Implications of Redshift Space Distortions

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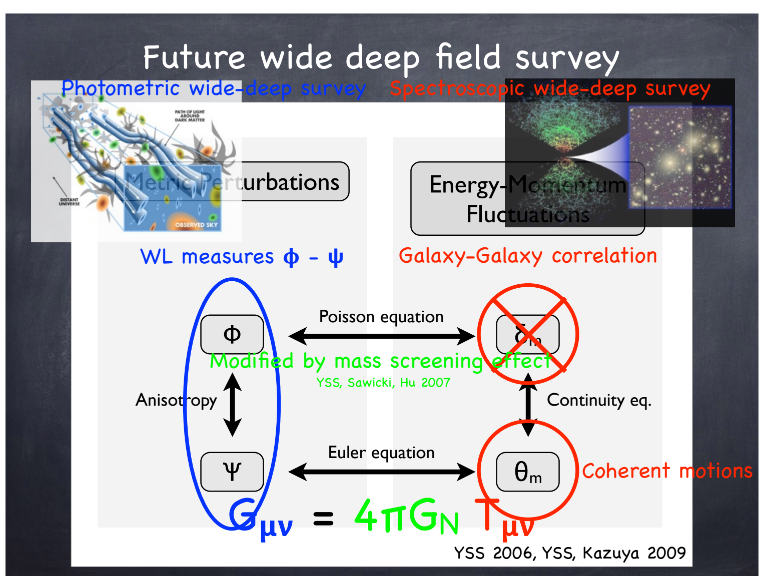
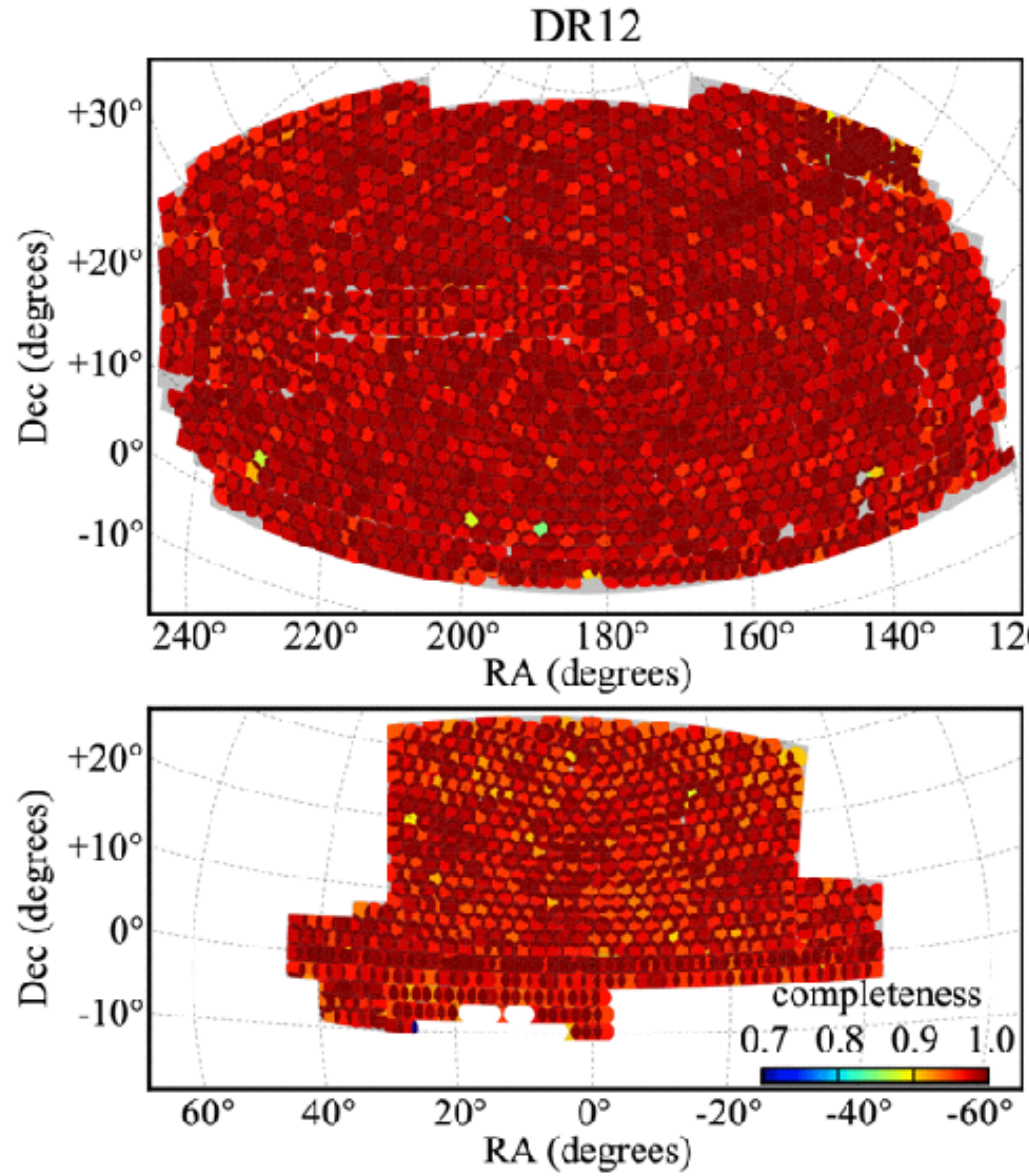
Galaxy clustering seen in redshift space

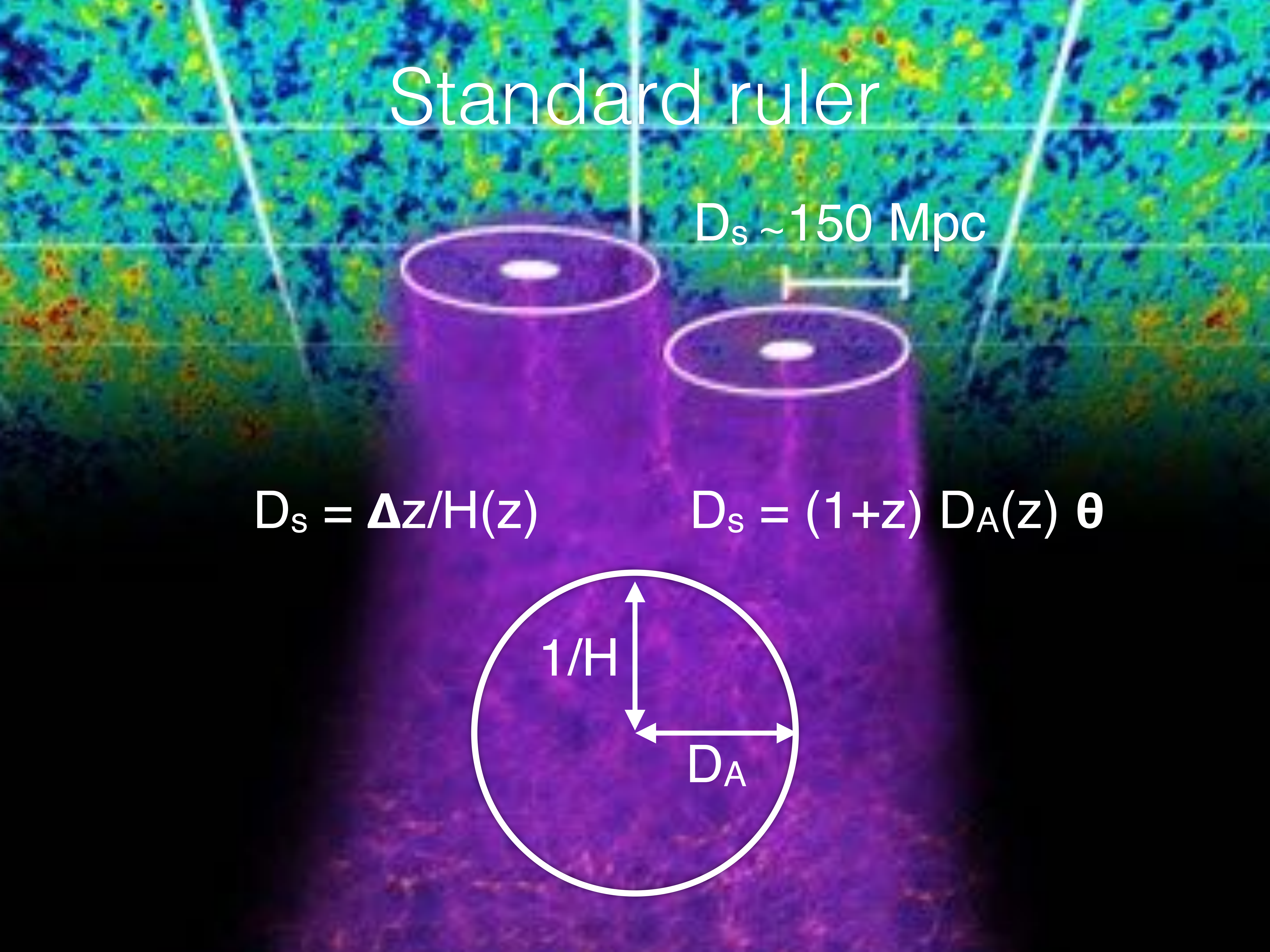
- Spectroscopy wide surveys have provided the key observables of distance measures and growth functions, such as 2dF, SDSS, WiggleZ, BOSS
- Most unknowns in the universe will be revealed through LSS





Alam et.al 2015; YSS, Koyama 2009

Standard ruler

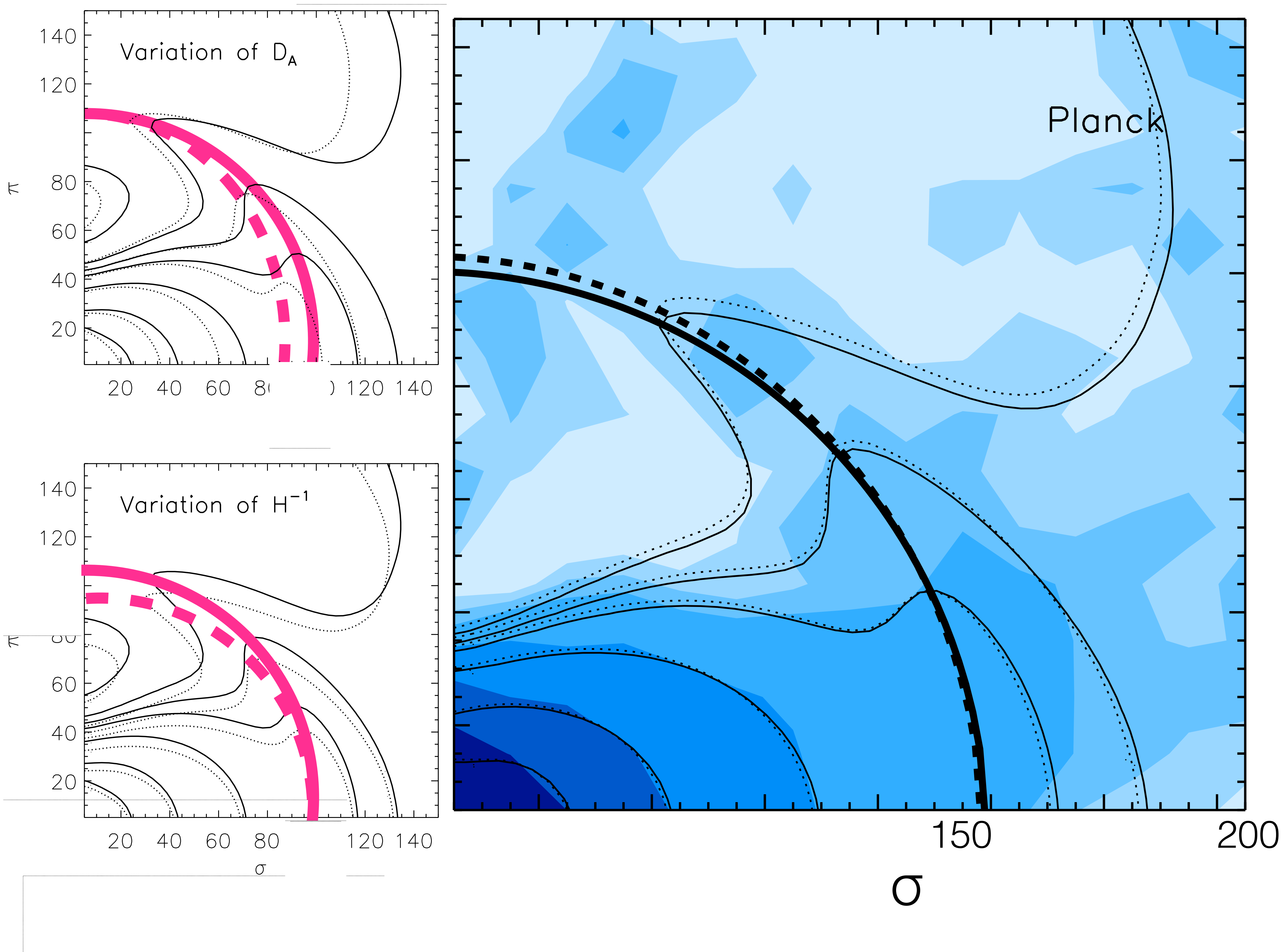


$D_S = \boldsymbol{\Delta} z/H(z)$

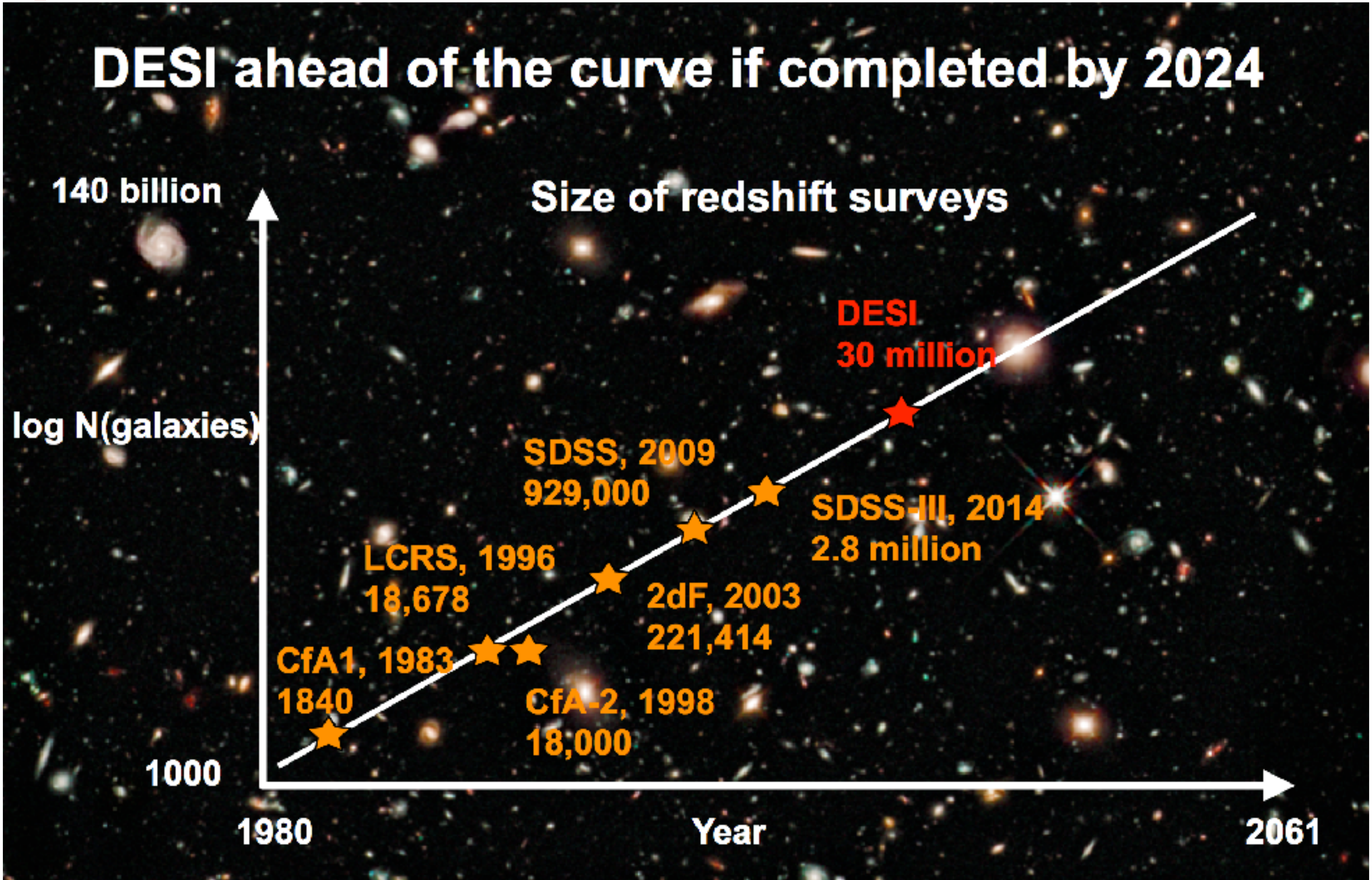
$D_S = (1+z)\, D_A(z)\, \boldsymbol{\theta}$

Risk free option to determine cosmic distance

(D_A, H^{-1})



History and plan for spectroscopy surveys



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 assumption:

    Inhomogeneous models: LTB, back reaction

Implication of cosmic acceleration

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Dynamical Dark Energy: modifying matter

Alternative mechanism to generate fine tuned vacuum energy

New unknown energy component

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

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:

Geometrical Dark Energy: modifying gravity

Presence of extra dimension

Non-linear interaction to Einstein equation

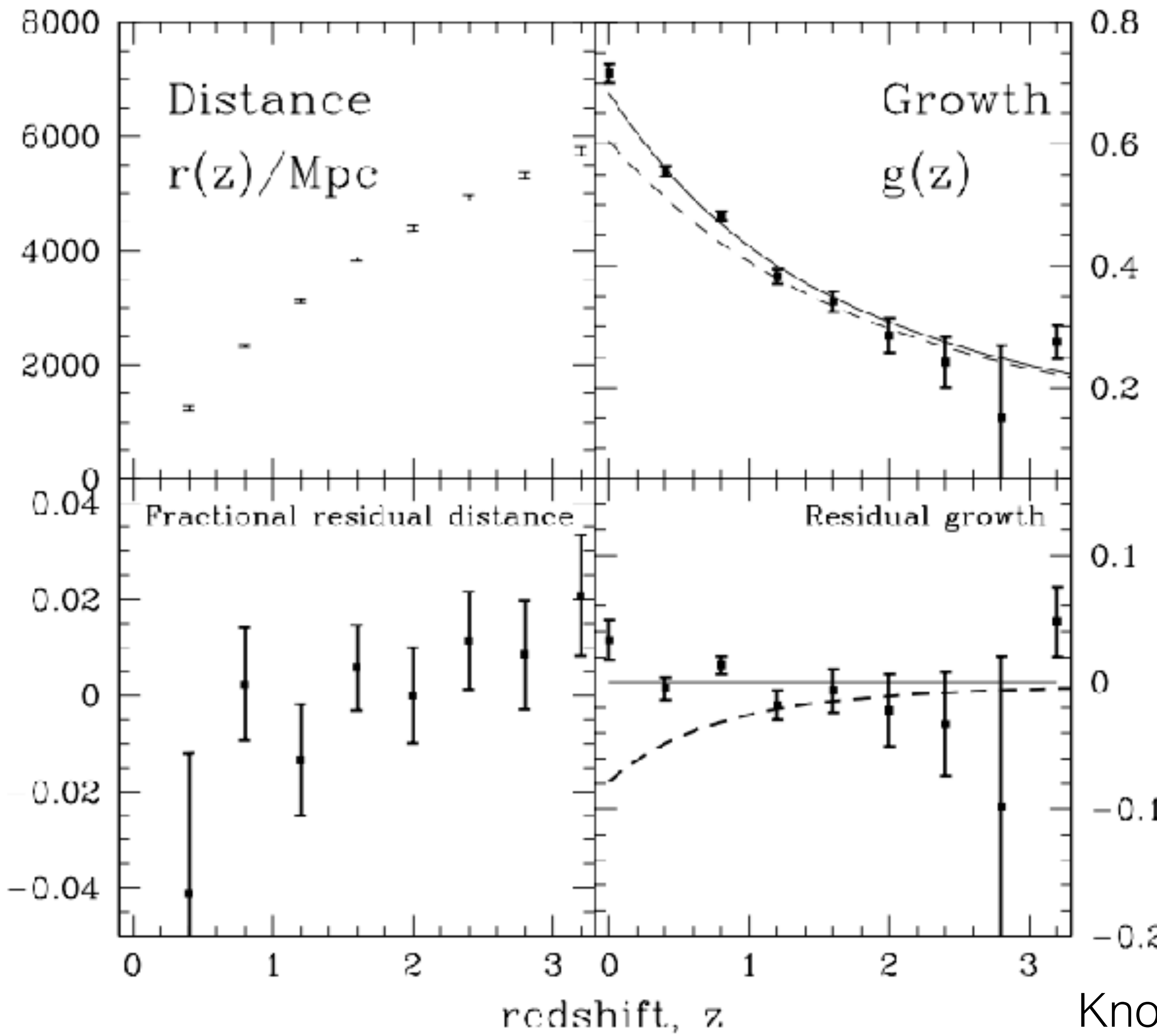
$$G_{\mu\nu} + \Delta G_{\mu\nu} = 4\pi G_N T_{\mu\nu}$$

- Failure of standard cosmology model: our understanding of the universe is still standing on assumption:

Inhomogeneous models: LTB, back reaction

Two windows on acceleration and gravitation

Their simultaneous determination allows for a consistency test and provides sensitivity to physics beyond the standard dark energy paradigm



