
Credits: ESA - M. Pédoussaut

Review of likelihood frameworks: Euclid

Matteo Martinelli
CosmoForward, Tenerife, 12/02/2026

euclid
consortium

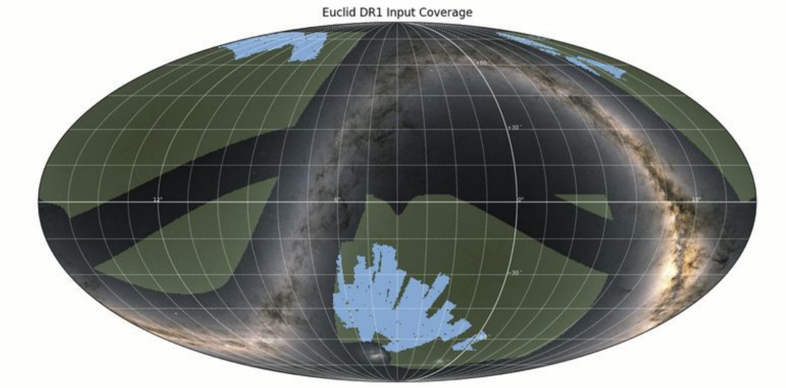
What Euclid will deliver

Euclid will provide a photometric and spectroscopic galaxy survey.

- Two instruments: VIS (visible) and NISP+grism (near infrared with spectroscopy)
- Area of 14000 sq deg
- Photometric catalogue ($0 < z < 2$) $\sim 10^9$ galaxies, $\sigma_z < 0.05\,(1+z)$
- Spectroscopic catalogue ($0.8 < z < 1.9$) $\sim 10^6$ galaxies, $\sigma_z < 0.001\,(1+z)$

2026 is the year of the first public data release of Euclid.

Release of the data collected from 14/02/2024 to 21/05/2025



Euclid primary probes

The main cosmological results of Euclid will be obtained analyzing the position, redshift and shape of the high number of galaxies observed.

Photometric survey (VIS+NISP)

- Weak gravitational lensing
- Galaxy clustering
- Galaxy-Galaxy lensing

Spectroscopic survey (NISP)

- Galaxy clustering
- BAO
- Full shape analysis

While these are the main probes, there are several other ways to extract cosmological information

- Strong lensing
- Clusters abundance
- Voids
- XCMB

Many more observables

Given the wide survey area and the high sensitivity, Euclid will also provide several other measurements!

- Quasars:
  high redshift objects that can be used to investigate the reionization epoch
- Active Galactic Nuclei:
  crucial to investigate galaxy evolution
- Microlensing
  possible detection of Black Holes and exoplanets
- Transients
  SNIa, Kilonovae (for bright sirens searches)

Euclid science ranges from cosmology to galaxy evolution. Many competing interests!

Primary probes theoretical predictions

Testing our cosmological model

From the photometric and spectroscopic surveys, we can extract 2pt correlation functions between galaxy positions and shape, with a tomographic approach.

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- Cross-correlation between probes (3x2pt)
- Need to model deep non-linear regime
- Modelling of systematic effects
- Transformation into real-space correlations

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Spectroscopic survey

- 3D galaxy power spectrum
- Projection into Legendre multipoles
- Need accurate modelling of redshift errors
- Modelling of systematic effects
- Transformation into real-space correlations

Photometric observables

We can obtain the angular power spectra for the photometric observables as

$$C_\ell^{X,Y}(z,z') = 4\pi \int \mathrm{d}\ln k \, W_\ell^X(k;z) \, W_\ell^Y(k;z') \, P_\zeta(k)$$

We can exploit the Limber and flat-sky approximations

$$j_\ell(x) \xrightarrow[\ell \gg 1]{} \sqrt{\frac{\pi}{2\ell+1}} \delta_\mathrm{D}\left(\ell + \frac{1}{2} - x\right)$$

This approximation fails at very large scales (it should not be relevant for DR1, limited area). Development of non-Limber calculations is ongoing.

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We can obtain the angular power spectra for the photometric observables as

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$$C_{i,j}^{X,Y}(\ell) = \int \mathrm{d}z \frac{W_i^X(z) W_j^Y(z)}{H(z) r^2(z)} P_{\delta\delta}\left(z, k = \frac{\ell + 1/2}{r(z)}\right)$$

$$W_i^g = b_g(z,k) n_i(z) H(z)$$

$$W_i^\epsilon = \frac{3}{2} H_0^2 \Omega_{m,0} (1+z) r(z) \int_z^{z_{max}} \mathrm{d}z' \, n_i(z') \left(1 - \frac{r(z)}{r(z')}\right) + W_i^{\mathrm{IA}}(z)$$

Euclid Collaboration, Cardone et al. (2025)

