Euclid and WFIRST-AFTA: NASA’s Dark Energy Program

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Euclid: Mapping the Geometry of the Dark Universe

2004: Dark Universe Mission Theme proposed to ESA’s Cosmic Vision programme
Oct 2007: **DUNE** and **SPACE** jointly selected for ESA Assessment Phase
April 2010: Single Euclid Consortium formed
2010-2011: Definition phase
July 2011: Red Book – Final Euclid Proposal
Oct 2011: **Cosmic Vision Approval of Euclid**
Jan 2013: NASA joins, nominates 40 US scientists for 1200+ member Euclid Consortium
2012-2020: Implementation phase
2020: launch
2020-2026: science operations
Goals of Euclid

Euclid will explore the nature of Dark Energy and Dark Matter by:

- Measuring the DE equation of state to FoM > 500: e.g. measuring $w_0$ and $w_a$ to a precision of 2% and 10% respectively, using both expansion history and structure growth.

- Measuring the growth factor exponent $\gamma$ with a precision of 2%, to distinguish General Relativity from modified-gravity theories.

- Testing the Cold Dark Matter paradigm for structure formation, and measuring the sum of the neutrino masses to a precision better than 0.02 eV (when combined with Planck data).

- Improving by a factor of 20 the determination of the initial condition parameters, compared to Planck alone.

Responsive to scientific goals outlined in NWNH Panel Reports:

- How did the universe begin?
- Why is the universe accelerating?
- What is dark matter?
- What are the properties of neutrinos?
Euclid Concept

Euclid is optimized for two complementary cosmological probes:

— Weak Gravitational Lensing
— Galaxy Clustering (Baryonic Acoustic Oscillations & Redshift Space Distortions)

Additional probes: galaxy clusters, integrated Sachs-Wolfe effect on microwave background

Euclid will survey 15,000 square degrees of the sky

— Imaging and photometry:
  • High precision visible imaging (galaxy shapes)
  • Near-Infrared Photometry (for photo-z)
— Near Infrared Spectroscopy (galaxy redshifts)
— Euclid is not optimized for supernova searches
The Euclid Mission

- 6-year science mission, in orbit at L2
- Telescope: three mirror astigmat, 1.2m primary mirror
- 0.5 deg$^2$ field of view for Visible and Near-IR imaging

Euclid’s two instruments will measure ~2 billion galaxy shapes and ~50 million spectra (depending on luminosity function)

- VIS: Visible imaging channel:
  - 36 CCD detectors, 0.1” pixels, 0.16” PSF FWHM; very broad band r+i+z (0.5-0.9µm), to measure galaxy shapes
- NISP: Near Infrared channel:
  - 16 HgCdTe detectors, supplied by NASA, 1-2µm:
    - Photometry: 0.3” pixels, 3 bands Y,J,H: for photo-z’s, when combined with visible colors from the ground
    - Slitless spectroscopy, R=250: for galaxy redshifts
Survey Data Releases

• Q2 2020 launch, ~6 months on-orbit verification, followed by 6 years of science survey operations

• “Quick release” of small survey areas at 14, 38, 62, 74 months after start of survey
  • Small areas only, not suitable for cosmology

• Survey will be released in stages:
  • 26 months after start (2500 deg$^2$, ~2023)
  • after 50 months (7500 deg$^2$, cumulative, ~2025)
  • after 86 months (15000 deg$^2$, cumulative)

• Released survey data will be accessible to the entire science community
## Euclid Science Reach

