Measuring Coherent Motions from Redshift Distortions

June 29th, WKYC 2011

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Contents

- Motivation
- Decomposition of spectra in redshift space
- Practice of decomposition using mocking maps
- Optimizing redshift survey for cosmological purpose
- Current measurement of coherent motions
- Cosmological test of GR using WL and coherent motions
- Conclusion

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Dark energy study prospects

- Precision measurements of distance, growth, and curvature: it is desirable for future surveys to provide results of the distance and growth of structure, so that different theoretical models can be discernible.

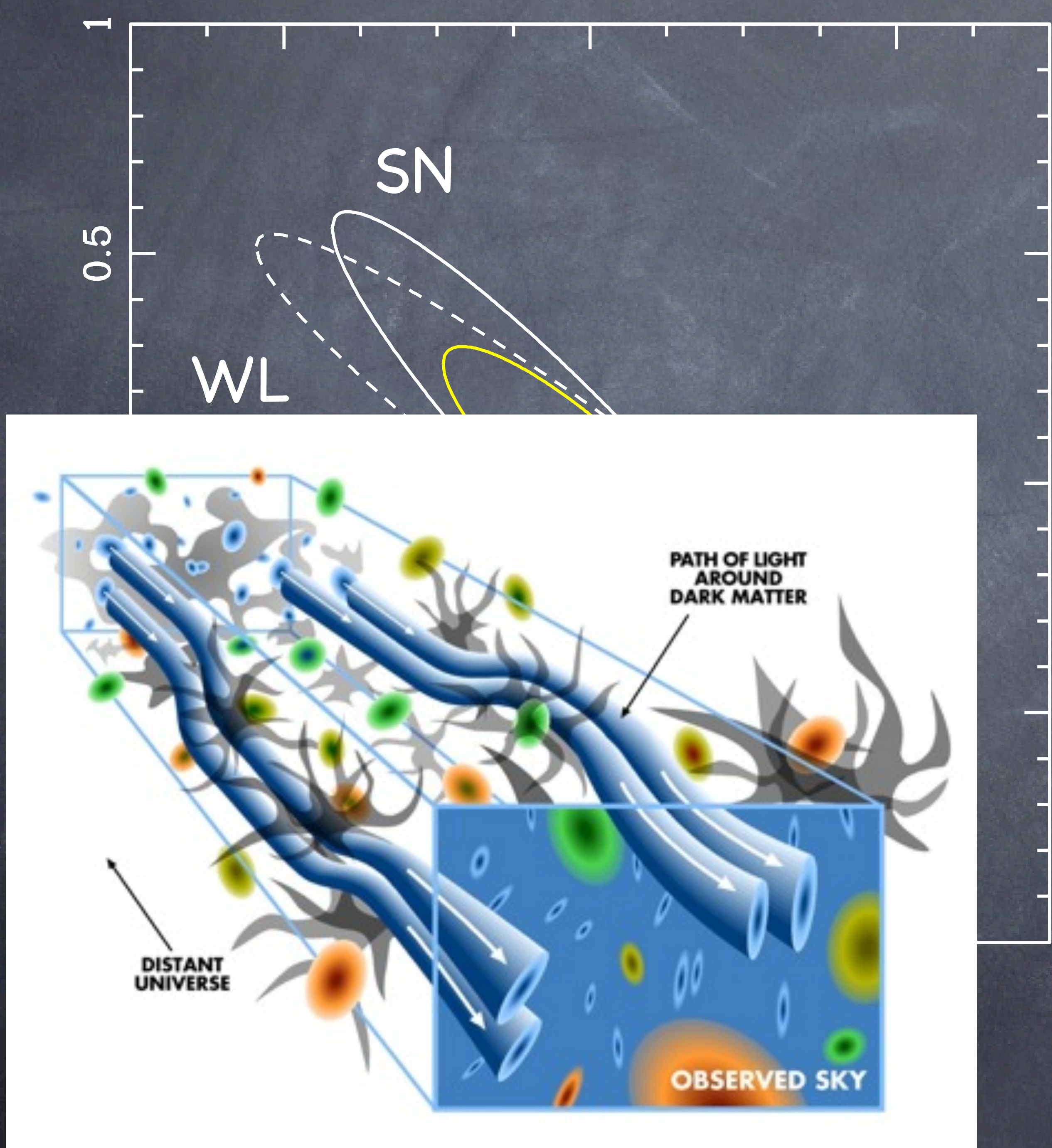
- Is dark energy a cosmological constant? : w=-1 even with generalized parameterization of all possibilities, e.g. variation of w, screening effect, induced anisotropy etc.

- Is dark energy isotropic and homogeneous? : we need examine the distribution, mean, and rms value of w over all the pixels to see.

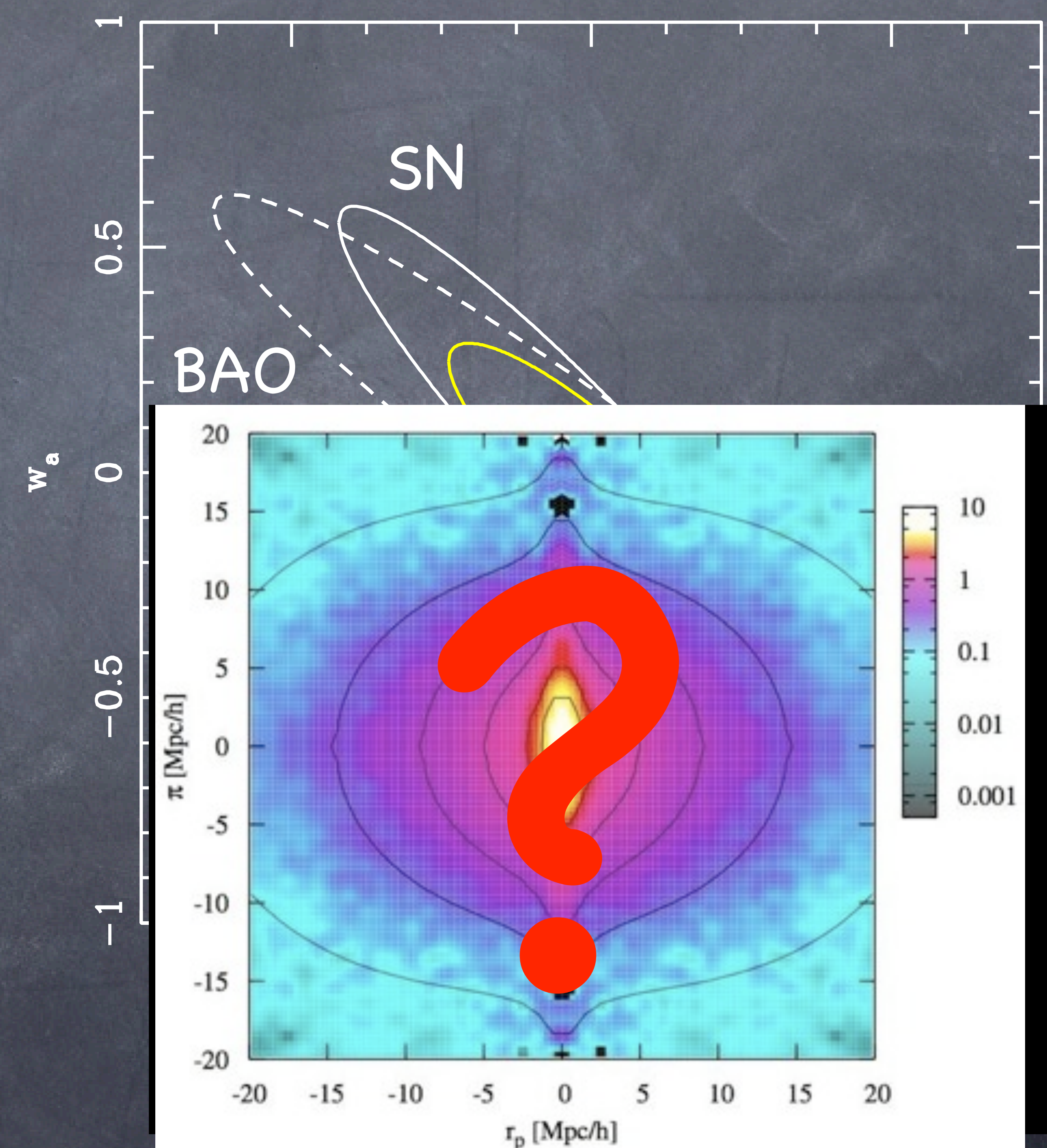
- Is acceleration caused by modified gravity instead? : we need at least two different probes, WL and coherent motions.

Wide-deep surveys

Photometric wide-deep survey



Spectroscopic wide-deep survey



Albrecht, Knox, YSS 2005

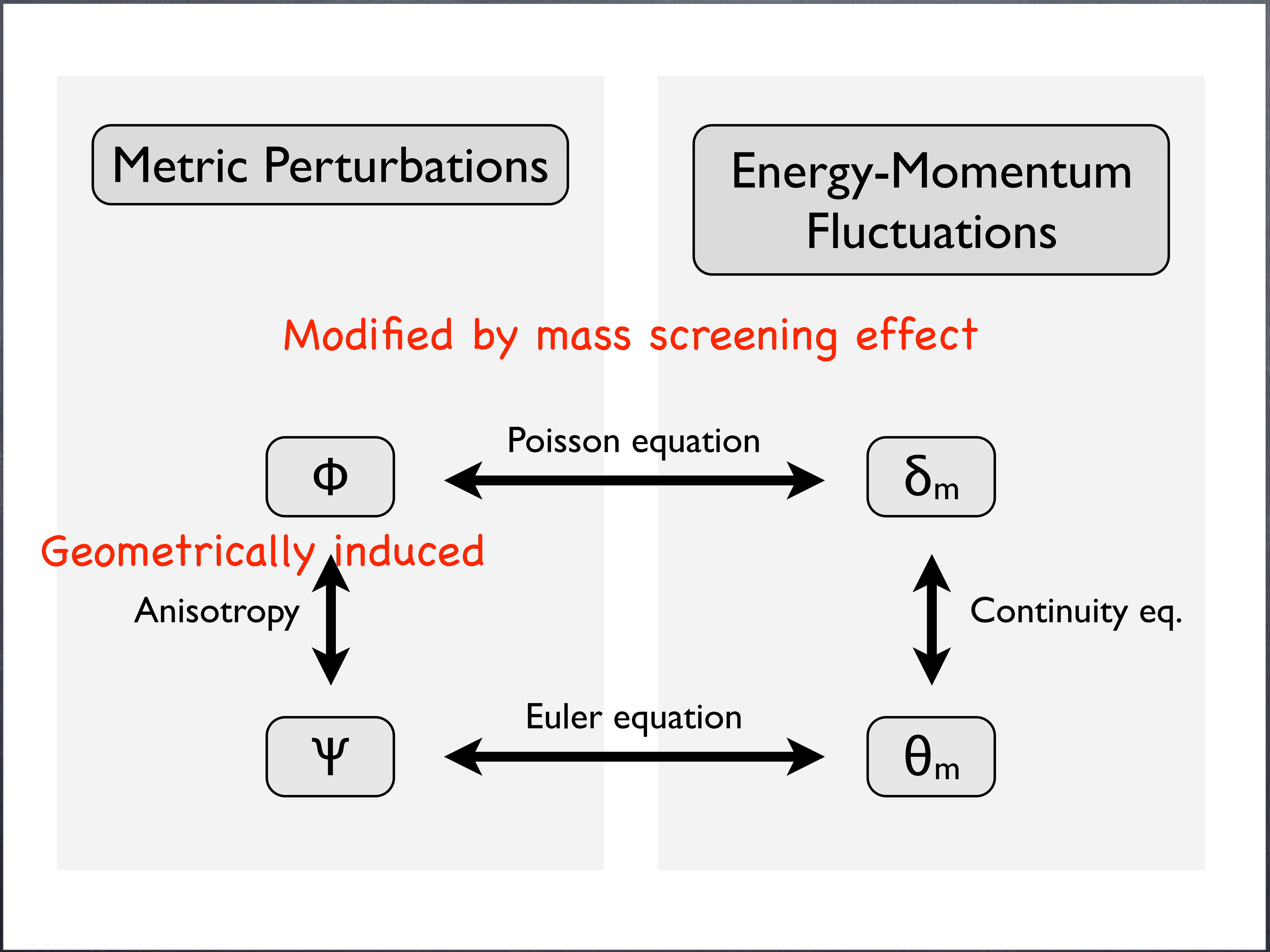
Beyond Standard Models

- With the level of precision available in these surveys, what they tell us about fundamental physics? : whether we can test GR cosmologically, whether we can constrain beyond Standard Model of particle physics.

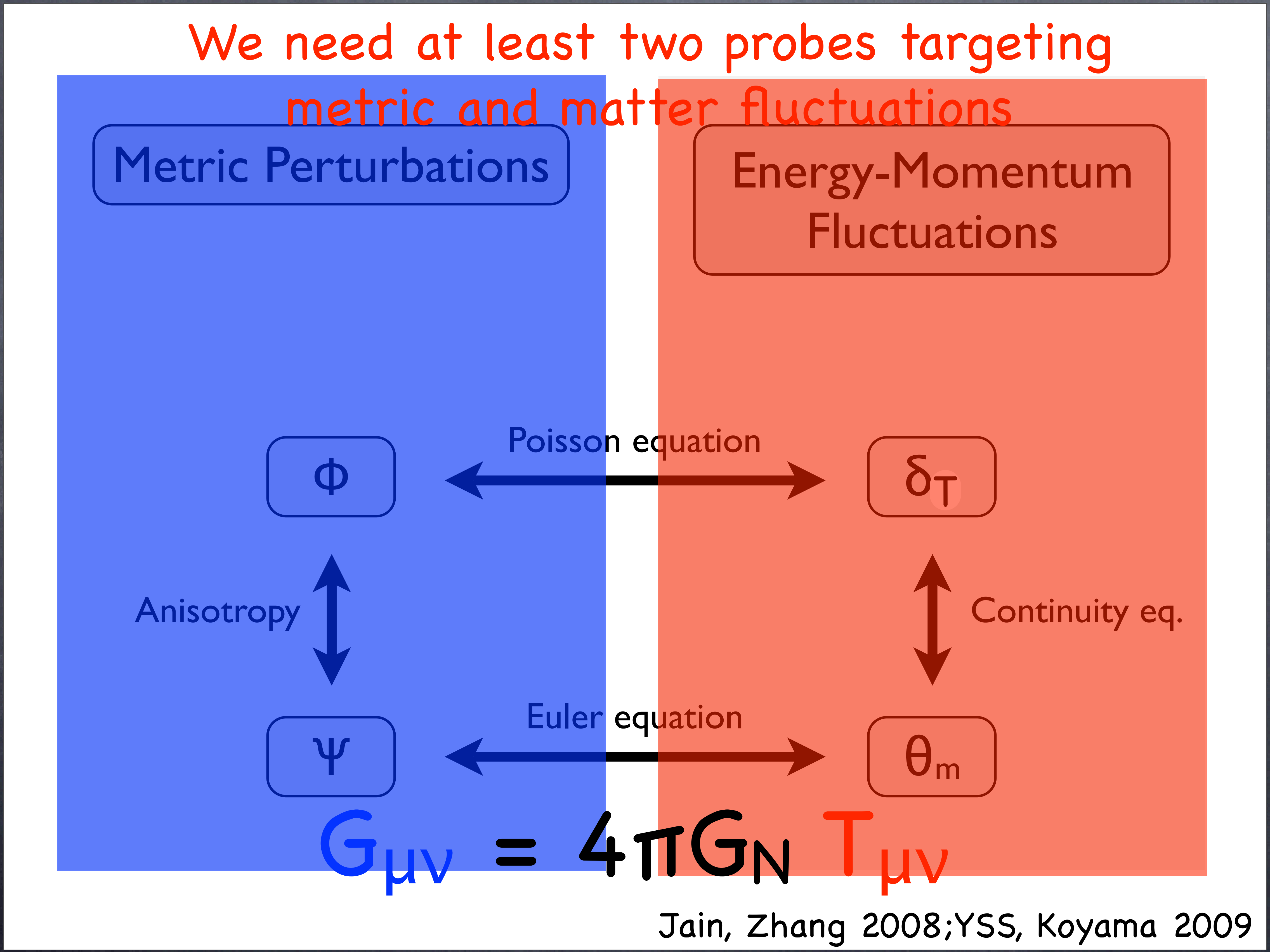
- What can a wide deep survey tell us about the basic assumptions behind the standard cosmology? : test cosmological principle (isotropy and homogeneity), and Gaussianity.

- What are the technical challenges to making these future surveys productive ?

Departures from standard DE

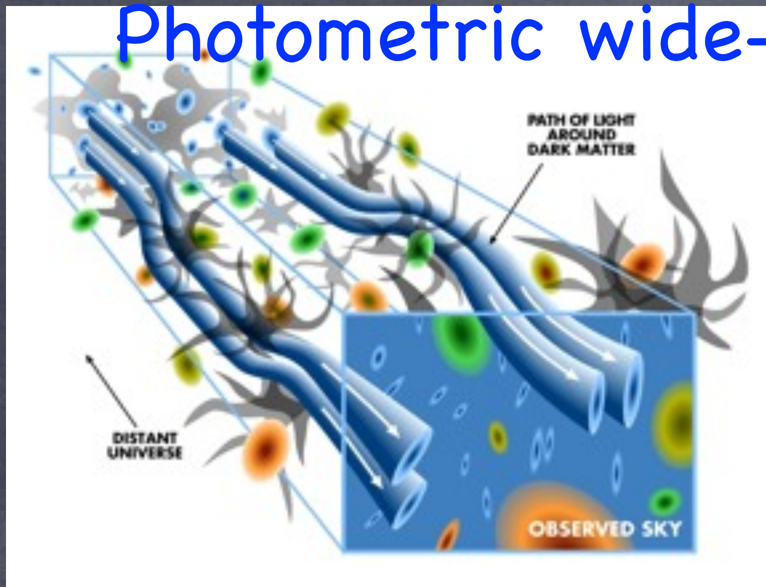


Observational service for theoretical models



Next generation of LSS test

Photometric wide-deep survey



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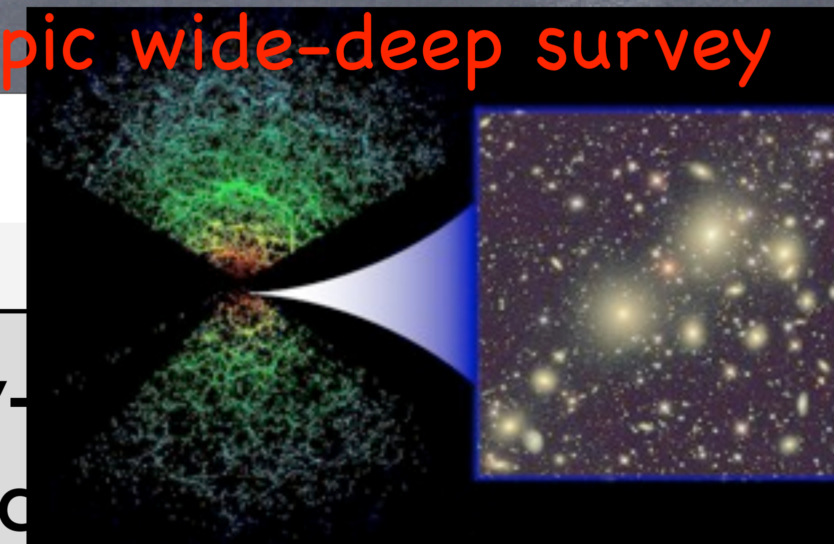


