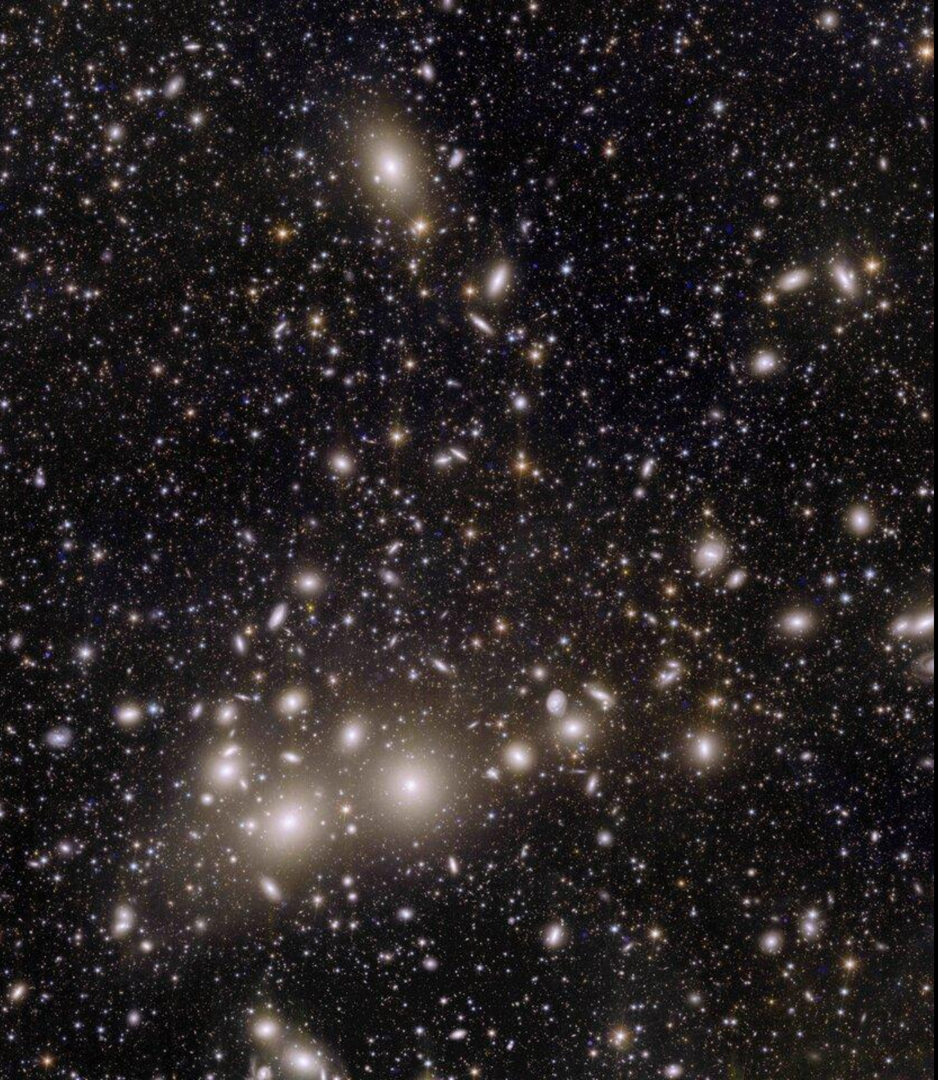


The ESA Euclid mission: a journey to understand the dark side of the universe

Guadalupe Cañas-Herrera,
European Space Agency Research Fellow

DPG-Frühjahrstagung 2025 der Sektion Materie und Kosmos
3rd April 2025

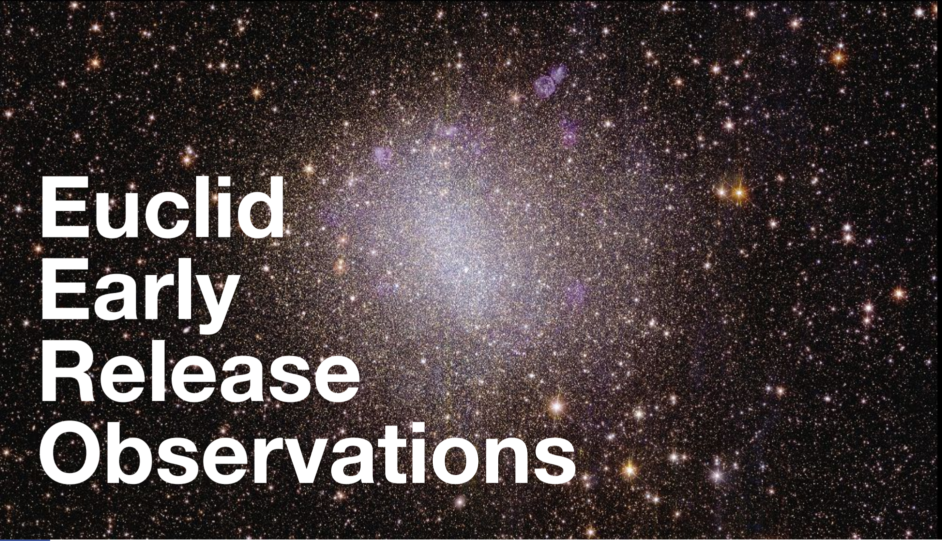
euclid consortium

Our Universe is dark







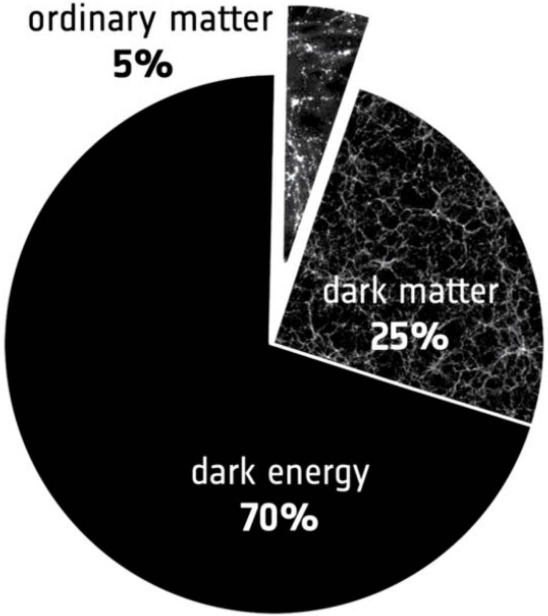
Euclid Early Release Observations

Euclid Early Release Observations were released to the public 6 months after launch, together with 10 scientific articles

One of those articles is the “Overview of the Euclid mission”, which serves as the foundation for this talk

Cosmology: where do we stand

A simple recipe for our Universe



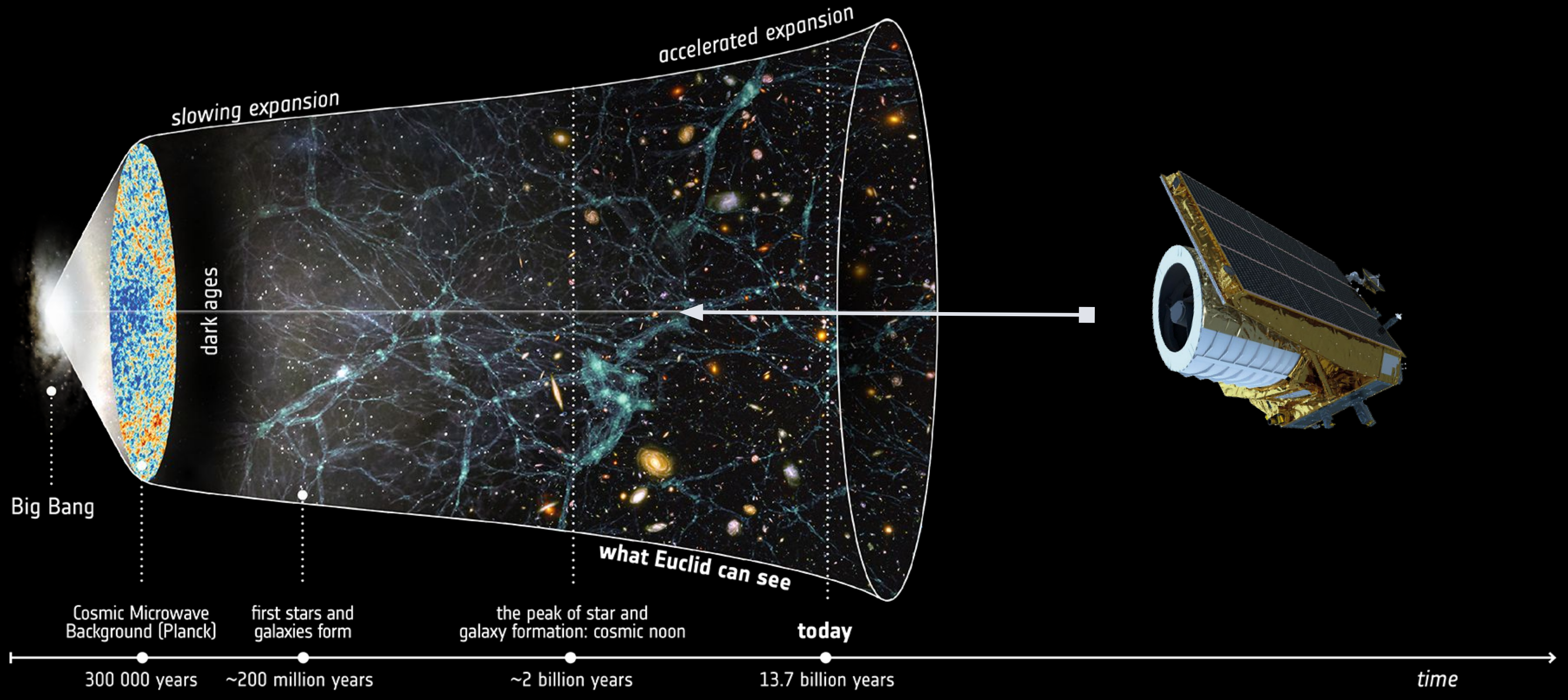
Credit: ESA

The simplest cosmological model has only few parameters

Ω_m	Ω_b	A_s	n_s
H_0	Ω_k	m_ν	Λ

Unveiling the dark components demands going beyond the **Standard Cosmological Model**

Timeline of the Universe



Credit: ESA/ATG

Euclid consortium

Better data comes with a cost

LIKELIHOOD

COVARIANCE MATRIX

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

DATA

THEORY

CLOE

Cosmology Likelihood for Observables in Euclid

How effectively do you account for systematic effects?

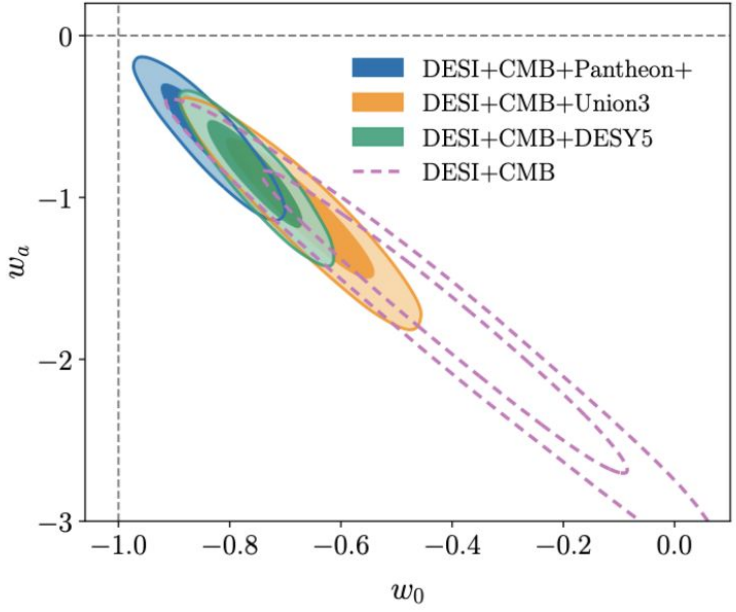
How accurately do you model your observables considering physical effects?

Credit: G. Cañas-Herrera

What do other experiments say

DESI

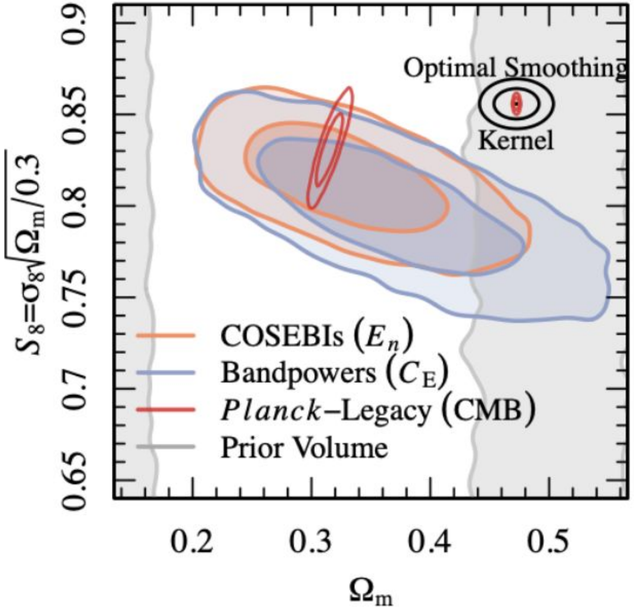
SPECTROSCOPIC BAOs



Credit: **DESI Collaboration, 25**

Kilo-Degree Survey (KiDS)

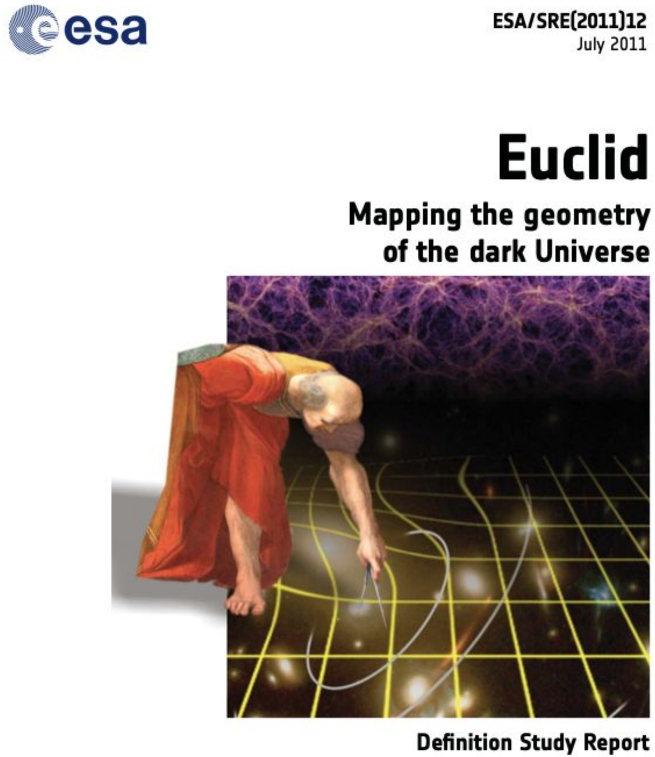
COSMIC SHEAR



Credit: **A. Wright, 25**

Euclid primary goals

Main objectives



Credit: ESA Euclid Definition Study report

Euclid is designed to understand the **nature** of **Dark Energy and Dark Matter**

