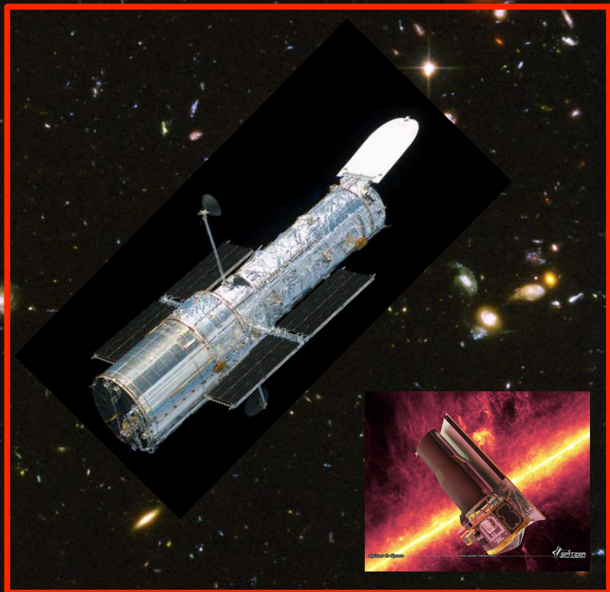


2012 Santa Cruz Galaxy Workshop
August 13, 2012

exploring the first billion years: galaxy buildup at early times

HUDF09

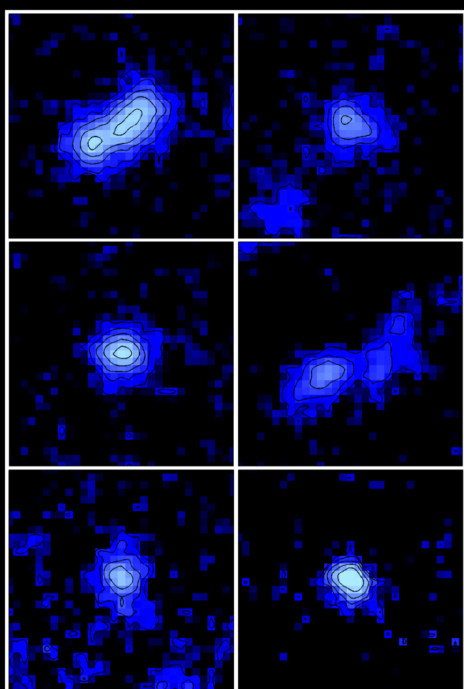
Garth Illingworth

(UCO & University of California, Santa Cruz)

special thanks to Rychard Bouwens, Pascal Oesch, Dan Magee

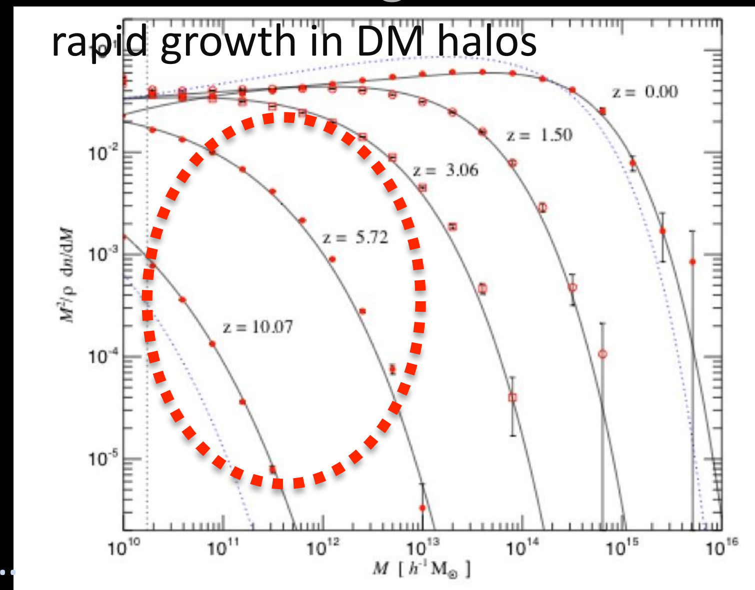
and the other HUDF09 team members: Marcella Carollo, Marijn Franx, Valentino Gonzalez, Ivo Labbe, Massimo Stiavelli, Michele Trenti, Pieter van Dokkum

motivation



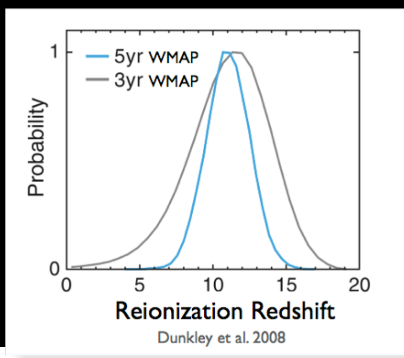
what are the key issues?
why is this first 1-2 billion year period interesting?

unique phase in the evolution of galaxies and of the universe...

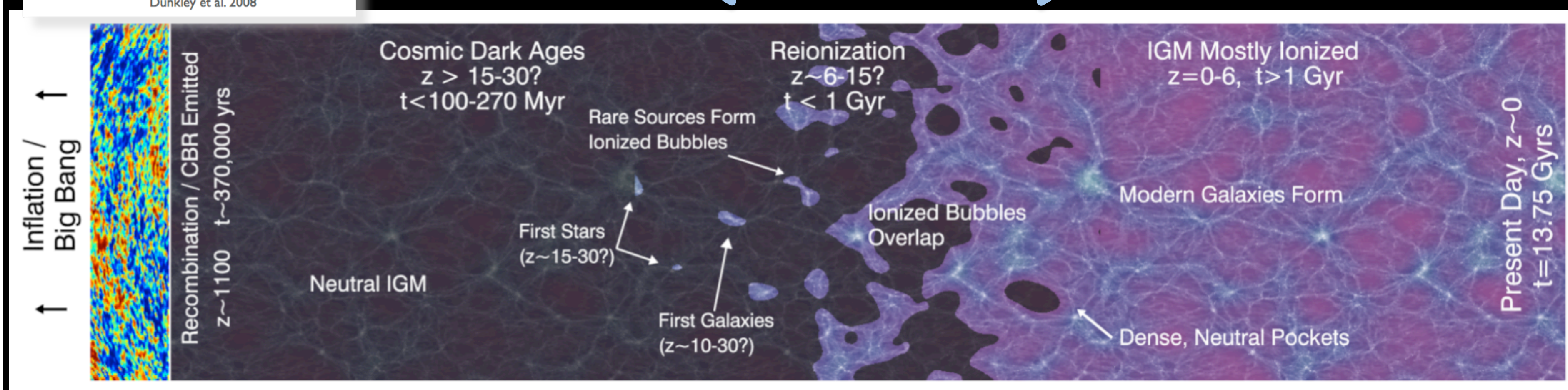


when the dark matter halos of massive (L*) galaxies first form...

when significant metals first form...

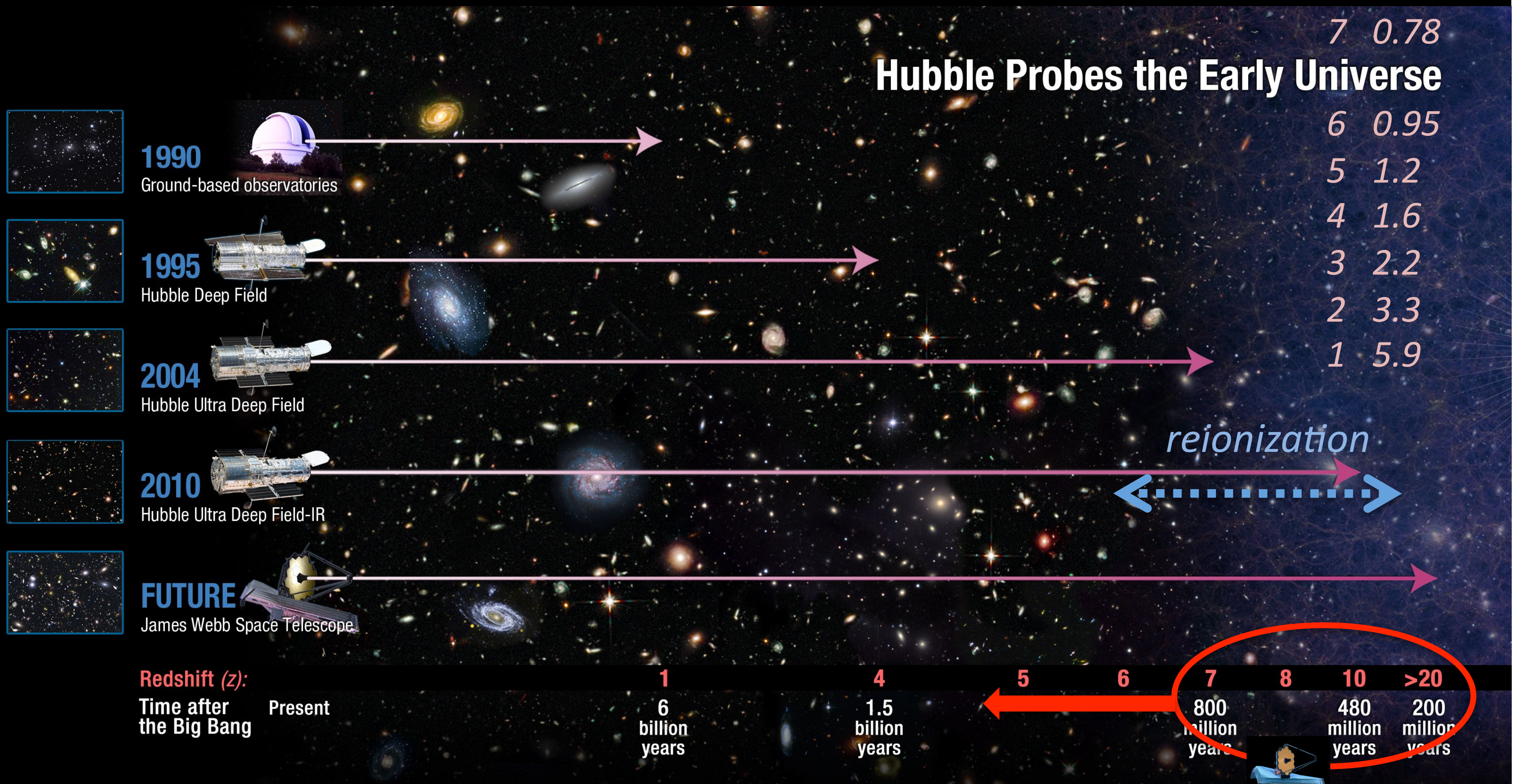


when the universe was reionized...



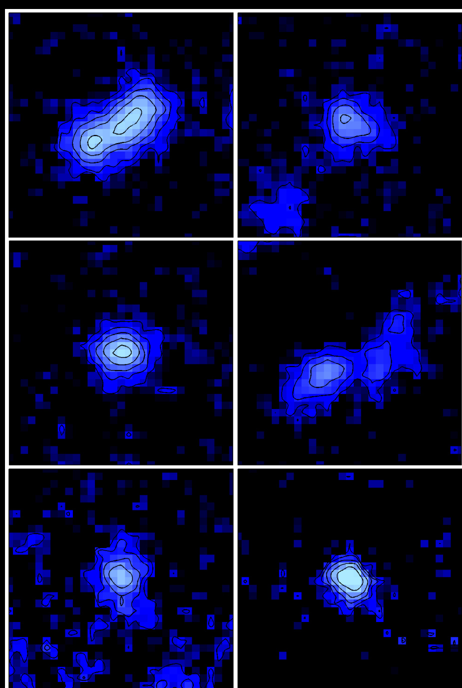
redshift limit vs year

z	t (Gyr)
20	0.18
15	0.27
10	0.48
8	0.65
7	0.78
6	0.95
5	1.2
4	1.6
3	2.2
2	3.3
1	5.9



the universe is 13.67 Gyr young

how did we get to where we are today?



the first billion years of galaxies: brought to you by some remarkable observatories

HST and Spitzer

while other facilities and advances in modeling have played key roles, these two telescopes are the central players

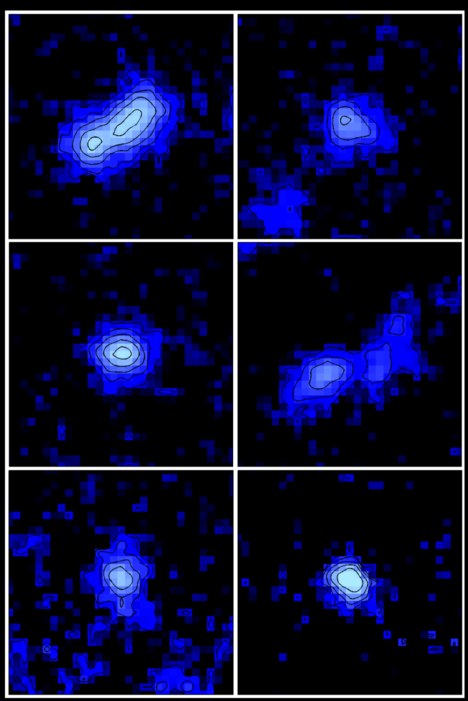
their data have revolutionized our understanding of galaxy buildup in the first 1-2 Gyr

and so they should have!

Hubble: 2.4m for $12B+ lifecycle cost (in current $; no launch costs) – 30 yrs from original idea to launch

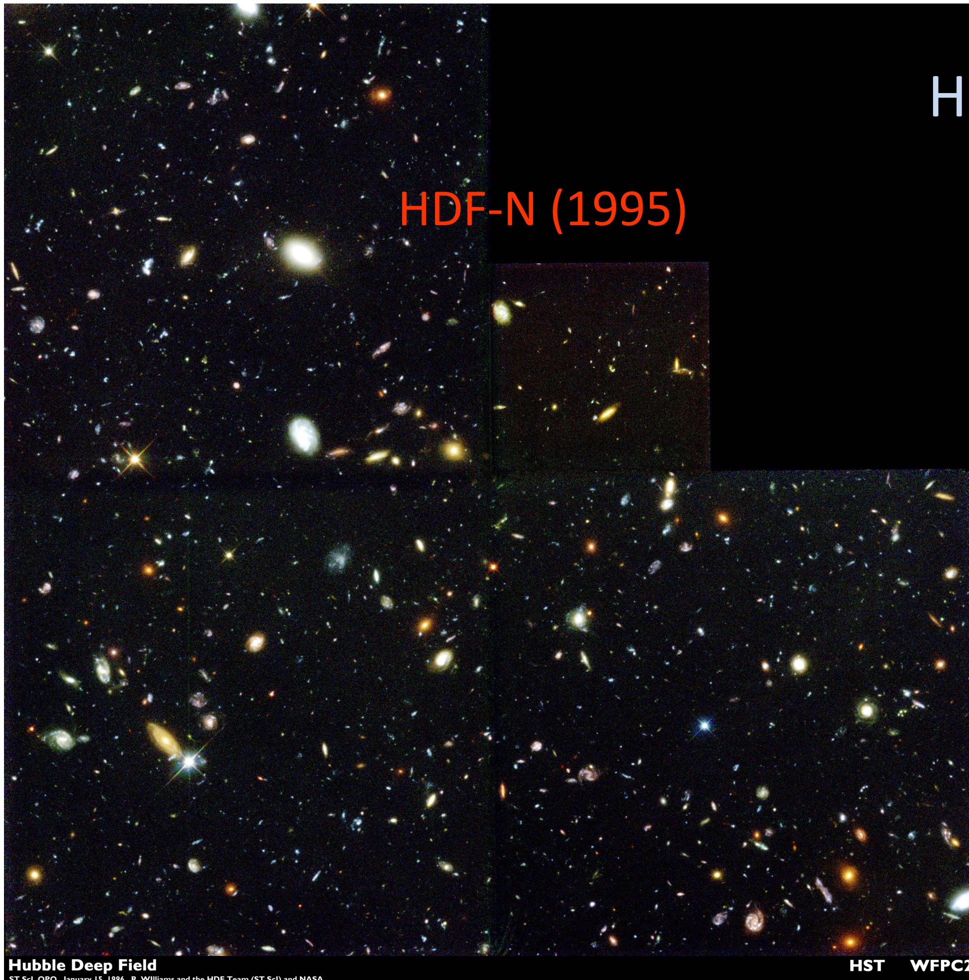
SIRTF/Spitzer: 85 cm $2B cryogenic telescope! >25 yrs from original idea to launch

