Wide Angle Effects in Galaxy Surveys

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I. INTRODUCTION

Motivation

- **recent advances in observation**
    - **larger sky coverage and higher redshift**
    - **measurements with higher statistical power**

Euclid, MS-DESI, SKA, LSST

- **recent advances in theory**
    - **general relativistic effect in galaxy clustering**

Yoo et al. 2009, Yoo 2010, Bonvin & Durrer 2011, Challinor & Lewis 2011

Jeong, Schmidt, Hirata 2012, Yoo, Hamaus, Seljak, Zaldarriaga 2012

- **motivation:**
    - **how accurate is *distant-observer approximation?***
    - ***is* wide angle effect degenerate with modified gravity?**

II. FORMALISM:

HOW TO QUANTIFY THE DEVIATIONS?

Redshift-Space Distortion

- **redshift-space vs real-space distances**
  - **distortion in observed redshift** $1+z=(1+\bar{z})(1+\delta z)$

$$s \equiv \int_0^z \frac{dz}{H} = r + \frac{1+z}{H}\delta z \simeq r + \mathcal{V}$$

$$\mathcal{V} \equiv \frac{1+z}{H}\, V \simeq \frac{1+z}{H}\, \delta z_\chi$$

- **conservation of galaxy number:** $n_z(s)\ d^3s = n_r(r)\ d^3r$
  - **full Kaiser formula:** $\delta_s = \delta_g - \left(\frac{d}{dr} + \frac{\alpha}{r}\right)\mathcal{V}$
  - **simple Kaiser formula:** $\delta_s = \delta_g - \frac{d\mathcal{V}}{dr}$
    with *distant-observer approximation*

Wide Angle Effect

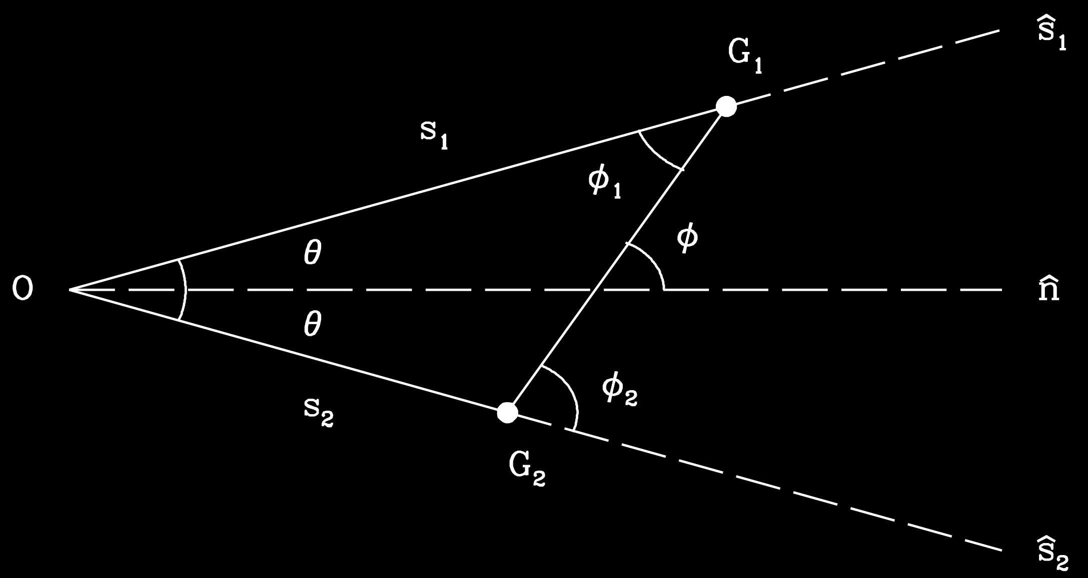
- What is "*wide angle*" effect?
  - deviation from the **distant-observer** approximation

$$\mu_1 = \hat{x}_1 \cdot \hat{k} \ , \quad \mu_2 = \hat{x}_2 \cdot \hat{k} \ , \quad \mu = \hat{x} \cdot \hat{k} \qquad \text{vs} \qquad \hat{x}_1 = \hat{x}_2$$

  - galaxies are far away from the observer:

    distant-observer approximation

  - velocity contribution: *nothing* to do with wide angle effect



Impact on Correlation

- **full Kaiser formula:**

$$\langle\delta_1\delta_2\rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot s} \left(b_1 + f_1\mu_1^2 - i\mu_1 \frac{\mathcal{R}_1}{k/\mathcal{H}_1}\right)\left(b_2 + f_2\mu_2^2 + i\mu_2 \frac{\mathcal{R}_2}{k/\mathcal{H}_2}\right) P_m(k)$$

- **full Kaiser formula with distant-observer approx.**

$$\langle\delta_1\delta_2\rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot s} \left(b + f\mu^2 - i\mu \frac{\mathcal{R}}{k/\mathcal{H}}\right)\left(b + f\mu^2 + i\mu \frac{\mathcal{R}}{k/\mathcal{H}}\right) P_m(k)$$

- **simple Kaiser formula with distant-observer approx.**

$$\langle\delta_1\delta_2\rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot s} \left(b + f\mu^2\right)^2 P_m(k)$$

