Joint galaxy clustering & lensing cosmological analysis

Eric Jullo

Laboratoire d'Astrophysique de Marseille

Lensing : coherent distortion of light rays

Credits: Matthew Becker, KITP workshop 2013

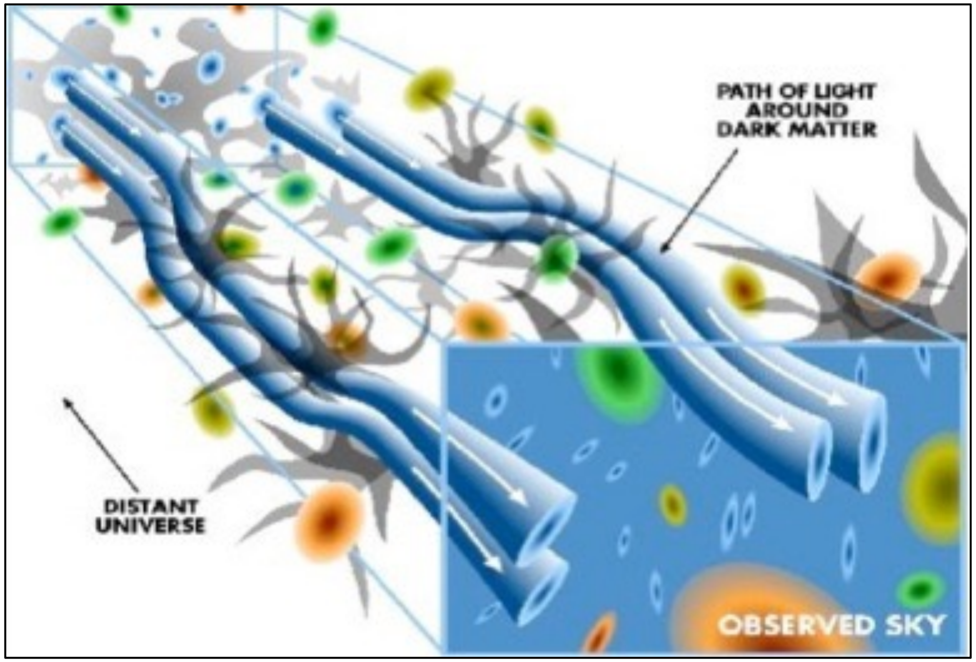
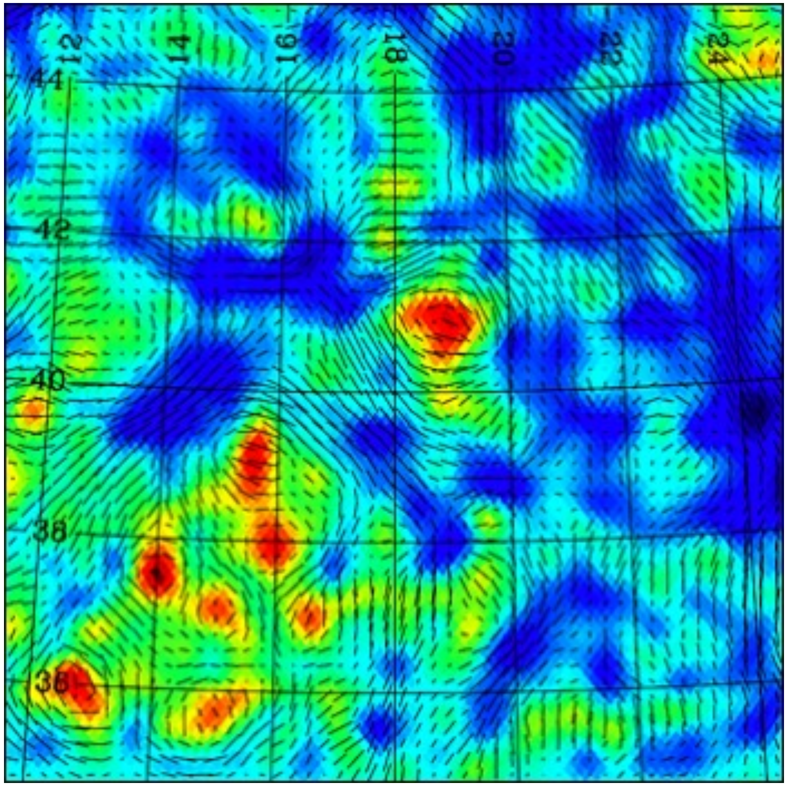


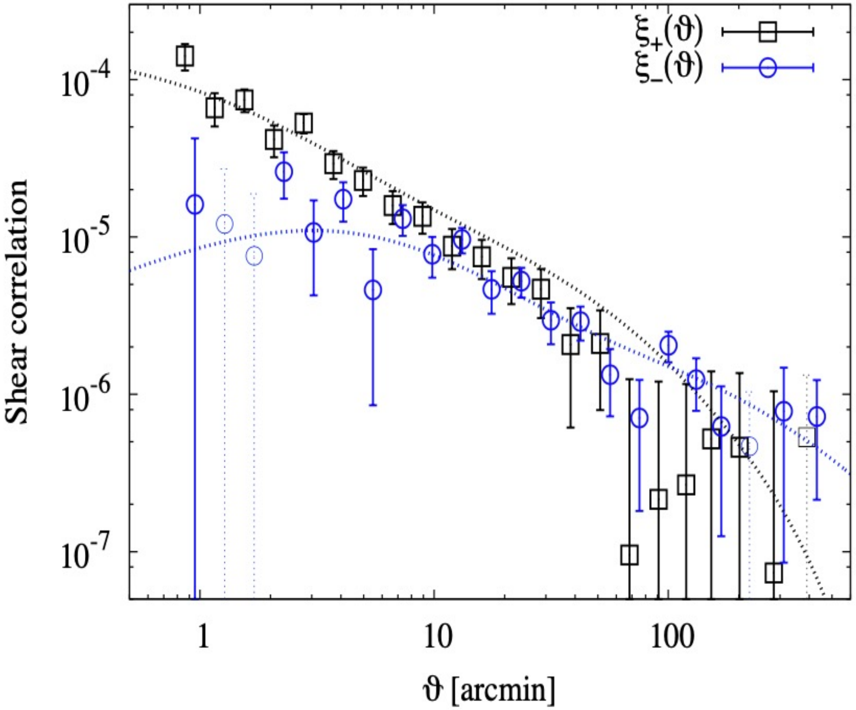
Illustration of the weak-lensing effect
Tiny effect 1% => cosmic shear



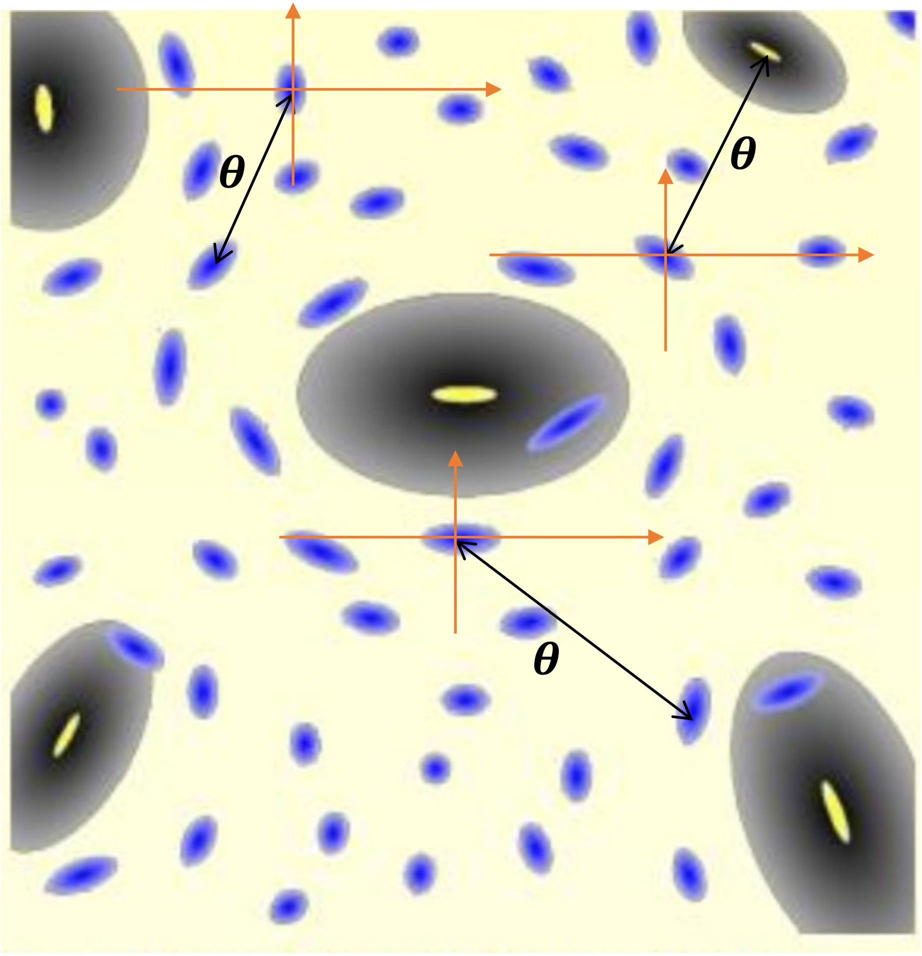
Observation of galaxy clusters (in red) and voids (in blue)

Cosmic-shear estimator

We measure the average signal as a function of separation



Kilbinger et al. 2012 (CFHTLens)



Cosmic shear estimator $\xi_{\pm}(\theta) = \langle e_1 e_1 \rangle \pm \langle e_2 e_2 \rangle(\theta)$

Cosmic shear equations

The effective projected convergence in physical units

$$\kappa = \Sigma/\Sigma_{crit} = \nabla\varphi/2 \Rightarrow \kappa_{\text{eff}}(\theta, D_s) = \frac{1}{c^2}\int_0^{D_s} \mathrm{d}D_d \, \frac{D_d D_{ds}}{D_s} \nabla\Phi(D_d\theta, D_d)$$

In comoving units, and as a function of density contrast

$$\kappa_{\text{eff}}(\theta, w_s) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{w_s} \mathrm{d}w_d \, n_d(w_d) \frac{w_d(w_s - w_d)}{w_s} \frac{\delta[w_d\theta, w_d]}{a(w_d)}$$

Power-spectrum

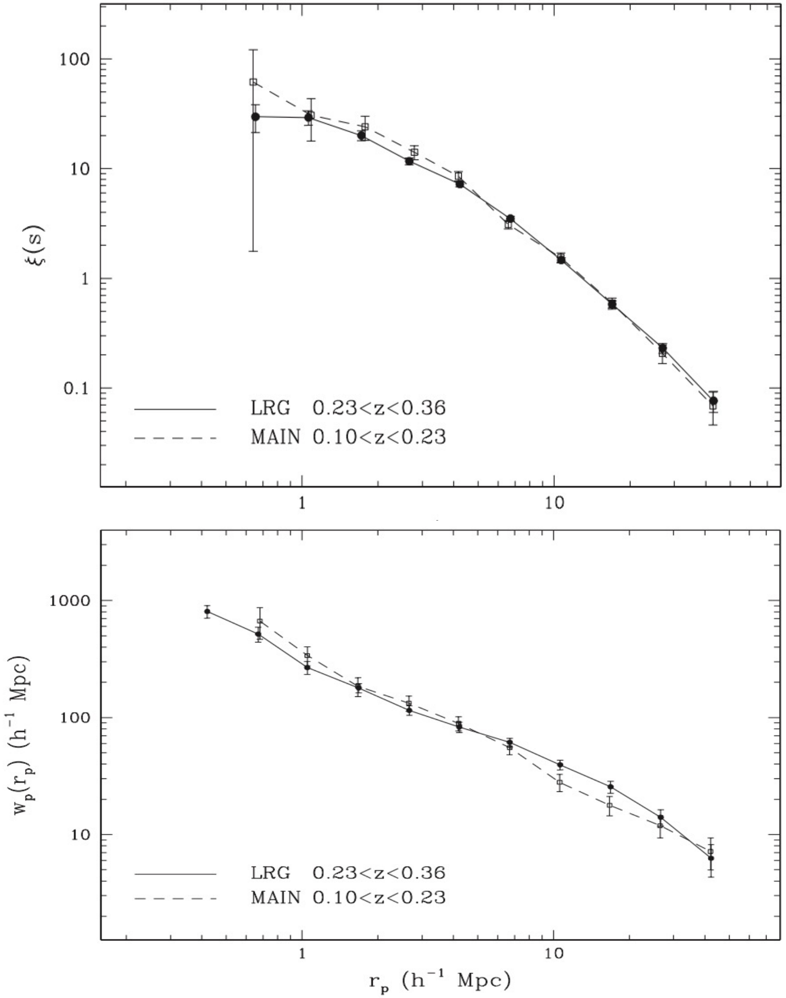
$$C_\kappa(\ell) = \int_0^{w_H} dw \, \frac{q_d(w) q_s(w)}{w^2} P_\delta\left(\frac{\ell}{w}, w\right)$$

