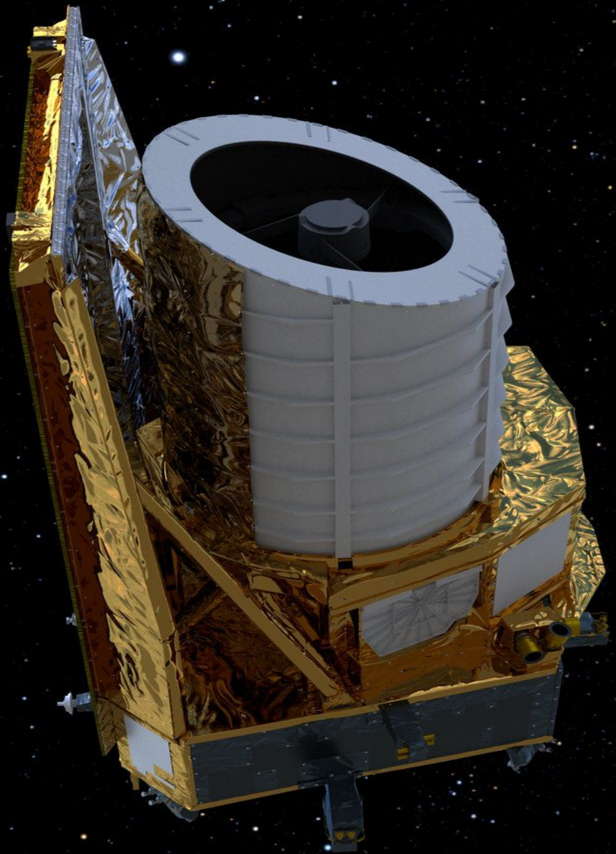


Euclid: constraints on initial conditions and implications for primordial features

Mario Ballardini
University of Ferrara

Istituto Nazionale di Fisica Nucleare

euclid consortium

Università degli Studi di Ferrara

Outline

- Euclid mission overview
  - What is Euclid and what does Euclid observe?
  - Early Release Objects and Q1 data release
- Initial conditions forecasts
  - Scalar spectral index
  - Running of the scalar spectral index
  - Primordial features
- Conclusions

Euclid Consortium

The Euclid Consortium

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

More than 2000 registered active member

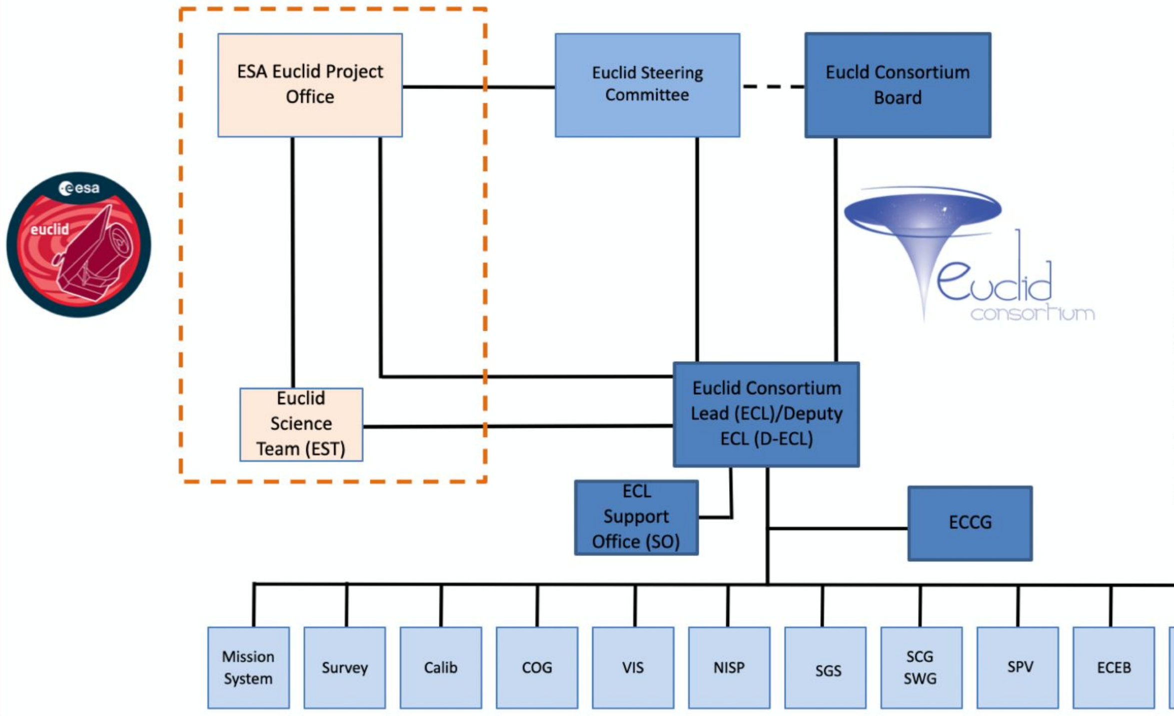
15 European countries
+ USA + Canada + Japan

Responsible of the Euclid instruments and the exploitation of the data

The Euclid Consortium

Euclid Consortium meeting in Leiden, March 2025

The Euclid Consortium & ESA Euclid

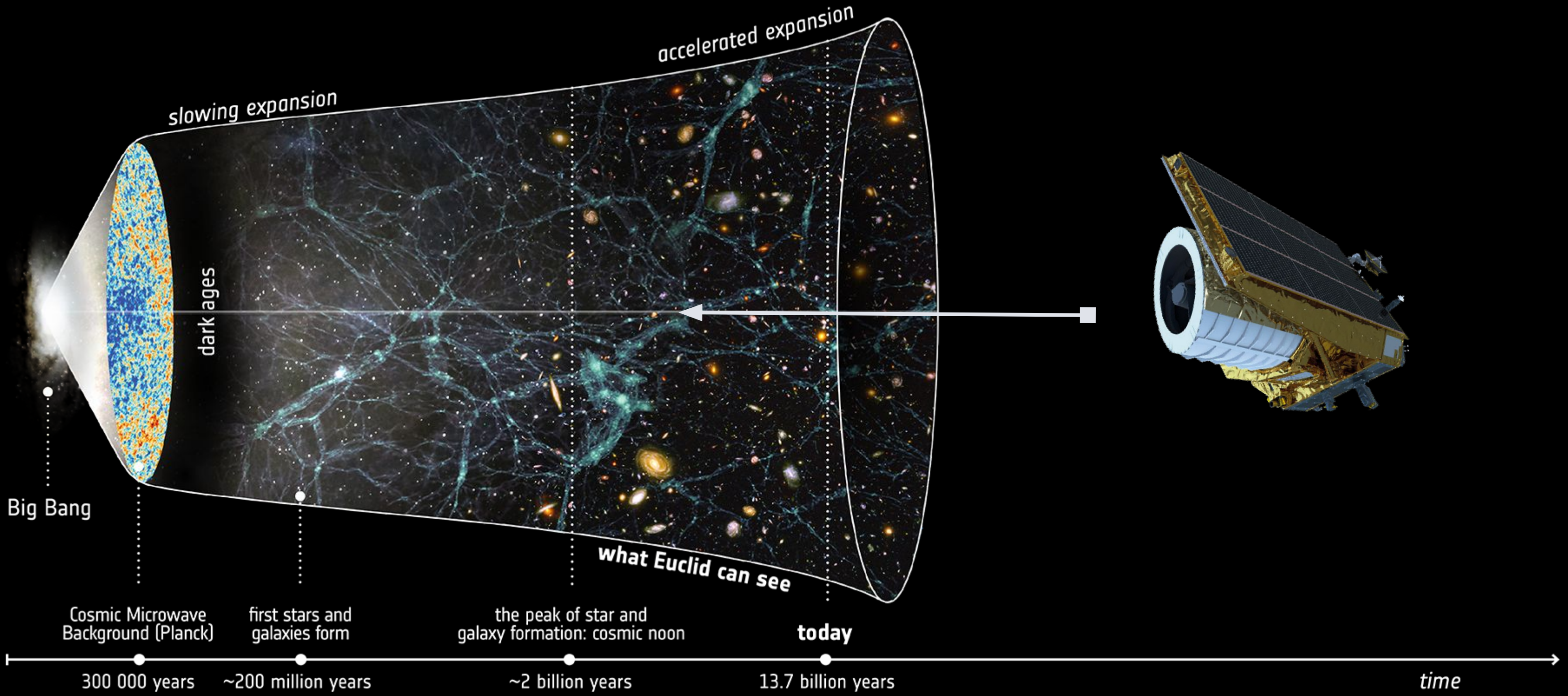


ECCG: Euclid Consortium Coordination Group
COG: Complementary Observations Group
SPV: Science Performance Verification
SCG: Science Coordination Group
SGS Science Ground Segment
SWG: Science Working Group
ECEB: Euclid Consortium Editorial Board
ECDC: Euclid Consortium Diversity Committee
COM: Communication group

Description of the Euclid Consortium structure, courtesy of the Euclid Consortium PI (Y. Mellier)

Primary Science

Timeline of the Universe



Credit: ESA/ATG

Main Objectives

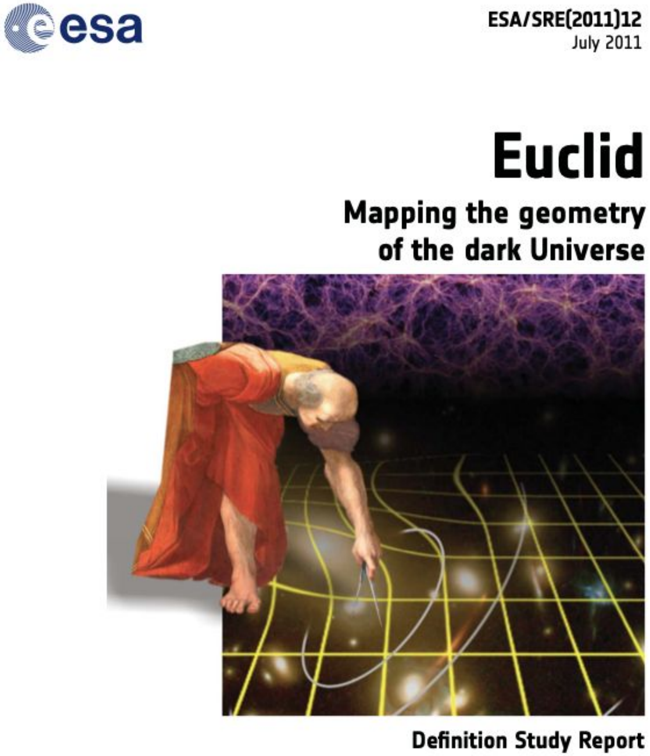


Table 1: Euclid Primary Science Objectives – see RD10 for a full description.

