Abell 2390, Euclid I_E, Y, H colour composite (*EC, Cuillandre et al 2024*)

Mapping large-scale structure with Euclid

Luigi Guzzo
Università degli Studi di Milano

on behalf of the Euclid Consortium

www.euclid-ec.org

Credits

All Euclid material shown here on behalf of (and approved by) the *Euclid Consortium* and ESA

For more information and proper credit to national space agencies and funding organisations: https://www.euclid-ec.org/

Pictures and movies: https://www.esa.int/Science_Exploration/Space_Science/Euclid

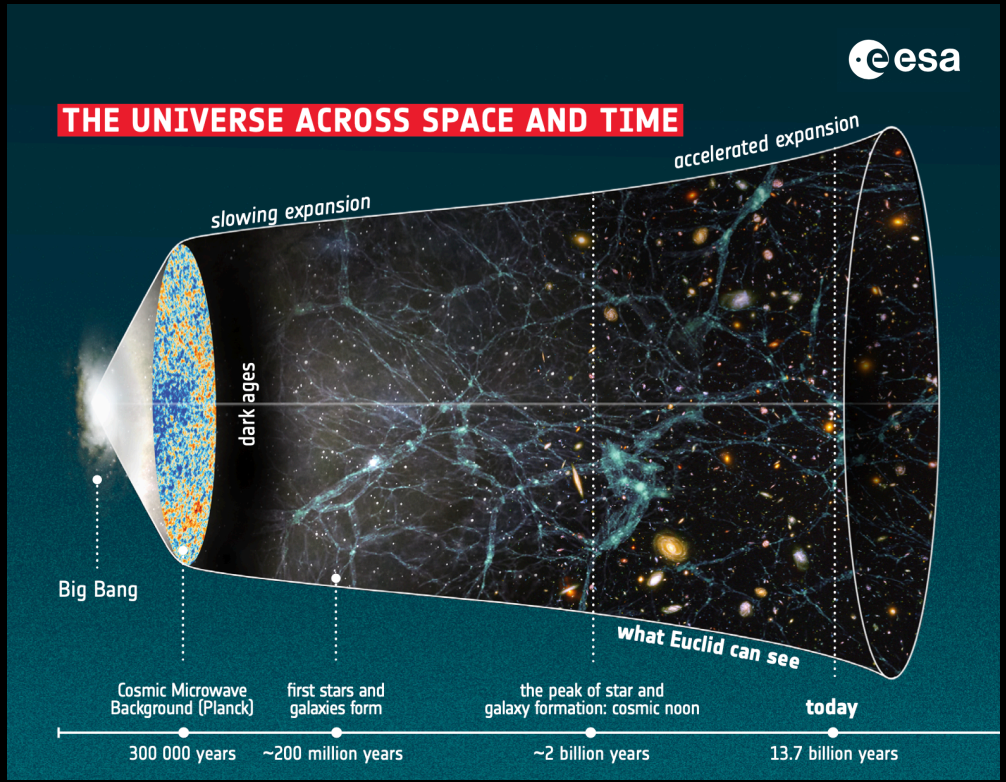
The standard model of cosmology: beautiful and puzzling

Mathematically simple

Physically hard to explain

Broad concordance

Emerging tensions?



Dark matter

- Where are the (cold) particles?

Dark energy

- Why Λ so small?
- Why Λ so fine-tuned?
- Evolving w(a)?

Neutrinos

- Mass?
- Hierarchy?

Primordial fluctuations

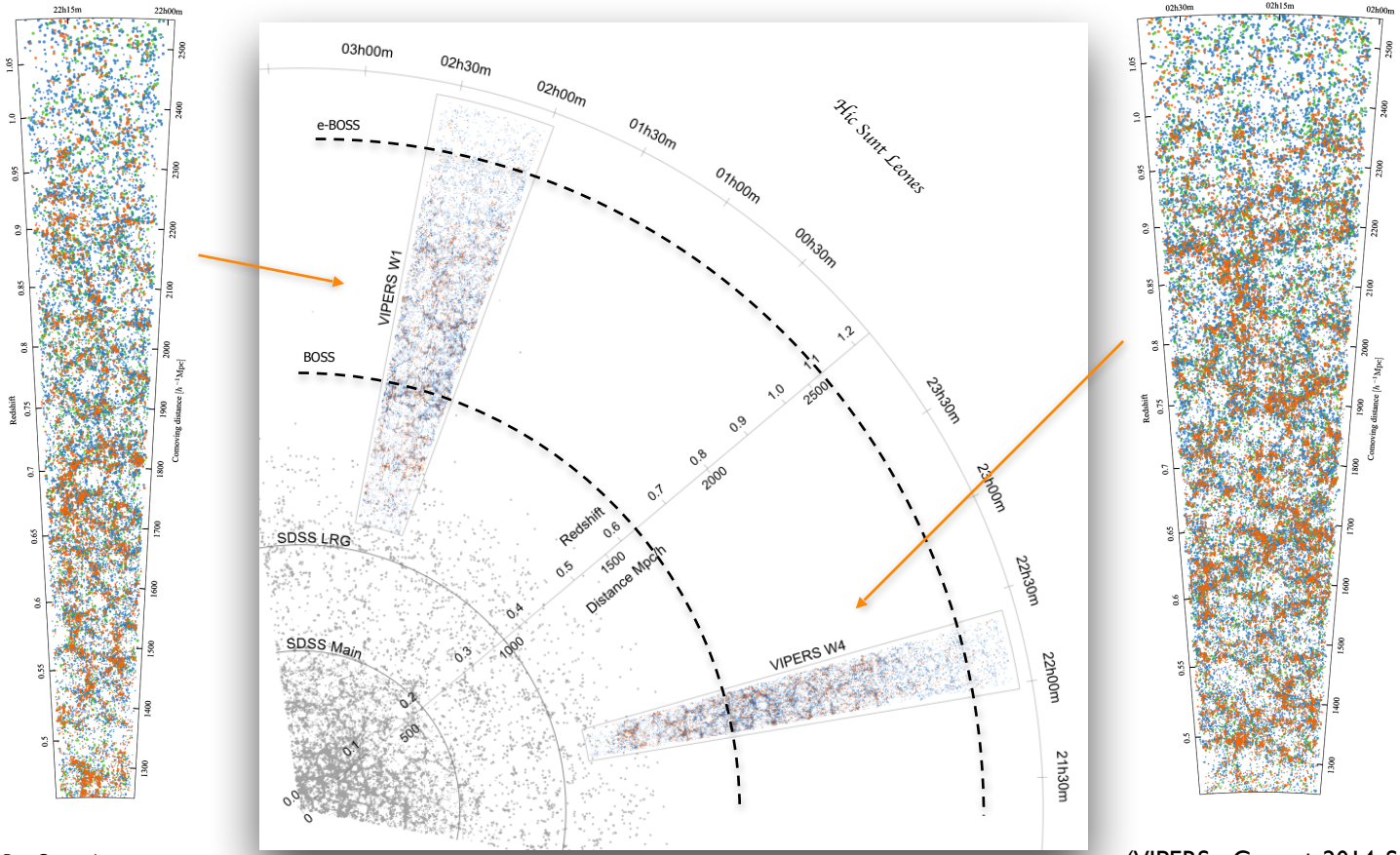
- What drove inflation?

Hubble rate / growth anomalies

- New physics or experimental systematics?

→ **All these can be measured from galaxy surveys**

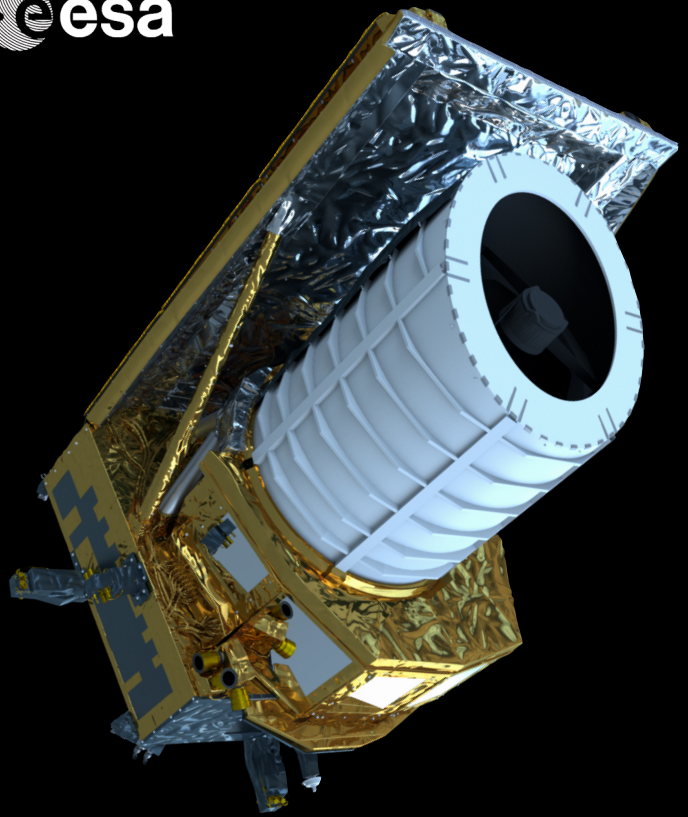
Galaxy redshift surveys: a pillar of the standard model of cosmology



(Artwork by Ben Granett)

(VIPERS - Guzzo+ 2014; Scodeggio+ 2017)

Euclid: the cartographer of the dark Universe

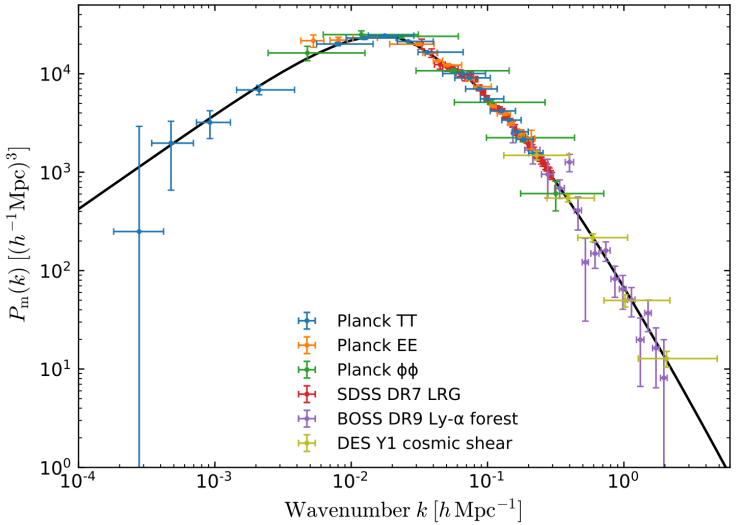


ESA Cosmic Vision 2007 medium-class mission program: two original proposals, SPACE (spectroscopy, Cimatti et al.) & DUNE (imaging, Refregier et al.)

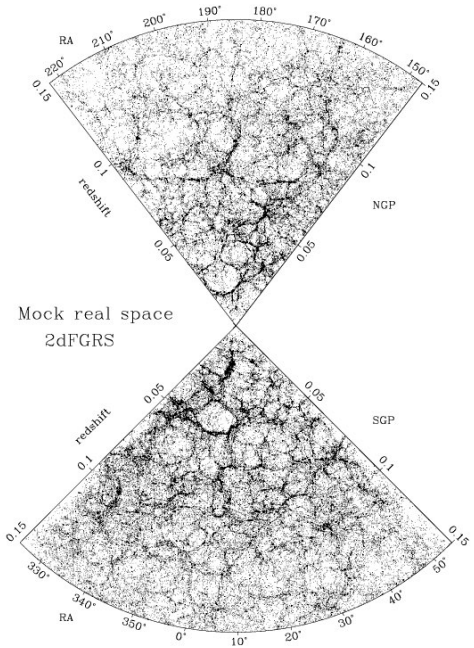
Both accepted and merged into **Euclid:** simultaneously map the visible and dark matter distribution over one-third of the sky, using galaxy redshifts and weak gravitational lensing

Euclid Consortium (EC) founded, to build 2 instruments and carry out the science program, through extra support from the national agencies. Led by Y. Mellier

Euclid galaxy clustering probe



- **The power spectrum of density fluctuations**
- **Baryon acoustic oscillations (BAO)** provide a cosmic standard ruler
- Measure the **expansion history** *H(z)* and angular diameter distance relation $d_A(z)$

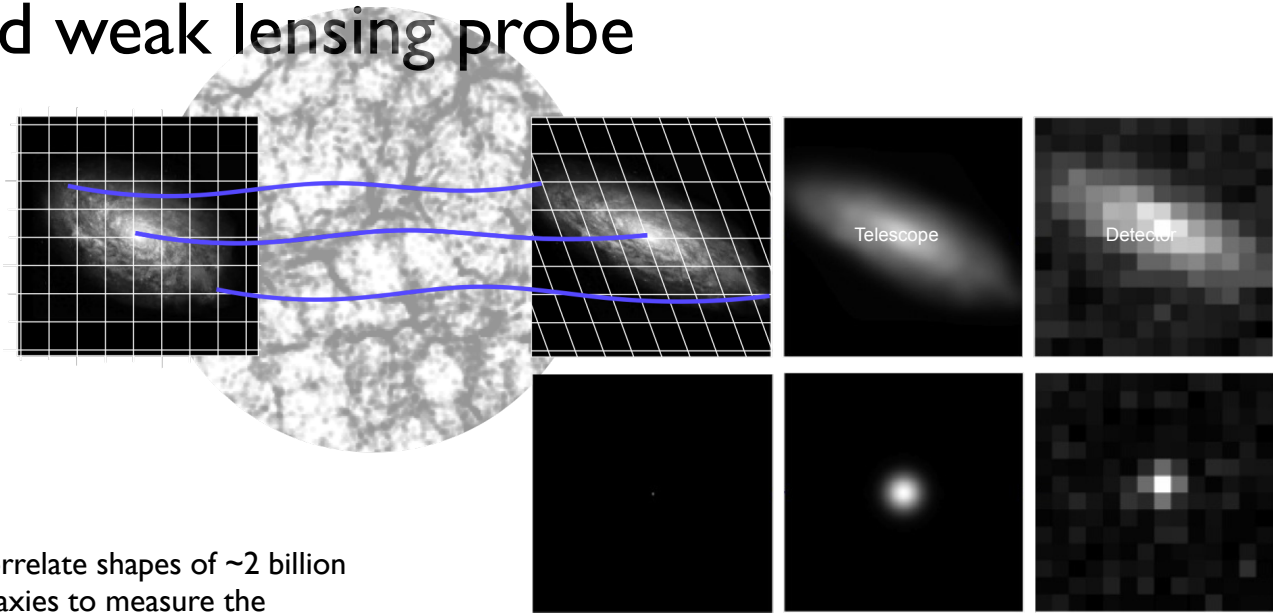


★ **Redshift-space distortions (RSD)** measure the **growth rate** of structure *f(z)*

