The cosmology mission of ESA's Euclid spacecraft

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I. THE Λ-CDM PARADIGM AND DARK ENERGY

At the heart of contemporary cosmology lies the accelerating cold dark matter paradigm (Λ-CDM), also referred to as the 'standard model of Big Bang cosmology' [1], which postulates the existence of dark energy and dark matter as large components of the Universe's energy makeup. Evidence for dark matter can be found in various astrophysical phenomena, including galaxy rotation curves, galaxy clusters, and the cosmic microwave background [2][3][4]. The centrepiece of this Λ-CDM model is the cosmological constant Λ, first introduced by A. Einstein in his field equations to obtain a static Universe model [5]. This constant is associated with the 'dark energy' in the Universe [6] and helps explain the accelerating nature of the expansion of the Universe that we measure. The need for this constant arises from Friedmann equation along with the fluid equation which suggests that the Universe should be contracting and falling into itself [7].

Many attempts have been made to investigate this parameter, with a prominent mission called 'Planck' launched by the European Space Agency (ESA) in years 2009-2013 which measured the relative density of dark energy as $\Omega_\Lambda = 0.686 \pm 0.020$ [8], meaning that the dark energy makes up around 68.6% of the energy in today's Universe.

II. EUCLID'S CORE SCIENTIFIC OBJECTIVES

To further refine the results and gain insight into the nature of our Universe, ESA devised a 'Cosmic Vision 2015-2025' program to advance the field of astrophysics, among which is the upcoming Euclid mission [9]. Euclid, developed by the European Space Agency (ESA) and the Euclid Consortium is a wide-angle space telescope launched on 1 July 2023. It belongs to the medium-class category with a budget cap of around 500 million euros. This mission aims to develop our understanding of the nature of the Universe by investigating four main themes [10]:

Firstly, the theory of dynamical dark energy will be investigated. This involves the understanding of whether dark energy evolves with the expansion of the Universe or remains constant in time. If this is the case, such dynamical dark energy could amplify the rate of the expansion of the Universe [11] and the cosmological 'constant' is not a constant value at all.

Secondly, the mission is designed to examine whether the Universe's apparent acceleration is due to the breakdown of General Relativity or cosmological assumptions. Modern cosmology relies on a set of assumptions, mainly the Cosmological Principle (CP), which states that our Universe is isotropic and homogeneous on large scales [12]. Data obtained from Euclid will be processed to determine if this, or breakdown of Einstein's geometric theory of relativity.

Furthermore, Euclid will pursue the information about nature of dark matter. This includes the mass scale of the neutrino - a particle that was thought to have no mass, but recent studies find that as it oscillates through its 'flavours', the neutrino changes its (non-zero) mass [13]. This is relevant to cosmology as the neutrino mass scale influences the cosmic structure formation, total mass-energy content of the Universe, therefore the expansion of the Universe. In addition to this, the mission also aims to investigate the number of relativistic species, as there are hints that there are more than three neutrino flavours [14].

Finally, another mission's outcome is the analysis of the power spectrum of 'primordial density fluctuations', and assessing whether they follow a Gaussian probability distribution. This would confirm or deny that the fluctuations are a result of random processes [15], and help advance the cosmological models of our Universe.

III. EXPERIMENTAL METHODOLOGIES

There are two main methods through which the Euclid mission plans to achieve its objectives:

Firstly, galaxy clustering, specifically utilizing baryon acoustic oscillations (BAO), as an experimental method. Galaxy clustering involves observing the distribution of galaxies in three dimensions, utilizing both their angular positions in the sky and their redshifts [16]. BAO, resulting from acoustic oscillations in the photon-baryon fluid at the time of recombination (an epoch when electrons and protons first formed electrically neutral hydrogen atoms) provide a standard ruler for cosmological measurements [17]. By analyzing the slight preference in co-moving length scale within the observed galaxy distribution, Euclid can infer their distances from us.

Moreover, Euclid uses weak lensing, also known as 'cosmic shear', to investigate dark energy and matter clustering. Weak lensing involves measuring the distortion of background galaxy images caused by foreground matter [18]. It uses the geometric weak lensing method, mapping foreground galaxies to estimate the mass on background galaxies to infer the cosmic expansion history [19]. However, the success of weak lensing as a method relies on accurate distance and shape measurements for all galaxies. This data is obtained through photometry, which measures the brightness of objects through filters sensitive to different wavelengths of light, which makes the redshift hard to infer. This is known as the 'photometric redshift challenge' and involves developing algorithms and machine learning techniques to analyze the patterns in the galaxies' light spectra and match them to known redshifts from spectroscopic observations [20].

