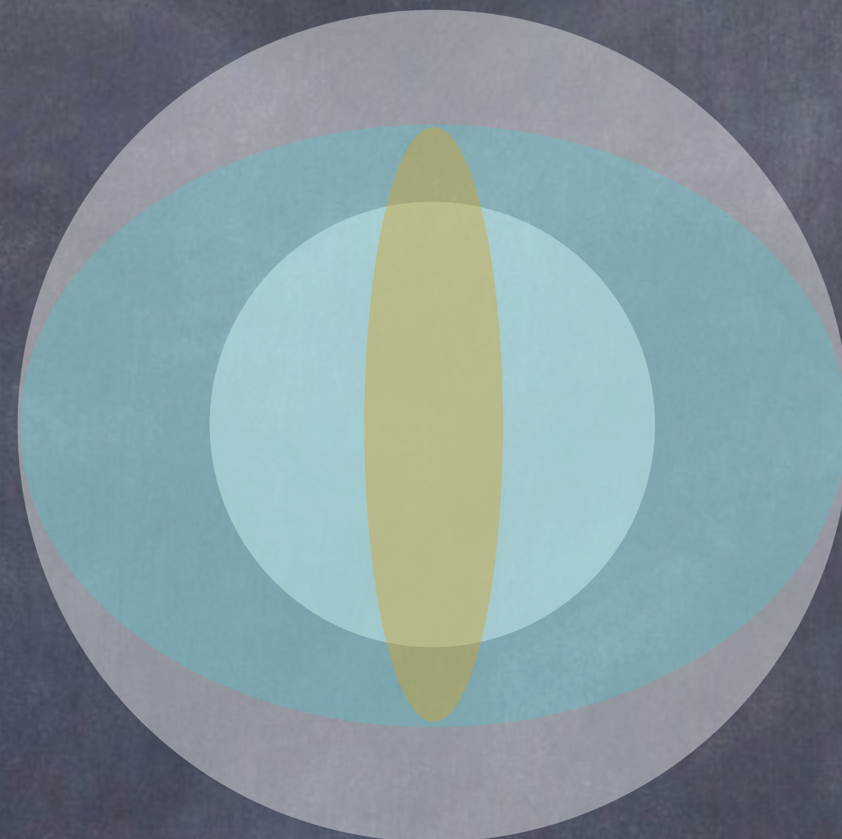
Improved redshift space distortion

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small scales

(Jackson 1972)

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

$$\downarrow$$

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

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

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)

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

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)