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EUCLID-RUBIN SYNERGIES: A SUMMARY FOR THE OCTOBER, 2020 IN2P3 SCIENTIFIC COUNCIL

The IN2P3 Rubin & *Euclid* Teams

1. INTRODUCTION

The European Space Agency selected *Euclid* in 2011. The American National Science Foundation (NSF) officially approved Rubin in 2014, though some parts began earlier construction with private financing. As both are modern observatories dedicated to surveying large, overlapping fractions of the celestial sky for cutting-edge cosmology, discussions of synergies between the two have been ongoing essentially since their conception.

In addition to the fact that they will be taking data simultaneously, two aspects of these experiments drive most of the synergies: different angular resolutions, and different wavelength coverage.

- Angular Resolution: The ground-based Rubin Observatory will have roughly 0.7", atmospheric-seeing-limited angular resolution, while *Euclid* will have an optical wavelength band with angular resolution of order 0.2".
- Spectral Resolution and Coverage: The space-based *Euclid* will have three infrared bands and a spectrometer, but a single optical band, which will benefit from the additional spectral resolution in the optical afforded by the five separate Rubin bands in the optical. This is illustrated in figure 1.

As flagship projects, both Rubin and *Euclid* will address wide arrays of different science. Here we focus on science of primary interest to the IN2P3 and for discussions of other topics (reionization, galaxy evolution, stellar and solar system science, etc.) we refer the interested reader to Rhodes *et al.* (2017), Capak *et al.* (2019) and Chary *et al.* (2019) for further information.

1.1. *Names*

To aid the reader, we note immediately that until recently the Vera C. Rubin Observatory (Rubin) was known as LSST (this now refers to the the Survey, rather than the Telescope), and the *Nancy Grace Roman Space Telescope* (*Roman*) was known as *WFIRST*. Note also that *Euclid* will have two instruments aboard – a wide-band optical imager known as *Euclid*/VIS and a near-infrared instrument, *Euclid*/NISP, which includes a photometer, sometimes referred to as NIP or NISP-P, and a spectrometer referred to as NIS or NISP-S.

2. PHOTOMETRIC REDSHIFTS

Both *Euclid* and Rubin will observe the sky in three dimensions, mapping both the directions of objects in the sky, and their distances. Traditionally, distances are estimated using redshifts obtained through spectroscopic measurements. Rubin and *Euclid* sources will, however, be too numerous to do spectroscopy on all of them – it would take too much telescope time. Both experiments will therefore be using *photometric redshifts* (*e.g.* DES 2015).

Photometric redshifts rely on multiband photometry with broad filters. Their derivation consists of fitting measured photometry with various SEDs for different classes of objects redshifted by different amounts and ultimately depends on having measurements of prominent "break" features present in galaxy spectra – for example, the 400 nm break in

