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ESO Public Surveys at VISTA: Lessons learned from Cycle 1 Surveys and the start of Cycle 2

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The ESO Public Surveys on VISTA serve the science goals of the survey teams while increasing the legacy value of ESO programmes, thanks to their homogeneity and the breadth of their sky coverage in multiple bands. These projects address a variety of research areas: from the detection of planets via microlensing, to stars, the Milky Way and Local Group galaxies, to extragalactic astronomy, galaxy evolution, the high-redshift Universe and cosmology. In 2015, as the first generation of imaging surveys was nearing completion, a second call for Public Surveys was opened to define a coherent scientific programme for VISTA until the commissioning of the wide-field multi-fibre spectrograph, 4MOST, in 2020. This article presents the status of the Cycle 1 surveys as well as an overview of the seven new programmes in Cycle 2, including their science goals, coverage on the sky and observing strategies. We conclude with a forward look at the Cycle 2 data releases and the timelines for their release.

Introduction

ESO has operated two telescopes that are mostly dedicated to Public Surveys since 2010: namely, the 4-metre Visible and Infrared Survey Telescope for Astronomy (VISTA; Sutherland et al., 2015) and the 2.6-metre VLT Survey telescope (VST; Arnaboldi et al., 1998; Capaccioli & Schipani, 2011). These provide coverage from the ultraviolet (0.33 micron) through to the *Ks*-band (2.15 microns). In 2012, Public Spectroscopic Surveys also started using the spectrographs Ultraviolet and Visual Echelle Spectrograph, UVES, GIRAFFE and the ESO Faint Object Spectrograph and Camera, EFOSC2. The spectroscopic surveys were further expanded in 2014 with the addition of two new surveys on Unit Telescope 3 (UT3) using the VIsible MultiObject Spectrograph (VIMOS).

As the first cycle of ESO Public Surveys with VISTA approached its sixth year of successful telescope operations in 2015, ESO opened the call for submission of letters of intent for a second cycle of Public Surveys to run until the end of 2020, the expected date for the decommissioning of the VISTA InfraRed CAMera (VIRCAM). Thirteen letters of intent were submitted by the community by the deadline of October 2015; these involved more than thirteen Principal Investigators (PIs) and 517 co-investigators, with an oversubscription factor of over twice the total available observing time. The joint VISTA/VST Public Survey Panel (PSP) was asked to review these letters to identify a well-balanced scientific programme for VISTA. An important consideration for the VISTA Cycle 2 Public Surveys was the exploration of scientific and observing parameter space that had not been covered by the previous surveys. These recommendations were passed to the Observing Programmes Committee (OPC) and the ESO Director General.

In this article, we provide an overview of the status of the VISTA imaging surveys that started in 2010 and their impact in terms of data releases and refereed publications. We then describe the selection process of the new surveys and provide a summary of their science goals, observing strategies, and the content and timelines of their planned data releases.

Looking further ahead, the construction and deployment of two wide-field spectrographs is foreseen: the Multi Object Optical and Near Infrared Spectrograph (MOONS; Cirasuolo et al., 2011) and the 4-metre Multi Object Spectroscopic Telescope (4MOST; de Jong, 2011) on the VLT and VISTA respectively. They have large multiplexing wide field capabilities and extended wavelength coverage. These spectrographs will be used for follow-up studies of interesting candidates identified via their colours and/or morphological properties from the Public Surveys and/or space missions (for example, the ESA satellite, Gaia, and eROSITA). In the current ESO instrument plan, the 4MOST spectrograph will replace the wide field near-infrared camera, VIRCAM, on VISTA, with commissioning being planned for the end of 2020.

VISTA Cycle 1 surveys: time allocation and current status

The first cycle of approved VISTA Public Surveys includes six imaging projects[1] that began observations in April 2010. Figure 1 shows the completion fractions of the requested time in their observing plans with respect to time. An overview of each of the Cycle 1 surveys is given in Table 1 along with their full titles and acronyms; a more complete description of each of these surveys is presented in *The Messenger* 154 (2013).

The overall time allocations for these surveys are between 1500 and 2200 hours, except for the VHS, which requires 4710 hours for completion. The VHS takes up 28 % of the allocated telescope time to date, while about 12 % goes to each one of the other surveys; additionally Chilean regular and other open-time programmes have been allocated 3 % and 4 % of time respectively. Figure 2 shows a pie chart summarising the time committed to the VISTA surveys between Periods 85 and 99, as a percentage of the total allocated telescope time.