urbations

Energy-
Fluc

WL measures Φ-Ψ

Galaxy-Galaxy correlation

Φ ⟷ (Poisson equation) ⟷ δ_m

Anisotropy: Φ ↕ Ψ

Continuity eq.: δ_m ↕ θ_m

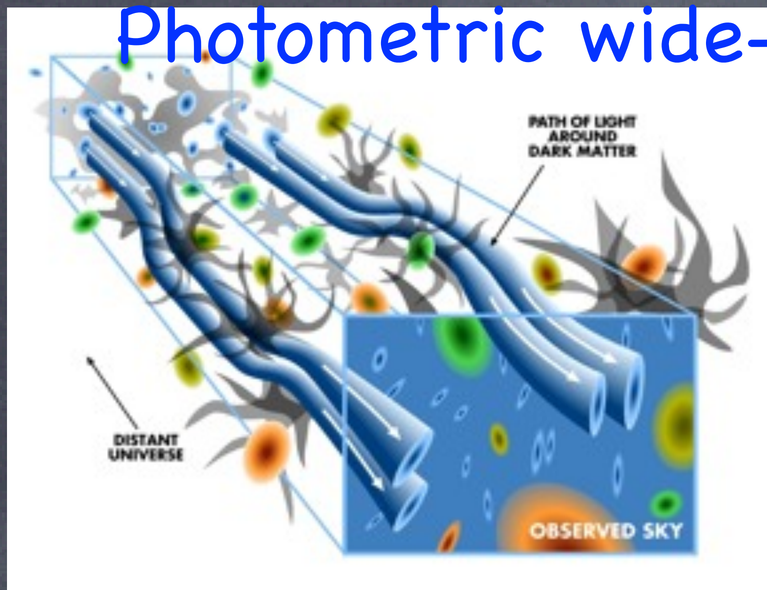
Ψ ⟷ (Euler equation) ⟷ θ_m

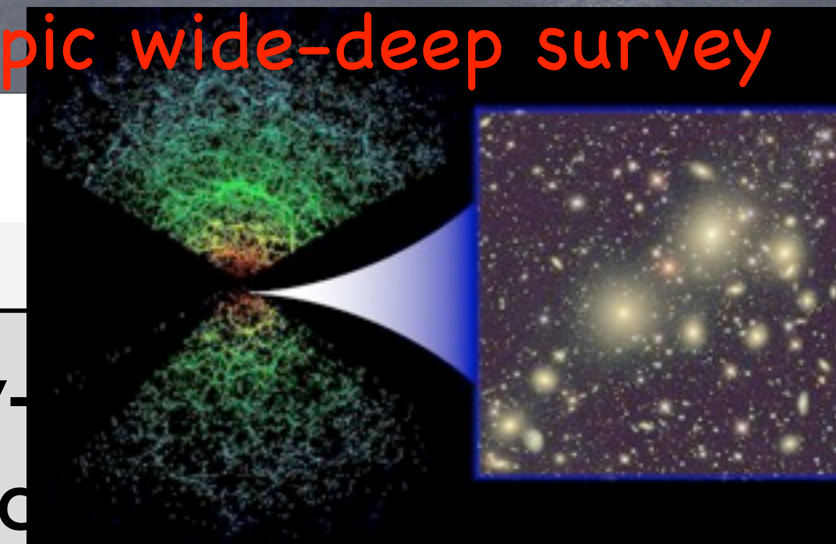
$$G_{\mu\nu} = 4\pi G_N T_{\mu\nu}$$

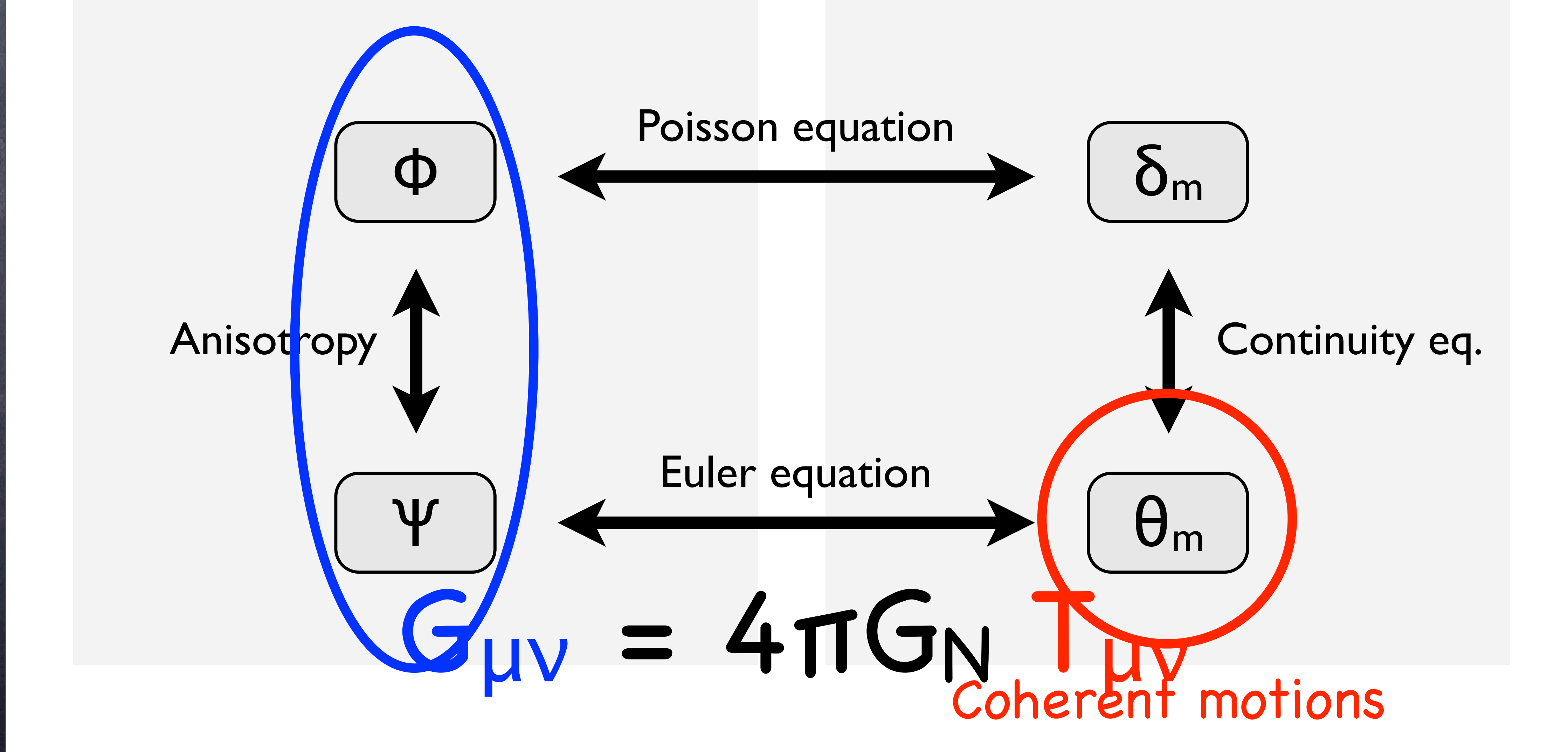
Next generation of LSS test

Photometric wide-deep survey

Spectroscopic wide-deep survey







WL measures Φ-Ψ

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

Coherent motions

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Developed techniques

Velocity measurements of nearby supernovae

Gordon, Land, Slosar (2008)

Velocity measurements of nearby galaxies

Feldman, Watkins, Hudson (2009)
Watkins, Feldman, Hudson (2009)
Lavaux, Tully, Mohayaee, Colombi (2010)

Analyzed CMB fluctuations on directions of X-ray clusteres

Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2008)
Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2009)

Measuring coherent motions from redshift distortions

YSS, Pervical (2008) White, YSS, Pervical (2009)
YSS, Sabiu, Nichol, Miller (2010)
YSS, Sabiu, Kayo, Nichol (2010)

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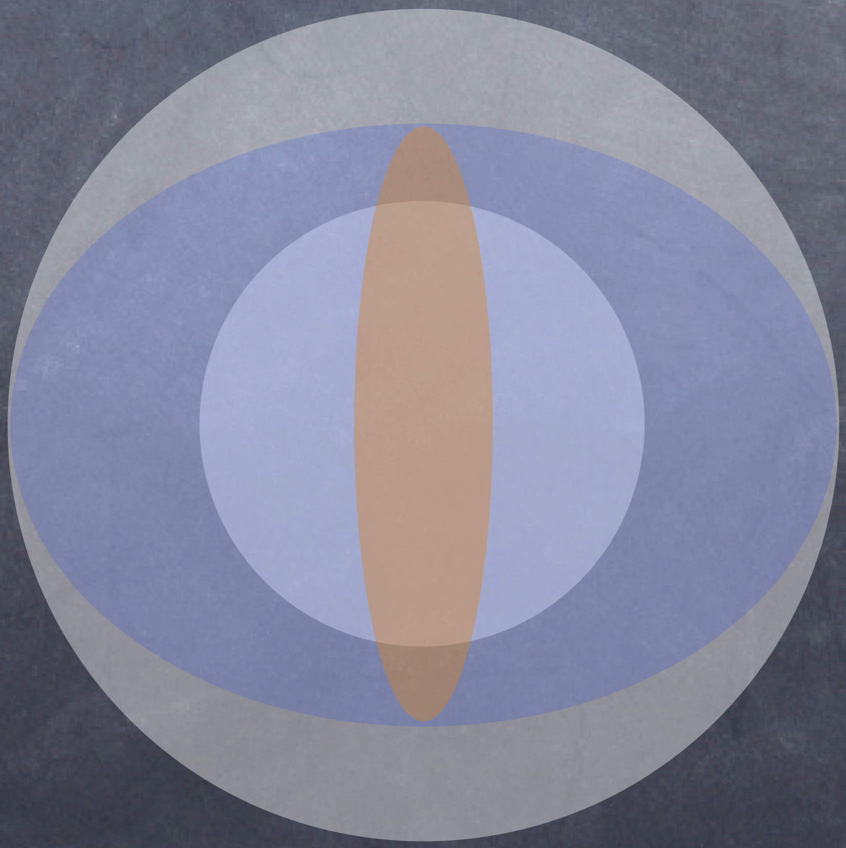
Correlation in redshift space

Galaxies (or Clusters) measure correlations amongst large scale local inhomogeneities, while the observed distortions in these correlations in redshift space can be used to extract information about peculiar velocities.

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

Squeezing effect at large scales

(Kaiser 1987)



Finger of God effect at small sclaes

(Jackson 1972)

Fisher analysis to decompose real spectra

We find that we can decompose peculiar velocity from the observed spectra in redshift space without using β. Errors can be estimated using Fisher matrix analysis, $P_s(k,\mu) = P_{gg}(k) + 2\mu^2 P_{g\Theta}(k) + \mu^4 P_{\Theta\Theta}(k)$

$$F_{\alpha\beta} = A\int k^2 dk \int d\mu \; dP_s(k,\mu)/dq_\alpha \, (V_{eff}/P_s)^2 \, dP_s(k,\mu)/dq_\beta$$

where $q_\alpha = (P_{gg}, P_{g\Theta}, P_{\Theta\Theta})$.

But we are not able to know all spectra, as we observe only monopole and quadrupole precisely,

$$\begin{aligned} P_s(k,\mu) &= P_{gg}(k) + 2\mu^2 P_{g\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) \\ &= (P_{gg} + 2/3 P_{g\Theta} + 1/5 P_{\Theta\Theta}) \, P_0(\mu) \quad ✔ \\ &+ (4/3\, P_{g\Theta} + 4/7 P_{\Theta\Theta}) \, P_2(\mu) \quad ✔ \\ &+ 8/35 P_{\Theta\Theta} \, P_4(\mu) \quad ✘ \end{aligned}$$

White, YSS, Percival 2009

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where $q_\alpha = (P_{gg}, P_{g\Theta}, P_{\Theta\Theta})$.

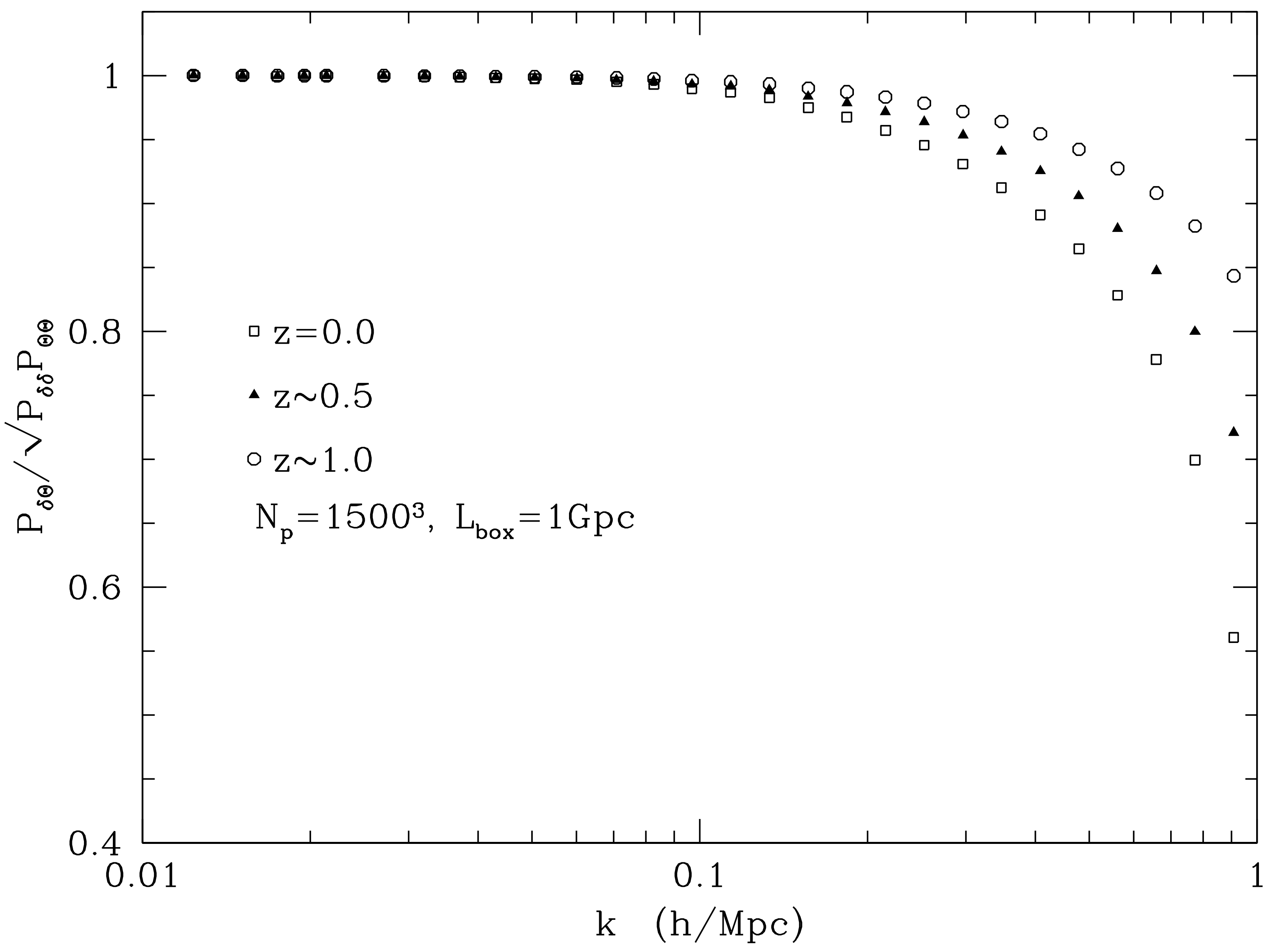
But we are not able to know all spectra, as we observe only monopole and quadrupole precisely,

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

The assumed perfect cross-correlation between P_{gg} and $P_{\Theta\Theta}$, so we convert measured $P_{g\Theta}$ into $P_{\Theta\Theta}$ using $P_{g\Theta}/\sqrt{P_{gg}\, P_{\Theta\Theta}} = 1$.

White, YSS, Percival 2009

Validation of perfect cross-correlation



White, YSS, Percival 2009

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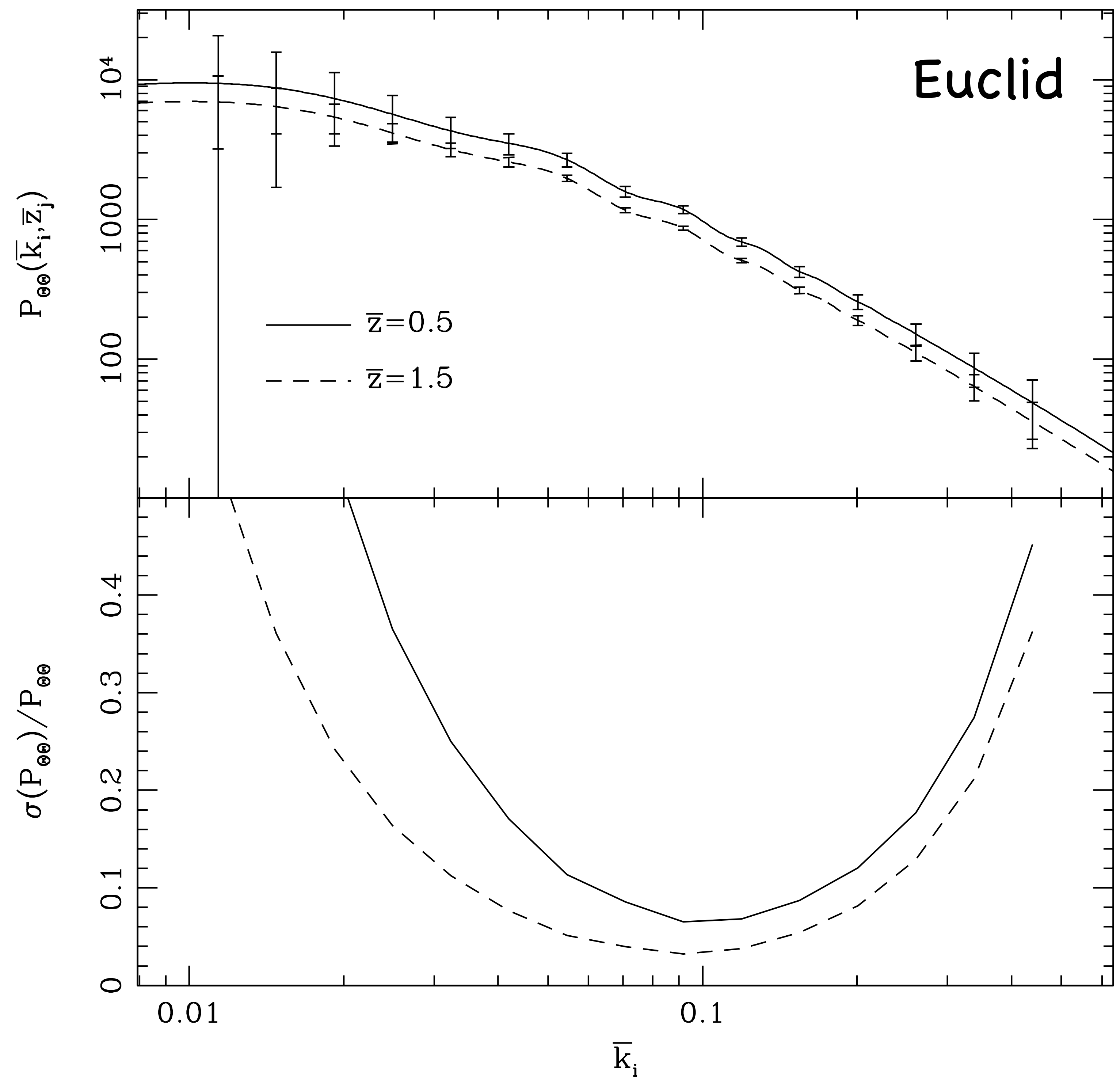
where $q_\alpha = (P_{gg}, P_{\Theta\Theta})$.

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

White, YSS, Percival 2009

Estimated coherent motion spectra, $P_{\Theta\Theta}$



White, YSS, Percival 2009

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$P_s(k)$ from time streaming Halo map

The Horizon simulation by Teyssier et.al.