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modified Gravity</th>
<th>Dark Matter</th>
<th>Initial Conditions</th>
<th>Dark Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$m_{\nu}$/eV</td>
<td>$f_{NL}$</td>
<td>$w_p$</td>
</tr>
<tr>
<td>Euclid Primary</td>
<td>0.010</td>
<td>0.027</td>
<td>5.5</td>
<td>0.015</td>
</tr>
<tr>
<td>Euclid All</td>
<td>0.009</td>
<td>0.020</td>
<td>2.0</td>
<td>0.013</td>
</tr>
<tr>
<td>Euclid+Planck</td>
<td>0.007</td>
<td>0.019</td>
<td>2.0</td>
<td>0.007</td>
</tr>
<tr>
<td>Current at 9/2011</td>
<td>0.2</td>
<td>0.58</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Euclid, later est.</td>
<td>0.04</td>
<td>0.02</td>
<td>$&lt;0.02$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>Improvement Factor</td>
<td>&gt;5</td>
<td>30</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

**Euclid Red Book** :

[sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983](http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983)
WFIRST-AFTA: Wide Field Infrared Survey Telescope – Astrophysics Focused Telescope Asset

- WFIRST, a near-infrared ‘dark-energy+’ mission, was the top large space priority for the Astro2010 Decadal Survey
- WFIRST-AFTA uses a 2.4 m telescope from another government agency
- WFIRST-ATFA is “a wide-field Hubble”, with a 0.28 deg\(^2\) field of view (larger than the full Moon, 100xJWST), infrared images almost as sharp as Hubble’s visible images, and both IFU and grism spectroscopy.

See the WFIRST-AFTA Science Definition Team’s final report at http://wfirst.gsfc.nasa.gov/
WFIRST-AFTA: beyond a successful Euclid mission

- WFIRST-AFTA is a larger telescope with finer resolution: 0.1” near-IR pixels (vs 0.3” for Euclid). Galaxy shapes measured in IR trace older stars; using 3 bands reduces systematic errors for weak lensing.

- AFTA Reference Mission surveys 2000 deg² at high Galactic latitude, looking ten times fainter (27 AB-mag) to image 3x as many galaxies per arcmin² – reduces statistical noise, the main uncertainty in BAO estimates.

- WFIRST-ATFA will sweep selected sky areas every 5 days to catch supernova explosions at high redshift, to z~1.7.

- Spectroscopy with IR grism (R~600) for ~20M galaxy redshifts; IFU (3”x3.15”, 0.6µm-2µm, R~100) for supernova followup.
ESANASA Partnership

- **ESA responsibilities**
  - Mission, Spacecraft, Launch vehicle, Ground Data System

- **Euclid Consortium (EC) responsibilities**
  - Mission, 2 instruments, Science Data Centers, Science

- **ESA/NASA MOU signed January 10, 2013**
    - Teledyne H2RG HgCdTe detector, SIDECAR ASIC, and flexible cryogenic cable. (16 flight models, 4 flight spares)
  - JPL Project Office (PM Ulf Israelsson, PS Michael Seiffert)
  - Detector characterization at GSFC Detector Characterization Lab (PCOS Program Office Mission Manager Tom Griffin)
  - NASA nominated 40 new EC members, competitively selected ($50M lifetime science team cost); US Science Lead Jason Rhodes
NASA: Euclid Science Teams Competition

• ESA-NASA MoU provided for NASA to nominate
  • 40 members to Euclid Consortium (EC)
  • 1 member of the Euclid Science Team (EST)
  • 1 member of the Euclid Consortium Board (ECB)

ROSES competition for funded teams:
  proposals due 31 August 2012; selections 7 December 2012

