Cosmology with type Ia Supernova gravitational lensing

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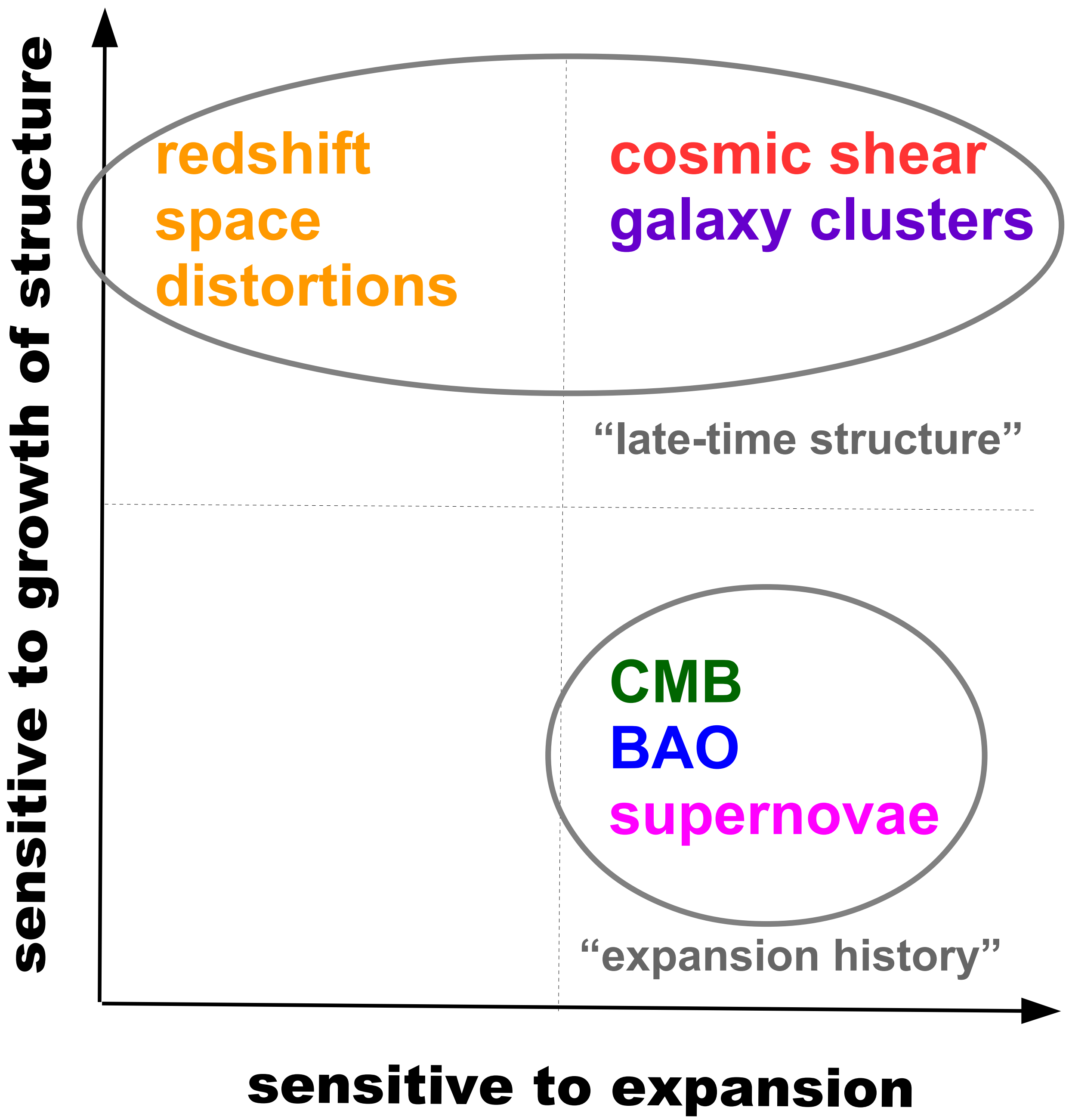
How to survey Dark Energy

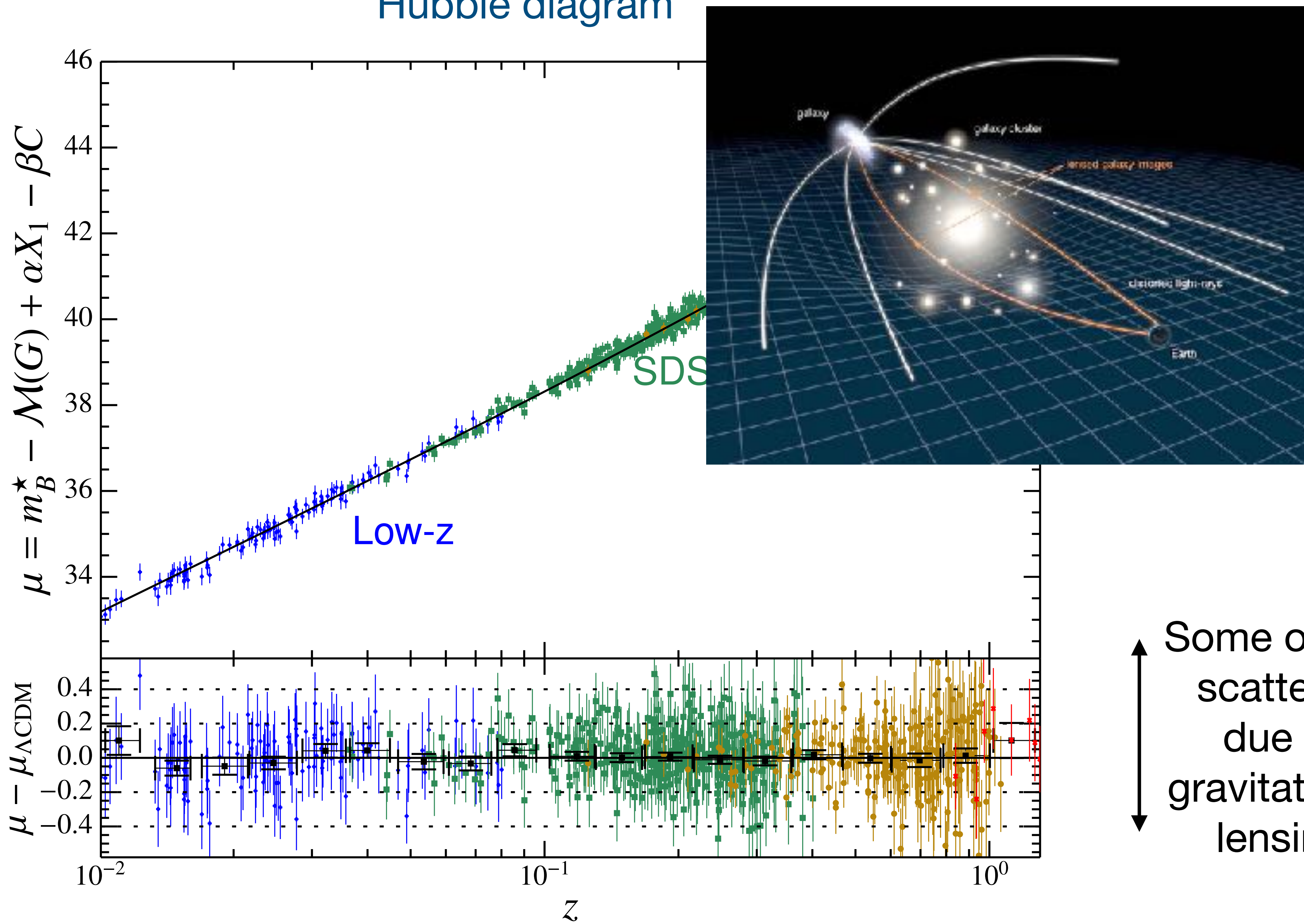


Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

- $\Omega_m \sim 0.3$
- $\Omega_\Lambda \sim 0.7$
- $\sigma_8 \sim 0.8$
- $h \sim 0.7$

Influence of growth of structure in SN lensing

Hubble diagram



Distance\magnitude

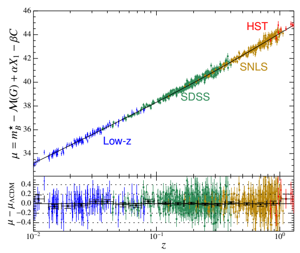
Redshift

Some of this scatter is due to gravitational lensing

Betoule M. et al, 2014

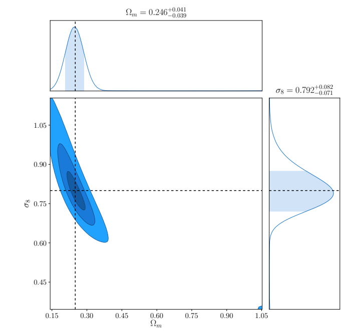
SN lensing

Impact on type Ia SN Cosmology



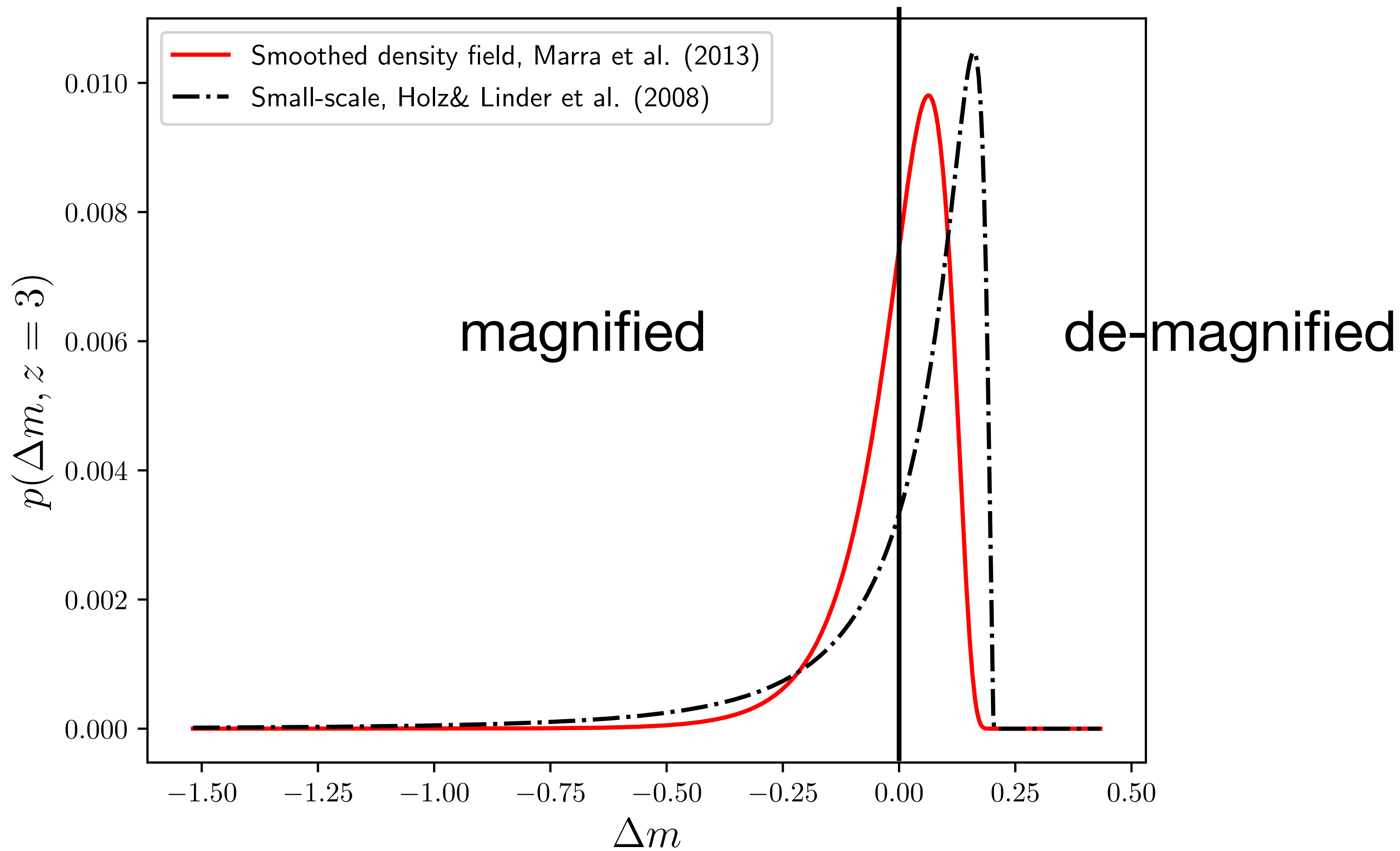
$$\mu = m_b - (M_b - \alpha x_1 + \beta c) - \frac{5}{\ln 10}\kappa$$

