Higher Order Weak Lensing Statistics in Euclid

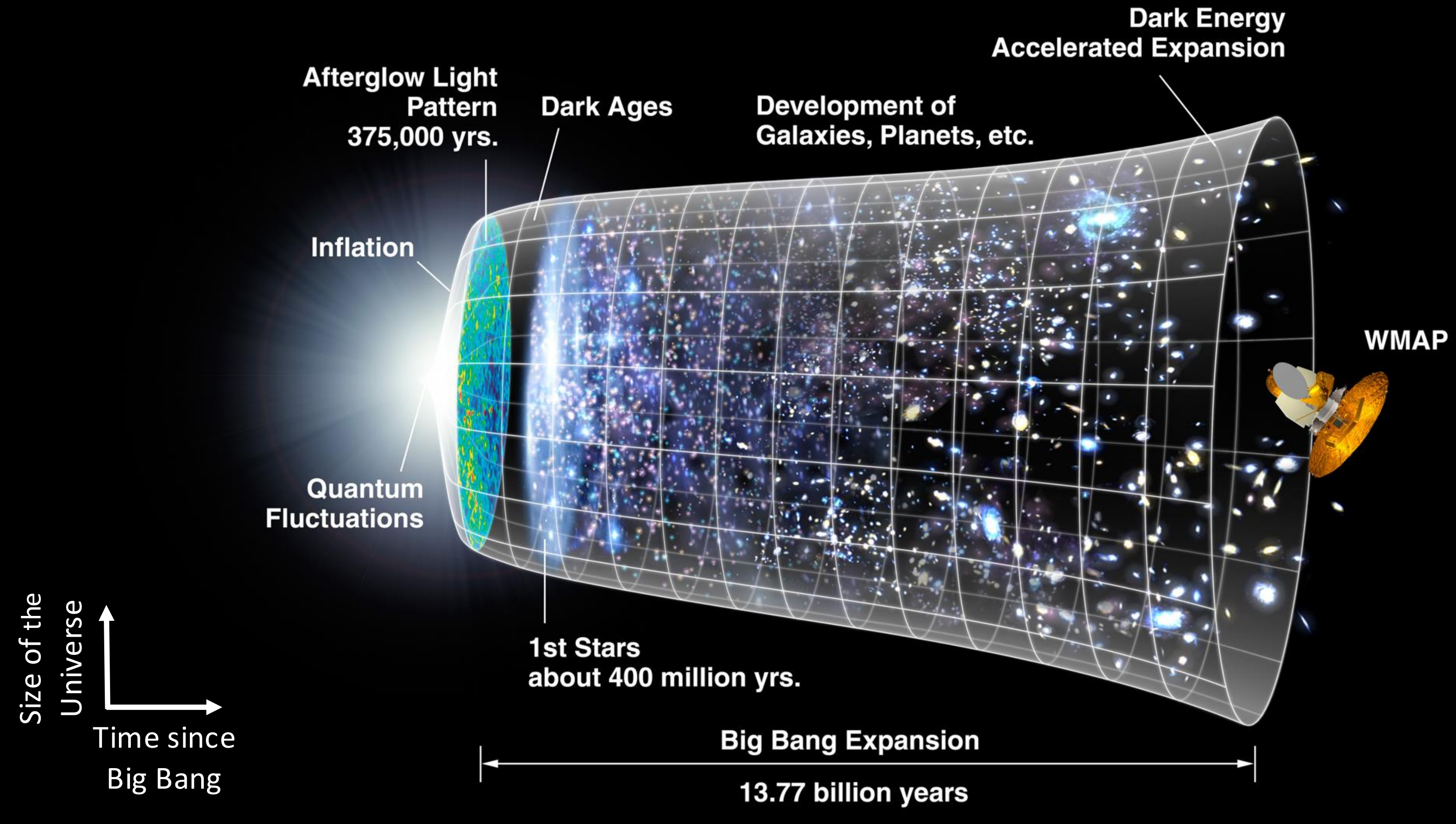
Nicolas Martinet – Heraklion, June 16th 2026

Higher Order Weak Lensing Statistics in Euclid

Kruse & Schneider 1999,2000:

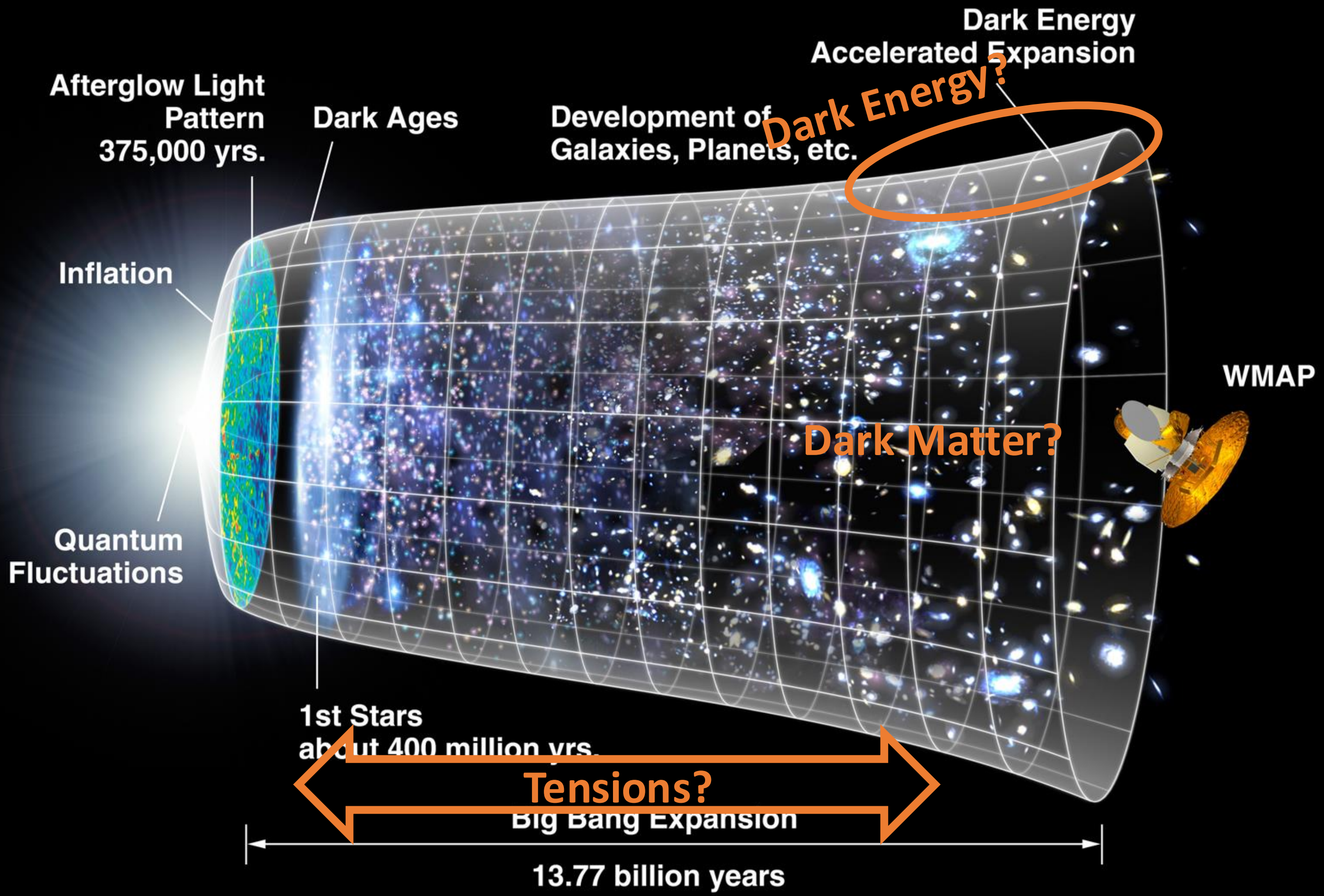
Peak statistics in a 25 deg^2 survey could easily distinguish between Ω_m=1 and Ω_m=0.3

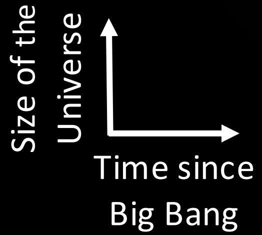
WHY ARE WE DOING IT?



NASA/WMAP science team

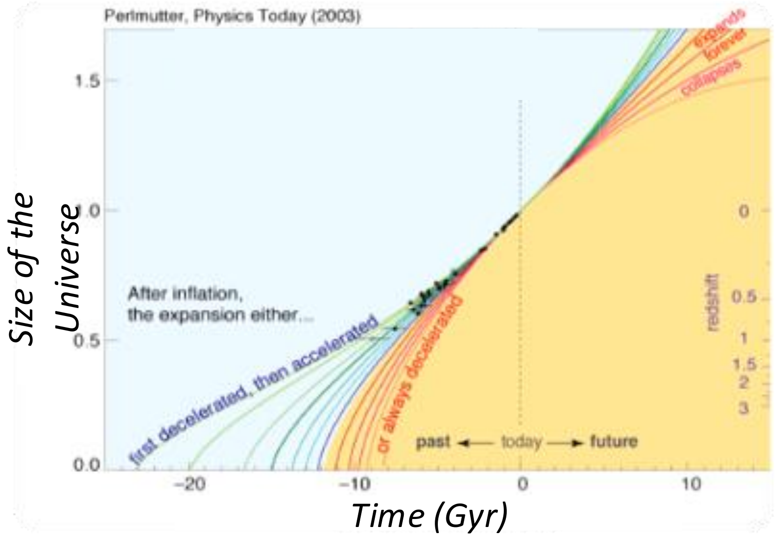
ΛCDM?

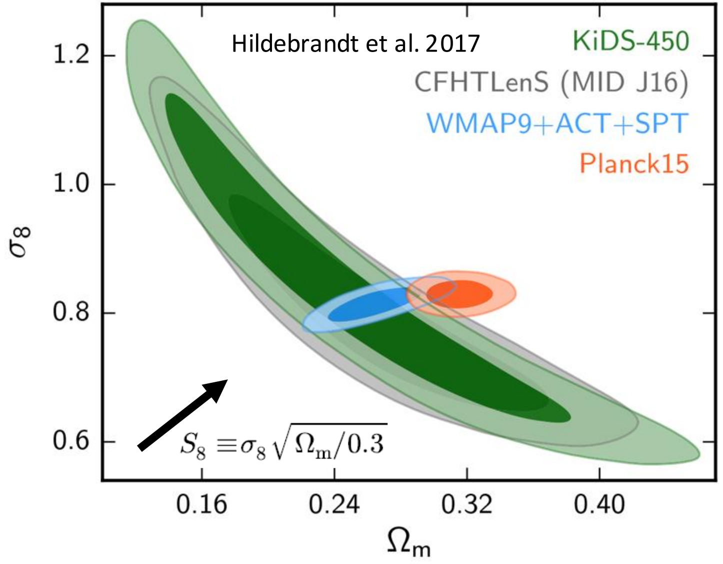




NASA/WMAP science team

Dark energy & cosmological tensions





$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

1. *Modified gravity*

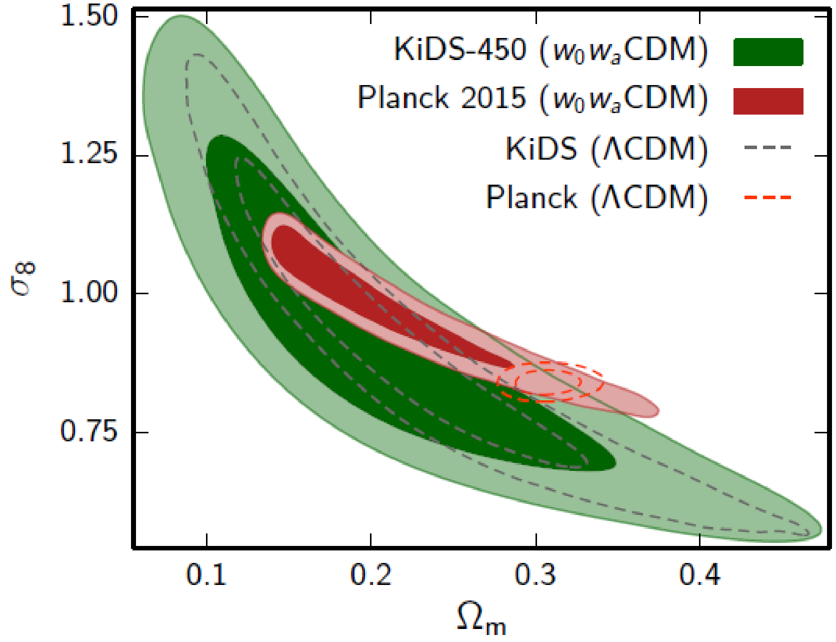
2. *Dark Energy* $P = w\rho, w \approx -1$

