Measuring Peculiar Motion using Redshift Space Distortion

Large Scale Structure and Galaxy Flows, Quy Nhon
July 6^{th} 2016

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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 assumption:

    Inhomogeneous models: LTB, back reaction

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Dynamical Dark Energy: modifying matter

Alternative mechanism to generate fine tuned vacuum energy

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

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:

Geometrical Dark Energy: modifying gravity

Presence of extra dimension

Non-linear interaction to Einstein equation

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

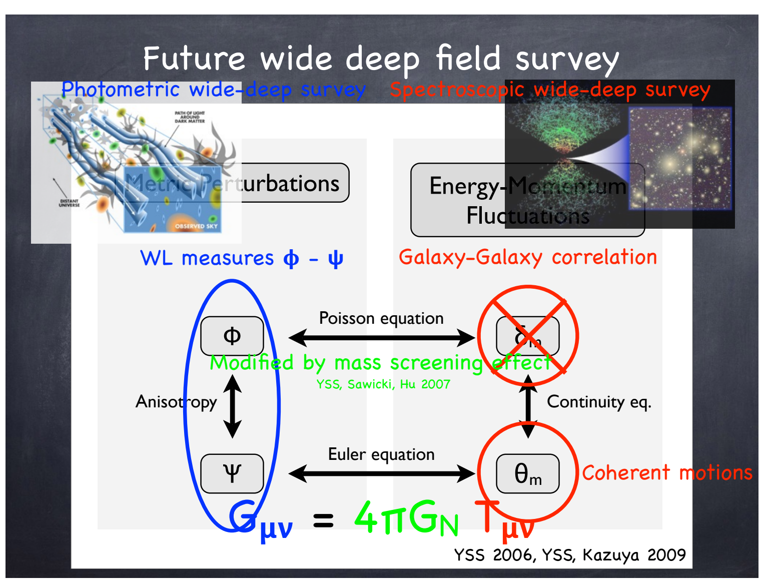
- Failure of standard cosmology model: our understanding of the universe is still standing on assumption:

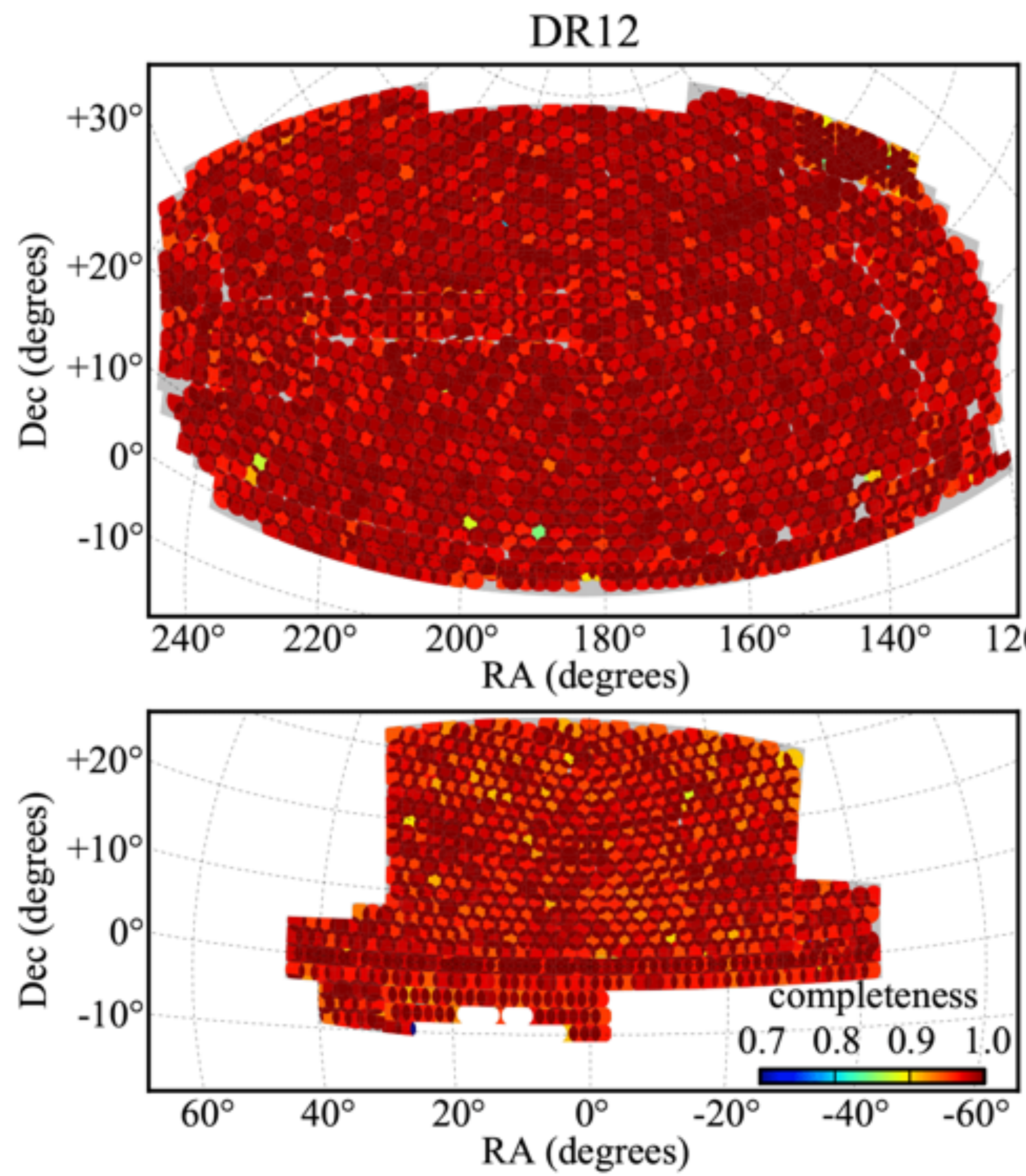
Inhomogeneous models: LTB, back reaction

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

Galaxy clustering seen in redshift space

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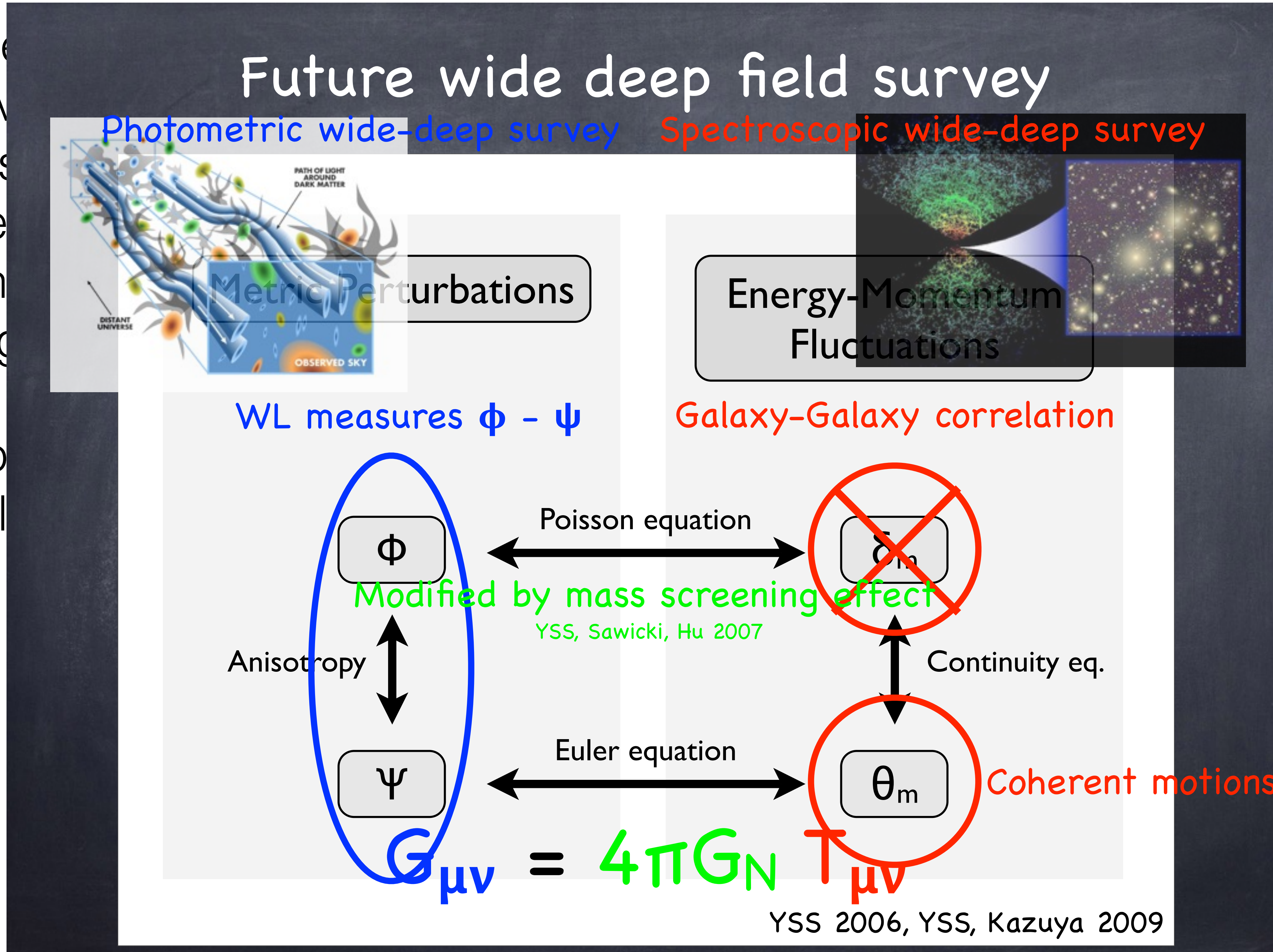
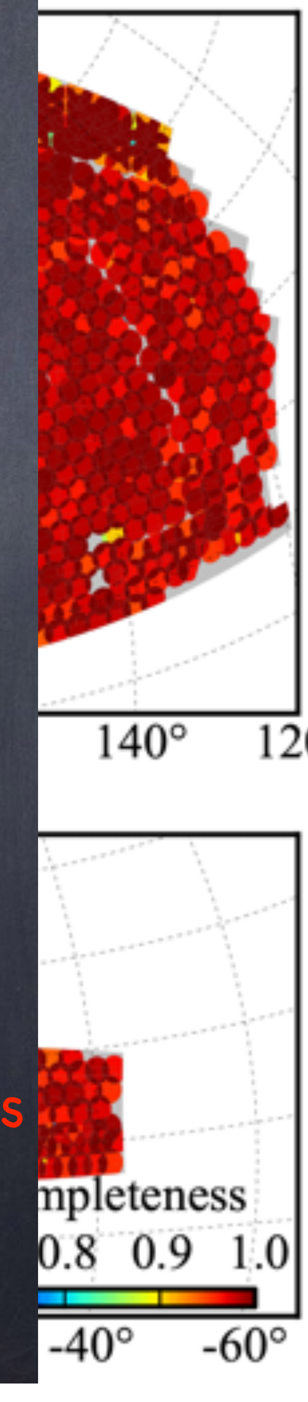
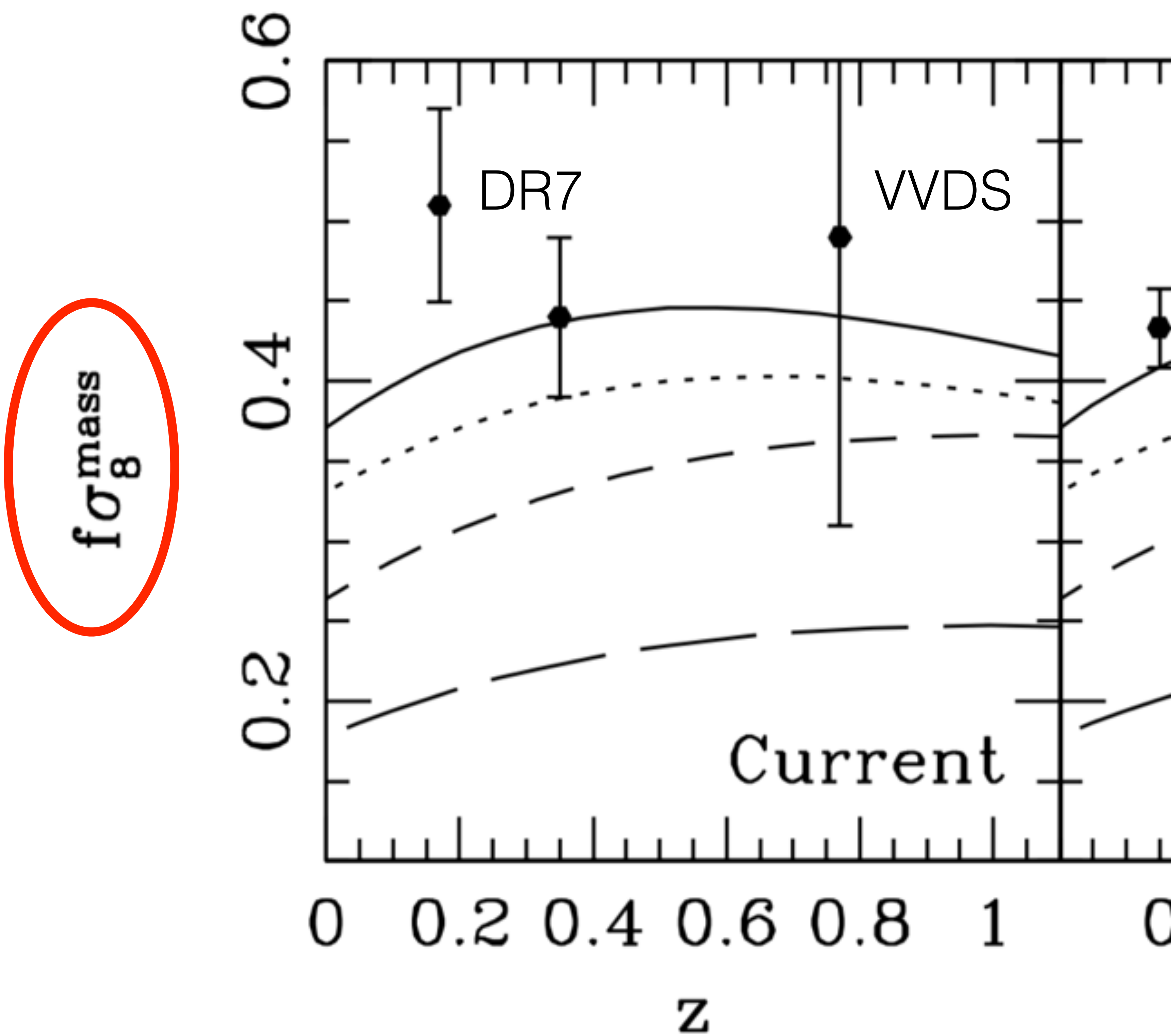