Knox, YSS, Tyson 2005

Galaxy clustering seen in redshift space

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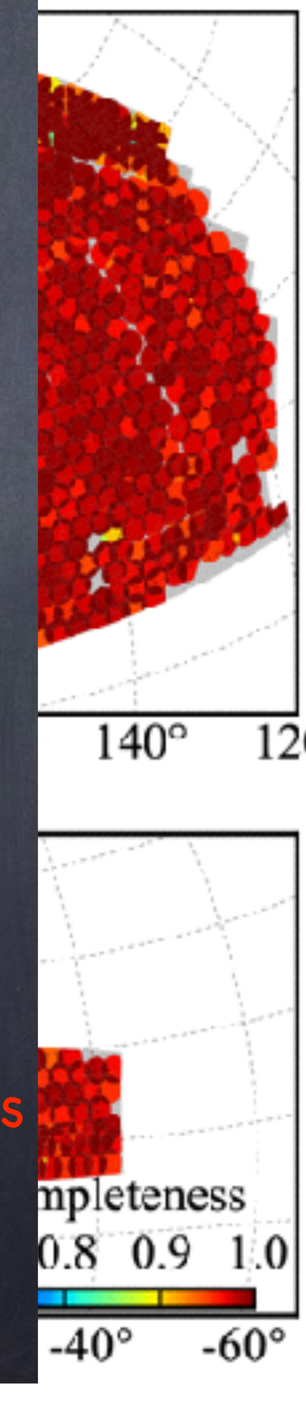
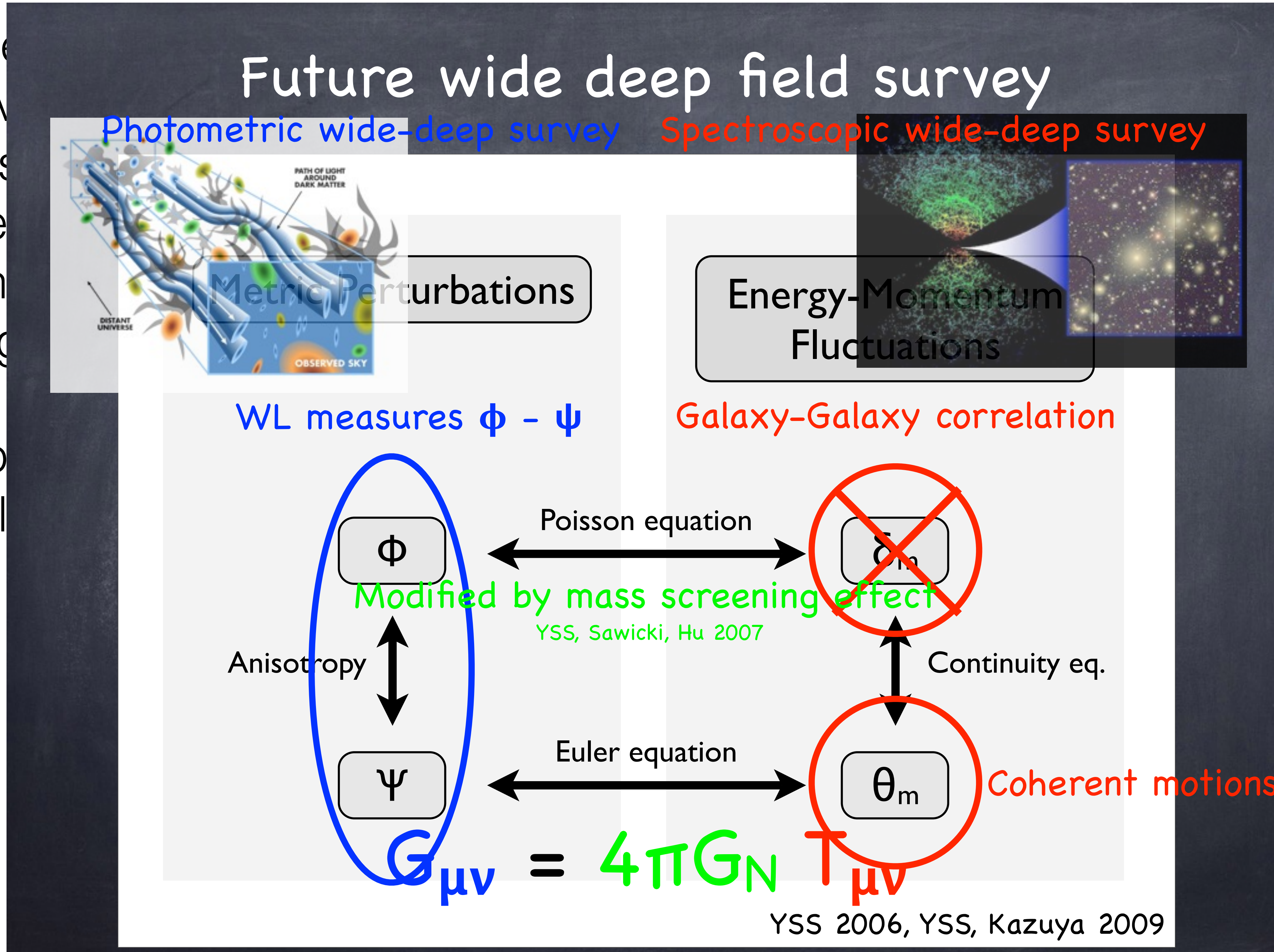
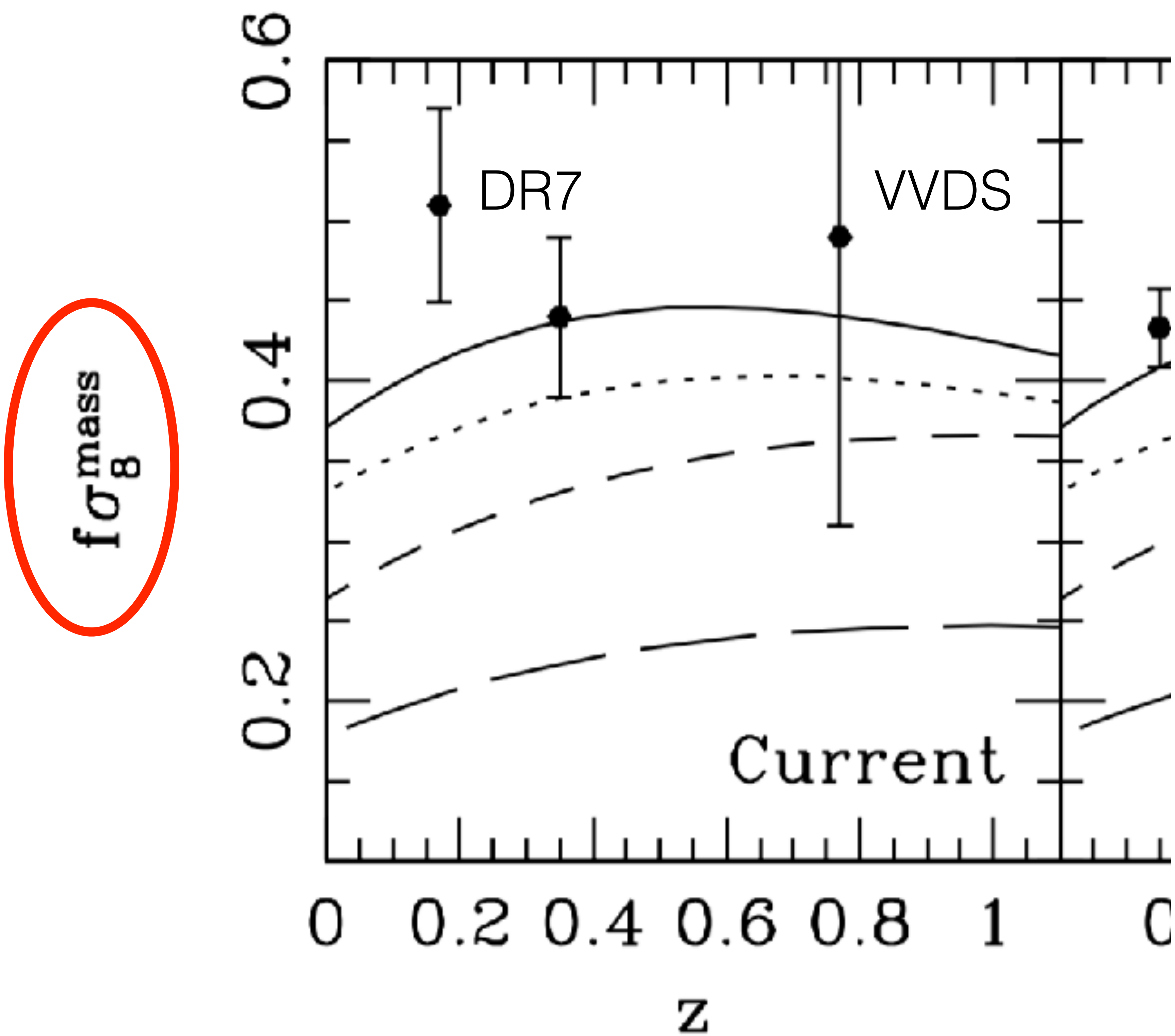




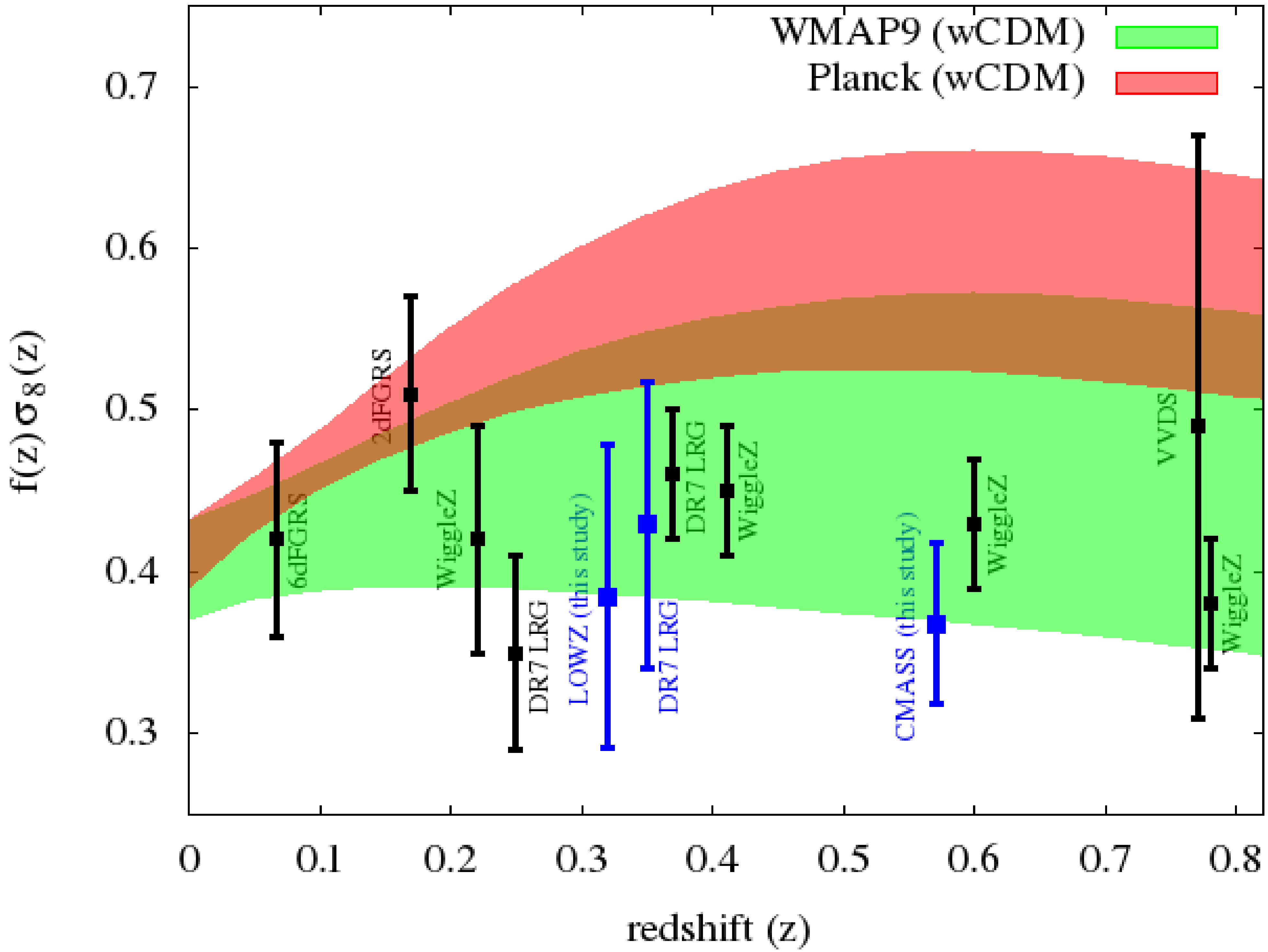
Cosmological probe of coherent motion

The first measured $f\sigma_8$

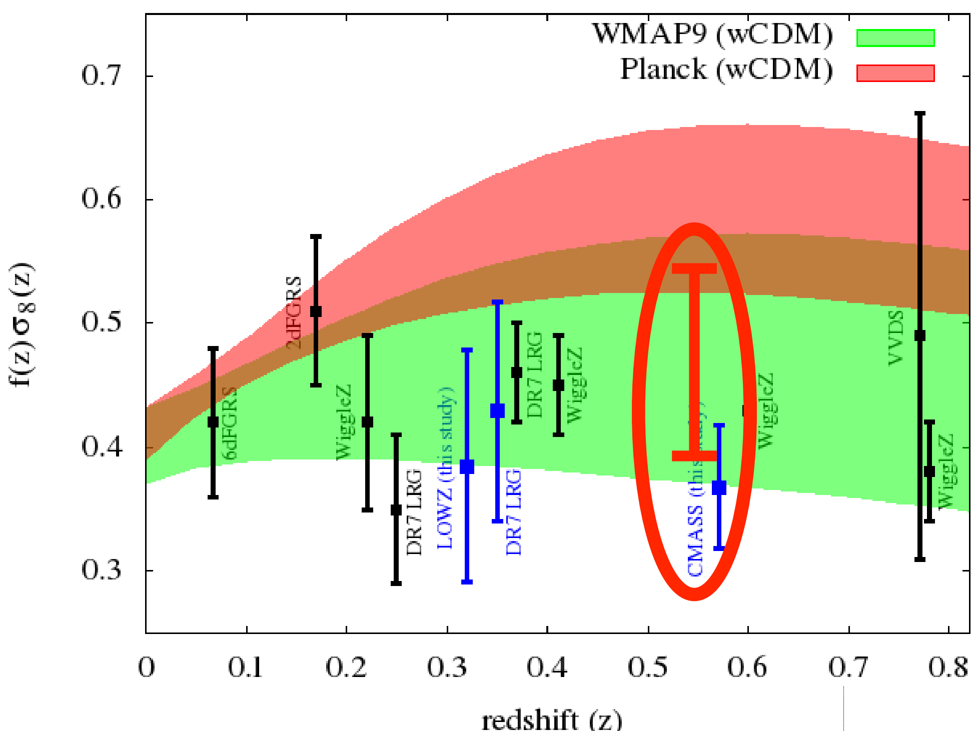


YSS, Percival 2009

Cosmological probe of coherent motion

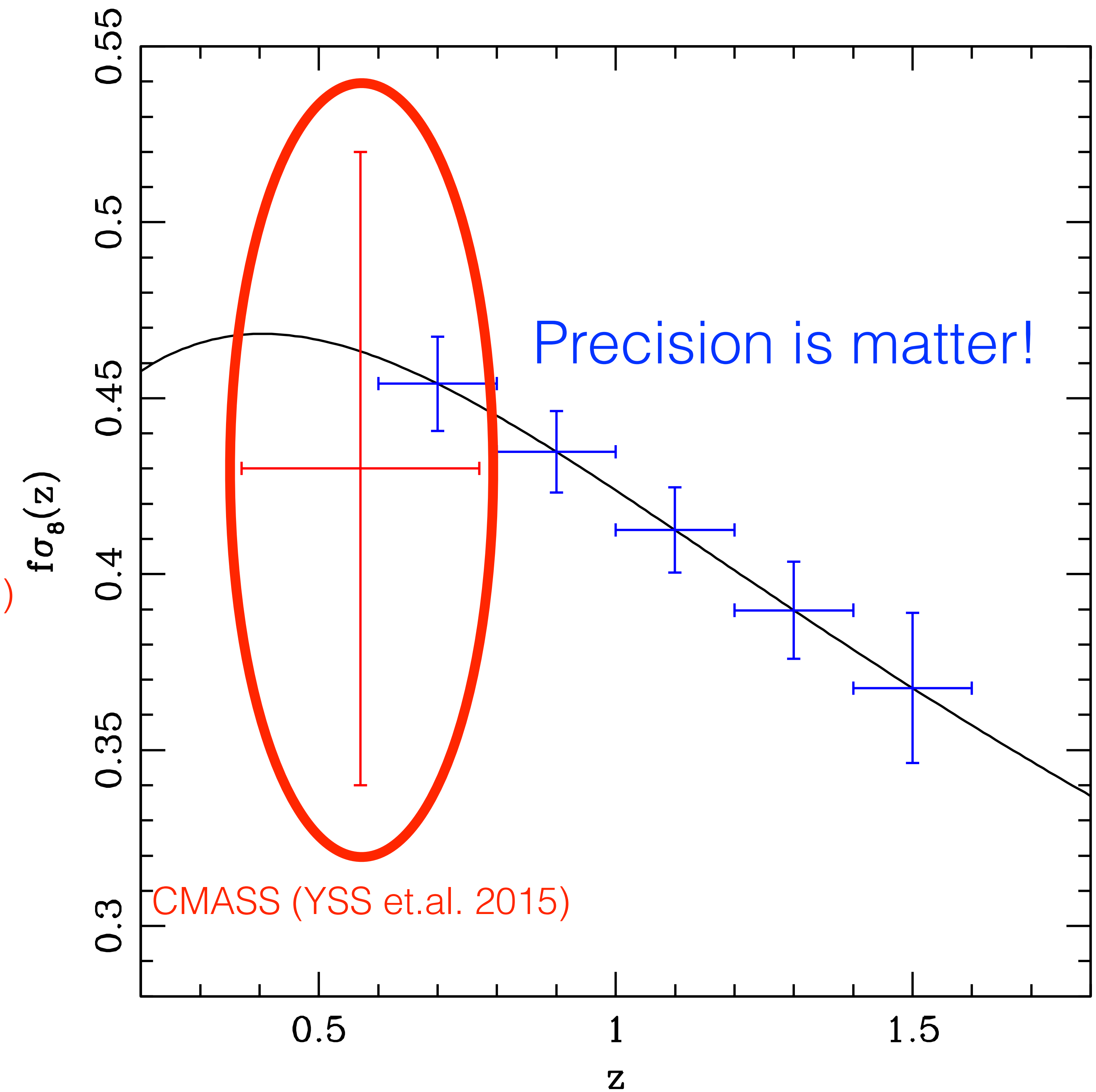


Cosmological probe of coherent motion



CMASS (Chuan et.al. 2015)

CMASS (YSS et.al. 2015)

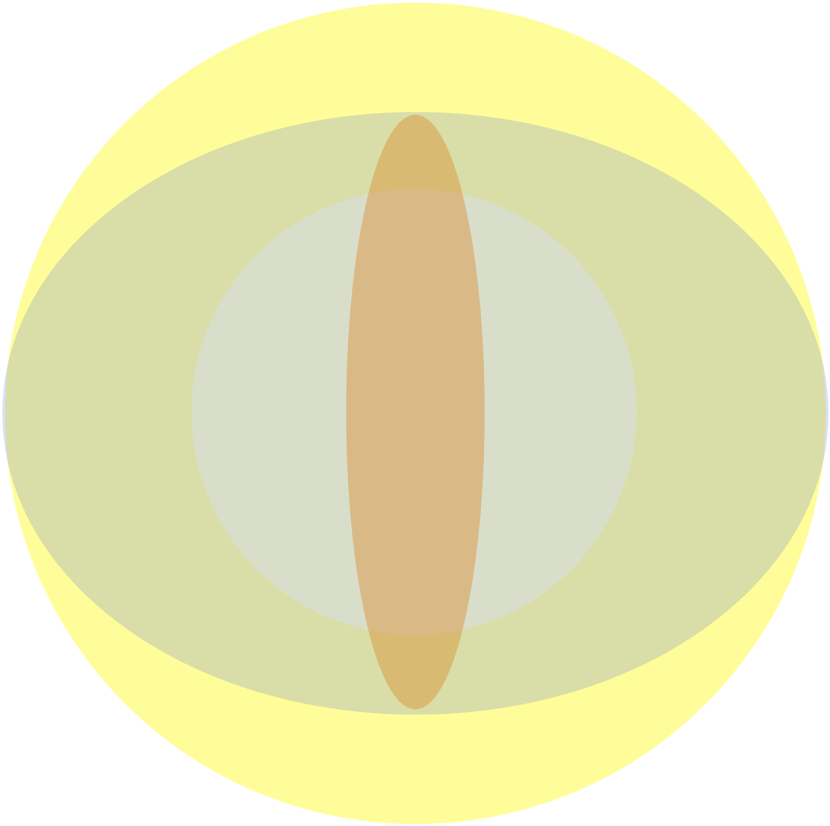


YSS, Taruya, Akira 2015

Power spectrum in redshift space

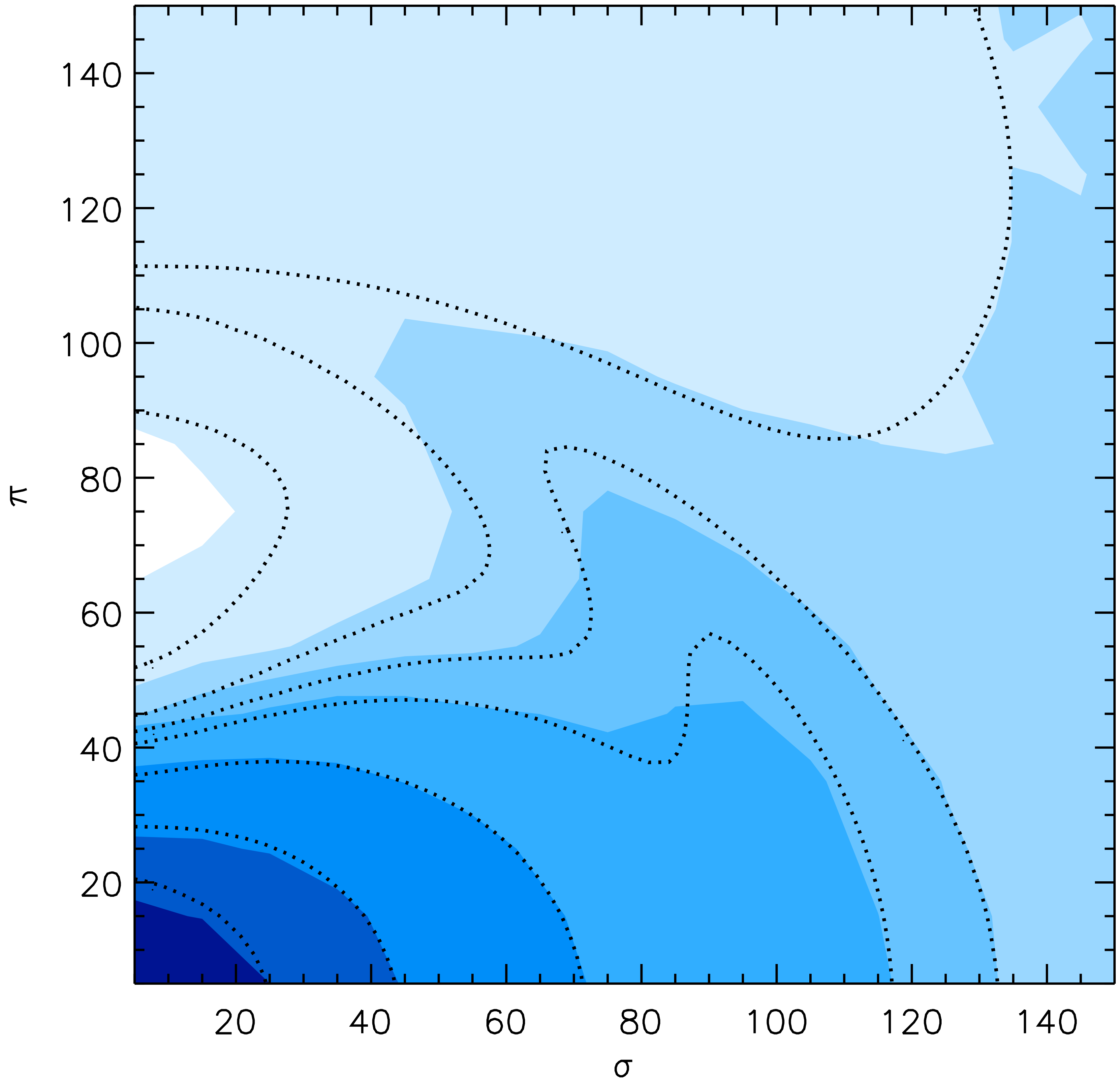
Squeezing effect at large scales

(Kaiser 1987)