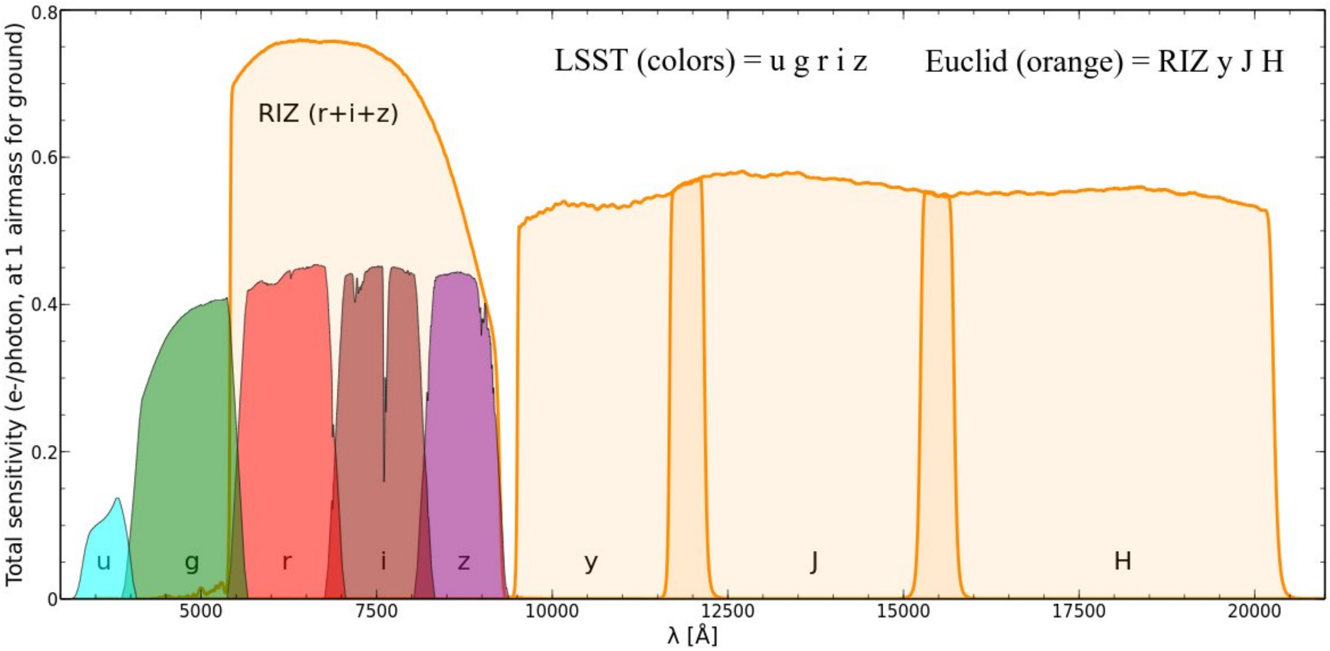

FIG. 1.— Figure 1 of Capak *et al.* (2019). Their caption (lightly edited): The planned imaging filters from Rubin (cyan/green/red/brown/purple) and *Euclid* (orange) are shown. *Euclid* will provide 0.16" FWHM imaging in a visible filter and similar quality 1-2 μm near-infrared imaging that will complement Rubin ("LSST" in the figure). Maximizing the overlap between these two data sets will optimize the science return of both projects.

red, early-type galaxies, or the Lyman break at 91 nm in blue, star-forming galaxies. The key is to have photometric bands which cover such break features throughout the redshift range of interest. An illustration from the Dark Energy Survey (DES) team is given in figure 2.

Figure 1 shows the Rubin and *Euclid* filters. The large *Euclid*/VIS optical band (the 'RIZ' band in orange towards the left of the figure) is very sensitive, but will not be discriminating in terms of redshift or object class. The three *Euclid* infrared bands, labeled 'y', 'J' and 'H' towards the right of will help, but will not allow *Euclid* to get redshifts for all the sources that larger optical band will detect. **It is only with supplementary optical band data from ground-based experiments such as Rubin, DES and CFHT that *Euclid* will be able to get a full complement of photometric redshifts.**

On the other hand, the addition of *Euclid* infrared data will notably improve Rubin's photometric redshifts, especially at $z > 1$ where key spectral features begin to redshift out of the visible filters into the infrared. Figure 3 shows that the combination of *Euclid* and Rubin data improves the accuracy of photometric redshift estimations significantly over those obtained using Rubin data alone (Capak *et al.* 2019).

This is discussed further in section 5.

3. SOURCE CONFUSION, DEBLENDING AND OTHER PSF EFFECTS

The apparent superposition of galaxies with other astrophysical objects along the line of sight, a problem known as *blending*, will be a challenge for upcoming, ground-based, deep, photometric galaxy surveys, such Rubin. Blending contributes to the systematic error budget of weak lensing studies by perturbing object detection and affecting photometric and shape measurements.

Euclid's VIS instrument will have a spatial resolution of about 0.2". Due to the effects of the atmosphere, Rubin expects seeing a number of times worse ($\sim$0.7"). The higher angular resolution of the *Euclid* VIS instrument provides additional information to Rubin bands, yielding significant reductions of errors and biases on galaxy shapes even at high blend rates and low SNR. This is illustrated in figure 4. The combination of data will also allow better separation of stars from galaxies and better identification of objects.

Recent IN2P3 work on this subject can be found in Arcelin *et al.* (2020).

4. SUPERNOVAE

Cosmological measurements using type Ia supernovae could greatly benefit from the synergy of Rubin and *Euclid*. The goal would be to convolve the high cadence, deep, multi-band imaging photometry of Rubin with near-infrared photometry and spectroscopy from *Euclid* to provide important information about host galaxies and improve the photometry and classification of Rubin transients.

Spectroscopic redshifts could be provided by *Euclid* using NISP-S for a fraction of supernovae host galaxies (Rhodes *et al.* 2017). This could help in understanding and removing systematic biases observed using photometry only. SNe Ia standardization could greatly benefit from the knowledge of the overall color, morphology, and metallicity of host galaxies derived from VIS and NISP data. Furthermore, high resolution imaging from VIS and NISP could enable

