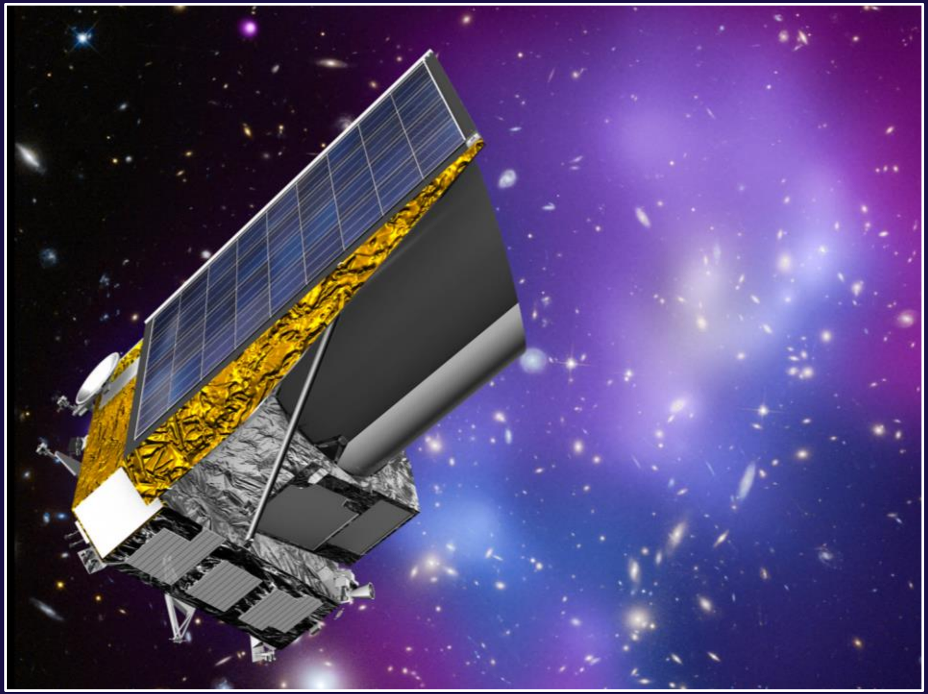
Science with Euclid

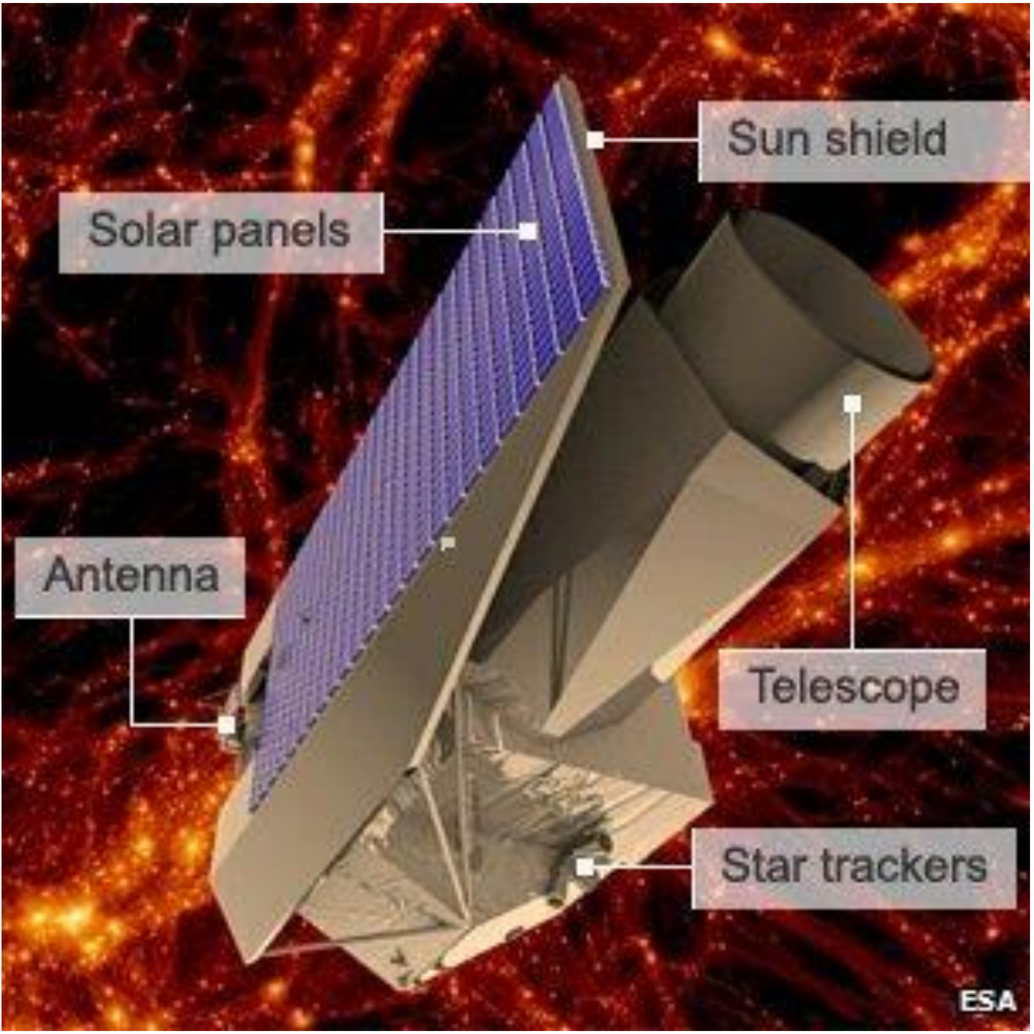


Carmelita Carbone (for the Euclid Consortium)

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS
Istituto di Astrofisica Spaziale e Fisica cosmica di Milano

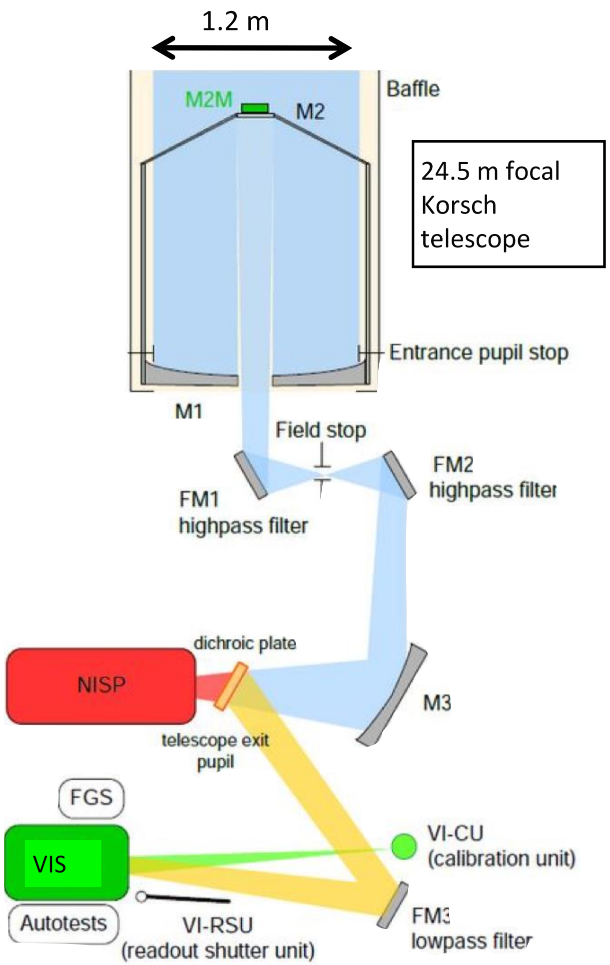
NuPhys2023: Prospects in Neutrino Physics
December 18th, King's College, London

The Euclid Mission



- Medium-class ESA mission
- 1.2m mirror telescope
- Optical imager (R+I+Z) (VIS)
- NIR-photometer (Y, J, H) (NISP-P)
- NIR-spectrograph slitless (NISP-S)
- **Launch July 2023**, Orbit L2
- Mission duration 6 years
- **Cosmology**
    - **Galaxy Clustering**
    - **Cosmic shear**
    - **Galaxy Clusters**
    - **Cosmic Voids**
    - **CMBX**
    - **Strong Lensing**
- **Legacy Science**

Euclid payload: two instruments for two probes



Overview of the PLM sub-systems – Courtesy Airbus Defence and Space.

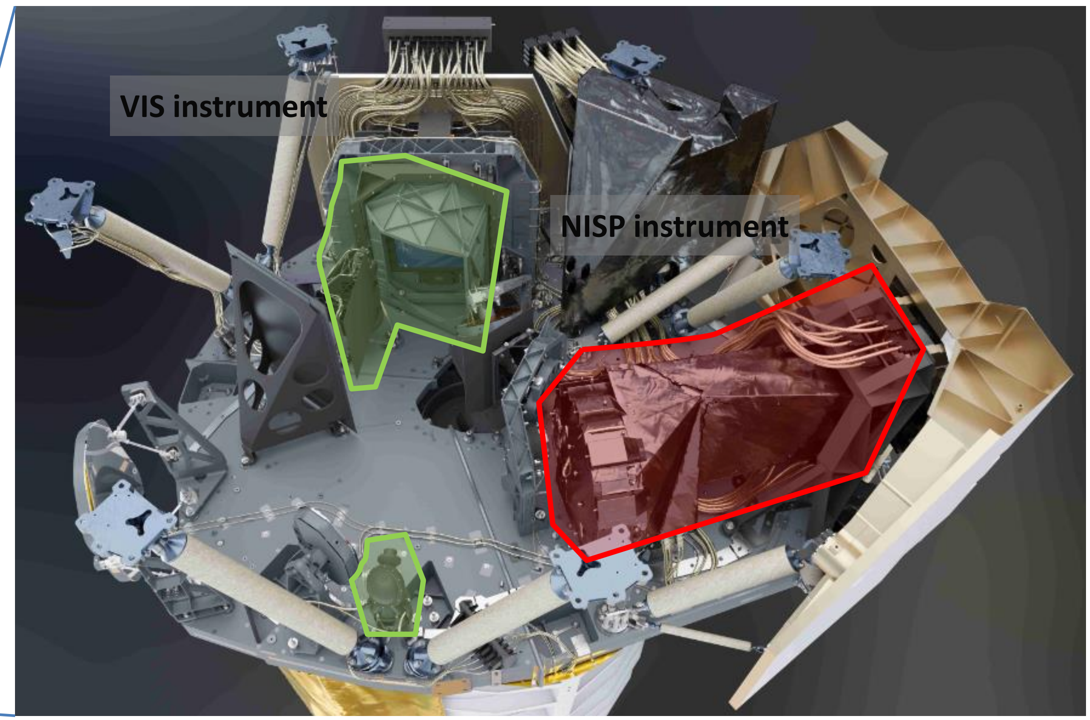
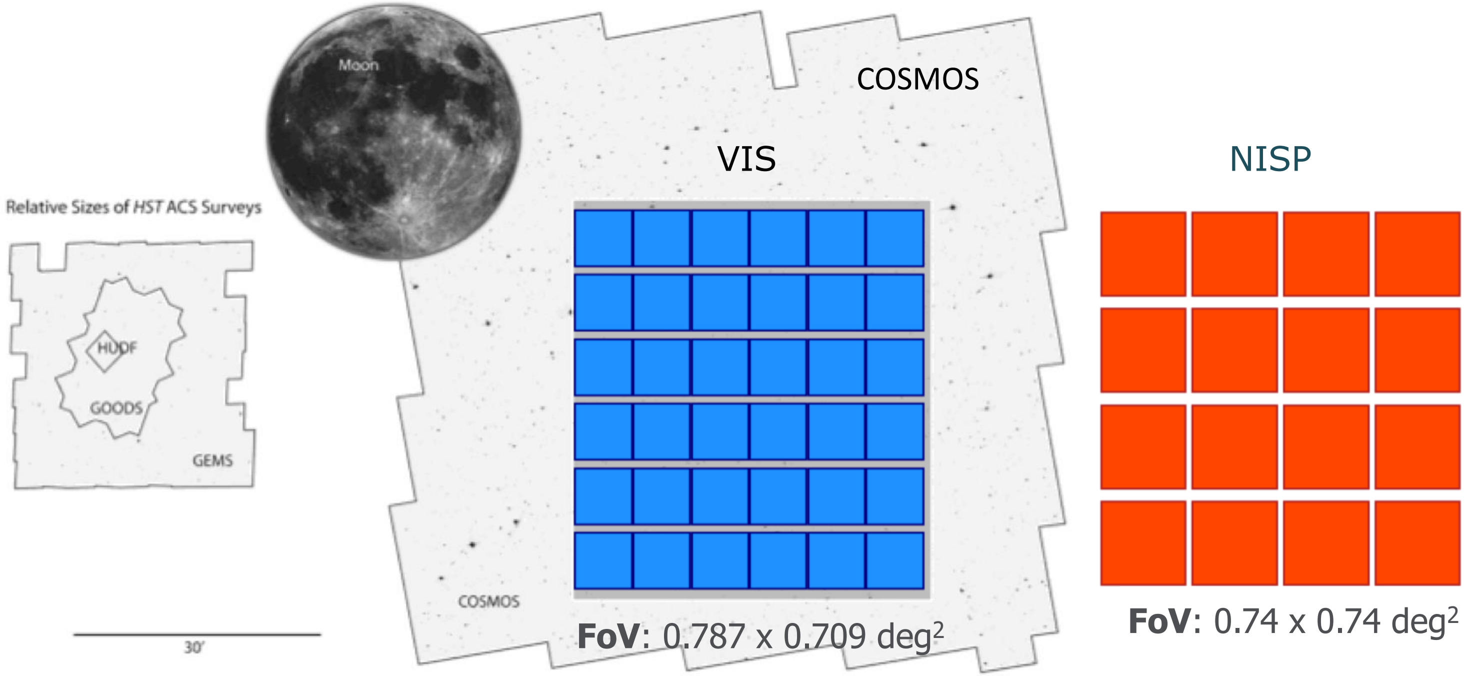


Photo: courtesy ESA/TAS

Euclid: dual wide-field imager



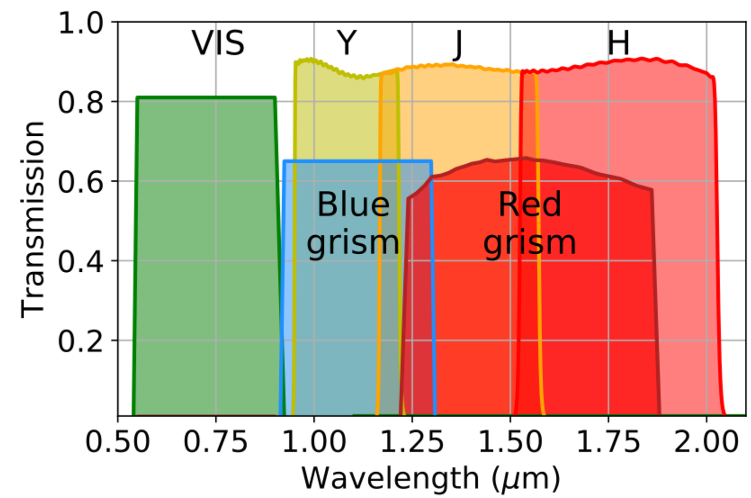
Credit: Space Telescope Science Institute/Nick Scoville (Caltech)

VIS and NISP are both wide field imagers covering about 0.55 deg^2

VIS has 36 CCDs with pixel size 0.1”, enabling the weak lensing science.

NISP has 16 detectors with pixel size 0.3”.
The spectroscopy resolution will be about 380, which will be well sampled with 13.4”/pixel.

