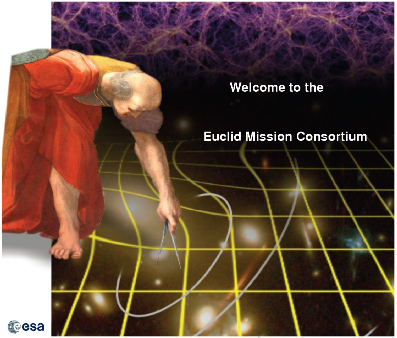


Euclid Space Mission

C. SOFIA CARVALHO

(CAAUL, LISBON & RCAAM, ATHENS)

11th HEL.A.S. Conference

11th September 2013

Our Understanding of the Universe:
The Universe evolved from a homogeneous state after the Big Bang, to a hierarchical assembly of galaxies at our epoch.

Assumptions:

- 76% dark energy: causes expansion to accelerate
- 20% dark matter: exerts gravitational attraction but does not emit/absorb light
- 4% baryonic matter: ordinary matter

Science drivers:
Understand the origin of the Universe's accelerating expansion

- Probe nature: dark energy or alternative theory of gravity
- Distinguish their effects decisively

Science drivers

Identity physical effects and observables sensitive to dark energy and/or gravity

- **Cosmic history of expansion:** equation of state of dark energy, $w(z)$.
- **Cosmic history of structure formation:** growth rate of structure γ.
- **Constraints:** mass of neutrinos, initial conditions in the very early Universe.

Identify required precision on the relevant cosmological parameters

- **Figure-of-Merit:** For $w(a) = w_p + w_a(a_p - a)$, pivotal scale chosen so that Δw_p and Δw_a are not correlated, $\mathrm{FoM} = 1/(\Delta w_p \times \Delta w_a)$.

Level-0 Requirements: Science drivers

Euclid Consortium

Science drivers are formally stated as Level-0 Requirements.

Main Scientific Objectives
Understand the nature of Dark Energy and Dark Matter by: • Reach a dark energy *FoM* > 400 using only weak lensing and galaxy clustering; this roughly corresponds to 1 sigma errors on w_p and w_a of 0.02 and 0.1, respectively. • Measure γ, the exponent of the growth factor, with a 1 sigma precision of < 0.02, sufficient to distinguish General Relativity and a wide range of modified-gravity theories • Test the Cold Dark Matter paradigm for hierarchical structure formation, and measure the sum of the neutrino masses with a 1 sigma precision better than 0.03eV. • Constrain n_s, the spectral index of primordial power spectrum, to percent accuracy when combined with Planck, and to probe inflation models by measuring the non-Gaussianity of initial conditions parameterised by f_{NL} to a 1 sigma precision of ~2.

[Euclid Red Book]

Optimal Cosmological Probes to meet L0

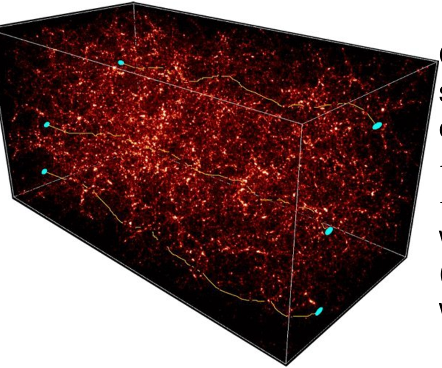
- Two physical effects, expansion and growth rate, may be degenerate
- Distinguish dark energy and alternative theory of gravity
  $\rightarrow$ Decouple Ψ and Φ
  $\rightarrow$ Need two probes
- High precision: **independent probes** used in the same fields with **different instruments** to minimize systematics
- Study of evolution of the Universe: **redshift information** in the range $0 < z < 2$, since acceleration dominates at low z
- Most sensitive probes on cosmological scales: **weak lensing** and **galaxy clustering**

  [Peacock et al. 2006, Albrecht et al. 2006]

Weak Lensing

Euclid Consortium

Coherent pattern of ellipticity + Photometric redshift
$\Rightarrow$ 2-point 3-dim cosmic shear measurements over $0 < z < 2$

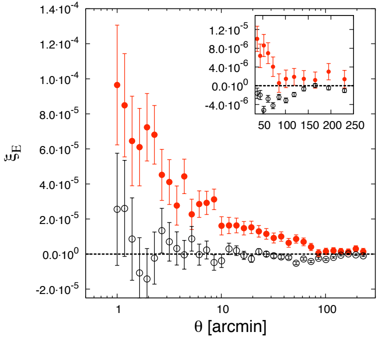


Gravitational potential of intervening structure perturbs paths of photons emitted by distant galaxies
$\rightarrow$ Images of galaxies appear distorted
$\rightarrow$ Distortion measures gravitational field which maps distribution of (dark+luminous) mass in 3 dimensions: weak lensing tomography