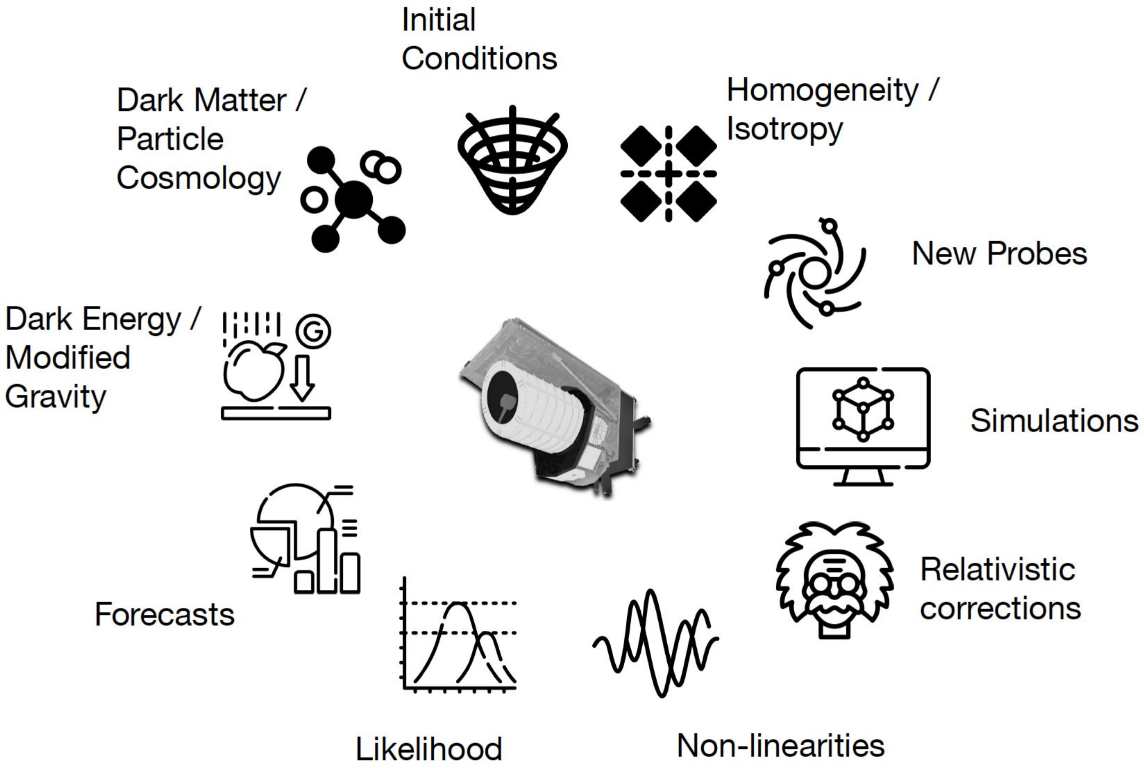
Reach a dark energy *Figure of Merit* > 400 using only Euclid primary probes

Measure the exponent of the growth factor with a 1 sigma precision < 0.02

Measure the sum of the neutrino masses with a 1 sigma precision better than 0.03 eV.

Constrain the spectral index and measure non-Gaussianity of initial conditions

Understanding the *dark* sector



Credit: S. Casas

Understanding the *dark* sector

Date of Issue 2015-08-25

Table 1: Euclid Primary Science Objectives – see RD10 for a full description.

Sector	Euclid Targets
Dark Energy	• Measure the cosmic expansion history to better than 10% for several redshift bins from $z = 0.7$ to $z = 2$. • Look for deviations from $w = -1$, indicating a dynamical dark energy. • Euclid *alone* to give $FoM_{DE} \geq 400$ (roughly corresponding to 1-sigma errors on w_p, & w_a of 0.02 and 0.1 respectively)
Test of Gravity	• Measure the growth index, γ, to a precision better than 0.02 • Measure the growth rate to better than 0.05 for several redshift bins between $z = 0.5$ and $z = 2$ • Separately constrain the two relativistic potentials φ and ψ • Test the cosmological principle
Dark Matter	• Detect dark matter halos on a mass scale between 10^8 and $>10^{15}$ M_{Sun} • Measure the dark matter mass profiles on cluster and galactic scales. • Measure the sum of neutrino masses, the number of neutrino species and the neutrino hierarchy with an accuracy of a few hundredths of an eV
Initial Conditions	• Measure the matter power spectrum on a large range of scales in order to extract values for the parameters σ_8 and n_s to 0.01. • For extended models, improve constraints on n_s and α with respect to Planck alone by a factor 2. • Measure the non-Gaussianity parameter f_{NL} for local-type models with an error better than ± 2.

Credit: ESA & Euclid Consortium

Understanding the *dark* sector

GR (LCDM) →

$$S = \frac{1}{16\pi G}\int \mathrm{d}x^4\sqrt{-g}\,(R - 2\Lambda + \mathcal{L}_m)$$

$$\mathrm{ds}^2 = -(1+2\Psi)\mathrm{dt}^2 + \mathrm{a}^2(1-2\Phi)\mathrm{dx}^2$$

$$\mathcal{S} = \int \mathrm{d}^4x\,\sqrt{-g}\left[\frac{1}{2}F(\varphi, R) - \frac{1}{2}K(\varphi)g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - U(\varphi)\right] - \int \mathrm{d}^4x\,\sqrt{-g}\mathcal{L}^i_m(g_{\mu\nu}, \Psi^i_m\zeta^i(\varphi)) \quad ,$$

f(R) — $F(\varphi, R)$

K-essence — $K(\varphi)$

Quintessence — $U(\varphi)$

DM-DE coupling, Neutrino coupling — $\Psi^i_m\zeta^i(\varphi)$

$$-k^2(\Phi(a,k) + \Psi(a,k)) \equiv 8\pi G a^2\Sigma(a,k)\rho(a)\delta(a,k)$$

$$-k^2\Psi(a,k) \equiv 4\pi G a^2\mu(a,k)\rho(a)\Delta(a,k)$$

$$\eta(a,k) \equiv \Phi(a,k)/\Psi(a,k) \quad .$$

Lensing — $\Sigma(a,k)$

Clustering — $\mu(a,k)$

Parameterizations

- Mathematical and physical consistency informs our **extensions** of General Relativity.
- Matter Lagrangian can contain Dark Sector interactions, non-cold Dark Matter species, non-universal couplings.

- At background and perturbations, many ***assumptions***:
- Homogeneity+Isotropy, (gravitational) anisotropic stress, relativistic corrections, slow-roll initial conditions.

Credit: S. Casas and Euclid Consortium Theory Science Working Group

Understanding the *dark* sector

GR (LCDM) →

$$S = \frac{1}{16\pi G}\int dx^4 \sqrt{-g}\,(R - 2\Lambda + \mathcal{L}_m)$$

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1-2\Phi)dx^2$$

f(R)

K-essence

Lensing

$$-k^2(\Phi(a,k)+\Psi(a,k)) \equiv 8\pi G a^2 \Sigma(a,k)\rho(a)\delta(a,k)$$

However, no mission is sent to space without a well-defined method to quantify its scientific performance. This is why space missions aim *easy.*

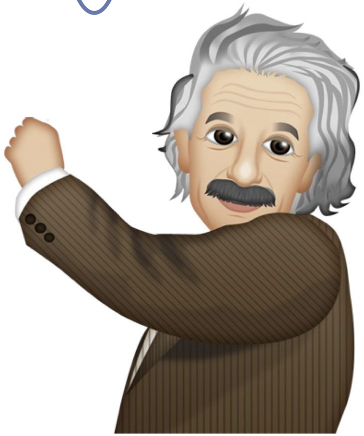
- Mathematical and physical consistency informs our **extensions** of General Relativity.
- Matter Lagrangian can contain Dark Sector interactions, non-cold Dark Matter species, non-universal couplings.

- At background and perturbations, many ***assumptions***:
- Homogeneity+Isotropy, (gravitational) anisotropic stress, relativistic corrections, slow-roll initial conditions.

Credit: S. Casas and Euclid Consortium Theory Science Working Group

Understanding the nature of dark energy

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

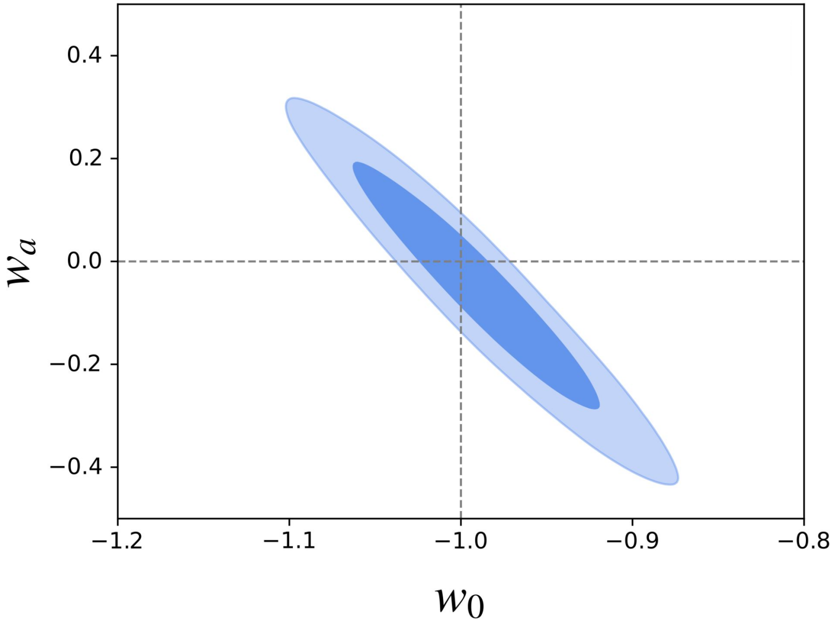


Parameterize the time-dependent equation of state for Dark Energy

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Credit: Einstein emoji

Understanding the nature of dark energy



Quantify constraining power using the Figure of Merit

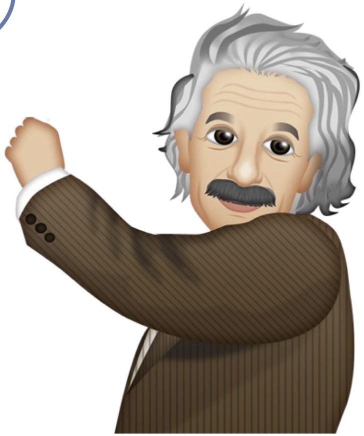
$$\mathrm{FoM} = \frac{1}{\sqrt{\det \mathrm{Cov}(w_0, w_a)}}$$

Goal: FoM > 400

2D Posterior distribution for the dark energy parameters. Credit: G. Cañas-Herrera.

Understanding gravity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$



Use γ-Linder parameterization to test a wide range of modified gravity models

$$f(z) = [\Omega_\mathrm{m}(z)]^{\gamma}$$

Credit: Einstein emoji

The Euclid Consortium

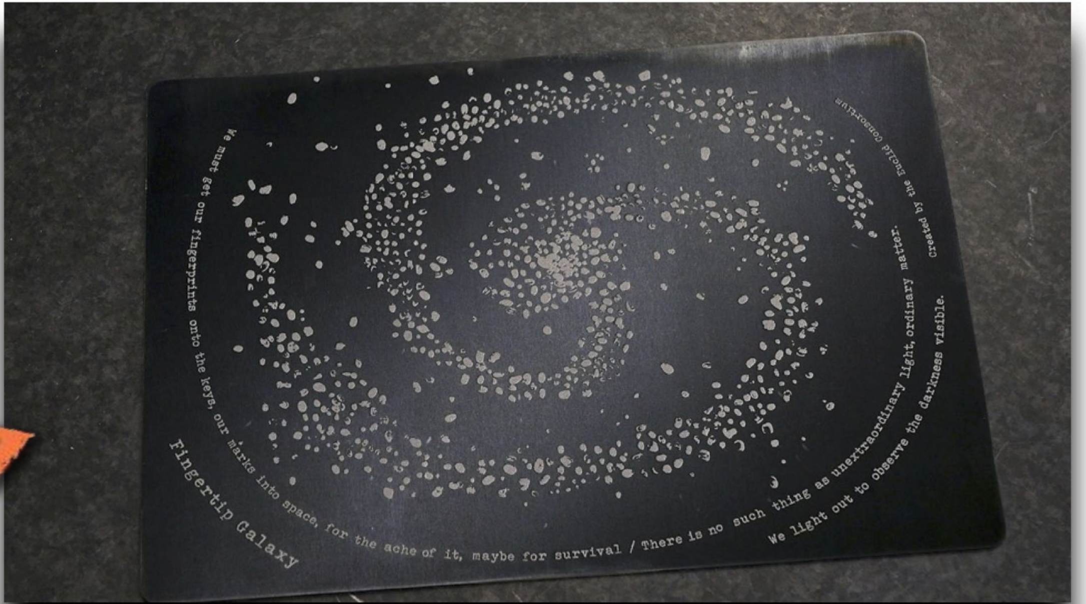
More than 2700 registered scientists

14 European countries + USA + Canada + Japan

Responsible of the Euclid instruments and the exploitation of the data

https://www.euclid-ec.org/

Fingertip galaxy

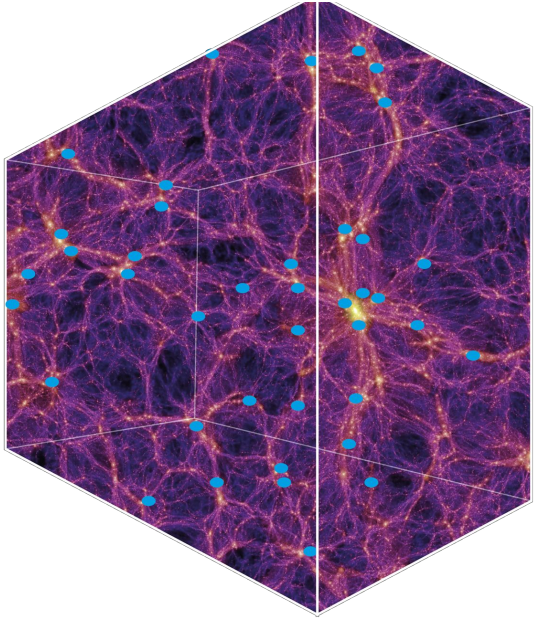


Fingertip galaxy, made with the contributions of many Euclid Consortium scientists in Helsinki 2019, located on Euclid before shifting to USA. Credit: ESA, T. Kitching, L. Pettibone

Primary Cosmological Probes

Cosmology from large-scale structure

Simulated dark matter distribution:



