

Euclid Quick Data Release (Q1)

XVI. Optical and near-infrared identification and classification of point-like X-ray selected sources

Euclid Collaboration: W. Roster^{1,*}, M. Salvato¹, J. Buchner¹, R. Shirley¹, E. Lusso^{2,3}, H. Landt⁴, G. Zamorani⁵, M. Siudek^{6,7}, B. Laloux^{8,1}, T. Matamoros Zatarain⁹, F. Ricci^{10,11}, S. Fotopoulou⁹, A. Ferré-Mateu^{12,13}, X. Lopez Lopez^{14,5}, N. Aghanim¹⁵, B. Altieri¹⁶, A. Amara¹⁷, S. Andreon¹⁸, N. Auricchio⁵, H. Aussel¹⁹, C. Baccigalupi^{20,21,22,23}, M. Baldi^{24,5,25}, A. Balestra²⁶, S. Bardelli⁵, P. Battaglia⁵, A. Biviano^{21,20}, A. Bonchi²⁷, E. Branchini^{28,29,18}, M. Brescia^{30,8}, J. Brinchmann^{31,32}, S. Camera^{33,34,35}, G. Cañas-Herrera^{36,37,38}, V. Capobianco³⁵, C. Carbone³⁹, J. Carretero^{40,41}, S. Casas⁴², M. Castellano¹¹, G. Castignani⁵, S. Cavuoti^{8,43}, K. C. Chambers⁴⁴, A. Cimatti⁴⁵, C. Colodro-Conde¹², G. Congedo⁴⁶, C. J. Conselice⁴⁷, L. Conversi^{48,16}, Y. Copin⁴⁹, F. Courbin^{50,51}, H. M. Courtois⁵², M. Cropper⁵³, A. Da Silva^{54,55}, H. Degaudenzi⁵⁶, G. De Lucia²¹, A. M. Di Giorgio⁵⁷, C. Dolding⁵³, H. Dole¹⁵, F. Dubath⁵⁶, C. A. J. Duncan⁴⁷, X. Dupac¹⁶, S. Dusini⁵⁸, S. Escoffier⁵⁹, M. Fabricius^{1,60}, M. Farina⁵⁷, R. Farinelli⁵, F. Faustini^{27,11}, S. Ferriol⁴⁹, F. Finelli^{5,61}, P. Fosalba^{62,7}, N. Fourmanoit⁵⁹, M. Frailis²¹, E. Franceschi⁵, S. Galeotta²¹, K. George⁶⁰, B. Gillis⁴⁶, C. Giocoli^{5,25}, J. Gracia-Carpio¹, B. R. Granett¹⁸, A. Grazian²⁶, F. Grupp^{1,60}, S. Gwyn⁶³, S. V. H. Haugan⁶⁴, W. Holmes⁶⁵, I. M. Hook⁶⁶, F. Hormuth⁶⁷, A. Hornstrup^{68,69}, P. Hudelot⁷⁰, K. Jahnke⁷¹, M. Jhabvala⁷², E. Keihänen⁷³, S. Kermiche⁵⁹, A. Kiessling⁶⁵, B. Kubik⁴⁹, M. Kümmel⁶⁰, M. Kunz⁷⁴, H. Kurki-Suonio^{75,76}, Q. Le Boulc'h⁷⁷, A. M. C. Le Brun⁷⁸, D. Le Mignant⁷⁹, S. Ligori³⁵, P. B. Lilje⁶⁴, V. Lindholm^{75,76}, I. Lloro⁸⁰, G. Mainetti⁷⁷, D. Maino^{81,39,82}, E. Maiorano⁵, O. Mansutti²¹, S. Marcin⁸³, O. Marggraf⁸⁴, M. Martinelli^{11,85}, N. Martinet⁷⁹, F. Marulli^{14,5,25}, R. Massey⁸⁶, D. C. Masters⁸⁷, E. Medinaceli⁵, S. Mei^{88,89}, M. Melchior⁹⁰, Y. Mellier^{91,70}, M. Meneghetti^{5,25}, E. Merlin¹¹, G. Meylan⁹², A. Mora⁹³, M. Moresco^{14,5}, L. Moscardini^{14,5,25}, R. Nakajima⁸⁴, C. Neissner^{94,41}, S.-M. Niemi³⁶, J. W. Nightingale⁹⁵, C. Padilla⁹⁴, S. Paltani⁵⁶, F. Pasian²¹, K. Pedersen⁹⁶, W. J. Percival^{97,98,99}, V. Pettorino³⁶, S. Pires¹⁹, G. Polenta²⁷, M. Poncet¹⁰⁰, L. A. Popa¹⁰¹, L. Pozzetti⁵, F. Raison¹, R. Rebolo^{12,102,13}, A. Renzi^{103,58}, J. Rhodes⁶⁵, G. Riccio⁸, E. Romelli²¹, M. Roncarelli⁵, R. Saglia^{60,1}, Z. Sakr^{104,105,106}, A. G. Sánchez¹, D. Sapone¹⁰⁷, B. Sartoris^{60,21}, J. A. Schewtschenko⁴⁶, M. Schirmer⁷¹, P. Schneider⁸⁴, T. Schrabback¹⁰⁸, A. Secroun⁵⁹, G. Seidel⁷¹, M. Seiffert⁶⁵, S. Serrano^{62,109,7}, P. Simon⁸⁴, C. Sirignano^{103,58}, G. Sirri²⁵, L. Stanco⁵⁸, J. Steinwagner¹, P. Tallada-Crespi^{40,41}, D. Tavagnacco²¹, A. N. Taylor⁴⁶, I. Tereno^{54,110}, S. Toft^{111,112}, R. Toledo-Moreo¹¹³, F. Torradeflot^{41,40}, I. Tutusaus¹⁰⁵, L. Valenziano^{5,61}, J. Valiviita^{75,76}, T. Vassallo^{60,21}, G. Verdoes Kleijn¹¹⁴, A. Veropalumbo^{18,29,28}, Y. Wang⁸⁷, J. Weller^{60,1}, A. Zacchei^{21,20}, F. M. Zerbi¹⁸, I. A. Zinchenko⁶⁰, E. Zucca⁵, V. Allevato⁸, M. Ballardini^{115,116,5}, M. Bolzonella⁵, E. Bozzo⁵⁶, C. Burigana^{117,61}, R. Cabanac¹⁰⁵, A. Cappi^{5,118}, D. Di Ferdinando²⁵, J. A. Escartin Vigo¹, L. Gabarra¹¹⁹, M. Huertas-Company^{12,6,120,121}, J. Martín-Fleitas⁹³, S. Matthew⁴⁶, N. Mauri^{45,25}, R. B. Metcalf^{14,5}, A. Pezzotta^{122,1}, M. Pöntinen⁷⁵, C. Porciani⁸⁴, I. Risso¹²³, V. Scottez^{91,124}, M. Sereno^{5,25}, M. Tenti²⁵, M. Viel^{20,21,23,22,125}, M. Wiesmann⁶⁴, Y. Akrami^{126,127}, I. T. Andika^{128,129}, S. Anselmi^{58,103,130}, M. Archidiacono^{81,82}, F. Atrio-Barandela¹³¹, C. Benoist¹¹⁸, K. Benson⁵³, D. Bertacca^{103,26,58}, M. Bethermin¹³², L. Bisigello²⁶, A. Blanchard¹⁰⁵, L. Blot^{133,130}, H. Böhringer^{1,134,135}, M. L. Brown⁴⁷, S. Bruton¹³⁶, A. Calabro¹¹, F. Caro¹¹, C. S. Carvalho¹¹⁰, T. Castro^{21,22,20,125}, F. Cogato^{14,5}, A. R. Cooray¹³⁷, O. Cucciati⁵, S. Davini²⁹, F. De Paolis^{138,139,140}, G. Desprez¹¹⁴, A. Díaz-Sánchez¹⁴¹, J. J. Diaz^{6,12}, S. Di Domizio^{28,29}, J. M. Diego¹⁴², A. Enia^{24,5}, Y. Fang⁶⁰, A. G. Ferrari²⁵, A. Finoguenov⁷⁵, A. Fontana¹¹, A. Franco^{139,138,140}, K. Ganga⁸⁸, J. García-Bellido¹²⁶, T. Gasparetto²¹, V. Gautard¹⁴³, E. Gaztanaga^{7,62,144}, F. Giacomini²⁵, F. Gianotti⁵, G. Gozaliasl^{145,75}, M. Guidi^{24,5}, C. M. Gutierrez¹⁴⁶, A. Hall⁴⁶, W. G. Hartley⁵⁶, S. Hemmati¹⁴⁷

* Corresponding author: wroster@mpe.mpg.de

C. Hernández-Monteagudo^{13,12}, H. Hildebrandt¹⁴⁸, J. Hjorth⁹⁶, J. J. E. Kajava^{149,150}, Y. Kang⁵⁶,
V. Kansal^{151,152}, D. Karagiannis^{115,153}, K. Kiiveri⁷³, C. C. Kirkpatrick⁷³, S. Kruk¹⁶, J. Le Graet⁵⁹,
L. Legrand^{154,155}, M. Lembo^{115,116}, F. Lepori¹⁵⁶, G. Leroy^{4,86}, G. F. Lesci^{14,5}, J. Lesgourgues⁴²,
L. Leuzzi^{14,5}, T. I. Liaudat¹⁵⁷, A. Loureiro^{158,159}, J. Macias-Perez¹⁶⁰, G. Maggio²¹, M. Magliocchetti⁵⁷,
F. Mannucci², R. Maoli^{161,11}, C. J. A. P. Martins^{162,31}, L. Maurin¹⁵, M. Miluzio^{16,163}, P. Monaco^{164,21,22,20},
C. Moretti^{23,125,21,20,22}, G. Morgante⁵, K. Naidoo¹⁴⁴, A. Navarro-Alsina⁸⁴, S. Nesseris¹²⁶,
F. Passalacqua^{103,58}, K. Paterson⁷¹, L. Patrizii²⁵, A. Pisani^{59,165}, D. Potter¹⁵⁶, S. Quai^{14,5}, M. Radovich²⁶,
S. Sacquegna^{138,139,140}, M. Sahlén¹⁶⁶, D. B. Sanders⁴⁴, E. Sarpa^{23,125,22}, A. Schneider¹⁵⁶, D. Sciotti^{11,85},
E. Sellentin^{167,38}, F. Shankar¹⁶⁸, L. C. Smith¹⁶⁹, K. Tanidis¹¹⁹, G. Testera²⁹, R. Teyssier¹⁶⁵, S. Tosi^{28,123},
A. Troja^{103,58}, M. Tucci⁵⁶, C. Valieri²⁵, A. Venhola¹⁷⁰, D. Vergani⁵, G. Verza¹⁷¹, P. Vielzeuf⁵⁹,
A. Viitanen^{73,11}, N. A. Walton¹⁶⁹, E. Soubrie¹⁵, and D. Scott¹⁷²

(Affiliations can be found after the references)

Received 18 March 2025 / Accepted 31 July 2025

ABSTRACT

To better understand the role of active galactic nuclei (AGN) in galaxy evolution, it is crucial to work with a complete and pure AGN sample. X-ray surveys are key to doing so, but their larger positional uncertainties complicate counterpart (CTP) association, further compounded by the limited availability of deep, uniform multi-wavelength ancillary data. *Euclid* is revolutionising this identification effort, offering extensive coverage of nearly the entire extragalactic sky, particularly in the near-infrared bands, where AGN are more easily detected. Using the first *Euclid* Quick Data Release (Q1), we validated the methods for identifying and classifying *Euclid* CTPs of known point-like sources from major X-ray surveys, including *XMM-Newton*, *Chandra*, and *eROSITA*. Using Bayesian statistics, combined with machine learning (ML), as incorporated in the algorithm *NWAY*, we identified the CTPs of 11 286 X-ray sources from the three X-ray telescopes. For the large majority of 10 194 sources, the association is unique, with the remaining ~10% of multi-CTP cases equally split between *XMM-Newton* and *eROSITA*. Six percent of the *Euclid* CTPs are detected in more than one X-ray survey. We then used ML to distinguish between Galactic (8%) and extragalactic (92%) sources. We computed photo-*z*s using deep learning for the 9259 sources detected in the tenth data release of the DESI Legacy Survey, reaching an accuracy and a fraction of outliers of roughly 5%. Based on their X-ray luminosities, all CTPs identified as extragalactic are classified as AGN, most of which appear as type I AGN according to their hardness ratios. With this paper, we release our catalogue, which includes identifiers, basic X-ray properties, the reliability of the associations, and additional property extensions, such as Galactic- or extragalactic classifications and photometric/spectroscopic redshifts. We also provide probabilities for sub-selecting the sample based on purity and completeness, in order to allow users to tailor the sample according to their specific needs.

Key words. methods: data analysis – catalogs – galaxies: active – galaxies: evolution – galaxies: photometry – X-rays: galaxies

1. Introduction

Active galactic nuclei (AGN¹), which rank among the most energetic phenomena in the Universe, play a pivotal role in shaping the evolutionary trajectories of galaxies throughout cosmic time. Their activity is fundamentally driven by the accretion of matter onto supermassive black holes (SMBHs) from their surrounding environment (e.g., Salpeter 1964; Lynden-Bell 1969; Pringle & Rees 1972; Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; Kormendy & Ho 2013). Situated at the centres of galaxies, AGN emit intense radiation across the entire electromagnetic spectrum, ranging from radio waves to γ -rays (e.g., Elvis et al. 1994; Urry & Padovani 1995; Padovani et al. 2017). While this is particularly true for quasi-stellar objects (QSOs), it is important to note that the range of activity, emission, and interaction of AGN span a broad spectrum, with different AGN exhibiting varying levels of energy outputs (e.g., Peterson 1997; Pierce et al. 2010; Pović et al. 2012; Bettoni et al. 2015).

Consequently, with enough coupling efficiency, this allows AGN to exert significant influence over both their host galaxies and the growth of their central SMBHs, where the interplay between AGN activity and the respective host is believed to regulate star formation and shape the morphology of galax-

ies. Here, energetic feedback drives powerful winds and outflows, impacting the surrounding interstellar and intergalactic medium (Greene et al. 2011; Cielo et al. 2018). These close connections are supported by fundamental scaling relations that link the SMBH mass to various galactic properties. Notable among these are the $M_{\text{BH}}-\sigma$ relation, which ties black hole (BH) mass to the velocity dispersion of stars in the galaxy’s bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2000), and the $M_{\text{BH}}-M_*$ relation, which connects it to the stellar mass of the host galaxy (Magorrian et al. 1998; Häring & Rix 2004; Gültekin et al. 2009; Sani et al. 2011; Shankar et al. 2016; Suh et al. 2020), thus pointing to an intricate co-evolution of the systems (Kormendy & Ho 2013; Heckman & Best 2014; Madau & Dickinson 2014; Euclid Collaboration: Bisigello et al. 2024). However, the physical mechanisms driving this connection remain under debate, highlighting the need to construct a complete picture of AGN diversity and complexity to better understand galaxy formation and transformation across the history of the Universe (e.g., Aird et al. 2010; Buchner et al. 2015; Georgakakis et al. 2015; Ananna et al. 2017; Morganti 2017; Delvecchio et al. 2017; Husemann & Harrison 2018; Harrison & Ramos Almeida 2024).

Despite significant advancements over the years, the current AGN census remains incomplete due to inherent biases introduced to individual samples by various multi-wavelength selection methods, as each favours specific properties of the

¹ We use this term interchangeably to indicate both the singular and plural cases.

population (Messias et al. 2014; Padovani et al. 2017; Delvecchio et al. 2017; Lyu et al. 2022; Green et al. 2024). Comprehensive wavelength coverage is vital for identifying diverse AGN across redshift, as each method that contributes to this coverage capitalises on the dominant physical processes of AGN activity, dominating the spectral energy distribution (SED) of its host galaxy (Padovani et al. 2017). For instance, radio observations are effective at identifying jet-dominated AGN (De Breuck et al. 2002; Smolčić et al. 2017), while optical diagnostics (Feltre et al. 2016), such as emission line ratios (e.g., BPT diagrams as in Baldwin et al. 1981; Veilleux & Osterbrock 1987; Juneau et al. 2014), are widely used to distinguish AGN from star-forming galaxies by probing ionisation mechanisms. Other selections include colour or variability (e.g., Richards et al. 2002; Bongiorno et al. 2010; Bovy et al. 2012; Donley et al. 2012; Kirkpatrick et al. 2013; Peters et al. 2015; Palanque-Delabrouille et al. 2016; Lusso & Risaliti 2016). Soft X-ray selection excels at detecting unobscured accretion-powered emission (e.g., Hasinger 2008; Brandt & Hasinger 2005; Nandra et al. 2015) and can be complemented by mid-infrared (MIR) observations (e.g., Stern et al. 2012; Assef et al. 2013), which can effectively penetrate dense dust clouds (Hickox & Alexander 2018). Notably, the significantly higher contrast between the intrinsic brightness of accreting SMBHs and their host galaxies in X-rays, as opposed to other wavelengths, makes this selection one of the most uncontaminated, and thus it provides pure AGN samples of a larger diversity (Xue et al. 2011a; Donley et al. 2012). To combine different observational perspectives of AGN, these X-ray samples must then be paired with ancillary multi-wavelength data.

In the past, identifying multi-wavelength counterparts (CTPs) for X-ray-selected sources was a significant hurdle in AGN characterisation and redshift estimation (Salvato et al. 2018). While combining data from multiple wavelengths is crucial for constructing a more complete picture of AGN, the process of cross-identifying sources remains complicated. Due to the significant positional uncertainties in X-ray surveys, confidently linking most X-ray sources to a single, definitive CTP in, for example, optical, infrared, or radio surveys, is challenging, except in the brightest cases. These uncertainties, along with the uneven spatial coverage of ancillary data, further complicate the task of reliably pinpointing AGN across different surveys. Consequently, a simple coordinate match is insufficient, and more sophisticated methods are needed for accurate cross-identification. For this purpose, machine learning (ML) algorithms that integrate multi-wavelength source classification approaches have become increasingly prevalent (e.g., Cavioti et al. 2014; Brescia et al. 2015; Karsten et al. 2023; Cooper et al. 2023; Daoutis et al. 2023; Zeraatgari et al. 2024; Pérez-Díaz et al. 2024; Mechbal et al. 2024).

The European Space Agency’s *Euclid* satellite will also help overcome this limitation due to its uniform depth and wide coverage (Laureijs et al. 2011; Euclid Collaboration: Mellier et al. 2025). At the same time, *Euclid*’s depth results in very high source densities, thus increasing the risk of unforced misidentification and chance alignments. Over its six-year mission lifetime, *Euclid* will cover a total of $\sim 14\,000\text{ deg}^2$ in the Euclid Wide Survey (EWS, Euclid Collaboration: Scaramella et al. 2022), and it is expected to detect billions of sources. In addition to its cosmological objectives, *Euclid* will play a crucial role in the detection and characterisation of AGN, as at least 10 million AGN are anticipated to be detected (Euclid Collaboration: Bisigello et al. 2024; Euclid Collaboration: Lusso et al. 2024; Euclid Collaboration: Selwood et al. 2025). To achieve these

goals, *Euclid* employs two main instruments: the VISible imager (VIS, Euclid Collaboration: Desprez et al. 2020; Euclid Collaboration: Cropper et al. 2025), covering wavelengths from 0.53 to $0.90\mu\text{m}$ (I_E), and the Near-Infrared Spectrometer and Photometer (NIS, Maciaszek et al. 2022; Euclid Collaboration: Jahnke et al. 2025). Operating in the near-infrared and with photometric measurements in three bands (Y_E , J_E , and H_E), *Euclid* covers in total the wavelength range from 0.95 to $2.02\mu\text{m}$ while also including a slitless spectrograph for the detection of emission lines.

