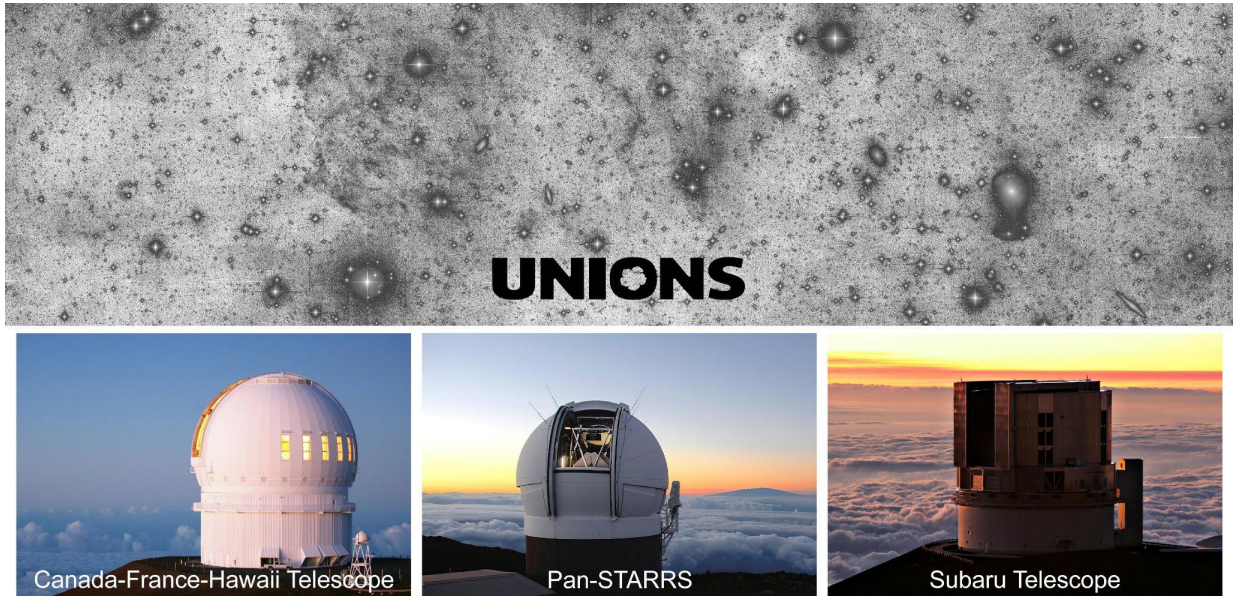
The Ultraviolet Near-Infrared Optical Northern Survey

UNIONS : a deep photometric survey of the northern sky open to the French scientific community

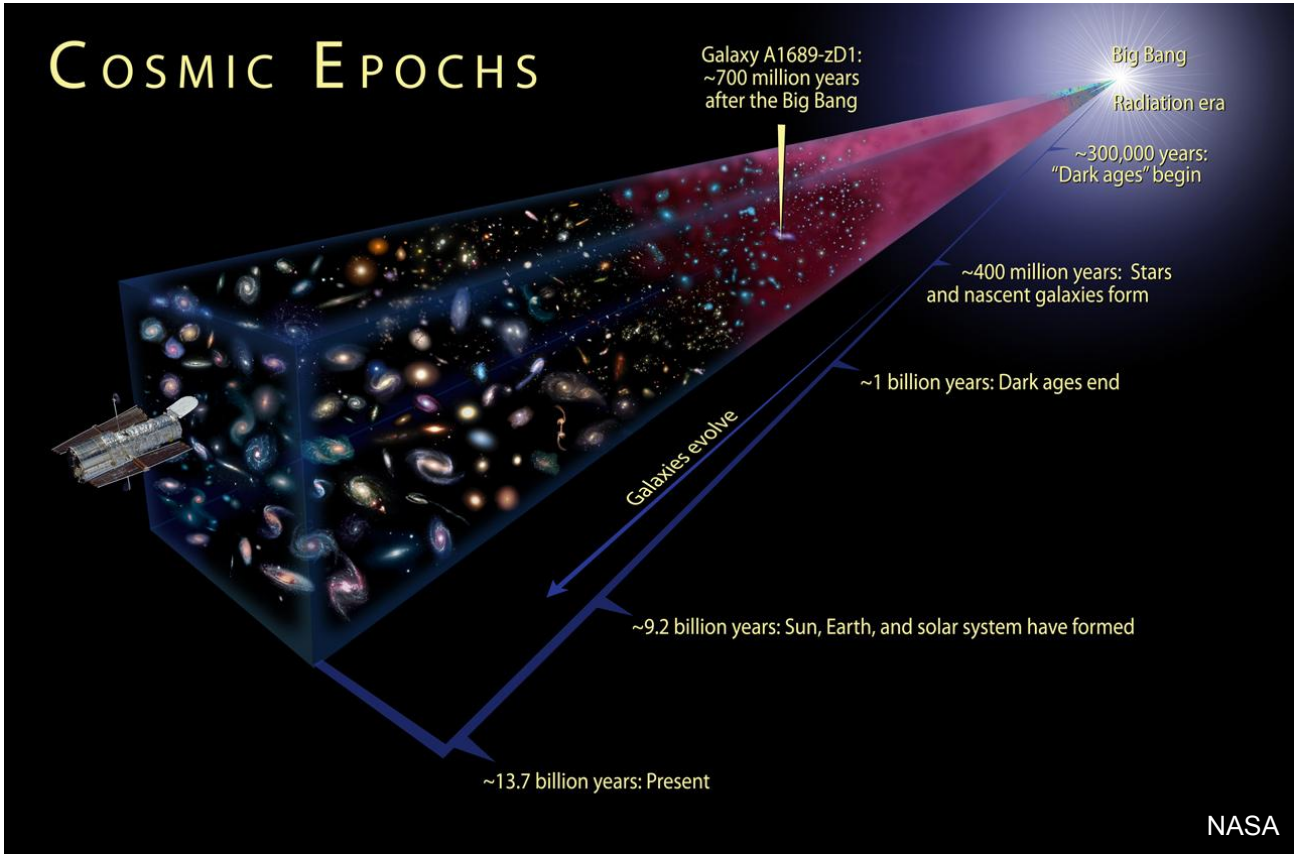


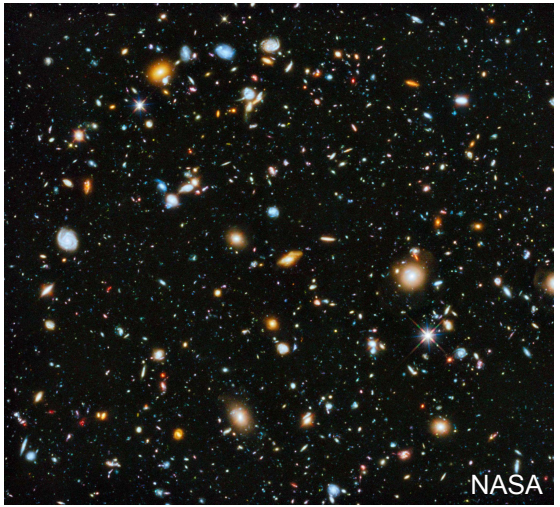
Jean-Charles Cuillandre (CEA Paris-Saclay)
on behalf of the UNIONS science collaboration & the Euclid Consortium

