Theory and likelihood in *Euclid*

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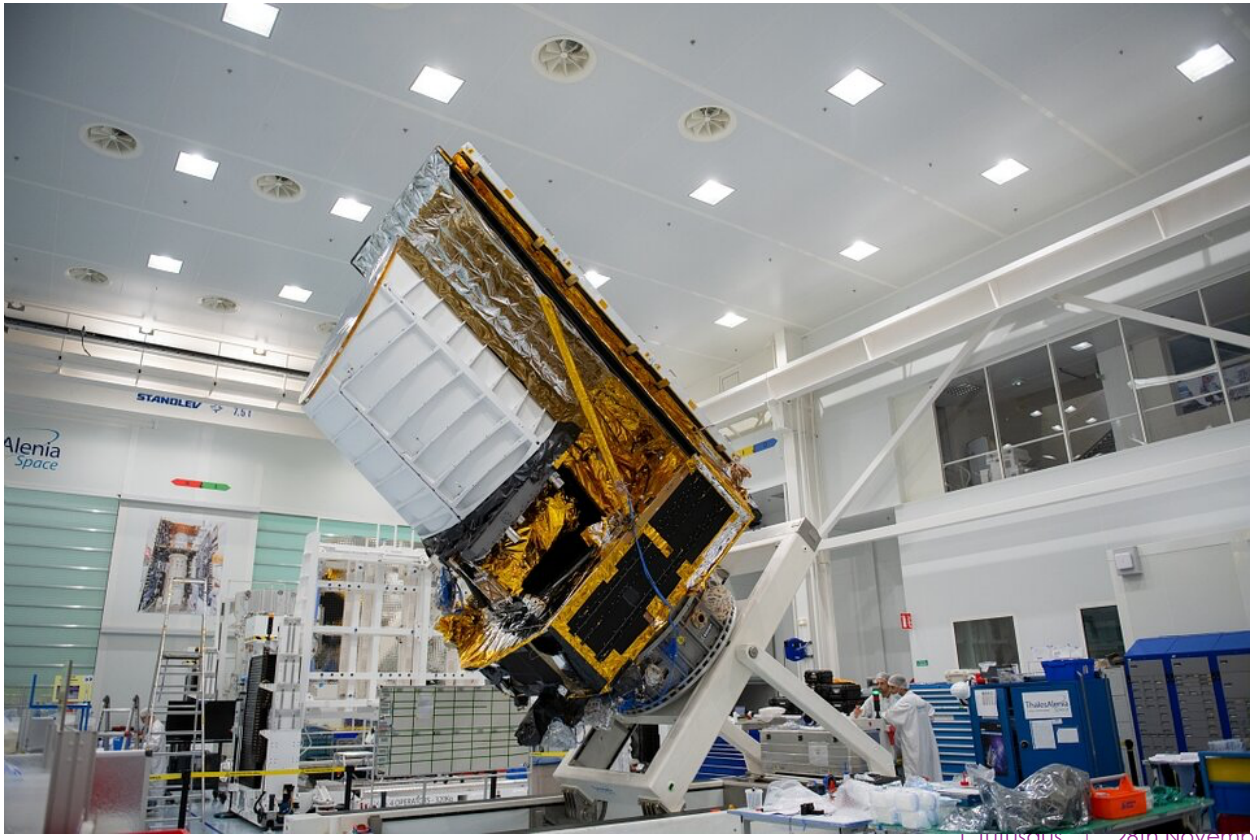
Contents

Introduction

- Euclid will measure the shape and redshift of millions of galaxies up to redshift ~2:



[Credit: ESA]

Introduction

- The survey will allow us to consider several cosmological probes:

Phot. clustering (GCp)
1.5×10^9 gal.
$z \in [0, 2.5]$

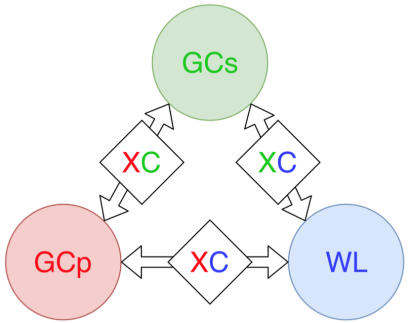
Weak lensing (WL)
1.5×10^9 gal.
$z \in [0, 2.5]$