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nonlinear power spectrum

IA modeling

bias modeling

$$C_{i,j}^{X,Y}(\ell) = \int \mathrm{d}z \frac{W_i^X(z) W_j^Y(z)}{H(z) r^2(z)} P_{\delta\delta}\left(z, k = \frac{\ell + 1/2}{r(z)}\right)$$

GR assumption

$$W_i^g = b_g(z,k) n_i(z) H(z)$$

binned galaxy distribution

$$W_i^\epsilon = \boxed{\frac{3}{2} H_0^2 \Omega_{m,0}(1+z)} r(z) \int_z^{z_{max}} \mathrm{d}z' n_i(z') \left(1 - \frac{r(z)}{r(z')}\right) + W_i^{\mathrm{IA}}(z)$$

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Spectroscopic observables

We can obtain also the observable for the spectroscopic survey, projecting the observed power spectrum into Legendre multipoles

$$P_{\rm obs}(k_{\rm ref}, \mu_{\rm ref}; z) = \frac{1}{q_\perp^2 q_\parallel} \left\{ \frac{\left[b\sigma_8(z) + f\sigma_8(z)\mu^2\right]^2}{1 + [f(z)k\mu\sigma_{\rm p}(z)]^2} \right\} \frac{P_{\rm dw}(k, \mu; z)}{\sigma_8^2(z)} F_z(k, \mu; z) + P_{\rm s}(z)$$

$$q_\perp(z) = \frac{D_{\rm A}(z)}{D_{\rm A, ref}(z)} \quad \text{and} \quad q_\parallel(z) = \frac{H_{\rm ref}(z)}{H(z)}$$

$$P_{\rm dw}(k, \mu; z) = P_{\delta\delta}(k; z)\, {\rm e}^{-g_\mu k^2} + P_{\rm nw}(k, \mu; z)\left(1 - {\rm e}^{-g_\mu k^2}\right)$$

$$g_\mu(k, \mu, z) = \sigma_{\rm v}^2(z)\left\{1 - \mu^2 + \mu^2\left[1 + f(z)\right]^2\right\}$$

$$F_z(k, \mu; z) = {\rm e}^{-k^2\mu^2\sigma_r^2(z)}$$

[Euclid Collaboration, Cardone et al. (2025)]

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AP effect

shot noise

$$q_\perp(z) = \frac{D_{\rm A}(z)}{D_{\rm A,ref}(z)} \quad \text{and} \quad q_\parallel(z) = \frac{H_{\rm ref}(z)}{H(z)}$$

fiducial cosmology

$$P_{\rm dw}(k,\mu;z) = P_{\delta\delta}(k;z)\,{\rm e}^{-g_\mu k^2} + P_{\rm nw}(k,\mu;z)\left(1-{\rm e}^{-g_\mu k^2}\right)$$

no BAO

$$g_\mu(k,\mu,z) = \sigma_{\rm v}^2(z)\left\{1-\mu^2+\mu^2[1+f(z)]^2\right\}$$

nonlinear BAO damping

$$F_z(k,\mu;z) = {\rm e}^{-k^2\mu^2\sigma_r^2(z)}$$

redshift error

[Euclid Collaboration, Cardone et al. (2025)]

Other nuisance effects

Several other effects need to be modelled if we want to have **accurate** theoretical predictions

Photometric observables

- Impact of mask -> pseudo-Cls
- Selection cut -> magnification bias
- Shear calibration -> multiplicative bias
- Extended IA modelling
- Baryons

Spectroscopic observables

- Line interlopers -> completeness and purity
- noise interlopers -> outliers
- non-linear RSD modelling

Not a systematic effect, but particular care must be taken in modelling non-linear effects: computation of non-linear power spectra and non-linear bias.

Also cutting out non-linear scales is not as trivial as it seems, e.g. for WL.
Wide kernels require BNT transformation.

Euclid Collaboration, Cardone et al. (2025)

Cosmological modelling and inference
cloe-org

Towards DR1 results

With the date of the first data release approaching, the Euclid consortium has created task forces dedicated to the required development.

For what concerns cosmological constraints, the main group tasked with the development of parameter estimation tools is the **Key Project for Joint Cosmology**, aiming at obtaining cosmological results from the combination of photometric and spectroscopic data.

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Within this group, the software for parameter estimation is developed: **cloe-org**, a hub for cosmological modeling and statistical inference focused on large-scale structure

Our goal: parameter estimation

The software the consortium wants to develop needs to:

$$P(\theta\,|\,d, M) = \frac{\mathcal{L}(d\,|\,\theta, M)\,\Pi(\theta\,|\,M)}{\mathcal{Z}(d\,|\,M)}$$

$$-\log\mathcal{L} \propto [d - T(\theta)]^{t}\,\mathrm{Cov}^{-1}\,[d - T(\theta)]$$

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All this is performed by cloe-org, which will soon be available as a GitHub organization.

