Testing Gravity with GGL and RSD in CFHT-S82 and CFHTLS

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In collaboration with

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CMASS in Stripe 82 + CFHTLS

BOSS/CMASS galaxies

28,039 redshifts $0.43 < z < 0.7$

Total area: 250 deg^2

CFHT-S82 catalog

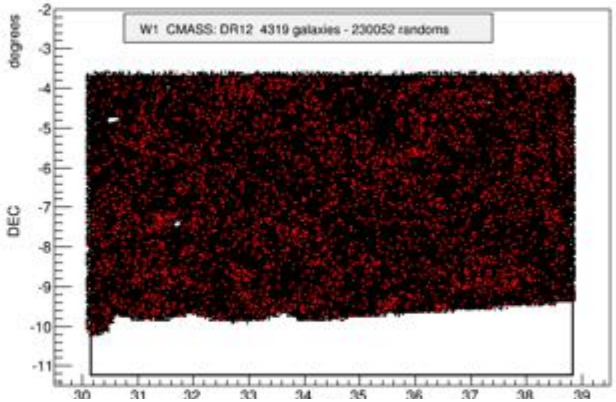
mag $i < 22.5$

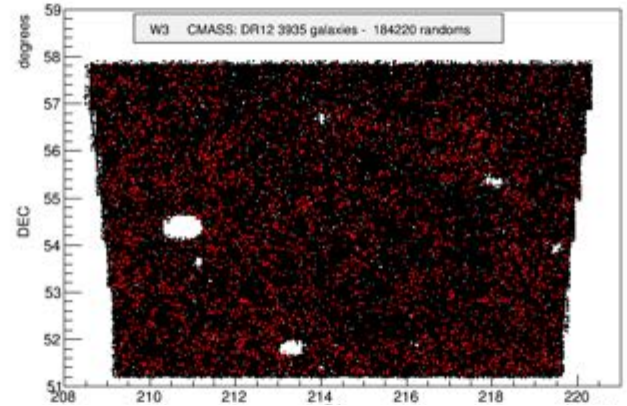
Lensing $b_z < 1\%$

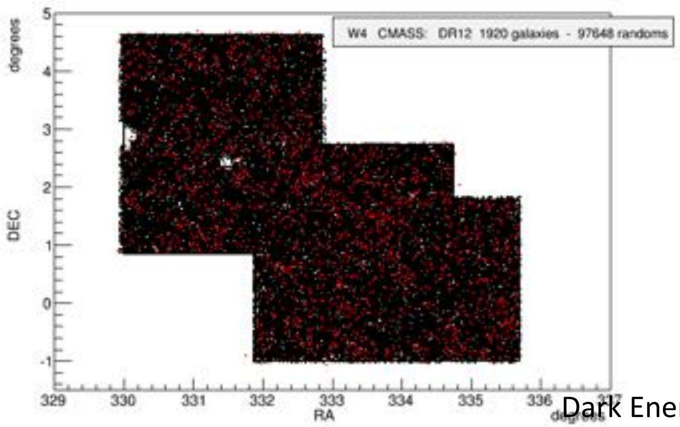
CFHTLens catalog

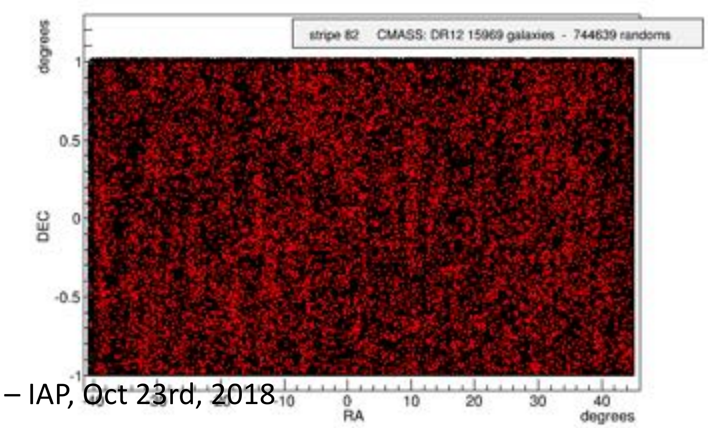
mag $i < 24$

Lensing $b_z < 2\%$



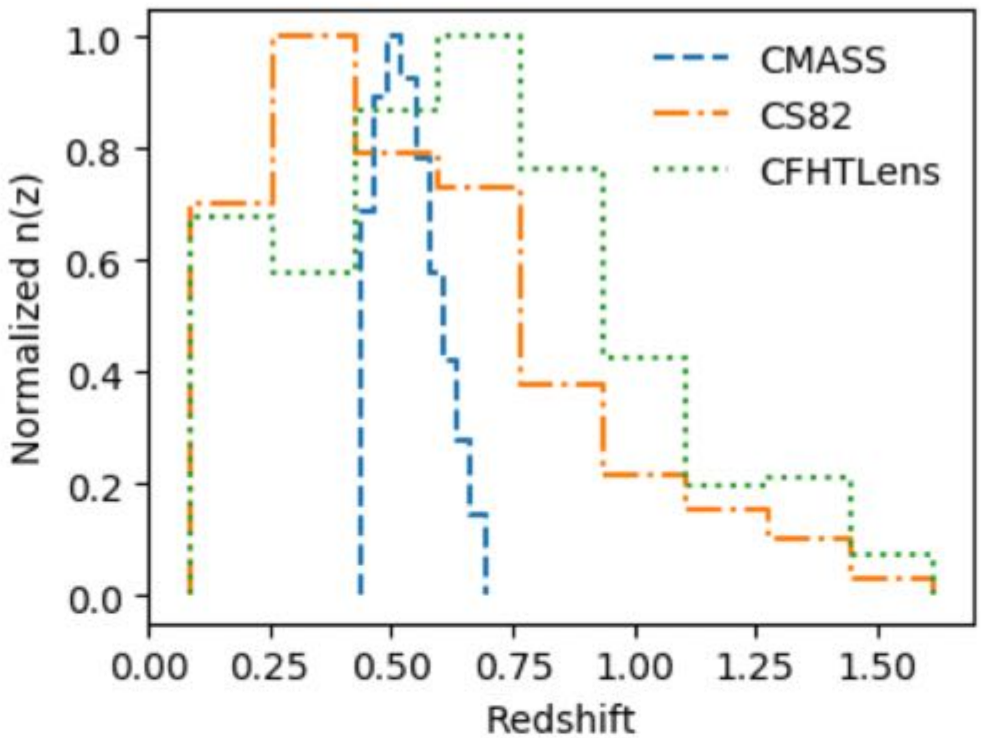






Redshift distributions

Field	# CMASS	SDSS area [deg^2]	SDSS field size [deg×deg]	Eff. area [deg^2]	# sources [$\times 10^6$]
S82	18,675	219.8	87.6×2.51	129.2	2.19
W1	3,924	54.14	8.66×6.3	63.8	1.66
W3	3,694	41.91	11.5×6.6	44.2	1.26
W4	1,746	22.16	5.7×5.61	23.3	0.62



Perturbation around FLRW

We assume a perturbed FLRW metric in Newtonian Gauge

$$ds^2 = -a(\tau)^2[1+2\Psi]d\tau^2 + a(\tau)^2[1-2\Phi]d\mathbf{x}^2$$

with Ψ and Φ the 2 Bardeen gravitational potentials

Assuming no anisotropic stress, $\Psi = -\Phi$

Lensing is sensitive to $\nabla^2\Phi$

Assuming Poisson equation we have $\nabla^2\Phi = 3/2\Omega_{m0}H_0{}^2a^{-1}\delta_m$

Redshift Space Distortion Clustering

In the linear regime the divergence of the velocity field is proportional to the density field

$$\theta = \mathrm{div}(\mathbf{v}) = -\beta\,\delta = -f\,\delta / b$$

where β is the anisotropy parameter, *b* is the linear bias of the galaxy population and

$$f = \mathrm{d}\ln D / \mathrm{d}\ln a \approx \Omega_m^{0.55}$$

is the **rate** of the growth factor D

The redshift space cross-power spectrum

$$P_{g\theta} \equiv -\langle \delta_g(\mathbf{k})\, \theta(-\mathbf{k}) \rangle$$

can be infered from PV.