Credits: B. Granett

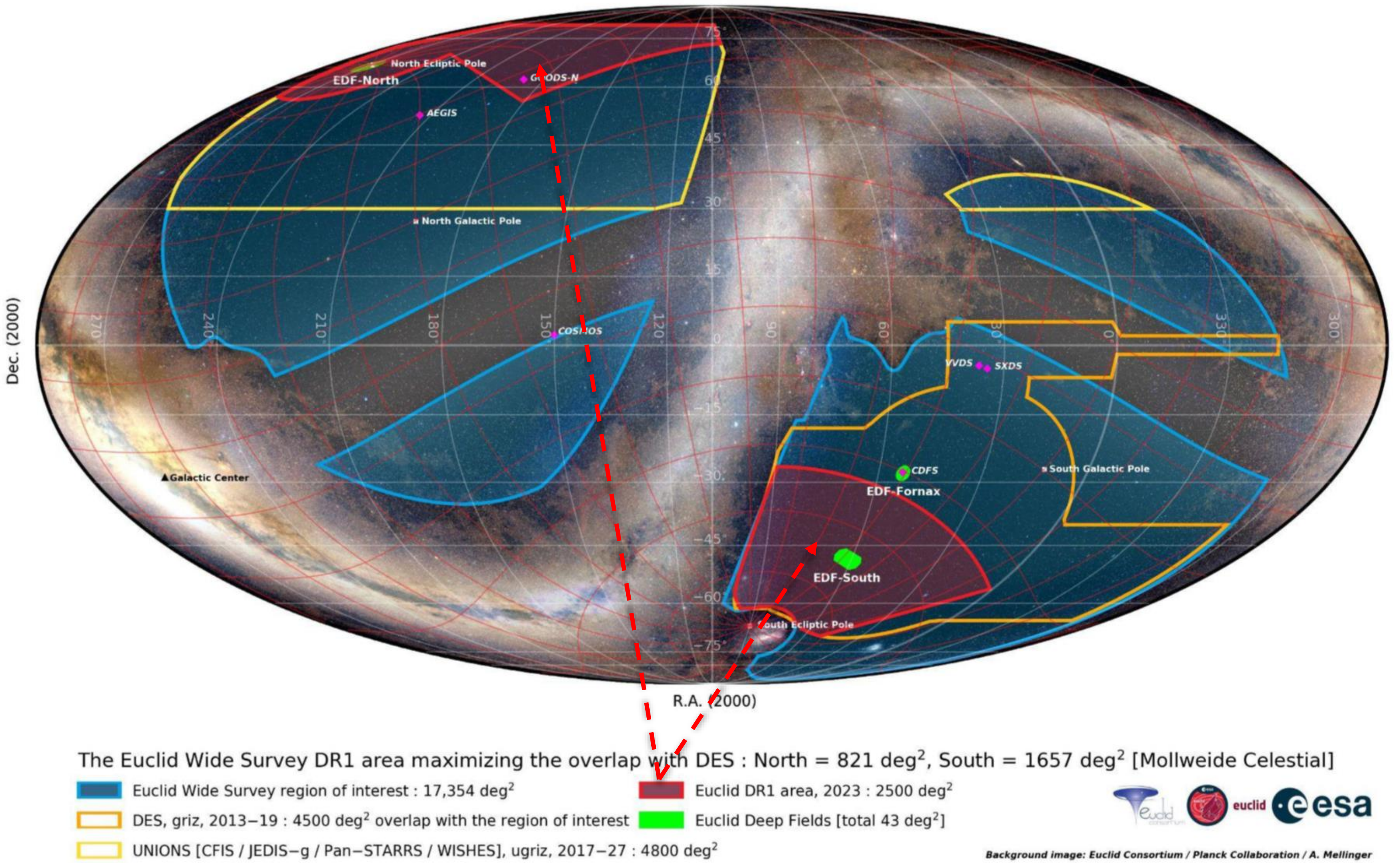


*Blue grism is exposed on Deep fields only

Euclid FoV comparison

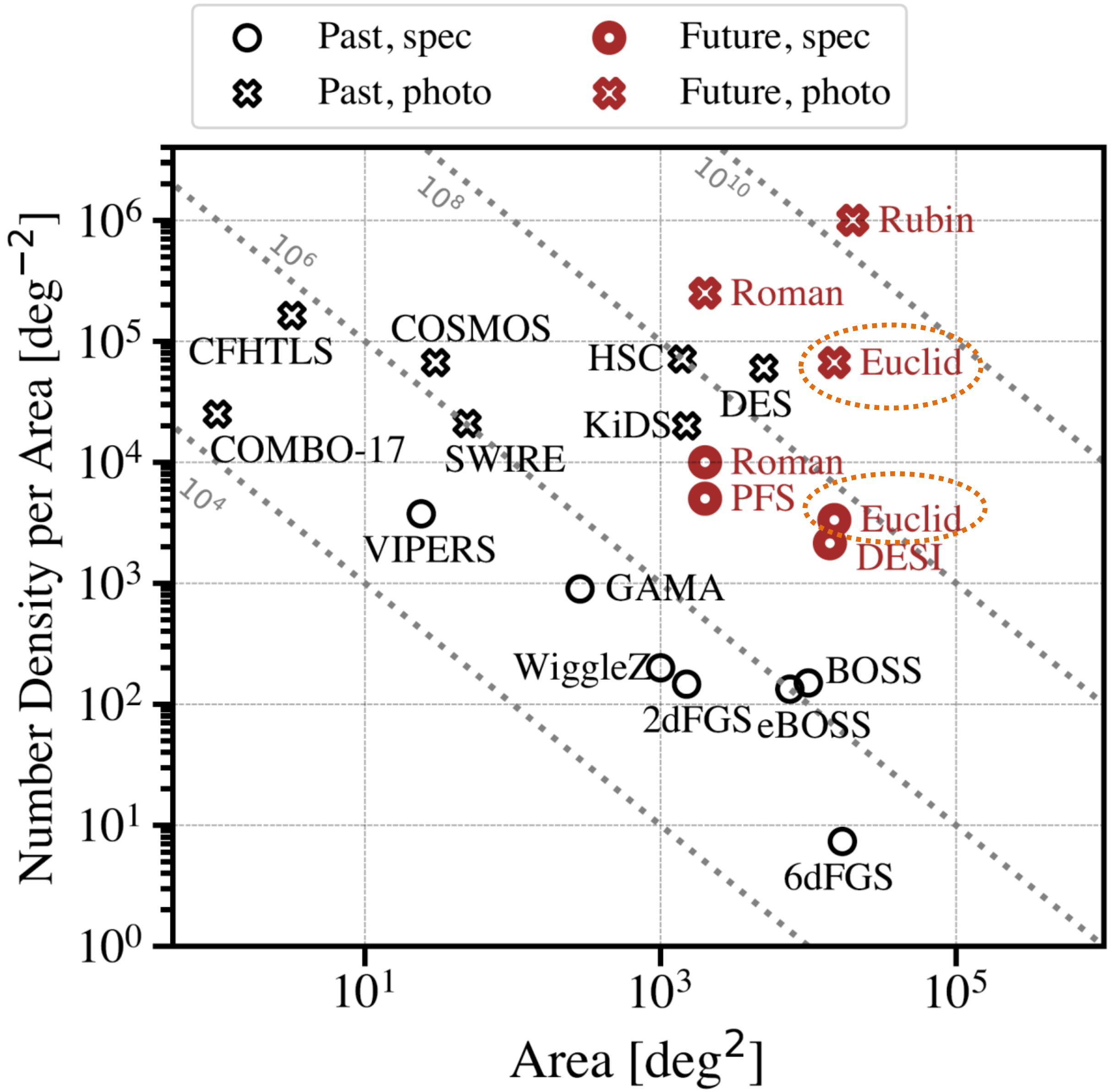
Credits: Yuzheng Kang

The Euclid sky



Credits: J.-C. Cuillandre and the ECSURV team

The Euclid survey in context



Hou et al. 2023

The Euclid Launch

Date: July 1, 2023

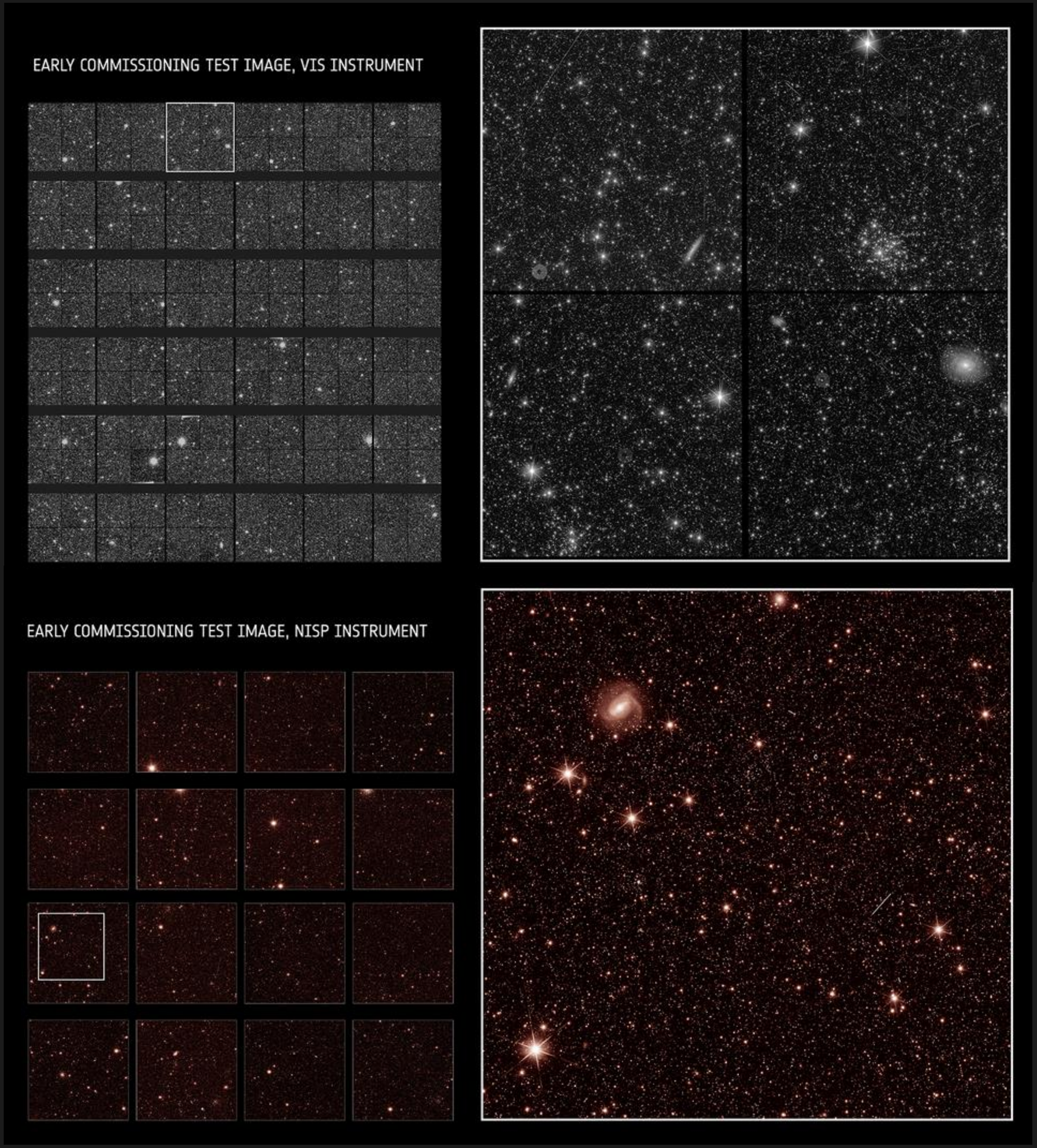
Launch site: Cape Canaveral, Florida

Launch vehicle: SpaceX Falcon 9

Destination: Sun-Earth Lagrange Point 2, 1.5 million km from Earth

Arrival: late July

Euclid early commissioning test images



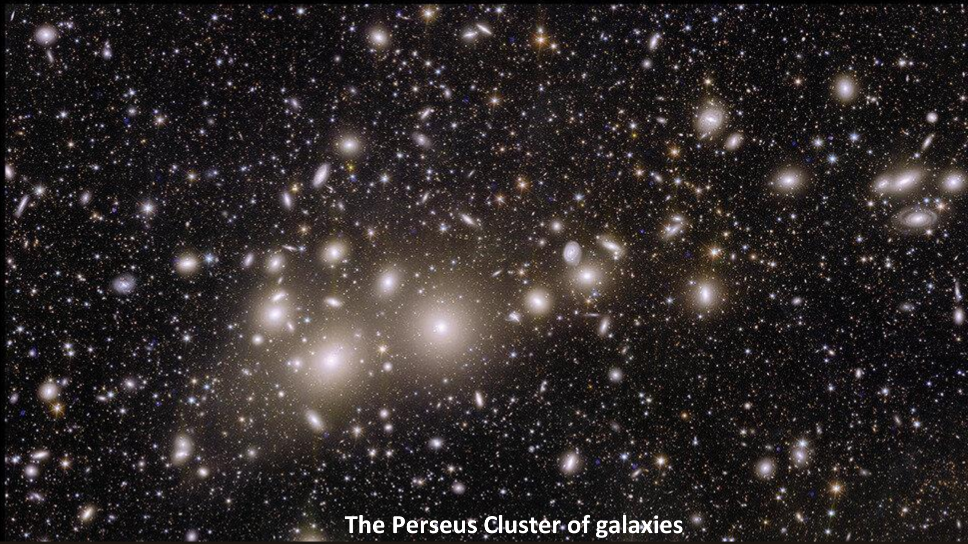
Early Release Observations: the dazzling edge of darkness


Spiral galaxy IC 342

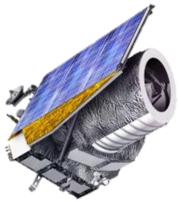

The Horsehead Nebula


Globular cluster NGC 6397

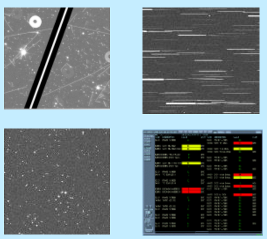

Irregular galaxy NGC 6822


The Perseus Cluster of galaxies

Euclid Data Products from OUs

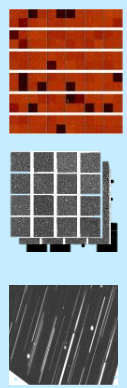


L1 Products

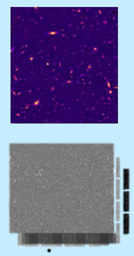


Unpacked raw science data & telemetry

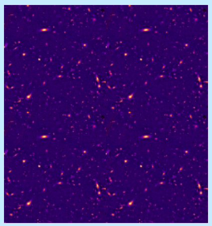
L2 Products



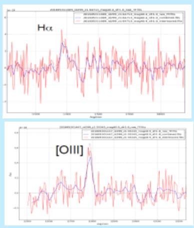
Calibrated Frames



Stacked Frames



Mosaics



Catalogues

- Object Position
- Photometry
- Spectra
- Photo-z
- Spec-z
- Ellipticities

L3 Products

Weak Lensing Power Spectrum

Galaxy Clustering 2-point Correlation Function

+ Legacy Science Products

Science-ready data

THE DARK ENERGY SURVEY

KiDS

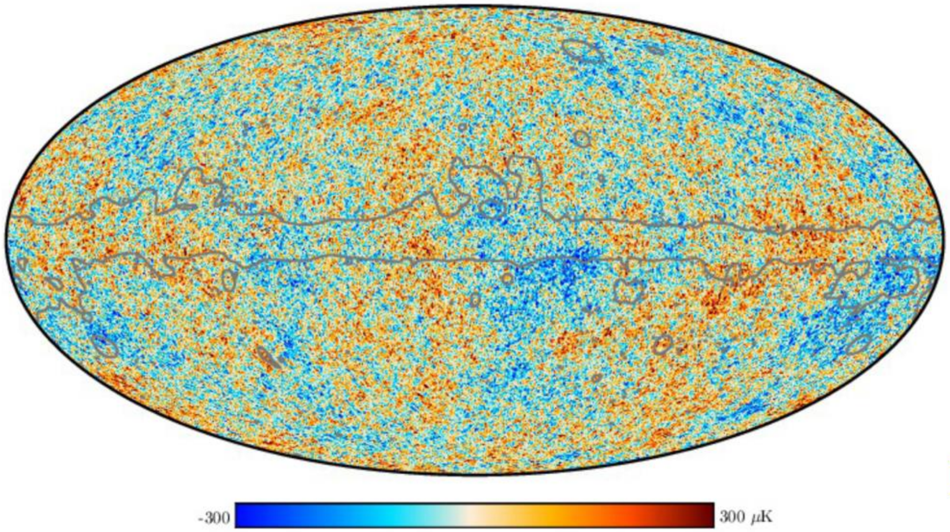
Data from external surveys

- **Shapes and Photo-z for ~10^9 galaxies**
- **Spectroscopic Redshifts for ~2×10^7 galaxies**

Euclid generates a series of data products available to the community via the **Euclid Archive System** (EAS).

The ΛCDM model from Planck

Planck Collaboration et al (2020):



The best fit model has 6 parameters:

$$\Omega_b h^2 = 0.02237 \quad (0.67\%)$$

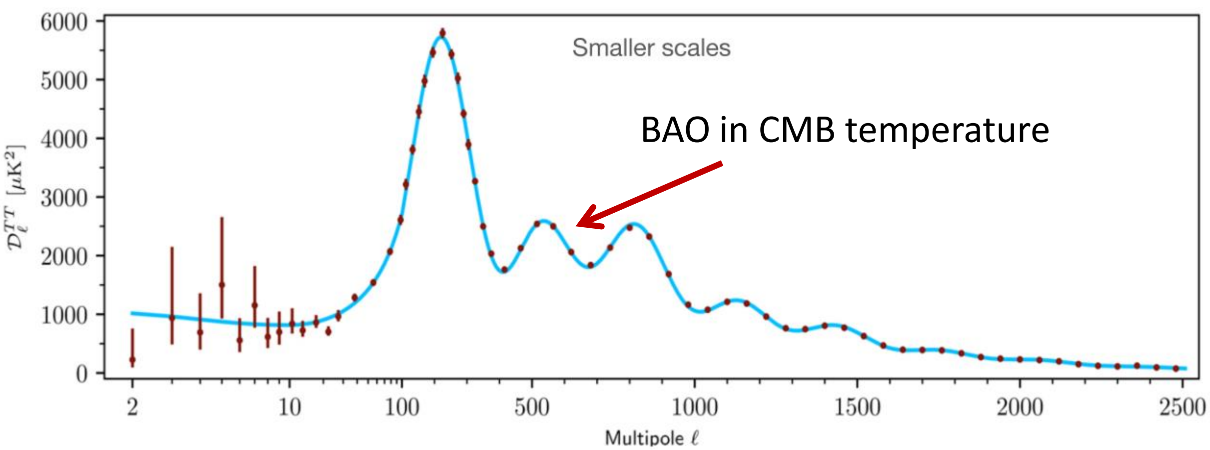
$$\Omega_c h^2 = 0.1200 \quad (1\%)$$

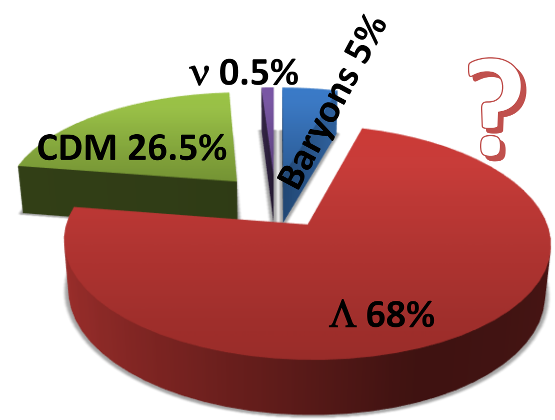
$$\theta_{MC} = 1.04092 \quad (0.03\%)$$

