Exploring the Dark Universe with Euclid

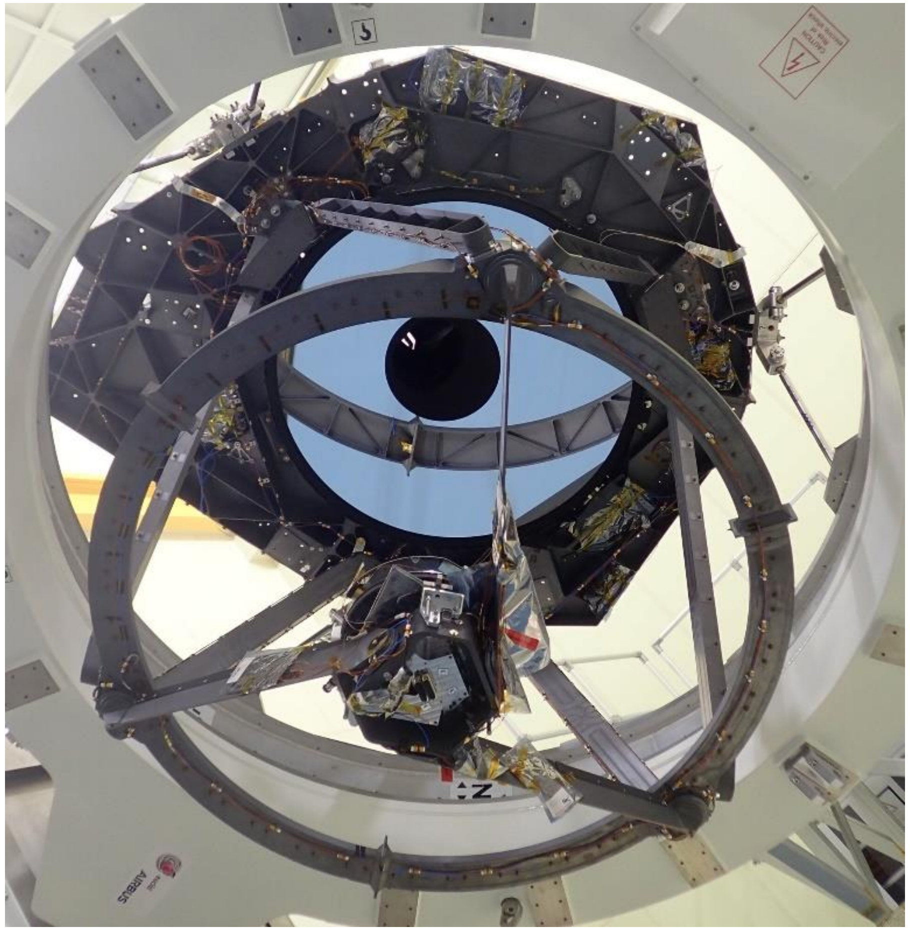
Martin Kunz
University of Geneva

for the Euclid Consortium

Euclid consortium

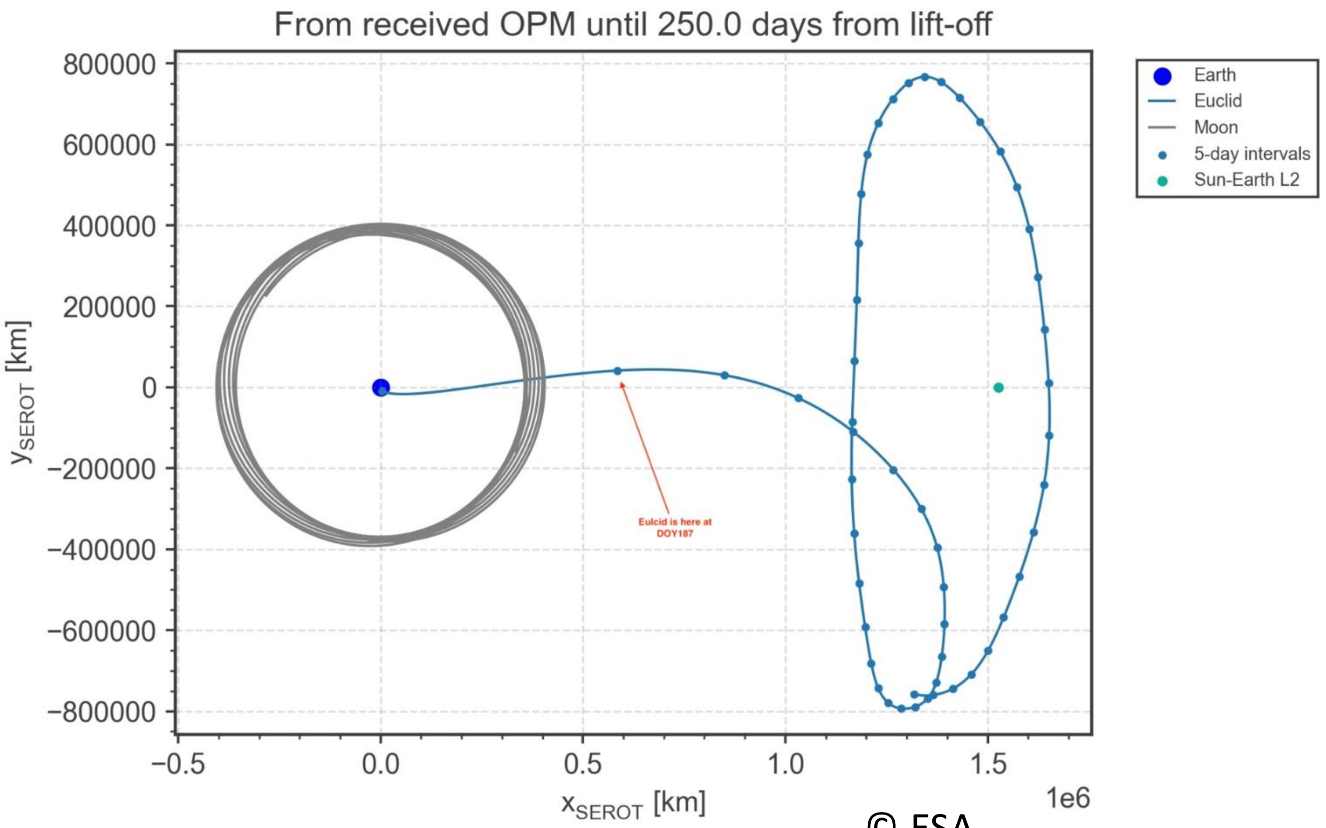
Euclid, an ESA M-class mission

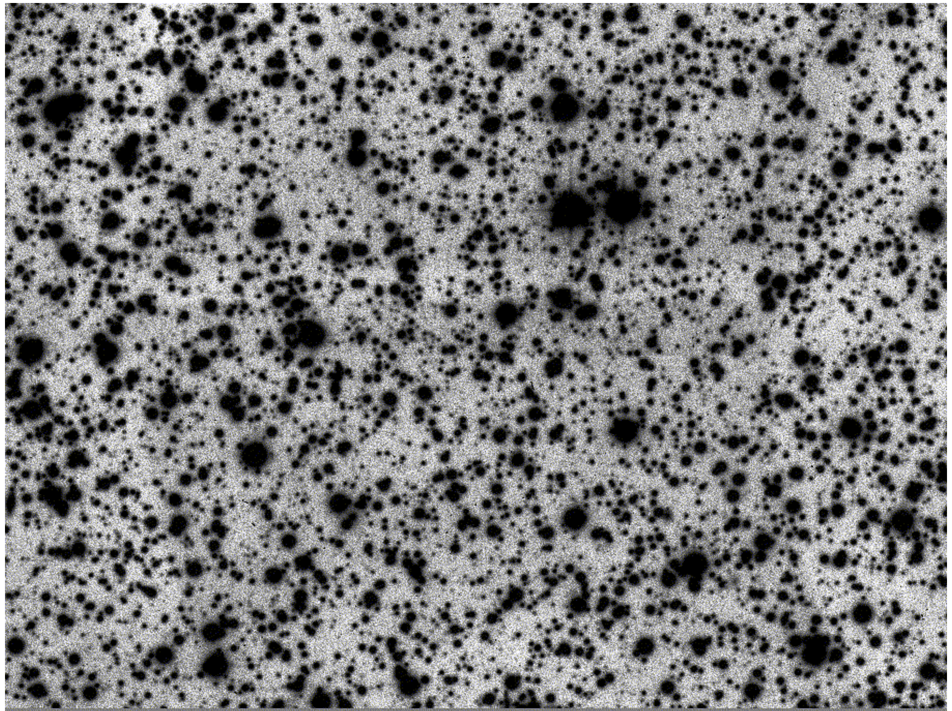
- Ca 4.7m tall, 3.7m wide
- 1988kg launch mass
- 1.2m primary mirror
- Near-infrared & optical instruments
- Launch: July 1st, 2023 on SpaceX Falcon 9
- Daily data rate of ca 100GB compressed data
- Nominal mission duration of 6 years, extension possible.