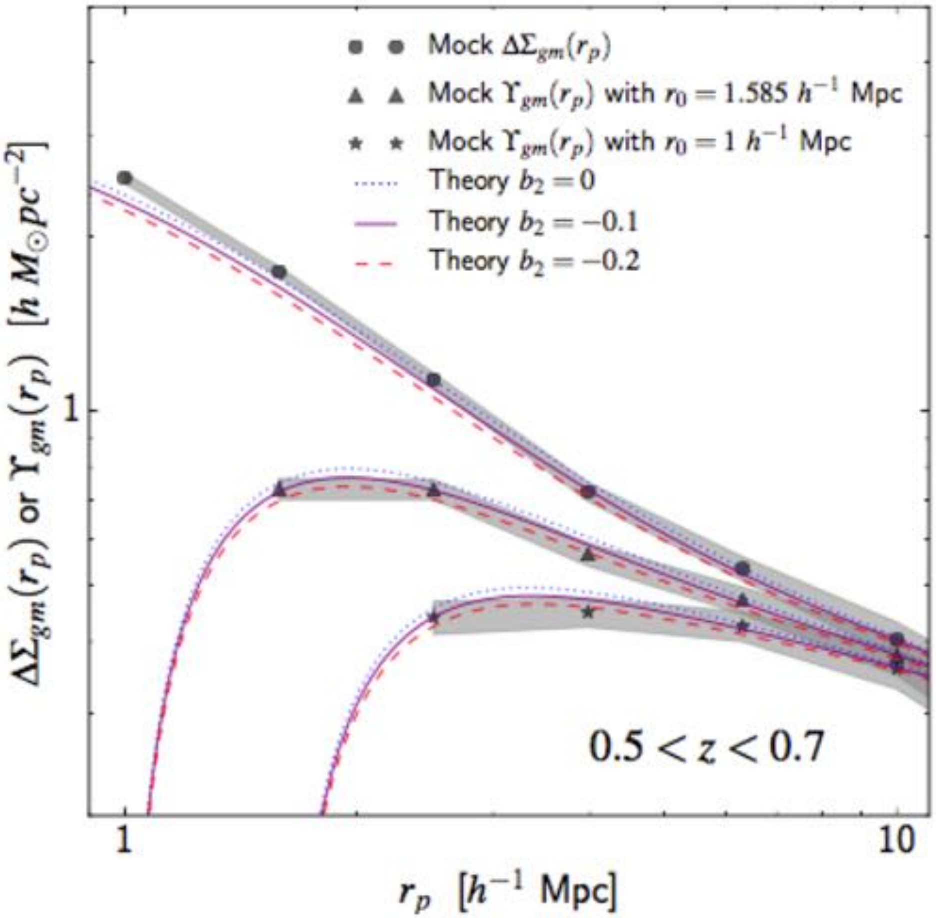
Galaxy bias model

- 4-th order perturbation model including (McDonald&Roy 2009)
  - Linear and non-linear terms b_1 and b_2
  - Non-local bias term b_{s2}
  - Tidal tensor term $s(x)$

$$\delta_g(\mathbf{x}) = \mathbf{b_1}\delta(\mathbf{x}) + \frac{1}{2}\mathbf{b_2}[\delta^2(\mathbf{x}) - \sigma^2] + \frac{1}{2}\mathbf{b_{s^2}}[\mathbf{s}^2(\mathbf{x}) - \langle \mathbf{s}^2 \rangle]$$

- Analytical simplification assuming coevolution of halo and matter density fields, and bias to be purely local in the initial conditions $b_{s2} = -4/7(b_1 - 1)$ (Baldauf+12)
- We include this model into our expressions for the power-spectra of lensing P_{gm} and RSD $P^s(k,\mu)$ (using Taruya+2010 non-linear model), and including Alcock-Paczynski effet

Expected lensing signals at small scales



- Excess surface mass density:

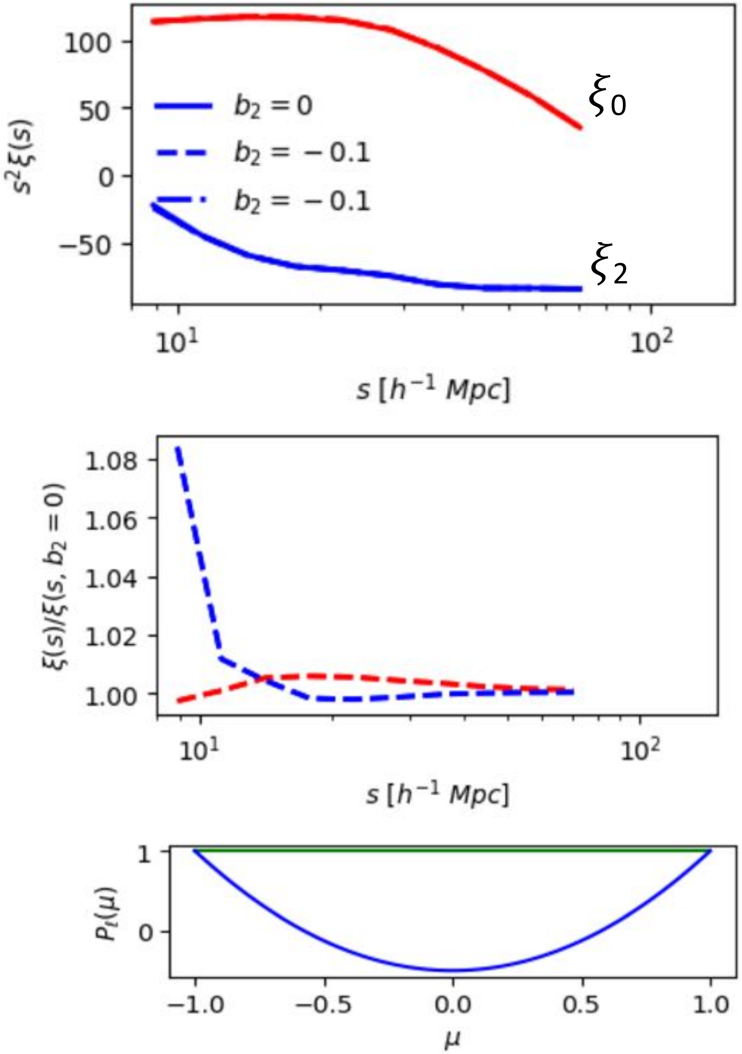
$$\Sigma_{\rm gm}(R) = \Omega_{\rm m}\rho_{\rm crit}\int_{-\infty}^{+\infty} g_l(\chi)\left[1+\xi_{\rm gm}(\sqrt{R^2+\chi^2})\right]{\rm d}\chi$$