Based on statistics gathered over three years (from October 2012 to September 2015), the total execution time of successfully observed OBs from the VISTA Cycle 1 surveys is 2340 hours per year. The time for open and Chilean time amounts to about 6 % of the total time in that period. Thus, 2490 hours/year are available for successful observations with VISTA. In 2015, the projected observations for the VISTA Cycle 1 surveys showed that observing time would become available in certain right ascension (RA) ranges; hence the need to release a call for VISTA Cycle 2 Public Surveys.

Survey ID, title & homepage	Science topic	Area (square degrees)	Filters	Magnitude limits	Observing time to 1 April 2017 (hours)
UltraVISTA http://home.strw.leidenuniv.nl/~ultravista/	Deep high-*z*	1.7 Deep	*Y J H Ks*	25.7 25.5 25.1 24.5	1780
		0.73 Ultra deep	*Y J H Ks*	26.7 26.6 26.1 25.6	
			NB118	26.0	
VHS — VISTA Hemisphere Survey http://www.ast.cam.ac.uk/~rgm/vhs/	All sky	17800	*Y J H Ks*	21.2 21.1 20.6 20.0	4490
VIDEO — VISTA Deep Extragalactic Observations Survey http://www-astro.physics.ox.ac.uk/~video	Deep high-*z*	12	*Z Y J H Ks*	25.7 24.6 24.5 24.0 23.5	1799
VVV — VISTA Variables in the Via Lactea http://vvvsurvey.org/	Milky Way	560	*Z Y J H Ks*	21.9 21.1 20.2 18.2 18.1	2157/Completed
VIKING — VISTA Kilo-Degree Infrared Galaxy Survey http://www.astro-wise.org/projects/VIKING/	Extragalactic	1500	*Z Y J H Ks*	23.1 22.3 22.1 21.5 21.2	2384
VMC — VISTA Magellanic Clouds Survey http://star.herts.ac.uk/~mcioni/vmc/	Resolved SFH	180	*Y J Ks*	21.9 21.4 20.3	1759

Table 1. General observational parameters for the Cycle 1 VISTA Public Surveys[1]. The columns illustrate the Public Survey programme acronym (column 1), a broad classification of the scientific goal (column 2), the targeted total area (column 3), the filters (column 4), the magnitude limits (10σ AB for VMC; otherwise 5σ AB) in the different filters (column 5) and the observing hours completed up to 1 April 2017 (column 6).

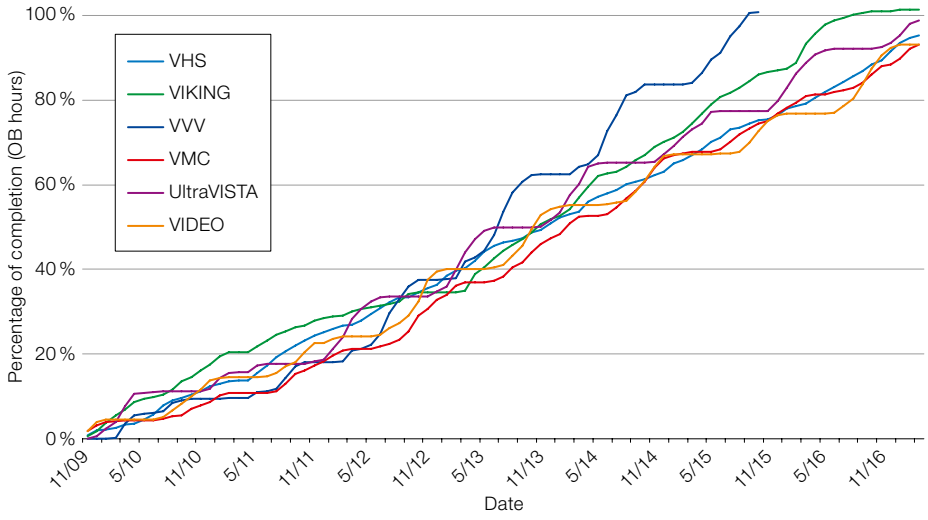


Figure 1. The percentage completion for the Cycle 1 VISTA Public Surveys with respect to the allocated time. Note that completion fractions include the observations taken during dry runs in 2009. The VVV completed its observations in October 2015. VIKING completed observations by the end of 2016, but requires the re-observation of a few tiles that were found to be out of the specified constraints. UltraVISTA, VHS, VMC and VIDEO all had completion fractions larger than 90 % by April 2017.