Time streaming halo caltalogue

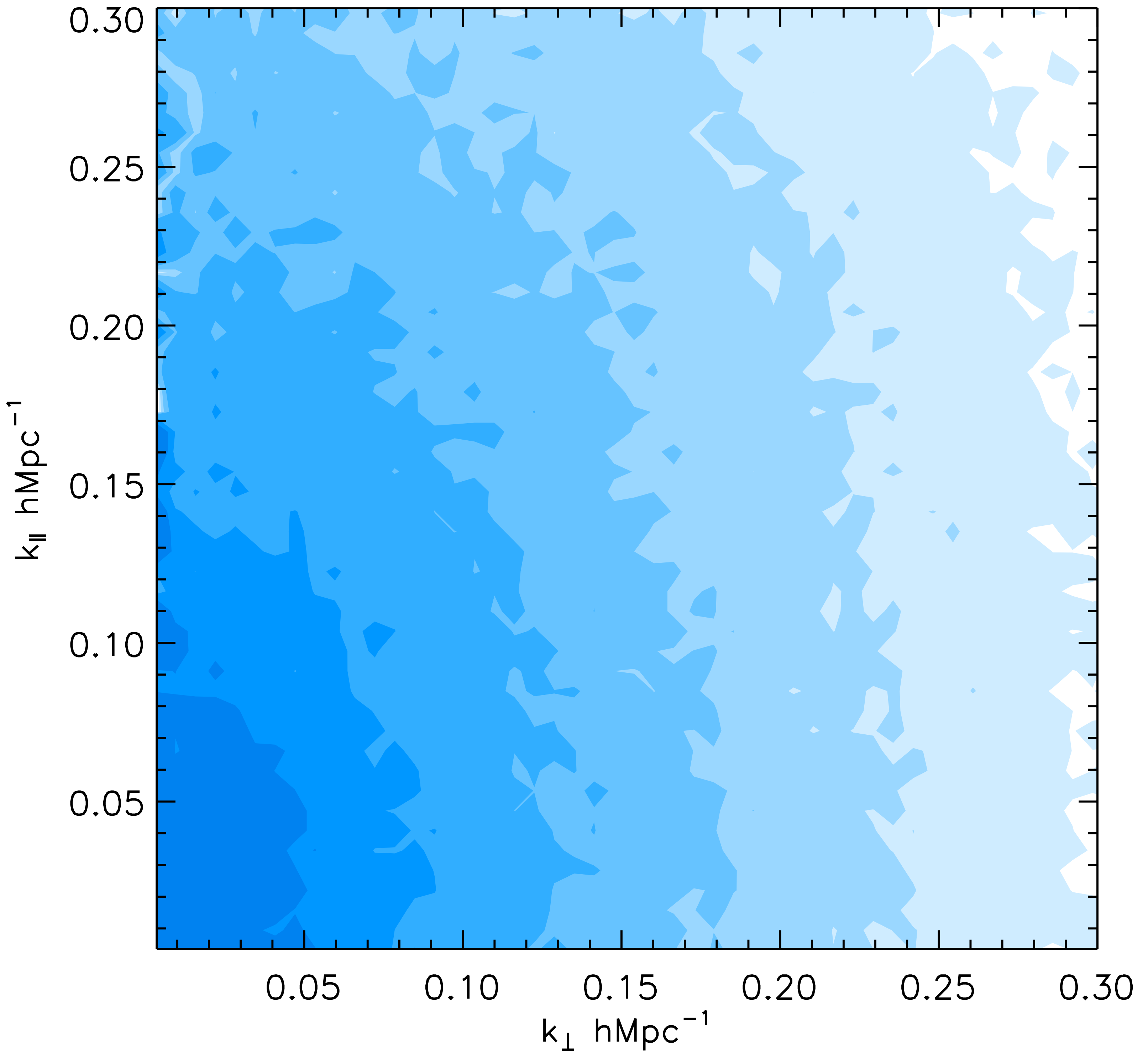
http://www.project-horizon.fr

Medium redshift z=0.8

Total volume $1\mathrm{Gpc}^3/h^3$

$P_s(k)$ from time streaming Halo map

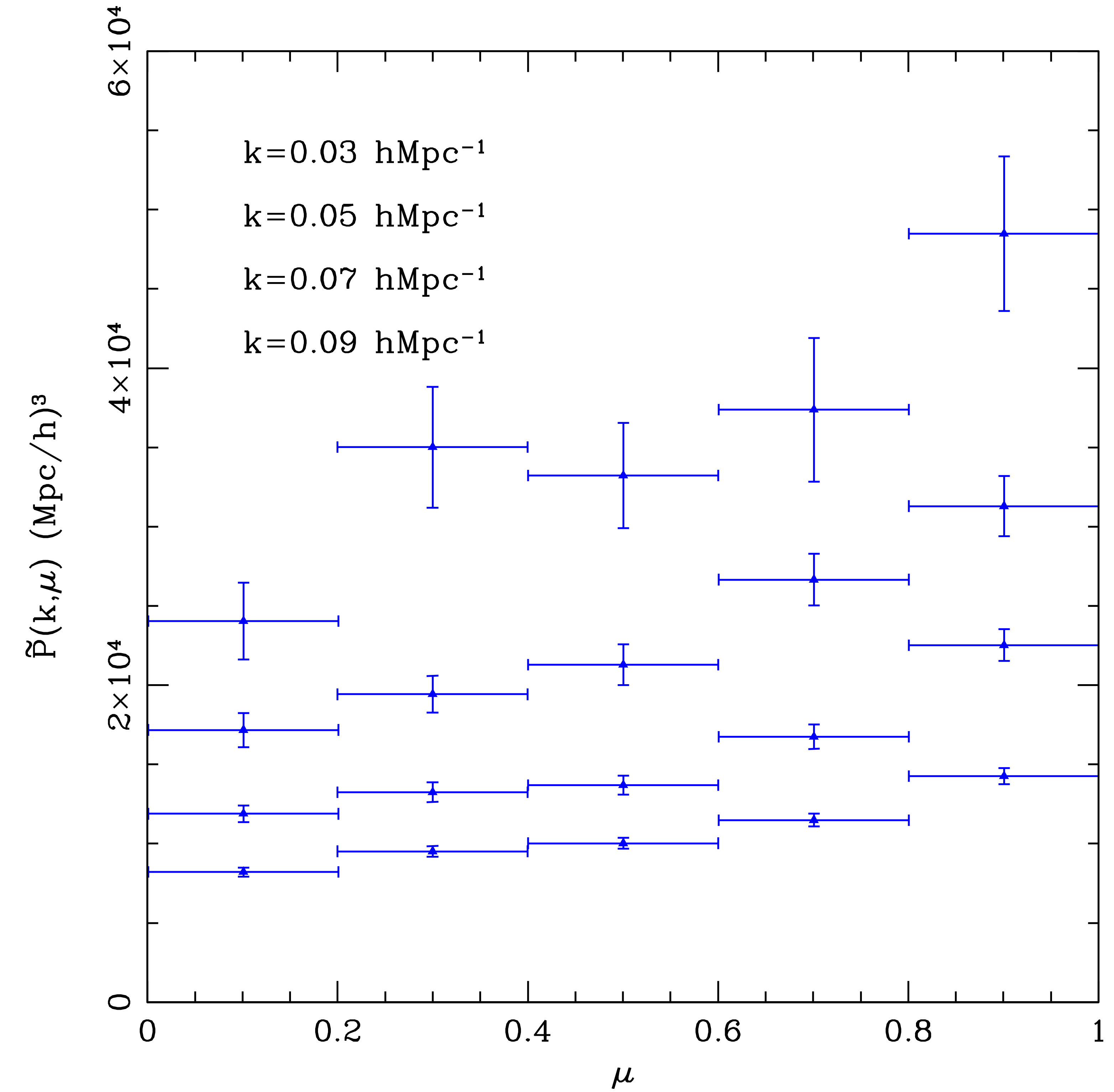
$$P_s(k,\mu) = P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)$$



YSS, Kayo 2010

$P_s(k,\mu)$ in polar coordinate

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



YSS, Kayo 2010

Decomposition in Kaiser limit

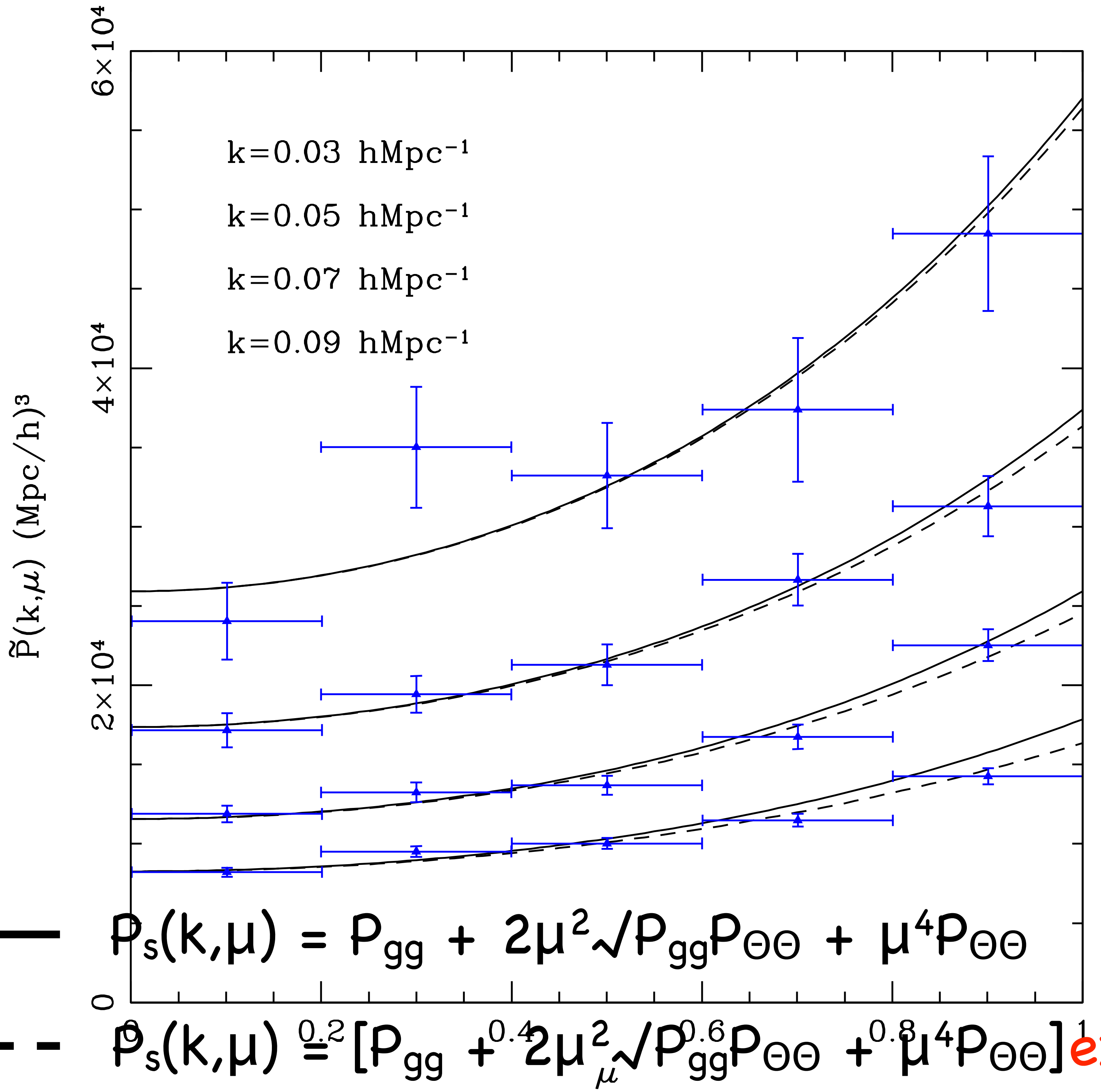
As $P_s(k,\mu)$ is given in polar coordinate, we can decompose $P_{\Theta\Theta}$ from measured spectra in each given bin μ using fitting formulation,

$$\chi_i^2 = \Sigma_p \Sigma_q [P_s^{ob}(k_i,\mu_p) - P_s^{th}(k_i,\mu_p)]\ Cov^{-1}{}_{pq}(k_i)\ [P_s^{ob}(k_i,\mu_q) - P_s^{th}(k_i,\mu_q)]$$

where $P_s^{th}(k_i,\mu_p) = P_{gg}(k_i) + 2\mu_p^2\sqrt{P_{gg}(k_i)P_{\Theta\Theta}(k_i)} + \mu_p^4 P_{\Theta\Theta}(k_i)$.

YSS, Kayo 2010

Velocity dispersion effect



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

$$P_s(k,\mu) = [P_{gg} + 2\mu^2\sqrt{P_{gg}P_{\Theta\Theta}} + \mu^4 P_{\Theta\Theta}]\exp[-(k\mu\sigma_v)^2]$$

YSS, Kayo 2010

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where $\cancel{P_s^{th}(k_i,\mu_p) = P_{gg}(k_i) + 2\mu_p^2\sqrt{P_{gg}(k_i)P_{\Theta\Theta}(k_i)} + \mu_p^4 P_{\Theta\Theta}(k_i).}$

$$P_s^{th}(k_i,\mu) = [P_{gg}(k_i) + 2\mu_p^2 P_{g\Theta}(k_i) + \mu_p^4 P_{\Theta\Theta}(k_i)] \exp[-(k_i\mu_p\sigma_v)^2]$$

Scoccimarro 2004

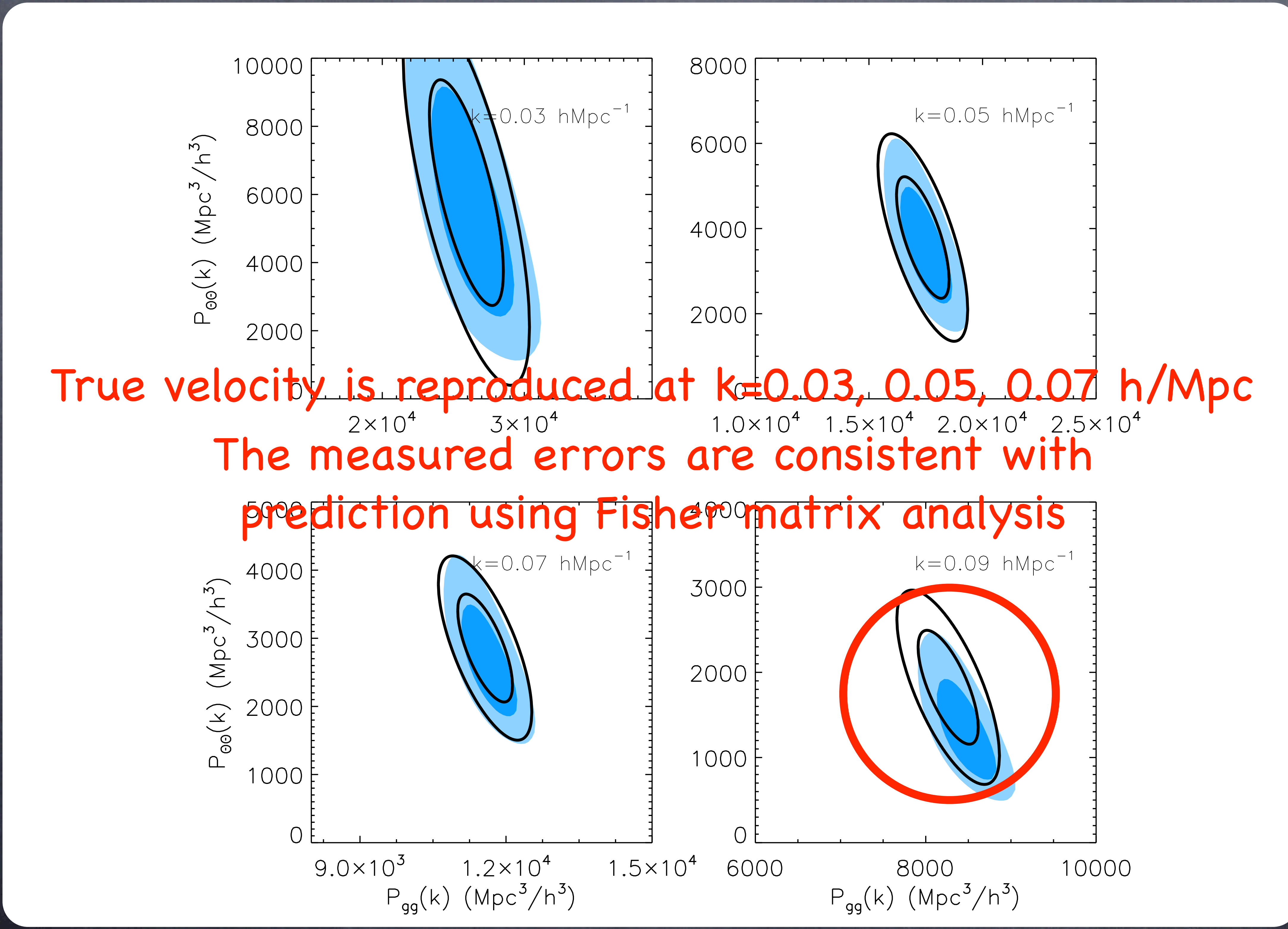
σ_v is estimated from $P_{\Theta\Theta}(k_i)$ at all selected bins,
e.g. k_i=0.03, 0.05, 0.07, 0.09 h/Mpc

$$\chi^2 = \Sigma_i \Sigma_p \Sigma_q [P_s^{ob}(k_i,\mu_p) - P_s^{th}(k_i,\mu_p)]\, Cov^{-1}{}_{pq}(k_i)\, [P_s^{ob}(k_i,\mu_q) - P_s^{th}(k_i,\mu_q)]$$

YSS, Kayo 2010

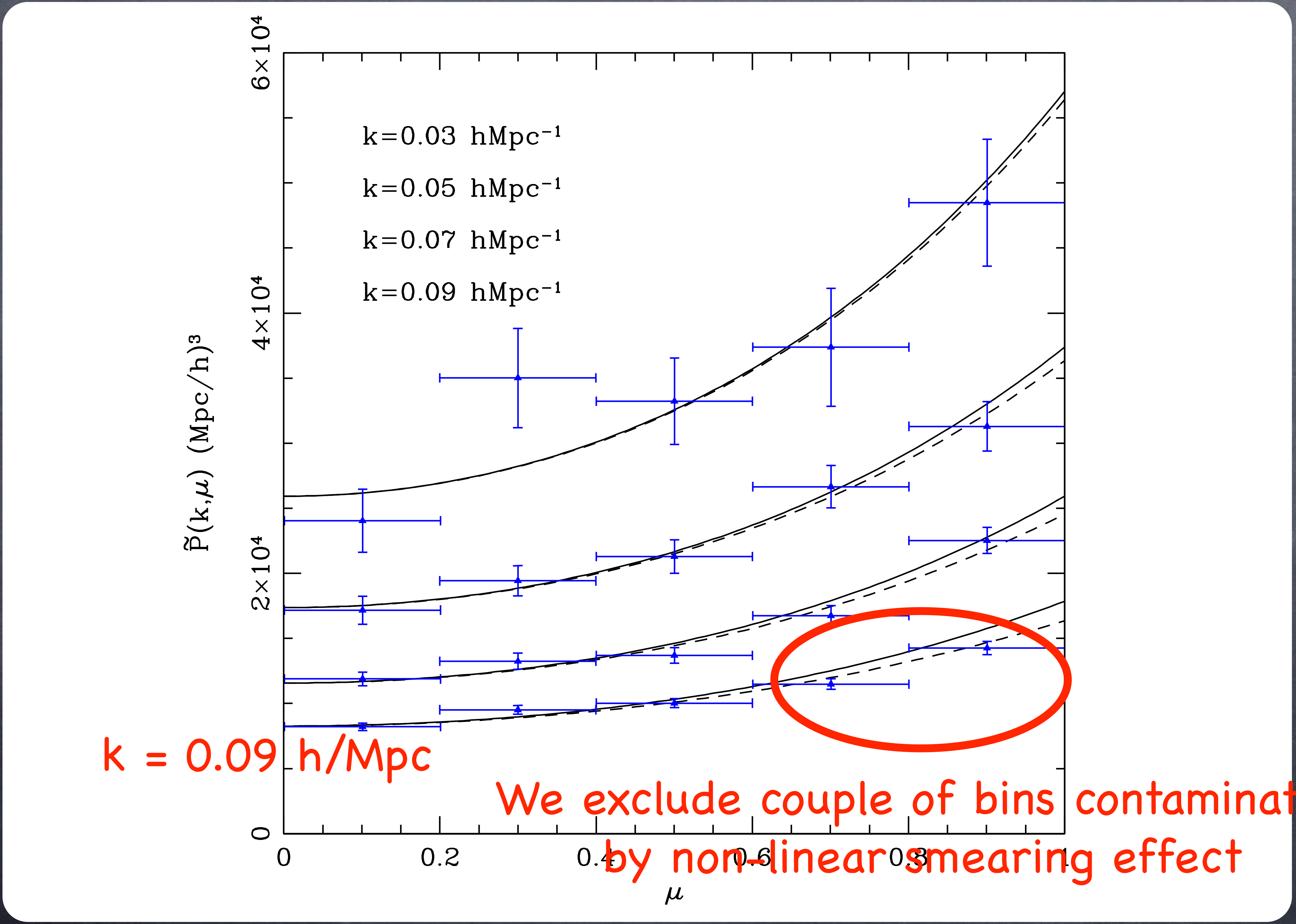
Decomposed Peculiar velocity

Fisher matrix (unfilled contours) Measurement (filled contours)