Credit: Springel+ (2005)

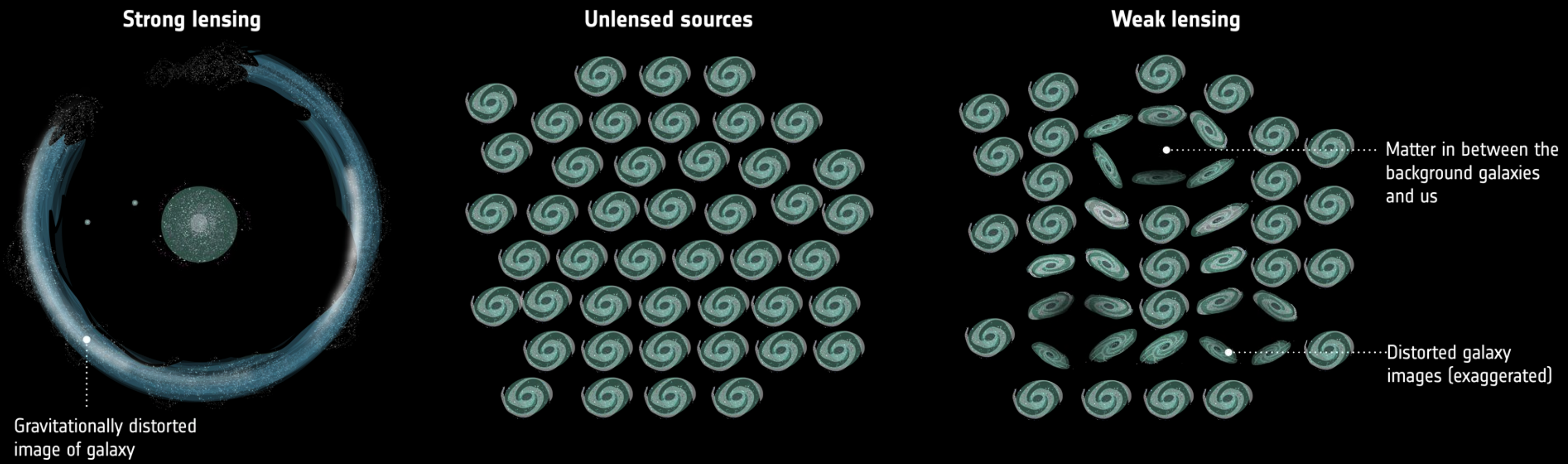
Size and distribution of structures depends on:

Amount of matter and clustering → Ω_m, σ_8

Expansion of Universe at different distances → w, Ω_Λ

But: We **cannot directly observe dark matter or dark energy**!

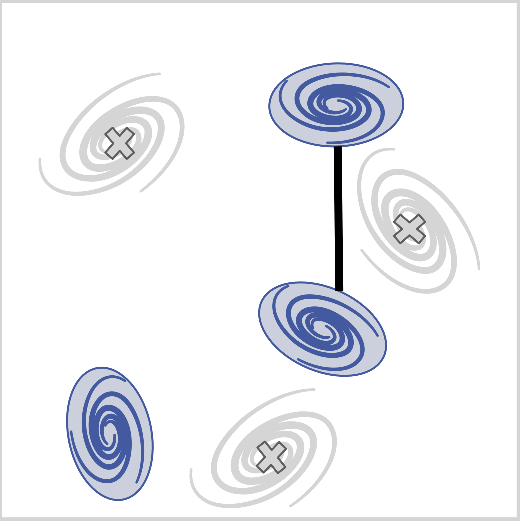
Weak gravitational lensing



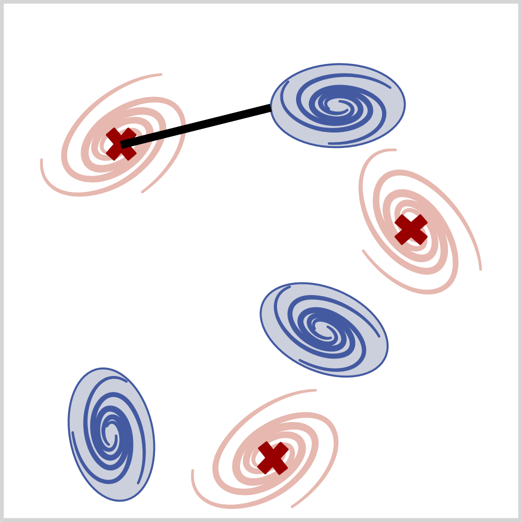
Credit: ESA/ATG

3 x 2-pt analyses

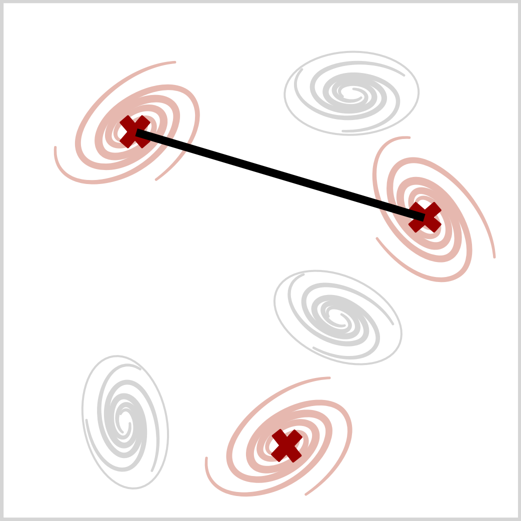
Shape-Shape
'Cosmic shear'



Position-Shape
'Galaxy-galaxy-lensing'

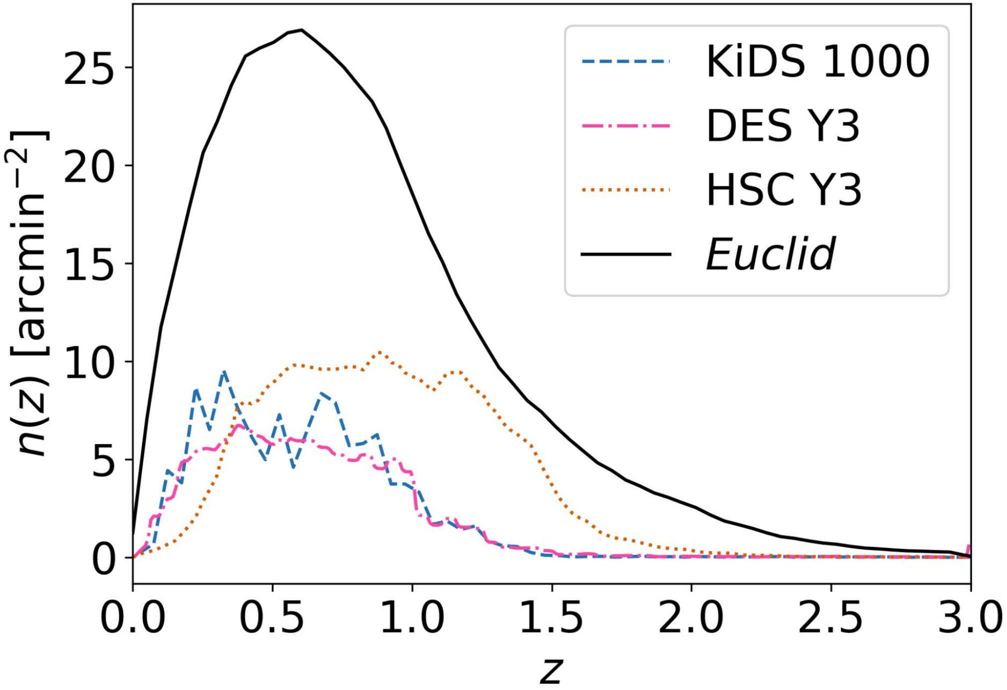


Position-Position
'Angular clustering'



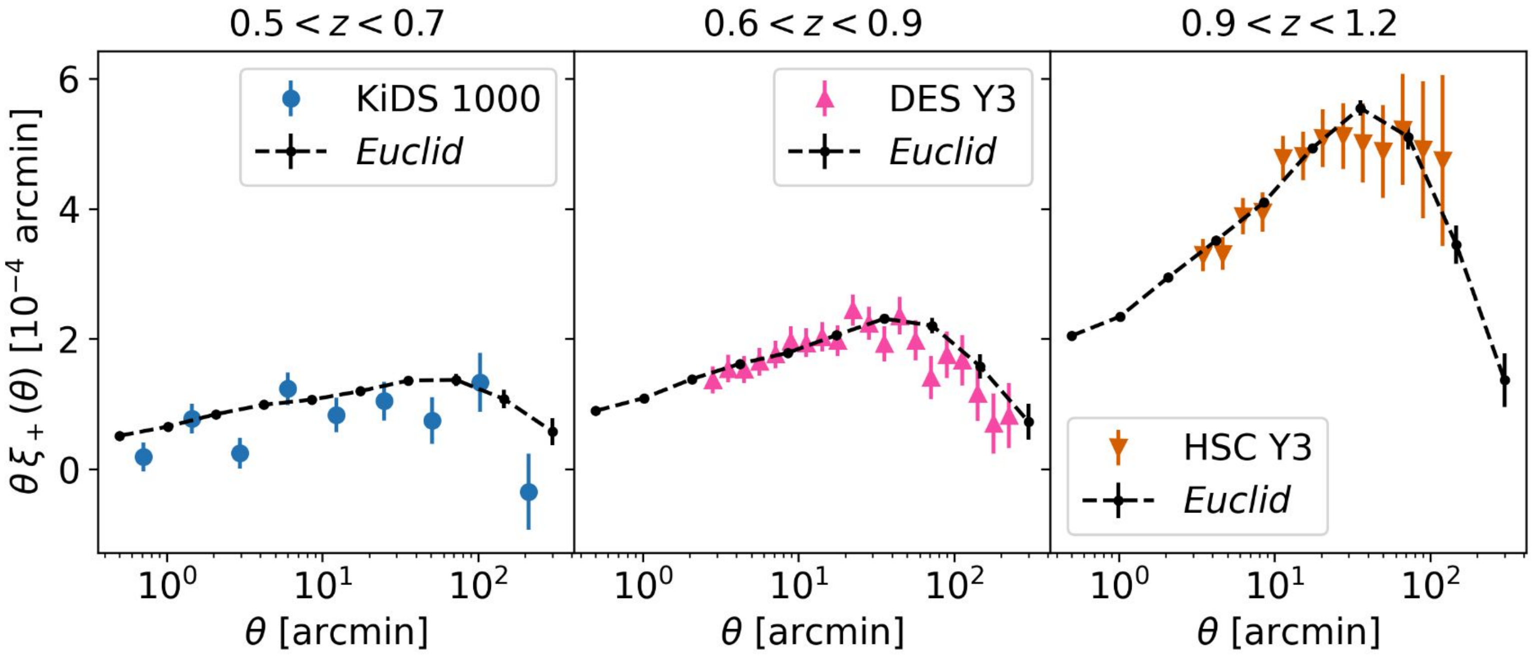
We combine **3** types of **2-pt correlations** to optimally **constrain cosmology from the photometric galaxy sample**

Going to higher redshifts…



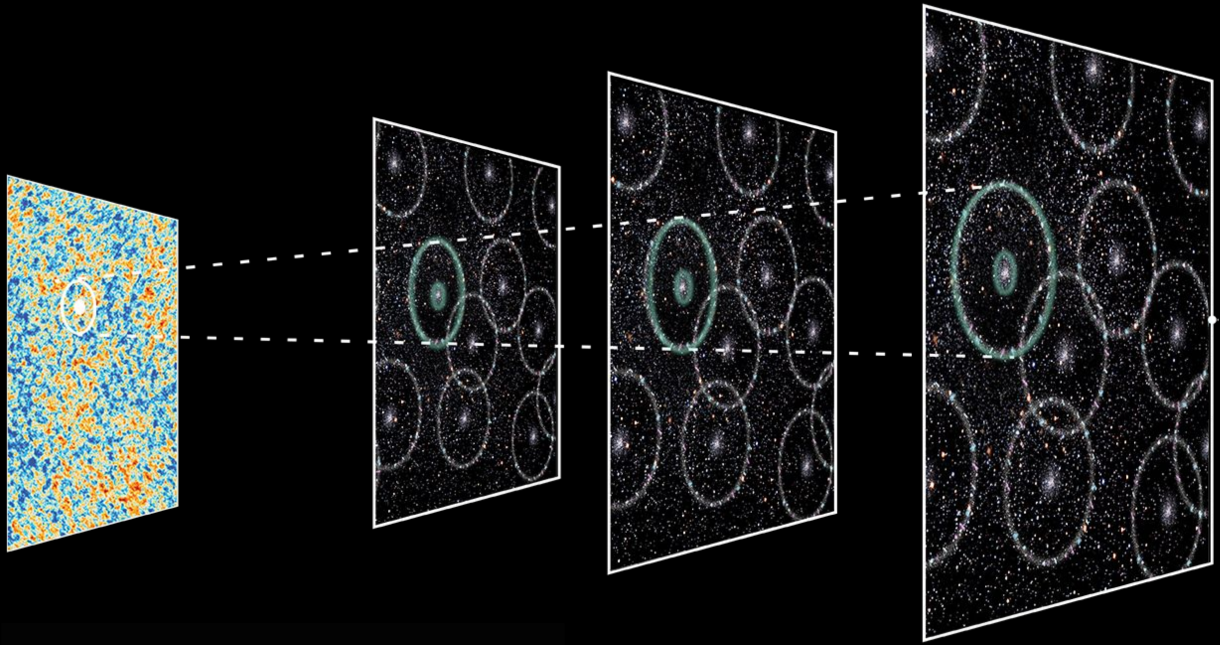
Euclid observes a **higher number density** of galaxies and many more sources at **higher redshifts** than Stage III surveys

Euclid's statistical power: photometry



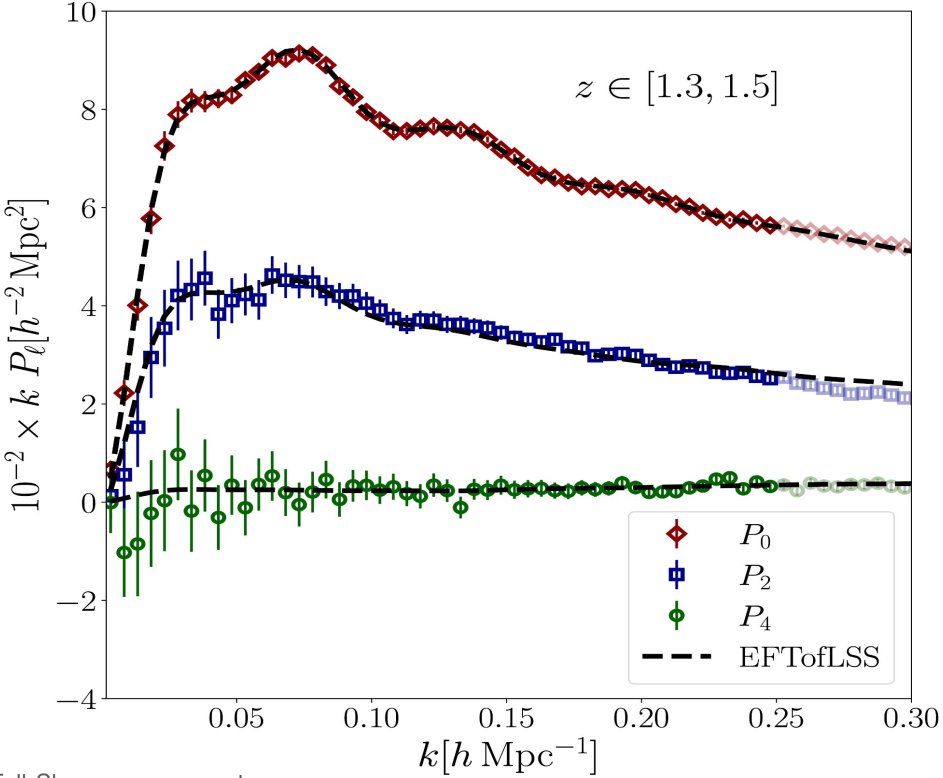
Order-of-magnitude increase in S/N compared to Stage III survey with galaxies following the same redshift distribution!