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

Anisotropy correlation without corrections



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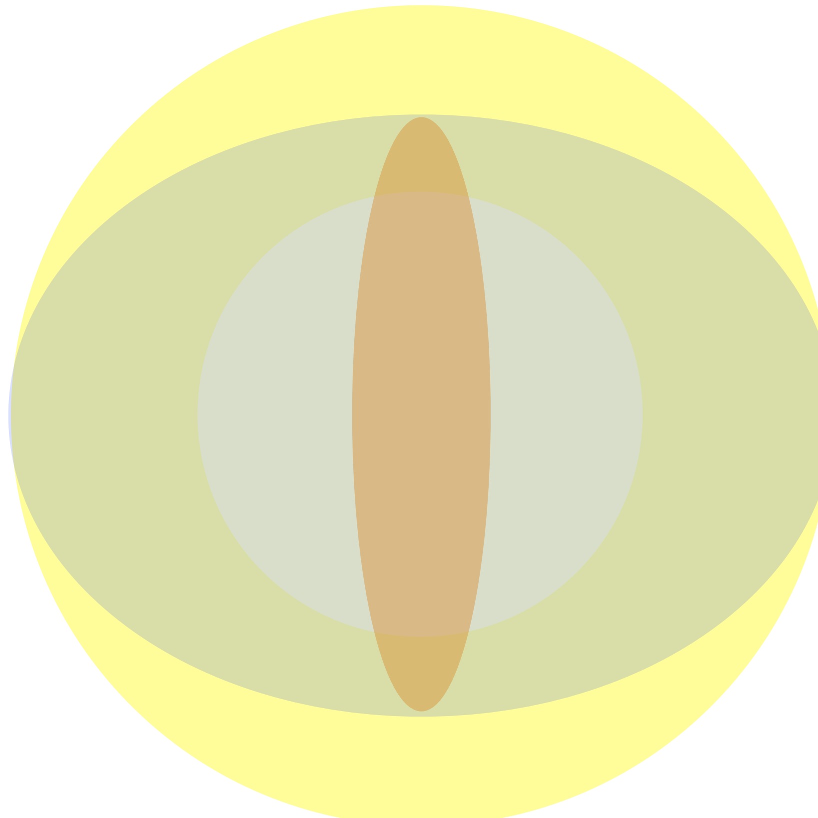


Non-linear corrections

Higher order polynomials

Finger of God effect

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

$$\Downarrow$$

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

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

Improved RSD model

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

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

$$\xi_\ell(s) = i^l \int k^2 dk\, P_l(k)\, j_l(ks)$$

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

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

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

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

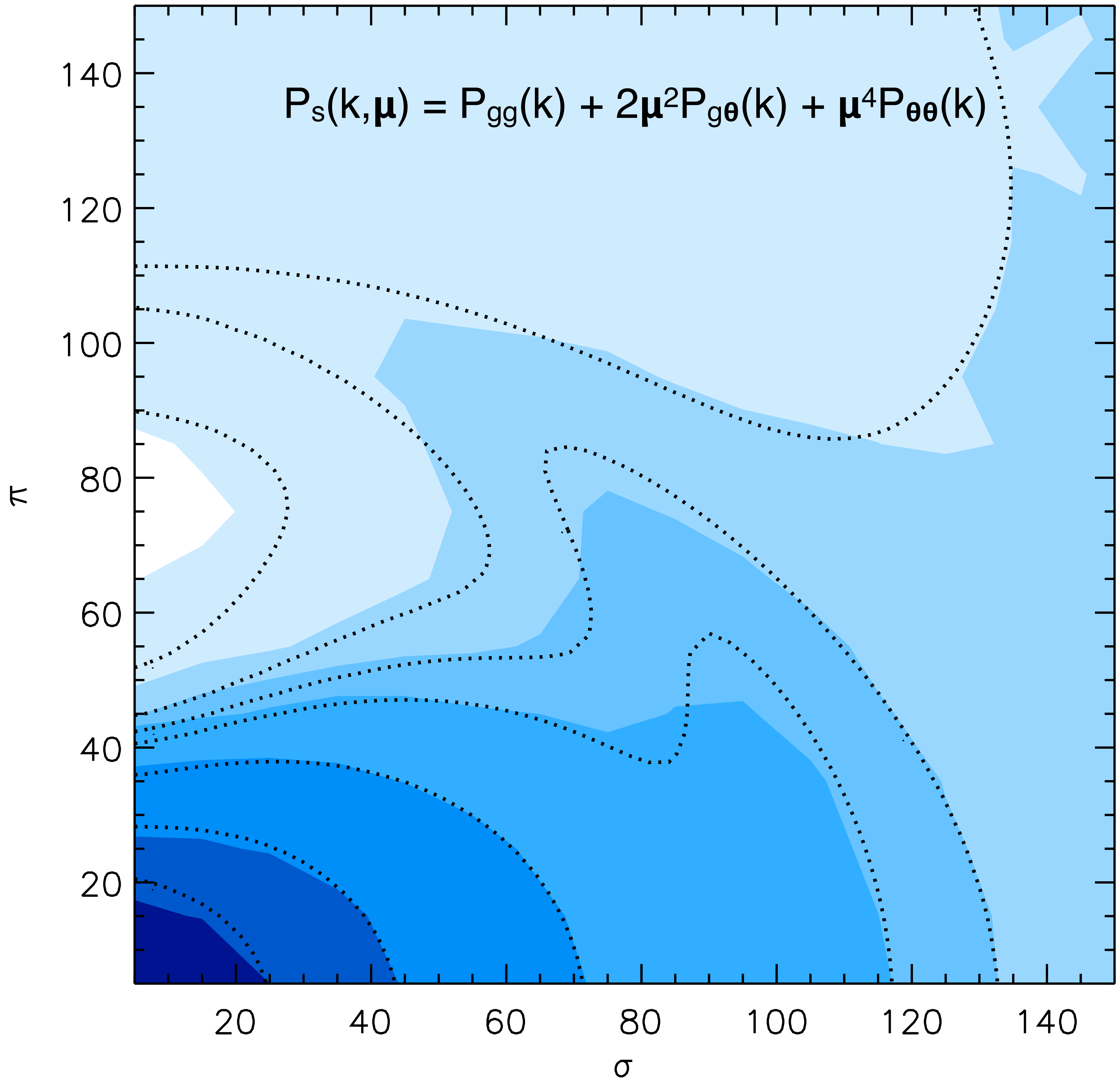
$$p_n(k) = 1/2\, [\, \gamma(n+1/2,\kappa)/\kappa^{n+1/2} Q_0(k) + \gamma(n+3/2,\kappa)/\kappa^{n+3/2} Q_2(k)$$

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

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

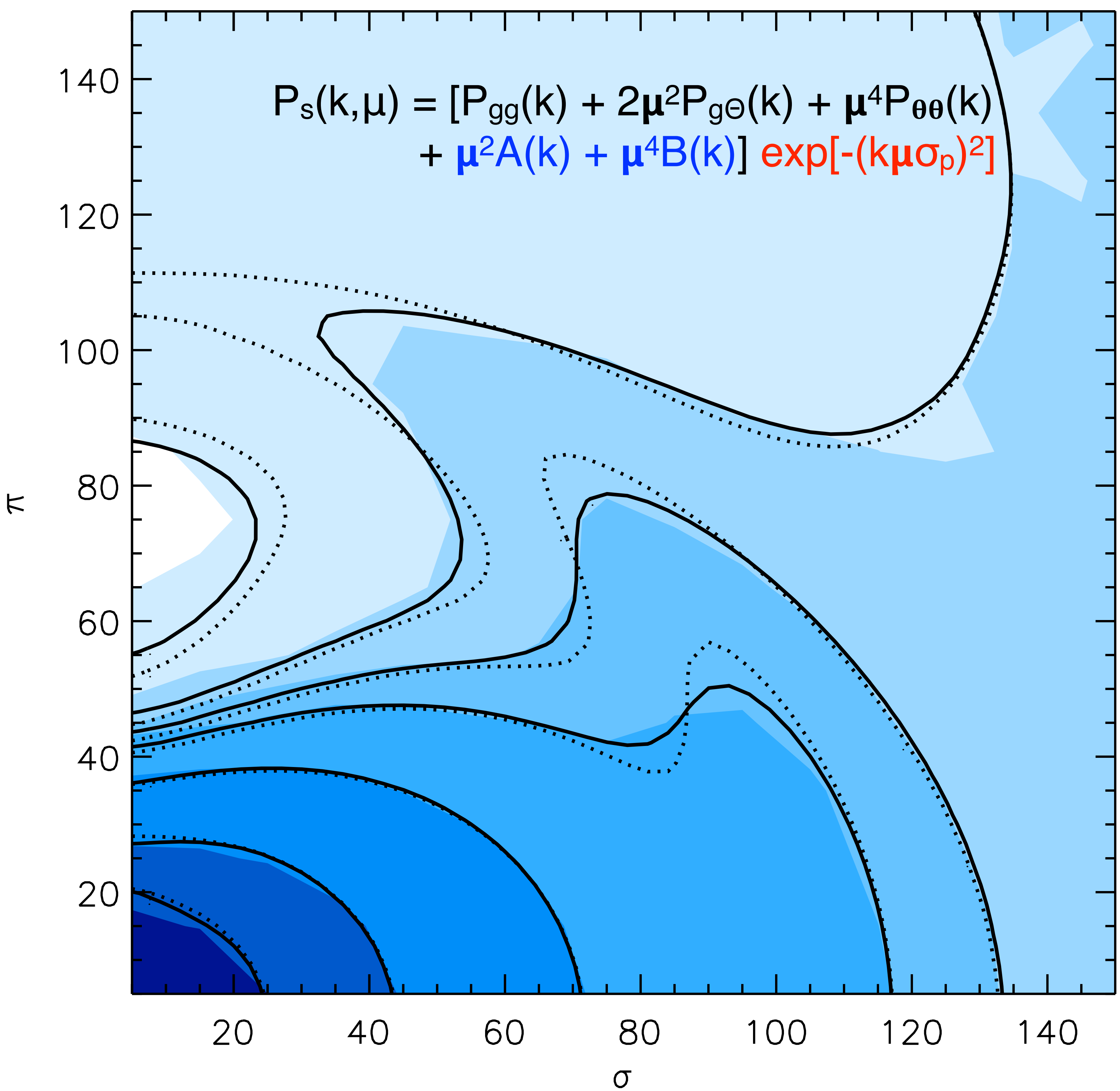
YSS, Okumura, Taruya 2014   Taruya, Nichimishi, Saito 2010

Anisotropy correlation without corrections



YSS et.al. 2015

Anisotropy correlation with corrections



YSS et.al. 2015

Mapping of clustering from real to redshift spaces

$$P_s(k,\boldsymbol{\mu}) = \int d^3x\, e^{ikx} \langle \boldsymbol{\delta\delta} \rangle$$

$$\Downarrow$$

$$P_s(k,\mu) = \int d^3x\, e^{ikx} \langle e^{jv} (\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta) \rangle$$

$$= \int d^3x\, e^{ikx} \exp\{\langle e^{jv} \rangle_c\} \left[\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c + \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c\right]$$

- Non-linear corrections: there is limit in the perturbative approach at smaller scales. We need find a way to combine the simulation result.
- Higher order polynomials: there is an infinite tower of cross correlation between velocity and density fields. We have to decide the order limit.
- The FoG effect: the exact functional form is unknown. Only thing that we know is that it is a function of velocity dispersion σ_p.

Mapping of clustering from real to redshift spaces

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$$P_s(k,\mu) = [P_{gg}(k) + 2\boldsymbol{\mu}^2 P_{g\Theta}(k) + \boldsymbol{\mu}^4 P_{\boldsymbol{\theta\theta}}(k) + A(k,\boldsymbol{\mu}) + B(k,\boldsymbol{\mu}) + T(k,\boldsymbol{\mu}) + F(k,\boldsymbol{\mu})]$$

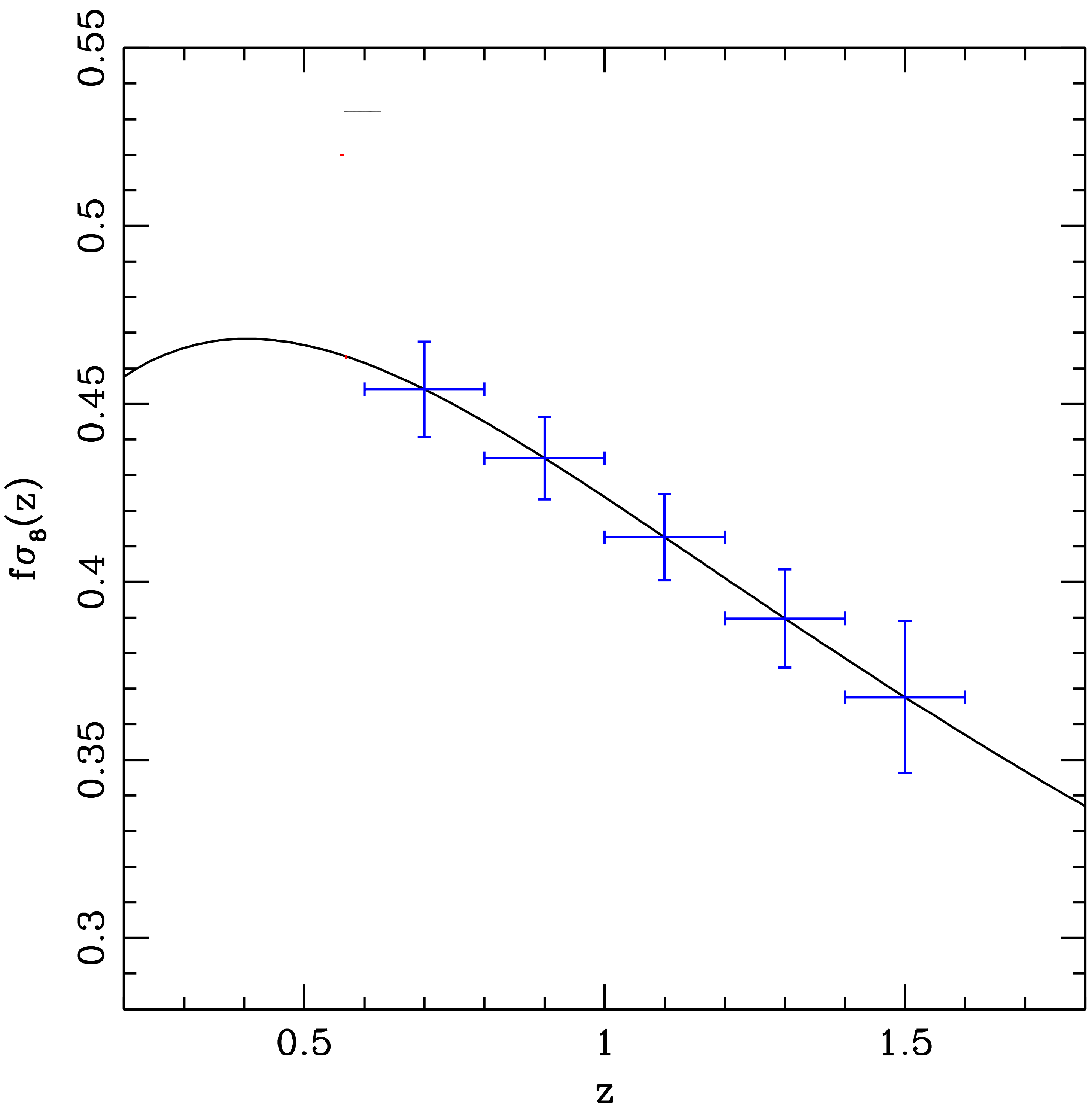
$$\exp[-(k\boldsymbol{\mu}\sigma_p)^2]$$

- Higher order polynomials are generated by density and velocity cross-correlation which generate the infinite tower of correlation pairs. We take the perturbative approach to cut off higher orders.
- The FoG effect consists of the one-point contribution and the correlated velocity pair contribution. The latter is perturbatively expanded as F term, and the former is parameterised using σ_p.

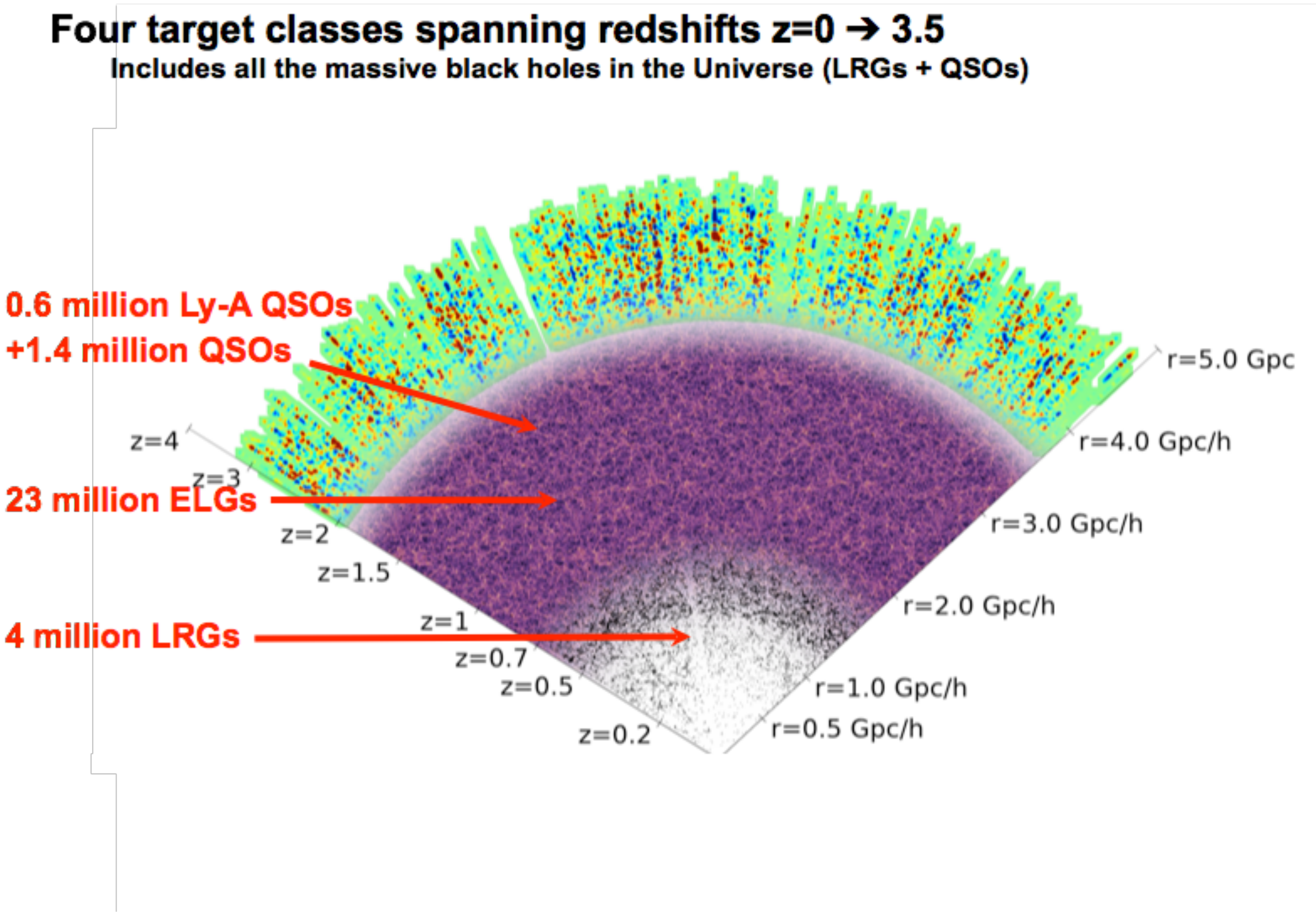
Yi, YSS 2016

Precision & Accuracy

The conservative measurement of growth function with k_{max}<0.1h/Mpc

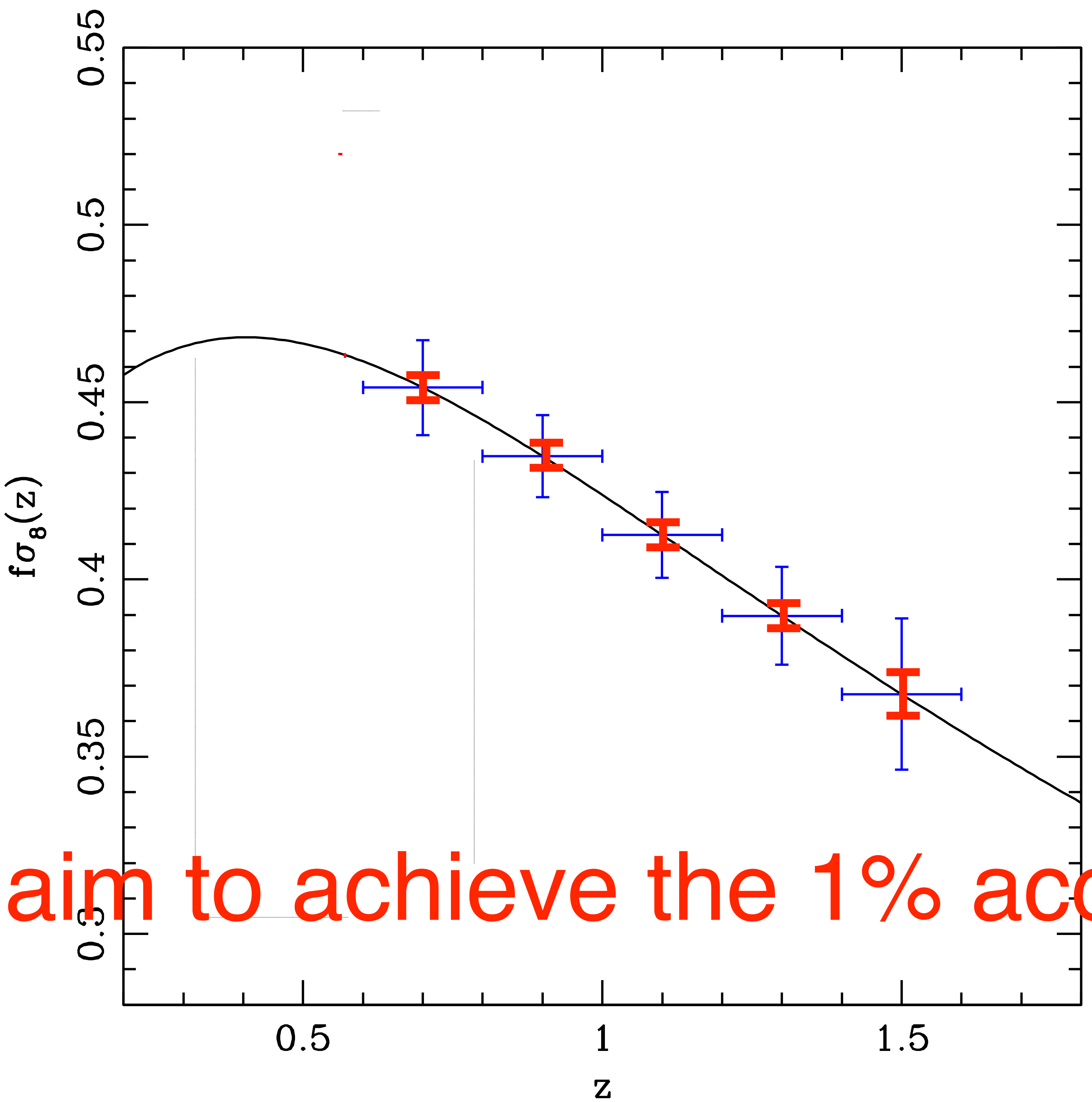


Galaxy clustering seen in redshift space



Precision & Accuracy

The measurement of growth function is improved up to the limit of shot noise about k_{max}<0.15h/Mpc



