Rubin-Euclid Derived Data Products

A platform for galaxy evolution studies

Jean-Charles Cuillandre (CEA Saclay / Université Paris-Saclay)
on behalf of the **DDP Working Group and Community**

A new era of all-sky surveys in the optical/near-IR

2023-2029

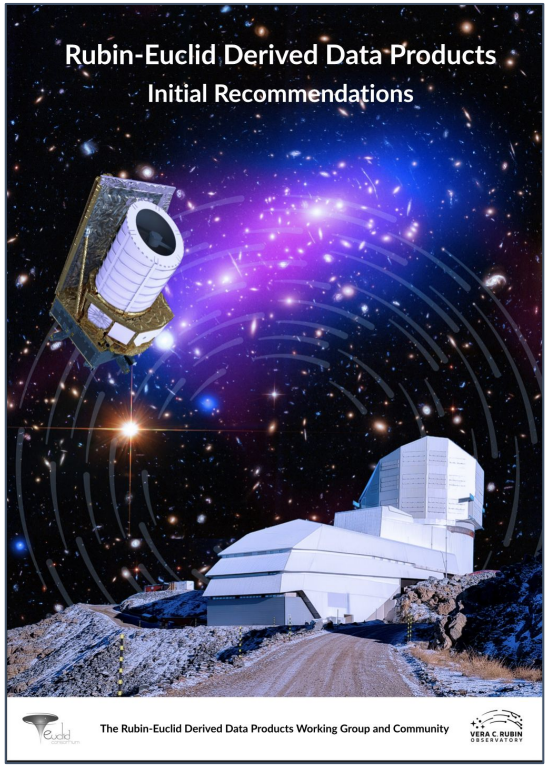
2024-2034

- Rubin-LSST (ground) and Euclid (space) : two projects motivated by the Dark Energy (core science).
- Complementary imaging datasets : deep optical multi-bands *vs* high resolution + near-infrared.

Rubin-Euclid Derived Data Products context

- The two projects have been talking to each other for nearly a decade.
- The data policies do not allow the Rubin pixels to be shared with the Euclid Consortium & vice-versa.
- A path forward spawned from the promise of maximizing the scientific return of both projects in a way that protects the unique science of each collaboration and is consistent with both data policies.
- All Derived Data Products will be shared openly across the two collaborations.
- The Derived Data Products bypass large parts of the Rubin-LSST and Euclid respective pipelines.
- Key photometry algorithms from Rubin-LSST and Euclid will be however adopted for the DDPs.

Rubin-Euclid DDPs initial recommendations



- Report released 21 December 2021, 78 pages, 120 authors in total, on the arXiv https://arxiv.org/abs/2201.03862 with a DOI.
- Provides recommendations for an initial set of DDPs covering:
  - Solar System, Milky Way, Transients, Nearby Universe, AGN & Galaxy Evolution, Clusters of Galaxies, Galaxy Clustering, Strong Lensing, Weak Lensing, Primeval Universe.
- Recommendations broadly grouped into two categories:
  - ***Cross-cutting DDPs (5):*** which will enable a wide range of complementary science goals,
  - ***Science-specific DDPs (58):*** which will enhance the science yield for a specific science case.
- Given the diversity in the complexity of the suggestions, a tiered approach is recommended to develop DDPs over the lifetime of both surveys: from simple catalog farming out and cutout exchange, to full blown joint pixel processing.

Management of the Rubin-Euclid DDPs effort

Rubin & Euclid senior management appointed 13 scientists each to a Derived Data Products Working Group (DDP-WG) with the first specific charge for 2021 (initial recommendations)

DDP-WG oversight committee :

- Rubin : Robert Blum, Phil Marshall, Željko Ivezić
- Euclid : Yannick Mellier, Jason Rhodes, René Laureijs

DDP-WG co-chairs : Leanne Guy for Rubin, Jean-Charles Cuillandre for Euclid

DDP-WG Rubin members : (about ⅓ also in Euclid)
Yusra Alsayyad, Etienne Bachelet, Manda Banerji, Franz Bauer, Jim Bosch, Tom Collett, Siegfried Eggl, Catherine Heymans, François Lanusse, Peter Melchior, Dara Norman, Michael Troxel

