Euclid

Document prepared for the IN2P3 Scientific Council of 2020-06-30

Summary

Euclid is a European Space Agency (ESA) mission conceived and built to study Dark Energy and Dark Matter. Launch is currently scheduled for August of 2022 and there will be more than six years of survey operations.

The IN2P3 has been heavily involved in the mission preparation, including integrating, characterizing and delivering one of the satellite's instruments, acquiring critical technical expertise that can be used for next-generation experiments.

Once Euclid data arrives, IN2P3 teams are especially interested in using it to study the growth, evolution and flows of large-scale structures in the Universe. We will, of course, need consistent, long-term support to enable scientific output commensurate with the hardware and technical contributions that have been made and will continue to be made to Euclid.

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Introduction

The goal of the Euclid mission is to study the dark sector of the Universe. It will explore how the Universe evolved over the past 10 billion years to address questions related to the fundamental physics of the nature and properties of Dark Energy, Dark Matter and gravity. Specifically, it will address the following key questions in fundamental cosmology:

1. Is Dark Energy merely a cosmological constant, as introduced by Einstein, or is it a scalar field that evolves dynamically with the expansion of the Universe?
2. Alternatively, is Dark Energy a symptom of some breakdown of General Relativity on the largest scales?
3. What are the nature and properties of Dark Matter?
4. What are the initial conditions in the Early Universe, which seeded the formation of cosmic structure?

Dark Energy represents around 68% of the energy content of the Universe today, and together with Dark Matter it dominates the Universe's matter-energy content. Both are poorly understood, but important, since they control the past, present and future evolution of Universe.

State of the Field

Over the past couple of decades, a combination of observations from Type 1a Supernovae, Baryon Acoustic Oscillations (BAO)[1], Cosmic Microwave Background (CMB) anisotropies, Large-Scale Structure formation and Weak Gravitational Lensing have led to the emergence and confirmation of the so-called Lambda/Cold Dark Matter cosmological model (ΛCDM). In this model, the Universe evolved from a homogeneous state just after the Big Bang, to a hierarchical assembly of galaxies, clusters and super-clusters today. The energy density of the resulting Universe is dominated by two poorly-understood components: First, approximately 70% of its energy density is in the form of some sort of Dark Energy, which is causing the Universe's Hubble expansion to actually accelerate. The existence and energy scale of Dark Energy are difficult to reconcile with our knowledge of fundamental physics. From this point of view, one key question is whether it behaves like the relatively simple cosmological constant, as introduced by Einstein, or whether it is still more complicated. Another quarter of the Universe's energy density is in the form of Dark Matter, which exerts a gravitational attraction like normal matter, but does not emit light. While several candidates exist in particle physics, it has not been directly detected and its nature is also poorly understood. One possibility to explain one or both of these puzzles is that Einstein's General Relativity, and thus our understanding of gravity, needs to be revised on cosmological scales. Together, Dark Energy and Dark Matter pose some of the most important questions in fundamental physics today, and are the primary focus of Euclid.

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[1] See, for example, Eisenstein 2005, New Astronomy Reviews Volume 49, Issues 7–9, November 2005, Pages 360-365.

Project

Euclid will study the effects of Dark Energy and gravity from their signatures on the Hubble expansion of the Universe and the on growth of cosmic structures. The team will use both weak lensing of galaxies and the clustering of galaxies seen through BAO and through Redshift-Space Distortions (RSD)[2]. BAO provide a direct distance-redshift probe to explore the expansion rate of the Universe. Weak Lensing probes the expansion rate and the growth rate of structure, and RSD probe the growth rate of cosmic structures and gravity. Combined, these three probes are solid and complementary probes of the effects of Dark Energy.

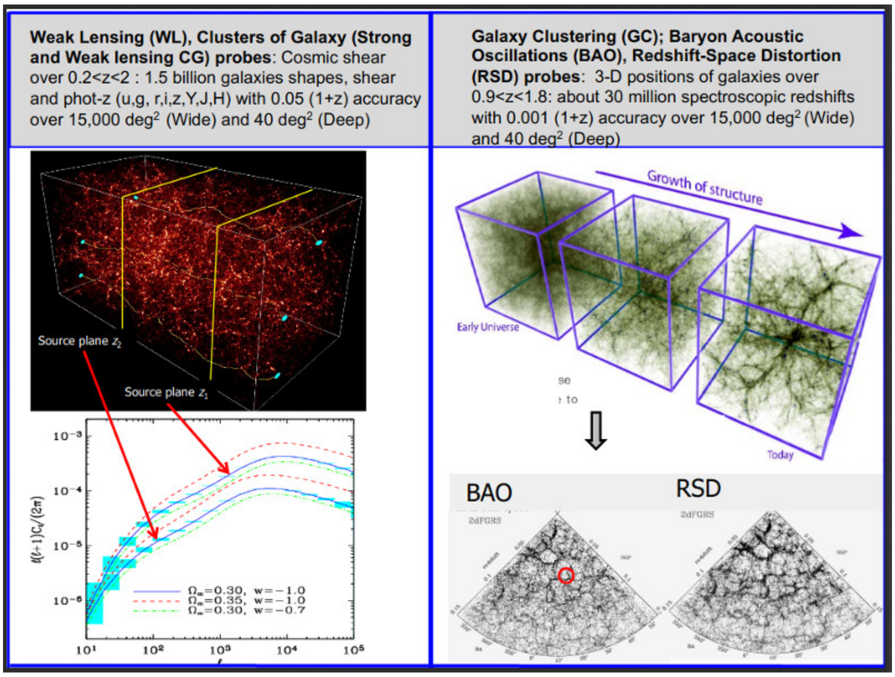

Figure 1: Representations of the primary Euclid cosmological probes from the Euclid Consortium Lead at the consortium meeting in May, 2002. Euclid exploits multiple signatures of the expansion of the Universe and of growth of cosmic structures: Weak Gravitation Lensing and Galaxy Clustering, including Baryonic Acoustic Oscillations and Redshift Space Distortions.

Mission Description

Euclid is a medium-class astronomy and astrophysics space mission selected by ESA in October 2011 and scheduled for launch in 2022.

Euclid will be equipped with a 1.2 m diameter Silicon Carbide mirror telescope feeding two instruments, VIS and NISP : a high quality, panoramic, visible imager (VIS), a near infrared, 3-filter (Y, J and H) photometer (NISP-P) and a slit-less spectrograph (NISP-S). With these instruments physicists will probe the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of dark matter and the 3-dimension distribution of structures from spectroscopic redshifts of galaxies and clusters of galaxies.

The satellite is planned to be launched on a Soyuz rocket and then travel to the second Sun-Earth Lagrangian point for over six years of observation. It will observe 15,000 square degrees of the darkest sky that is free of contamination by light from our Galaxy and our Solar System. Three "Euclid Deep Fields" covering around 40 square degrees in total will be also observed.

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[2] Kaiser, N., *Monthly Notices of the Royal Astronomical Society*, Volume 227, Issue 1, July 1987.

The complete survey represents hundreds of thousands images and several tens of Petabytes of data. About 10 billion sources will be observed by Euclid out of which more than a billion will be used for weak lensing, and several tens of millions of galaxy redshifts will be measured and used for galaxy clustering.

