XDF
Hubble's eXtreme Deep Field

What is XDF and what went into making this unique image from a decade of observations on the Hubble UltraDeep Field?

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The Making of the XDF from a decade of data on the HUDF

The XDF includes ALL data taken by Hubble on the small patch of sky first imaged as the Hubble Ultra-Deep Field (HUDF). These images were taken over a decade from mid-2002 through to early 2013. The XDF is an exposure of 2 million seconds total from Hubble's two premier cameras, the Advanced Camera (ACS) and the Wide Field Camera 3 (WFC3). It consists of 2963 separate exposures from the ACS and WFC3/IR. ACS flew on the Shuttle to Hubble in 2002 on servicing mission SM3B, while the Wide Field Camera 3 (WFC3) flew to Hubble in 2009 on the final Hubble Shuttle mission (SM4).

The original HUDF data demonstrated the power of Hubble's new ACS camera in 2004. The original HUDF contributes, by time, a little more that half to the XDF, but only contains data in the optical ("visible") region of the spectrum. In 2009 and 2010, the HUDF09 project took images towards the red end of the spectrum in the near-infrared with the new WFC3/IR camera. These new data doubled the waveband coverage and enabled exploration of a new realm of the most distant galaxies for the first time. The HUDF09 field with WFC3/IR and ACS contributed around 20% of the data by time to XDF. A subsequent study HUDF12 added more WFC3/IR data that enhanced the overall dataset by about another 10% by time, though both the HUDF09 and HUDF12 images contributed unique IR data that is essential for finding the earliest galaxies. The HUDF and HUDF09/12 fields are shown in the first and second panels of the "Hubble Dataset Used to Build Up the XDF" figure on page 4.

The XDF/HUDF09 team then took ALL the other data on this region taken by numerous programs (page 6) and combined it through a very laborious and careful series of steps into one incredibly deep image, the eXtreme Deep Field (XDF). These data fall at many locations and orientations and much careful checking was needed to make sure all the Hubble ACS and WFC3 images could be properly aligned and added together. The contributions from these other programs comprised nearly a quarter of the time, of which the largest was the CANDELS images from ACS and WFC3. The numerous images are shown in third panel of the "Hubble Dataset Used to Build Up the XDF" figure.

The XDF was then assembled using data from every image over the last decade from ACS and the WFC3 (the orange region in the fourth panel of the "Hubble Dataset Used to Build Up the XDF" figure). XDF reaches back around 13.2 billion years, to just 450 million years after the Big Bang. The history of galaxies — from soon after the first galaxies were born to the appearance of the great galaxies of today, like our Milky Way — is laid out in this one remarkable image.

The XDF combined image goes incredibly faint. The combined image XDF reaches to approximately one ten-billionth of what the eye can see. In astronomer-speak, XDF reaches to a 5 sigma limit is 31.2 AB mag (the limit for a 5 sigma detection of a point source, like a star, corrected to total magnitude, is ~30.7 AB magnitude). This is equivalent to a 1 sigma noise fluctuation of 32.9 AB mag, as measured directly in a 0.33" aperture.

The XDF is such an important field that it will be imaged in the future and more data will be added, but future gains will be slow until JWST is launched.. The first deep data in the ultra-violet from WFC3/UVIS has already been obtained. The ultra-violet imaging complements the redder optical/IR XDF and is being used by astronomers to study galaxies at later times when they are in transition to galaxies like today's galaxies (including our Milky Way and Andromeda). The ultraviolet data has not been included since the UV data is relatively noisy and also cannot reveal galaxies in the first 2 billion years due to the absorbing effects of hydrogen in the universe.

