Ultra-deep *K*-band Imaging of the Hubble Frontier Fields

Gabriel B. Brammer[1]
Danilo Marchesini[2]
Ivo Labbé[3]
Lee Spitler[4,5]
Daniel Lange-Vagle[1,2]
Elizabeth A. Barker[1]
Masayuki Tanaka[6]
Adriano Fontana[7]
Audrey Galametz[8]
Anna Ferré-Mateu[9]
Tadayuki Kodama[6]
Britt Lundgren[10]
Nicholas Martis[2]
Adam Muzzin[11]
Mauro Stefanon[3]
Sune Toft[12]
Arjen van der Wel[13]
Benedetta Vulcani[14]
Katherine E. Whitaker[15,16]

[1] Space Telescope Science Institute, Baltimore, USA
[2] Physics and Astronomy Department, Tufts University, Medford, USA
[3] Leiden Observatory, Leiden University, the Netherlands
[4] Department of Physics & Astronomy, Macquarie University, Sydney, Australia
[5] Australian Astronomical Observatory, North Ryde, Australia
[6] National Astronomical Observatory of Japan, Tokyo, Japan
[7] INAF, Osservatorio Astronomico di Roma, Monteporzio, Italy
[8] Max-Planck-Institut für extraterrestrische Physik, Garching, Germany
[9] Subaru Telescope, Hilo, USA
[10] Department of Astronomy, University of Wisconsin, Madison, USA
[11] Kavli Institute for Cosmology, Cambridge University, United Kingdom
[12] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Denmark
[13] Max-Planck-Institut für Astronomie Heidelberg, Germany
[14] School of Physics, University of Melbourne, Australia
[15] Department of Astronomy, University of Massachusetts Amherst, USA
[16] Hubble Fellow

We have recently completed a deep near-infrared imaging survey with the High Acuity Wide Field *K*-band Imager (HAWK-I), nicknamed KIFF (*Ks*-band Imaging of the Frontier Fields). KIFF provides ultra-deep images of six fields around massive galaxy clusters that have also recently been observed with the Hubble and Spitzer Space Telescopes as part of the Frontier Fields programme. Each of the KIFF mosaics is among the deepest *Ks*-band images ever obtained, and, with a boost from strong gravitational lensing by the galaxy clusters, they will be used to reveal the stellar populations of galaxies seen only a few hundred million years after the Big Bang. Fully reduced images are made available to the community through the Phase 3 infrastructure of the ESO Science Archive Facility.

Context: Deep near-infrared extragalactic imaging surveys

During the last two decades, near-infrared (NIR) imaging has taken its place at the forefront of studies of galaxy formation and evolution, enabling transformational advances in our understanding of galaxy populations at early cosmic times. Detections of galaxies in the *K*-band (2.2 μm) have provided the first opportunity to construct a comprehensive picture of the population of galaxies in the early Universe. The *K*-band has enabled the discovery of galaxies at $z > 2$ that are faint at observed optical (rest-frame ultraviolet [UV]) wavelengths, owing to their evolved stellar populations and/or significant amount of dust extinction (for example, Franx et al., 2003; Labbé et al., 2003).

In fact, these galaxies, which dominate the high-mass end of the high-z galaxy population, were previously missed by rest-frame UV selection techniques, such as *U*-dropout galaxies (for example, van Dokkum et al., 2006). Imaging in the *K*-band allows for direct sampling of rest-frame wavelengths longer than the Balmer break out to $z \approx 5$. Sampling the rest-frame optical wavelength regime is critical for high-z studies, as it is significantly less affected by dust obscuration and is a better probe of the galaxy stellar mass compared to the rest-frame UV, which is more sensitive to unobscured star formation (for example, Fontana et al., 2006).

The next Frontier

The latest effort to further our knowledge of galaxy formation and evolution is the Hubble Space Telescope (HST) Frontier Fields (HFF) programme[1] (Lotz et al., 2016). The HFF programme is a multi-cycle Hubble programme consisting of 840 orbits of Director's Discretionary (DD) time that is imaging six deep fields centred on strong lensing galaxy clusters in parallel with six deep blank fields (Figure 1). The primary science goals of the twelve HFF fields are to: 1) reveal the population of galaxies at z = 5–10 that are intrinsically 10–50 times fainter than any presently known; 2) solidify our understanding of the stellar masses and star formation histories of faint galaxies; 3) provide the first statistically meaningful morphological characterisation of star-forming galaxies at $z > 5$; and 4) find $z > 8$ galaxies magnified by the cluster lensing, with some bright enough to be accessible to spectroscopic follow-up. Alongside the HST observations, the Spitzer Space Telescope has devoted 1000 hours of DD time to imaging the HFF fields at 3.6 μm and 4.5 μm with the InfraRed Array Camera (IRAC).

