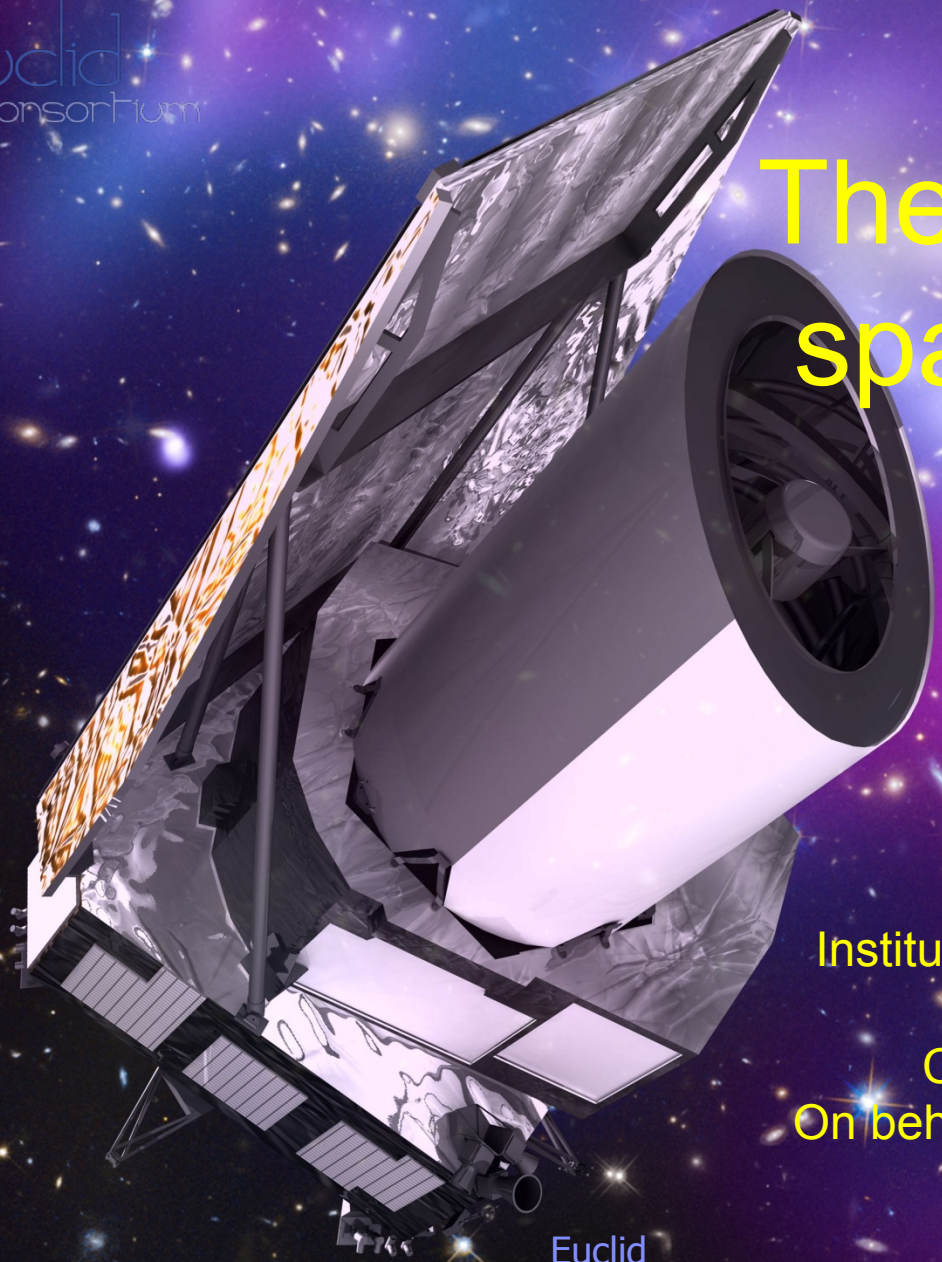
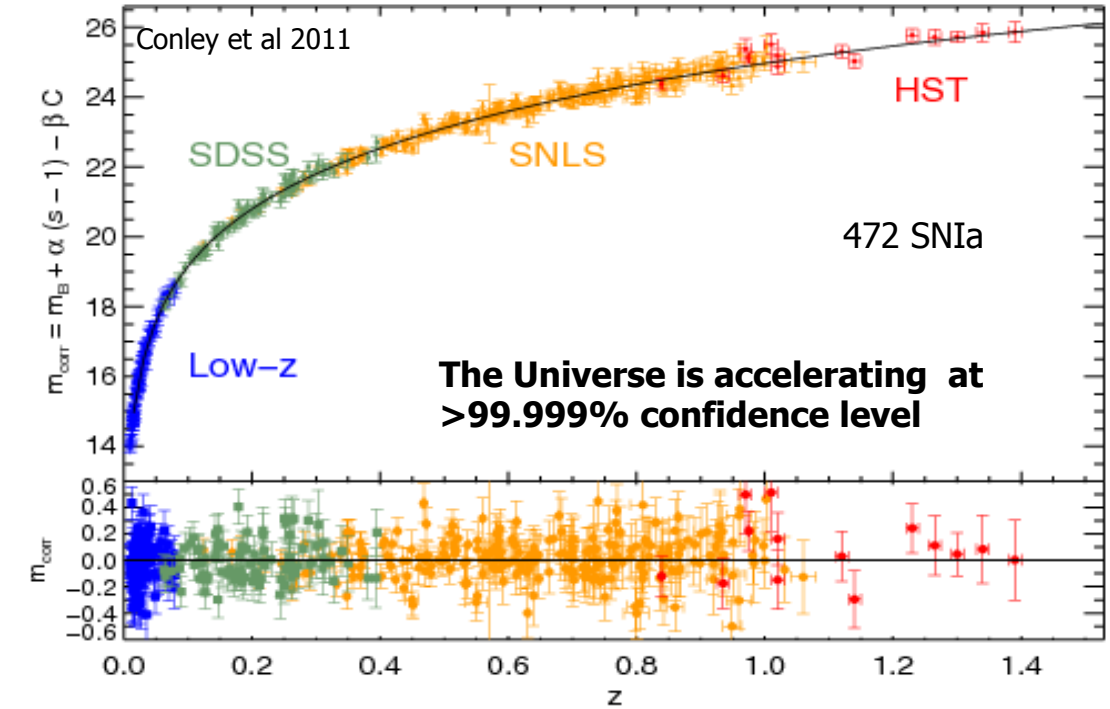
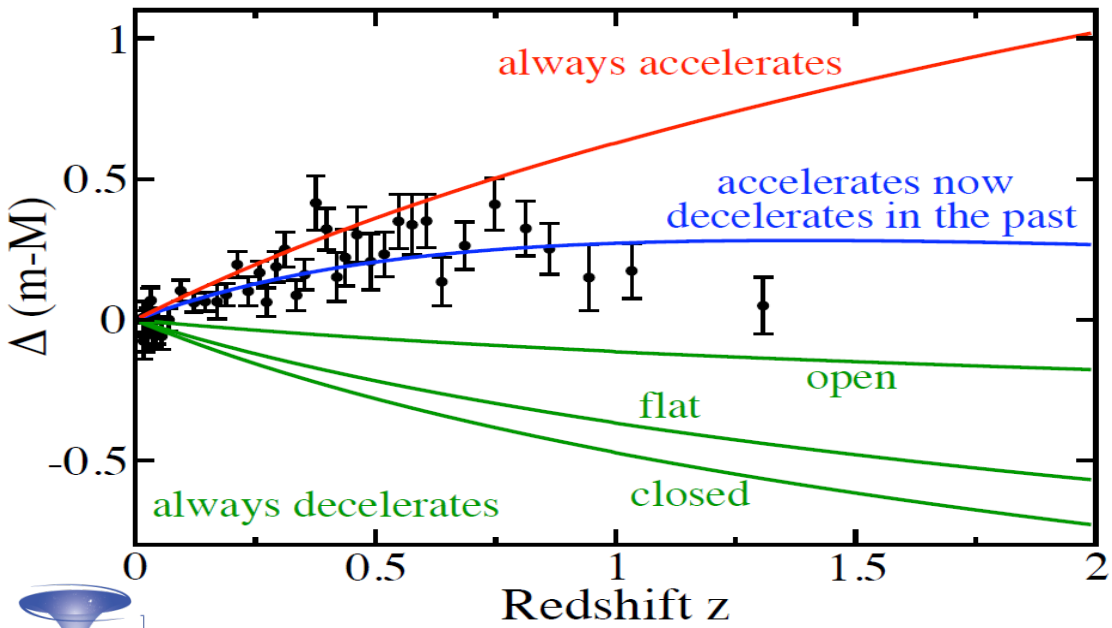


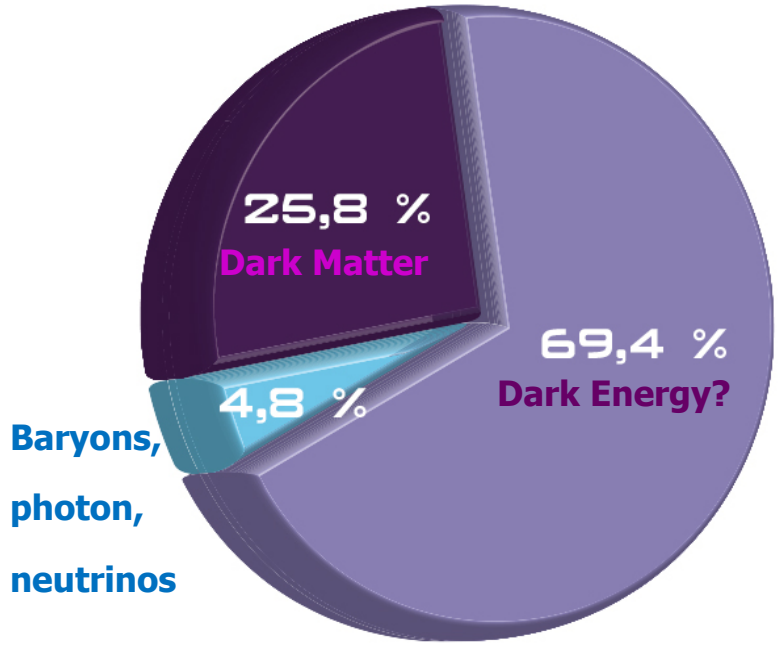
# The ESA Euclid space mission

**Y. Mellier**
Institut d' Astrophysique de Paris
and
CEA/IRFU/SAp Saclay
On behalf of the Euclid Consortium

# The accelerating Universe




The Planck collaboration.

Ade et al 2013

# Why is the expansion accelerating?

- Dark Energy: a new component/interaction of unknown nature that opposes the gravitation on cosmological scales, as a negative pressure?

- Modified Gravity: Einstein's General Relativity is not a good description of gravitation at cosmological scales?

- Other ? … Complex DE/MG models, Cosmological Principle ?

# The dark universe after Planck

- Parameterising our ignorance:

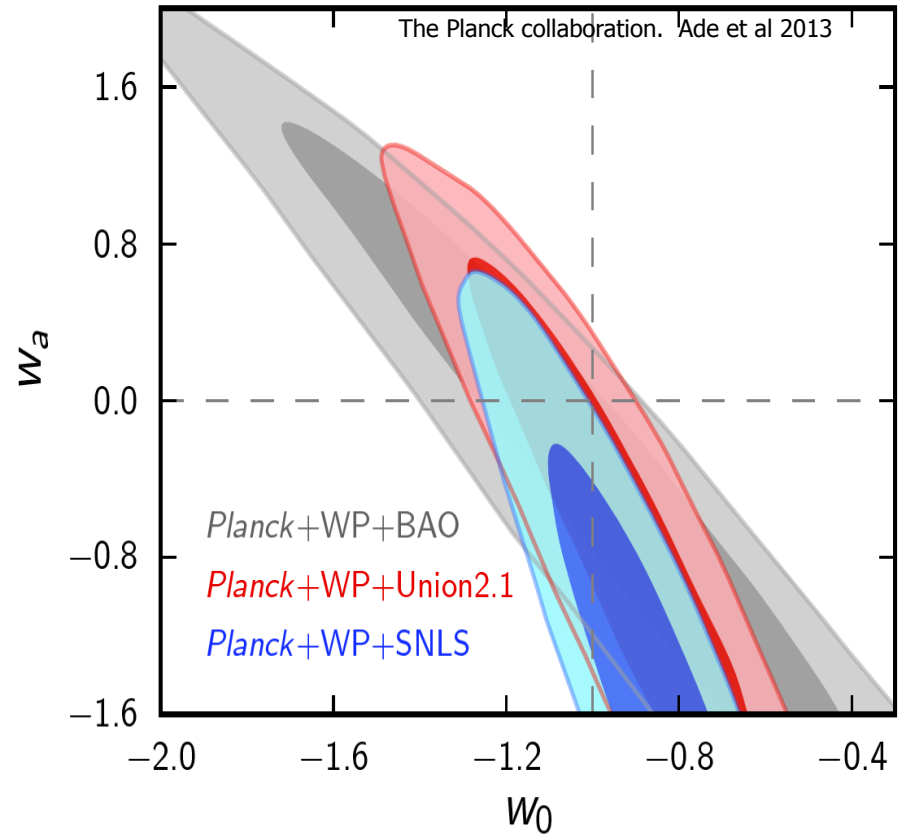
DE equation of state: $P/\rho = w$ , and $w(a) = w_p + w_a(a_p - a)$

Growth rate of structure formation gravity: $f \sim \Omega^{\gamma}$ ; $\gamma = 0.55$ =GR

**After Planck:** *w* may not be -1 or may vary with time ...

BUT Planck cannot probe its effects with sufficient details and explore its very nature...

different probes are needed...



# Cosmological probes of dark energy

Expansion Rate (BAO):

$$H(z) = H_0 \left[ \Omega_{\rm M}(1+z)^3 + \Omega_{\rm DE} \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE}(0)} + \Omega_{\rm K}(1+z)^2 \right]^{1/2}$$

Distance (SN, BAO, CMB):

$$D(z) = \frac{1}{(|\Omega_{\rm K}|H_0^2)^{1/2}} S_{\rm K} \left[ (|\Omega_{\rm K}|H_0^2)^{1/2} \int_0^z \frac{dz'}{H(z')} \right]$$

Growth (WL, clusters):

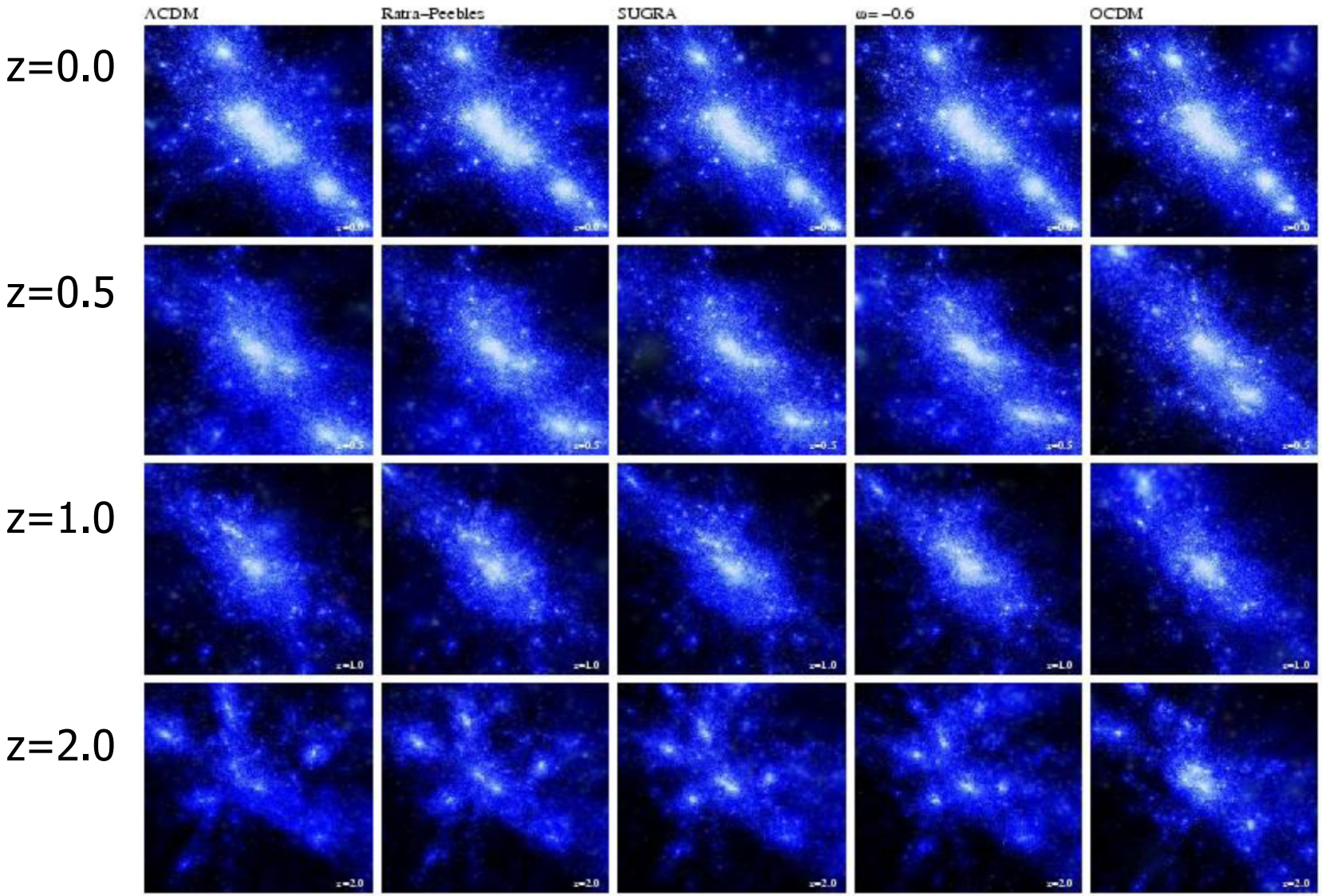
$$G'' + \left(4 + \frac{H'}{H}\right) G' + \left[3 + \frac{H'}{H} - \frac{3}{2}\Omega_{\rm M}(z)\right] G = 0$$

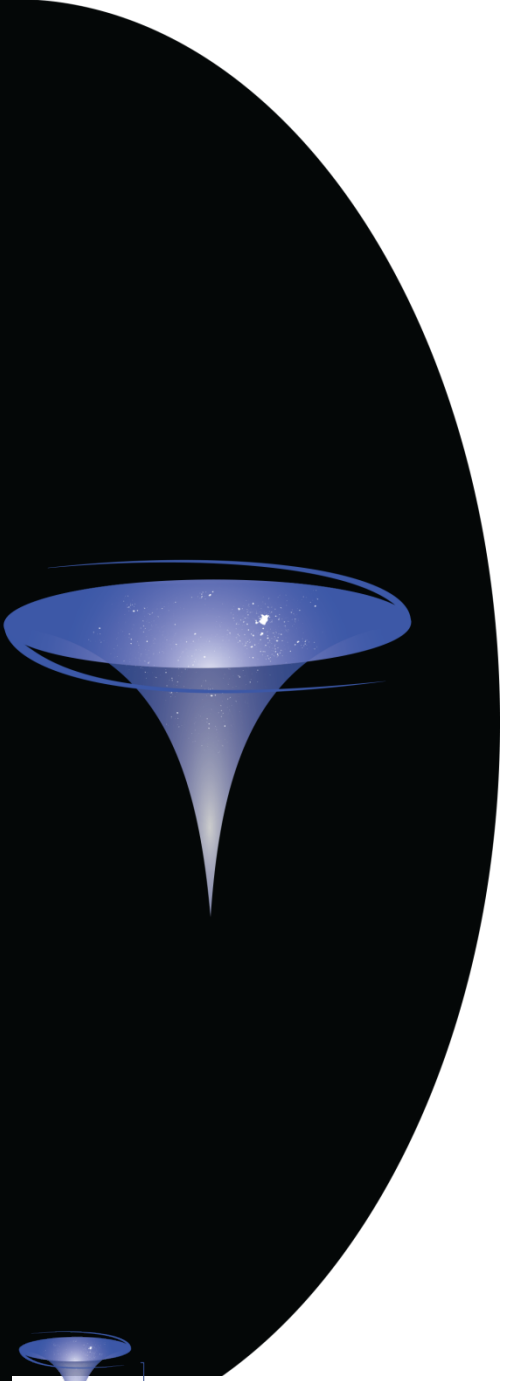
$$G = D_1/a$$

Measuring the metrics:

$$\mathrm{d}s^2 = a^2(\eta)[-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)\gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j]$$

# Tiny differences between DE/MG models





# 1. Euclid Scientific Mission

# 2. Euclid Implementation

# 3. Euclid Performance

# Euclid Primary Objectives: the Dark Universe

- Understand the origin of the Universe's accelerating expansion
- Probe the properties and nature of Dark Energy and Gravity,

- Probe the effects of Dark Energy, Dark Matter and Gravity by:
  - Using at least 2 independent but complementary probes (5 probes)
  - Tracking their observational signatures on the
    - Geometry of the universe: Weak Lensing (WL), Galaxy Clustering (GC)
    - Cosmic history of structure formation: WL, Redshift-Space Distortion (RSD), Clusters of Galaxies (CL)
  - Controling systematic residuals to an unprecedented level of accuracy.

# Distinguishing *decisively*

Assuming:

- DE equation of state: $P/\rho = w$ , and $w(a) = w_p + w_a(a_p - a)$
- Growth rate of structure formation: $f \sim \Omega^{\gamma}$ ;

- Nature of dark energy
  - Distinguish effects of $\Lambda$ and dynamical DE: Measure $w(a)$ → slices in redshift
  - From Euclid data alone, get FoM=$1/(\Delta w_a \times \Delta w_p) > 400$→ ~1% precision on w's.

    → if data consistent with $\Lambda$, and FoM > 400 : $\Lambda$ favoured with odds of more than 100:1 = a "decisive" statistical evidence.

- Nature of gravity on cosmological scales
  - Probe growth of structure → slices in redshift ,
  - Separately constrain the metrics potentials ($\Psi$,$\Phi$) as function of scale and time
  - Distinguish effects of GR from MG models with very high confidence level:

    → absolute 1-σ of 0.02 on the growth index, $\gamma$ , from Euclid data alone.

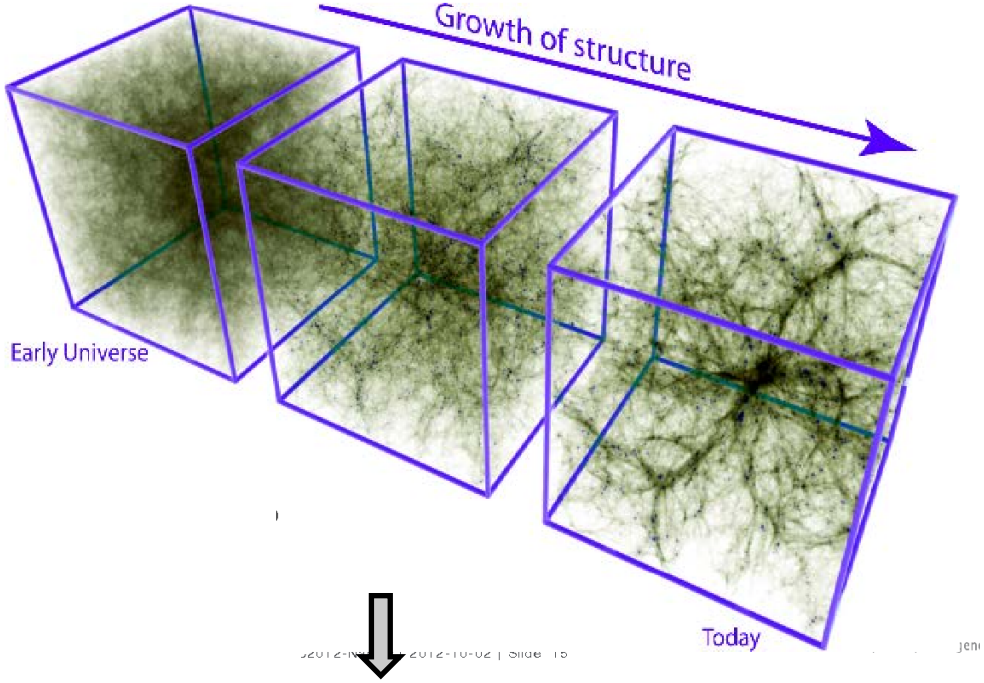
    → WL and RSD are differently sensitive to $\Psi$, $\Phi$: $\Psi + \Phi$ (WL) ; $\Phi$ (GC, RSD)

# Galaxy Clustering: BAO + RSD

3-D position measurements of galaxies over 0.7<z<1.8

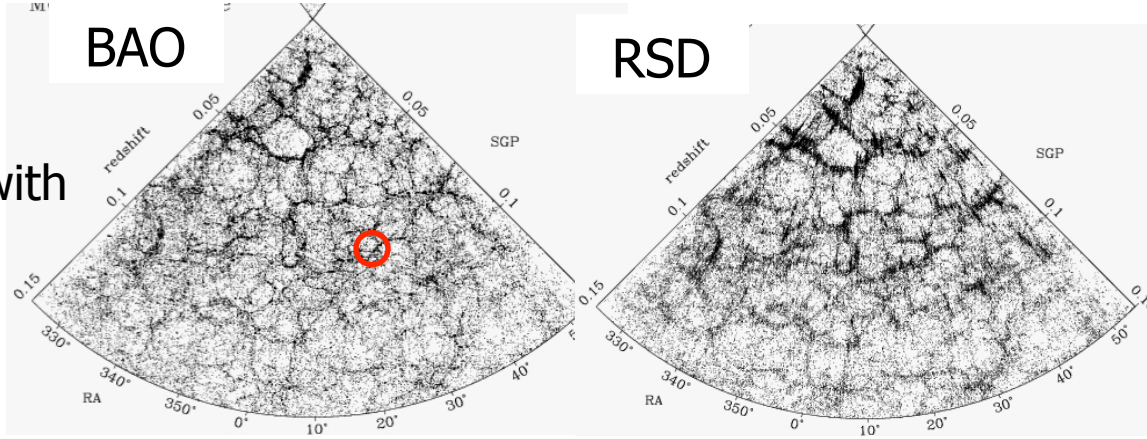
- Probes expansion rate of the Universe (BAO) and clustering history of galaxies induced by gravity (RSD); $\gamma$, $H(z)$.