We aim to achieve the 1% accuracy

Open new window to test cosmological models

(D_A, H^{-1}, G_δ, G_Θ, FoG)

Standard model	New physics
Cold dark matter	Quintessence dark energy
Massless neutrino	Phantom dark energy

Λ

Open new window to test cosmological models

(D_A, H^{-1}, G_δ, G_Θ, FoG, New, New, …)

Standard model		New physics
Cold dark matter		Quintessence dark energy
Massless neutrino		Phantom dark energy
Hot or warm dark matter	Λ	Decaying vacuum
Massive neutrino		Chameleon type gravity
Interacting dark matter		Dilaton or Symmetron
Unified dark matter		Vainstein type gravity
		Inhomogeneity of universe
		non-Friedman universe

Precise determination on Ω_Λ

$(D_A, H^{-1}, G_\delta, G_\Theta, \mathrm{FoG})$

Standard model

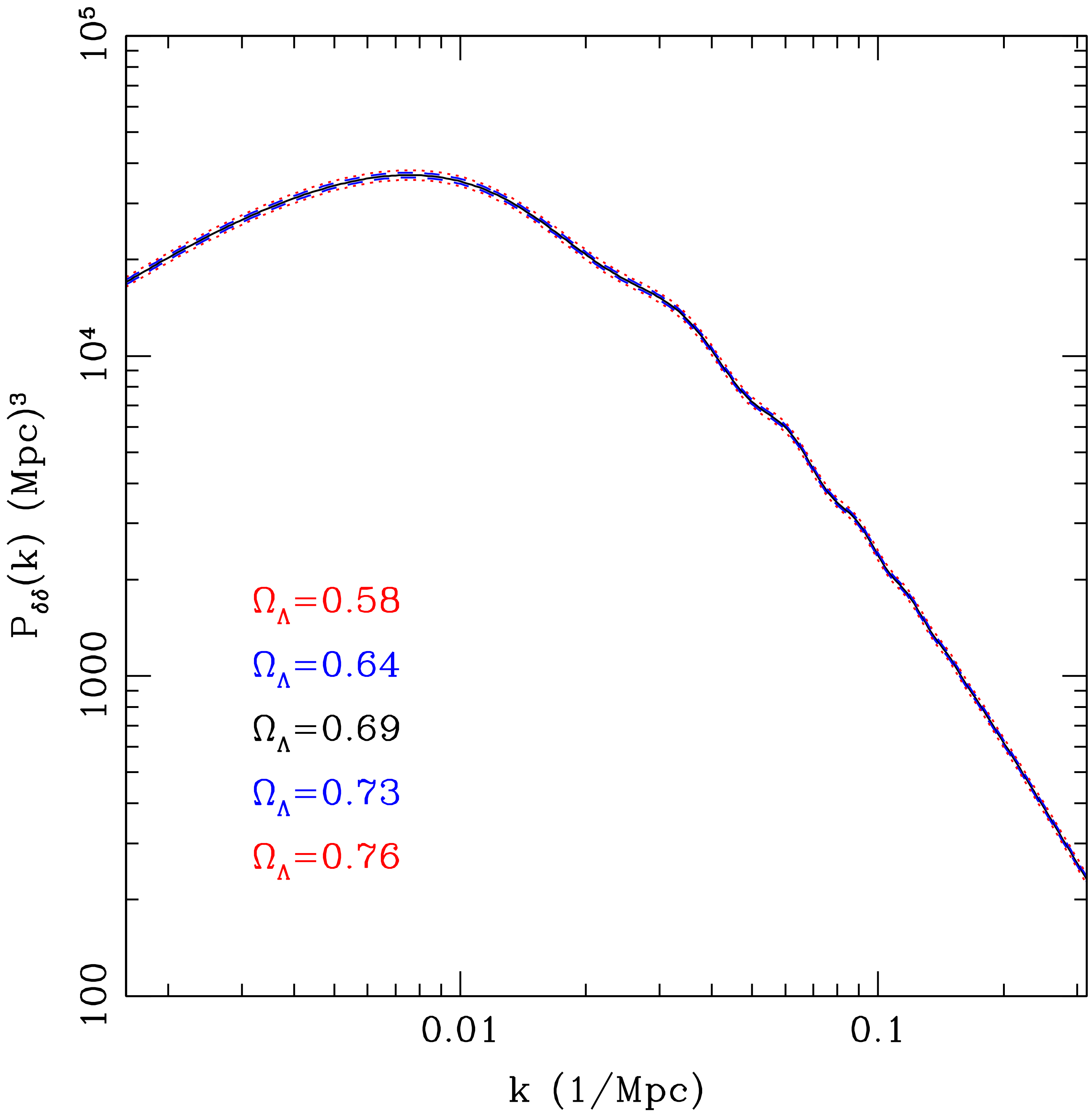
Cold dark matter

Massless neutrino

Λ

The measured spectra with different Ω_Λ

We vary Ω_Λ coherently with BAO statistics, i.e. the observed sound horizon is fixed



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$$= \int d^3x\, e^{ikx} \exp\{\langle e^{jv}\rangle_c\} [\langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c + \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c \langle e^{jv}(\boldsymbol{\delta}+\boldsymbol{\mu}^2\Theta)\rangle_c]$$

$$P_s(k,\mu) = [P_{\delta\delta}(k) + 2\boldsymbol{\mu}^2 P_{\delta\Theta}(k) + \boldsymbol{\mu}^4 P_{\Theta\Theta}(k) + A(k,\boldsymbol{\mu}) + B(k,\boldsymbol{\mu}) + T(k,\boldsymbol{\mu}) + F(k,\boldsymbol{\mu})]$$
$$\exp[-(k\boldsymbol{\mu}\sigma_p)^2]$$

- Non-linear corrections: there is limit in the perturbative approach at smaller scales. We need find a way to combine the simulation result.
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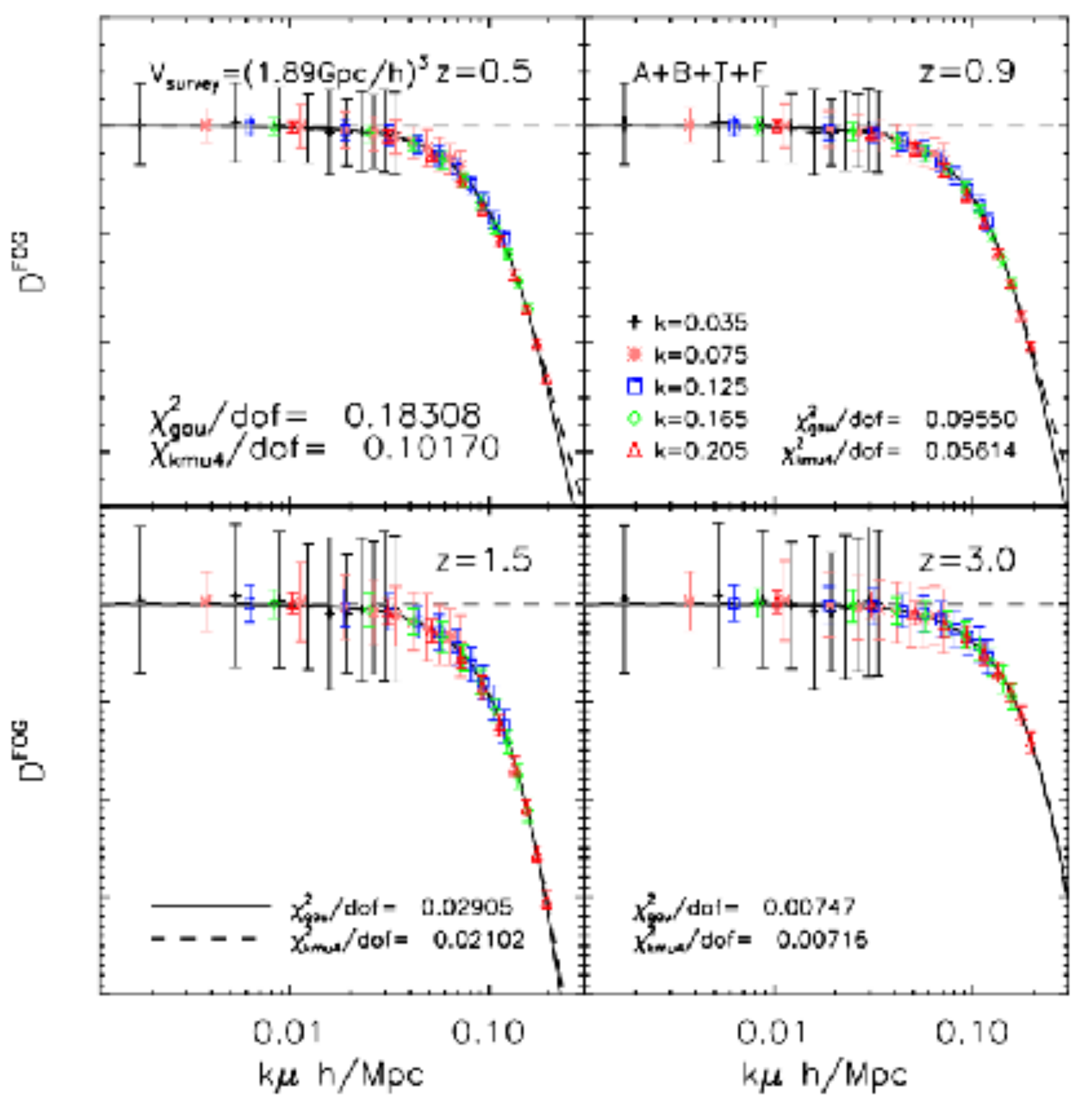
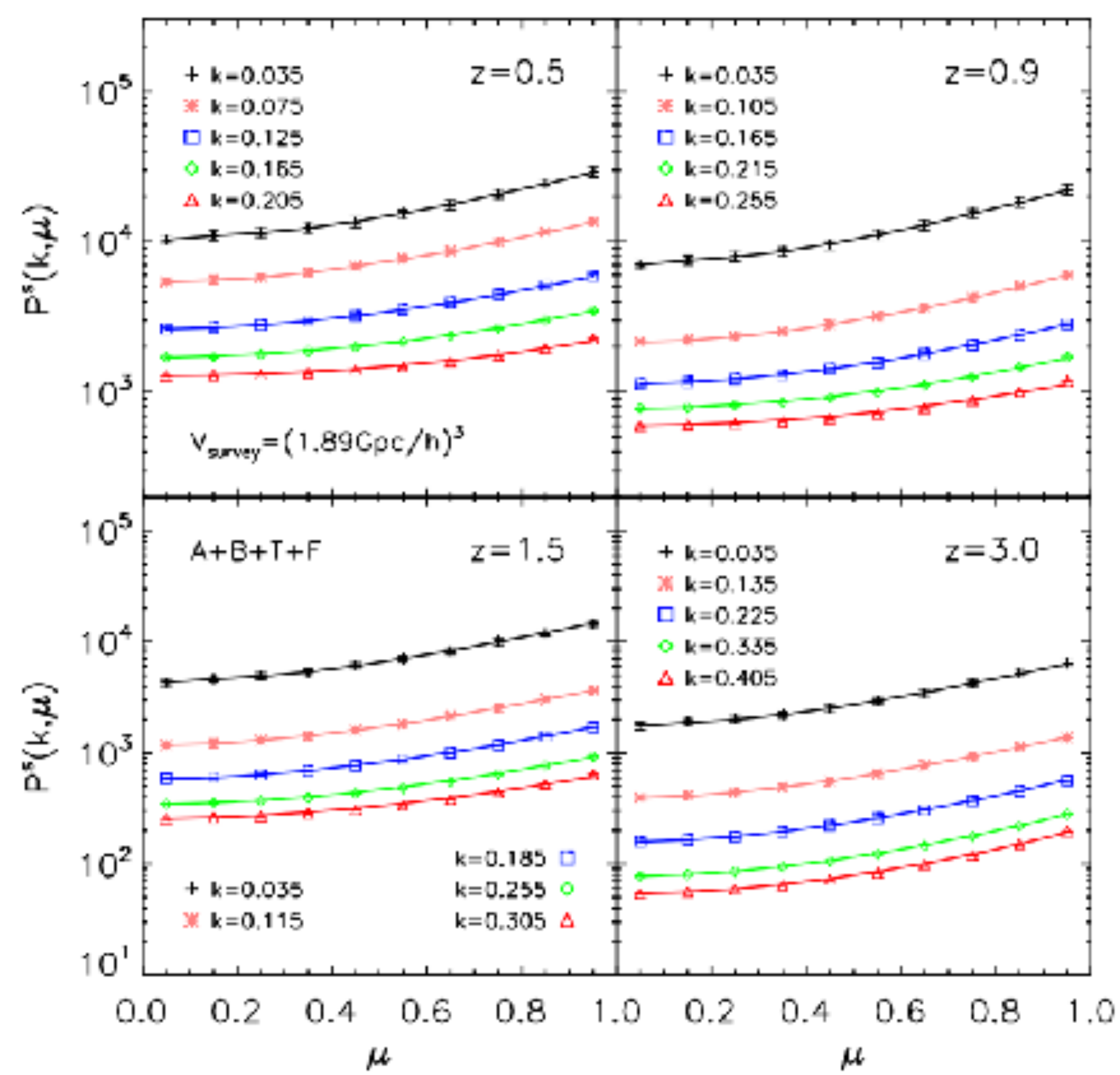
Yi, YSS 2016

Mapping of clustering for Dark Matter

$$D^{FoG} = P_s(k,\mu)/[P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$$

- The residual term is well fitting to Gaussian FoG function
- The estimated spectrum is well matching to the observed





Yi, YSS 2016

Mapping of clustering for Halo I

$P_s(k,\mu) = [P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$
$\exp[-(k\mu\sigma_p)^2]$

↓

$P_s(k,\mu) = [P_{hh}(k) + 2\mu^2 P_{h\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$
$\exp[-(k\mu\sigma_p)^2]$

- Before we model the halo bias, we test it whether this mapping formulation is valid for halo clustering
- The halo density fluctuations are measured after cleaning the stochastic noise, which is given by

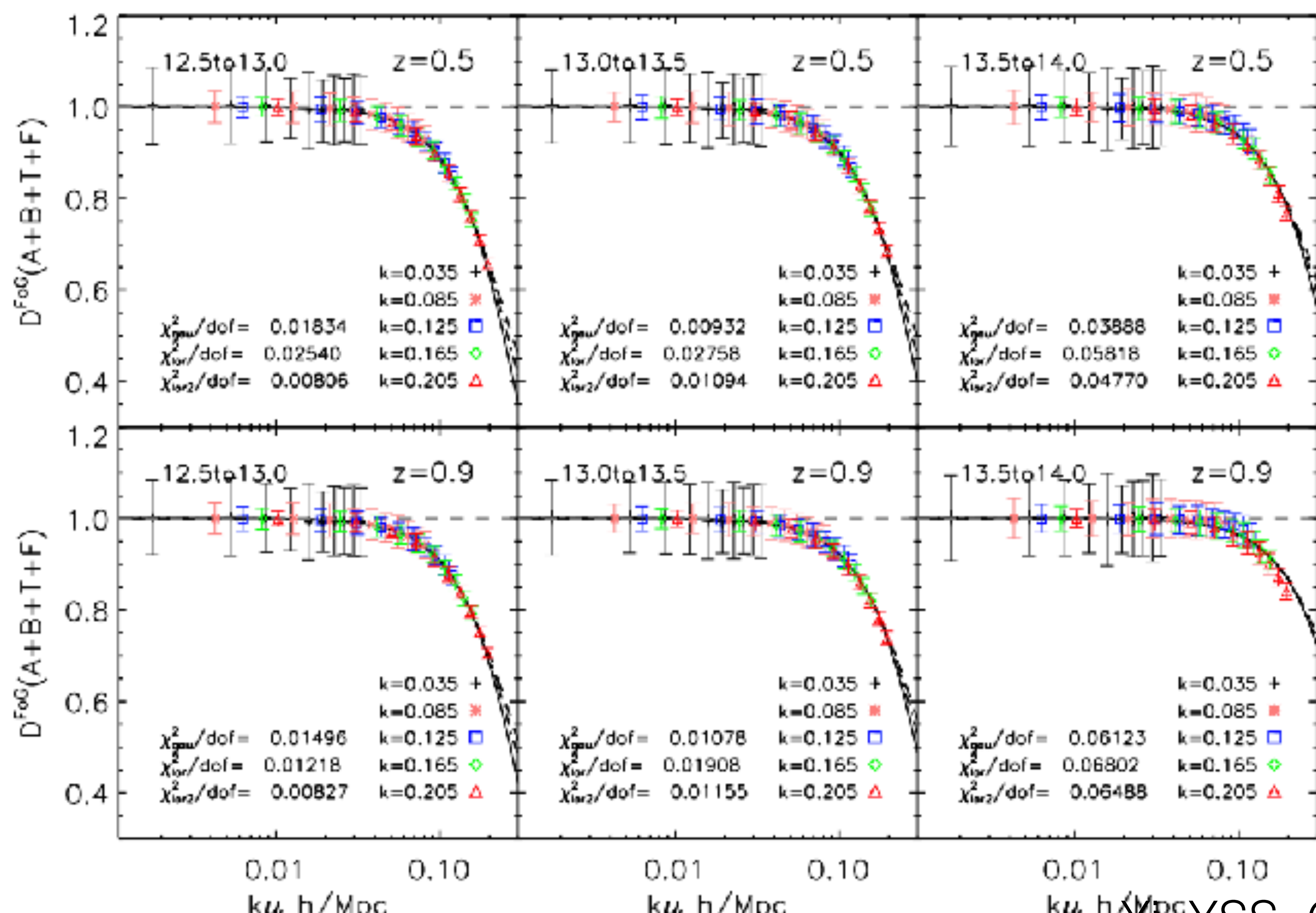
$$b(k) = P_{\tilde{\delta}_h \delta}(k)/P_{\delta\delta}(k)\,,$$
$$P_{\epsilon\epsilon} = P_{\tilde{\delta}_h \tilde{\delta}_h} - P_{\delta_h \delta_h} = P_{\tilde{\delta}_h \tilde{\delta}_h} - b^2(k) P_{\delta\delta}\,.$$

Yi, YSS, Oh 2017 prepared

Mapping of clustering for Halo I

$$D^{FoG} = P_s(k,\mu)/[P_{hh}(k) + 2\mu^2 P_{h\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$$

- The residual term which is the subtraction of the measured spectrum by the perturbed terms including halo density fluctuations is well fitting to Gaussian FoG function as well



Yi, YSS, Oh 2017 prepared

Mapping of clustering for Halo II

$P_s(k,\mu) = [P_{hh}(k) + 2\mu^2 P_{h\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]$
$\exp[-(k\mu\sigma_p)^2]$

- Now we model halo bias, based upon the following treatment;

$$\delta_h(\boldsymbol{x}) = b_1\delta(\boldsymbol{x}) + \frac{1}{2}b_2[\delta(\boldsymbol{x})^2 - \sigma_2] + \frac{1}{2}b_{s2}[s(\boldsymbol{x})^2 - \langle s^2\rangle] + \textit{higher order terms}\,.$$

- We exploit the measured template using dark matter simulation, and to express halo density fluctuations with bias parameters

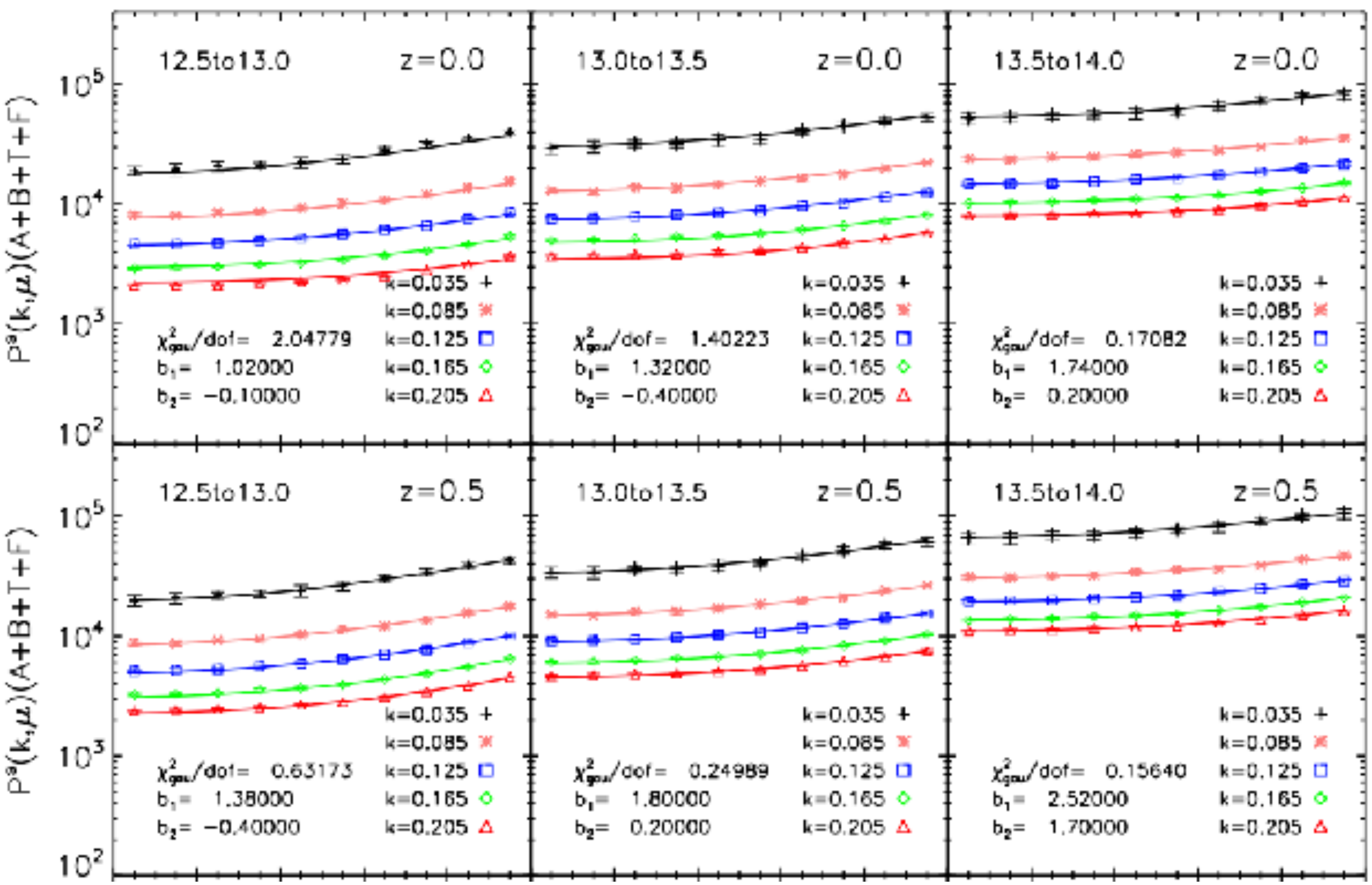
$$\begin{aligned}
P_{\delta_h\delta_h}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2b_1P_{b2,\delta}(k) + 2b_{s2}b_1P_{bs2,\delta}(k) \\
&\quad + 2b_{3\mathrm{nl}}b_1\sigma_3^2(k)P_{\mathrm{m}}^{\mathrm{L}}(k) + b_2^2P_{b22}(k) + 2b_2b_{s2}P_{b2s2}(k) + b_{s2}^2P_{bs22}(k)\,, \\
P_{\delta_h\theta_h}(k) &= b_1P_{\delta\theta}(k) + b_2P_{b2,\theta}(k) + b_{s2}P_{bs2,\theta}(k) + b_{3\mathrm{nl}}\sigma_3^2(k)P_{\mathrm{m}}^{\mathrm{L}}(k)\,, \\
P_{\delta_h\delta}(k) &= b_1P_{\delta\delta}(k) + b_2P_{b2,\delta}(k) + b_{s2}P_{bs2,\delta}(k) + b_{3\mathrm{nl}}\sigma_3^2(k)P_{\mathrm{m}}^{\mathrm{L}}(k)\,.
\end{aligned}$$