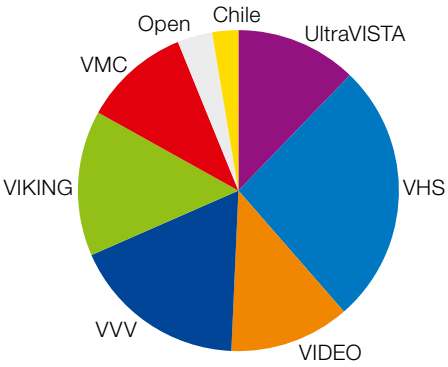


Figure 2. Pie chart showing VISTA time allocation to the Cycle 1 and 2 surveys, as well as Chilean and open time programmes, since Period 85.

The scientific impact of the VISTA surveys and legacy value of the data products

The VISTA surveys produce large, coherent data sets. The constant monitoring of the system stability and the observations of standard stars in combination with the extensive data reductions carried out by the data centres[2, 3, 4] provide for uniform data with many astrophysical applications. The VISTA survey data are listed on the Phase 3 data release manager page[5] and can be searched using the ESO Science Archive Facility[6] (SAF, see Arnaboldi et al., 2014; Retzlaff et al., 2016).

Current active releases provide more than 40 TB of science data products from the VISTA Cycle 1 surveys which have been delivered by the teams. These products, including calibrated images, source lists, photometric catalogues and light curves for multi-epoch observations, are available to the community for their independent scientific research. There are also approximately 12 TB of additional science data products for VISTA, which have been superseded by newer products but remain available on demand by archive users, for example, for verification purposes.

Astronomers have access to images, covering 11 × 10^3 square degrees area in *Y*-, *J*- and *Ks*-bands from VHS, and deep images plus catalogues from the UltraVISTA, VIDEO and VIKING surveys. For example, they can extract measurements from the billion-source catalogue for stars in the Milky Way bulge from the VVV survey, or from the light curves of Cepheid stars in the Magellanic Clouds in VMC. Community use can be quantified by means of the downloaded volume of the VISTA Cycle 1 survey data, and the

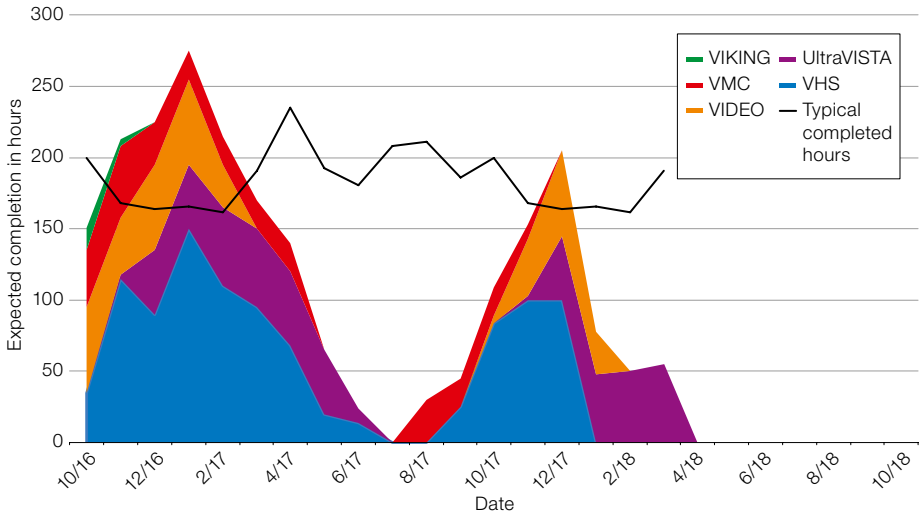
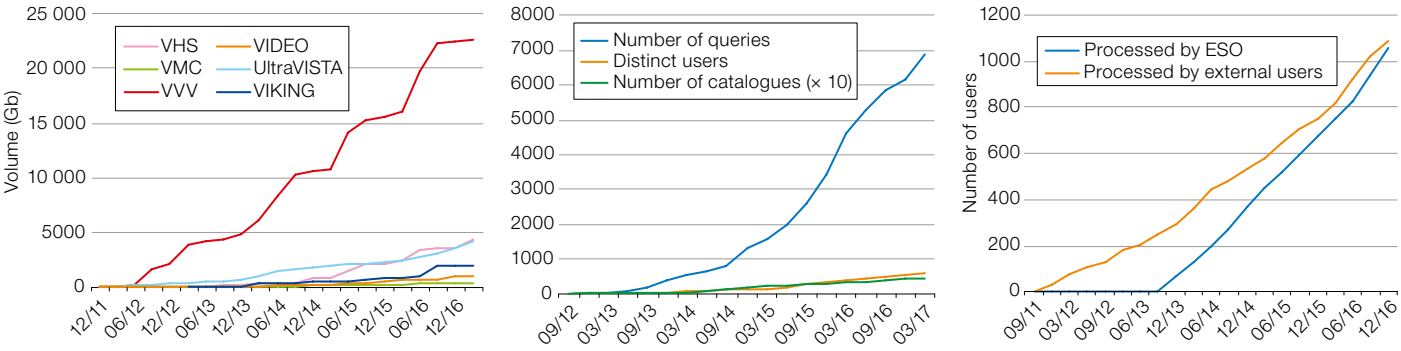