The whole sky is our window on the Universe

Axel Mellinger

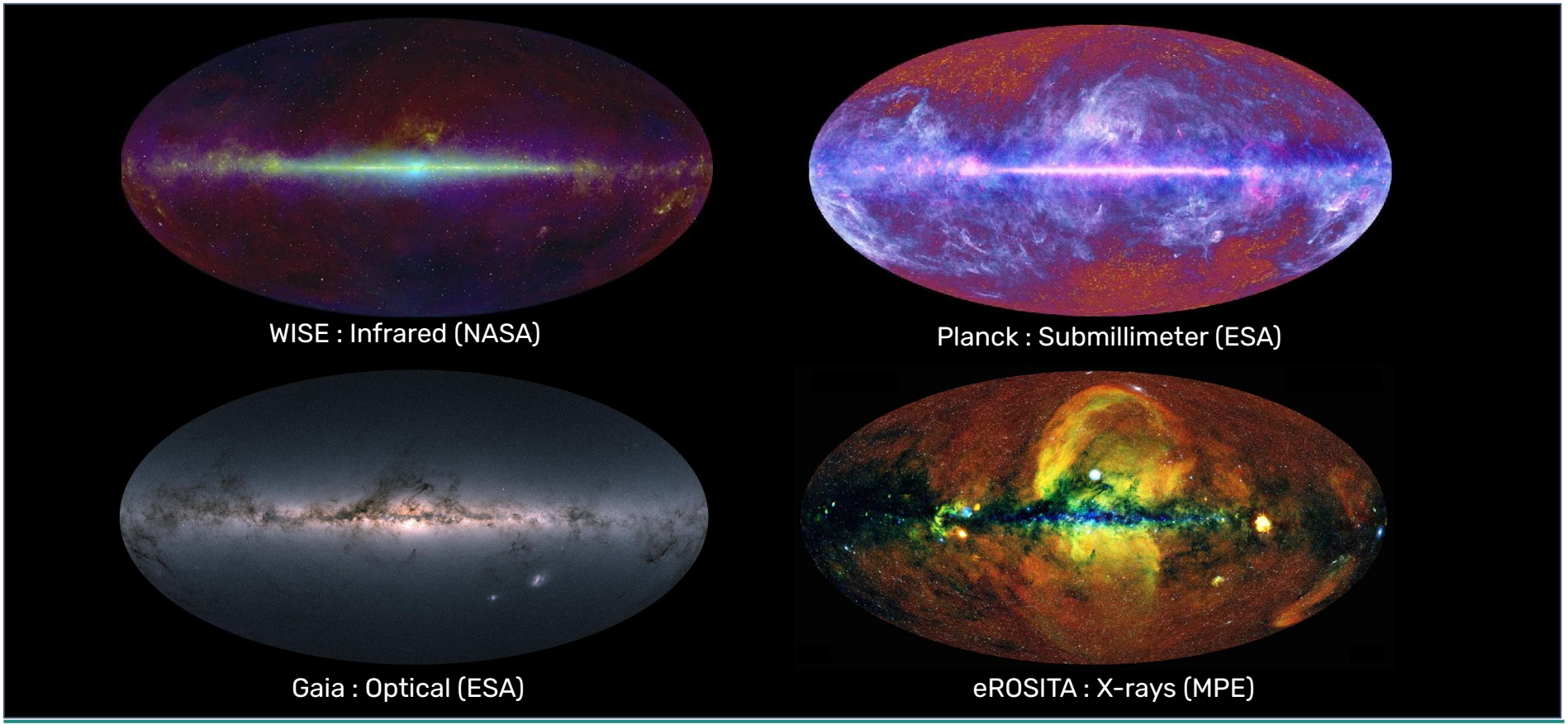
The Universe as a laboratory



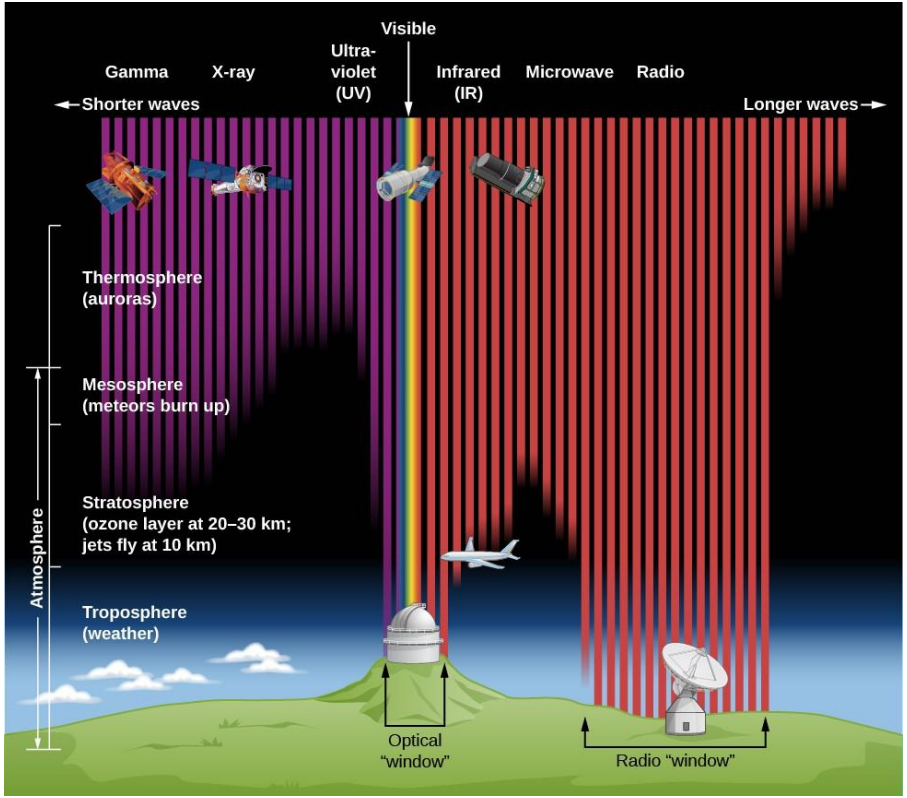


Studying a small area of the sky (e.g. Hubble Deep Field) is scientifically potent but not representative of the whole Universe and offers a limited sample of objects.

Modern precision science has moved to all-sky

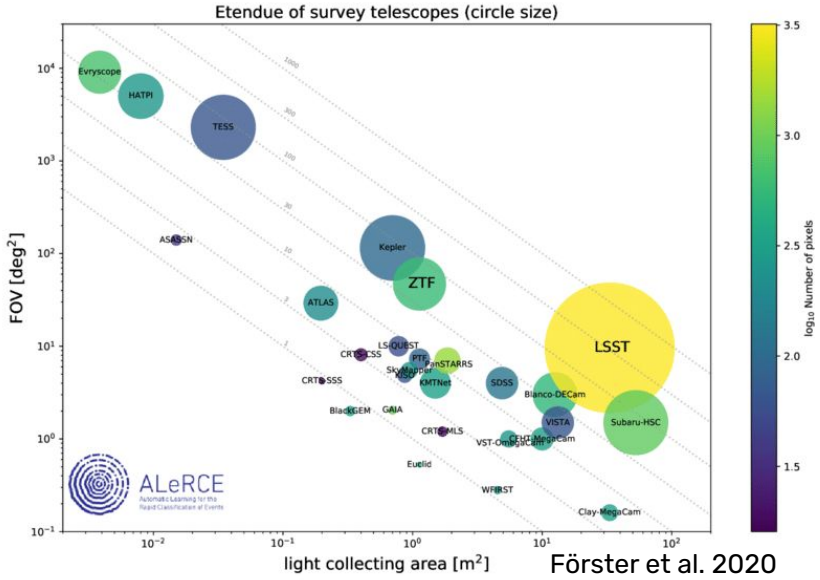


Access to the electromagnetic spectrum & Etendue



STScI/JHU/NASA

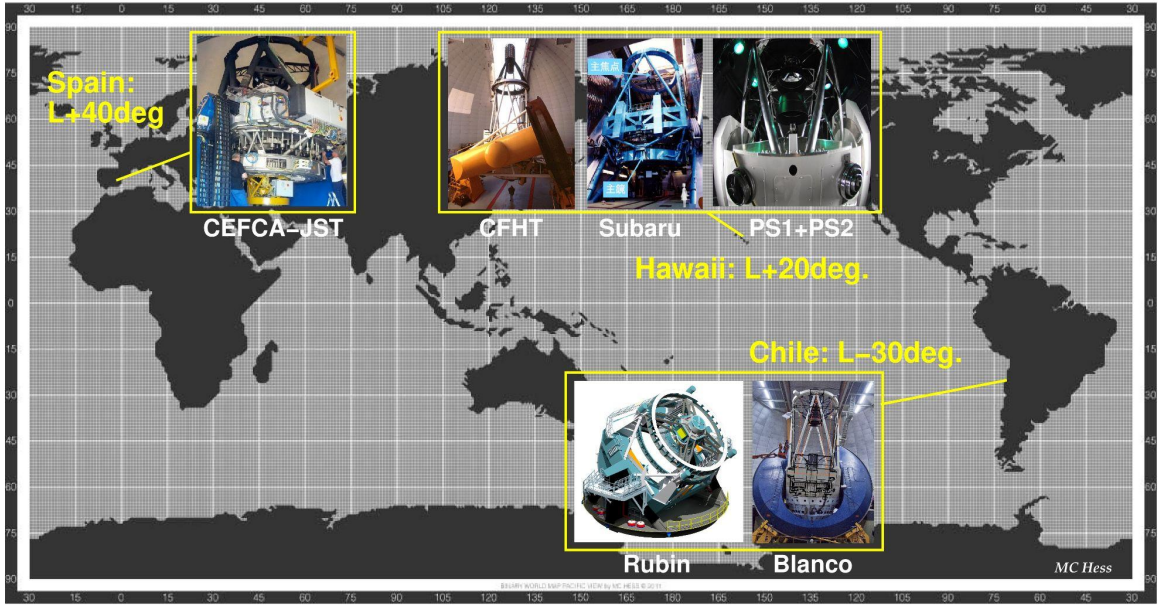
The "Etendue" is a metric illustrating the capacity of a telescope to cover large areas of the sky to a certain depth.



Förster et al. 2020

The most powerful ground-based wide-field imagers

All 6 current and future ground-based wide field imaging telescopes for optical and near-infrared astronomy



Etendue

Facility	Year	Aper.	FOV	IQ[r]	CCD class	Type	Hemisphere
Rubin	2023	6.6m	9.6 sq.deg.	0.8"	Deep depletion	Surveyor	South
Subaru	2013	8.2m	1.8 sq.deg.	0.6"	Fully depleted	Observatory	North
Blanco	2013	4.0m	3.0 sq.deg.	1.0"	Fully depleted	Observatory	South
JST	2022	2.5m	4.8 sq.deg.	0.8"	Deep depletion	Surveyor	North
PS1+PS2	2019	2x1.5m	7.0 sq.deg.	1.0"	Fully depleted	Surveyor	North
CFHT	2003	3.6m	1.0 sq.deg.	0.6"	EPI	Observatory	North