- Annular Differential Surface Density (ASAD):

$$\Upsilon(R;R_0) \equiv \Delta\Sigma(R) - \frac{R_0^2}{R^2}\Delta\Sigma(R_0)$$

Baldauf et al., 2010

Bias dependence on non-linear b_2

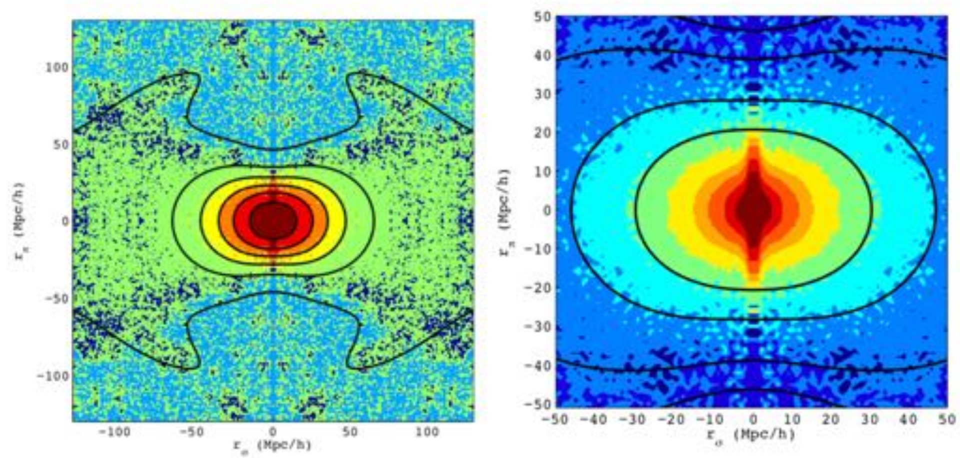


- Correlation function

$$\xi(s,\mu) = \frac{GG(s,\mu) - 2GR(s,\mu) + RR(s,\mu)}{RR(s,\mu)}$$

- Monopole and Quadrupole

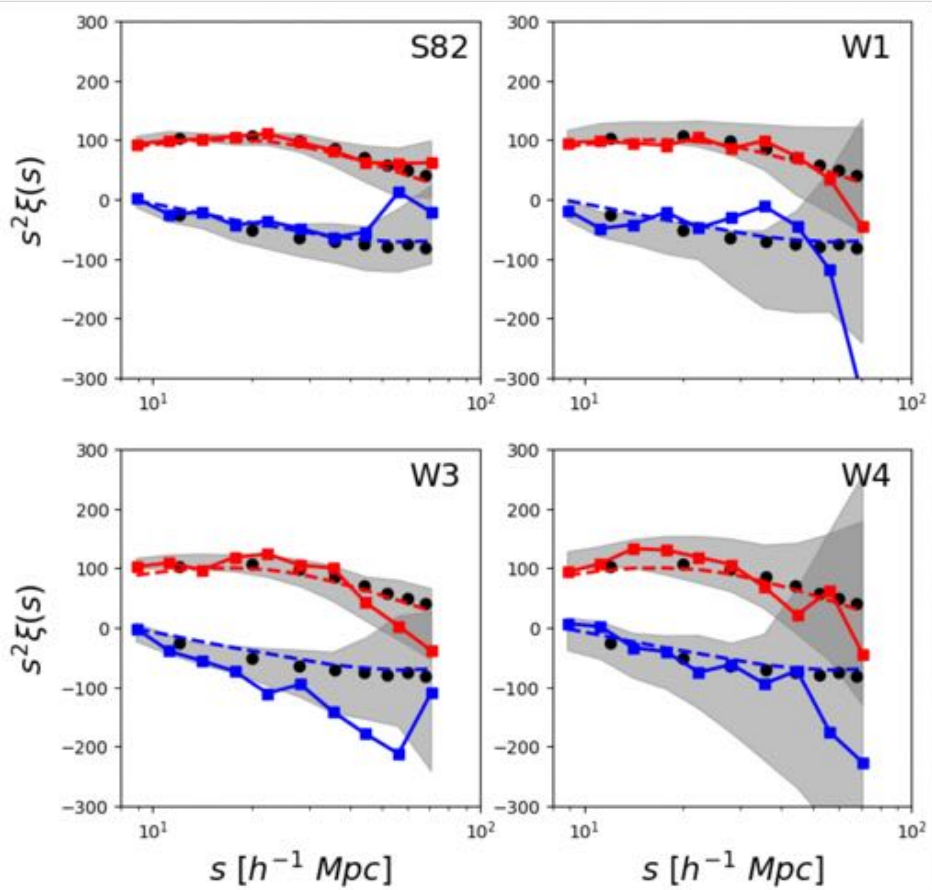
$$\xi_\ell(s) = \frac{2\ell+1}{2}\int_{-1}^{1}\xi(s,\mu)L_\ell(\mu)\mathrm{d}\mu$$



