

Simulation-based inference with the integrated 3PCF

From a validated pipeline to DES Y3 constraints

David Gebauer

PhD student with Cora Uhlemann

with A. Halder, Z. Gong, S. Seitz and D. Anbajagane



Funded by
the European Union

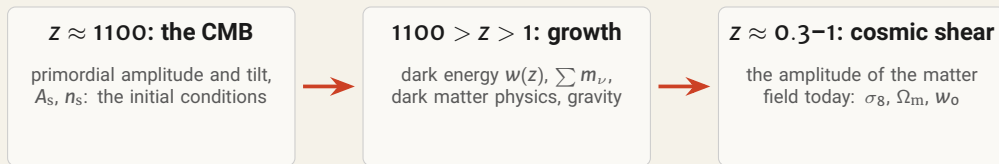


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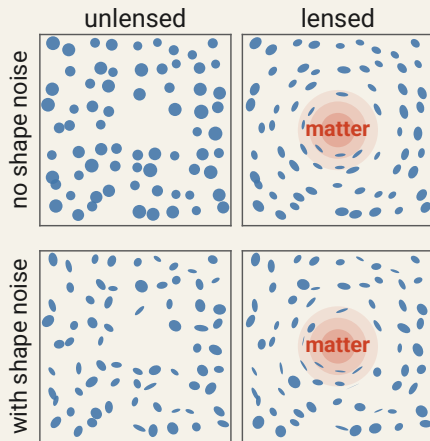
Why cosmic shear



- Planck: initial conditions, Λ CDM predicts $S_8 = \sigma_8 \sqrt{\Omega_m/0.3} \approx 0.83$ today
- Lensing: the amplitude today, all matter, no galaxy bias
- Mismatch: physics in between ($w(z)$, $\sum m_\nu$, dark matter, gravity)
- Status: Stage-III lensing $\approx 2\sigma$ low in S_8

⇒ **Lensing tests how the initial conditions of the CMB grew**

Weak gravitational lensing

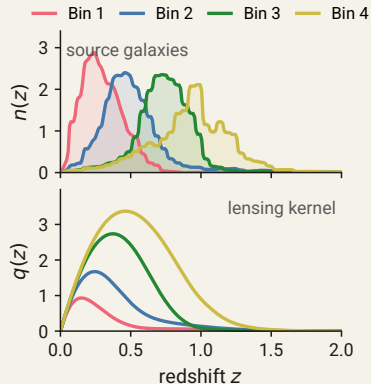


- Matter along the line of sight deflects the light of distant galaxies
- Sensitive to all matter $\rightarrow$ no tracer bias
- The shear γ distorts the galaxy shapes, the convergence κ magnifies them
- $|\gamma| \sim 1\%$, intrinsic ellipticities $\sim 30\%$
- $e^{\text{obs}} \approx e^{\text{int}} + \gamma$ with $\langle e^{\text{int}} \rangle = 0$

$\Rightarrow$ **Galaxy shapes trace the total matter distribution**

Cosmic shear: a projection of the matter density field

$$\kappa(\theta) = \frac{3H_0^2 \Omega_m}{2c^2} \int_0^{\chi_H} d\chi \frac{q(\chi)}{a(\chi)} \delta(\chi\theta, \chi), \quad \gamma \leftrightarrow \kappa$$



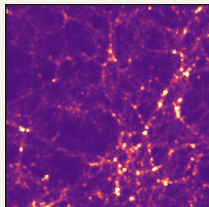
DES Y3 source redshift distributions and lensing kernels $q(z)$

- Sources in 4 tomographic bins with photometric redshifts
- Mixes scales $10^{-3} < k < 10^1$ (non-linear regime, baryonic feedback)
- Amplitude $\propto \Omega_m \sigma_8$
- w_0 through growth and distances

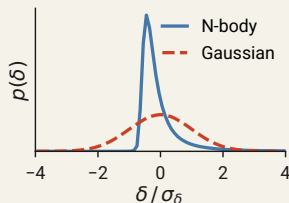
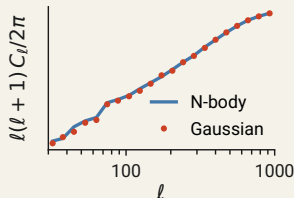
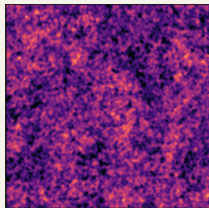
⇒ **Constrains S_8 , Ω_m and weakly w_0 from the non-linear matter field**