The details of how the XDF was generated from the decade-long source data from the HUDF region can be found in the paper that was written about the XDF ("The HST eXtreme Deep Field (XDF): Combining All ACS and WFC3/IR Data on the HUDF Region into the Deepest Field Ever", Illingworth, G. D.; Magee, D.; Oesch, P. A.; Bouwens, R. J.; Labbé, I.; Stiavelli, M.; van Dokkum, P. G.; Franx, M.; Trenti, M.; Carollo, C. M.; Gonzalez, V., 2013, ApJS, 209, 6). The paper was published in ApJS in 2013 and can be found at: http://adsabs.harvard.edu/abs/2013ApJS..209....6I More information can also be found at: http://xdf.ucolick.org/xdf.html

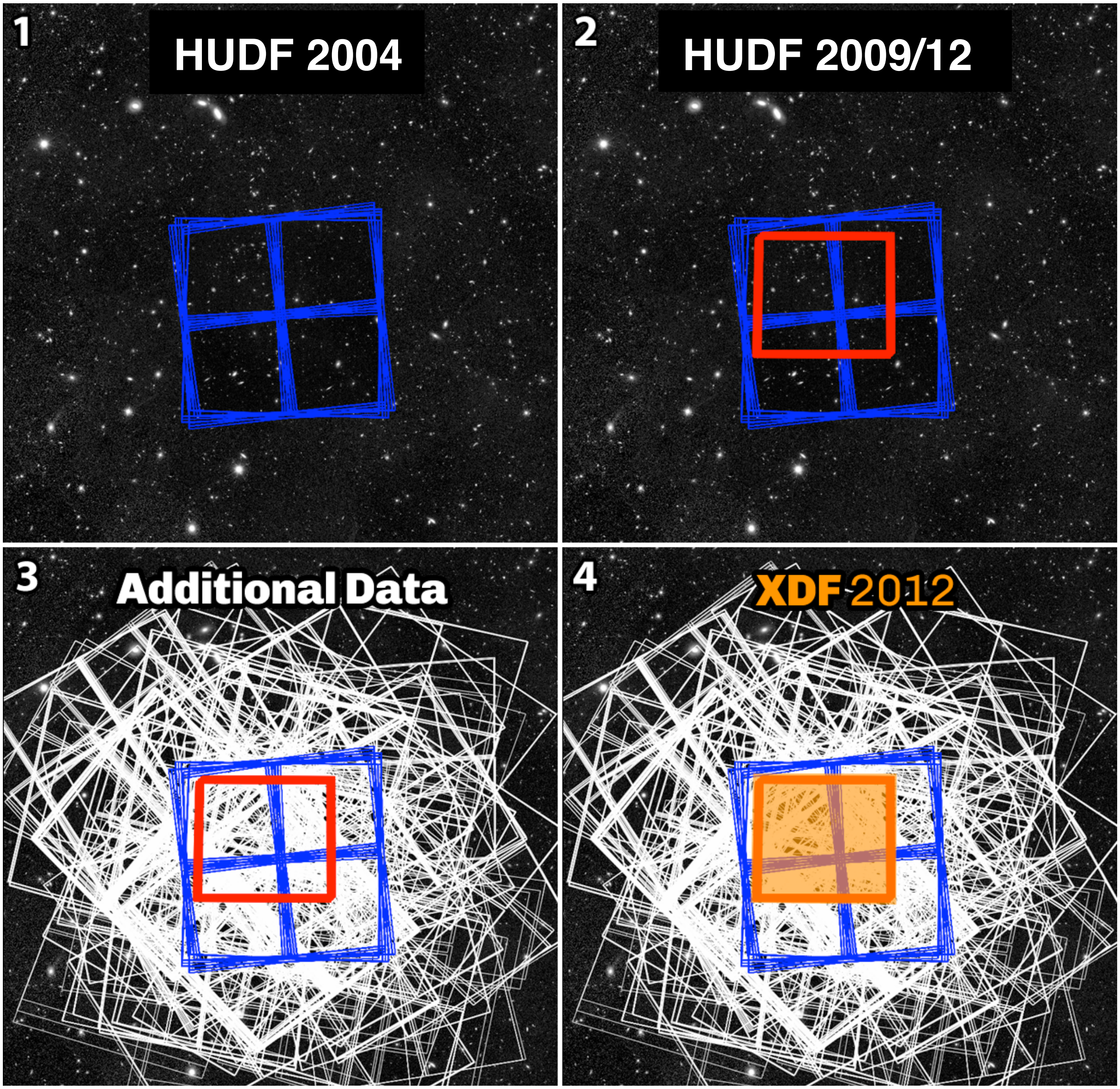
XDF Summary

Position (J2000)	**R.A. $03^h\,32^m\,38^s.5$; Decl. $-27°\,47'\,00''$**
Area of XDF	**4.7 arcmin^2**
Instruments	**ACS/WFC and WFC3/IR**
Exposure Dates	**2002 July to 2012 December[a]**
Total Exposure Time	**~2 million seconds taken over ~50 days**
Number of Exposures	**2963 (1972 ACS/WFC; 991 WFC3/IR)**
Number of Galaxies in XDF	**7120**
Typical depths	**~30 AB mag (5σ) in most filters**
Combined depth	**31.2 AB mag (5σ) for a flat f_ν source**
Archive Link	**http://archive.stsci.edu/prepds/xdf/**

Notes: Depths are for 5σ detections measured in circular apertures of 0. 35” diameter (not corrected to total magnitudes).

[a] Date when last HUDF12 exposure became publicly available on the *HST* archive.

Hubble Dataset Used to Build Up the XDF



The Story Behind the XDF

XDF resulted from the realization in late 2011 that all the data taken over the last ten years with the Advanced Camera and the Wide Field Camera 3 on the Hubble UltraDeep Field had not been combined into a single extremely deep image.

In discussions in late 2011 with an influential congressman, while doing the JWST Congressional hearing, Garth Illingworth realized that the HUDF images and posters found in many congressional offices, and used as educational materials across the country, were those from 2004. Our HUDF "deepest image" was out of date, even though it still looked good. A large number of new images had been taken since 2004. Hubble (and JWST) really needed a new "deepest" image for digital displays and a new poster to adorn walls all around the country.