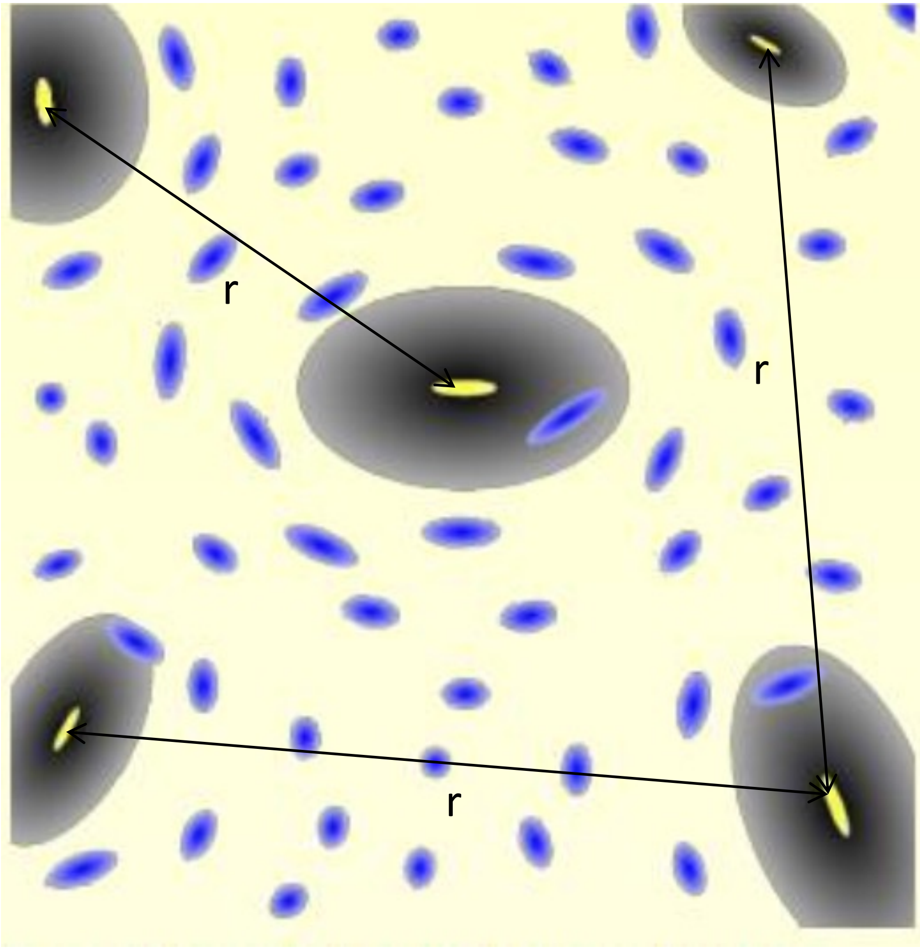
with $q_i(w) = \frac{3H_0^2\Omega_m}{2c^2}\frac{w}{a(w)}\int_w^{w_H} dw' \, n_i(w) \frac{w'-w}{w'}$ and $P_\delta(k) \propto \sigma_8^2$

Correlation function

$$\xi_\pm(\theta) = \frac{1}{2\pi}\int \mathrm{d}\,\ell \, C_\kappa(\ell) J_{0,4}(\ell\theta)$$

Clustering estimators





Zehavi et al. 2004

Clustering $\xi(r) = \frac{DD-2DR+RR}{RR}$ Landy & Szalay 1993

GGL in angular or comoving scales

Power-spectrum

$$C_{g\gamma}(\ell) = \int_0^{w_H} dw \frac{n_d(w) q_s(w)}{w^2}\, br\, P_\delta\left(\frac{\ell}{w}, w\right)$$

Correlation functions

$$\gamma_t(\theta) = \frac{1}{2\pi} \int \mathrm{d}\,\ell\; C_{g\gamma}(\ell) J_2(\ell\theta)$$

$$\Sigma(R) = \Omega_m \rho_c \int \xi_{gm}\left(\sqrt{R^2 + w^2}\right) dw$$

Differential surface mass density

$$\Delta\Sigma(R) = \gamma_t(w_d\theta)\, \Sigma_{\rm crit}(w_d)$$

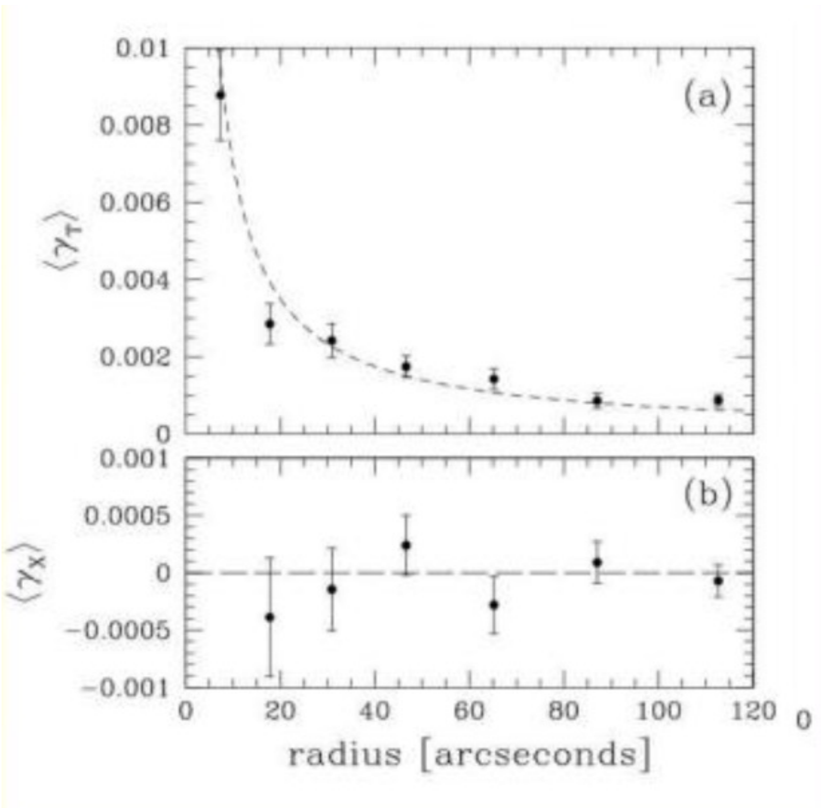
$$\Delta\Sigma(R) = \overline{\Sigma_{gm}}(R) - \Sigma_{gm}(R)$$

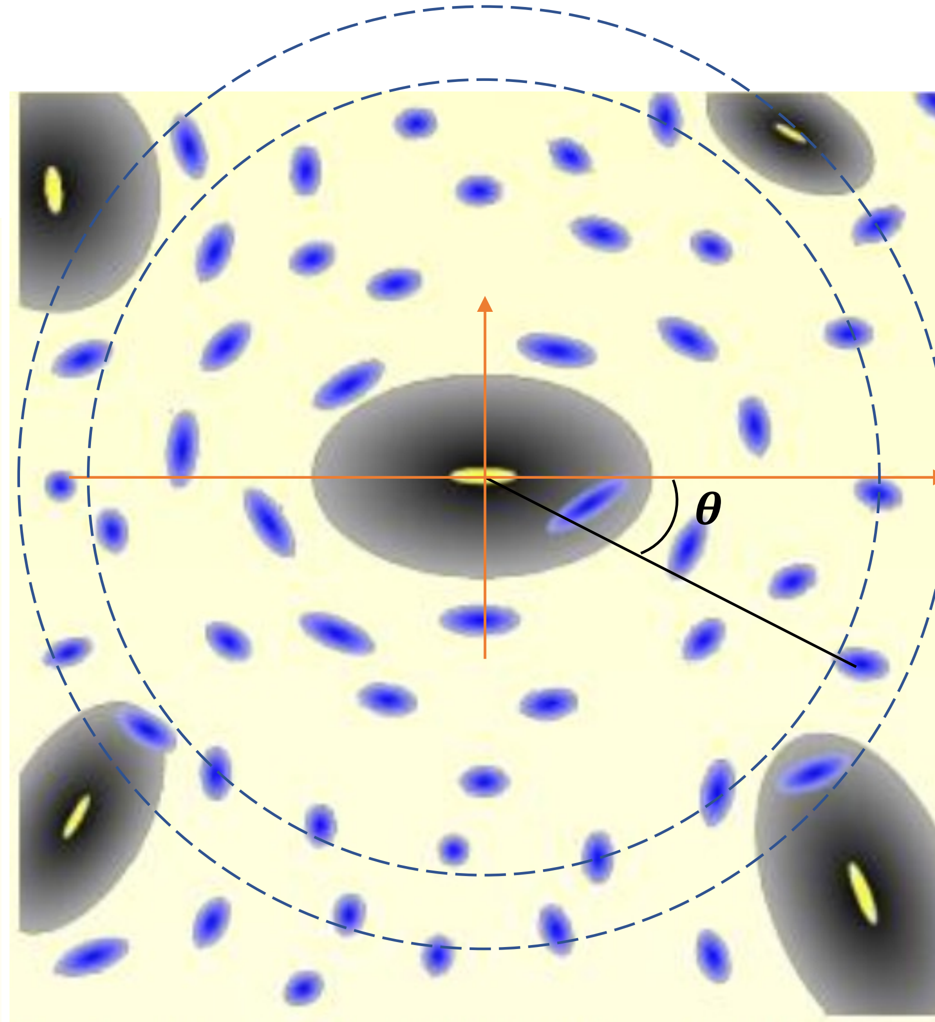
with $\Sigma_{\rm crit}^{-1}(w_d) = \int_{w_d}^{w_H} dw_s\, n_s(w_s) \frac{1}{\Sigma_{\rm crit}(w_d, w_s)}$ and $\Sigma_{crit}(w_d, w_s) = \frac{c^2}{4\pi G} \frac{w_s}{w_d w_{ds}}$

=> This is what people now use in wide field analysis

Galaxy-Galaxy lensing estimator

We measure the average signal around many lenses



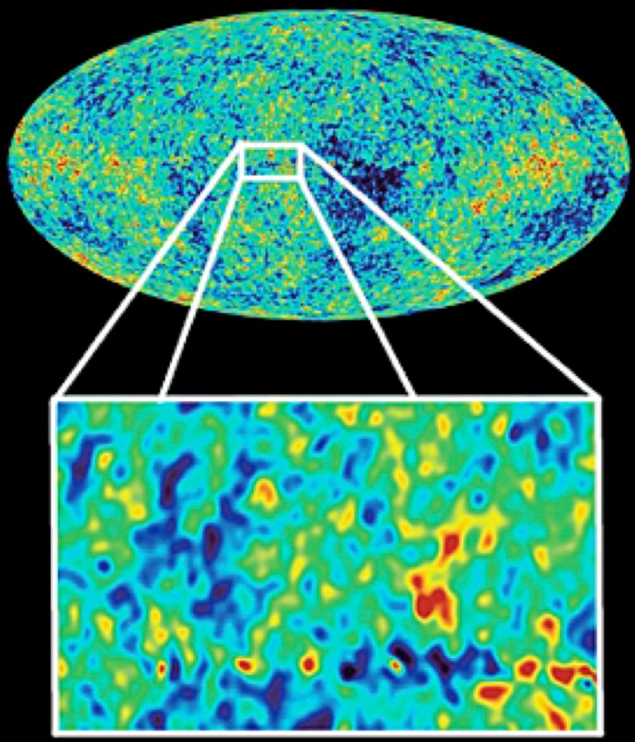


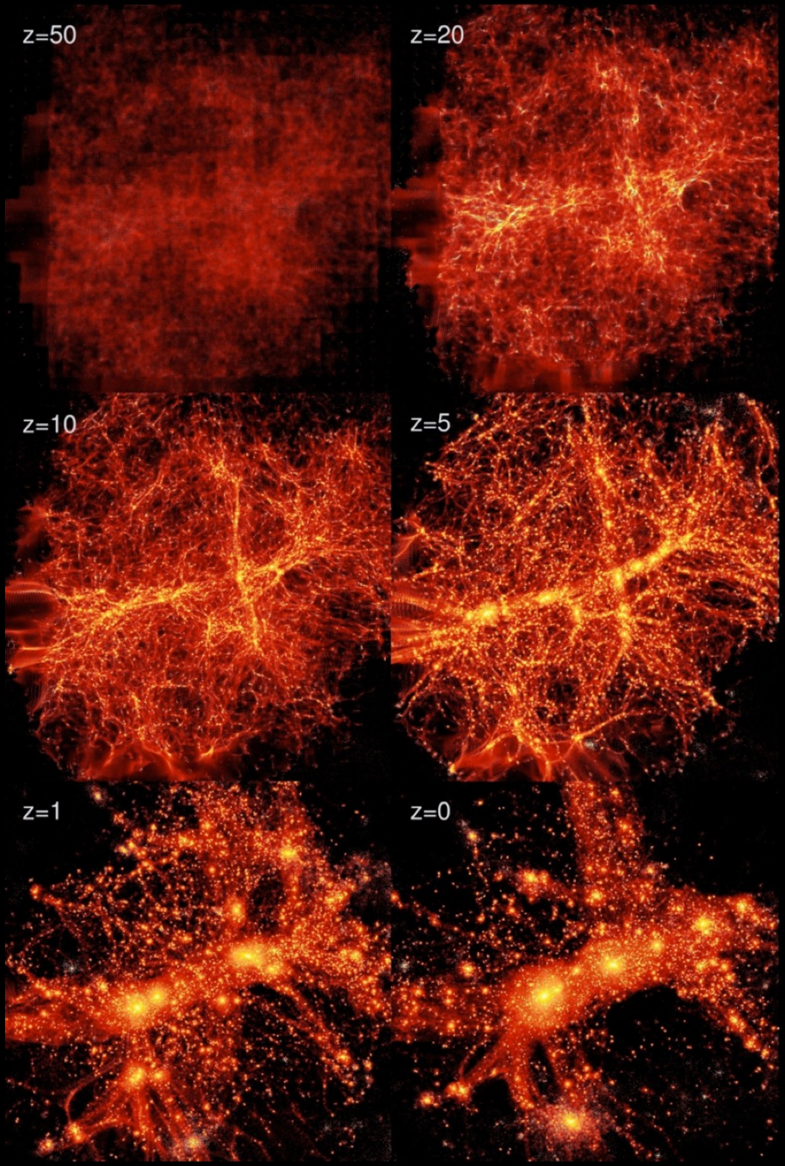
Hoekstra et al. 2004

GGL estimator $\langle \gamma_t \rangle = -\langle e_1 \cos(2\theta) + e_2 \sin(2\theta) \rangle$