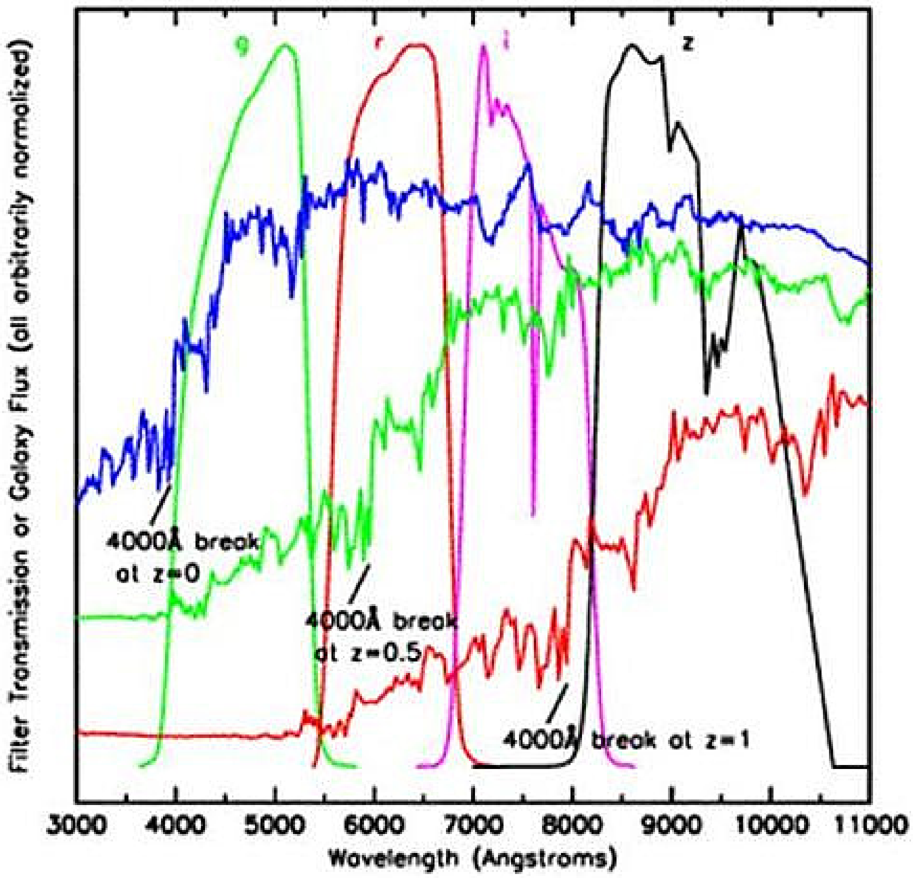

Fig. 2.— An example of how an experiment's response changes with source redshift from DES (2015). Their description: DES will take advantage of the fact that the light spectrum of galaxies has a relatively sharp drop at a wavelength of 400 nm, referred to as the 4000 Å break. The drop can be seen in the blue line, which shows the relative amount of light in each wavelength that would be received from a typical galaxy. This blue line shows the light spectrum for a nearby galaxy with "z=0". As the galaxy becomes more and more distant from Earth and recedes at a faster rate due to the expansion of the Universe, this drop will be observed here on Earth at higher and higher wavelength. This shift toward the longer wavelength (red) end of the spectrum can be seen in the green and red lines on this plot, which are for galaxies with z=0.5 and z=1.0 respectively.

local measurements of host galaxy properties (e.g. local star-formation specific rate), key parameters to improve the knowledge of type Ia supernovae as "standard candles".

Euclid measurements could also lead to improvement of classification and photometry of Rubin transients by supplying serendipitous spectra (from NISP-S) for many long-lived Rubin transients such as superluminous supernovae, hence providing a training set for classification. Combining a few serendipitous NIR *Euclid* data points overlapping with Rubin could improve our understanding of Type Ia supernovae in the near-infrared domain using model-fitting of joint data of the second luminosity peak of type Ia SN in the NIR (Rhodes *et al.* 2017).