- Need high precision 3-D distribution of galaxies with spectroscopic redshifts.




Euclid:

30 million spectroscopic redshifts with 0.001 (1+z) accuracy over 15,000 deg$^2$



# Weak Lensing tomography and 3D lensing

Cosmic shear over 0<z<2

$$\kappa_{eff} = \frac{3H_0^2\Omega_0}{2c^2}\int_0^{\omega}\frac{f_K(\omega-\omega')\,f_K(\omega')}{f_K(\omega)}\frac{\delta\left[f_K(\omega')\boldsymbol{\theta};\omega'\right]}{a(\omega')}\mathrm{d}\omega'$$

- Probes distribution of matter (Dark +Luminous): expansion history, growth rate of structure formation.

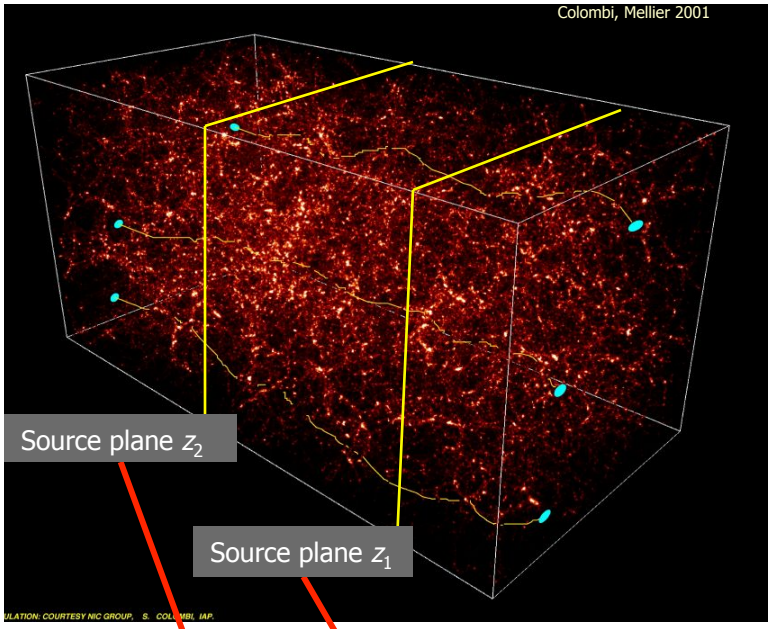
→ Shapes+distance of galaxies: shear amplitude, and bin the Universe into slices.

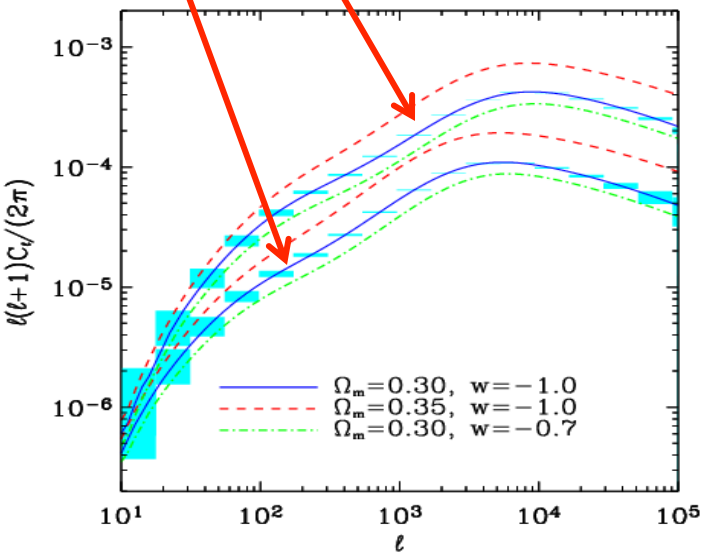
→ "Photometric redshifts" sufficient for distances: optical+NIR data.

Euclid:

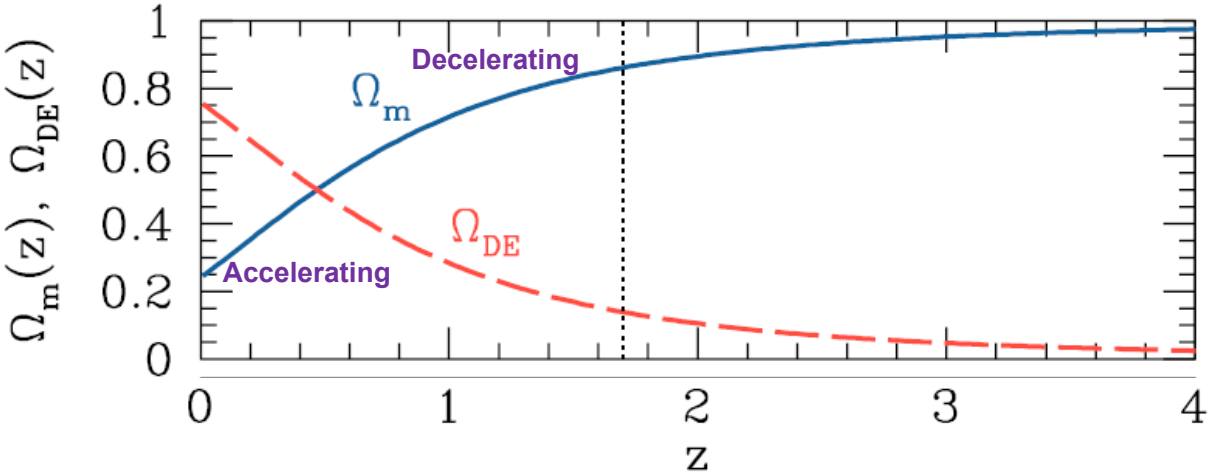
WL with 1.5 billion galaxies

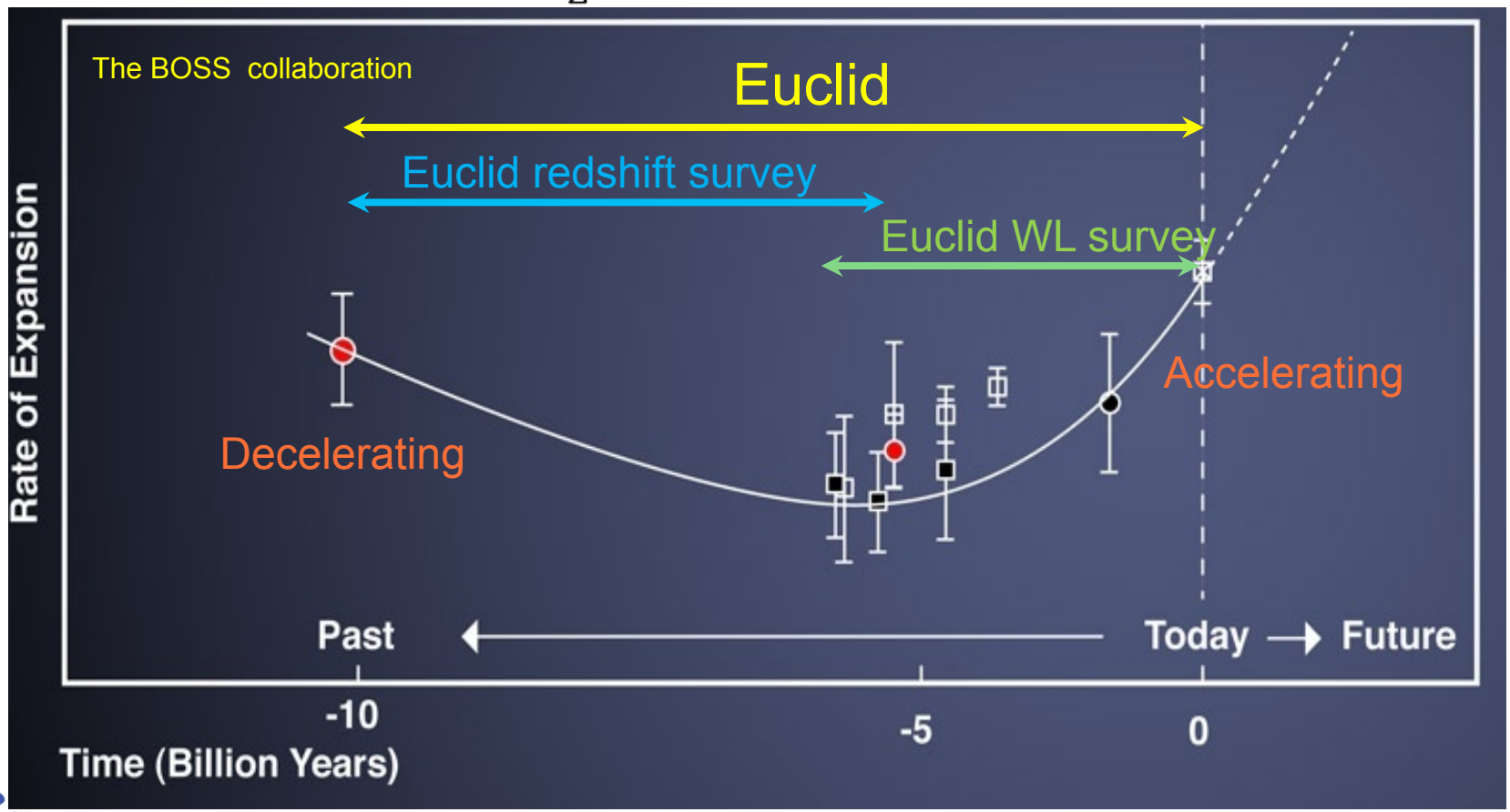
over 15,000 deg$^2$



# Universe explored by Euclid: DM/DE transition era



# Photometric redshifts needed for Euclid

Colombi, Mellier 2001

- Weak Lensing : redshifts of 1.5 x$10^9$ sources to
  - Slice the universe
  - Control contamination by intrinsic alignments of galaxies

$$\langle \epsilon_i \epsilon_j \rangle = \underbrace{\langle \gamma_i \gamma_j \rangle}_{\text{GG}} + \underbrace{\langle \epsilon_i^s \epsilon_j^s \rangle}_{\text{II}} + \underbrace{\langle \gamma_i \epsilon_j^s \rangle + \langle \epsilon_i^s \gamma_j \rangle}_{\text{GI}}$$

- Redshifts of Euclid clusters: (60,000 clusters, 5,000 giant arcs) → synergy with Planck and eROSITA
- Redshifts of sources and lenses: needed at least in the range 0.2<z<2

→ Photo-z needed with VIS+NIR data

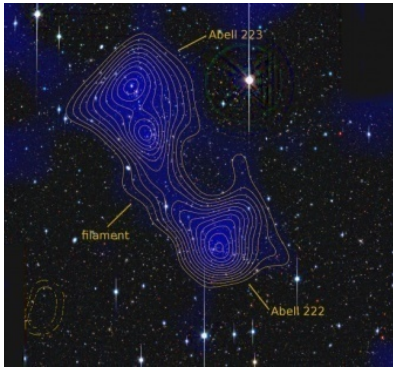
HST/ACS credit NASA/ESA

Galaxy halos

HST/ACS; credit NASA/ESA

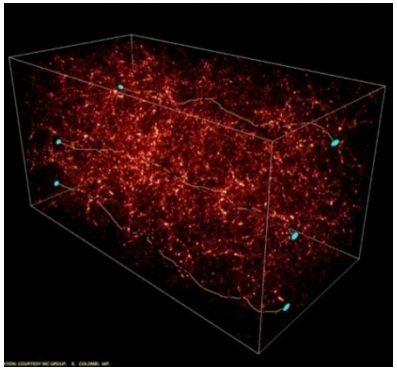
Clusters of galaxies

Dietrich et al 2012



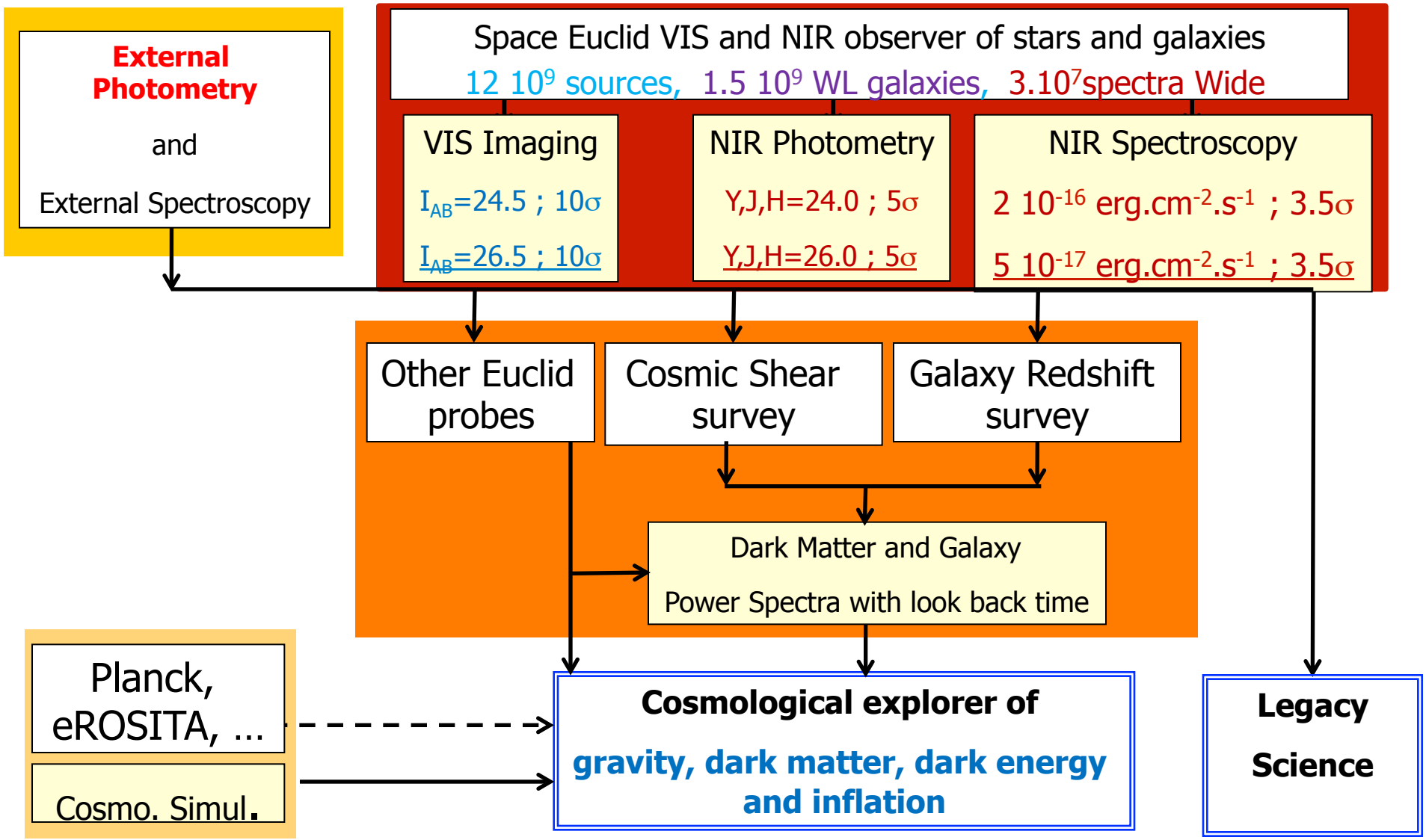

Filaments between clusters

Colombi/Mellier



Cosmic shear

# Euclid Survey Machine: 15,000 deg$^2$ + 40 deg$^2$ deep



1. Euclid Scientific Mission

2. Euclid Implementation

3. Euclid Performance

# Requirements to Design the Mission

| | Wide survey | Deep survey |
|---|---|---|
| **Survey: 6 years** | | |
| size | 15, 000 deg $^2$ | 40 deg$^2$ N/S |
| **VIS imaging** | | |
| Depth | $n_{gal}$ > 30/arcmin$^2$ $M_{AB}$ =24.5, 10σ for gal size 0.3 » → <z> ~0.9 | $M_{AB}$ = 26.5 |
| PSF size knowledge | $\sigma[R^2]/R^2<10^{-3}$ | |
| Multiplicative bias in shape | $\sigma[m]<2\ .10^{-3}$ | |
| Additive bias in shape | $\sigma[c]<2\ .10^{-4}$ | |
| Ellipticity RMS | $\sigma[e]<2\ .\ 10^{-4}$ | |
| **NIP photometry: YJH** | | |
| Depth | 24 $M_{AB}$ | 26 $M_{AB}$ |
| **NIS spectroscopy: 4 R exp., 3 R orientations** | | |
| Flux limit (erg/ cm$^2$/s) | 2 $10^{-16}$ | 5 $10^{-17}$ |
| Completness | > 45 % | >99% |
| Purity | >80% | >99% |
| Confusion | 3 rotations | >12 rotations |

## WL and systematics

$$\gamma^{obs} = (1+m)\times\gamma^{true} + c$$

$$C_l^{true} \approx \left[1+2\langle m\rangle\right]\times C_l^{obs} \quad +\langle c^2\rangle$$

- Small PSF, Knowledge of the PSF size
- Knowledge of distortion
- Method to correct distortion
- Method to correct Non-convolutive PSF
- Stability in time → space telescope
- Visible photom photo-z accurary: 0.05x(1+z)
- Catastrophic z < 10%

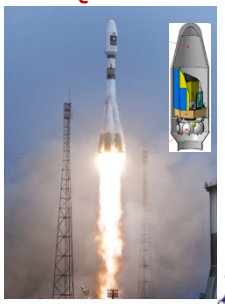
## GC and systematics

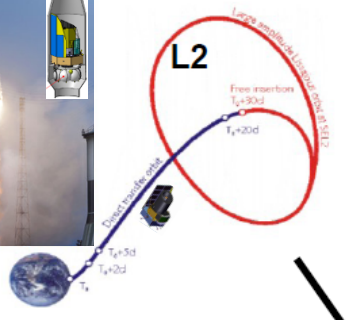
- Understand selection→Deep field (photo+spectro)
  - Completeness
  - Purity

# The ESA Euclid space mission

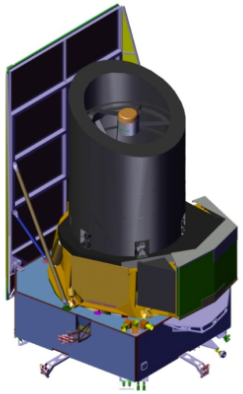
Soyuz@Kourou

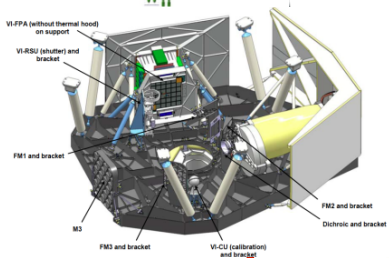
Q1 2020





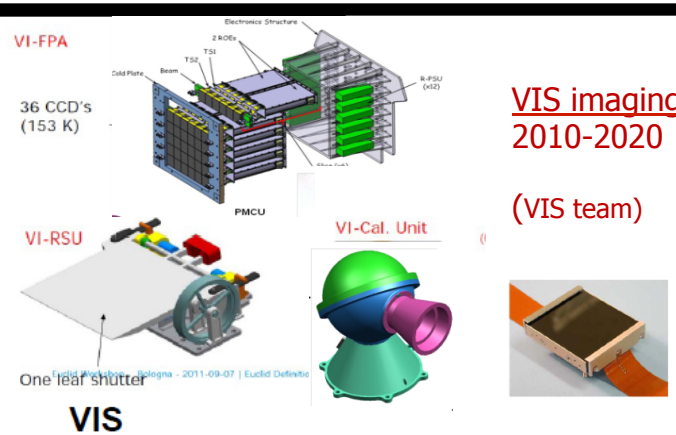

PLM+SVM: 2010-2019





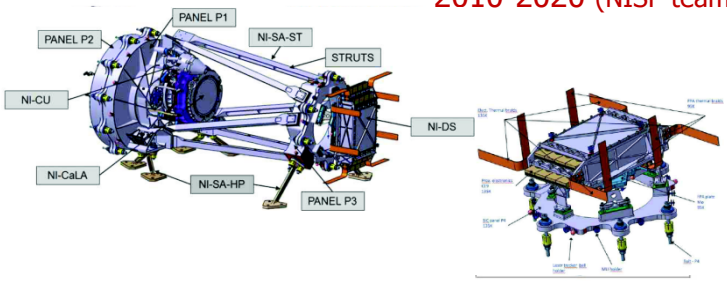

VIS imaging: 2010-2020

(VIS team)

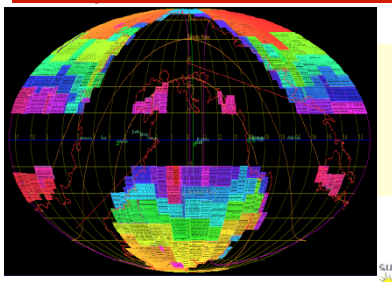


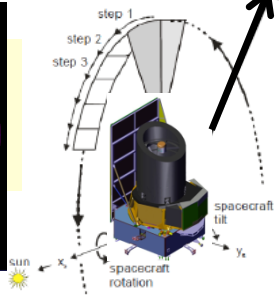

NIR spectro-imaging

2010-2020 (NISP team)




Surveys: 2010-2028 (Survey WG)






6 yrs - 15,000 deg$^2$

Commisionning – SV

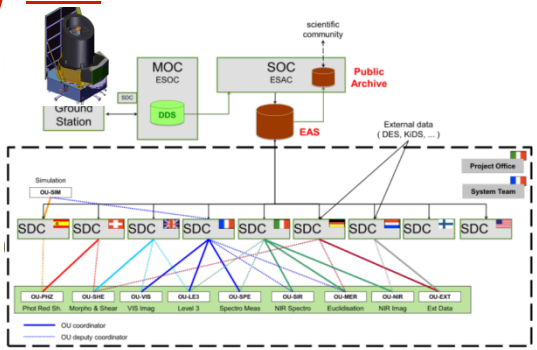
Euclid opération:

5.5 yrs:Euclid Wide+Deep

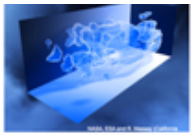
+: SNIa, mu-lens, MW?

