European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **95A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–8**

Ultra-Deep K_s-band imaging of the *HST* Frontier Fields Year 3 Clusters

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 82 hours SM

The *HST* Frontier Fields (HFF) programme is a multi-cycle campaign with the Hubble Space Telescope that will image 6 deep fields centered on strong lensing galaxy clusters in parallel with 6 deep blank fields. Here we propose to continue our P92 *VLT* legacy programme and image the year 3 (2015) Frontier Fields in the K_s-band with HAWK-I down to $K_s = 26.5$ (AB, 5σ). The K_s band at 2.2 μm crucially fills the gap between the reddest *HST* filter (1.6 μm $\sim H$) and the IRAC 3.6 μm passband, greatly improving the constraints on both the redshifts and the stellar-population properties of galaxies extending well below the characteristic stellar mass across most of the age of the universe, down to, and including, the redshifts of the targeted galaxy clusters ($z \lesssim 0.5$). We waive the proprietary rights to the HAWK-I observations in order to make this unparalleled dataset immediately available to the community.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	95	HAWKI	79h	any	n	0.6	CLR	s	
B	95	HAWKI	3h	any	n	0.6	PHO	s	

4. Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

6. Principal Investigator: Gabriel Brammer, brammer@stsci.edu, US, Space Telescope Science Institute

6a. Co-investigators:

D.	Marchesini	Tufts University,Department of Physics and Astronomy,US
I.	Labbé	Sterrewacht,University of Leiden,NL
A.	Fontana	INAF - Osservatorio Astronomico di Roma,I
A.	Muzzin	Sterrewacht,University of Leiden,NL

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale: Galaxy formation is one of the major unsolved problems in astrophysics. The key question is how the $\sim 10^{-6}$ density fluctuations inferred from the cosmic microwave background radiation at redshift $z \sim 1100$ [1] subsequently evolved into stars, galaxies, and clusters of galaxies that we see today. The standard paradigm of structure formation is that of hierarchical assembly in a universe dominated by cold dark matter (CDM). CDM galaxy formation models postulate that DM haloes form in a dissipationless, gravitational collapse, and the stellar content of galaxies forms out of gas inside these structures following the radiative cooling of baryons [2].

The *HST* Frontier Fields: Through a large investment (560 orbits) of Director's Discretionary (DD) time, the Hubble Space Telescope (*HST*) is currently embarking on a multi-cycle campaign to investigate the distant universe ($1 \lesssim z \lesssim 12$). The *HST* Frontier Fields (HFF) programme has already imaged two deep fields centered on strong lensing galaxy clusters with two deep blank fields in parallel (Fig. 1). Four more clusters and deep fields are planned for the next two *HST* cycles, two of which are visible from the *VLT*. The primary science goals of the twelve HFF fields are to 1) reveal the population of galaxies at z=5–10 that are 10–50 times fainter intrinsically than any presently known, 2) solidify our understanding of the stellar masses and star formation histories of sub-$L^\star$ galaxies, 3) provide the first statistically meaningful morphological characterization of star-forming galaxies at $z > 5$, and 4) to find $z > 8$ galaxies magnified by the cluster lensing, with some bright enough to make them accessible to spectroscopic follow-up. The HFF will image 12 times the area of the HUDF (total areas of $\sim$55 arcmin^2 and $\sim$135 arcmin^2 by WFC3/IR and ACS, respectively) with the ACS $B_{435}V_{606}I_{814}$, and the WFC3 $Y_{105}J_{125}H_{140}H_{160}$ filters, reaching a 5σ total magnitude limit of H_{160}=28.7 AB mag. Furthermore, the HFF are being observed with IRAC at 3.6μm and 4.5μm with 1000 hours of *Spitzer* DD time.

