Probe combination in *Euclid* to go beyond the standard model

Isaac Tutusaus (ICE-CSIC/IEEC/IRAP)
tutusaus@ice.csic.es

ICE INSTITUT DE CIÈNCIES DE L'ESPAI CSIC IEEC
EXCELENCIA MARÍA DE MAEZTU
irap astrophysique & planétologie
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

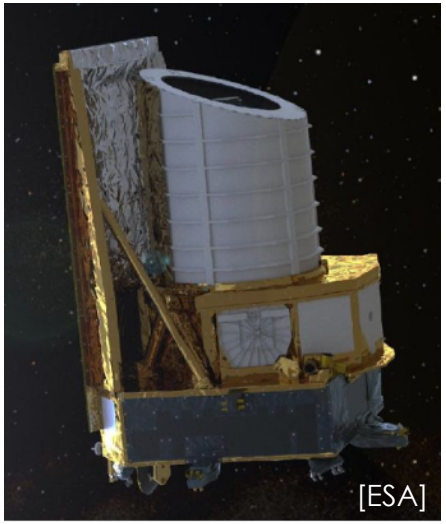
Outline

- Introduction
- *Euclid* core science
- *Euclid* since launch
- Probe combination in *Euclid*
- Going beyond the standard model
- Conclusions

Introduction

- In the coming years **observational cosmology** will reap the benefits from the **investment in large projects** to better understand the Universe

- *Euclid*:
  - Largest European project
  - Exquisite measurements to shed new light on the dark components
  - Different probes are considered

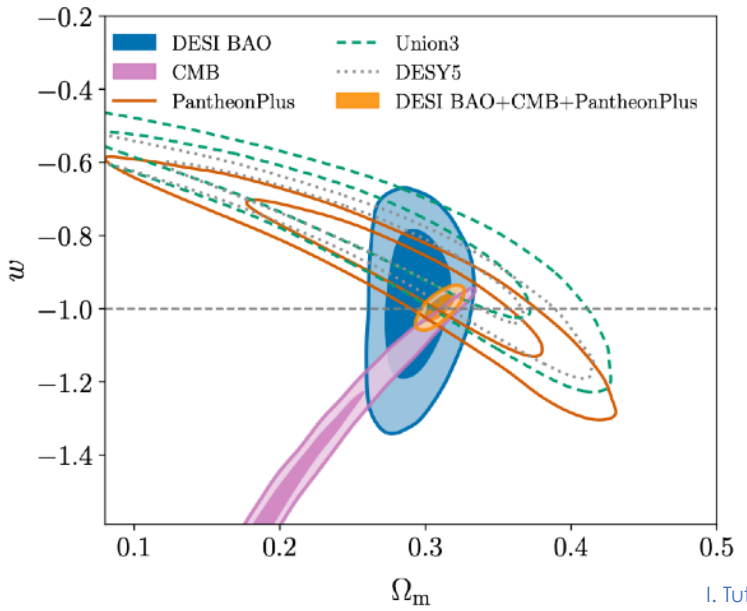

[ESA]

Introduction

Combining different **probes** is one of the most powerful ways to **constrain a cosmological model**:

- sensitive to different aspects of how **gravity** acts in the cosmos
- different **degeneracies** and **systematic** effects

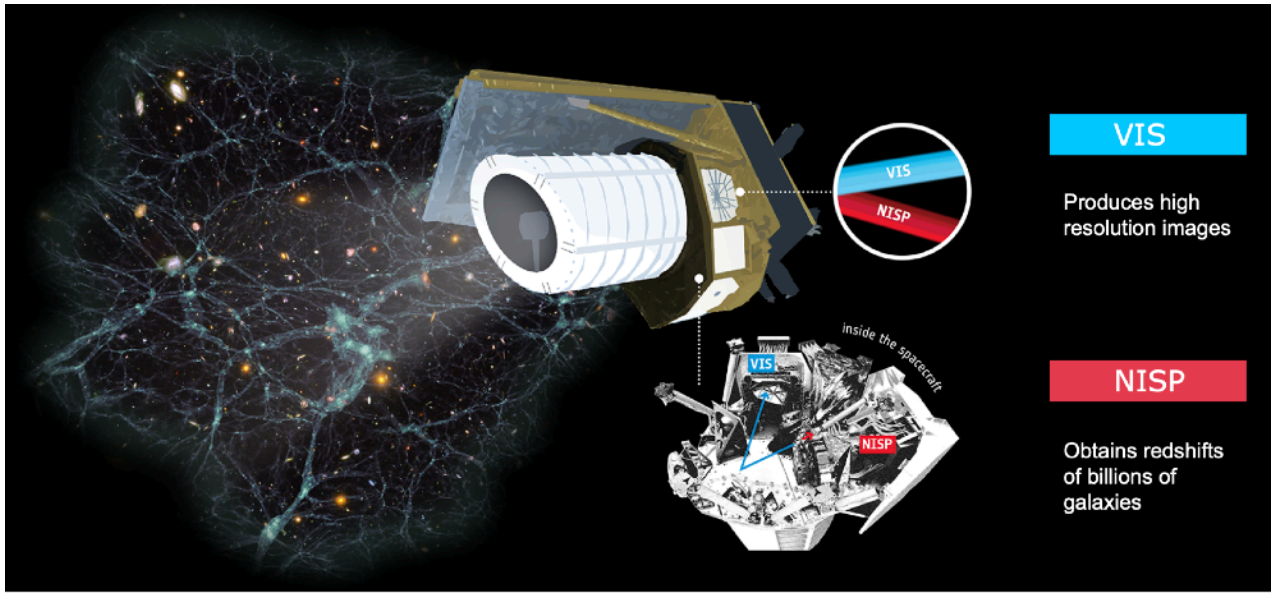
Example:



[DESI Collaboration: Adame et al. 2025]

Introduction

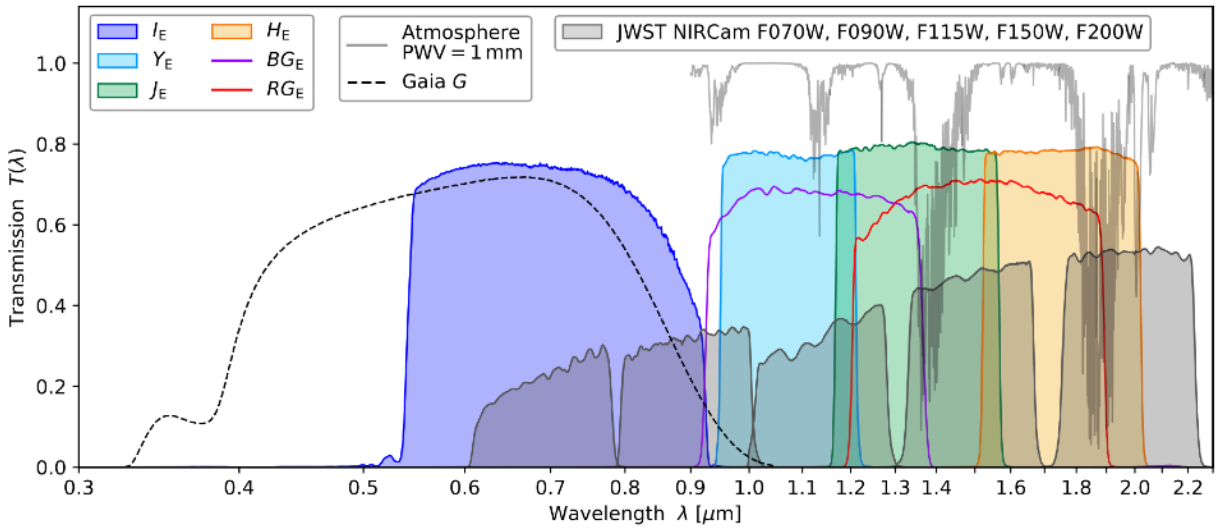
- *Euclid*:
  - **Survey** started on Feb 14th, 2024 — 1st stage-IV weak lensing survey **in operations**
- It contains 2 instruments onboard:
  - Visible instrument (VIS) — **imaging**
  - Near Infrared Spectrometer and Photometer (NISP) — **imaging** and **spectroscopy**



[ESA/ATG]

Introduction

- *Euclid* alone cannot provide measurements in different optical bands:
  - Necessary to combine with **ground-based data** for photometric redshifts



[Euclid Collaboration: Mellier et al. 2024]

- **Combination of probes** (and data) is a **key ingredient** in *Euclid*'s analysis

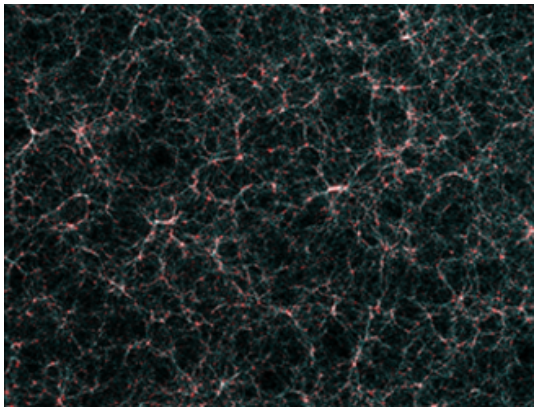
Euclid core science

- **Galaxy surveys** — powerful **source** of cosmological information
- Sensitive to **expansion** and large-scale **structure** — **dark matter** and **dark energy**