Genesis & Calendar

As outlined in the mission timeline Figure, the Euclid proposal was selected by the European Space Agency (ESA) for further consideration in 2008. IN2P3 participation in Euclid was considered by the IN2P3 Scientific Council in 2012.

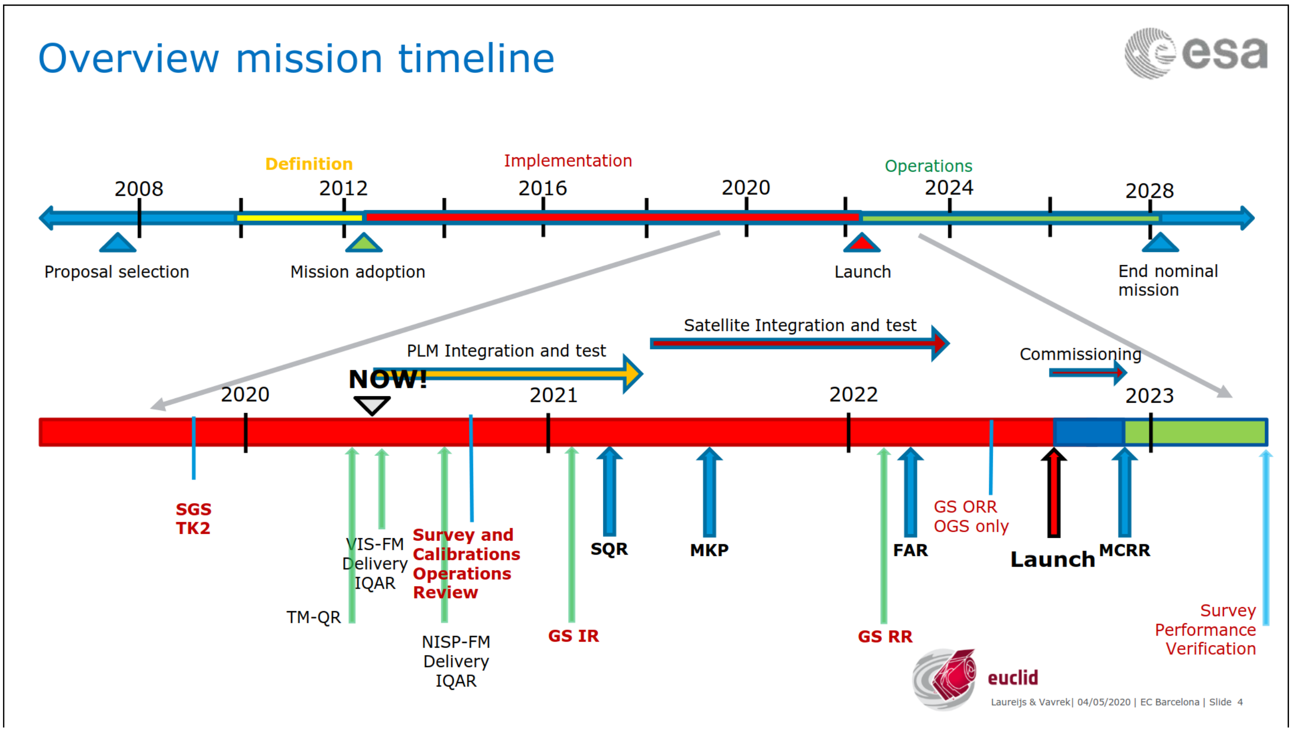

Figure 2: Overview of current mission time-line from the Project Scientist at the May, 2020 Euclid ConsortiumMeeting.

After the mission definition phase, Euclid was adopted by ESA in 2012. We are now in the implementation phase.

For the IN2P3, a major milestone has just been passed, with the delivery of the NISP instrument this month (May 19, 2020).

The Ground Segment, to which the IN2P3 is heavily contributing, will have it's next major review, the Ground Segment Intermediate Review, at the end of 2020. It will also have a Readiness Review before launch, which is currently scheduled for August, 2022.

After launch, the satellite and instruments will go through commissioning, during which the IN2P3 may be called upon to tune and evaluate the NISP instrument.

The survey operations are planned for six years, with three Quick Releases and Data Releases spaced through the operation phase.

The post-operation phase is less-well defined at the moment (meaning 2028 and later, at the moment), but should ultimately be considered, as IN2P3 science analysis will not end with the shutdown of the satellite itself. It will take time for the data to be finalized and published, and given the rush for releases, the IN2P3 should probably plan on analysis continuing at least a couple of years after the last scheduled Euclid data release, which itself will be roughly a year after the end of survey operations.

IN2P3 Participation

As of May, 2020, the Euclid community includes 16 countries (Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, Italy, the Netherlands, Norway, Portugal, Romania, the United Kingdom, and the United States), with of order 250 laboratories & institutions and 2200 register members (of which 1300 are "active", meaning that they are "tracked" by the Euclid system.). It is a complicated system, and the IN2P3 is involved in a number of the parts. And organizational chart is shown below, with red circles indicating where significant contributions from the IN2P3 appear.

