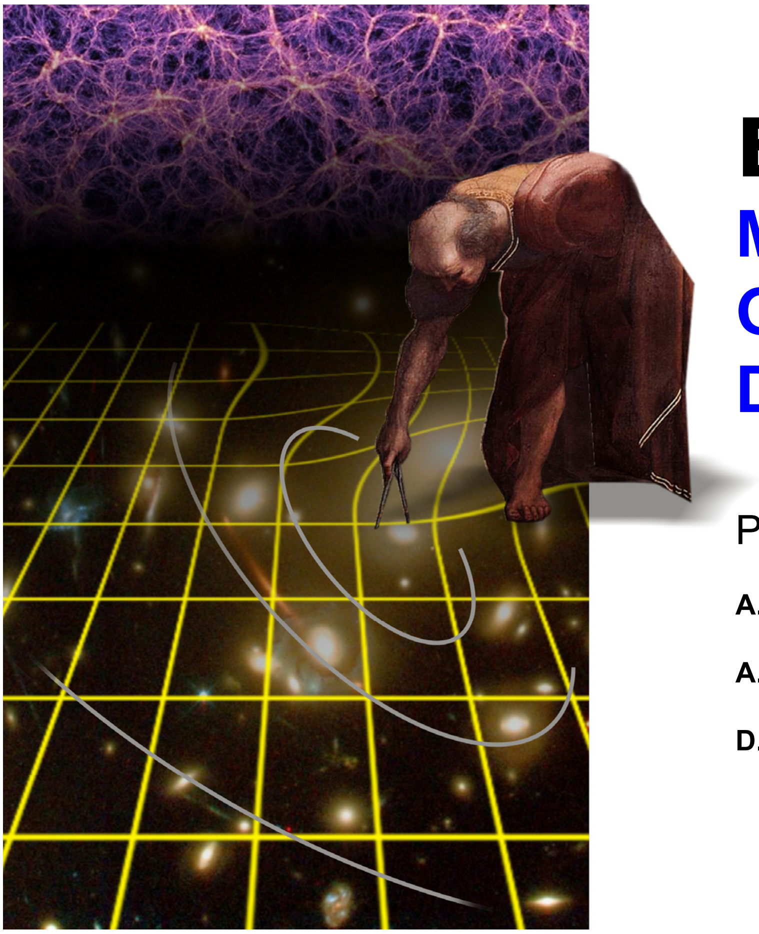


# Euclid

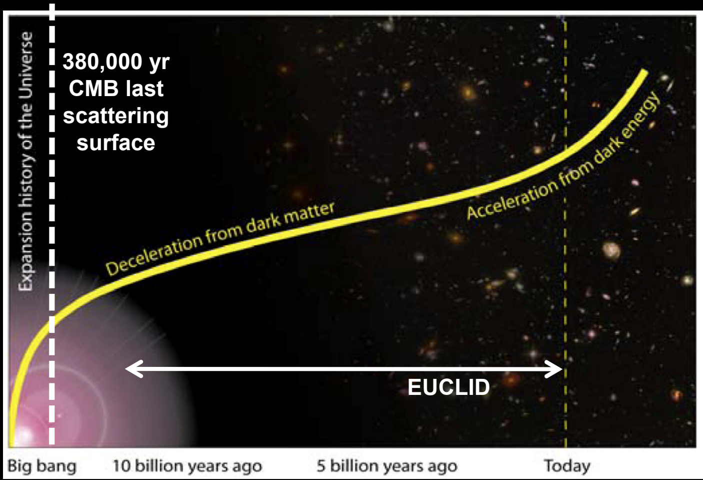
## Mapping the Geometry of the Dark Universe

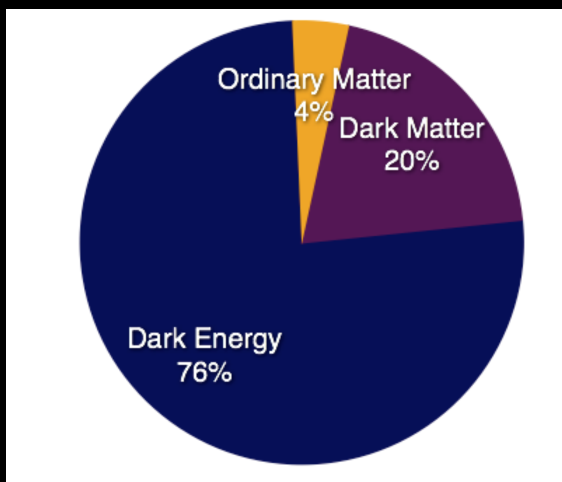
Presentations by


**A. Refregier (CEA Saclay)**
***Imaging Survey***
**A. Cimatti (Univ. Bologna)**
***Spectroscopic Survey***
**D. Lumb (ESA)**
***Mission implementation***


# Outstanding questions in cosmology

- ❑ the nature of the Dark Energy
- ❑ the nature of the Dark Matter
- ❑ the initial conditions (Inflation Physics)
- ❑ modifications to Gravity



# Euclid concept

- High-precision survey mission to map the geometry of the Dark Universe
- Optimized for two complementary cosmological probes:
  - Weak Gravitational Lensing
  - Baryonic Acoustic Oscillations

  Additional probes: clusters, redshift space distortions, ISW
- Full extragalactic sky survey with 1.2m telescope at L2:
  - Imaging:
    - High precision imaging at visible wavelengths
    - Photometry/Imaging in the near-infrared
  - Near Infrared Spectroscopy
- Legacy science for a wide range of areas in astronomy
- Survey Data public after one year



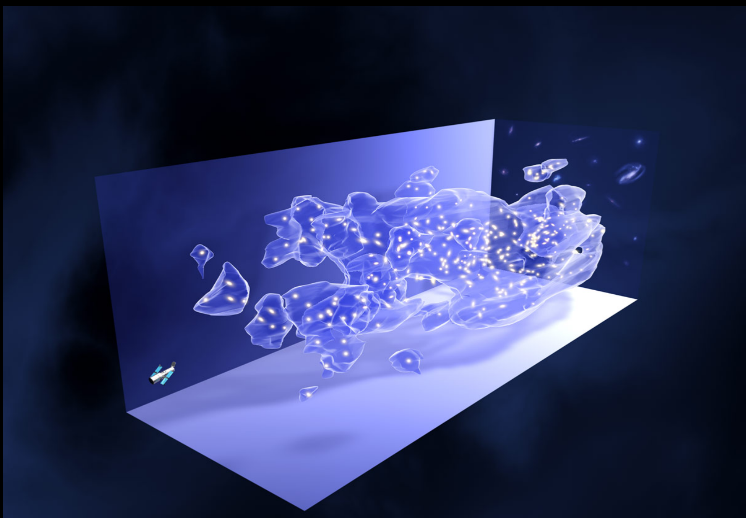
# Imaging the Dark Universe with Euclid

# Weak Gravitational Lensing

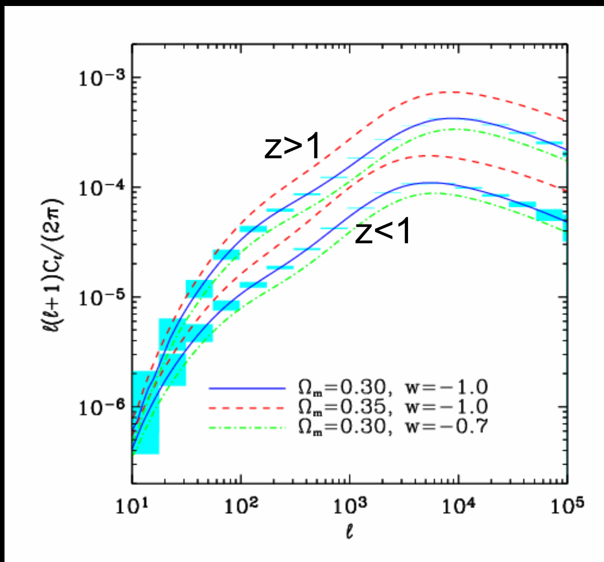
Weak Lensing:

- Map the 3D distribution of Dark Matter in the Universe
- Measures the mass without assumptions in relation between mass and light
- Very sensitive to Dark Energy through both geometry and growth

→ Need measurements of galaxy shape and photometric redshifts



Massey et al. 2007






# Current status of Dark Energy

Dark Energy:

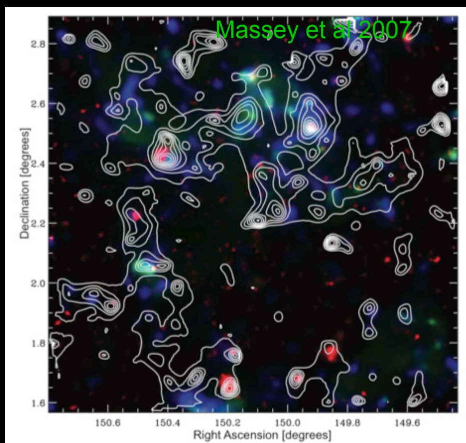
- Affects cosmic geometry and structure growth
- Parameterised by equation of state parameter:

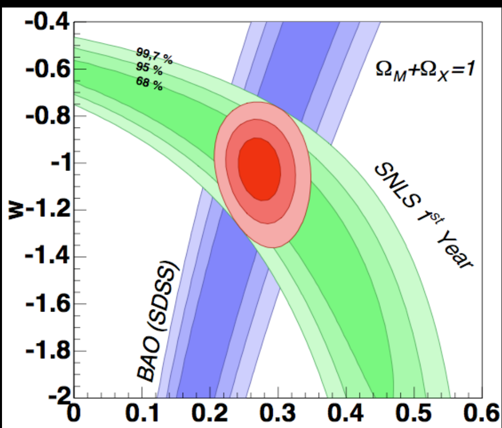
w(z)=ρ/p, constant w=-1 for cosmological constant

Current constraints: 10% error on constant w

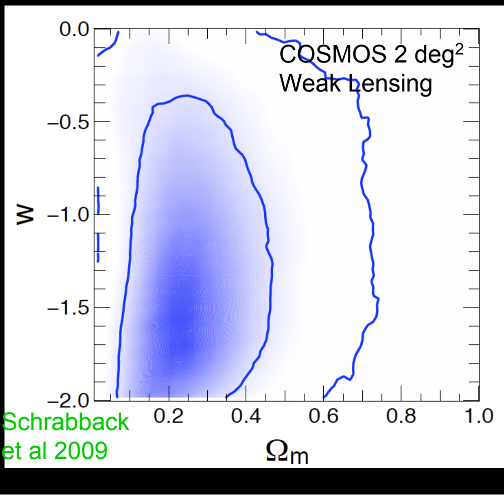
For definite answers on DE: need to reach a precision of 1% on (varying) w and 10% on $w_a$=dw/da