Ground data

SGS: 2010-2028

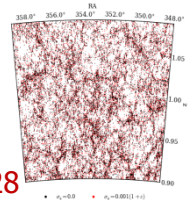


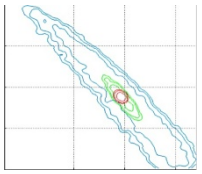

~100 PB data processing (EC-SGS team)



SWG:

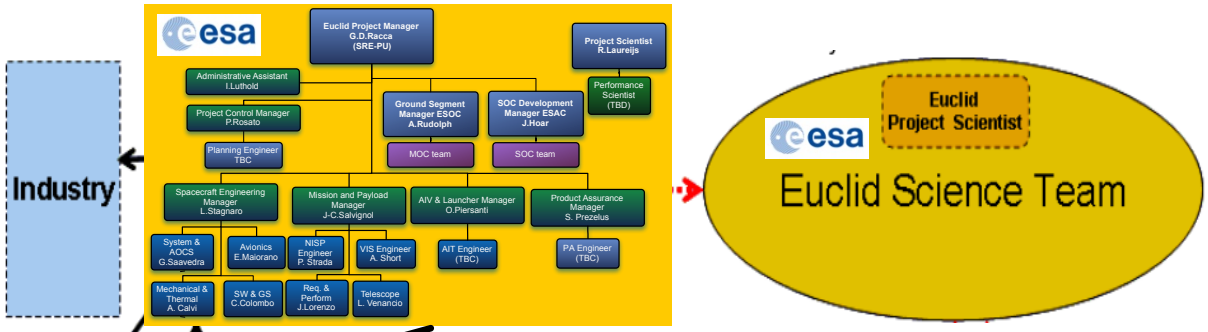
2019-2028





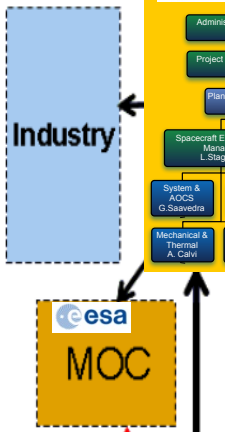
Science analyses

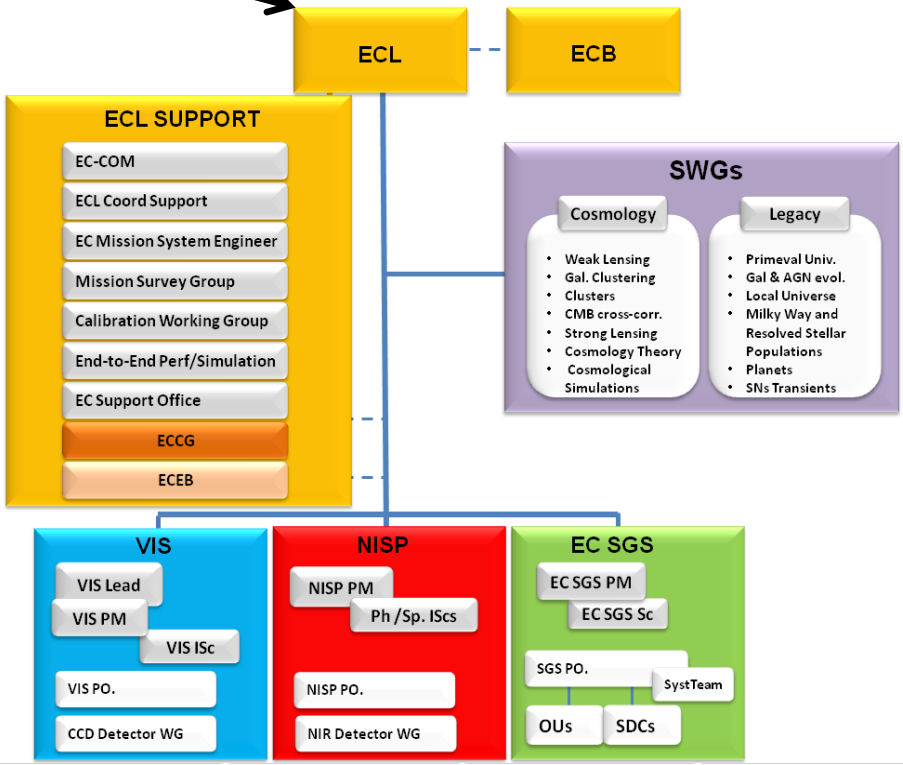
# Euclid Collaboration/Consortium











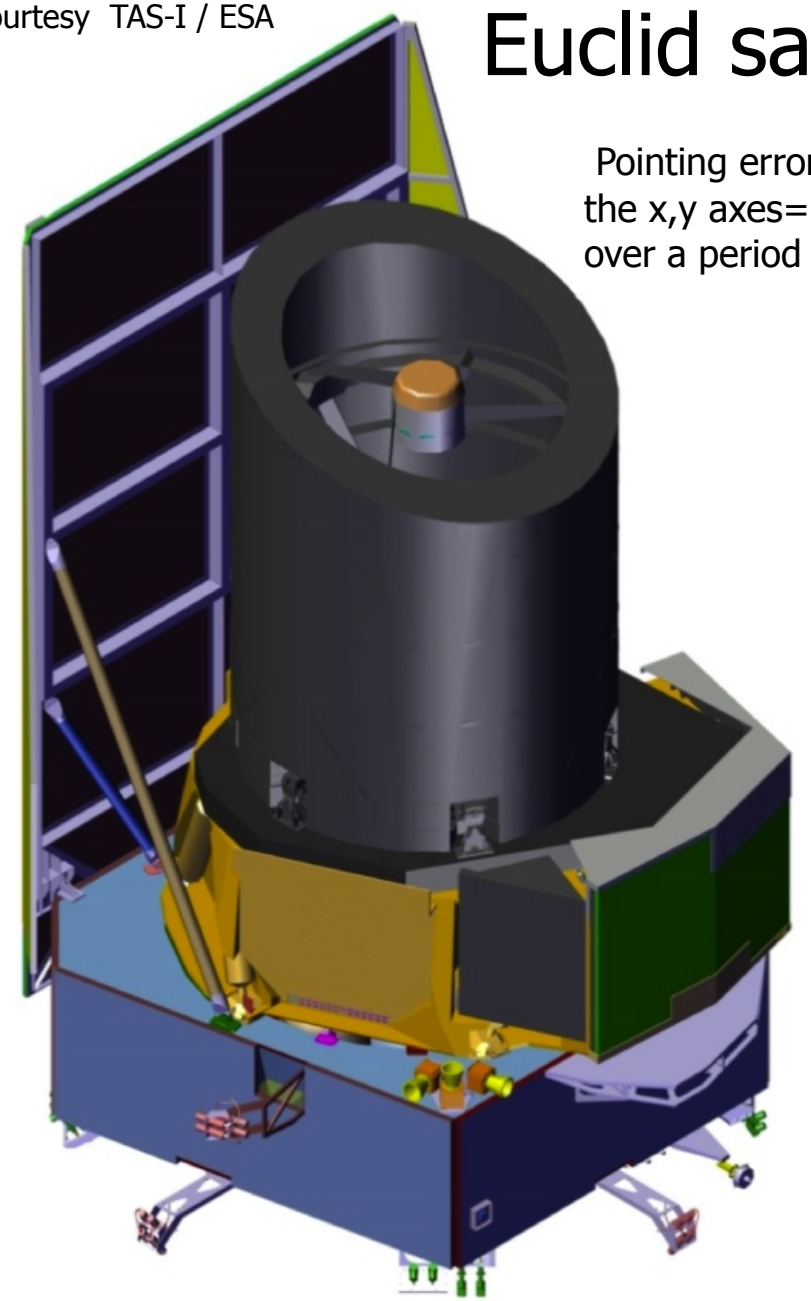

## Euclid Consortium

- 1250 members,
- 125 Labs
- 15 countries:

Austria, Belgium, Denmark, France, Finland,, Germany, Italy, The Netherlands, Norway, Portugal, Romania, Spain, Switzerland, UK US/NASA and Berkeley labs.

Courtesy TAS-I / ESA

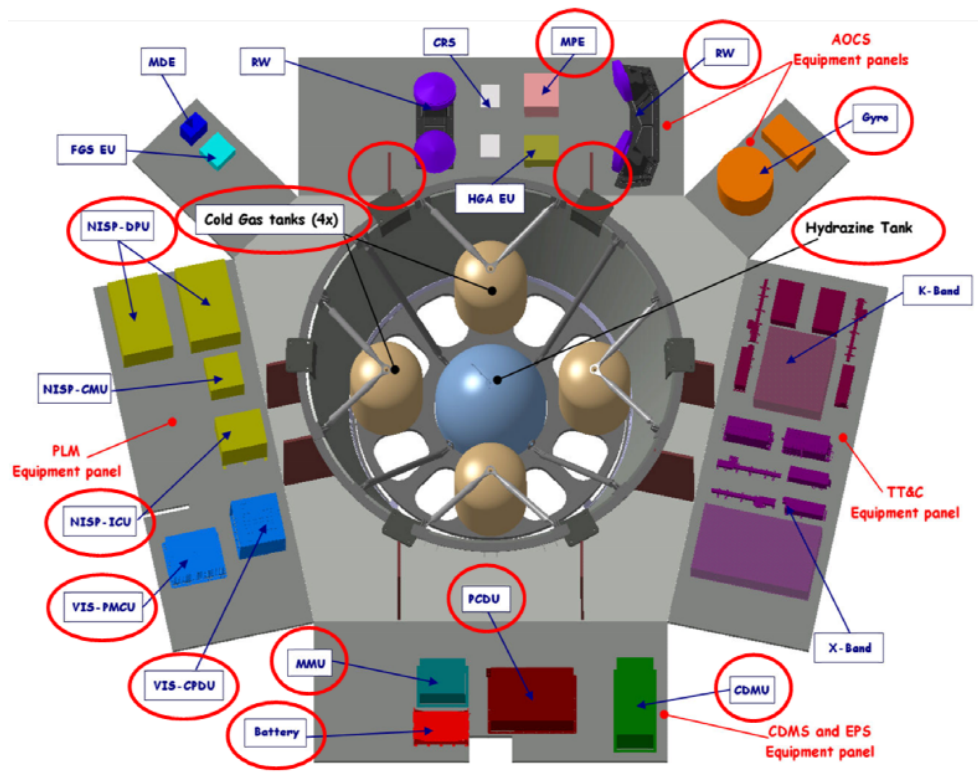
# Euclid satellite: Thales Alenia Space



Pointing error along the x,y axes= 25mas over a period 700 s.

- Total Mass of the satellite : 2 200 kg
- Dimensions:

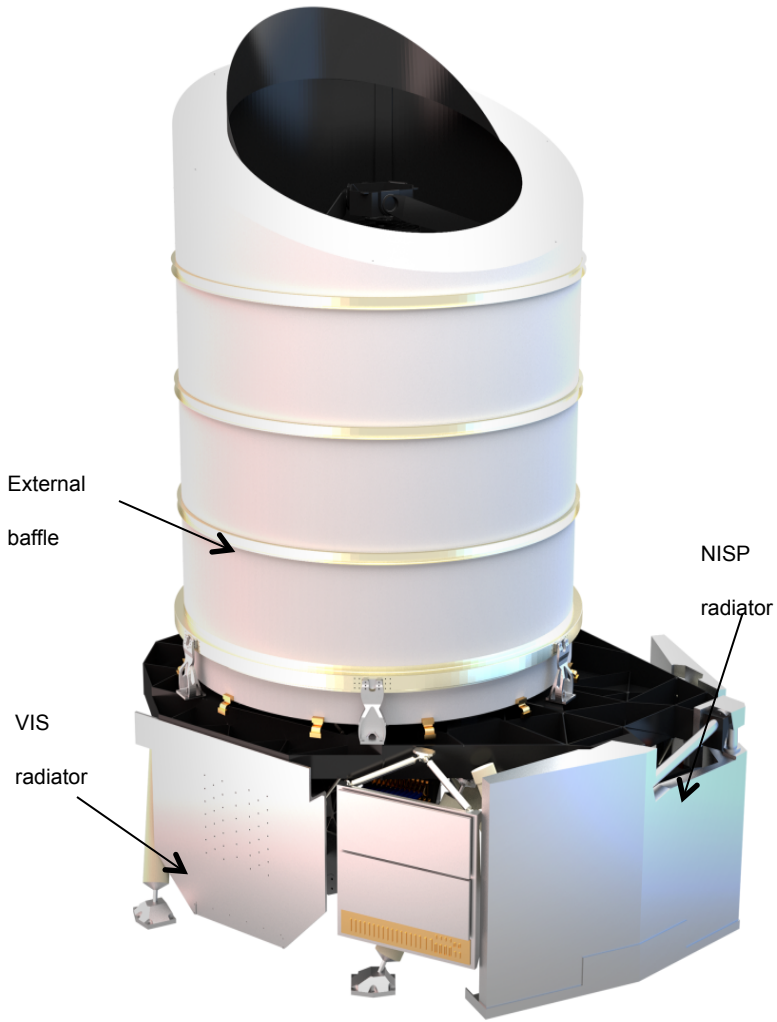
  4,5 m x 3 m

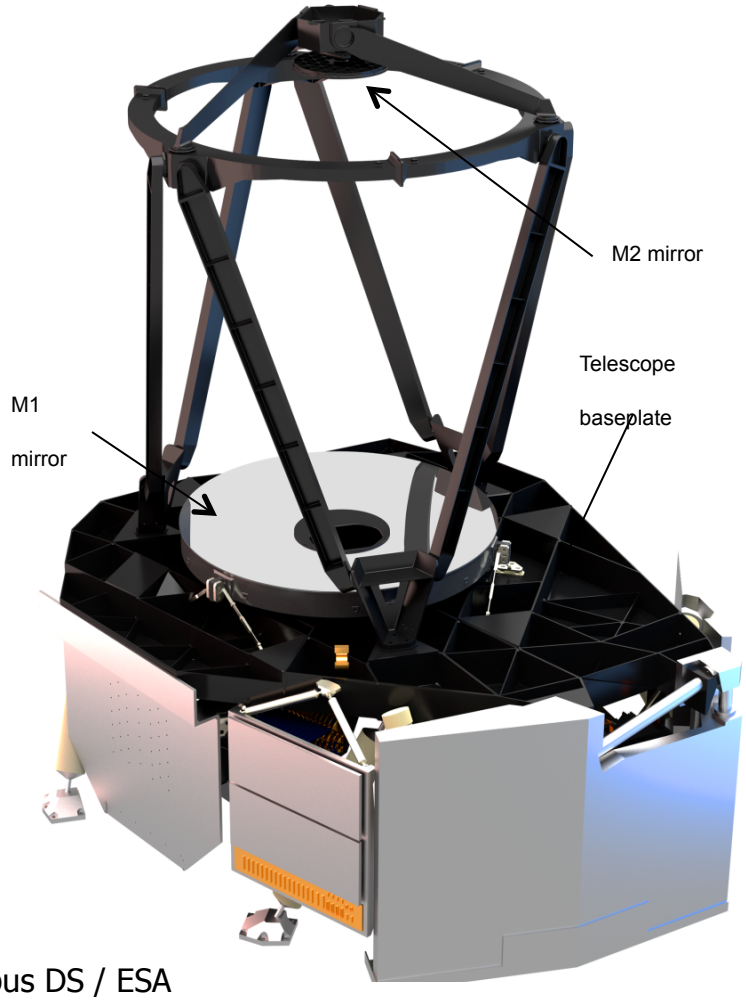


# Euclid telescope: Airbus DS

- Télescope 1,2 m: FoV: 0.54 deg$^2$
- Miror in Silicon Carbide= ultra-stable:

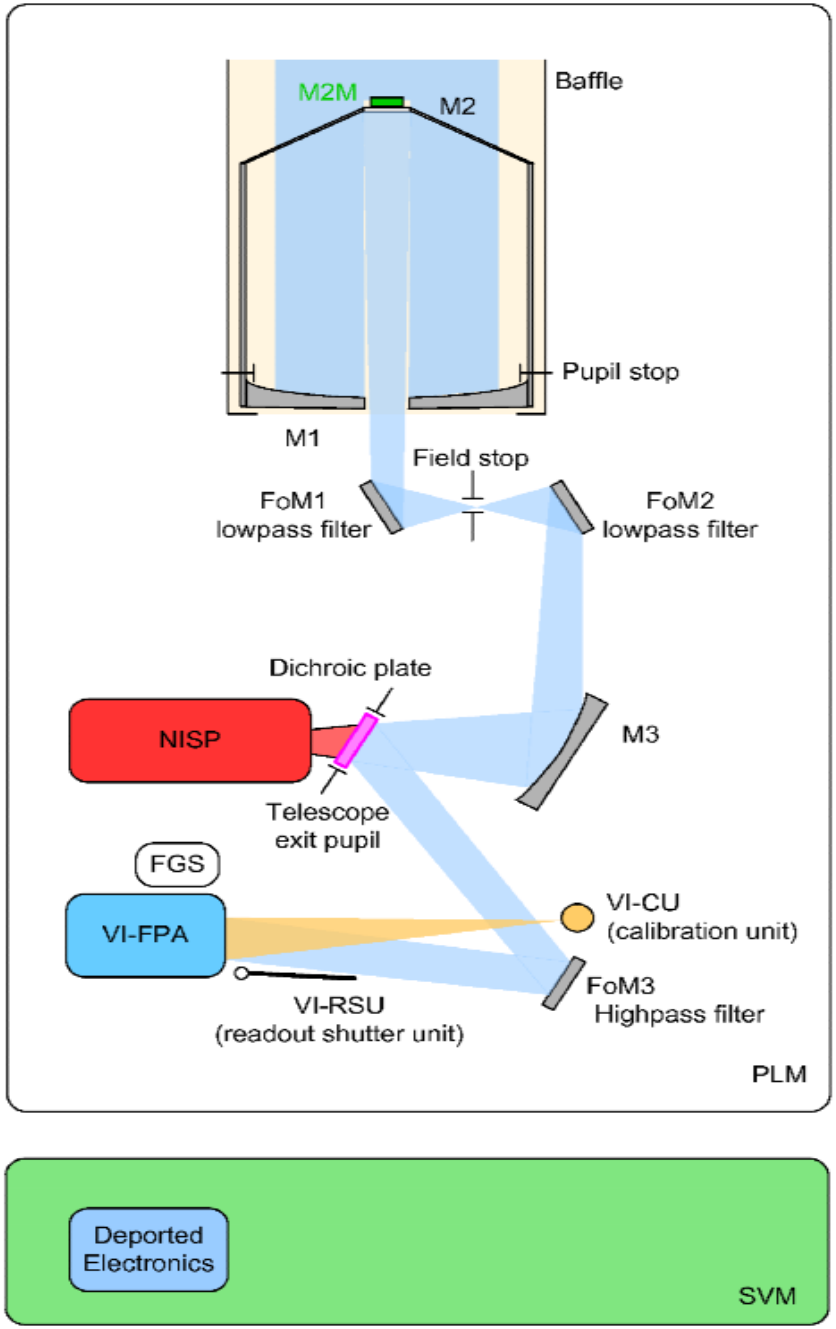
  Temp.: -150 deg. Stability +:- 0.05 deg.