- ***R*: velocity contribution**

Szalay, Matsubara, Landy 1998

Szapudi 2004, Papai & Szapudi 2008

Covariance Matrix

- **how to quantify the deviation?**
  - **easier in Fourier space:**

$$\mathrm{Cov}[P_l^s(k)P_{l'}^s(k')] = \frac{(2l+1)(2l'+1)}{2}\delta_{kk'}\int d\mu_k\ \mathcal{P}_l(\mu_k)\mathcal{P}_{l'}(\mu_k)\left[P_s(k,\mu_k)+\frac{1}{\bar{n}_g}\right]^2$$

  - **redshift-space multipoles are *weakly correlated*, but *independent* at each wavenumber**

- **strategy:**
  - **compute the *full* correlation for each pair**
  - **average over *all triangles*, given** (μ, s)
  - **compare deviation with error bars**

Full Kaiser Formula

- in light of the *general relativistic* formula:

  two errors in wide angle formula

  - valid for galaxy sample: *independent* of luminosity

    missing correction for typical samples

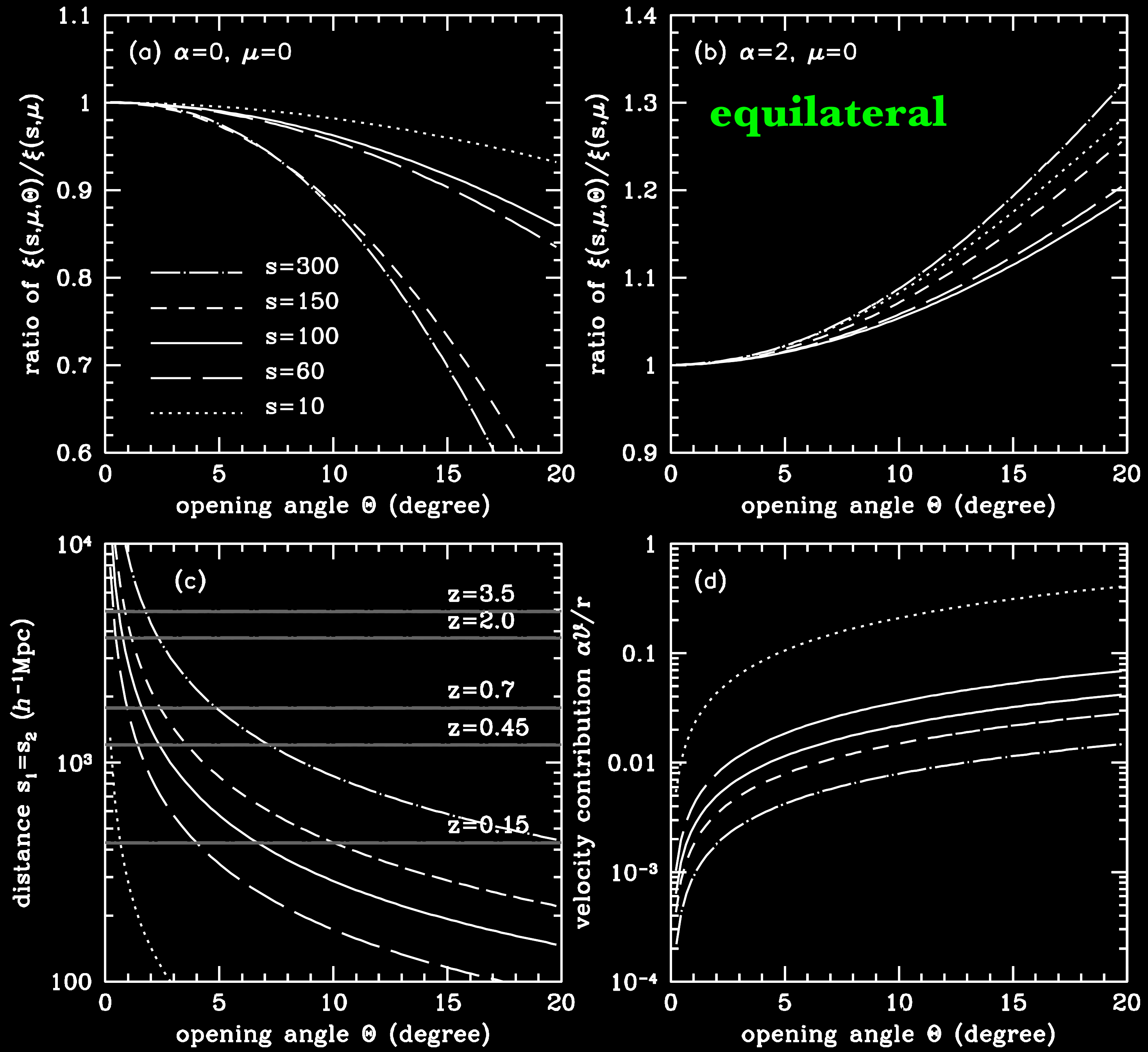
  - derivative in Jacobian: *missing correction*
    - total derivative along the *past light cone*
    - spatial derivative: usual term
    - time derivative: additional velocity

