

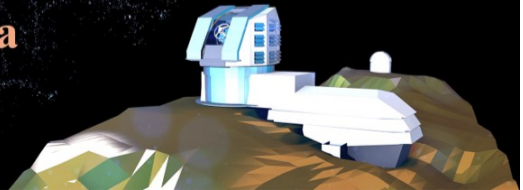


Fourth Workshop on **Current Challenges in Cosmology**

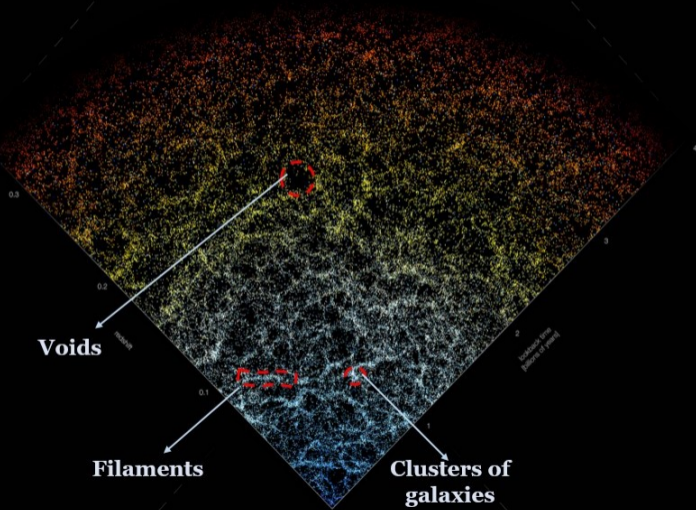
Enhancing cosmological constraints with joint galaxy clustering and weak lensing analysis

Lina Julieth Castiblanco Tolosa

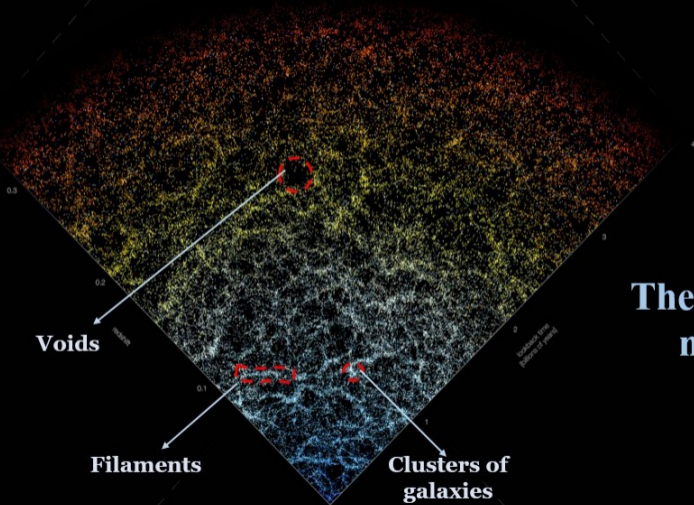
**UNIVERSITÄT
BIELEFELD**



The large-scale structure of the universe, LSS

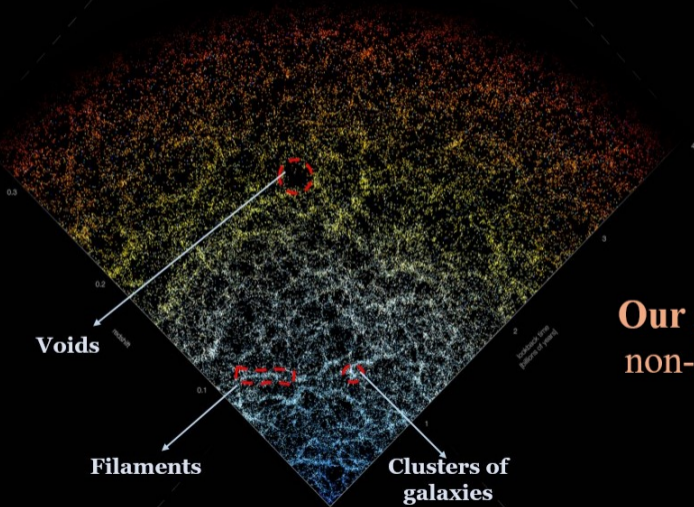


The large-scale structure of the universe, LSS



The late-time Universe is
nonlinear and non-
Gaussian

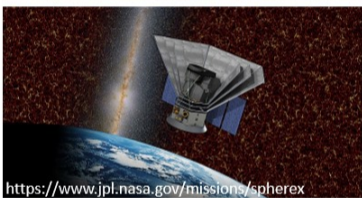
The large-scale structure of the universe, LSS