Whereas the main goal of the HFF is to explore the galaxy population in the first billion years of cosmic history, this dataset will be unique for its combination of surveyed area and depth for studies of galaxy evolution across most of the age of the universe, down to, and including, the redshifts of the targeted clusters of galaxies ($z \approx 0.3$–0.5). Specifically, the relatively large survey area of the HFF will allow for the assembly of a large sample of galaxies at z>1, and its depth will enable detailed measurements of their stellar populations and morphologies. Fig. 2a shows the cumulative number counts $N(> z)$ as a function of redshifts in two Frontier Fields clusters we observed with HAWK-I in P92: we expect more than a thousand galaxies at z>1 and hundreds at z>3 in the combined HAWK-I+HFF survey to K_s=26.5 (with many additional galaxies detected in the deeper *HST* imaging with robust upper limits in K_s).

B – Immediate Objective: The observations proposed here will provide deep HAWK-I K_s-band imaging to fill the large gap in the wavelength coverage between the *HST* H_{160} and IRAC 3.6 μm filters of the ongoing *HST* Frontier Fields survey. These observations at 2.2 μm are critical for enabling galaxy studies over the full 8–9 Gyr of cosmic history sampled by the HFF with an unprecedented combination of depth and area. The addition of the K_s-band significantly improves the precision of both photometric redshifts and derived properties of galaxies' stellar populations, such as their stellar mass, at z>2 and even at z>4 (Fig. 2b). The HFF+HAWK-I survey will provide, for the first time, a statistically large sample of galaxies down to stellar masses $\log(M/M_\odot) \sim 8.5(9.5)$ at $z = 1.5(4.5)$, i.e., orders of magnitude below the characteristic stellar mass of the stellar mass function, $M^\star \approx 10^{11}$ M$_\odot$ (e.g., [3,4]). At high redshifts z>8, the K_s-band photometry will help constrain the Lyman-break redshifts and increase the wavelength lever arm for measuring the redshift evolution of the rest-frame UV slopes (i.e., dust content and/or metallicity) of the first galaxies [5, 6] (see Fig. 2c).

We will use the combined HFF+HAWK-I dataset to address the critical question of whether or not quiescent galaxies are in place in significant numbers at z>4 (Fig. 2). Recent deep near-infrared surveys have pushed the discovery of "red sequence" galaxies to $z \sim 2$ (e.g., [4,7,8]). Wide-area surveys have discovered a few such galaxies at $z\sim4$ but only the most massive galaxies are accessible at the existing survey depths [9,4,11,12]. The deep *HST* photometry alone will be insufficient to robustly characterize red galaxies at z>3 as even the H-band lies on the UV side of the Balmer/4000Å break at these redshifts [9,10] (Fig. 2b); the K_s-band is required to select galaxies at rest-frame optical wavelengths avoiding confusion challenges of the redder IRAC bands. Combined with the HFF fields we observed in P92, the proposed programme is needed to reduce the uncertainties due to cosmic variance below 50% for $\sim 10^{10.5}$ M$_\odot$ galaxies at $z\sim6$. These uncertainties are substantial in the small HUDF area, which results in only loose upper limits on the fraction of quiescent galaxies at z>4 [3].

Our team has extensive experience processing deep K_s-band observations (including HAWK-I, [5] and Fig. 1). We are committed to providing a valuable resource to the community to make the most productive use of a large investment of *VLT* time: we waive the proprietary period on the HAWK-I observations, and we will provide a public release of reduced, registered mosaics within one year of completing the integration on each of the two survey fields, as demonstrated by our P92 programme (`http://gbrammer.github.io/HAWKI-FF/`).