DDP-WG Euclid members : (about ⅓ also in Rubin)
Eric Aubourg, Hervé Aussel, Chris Conselice, Adriano Fontana, Henk Hoekstra, Isobel Hook, Konrad Kuijken, Joe Mohr, Michele Moresco, Reiko Nakajima, Stéphane Paltani, Daniel Stern

+2 experts (both Euclid+Rubin) : Benoit Carry (Solar System) & Annette Ferguson (Local Volume)

The DDPs broadly pertain to galaxy evolution

7.1 Solar System

Contributors: *Siegfried Eggl (WG), Benoit Carry, Matthew M. Knight, Hayden Smotherman, Colin Snodgrass*

7.2 Milky Way halo & Local Volume

Contributors: *Annette Ferguson, Keith Bechtol, Jeff Carlin, Roelof de Jong, Ariane Lançon, Søren Larsen, Marina Rejkuba*

7.3 The Galactic Plane

Contributors: *Etienne Bachelet (WG), Robert Blum, Hervé Bouy, Leo Girardi, Rodrigo Ibata, Eduardo L. Martin*

7.4 Local Universe

Contributors: *Christopher Conselice (WG), Jean-Charles Cuillandre (WG), Ivan Baldry, Sarah Brough, Michele Cantiello, Jeff Carlin, Chris Collins, Pierre-Alain Duc, Annette Ferguson, Leslie Hunt, Sugata Kaviraj, Johan Knapen, Ariane Lançon, Søren Larsen, Mireia Montes, Polis Papaderos, Reynier Peletier, Javier Roman, Crescenzo Tortora, Chris Usher, Karina Voggel, Aaron Watkins*

7.5 Transients

Contributors: *Isobel Hook (WG), Etienne Bachelet (WG), Pierre Astier, Maria Teresa Botticella, Enrico Cappellaro, Stefano Cavuoti, Jose Diego, Dominique Fouchez, Melissa Graham, Jens Jasche, Rubina Kotak, Guilhem Lavaux, Florent Leclercq, Giuseppe Longo, Seppo Matilla, Gautham Narayan, Stephen Smartt, Charling Tao, Sjoert van Velzen, Benjamin Wandelt*

7.6 Galaxy Evolution

Contributors: *Manda Banerji (WG), Michele Moresco (WG), Viola Allevato, Laura Bisigello, Micol Bolzonella, Jarle Brinchmann, Olga Cucciati, Raphaël Gavazzi, Peter Hatfield, Olivier Ilbert, Clotidle Laigle, Guilhem Lavaux, Claudia Maraston, Manuela Magliocchetti, Henry Joy McCracken, Lucia Pozzetti, E. Sarpa, M. Shuntov, Margherita Talia, Niraj Welikala, Ilsang Yoon, Elena Zucca*

7.7 Active Galactic Nuclei

Contributors: *Franz E. Bauer (WG), Manda Banerji (WG), Viola Allevato, Sotiria Fotopoulou, Hermine Landt, Xin Liu, Maurizio Paolillo, Ilsang Yoon*

7.8 Cosmology from weak gravitational lensing, galaxy clustering and galaxy clusters

Contributors: *Catherine Heymans (WG), Konrad Kuijken (WG), James Bosch (WG), Henk Hoekstra (WG), Francois Lanusse (WG), Peter Melchior (WG), Michele Moresco (WG), Stéphane Paltani (WG), Michael Troxel (WG), Stefano Andreon, Adam Amara, Sandro Bardelli, Micol Bolzonella, Stefano Camera, Francisco Castander, Ranga Ram Chari, N. Elisa Chisari, Olga Cucciati, Melissa Graham, Daniel Gruen, Hendrik Hildebrandt, Olivier Ilbert, Benjamin Joachimi, Rémy Joseph, C. Danielle Leonard, Anja von der Linden, Matteo Maturi, Lauro Moscardini, Emiliano Munari, Roser Pello, Mario Radovich, Barbara*

7.9 Strong Lensing

Contributors: *Tom Collett (WG), Timo Anguita, Simon Birrer, Frédéric Courbin, Tansu Daylan, Jose Diego, Brenda Frye, Raphael Gavazzi, Rémy Joseph, Phil Marshall, Ben Metcalf, Dominique Sluse, Graham Smith, Alessandro Sonnenfeld, Aprajita Verma, Giorgios Vernardos*