Growth of perturbations

Measure the fluctuations of density as a function of redshift (z) and scale (k)





Redshift space distortion

Galaxies possess coherent "peculiar velocities" on top of the overall cosmological expansion

Redshift space distortion

- These velocities are driven by the matter distribution, according to gravitational physics

- For example in linear perturbation theory:

$$\theta = \vec{\nabla}.\vec{v} = -f\delta_m$$

- in terms of the growth rate $f = d(\ln G) / d(\ln a)$

$G(a)$: Growth factor of the Universe

- The dependence of f on scale and time is a key discriminator between gravity models

Lensing in GR

In the perturbed Friedman-Robertson-Walker metric

$$ds^2 = \underbrace{(1 + 2\Psi)}_{\text{time}} dt^2 - a^2 \underbrace{(1 + 2\Phi)}_{\text{space}} dx^2$$

a(t) : scale factor $1 \rightarrow 0$ (Today → Big Bang)

Φ and Ψ : Bardeen potentials. In GR $\Phi = -\Psi$

Lensing is a projected effect => sensitive to $\nabla^2(\Phi - \Psi)$ along the line-of-sight

Testing GR with RSD + Lensing

1. Smoking gun observational estimator (Zhang et al. 2007)

$$E_G = \frac{\text{Lensing}}{\text{RSD}} = \frac{\nabla^2(\Phi-\Psi)}{3H_0^2 a^{-1} f\,\delta_m} \rightarrow \frac{\Omega_m}{f} \text{ in GR}$$

2. Phenomenological model (Amendola et al. 2008)

$$2\nabla^2\Psi = 8\pi G a^2 (1+\mu)\rho_m\delta_m$$
$$2\nabla^2(\Phi-\Psi) = 8\pi G a^2 (1+\Sigma)\rho_m\delta_m$$

Historical review before Stage III

Combined clustering and lensing on wide field surveys :

Hoekstra et al. 2002 on 50deg2 field (RCS+VIRMOS-DESCART surveys) to study galaxy bias and galaxy-lensing correlation factor *r*. They used $M_{ap}(\boldsymbol{\theta})$, $N_{ap}(\boldsymbol{\theta})$ and $MN_{ap}(\boldsymbol{\theta})$

Sheldon et al. 2004 used SDSS (3800 deg2) and also found r~1. They used $\Delta\Sigma$ and $w_p(r_p)$

Simon et al. 2007 used GaBoDS (15 deg2) to measure bias at redshift z ~ 0.6. They used $M_{ap}(\boldsymbol{\theta})$, $N_{ap}(\boldsymbol{\theta})$ and $MN_{ap}(\boldsymbol{\theta})$.

Reyes et al. 2010 used SDSS to measure E_G. They used $\Delta\Sigma$ and $w_p(r_p)$ and $\boldsymbol{\beta}$ from Tegmark et al. 2006

Jullo et al. 2012 used COSMOS (1 deg2) to measure bias up to z ~ 1. They used $M_{ap}(\boldsymbol{\theta})$, $N_{ap}(\boldsymbol{\theta})$ and $MN_{ap}(\boldsymbol{\theta})$.

Mandelbaum et al. 2012 used SDSS to constrain cosmological parameters. They used $\Delta\Sigma$ and $w_p(r_p)$.

Leauthaud et al. 2011 used COSMOS (1 deg2) to study the SHMR up to z~1. They used $\Delta\Sigma$ and $w_p(r_p)$.

Coupon et al. 2014 used CFHTLens/VIPERS (23.1 deg2) to study the SHMR up to z~0.8. They used $\Delta\Sigma$ and $w_p(r_p)$.

More et al. 2014 used CFHTLens+BOSS (105 deg2) to estimate Ω_m and σ_8. They used $\Delta\Sigma$ and $w_p(r_p)$.

Leauthaud et al. 2016 used CFHTLens+Stripe82+BOSS (250 deg2) and found small value of S8. They used $\Delta\Sigma$ and $w_p(r_p)$

Blake et al. 2016 used CFHTLens+RCS+WiggleZ+BOSS (466 deg2) to measure E_G at z~0.5. They used $\Delta\Sigma$ and RSD. Linear bias.

de la Torre et al. 2017 used CFHTLens+VIPERS (23.5 deg2) to measure E_G at z~0.8. They used $\Delta\Sigma$ and RSD. Non linear bias.

Amon et al. 2017 used KiDS+2dFLenS+GAMA+BOSS (350deg2) to measure E_G up to z<0.9. They used $\Delta\Sigma$ and RSD. Linear bias

Jullo et al. 2019 used CFHTLens+Stripe82+CMASS (250 deg2) to measure E_G at z~0.5. They used $\Delta\Sigma$ and RSD. Non linear bias

Historical review before Stage III
Summary

About 20 years of debate whether using γ_{t} ($\boldsymbol{\theta}$) or $\Delta\Sigma$(R)

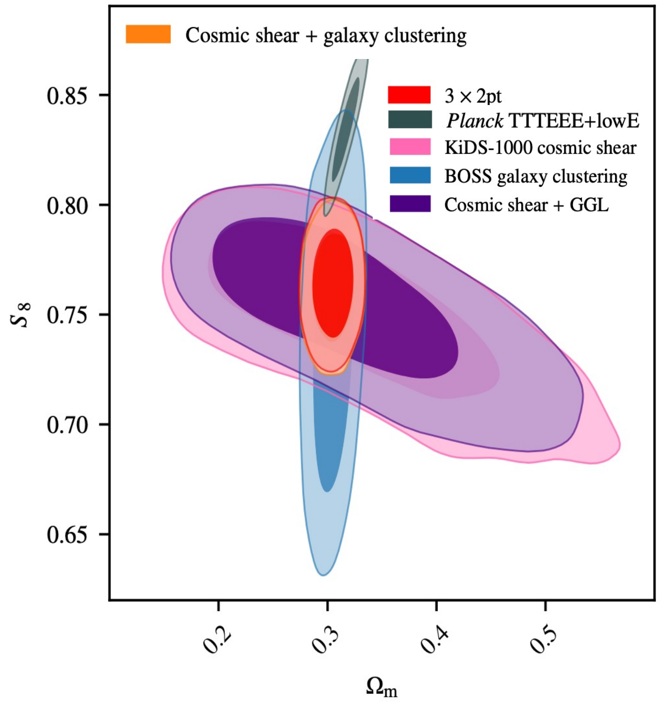
- It depends on the survey depth (Shirasaki et al. 2018)
- For magnification bias, it's cleaner to use γ_{t} ($\boldsymbol{\theta}$) (personal opinion)

Long lasting use of lensing mass aperture $\mathrm{M}_{\mathrm{ap}}(\boldsymbol{\theta})$ for cosmic-shear. Now $\xi\pm(\boldsymbol{\theta})$ used instead.

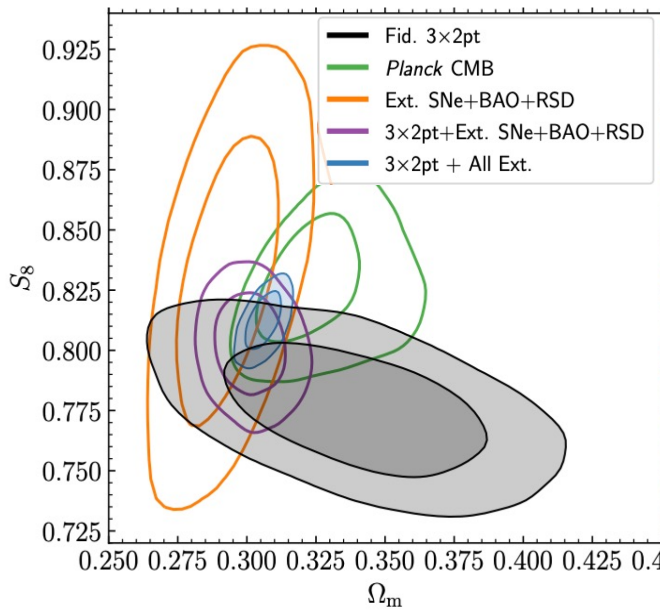
Joint RSD and lensing full-scale modeling with Blake et al. (2016) and de la Torre et al. (2017)