Figure 3. (Left) A histogram of the expected hours of observations for the Cycle 1 VISTA surveys in the period October 2016 to April 2018. The areas are colour coded according to the Cycle 1 survey acronyms. The full line indicates the typical completed hours per month based on VISTA operations over the previous 4.5 years. The available time between the colored areas and the black line was assigned to the new projects selected during the second VISTA call. Some Cycle 2 surveys began observations before April 2017, to exploit time freed up over certain RA ranges by the completion of some Cycle 1 surveys).

Figure 4. (Lower) Cumulative curves describing the volume download (Gb) by archive users of the Cycle 1 VISTA science products (left) and the number of queries (centre) and distinct users (right) accessing the ESO catalogue query interface (see Romaniello et al. [2016] for more information).



number of distinct queries of the catalogues that have been published through the query interface (see Figure 4).

A robust legacy from the Cycle 1 surveys is also demonstrated by the sizeable contribution to the total number of refereed publications based on VISTA data. Among the merit parameters that quantify the scientific impact of the first cycle of VISTA Public Surveys, there are the number of refereed publications by the survey teams and archive users. By April 2017, there were more than 300 refereed publications based on the data generated by the Cycle 1 surveys, according to the ESO Telescope Bibliography[7]. The numbers of refereed publications are as follows: VHS 45; UltraVISTA 82; VVV 129; VIDEO 25; VIKING 32; and VMC 34. A total of 86 refereed publications (~ 25 % of the total) are based on VISTA archival data (raw or reduced) and come from authors who were not co-investigators in the Public Survey proposals.

VISTA Cycle 2 surveys: science goals and observing strategies

In this section we provide an overview of the selection process of the Cycle 2 surveys and a summary of their science goals, observing strategies and relevant milestones. As noted earlier, the process of selecting and defining the second cycle of VISTA surveys started in October 2015 with the submission of 13 letters of intent from the community. The PSP met in January 2016 and recommended seven projects that were subsequently invited to submit formal proposals for the May 2016 OPC meeting. Following their review and endorsement by the PSP, the OPC and the Director General, the teams prepared Survey Management Plans (SMPs), which were in turn reviewed by the ESO survey team. This process was completed in January 2017, with the publication of the approved SMPs on the ESO Public Surveys web pages[1] and their announcement in the ESO Science Newsletter[8]. The seven new projects formally began observations on 1 April 2017. The full titles and acronyms of each of these surveys are given in Table 2 along with a brief summary of their observing parameters; in Figure 5 and 6 we show the footprints of the approved surveys and the requested hours in each RA bin per year, together with an illustration of the available hours per year.

The majority of the new surveys explore the time domain. When the VVVX reaches completion in 2020, its multi-epoch observations will have a baseline of over ten years (when combined with the Cycle 1 VVV survey). The science quality and the constant monitoring of the stability of the VISTA/VIRCAM system support the requirements of these surveys to measure accurate and consistent stellar positions and fluxes in several bands, over this timeframe. VINROUGE exploits the stability of VISTA in combination with the efficiency of the Target of Opportunity (TOO) mode to trigger the quick follow-up and monitoring of transient events.