‘eye of Euclid’ ©Airbus

Euclid transfer to L2

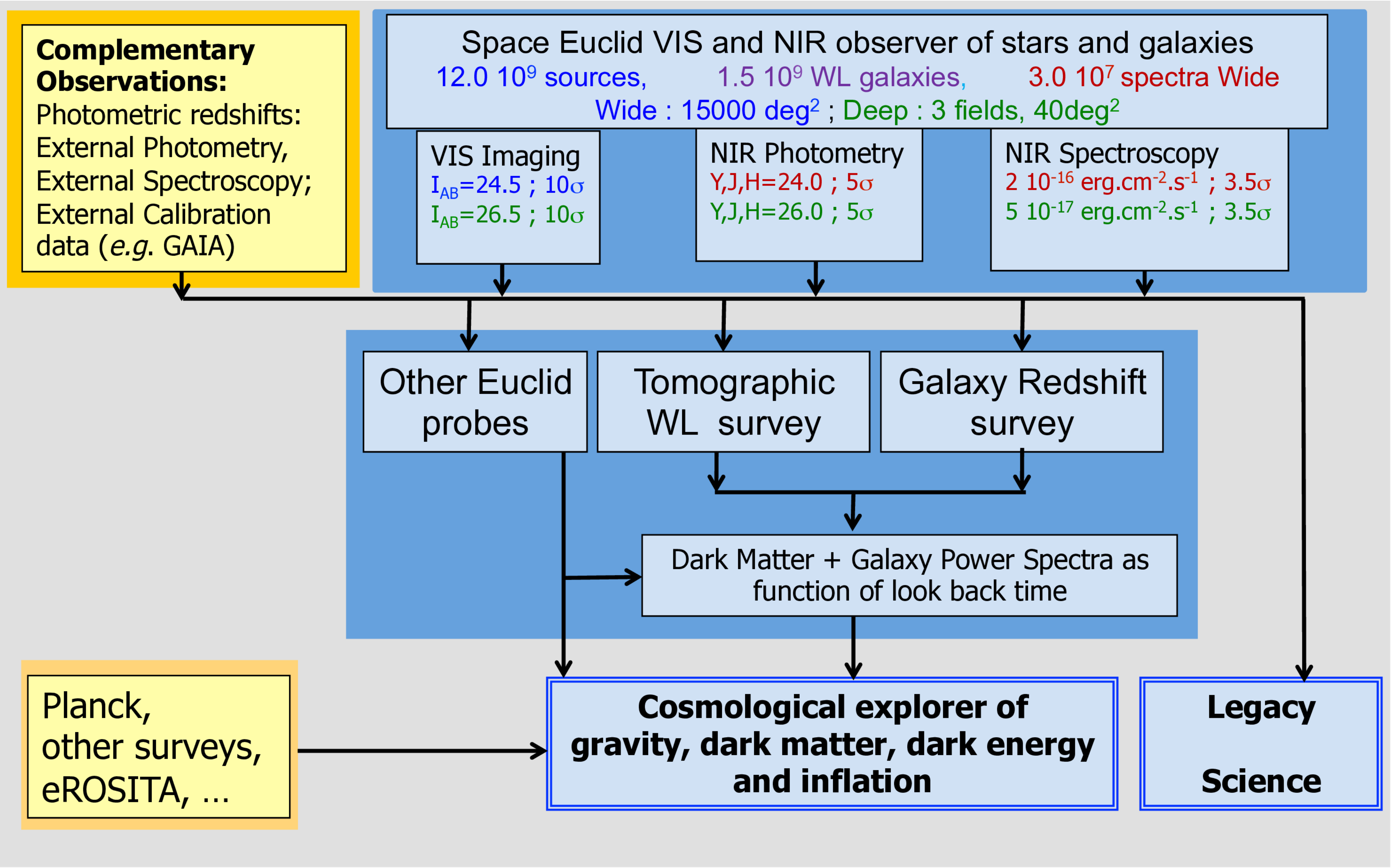




Euclid moving to L2 by CFHT-MegaCam / 12-07-2023

Euclid observations

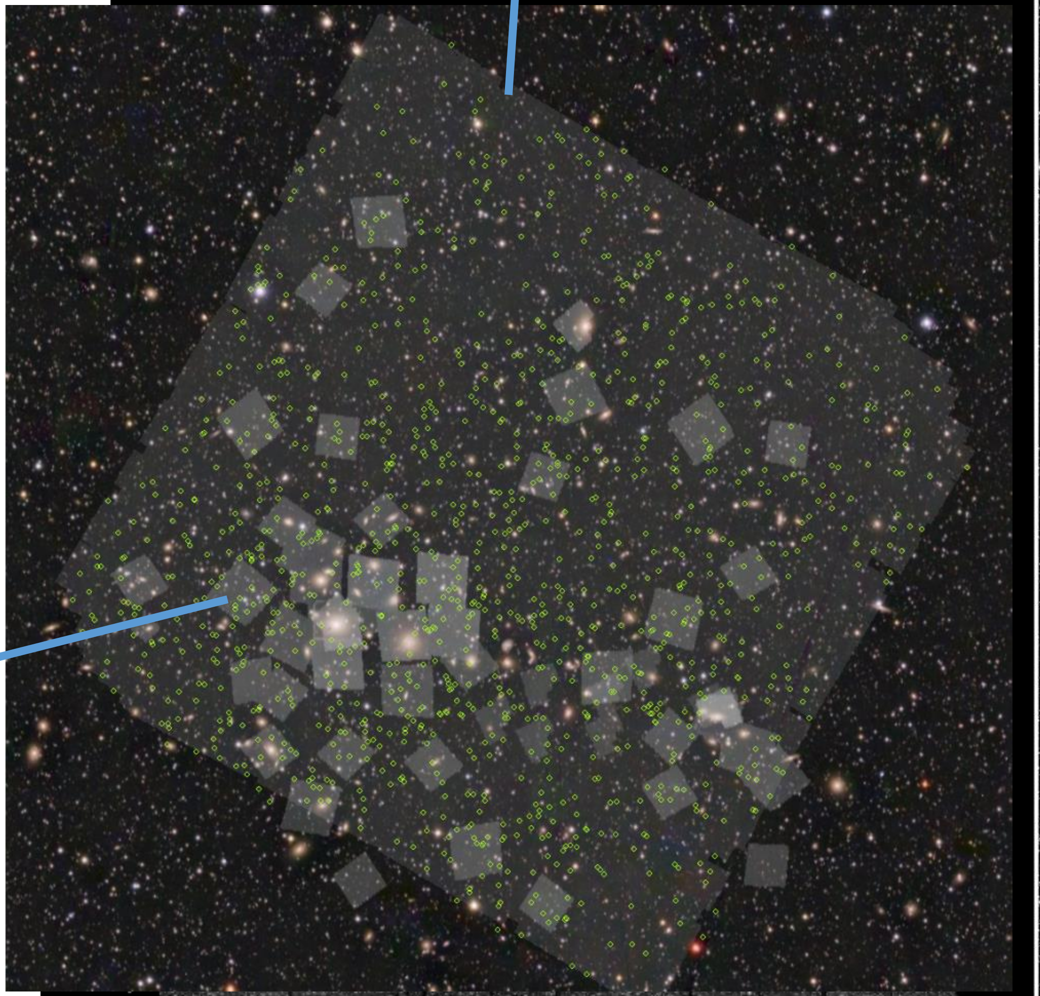
For latest numbers, see Euclid. I. Overview of the Euclid mission, arXiv:2405.13491



VIS commissioning

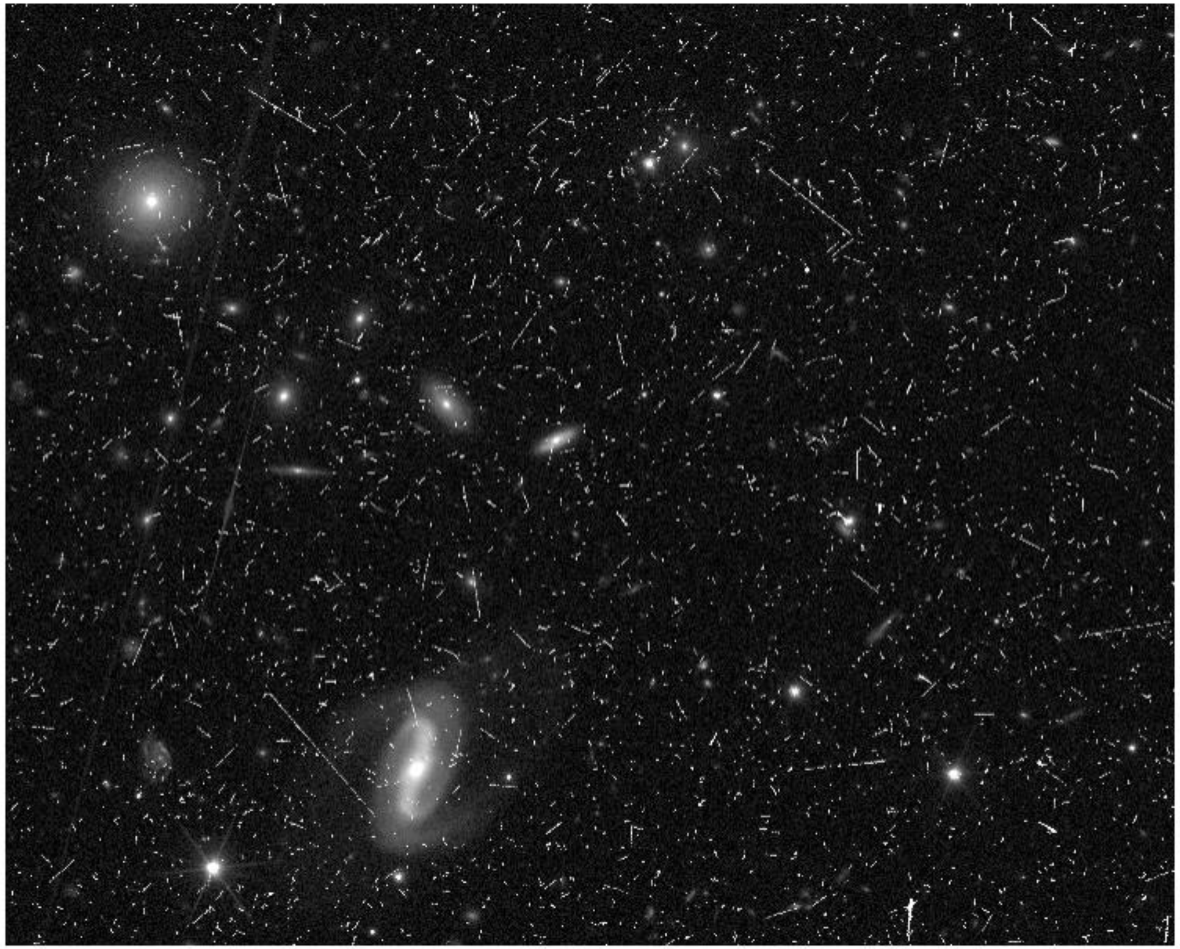
FOV 42’x44’