Whereas the main goal of the HFF is to explore the galaxy population in the first billion years of cosmic history, this dataset, unique in its combination of surveyed area, multi-wavelength coverage and depth, is also well suited for studies of galaxy evolution across most of the age of the Universe, down to, and including, the redshifts of the targeted galaxy clusters ($z \approx$ 0.3–0.5).

KIFF: A synergy between the VLT and space-based observatories

The space-based HFF data alone, however, are not sufficient to robustly characterise red galaxies at $z \gtrsim 3$ because the near-infrared H_{160}-band of the HST Wide Field Camera 3 IR channel (WRF3/IR) lies on the UV side of the rest-frame optical Balmer/4000 Å break at these redshifts. This mismatch results in sub-optimal accuracies in the assignment of the photometric redshifts and stellar population properties (e.g., stellar mass and rest-frame optical colour; Muzzin et al., 2009). Very deep *K*-band imaging is required to

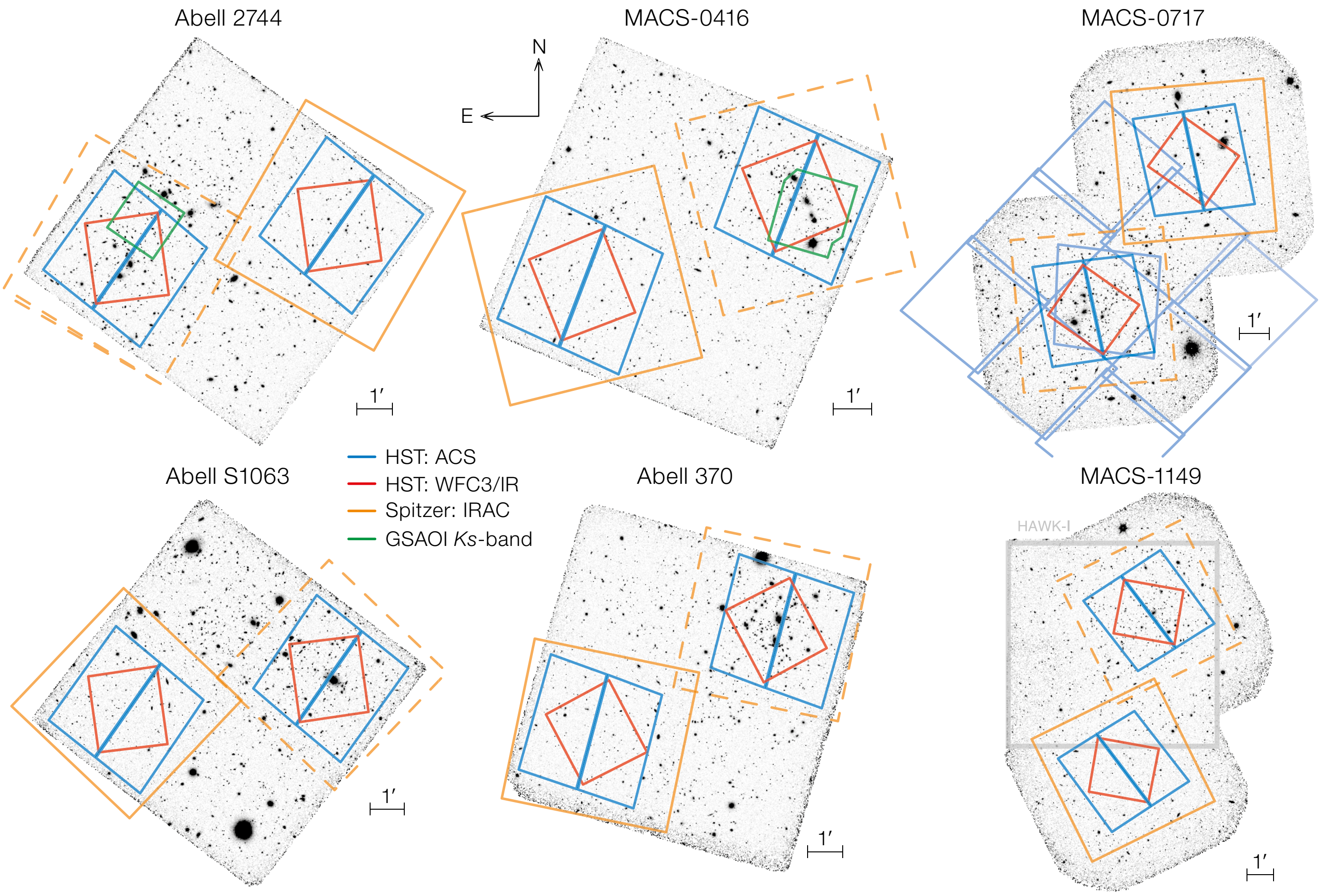

Figure 1. The layout of the imaging data in the Frontier Fields clusters: HAWK-I and MOSFIRE images with HST cluster and parallel fields (Advanced Camera for Surveys [ACS] in blue, WFC3/IR in red, Spitzer IRAC in orange) and additional Gemini South Adaptive Optics Imager (GSAOI) in green (Schirmer et al., 2015). From Brammer et al. (2016).

significantly improve the precision of both photometric redshifts and derived stellar population properties. Moreover, at $z > 8$–9, the *K*-band data help to constrain the Lyman-break redshifts (for example, Bouwens et al., 2013) and increase the wavelength lever arm for measuring the redshift evolution of the rest-frame UV slopes (i.e., the dust content and/or metallicity) of the first galaxies (Bouwens et al., 2013).