Clustering of Galaxies



Credit: ESA/ATG

Euclid's statistical power: spectroscopy



Predictions for Euclid Spectroscopic Full-Shape power spectrum
Data vectors. Credit: Euclid Consortium

Spacecraft & Instruments

Launch

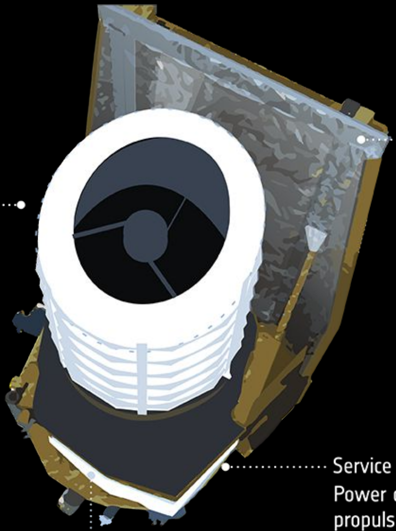
Euclid launched on a Falcon 9, SpaceX, on 1st July 2023, from Cape Canaveral. Credit: ESA

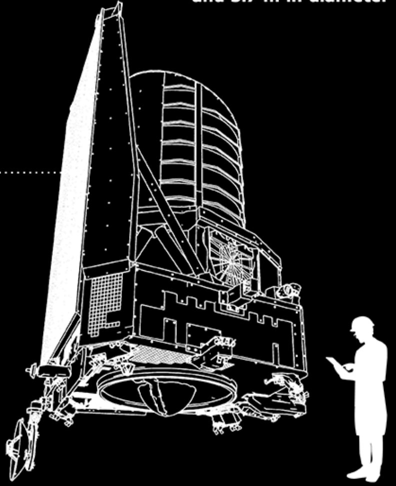
Spacecraft

Euclid's mass in orbit will be

2 tonnes

- 800 kg payload module
- 850 kg service module
- 40 kg balancing mass
- 210 kg propellant

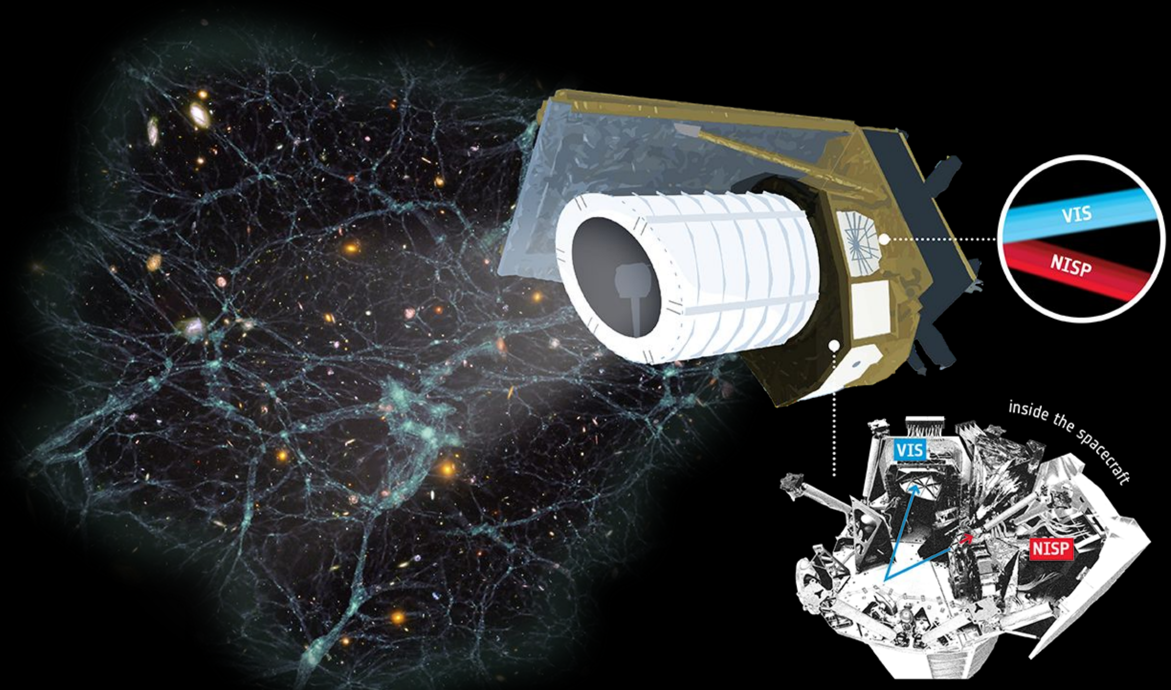




* VIS: VISible instrument
NISP: Near-Infrared Spectrometer and Photometer

Credit: ESA/ATG

Instruments



VIS

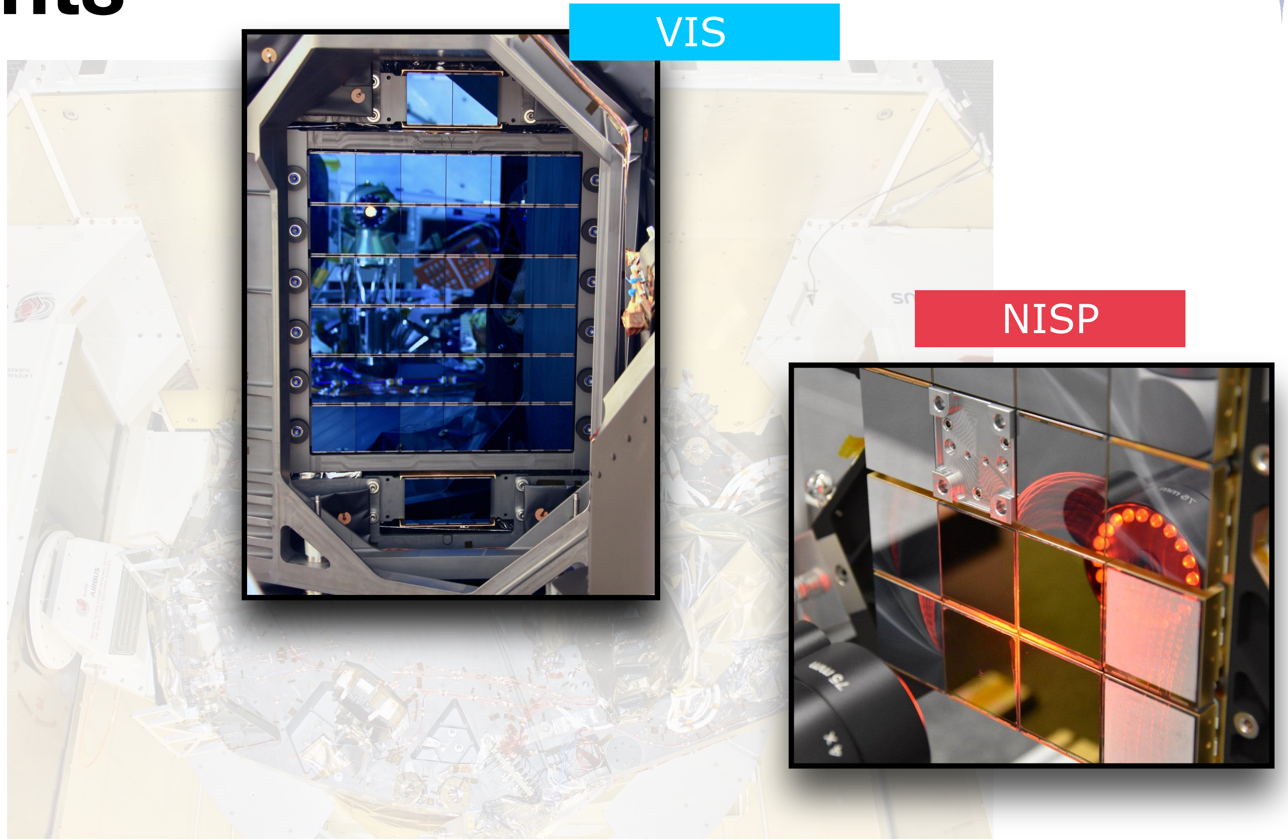
Produces high resolution images

NISP

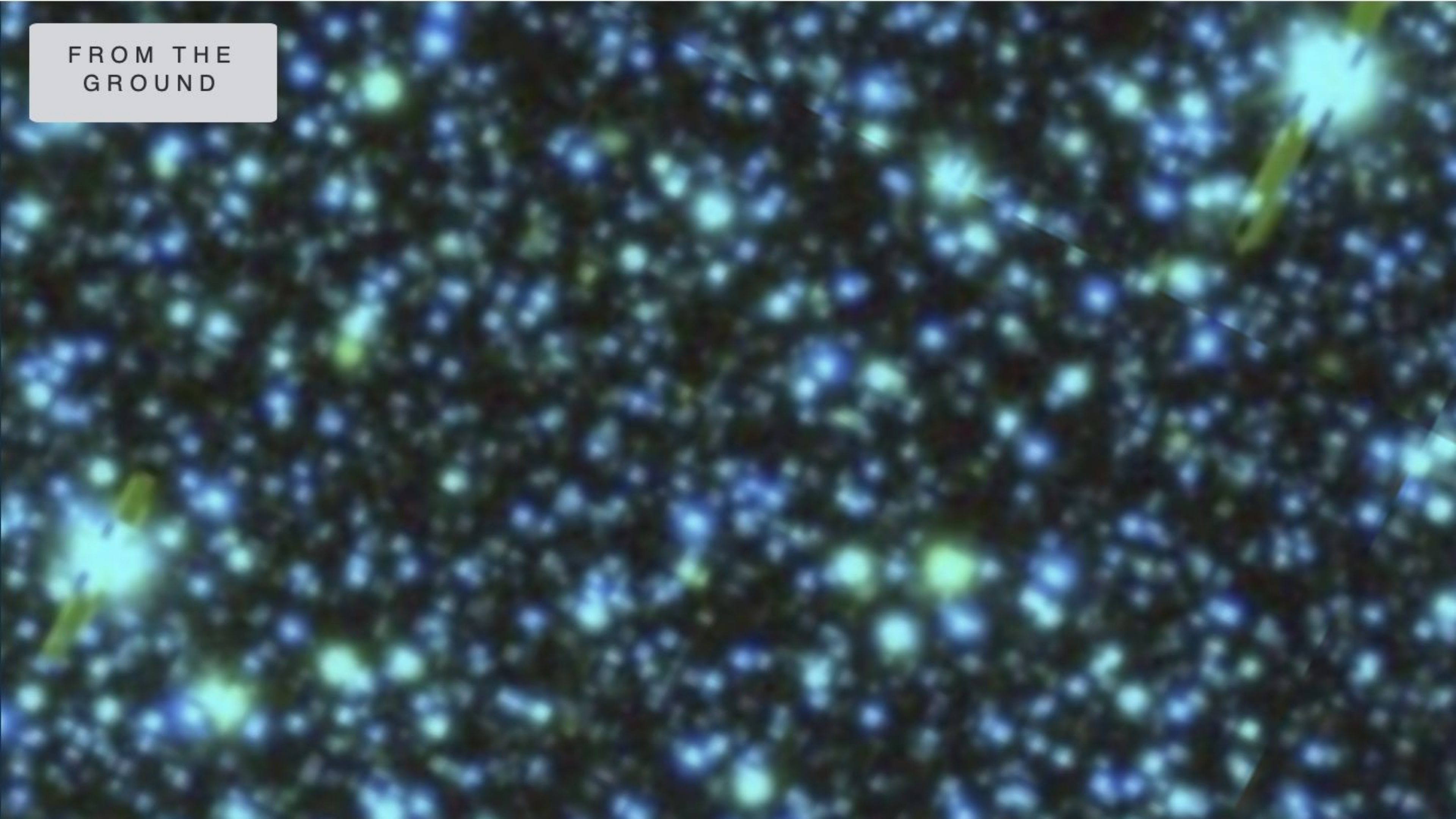
Obtains redshifts of billions of galaxies