III. RESULTS

Yoo & Seljak, ***in preparation***

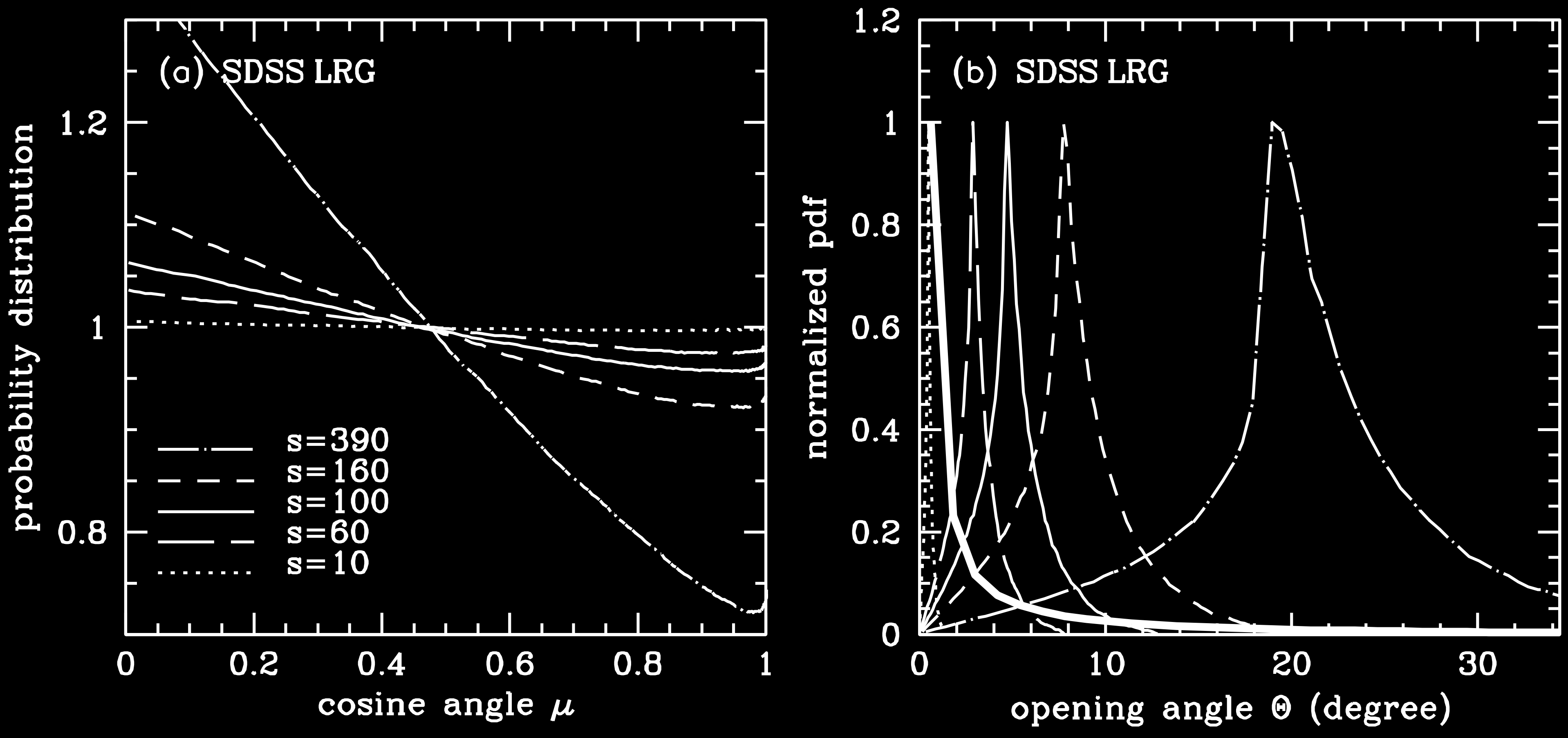
III. RESULTS

- **deviation: velocity contribution, "*wide angle*"**
- **velocity contribution ~ *V/r* due to volume effect (r: distance to galaxies)**
- **number of pairs is ~ volume**
- ***no wide-angle galaxy pairs***