The Hubble UltraDeep Field (HUDF) was observed in 2003 with the then-new Hubble Advanced Camera (ACS) that had been placed into Hubble in 2002 by the Shuttle astronauts during the servicing mission SM3B. The ACS HUDF was released as a public image in 2004. The new infrared Wide Field Camera 3 (WFC3) was added to Hubble in 2009 by the Shuttle astronauts in the final Hubble servicing mission (SM4). The HUDF was observed as part of the HUDF09 program in 2009 as one of the first set of images taken by the new infrared camera of WFC3 (WFC3/IR). These first observations were released as the HUDF09 image in early 2010. The HUDF09 observations were finally finished in winter 2011.

The HUDF and HUDF09 have been released individually, but a combined image of ALL the images ever taken on the Hubble UltraDeep Field had not been done. Over the last decade fifteen different programs had taken data in this region, dominated by the original HUDF, the HUDF09, the CANDELS, supernova search programs, and a variety of others (with the the HUDF12 program in fall 2012).

After discussions with members of the HUDF09 team we decided to collect and process all the data for an "everything on the HUDF" image. An initial discussion with Space Telescope Science Institute (STScI) confirmed for us that this was an idea worth pursuing. We started the assembly of all the images in early winter 2012.

The images came from different cameras with different orientations and different amounts of overlap. Since very large numbers of individual images were involved, the processing and cross-checking involved a lot of effort and time. Refining the software and testing procedures, and assembling, checking and testing the co-added images, was a lengthy and time consuming task involving the XDF core team (Dan Magee, Pascal Oesch, Rychard Bouwens and Garth Illingworth) that continued through the spring of 2012.

The image was finally ready in its first version by early summer 2012. Detailed communications with STScI regarding an image release ensued. Plans were developed for a number of products, in addition to the color image of the XDF. The products included a fly-through of the galaxies, explanatory images and text, and educational posters. The image was named the eXtreme Deep Field (XDF) from a name developed and used earlier by the HUDF09 team in a proposal. Given that the combined image involved 10 years of data from numerous programs, and that it represented a stunning achievement of Hubble -- the "deepest image of the sky ever taken" -- the updated XDF name seemed most appropriate.