Our goal: extract maximal non-Gaussian information



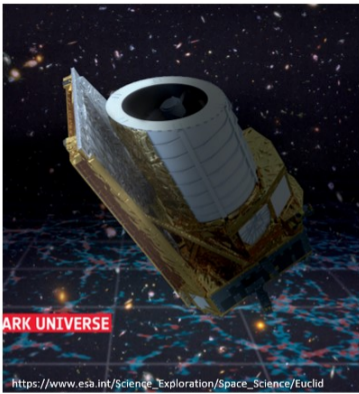
<https://www.desi.lbl.gov/>



<https://www.jpl.nasa.gov/missions/spherex>



<https://www.sdss3.org/>



https://www.esa.int/Science_Exploration/Space_Science/Euclid



<https://gallery.lsst.org/bp/#/>



<https://www.physics.ox.ac.uk/research/group/square-kilometre-array-ska>

**We are in the era of
precision cosmology**

<https://mapoftheuniverse.net/>

Galaxy clustering

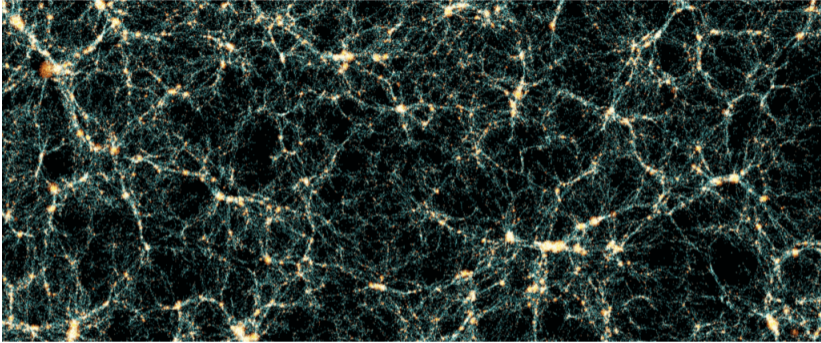


Image extracted from the Euclid Flagship simulations catalogue. Credits: Jorge Carretero and Pau Tallada

- Galaxies trace the underlying matter distribution across cosmic time.
- Encodes information about cosmology and structure growth

Galaxy clustering

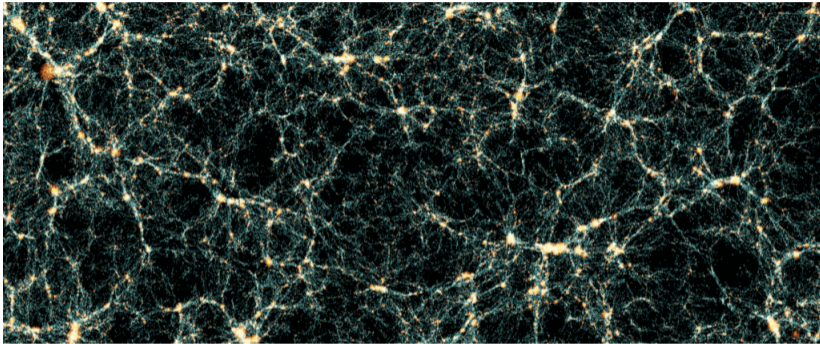
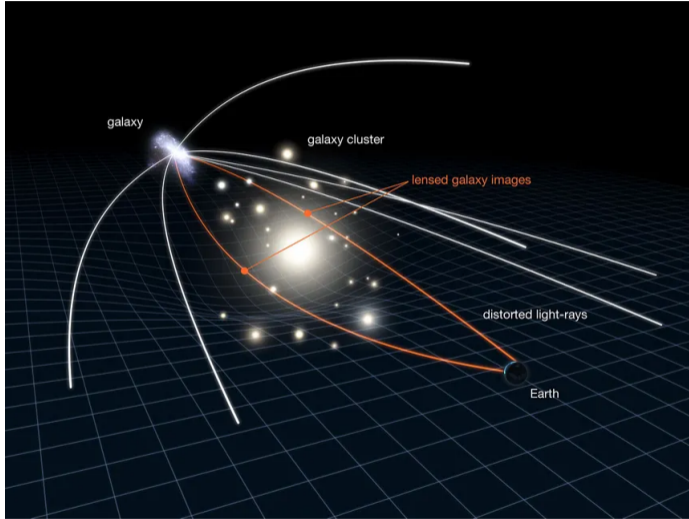


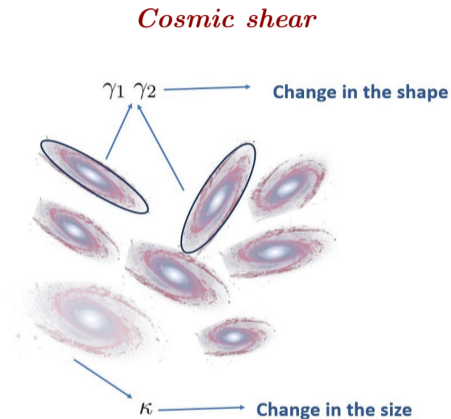
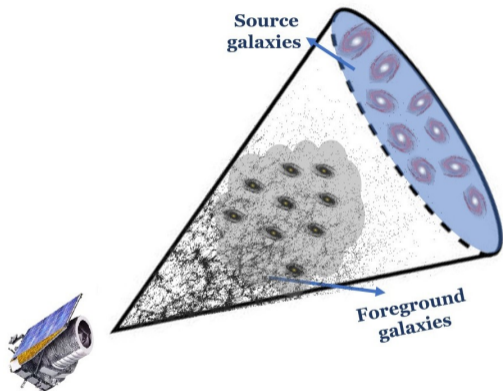
Image extracted from the Euclid Flagship simulations catalogue. Credits: Jorge Carretero and Pau Tallada