★ Test "beyond Einstein" scenario, as alternative to L

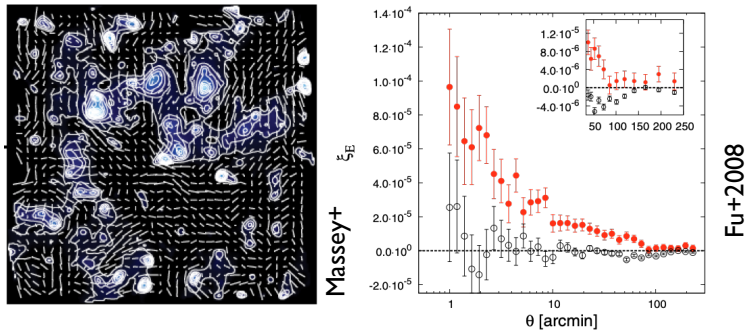
★ A key original feature in the SPACE/Euclid proposal (LG+ 2008, Nature, 451, 541)

Euclid weak lensing probe

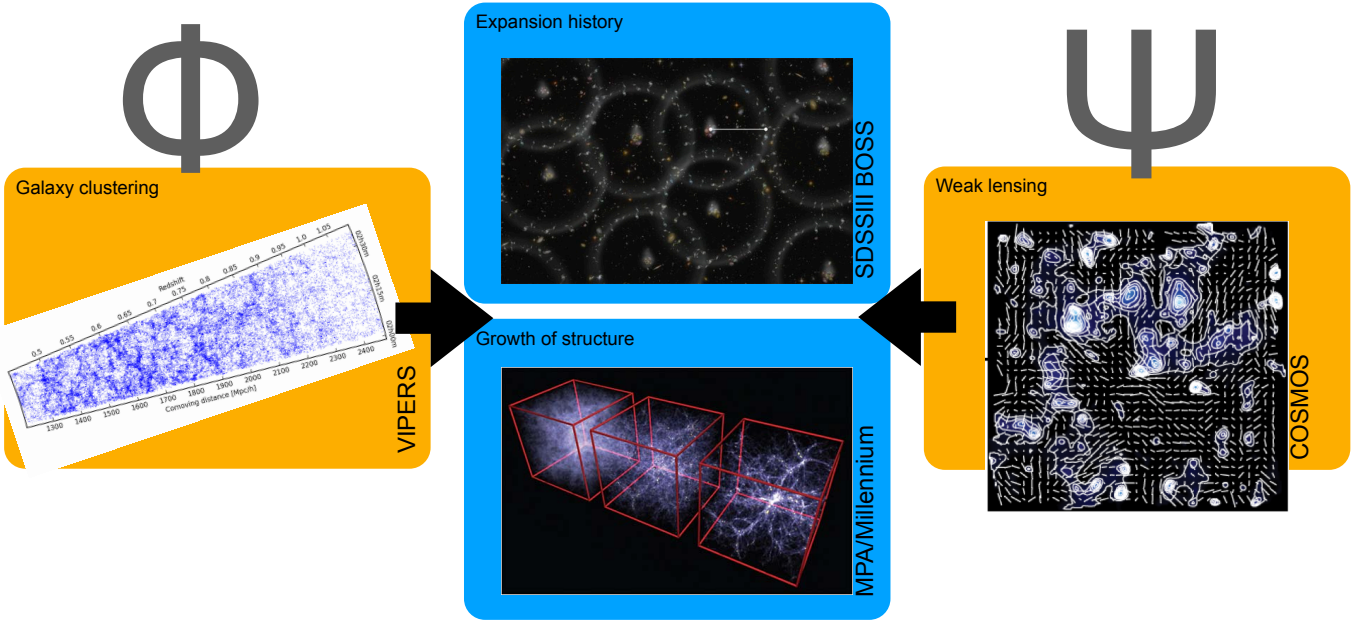


Light propagation through large-scale structure results in a lensed image

- ★ Correlate shapes of ~2 billion galaxies to measure the cosmological signal at 10^{-3} in ellipticity
- ★ **Measure clustering in the full mass distribution**
- ★ **Trace combined growth and expansion histories**



Euclid: unveiling gravity and dark energy



…and also…

- Clusters
- CMB cross-correlations
- Strong lensing
- Galaxy evolution

and much more…

(artwork by Ben Granett)

The Euclid Consortium

More than 2700 registered scientists,
EC Lead: Y. Mellier

15 European countries + USA + Canada + Japan

Responsible for the two Euclid instruments and the reduction and analysis of the data (Science Ground Segment)

The Euclid Consortium

Euclid Consortium meeting in Rome, June 2024

Spacecraft

- Satellite: Thales-Alenia Space
- Payload (telescope): Airbus Defence and Space

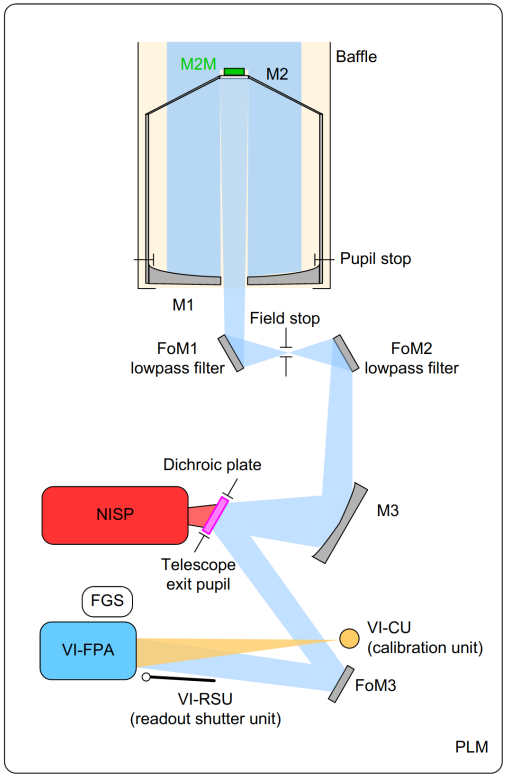
- Launch mass: 1988 kg
- Propellant: 137 kg hydrazine, lasting 14 years
- Data downlink: 4h / day, 820 Gbit

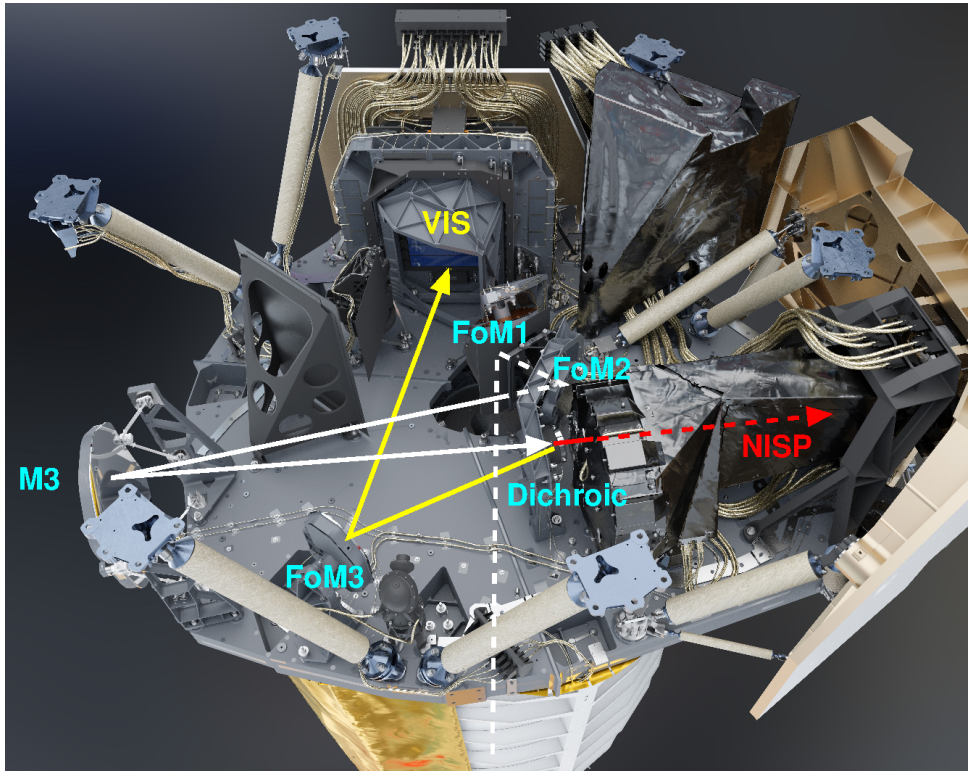
- 1.2m Korsch telescope in off-axis configuration
- Field of view 0.7 x 0.7 degrees

- Simultaneous observations (dichroic beam splitter)
- **VIS** (optical imaging)
- **NISP** (NIR imaging and slitless spectroscopy)

Euclid in Cannes / France, February 2023
Credit: ESA / M. Pedoussaut

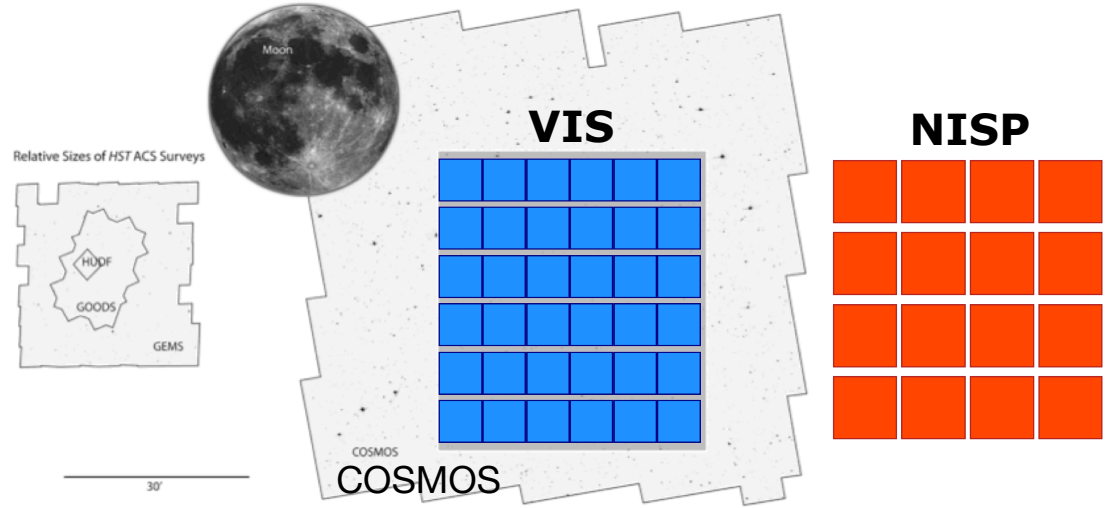
Euclid payload: two instruments for two probes



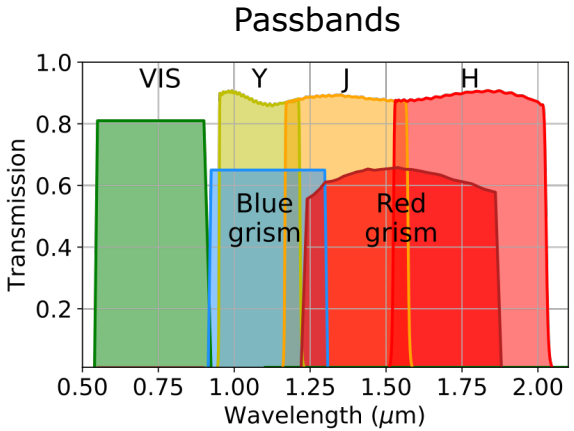


Credit: Airbus Defence and Space

Twin wide-field imagers & NIR spectrograph

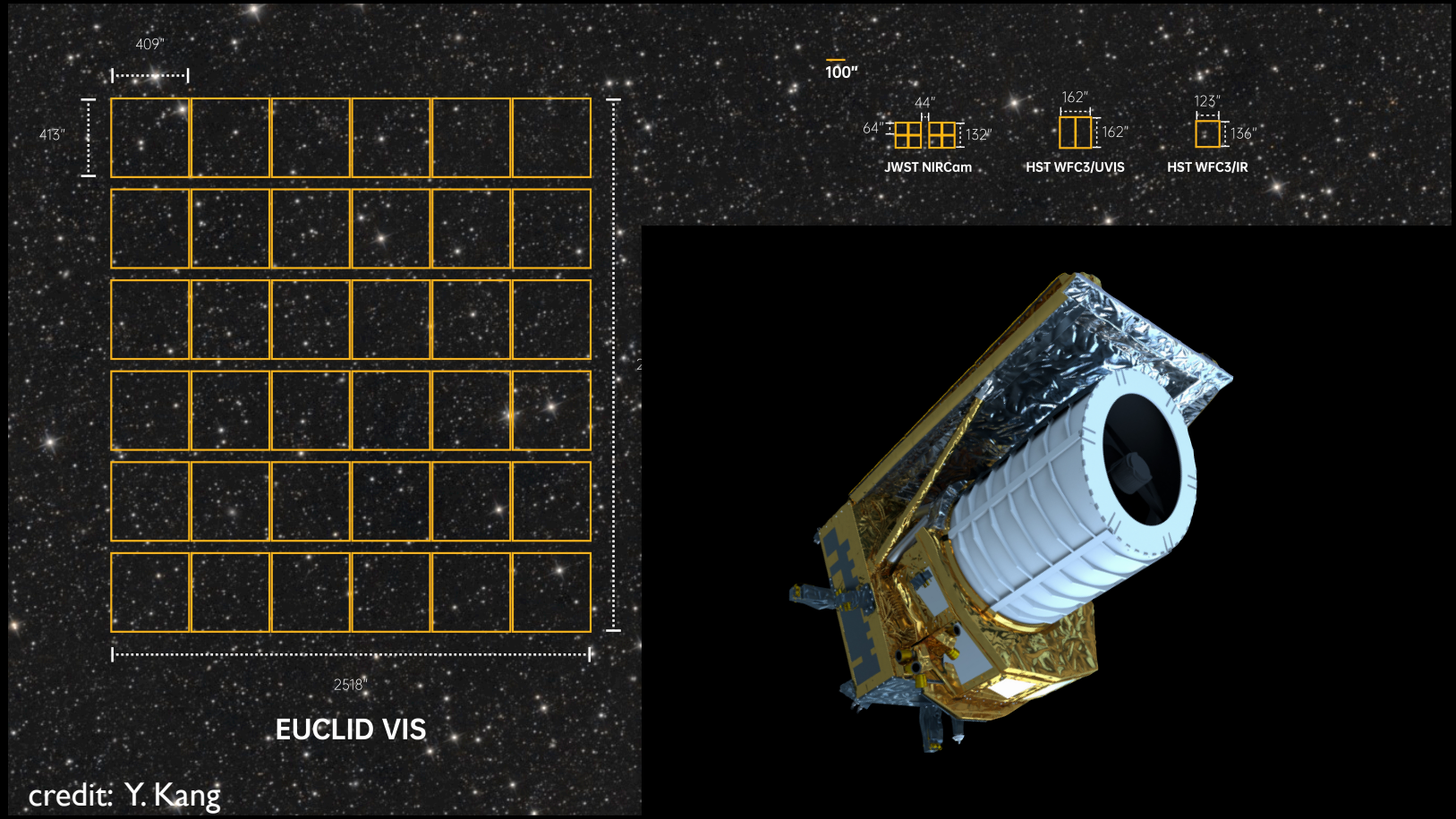


Credit: Space Telescope Science Institute/Nick Scoville (Caltech)



→ **Euclid is the first panoramic space telescope ever: 10 deg² / day in the Wide survey**