The cloe-org organization

cloe-org

cloe-org

Hub for cosmological modeling and statistical inference focused on large-scale structure

cloe-maintainers

About

Team in charge of providing maintaince to the cloe-org ecosystem

Members

Find a member...

5 members 0 child team members

- Chiara Moretti chiaramoretti Maintainer
- Guadalupe Cañas-Herrera gcanasherrera
- AndreaPezzotta Maintainer
- Marco Bonici marcobonici
- Pedro Carrilho PedroCarrilho Maintainer

The cloe-org organization

Several repositories are available in cloe-org

Repository Name	Description
cloelib	Computation of the theoretical predictions for Euclid primary observables
cloelike	Euclid likelihood module for photometric and spectroscopic primary observables
playground	Tutorials, examples and DEMO notebooks
blindspot	Generation of blinding shifts for cosmological analyses
darkflipper	Computation of Figure of Merit and Figure of Bias measurements

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The main tools for parameter estimation are:

- **cloelib**: computation of theoretical predictions of Euclid primary probes
- **cloelike**: likelihood module for primary probes

The maintainers of cloe-org established an open science approach.
Development will be open to external contributions

A collective effort

cloe-org is a joint effort of the consortium. Currently it has 140 members and 30 contributors.

Contribution Guidelines

Each repository may have its own specific contribution guidelines, but you can find general principles here.

The `cloelib`, `cloelike` and `playground` repositories follow the All Contributors approach to recognize all types of contributions.

You can find the list of contributors in the README files of each repository. This helps us acknowledge everyone who contributes, whether through code, documentation, bug reports, or other support.

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The goal is to involve the global community. Currently not public, but this will change soon.
You can also request early access writing to the cloe-org maintainers

How to Get Involved

We welcome contributions from everyone! If you're interested in collaborating or contributing, here's how you can get started:

1. **Explore our repositories** – Check out the codebases and documentation.
2. **Open an issue** – Found a bug, have a feature request, or need help? Open an issue in the respective repository.
3. **Submit a pull request (PR)** – Contribute code, documentation, or improvements. Please follow the contribution guidelines provided in each repo.
4. **Join discussions** – Engage with us in Discussions or raise questions in issues.

List of contributions (partial)

- Spectroscopic observables: Chiara Moretti, Andrea Pezzotta
- Photometric observables: Guadalupe Cañas-Herrera
- Correlation functions for photo-z: Zahra Baghkhani, Laila Linke
- COSEBIs: Casper Vedder
- Non-Limber calculations: Matteo Baratto
- Non-linear corrections: Pedro Carrilho
- Validation: Jose Coloma
- jaxcosmo link: Marco Bonici
- Overall architecture and interfaces: Guadalupe Cañas-Herrera

cloelib: getting theoretical predictions

The calculations for theoretical predictions are performed by cloelib.

This takes as input fundamental cosmological ingredients (expansion history, matter power spectra) and computes correlation functions, also dealing with the systematic effects.

Input parameters: cosmological and nuisance

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- CAMB
- CLASS
- modifications of these codes
- Emulators (e.g. CosmoPower, HMCode2020Emu,...)

euclid consortium

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Non-linear corrections for power spectra are also obtained from Boltzmann solvers (halo model) or using emulators. Significant effort is ongoing to obtain corrections also in extended cosmologies.

Sampling

cloelib and cloelike do not depend on specific code for sampling

Your favourite sampler can in principle be interfaced with cloelib and cloelike!

Current work relies on an interface with the nested sampler Nautilus , but the code can be interfaced with existing frameworks (Cobaya, CosmoSIS)

cloe-org also has support for JAX automatic differentiation

This will allow to also use more sophisticated samplers applying gradient approaches, e.g. Hamiltonian Monte Carlo.

How fast is CLOE?

- Euclid DR1 WL Cells: 51.6 ms
- Euclid DR1 WL pseudo-Cells: 95.3 ms
- Euclid DR1 3x2pt Cells: 0.236 s
- Euclid DR1 3x2pt pseudo-Cells: 0.363 s

[Credit: Guadalupe Cañas-Herrera]

Free parameters

Having a fast code and a good sampling strategy is crucial.

To accurately model all observational and systematic effects, we need **MANY** parameters

Typical DR1-like run: 45-65 cosmological+nuisance free parameters (3x2pt+GCspec)

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Baseline cosmology (depends on data combination) : flat w_0w_aCDM (+m_ν ?)