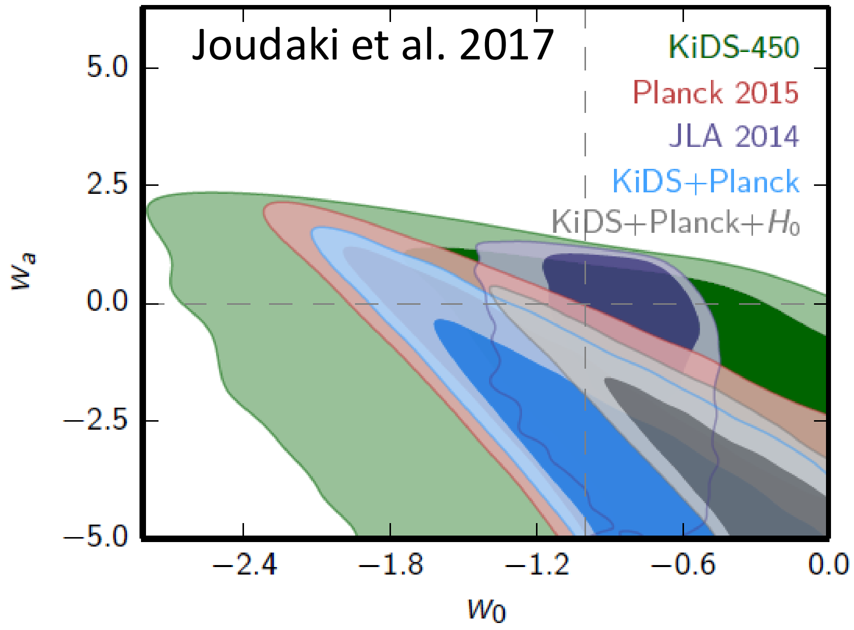
3. *Cosmological constant*

- New physics
- Statistical fluctuation
- Systematic biases (CMB or lensing)