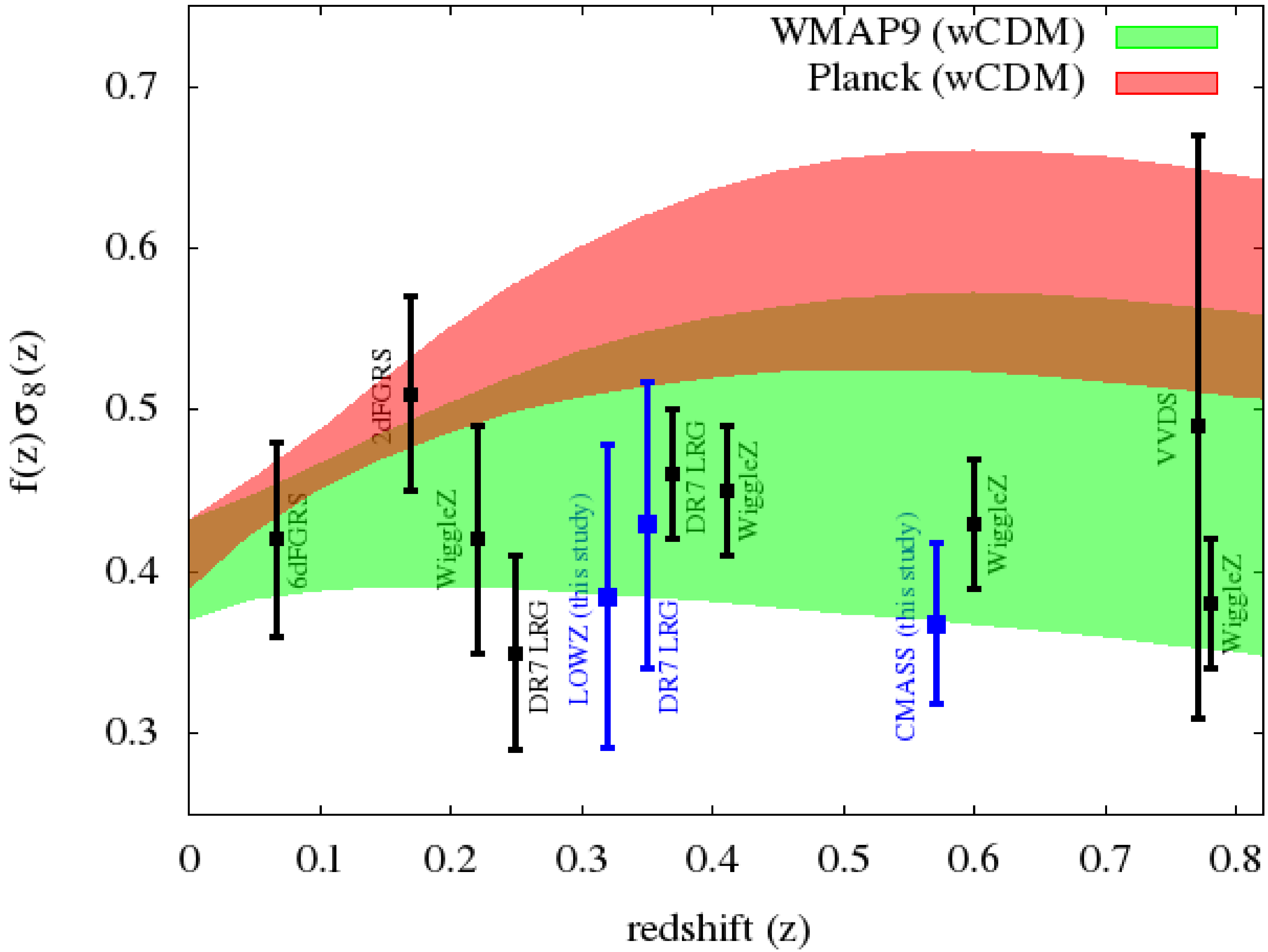
Cosmological probe of coherent motion

The first measured $f\sigma_8$

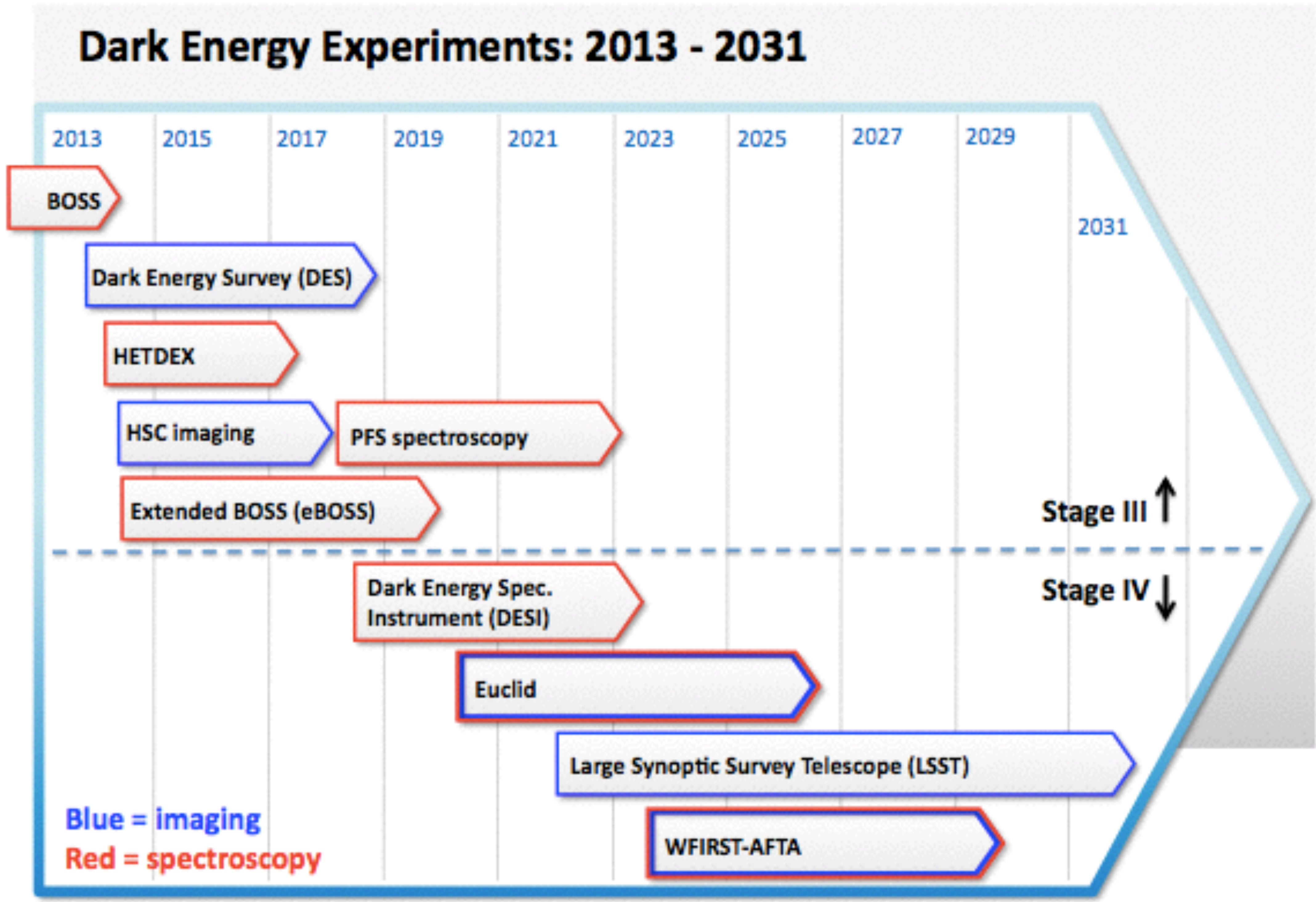


YSS, Percival 2009

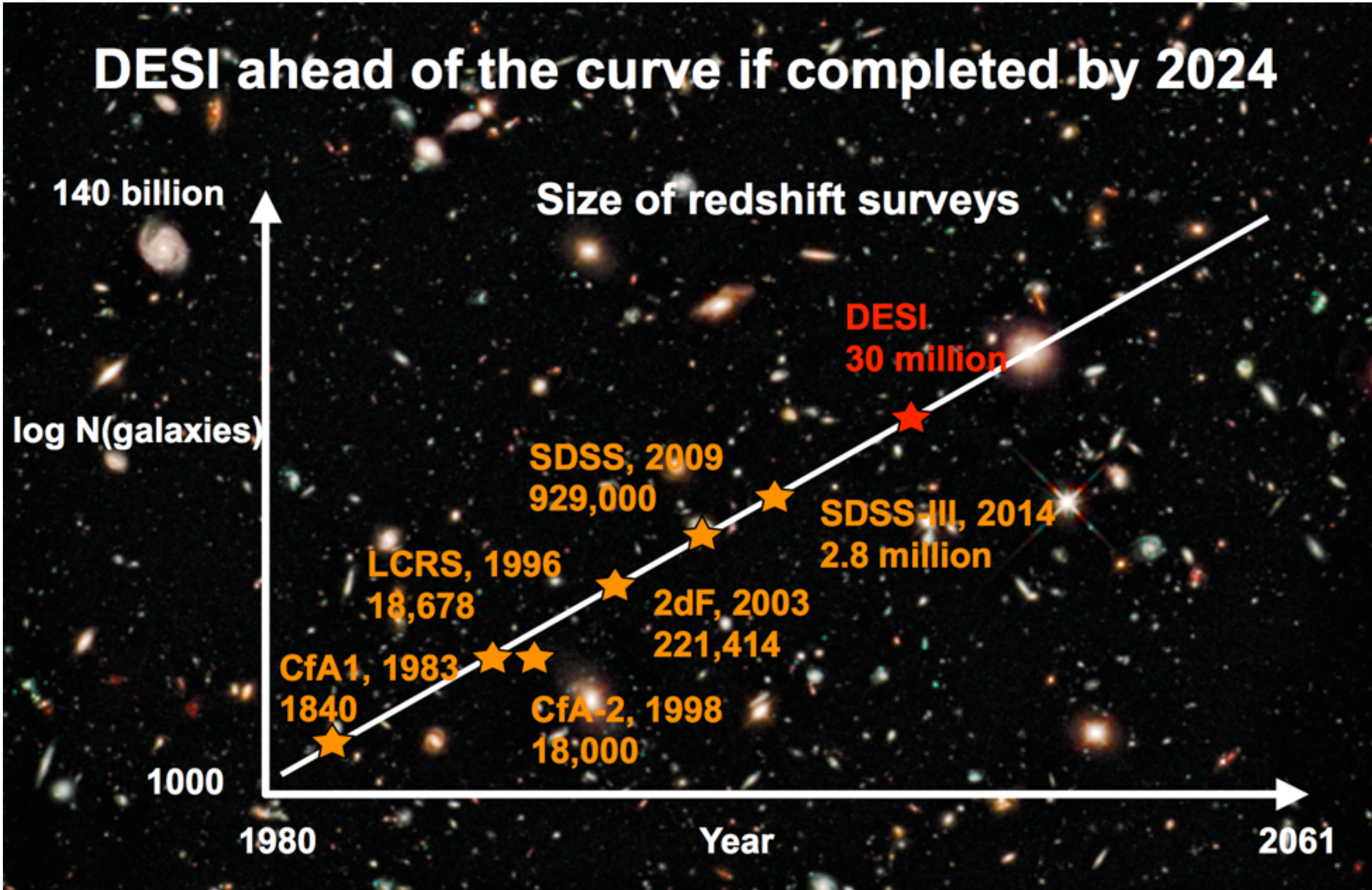
Cosmological probe of coherent motion



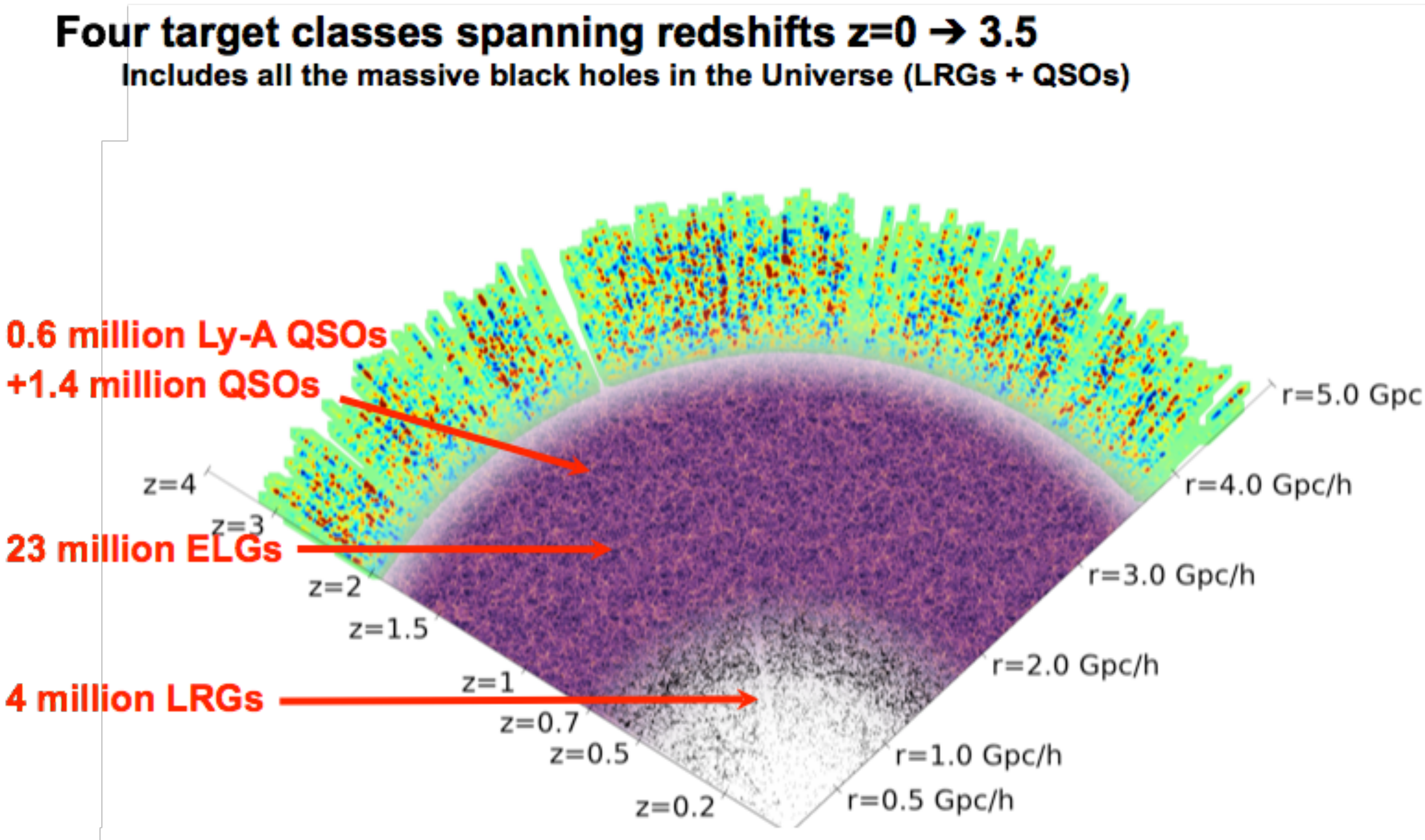
Planned surveys in the future



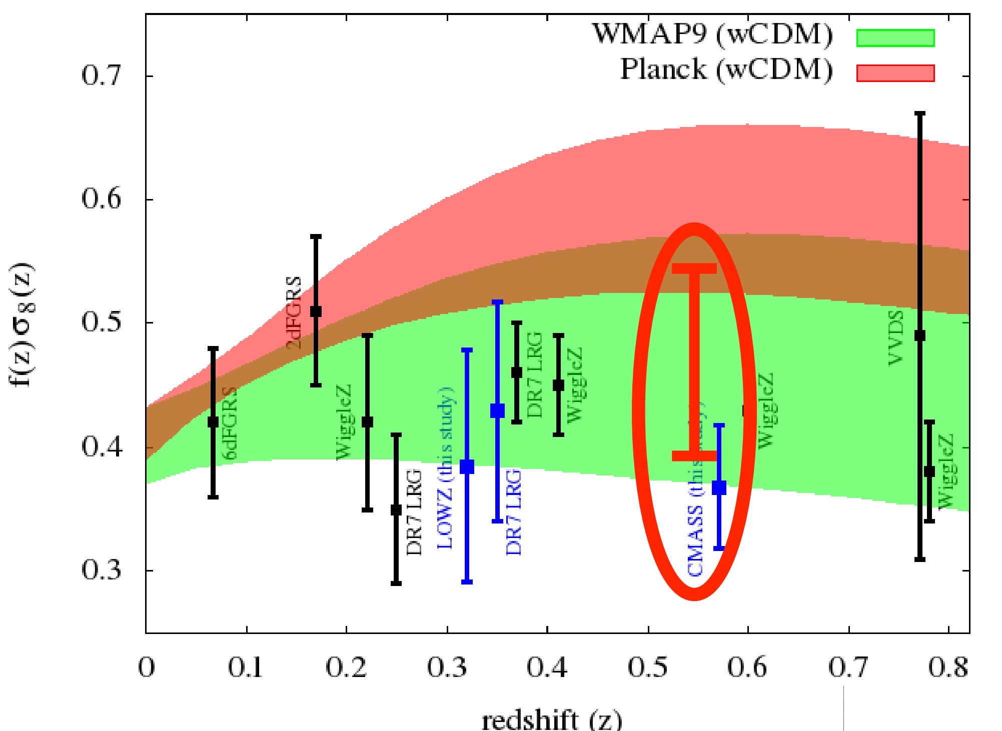
History and plan for spectroscopy surveys



Galaxy clustering seen in redshift space

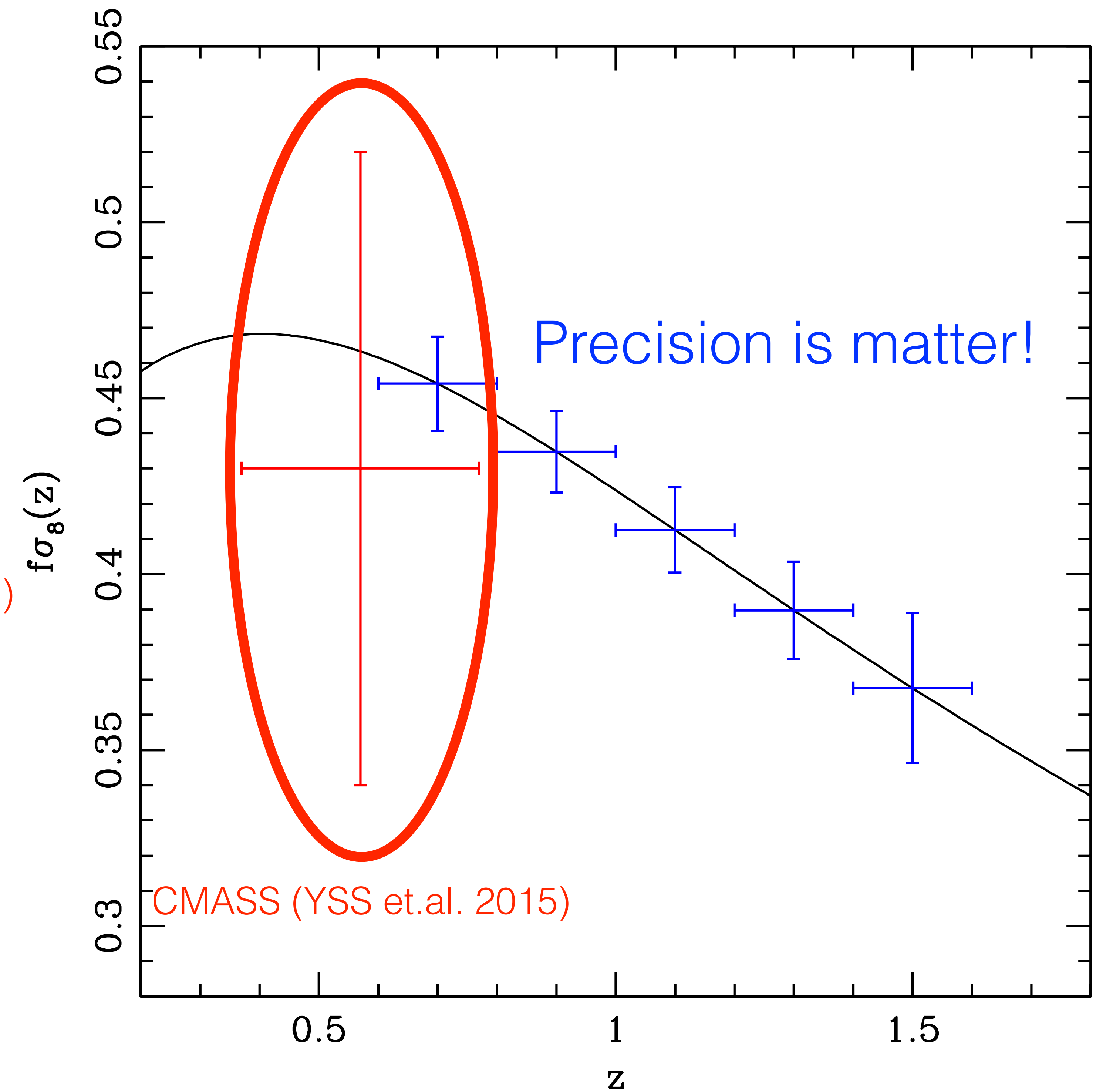


Cosmological probe of coherent motion



CMASS (Chuan et.al. 2015)

CMASS (YSS et.al. 2015)