STAGE III 3x2pt results

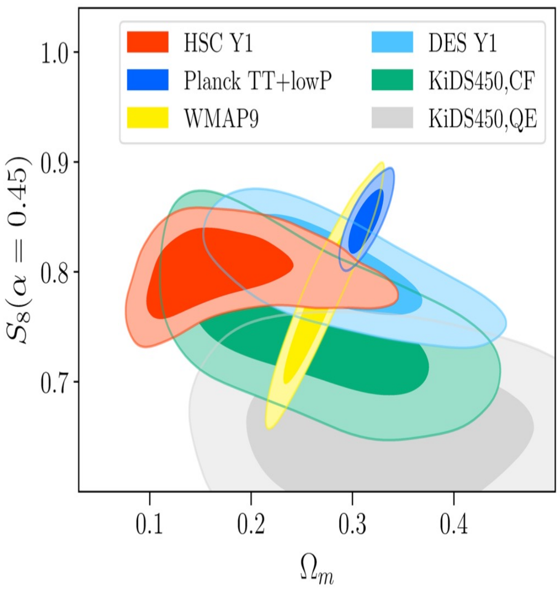
KiDS -- Heymans et al. 2021



Dark Energy Survey collaboration 2021

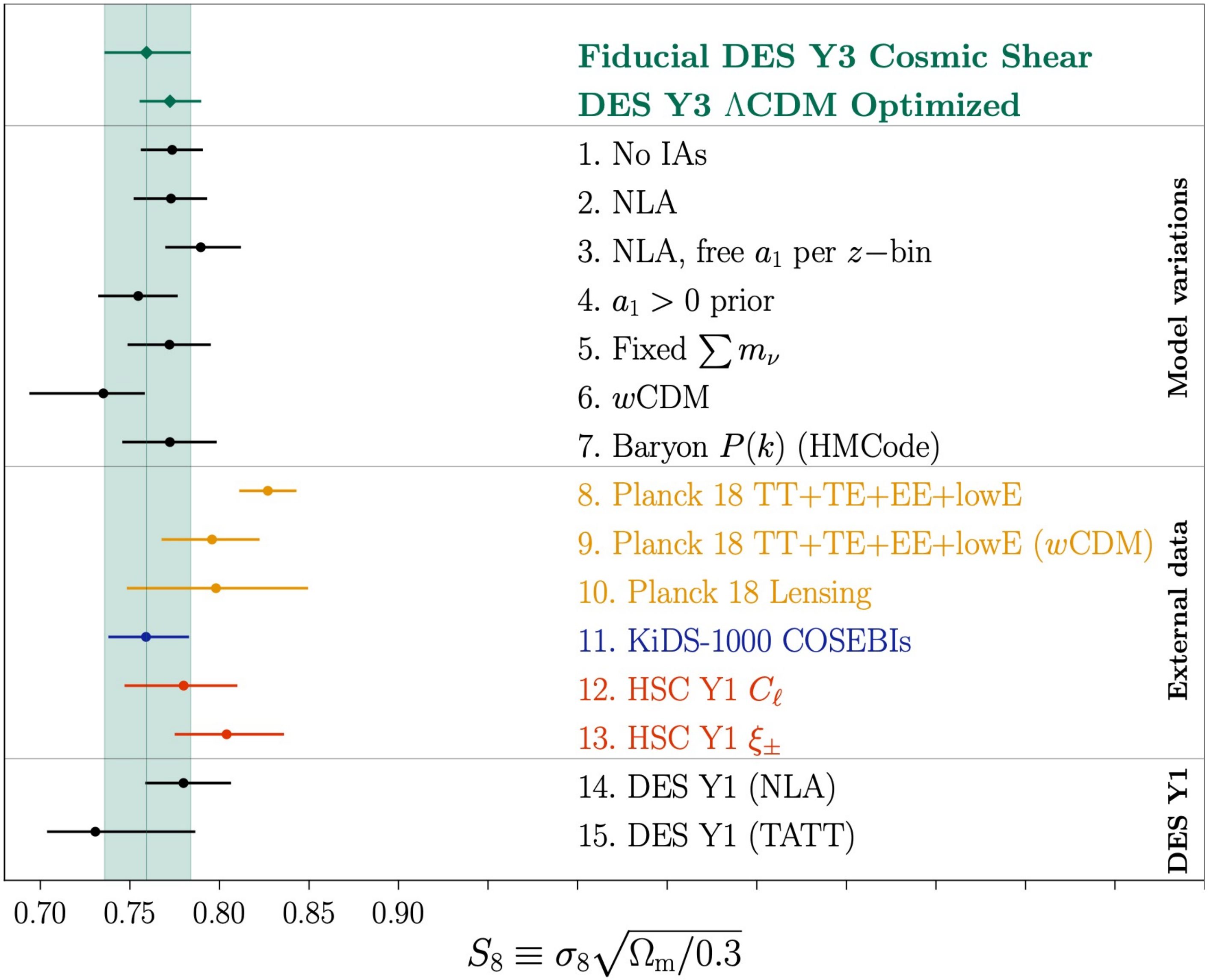


HSC -- Hikage et al. 2019



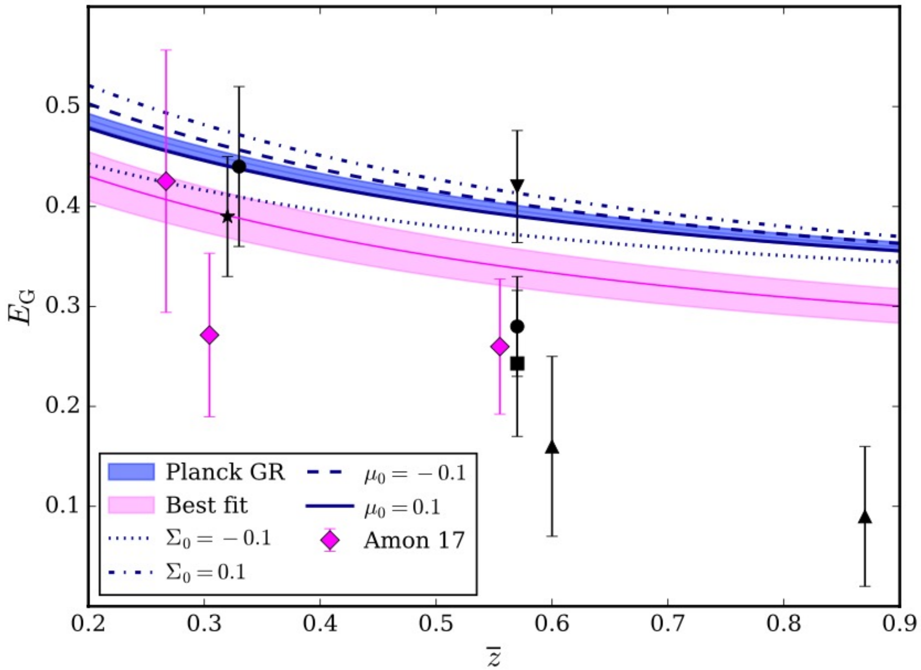
STAGE III 3x2pt results

Secco et al. 2022

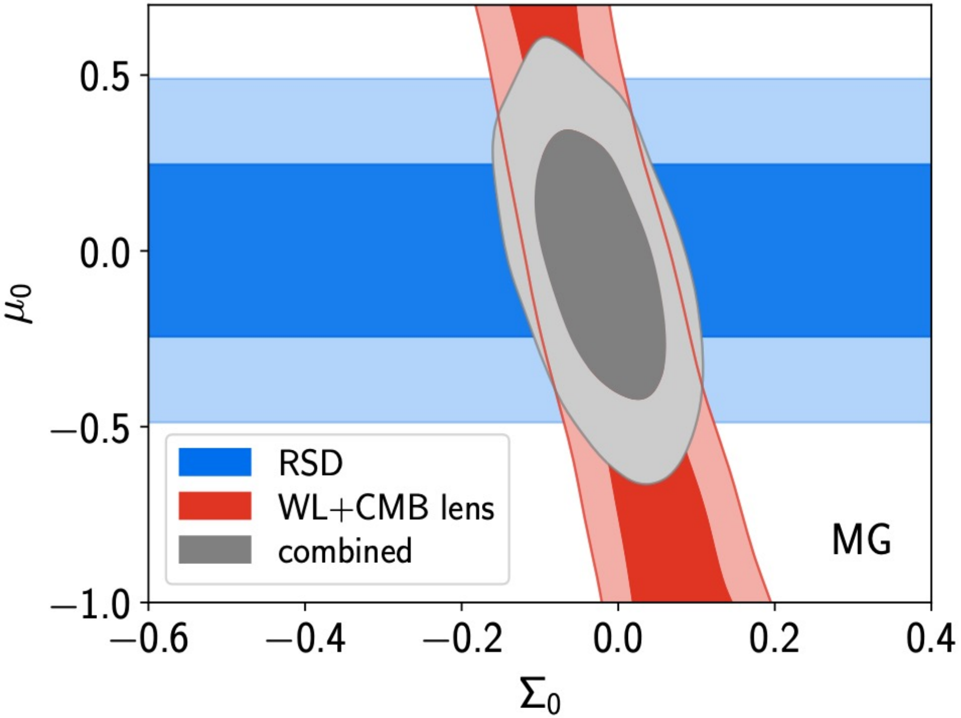


Joint lensing & RSD
Latest constraints on MG

KiDS collaboration, Amon et al. 2017

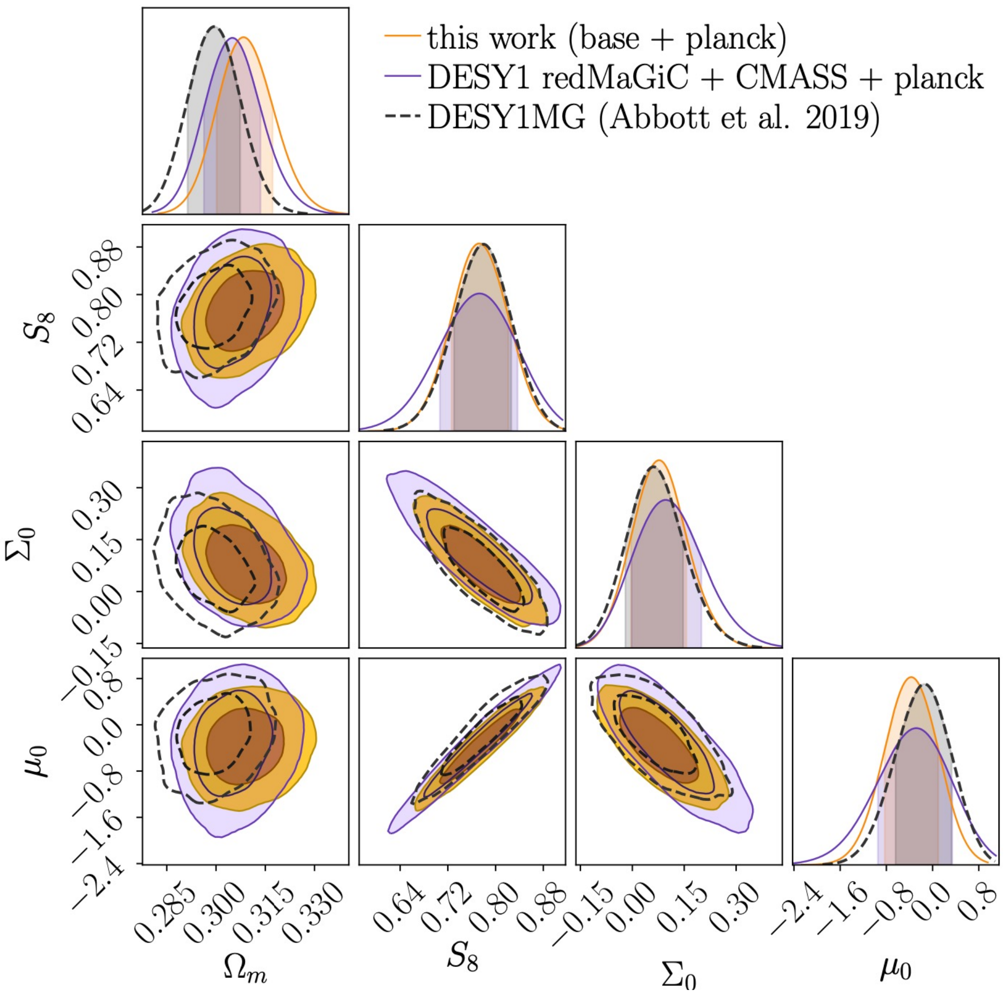


eBOSS collaboration 2020



Joint lensing & RSD
DES-Y1 MG results

Lee et al. 2021



=> In DES-Y3, since S8 is a bit larger then Σ_0 and μ_0 should be more in agreement with GR

Some systematic errors to deal with

- Redshift estimations
- Shape noise
- Modeling issues:
    - Non-linear bias modeling
    - Magnification bias
    - Galaxy Halo Connection biases

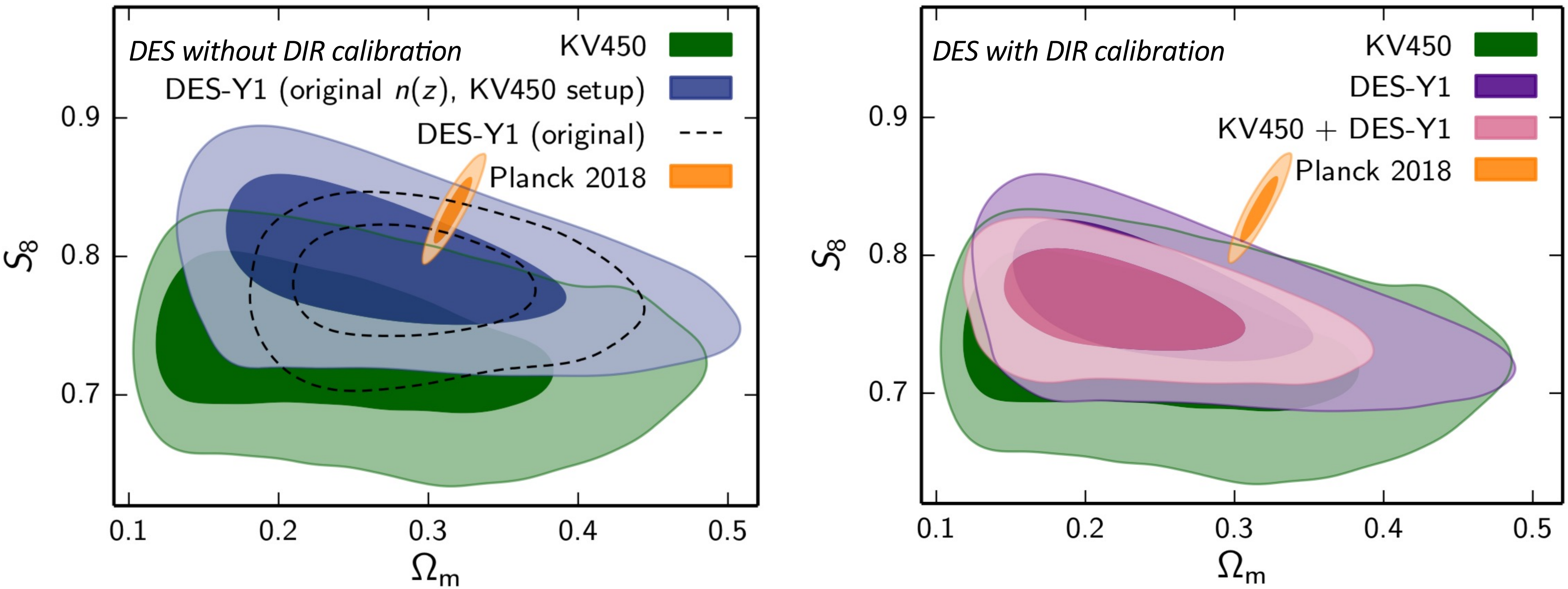
In HSC Y3 (Li et al 2022) just identified a couple of issues that impede the final cosmological analysis:

i) PSF model shape residual

ii) Star-galaxy shape correlation additive systematics

Revealing redshift bias

Joudaki et al. 2019

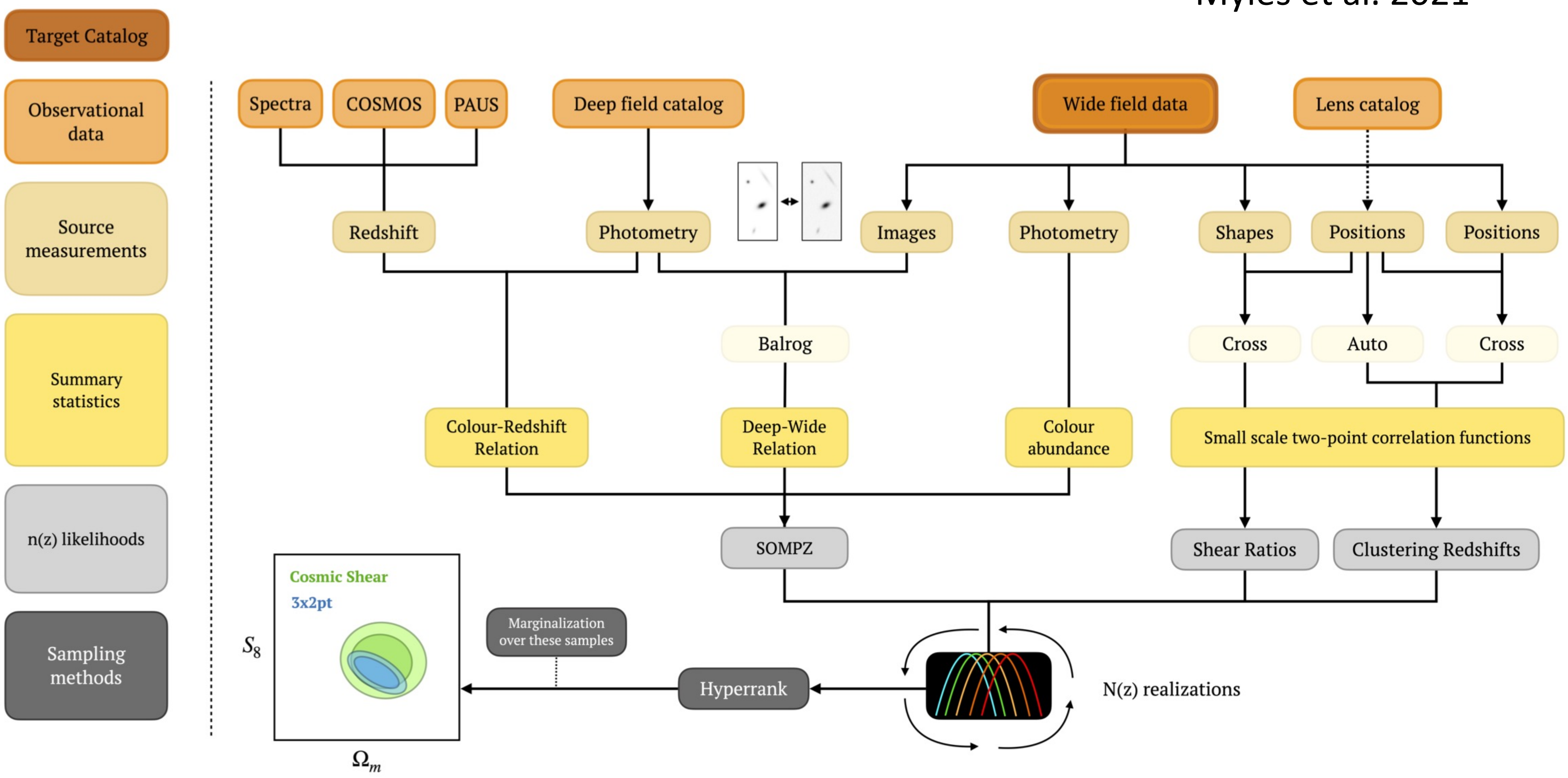


⇒ The calibration of the DES-Y1 data with spectroscopic redshift (DIR method) as used in the KIDS analysis leads to agreement between the 2 surveys

⇒ Enhanced discrepancy at 2.5σ with Planck result => new cosmology?

DES-Y3 analysis
Photometric redshift calibration

Myles et al. 2021

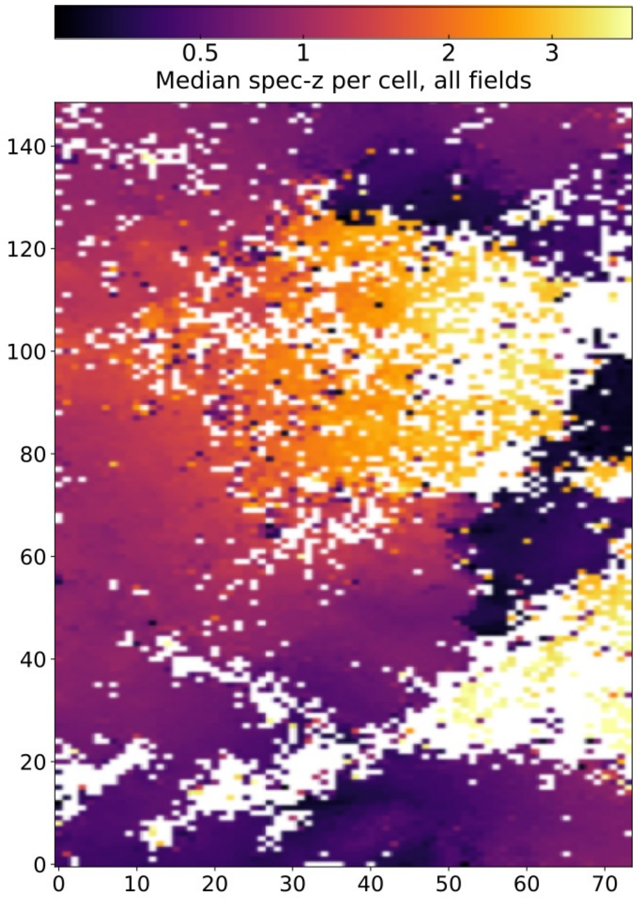


Collective spectroscopic redshift effort

Master et al. 2019

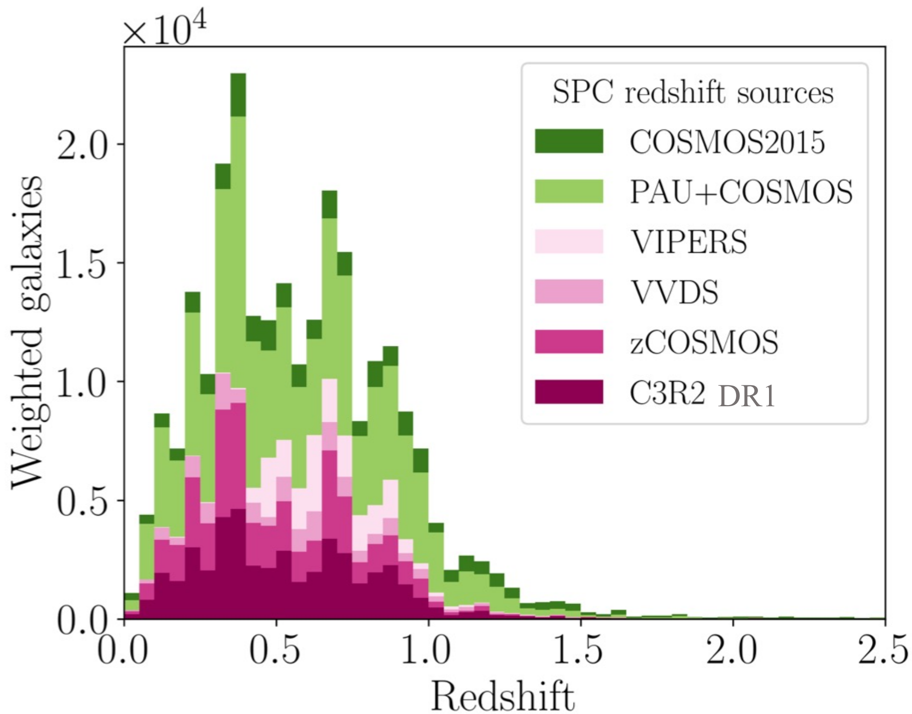
Goal: calibrate Euclid & WFIRST

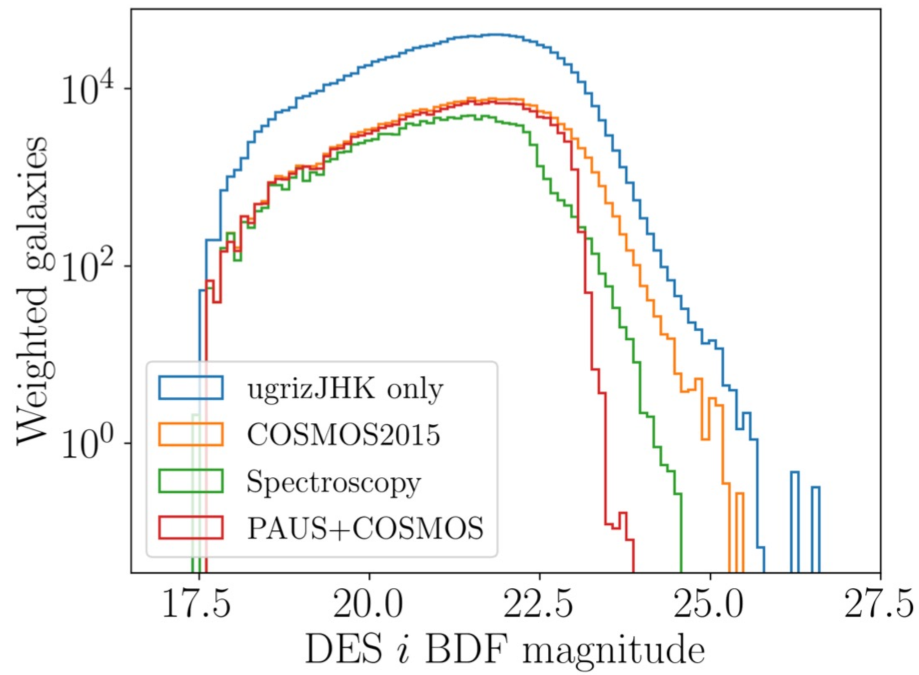
- Observed fields
  - VVDS-2h, COSMOS, EGS
- Keck observations
  - DEIMOS, LRIS, MOSFIRE
- Current status
  - DR1 1283 redshifts
  - DR2 4454 redshifts



DES-Y3 analysis
Spectroscopic calibration samples

Myles et al. 2021

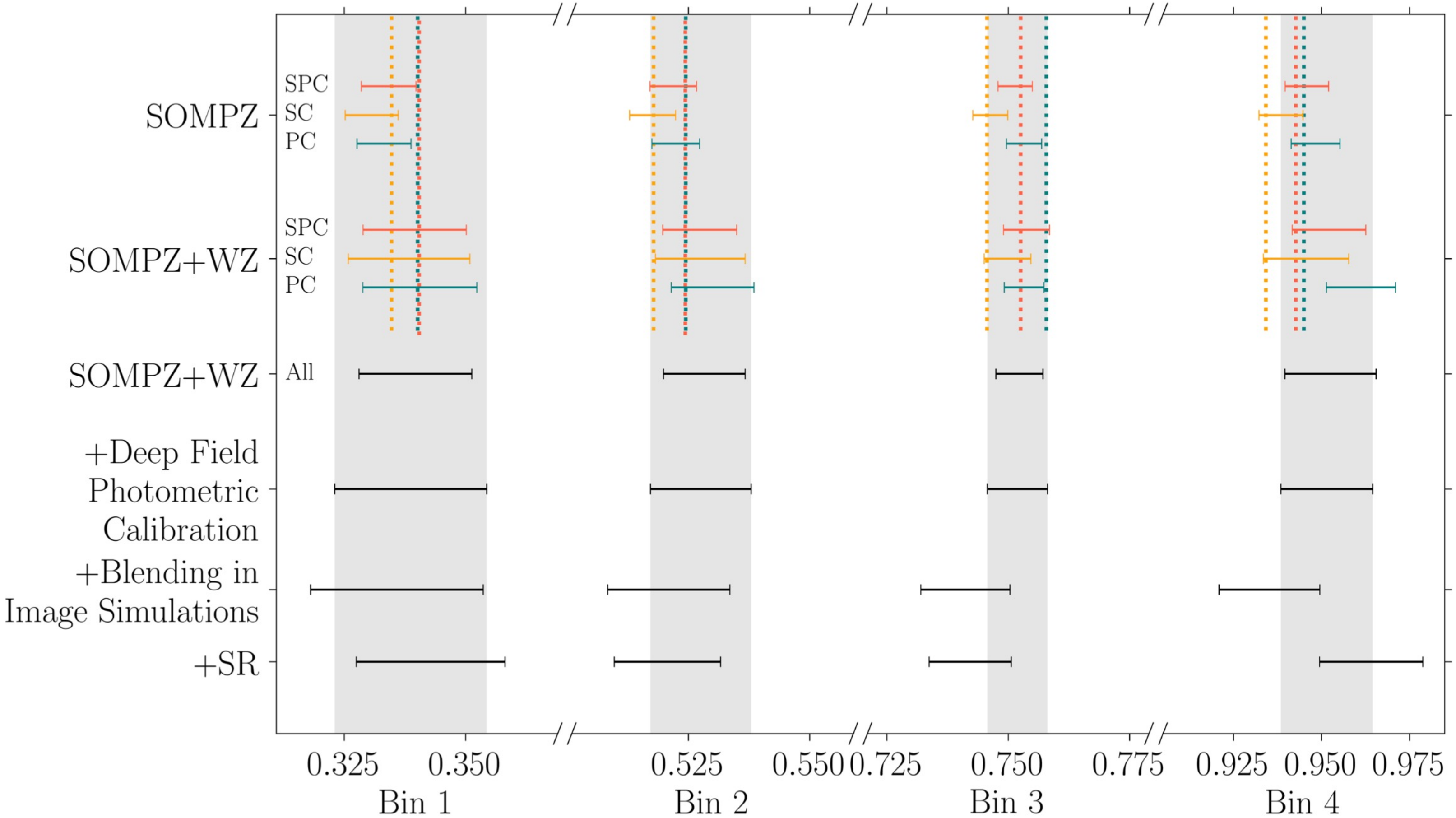




⇒ Several problems of completeness, hence the multiple techniques of calibrations
⇒ It seems not a good idea to use BOSS+eBOSS for redshift calibration

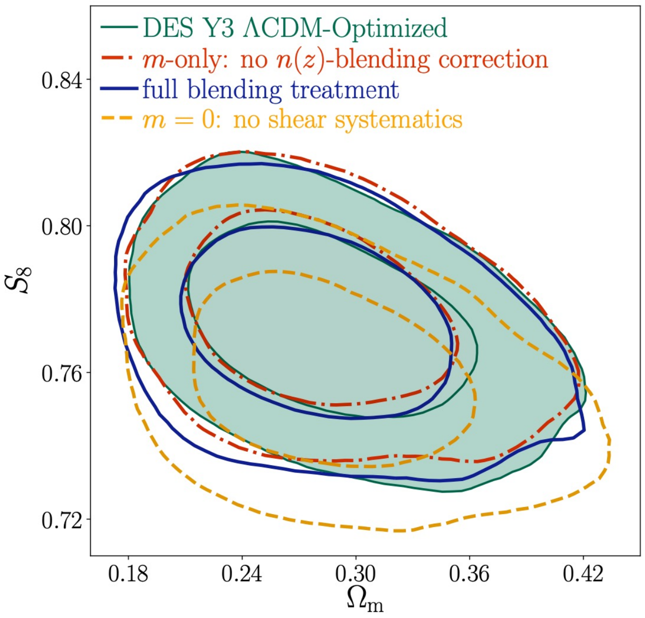
DES-Y3 analysis
Everytime adding more systematics