Going beyond ΛCDM

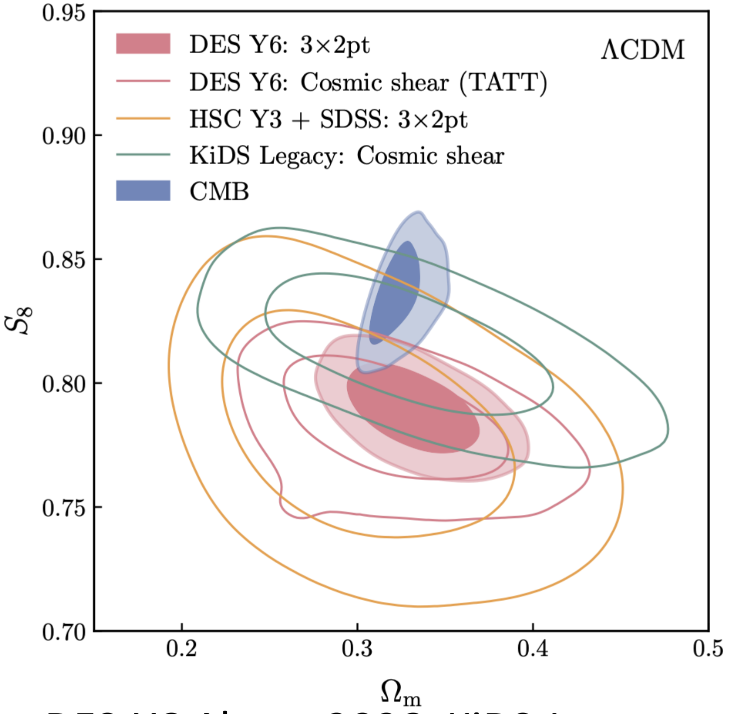
$$w(a) = w_0 + (1 - a)w_a$$



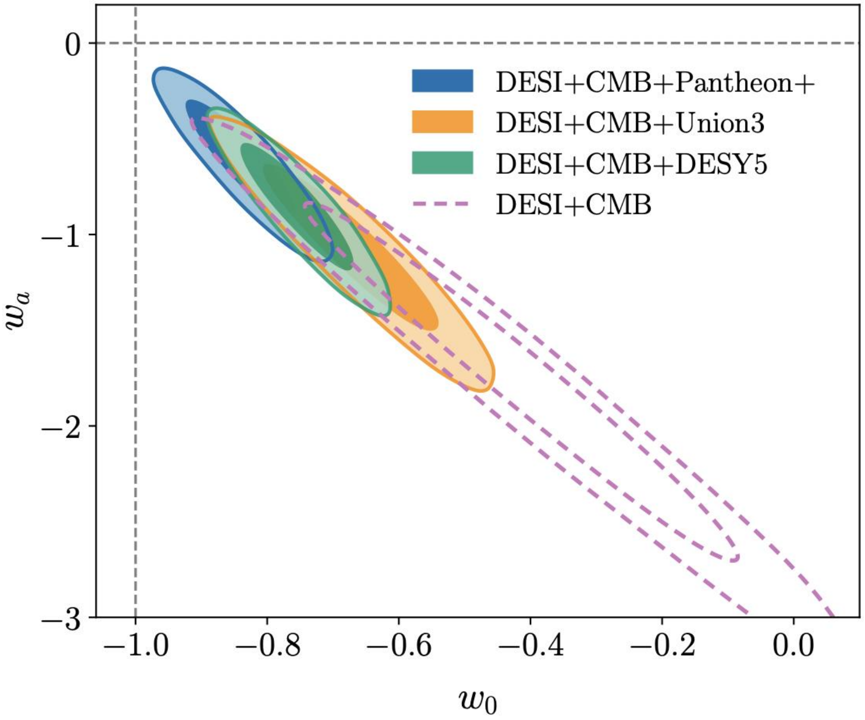


- Evolving DE can solve the S_8 tension

Latest results: DES/KiDS/HSC + DESI

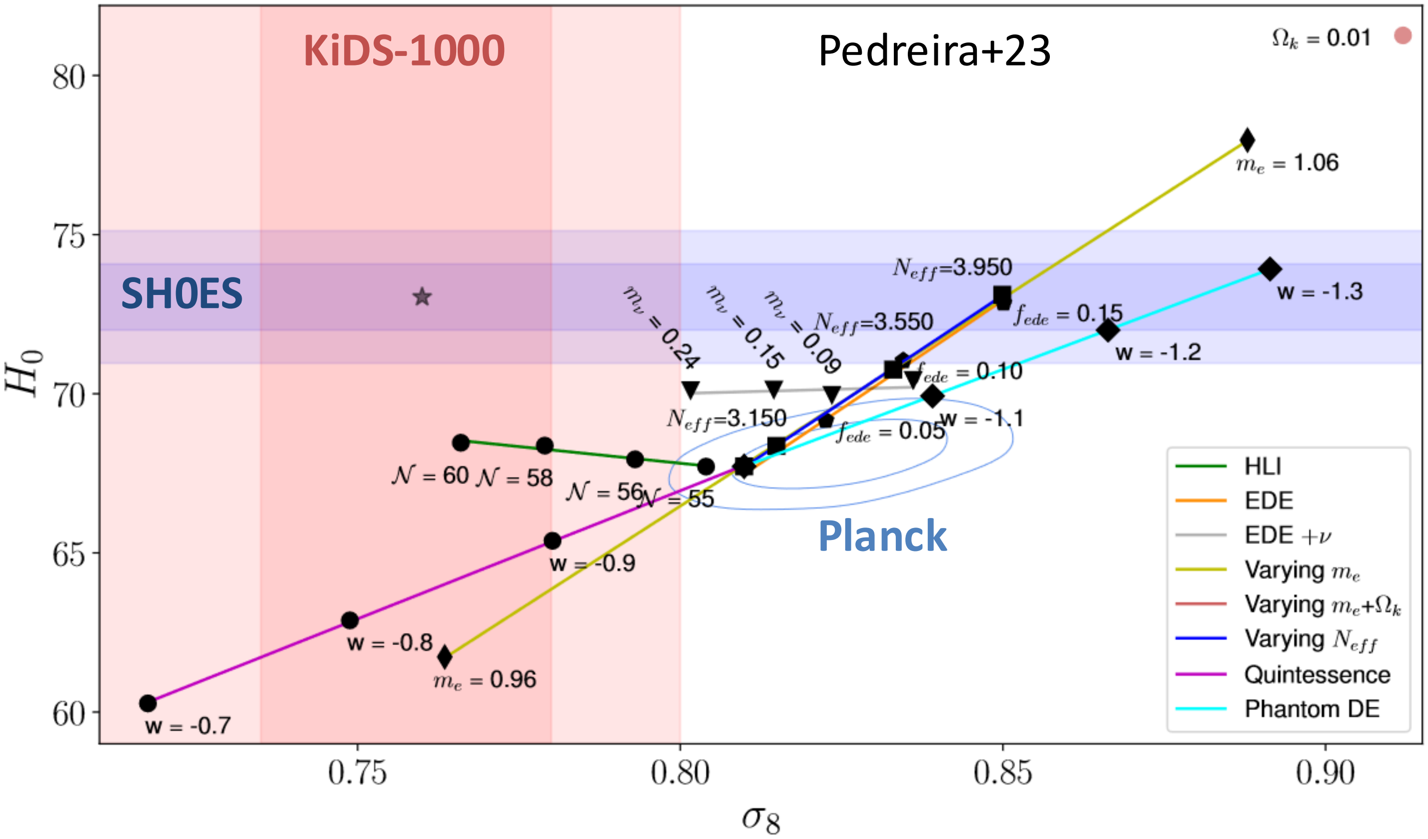


DES-Y6 Abott+2026, KiDS-Legacy Wright+25, HSC Y3 Zhang+25

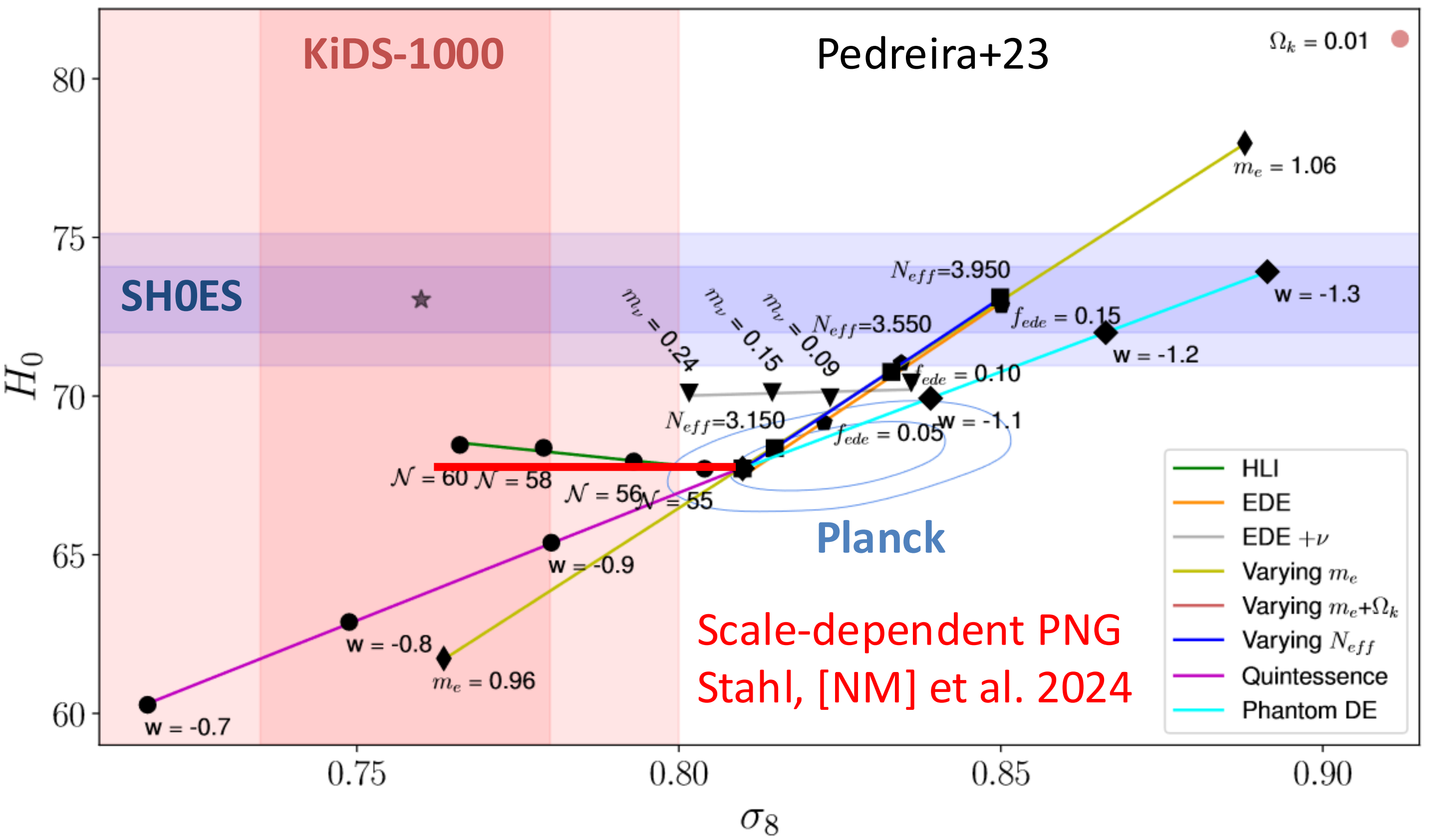


DESI DR2 2025

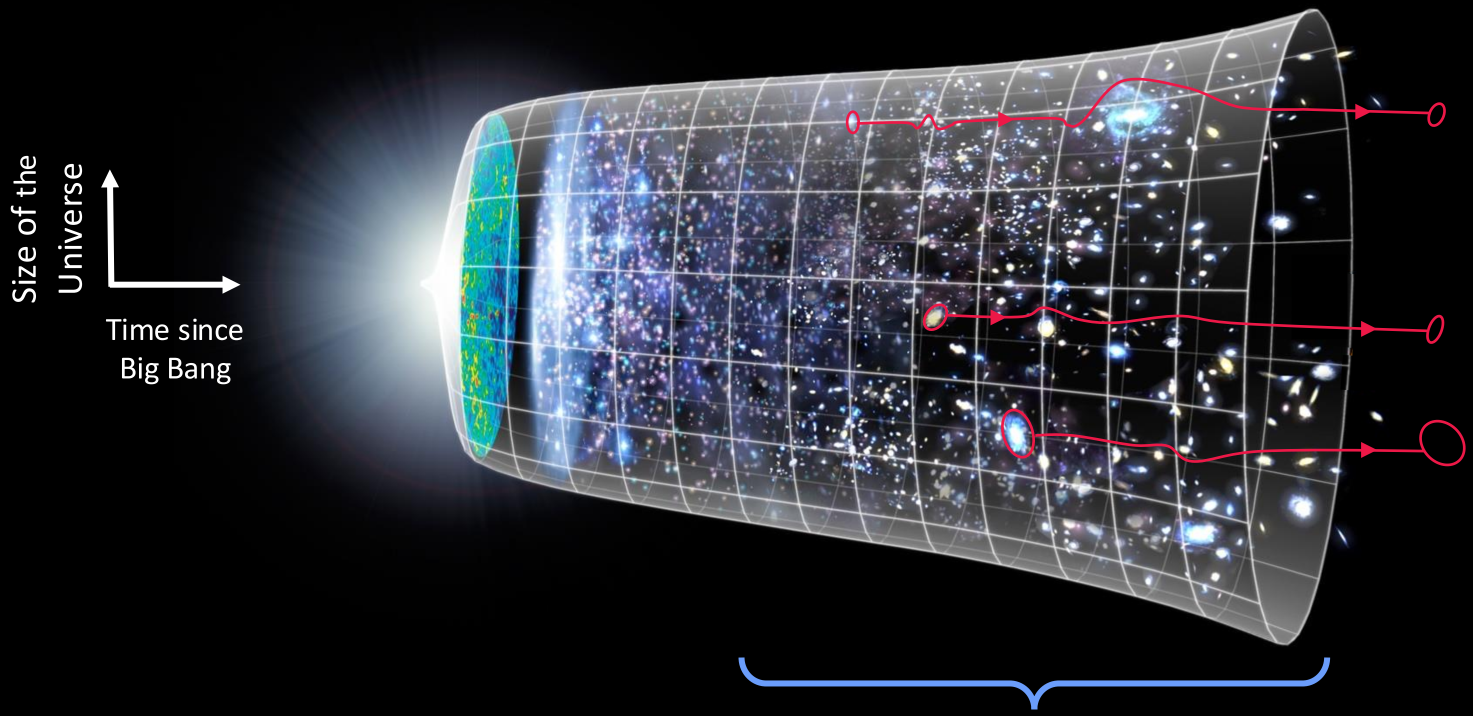
What about the tension around H_0?



Towards more complex cosmological models?

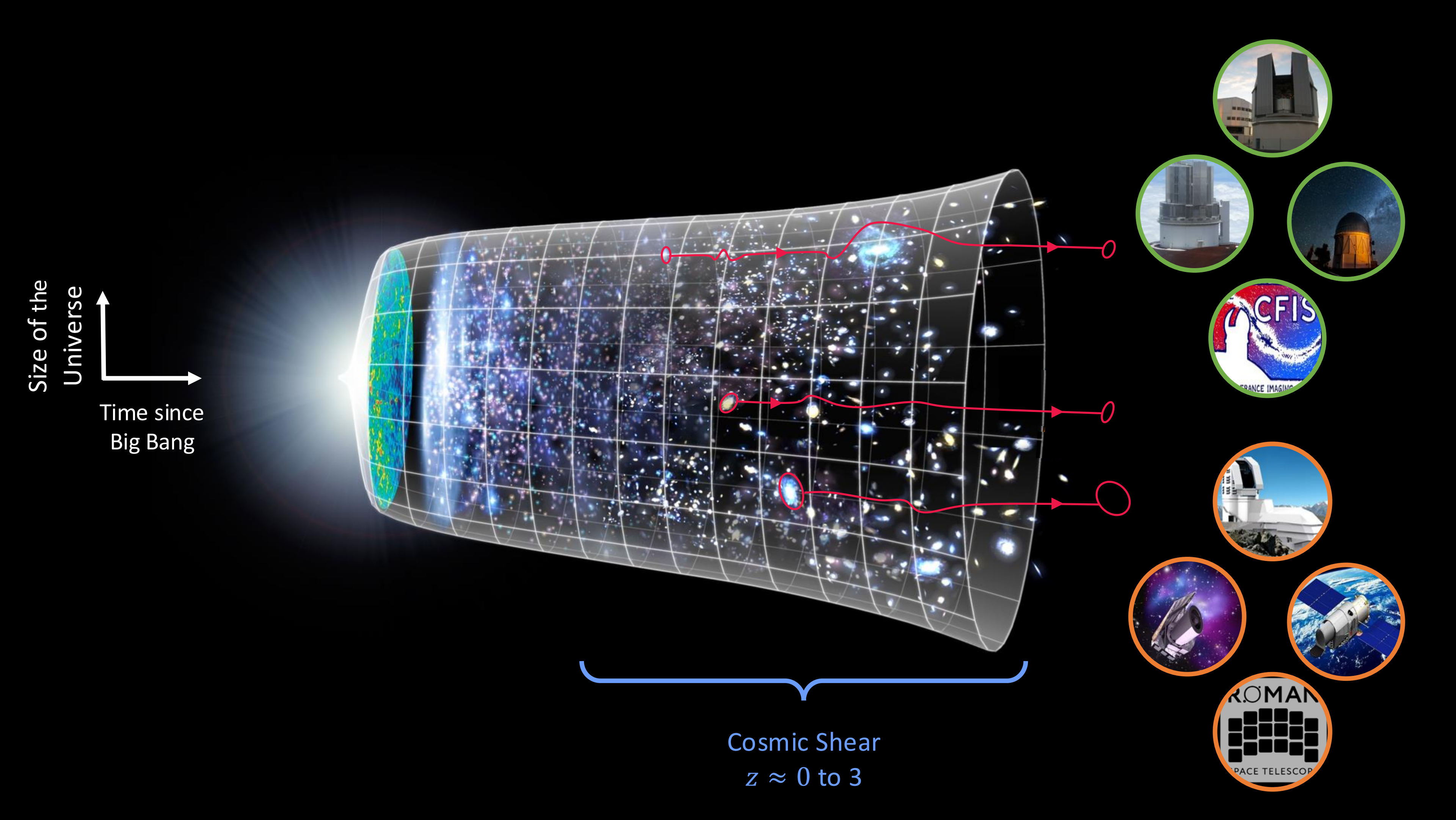


HOW ARE WE DOING IT?



Cosmic Shear

$z \approx 0$ to 3


Size of the Universe
Time since Big Bang
CFIS
Cosmic Shear
$z \approx 0$ to 3

Shear calibration

Ellipticities (ε_1, ε_2)

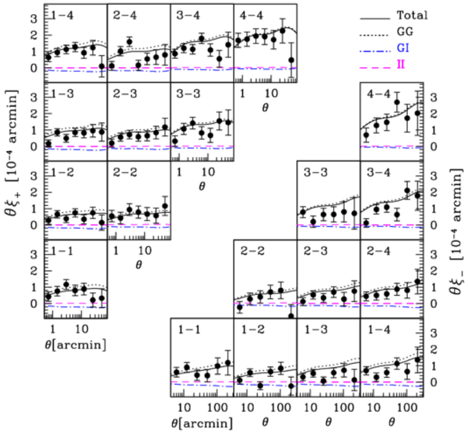
Observations

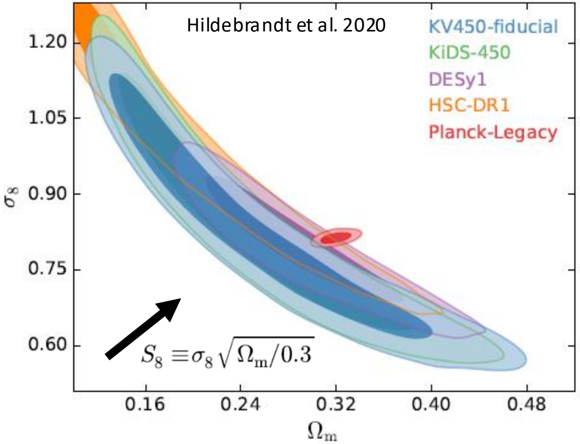
Redshifts (z)

Spectroscopic calibration

Estimator: shear 2-point correlation function

$$\hat{\xi}_{\pm}^{ij}(\theta) = \frac{\sum_{ab} w_a w_b \left[\epsilon_t^i(\vec{x}_a)\epsilon_t^j(\vec{x}_b) \pm \epsilon_\times^i(\vec{x}_a)\epsilon_\times^j(\vec{x}_b)\right]}{\sum_{ab} w_a w_b}$$





Theoretical prediction

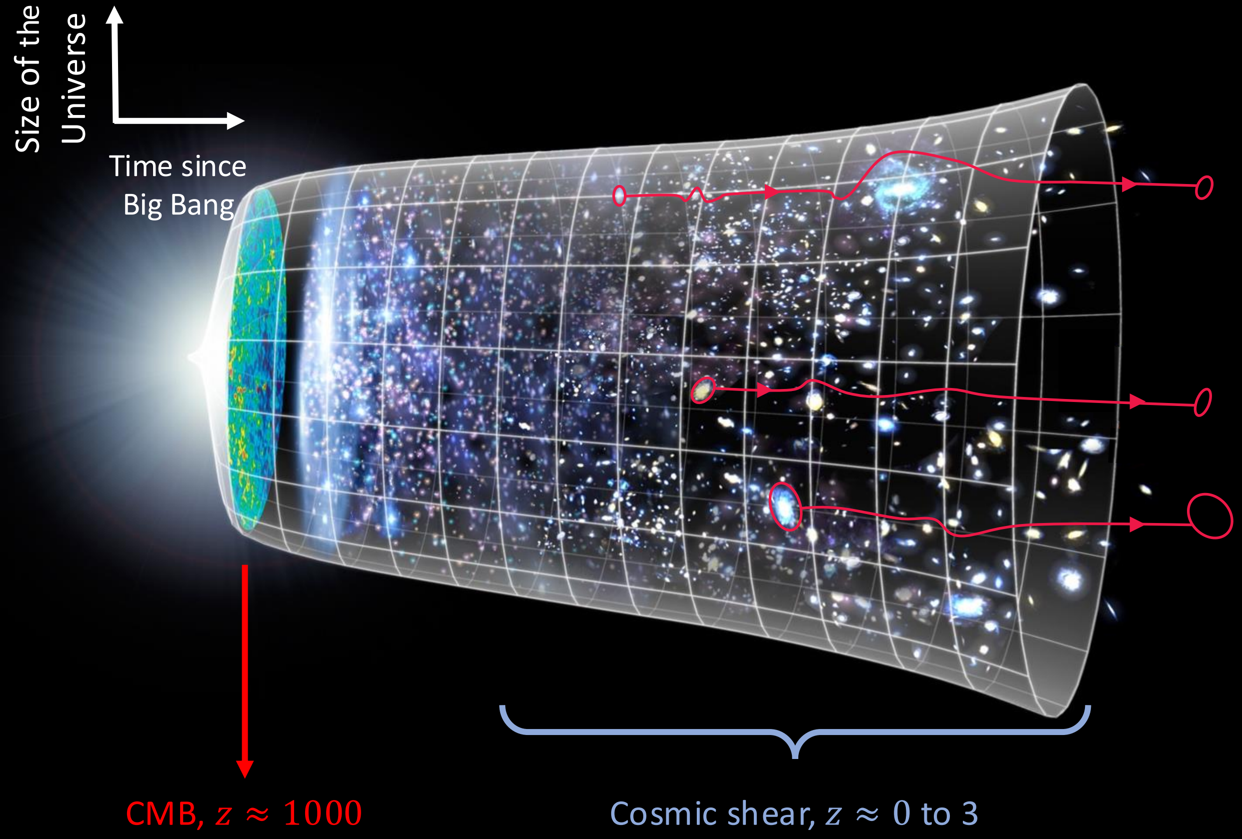
$$\xi_{\pm}^{ij}(\theta) = \frac{1}{2\pi} \int \mathrm{d}\ell\, \ell\, P_\kappa^{ij}(\ell)\, J_{0,4}(\ell\theta)$$

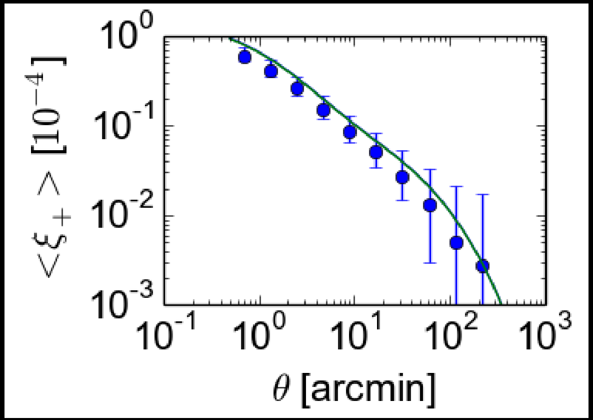
$$P_\kappa^{ij}(\ell) = \int_0^{\chi_\mathrm{H}} \mathrm{d}\chi\, \frac{q_i(\chi) q_j(\chi)}{[f_K(\chi)]^2}\, P_\delta\left(\frac{\ell}{f_K(\chi)}, \chi\right)$$

$$q_i(\chi) = \frac{3H_0^2\Omega_\mathrm{m}}{2c^2} \frac{f_K(\chi)}{a(\chi)} \int_\chi^{\chi_\mathrm{H}} \mathrm{d}\chi'\, n_i(\chi') \frac{f_K(\chi'-\chi)}{f_K(\chi')}$$