Cosmology with type Ia SN lensing



$$\kappa_{g_i} = \frac{3H_0^2\Omega_m}{2c^2}\sum_j \delta_{g_{i,j}} \frac{(r_s - r_j)r_j}{r_s a_j} dr_j$$

Cosmology with type IA SN lensing: Probabilistic approach



Lensing magnification (in magnitude)

Assume a universal PDF that describes the probability of a given SN at redshift z to be magnified or demagnified

- Moments of the Hubble diagram residuals at different redshift bins

$$f(\Omega_m, \sigma_8, z)$$

$$\mu_1 = 0$$

$$\mu_2 = \sigma^2_{lens} + \sigma^2_I$$

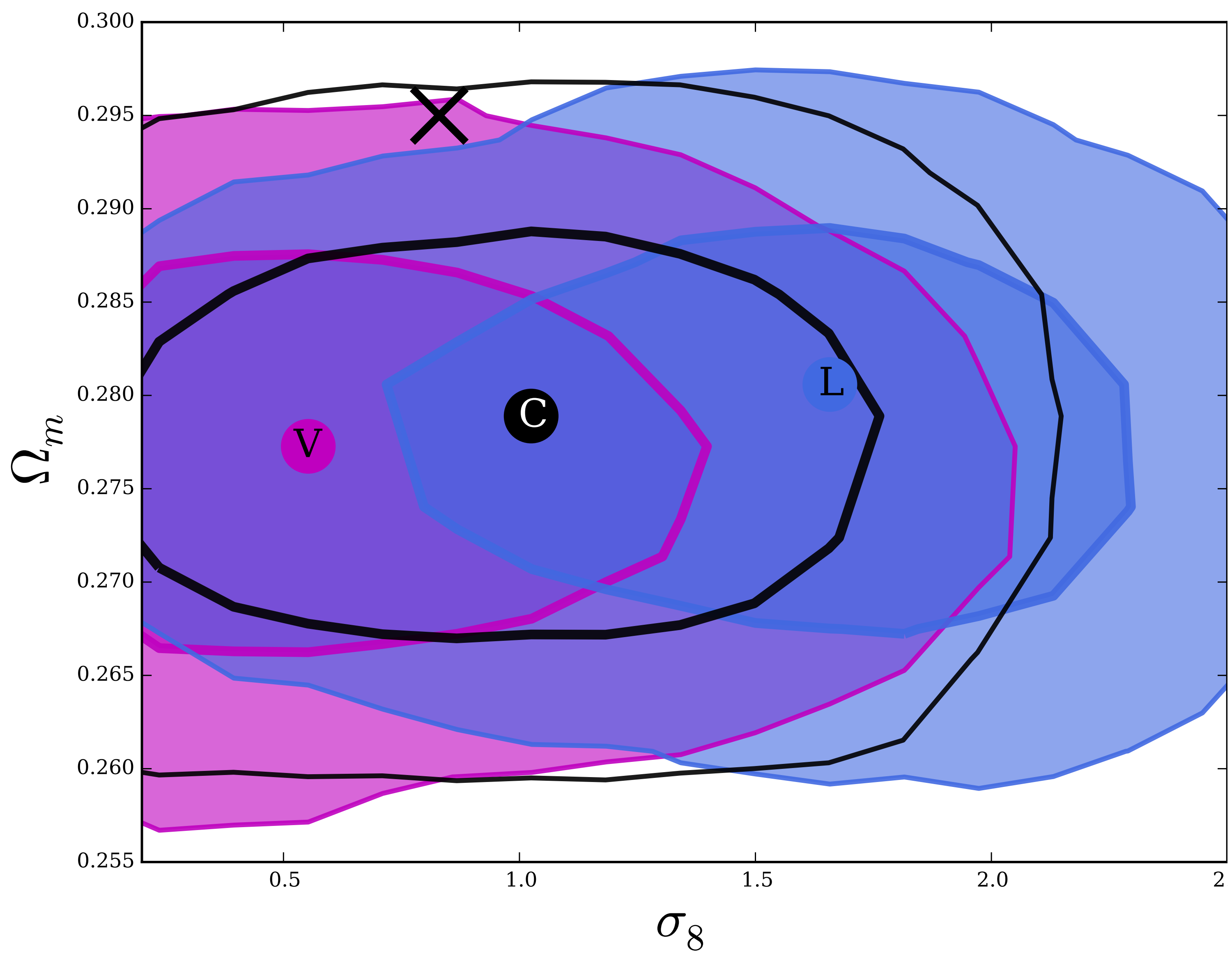
$$\mu_3 = \mu_{3,lens} + \mu_{3,I}$$

$$\mu_4 = \mu_{4,lens} + \mu_{4,I} + 3\mu_2^2 - 3\sigma^4_{lens}$$

- Free parameters of the model:

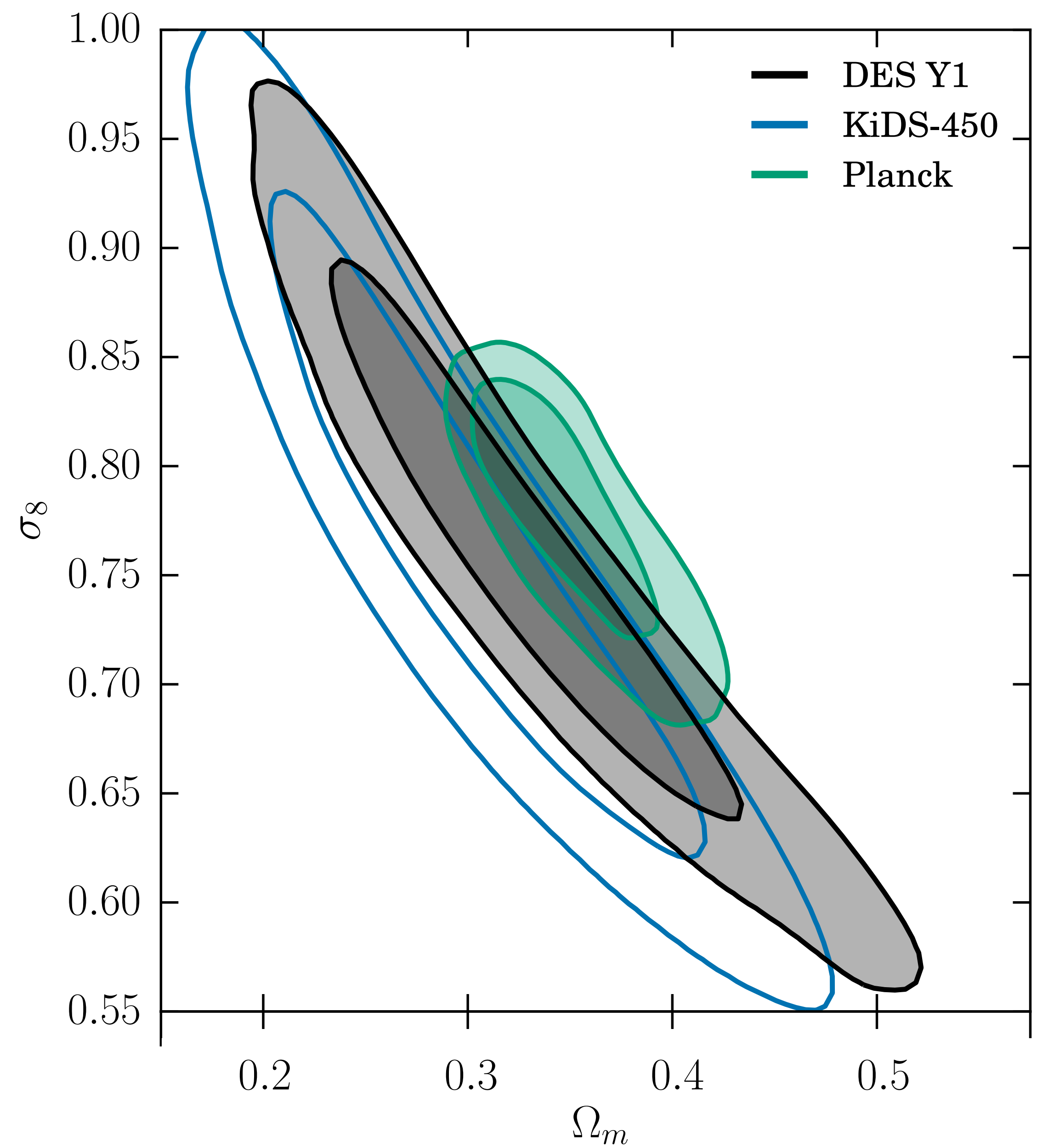
$$\{\Omega_m, \sigma_8, \sigma_I, \mu_{3,I}, \mu_{4,I}\}$$