- Galaxies trace the underlying matter distribution across cosmic time \implies Bias tracer
- Encodes information about cosmology and structure growth

Gravitational weak lensing



Gravitational weak lensing

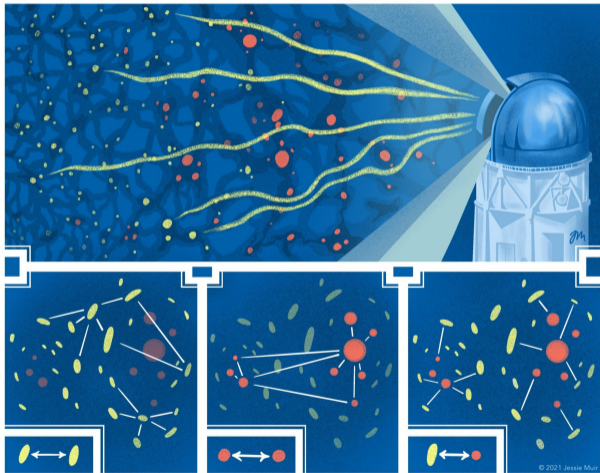


$$|\gamma_1| \ll 1 \quad |\gamma_2| \ll 1 \quad |\kappa| \ll 1$$

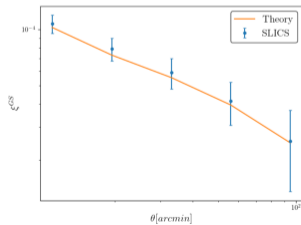
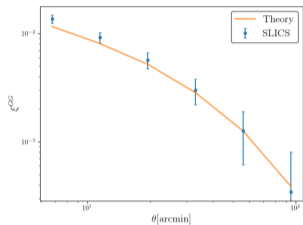
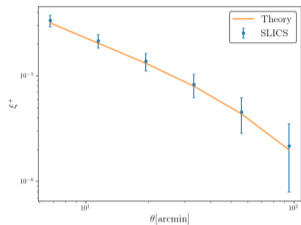
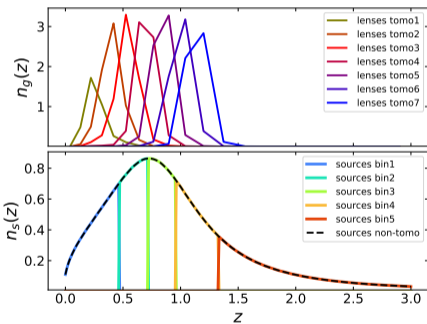
The weak lensing convergence κ is defined as the line-of-sight projection of the matter density distribution between the observer and the galaxy source

Two-point correlation functions (3×2 -point correlations)

- Powerful and robust probes of cosmology.
- Sensitive to geometry and structure growth.
- Missing non-Gaussian information from nonlinear evolution.



Two-point correlation functions (3×2 -point correlations)



Higher-order statistics Forecast for Euclid

- HOS capture extra cosmological information beyond 2-point statistics.
- HOS + 2-point statistics break degeneracies and improve constraints.

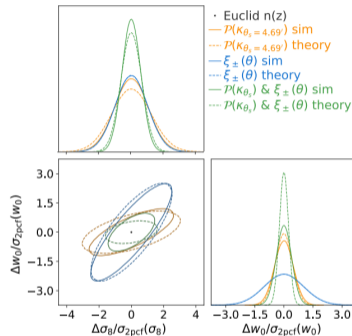
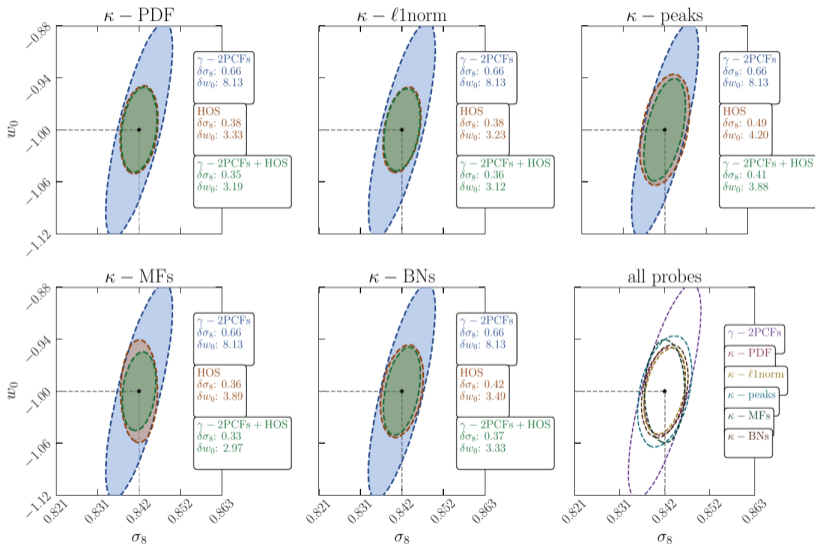


Fig. 43. Constraints on σ_8 and w_0 from a Fisher analysis of ξ_{\pm} and the convergence PDF, when keeping all other cosmological parameters fixed, normalised by the constraints of second-order statistics alone. We assumed a *Euclid*-like source redshift distribution to derive the results. The ξ_+ and ξ_- values were taken in the range of 1:65 to 201'. The PDF was measured for convergence fields smoothed by a tophat filter of radius 4:69. Covariances were estimated from the SLICS (Harnois-Déraps et al. 2018), derivatives were either modelled analytically (dashed lines) or estimated from the DUSTGRAIN-pathfinder simulations (Giocoli et al. 2018, solid lines).