With the first *Euclid* Quick Data Release (Q1), we can now begin building and testing the necessary machinery for identifying and characterising AGN previously selected in the X-rays. We aim to leverage *Euclid*’s depth, resolution, and wavelength coverage to provide more secure associations of these AGN. Moreover, this initial testing will form the foundation for refining our methods and ensuring accurate AGN identification as more data become available over the next years.

In this paper, we address the task of reliably associating X-ray sources with their *Euclid* CTPs and investigate their respective NIR properties as a function of X-ray flux, among other properties. The paper is structured as follows: In Sect. 2 we give an overview of the Q1 data. In Sect. 3 we introduce the X-ray source catalogues used in this work, while Sect. 4 provides an outline of the approach to identifying CTPs. In Sect. 5, using a sample of sources clearly characterised with the tenth Data Release of the Legacy Survey (Dey et al. 2019), we describe how we assign a Galactic- or extragalactic nature to our sources using *Euclid* photometry. In Sect. 6, we compute photometric redshifts for all CTPs. Section 7 displays CTP sample properties, and in Sect. 8 we explain the release of the catalogues and how to use them. Finally, a summary and discussion are given in Sect. 9.

In this paper, unless stated otherwise, we express magnitudes in the AB system (Oke & Gunn 1983) and adopt a flat Λ CDM cosmology with $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ to facilitate direct comparison with similar works from literature.

2. Euclid Q1 fields

Euclid Q1 marks the initial data release with a footprint area of $\sim 63.1\text{ deg}^2$ (Euclid Collaboration: Mellier et al. 2025). It consists of observations making up the Euclid Deep Survey (EDS), selected for their considerable multi-wavelength coverage. However, the data is currently at the depth of the EWS, with a 5σ depth of $I_E(\text{AB}) = 24.5$ for point sources. The EDS targets three important Euclid Deep Fields (EDFs; see Fig. 1): the EDF Fornax (EDF-F), EDF South (EDF-S), and the EDF North (EDF-N). For more details, we refer the reader to Euclid Collaboration: Aussel et al. (2026).

The catalogues provide comprehensive photometric information across all four *Euclid* bands (Euclid Collaboration: McCracken et al. 2026; Euclid Collaboration: Polenta et al. 2026; Euclid Collaboration: Romelli et al. 2026). In addition to the *Euclid* bands, the catalogue is supplemented with ground-based photometry in the *ugriz* optical bands, where available, sourced from various instruments depending on their access to the northern or southern extragalactic sky. Photometric measurements are provided as both template/Sérsic model fits and fluxes extracted within apertures corresponding to radii of 1–4 times the seeing full-width at half maximum (FWHM).

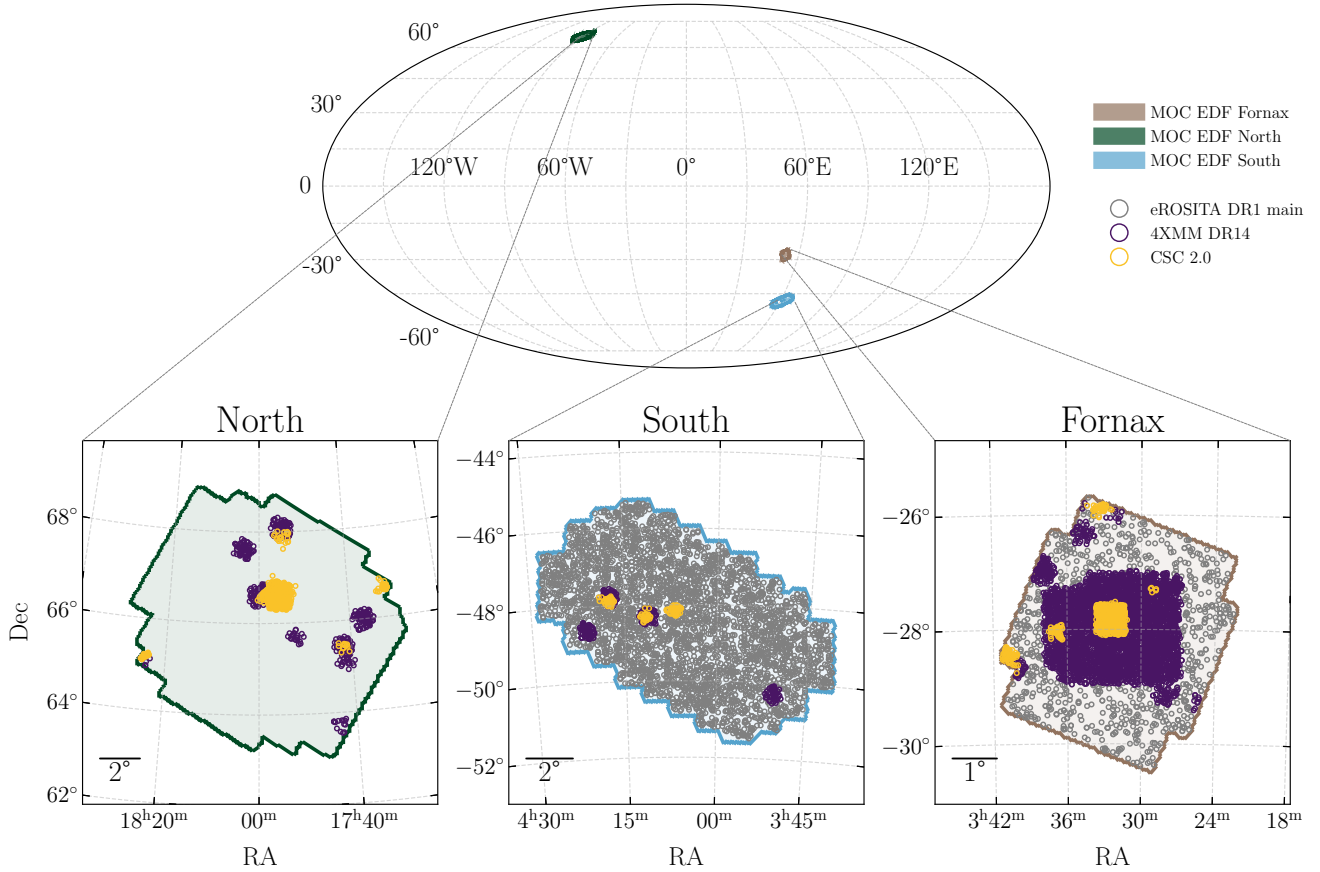


Fig. 1. Sky coverage of the EDF fields and corresponding X-ray source distributions. Top: Mollweide projection of the sky indicating the locations of EDF-N, EDF-S, and EDF-F using their multi-order coverage maps (MOCs). Bottom: Zoomed-in views of each EDF overlaid with X-ray sources from the eROSITA-DE DR1 catalogue (grey), the XMM-Newton 4XMM DR14 catalogue (purple), and the *Chandra* Source Catalog 2.0 (orange), to illustrate the overlap between *Euclid*'s deep fields and existing X-ray source catalogues.

3. The X-ray surveys

X-ray surveys are often constrained by the flux detection limit of the most sensitive X-ray telescopes, which typically operate with small fields of view. Therefore, surveys with different observational strategies need to be combined to facilitate the characterisation of the full AGN population. Pencil-beam surveys that provide exceptionally deep observations, valuable for probing faint AGN and for characterising the low-luminosity end of the AGN population, are limited in sky coverage and, consequently, miss rare (bright or distant) sources (e.g., Brusa et al. 2010; Hsu et al. 2014; Nandra et al. 2015; Marchesi et al. 2016; Luo et al. 2017; Oh et al. 2018). Subsequently, the data releases of XMM-Newton 4XMM DR14 (Webb et al. 2020) and *Chandra* Source Catalogue 2 (CSC 2.0, Evans et al. 2024) feature outstanding sensitivity for X-ray-selected sources but cover relatively small regions of the sky.

On the other hand, wide-area surveys are crucial for complementing pointed observations and uncovering those AGN missed (e.g., Ananna et al. 2017; Fotopoulou et al. 2016). Therefore, we incorporate data from the extended *Roentgen* Survey with an Imaging Array (eROSITA; Predehl et al. 2021) DR1 main sample (Merloni et al. 2024). As part of the ongoing eROSITA All-Sky Survey (eRASS), these data provide homogeneous, soft X-ray coverage of the entire extragalactic sky. While eROSITA's positional accuracy is somewhat poorer than that of XMM-Newton and *Chandra*, its unparalleled breadth allows us to include a significantly larger sample of sources, enhancing the

statistical power of our analysis and ensuring a more comprehensive AGN census (see Fig. 1 and Table 1). In the following subsections, we describe the selection criteria applied to the catalogues from each X-ray survey.

3.1. XMM-Newton

The XMM-Newton space-telescope provides some of the deepest and most detailed X-ray imaging available, with a spatial resolution of approximately $6''$ and positional uncertainties typically below $1-2''$. The data used in this study includes both targeted and serendipitous observations, selected from the 4XMM DR14 catalogue², the most recent of the XMM releases³. The catalogue offers multi-band flux measurements and quality flags. To prepare the sample, point-like sources were filtered based on their extent likelihood and positional uncertainties: $SC_EXT_ML < 10$, $SC_EXTENT < 10$ and $SC_POSERR < 10''$, where the threshold for the positional uncertainty is motivated by the respective distribution as a function of flux as shown in Fig. 2. This effectively reduces the computational load for cross-matching with *Euclid*. To be consistent with other X-ray surveys,

² Catalogue and data model description available at <https://cdsarc.cds.unistra.fr/viz-bin/cat/IX/69>

³ We note that dedicated XMM observations targeting the Fornax field are ongoing. These additional data are not included in this work but may be used to refine and extend the CTPs in future.

Table 1. Sample sizes for the three X-ray catalogues at various stages.

X-ray catalogue (1) Unit	MOC (2) [deg ²]	Number of sources (3)	AND point-like (4)	AND POSERR < limit (5)	EDF-F (6)	EDF-N (7)	EDF-S (8)
4XMM DR14	6.18	692 109	612 521	612 504	4523	445	273
CSC 2.0	1.31	317 167	296 473	296 162	1016	506	147
eROSITA DR1 main	43.14	898 812	879 153	878 984	1012	0	3369

Notes. (1) Areas covered by the X-ray survey MOCs in the Q1 footprint (see Fig. 1), (2) X-ray catalogue, (3) total number of X-ray sources (starting from unique source ID entries and QFs set to zero), (4) after applying the point-like source criterion, and (5) after following the application of the positional error threshold. Columns (6), (7), and (8) give the respective number of sources in each EDF.

we computed the X-ray flux, F_X , for the 0.5–2 keV band as

$$F_X = \text{SC_EP_2_FLUX}_{0.5-1.0\text{ keV}} + \text{SC_EP_3_FLUX}_{1.0-2.0\text{ keV}} \quad (1)$$

and its uncertainty as

$$\text{EF}_X = \sqrt{\text{SC_EP_2_FLUX_ERR}^2 + \text{SC_EP_3_FLUX_ERR}^2} \quad (2)$$

by combining the 0.5–1 keV and 1–2 keV band fluxes and errors.

3.2. Chandra

The *Chandra* X-ray space telescope provides sub-arcsecond angular resolution, which allows for precise localisation of sources and makes it particularly effective in crowded or complex fields. Our sample incorporates sources from the CSC 2.0 catalogue⁴. To subsample only point-like sources, we selected sources with the extended flag, f_e , set to zero. The 0.5–2 keV X-ray flux and its uncertainty were computed as

$$F_X = \text{Flux}_{0.5-1.2\text{ keV}} + \text{Flux}_{1.2-2.0\text{ keV}}, \quad (3)$$

$$\text{EF}_X = \sqrt{(\text{B_Fluxs} - \text{b_Fluxs})^2 + (\text{B_Fluxm} - \text{b_Fluxm})^2}, \quad (4)$$

with $\text{Flux}_{0.5-1.2\text{ keV}}$ and $\text{Flux}_{1.2-2.0\text{ keV}}$ referring to the default CSC 2.0 soft and medium bands, respectively, while (B) and (b) represent the upper and lower 1σ error margins. The positional uncertainties were determined using the 2σ errors along the semi-major (r_0) and semi-minor (r_1) axes of the error ellipse provided in the source catalogue as

$$\text{C_POSERR} = \sqrt{\frac{(r_0/2)^2 + (r_1/2)^2}{2}}, \quad (5)$$

and we downsampled the CSC 2.0 catalogue such that $\text{C_POSERR} < 10''$ to be consistent with 4XMM DR14 (see Fig. 2).

3.3. eROSITA

The eROSITA-DE DR1 main catalogue⁵ offers comprehensive coverage of the western galactic hemisphere. While it does not include the EDF-N region (see Fig. 1), with a half energy width

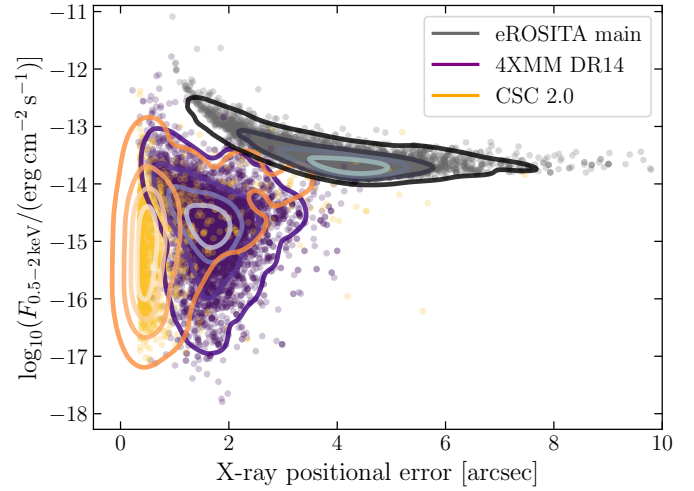


Fig. 2. X-ray fluxes in the 0.5–2 keV band plotted against positional uncertainties for sources from the 4XMM DR14, CSC 2.0, and eROSITA-DE/DR1 catalogues.

(HEW) of $26''$ and a soft X-ray energy range of 0.2–2.3 keV, eROSITA offers a uniform data set ideal for large statistical studies. The data preparation for eROSITA included filtering for reliable point-source detections with $\text{EXT_LIKE} = 0$. Additionally, we required that all nine quality flags (QFs) are set to zero, and applied a cut in positional uncertainty of $\text{POS_ERR} < 20''$ (refer to Table 1).

The choice to permit larger positional uncertainties in the eROSITA DR1 sample, as opposed to the XMM-Newton and Chandra samples, is guided by the comparison of their error distributions shown in Fig. 2. This approach ensures the retention of the majority of the sample while excluding only a small number of outliers with exceptionally high positional errors. We intentionally avoid applying more restrictive criteria, such as minimum flux, signal-to-noise ratio (S/N), isolated environments, detection likelihoods, or other observational limitations, in order to prevent excluding sources that could potentially be identified by *Euclid*. An overview of the sample sizes is given in Table 1. By setting this threshold, we aim to optimise the balance between maintaining a robust sample and minimising the computational effort required for CTP identification within the defined error limits.

4. Identification of CTPs

Until recently, the identification of CTPs was primarily performed using maximum likelihood matching (e.g.,

⁴ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=IX/57&-to=3>

⁵ https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/Catalogues_dr1/

Sutherland & Saunders 1992). This approach considers the separation between sources in the primary catalogue (e.g. X-ray) and the secondary multiwavelength catalogue, the positional uncertainties of the primary sources, and the magnitude distribution of sources in the ancillary catalogues within a certain radius from the primary sources. While this method has been applied successfully in cases with small positional errors and bright sources (see e.g., Naylor et al. 2013; Brusa et al. 2010; Xue et al. 2011b), its reliability decreases in situations where positional errors are large, and more than one photometric point is necessary for identifying the correct CTP or when multiple potential CTPs exist within the search radius. In such cases, positional matching often fails to provide a robust identification.

4.1. NWAY

To address these challenges, Bayesian statistics needs to be invoked (Budavári & Szalay 2008). With this in mind, algorithms such as NWAY (Salvato et al. 2018), and XMATCH (Pineau et al. 2017) were developed. Unlike the others, NWAY also allows for the adoption of priors in addition to positional matches between multiple catalogues. It refines its matching procedure by being able to supplement one or more features, such as colours, magnitudes, and S/N, into likelihood ratios used for CTP identification. These priors based on (anti-) correlations between source properties of the target and field populations allow NWAY to improve the likelihood of finding true matches, boosting the accuracy significantly over methods that rely solely on positional information.

4.1.1. The integration of priors in NWAY

Colour and magnitude priors are posteriors that encode knowledge from data or probabilistic distributions that describe the expected properties of true CTPs for the sources in the primary catalogue. For example, an AGN selected in X-rays is likely to have distinct colours (e.g. redder MIR colours due to dust) and magnitudes compared to stars or inactive galaxies. The difference between the methods resides then in the adoption of specific features able to distinguish an X-ray emitter (regardless of its Galactic or extragalactic nature) from a random source in the field (Salvato et al. 2022). NWAY uses these priors to add additional dimensions to calculate a more nuanced likelihood ratio. This reduces ambiguity, especially in crowded fields or cases with large positional uncertainties.

For instance, in the ROSAT All-Sky Survey (2RXS, Boller et al. 2016), Salvato et al. (2018) improved CTP identification by incorporating a 2D prior based on the W2 magnitude and W1–W2 colour from AllWISE (Wright et al. 2010), effectively separating out AGN. In the more recent application to the eROSITA Final Equatorial-Depth Survey (eFEDS, Brunner et al. 2022), Salvato et al. (2022) defined a prior that utilised not only magnitudes and colours from the Legacy Survey Data Release 10 (LS10, Dey et al. 2019), but also S/N in all bands (*griz*, W1, W2, W3, and W4), as well as properties, such as proper motion, from *Gaia* DR3 (Vallenari et al. 2023) when available. For further details on the formalism, we refer to the NWAY documentation⁶.