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 Definition Study report

Spacecraft & Instruments

Spacecraft

4.7m tall
3.7m total diameter
1.2m diameter main mirror
2 tonnes

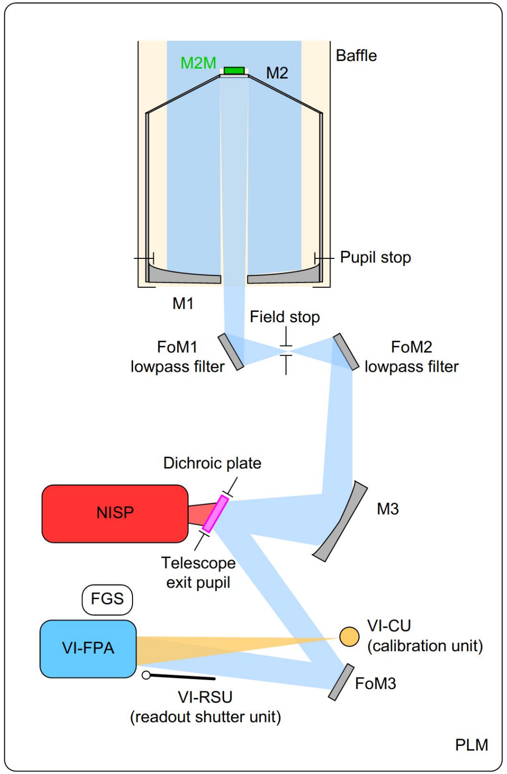
Sunshield

Solar panels

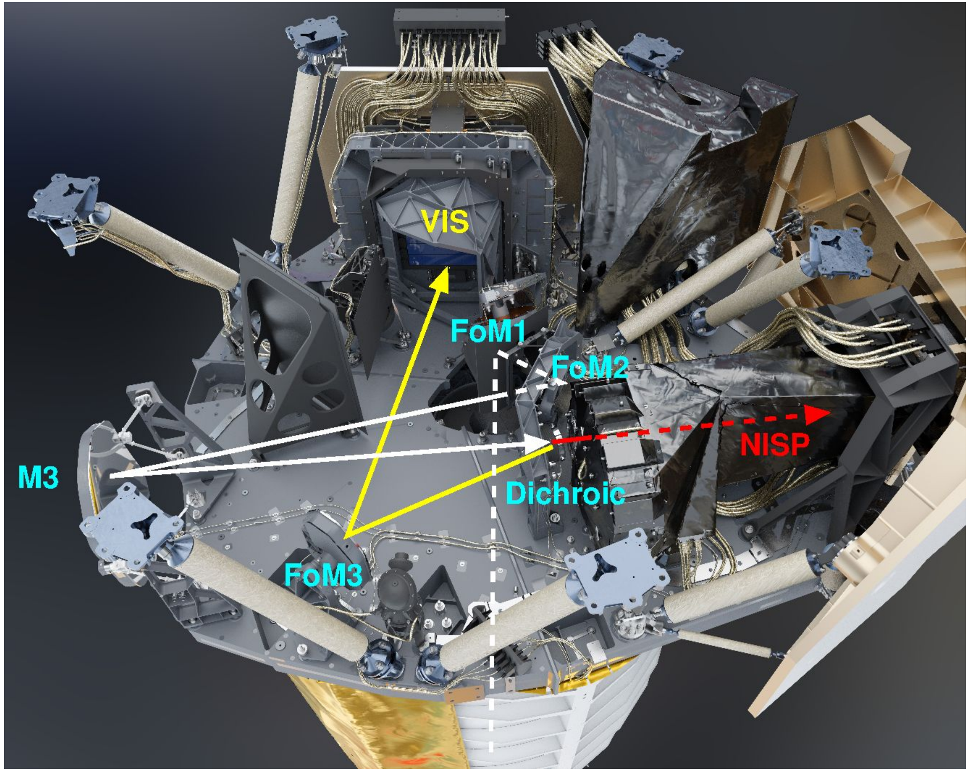
Service module

VIS and NISP

Payload Module: Optical path and instruments



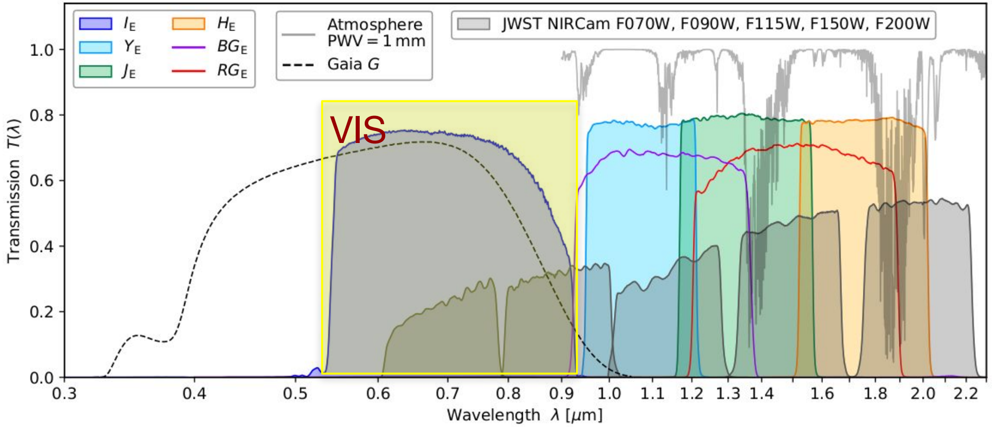
Optical layout
Credit: Airbus Defence and Space

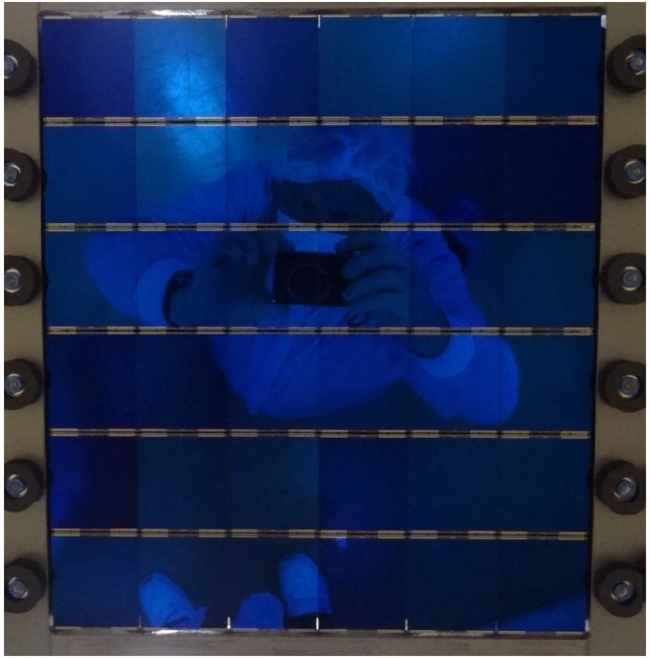


Layout of the instruments. The telescope is below, observing downwards.
Credit: Airbus Defence and Space; annotations by EC

VIS (VISible Instrument)

- Focal-plane instrument, no fore-optics
- 36 4k x 4k CCDs, 0.1” / pixel
- Readout time 72 seconds
- 530–920 nm wavelength range defined by coated mirrors, detectors, and dichroic beamsplitter
- Blade shutter
- Calibration lamp (6 wavelengths)
- Depth: 26.2 AB mag (5σ point source)

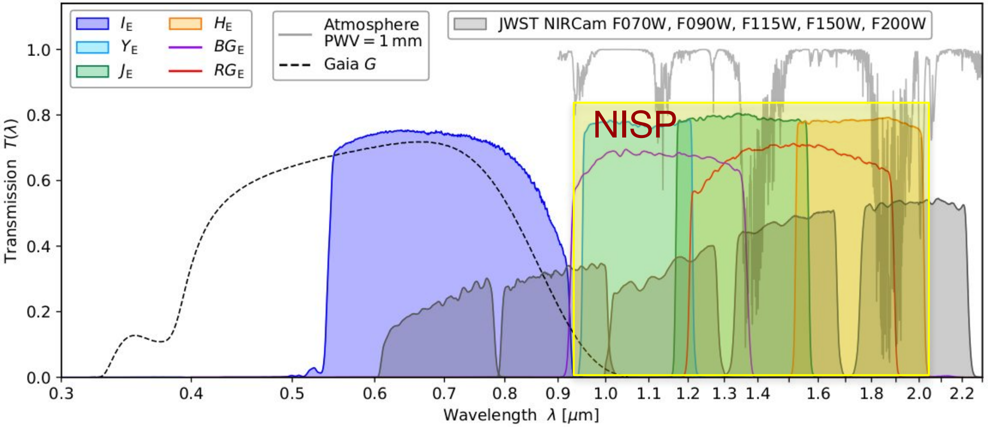


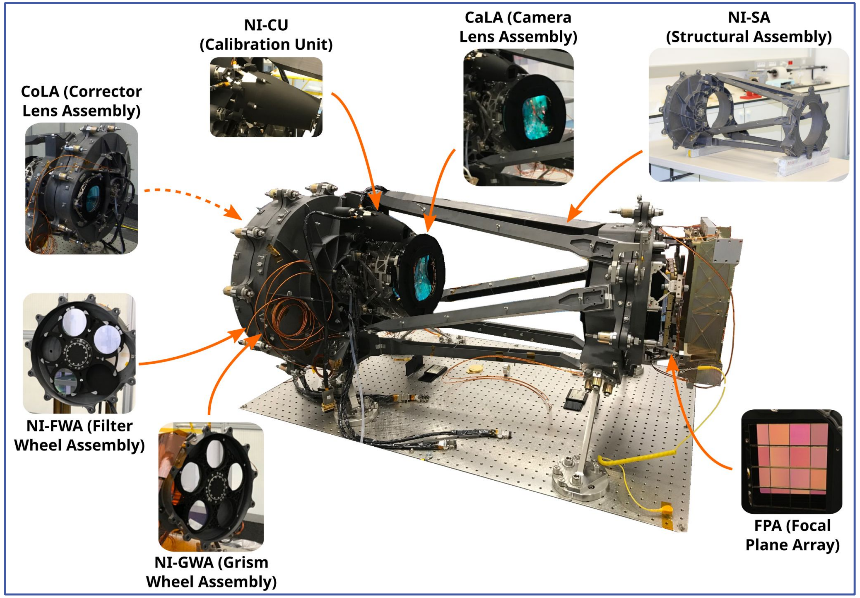


VIS instrument
Credit: EC VIS team

NISP (Near Infrared Spectrometer and Photometer)

- 16 detectors, 0.3” / pixel
- 3 photometric bands
- 2 spectroscopic bands
- Spectral resolution: R~480
- Calibration lamp (5 wavelengths)
- Depths:
  24.5 AB mag (5σ point source)
  2 10^{-16} erg/s/cm^2 (line flux)





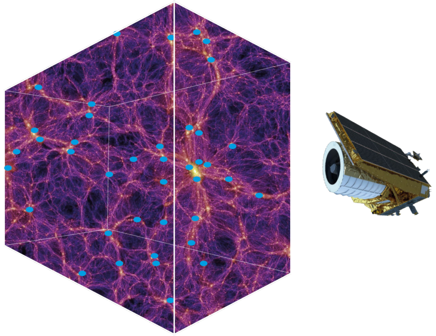
Credit: Euclid collaboration: Jahnke et al. (2024)
https://ui.adsabs.harvard.edu/abs/2024arXiv240513493E/abstract

Primary Probes

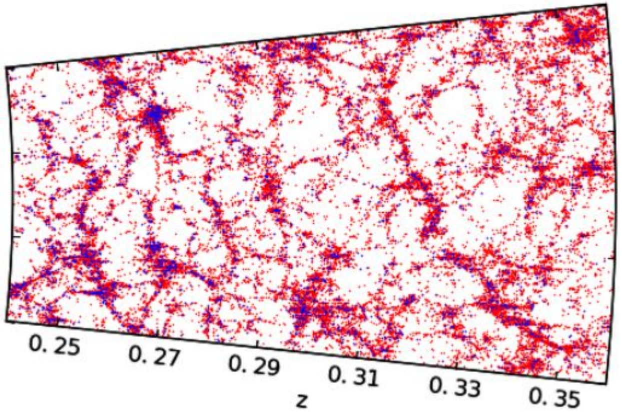
Two primary probes of the LSS

Galaxy clustering

Spectroscopic



Credit: Springel+ (2005) (Background) ESA/ATG medialab (spacecraft)



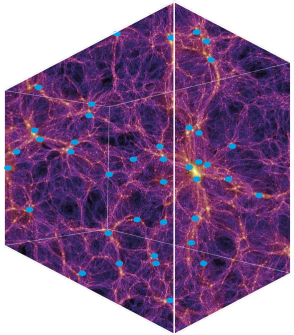
Stothert+ (2018)

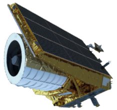
3-D position measurements of galaxies over $0.9 < z < 1.8$

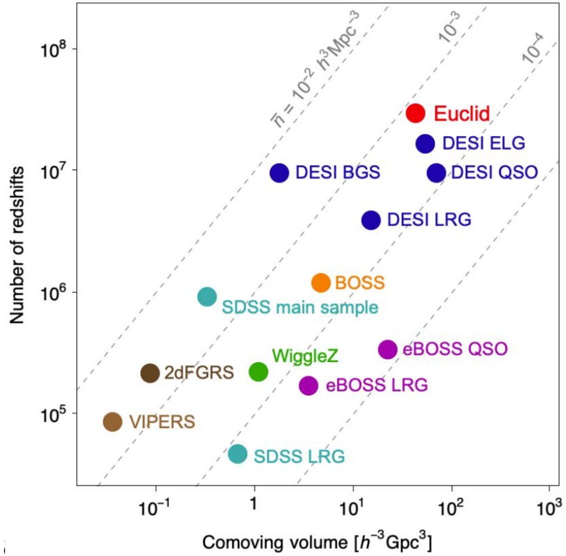
- Probes expansion rate of the Universe (BAO) and growth of structure induced by gravity (RSD); expansion history, ψ potential
- Need high precision 3-D distribution of galaxies with spectroscopic redshifts
- 25M spectroscopic redshifts with 0.001 (1+z) accuracy over 14,000 deg^2