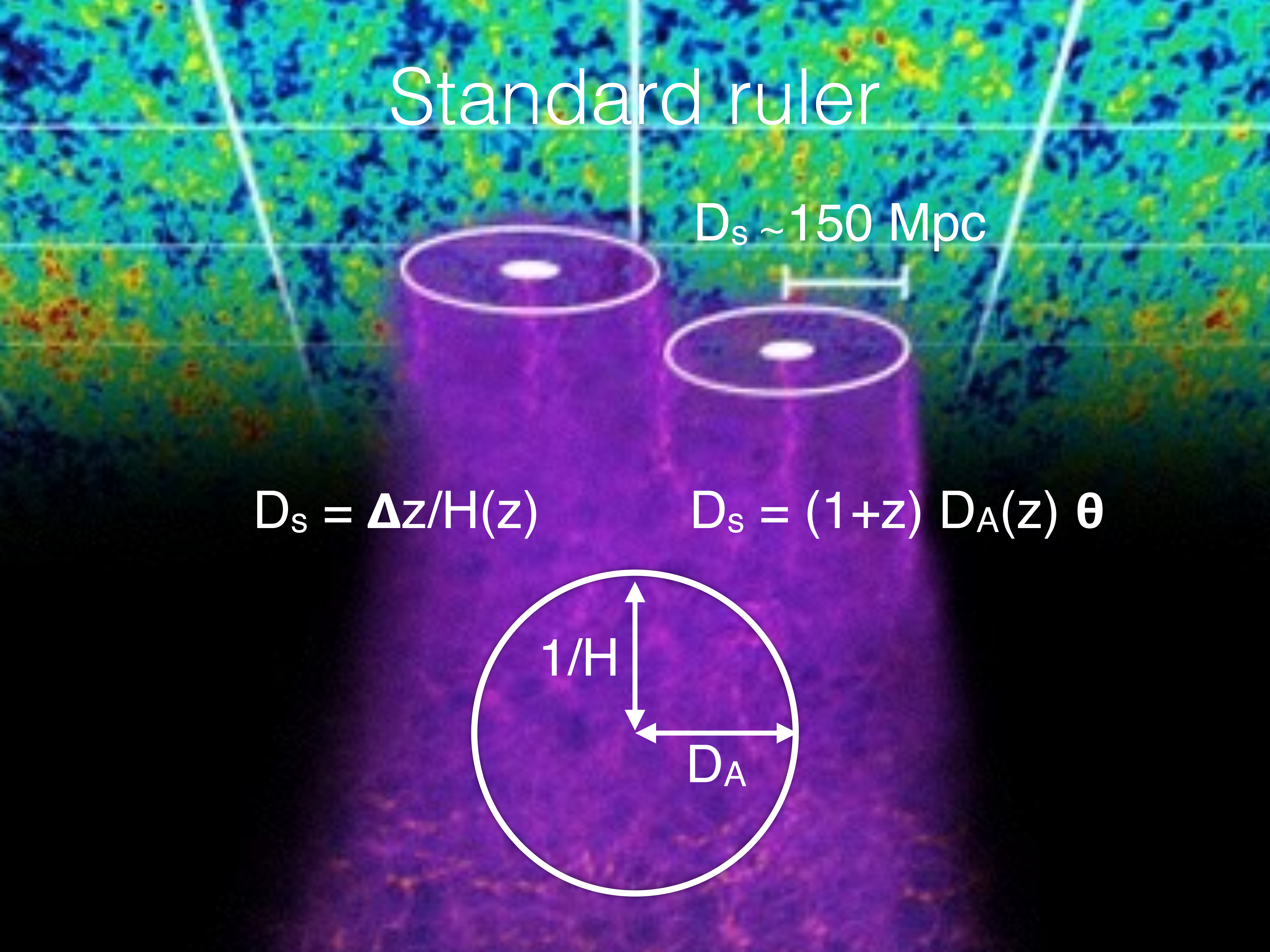
YSS, Taruya, Akira 2015

Key cosmological observables of the universe

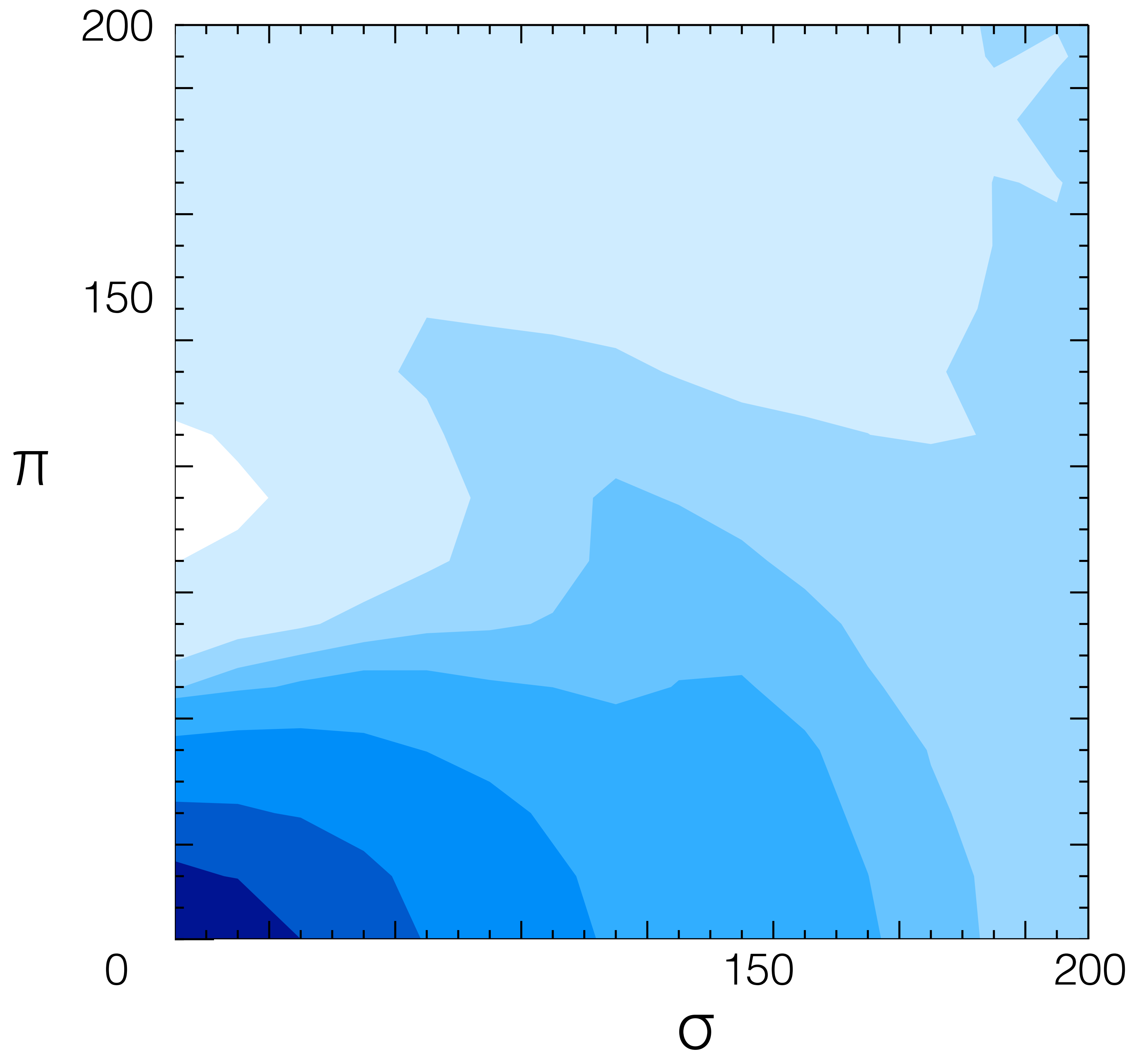
- Angular diameter distance D_A: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

- 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.

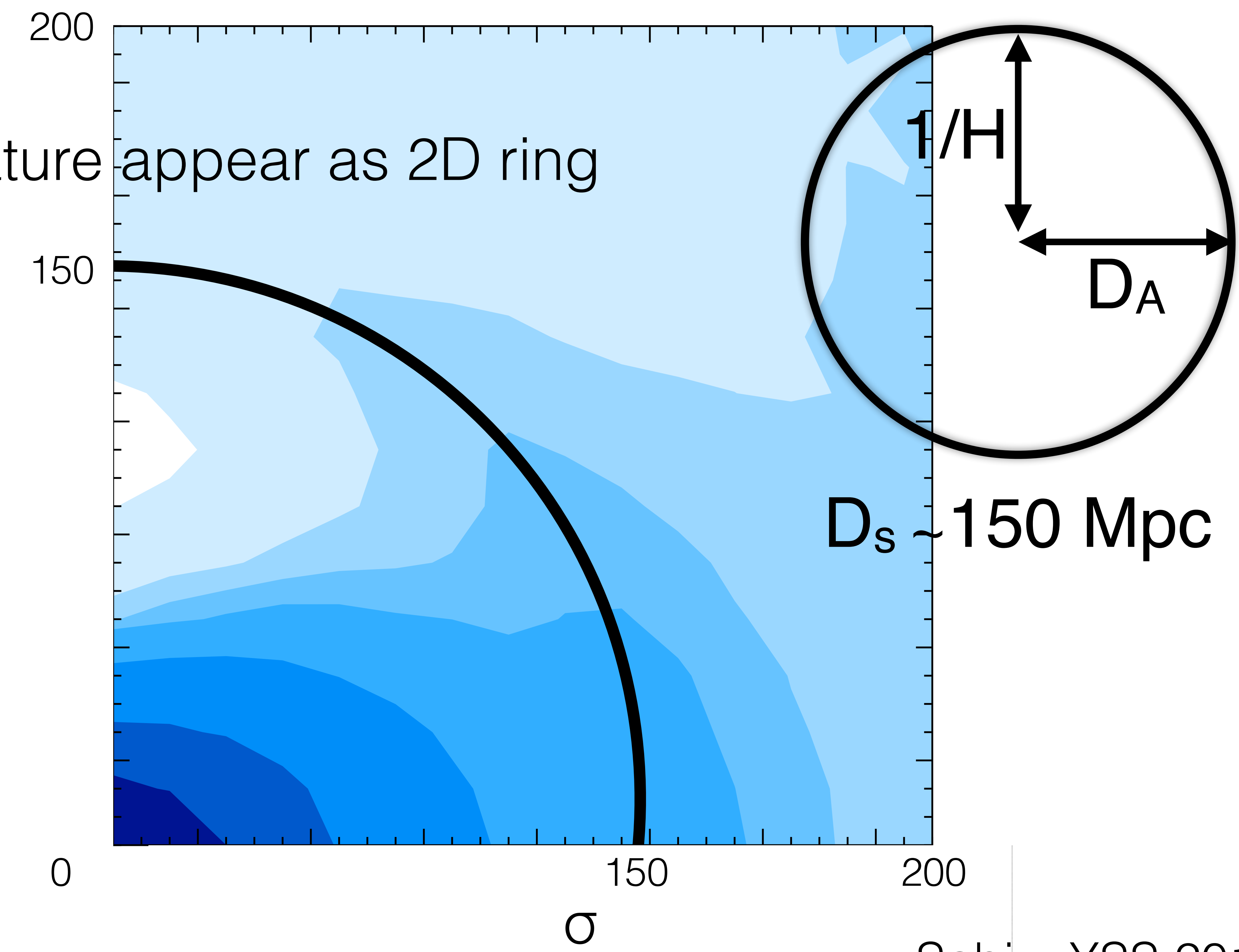

Standard ruler
D_S ~150 Mpc
$D_S = \Delta z / H(z)$
$D_S = (1+z)\, D_A(z)\, \theta$
1/H
D_A

Anisotropy galaxy clustering



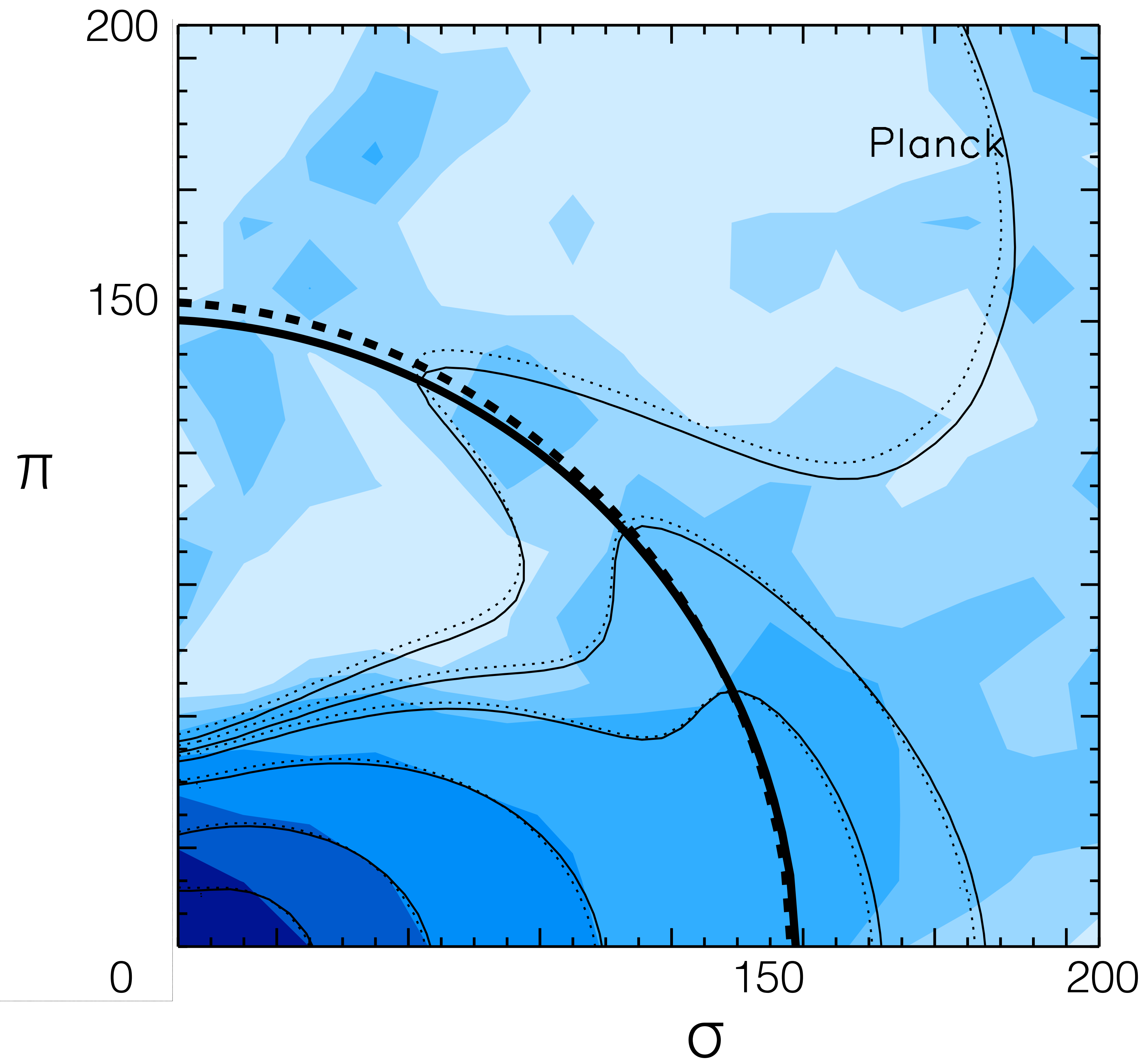
Anisotropy galaxy clustering

BAO signature appear as 2D ring



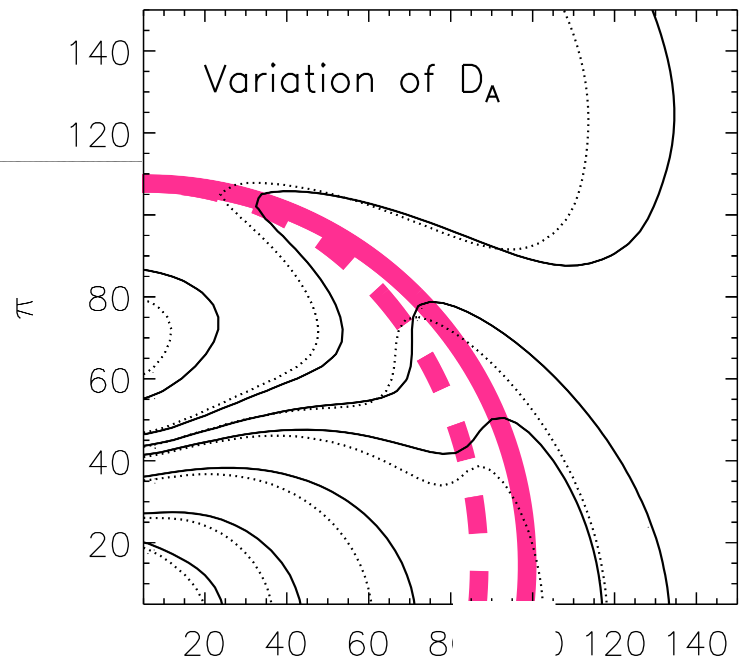
Sabiu, YSS 2016

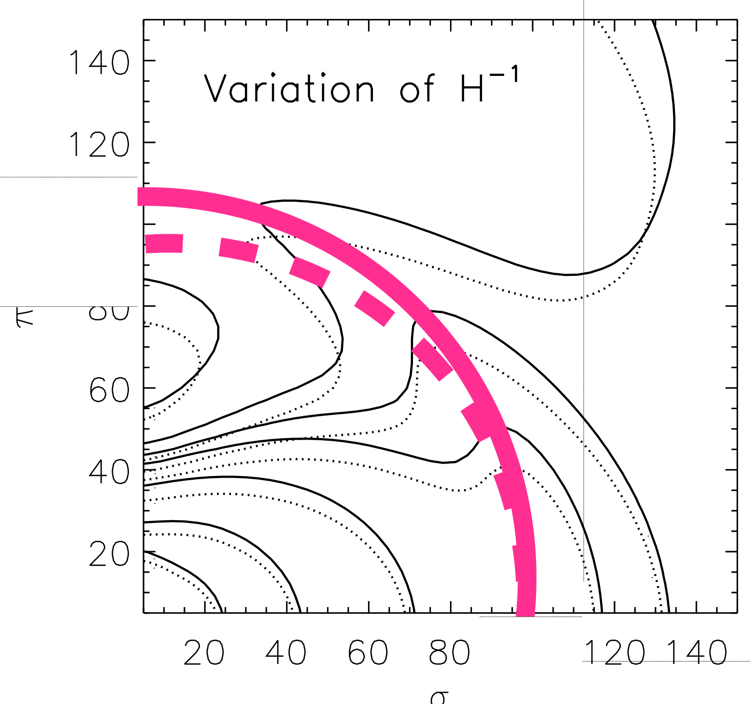
Measured anisotropy galaxy clustering

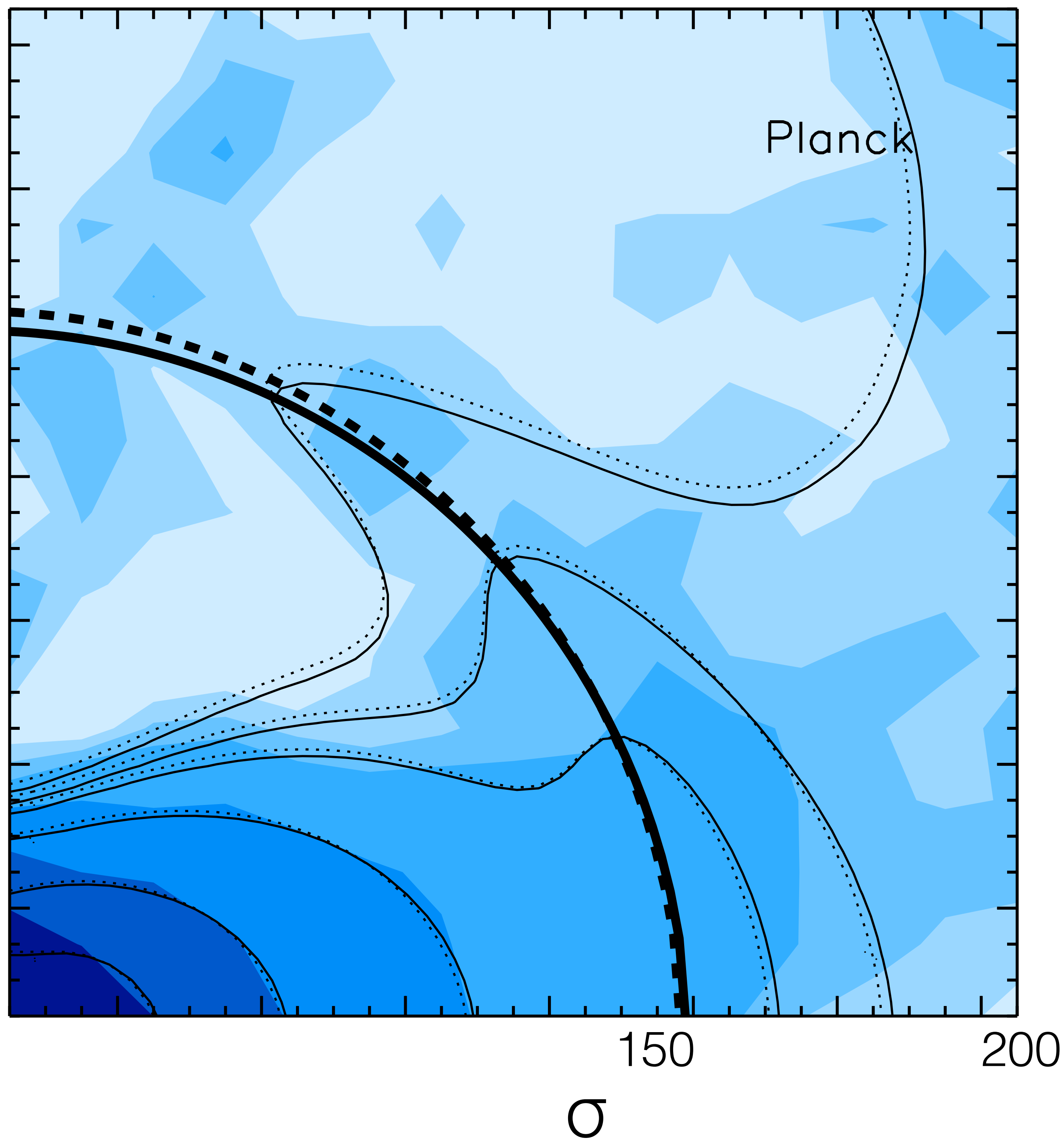


Perpendicular and radial distance measures

(D_A, H^{-1}, G_δ, G_Θ, FoG)