Credit: ESA/ATG

Instruments

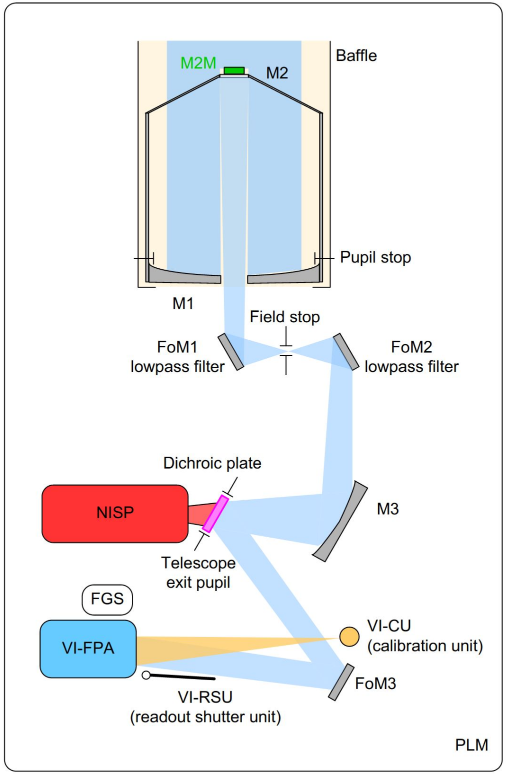


Euclid instruments
Credit: EC VIS and NISP teams

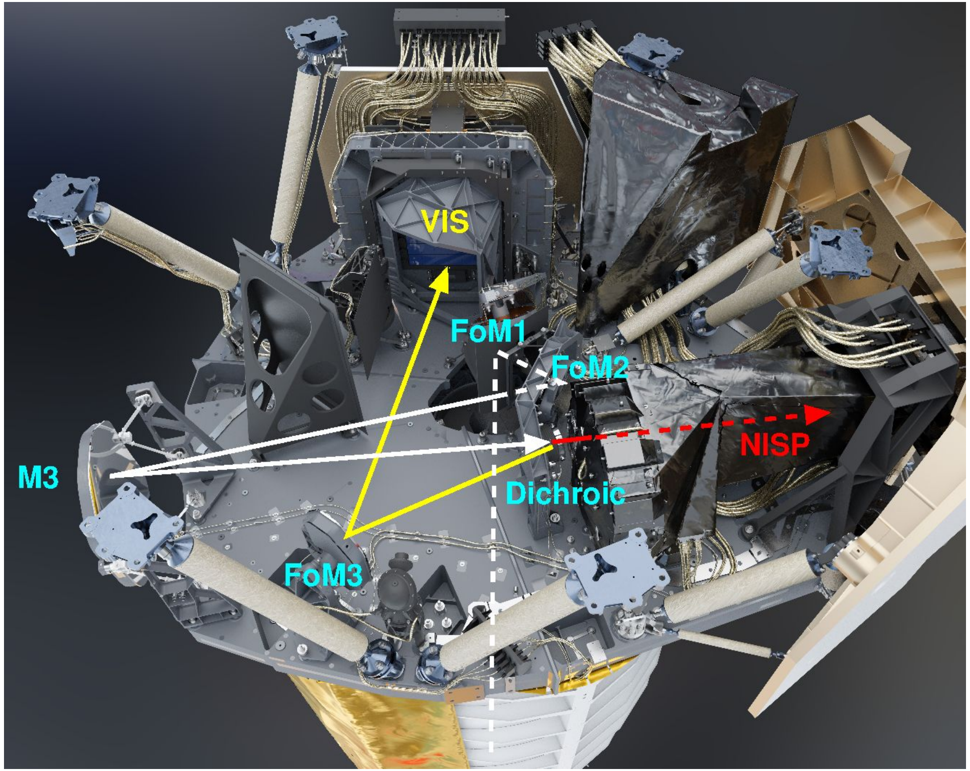

FROM THE GROUND


FROM
SPACE
esa
euclid

Payload Module: Optical path and instruments



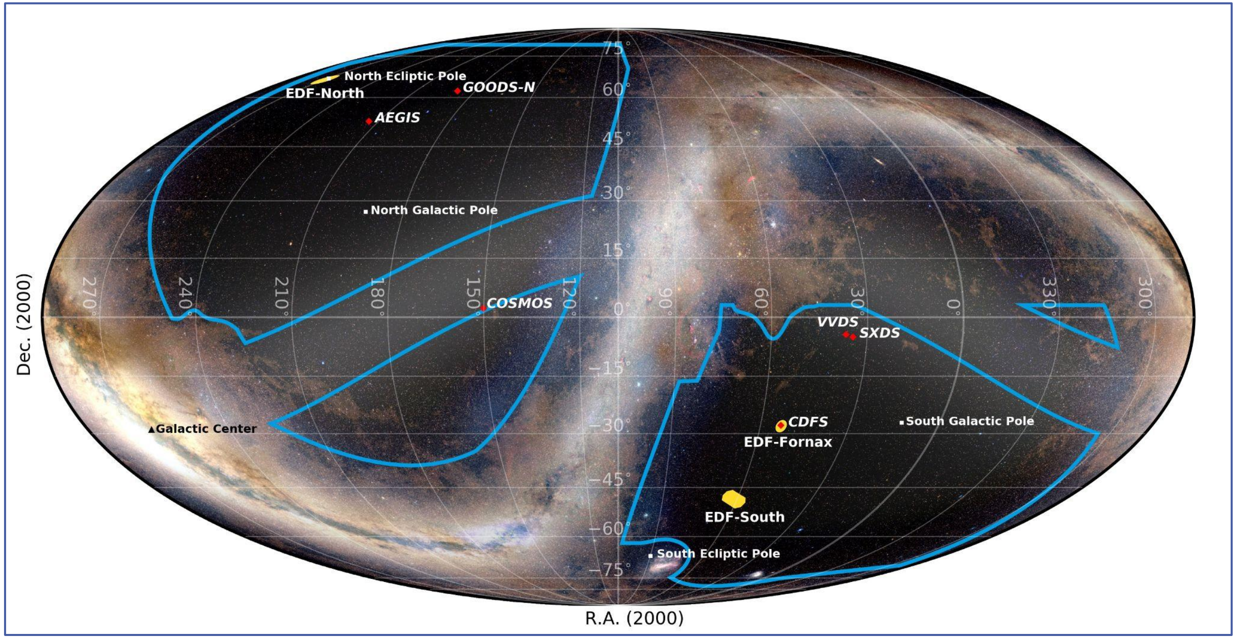
Optical layout
Credit: Airbus Defence and Space



Layout of the instruments. The telescope is below, observing downwards.
Credit: Airbus Defence and Space; annotations by EC

Euclid Surveys

Euclid Wide & Deep Surveys



Euclid region of interest (RoI) in an all-sky Mollweide projection.
Blue borders enclose the 16 000 square degree RoI that contains the Wide Survey.
The Euclid Deep Fields are shown in yellow and the auxiliary fields with red marks (not to scale).

- Wide Survey covers about 14000 square degrees.
- So far, we have collected approximately 2500 square degrees.
- This is the data we will use for the first
- This month, 500 square degrees will be re-processed

Euclid first quick data release

EUCLID Q1 CONTENTS

Information on Euclid Quick Data Release 1 contents.

EUCLID Q1 PAPERS

Papers related to Euclid Quick Data Release 1.

EUCLID Q1 DOCUMENTATION

The documentation for Euclid Quick Data Release 1, describing the processing of the data from raw to Euclid Q1 data products.

EUCLID Q1 DATA ACCESS

How to access the Euclid Quick Data Release 1.

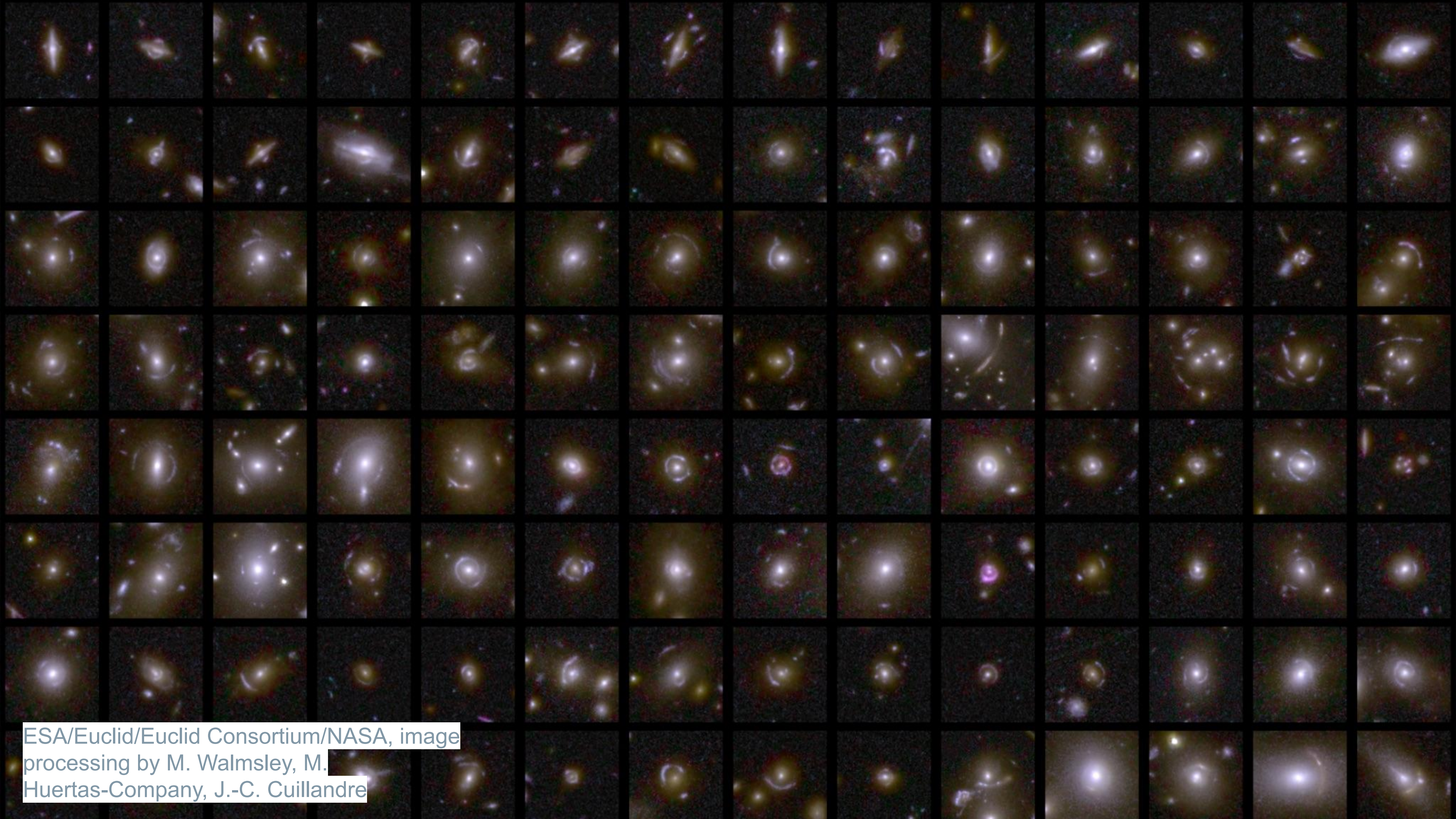
EUCLID Q1 DATA MODEL

Information of the Euclid data model.

EUCLID Q1 KNOWN ISSUES

A list of the issues found with Euclid Q1 data after publication. If you find an issue with the data, please contact the Euclid Helpdesk.

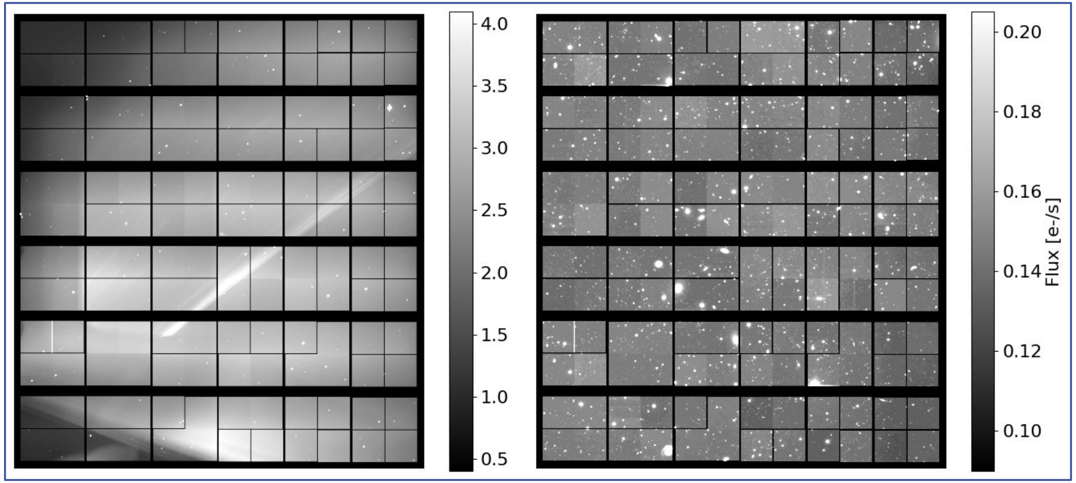
Credit: ESA & Euclid Consortium

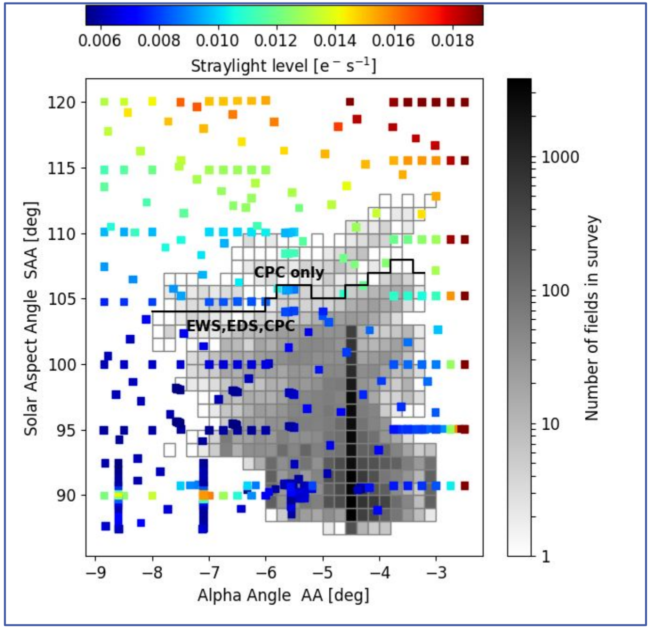


ESA/Euclid/Euclid Consortium/NASA, image processing by M. Walmsley, M. Huertas-Company, J.-C. Cuillandre

Performance Verification & challenges

Internal straylight





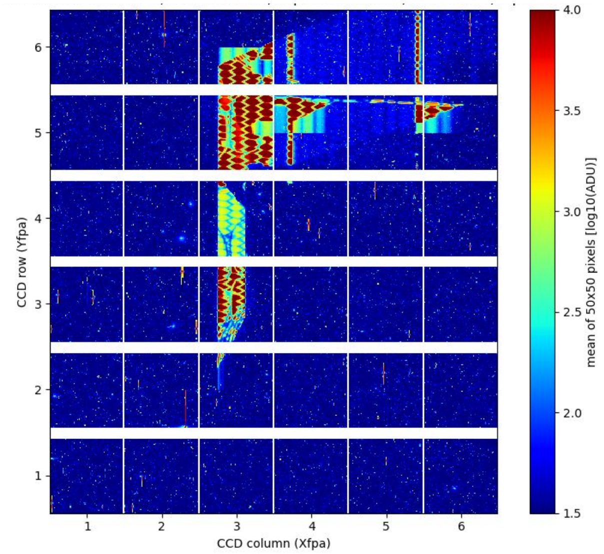
Left: Sunlight hitting a thruster nozzle reaches VIS detectors. NISP is unaffected

Middle: Straylight is largely avoided by orienting Euclid so that nozzle is in shadow

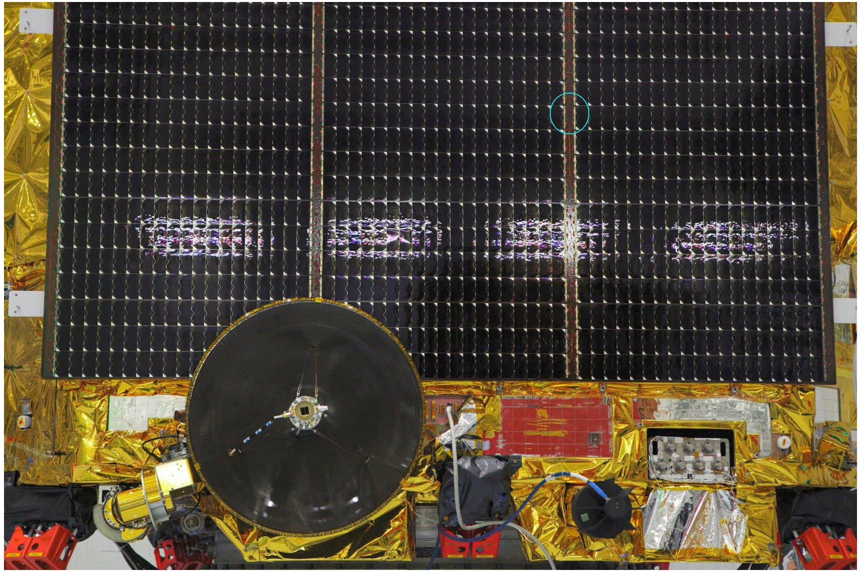
Right: The survey was fine-tuned to select low-straylight conditions, only.