Two primary probes of the LSS

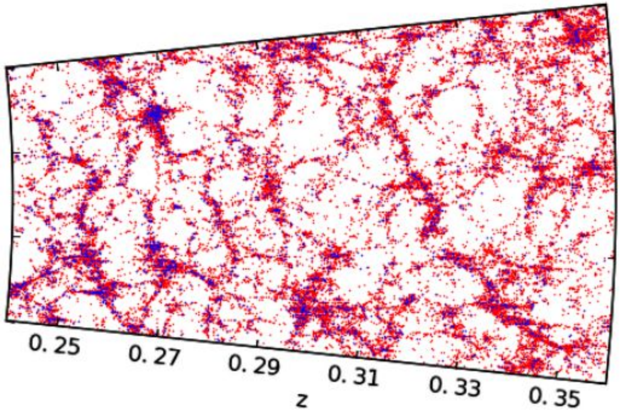
Galaxy clustering







Spectroscopic



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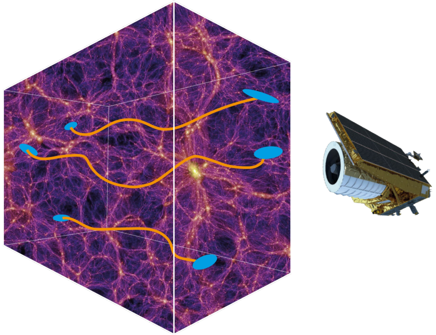
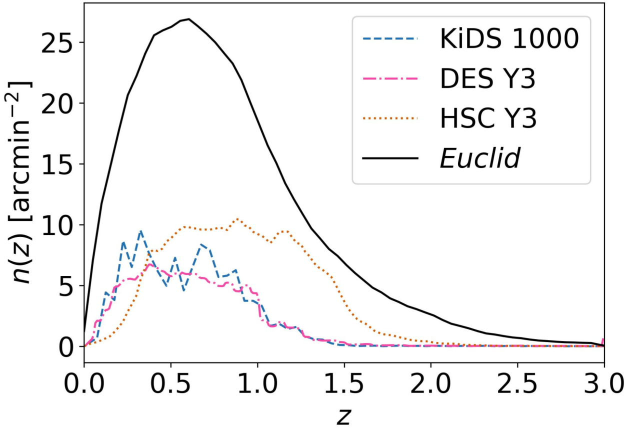
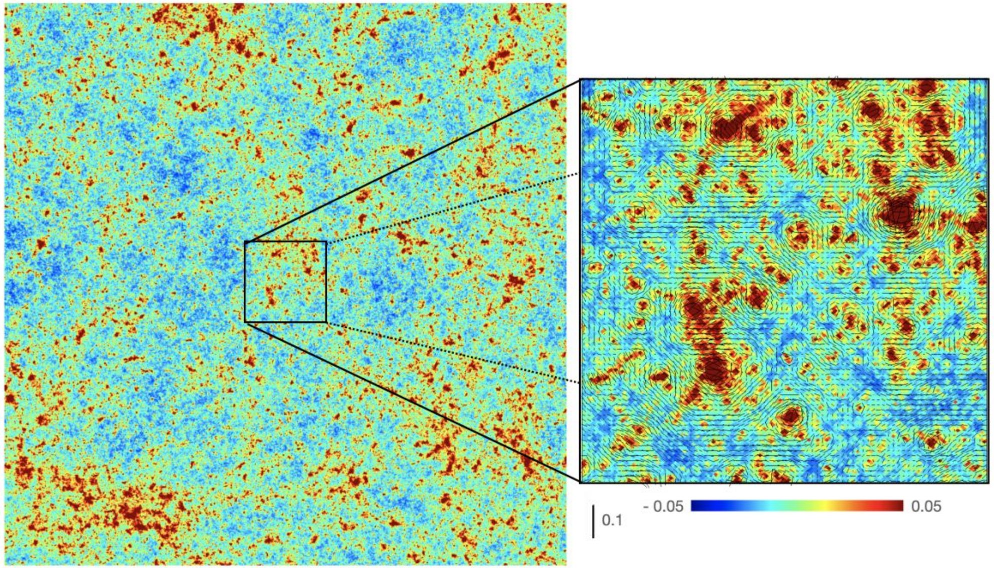
Two primary probes of the LSS

Cosmic shear





Galaxy shapes trace the L.O.S. mass distribution

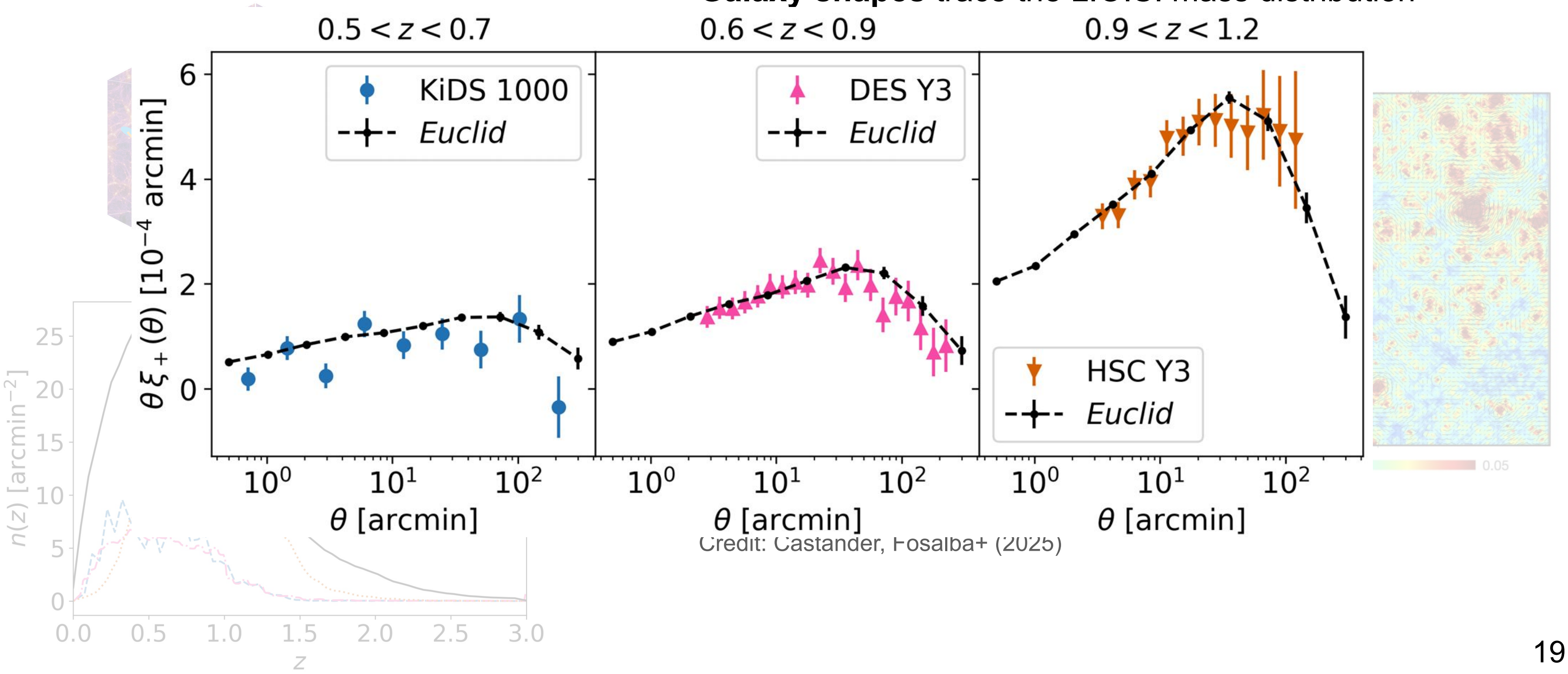


Credit: Castander, Fosalba+ (2025)

Two primary probes of the LSS

Cosmic shear

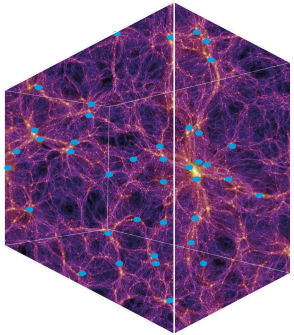
Galaxy shapes trace the L.O.S. mass distribution

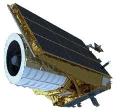


Credit: Castander, Fosalba+ (2025)

Two primary probes of the LSS

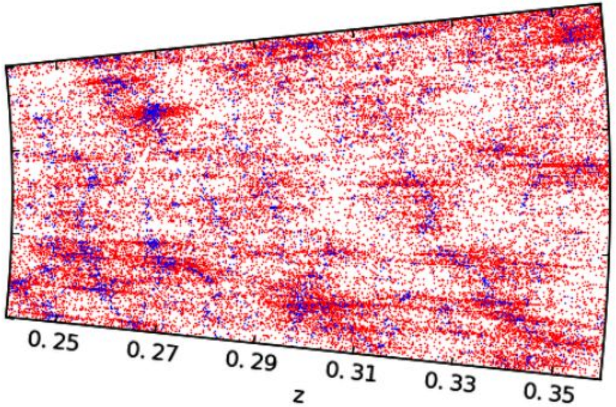
Galaxy clustering



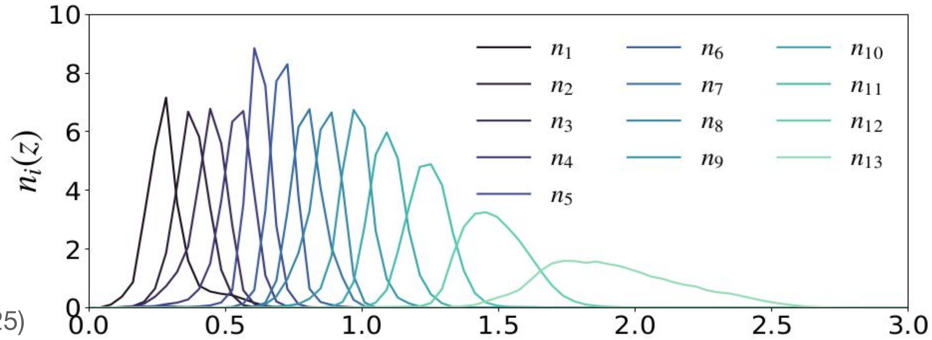


Photometric

σ(z) < 0.05 (1 + z)



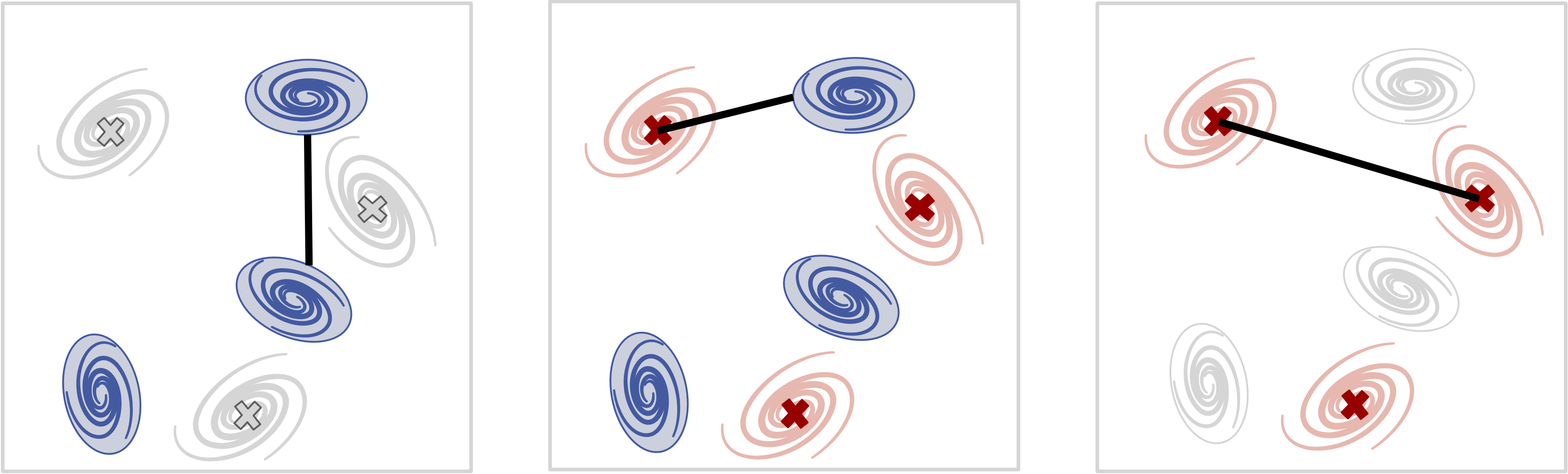
2D angular distribution in tomographic bins



Credit: Mellier+ (2025)

3 x 2-pt analyses

Shape-Shape *'Cosmic shear'*	**Position-Shape** *'Galaxy-galaxy-lensing'*	**Position-Position** *'Angular clustering'*



