Cosmic shear simulations for the analysis of LSST data using HOS

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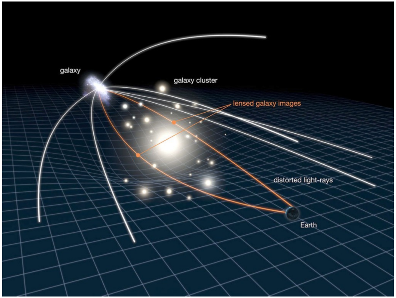
Outline

1. Weak lensing and HOS
2. Generation of the simulations
3. Results
4. Conclusions

Weak gravitational lensing

Weak gravitational lensing **distorts the images of background objects** due to the presence of a foreground matter distribution.



Credits: NASA/ESA

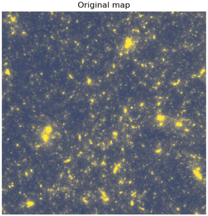
Three lensing regimes:

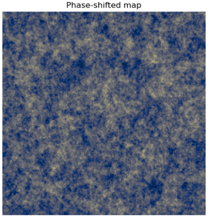
- Cluster lensing. The foreground object is a cluster. Distortions of $\sim$10%.
- Galaxy-galaxy lensing. The foreground object is a galaxy. Distortions of $\sim$1%.
- **Cosmic shear**. Caused by **large-scale structure (LSS)**. Distortions of $\sim$0.1-1%.

Cosmic shear is traditionally analyzed using two-point functions...

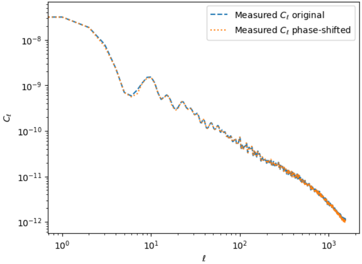
Why higher-order statistics?

1. Two-point functions do not give us information about non-Gaussian features.





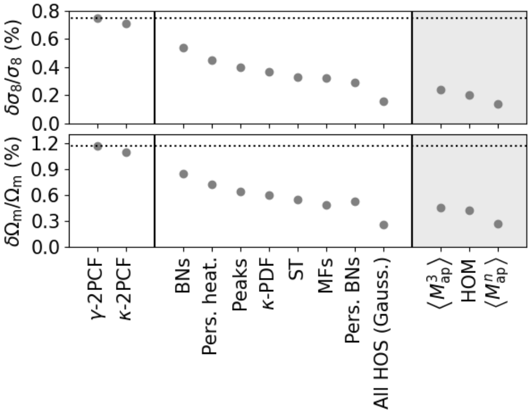
$\longrightarrow$



Different structures but same C_ℓ!

Why higher-order statistics?

2. Two-point functions + HOS = better constraints on cosmological parameters.



Credits: *Euclid* preparation XXVIII - A&A 675, A120 (2023)

Motivation and context

- HOS are a **powerful tool for cosmology**.
- However, they usually lack theoretical predictions.
- Therefore, **we rely on simulations**, which are computationally expensive.
- When generating simulations, we need to **optimize their accuracy vs computing resources** (charged node hours + storage) as a function of
    - volume.
    - mass resolution (mass/particle).
    - number of redshift snapshots.

> Goal: optimize the generation of upcoming **lensing and clustering** simulations needed for the **analysis of LSST data with HOS**.

DESC project: [282] Simulations for Higher-Order-Statistics
https://portal.lsstdesc.org/DESCPub/app/PB/show_project?pid=282

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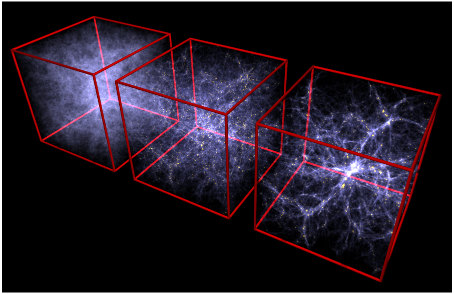
HACC simulations

We construct our lightcones from ***N*-body dark matter (DM) box simulations** produced with the Hybrid Accelerated Cosmology Code (HACC).