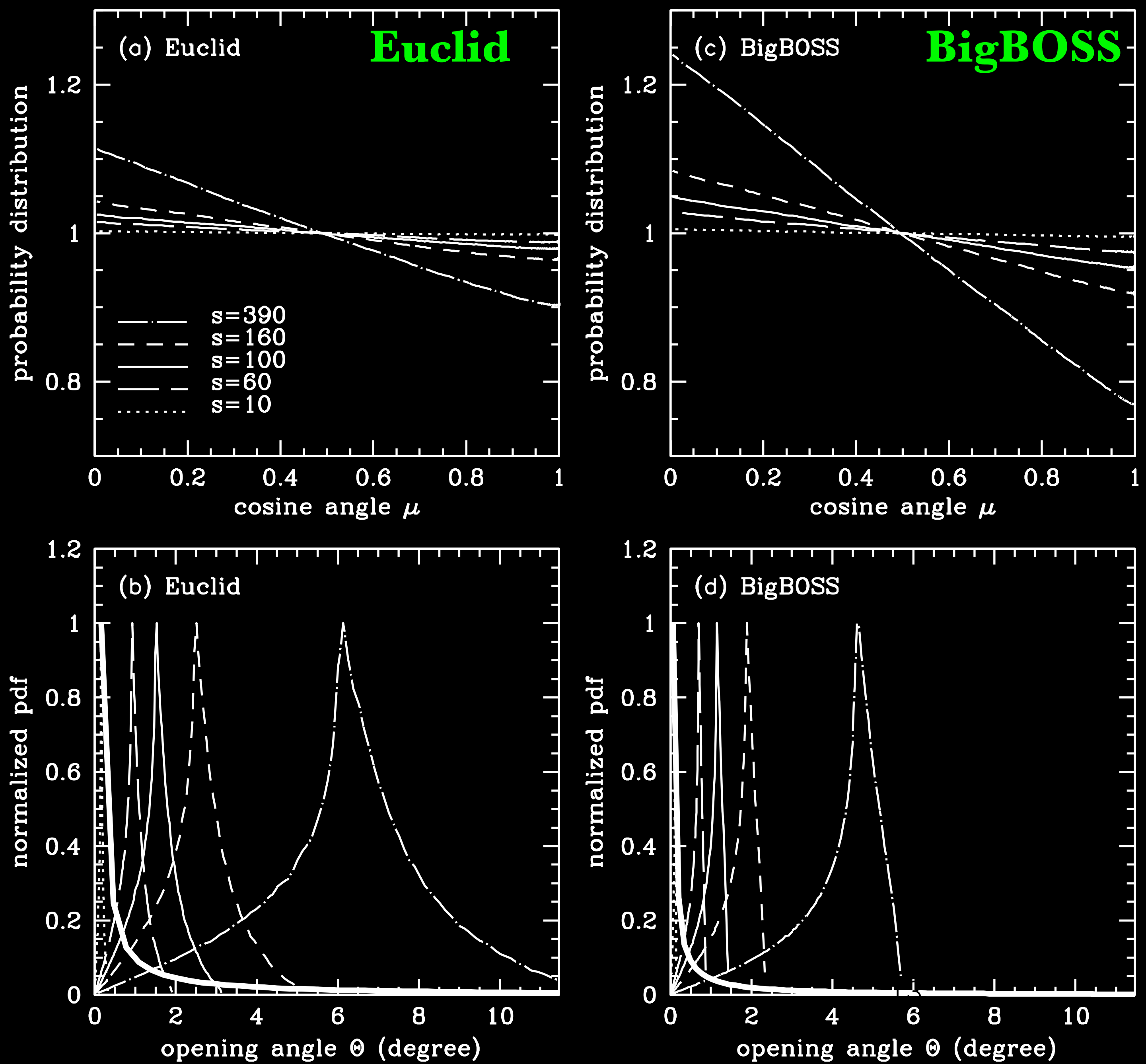


PDF of Triangular Configuration

- **simple survey geometry (no hole, no disjoint region)**
- **typical pairs have *small opening angle!***
- ***non-uniform* distribution of μ**

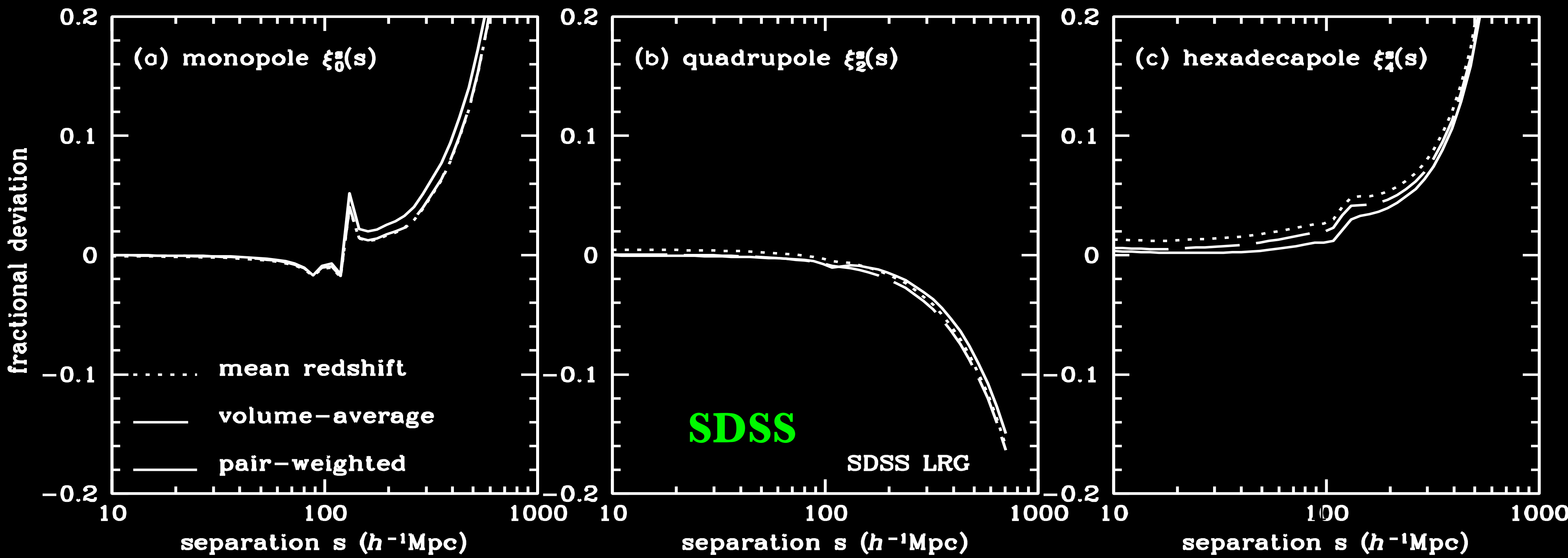


- **Euclid & BigBOSS**
- **more sky coverage: *more uniform* cosine distribution**
- **factor of few farther away: *smaller* opening angle**