Cosmology with type IA SN lensing: Probabilistic approach



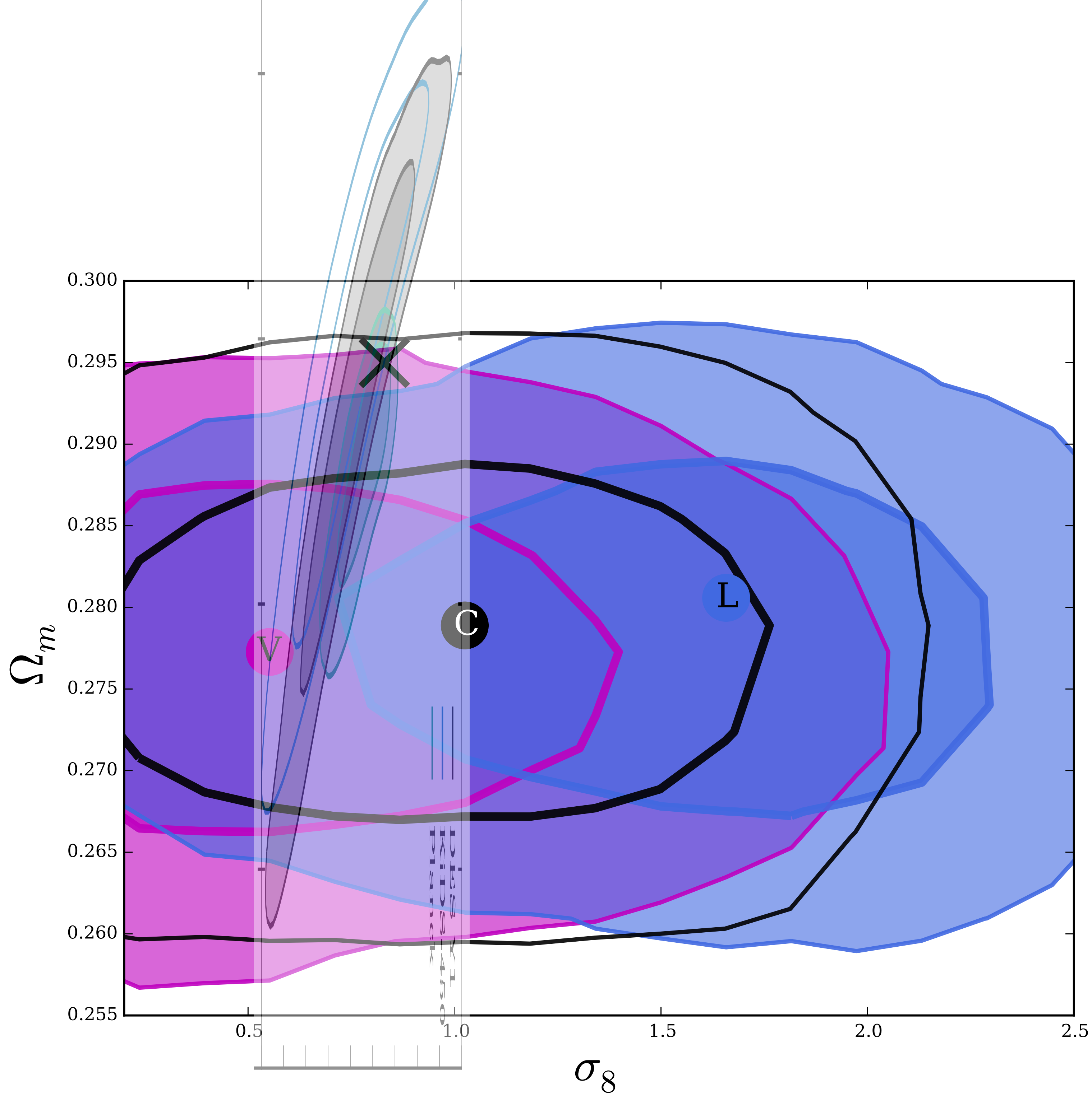
Macaulay E. et al, 2017

Best fit to JLA Supernova Sample



DES-Y1: Troxel M. et al. 2017

DES-Y1 galaxy shear-shear



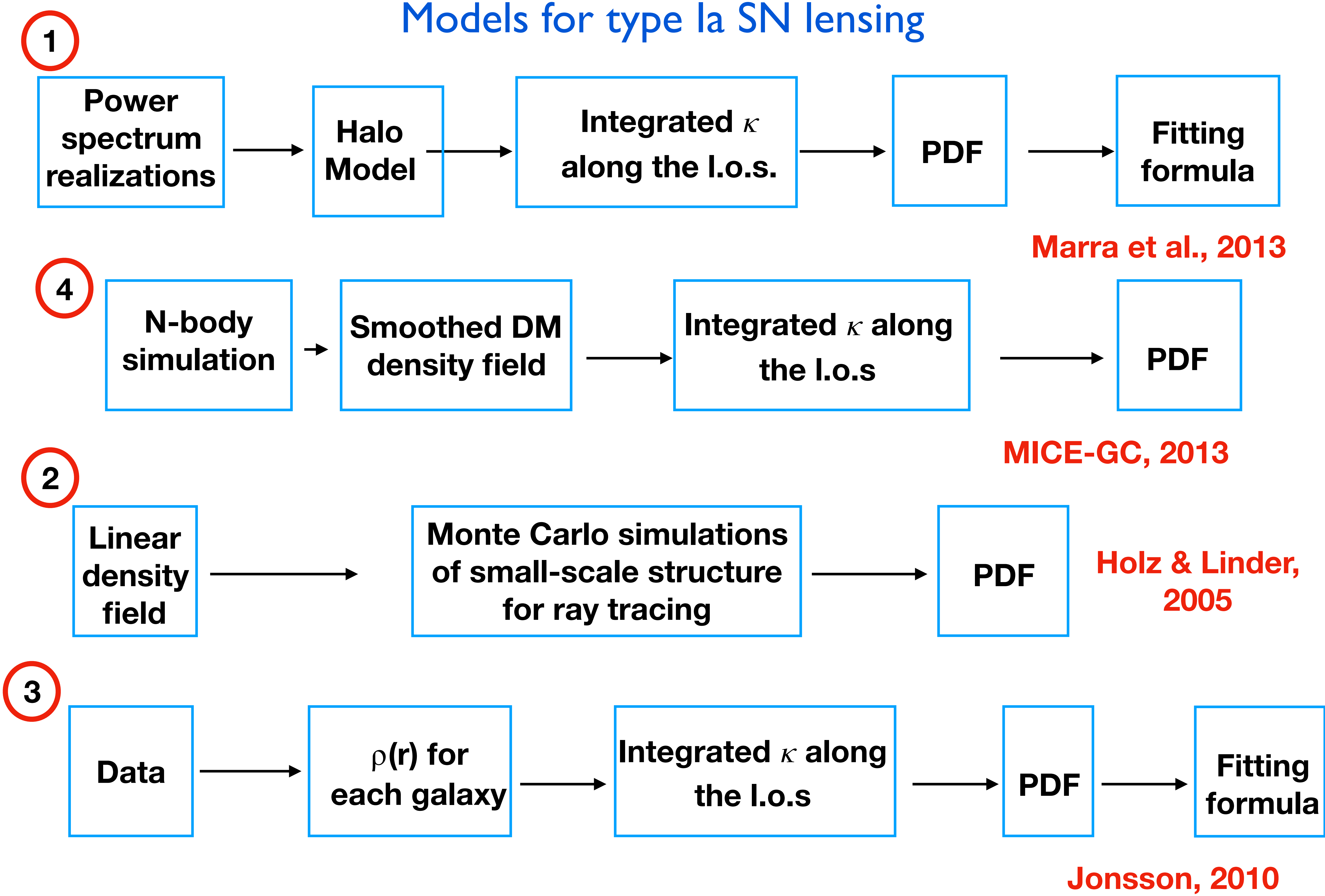
Macaulay E. et al, 2017

DES-Y1: Troxel M. et al. 2017

Best fit to JLA Supernova Sample

DES-Y1 galaxy shear-shear

Models for type Ia SN lensing

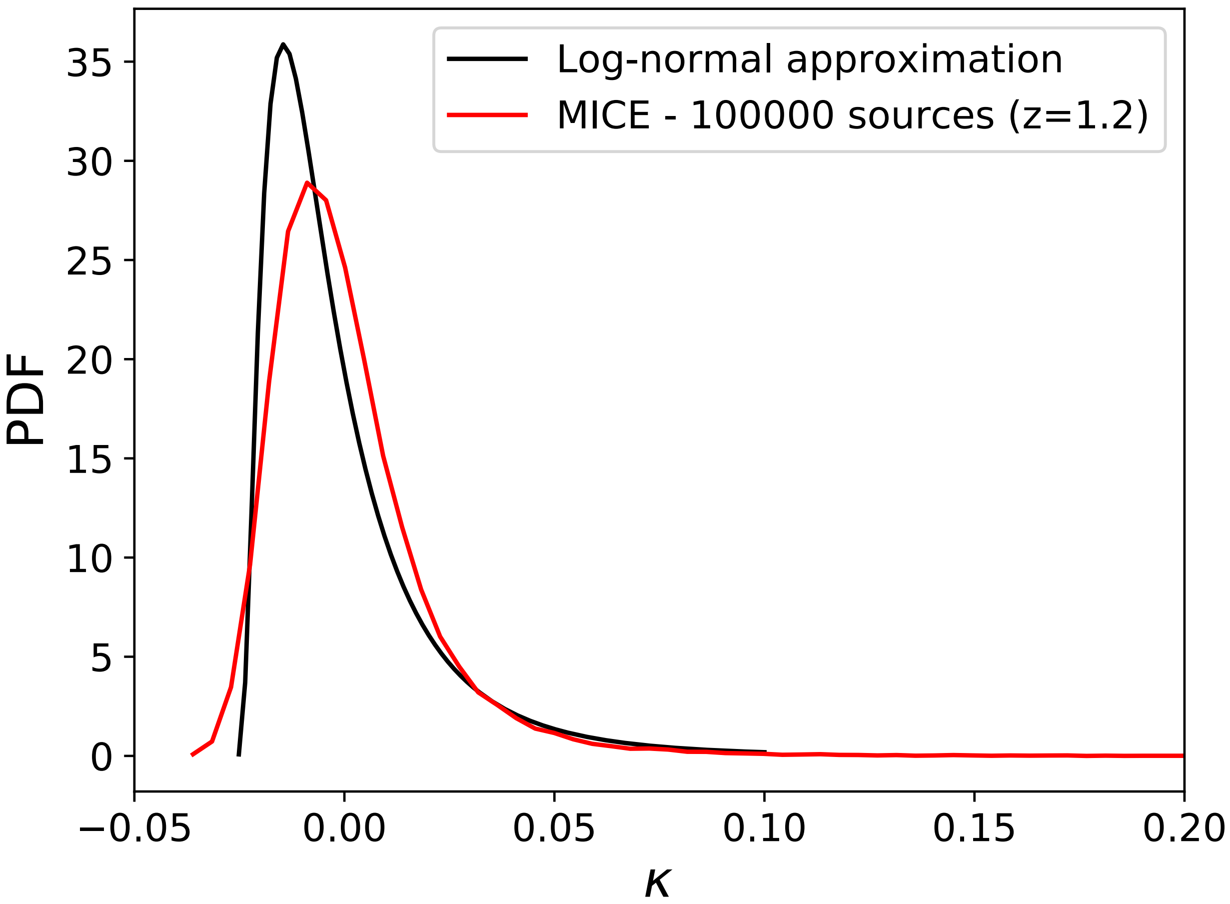


1) Log-normal approach

$$p(\kappa) = \frac{exp\left[-\frac{\log(\kappa+\mu_{logn})-\bar{\kappa}-\mu_{gauss}}{2\sigma_{gauss}}\right]}{\sqrt{2\pi}\sigma_{gauss}(\kappa+\mu_{logn}-\bar{\kappa})}$$

$$\mu_{gauss} = \frac{1}{2}\log\left[\frac{\mu_{logn}^2}{1+\sigma_{gauss}^2/\mu_{logn}^2}\right]$$

$$\sigma_{gauss}^2 = \log\left[1+\sigma_{logn}^2/\mu_{logn}^2\right]$$



$$\sigma_{\rm lens}(z,\sigma_8,\Omega_{m0}) = \frac{0.0004-0.00176\sigma_8+(-0.035+\sigma_8\,\Omega_{m0}+0.0453\sigma_8)z}{(2.19+\sigma_8^2)\Omega_{m0}z+3.19\,\exp\left[0.365/(0.193+z)\right]};$$

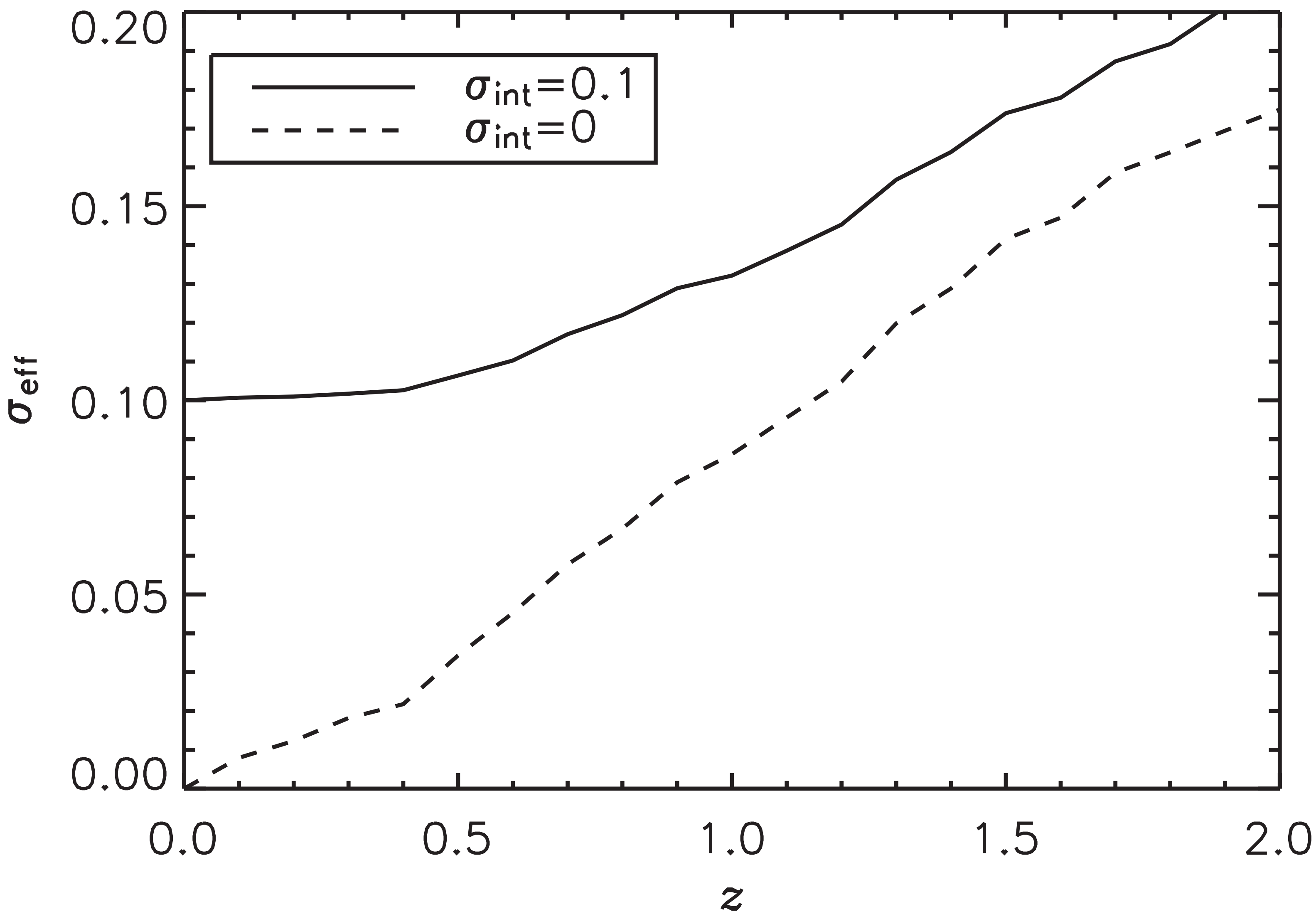
$$\mu_{3,\rm lens}^{1/3}(z,\sigma_8,\Omega_{m0}) = \frac{\sigma_8^2\,\Omega_{m0}\,z^2}{\sigma_8\sqrt{z}+1.1z+\left(4.24\sigma_8^2-\Omega_{m0}^2\right)\Omega_{m0}\,z^2+0.118(1-\sigma_8)z^3};$$

$$\mu_{4,\rm lens}^{1/4}(z,\sigma_8,\Omega_{m0}) = \frac{(-0.029+0.1\sigma_8+0.47\Omega_{m0}\sigma_8)z}{\exp\left[(-0.029+0.1\sigma_8+0.47\Omega_{m0}\sigma_8)z+\frac{0.021}{0.018+\Omega_{m0}\sigma_8 z}\right]+0.3z}.$$

Marra, Quartin & Amendola, 2013

Create realizations for different parameter values and estimate fitting formulas.