Euclid is a unique panoramic telescope

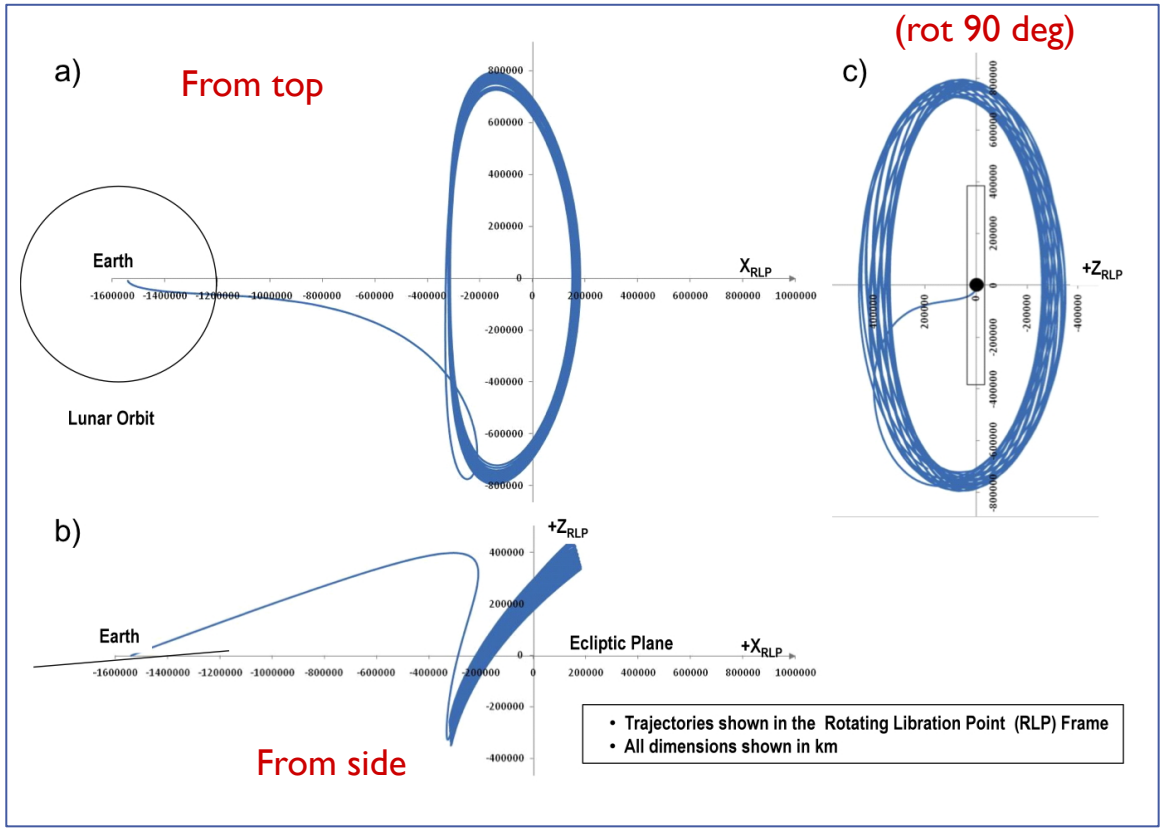


Euclid launch: 1st July 2023

Euclid launched on a Falcon 9 on 1st July 2023, from Cape Canaveral. (Credits: ESA, NASA & Space-X)

L2 halo orbit (exemplified using JWST)

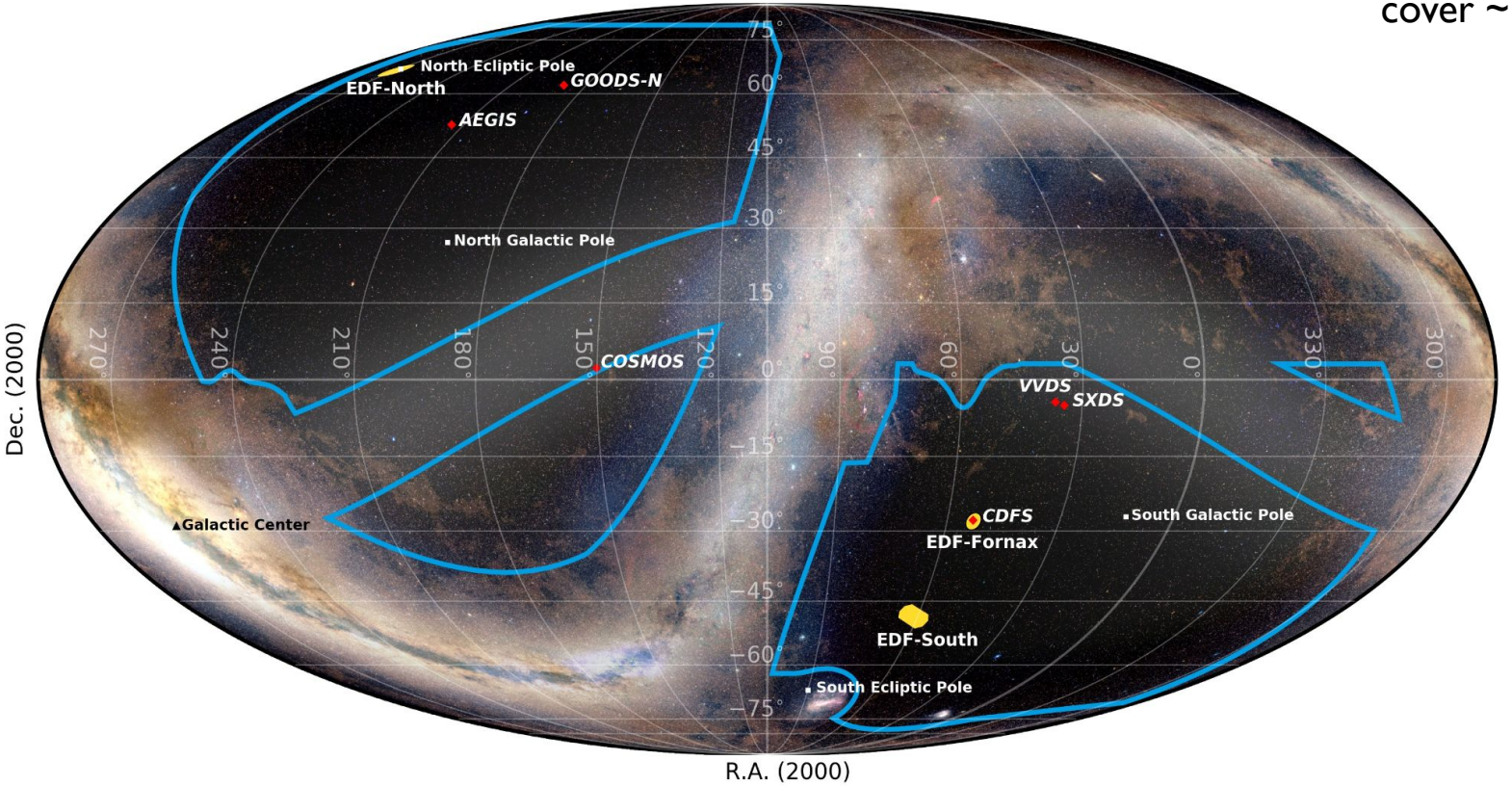
- *R*~1,000,000 km
- Periodic, 180 days
- Sun-Earth angle as seen from Euclid: 35°
- Eclipse-free (no lunar shadow passages)
- Thermally stable



Credit: STScI

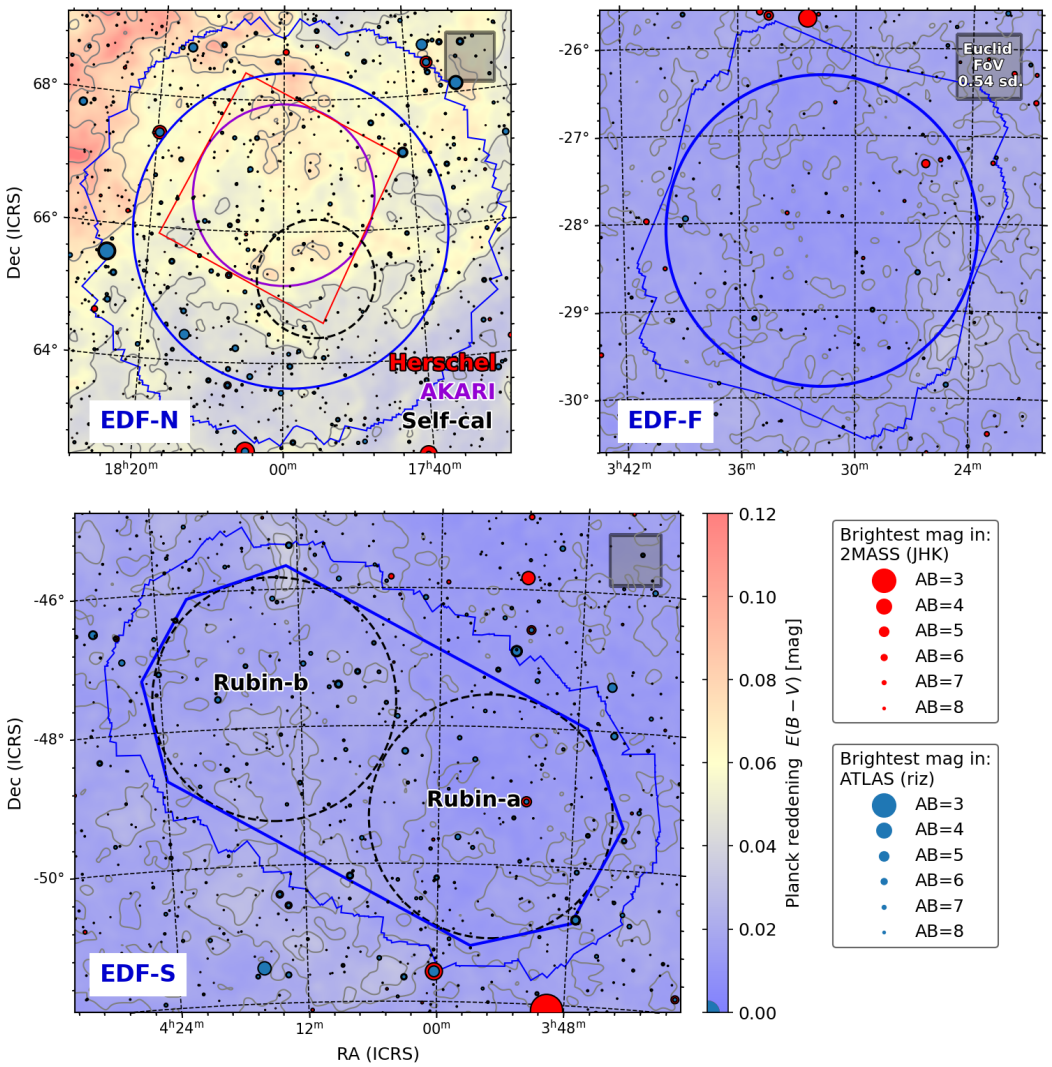
Euclid Wide Survey

Wide Survey will cover ~14,000 deg^2



- Blue: 16 000 deg^2 Region of Interest, containing the Wide Survey.
- Yellow: Euclid Deep Fields
- Red: auxiliary fields (not to scale).

Euclid Deep Survey



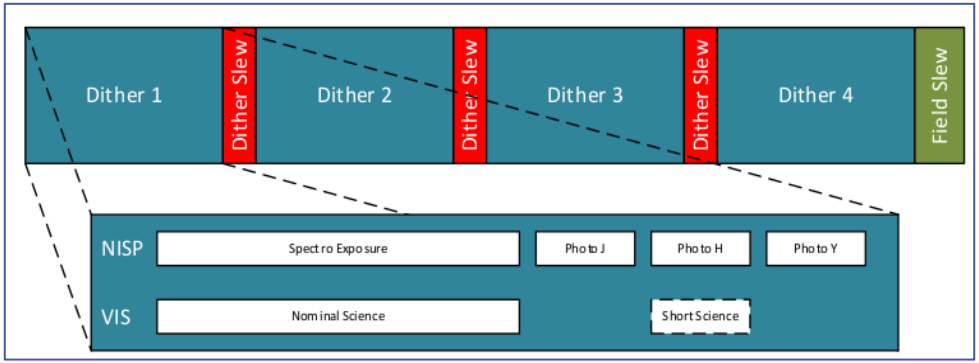
- 3 fields: EDF-North, -South, -Fornax (CDFS)
- Total area: 63 deg^2
- 5x the depth (signal-to-noise ratio) of wide survey
- Continuous visits over 6 years
- Includes blue grism observations

Reference Observing Sequence (ROS)

Used for the Wide and Deep surveys.

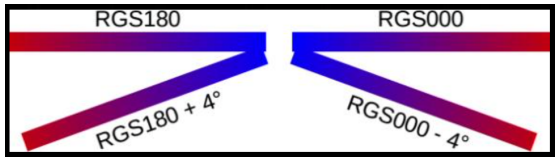
Parallel VIS and NISP exposures; inline calibrations

Each survey field observed with 1 ROS,
4 dither positions:

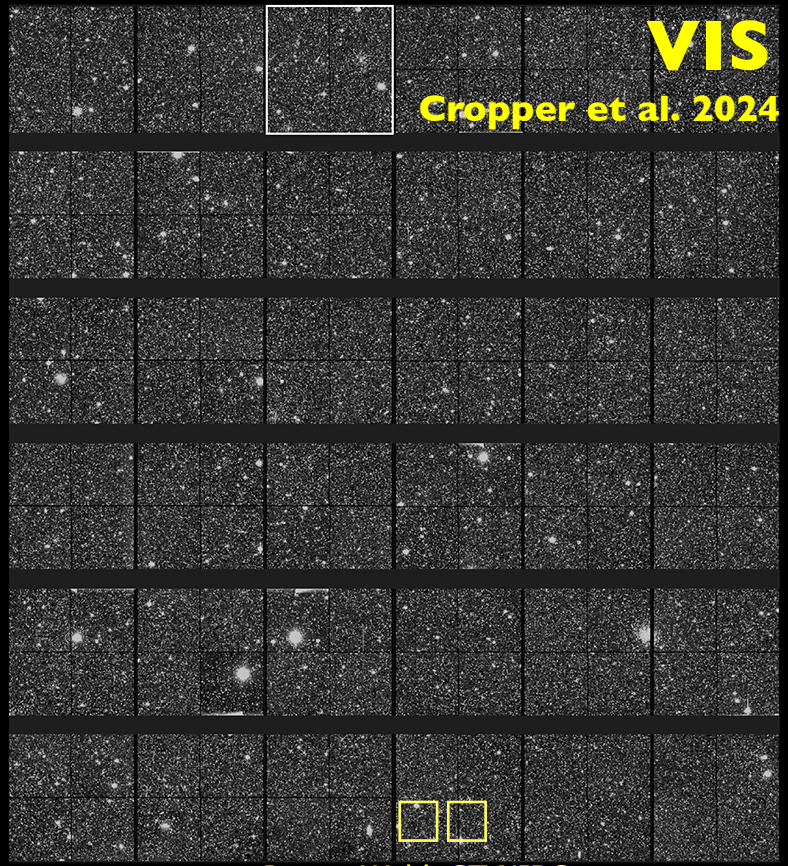


VIS	
4 I_E-band nominal exposures	566 s each
2 I_E-band short exposures	95 s each
Bias	2 per day
Dark	4 per day
Flat	6 per day
Trap pumping	6 per day
Charge injection	8 per day
NISP	
4 red-grism spectro exposures	574 s each
4 Y_E-band exposures	112 s each
4 J_E-band exposures	112 s each
4 H_E-band exposures	112 s each
1 Dark	112 s