→ Objective for Euclid imaging




Astier et al. 2005



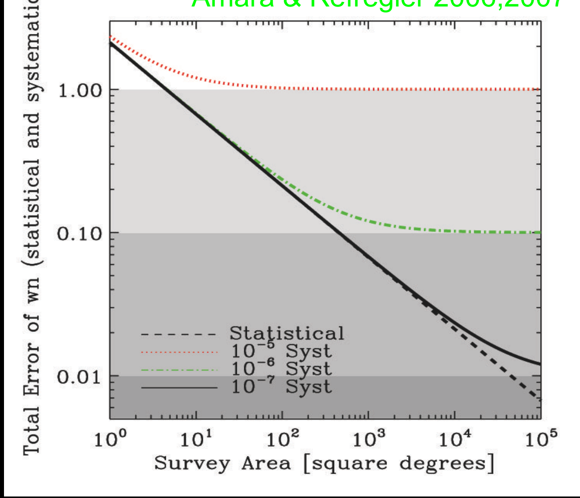

Schrabback et al 2009

# Requirements for Weak Lensing

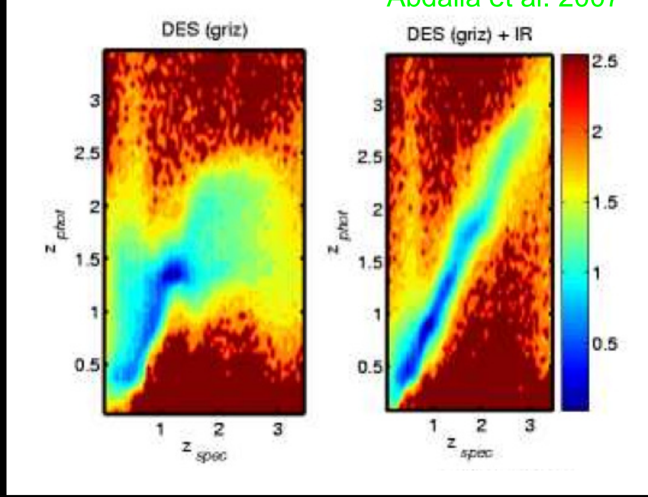
Statistics: optimal survey geometry: wide rather than deep for a fixed survey time, → need 20,000 deg$^2$ to reach ~1% precision on w

Redshift bins: good photo-z for redshift binning and intrinsic alignments → need deep NIR photometry

Systematics: must gain 2 orders of magnitude in systematic residual variance → need about 50 bright stars to calibrate PSF



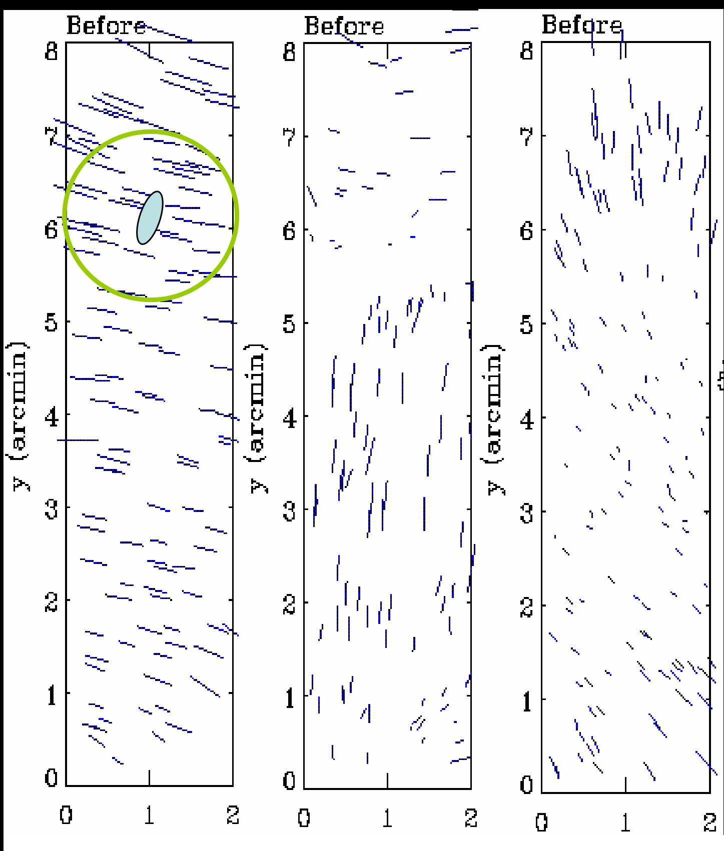

Amara & Refregier 2006,2007




Abdalla et al. 2007



# The need for space



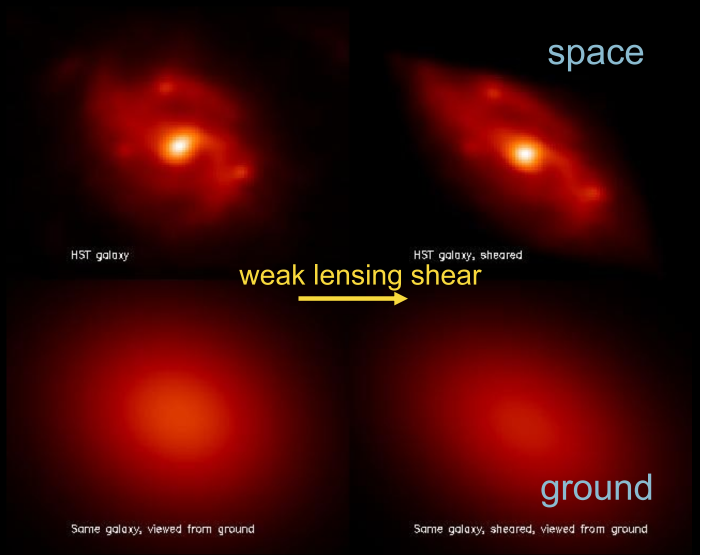

Ground PSF calibration and deconvolution

Euclid in space compared to ground:

No atmospheric seeing, absorption, windshake, etc

- PSF size 5x smaller
- PSF stability 10x better
- NIR photometry 3 mag deeper

→ Needed to meet WL requirements



# Imaging instrument and control of systematics

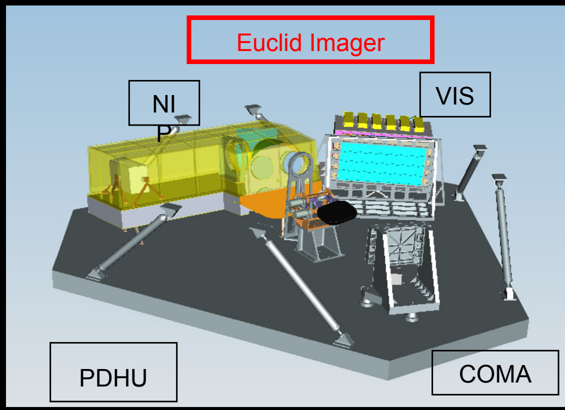
Imaging instrument: optimised for weak lensing

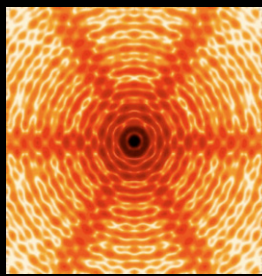
- Visible imaging channel: 0.5 $deg^2$, 0.10'' pixels, 0.16'' PSF FWHM, broad band R+I+Z (0.55-0.92mu), CCD detectors, galaxy shapes
- NIR photometry channel: 0.5 $deg^2$, 0.3'' pixels, 3 bands Y,J,H (1.0-2.0mu), HgCdTe detectors, photo-z's

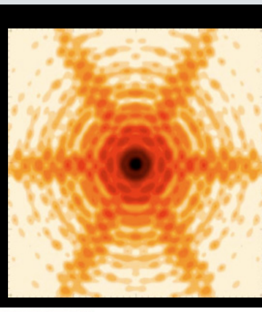
Control of systematics:

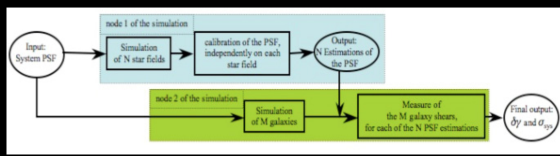
- Tight requirements on PSF ellipticity and stability, thermo-elastic distortions, attitude control, detector performance
- Instrument performance simulations
- Integrated data handling and calibration chain

Euclid Imaging Consortium (EIC):
130 people, 25 institutes, 7 countries










# Euclid Imaging Surveys

Wide Survey: Extragalactic sky (20,000 $deg^2$ = $2\pi$ sr)

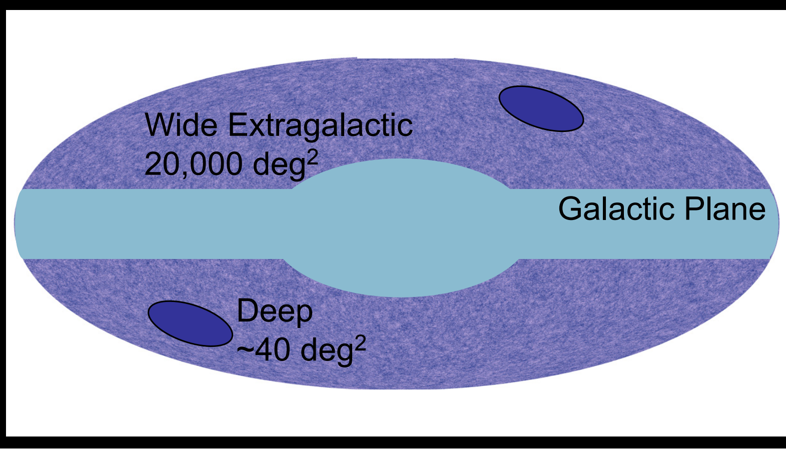
- Visible: Galaxy shape measurements to $RIZ_{AB} \leq 24.5$ (AB, $10\sigma$) at 0.16" FWHM, yielding 30-40 resolved galaxies/$amin^2$, with a median redshift $z$~ 0.9
- NIR photometry: Y, J, H ≤ 24 (AB, $5\sigma$ PS), yielding photo-z's errors of 0.03-0.05(1+$z$) with ground based complement (PanStarrs-2, DES. etc)
- Concurrent with spectroscopic survey

Deep Survey: 40 $deg^2$ at ecliptic poles

- Monitoring of PSF drift (40 repeats at different orientations over life of mission)
- Produces +2 magnitude in depth for both visible and NIR imaging data.