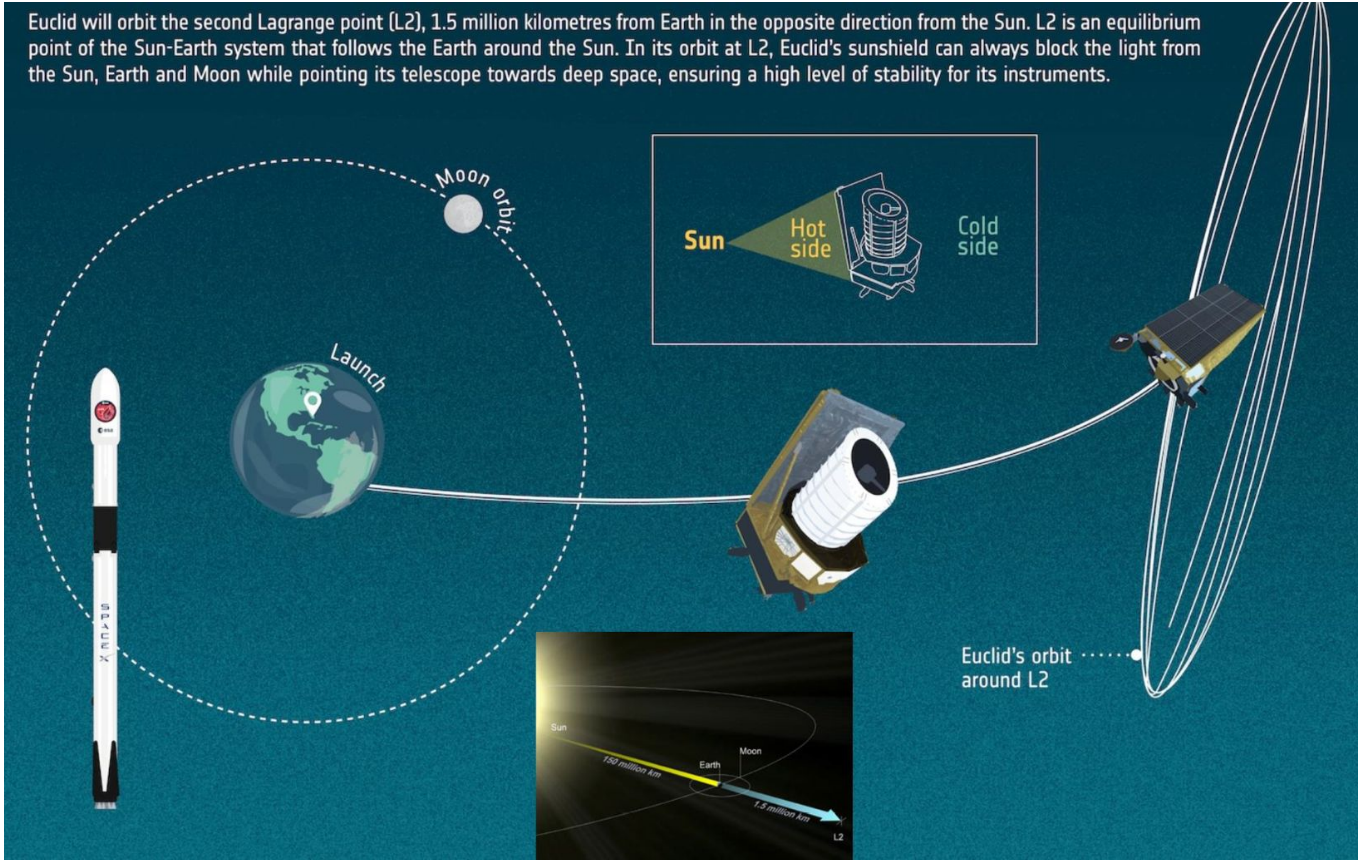
We combine **3** types of **2-pt correlations** to optimally **constrain cosmology from the photometric galaxy sample**

Launch

Euclid Launch

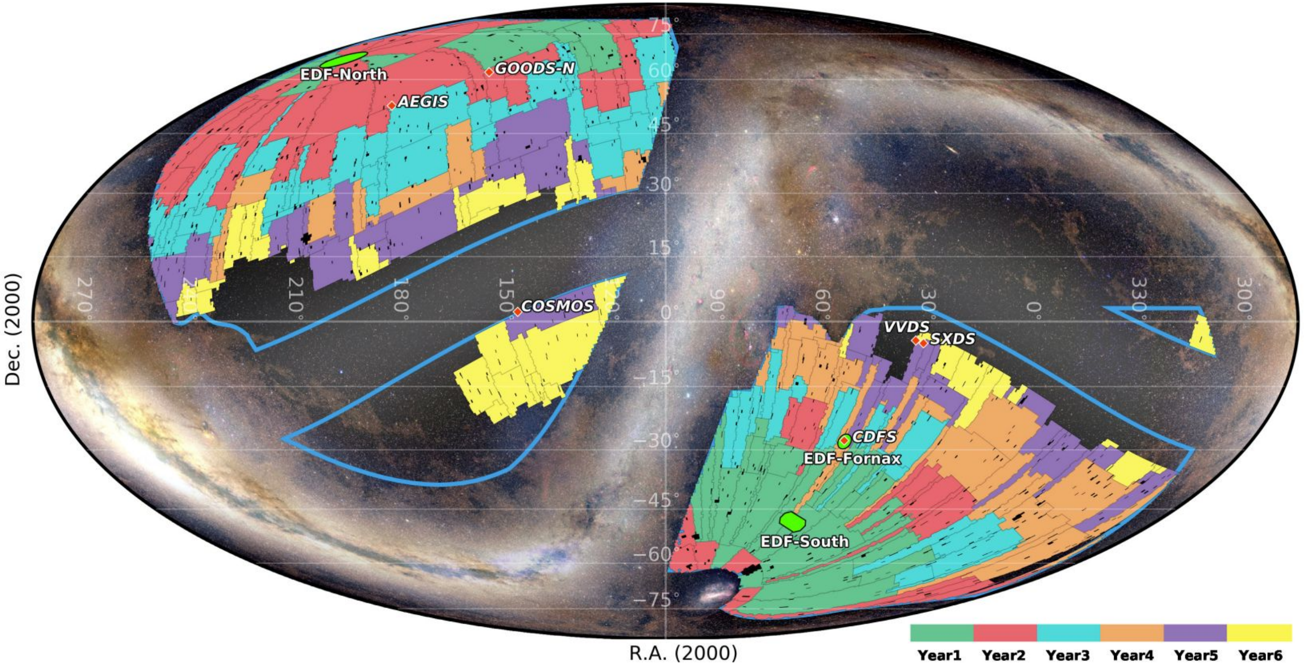
Euclid launched on a Falcon 9, SpaceX, on **1st July 2023**, from Cape Canaveral. Credit: ESA

Euclid Journey to L2



Survey

Euclid Wide Survey



Euclid Wide Survey

- 14000 deg^2
- 1.5B gal with photometric redshift and shape measurement (n_g = 30 gal/$arcmin^2$)
- 25M of galaxies with spectroscopic redshift

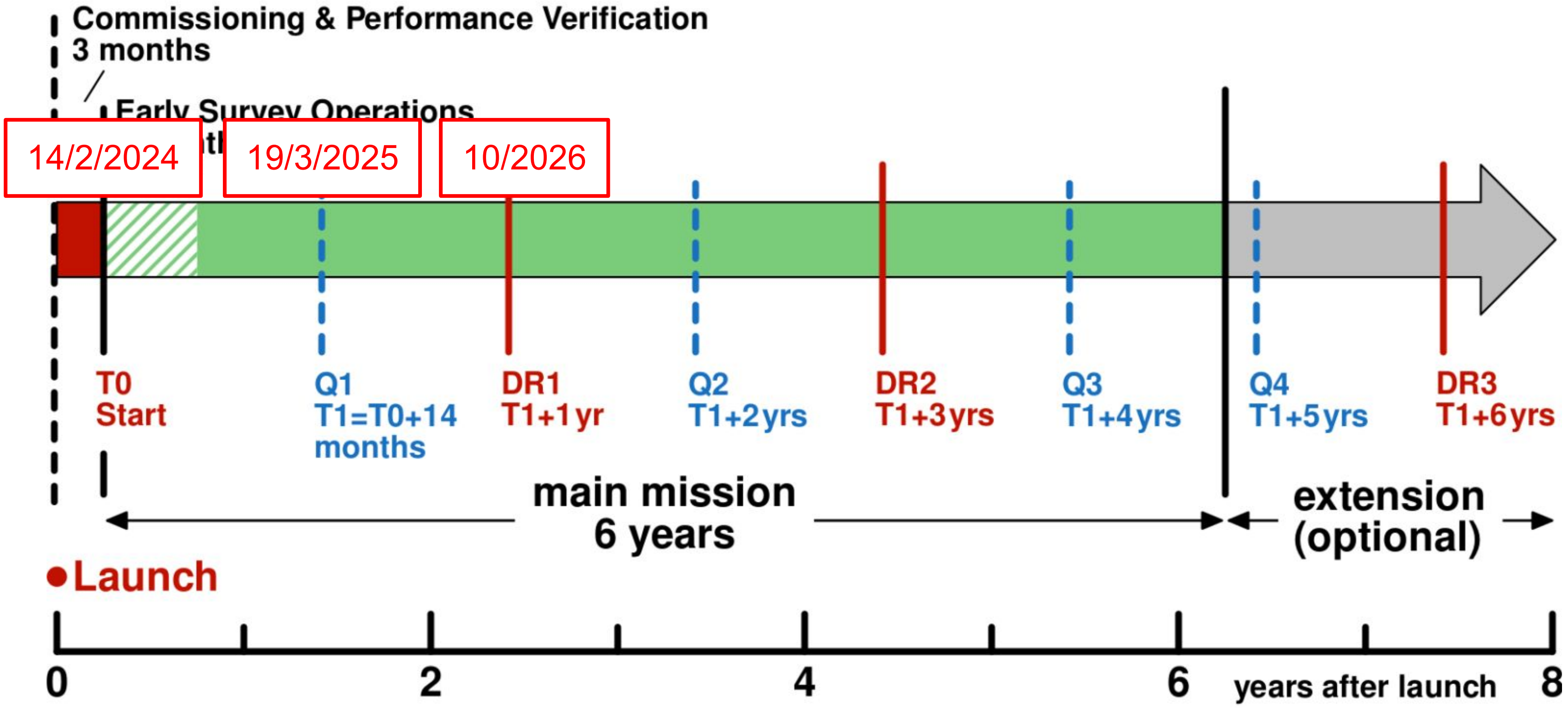
Euclid Deep Survey

- n_g = 50 gal/$arcmin^2$
- 3 fields
  - EDF-N: 23 deg^2
  - EDF-S: 28 deg^2
  - EDF-F: 12 deg^2

- Duration: 6 years survey
- Euclid will observe 10 deg^2/day of the Euclid Wide Survey
- 12% of Euclid time is spent on Euclid Deep Survey

Euclid collaboration: Scaramella et al. (2022)

Data Releases



Credit: ESA

Early Release Observations

Teaser images released in November 2023

More images released in May 2024, along with a set of Early Release Observations papers

List of Early Release Observation papers

- Euclid: ERO – Programme overview and pipeline for compact- and diffuse-emission photometry, *Cuillandre et al.*
- Euclid: ERO – A glance at free-floating new-born planets in the σ Orionis cluster, *Martin et al.*
- Euclid: ERO – Unveiling the morphology of two Milky Way globular clusters out to their periphery, *Massari et al.*
- Euclid: ERO – Deep anatomy of nearby galaxies, *Hunt et al.*
- Euclid: ERO – Globular clusters in the Fornax galaxy cluster, from dwarf galaxies to the intracluster field, *Saifollahi et al.*
- Euclid: ERO– Overview of the Perseus cluster and analysis of its luminosity & stellar mass functions, *Cuillandre et al.*
- Euclid: ERO – Dwarf galaxies in the Perseus galaxy cluster, *Marleau et al.*
- Euclid: ERO – The intracluster light and intracluster globular clusters of the Perseus cluster, *Kluge et al.*
- Euclid: ERO – A preview of the Euclid era through a magnifying lens, *Atek et al.*
- Euclid: ERO – NISP-only sources and the search for luminous z = 6 – 8 galaxies, *Weaver et al.*

https://www.cosmos.esa.int/web/euclid/ero-papers

Q1 Data Release

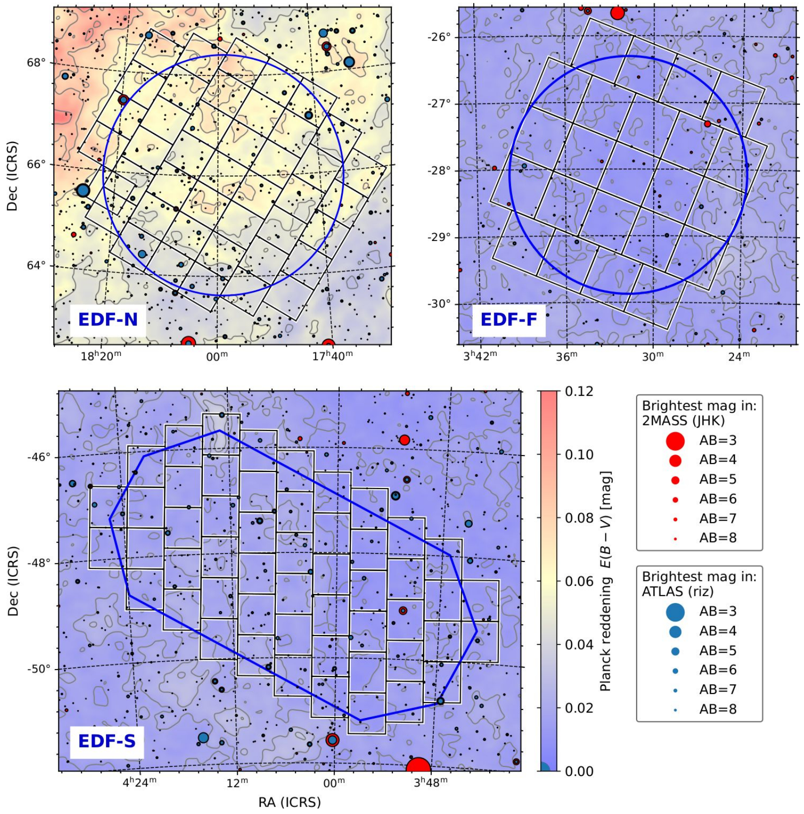
Euclid Quick data release 1

- 63.1 deg²

- Approximately 26 million detections

- The release primarily aimed at a variety of astrophysical studies, providing VIS and NISP images, NISP spectroscopy, external ground-based data, catalogues, and masks