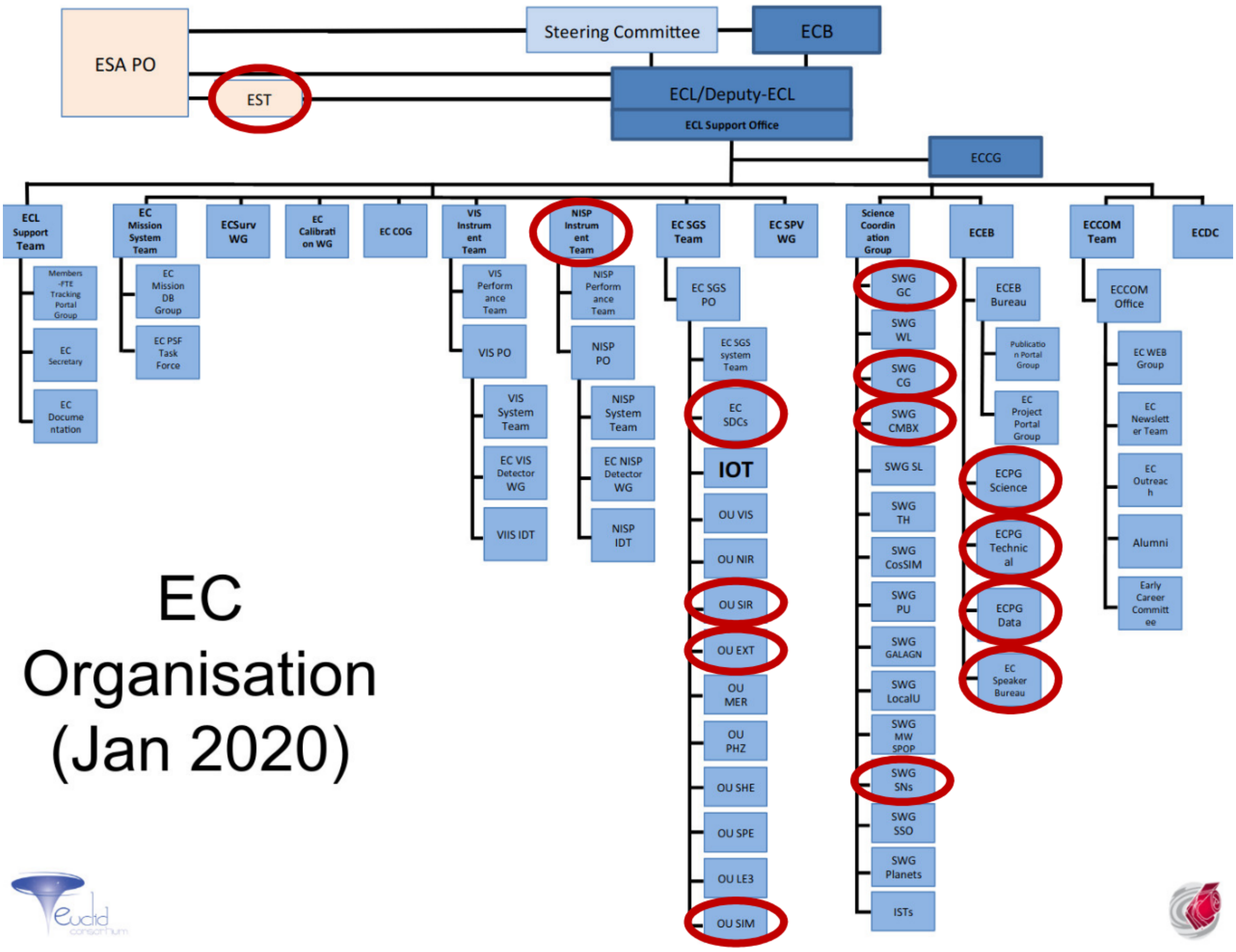

Figure 3: Euclid Consortium organization chart as of January, 2020. We have highlighted those parts to which the IN2P3 contributes regularly.

IN2P3 Scientist Positions in the Project

Here we note some of the “named” positions of responsibility held by IN2P3 members in the Euclid project.

- Euclid Science Team Members: A. Ealet (W. Gillard is her deputy)
- NISP Instrument Detector Scientist: R. Barbier (on detachment from IP2I)
- NISP Instrument Model Owner: Julien Zoubian
- EC Science Publication Group Members: A. Ealet
- EC Technical Publication Group Members: A. Ealet & A. Secroun
- EC Data Release Publication Group Members: S. Escoffier
- EC Speakers Board Members: J. G. Bartlett
- Euclid Science Working Group Co-Coordinators
    - SNe & Transients: C. Tao
    - Clusters of Galaxies: J. Bartlett
    - Galaxy Clustering
        - Additional Probes WP: A. Hawken
- Science Ground Segment Working Group coordination:
- Internal Data: J.F. Macías-Pérez
- Euclid France Science Data Center Reference Scientist: K. Ganga
- Science Ground Segment OU-SIR co-lead: Y. Copin
- Euclid Consortium “Founders” were decided by the Euclid Consortium Board in 2019. For the IN2P3, they are Anne Ealet (+ R. Cledassou, originally at CNES)
- Euclid Consortium “Builder” Status is conferred on those Euclideans who have made key, long-term contributions, especially to Euclid infrastructure. For the IN2P3, as of Jan. 2020, there are 7, of 34 French and 148 total. They are Rémi Barbier (on detachment at the moment), Jean-Claude Clemens, Sylvain Ferriol, Bogna Kubik, Quentin Le Boulc’h, Aurélia Secroun, Gérard Smadja, Julien Zoubian.
- 2019 Euclid STAR Prize Instrument Award went to the NISP team, including specifically Laurence Caillat, Romain Legras, Jean-Claude Clemens, Aurélia Secroun, William Gillard and Jérôme Royon from CPPM and Alain Castera, Gérard Smadja, Anne Ealet, Clement Buton, Sylvain Ferriol, and Bogna Kubik from Lyon (current institutes).
- 2020 Euclid STAR Prize Student Award went to Philippe Baratta from CPPM.

Technical Achievements and Resources Furnished by the IN2P3

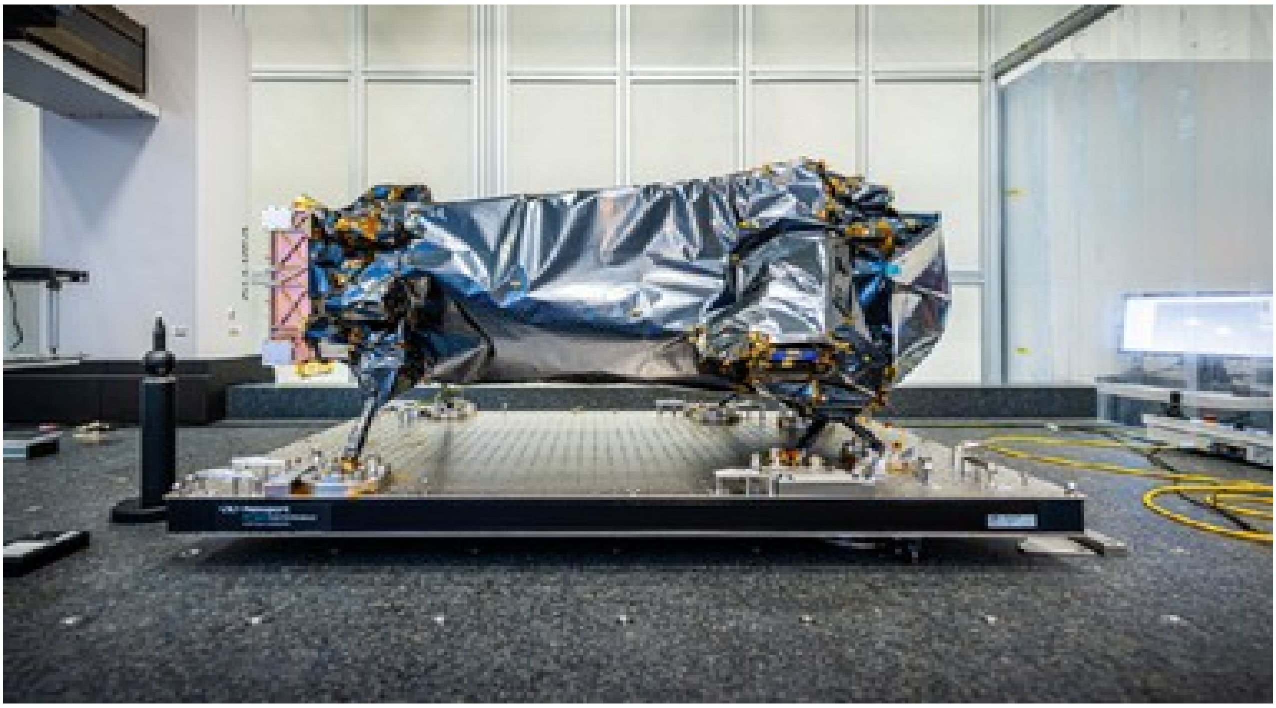

Figure 4: The NISP instrument was recently delivered to the European Space Agency.

NISP

The highest-profile technical achievement of the IN2P3 for Euclid must be the May 19, 2020 delivery to ESA of the Near Infrared Spectrometer and Photometer (NISP) instrument, a 4×4 grid of 2048×2048 pixel arrays of infrared detectors. CPPM was in charge of the integration of the focal plane and, in collaboration with the IP2I and LPSC, is in charge of the characterization and verification of the performance of these detectors. The CPPM team is also responsible for the spectroscopic calibration of the NISP instrument and its optical characterization. Electromagnetic compatibility tests of the NISP flight harness and detectors were done by LPSC.