Possible additional Galactic surveys:

- Short exposure Galactic plane
- High cadence microlensing extra-solar planet surveys could be easily added within Euclid mission



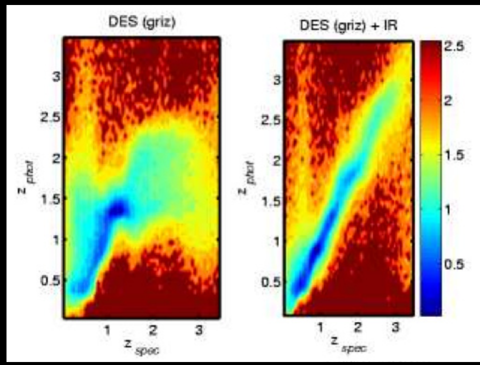
# Ground-Space Synergy

To achieve photometric redshift precision of σ(z)/(1+z)=0.03(goal)-0.05(rq't), combine Euclid visible/NIR photometry with visible photometry from the ground

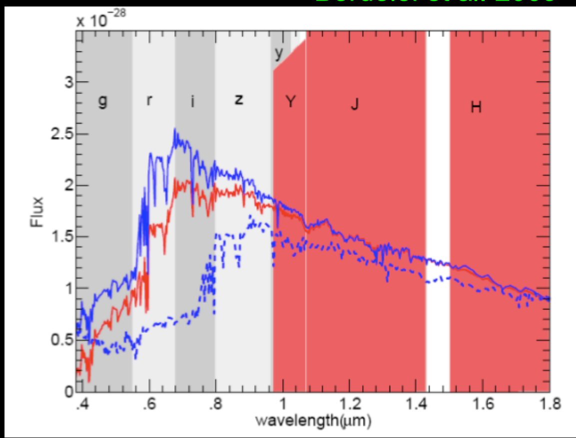
DES+Pan-STARRS2 will provide necessary depth and combined sky coverage, LSST+PS4 would provide even better photo-z's

→ see letters of support from DES and PS projects

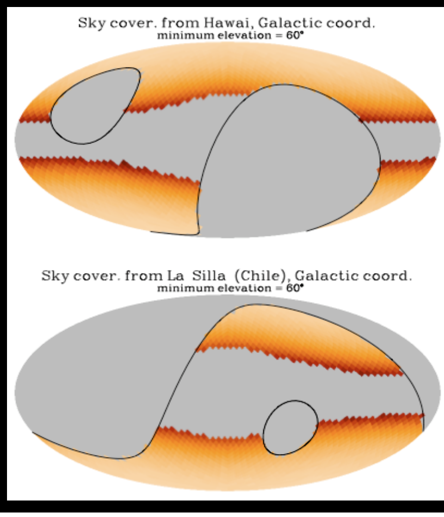
Abdalla et al. 2007




Bordoloi et al. 2009



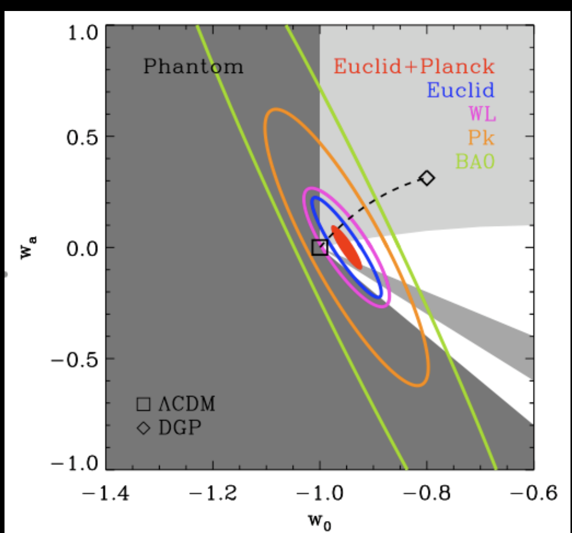

Paulin-Henriksson et al. 2009






# Impact on Cosmology

| | $\Delta w_p$ | $\Delta W_a$ | $\Delta\Omega_m$ | $\Delta\Omega_\Lambda$ | $\Delta\Omega_b$ | $\Delta\sigma_8$ | $\Delta n_s$ | $\Delta h$ | DE FoM |
|---|---|---|---|---|---|---|---|---|---|
| Current+WMAP | 0.13 | - | 0.01 | 0.015 | 0.0015 | 0.026 | 0.013 | 0.013 | ~10 |
| Planck | - | - | 0.008 | - | 0.0007 | 0.05 | 0.005 | 0.007 | - |
| Weak Lensing | 0.03 | 0.17 | 0.006 | 0.04 | 0.012 | 0.013 | 0.02 | 0.1 | 180 |
| Imaging Probes | 0.018 | 0.15 | 0.004 | 0.02 | 0.007 | 0.0009 | 0.014 | 0.07 | 400 |
| Euclid | 0.016 | 0.13 | 0.003 | 0.012 | 0.005 | 0.003 | 0.006 | 0.020 | 500 |
| Euclid +Planck | 0.01 | 0.066 | 0.0008 | 0.003 | 0.0004 | 0.0015 | 0.003 | 0.002 | 1500 |
| Factor Gain | 13 | >15 | 13 | 5 | 4 | 17 | 4 | 7 | 150 |



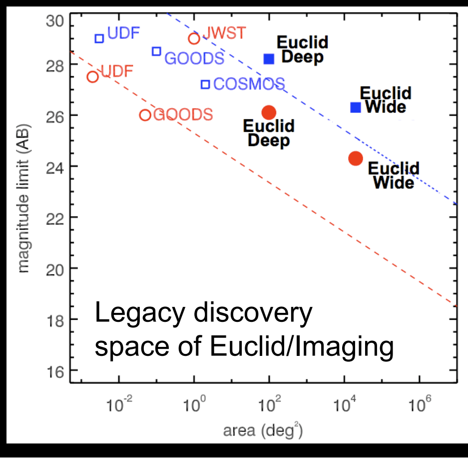

Euclid Imaging will challenge all sectors of the cosmological model:

- Dark Energy: $w_p$ and $w_a$ with an error of 2% and 13% respectively (no prior)
- Dark Matter: test of CDM paradigm, precision of 0.04eV on sum of neutrino masses (with Planck)
- Initial Conditions: constrain shape of primordial power spectrum, primordial non-gaussianity
- Gravity: test GR by reaching a precision of 2% on the growth exponent $\gamma$ ($d\ln\delta_m/d\ln a \propto \Omega_m^\gamma$)

→ Uncover new physics and map LSS at 0<z<2: Low redshift counterpart to CMB surveys

# Imaging Legacy Science

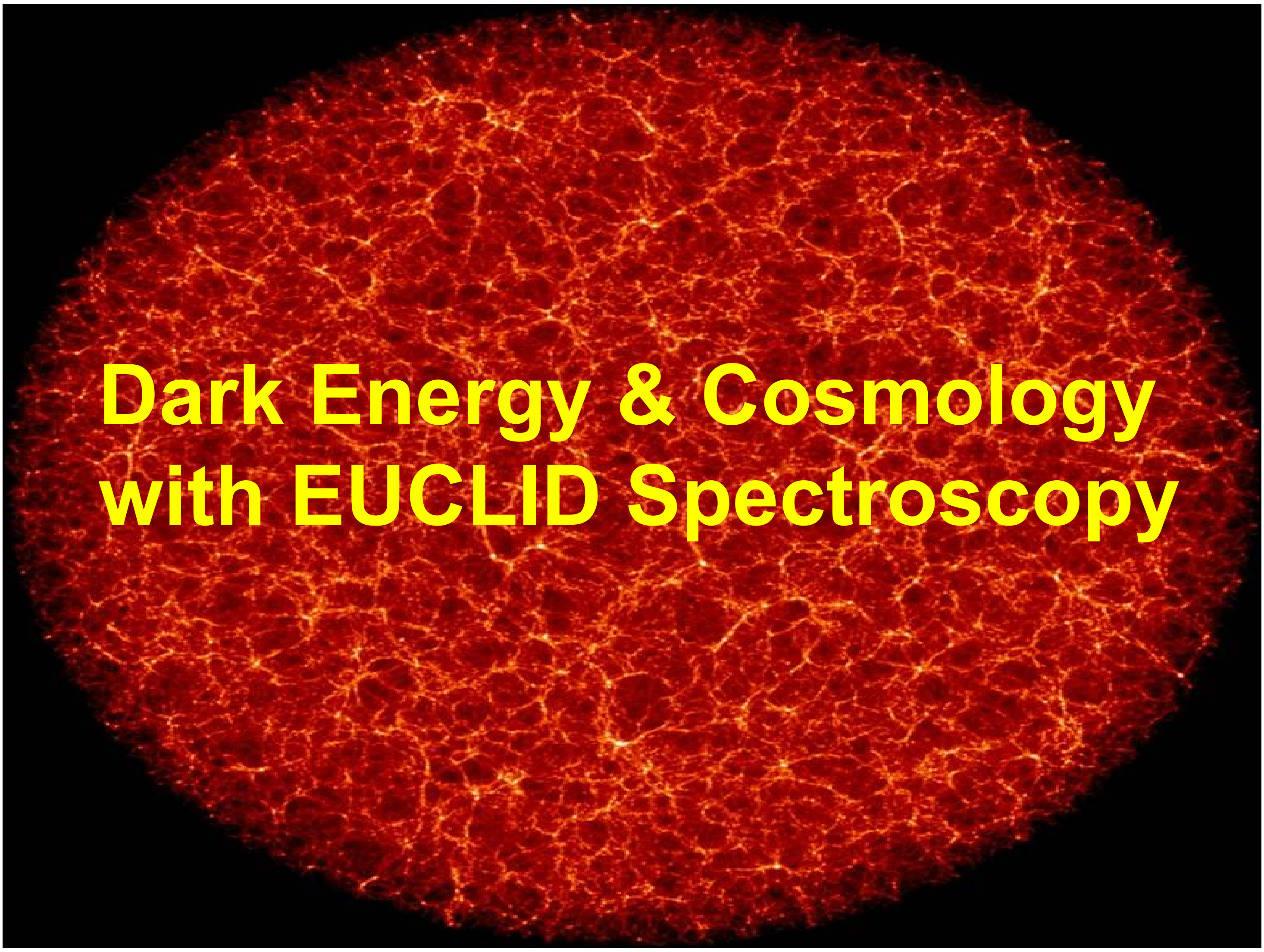
- Map relation between Galaxy Mass and Light: correlation of WL mass map with galaxy distribution and properties/morphologies
- Constrain physical drivers of star formation: galaxy morphology and NIR properties; SNe rate (Detection of ~3000 Type Ia and Type II supernovae in deep survey)
- High-z objects: Using the Ly-dropout technique in MD survey, detect $10^{3-4}$ star forming galaxies at z~8, $10^{2-3}$ at z~10, ~10 at z~12; also detect $10^{2-4}$ quasars at z~7, and $10^{1-3}$ at z~9
- Galaxy Clusters: NIR detection of several 100 Virgo-like clusters and several 1000 $10^{13}$ $M_{sun}$ at z>2, mass detection of 40,000 clusters at z~0.3-0.7, well matched to Planck and eRosita cluster sample
- Strong-Lensing systems: ~$10^5$ Galaxy-galaxy lenses, ~$10^3$ galaxy-quasar lenses, 5000 strong lensing arcs in clusters
- Exo-planets: make census earth mass planets through microlensing