The non-Gaussian field

N-body shell at $z \approx 0.2, 15^\circ \times 15^\circ$



Gaussian field, same C_ℓ



- Shear two-point correlation function is a weighted projection of $P_\delta(k)$

$$\xi_{\pm}(\theta) = \int \frac{\ell d\ell}{2\pi} J_{0/4}(\ell\theta) P_{\kappa}(\ell)$$

- Complete for a Gaussian field, as the initial conditions are
- Gravitational collapse induces non-Gaussianities

⇒ **Beyond-2-point statistics recover non-Gaussian information**

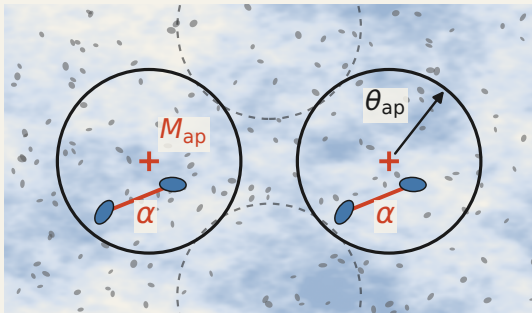
Which higher-order statistic?

Statistic	Information captured	Measurement cost	Analytic model
2PCF	Gaussian part	low, pairs	yes
3PCF	full bispectrum	high, triplets	yes, expensive
i3PCF	squeezed bispectrum	low, pairs + filter	yes
Map level	everything	very high	no

- Every statistic beyond the 2PCF needs simulations for its likelihood
- Analytic model as independent check of the simulation pipeline
- 2PCF + i3PCF, measured from the same galaxy pairs, both with analytic models

⇒ **The i3PCF adds bispectrum information at two-point cost**

The integrated 3-point correlation function



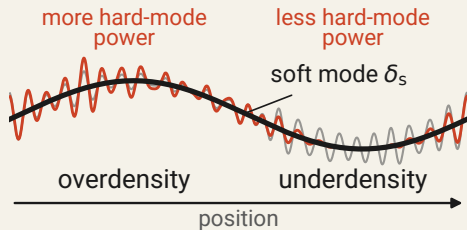
Sketch after Halder et al. 2023

- Aperture mass M_{ap} at the centre of a patch, with a compensated filter of radius θ_{ap}
- Local 2PCF $\xi_{\pm}(\alpha)$ from the galaxy pairs inside the patch
- Correlate the two over all patches

$$\zeta_{\pm}(\alpha) = \langle M_{\text{ap}} \xi_{\pm}(\alpha) \rangle_{\text{patches}}$$

⇒ **An integrated shear bispectrum, measured with pairs and a filter sum**

Why the i3PCF

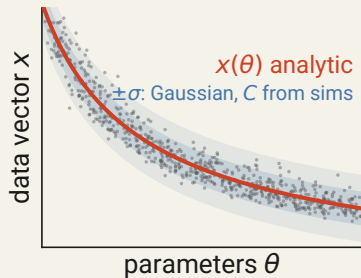


Grey: without mode coupling. Sketch after E. Komatsu

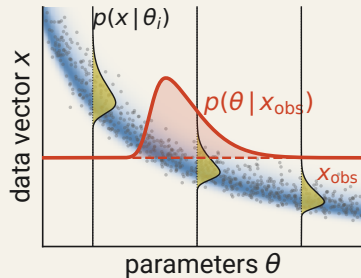
$$B(k_s, k_h) \xrightarrow{k_s \ll k_h} \frac{\partial \ln P(k_h)}{\partial \delta_s} P(k_s) P(k_h)$$

- Squeezed bispectrum: response of the hard-mode power to a soft mode
- Gravitational coupling, from the response of $P(k)$
- Cost: pairs + filter, $\mathcal{O}(n^2)$, on GPU with CosmoFuse

Simulation-based inference



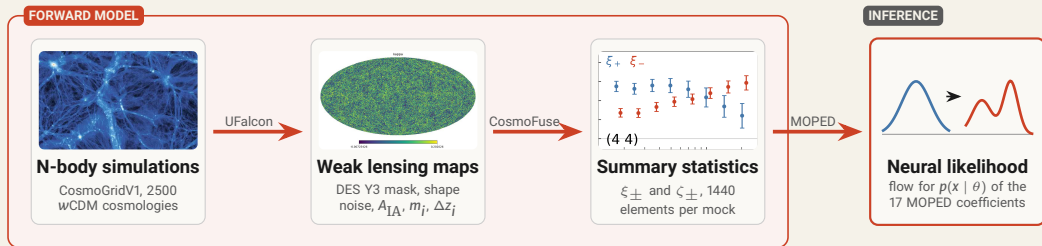
Traditional: analytic model for the mean $x(\theta)$,
Gaussian likelihood, covariance from simulations