Spec. clustering (GCs)
5×10^7 gal.
$z \in [0.9, 1.8]$

The Euclid Mission: baseline and options — Euclid Consortium

SURVEYS In ~5.5 years					
	Area (deg2)	Description			
Wide Survey	**15,000 deg²**	Step and stare with 4 dither pointings per step.			
Deep Survey	**40 deg²**	In at least 2 patches of > 10 deg² 2 magnitudes deeper than wide survey			
PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg²	0.763×0.722 deg²			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux
	Shapes + Photo-z of $n = 1.5 \times 10^9$ galaxies			z of n=5x10⁷ galaxies	
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250
Possibility other surveys: SN and/or μ-lens surveys, Milky Way ?					

Ref: Euclid RB, arXiv:1110.3193



Observatoire Midi-Pyrénées OMP — irap astrophysique & planétologie

Introduction

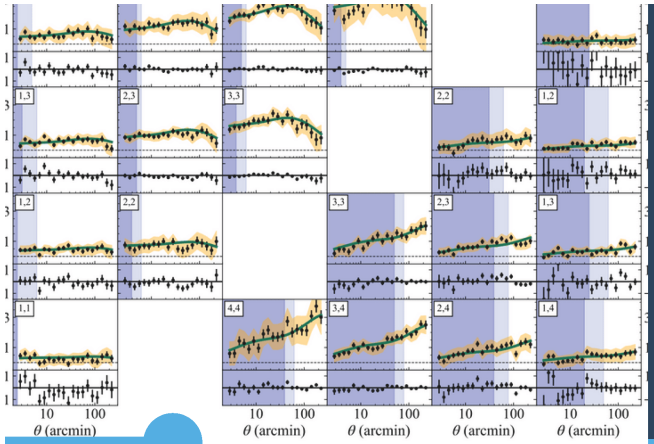
- With Euclid we will:
  - Constrain dark energy
  - Constrain dark matter
  - Test the theory of gravity at cosmological scales
- But in order to perform the analyses we need a **theory** model to compute our predictions and a **likelihood** to compare the measurements against the predictions

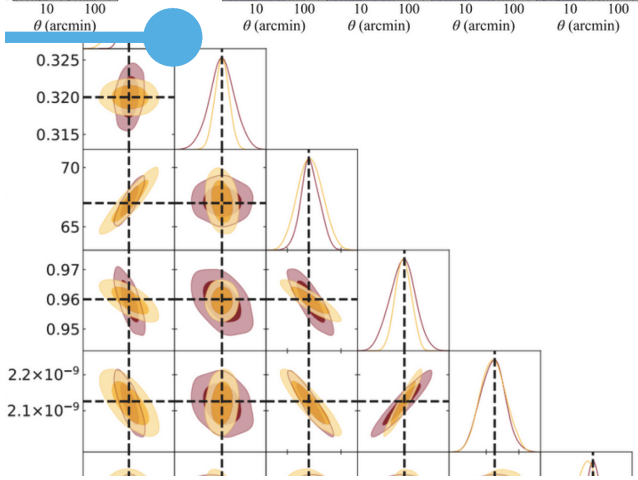
Likelihood

- Main goal: Implement the Euclid likelihood for:
  - Spectroscopic galaxy clustering (BAO+RSDs)
  - Photometric galaxy clustering
  - Weak lensing
  - Cross-correlations (galaxy-galaxy lensing)
  - Additional probes
  - Extended models

Likelihood

Main goal:





From Euclid Data

3x2pt (pseudo Cl and/or 2pt CFs)
GCsp (Legendre multipoles and/or 2pt CFs)
3x2pt systematics (photo - z, shear, etc.)
GCsp systematics (purity, completeness, etc.)