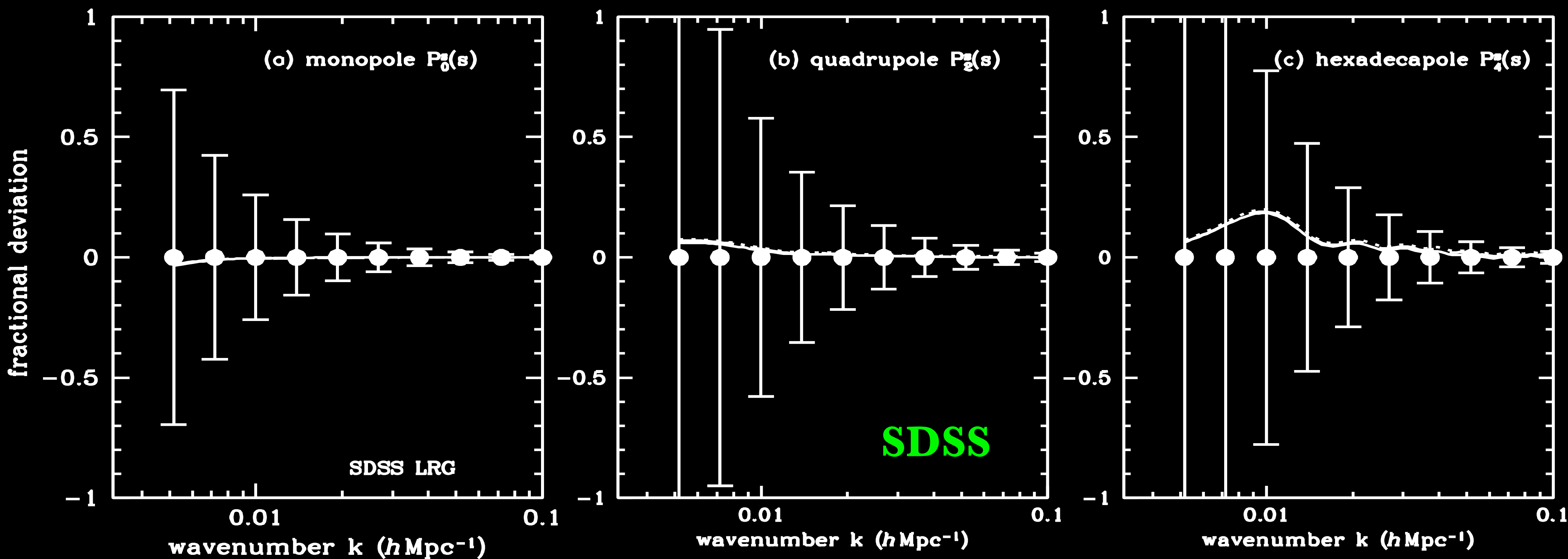
Systematic Errors in Correlation

- deviation of **simple Kaiser formula** with **distant-observer approximation** from the full redshift-space
- *negligible* on small scales
- *large* on large scales, but *difference* is $\Delta\xi \simeq 10^{-5}$