- Boxes are evolved from redshift 200 to 0.
- A total of **101 snapshots are stored**, from redshift 4 to 0 (linear spacing in a).
- Simulations are produced in pairs to cancel out cosmic variance.

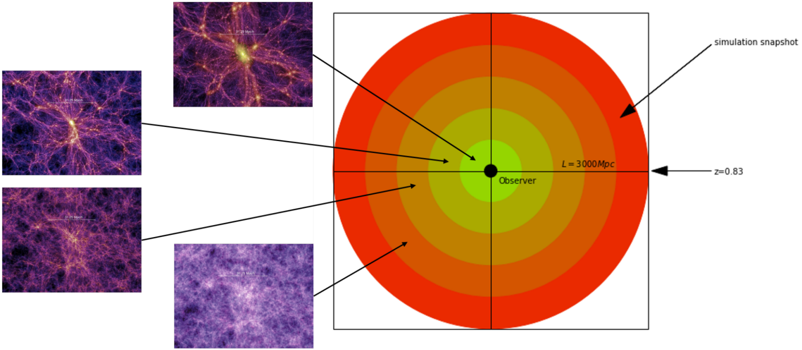
By default:

- Number of DM particles: $N_p = 2048^3$.
- Mass per particle: $2.6 \times 10^9 M_\odot$.
- Size of the box: $L_{\rm box} = 600$ Mpc$/h$.



Credits: V. Springel - MPA-Garching Data Visualization

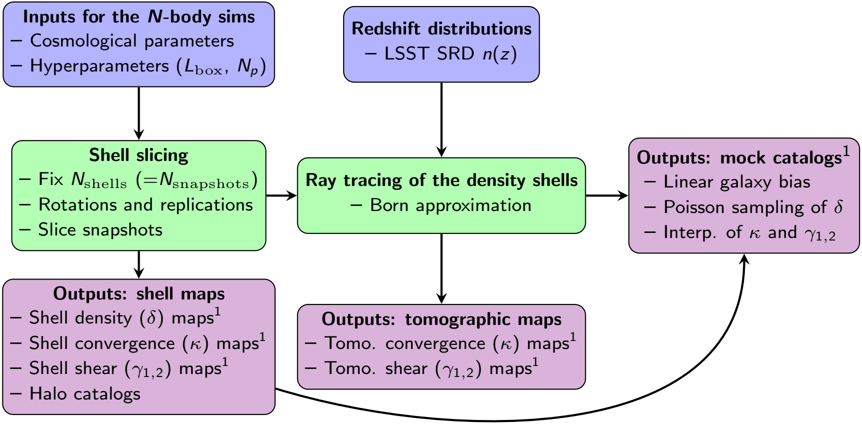
From HACC to lightcones



Credits: R. Booth (2024)

↑ # snapshots ↔ ↑ info about z evolution ✓ ↔ ↑ expensive and ↑ storage !

Pipeline flowchart



Code: `Pollux` (https://github.com/LSSTDESC/pollux.git)

[1] We can measure HOS from these

Outline

Tests

Steps:

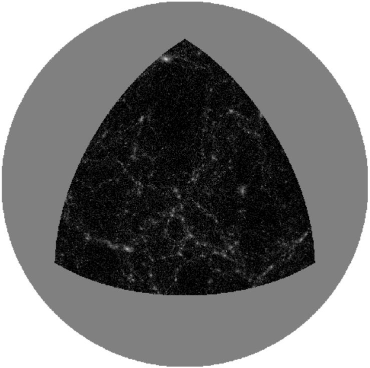
1. We produce lightcones for the two simulation seeds (five observers per simulation seed).
2. We measure the **angular power spectrum** (C_ℓ) from the κ maps.
3. We measure the second, **third and fourth**[1] moments of κ.
4. We average the C_ℓ and the κ moments over the two simulation seeds and the five observers.