To Cosmological Constraints

dark energy equation of state
nature of dark matter
initial conditions
modified gravity theories

[Credit: V. Cardone]

Likelihood

- Main goal: Implement the Euclid likelihood

- Inter-Science Working Groups Task-forces:
  - Likelihood (IST:L). Leads: V. Cardone, S. Joudaki, V. Pettorino (A. Sánchez) + ~20 members (more than 20% FTE)
  - Nonlinear (IST:NL). Leads: M. Crocce, C. Giocoli, A. Pourtsidou + ~20 members (more than 20% FTE)

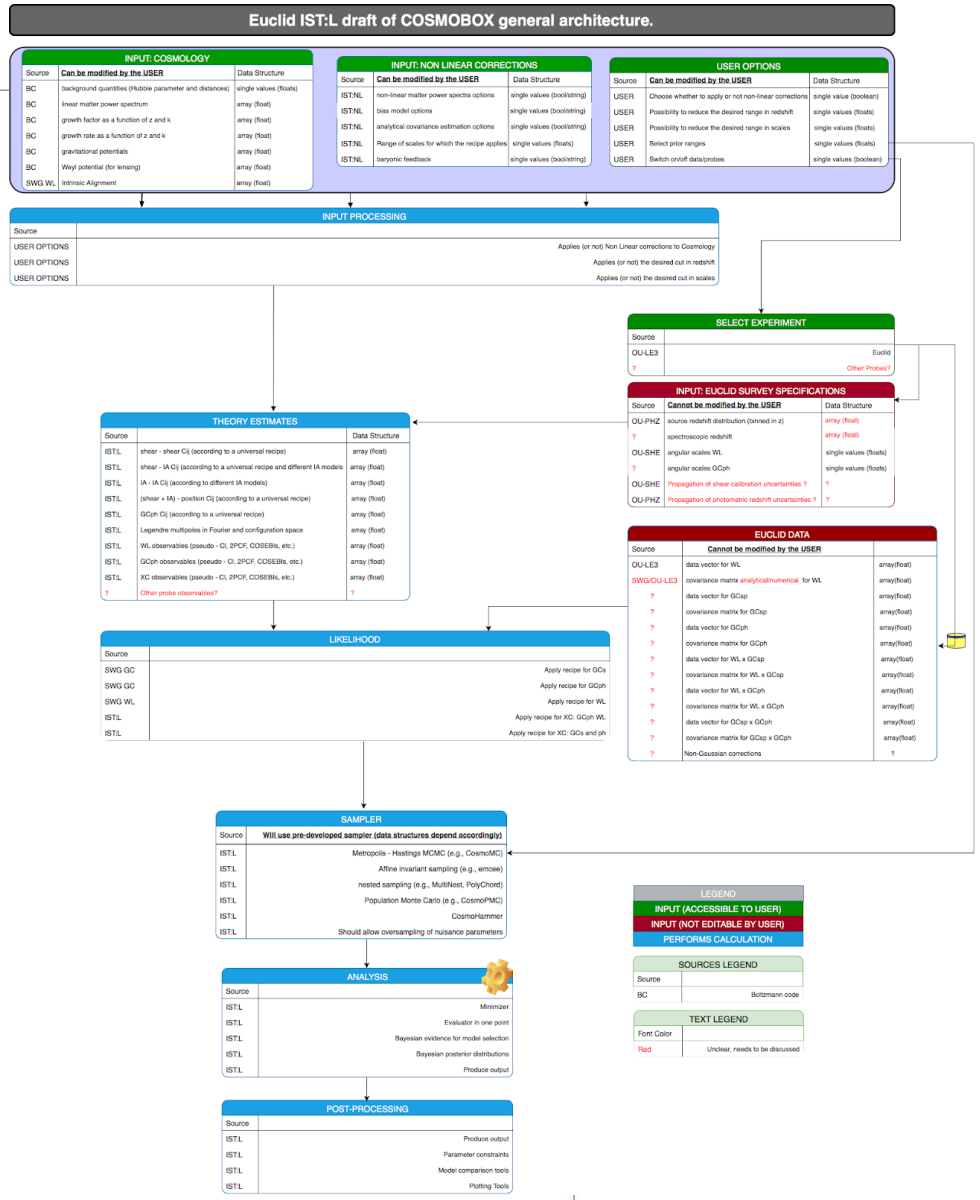
Likelihood

IST:L first steps:

- Agreed on a **first minimal recipe** for the primary probes with the Science Working Groups contact points
- Defined a **data model** and **use cases**
- Discussed available **CosmoBoxes** and selected Cobaya (CosmoSIS)
- Adoption of workflow with **AGILE** management concepts + **Slack** for everyday interactions
- Implemented **development guidelines**
- **Code training** for the group members: Continuous integration, API documentation, git development guidelines

Likelihood

- IST:L first steps:
  - Defined a data model and use cases:
    - DM: illustrates input, output, interfaces
    - Use cases: how is the user supposed to use the code?