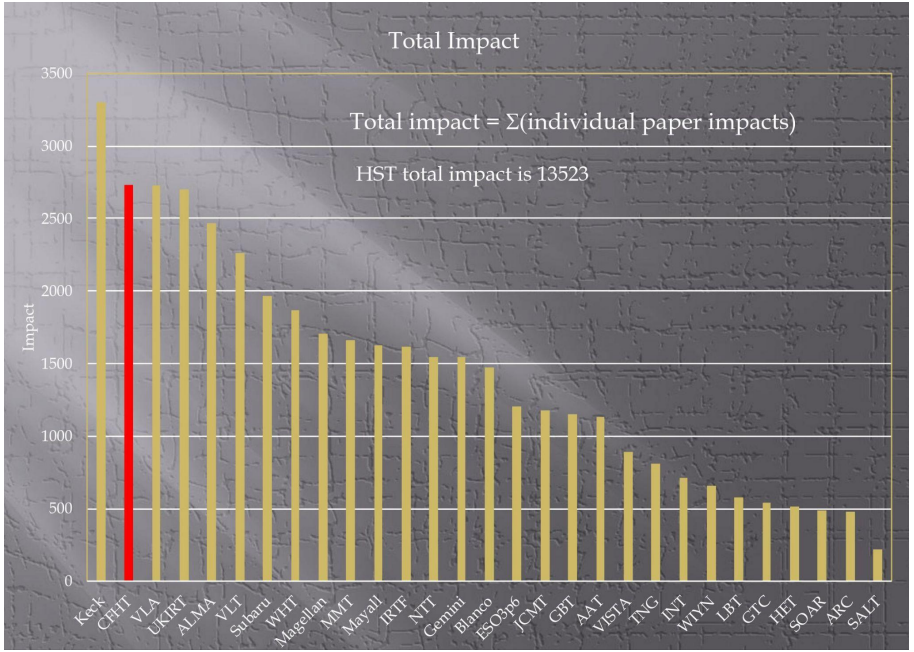
Trends from 20 years of CFHT-MegaCam observing

- 236 observing runs, 3057 nights (42% of the telescope time)
- 312103 science images
- 1309 individual PI programs (from one hour to tens of hours long)
- 1 Legacy Survey: CFHT Legacy Survey, 2003-2008, 450 nights: Dark Energy, Dark Matter, Galaxy Evolution
- 7 Large Programs (smaller surveys):

The Pan-Andromeda Archaeological Survey (PandAS)	2009-2012	50 nights	Local Group
The Next Generation Virgo Cluster Survey (NGVS)	2009-2012	150 nights	Local Universe
The CFHT Legacy for the u-band all-sky universe (Luau)	2013-2016	60 nights	The Galaxy
Mass Assembly of early-type GaLAxies with Structures (MATLAS)	2013-2016	50 nights	Local Universe
VESTIGE: Virgo Environmental Survey Tracing Ionised Gas Emission	2017-2021	50 nights	Local Universe
Canada-France Imaging Survey (CFIS-UNIONS)	2017-2024	415 nights	The Galaxy, Local Universe, Cosmology
The Classical and Large-a Distant Solar SYstem (CLASSY) Survey	2022-2024	50 nights	Solar System

Survey science engages communities & fuels impact

CFHT word cloud from all article titles



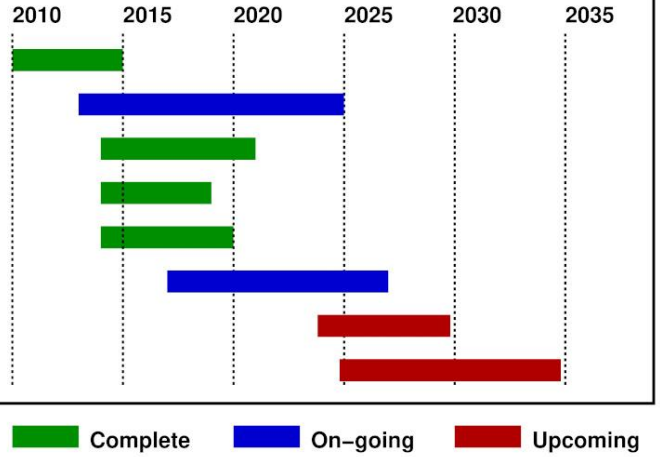
CFHT & world (2019): total impact (no HST & Sloan)

Source: Dennis Crabtree (HIA)

Main large deep optical/near-IR surveys 2010-2030

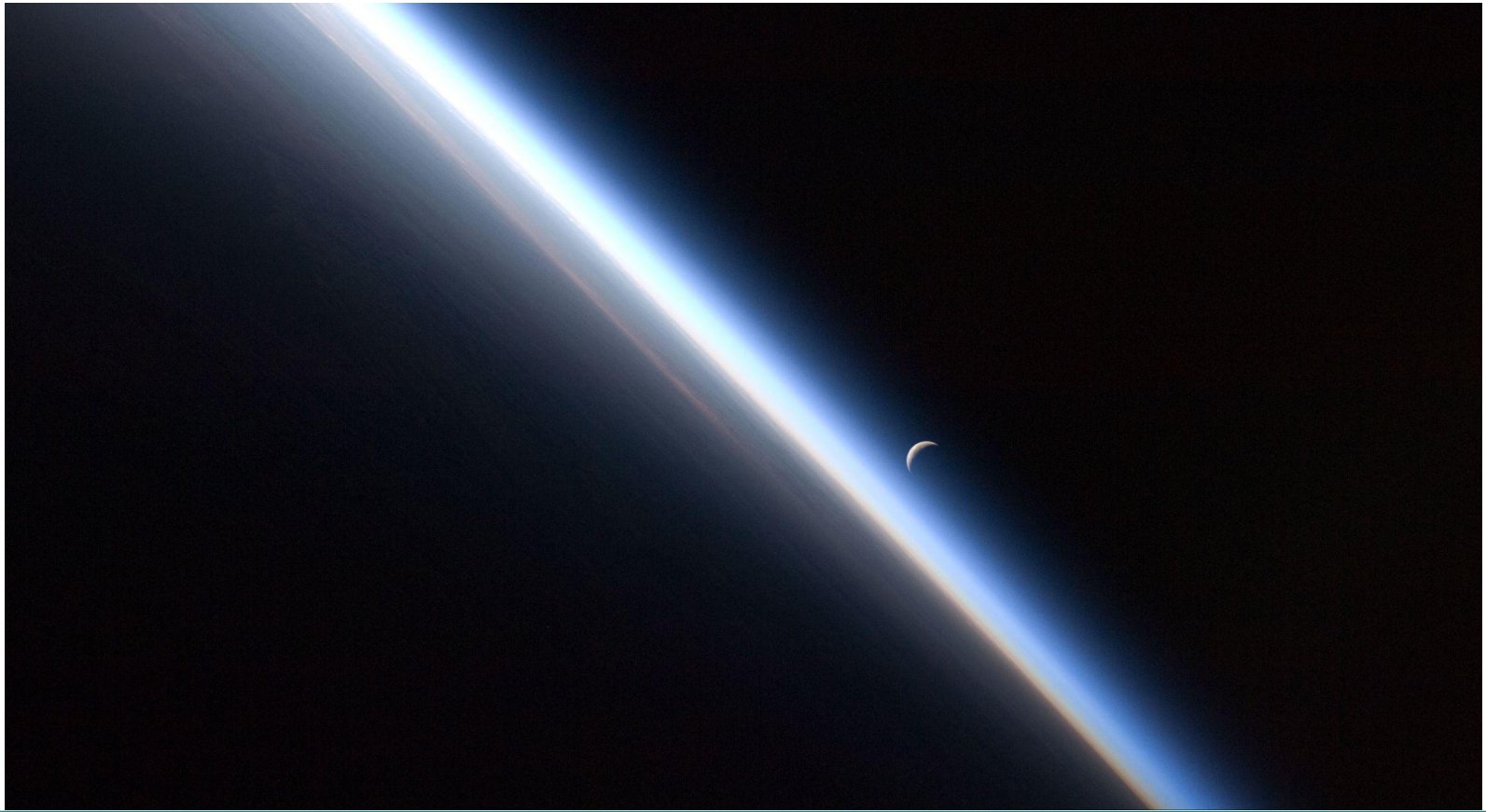
All–sky type deep wide–field imaging surveys in the optical and near–infrared in the 2010s/2020s/2030s

Telescope / Survey	Photometric Bands	5–sigma PSF	Area	Res.	Region	Metric
Pan–STARRS PS1	g, r, i, z, y	i 23.1	31000	1.1"	3 Pi	1.1"
Gaia	G, BP, RP	G 21.0	41000	0.4"	All sky	0.4"
Subaru HSC SSP Wide	g, r, i, z, y	i 26.4	1400	0.7"	EG North	0.7"
DESI Imaging Legacy Survey	g, r, z	r 24.0	14000	1.0"	EG North	1.0"
Blanco DES	g, r, i, z, y	i 25.1	5000	0.9"	EG South	0.9"
UNIONS (CFHT Pan–STARRS Subaru)	u, g, r, i, z	r 25.3	5000	0.7"	EG North	0.7"
Euclid Wide	VIS, Y, J, H	VIS 26.2	15000	0.2"	EG	0.2"
Rubin LSST Wide–Fast–Deep	u, g, r, i, z, y	i 26.8	18000	0.8"	South	0.8"

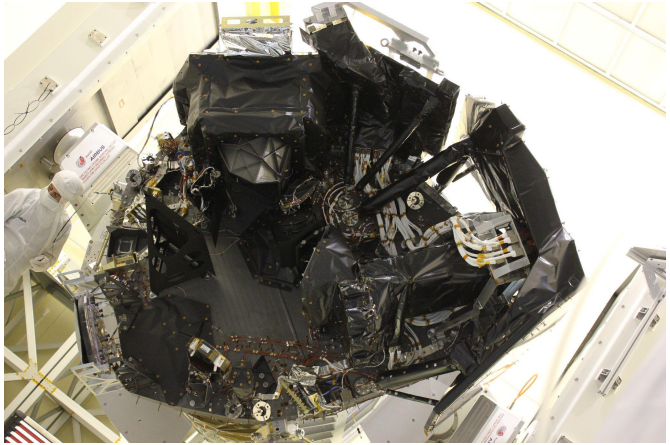


Area : square degrees
Sky : All Sky or Extragalactic Sky (EG) in the Northern and/or Southern Hemispheres