Survey Acronym	Survey title & homepage	PI	Area (square degrees)	Filters	Total hrs	Multi-epoch observations
VINROUGE	Kilonova counterparts to Gravitational wave sources http://www.star.le.ac.uk/nrt3/VINROUGE/	N. Tanvir	~300 (10 triggers)	*Y J Ks*	420	yes
Cont. UltraVISTA	Completing the legacy of UltraVISTA http://home.strw.leidenuniv.nl/~ultravista/	J. Dunlop, M. Franx, J. Fynbo, O. Le Fèvre	0.75	*J H Ks*	756	no
VVVX	Extending VVV to higher Galactic latitudes http://vvvsurvey.org/	D. Minniti, P. Lucas	1700	*J H Ks*	1985	yes
VEILS	VISTA Extragalactic Infrared Survey http://www.ast.cam.ac.uk/~mbanerji/VEILS/veils_index.html	M. Banerji	9	*J Ks*	1153	yes
GCAV	Galaxy Clusters at VIRCAM http://www.GCAV.it	M. Nonino	30	*Y J Ks*	560	no
VISIONS	VISTA star formation atlas https://visions.univie.ac.at/	J. Alves	550	*J H Ks*	553	yes
SHARKS	Southern Herschel-Atlas Regions *K*-band survey http://sharks.roe.ac.uk/	I. Oteo	300	*Ks*	1200	no

Table 2. Overview of the Cycle 2 VISTA Public Surveys. The columns illustrate the Public Survey acronym (column 1), the survey title (column 2), the PI name (column 3), the area covered (column 4), the filters (column 5), the total hours requested (column 6) and the request for multi epoch observations (column 7).

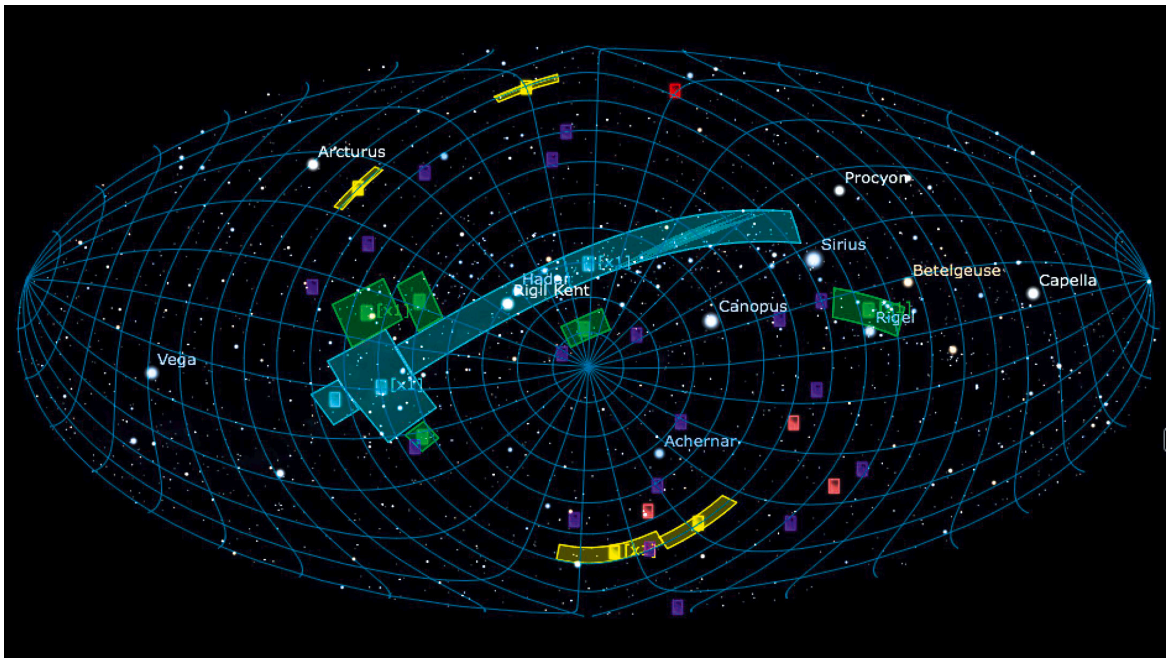


Figure 5. Sky coverage of the Cycle 2 VISTA Public Surveys. The colour coded footprints of their targeted areas are: VVVX (light-blue); VISIONS (green); SHARKS (yellow); GCAV (violet); VEILS (light-red), UltraVISTA (red). As pointings for VINROUGE are set by gravitational-wave triggers, they cannot be included here.