Likelihood

IST:L first steps:

- Discussed available CosmoBoxes and selected Cobaya (CosmoSIS)

Code	Language	CAMB+CLASS	Modularity	Maintainance	Default Samplers	Other samplers available	Analysis tools	Postprocessing	Main developer in Euclid	Used in collaborations	Contacts within Euclid	Speed
Cobaya	python	✓	✓	✓	3/5	✓	5/5	GetDist	✗	Simons Observatory	G. Cañas Herrera M. Martinelli	?
CosmoMC	fortran	✗	✗	✓	2/5	✓	4/5	GetDist	✗	Planck	S. Joudaki M. Martinelli	?
CosmoSIS	C++ fortran python	✓	✗	✓	3/5	✓	5/5	internal/GetDist	✗	DES	I. Tutusaus	?
MontePython	python	✗	✓	✗	2/5	✓	4/5	internal/GetDist	✓	Planck	M. Archidiacono S. Clesse J. Lesgourgues	?

Samplers:

1. Metropolis-Hastings
2. Nested Sampling
3. MCMC hammer
4. Population MonteCarlo
5. Oversampling of nuisance parameters

Analysis tools:

1. Minimizer
2. Evaluator in one point
3. Bayesian Evidence
4. Bayesian posterior
5. Produces output chains

Modularity:
how much the code needs to be modified when adding a new likelihood.

✓ High
✗ Average
✗ Low

Maintainance:
guaranteed updates of the code, including addition of new data

✓ High
✗ Average
✗ Low

Likelihood

IST:L workflow with AGILE management:

- Gitlab, taskboard, scrum master and team development
- A specific (small) development task emerges
- IST:L leads assign it to a development team and add it on the taskboard

- Team members periodically rotate.
- All members encouraged to contribute to the whole project

[Credit: V. Pettorino]

Likelihood

How are the likelihood recipes decided:

- The likelihood work package of the different Science Working Groups test different recipes and identify the one(s) that should be used with real data.
- IST:L implements the chosen recipes through the creation of small tasks (AGILE management).
- IST:L uses existing codes for testing, but all the code adapted/ merged/improved in the official likelihood follows the development guidelines (high standard).

Likelihood

Euclid likelihood: CLOE

CLOE

COSMOLOGY
LIKELIHOOD
OBSERVABLES
EUCLID

CONCEPT

code in modular blocks
individuate what is needed
input from SWGs and OUs
connection with IST:NL
interface with SWGs codes

RECIPE

observables to consider
from theory to observables
include systematics
input quantities
output quantities

DATASET

3x2pt PseudoCl
3x2pt 2PCF
3x2pt COSEBIs
GCsp Legendre multipoles
GCsp 2PCF

LIKELIHOOD

covariance matrix
Gaussian vs non Gaussian
priors and scale cuts
sampling
additional cosmoligical probes

[Credit: V. Cardone]

Likelihood

CLOE v1.0:

- Internally released on May 2021 (not yet to be used for scientific papers or tests of scale cuts and models)
- Probes: spectroscopic and photometric GC, WL, and GGL (Legendre multipoles and harmonic space power spectra)
- Gaussian likelihood with Gaussian covariance
- Linear matter power spectrum
- No systematic uncertainties

Likelihood

CLOE v1.1:

- New user interface: Through executables and command lines or yaml configuration files
- Masking vector: Observables and scale cuts to consider
- Speed and documentation improvement and bug fixing
- Interface with IST:NL in place

Likelihood

- CLOE v2.0 (to be released and used for scientific papers):
  - Updates recipes:
    - Magnification bias (GCph and GGL)
    - Linear RSD (GCph and GGL)
    - Non flat models
    - Different n(z) for source and lens samples
    - Multiplicative shear and photometric redshift uncertainties
    - Nonlinear matter power spectrum (IST:NL)