$$\tau = 0.0544 \quad (13.4\%)$$

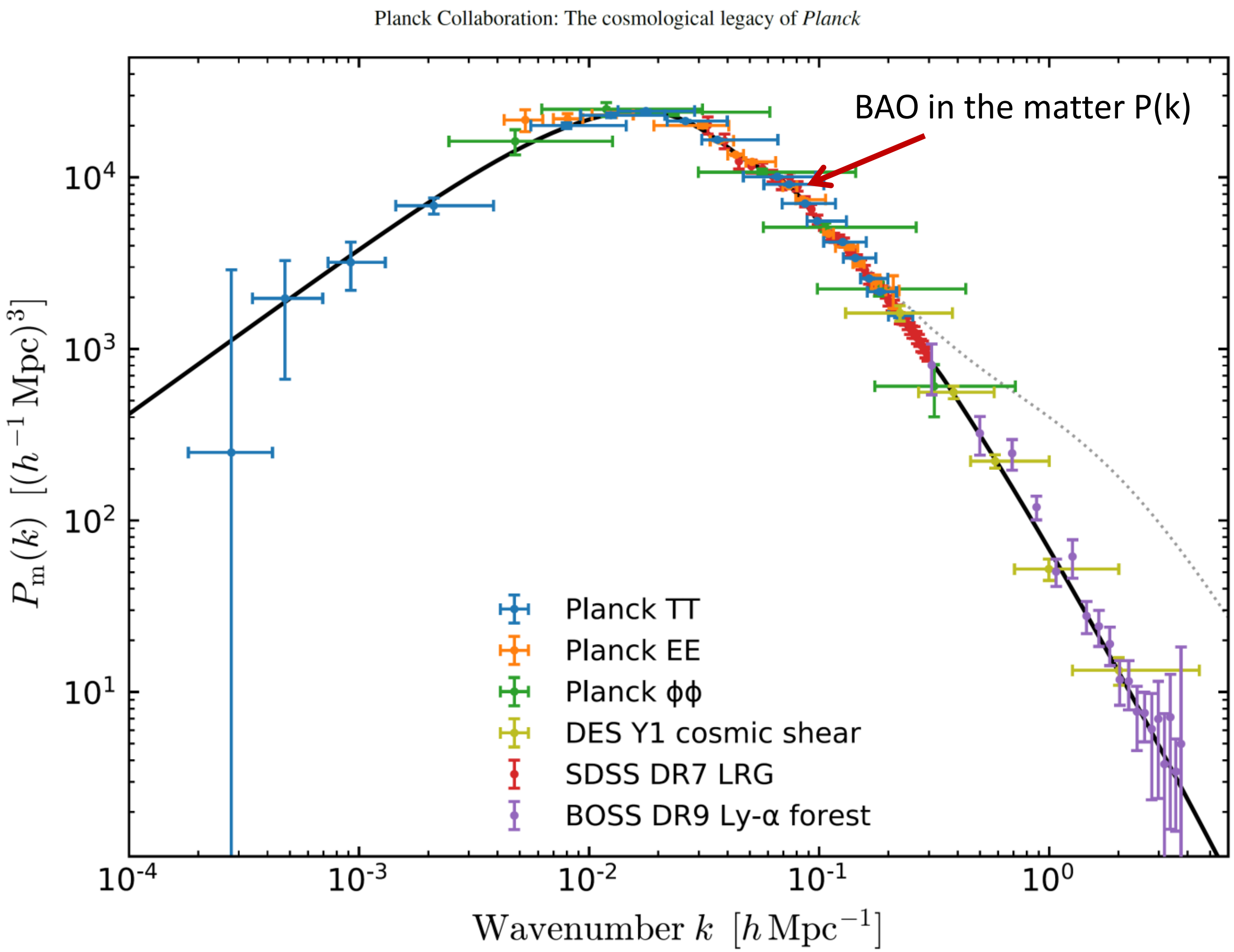
$$\ln\left(10^{10} A_s\right) = 3.044 \quad (0.46\%)$$

$$n_s = 0.9649 \quad (0.44\%)$$





The ΛCDM model from Planck & galaxy-surveys: matter power spectrum



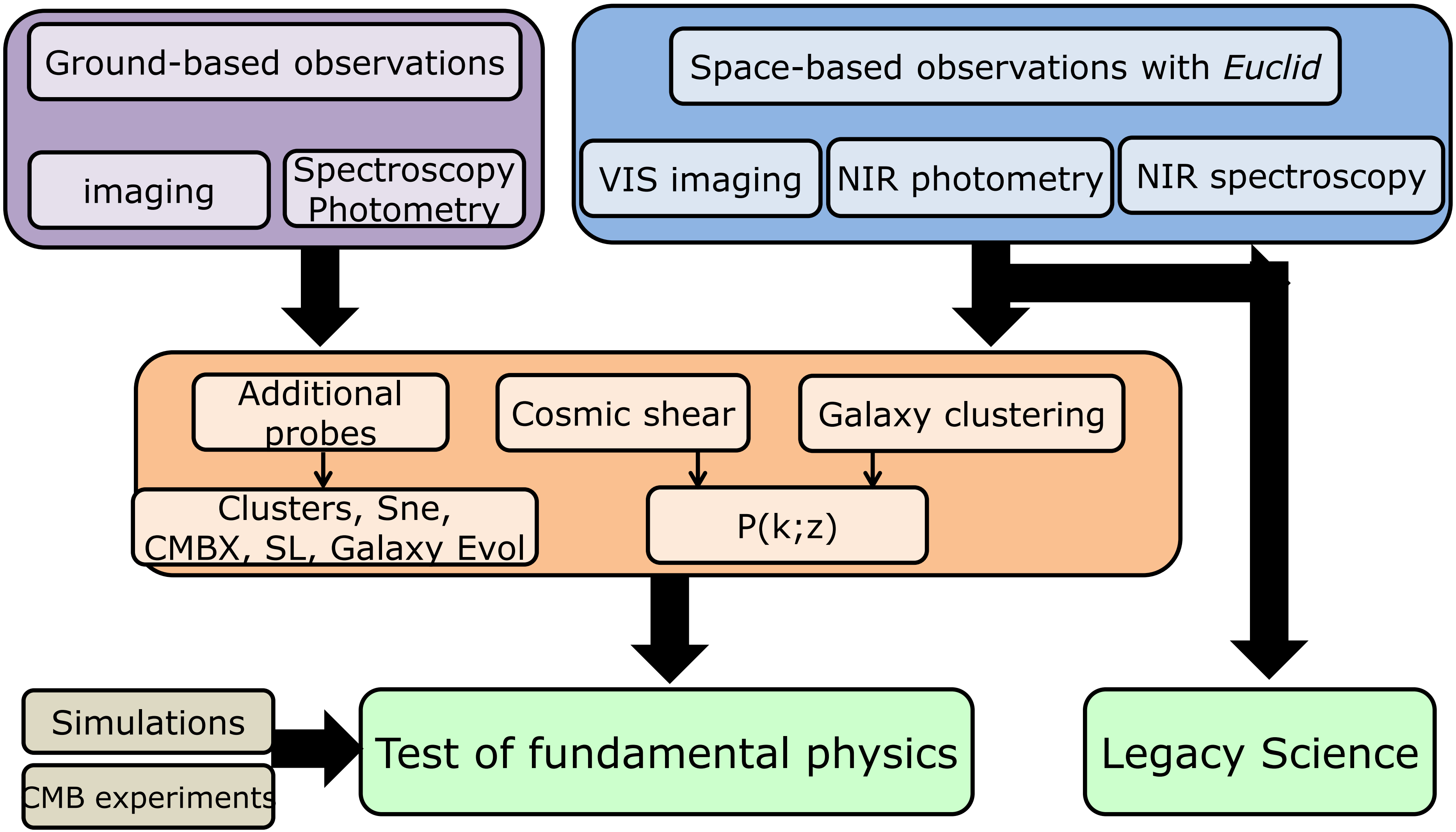
Euclid Top Level Science Requirements

Dark Energy	Test of Gravity
• Measure the cosmic **expansion history** to **better than 10%** in redshift bins 0.9 < z < 1.8. • Look for **deviations from** $w_0 = -1$, indicating dynamical Dark energy. • Euclid primary probes to give FoM_{DE} **> 400** (**1-sigma errors on** w_0 **and** w_a **of 0.02 and 0.1 respectively**)	• Measure the growth rate to better than 0.02 in redshift bins between 0.9 < z < 1.8. • Measure the **growth index, γ, with a precision better than 0.02.** • Separately constrain the two relativistic potentials. ψ and φ· • Test the cosmological principle.
Dark Matter	**Initial conditions**
• Detect Dark matter halos on a mass scale $10^8 < M/M_\odot < 10^{15}$. • Measure the Dark matter mass profiles on cluster and galactic scales. • Measure the **sum of neutrino masses with an accuracy of 0.03 eV.**	• Constraint σ_8 **and** n_s **to a 1-sigma accuracy of 0.01.** • For extended models, improve constraints on spectral indices compared to Planck alone by a factor ~2. • Measure **non-Gaussianity:** $\Delta f_{NL} = \pm 2$.

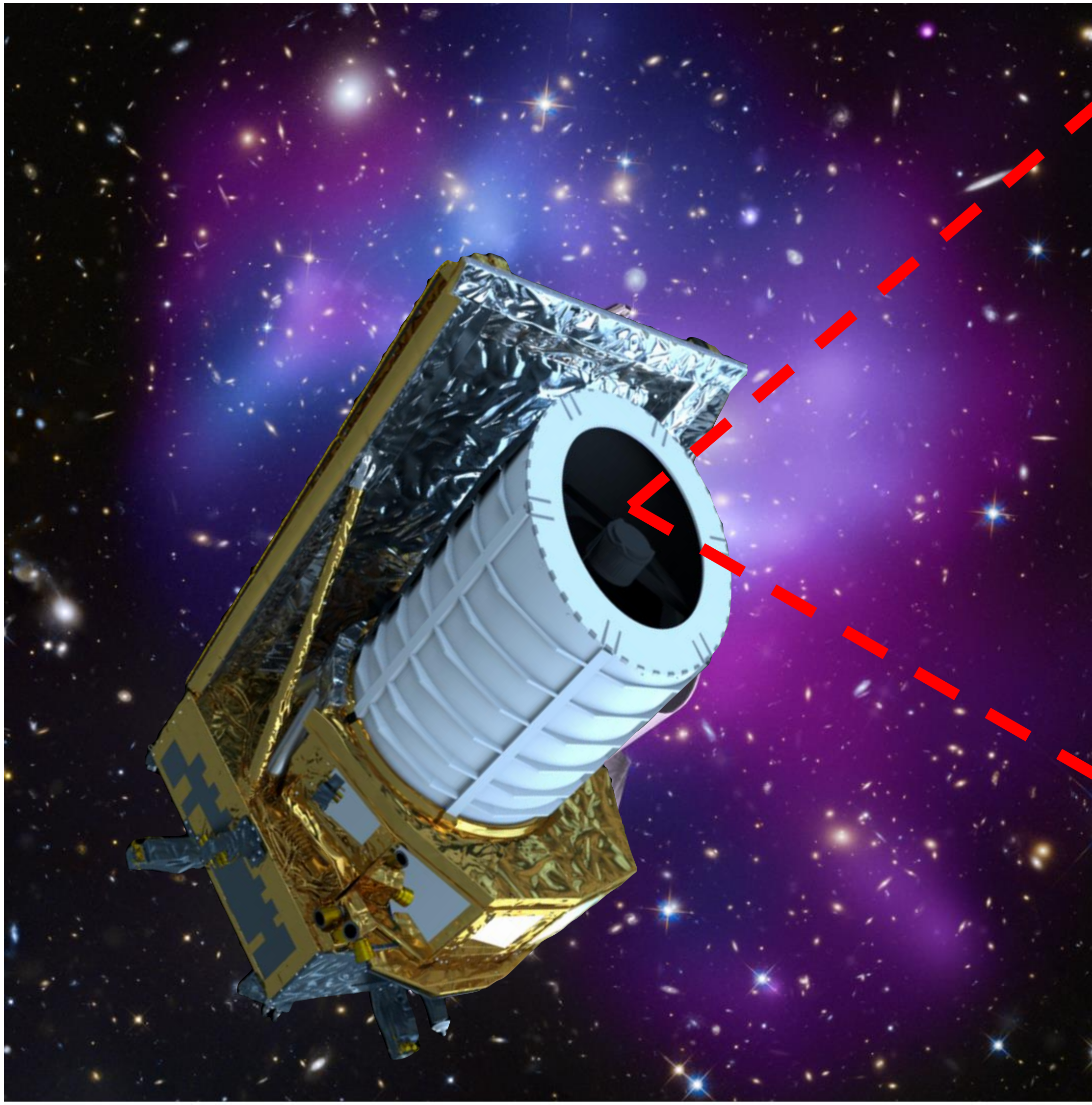
- *DE equation of state:* $P/\rho = w$ *with* $w(a) = w_p + w_a(a_p - a)$
- *Growth rate of structure formation:* $f \sim \Omega^\gamma$;
- *FoM=1/(*$\Delta w_a \times \Delta w_p$*) > 400 →   ~2% precision on* w_p

Euclid Redbook 2011

How to do this with Euclid

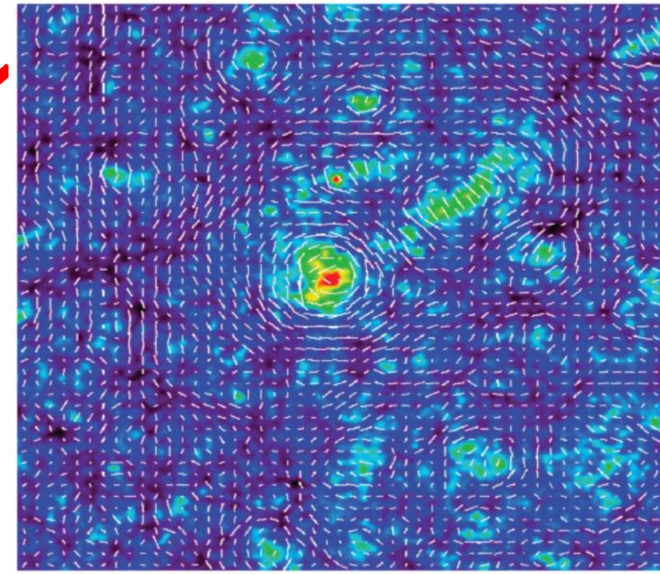


How to do this with Euclid: double approach to the dark sector

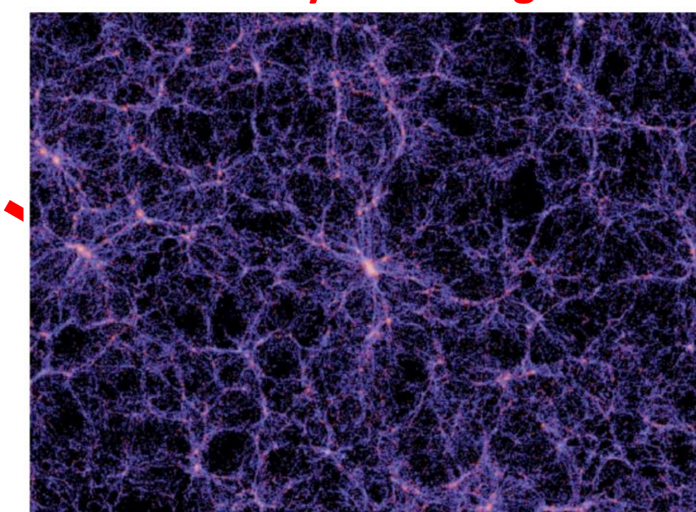


An artist view of the Euclid Satellite – © ESA

Weak lensing



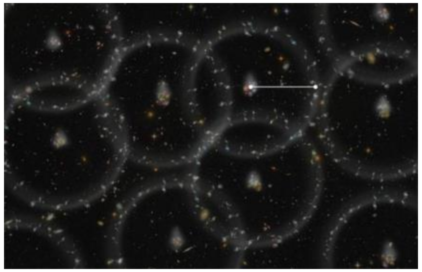
Galaxy Clustering

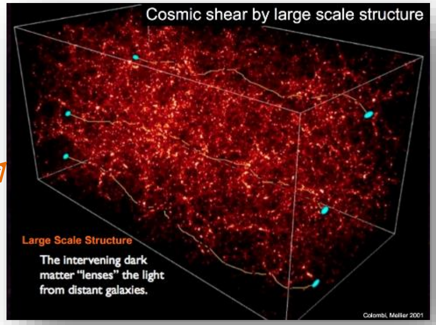


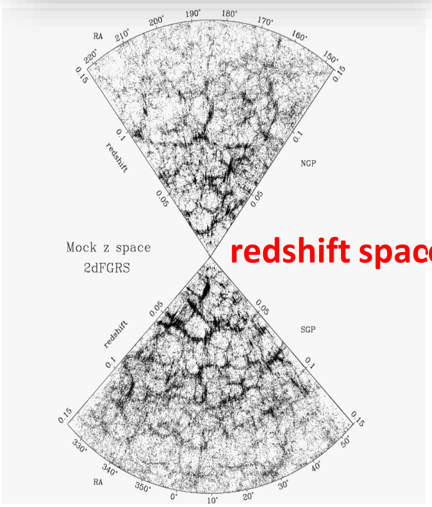
Euclid answers both questions

1. Measure **expansion history *H*(z)** to high accuracy, as to detect percent variations of DE *equation of state* w(z) with robust control of systematics. Achieve this through
   - A. Using the scale of **Baryon Acoustic Oscillations (BAO)** in the clustering pattern of galaxies as a standard ruler
   - B. Using **galaxy shape distortions** induced by Weak Gravitational Lensing

2. Measure at the same time ***the growth rate of structure*** from the same probes, to detect modifications of gravity:
   - A. Weak Lensing (WL) Tomography
   - B. Clustering **redshift-space distortions** (RSD)





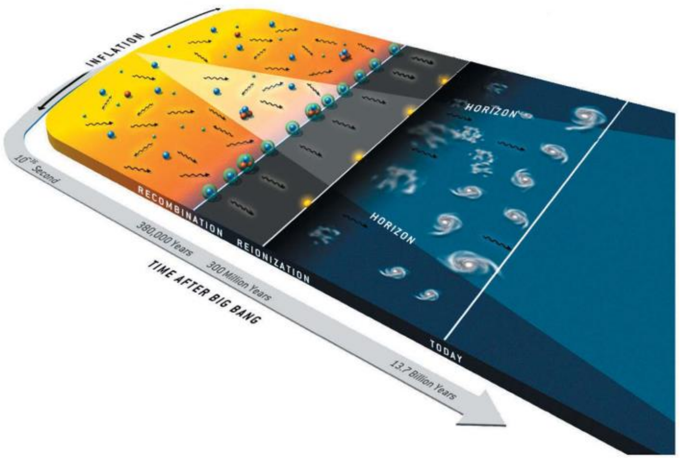


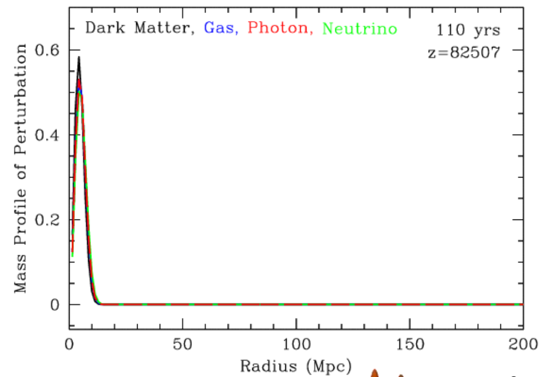
Eke & 2dFGRS 2003

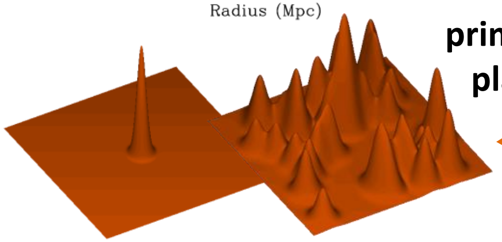
Baryon Acoustic Oscillations (BAO)

In the early universe prior to recombination, the free electrons couple the baryons to the photons through Compton interactions, so these three species move together as a single fluid.