z~0.5-1 galaxies were
"high redshift" before Hubble and the HDFs



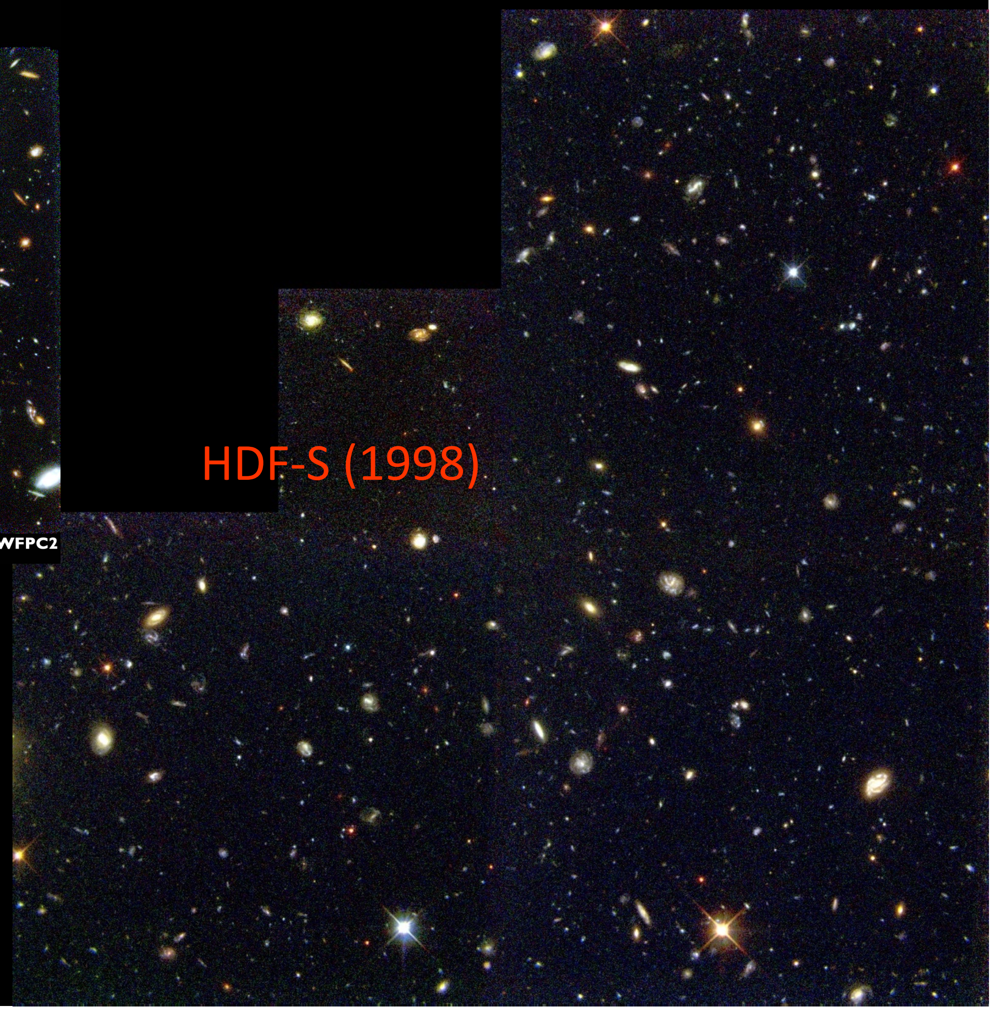
Hubble Deep Fields

HDF-N (1995)



these public datasets revolutionized studies of distant galaxies

HDF-S (1998)



- HST WFPC2 images in four colors
- images with high spatial resolution
- images with high photometric accuracy

- *photometric redshifts from colors*

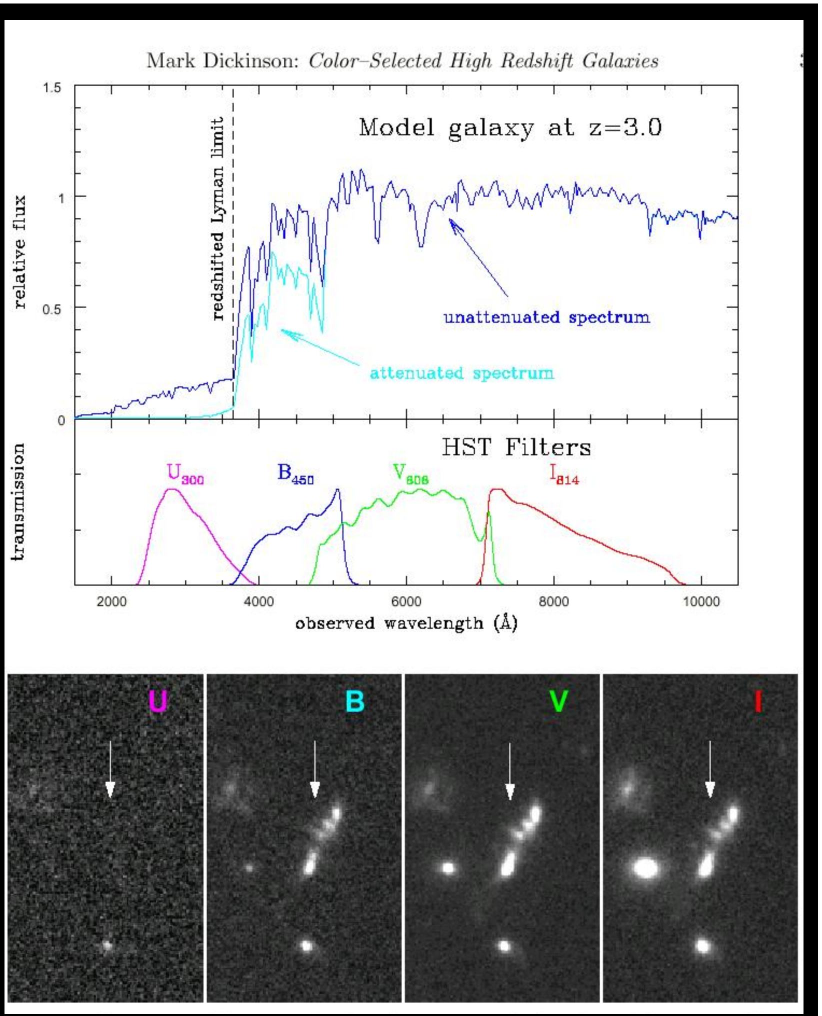
finding high-redshift galaxies

"Lyman Break" – strong signal from the break at the Lyman limit and at Lyα

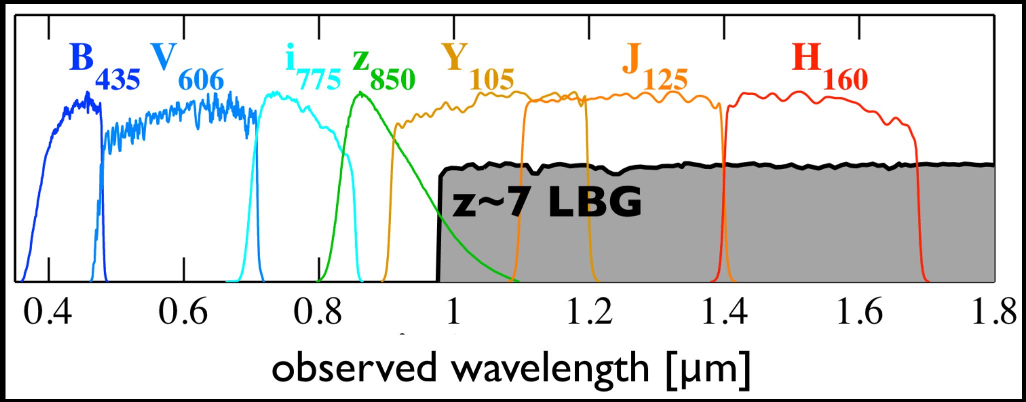
"contamination" is a key problem

we use data below the Lyman break with a χ^2_{opt} weighting to eliminate contamination.

deeper images below the break are *crucial – it is pointless having deep images redward of the break and shallower images blueward of the break*

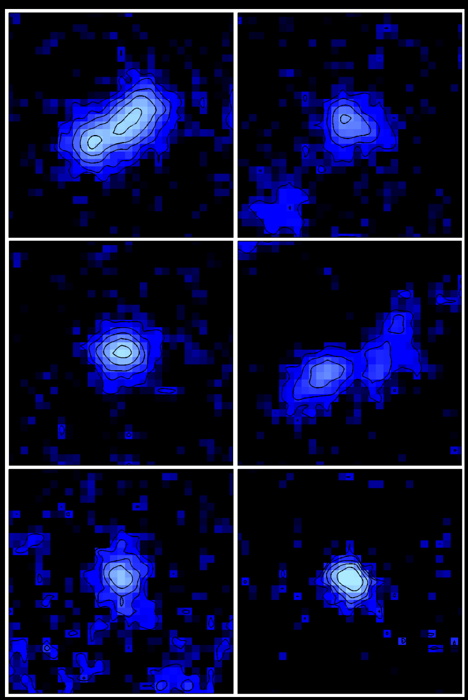


z~3



z~7

first z~8 galaxies from WFC3/IR in 2009

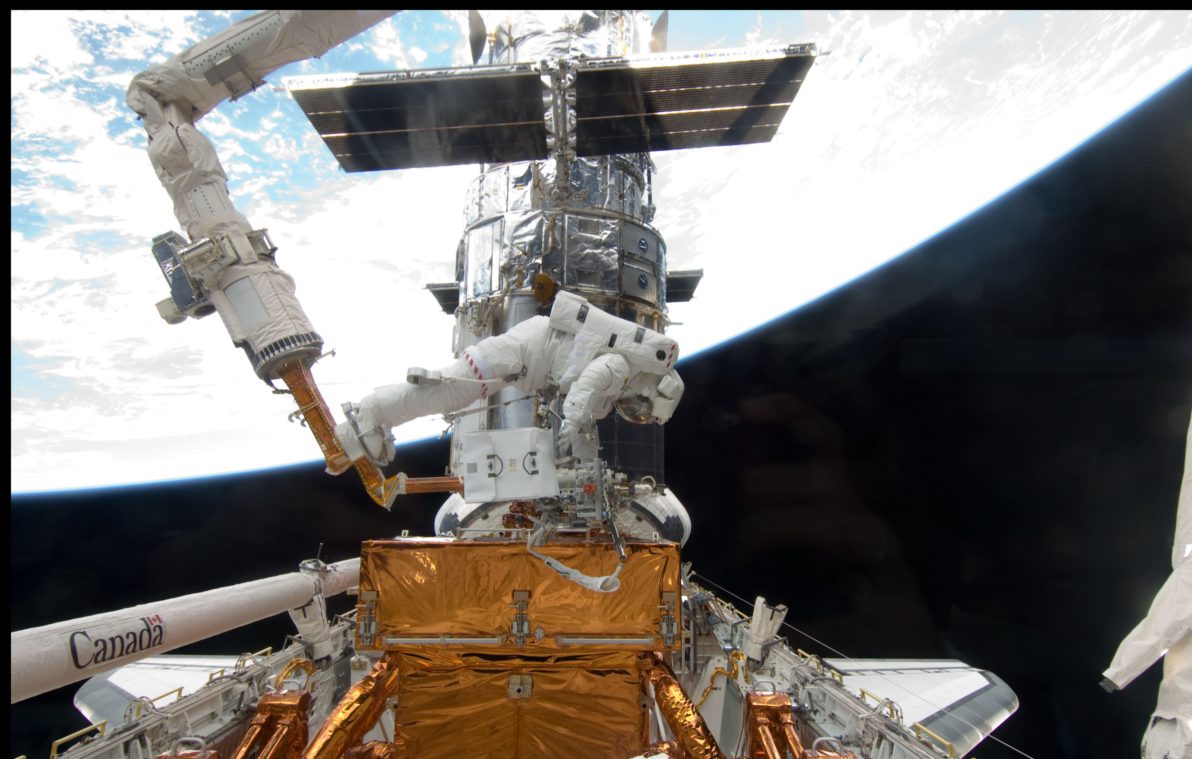


HST SM4 => WFC3/IR and COS

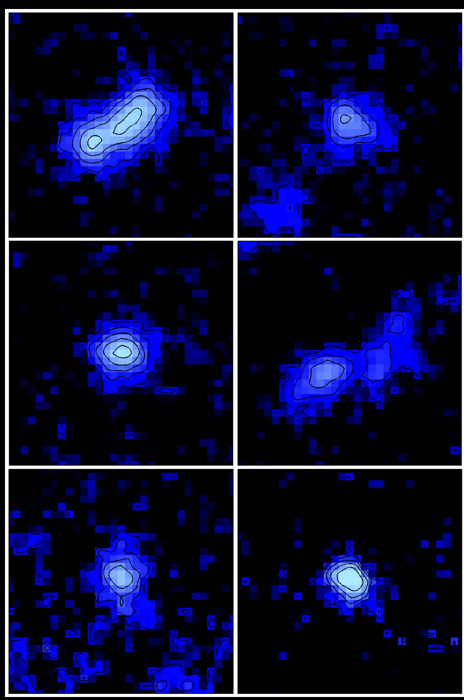
SM4 launch on Atlantis – 2009

>$100M instruments in a
>$1.5B servicing mission
(plus shuttle launch costs)

The new WFC3/IR and
WFC3/UVIS have opened
up new vistas for distant
galaxy studies. Along with
rejuvenated ACS and STIS…