7.10 Primaeval Universe

Contributors: *Adriano Fontana (WG), Manda Banerji (WG), Rebecca Bowler, Marco Castellano, Jean-Gabriel Cuby, Daniel Mortlock, Sune Toft*

DDPs contributing community : Rubin & Euclid

350 scientists registered on the Rubin-Euclid DDP forum throughout 2021:

Natasha Abrams
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Stefano Andreon
Bob Armstrong
Etienne Bachelet
Manda Banerji
Oliver James Bartlett
Victor J. S. Bejar
Maciej Bilicki
Jonathan Blazek
Angela Bongiorno
Quentin Le Boulc'h
Malcolm Bremer
Sarah Brough
Patricia Burchat
Enrico Cappellaro
Jon Carrick
Gianluca Castignani
Nora Elisa Chisari
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Asantha Cooray
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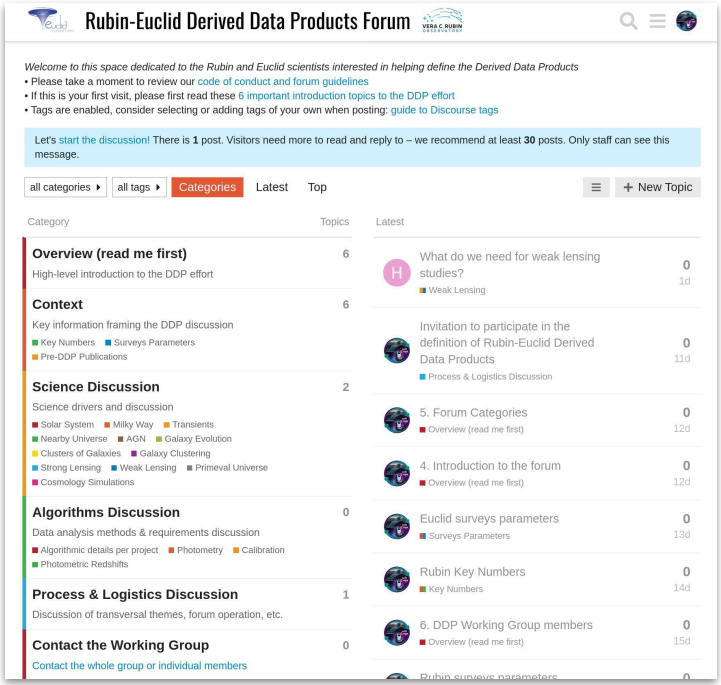
Eleni Tsaprazi
Hector Manuel Velazquez
Benjamin Wandelt
Niraj Welikala
Vivienne Wild
Stijn Wuyts
Mijin Yoon
Yuanyuan Zhang

A virtual discussion open to all in Rubin & Euclid

- The DDP discussion focused on the scientific motivation and nature, not the creation, of the DDPs.
- Standalone, world-public, project-independent forum: https://community.rubin-euclid-ddp.org
- Open to all data rights holders in both the Rubin Euclid communities – this approach ensured that everyone had a chance to contribute to the debate.
- Categories for science topics and algorithms instigated by DDP-WG members.
- The discussion was the basis for the DDP report.



The “Discourse - Civilized Discussion” platform ensures community exchanges with the power of asynchronicity across continents.

Digest of suggested extragalactic DDPs per science topic

- Nearby Universe (yearly)
  - Image: large Rubin and Euclid cutouts centered on a selection of galaxies in all the Rubin+Euclid bands (u-g-r-i-z + VIS-Y-J-H)
  - Catalog: matched Rubin-Euclid photometry of extragalactic globular clusters detected by Euclid
  - Image: Rubin and Euclid image cutouts of the extragalactic globular clusters candidates
  - Image: Rubin and Euclid cutouts (from small to large) for diffuse emissions (LSB: tidal streams, galaxies, groups, clusters)
  - Catalog: fluxes (all Rubin+Euclid bands) and structural measurements of LSB sources