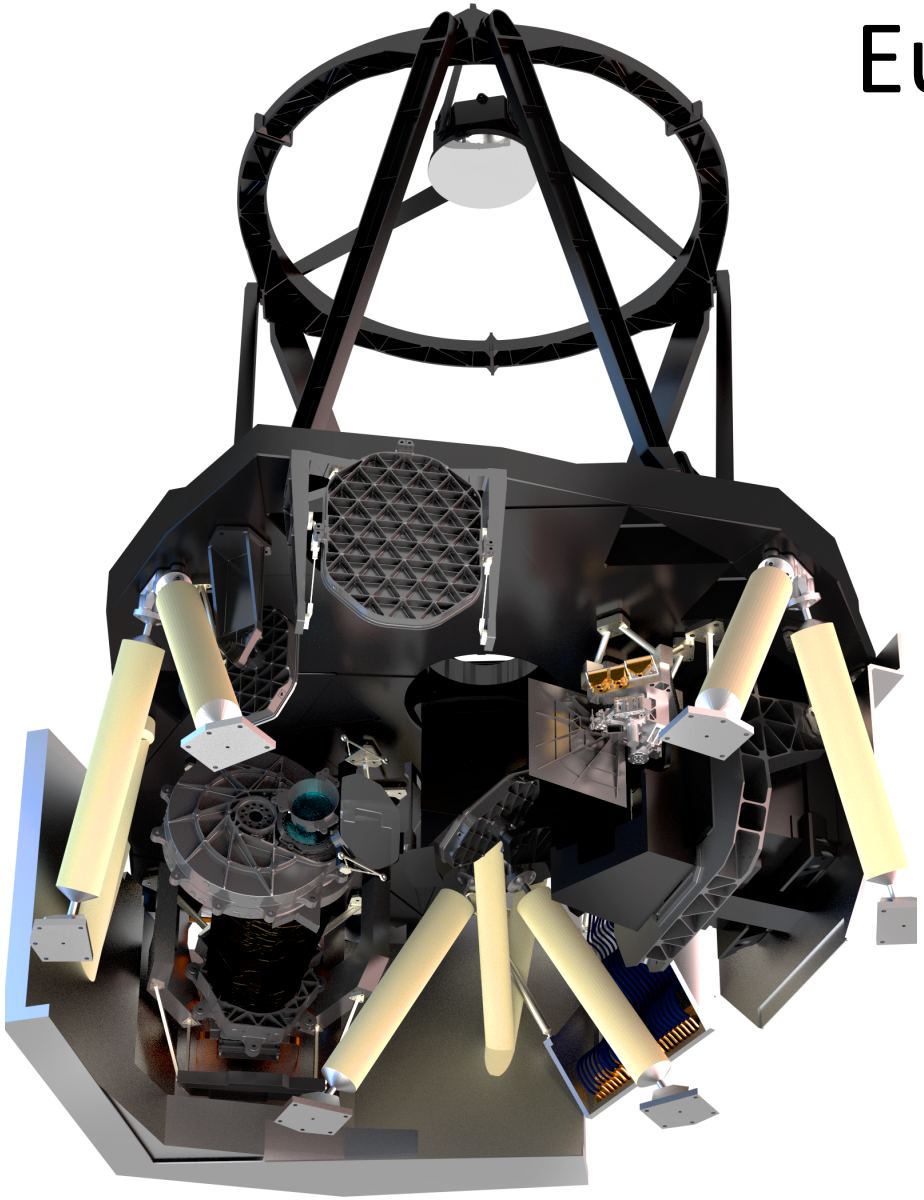



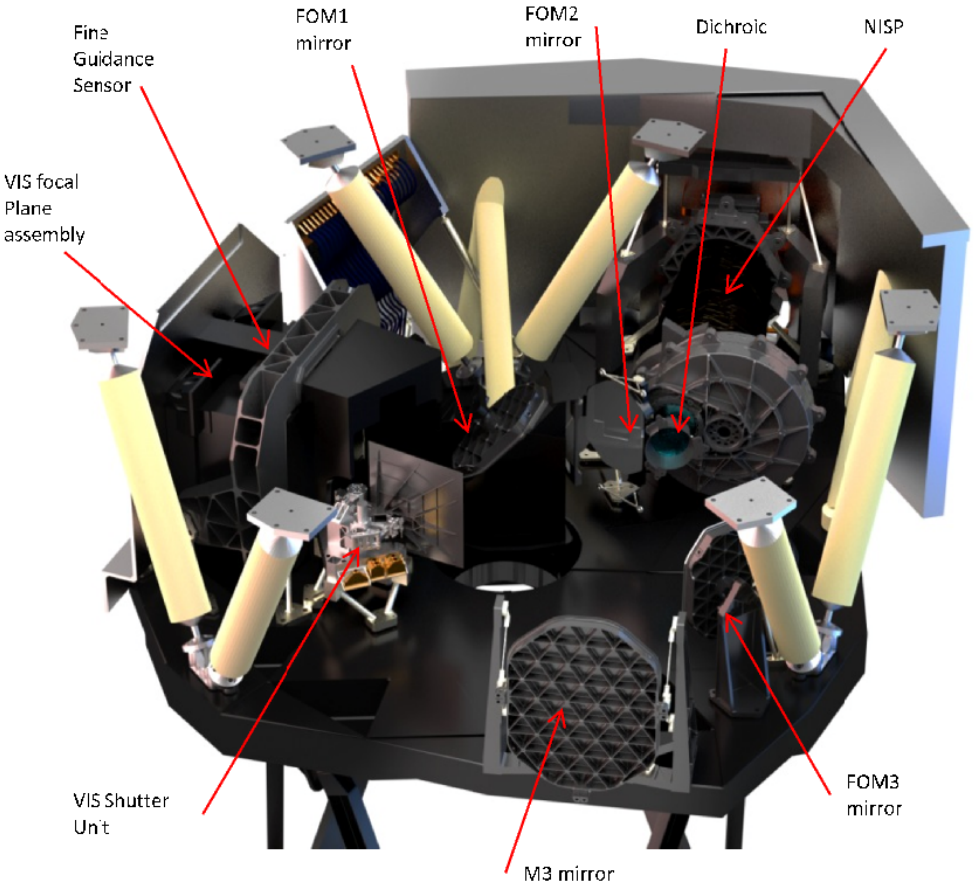

Courtesy Airbus DS / ESA

# Euclid PLM: system overview



# Euclid payload



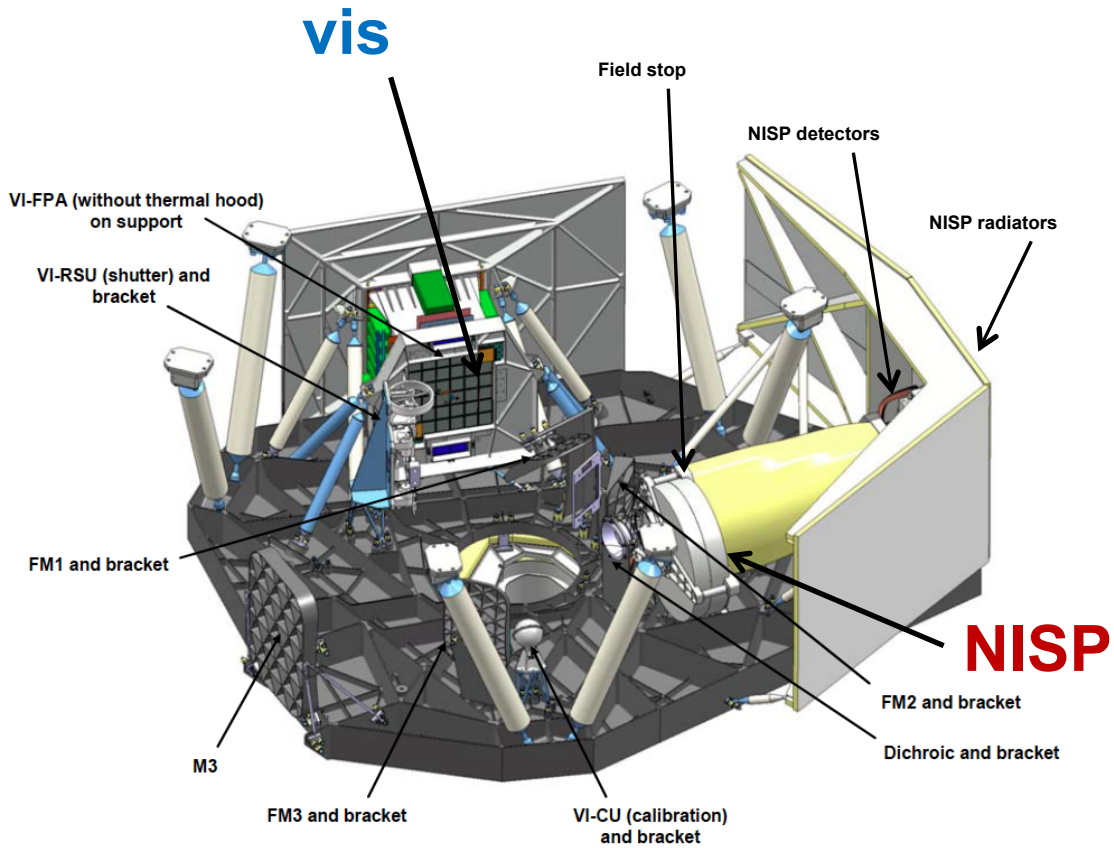



Common VIS and NIR FoV = 0.54 deg$^2$

Courtesy Airbus DS / ESA

# PLM and scientific instruments

From Thales Alenia Italy, Airbus DS, ESA Project office and Euclid Consortium

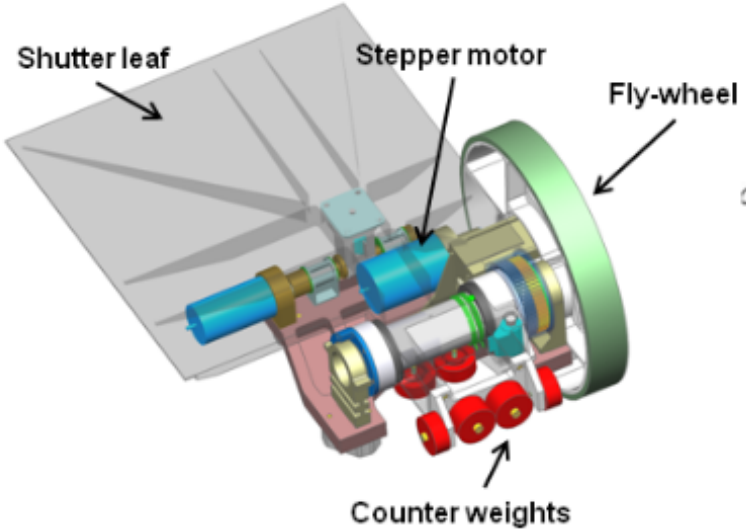


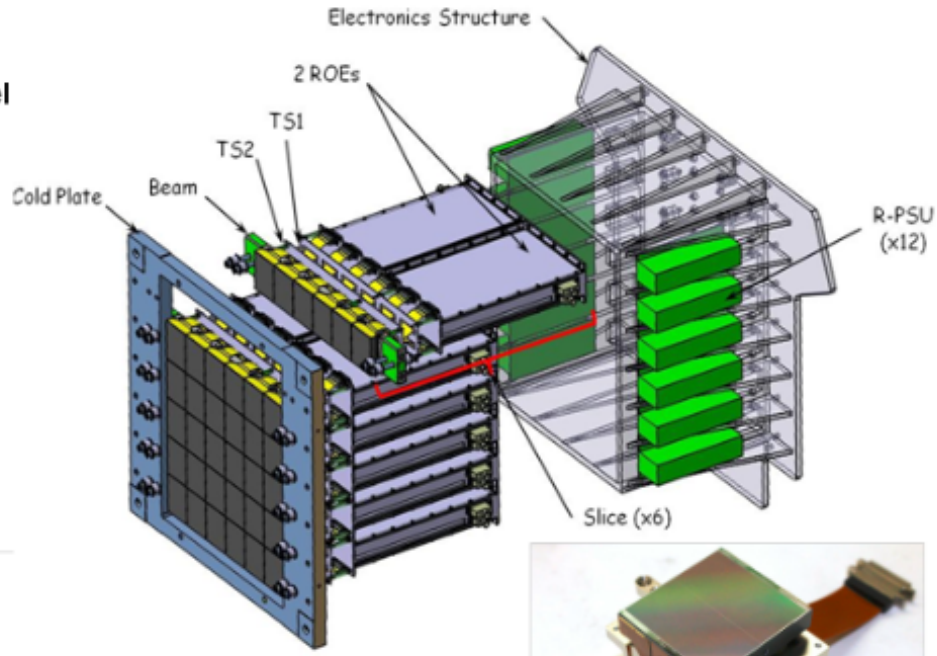

Common VIS and NIR FoV = 0.54 $deg^2$

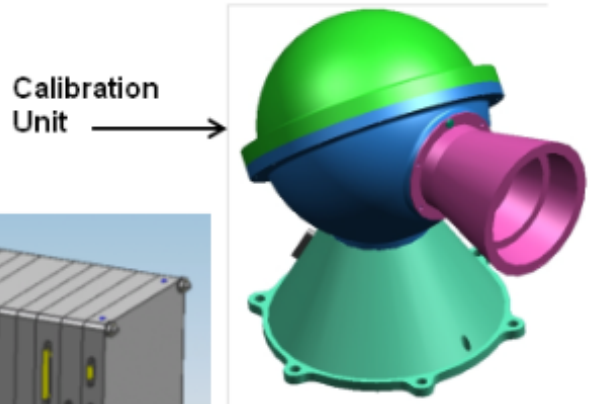
# VIS

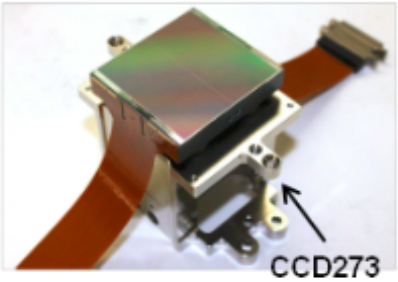
Courtesy: S. Pottinger, M. Cropper and the VIS team

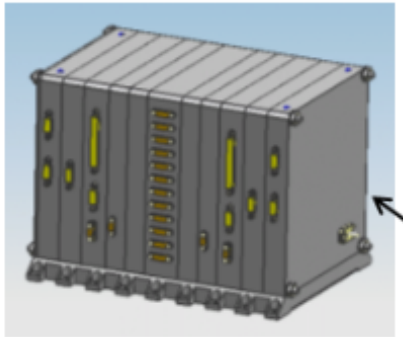
- large area imager – a 'shape measurement machine'
- 36 4kx4k CCDs with 12 micron pixels
- 0.1 arcsec pixels on sky FoV = 0.54 deg$^2$
- bandpass 550-900 nm – (wide band channel)
- limiting magnitude for wide survey of magAB = 24.5 for 10$\sigma$ (extended)
- data volume – 520Gbit/day

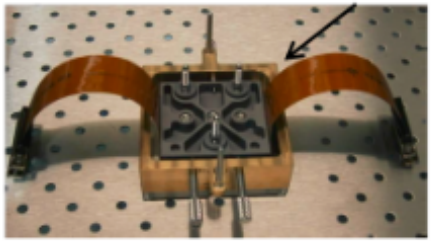


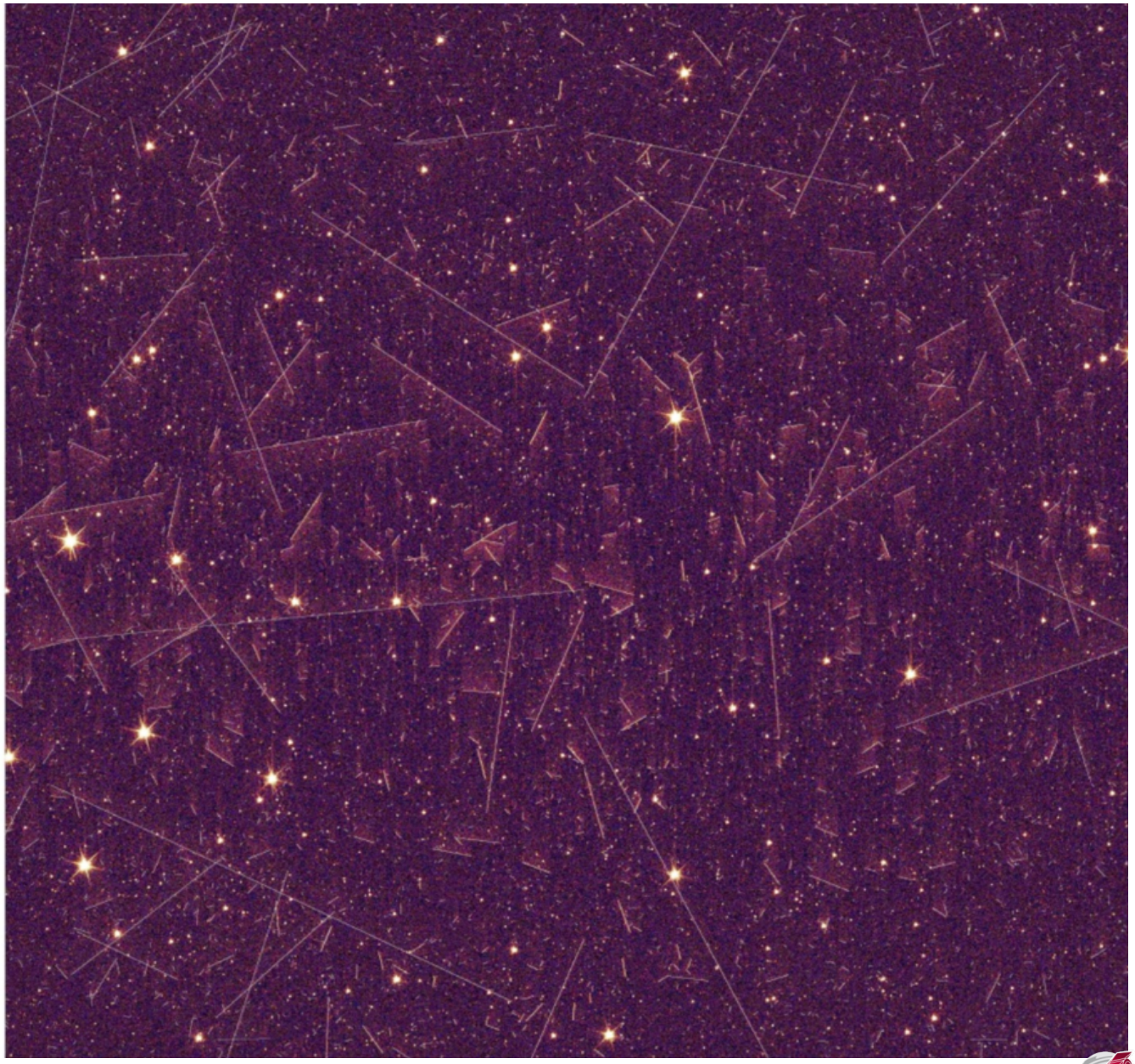


# VIS performance:imaging

A 4kx4k view of the Euclid sky

VIS image: cuts made to highlight artefacts



Courtesy Mark Cropper,

Sami M. Niemi

# NISP instrument

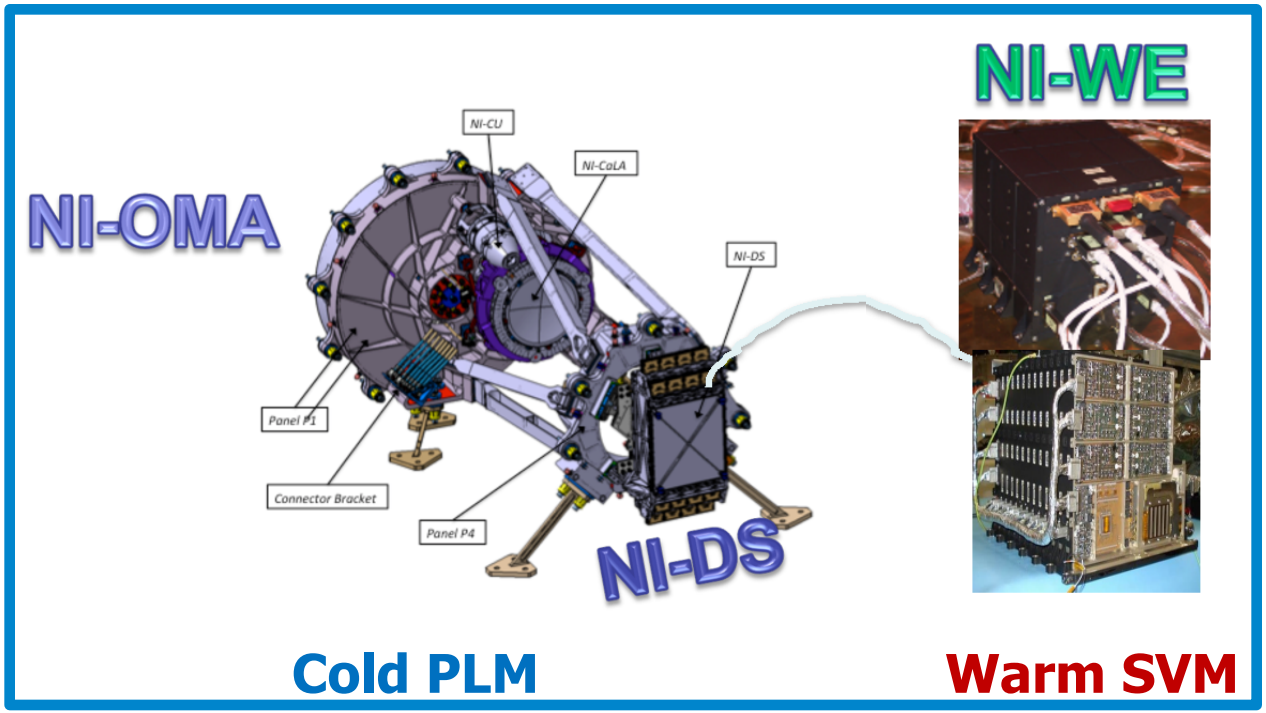
Courtesy: T. Maciaszek and the NISP team

- 3 main assemblies:
  - **NI-IOMA**: Opto Mechanical Assembly in the satellite Payload Module
  - **NI-DS** : Detection System mounted in NI-OMA
  - **NI-WE**: Warm Electronics in the warm satellite Service Module

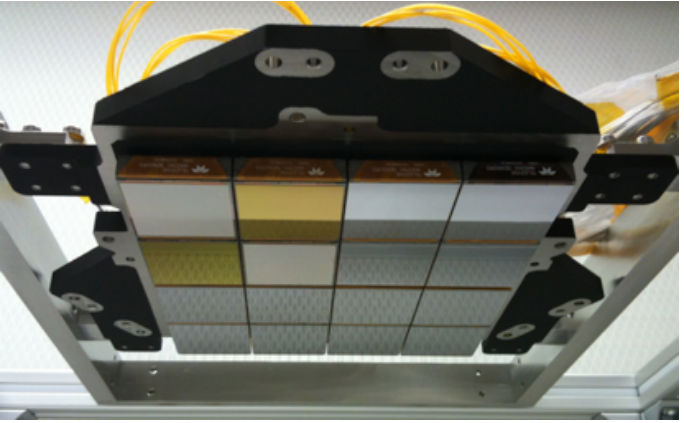
- Fov: 0.55x0.55 deg2
- Mass : 160 kg
- Power < 200 W
- Telemetry: 240 Gbt/day
- Size: 1m x 0.5 m x 0.5 m
- 16 2kx2K H2GR detectors
- 0.3 arcsec pixel on sky

(Wide survey only with R-grism)

- Limiting mag AB: 24 (5 $\sigma$ )

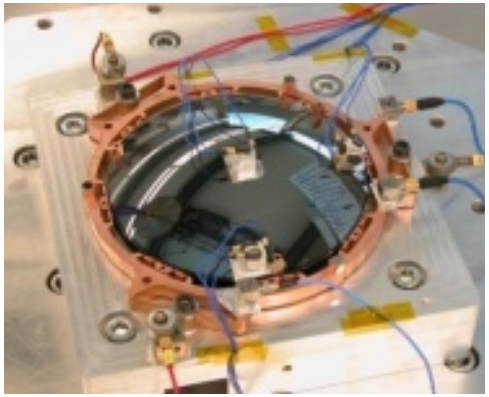


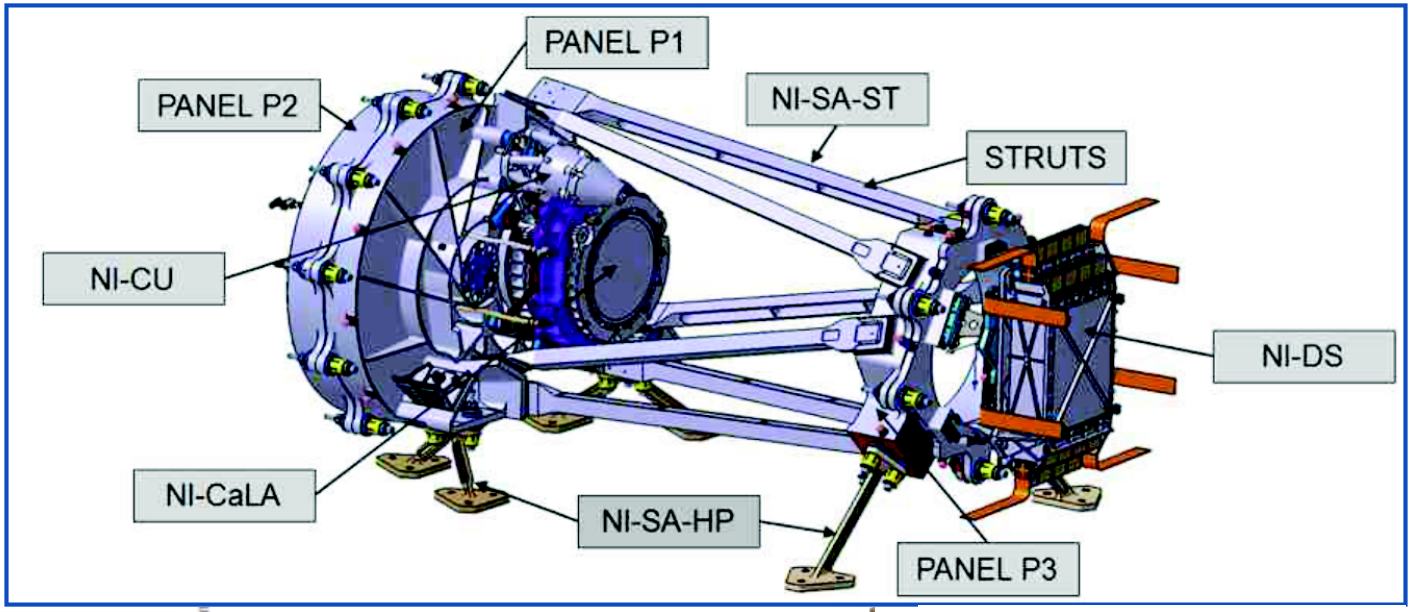

- **3 Filters**: Y (920-1146nm), J (1146 – 1372nm), H (1372 – 2000nm)
- **4 grisms**: 1B (920 – 1250nm) , 3R (1250 – 1850nm)

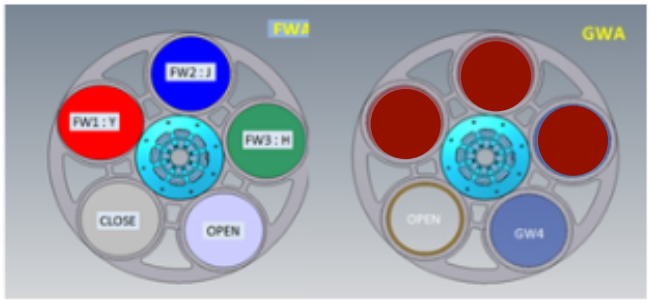


# NISP

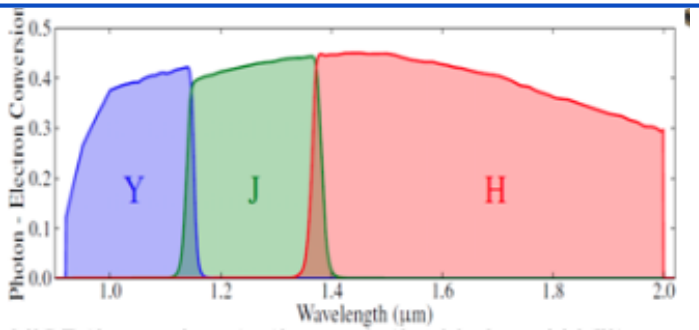
Courtesy: T. Maciaszek
and the NISP team