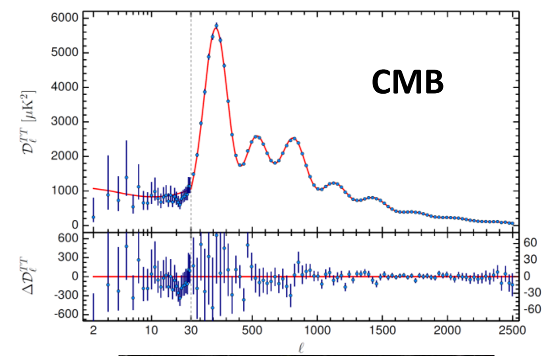
The primordial cosmological perturbations on small scales excite sound waves in this relativistic plasma, which results in the pressure-induced oscillations and acoustic peak.

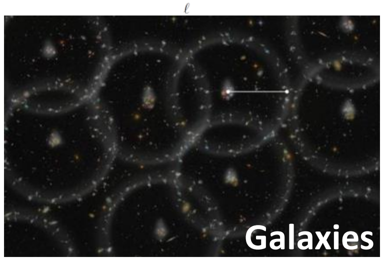






primordial plasma





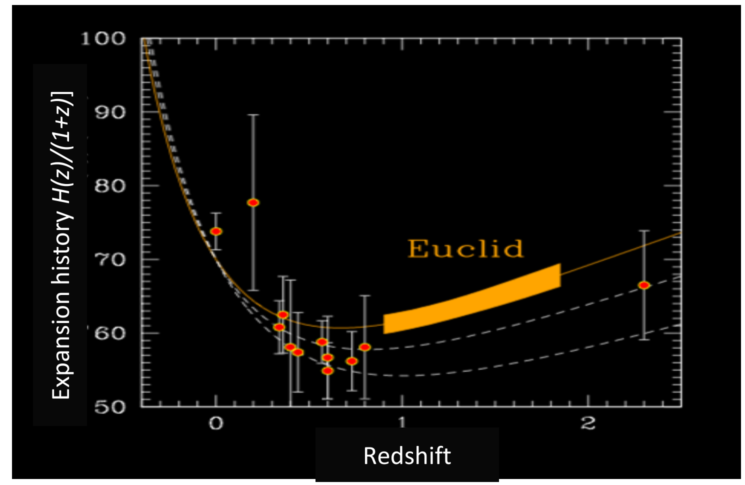
The memory of these baryon acoustic oscillations (BAO) still remain after the epoch of recombination in the ***CMB anisotropies*** and the ***galaxy distribution***.

Euclid GCsp: measuring the background expansion via BAO at 10% precision

Guzzo & GC-SWG (2015)

- **BAO** as a *standard ruler*

- Sensitive to the expansion history ***H(z)*** and angular diameter distance relation $D_A(z)$

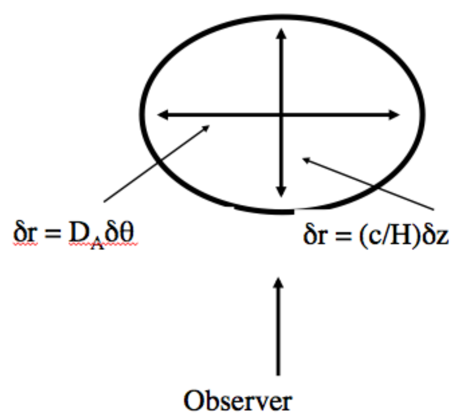


$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz = 147.49 \pm 0.59 \text{ Mpc}$$

need of precise redshifts

$$r_{\parallel} = \frac{c\Delta z}{H(z)}$$

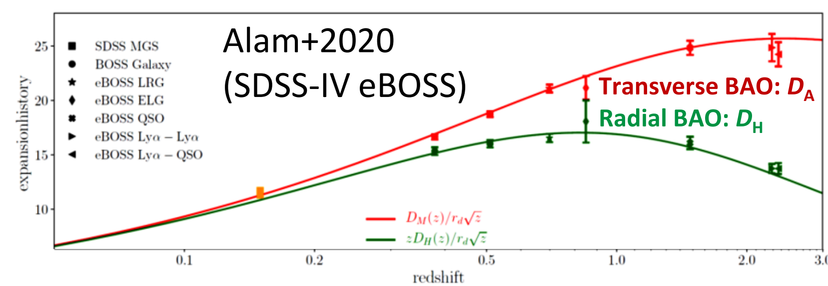
$$r_{\perp} = (1+z) D_A(z) \Delta\theta$$



$$D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)} \qquad D_M(z) = (1+z) D_A(z)$$

$$D_H(z) = c/H(z)$$

$$H(z) = h\sqrt{\Omega_m (1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z} dz\right]}$$



- **Test "beyond *Λ*" scenario, i.e. an evolving equation of state**

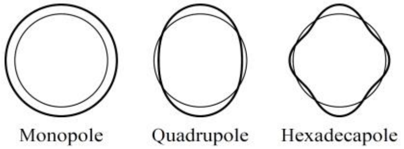
Redshift Space Distortions (RSD)

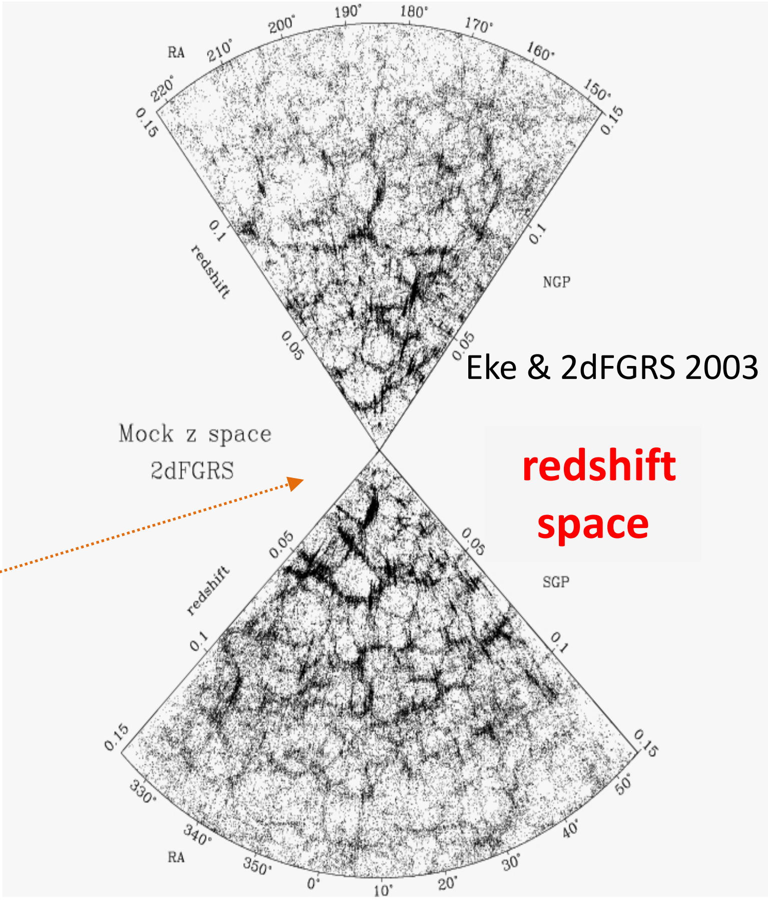
Growth rate produces peculiar velocities, which combine with the cosmological Hubble flow in measured redshifts

$r \equiv H_0 d$ $\quad$ $s = r + v$ $\quad$ $s \equiv cz$

observed distance

The galaxy correlation function becomes *anisotropic*





RSDs: 1) the **Kaiser effect** which *flattens* the galaxy distribution and is caused by coherent motions of galaxies falling inwards towards the cluster centre. The Kaiser effect is smaller and occurs on larger scales than FoGs.

2) the **FoG (fingers-of-God) nonlinear effect** which *elongates* the galaxy distribution along the line-of-sight, caused by the Doppler shift due to random galaxy peculiar velocities within the cluster

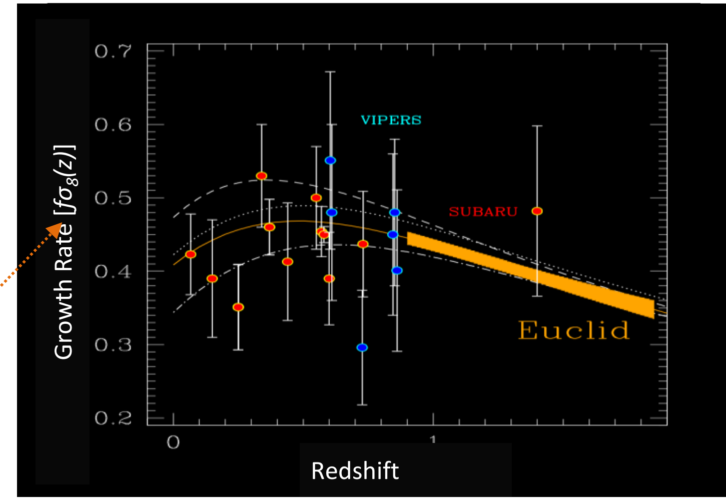
GCsp: measuring the structure growth with RSD at 2% precision

- RSDs probe the growth rate of structure

$$z_{\rm obs} = z_{\rm c} + \frac{v_\parallel}{c}(1 + z_{\rm c}) \qquad \frac{\xi(s)}{\xi(r)} \overset{\text{linear limit}}{=} 1 + \frac{2\beta}{3} + \frac{\beta^2}{5}$$

$$\beta = f(z)/b(z) \simeq \Omega_{\rm m}(z)^\gamma / b(z)$$

Guzzo & GC-SWG (2015)



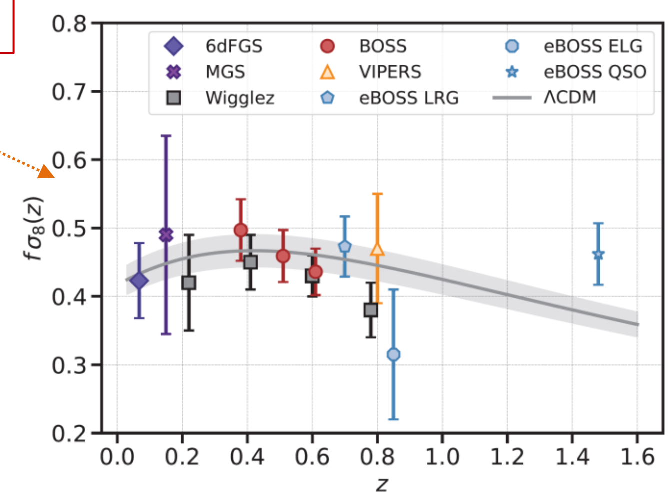
Observed *anisotropic* galaxy power spectrum

$$P_{\rm zs}(k,\mu,z) = \left[\frac{1}{1+(f(z)k\mu\,\sigma_{\rm p}(z))^2}\right](b(z)\sigma_8(z) + f(z)\sigma_8(z)\mu^2)^2\,\frac{P_{\rm dw}(k,z)}{\sigma_8^2(z)}$$

$$P_{\rm dw}(k,z) = [P_{\rm m}(k,z) - P_{\rm nw}(k,z)]\,{\rm e}^{-g_\mu k^2} + P_{\rm nw}(k,z)$$

BAO only x damping + Broadband

$$g_\mu(k,\mu,z) = \sigma_{\rm v}^2(z)\left[1-\mu^2+\mu^2\,(1+f(z))^2\right]$$

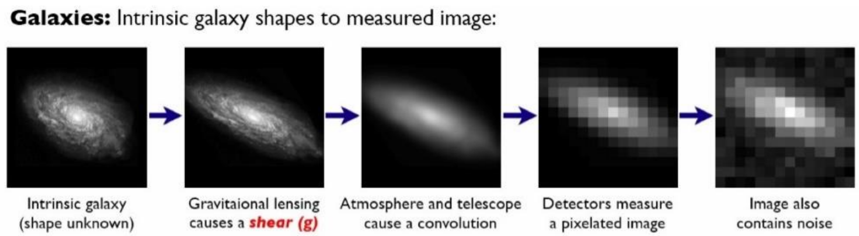


Hou etal 2023

- Test "beyond Einstein" scenario as alternative to GR

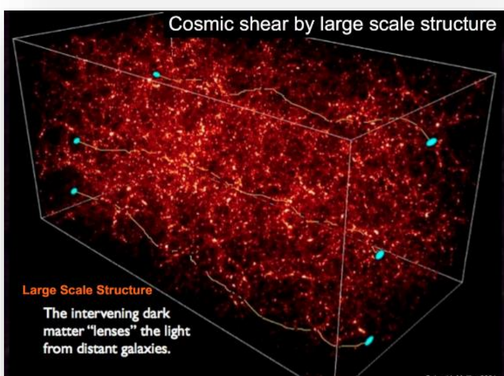
Weak Gravitational Lensing

- The statistics of shape correlations as a function of angular scale and redshift can be used to *directly* infer the statistics of the density fluctuations and therefore cosmology.



Adapted from Bridle et al 2011

- The lensing kernel is most sensitive to structure halfway between the observer and the source. But the kernel is broad: we do not need precise redshifts for the sources: photometric redshifts are fine
- Also, since the kernel is broad the tomographic bins are very correlated

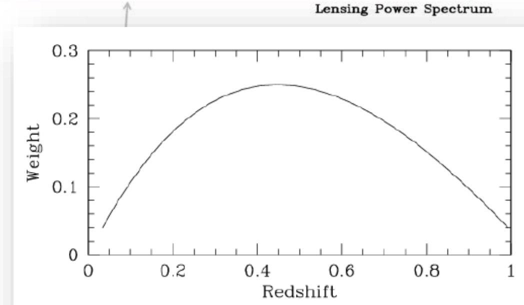


Geometry

Large Scale Structure

$$C_{ij}(\ell) = \int_0^{r_H} \mathrm{d}r\, W_{ij}^{GG}(r) P_{\delta\delta}\left(\frac{\ell}{S_k(r)}; r\right)$$

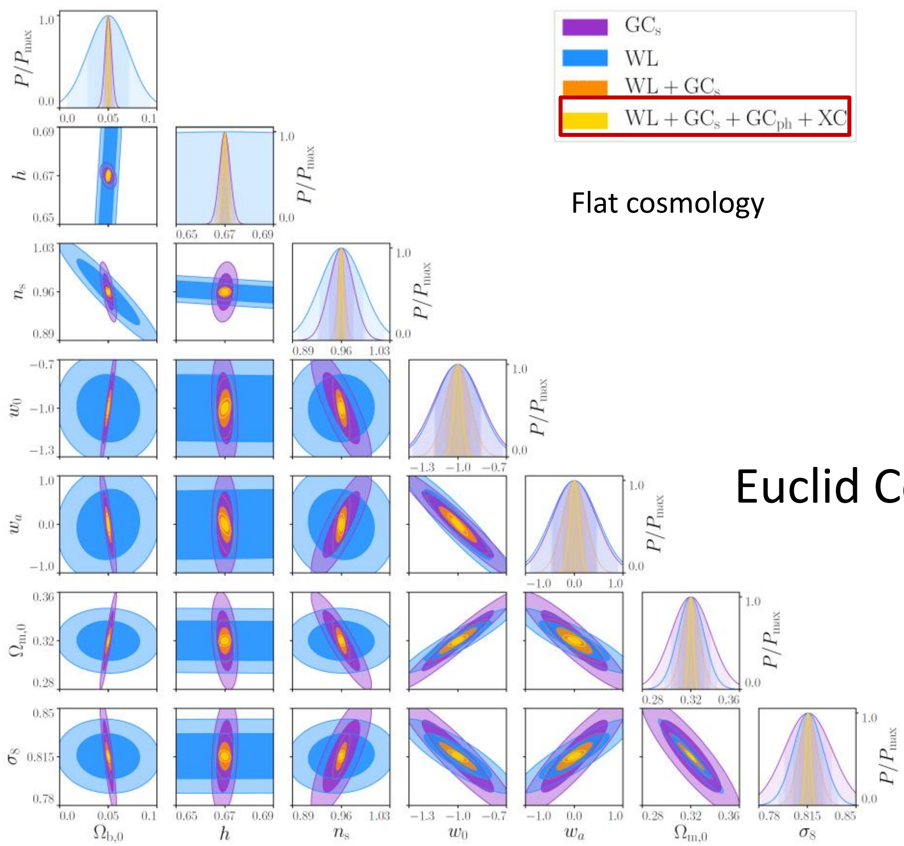
Lensing Power Spectrum



Measures a combination of geometry (Hz) and growth

- To achieve the science goals we need to measure the matter distribution as a function of redshift: weak lensing tomography requires redshifts for the sources.