- AGN & Galaxy Evolution (yearly)
  - Catalog: kpc-scale quasar tight pairs and lensed quasars by Euclid along Rubin single-epoch images photometry
  - Catalog: Rubin+Euclid photometry for all Euclid detected sources to 1) identify AGN & QSO candidates 2) derive high quality photometric redshifts and probability distribution functions
  - Catalog: Rubin light-curves in the g, r and i-filters for the low-redshift (z<1) type 1 AGN identified in Euclid deep fields
  - Image: postage stamp multi-wavelength cutouts from Rubin and Euclid around the positions of known spectroscopically confirmed quasars
  - Image: cutouts of galaxies detected in all bands (g,r,i,z,Y,J,H) in the two surveys overlap area at maximums depths
  - Catalog: aperture-matched and total fluxes, including all Rubin and Euclid bands for all Euclid detected sources, are needed to enable the derivation of high quality object classification, photometric redshifts, and physical properties of galaxies and AGN
  - Image: cutout images represent an added value to be used in combination with photometry to develop new methods
  - Catalog: Posterior of model-fitting photometry on Rubin data (e.g. positions, fluxes, pre-seeing morphological parameters, as fitted to each Rubin-detected galaxy)
  - Catalog: Posterior of model-fitting photometry on Euclid data (ideally using the former as a prior)
  - Spectra: pixel-level Euclid slitless data (for which the combination of the former is used as a prior)
  - Catalog: photometric apertures and total fluxes in all Rubin and Euclid bands for all Euclid detected sources
  - Image: cutouts in all bands for Euclid detected sources would be valuable to improve the photoz-z estimates (e.g. with ML algorithms)

Digest of suggested extragalactic DDPs per science topic

- Clusters of Galaxies (yearly)
  - Catalog: aperture-matched and total fluxes in Rubin and Euclid bands for all galaxies in clusters are needed to trace the galaxy population across all redshifts without gaps
  - Image: pixel-level data would allow to study the properties of the intracluster light in clusters
  - Similar products at Weak Lensing

- Galaxy Clustering (yearly)
  - Catalog: richest Rubin+Euclid photometric catalog to enhance photo-z accuracy and derive accurate galaxy properties
  - Catalog: photo-z, stellar masses and lensing shear measurements from a cross-matched area of the sky on scales of 0.001 to 10 deg e.g. deep drilling fields
  - Catalog: Production of 1) Galaxy number counts, 2) Galaxy correlation functions and 3) Galaxy-galaxy lensing based on these measurements, ideally broken down by by stellar mass and star-formation rate
  - Catalog: Euclid spectro-z catalogue and LSST photometric galaxy catalogue and survey selection description

- Strong Lensing (daily, yearly)
  - Catalog and Image: A single catalog of lens candidates, comprising the union (superset) of the input Euclid and LSST candidates, with new columns showing suitable lens probabilities [Tier 1] up to a single database of lens candidates as in C2, but with image cutouts stores containing 10-band multi-epoch cutout image set (including weight and PSF images) plus Euclid spectra [Tier 3]
  - Catalog: imminent microlensing event alerts require access to Euclid lens models, high resolution imaging, and potentially spectra, LSST light curves for known and candidate lensed quasars in real time

Digest of suggested extragalactic DDPs per science topic

- Weak Lensing and photo-z (yearly)
  - Catalog (Tier 1) [two independant catalogs]: catalog based DDP creation with exchange of list-driven photometry Rubin pixels for Euclid sources, and list-driven Euclid-NIR photometry on Rubin sources, or a Euclid-VIS based blending flag for Rubin sources (effectively builds on what both projects have been developing independently)
  - Catalog (Tier 2): joint pixel Rubin+Euclid processing to combine shapes with photometry
  - Catalog: combination of Euclid & Rubin sources pre-shear calibration
  - Image: pixel-level combination would allow for shape measurements tailored to increasing the signal-to-noise of alignment measurements
  - Catalog: PZ estimates of LSST objects as point estimates, uncertainties, and posteriors. If possible, a catalog of joint photometry would enable the application of task-specific PZ algorithms (e.g., for clusters, AGN)
  - Catalog: probability distribution functions (PDF) of the redshifts (and any value derived from the PDFs) for Euclid VIS selected sources, while at the same time, physical parameters could be derived for all of these sources based on multi-band photometry (enriched catalogs or joint pixel processing). Additional science can be obtained by providing the merged photometric catalogue.