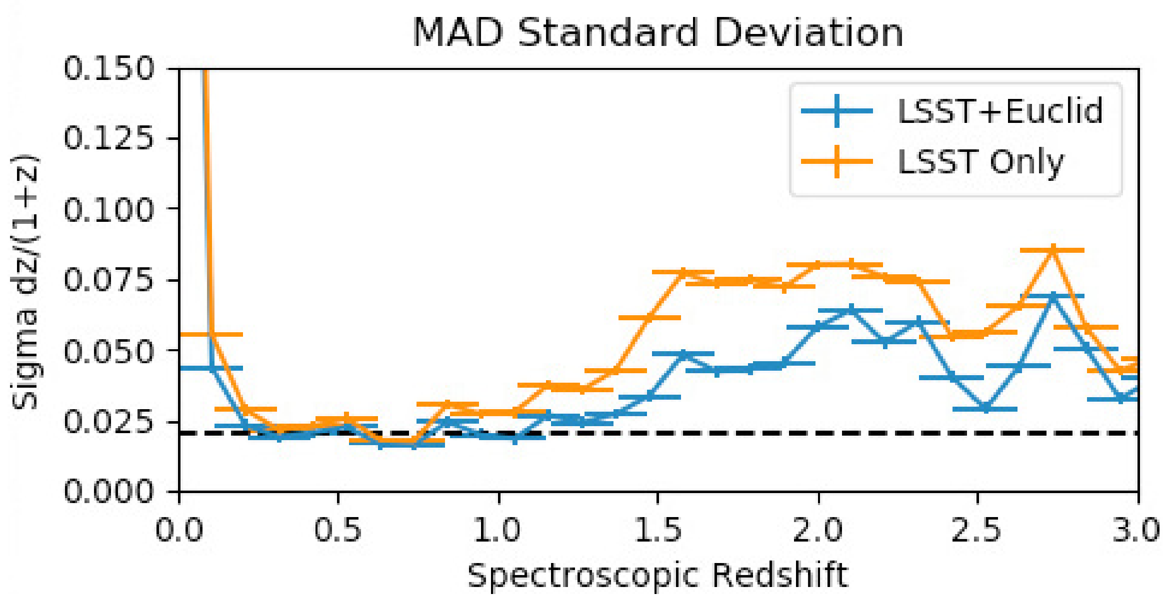

FIG. 3.— Part of figure 2 of Capak *et al.* (2019), showing improvements on photometric redshifts obtained when using a combination of Rubin and *Euclid* data versus when Rubin data alone are used.

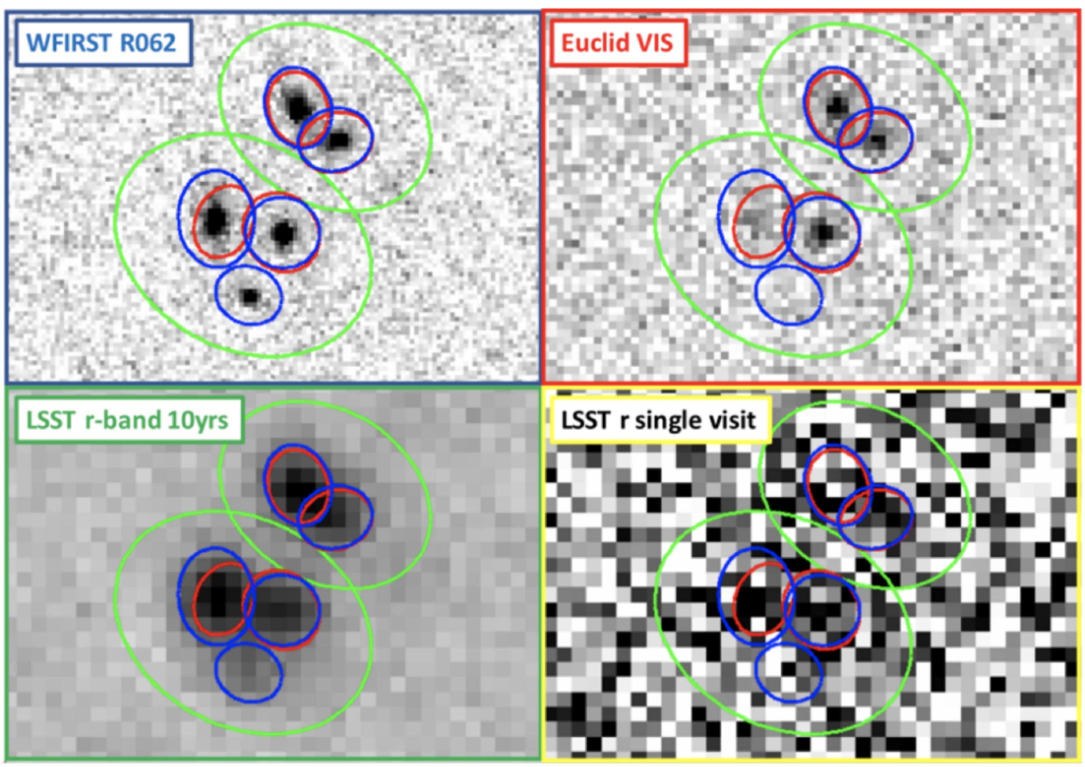

FIG. 4.— Figure 2 of Chary *et al.* (2019). Their caption (lightly edited): An illustration of source confusion in an optical band (centered at 6000 Å) from the three primary surveys [*Euclid*, Rubin, and *Roman*], along with the isophotes derived from photometry on each of the images. The green isophotes are derived from the Rubin r-band full-depth data of 27.5AB mag, the red isophotes are from the *Euclid* only VIS data while the blue isophotes are for the deeper *Roman* data. The sources are barely detected in the Rubin single epoch data. In the absence of the deeper, space-resolution data, source confusion would result in both erroneous shape and photometry estimates in Rubin data and also affect catalog matching. Conversely, both *Euclid* and *Roman* rely on deconfused optical photometry from Rubin to get reliable photometric redshifts for galaxies that are detected in their respective surveys.