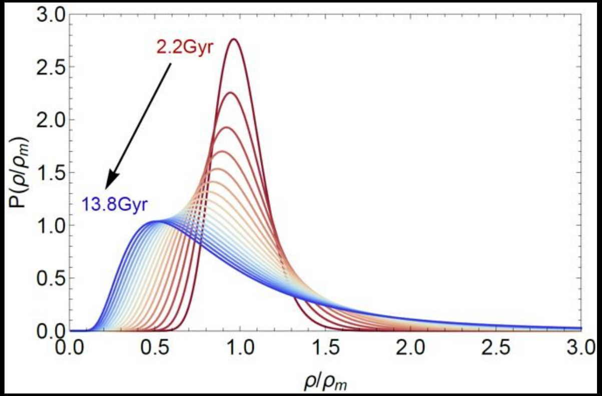
Systematic biases

- Shear calibration (m, c)
- Mean redshift (Δz)
- Intrinsic alignment (A_{IA})
- Baryons (B)





Shear two-point correlation function (shear-2PCF)



Evolution of the matter distribution with redshift - Courtesy Sandrine Codis

Shear calibration

Ellipticities
(ε_1, ε_2)

Observations

Redshifts (z)

Spectroscopic calibration

Estimator: shear 2-point correlation function

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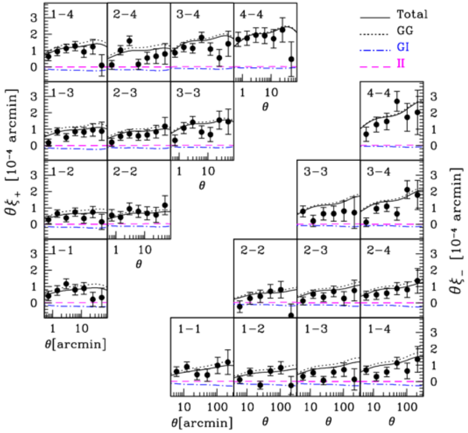

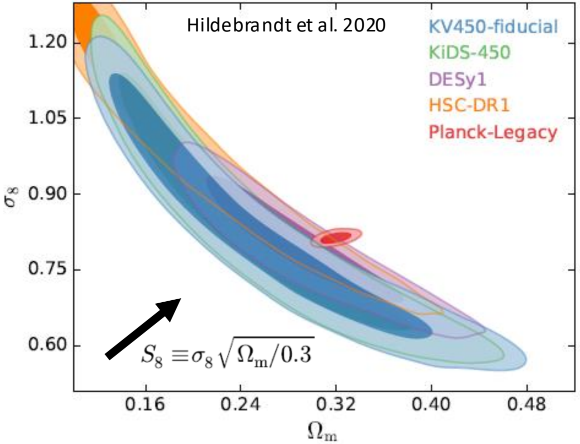

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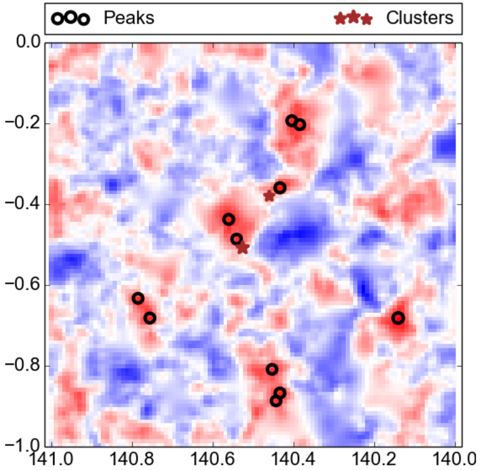
Systematic biases

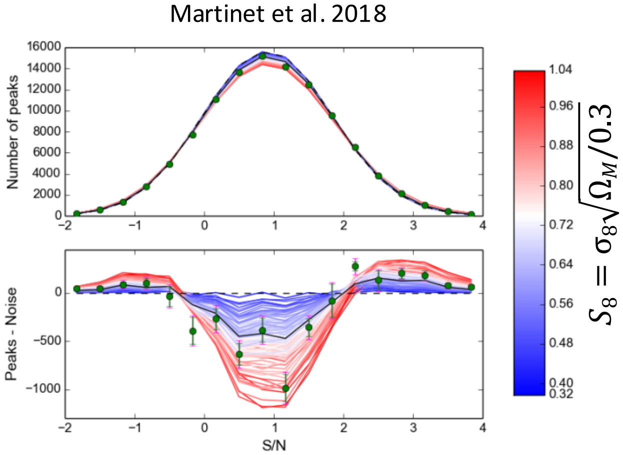
- Shear calibration (m, c)
- Mean redshift (Δz)
- Intrinsic alignment (A_{IA})
- Baryons (B)

Shear calibration

Ellipticities $(\varepsilon_1, \varepsilon_2)$

Estimator: peak counts



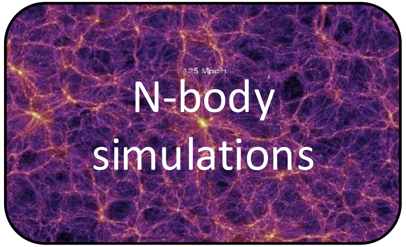


Observations

Redshifts (z)

Spectroscopic calibration

Numerical prediction



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Shear calibration

Ellipticities $(\varepsilon_1, \varepsilon_2)$

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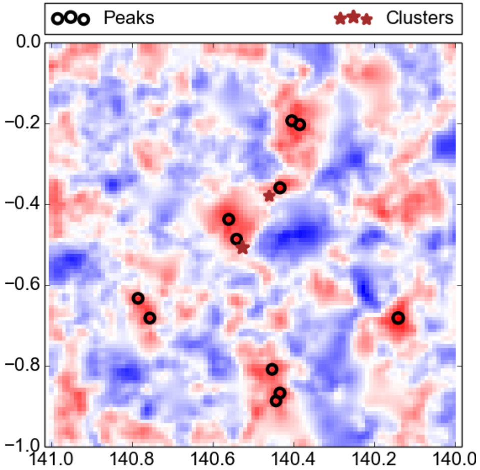
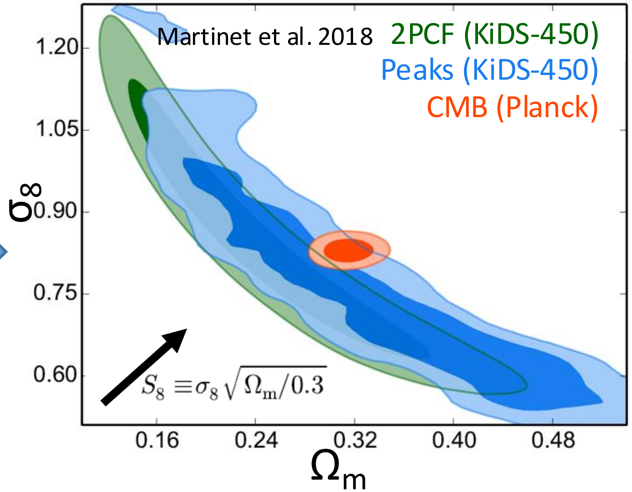
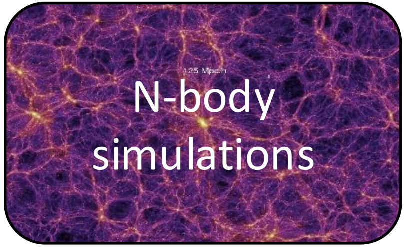




- First peaks and 2PCF combination (20% improvement)

Numerical prediction



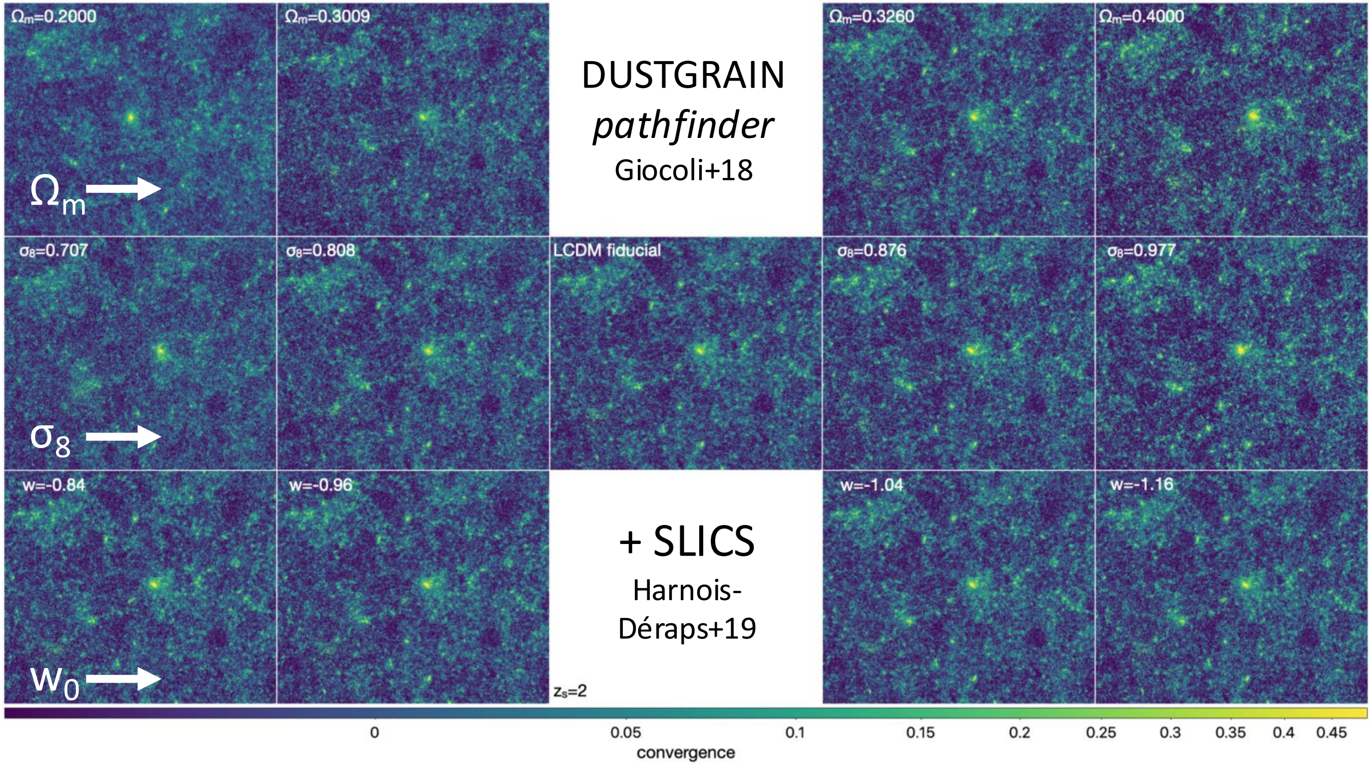
Systematic biases

- Shear calibration (m, c)
- Mean redshift (Δz)
- Intrinsic alignment (A_{IA})
- Baryons (B)

EUCLID HIGHER ORDER WEAK LENSING STATISTICS (HOWLS)

HOWLS community challenge

Set of HOWLS simulated mass maps

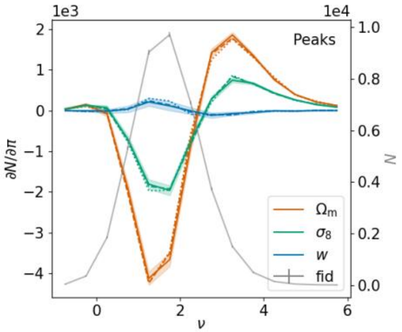


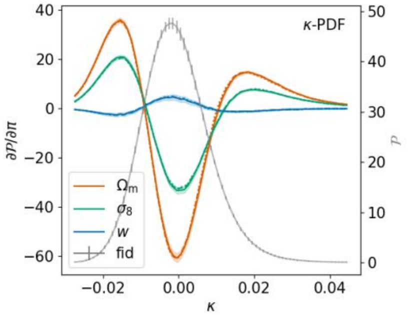
- 12 cosmologies + SLICS covariance
- Realistic Euclid mocks (n(z), shape noise)
- Mass maps distributed to community
- Fisher forecasts
- Data set released with the paper

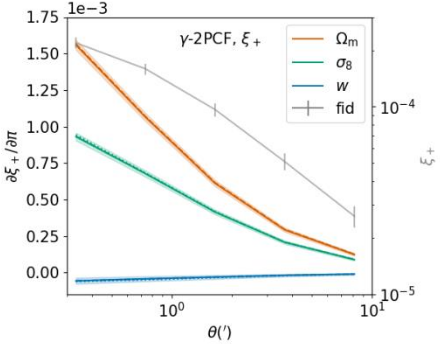
Summary statistics

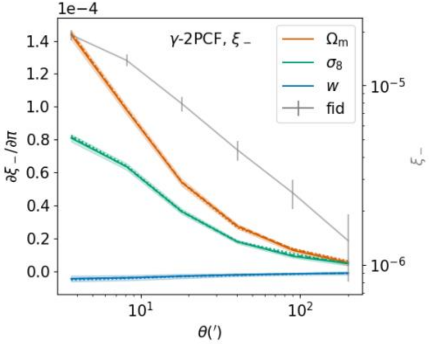
Field	Statistics	Abbreviation	Teams
γ	two-point correlation functions	γ-2PCF (ξ_+/ξ_-)	1 (+1)
κ	two-point correlation function	κ-2PCF (ξ_κ)	1 (+2)
κ	one-point probability distribution function	κ-PDF ($\mathcal{P}$)	1
κ	higher order moments	HOM ($\mathcal{M}$)	2 (+2)
$M_{\mathrm{ap}}(\gamma)$	third order moments	$\langle M_{\mathrm{ap}}^3 \rangle$	1
$M_{\mathrm{ap}}(\gamma)$	n-th order moments	$\langle M_{\mathrm{ap}}^n \rangle$	1
$M_{\mathrm{ap}}(\kappa)$	peak counts	peaks (N)	1 (+2)
κ	Minkowski functionals	MFs (V_0, V_1, V_2)	1 (+2)
κ	Betti numbers	BNs (β_0, β_1)	1 (+2)
$M_{\mathrm{ap}}(\gamma)$	persistent homology Betti numbers	pers. BNs (β)	1
$M_{\mathrm{ap}}(\gamma)$	persistent homology heatmap	pers. heat. (h)	1
κ	scattering transform coefficients	s_1, s_2	1