Jason Rhodes (JPL) selected for EST and ECB

Total of 3 science proposals selected: PIs Rhodes, Kashlinsky, Chary

Join 14 members of US community already part of Euclid Consortium

54 US scientists are now full members of the Euclid Consortium

IPAC is studying NASA contributing a US Euclid Science Data Center, this center is NOT included in ESA-NASA MoU, expect decision in 2014
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modified Gravity</th>
<th>Dark Matter (m_ν/eV)</th>
<th>Initial Conditions (f_{NL})</th>
<th>Dark Energy (w_p, w_a)</th>
<th>FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euclid Primary</td>
<td>0.01</td>
<td>0.027</td>
<td>5.5</td>
<td>0.015, 0.150</td>
<td>430</td>
</tr>
<tr>
<td>Euclid All</td>
<td>0.009</td>
<td>0.020</td>
<td>2.0</td>
<td>0.013, 0.048</td>
<td>1540</td>
</tr>
<tr>
<td>Euclid+Planck</td>
<td>0.007</td>
<td>0.019</td>
<td>2.0</td>
<td>0.007, 0.035</td>
<td>4020</td>
</tr>
<tr>
<td>Current at 9/2011</td>
<td>0.2</td>
<td>0.58</td>
<td>100</td>
<td>0.1, 1.5</td>
<td>~10</td>
</tr>
<tr>
<td>Improvement Factor</td>
<td>30</td>
<td>30</td>
<td>50</td>
<td>&gt;10, &gt;50</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

From Euclid Red Book:
sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983
Euclid Mission: Red Book

<table>
<thead>
<tr>
<th>SURVEYS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wide Survey</strong></td>
<td>15,000 deg$^2$ Step and stare with 4 dither pointings per step.</td>
</tr>
<tr>
<td><strong>Deep Survey</strong></td>
<td>40 deg$^2$ In at least 2 patches of &gt; 10 deg$^2$ 2 magnitudes deeper than wide survey</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PAYLOAD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope</strong></td>
<td>1.2 m Korsch, 3 mirror anastigmat, f=24.5 m</td>
</tr>
<tr>
<td><strong>Instrument</strong></td>
<td>VIS NISP</td>
</tr>
<tr>
<td><strong>Field-of-View</strong></td>
<td>0.787×0.709 deg$^2$ 0.763×0.722 deg$^2$</td>
</tr>
<tr>
<td><strong>Capability</strong></td>
<td>Visual Imaging NIR Imaging Photometry NIR Spectroscopy</td>
</tr>
<tr>
<td><strong>Wavelength range</strong></td>
<td>550–900 nm Y (920-1146nm), J (1146-1372 nm) H (1372-2000nm) 1100-2000 nm</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>24.5 mag 10σ extended source 24 mag 5σ point source 24 mag 5σ point source 24 mag 5σ point source 3 $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ 3.5σ unresolved line flux</td>
</tr>
<tr>
<td><strong>Detector Technology</strong></td>
<td>36 arrays 4k×4k CCD 16 arrays 2k×2k NIR sensitive HgCdTe detectors</td>
</tr>
<tr>
<td><strong>Pixel Size</strong></td>
<td>0.1 arcsec 0.3 arcsec 0.3 arcsec R=250</td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td></td>
</tr>
</tbody>
</table>

Ref: Euclid RB arXiv:1110.3193

~2 billion galaxy shapes and ~50 million spectra
A 2.4m telescope offers sensitive sharp images at optical and near IR wavelengths across a wide field. With higher resolution and sensitivity in the near IR than planned for the early WFIRST designs, AFTA will be an even more powerful and compelling mission.

AFTA offers both a rich program of community observations and directed programs that address fundamental astronomy questions:
• What is dark energy?
• Is our solar system special?
• Are the planets around nearby stars like those of our own solar system?
• How do galaxies form and evolve?
WL: A completely different regime

- WL with AFTA survey would reach $>80$ galaxies per square arcminute — vs $\sim30$ w/Euclid, and even fewer from the ground
- With a deeper survey AFTA could reach HUDF depths of $>300$ galaxies per square arcminute

This is a fundamentally different WL regime that is not possible from the ground or with a 1.3 meter class telescope due to PSF size.