Space astronomy to circumvent Earth's atmosphere



The ESA Euclid space telescope is now completed

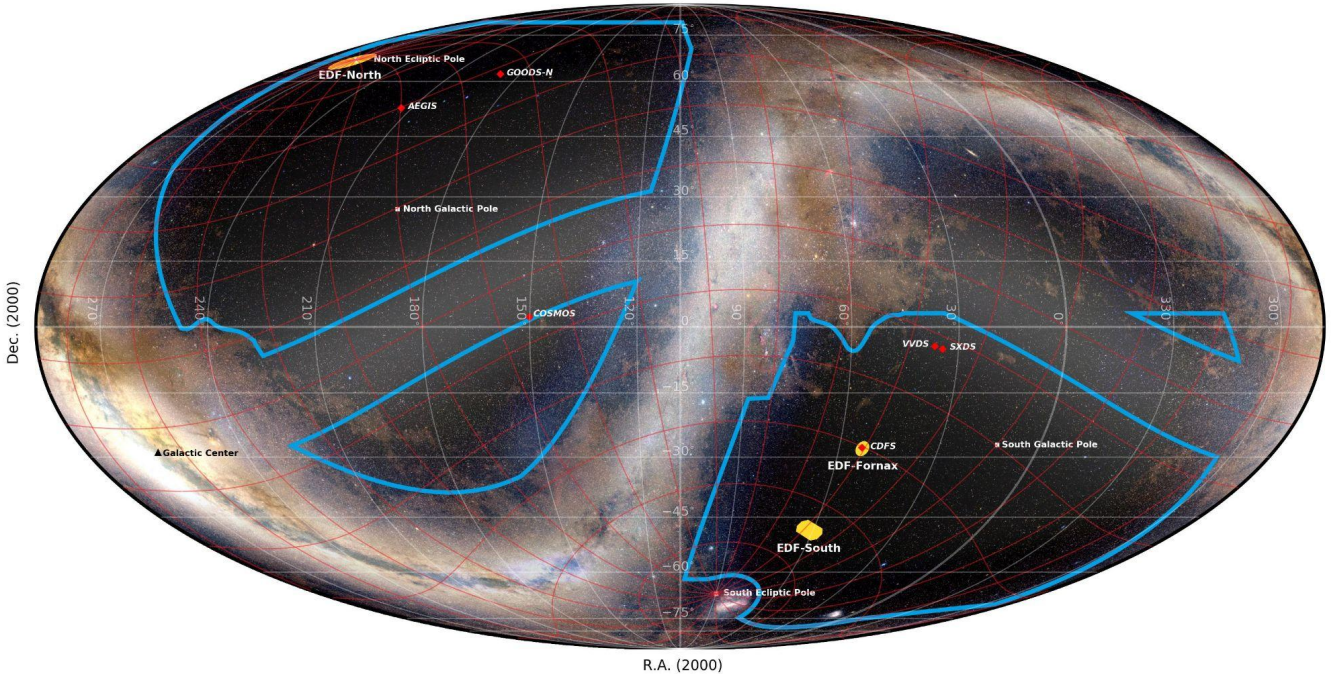


Baseplate with the VIS & NISP instruments

Material provided by ESA, Airbus, Thales Alenia Space

Euclid at Thales Alenia Space in Cannes, 22 February 2023

The Euclid Wide Survey (2023-29) is 35% of the sky



The 15,000 deg.^{2} Euclid Wide Survey, the 53 deg.^{2} Euclid Deep Survey, and the 6 deep auxiliary fields (6.5 deg.^{2}) [Mollweide Celestial]

Euclid Wide Survey region of interest : 16 Kdeg.^{2} compliant with a 15 Kdeg.^{2} survey

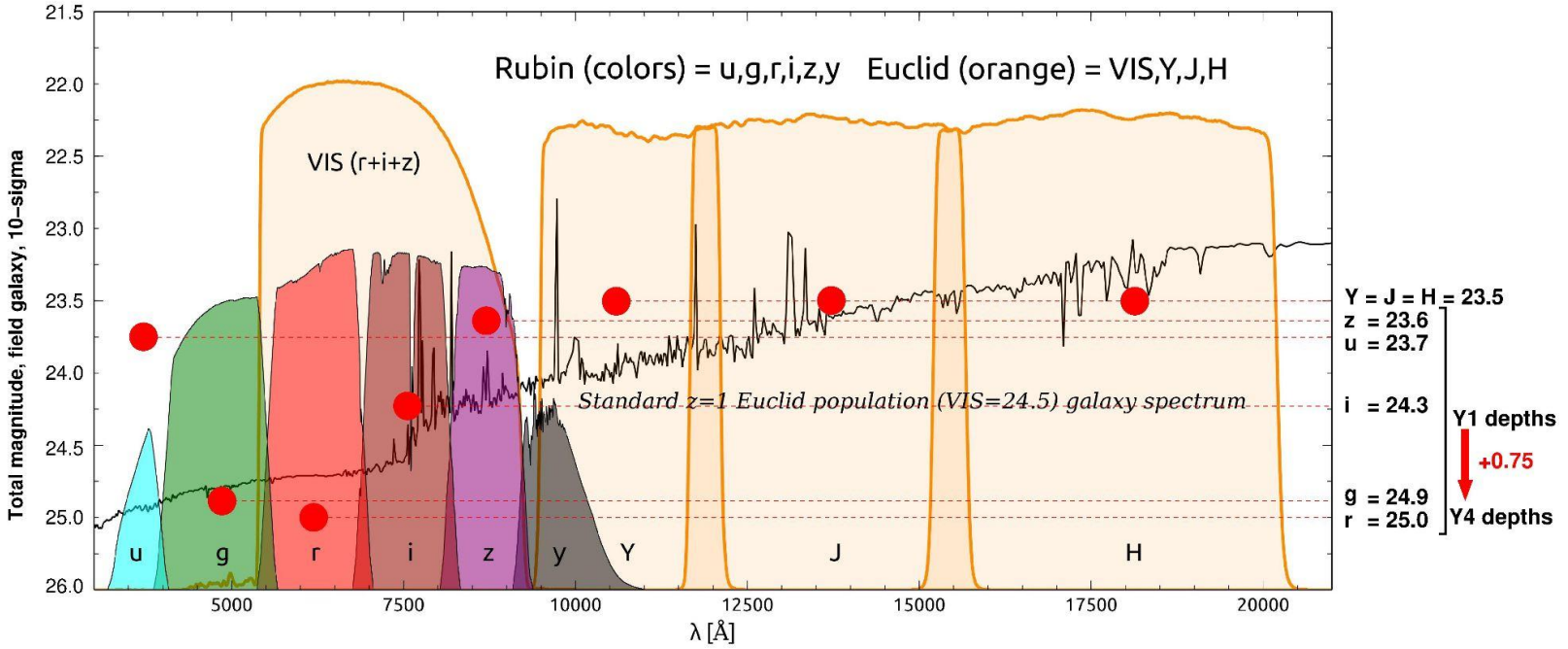
Euclid Deep Fields : North=20 deg.^{2}, Fornax=10 deg.^{2}, South=23 deg.^{2}

Euclid deep auxiliary fields (GOODSN=0.5, AEGIS=1, COSMOS=2, VVDS=0.5, SXDX=2, CDFS=0.5 deg.^{2})

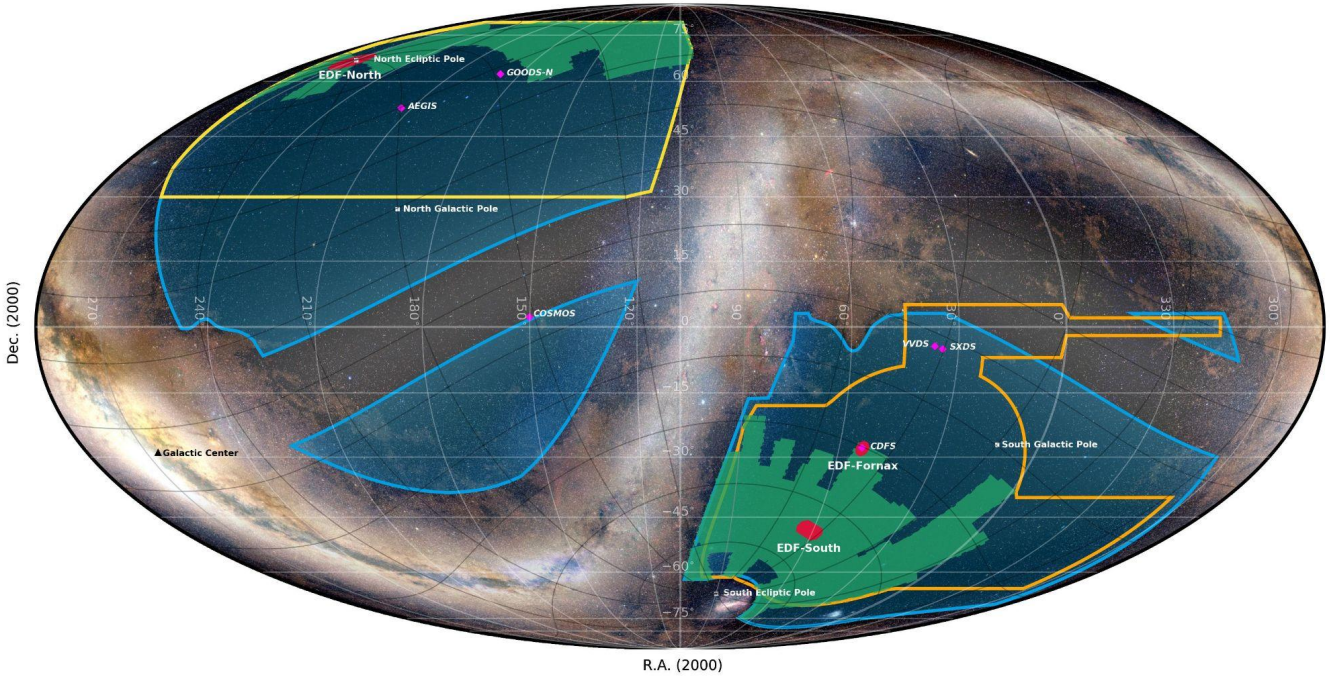
Background image: Euclid Consortium / Planck Collaboration / A. Mellinger