Higher-order statistics Forecast for Euclid



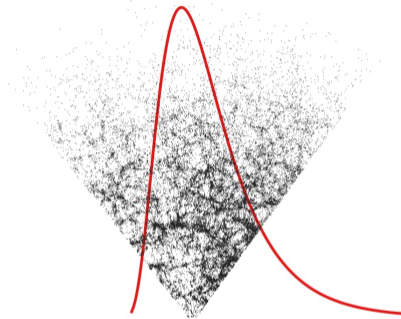
One-Point statistics

Encodes non-Gaussian information

Powerful for extracting cosmological information

Easy to measure

Predicted with high accuracy on mildly nonlinear scales



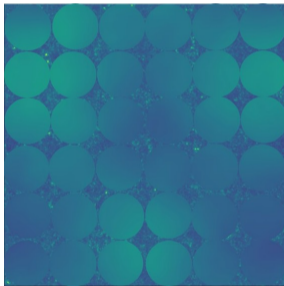
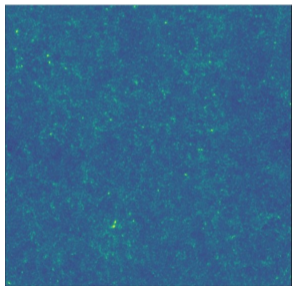
Galaxy clustering N_g

C.Uhlemann, O.Friedrich,
F.Villaescusa-Navarro, A.Banerjee,
S.Codis (2019)

Weak lensing κ

A. Barthelemy, S. Codis,
C.Uhlemann, F.Bernardeau,
R.Gavazzi (2020)

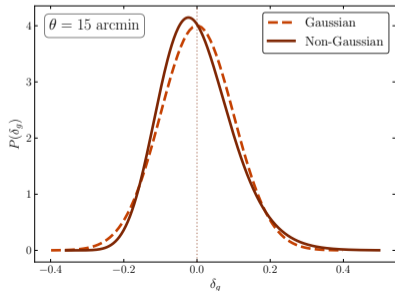
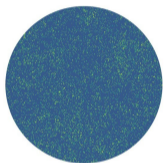
Measuring the one-point PDF



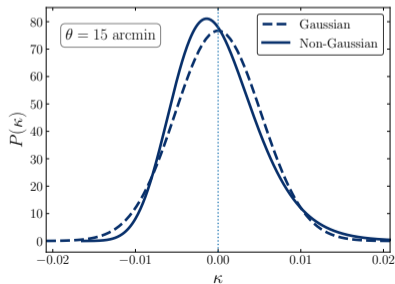
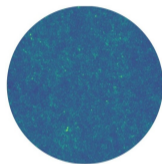
- Divide the distribution into various volumes
- Overlapping cells are allowed
- Smooth the field on each cell
- Count objects in each cell
- Plot a histogram

One-Point statistics

Galaxy clustering



Weak lensing

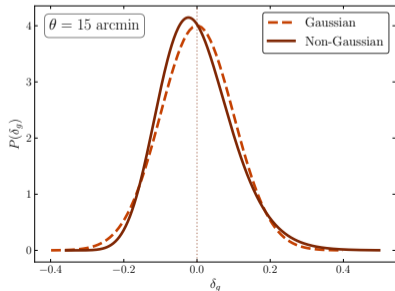
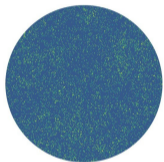


The PDFs are completely characterized by:

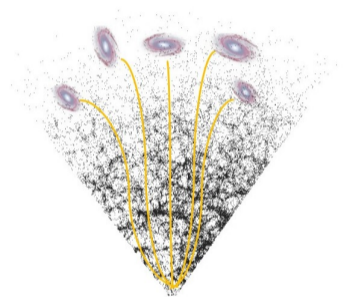
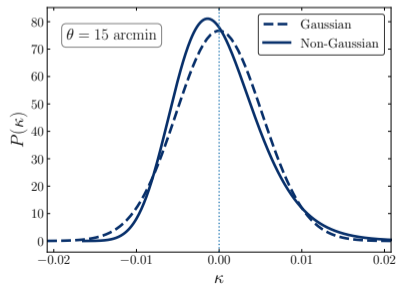
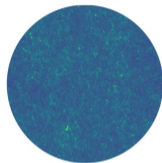
- Variance $\sigma^2 = \langle \delta^2 \rangle$
- Skewness $S_3 \sim \langle \delta^3 \rangle$
- Higher order correlation functions

One-Point statistics

Galaxy clustering

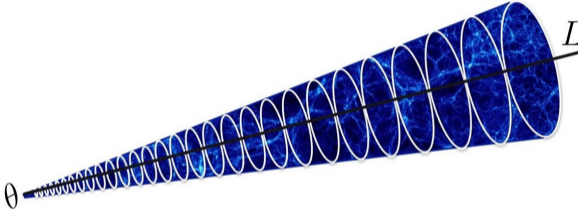


Weak lensing



Full Joint-PDF shape
disentangles tracer bias from
structure growth.