+ dark matter
- dark energy

⇩

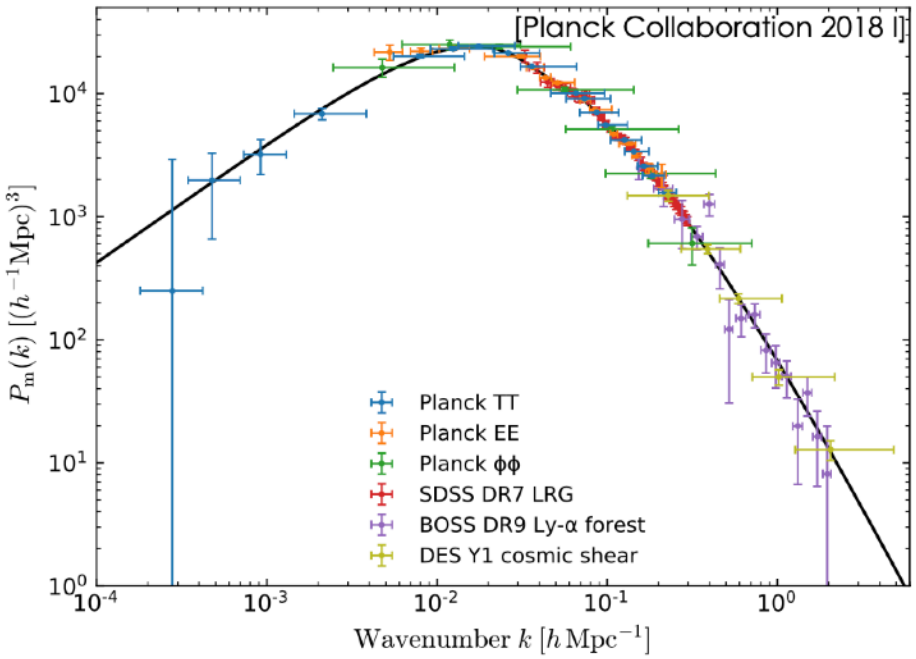
+ structure



[Carretero, Tallada, Serrano, Euclid Consortium]

Euclid core science

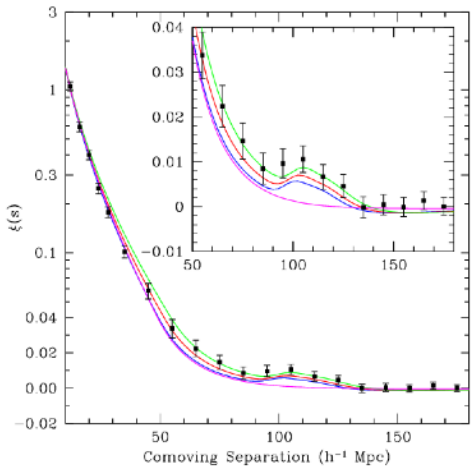
- **Galaxy surveys** — powerful **source** of cosmological information
- Main **summary statistic**: matter/galaxy power spectrum

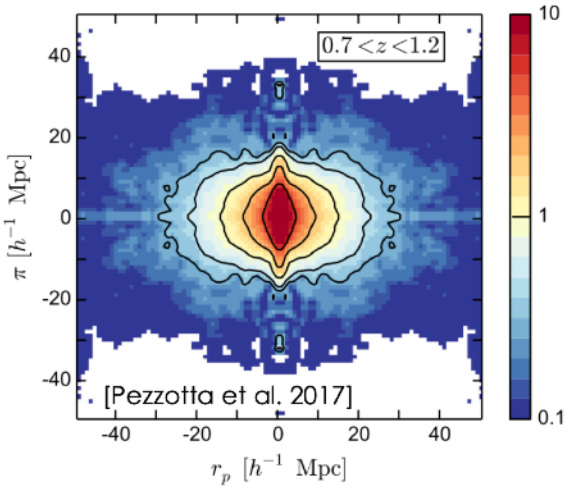


- New scales probed by galaxy surveys

Euclid core science

- (Spectroscopic) **galaxy clustering** (GC)
- Baryon acoustic oscillations:
  - Provide a **cosmic ruler**
  - Sensitive to the **expansion** history and the angular-diameter **distance**
- Redshift-space distortions:
  - Sensitive to the **growth rate** of structures
  - Tests of **modified gravity**

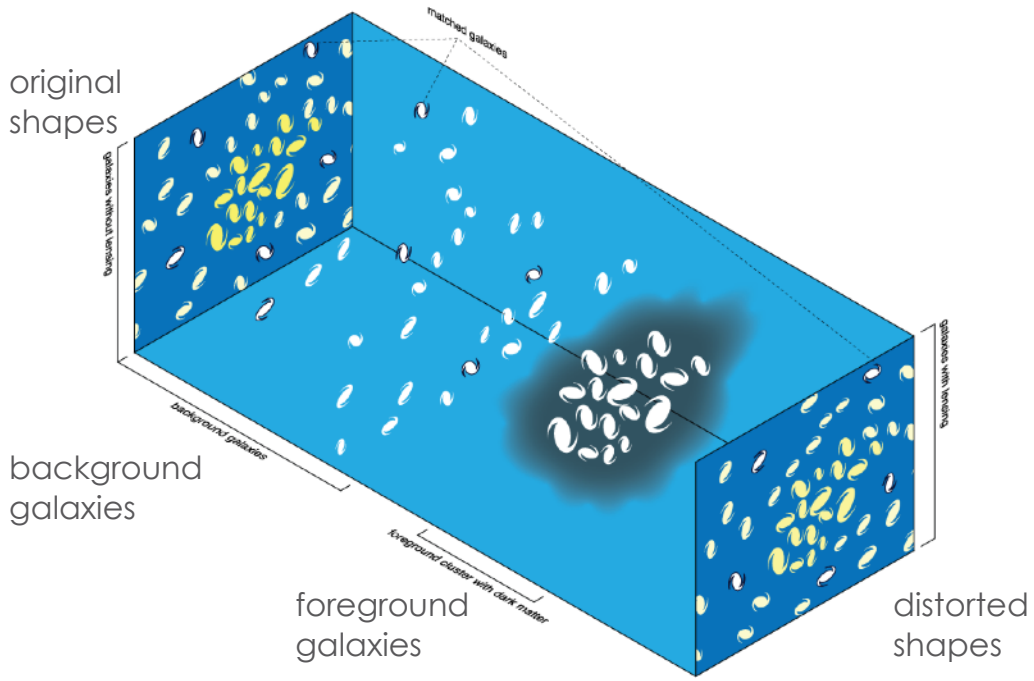




Euclid core science

(Photometric) **weak lensing** (WL):

- information about **mass distribution** imprinted on galaxy images
- sensitive to **matter density**, initial conditions, and **growth of structures**

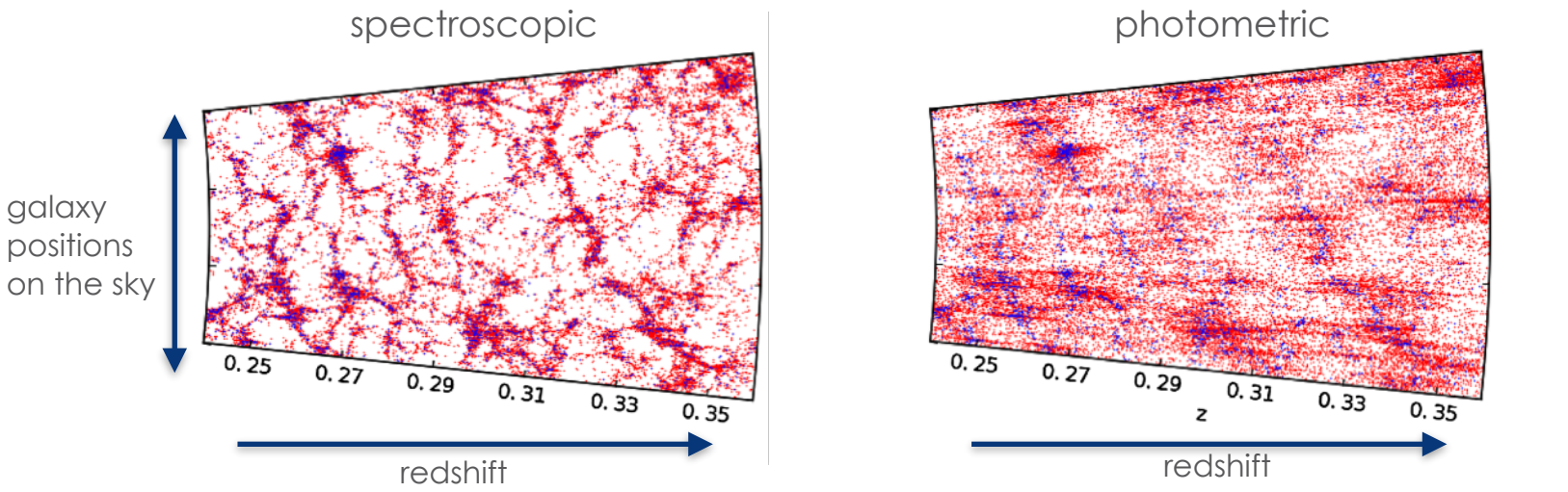


[M. Sachs]

Euclid core science

Photometric galaxy clustering:

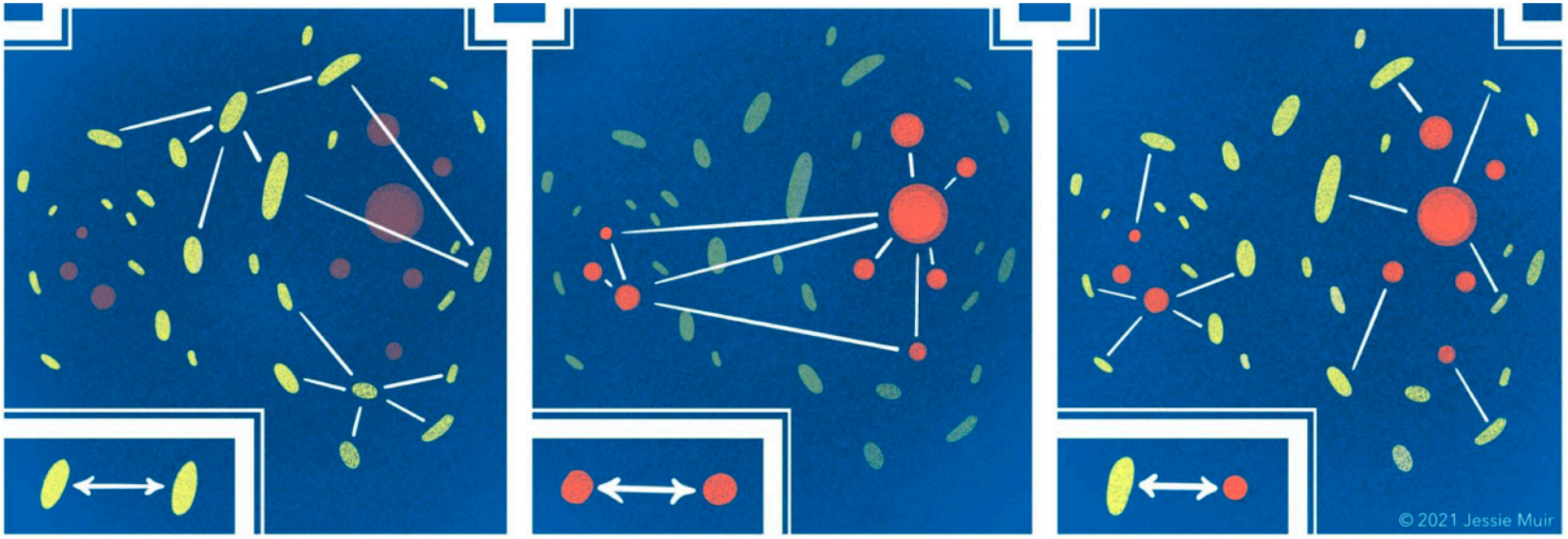
- loss of radial information
- higher number density & different systematic uncertainties
- **source** of cosmological information