Basic results delivered, i.e. what was promised to ESA:

- w_0w_aCDM
- ΛCDM+m_ν
- ΛCDM+γ_{MG}

Main Scientific Objectives
Understand the nature of Dark Energy and Dark Matter by:
• Reach a dark energy *FoM* > 400 using only weak lensing and galaxy clustering; this roughly corresponds to 1 sigma errors on w_p and w_a of 0.02 and 0.1, respectively.
• Measure γ, the exponent of the growth factor, with a 1 sigma precision of < 0.02, sufficient to distinguish General Relativity and a wide range of modified-gravity theories
• Test the Cold Dark Matter paradigm for hierachical structure formation, and measure the sum of the neutrino masses with a 1 sigma precision better than 0.03eV.
• Constrain n_s, the spectral index of primordial power spectrum, to percent accuracy when combined with Planck, and to probe inflation models by measuring the non-Gaussianity of initial conditions parameterised by f_{NL} to a 1 sigma precision of ~2.

[Laureijs et al. (2011) Euclid Red Book]

Testing and validation

The code is developed with CI/CD testing approach to verify any new implementation.

The final product will undergo validation tests to verify correct implementation and that no numerical artifact can impact the analysis (see Euclid Collaboration: Martinelli et al. (2025) for the validation of a previous version of the code)

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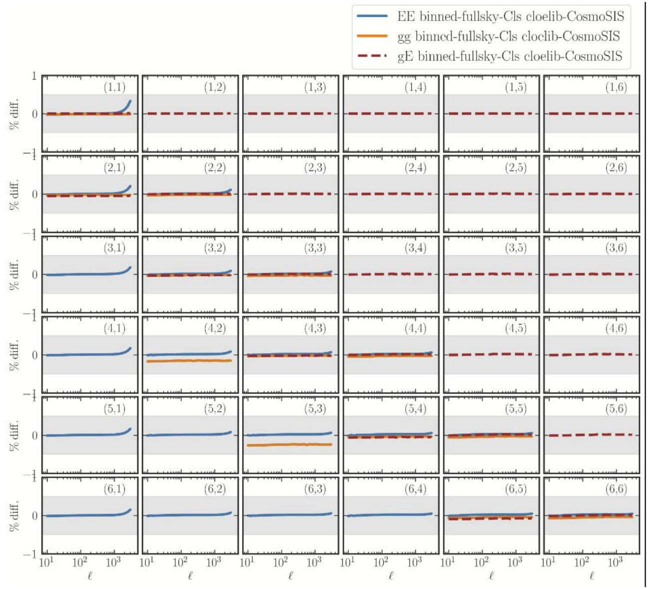
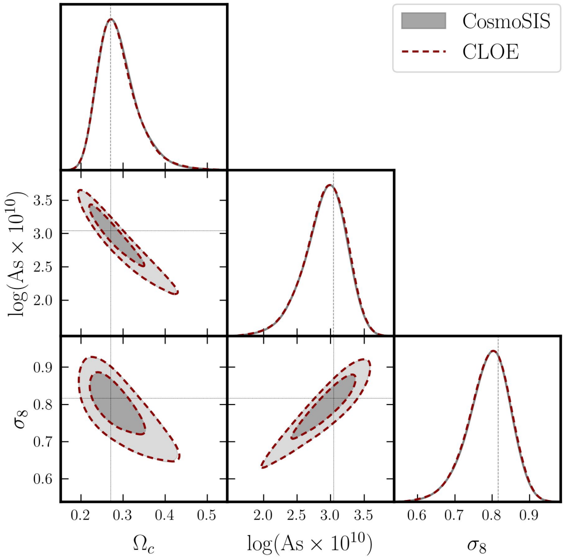
Preliminary validation already ongoing: comparison with CosmoSIS on simulated DR1 products





[Credit: Jose Coloma]

Other probes and models

Euclid cosmological power is not limited to its primary probes.

The consortium has several groups focusing on other probes (e.g. clusters, voids) or cross-correlation with other datasets (e.g. CMB).

Development for this is moving forward in parallel. Pull requests to the main code are ongoing, aiming at including these probes into the main code.

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What about external likelihoods?

By itself cloe-org does not include external likelihoods (CMB, SN, BAO…).
Interfaces of cloe-org tools with existing cosmological frameworks are being developed.
Soon to come:

- Cobaya
- CosmoSiS

Summary

- Euclid delivers a galaxy catalogue (positions, shape, redshift) with extreme precision
- To obtain reliable cosmological constraints we need accurate modelling: significant effort is take to model systematic/non-cosmological effects (IA, galaxy bias, non-linear scales, ...)
- cloe-org is the container for the work of the consortium. The main effort is on **cloelib** (theoretical predictions) and **cloelike** (likelihood), developed as an open source software. Example notebooks and playground repositories are provided.
- Main dependencies on codes for cosmological quantities (CAMB/CLASS/emulators). Tools to build the required mamba/conda environments are contained in cloe-org
- Interfaces with existing cosmological frameworks (Cobaya/CosmoSIS) are being developed, allowing to combine Euclid with other cosmological likelihoods.
- **cloe-org will soon be open to external contributions. Help us create a great tool for cosmological analysis!**