Yi, YSS, Oh 2017 prepared

Mapping of clustering for Halo II

$P_s(k,\mu) = [P_{hh}(k) + 2\mu^2 P_{h\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu) + T(k,\mu) + F(k,\mu)]\, D^{FoG}$

- The estimated halo spectrum using the bias model based upon perturbed terms which are computed using dark matter simulations agrees with the measured spectrum



Yi, YSS, Oh 2017 prepared

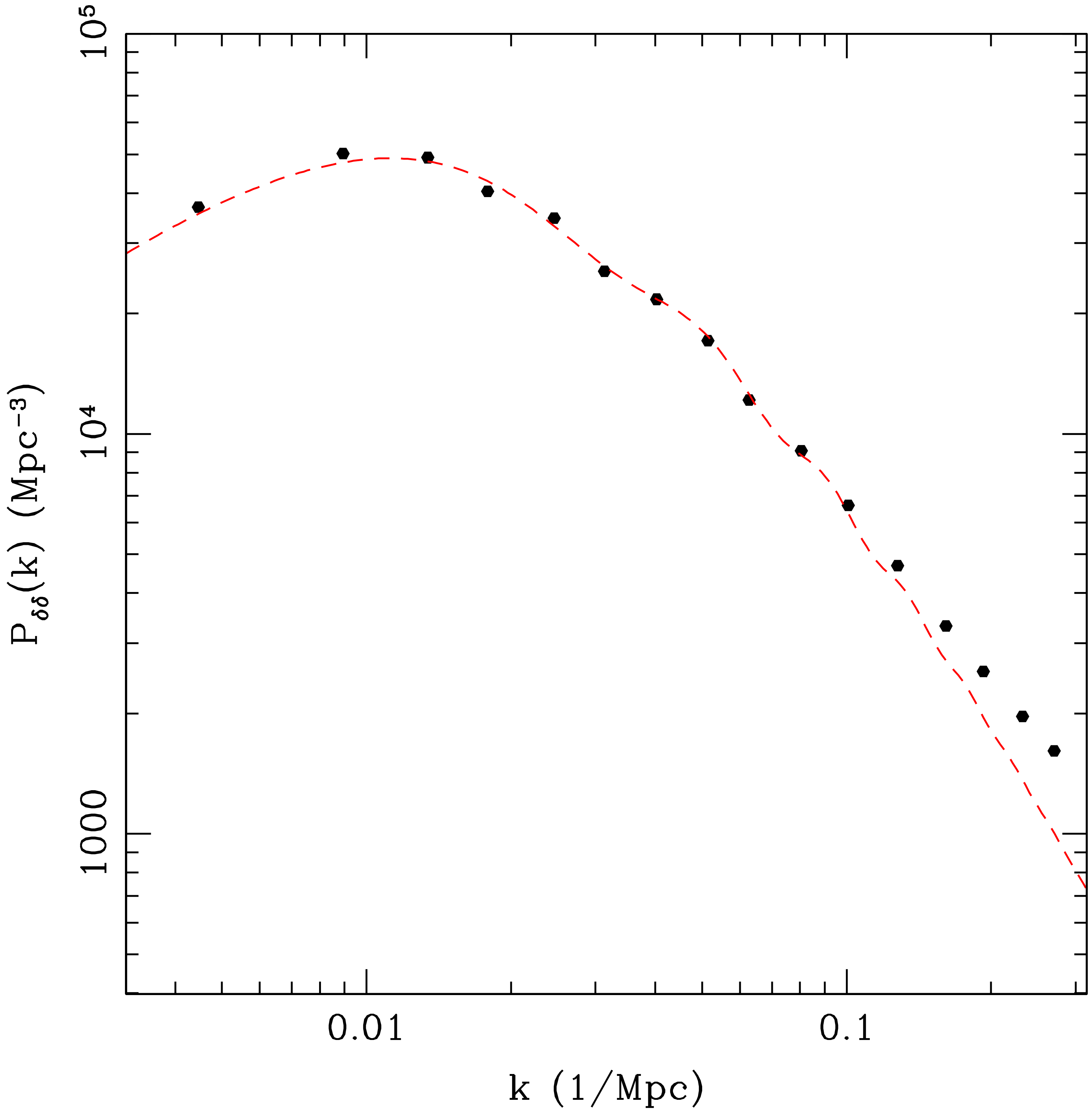
Accurate measurement of growth function

- The template should be made independent of the types of biased tracers, and it is prepared using dark matter particle simulations
- The structure formation grows coherently from the last scattering surface to the present epoch in most dark energy models. We test whether we can exploit the fiducial template to generate different cosmological models which is different by growth functions
- Non-linear spectrum: we use the perturbative theory and the simulation measurement, in order to classify the different growth function dependences
- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication
- We keep the same Gaussian FoG with one single parameter σ_p

YSS, Yi, Oh, Taruya 2017 prepared

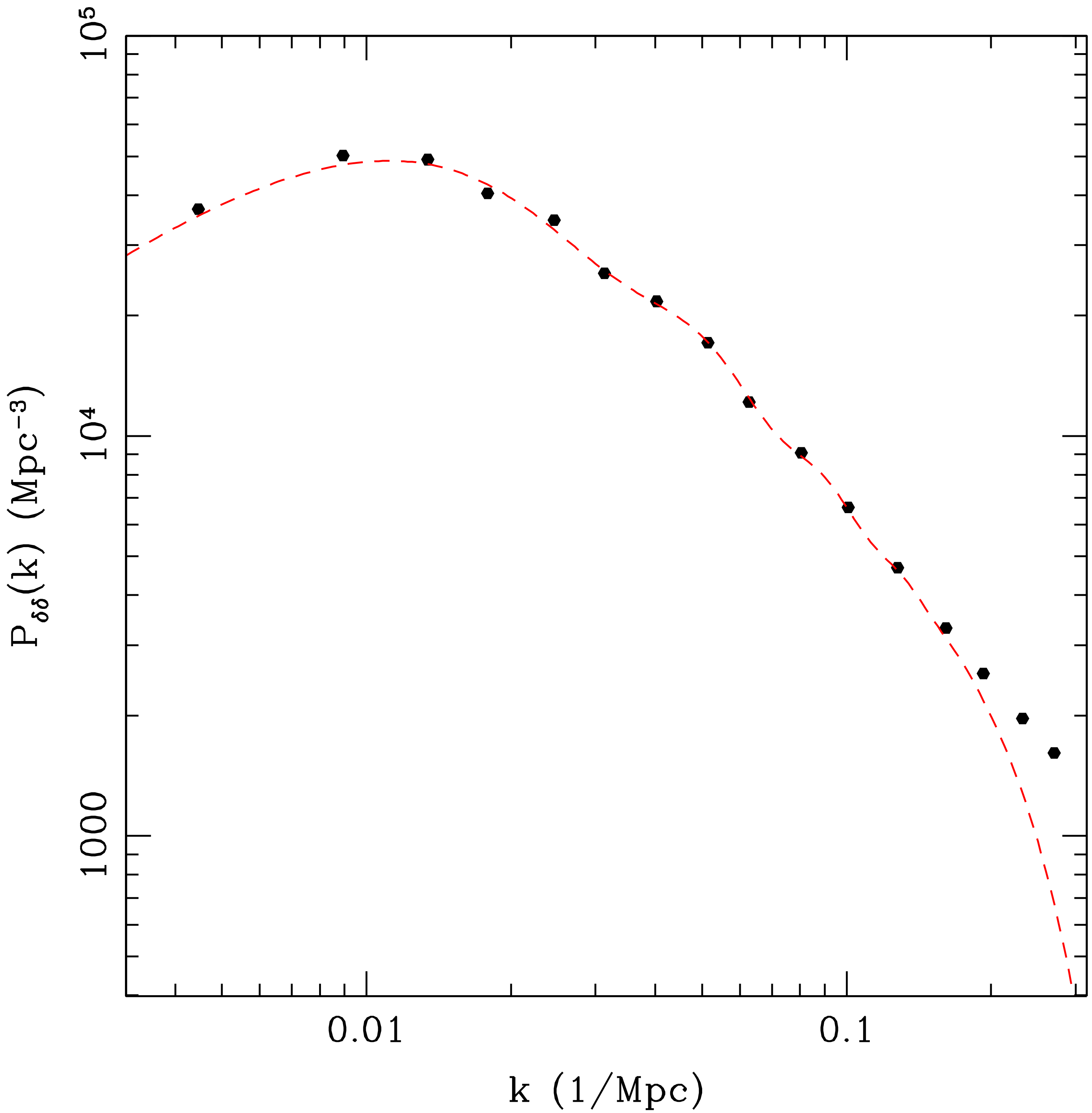
The nonlinear physics contamination

The discrepancy between linear prediction and measurement



The nonlinear physics contamination

Theoretical prediction is improved by perturbation theory by two loop corrections



The growth function dependence of non-linearity

- Non-linear spectrum: we use the perturbative theory and the simulation measurement, in order to classify the different growth function dependences

$$\bar{P}_{XY}(k,z) = \bar{P}^{\rm th}_{XY}(k,z) + \bar{P}^{\rm res}_{XY}(k,z),$$

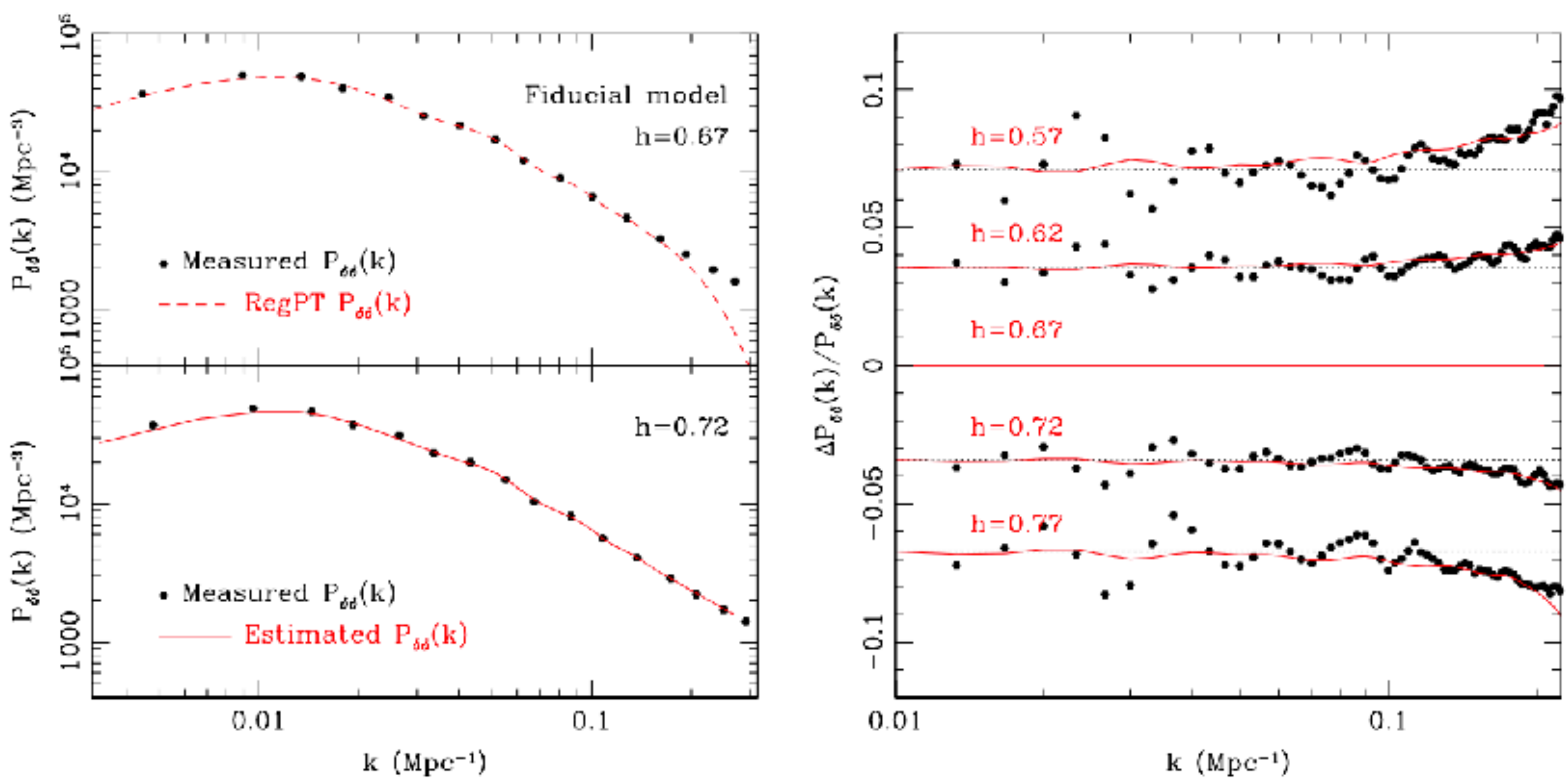
$$\begin{aligned}
\bar{P}_{XY}(k,z) &= \bar{\Gamma}^{(1)}_X(k,z)\bar{\Gamma}^{(1)}_Y(k,z)\bar{P}^i(k) \\
&+2\int \frac{d^3\vec{q}}{(2\pi)^3}\bar{\Gamma}^{(2)}_X(\vec{q},\vec{k}-\vec{q},z)\bar{\Gamma}^{(2)}_Y(\vec{q},\vec{k}-\vec{q},z)\bar{P}^i(q)\bar{P}^i(|\vec{k}-\vec{q}|) \\
&+6\int \frac{d^3\vec{p}d^3\vec{q}}{(2\pi)^6}\bar{\Gamma}^{(3)}_X(\vec{p},\vec{q},\vec{k}-\vec{p}-\vec{q},z)\bar{\Gamma}^{(3)}_Y(\vec{p},\vec{q},\vec{k}-\vec{p}-\vec{q},z)\bar{P}^i(p)\bar{P}^i(q)\bar{P}^i(|\vec{k}-\vec{p}-\vec{q}|),
\end{aligned}$$

$$\begin{aligned}
\bar{P}^{\rm res}_{XY} = \bar{G}_X\bar{G}_Y\bar{G}^4_\delta \Big\{ &\left[\bar{\mathcal{O}}^{(1)}_{Y,5} + {\rm higher}\right]\bar{P}^i + \left[\bar{\mathcal{O}}^{(1)}_{X,5} + {\rm higher}\right]\bar{P}^i, \\
&+\int\left[\bar{\mathcal{O}}^{(2)}_{Y,4}\bar{F}^{(2)}_Y + {\rm higher}\right]\bar{P}^i\bar{P}^i + \int\left[\bar{\mathcal{O}}^{(2)}_{X,4}\bar{F}^{(2)}_X + {\rm higher}\right]\bar{P}^i\bar{P}^i, \\
&+\int\int\left[\bar{\mathcal{O}}^{(3)}_{Y,3}\bar{F}^{(3)}_Y + {\rm higher}\right]\bar{P}^i\bar{P}^i\bar{P}^i + \int\int\left[\bar{\mathcal{O}}^{(3)}_{X,3}\bar{F}^{(3)}_X + {\rm higher}\right]\bar{P}^i\bar{P}^i\bar{P}^i\Big\}.
\end{aligned}$$

YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of non-linearity

- Non-linear spectrum: we use the perturbative theory and the simulation measurement, in order to classify the different growth function dependences



YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of higher order polynomial

- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication

$$\bar{A}(k,\mu) = j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle A_1 A_2 A_3 \rangle_c = \sum_{n=1}^{6} \bar{A}_n$$

$$\bar{A}_1 = 2j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle \bar{u}_z(\boldsymbol{r})\bar{\delta}(\boldsymbol{r})\bar{\delta}(\boldsymbol{r}')\rangle_c$$

$$\bar{A}_2 = j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle u_z(\boldsymbol{r})\delta(\boldsymbol{r})\,\nabla_z u_z(\boldsymbol{r}')\rangle_c$$

$$\bar{A}_3 = j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle u_z(\boldsymbol{r})\,\nabla_z u_z(\boldsymbol{r})\delta(\boldsymbol{r}')\rangle_c$$

$$\bar{A}_4 = 2j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle u_z(\boldsymbol{r})\,\nabla_z u_z(\boldsymbol{r})\,\nabla_z u_z(\boldsymbol{r}')\rangle_c$$

$$\bar{A}_5 = j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle -\delta(\boldsymbol{r})u_z(\boldsymbol{r}')\,\nabla_z u_z(\boldsymbol{r}')\rangle_c$$

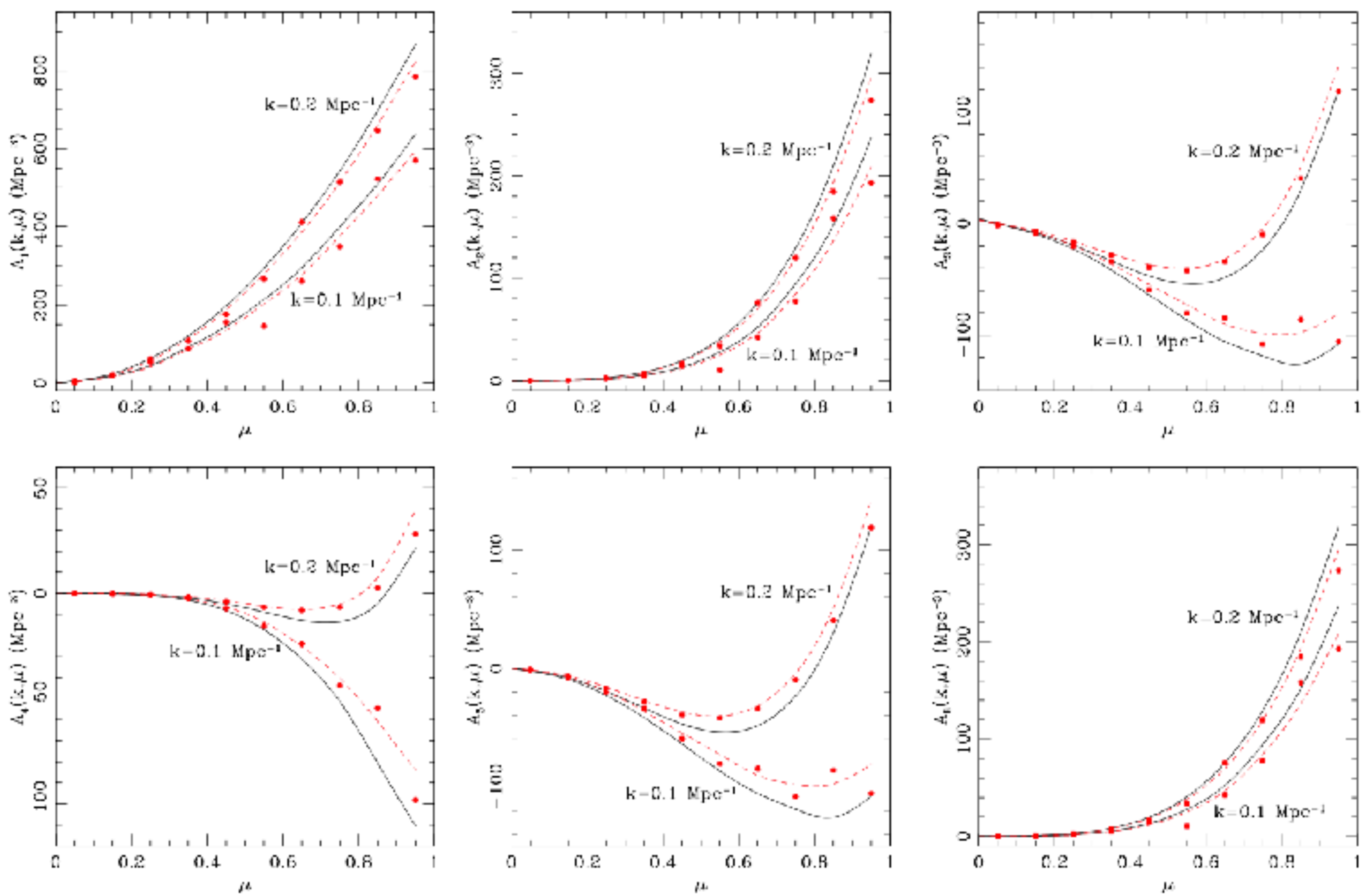
$$\bar{A}_6 = j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \;\langle -\nabla_z u_z(\boldsymbol{r})u_z(\boldsymbol{r}')\delta(\boldsymbol{r}')\rangle_c$$

$$\begin{aligned}
\bar{A}(k,\mu) &= \sum_{n=1}^{6} A_n \\
&= \left(G_\delta/\bar{G}_\delta\right)^2 \left(G_\Theta/\bar{G}_\Theta\right) \bar{A}_1 + \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{A}_2 \\
&+ \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{A}_3 + \left(G_\Theta/\bar{G}_\Theta\right)^3 \bar{A}_4 \\
&+ \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{A}_5 + \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{A}_6
\end{aligned}$$

YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of higher order polynomial

- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication



YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of higher order polynomial

- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication

$$\bar{B}(k,\mu) = j_1^2 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\; \langle A_1 A_2\rangle_c \langle A_1 A_3\rangle_c$$
$$= \sum_{n=1}^{4} \bar{\mathcal{B}}_n$$