1. VINROUGE — VIsta Near-infraRed Observations Unveiling Gravitational wave Events — PI Nial Tanvir (University of Leicester)

This survey will conduct near-infrared follow-up imaging of the error regions for gravitational wave (GW) detections identified by the Laser Interferometer Gravitational-Wave Observatory (LIGO)-Virgo Collaboration. It will specifically target events that are likely to be due to a merger of a compact binary pair including at least one neutron star. Such systems are also expected to give rise to r-process kilonovae/macronovae, with spectral energy distributions peaking in the near-infrared in the days following the merger. Detection of an electromagnetic (EM) counterpart would trigger considerable further follow-up, providing the route to the redshift and host environment, and heralding a new era of GW-EM astrophysics. The Public Survey strategy will evolve over the course of the survey, as the behaviour of kilonovae is better characterised, and its strategy will be tailored to the parameters of each event. The total time requested by this survey project is 420 hours, nominally for up to ten triggers, resulting in a coverage of ~300 square degrees. The baseline plan is to image the first visit in three filters (*Y*, *J*, *Ks*) and one filter (*J*) at a repeat epoch to probe variability. Typically the limiting magnitude of the images is expected to reach J_{AB} = 21.

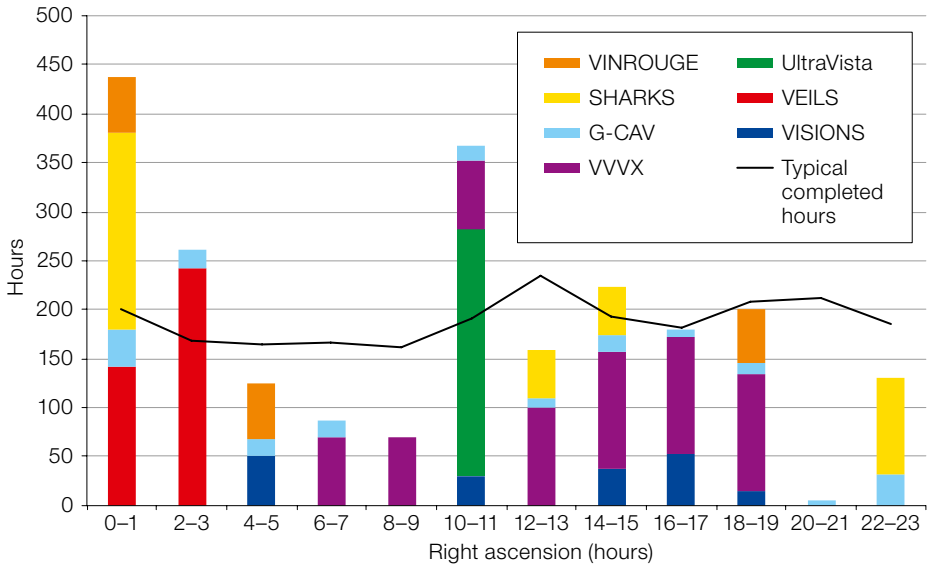


Figure 6. Requested hours per RA bin per year for the Cycle 2 VISTA Public Surveys. The continuous black line shows the typical available hours, based on the performance of VISTA in the previous 4.5 years. The RA range for VINROUGE shown here is set by the time of the year during which gravitational wave alerts may be triggered by the LIGO-Virgo collaboration.

2. Completing the legacy of UltraVISTA — PI Jim Dunlop (University of Edinburgh), Marijn Franx (Leiden Observatory), Johan Fynbo (University of Copenhagen), Olivier Le Fèvre (Laboratoire d'Astrophysique de Marseille)