VIS:
36 Si CCD’s
4096x4132
0.1”/pixel
530-920 nm

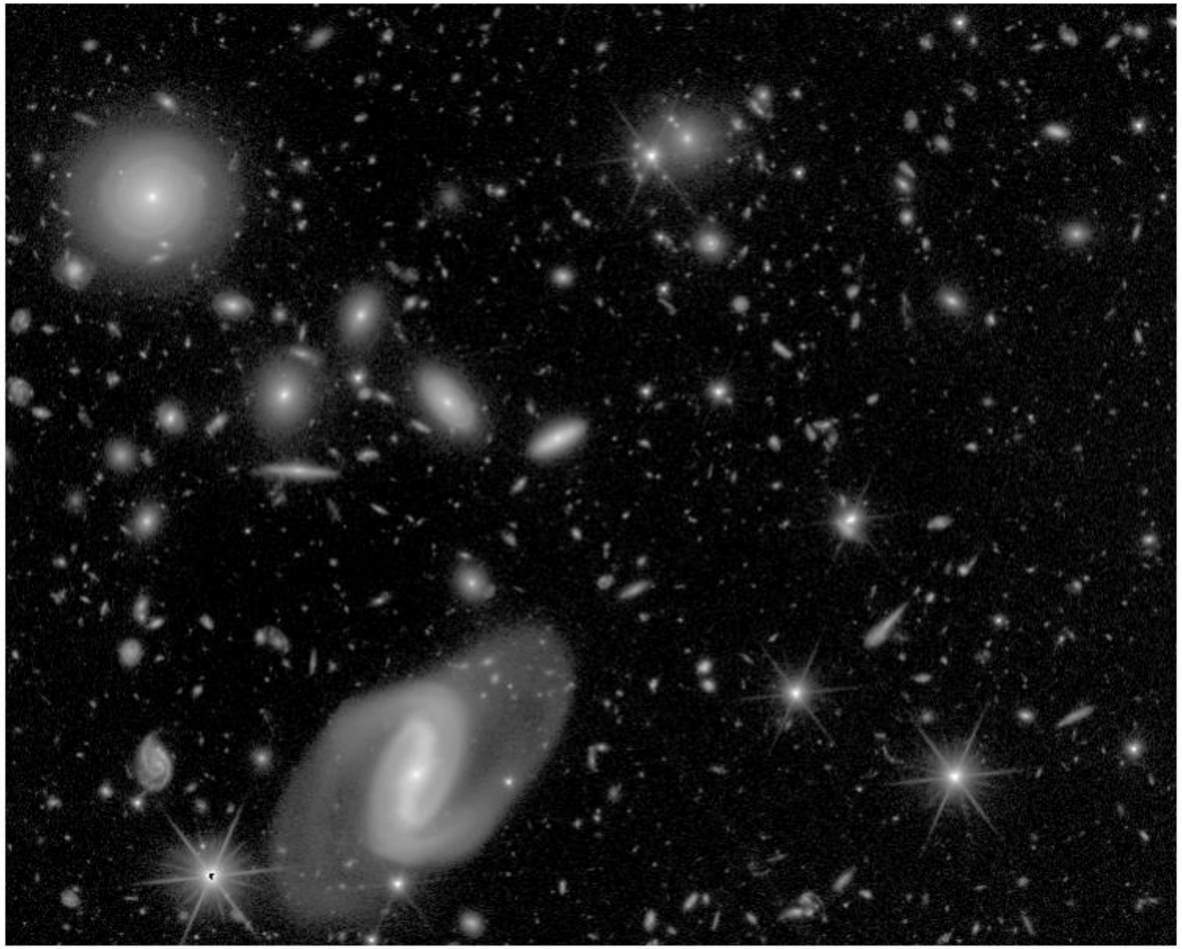


Stacking and cleaning

Euclid. I. Overview of the Euclid mission, arXiv:2405.13491



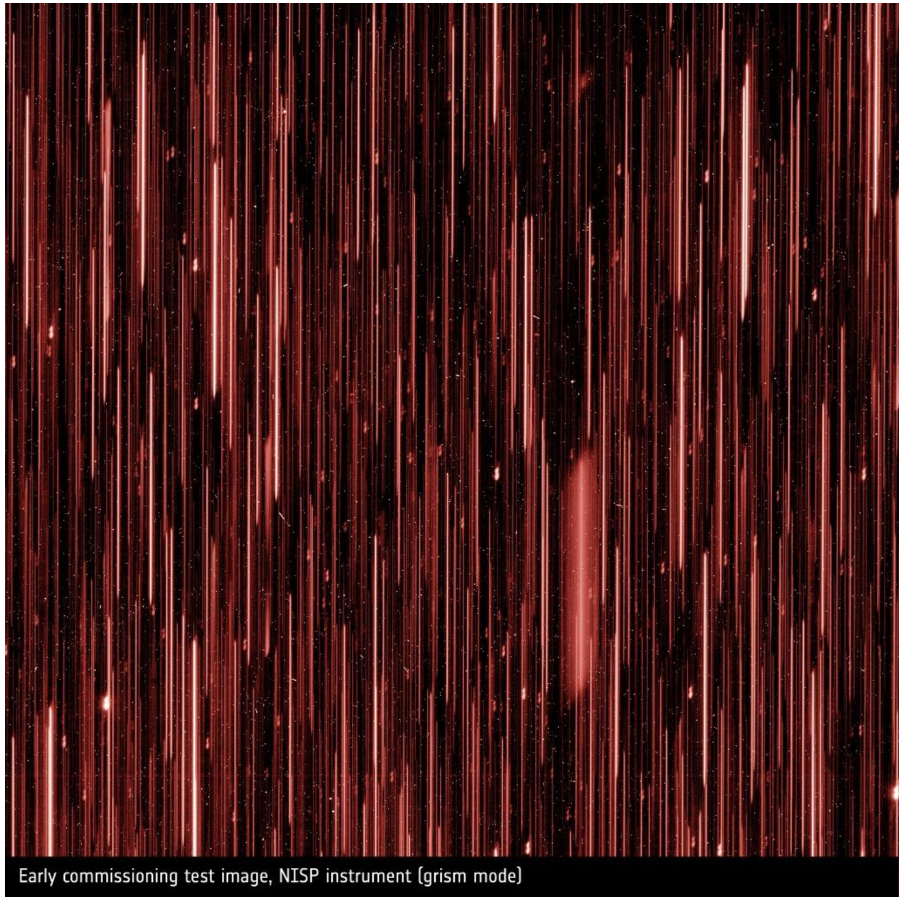
Unprocessed single VIS exposure

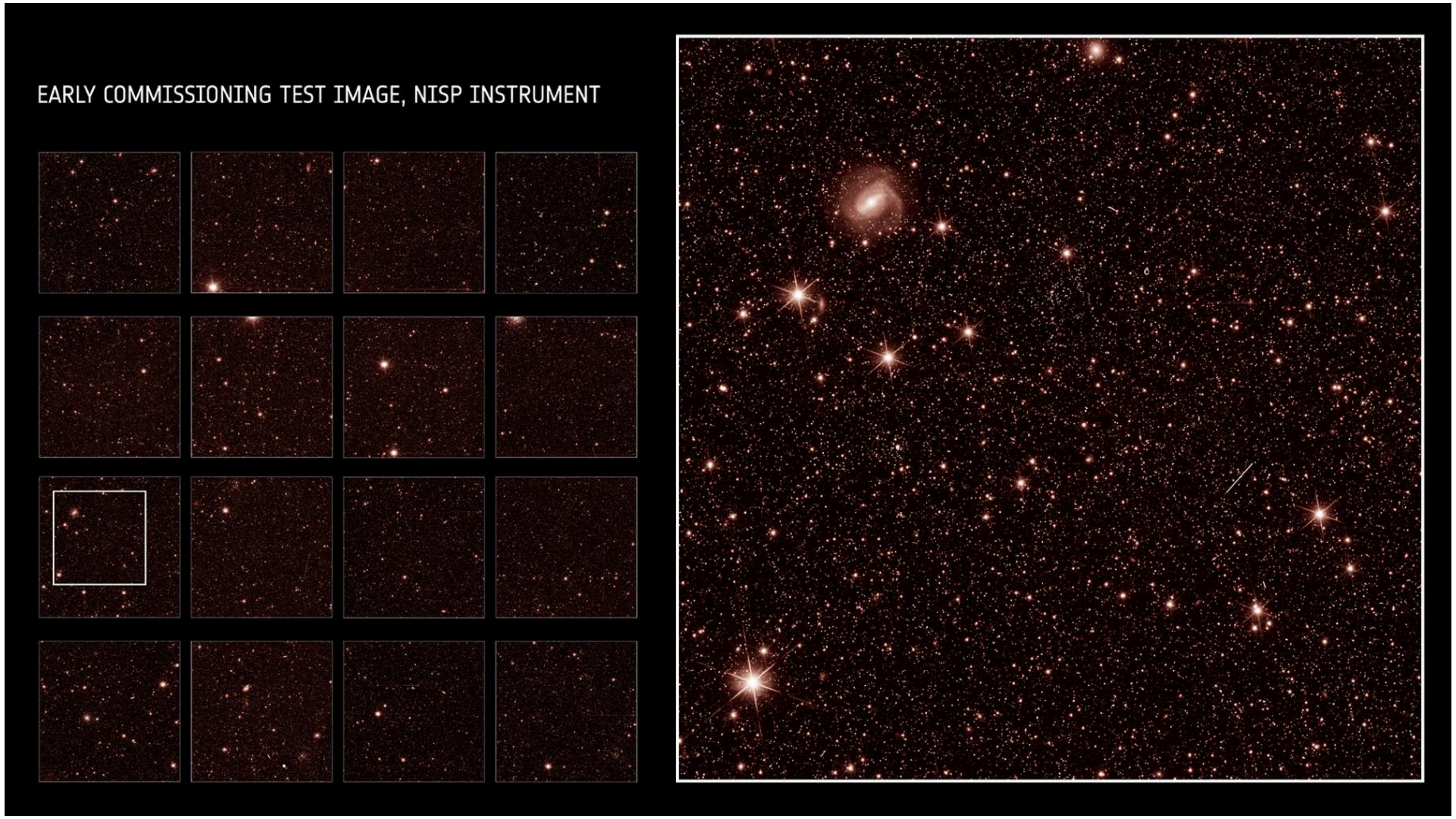


Stack of 42 exposures

NISP commissioning

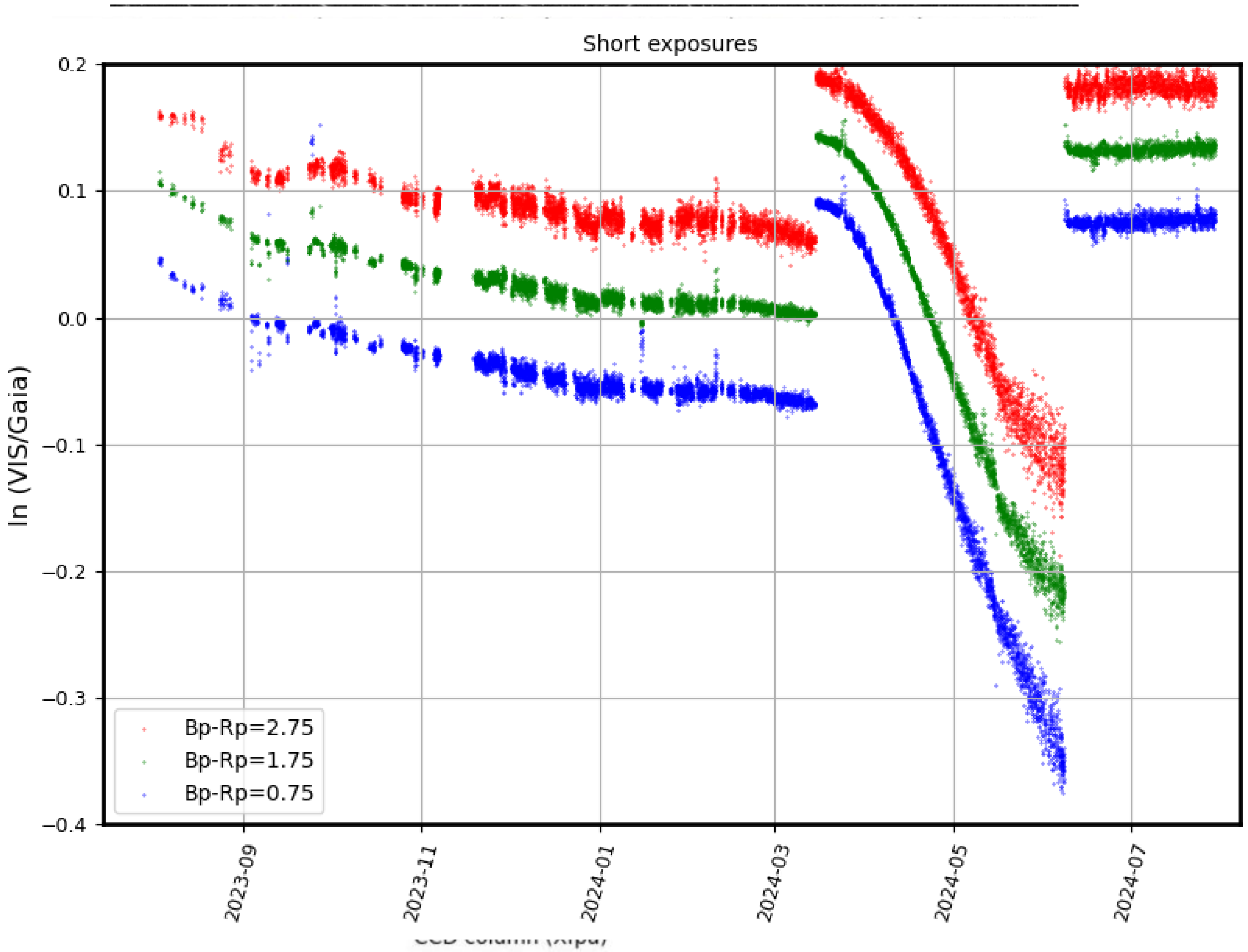
FOV 42’x44’ **NISP**: 16 HgCdTe arrays 2048x2048 0.3”/pixel Y/J/H-band imaging & R>400 slitless spectr.