PDF modelling for Projected fields



$$\delta_i(\hat{\mathbf{n}}) = \int_0^\infty d\chi w_i(\chi) \delta_{3D}(\chi \hat{\mathbf{n}}, \chi)$$

Weak lensing convergence

$$w_\kappa(\chi) = \frac{3\Omega_m H_0^2}{2c^2} \int_z^\infty dz' \frac{[\chi(z') - \chi(z)] \chi(z)}{\chi(z')} (1+z) n_s(z')$$

Encodes the cosmological information

Projected galaxies

$$w_g(\chi) = n_g(z(\chi)) \frac{dz}{d\chi}$$

PDF modelling from the *Large Deviation Theory*

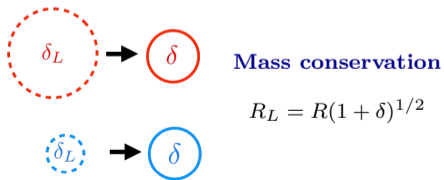
Oliver Friedrich, Lina Castiblanco, Anik Halder, Cora Uhlemann (doi:10.1093/mnras/staf2181)

Early time PDF

$$p(\delta_L) \sim \exp(-\delta_L^2/2\sigma_L^2), \quad \sigma_L^2 \rightarrow 0$$

Cylindrical collapse

$$\delta_L \simeq \nu \left(1 - \rho^{-1/\nu}\right), \quad \nu_{2D} = \frac{7}{5}$$



Late time PDF with LDT

CGF: $\phi_\theta(\lambda_g, \lambda_\kappa) \rightarrow$ Encodes all $\langle \delta_{\text{cyl}}^n \rangle_c$

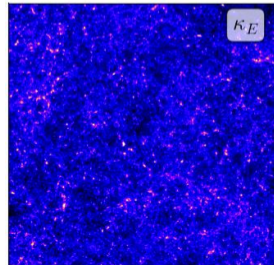
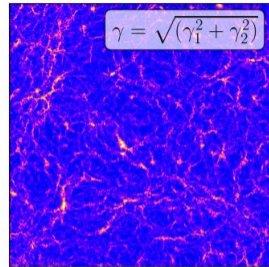
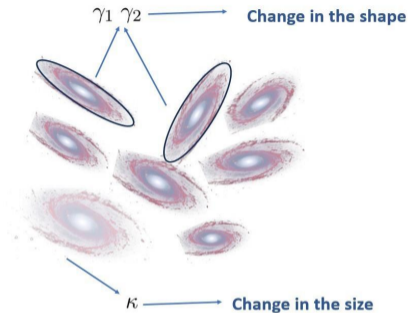


Inverse Laplace transformation



$$P(\delta_g, \kappa) = \int \frac{d\lambda_g d\lambda_\kappa}{(2\pi)^2} e^{\phi_\theta(i\lambda_g, i\lambda_\kappa) - i\lambda_g \delta_g - i\lambda_\kappa \kappa}$$

Convergence reconstruction



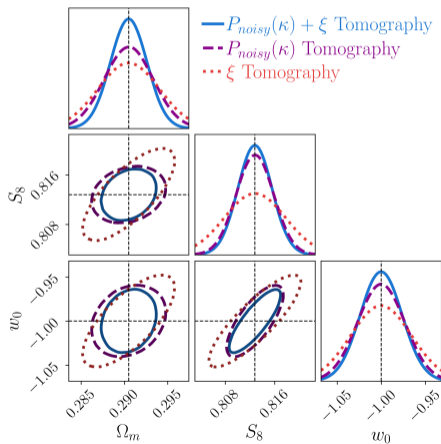
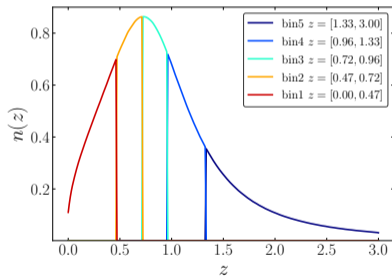
Kaiser-Squires reconstruction

Take into account the mixing of frequencies

Barthelemy, A.Halder, Z.Gong,
C.Uhlemann, (2023)

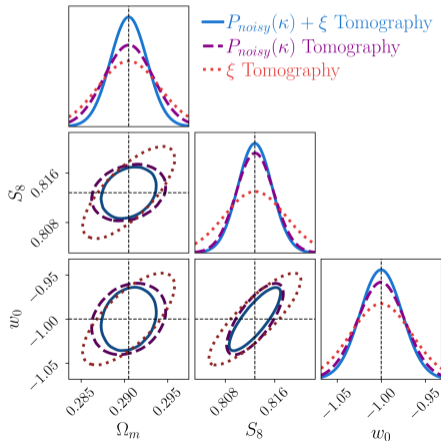
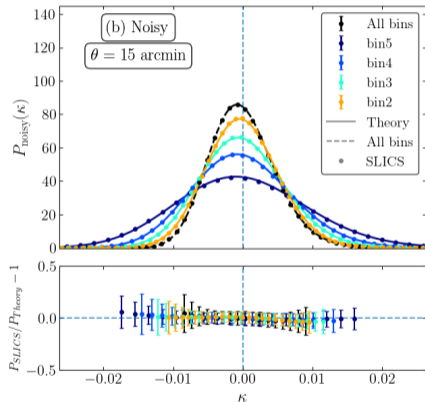
Tomographic analysis with the κ PDF