SBI: simulate (θ, x) pairs, learn $p(x | \theta)$ with a
neural density estimator, slice at the data

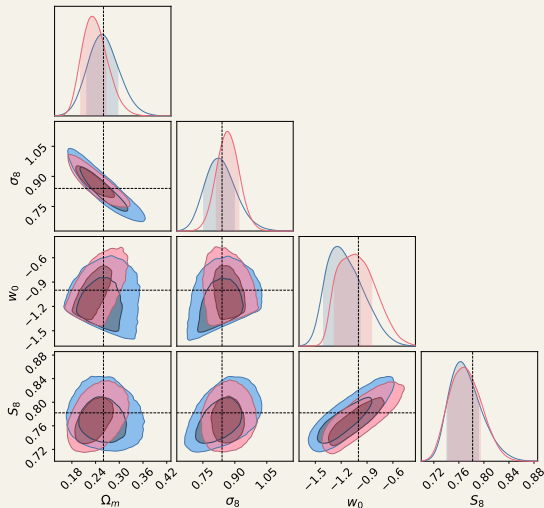
- No explicit model of the likelihood needed
- All effects are simulated in the forward model
- Sample the learned likelihood with MCMC to get $p(\theta | x_{\text{obs}})$

The SBI3PCF framework (Paper 1, arXiv:2510.13805)



- 17 parameters: 6 w CDM, baryonification (M_c , ν), NLA A_{IA} , 4 shear biases m_i , 4 redshift shifts Δz_i
- DES Y3 mask and per-pixel shape noise from the catalogue; 2500 cosmologies, 70,000 mocks, 16,000 fiducial footprints
- Forward model validated against analytic predictions; source clustering and reduced shear negligible for DES Y3

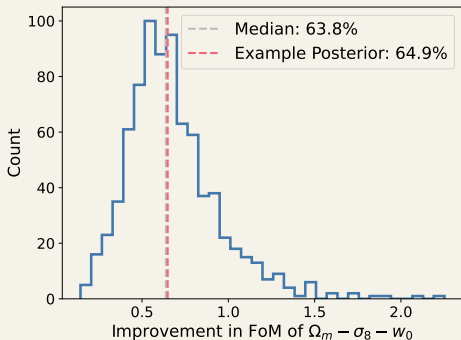
Paper 1: constraints on a DES Y3-like mock



- Single noisy mock at the fiducial cosmology (dashed lines)
- 2PCF alone and 2PCF + i3PCF
- True Ω_m , σ_8 , S_8 recovered without bias; w_0 weakly constrained, as for any cosmic shear analysis
- Coverage test passed on 1250 test mocks: the credible intervals are calibrated

⇒ Adding the i3PCF tightens σ_8 and Ω_m most

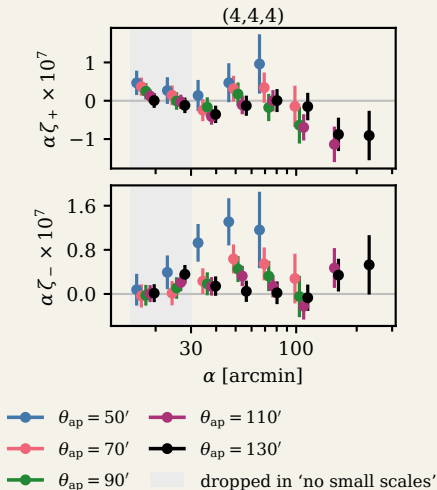
Paper 1: expected gain from the i3PCF



- 800 independent fiducial noise realisations
- Figure of merit $1/\sqrt{\det \text{Cov}}$ in $\Omega_m - \sigma_8 - w_0$
- Median improvement **63.8 %**, every realisation positive
- Largest gain for σ_8 : 68 % interval 31 % narrower

⇒ **The i3PCF provides a significant improvement in parameter constraints**

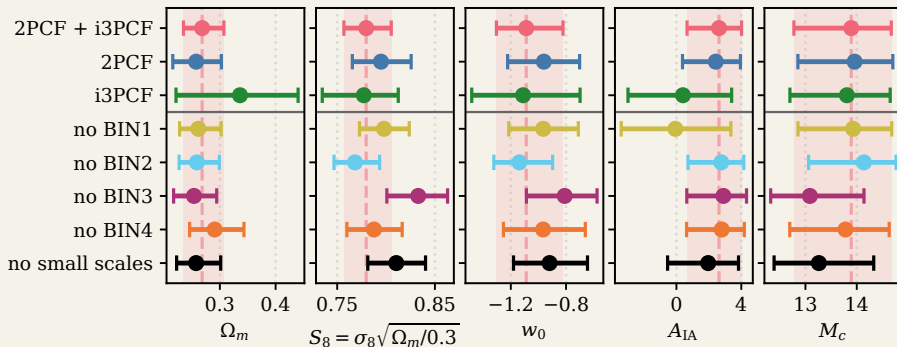
DES Y3: first detection of the i3PCF on survey data