- Overview of the content of the release in “Euclid Collaboration: Aussel+, 2025”



https://www.euclid-ec.org/science/q1/

Constraints on Initial Conditions

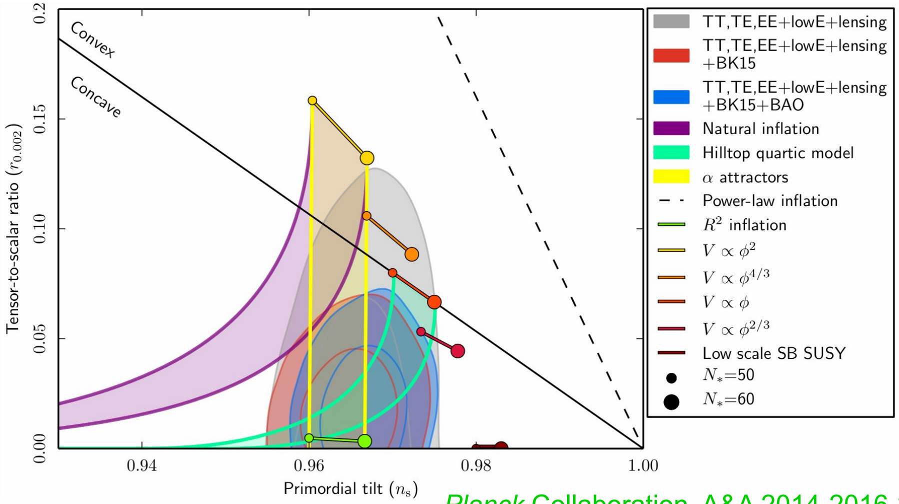
Primordial Power Spectrum

Single-field slow-roll inflation predicts an almost scale-invariant power spectrum:

$$\mathcal{P}_{\mathcal{R}}(k) \equiv \frac{k^3}{2\pi^2}|\mathcal{R}(k)|^2 = A_s\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$\ln(10^{10}A_s) = 3.044 \pm 0.014$$
$$n_s = 0.9649 \pm 0.0042$$

[68% CL, *Planck*]



Planck Collaboration, A&A 2014-2016-2020
Martin, Ringeval, Vennin, PDU 2014-2024

Primordial Gravitational Waves, not the perfect smoking gun:

1) Measuring such a tensor spectrum would not be enough to point to a specific inflationary models
2) Not measuring such a tensor spectrum would not rule out cosmic inflation

Primordial Power Spectrum

Single-field slow-roll inflation predicts an almost scale-invariant power spectrum:

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$$\ln(10^{10} A_s) = 3.044 \pm 0.014$$
$$n_s = 0.9649 \pm 0.0042$$

[68% CL, *Planck*]

Euclid Collaboration: Blanchard+, A&A 2020

All probe combination GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$									
Setting	$\Omega_{m,0}$	$\Omega_{b,0}$	$\Omega_{DE,0}$	w_0	w_a	h	n_s	σ_8	γ
ΛCDM flat									
Pessimistic	0.0067	0.025	–	–	–	0.0036	0.0049	0.0031	–
Optimistic	0.0025	0.011	–	–	–	0.0011	0.0015	0.0012	–
w_0, w_a flat									
Pessimistic	0.0110	0.035	–	0.036	0.15	0.0053	0.0053	0.0049	–
Optimistic	0.0060	0.015	–	0.025	0.091	0.0015	0.0019	0.0022	–

- The forecasted uncertainties correspond to 0.0051–0.0014
- Reduced by factors of 2 (1.3) and 2.7 (1.5) when combined with *Planck* or SO

Euclid Collaboration: Ilic+, A&A 2022

Primordial Power Spectrum

Single-field slow-roll inflation predicts an almost scale-invariant power spectrum:

$$\mathcal{P}_{\mathcal{R}}(k) \equiv \frac{k^3}{2\pi^2}|\mathcal{R}(k)|^2 = A_s \left(\frac{k}{k_*}\right)^{n_s-1}$$

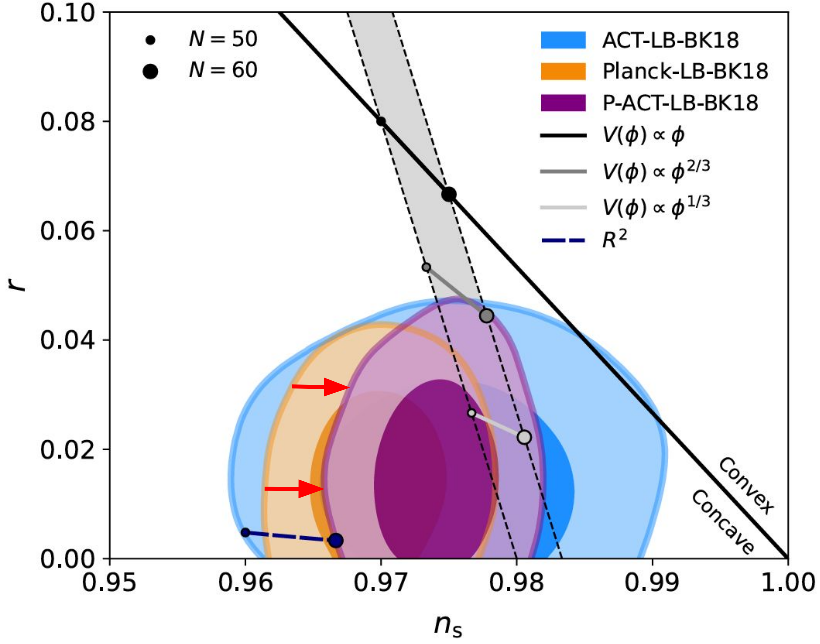
$$n_s = 0.9743 \pm 0.0034$$

[68% CL, *Planck*+ACT+DESI]

The results from *Planck* + BICEP/Keck, when combined with ACT and/or DESI BAO, suggest a larger value for the scalar spectral index

Ferreira+, 2025

ACT Collaboration, JCAP 2025

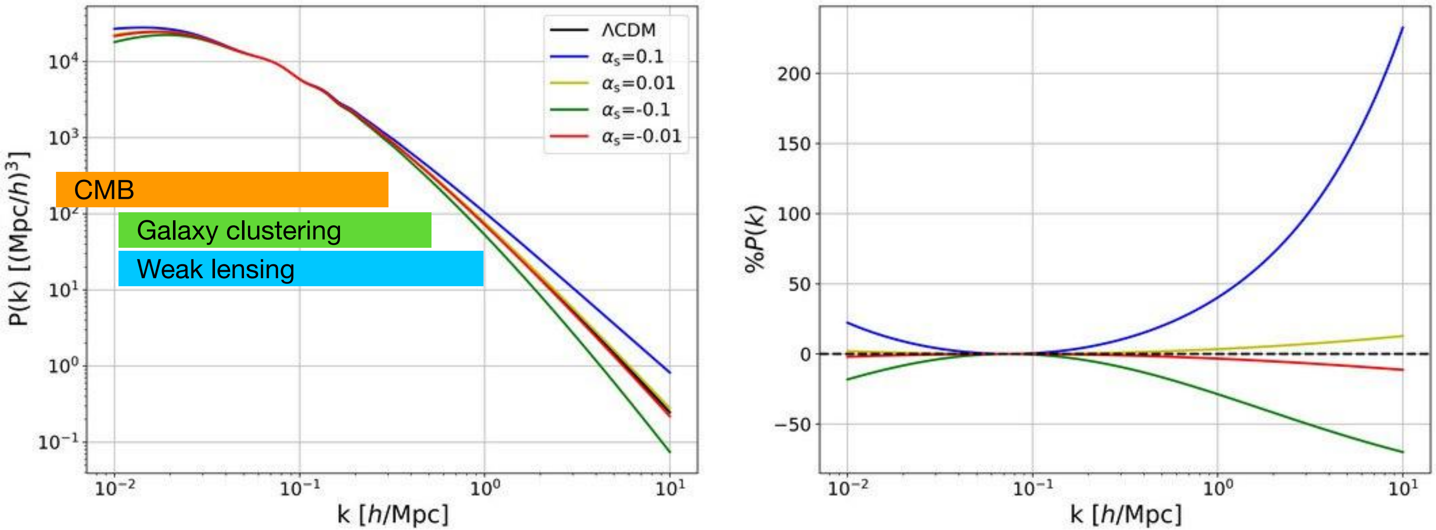


Primordial Power Spectrum - Running

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)}$$

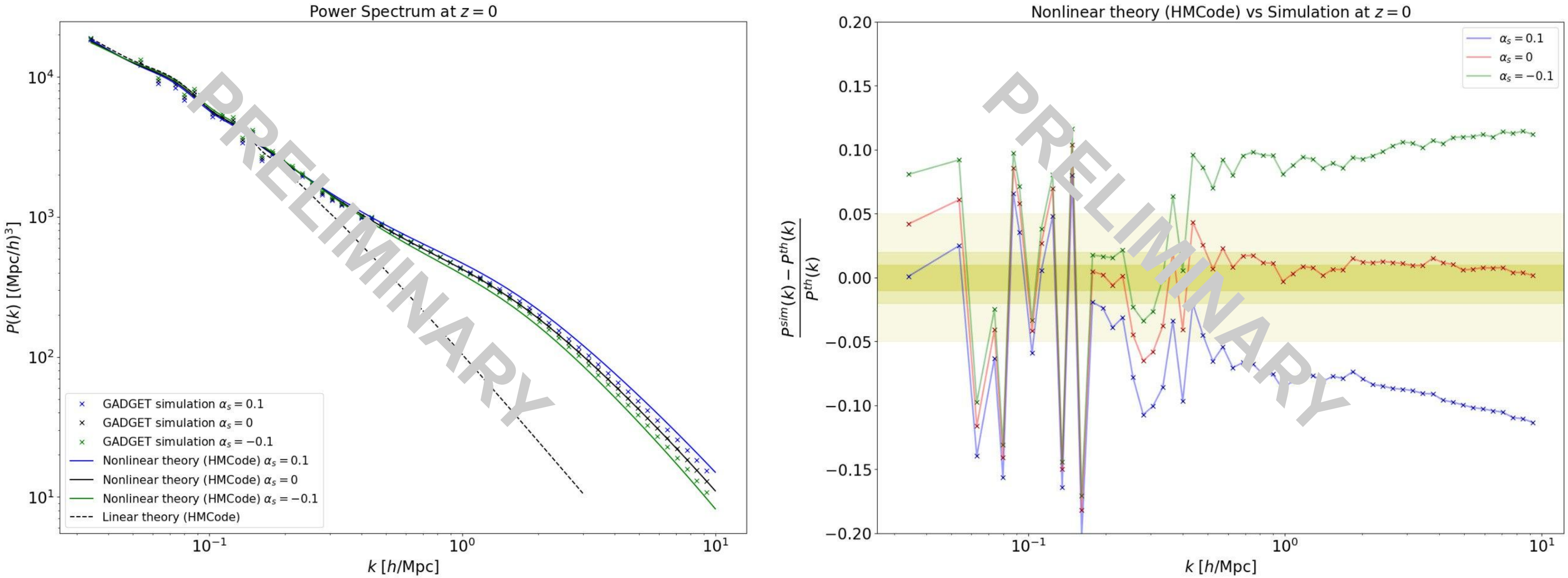
$$n_s = 0.9659 \pm 0.0040$$
$$dn_s/d\ln k = -0.0041 \pm 0.0067$$

[68% CL, *Planck*]