Euclid critically depends on ground-based surveys

Deep u,g,r,i,z photometry is necessary to derive the photometric redshift of 1.5 billion galaxies observed by Euclid to constraint the evolution of Dark Energy through time with cosmic shear



UNIONS & DES are key to Euclid's early science (DR1)

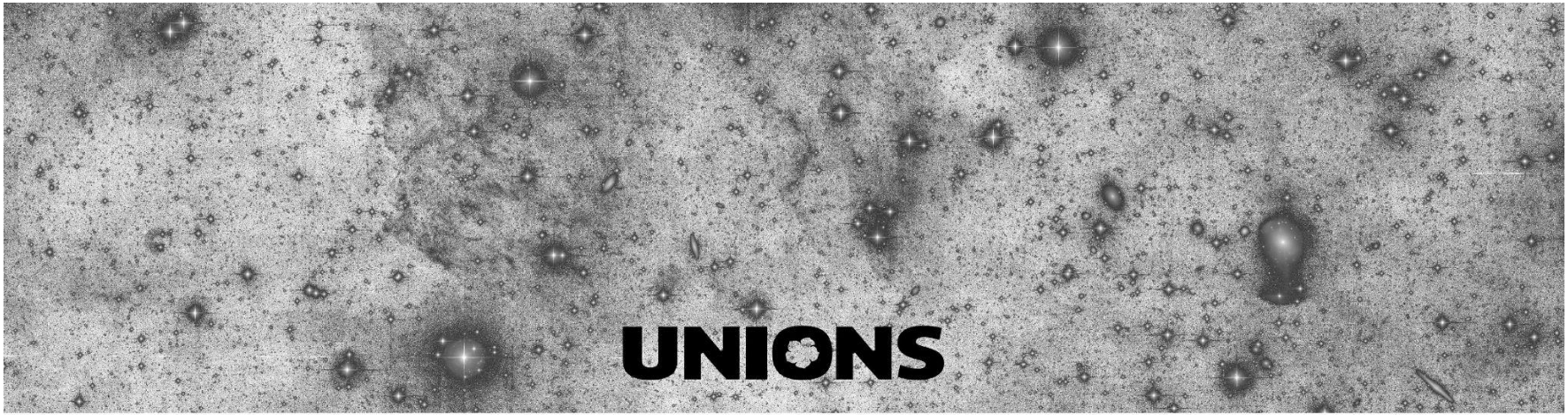


The Euclid Wide Survey Year1 = DR1 area (RSD2023A) : Northern sky = 823 deg^2, Southern sky = 1968 deg^2 [Mollweide Celestial]

- Euclid Wide Survey region of interest (RoI) : 16,217 deg^2
- DES, griz, 2013–19 : 4500 deg^2 overlap with the RoI
- UNIONS, ugriz, 2017–24 : 4500 deg^2 overlap with the RoI
- Euclid Year1 (DR1) area, 2024 : 2791 deg^2
- Euclid Deep Fields [total 53 deg^2]
- Euclid deep auxiliary fields marker

Background image: Euclid Consortium / Planck Collaboration / A. Mellinger

A collaboration through 3 Hawai'i based telescopes



A Canada, France, Hawaii, Japan collaboration

- UNIONS is a science collaboration of more than 200 members between:
  - The Canada-France Imaging Survey (CFIS) team: Canada and France
  - The Pan-STARRS team: Institute for Astronomy (IfA, University of Hawaii)
  - The Wide Imaging with Subaru Hyper Suprime-Cam of the Euclid Sky (WISHES): Japan
  - The Waterloo Hawaii IfA G-band Survey (WHIGS): Canada and IfA
- UNIONS is governed by a science-focused MoU to help enable great science

Origins and motivations

- Ground-based support for Euclid in the northern sky is a major reason the different surveys exist to contribute to hundreds of millions of photometric redshifts critical to this Stage IV Dark Energy mission
- UNIONS supports the Euclid survey strategy by internally optimizing the observing plan (sky priorities)
- UNIONS is a collaboration between these ground-based surveys, independent of Euclid
- UNIONS core science drivers were critical to get observing time, building on the complementarity with existing data sets such as Gaia, PS1, and BOSS spectroscopy, and then UNIONS by itself:
  - ➢ Near field cosmology: pushing Gaia science into the outer halo of the Galaxy
  - ➢ Weak lensing: capitalizing on northern spectroscopy with exquisite imaging quality
  - ➢ Galaxy evolution: photo-z (i.e. rich catalog), morphology (especially at low surface brightness)
- As the multi-band overlap between the four surveys rapidly increases, so do the science possibilities!

UNIONS is becoming the definitive deep, wide optical survey of the northern hemisphere throughout the 2020s and beyond.

UNIONS as a fertile ground for Early Career Members

UNIONS has more than 200 collaborators from Canada, France, Hawaii, Japan & other nations

- To date, 27 papers have been accepted or published using UNIONS data
- The majority of these papers have used only 1 band of UNIONS data (CFHT started first)
- The first multi-band papers are being written now - expect an increase in publication rate now that the overlap areas are larger
- 24 of these papers are led by students or postdocs

There are currently 15 students (Masters and PhD) and 9 postdocs working on UNIONS science (based in whole or in part on UNIONS data), and 1 undergraduate

- 8 students have already completed their graduate theses based on UNIONS data
- 11 theses are ongoing

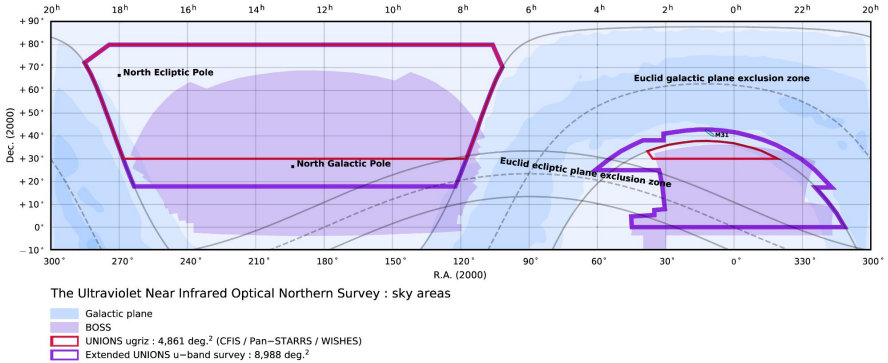
UNIONS is a promising multi-band survey as a training platform in wide field optical astronomy for the upcoming generation of Canadian, French, Hawaiian and Japanese astronomers.

Refereed articles based on UNIONS (2017-2023)

27. Chu, A., et al., 2023, A&A, in press, "A UNIONS view of the brightest central galaxies of candidate fossil groups"
26. Lim, S., et al., 2023, MNRAS, in press, "Constraints on galaxy formation from the cosmic-infrared-background /optical-imaging cross-correlation using Herschel and UNIONS"
25. Bickley, R., et al., 2022, MNRAS, 519, 6149, "AGN in CNN-identified post mergers in the Ultraviolet Near-Infrared Optical Northern Survey (UNIONS)"
24. Smith, S., et al., 2022, ApJ, in press, "Discovery of a new Local Group galaxy candidate in UNIONS: Bootes V" ¨
23. Aycoberry, E., et al., 2022, ApJ, 671, 17, "UNIONS : impact of systematic errors on weak-lensing peak counts"
22. Robison, B., et al., 2022, MNRAS, 523, 1614, "The shape of dark matter haloes: results from weak lensing in the Ultraviolet Near-Infrared Optical Northern Survey (UNIONS)"
21. Savary, E., et al . 2022, A&A, 666, 1, "A search for galaxy-scale strong gravitational lenses in UNIONS"
20. Chan, J. H. H., et al. 2022, A&A, 659, 140, "Discovery of Strongly Lensed Quasars in UNIONS"
19. Wilkinson, S., et al., 2022, MNRAS, 516, 4354, "The merger fraction of post-starburst galaxies in UNIONS"
18. Ellison, S., et al., MNRAS, 517, L92, "Galaxy mergers can rapidly shut down star formation"
17. Bickley, R., et al., 2022, MNRAS, 514, 3294, "Star formation characteristics of CNN-identified post-mergers in the Ultraviolet Near Infrared Optical Northern Survey (UNIONS)"
16. Farrens, S., et al., 2022, A&A, 664, A141, "A modular weak lensing processing and analysis pipeline"
15. Guinot, A., et al., 2022, A&A, 666, 162, "ShapePipe: a new shape measurement pipeline and weak-lensing application to UNIONS/CFIS data"
14. Sola, E., et al., 2022, A&A, 662, 124, "Characterization of LSB structures in annotated deep images"
13. Roberts, I., et al., 2022, MNRAS,509, 1342, "Ram Pressure Candidates in UNIONS"
12. Jensen, J., et al., 2021, MNRAS, 507, 1923, "Uncovering fossils of the distant Galaxy with UNIONS: NGC 5466 and its stellar stream"
11. Bickley, R., et al., 2021, MNRAS, 504, 372, "Convolutional neural network identification of galaxy post-mergers in UNIONS using IllustrisTNG"
10. Fantin, N., et al., 2021, ApJ, 913, 30, "The Mass and Age Distribution of Halo White Dwarf Candidates in the Canada-France Imaging Survey"
9. Liaudat, T., et al., 2021, A&A, A27, "Multi-CCD modelling of the point spread function"
8. Thomas, G., et al., 2020, ApJ, 902, 89, "The Hidden Past of M92: Detection and Characterization of a Newly Formed 17◦Long Stellar Stream Using the Canada-France Imaging Survey "
7. Fantin N., et al., 2019, ApJ, 877, 148, "The Canada France Imaging Survey: Reconstructing the Milky Way from its white dwarf population"
6. Thomas, G., et al., 2019, ApJ, 866, 10, "Dwarfs or giants? Stellar metallicities and distances from ugrizG multi-band photometry"
5. Ellison, S., et al., 2019, MNRAS, 487, 2491, "A definitive merger-AGN connection at z~0 with CFIS: mergers have an excess of AGN and AGN hosts are more frequently disturbed"
4. Thomas, G., et al. 2019, MNRAS, 483, 3, "A-type stars in the Canada-France Imaging Survey - II. Tracing the height of the disc at large distances with Blue Stragglers"
3. Thomas, G., et al., 2018, MNRAS, 481, 4, "A-type stars in the Canada-France Imaging Survey I. The stellar halo of the Milky Way traced to large radius by blue horizontal branch stars"
2. Ibata, R., et al., 2017, ApJ, 848, 2, 129, "Chemical Mapping of the Milky Way with CFIS:Non-parametric Metallicity-Distance Decomposition of the Galaxy"
1. Ibata, R., et al., 2017, ApJ, 848, 2, 128, "The Canada-France Imaging Survey: First Results from the u-Band Component"