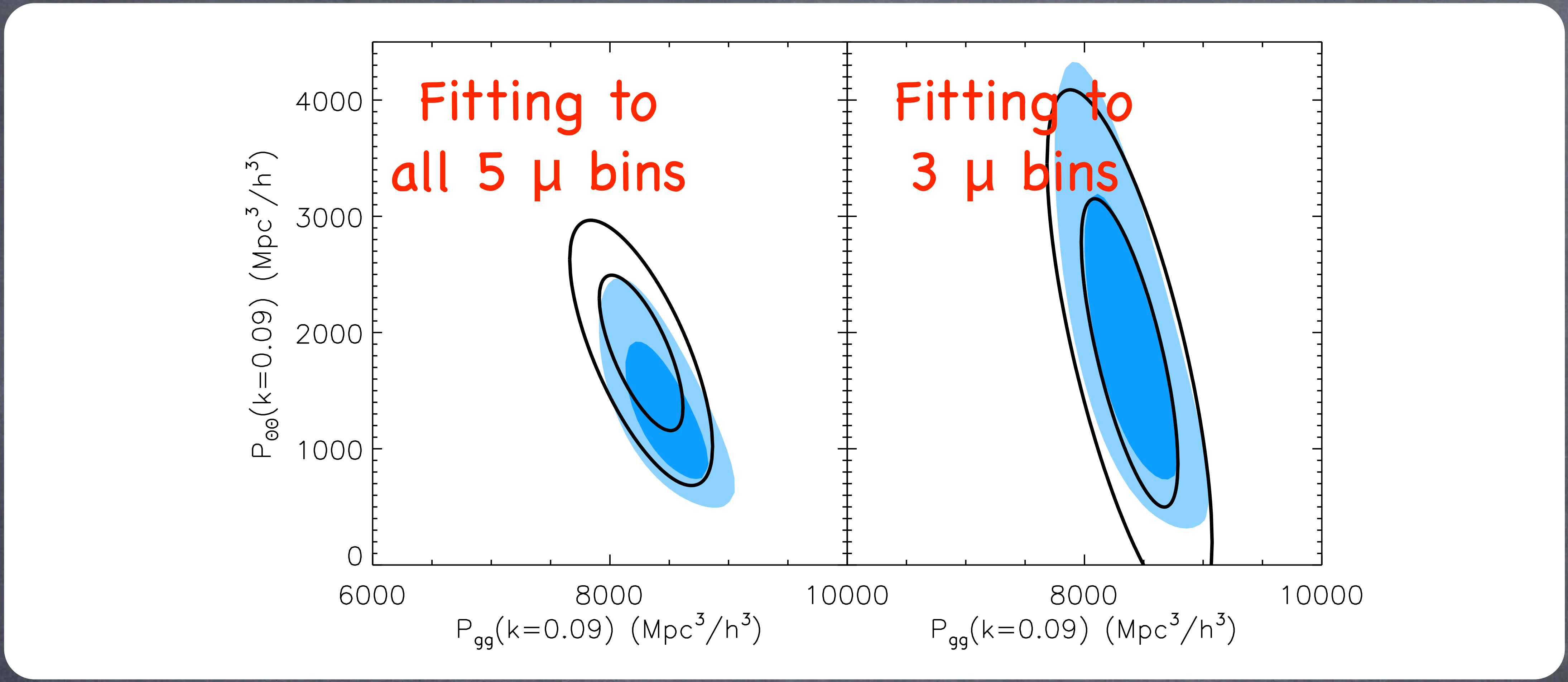
YSS, Kayo 2010

Cut-off strategy



YSS, Kayo 2010

Threshold limit



Detectability can be extended up to k ~ 0.1 h/Mpc
at the cost of weakened constraint.

YSS, Kayo 2010

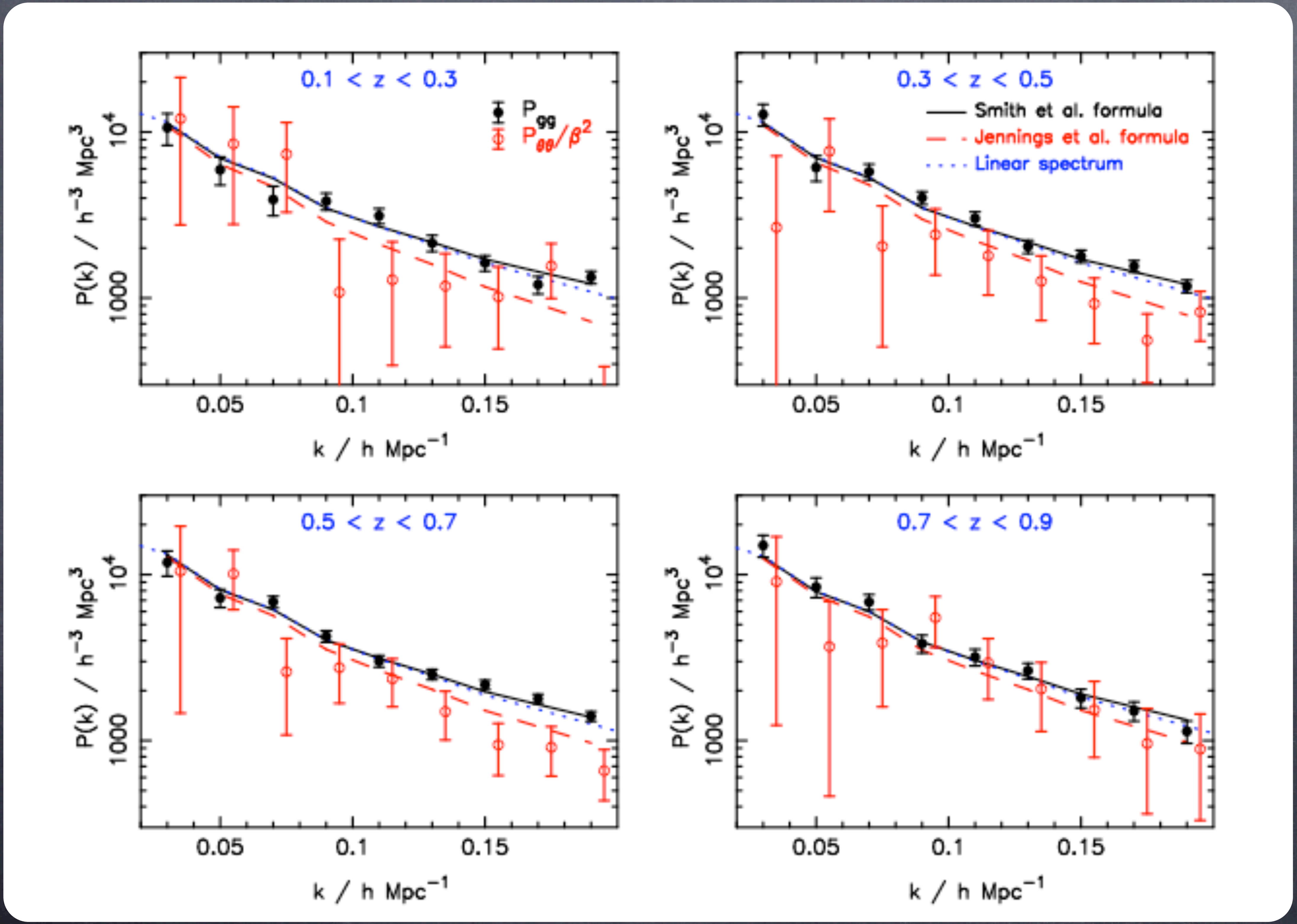
Measurements

Measurements from Wiggle-z experiments

Four tomographic bins at z=0.2, 0.4, 0.6, 0.8

Blake, et.al. 2011

Measurements



Blake, et.al. 2011

Model independent extraction

Tang, Kayo, Takada 2011

Snap shot at z=0

Total volume 1Gpc^3/h^3

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)]\exp[-(k\mu_p\sigma_v)^2]$$

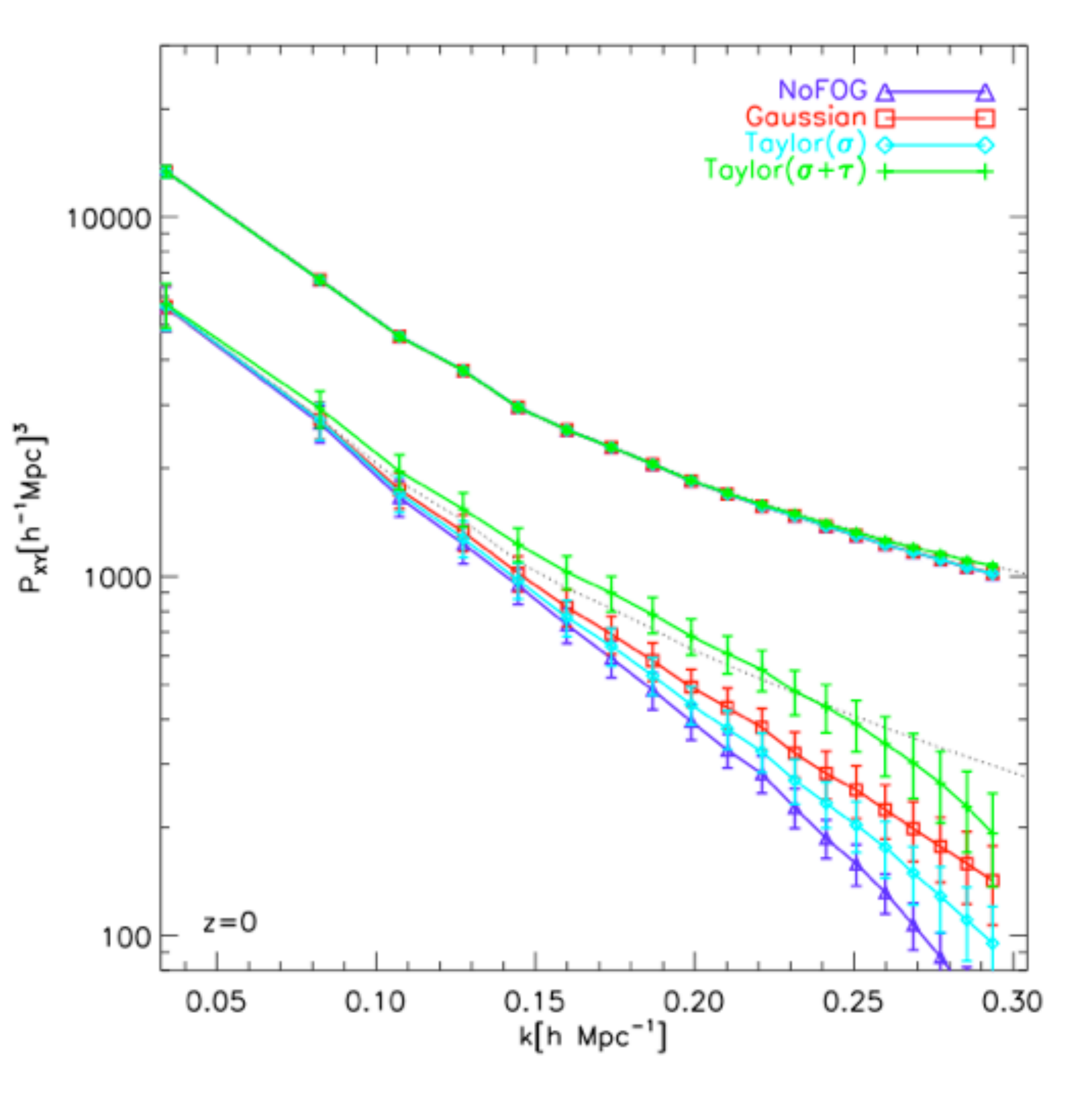
$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)][1-(k\mu_p\sigma)^2+(k\mu_p\tau)^4/2]$$

Tang, Kayo, Takada 2011

Decomposed $P_{XY}(k)$ of dark matter

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)] \exp[-(k\mu_p\sigma)^2]$$

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)] [1-(k\mu_p\sigma)^2+(k\mu_p\tau)^4/2]$$

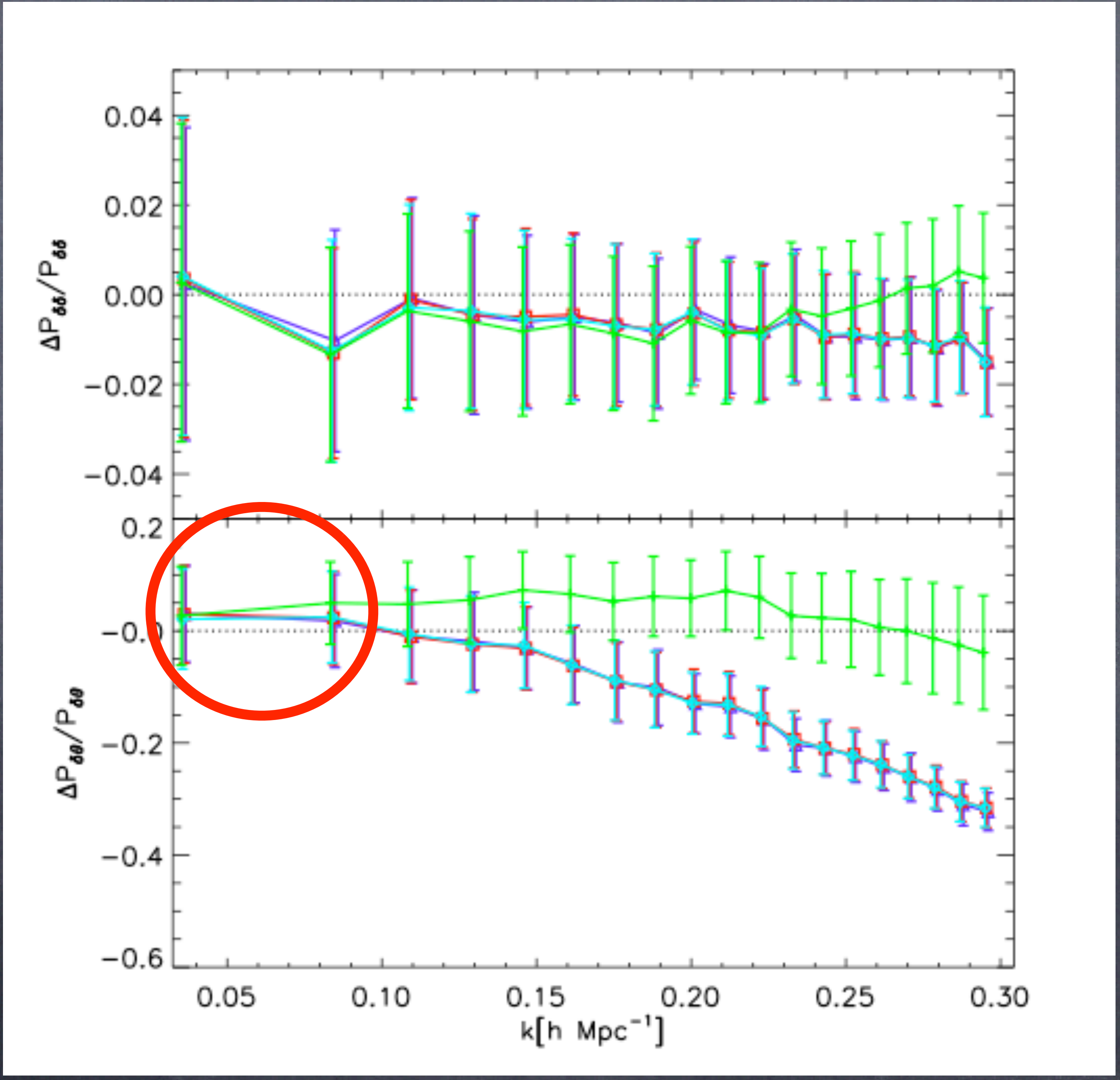


Tang, Kayo, Takada 2011

Decomposed $P_{XY}(k)$ of halo

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)]\exp[-(k\mu_p\sigma)^2]$$

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)]\,[1-(k\mu_p\sigma)^2+(k\mu_p\tau)^4/2]$$



Tang, Kayo, Takada 2011

$P_s(k)$ from larger Halo map

The Horizon simulation at KIAS by Kim, Park, Gott

Snap shot at z=0

Total volume $6.5^3 Gpc^3/h^3$

YSS, et.al 2011 Prepared

Theoretical prior on FoG at linear regime

Two different approaches to formulate redshift distortion effect, 1) streaming model, 2) Kaiser effect,

1) streaming model: formulating FoG effect at smaller scale

2) Kaiser effect: formulating redshift distortion at large scale

The limit of streaming model at linear regime was derived in Fisher 1995, and shows the agreement between both approaches.