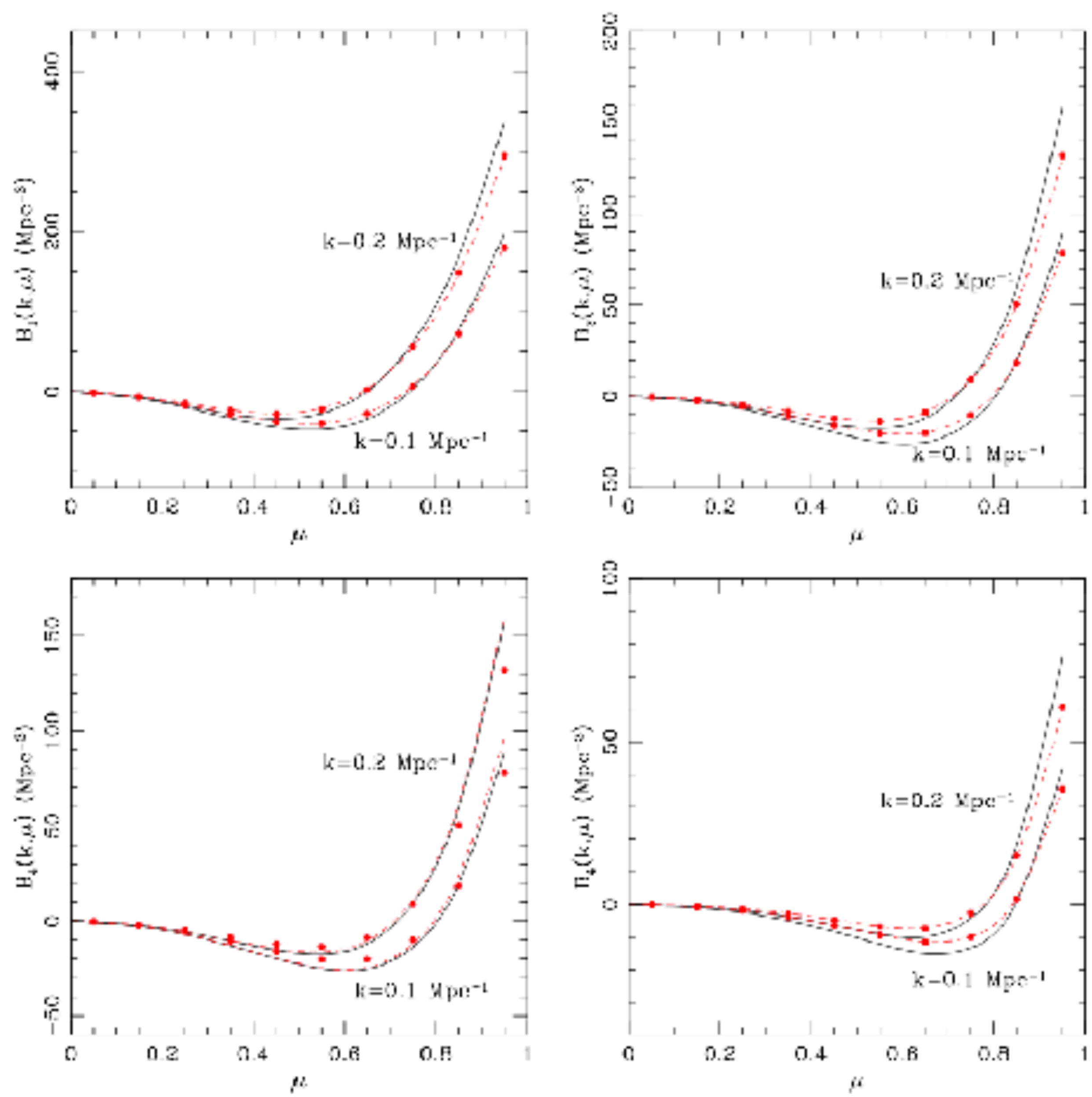
$$\bar{\mathcal{B}}_1 = j_1^2 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\; \langle -u_z(\boldsymbol{r}')\delta(\boldsymbol{r})\rangle_c \langle u_z(\boldsymbol{r})\delta(\boldsymbol{r}')\rangle_c$$
$$\bar{\mathcal{B}}_2 = j_1^2 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\; \langle -u_z(\boldsymbol{r}')\delta(\boldsymbol{r})\rangle_c \langle u_z(\boldsymbol{r})\, \nabla_z u_z(\boldsymbol{r}')\rangle_c$$
$$\bar{\mathcal{B}}_3 = j_1^2 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\; \langle -u_z(\boldsymbol{r}')\, \nabla_z u_z(\boldsymbol{r})\rangle_c \langle u_z(\boldsymbol{r})\delta(\boldsymbol{r}')\rangle_c$$
$$\bar{\mathcal{B}}_4 = j_1^2 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\; \langle -u_z(\boldsymbol{r}')\, \nabla_z u_z(\boldsymbol{r})\rangle_c \langle u_z(\boldsymbol{r})\, \nabla_z u_z(\boldsymbol{r}')\rangle_c$$

$$\bar{B}(k,\mu) = \sum_{n=1}^{4} \mathcal{B}_n$$
$$= (G_\delta/\bar{G}_\delta)^2 (G_\Theta/\bar{G}_\Theta)^2 \bar{\mathcal{B}}_1 + (G_\delta/\bar{G}_\delta)(G_\Theta/\bar{G}_\Theta)^3 \bar{\mathcal{B}}_2$$
$$+ (G_\delta/\bar{G}_\delta)(G_\Theta/\bar{G}_\Theta)^3 \bar{\mathcal{B}}_3 + (G_\Theta/\bar{G}_\Theta)^4 \bar{\mathcal{B}}_4$$

YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of higher order polynomial

- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication



YSS, Yi, Oh, Taruya 2017 prepared

The growth function dependence of higher order polynomial

- Higher order polynomials: we split different growth function dependent terms in pieces, and apply zeroth order growth function multiplication

$$
\begin{aligned}
\bar{T}(k,\mu) &= \frac{1}{2} j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle A_1^2 A_2 A_3 \rangle_c, \\
&= \sum_{n=1}^{7} \bar{\mathcal{T}}_n
\end{aligned}
$$

$$
\begin{aligned}
\bar{\mathcal{T}}_1 &= j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle u_z(\boldsymbol{r}) u_z(\boldsymbol{r}) \delta(\boldsymbol{r}) \delta(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_2 &= j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle u_z(\boldsymbol{r}) u_z(\boldsymbol{r}) \delta(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_3 &= j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle u_z(\boldsymbol{r}) u_z(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}) \delta(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_4 &= j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle u_z(\boldsymbol{r}) u_z(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_5 &= \frac{1}{2} j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle -2 u_z(\boldsymbol{r}') u_z(\boldsymbol{r}) \delta(\boldsymbol{r}) \delta(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_6 &= j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle -2 u_z(\boldsymbol{r}') u_z(\boldsymbol{r}) \delta(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}') \rangle_c \\
\bar{\mathcal{T}}_7 &= \frac{1}{2} j_1^2 \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \, \langle -2 u_z(\boldsymbol{r}') u_z(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}) \, \nabla_z u_z(\boldsymbol{r}') \rangle_c
\end{aligned}
$$

$$
\begin{aligned}
\bar{T}(k,\mu) &= \sum_{n=1}^{3} \mathcal{T}_n \\
&= \left(G_\delta/\bar{G}_\delta\right)^2 \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{\mathcal{T}}_1 + \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^3 \bar{\mathcal{T}}_2 + \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^3 \bar{\mathcal{T}}_3 \\
&+ \left(G_\Theta/\bar{G}_\Theta\right)^4 \bar{\mathcal{T}}_4 + \left(G_\delta/\bar{G}_\delta\right)^2 \left(G_\Theta/\bar{G}_\Theta\right)^2 \bar{\mathcal{T}}_5 + \left(G_\delta/\bar{G}_\delta\right) \left(G_\Theta/\bar{G}_\Theta\right)^3 \bar{\mathcal{T}}_6 + \left(G_\Theta/\bar{G}_\Theta\right)^4 \bar{\mathcal{T}}_7
\end{aligned}
$$

YSS, Yi, Oh, Taruya 2017 prepared

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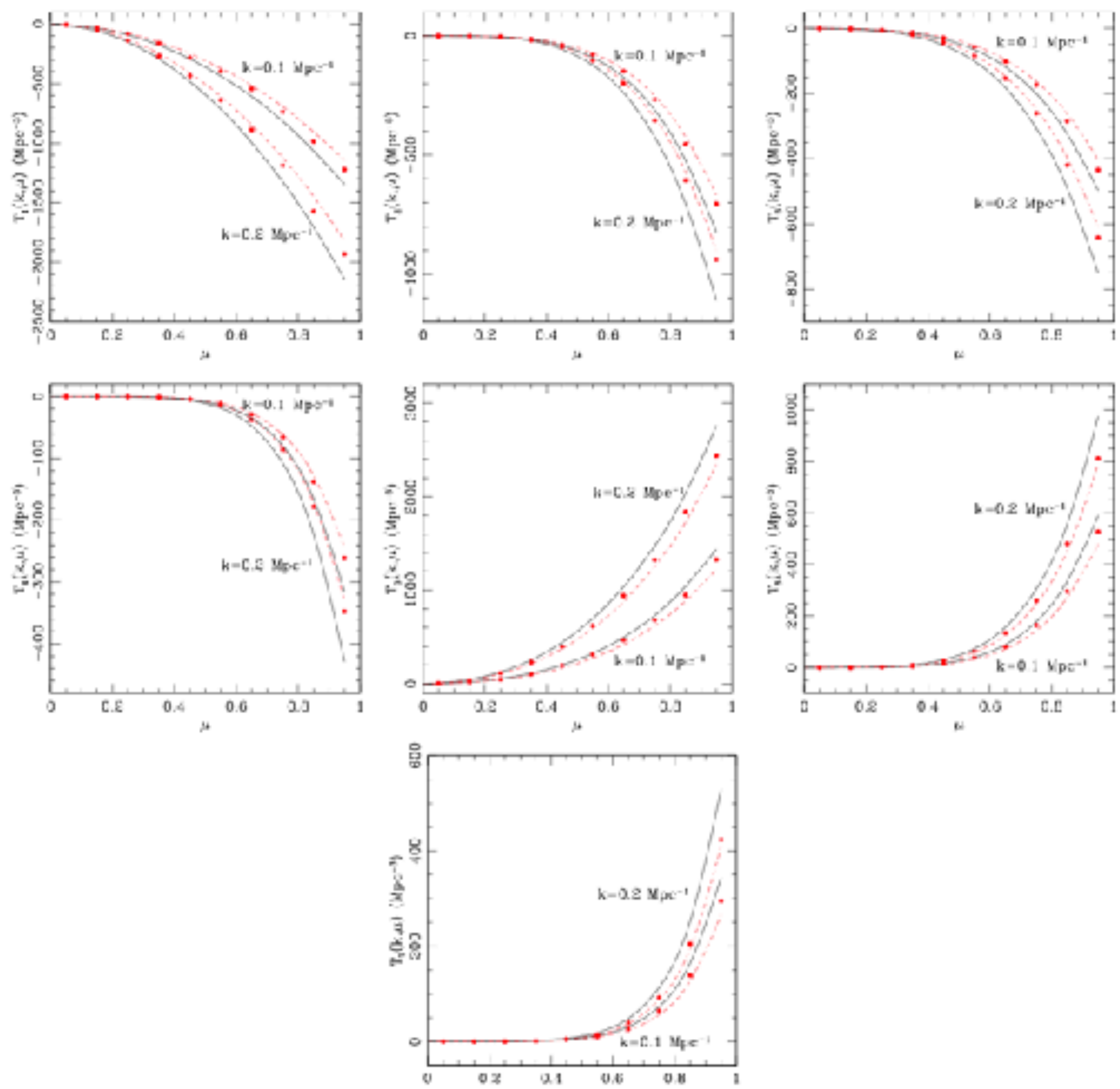
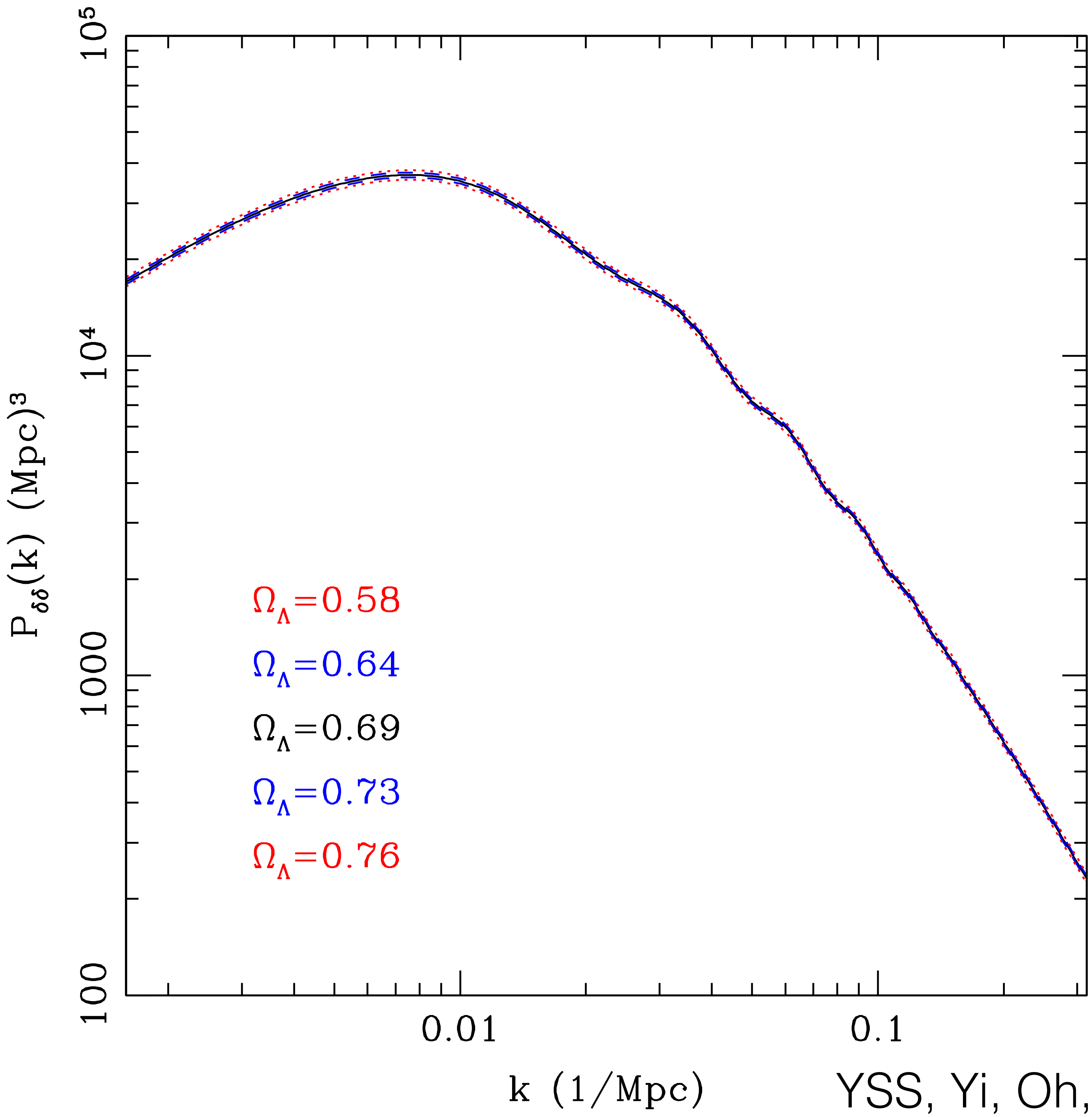


YSS, Yi, Oh, Taruya 2017 prepared

The measured spectra with different Ω_Λ

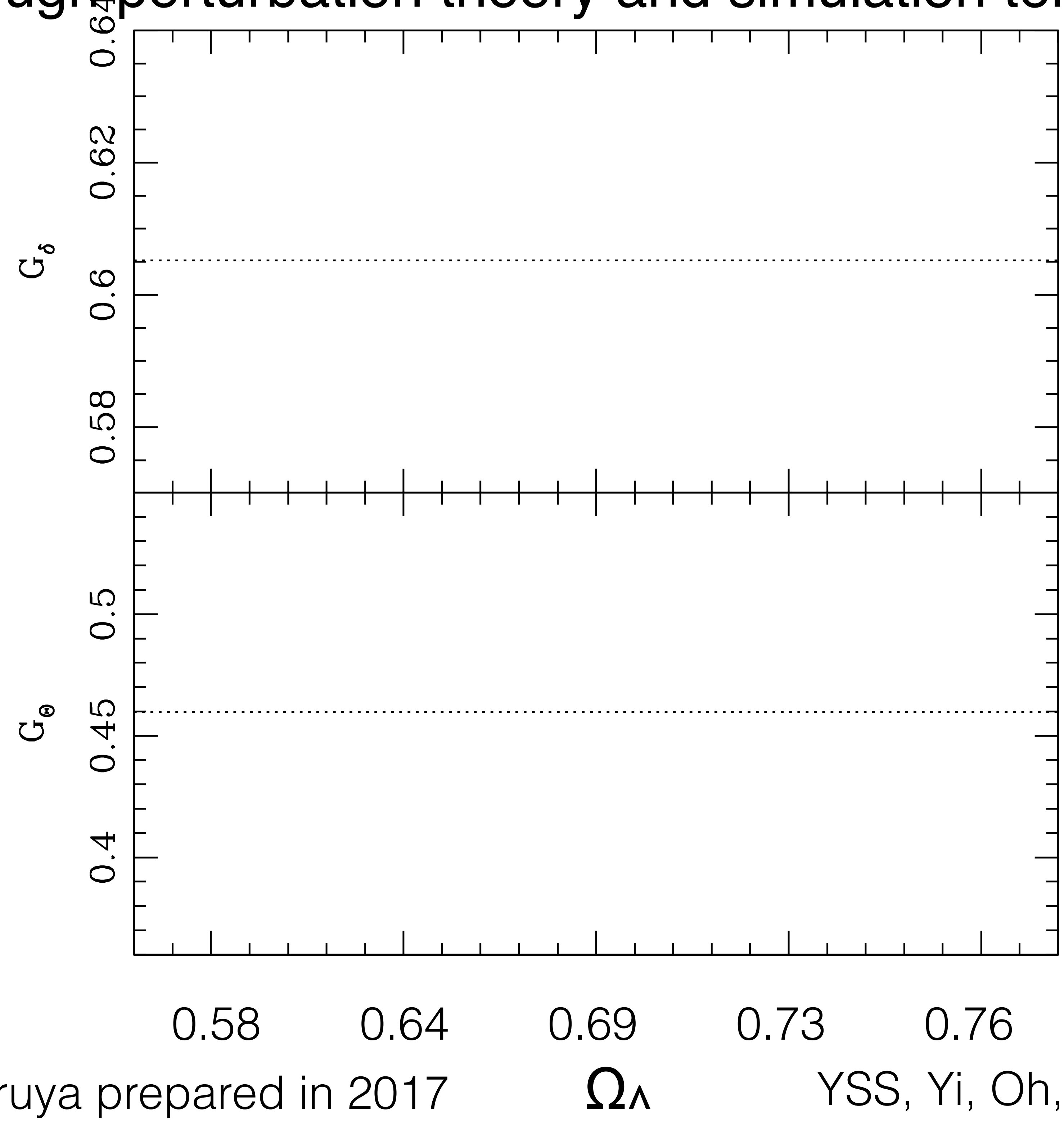
We vary Ω_Λ coherently with BAO statistics, i.e. the observed sound horizon is fixed



YSS, Yi, Oh, Taruya 2017 prepared

The accurate measurement of growth functions

We achieve the 1% accuracy measurement after a long journey through perturbation theory and simulation template



YSS, Yi, Oh and Taruya prepared in 2017

YSS, Yi, Oh, Taruya 2017 prepared

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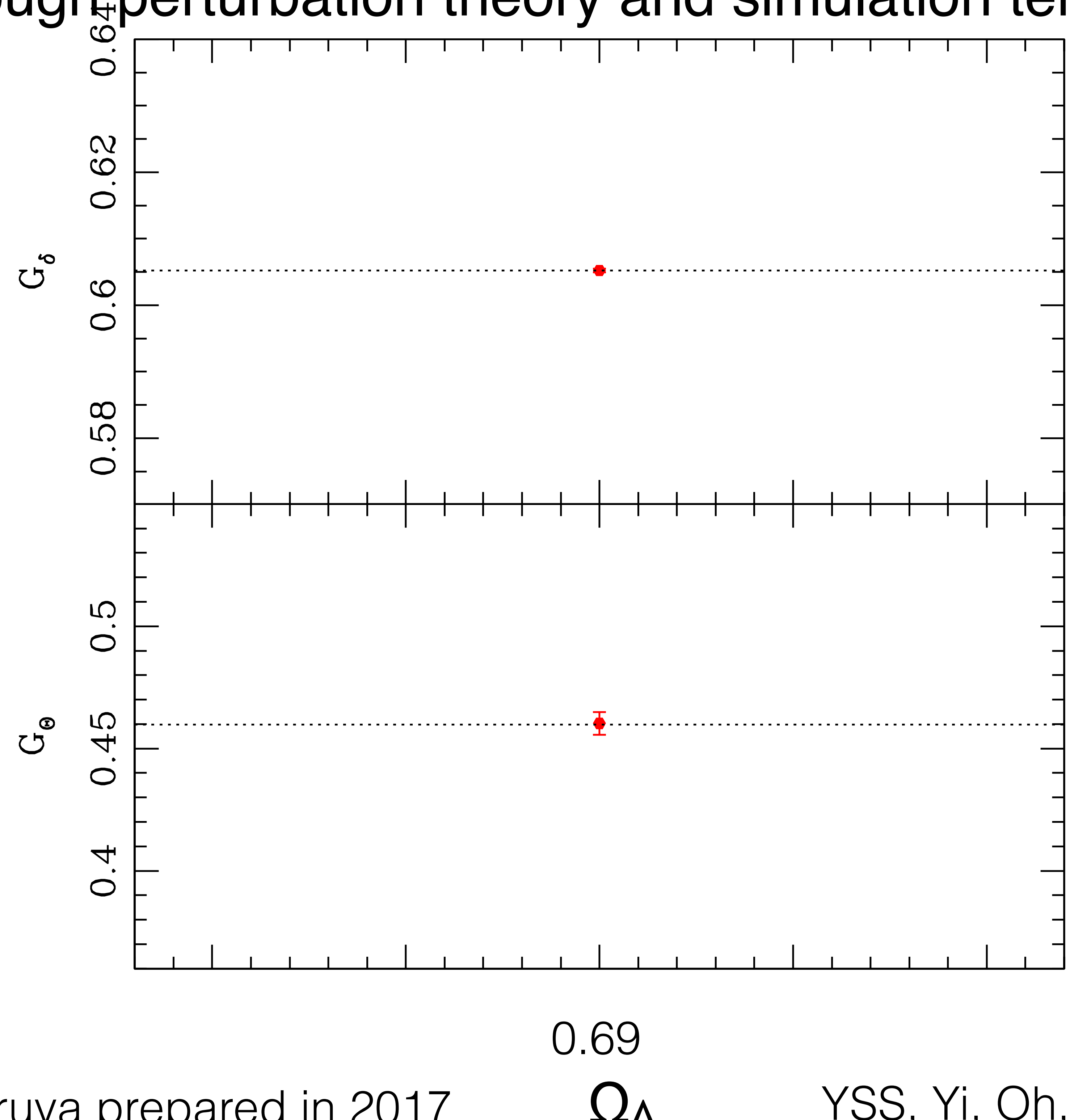