IV. TECHNOLOGICAL ADVANCEMENTS

Positioned at the Sun-Earth second Lagrange point L2, Euclid is approximately 1.5 million km beyond Earth's orbit, and is expected to operate for at least six years [21]. Its payload had a mass of 2160kg, launched with the help of a Falcon 9 rocket from Cape Canaveral. The payload of Euclid included two primary instruments: the Visible Imaging Channel (VIS) and the Near Infrared Spectrometer and Photometer (NISP). The VIS instrument operates in the optical range (550 - 900nm), delivering high-resolution imaging capabilities with a field of view comparable to the size of the full moon. On the other hand, the NISP instrument extends into the near-infrared regime ($0.9 - 2.0\ \mu$m), offering both imaging and spectroscopic functionalities with impressive spatial and spectral resolutions. Its 1.2m diameter Korsch-style telescope is designed to correct for spherical aberration, coma, astigmatism, and field curvature [22] to ensure the best quality data possible. The focal length of this telescope is 24.5m with a collecting area of just over 1m^2. The telescope is powered using solar panels that help Euclid stabilise the orientation with an incredibly small correction error or just ~ 35 milliarcseconds. The data amassed from the telescope to Cebreros ground station in Spain at a rate of 55 megabits per second [23].

V. ANALYSIS OF EUCLID'S DATA

Euclid is set to generate outstanding amounts of data, mapping ~ 15000 square degrees of the sky, over 1 billion galaxies and 100 million spectra [24] to analyse. This is forecast to take up petabytes (10^{15} bytes) of images and terabytes (10^{12}) of catalogued data. In order to extract and analyse the results of the mission, ESA's taps into resources of multiple nations around the World, with 14 different countries collaborating together to prepare and filter relevant data stored in 9 data centres around the world. The collaboration encompasses over 1400 people from countries all over Europe [25], making it one of the greatest international collaborations in modern cosmology. The mission is set to last about 6.5 years and the data is set to release in multiple batches. As new data is obtained, it will be released periodically every year from the point of first 'quick release' (Q) [26]. After that, the releases will alternate between Q releases and main 'data releases' (DR). Q releases are supposed to give a sample of the data to be expected, and to allow scientists to improve their data analysis tools, while DRs contain characterized and validated data.

VI. EUCLID'S LEGACY

The Euclid mission will provide countless resources for use far beyond its mission objectives. Through its exploration of various cosmic phenomena, including galaxy imaging and active galactic nucleus (AGN) evolution [27] to the co-evolution of galaxies and black holes with its spectral methods [28]. Euclid is on track to establish legacy akin to that of Hubble Space telescope [29], changing the outlook on astrophysics and cosmology for the scientific community and general public alike.

REFERENCES

[1] Nathalie Deruelle and Jean-Philippe Uzan. *Relativity in Modern Physics*. Ed. by Patricia de Forcrand-Millard. 1st ed. Oxford University Press, 2018-08-30.

[2] E. Corbelli and P. Salucci. "The Extended Rotation Curve and the Dark Matter Halo of M33". In: *Monthly Notices of the Royal Astronomical Society* 311.2 (2000), pp. 441–447.

[3] Steven W. Allen, August E. Evrard, and Adam B. Mantz. "Cosmological Parameters from Clusters of Galaxies". In: *Annual Review of Astronomy and Astrophysics* 49.1 (2011), pp. 409–470.

[4] Sungwook E. Hong and et al. "Revealing the Local Cosmic Web from Galaxies by Deep Learning". In: *The Astrophysical Journal* 913.1 (2021), p. 76.

[5] Albert Einstein. "Cosmological Considerations in the General Theory of Relativity". In: *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften* Part 1 (1917), pp. 142–152.

[6] P. J. E. Peebles and B. Ratra. "The Cosmological Constant and Dark Energy". In: *Reviews of Modern Physics* 75.2 (2003), pp. 559–606.