Given the length of time needed to develop all the release products, the schedule of summer vacations by key people and the focused media attention on the Mars Curiosity Rover landing in August 2012, the release was tentatively scheduled for September 2012. The final date chosen to fit with development of the data products and other NASA press releases was September 25, 2012. Following the media briefing the XDF team continued to work on incorporating the latest datasets as well (the HUDF12) and eventually completed the processing of 2963 exposures totaling about 2 million secs of data taken over about 50 days of wall-clock time. The final images were extensively tested and checked as discussed in the XDF paper.

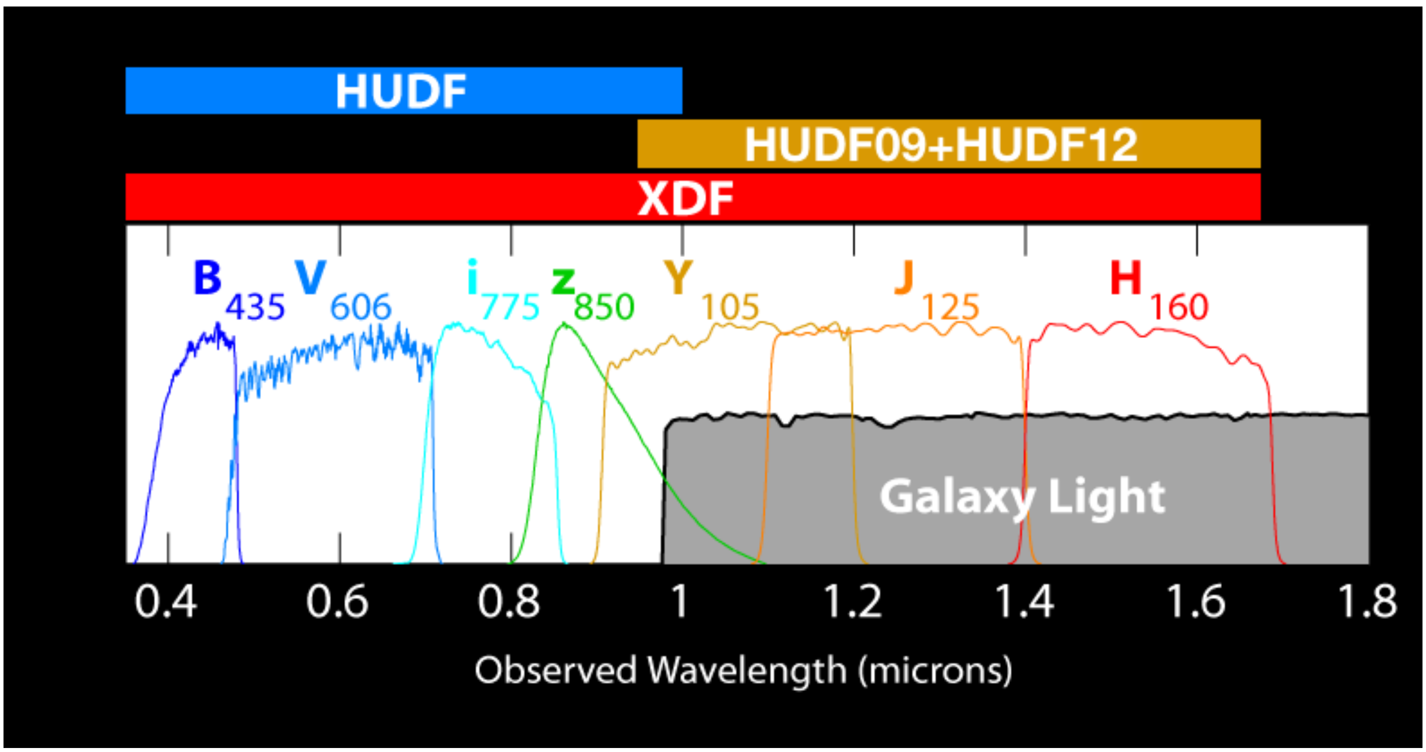
Following testing the XDF images were released to MAST in early 2013 at: http://archive.stsci.edu/prepds/xdf/
This release incorporated the 2963 exposure from the original HUDF through the HUDF12. A paper was also prepared and submitted to ApJ. This paper was published in ApJS in 2013 and can be found at: http://adsabs.harvard.edu/abs/2013ApJS..209....6I