The NISP focal plane, with 0.3 arc-second pixels, covers a field of view of 0.53 degree^2, shared with the other Euclid instrument. The spectroscopic channel will be equipped with low-resolution, near-infrared grisms for spectra which will provide redshifts for about 30 million emission-line galaxies over the redshift range 0.7 to 2.0. The NISP spectroscopic data will primarily be used to describe the distribution and clustering of galaxies and how they changed over the last 10 billion years under the effects of the Dark Matter and Dark Energy content of the Universe and of gravity.

While it is not strictly a NISP issue, we note here also that the IP2I (LMA) is in charge of the dichroic plate characterization bench. The dichroic splits and steers incoming light towards the two instruments.

SGS

The Euclid data is processed by the Euclid Science Ground Segment (SGS), which is distributed among countries with significant contributions to the project. It is organized into different Organizational Units (OUs), which are multi-national and which are in charge of defining the data analysis algorithms, and into Science Data Centers (SDCs), which are national and which are charged with implementing the reduction pipelines in order to produce the Euclid catalogs and other data products for the consortium and for ESA. The CC-IN2P3 serves at the production center for the French SDC. The Euclid data products become public after a proprietary period.

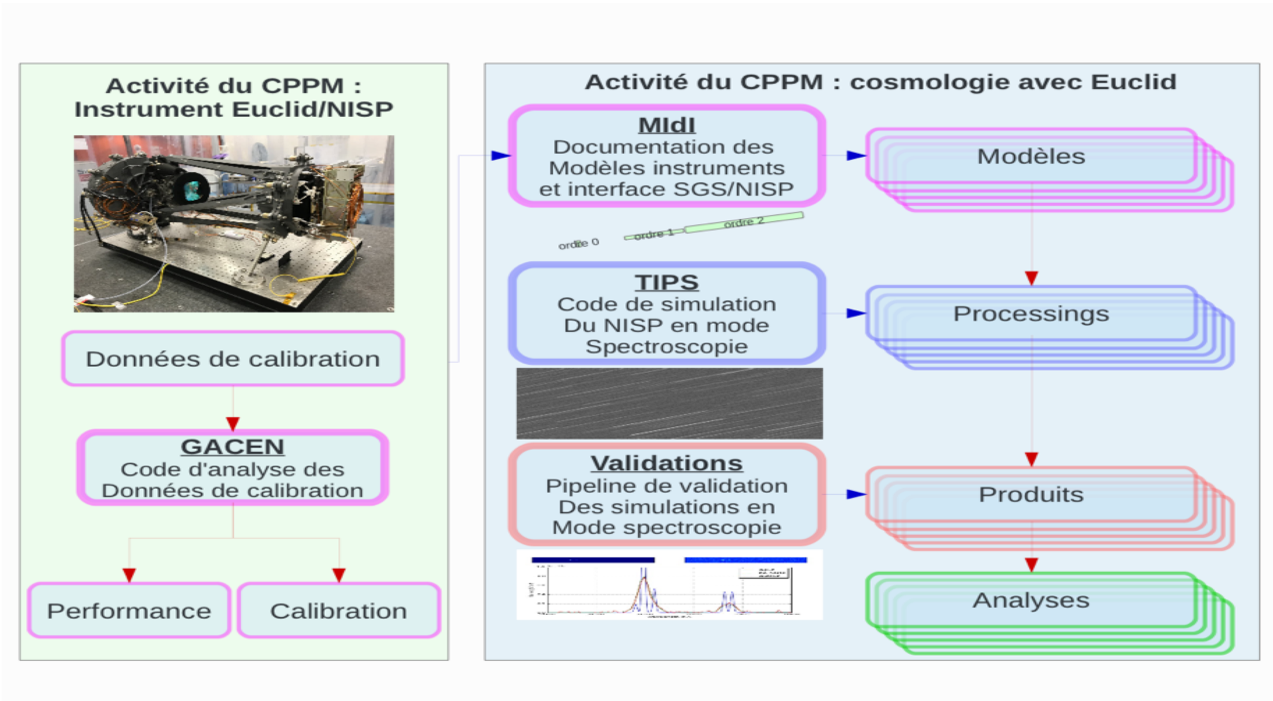

Figure 5: Software Development for NISP.

Euclid simulations (OU-SIM)

Simulations are crucial to cosmology missions, both before launch, in order to plan various aspects of the mission, and after launch, for the analyses themselves.

The IN2P3 has been heavily contributing to the Euclid simulation effort by (co-) leading the Euclid simulation “organizational unit” (OU) and by furnishing computing resources necessary for actually making the simulations (see next section). The IN2P3 has the responsibility of developing the NISP-S simulator (called TIPS) and the validation software for the simulator and the images it produces. These tools are used everywhere from the core simulation software to its integration in the Euclid architecture and simulations pipeline. As this is one of the major simulators in Euclid, it takes part in all the reviews deliveries and also the SGS scientific challenges. This simulator depends upon instrument and IR detector knowledge in general and our NISP expertise in particular.

The IN2P3 has the responsibility of co-coordinating the Euclid simulations deployment, integration and production, in addition to coordinating the Euclid France simulation developments and production activities, all the while reporting on this at CNES and ESA reviews.

Spectroscopy pipeline (OU-SIR/SPE)

The IN2P3 contributes to the reduction and analysis of the slitless spectroscopy data from the NISP-S instrument. Working with, on the one hand, the instrumental teams, and on the other hand with cosmological analysis groups, the objective is to build an efficient and robust spectral data reduction and analysis pipeline (SIR/SPE) which will allow us to accomplish the massive task of processing hundreds of millions of spectrograms. Notably, in relation with the detector characterization team, the IN2P3 is responsible for addressing the effects of persistence in the IR detectors.

External data (OU-EXT)

While agreement has not yet been reached (see section on Synergy with Rubin below), the union of Euclid and Rubin bands will be far more powerful than using only Euclid bands to infer the redshifts of Euclid galaxies. As the IN2P3 is involved in both experiments and, crucially, the data from both missions are to be housed at the CC-IN2P3, the APC has begun preparations for using the Rubin pipeline with Euclid.

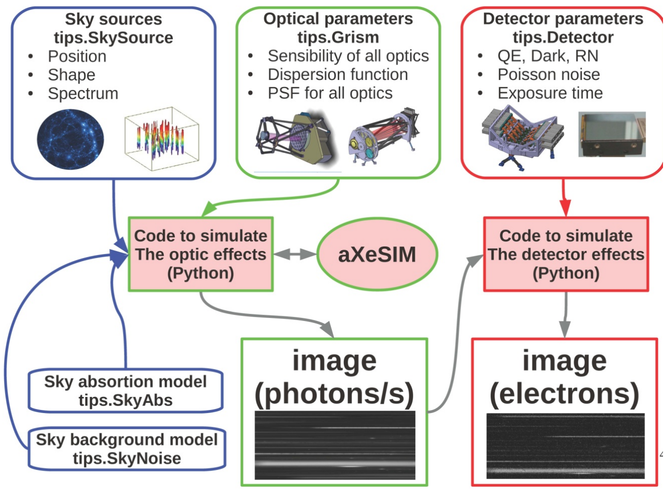

Figure 6: Schematic view of TIPS.