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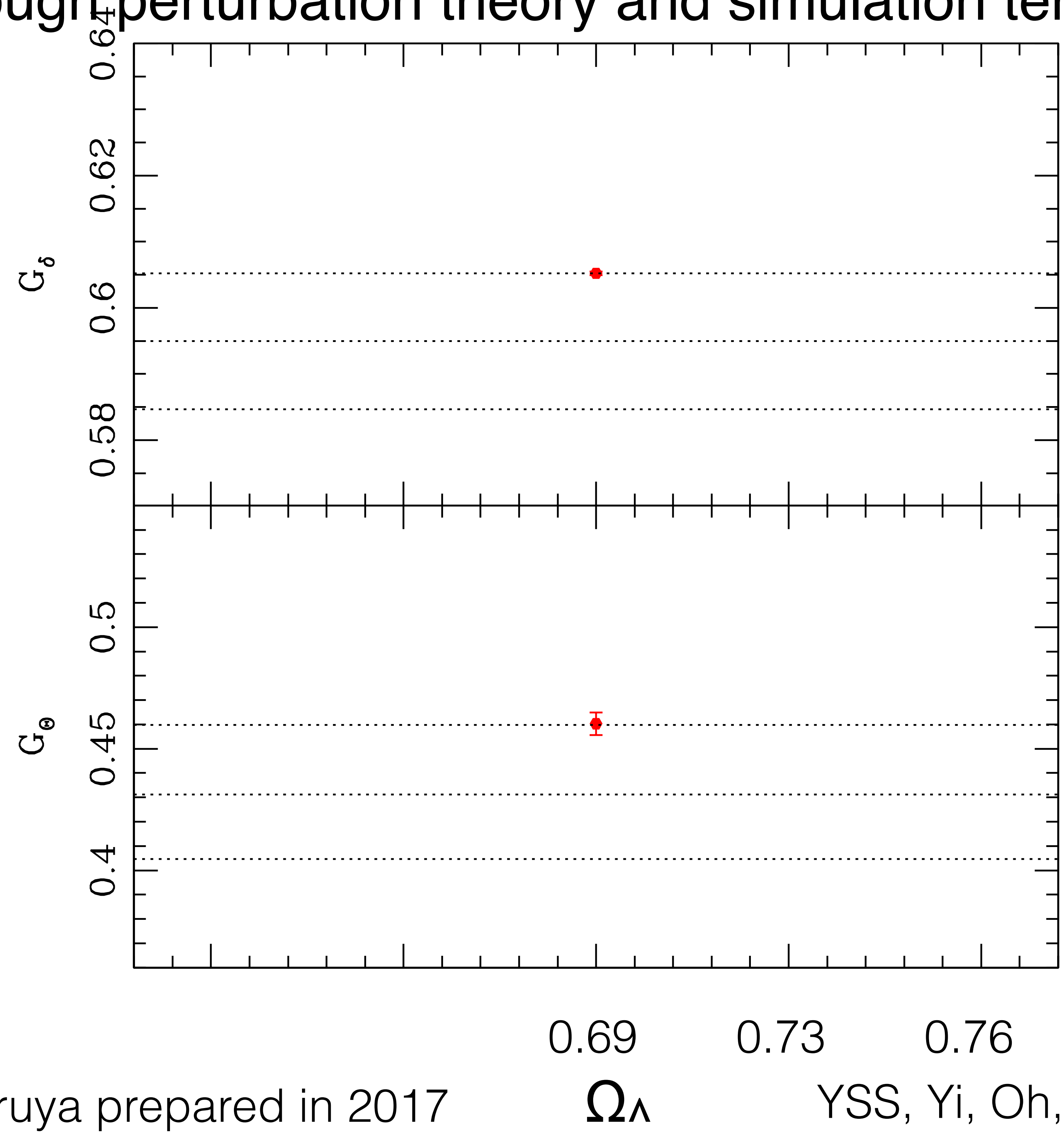

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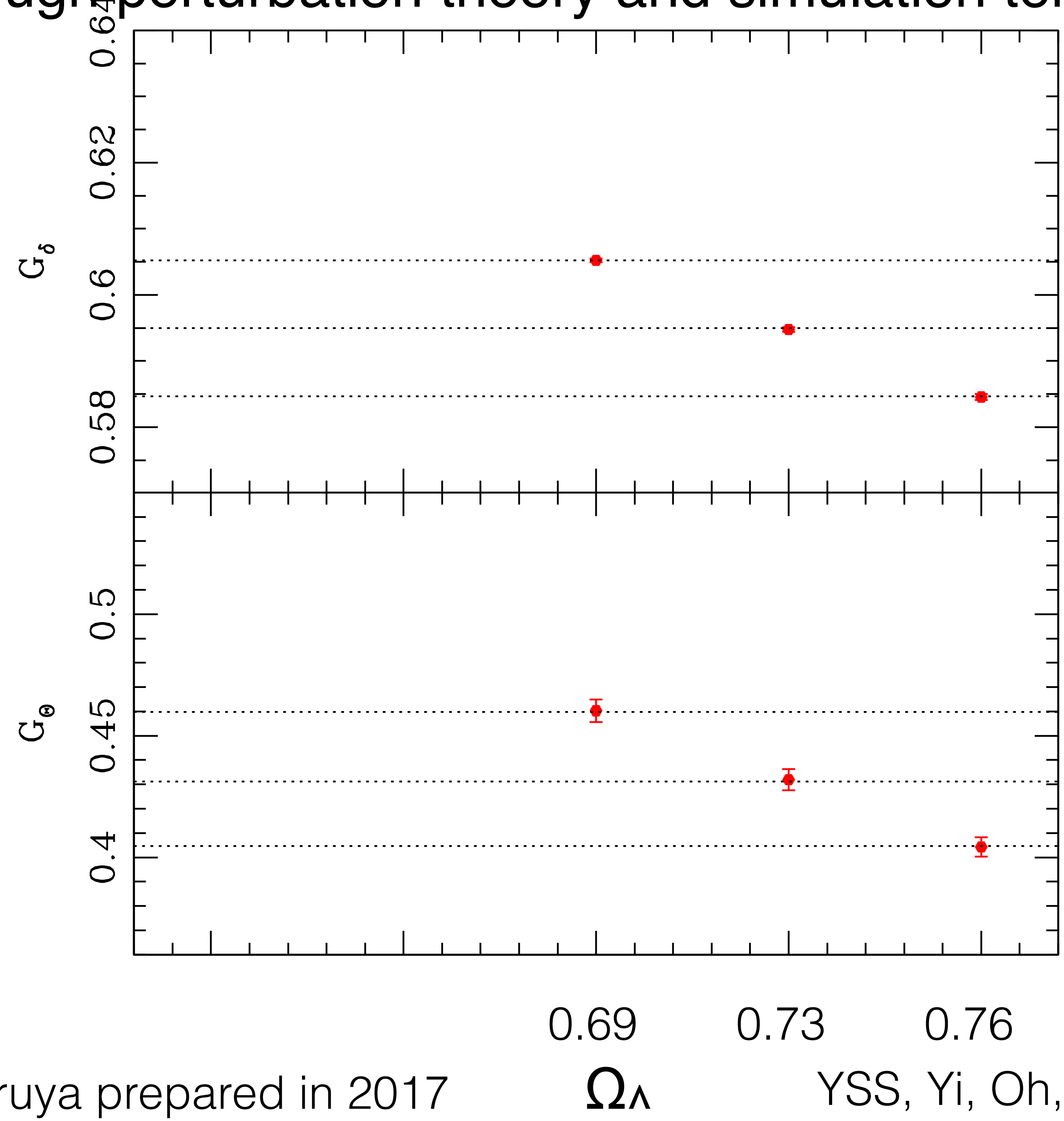

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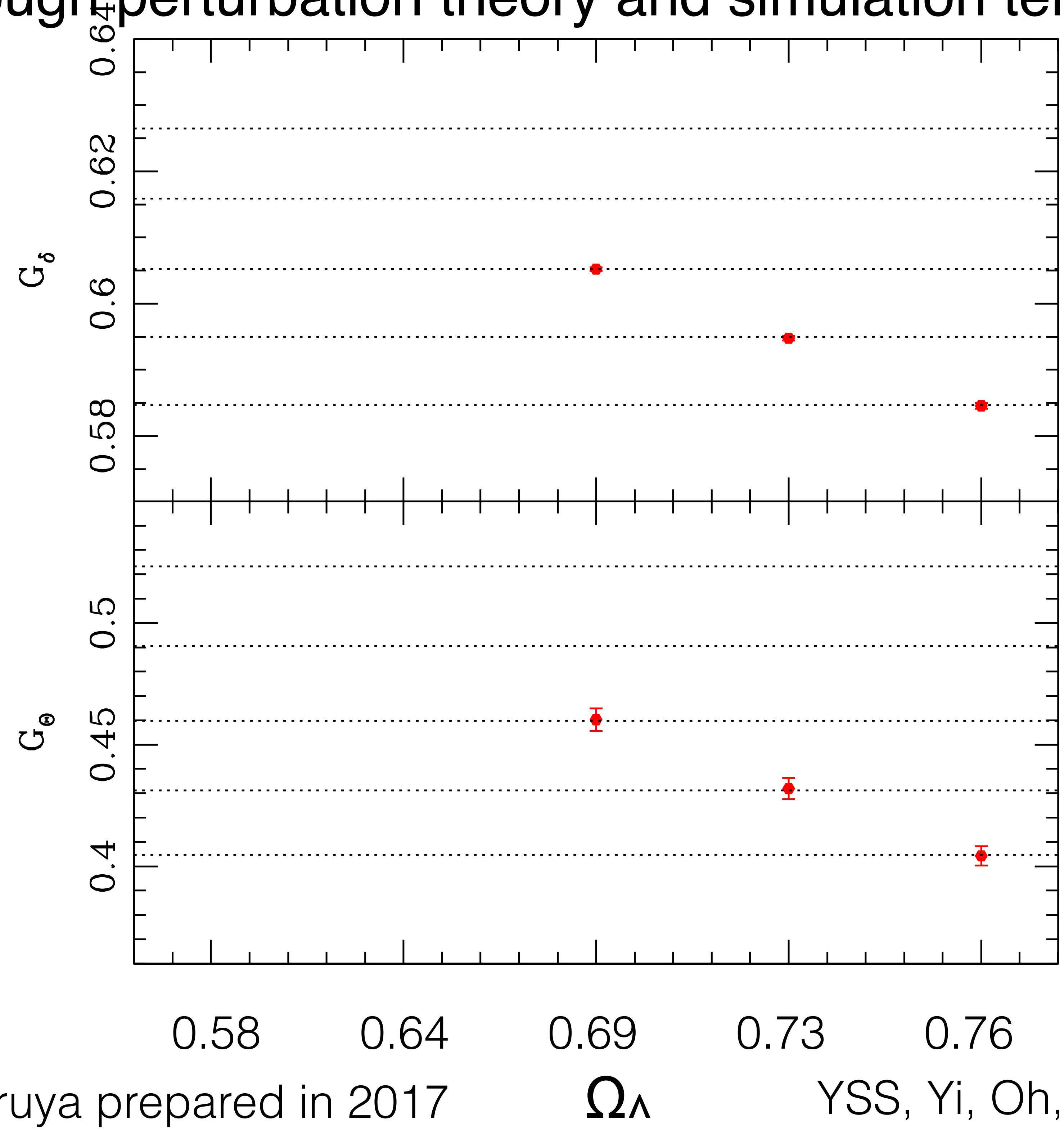

YSS, Yi, Oh and Taruya prepared in 2017

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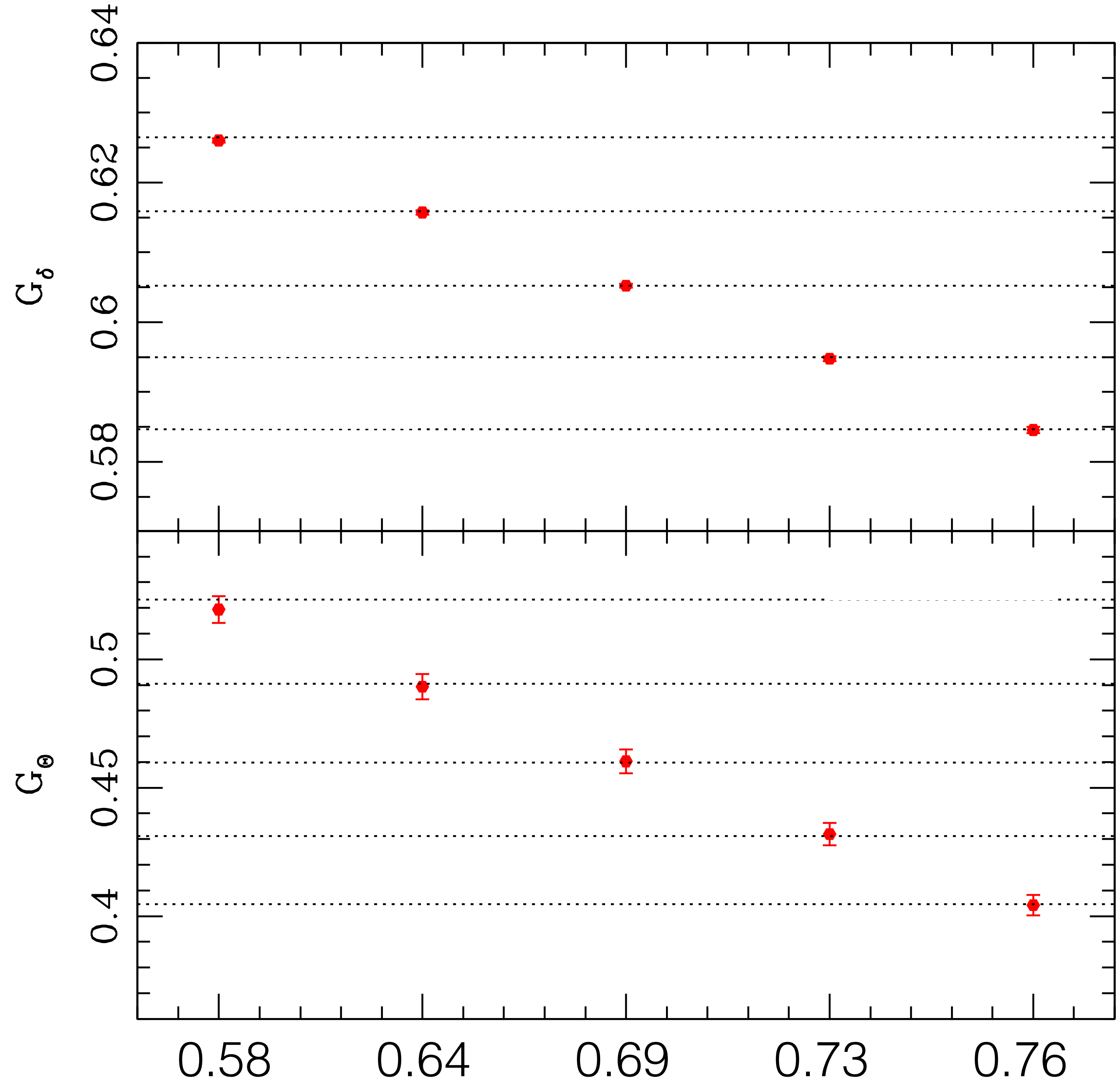


YSS, Yi, Oh and Taruya prepared in 2017

Ω_Λ

YSS, Yi, Oh, Taruya 2017 prepared

Precise determination on Ω_Λ

(D_A, H^{-1}, G_δ, G_θ, FoG)

Standard model

Cold dark matter

Massless neutrino

Λ

Open new window to test cosmological models

(D_A, H^{-1}, G_δ, G_Θ, FoG)

Standard model	New physics
Cold dark matter	Quintessence dark energy
Massless neutrino	Phantom dark energy

Λ

Open new window to test cosmological models

(D_A, H^{-1}, G_δ, G_Θ, FoG, , New, …)

New physics

Λ

Chameleon type gravity

Probing modified gravity

$d\boldsymbol{\delta}_m/dt + \boldsymbol{\theta}_m/a = 0$

$d\boldsymbol{\theta}_m/dt + H\boldsymbol{\theta}_m = k^2\boldsymbol{\psi}/a$

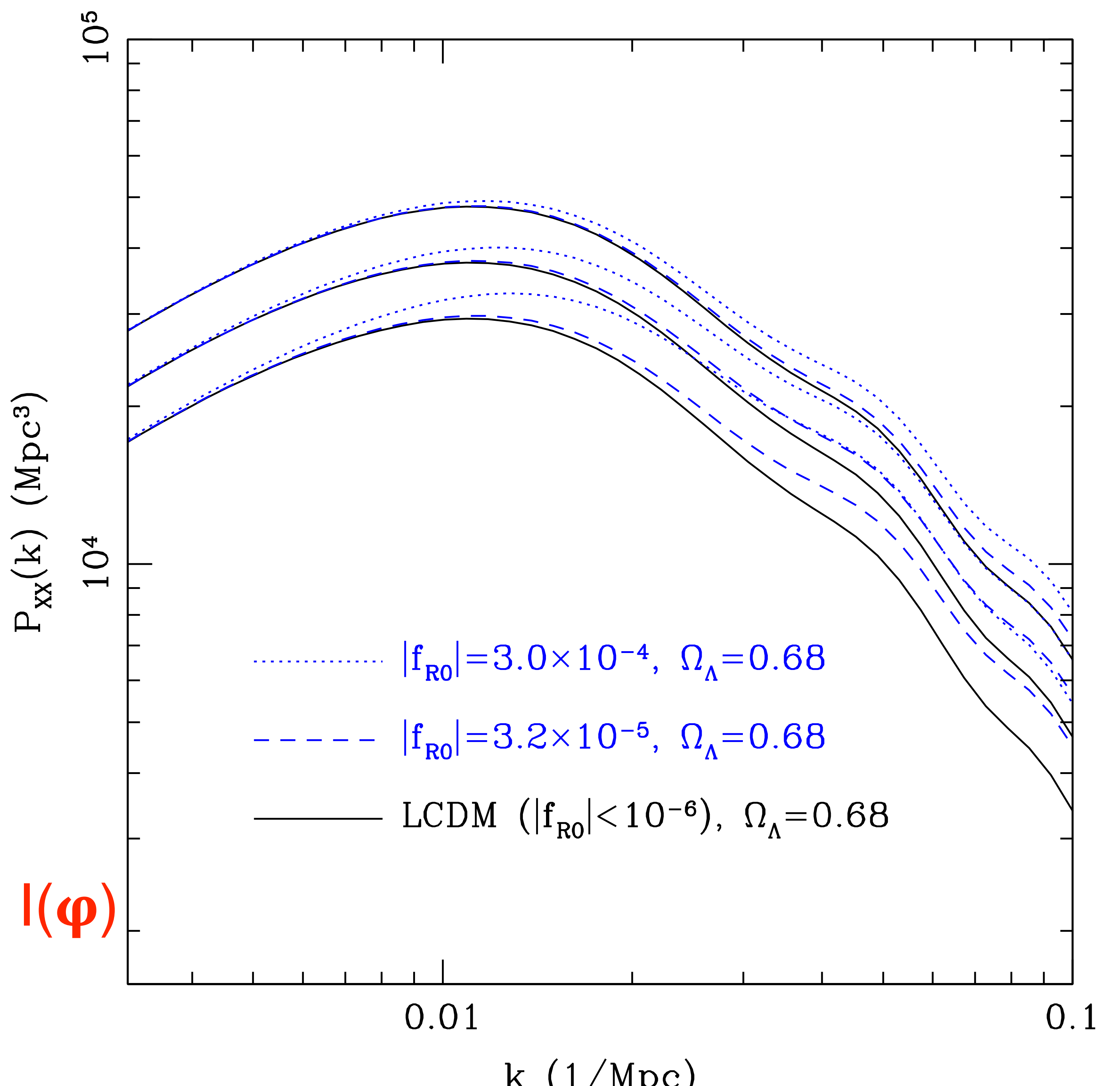
$k^2\,\boldsymbol{\phi} = 3/2\; H_0^2\Omega_m\; \boldsymbol{\delta}_m/a\; F(\boldsymbol{\epsilon})$

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

$\boldsymbol{\phi}_{fR} - \boldsymbol{\psi}_{fR} = \boldsymbol{\varphi}$

$k^2\,\boldsymbol{\psi} = -3/2\; H_0^2\Omega_m\; \boldsymbol{\delta}_m/a - 1/2\; k^2\boldsymbol{\varphi}$

$(1+w_{BD})\; k^2/a^2\; \boldsymbol{\varphi} = 3H_0^2\Omega_m\; \boldsymbol{\delta}_m/a - I(\boldsymbol{\varphi})$



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

YSS et.al. 2015

Probing modified gravity

$d\boldsymbol{\delta}_m/dt + \boldsymbol{\theta}_m/a = 0$

$d\boldsymbol{\theta}_m/dt + H\boldsymbol{\theta}_m = k^2\boldsymbol{\psi}/a$

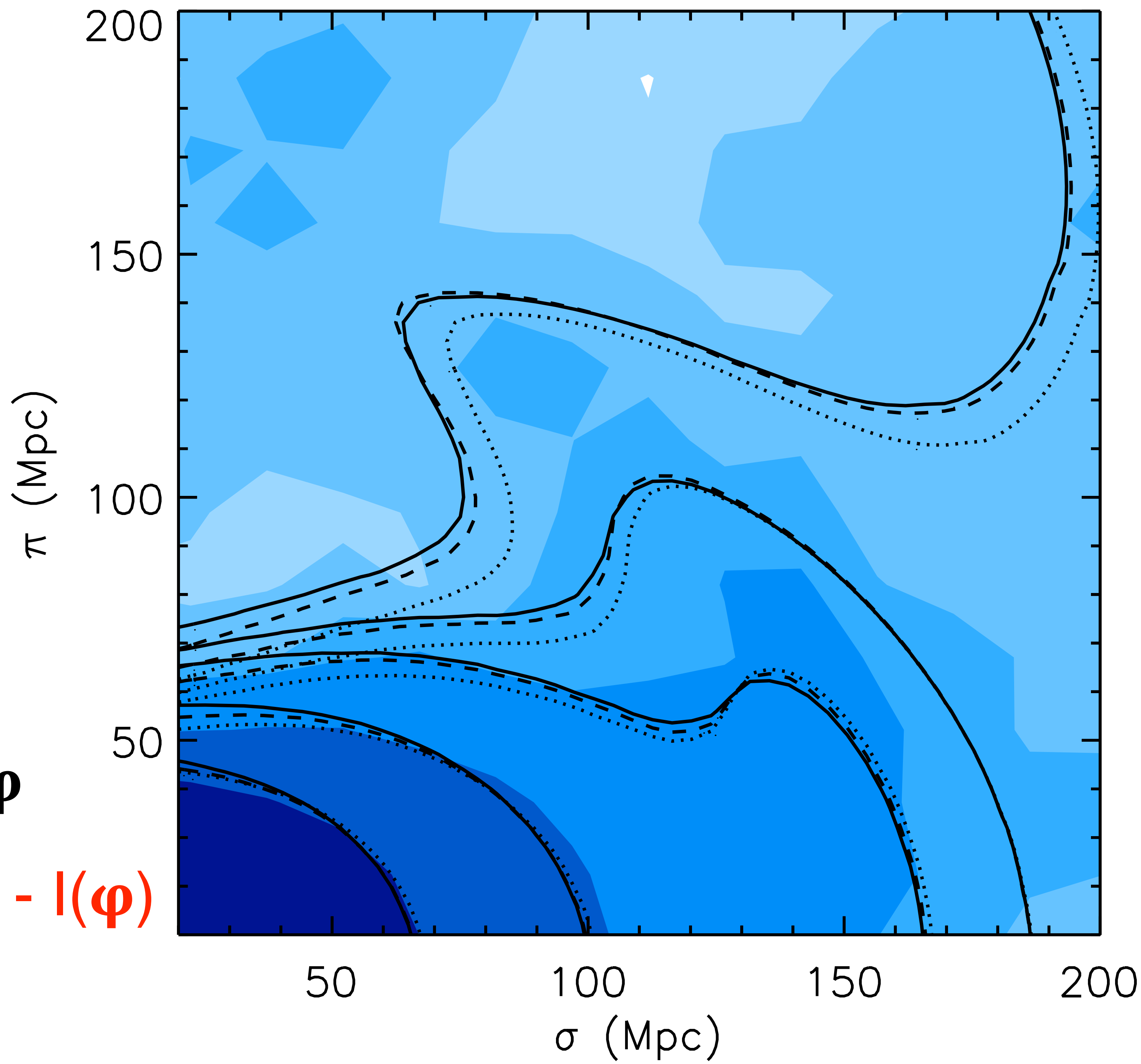
$k^2\,\boldsymbol{\phi} = 3/2\ H_0^2\Omega_m\ \boldsymbol{\delta}_m/a\ F(\boldsymbol{\epsilon})$

