Master's degree internship presentation: Combining weak lensing and redshift-space distortions

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Stakes

Several future surveys (Euclid, LSST, SKA) will collect data on billions of galaxies $\implies$ constrain the dark sector.

1. Gravitational lensing $\rightarrow$ probes of gravitational potentials between source and observer.
2. Redshift-space distortions (RSD, i.e. apparent asymmetry in the galaxies distribution, due to their own speed) $\rightarrow$ probes of densities, velocities and potentials of the sources.

$\rightarrow$ What are the crossed influence of gravitational lensing and RSD on the apparent distribution/properties of galaxies? $\implies$ How can it help to probe the dark sector?

Context: gravitational lensing

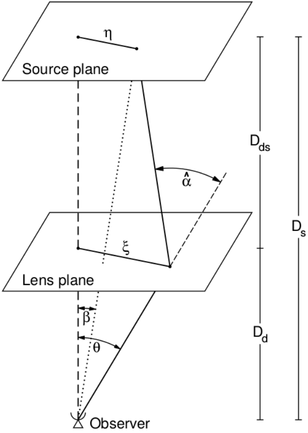


Figure 1 – Weak lensing formalism.
Credits: Bartelmann & Schneider 2001.

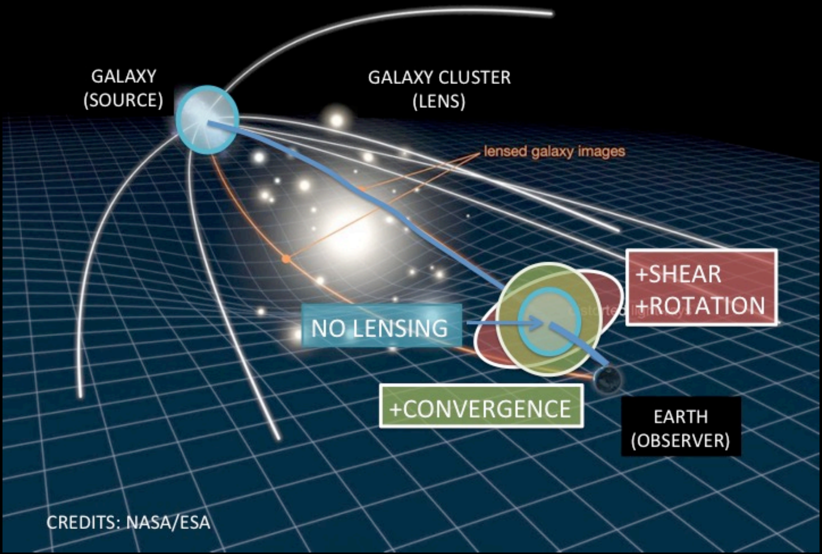
Amplification matrix $\mathcal{A}$:

$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix} \tag{1}$$

and κ convergence parameter:

$$\kappa = 1 - \frac{1}{2}\,\mathrm{Tr}(\mathcal{A}). \tag{2}$$

Weak lensing



Context: Redshift-space distortions

Presumably: redshift of a distant object $\Longrightarrow$ distance:

$$1 + z = \frac{a_0}{a}, \qquad (3)$$

but source has peculiar speed $\boldsymbol{v}$:

$$1 + z = \frac{a_0}{a}\left[1 + \frac{\boldsymbol{v}\cdot\boldsymbol{n}}{c}\right]. \qquad (4)$$

• Instance of possible blue- or red-shift not caused by the Hubble flow but by the Doppler effect.

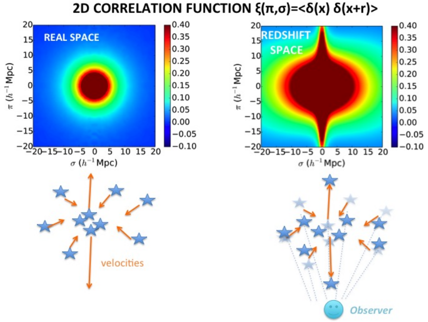


Figure 2 – RSD in a nutshell.