Dispersion orientation
in each dither

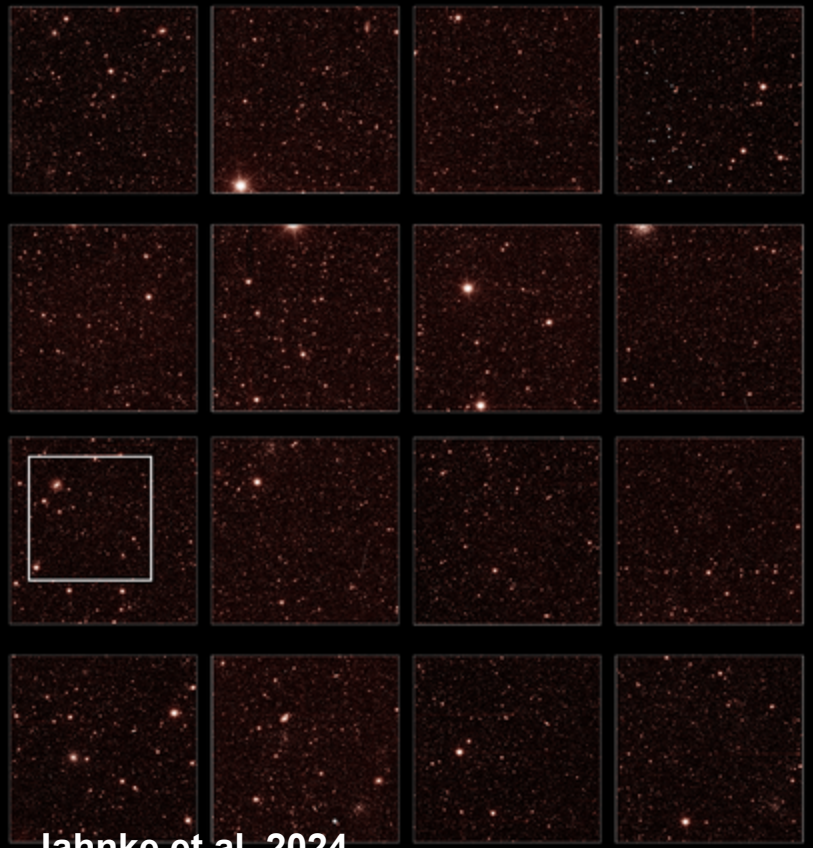


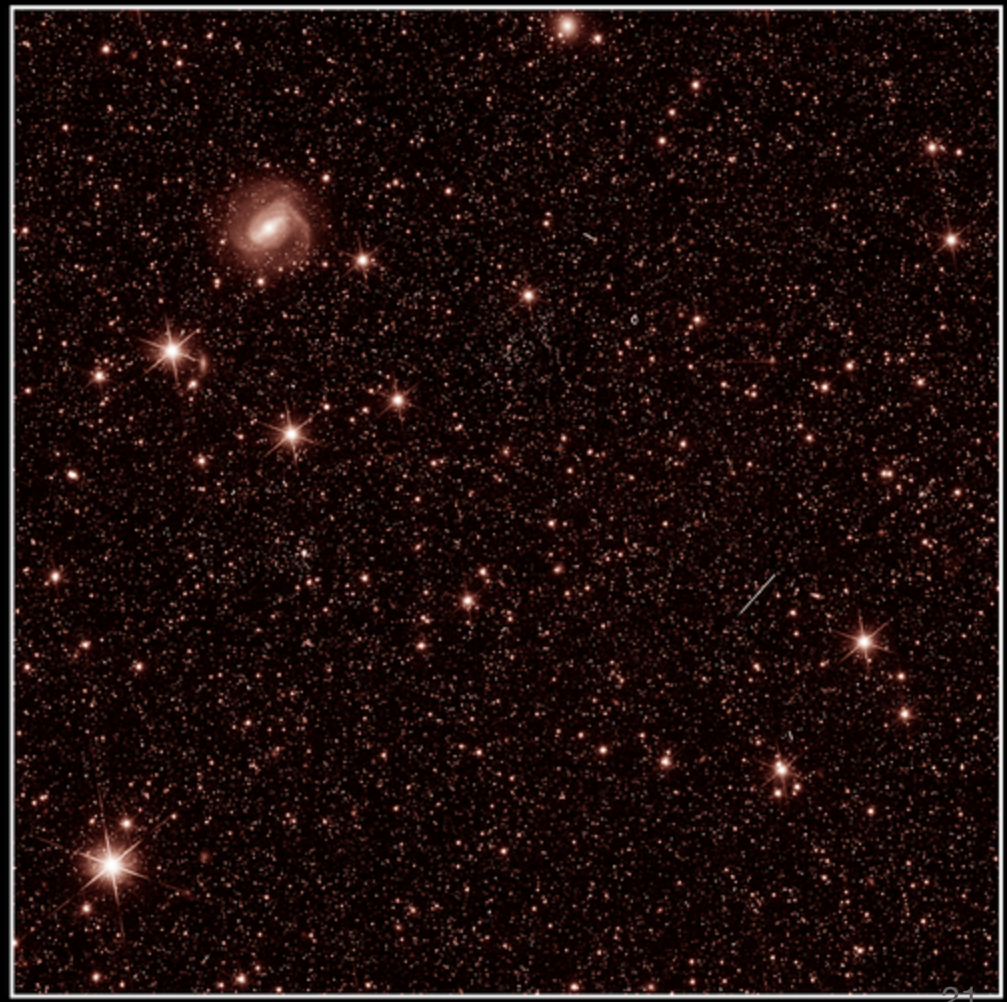
EARLY COMMISSIONING TEST IMAGE, VIS INSTRUMENT



James Webb ST NIRCam

NISP

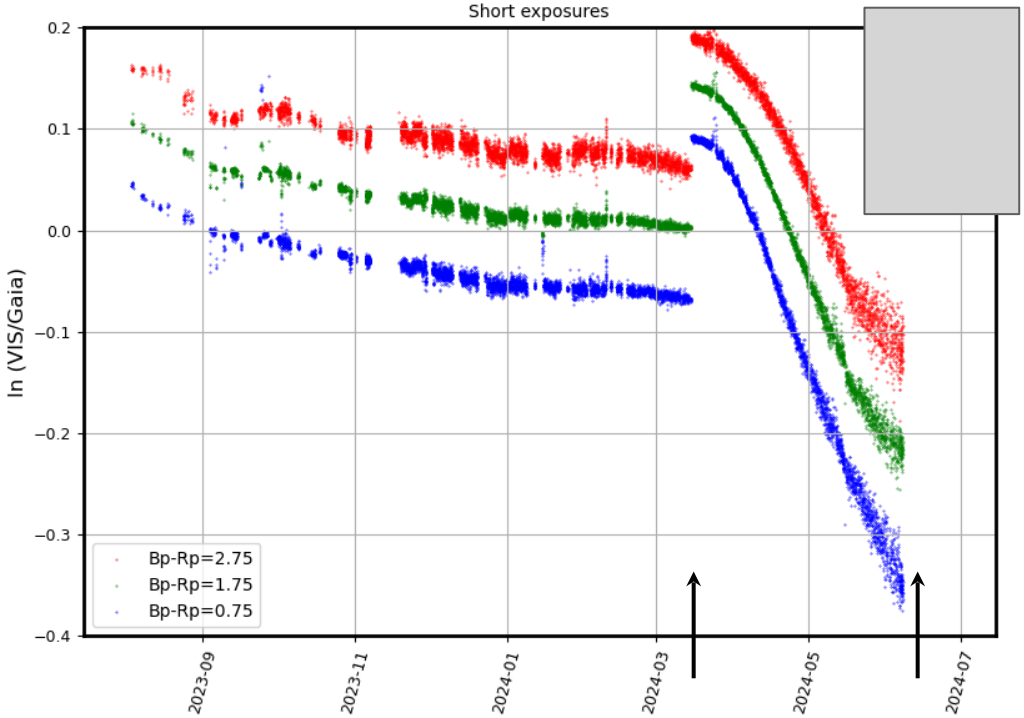




Jahnke et al. 2024

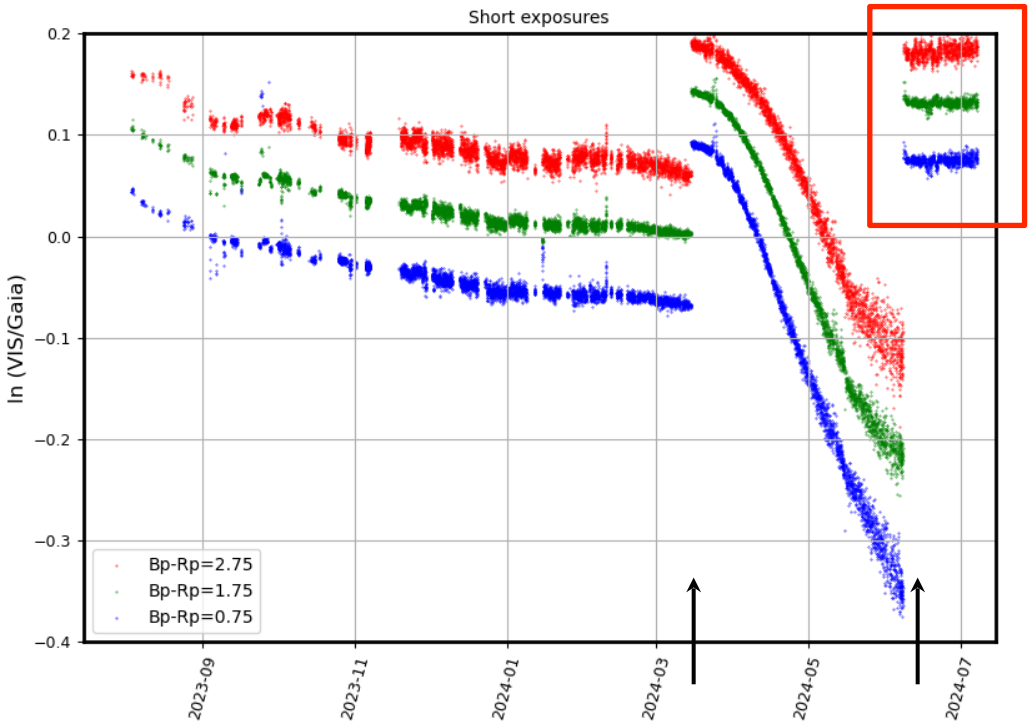
Early troubles: ice contamination

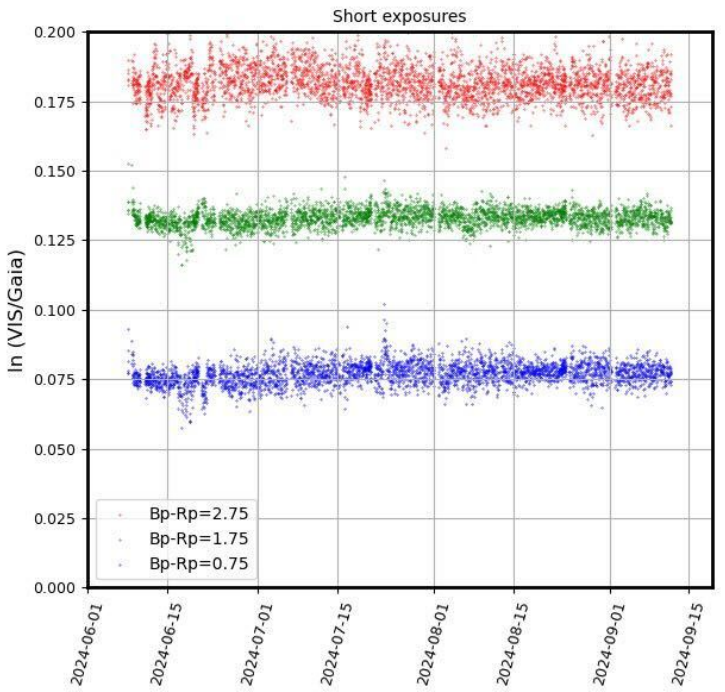
Credit: K. Kuijken



Early troubles: ice contamination

Two decontamination campaigns





Credit: K. Kuijken

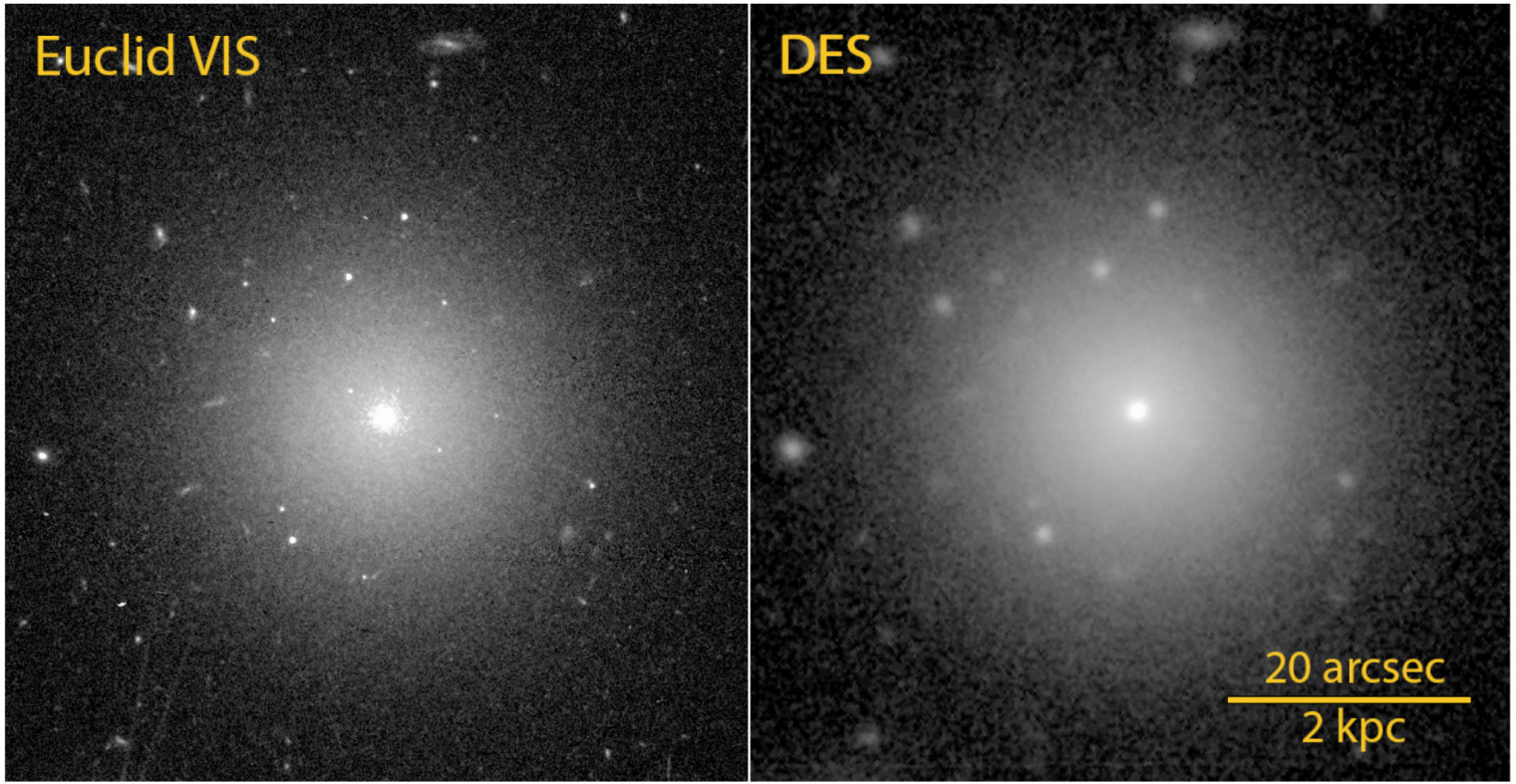
Strong lenses

Early Release Observations (EROs)