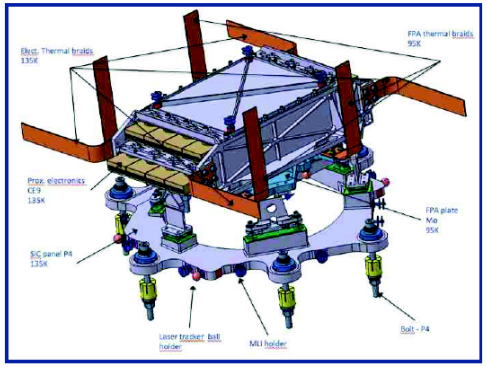


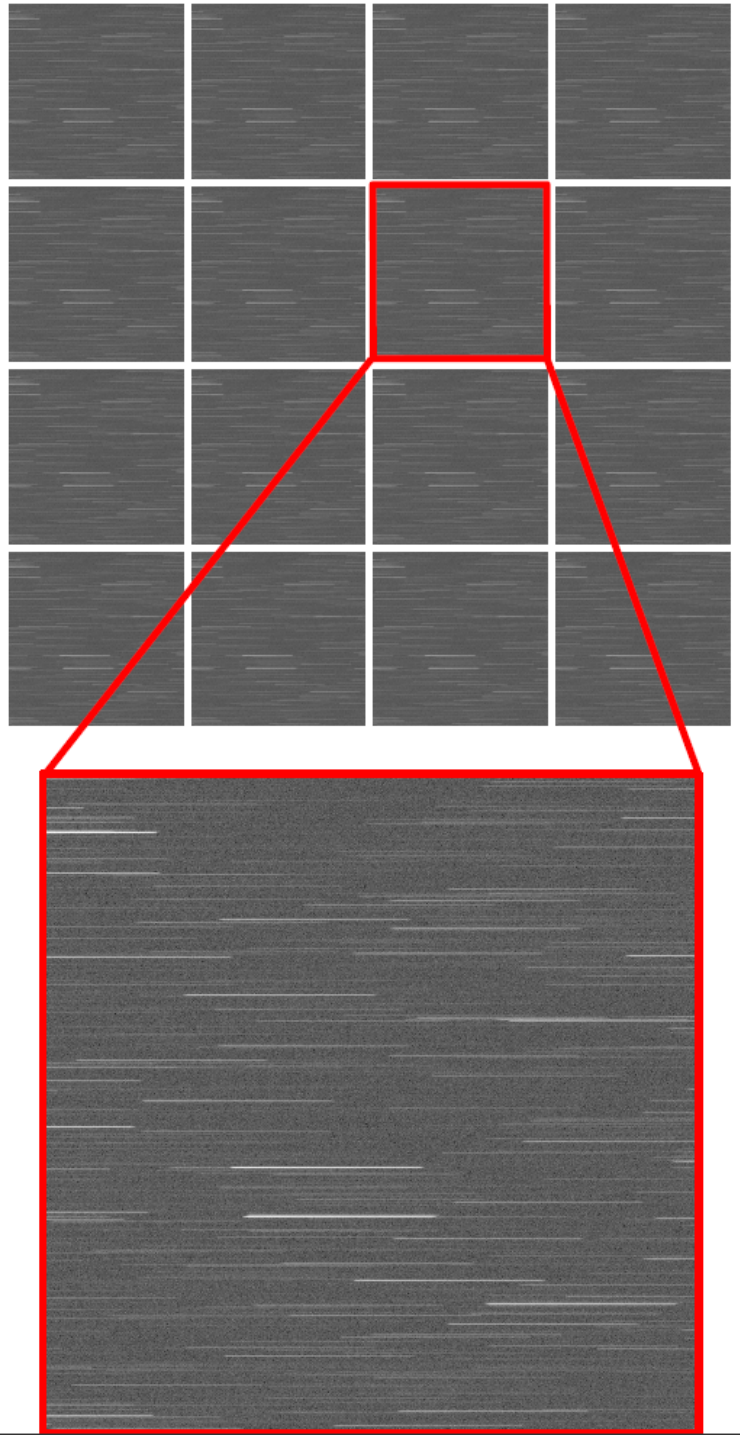

Filters and grisms positions in wheels



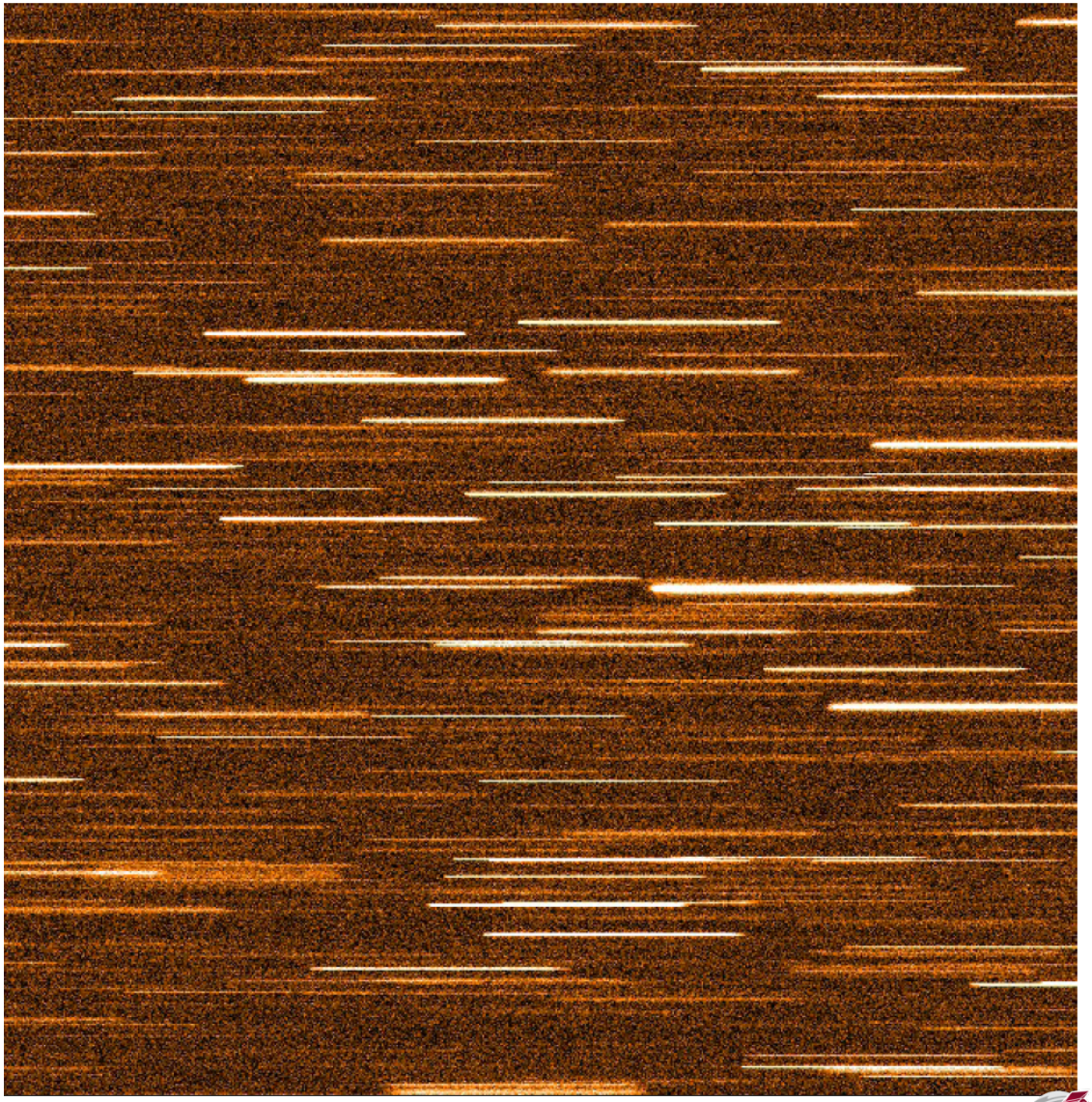

NISP throughputs through the Y, J and H filters



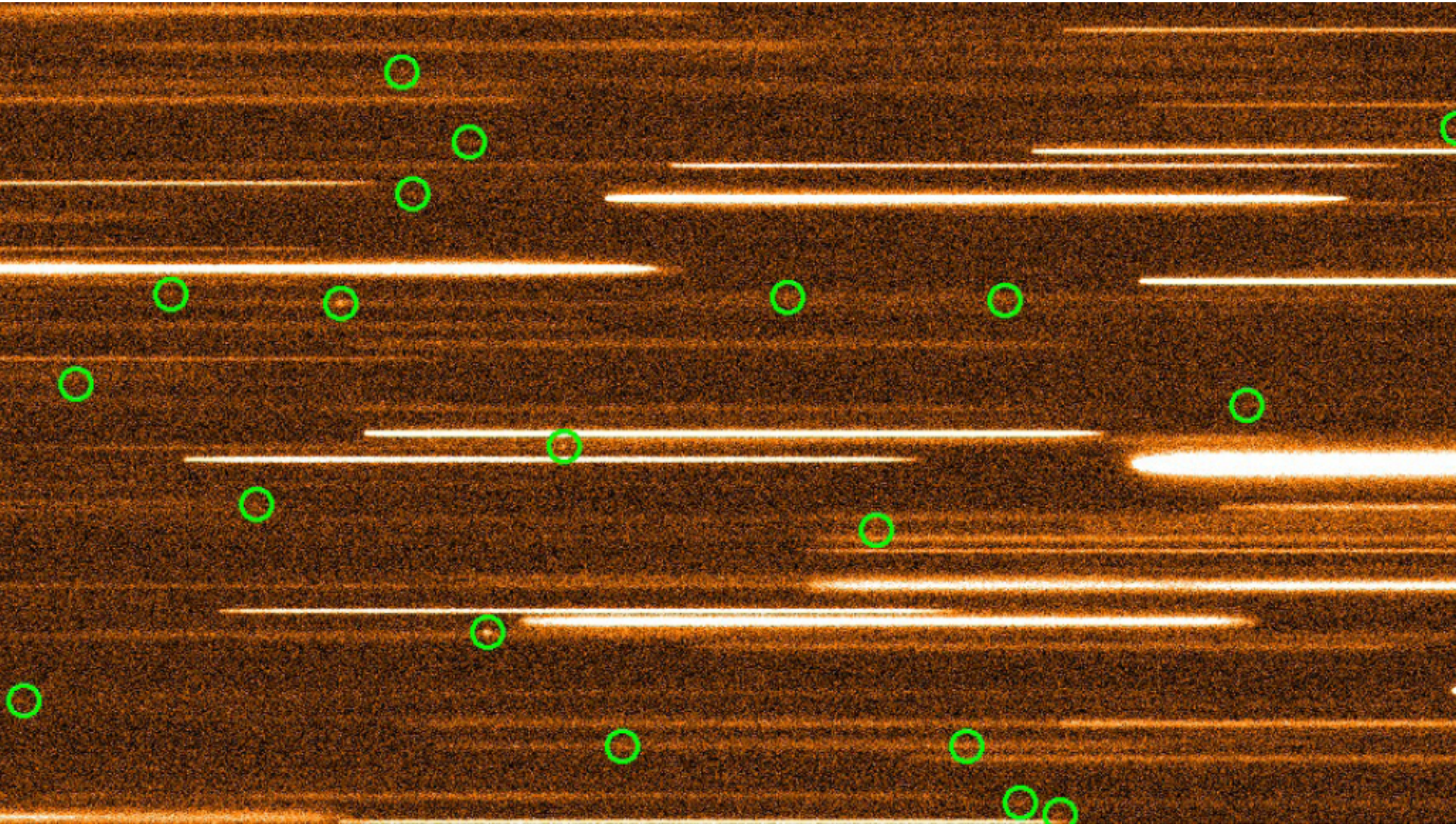
# NISP-spectroscopy (2015 simulations)



From P. Franzetti, B. Garilli, A. Ealet, N. Fourmanoit & J. zoubian



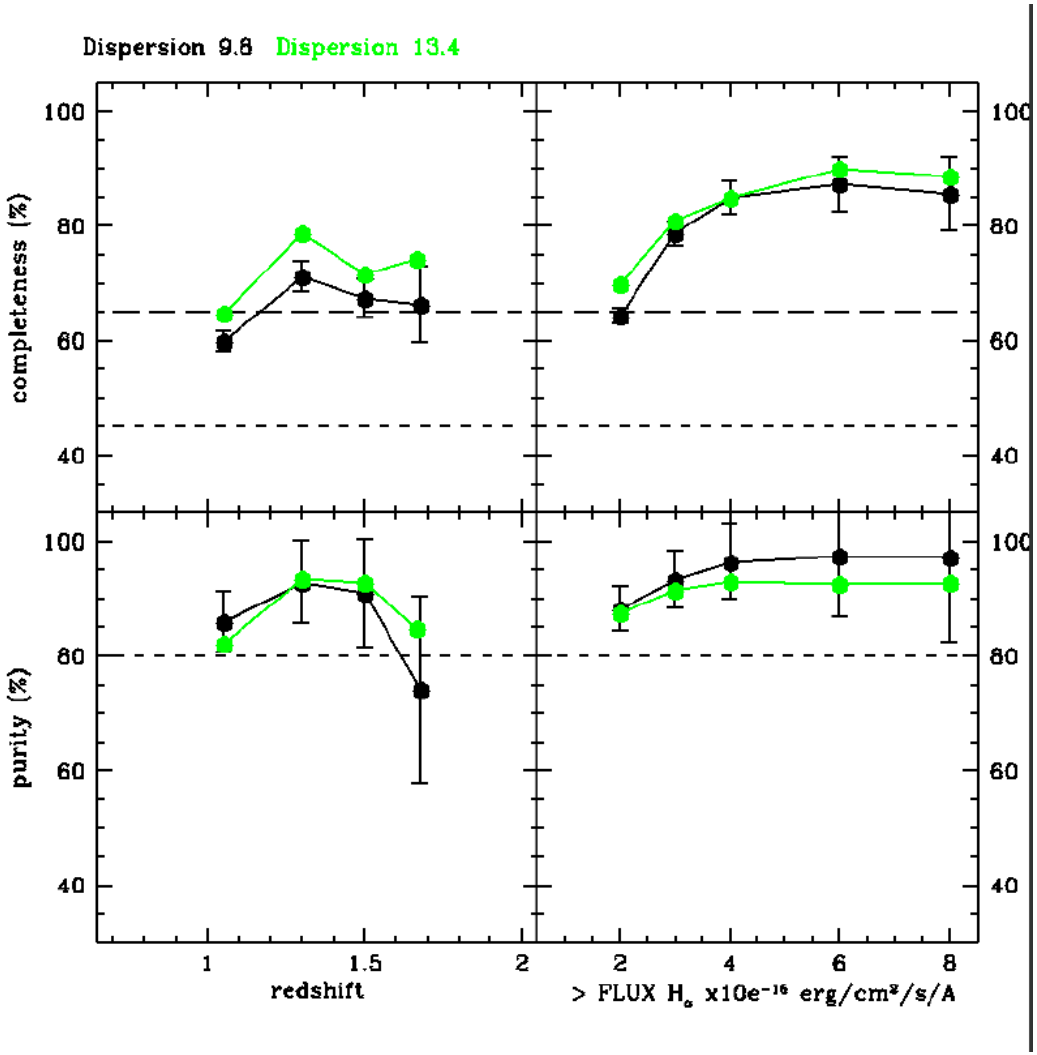
# NISP spectroscopy (2015 simulations)

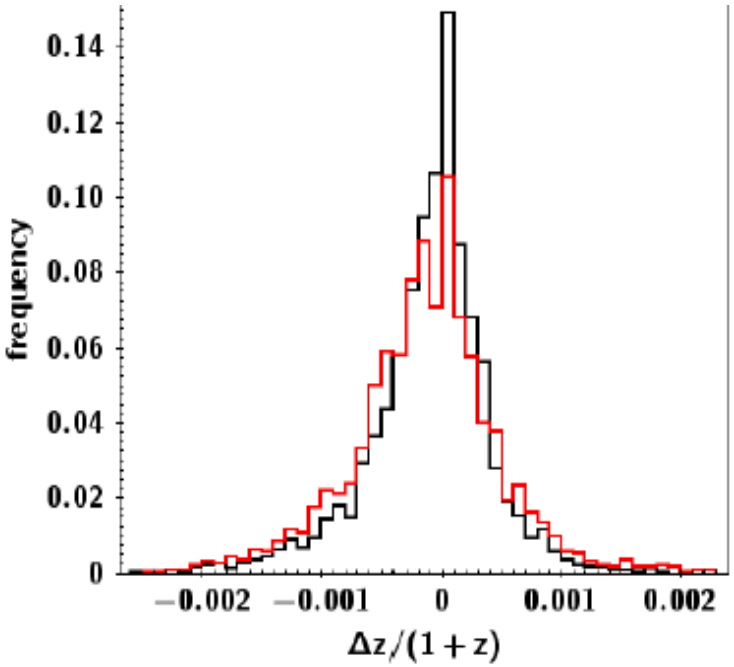


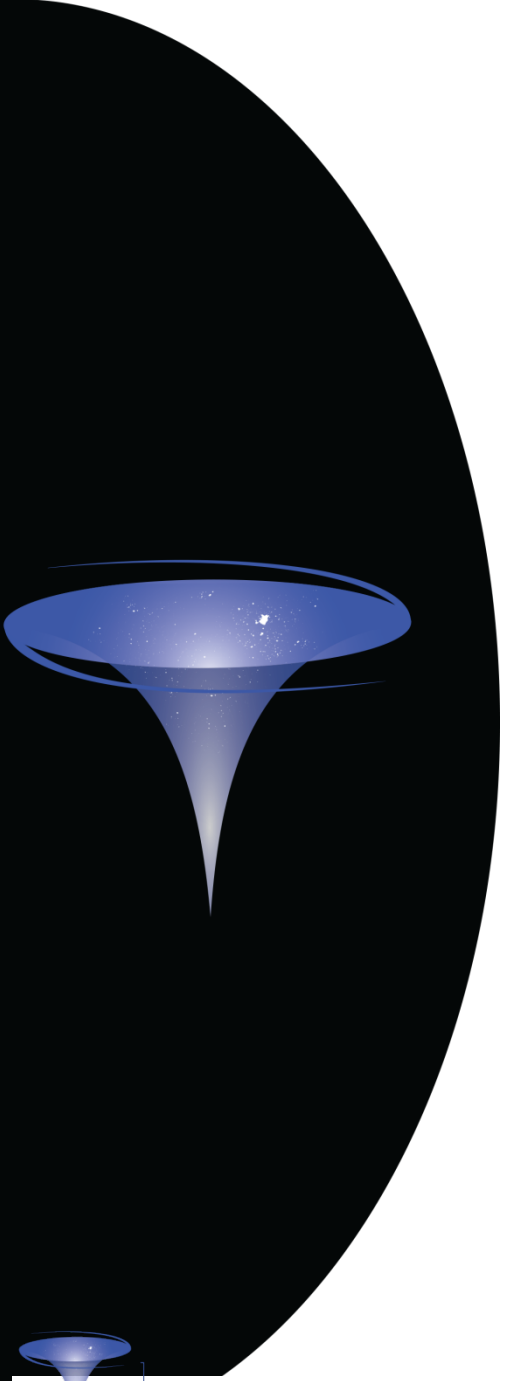
From P. Franzetti & B. Garilli

# NISP performance for galaxy clustering

From P. Franzetti & B. Garilli





1. Euclid Scientific Mission

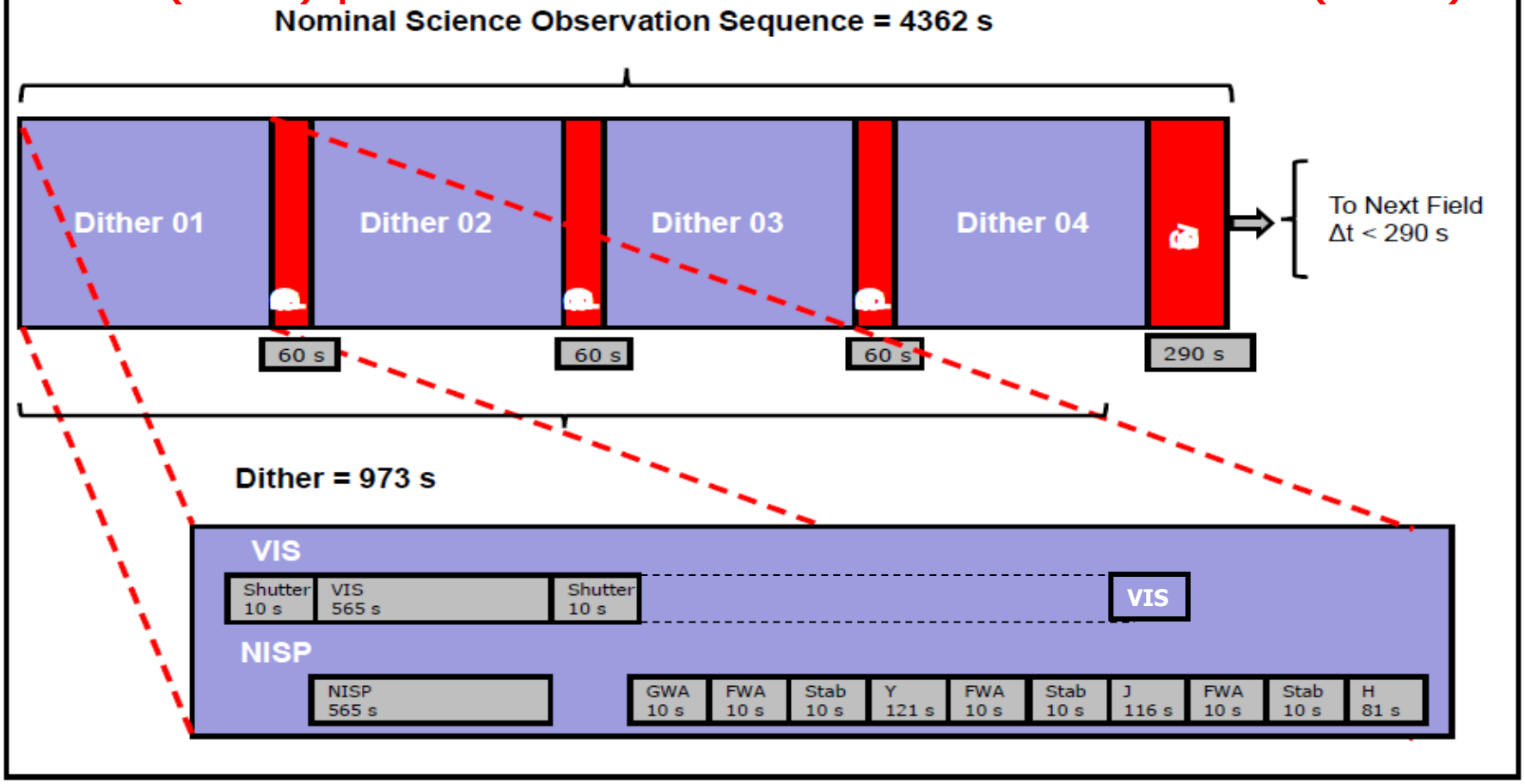
2. Euclid Implementation

3. Euclid Performance

# Obs. sequence: 4 (VIS+NISP) frames/pointing

## For the wide: one pass only

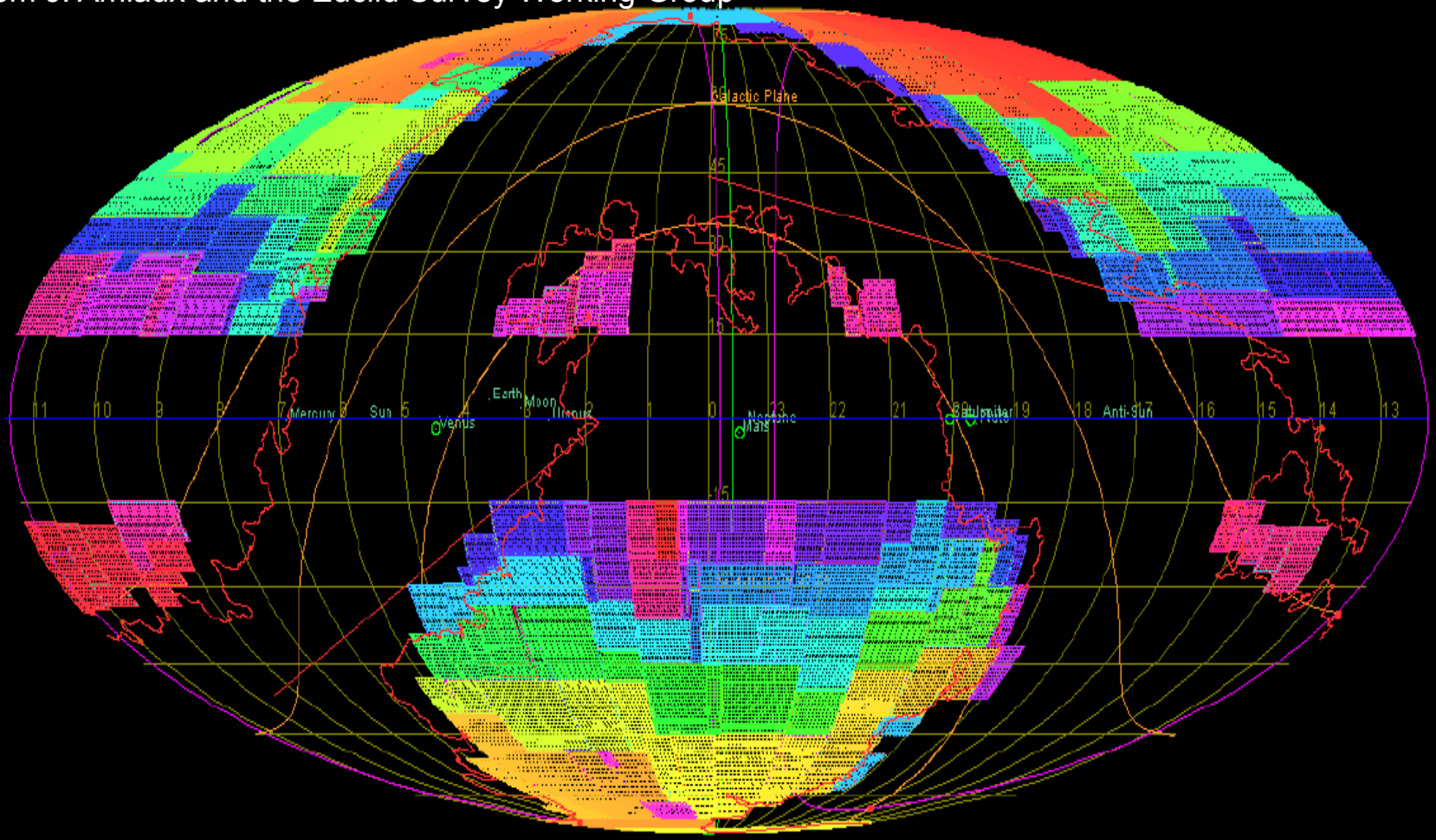
95% (90%) pixels covered at least 3 times with VIS (NISP)