Lina Castiblanco, Cora Uhlemann, Joachim Harnois-Déraps, Alexandre Barthelemy (doi: 10.33232/001c.121302)



Tomographic analysis with the κ PDF

Lina Castiblanco, Cora Uhlemann, Joachim Harnois-Déraps, Alexandre Barthelemy (doi: 10.33232/001c.121302)



The theoretical predictions are accurate by less than 5%-level around the PDF peak.

Projected Galaxy PDF modelling

Galaxies trace matter, with:

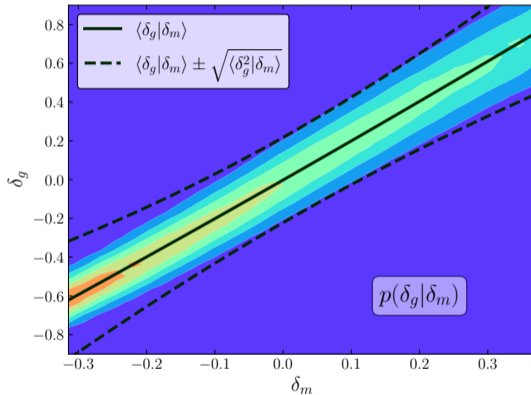
Galaxy bias

$$\nearrow \langle \delta_g | \delta_m \rangle \rightarrow (b_1^E, b_2^E)$$

$p(\delta_g | \delta_m)$

$$\searrow \frac{\langle \delta_g^2 | \delta_m \rangle}{\langle \delta_g | \delta_m \rangle} \rightarrow (\alpha_0, \alpha_1, \alpha_2)$$

Stochasticity



Spectroscopic tracer One-Point Statistics

Beth McCarthy Gould, Lina Castiblanco, Cora Uhlemann, Oliver Friedrich (doi:10.33232/001c.127800)

Galaxy bias

$$\langle \delta_t | \delta_m \rangle$$

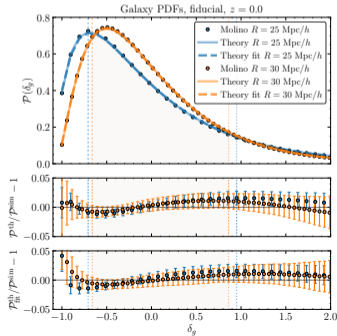
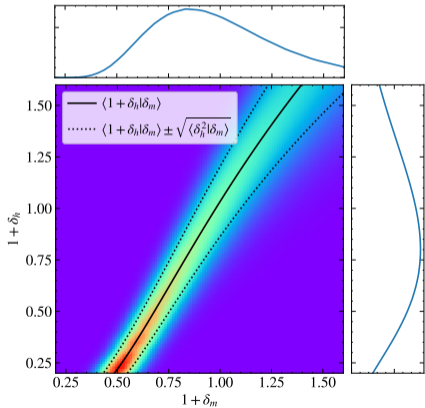
Gaussian Lagrangian model

Stucker et al. 2024

Shot noise

$$\langle \delta_t^2 | \delta_m \rangle \propto \alpha_0 + \alpha_1 \delta_m + \alpha_2 \delta_m^2$$

Friedrich et al. (2022)

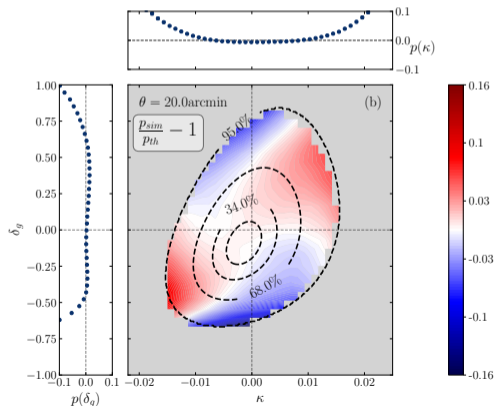
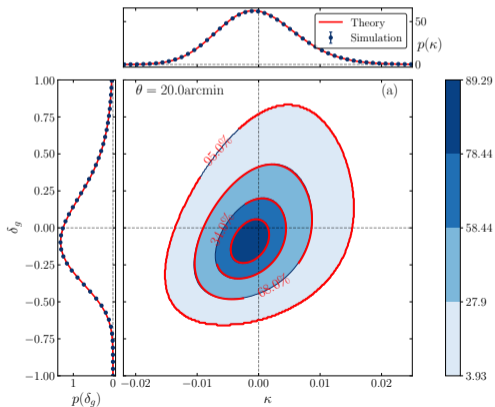


Joint PDF of galaxy clustering and weak lensing

Oliver Friedrich, Lina Castiblanco, Anik Halder, Cora Uhlemann (doi:10.1093/mnras/staf2181)