X-ray contamination

X-rays from Solar flares penetrate sunshield and reach VIS
Average area loss during Solar maximum: 3-4%



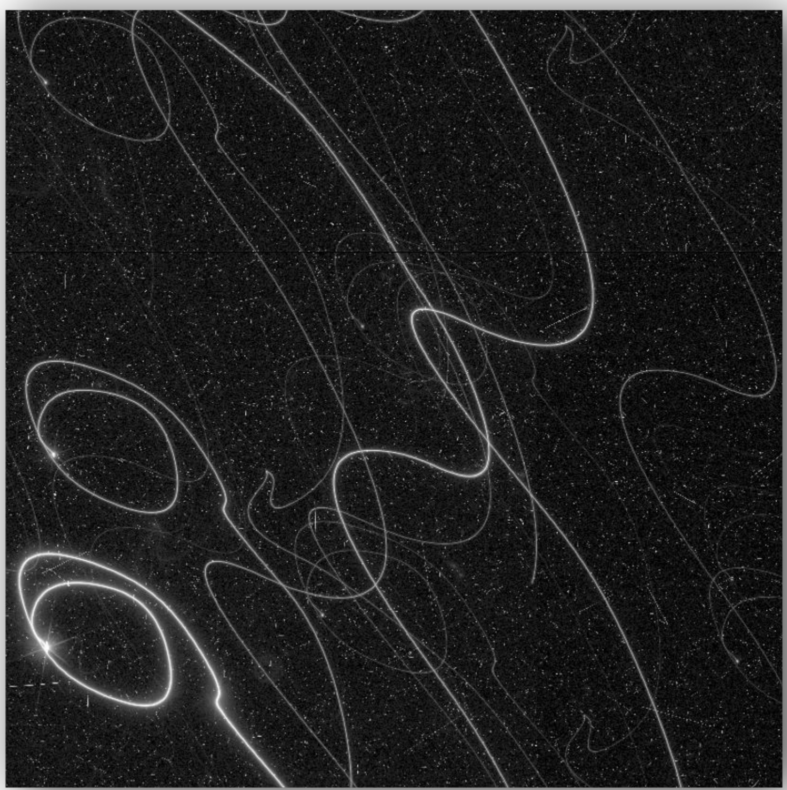
VIS image taken during an X-class flare.
Weak flares cause isolated cosmics.
Strong flares result in contiguous area loss.



X-rays enter through the major gaps between solar cells.

Credit: J.-C. Cuillandre

Fine Guidance Sensor



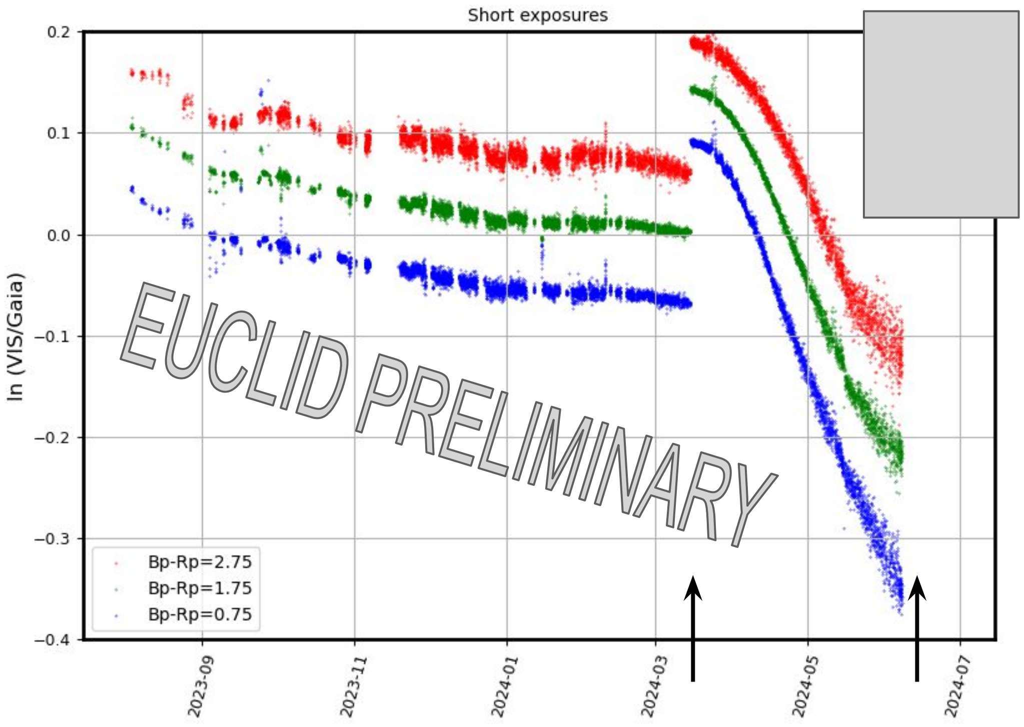
Credit: ESA & VIS Team

- Euclid failed to use stars to ‘focus’ exposures
- In the image: loopy star trails show the effect of the Fine Guidance Sensor intermittently losing its guide stars
- Update of the software was necessary

Ice contamination

Ice contamination

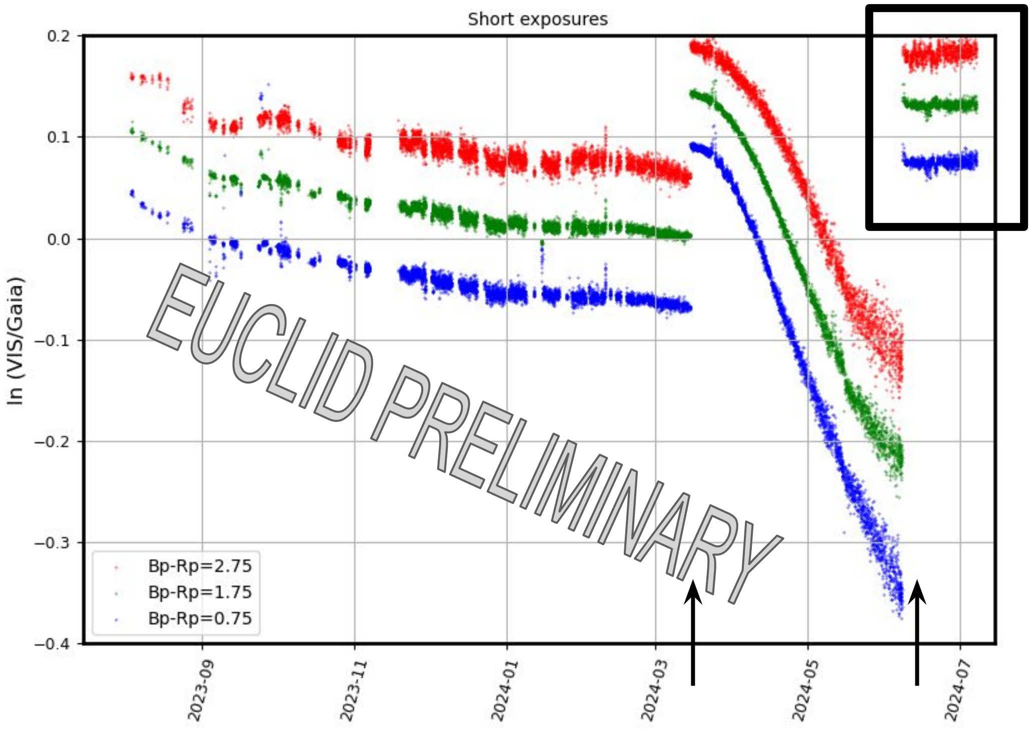
ESA has performed two decontamination campaigns.

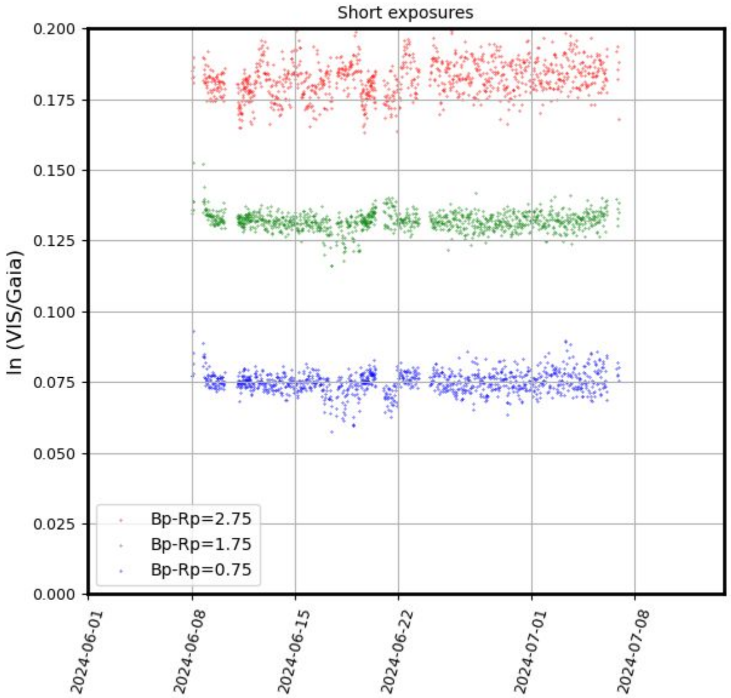


Credit: K. Kuijken

Ice contamination

ESA has performed two decontamination campaigns.