2) Ray tracing including compact objects

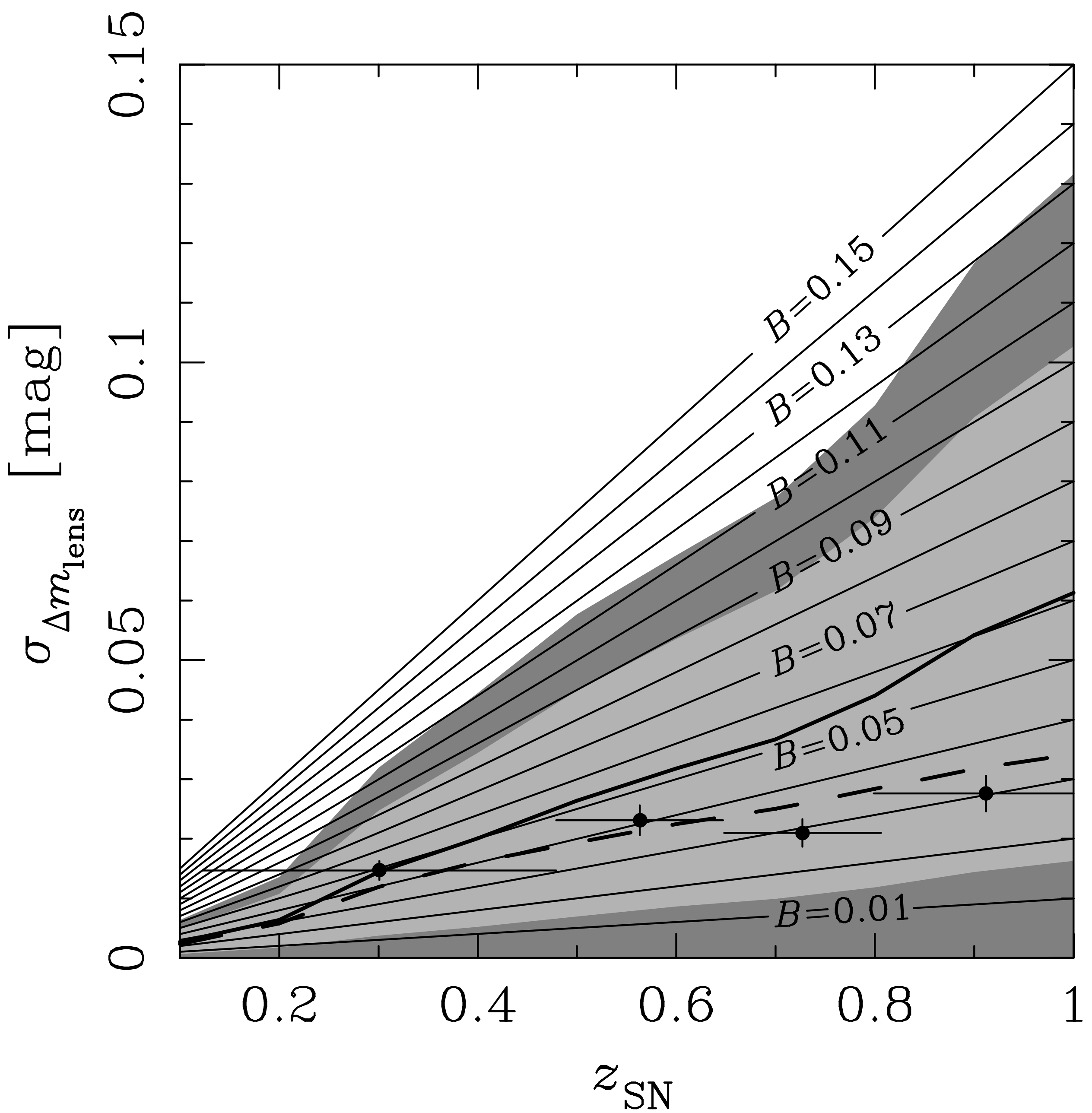


Holz & Linder 2005

Ray tracing including small scales clustering

$$\sigma_{\delta m} = 0.088z$$

3) Use data to reconstruct halo model

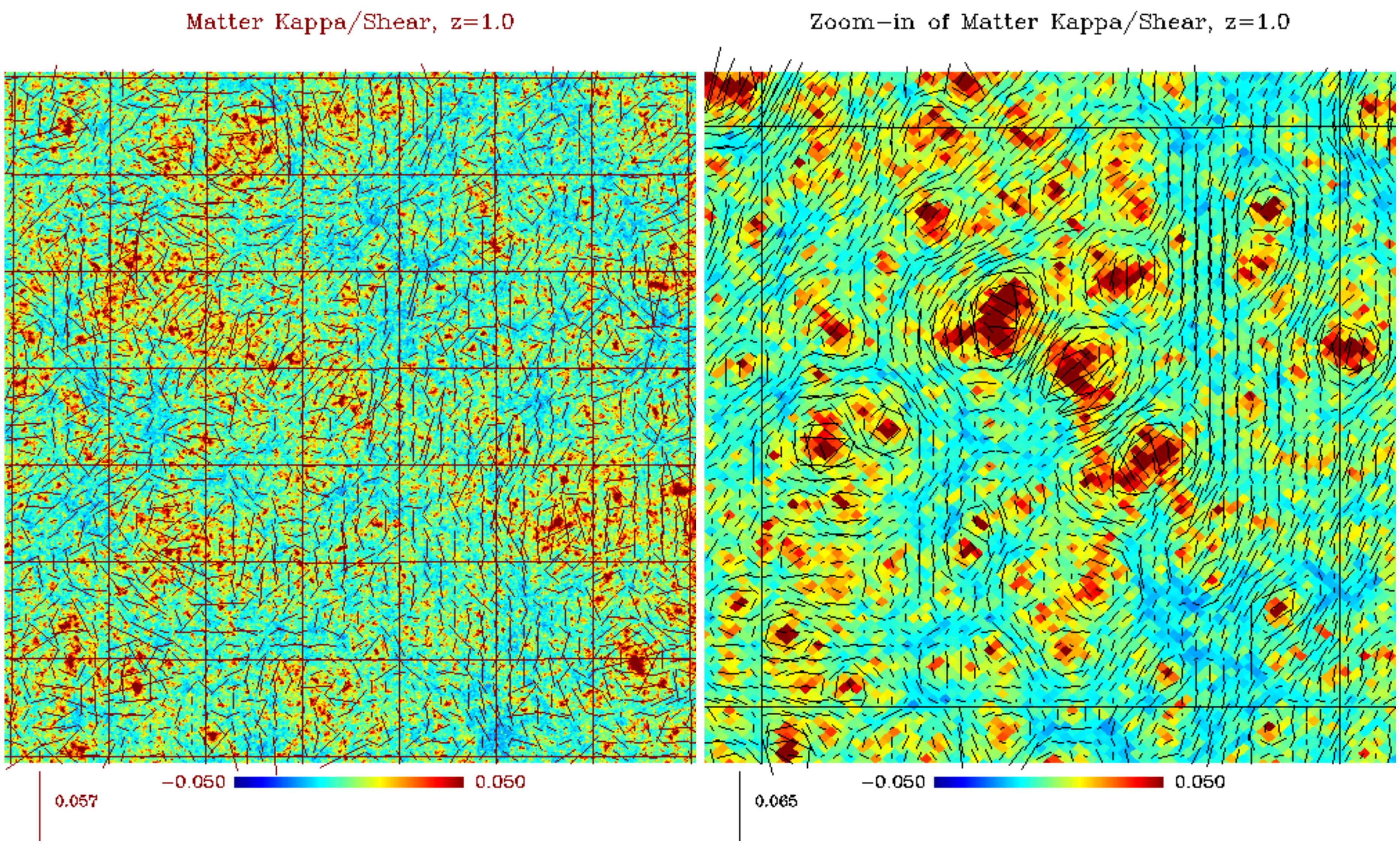


Jonsson et al. 2010

Measure the dispersion obtained by fitting halo model to observed dispersion in the Hubble diagram

$$\sigma_{\delta m} = 0.055z$$

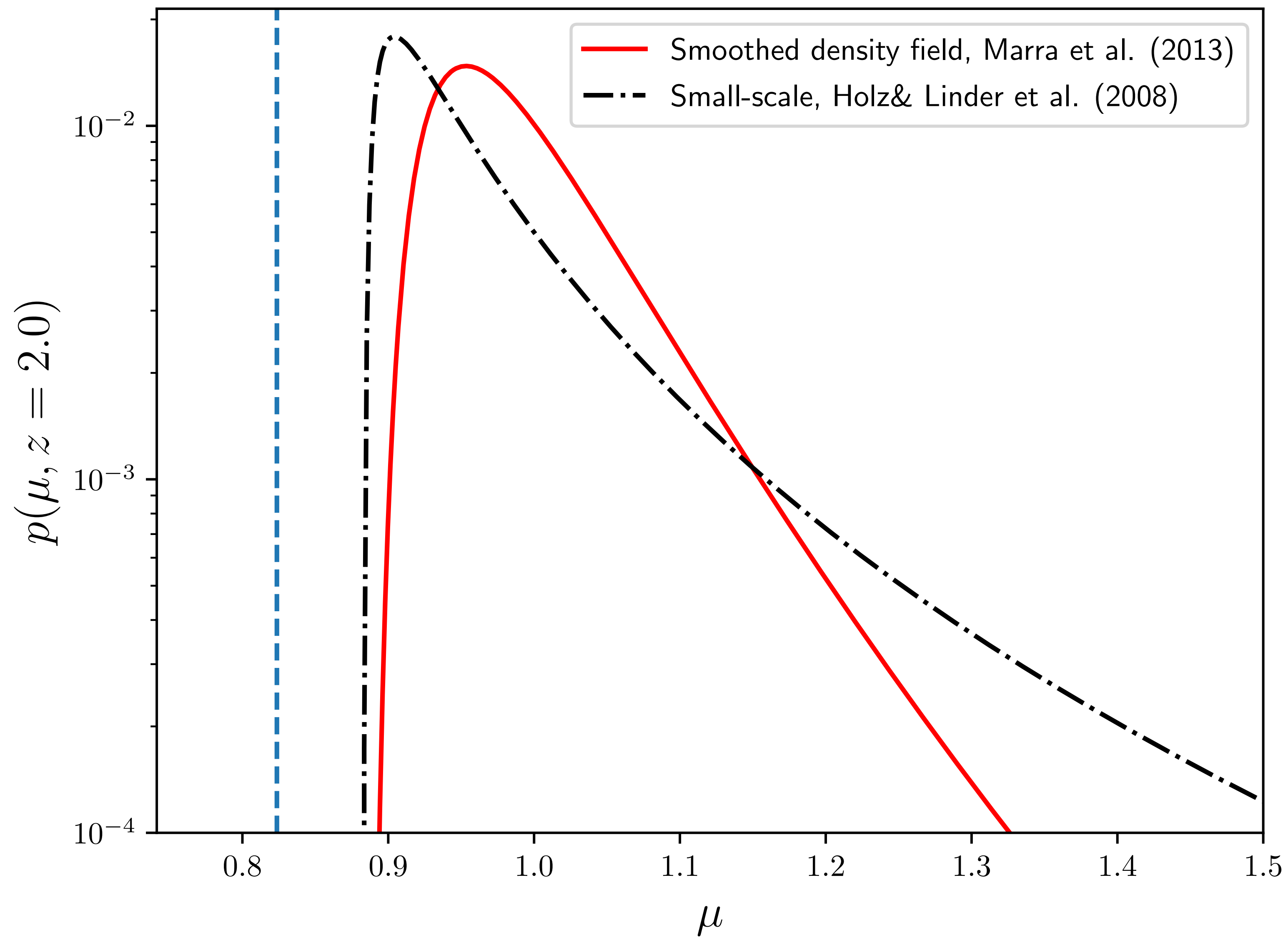
4) From N-body simulation light-cone



MICE simulations, Fosalba et al, 2014

$$\kappa_i = \frac{3H_0^2\Omega_m}{2c^2}\sum_j \delta_{i,j}\frac{(r_{source}-r_j)r_j}{r_s a_j}dr_j$$