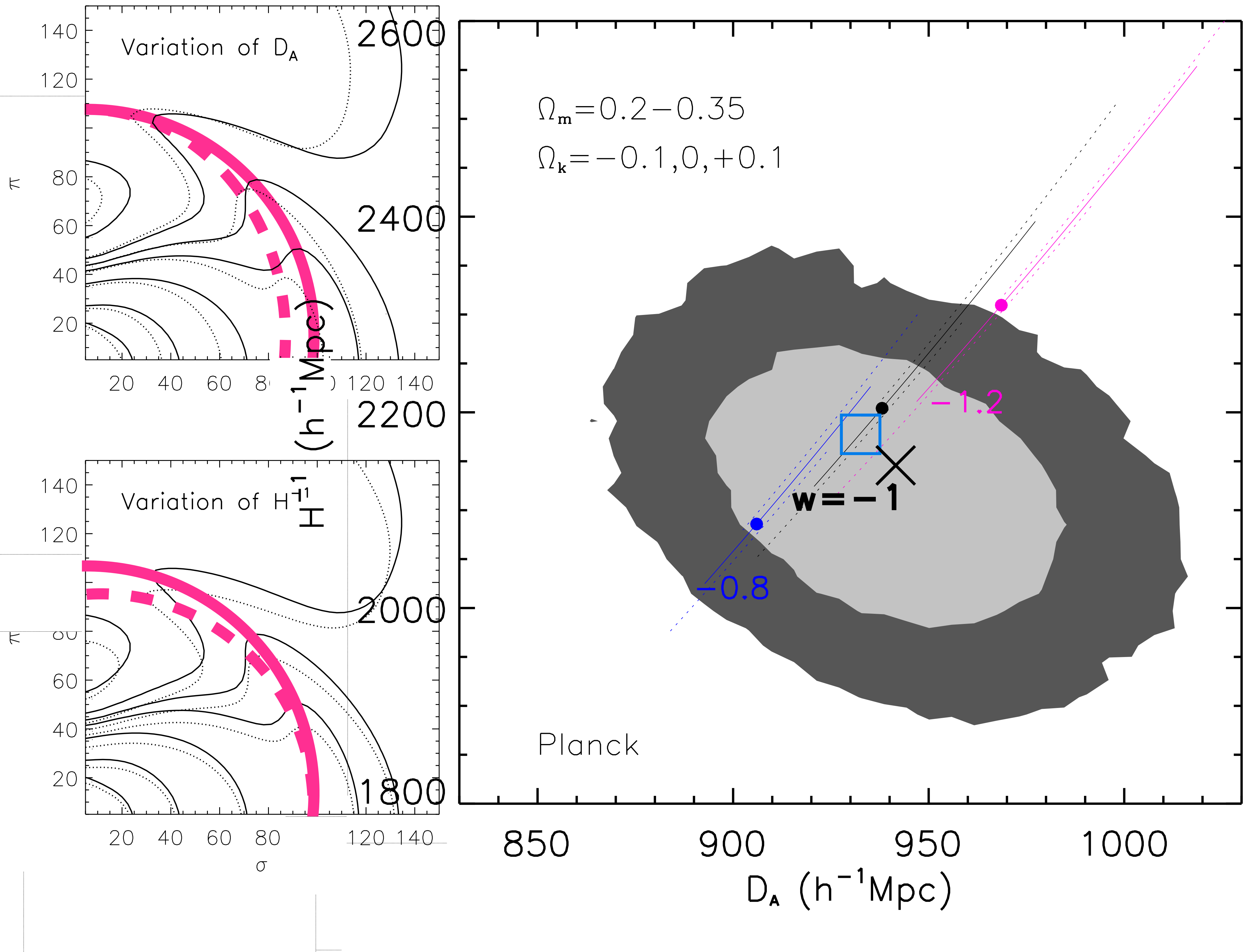






Perpendicular and radial distance measures

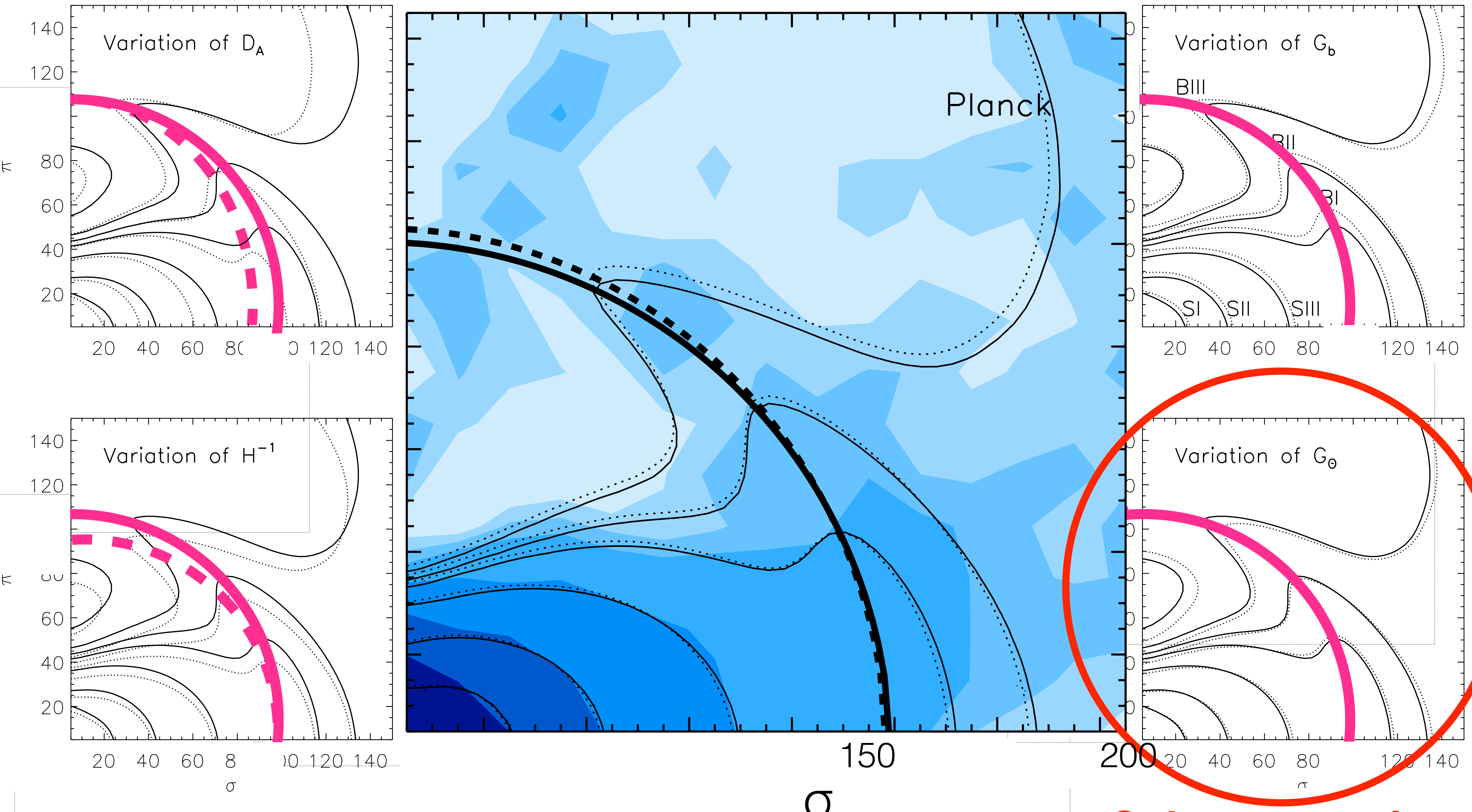
(DA, H-1, Gδ, Gθ, FoG)



Growth function measurements

(D

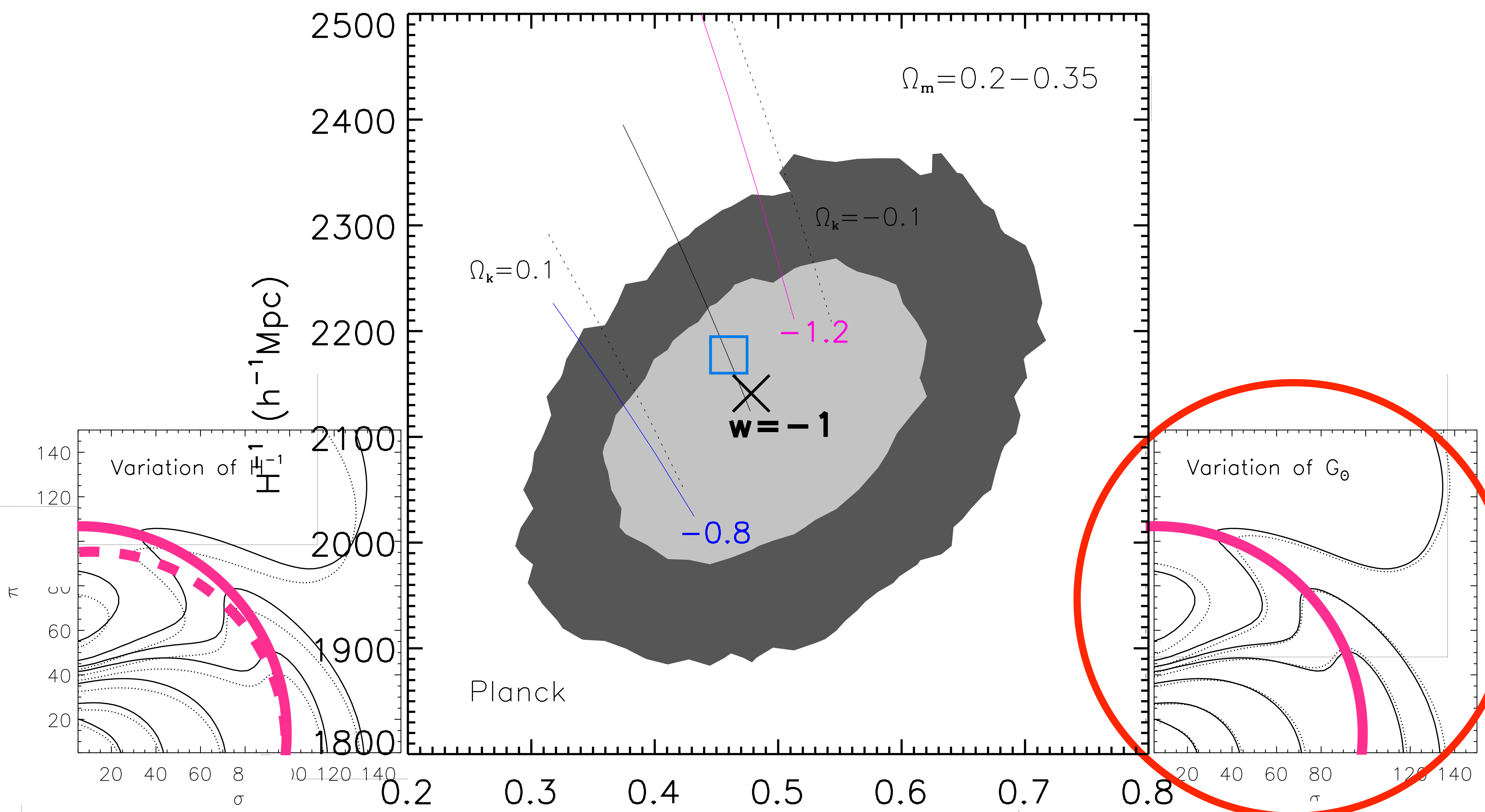
(${D_A}$, H^{-1}, G_δ, G_Θ, FoG)



Coherent motion

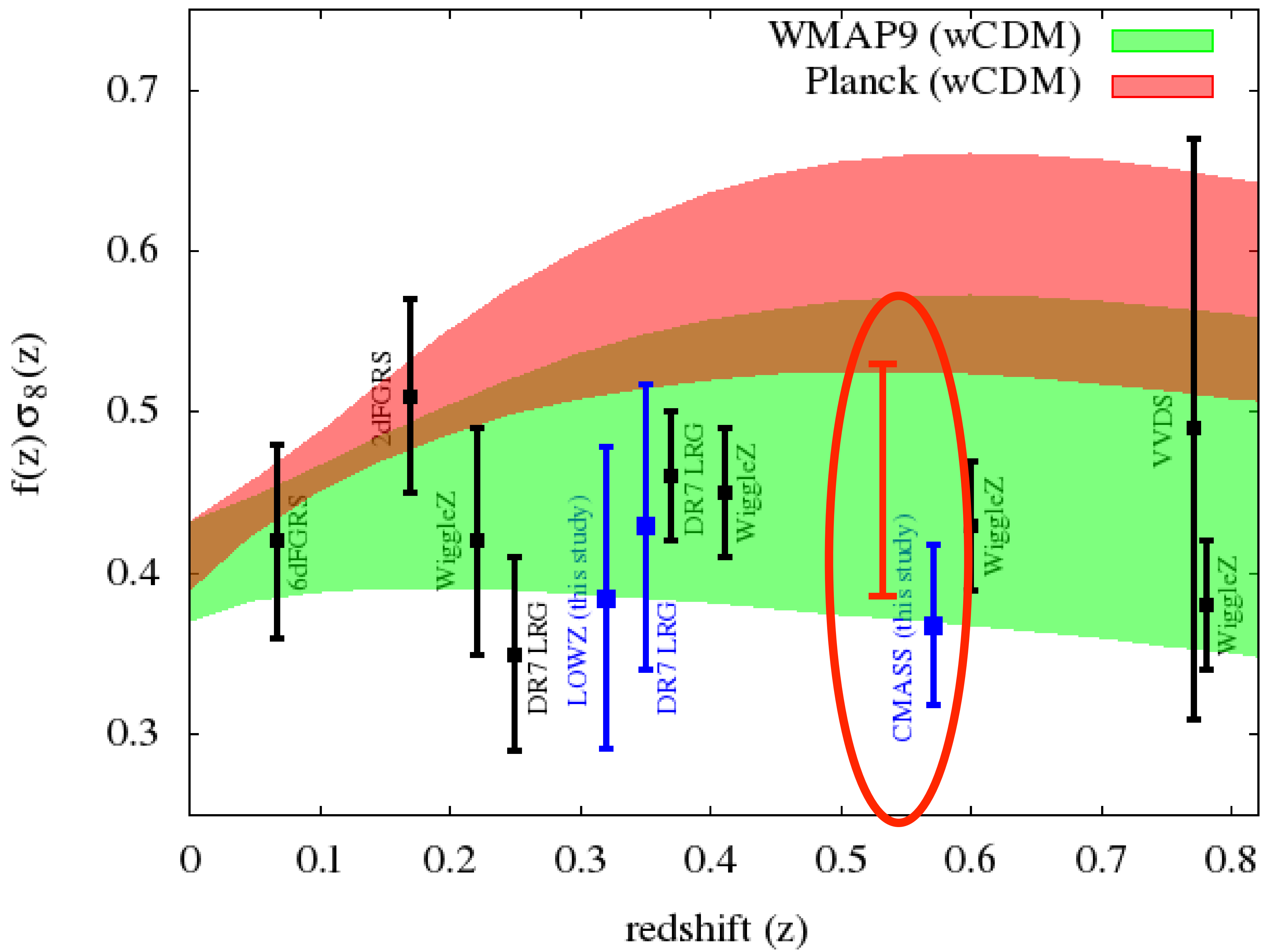
Growth function measurements

(D_A, H^{-1}, G_δ, G_Θ, FoG)



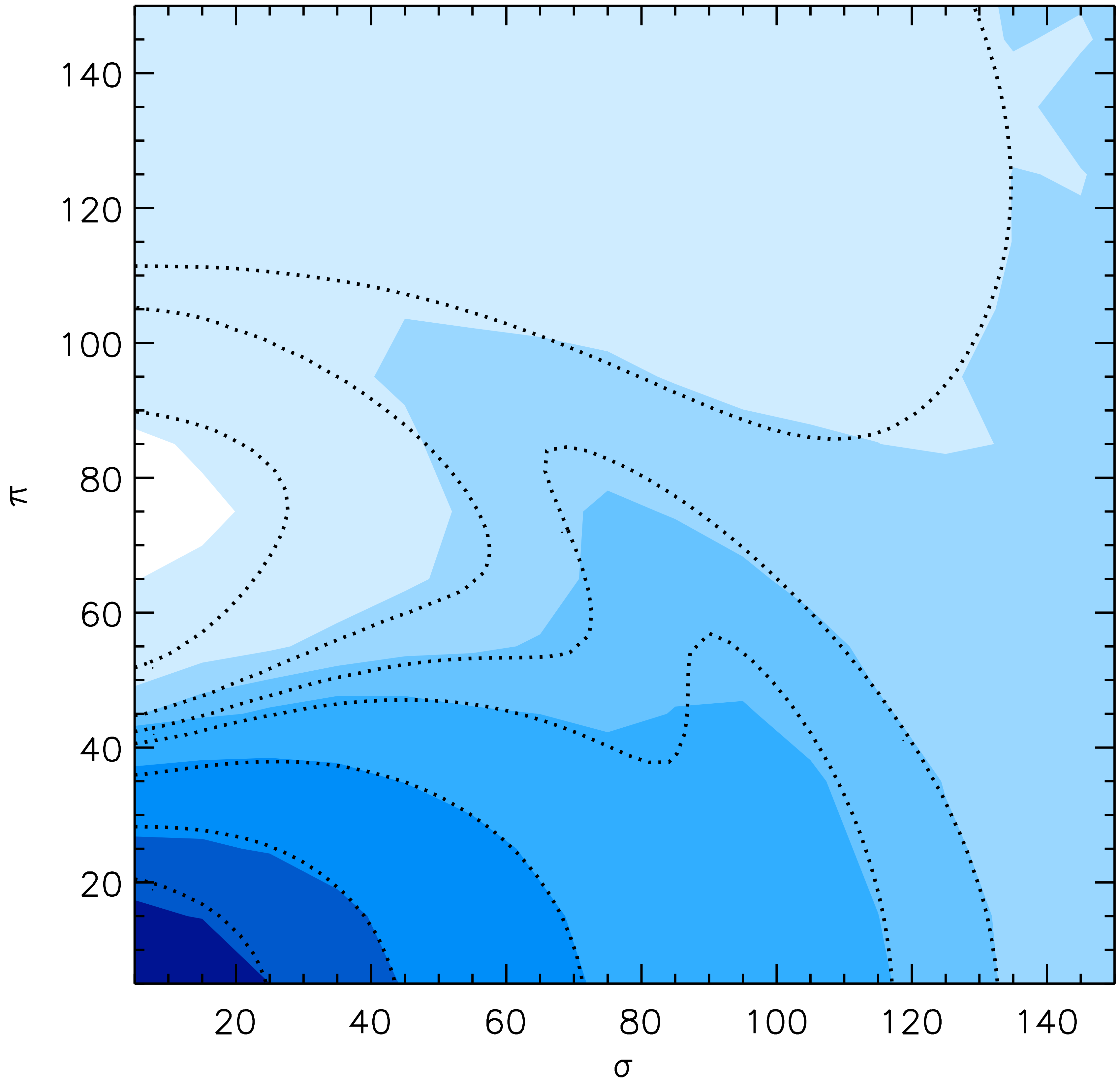
Coherent motion

Cosmological probe of coherent motion



YSS et.al. 2015

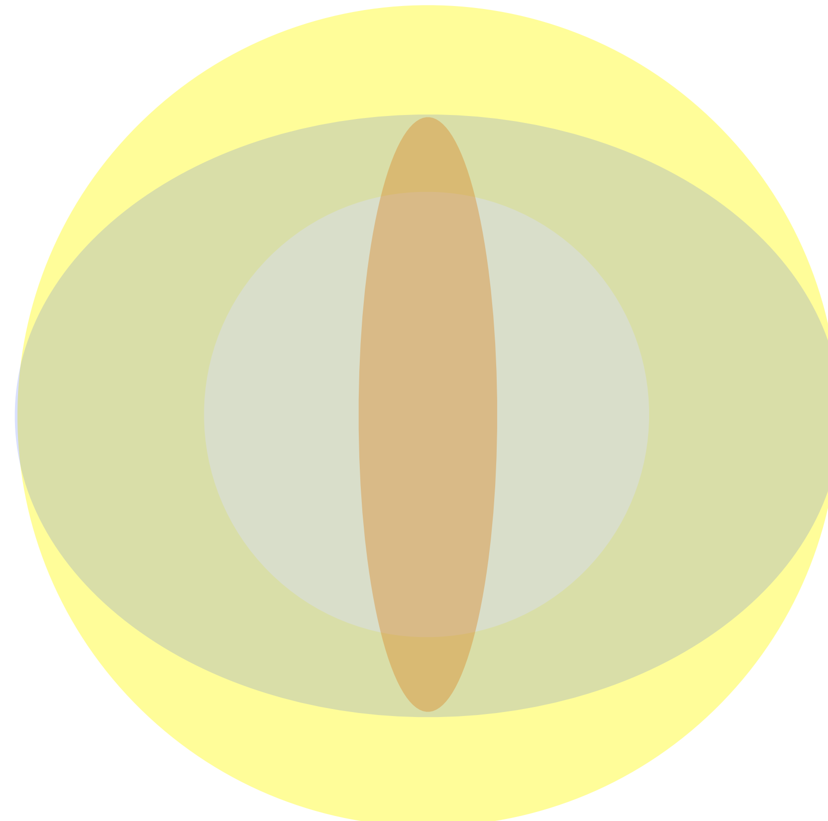
Anisotropy correlation without corrections



Improved RSD model

Squeezing effect at large scales

(Kaiser 1987)