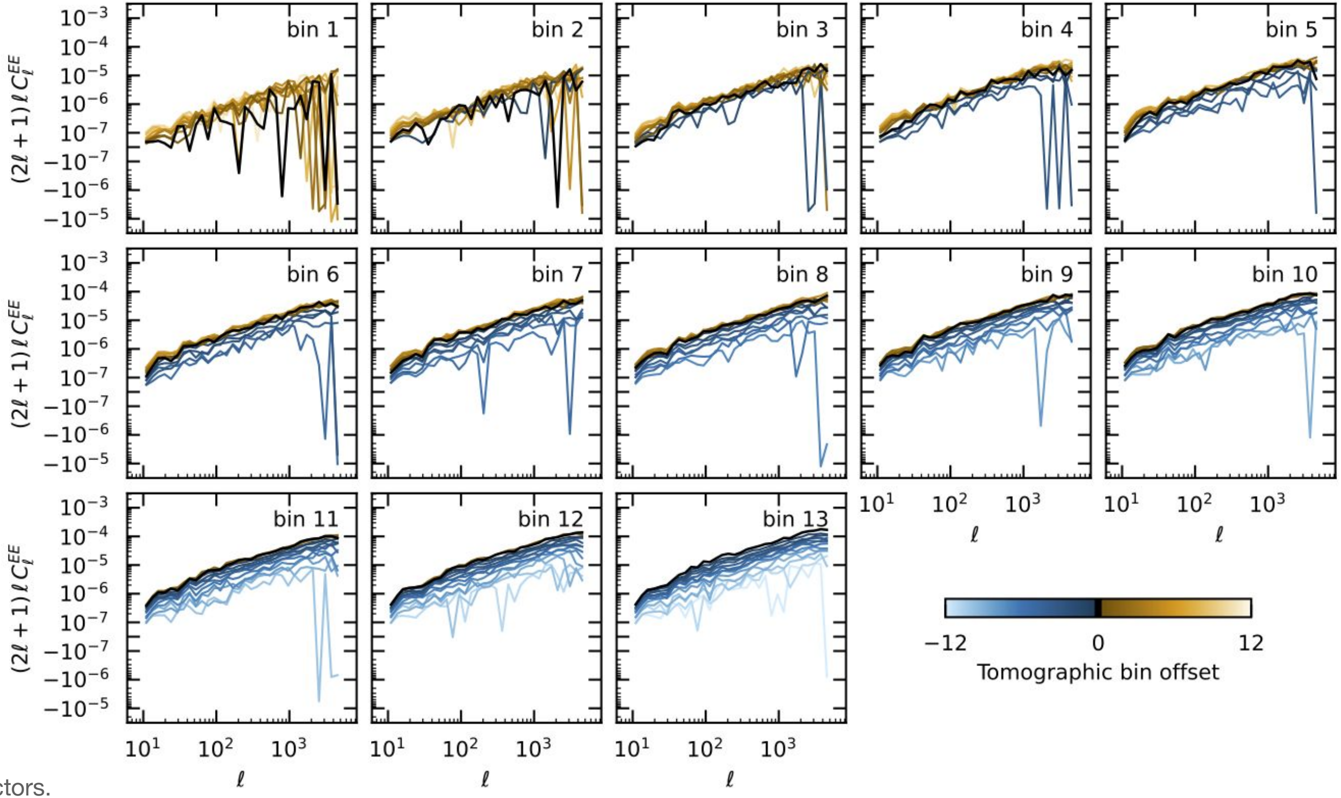




Credit: K. Kuijken

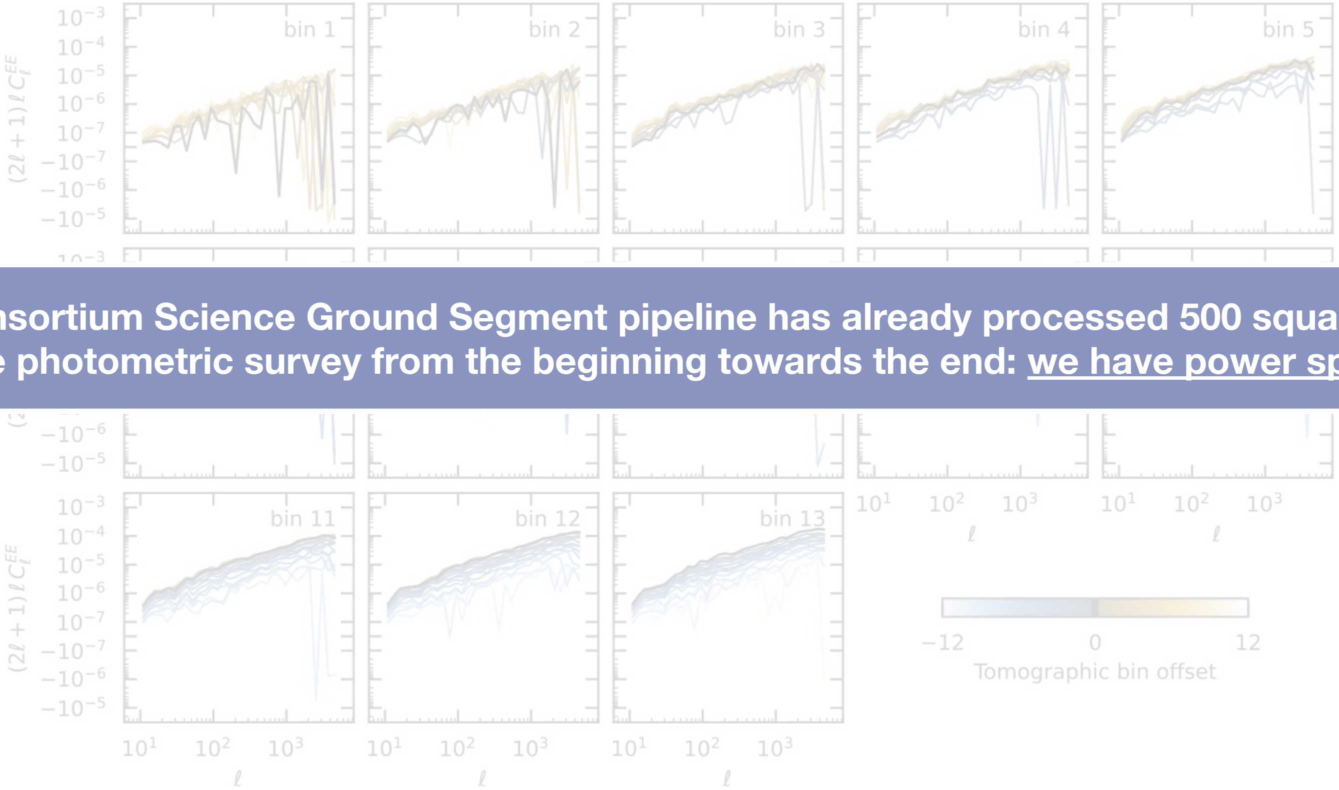
Survey data products

3x2pt statistics: shear-shear



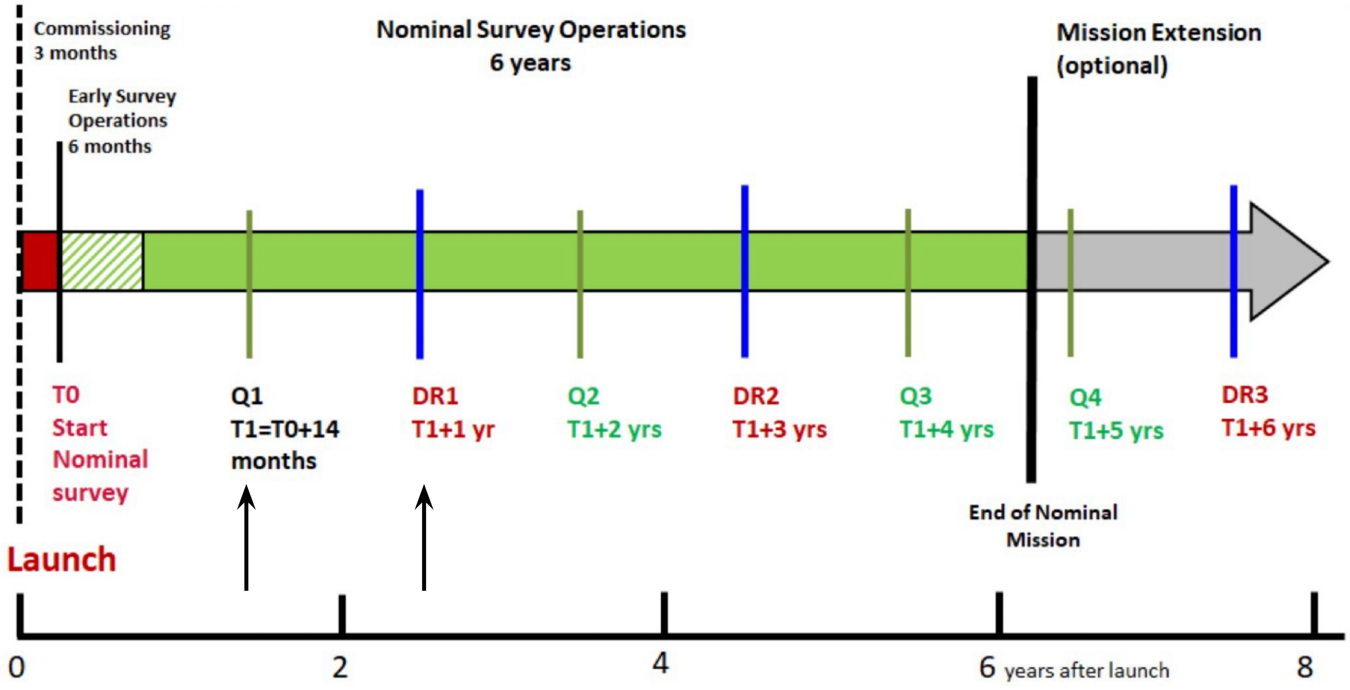
Euclid Shear Data vectors.
Credit: N. Tessore

3x2pt statistics: end-to-end



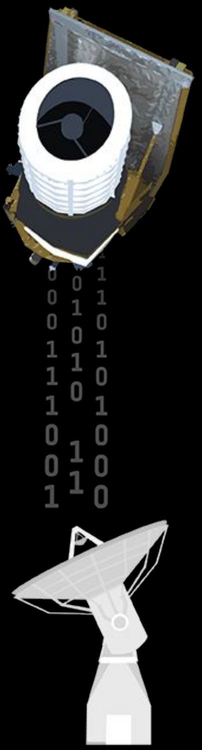
Euclid Consortium Science Ground Segment pipeline has already processed 500 square degrees of the photometric survey from the beginning towards the end: we have power spectra

Data releases



Credit: ESA

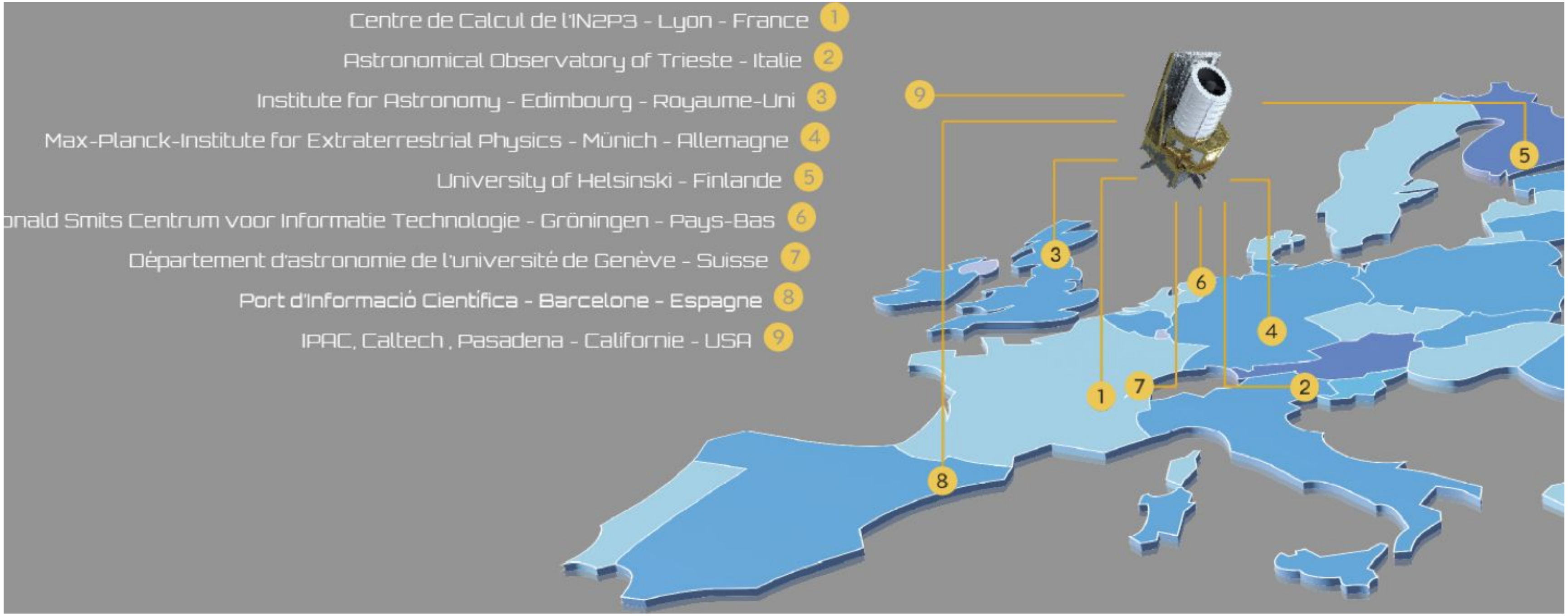
Data transfer



- Collecting 30 Petabytes of unprocessed data
- Communications from L2, to ESOC (Germany), to ESAC (Madrid), once per day
- Distribution along different dedicated data centres

Credit: ESA/ATG

Euclid Science Data centers



Credit: Euclid Consortium

Cosmology with primary probes

Cosmological inference: overview

Theoretical Predictions

COMPUTE EUCLID PRIMARY OBSERVABLES ACCORDING TO THE THEORY

Non-linear cosmology

MODEL NON-LINEAR SCALES FOR POWER SPECTRA

Euclid data as input

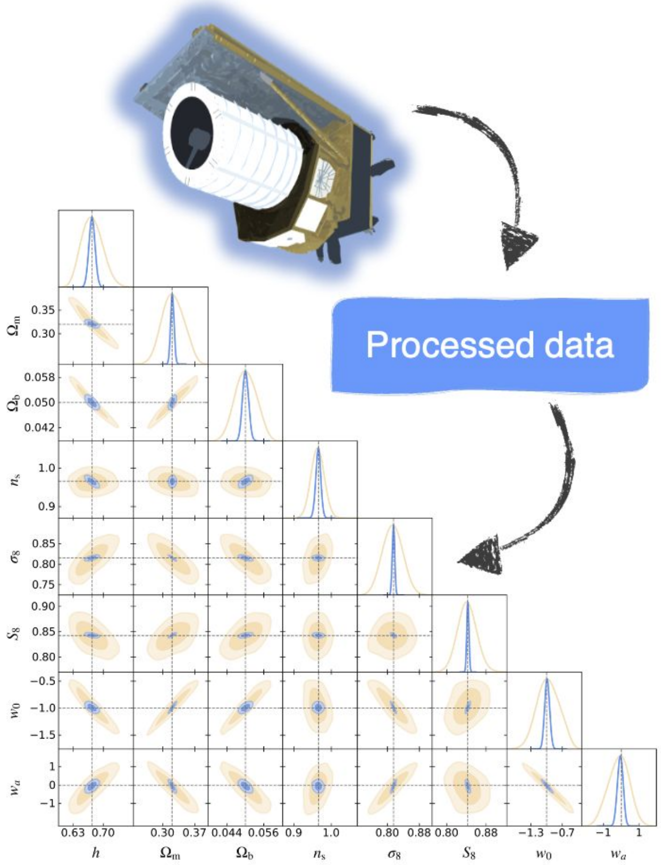
DATA VECTORS ARE PROVIDED BY THE EUCLID SCIENCE GROUND SEGMENT

Likelihood computation

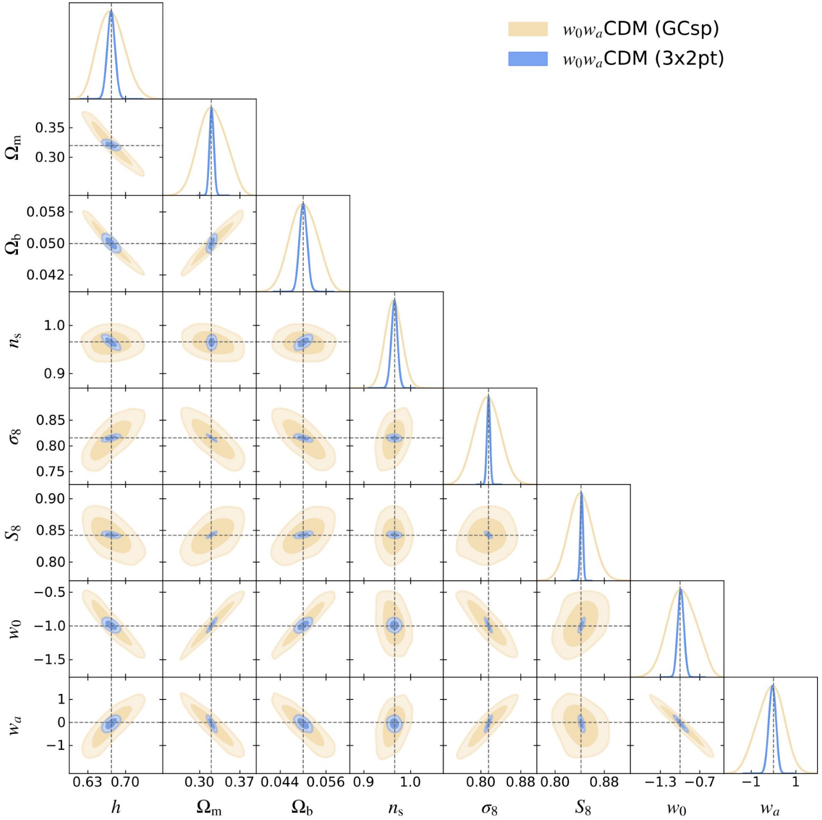
WE COMPARE THEORY AGAINST DATA DOING A STATISTICAL ANALYSIS