4.1.2. Q1 prior

In this work, we have adopted the same principle as described in the previous subsection, but restricted ourselves to using only photometric features from *Euclid*. To build priors based on multiple features, NWAY can incorporate probabilities derived from ML models, such as a random forest (RF) classifier (the *sklearn* implementation, Pedregosa et al. 2011). We start by utilising the training sample presented in Salvato et al., in prep., comprising secure CTPs to X-ray sources from 4XMM DR11 (Webb et al. 2020) and CSC 2.0, for training the RF model, as presented by Salvato et al. (2022). NWAY is then applied to identify CTPs for these X-ray sources in the EDF catalogues. A search radius of three times the positional error threshold is set around each X-ray source to include all potential EDF matches within this radius. This large search radius ensures that widely separated CTPs are not missed, even for sources with the largest positional uncertainties. The sky coverage of each X-ray sample per EDF is calculated to account for overlapping search windows. Specifically, while the coverage for the X-ray sample is given by its multi-order coverage map (MOC) or pointing, the EDF coverage was derived as

$$A_{\text{field}} = N_{\text{X-ray}} \pi (\text{POSERR})^2 - A_{\text{overlap}}, \quad (6)$$

where $N_{\text{X-ray}}$ corresponds to the number of X-ray sources and A_{overlap} is the overlapping area of adjacent search windows. Following the methodology outlined in Salvato et al. (2018), these coverage areas are used to compute the number densities, which inform two key probabilities: p_{any} (the probability that an X-ray source has a CTP) and p_{i} (the probability that each EDF source within the search radius is the correct CTP). NWAY identifies the most likely CTP for each X-ray source by selecting the EDF source with the highest p_{i} value. This CTP is considered the primary match. To assess the reliability of this identification, the p_{any} value is used as a confidence threshold. All sources identified as primary matches (`match_flag == 1`) with $p_{\text{any}} > 0.85$, form the target sample. In addition, for every X-ray source, all other EDF sources within the search radius that are not the primary match are collected into a field population, provided $p_{\text{any}} < 0.1$. This field population serves as a representation of non-X-ray sources, providing a comparison set for training the RF. To label the data sets, X-ray CTPs are assigned a target class of ‘1’, while field objects are labelled as ‘0’. The *Euclid*-only training features utilised for the RF classifier are outlined in Table 2. At present, photometry and colours from different apertures are not included as features, as the aperture sizes vary between sources despite sharing the same designation.

Future data releases may standardise aperture sizes across all objects, also enhancing the RF classifier’s ability to leverage the relationship between light profiles and X-ray emission. To evaluate model performance, 15% of the training dataset (6000 fields and 1730 target sources) is randomly set aside as a test set. The RF model is configured with 200 decision trees, with splits allowed if at least 25 samples remain in a branch. Per decision tree construction, 10 photometric features are considered, and bootstrap sampling is applied to the training set for building the ensemble of trees. Since the data set is highly imbalanced, with field objects vastly outnumbering CTPs of X-ray sources, a weighting scheme is implemented to automatically adjust the contribution of each class during training (Salvato et al. 2022). This ensures the model effectively learns to differentiate between the two classes despite the imbalance. The classifier outputs a probability score $P_{\text{X-ray}}$, the predicted likelihood of a candidate CTP being X-ray emitting. $P_{\text{X-ray}}$ is used for class prediction,

⁶ <https://github.com/JohannesBuchner/NWAY>

Table 2. Overview of *Euclid* features used to train the RF classifier for the photometric prior used in *NWAY*.

Feature	Description
dered_*_flux	dereddened template flux in I_E , Y_E , J_E , and H_E
colour_*	dereddened template colour for $I_E - Y_E$, $I_E - J_E$, $I_E - H_E$, $Y_E - J_E$, $Y_E - H_E$, and $J_E - H_E$
snr_*	S/N for template I_E , Y_E , J_E , and H_E
point_like_prob	probability between 0 and 1 that the source is point-like
vis_det	binary flag, where $\begin{cases} \text{source is detected in the VIS mosaic (1),} \\ \text{source is only detected in the NIR mosaic (0)} \end{cases}$

Notes. Dereddened fluxes are calculated by correcting for Milky Way (MW) extinction, following the procedure for obtaining intrinsic magnitudes described by [Cuillandre et al. \(2025\)](#).

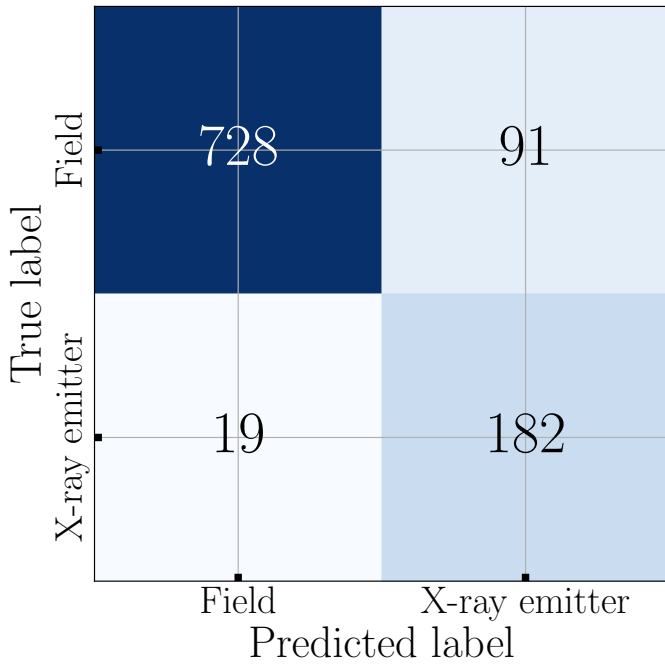


Fig. 3. Confusion matrix from the RF prediction on an independent test set. X-ray sources are labelled as ‘X-ray emitter’, while field objects are labelled as ‘Field’. Numbers on the diagonal correspond to correctly predicted classes of TP (bottom right) and TN (top left), while those off-diagonal refer to falsely predicted classes of FP (top right) and FN (bottom left).

where *NWAY* retains candidates with $P_{X\text{-ray}} < 50\%$ if their astrometric configuration strongly supports a match. Importantly, the probability $P_{X\text{-ray}}$ is derived exclusively from photometric properties, independent of positional uncertainties, enabling it to be seamlessly integrated into *NWAY*’s Bayesian framework, complementing astrometric priors with photometric information.

We quantify the classification quality by comparing the input labels and predicted classes as: (i) true positive (TP, where label=1 and prediction=1); (ii) true negative (TN, where label=0 and prediction=0); (iii) false positive (FP, where label=0 and prediction=1); and (iv) false negative (FN, where label=1 and prediction=0). The model’s performance is summarised in the confusion matrix shown in Fig. 3, assessed by acquiring these values for the test set (see e.g., [Fotopoulou & Paltani 2018](#)). We defined the following measures of quality for the classifier:

- accuracy = $(TP+TN)/(TP+TN+FP+FN)$;
- precision = $TP/(TP+FP)$;

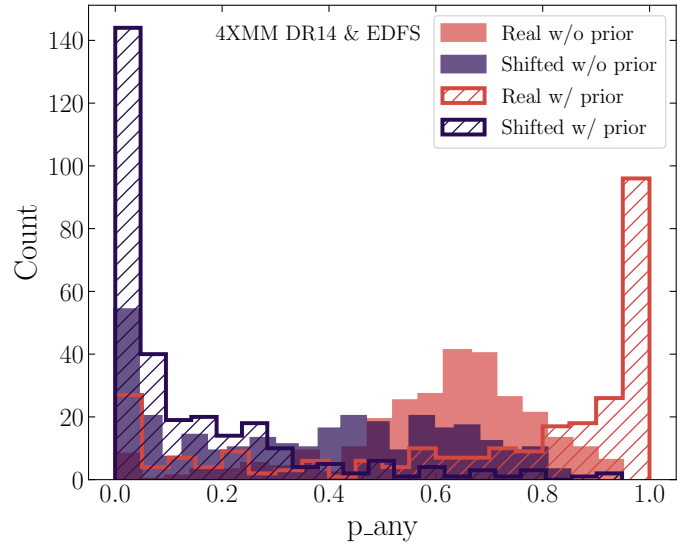


Fig. 4. Example of p_{any} , the probability that an X-ray source has a *Euclid* CTP, showing distributions for both random and real X-ray sources before (filled) and after (hatched) incorporating the photometric prior in *NWAY*. For the random sources, the inclusion of the prior shifts the p_{any} values to lower values, indicating that most associations are due to chance alignments. Conversely, for the real sources, the prior shifts the p_{any} values to higher values, highlighting the increased confidence in the true matches, demonstrating the positive impact of the prior in distinguishing real CTPs from random associations.

- recall = $TP/(TP+FN)$;
- fall-out = $FP/(TN+FP)$.

The trained model achieves strong performance, with a high accuracy of 89% and a recall of 91%, indicating that most real X-ray emitters are correctly identified. The contamination rate remains low, with a fractional leakage of 11%. The fall-out fraction can, in principle, be reduced by including more field objects, though at the price of reduced recall.

To better understand the model’s decision-making process, we performed a detailed feature importance analysis. This revealed that while most features contribute marginally to the classification, a few stand out as particularly informative. Specifically, features related to the de-reddened H_E band, including the flux, the S/N, and respective colour combinations, headed by $Y_E - H_E$, as well as the point-like probability, emerge as the most significant predictors. For a more comprehensive overview of feature contributions, we refer the reader to Appendix A.

Table 3. Breakdown of the CTP sample.

X-ray catalogue	X-ray sources	CTPs	AND match_flag == 1	AND in LS10	AND S/N _r ≥ 3	$P_{\text{Gal}} < 0.5$	w/spec-z
4XMM DR14	5241	5885	5239	4107	4033	5486	953
CSC 2.0	1669	1712	1666	993	958	1625	502
eROSITA DR1	4381	5048	4381	4159	4141	4375	321
Total:	11 291	12 645	11 286	9259	9132	11 486	1776

Notes. (1) X-ray catalogue, (2) number of X-ray sources, (3) number of CTP candidates, (4) unique CTPs with match_flag == 1, (5) unique CTPs successfully matched to LS10, (6) unique CTPs in LS10 with S/N_r ≥ 3. The respective number of CTP candidates that we consider to be extragalactic is given in Column 7, while the number of candidates with publicly available spectroscopic redshifts is given in Column 8.

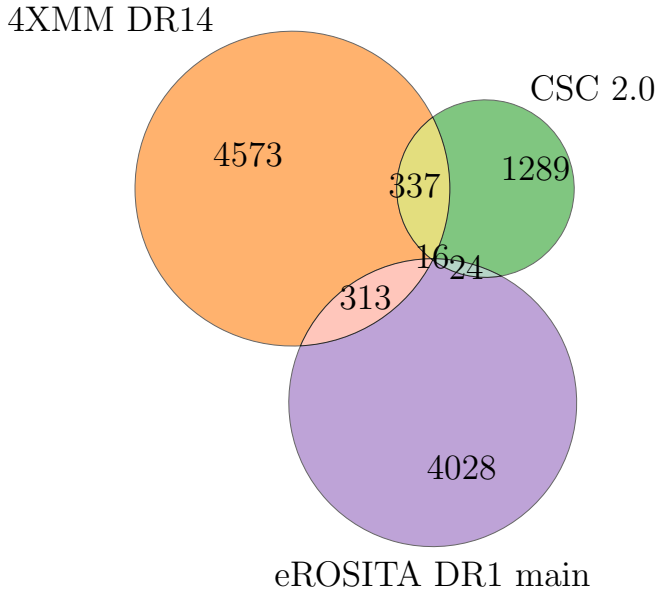


Fig. 5. Venn diagram illustrating the overlap of shared *Euclid* CTPs among the three X-ray samples, 4XMM DR14, CSC 2.0, and eROSITA DR1 main, as listed in Table 3. The diagram shows the distribution of sources that are uniquely or jointly identified by the surveys, with larger overlapping areas indicating stronger agreement among the surveys.

4.2. Adding the X-ray emitter prior to NWay

The a priori probability of a *Euclid* source being an X-ray emitter, $P_{\text{X-ray}}$, is now incorporated as a prior into the NWay framework to enhance our CTP identification process. To visualise the positive impact of the inclusion of this prior, we plot the distribution of p_{any} both before and after the inclusion of the X-ray emitter prior (see Fig. 4). Incorporating the prior shifts the distribution of p_{any} to higher values, making the identification of true CTPs more reliable. Notably, the inclusion of the prior also changes the respective CTP in about 30% of the cases, indicating that for those sources that are indeed not the CTP after adding the prior, the p_{any} value has been decreased.

In total, we associated 12 645 CTP candidates. Among these, 11 286 sources (about 90%) have match_flag == 1, indicating that they have the highest probability p_i to be considered reliable CTPs. The remaining candidates, with match_flag == 2, represent secondary but plausible matches that are not ruled out entirely. We found 1092 X-ray sources with multiple CTPs, the vast majority of which are made up by XMM-Newton and eROSITA, with only *Chandra* providing the required positional

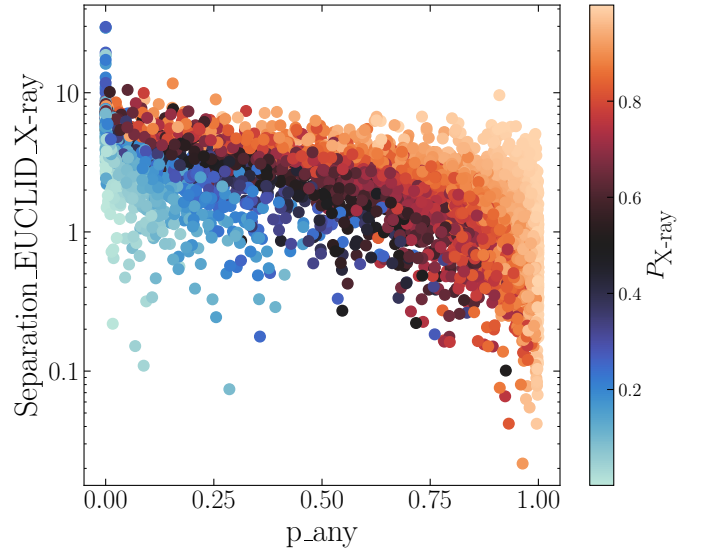


Fig. 6. Relationship between the separation (in arcseconds) between X-ray sources from 4XMM DR14 and their selected CTP as a function of p_{any} colour-coded by $P_{\text{X-ray}}$. The plot highlights that a minimal (or very small) fraction of matches have separations above 10'', and p_{any} is enhanced by the probability to be X-ray emitting.

accuracy for *Euclid* to have a few sources with multiple plausible CTPs. While most of the multi-CTP cases are made up of two candidates, a few cases with more than two CTPs are introduced, predominantly by eROSITA, given its larger positional uncertainty. Notably, only five X-ray sources within the Q1 footprint (see Table 1) lack an association entirely, possibly due to boundary effects where the true CTP falls outside the region covered by the EDFs.

With this catalogue, several scenarios emerged in terms of the relationships between CTPs and X-ray sources:

1. Two X-ray entries from different surveys are assigned to a single CTP. This scenario suggests but does not confirm the possibility of a single physical source being detected by two different X-ray surveys.
2. Two X-ray entries from the same survey are assigned to a single CTP. Here, we can confidently state that two distinct physical sources are selected, though both are associated with the same *Euclid* ID.
3. Cases where a single *Euclid* ID is linked to multiple entries from two or even all three X-ray surveys.
4. Two X-ray entries where the same X-ray source, detected by multiple surveys, is matched to distinct *Euclid* CTPs.

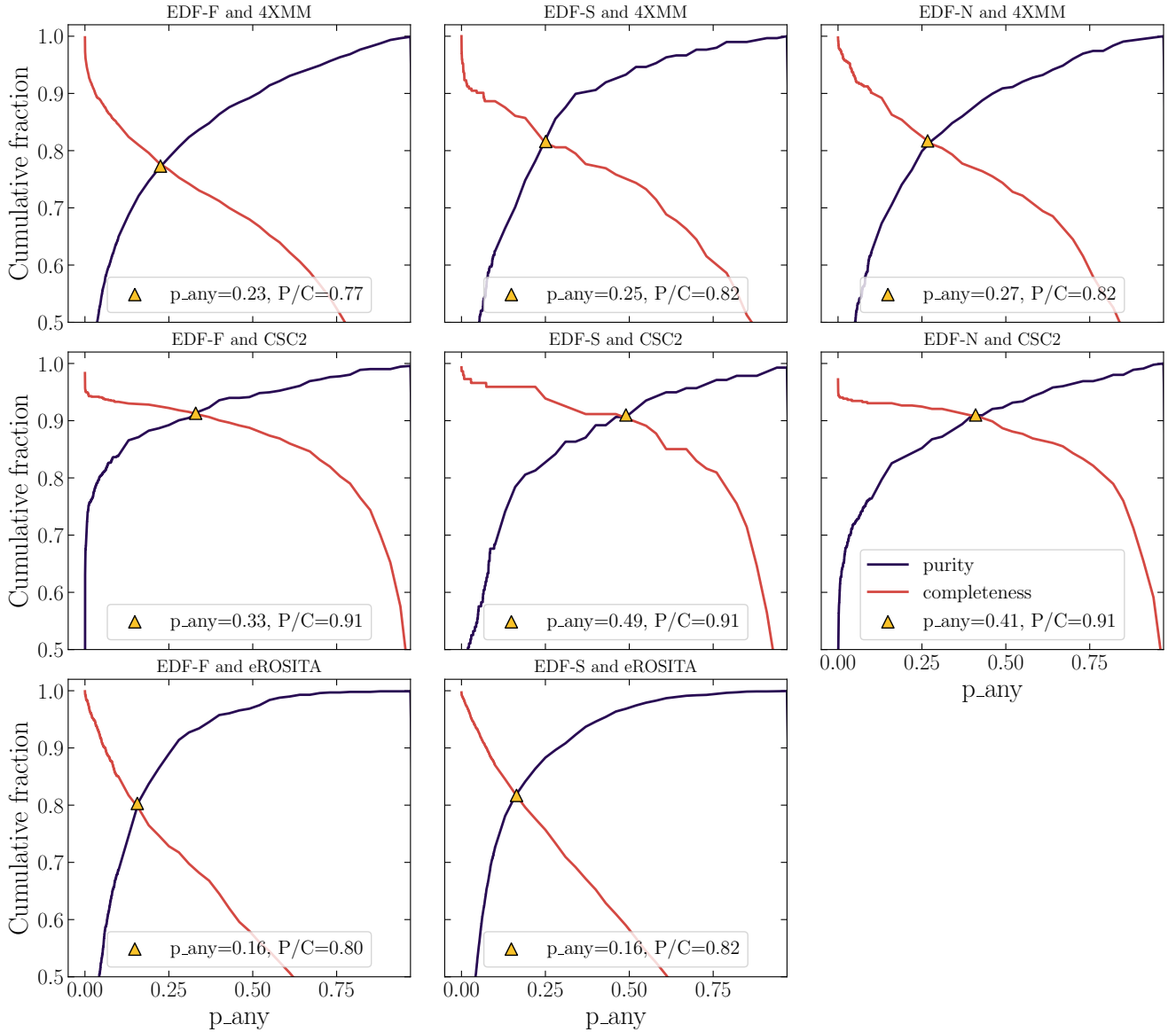


Fig. 7. Purity (red) and completeness (purple) as a function of p_{any} for matches between the different EDFs and the three X-ray catalogues: 4XMM DR14 (top row), CSC 2.0 (middle row), and eROSITA DR1 (bottom row). Based on these figures, users can adopt the p_{any} value threshold that enhances purity or completeness, depending on their scientific preference. The intersection point serves as a threshold for the p_{any} selection.