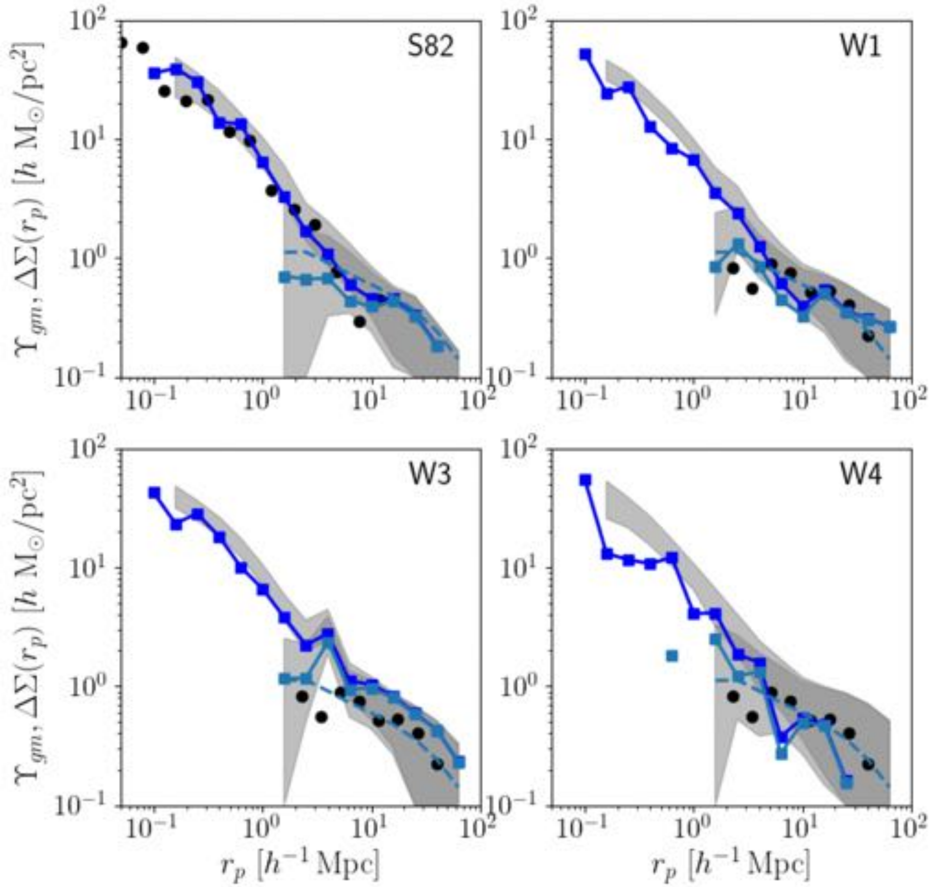
Reid et al., 2012

Lensing with CMASS

CMASS RSD



CMASS Lensing

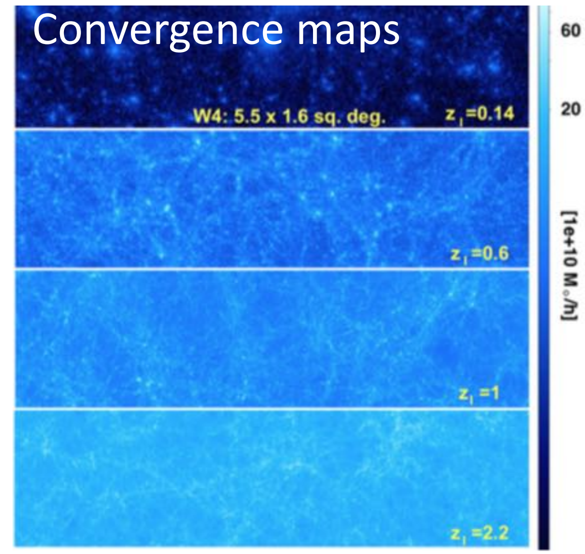


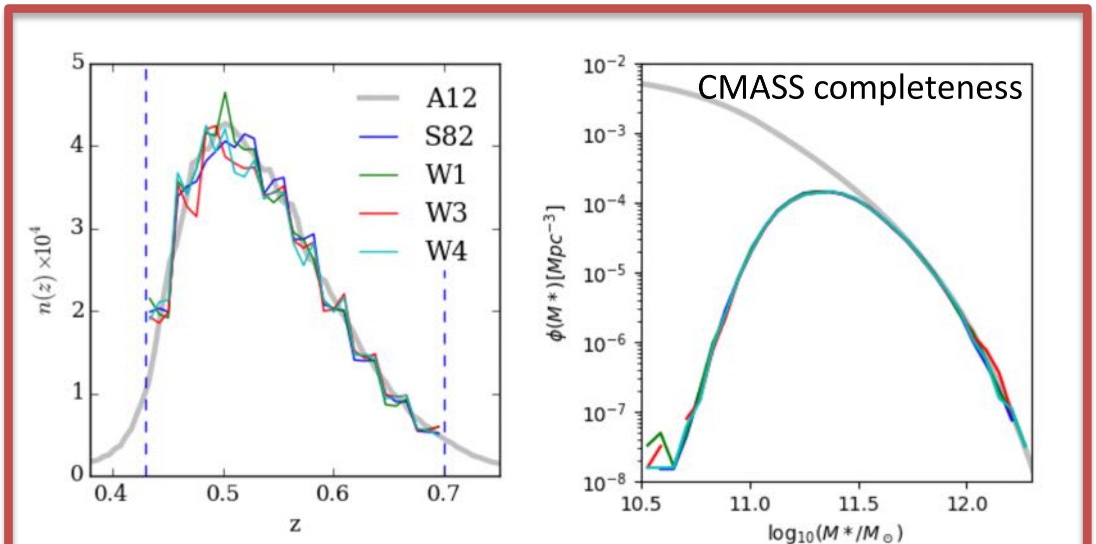
Lensing and clustering simulation

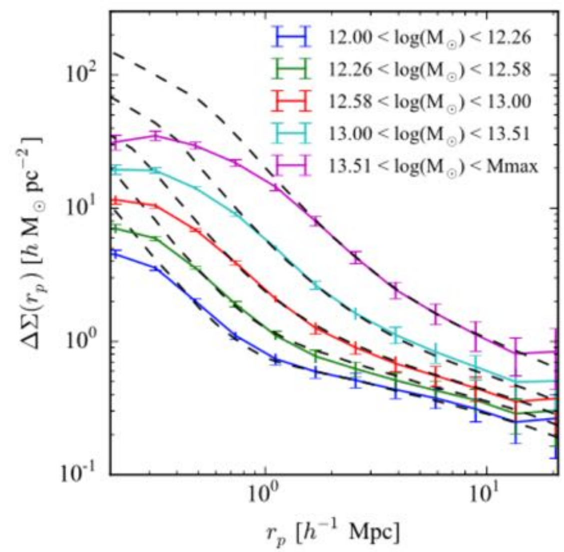
We used Big-Multidark simulation L=2.5 Gpc/h to produce lightcones extending on 0 < z < 2.3

1) Ray-tracing to produce WL mock catalogs (*Giocoli et al. 2016, Metcalf & Petkova 2014*)

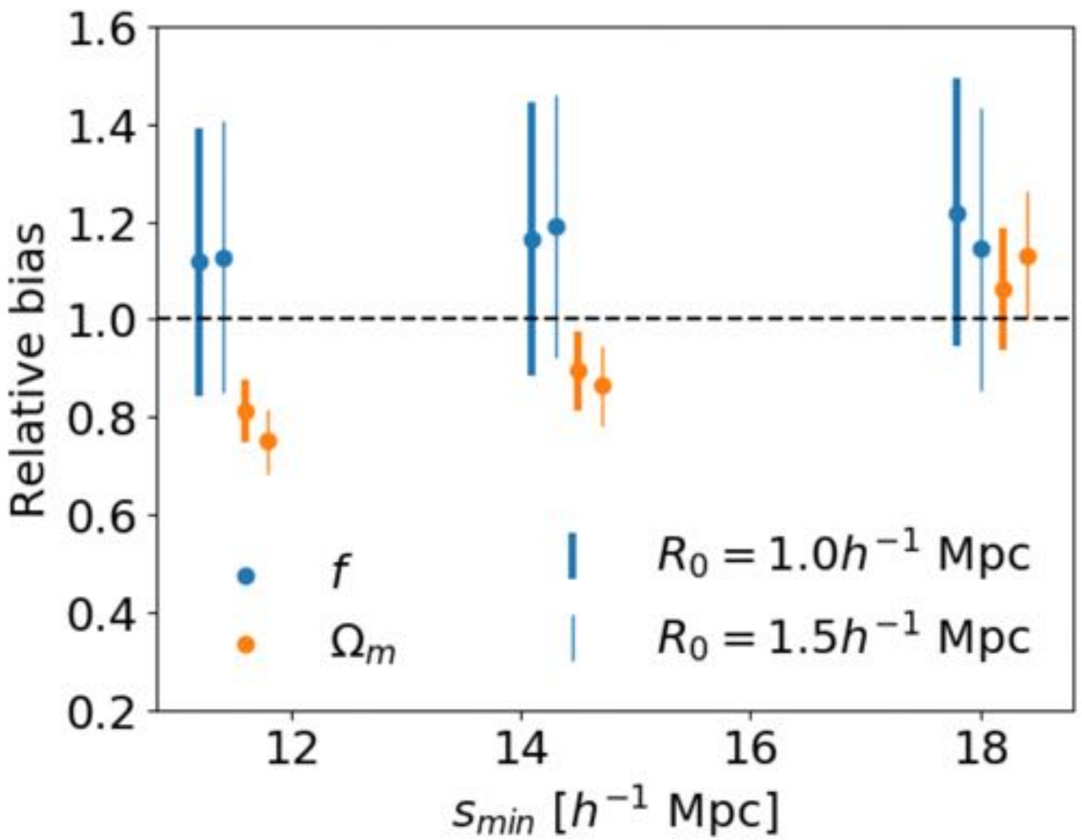
2) Populating halos with VIPERS and CMASS galaxies using HOD and SHAM techniques (*de la Torre et al. 2013*, *Rodriguez-Torres et al. 2015*)







Bias on the RSD side



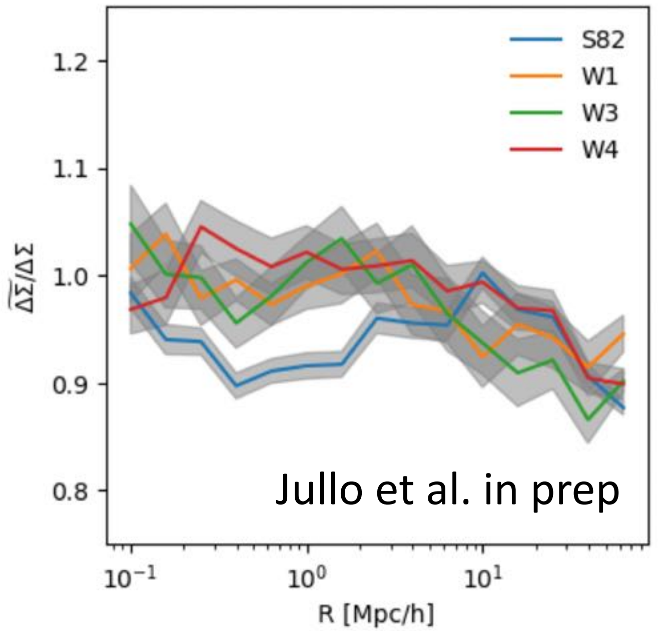
Less biased if only selecting ξ_0 and ξ_2 at scale s_{min} > 17.8 h^{-1} Mpc
Ω_m depends little on s_{min}