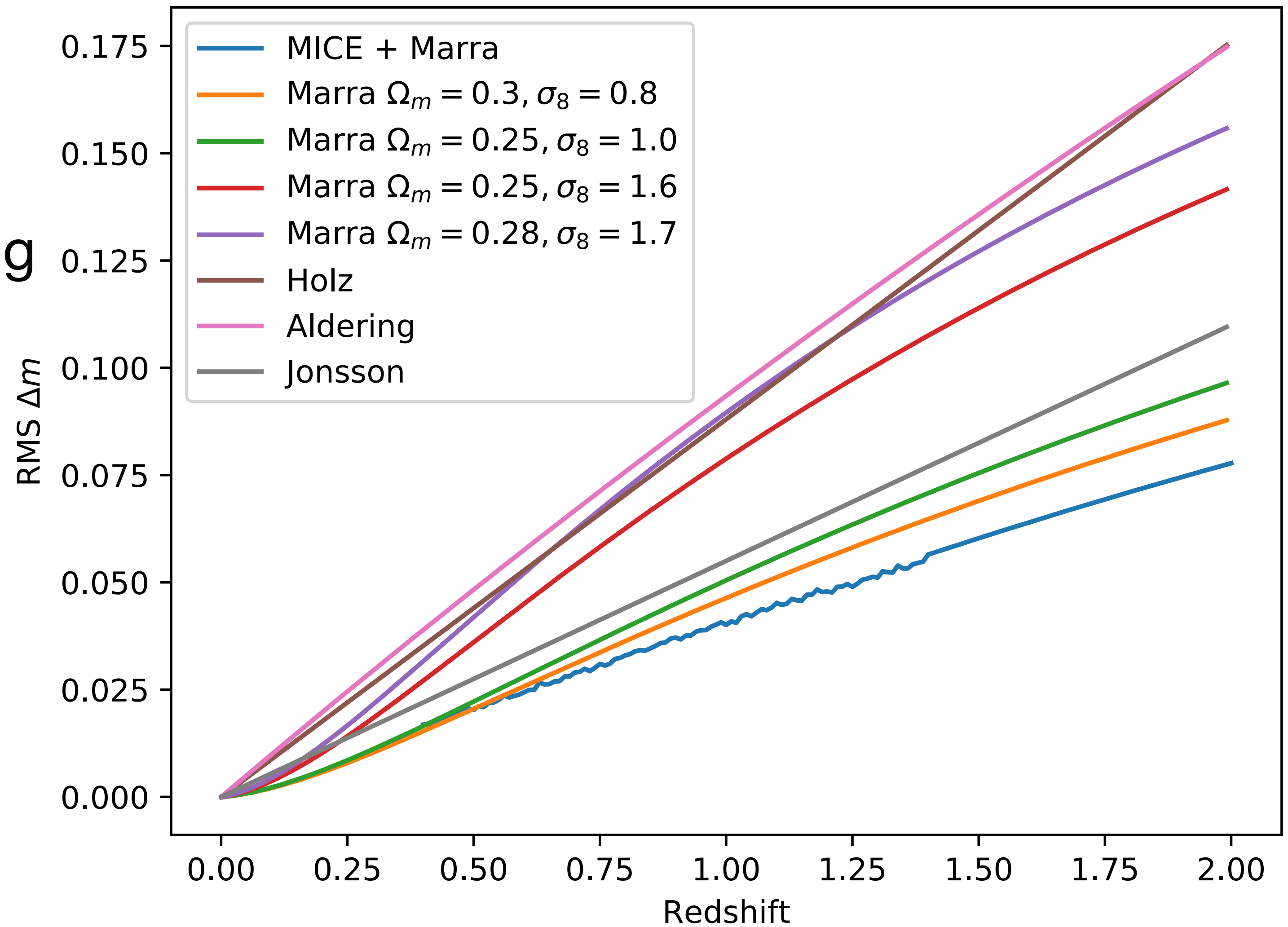
Different predictions for LSS effect on lensing probabilities



Lensing magnification

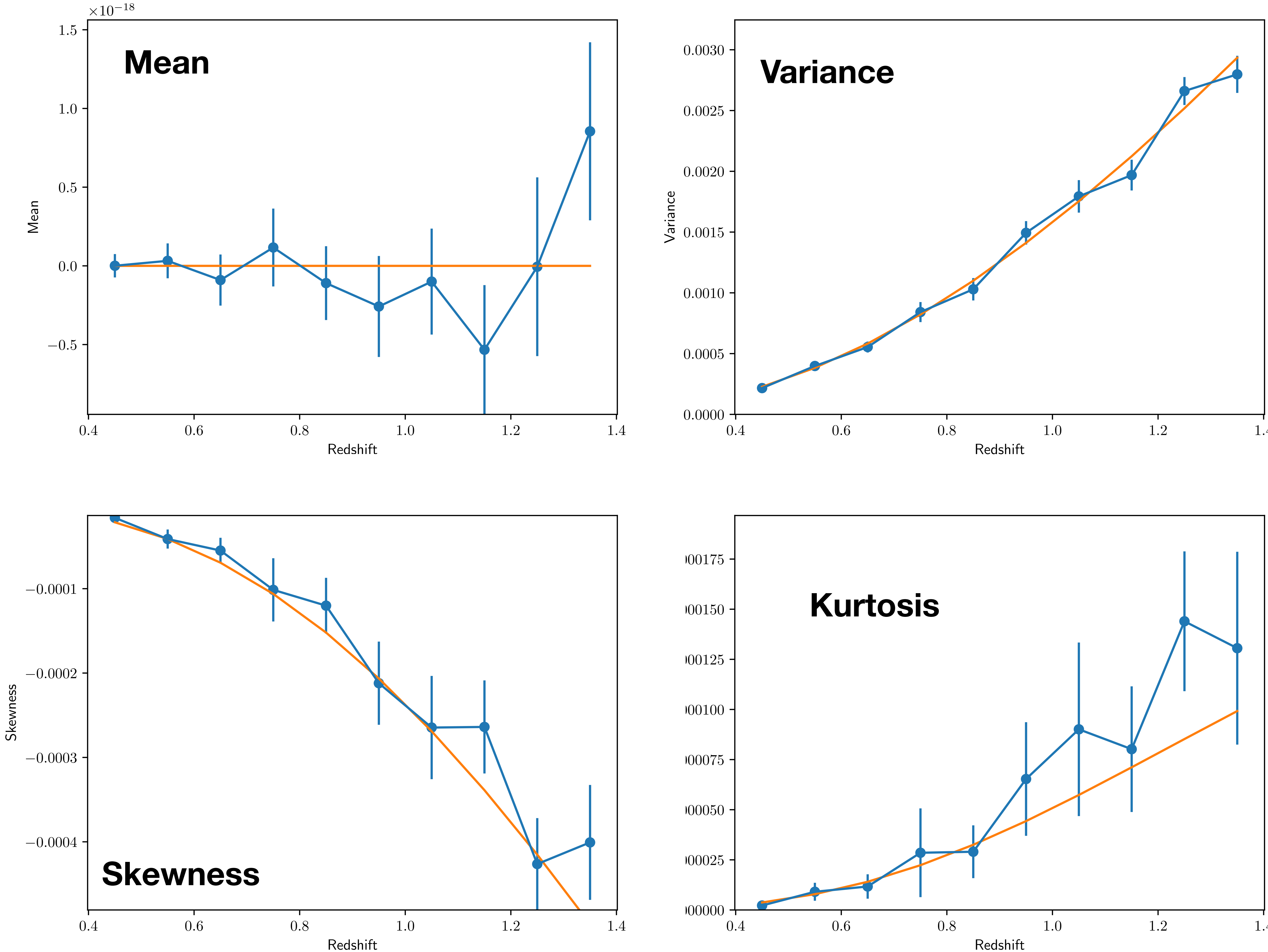
Different predictions for LSS effect on lensing probabilities

RMS of lensing dispersion

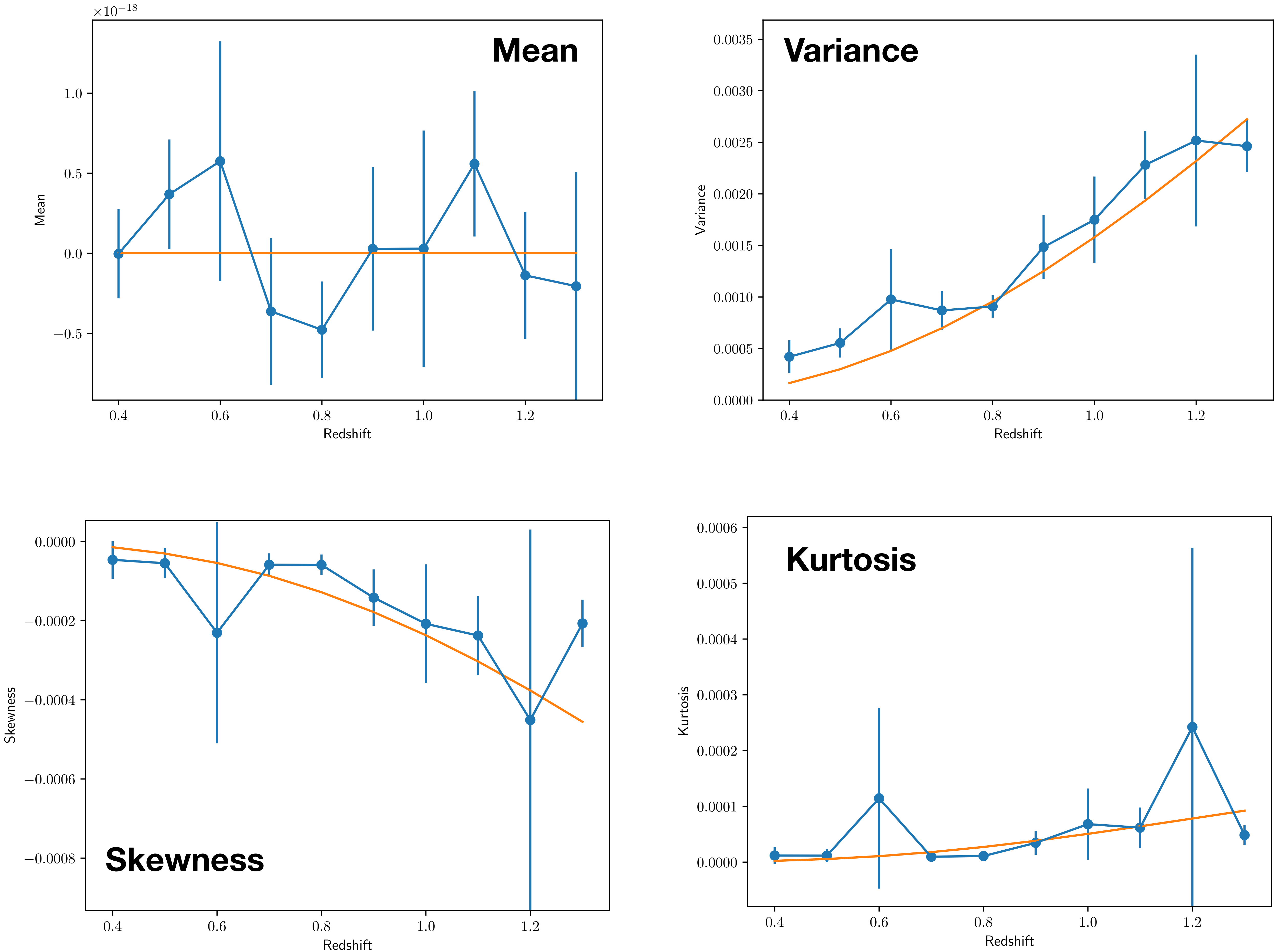


Redshift

Differences between models up to a factor of 2.