- DES Y3 shape catalogue: 100 million galaxies, 4143 deg², 4 redshift bins, on 7' pixels
- Same estimators, mask and pixel weights for the data and every mock
- S/N: 2PCF 33.5, i3PCF 38.0, 2PCF + i3PCF 50.3; each aperture radius at S/N 11–15

⇒ **The i3PCF is clearly detected on Stage-III data**

Internal consistency of the blinded measurement



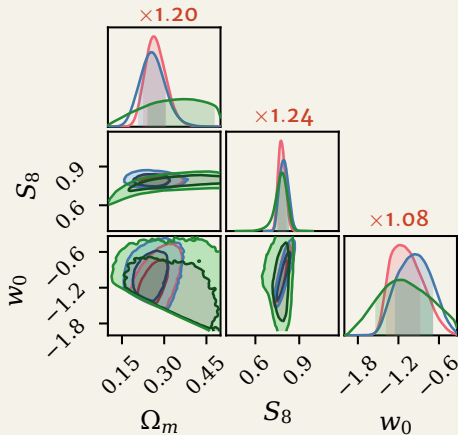
Blind analysis:

- ellipticities rescaled by an unknown factor
- all analysis choices frozen
- list of tests must be passed

Variations of the data vector:

- drop one tomographic bin
- drop two smallest angular bins

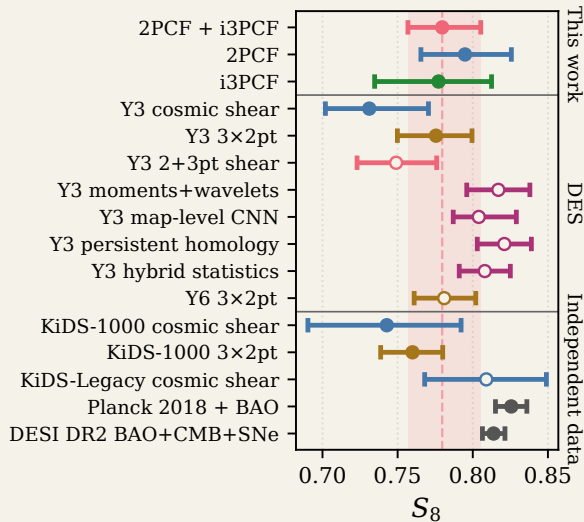
w CDM constraints from DES Y3



	Ω_m	S_8	w_0
2PCF	$0.258^{+0.045}_{-0.042}$	$0.795^{+0.031}_{-0.029}$	$-0.96^{+0.26}_{-0.26}$
i3PCF	$0.336^{+0.104}_{-0.115}$	$0.777^{+0.035}_{-0.042}$	$-1.11^{+0.41}_{-0.37}$
2PCF + i3PCF	$0.268^{+0.039}_{-0.033}$	$0.780^{+0.026}_{-0.023}$	$-1.09^{+0.27}_{-0.22}$

- The 2PCF constrains S_8
- i3PCF constrains $\sigma_8 \Omega_m^\alpha$ with $\alpha > 0.5$
- The joint posterior sits at the intersection
- Only weak constraint on feedback:
 $\log M_c = 13.9^{+0.8}_{-1.1}$
- FoM(Ω_m, S_8, w_0) $\times 1.57$ over the 2PCF

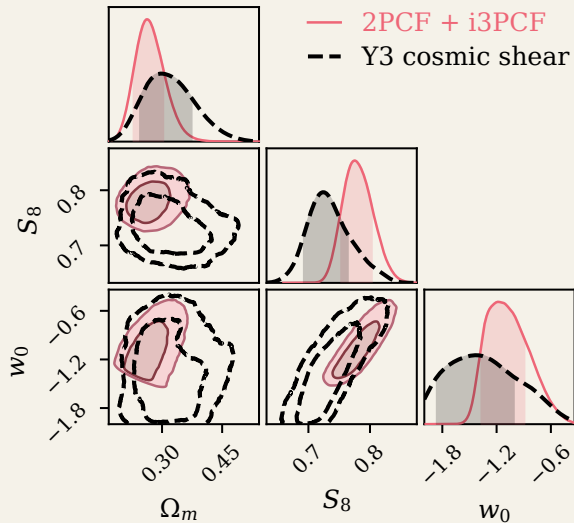
Comparison with literature



- S_8 within 0.1σ of DES Y3 3×2 pt
- 2PCF-only result consistent with the official DES Y3 cosmic shear chain
- Map-based SBI results higher in S_8
- Parameter-shift tension with independent data:
 - 0.4σ KiDS-1000,
 - 1.6σ DESI DR2
 - 2.2σ for Planck 2018 + BAO