References: **[1]** Larson, D., et al. 2011, ApJS, 192, 16 **[2]** White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341 **[3]** Lundgren, B., et al. 2014, ApJ, 780, 34 **[4]** Muzzin, A., et al., 2013a, ApJ, 777, 18 **[5]** Bouwens, R. et al., 2013, ApJL, 765, 16 **[6]** Bouwens, R. et al., 2012, ApJ, 754, 83 **[7]** Brammer, G. et al., 2009, ApJL, 706, 173 **[8]** Brammer, G. et al., 2011, ApJ, 739, 24 **[9]** Marchesini, D. et al., 2010, ApJ, 725, 1277 **[10]** Brammer, G. & van Dokkum, P, 2007, ApJL, 718, 73 **[11]** Straatman, C. et al. 2014, ApJ, 783, L14 **[12]** Spitler, L. et al. 2014, 2014, ApJ, 787, L36

7. Description of the proposed programme and attachments

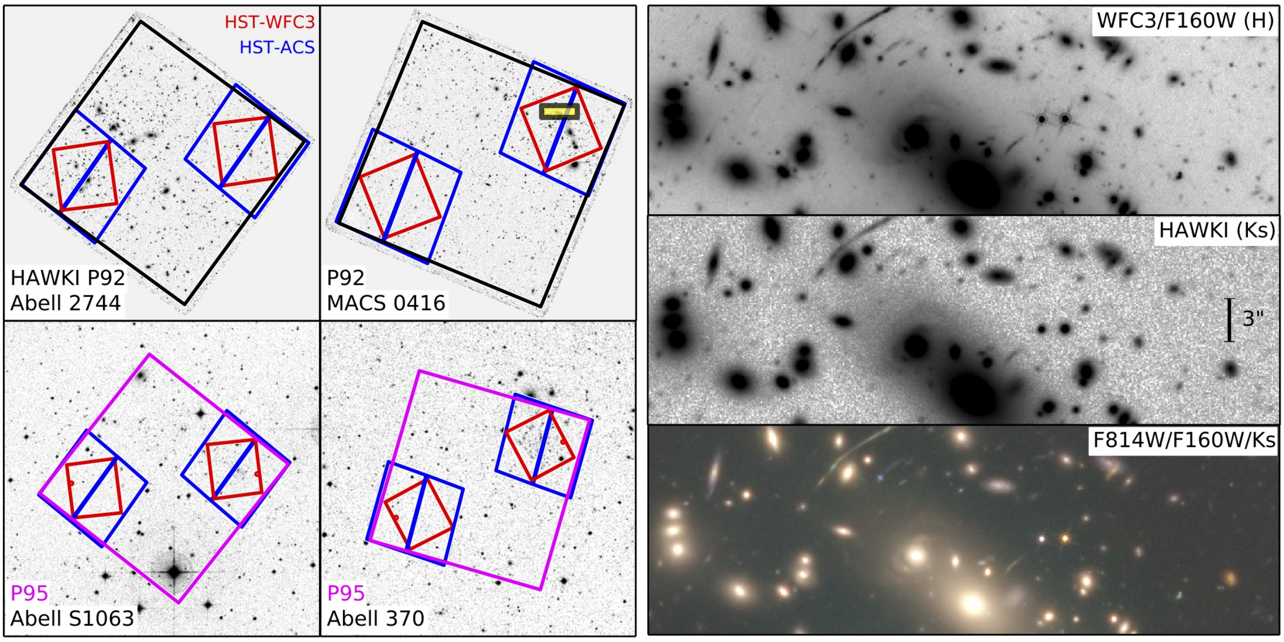

Fig. 1. *Left:* Layout of the existing P92 (PI: Brammer) and proposed P95 HAWK-I pointings on the four *HST* Frontier Fields targets visible from the *VLT*. The $7.5' \times 7.5'$ HAWK-I field of view is perfectly suited to provide simultaneous ultra-deep K_s-band imaging of both the cluster and parallel *HST* fields. *Right:* Cutout of the MACS 0416 field (yellow box at left). The existing and proposed HAWK-I K_s-band imaging provide a critical scientific complement to the ultra-deep *HST* survey, with superb image quality ($0''.4$ FWHM) and sensitivity reaching $K_s = 26.3$ AB (**total**, 5σ, point source).