130 z~7 and z~8 galaxies (and z~10) from WFC3/IR by 2010



new capabilities can produce amazing gains

WFC3/IR *vs* NICMOS

a z~7 galaxy took ~100 orbits with NICMOS
– with WFC3/IR it takes a few orbits

WFC3/IR has a "discovery efficiency" ~40X NICMOS

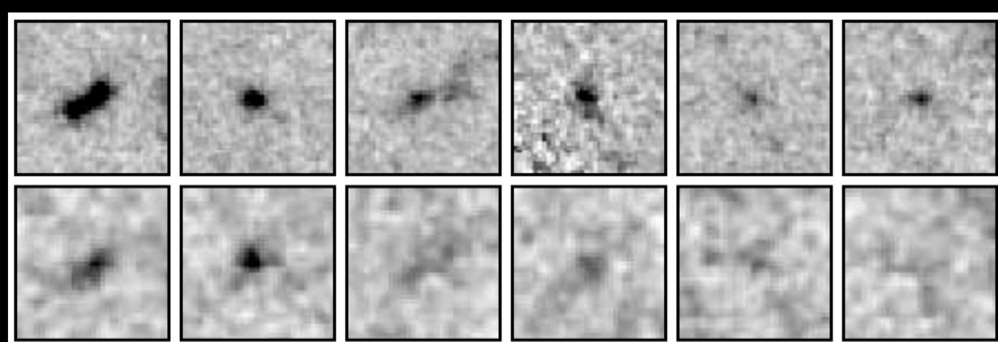
Finding z>6.5 galaxies

NICMOS: 12 galaxies in 10 yrs

WFC3/IR: 20 galaxies in first 2 weeks

WFC3/IR: >100 galaxies in 2 years

comparing the old and new Hubble infrared cameras



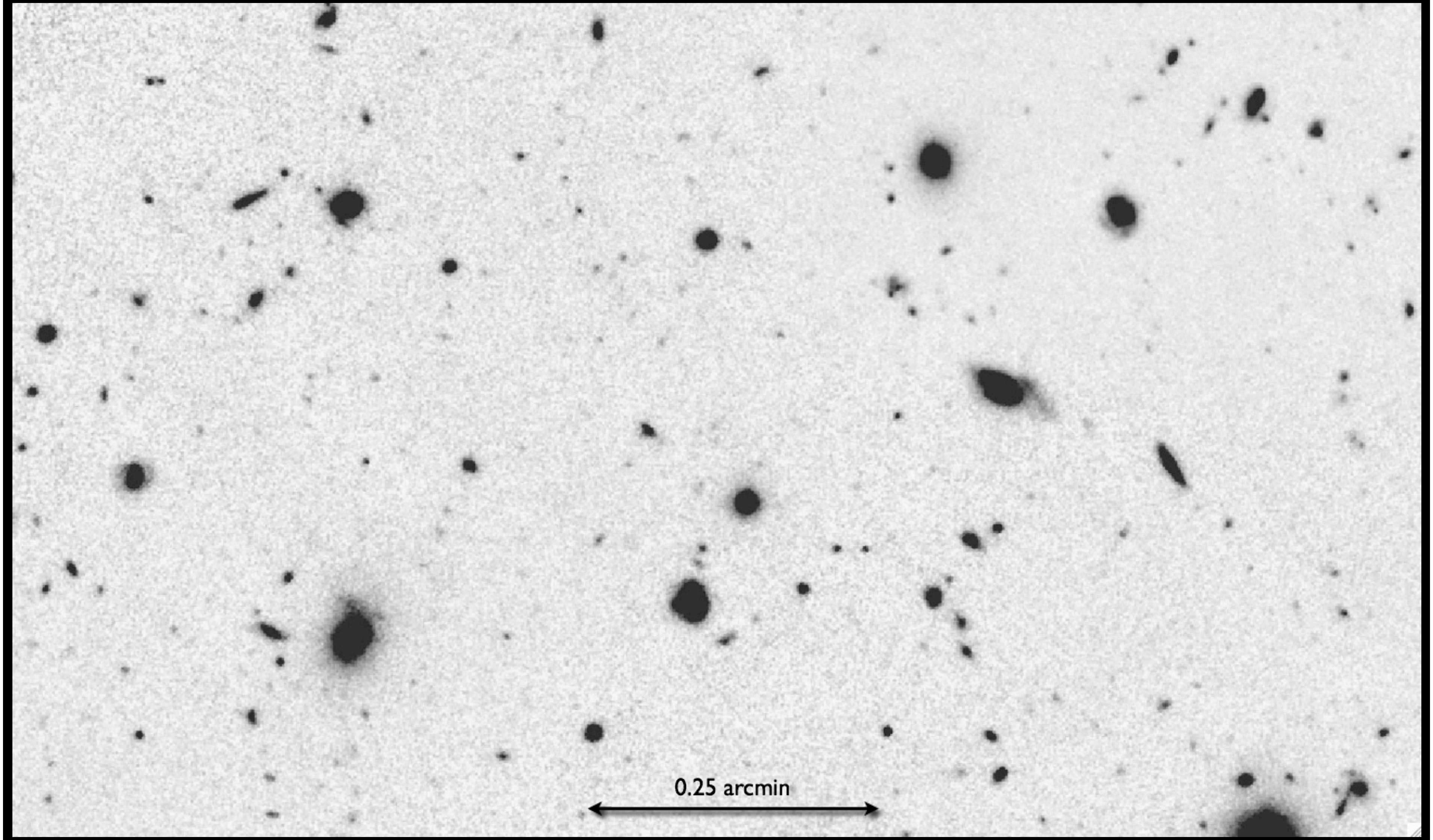
WFC3/IR

NICMOS

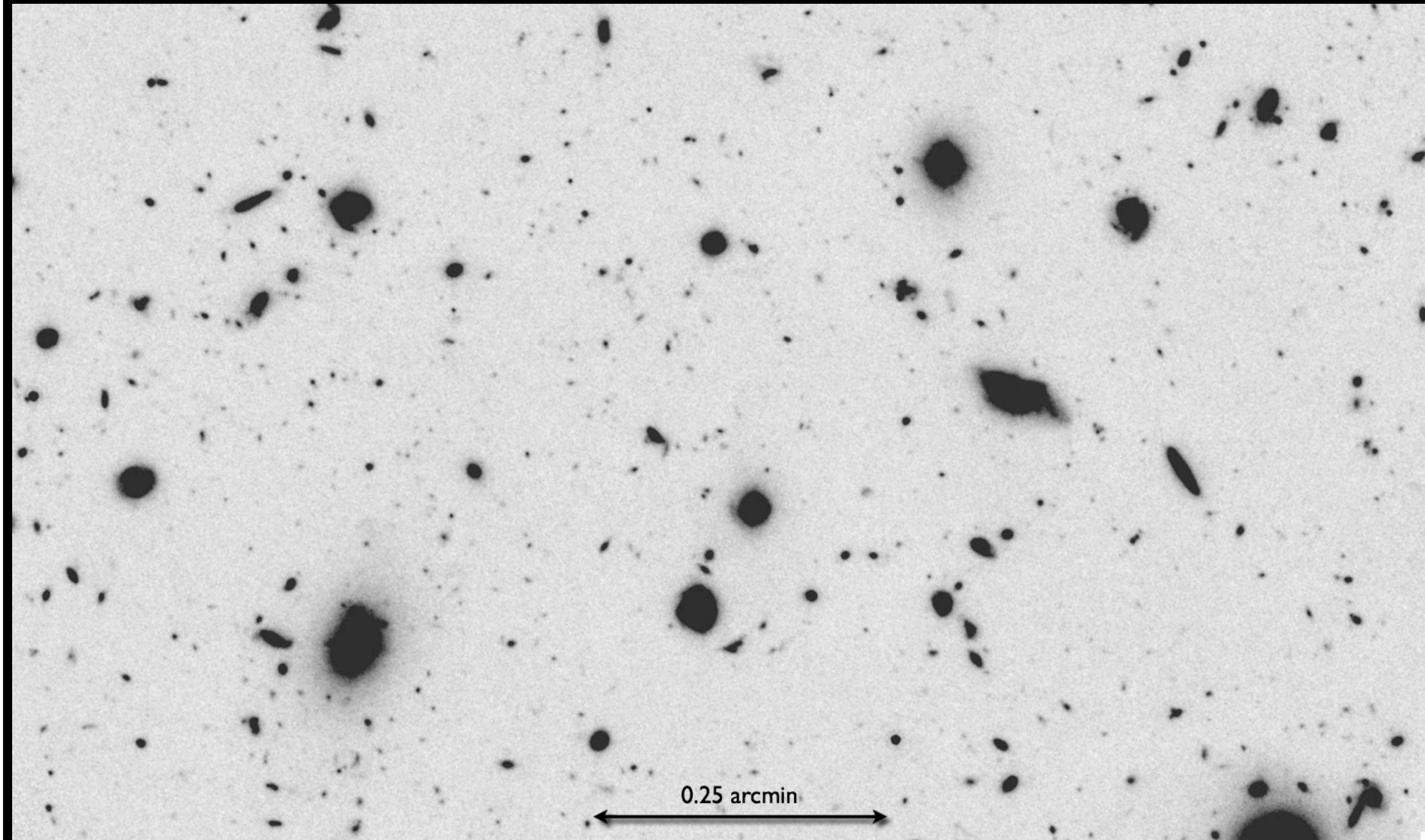
Oesch et al 2010

z~7 galaxies 2.2" x 2.2"

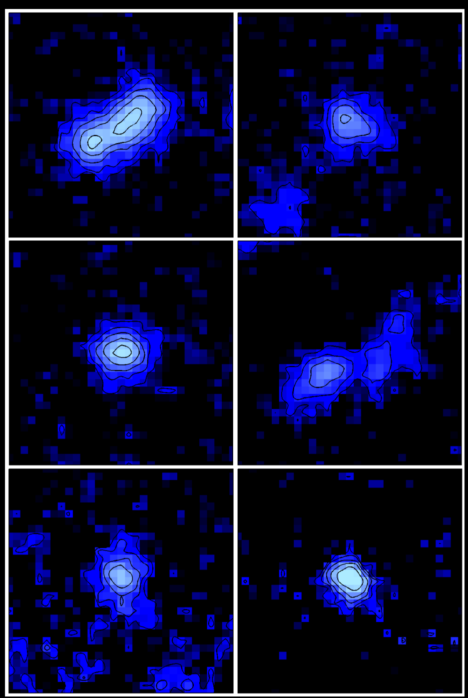
NICMOS HUDF – 72 orbits



WFC3/IR HUDF09 – 34 orbits

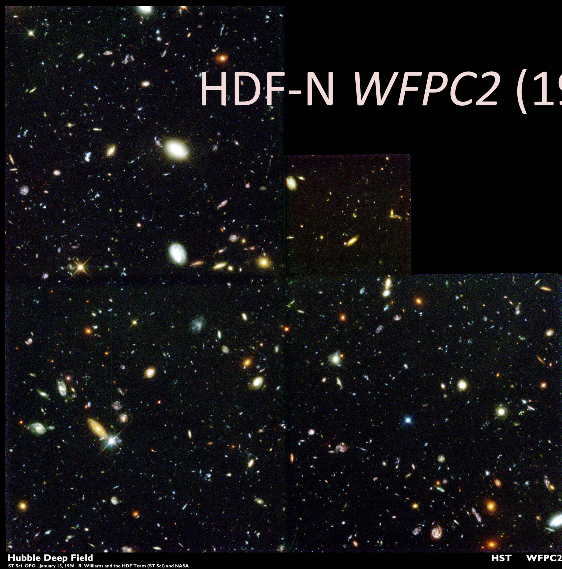


the value of multi-wavelength public datasets with zero proprietary period!



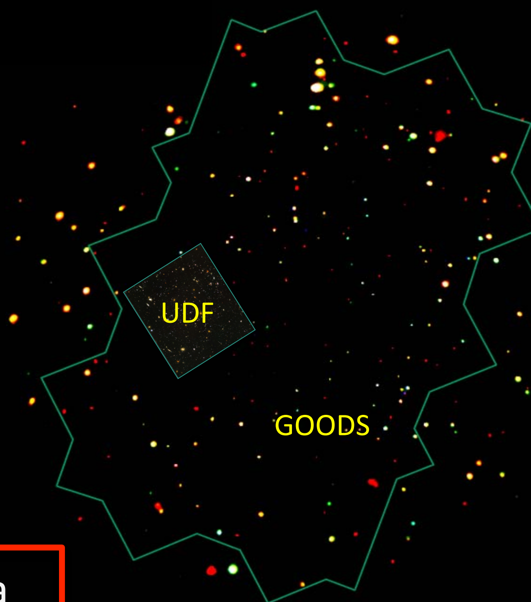
Hubble's remarkable track record in opening up the distant universe with public datasets

HDF-N *WFPC2* (1995)



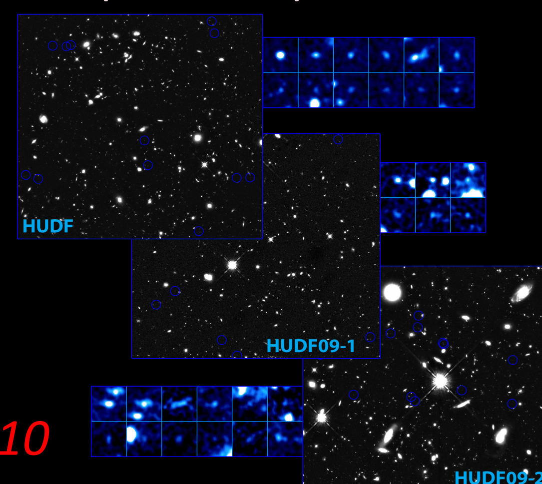
z~2-3-4

CDF-S *ACS* (2003)



z~4-6

HUDF09+ERS *WFC3/IR* (2009/10)

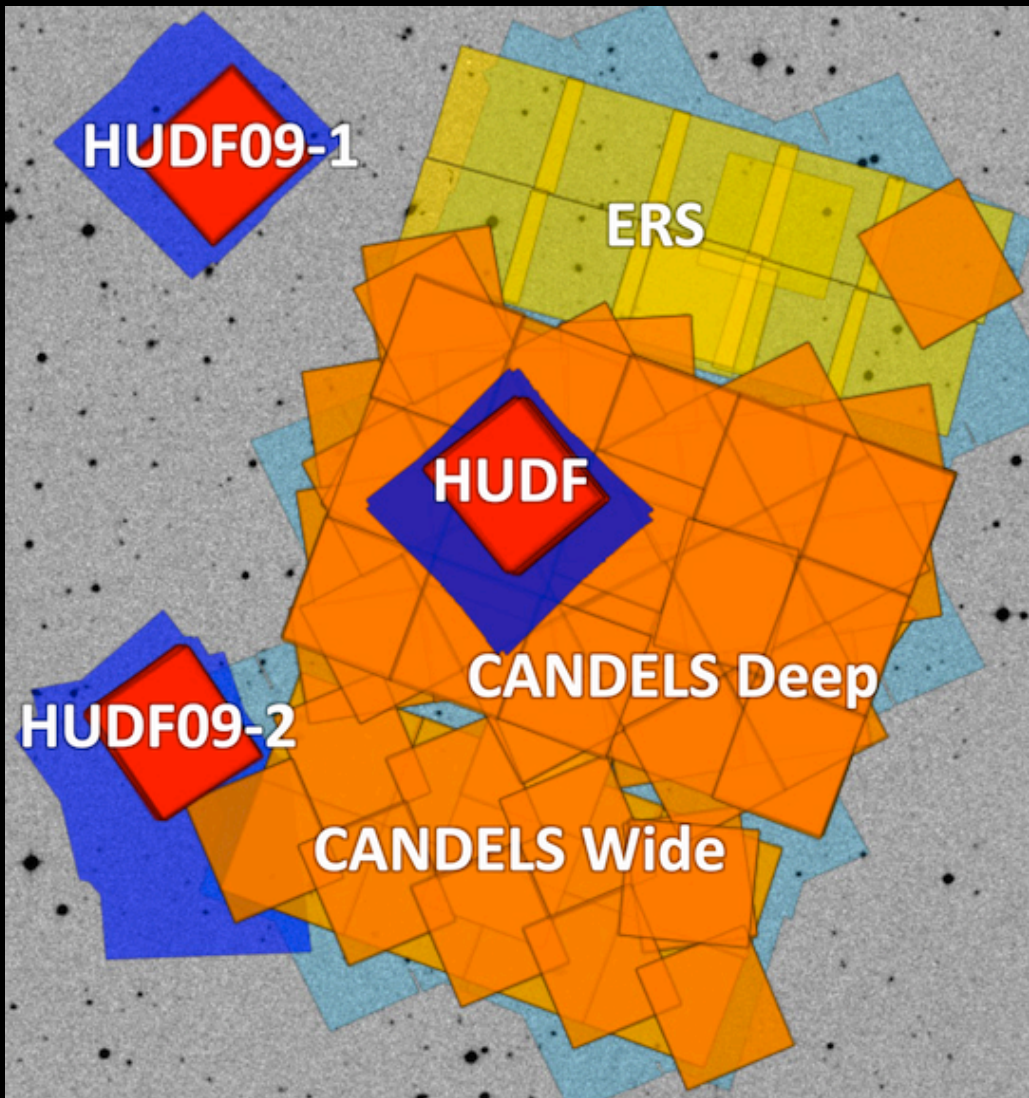


HUDF09 HST WFC3/IR z~8 Galaxies

z~7-8-10

thanks to STScI/Spitzer/Chandra directors who had the vision to do deep fields with **zero** proprietary period (often over resistance from the community and TACs)

CDF-S region is rich in data (HST, Spitzer, Chandra, etc)



ALL PUBLIC DATA

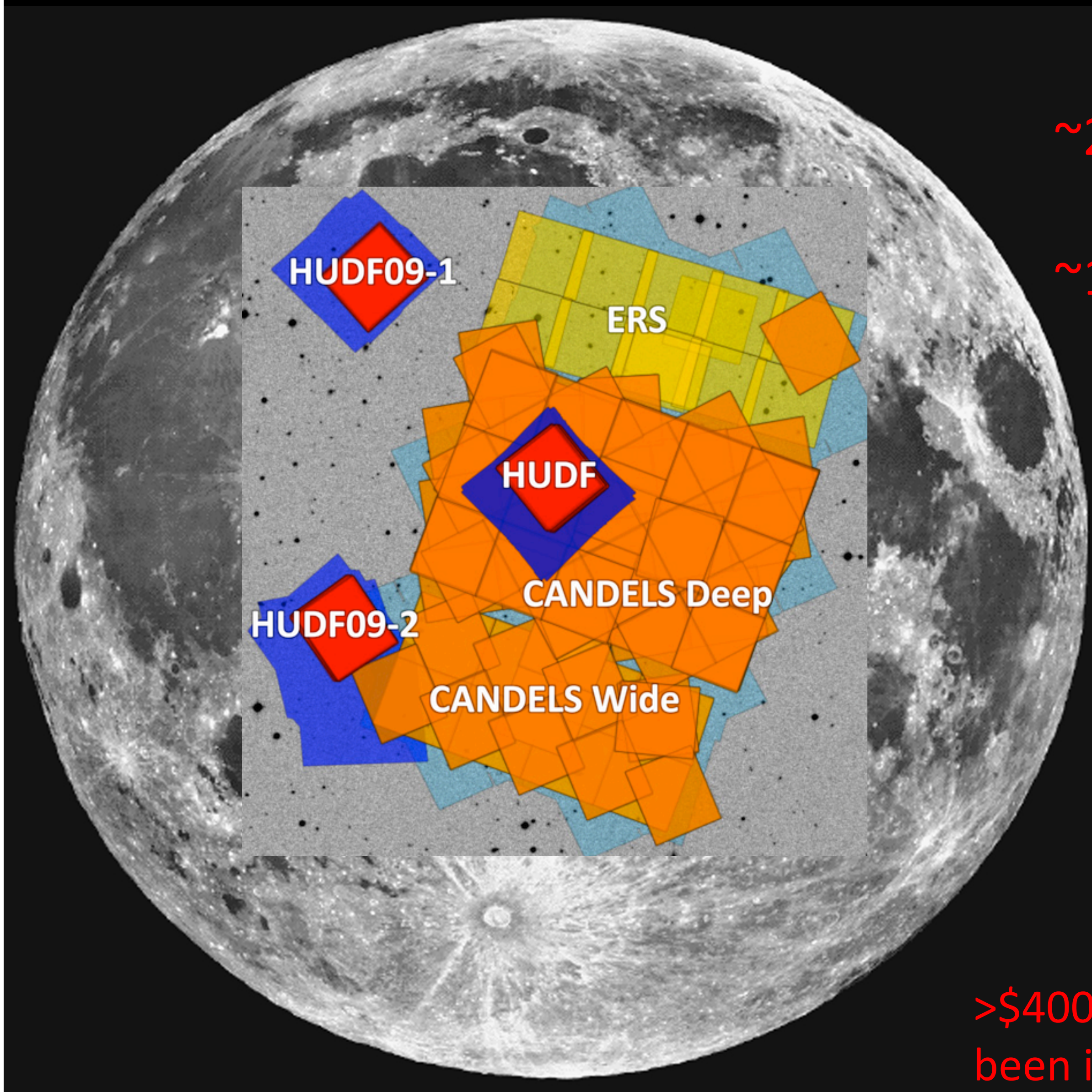
Chandra Deep Field-South

1999-2000	Chandra 1Ms
2002-2003	ACS GOODS
2003	ACS HUDF
2003	NICMOS HUDF
2004	Spitzer GOODS
2003-2007	NICMOS
2004	GRAPES
2005	HUDF05
2009	ERS
2009-2010	HUDF09
2009-2010	Spitzer SEDS
2010-2011	Chandra 3Ms
2010-2012	CANDELS
2010-2012	3D-HST
2010-2011	Spitzer IUDF10
2011-2012	Spitzer Deep
2011-2012	HUDF UVIS

not public

[2012 HUDF WFC3/IR]