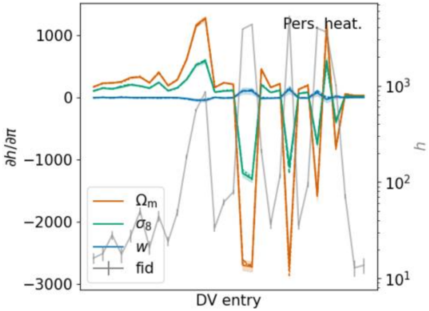
- 12 different statistics
- 12 independent teams
- 24 data vectors





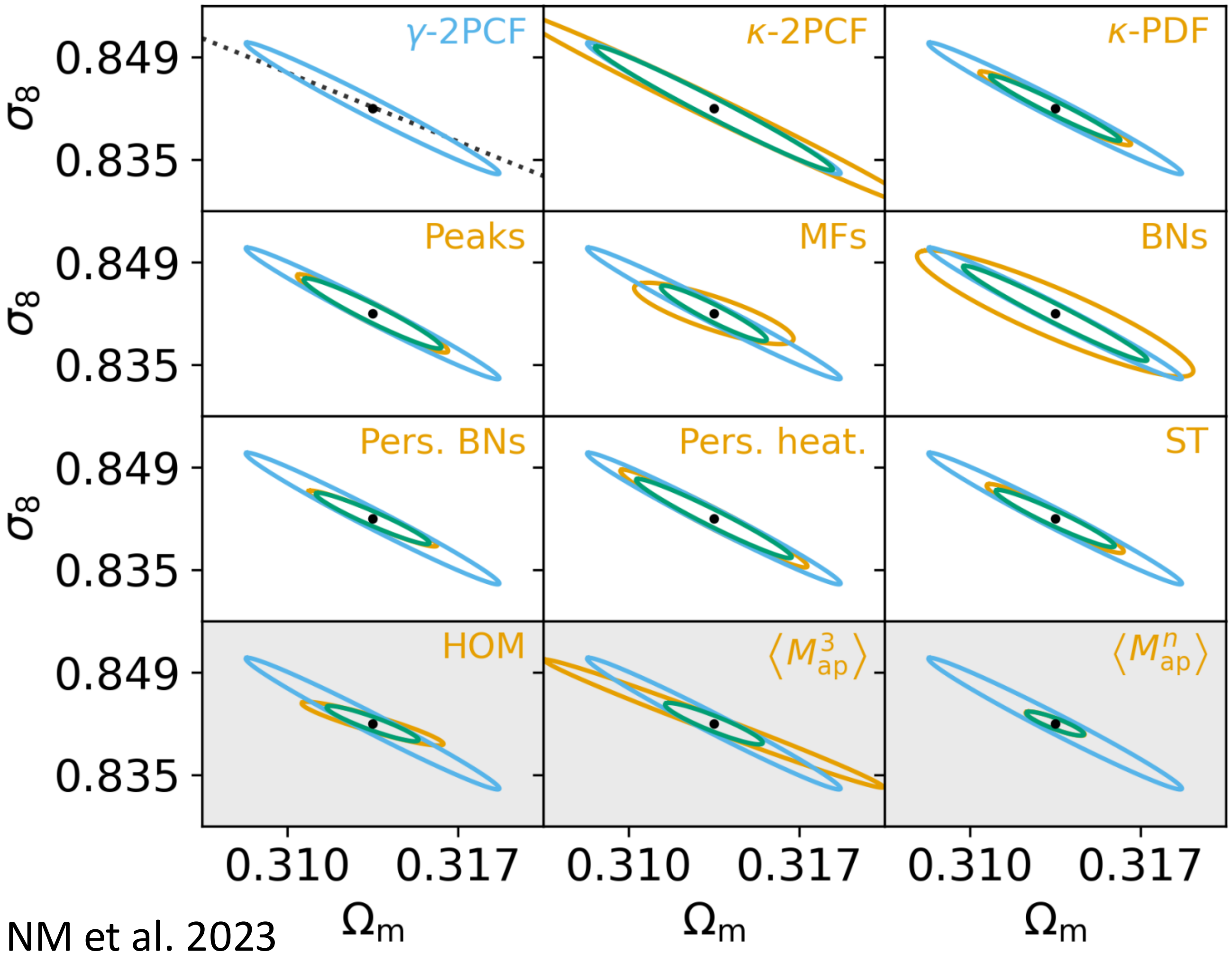






Fisher forecasts

- Every higher order statistic outperforms the shear-2PCF



Euclid Collaboration XXVIII, NM et al. 2023

Shear calibration

Ellipticities (ε_1, ε_2)

Observations

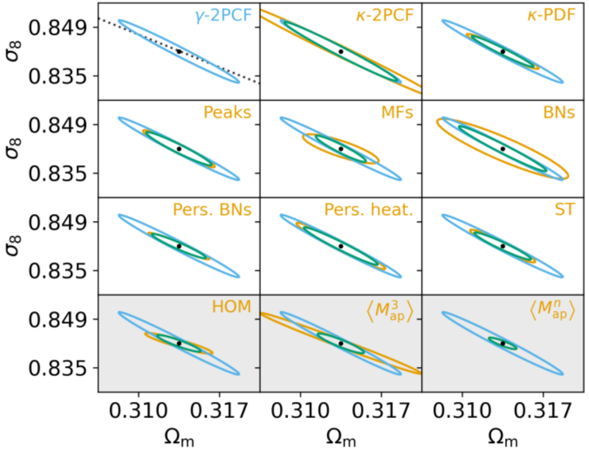
Redshifts (z)

Spectroscopic calibration

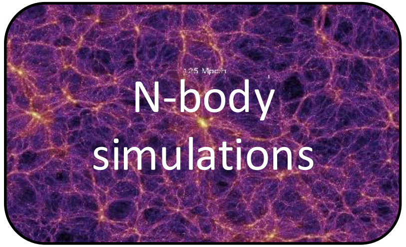
Estimator: Higher Order Weak Lensing Statistics (HOWLS)

Statistics
γ-2PCF
κ-2PCF
Moments
Third order $M_{\rm ap}$
Lensing PDF
Peak counts
Minkowski functionals
Betti numbers
Persistent homology
Scattering transforms

Euclid Collab. XXVIII, 2023



Numerical prediction

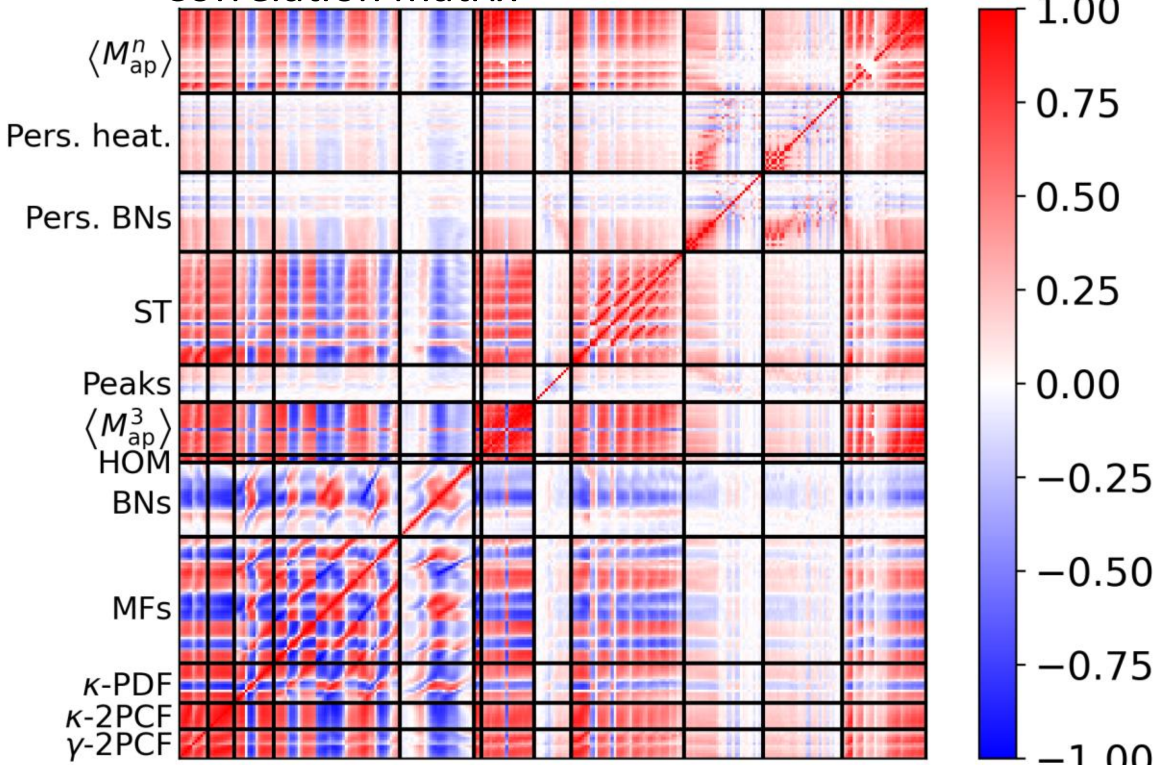


Systematic biases

- Shear calibration (m, c)
- Mean redshift (Δz)
- Intrinsic alignment (A_{IA})
- Baryons (B)

Towards a combination

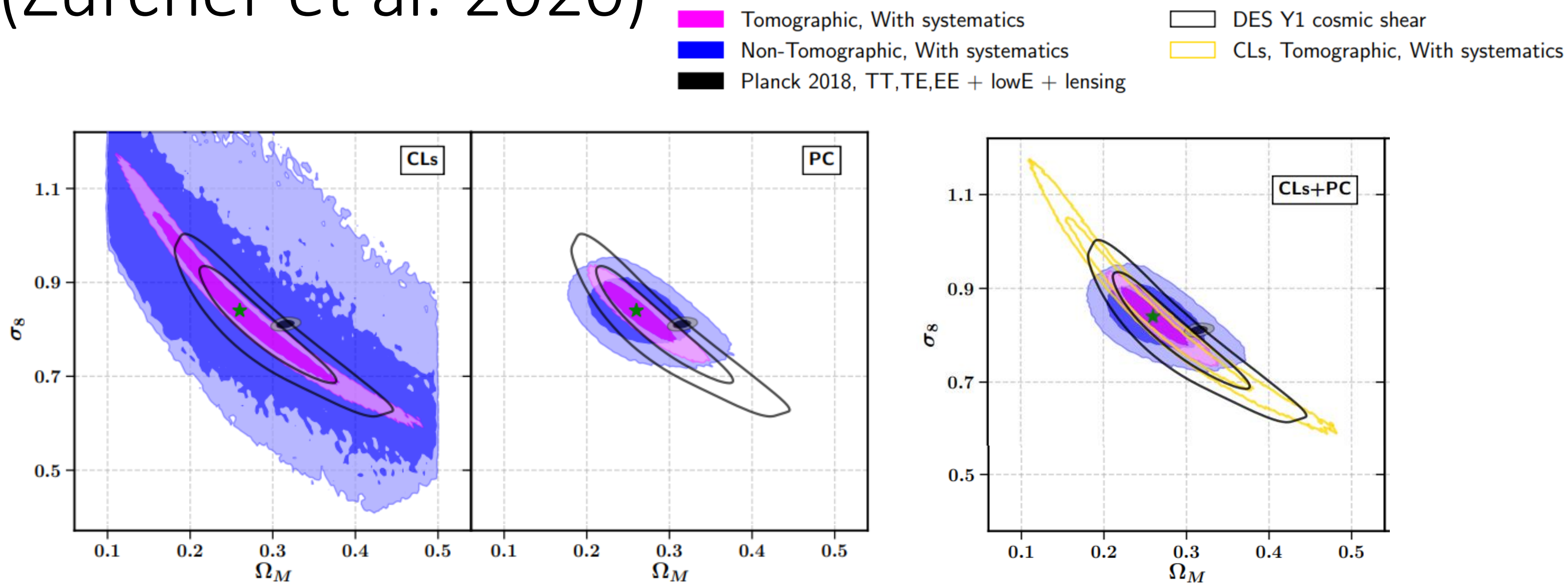
Correlation matrix



Euclid Collaboration XXVIII, NM et al. 2023

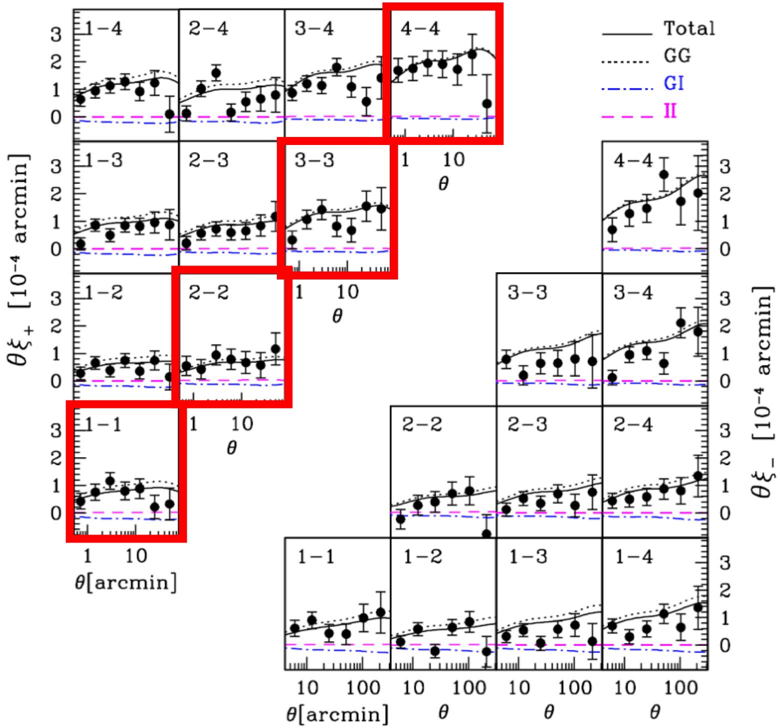
PROBING DARK ENERGY WITH TOMOGRAPHY

DES-Yr3 peak prediction with tomography (Zürcher et al. 2020)