It is interesting to derive FoG effect on redshift distortion at linear regime using streaming model. We make the following assumption,

coherent v_z in Mpc/h unit << correlation length

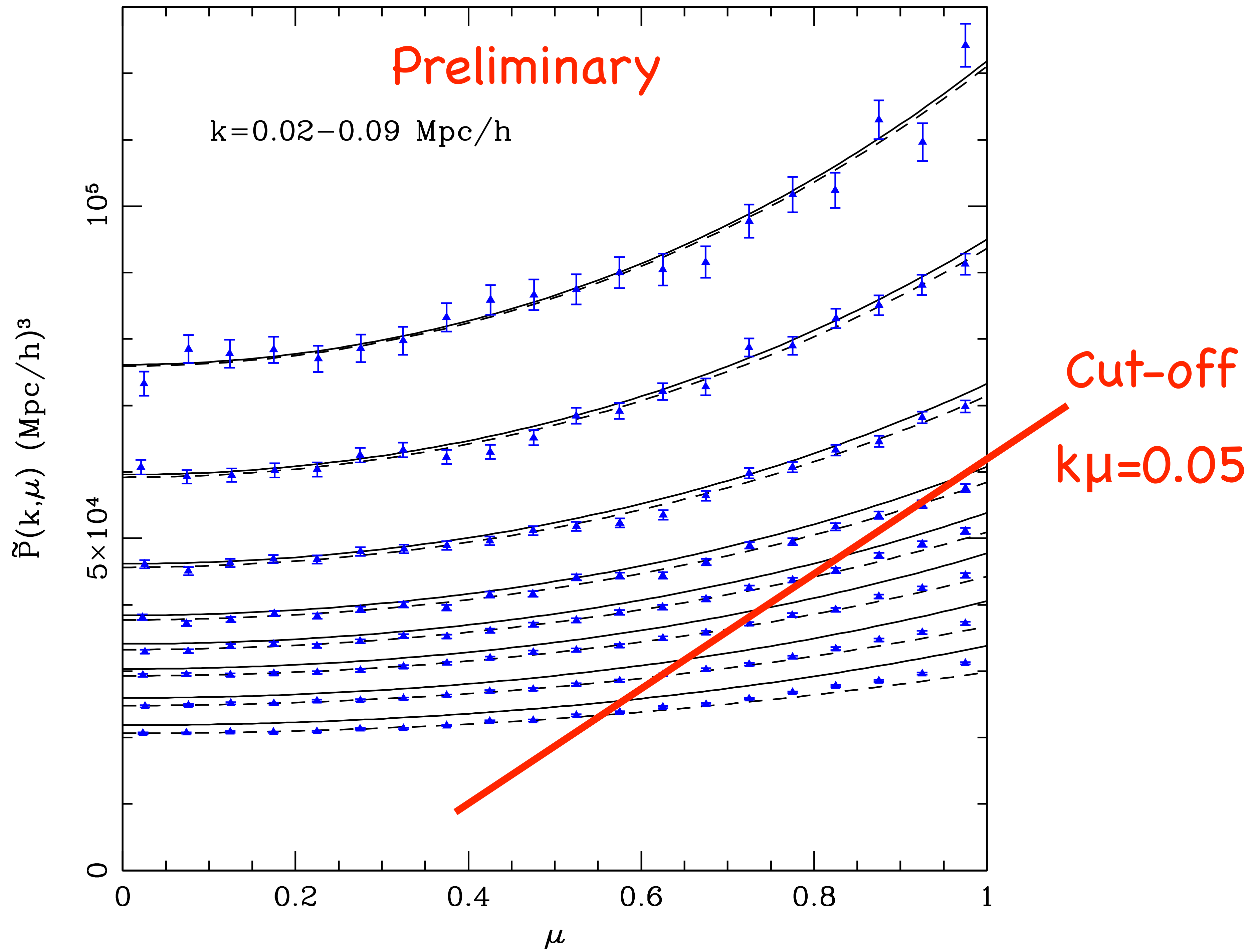
Then,

$$P_s^{th}(k_i,\mu) = [P_{gg}(k_i) + 2\mu_p^2 P_{g\Theta}(k_i) + \mu_p^4 P_{\Theta\Theta}(k_i)] \exp[-(k_i\mu_p\sigma_v)^2]$$

Desjacques, Sheth 2009; YSS, et.al. 2011 Prepared

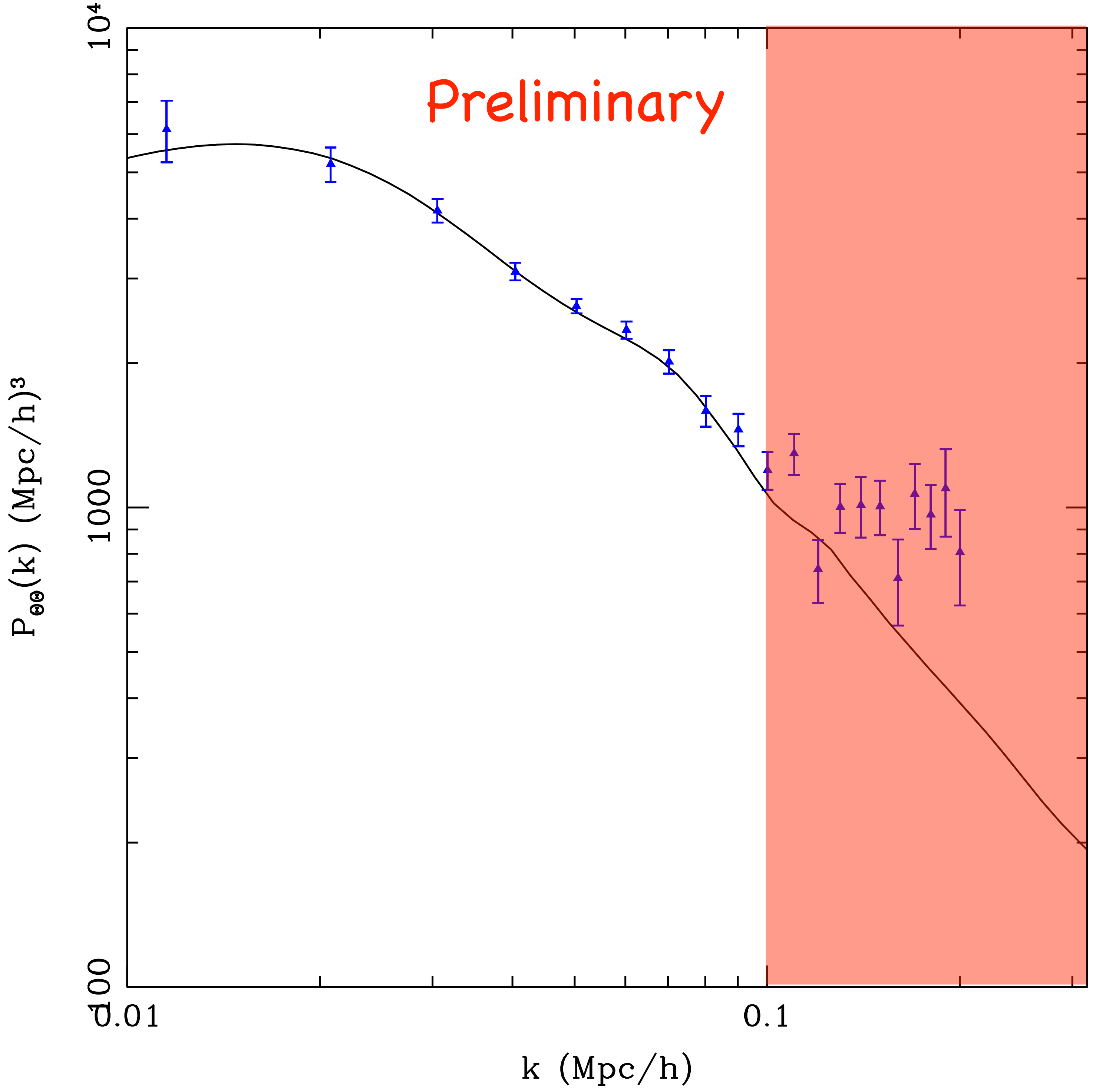
$P_s(k,\mu)$ in polar coordinate

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)]\exp[-(k\mu_p\sigma_v)^2]$$

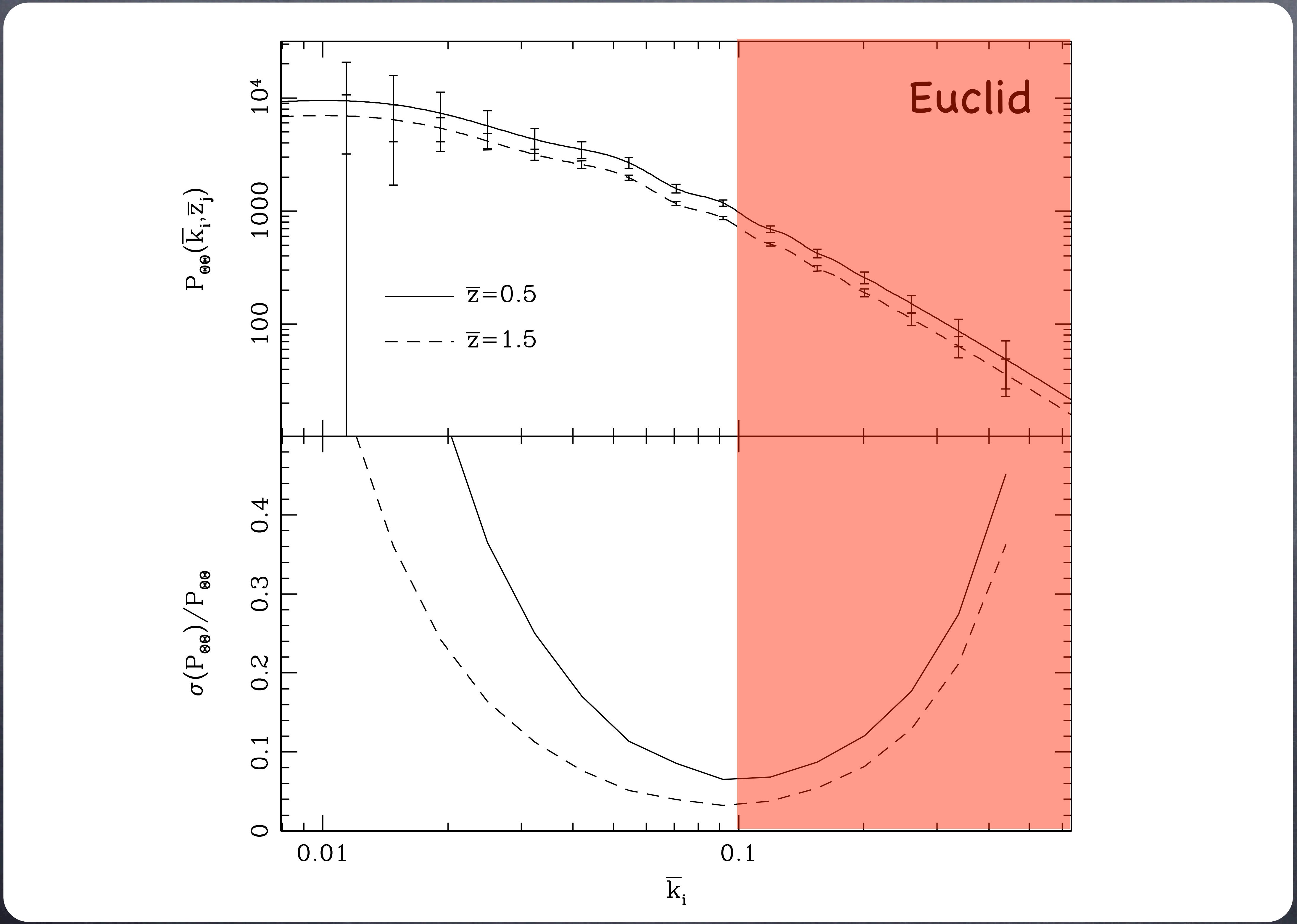


Decomposed $P_{\Theta\Theta}(k)$

$$P_s(k,\mu) = [P_{gg}(k) + 2\mu^2\sqrt{P_{gg}(k)P_{\Theta\Theta}(k)} + \mu^4 P_{\Theta\Theta}(k)]\exp[-(k\mu_p\sigma_v)^2]$$



Estimated coherent motion spectra, $P_{\Theta\Theta}$



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Cosmological constraint from decomposed $P_{\Theta\Theta}$

Spectra $P_{\Theta\Theta}$ are given by,

$$P_{\Theta\Theta}(k,a) = \frac{8\pi^2}{25} \frac{k}{H_*^4 \Omega_m^2} A_S^2 \left(\frac{kh}{k_p}\right)^{n_S - 1} T_\Phi^2(kh) g_\Theta^2(a).$$

CMB priors for cosmological test with $P_{\Theta\Theta}$,

Primordial information - amplitude and spectral index

Shape of spectra - transfer function

We probe dark energy or modified GR using growth factor g_Θ,

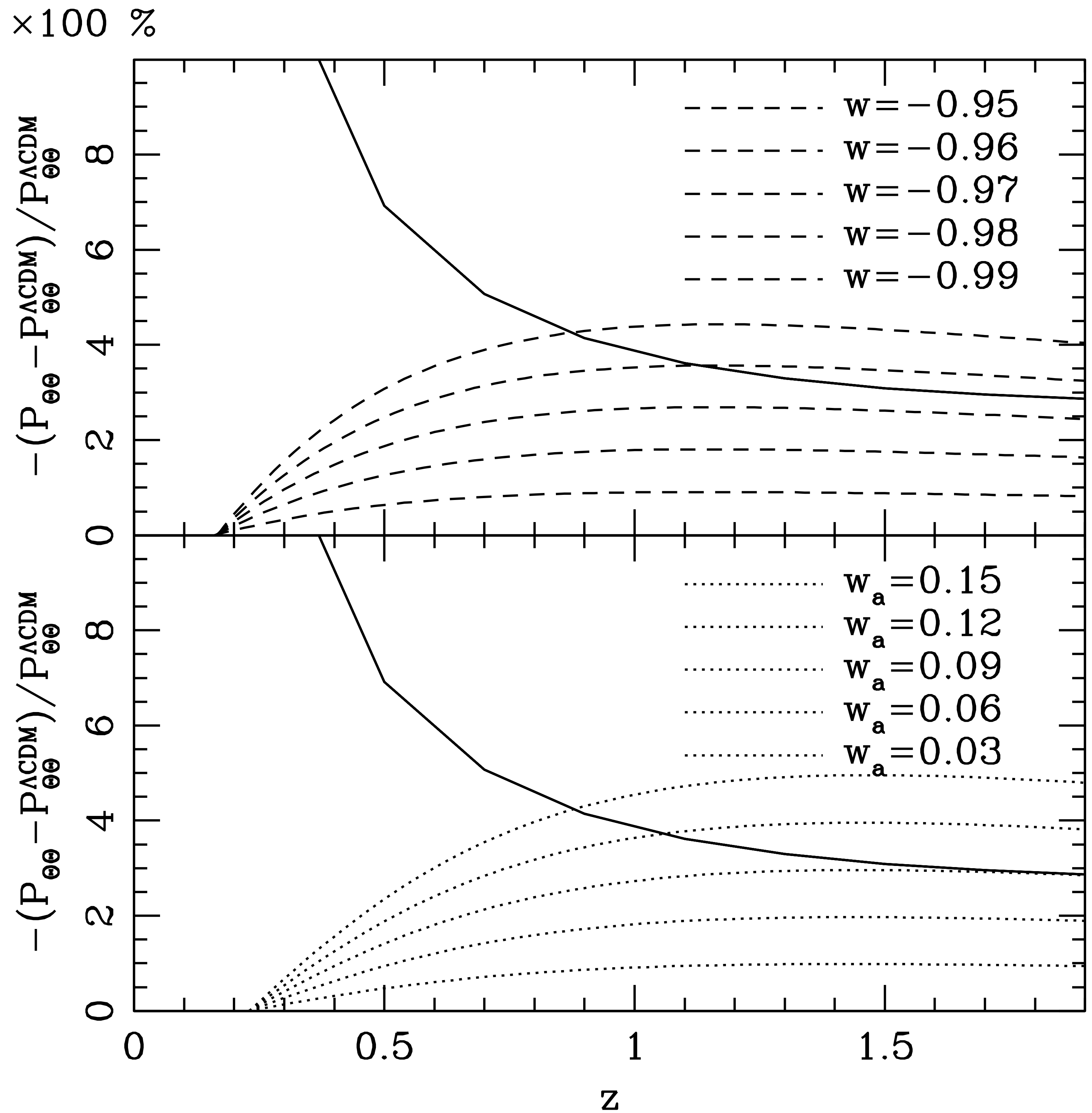
$d\delta_m/dt + \theta_m/a = 0$ $\quad$ $d\theta_m/dt + H\theta_m = k^2\Psi/a$

$k^2\Phi = 3/2\ H_0{}^2\Omega_m\ \delta_m/a\ + k^2\varphi$ $\quad$ $\Phi = -\Psi\ + \varphi$

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

YSS 2011

Dark energy constraint from $P_{\Theta\Theta}$



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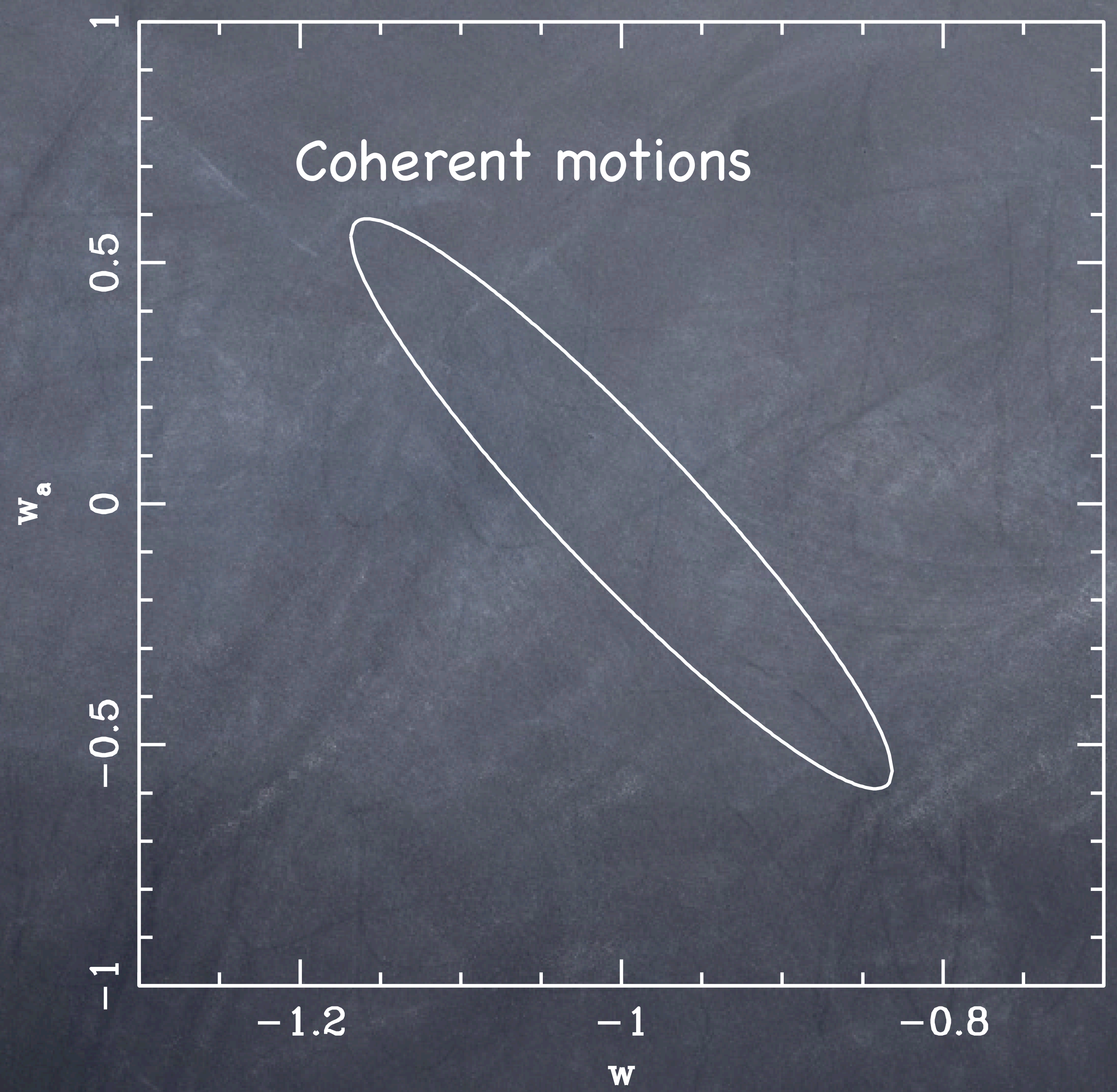
Cosmological constraint from $P_{\Theta\Theta}$

Cosmological constraints from $P_{\Theta\Theta}$ are estimated using Fisher matrix analysis,

$$F_{mn}^{\Theta\Theta} = \sum_{k=1}^{N_k^{\mathrm{cut}}} \sum_{z_j=0}^{2} \frac{\partial P_{\Theta\Theta}(k_i, z_j)}{\partial x_m} \frac{1}{\sigma_{P_{\Theta\Theta}^{\mathrm{dec}}}(k_i, z_j)^2} \frac{\partial P_{\Theta\Theta}(k_i, z_j)}{\partial x_n} .$$