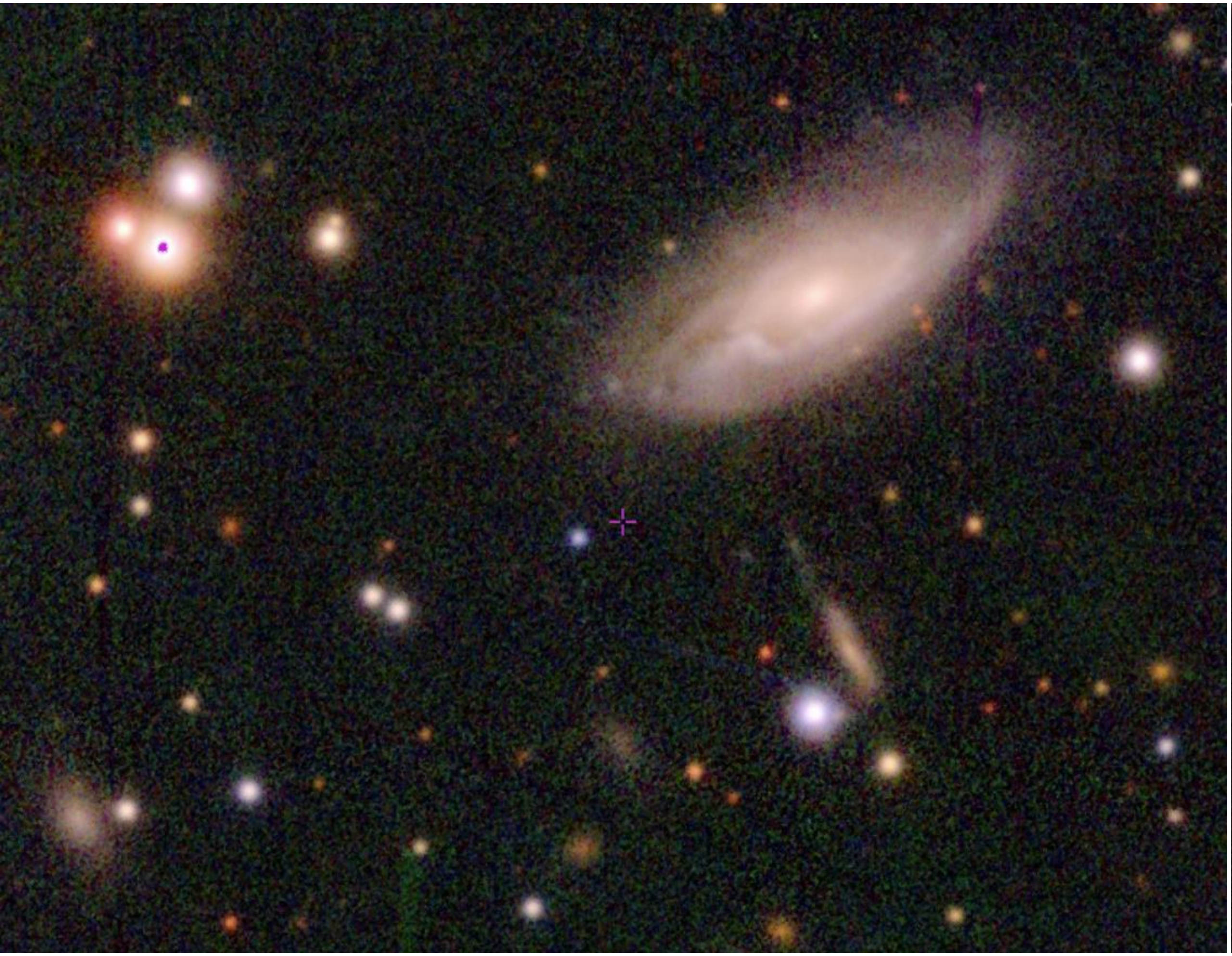
In space, no-one can hear you scream

- Cosmic rays: A fact of life at L2 …
- Straylight: A thruster nozzle scatters light past the sun shield through the thermal insulation and via a VIS shutter mounting leg to the VIS focal plane. Requires turning the satellite.
- X-rays from solar flares: X-rays can penetrate the sun shield in the gaps between the solar panels.
- Fine Guidance Sensor: Uses CCD’s at the edge of the focal plane. Cosmic rays were mistaken as guide stars, leading to a loss of tracking. A software patch has restored nominal performance.
- Ice deposits: Insulation absorbs moisture before launch. Outgasses in space and is deposited as ice on cold objects. Euclid has heaters, but in space, there are always surprises.



Example image : Perseus cluster

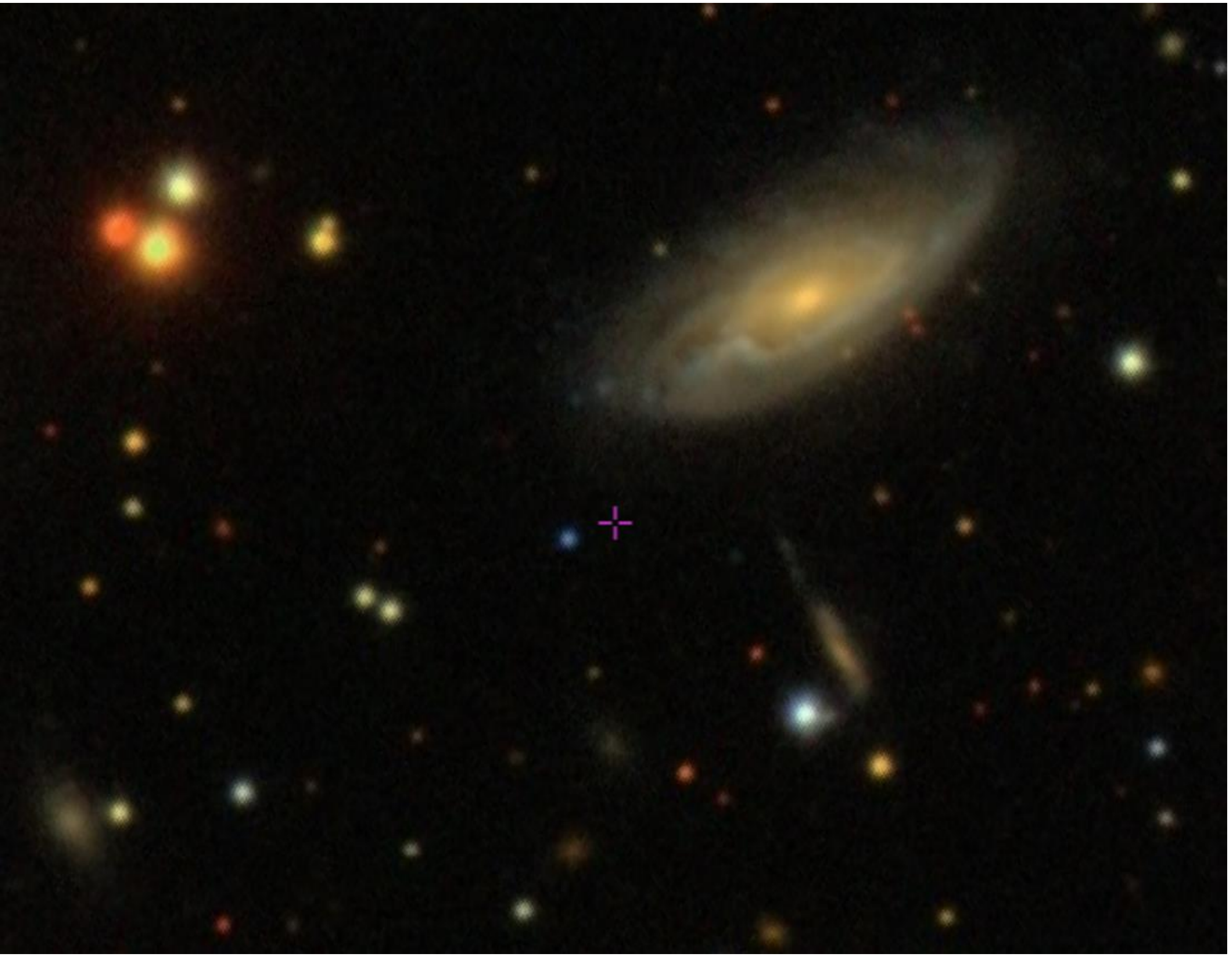
https://sky.esa.int/



PanSTARRS DR1

Euclid ERO

https://sky.esa.int/



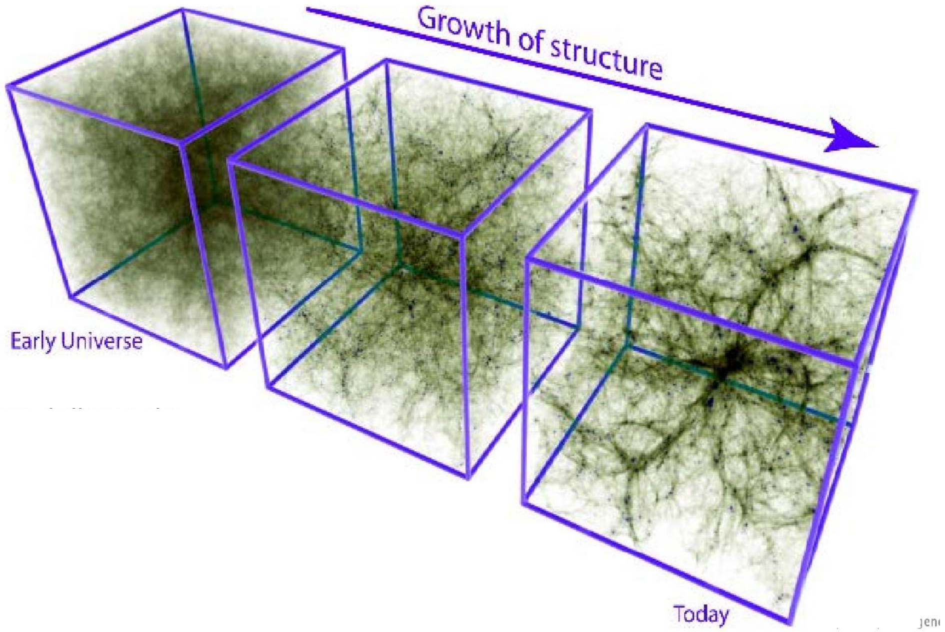
SDSS DR9

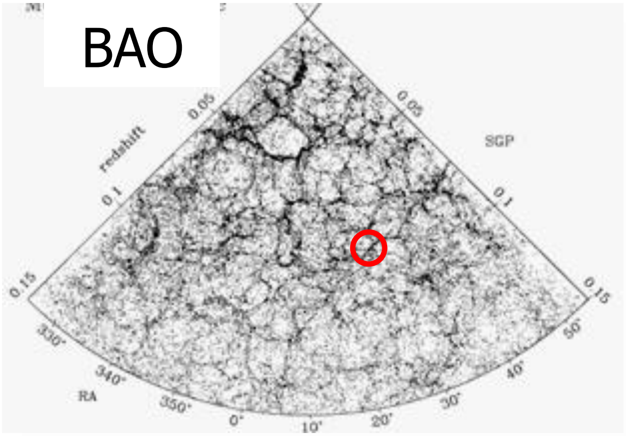
Euclid ERO

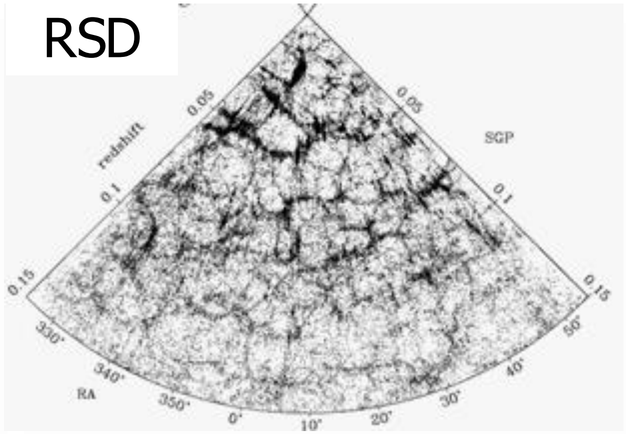
Galaxy clustering: BAO / RSD / P(k)