Convergence of distant galaxies:

$$\boldsymbol{\kappa}(\hat{\boldsymbol{n}}) = \frac{3}{2}\Omega_m H_0^2 \int_{\eta_{gal}}^{\eta_0} d\eta\, \frac{\eta}{a(\eta)}\, g(\eta)\, \delta(\eta\hat{\boldsymbol{n}},\eta),$$

$$g(\eta) = \int_{\eta_{gal}}^{\eta} d\eta' \,(dN/d\eta') \frac{\eta'-\eta}{\eta'}$$



Amount of distortion depends on observer-lens-source geometry
→ Constrains expansion history

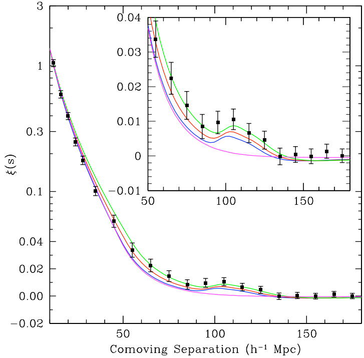
Dark matter distribution in redshift
→ Directly measures growth rate

Probe of expansion and growth

[Fu et al 2007]

Galaxy clustering

Distribution of galaxies + Spectrometric redshift
$\Rightarrow$ 2-point 3-dim position measurements over $0.7 < z < 2.1$

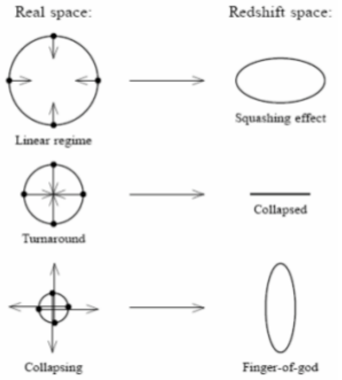


Baryon-photon perturbations travel as a sound wave from epoch of recombination
$\rightarrow$ Imprint standard preferential distance among galaxies that increases as the Universe expands
$\rightarrow$ Excess of correlation on this scale

Probe of expansion

[Eisenstein et al 2005]

Galaxy clustering



Galaxy peculiar velocities distorts clustering pattern in redshift space [Kaiser 1987]
$\rightarrow$ On large scales, peculiar velocities take the form of coherent bulk flows towards clusters and away from voids
$\rightarrow$ Independent measurement of growth rate $f(z) = \Omega_m(z)^\gamma$

Combine with growth from lensing tomography:
$\rightarrow$ Detect gravitational slip, $\Psi - \Phi$
$\rightarrow$ Break degeneracy between dark energy and alternative theory of gravity [Guzzo et al. 2008, Percival & White 2009]

Probe of growth rate of structure

Combine the primary probes

Combination of **deep imaging survey** + **extensive redshift survey** over the same area of the sky is more powerful than isolated surveys.

Extra goals:

- WL and GC both probe power matter spectra
  $\rightarrow$ Probe of neutrino mass and non-Gaussianity
- Lensing tomography + Luminous matter distribution
  $\rightarrow$ Measurement of galaxy bias

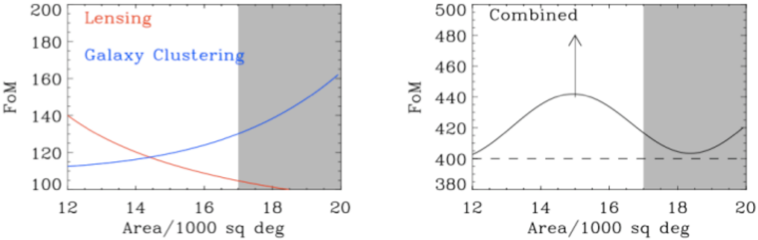
Data consist of:

- Internal data: Wide survey + Deep survey (yields spectroscopic data to calibrate photometric redshifts)
- External data: Ground-based photometry + Deep spectroscopic redshift

Euclid Consortium

How do L0 requirements translate into L1 probe requirements?

- Assume a fixed total survey time $T = \text{Area} \times \text{Exposure}$.
- Assess corresponding **precision** (statistics: large number of galaxies, large volume) and **accuracy** (systematics)
- For combined survey, obtain FoM=FoM(Area)



Req. ID	Parameter	Requirement	Goal
WL.1-1 & GC.1-1	Survey Area	>15,000 deg^2	>20,000 deg^2

[Euclid Red Book]

Level-1 Requirements: Instruments

Euclid Consortium

Which instruments are needed to fulfill the L1 scientific requirements?