Dark energy constraint from $P_{\Theta\Theta}$



YSS 2011

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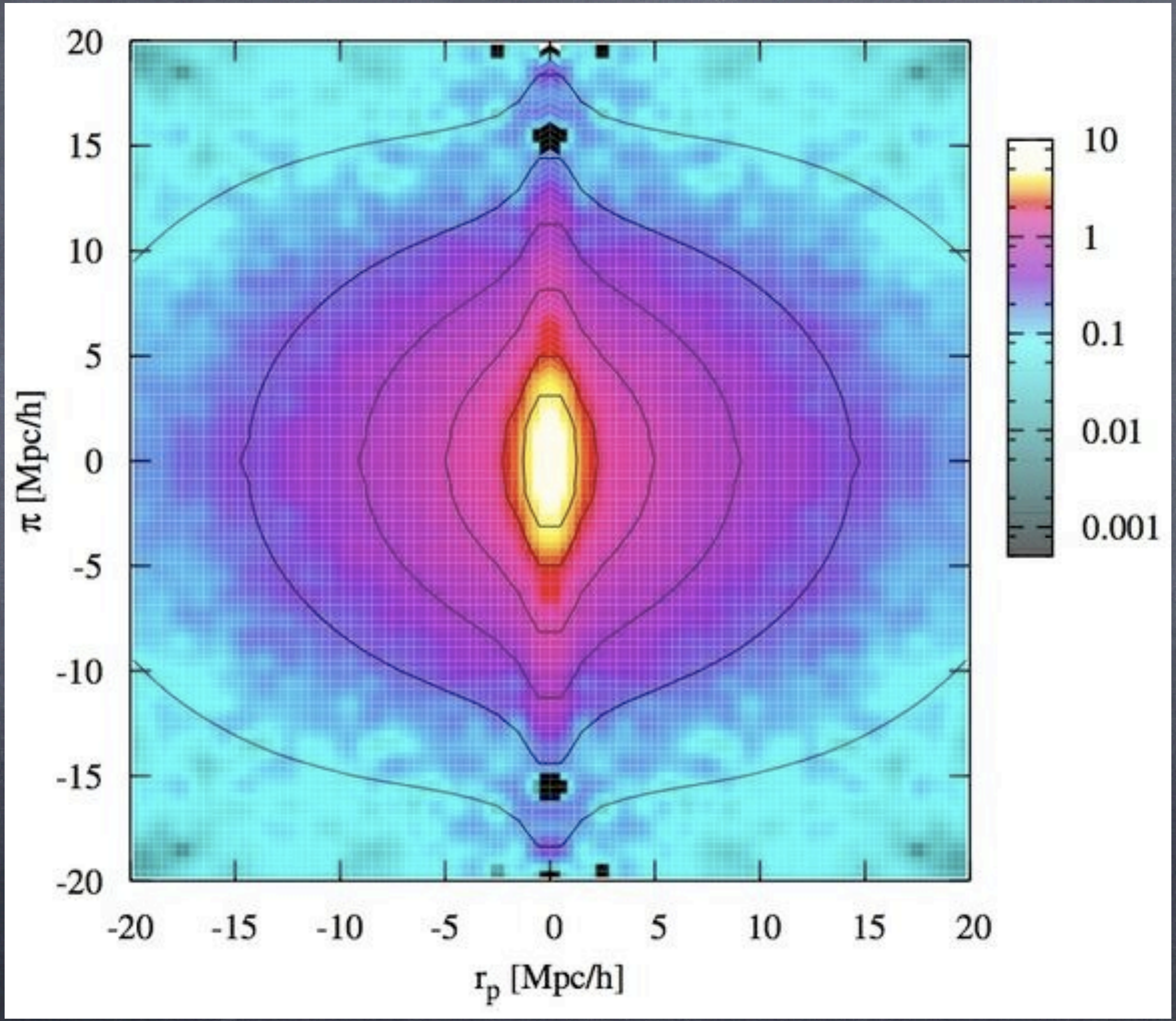
Correlations in configuration space



Guzzo et.al. VIPER collaboration

Decomposition in configuration space

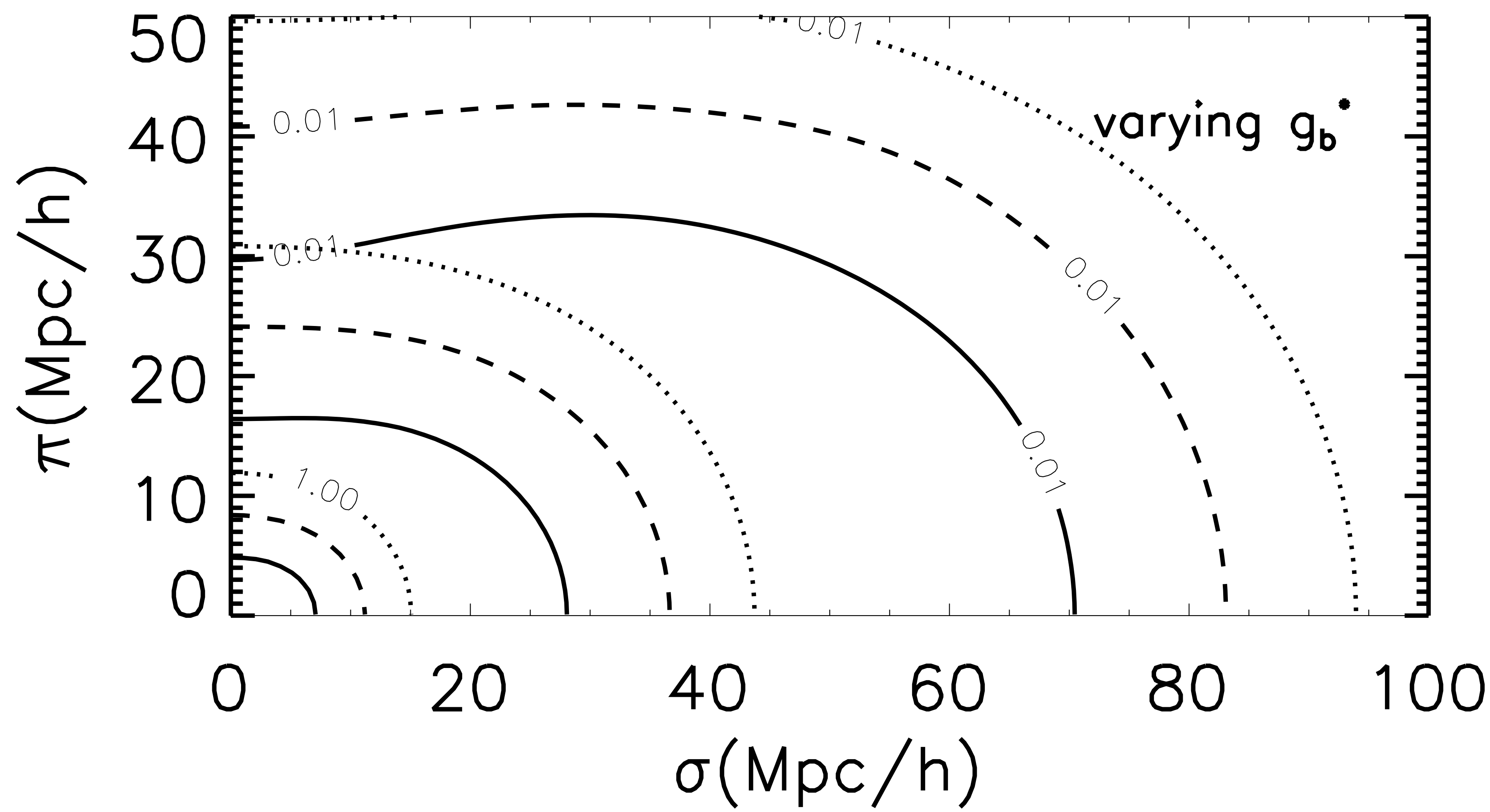
In the linear regime of the standard gravitational instability theory, the Kaiser effect (the observed squeezing due to coherent infall around large-scale strutures) can be written in the configuration space as,

$\xi(\sigma,\pi) = (g_b^2+g_b g_\Theta+g_\Theta^2)\ \xi_0(r)$	Monopole
$-\ (g_b g_\Theta+g_\Theta^2)\ \xi_2(r)$	Quadrupole
$+\ g_\Theta^2\ \xi_4(r)$	Hexadecapol

The inverse signature in quadrupole induces squeezing effect. The leading order of monopole is galaxy-galaxy correlation, and the leading order of quadrupole is galaxy-velocity cross-correlation. Here we assume the perfect cross-correlation coefficient.

YSS, Sabiu, Nichol, Miller 2011

Variation of g_b



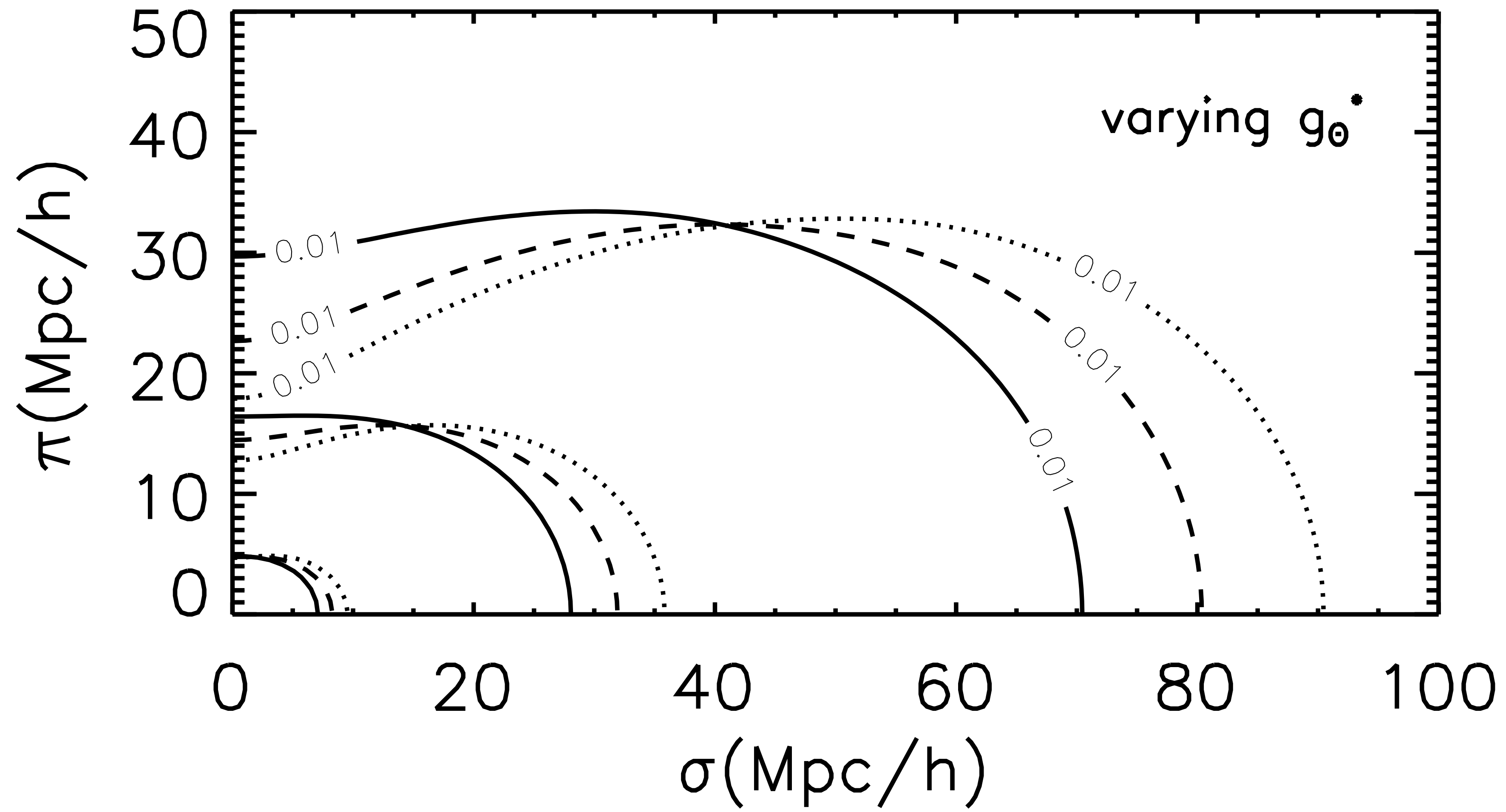
$$\xi(\sigma,\pi) = (g_b^2+g_b g_\Theta+g_\Theta^2)\,\xi_0(r)$$

$$-\,(g_b g_\Theta+g_\Theta^2)\,\xi_2(r)$$

$$+\,g_\Theta^2\,\xi_4(r)$$

YSS, Sabiu, Nichol, Miller 2011

Variation of g_Θ



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$$+ g_\Theta{}^2\ \xi_4(r)$$

YSS, Sabiu, Nichol, Miller 2011

Parameterizing $\xi(\sigma,\pi)$

$$\xi(\sigma,\pi) = (g_b^{*2}+g_b^{*}g_\Theta^{*}+g_\Theta^{*2})\ \xi_0^{*}(r) - (g_b^{*}g_\Theta^{*}+g_\Theta^{*2})\ \xi_2^{*}(r) + g_\Theta^{*2}\ \xi_4^{*}(r)$$

In Kaiser effect:

$$\xi_l^{*}(r) = \int k^2 dk/2\pi^2\, D_m^{*}(k)\ j_l(kr)$$

$$D_m^{*}(k) = 4/9\ k^4/H_*^4 \omega_m^2\ D_\Phi^{*}(k) \qquad (H_* = 1/2997\ \mathrm{Mpc}^{-1})$$

$$D_\Phi^{*}(k) = 2\pi^2/k^3\ 9/25\ \Delta_{\zeta i}^2\ T_\Phi^2(k) \qquad (\Delta^{*}{}_{\zeta i}^2 = 2.43\times10^{-9}(k/k_p)^{(ns-1)})$$

In Kaiser effect + velocity dispersion:

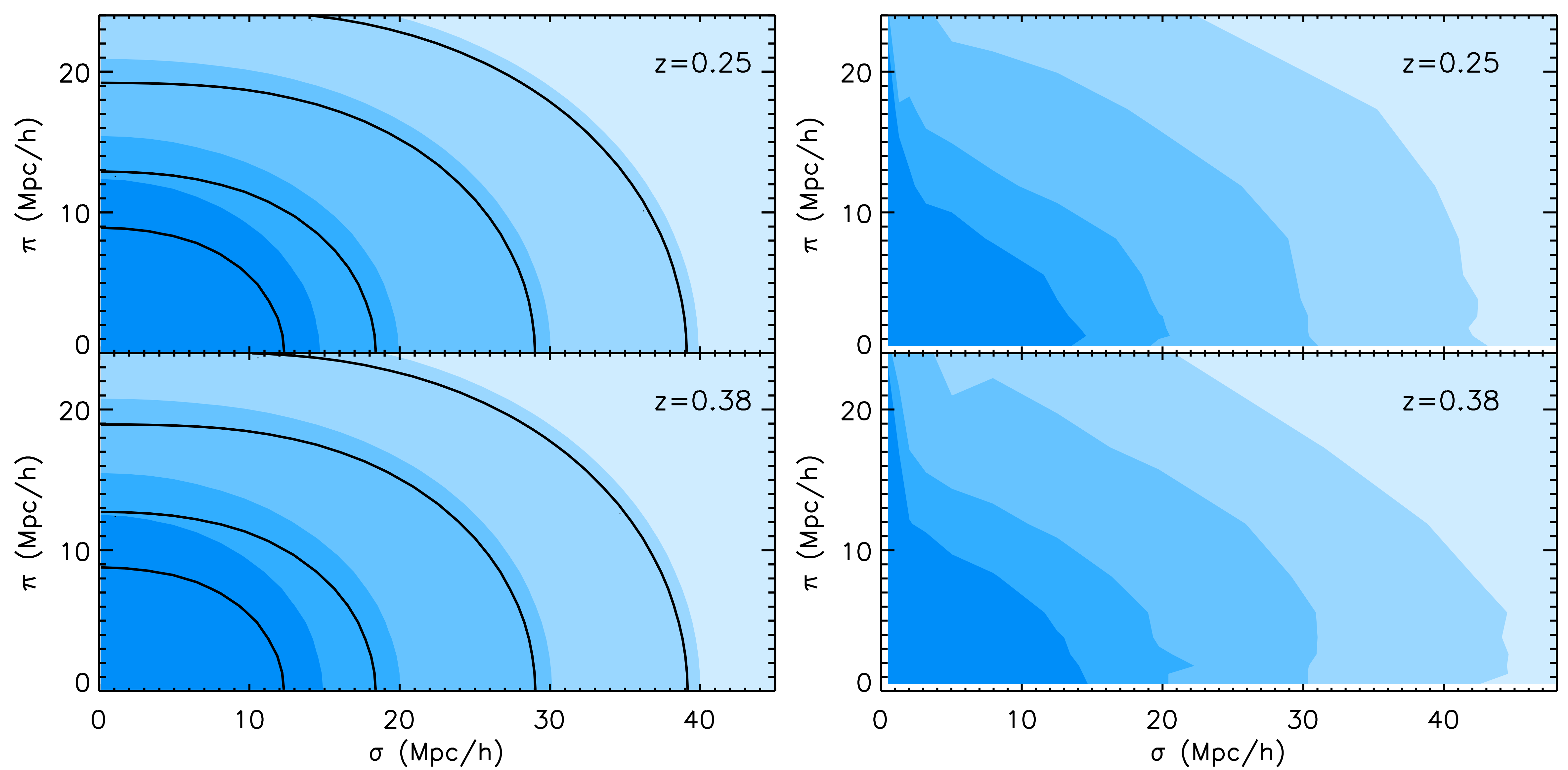
$$\xi_l^{*}(r) = \int k^2 dk d\mu/(2\pi)^2\, D_m^{*}(k)\ e^{-(k\mu\sigma v)2} \cos(kr\mu)\ P_l(\mu)$$

YSS, Sabiu, Kayo, Nichol 2011

ξ(σ,π) diagram of SDSS DR7 LRG

Kaiser effect (unfilled contours) Modified Kaiser effect (filled contours)