Total relativistic RSD calculations:

$$\delta z = \frac{a_0}{a}\left[\frac{\boldsymbol{v}\cdot\boldsymbol{n}}{c} - \frac{\psi - \psi_0}{c^2} + \frac{1}{2}\left(\frac{v}{c}\right)^2 - \frac{1}{c^2}\int_{\eta}^{\eta_0} \frac{\partial(\phi + \psi)}{\partial \eta} \mathrm{d}\eta'\right]. \qquad (5)$$

$\Rightarrow$ Overdensity $\delta = \rho/\langle\rho\rangle - 1$ in redshift space different from real space.

Data: simulations and catalogs

⇒ Breton et al., 2019: "RayGalGroupSims": large N-body simulations & relativistic ray-tracing $\implies$ for the first time unified treatment of relativistic RSD and weak-lensing in high-resolution simulation.

⇒ Large halo catalog, taking all relativistic corrections into account.

⇒ Analysis of ΛCDM simulations (WCDM just completed).

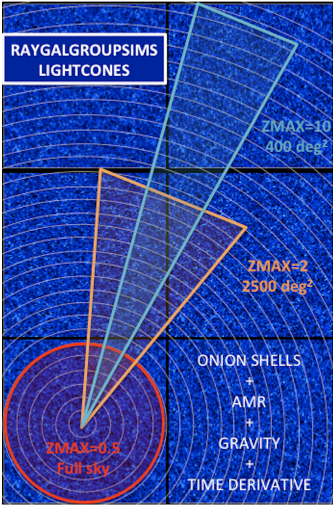


Figure 3 – We used the full sky catalogs.

Observables

The cross-power spectrum allows to look different modes in the correlation function of Θ and Ξ (2 scalars), with comoving distance $\mathcal{R}$:

$$P_{\Theta\Xi}(k, \mathcal{R}_\Theta, \mathcal{R}_\Xi) = \frac{1}{(2\pi)^3} \langle \Theta^*(\boldsymbol{k}, \mathcal{R}_\Theta) \Xi(\boldsymbol{k}, \mathcal{R}_\Xi) \rangle, \tag{6}$$

we will use the cross-correlation coefficients D_l for our matter analysis:

$$D_l^{\Theta\Xi} = \frac{l(l+1)}{2\pi} C_l^{\Theta\Xi} = \frac{l(l+1)}{4\pi^3} \int \mathrm{d}^3\boldsymbol{k}\ j_l(k\mathcal{R}_\Theta) j_l(k\mathcal{R}_\Xi)\ P_{\Theta\Xi}(k), \tag{7}$$

where j_l is the spherical Bessel function.

Example: $\Theta = \delta$ and $\Xi = \kappa$.
We will analyse the cases δ - δ, δ - κ and κ - κ.

Analysis tools

Terminology:

Comoving angular positions are in a FLRW Universe, without gravitational lenses;

Observed angular positions are taking lensing into account;

redz0 refers to a redshift calculation without any corrections;

redz5 refers to a redshift which includes all relativistic perturbations.

Analysis tools:

Linear relativistic calculation & Halofit model (for the non-linear regime): Class (Blas, Lesgourges & Tram 2011);

Cross power spectrum estimator: Polspice (Chon et al., 2003).

Results: Comoving non RSD

Remark: non-linear regime starts around $l = 50 - 70$

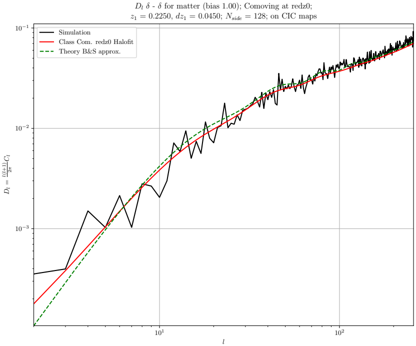


Figure 4 – D_l δ - δ cross-correlation.