The purpose of this survey is to complete the legacy of UltraVISTA by delivering the deepest degree-scale near-infrared imaging of the sky, within the unparalleled Cosmic Evolution Survey (COSMOS) field. This three-year programme will bring the *J*, *H* and *Ks* imaging across the full 1.5 square degrees footprint of VIRCAM to the same depths as has been achieved within the ultra-deep strips of the Cycle 1 UltraVISTA programme at Data Release 4; i.e., $J = 26.0$, $H = 25.7$, $Ks = 25.3$ (AB mag, 5σ, 1.8-arcsecond apertures). This will be well matched to the depths of the optical imaging from the new Subaru Hyper-SuprimeCam deep survey, and to the depths of the SPitzer Large Area Survey with Hyper-Suprime-Cam (SPLASH) using the Spitzer telescope. This 756-hour survey will deliver new results on the galaxy UV luminosity function out to redshift, $z = 8$ and the galaxy stellar mass function out to redshift, $z = 6$. It will also be a key resource for the study of dust-enshrouded star-forming galaxies, and for identifying spectroscopic targets for NASA's James Webb Space Telescope (JWST). This project maximises the value of the VISTA time already invested in the COSMOS field, and will secure the long-term legacy of VISTA for studies of the distant Universe.

3. VVVX — The VVV eXtended ESO Public Survey — PIs Dante Minniti (Universidad Andres Bello, Santiago de Chile), Philip Lucas (University of Hertfordshire)

The Cycle 1 Survey, VVV, mapped the Milky Way bulge and the adjacent southern mid-plane repeatedly over six years. The new VVVX survey, will fill the gaps left between the VVV and VHS areas and extend the baseline of VVV further, enabling proper motion measurements of < 0.3 milliarcseconds per year in the optically obscured regions where the Gaia satellite mission is limited by extinction. VVVX will take ~ 2000 hours, and cover 1700 square degrees of the southern sky, for the range of Galactic longitude, $20° \leq l \leq 130°$ (7 h < RA < 19 h). VVVX will provide a deep *JHKs* catalogue of about 2×10^9 point sources, as well as a *Ks*-band catalogue of ~ 10^7 variable sources. Within the area overlapping with the Cycle 1 VVV survey, VVVX will produce a 5-D map of the surveyed region by combining positions, distances and proper motions of well-understood distance indicators (for example, red clump stars, and RR Lyrae and Cepheid variables) in order to unveil the inner structure of the Milky Way. The VVV and VVVX catalogues will complement those from Gaia with very red sources and will feed spectroscopic targets for the forthcoming ESO high-multiplex spectrographs, MOONS and 4MOST.

4. VEILS — The VISTA Extragalactic Infrared Legacy Survey — PI Manda Banerji (University of Cambridge)

This is a deep *J* and *Ks*-band transient and wide-field survey with the following primary goals: to understand the epoch of reionisation and the build-up of massive galaxies; and constrain the cosmological equation of state using Type Ia supernovae and active galactic nuclei dust lags. VEILS will cover 9 square degrees over three fields: the European Large Area ISO Survey (ELAIS) S1 (RA = 00 h 30 m; Dec = −43° 00′); the Chandra Deep Field South, CDF-S (RA = 03 h 36 m; Dec = −28° 00′); and XMM-Newton Large scale Synoptic Survey field, the XMM-LSS (RA = 02 h 22 m; Dec = −06° 00′). The proposed per-epoch survey depths are $J < 23.5$ and $Ks < 22.5$ mag in all fields and in total 33–50 epochs per field per filter are expected over the entire duration of the survey. VEILS will take a total of 1153 hours (128 nights) in < 1 arcsecond seeing conditions to complete the survey.

5. GCAV — Galaxy Clusters At VIRCAM — PIs Mario Nonino (INAF, Trieste)

GCAV is a 560-hour infrared survey of a sample of 20 galaxy clusters, evenly distributed over the 0-24h RA range, which will mainly explore galaxy evolution over a broad, and largely unexplored, range of cluster environments.

All of the selected clusters have already been observed by the Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) by the following programmes: Cluster Lensing And Supernovae Search with Hubble (CLASH), Hubble Frontier Fields (HFF) and the Frontier Fields and Reionisation Lensing Cluster Survey (RELICS). Furthermore, a wealth of ground based ancillary data, from optical imaging and spectroscopy to radio observations, is available for most of the proposed clusters. The total area coverage is about 30 square degrees and the expected

depths are 24.5, 24.0, and 23.0 mag for *Y*, *J* and *Ks* respectively (5σ in point sources). The wide-area coverage coupled with the expected depths will also open up further scientific studies, for example, the search for high redshift quasars, lensed quiescent galaxies, L and T dwarfs, as well as infrared Galactic star counts and colours.