Level-3 (OU-LE3)

- *Cluster selection function (APC, LPSC)*. The selection function for the galaxy cluster catalog is a key element of the cluster cosmological analysis. The APC is developing methods and generating mock catalogs to evaluate the selection function. It is important to quantify the probability of detecting clusters as a function of their internal properties. This is done by running the cluster detection algorithms on mock catalogs with varying cluster properties. The same mock catalogs will also be used as random catalogs for calculating the cluster-cluster correlation function and power spectrum.
- LE3 Internal data masks are addressed by LPSC.

SDC-Dev

The APC contributes heavily to the creation, maintenance and expansion of the CODEEN collaborative development environment used for developing the Euclid pipeline. This software is housed at the CC-IN2P3, is developed in close collaboration with the CNES and is used by the entire Euclid team.

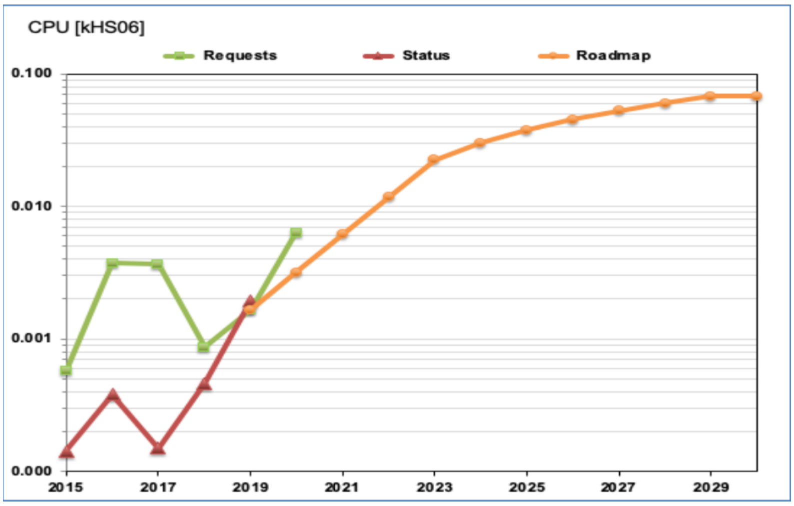

Figure 7: Processing contributions from the CC-IN2P3 passed and planned for Euclid. In both this Figure and the next, the orange curve, labeled 'Roadmap' represents the long-term plans. The green curve is what has been requested on a year-by-year basis, and the red curve is what is actually used.

SDC-Fr (CC-IN2P3)

The French portion of the Euclid Science Data Center (SDC-France) is one of nine different national data centers for Euclid. The IN2P3 Computing Center (CC-IN2P3) hosts the French portion of the Euclid Science Data Center pipeline production environment (SDCFr-Prod). As such, the French Space Agency (CNES) finances non-permanent employee contributions, and the CC-IN2P3 furnishes computing hardware and permanent employee contributions. The workforce at the CC-IN2P3 is expected to remain flat from now through launch and the first Euclid data release.

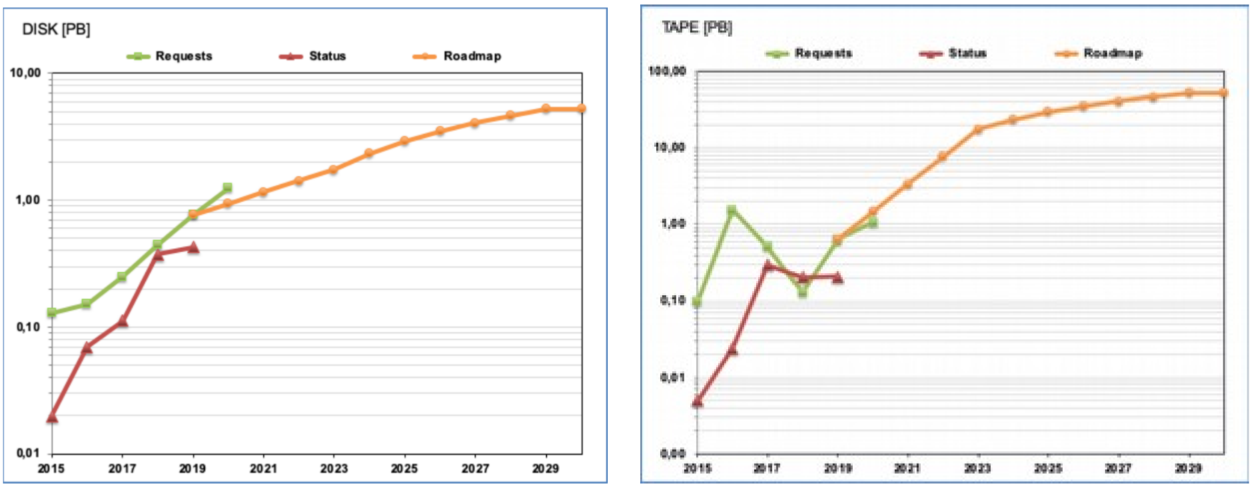

Figure 8: Disk and tape storage contributions from the CC-IN2P3 planned for Euclid.

Workforce

Here we present aspects of the IN2P3 workforce dedicated to Euclid. The figures come from different sources, so they are a bit heterogeneous, but they do convey the correct impression –

that the IN2P3 has made significant technical contributions to the preparations for Euclid, and that to date the scientific contributions (as measured by IN2P3 participation in the Euclid Science Working Groups) are an order of magnitude smaller.

Recent

In the Table below, we show the IN2P3 workforce applied to Euclid in each of the four IN2P3 “Projets” which are part of the Euclid “Master Project”. These data, directly from the IN2P3 NSIP database, only include figures from 2016 through 2019. The first set of data on the left shows the total number of work weeks applied. The second set of data, in the center, shows the number of individuals involved, regardless of their level of contributions.

	Work-Weeks				Individuals					Work-Years			
	2016	**2017**	**2018**	**2019**	**2016**	**2017**	**2018**	**2019**		**2016**	**2017**	**2018**	**2019**
NISP	828	836	683	311	37	46	33	20	**NISP**	20.7	20.9	17.1	7.8
Physics			83	212			9	11	**Physics**	0.0	0.0	2.1	5.3
SGS	437	556	544	576	21	30	28	30	**SGS**	10.9	13.9	13.6	14.4
CC-IN2P3	95	105	191	164	4	5	7	7	**CC-IN2P3**	2.4	2.6	4.8	4.1
	1360	1497	1501	1263	62	81	77	68		34.0	37.4	37.5	31.6

Table 1: IN2P3 workforce contributions from the IN2P3 according to NSIP. The first set of columns gives the estimates of work in person-weeks. The second set of columns gives the number of individuals involved, highlighting the fact that not all individuals work full-time on Euclid. The last set of columns is derived from the first, as an attempt to give an estimate of the number person-year equivalents. It is simply the first set of columns divided by 40 (to account for the fact that there are holidays, etc.).