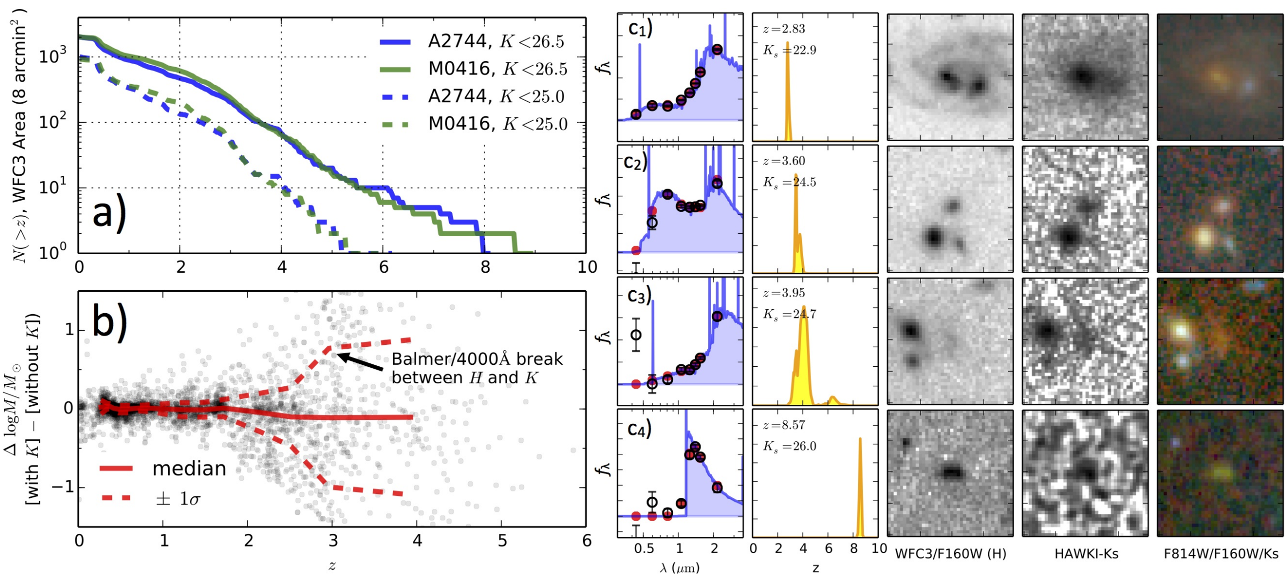

Fig. 2. *a)* Cumulative number counts $N(>z)$ of sources in the combined deep HAWK-I/K_s + WFC3/IR area (8 arcmin^2/field). Only a few bright $z \sim 8$ candidates (see c_4) are seen in each field (see panel c.4), so *all* of the FF clusters must be observed to maximize the high-z, K_s-detected sample. *b)* Without K_s-band photometry that samples rest-frame optical wavelengths at $z > 2.5$, the uncertainty in stellar mass estimates is extremely large ($\sigma \sim 1$ dex). *Panels* c_{1-4}) Example *HST*+K_s SED fits from the P92 clusters. c_1 is a remarkable evolved galaxy at $z \sim 2.8$ with a prominent bulge and an extended grand-design spiral disk. c_2 and c_3 show significant evolved components only apparent in the K_s-band photometry. c_4 is a robust $z \sim 8.6$ Lyman-break Y-dropout galaxy with an unambiguous K_s-band detection ($K_s = 26.0$) that constrains its rest-frame UV spectral slope.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: These K_s-band observations can be obtained at any lunar phase.

Time Justification: (including seeing overhead)

As the figure of merit for achieving the goals of this program, we require detecting a galaxy with 1/10th of the characteristic stellar mass of the stellar mass function at z=4.5 ($\sim 10^{10}\,M_\odot$). This ensures that such galaxies will be detected in sufficient numbers in the volume probed by the 4 *HST* ACS+WFC3 pointings covered here with HAWK-I. Scaling the mass completeness limits UltraVISTA [4], we require a 5σ depth of K_s=26.5 (AB; point source). This is ∼3 mag deeper than UltraVISTA DR1 and almost 2 mag deeper than zFOURGE [12].