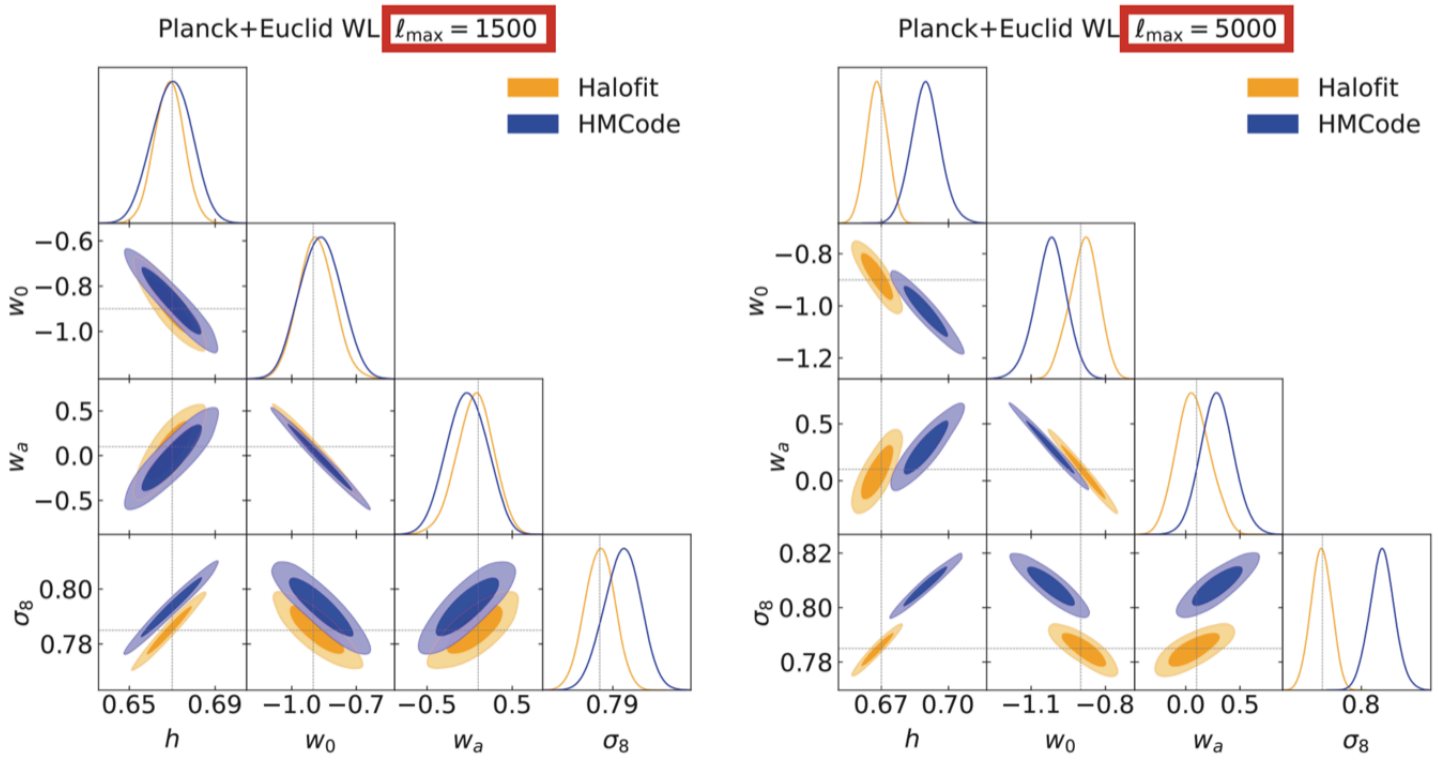
Likelihood

- CLOE v2.0 (to be released and used for scientific papers):
  - More realistic observables:
    - 2PCF for 3x2pt
    - Pseudo-Cl's for harmonic space analysis
    - 2PCF for spectroscopic GC
    - BNT transform to remove small scales
    - Scale cuts (IST:NL)
    - Gaussian + Super Sample Covariance

Likelihood

IST:NL:

- Using wrong or incomplete models will bias our results!