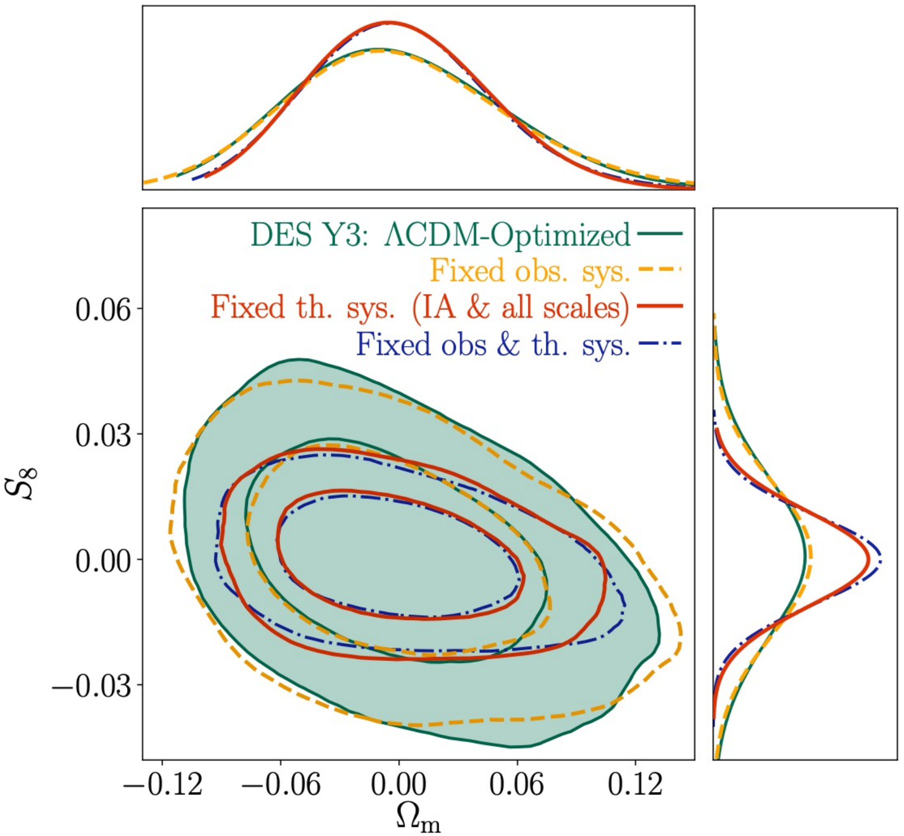
Myles et al. 2021



DES-Y3 analysis
Cosmological biases

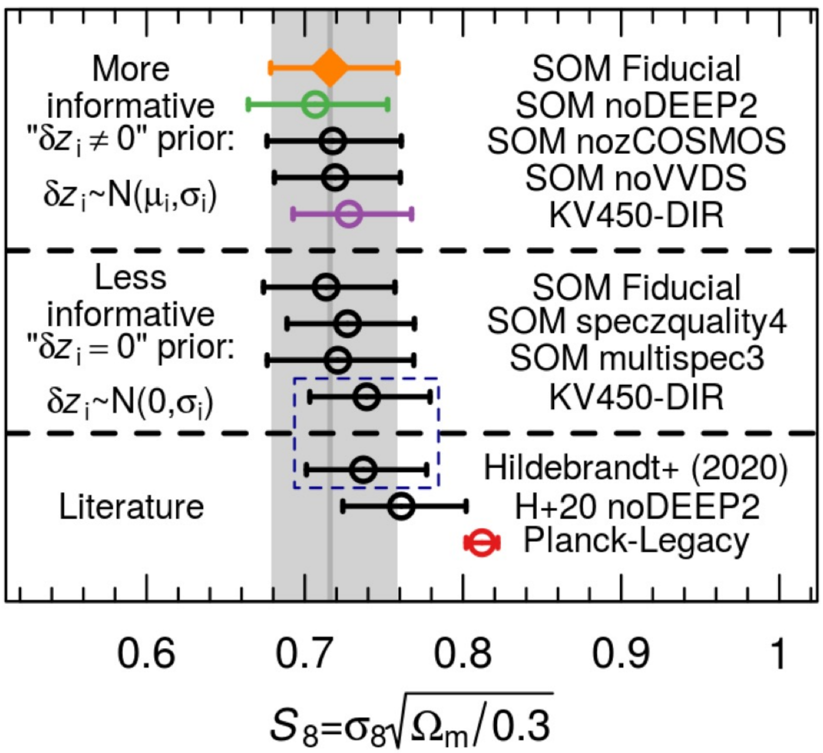
Amon et al. 2021

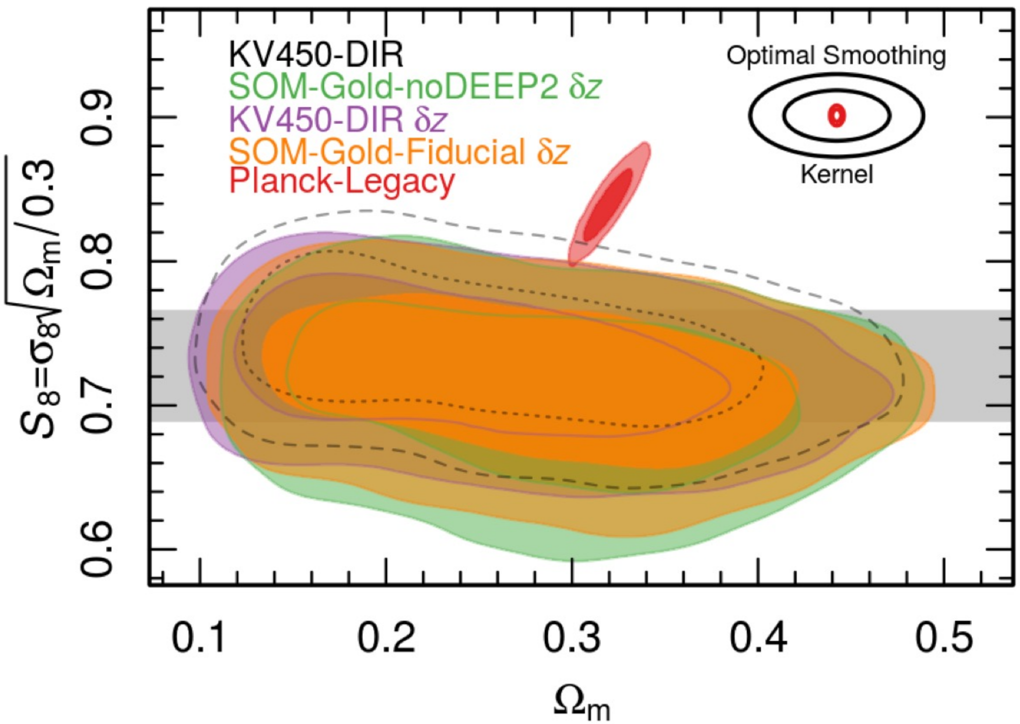




KiDS analysis
Redshift calibration and cosmological biases

Wright et al. 2021



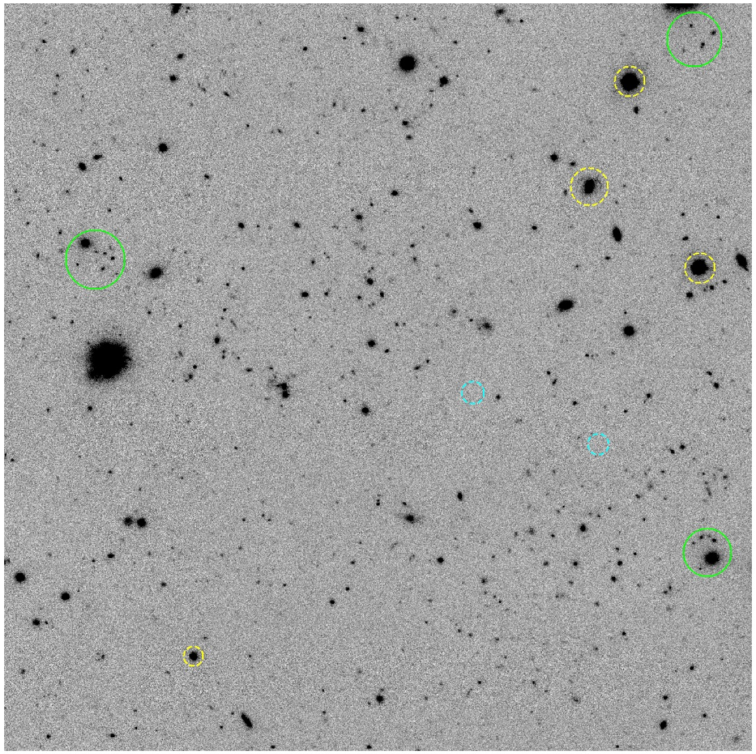


Spectroscopic calibration datasets: CDFS, zCOSMOS, DEEP2, G15Deep, VVDS
Photometric noise and spectroscopic selection effects contribute equally to the scatter

KiDS analysis
Image simulations

Kannawadi et al. 2019

- Realistic simulations of the VST r-band images (HST ACS input morphology)
- Observation depth variation
- Shear calibration for each tomographic bin
- Photometric redshifts calibration (nine-band photometry per galaxy)

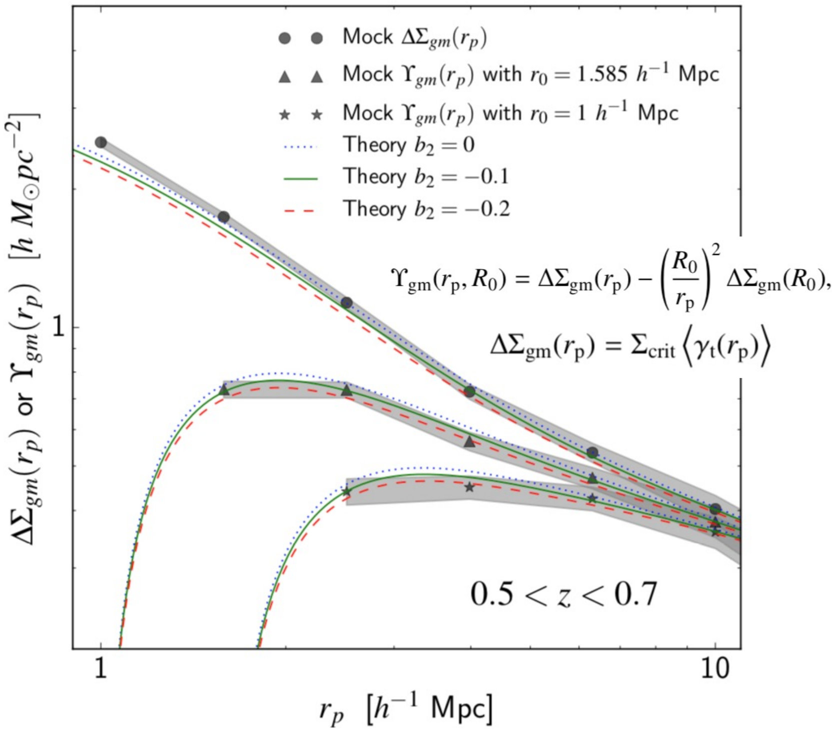


Modeling issues
Pushing to small scales

de la Torre et al. 2017

In DES and KIDS analysis, they assume a linear galaxy-bias model, e.g.

$$\gamma_t^{ij}(\theta) = b^i(1+m^j)\int \frac{dl\, l}{2\pi} J_2(l\theta) \int d\chi n_1^i(z(\chi)) \times \frac{q_s^j(\chi)}{H(z)\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right),$$



$\Rightarrow$ They put the complexity in P_{NL} with e.g. emulators

There are alternative models, but with more free parameters

$$\delta_g(\boldsymbol{x}) = b_1\delta(\boldsymbol{x}) + \frac{1}{2}b_2\left[\delta^2(\boldsymbol{x}) - \sigma^2\right] + \frac{1}{2}b_{s^2}\left[s^2(\boldsymbol{x}) - \langle s^2\rangle\right] + O(s^3(\boldsymbol{x})),$$

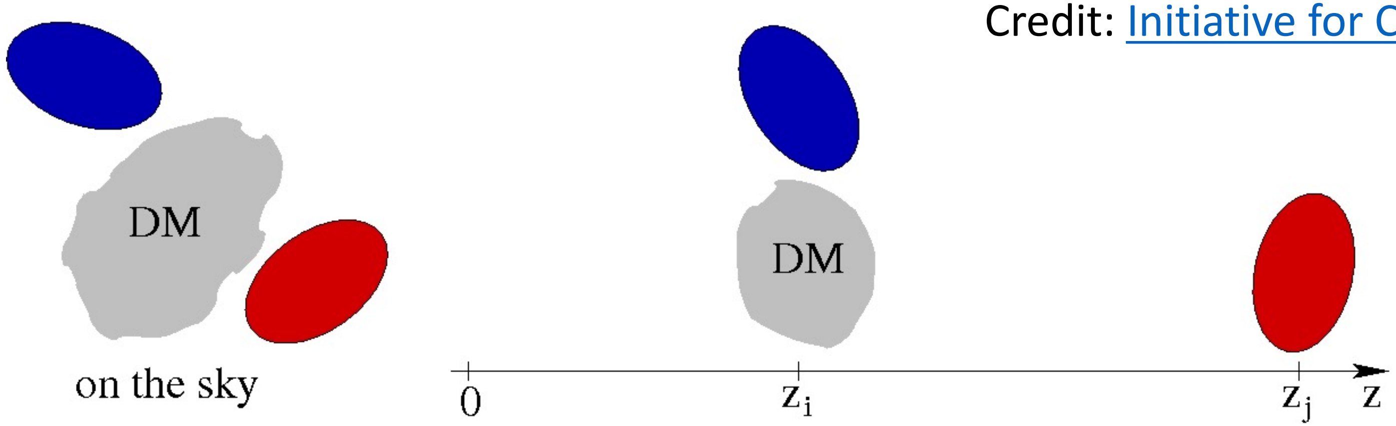
McDonald & Roy 2009

=> Being implemented for Euclid now as well

Modeling issues
Intrinsic alignment

- Intrinsic alignment tells us about galaxy formation (e.g. in filaments, Hirata et al. 2004, Chisari et al. 2016). It is a contaminant in cosmic shear analysis. It is quite negligible in GGL analysis (Amon et al. 2022)

Credit: Initiative for Cosmology



Two types of contribution

- Fake correlation between galaxies infalling in the same halo : II signal

=> More important (1—10%) when $z_i \sim z_j$.