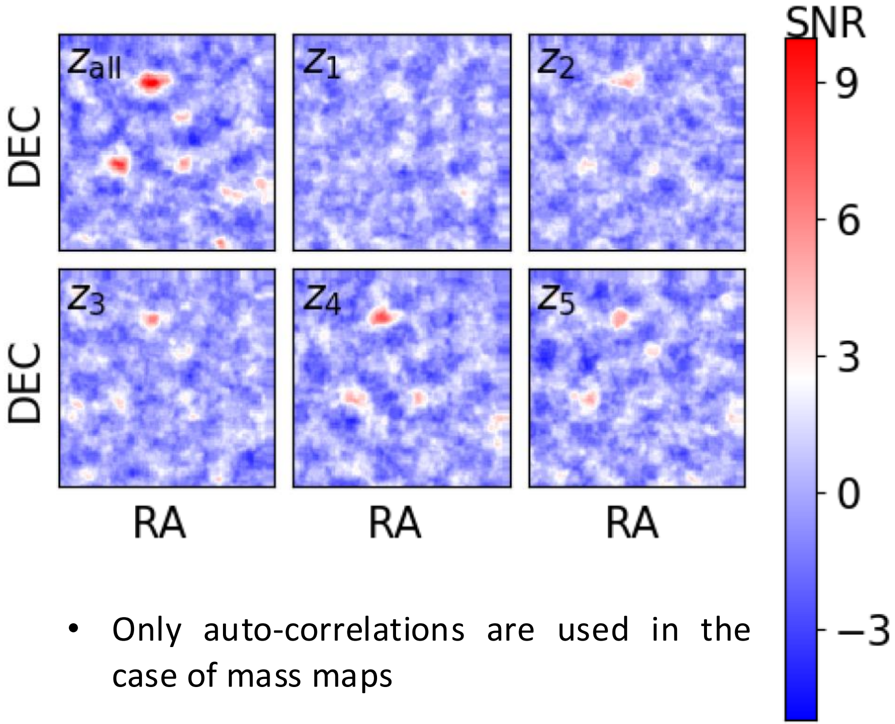


- Constraints on S_8 improved by 25%
- Tomography works better for 2-pt statistics than for peaks

Improving tomography



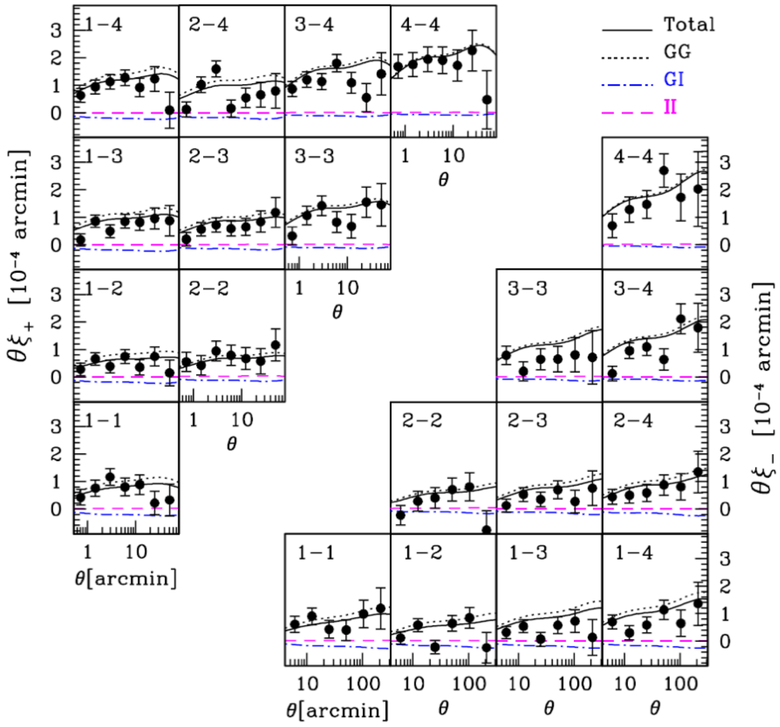
Tomographic 2PCF (Hildebrandt et al. 2017)



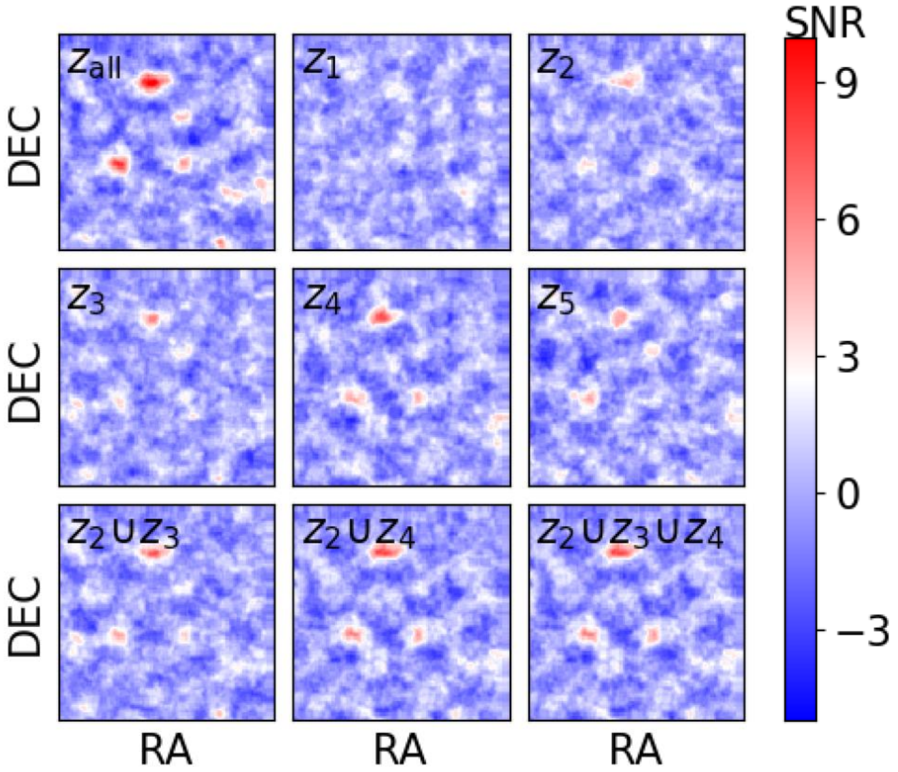
- Only auto-correlations are used in the case of mass maps

Tomographic mass map (before Martinet et al. 2021a)

Improving tomography



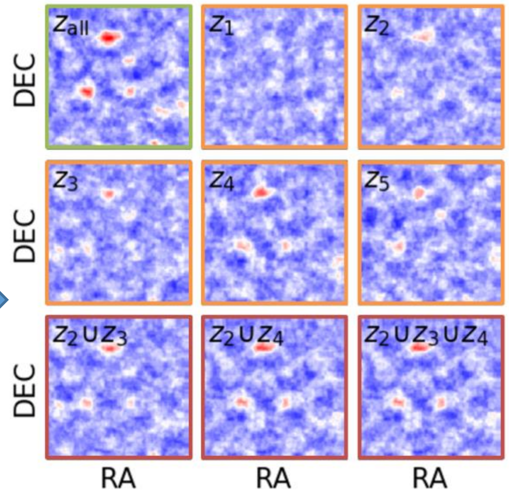
Tomographic 2PCF (Hildebrandt et al. 2017)

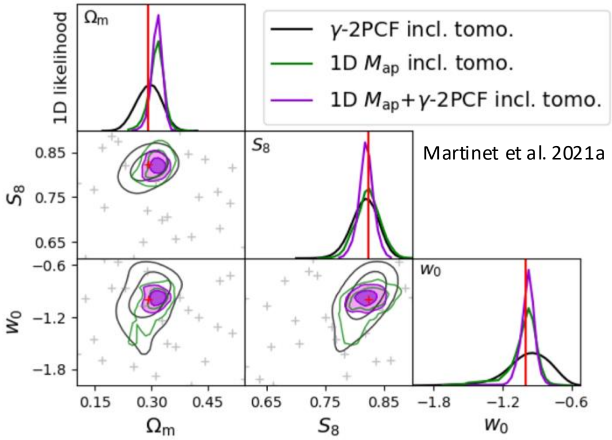


Tomographic mass map (Martinet et al. 2021a)

Shear calibration

Estimator: peak counts





Martinet et al. 2021a

Ellipticities (ε_1, ε_2)

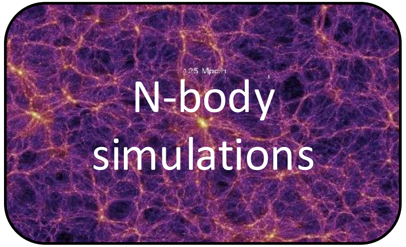
Observations

Redshifts (z)

Spectroscopic calibration

- First combined forecasts on w_0
- x3 improvement on w_0 compared to 2PCF alone

Numerical prediction



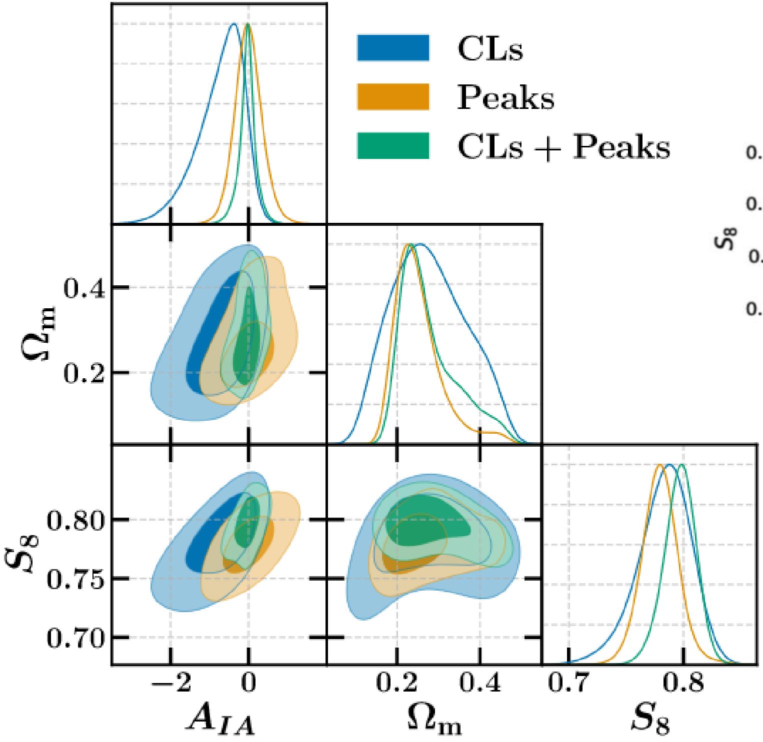
Systematic biases

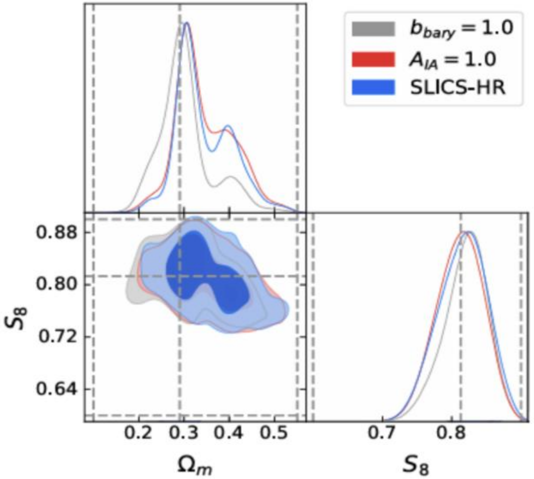
- Shear calibration (m, c)
- Mean redshift (Δz)