Among the surveys, only eROSITA uniformly covers two of the three fields. In contrast, other surveys consist of pointed observations with differing depths and catalogues across distinct bands, meaning sources are not always detected at the same flux levels. As a result, the overlap between catalogues is complex and interpreting source matches becomes challenging. At this stage, gaps in coverage further limit the significance of overlap checks. Keeping this in mind, we find 674 pairs which either correspond to case one or two, as well as 16 triplets referring to case three, as shown in Fig. 5. We deliberately choose not to quantify case four, as there is currently no definitive way to resolve it with certainty. A breakdown of the CTP sample is given in Table 3.

4.3. Purity and completeness

To calibrate a reliable p_{any} cut-off, we performed the NWAY procedure (using the same prior) on a duplicate sample of the

X-ray sources, referred to as ‘randoms’. These randoms were generated by displacing the positions of the X-ray sources to lie beyond the search radius, ensuring that any matches with multiwavelength CTPs are purely coincidental. By comparing the distribution of p_{any} values for both the original X-ray sample and the randoms, we could assess the impact of the prior by examining the two histograms in Fig. 4. The figure shows how the p_{any} value for the randoms is usually lower than for the real sample of X-ray sources, indicating that in a random position in the sky, there are no sources that have the same features as a typical X-ray emitter. For the few sources for which p_{any} remains high, either the prior was not representative enough, or, deeper data in the future will potentially reveal a fainter X-ray source.

To further assess the impact of incorporating $P_{\text{X-ray}}$ into the NWAY procedure, we compared the p_{any} values as a function of the separation distance between the primary (X-ray) and

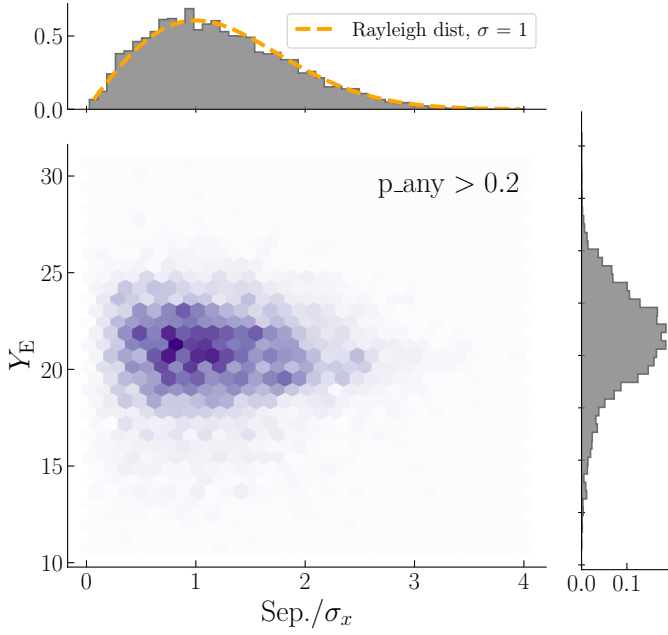


Fig. 8. Separation between the X-ray position and the selected CTP, where the Y_E magnitude for sources with CTPs ($p_{\text{any}} > 0.2$) is plotted against the normalised 1-dimensional positional error of the X-ray sources. The hexagonal bins are colour-coded linearly based on the count of sources within each bin. Marginal histograms show the distribution along the axes, with a linear y -axis scale. The expected 1σ Rayleigh distribution for the normalised separations is overlaid in orange.

secondary (multi-wavelength) sources. Figure 6 presents the separation between the 4XMM sources and the associated CTP in EDF-F as a function of p_{any} . The sources with a higher probability of being correct also have a high probability of being X-ray emitters, even at larger separations, the latter being mostly smaller than $10''$. CTPs of little separation and low p_{any} showcase scenarios of chance alignments where objects appear close but do not show significant $P_{\text{X-ray}}$. Next, we focused on evaluating the purity and completeness of the CTP samples based on how they are sub-selected. In this context, we defined completeness as the cumulative fraction of sources with p_{any} higher than a certain value and purity as the fraction of sources with p_{any} higher than the value in the random sample. This gives a measure of how often the CTP in the real sample is associated to a CTP only by chance.

Figure 7 shows both the purity and completeness for each EDF and X-ray survey as well as the ‘sweet spot’ for the best trade-off between these quantities as a function of p_{any} . Variations in the distributions result from differences in the positional uncertainties of the X-ray surveys and the source densities within both the X-ray data and the corresponding EDF. Depending on the scientific goal, a user interested in creating a catalogue that is extremely complete or pure is hence free to select sources with a p_{any} beyond a certain threshold. For the rest of the work, we adopt the intersection between the purity and completeness curves as the threshold. In all fields, purity and completeness are at least 80%, with the *Chandra* catalogues unsurprisingly having the most reliable associations, reaching values of about 90%. Interestingly, the impact of the higher spatial resolution of *Chandra* is clear in the EDF-F field, where Fornax, the second richest galaxy cluster of the local Universe, is located. In such a

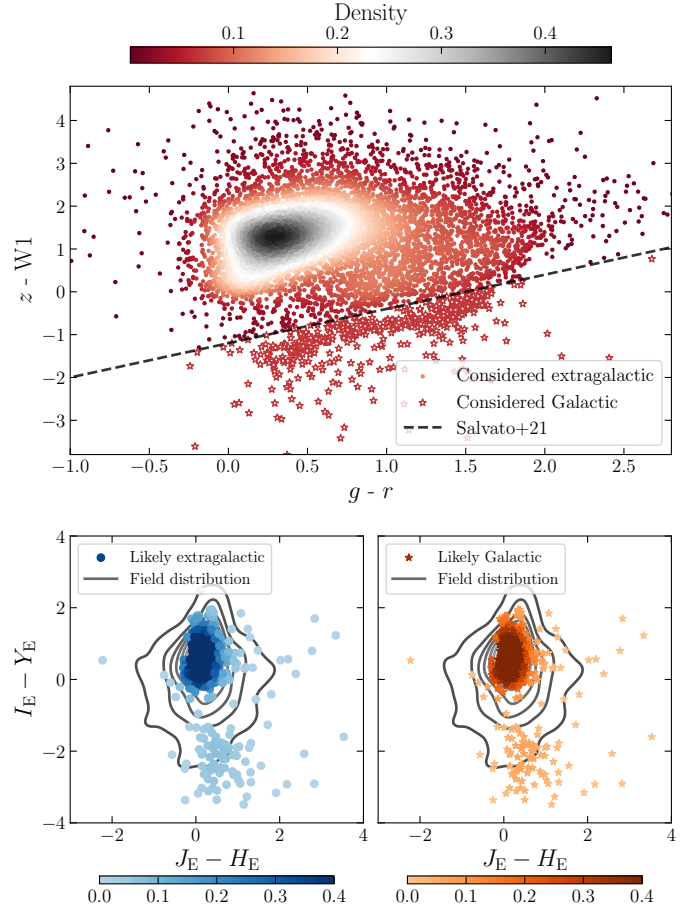


Fig. 9. Upper row: Colour-colour plot showing the positional matched *Euclid* CTPs to LS10 sources with ‘good’ photometry ($S/N > 3$), adapted from Salvato et al. (2022). This distribution is used to segment sources into Galactic and extragalactic classes. Lower row: *Euclid* colours for extragalactic (left) and Galactic (right) distributions plotted on top of the contours of *Euclid* field sources. The plots confirm that *Euclid* colours cannot differentiate between Galactic and extragalactic sources since both distributions are very similar.

dense environment, it is more challenging to identify the correct CTP given the resolution of 4XMM and eROSITA.

To conclude this part, we assessed the stability of the method by examining the impact of RF hyperparameters such as the minimum leaf size and features per tree. Variations in these parameters mainly shift the intersection of purity and completeness curves along the p_{any} axis, with smaller leaf sizes enhancing subclass specificity and subtly altering the intersection point.

4.4. Separation and magnitude distribution of CTPs

The distribution of observed X-ray-optical separations, normalised by the X-ray positional uncertainty, is presented in Fig. 8 as a function of the CTP’s Y_E -band magnitude. For a quality-selected sample of $p_{\text{any}} > 0.2$, this distribution well aligns with the expected Rayleigh distribution for a scale factor of $\sigma = 1$, indicating consistent behaviour with statistical expectations, demonstrating the reliability of the matching process (e.g., Salvato et al. 2022). The bulk of the sources have a mean separation of $1''.22$ and $Y_E = 20.65$.

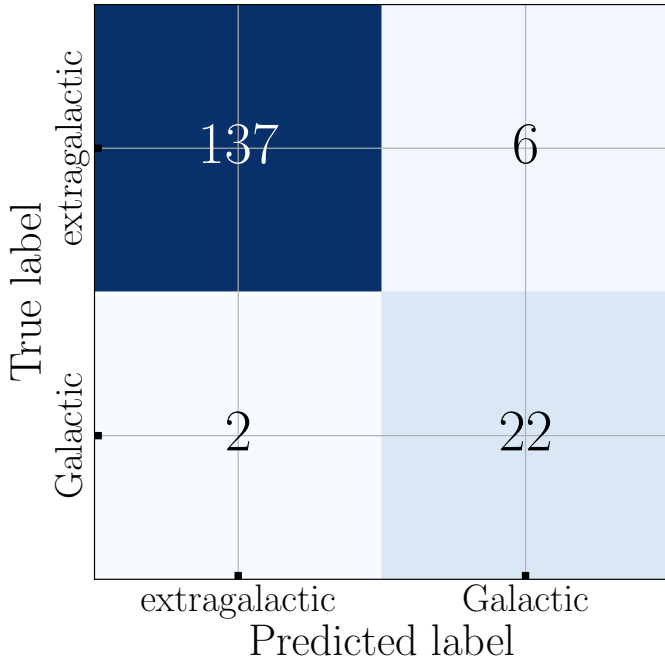


Fig. 10. Confusion matrix from the RF Galactic-extragalactic classifier applied to an independent test set. Sources classified as residing within the Milky Way are labelled as ‘Galactic’, while field objects are labelled as ‘extragalactic’.

5. Characterisation and classification of CTPs

Once the CTPs have been identified, it is essential to categorise the sources in order to study the underlying physical processes and populations. The primary distinction is between extragalactic sources (such as galaxies or faint and bright AGN) and galactic sources (including stars and compact objects). In the following section, we outline the methodology used for classifying the sources and the validation tests conducted to ensure the accuracy of the classification, the results of which are summarised in Table 3.

5.1. Galactic and extragalactic sources

The four *Euclid* bands alone lack the discriminatory power required to reliably separate Galactic from extragalactic sources, given the broadness of the optical filter, where most of the differences within the SED occur. As demonstrated in *Euclid* Collaboration: Bisigello et al. (2024), no combination of *Euclid*-only photometry achieves satisfactory fractions of purity and completeness for this task. Moreover, the ground-based photometry added to the Q1 catalogues is not completely cross-calibrated at this stage, and differences in quality and bands available differ from field to field. For this reason, we decided to use the photometry available in LS10, providing us with well-calibrated and reasonable depth in *griz* from DECam Legacy Survey observations, including data from the Dark Energy Survey (DES, *Dark Energy Survey Collaboration* 2016), Beijing-Arizona Sky Survey (BASS, *Zou et al.* 2017), and the Mayall *z*-band Legacy Survey (MzLS, *Silva et al.* 2016), as well as W[1,2,3,4] from the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE, *Mainzer et al.* 2011; *Lang* 2014; *Meisner et al.* 2017). We match the 11 286 CTPs to LS10 using a 1'' positional tolerance and find an association for 82% of our

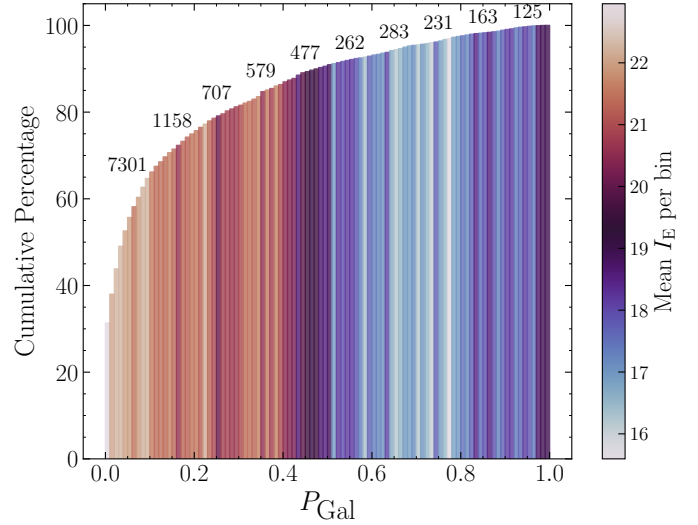


Fig. 11. Cumulative histograms showing the respective percentage of CTPs as a function of P_{Gal} . Values of $P_{\text{Gal}} < 0.5$ correspond to sources classified as extragalactic, while values above 0.5 classify them as being Galactic. Only roughly 8% of sources have $P_{\text{Gal}} > 0.5$, indicating a predominantly extragalactic population. In addition, each bin of the histogram is coloured by its mean I_E magnitude, while the sum of each set of ten adjacent bins is printed on top.

sources, see Table 3. Next, we apply a cut of $S/N > 3$ in the g , r , z , and W1 bands to minimise the relative impact of photometric uncertainties. The selected sources are then plotted on the z –W1 versus g – r colour-colour plane, to distinguish between Galactic and extragalactic objects (see Fig. 9). Using the separation line defined in *Salvato et al.* (2022), we preliminarily classify sources based on their location relative to the threshold. Objects above the threshold are flagged as extragalactic, while those below are classified as Galactic.

These classifications are then used to create individual subplots (lower panels of Fig. 9), displaying the sources by their classification using only *Euclid* colours. As highlighted in *Euclid* Collaboration: Bisigello et al. (2024), the Galactic and extragalactic sources trace almost the same feature space, confirming that *Euclid* photometry alone, comprising the I_E , Y_E , J_E , and H_E bands, does not provide sufficient information to reliably distinguish between the two populations.

5.2. Probabilistic classifier approach

To overcome this limitation, we followed the methodology outlined in Sect. 4.1.1, training an RF classifier using the same *Euclid*-only features listed in Table 2. However, this time we labelled the sample based on the classification derived from the z –W1 versus g – r plot, setting Galactic objects (396) to ‘1’ and extragalactic objects (1000) to ‘0’. Using the trained model, we assigned a Galactic or extragalactic label to each *Euclid* CTP, providing a probabilistic classification, P_{Gal} , for robust downstream analyses.

We present the respective confusion matrix in Fig. 10 and note a recall of 92%, with a limited fall-out of 4%. For more details on the feature correlations, see Appendix A. To further validate the RF performance, we examine the galactic probability distribution (P_{Gal}) for the unique CTP candidates sample. Less than 10% of sources have $P_{\text{Gal}} > 0.5$, indicating effective separation of Galactic and extragalactic populations. A comparison

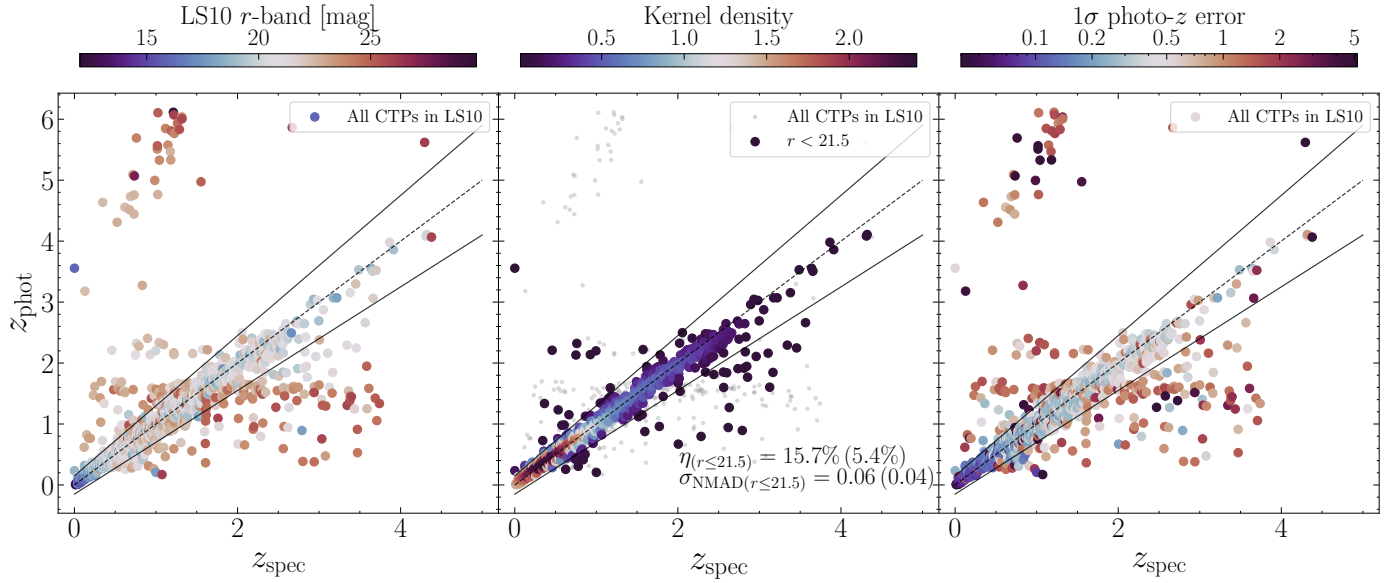


Fig. 12. Left: Photo- z vs spec- z for all CTPs matched to LS10 colour-coded by the LS10 r -band magnitude. Centre: Same distribution colour-coded according to the kernel density for sources with $r \leq 21.5$. Right: Same distribution colour-coded by the 1σ photo- z error ($z_{\text{phot,lsu}} - z_{\text{phot,lsl}}$). Sources closely following the identity line exhibit significantly lower errors as opposed to outliers, reflecting the photometric uncertainties of faint sources in LS10.

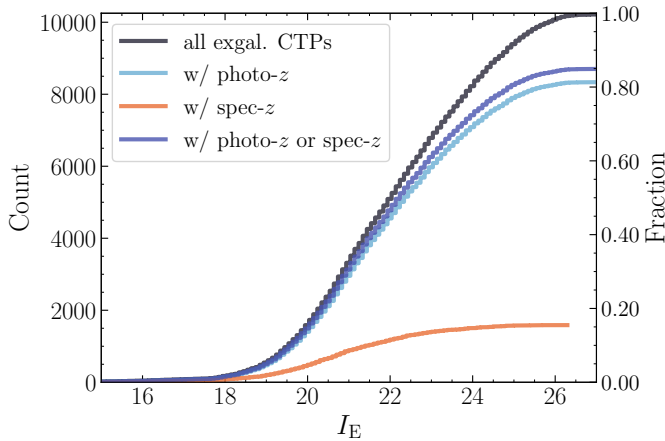


Fig. 13. Cumulative histogram showing the number of extragalactic CTPs according to $P_{\text{Gal}} \leq 0.5$ with spec- and/or photo- z as a function of their I_E magnitude.

with the Euclid Collaboration: Matamoro Zatarain et al. (2026) classification reveals that 97% of sources classified as Galactic there, also have $P_{\text{Gal}} > 0.5$, confirming good agreement. Additionally, the colour-coding of Fig. 11 reveals that most sources classified as being Galactic make up the bright end of the sample, with the most intense colour gradient surrounding $P_{\text{Gal}} = 0.5$ and a couple of sources towards high P_{Gal} interestingly appearing increasingly fainter again, probably due to different populations of stars, subject to their location in the extragalactic sky.