- Fake correlation between infalling galaxies and background galaxies: GI signal

=> More important (~5%) when $z_j >> z_i$

Modeling issues
Boost factor

Mitigation solution proposed in Mandelbaum et al. 2013, Simet et al. 2016

- Account for intrinsic alignment (IA) and and increase of sources density in high-density regions compared to a random distribution of lenses

$$B(R) = \frac{\sum_{\rm ls} w_{\rm l} w_{\rm s}}{\sum_{\rm rs} w_{\rm r} w_{\rm s}}$$

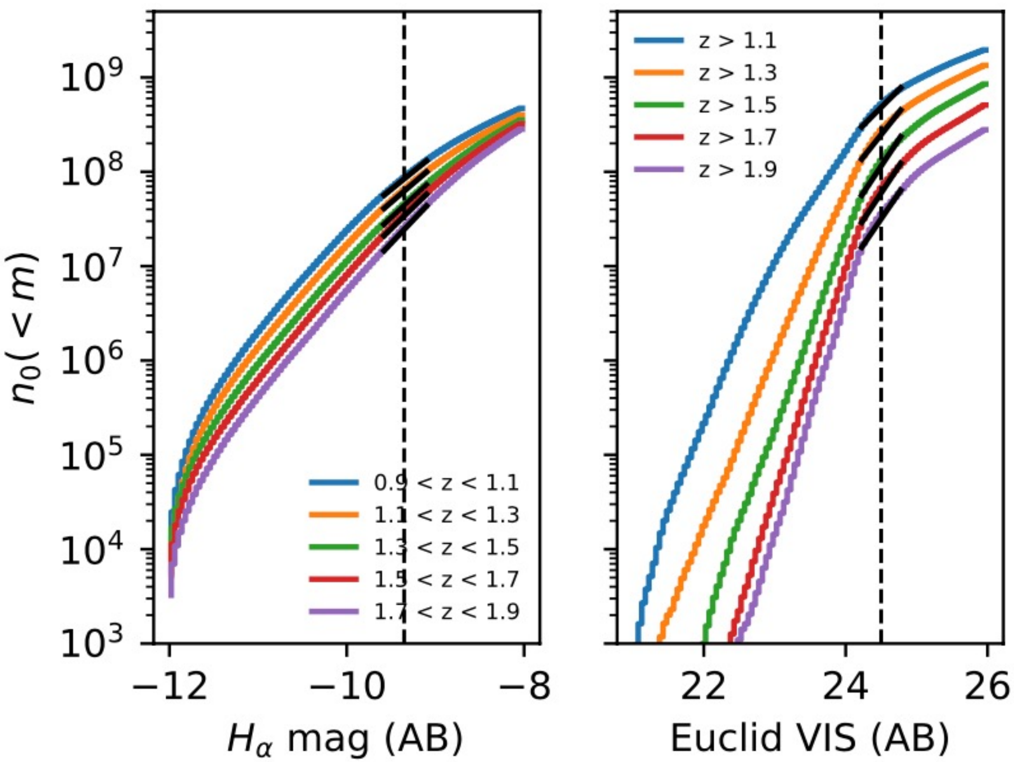
$$\Delta\Sigma(R) = B(R)\Delta\Sigma_{\rm l}(R) - \Delta\Sigma_{\rm r}(R)$$

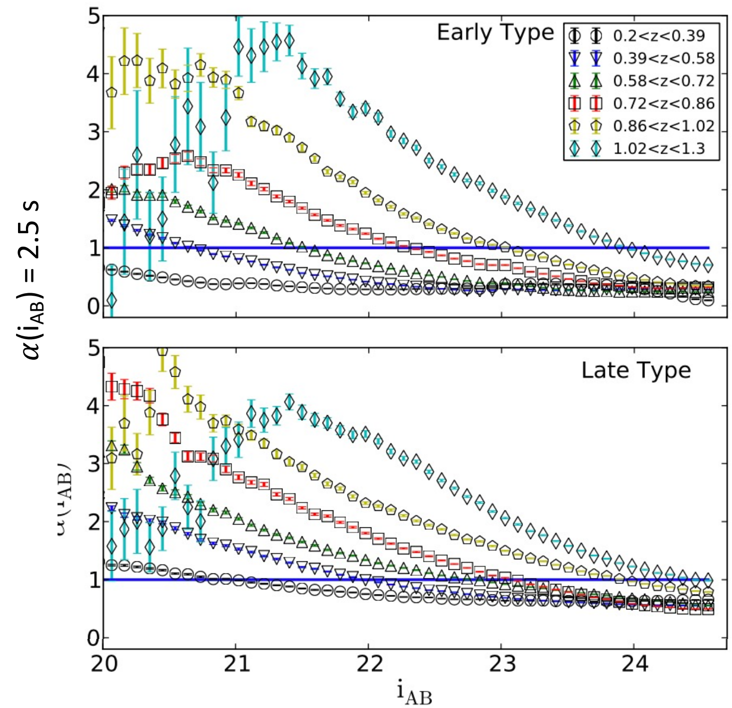
- Not to confuse with magnification bias (all scales effect)

Magnification effect description

Duncan et al. 2013

Euclid Flagship counts (Jullo et al. in prep)



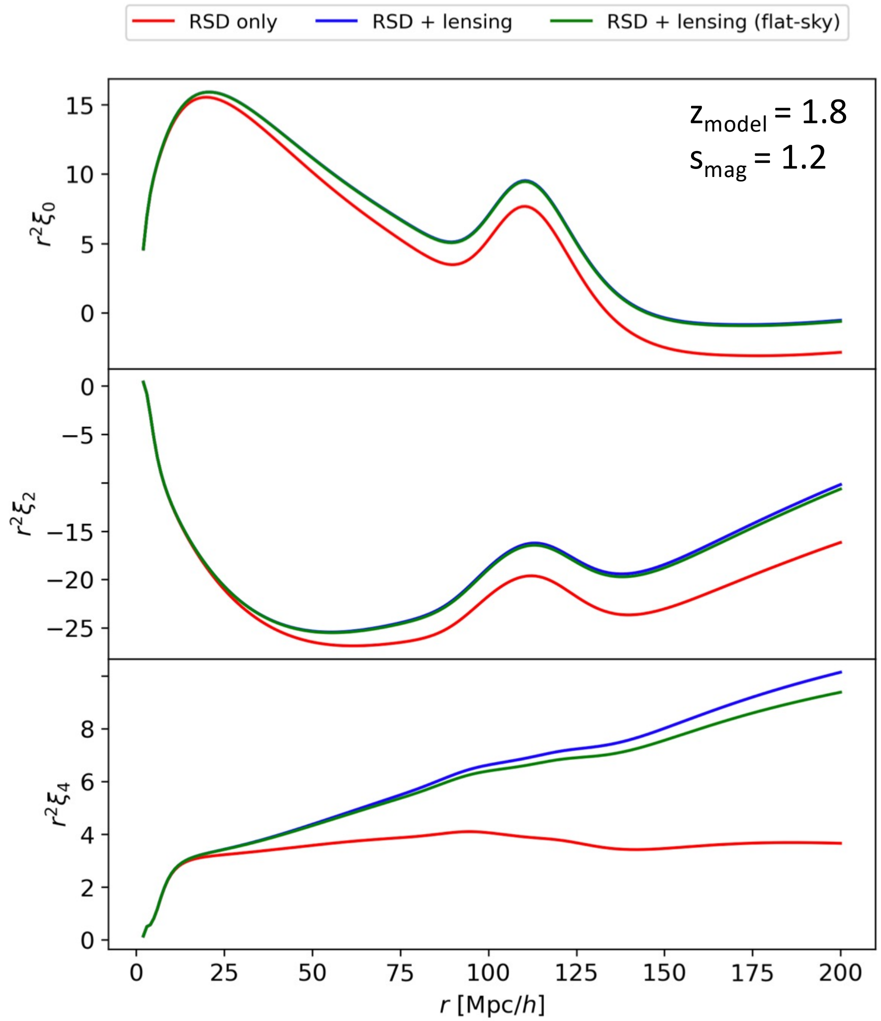


$$s = \left. \frac{d \log_{10} N(< \text{mag})}{d\ \text{mag}} \right|_{\text{mag}=\text{mag}_{\text{lim}}}$$

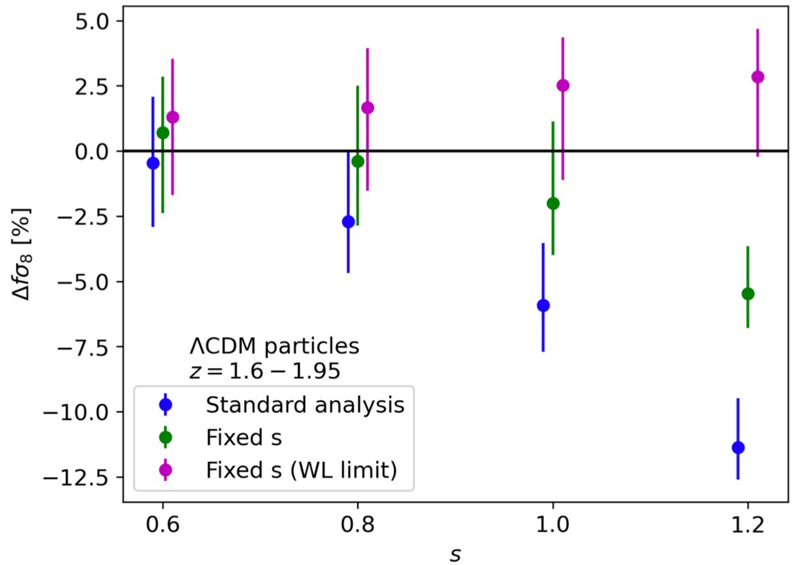
If s = 0.4 => no magnification bias, because lensed area compensated by number counts

Magnification effect in Euclid

RSD analysis



Breton et al. 2022



=> Important impact in Euclid RSD analysis

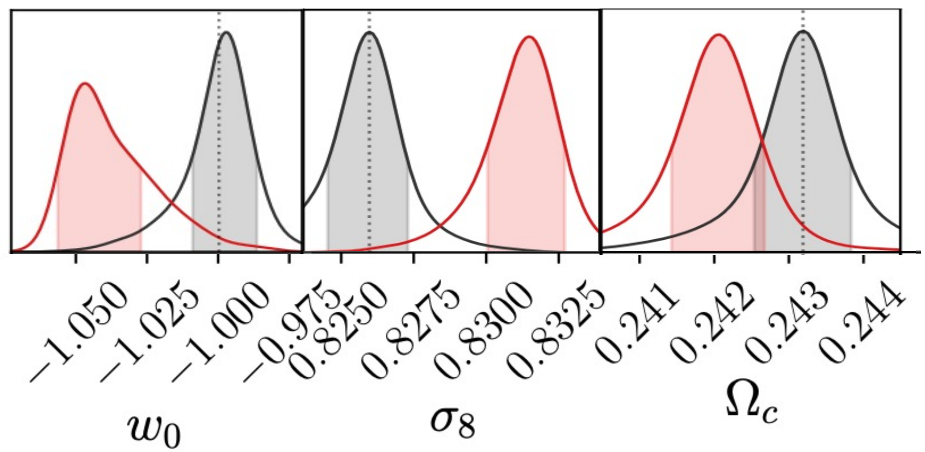
=> For DESI, how much is it for QSO and Lya forest?