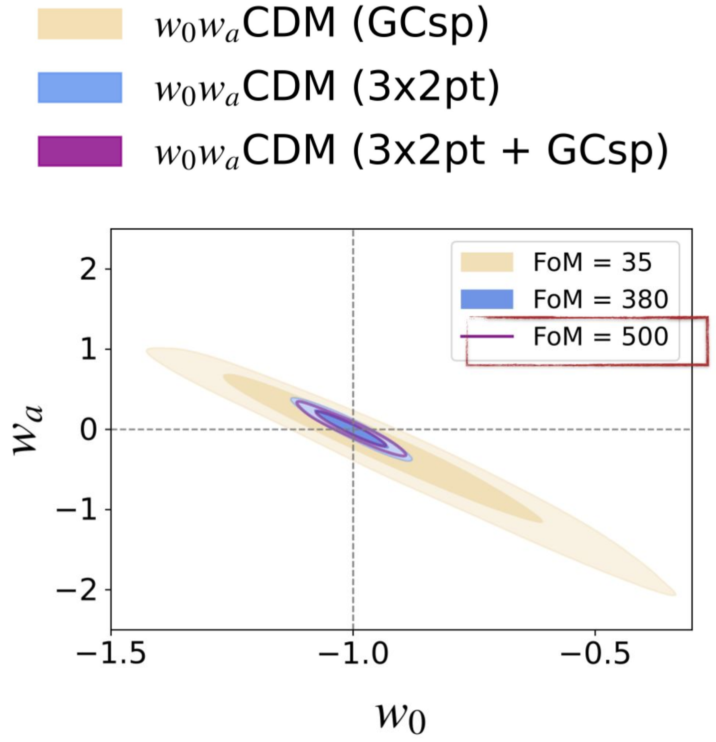
Cosmological parameters

PRODUCE THE BAYESIAN STATISTICAL ANALYSIS TO OBTAIN CONSTRAINTS ON COSMOLOGICAL PARAMETERS



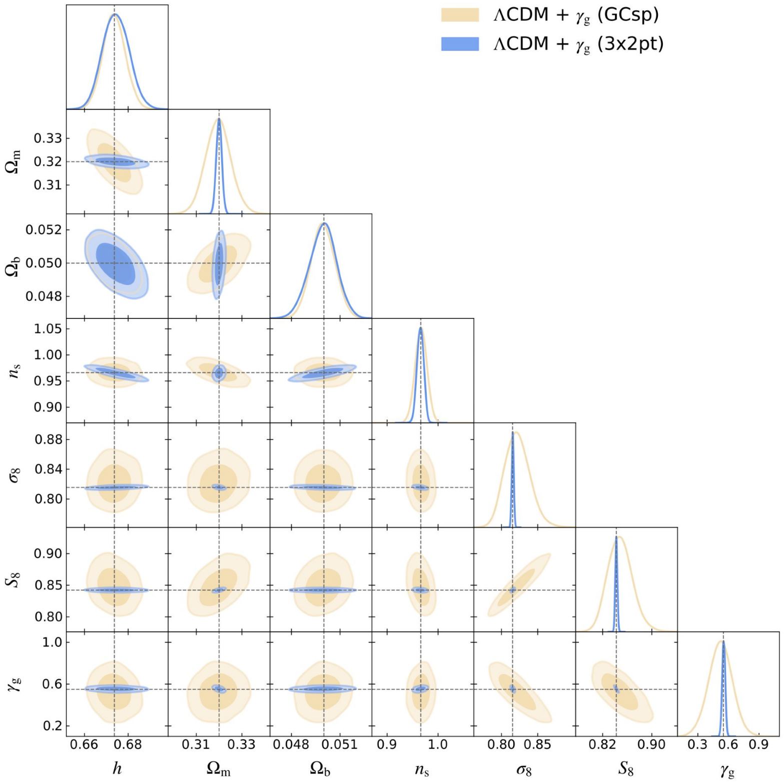
Expected parameter constraints

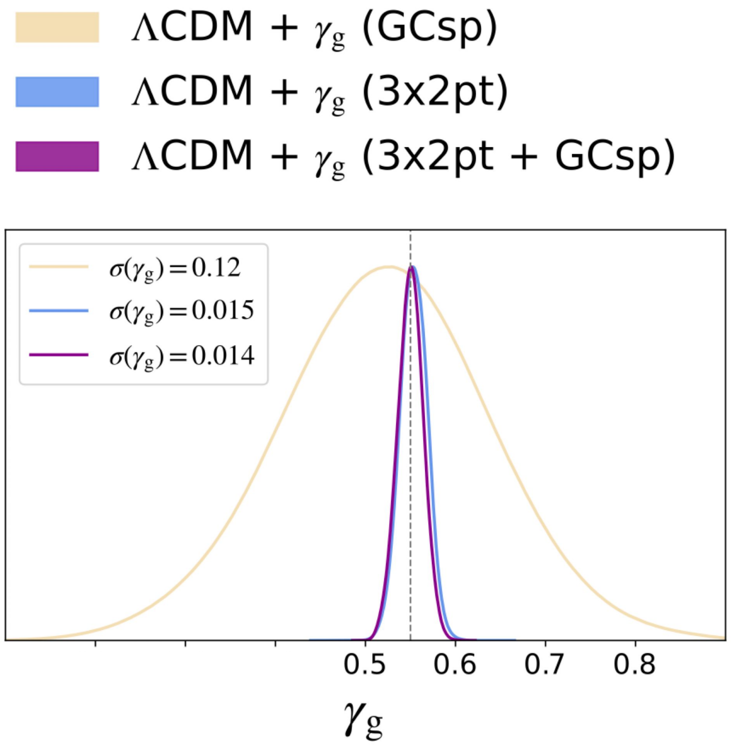




Euclid constraining power. Credit: G. Cañas-Herrera

Expected parameter constraints

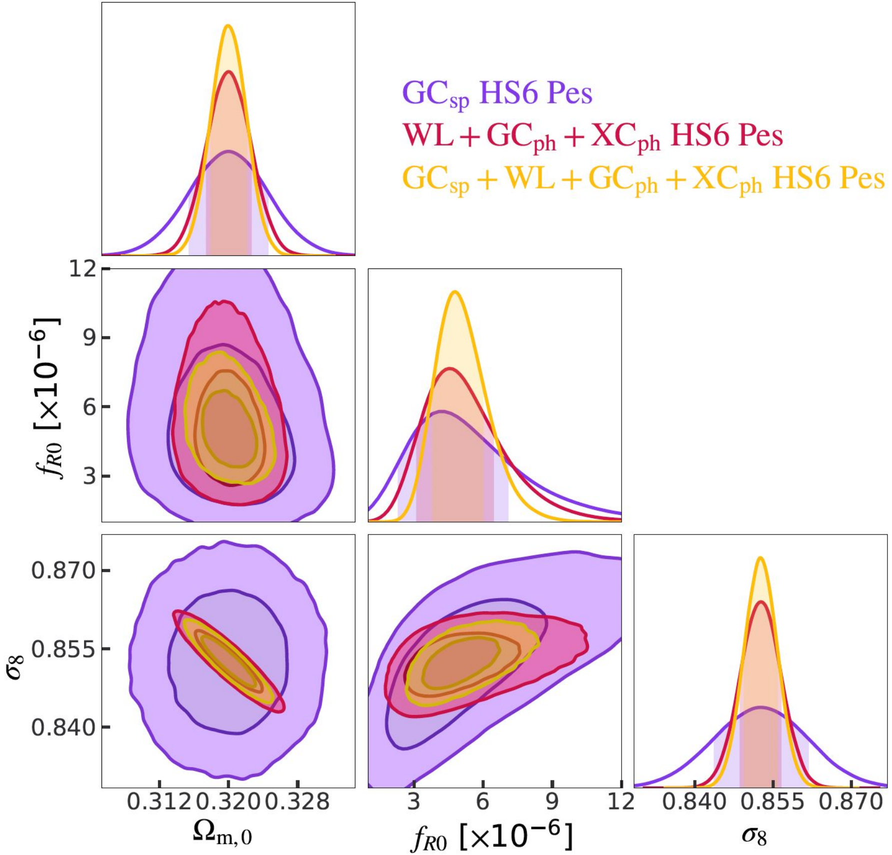




Euclid constraining power. Credit: G. Cañas-Herrera

But, we do care about modified gravity

Forecast constraints on f(R)



Credit: S. Casas

Conclusions & outlook

Outlook

Euclid is currently surveying 10 deg^2 per day in a mission to last 6 years

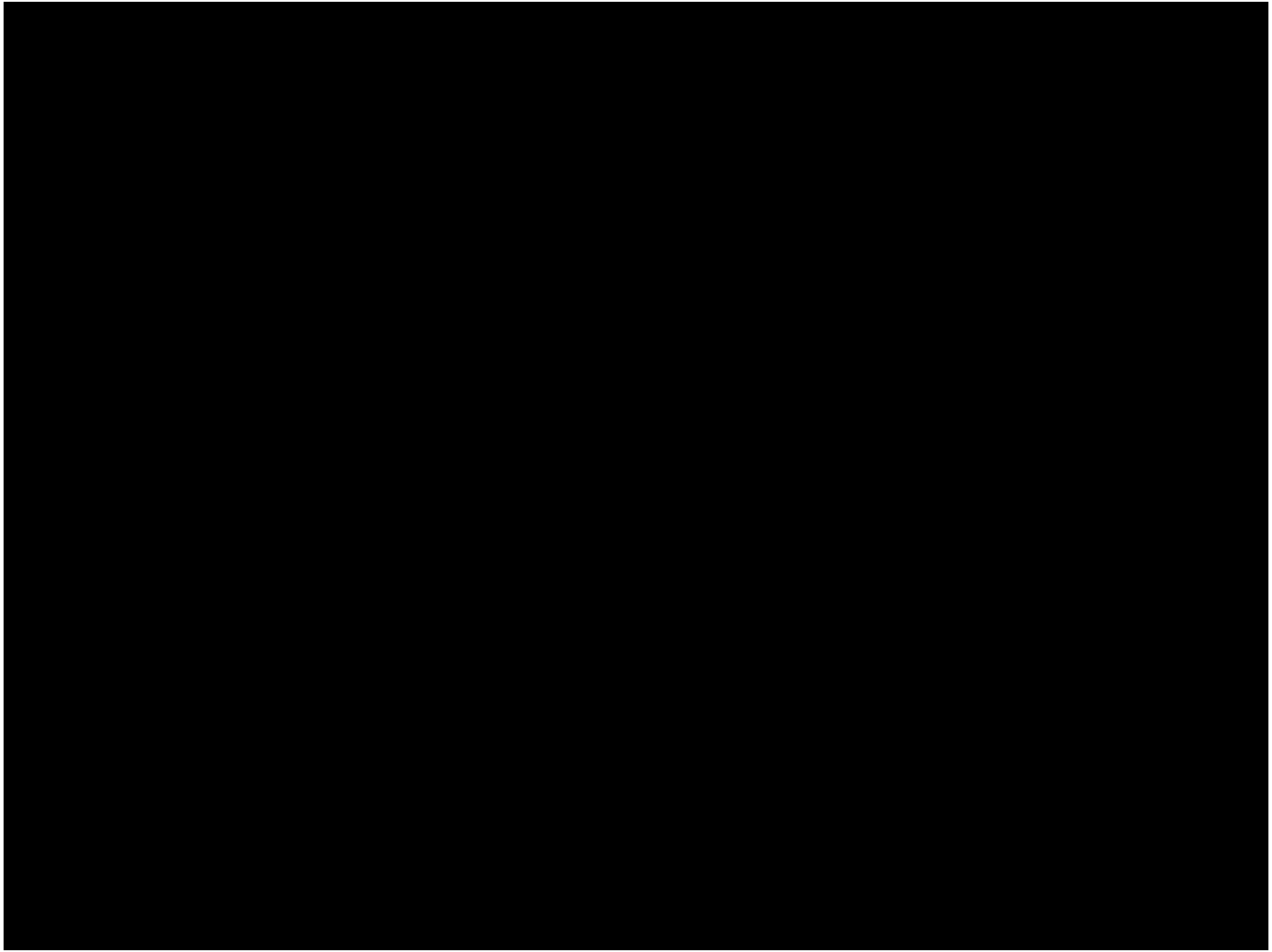
The goal is to map one third of the sky (14000 deg^2), first data release after one year of operations (2000 deg^2, fall 2026)

Euclid is currently the only multi-probe large-scale structure survey experiment in operations

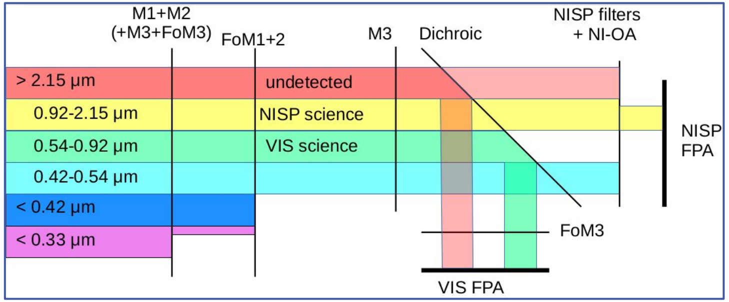
Euclid first quick data release offers a snapshot of the potential of Euclid for Legacy Science

euclid
consortium

General Outreach material

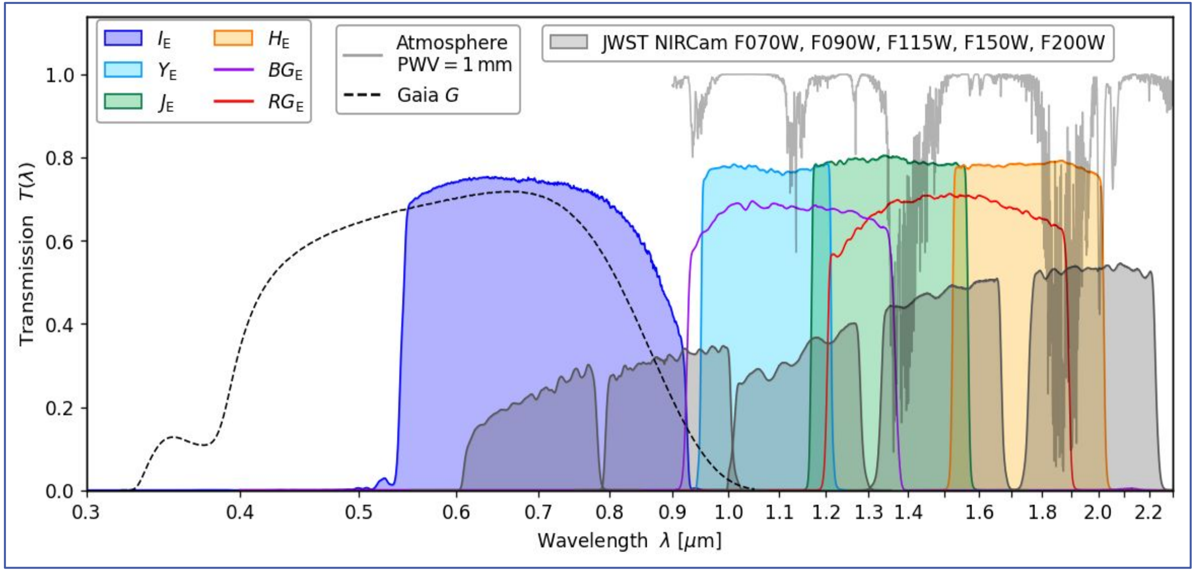


Passbands



Chromatic selection function of the payload module. Euclid uses a largely reflective design. Passbands are defined considerably by mirror coatings.

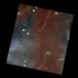
Euclid passbands compared to Gaia, atmosphere, and JWST



Chris Pattison

Hubble

Chris Pattison



This is a single Hubble pointing at the same scale.