UNIONS sky area and time allocation

UNIONS = CFHT (u,r) + Pan-STARRS (i,z) + Subaru (g,z)



CFHT: 3 Large Programs (473 nights, 2015-2024)
- u : DEC>+0 on the SGC*, and DEC>+18 on the NGC*
- r : DEC>+30

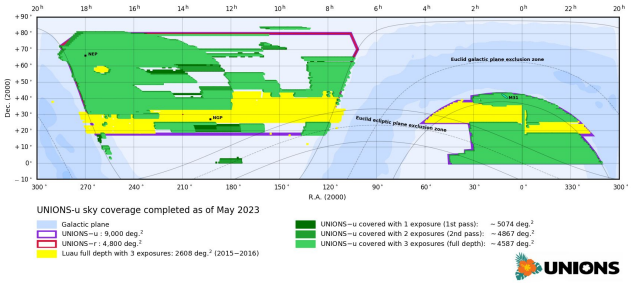
**SGC = South Galactic Cap, NGC = North Galactic Cap*

Subaru: Waterloo-Hawaii-IfA G-band Survey
- g : DEC>+30 (20 nights, 2019-2024)

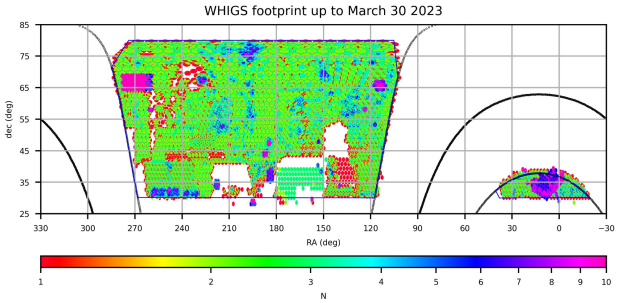
Pan-STARRS: (40% of PS1+PS2 since 2017)
- i : DEC>+30 (integration from NEOs search)
- z : +30<DEC<+42

Subaru: Wide Imaging with Subaru HSC of the Euclid Sky
- z : DEC>+42 (40 nights, 2020-2024)

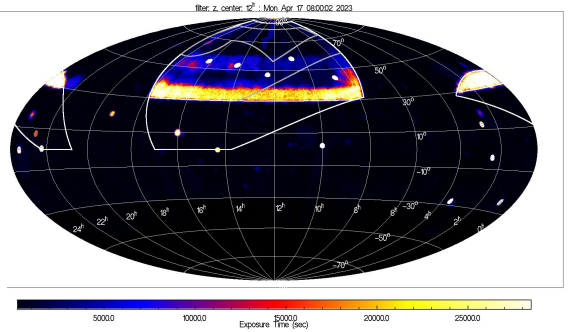
UNIONS ugriz sky coverage status (May 2023)



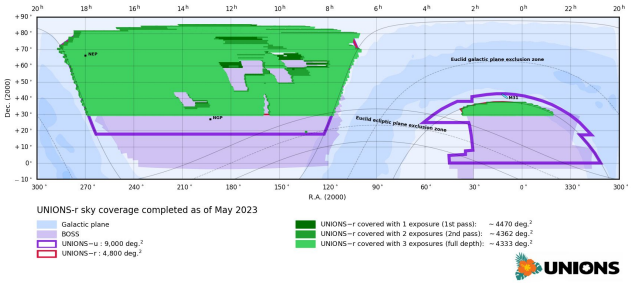
CFHT u



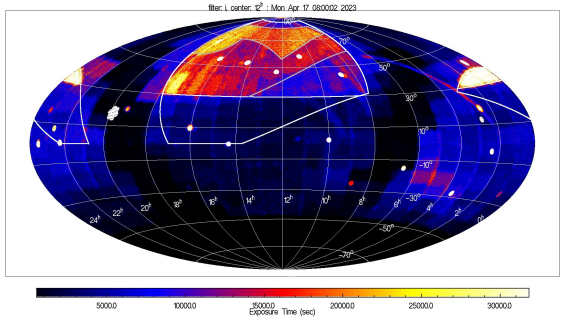
Subaru g



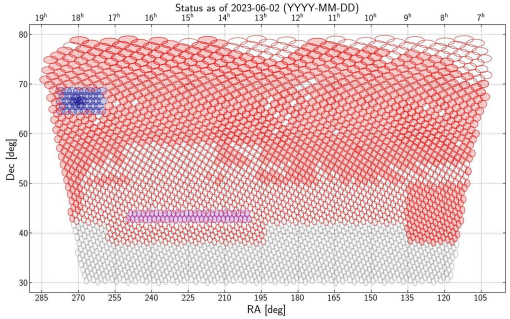
Pan-STARRS z



CFHT r



Pan-STARRS i



Subaru z

UNIONS explores today some science of the LSST era

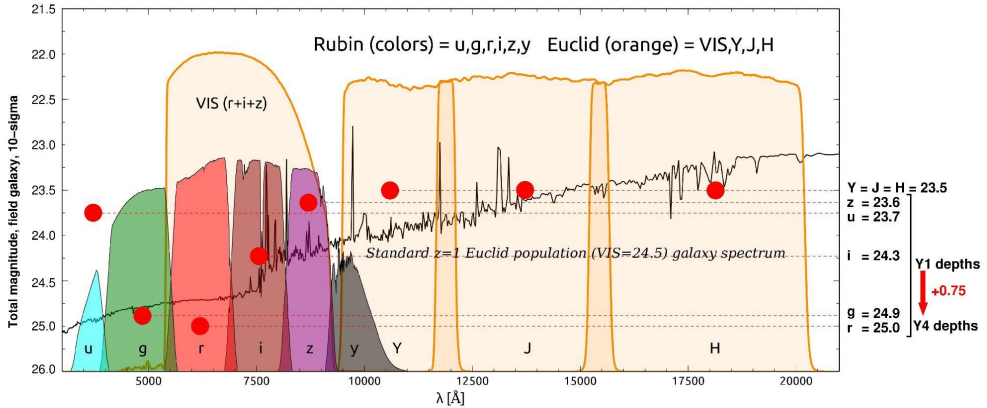


Photo-z depth metric proxy (for all): point source in 2 arcseconds diameter aperture, 10σ

- Euclid (median over the Euclid sky): *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*

UNIONS ≃ LSST Year 1 depths

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

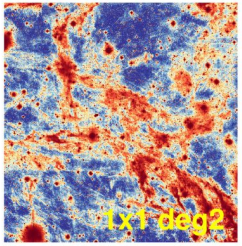
UNIONS r-band low surface brightness performance

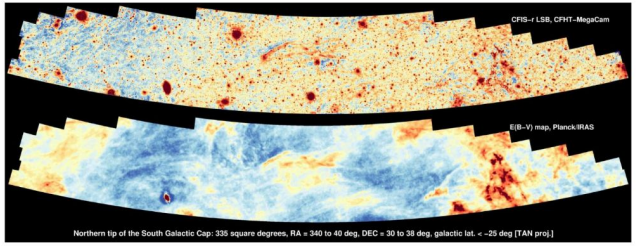
>28

>30

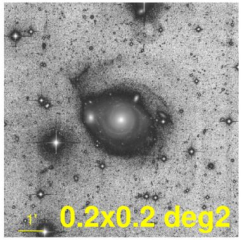
>32

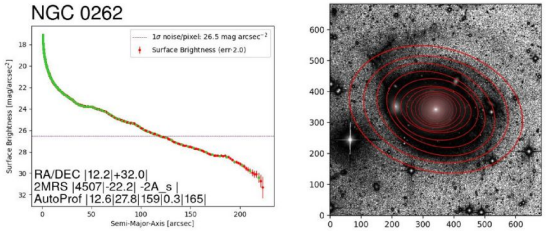
magnitude per square arcsecond



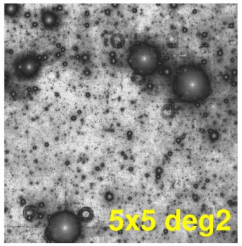


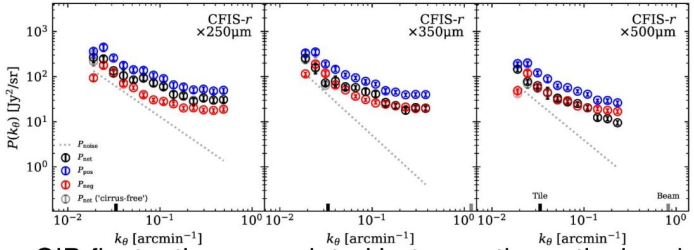
Direct detection regime (cirrus, streams), also enables large sky mosaics