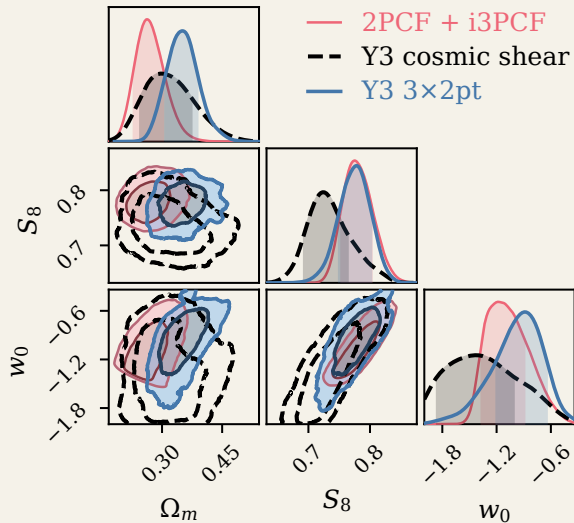
⇒ **No significant tension**

Comparing with literature



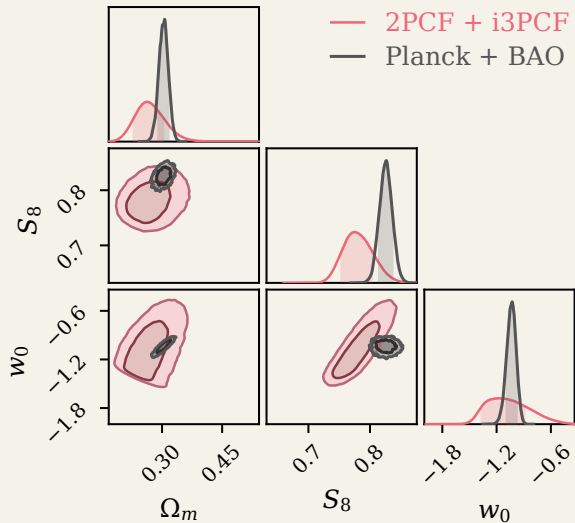
- Caveat: different w_0 priors
- Joint analysis overlaps DES Y3 cosmic shear

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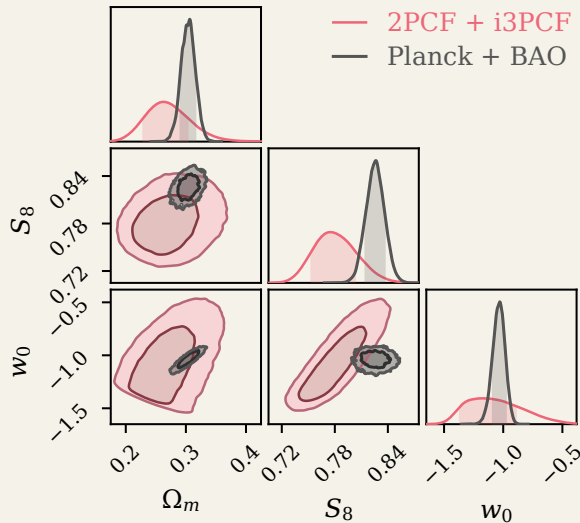
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- Planck 2018 + BAO lies in high- Ω_m , high- S_8 corner
- Shift is:
 - 1.3σ in (Ω_m, S_8)
 - 2.2σ in (Ω_m, S_8, w_0)

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⇒ **Lensing prefers lower S_8**

Summary & outlook

- ⇒ We have a forward model validated with analytical predictions
- ⇒ First i3PCF detection on survey data ⇒ First SBI analysis of a 3-point shear statistic
- ⇒ Blinded DES Y3 analysis passed all pre-unblinding tests
- ⇒ $S_8 = 0.780^{+0.026}_{-0.023}$, $\Omega_m = 0.268^{+0.039}_{-0.033}$, $w_0 = -1.09^{+0.27}_{-0.22}$
- ⇒ FoM $\times 1.57$ over the 2PCF from scales $\geq 15'$
- ⇒ No tension with external data

Next:

- Add more summary statistics (1-pt PDF)
- Go to multi-probe (GC, CMB lensing)



Paper 1



gebauer.ai