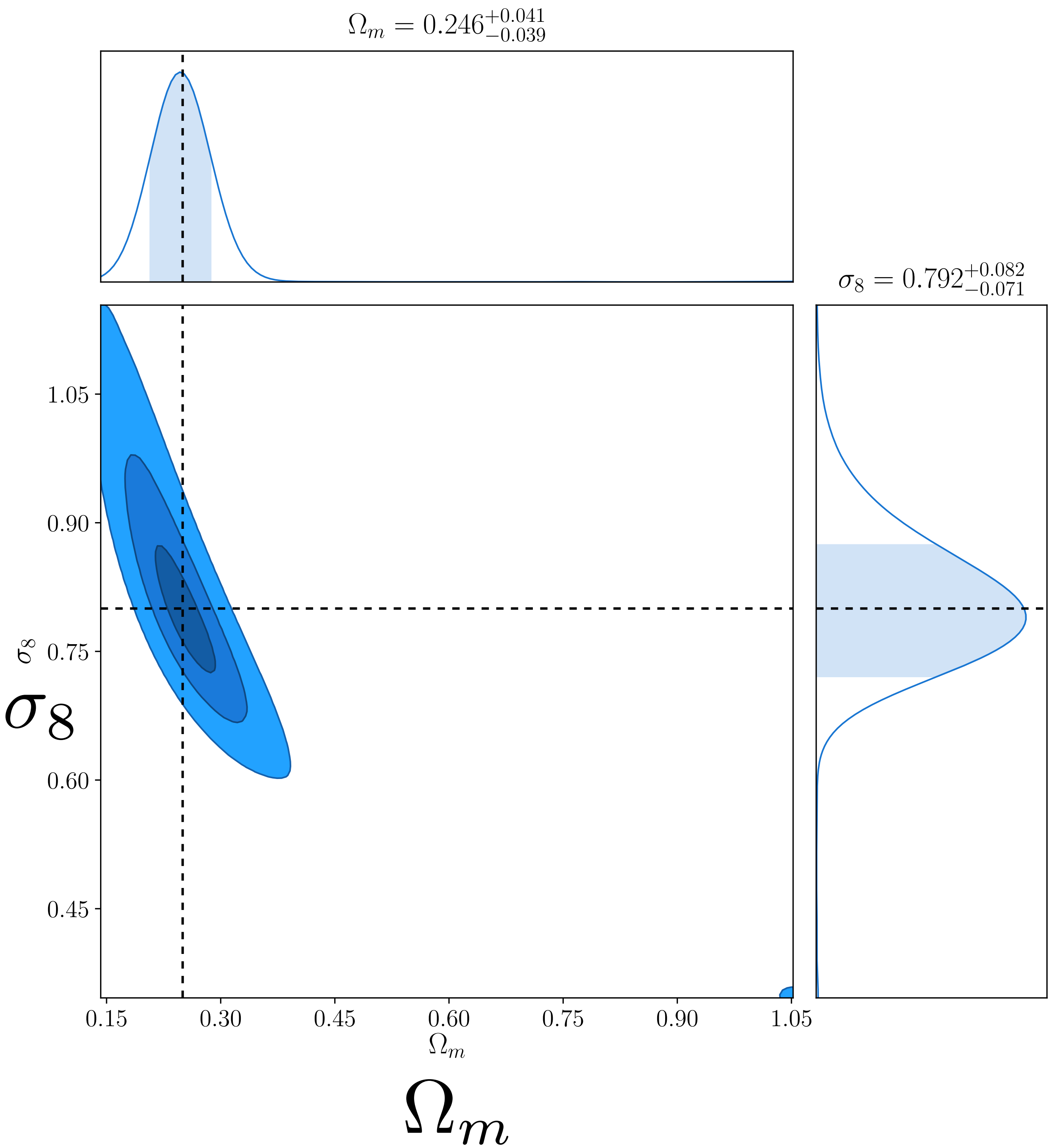


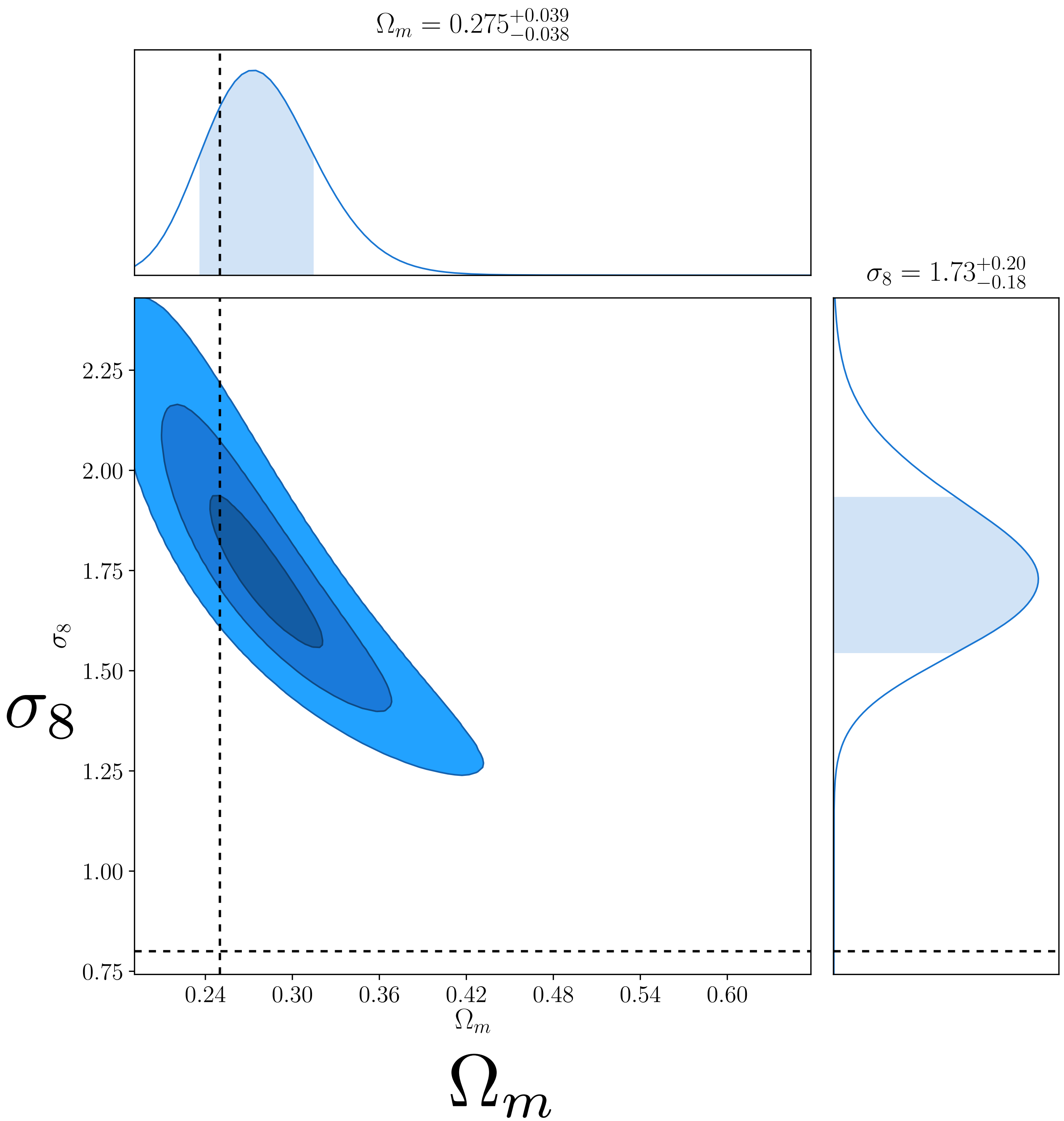
Mean
×10^−18
1.5
1.0
0.5
0.0
−0.5
0.4
0.6
0.8
1.0
1.2
1.4
Redshift
Variance
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Skewness
−0.0001
−0.0002
−0.0003
−0.0004
Kurtosis



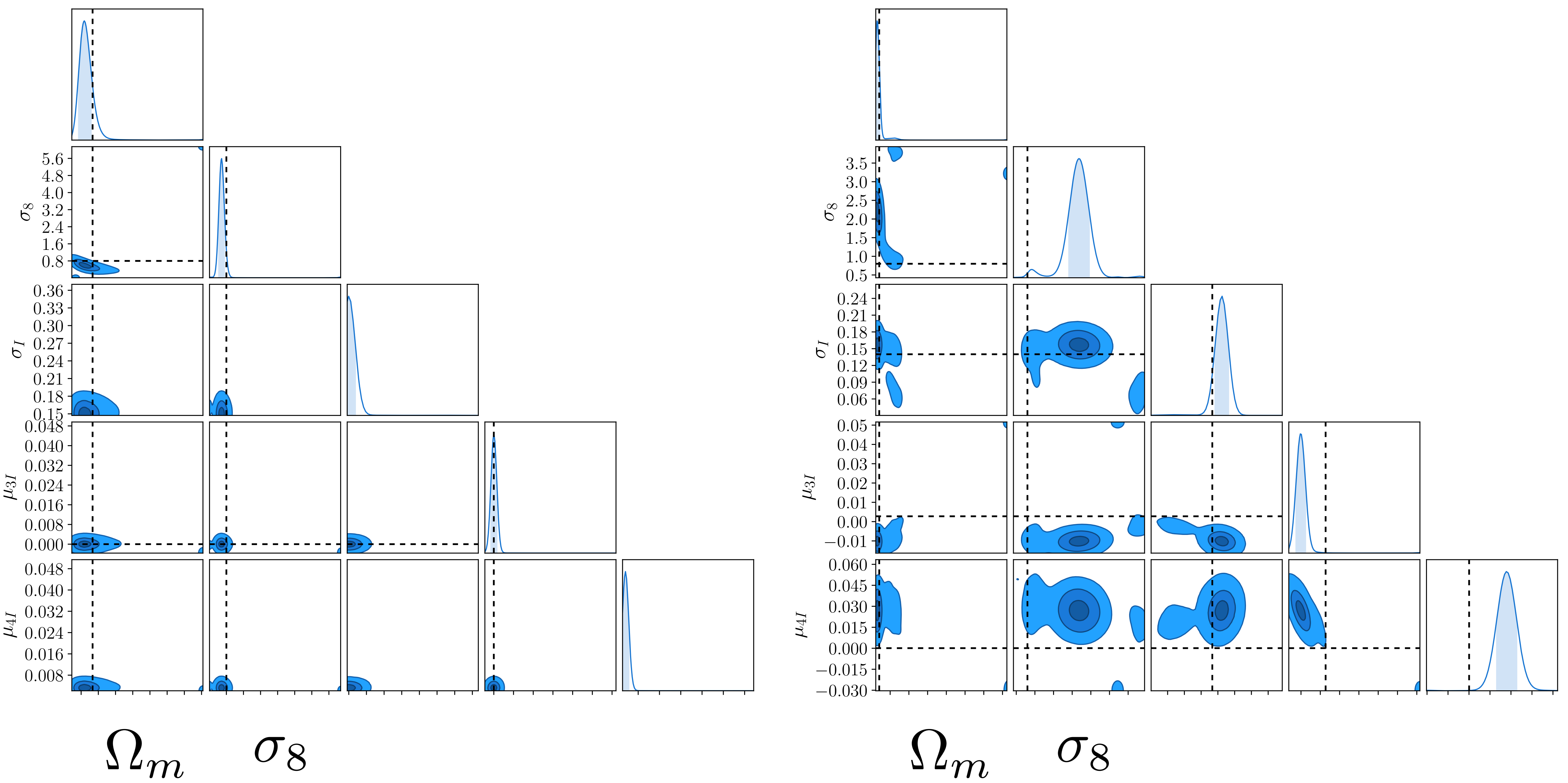
Mean
×10^−18
1.0
0.5
0.0
−0.5
0.4
0.6
0.8
1.0
1.2
Redshift
Variance
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.4
0.6
0.8
1.0
1.2
Redshift
Skewness
0.0000
−0.0002
−0.0004
−0.0006
−0.0008
0.4
0.6
0.8
1.0
1.2
Redshift
Kurtosis
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
0.4
0.6
0.8
1.0
1.2
Redshift