In order to resolve this issue of the lack of deep *K*-band data over the HFF, we executed the KIFF programme[2] to image four of the HFF clusters in the *Ks*-band (filter centred at 2.15 μm, width 0.32 μm) using the HAWK-I imager mounted on Unit Telescope 4 of the Very Large Telescope (VLT) to a depth comparable to that of the HST data. Coverage of two of the HFF clusters not visible from Paranal was obtained with the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE) mounted on the Keck I telescope at Mauna Kea. Table 1 lists the six pointings with summary details of the observations and their depth and image quality.

Table 1. KIFF observations of the Hubble Frontier Fields.

Field	Cluster Redshift	R.A.	Dec.	Instrument	Exp. time (hours)	Depth (AB mag)	FWHM (arcsec)
Abell 2744	0.31	00:14:21	−30:23:50	HAWK-I	29.3	26.0	0.39
MACS-0416	0.40	04:16:09	−24:04:28	HAWK-I	25.8	26.0	0.36
Abell S1063	0.35	22:49:01	−44:32:13	HAWK-I	27.9	26.0	0.39
Abell 370	0.38	02:40:03	−01:36:23	HAWK-I	28.3	26.0	0.35
MACS-0717	0.55	07:17:34	+37:44:49	MOSFIRE	8.1	25.3	0.49
MACS-1149	0.54	11:49:36	+22:23:58	MOSFIRE+HAWK-I	15.6	25.1	0.54

The *Ks*-band data

HAWK-I images of the four southern HFF clusters were obtained in Service Mode in Periods 92 (2013–2014) and 95 (2015–2016). Reaching depths approaching those of the HST and Spitzer images requires long integrations in the *Ks*-band: each of the HAWK-I fields was observed for more than 25 hours on-source. The large 7 × 7 arcminute field of view of the HAWK-I instrument is perfectly suited to covering the two deep Hubble pointings in each field, and this instantly improves the observing efficiency of this