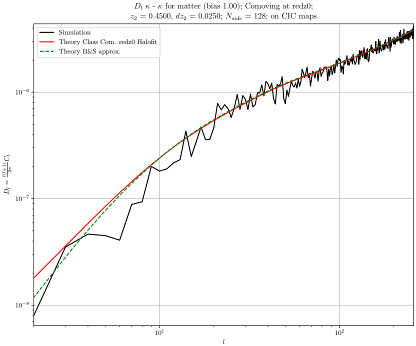


Figure 5 – D_l κ - κ is quite accurate

In D_l δ - δ, there is shot noise $\rightarrow$ in progress.

Results: Comoving non RSD

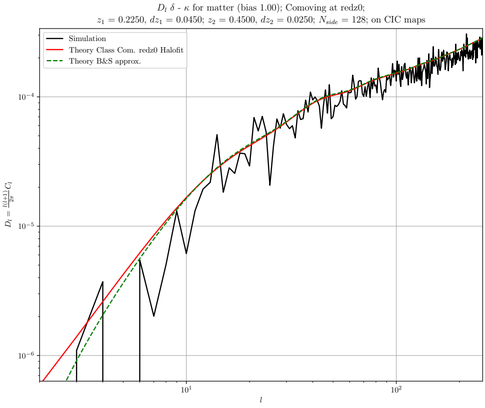


Figure 6 – D_l δ - κ cross-correlation.

Offsetting the shot noise would probably lead to $D_l^{\delta\kappa} \sim 10\%$ smaller than expected for $l > 100 \Rightarrow$ important discrepancy with Class predictions.

Comparing several cases: $D_l^{\delta\delta}$ relativistic corrections

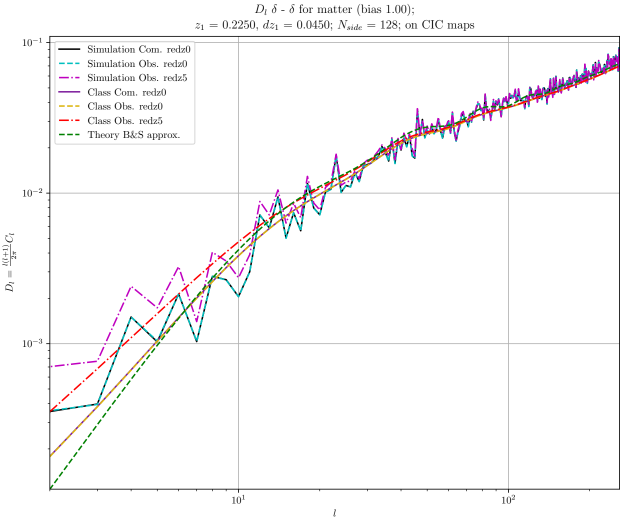


Figure 7 – All $D_l^{\delta\delta}$ cross-correlation corrections.

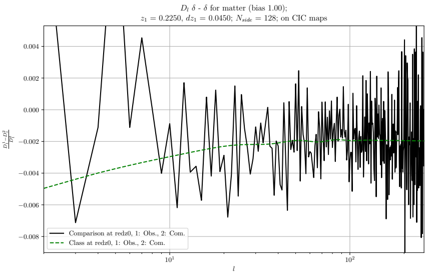


Figure 8 – $D_l^{\delta\delta}$ comparison with and without lensing (in the case redz0): we see the lensing effect.

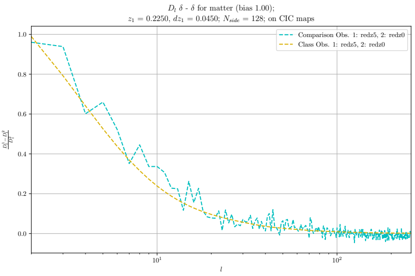


Figure 9 – Comparison with and without RSD (in the case observed): we see the RSD effects.

$\Rightarrow$ RSD more important role than lensing.

$\Rightarrow$ Small discrepancy on RSD effects comparison between Class and the simulations, at very large l.