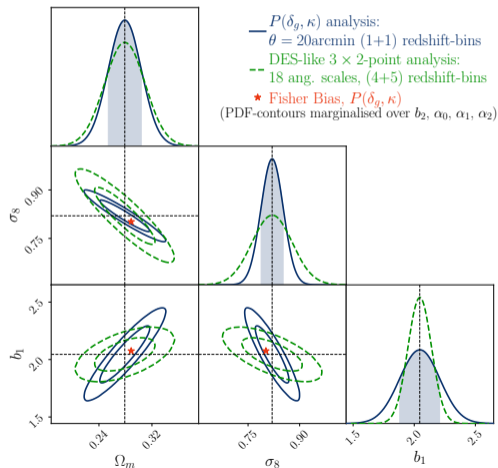
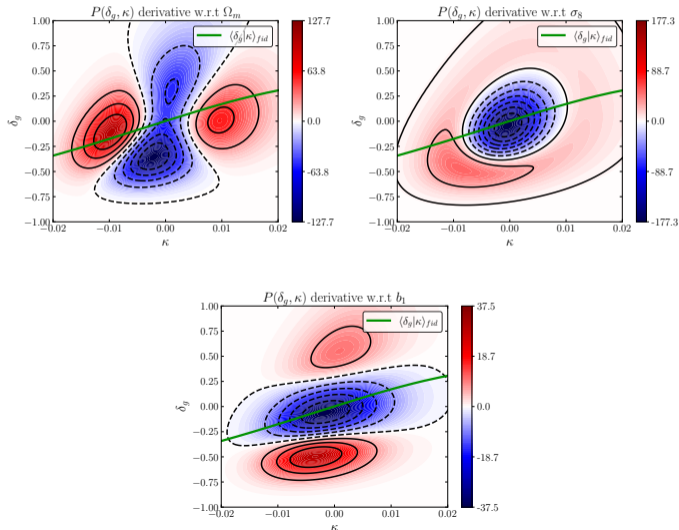
$$p_{\text{noisy}}(\kappa) = p_{SN}^G * P(\kappa), \quad \sigma_{SN}^2 = \frac{\sigma_\epsilon^2}{n_g \Omega_\theta}$$

Better than 16% accuracy in the central region.



Joint PDF of galaxy clustering and weak lensing

Oliver Friedrich, Lina Castiblanco, Anik Halder, Cora Uhlemann, (doi:10.1093/mnras/staf2181)



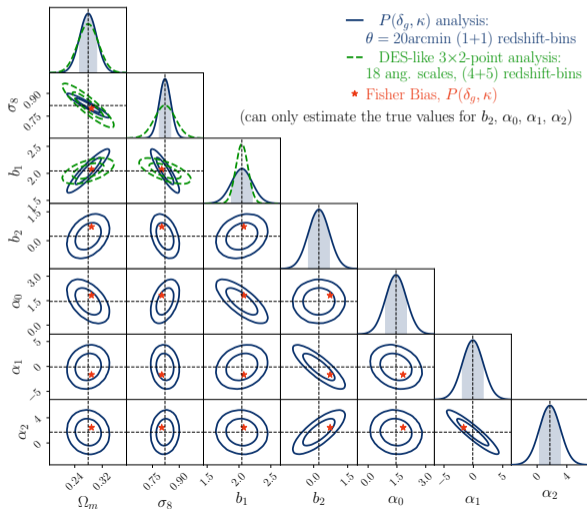
Joint PDF of galaxy clustering and weak lensing

Oliver Friedrich, Lina Castiblanco, Anik Halder, Cora Uhlemann (doi:10.1093/mnras/staf2181)

$P(\delta_g, \kappa)$ captures information beyond 2-pt correlations

$P(\delta_g, \kappa)$ constrains Ω_m, σ_8 like 3×2 .

Combining analyses exploits complementary information for tighter constraints.



Including WL Systematics: Intrinsic alignment

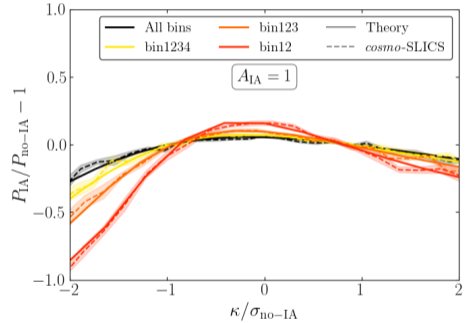
Intrinsic alignment arise from tidal gravitational fields.

Non-linear alignment model

$$\delta_{\text{IA}}(\chi\boldsymbol{\theta}, \chi) = -A_{\text{IA}} \left(\frac{1+z}{1+z_0} \right)^{\alpha_{\text{IA}}} \frac{\bar{C}\bar{\rho}(z)}{D(z)} \delta(\chi\boldsymbol{\theta}, \chi)$$

$$w(\chi) \rightarrow w(\chi) + A(z)n(z)$$

Barthelemy et al. 2023



Castiblanco et al. 2024

Including WL Systematics: Intrinsic alignment

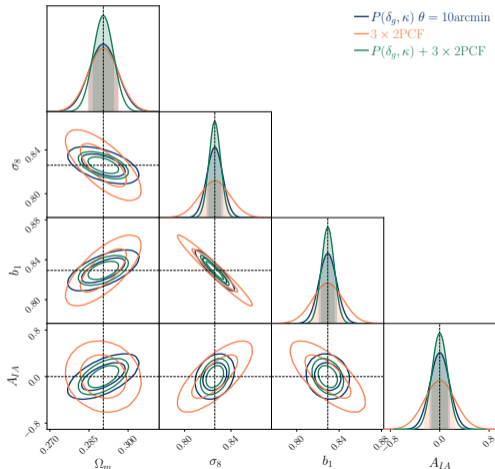
Arise from tidal gravitational fields.