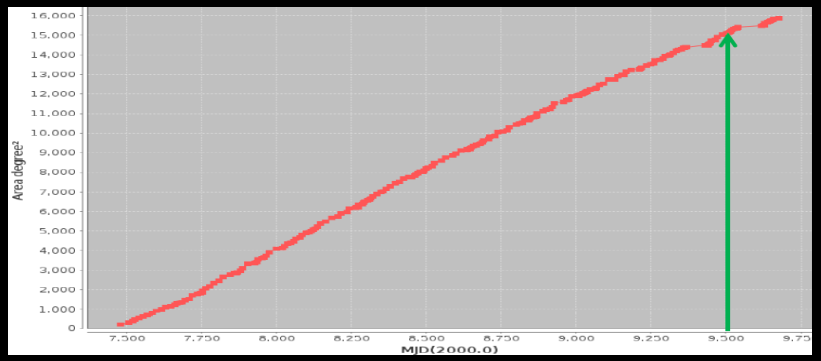



Data transfer to Earth: 4 hours/day

From J. Amiaux and the ESSWG

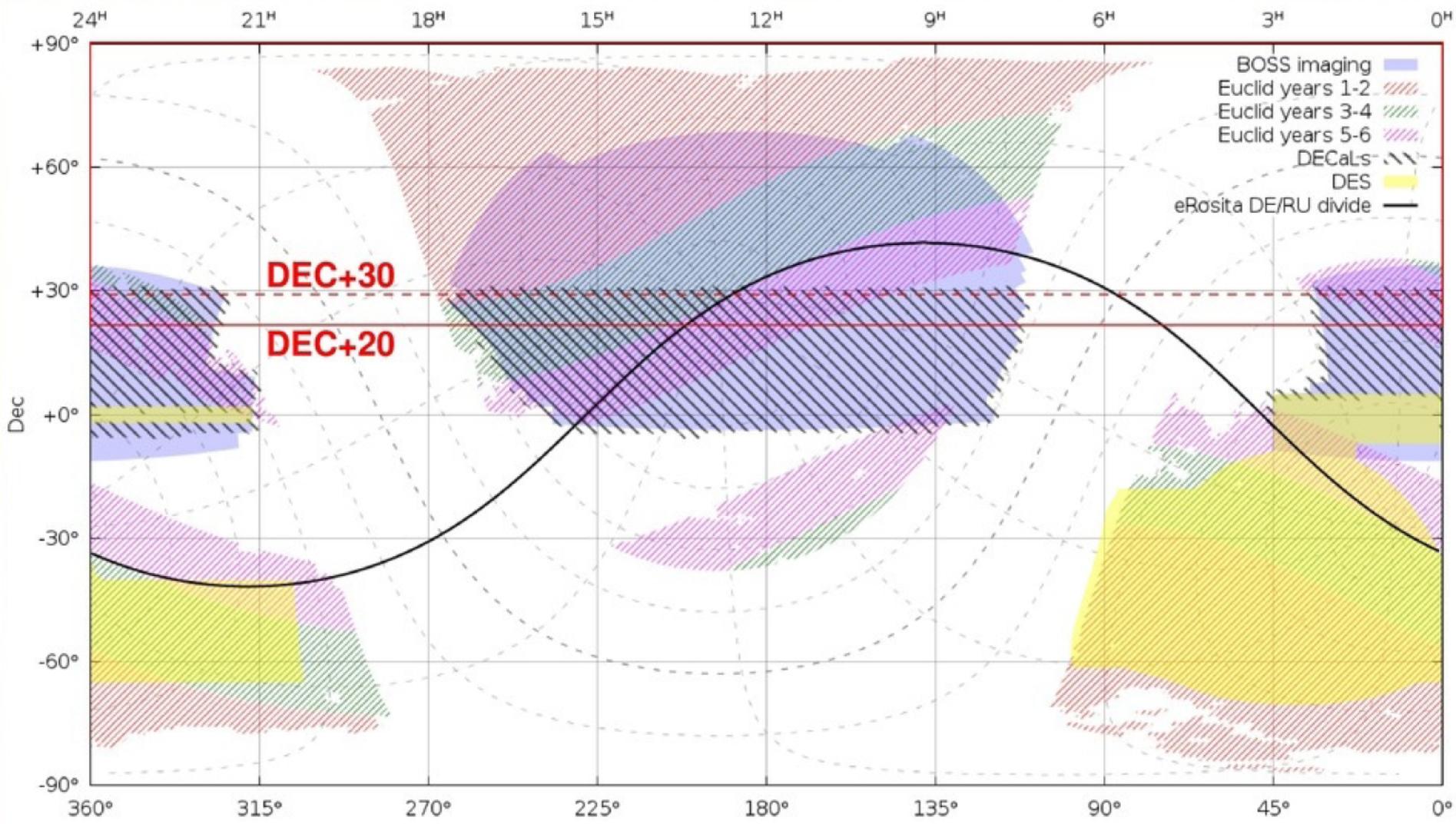
From J. Amiaux and the Euclid Survey Working Group



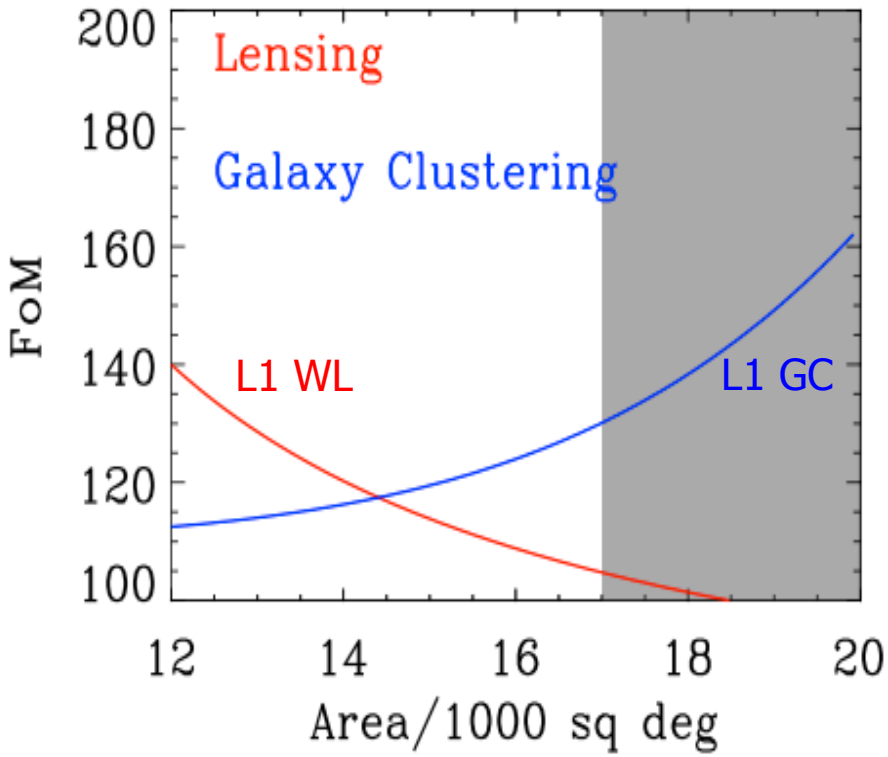
# Euclid Survey (baseline)

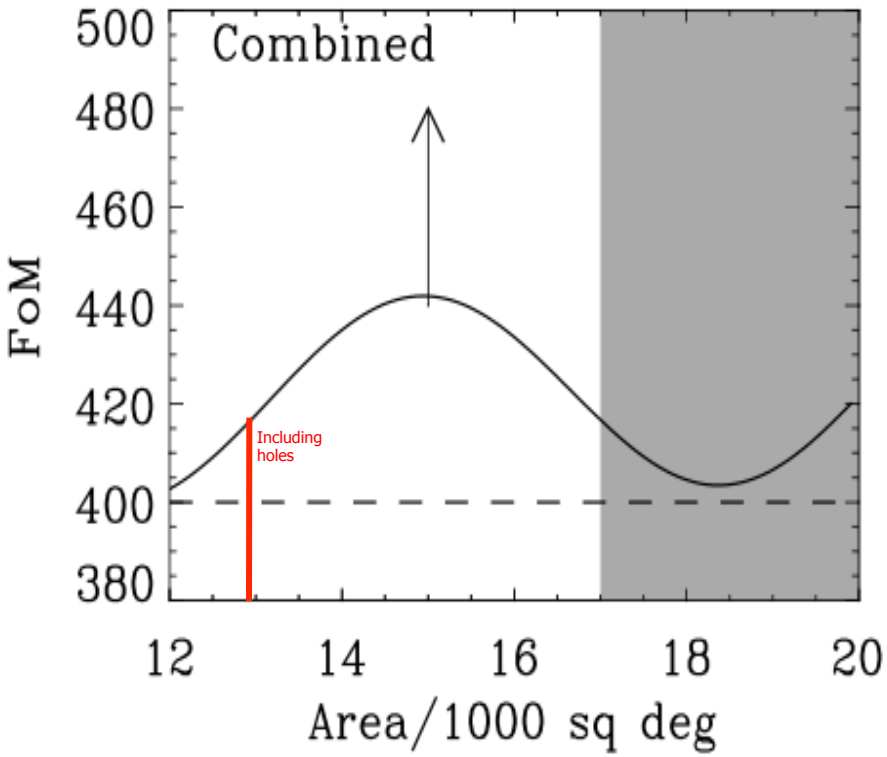
# Euclid DES, BOSS and LSST access to north (not final)




From J.-C. Cuillandre (Euclid survey working group and PI CFIS at CFHT)

# Sky coverage 2012




FoM with constraints on survey duration

# Simulation of M51 with VIS

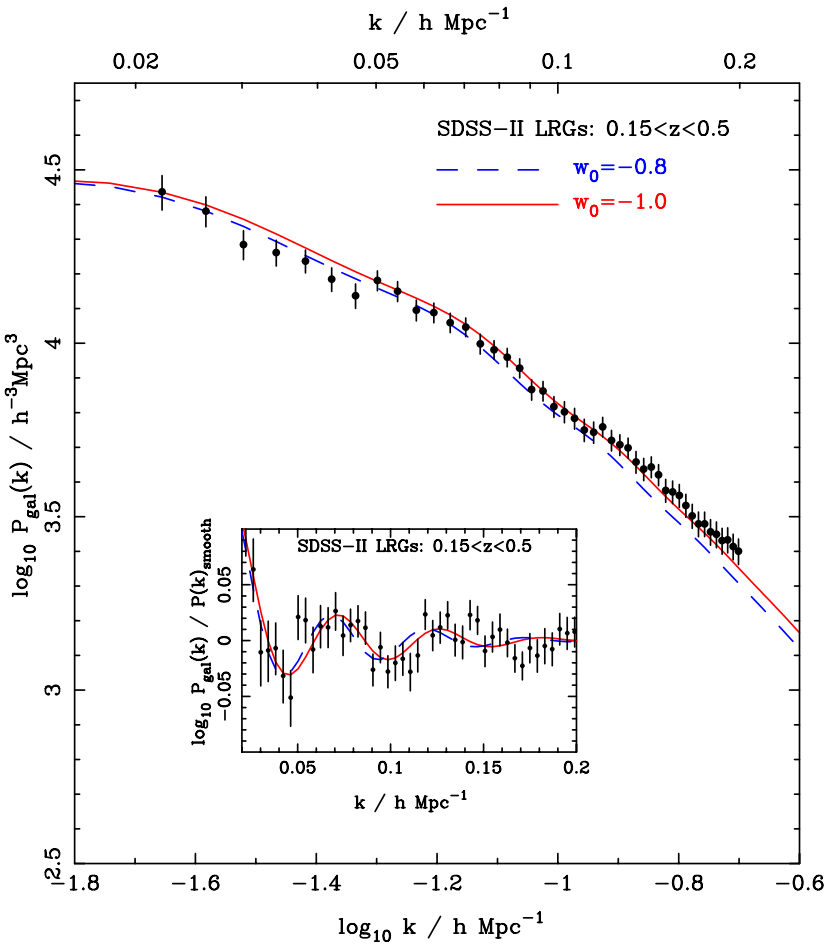
(Courtesy J. Brinchmann and S. Warren )

Messier 51 galaxy at z~0.1 and 0.7:

Euclid will get the resolution of Sloan Digital Sky Survey but at z=1 instead of z=0.05.

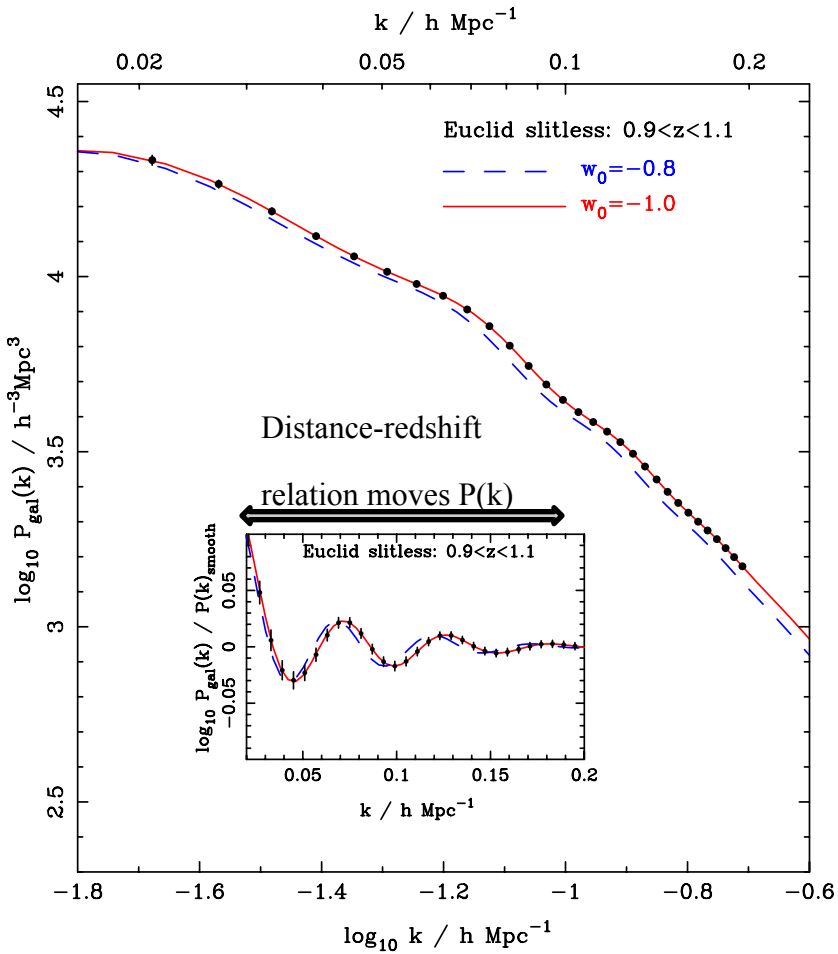
Euclid will be 3 magnitudes deeper → Euclid Legacy = Super-Sloan Survey

# BAO : SDSS vs Euclid




SDSS today

0.15<z<0.5

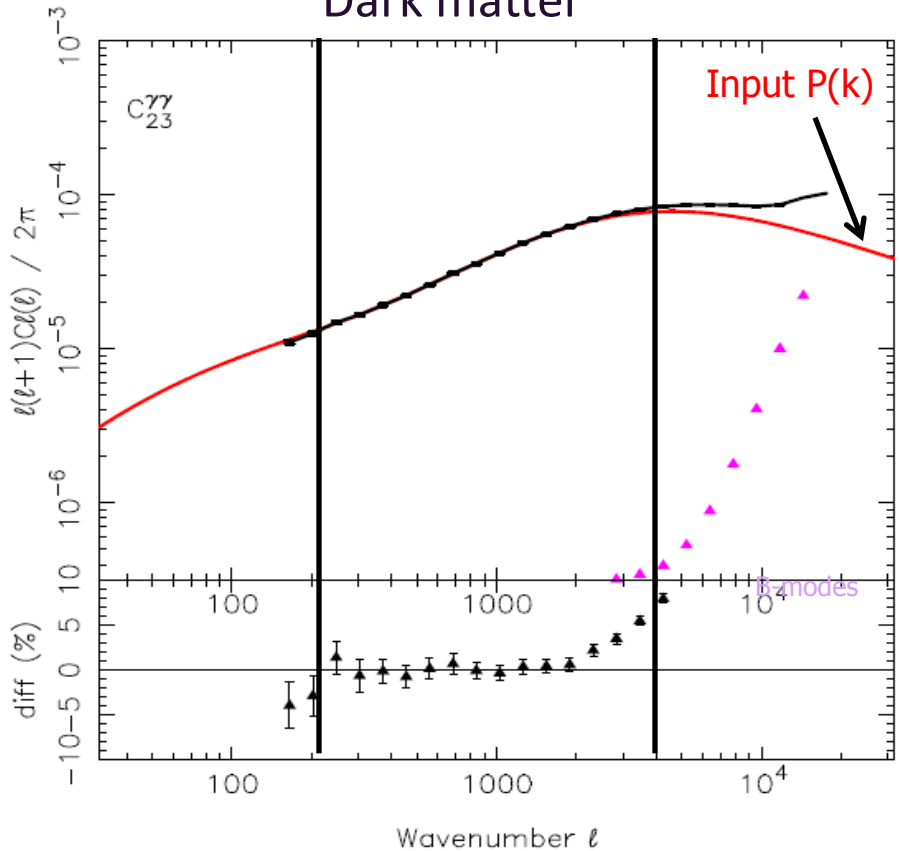



EUCLID expected

0.7<z<2.0

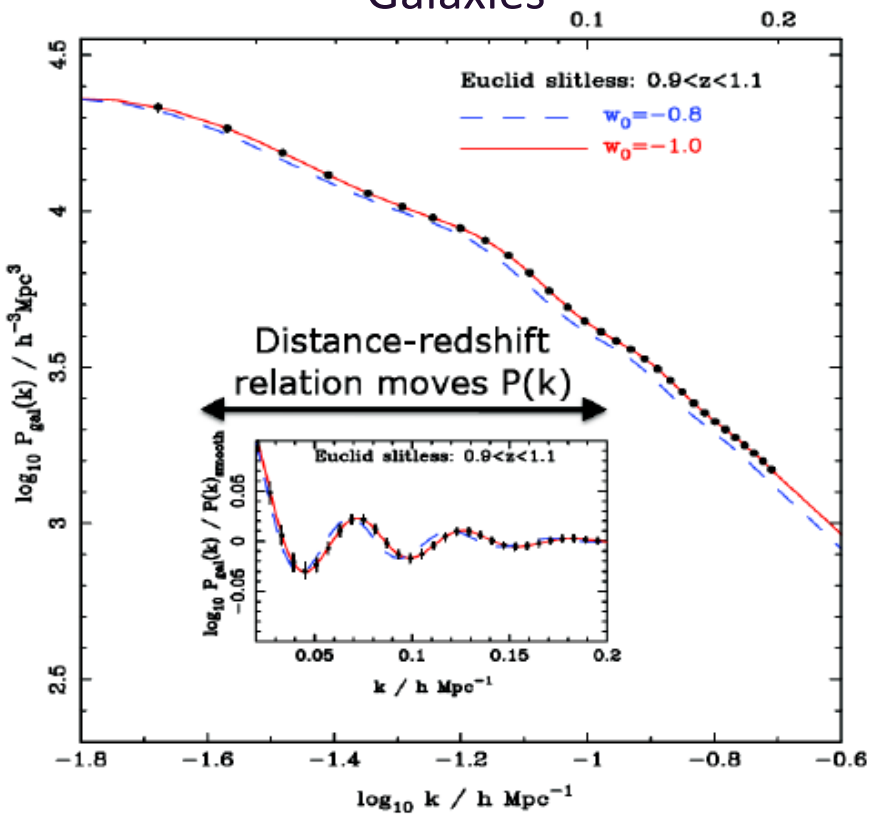
# Euclid: Combining WL and GC data

## Dark matter



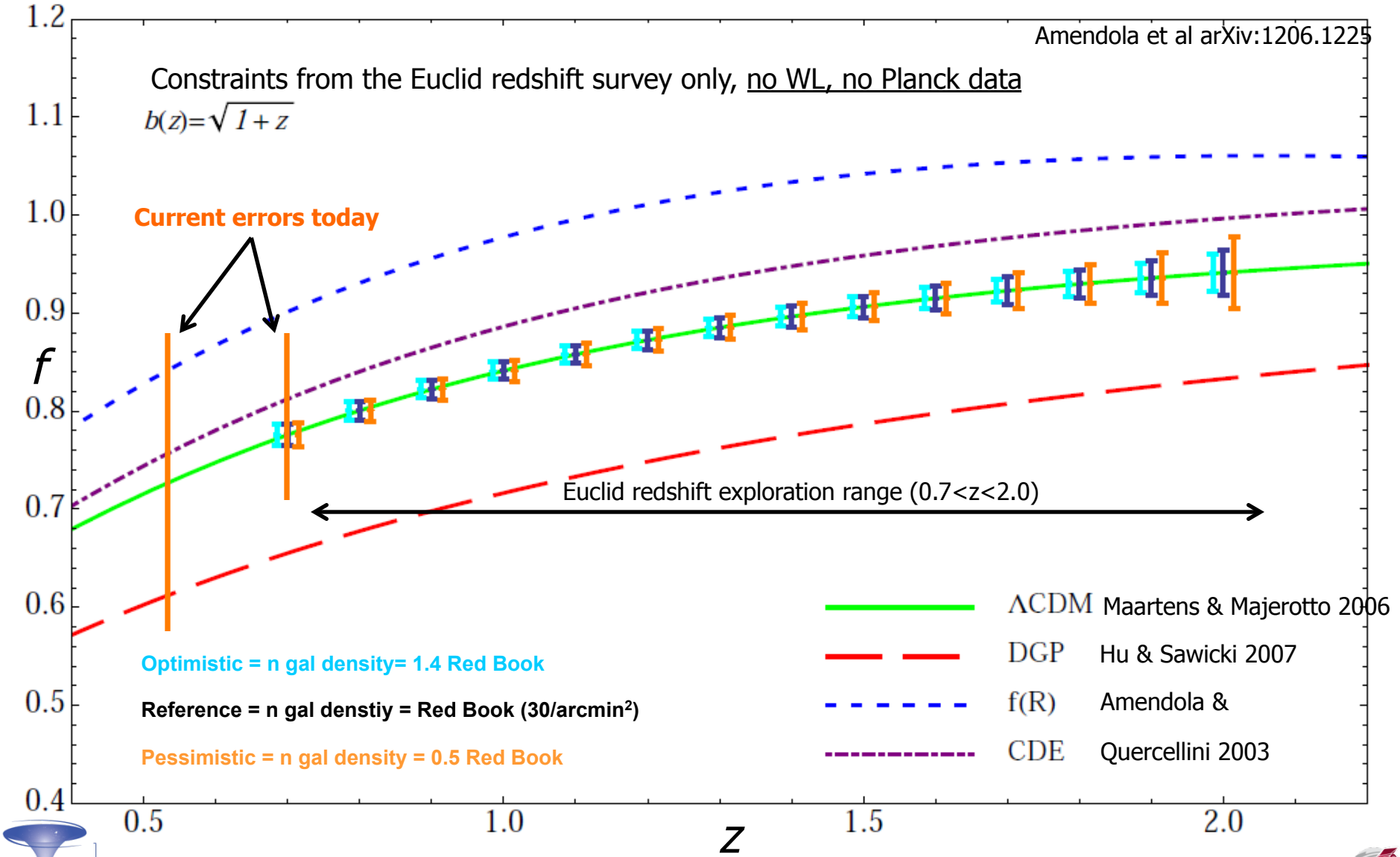

- Tomographic WL shear cross-power spectrum for 0.5 < z < 1.0 and 1.0 < z < 1.5 bins.
- Percentage difference [*expected* – *measured*] power spectrum: recovered to 1% .

## Galaxies

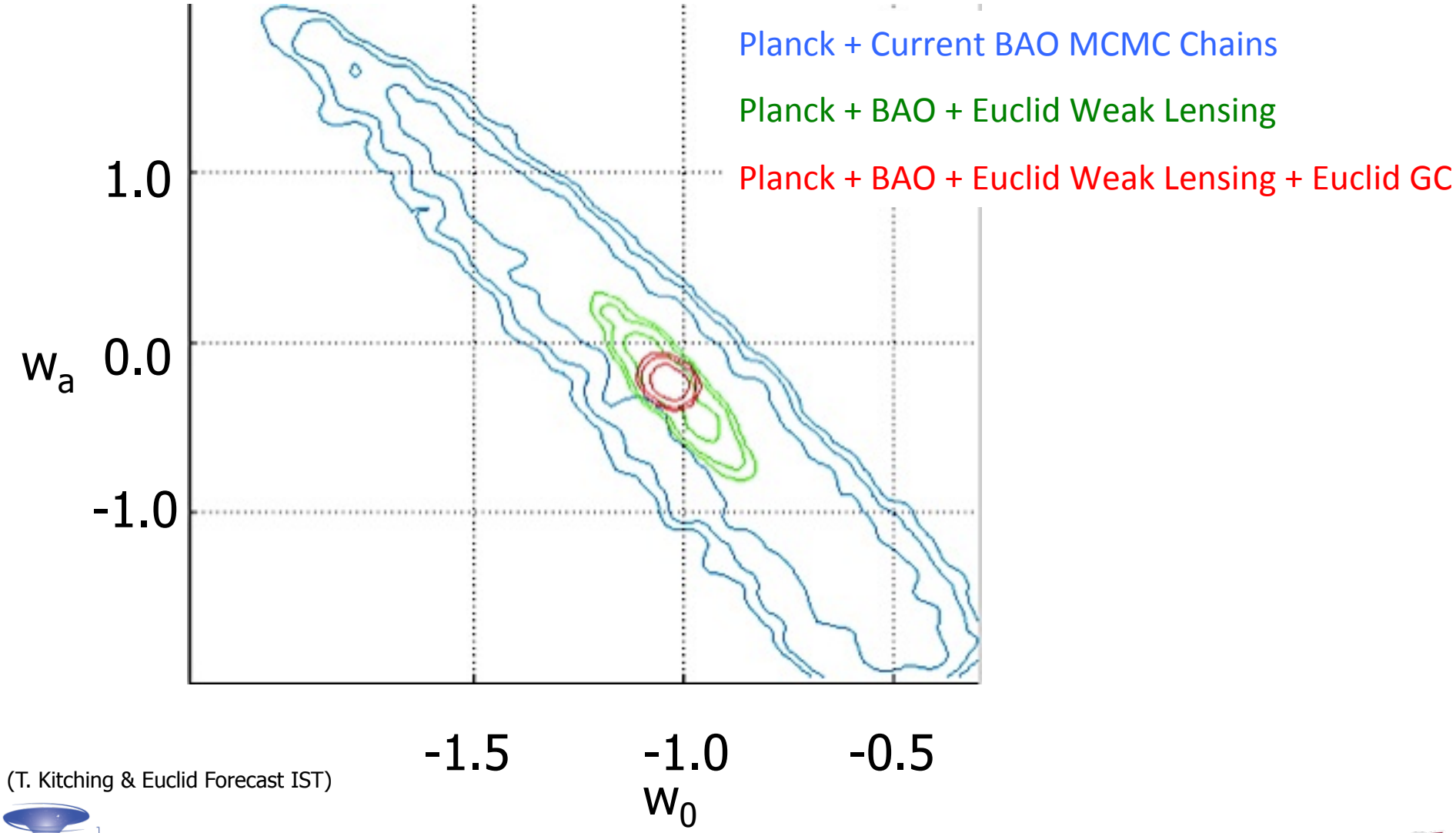



- $V_{eff} \approx 19\ h^{-3}\ Gpc^3 \approx$ 75x larger than SDSS
- Redshifts 0.7<z<1.85
- Percentage difference [*expected* – *measured*] power spectrum: recovered to 1% .