The data set on the right of the Table is exactly the same data as that on the left, the work-weeks, simply divided by 40, in an attempt to give the reader a simple conversion to something approximating FTEs. This approximate FTE estimate is also shown in the “IN2P3 Euclid Workforce” Figure.

We note that the IN2P3 Euclid “Physics” Project, was introduced in 2018 to help organize the IN2P3 Euclid team’s transition from technical and preparatory work to future scientific exploitation.

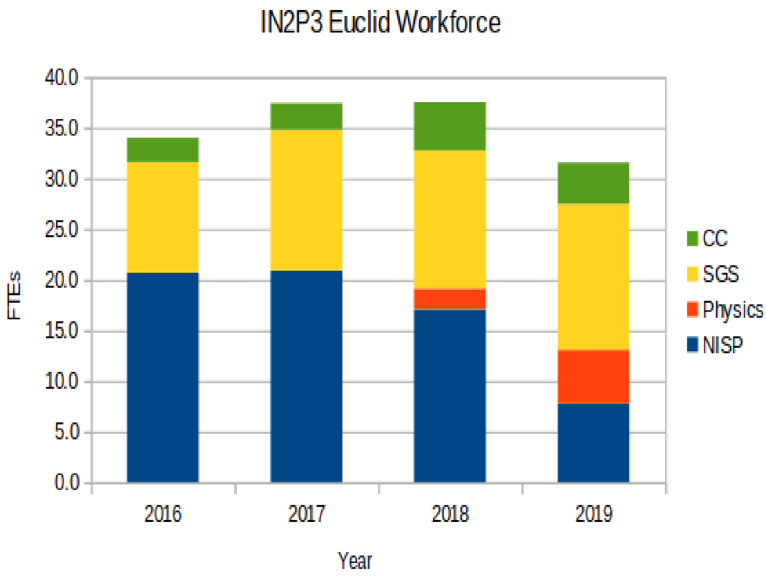

Figure 9: Chart of data from the previous Table.

This Year

In order to have a snapshot of the IN2P3 Euclid effort today, the Table below includes information about the four labs working on Euclid, along with the CC-IN2P3. The second column includes the names of all individuals currently working on the project (as collected during an exercise by all French labs working on Euclid in April, 2020). The third column, from the international Euclid time tracking tool, includes the sum of all effort for each lab prior to 2020 (that is, from roughly 2011 or earlier in a few cases, through 2019). The final column, from the same source, shows the effort dedicated to the Euclid Science Working Groups (it is a subset of the work in the third column).

Lab	Names of those Working on Euclid this Year at these Institutes	Total FTE Euclid <2020	Total FTE SWG <2020
APC	Aubourg, Bartlett, **Boizard**, Boucaud, Cavet, Colley, Ganga, Giraud-Héraud, Le Jeune, **Murray**, **Pollack**, Rosset, Souchal (13)	34.8	3.2
CC-IN2P3	Le Boulc'h, Lemrani, **Mainetti** (3)	11.6	
CPPM	**Aubert, Auphan, Baratta, Benielli,** Caillat, Clemens, Cousinou, Curtil, Escoffier, Gillard, **Gouyou-Beauchamps,** Henry-Couannier, Kermiche, Laugier, Logier, Niclas, **Ntelis**, Royon, Secroun, Tao, Tilquin, Zoubian (22)	78.3	3.8
IP2I	Barbier, Borja, Copin, Courtois, Ealet, Ferriol, Fourmanoit, Guinet, Kubik, **Lezmy**, Smadja (11)	33.7	0.2
LPSC	Catalano, Odier, **Jimenez-Muñoz**, Macías-Pérez, Marpaud, Marton, Perotto, Stassi (8)	4.0	

Table 2: A snapshot of IN2P3 human resources dedicated to Euclid to this point. [3]

Future

As is shown in the tables and charts above, the IN2P3 has already invested hundreds of FTEs in preparation for the Euclid mission, and will, of course, continue to do so though instrument checkout and calibration and through development of numerous pieces of the pipeline to deliver the Euclid products to the community.

As is noted in the following section, IN2P3 researchers are also excited to exploit the Euclid data to understand the large-scale structure of the Universe. We emphasize, however, that given the sheer size of the preparatory development, it is difficult to imagine that the IN2P3 Euclid team will be able to apply an equivalent number of resources in the exploitation of the data — we simply do not have as many people to work on the exploitation as on the preparation at the moment.

Theses

As requested, the following is a list of IN2P3 theses in production or produced by the project.

- Lezmy, Jérémy, IP2I, Champs de vitesses pour $F\sigma_8$ local et plus lointain avec Euclid, Courtois, 2022
- Jiménez-Muñoz, Alejandro, LPSC, *Clusters of galaxies selection and NISP noise properties*, Macias-Perez, 2021
- Gouyou-Beauchamps, Sylvain, CPPM, *Contraindre les propriétés des neutrinos avec la mission spatiale Euclid*, Escoffier, 2021
- Murray, Calum, APC, *Preparing the euclid dark energy survey with clusters*, Bartlett, 2020

[3] Figures were found by searching by laboratory. This is prone to errors, as people move between labs. To try to address this, we have added A. Pisani to CPPM (presently in Princeton), all but one year for A. Ealet (presently in Lyon), and we have added 14 FTEs for CPPM engineers who seem to have been counted by the lab, but have not kept their hours current in the Euclid tracking tool.

- Baratta, Philippe, CPPM, *Testing cosmology beyond the standard model with the large scale structures of the universe and Euclid*, Ealet, 2020
- Outini, Mehdi, IP2I, *Mesure de la cinématique interne des galaxies en spectroscopie sans fente*, Copin, 2019
- Van Tuan Bui, APC, *A study of the large-scale structure of the universe with galaxy clusters : from Planck to Euclid*, Rosset, 2019
- Serra, Benoît, CPPM, *Caractérisation des détecteurs infrarouges de la mission spatiale Euclid : étude des performances des détecteurs infrarouges H2RG*, Ealet, 2016
- Fromenteau, Sébastien, APC, *Modélisation et reconstruction et reconstruction des amas de galaxies dans le domaine optique/infrarouge*, Bartlett, 2010

Risks and Mitigation Steps Taken or to Take

Below we briefly outline some of the risks that currently preoccupy the IN2P3 Euclid team.