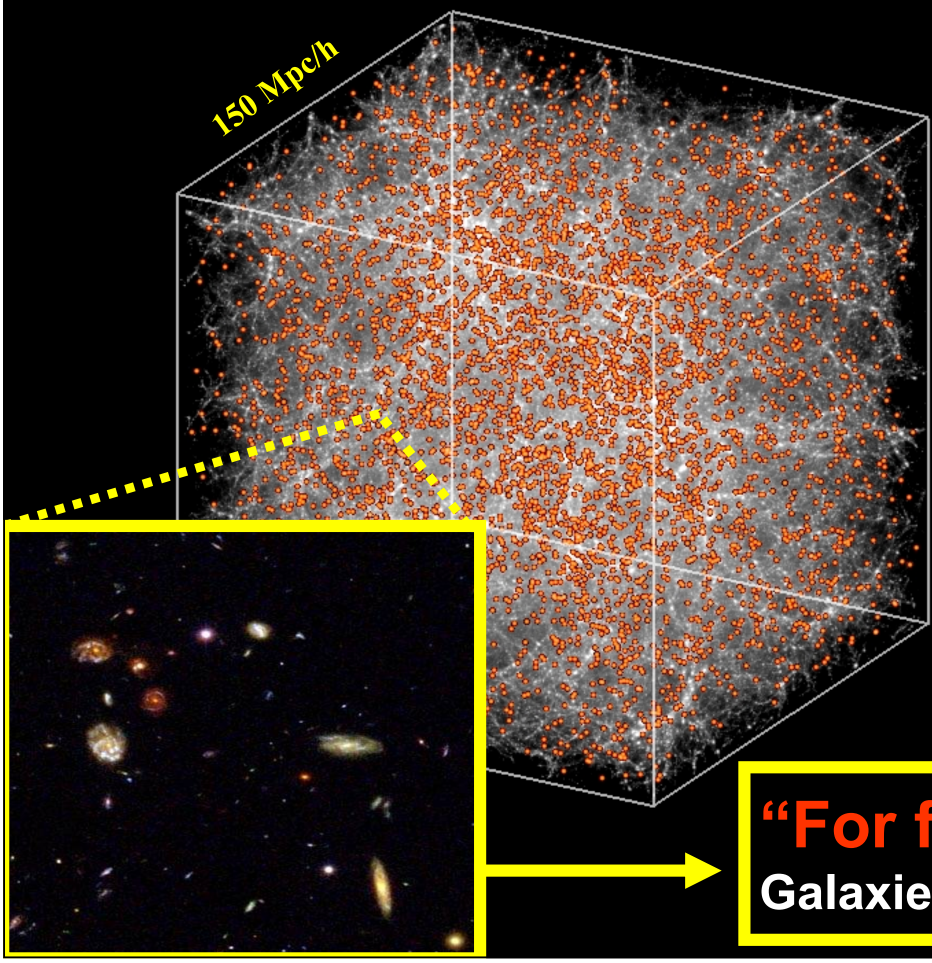

# Imaging the Dark Universe

- ❑ Euclid concept: high-precision survey mission, optimised for Weak Lensing and BAO, tight control of systematics, strong link between science and instrumentation, matched survey speeds, synergy with ground based surveys
- ❑ Euclid imaging will achieve definite constraints on Dark Energy and challenge all sectors of the cosmological model
- ❑ Euclid imaging will provide unique legacy science: galaxy evolution, high-z objects, clusters, strong lensing, and with a survey extension exoplanets and Milky Way
- ❑ Euclid has received broad support from the European science community: ESA/ESO WG on Fundamental Cosmology, Astronet, National agencies



# Dark Energy & Cosmology with EUCLID Spectroscopy

## 3-D Evolutionary Map of the Universe



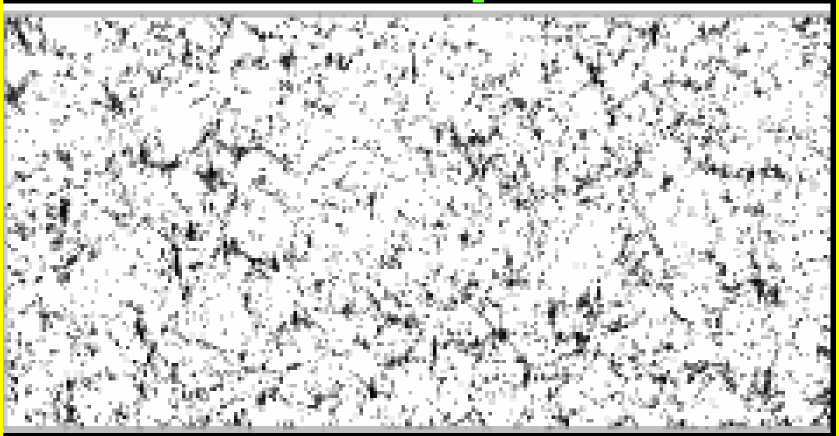

- For each galaxy: RA, Dec, Redshift
  → **3-D map**

- Boxes at different redshifts:
  → **Evolution**

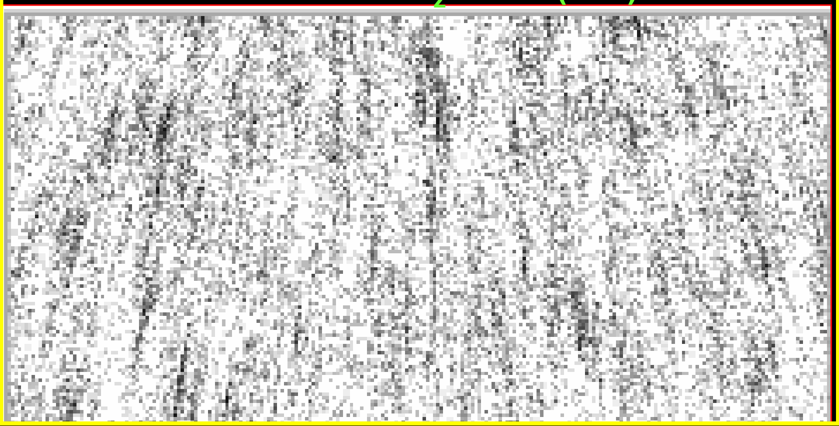
**“For free”:**
**Galaxies, AGNs**

# WHY SPECTROSCOPY ?

Spectroscopic redshifts: $\sigma_z = 0.001(1+z)$



Photometric redshifts: $\sigma_z = 0.02(1+z)$

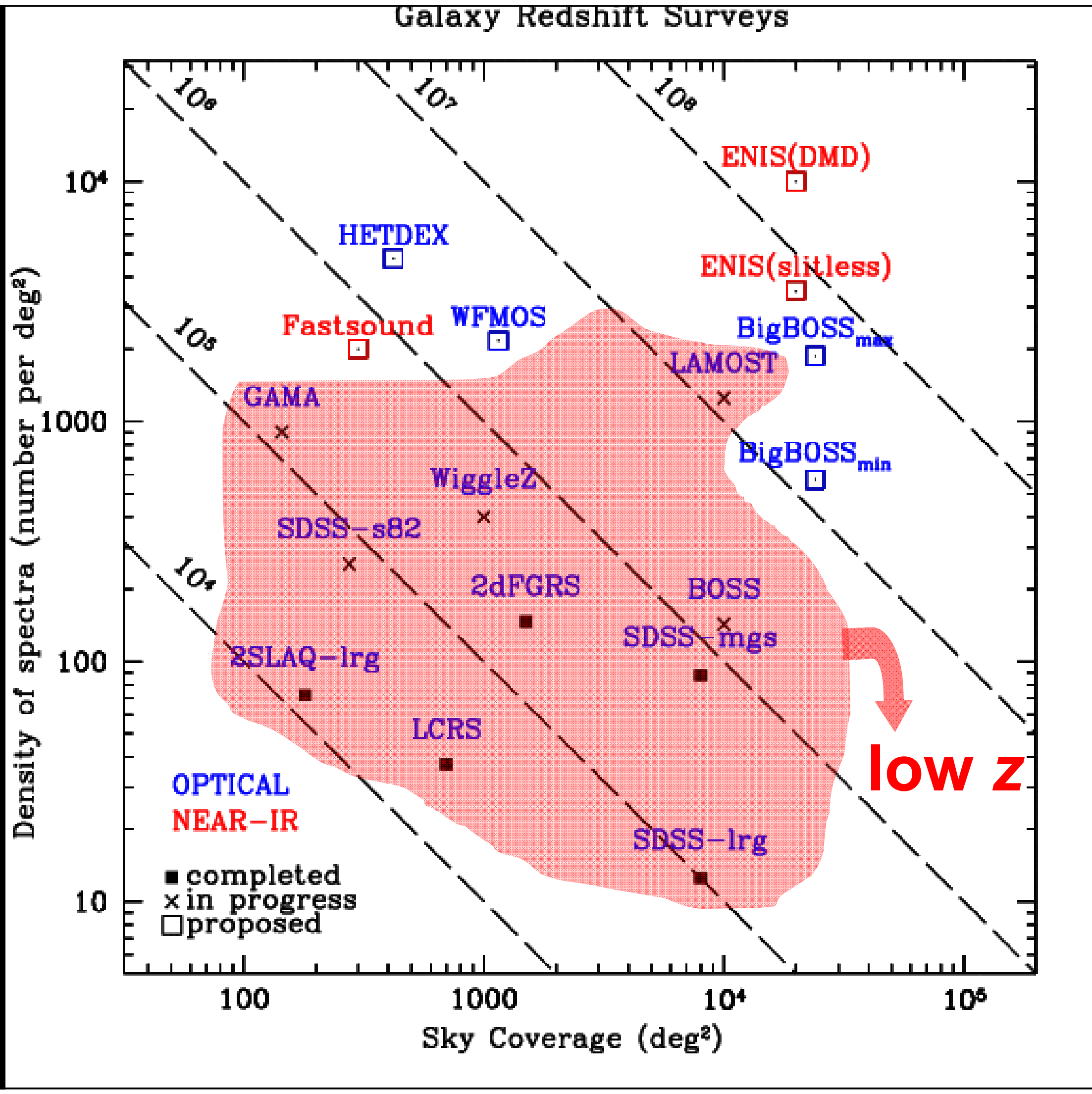


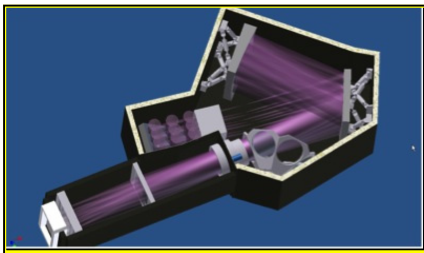
# WHY FROM SPACE ?