- Primeval Universe (yearly)
  - Catalog and Image: i) estimated fluxes and uncertainties, ii) postage stamp images and iii) local background estimates (preferably accounting for nearby objects) for all sources detected by Euclid, either i) matching to Rubin or ii) assuming the Euclid position in the case of non-detections
  - Catalog: z > 7 candidates will be selected in Euclid YJH photometry, requiring Rubin fluxes at the position of these candidates, stacked measurement from combined Rubin bands would also be required, to detect any flux that would indicate a low-redshift interloper
  - Image: cut-outs of the Rubin data at the positions of the Euclid candidates would be required, to allow for stacking and smoothing to confirm or deny the high-redshift nature of the sources

Trends and commonalities of the proposed DDPs

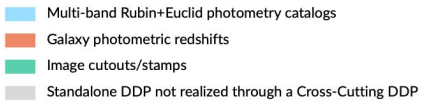
- Catalogs vastly dominate in the pool of suggested DDPs, then images (cutouts) and spectra (limited requests)
- Transient science is present across several science topics
- The most commonly requested catalog is a multi-band ugrizyYJH merged photometry catalog (with physical parameters)
- Deblending information and star/galaxy separation often appears in the proposed DDPs
- Postage stamps / cutouts are often identified as a critical DDP component (transients, dropouts) or an added bonus
- Large cutouts are requested for complex objects (nearby galaxies, or clusters of galaxies as a single entities)

The great diversity in the complexity of the suggestions confirmed the need for a tiered approach to developing DDPs : from simple catalog merging and cutouts exchange, enriching each side's catalog with provided algorithms, up to full blown joint pixel processing

Tiered prioritization of recommended DDPs

Cross-Cutting (CC)

DDP-1-CC	B	P1+U1+YR	T1	Multi-band Rubin+Euclid photometry list-driven catalogs
DDP-2-CC	B	P1+U2+DR	T2	Multi-band Rubin+Euclid forced photometry catalog from joint-pixel processing
DDP-3-CC	B	P2+U2+DR	T3	Multi-band Rubin+Euclid deblended photometry catalog from joint-pixel processing
DDP-4-CC	B	P2+U2+DR	T3	Galaxy "pixel" photometric redshifts
DDP-5-CC	B	P1+U1+RT	T0	Image cutouts/stamps delivery service



Column 1: DDP identifier

Column 2: Benefit, **B**=Both communities, **R**=Rubin, **E**=Euclid

Column 3	Tier	Description
P1 + U1 + RT	T0	Ready when both telescopes observe the same sky in 2023
P1 + U1 + YR	T1	In conjunction with the Rubin-LSST Year 1 release in 2025
P1 + U2 + DR	T2	In conjunction with the Euclid DR2 and LSST Year 3 in 2027
P2 + U2 + DR	T3	In conjunction with the Euclid DR3 and LSST Year 4 in 2029
Non-baseline	T4	Pending definition of Euclid's non-allocated time (illustrative DDPs)

P: Relative scientific **P**riority.

U: **U**rgency, timescale on which the DDP is needed, e.g time-sensitive/small area DDPs might be worth producing and sharing before producing DDPs from a fuller analysis of a larger area.

RT/YR/DR: Cadence for producing DDPs. RT= Real-Time (~ day) for transients, YR = "Yearly Release" matching the Rubin-LSST releases, DR = "Data Releases" for products that can wait for longer timescales, such as Euclid DR3.

Recommendations for cross-cutting DDPs

DDP-1-CC: Multi-band Rubin+Euclid list-driven photometry catalogs:
Photometric redshifts are at the heart of the high-profile cosmology science cases of both surveys, with stringent accuracy requirements that cannot be met using a combination of two independent photometry catalogs. ***At a minimum,*** a list-driven photometry source exchange for point sources and galaxies detected in all r,i,z and Y,J,H bands across both catalogs above 5-sigma. **Timescale**: As soon as the two surveys overlap.