Forecasts of Euclid scientific performance



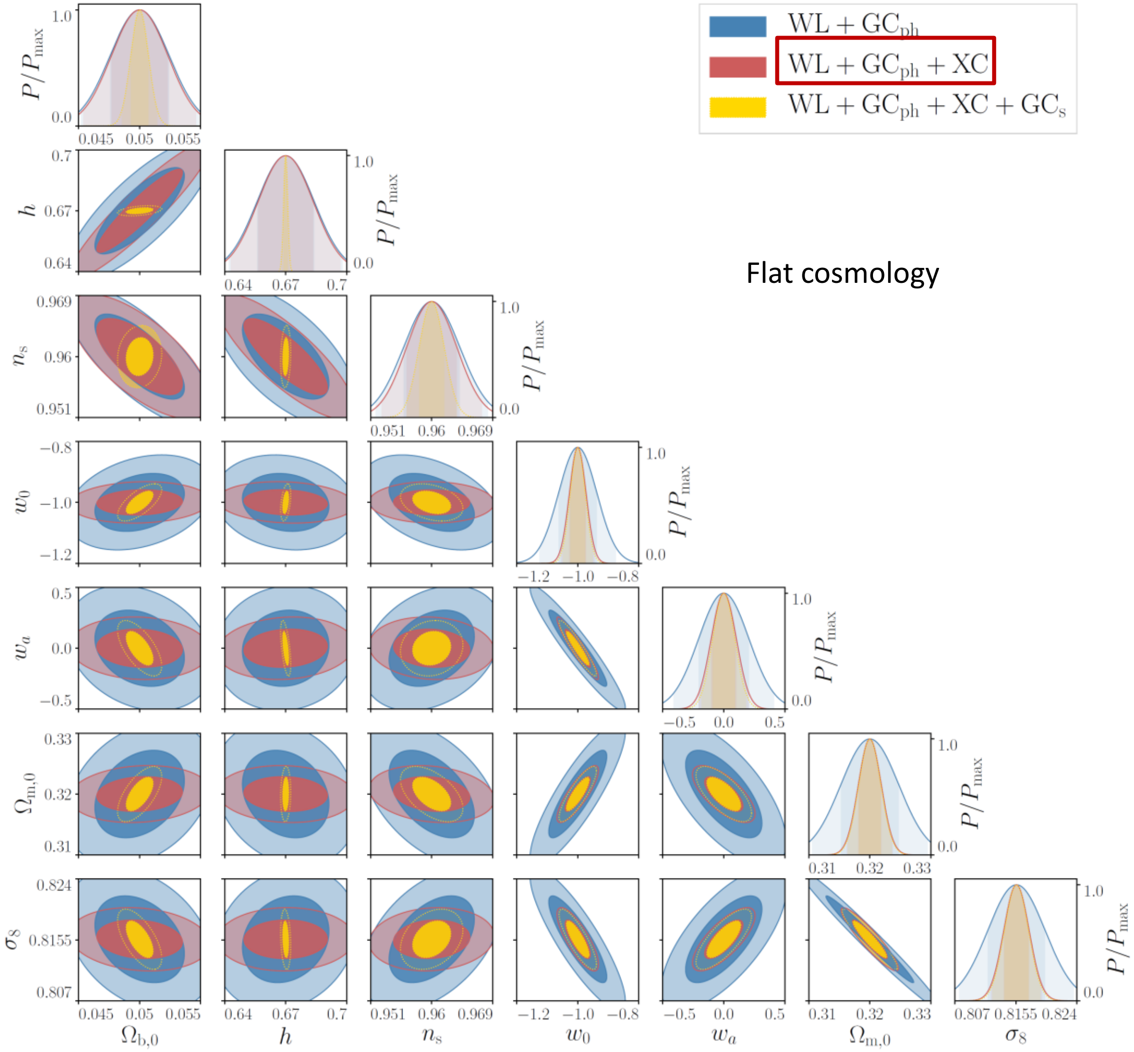
Flat cosmology

REFERENCE PAPER:
Euclid Consortium, arXiv:1910.09273

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
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

Probe combination is key to high precision and accuracy

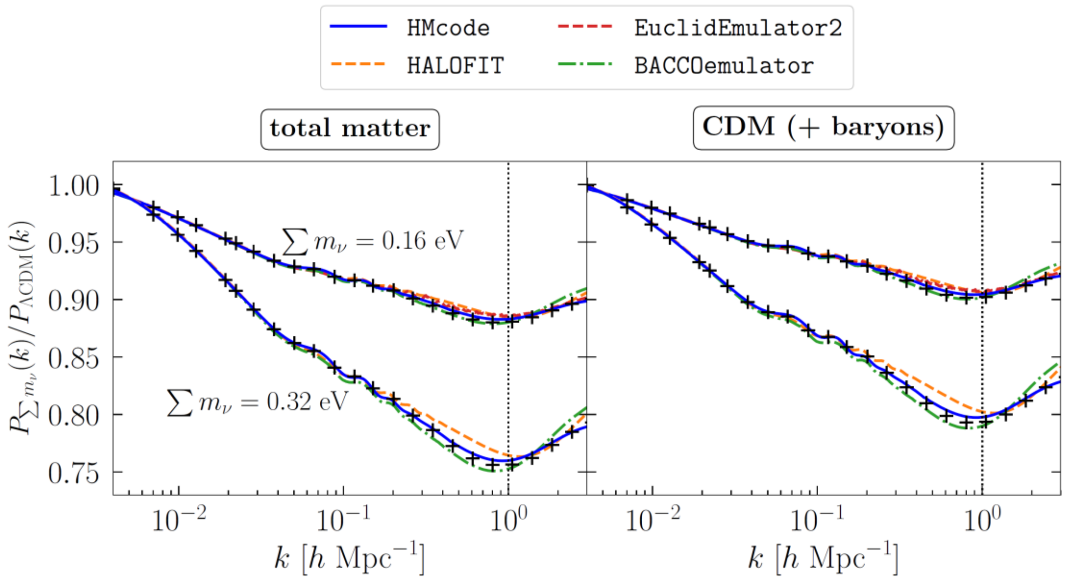
REFERENCE PAPER: Euclid Consortium, arXiv:1910.09273



Constraining neutrinos with Euclid

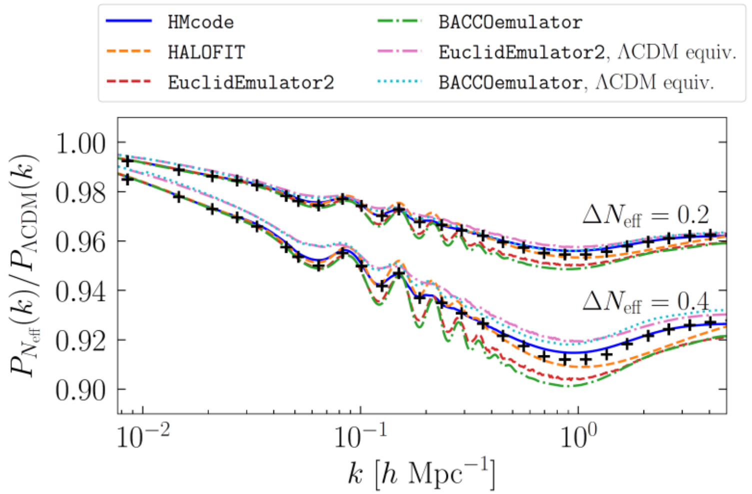
(pre-launch KP under internal EC review)

PRELIMINARY



Nonlinear matter P(k) suppression due to free-streaming massive neutrinos

Archidiacono et al. in prep

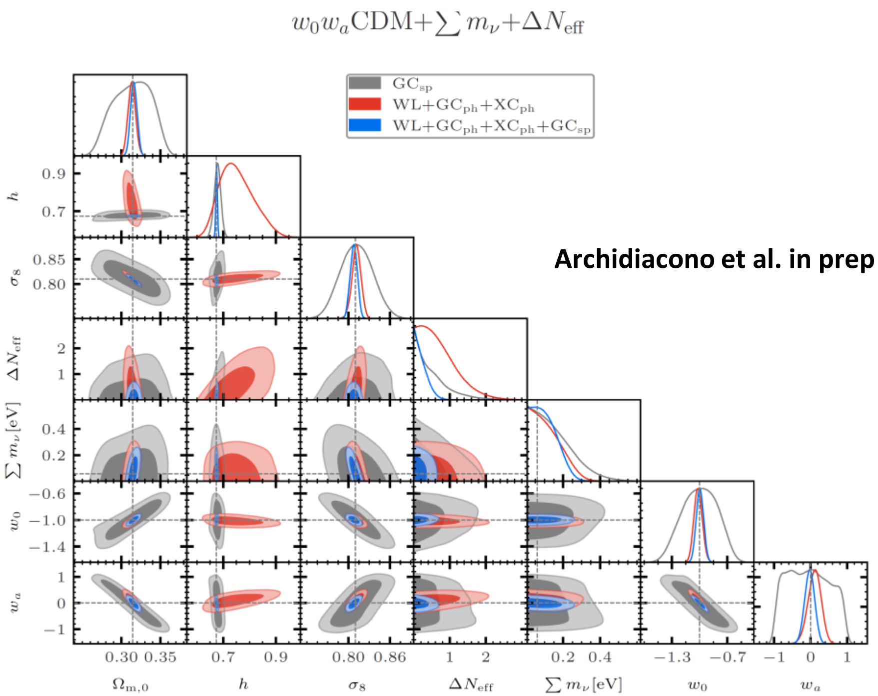


Nonlinear matter P(k) suppression due to the number of relativistic species

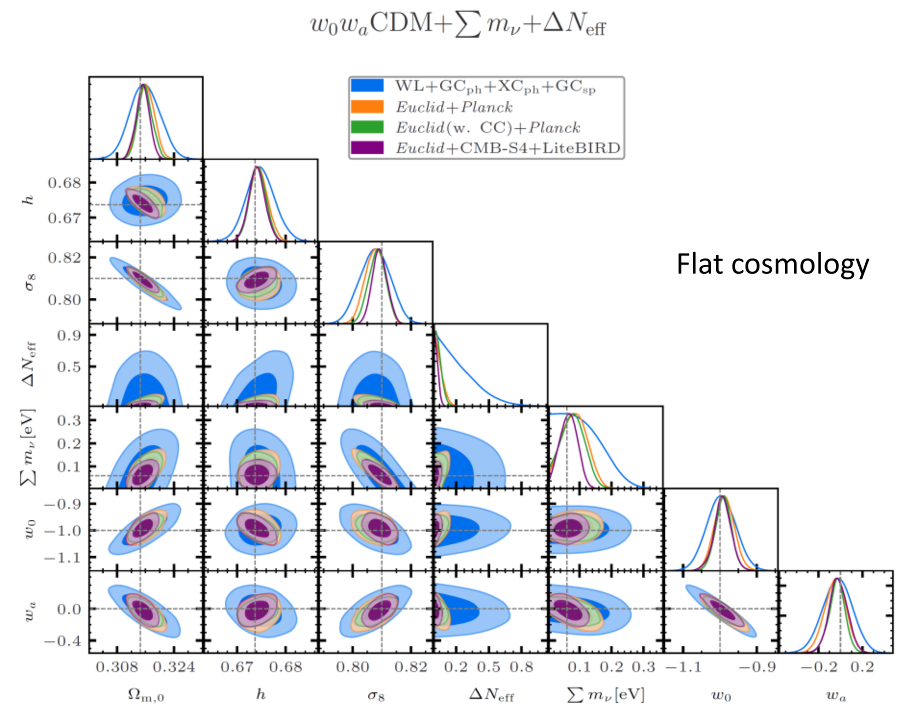
Constraining neutrinos with Euclid

(pre-launch KP under internal EC review)

PRELIMINARY



Archidiacono et al. in prep



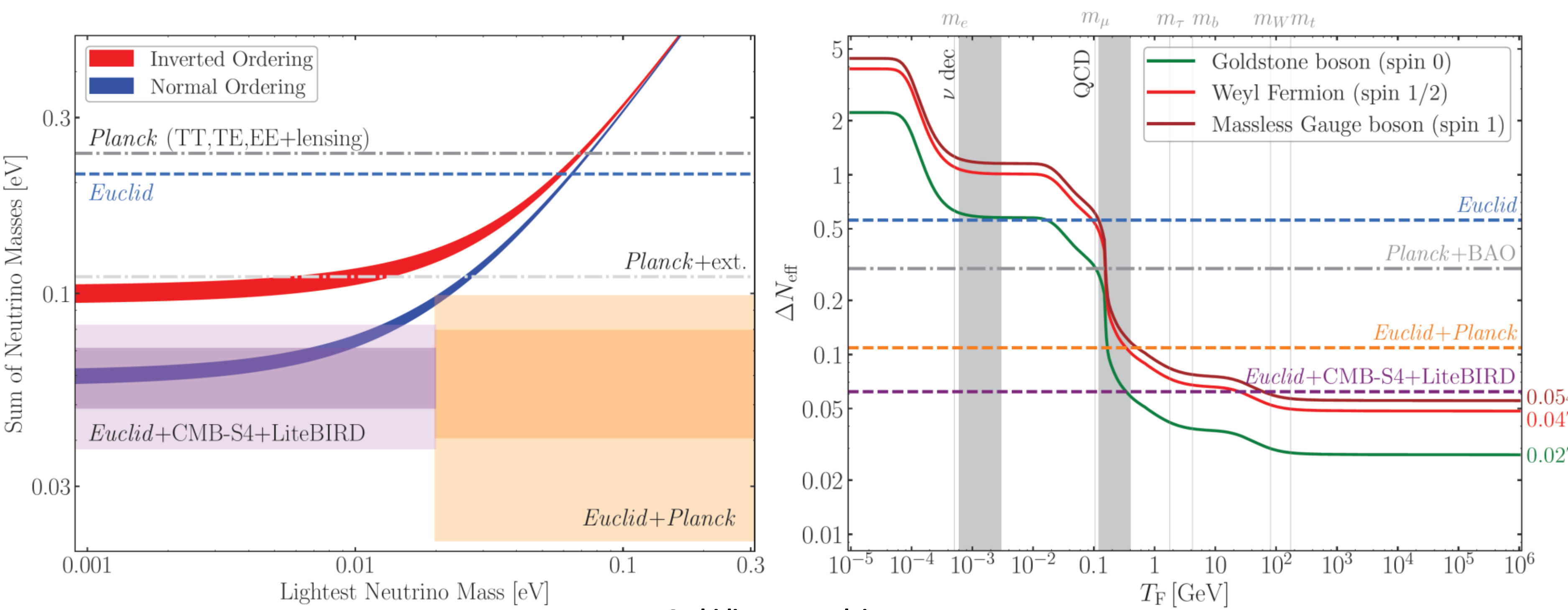
Flat cosmology

$w_0 w_a$CDM + $\sum m_\nu$ + $\Delta N_{\rm eff}$	$\Omega_{\rm m,0}$	$100\,\Omega_{\rm b,0}$	h	$n_{\rm s}$	σ_8	$\sum m_\nu$[meV]	$\Delta N_{\rm eff}$	w_0	w_a
Euclid-only									
GC$_{\rm sp}$	0.0260	0.56	0.013	0.031	0.024	< 350	< 1.48	0.20	0.40
WL+GC$_{\rm ph}$+XC$_{\rm ph}$	0.0049	0.38	0.065	0.029	0.0065	< 260	< 1.71	0.05	0.18
WL+GC$_{\rm ph}$+XC$_{\rm ph}$+GC$_{\rm sp}$	0.0043	0.18	0.0030	0.0059	0.0054	< 220	< 0.57	0.04	0.14
WL+GC$_{\rm ph}$+XC$_{\rm ph}$+GC$_{\rm sp}$+CC	0.0030	0.14	0.0021	0.0055	0.0043	< 220	< 0.48	0.03	0.09
Euclid+CMB									
Euclid+*Planck*	0.0022	0.033	0.0019	0.0021	0.0034	41	< 0.13	0.03	0.10
Euclid(w. CC)+*Planck*	0.0020	0.030	0.0016	0.0022	0.0030	39	< 0.10	0.02	0.08
Euclid+CMB-S4+LiteBIRD	0.0019	0.026	0.0017	0.0015	0.0025	28	< 0.061	0.03	0.09

Constraining neutrinos with Euclid

(pre-launch KP under internal EC review)

PRELIMINARY



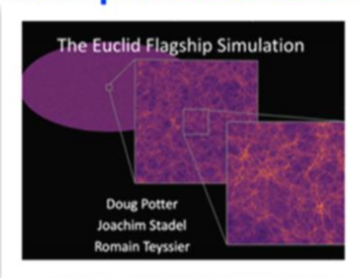
Archidiacono et al. in prep

Assuming that the true value of the neutrino mass sum is the minimum allowed by neutrino oscillation experiments in normal ordering, the combination Euclid+CMB-S4+LiteBIRD will rule out the inverted ordering at more than 3σ

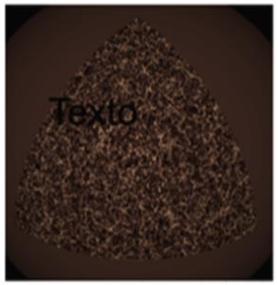
The Role of simulations

The Flagship galaxy mock: end2end pipeline

3D particle LC

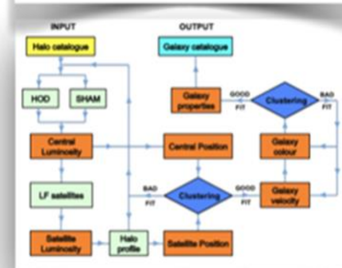


All-sky Halo catalog

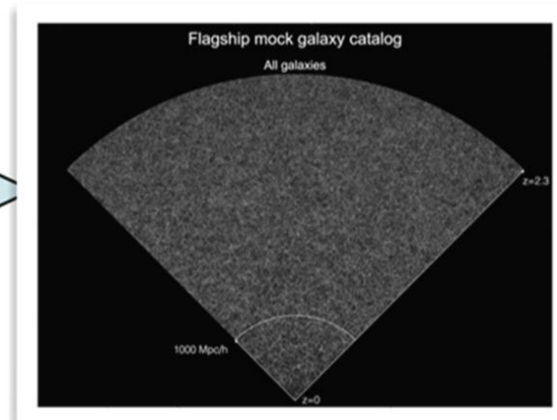


Massive coordinated efforts:
- modular galaxy pipeline
- big-data platform (CosmoHub)
- mock validation