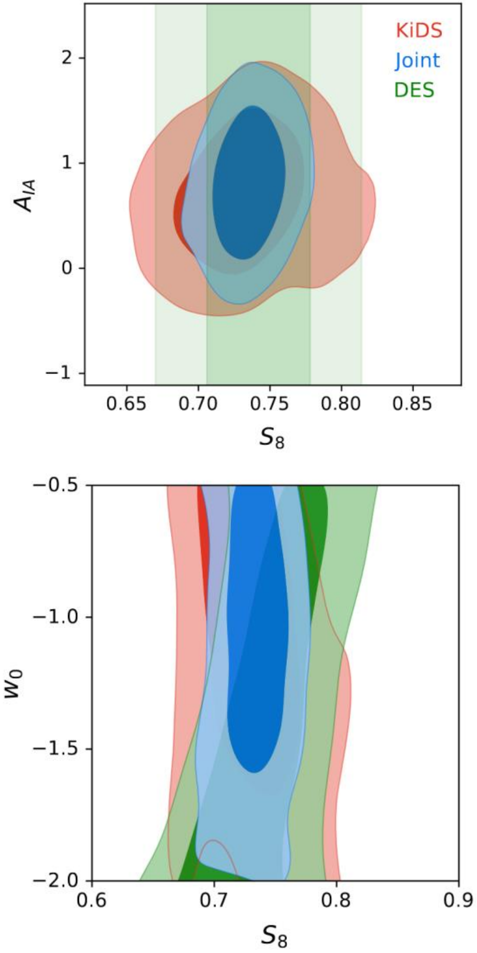
Harnois-Déraps, Martinet et al. 2021

- Intrinsic alignment (A_{IA}) Harnois-Déraps, Martinet et al. 2022
- Baryons (B) Martinet et al. 2021b

State of the art for peaks







DES-Y3: Zürcher+22

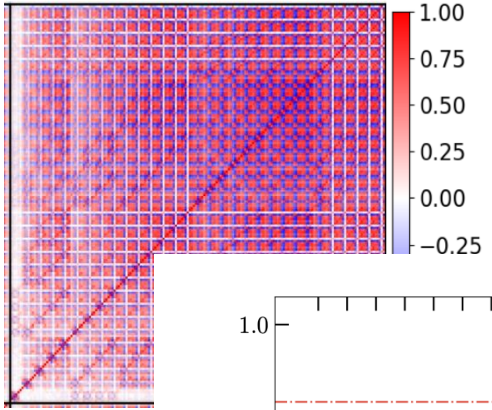
KiDS1000+DES-Y1: Harnois-Déraps, NM et al. 2024

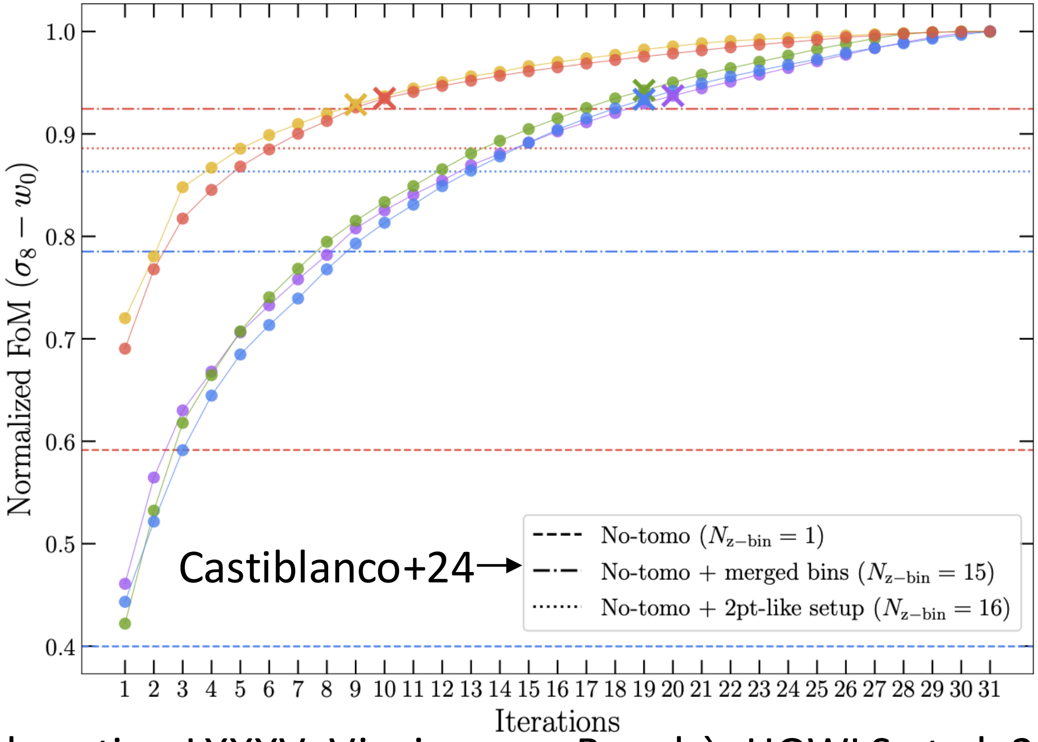
Simone Vinciguerra (PhD)

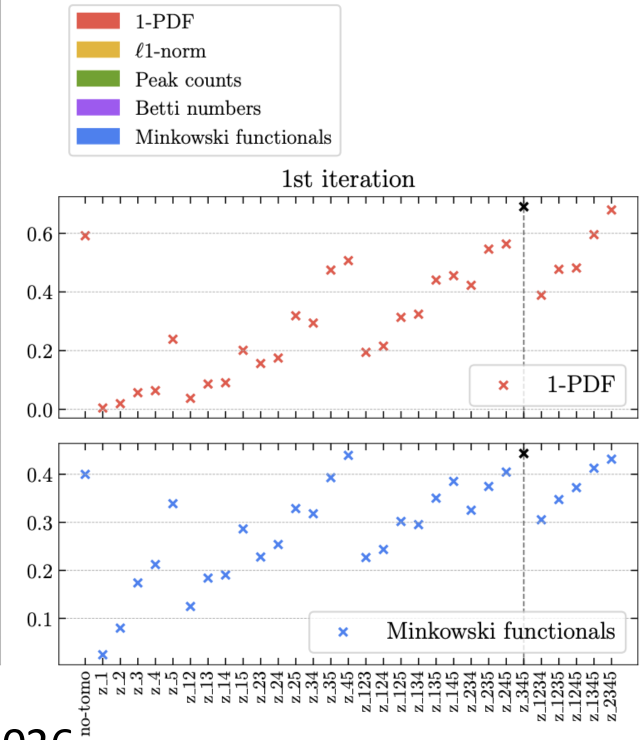
Filippo Bouchè (PhD)

TOWARDS EUCLID DR1

Optimizing tomography

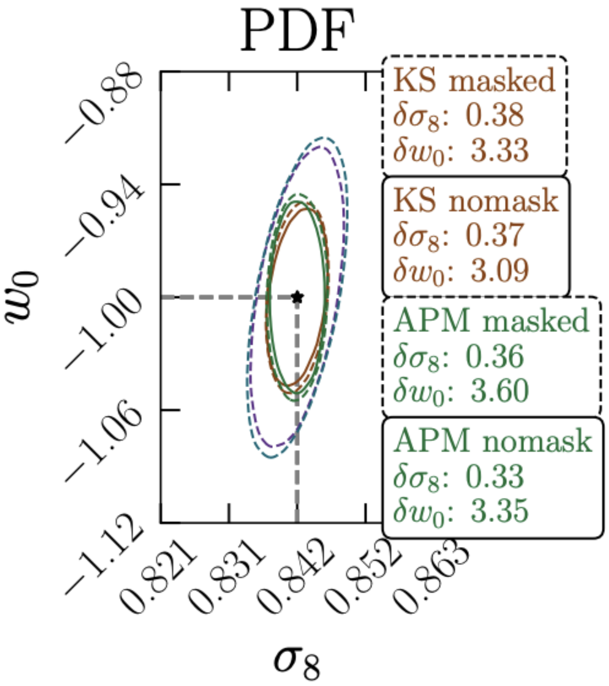


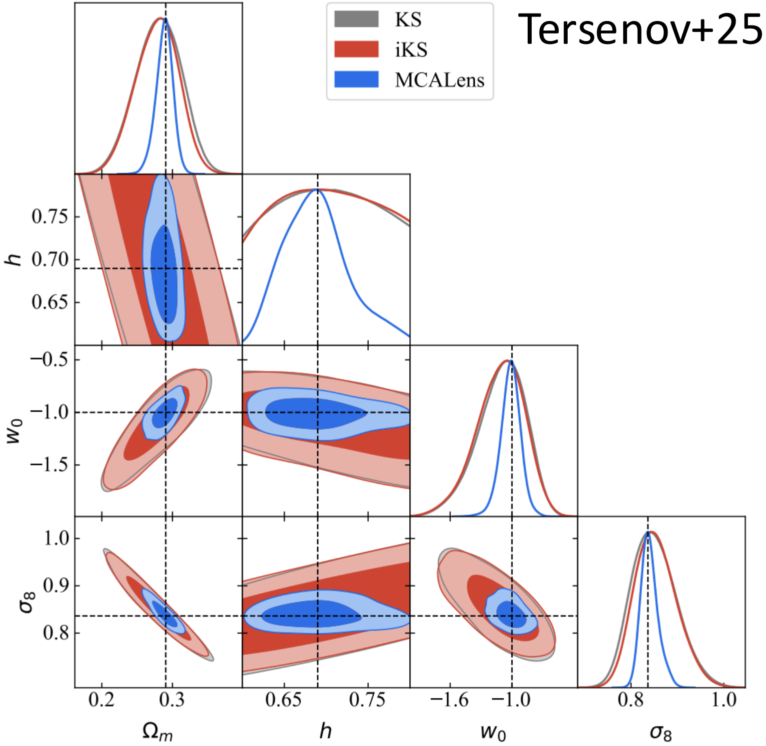




Euclid Collaboration LXXXV: Vinciguerra, Bouchè, HOWLS et al. 2026

Mass mapping

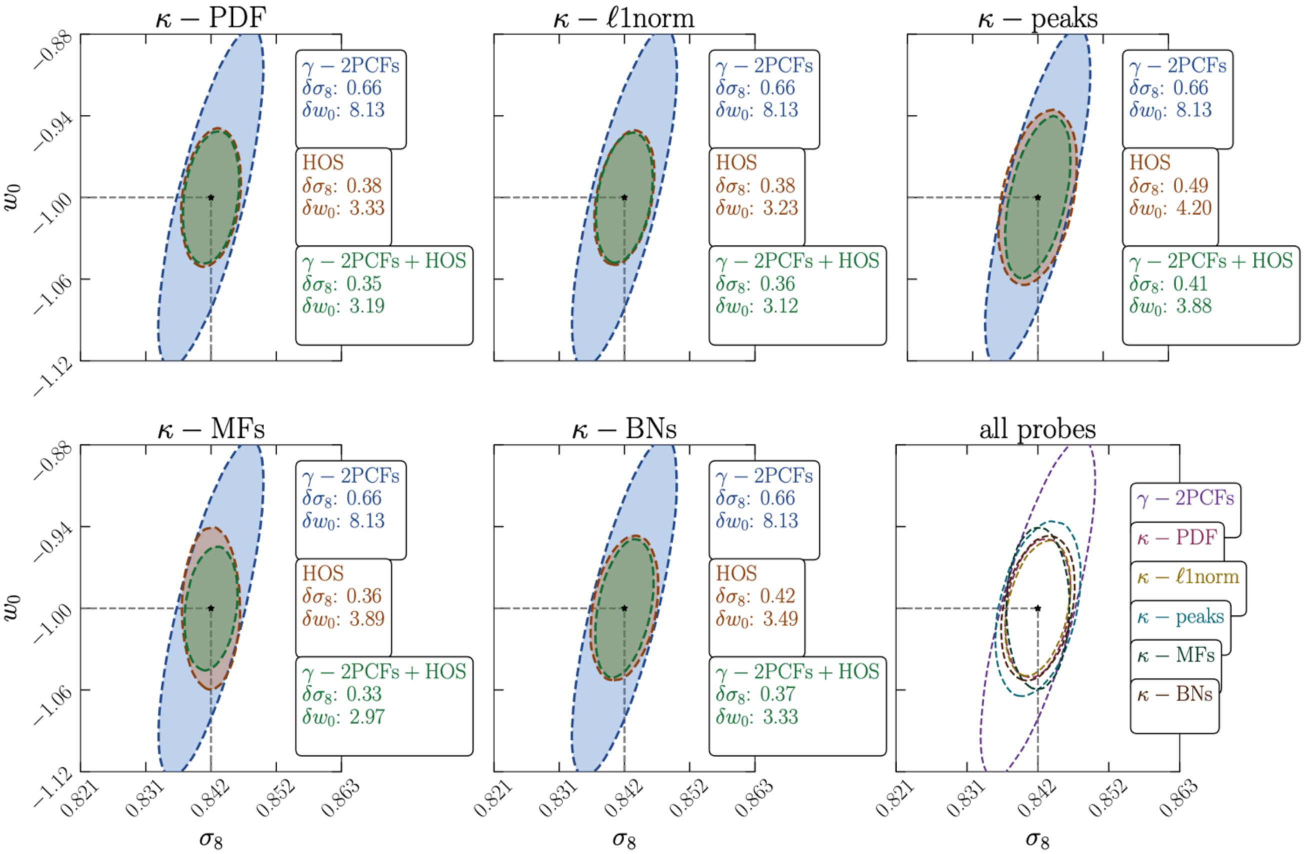




Tersenov+25

Euclid Collaboration LXXXV: Vinciguerra, Bouchè, HOWLS et al. 2026

HOWLS DR1 forecasts



Euclid Collaboration LXXXV: Vinciguerra, Bouchè, HOWLS et al. 2026

HOWLS Coordinators

NATALIA CORA NICOLAS

1 SIMULATIONS

MARCO JOACHIM IRATI RAUL
GIOVANNI JEGER TOMASZ SIMONE

Available

- density shells
- homogeneous ray-tracing via Born approximation
- baryonification
- IA model
- common post-processing pipeline