[Stothert et al. 2018]

Euclid core science

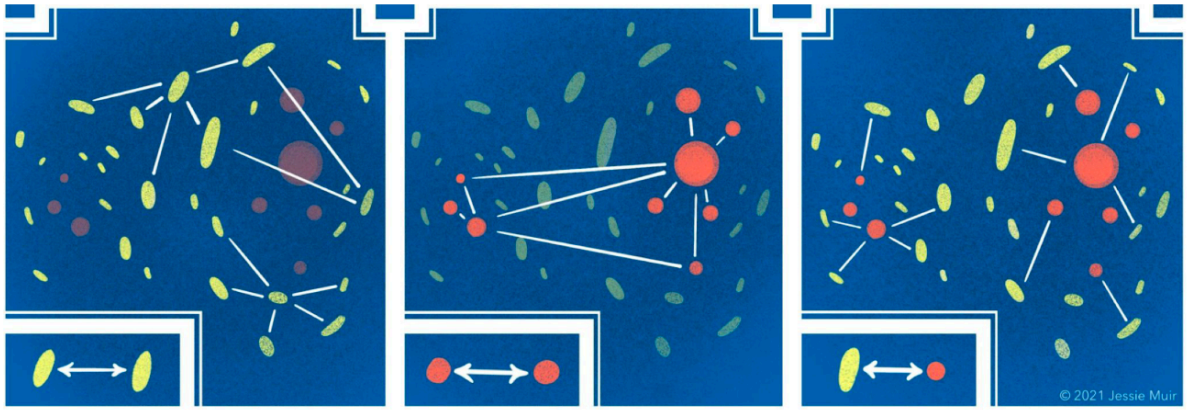
- Combined **3x2pt** analysis from **photometric** data:

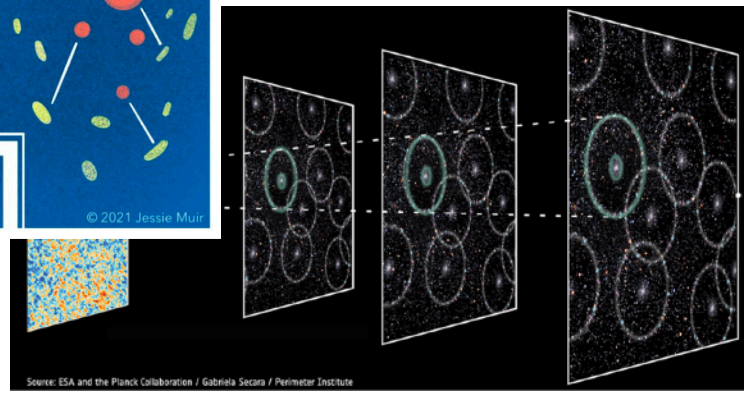


WL | Photometric galaxy clustering | Galaxy-galaxy lensing

Euclid core science

- *Euclid* has been designed to perform both a **photometric** and a **spectroscopic** survey
- **Baseline** analysis: 3x2pt from the photometric data + spectroscopic galaxy clustering (probably negligible cross-covariance)





Euclid core science

- **Cross-covariance** between spectroscopic galaxy clustering and 3x2pt:
  - **High-redshift** spectroscopic sample vs **low-redshift** weak lensing kernel
  - **Different modes** probed by spectroscopic vs photometric probes (Taylor & Markovic 2022)
  - Currently estimating the **cross-covariance for *Euclid* DR1**
- Next step: Cross-correlations as an additional data vector?

Euclid since launch

Launch 1st of July 2023:

- Cape Canaveral, Florida, USA with a Space X Falcon 9
- Destination: 2nd Lagrange point

[Space X; ESA]

Euclid since launch

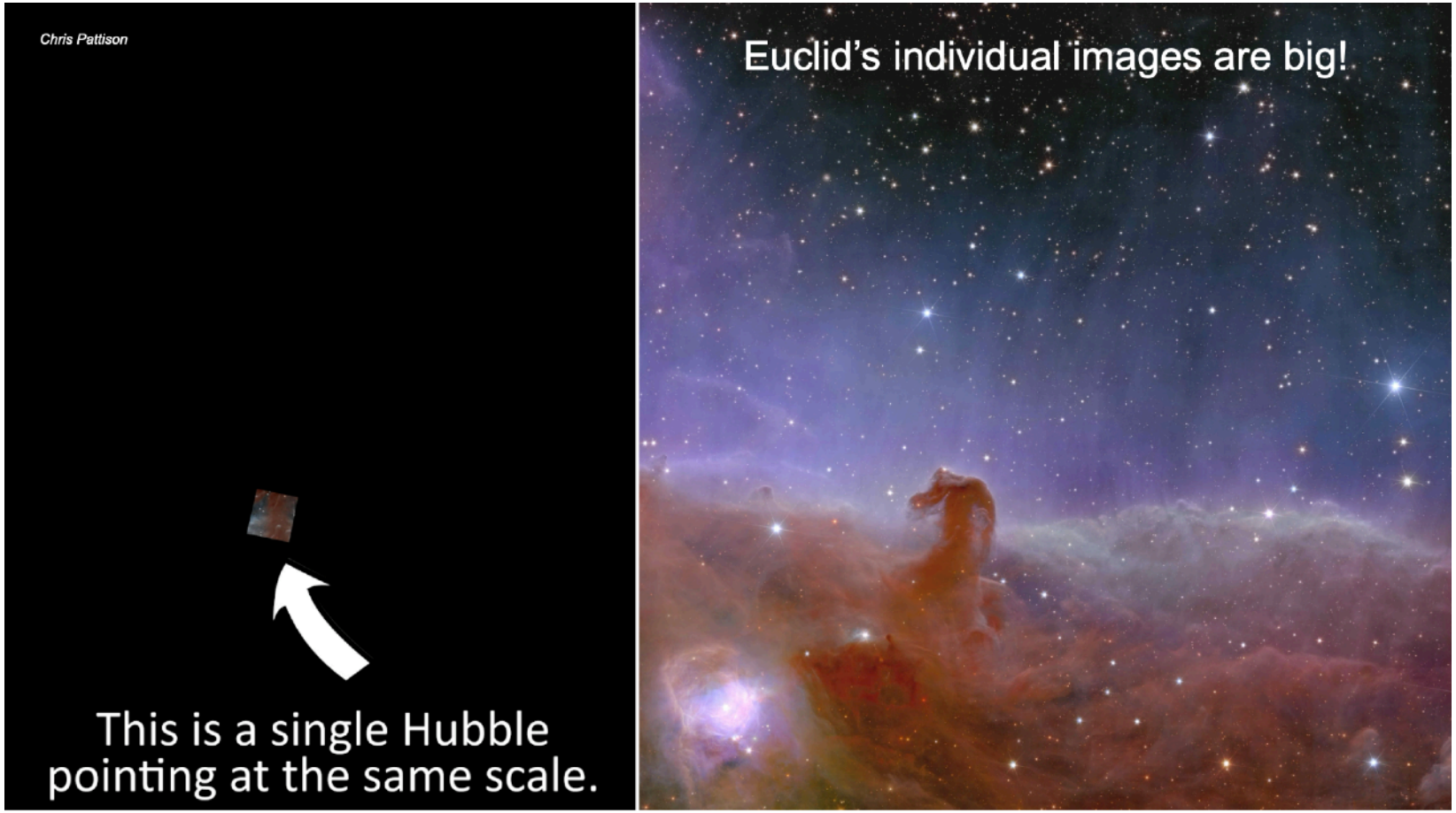
Early Release Observations:

- 24h of observations to allocated targets
- 10 images (new low-mass dwarf galaxies, very distant galaxies,…)

[ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi]

Euclid since launch

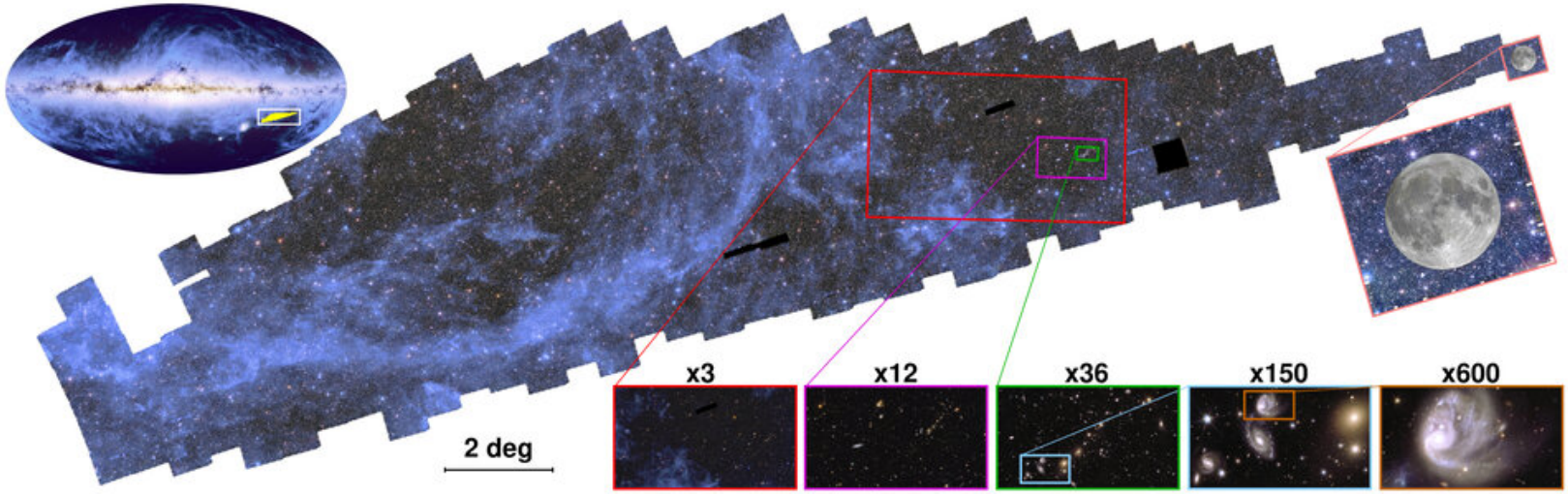
Early Release Observations:



Euclid since launch

1% of the wide survey:

- 260 observations taken in 2 weeks
- 132 sq deg, 100M sources, 14M galaxies for cosmology



[ESA/Euclid/Euclid Consortium/NASA, CEA Paris-Saclay, image processing by J.-C. Cuillandre, E. Bertin, G. Anselmi; ESA/Gaia/DPAC; ESA/Planck Collaboration]

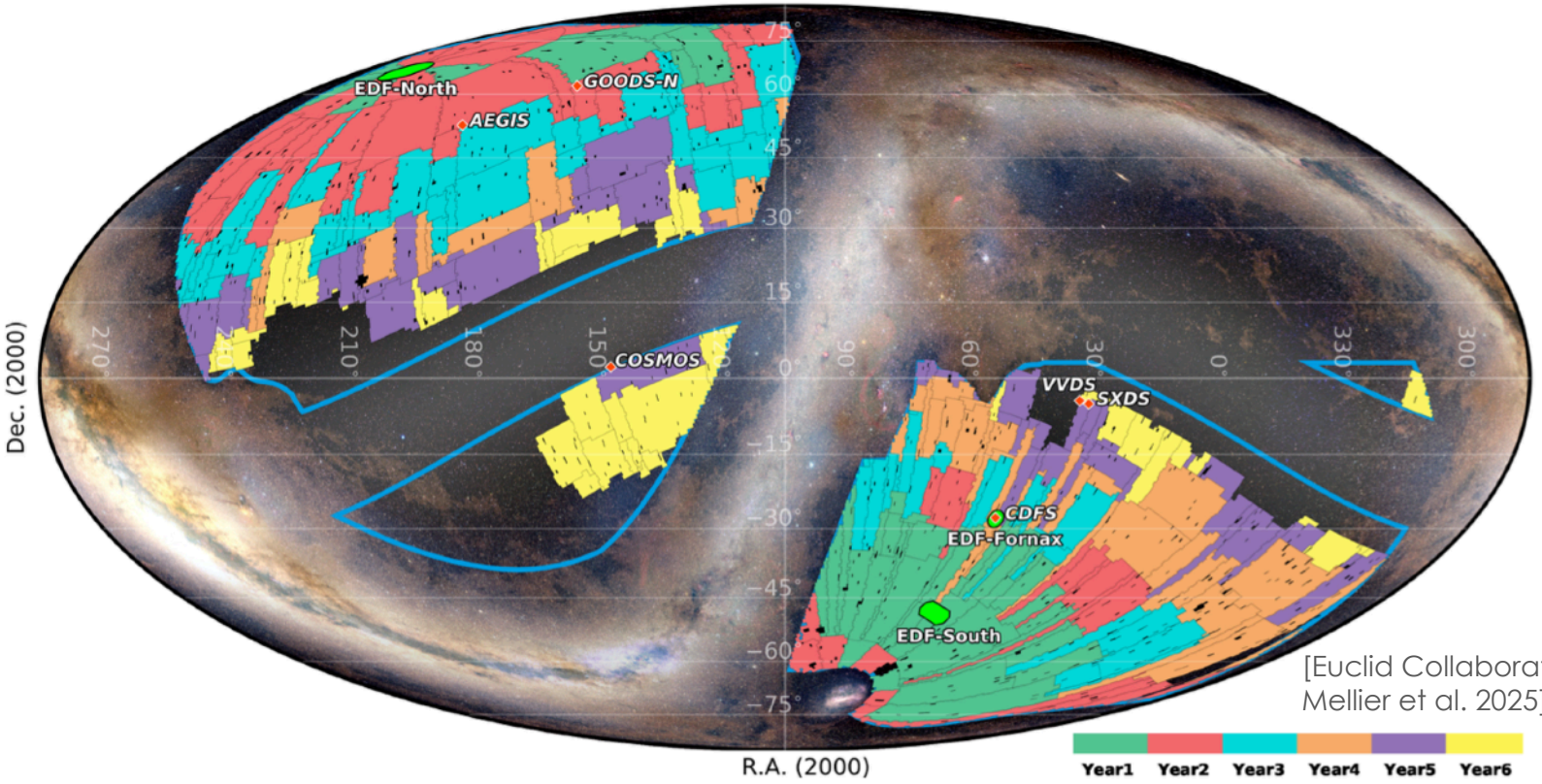
Euclid since launch

Quick data release 1 (Q1):

- Public release of the data (and first batch of papers) in March 2025
- 63 sq deg
- 27 science papers + 7 data/technical papers (more in fall 2025)
- Non-cosmological science for the moment: Milky Way, galaxy morphology, galaxy evolution, proto-clusters, transient objects,…

Probe combination in *Euclid*

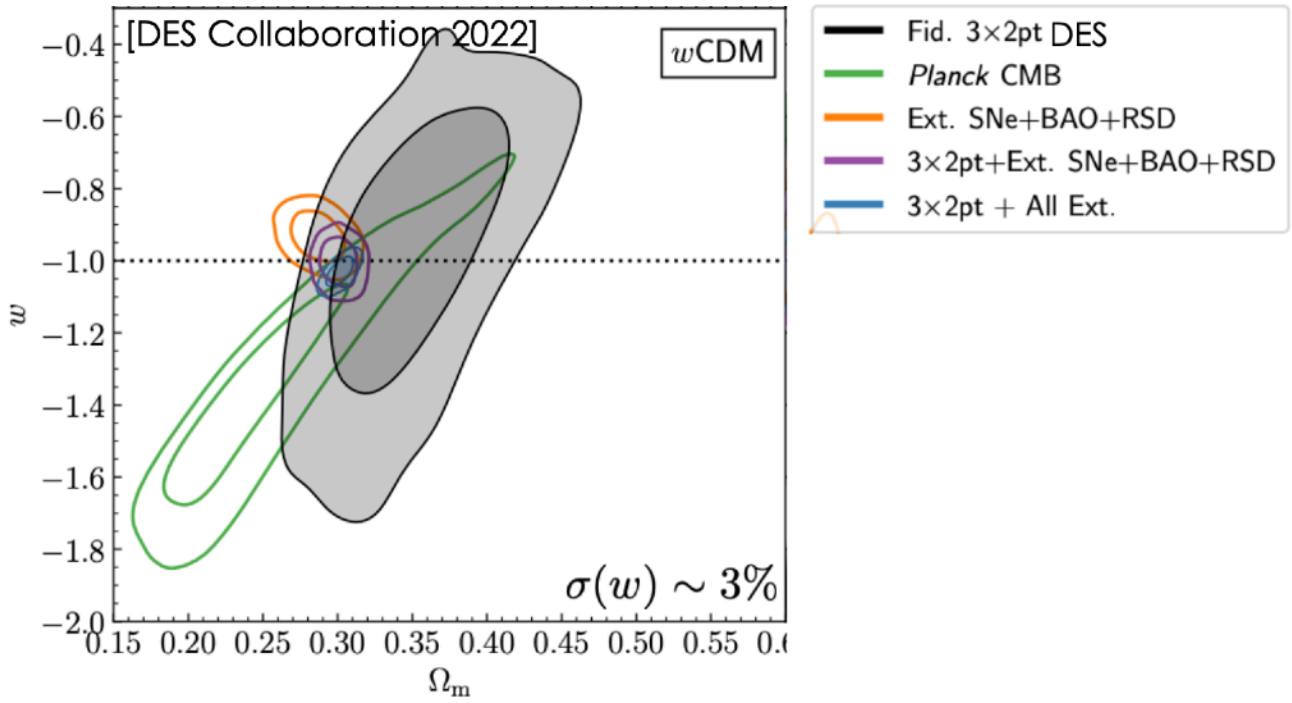
- *Euclid* will cover about **14 000 sq. deg.** of extragalactic sky in **6 years**



[Euclid Collaboration: Mellier et al. 2025]

Probe combination in *Euclid*

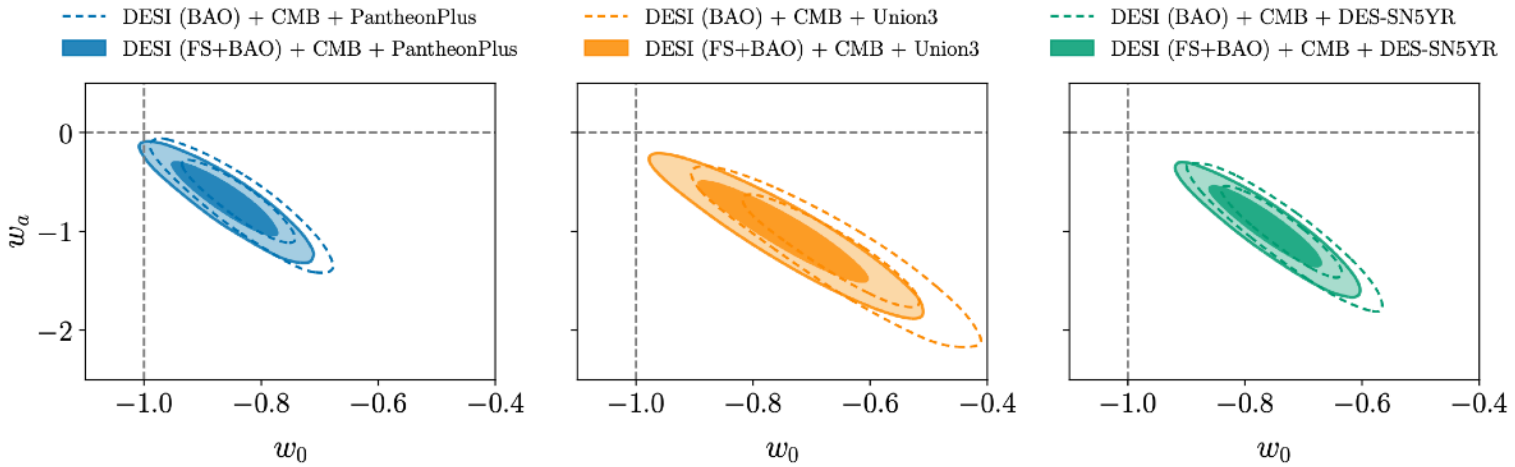
- All probes with **stage-III** galaxy surveys:



- **~3% constraint** on the dark energy equation of state parameter (constant)

Probe combination in *Euclid*

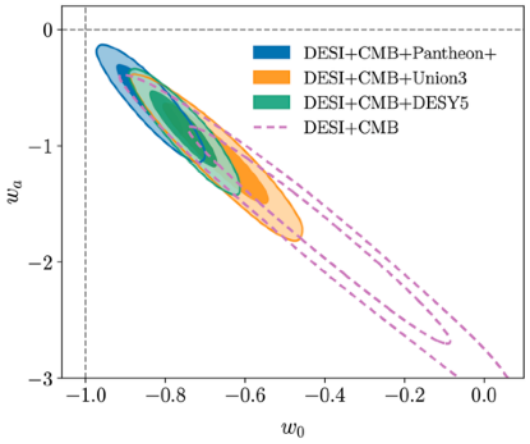
- First *spectroscopic* **stage-IV** data: Dark Energy Spectroscopic Instrument DR1



- **~6%** constraint on w_0 and **~0.3** uncertainty on w_a

[DESI Collaboration 2025a]

- Improved with DR2

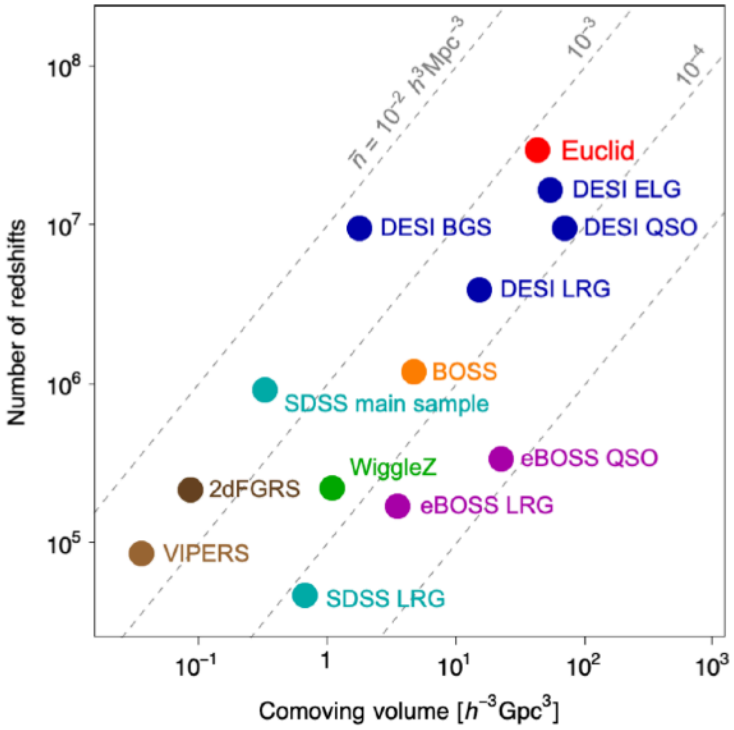


[DESI Collaboration 2025b]

Probe combination in *Euclid*

Spectroscopic galaxy clustering:

- More than 10^7 spectroscopically-detected galaxies at high redshift (0.9-1.8)

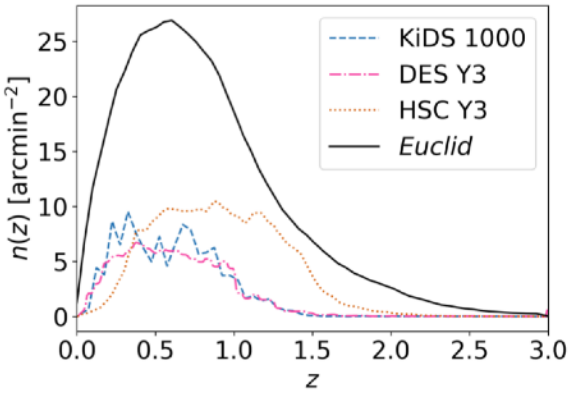


[Euclid Collaboration: Mellier et al. 2025]

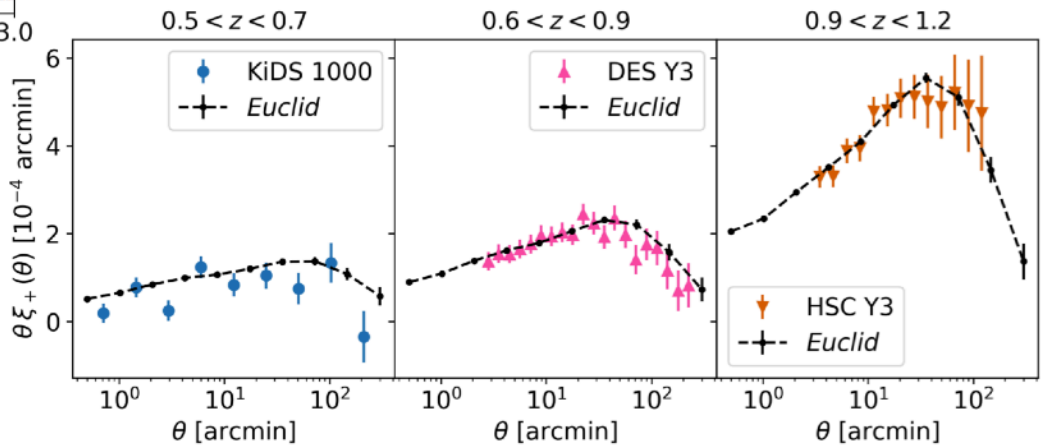
Probe combination in *Euclid*

Weak lensing:

- More than a billion shapes of galaxies up to high redshift



[Euclid Collaboration: Mellier et al. 2025]



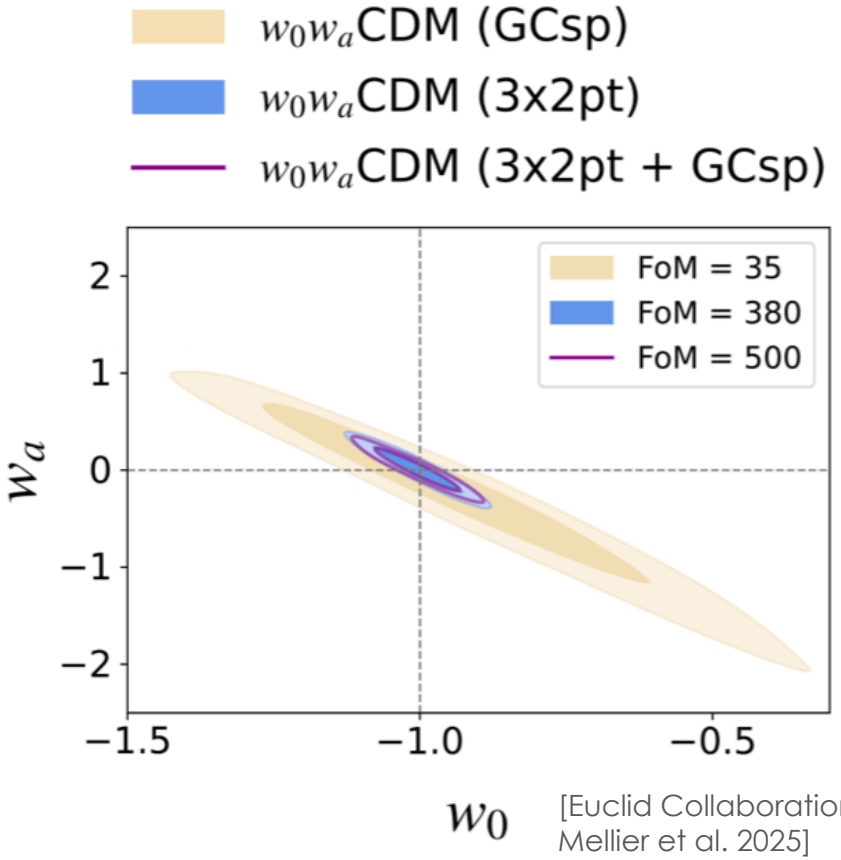
Probe combination in *Euclid*

- Very **precise** constraints on the nature of **dark energy**

- Dark energy equation of state parameter:

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

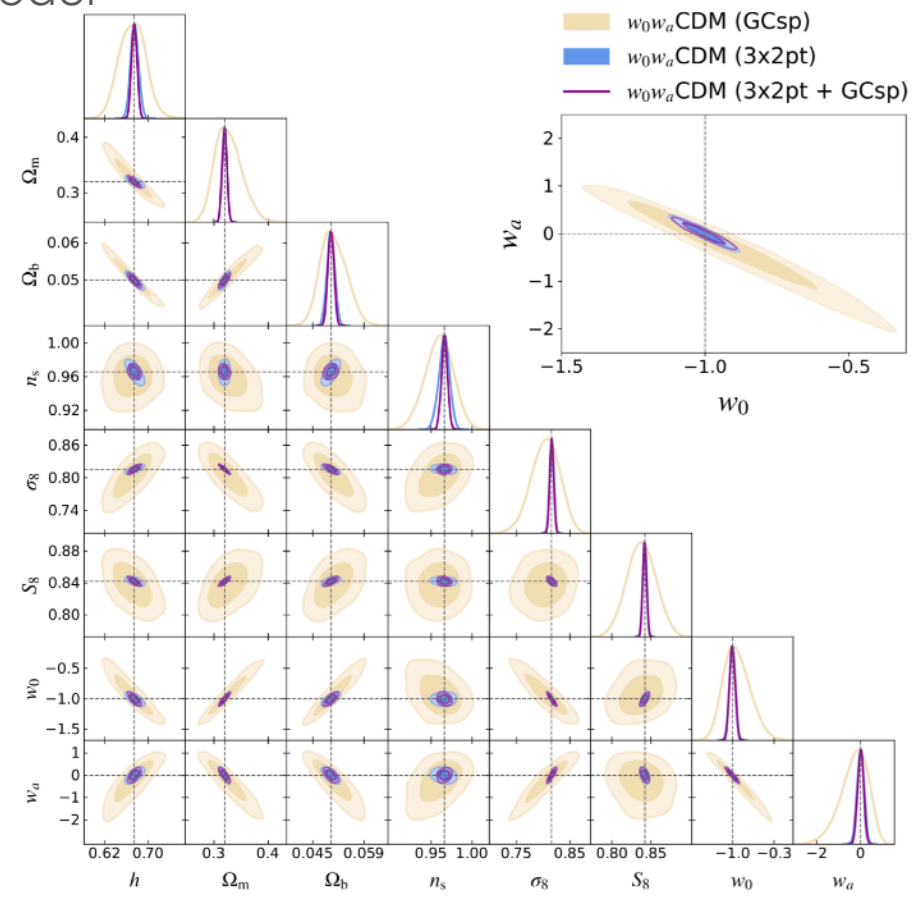
- **x2 more precise** than **combined** current constraints with *Euclid* main probes **alone**



[Euclid Collaboration: Mellier et al. 2025]

Probe combination in *Euclid*

- Also very precise constraints on the other parameters of the standard model



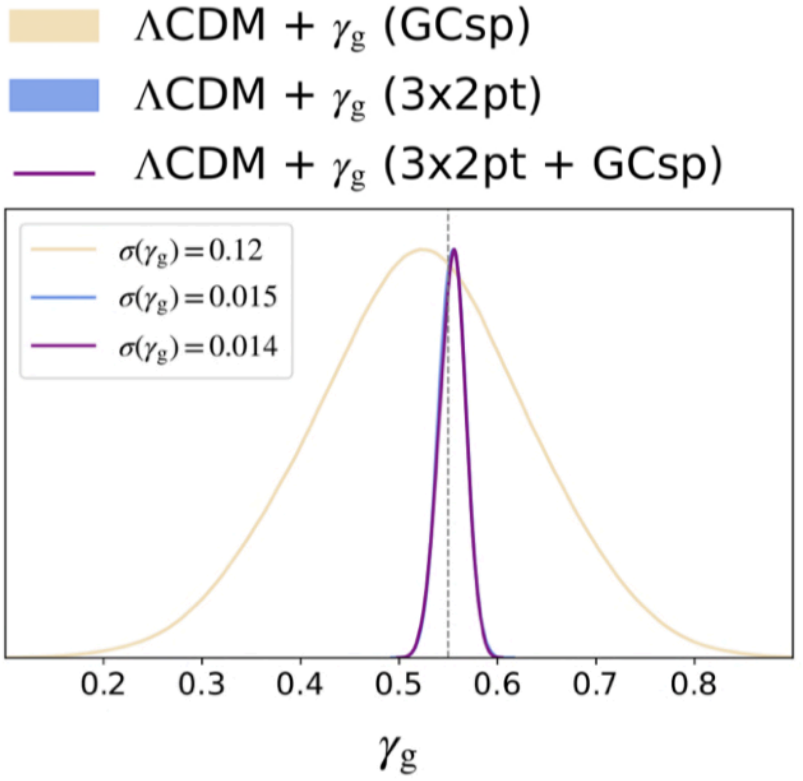
[Euclid Collaboration: Mellier et al. 2025]

Going beyond the standard model

- *Euclid* will allow us to constrain simple modified gravity models

- Linear growth rate of matter perturbations:

$$f_{\rm g}(z) \equiv \frac{{\rm d}\ln g_+(z)}{{\rm d}\ln a} \simeq [\Omega_{\rm m}(z)]^{\gamma_{\rm g}}$$

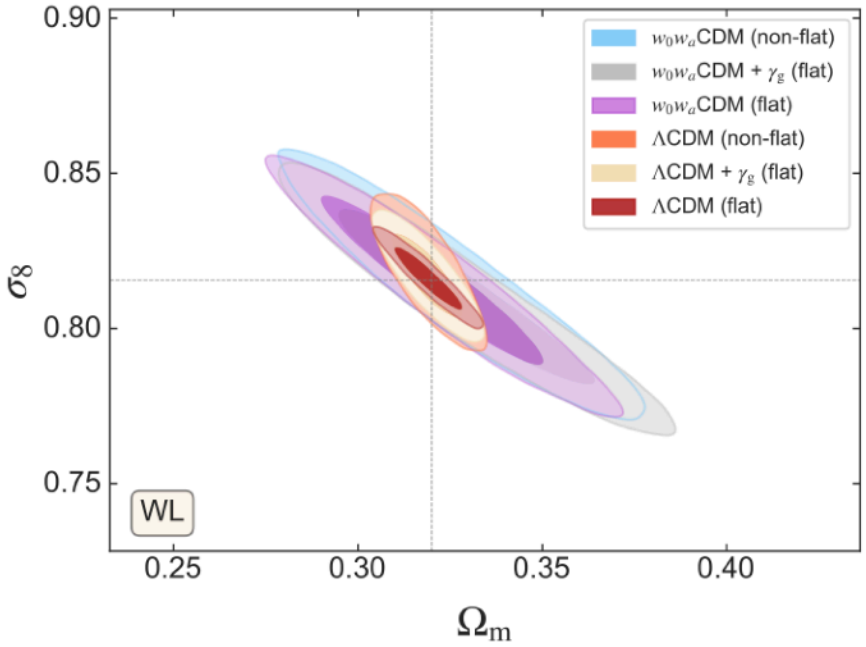


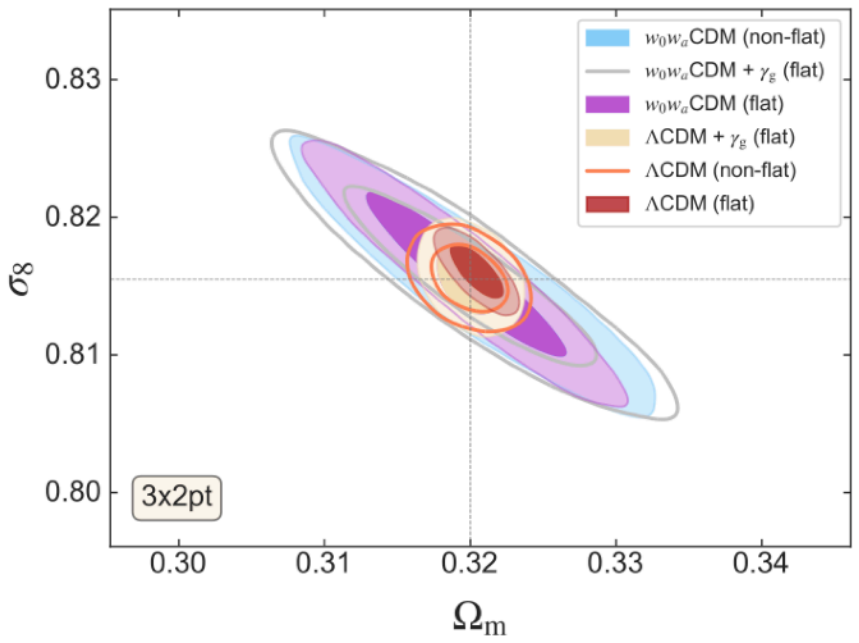
[Euclid Collaboration: Mellier et al. 2025]

Going beyond the standard model

- Using the latest DR3 specifications

[Euclid Collaboration: Cañas-Herrera et al. 2025]





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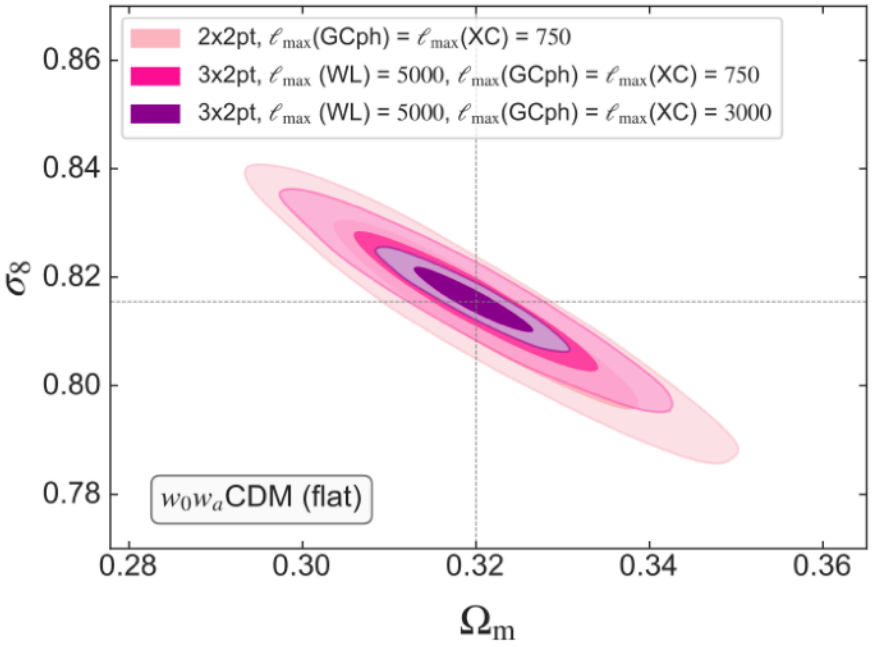
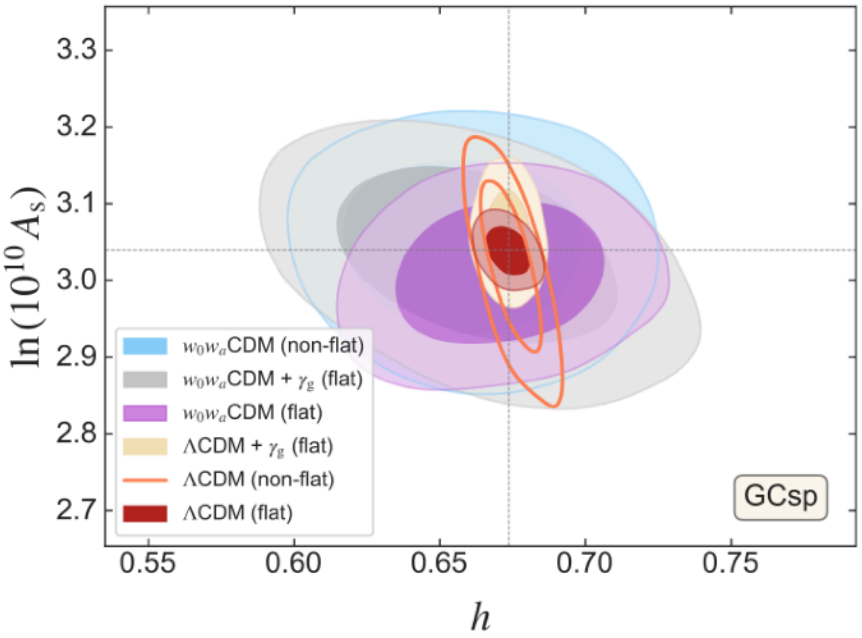
[Euclid Collaboration: Cañas-Herrera et al. 2025]