6. Redshifts

The catalogues of CTPs we make available in this paper include spectroscopic redshifts (spec- z s), where available. This was done by matching their coordinates to a compilation of publicly available redshifts (Kluge et al. 2024, Igo et al., in prep.). However, this compilation is rich in duplications; hence, the details of the

cleaning are described in Sect. 3.1 of Saxena et al. (2024). While spec- z s provide highly accurate distance measurements, they are inherently limited to a subset of typically brighter objects. As a result, only 16% of the CTP sample benefits from publicly available spec- z coverage (refer to Table 3).

6.1. Photometric redshifts

To achieve a more complete characterisation of the CTPs, photometric redshifts (photo- z) are essential. However, achieving reliable photo- z s for AGN remains significantly more challenging than for inactive galaxies, despite notable advances in recent years (see Salvato et al. 2019, for a review). The current Q1 photo- z s (Euclid Collaboration: Tucci et al. 2026), derived using Phosphoros (Paltani et al., in prep.), are estimated from total fluxes and fine-tuned for inactive galaxies. This approach neglects the photometric signatures of active nuclei, whose emission can dominate the observed flux and hide key host galaxy features, crucial for breaking colour-redshift degeneracies (Salvato et al. 2019). Instead, studies have demonstrated that incorporating aperture or pixel-based analyses can significantly enhance the accuracy of such photo- z estimates. Consequently, to compute reliable photo- z s for AGN-dominated objects in a dedicated effort, we utilise PICZL (Roster et al. 2024), an ML algorithm that significantly improves photo- z estimation for AGN by directly predicting redshifts from imaging, eliminating the need for manual feature extraction or combination of various surveys. Building on its predecessor, CIRCLEZ (Saxena et al. 2024), which analysed aperture-based photometric variations, PICZL advances to pixel-level resolution, leveraging the raw images for improved precision. As a result, for sources bright enough to successfully match the LS10 catalogue, we are able to produce reliable photo- z s (refer to Table 3). As in the original work, the uncertainty of the photo- z s in terms of 1σ error increases with the faintness of the sources (see Fig. 12 and Roster et al. 2024, for more details).

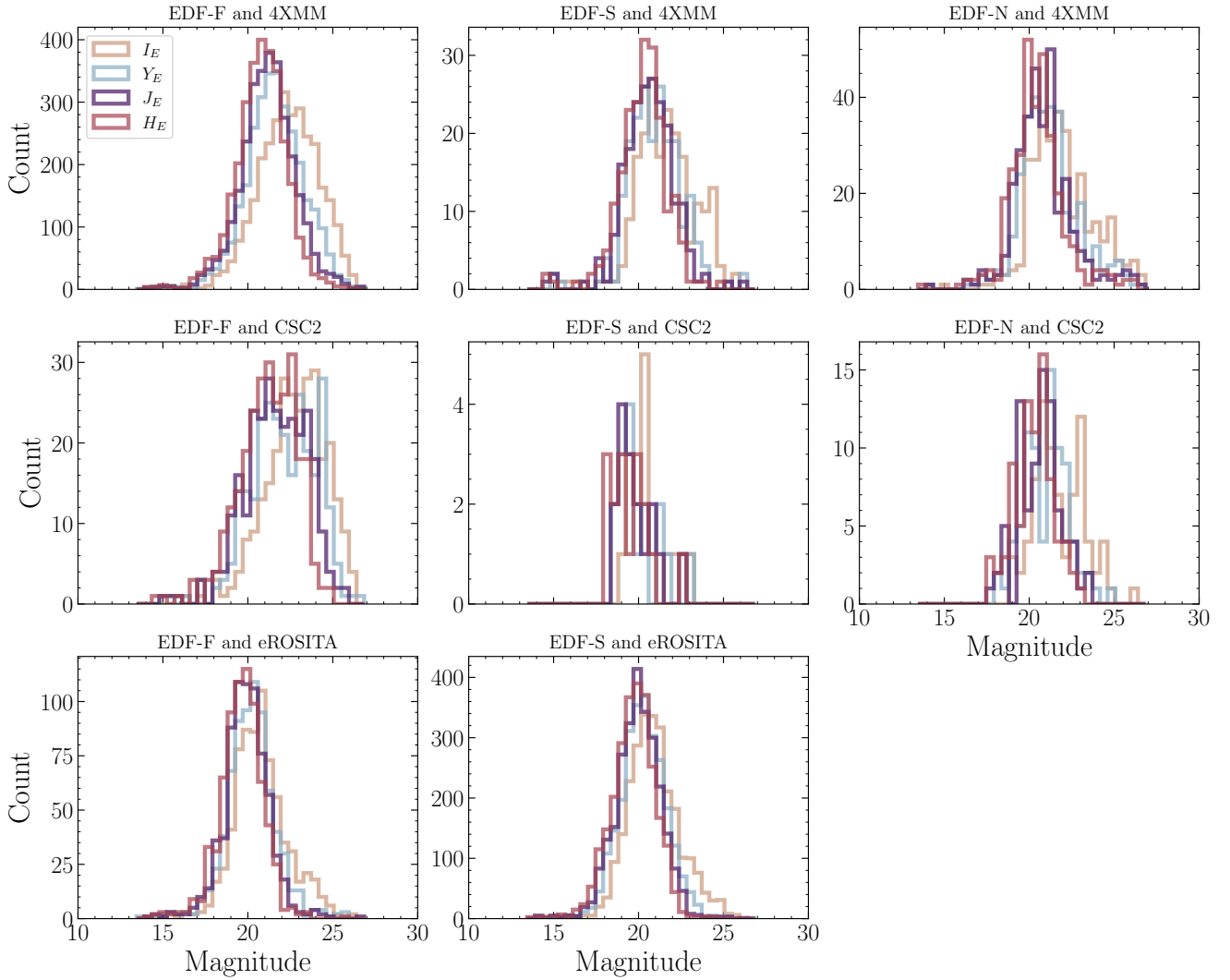


Fig. 14. Distribution of source counts for each combination of EDF (EDF-F, EDF-S, and EDF-N) and X-ray survey (4XMM on top row, CSC 2.0 in the middle one, and eROSITA DR1 in the bottom panels). Each plot presents the histograms corresponding to the four *Euclid* bands, depicting the count of sources as a function of magnitude.

This study does not incorporate *Euclid* photometry in the photo- z estimation, as doing so would require a dedicated pipeline, including re-training on *Euclid* imaging and assembling a spectroscopic AGN training set from the Q1 field. Given the small and incomplete nature of such a sample, especially at the faint end, this effort is deferred until DR1 becomes available. An additional challenge lies in the heterogeneous photometric coverage across Q1: while *Euclid* provides uniform measurements in I_E , Y_E , J_E , and H_E , these are complemented by ground-based data of varying depth and filter sets, leading to inconsistencies in photo- z quality. Consequently, to ensure robustness and comparability, we opted to rely on established methods, with PICZL offering high completeness and reliable redshifts for $\sim 82\%$ of the X-ray sources detected in LS10⁷ (see Fig. 13). Nonetheless, we recognise the potential of *Euclid* photometry to enhance our performance, particularly for faint sources and at high redshifts (Graham et al. 2020). As illustrated in the left panel of Fig. 12, numerous faint sources are dispersed horizontally around $z_{\text{phot}} \sim 1.6$, as no strong spec-

tral breaks can be captured by the Legacy filters around this redshift (Roster et al. 2024). Access to *Euclid*'s NIR bands Y_E , J_E , and H_E will enable more accurate redshift recovery in this range.

For all EDF CTPs of an X-ray source detected in LS10, PICZL provides full redshift posterior distributions (PDZ), derived from de-reddened calibrated images in the g , r , i , and z bands, supplemented by $W1$, $W2$, $W3$, and $W4$ catalogue-based aperture photometry without imposing any S/N cuts. The method is agnostic to the morphological classification of the source, applying equally to extended and point-like objects. As output, PICZL provides the dominant mode of the PDZ as a point prediction, along with uncertainties quantified as 1σ confidence intervals. Notably, we compute photo- z s also for those CTPs matched to LS10, which we believe to be Galactic. This approach accounts for the inherent uncertainty in the probabilities produced by our model and classification threshold. To ensure flexibility for users, we include both classifications and photo- z estimates in the released catalogue (see Sect. 8). This allows users to tailor their selection criteria to their preferences while retaining access to the full set of photo- z values.

⁷ Future PICZL versions will make use *Euclid* imaging, possibly combined with LSST (Ivezic et al. 2019).

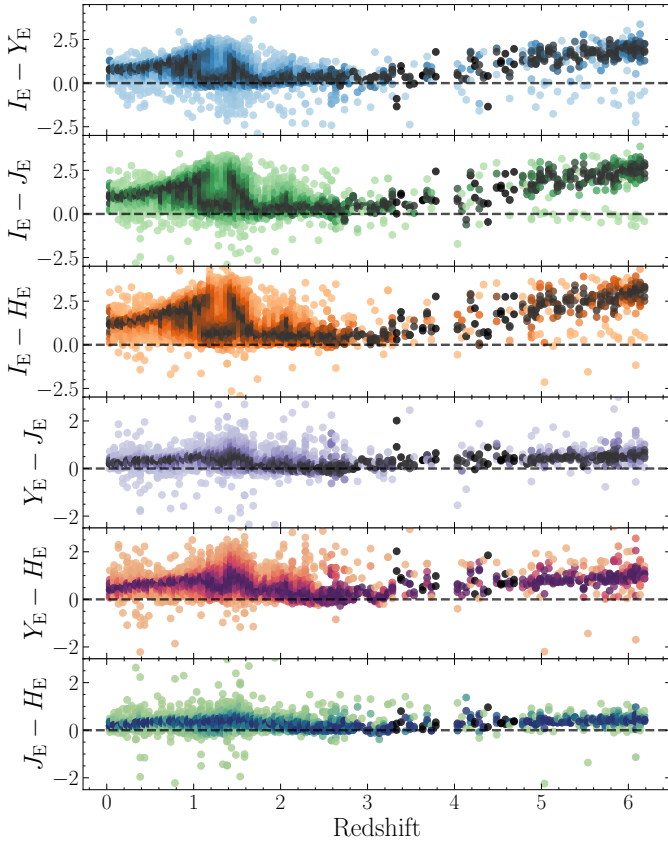


Fig. 15. Colour-redshift relation for all *Euclid* band combinations. Each panel is divided into redshift windows, with the density of points within each bin colour-coded along the dimension of the y -axis, illustrating spectral features in the SED.

6.2. Photo- z quality

To evaluate the reliability of our photo- z estimates, we employed standard metrics commonly implemented in the literature, including (a) the accuracy σ_{NMAD} as a measure of the scatter between the prediction and truth values of the sample, which is defined as

$$\sigma_{\text{NMAD}} = 1.4826 \text{ median} \left[\frac{|z_{\text{phot}} - z_{\text{spec}}|}{(1 + z_{\text{spec}})} \right]; \quad (7)$$

and (b) the fraction of outliers, η , that quantifies the proportion of sources whose redshift estimates deviate significantly from their corresponding spectroscopic redshift. Specifically, this is defined as the fraction of objects for which

$$\eta = \frac{|z_{\text{phot}} - z_{\text{spec}}|}{(1 + z_{\text{spec}})} > 0.15. \quad (8)$$

We evaluated the performance of the photo- z s by comparing them to the spec- z s, as shown in the middle panel of Fig. 12. For the subsample of bright sources with $r < 21.5$, corresponding to those that have smaller photometric errors within our dataset, we find a fraction of outliers of 5.4%, with a σ_{NMAD} of roughly 0.04 as opposed to $\eta = 15.7\%$ and $\sigma_{\text{NMAD}} = 0.06$ observed for the entire sample. The catastrophic outliers at $z_{\text{phot}} > 4$ appear as faint ($r > 24$), galaxy-dominated objects with larger photometric errors in LS10 and highly degenerate PDZs. In scientific studies involving photo- z s, it is crucial to account for such uncertainties and in turn, photo- z algorithms should provide reliable error

estimates. PICZL achieves this effectively as shown in the right panel of Fig. 12, with small errors closely following the identity line and larger ones capturing photometric uncertainties. Despite occasional higher uncertainties, point estimates remain robust, ensuring that for applications such as luminosity functions, the entire PDZs remain valuable.

In Fig. 13, we present the cumulative distribution of CTP I_E band magnitudes along with the corresponding fractions of sources for which spec- and/or photo- z s from PICZL are available. The figure demonstrates that redshift completeness is very high up to around $I_E \leq 22$, beyond which the availability of reliable photo- z estimates begins to decline. In addition to spectroscopic selection effects, this is due to fainter sources which, while clearly detected in *Euclid*, often lack sufficient optical coverage or exhibit photometric uncertainties too large to yield robust photo- z values. Future releases of PICZL, adapted to directly process *Euclid* imaging and incorporating the deeper and more complete photometry expected from the Legacy Survey of Space and Time (LSST; Ivezić et al. 2019), will markedly enhance photo- z performance for fainter AGN.

We compared our photo- z estimates with those from Duncan (2022), who combined ML and SED fitting to derive redshifts for all extragalactic sources in the 8th data release of the Legacy Survey (LS8). In EDFN, where LS10 photometry corresponds roughly to that of LS8, PICZL achieves a slight improvement in σ_{NMAD} (from 0.10 to 0.08) and a notable reduction in η (from 25% to 14%), without applying magnitude cuts. In the two additional fields covered by LS10-South (Zenteno et al. 2025), where PICZL also benefits from deeper WISE and added i-band photometry, the improvements are even more pronounced, with σ_{NMAD} improving from 0.09 to 0.05, and η dropping from 23% to 12%. Likewise, while the photo- z s from Zhou et al. (2021, 2023), computed with LS10 photometry, perform extremely well for inactive galaxies, a trend similar to Duncan (2022) is observed for AGN, where the accuracy is known to decline⁸. For high-redshift ($z > 3$) X-ray selected AGN, we compared our estimates to those of Pouliazis et al. (2025), computed using LS10 supplemented with near-infrared photometry from the VISTA Hemisphere Survey (VHS; McMahon et al. 2013). Of the 45 sources in common, only two have spec- z for which both photo- z agree, preventing any meaningful additional comparison. Instead, we can assess our photo- z quality for X-ray selected AGN at the faint end by benchmarking them against studies that employ significantly deeper and broader photometric datasets.

7. Properties of the CTP sample

Having successfully selected, classified, and vetted our CTPs, we now turn to an analysis of their properties. From this point forward, we refer to CTPs as those sources meeting the criteria of $P_{\text{Gal}} \leq 0.5$ and $p_{\text{any}} > 0.05$. This refined selection yields a total of 9294 sources from the initial 11 286 entries having `match_flag` = 1.

Building on this approach, we note that a similar comparison has already been presented in Roster et al. (2024), where PICZL photo- z s were evaluated against the XMM-SERVS catalogues from Chen et al. (2018) and Ni et al. (2021). Here, we extend this strategy by comparing our photo- z results with the 7 Ms Source Catalog from the *Chandra* Deep Field-South (CDFs, Luo et al. 2017). This catalogue is particularly well-suited for faint-end validation, as it includes photo- z s derived using high-quality multi-band data, largely informed by Hsu et al. (2014).

⁸ With η reaching up to $\sim 33\%$ in some subsets (priv. comm.).

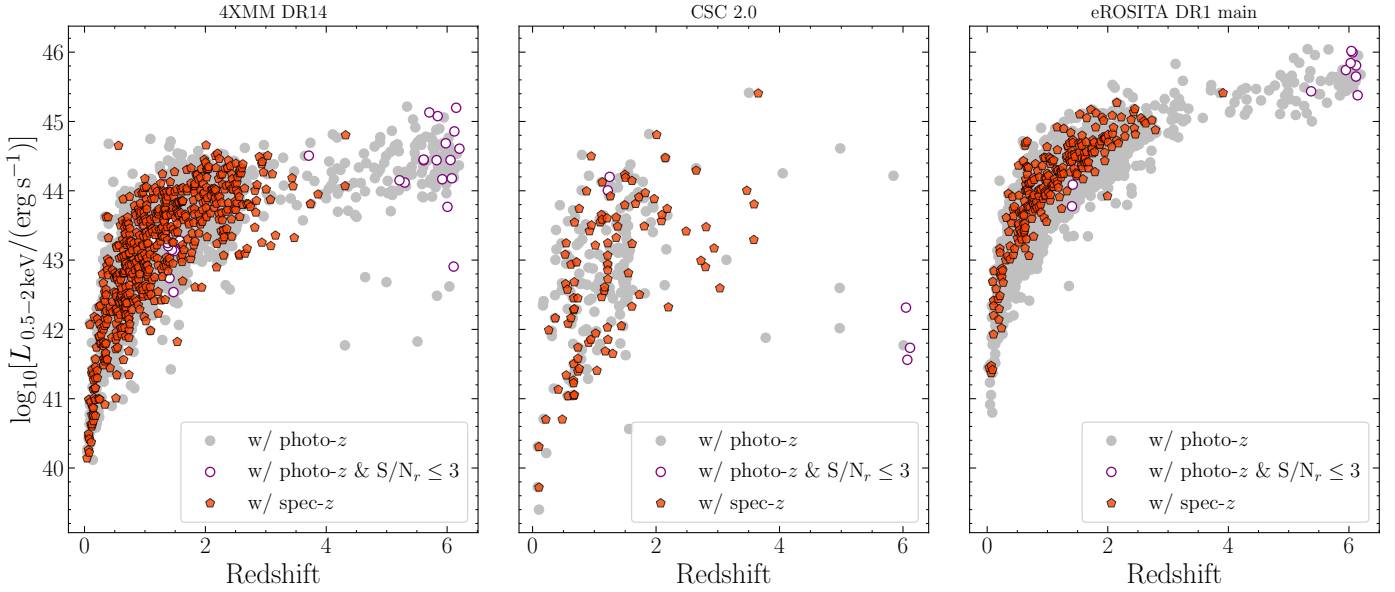


Fig. 16. X-ray luminosity as a function of redshift for the different surveys: 4XMM DR14 (left), CSC 2.0 (centre), and eROSITA DR1 main, (right). Grey circles represent sources with photometric redshifts, while orange pentagons indicate sources with spectroscopic redshifts. Less reliable photometric redshifts of $S/N_r \leq 3$ in LS10 are highlighted by a purple outline.

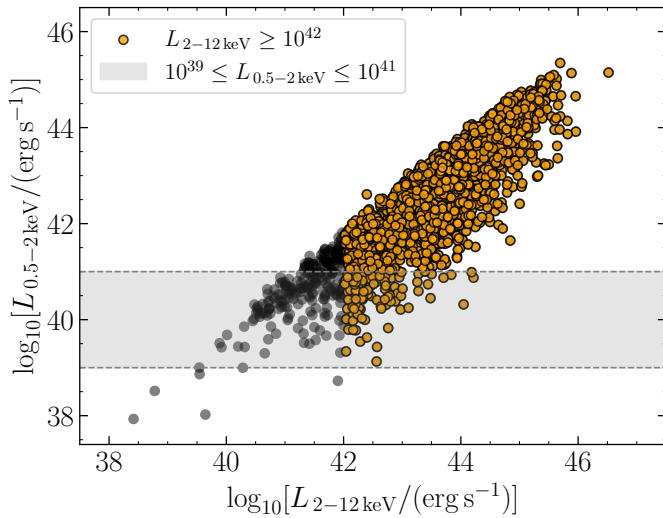


Fig. 17. Scatter plot of soft X-ray luminosities vs hard X-ray luminosities for their hard-band luminosities in the 4XMM-DR14 sample. Sources classified as AGN based on their hard-band luminosities are highlighted with orange markers. Using this classification, we establish a corresponding threshold in soft-band luminosity.