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

$\boldsymbol{\phi}_{fR} - \boldsymbol{\psi}_{fR} = \boldsymbol{\varphi}$

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

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



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

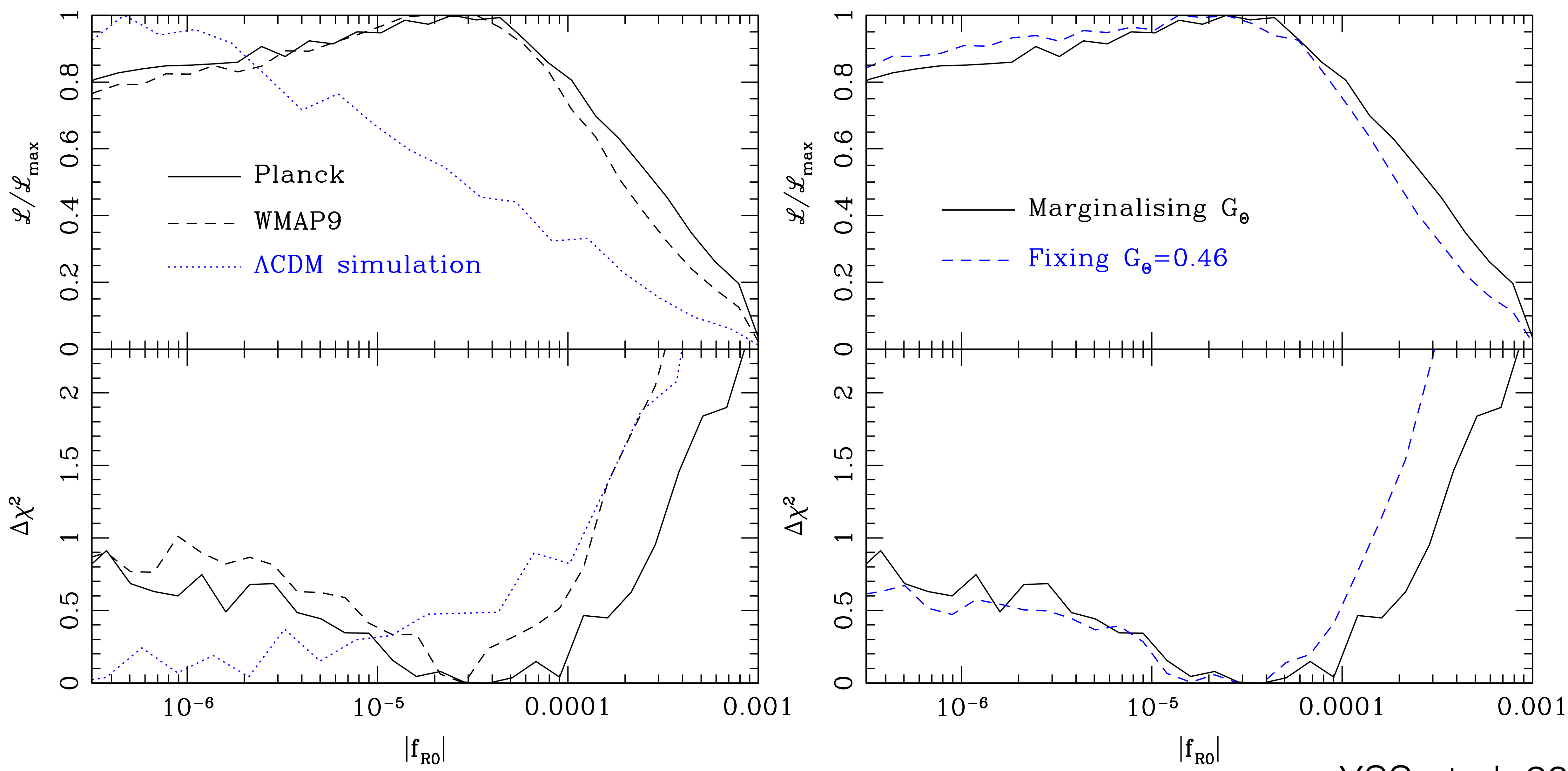
YSS et.al. 2015

Probing modified gravity

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

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

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



YSS et.al. 2015

Open new window to test cosmological models

(D_A, H^{-1}, G_δ, G_Θ, FoG, New, , …)

Standard model

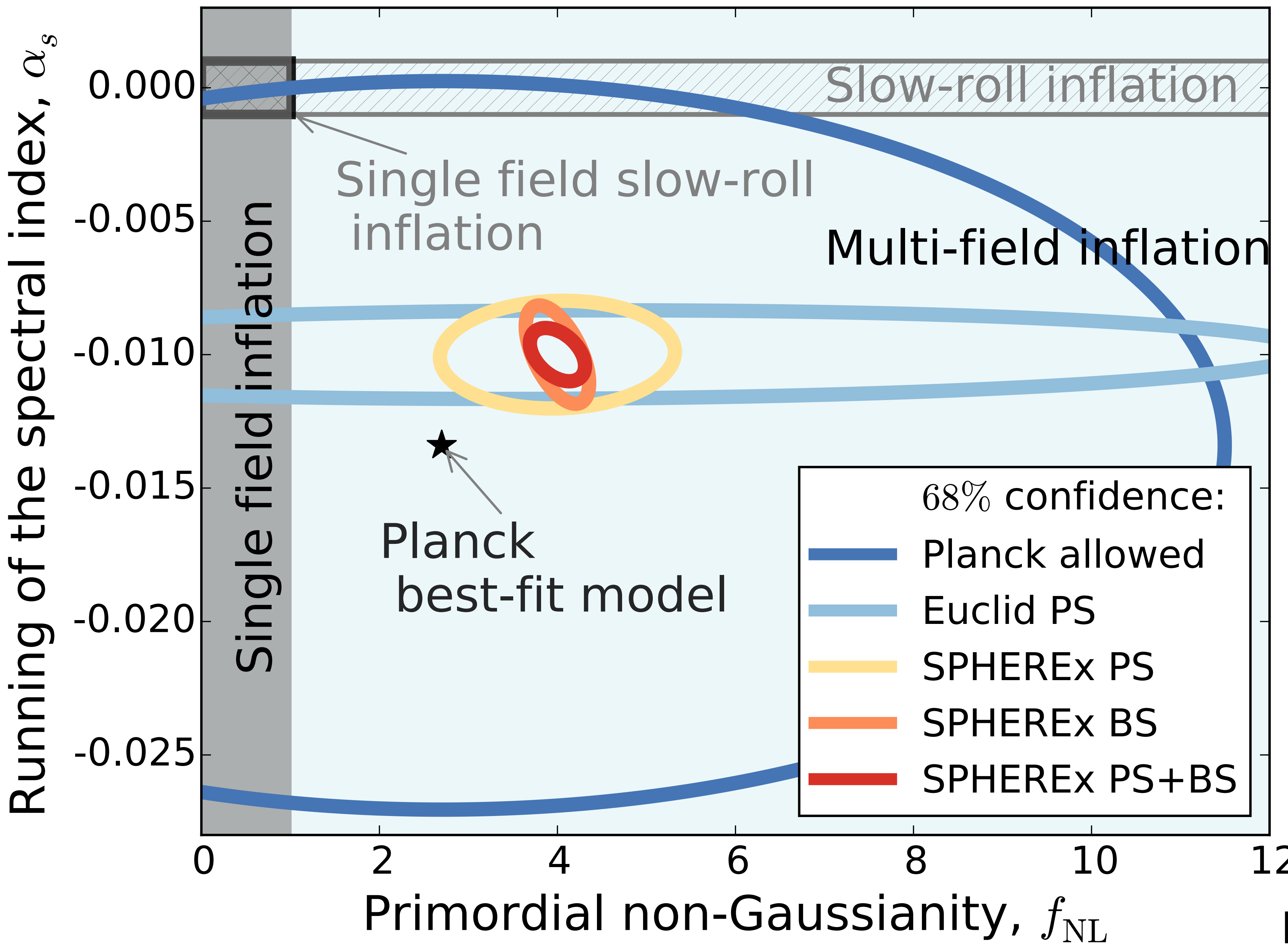
Massive neutrino

Λ

See Minji's Talk on Fri

Constraints on initial conditions

With the given horizon scale survey, we are accessible to initial condition FoM



Dore et.al. 2015

Full covariance approach

Fisher matrix is given by

$$F_{\alpha\beta} = \boldsymbol{\Sigma}_k \boldsymbol{\Sigma}_{k1k2k3} \, (\boldsymbol{\partial} S/\boldsymbol{\partial} p_\alpha) \, C^{-1} \, (\boldsymbol{\partial} S/\boldsymbol{\partial} p_\beta)$$

where the vector field S is given by

$$S = \begin{pmatrix} P(k,\boldsymbol{\mu}) \\ B(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2) \end{pmatrix}$$

The full covariance matrix is given by,

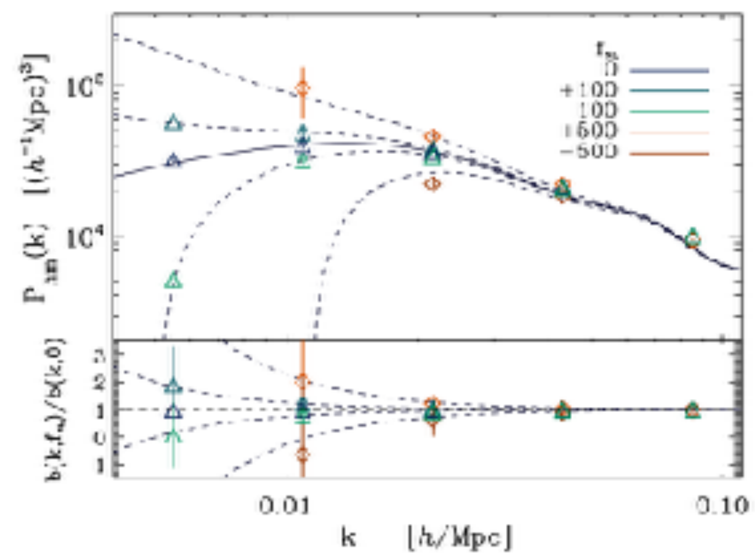
$$C^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BB}^{-1}M & C_{BB}^{-1}+C_{BB}^{-1}C_{Bp}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

This full covariance calculation is performed for DESI forecast.

Full covariance approach

Fisher matrix is given by

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



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,

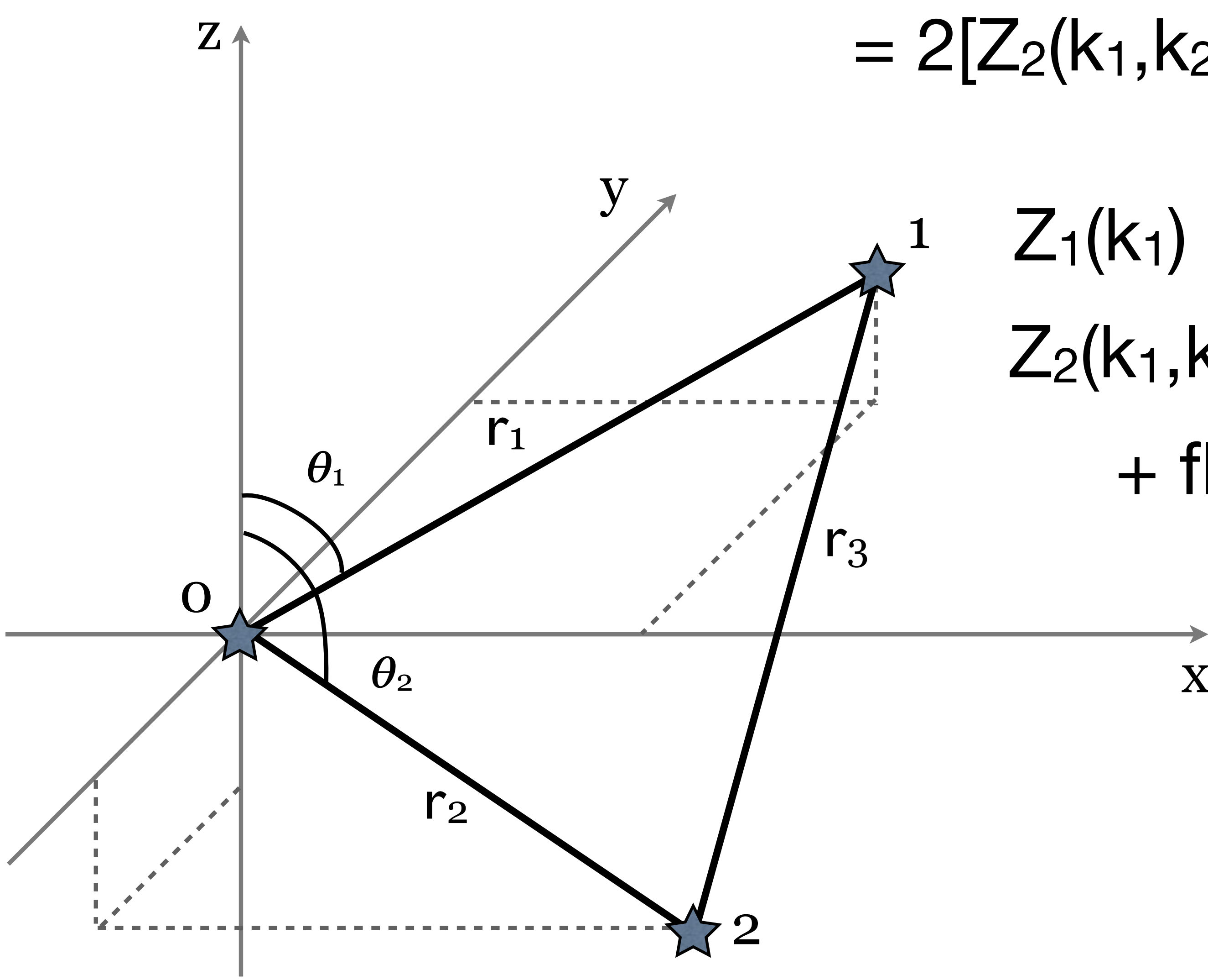
$$C^{-1} = \begin{pmatrix} M & -MC_{PB}C_{BB}^{-1} \\ -C_{BB}^{-1}C_{BB}^{-1}M & C_{BB}^{-1}+C_{BB}^{-1}C_{Bp}MC_{PB}C_{BB}^{-1} \end{pmatrix}$$

This full covariance calculation is performed for DESI forecast.

Bispectrum in redshift space

$$B(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2) = D^{B}{}_{FoG}\, B^{PT}(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2)$$

$$B^{PT}(k_1,k_2,k_3,\boldsymbol{\mu}_1,\boldsymbol{\mu}_2)$$
$$= 2[Z_2(k_1,k_2)Z_1(k_1)Z_2(k_2)P(k_1)P(k_2) + \text{cyclic}]$$



$$Z_1(k_1) = b+f\boldsymbol{\mu}_1^2$$

$$Z_2(k_1,k_2) = b_2/2 + bF_2 + f\boldsymbol{\mu}_{12}G_2$$
$$+ fk_{12}\boldsymbol{\mu}_{12}/2[\boldsymbol{\mu}_1/k_1Z_2(k_2)+\boldsymbol{\mu}_1/k_1Z_2(k_2)]$$

Sabiu, YSS 2016 prepared

YSS, Taruya, Akira 2015

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,

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

This full covariance calculation is performed for DESI forecast.

The ultimate cosmological test on GR

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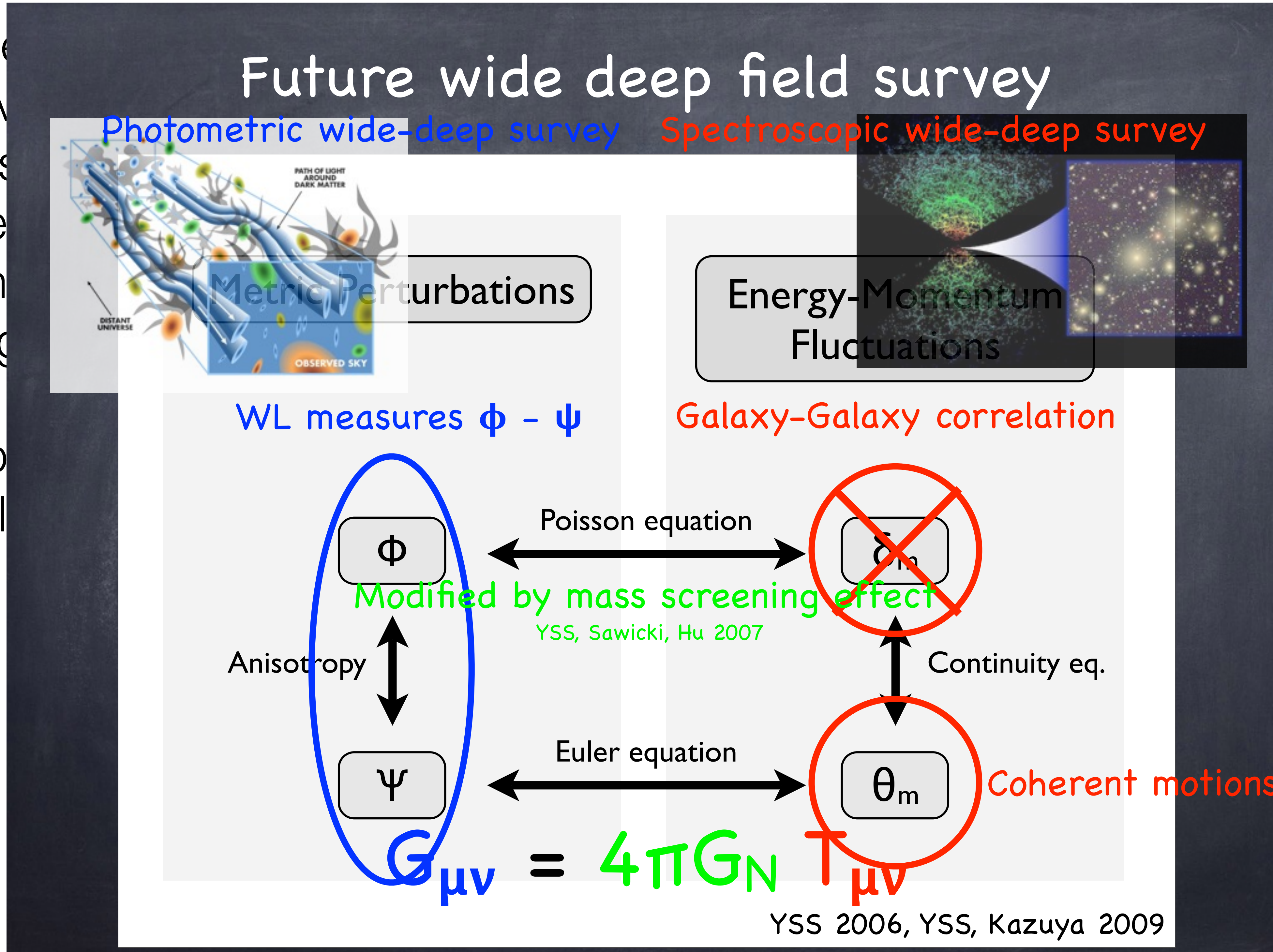

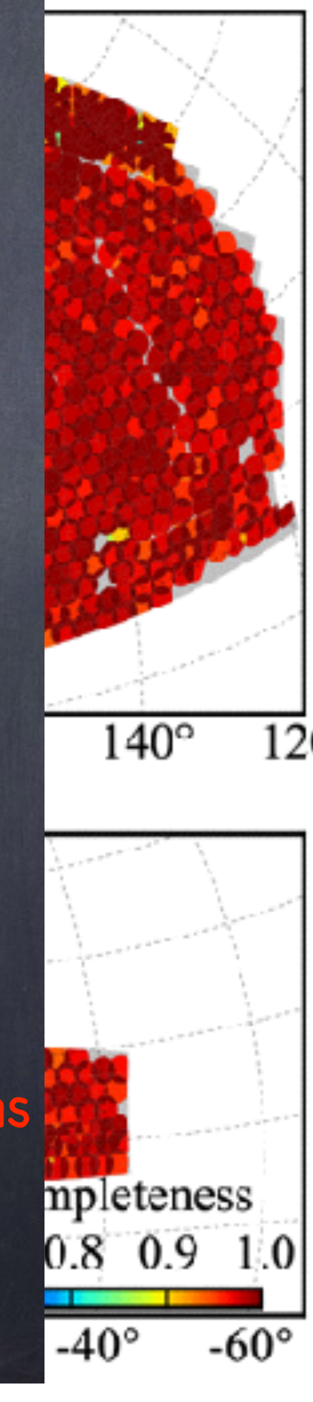

Conclusion

- We are confident of precise and accurate measurements of growth functions within 1% fractional error, for the cosmological model in which growth function evolves coherently.
- The same method can be applicable for modified gravity and massive neutrino constraints, but we need to produce those simulation.
- Spectroscopy survey provides us with a way to test initial conditions using inflationary parameter FoM. It makes sense that we cover as much as sky we can, to access to horizontal scale.
- The southern sky coverage is attractive to the community who is looking for test of GR cosmologically.
- We are nearly ready to maximally exploit the informations provided to us in next decade.