Effect on cosmological parameters

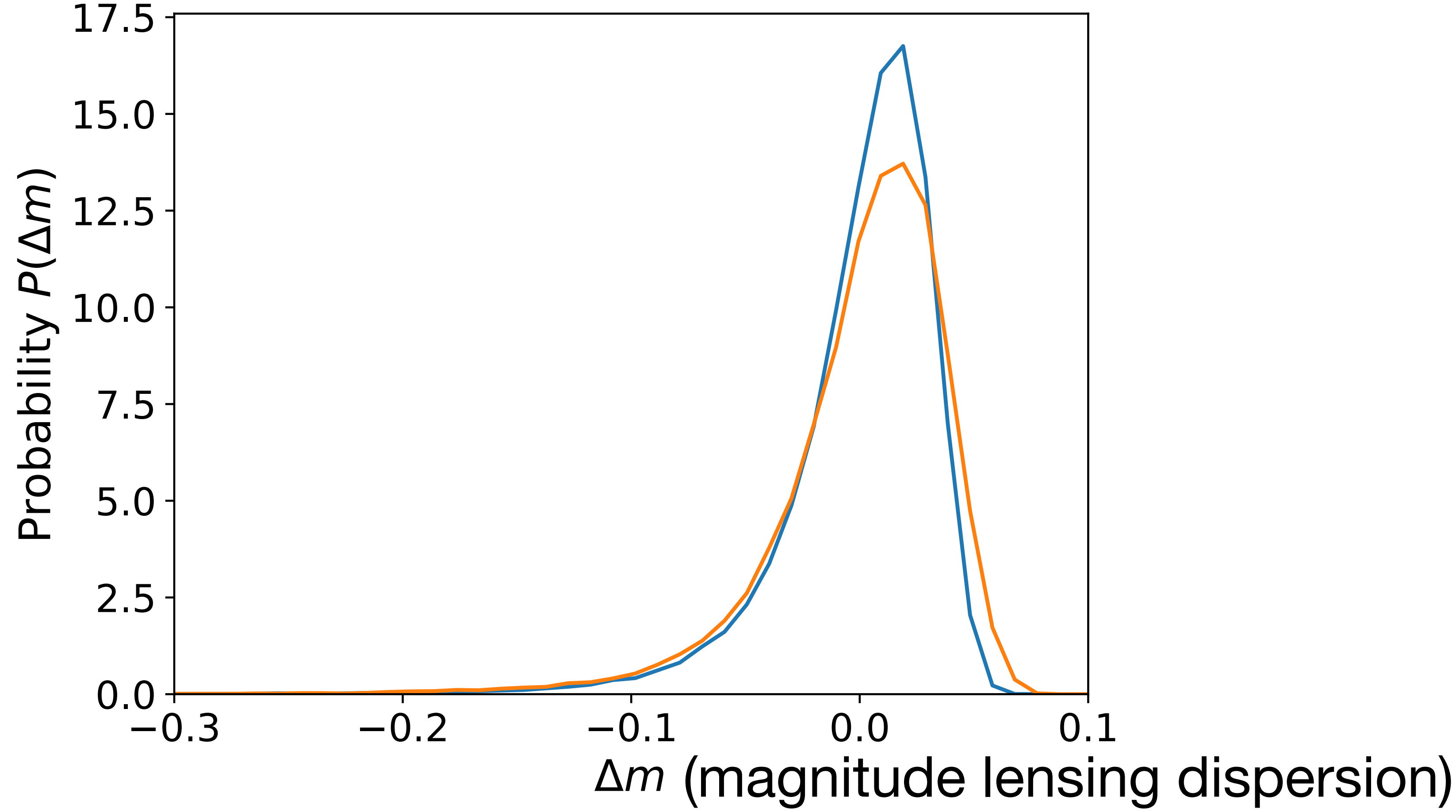


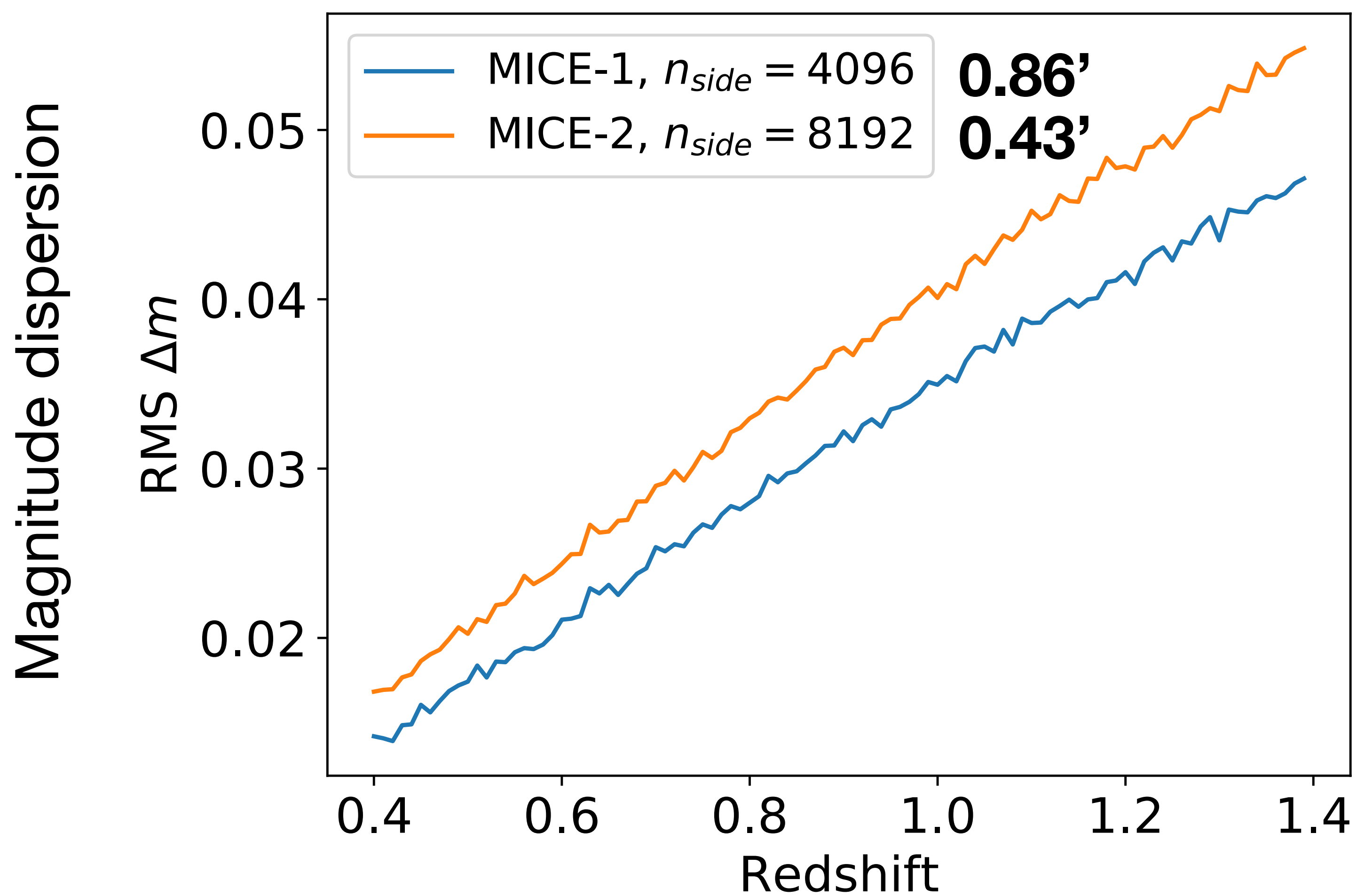


Effect on cosmological parameters



Effect of smoothing scale





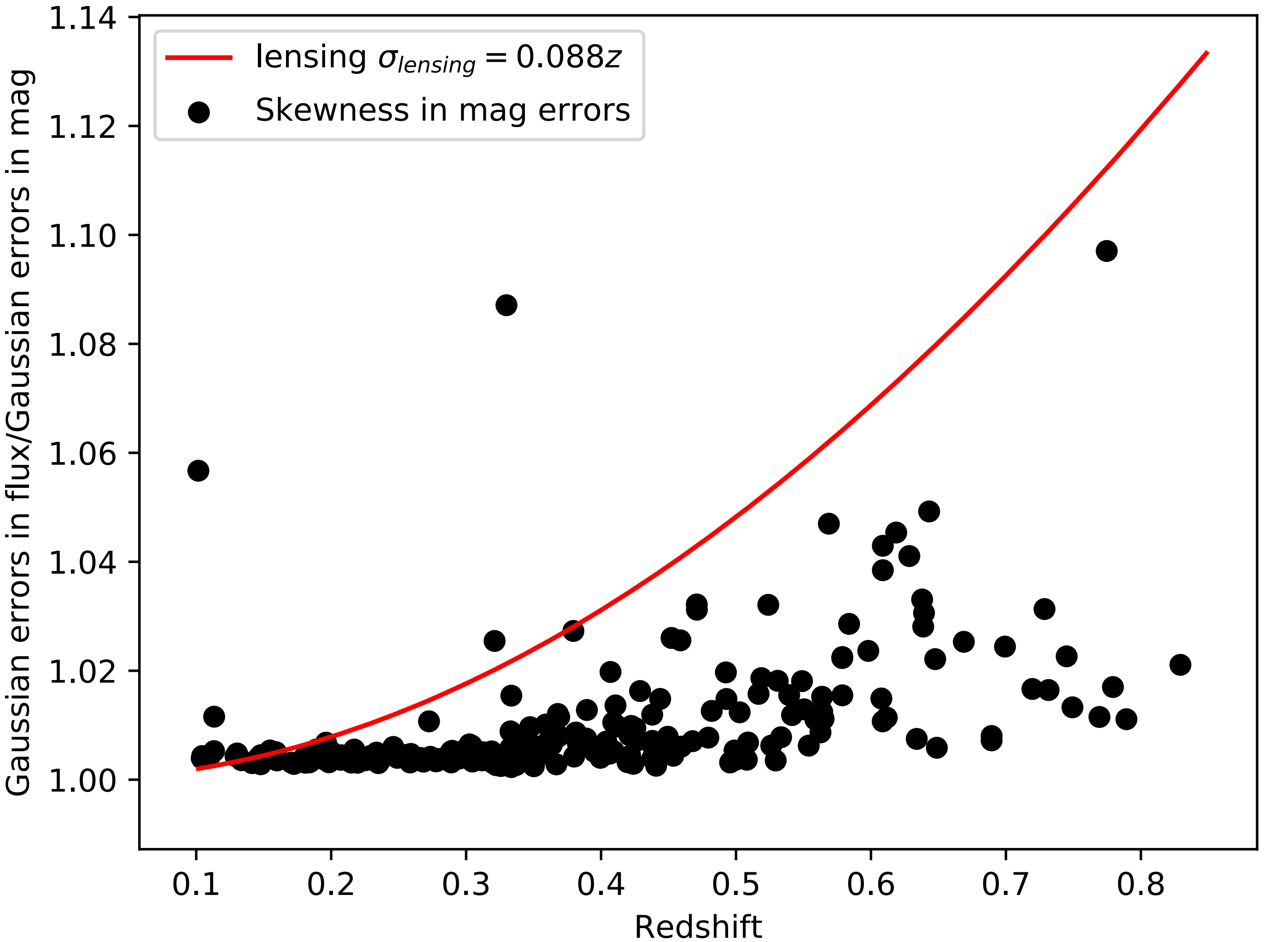
Skewness in the magnitude error distribution

We transform the JLA mag error, assuming is Symmetric (gaussian) to asymmetric values in flux for the 1-sigma confidence interval.

$$m - m_{ref} = -2.5\log_{10}\left(\frac{f}{f_{ref}}\right)$$

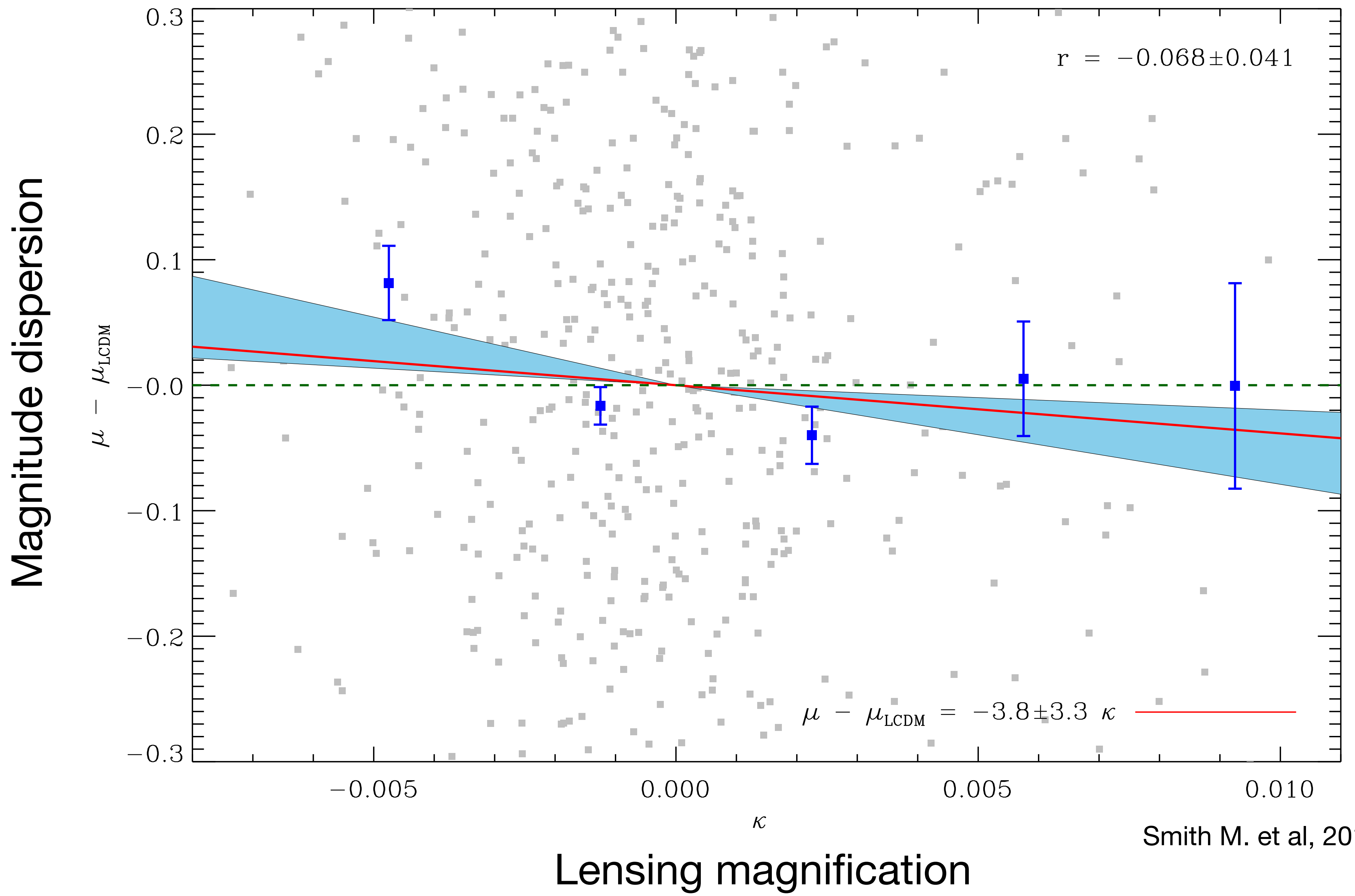
We assume the flux values should be symmetrical and then we transform back to asymmetric values in magnitude. We estimate the width of the confidence interval