Utilising up to 38 intermediate and broad bands spanning the ultraviolet (*GALEX*, [Martin et al. 2005](#)) to the mid-infrared (*Spitzer*/IRAC, [Cardamone et al. 2010](#)), their work has resulted in one of the most comprehensive SED-fitting datasets for faint X-ray-selected sources to date. To ensure a proper one-to-one comparison between sources, we match our CTP catalogue to that of [Luo et al. \(2017\)](#) using the respective CTP coordinates. We recover the same CTPs across the full sample, with 97.5% of sources showing offsets below $0''.8$, with the largest observed separation being $1''.8$. Indicating robust matches, this consistency highlights the overall quality of our CTPs that can be attributed to the effectiveness of the *Euclid*-based prior used

with *NWAY*, providing a solid foundation for future applications. For the 400 sources with spec-zs matched between this work and [Luo et al. \(2017\)](#), we compare the two datasets by evaluating η and σ_{NMAD} as a function of r -band magnitude from the Wide Field Imager (WFI; [Giavalisco et al. 2004](#)). As depicted in Fig. B.1, PICZL achieves a lower fraction of outliers than [Luo et al. \(2017\)](#) for $r \lesssim 22.3$, though at larger σ_{NMAD} due to using only four shallower optical and WISE mid-IR bands. However, even up to $r \lesssim 24$ (25) PICZL extrapolation results in outlier fractions of $\eta \approx 7\%$ (13%), which is lower compared to, for example, eROSITA/eFEDS ([Salvato et al. 2022](#)), where the fraction is $\eta = 14.1\%$, despite using many more and deeper bands. Given the overall quality of [Luo et al. \(2017\)](#), we decided to extend redshift completeness in this work by incorporating 378 unique photo-zs from the 7 Ms Source Catalog.

Figure 14 illustrates the magnitude distribution of our CTPs, grouped by the match between EDFs and the corresponding X-ray survey (4XMM DR14, CSC 2.0, and eROSITA DR1, respectively). The 4XMM and CSC2 distributions show their ability to detect fainter X-ray sources, which correlates with the identification of fainter optical CTPs. In contrast, the eROSITA DR1 distributions exhibit brighter median magnitudes, consistent with the shallowness of the survey (see Fig. 2). Additionally, the figure suggests a possible bimodal distribution at the faint end in the optical band for both 4XMM and CSC 2.0, at least in EDF-N and EDF-S. The majority of sources in the second, faint peak of the distribution show X-ray fluxes $F_{(0.5-2\text{keV})} \leq 10^{-14.5} \text{ erg cm}^{-2} \text{ s}^{-1}$, with no obvious drop off in p_{any} , and the distribution will be studied further in other papers.

7.1. Colour-redshift relation

Redshifts, spectroscopic and photometric, are available for 81% of the CTPs, allowing us to analyse their *Euclid* colours as a function of redshift, as shown in Fig. 15. The colour-coded kernel density is plotted along the y -axis dimension within each bin, providing a visual trace of how the physical colours of the CTP sample vary as a function of redshift.

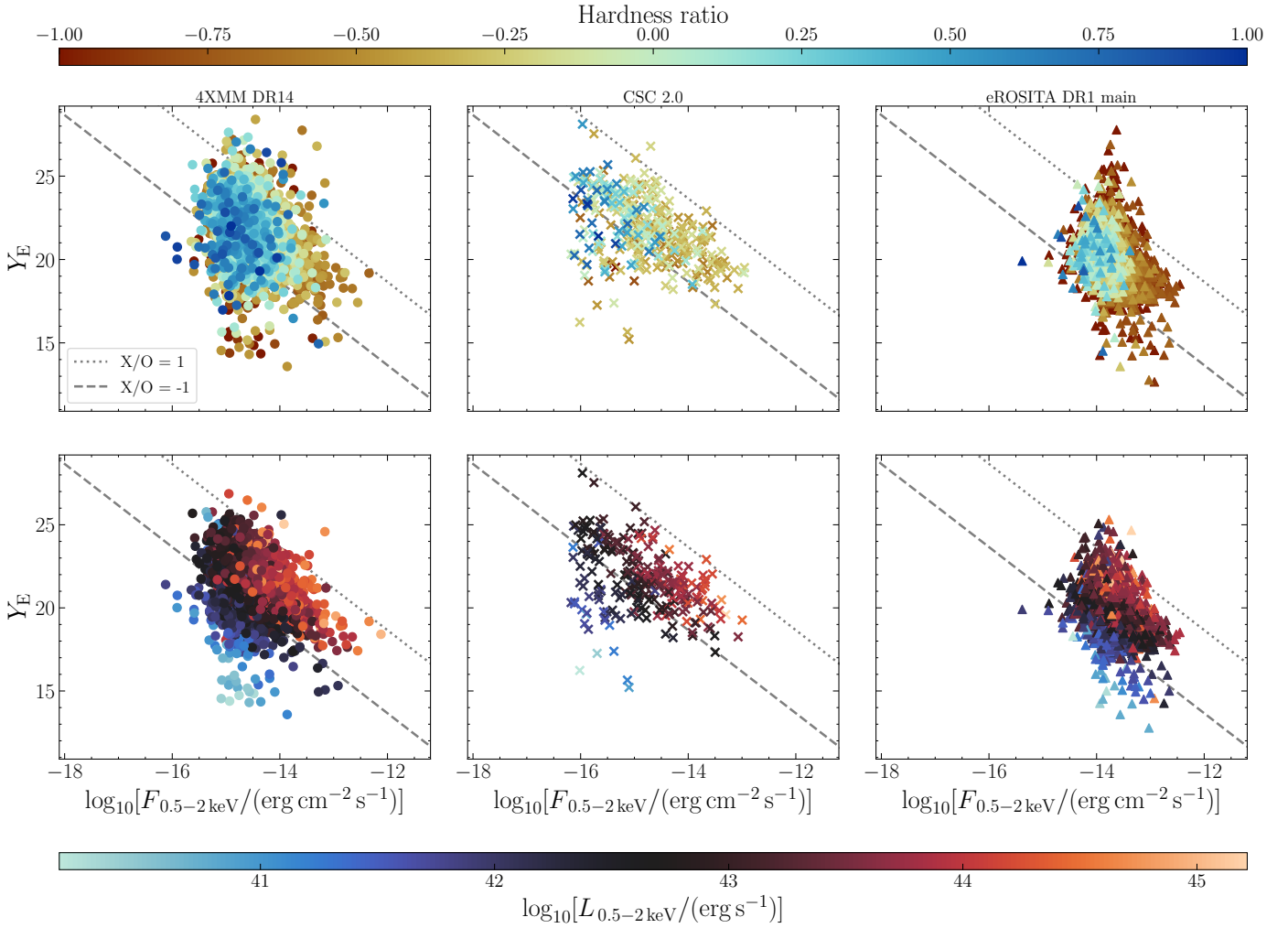


Fig. 18. Distribution of the Y_E magnitude as a function of soft X-ray flux for the three catalogues studied in this work: 4XMM DR14 (left), CSC 2.0 (centre), and eROSITA DR1 main (right). In each subplot, the dashed lines indicate the $|X/O| = 1$ trend, with sources lying between the lines ($|X/O| < 1$) usually being identified as AGN. The scatter points are colour-coded by their respective hardness ratio (top) and X-ray luminosity (bottom), when available. The markers are plotted in order of increasing hardness ratio.

A notable feature in the data is the detection of the Balmer break at $z \approx 1.3$, particularly prominent in colours including the I_E filter. Unsurprisingly, NIR-only colour combinations display relatively few discernible features (compare e.g., Figure 7 in Temple et al. 2021). As iterated before, *Euclid* filters alone lack the fidelity to catch variations in the SED of sources, a caveat that we will be able to overcome in combination with upcoming surveys, especially LSST.

7.2. X-ray luminosities

For the rest of the analysis, we restrict the CTP sample to those 7345 extragalactic sources with a soft X-ray flux $S/N_x \geq 2$ in order to reduce potential spurious X-ray detections. In Fig. 16, we observe a clear distinction between pointed observations taken with XMM-Newton and Chandra at various depths versus the homogenous all-sky coverage provided by eROSITA. The complete coverage of eROSITA results in a tighter correlation between luminosity and redshift, despite the presence of a few points away from the general trend, with $S/N_x < 3$. Another reason for their offset from the general trend could be erroneous photo- z . On the other hand, XMM-Newton and Chandra cata-

logues include a mixture of pointed observations, resulting in a less smooth distribution between redshift and luminosity.

In all three panels, we indicate with open circles sources with low S/N_r , presumably representing examples of increased redshift uncertainties. Notably, most of the results shown focus on objects with redshifts of $z < 4$. Sources with higher redshifts, while present, should be approached with caution due to potential inaccuracies. However, the future availability of LSST photometry will enable the exploration of this parameter regime by probing fainter sources with smaller errors, thus improving the reliability of redshift estimates for these populations.

In studies such as that of Georgakakis & Nandra (2011), AGN are typically defined as sources with X-ray luminosities exceeding $L_{(2-10 \text{ keV})} \geq 10^{42} \text{ erg s}^{-1}$, since normal galaxies may be an important source of contamination below this limit (Lehmer et al. 2012; Aird et al. 2015). However, it is important to note that this threshold was established based on pencil-beam surveys, suggesting that it should be revisited now that wide-area surveys and deep optical data are accessible. X-ray luminosities of AGN in the soft X-ray band (0.5–2 keV) can vary significantly, depending on the AGN type and redshift. In literature, values can range from $L_{(0.5-2 \text{ keV})} \geq 10^{41} - 10^{46} \text{ erg s}^{-1}$ or even

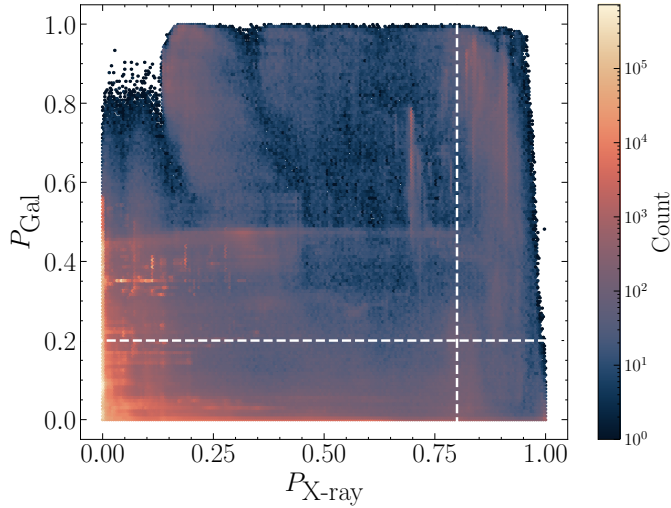


Fig. 19. Hexbin plot illustrating the relationship between the probability of being an X-ray emitter and the probability of being Galactic for all sources in Q1. The plot is colour-coded by the logarithmic kernel density. Orientation lines are included at an X-ray probability of 0.8 and a Galactic probability of 0.2.

less when considering low-luminosity AGN (Hasinger et al. 2005; Ebrero et al. 2009; Civano et al. 2012; Kawamuro et al. 2013). According to Georgakakis et al. (2007), for example, X-ray detected starburst galaxy candidates, though more likely in case of *Chandra* as opposed to eROSITA (Kyritsis et al. 2025), can represent about 20% of the X-ray source population in the luminosity interval $L_{(2-10\text{ keV})} \geq 10^{40}-10^{42} \text{ erg s}^{-1}$. This fraction is also likely to be an upper limit because some of the galaxy candidates may turn out to be low-luminosity AGN, such that distinguishing between these sources can be challenging. Consequently, with sources from XMM-Newton, where both soft and hard (2–12 keV)⁹ band fluxes are available, we show that, to retain all sources in this parent catalogue that are classified as AGN using the hard band limit, a soft-band luminosity threshold of $L_{(0.5-2\text{ keV})} \geq 10^{39} \text{ erg s}^{-1}$ is required (refer to Fig. 17). Given the results of both all-sky and pencil beam surveys, at soft luminosities in the range $10^{39}-10^{41} \text{ erg s}^{-1}$, AGN still appear to represent the dominant population. Nonetheless, future studies are required to determine the nature of these low-luminosity AGN at soft energies. Applying this more inclusive threshold defined in Fig. 17 to our extragalactic CTP sample, all of the 6653 (91%) sources that we were able to compute X-ray luminosities for, meet the AGN definition criterion, 49 of which have $L_{(0.5-2\text{ keV})} < 10^{41} \text{ erg s}^{-1}$.

7.3. AGN type

In Fig. 18, we plot the respective Y_E -band magnitudes as a function of the soft X-ray fluxes for all CTPs classified as extragalactic. We add the $|X/O| = 1$ lines (Maccacaro et al. 1988), which confine the typical AGN locus (see also e.g., Salvato et al. 2011; Civano et al. 2012), defined as

$$X/O = \log_{10}(F_x/F_{\text{opt}}) = \log_{10}\left(\frac{F_x/F_{\text{opt}}}{\text{erg cm}^{-2} \text{ s}^{-1}}\right) \frac{m_{\text{opt}}}{2.5} + C, \quad (9)$$

⁹ We assume that at zero order, the luminosities between (2–10) and (2–12) keV are approximately the same.

where F_x is the X-ray flux in a given energy range, m_{opt} and C correspond to the magnitude and a constant which both depend on the specific filter used in the optical observations. For Y_E we find $C = 5.53$. To further assess the AGN type of our CTPs, we colour-code the plots in the bottom row of Fig. 18 by the X-ray luminosity and the top row by hardness ratio (Hasinger et al. 2005; Cappelluti et al. 2007; Salvato et al. 2009), defined as

$$\text{HR} = \frac{\text{Count rate}_{\text{hard}} - \text{Count rate}_{\text{soft}}}{\text{Count rate}_{\text{hard}} + \text{Count rate}_{\text{soft}}}, \quad (10)$$

where soft corresponds to the 0.5–2.0 keV detection band, and hard refers to 2.0–12.0 keV PN thin for 4XMM DR14, 2.0–7.0 keV ACIS-I for *Chandra*, and 2.0–5.0 keV for eROSITA DR1 respectively, to account for each instrument’s flux sensitivity. This ensures as much consistency as possible across the different surveys, to make the different instruments somewhat comparable. A negative HR value indicates soft, unobscured sources (type I), and a positive HR value suggests harder, likely obscured sources (type II). We examine the HR distributions for all three telescopes to assess differences in their observed AGN populations. However, a non-negligible fraction of sources lack hard-band detections: approximately 47.6% for eROSITA, 14.5% for XMM-Newton, and 7.3% for *Chandra*. These non-detections, especially in the case of eROSITA, naturally shift the medians of the true HR distributions and introduce selection biases. As shown in Fig. C.1, we find that the eROSITA HR distribution median is $\text{HR} \approx -0.88$, while that of *Chandra* and (XMM-Newton) show a similar tendency towards harder values with medians of $\text{HR} \approx -0.33$ (–0.39). These HR medians can then be used to compute ‘effective’ photon indices Γ_{eff} , which we find to be $\Gamma_{\text{eff}} = 2.18$ for eROSITA, $\Gamma_{\text{eff}} = 1.65$ for *Chandra*¹⁰ and $\Gamma = 1.51$ for XMM-Newton, assuming negligible column density. As expected, the greater sensitivity of XMM-Newton and *Chandra* at higher energies allows them to detect harder and possibly mildly obscured AGNs that are missed by eROSITA. Conversely, eROSITA tends to detect brighter AGN which exhibit softer X-ray spectra. As the markers in Fig. 18 are plotted in order of increasing HR, many softer sources in the background are being covered up and predominantly fall within the X/O boundaries, classifying them as AGN, with differently weighted populations visible for every X-ray survey. As observed for XMM-Newton and *Chandra*, this includes a population of sources with $F_{(0.5-2\text{ keV})} < 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ lying below the X/O boundaries, potentially corresponding to starburst galaxies, low-luminosity AGN, or obscured AGN. However, the majority of these sources show $S/N_x \leq 3$ in the soft X-ray band, suggesting that a few of these may be spurious detections. It is also plausible that these sources are intrinsically variable, suggesting that they were observed in different states of appearance. Overall, our distribution follows the findings of Merloni et al. (2014), which show that only approximately 80% of AGN selected by their SED, spectral features and HR, match their expected type I/II class.

8. Release of the catalogue

The catalogue containing the CTP properties of the EDF point-like X-ray sources is available at the CDS (see Data availability section). A detailed description of the

¹⁰ Adopting CHANDRA-Cycle 11 as a representative benchmark, as it reflects an intermediate instrumental state within the ~20-year span of observations included in CSC 2.0, accounting for the effects of detector degradation over time.

columns and their content is provided in Appendix D. The catalogue includes unique identifiers for all relevant surveys as well as the basic X-ray and *Euclid* properties (Columns 1–14). For the full list of available columns, please refer to the original catalogues introduced in Sect. 3 and, for example, [Euclid Collaboration: McCracken et al. \(2026\)](#), [Euclid Collaboration: Polenta et al. \(2026\)](#), [Euclid Collaboration: Romelli et al. \(2026\)](#). Columns 15–24 present the results of the CTP association, followed by key parameters derived from *NWAY*. Photometric data from LS10 are reported in Columns 25–27. Spectroscopic information, when available, is included in Columns 28–32. Lastly, the photometric redshift parameters from the PICZL algorithm, as well as quantities computed with such, are listed in Columns 33–39.

9. Conclusions and outlook

In this paper, we have presented the procedure adopted for the identification, classification, and study of the *Euclid* CTPs of the point-like sources selected from *XMM-Newton*, *Chandra*, and *eROSITA* X-ray, detected in Q1. We summarise the most important results in the following.