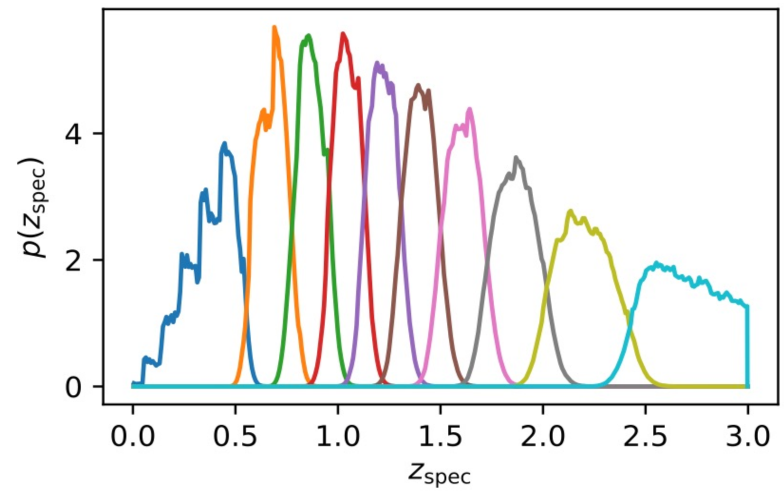
Magnification effect in Euclid
3x2pt analysis

Duncan et al. 2022

Analysis details

- Estimators used w($\boldsymbol{\theta}$), γt($\boldsymbol{\theta}$) and ξ±($\boldsymbol{\theta}$)
- Euclid like density of sources at mag=24
- Magnification bias s = 0.52 (i.e. α=1.3, Deshpande et al. 2020)



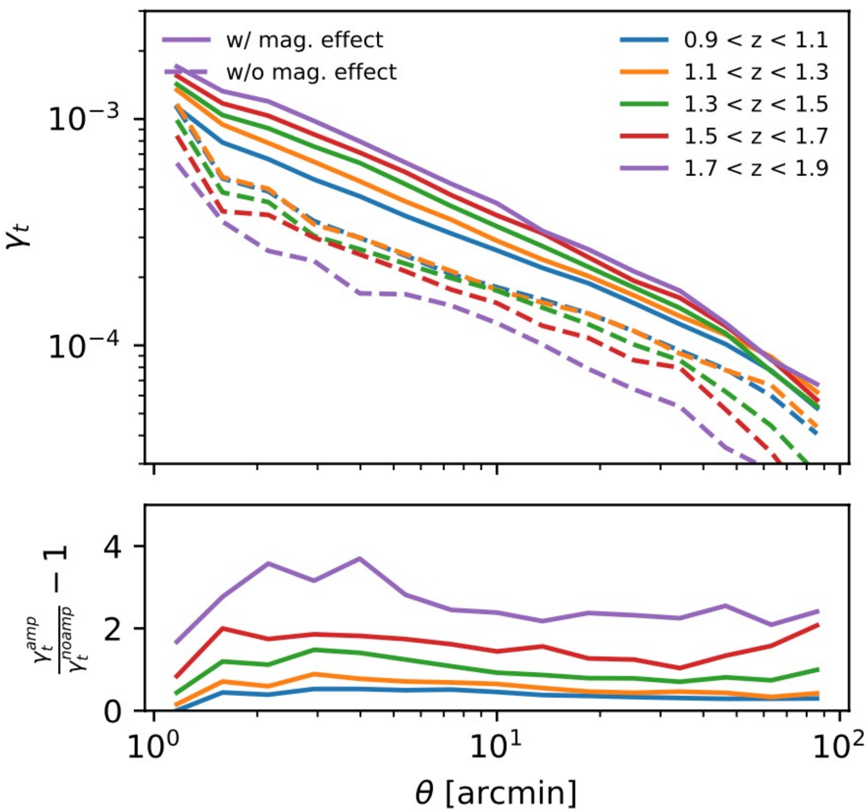


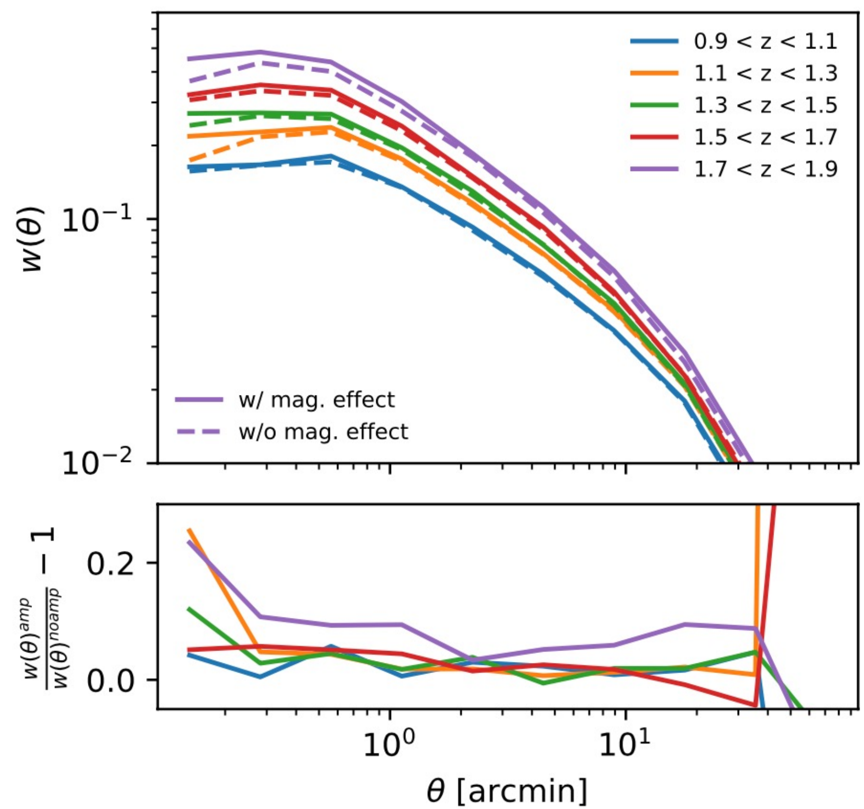
Based on SLICS simulations

=> Significant impact of lensing magnification bias on cosmological parameters in Euclid

Magnification effect in Euclid
GGL with the spectroscopic sample

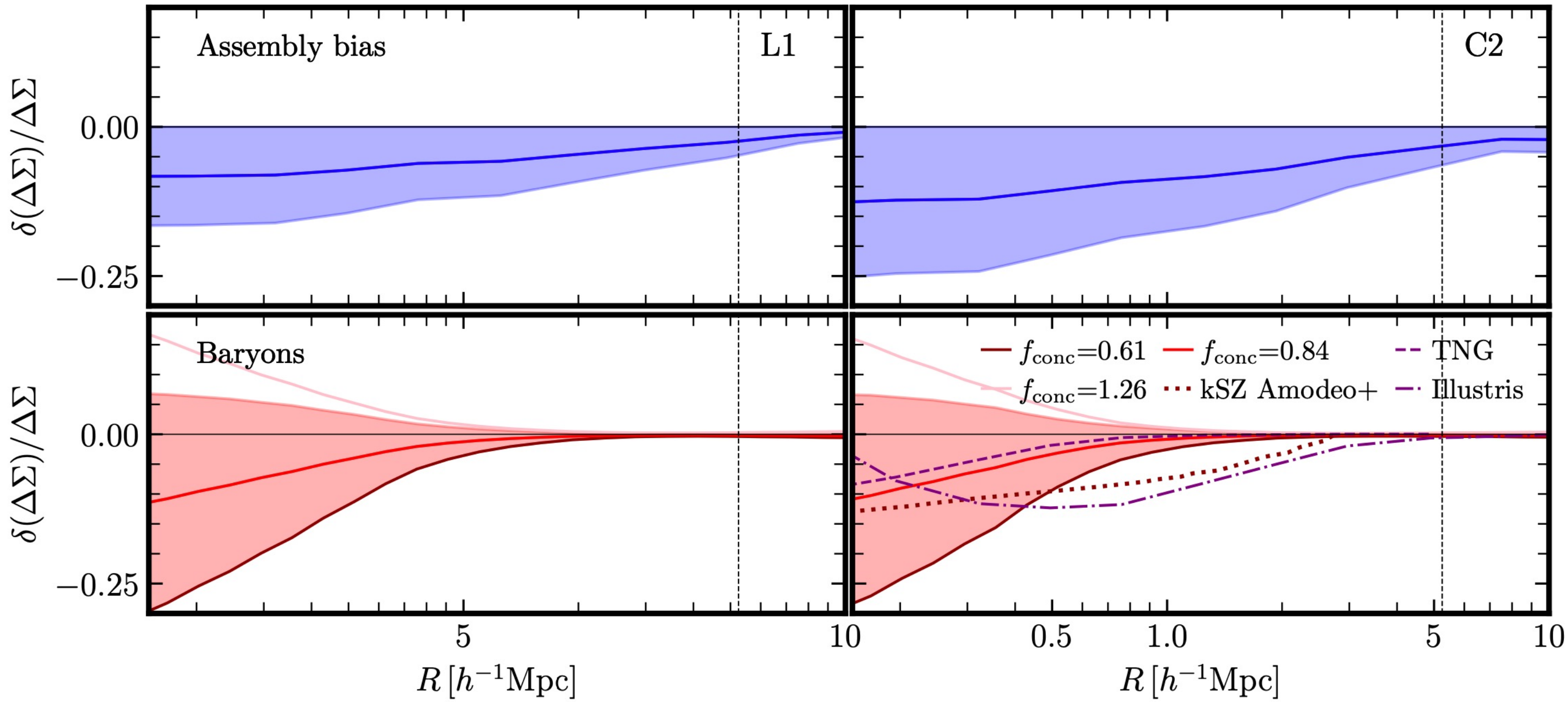
Jullo et al. in prep



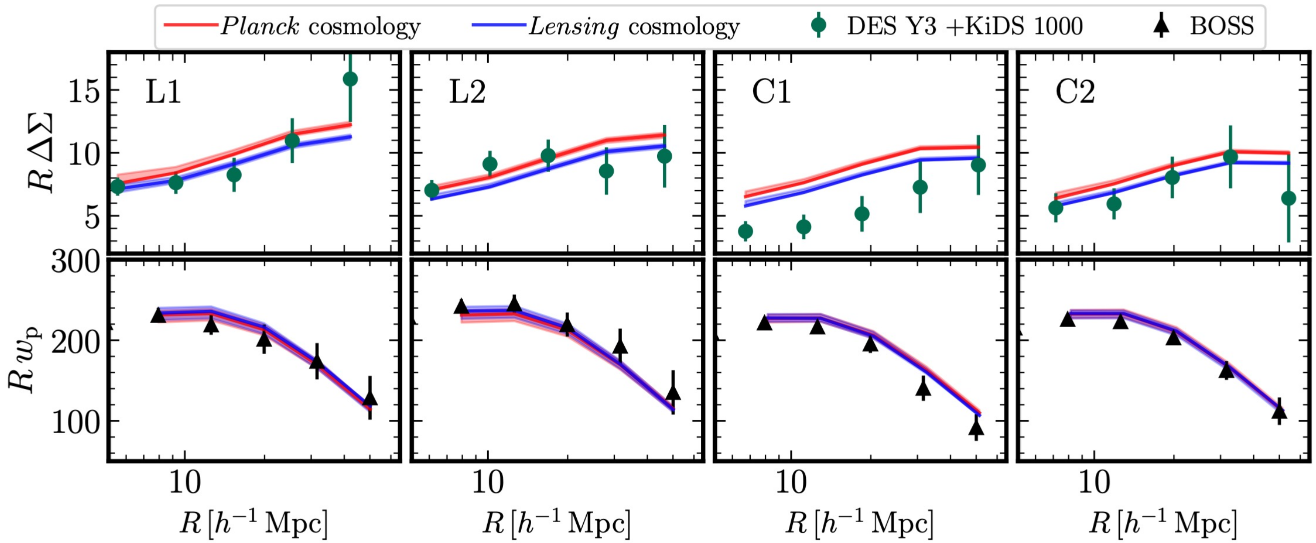


Galaxy Halo Connection
Assembly bias

Consistent lensing and clustering in a low-S8 Universe with BOSS, DES Year 3, HSC Year 1 and KiDS-1000, Amon et al. 2022



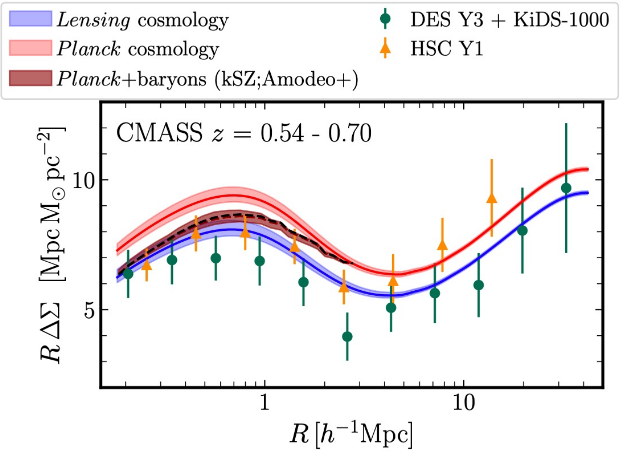
Galaxy Halo Connection
Amon et al. 2022



Error budget:

- Assembly bias ~15%, but negligible at R > 5.25 h Mpc-1
- Baryons bias ~10%, but negligible at R > 1 h Mpc-1

=> Remaining problem with CMASS C2 sample at about 5Mpc/h



Conclusion

Back in 2006: Dark Energy Task Force (Albrecht et al)

« *If* the systematic errors are at or below the level asserted by the proponents, it is likely to be the most powerful individual Stage-IV technique »

16 years later:

- Is the lensing low-S8 issue real? Current studies require large field coverage => lensing with Euclid

In the future (higher redshift & more precision), there is no other option than introducing lensing in clustering analysis (magnification bias)