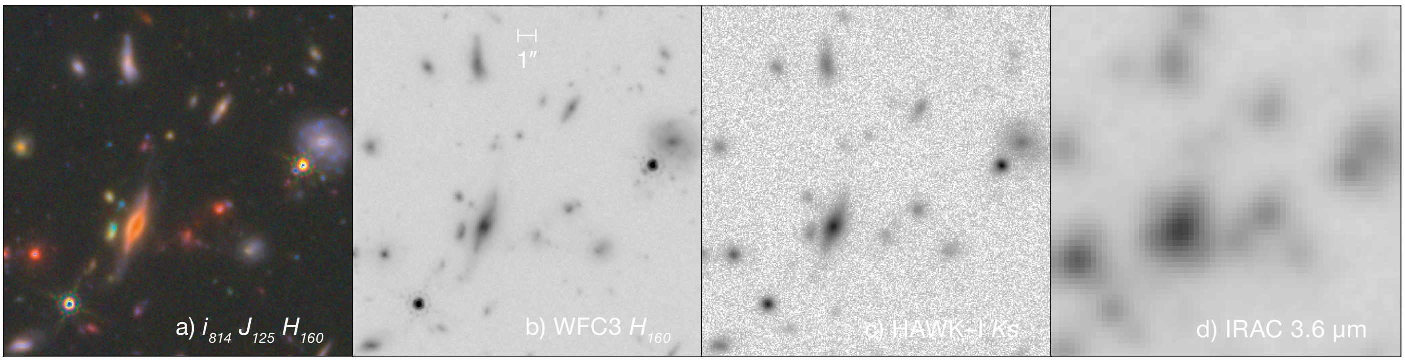

Figure 2. A 20 × 20 arcsecond cutout from the MACS-0416 parallel field (see Figure 1, upper centre, east field) as an example of the Hubble Frontier Fields imaging. (a) HST colour composite from I_{814}-, J_{125}- and H_{160}-band images. (b) The near-infrared HST H_{160} image (greyscale). (c) The HAWK-I *Ks*-band image. (d) Spitzer IRAC 3.6 µm image. From Brammer et al. (2016).

programme by a factor of two over comparable instruments with smaller fields of view (MOSFIRE, for example, requires two pointings). Figure 1 shows the layout of the HAWK-I mosaics and the accompanying deep Hubble and Spitzer data. The deep KIFF mosaics cover a combined area of 490 square arcminutes.

The depth of the *Ks*-band images and their utility, in concert with the Hubble images at bluer wavelengths, are very sensitive to the image quality achieved. Our Service Mode constraints required very good seeing and transparency conditions, and it is a testament to the excellent observing efficiency and outstanding sky conditions at the VLT and Cerro Paranal that these conditions were met within single observing periods for such long total integrations per field. The final image quality of the HAWK-I mosaics is superb — better than 0.4 arcseconds (point source full width half maximum [FWHM]) for all cases and reaching just 0.35 arcseconds in the Abell 370 field. The final depth of the deep HAWK-I mosaics reaches an AB magnitude of 26.0 (5σ for point sources), competitive with the deepest *Ks*-band images previously obtained (see the HUGS project; Fontana et al., 2014a, 2014b).

An example comparison of the KIFF *Ks*-band and space-based Frontier Fields imaging is illustrated in Figure 2, showing just a small cutout of the MACS-0416 "parallel" field (the full KIFF coverage is some 4400 times larger than the 20 × 20 arcsecond area shown). The deep optical and near-infrared Hubble imaging provide spectacular spatially resolved information on physical scales of just ~1 kpc (Figure 2a). However, there are many red galaxies clearly visible in the cutout that are predominantly at redshifts $z > 2$, where even the reddest WFC3/IR filter, H_{160} (Figure 2b), only probes rest-frame UV wavelengths and is therefore most sensitive to young, UV-bright star-forming galaxies. The KIFF imaging (Figure 2c) bridges the gap between Hubble and Spitzer and provides high-fidelity rest-frame optical images of galaxies at $z > 2$.

Improved constraints on the redshifts and intrinsic properties of distant galaxies

To explore the quantitative constraints provided by the deep *Ks*-band imaging, we have computed photometric redshifts and derived rest-frame colours and mass-