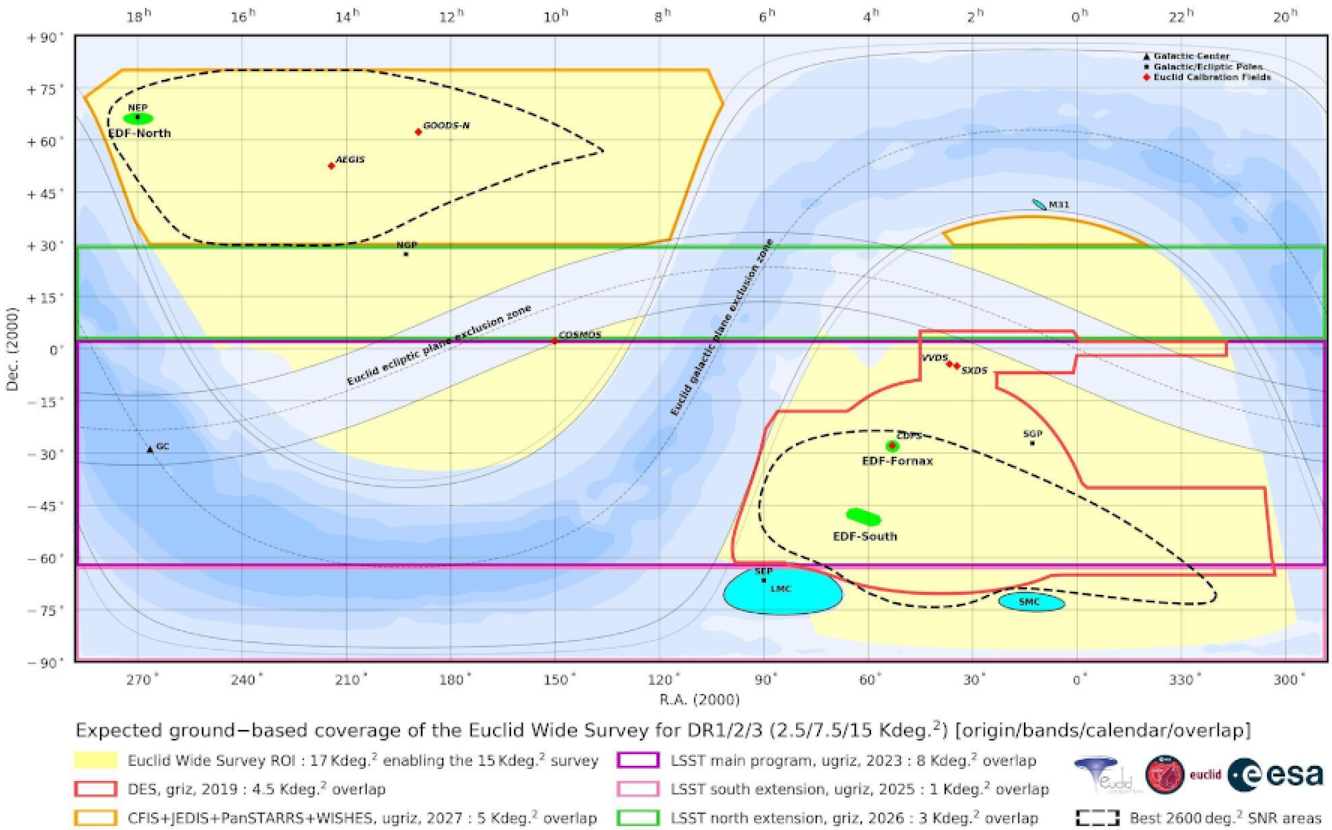

Fig. 5.— Updated Figure 6 of Rhodes *et al.* (2017). Their caption (lightly edited): Rubin survey areas and photometric bands and the Euclid Wide Survey with its exclusion zone (blue: Galactic plane + ecliptic plane + reddening). We indicate in the legend the number of square degrees from the Rubin surveys that overlap the Euclid Wide Survey in the relevant photometric bands.

5. SKY COVERAGE

Direct combination of the Rubin and Euclid data can only be done, obviously, over regions of the sky which have been observed by both. Euclid will observe roughly 15,000 square degrees of the sky, avoiding the Galactic and ecliptic planes. This is shown as the light yellow background in figure 5.

As noted in section 2, *Euclid* needs complementary, ground-based data. In the northern hemisphere, data is being taken by the UNIONS collaboration, a combination of the Canada-France-Hawaii Telescope CFIS (Canada-France Imaging Survey program, r-band), JEDIS-g on CEFCA's JST2.5 (Javalambre-Euclid Deep Imaging Survey in g-band), Pan-STARRS1 and Pan-STARRS2 telescopes for the i-band as a consequence of their NEO search, and WISHES (Wide Imaging with Subaru HSC of the *Euclid* Sky, z-band). The sky regions covered by this group is indicated using the dark yellow outline. For the southern hemisphere, in the absence of an agreement with Rubin, data from the Dark Energy Survey (DES) would be used, although the DES is known to be too shallow for *Euclid* in the z-band (-0.4 mag.). DES's footprint on the sky is shown with the red outline in figure 5.