Non-linear corrections

Higher order polynomials

Finger of God effect

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

$$\Downarrow$$

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

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

Improved RSD model

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

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

$$\boldsymbol{\xi}_\ell(s) = i^l \int k^2 dk\, P_l(k)\, j_l(ks)$$

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

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

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

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

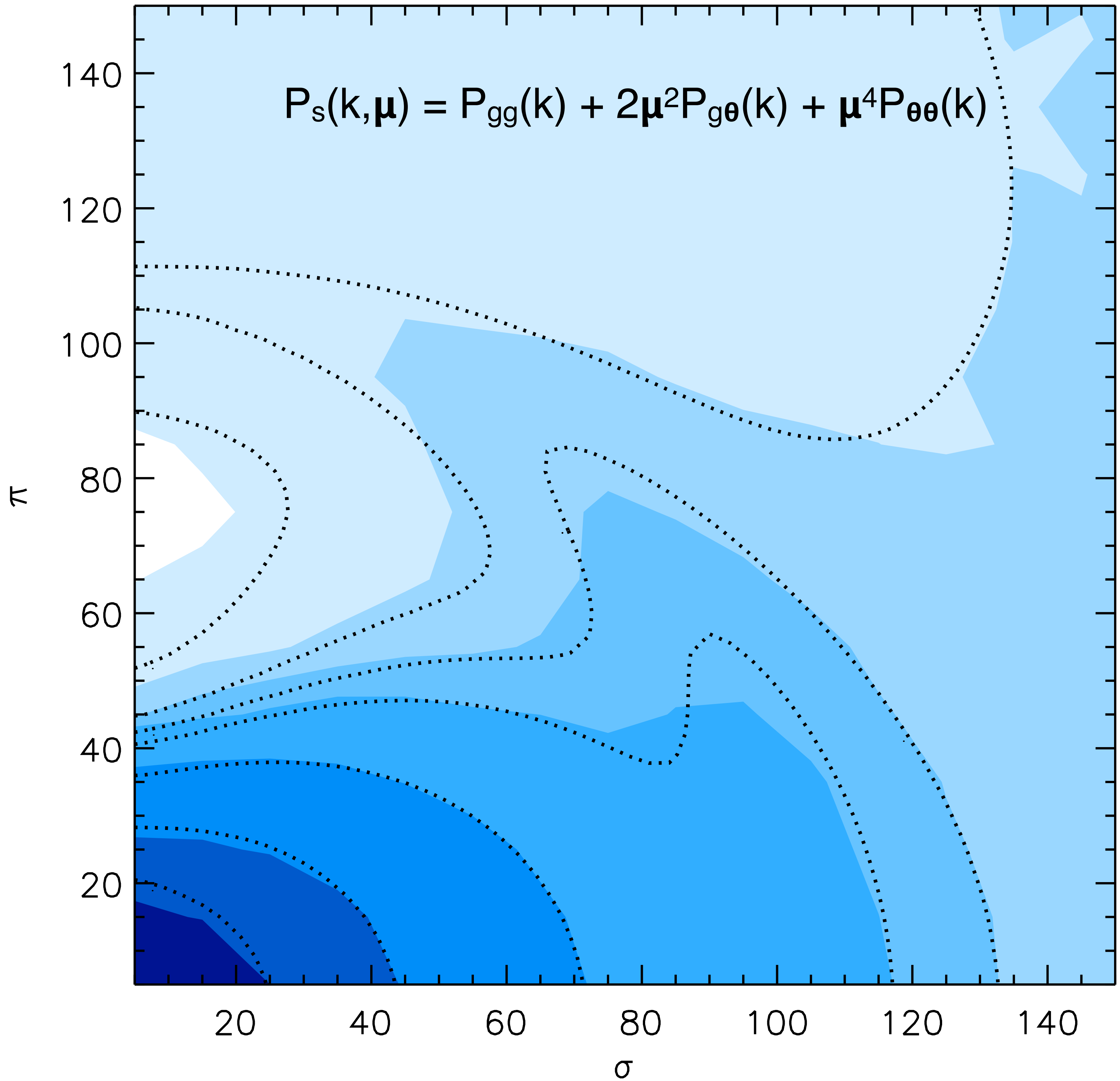
$$p_n(k) = 1/2\, [\, \boldsymbol{\gamma}(n+1/2,\boldsymbol{\kappa})/\boldsymbol{\kappa}^{n+1/2} Q_0(k) + \boldsymbol{\gamma}(n+3/2,\boldsymbol{\kappa})/\boldsymbol{\kappa}^{n+3/2} Q_2(k)$$

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

$$\boldsymbol{\kappa} = k^2 \sigma^2_p$$

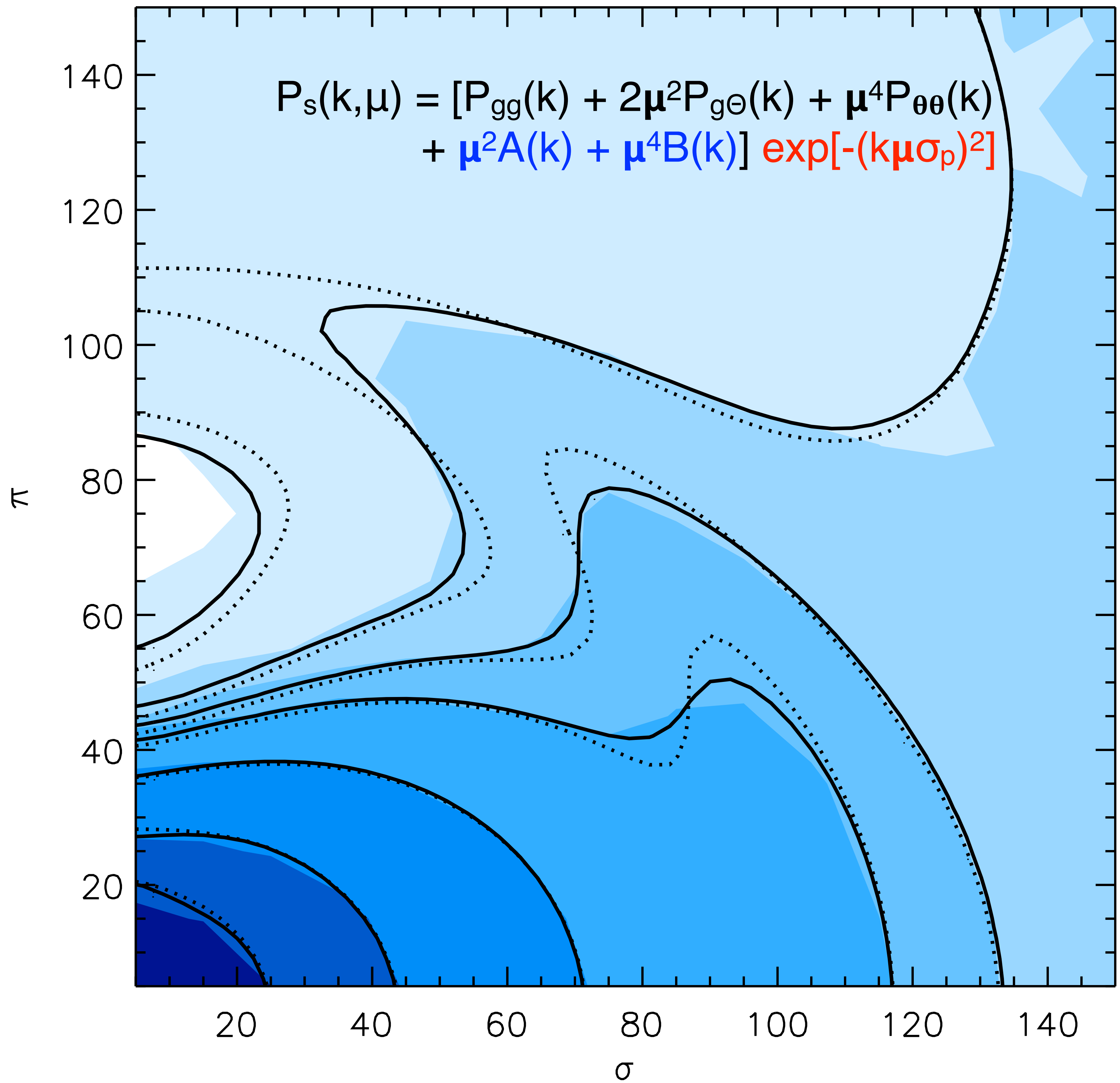
YSS, Okumura, Taruya 2014   Taruya, Nichimishi, Saito 2010

Cosmological probe of coherent motion



YSS et.al. 2015

Cosmological probe of coherent motion



YSS et.al. 2015

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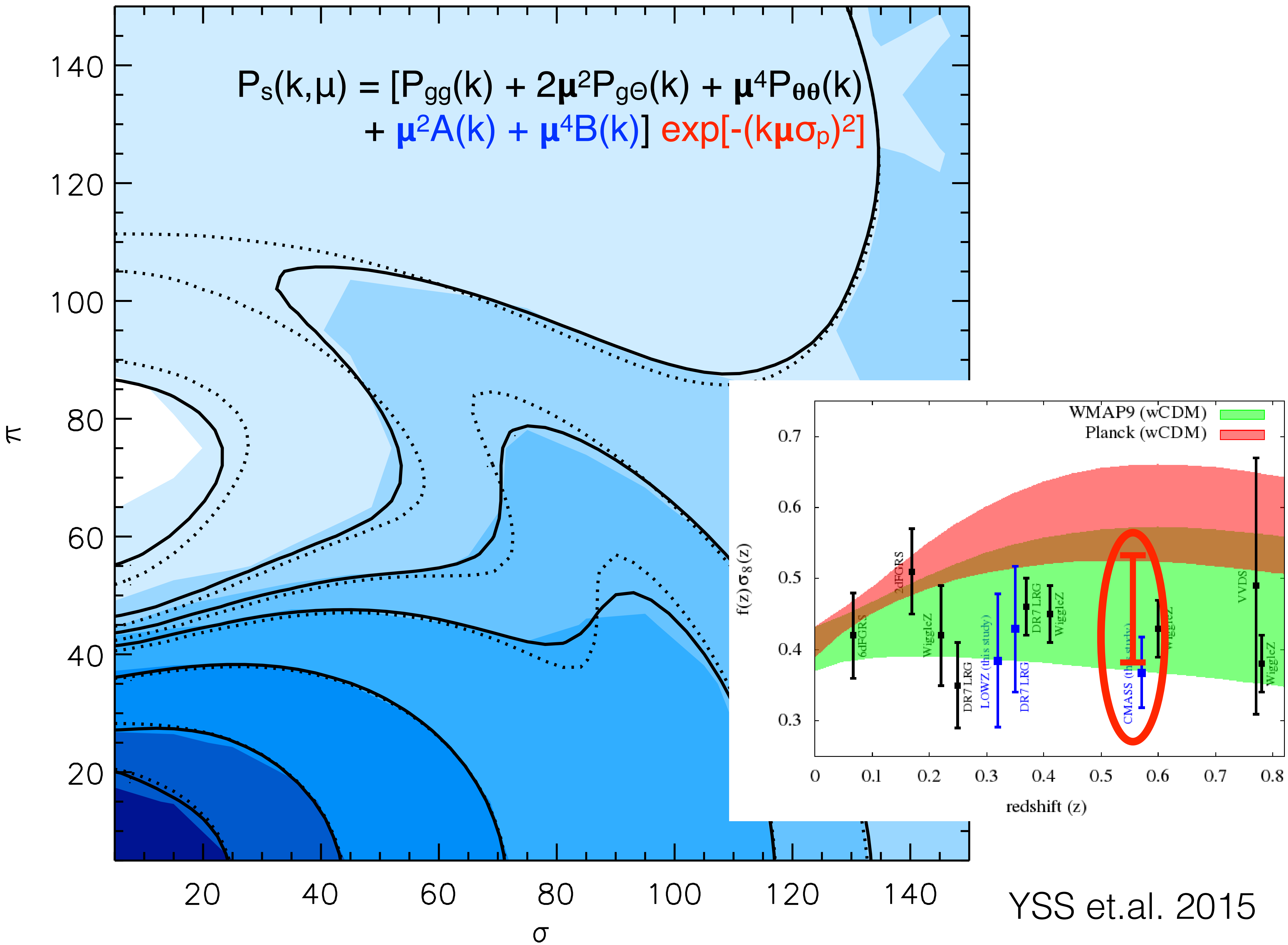


YSS et.al. 2015

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		Decaying vacuum
Massive neutrino	Λ	Chameleon type gravity
Interacting dark matter		Dilaton or Symmetron
Unified dark matter		Vainstein type gravity
		Inhomogeneity of universe
		non-Friedman universe

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

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

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

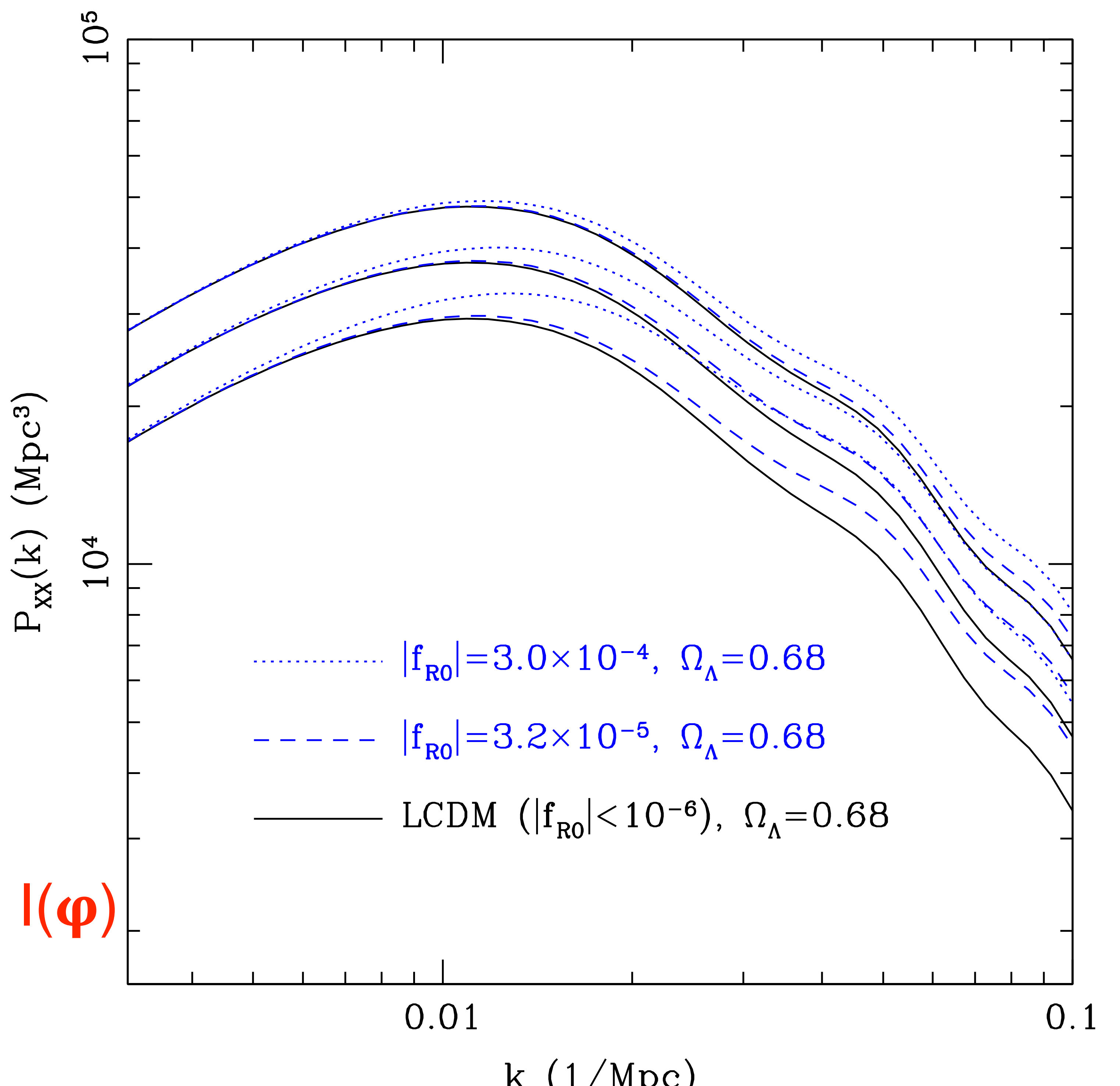
$k^2\,\boldsymbol{\phi} = 3/2\,H_0^2\Omega_m\,\boldsymbol{\delta}_m/a\,F(\boldsymbol{\epsilon})$

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

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

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

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



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

YSS et.al. 2015

Probing modified gravity

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

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

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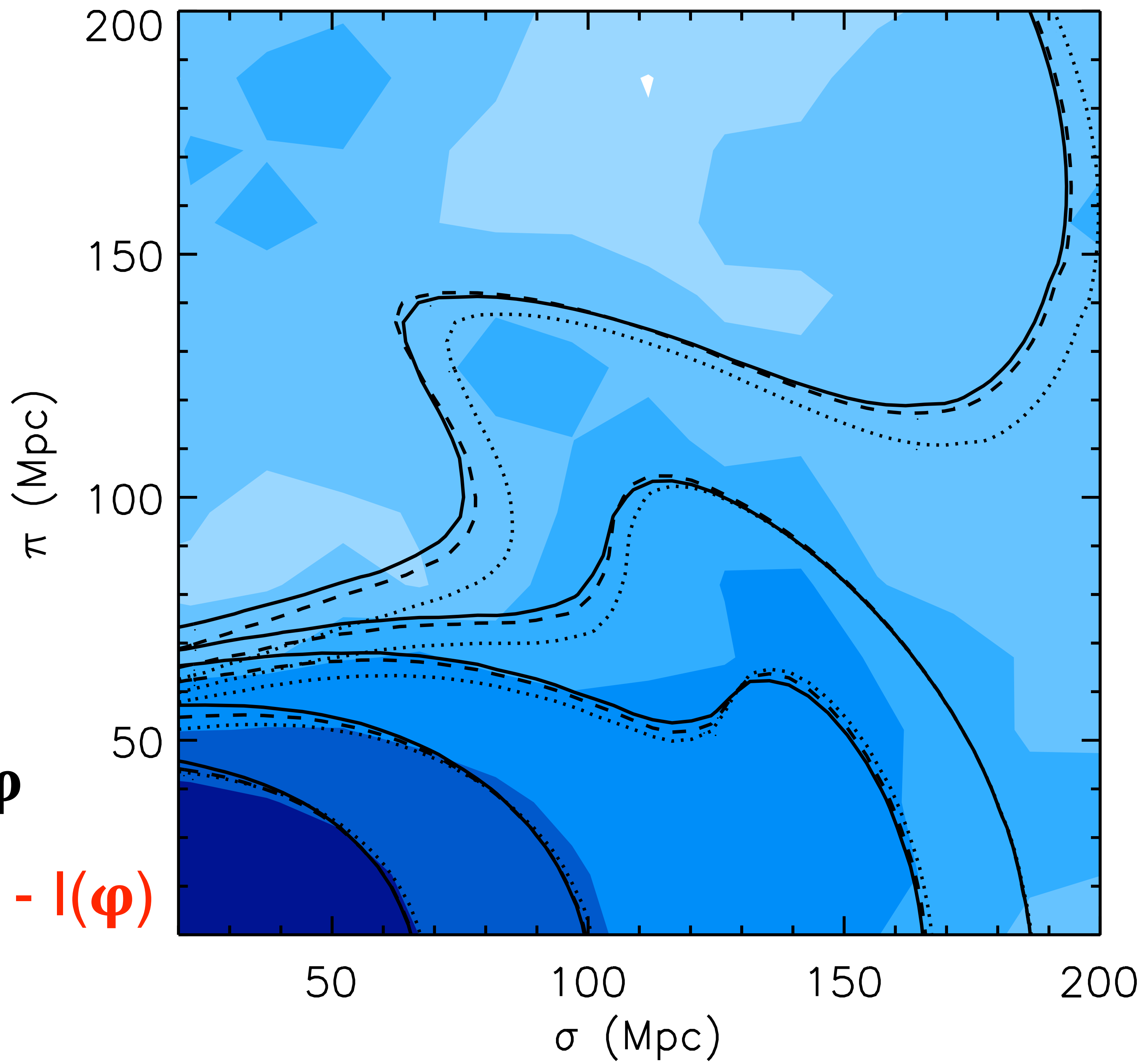
$k^2\,\boldsymbol{\psi} = -3/2\, H_0^2\Omega_m\, \boldsymbol{\delta}_m/a\, G(\boldsymbol{\epsilon})$