Credit: ESA / Euclid / EC / NASA / Cuillandre / Schirmer

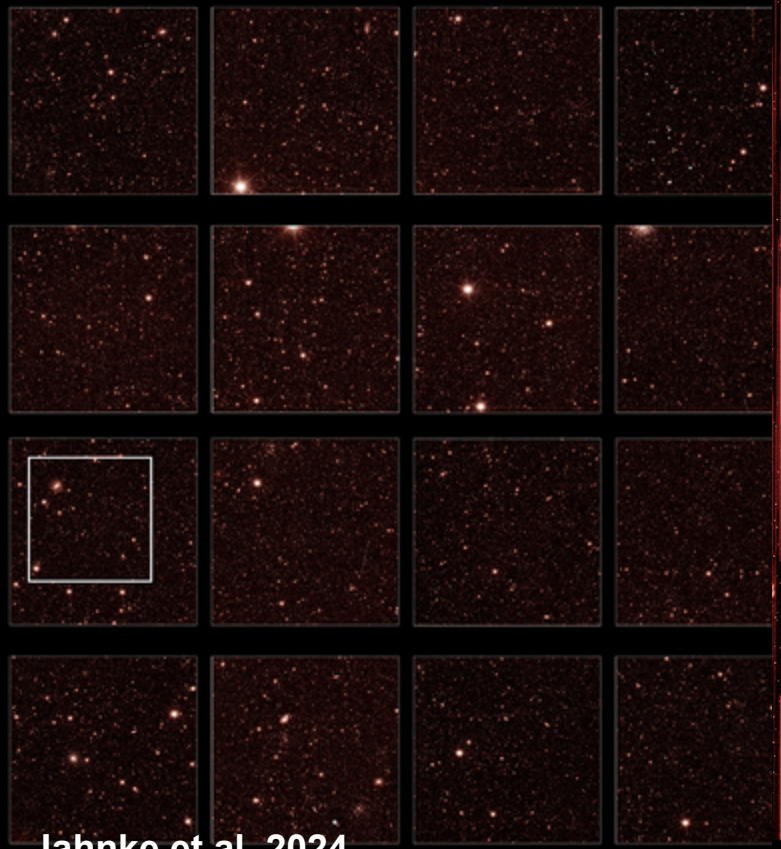
Early Release Observations (EROs), May 2024

Globular clusters in nearby galaxies

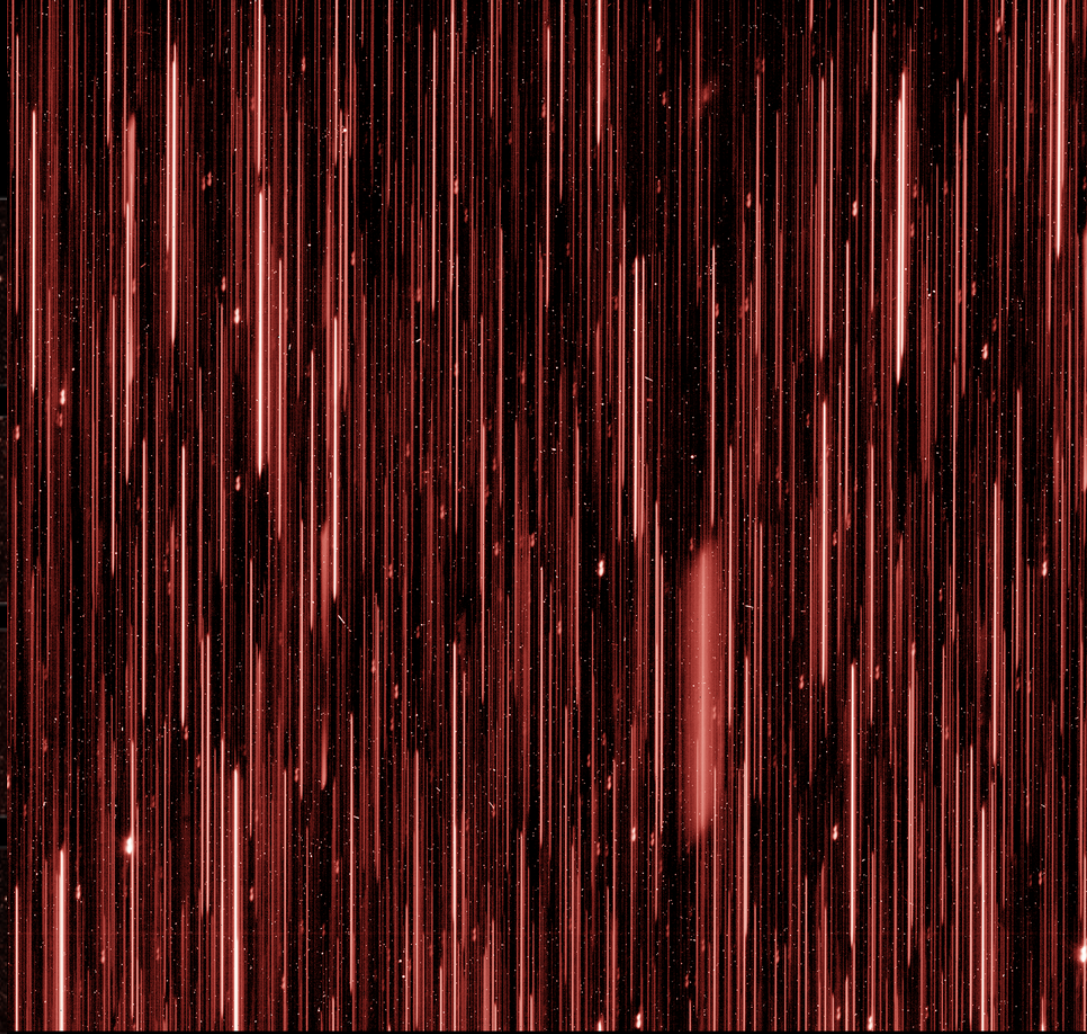


Euclid versus ground-based imaging for a dwarf galaxy in the Fornax cluster (Saifollahi et al. 2024)

NISP

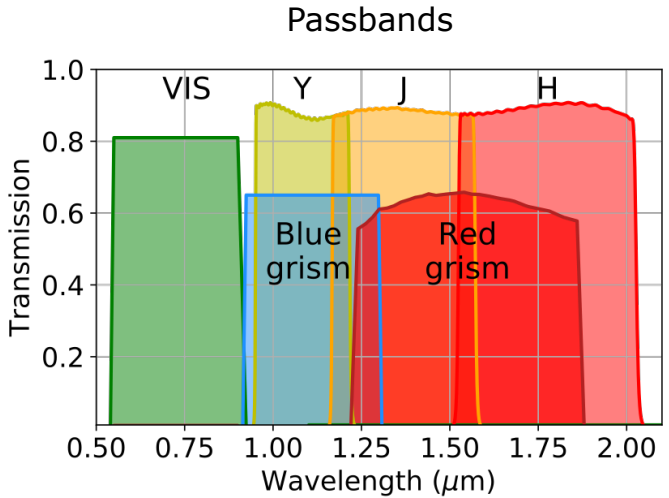


Jahnke et al. 2024

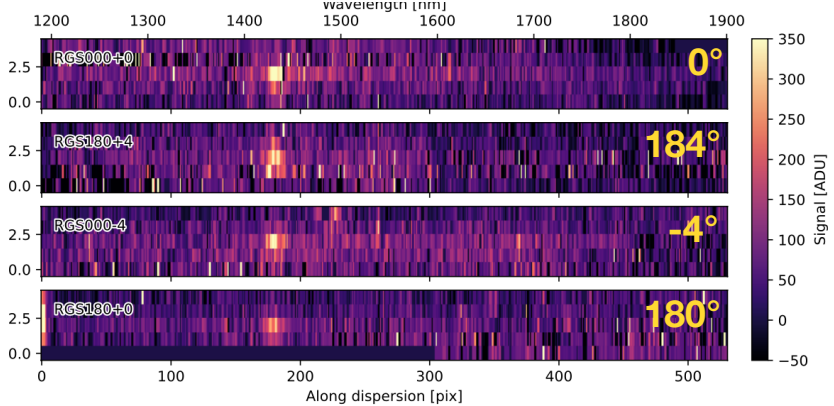


Grism channel

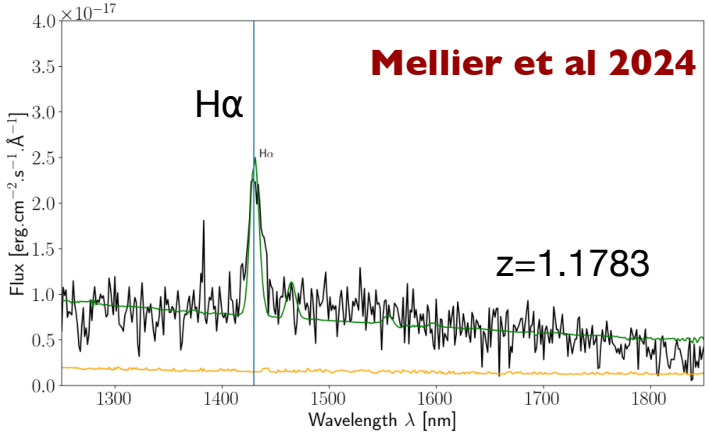
NISP slitless spectroscopy



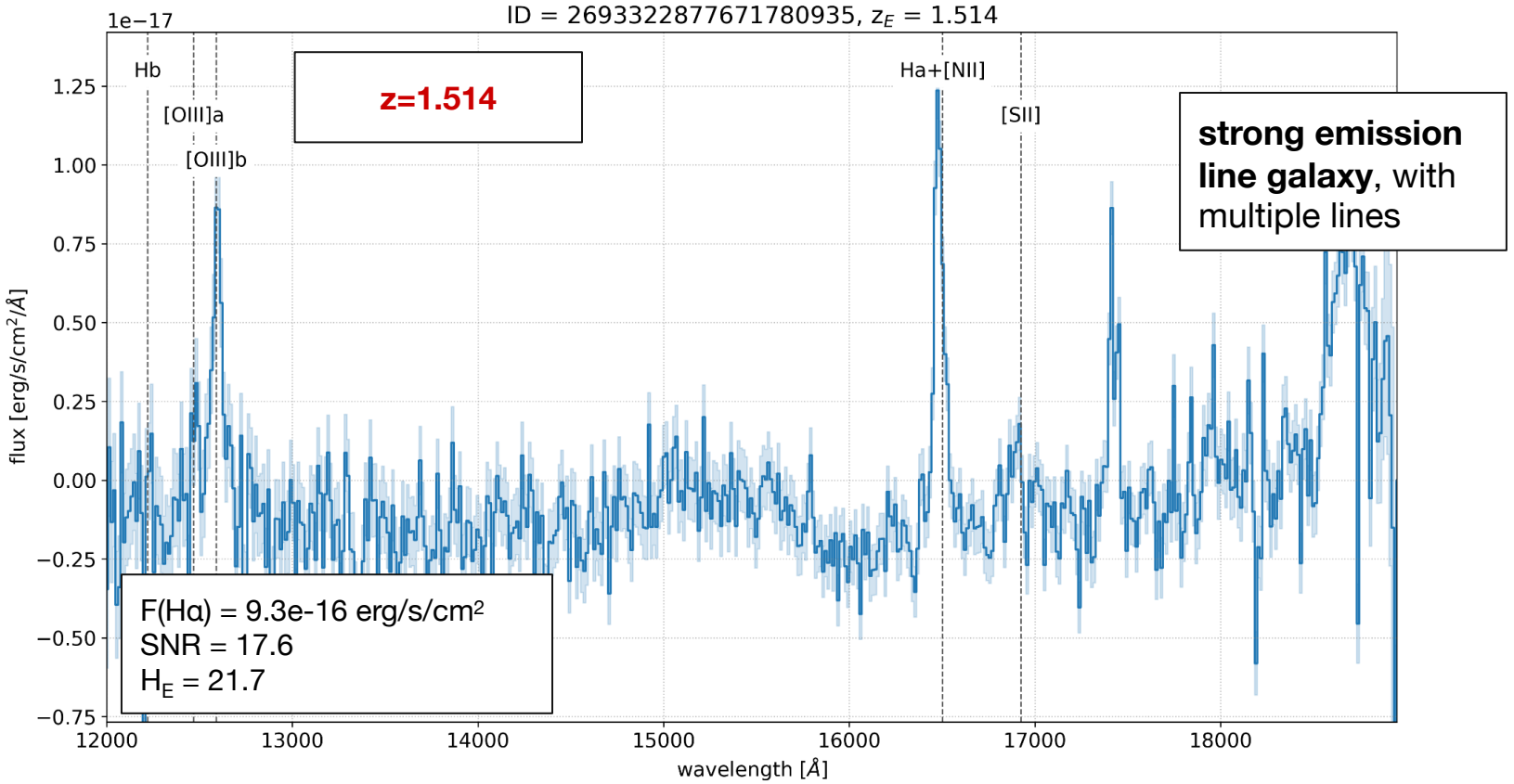
Red grism 2D extractions



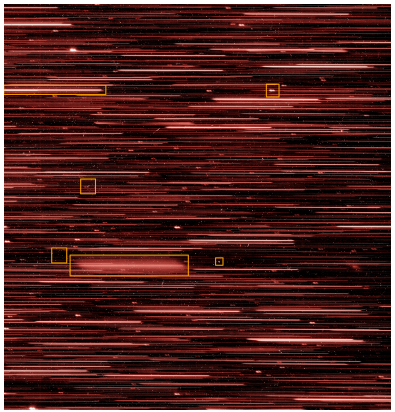
- **Wide survey**: **red grisms**, 1.2 -1.9 μm, 13A/pix, target Hα emission line galaxies at z = 0.9 to 1.8, at nominal line flux limit: 2 x10^{-16} erg/s/cm^2.
- **Deep Survey**: **red grisms** & **blue grism** (0.9-1.
μm, 13A/pix.
- **Slitless observing mode:** significant data processing required



Examples of high SNR spectra



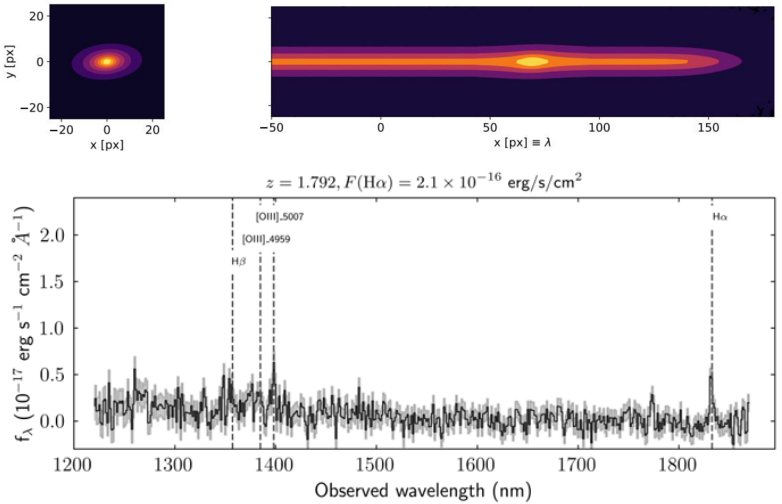
NISP slitless spectroscopy



Euclid is the **first large-scale application** of this technique.