6. VISIONS — VISTA Star Formation Atlas — PI João Alves (University of Vienna)

VISIONS is a sub-arcsecond near-infrared survey of all nearby (< 500 parsecs) star formation complexes accessible from the southern hemisphere. This atlas will become the community's reference star formation database, covering the mass spectrum down to a few Jupiter masses and spatial resolutions reaching 100–250 au. The survey will cover a total of ~ 550 square degrees distributed over the six star forming complexes of Ophiuchus, Lupus, Corona Australis, Chamaeleon, Orion, and the Pipe Nebula. These are due to be completed within three years of the start of observations.

VISIONS is separated into three phases. The first phase will conduct *H*-band imaging of the target regions distributed over six epochs, with an effective exposure time of 60 seconds and a limiting magnitude of *H* ~ 19 mag. The immediate objective is to derive positions and proper motions of the embedded and dispersed young stellar population that is inaccessible to Gaia, as well as to provide photometry to complement the first generation VHS survey that fully covered all target regions in the *J*- and *Ks*-bands. In the second phase, VISIONS will carry out a set of deep observations that will image the high-column density regions of the star-forming complexes. The deep imaging in *J*-, *H*-, *Ks*-bands of 57 pointings, with a 600-second exposure time per pointing, will reach limiting magnitudes of *J* ~ 21.5 mag, *H* ~ 20.5 mag, and *Ks* ~ 19.5 mag. The third phase is to observe a set of additional six control fields with the same limiting magnitudes and a similar strategy as the deep observations, for statistical comparison with the galactic field population. The total requested time for VISIONS amounts to 553 hours.

7. SHARKS — Southern H-ATLAS Regions *Ks*-band Survey — PI Ivan Oteo (University of Edinburgh)

SHARKS is a wide and deep VISTA Public Survey over the South Galactic Pole and the fields covered by the GAlaxy and Mass Assembly (GAMA) and Herschel-Astrophysical Tetrahertz Large Area Survey (H-ATLAS) in the *Ks*-band. This survey covers 300 square degrees to a 5σ depth of *Ks* ~ 22.7 AB mag in 1200 hours. The SHARKS fields will also be followed up by a number of future deep and/or wide far-IR and radio surveys.

The main goals of this survey are as follows: to provide the best possible counterpart identification for ~ 90 % of the sources detected in the redshift range, $0 < z < 3$, by H-ATLAS, the Low Frequency Array (LOFAR), the Square Kilometre Array (SKA), and the Australian SKA Pathfinder (ASKAP); to produce a sample of a thousand strong lenses for cosmography studies; and, to study the evolution of the most massive structures in the Universe. The depth of the deepest available observations over the proposed fields (VIKING survey, *Ks* < 21.2 AB mag at 5σ) is currently not enough to accomplish any of these aims. The SHARKS fields will also overlap with future optical observations (using the Large Synoptic Survey Telescope) and with observations in the near-infrared (using ESA's Euclid mission), representing a complementary dataset with an extensive legacy.

Science data products from Cycle 2 surveys

The science policies concerning the return of science data products also apply to the VISTA Cycle 2 surveys. A short summary of the timeline for the delivery of their data products from their survey management plans is presented here. The first delivery of data products such as images and source lists is expected 1.5 years after the start of observations of the surveys, i.e., in October 2018. The aperture-matched multi-band catalogues and light curves should become available a year later in a second data release. The catalogues may not be limited to VISTA near-infrared photometry, as several teams have committed to delivering multi-wavelength data, including optical (for example, HST), radio (for example, LOFAR) or X-ray measurements. The time domain also plays a major role in setting the legacy value of the VISTA Cycle 2 surveys. For example, the multi-messenger astronomy nature of the GW-EM observations by VINROUGE, or the delivery of photometric catalogues with proper motions for millions of Milky Way stars in the Bulge by VVVX and their synergy with the results from Gaia, will have a transformational impact on the science carried out by the ESO community.

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Links

[1] ESO Public Surveys: http://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html
[2] Cambridge Astronomy Survey Unit: http://casu.ast.cam.ac.uk/
[3] Wide Field Astronomy Unit: http://www.roe.ac.uk/ifa/wfau/
[4] TERAPIX: http://terapix.iap.fr/
[5] Phase 3 releases: http://www.eso.org/sci/observing/phase3/data_releases.html
[6] ESO Science Archive Facility: http://archive.eso.org/wdb/wdb/adp/phase_main/form
[7] telbib: http://telbib.eso.org
[8] ESO Science Newsletter: http://www.eso.org/sci/publications/newsletter/