Prediction with b=1.82 Measurement from SDSS DR7 LRG

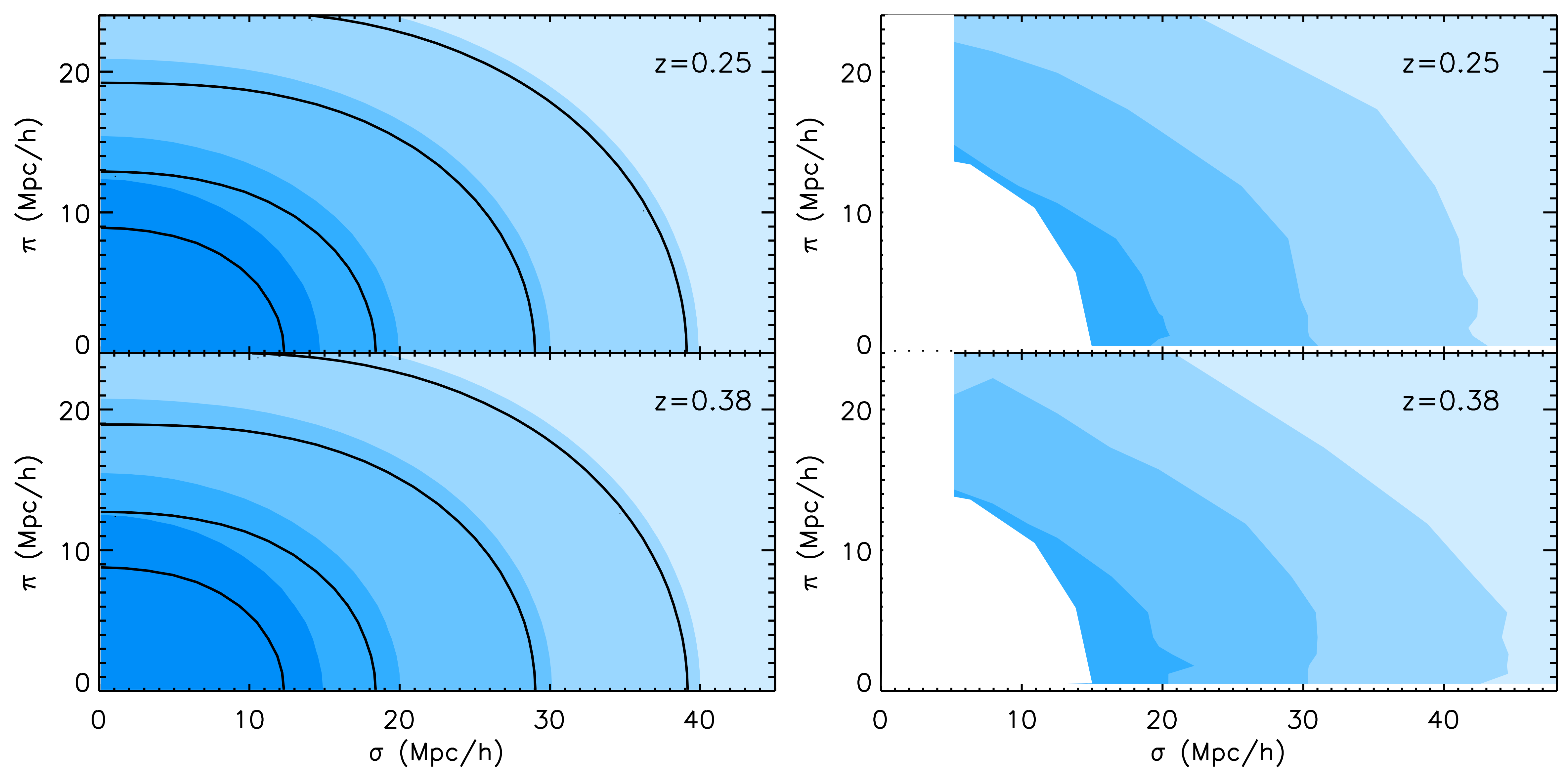


YSS, Sabiu, Kayo, Nichol 2011

Cut off for fitting

Cut off #1: perfect correlation is not available around k=0.1 h/Mpc

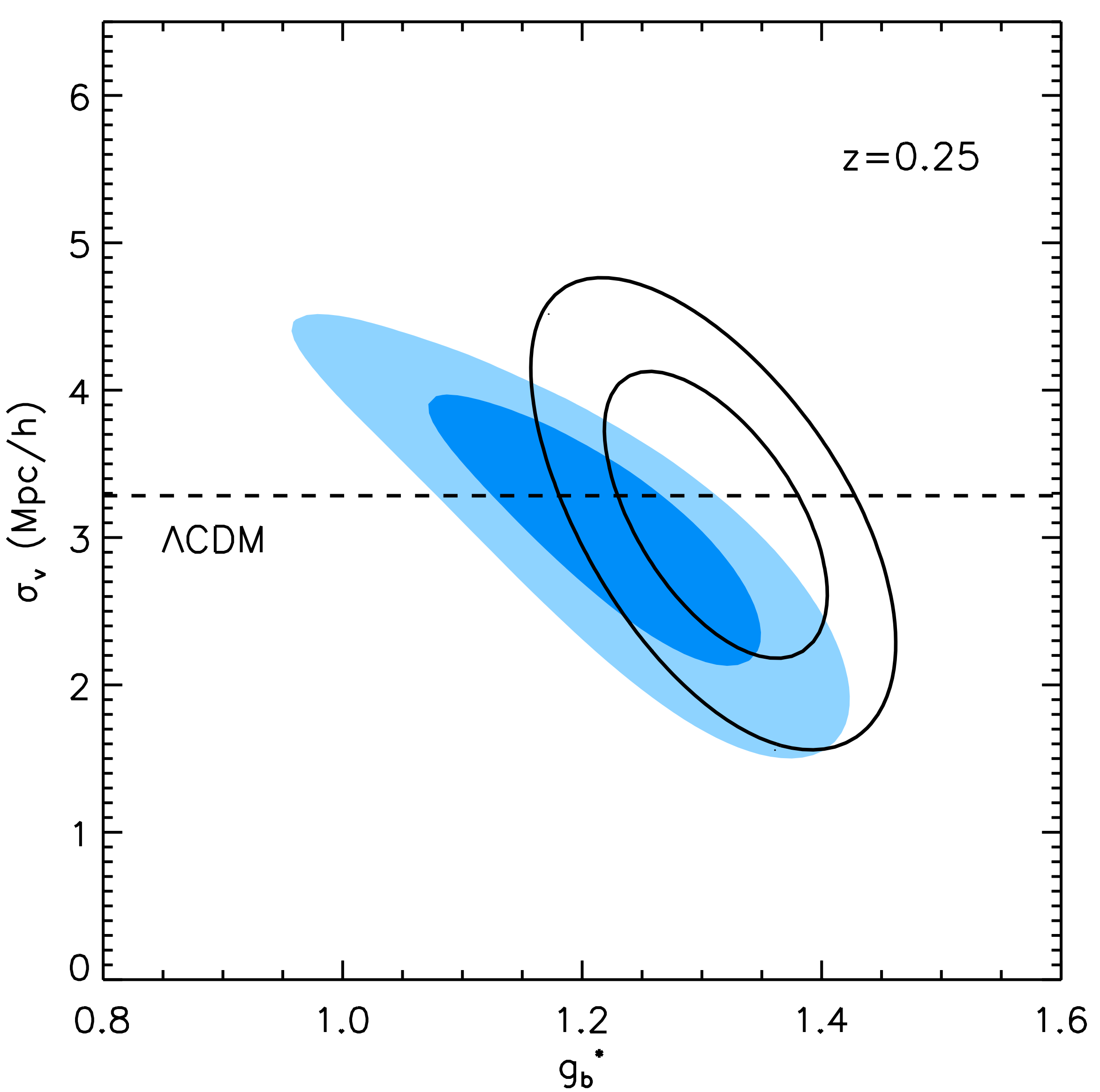
Cut off #2: non-linear line of smearing effect



YSS, Sabiu, Kayo, Nichol 2011

Measured bulk flow motions

Kaiser effect (unfilled contours) Modified Kaiser effect (filled contours)



YSS, Sabiu, Kayo, Nichol 2011

Measured quantities from redshift distortions

	$z = 0.25$	$z = 0.38$
$g_\Theta^* \equiv f\sigma_8^{M*}$	0.39 ± 0.08 (0.41)	0.43 ± 0.08 (0.42)
σ_v (in h/Mpc)	3.1 ± 0.6 h/Mpc (3.2)	3.5 ± 0.6 h/Mpc (3.4)
σ_v^{km} (in km/s)	277 ± 55 km/s (294)	300 ± 57 km/s (293)
β (Kaiser + v.d.)	0.32 ± 0.067	0.36 ± 0.075
β (Kaiser only)	0.30 ± 0.063	0.32 ± 0.065
b (Kaiser + v.d.)	1.82 ± 0.13	1.92 ± 0.16
b (Kaiser only)	1.96 ± 0.10	2.11 ± 0.10

YSS, Sabiu, Kayo, Nichol 2011

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YSS, Sabiu, Kayo, Nichol 2011

Measured coherent motions in discrepancy

Velocity measurements of nearby galaxies

Feldman, Watkins, Hudson (2009)
Watkins, Feldman, Hudson (2009)
Lavaux, Tully, Mohayaee, Colombi (2010)

Large bulk flow

Analyzed CMB fluctuations on directions of X-ray clusteres

Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2008)
Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2009)

Large bulk flow

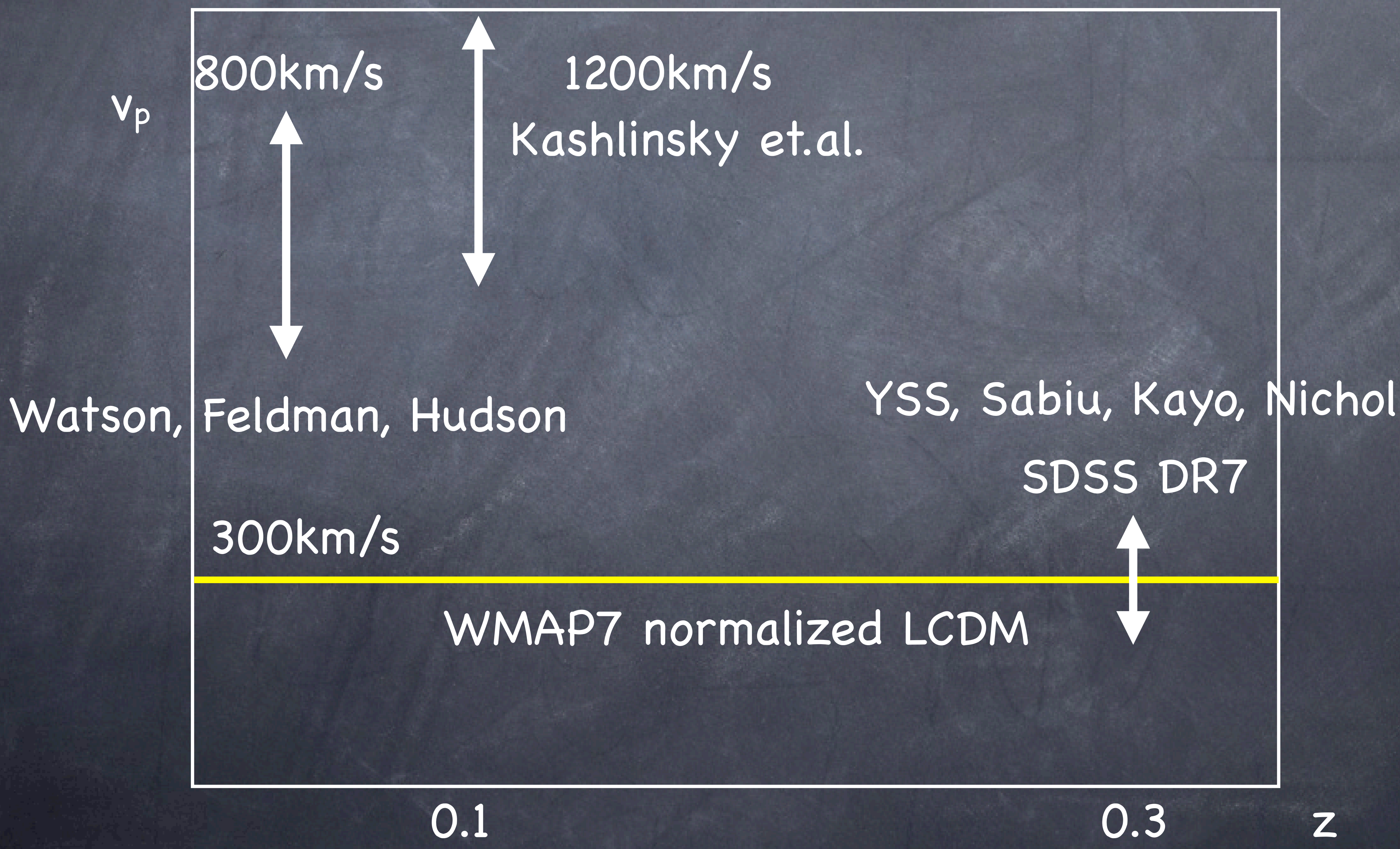
Measuring coherent motions from redshift distortions

YSS, Pervical (2008)
White, YSS, Pervical (2009)
YSS, Sabiu, Nichol, Miller (2010)
YSS, Sabiu, Kayo, Nichol (2010)

Support LCDM Universe

Measured coherent motions in discrepancy

Bulk flow motions are averaged from directly measured peculiar velocity at local universe, which disagree with concordance LCDM model normalized with WMAP7.



Measured coherent motions in discrepancy

Velocity measurements of nearby galaxies

Feldman, Watkins, Hudson (2009)
Watkins, Feldman, Hudson (2009)
Lavaux, Tully, Mohayaee, Colombi (2010)

Possible presence of dark flow at near horizon scale

Analyzed CMB fluctuations on directions of X-ray clusteres

Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2008)
Kashlinsky, Atrio-Barandela, Kocevski, Ebeling (2009)

Coherent motions against CMB isotropy frame

Measuring coherent motions from redshift distortions

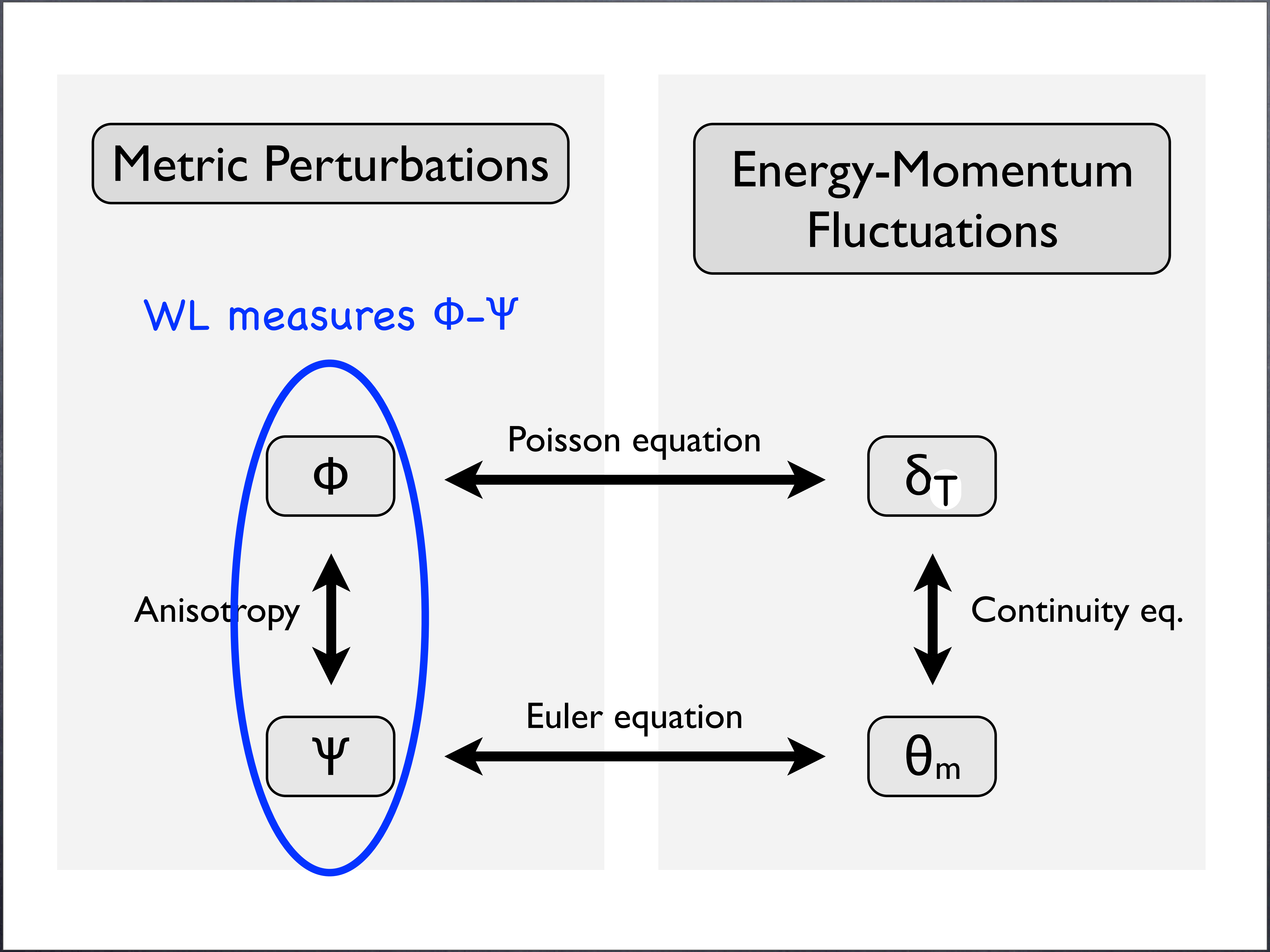
YSS, Pervical (2008)
White, YSS, Pervical (2009)
YSS, Sabiu, Nichol, Miller (2010)
YSS, Sabiu, Kayo, Nichol (2010)

Coherent motions in rest frame

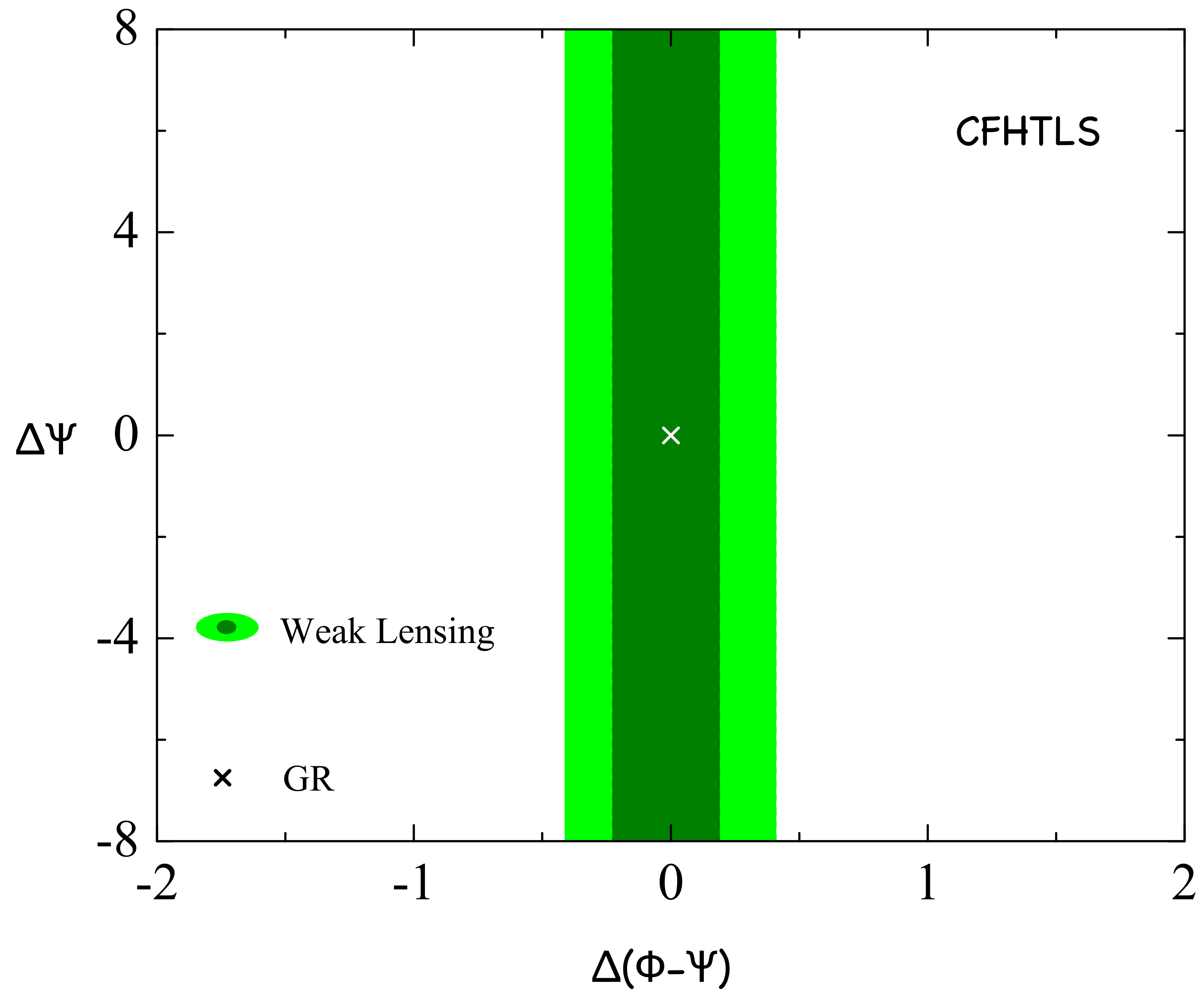
Contents

- Motivation
- Decomposition of spectra in redshift space
- Practice of decomposition using mocking maps
- Optimizing redshift survey for cosmological purpose
- Current measurement of coherent motions
- Cosmological test of GR using WL and coherent motions
- Conclusion