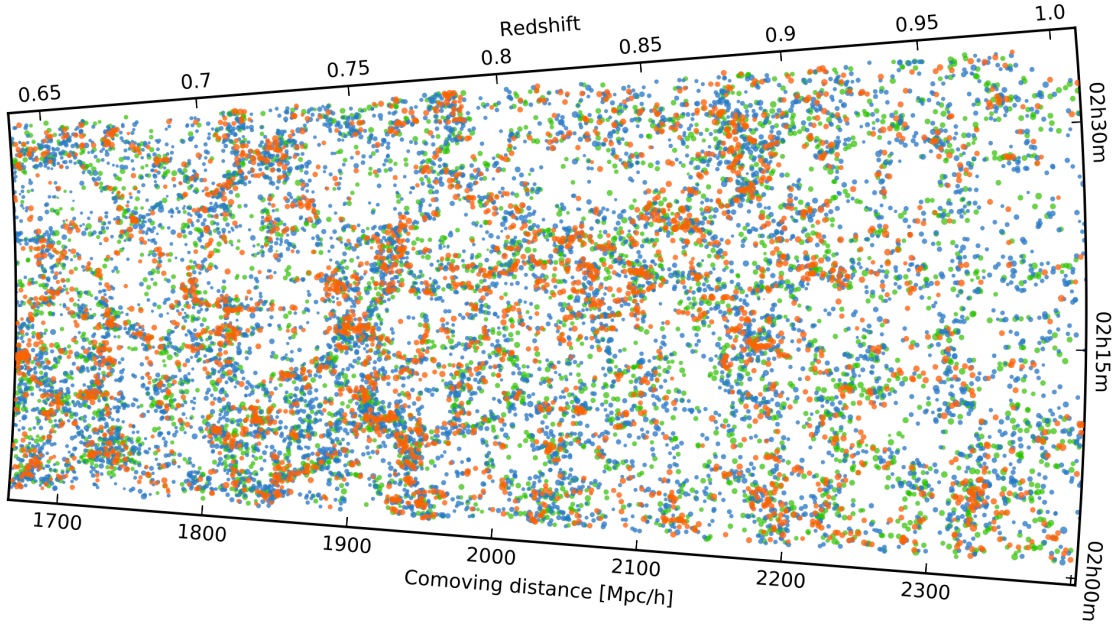
PROS:

- Technically simpler: no fibres, no moving slits → ideal for space
- All sources in the field of view are dispersed → high statistics
- No pre-selected targets → science samples can be selected *a posteriori* with different criteria, exploring systematics and optimising tracers (based on colours, etc.)



Optimise tracers for science? Different galaxies trace structure differently…

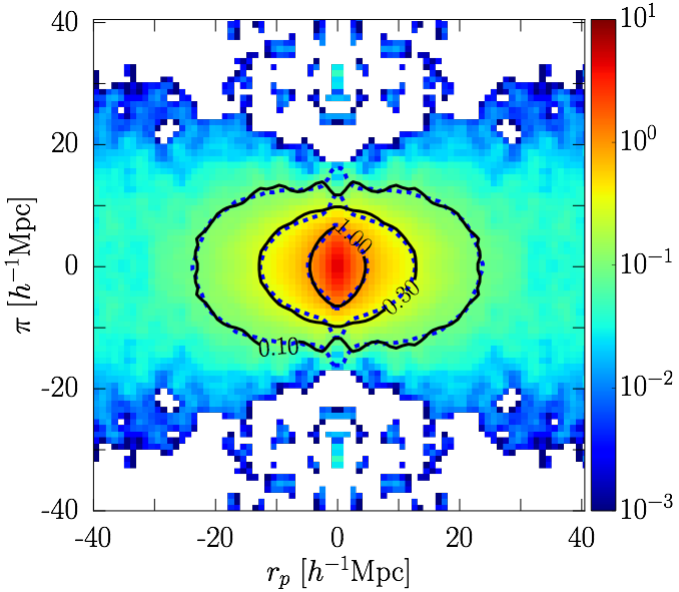
A piece of VIPERS with galaxies painted by (U-B) rest frame colour



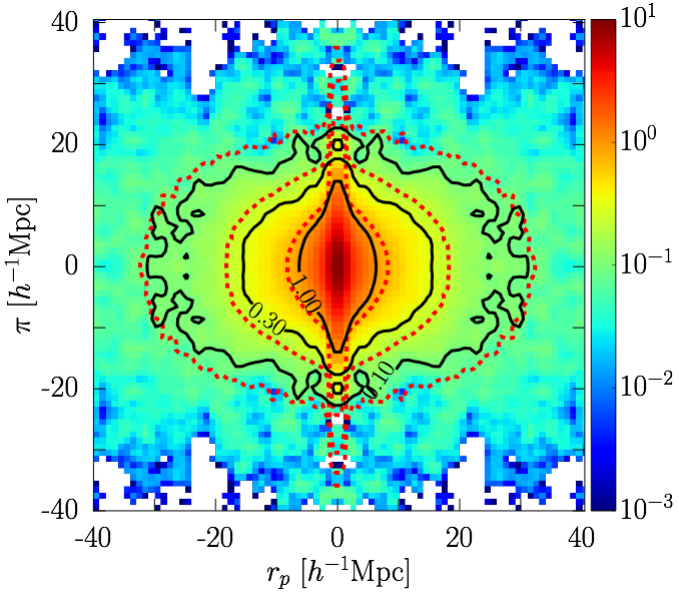
(VIPERS - Guzzo+ 2014; Scodeggio+ 2017)

…and the velocity field too: optimise modelling thereof

Blue

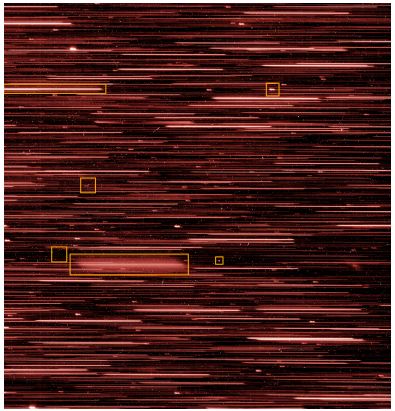


Red



(Mohammad+ 2018, arXiv:1708.00026)

NISP slitless spectroscopy



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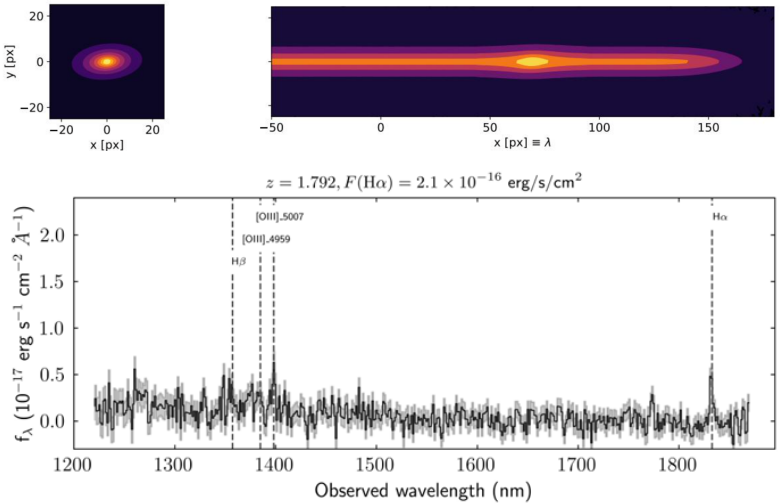
CONS:

- No parent sample: Completeness? Purity?
- Contamination from adjacent overlapping spectra
- Resolution is low (to keep spectra short) and size-dependent
- Contamination from zeroth (and 2nd) orders

- NIR detector persistence from previous exposures
- low SNR (~40 min exp, 1.2m telescope, z>0.9)

⇒ **high level of contamination**

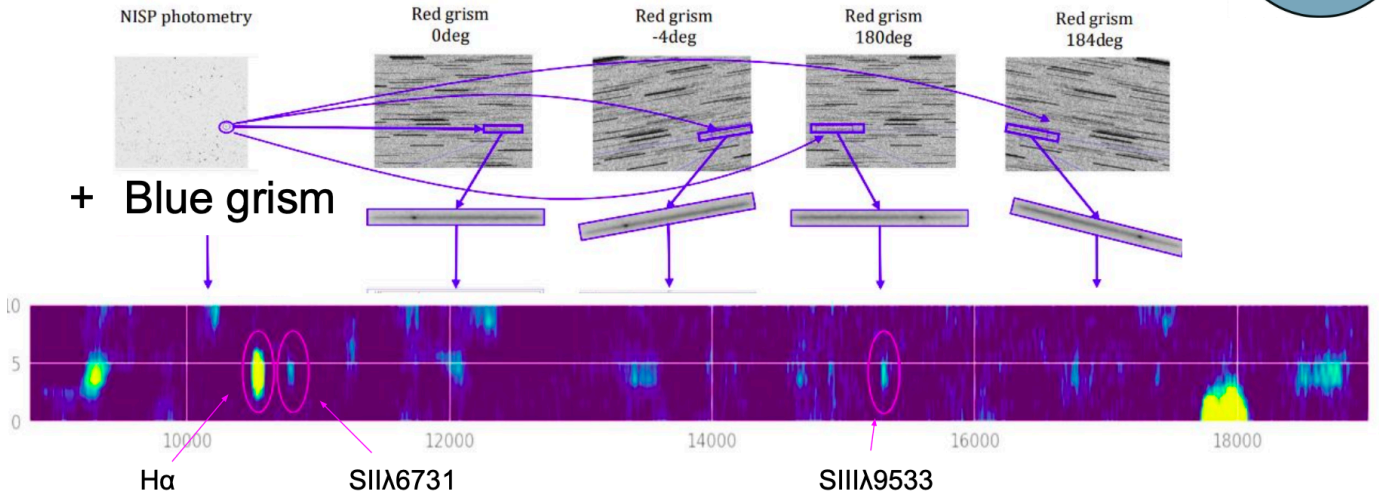


There is much more in the spectroscopy, than just the redshift

Granett+, in preparation

gelsa: harnessing slitless spectroscopy

Euclid preliminary



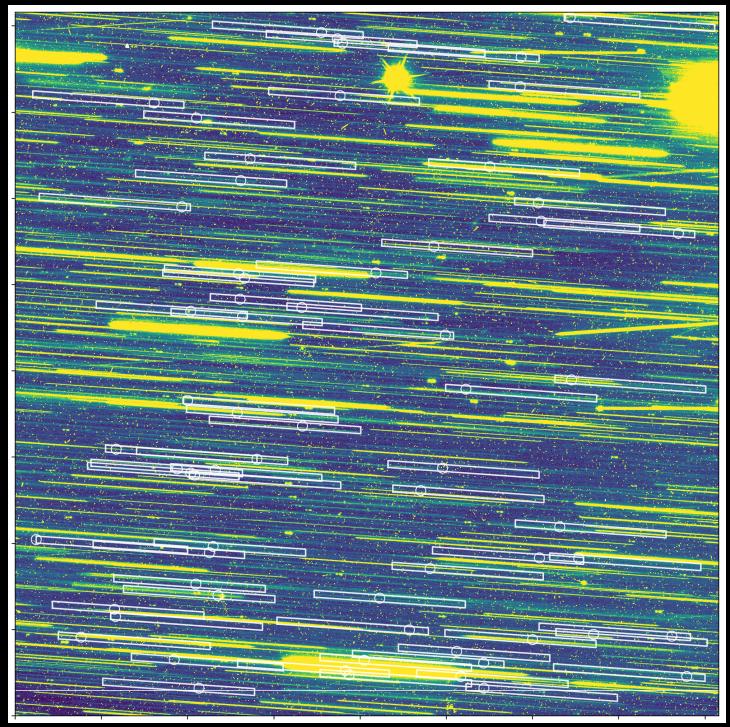
from Granett et al., in prep.

Funded by the European Union

"ELSA: Euclid Legacy Science Advanced analysis tools" (Grant Agreement no. 101135203) is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Innovate UK. Neither the European Union nor the granting authority can be held responsible for them.