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.
- 30 million spectroscopic redshifts with 0.001 (1+z) accuracy over 14,000 deg^2



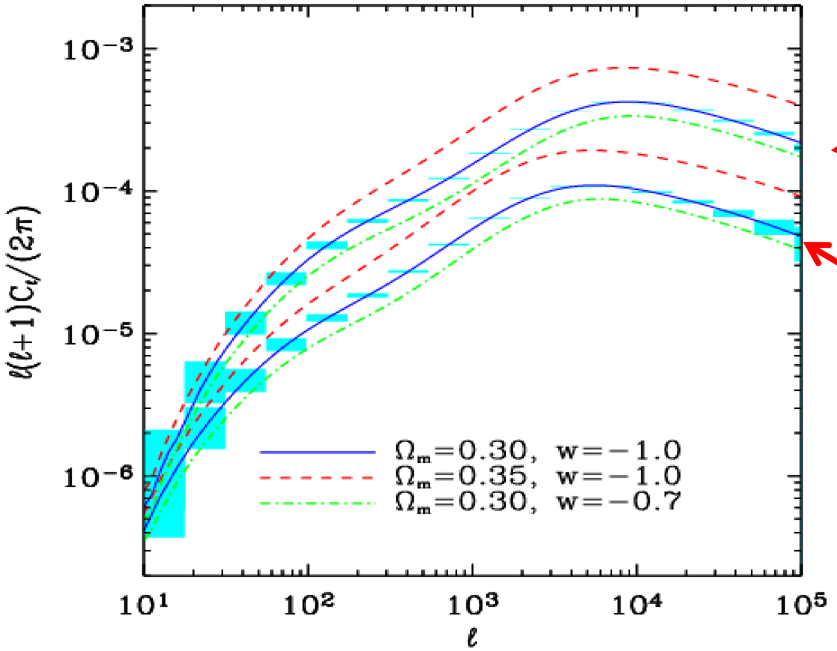


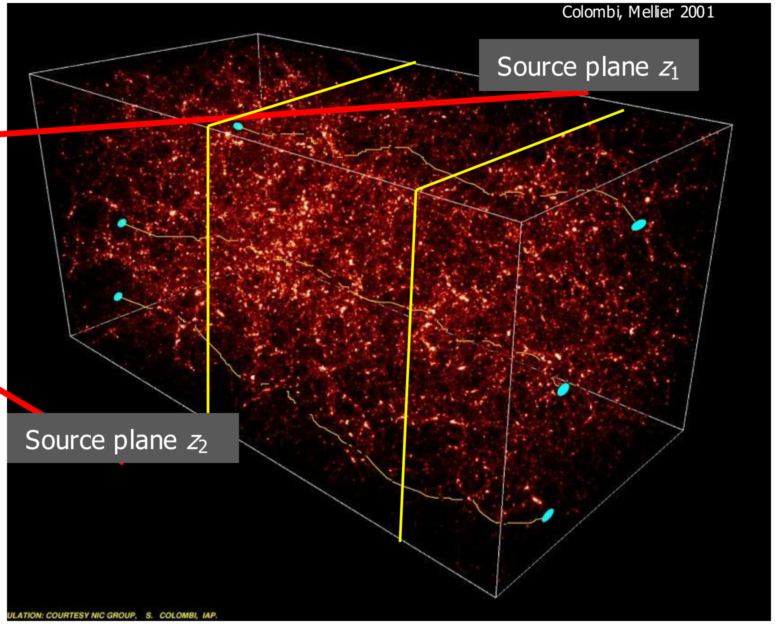


Weak lensing / photometric survey

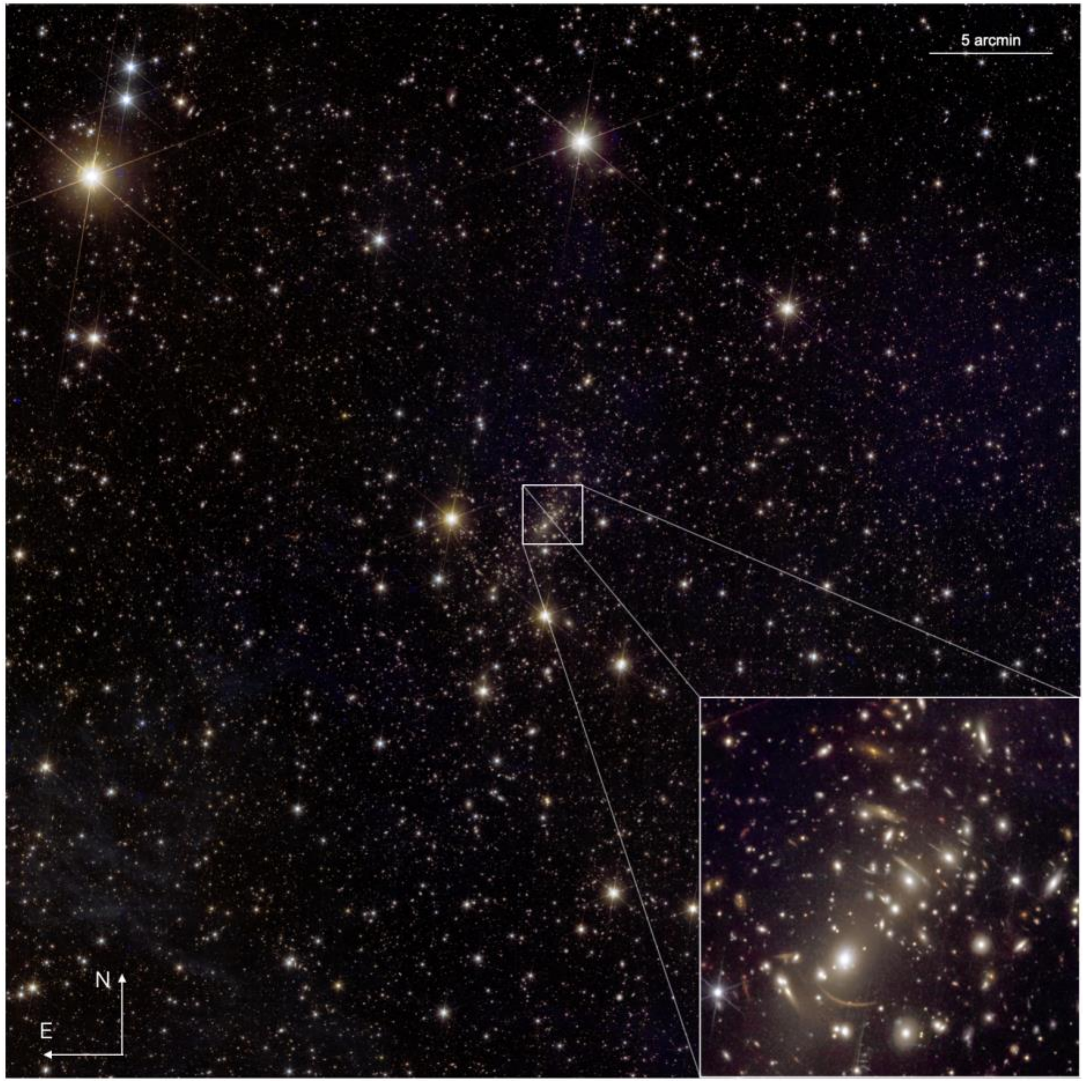
Cosmic shear over 0<z<2

- Probes distribution of matter (Dark +Luminous): expansion history, lensing potential φ+ψ.
  → Shapes+distance of galaxies: shear amplitude, and bin the Universe into slices.
  → "Photometric redshifts" sufficient for distances: optical+NIR data.
- WL + GCph (3x2pt) with 1.5 billion galaxies over 14,000 deg^2





Other probes : strong lensing

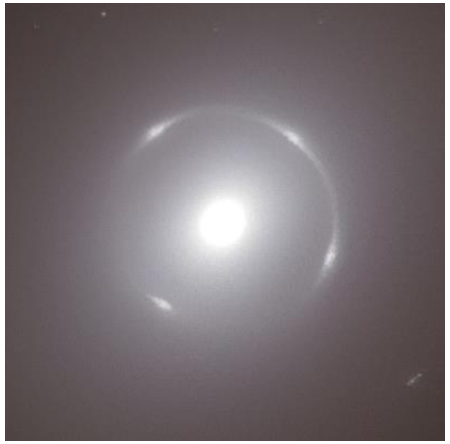


A2390 field (Euclid ERO, arXiv:2405.13504)

Q1 release (1 week of observations, 63 deg^2):
500 strong lenses (candidates), by end of 2026
7k SL, end of mission ~ 10^5 SL!

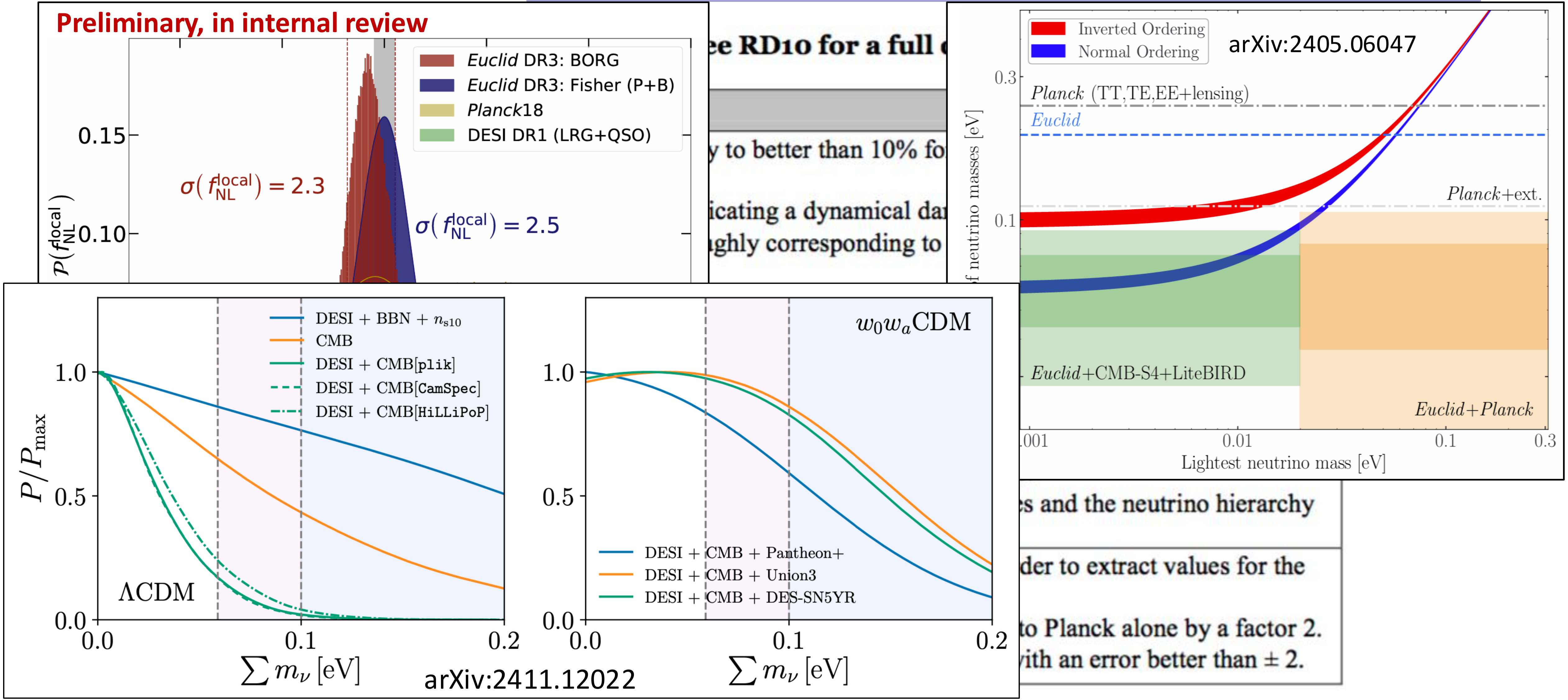
No human experts will be able to find this many lenses… Q1 used a combination of citizen science, expert review and AI models for both SL and galaxy classification.