# Exploration of DE models with Euclid (redshifts only)



# Constraints on w: Updates (post-Planck) on Red Book (VIS+NISP)




(T. Kitching & Euclid Forecast IST)

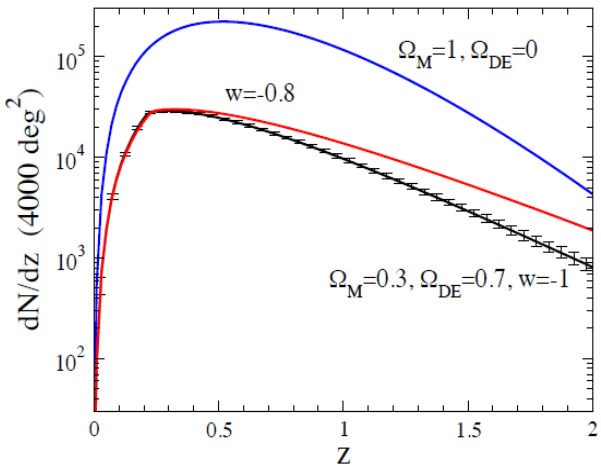
# Clusters of galaxies

mass function;
calibrated from simulations
to ~10% accuracy

$$\frac{d^2 N}{d\Omega\, dz} = n(z)\, \frac{r(z)^2}{H(z)}$$

observed

= dV / (dΩdz); exactly
predictable given
a cosmological model



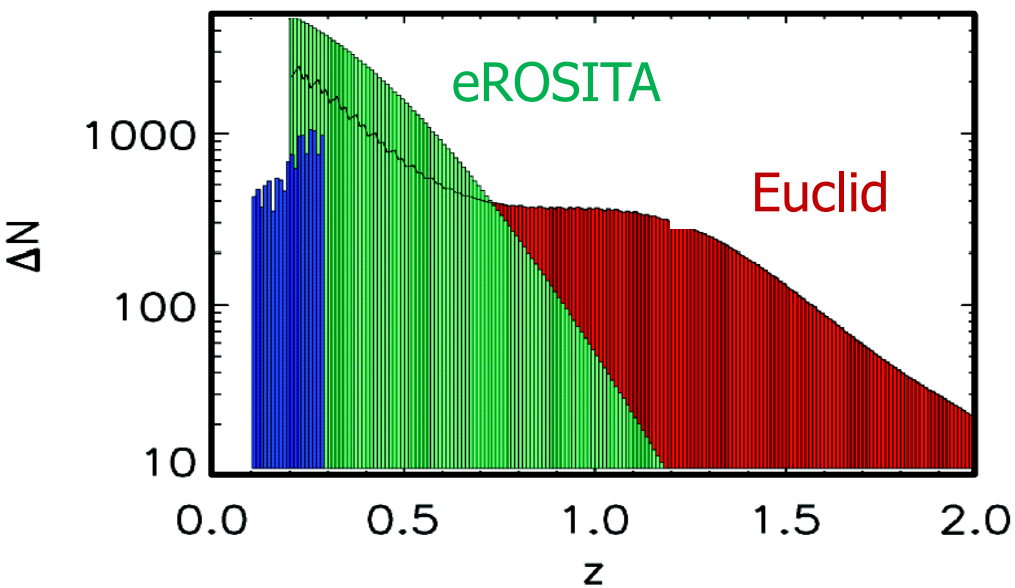

- Probe of peaks in density distribution
- Nb density of high mass, high redshift clusters very sensitive to
  - primordial non-Gaussianity and
  - deviations from standard DE models
- Euclid data will get for free:
  - 60,000 clusters between 0.2<*z*<2 , $10^4$ at *z*>1.
  - ~ 5000 giant gravitational arcs (→ SL+WL mass)

  → very accurate masses for the whole sample of clusters (WL)

  → dark matter density profiles on scales >100 kpc

Synergy with Planck and eROSITA

Max BCG



# Euclid Post-Planck Forecast for the Primary Program

**Assume systematic errors are under control**

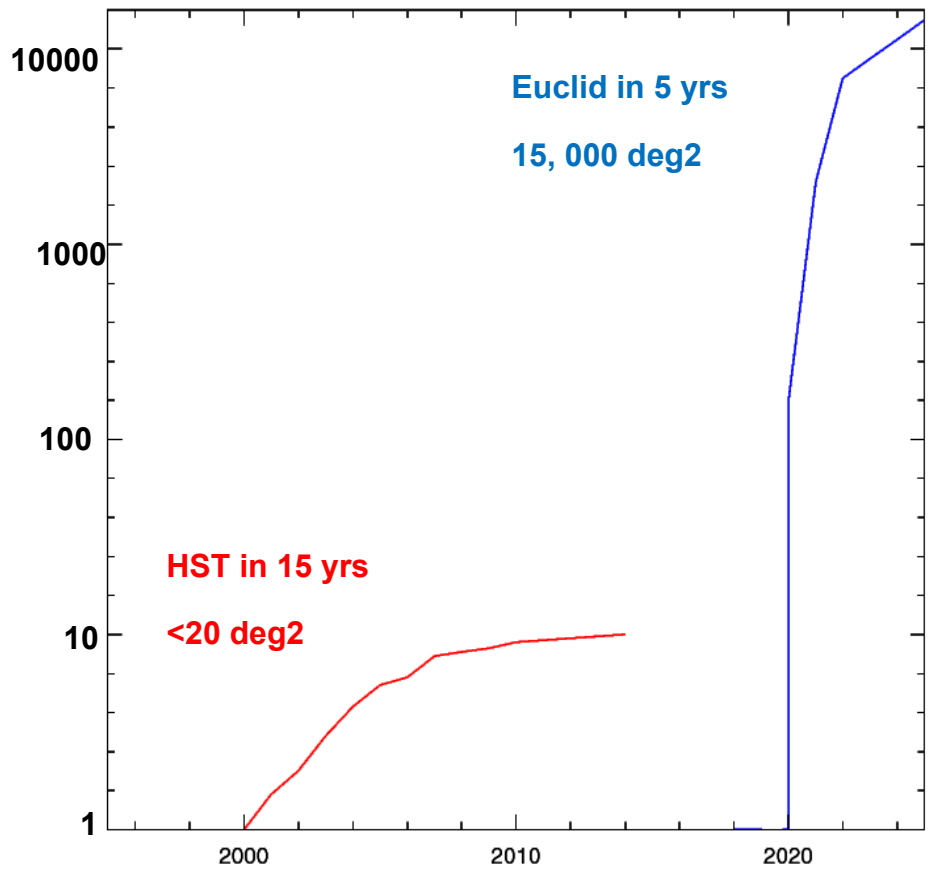
| Ref: Euclid RB arXiv: 1110.3193 | Modified Gravity | Dark Matter | Initial Conditions | Dark Energy | | |
|---|---|---|---|---|---|---|
| **Parameter** | $\gamma$ | $m_\nu$ /eV | $f_{NL}$ | $w_p$ | $w_a$ | FoM $= 1/(\Delta w_0 \times \Delta w_a)$ |
| Euclid primary (WL+GC) | 0.010 | 0.027 | 5.5 | 0.015 | 0.150 | 430 |
| **EuclidAll (clusters,ISW)** | **0.009** | **0.020** | **2.0** | **0.013** | **0.048** | **1540** |
| Euclid+Planck | 0.007 | 0.019 | 2.0 | 0.007 | 0.035 | **6000** |
| **Current (2009)** | **0.200** | **0.580** | **100** | **0.100** | **1.500** | **~10** |
| **Improvement Factor** | **30** | **30** | **50** | **>10** | **>40** | **>400** |

- DE equation of state: $P/\rho = w$ , and $w(a) = w_p + w_a(a_p - a)$
- Growth rate of structure formation: $f \sim \Omega^{\gamma}$ ;
- From Euclid data alone, get FoM=$1/(\Delta w_a \times \Delta w_p) > 400$ → ~1% precision on w's.

# Euclid: revolution in wide field surveys for the whole scientific community

- Very large samples
  - → Diversity of populations
  - → Dstribution functions
  - → ~50,000 clusters of galaxies
- Exquisite imaging of galaxies
  - → Morphological studies, mergers, strong galaxy-scale lenses
- Strong and Weak Lensing
  - → Galaxy evolution as function of halo properties
  - → Galaxy alignement
  - → 5000 clusters with giant arcs
- Huge volumes and numbers
  - → Rare sources, probing the extremes
- NIR Spectroscopy
  - → Metals, star formation@ z>1
  - → Cool stars
  - → Very high-z QSOs

From J. Brinchmann 2013

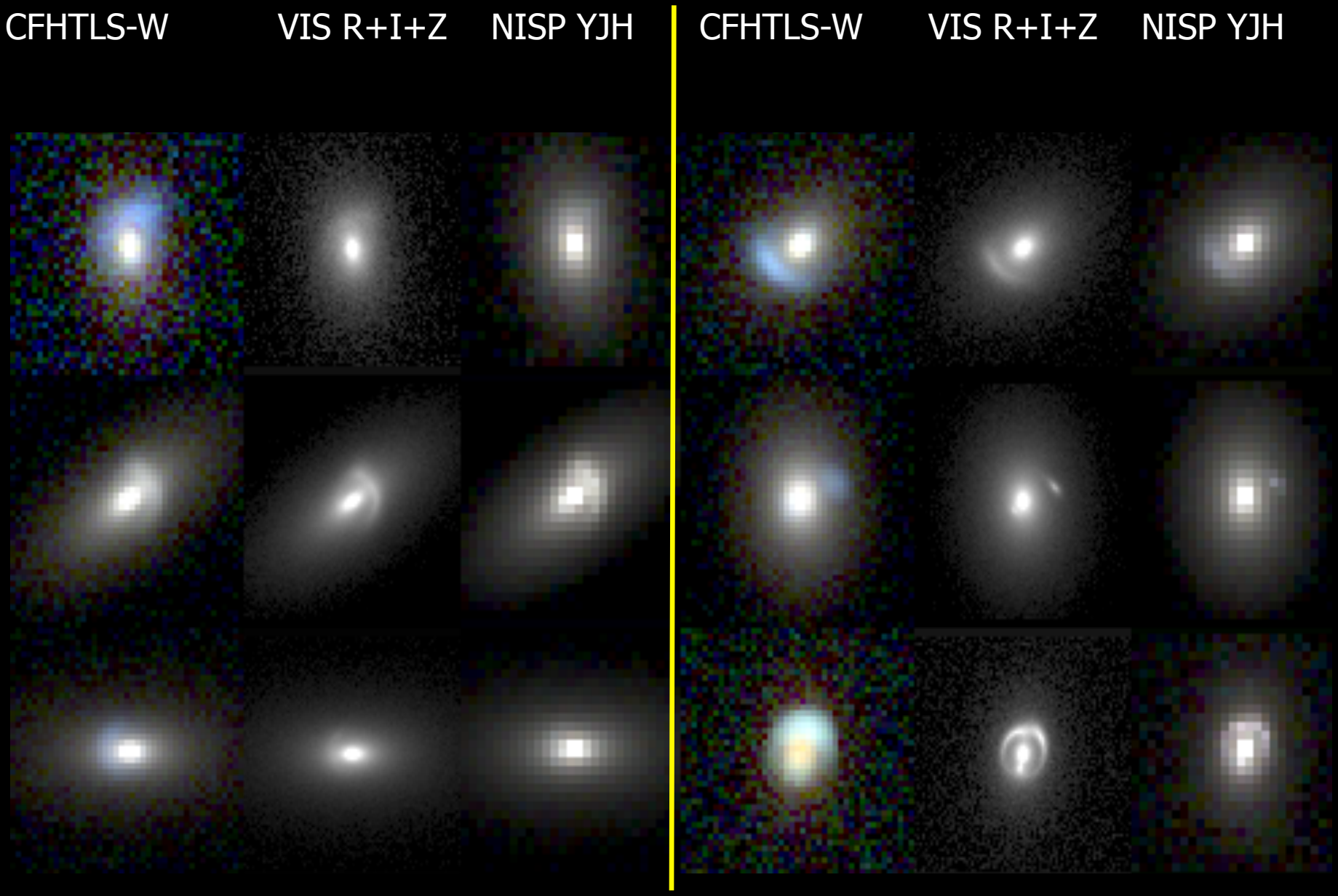


# Euclid VIS+NISP Legacy

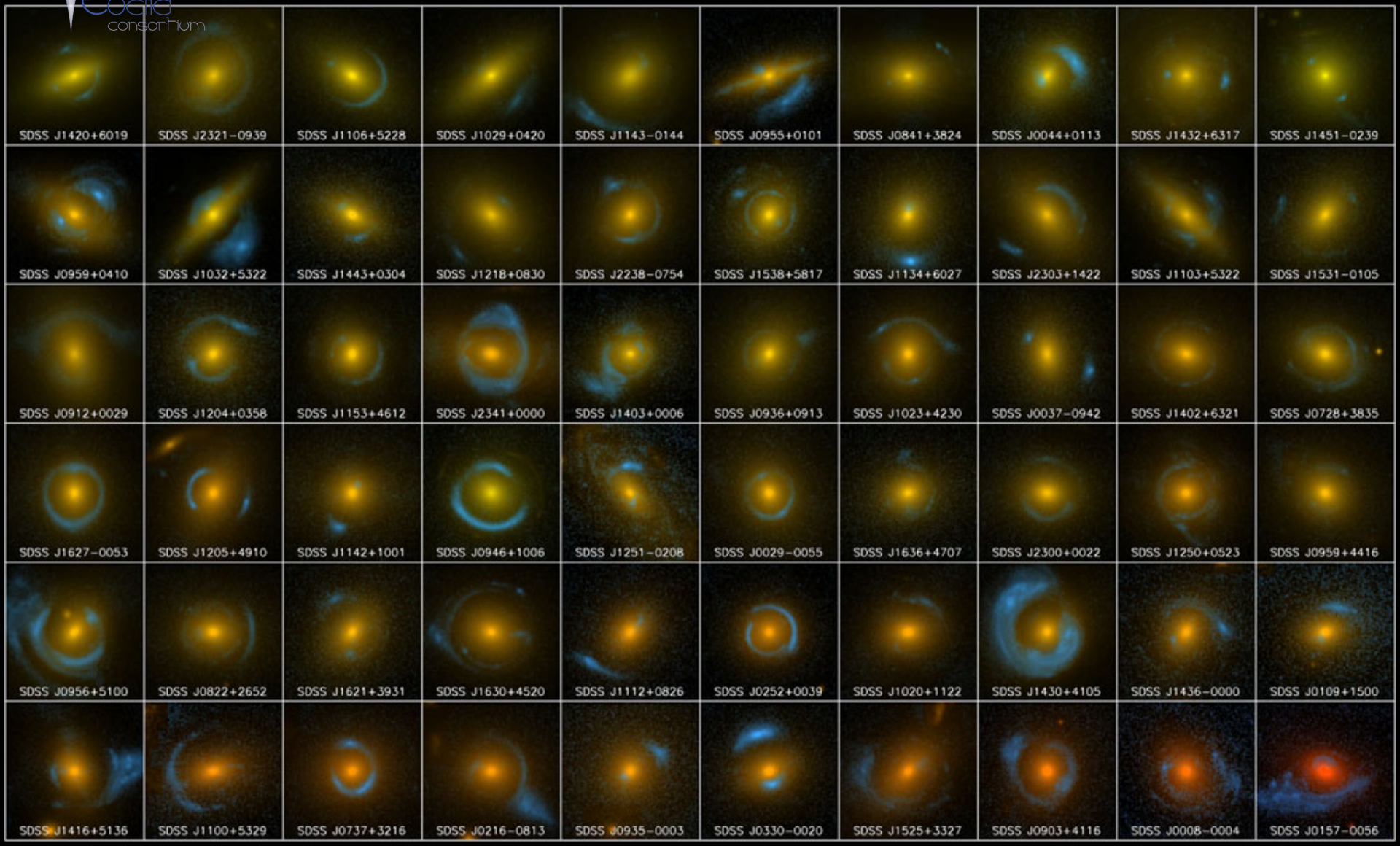
- 12 billion sources, 3-$\sigma$
- 30-50 million redshifts;
- A mine of images and spectra for the community for several decades;
- A reservoir of targets for JWST, GAIA, E-ELT, TMT, ALMA, Subaru, VLT, etc…
- Synergy with LSST, e-ROSITA, SKA

| Objects | Euclid | Before Euclid |
|---|---|---|
| Galaxies at 1<z<3 with precise mass measurement | ~$2\times10^8$ | ~$5\times10^6$ |
| Massive galaxies (1<z<3)) | Few hundreds | Few tenss |
| H$\alpha$ Emitters with metal abundance measurements at z~2-3 | ~$4\times10^7/10^4$ | ~$10^4$/~$10^2$ ? |
| Galaxies in clusters of galaxies at z>1 | ~$2\times10^4$ | ~$10^3$ ? |
| Active Galactic Nuclei galaxies (0.7<z<2) | ~$10^4$ | <$10^3$ |
| Dwarf galaxies | ~$10^5$ | |
| $T_{eff}$ ~400K Y dwarfs | ~few $10^2$ | <10 |
| Lensing galaxies with arc and rings | ~300,000 | ~10-100 |
| Quasars at z > 8 | ~30 | None |

# Simulations of gravitational arcs and Einstein rings with Euclid



# SLACS (~2010 - HST)



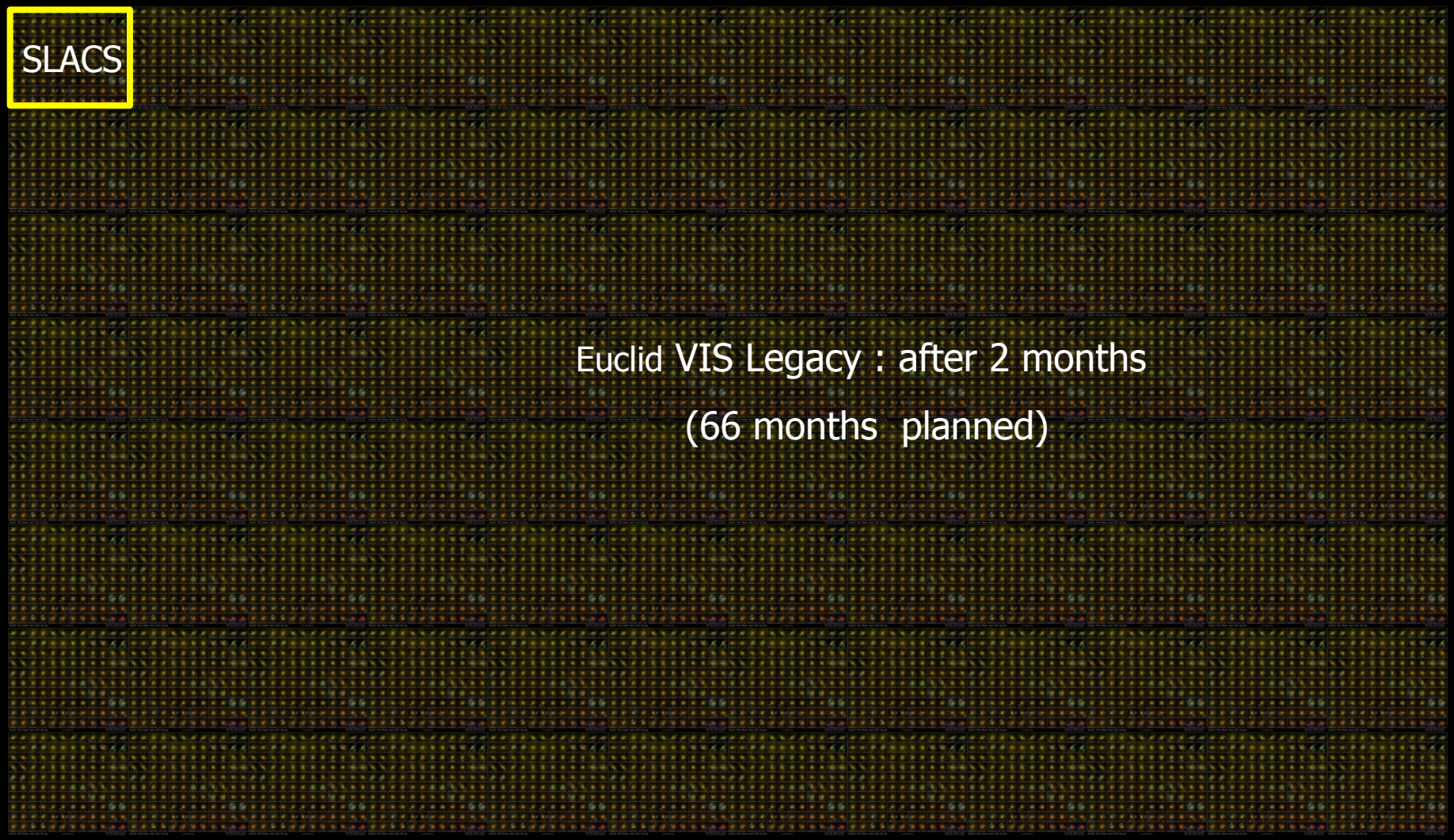

SLACS: The Sloan Lens ACS Survey

www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

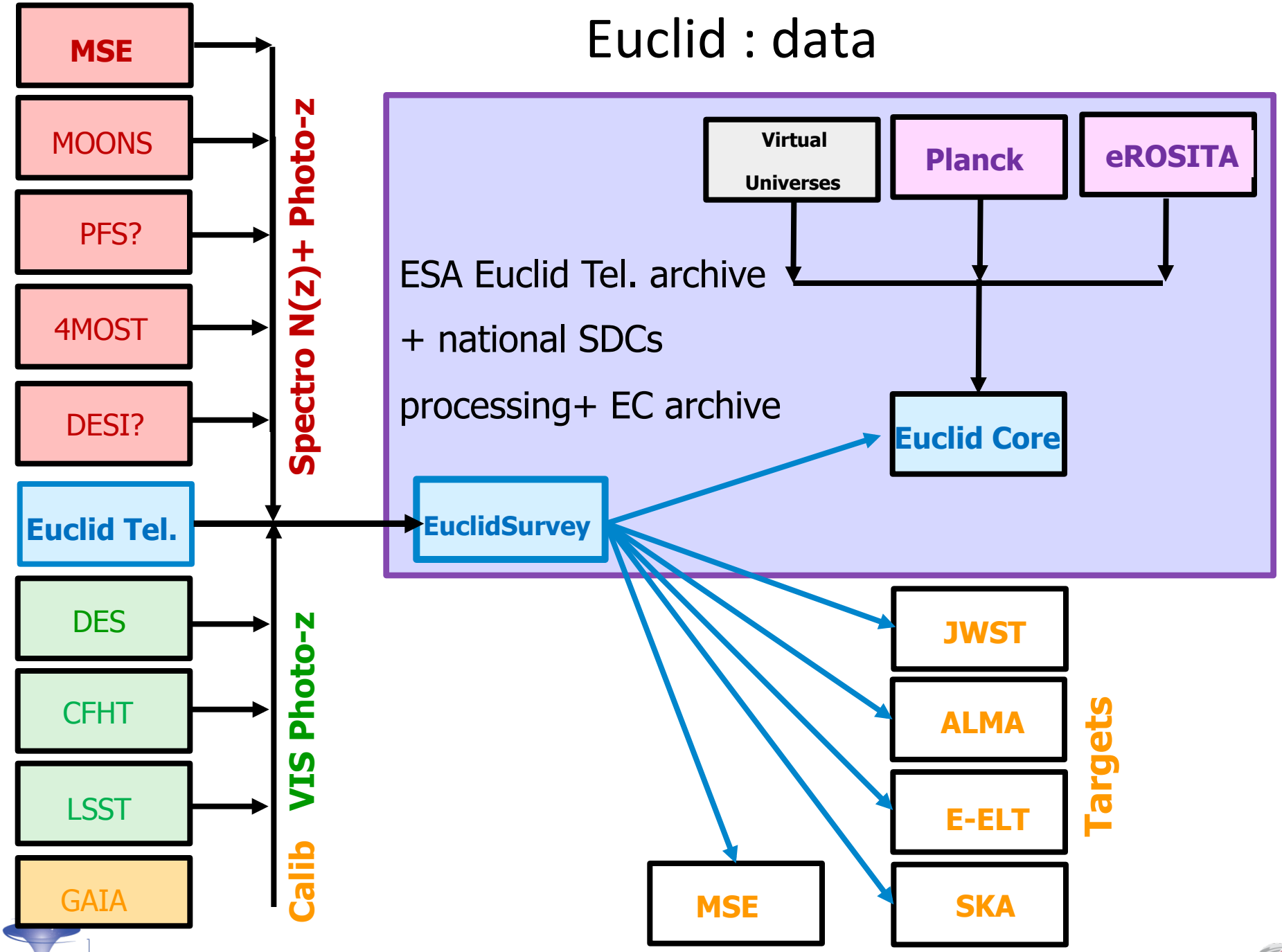
SLACS



Euclid VIS Legacy : after 2 months

(66 months planned)