Missing

- band-limiting
- baryonification validation
- DR1-tiling
- IA, SC & ph-z maps
- north & south n(z) processing
- BACCO-rescaling prior extension

2 STATISTICS MEASUREMENTS

MARCO FILIPPO SIMONE

Available

- shear-2pt
- HOM
- maxima & minima
- PDF
- MFs
- voids

multi-scale filtering (top-hat)

Missing

- WPH
- Persistent Homology

3 STATISTICS THEORY

LINA CORA ANDREAS
ALEXANDRE VINCENZO ALESSANDRO

Available

- shear-2pt
- PDF
- l1-norm
- DSS

Missing

- HOM, MFs
- systematic modelling

4 EMULATOR

KARTHIKA JOACHIM DANIELA LINA

Available

- GPs for multiple HOS
- optimal cosmology grid via 2pt

Missing

- GPs for maxima & minima, MFs
- possible extension to MLP
- optimal cosmology grid via PDF
- numerical emulator stability

5 LIKELIHOOD

ZEYNAB ELENA

Available

- skew-normal fitting oipeline (tested on subset of HOS)

Missing

- emulator error propagation into likelihood
- skew-normal fit for remaining HOS
- DR1 skew-normal fits
- compression (bonus)

6 INFERENCE

DANIELA LINA FILIPPO

Available

- EMCEE sampler
- Gaussian likelihood
- multi-scale and tomographic chains

Missing

- non-Gaussian likelihood
- CLOE implementation (TBD)

7 BEYOND LCDM

FILIPPO ALESSANDRO
JOACHIM

Available

- GR flat-sky end2end from kappa tiles of GR pipeline

Missing

- Boost factor emulation
- Gravity-dependent systematics
- beyond-GR chains

8 SHEAR × PHOTOMETRIC CLUSTERING

TOMASZ LINA

Available

- DSS theory code

Missing

- RR2 mocks
- emulation
- inference

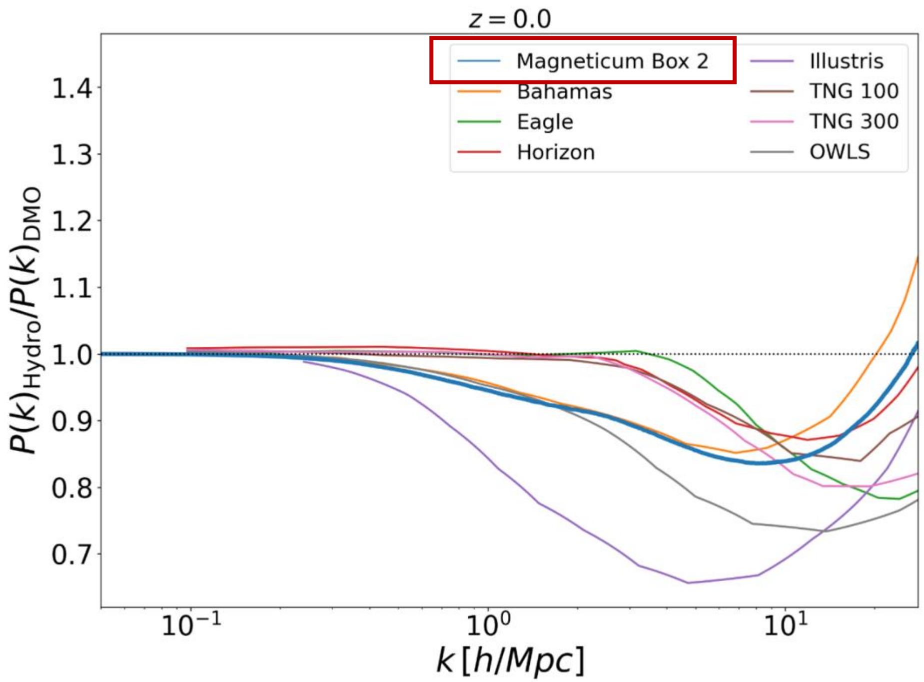
Available: items already implemented or in place **Missing:** items not yet available or still to be done

DR1 Readiness overview for HOWLS working group.
Blocks are ordered along the analysis pipeline (left → right).

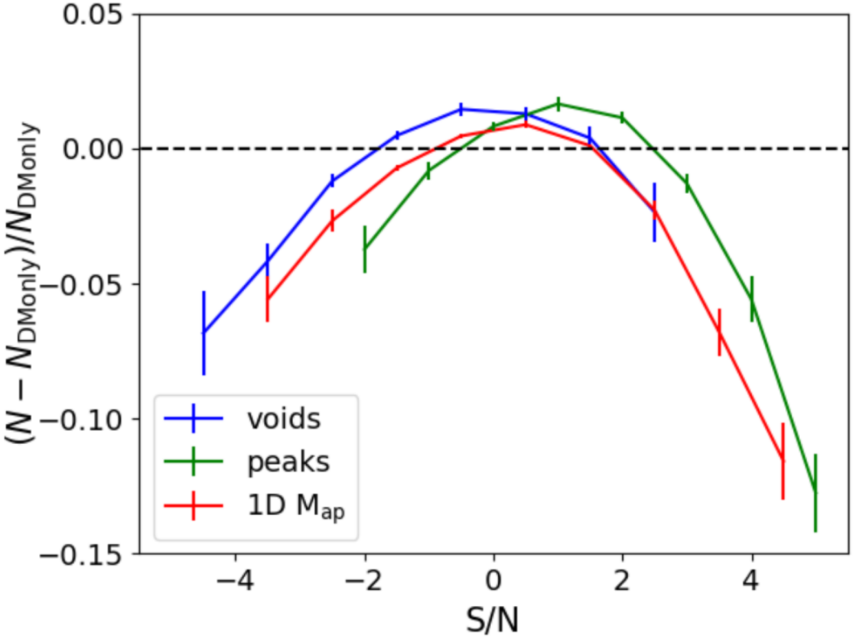
Summary & Challenges

- Euclid HOWLS team rocks!
- DR1 analysis ongoing; 2x better constraints than 2pt on S8 & w
- Systematic biases are still challenging
- Euclid Forward Modelling team for implicit likelihood (see Simone's talk on Wed.)

Impact of baryons



Impact on the matter power spectrum

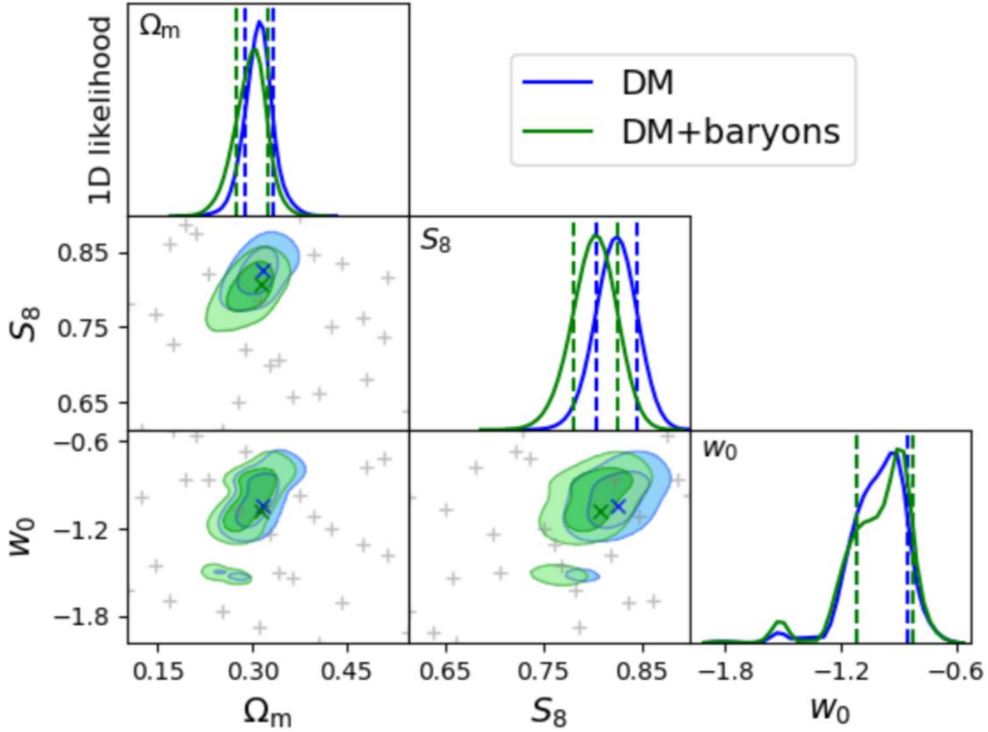


Impact on mass map statistics

➢ Baryons modify matter distribution on small scale

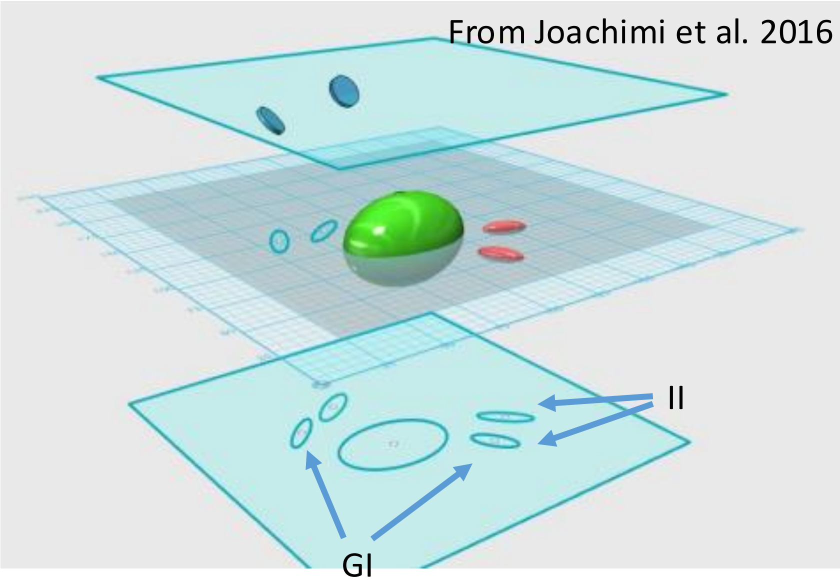
Impact of baryons (Martinet et al. 2021b)

- Magneticum (www.magneticum.org) hydrodynamical simulations
- Few percent effect on S_8… but can be controlled
- Problem of uncertainty in AGN feedback



Impact of baryons on mass map constraints with Euclid mocks (with tomography, 100 deg²)

Impact of IA (Harnois-Deraps, NM et al. 2022)



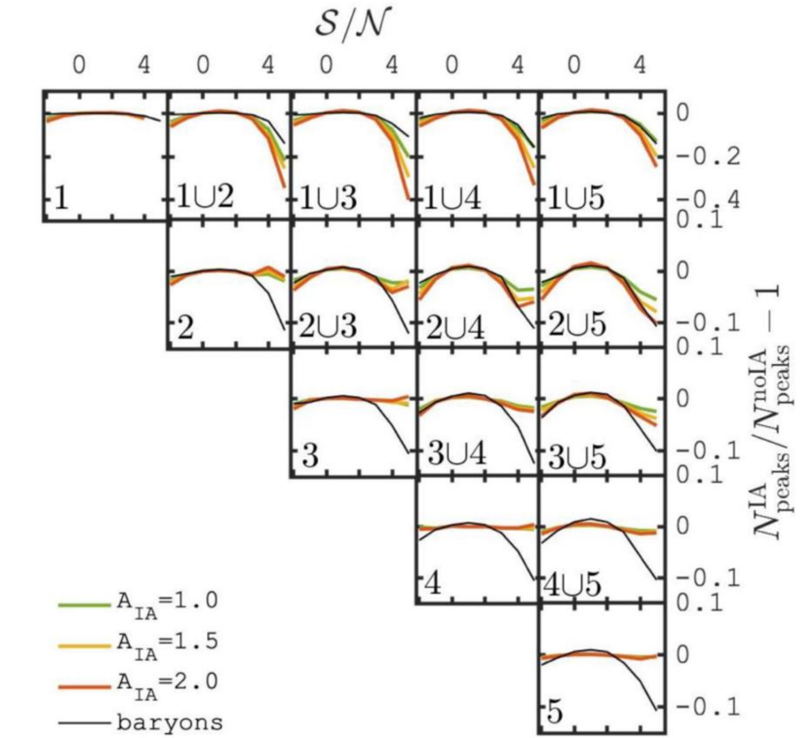
Intrinsic alignments (Hirata & Seljak 2004)

Impact of intrinsic alignment (Harnois-Déraps et al. 2022)

$$\epsilon_1^{\mathrm{IA}} = -\frac{A_{\mathrm{IA}}\bar{C}_1\bar{\rho}(z=0)}{D(z)}(s_{xx}-s_{yy}) \quad , \epsilon_2^{\mathrm{IA}} = -\frac{2A_{\mathrm{IA}}\bar{C}_1\bar{\rho}(z=0)}{D(z)}s_{xy}$$

tidal tensor

Amplitude of IA = new free parameter



Impact of intrinsic alignment (Harnois-Déraps et al. 2022)