CDF-S region is rich in data (HST, Spitzer, Chandra, etc)



Chandra Deep Field-South

1999-2000 Chandra 1Ms
2002-2005 ACS GOODS
2003 ACS HUDF
2003 NICMOS HUDF
2004 Spitzer GOODS
2005-2007 NICMOS
2004 GRAPES
2005 HUDF05
2009 ERS
2009-2010 HUDF09
2009-2010 Spitzer SEDS
2010-2011 Chandra 3Ms
2010-2012 CANDELS
20-2012 3D-HST
2010-2011 Spitzer IUDF10
2011-2012 Spitzer Deep
2011-2012 HUDF UVIS

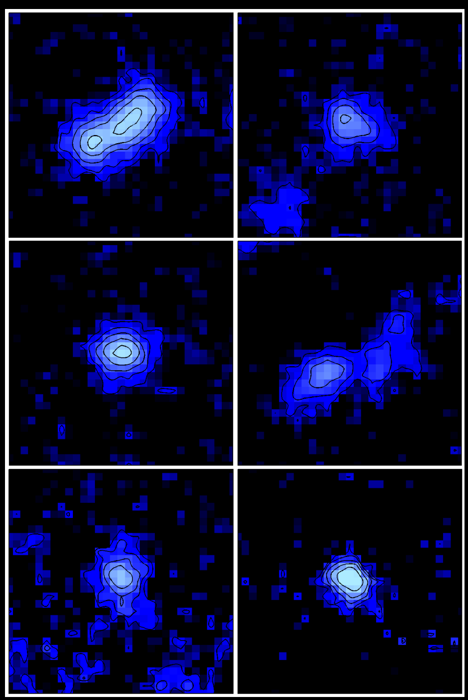
~2/3 yr of Hubble time

~1/3 yr each on
Chandra and Spitzer!

>$400M of public funds have
been invested in this tiny region

what have we learnt?

see Pascal's and Rychard's talks for the beef.....



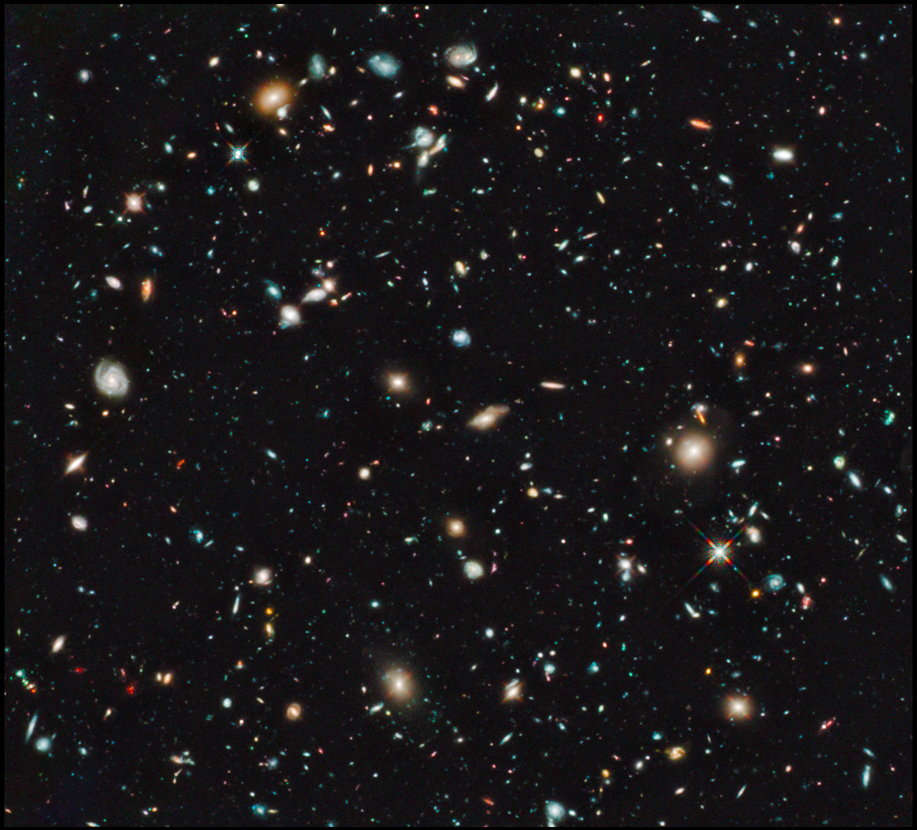
goal is to provide an accurate and complete census of z>3 galaxies and their properties (masses, colors, sizes, star formation rates, volume densities, etc.)

z	t (Gyr)	# galaxies
4	1.6	4000
5	1.2	2500
6	1.0	700
7	0.8	140
8	0.7	85
9	0.6	1
10	0.5	1

what have we learnt from the new HUDF09 WFC3/IR data?

2009:
10 papers in
first 3 months

Bouwens et al 0909.1803
Oesch et al 0909.1806
Bunker et al 0909.2255
McLure et al 0909.2437
Bouwens et al 0910.0001
Yan et al 0910.0077
Labbé et al 0910.0838
Bunker et al 0910.1098
Labbé et al 0911.1365
Finkelstein et al 0912.1338

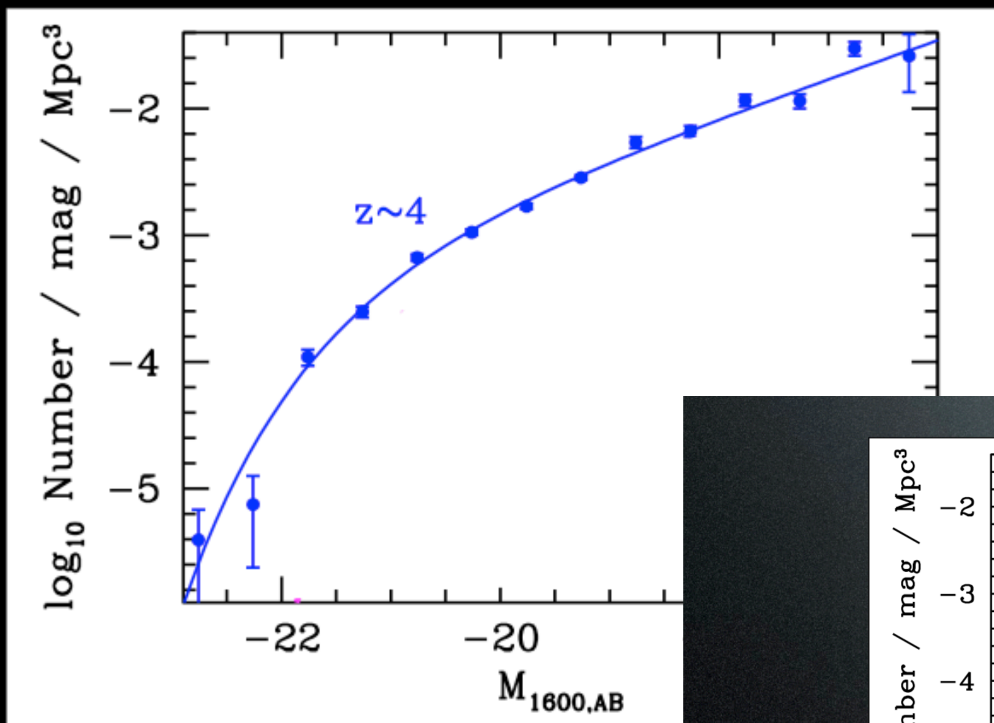


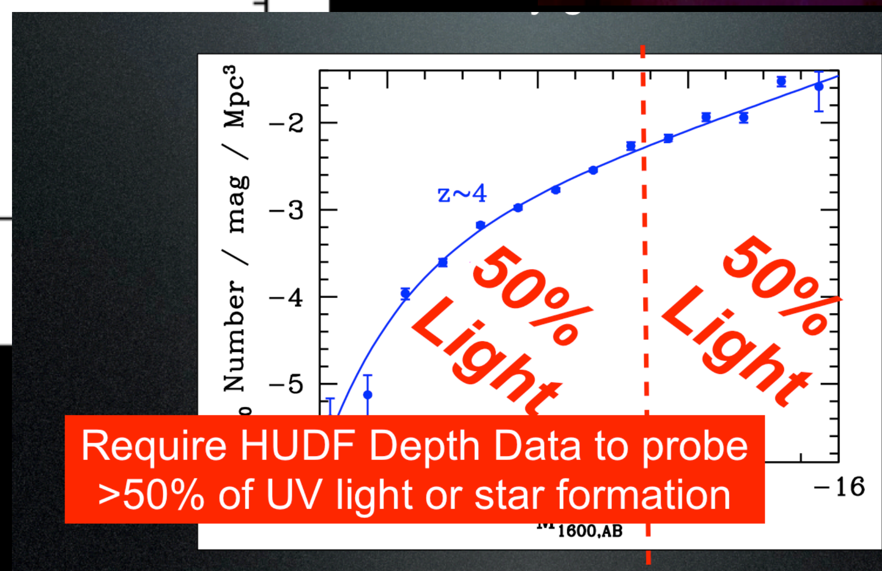
Now: ~40 papers from ~6 groups in just 3 years (22 papers from the HUDF09 team)…

fully processed *and combined* image data delivered to STScI

HUDF09 deepest IR image to date – Ellis et al HUDF12 image in 4 months will add a new filter and a very useful 0.7 mag

why is it important to go faint?

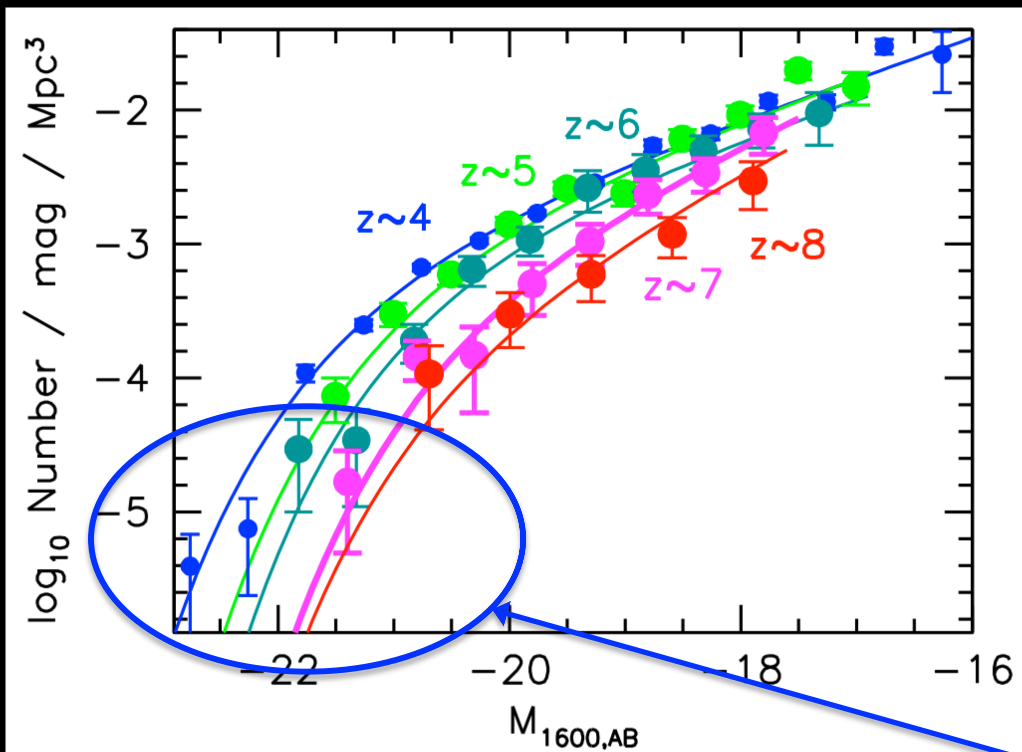


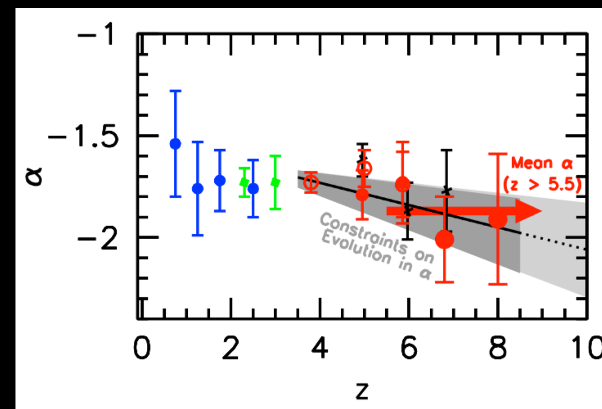


UV luminosity function

luminosity functions
from all HUDF09, ERS and CANDELS (2011)

z~4, 5, 6, 7, 8 LFs





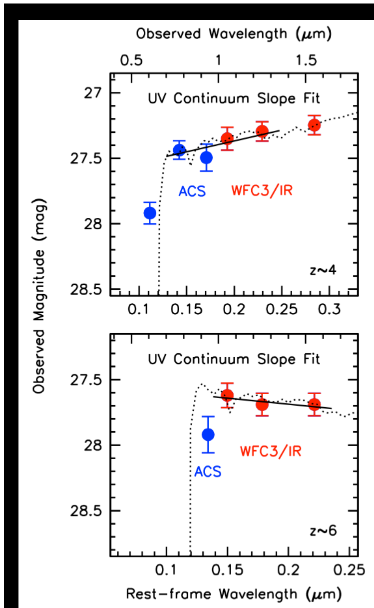
the slope is very steep at the faint end below L* (α ~ -1.7 to -2)

L* increases with time

most of the integrated UV flux at high-redshift comes from sub-L* low luminosity galaxies