Telescope with primary mirror of 1.2m diam, FoV of 0.54 deg^2

- VIS: Wide-band visible imaging
- NISP: NIR imaging and NIR spectroscopy

VIS + NISP in photometry → Weak lensing
NISP in slitless spectroscopy → Spectroscopic galaxy survey

Euclid Consortium

L1 Requirements for Weak Lensing

- WL signal represents $\sim$1% change in galaxy ellipticity
  $\Rightarrow$ Need large number of galaxies
- *FoM* $> 400 \Rightarrow$ Surface density must be > 30 gal/arcmin^2

How do L1 translate into L2 instrument requirements?

- Useful galaxies are those that are distant (to maximise lensing effect) and resolved (to measure shape)
  $\Rightarrow$ Photometry down to $m_{AB} \sim 24$
  $\Rightarrow$ Need small and stable point-spread function (PSF)

Req. ID	Parameter	Requirement	Goal
WL.1-2	Density of galaxies	>30 gals/arcmin^2	>40 gals/arcmin^2
WL.1-3	Median redshift	>0.8	
WL.2.1-1	Wavelength Coverage	550nm–900nm	
WL.2.1-2	Number of visible Filters: NF	≥1	≥2
WL.2.1-3	Vis PSF Size: FWHM	≤0.18 arcsec	

[Euclid Red Book]

L1 and L2 for NISP Photometry

How do L1 translate into L2 instrument requirements?

- Photo-z suffice to remove intrinsic alignments
  $\Rightarrow$ As error wrt true redshift increases, info is diluted
  $\Rightarrow$ Dilution must occur on scales smaller than cluster's
- Accuracy of photo-z dictated by number of filters
  $\Rightarrow$ Revised to 1 filter because of PSF colour gradient
- Photo-z should be uniform within a field and between fields
  $\Rightarrow$ relative photometric accuracy $< 1.5\%$

Req. ID	Parameter	Requirement	Goal
WL.1-5	Redshifts error ($\sigma(z)/(1+z)$)	≤ 0.05	≤ 0.03
WL.1-6	Catastrophic failures	10%	5%
WL.1-7	Error in mean redshift in bin	<0.002	
WL.2.1-17	NIR wavelength range	920 to ≥1600nm	
WL.2.1-18	NIR number of filters:	≥3	
WL.2.1-19	NIR PSF size:	EE50 and EE80 Y: (<0.30", <0.62") J: (<0.30", <0.63") H: (<0.33", <0.70")	
WL.2.1-20	NIR Pixel scale:	0.3±0.03 arcsec	
WL.2.1-21	Relative Photometric Accuracy	<1.5%	

[Euclid Red Book]

Level-1 and Level-2 Requirements for GC

Euclid Consortium

L1 Requirements for Galaxy Clustering

- *FoM* $> 400 \Rightarrow$ Need correct redshift for 3500 gal/deg^2

How do L1 translate into L2 instrument requirements?

- $H\alpha$ (n=3 to n=2) emitting galaxies
  $\Rightarrow$ Flux limit 3.10^{-16}erg cm^{-2}s^{-1} at 1600 nm (SNR=3.5 σ)
- High completeness $\Rightarrow N_{meas}/N_{total} > 45\%$
- High confusion due to overlapping spectra (slitless)
  $\Rightarrow$ Requires multiple observation of same FoV with different orientations
  $\Rightarrow$ An additional deep survey

Req. ID	Parameter	Requirement	Goal
GC.1-2	Galaxy sky density	3,500 / deg^2	5,000 / deg^2
GC.1-8	Bias of all galaxies	>1	
GC.1-9	Bias, upper quartile in redshift	>1.3	
GC.2.1-1	Flux limit	$\leq 3\times10^{-16}$ erg cm^{-2} s^{-1}	
GC.2.1-2	Completeness	>45%	
GC.2.1-3	Flux limit at all wavelengths	<120% of GC.2.1-1	

[Euclid Red Book]