Compare with original estimation for the error and the expected lensing error from Holz & Linder



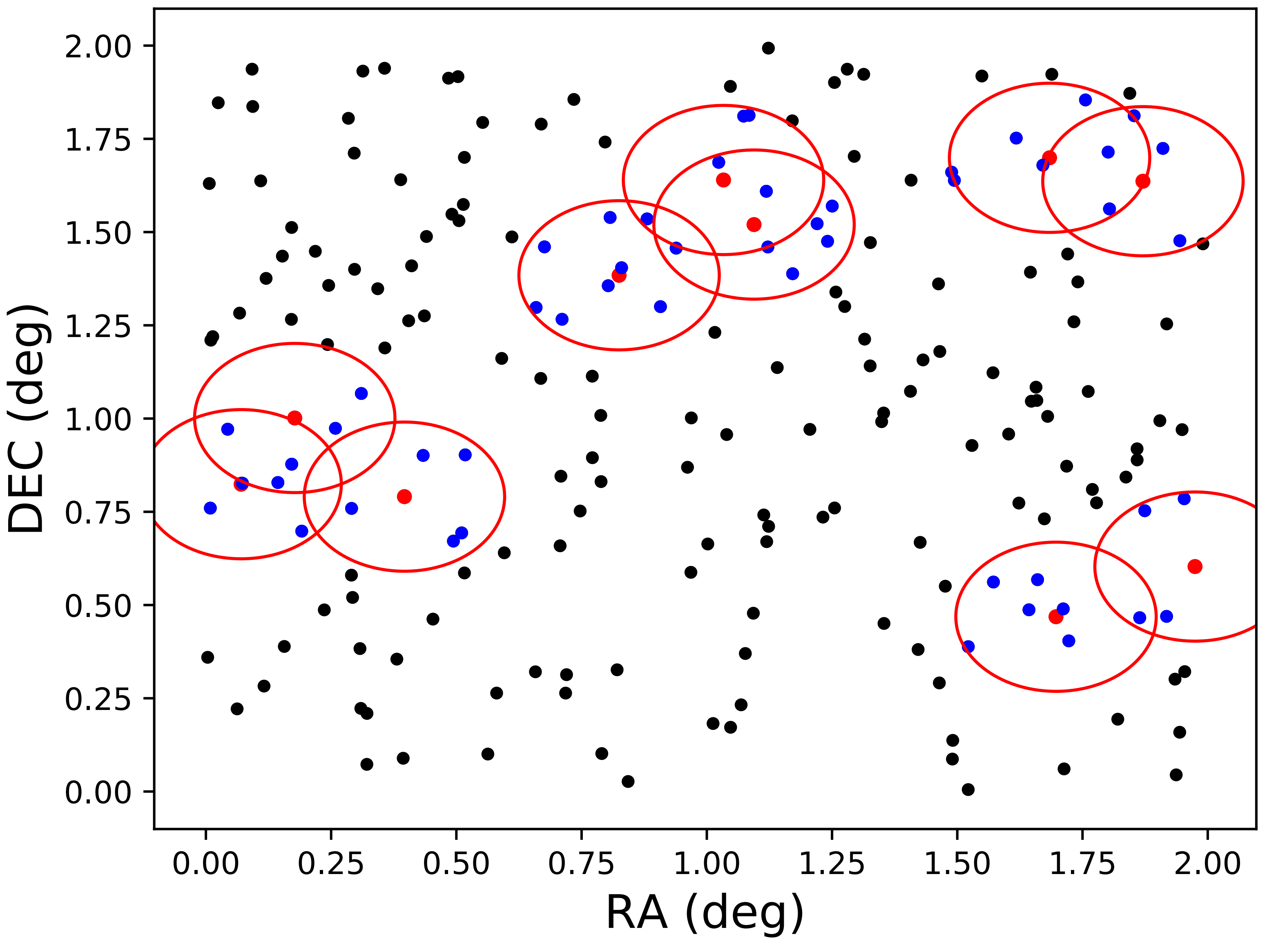
If the mag errors PDF is skewed then the errors increase, but below the lensing effect.

Cross-correlation magnitude-lensing

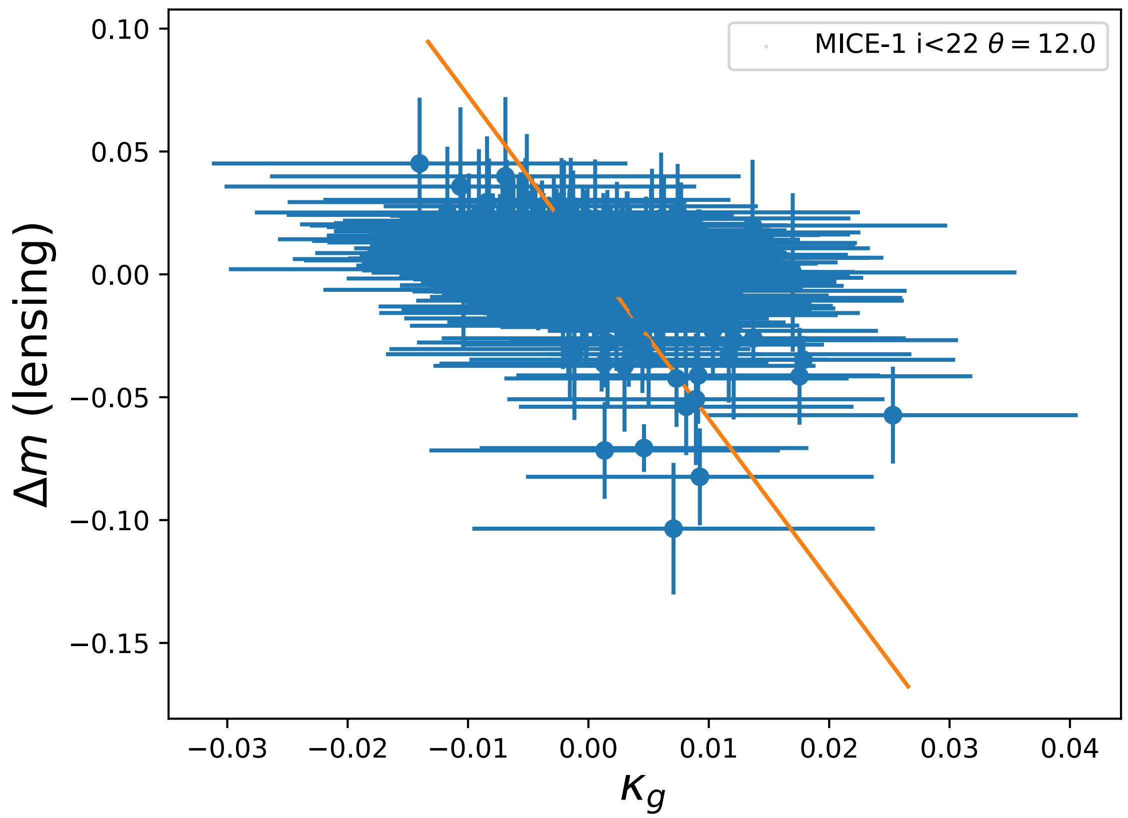


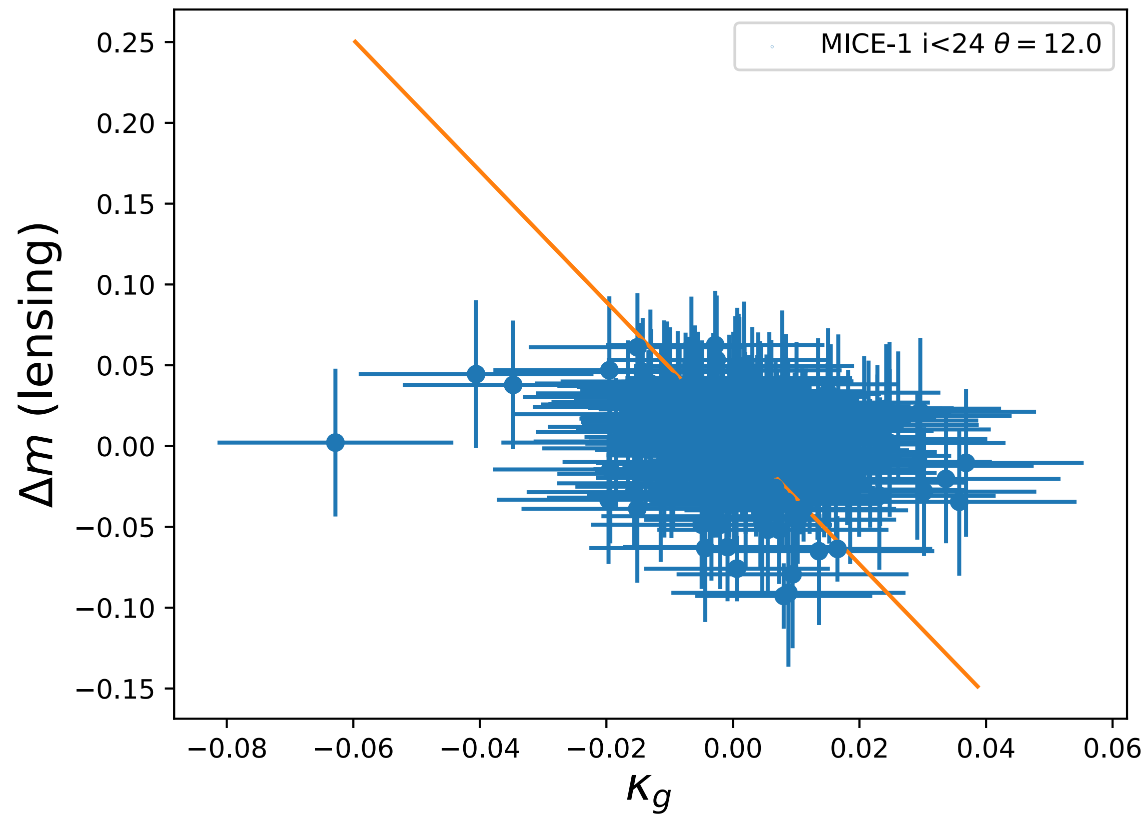
Smith M. et al, 2014

Magnification measurements



Mock catalogues correlation





$$\kappa_{g_i} = \frac{3H_0^2\Omega_m}{2c^2}\sum_j \delta_{g_{i,j}} \frac{(r_s - r_j)r_j}{r_s a_j} dr_j$$

$$\mu = m_b - (M_b - \alpha x_1 + \beta c) - \frac{5}{\ln 10 b_g}\kappa_g$$

Galaxy bias not well recovered

$$\begin{aligned} b_{g,BF}(i<22) &= 0.33 \pm 0.54, \\ b_{g,BF}(i<24) &= 0.54 \pm 0.80 \end{aligned}$$

Conclusions & Outlook

- Supernova brightness is affected by gravitational lensing. The relevance of this effect increases with redshift. The effect of small-scale clustering on the type Ia SN lensing is important and cannot be neglected. Include different set of 4-moments and smoothing scales in the analysis.

- We need to develop ray-tracing simulations that include the properties of compact structures along the line of sight to define the theoretical model for the lensing PDFs.

- Alternative is to measure direct correlation between the dispersion in the Hubble diagram and lensing maps. If using density fields to reconstruct magnification we must find a better estimator for magnification.

- Other systematics adding intrinsic skewness may affect the lensing detection.

Thank you!

감사합니다