- Utilising *NWAY* ([Salvato et al. 2018](#)) supplemented by a prior on X-ray emission based on properties of a 4XMM DR11 and CSC 2.0 training sample, we achieved highly accurate CTP identifications while relying on *Euclid* photometry only (see Sect. 4). By randomising the X-ray position and repeating the same procedure for the association, we quantified for each X-ray source the probability of chance associations. Users will be able to create subsamples of CTPs of desired purity and completeness by applying more restrictive or inclusive p_{any} cuts (probability of an X-ray source having a CTP; see Fig. 7).
- Altogether, we have identified 12 645 CTPs, with only about 10% of the sources having more than a single possible CTP. These are mostly in the *XMM-Newton* and *eROSITA* surveys, due to their larger positional uncertainties compared to *Chandra*. We attribute this performance to the availability of extensive X-ray detected samples with secure CTPs and deep, homogenised multiwavelength photometry spanning optical to MIR wavelengths enabling robust SED construction for training. Further expansion to broader multiwavelength coverage will improve the quality of CTP identification, particularly for *Euclid* DR1.
- We trained an RF algorithm to classify objects as Galactic or extragalactic using solely *Euclid* photometry in Sect. 5. We previously trained another RF on a sample of secure Galactic and extragalactic sources detected in LS10, using $g - r$ over z -W1 thresholds, as presented in [Salvato et al. \(2022\)](#), effectively breaking the degeneracy in classification that arises when relying on *Euclid* photometry alone (see [Euclid Collaboration: Bisigello et al. 2024](#)). We validated these classifications by comparing to [Euclid Collaboration: Matamoro Zatarain et al. \(2026\)](#).
- We also added spectroscopic redshifts for 16% of the CTP sample using publicly available data. For the 82% of the sample detected in LS10, we computed photo- z using PICZL ([Roster et al. 2024](#)), reaching up to $z \approx 6$. However at these high redshifts, the values are associated with large uncertainties. With all of these redshifts, we investigated the colour-redshift relation of our sample in addition to computing their X-ray luminosities (refer to Sect. 6). We find that all of our CTPs pass our soft X-ray luminosity threshold to be consid-

ered an AGN, with more of them appearing as bright type I sources rather than type II.

- As the primary outcome of this paper, we present the CTP catalogue, which includes a wealth of information such as IDs, basic X-ray properties, *NWAY* outputs, classification probabilities, and redshift data (see Sect. 8). By providing probabilities for all applicable sample characteristics, we ensure users have the flexibility to make informed selections tailored to their specific scientific goals, without being constrained by predefined thresholds or assumptions.

The RF models used for the identification of the CTPs and their classification as Galactic or extragalactic, can be applied blindly to the entire Q1 catalogue. For each source, they provide the probability of being an X-ray emitter as well as an extragalactic source, despite not having been detected by any of the three X-ray surveys yet. Consequently, as illustrated in Fig. 19, limiting the selection of Q1 sources to those with $P_{\text{X-ray}} > 0.8$ and $P_{\text{Gal}} > 0.2$ while excluding *Euclid* sources classified as CTPs in this study yields a final sample of 135 303 objects. Notably, 73 of these objects have been successfully cross-matched geometrically with the little red dots (LRDs) sample introduced by [Euclid Collaboration: Bisigello et al. \(2026\)](#), where the matches predominantly occupy the bright end of the LRD magnitude distribution. A forthcoming paper will explore the multi-wavelength nature of the likely extragalactic high $P_{\text{X-ray}}$ sources that remain undetected in current X-ray surveys.

Data availability

The catalog is available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/711/A16>

Acknowledgements. WR and MS acknowledge DLR support (Foerderkennzeichen 50002207). This work has benefited from the support of Royal Society Research Grant RGS/R1/231450. This research was supported by the International Space Science Institute (ISSI) in Bern, through ISSI International Team project N. 23-573 “Active Galactic Nuclei in Next Generation Surveys”. BL and FR acknowledge the support from the INAF Large Grant “AGN and Euclid: a close entanglement” Ob. Fu. 01.05.23.01.14. This research has made use of data obtained from the Chandra Source Catalog provided by the Chandra X-ray Center (CXC), and the 4XMM *XMM-Newton* serendipitous source catalogue compiled by the *XMM-Newton* Survey Science Centre consortium. This work is based on data from *eROSITA*, the soft X-ray instrument aboard SRG, a joint Russian-German science mission supported by the Russian Space Agency (Roskosmos), in the interests of the Russian Academy of Sciences represented by its Space Research Institute (IKI), and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The SRG spacecraft was built by Lavochkin Association (NPOL) and its subcontractors, and is operated by NPOL with support from the Max Planck Institute for Extraterrestrial Physics (MPE). The development and construction of the *eROSITA* X-ray instrument was led by MPE, with contributions from the Dr. Karl Remeis Observatory Bamberg & ECAP (FAU Erlangen-Nuernberg), the University of Hamburg Observatory, the Leibniz Institute for Astrophysics Potsdam (AIP), and the Institute for Astronomy and Astrophysics of the University of Tübingen, with the support of DLR and the Max Planck Society. The Argelander Institute for Astronomy of the University of Bonn and the Ludwig Maximilians Universität Munich also participated in the science preparation for *eROSITA*. Based on data from UNIONS, a scientific collaboration using three Hawaii-based telescopes: CFHT, Pan-STARRS, and Subaru www.skysurvey.cc and data from the Dark Energy Camera (DECam) on the Blanco 4-m Telescope at CTIO in Chile <https://www.darkenergysurvey.org>. This work uses results from the ESA mission *Gaia*, whose data are being processed by the Gaia Data Processing and Analysis Consortium <https://www.cosmos.esa.int/gaia>. The authors thank Pietro Baldini for valuable additional feedback and discussion. The Euclid Consortium acknowledges the European Space Agency and a number of agencies and institutes that have supported the development of *Euclid*, in particular the Agenzia Spaziale Italiana, the Austrian Forschungsförderungsgesellschaft funded through BMK, the Belgian Science Policy, the Canadian Euclid Consortium, the Deutsches Zentrum für Luft- und Raumfahrt, the DTU Space and the Niels Bohr Institute in Denmark, the French Centre National d’Etudes Spatiales, the Fundação para a Ciência e a Tecnologia,

the Hungarian Academy of Sciences, the Ministerio de Ciencia, Innovación y Universidades, the National Aeronautics and Space Administration, the National Astronomical Observatory of Japan, the Nederlandse Onderzoekschool Voor Astronomie, the Norwegian Space Agency, the Research Council of Finland, the Romanian Space Agency, the State Secretariat for Education, Research, and Innovation (SERI) at the Swiss Space Office (SSO), and the United Kingdom Space Agency. A complete and detailed list is available on the *Euclid* web site (www.euclid-ec.org). This work has made use of the *Euclid* Quick Release (Q1) data from the *Euclid*/mission of the European Space Agency (ESA), 2025, <https://doi.org/10.57780/esa-2853f3b>. This work has made use of CosmoHub, developed by PIC (maintained by IFAE and CIEMAT) in collaboration with ICE-CSIC. CosmoHub received funding from the Spanish government (MCIN/AEI/10.13039/501100011033), the EU NextGeneration/PRTR (PRTR-C17.11), and the Generalitat de Catalunya.

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- ¹ Max Planck Institute for Extraterrestrial Physics, Giessenbachstr. 1, 85748 Garching, Germany
- ² INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
- ³ Dipartimento di Fisica e Astronomia, Università di Firenze, via G. Sansone 1, 50019 Sesto Fiorentino, Firenze, Italy
- ⁴ Department of Physics, Centre for Extragalactic Astronomy, Durham University, South Road, Durham DH1 3LE, UK
- ⁵ INAF-Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
- ⁶ Instituto de Astrofísica de Canarias (IAC), Departamento de Astrofísica, Universidad de La Laguna (ULL), 38200 La Laguna, Tenerife, Spain
- ⁷ Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, 08193 Barcelona, Spain
- ⁸ INAF-Osservatorio Astronomico di Capodimonte, Via Moiarriello 16, 80131 Napoli, Italy
- ⁹ School of Physics, HH Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK
- ¹⁰ Department of Mathematics and Physics, Roma Tre University, Via della Vasca Navale 84, 00146 Rome, Italy
- ¹¹ INAF-Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monteporzio Catone, Italy
- ¹² Instituto de Astrofísica de Canarias, Vía Láctea, 38205 La Laguna, Tenerife, Spain
- ¹³ Universidad de La Laguna, Departamento de Astrofísica, 38206 La Laguna, Tenerife, Spain
- ¹⁴ Dipartimento di Fisica e Astronomia “Augusto Righi” – Alma Mater Studiorum Università di Bologna, via Piero Gobetti 93/2, 40129 Bologna, Italy
- ¹⁵ Université Paris-Saclay, CNRS, Institut d’astrophysique spatiale, 91405 Orsay, France
- ¹⁶ ESAC/ESA, Camino Bajo del Castillo, s/n., Urb. Villafranca del Castillo, 28692 Villanueva de la Cañada, Madrid, Spain
- ¹⁷ School of Mathematics and Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK
- ¹⁸ INAF-Osservatorio Astronomico di Brera, Via Brera 28, 20122 Milano, Italy
- ¹⁹ Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France
- ²⁰ IFPU, Institute for Fundamental Physics of the Universe, via Beirut 2, 34151 Trieste, Italy
- ²¹ INAF-Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34143 Trieste, Italy
- ²² INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste TS, Italy
- ²³ SISSA, International School for Advanced Studies, Via Bonomea 265, 34136 Trieste TS, Italy
- ²⁴ Dipartimento di Fisica e Astronomia, Università di Bologna, Via Gobetti 93/2, 40129 Bologna, Italy
- ²⁵ INFN-Sezione di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
- ²⁶ INAF-Osservatorio Astronomico di Padova, Via dell’Osservatorio 5, 35122 Padova, Italy
- ²⁷ Space Science Data Center, Italian Space Agency, via del Politecnico snc, 00133 Roma, Italy
- ²⁸ Dipartimento di Fisica, Università di Genova, Via Dodecaneso 33, 16146 Genova, Italy
- ²⁹ INFN-Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
- ³⁰ Department of Physics “E. Pancini”, University Federico II, Via Cinthia 6, 80126 Napoli, Italy
- ³¹ Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, PT4150-762 Porto, Portugal
- ³² Faculdade de Ciências da Universidade do Porto, Rua do Campo de Alegre, 4150-007 Porto, Portugal
- ³³ Dipartimento di Fisica, Università degli Studi di Torino, Via P. Giuria 1, 10125 Torino, Italy
- ³⁴ INFN-Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
- ³⁵ INAF-Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese (TO), Italy
- ³⁶ European Space Agency/ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
- ³⁷ Institute Lorentz, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands
- ³⁸ Leiden Observatory, Leiden University, Einsteinweg 55, 2333 CC Leiden, The Netherlands
- ³⁹ INAF-IASF Milano, Via Alfonso Corti 12, 20133 Milano, Italy
- ⁴⁰ Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avenida Complutense 40, 28040 Madrid, Spain
- ⁴¹ Port d’Informació Científica, Campus UAB, C. Albareda s/n, 08193 Bellaterra (Barcelona), Spain
- ⁴² Institute for Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, 52056 Aachen, Germany
- ⁴³ INFN section of Naples, Via Cinthia 6, 80126 Napoli, Italy
- ⁴⁴ Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
- ⁴⁵ Dipartimento di Fisica e Astronomia “Augusto Righi” – Alma Mater Studiorum Università di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
- ⁴⁶ Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
- ⁴⁷ Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK
- ⁴⁸ European Space Agency/ESRIN, Largo Galileo Galilei 1, 00044 Frascati, Roma, Italy
- ⁴⁹ Université Claude Bernard Lyon 1, CNRS/IN2P3, IP2I Lyon, UMR 5822, Villeurbanne F-69100, France
- ⁵⁰ Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, 08028 Barcelona, Spain
- ⁵¹ Institució Catalana de Recerca i Estudis Avançats (ICREA), Pas-seig de Lluís Companys 23, 08010 Barcelona, Spain
- ⁵² UCB Lyon 1, CNRS/IN2P3, IUF, IP2I Lyon, 4 rue Enrico Fermi, 69622 Villeurbanne, France
- ⁵³ Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK

- ⁵⁴ Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Edifício C8, Campo Grande, PT1749-016 Lisboa, Portugal
- ⁵⁵ Instituto de Astrofísica e Ciências do Espaço, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal
- ⁵⁶ Department of Astronomy, University of Geneva, ch. d'Ecogia 16, 1290 Versoix, Switzerland
- ⁵⁷ INAF-Istituto di Astrofisica e Planetologia Spaziali, via del Fosso del Cavaliere, 100, 00100 Roma, Italy
- ⁵⁸ INFN-Padova, Via Marzolo 8, 35131 Padova, Italy
- ⁵⁹ Aix-Marseille Université, CNRS/IN2P3, CPPM, Marseille, France
- ⁶⁰ Universitäts-Sternwarte München, Fakultät für Physik, Ludwig-Maximilians-Universität München, Scheinerstrasse 1, 81679 München, Germany
- ⁶¹ INFN-Bologna, Via Innerio 46, 40126 Bologna, Italy
- ⁶² Institut d'Estudis Espacials de Catalunya (IEEC), Edifici RDIT, Campus UPC, 08860 Castelldefels, Barcelona, Spain
- ⁶³ Herzberg Astronomy and Astrophysics Research Centre, 5071 W. Saanich Rd. Victoria, BC V9E 2E7, Canada
- ⁶⁴ Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, 0315 Oslo, Norway
- ⁶⁵ Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
- ⁶⁶ Department of Physics, Lancaster University, Lancaster LA1 4YB, UK
- ⁶⁷ Felix Hormuth Engineering, Goethestr. 17, 69181 Leimen, Germany
- ⁶⁸ Technical University of Denmark, Elektrovej 327, 2800 Kgs. Lyngby, Denmark
- ⁶⁹ Cosmic Dawn Center (DAWN), Denmark
- ⁷⁰ Institut d'Astrophysique de Paris, UMR 7095, CNRS, and Sorbonne Université, 98 bis boulevard Arago, 75014 Paris, France
- ⁷¹ Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
- ⁷² NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ⁷³ Department of Physics and Helsinki Institute of Physics, Gustaf Hållströmin katu 2, University of Helsinki, 00014 Helsinki, Finland
- ⁷⁴ Université de Genève, Département de Physique Théorique and Centre for Astroparticle Physics, 24 quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland
- ⁷⁵ Department of Physics, P.O. Box 64, University of Helsinki, 00014 Helsinki, Finland
- ⁷⁶ Helsinki Institute of Physics, Gustaf Hållströmin katu 2, University of Helsinki, 00014 Helsinki, Finland
- ⁷⁷ Centre de Calcul de l'IN2P3/CNRS, 21 avenue Pierre de Coubertin 69627 Villeurbanne Cedex, France
- ⁷⁸ Laboratoire d'étude de l'Univers et des phénomènes eXtremes, Observatoire de Paris, Université PSL, Sorbonne Université, CNRS, 92190 Meudon, France
- ⁷⁹ Aix-Marseille Université, CNRS, CNES, LAM, Marseille, France
- ⁸⁰ SKA Observatory, Jodrell Bank, Lower Withington, Macclesfield, Cheshire SK11 9FT, UK
- ⁸¹ Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy
- ⁸² INFN-Sezione di Milano, Via Celoria 16, 20133 Milano, Italy
- ⁸³ University of Applied Sciences and Arts of Northwestern Switzerland, School of Computer Science, 5210 Windisch, Switzerland
- ⁸⁴ Universität Bonn, Argelander-Institut für Astronomie, Auf dem Hügel 71, 53121 Bonn, Germany
- ⁸⁵ INFN-Sezione di Roma, Piazzale Aldo Moro, 2 – c/o Dipartimento di Fisica, Edificio G. Marconi, 00185 Roma, Italy
- ⁸⁶ Department of Physics, Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK
- ⁸⁷ Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA
- ⁸⁸ Université Paris Cité, CNRS, Astroparticule et Cosmologie, 75013 Paris, France
- ⁸⁹ CNRS-UCB International Research Laboratory, Centre Pierre Binétruy, IRL2007, CPB-IN2P3 Berkeley, USA
- ⁹⁰ University of Applied Sciences and Arts of Northwestern Switzerland, School of Engineering, 5210 Windisch, Switzerland
- ⁹¹ Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France
- ⁹² Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
- ⁹³ Aurora Technology for European Space Agency (ESA), Camino bajo del Castillo, s/n, Urbanización Villafranca del Castillo, Villanueva de la Cañada, 28692 Madrid, Spain
- ⁹⁴ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
- ⁹⁵ School of Mathematics, Statistics and Physics, Newcastle University, Herschel Building, Newcastle-upon-Tyne NE1 7RU, UK
- ⁹⁶ DARK, Niels Bohr Institute, University of Copenhagen, Jagtvej 155, 2200 Copenhagen, Denmark
- ⁹⁷ Waterloo Centre for Astrophysics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
- ⁹⁸ Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
- ⁹⁹ Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada
- ¹⁰⁰ Centre National d'Etudes Spatiales – Centre spatial de Toulouse, 18 avenue Edouard Belin, 31401 Toulouse Cedex 9, France
- ¹⁰¹ Institute of Space Science, Str. Atomistilor, nr. 409 Măgurele, Ilfov 077125, Romania
- ¹⁰² Consejo Superior de Investigaciones Científicas, Calle Serrano 117, 28006 Madrid, Spain
- ¹⁰³ Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, Via Marzolo 8, 35131 Padova, Italy
- ¹⁰⁴ Institut für Theoretische Physik, University of Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
- ¹⁰⁵ Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, CNRS, UPS, CNES, 14 Av. Edouard Belin, 31400 Toulouse, France
- ¹⁰⁶ Université St Joseph, Faculty of Sciences, Beirut, Lebanon
- ¹⁰⁷ Departamento de Física, FCFM, Universidad de Chile, Blanco Encalada 2008, Santiago, Chile
- ¹⁰⁸ Universität Innsbruck, Institut für Astro- und Teilchenphysik, Technikerstr. 25/8, 6020 Innsbruck, Austria
- ¹⁰⁹ Satlantis, University Science Park, Sede Bld 48940, Leioa-Bilbao, Spain
- ¹¹⁰ Instituto de Astrofísica e Ciências do Espaço, Faculdade de Ciências, Universidade de Lisboa, Tapada da Ajuda, 1349-018 Lisboa, Portugal
- ¹¹¹ Cosmic Dawn Center (DAWN)
- ¹¹² Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200 Copenhagen, Denmark
- ¹¹³ Universidad Politécnica de Cartagena, Departamento de Electrónica y Tecnología de Computadoras, Plaza del Hospital 1, 30202 Cartagena, Spain
- ¹¹⁴ Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
- ¹¹⁵ Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Giuseppe Saragat 1, 44122 Ferrara, Italy
- ¹¹⁶ Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Via Giuseppe Saragat 1, 44122 Ferrara, Italy
- ¹¹⁷ INAF, Istituto di Radioastronomia, Via Piero Gobetti 101, 40129 Bologna, Italy
- ¹¹⁸ Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Bd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France
- ¹¹⁹ Department of Physics, Oxford University, Keble Road, Oxford OX1 3RH, UK
- ¹²⁰ Université PSL, Observatoire de Paris, Sorbonne Université, CNRS, LERMA, 75014 Paris, France
- ¹²¹ Université Paris-Cité, 5 Rue Thomas Mann, 75013 Paris, France