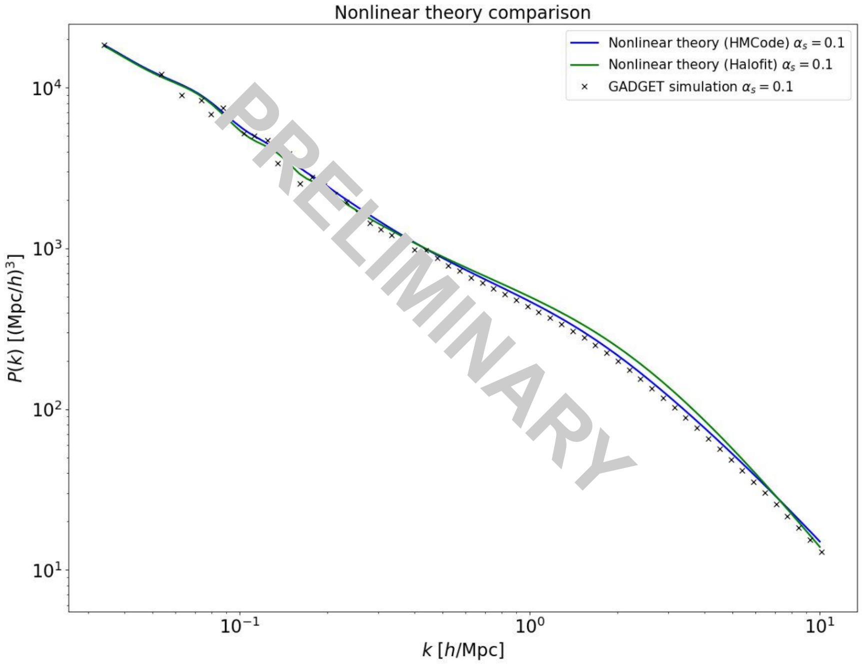
- Accurate predictions on nonlinear scales are essential for robust cosmological inference
- Small-scale effects (e.g., baryonic feedback, intrinsic alignments, …) must be consistently modeled and included

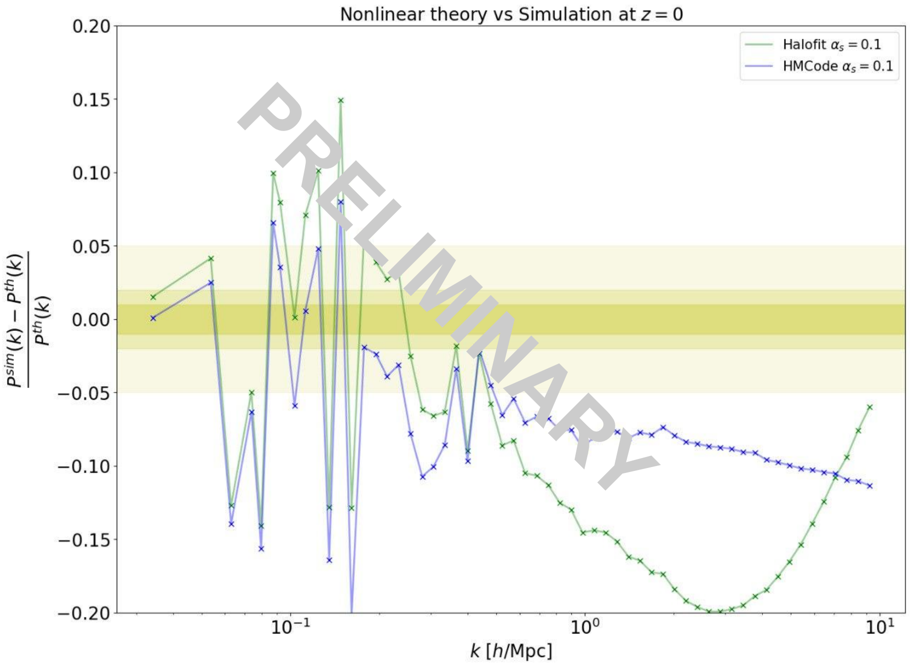
Primordial Power Spectrum - Running



Credit: Antonio Raffaelli

Primordial Power Spectrum - Running



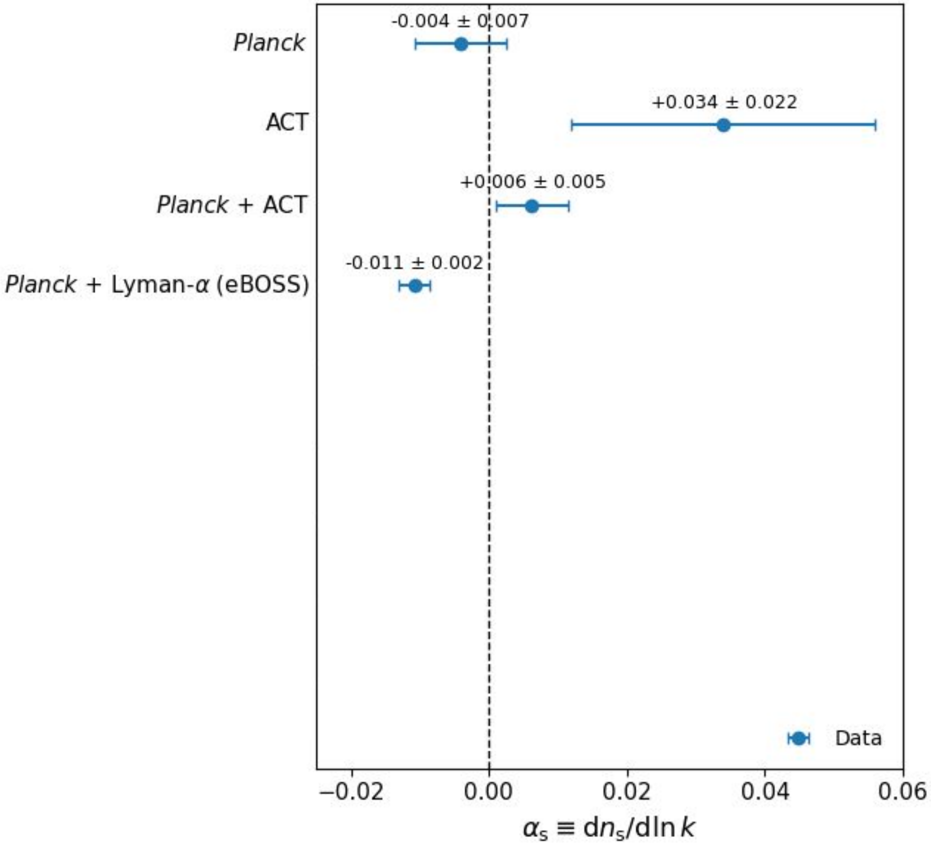


Credit: Antonio Raffaelli

Primordial Power Spectrum - Running

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)}$$

$$\alpha_s \simeq -\epsilon_2(2\epsilon_1 + \epsilon_3)$$



Primordial Power Spectrum - Running

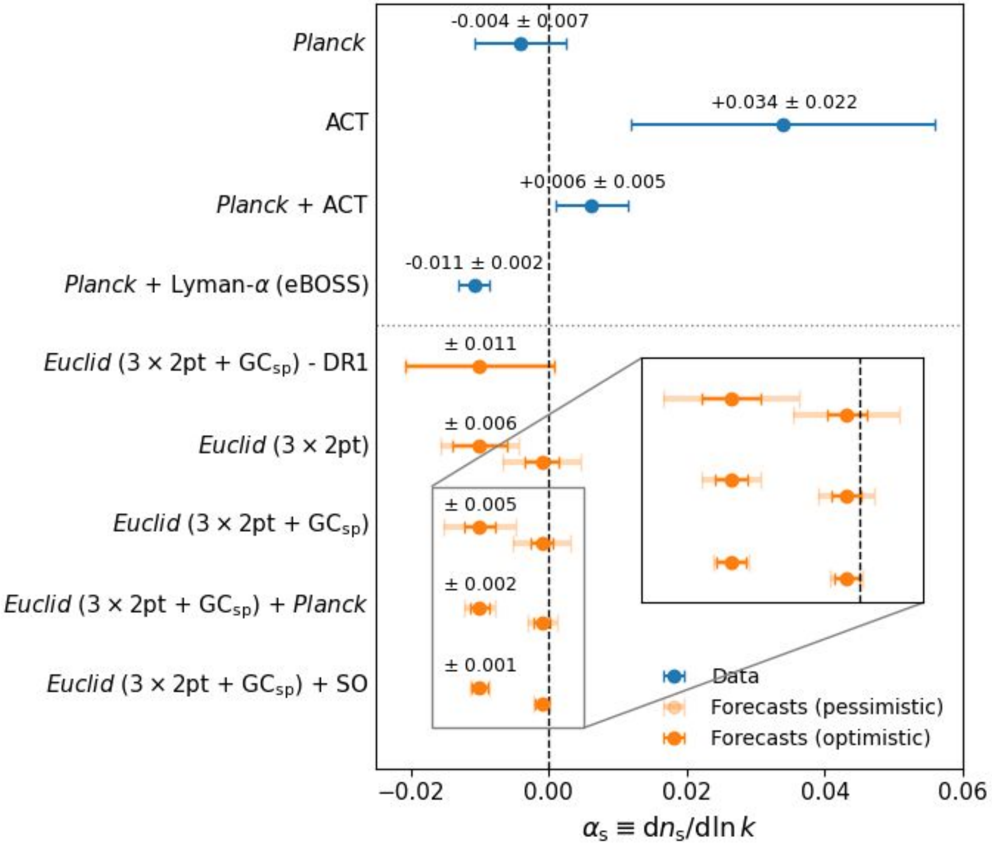
$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\frac{1}{2}\alpha_{\rm s}\ln(k/k_*)}$$

$$\alpha_{\rm s} \simeq -\epsilon_2(2\epsilon_1 + \epsilon_3)$$

Single-field slow-roll inflationary models (in agreement with cosmological data) have a precise prediction for the running of the scalar spectral index:

$$|\alpha_{\rm s}| \sim 10^{-4}\text{–}10^{-3}$$

Martin, Ringeval, Vennin, EPL 2024



Primordial Power Spectrum - Running

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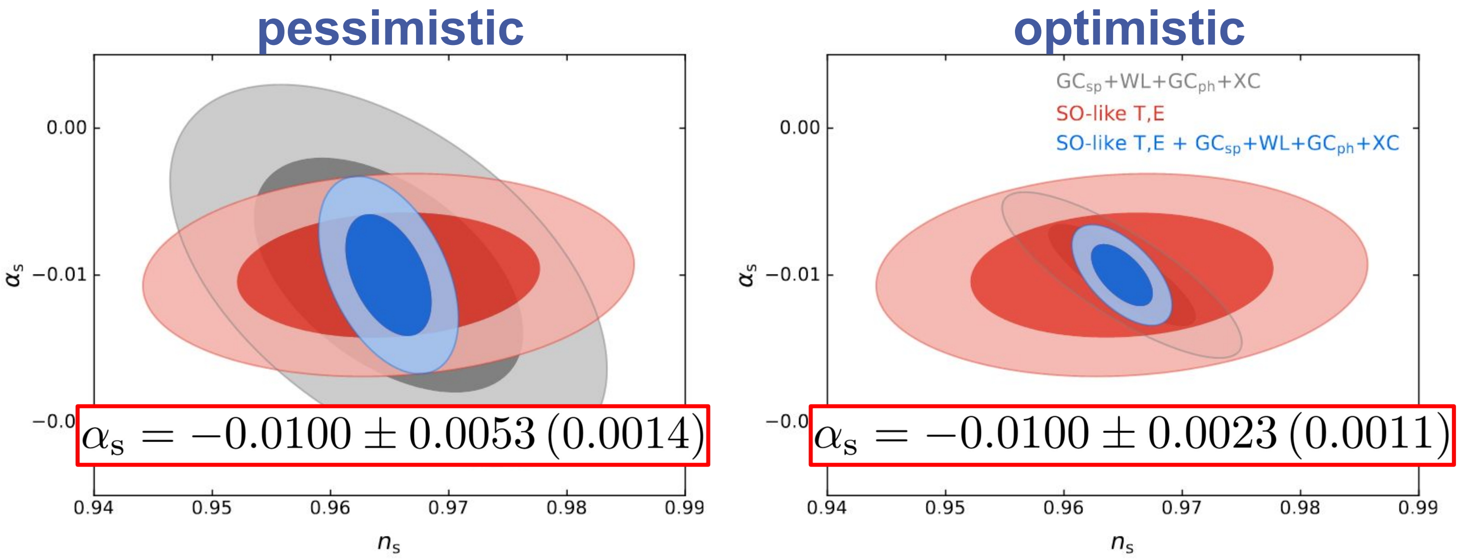
$$n_s = 0.9659 \pm 0.0040$$
$$\mathrm{d}n_s/\mathrm{d}\ln k = -0.0041 \pm 0.0067$$

[68% CL, *Planck*]



Pessimistic: $\alpha_s = -0.0100 \pm 0.0053\,(0.0014)$

Optimistic: $\alpha_s = -0.0100 \pm 0.0023\,(0.0011)$

Euclid Collaboration: Finelli+, 2025

Features in the Primordial Power Spectrum

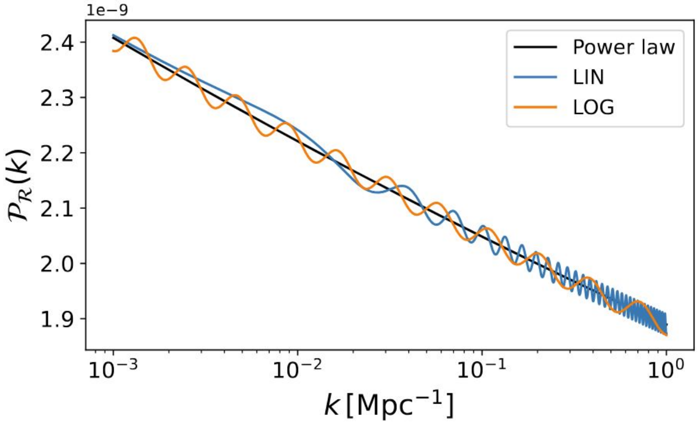
For a single clock:

- Excitations in time (changing equation-of-state during inflation at fixed time or speed of sound change) lead to linear oscillations (also known as sharp feature).
  Starobinsky, SJETPL 1992
  Adams, Cresswell, Easther, PRD 2001
  Chen, Easther, Lim, JCAP 2007
  Achucarro+, JCAP 2011

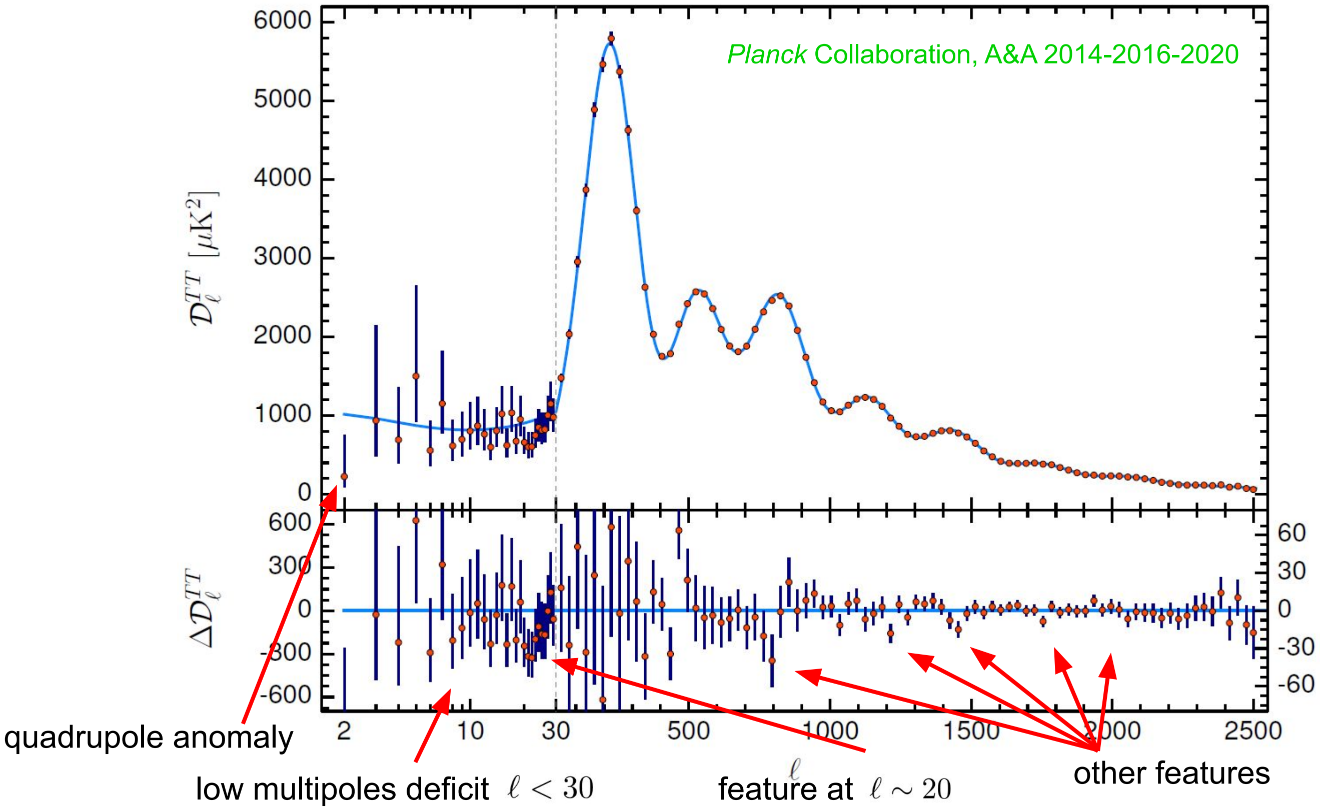
- Excitations in scale (oscillatory potential or initial state modifications at some fixed scale) lead to logarithmic oscillations (also known as resonant model).
  Chen, Easther, Lim, JCAP 2008
  Chen, JCAP 2012

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R},0}(k)\left[1 + \delta P^{\mathrm{X}}(k)\right]$$

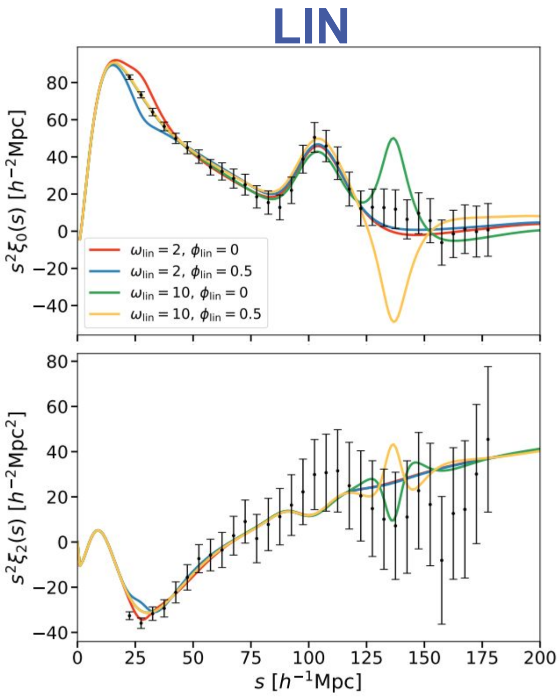
$$\boxed{\delta P^{\mathrm{X}}(k) = \mathcal{A}_{\mathrm{X}} \sin\left(\omega_{\mathrm{X}}\Xi_{\mathrm{X}} + 2\pi\phi_{\mathrm{X}}\right)}$$



Features in the CMB temperature APS



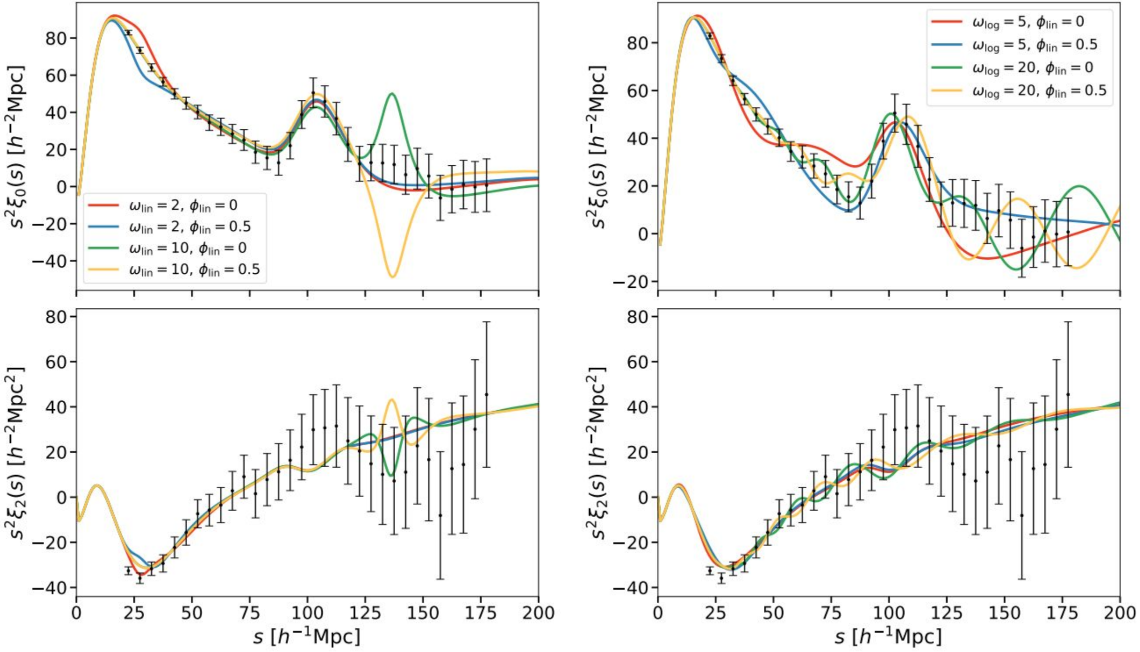
Features in the Primordial Power Spectrum



Ballardini+, PRD 2023

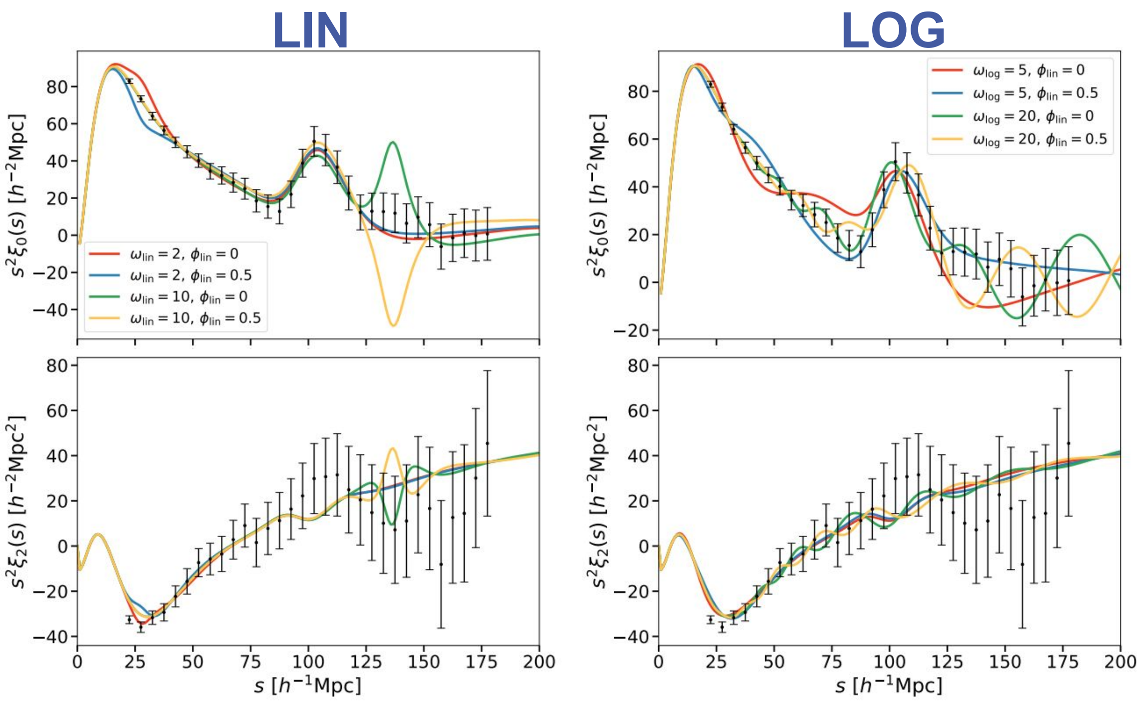
Features in the Primordial Power Spectrum

LIN **LOG**



Ballardini+, PRD 2023

Features in the Primordial Power Spectrum



First analysis of the BOSS galaxies and eBOSS quasars have been based on double template fitting (baryon oscillations and primordial oscillations) in Fourier space

Beutler+, PRR 2019
Mergulhão, Beutler, Peacock, JCAP 2023

and on the 2PCF

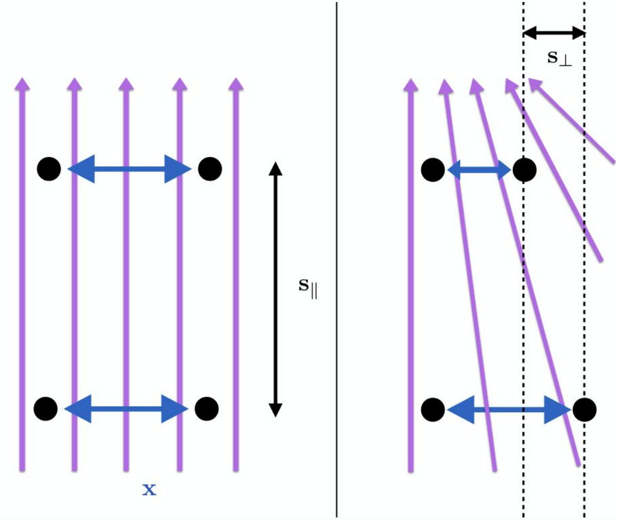
Ballardini+, PRD 2023

Nonlinear Damping of Wiggles

- Large-scale (IR) displacements generated by an approximately homogeneous bulk flow do not affect the 2PCF