As one can infer from the figure, however, it's obvious that Euclid needs more coverage and depth than DES provides. Rubin, located in the Chilean Andes at 30°14′40.7″ S/70d44m57.9s W, can image the southern hemisphere, and a portion of the northern hemisphere. This is shown schematically as the purple-, pink- and green-outlined areas in Figure 5.

Rubin data is therefore critical to Euclid in order to extend the optical-band data beyond the DES footprint and to fully cover the southern hemisphere. Synergy between *Euclid* and Rubin could be further reinforced by extending the Rubin footprint of the main survey (outlined in green in the figure) to the north and the south (purple and red outlines) in the g,r,i and z-bands (u-band would be too expensive at such high airmass). This larger overlap would lead to an improvement of the Rubin's Dark Energy constraints by 30-69 % (Capak *et al.* 2019).

Additionally, Rubin's "Deep Drilling Field" program will include the survey of four fields (COSMOS, *XMM*-LSS, CDFS, ELAIS-S1) plus probably one or two more whose location is not defined yet. An agreement was reached early 2019 between the Rubin governance and ESA/*Euclid* Consortium for having a fifth field overlapping with the *Euclid* deep field in the south region, a field that has been carefully selected in coordination with the Rubin, *Euclid* and *Roman* groups (Tri Agency Group, Capak *et al.* 2019). Such combined effort would allow Rubin to probe higher redshift domains for type Ia supernovae by using NIR measurements of *Euclid*.

6. DATA REDUCTION

There is currently no agreement between Rubin and *Euclid*, so the data sets are treated completely separately. The fact, however, that the CCIN2P3 houses data from both surveys should allow the IN2P3 to leverage resources, if the appropriate agreements can be reached.

In fact, the Rubin-specific part of the *Euclid* image simulation pipeline already uses the public Rubin simulation code. When the DDP-WG ultimately defines common data products, this work might be made even easier.

7. FORMAL COLLABORATION

A "Rubin-*Euclid* Derived Data Product Working Group" (DDP-WG) has been established (DDP 2020). It will recommend a science-driven initial set of "Derived Data Products" (DDPs) which would be promptly shared between all *Euclid* Consortium and Rubin scientific data rights holders, in a way that protects the unique science of each collaboration and respects the data policies of each collaboration. The DDP-WG will take broad input from both science communities in establishing the recommended DDPs.

While the DDP-WG will not be the group that will decide who makes the DDPs, where they are made, how they are made, or what funding mechanism will pay for that effort, the idea is that this initial set of DDPs, if approved, would form the basis of a Letter of Intent signed by both Rubin Observatory and *Euclid* leadership to actually create those DDPs. The DDP-WG would then remain a science-focused, standing committee that would recommend further DDPs as both the *Euclid* and Rubin surveys progress.

The group, which includes an IN2P3 member, has been appointed. A virtual workshop is anticipated in a few months in order to help collect the input the group will need from both science communities. This workshop would be open to the larger *Euclid* and Rubin Observatory communities, not just the DDP-WG.

8. SYNERGY WITH OTHER OPTICAL/IR LARGE-SCALE STRUCTURE COSMOLOGICAL SURVEYS

Having been conceived and selected simultaneously and having similar goals and observation strategies, it's natural that the synergies between *Euclid* and Rubin have been thoroughly discussed. One thing we must point out here, however, is that there are *a number* of experiments currently under development that should also be included when talking about upcoming large-scale structure mapping in future cosmology experiments. We note that a first meeting including the Simons Observatory (SO), CMB-S4, *Hubble*, *Roman*, *SPHEREx*, DESI and CCAT-p was held June 26$^{\text{th}}$ to begin exploiting science and software synergies over the range of upcoming large-scale structure measurements. This meeting, organized by the SO team, is an indicator of the interactions and synergies that should be anticipated for the next generation of Large Scale Structure experiments. The PNCG "Action Specific Dark Energy" may be interested in following these developments, and the IN2P3 may also want to follow it with a GdR.

8.1. *DESI*

The Dark Energy Spectroscopic Instrument (DESI) is a multi-fiber, optical spectrograph installed on the Kitt Peak National Observatory Mayall 4 m telescope. Designed to map the large-scale structure of the Universe from redshift 0 to 3.5, DESI will conduct a 5-year survey of galaxies and quasars, covering 14,000 deg^2 and yielding 34 million redshifts. DESI will begin its survey at the end of 2020. Like *Euclid* and Rubin, the DESI spectroscopic survey will accurately measure the Universe's expansion history, H(z), through the BAO scale, and measure the growth of structures $f\sigma_8$ traced by the velocity fields in redshift space – the so-called Redshift Space Distortions (RSD).