Hubble Programs Contributing to the XDF

9352	11	The Deceleration Test from Treasury Type Ia Supernovae at Redshifts 1.2 to 1.6
9425	11	The Great Observatories Origins Deep Survey: Imaging with ACS (GOODS)
9488	11	Cosmic Shear - with ACS Pure Parallel Observations
9575	11	ACS Default (Archival) Pure Parallel Program
9793	12	The Grism-ACS Program for Extragalactic Science (GRAPES)
9978	12	The Ultra Deep Field with ACS (HUDF)
10086	12	The Ultra Deep Field with ACS (HUDF)
10189	13	Probing Acceleration Now with Supernovae (PANS)
10258	13	Tracing the Emergence of the Hubble Sequence Among the Most Luminous and Massive Galaxies
10340	13	Probing Acceleration Now with Supernovae (PANS)
10530	14	Probing Evolution And Reionization Spectroscopically (PEARS)
11359	17	Panchromatic WFC3 survey of galaxies at intermediate z: Early Release Science program for Wide Field Camera 3 (ERS)
11563	17	Galaxies at z~7-10 in the Reionization Epoch: Luminosity Functions to <0.2L* from Deep IR Imaging of the HUDF and HUDF05 Fields (HUDF09)
12060	18	Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey -- GOODS-South Field, Non-SNe-Searched Visits (CANDELS)
12061	18	Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey -- GOODS-South Field, Early Visits of SNe Search (CANDELS)
12062	18	Galaxy Assembly and the Evolution of Structure over the First Third of Cosmic Time - III (CANDELS)
12099	18	Supernova Follow-up for MCT (CANDELS)
12177	18	3D-HST: A Spectroscopic Galaxy Evolution Treasury (3DHST)
12498	19	Did Galaxies Reionize the Universe? (HUDF12)

XDF Compared to HUDF and HUDF09/12

XDF takes ALL the data that has been taken on the HUDF field between 2002 and 2012 - this means HUDF, HUDF09, CANDELS, HUDF12 and many other programs. No other release has done this. This makes the deepest image from Hubble ever, with the widest spectral coverage image from Hubble on the HUDF. In total, 2963 exposures totaling 2 million secs make up the XDF. XDF contains over 7000 galaxies. An example galaxy spectrum is shown. This example is a galaxy that is essentially invisible to the Advanced Camera for Surveys. It is so distant that its light has been shifted to the red so far by the expansion of the universe that it is only seen in the infrared with the Wide Field Camera 3 (in HUDF09 and HUDF12). This example galaxy is seen about 12.8 billion years ago, just 800 million years after the Big Bang.