DDP-2-CC: Multi-band Rubin+Euclid forced photometry catalog based on joint-pixel processing:
Starting with object detections across both surveys based on the DDP-1-CC selection function, measure PSF, aperture and total fluxes and/or upper limits across all bands using matched images in the other survey. **Timescale**: Post Euclid/Rubin DR1/Y1. Incrementally increasing in area / depth / complexity through the lifetime of both surveys.

DDP-3-CC: Multi-band Rubin+Euclid deblended photometry catalog from joint-pixel processing:
Starting with object detections across both surveys based on the DDP-1-CC selection function, measure deblended component with VIS and total fluxes and/or upper limits across all u,g,r,i,z,y,Y,J,H bands using matched images in both survey datasets, while respecting the data policy driven DDP-1-CC source selection function. This represents the most complex approach. **Timescale**: Post Euclid/Rubin DR1/Y1. Incrementally increasing in area / depth / complexity through the lifetime of both surveys.

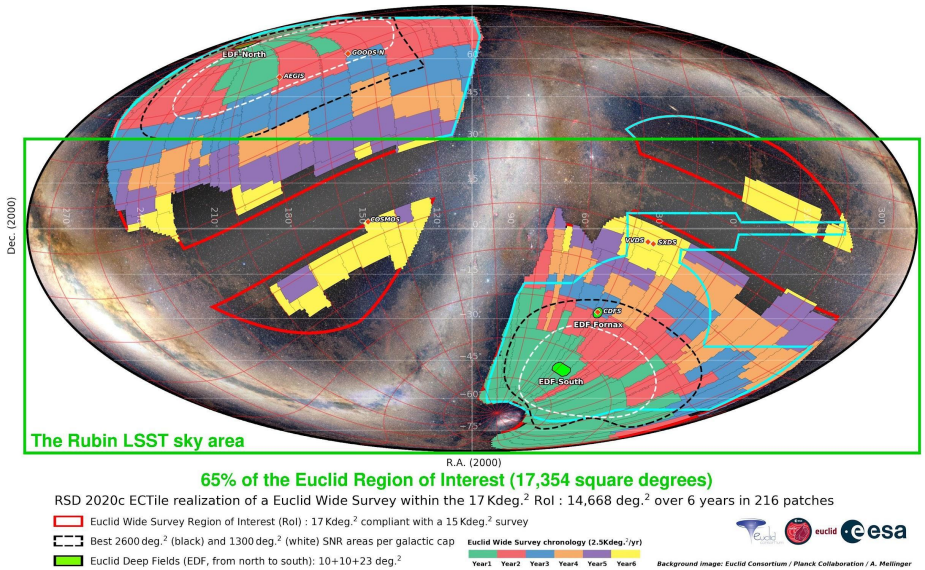
Recommendations for cross-cutting DDPs

DDP-4-CC: Galaxy “pixel” photometric redshifts with machine learning:
Full probability distributions for the photometric redshift estimates are required for all science cases which need to propagate errors into physical parameters using a range of algorithms incorporating both empirical/training-set based methods and template-fitting run on the joint multi-wavelength catalogs. Joint-pixel analysis with machine learning will further benefit photometric redshift estimates at both surveys depth limits in particular when deblending becomes an issue for Rubin. Similar selection function as the above photometric catalogs DDPs.
Timescale: Post Euclid and Rubin DR1. Incrementally increasing in area / depth / complexity through the lifetime of both surveys.

DDP-5-CC: Image cutouts/stamps delivery service:
Exchange of Image cutouts (pixels) on small areas of the sky will enable key scientific investigations, e.g transient science, strong lensing, and drop-out science. Sharing within the two projects a limited number of pixels driven by the angular size of the source of interest is compatible with the DDP definition considering the scientific return of a highly specific usage. **Timescale:** As soon as the two surveys overlap.

Survey Strategy Optimization for DDPs

A key factor in maximizing the impact of Rubin-Euclid DDPs is the coordination of each survey's observing strategy; maximizing the spatial and temporal overlap of the two surveys will enhance almost all science domains.