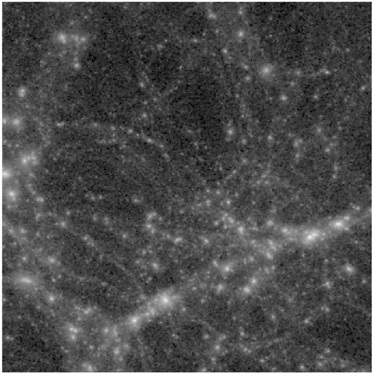
We run the previous steps varying the

- number of snapshots: $N_{\rm snapshots} = \{26,\ 34,\ 51,\ 101\}$.
- number of particles: $N_p = \{2048^3,\ 1024^3\}$.

[1] The third and fourth moments contain non-Gaussian information.

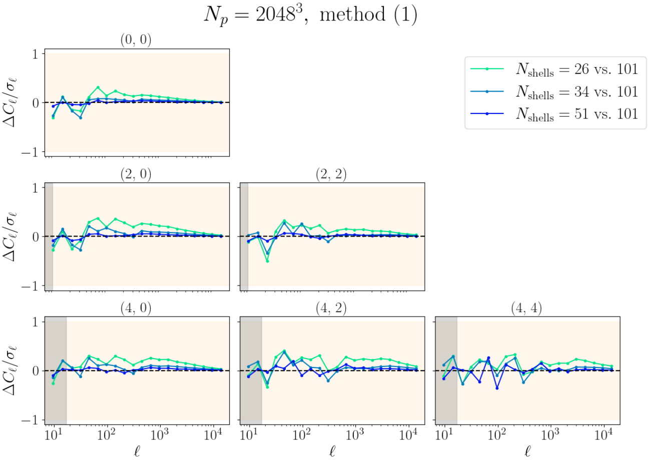
Results: δ map ($N_{\mathrm{snapshots}} = 26$)





δ map of a lightcone shell for one of our simulations. For this particular shell, the redshift slice is given by $z \in (0.016, 0.050)$.

Results: convergence of the C_ℓ with $N_{\rm shells}$



$C_\ell^{N_{\rm shells}}$ vs. C_ℓ^{101}.

Pairwise χ^2 vs. 101

$$\chi^2 = \sum_{ij}\sum_{mn}\sum_{\ell\ell'}\left(C_\ell^{(ij),A} - C_\ell^{(ij),B}\right)\left[\mathrm{Cov}^{-1}\right]_{\ell\ell'}^{(ij),(mn)}\left(C_{\ell'}^{(mn),A} - C_{\ell'}^{(mn),B}\right).$$

N_{shells}	26	34	51	101
26	−−	2.1 (1.2)	4.2 (2.5)	6.2 (2.9)
34	−−	−−	1.7 (1.0)	3.0 (1.9)
51	−−	−−	−−	1.3 (0.74)
101	−−	−−	−−	−−

Pairwise χ^2 for $N_p = 2048^3$ (1024^3).

Moments of κ

The convergence maps are smoothed by a top-hat filter of smoothing length ϑ, $\kappa(\boldsymbol{\theta}) \to \kappa_\vartheta(\boldsymbol{\theta})$.