Bouwens et al 2011b, 2012a

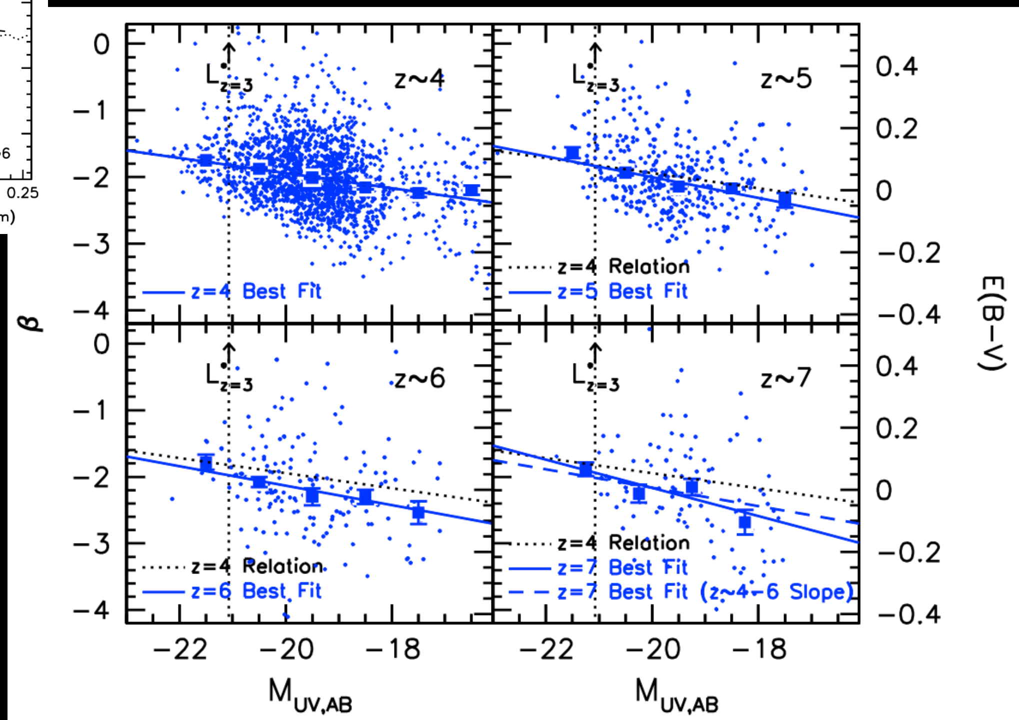
UV continuum slope results

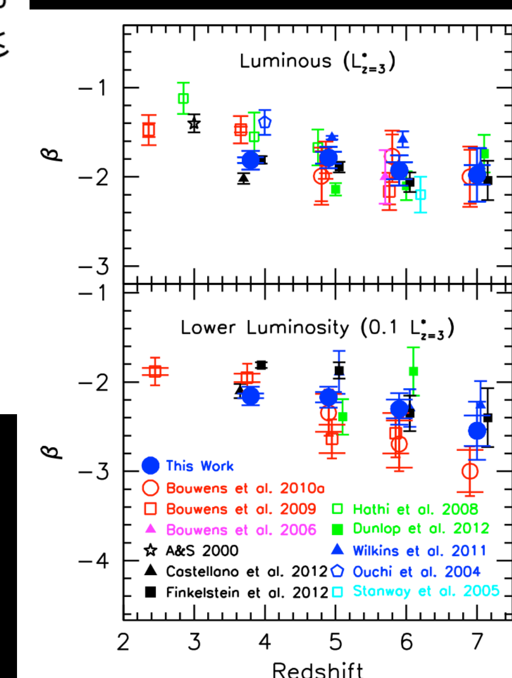


UV-continuum slope β
most sensitive to dust

at z>~4, low luminosity and high z galaxies have very low (zero?) dust

$f_\lambda \sim \lambda^\beta$

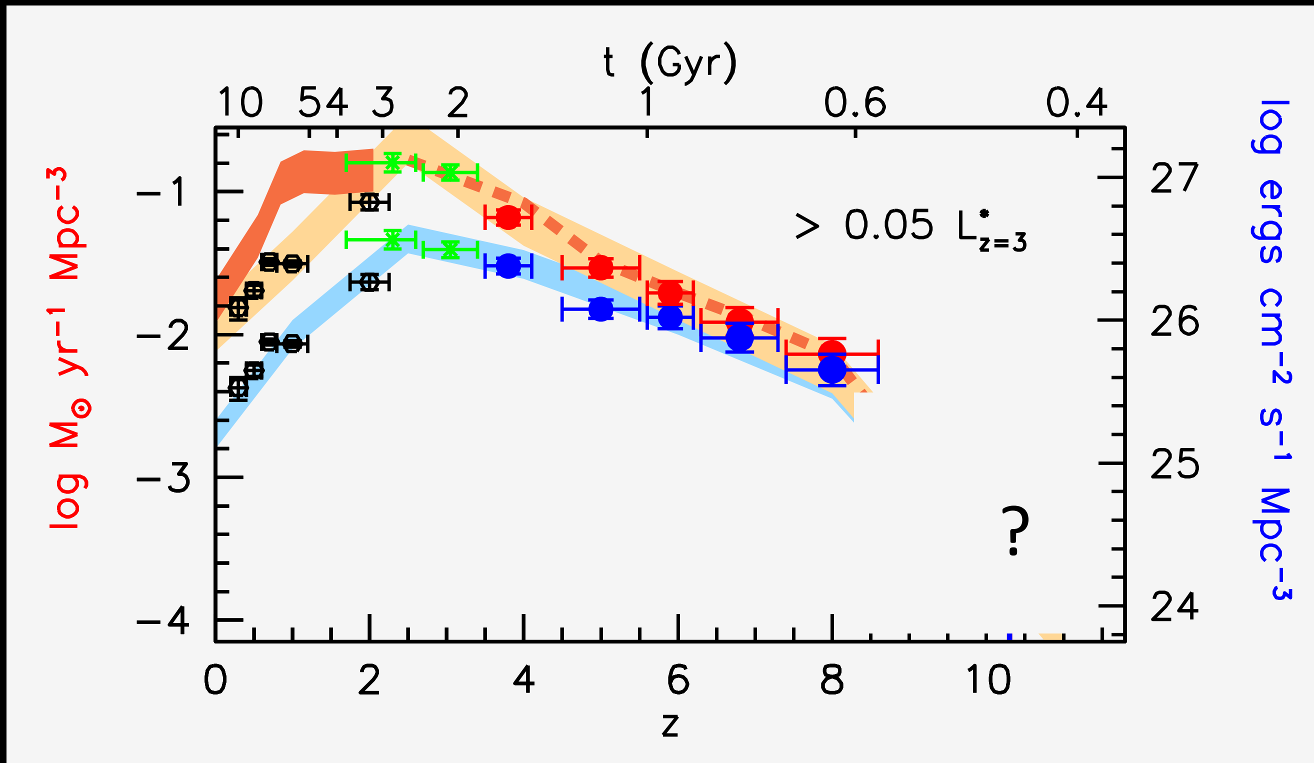




trends with luminosity & with redshift

Bouwens et al 2012b

luminosity density and star formation rate density vs redshift

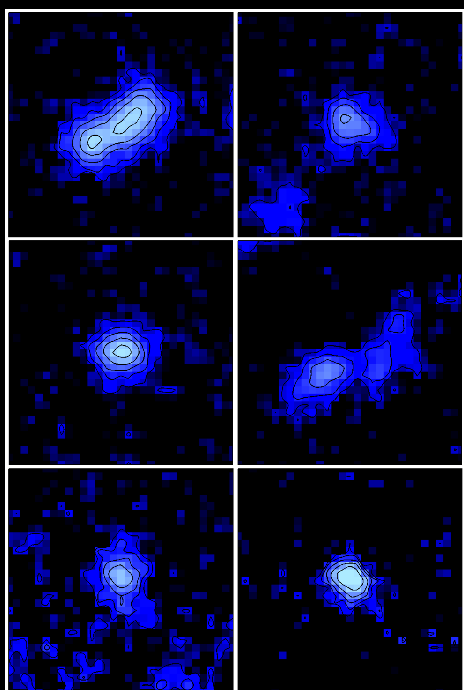


star formation rate (orange) from light corrected for dust absorption

estimate contribution of ULIRGS and similar very luminous galaxies as well

Bouwens et al 2011d

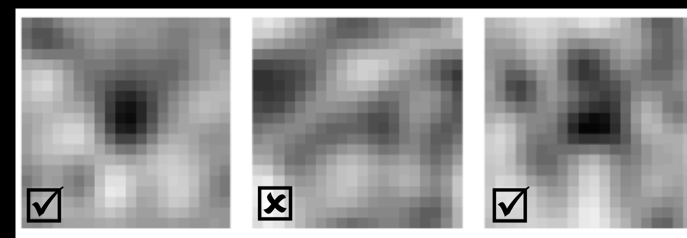
not just light – mass also



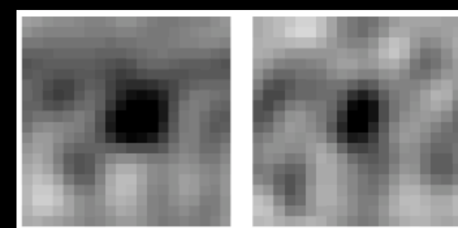
Spitzer + HST is a powerful combination

galaxies at z~8 from Spitzer IRAC

some individual z~8 Spitzer 3.6 µm images



z~8 stacked Spitzer images



3.6 µm   4.5 µm

WFC3/IR Hubble and Spitzer results together show us that z~8 galaxies could well have been forming stars two-to-three hundred million years earlier (at z>10-11)

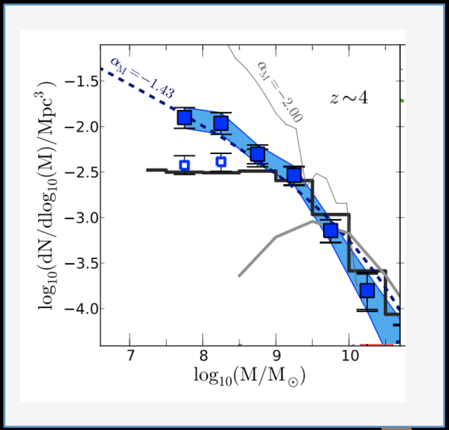
Labbé/Gonzalez et al 2010b

more z~8 detections from IUDF10 – see later talks

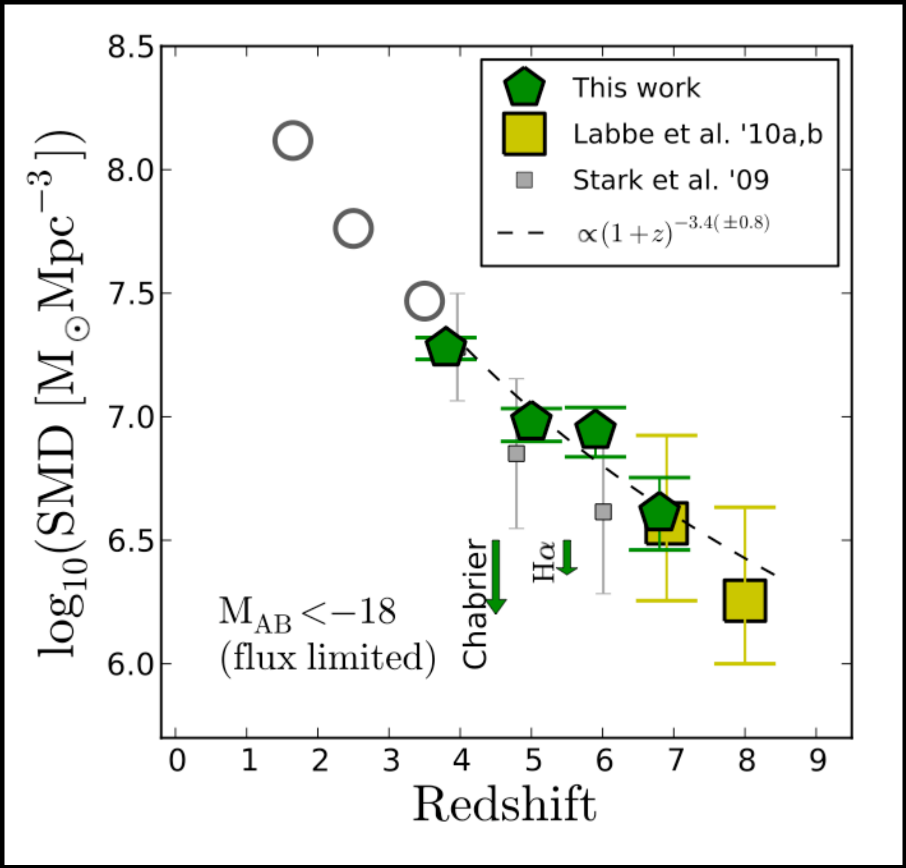
mass densities at high redshift from the mass functions

Gonzalez et al 2011

from Spitzer and Hubble we get masses of galaxies

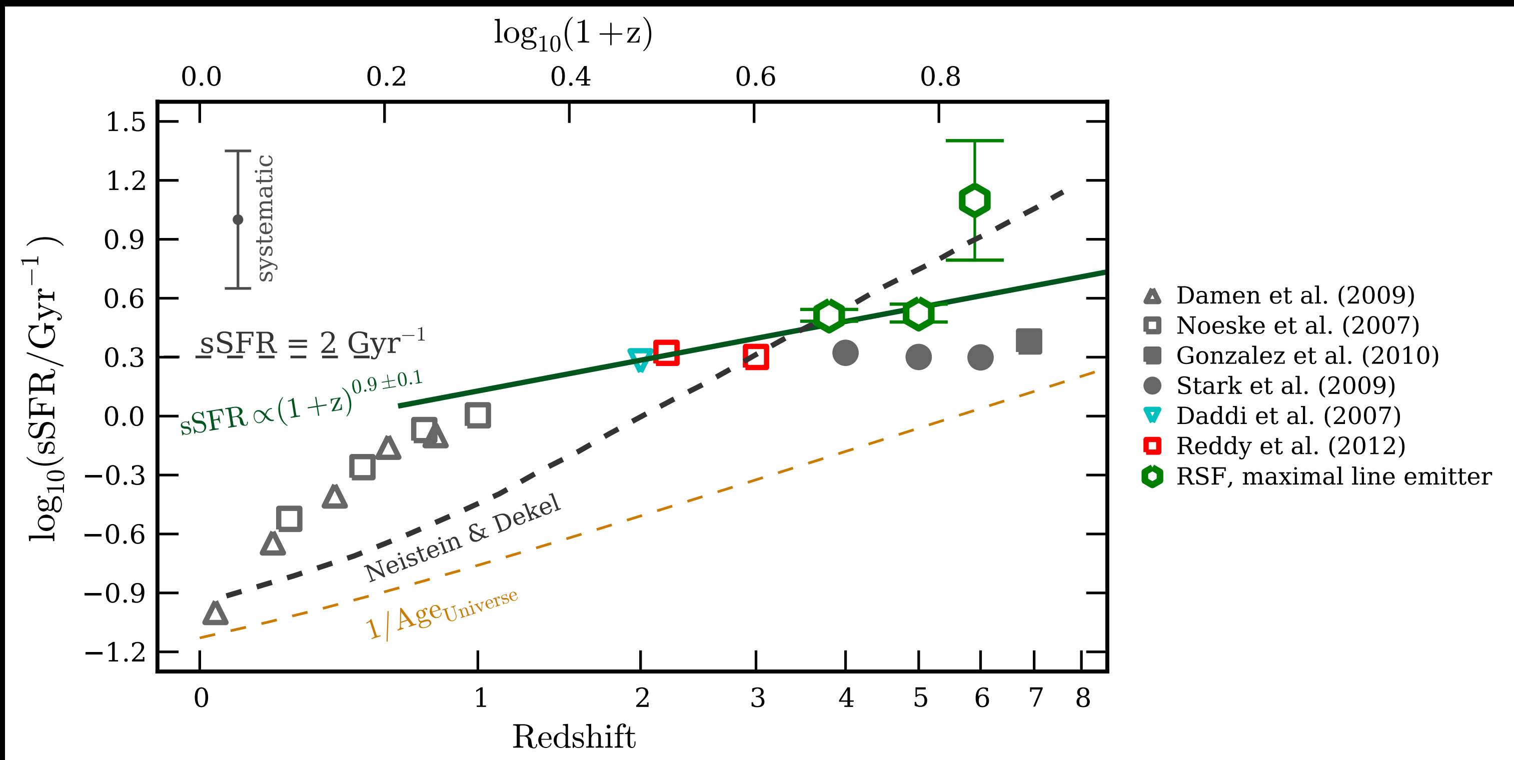


mass function at z~4



stellar mass density evolution

specific star formation rates sSFR

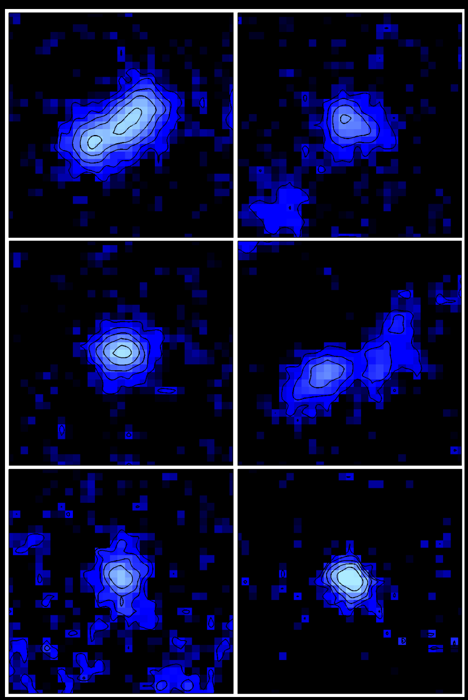


latest results from Gonzalez et al 2012

sSFR at z>2 still "flat"

rising star formation (RSF) and corrected for emission lines and dust

towards the first galaxies!