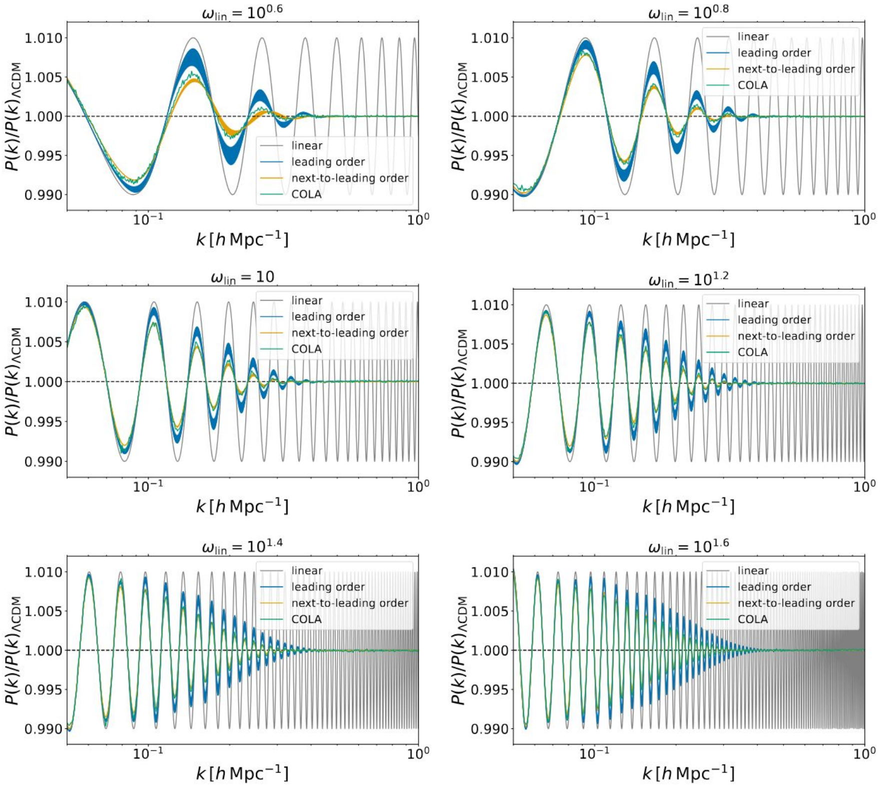
- If the flow is not perfectly homogeneous, the resulting relative displacements lead to a net suppression

- IR contributions can be systematically resummed at all orders, allowing one to capture the non-perturbative nature of the effect



Credit: Ivanov (2022)

Features in the Primordial Power Spectrum



Euclid Collaboration: Ballardini+, A&A 2023

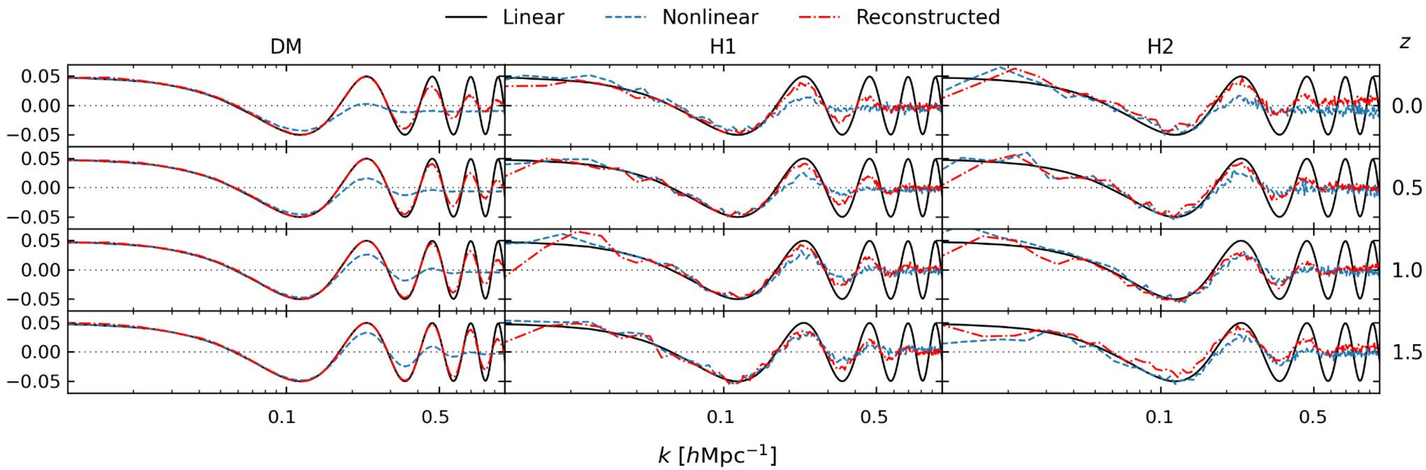
- The damping can be calculated in perturbation theory by IR resummation
  Blass+, JCAP 2016 I-II
  Vasudevan+, JCAP 2019
  Beutler+, PRR 2019
  Ballardini+, JCAP 2020
  Ballardini, Barbieri, JCAP 2025

- Differences ~ 1% (slightly larger for frequencies lower than the BAO one) at Leading Order and < 1% at Next-to-Leading Order

- First application where LSS constraints are already compatible if not better than the CMB Calderon+, 2025; Ballardini+ to appear

Nonlinear reconstruction

We have successfully tested the method on reconstructing some initial primordial features from the late-time DM and halo density fields:



Li, Zhu, Li, MNRAS 2022

Power spectrum and bispectrum combination

- Oscillatory primordial features also generate correlated signals in terms of non-Gaussianities and specific features appear also in the higher-order correlators. Indeed, primordial features can also be searched for in the bispectrum, or jointly in the power spectrum and bispectrum

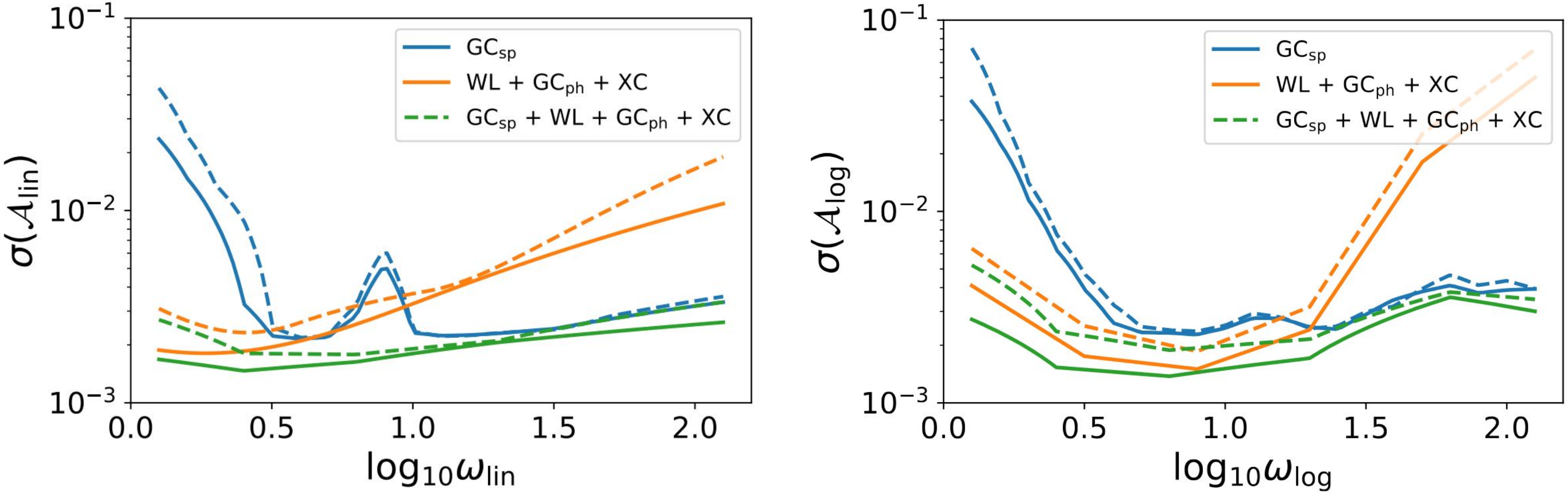
- The bispectrum will have preserved scaling argument (linear vs logarithmic)

$$B^{lin}(k_1, k_2, k_3) = f_{NL}^{lin} \frac{6A^2}{k_1^2 k_2^2 k_3^2} \sin\left[\omega_{\rm lin}^B \frac{K}{k_*} + 2\pi\phi_{\rm lin}^B\right]$$

$$B_\Phi^{log}(k_1, k_2, k_3) = f_{NL}^{log} \frac{6A^2}{k_1^2 k_2^2 k_3^2} \sin\left[\omega_{\rm log}^B \ln\left(\frac{K}{k_*}\right) + 2\pi\phi_{\rm log}^B\right]$$

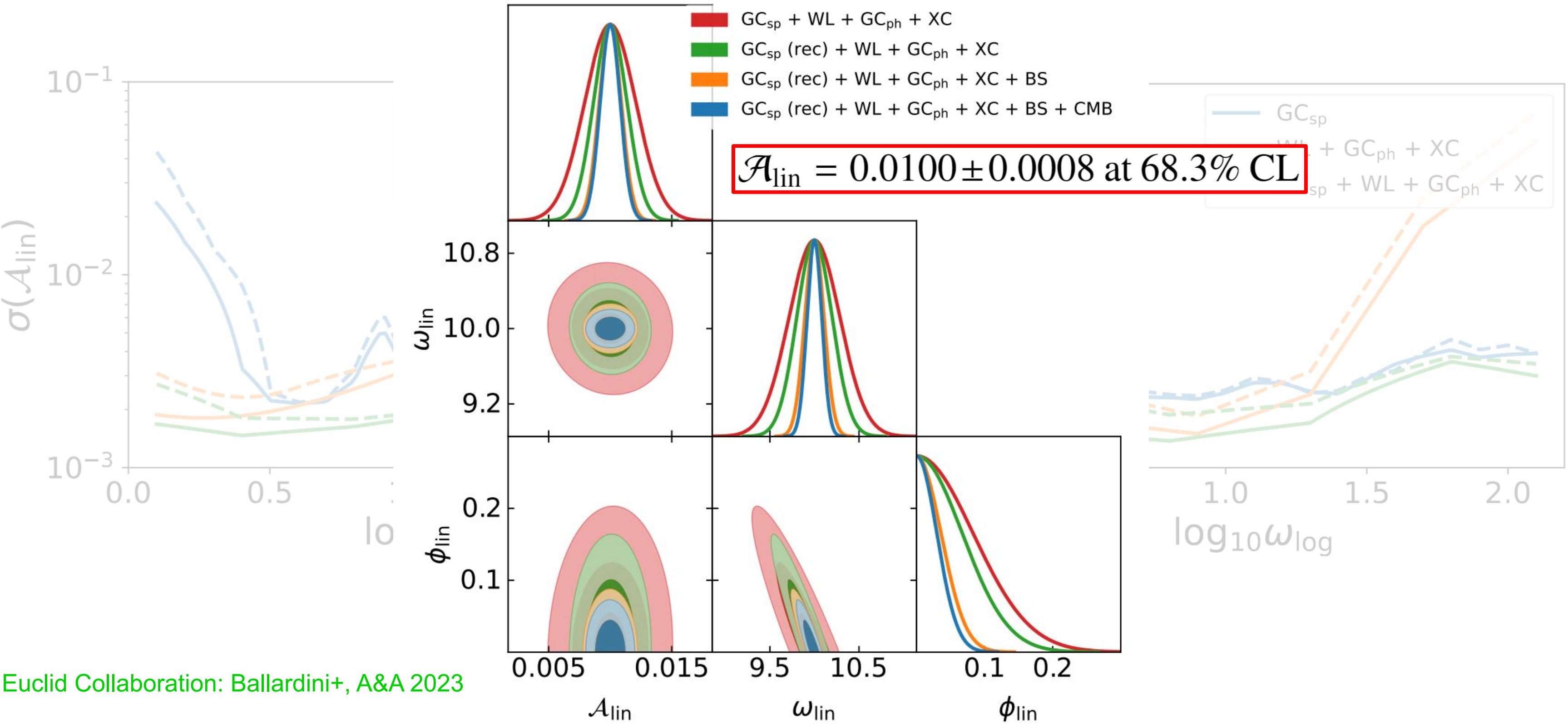
Chen, Easther, Lim, JCAP 2007
Bravo+, JCAP 2018
Karagiannis+, in preparation 2025

Forecasts for oscillatory features



Euclid Collaboration: Ballardini+, A&A 2023

Forecasts for linear features



Euclid Collaboration: Ballardini+, A&A 2023

Conclusions & outlook

Conclusions and outlook

Euclid launched on July 1st 2023, operates from L2, and is currently surveying 10 deg^2 per day

The goal is to map one third of the sky (14000 deg^2), first data release in october 2026 (1900 deg^2)

Euclid aims to unveil the nature of Dark Matter and Dark Energy by using weak gravitational lensing and galaxy clustering but will also be fundamental to improve our understanding on scalar initial conditions

A wide range of scientific cases will benefit from Euclid data: spatial curvature, the scalar spectral index and its runnings, isocurvature perturbations, primordial features, primordial non-Gaussianity, …

See: Euclid Collaboration: Ballardini+, A&A 2023, Euclid Collaboration: Andrews+, 2024, Euclid Collaboration: Finelli+, 2025

Euclid
consortium