# Euclid : data

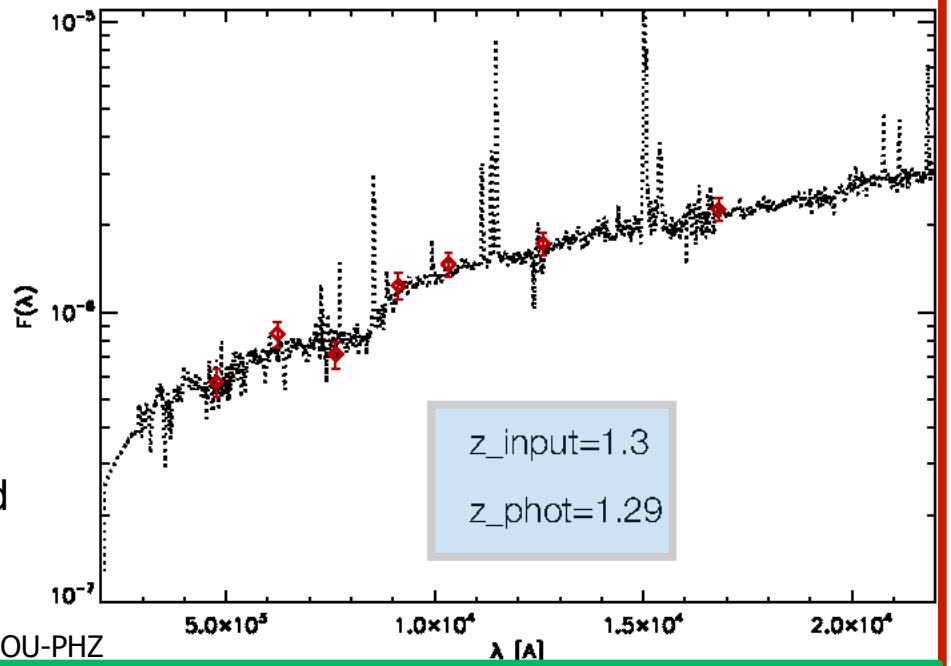

MSE
MOONS
PFS?
4MOST
DESI?
Euclid Tel.
DES
CFHT
LSST
GAIA
Spectro N(z)+ Photo-z
VIS Photo-z
Calib
Virtual Universes
Planck
eROSITA
ESA Euclid Tel. archive
+ national SDCs
processing+ EC archive
Euclid Core
EuclidSurvey
JWST
ALMA
E-ELT
SKA
MSE
Targets

# Euclid+ground: photo-z of billion lensed galaxies and ~50,000 clusters

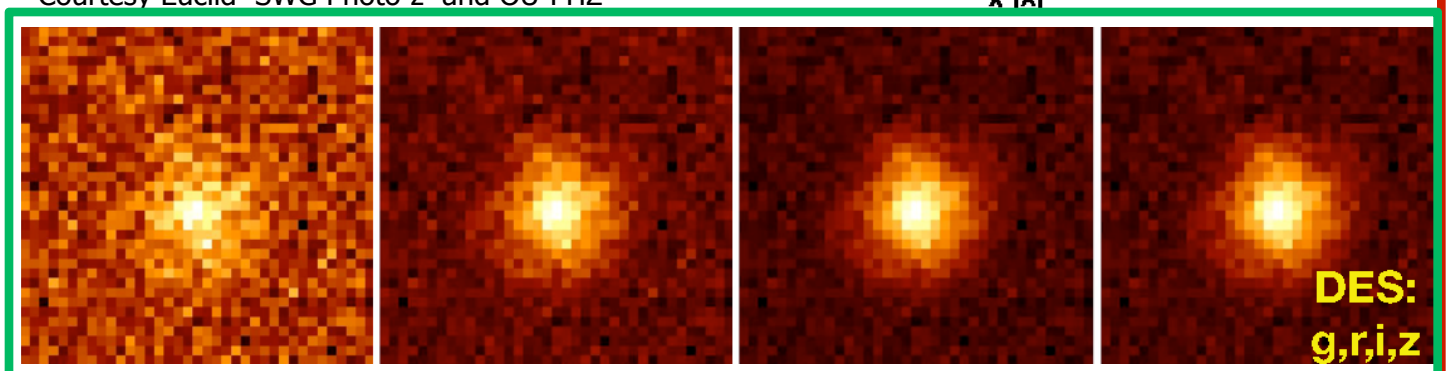
**Requirements:**

- get photo-z for ~all WL galaxies
- cover the whole Euclid sky (15000 deg$^2$)
- accuracy = 0.05x(1+z)

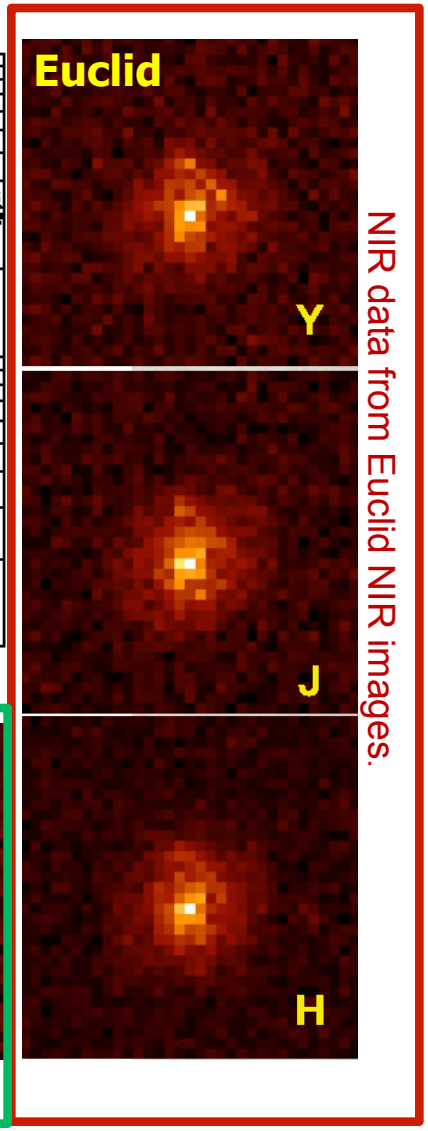
→ 4 optical bands needed




Courtesy Euclid SWG Photo-z and OU-PHZ



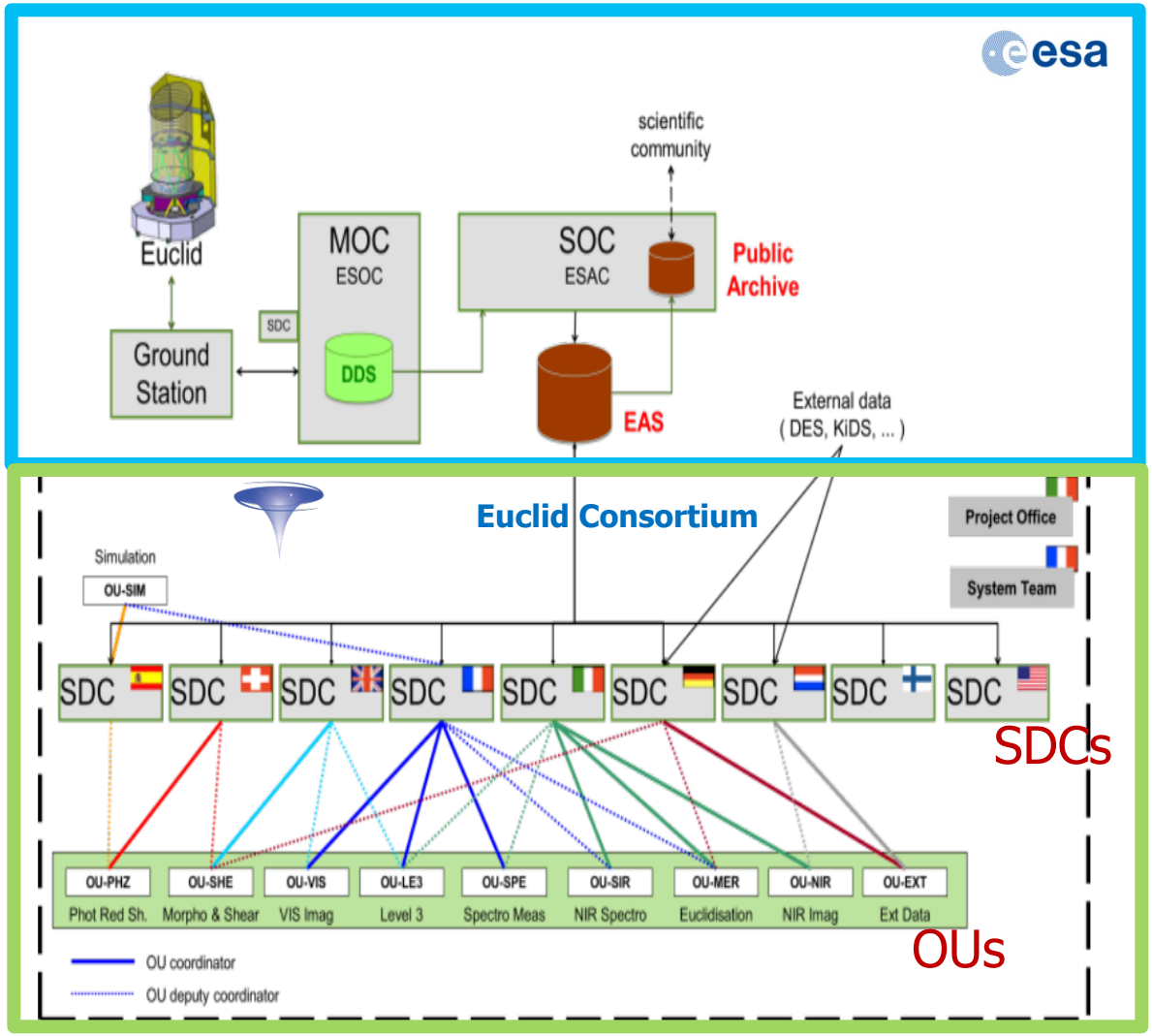

Visible data obtained from ground based telescopes




NIR data from Euclid NIR images.

# Science Ground Segment: EC, ESAC, ESOC, SDC

Courtesy: F. Pasian, M. Sauvage, J. Hoar, C. Dabin EC SGS and ESAC




**Complex organisation**:

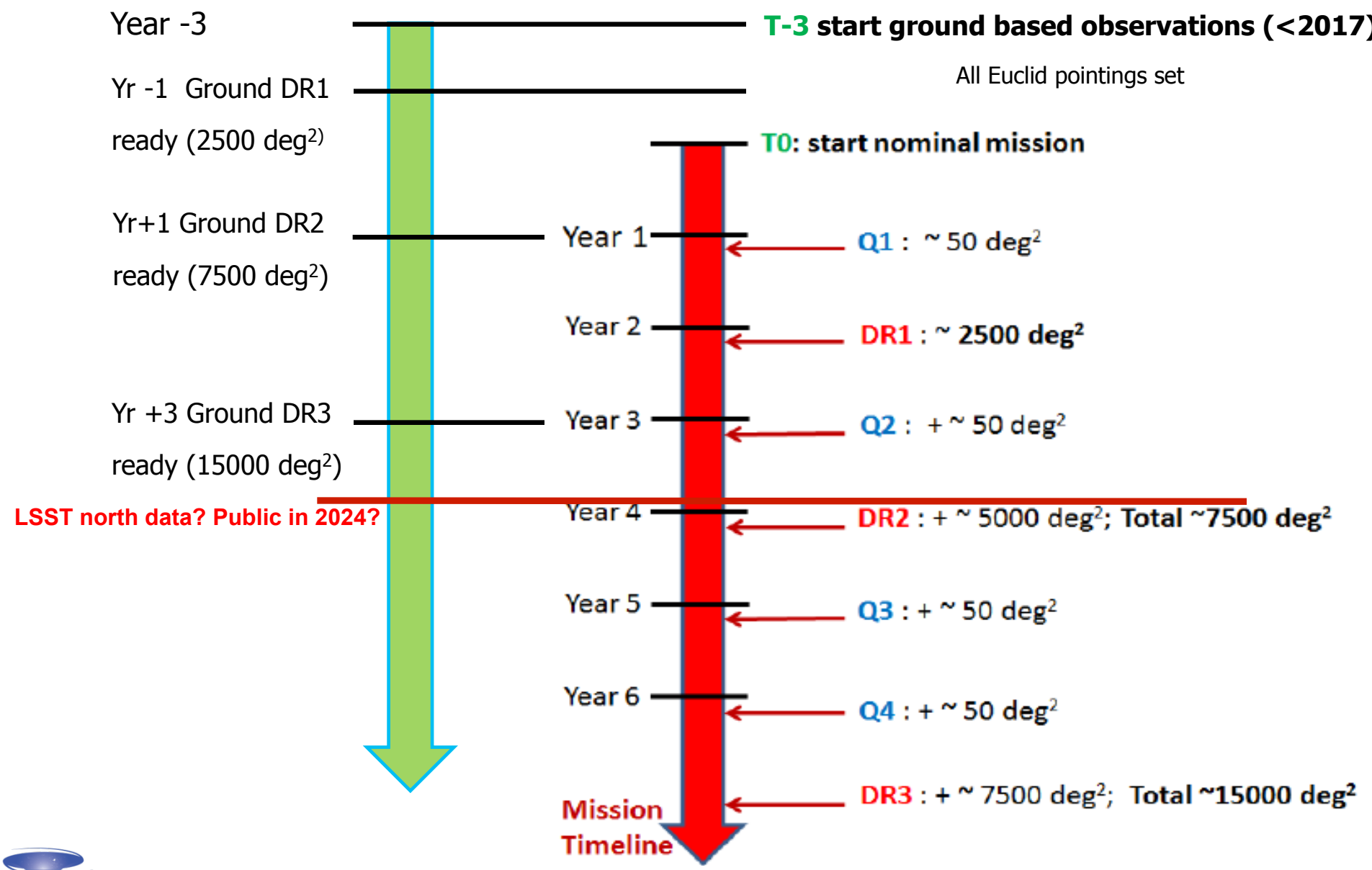
- 10 Organisation Units
- 9 Science Data Centers

**Data**: huge volumes, heterogeneous data sets

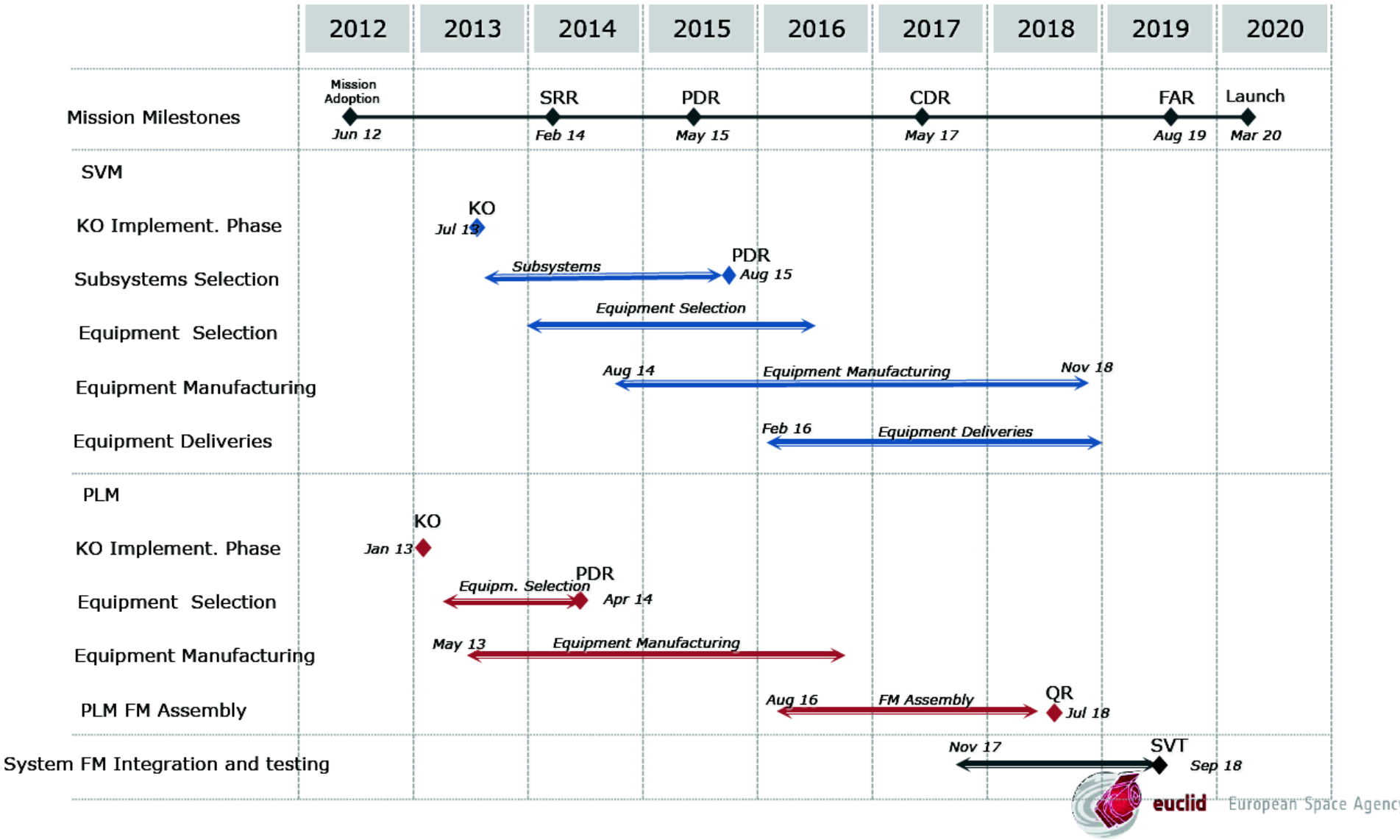
- VIS+NIR imagery and morphometry, photometry , spectroscopy
- data from ground and space
- ~100 Pbytes
- 1+ million images
- > $10^{10}$ sources (>3-sigmas)

Cost SGS = 50% of Euclid Consortium contributions.

# Euclid data release



# Euclid Schedule (Oct 2014)



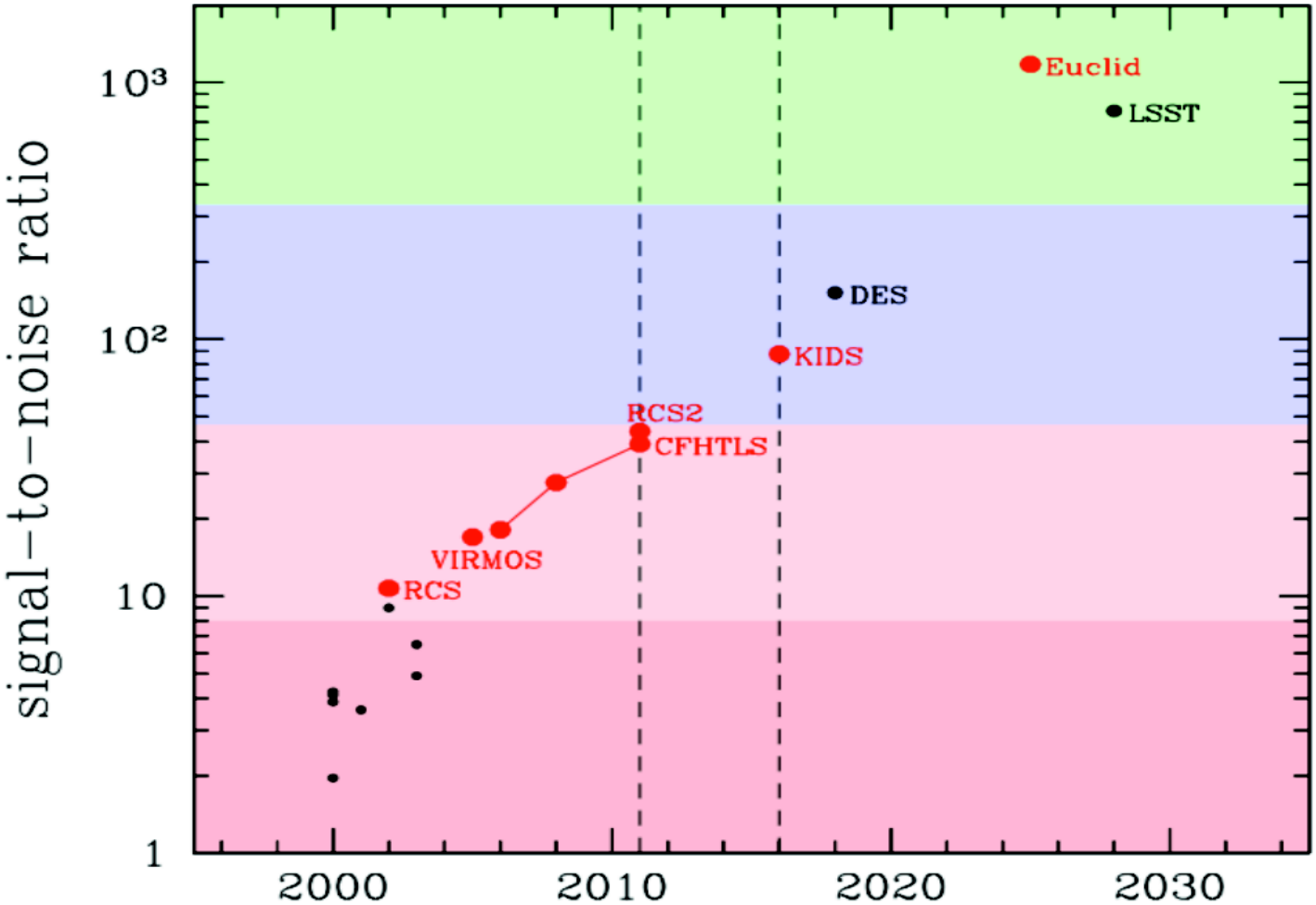

Courtesy. G. Racca/ESA

# Conclusion

# Challenges of Euclid

- **EC Management**: 1250 persons, 120 labs, 14 countries:
- **Data management and processing**: huge volume, multi-wavelength data, gro und + space, NIR+VIS, 10 SDCs , archive → data, algorithm and hardware challenges
- **Shape measurements/systematics**
  - Control multiplicative and additive biases, shape measurement algorithms
- **Photometric redshifts**:
  - Ground based photometry in 4 bands : 15,000 $deg^2$ (i.e. north and south)
- **Numerical simulations** with power spectrum to a 1% accuracy :
  - Underlying physics: e.g. numerical simulations with baryons
  - Numerical simulations of a large number of DE, GR models
  - $10^3$ to $10^5$ simulations to estimate covariance matrices
- **End-to-End performances**
- **Spectroscopic surveys to**:
  - Calibrate deep photo-z and understand BAO and RSD samples

# Measuring shear in next generation wide field cosmic shear surveys



# Summary: Euclid science objectives

| Sector | Euclid Targets |
|---|---|
| Dark Energy | • Measure the cosmic expansion history to better than 10% for several redshift bins from $z = 0.7$ to $z = 2$.<br>• Look for deviations from $w = -1$, indicating a dynamical dark energy.<br>• 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, $\gamma$, with a precision better than 0.02<br>• Measure the growth rate to better than 0.05 for several redshift bins between $z = 0.5$ and $z = 2$<br>• Separately constrain the two relativistic potentials $\Psi, \Phi$.<br>• Test the cosmological principle |
| Dark Matter | • Detect dark matter halos on a mass scale between $10^8$ and $>10^{15}$ $M_{Sun}$<br>• Measure the dark matter mass profiles on cluster and galactic scales<br>• 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 $\sigma_8$ and $n$ to a 1-sigma accuracy of 0.01.<br>• For extended models, improve constraints on $n$ and $\alpha$ wrt to Planck alone by a factor 2.<br>• Measure the non-Gaussianity parameter $f_{NL}$ for local-type models with an error better than +/-2. |

# Summary: the post-Planck cosmology mission

Euclid will

- Explore the dark universe as a whole: DE, DM, MG (in particular neutrinos), inlfation
- Use 5 cosmological probes, with at least 2 independent
- Get the percent precision on w and the growth factor
- Prepare a revolution for wide field VIS and NIR surveys
- Prepare the next generation wide field panchromatic all sky surveys: GAIA, LSST, WFIRST, e-ROSITA, SKA

Euclid Legacy = 12 billion sources, >30 million redshifts;

- A mine of images and spectra for the community for years;
- A reservoir of targets for JWST, E-ELT, TMT, ALMA, VLT
- A set of astronomical catalogues useful until 2040+

A fantastic project for next generation scientists

Euclid
consortium
Thank you