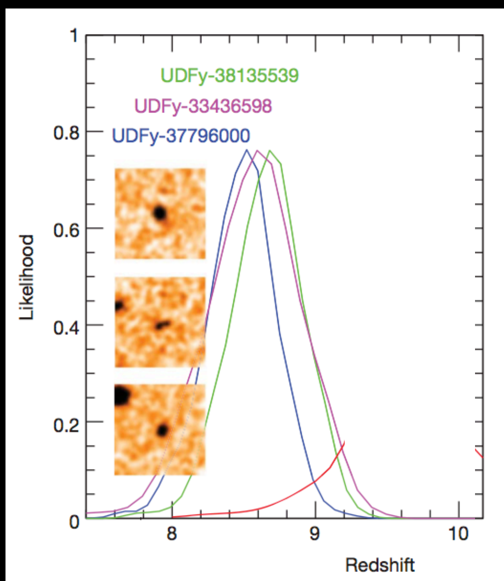


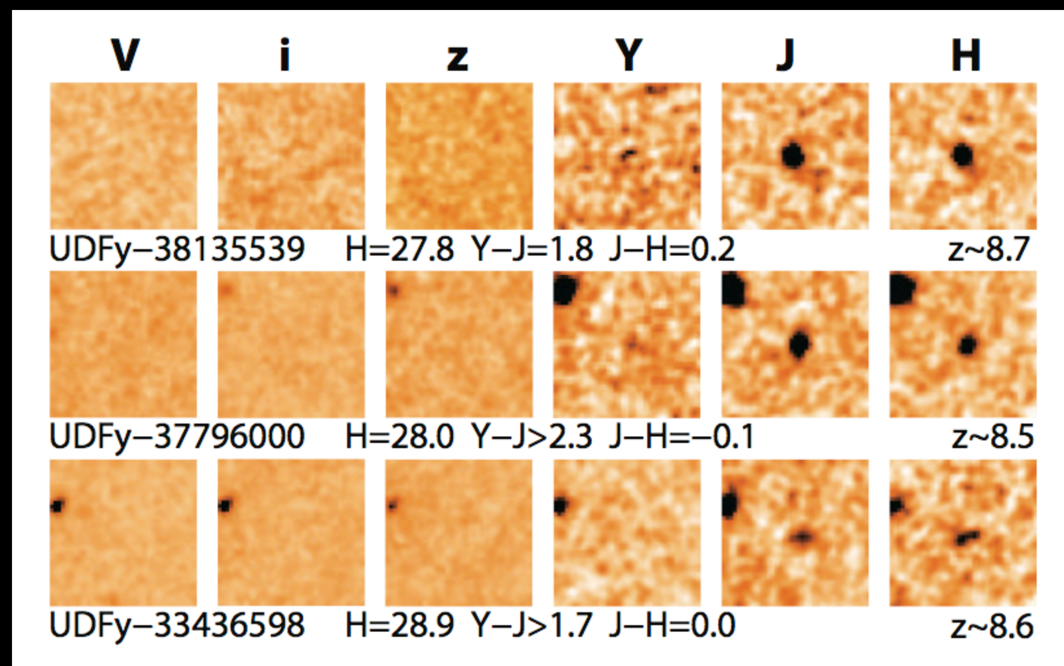
& why we need JWST….

z~8.5 galaxies

careful analysis of the colors of the z~8 galaxies in the full HUDF09 dataset led to 3 galaxies at z~8.5

– starting to find objects between z~8 and z~10





8.5

Bouwens, Illingworth & HUDF09 team – Nature Jan 27 2011

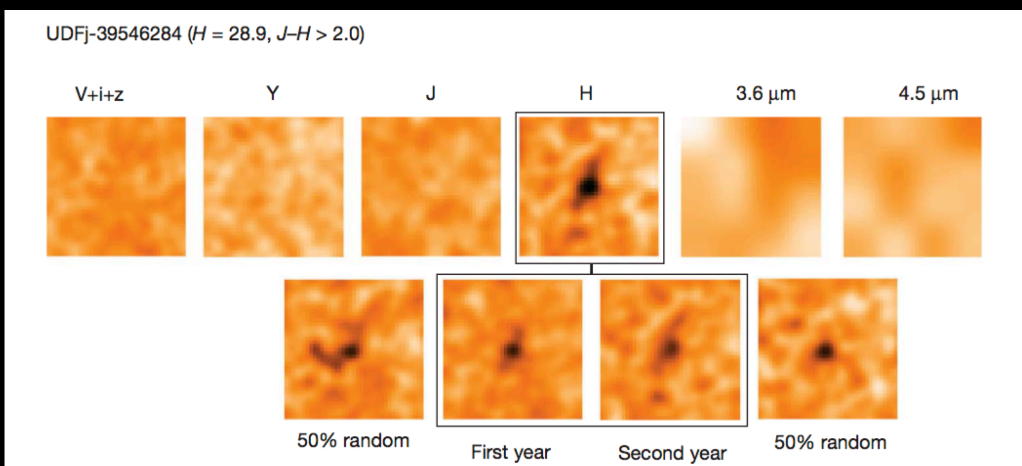
z~10 galaxy – at 480 million years – just 4% of the current age of the universe

10

extensive search of HUDF optical and IR data – detected a very probable z~10.4 galaxy

this source is detected at nearly 6σ in the WFC3/IR H band

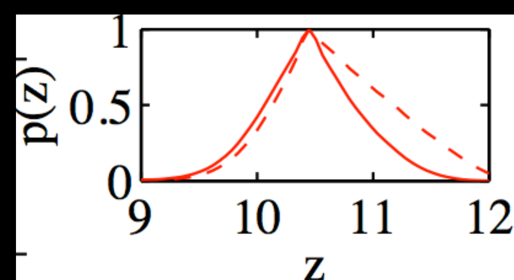
Bouwens, Illingworth & HUDF09 team – Nature Jan 27 2011



extensive tests in this followup paper largely ruled out low redshift SEDs

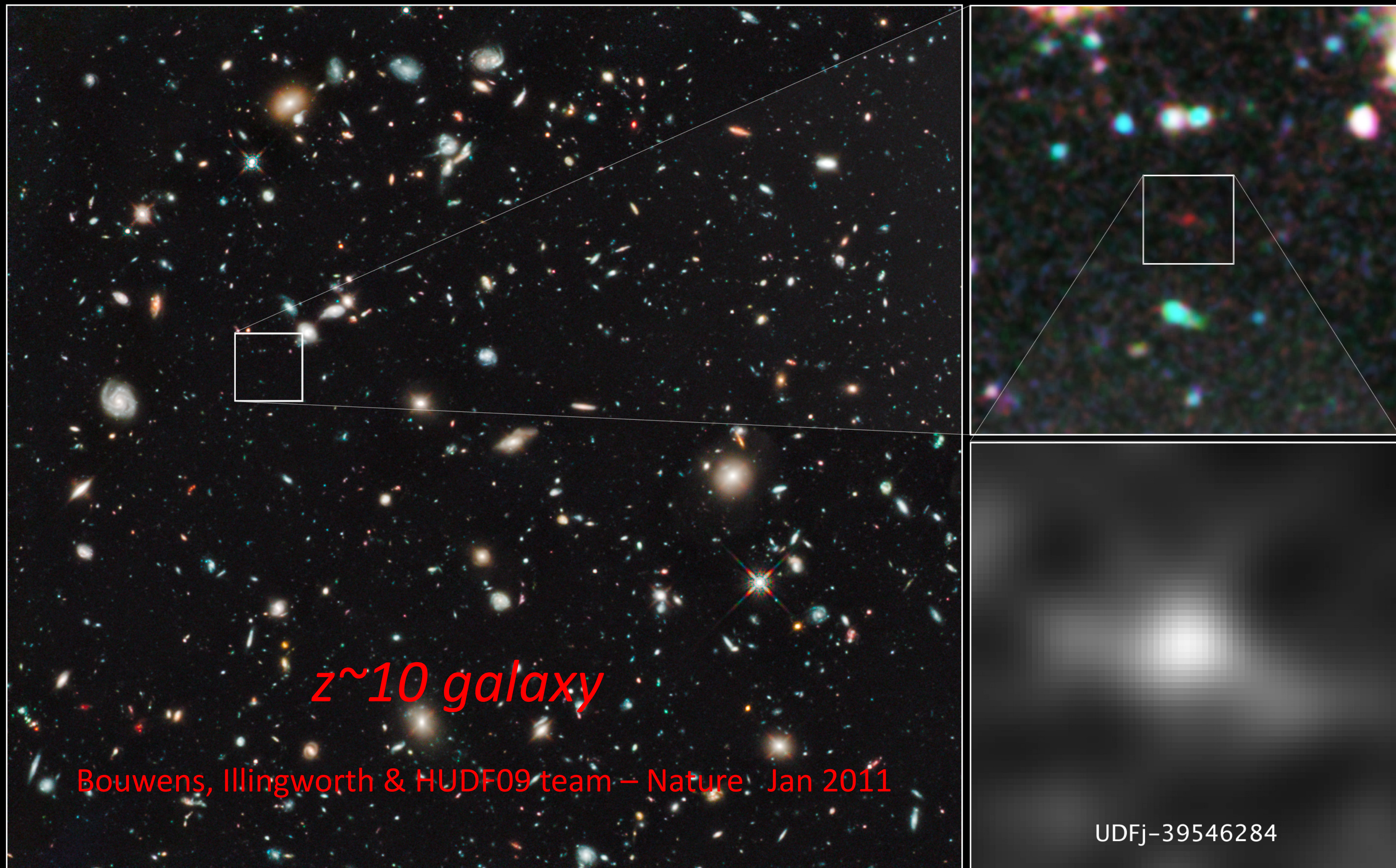
Oesch et al 2012

object excluded from being a z~2.7 dusty galaxy at 99% confidence



z~10 candidate(s) to be confirmed by 2012 Ellis et al 2012 WFC3/IR data (?)

possible second z~10 candidate identified in HUDF09 with ~4.5σ detection (HUDF12?)



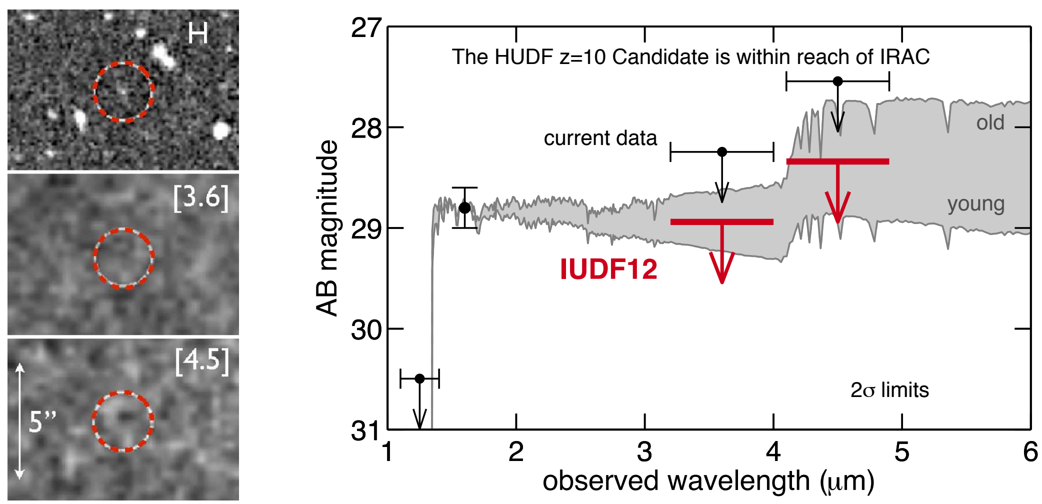
Hubble Ultra Deep Field 2009-2010

Hubble Space Telescope • WFC3/IR

NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team

STScI-PRC11-05

z~10 galaxy



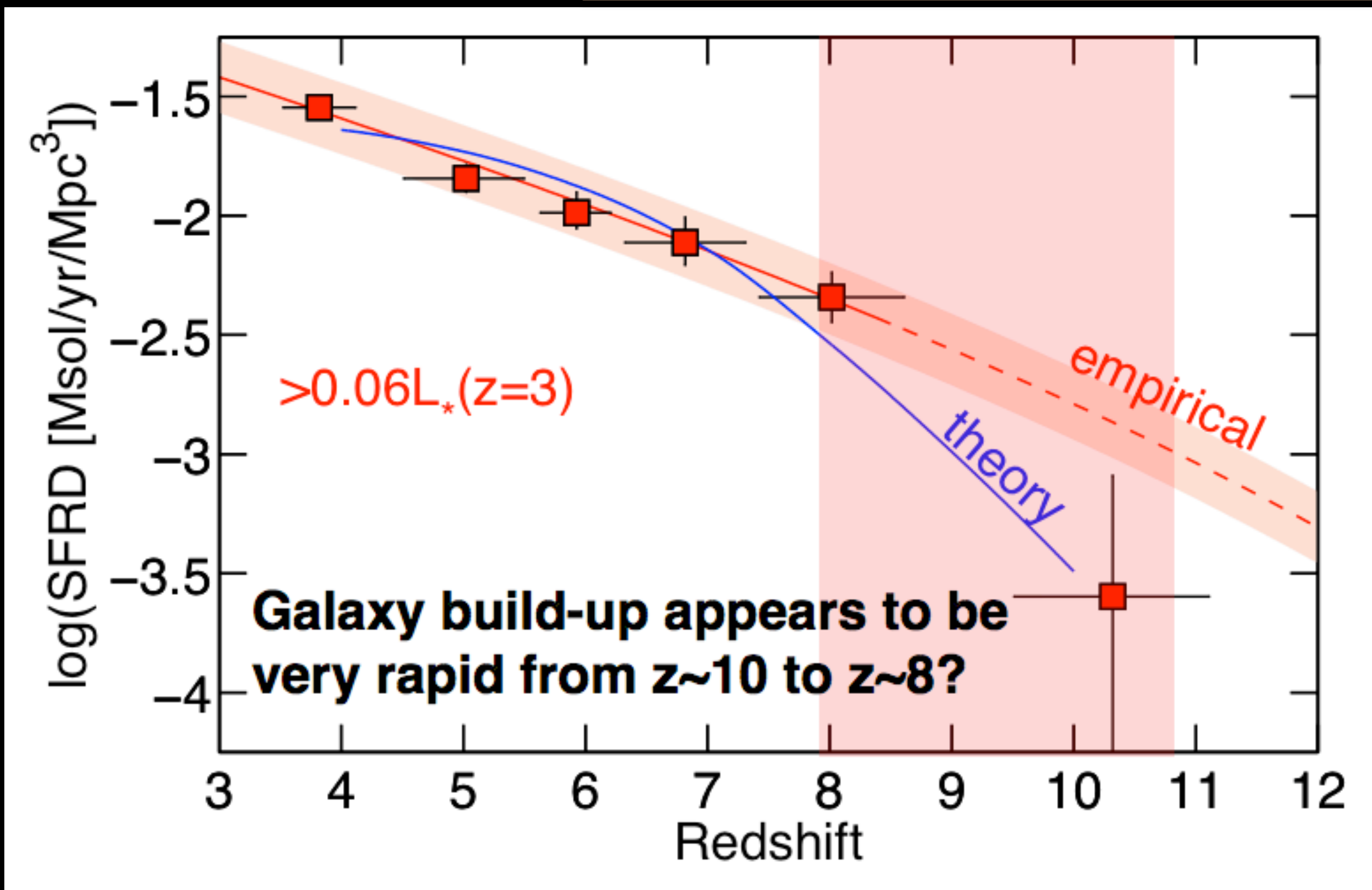
marginal detection (~1.5σ) of z=10 candidate galaxy

hot off the analysis – latest IRAC IUDF10 data on z~10 galaxy……

from Ivo Labbe

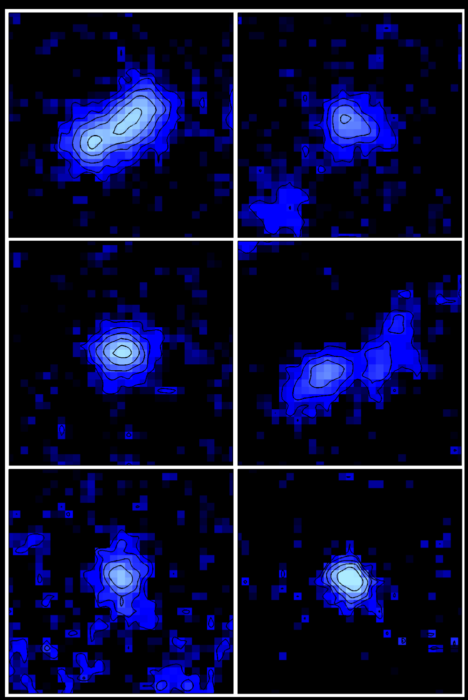
note that the z~10 galaxy could well be detectable with deeper IRAC data *is the global star formation rate changing more rapidly from z~10 to z~8?*

current results suggest that it might be...