DESI and *Euclid*, along with purely photometric surveys like Rubin, address several questions in cosmology to test the ΛCDM model and General Relativity:

- Purely photometric surveys use tomographic methods on galaxy distributions. Spectroscopic measurements allow more precise 3D mapping of galaxy clustering. The comparison of these two methods is a good test of our understanding of the instruments and of the consistency of the cosmological model.
- One way to resolve the degeneracy between the two observables $f(z)$ and σ_8, the growth of structure and the amplitude of the matter power spectrum, is to combine the galaxy-galaxy lensing from the RSD probe (Jullo *et al.* 2019), from both spectroscopic data (from *Euclid*-NIS and DESI) and photometric data (from *Euclid*-NIP, *Euclid*-NIR and Rubin).

Lastly, since *Euclid* and DESI do not observe exactly the same tracers of matter, the $H\alpha$ emission-line galaxies for *Euclid* and the $[OII]$ emission-line galaxies for DESI (among the 4 tracers of DESI), the comparison of clustering galaxy measurements between both surveys will allow us to test for astrophysical systematics.

8.2. Nancy Grace Roman Space Telescope *(formerly* WFIRST*)*

The *Roman Space Telescope* is a NASA observatory designed to study Dark Energy, exoplanets, and other infrared astrophysics. The telescope has a 2.4 m primary mirror and will have two instruments, the Wide Field Instrument and the Coronagraph Instrument. The Wide Field Instrument will have a field of view that is 100 times greater than the Hubble infrared instrument, capturing more of the sky with less observing time than Hubble. As the primary instrument, the Wide Field Instrument will measure light from a billion galaxies over the course of the mission lifetime. Scheduled for launch "in the mid-2020s", *Roman* will have a primary mission lifetime of 5 years, with a potential 5 year extended mission.

While there have been some preliminary, tentative discussions, to this point we are unaware of any substantive collaboration plans between France and *Roman*.

8.3. SPHEREx

SPHEREx, the *Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer*, is a NASA MIDEX mission scheduled for launch in 2023 with a baseline two-year mission (Doré *et al.* 2018). It will make 0.75-to-5 μm spectra of every 6.2×6.2 arcsec pixel on the sky.

The *SPHEREx* team has proposed three specific science investigations to be carried out with this unique data set, the most pertinent for the IN2P3 being to constrain the physics of Inflation by measuring galaxy redshifts over a large cosmological volume. This stated goal is manifestly synergistic with experiments with IN2P3 participation such as LiteBIRD, but since it will be done by mapping the 3D positions of many nearby galaxies, it is also synergistic with all of the large-scale structure mapping efforts listed here. The *Euclid* and *Roman* spectroscopic surveys concentrate on redshifts z>1 to best study dark energy. By contrast, *SPHEREx* focuses at redshifts z<1. Combining these surveys will measure galaxy clustering over the full range over which dark energy begins to dominate the expansion of the Universe.

In addition, the spectroscopic nature of *SPHEREx*'s measurements will be useful for determining redshifts for those objects that *SPHEREx* can see and, importantly for IN2P3 researchers, *SPHEREx*'s ability to detect clusters and voids at redshifts complementary to those of *Euclid* will further constraints on cosmology using these objects.

To this point there is no IN2P3 involvement in *SPHEREx* – it's a much more recent addition to the field than other experiments here – though some initial contacts between *Euclid* and *SPHEREx* have been made.

9. COMBINING WITH OTHER MESSENGERS

The correlation of high angular resolution CMB maps with galaxy surveys is a rapidly advancing field opening new research directions in cosmology, fundamental physics and large-scale structure studies. Given the differences in frequency and angular resolution, experiments such as the South Pole Telescope (SPT), the Atacama Cosmology Telescope (ACT), the Simons Observatory (SO, start date 2022) and the future CMB Stage 4 (CMB-S4, start date latter half of 2020s) are not always associated with each other, but as different methods for measuring large-scale structure in the cosmos, they should be. Another promising multimessenger approach concerns synergies between galaxy surveys and gravitational waves detections.

9.1. *CMB*

Combining *Euclid* and Rubin with SO and CMB-S4 will provide powerful new probes of dark energy, gravity, the neutrino sector and the distribution of dark matter and baryons throughout the cosmic web. Because the CMB is the most distant backlight (z∼1000), these probes reach redshifts inaccessible by other techniques.

We give two examples, pictured schematically in Figure 6. The first involves cross correlation of CMB lensing maps with galaxy tracers from *Euclid*. The CMB carries information on the mass distribution projected along the line-of-sight back to z=1000. By cross-correlating CMB lensing maps with *Euclid* galaxies, we can divide the lensing signal into redshift slices, thereby reconstructing the evolution of the matter distribution back to redshifts well beyond unity. This evoltion, quantified through the matter power spectrum in the redshift slices, probes dark energy, gravity and the neutrino mass scales.