Constraint on departure of Φ-Ψ using WL

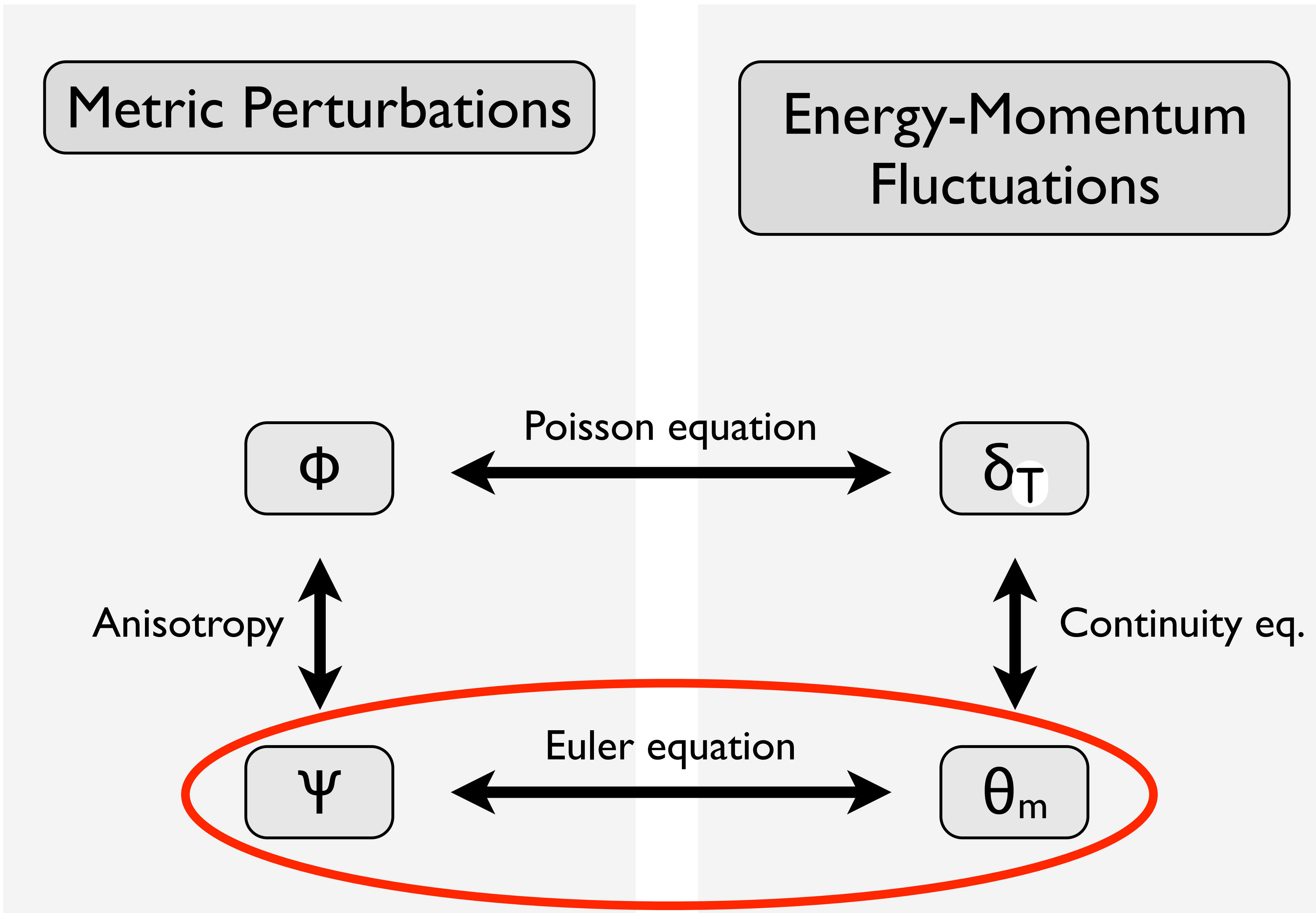


Constraint on departure of Φ-Ψ using WL



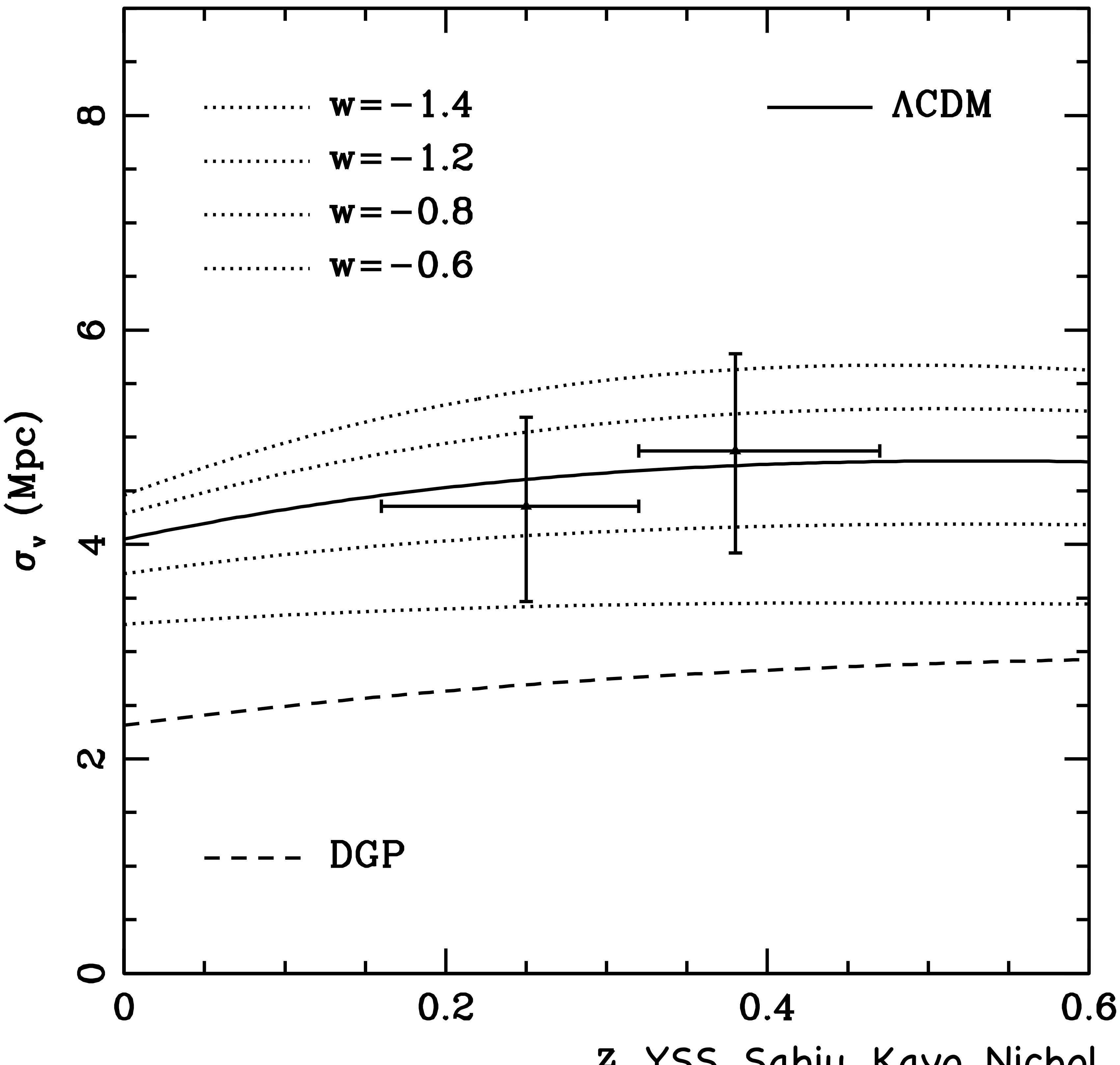
YSS, Zhao, Koyama, Nichol, Bacon, Pogosian 2010

Constraint on Φ-Ψ and Ψ using WL and CM



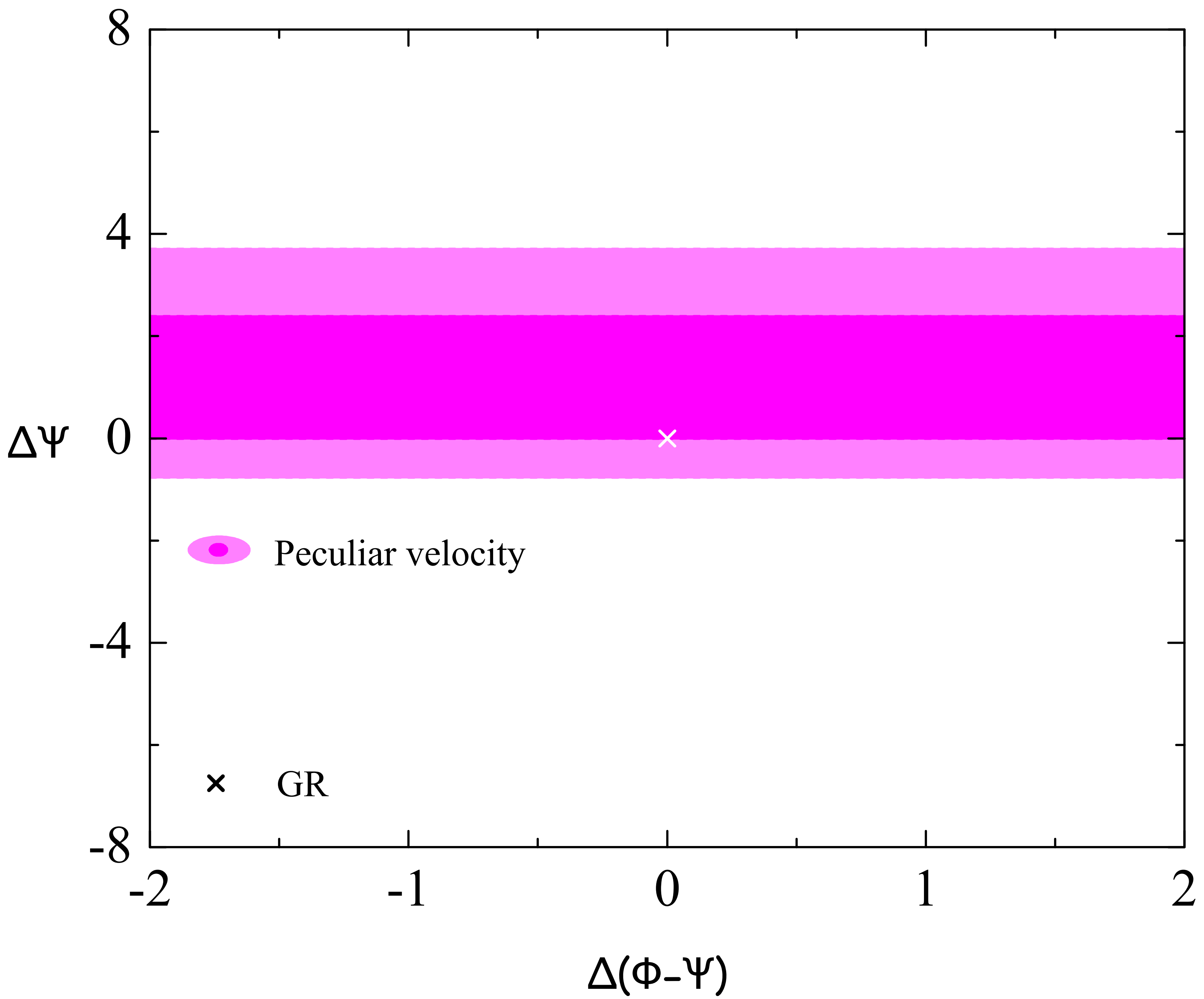
PV measures θ and estimates Ψ

Measured coherent motions from DR7



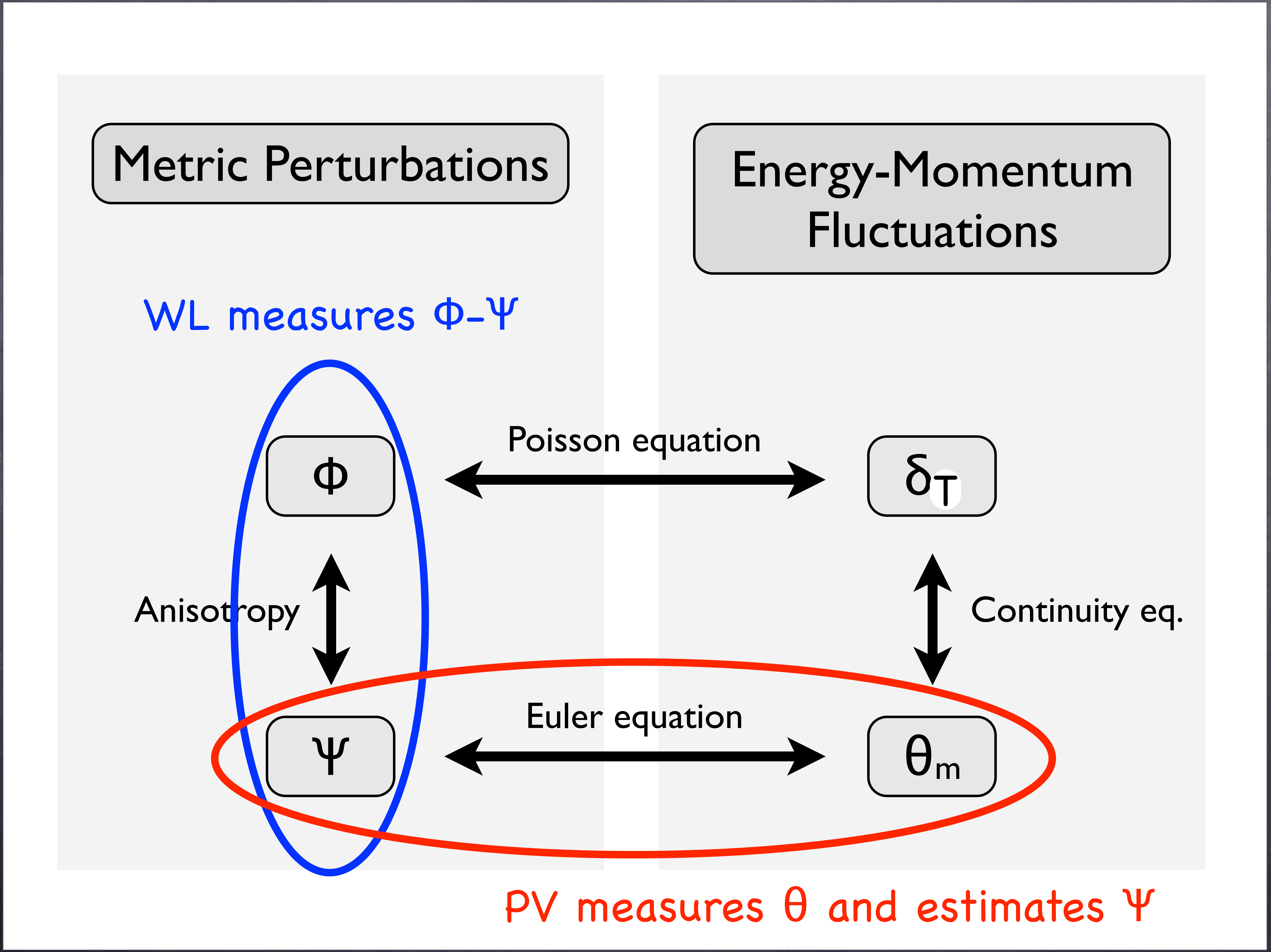
YSS, Sabiu, Kayo, Nichol 2010

Constraint on departure of Ψ using CM



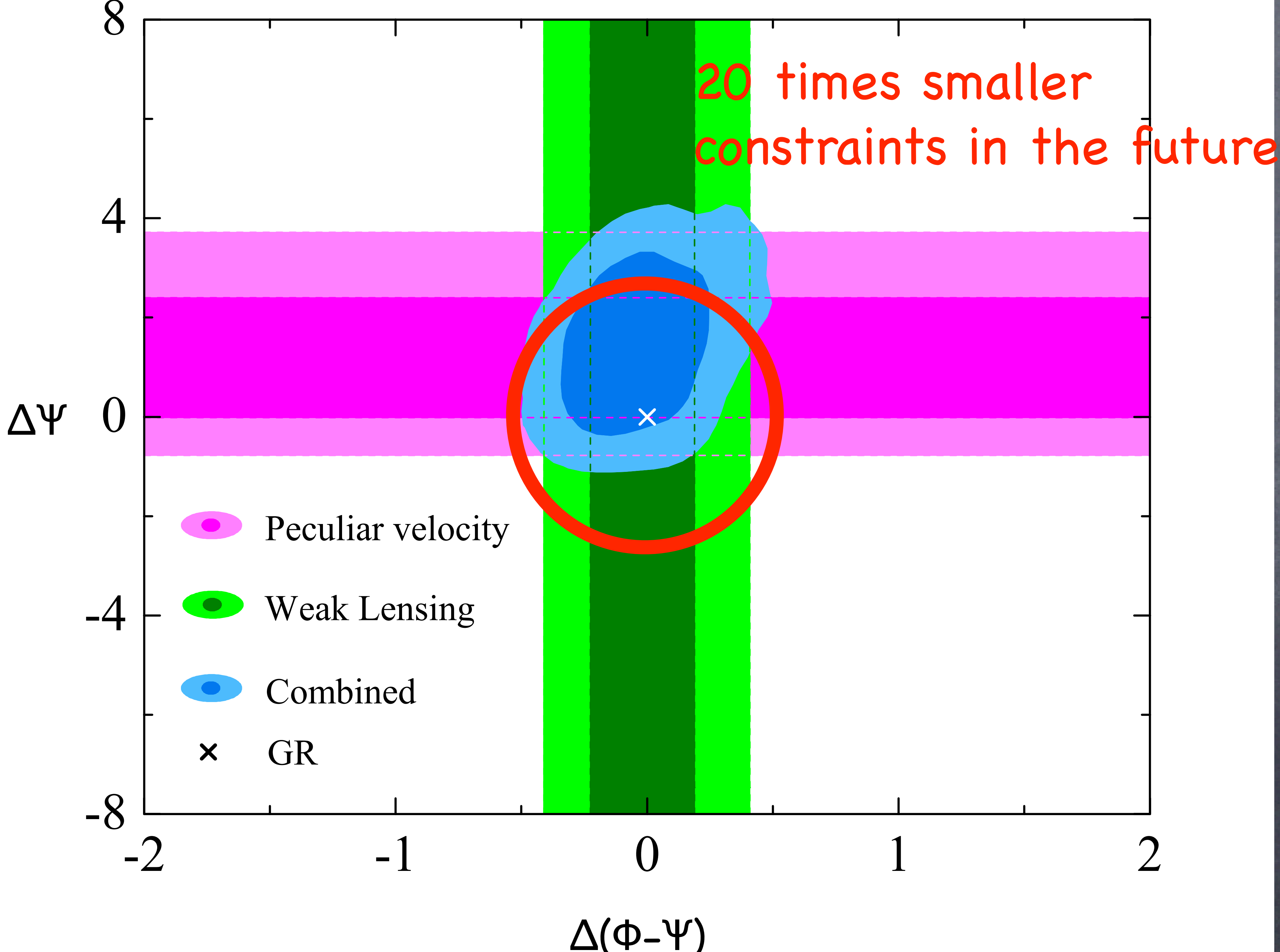
YSS, Zhao, Koyama, Nichol, Bacon, Pogosian 2010

Constraint on Φ−Ψ and Ψ using WL and CM



Constraint on Φ-Ψ and Ψ using WL and CM

Synergy effect between Coherent motions and WL



YSS, Zhao, Koyama, Nichol, Bacon, Pogosian 2010;Daniel, Linder 2010

Discussion

- How to coherently combine both different statistics, BAO and coherent motions?

- How to formulate theory of redshift distortion in model independent way? (open comments)

- How to extend our study from dark matter limit to observable galaxies?

- Other systematic uncertainties ?