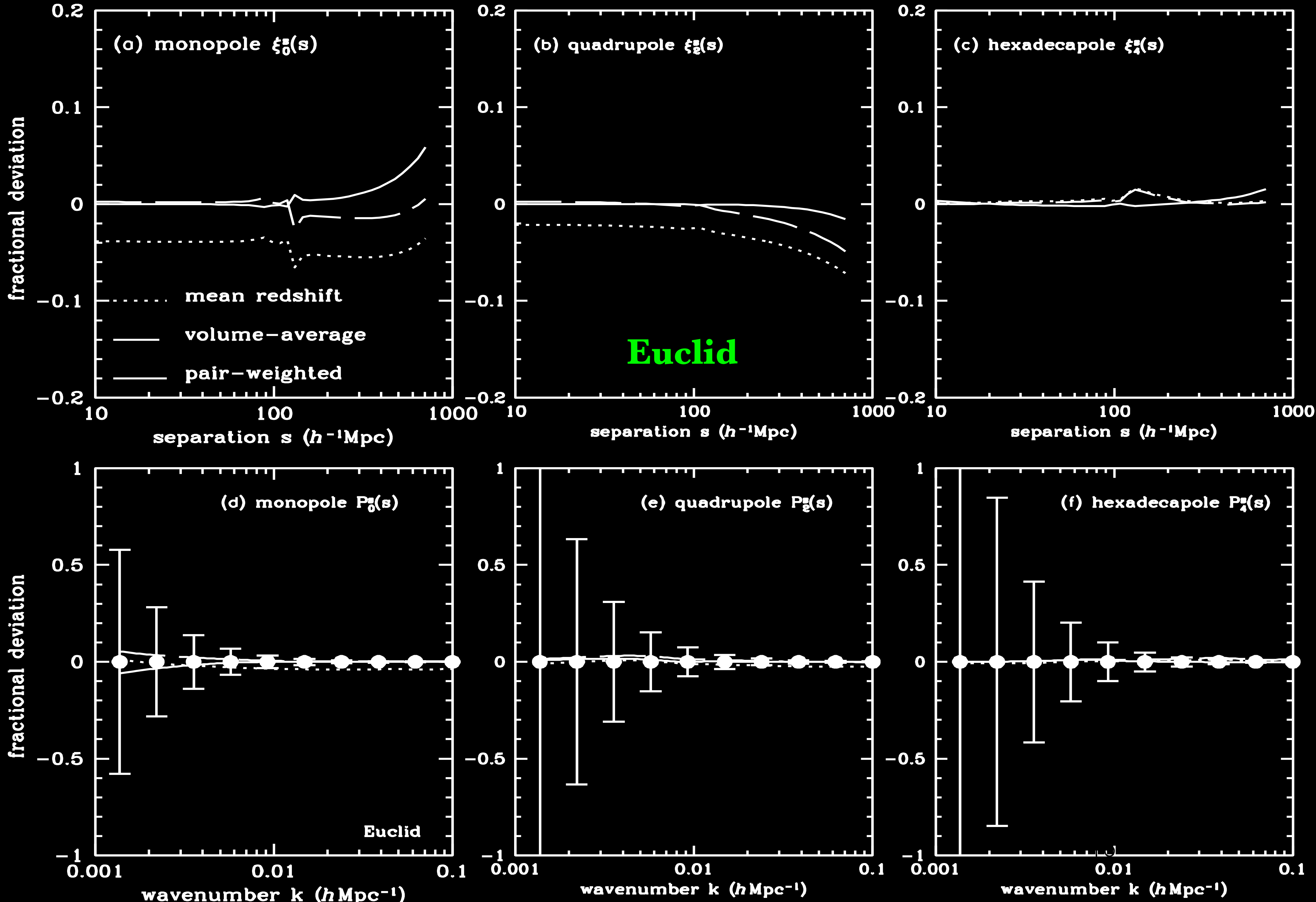


Systematic Errors

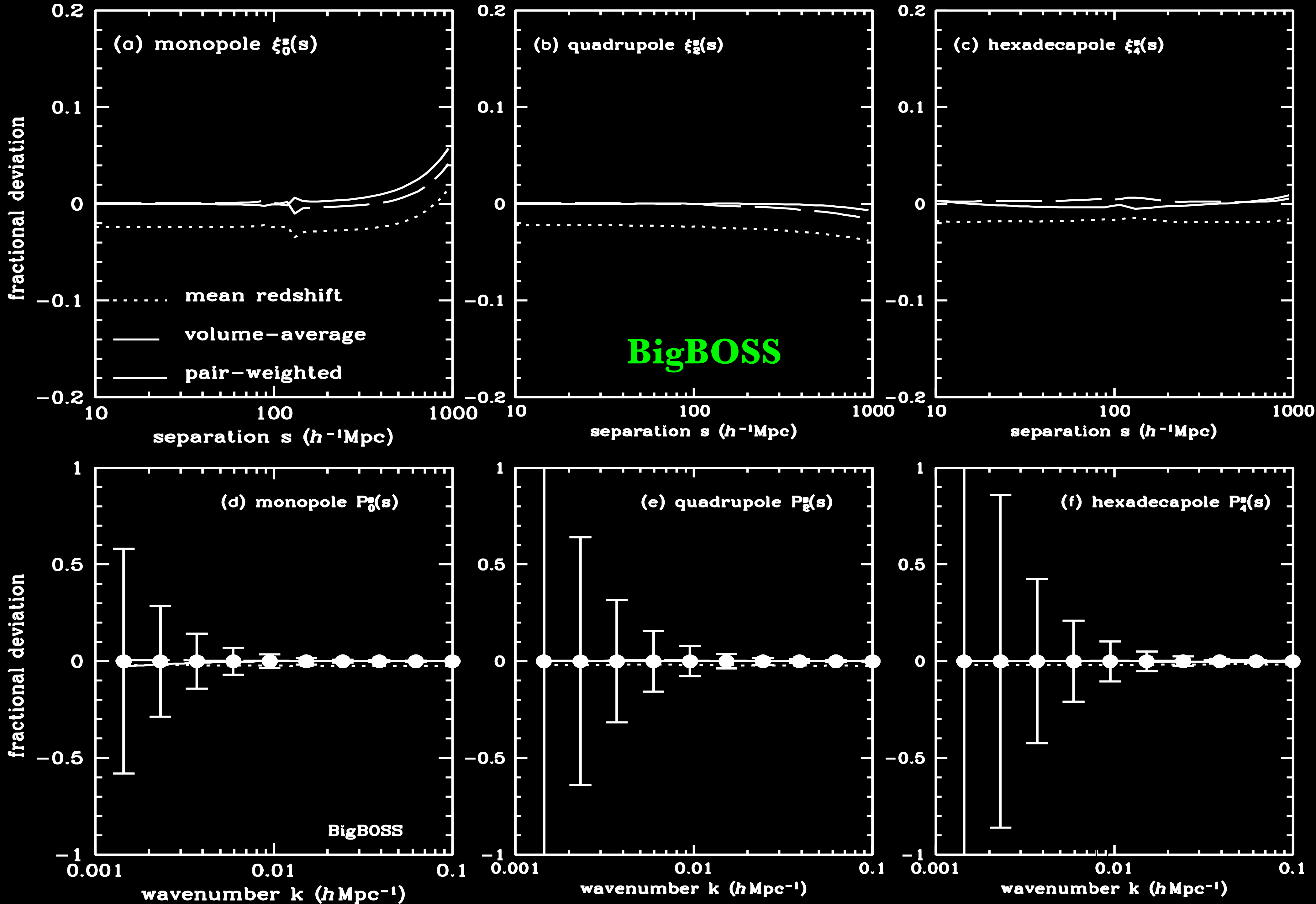
- **error bars are in practice larger and correlated**
- **systematic errors in the SDSS measurements:** ***completely negligible!***