- No atmosphere
- ≈ 500x less background
- Stable PSF
- Homogeneous data
- Easy to reach z ≈ 2+
- Clean selection function
- Unbeatable speed
- Multi-probe experiment

# WHY NEAR-IR ?

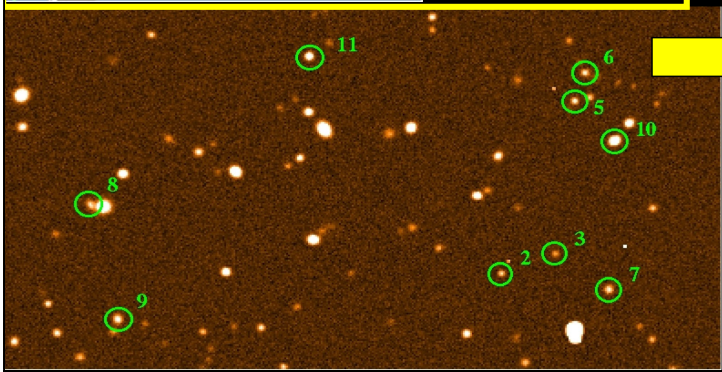
- 0.5 < z < 2 with Hα
- Less dust extinction
- Higher legacy value



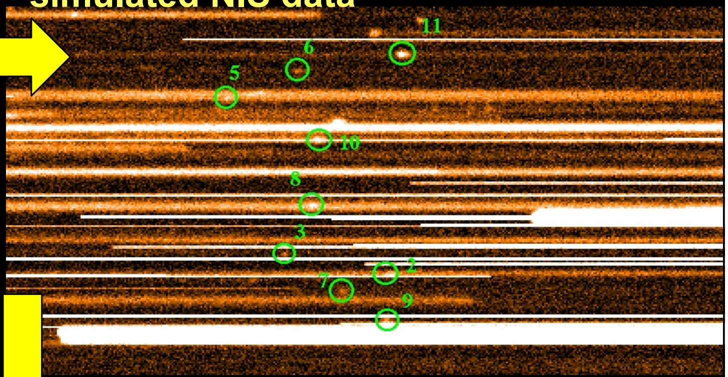


λ/Δλ=500
1-2 μm
FoV=0.5 $deg^2$

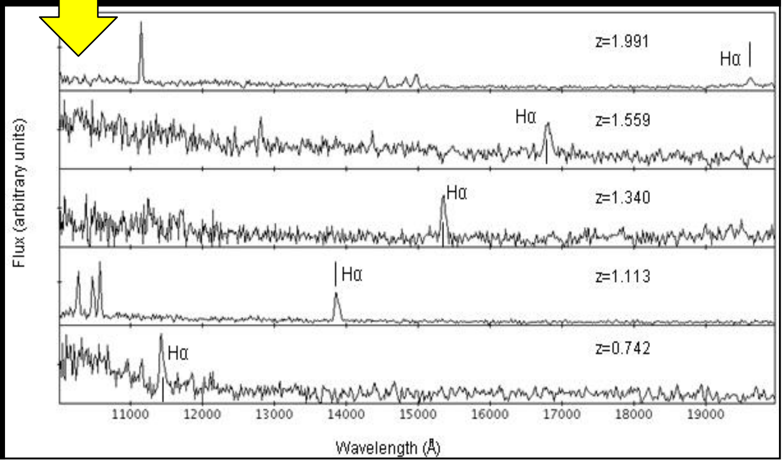
# Slitless spectroscopy (baseline)

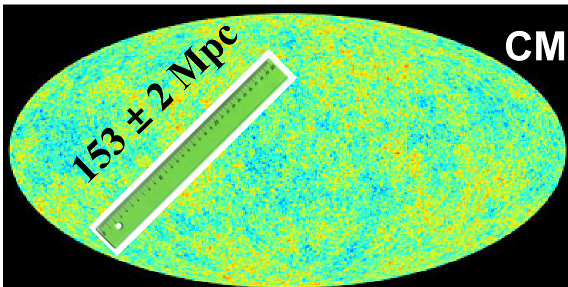



simulated NIS data



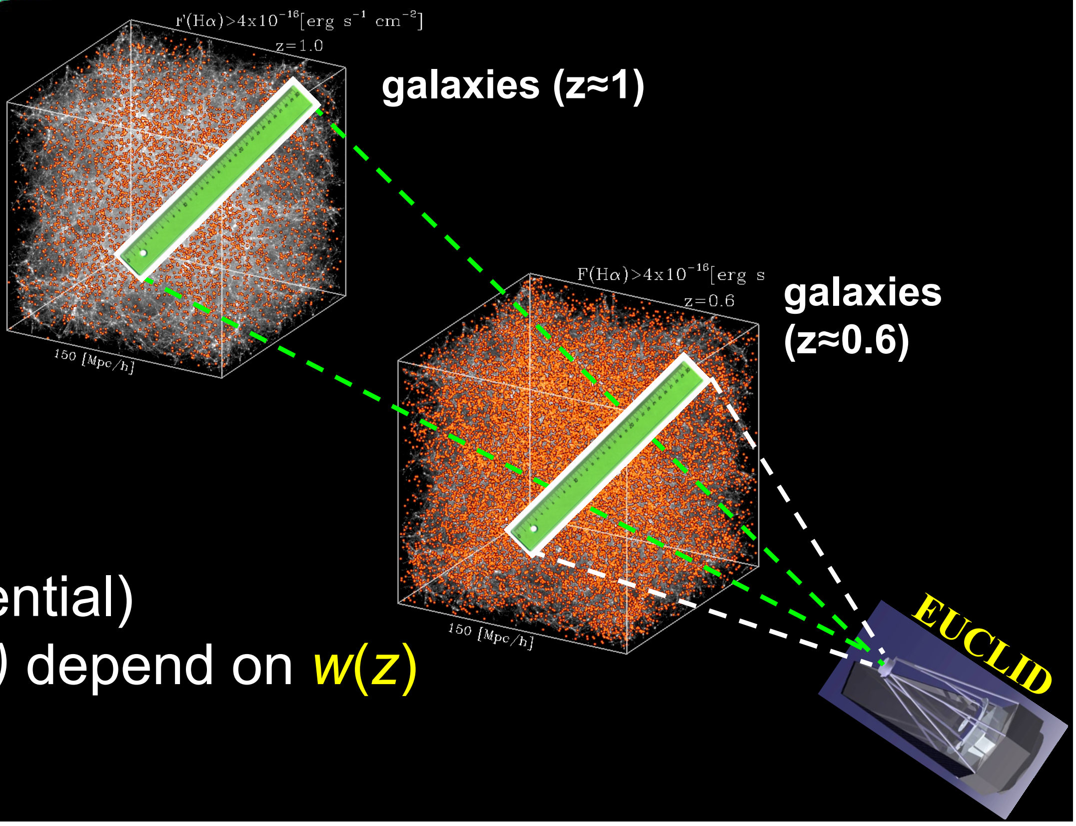

- Star-forming galaxies
- 0.5<z<2 (Hα)
- $F_{line}$> 4x$10^{-16}$ erg/s/$cm^2$ (H<19.5)
- $\sigma_z \leq 0.001(1+z)$
- Redshift success rate ≥ 50%
- N(gal) ≈ 7 x $10^7$
- Sky coverage = 20,000 $deg^2$
- Mission duration ≤ 5 years



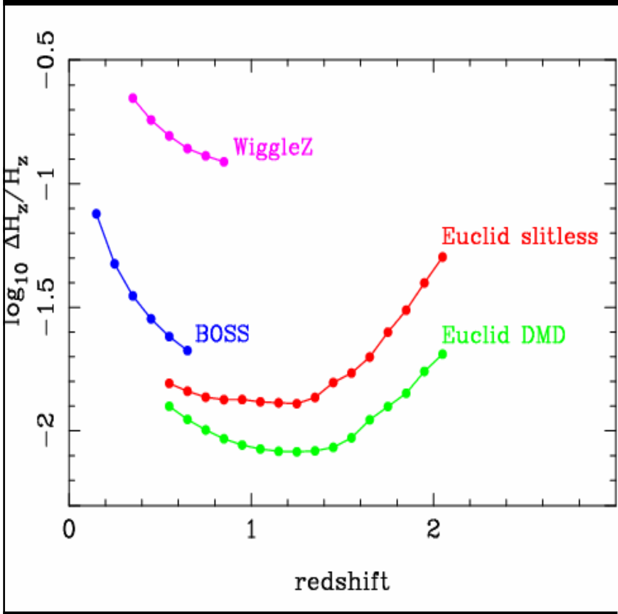



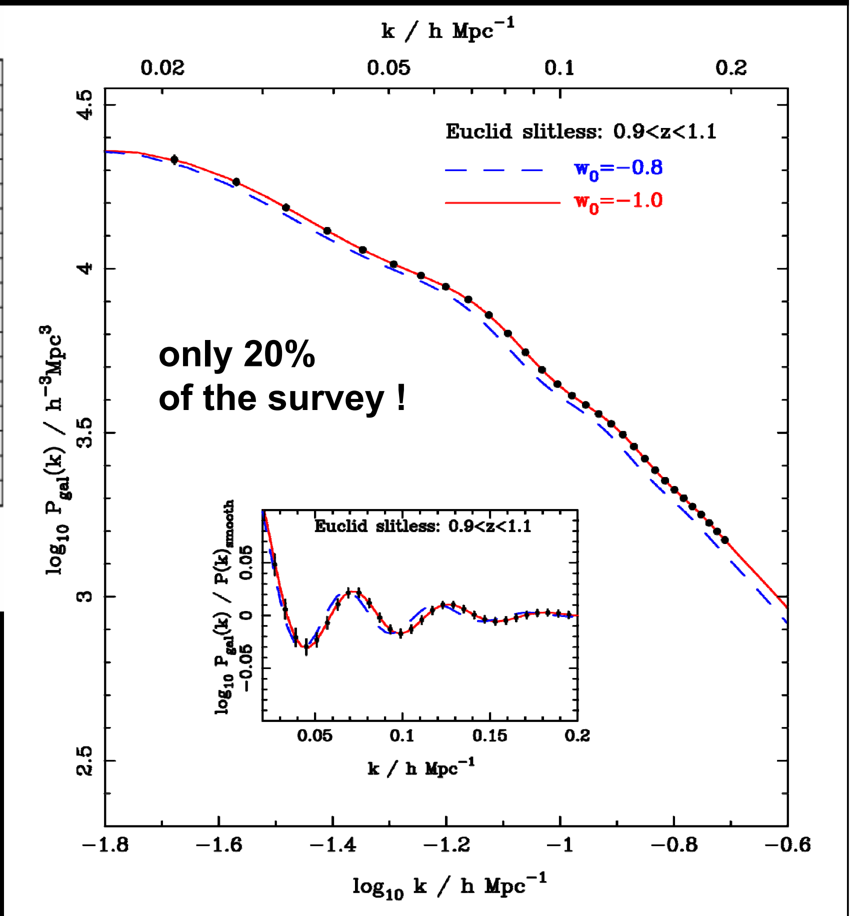

CMB (z≈1000)


# Baryonic Acoustic Oscillations (BAO)




- $H(z)$ (radial)
- $D_A(z)$ (tangential)
- $H(z)$ & $D_A(z)$ depend on $w(z)$



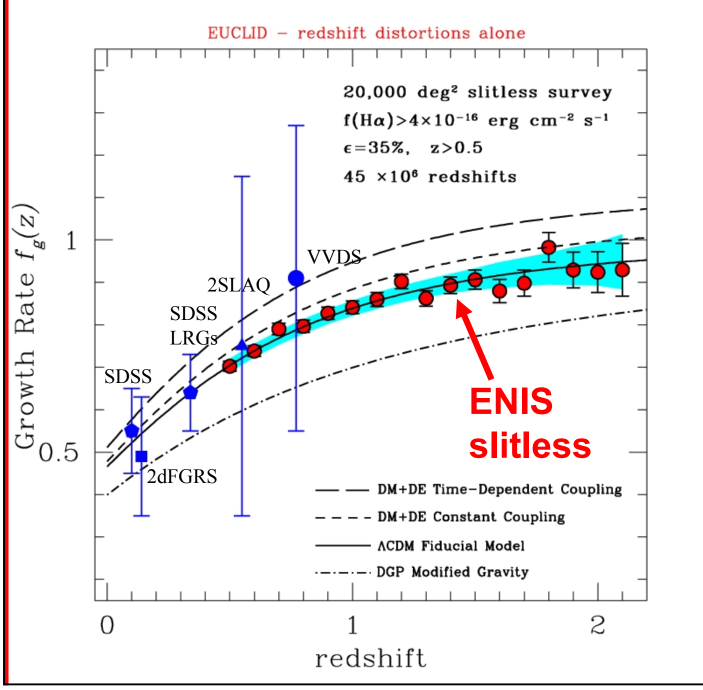




- $V_{eff} \approx 19\ h^{-3}\ Gpc^3$ ≈ 75x larger than now (i.e. SDSS) !
- $dw_p$, $dw_a$ = 2%, 17% (with Planck) (FoM≈300)
- FoM(imaging+spectroscopy+Planck)≈ 1500 (150x better than now !)