(Euclid will be a treasure trove for astrophysics!)



Altieri's lens in NGC 6505
arXiv:2502.06505

Euclid main science objectives



Euclid main science 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.

DE/MG

How to model Dark Energy?

fundamental (action-based) models

effective field theories (action-based)

equivalent fluid description

phenomenological metric parameters

cosmological observations

more physical

more general

constrain physics

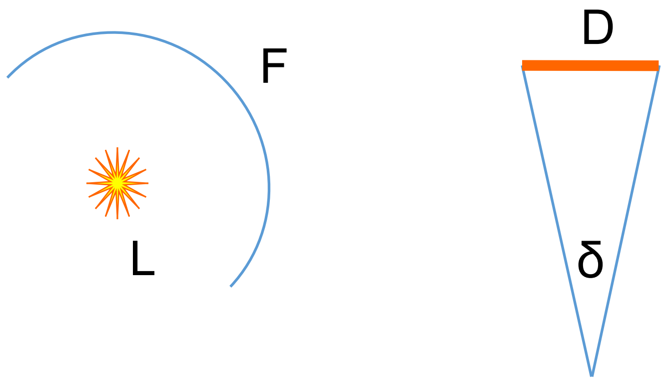
not independent

test for deviations

Euclid consortium

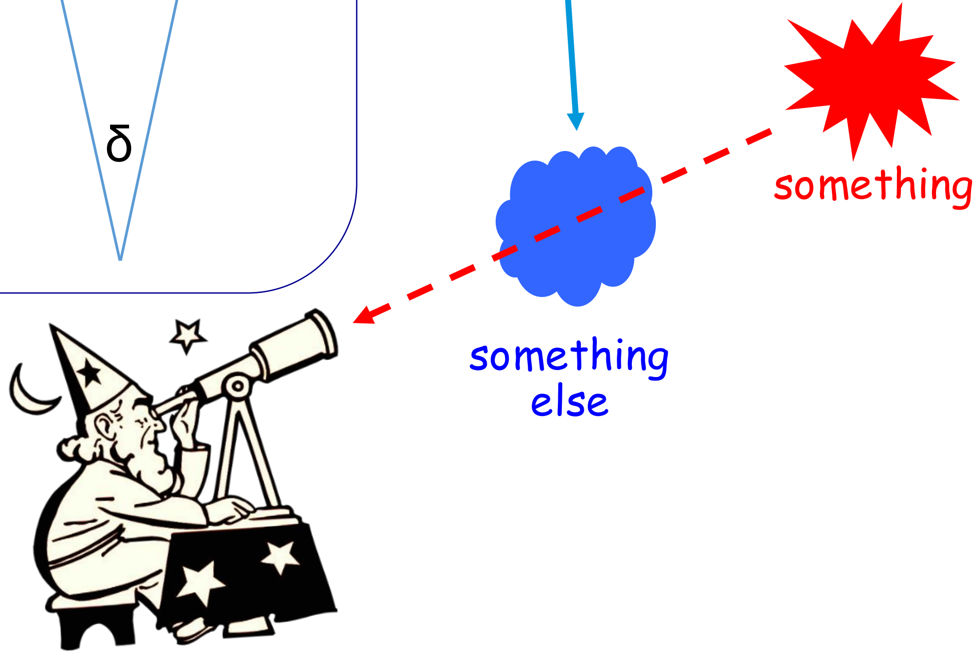
Phenomenology of the Dark Side

distances $d \sim \int_0^z \frac{dz}{H(z)}$



(metric) → geometry → $G_{\mu\nu} = 8\pi G T_{\mu\nu}$ ← stuff (what is it?)

(your favourite theory)



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\dot{\rho} = -3\frac{\dot{a}}{a}(1+w)\rho$$

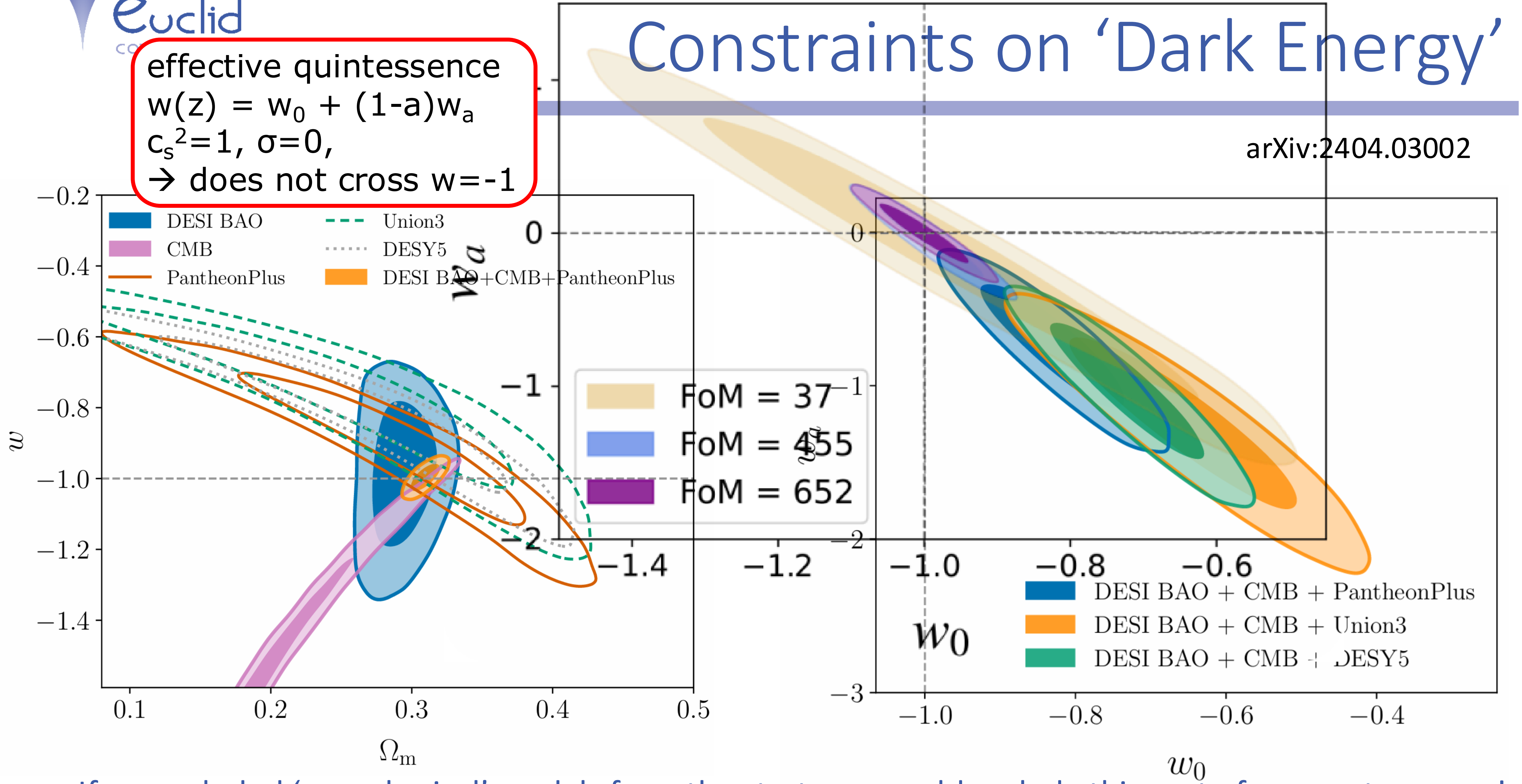
$p = w\, \rho$

Euclid. I. Overview of the Euclid mission, astro-ph/2405.13491

Constraints on 'Dark Energy'

effective quintessence
$w(z) = w_0 + (1-a)w_a$
$c_s^2=1$, $\sigma=0$,
→ does not cross w=-1

arXiv:2404.03002



- If we excluded 'non-physical' models from the start, we would exclude this part of parameter space!
- Real or not? Need more data – and for systematics, Euclid will tell! (Maybe not yet at DR1)

Euclid Figure of Merit

w_0, w_a FoM	Flat	Non-flat
Linear setting		
GC_s	40	19
Pessimistic setting		
GC_s	14	10
WL	23	5
GC_s+WL	99	40
GC_{ph}+WL	64	14
GC_s+WL+GC_{ph}	123	49
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	367	59
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	377	128
Optimistic setting		
GC_s	55	19
WL	44	12
GC_s+WL	157	87
GC_{ph}+WL	235	129
GC_s+WL+GC_{ph}	398	218
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	1033	326
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	1257	500

Euclid prep VII: Forecast validation
Blanchard et al, arXiv:1910.09273

Comments:

- FoM ~ inverse of w_0/w_a error ellipse.
- ESA expects a FoM of 400 for Euclid alone.
- Errors on w_0/w_a :
  - Planck + BAO/SN-Ia : 0.080 / 0.3
  - Planck + BAO/RSD WL : 0.2 / 0.6
  - Euclid 3x2pt pessimistic: 0.042 / 0.17
  - Euclid 3x2pt optimistic : 0.027 / 0.10
- Euclid error on w const : 0.0087
- Adding CMB can improve errors by ca 50% cf Ilic et al, arXiv:2106.08346
- There are other probes (eg clusters, strong lensing) and combinations (6x2pt, external).