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

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

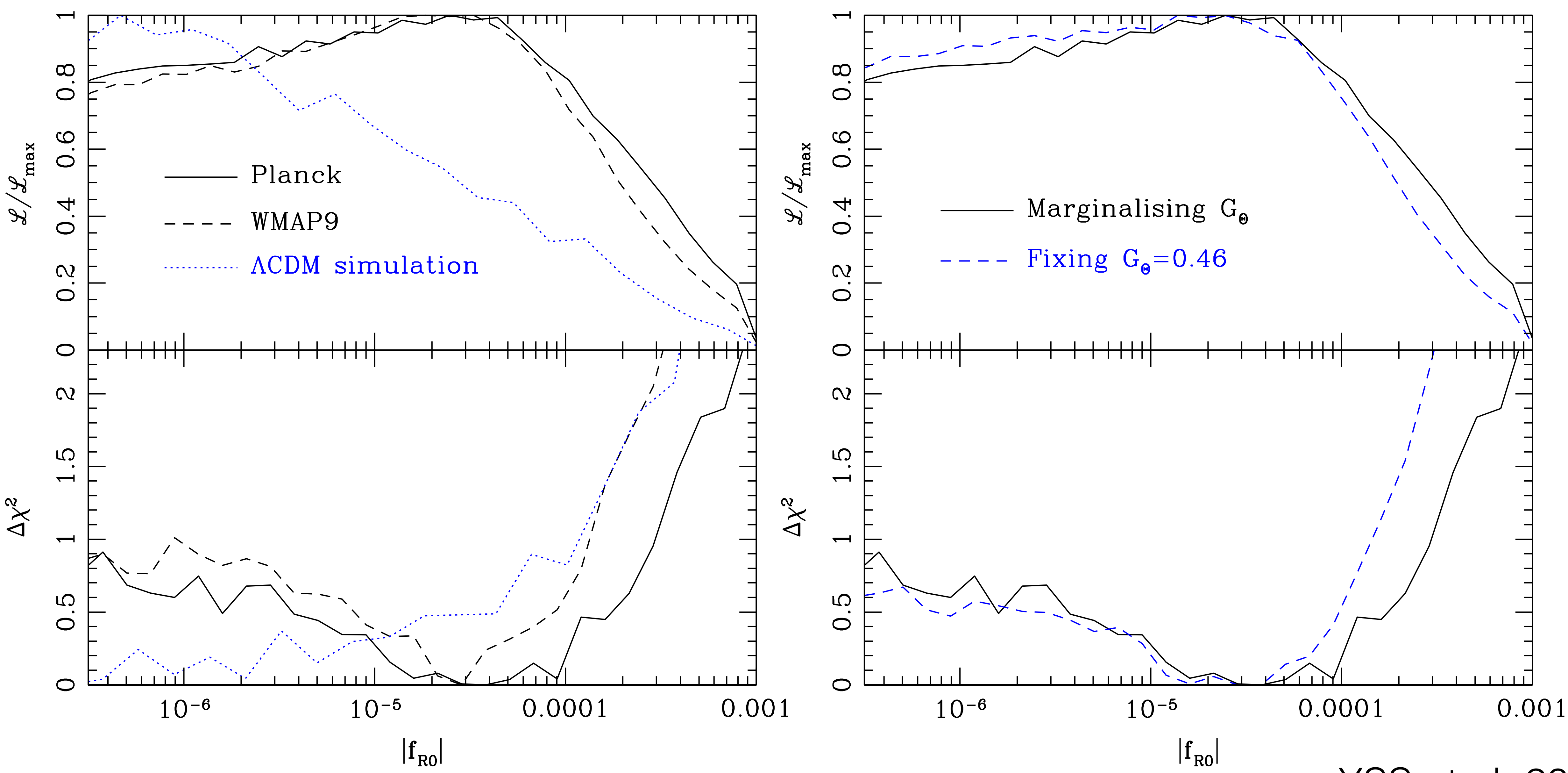
YSS et.al. 2015

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, , …)

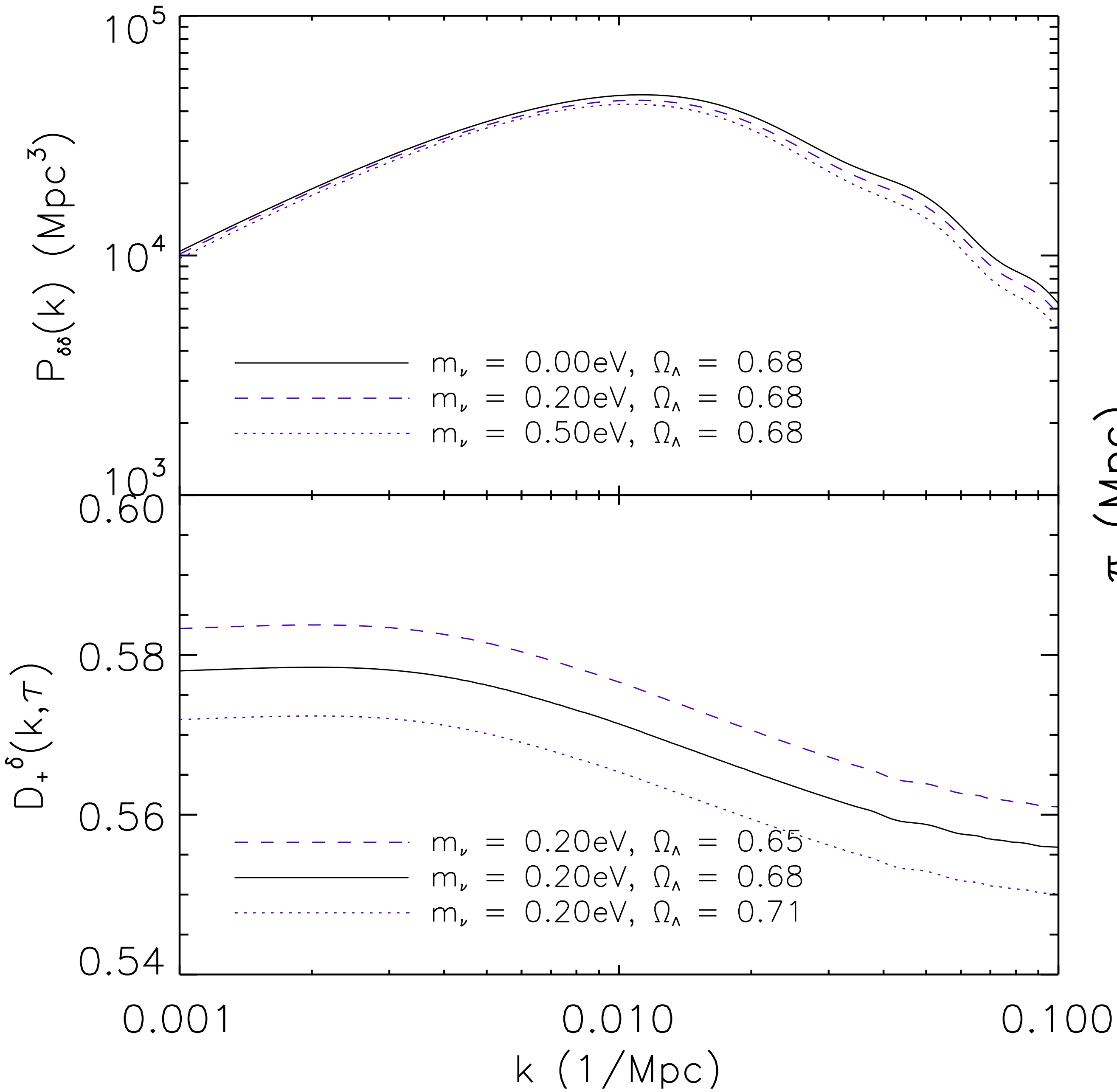
Standard model

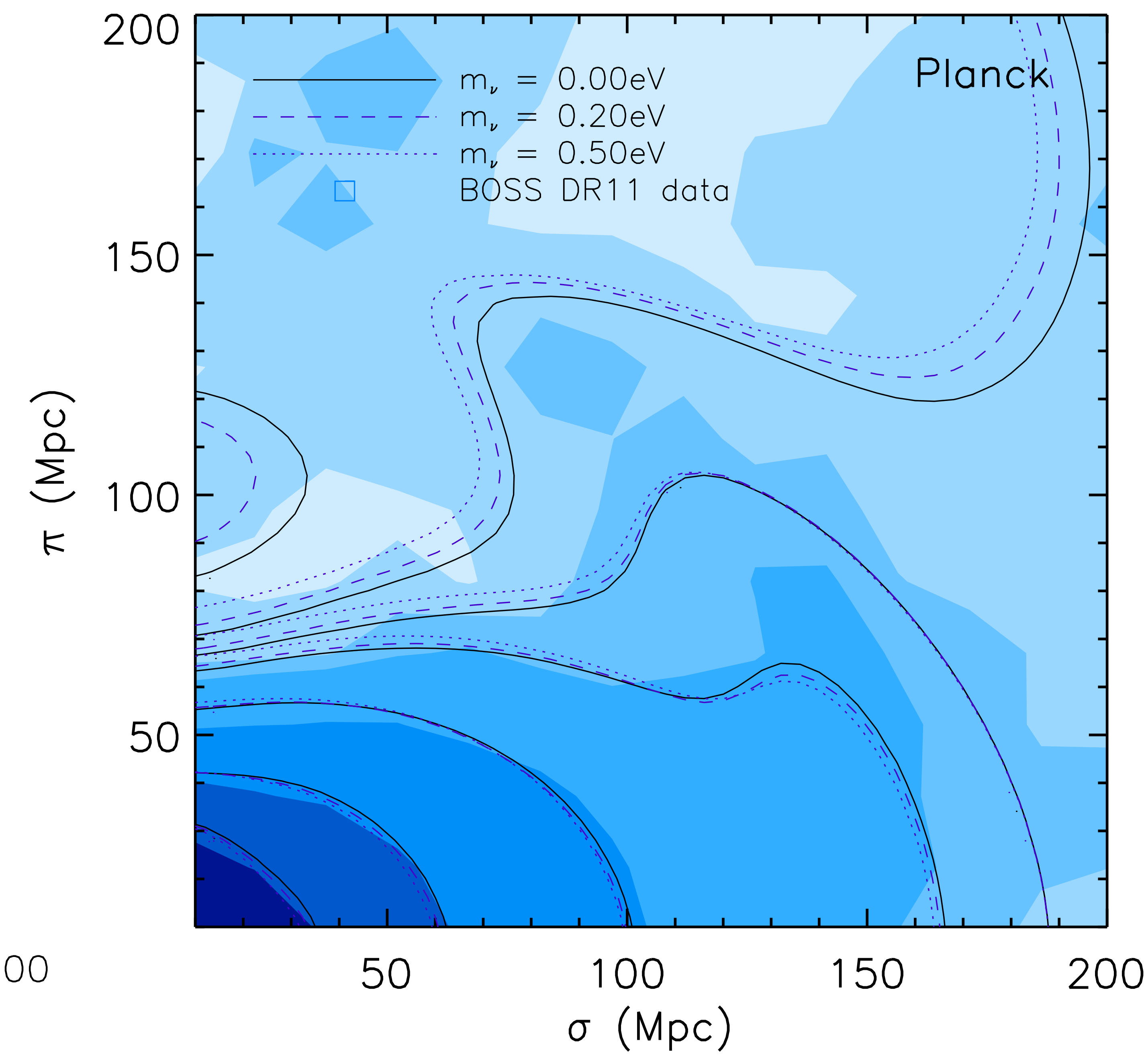
Massive neutrino

Λ

Probing neutrino mass

We build the neutrino RSD templates at small mass limit m_ν<1eV

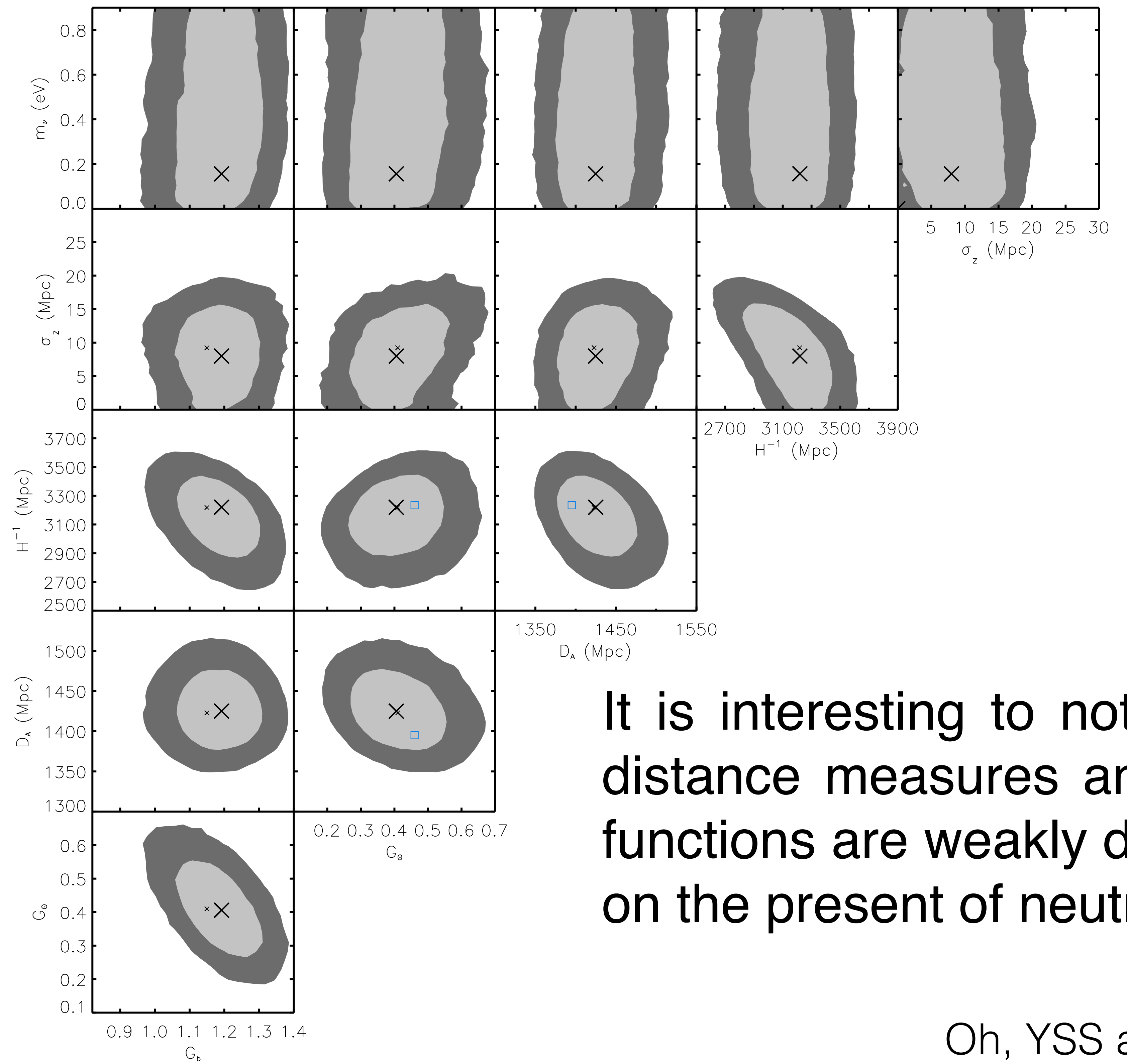




Oh, YSS arXiv:1607.01074

Probing neutrino mass

(D_A, H^{-1}, G_δ, G_Θ, FoG, m_ν)



It is interesting to note that all distance measures and growth functions are weakly dependent on the present of neutrino mass

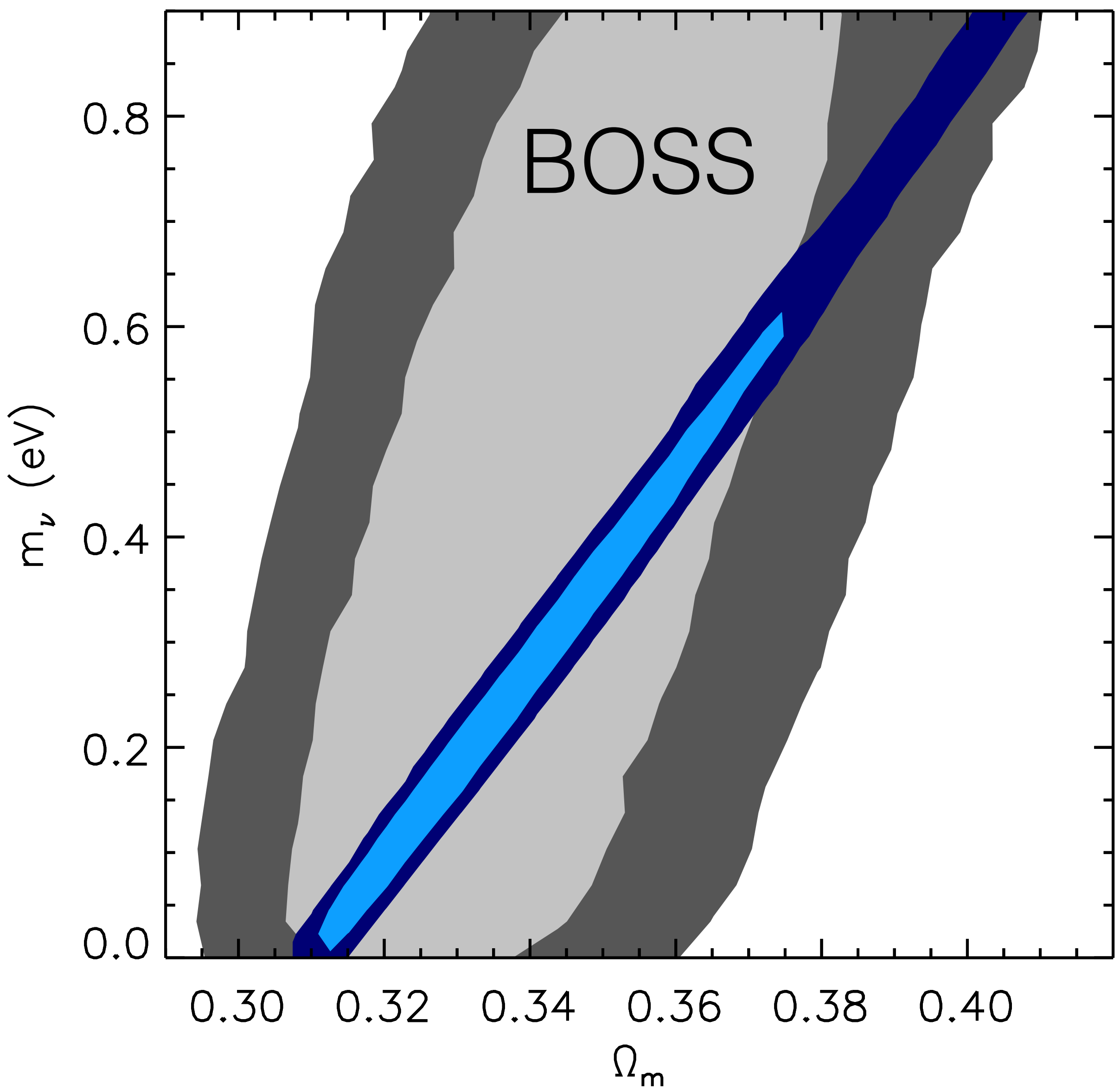
Oh, YSS arXiv:1607.01074

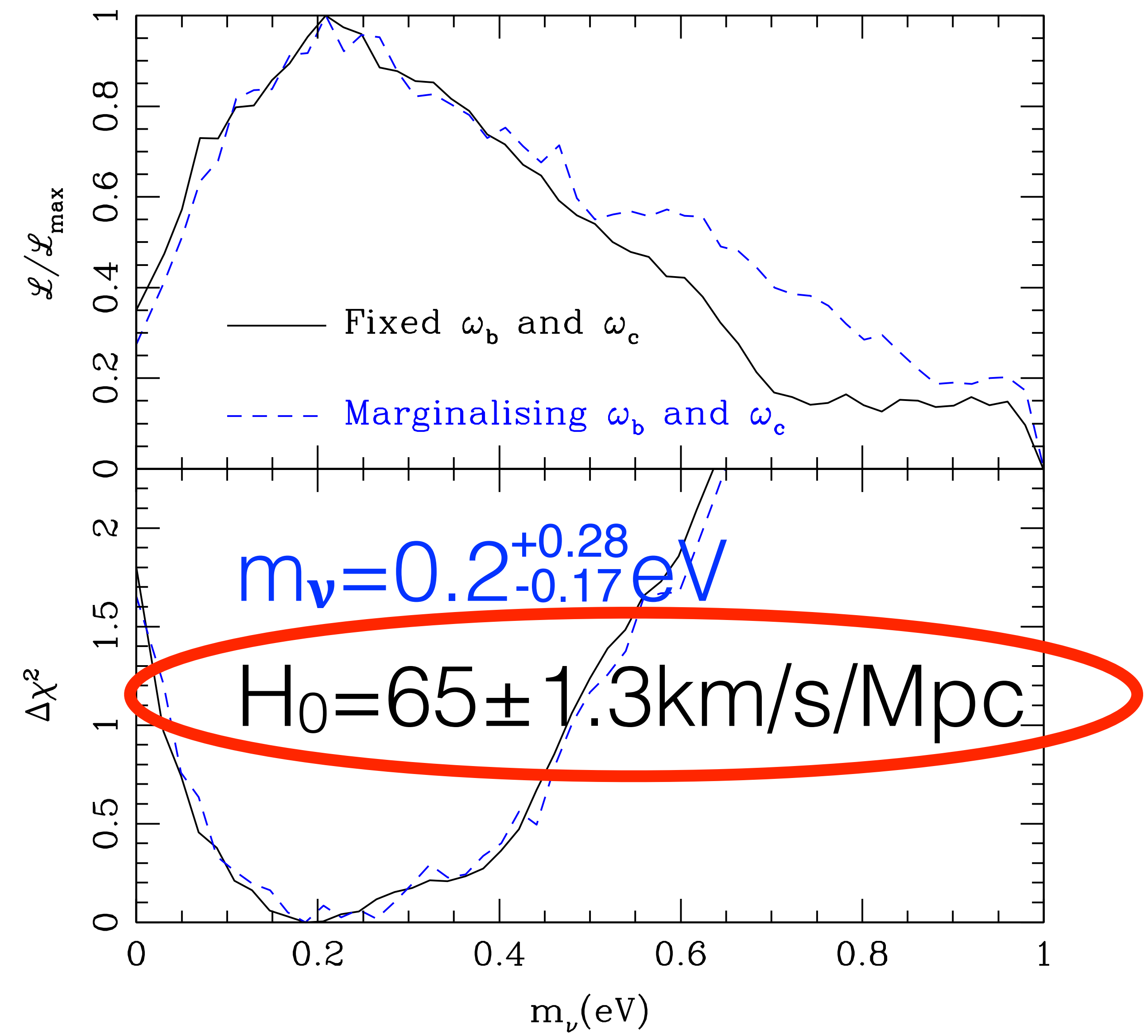
Excavating neutrino mass buried under LSS