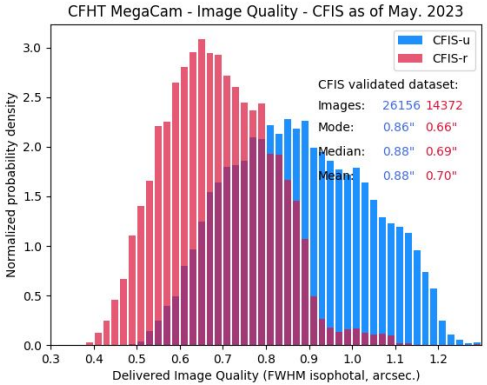
Radially integrated galactic profiles

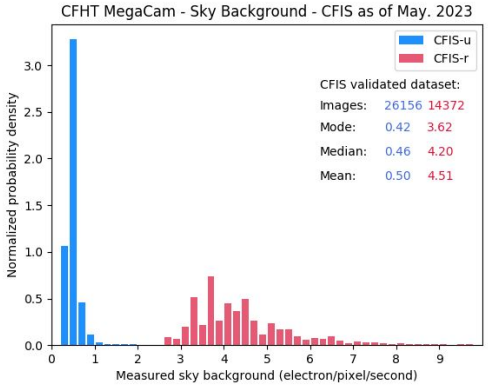


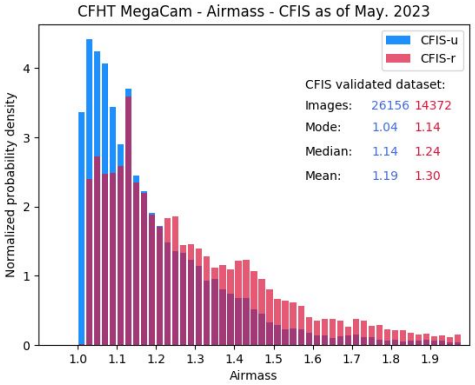


Cross–correlation, e.g. CIB fluctuations correlated between the optical and submm bands

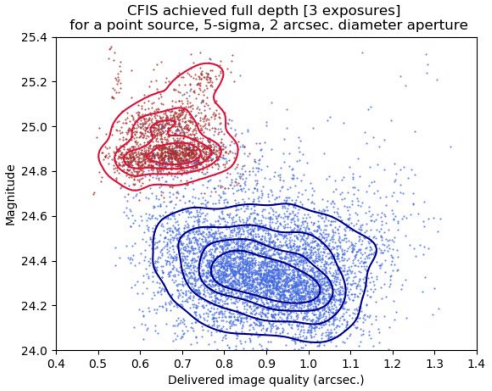
UNIONS u,r dataset is built on CFHT's strengths







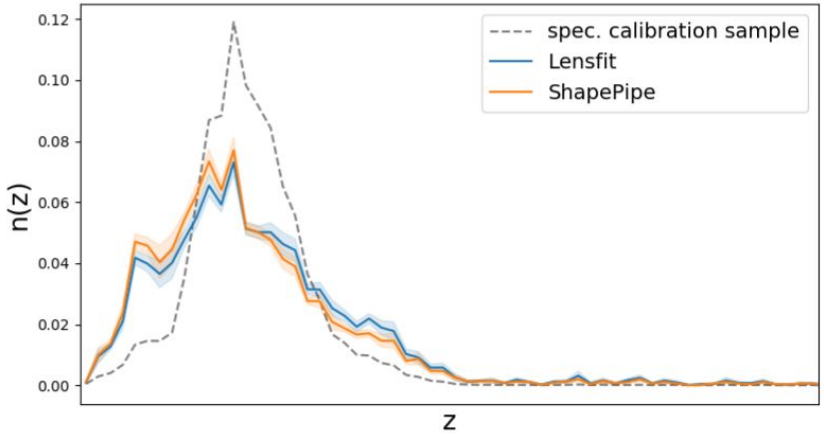
- Field-of-view (1.1 square degree)
- Image quality (0.7" r-band)
- u-band sensitivity (in 4mn)
- r-band sensitivity (in 6mn)
- MegaCam SNR mode
- MegaCam LSB mode



UNIONS redshift calibration

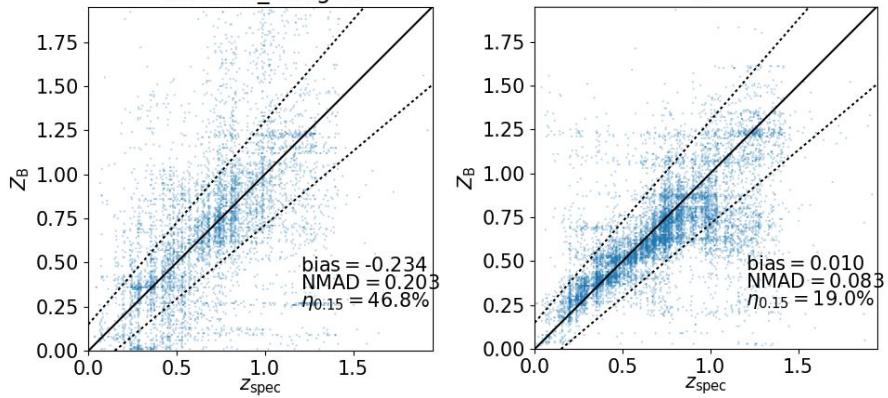
- Accurate redshift distribution is key to cosmological analyses: clustering redshift & photometric redshift
- UNIONS r-band n(z) can be robustly constrained with a SOM method for 2D cosmic shear analyses
- SOM (Self-Organizing Maps) match self-similar galaxies in magnitude/colour space based on a reference
- Turning to tomographic cosmic shear analyses as UNIONS now offers large overlap between u,g,r,i,z

Over 3500 square degrees in r-band



UNIONS standard photometry on u,g,r,i,z stacks

PSF-homogenised photometry on u,g,r,i stacks



From the UNIONS Photo-z group: H. Hildebrandt, A. Wittje, A. Wright, J.-L. van den Busch et al.

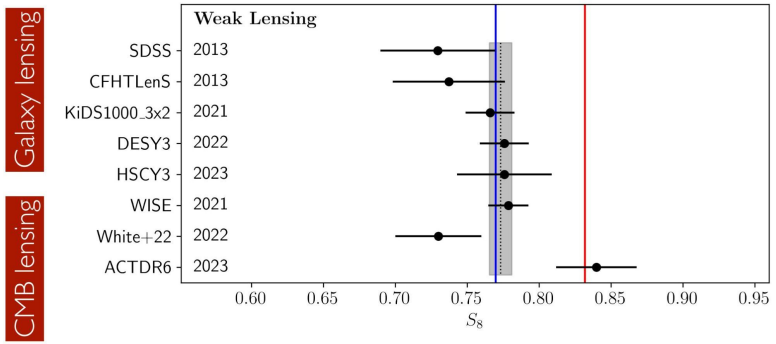
The UNIONS weak lensing science has reached maturity

- **Galaxies**
  - dependence on mass, redshift and environment
  - tidal stripping of DM haloes of satellites
  - assembly bias
  - ultra-diffuse galaxies (UDGs)
- Masses of **clusters** of galaxies
  - redMapper, Planck, XMM, eBOSS
- Filaments of the **cosmic web**

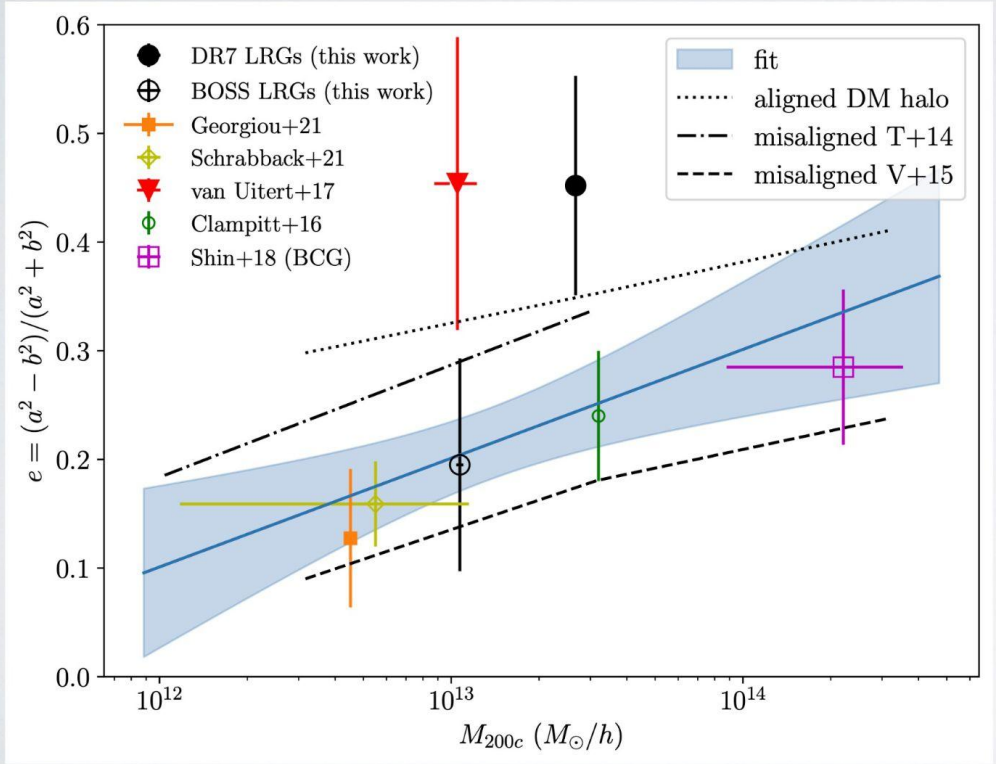
- *The weight of emptiness*: negative masses of **cosmic voids**
- **Large-scale structure:** DM mass maps
  - Cross-correlations between mass and CMB, tSZ
  - Galaxy density (eBOSS/DESI)
  - Peaks and higher order statistics
- Testing **General Relativity**: UNIONS vs. eBOSS
- Cosmic shear and S_8 — **This is by far the most difficult one**