Comparing several cases: $D_l^{\delta\kappa}$ relativistic corrections

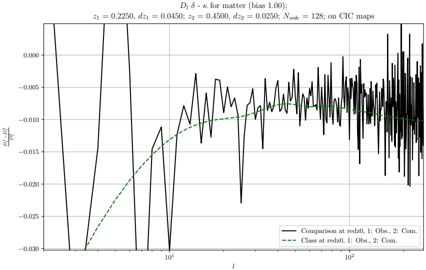


Figure 10 – $D_l^{\delta\kappa}$ comparison with and without lensing (in the case redz0): we see the lensing effect.

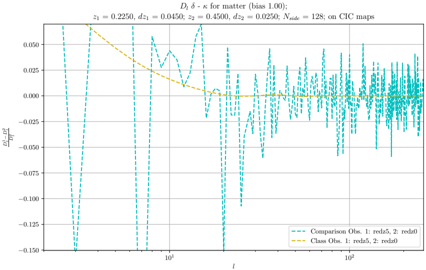


Figure 11 – Comparison with and without RSD (in the case observed): we see the RSD effects.

$\Rightarrow$ For D_l δ - κ, lensing is more important than RSD (nought is mean value).

$\Rightarrow$ Often neglected effect $\rightarrow$ increasing importance with redshift, will be $> 10\%$ in future surveys like Euclid (Ghosh et al., 2018).

$D_l^{\delta\kappa}$ discrepancy still ongoing: any insight welcome!

•Could it be Limber approximation?

$$j_l(k\mathcal{R}) \to \sqrt{\frac{\pi}{2l}}\delta_D(l - k\mathcal{R}) \tag{8}$$

•Could it be line of sight effect? In the Born approximation, with Φ the newtonian potential and $\mathcal{R}_S$ the comoving distance to the source:

$$\begin{aligned}\kappa(\theta) = &\int_0^{\mathcal{R}_S} \mathrm{d}\mathcal{R} \frac{\mathcal{D}(\mathcal{R}_S - \mathcal{R})\mathcal{D}(\mathcal{R})}{\mathcal{D}(\mathcal{R}_S)} \\ &\left[\frac{3H_0^2\Omega_m}{2c^2}(1+z)\delta(\mathcal{D}(\mathcal{R})) - \frac{1}{c^2}\frac{\partial^2}{\partial\xi_3^2}\Phi(\mathcal{D}(\mathcal{R})\boldsymbol{\theta}, \mathcal{R})\right] \\ &= \kappa_\perp + \kappa_\parallel.\end{aligned} \tag{9}$$

$\to \kappa_\parallel$ always neglected $\Rightarrow$ could it be it?

Test of Limber and line of sight approximation.

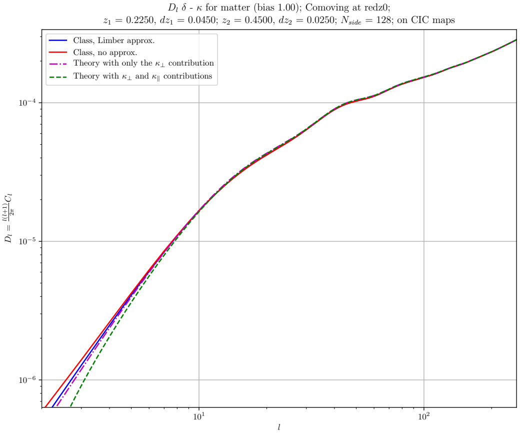


Figure 12 – $D_l^{\delta\kappa}$ in different theories.

$\Longrightarrow$ On small $l < 10$, $\kappa_{||}$ is quite significant.

Conclusion & open questions

We have managed to:

•Accurately reproduce D_l for δ - δ and κ - κ, and point out a discrepancy in D_l δ - κ,

•Compute all the corrections (relativistic RSD & lensing) at once, and analyse the different cross contributions,

•Compute the usually neglected $\kappa_{\parallel}$.

Perspectives:

- Higher resolution $\rightarrow$ larger l, provided to correct shot noise,

- Matter $\rightarrow$ Haloes, subhaloes, galaxies,

- Observational effects (magnification bias and selection effects),

- Shear and reduced shear,

- The strong lensing effect and strong lensing connection.

Open question:

$\star$ Why are the $D_l^{\delta\kappa}$ from the simulations under the prediction?

Thank you for your attention