[Martinelli et al. 2021]

Likelihood

IST:NL (CLOE v2.0):

- Perturbation theory for spectroscopic GC: 1-loop PT with counter terms (FAST-PT)
- Nonlinear matter power spectrum / emulators for photometric probes: Halofit, HMCode, BACCO, Euclid Emulator 2
- Baryonic modeling / emulators: BACCO, BCEmu, HMCode
- Intrinsic alignments: NLA, TATT, Halo model
- 3x2pt theory covariance: Gaussian+SSC (PySSC)

Theory

- Main goal: Test beyond LCDM
  - Prepare beyond-standard analysis; select and study beyond-standard models
  - Provide vision for new interesting models and probes
  - Support Science Working Groups and IST:L/IST:NL for theory
  - Leads: F. Finelli, M. Kunz, V. Pettorino, A. Silvestri

Theory

- Structure: work packages

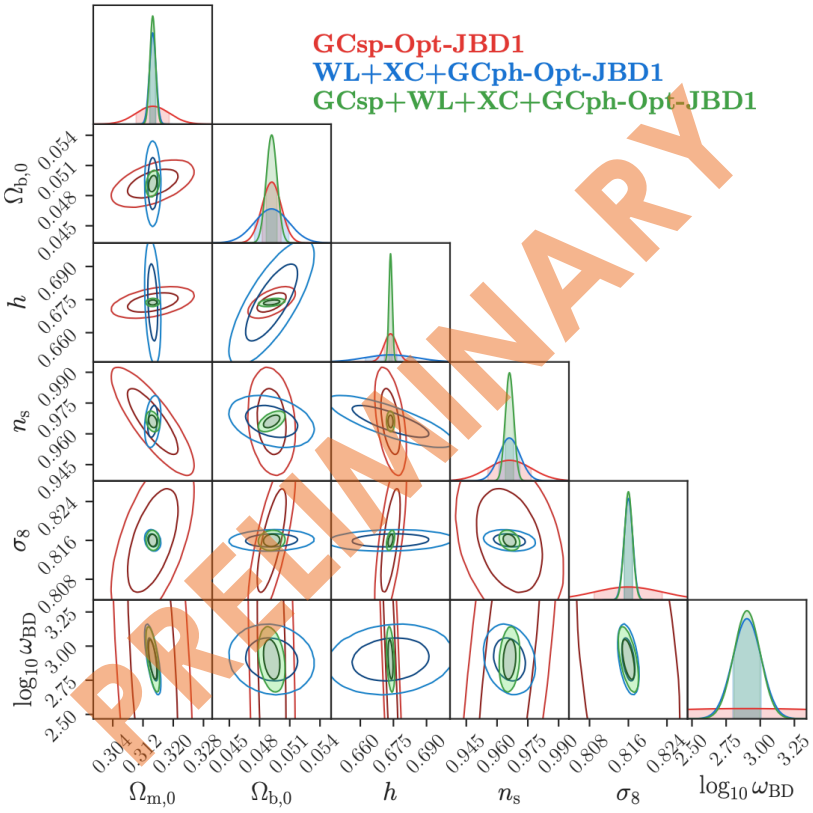
  - Dark energy and modified gravity
  - Dark matter
  - Initial conditions
  - Homogeneity and isotropy
  - Extended forecasts
  - Nonlinearities
  - Relativistic effects
  - Likelihood
  - Additional probes
  - Simulations

Theory

- Structure: key projects
  - Forecasts for beyond standard models in cosmology and fundamental physics (Y. Akrami, S. Casas, A. Silvestri)
  - Relativistic effects (D. Bertacca, F. Lepori)
  - Simulations and nonlinearities beyond LCDM (M. Baldi, F. Vernizzi)
  - ~15 scientific pre-launch papers planned