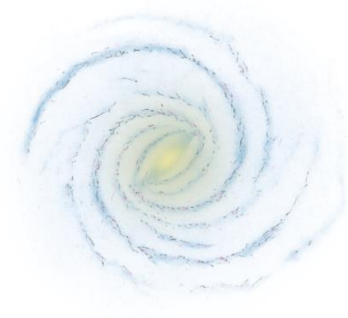
Metric phenomenological parameters

(e.g. Amendola et al, arXiv:0704.2421)

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

→ characterize deviation of metric from reference (like PPN but in a cosmological context)
→ Geometry instead of fluid properties

Light deflection (lensing) : $\nabla_\perp(\Phi+\Psi)$



Acceleration : $\nabla\Psi$
(RSD)

(of course there are many other observations)

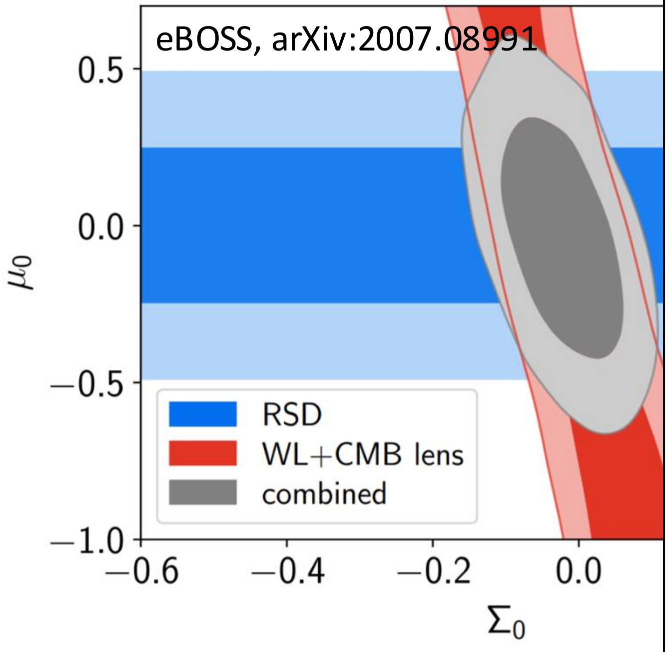
$$-k^2\Psi = \frac{4\pi G_{\mathrm{N}}}{c^2}\,a^2\mu(a,k)\left[\bar{\rho}\Delta + 3\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\right],$$

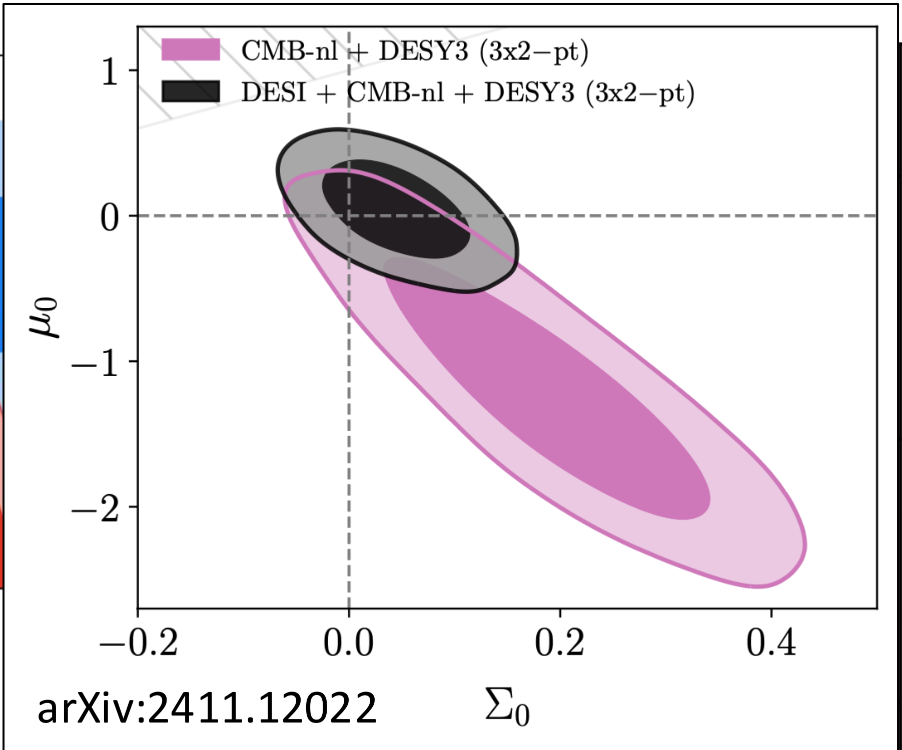
$$-k^2(\Phi+\Psi) = \frac{8\pi G_{\mathrm{N}}}{c^2}\,a^2\Big\{\Sigma(a,k)\left[\bar{\rho}\Delta + 3\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\right] - \frac{3}{2}\mu(a,k)\left(\bar{\rho}+\bar{p}/c^2\right)\sigma\Big\},$$

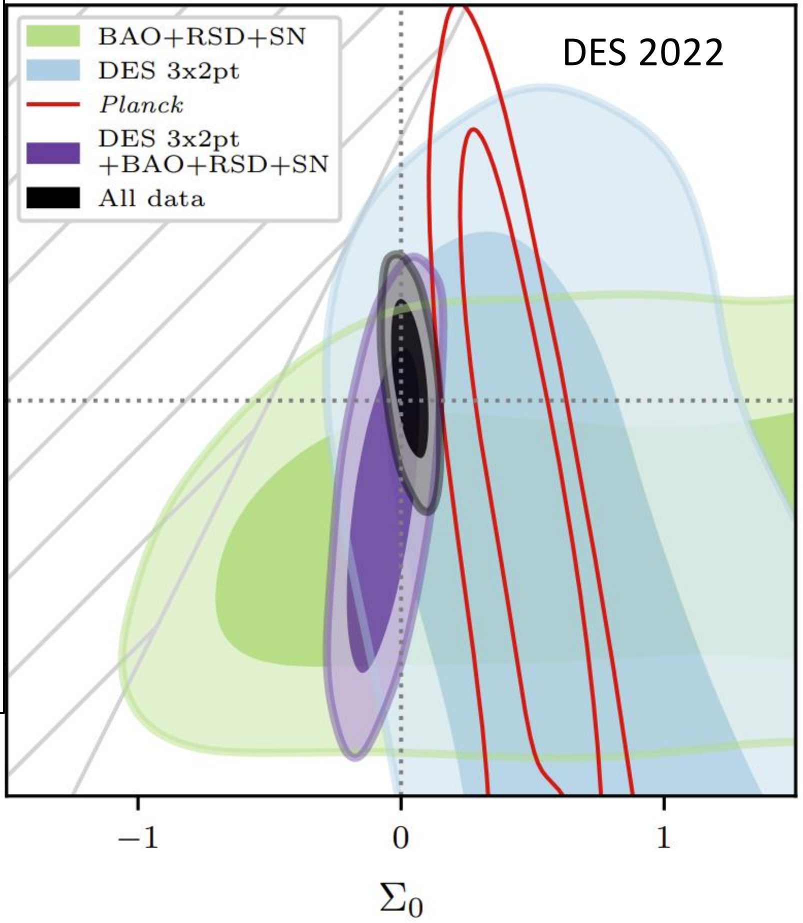
Alternatively replace one by slip, an observable and 'MG' diagnostic : $\eta = \Phi/\Psi$.

$$\Sigma = \frac{1}{2}\mu(1+\eta)$$

Constraints on “Modified Gravity”





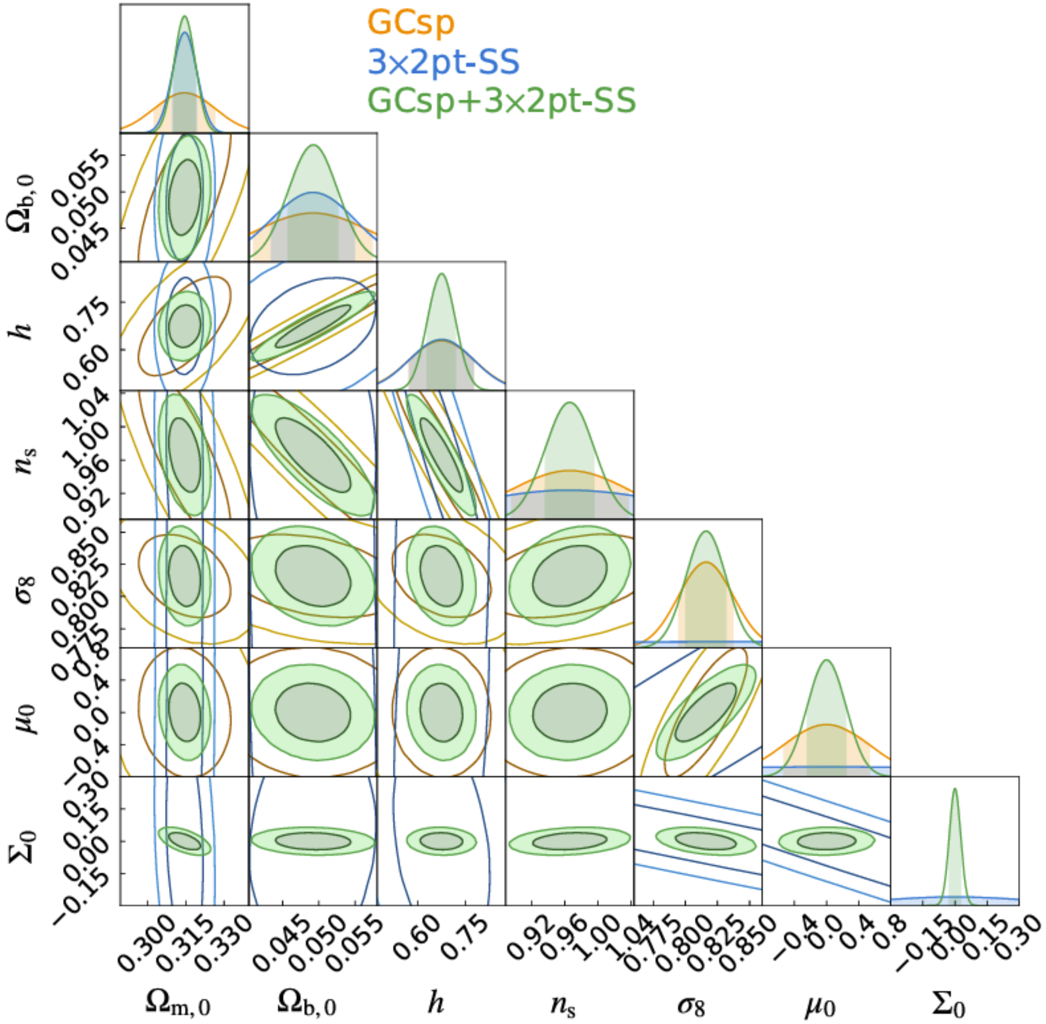


- Σ: ($\Phi+\Psi$) → lensing
  Limit: ~ 0.05
- μ: Ψ → acceleration of massive particles
  Limit: ~ 0.25

Need to careful about background choice, parametrisations and fixed parameters.

Constraints on “Modified Gravity”

Euclid Collaboration, Albuquerque et al, in internal review



GCsp + 3x2pt,
proportional to $\Omega_{DE}(z)$:

- $\sigma(\Sigma) \sim 0.026$
- $\sigma(\mu) \sim 0.23$

→ Combine with additional data for stronger constraints.