III. RESULTS


(a) monopole $\xi_0^s(s)$
(b) quadrupole $\xi_2^s(s)$
(c) hexadecapole $\xi_4^s(s)$
mean redshift
volume−average
pair−weighted
Euclid
fractional deviation
separation s (h^{-1}Mpc)
(d) monopole $P_0^s(s)$
(e) quadrupole $P_2^s(s)$
(f) hexadecapole $P_4^s(s)$
Euclid
wavenumber k (hMpc^{-1})

III. RESULTS


(a) monopole $\xi_0^s(s)$
(b) quadrupole $\xi_2^s(s)$
(c) hexadecapole $\xi_4^s(s)$
mean redshift
volume−average
pair−weighted
BigBOSS
fractional deviation
separation s (h^{-1}Mpc)
0.2
0.1
0
−0.1
−0.2
10
100
1000
(d) monopole $P_0^s(s)$
(e) quadrupole $P_2^s(s)$
(f) hexadecapole $P_4^s(s)$
BigBOSS
wavenumber k (h Mpc^{-1})
1
0.5
0
−0.5
−1
0.001
0.01
0.1

Caveats

- **deviation in redshift-space correlation: *negligible!***
- **power spectrum in practice:**
  - **distant-observer approximation: *accurate!***
  - ***differently* measured! not just Fourier Transform**
  - ***some issues* are present! not wide angle effect**
  - **traditional FKP: simple Fourier transformation**

    Feldman, Kaiser, Peacock 1994, Percival et al. 2001, 2007, 2010
  - **spherical Fourier analysis: complicated, natural**

    Heavens & Taylor 1995, Tegmark et al. 2004, 2006

FKP Method

- **traditional FKP method:**

$$\langle P_l^s(k)\rangle = (-i)^l(2l+1)\int d^3s_1 \int d\ln s\; s^3 j_l(ks)$$

$$\times \int d^2\hat{s}\; \mathcal{P}_l(\hat{z}\cdot\hat{s})\; \bar{n}_g^w(s_1)\; \bar{n}_g^w(s_2)\; \xi_s(s_1, s_1 - s)$$

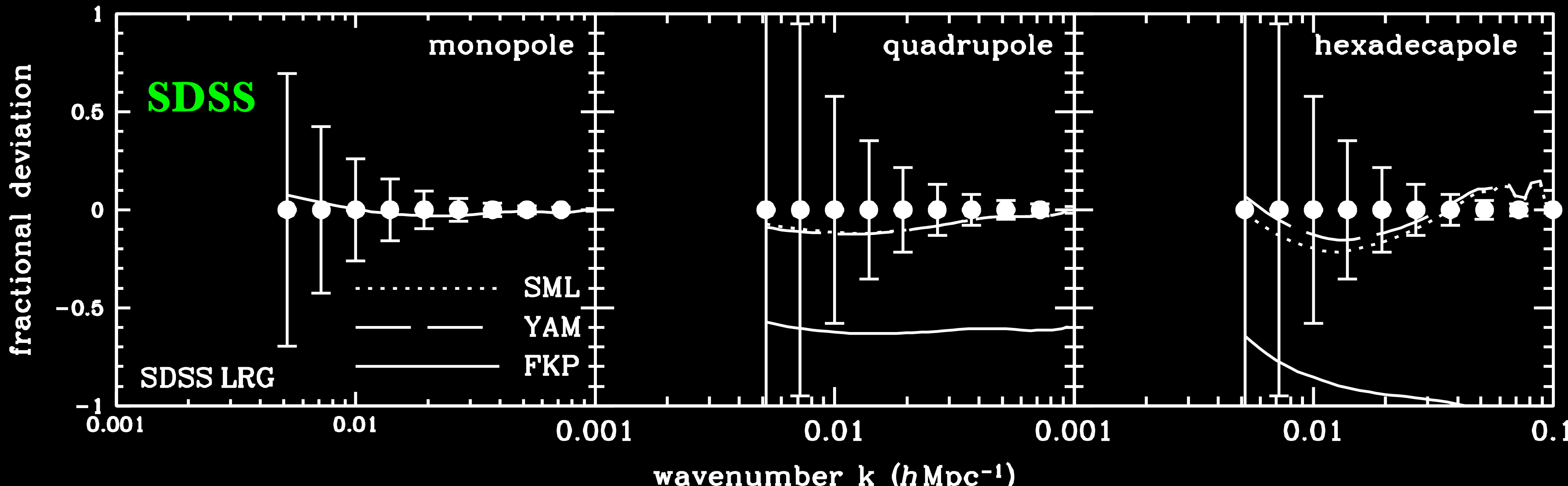
  - **window function convolved power spectrum**