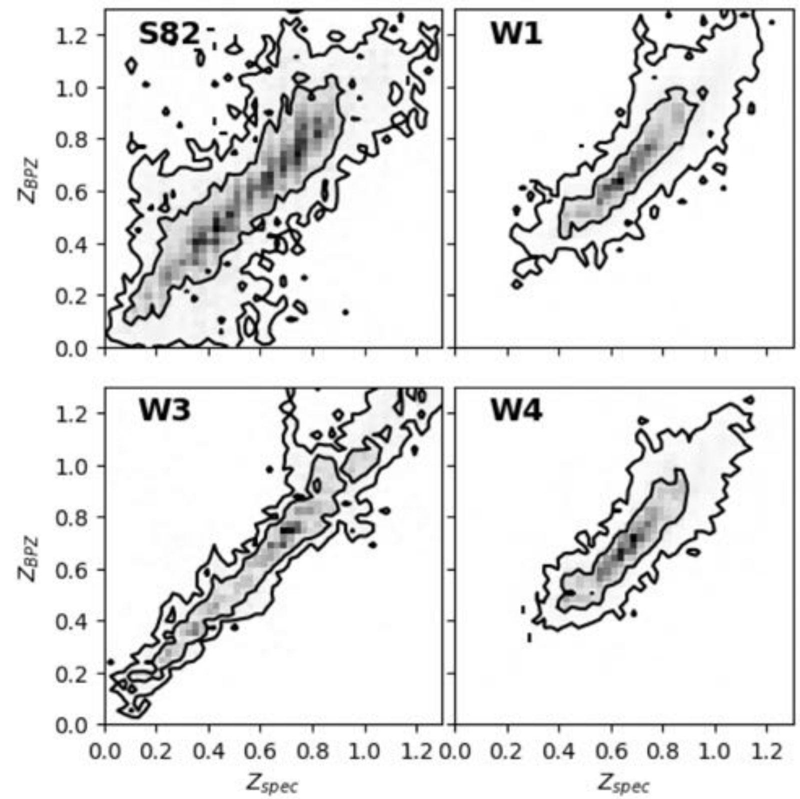
Case with real data: CMASS & CFHT-S82/LS

Measurement of GGL in 250 deg2 of CFHT-S82/LS fields
zSpec from

- VVDS $i_{AB} < 22.5$,
- DEEP2 $R_{AB} < 24.1$,
- PRIMUS $i_{AB} < 23.5$,
- VIPERS $i_{AB} < 22.5$,
- SDSS-DR13

90% spectro complete in S82 at $i_{AB} < 22.5$
90% spectro complete in CFHTLS at $i_{AB} < 24$





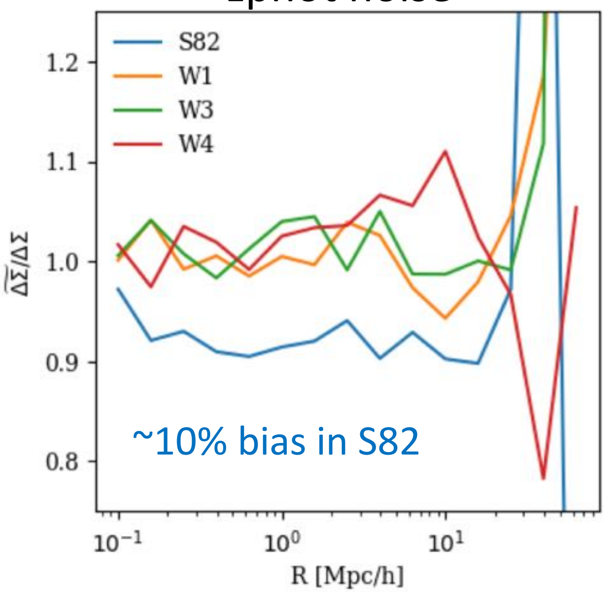
10% bias due to zphot in CS82 with 22.5 cut

Variance and bias from lensing shape and photometric redshift noise

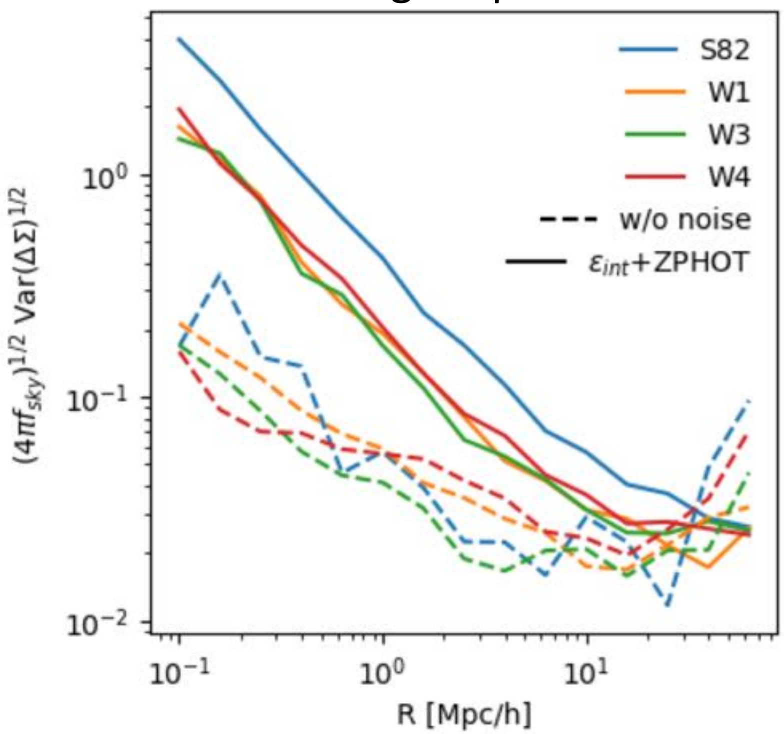
Reminder

- S82 selection mag i < 22.5
- CFHT selection mag i < 24

zphot noise



Lensing shape noise



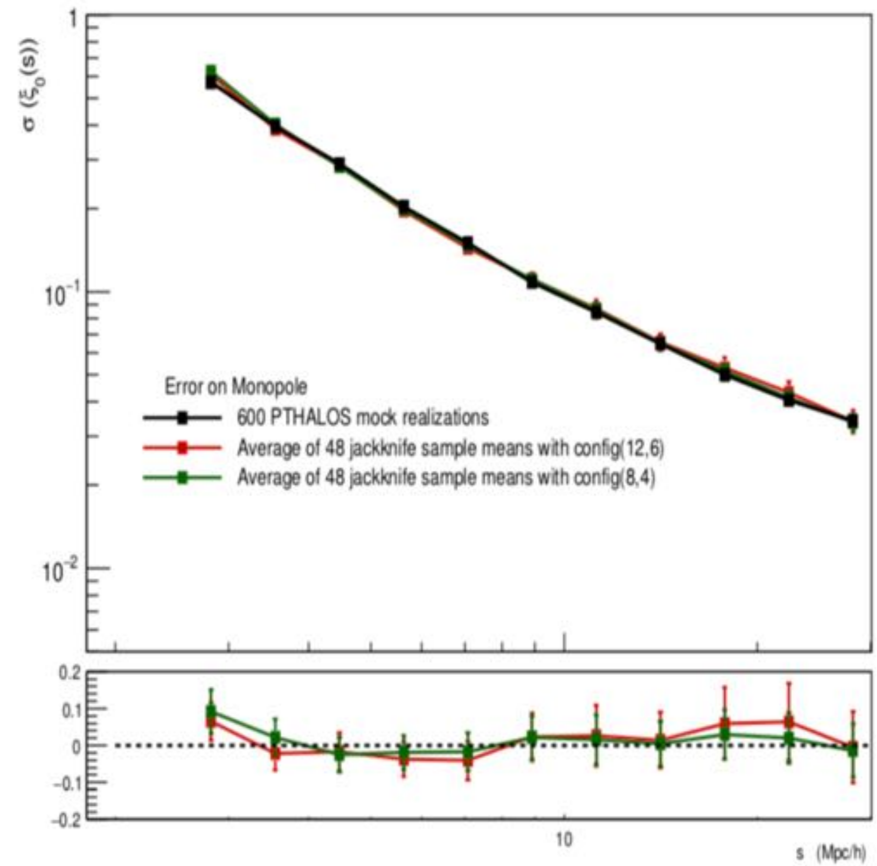
Lensing shape and zphot noise introduce noise and bias