HOD/SHAM Galaxy assignment pipeline

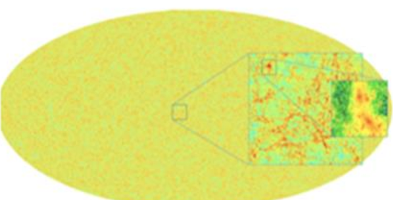


Flagship galaxy mock
[Lightcone to z< 3]

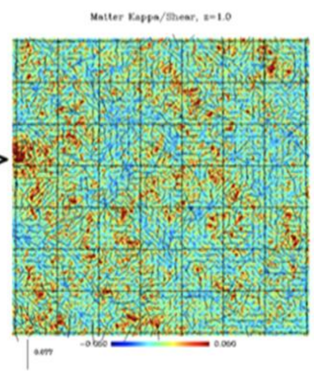


One octant of the sky

All-sky 2D DM counts maps



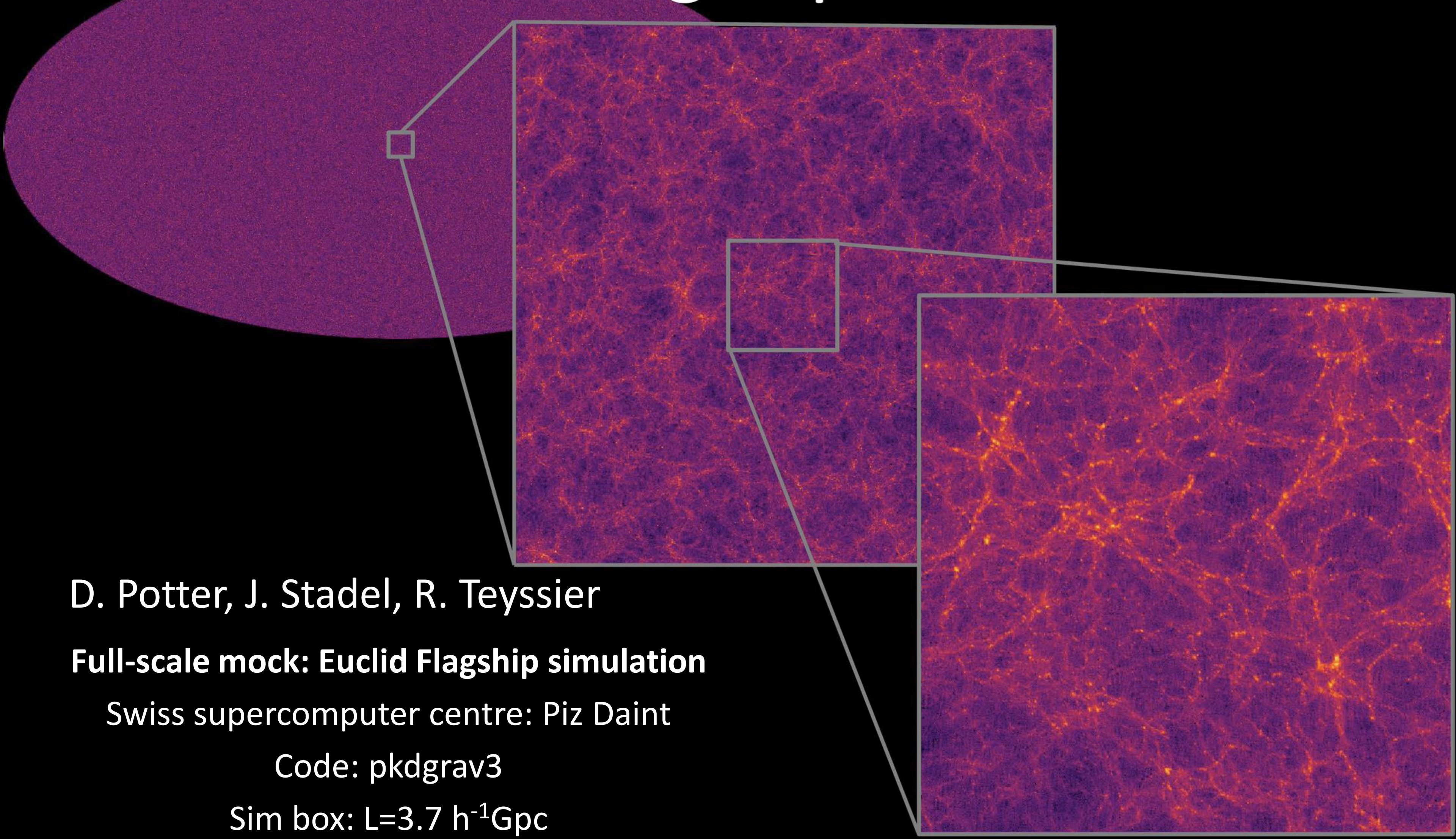
All-sky Lensing maps



- Pipeline has been **continuously improved** since first FS1 mock release to EC
- **WIDE survey mock** (~ few billion galaxies) can be **produced in few hours** @ Spanish SDC

Credits: P. Fosalba & the CoS-SWG

The Euclid Flagship Simulation



D. Potter, J. Stadel, R. Teyssier

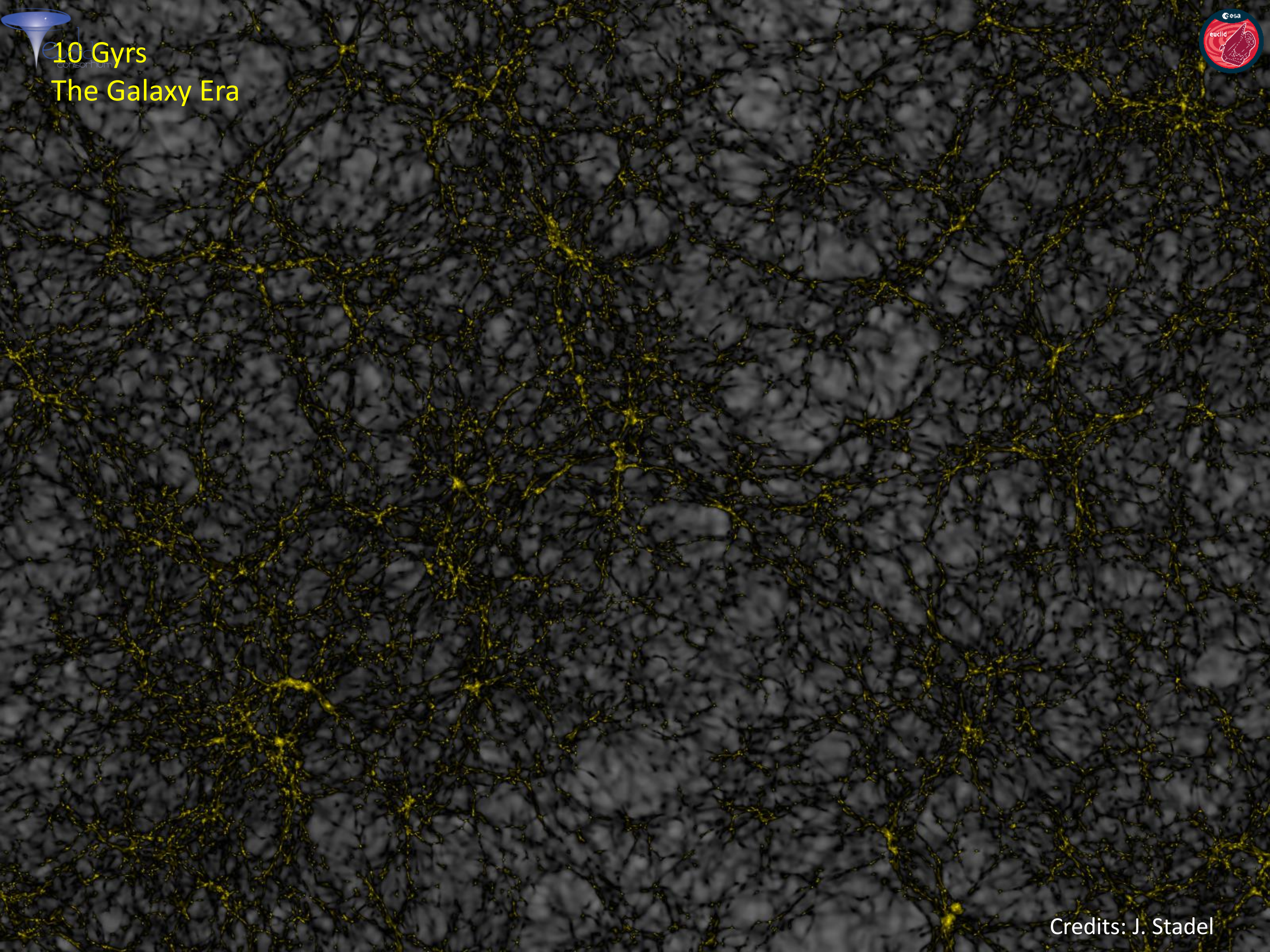
Full-scale mock: Euclid Flagship simulation