Theory

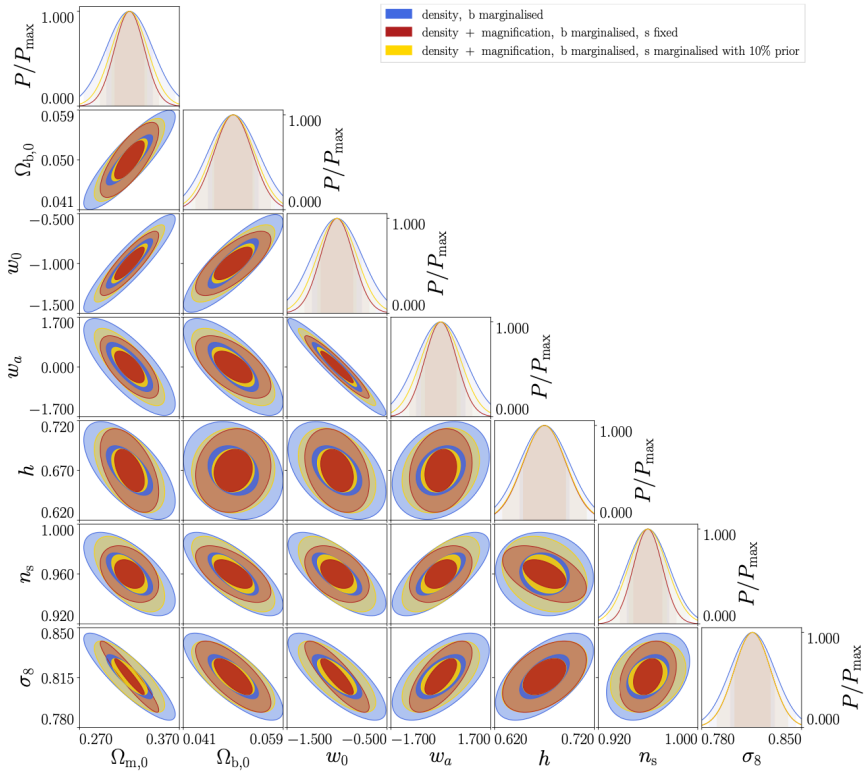
- Example: Euclid will constrain scale-independent modified-gravity models:
  - Jordan-Brans-Dicke, Dvali-Gabadadze-Porrati, K-Mouflage:

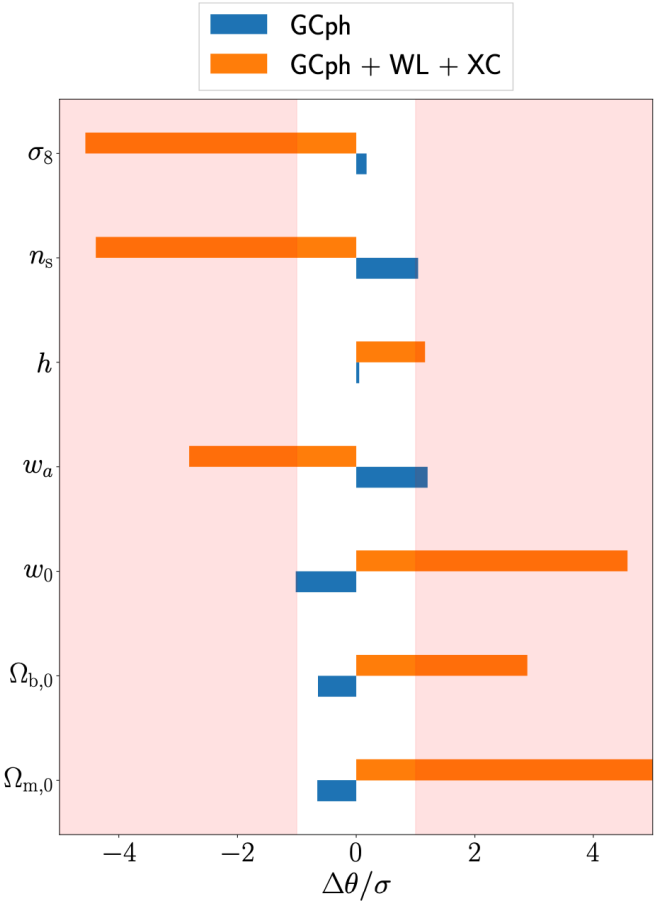


[Frusciante et al. in prep]

Theory

- Example: Magnification effects cannot be neglected for GCph and GGL:





[Euclid Collaboration: Lepori et al. 2022]

Conclusions

- Two Inter-Science Working Groups Task-forces have been created to develop the **official Euclid likelihood** (IST:L) **accounting for nonlinearities** (IST:NL)
  - The first version of the code CLOE ready to be used for scientific results will soon be released. Further improvements are expected before the analysis of real data
- The **theory** science working group has been established to define the **extended models to be tested** and support the other groups and IST:L/IST:NL to properly **perform the analysis beyond LCDM**
  - Multiple extensions beyond LCDM are being considered: dark energy and modified gravity, dark matter, initial conditions, homogeneity and isotropy, relativistic effects