# More cosmology with the ENIS dataset

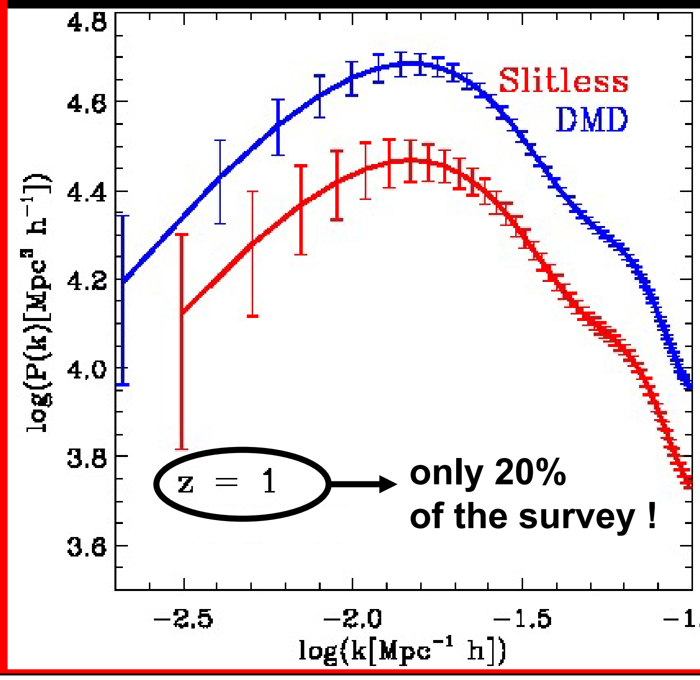
## Redshift Space Distortions

Anisotropy of radial vs tangential clustering
Impossible with photometric redshifts !
Test of Modified Gravity theories
Break degeneracies for models with same H(z)

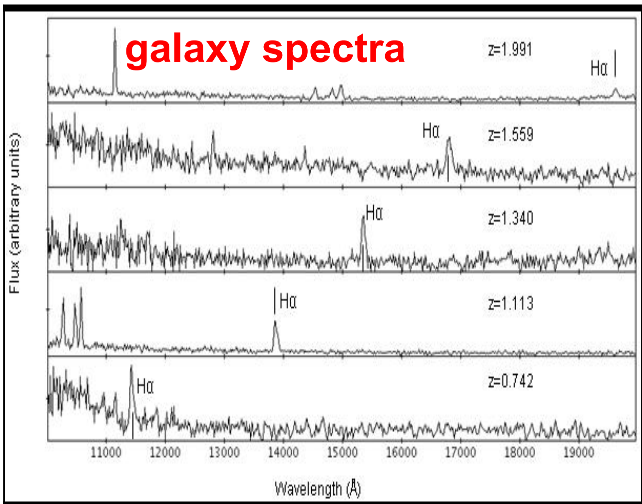



## Full Power Spectrum P(k)

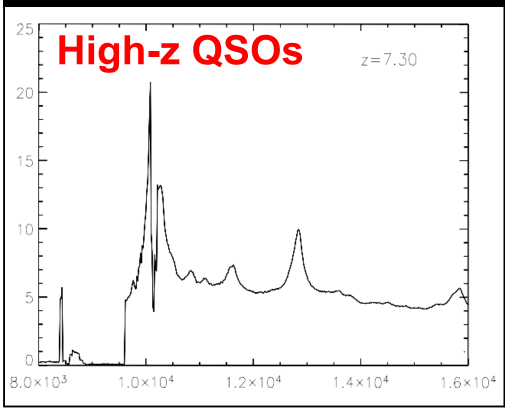
Primordial fluctuations
Models of inflation
Complementary to CMB

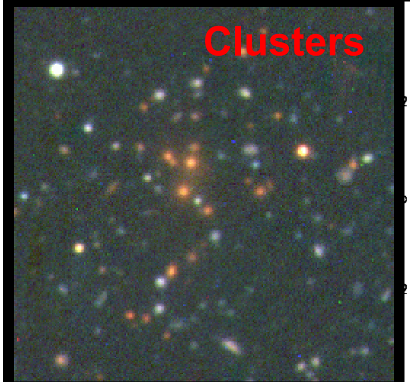


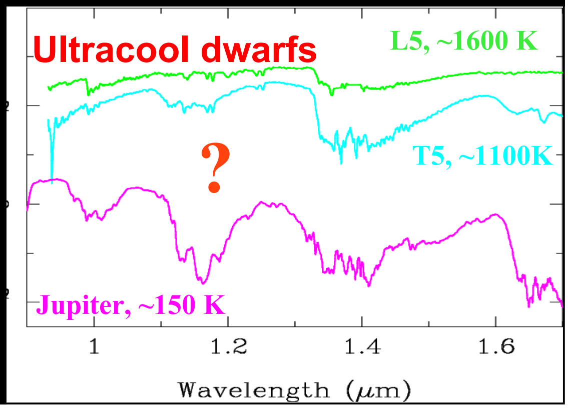
# Immense Legacy Value !

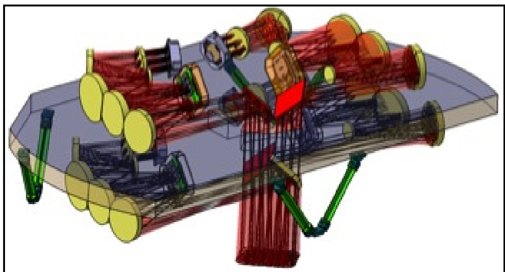


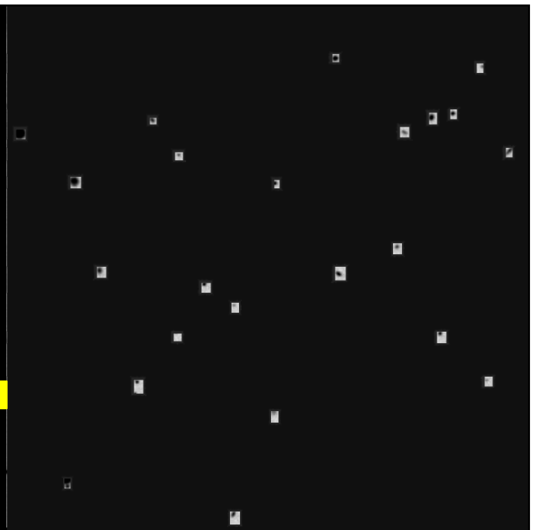

- ≈70 million galaxies & AGNs: >1000x more redshifts than now at z ~1 and >70x than SDSS !
- Statistical studies with unprecedented statistics
- ≈ 10,000 clusters of galaxies at z < 1
- Clustering and halo statistics
- The largest unbiased survey for high-z QSOs
- Most luminous objects at z > 7 in *Deep Survey*
- Our Galaxy (ultracool dwarfs, IMF…), **+GAIA**
- **Synergies: VIS/NIP, multi-λ surveys, JWST**



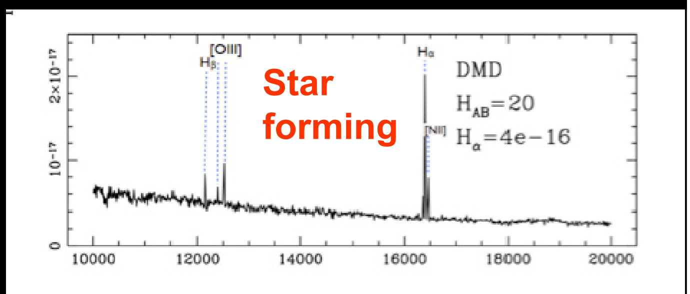



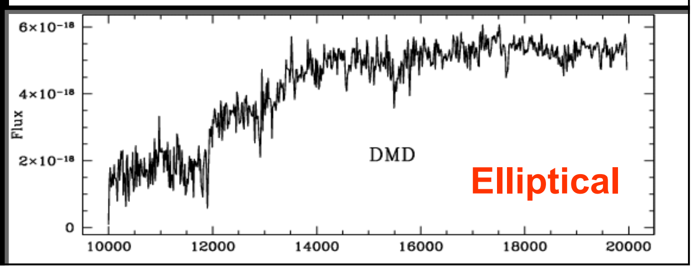



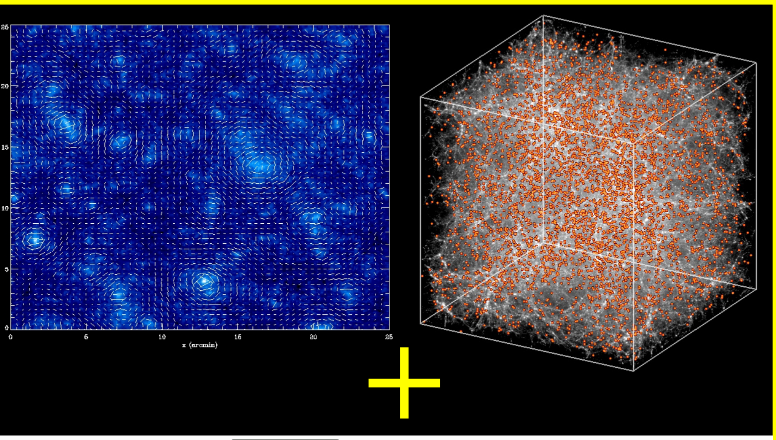
## DMD "slit" spectroscopy (optional)

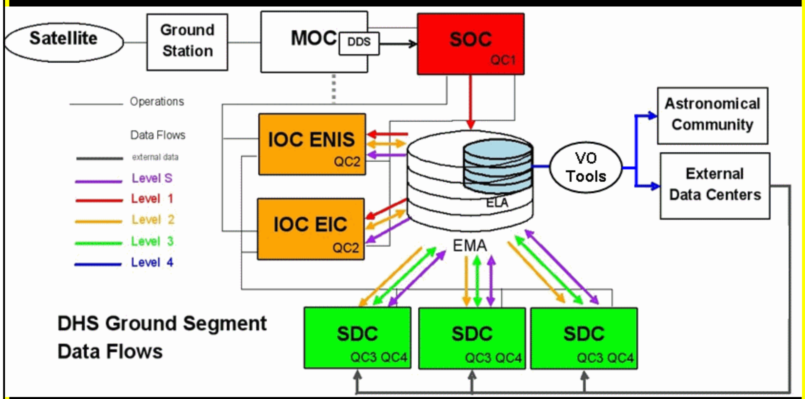



- Deeper spectra (H<22)
- All galaxy types (+E/S0)
- +Clusters at z>1
- N(gal) ≈ $2\times10^{8}$
- 0 < z < 2.5 (Wide Survey)
- $V_{eff}$ = 50 $h^{-3}$ $Gpc^{3}$
- >$10^{6}$ galaxies at 2<z<10 (Deep Survey)
- Extra gain of cosmology & legacy value