- Dichroic chromaticity. The dichroic which splits the beam between the VIS (reflection) and NISP (transmission) instruments has unforeseen chromaticity caused by its complex, multi-layer coatings. This could significantly affect the VIS PSF properties, a key element for the weak-lensing analysis. A procedure is being developed (ESA/CNES/IN2P3) to fully characterize the spare dichroic, and build a chromatic model applicable to the flight model. While this applies more to the VIS instrument than to NISP (associated with the IN2P3), the risk for the IN2P3 associated with this, other than an impact on lensing science (which is shared by all), is simply that the IN2P3 may be called upon to follow-up on their characterization of the dichroic.
- Launch. Euclid is scheduled for launch in mid-2022 on a Soyuz launcher. ESA’s contract with the Russians also ends around this time. There is little margin in the Euclid delivery schedule, so if there are more delays, significant costs or delays associated with changing launcher must be anticipated.
- Instrument Operation Team. Organization of the IOTs, which are in charge of the instrument tuning and control during the mission, is being progressively addressed, but with loose connections to the Instrument Development Teams and SGS teams. IN2P3 teams, having played a significant role in both activities, should be integrated into to the discussions in a timely fashion, and their contribution to the operations should be properly defined.
- RGS270. During the last phase of the NISP-S instrumental tests, it was determined that one of the three grisms (the dispersing elements for spectroscopy) does not meet requirements and cannot be used as is. A dedicated RGS270 investigation team was set up, and has now delivered a detailed report to ESA on the issue and possible mitigation steps. Notably, a new spectroscopic operation mode (“K strategy”) only using the two available grisms is counseled. While the full performance verification, up to the final cosmological figure of merit, has not been completed, intermediate results indicate that, given the new observing procedure, along with the fact that the other parts of the optical system surpass specifications, will provide as good performances as initially requested.
- Synergy with Rubin. The IN2P3 has involvement in both Euclid and Rubin, and has intended to leverage this for more efficient science output. As noted below, Euclid and Rubin have begun to define work to be done together. To this point, however, despite effort

to the contrary, the IN2P3 has not been included in this planning. Being left out represents a risk, for example, to exploiting much of the "OU-EXT" work done to this point.

- The synergy section of this document below notes some of the future experiments that are being implemented in this domain; it is a growth industry. As underlined and outlined in the IN2P3 Prospective GT08 Whitepaper *Detecteurs infrarouge grand format bas bruit – large array low noise infrared detectors* by Secroun et al.[4] the IN2P3 has developed expertise in a critical element of these future experiments. There is a risk that this expertise will be lost after Euclid if it is not supported.

Anticipated Involvement Envisaged for Scientific Exploitation and Expected Scientific Return

The primary IN2P3 scientific goal for Euclid is to construct a complete view of the evolution and relative distributions of galaxies (i.e., stellar mass), gas and dark matter in the Universe by combining (stacking and cross-correlating) Euclid data with other survey data; for example, CMB, X-ray or radio surveys. We will develop the tools needed to make these measurements and the theoretical modeling needed for their interpretation. These tasks include:

- **Cosmology with galaxy clustering** : galaxy clustering is a primary probe in Euclid. Anisotropic BAO studies provide a direct measurement of the expansion history of the Universe, and, at the same time, redshift space-distortions due to peculiar velocities that distort the line-of-sight cosmological distances provide powerful constraints on the growth rate of structure. We are deeply involved in this kind of analysis (in configuration space and Fourier space). Our work focus on neutrino mass constraints, RSD analysis and fast generation of mock catalogs to compute the covariance matrix.
- **Cosmology with cosmic voids** : cosmic voids are low-density environments that account for about 80% of the total volume of the observable Universe. Several studies suggest that cosmic voids not only represent a key constituent of the cosmic mass distribution, but are also one of the cleanest probes to test cosmology. At IN2P3 we are strongly involved the voids analyses. Our work includes RSD analysis around cosmic voids to give constraints on the growth of structure, weak lensing with voids, and we are interested by cross-correlation between voids and CMB.
- **Cosmology with clusters of galaxies**: Cluster abundance and its evolution is a sensitive probe of structure growth and the presence of Dark Energy; as such, it is recognized as a critical Euclid secondary cosmological probe that will break degeneracies when combined with Euclid's two primary probes to improve cosmological constraints. A notable example is the power of the cluster probe to constrain the neutrino sector. Critical steps in the cluster cosmology analysis are determination of the cluster selection function, cluster mass measurements and construction of the cluster likelihood function. We are heavily invested in all of these steps. Our work on clusters includes multi-wavelength analysis using data and surveys external to Euclid, such as CMB (e.g., Planck, NIKA2, Simons Observatory and CMB=S4) and X-ray (e.g., ROSAT, XMM-Newton, Chandra and eRosita) surveys; this will be used to improve our understanding of Euclid cluster selection by comparison to surveys in other wavebands, to tighten cluster mass measurements

[4] https://indico.in2p3.fr/event/19979/attachments/55521/74638/SECROUN_Contribution_ProspectivesIN2P3_DetecteurIR.pdf

using mass proxies at other wavelengths and to merge the Euclid cluster catalog with other cluster catalogs to perform a comprehensive cluster cosmological analysis.

- Cross-correlating Euclid galaxy, QSO and cluster samples with CMB, X-ray, UV, IR and radio observations to measure gas content and physical state, and star formation rates as a function of object properties, e.g., galaxy morphology, color, H_α line-strength. In the pre-launch phase, we will develop and test our infrastructure using Euclid simulations (e.g., Flagship). We will enhance the Flagship simulations with models for the gas distribution. The product of this work will be enhanced simulations available to the collaboration.
- Cross-correlating Euclid galaxy, QSO and cluster masses out to high redshift through lensing (weak gravitational lensing from Euclid and also CMB lensing). In the pre-launch phase, we will test our lensing methodologies on Euclid simulations (e.g., Flagship). We've already been involved in this kind of analysis with BOSS and CFHTLenS data.
- Reionization studies, if possible, through cross-correlating high-z Euclid samples with CMB.
- Velocity fields from RSD and relation to CMB features: Peculiar velocity fields are direct probes of $f\cdot\sigma_8$ (a measure of the growth of structure) and the expansion rate. They can be used to define large scale structures dynamically: basins of attraction and their duals. These basins of attraction are dynamic definitions of large scale structure that can be studied for profile evolution in Euclid, growth factor, and more. Peculiar velocity fields can be inferred, for example, from RSD via 2LPT or via forward modeling. We have coded a methodology that allows us to partition coherent volumes in the Universe. Once some LSS is dynamically defined in the Euclid survey, we will look for cross-correlation with CMB features, as was done in Courtois et al. (2017): *Cosmicflows-3: Cold Spot Repeller?*

Synergy and Competition

The nature of the Cosmological Constant has been pondered at least since immediately after the discovery of cosmic acceleration[5] [6]. It is the subject of several current and future experiments that will survey the sky. These include the Dark Energy Spectroscopic Instrument[7] (DESI), the Dark Energy Survey[8] (DES), the Kilo-Degree Survey[9] (KiDS),the Vera C. Rubin Observatory[10] and the Nancy Grace Roman Space Telescope[11].

Synergy with Ground-Based Projects

The photometric redshifts for Euclid galaxies will be derived from the three Euclid NIR bands complemented by ground-based photometry in visible bands from collaborations with ground-based projects such as CFHT/CFIS, Rubin, DES and Pan-STARRS.

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5 A. G. Riess et al., Astron. J. 116, 1009 (1998).
6 S. Perlmutter et al., Astrophys. J.517, 565 (1999).
7 https://www.desi.lbl.gov/
8 https://www.darkenergysurvey.org/
9 http://kids.strw.leidenuniv.nl/
10 The recently renamed LSST. https://www.lsst.org/
11 The recently renamed WFIRST. https://roman.gsfc.nasa.gov/

Rubin (formerly LSST)[12]

The Vera C. Rubin Observatory will conduct a 10-year survey, now called the Legacy Survey of Space and Time in order to preserve the telescope's earlier acronym. Rubin will deliver a 500 petabyte set of images and data products that will, like those of Euclid, address the structure and evolution of the Universe and the objects in it.