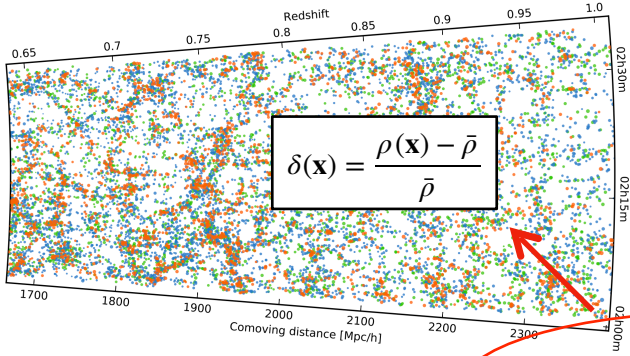
Doing cosmology requires understanding and modelling the data selection function

Image courtesy of ESA



What does it mean measuring it, in practice…

- **Science comes from overdensities δ(x)**
  - Need galaxy catalogue
  - Need survey mask (shape, holes, sensitivity…):
    - angular completeness
    - radial completeness
    - radial/angular fluctuations



Need to know where we **could** have seen galaxies in the Universe, had they existed

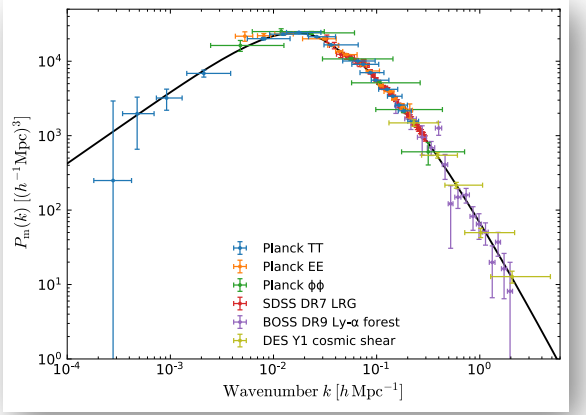
- Once this is understood, **2-point statistics of δ field** contains most (not all) information:

- **power spectrum**

$$\langle \delta(\mathbf{k_1})\delta(\mathbf{k_2})\rangle = (2\pi)^3 \delta_D(\mathbf{k_1} - \mathbf{k_2}) P(k_1)$$

- **correlation function**

$$\begin{aligned} \xi(\mathbf{x_1}, \mathbf{x_2}) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x_2})\rangle \\ &= \xi(\mathbf{x_1} - \mathbf{x_2}) \\ &= \xi(|\mathbf{x_1} - \mathbf{x_2}|) \end{aligned}$$



Systematics in the spectroscopic sample

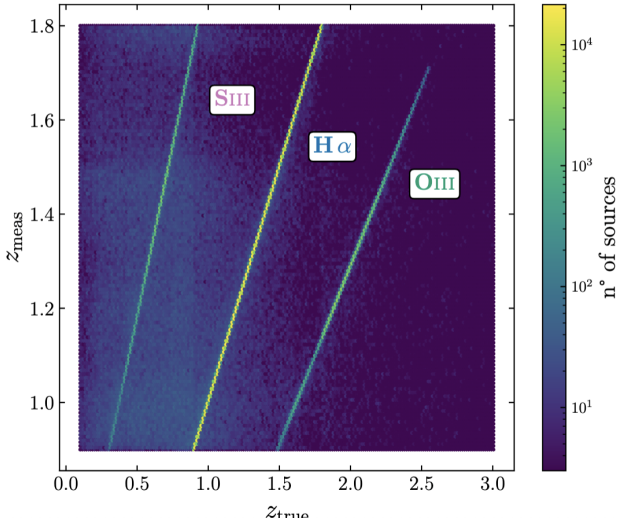
1. **angular systematics**

   modulation of the galaxy number density across the sky

1. **redshift errors**

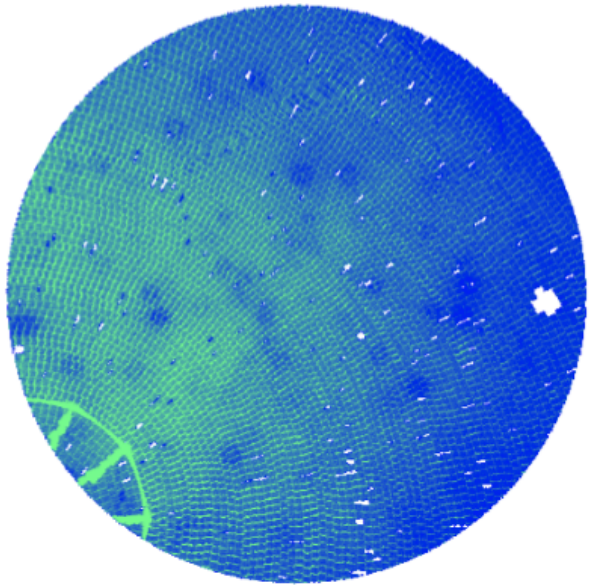
   redshift contaminants: **line** and **noise** interlopers

$$\frac{1+z_{\rm true}}{1+z_{\rm meas}} = \frac{\lambda_{\rm meas}}{\lambda_{\rm true}}$$



Risso & EC, arxiv:2505.04688

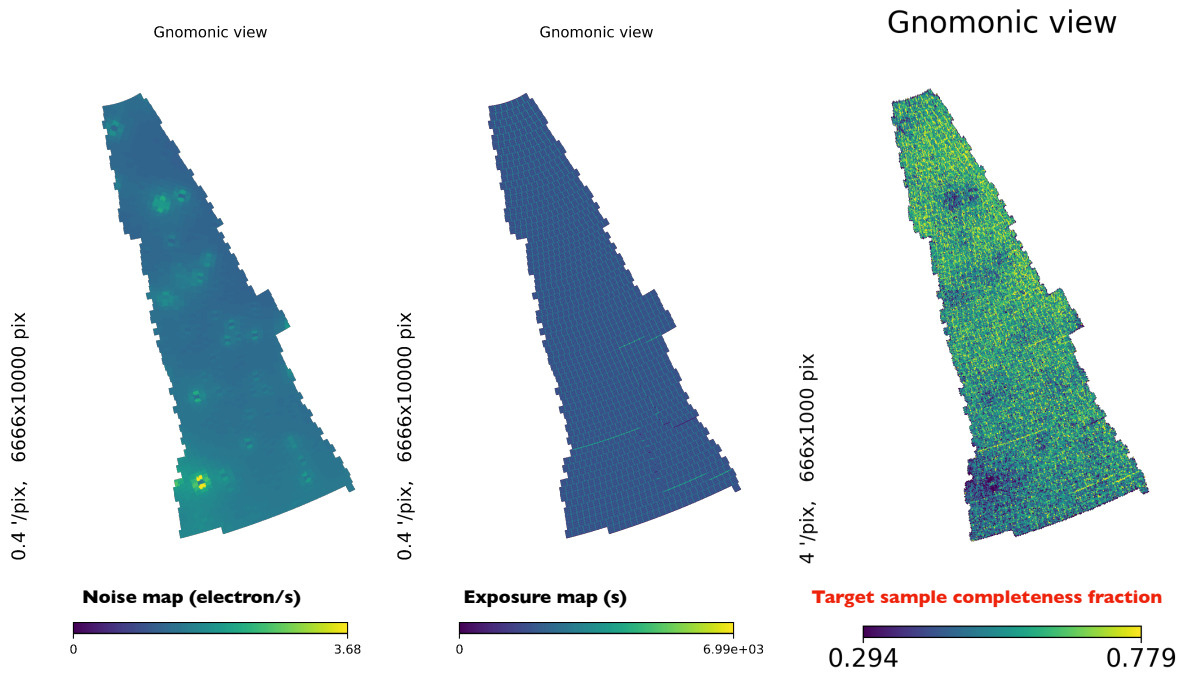
Passalacqua & EC, 2025, in preparation



Monaco & EC, 2025 to be submitted

Granett & EC, 2025 in preparation

Angular systematics include **background noise**, **exposure map**, **completeness…**

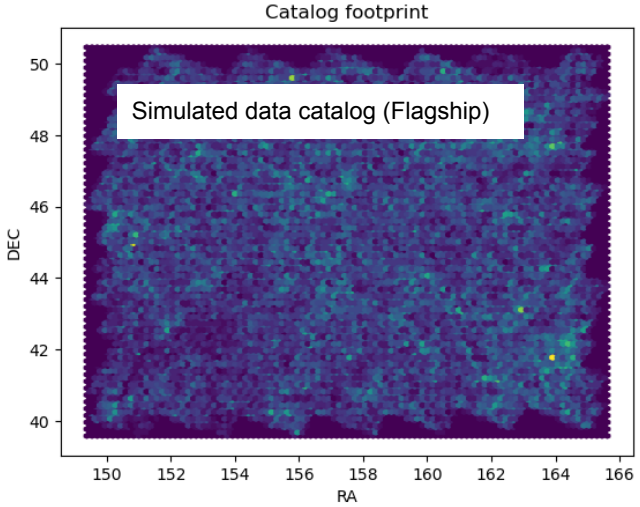


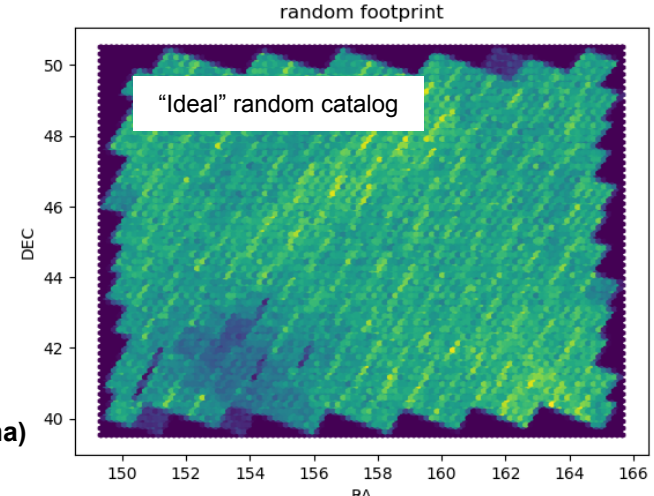
- **Zodiacal light**
- **Milky Way straylight**
- **Detector noise**

B. Granett, P. Monaco, S. de la Torre, D. Markovic, I. Risso, F. Passalacqua, C. Scarlata & many others (DR1 Key Projects GC2 and GC3)

Building the spectroscopic visibility mask

- Slitless spectroscopy: no *a priori* target sample known, how do we build a mask?
- **The selection function is *not a simple angular mask*,** but depends on **RA, Dec, z, line flux, angular size, …**
- The **Euclid spectroscopic visibility mask (VMSP)** characterises the selection function through a **random catalogue**:
  - Traces spurious fluctuations in the mean density of the spectroscopic sample;
  - Poisson sampling (no clustering signal);
  - 50x data sample



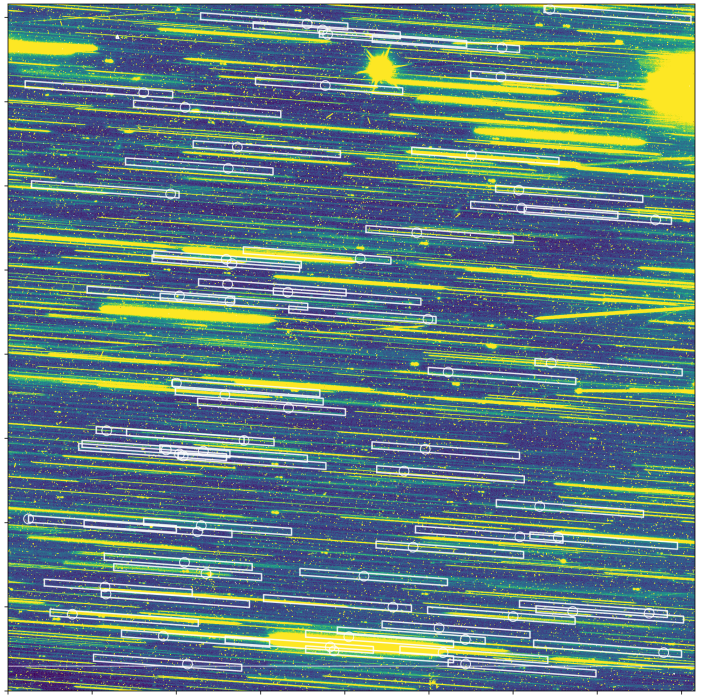


(slide by Ben Granett)

(PhD work Antonio Farina)

Random catalog production

- The random catalog is built by **forward modelling the selection function**.
- **Synthetic galaxies** (randoms) are placed over the Wide Survey area;
- The **noise at the location of the emission lines** is read from NISP-S calibrated frames to compute **SNR for the randoms;**
- The **detection model maps the SNR to detection probability;**
- The random catalog is **weighted by the detection probability;**
- **Tested / validated through the Deep Fields data and simulations**

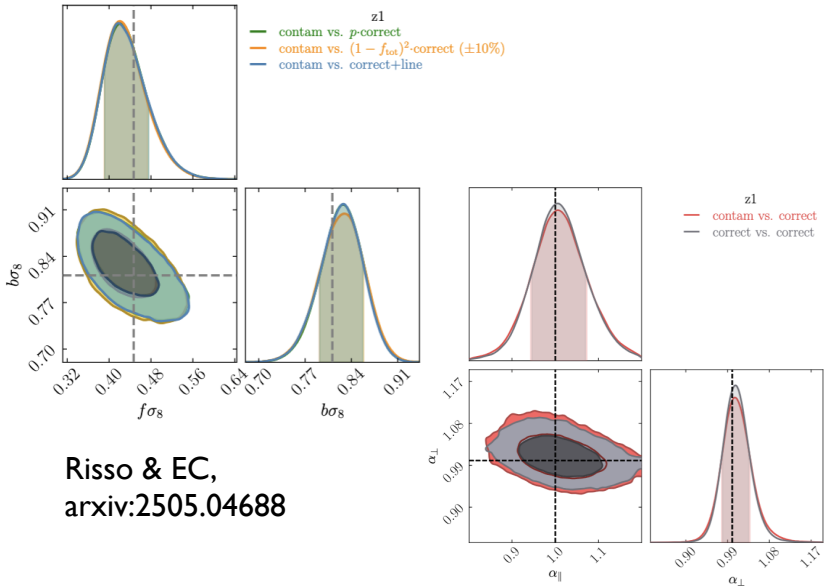


- **Single NISP detector (Red grism RGS000, Tilt -4).**
- **Polygons mark randoms and the location of the Halpha line.**

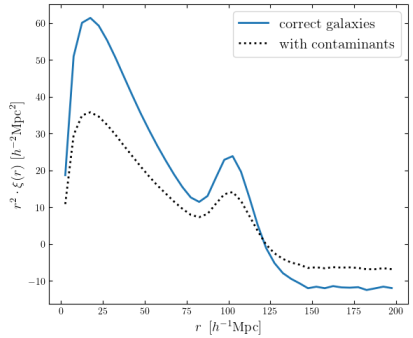
B. Granett, P. Monaco, S. de la Torre, D. Markovic, I. Risso, F. Passalacqua, C. Scarlata & many others (DR1 Key Projects GC2 and GC3)

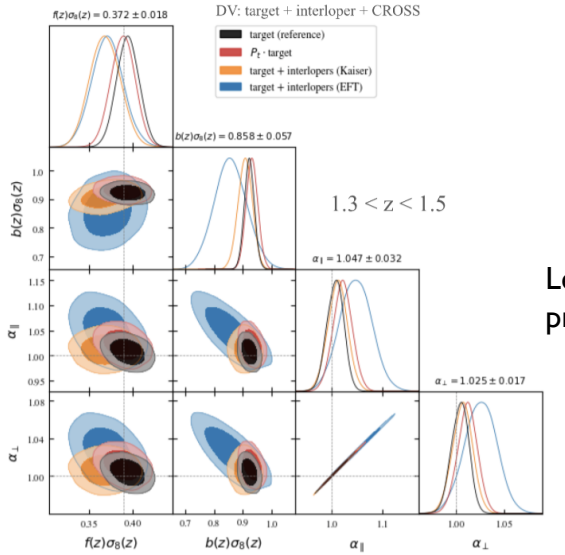
Modelling the impact on two-point statistics

$$\xi_{\rm m} = (1-f_{\rm tot})^2\,\xi_{\rm c} + f_\ell^2\,\xi_\ell + f_{\rm n}^2\,\xi_{\rm n} + [\text{cross terms}] \simeq (1-f_{\rm tot})^2\,\xi_{\rm c}$$