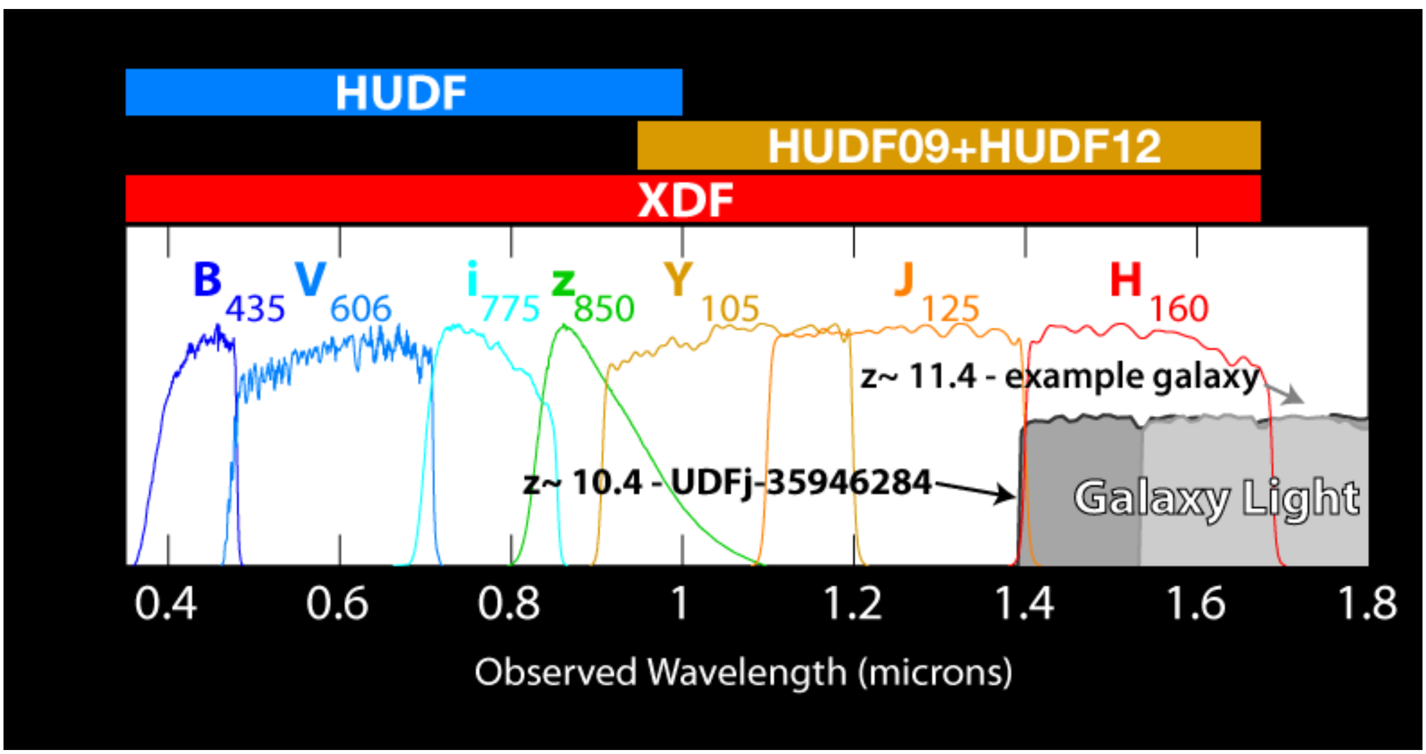


What is Hubble's Distance Limit?

As galaxies get more distant their light is "redshifted" by the expansion of the universe. Ultimately the galaxy light moves so far to the red that it becomes invisible to Hubble's cameras. This effect is shown here. The most distant galaxy found in the HUDF09 image, UDFj-39546284, was thought to be at "redshift" 10.4 (represented by "z" as in z~10.4), about 500 million years after the Big Bang. The light from UDFj-39546284 appears just in the reddest filter H_{160} of the WFC3/IR camera on Hubble, as shown in the figure below. The later data from the HUDF12 images showed that UDFj-39546284 was an enigmatic object and even more interesting than first thought. UDFj-39546284 was not at z~10.4, but could only be at z~12 or at z~2. This still remains unresolved.

The ability of Hubble to see even more distant galaxies gets quickly worse. By "redshift" 11.4, just 400 million years after the Big Bang, or about 13.3 billion years ago, the light from a galaxy is only partially visible to Hubble in the reddest filter (a hypothetical example galaxy at 11.4 is shown in the figure). Even though a z~11.4 galaxy is just 80 million years closer to the Big Bang than one at z~10, it is a great deal fainter and a lot harder for Hubble to see. Since galaxies are getting rapidly fainter at earlier times, "redshift" z~11 or so is around the practical limit for Hubble. This becomes JWST territory.

Galaxies closer to the Big Bang than about redshift 11.5-12, or about 370-400 million years from the Big Bang, cannot be seen by Hubble. James Webb Space Telescope is required to see the "first galaxies". And only the very brightest galaxies around 400-500 Myr after the Big Bang can be seen with Hubble. To see how galaxies of all sizes grow in the first 500 Myr of the Universe falls into the realm of JWST — our future "first galaxies" telescope. The infrared images from the HUDF09 and HUDF12 programs are essential for searching for galaxies at these early times.