For NDIT×DIT = 4×15 s exposures, the HAWK-I Exposure Time Calculator predicts that the required depth can be reached in 30 hours on-source, per field. This estimate assumes airmass=1.2 and seeing of 0.″6 in the V-band. While the seeing constraint implies an additional expense in terms of observing efficiency, the resulting seeing of ∼0.″45 in the K_s-band is necessary to match, as well as possible, the high-resolution *HST* imaging (0.″18 in H_{160}) of the crowded HFF cluster fields. An additional 11 hours per field is required for the acquisition and per-exposure overheads. Thus we request a total allocation of 41×2=82 hours for the full integrations on the final two southern *HST* Frontier Fields. Our experience with the P92 allocation of HAWK-I imaging of the first two Frontier Fields clusters (Abell 2744 and MACS 0416, see Figs. 1 & 2) confirms the sensitivity and overhead estimates. With an identical time request (41 h / field), the full mosaics reach 5σ depths at *total* magnitude $K_s = 26.3$. The modest difference with respect to the ETC prediction is primarily the result of flux in the extended wings of the PSF beyond that of the Gaussian profile assumed by the ETC. In the Abell 2744 field with 15 s DITs, we achieved 29.4 h on-source. A bright star in the MACS 0416 field required shorter DITs and lower observing efficiency, resulting in 25.5 h on-source.

We readily acknowledge that this proposal request represents a significant investment of valuable *VLT* observing time. However, this is in keeping with even larger time investments with the *Hubble* and *Spitzer* Space Telescopes and represents a unique opportunity for the *VLT* to provide a critical and lasting contribution to these forefront survey fields. The requested allocation will truly probe parameter space unexplored from the ground and currently impossible to obtain from space; the HAWK-I image proposed here will be almost one magnitude deeper than the final depth of the wider-area UltraVISTA survey ($K_s < 25.6$). Furthermore, taking into account the roughly factor-of-two (0.75 mag) magnification by the massive foreground galaxy clusters, *the proposed ultra-deep K_s-band integration is equivalent to an allocation of over 300 hours on blank survey fields.* While the cluster magnification comes at a cost of a smaller survey volume, the faint luminosities probed will otherwise only be accessible with future facilities such as the E-ELT and the JWST.

8a. Telescope Justification:

To match the depth and relatively large area of the *HST* Frontier Fields, we require a large telescope aperture and an infrared instrument with a large field of view (7.5 arcmin). The field of view of *VLT*/HAWK-I is perfectly matched to cover both the cluster and parallel areas of the Frontier Fields in a single pointing (Fig. 1). No other large 8–10m-class telescope currently provides a NIR imager wide enough to cover both the *HST* cluster and parallel fields at once, instantly decreasing their observing efficiency for this programme by a factor of two. The proposed ultra-deep HAWK-I coverage of the HFF survey builds on ESO's pioneering history of obtaining ultra-deep K-band images of the HUDF with ISAAC (Labbé et al. 2003) and HAWK-I (Bouwens et al. 2013), now over a significantly larger survey area (∼225 arcmin^2 over both P92 and P95, as proposed here).

8b. Observing Mode Justification (visitor or service):

The HAWK-I observations we propose are straightforward imaging acquisitions of large survey fields, and the full integrations that require very good and uniform image quality can be most efficiently scheduled in Service Mode throughout P95. We do not have specific timing constraints, so the observations can be easily scheduled around the AOF-related activities at UT4.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

PI G. Brammer was PI of 2 *VLT* programs since P90:

090.A-0215, "Testing the Possible Redshift Variation of the Stellar Initial Mass Function with *VLT*/X-shooter", 6 h, X-shooter. This programme was assigned priority B and no observations were obtained.