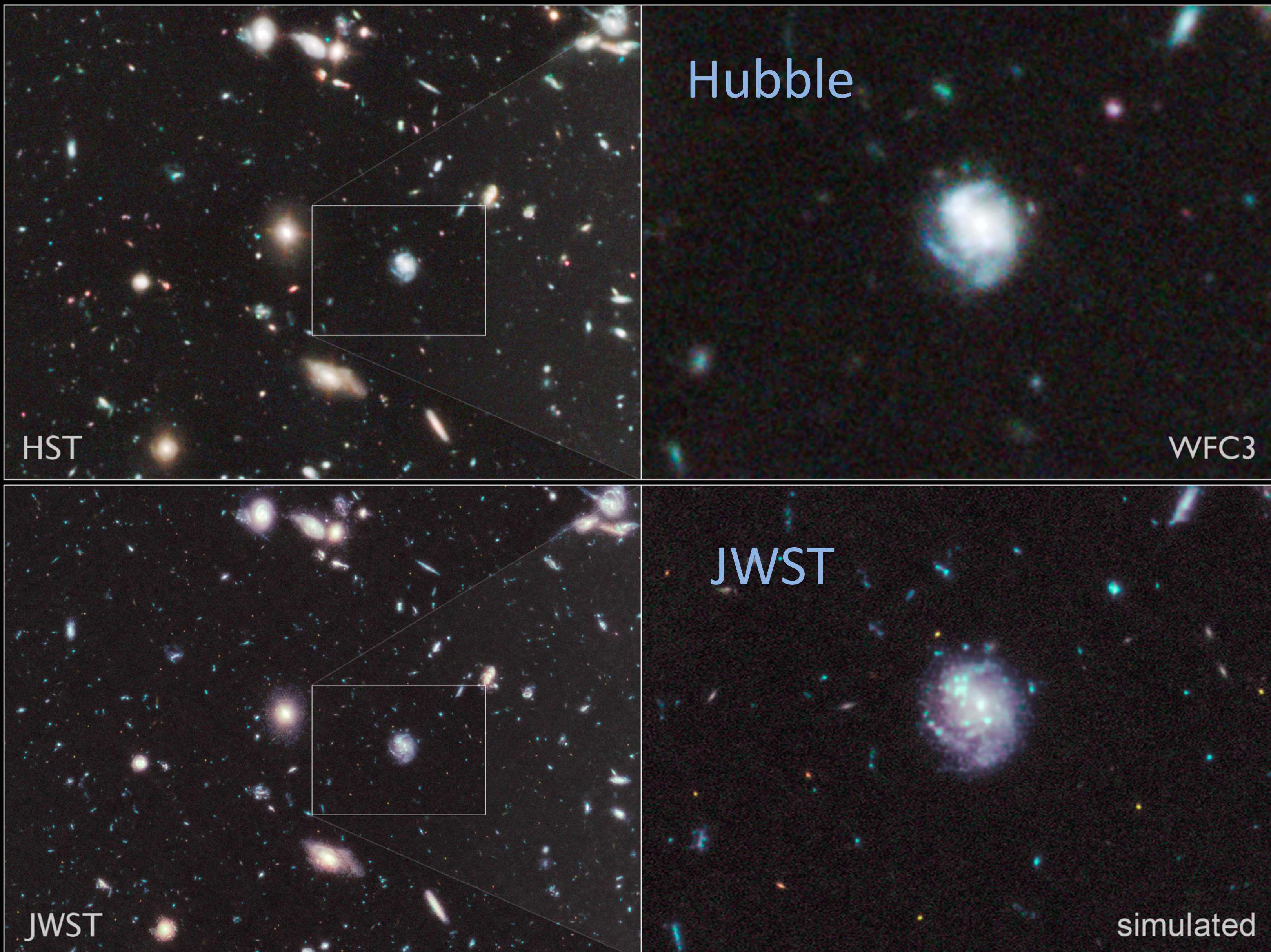
Oesch et al 2012

JWST!



we really need JWST!!....

JWST resolution and sensitivity will make a huge difference



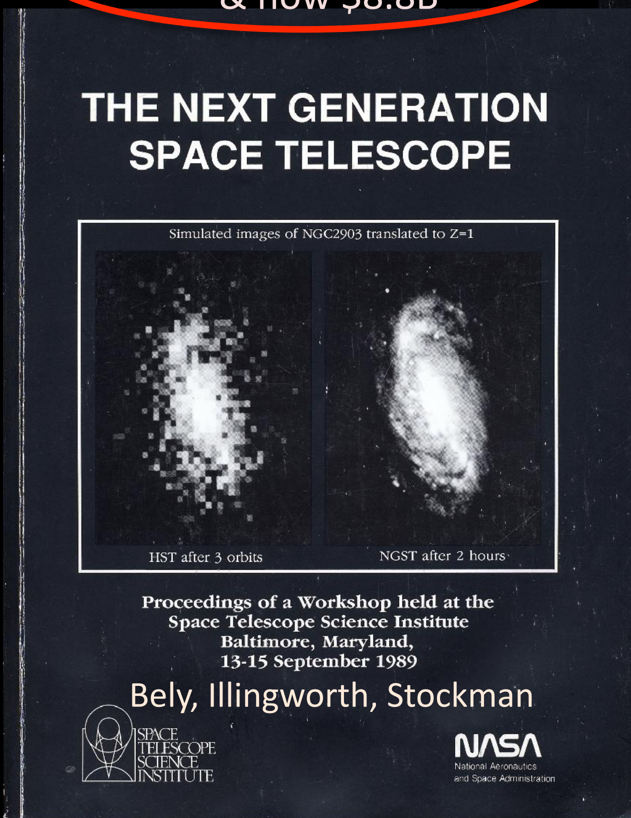
(z~1)

NGST/JWST: how it started...

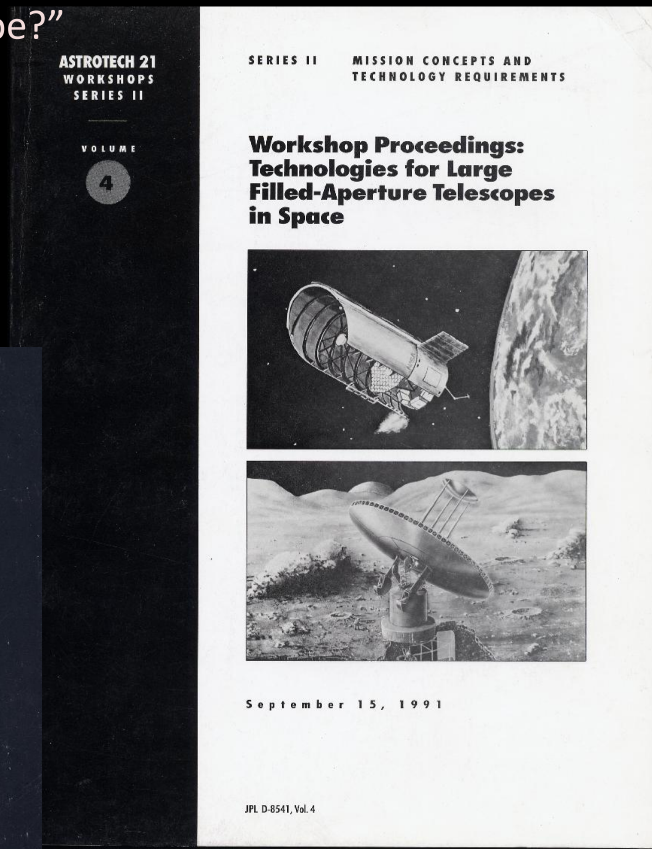
1987 – Riccardo Giacconi asked me
“what comes after space telescope?”

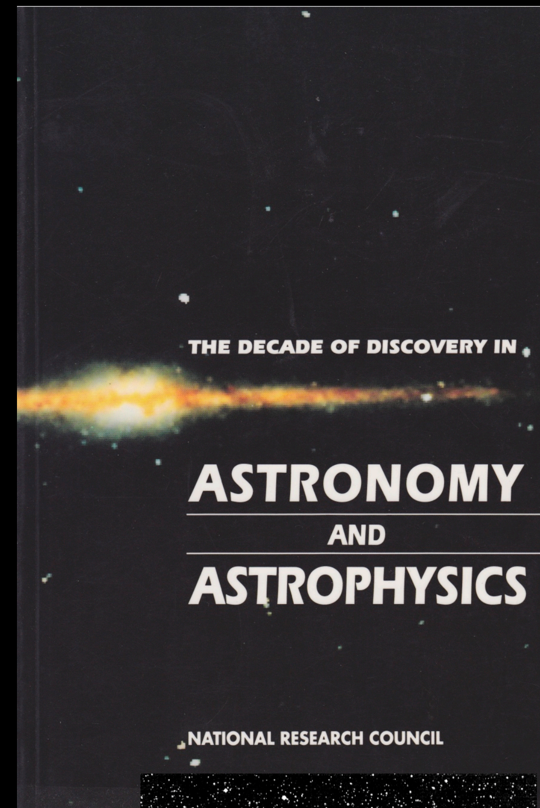
A few of us started thinking and
NGST arose.... now JWST

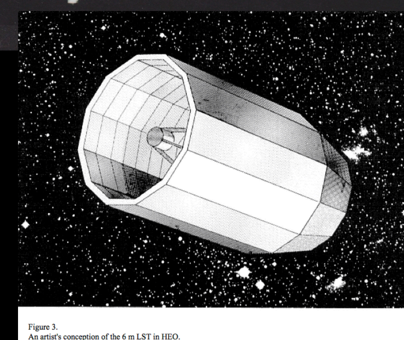
1987-2018 => 31 years
& now $8.8B



Bely, Illingworth, Stockman







1990 decadal panel (UV-Optical from Space)
recommended LST (NGST) at a cost of $2B (1990 $)

alas, not accepted by full committee!

NGST/JWST: how it started…

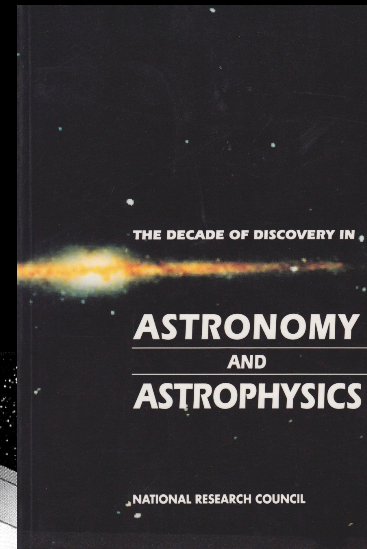
UV-OPTICAL FROM SPACE 74

A more complete outline of the recommended program can be found in §II (Implementation of the Science Program). The recommended program is:

SIZE	PROJECT	Cost	Start	Finish
Large:	LST-6 m HST Successor	$2000M	1998	2009
Moderate:	Explorer Enhancement	$300M	1993	2000
Moderate:	HST Third Generation Instruments	$150M	1994	2000
Moderate:	Imaging Astrometric Interferometer	$300M	1997	2004
Small:	SMEX UV Survey.	$30M	1995	1998
Small:	Space Optics Demonstration	$30M	1993	2000
Small:	Supporting Ground-based Capabilities	$25M	1993	2000
Technology:	Technologies for Space Telescopes	$30M	1993	2000

Large:

LST (*Large Space Telescope*): The LST is a 6 m Observatory-class telescope incorporating UV to IR imagers and spectrographs. Passive-cooling and high-performance optics result in large gains in scientific capability over HST. A high priority goal is location beyond Low Earth Orbit (e.g., HEO - High Earth Orbit). This telescope is an excellent candidate for strong international participation. For operation by 2009 a start date of 1998 is considered necessary. Advances in technology and HEO operation will break away from the HST cost curve and lead to an expected cost of $2000M.



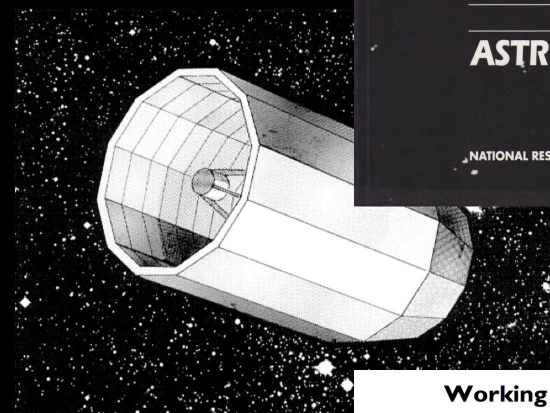


Figure 3.
An artist's conception of the 6 m LST in HEO.

UV-OPTICAL FROM SPACE PANEL

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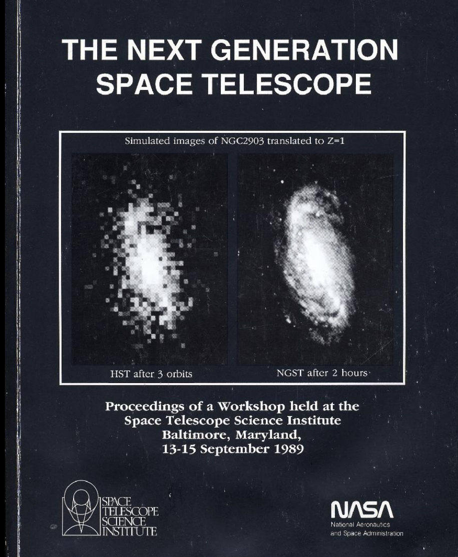
Working Papers

Astronomy and Astrophysics Panel Reports

NATIONAL ACADEMY PRESS
Washington, D.C. 1991

Astronomy and Astrophysics Survey Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

Bely, Illingworth, Stockman



1990 Decadal panel estimated NGST (LST) cost as $2B (1990 $)

note that $2B in 1990 $ is $3.6-$5.3B in FY2012 $
(regular inflator – technology project inflator)

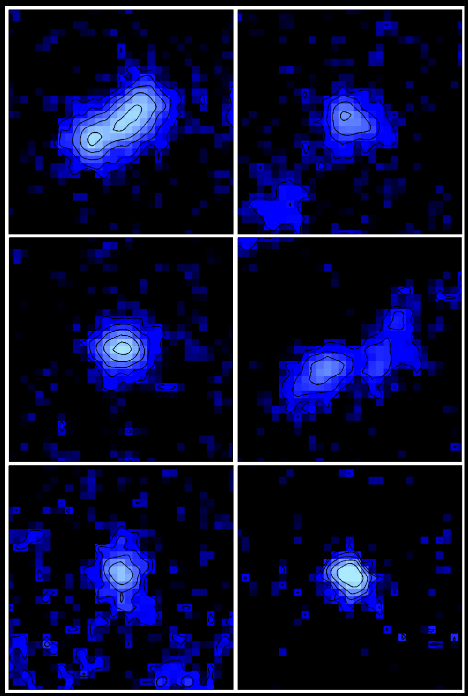
cf. 2000 Decadal estimate of $1B ($1.3-$1.6B in FY2012 $!)

the first billion years of galaxies:
coming in exquisite detail….