Measurements around random lenses decrease large scale variance (see also Shirasaki et al. 2017)

Covariance matrices with mocks resampling

Escoffier et al. 2016

Fields	# of Mocks	# of Mocks resampling
W1	15	720
W3	11	704
W4	27	729
Stripe82	4	3840



Resampling of the **lensing** and **zphot noise** in the mocks to decrease the noise in the covariance matrices

Mean covariance $$\bar{C}_{ij} = \frac{1}{N_m \times N_r} \sum_{m=1}^{N_m \times N_r} {}^{(m)}\hat{C}_{ij}^{JK}$$

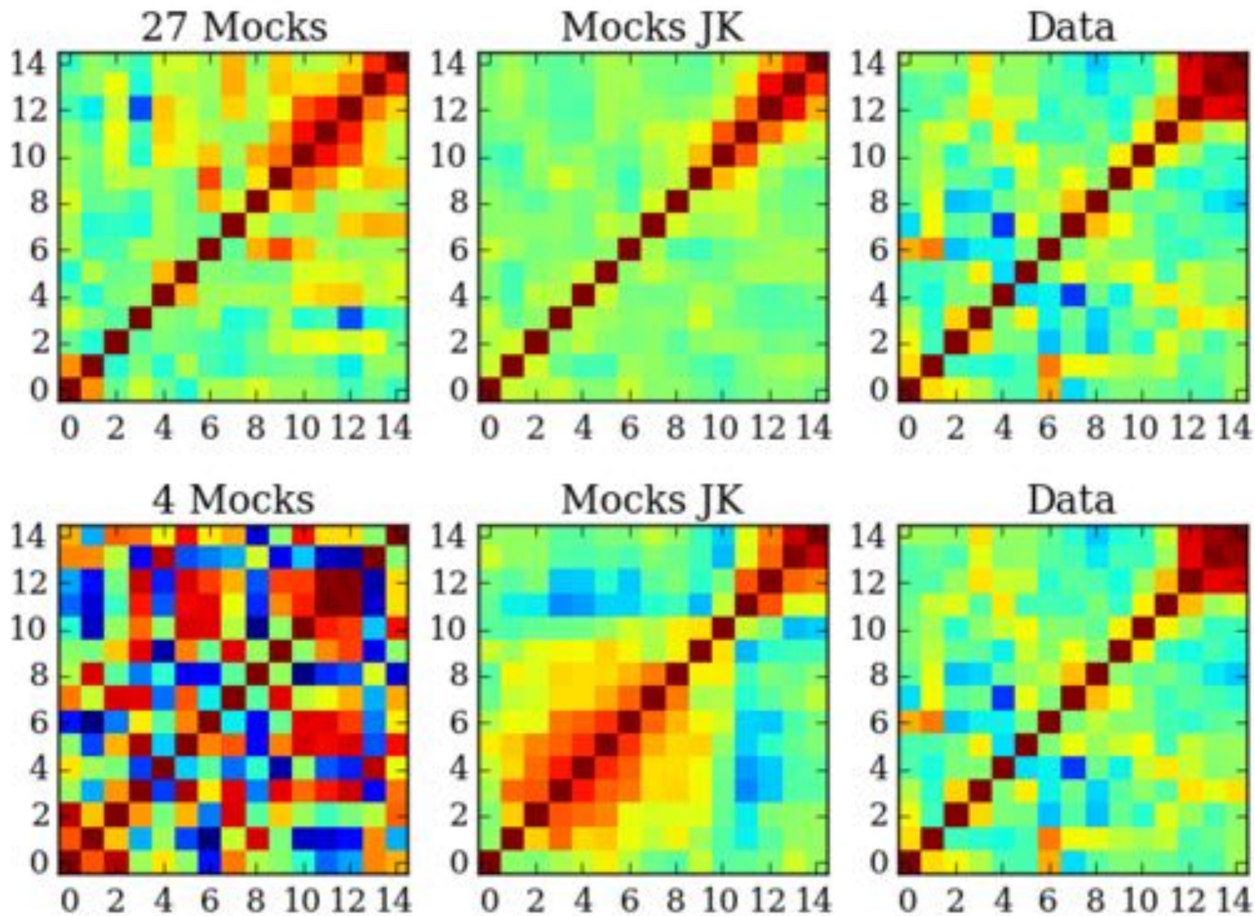
Precision matrix $$\hat{\Phi}_{ij} = [\bar{C}_{ij}]^{-1}$$

Data vs Mocks resampling

Comparison for

W4 ➔

S82 ➔

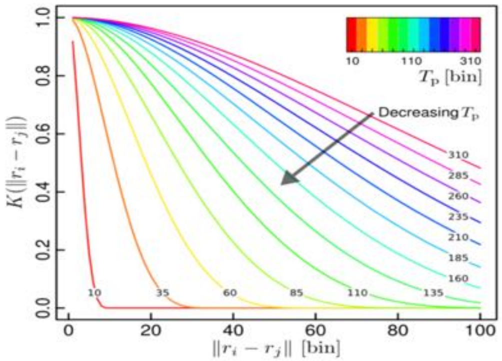


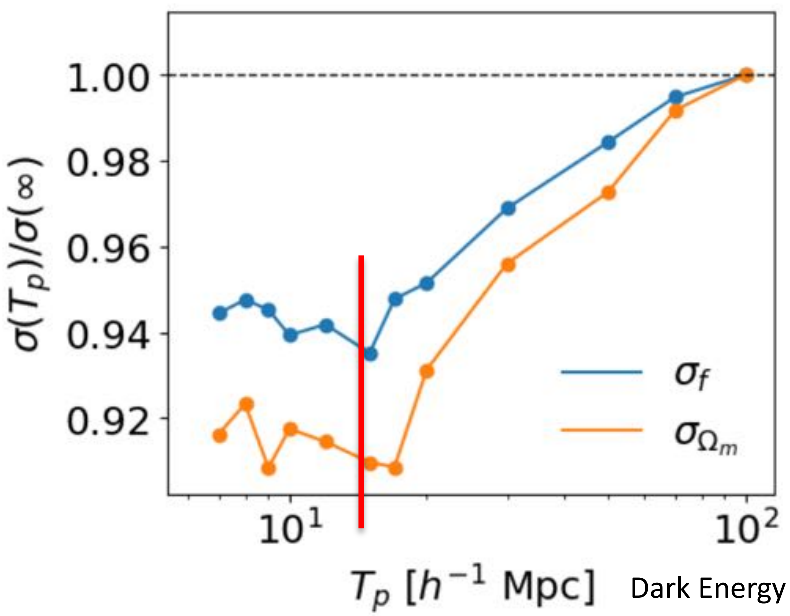
Error on mocks w/o JK > Error with data JK > Error with mocks JK