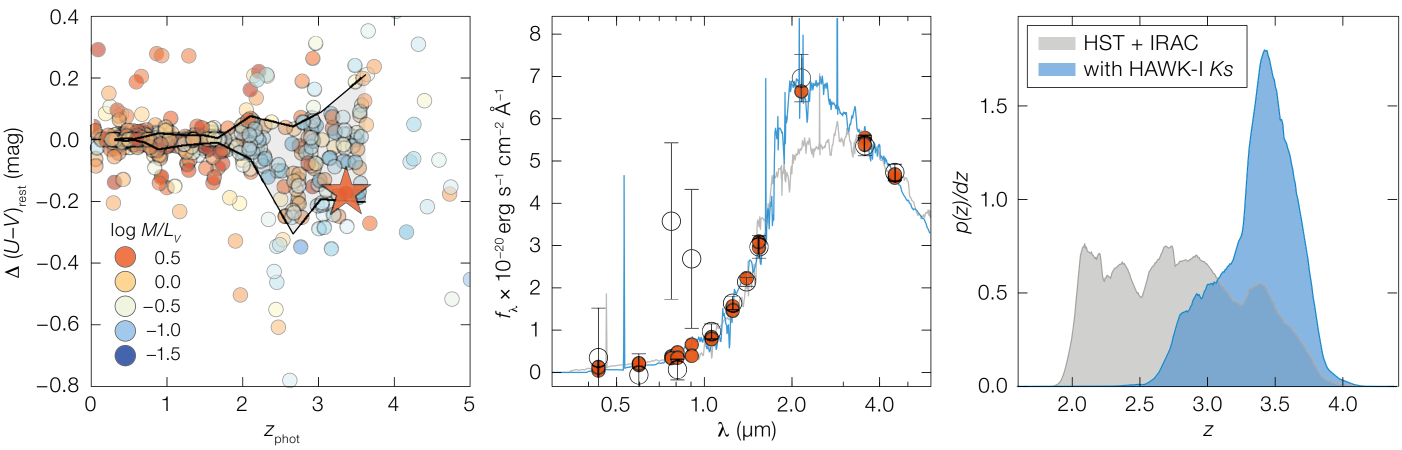

Figure 3. a) Difference in derived rest-frame *U–V* colours of Hubble Frontier Fields galaxies with and without including the *Ks*-band photometry. Points are colour-coded by their mass-to-light ratio. The selected galaxy whose SED is shown in (b) is indicated by a red star. b) Spectral energy distribution (SED) of the selected galaxy. The SED fits, with the *Ks*-band photometry excluded (grey line) and included (blue line), are shown. c) Photometric redshift probability distribution for the selected galaxy. The effect of including the HAWK-I *Ks*-band photometry alters the redshift distribution to that shown in blue (compared to the grey curve), now favouring an evolved stellar population at $z \sim 3.5$. From Brammer et al. (2016).

to-light ratios for photometric catalogues with and without the *Ks*-band photometry included. The left panel of Figure 3 shows the difference in the rest-frame *U–V* colours, which probes the strength of the Balmer/4000 Å break, and is a proxy for the age and mass-to-light ratio of the underlying stellar population. The scatter in the *U–V* colours with and without including the *Ks*-band information is low at $z < 2$, where the fit is constrained predominantly by the deep HST photometry. At $z > 2$, however, as the rest-frame *V*-band is redshifted beyond the near-infrared H_{160} filter, the scatter increases dramatically, reaching $\sigma > 0.1$ magnitudes at $z \sim 3$. This is much larger than the photometric uncertainties in the adjacent space-based photometric bands would suggest, as all of these galaxies with *H* mag. ~26 are detected in the deep WFC3 and IRAC images at >> 10σ.

The right two panels of Figure 3 show a single galaxy that illustrates how these systematic effects are not trivial and will likely result in biases in the interpretation of the galaxy population properties derived from the HST and IRAC observations alone. The spectral energy distribution (SED) shown rises steadily through the reddest WFC3/IR bands and then shows a sharp break with bright detections in the IRAC bands. The *Ks*-band measurement at 2.15 μm reduces the range of allowed photometric redshifts by a factor of two by pinpointing a strong Balmer break at z ~ 3.4. Even though the measured H_{160}–*Ks* colour is redder than that inferred from the HST + IRAC photometry alone, the final rest-frame *U–V* colour is actually bluer as a result of the higher preferred redshift. Evolved galaxies at $z > 3$, such as the one shown in Figure 3b, are an intriguing population deserving of detailed study in their own right, and the combined Frontier Fields Hubble + *Ks* + IRAC dataset is ideally suited to this purpose.

Public data release

Following the public release of the rich treasure trove of Hubble and Spitzer HFF data, we have made the final science and inverse variance mosaics of all six KIFF fields publicly available via the ESO Phase 3 data products interface[3]. For a complete presentation of the KIFF observations, analyses, and data products, see Brammer et al. (2016).

References

Bouwens, R. J. et al. 2013, ApJL, 765, L16
Brammer, G. B. et al. 2016, ApJS, in press, arXiv:1606.07450
Franx, M. et al. 2003, ApJL, 587, L79
Labbé, I. et al. 2005, ApJL, 624, L81
Lotz, J. M. et al. 2016, ApJ, submitted, arXiv:1605.06567
Fontana, A. et al. 2006, A&A, 459, 745
Fontana, A. et al. 2014, A&A, 570, A11
Fontana, A. et al. 2014b, The Messenger, 155, 42
Muzzin, A. et al. 2009, ApJ, 701, 1839
van Dokkum, P. G. et al. 2006, ApJL, 638, L59

Links

1 Frontier Fields web page at STScI: http://www.stsci.edu/hst/campaigns/frontier-fields/
2 KIFF news and updates: https://github.com/gbrammer/HAWKI-FF
3 KIFF Phase 3 data release: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=092.A-0472&release_tag=1

ESO & D. Coe (STScI)/J. Merten (Heidelberg/Bologna)

FORS1 image (6.7 × 6.7 arcminutes) of the merging galaxy cluster Abell 2744, one of the clusters selected for study in the Frontier Fields programme. This colour image is formed from *V*-, *R*- and *I*-band images; see Release eso1120 for more details.