- Does not necessarily help with DE FoM (wide$>$deeper for FoM)
- Much better calibration data
- Much better for understanding dark matter
Channel field layout for AFTA-WFIRST wide field instrument

0.788° wide
0.427° high

X gaps 2.5mm
Y gaps 8.564mm

18 NIR detectors
0.11 arcsec/pixel 0.28 deg²

Moon (average size seen from Earth)

Detector Layout on Sky

Slitless spectroscopy with grism in filter wheel
R_q ~ 100 arcsec/micron

Each square is a H4RG-10
4k x 4k, 10 micron pitch
288 Mpxels total
## WFIRST-AFTA Extragalactic Surveys

<table>
<thead>
<tr>
<th>Implementation</th>
<th>WFIRST DRM1</th>
<th>WFIRST DRM2</th>
<th>AFTA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Imaging Survey</strong>*</td>
<td>1.3 m unobs</td>
<td>1.1 m unobs</td>
<td>2.4 m obs</td>
</tr>
<tr>
<td>[4 filters for all; depths are 5σ isolated pt src]</td>
<td>36 H2RG 0.18”/p</td>
<td>14 H4RG 0.18”/p</td>
<td>20 H4RG 0.0975”/p</td>
</tr>
<tr>
<td>0.92—2.40 μm</td>
<td>0.92—2.40 μm</td>
<td>0.92—2.17 μm</td>
<td></td>
</tr>
<tr>
<td>26.0—26.2 mag AB</td>
<td>25.8—26.0 mag AB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2800 deg²/yr</td>
<td>2900 deg²/yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EE50 = 0.15—0.21”</td>
<td>EE50 = 0.18—0.25”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.92—2.17 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26.9—27.3 mag AB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1080 deg²/yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak Lensing</td>
<td>30, 33, 32 gal/am²</td>
<td>24, 26, 25 gal/am²</td>
<td>79, 82, 72 gal/am²</td>
</tr>
<tr>
<td>[reddest 3 filters]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redshift Survey</td>
<td>z = 1.28—2.66</td>
<td>z = 1.59—2.66</td>
<td>z = 1.13—2.20</td>
</tr>
<tr>
<td>[≥7σ Hα detections]</td>
<td>4900 gal/deg²</td>
<td>2900 gal/deg²</td>
<td>4900 gal/deg²</td>
</tr>
<tr>
<td></td>
<td>2900 deg²/yr</td>
<td>4400 deg²/yr</td>
<td>4000 deg²/yr</td>
</tr>
</tbody>
</table>

* AFTA could in principle support an accelerated imaging mode matching the WFIRST DRM1 survey rate of 2800 deg²/yr. This reaches depth of 25.8—26.0 mag AB and 26/31/32 galaxies per arcmin². This survey is heavily read noise limited (90 s exposures) so may not be the best use of a big telescope.
**Wide-Field Instrument**

- Imaging & spectroscopy over 1000s sq deg.
- Monitoring of SN and microlensing fields
- 0.7 – 2.0 micron bandpass
- 0.28 sq deg FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 4 filter imaging, grism + IFU spectroscopy

**Coronagraph (study option)**

- Imaging of ice & gas giant exoplanets
- Imaging of debris disks
- 400 – 1000 nm bandpass
- $10^{-9}$ contrast
- 100 milliarcsec inner working angle at 400 nm
Frontiers of Knowledge

As envisioned in NWNH, AFTA uses multiple approaches to measure the growth rate of structure and the geometry of the universe to exquisite precision. These measurements will address the central questions of cosmology.

Imaging Survey
- Map over 2000 square degrees of high latitude sky
- 500 million lensed galaxies (70 arcmin$^2$)
- 40,000 massive clusters

Supernova Survey
- wide, medium, & deep Imaging + IFU spectroscopy
- 2700 type Ia supernovae
- $z = 0.1$–1.7

Trace the Distribution of Dark Matter Across Time

Why is the universe accelerating?
- What are the properties of the neutrino?
- What is Dark Matter?

Measure the Distance Redshift Relationship

Spectroscopic Survey
- 20 million H$_\alpha$ galaxies, $z = 1$–2
- 2 million [OIII] galaxies, $z = 2$–3

Multiple measurement techniques each achieve 0.1-0.4% precision