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How to model Dark Energy?

fundamental (action-based) models

effective field theories (action-based)

equivalent fluid description

phenomenological metric parameters

cosmological observations

more physical

more general

constrain physics

not independent

test for deviations

EFT of DE

$$S^{(2)} = \int d^3x dt a^3 \frac{M^2}{2}\left[\delta K_{ij}\delta K^{ij} - \delta K^2 + (1+\alpha_T)\left(R\frac{\delta\sqrt{h}}{a^3} + \delta_2 R\right) + \alpha_K H^2 \delta N^2 + 4\alpha_B H\, \delta K\, \delta N + (1+\alpha_H) R\, \delta N\right]$$

(Bellini & Sawicki 2014, Gleyes et al 2015)

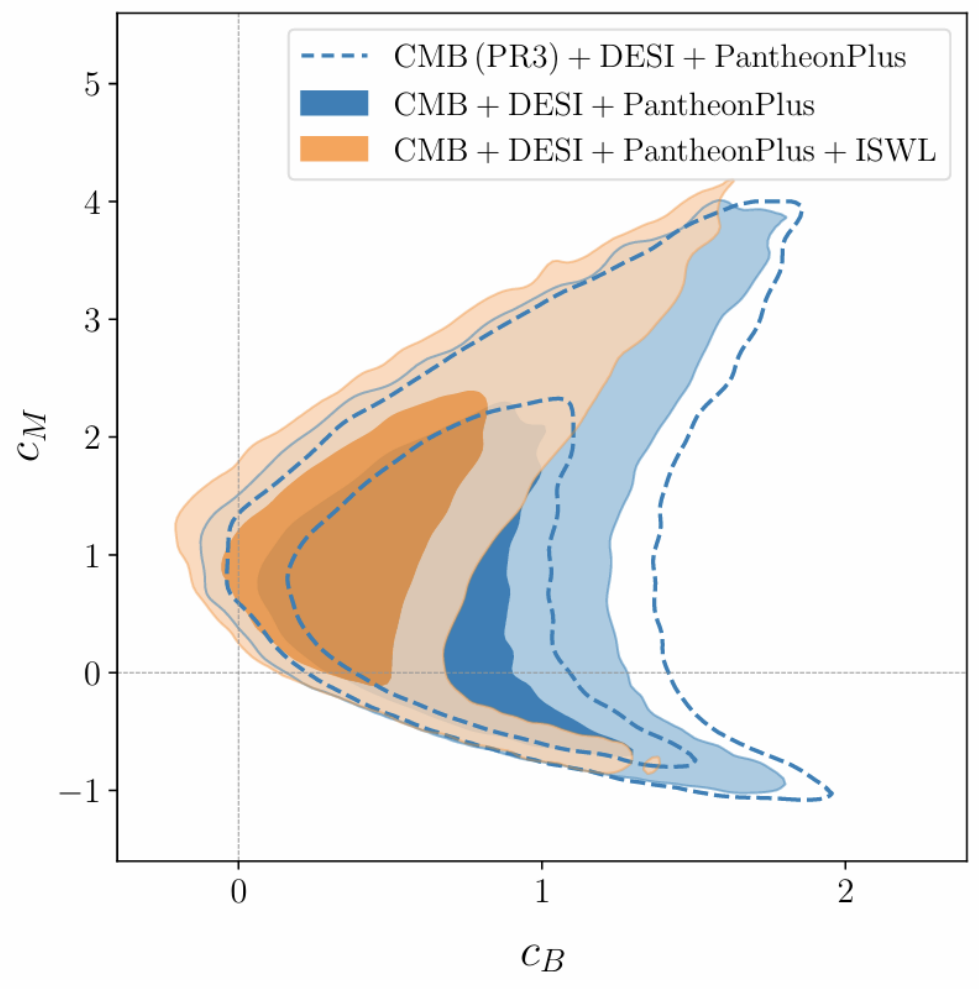
- **H(t):** background evolution → for us parametrised as w(z)
- **α_K(t):** "kineticity" – kinetic energy : large α_K = small c_s^2 → difficult to constrain [i.e. can fix]
- **α_B(t):** "braiding" – mixing of kinetic terms and metric, contributes to DE clustering
- **α_M(t):** "Planck mass run rate", $\alpha_M = 1/(2H)\, d(\ln M^2)/dt$, contributes to anisotropic stress, 'modified gravity'
- **α_T(t):** "tensor speed excess", also contributes to anisotropic stress → small since GW speed = light speed (?)
- **α_H(t):** "beyond Horndeski", higher order term in Einstein eq. that cancels in e.o.m. → also strong limits

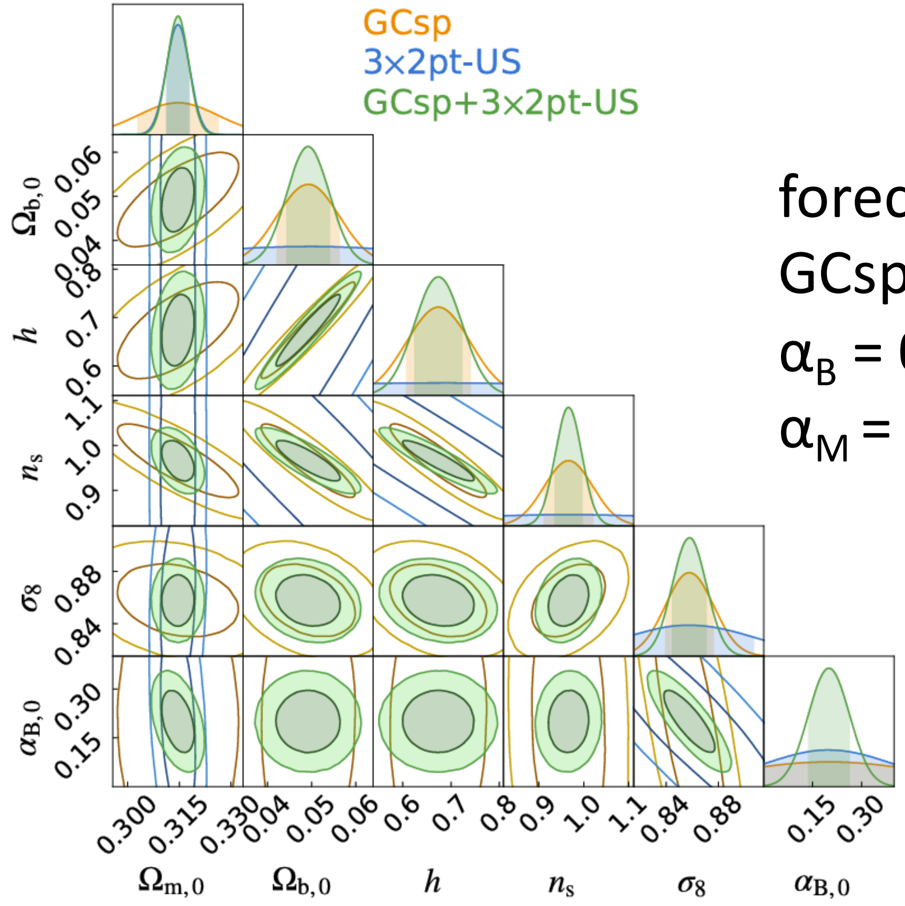
- This model class can cross w=-1
- In the EFT philosophy, these are 'properties of the material' (i.e. dark energy) and to be measured from data, there is no a priori hierarchy in EFT's
- There are also stability conditions on the α_i like $c_s^2>0$, $c_T^2>0$, positive kinetic terms, cf Bellini & Sawicki 2014

Constraints on “Modified Gravity”

Euclid Collaboration, Albuquerque et al, in internal review

Chudaykin+, arXiv:2503.09893





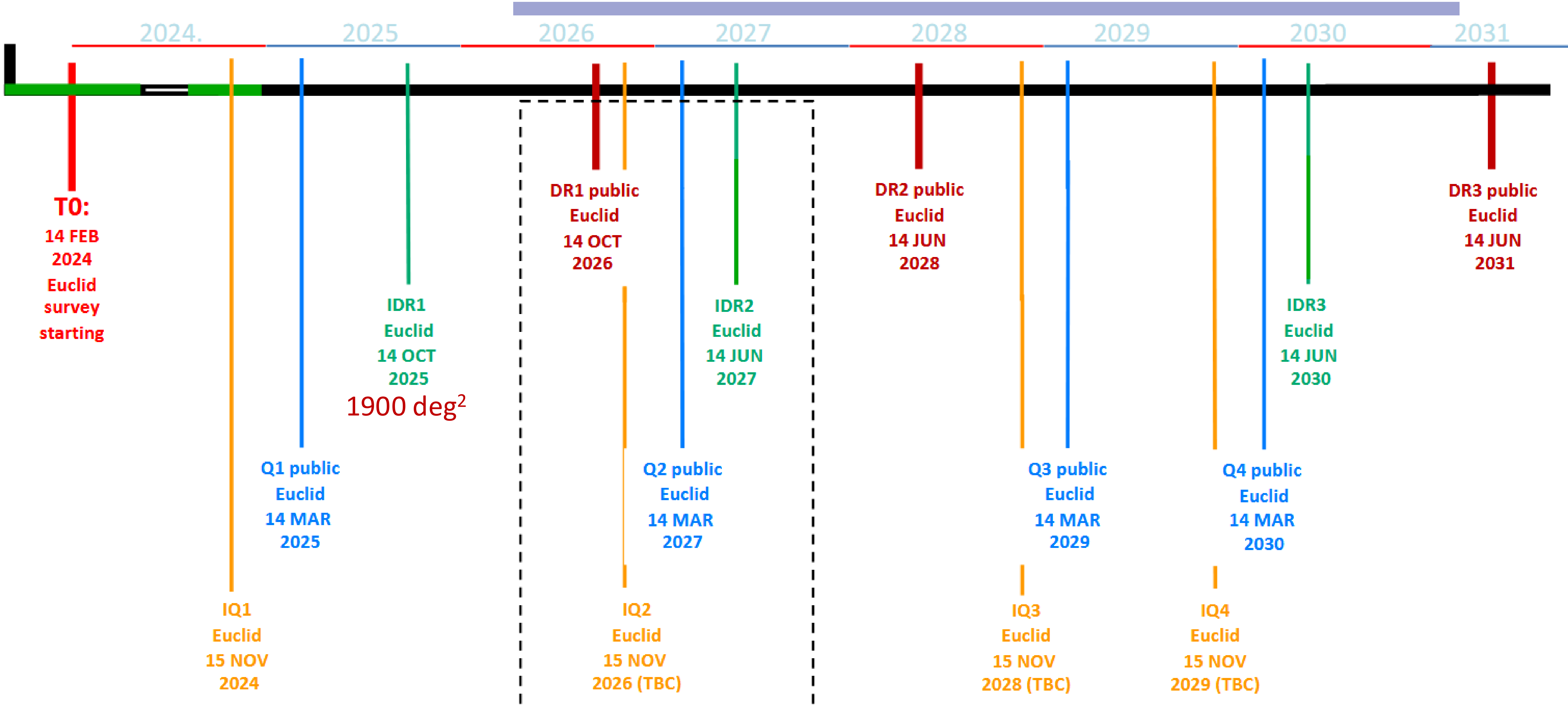
forecast (linear in a)

GCsp + 3x2pt :

α_B = 0.2 +/- 0.06

α_M = 0 (fixed)

Euclid timeline



Conclusions

- Euclid was successfully launched and is producing copious amounts of data. The first 'cosmology' data release will be in October 2026. Meanwhile, see also https://esa.int/euclid and esasky for updates, images, etc.
- Decades of development, but still many things to think about :
  - Simply finding stuff in the data deluge – is ML/AI the (only) answer?
  - Beyond power spectrum : is bispectrum enough? Field-level inference?
  - Accelerated inference, emulators, differential likelihoods, improved samplers
  - Non-linear scales & baryons
  - Cross-correlations – good for statistics and for systematics, but is data compatible?
  - New (or new old) observables (e.g. strong lensing, magnification, clusters, …)
  - Are the target theories all known and well understood? **(Certainly not!)**
- Much is still to be discovered, now with new data!


Thank you!