[7] A. Friedman. "Über die Krümmung des Raumes". In: *Z. Phys.* 10.1 (1922), pp. 377–386.

[8] Planck Collaboration. "Planck 2013 results. I. Overview of products and scientific results". In: *Astronomy & Astrophysics* 571 (2014), A1.

[9] Giuseppe D Racca et al. "The Euclid mission design". In: *Space telescopes and instrumentation 2016: optical, infrared, and millimeter wave*. Vol. 9904. SPIE. 2016, pp. 235–257.

[10] R Laureijs et al. "Euclid mission status". In: *Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave*. Vol. 9143. SPIE. 2014, pp. 132–139.

[11] Hai-Chao Zhang. "Dynamical dark energy can amplify the expansion rate of the Universe". In: *Physical Review D* 107.10 (May 2023). ISSN: 2470-0029. DOI: 10.1103/physrevd.107.103529. URL: http://dx.doi.org/10.1103/PhysRevD.107.103529.

[12] Konrad Rudnicki. *The cosmological principles*. 1995.

[13] Christian Weinheimer and Kai Zuber. "Neutrino masses". In: *Annalen der Physik* 525.8-9 (2013), pp. 565–575.

[14] Signe Riemer-Sørensen et al. "Simultaneous Constrains on the Number and Mass of Relativistic Species". In: *The Astrophysical Journal* 763.2 (Jan. 2013), p. 89.

[15] David H Weinberg. "Reconstructing primordial density fluctuations–I. Method". In: *Monthly Notices of the Royal Astronomical Society* 254.2 (1992), pp. 315–342.

[16] Isaac Tutusaus et al. "Euclid: The importance of galaxy clustering and weak lensing cross-correlations within the photometric Euclid survey". In: *Astronomy & Astrophysics* 643 (2020), A70.

[17] Stefano Anselmi et al. "Cosmic distance inference from purely geometric BAO methods: Linear Point standard ruler and Correlation Function Model Fitting". In: *Physical Review D* 99.12 (2019), p. 123515.

[18] Yannick Mellier. "Probing the universe with weak lensing". In: *Annual Review of Astronomy and Astrophysics* 37.1 (1999), pp. 127–189.

[19] Sandrine Pires et al. "Euclid: Reconstruction of weak-lensing mass maps for non-Gaussianity studies". In: *Astronomy & Astrophysics* 638 (2020), A141.

[20] G. Desprez and Paltani et. al. "Euclid preparation: X. The Euclid photometric-redshift challenge". In: *Astronomy amp; Astrophysics* 644 (Nov. 2020), A31. ISSN: 1432-0746. DOI: 10.1051/0004-6361/202039403. URL: http://dx.doi.org/10.1051/0004-6361/202039403.

[21] Giuseppe D Racca et al. "The Euclid mission design". In: *Space telescopes and instrumentation 2016: optical, infrared, and millimeter wave*. Vol. 9904. SPIE. 2016, pp. 235–237.

[22] Dietrich Korsch. "Closed form solution for three-mirror telescopes, corrected for spherical aberration, coma, astigmatism, and field curvature". In: *Applied Optics* 11.12 (1972), pp. 2986–2987.

[23] *Euclid Service Module*. Webpage. Last Update: 19 September 2019. European Space Agency (ESA). URL: https://sci.esa.int/web/euclid/-/service-module.

[24] Rene Laureijs et al. "Euclid definition study report". In: *arXiv preprint arXiv:1110.3193* (2011).

[25] Sotiria Fotopoulou. *EUCLID: A Space Mission to Map the Dark Universe*. Talk. University of Bristol, Mar. 2024.

[26] *Euclid Data Release Timeline*. Webpage. Recovered 12/04/2024. URL: https://euclid.caltech.edu/page/data-release-timeline.

[27] Andrea Merloni and Sebastian Heinz. "Evolution of Active Galactic Nuclei". In: *Planets, Stars and Stellar Systems*. Springer Netherlands, 2013, pp. 503–566.

[28] Lawrence E Kidder et al. "Black hole evolution by spectral methods". In: *Physical Review D* 62.8 (2000), p. 084032.

[29] CA Christian. "The public impact of the hubble space telescope: A case study". In: *Organizations and Strategies in Astronomy: Volume 5*. Springer, 2004, pp. 203–216.