# Why EUCLID ?

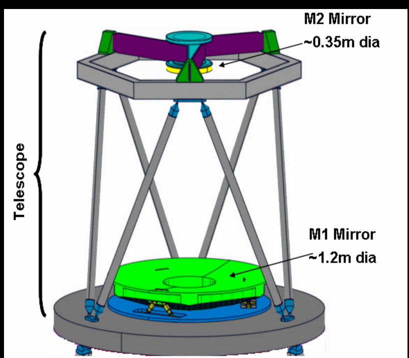


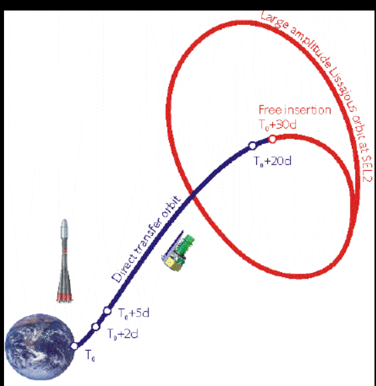


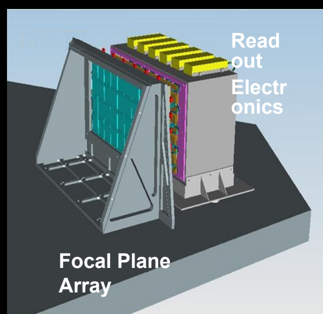

- **"The" high precision Dark Energy & Cosmology mission**
- **Essential and unbeatable synergy of imaging + spectroscopy:**
  - control of systematic errors
  - complementary mapping of the same large scale structure
  - complementary tests of Gravitation
  - dark vs luminous matter clustering
- **Immense legacy value**
- **EUCLID (ima+spec) will impact the whole astrophysics and cosmology for decades to come**

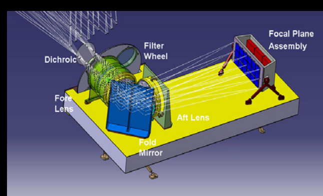
# Mission Implementation

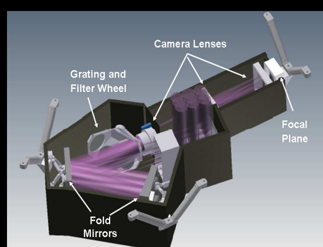
**David Lumb, ESTEC SRE-PA**



# Mission Introduction - Requirements

*Driving Science Requirements*

**Wide Extragalactic Survey**
**20 000 °²**

**Properly Sample Galaxies**
**PSF <0.2 arcsec**
**Ellipticity < 20%**
**Stable <0.02% rms**
**Red shifts** $\sigma_z/(1+z) \leq 0.001$

**VIS, NIP imaging instruments**
**NIS spectrometer**
**Same FOV & Dithered**

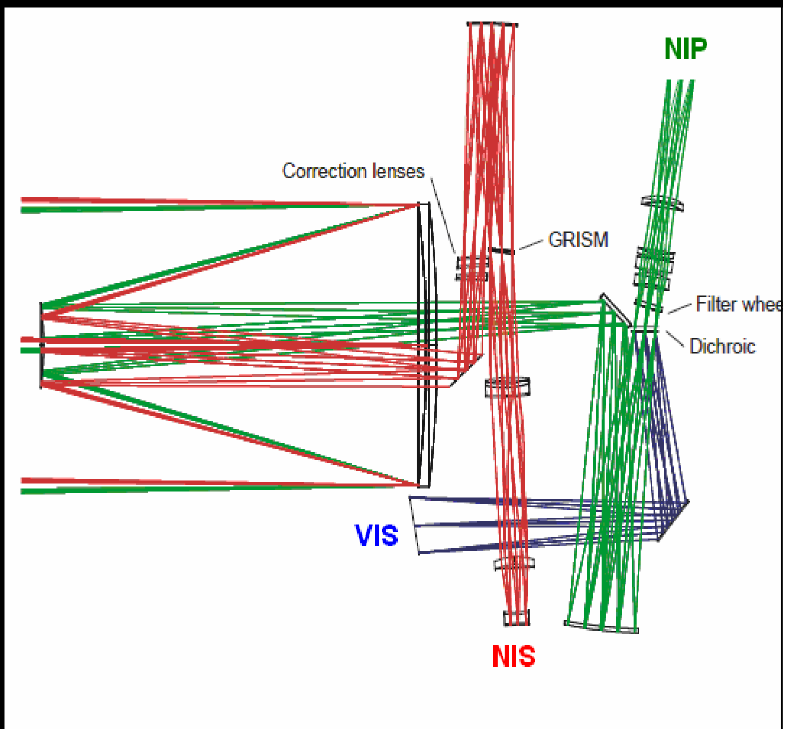
*System Requirements*

**L2 orbit**
**4.5 yrs Science mission**
**Step and Stare observation strategy**
**850Gbit/day = K band Cebreros**
**Pointing Stability**
**RPE < 25mas (500seconds)**
**APE < 10 as**
**AME < 100mas**
**36 CCDs and 26 NIR arrays**



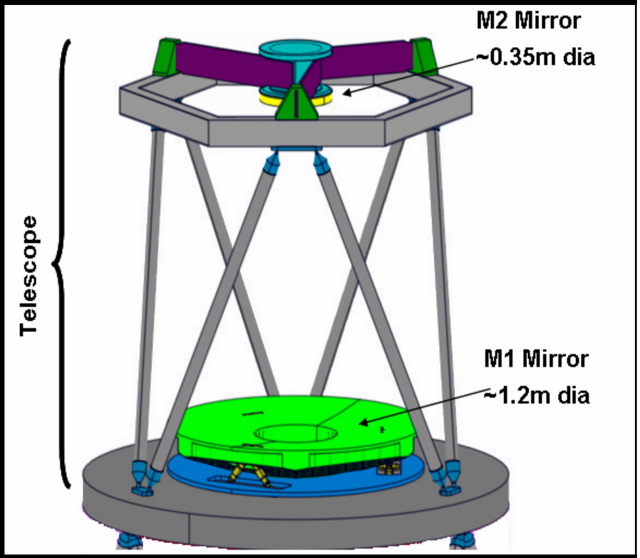
# Telescope ( 1 / 2 )

- **High resolution imaging across a wide waveband, simultaneously with a spectroscopic channel**
- **Similar fields of view with >0.5 degree², and focal scale tuned to existing CCD and NIR detectors**
- **A common design provided by ESA SRE-P for both industries and consortia**
- **Teams arranged folding to accommodate a compact Payload Module**



# Telescope (2 / 2 )

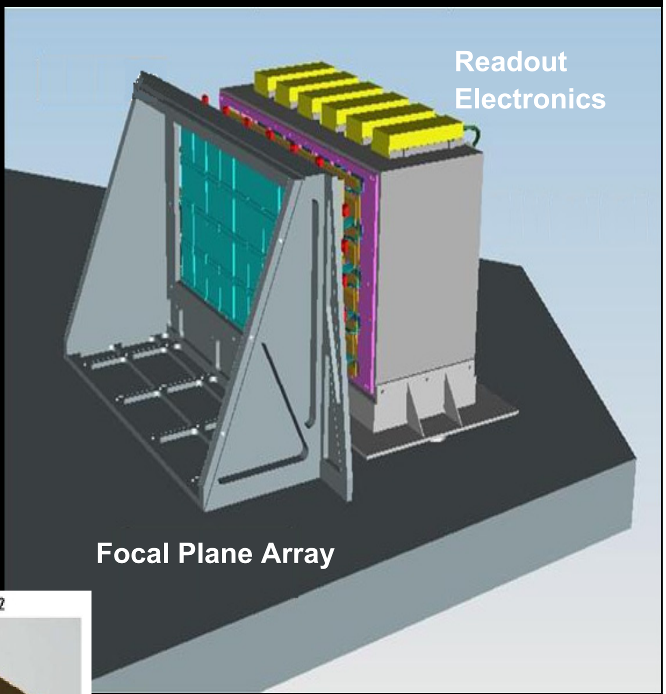
- A **1.2m diameter** Korsch-type telescope with diffraction limited imaging performance
- One industry solution is **SiC** (at 150K) passive thermal control
- Complementary approach uses actively controlled **Zerodur** at the maximum temperature (240K) for acceptable internal background
- Stability **~20μm** on focus required for PSF stability ( **~10's mK** )






# VIS

- Part of Weak Lensing Science package
- 1° x 0.5 ° field of view covered by 36 CCDs (*e2v CCD203 heritage Solar Dynamics Observer)*
- Broad **r, i, z** waveband (550-920nm)
- 150K passively cooled
- Each field covered by 4 exposures of ~500s and small spacecraft dither manoeuvre to fill gaps
- **0.1 arcsec pixels** to over-sample PSF
- Prototype proximity electronics development already started

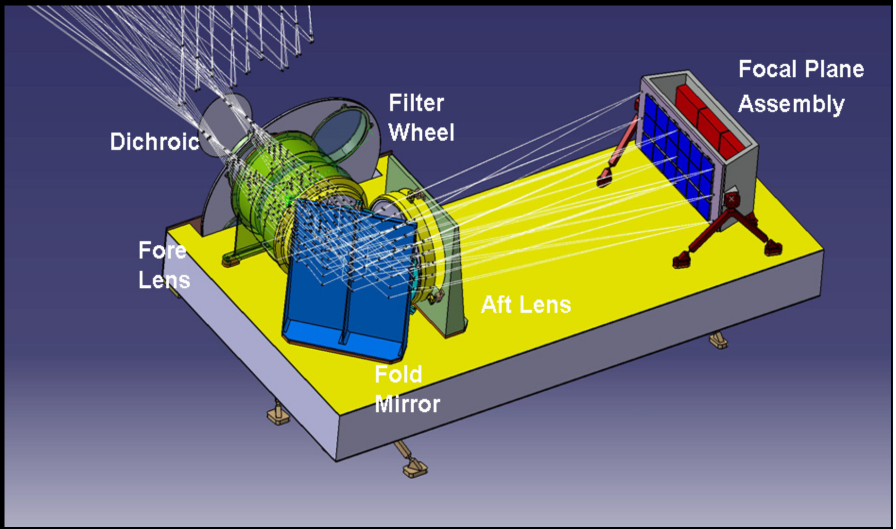




*Existing 4k x 4k*

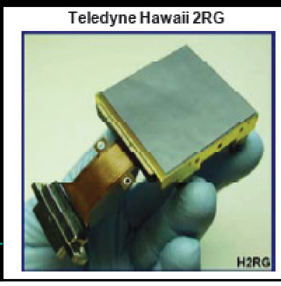
# NIP

- **Also part of Weak Lensing Science package**
- **1° x 0.5 ° field of view co-aligned with VIS**
- **Covered by 18 NIR detectors (*Teledyne Hawaii HgCdTe*)**
- ***0.3 arcsec pixels***
- ***Passively cooled ~100K***
- **3 Filter bands Y, J, H each observed ~100s during each of the 4 exposures of VIS**