The measured neutrino mass is $m_\nu = 0.2^{+0.28}_{-0.17}$ eV

The combined constraints on m_ν is distinguishable from massless m_ν

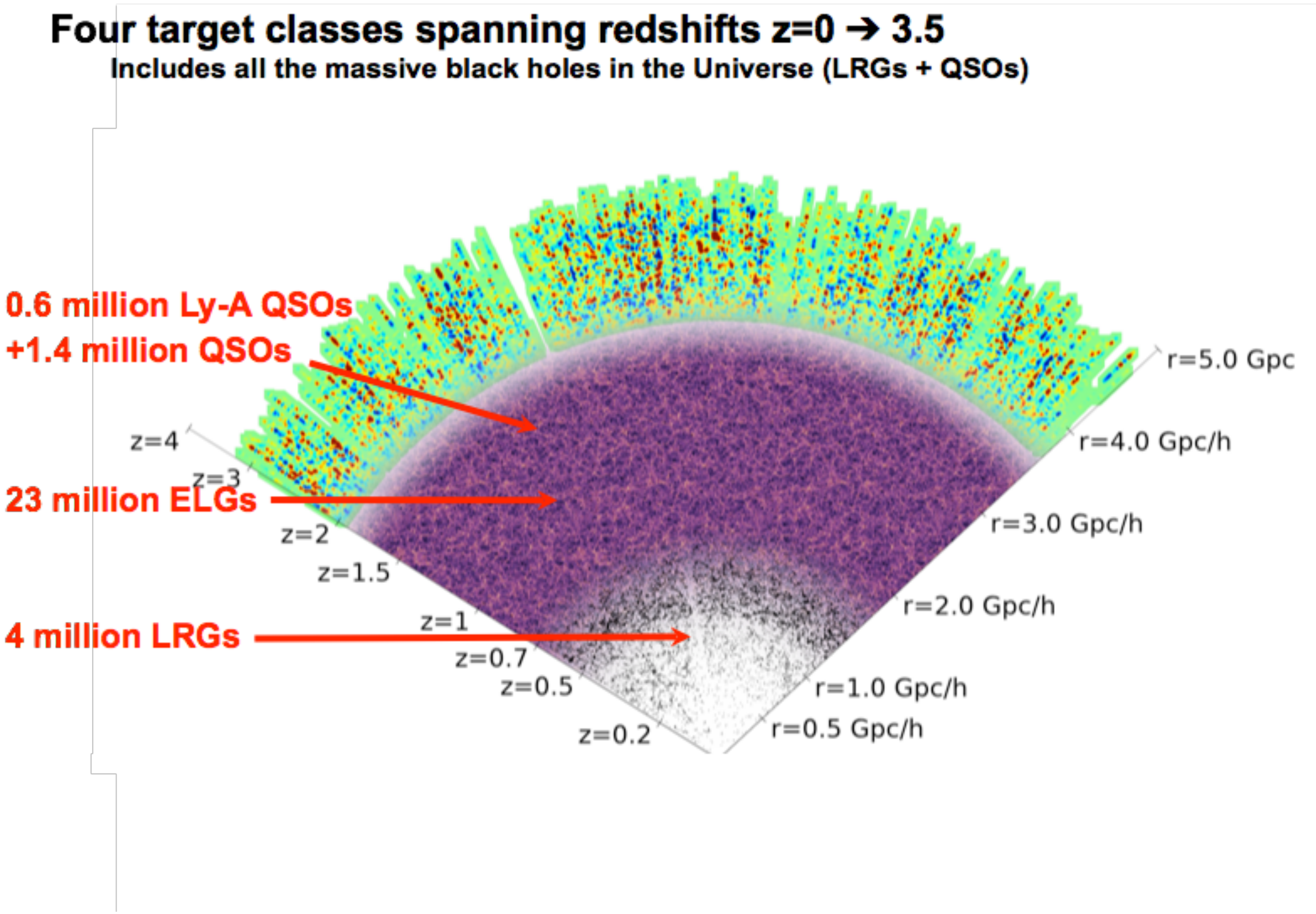
CMB distance measure





Oh, YSS arXiv:1607.01074

Challenge to the future precision cosmology



Mapping of clustering from real to redshift spaces

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

$$\Downarrow$$

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

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

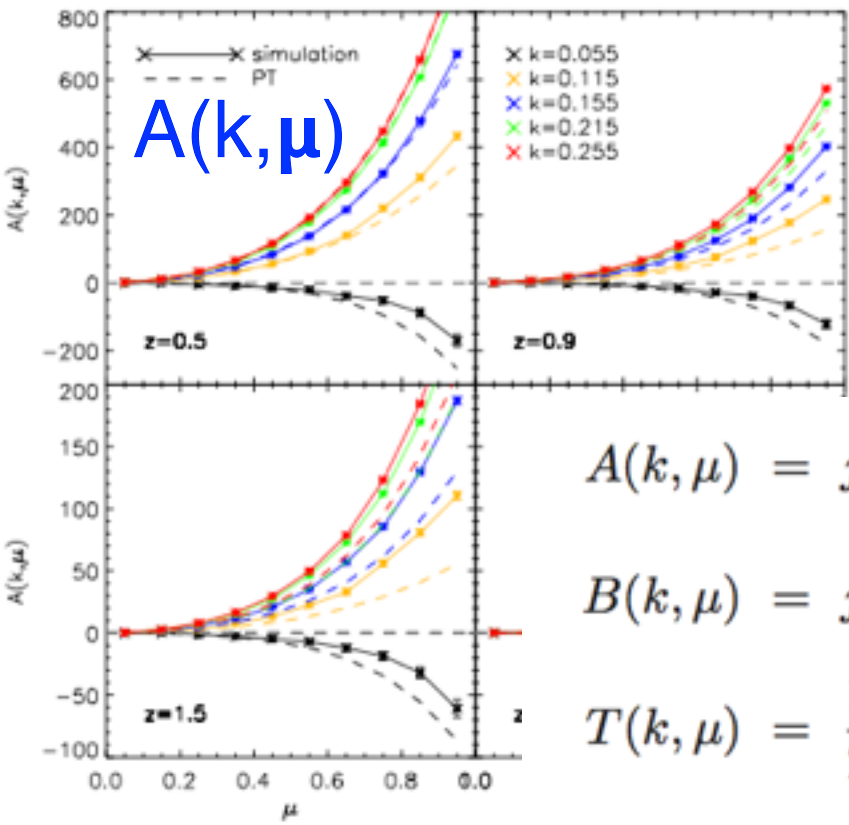
$$P_s(k,\mu) = [P_{gg}(k) + 2\boldsymbol{\mu}^2 P_{g\Theta}(k) + \boldsymbol{\mu}^4 P_{\boldsymbol{\theta\theta}}(k) + A(k,\boldsymbol{\mu}) + B(k,\boldsymbol{\mu}) + T(k,\boldsymbol{\mu}) + F(k,\boldsymbol{\mu})]$$

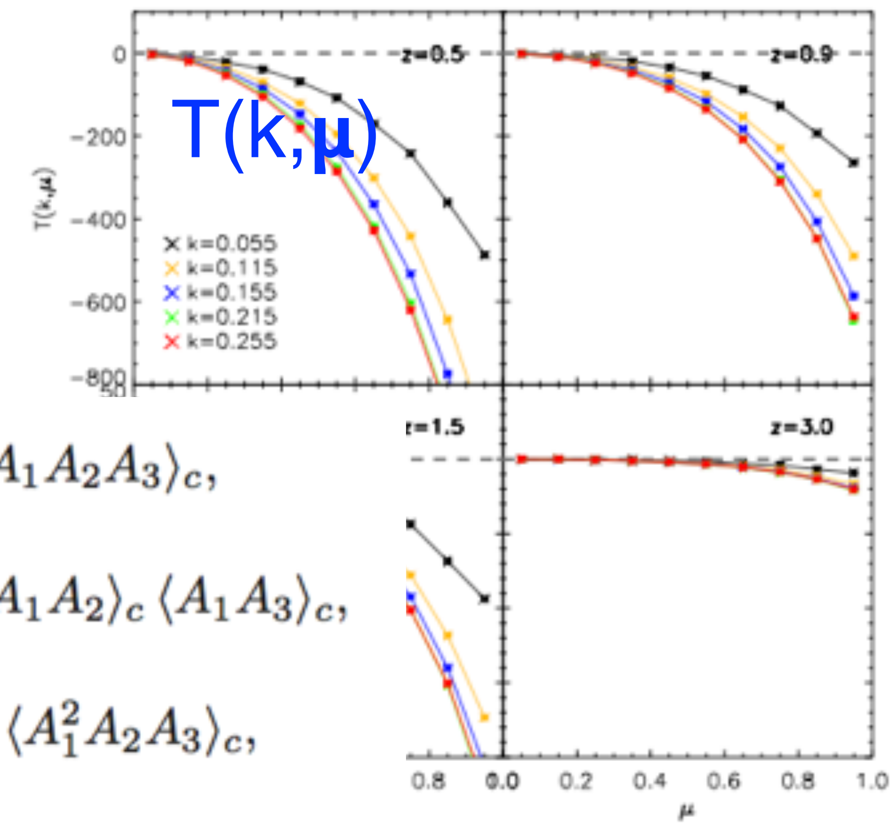
$$\exp[-(k\boldsymbol{\mu}\sigma_p)^2]$$

- 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

Direct measurement of higher order polynomials



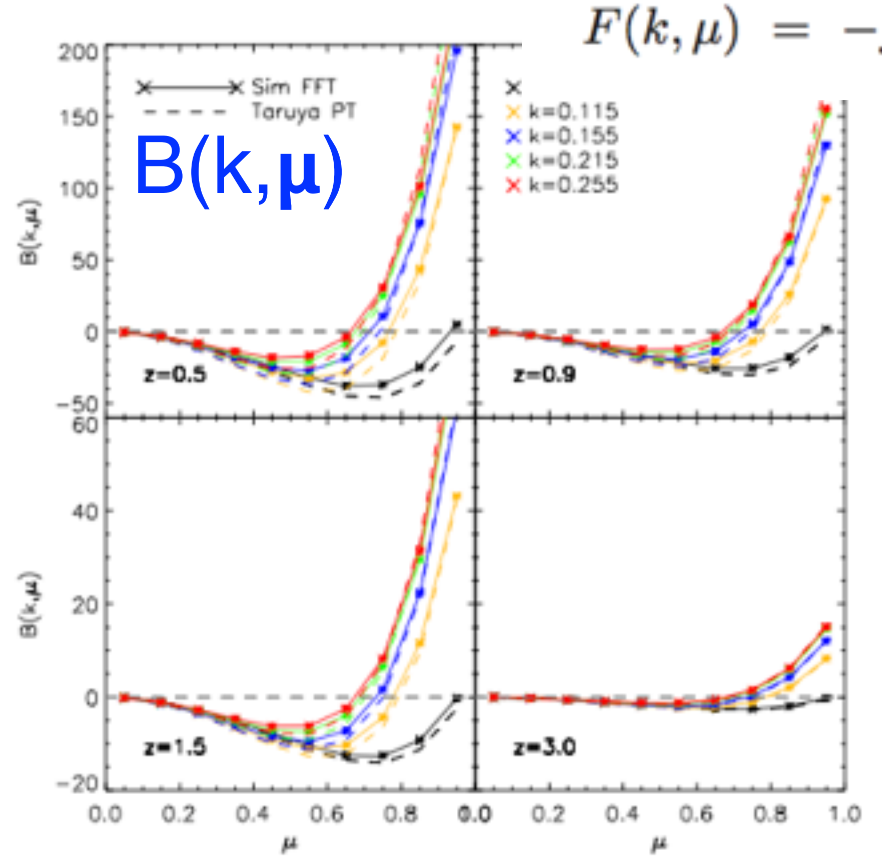


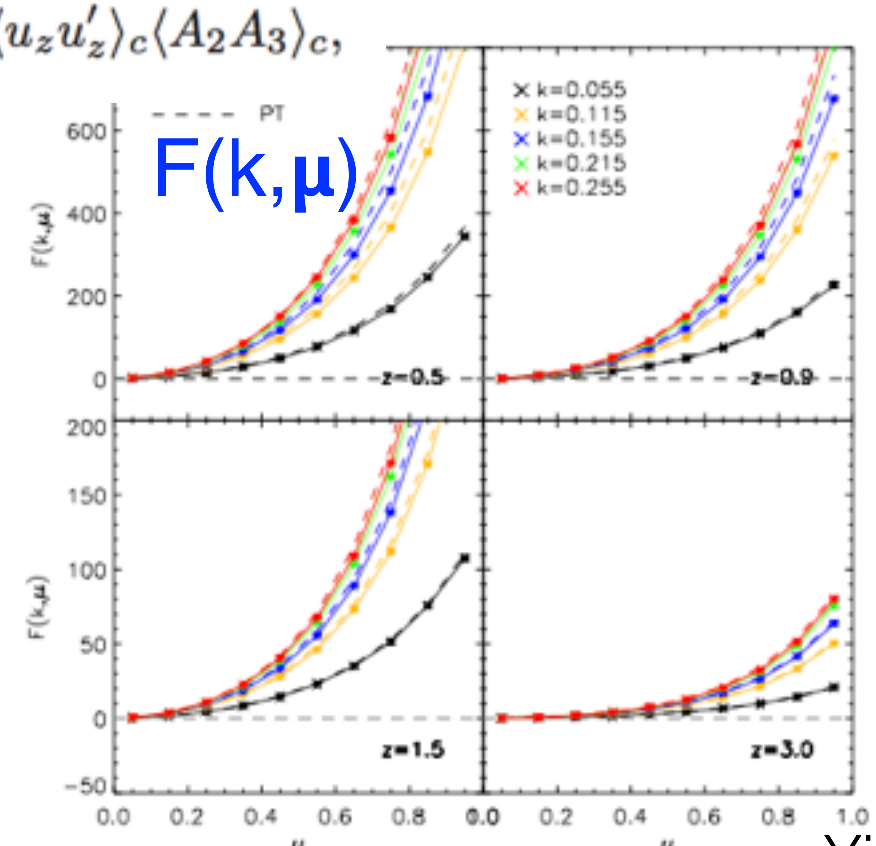
$$A(k,\mu) = j_1 \int d^3\boldsymbol{x}\ e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\ \langle A_1 A_2 A_3\rangle_c,$$

$$B(k,\mu) = j_1^2 \int d^3\boldsymbol{x}\ e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\ \langle A_1 A_2\rangle_c\ \langle A_1 A_3\rangle_c,$$

$$T(k,\mu) = \frac{1}{2} j_1^2 \int d^3\boldsymbol{x}\ e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\ \langle A_1^2 A_2 A_3\rangle_c,$$

$$F(k,\mu) = -j_1^2 \int d^3\boldsymbol{x}\ e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\ \langle u_z u_z'\rangle_c \langle A_2 A_3\rangle_c,$$