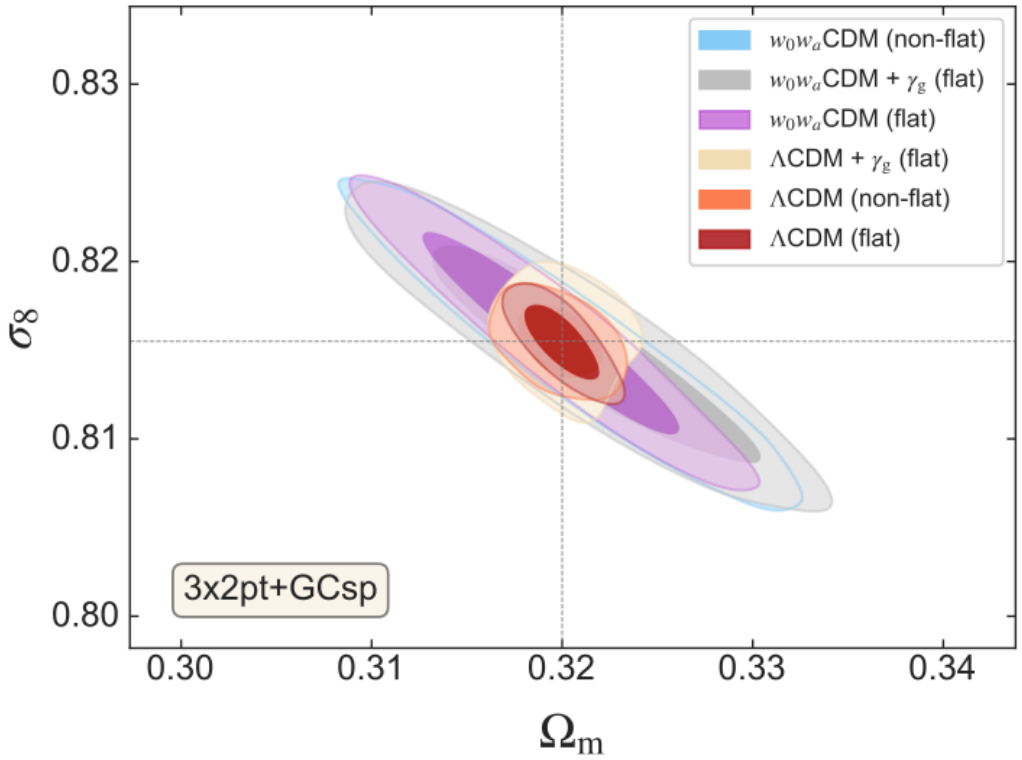




Going beyond the standard model

- Using the latest DR3 specifications

[Euclid Collaboration: Cañas-Herrera et al. 2025]



Going beyond the standard model

- *Euclid* will also allow us to test even more general dark energy and modified gravity models

- mu-Sigma parametrization:

  - Perturbed FLRW metric: $\mathrm{d}s^2 = -(1+2\Psi)\,c^2\,\mathrm{d}t^2 + a^2(t)\,(1-2\Phi)\,\delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j\,,$

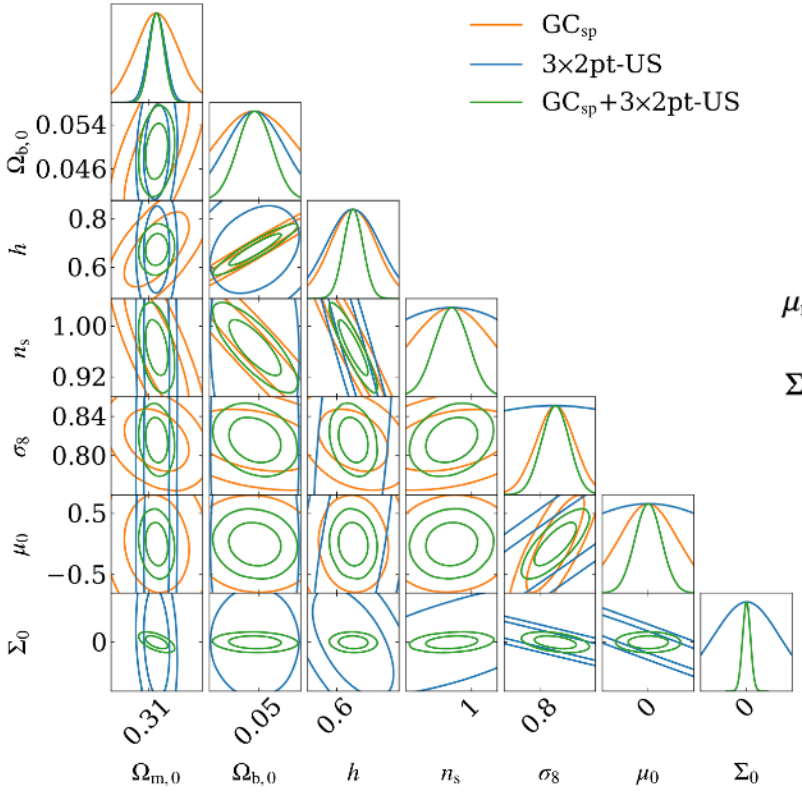
  - Link between gravitational potentials and matter perturbations:

$$-k^2\Psi = \frac{4\pi G_{\mathrm{N}}}{c^2}\,a^2\mu_{\mathrm{mg}}(a,k)\left[\bar{\rho}\Delta + 3\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\right],$$

$$-k^2\,(\Phi+\Psi) = \frac{8\pi G_{\mathrm{N}}}{c^2}\,a^2\left\{\Sigma_{\mathrm{mg}}(a,k)\left[\bar{\rho}\Delta + 3\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\right] - \frac{3}{2}\mu_{\mathrm{mg}}(a,k)\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\right\},$$

Going beyond the standard model

- *Euclid* will also allow us to test even more general dark energy and modified gravity models



$$\mu_{mg}(z) = 1 + \frac{\Omega_{DE}(z)}{\Omega_{DE}(z=0)}\mu_0\,,$$

$$\Sigma_{mg}(z) = 1 + \frac{\Omega_{DE}(z)}{\Omega_{DE}(z=0)}\Sigma_0\,,$$

[Euclid Collaboration: Albuquerque et al. 2025]

Going beyond the standard model

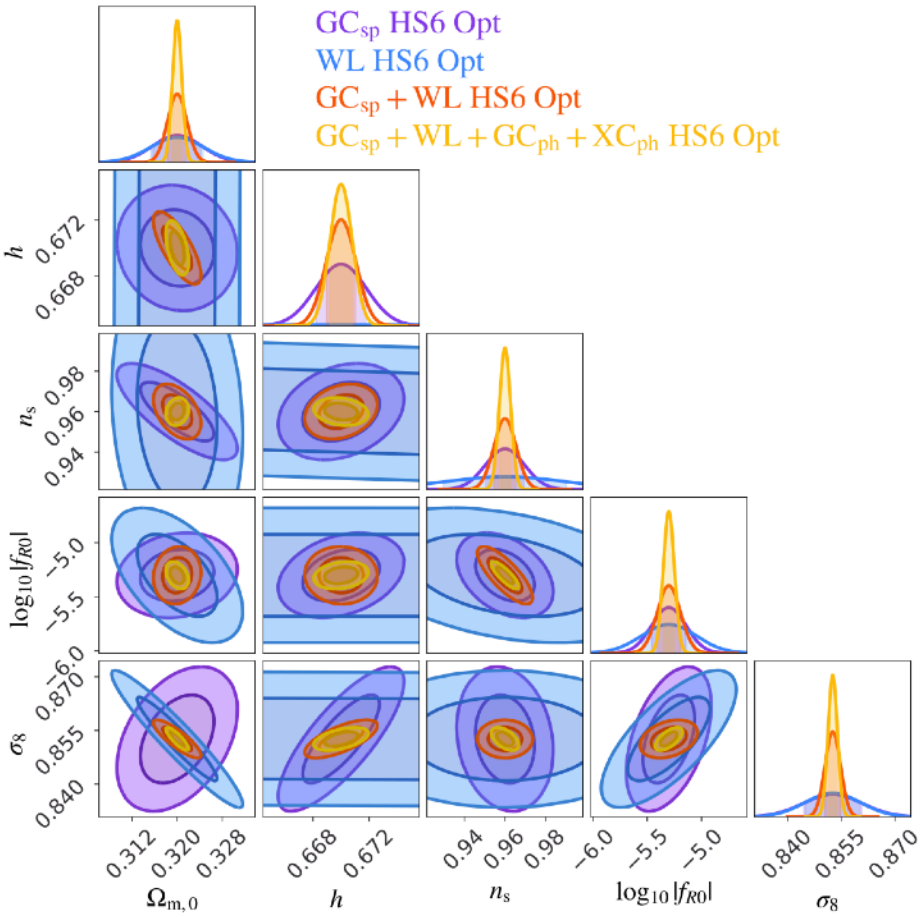
- *Euclid* will also allow us to test even more general dark energy and modified gravity models