- ¹²² INAF – Osservatorio Astronomico di Brera, via Emilio Bianchi 46, 23807 Merate, Italy
- ¹²³ INAF-Osservatorio Astronomico di Brera, Via Brera 28, 20122 Milano, Italy, and INFN-Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
- ¹²⁴ ICL, Junia, Université Catholique de Lille, LITL, 59000 Lille, France
- ¹²⁵ ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data e Quantum Computing, Via Magnanelli 2, Bologna, Italy
- ¹²⁶ Instituto de Física Teórica UAM-CSIC, Campus de Cantoblanco, 28049 Madrid, Spain
- ¹²⁷ CERCA/ISO, Department of Physics, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA
- ¹²⁸ Technical University of Munich, TUM School of Natural Sciences, Physics Department, James-Frank-Str. 1, 85748 Garching, Germany
- ¹²⁹ Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany
- ¹³⁰ Laboratoire Univers et Théorie, Observatoire de Paris, Université PSL, Université Paris Cité, CNRS, 92190 Meudon, France
- ¹³¹ Departamento de Física Fundamental, Universidad de Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain
- ¹³² Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, UMR 7550, 67000 Strasbourg, France
- ¹³³ Center for Data-Driven Discovery, Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
- ¹³⁴ Ludwig-Maximilians-University, Schellingstrasse 4, 80799 Munich, Germany
- ¹³⁵ Max-Planck-Institut für Physik, Boltzmannstr. 8, 85748 Garching, Germany
- ¹³⁶ California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, USA
- ¹³⁷ Department of Physics & Astronomy, University of California Irvine, Irvine, CA 92697, USA
- ¹³⁸ Department of Mathematics and Physics E. De Giorgi, University of Salento, Via per Arnesano, CP-I93, 73100 Lecce, Italy
- ¹³⁹ INFN, Sezione di Lecce, Via per Arnesano, CP-I93, 73100 Lecce, Italy
- ¹⁴⁰ INAF-Sezione di Lecce, c/o Dipartimento Matematica e Fisica, Via per Arnesano, 73100 Lecce, Italy
- ¹⁴¹ Departamento Física Aplicada, Universidad Politécnica de Cartagena, Campus Muralla del Mar, 30202 Cartagena, Murcia, Spain
- ¹⁴² Instituto de Física de Cantabria, Edificio Juan Jordá, Avenida de los Castros, 39005 Santander, Spain
- ¹⁴³ CEA Saclay, DFR/IRFU, Service d'Astrophysique, Bat. 709, 91191 Gif-sur-Yvette, France
- ¹⁴⁴ Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK
- ¹⁴⁵ Department of Computer Science, Aalto University, PO Box 15400, Espoo FI-00076, Finland
- ¹⁴⁶ Instituto de Astrofísica de Canarias, c/Vía Lactea s/n, La Laguna 38200, Spain. Departamento de Astrofísica de la Universidad de La Laguna, Avda. Francisco Sanchez, La Laguna 38200, Spain
- ¹⁴⁷ Caltech/IPAC, 1200 E. California Blvd., Pasadena, CA 91125, USA
- ¹⁴⁸ Ruhr University Bochum, Faculty of Physics and Astronomy, Astronomical Institute (AIRUB), German Centre for Cosmological Lensing (GCCL), 44780 Bochum, Germany
- ¹⁴⁹ Department of Physics and Astronomy, Vesilinnantie 5, University of Turku, 20014 Turku, Finland
- ¹⁵⁰ Serco for European Space Agency (ESA), Camino bajo del Castillo, s/n, Urbanización Villafraña del Castillo, Villanueva de la Cañada, 28692 Madrid, Spain
- ¹⁵¹ ARC Centre of Excellence for Dark Matter Particle Physics, Melbourne, Australia
- ¹⁵² Centre for Astrophysics & Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
- ¹⁵³ Department of Physics and Astronomy, University of the Western Cape, Bellville, Cape Town 7535, South Africa
- ¹⁵⁴ DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK
- ¹⁵⁵ Kavli Institute for Cosmology Cambridge, Madingley Road, Cambridge CB3 0HA, UK
- ¹⁵⁶ Department of Astrophysics, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ¹⁵⁷ IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette Cedex, France
- ¹⁵⁸ Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, Stockholm SE-106 91, Sweden
- ¹⁵⁹ Astrophysics Group, Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
- ¹⁶⁰ Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 53, Avenue des Martyrs, 38000 Grenoble, France
- ¹⁶¹ Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 2, 00185 Roma, Italy
- ¹⁶² Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
- ¹⁶³ HE Space for European Space Agency (ESA), Camino bajo del Castillo, s/n, Urbanización Villafraña del Castillo, Villanueva de la Cañada, 28692 Madrid, Spain
- ¹⁶⁴ Dipartimento di Fisica – Sezione di Astronomia, Università di Trieste, Via Tiepolo 11, 34131 Trieste, Italy
- ¹⁶⁵ Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA
- ¹⁶⁶ Theoretical astrophysics, Department of Physics and Astronomy, Uppsala University, Box 516, 751 37 Uppsala, Sweden
- ¹⁶⁷ Mathematical Institute, University of Leiden, Einsteinweg 55, 2333 CA Leiden, The Netherlands
- ¹⁶⁸ School of Physics & Astronomy, University of Southampton, Highfield Campus, Southampton SO17 1BJ, UK
- ¹⁶⁹ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
- ¹⁷⁰ Space physics and astronomy research unit, University of Oulu, Pentti Kaiteran katu 1, FI-90014 Oulu, Finland
- ¹⁷¹ Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, 10010 New York, NY, USA
- ¹⁷² Department of Physics and Astronomy, University of British Columbia, Vancouver BC V6T 1Z1, Canada

Appendix A: RF parameters

Understanding which features are most relevant to our model estimates is crucial for predictive accuracy. An ML model operating as a black box may produce predictions, but the lack of transparency raises questions about the reliability of the outcomes. This not only hinders immediate interpretability but also complicates post-analyses. The ML branch investigating the role each feature plays in the model's predictions is commonly referred to as 'feature importance'. To this end, we compute SHapley Additive exPlanations (SHAP; Lundberg & Lee 2017; Rozenberczki et al. 2022; Chen et al. 2022) values, based on a game-theoretic approach, by calculating the partial relevance for each feature. Based on a conditional expectation function, features are assigned importance values given their impact on test sample predictions. For a total achievable value v , SHAP values ϕ are computed via

$$\phi_f(v) = \frac{1}{p} \sum_S \frac{[v(S \cup \{f\}) - v(S)]}{\binom{p-1}{k(S)}}. \quad (\text{A.1})$$

Given a given feature f , the summation is taken over all subsets S of the feature set $F = 1, 2, 3, \dots, p$, which one can construct after excluding f . The size of S is given by $k(S)$ while $v(S)$ and $v(S \cup \{f\})$ refer to the value achieved by per subset before and after f joins S , respectively. This ensures that the contribution of each feature to a prediction collectively adds up to the value of the prediction as

$$\sum_{f=1}^{f=p} \phi_f(v) = v(F). \quad (\text{A.2})$$

However, achieving optimal accuracy in large modern data sets often involves complex models such as ensembles or deep-learning frameworks. Since it would be unfeasible to compute contributions across all possibilities of the feature space, we approximate SHAP values through Deep SHAP (Rozenberczki et al. 2022; Chen et al. 2022), which efficiently combines values computed for smaller network components into comprehensive values for the entire network, avoiding the need for heuristic choices in linearising components. The sign of SHAP values denotes whether a feature contributes to an increase or decrease in the predictive output, while the magnitude of the SHAP value quantifies the extent of the feature's influence on the prediction. Features with SHAP values close to zero for individual sources can be considered negligible or non-influential in this scenario. As a consequence, a feature can be seen as most influential if it exerts the most influence on the output across all predictions (Dey et al. 2022).

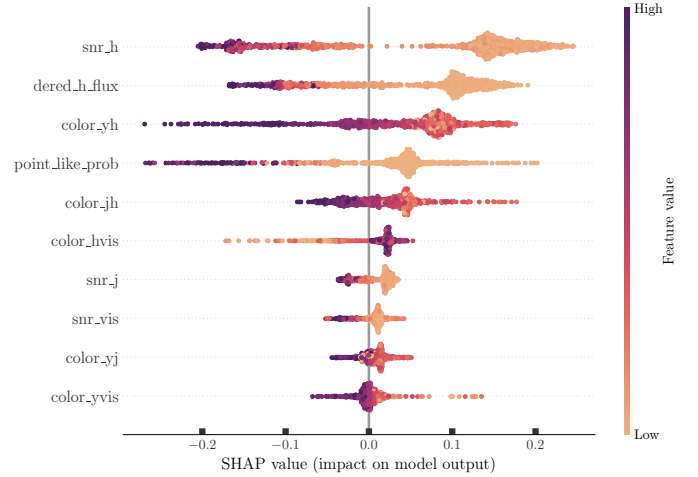


Fig. A.1. ‘Beeswarm’ plot showing the SHAP values for the features used in the RF model introduced in Sect. 4.1.2. Each point represents a SHAP value for a specific feature and data instance, illustrating the impact of that feature on the model's predictions. Features are sorted by their mean absolute SHAP values, with the most influential features appearing at the top. The colour gradient indicates the relative feature value (i.e. low to high), providing insight into how feature magnitude correlates with its effect on predictions.

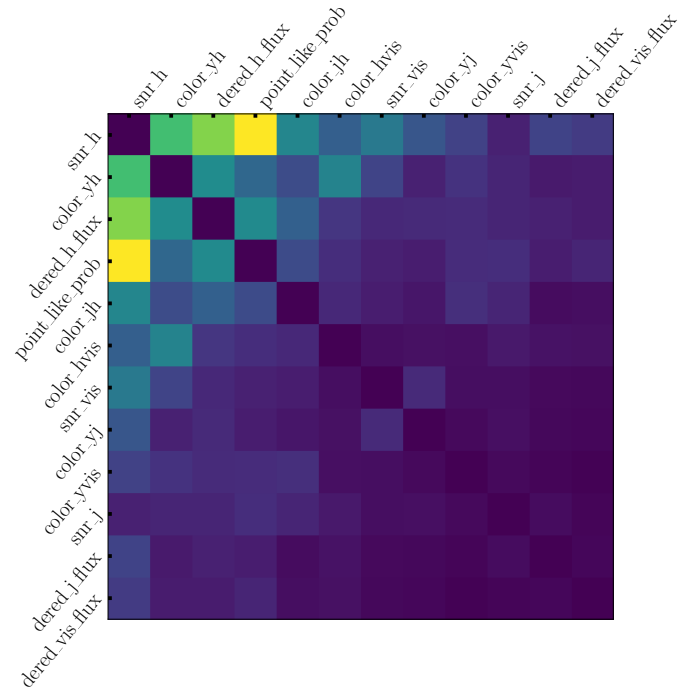


Fig. A.2. Correlation matrix displaying the pairwise Pearson correlation coefficients between the features used in the RF model introduced in Sect. 4.1.2. The colour intensity indicates the strength and direction of the correlations, with positive correlations shown in warm colours (yellow) and negative correlations in cool colours (blue). This visualisation helps identify interdependencies among features, which can inform feature selection and the interpretation of model performance.

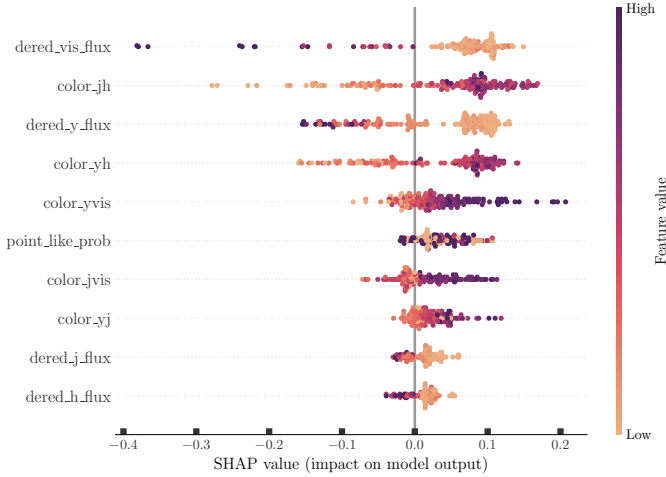


Fig. A.3. ‘Beeswarm’ plot showing the SHAP values for the features used in the RF model introduced in Sect. 5.2. Each point represents a SHAP value for a specific feature and data instance, illustrating the impact of that feature on the model’s predictions. Features are sorted by their mean absolute SHAP values, with the most influential features appearing at the top. The colour gradient indicates the relative feature value (i.e. low to high), providing insight into how feature magnitude correlates with its effect on predictions.

Appendix B: Photometric redshift comparison

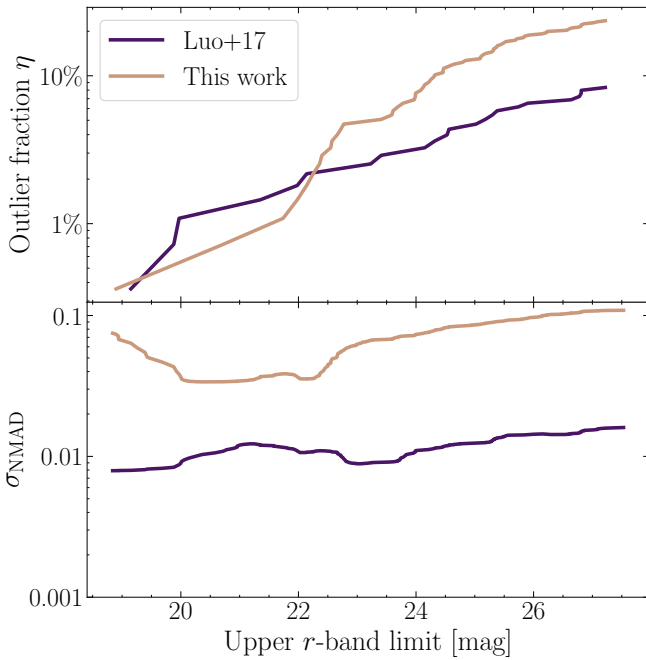


Fig. B.1. Outlier fraction (top panel) and accuracy (bottom panel) as a function of limiting r -band magnitude for PICZL and Luo et al. (2017). While the accuracy of Luo et al. (2017) is superior to that reached by PICZL, the fraction of outliers for bright sources ($r \lesssim 22.3$) is lower for PICZL.

Appendix C: HR to effective photon index

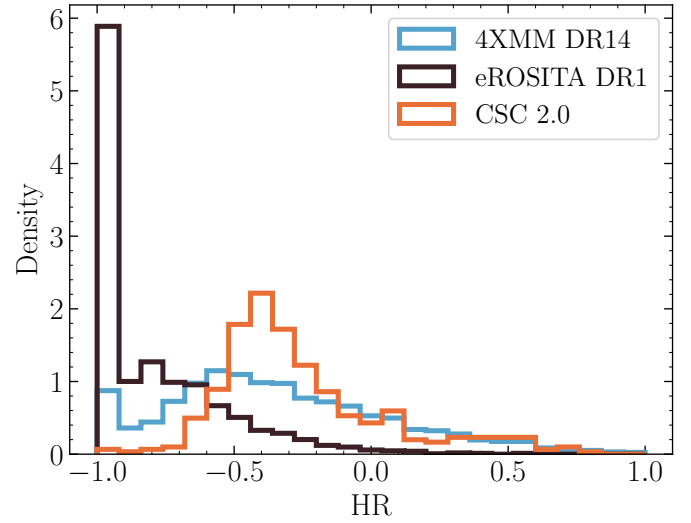


Fig. C.1. Distribution of X-ray hardness ratio (HR) for eROSITA DR1_{0.5–2 keV}, 4XMM DR14_{2–12 keV} and CSC2_{0.5–2 keV} sources. The distributions reflect differences in survey depth, energy band definitions, and source selection. While eROSITA shows a distribution skewed towards softer sources ($HR \rightarrow -1$), both 4XMM and CSC2 display peaks at harder HR values, consistent with their greater sensitivity to moderately obscured or intrinsically harder AGN.

Appendix D: Column description of released CTP catalogue

1. **Xray_EUCLID_ID**: Concatenation of X-ray_ID and EUCLID_ID (unique)
2. **Xray_ID**: X-ray source identifier (unique)
3. **Xray_RA**: J2000 Right Ascension of the X-ray source in the parent catalogue (deg)
4. **Xray_DEC**: J2000 Declination of the X-ray source in the parent catalogue (deg)
5. **Xray_CAT**: X-ray source catalogue
6. **Xray_pos_err**: Positional uncertainty of X-ray source (arcsec)
7. **Fx**: Mean 0.5–2 keV X-ray flux from all detections of the X-ray source ($\text{erg cm}^{-2} \text{s}^{-1}$)
8. **EFx**: Error on the mean 0.5–2 keV X-ray flux from all detections of the X-ray source ($\text{erg cm}^{-2} \text{s}^{-1}$)
9. **S_Nx**: Signal-to-noise ratio for Fx/EFx
10. **HR**: Count rate derived hardness ratio considering soft 0.5 – 2.0 keV and hard (4XMM DR14: 2.0 – 12.0 keV, CSC 2.0: 2.0 – 7.0 keV, and eROSITA: 2.0 – 5.0 keV) bands.
11. **EDF**: *Euclid* deep field
12. **EUCLID_ID**: EUCLID source identifier (unique)
13. **EUCLID_RA**: J2000 Right Ascension of the counterpart in Q1 catalogue (deg)
14. **EUCLID_DEC**: J2000 Declination of the counterpart in Euclid catalogue (deg)
15. **EUCLID_pos_err**: Positional uncertainty of *Euclid* source (arcsec)
16. **EUCLID_P_Xray**: Probability to be an X-ray emitter based on the RF
17. **EUCLID_P_Gal**: Probability of being a Galactic rather than extragalactic source based on the RF

18. **Separation_EUCLID_Xray**: Distance between *Euclid* and X-ray source (arcsec)
19. **dist_bayesfactor**: Logarithm of ratio between prior and posterior, from separation, positional error, and number density (see Appendix in [Salvato et al. 2018](#))
20. **dist_post**: Distance posterior probability comparing this association versus no association (see Appendix in [Salvato et al. 2018](#))
21. **bias_EUCLID_Xray_proba**: Probability weighting introduced by the *Euclid*-based prior (1 indicates no change)
22. **p_single**: Same as dist_post, but weighted by the prior (see Appendix in [Salvato et al. 2018](#))
23. **p_any**: Probability that there is a counterpart in LS10 for each X-ray entry (see Appendix in [Salvato et al. 2018](#))
24. **p_i**: Relative probability of the X-ray/*Euclid* match (see Appendix in [Salvato et al. 2018](#))
25. **match_flag**: 1 for the most probable match; 2 for almost as good solutions ($p_i/p_{ibest} > 0.5$)
26. **LS10_FULLID**: Unique identifier of the LS10 source matched to the *Euclid* CTP (concatenation of RELEASE, BRICKID, and OBJID)
27. **LS10_RA**: J2000 Right Ascension of the LS10 source (deg)
28. **LS10_DEC**: J2000 Declination of the LS10 source (deg)
29. **ra_spec**: J2000 Right Ascension of the spec-z match to the *Euclid* CTP (deg)
30. **dec_spec**: J2000 Declination of the spec-z match to the *Euclid* CTP (deg)
31. **z_spec**: Spectroscopic redshift
32. **z_err**: Error on the spectroscopic redshift
33. **Cat_spec**: Parent catalogue of the spec-z
34. **phz**: PICZL photometric redshift (see [Roster et al. 2024](#))
35. **phz_1sl**: PICZL lower 1 sigma error
36. **phz_1su**: PICZL upper 1 sigma error
37. **phz_Luo17**: Photometric redshift (see [Luo et al. 2017](#))
38. **z_final**: Spec-z when available; otherwise [Luo et al. \(2017\)](#) and PICZL photo-z
39. **Lx**: Rest-frame X-ray luminosity, assuming FlatLambdaCDM from `astropy.cosmology`