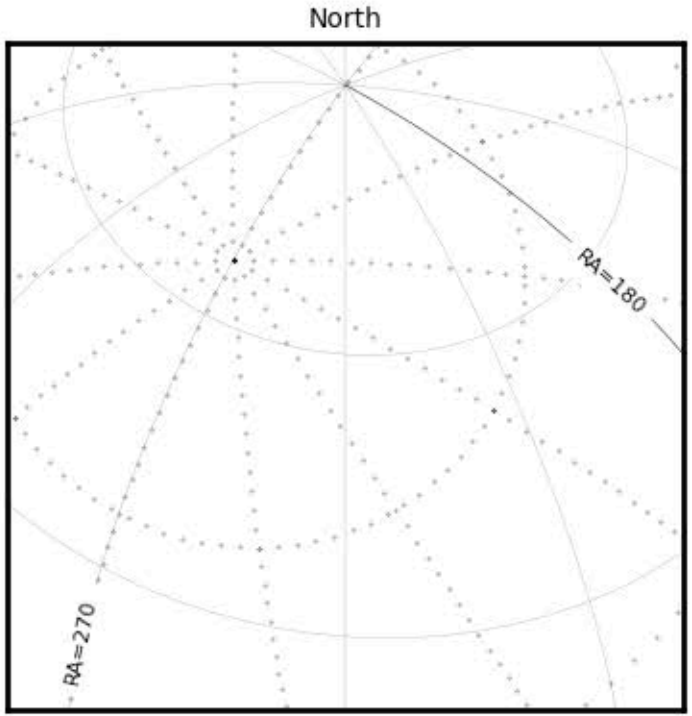
Risso & EC, arxiv:2505.04688

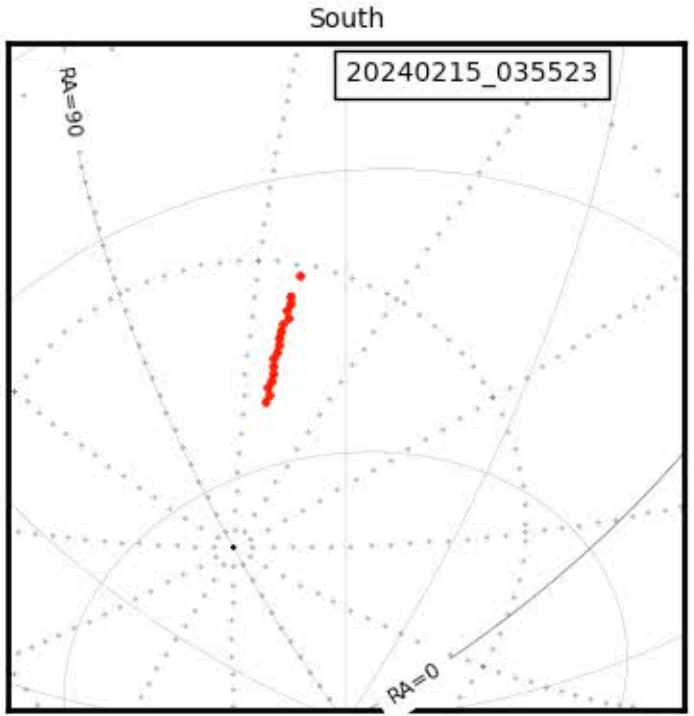




Lee & EC 2025, in prep.

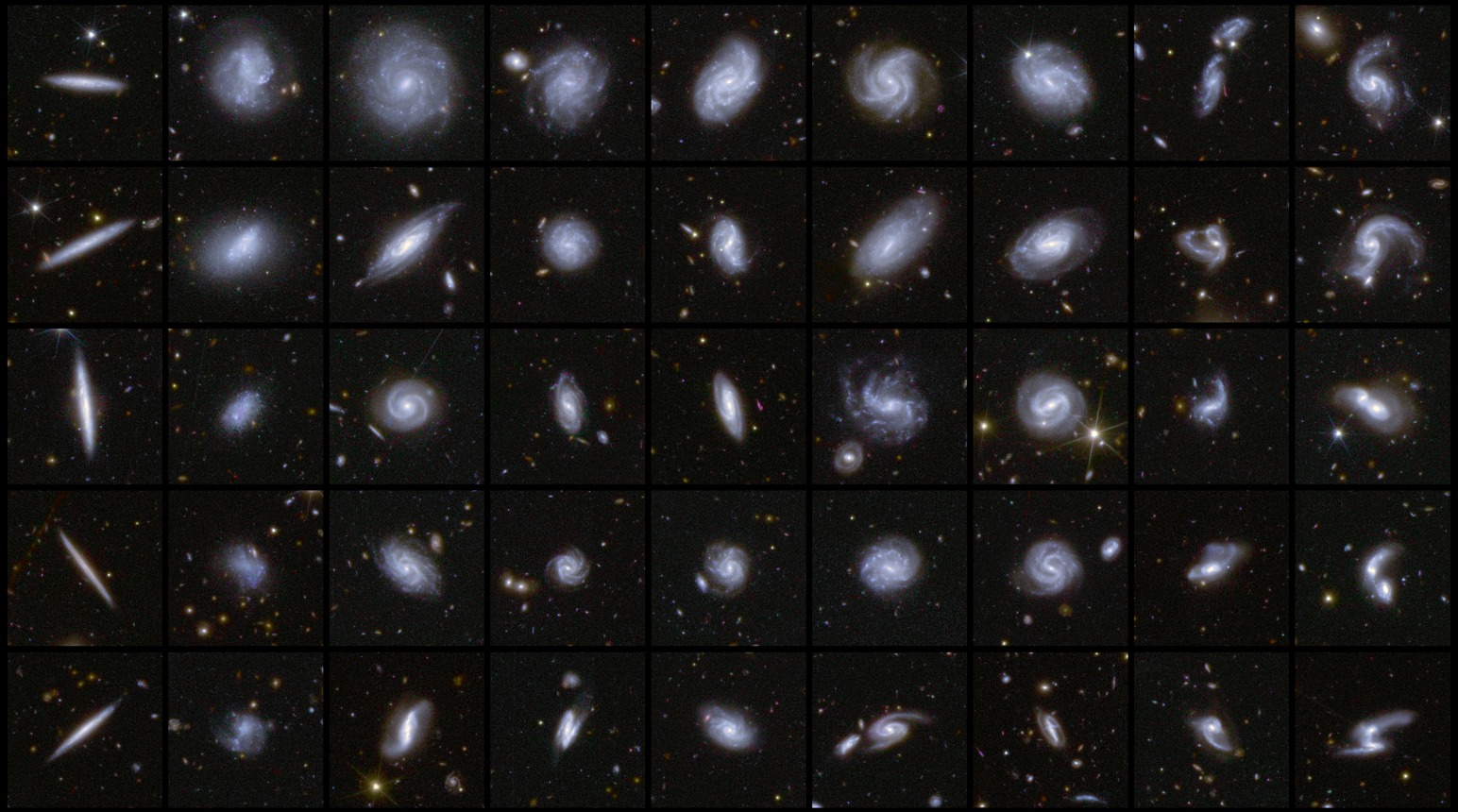
Wide Survey unfolding…



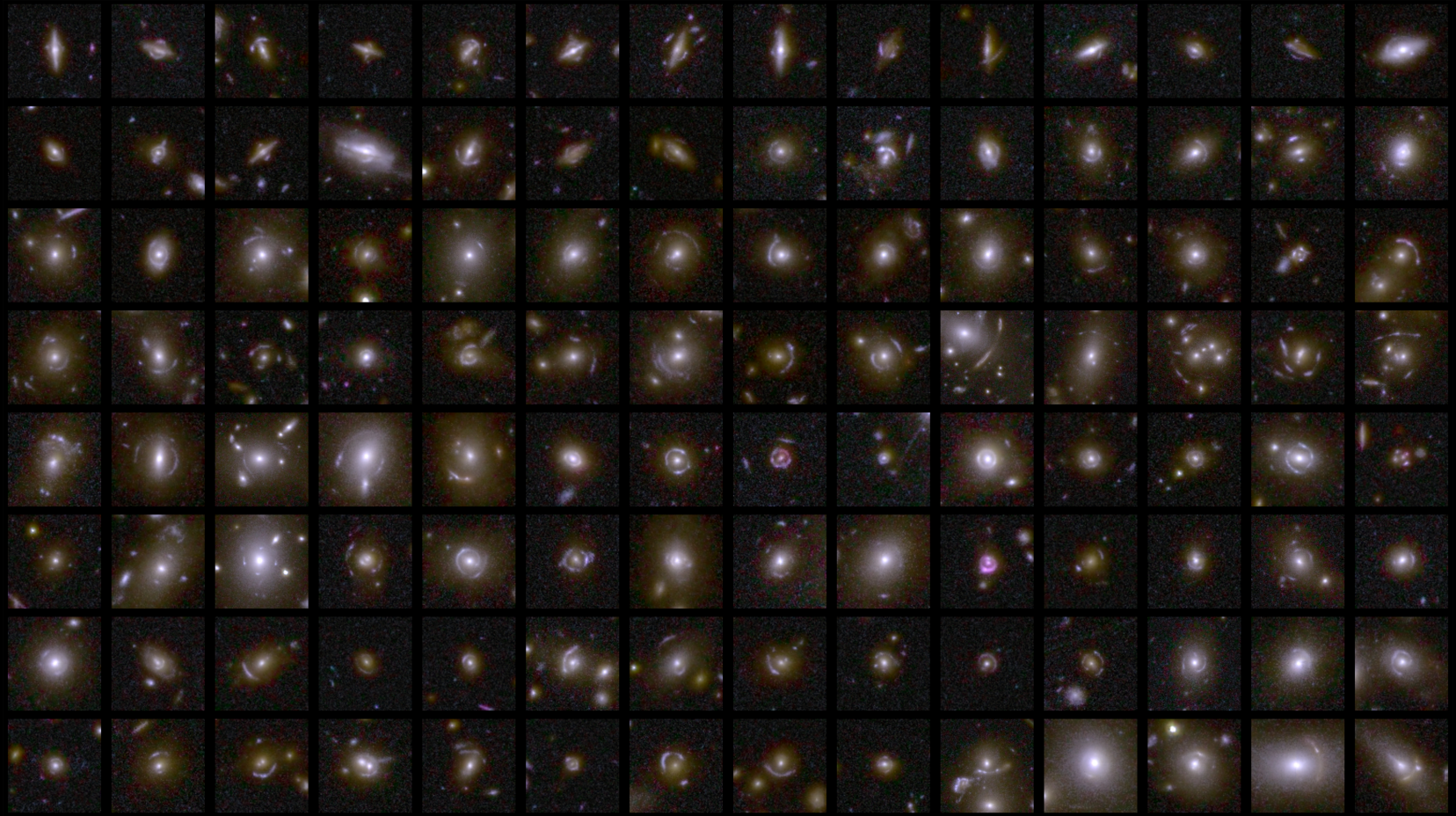


Movie by K. Kuijken

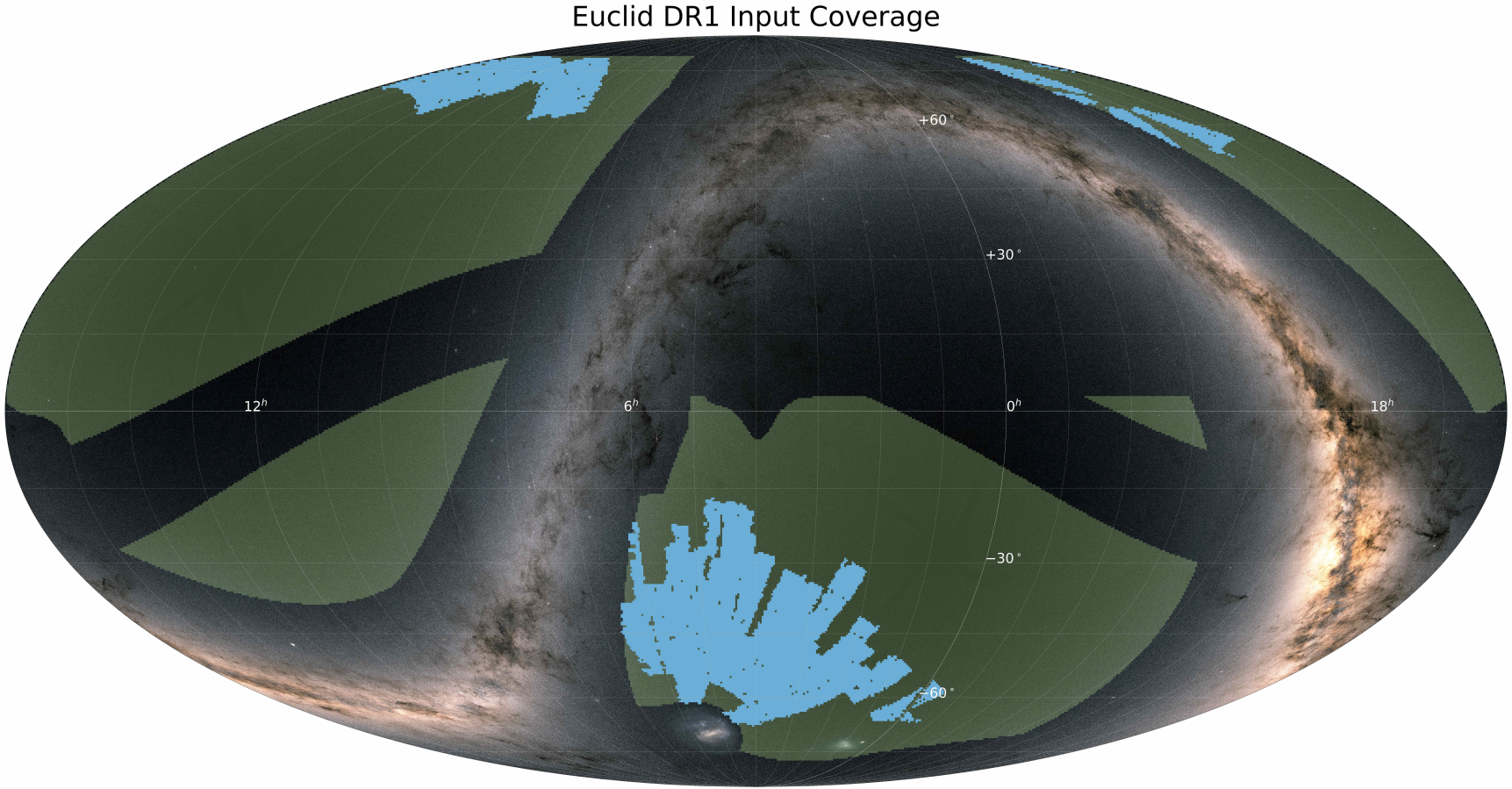
19 March 2025 - Q1 data release: first look at ~60 deg2 of Wide-Survey data



Q1 data release: strong gravitational lenses



Fall 2026 - **Euclid DR1**,1900 deg^2: expected footstep



Outlook

Euclid is a terapixel machine regularly delivering unique quality data (10 deg² of Wide Survey per day). Early issues (guiding system, stray light, ice deposition) solved / monitored. Others (X-ray / proton flares) handled routinely

March 2025 Q1 release (63 deg² - one pass on the Deep Fields) gave a glimpse of Euclid enormous scientific content: 20 papers focusing on Euclid "legacy" science (galaxies, QSOs, many strong lenses), plus another 7 describing the data

Spectroscopic data are complex: strong effort to constantly improve the pipeline and turn Euclid observing mode to our advantage: select multiple science samples to cross check different impact of systematics, with flexible theoretical modelling

As of August 30 2025, more than 3000 deg2 of Wide Survey done. Aiming at 14000 deg² in further ~5 years. Data release 1 (DR1 - ~2000 deg²) in fall 2026 (see Mellier et al. overview paper, arXiv:2405.13491)

With its combination of probes, Euclid promises to measure large-scale structure statistics to exquisite precision and unmatched accuracy: shed light on the dark energy conundrum while building an inestimable legacy for decades of astronomical research

Side deviation (following up Mischa's talk): VIPERS example of joint 2-point + 3-point constraints

(Veropalumbo, Saez-Casares, et al. 2021, MNRAS, 507, 1184)