- f(R) gravity:

$$S = \frac{c^4}{16\pi G_{\rm N}} \int {\rm d}^4x \sqrt{-g}\,[R + f(R)]$$

  - Hu-Sawicki model:

$$f(R) = -6\Omega_{\rm DE,0}\frac{H_0^2}{c^2} + |f_{R0}|\frac{\bar{R}_0^2}{R}$$

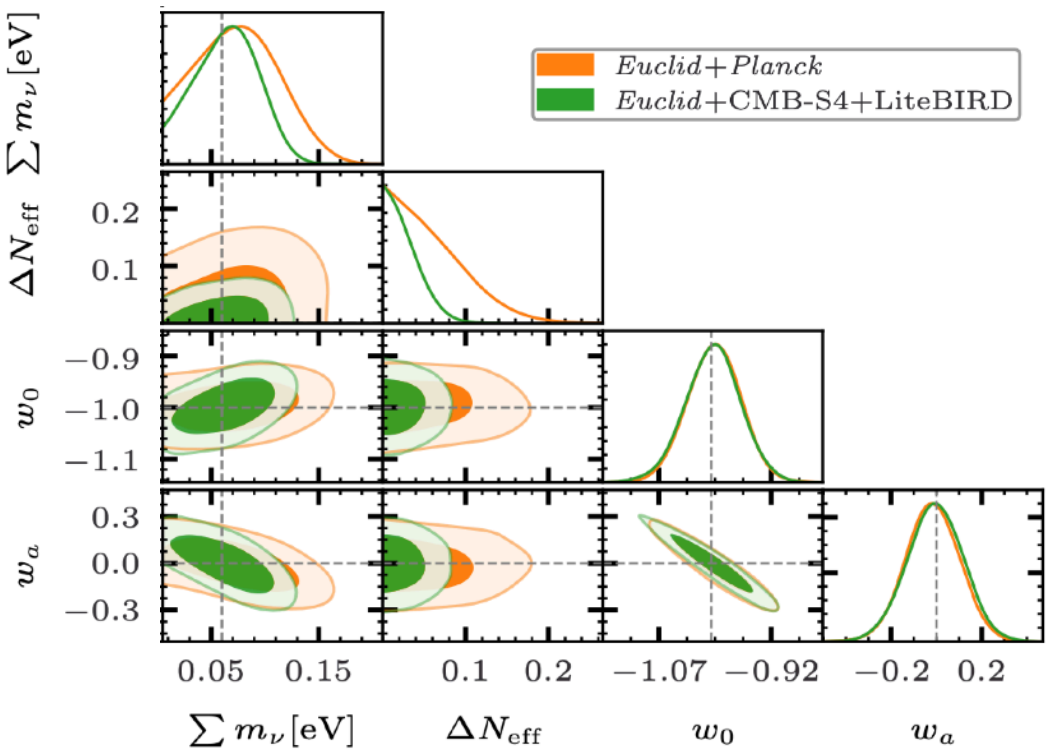


[Casas et al. 2023; Euclid Collaboration: Koyama et al. 2025]

Going beyond the standard model

- *Euclid* will help us test **neutrinos** and other **particles beyond the standard model**

  - Neutrino sensitivity of *Euclid* alone: 56 meV (in LCDM)
  - *Euclid* + *Planck*: 23 meV
  - Evidence for a non-zero neutrino mass at 2.6 sigma (4 sigma with future data)

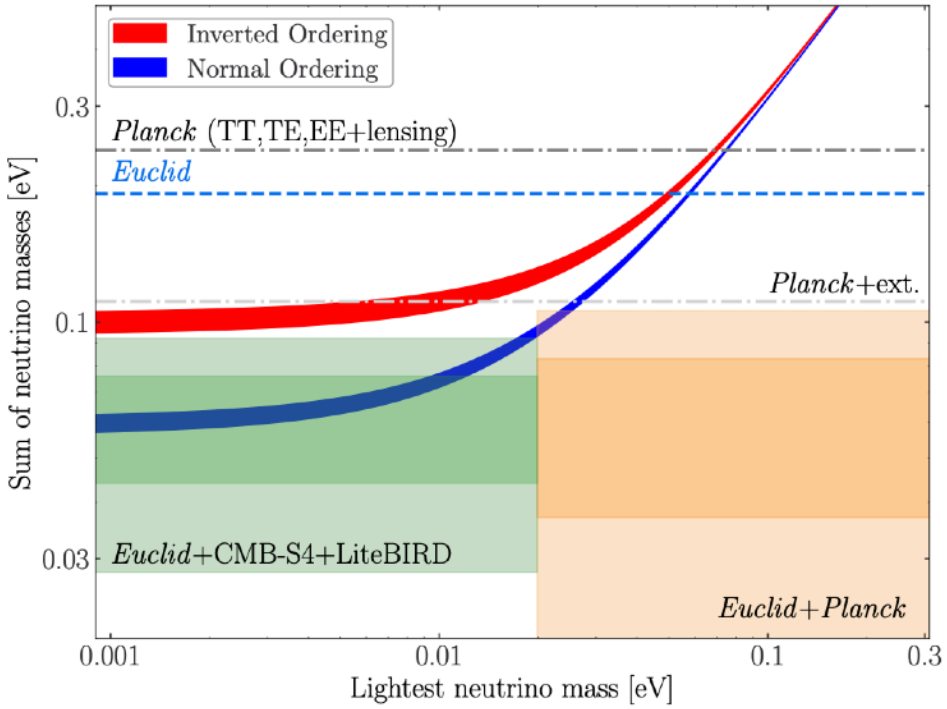


[Euclid Collaboration: Archidiacono et al. 2025]

Going beyond the standard model

- *Euclid* will help us test **neutrinos** and other **particles beyond the standard model**

  - If the true sum of neutrino masses is 0.06 eV (normal ordering), *Euclid* + future cosmic microwave background data will rule out inverted ordering at 2.5 sigma

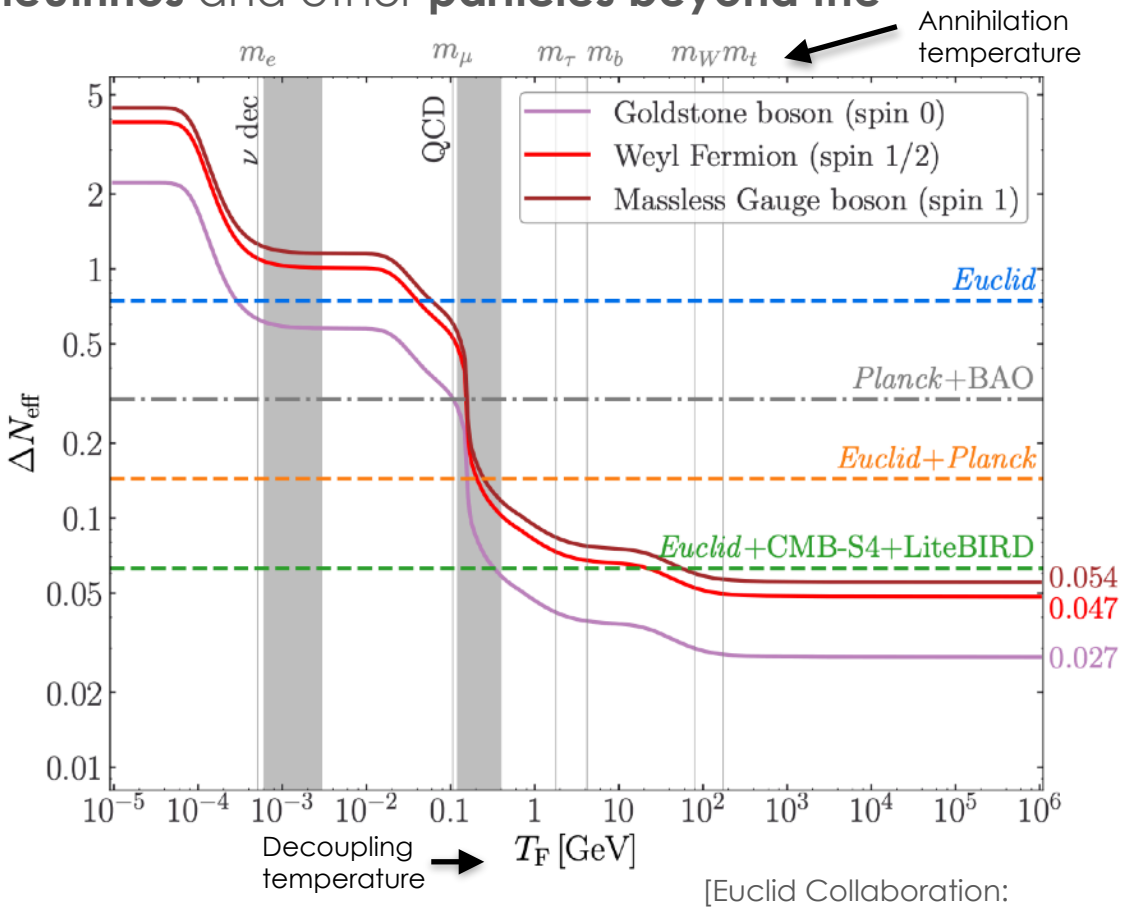


[Euclid Collaboration: Archidiacono et al. 2025]

Going beyond the standard model

Euclid will help us test **neutrinos** and other **particles beyond the standard model**

- Adding *Euclid* improves the current limit on the presence of new light particles by more than a factor 2



[Euclid Collaboration: Archidiacono et al. 2025]

Conclusions

- *Euclid* will provide exquisite measurements to perform **galaxy clustering** and **weak lensing** analyses
- **Probe combination** is key to get the most amount of information from the data — spectroscopic GC and photometric 3x2pt
- **Additional cosmological probes** are also being considered (galaxy clusters, correlations with the cosmic microwave background,…)
- *Euclid* will help us shed light on the **dark sectors** of the Universe and test gravity
- A lot of non-cosmological science is planned (Milky Way, galaxy morphology, galaxy evolution, proto-clusters, transient objects,…)
- The **first data release** will be public on 21st October 2026