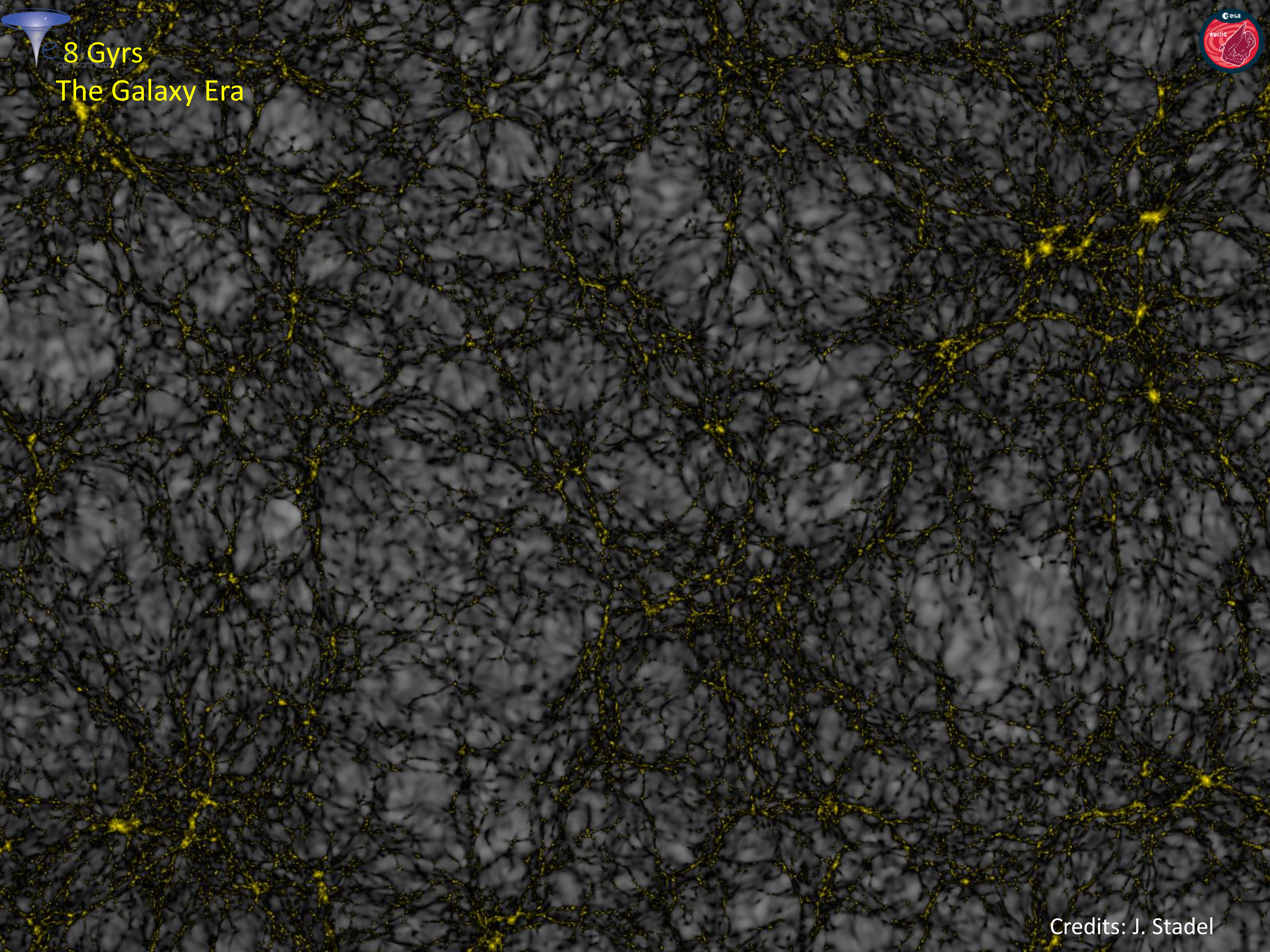
Swiss supercomputer centre: Piz Daint

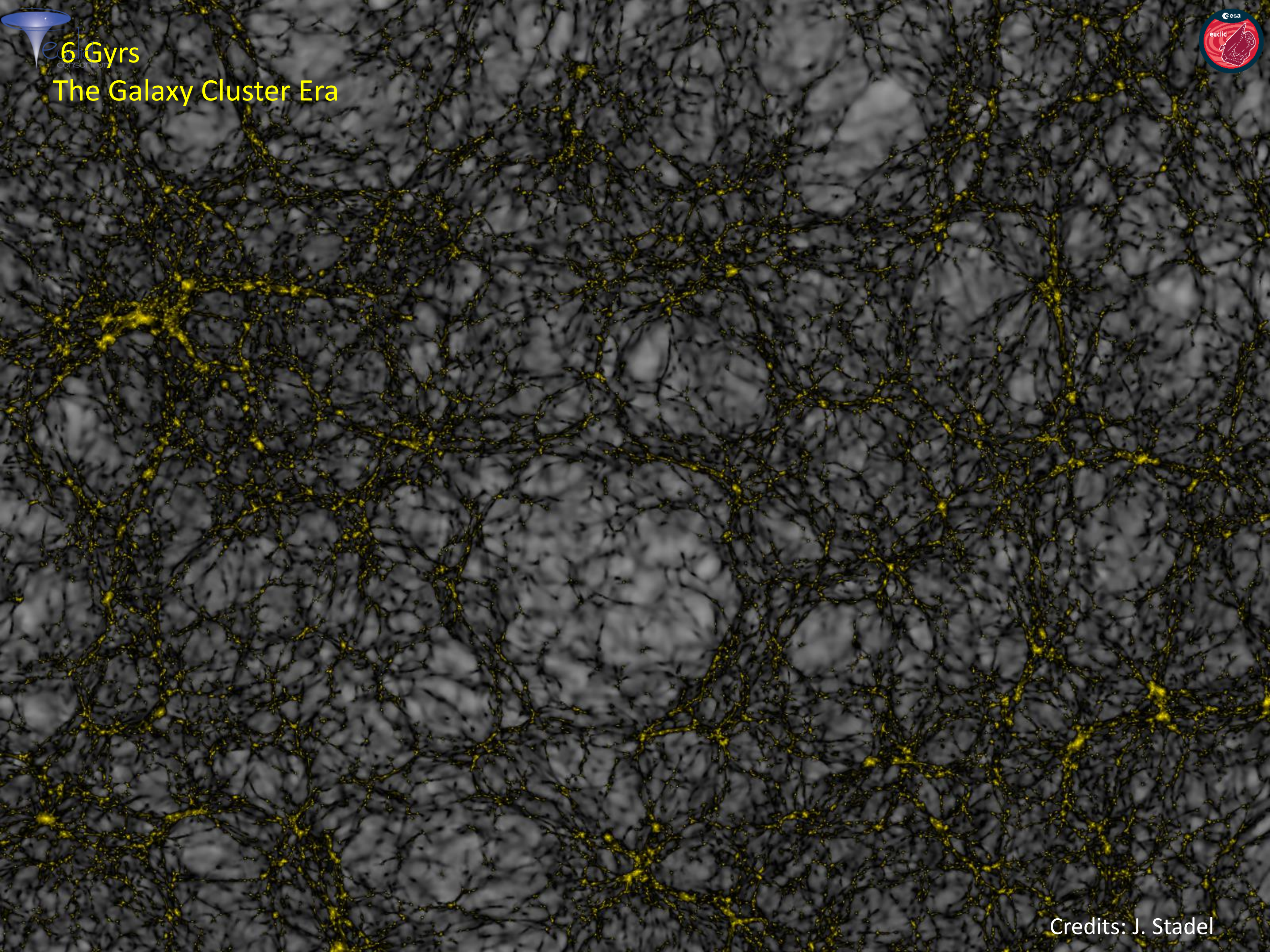
Code: pkdgrav3

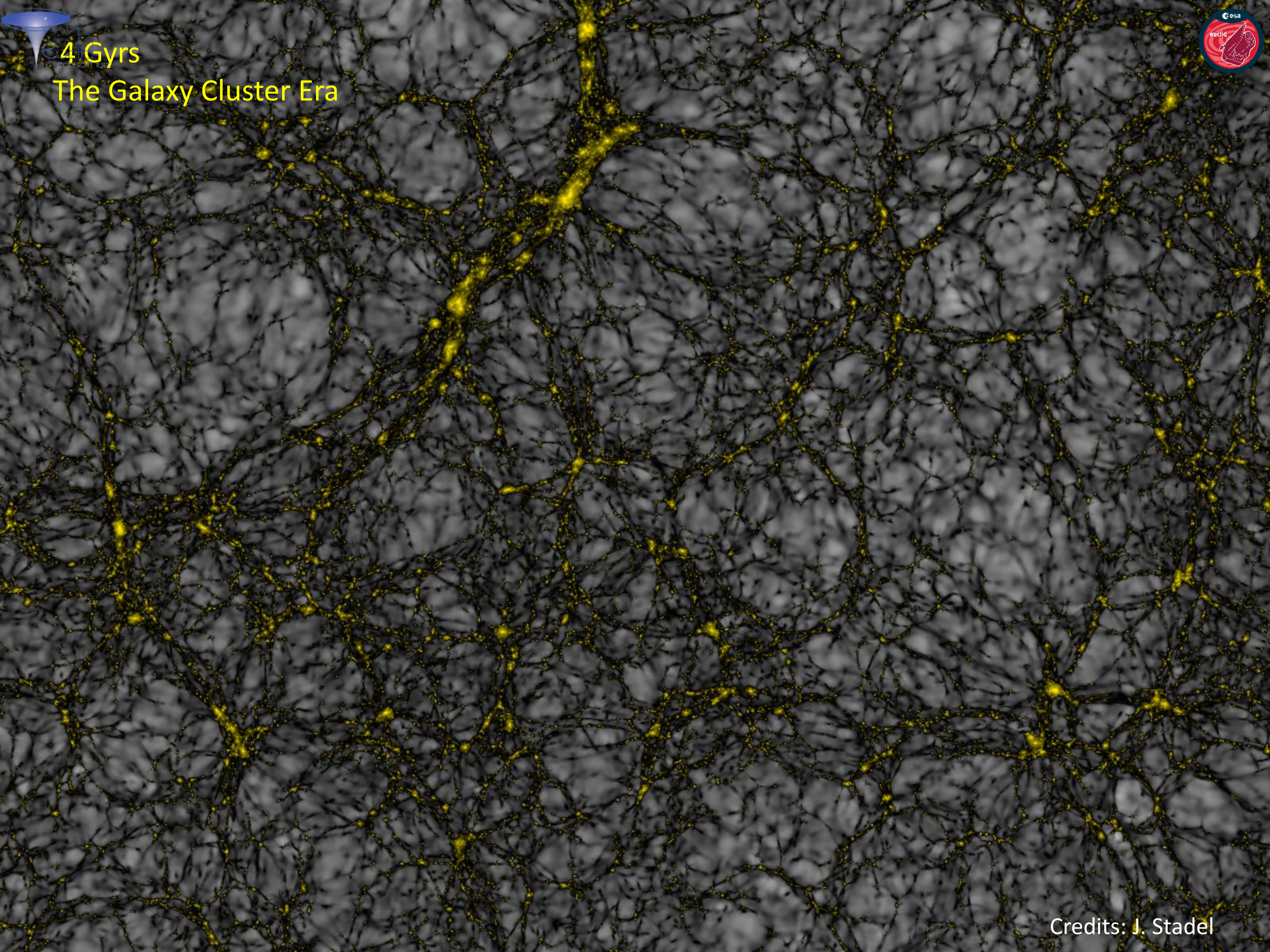
Sim box: $L=3.7\ h^{-1}$Gpc

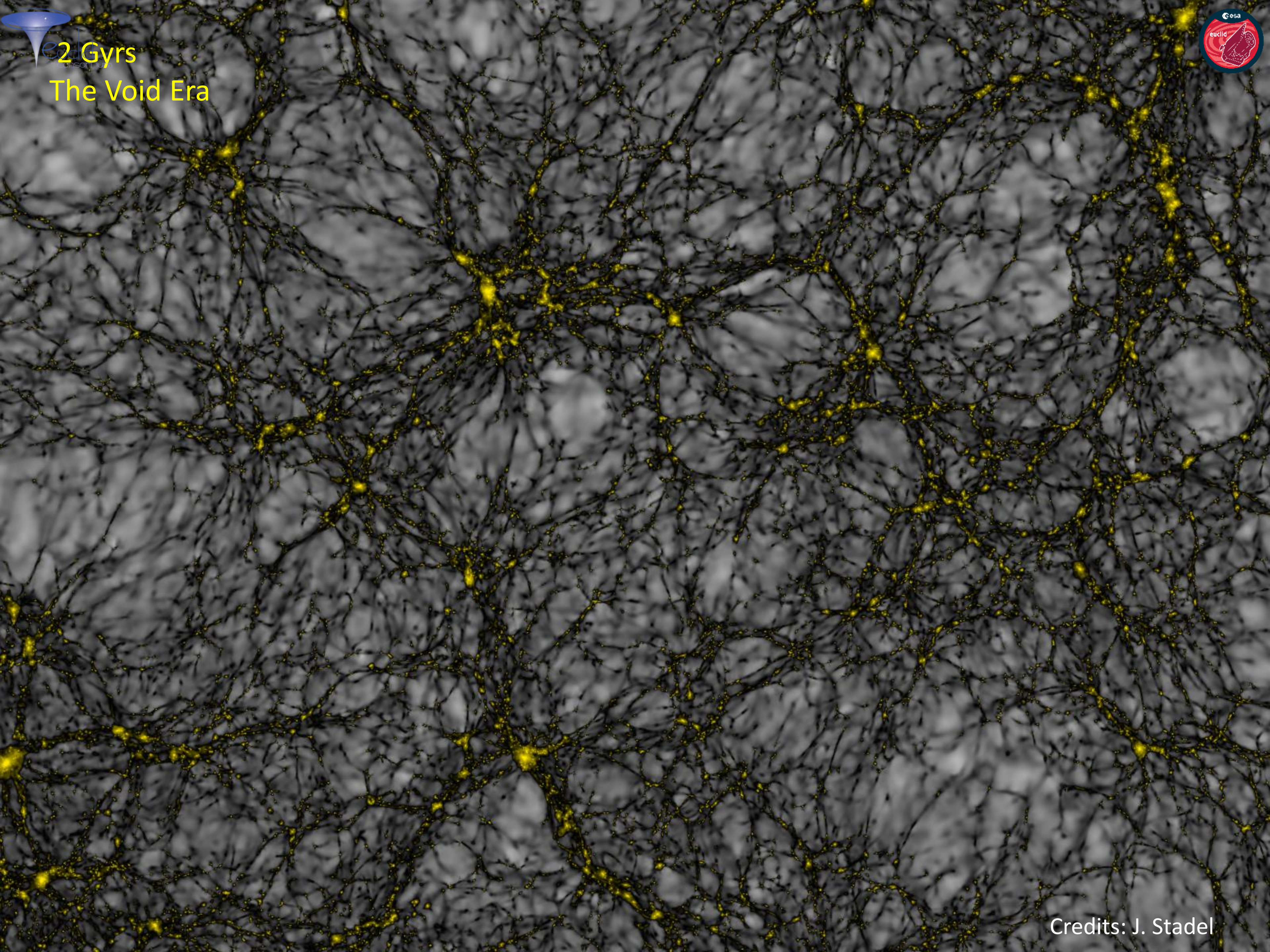
N_{part}=2 trillion $M_p=2.4\ 10^9\ M_{sun}$


10 Gyrs
The Galaxy Era
Credits: J. Stadel

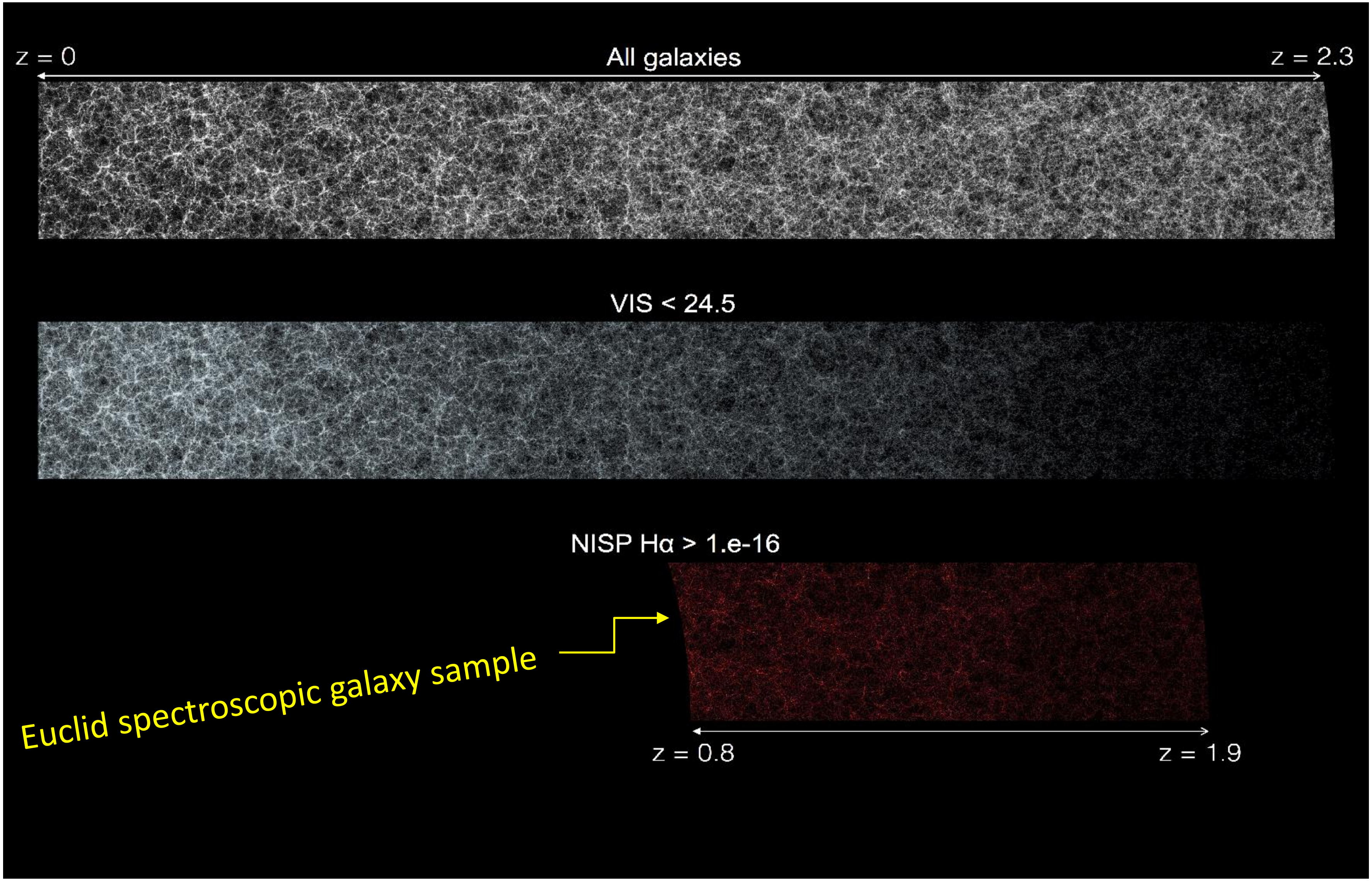

8 Gyrs
The Galaxy Era
Credits: J. Stadel


6 Gyrs
The Galaxy Cluster Era
Credits: J. Stadel

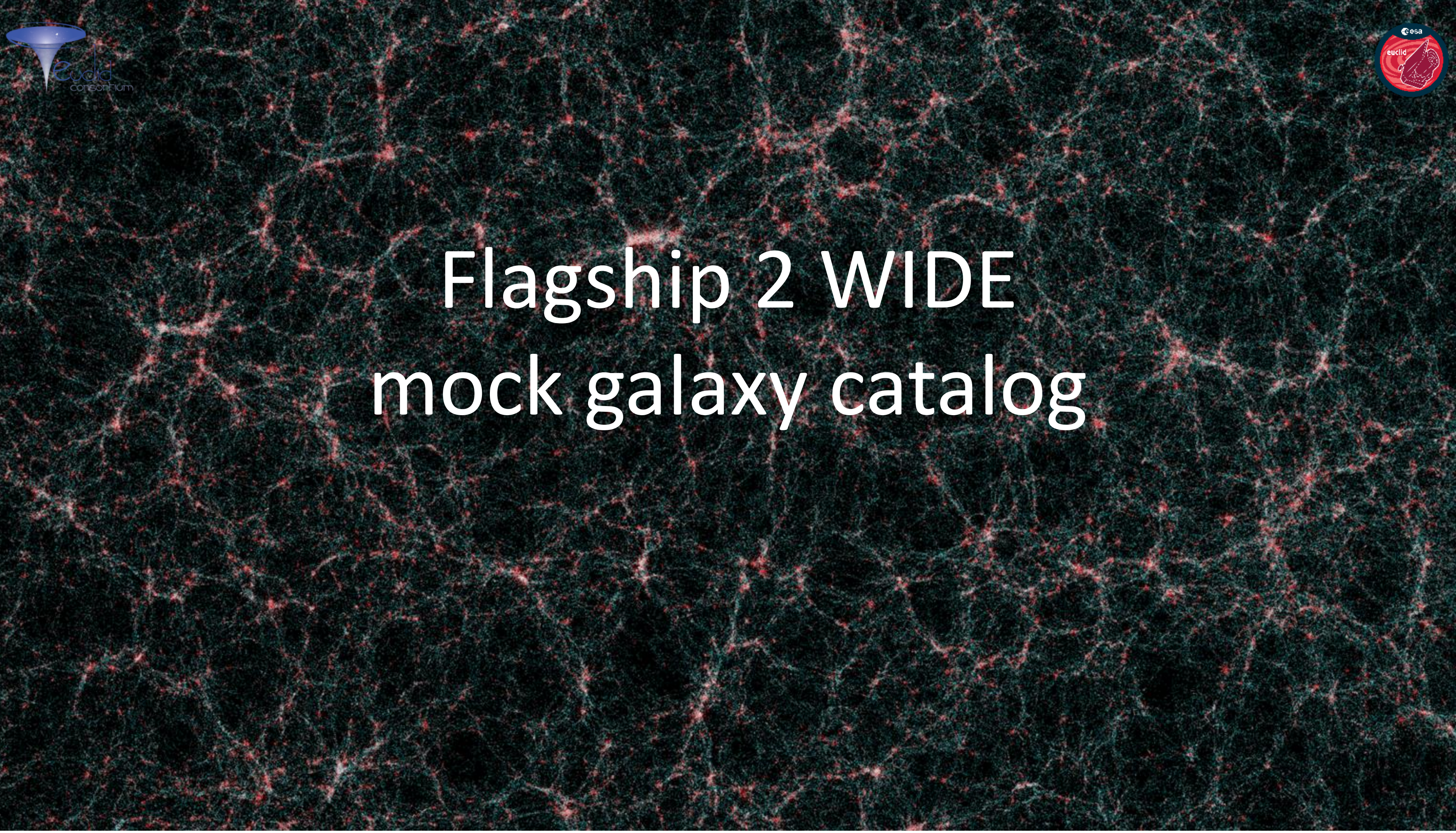

4 Gyrs
The Galaxy Cluster Era
Credits: J. Stadel


2 Gyrs
The Void Era
Credits: J. Stadel

Euclid Flagship Simulation 1: mock galaxy lightcones



Credits: P. Fosalba



Flagship 2 WIDE mock galaxy catalog

Doug Potter Joachim Stadel Romain Teyssier

- WIDE
  4.1 trillion dark matter (DM) particles
  DM particle mass = 10^9 M_{sun}/h
  L_{BOX} = 3600 Mpc/h

- DEEP
  0.9 trillion DM particles
  DM particle mass = 10^8 M_{sun}/h
  L_{BOX} = 1000 Mpc/h

Specification of the Reference Cosmology

$\boldsymbol{\Omega_m}$**= 0.319**
$\boldsymbol{\Omega_b}$**= 0.049**
$\boldsymbol{\Omega_\Lambda}$**= 0.681 -** $\boldsymbol{\Omega_{RAD}}$ **-** $\boldsymbol{\Omega_\nu}$
$\boldsymbol{\Sigma m_\nu}$**= 0.06 ev** (minimal, see across)
$\mathbf{T_{CMB}}$**= 2.7255 K**
$\mathbf{A_s}$ **= 2.1 × 10**$^{-9}$ (roughly $\boldsymbol{\sigma}_8$= 0.83)
$\mathbf{k_{pivot}}$ **= 0.05/Mpc**
h = 0.67
$\mathbf{n_s}$**= 0.96**
$\mathbf{w_0}$**= -1**
$\mathbf{w_a}$**= 0**

Using the normal hierarchy with m_1 = 0 and data from https://arxiv.org/pdf/1708.01186.pdf

Δm_21² = 7.55 × 10^{-5} eV²,
Δm_31² = 2.50 × 10^{-3} eV²,
and so
m_1 = 0 (by choice),
m_2 = 8.68907 × 10^{-3} eV,
m_3 = 5.00000 × 10^{-2} eV

mv = [0, 8.68907 × 10^{-3} **eV, 5.00000 × 10**$^{-2}$ **eV]**
(giving Σmv = 0.05868907 eV)

Effects of light neutrinos, photon anisotropies and GR corrections linearly included (Tram et al. 2018) via the realisation of these perturbation fields on a grid, obtained via CLASS and added to the ordinary matter potential grid, in the so-called Nbody gauge (Fidler et al. 2016).