Non-linear alignment model

$$\delta_{IA}(\chi\theta, \chi) = -A_{IA} \left(\frac{1+z}{1+z_0} \right)^{\alpha_{IA}} \frac{\bar{C}\bar{\rho}(z)}{D(z)} \delta(\chi\theta, \chi)$$

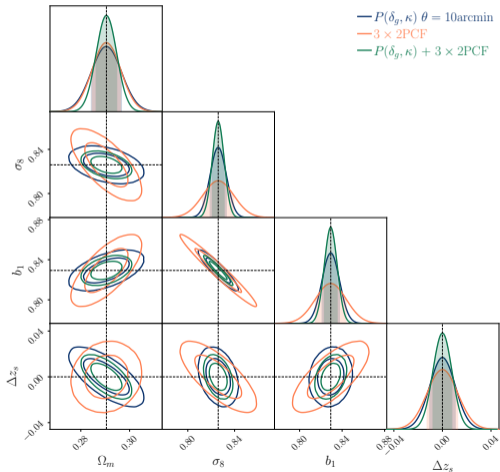
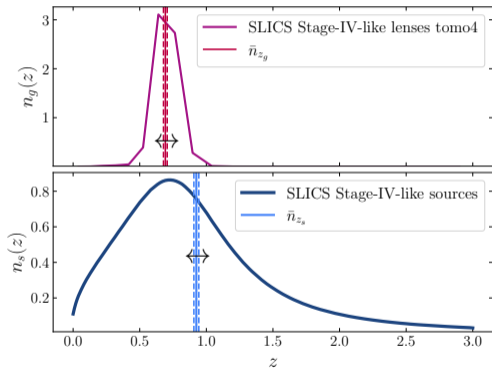
$$w(\chi) \rightarrow w(\chi) + A(z)n(z)$$

Barthelemy et al. 2023

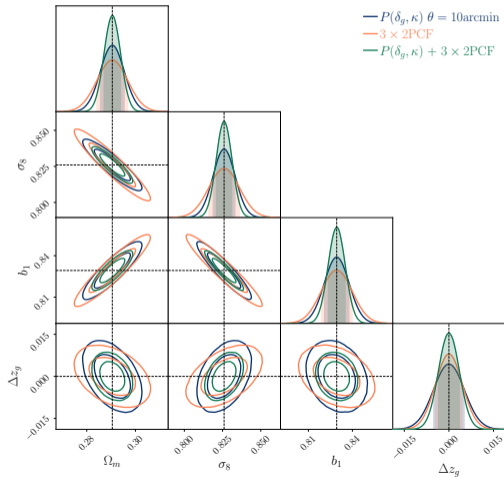
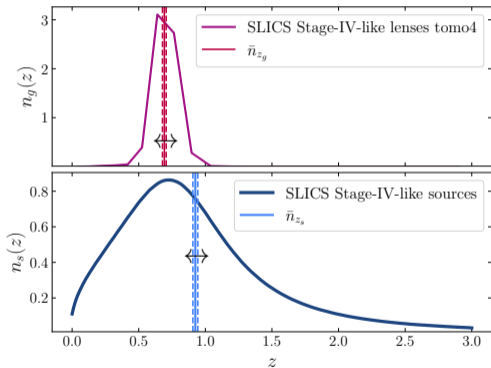


Castiblanco et al. in progress

Including WL Systematics: Redshift uncertainty in sources

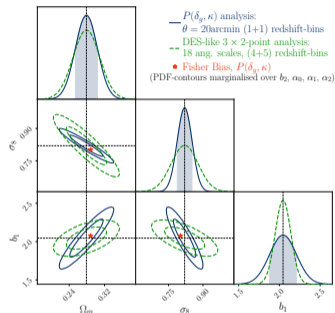
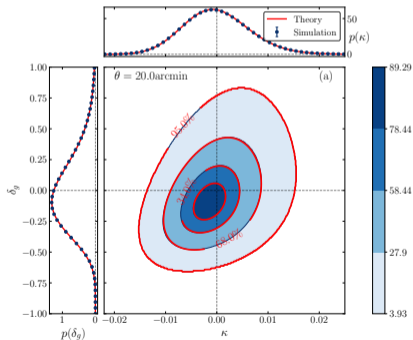


Including WL Systematics: Redshift uncertainty in lenses



Conclusions

- Joint analysis disentangles cosmology from galaxy bias and stochasticity.
- The joint PDF complements 3×2 -pt by capturing mixed higher-order moments.



- Joint $P(\delta_g, \kappa)$ model is flexible and accounts for systematics:
 - Shape noise
 - Intrinsic alignments
 - Redshift uncertainties

*Thank
you*