The observatory houses an 8.4-meter telescope with an exceptionally wide field of view that allows the experiment to survey the visible sky in three nights. It is located on the Cerro Pachón ridge in Chile. Operations are currently scheduled to begin in 2023.

On the international level, discussions are ongoing between the Euclid and Rubin teams. Observations will begin at roughly the same time for both observatories, though Rubin will observe longer. A joint "Derived Data Product" working group is being formed at this time (May, 2020), which is tasked with defining any derived products that might be shared between the two observatories.

From the Euclid point of view, access to Rubin (and other instruments such as the CFHT) enables accurate estimation of photometric redshifts. What else might Euclid want from Rubin?

1. Greater overlap (currently ~7000 square degrees)
2. Coverage of Euclid Deep Fields
3. Cadence coordination on Deep Fields. There is a preliminary, "handshake" agreement from Rubin to cover Euclid Southern Deep Field, provided scheduling allows it and the data from both Rubin and Euclid are released to both communities
4. Euclid has already worked on sophisticated simulation products; for example, the Euclid Flagship Simulation. Given the heavy need of simulations for both observatories, sharing simulation resources might represent significant savings.

On the IN2P3 level: The IN2P3 is deeply involved in the data reduction for both Rubin and Euclid, and major processing for both will take place at the CC-IN2P3. This provides an opportunity for expertise sharing (always strictly adhering to each experiment's data policy, of course). Rubin image sizes and data set volumes are larger than those from Euclid. This may benefit Euclid, for example, as the Rubin team must develop optimized processing for the large Rubin data set, and Euclid should be able to use many of the same optimizations.

DESI

The Dark Energy Spectroscopic Instrument (DESI) is a ground-based dark energy experiment sited on the Kitt Peak National Observatory Mayall 4m telescope (Arizona, USA). DESI will conduct a five-year survey designed to cover 14,000 deg2 and to map the large-scale structure of the Universe at $0 < z < 3.5$ by measuring 37 million redshifts (Aghamousa et al. 2016).The survey will make spectroscopic observations of four distinct classes of extragalactic sources: bright galaxies, luminous red galaxies (LRGs), star-forming emission-line galaxies (ELGs) and quasars (QSOs). The complementarity of DESI and Euclid in terms of galaxy clustering will allow us to check

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[12] More information can be found at https://www.lsst.org.

source-related systematics on the common redshift range from z=1 to z=2. DESI will begin its survey in autumn 2020. At the IN2P3 level, the CPPM and LPNHE laboratories are involved in the DESI project, enabling these teams to prepare galaxy clustering science for the Euclid mission.

Simons Observatory[13]/CMB Stage 4[14]

The Simons Observatory (SO) is a cosmic microwave background (CMB) experiment being built on Cerro Toco in Chile, due to begin observations in the early 2020s. Its key science goals are to characterize the primordial CMB perturbations, measure the number of relativistic species and the mass of neutrinos and to test for deviations from a cosmological constant, among others. The high-resolution sky maps will constrain cosmological parameters derived from the CMB power spectrum damping tail, gravitational lensing of the microwave background, the primordial bispectrum, and the thermal and kinematic Sunyaev-Zel'dovich effects, and will aid in delensing the large-angle polarization signal to measure the tensor-to-scalar ratio. The survey will also provide a legacy catalog of 16 000 galaxy clusters and more than 20 000 extragalactic sources on 40% of the sky overlapping with the majority of the Rubin sky region and partially with the DESI.

The Simons data will offer high sensitivity, high angular resolution CMB maps for cross-correlation studies and for observing the Sunyaev-Zeldovich (SZ) effect in Euclid clusters over the Southern Sky. There are plans for discussions between the Simons Observatory and the Euclid Galaxy Cluster and Euclid CMBXC Science Working Groups. The CoViD19 crisis has delayed these, but they will be resumed as soon as possible.

After Simons, CMB-S4 is the next generation (or ``stage'') of ground-based CMB work. The basic framework would be to continue CMB work such as Simons at established sites at the South Pole and in Chile. It expressly aims to be independent of satellite and balloon work, though it endeavors to be complementary with them.

The goals of Stage 4 will be to set even more restrictive limits on the inflationary Tensor-to-Scalar Ratio, r, to confirm and/or bound the existence (or not) of particles present in the early Universe, a detection of the sum of the masses of neutrinos, rather than an upper limit, and to improve our understanding of Dark Energy, in conjunction with other cosmological measurements. It is scheduled to begin in 2027.

NIKA2

- Follow-up: millimeter observations via the SZ effect of rare clusters of galaxies detected by EUCLID to determine their thermodynamic properties: electron pressure and temperature, and hydrostatic mass
- Scaling laws: determination of EUCLID cluster masses via the tSZ based scaling relations.

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13 More information about the Simons Observatory can be found at https://simonsobservatory.org/.

14 More information about CMB Stage 4 can be found at https://cmb-s4.org/.

Synergy with Spaced-Based Projects

SPHEREx[15]

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. SPHEREx will carry out a spectral survey at wavelengths between 0.75 and 5 μm with spectral resolution ranging from 35 to 130, depending upon frequency band. At the end of its two-year mission, SPHEREx will have a spectrum of each 6.2×6.2 $arcsec.^2$ pixel on the sky.

While there is currently no IN2P3 involvement with SPHEREx, we note that catalogs from SPHEREx, with spectra of galaxies at $z<1$, will be complementary to those from Euclid, and that for some classes of objects, combination of Euclid and SPHEREx data would provide for an even more powerful photometric-redshift catalog. SPHEREx is also predicted to detect even more voids than Euclid, and could be of direct interest to the IN2P3 science goals noted above.[16]

The Nancy Grace Roman Space Telescope[17]

The Nancy Grace Roman Space Telescope (until recently called WFIRST) bills itself as being similar to the Hubble Space Telescope (HST) but its Wide Field Instrument will image a far larger area of sky. It will address many science topics, some of which overlap strongly with Euclid. Once again, there has been no formal effort made towards an IN2P3 contribution to the Roman Satellite, but given the weight it will carry in addressing the science of interested to IN2P3 Euclid members, it would be prudent to at least push forward an organized investigation into the possibilities, probably in conjunction with other institutes such as INSU.

Action Dark Energy

The study of Dark Energy is important not only to the IN2P3, but also to INSU, INP and IRFU.

Unsurprisingly, the French cosmology community has mobilized itself around this issue, with significant involvement in several ambitious experiments, of which two high-profile examples are the Euclid satellite and the Rubin Observatory. But also with a significant effort in others such as DESI and the Simons Observatory. This atmosphere has led to the observation that better, multi-year coordination of these initiatives on theoretical, methodological and observational levels would be particularly welcome for all researchers concerned, to provide young researchers with a forum for exchanges and meetings, to identify synergies and the community's main lines of strength, to define the means of action to ensure optimum visibility for the French community and to organize reflection on the prospects for the next generations of experiments.

The “Action Dark Energy” provides some of these[18].

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[15] More information can be found at https://spherex.caltech.edu/.

[16] More information about SPHEREx synergy with Euclid can be found at https://arxiv.org/pdf/1805.05489.pdf.

[17] More information can be found at https://roman.gsfc.nasa.gov/.

[18] As an example of the work done, the website for the Action’s November, 2019 meeting can be found at https://indico.in2p3.fr/event/18904/.