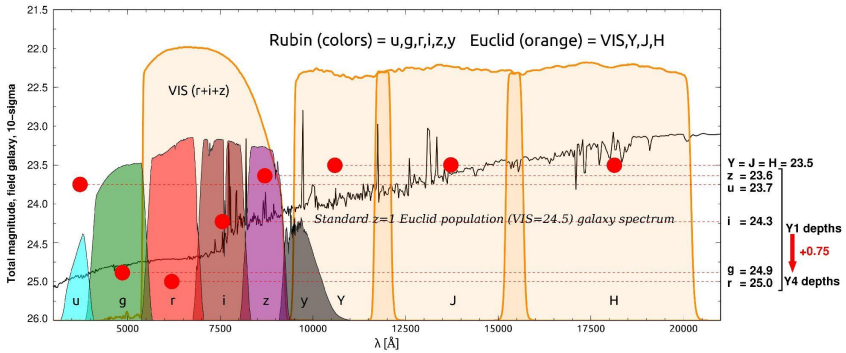
- Wide surveys: Large overlap area of up to approximately 9000 square degrees.
- LSST Cadence Note – *Enhancing LSST Science with Euclid synergy and a mini-survey of the northern sky to Dec < +30*. Modifications to the Rubin Wide-Fast-Deep towards an extended footprint driven by dust extinction already enhances Euclid synergy (9400 deg2 overlap).
- 2 overlapping deep fields: Rubin and Euclid will both observe EDF-Fornax (10 sq deg) and EDF-South (23 sq deg).

Euclid Data Releases & expected ground depths

Photo-z depth metric proxy (for all): point source in 2 arcseconds diameter aperture, 10σ

- Euclid (median over the RoI): *VIS=25.0, Y=J=H=23.5*
- DES in Euclid DR1/2/3: *g=24.7, r=24.4, i=23.8, z=23.1*
- UNIONS in Euclid DR1: *u=23.6, g=24.5, r=24.1, i=23.2, z=23.4*
- UNIONS in Euclid DR2: *u=23.6, g=24.5, r=24.1, i=23.4, z=23.4*
- UNIONS in Euclid DR3: *u=23.6, g=24.5, r=24.1, i=23.6, z=23.4*
- Rubin LSST* Y1 in Euclid DR2: *u=23.7, g=24.9, r=25.0, i=24.3, z=23.6*
- Rubin LSST* Y1 to Y4 in Euclid DR3: *u=24.4, g=25.6, r=25.7, i=25.0, z=24.3*

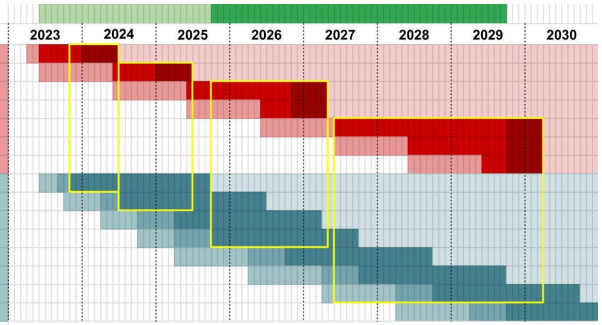
*Rubin-LSST DDP main releases depth with point source PSF performance scaled to the 2” diam. metric



Timescales and data releases

Rubin-Euclid Coordination Timeline

Survey	Data Release	
Euclid	Q1	Misc. sky areas (EDF, etc), total 50 sq deg
Euclid	DR1	Euclid Y1 (2500 sq deg, << 1000 sq deg overlap)
Euclid	Q2	Euclid Y2
Euclid	DR2	Euclid Y3 (7500 sq deg, ~3000 sq deg overlap)
Euclid	Q3	Euclid Y4
Euclid	Q4 (TBC)	Euclid Y5
Euclid	DR3	Euclid Y6 (15000 sq deg, ~7000 sq deg overlap)
LSST	DP1	LSST ComCam
LSST	DP2	LSST SV (~1000 sq deg, 180 visits / Y2 depth)
LSST	DR1	LSST First 6 Months
LSST	DR2	LSST Y1 (90 visits)
LSST	DR3	LSST Y2 (180 visits)
LSST	DR4	LSST Y3 (270 visits)
LSST	DR5	LSST Y4 (360 visits)
LSST	DR6	LSST Y5 (450 visits)



Assumptions:

February 2023	Euclid mission launch date
April 2024	LSST survey start

Surveys color keys:

	Observing
	Processing
	Proprietary Access
	Public Access

Notes:

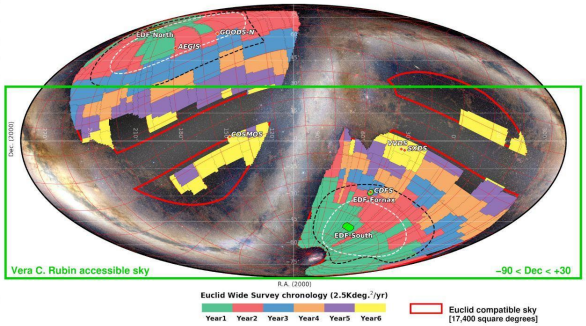
(a) LSST data release dates may move by +/3 months as the operations team adapts to circumstances.

(b) Euclid plan additional quick releases containing specific featured data products made with the Y2 ("Q2") , Y4 ("Q3") and Y5 ("Q4", TBC) data. The data from these years will be available to the Euclid Consortium to use while they are being processed, there just won't be an internal release of a full data release dataset.

(c) The overlap between Euclid Y1 and LSST SV is potentially quite small, because Rubin commissioning observations are needed at a wide range of latitude (and the best calibration pre-cursor data tends to be closer to equatorial). The SIT-Com team's field selection is not yet determined.

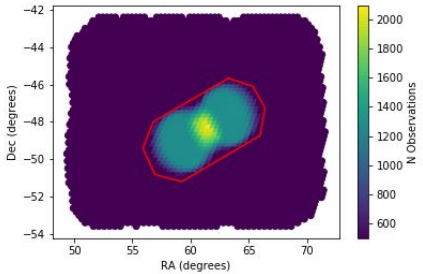
(d) DDP transient science can start in 2023 with limited sky overlap (green bar).

(e) LSST Y1 leads to matched survey depths for photo-z estimation: the production of related DDPs (photometric catalogs) spans 4 years (top darker green bar, 2025 to 2029) based on LSST Y1 to Y4 yearly data releases progressively matched to the Euclid survey increasing overlap.

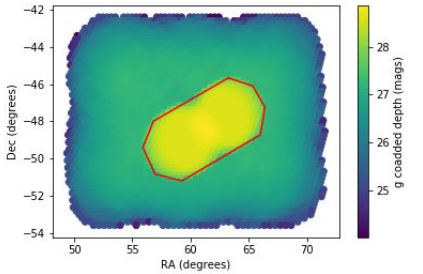


- Recommended DDPs should be produced as soon as Rubin and Euclid observe a common area of the sky, e.g. as early as 2024 in an investigative manner (limited overlap) in order to be mature in time for 2025: Euclid Y1+Y2 + LSST Y1.
- DDPs that will enable transient science should materialize on a short timescale, e.g. 24 hr and based on a fast joint processing.
- More complex DDPs would fit better in the context of the annual Rubin data release scenario.

Open sharing of photometric data on a small area



Two Rubin Deep Drilling Fields at half-depth on EDF-South



... or a uniform depth on EDF-South with an optimized Rubin dithering (favored)

- Openly sharing all imaging pixel data over a common small area of the sky across both projects will enable the early development of methods, algorithms and software that will be beneficial to all DDPs before embarking on full scale processing,
- ... while also allowing both communities to investigate delivered DDPs in depths and propose paths for further improvements in future releases.
- The report recommended for this purpose the now confirmed Rubin deep field over the 23 sq degree EDF-South.
- A MoU is now in preparation between the Euclid Consortium and the Rubin Observatory.

Credit: P. Joachim

Rubin-Euclid Derived Data Products summary

- There is no lesser partner in this effort to maximize the science return of both projects.
- The proposed DDPs are fair to both scientific collaborations and benefit many in each project.
- There is no selection of DDPs based on a scientific comparison between domains.
- Cross-cutting DDPs that serve many scientific domains are however championed (photometric catalogs).
- For Euclid to achieve its core science goals (photo-z), some legacy Euclid science might lose an edge.
- The DDP working group carefully rejected the proposed DDPs that gave too much away.
- The report recommend to implement the recommendations in whole.
- The DDPs are presented in 4 tiers of importance and timing that address some competitive aspects.