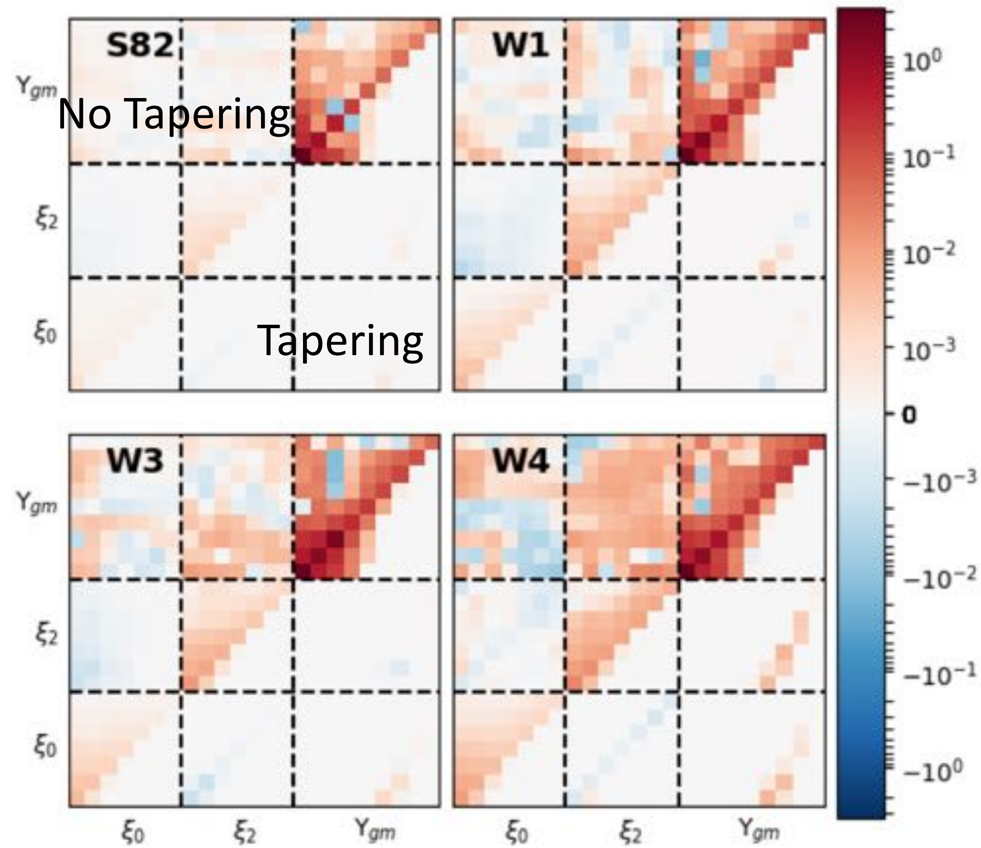
Tapering method

Paz & Sánchez 2015

Tapering assumes correlation btw distance data point is negligible

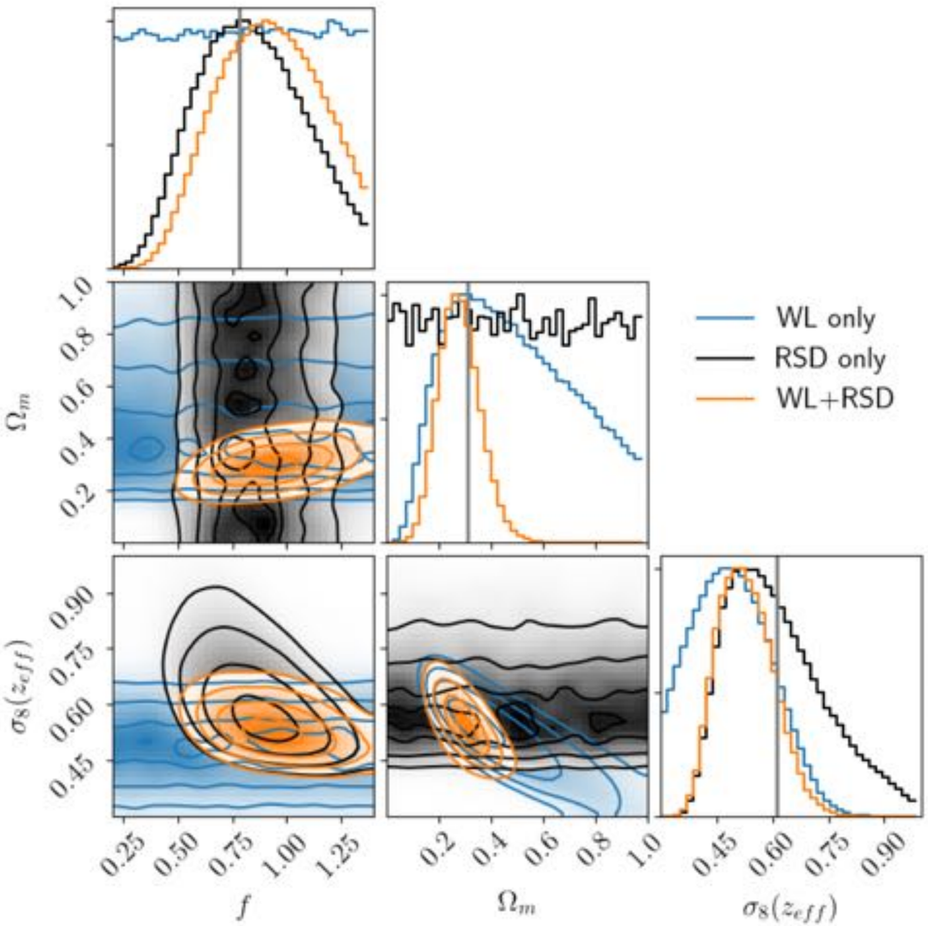


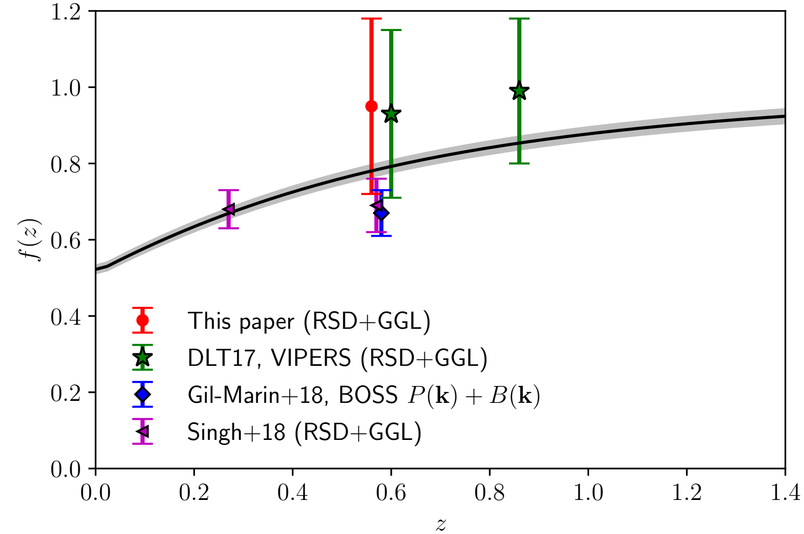




➔ Best tapering scale is $T_p = 12h^{-1}$ Mpc

Results on cosmological parameters





Combining clustering and lensing

- Combine 3D clustering and lensing measurements using estimators such as:

Zhang et al. 2007

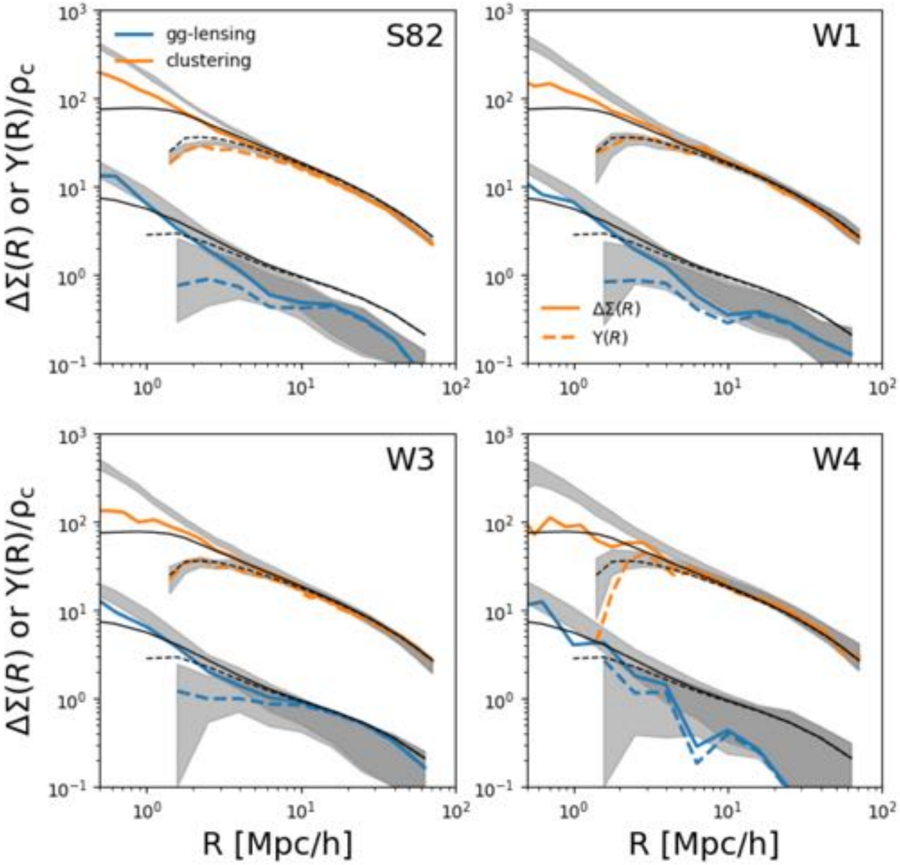
$$E_G \equiv \frac{\nabla^2(\psi - \phi)}{3H_0^2 a^{-1}\beta\delta} = \frac{1}{\beta}\frac{\Upsilon_{gm}}{\Upsilon_{gg}} \propto \frac{b}{f}\frac{\Omega_{M0}}{b} \approx \frac{\Omega_{M0}}{f}$$

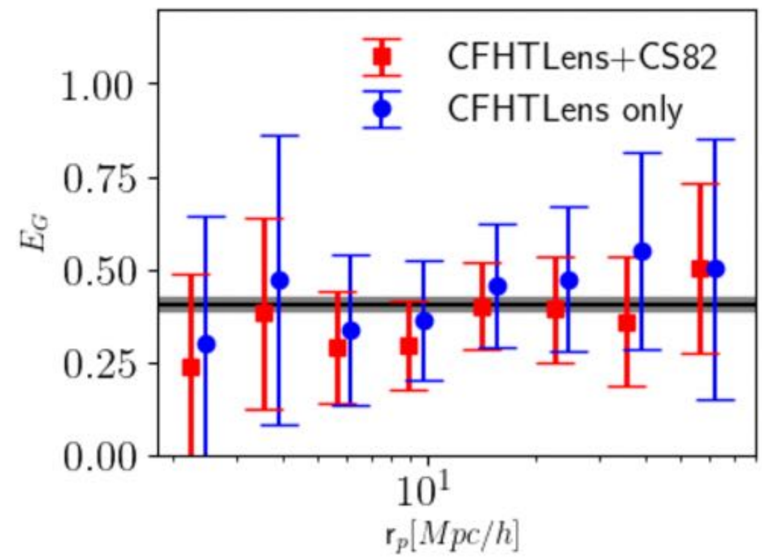
Lensing: sensitive to galaxy bias and matter density

Clustering: sensitive to redshift-space distortions and galaxy bias

- Cosmological interpretation :
  - Galaxy-galaxy clustering → $P_{gg}(k)$ proportional to $\boldsymbol{b^2 \sigma^2_8}$
  - Galaxy-galaxy lensing → $P_{gm}(k)$ proportional to $\boldsymbol{b\, \sigma^2_8\, \Omega_m}$

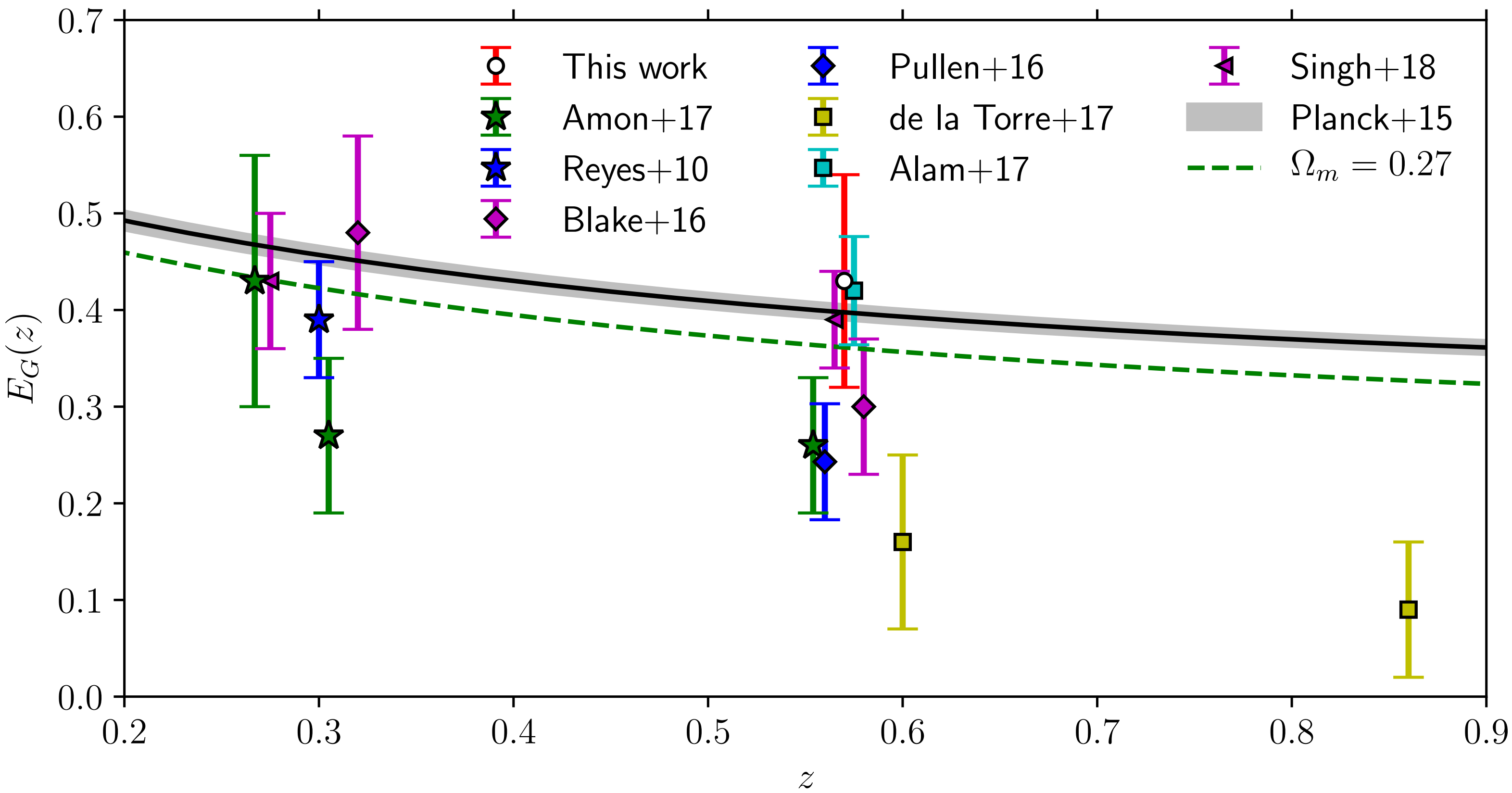
Results with E_G





We don't observe any significant deviation of E_G from GR predictions

Evolution of E_G with redshift



Conclusion

- Combination of RSD and GGL provides direct way to test gravity and LCDM model
- Light-cone lensing simulations are needed to properly estimate statistical errors
- Spectroscopic data is crucial to calibrate the redshifts of the lensing sources
- Our results are in agreement with Planck+18 predictions at z=0.57