*Existing*

*2k x 2k*

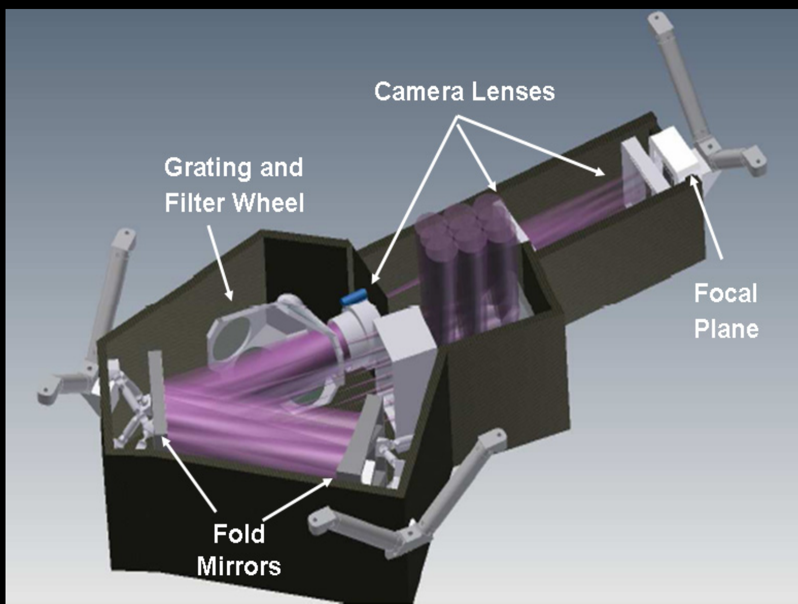



– **Provides the Near-IR photometric z that is infeasible from ground and essential for tomography**



# NIS

- **Slitless spectrometer, R~500 from 1 to 2 μm**
- **Field of View comparable with Imaging Channel (but displaced ~1.5°)**
- **2 pixels/resolution element requires 2x4 Hawaii detector arrays**
- **Passive cooled to ~100K**
- **Cryogenic lenses and filter wheel with JWST heritage**
- **Source confusion minimised with grating orientation changed per field dither**



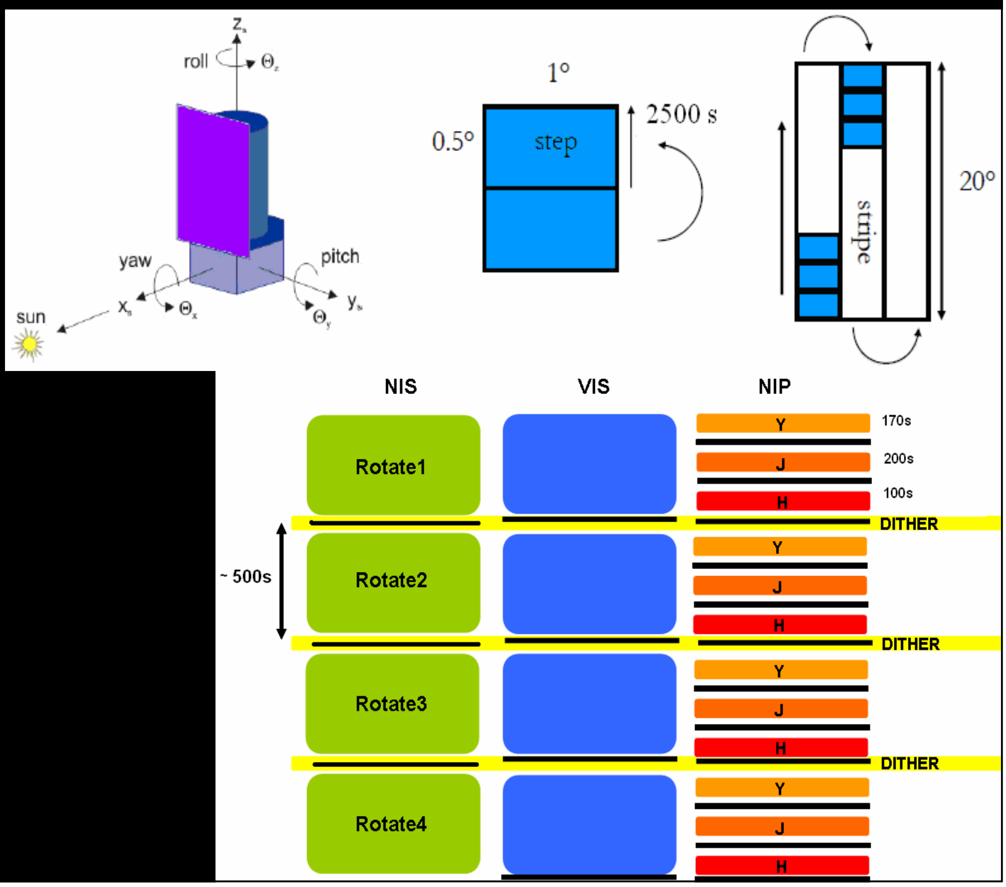
# System Design – (1) Pointing & Stability

- Relative Pointing Error budgeted as **25 marcsec/ 500s** exposure
- Requires a Fine Guidance Sensor (*in VIS focal plane*) and low noise actuators (*GAIA cold gas or DLR magnetic RW*)
- Absolute Pointing Acquisition **<10 arcsec** to guarantee correct field overlaps (*Standard state of art star tracker*)
- Absolute Measurement Accuracy **0.1 arcsec** – to ensure zero wavelength scale (*combination of star trackers and VIS science data stream)* but needs budget for VIS-to-NIS stability



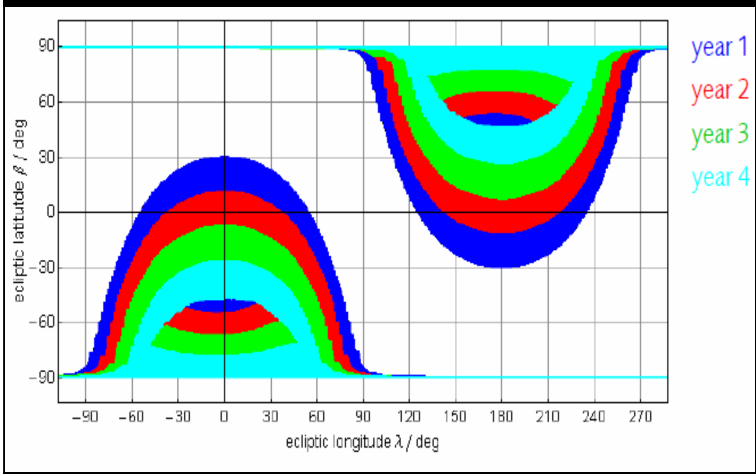
# System Design – (2) Sky Scanning Strategy

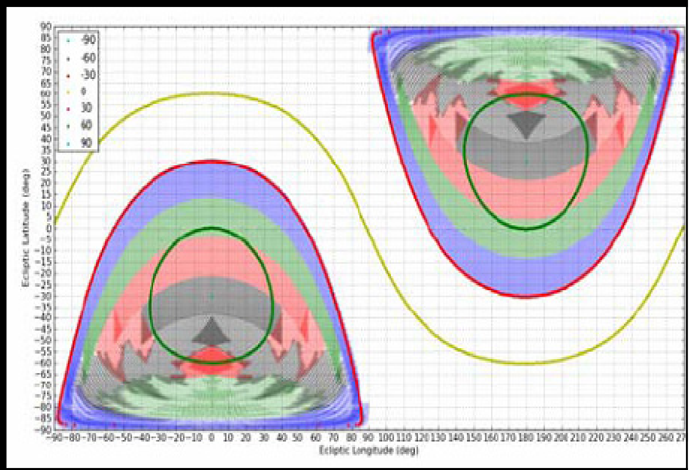
- Keep Sun Aspect Angle <30°, pointing scans orthogonal to the sun direction
- Each field observed **~2500s**, then *step and stare* along a strip **20°/day**
- Each field composed of **4** ***dithered*** pointings to overlap the chip gaps



# System Design – (3) Mission Profile & Sky Coverage

- Launch with Soyuz – Fregat from Kourou. Direct injection SEL2 (thermally stable). Sized for 5 years science mission
- Both industries confirm complete coverage of 20,000 sq deg assuming reasonable efficiency of dither & slews ~75%

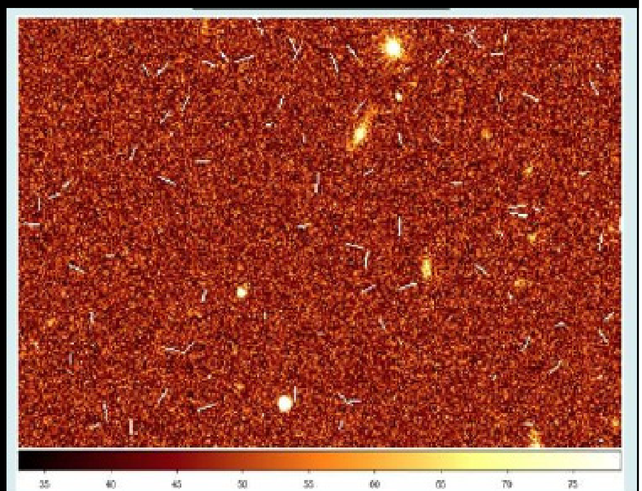




# System Design – (4) Data

- **VIS 600Mpixels**, all data sent to ground for CR rejection and processing. Compression tested ~2.8 lossless with RICE algorithm
- NIP and NIS data are sampled during accumulation for noise reduction and CR removal *comparable GAIA DHS*
- **100Mpixels total in NIR** ( but multiple filters and lower compressibility)
- **36 Fields/day = 850 Gbit** compressed




- K band (26GHz) from L2 - first ESA mission & need to upgrade ground segment & on-board transponders (in progress)
- Rapid quick-look check for data quality (reschedule lost fields while SAA is within bounds)

# GS / Distributed Mission Archive 5Pb

- Allows quality control at all levels
  - Operational feedback & monitoring to SOC/MOC
  - all aspects propagation as systematic errors ← IOCs ↔ SDCs
- Connect instrument & science teams
  - Exchange & verify results
  - Connect to Ground based observations & external data – *agreements with (e.g.) PanStarrs / DES*
  - Connect simulated data
- Euclid Legacy Archive
  - Science ready data -> VO
  - Re-processing raw data to the ELA – additional studies
- Building upon experience in ESA missions
  - Planck and Gaia, but also XMM and Integral



# Budgets

| | *Mass (kg)* | *Power (W)* |
|---|---|---|
| Payload Module | 855 | 350 |
| Service Module | 691 | 595 |
| Propellant | 150 | |
| Adapter / or Power losses | 100 | 58 |
| Margin 20%) | 309 | 201 |
| Total | 2105 | 1204 |

## Radiometric Performance

| | VIS | NIP | NIS |
|---|---|---|---|
| Plate Scale | 0.1” | 0.3 ” | R=500 2pixels |
| Magnitude (AB) | 24.5 | 24 5 | 19.1 (4 $10^{-16}$ erg.$cm^{-2}$.$s^{-1}$) |
| SNR | 14.3 | 7.1 | 5 (spectral element) |
| Radiometric aperture | 1.3” | 0.5 ” | 3×5 pixels |

# Review Recommendations

- **Mission considered feasible**
- **Schedule too optimistic with lean development model assumptions**
- **Mass is at limit of Soyuz & design uncertainties of payload demand higher margin**
- **DMD slit spectrometer not compatible with M-class TRL**
- **Attention should be given to : *NIR detectors procurement, improved interface definition for testing, pointing performance***
- **Lacking thermomechanical analysis to confirm the stability w.r.t. sun angles (scanning law)**