L1 and L2 for NISP Spectroscopy

- Zodiacal dust scatters light
  ⇒ Define low-rank regions

Req. ID	Parameter	Requirement	Goal
GC.1-3	Redshift accuracy	$\sigma(z)<0.001(1+z)$	
GC.1-4	Systematic offset in redshift	<1/5 redshift accuracy	
GC.1-5	Redshift range	$0.7<z<2.05$	also gals $z<0.7$
GC.1-6	Median of redshift distribution	>1	>1.1
GC.1-7	Upper quartile of redshifts	>1.35	
GC.1-10	fraction of catastrophic failures	f<20%	
GC.1-11	fraction of catastrophic failures	known to 1%	
GC.1-12	mean redshift in 0.1 redshift bin	known to 0.1%	
GC.2.1-4	Spectral range: lower limit Spectral range: upper limit	less than 1.1 micron greater than 2.0 micron	
GC.2.1-5	Spectral resolution	>250	
GC.2.1-6	Resolution element	sampled by > 2 pixels	
GC.2.1-7	Wavelength error	line sampling f < 0.25	
GC.2.1-8	PSF size and shape in spectroscopic mode	FWHM<0.6" and rEE80 radius <0.6"	
GC.2.1-9	Stray light	<20% of Zodiacal light at ecliptic poles	
GC.2.1-10	Subsample of galaxies	>140,000 gals, with >99% purity	

[Euclid Red Book]

Build a reference survey

Goal is to build a reference survey complaint with:

- covering > 15000 deg^2 in < 6 years
- $\langle N_{gal} \rangle > 30/\text{arcmin}^2$, avoiding low-rank regions
- given FoV, exposure time, dithering pattern

Must include:

- Calibration fields
- Deep field: 2 magnitudes deeper than wide survey, total area ~ 40 deg^2 $\rightarrow$ Calibration + Legacy Science

Dithering pattern allows:

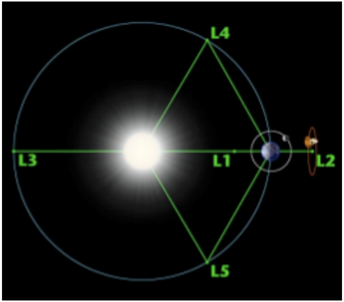
- subtraction of cosmic rays
- countering of radiation damage effects
- reconstitution of sub-pixel spatial resolution images

Build a reference survey

Task is being done by the **Euclid Sky Survey Working Group.** It is an ESA-Euclid Consortium joint group with team members:

- ESA/ESTEC (project scientist, system engineer)
- ESA's Space Astronomy Centre: science operation
- ESA's Space Operation Centre: mission operation
- Euclid Consortium survey scientist
- Italian dithering implementation group
- Portuguese strategy implementation group

Sky survey reference implementation

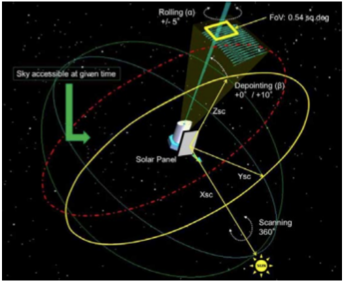


Spacecraft orbits around the 2nd Lagrange point, which orbits around the Sun.

At given time, there is narrow band in ecliptic longitude available for observations: limited range of **solar aspect angle** for thermal stability.

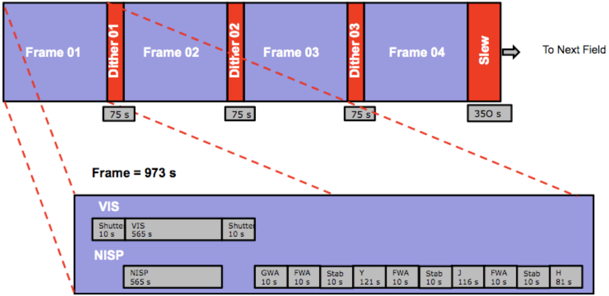
Need to determine a sequence of FoV's in a **step-and-stare** procedure according to **operational constraints** (pointing, propellant and max number of slews, exposure time), while meeting scientific requirements.

[Amiaux et al. 2012]



Dithering strategy

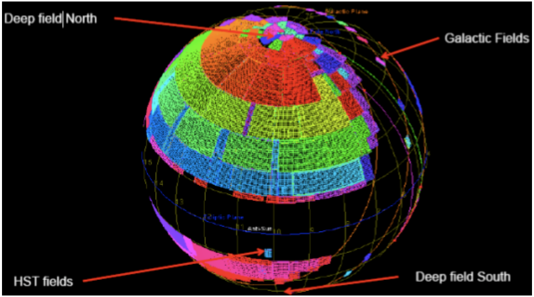
A FoV is composed of four frames of 0.54 deg^2 common area, observed with a dither step in-between



[Amiaux et al. 2012]

- During each frame: simultaneous VIS and NISP spectroscopic exposures, followed by NISP photometric exposures
- After each frame: dither-to-dither slew
- After dither-to-dither three slews: field-to-field slew

Survey strategy

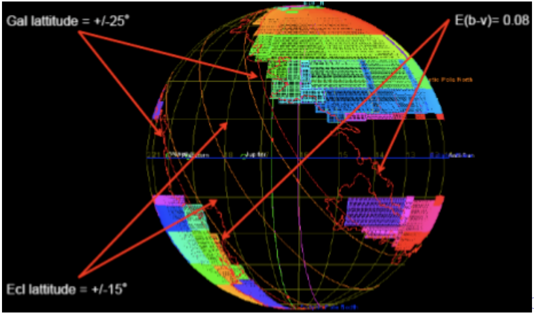


A sequence of FoV's, calibration fields and two deep fields.