From M. Hudson, L. Van Waerbeke & the UNIONS lensing team

Weak lensing S_8 measurements since 2010



UNIONS weak lensing science : dark matter haloes shape



DM haloes of luminous red galaxies are elliptical
e = 0.46±0.10
corresponding to a triaxial ellipsoid
1 : 0.6 : 0.5

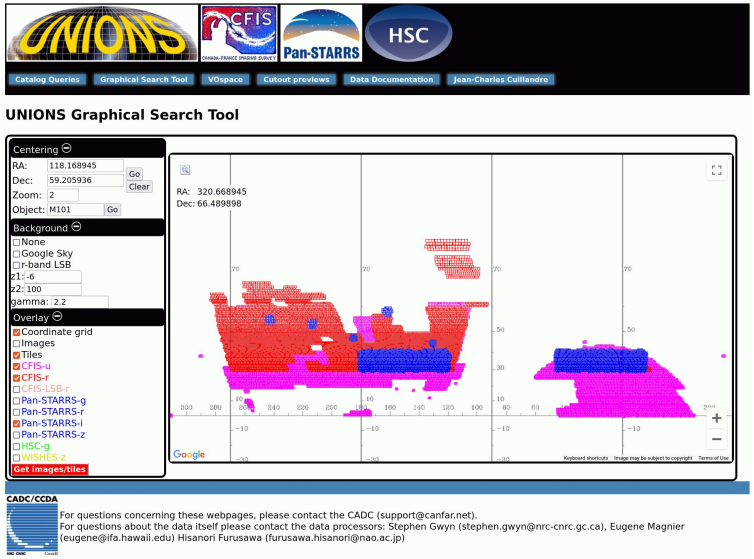
With full UNIONS photo-z, errors will shrink by factors of
~4

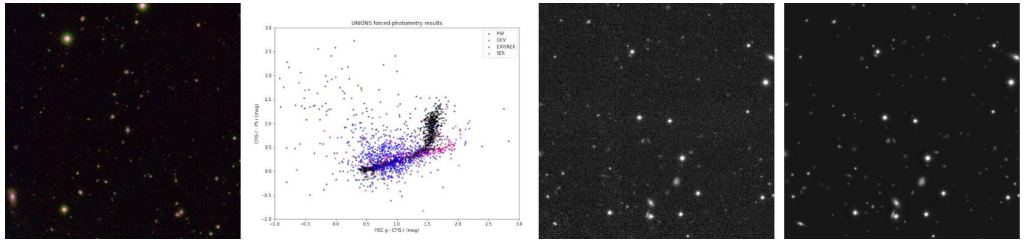
Robison et al. 23, in press

Centralized data access at CADC in Canada (CANFAR)

Once access is granted through the collaboration, images and catalogs can be downloaded at the main data page accessible via the CADC:

https://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/community/unions/csky.html

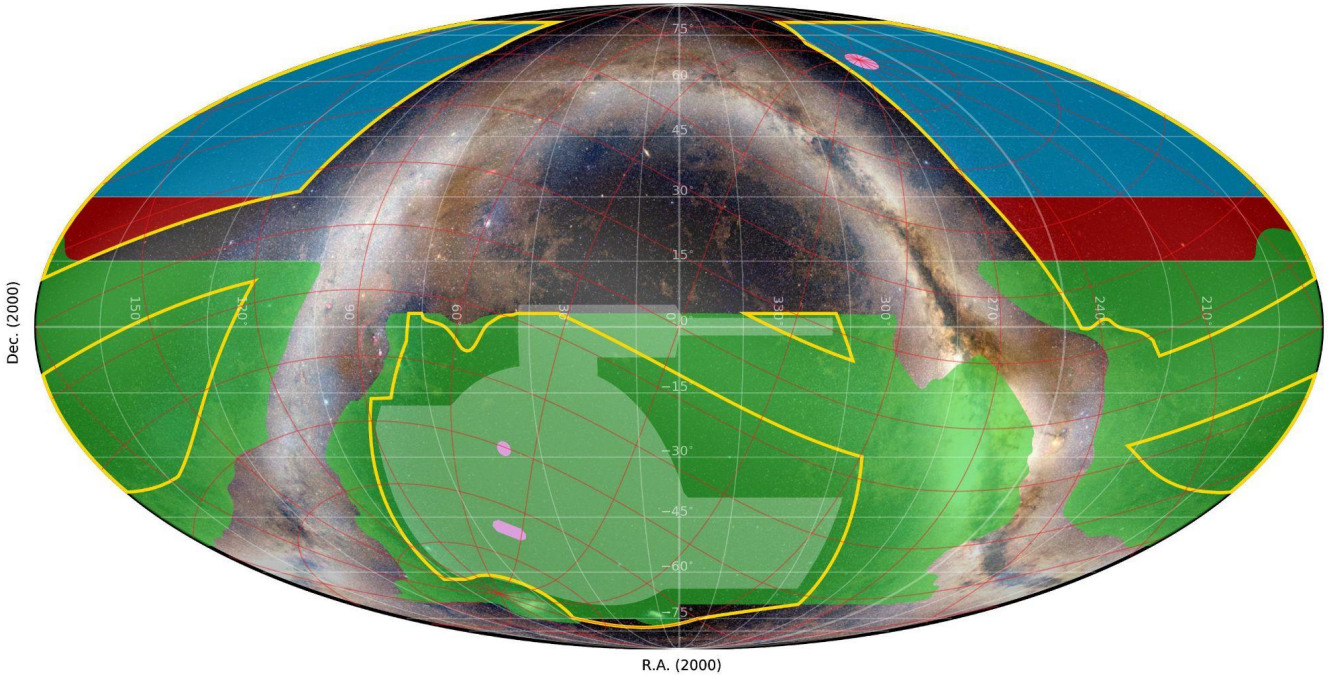




Left: Seeing and PSF mismatch between Pan-STARRS on Haleakala (in green) and CFHT and Subaru on Maunakea (blue and red) highlight the need for a forced photometry approach like Tractor or HSCpipe. Center left: Tractor color-color diagram of all fitted sources in a small sky area observed by the different telescopes, the stellar locus (black dots) is tight, pointing to a solid match of the various datasets. Right side: a CFIS-r image and the Tractor image of the PSF and galaxies models derived for each CFIS-r source.

- Image stacks and catalogs of point sources and distant galaxies are the basis of our internal DRs

Euclid evolved survey area & UNIONS extension plan



Ground−based coverage of the 16 Kdeg^2 Euclid Wide Survey Region of Interest [origin/bands/overlap/calendar] [Mollweide Celestial]

- DES (Blanco), griz : 4.8 Kdeg^2 overlap since 2019
- LSST Wide−Fast−Deep (Rubin), ugriz : 10.2 Kdeg^2 overlap by 2026
- UNIONS (CFHT/Pan−STARRS/Subaru), ugriz : 4.5 Kdeg^2 by 2025
- UNIONS extended, ugriz : 1.4 Kdeg^2 by 2027
- Euclid Region of Interest : 16.2 Kdeg^2
- Euclid Deep Fields [53 deg^2]

Background image: Euclid Consortium / Planck Collaboration / A. Mellinger

How to join UNIONS

Who can join and how:

- For France: any scientist (grad students to permanent staff) based in a French research lab
- Contact the UNIONS Steering Group (unions-sg@cfht.hawaii.edu) to describe your science program and state that you read and endorse the UNIONS rules (https://www.skysurvey.cc/collaboration/)
- Once integrated in the collaboration (mailing list, etc. - first create your CADC account) you can consult all on-going science activities on the UNIONS “Who Does What” internal wiki page and add your own science project or seek collaborations
- There is no guarded science in UNIONS, but openness is enforced and collaboration is encouraged as members must endorse a set of simple rules, our goal being to enable great science

The UNIONS Steering Group is committed to help you realize your science:

- Canada & France : Jean-Charles Cuillandre (co-PI France), Alan McConnachie (co-PI Canada), Mike Hudson (science lead Lensing), Rodrigo Ibata (science lead Galaxy), Stephen Gwyn (data management lead), and Michael Balogh, Ray Carlberg, Raphael Gavazzi, Vanessa Hill, Yannick Mellier
- Pan-STARRS (IfA-UH) : Ken Chambers (Director), Eugene Magnier, Richard Wainscoat
- Japan : Masamune Oguri (PI), Hisanori Furusawa, Satoshi Miyazaki

The Ultraviolet Near-Infrared Optical Northern Survey

UNIONS

- The UNIONS ambitious science is now shifting into high gear
- UNIONS champions the upcoming generation of astronomers
- Full completion of UNIONS is a top priority in Canada and France
- The UNIONS extension to connect to the LSST down to DEC+15 deg (1400 square degrees, +30% in area) gives a new opportunity to exploit CFHT (g&r bands)
- Follow the UNIONS scientific activities at www.skysurvey.cc