- Second moment (or covariance):

$$\langle \kappa_\theta^2 \rangle^{ij} = \langle (\kappa_\vartheta^i(\boldsymbol{\theta}) - \langle \kappa_\vartheta^i(\boldsymbol{\theta}) \rangle) \cdot (\kappa_\vartheta^j(\boldsymbol{\theta}) - \langle \kappa_\vartheta^j(\boldsymbol{\theta}) \rangle) \rangle.$$

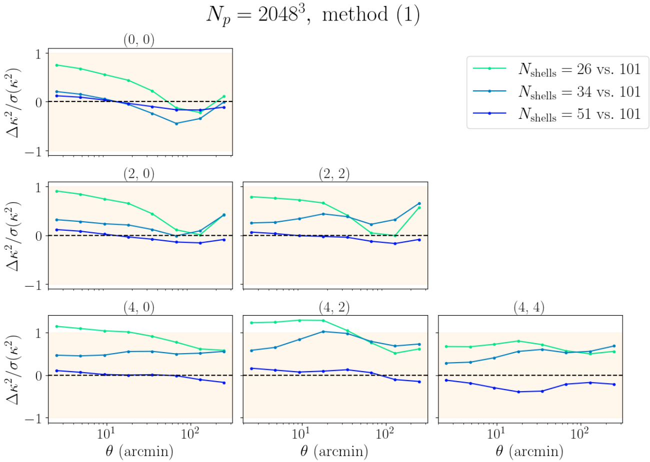
- Third moment (or skewness):

$$\langle \kappa_\theta^3 \rangle^{ijk} = \langle (\kappa_\vartheta^i(\boldsymbol{\theta}) - \langle \kappa_\vartheta^i(\boldsymbol{\theta}) \rangle) \cdot (\kappa_\vartheta^j(\boldsymbol{\theta}) - \langle \kappa_\vartheta^j(\boldsymbol{\theta}) \rangle) \cdot (\kappa_\vartheta^k(\boldsymbol{\theta}) - \langle \kappa_\vartheta^k(\boldsymbol{\theta}) \rangle) \rangle.$$

- Fourth moment (or kurtosis):

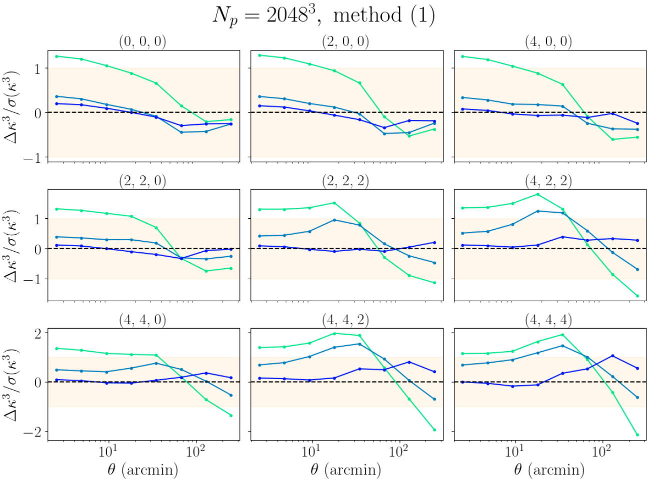
$$\begin{aligned}\langle \kappa_\theta^4 \rangle^{ijkl} = \langle (\kappa_\vartheta^i(\boldsymbol{\theta}) - \langle \kappa_\vartheta^i(\boldsymbol{\theta}) \rangle) \cdot (\kappa_\vartheta^j(\boldsymbol{\theta}) - \langle \kappa_\vartheta^j(\boldsymbol{\theta}) \rangle) \\ \cdot (\kappa_\vartheta^k(\boldsymbol{\theta}) - \langle \kappa_\vartheta^k(\boldsymbol{\theta}) \rangle) \cdot (\kappa_\vartheta^l(\boldsymbol{\theta}) - \langle \kappa_\vartheta^l(\boldsymbol{\theta}) \rangle) \rangle.\end{aligned}$$