092.A-0472, "Ultra-Deep K_s-band imaging of the *HST* Frontier Fields", 82 h, HAWK-I. This programme observed the first two FF clusters, with observations completed in Feb 2014; see Figs. 1 & 2. The images have been reduced and the mosaics are made freely available to the community `[http://gbrammer.github.io/HAWKI-FF/]`. The images will be submitted to ESO as a Phase 3 data product in Fall 2014, and a survey description paper is in preparation.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

There is 21 h of archival HAWK-I J-band coverage of the Abell 370 field from programme 091.A-0108(B). The ESO proposal information page indicates that the programme was originally allocated 10.4 h, so it is likely that much of the archival data did not satisfy the observing constraints and will be of lesser quality. In any case, there is no archival *VLT* 2.2 μm K_s-band imaging of either field, which is required to complement the 0.4–1.6 μm *HST* survey.

9b. GTO/Public Survey Duplications:

10. Applicant's publications related to the subject of this application during the last 2 years

Bouwens R., et al., 2013, ApJL, 765, 16: "Photometric Constraints on the Redshift of $z \sim 10$ candidate UDFj-39546284 from deeper WFC3/IR+ACS+IRAC observations over the HUDF"

Brammer G., et al., 2013, ApJL, 765, 2: "A Tentative Detection of an Emission Line at 1.6 μm for the $z \sim 12$ Candidate UDFj-39546284"

Marchesini, D., et al., 2014, ApJ, 794, 65 (arXiv/1402.0003): "The Progenitors of Local Ultra-massive Galaxies Across Cosmic Time: from Dusty Star-bursting to Quiescent Stellar Populations"

Marsan, C., et al., 2014, ApJ, submitted (arXiv/1406.0002): "Spectroscopic Confirmation of an Ultra Massive and Compact Galaxy at $z = 3.35$: A Detailed Look at an Early Progenitor of Local Most Massive Ellipticals"

Muzzin, A., et al., 2013, ApJS, 206, 8: "A Public Ks-selected Catalog in the COSMOS/UltraVISTA Field: Photometry, Photometric Redshifts and Stellar Population Parameters"

Muzzin, A., et al., 2013, ApJ, 777, 18: "The Evolution of the Stellar Mass Functions of Star-Forming and Quiescent Galaxies to $z = 4$ from the COSMOS/UltraVISTA Survey"

Skelton, R., et al., 2014, ApJ, in-press (arXiv/1403.3689): "3D-HST WFC3-selected Photometric Catalogs in the Five CANDELS/3D-HST Fields: Photometry, Photometric Redshifts and Stellar Masses"

Stefanon, M., et al., 2013, ApJ, 768, 92: "What Are the Progenitors of Compact, Massive, Quiescent Galaxies at $z = 2.3$? The Population of Massive Galaxies at $z > 3$ from NMBS and CANDELS"

Stefanon, M., et al., 2014, ApJ, submitted (arXiv/1408.3416): "Stellar mass functions of galaxies at $4 < z < 7$ from an IRAC-selected sample in COSMOS/UltraVISTA: limits on the abundance of very massive galaxies"

Straatman, C., et al., 2014, ApJ, 783, 14: "A Substantial Population of Massive Quiescent Galaxies at $z \sim 4$ from ZFOURGE"

van der Wel., A., et al., 2014, ApJ, 788, 28: "3D-HST+CANDELS: The Evolution of the Galaxy Size-Mass Distribution since $z = 3$"

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
AB	AS1063	22 48 44	-44 31 48	41.0	26.5	7 min	z=0.348 cluster	
AB	A370	02 39 53	-01 34 36	41.0	26.5	7 min	z=0.375 cluster	

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
95	HAWKI	A	IMG	Ks
95	HAWKI	B	IMG	Ks

6b. Co-investigators:

...continued from Box 6a.

E.	Barker	Space Telescope Science Institute,US
A.	Galametz	Max Planck Institut fuer extraterrestrische Physik,D
M.	Stefanon	Sterrewacht,University of Leiden,NL
S.	Toft	Dark Cosmology Centre, Niels Bohr Institute,DK
K.	Whitaker	NASA/GSFC,US
A.	van der Wel	Max Planck Institut fuer Astronomie,D