High-priority regions: galactic poles + high ecliptic latitude

Low-rank regions:
→ dense star regions
→ extinction lines
(galactic plane+zodiacal light)

Plan:
→ Automate procedure for building sequence
→ Criteria for optimisation
→ Fill gaps when observing calibration fields
→ Statistics of the survey



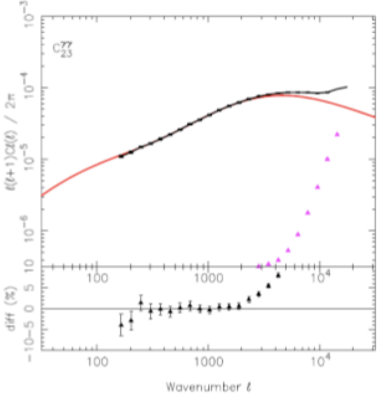
Expected cosmological results

The reference survey:

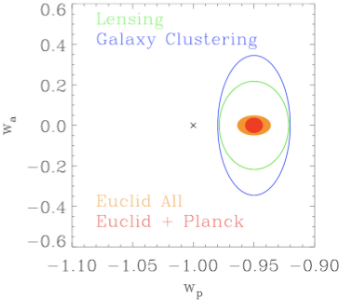
- will contain $\sim$ 40000 wide-field FoV's
- with an exposure time of 4500 s (19 fields observed/day)
- with a density of galaxies 26-36 gal/arcmin^2

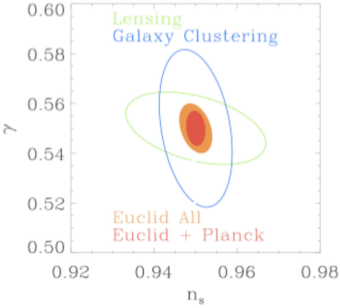
$\Rightarrow \sim 2.10^9$ (faint, WL) galaxies, 5.10^7 will have spectroscopic z.

$\Rightarrow$ Reconstruction of power spectrum to 1%. [Euclid Red Book]



Combination with additional probes





- **Cosmic microwave background:** Detection of integrated Sachs-Wolfe effect, due to decaying gravitational potentials of large-scale structure at low z, hence sensitive to derivative of growth factor
- **Clusters of galaxies:** Euclid expected to detect $\sim$ 60000 clusters with $SNR > 3$ in $0.2 < z < 2$, hence good statistics for cluster-based constraints on cosmological parameters.

Improvement factors

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	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	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

[Euclid Red Book]

Additional surveys

The reference survey (wide survey + deep fields + calibration) will be completed with margin of 6 months, leaving free time for additional surveys.

Three currently under discussion:

- **Supernovae:** 6-month survey in final year with 4-day cadence, plus SN detections in deep field
- **Micro-lensing:** 30-day survey in the galactic bulge, 20-minute cadence
- **Milky way:** galactic plane survey for star formation and galactic structure

Euclid Legacy

Although the survey is designed to meet the requirements for the two primary cosmological probes, it will provide data stets of great value for astrophysics.

Examples: ["Euclid Definition Study Report," Laureijis et al. arXiv:1110.3103]

The high-redshift Universe

- Hundreds of $z > 7$ galaxies brighter than $J = 26$ $\rightarrow$ Clustering
- Tens of quasars of $z > 8$ brighter than $J = 22$ $\rightarrow$ Reionization

Galaxy evolution at $1 < z < 3$

- Clustering over a range of galaxy properties
- Merger samples increase by 4 orders of magnitude
- Detection of 10^6 Type-1 AGN's, 10^4 Type-2 AGN's

Relationship between dark and baryonic matter

- Strong lensing: 3.10^5 galaxy-scale strong lenses, 1000 multiple quasars, 5000 clusters with arcs

Local Group

- Resolve stellar population of galaxies within 5 Mpc
- Detect 10^5 dwarf galaxies

Synergies with facilities that have a large collecting area but a small FoV (JWST, E-ELT, ALMA)

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