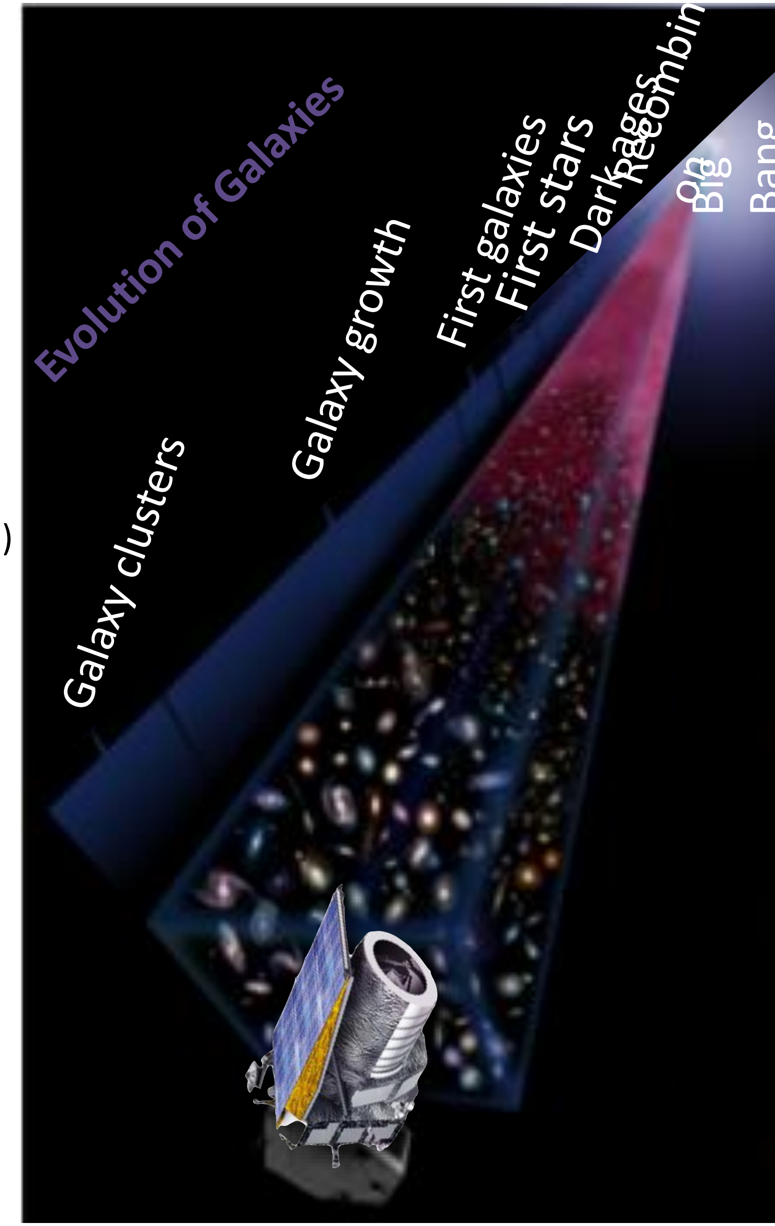
IC are generated at z=200 (1LPT) as well as all the background quantities (H(a), a(t), Ω_ν(a)…)

Agreement with CLASS on linear scales at 0.1%

Credits: J. Stadel

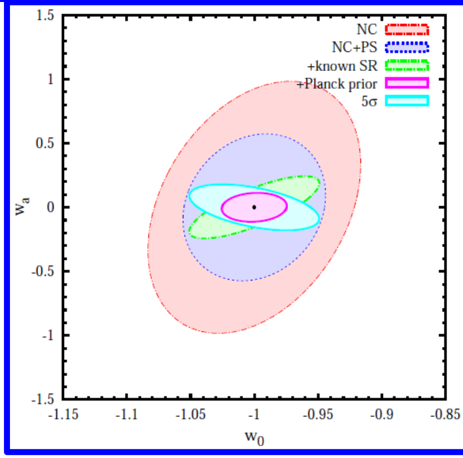
Euclid additional science: beyond the primary probes

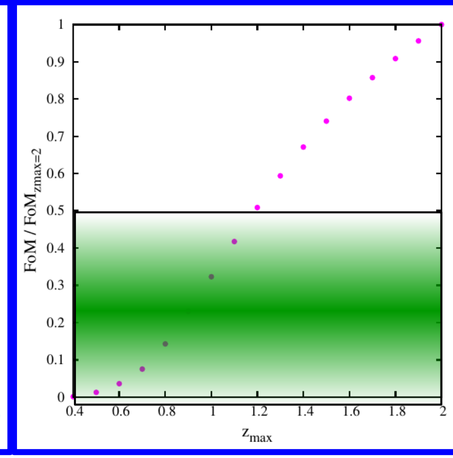
- 10^5 **galaxy clusters** (Sartoris+16)
- **Cosmic Voids**
- **Cross-correlations with CMB** temperature and lensing
- 10^5 **strong gravitational lenses**
- Transients in Deep fields
  - ~50 **Super-luminous SNe** / year (Inserra+17)
- Galaxy formation and evolution
  - Census of **AGN** at 1 < z < 3
  - Galaxy **morphologies** at z > 1
  - **Lyman break galaxies** at z > 7
  - High-z **quasars**
- Milky Way
  - Census of **brown dwarf** stars
  - **Satellites & environs**

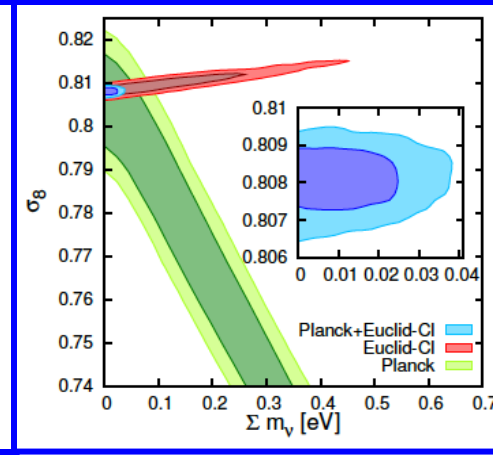


Euclid Galaxy Cluster Science

Impact of the observable-mass relation uncertainties: Euclid will internally calibrate the scaling relations







Impact of high redshit clusters: Euclid will see clusters at z>1.5.
Adding clusters with 1.2<z<2 double the cluster number counts FoM

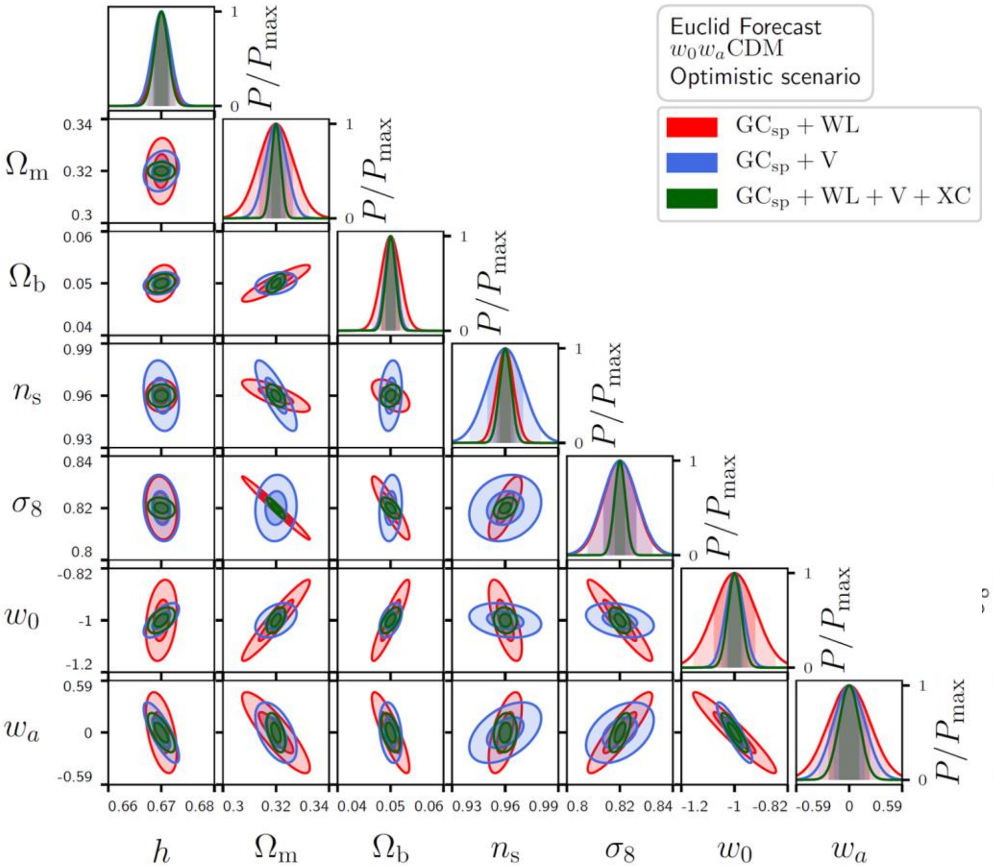
Clusters are conceptually and observationally independent of geometrical probes.

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν /eV	f_{NL}	w_p	w_a	FoM
Euclid primary (WL+GC)	0.010	0.027	5.5	0.015	0.150	430
Euclid All (Including Clusters)	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current (2009)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>40**	**>400**

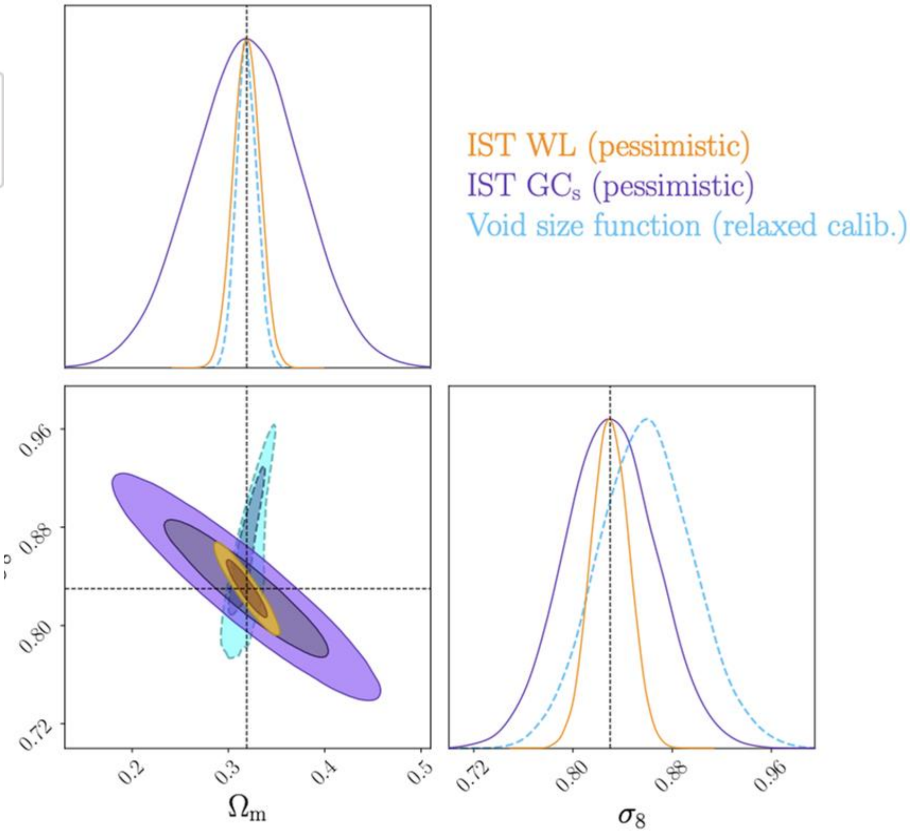
B. Sartoris Costanzi,BS+13, Sartoris+16

Credits: L. Moscardini

Cosmic voids!
Parameter inference from photo&spectro voids



Bonici & EC 2022



Contarini & EC 2021

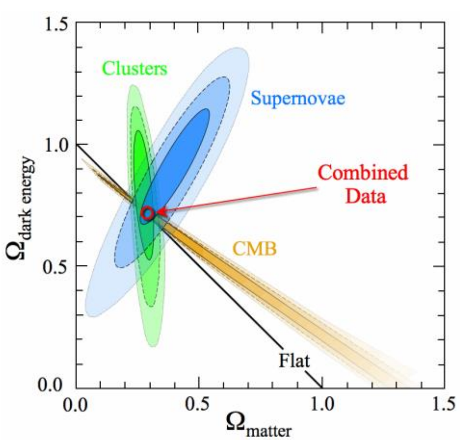
Euclid cross Planck

Pre-Launch KP: Complementary to forecasts for primary probes
Publication: Ilic & the Euclid Consortium 2021, A&A, arXiv:2106.08346

Key figures:

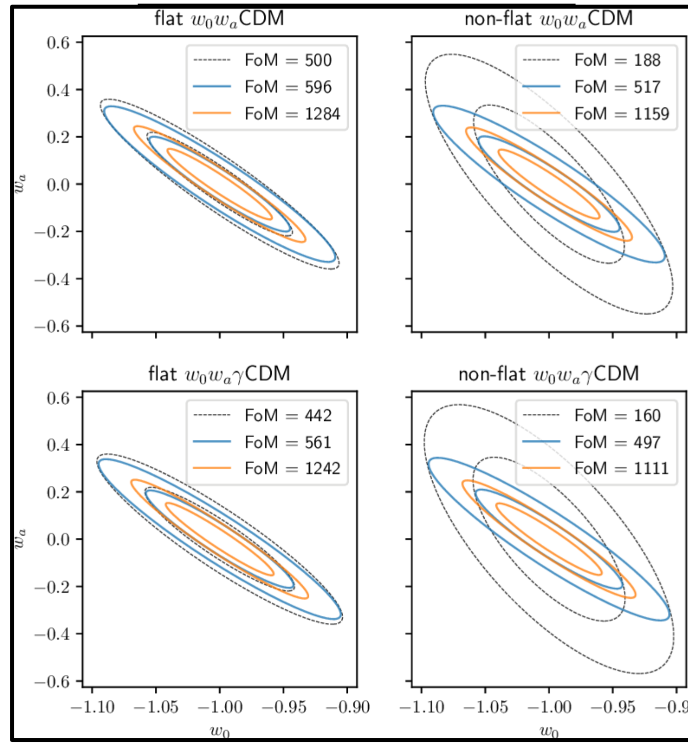
- 3 LSS probes: GC_{ph}, GC_{sp}, WL
- 3 CMB probes: T, E, ϕ
- 6 cosmological models (incl. w_0/w_a, Ω_k, γ)
- 2 Euclid scenarii (pessimistic/optimistic)
- 3 CMB setups (Planck-like, SO, CMB-S4)
- 2 scientific cases:
    - Euclid + CMB ϕ (all "matter probes")
    - Euclid + full CMB

w_0w_a FoM including CMBX >1100



Euclid only
Euclid + CMB ϕ
Euclid + full CMB

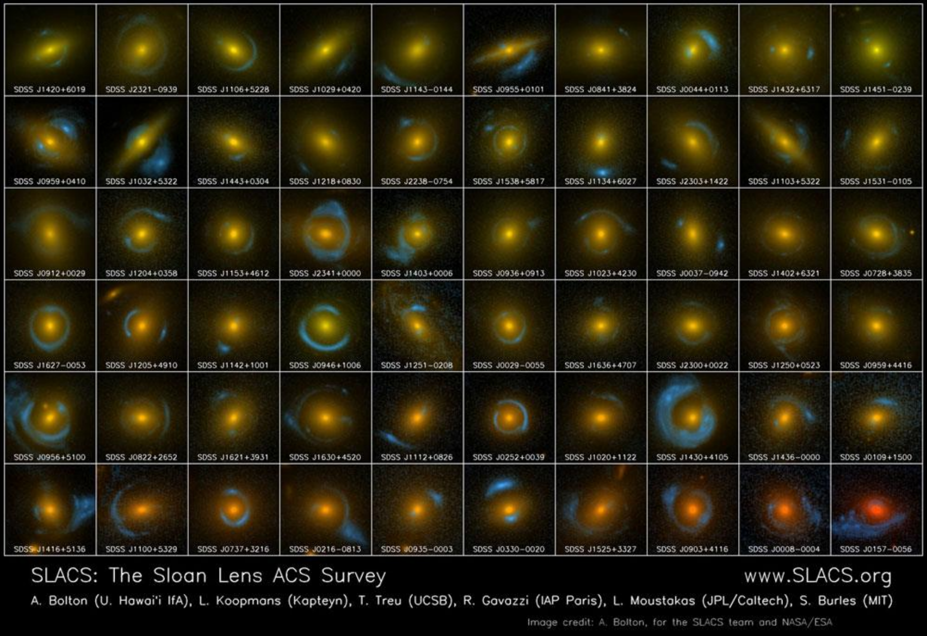
Pessimistic Euclid + SO



Credits: C. Baccigalupi

With Euclid VIS: ~3300 such lenses in two months!

SLACS

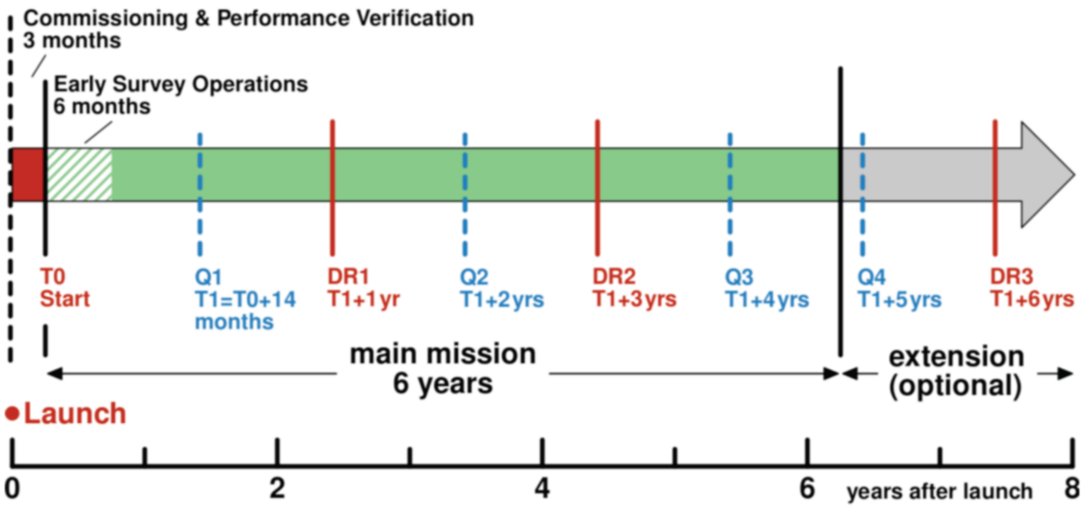


In the full Wide survey (60 months):

- **200,000 strong lenses around early-type galaxies;**
- **2300 lensed QSOs, of which ~16% quadruple lenses**
- **9000 cluster arcs with l/w>5 (~1300 with l/w>10)**

(Euclid Strong Lensing SWG white paper, based on ray-tracing simulations, Boldrin et al. 2016)

Euclid Data Releases Timeline



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Q1 (~50 deg²)
DR1 (2500 deg²)
DR2 (7500 deg²)
DR3 (15000 deg²)

- Three public data releases, with an increasing fraction of the survey:
  - DR1: ~ mid 2025 (1/6 of the survey)
  - DR2: ~ 2027 (1/2 of the survey)
  - DR3: ~ 2031 (full survey)
- Each Data Release will be coupled with papers containing results from the official analysis.
- The Euclid consortium web page: https://www.euclid-ec.org/
- ESA's Euclid page: https://www.esa.int/Science_Exploration/Space_Science/Euclid


esa
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SUCCESSFUL
2024
Euclid
consortium