- **problems:**
  - **line-of-sight direction is *z-direction for all pairs!***
  - **non-uniform distribution of μ : *unaccounted!***
  - **pair-dependent method:** $\mathcal{P}_l(\hat{z}\cdot\hat{s}) \quad \rightarrow \quad \mathcal{P}_l(\hat{n}\cdot\hat{s})$

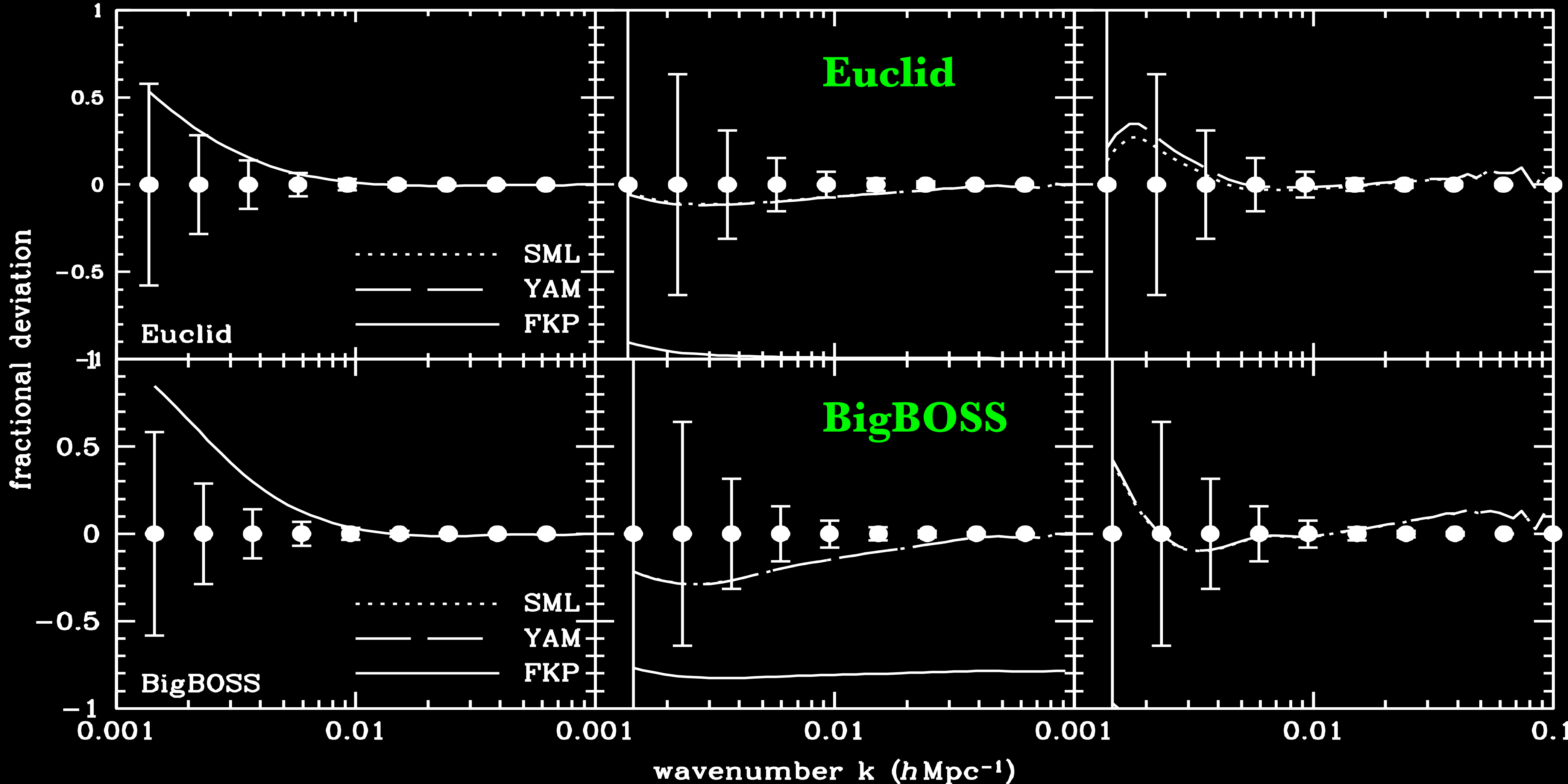
Yamamoto et al. 2006

SDSS Power Spectrum

- FKP monopole: *good!*, FKP quadrupole: *bad!*
  FKP hexadecapole: *awful!*
- non-uniform distribution: *negligible error!*
- line-of-sight dependent pair-weighting: *work well!*



- even FKP monopole becomes *problematic!*
- non-uniform distribution: *non-negligible error!*
- line-of-sight dependent pair-weighting: *work well!*



IV. TAKE-HOME MESSAGE:
HOW TO INTERPRET THE RESULTS?

Take Home Message

- **distant-observer approximation**: ***accurate!***
  - **galaxies are sufficiently far away**
  - **no degeneracy with modified gravity**

- **power spectrum measurements**: ***ok for now!***
  - **monopole is ok, but higher multipole *not***
  - **further refinement is needed for Euclid, BigBOSS**

- **wide angle formalism**: ***simple and accurate!***
  - **no harm to use it**
  - **one can be creative in designing surveys**

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