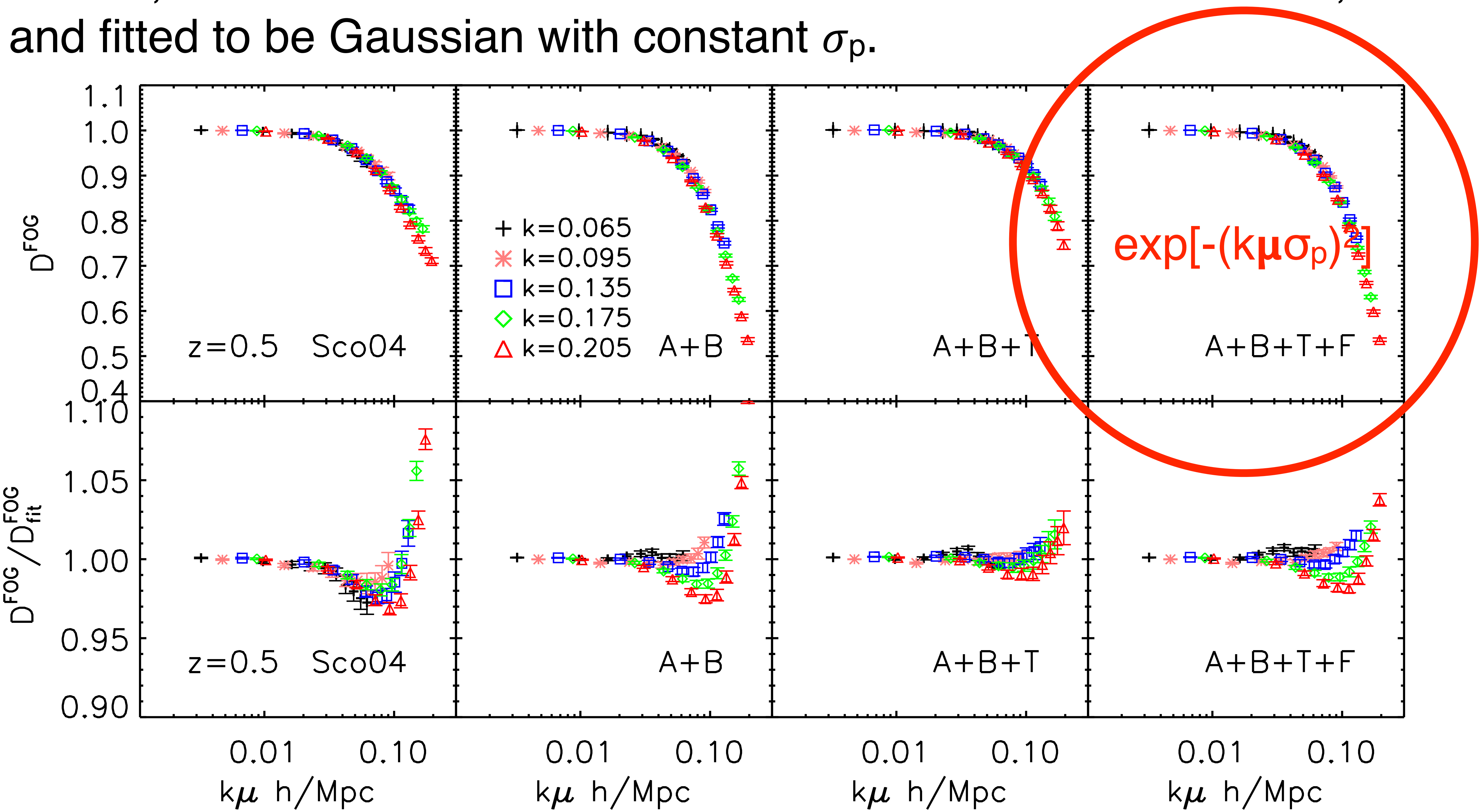


Yi, YSS 2016

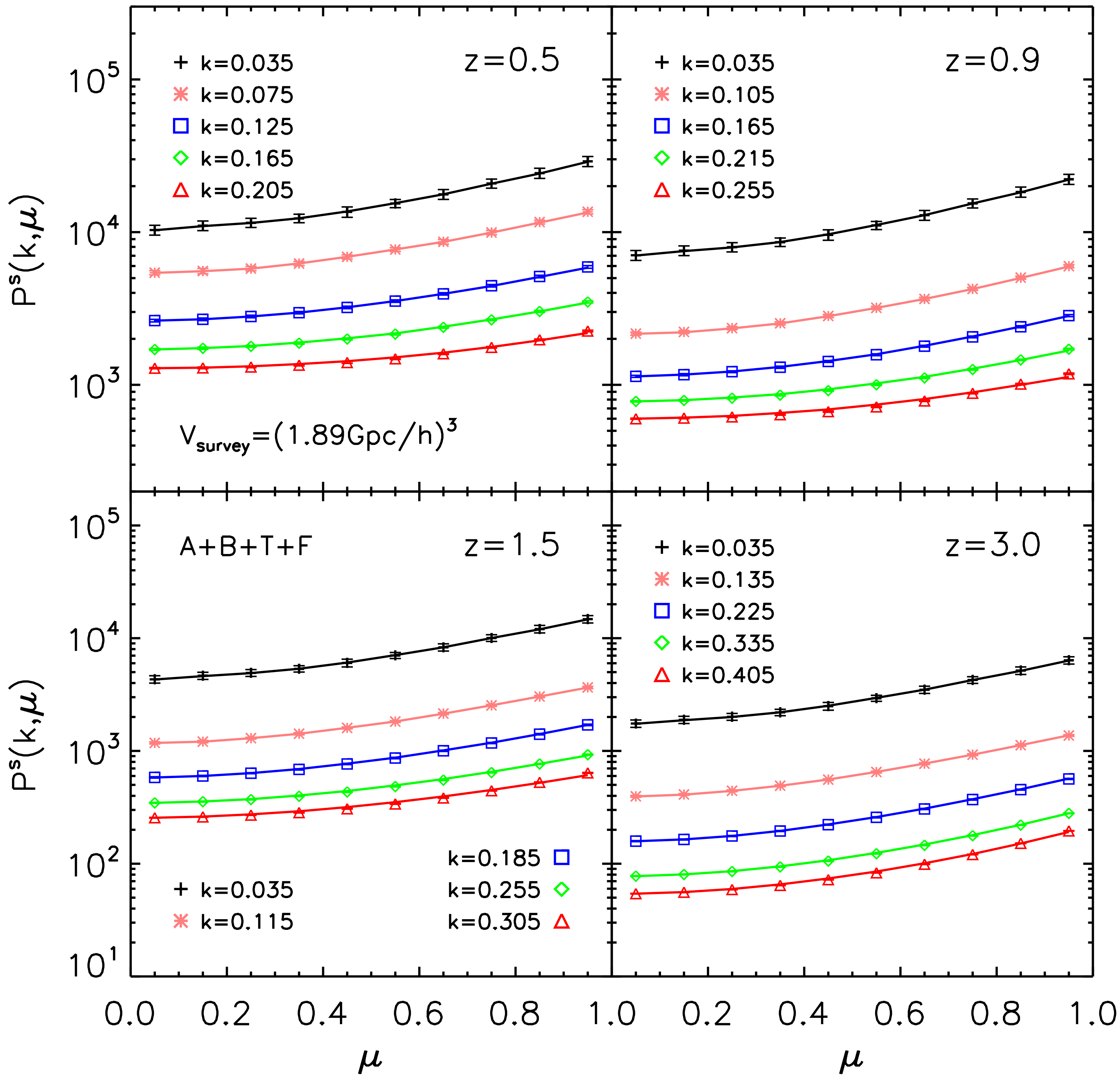
The residual FoG

Yi, YSS 2016

We subtract out the perturbative higher order polynomials, and the remaining's can be considered to be FoG effect. If our formulation is correct, those all residuals should be consistent in terms of scale, and fitted to be Gaussian with constant σ_p.



Challenge to the precision cosmology

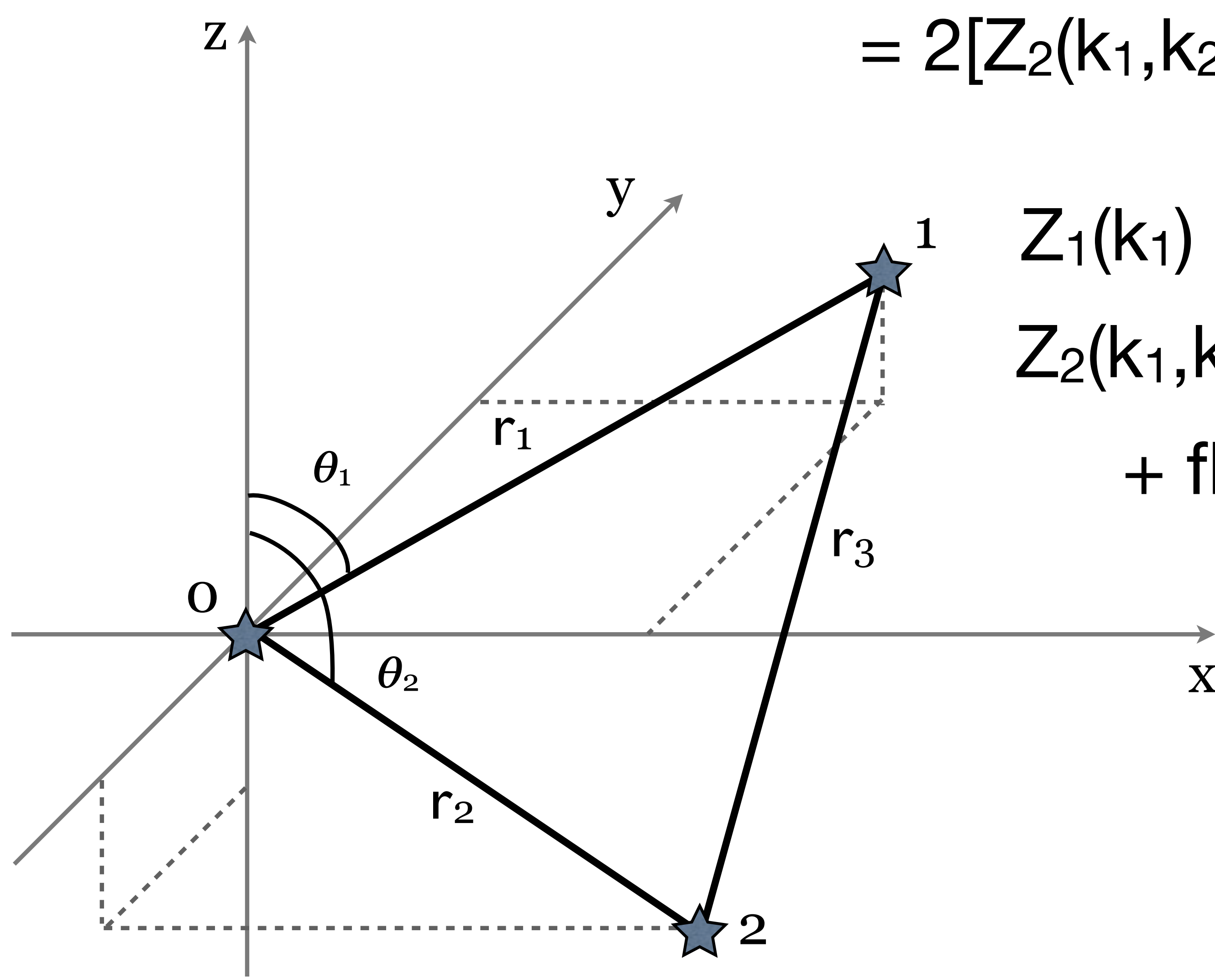


Yi, YSS 2016

Bispectrum in redshift space

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

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



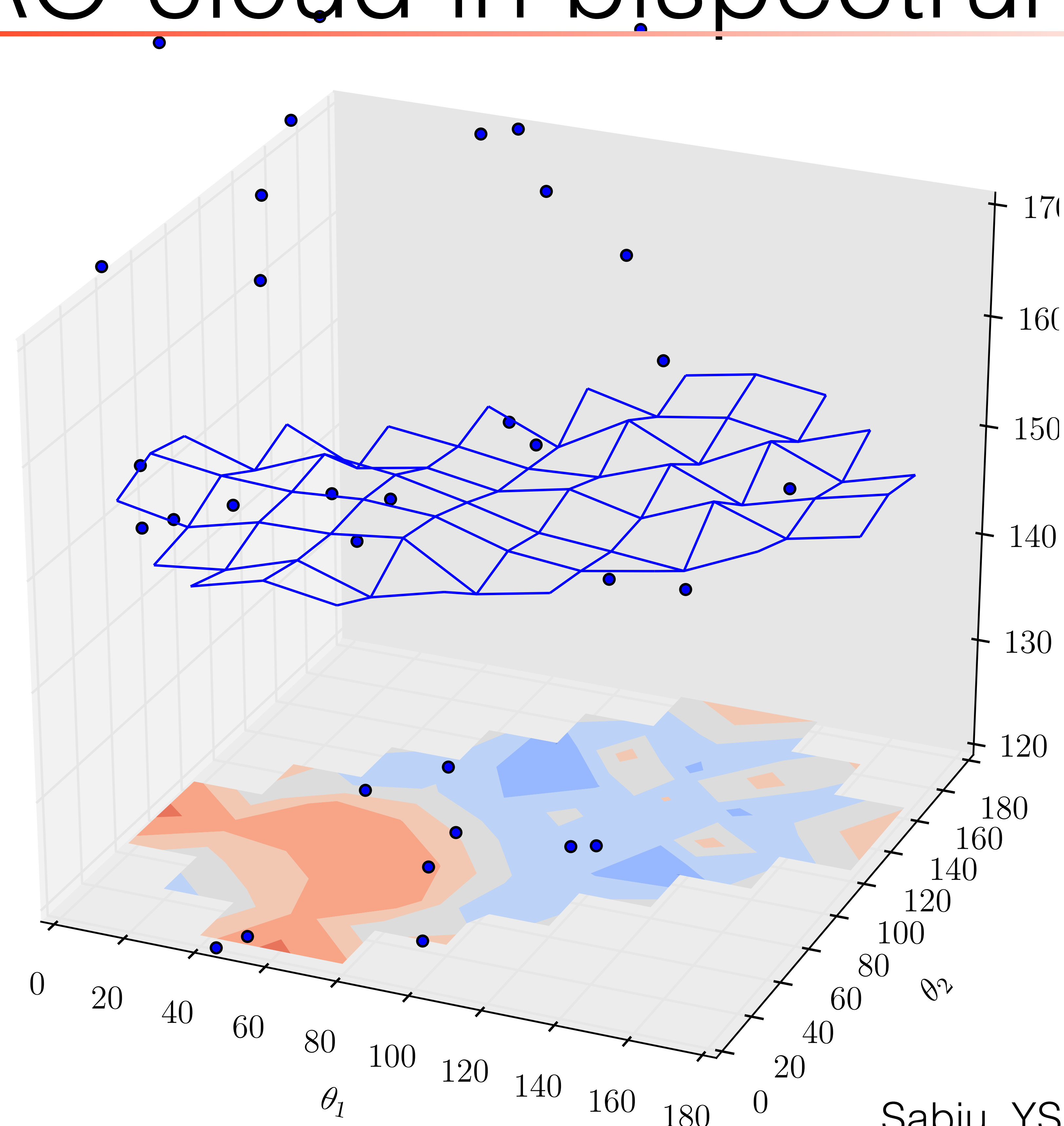
$$Z_1(k_1) = b+f\boldsymbol{\mu}_1{}^2$$

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

Sabiu, YSS 2016 prepared

YSS, Taruya, Akira 2015

BAO cloud in bispectrum



Sabiu, YSS 2016 prepared

The full RSD theory for bispectrum

First order (equivalent to Kaiser term)

$$\Big[\langle\Delta\Delta'\Delta''\rangle_c$$
$$+j_1\left(\langle V\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c\right)$$
$$+j_2\left(\langle V'\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c\right)$$

Second order

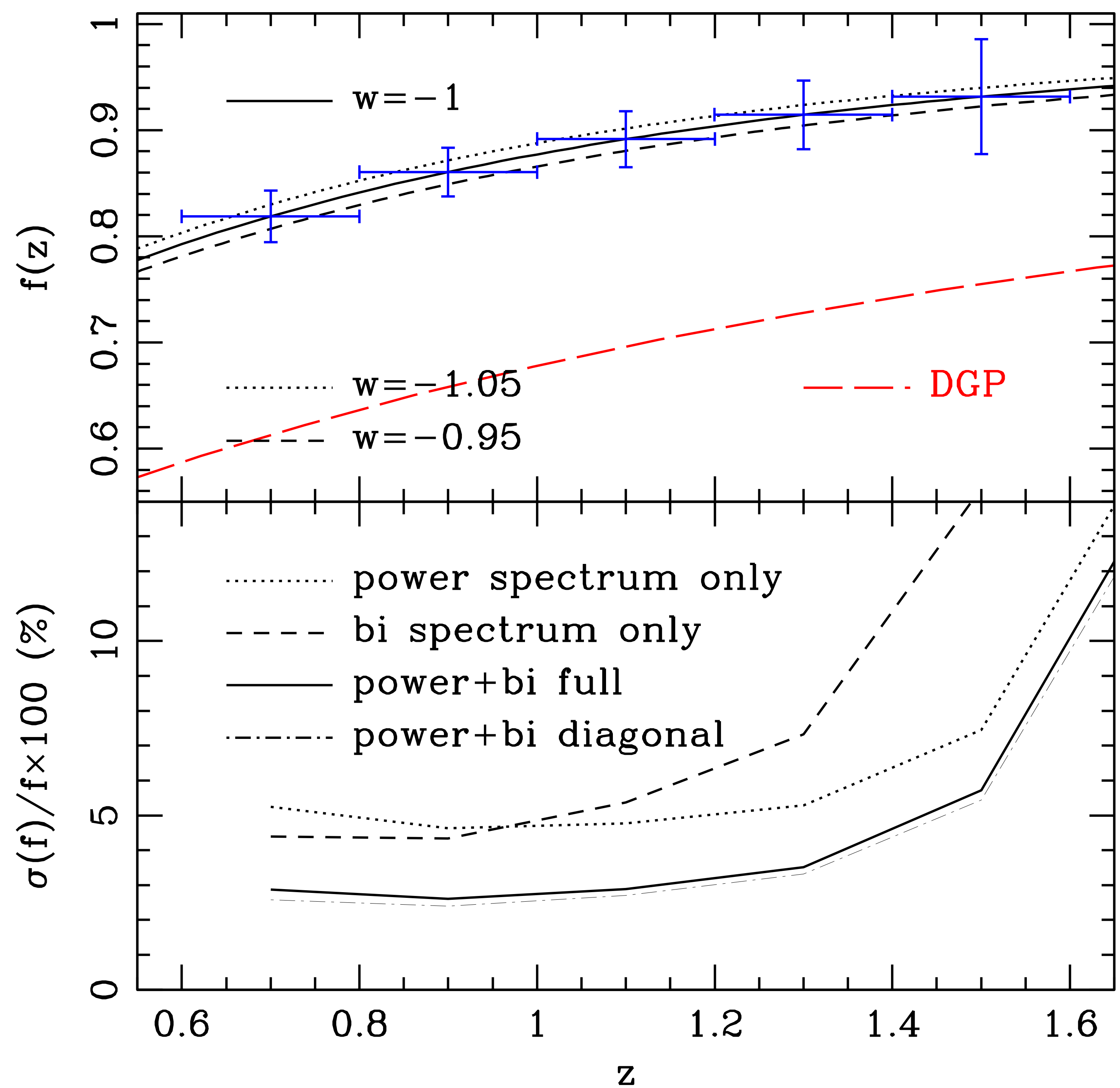
$$+j_1j_2(\langle VV'\Delta\Delta'\Delta''\rangle_c+\langle\Delta\Delta'\rangle_c\langle VV'\Delta''\rangle_c+\langle\Delta''\Delta\rangle_c\langle VV'\Delta'\rangle_c+\langle\Delta'\Delta''\rangle_c\langle VV'\Delta\rangle_c$$
$$+\langle V\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle V'\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle V\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle V'\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c$$
$$+\langle V\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c+\langle V'\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c)$$
$$+j_1^2(\frac{1}{2}\langle V^2\Delta\Delta'\Delta''\rangle_c+\frac{1}{2}\langle\Delta\Delta'\rangle_c\langle V^2\Delta''\rangle_c+\frac{1}{2}\langle\Delta''\Delta\rangle_c\langle V^2\Delta'\rangle_c+\frac{1}{2}\langle\Delta'\Delta''\rangle_c\langle V^2\Delta\rangle_c$$
$$+\langle V\Delta\Delta'\rangle_c\langle V\Delta''\rangle_c+\langle V\Delta''\Delta\rangle_c\langle V\Delta'\rangle_c+\langle V\Delta'\Delta''\rangle_c\langle V\Delta\rangle_c)$$
$$+j_2^2(\frac{1}{2}\langle V'^2\Delta\Delta'\Delta''\rangle_c+\frac{1}{2}\langle\Delta\Delta'\rangle_c\langle V'^2\Delta''\rangle_c+\frac{1}{2}\langle\Delta''\Delta\rangle_c\langle V'^2\Delta'\rangle_c+\frac{1}{2}\langle\Delta'\Delta''\rangle_c\langle V'^2\Delta\rangle_c$$
$$+\langle V'\Delta\Delta'\rangle_c\langle V'\Delta''\rangle_c+\langle V'\Delta''\Delta\rangle_c\langle V'\Delta'\rangle_c+\langle V'\Delta'\Delta''\rangle_c\langle V'\Delta\rangle_c)\Big]$$

FoG term

$$\exp\Big\{\frac{1}{2}(j_1^2+j_2^2+j_3^2)\sigma_z^2-j_1^2\langle u_z(\vec{r})u_z(\vec{r}')\rangle_c-j_2^2\langle u_z(\vec{r})u_z(\vec{r}'')\rangle_c$$
$$+j_1j_2\left[\langle u_z(\vec{r}')u_z(\vec{r}'')\rangle_c-\langle u_z(\vec{r})u_z(\vec{r}')\rangle_c-\langle u_z(\vec{r})u_z(\vec{r}'')\rangle_c\right]\Big\}$$

YSS et.al. 2016 prepared

Improved coherent motion in the future



YSS, Taruya, Akira 2015

Conclusion

- We measure coherent motion of the universe with BOSS catalogue using RSD perturbative theory, which provides us with trustable measurements.
- The full perturbative approaches allow us to prove the exotic cosmic acceleration model such as modified gravity of f(R) gravity.
- We probe the non-trivial neutrino mass about 0.2eV, and the measured Hubble constant gets to be even smaller about 65.
- The future experiment opens new precision cosmology era, and we are ready for the challenge. Our new RSD theoretical model is promising to probe coherent motion in a percentage precision.
- The combination of power and bi spectra is essential to probe the coherent motion tightly. We make lots of efforts for it.