Results: convergence of $\langle \kappa^2 \rangle$ with N_{shells}



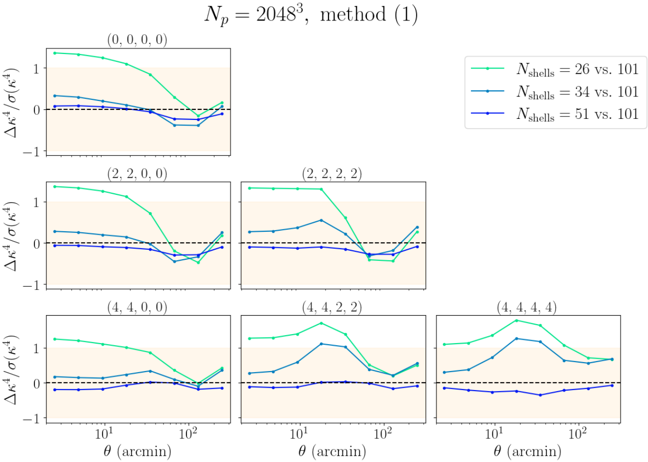
$\langle \kappa^2_{N_{\mathrm{shells}}} \rangle$ vs. $\langle \kappa^2_{101} \rangle$.

Results: convergence of $\langle \kappa^3 \rangle$ with N_{shells}



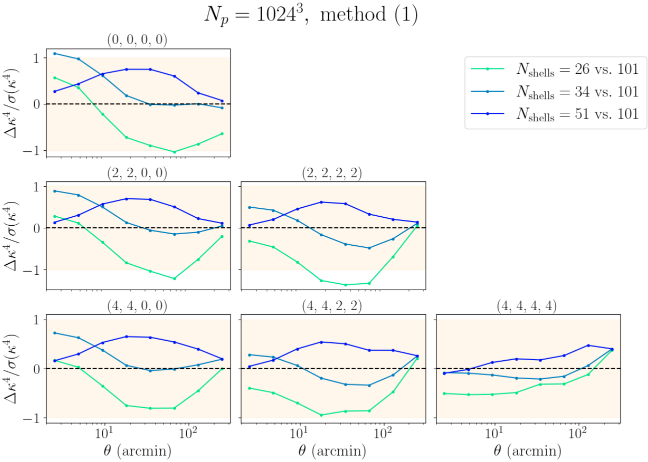
$\langle \kappa^3_{N_{\mathrm{shells}}} \rangle$ vs. $\langle \kappa^3_{101} \rangle$.

Results: convergence of $\langle \kappa^4 \rangle$ with $N_{\rm shells}$



$\langle \kappa^4_{N_{\rm shells}} \rangle$ vs. $\langle \kappa^4_{101} \rangle$.

Results: $\langle \kappa^4 \rangle$ vs. 101 ($N_p = 1024^3$)



$\langle \kappa^4_{N_{\rm shells}} \rangle$ vs. $\langle \kappa^4_{101} \rangle$.

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Conclusions

Goal: optimize the generation of upcoming **lensing and clustering** simulations needed for the **analysis of LSST data with HOS**.

- Optimization of the simulations:
  1. We need, at least, $N_{\rm shells} = 51$.
  2. $N_p = 1024^3$: enough for two-point statistics but not for HOS. $N_p = 2048^3$ looks good for both.
  3. We also tested other algorithms for building the lightcones: consistency between them.
- Related ongoing projects/tasks:
  1. development of `Pollux` (C. Doux).
  2. baryonification of the dark matter shells (A. Vera).
  3. intrinsic alignment studies (J. Harnois-Deraps).
  4. measure different HOS (J. Armijo).
- Next steps:
  1. Comparison with theory.
  2. Run simulations at different cosmologies.

Other projects

- **Dark Energy Spectroscopic Instrument (DESI)**: angular BAO from $w(\theta)$.
  - No need to assume cosmology to transform $z \to d$.
  - Comparison with the fiducial DESI results.

- **Dark Energy Survey (DES)**: combination of DES BAO + DESI BAO.
  - New DES BAO likelihood removing the overlapping area with DESI.
  - Inference of cosmological parameters combining DES BAO + DES SN + DESI BAO + Planck CMB
  - Constraints on **dynamical dark energy**.

Thank You!