XDF Image Release Description
(09/25/12 Press Release)

Like photographers assembling a portfolio of best shots, astronomers have assembled a new, improved portrait of mankind's deepest-ever view of the universe. Called the eXtreme Deep Field, or XDF, the photo was assembled by combining 10 years of NASA Hubble Space Telescope photographs taken of a patch of sky at the center of the original Hubble Ultra Deep Field. The XDF is a small fraction of the angular diameter of the full Moon.

The Hubble Ultra Deep Field is an image of a small area of space in the constellation Fornax, created using Hubble Space Telescope data from 2003 and 2004. By collecting faint light over many hours of observation, it revealed thousands of galaxies, both nearby and very distant, making it the deepest image of the universe ever taken at that time.

The new full-color XDF image reaches much fainter galaxies, and includes very deep exposures in red light from Hubble's new infrared camera, enabling new studies of the earliest galaxies in the universe. The XDF contains about 5,500 galaxies even within its smaller field of view. The faintest galaxies are one ten-billionth the brightness of what the human eye can see.

Magnificent spiral galaxies similar in shape to our Milky Way and the neighboring Andromeda galaxy appear in this image, as do the large, fuzzy red galaxies where the formation of new stars has ceased. These red galaxies are the remnants of dramatic collisions between galaxies and are in their declining years. Peppered across the field are tiny, faint, more distant galaxies that were like the seedlings from which today's striking galaxies grew. The history of galaxies — from soon after the first galaxies were born to the great galaxies of today, like our Milky Way — is laid out in this one remarkable image.

Hubble pointed at a tiny patch of southern sky in repeat visits (made over the past decade) for a total of 50 days, with a total exposure time of 2 million seconds. More than 2,000 images of the same field were taken with Hubble's two premier cameras — the Advanced Camera for Surveys and the Wide Field Camera 3, which extends Hubble's vision into near-infrared light — and combined to make the XDF.

"The XDF is the deepest image of the sky ever obtained and reveals the faintest and most distant galaxies ever seen. XDF allows us to explore further back in time than ever before," said Garth Illingworth of the University of California at Santa Cruz, principal investigator of the Hubble Ultra Deep Field 2009 (HUDF09) program.

The universe is 13.7 billion years old, and the XDF reveals galaxies that span back 13.2 billion years in time. Most of the galaxies in the XDF are seen when they were young, small, and growing, often violently as they collided and merged together. The early universe was a time of dramatic birth for galaxies containing brilliant blue stars extraordinarily brighter than our Sun. The light from those past events is just arriving at Earth now, and so the XDF is a "time tunnel into the distant past." The youngest galaxy found in the XDF existed just 450 million years after the universe's birth in the big bang.

Before Hubble was launched in 1990, astronomers could barely see normal galaxies to 7 billion light-years away, about halfway across the universe. Observations with telescopes on the ground were not able to establish how galaxies formed and evolved in the early universe.

Hubble gave astronomers their first view of the actual forms and shapes of galaxies when they were young. This provided compelling, direct visual evidence that the universe is truly changing as it ages. Like watching individual frames of a motion picture, the Hubble deep surveys reveal the emergence of structure in the infant universe and the subsequent dynamic stages of galaxy evolution.

The infrared vision of NASA's planned James Webb Space Telescope (Webb telescope) will be aimed at the XDF. The Webb telescope will find even fainter galaxies that existed when the universe was just a few hundred million years old. Because of the expansion of the universe, light from the distant past is stretched into longer, infrared wavelengths. The Webb telescope's infrared vision is ideally suited to push the XDF even deeper, into a time when the first stars and galaxies formed and filled the early "dark ages" of the universe with light.

The XDF/HUDF09 team members are G. Illingworth (University of California, Santa Cruz), R. Bouwens (Leiden University), M. Carollo (Swiss Federal Institute of Technology, Zurich (ETH)), M. Franx (Leiden University), V. Gonzalez (University of California, Santa Cruz), I. Labbe (Leiden University), D. Magee and P. Oesch (University of California, Santa Cruz), M. Stiavelli (Space Telescope Science Institute), M. Trenti (University of Cambridge), and P. van Dokkum (Yale University).

Source: HubbleSite