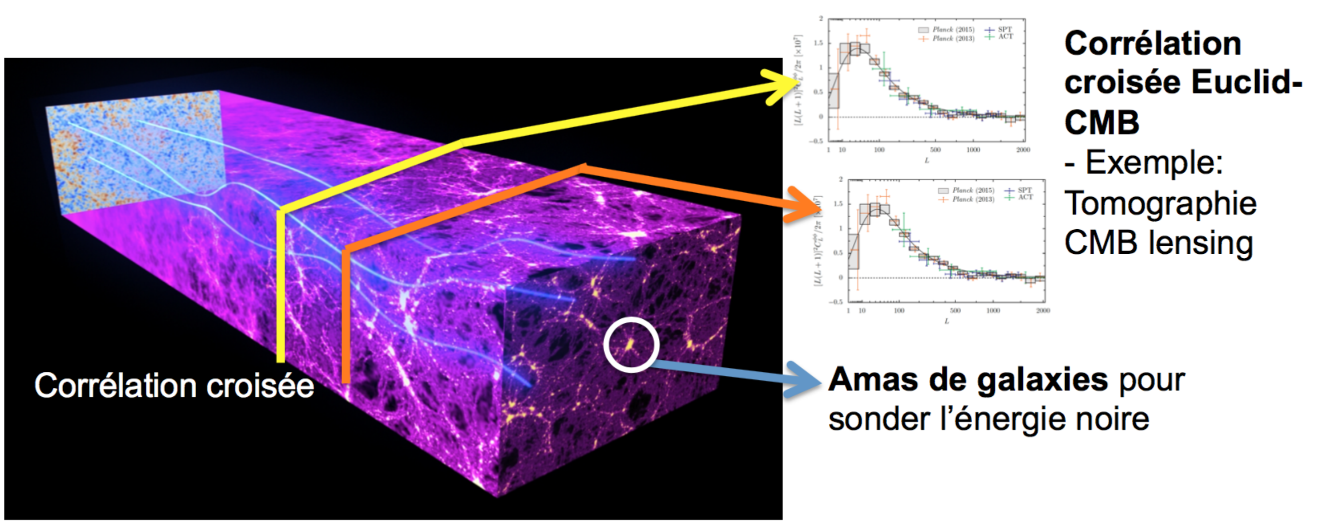

Fig. 6.— Cosmology from combining *Euclid* with CMB surveys. This schematic shows light traveling from the CMB surface of last scattering through large-scale structure evolving over time. During this processes, the light is imprinted with the tell-tale signatures of gravitation lensing and the Sunyaev-Zeldovich effect induced by hot gas in galaxy clusters. By cross-correlating *Euclid* galaxies with CMB lensing maps, we can follow the evolution of large-scale structure by measuring the matter power spectrum in redshift bins – that is, we can do 3d tomography. The combination of *Euclid* and the CMB will, moreover, produce a galaxy cluster catalog with accurate mass measurements out to high redshifts. These are two examples of powerful probes of dark energy, gravity and the neutrino mass scale.

The second example is the use of galaxy cluster evolution as a cosmic probe. Cluster abundance is exquisitely sensitive to the amplitude of the matter power spectrum. The evolution of the cluster abundance with redshift is therefore potentially the most powerful probe of dark energy, gravity and the neutrino mass scale. Clusters will be detected by both *Euclid*, as galaxy over-densities, and CMB surveys, through the Sunyaev-Zeldovich effect. Combined, the two will produce highly complete cluster catalogs with low contamination out to redshifts $z > 2$. Moreover, the lensing data from *Euclid* at $z < 1$ combined with CMB lensing at $z > 1$ will accurately determine cluster masses, a critical measurement when using clusters as cosmological probes.

The IN2P3 has expertise and a long history in large-scale structure studies, galaxy clusters and CMB lensing measurements. The IN2P3-associated IRL Pierre Binetruy includes members of the Simons Observatory, and APC counts members of the CMB-S4 collaboration.

9.2. *Gravitational waves*

During the next decade, gravitational waves will be observed from hundreds of binary inspiral events. When the redshifts of the host galaxies are known, these events can be used as "standard sirens", sensitive to the expansion rate of the Universe H_0. The next generation of spectroscopic galaxy surveys will play a crucial role in reducing systematic uncertainties in H_0 from standard sirens, particularly for the numerous "dark sirens" which do not have an electromagnetic counterpart. The cross-correlation of large-scale structures of the Universe with gravitational wave detections from future experiments like Einstein Telescope or LISA is expected to provide competitive estimates of H_0, helping to illuminate the current tension between existing measurements.

In addition to the measure of the distance-redshift relation of "standard sirens", combination between weak lensing from galaxy surveys and GW magnification could help to constrain dynamical dark energy and modified gravity models.

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