JWST

in its 5-10 yr life this $8.8B telescope will revolutionize our knowledge of galaxies in the first 1-2 Gyr…..

thoughts for the future – preparing for JWST

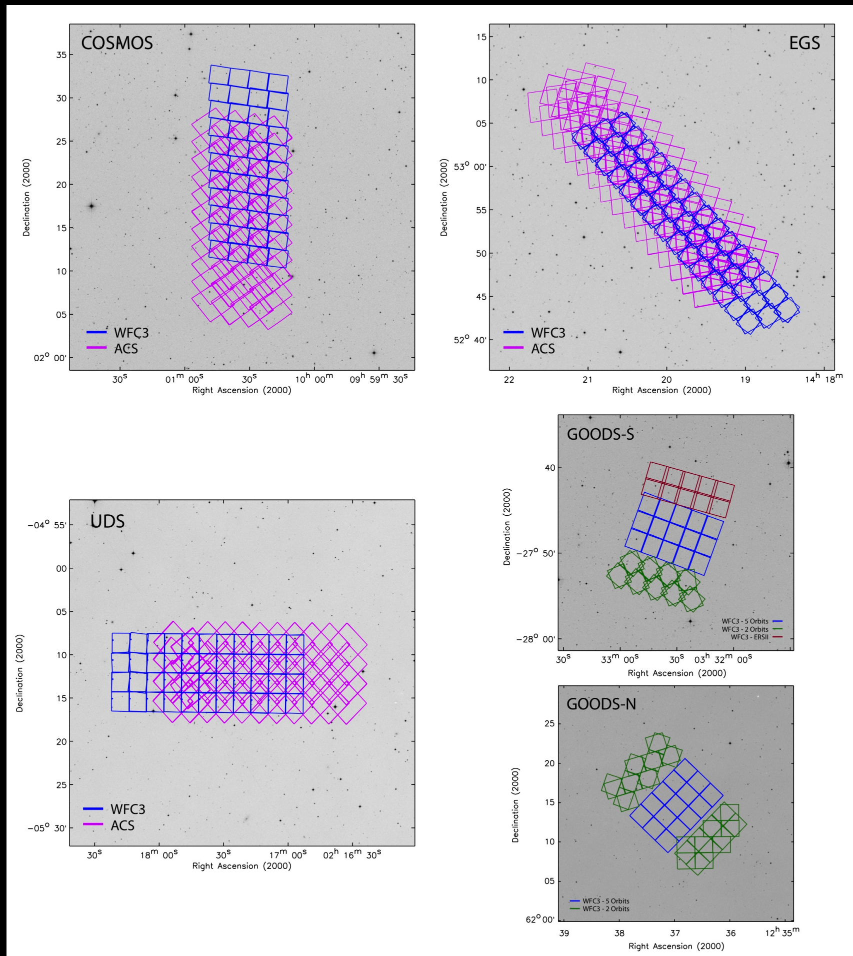


there are a variety of approaches to getting data for high redshift galaxies…

what are the best datasets for moving forward towards JWST and for learning about galaxies in the first 1-2 Gyr (z>3)?

wide fields

wide shallow fields



GOODS + CANDELS are excellent and extremely important datasets (and their many fields minimize cosmic variance)

CANDELS

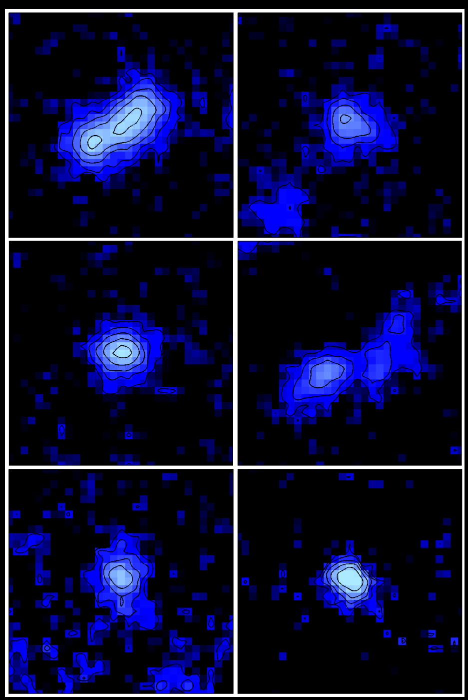
CANDELS to date:
17 team papers, of which
~3-4 are z>3
~6 HUDF09 papers also use CANDELS data

wide-field data are great for:

1) z~2-3 SFR peak studies
2) bright objects at z>3
3) unusual objects
4) potential spectroscopic samples
5) lower redshift galaxies (z~1-ish)

BUT shallower data is not so good for studying faint galaxies that dominate the mass and light at z>3
– or for studies at z>3 requiring good S/N (colors) over a wide luminosity baseline
– or for getting large z>6 samples

thoughts for the future

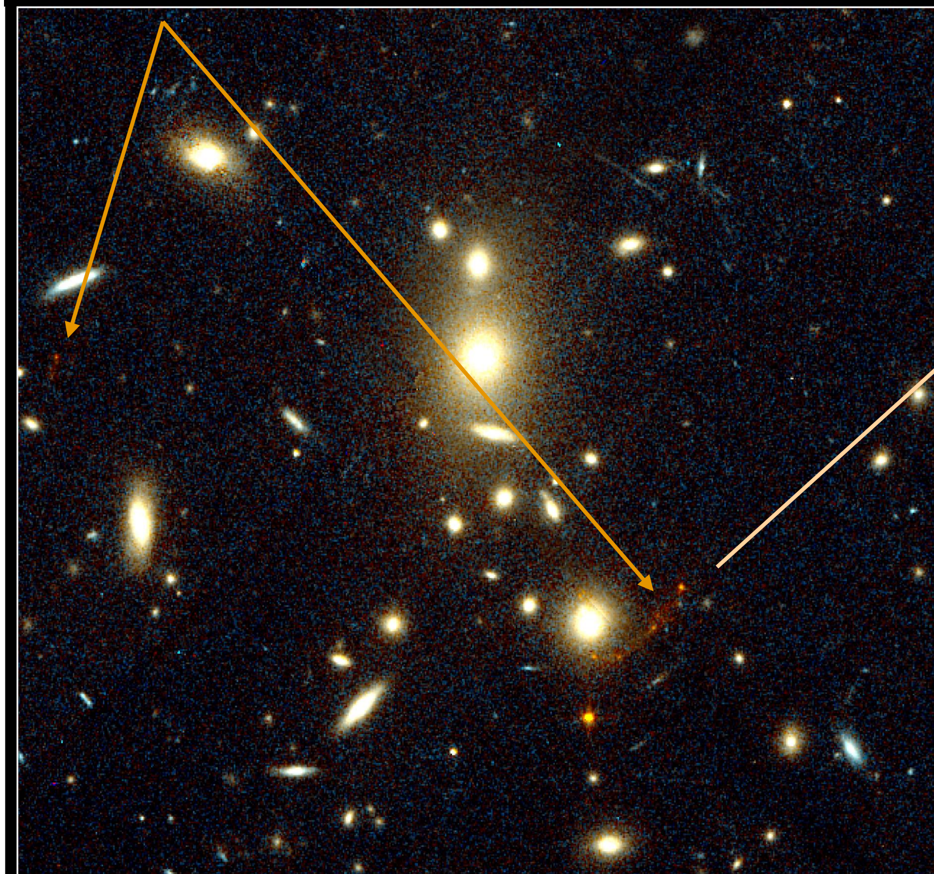


what are the best datasets for moving forward towards JWST and for learning about galaxies in the first 1-2 Gyr (z>3)?

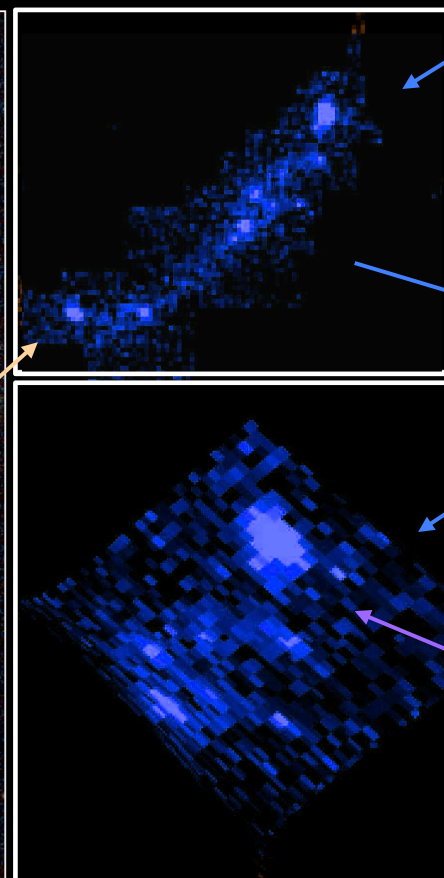
lensing clusters

star formation occurs in compact regions

lensed galaxy at redshift 4.9 – 12.4 billion years ago
– lensed by a rich cluster of galaxies at redshift z~0.3



Gravitationally Lensed Image of Highest Redshift Galaxy
Hubble Space Telescope • WFPC2



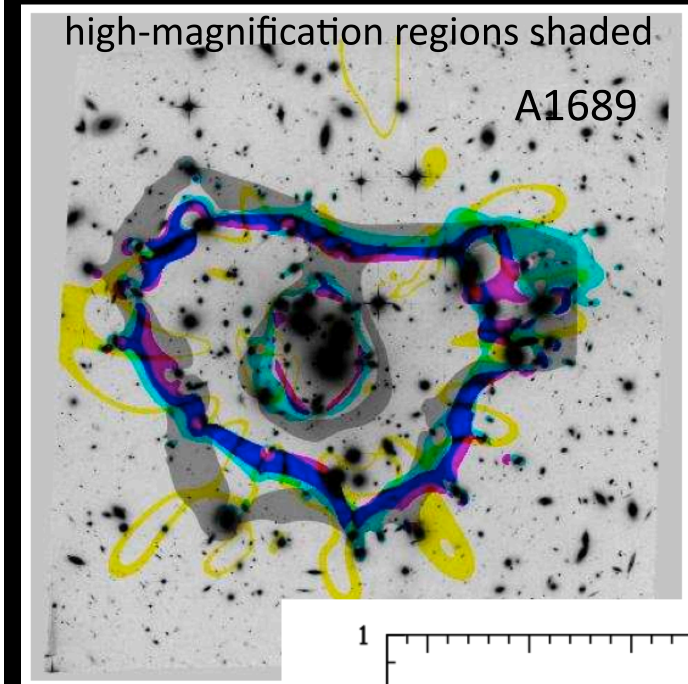
distorted fold image of a 10-20x magnified, redshift 5 galaxy

remove the distortion caused by the cluster – get a >10x magnified image of a galaxy at redshift 5

(TMT AO resolution)

- *significant fraction of total star formation in "blob"*
- *just a few hundred pc in size*

Franx, Illingworth et al 1997



lensing clusters

CLASH:

11 papers (team + community)

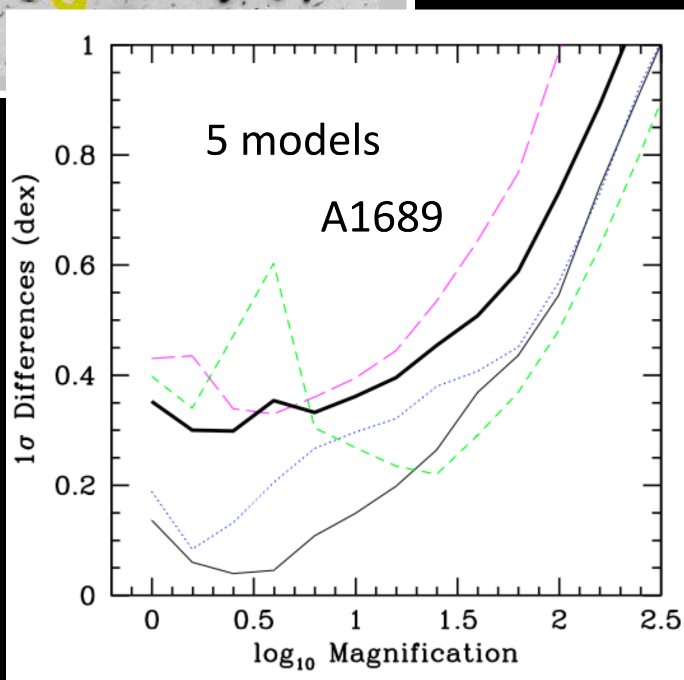
3 on individual detections at high redshift

Bouwens, Illingworth et al 2009 – draft

lensing clusters are great for:

1) detecting faintest high-z objects

2) structure of (modest) sample of highly-magnified high-z galaxies



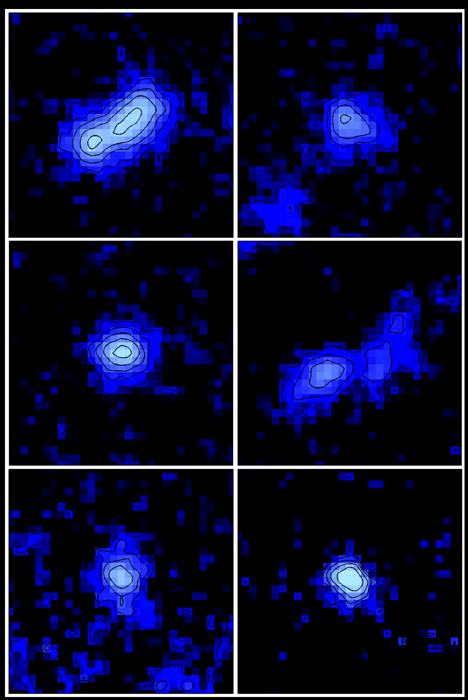
2x dispersion in magnifications <~30!

1) not for statistically-robust samples

2) nor can source plane volumes be established accurately – subject to large systematic uncertainties in magnification

unfortunately, for obtaining high-redshift galaxy samples strong lensing cluster observations are both inefficient and inaccurate

thoughts for the future



what are the best datasets for moving forward towards JWST and for learning about galaxies in the first 1-2 Gyr (z>3)?

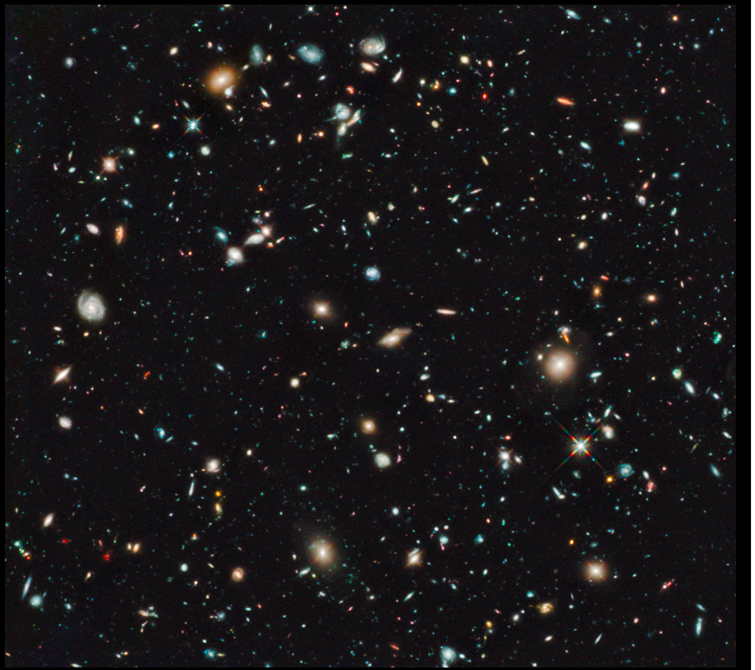
deep fields

we only have one very deep field: the HUDF

HUDF, and its two “flanking fields” that are not as deep nor separated enough to help re cosmic variance, is *the only truly* deep field we have!!

even with just one small field the 192 orbit HUDF09 program has resulted in ~40 papers since late 2009

this is the highest publication rate per orbit per year *for high redshift galaxies* from all recent programs



the current MCT programs are invaluable datasets, but they alone are not adequate for characterizing galaxies at z~4 and earlier

unfortunately, some in competing areas are saying that added deep field data is NOT necessary

this is very unwise, it appears very parochial, and will limit high redshift studies – and the productivity of JWST in one of its key level one areas

we only have one very deep field: the HUDF

z>3 studies need more deep fields

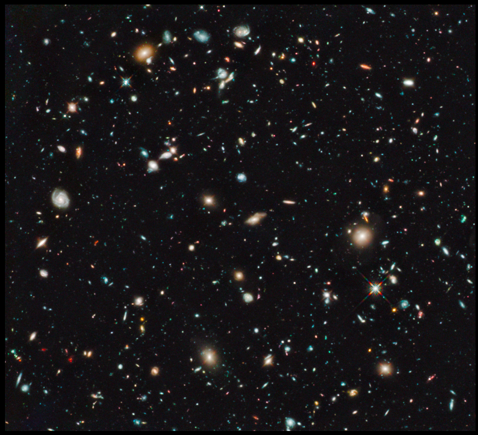
JWST needs more deep fields if it is to accomplish its level one objectives

how deep??
consider the Ellis et at HUDF12 program – 128 orbits WFC3/IR

proprietary data is coming in over the next two months – adds new filter F140W and takes other IR filters slightly deeper

expect to confirm z~10.4 galaxy
and expect to add:
~15-20 z~8 galaxies (currently 85)
~3-5 z~9 galaxies (currently 1)
~1-2 z~10 galaxies (currently 1-2)

hard work at this stage – need substantial investment of time to add fields that are valuable for JWST and current studies



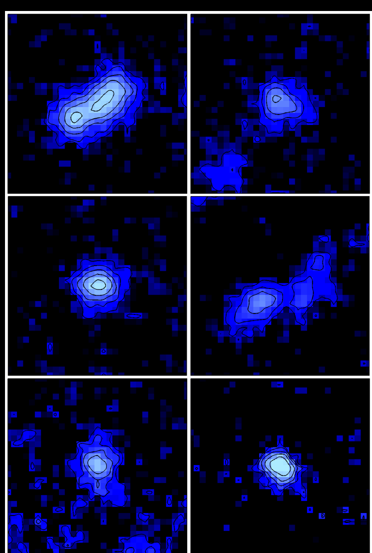
it is not easy to do more with HST but the timing is critical

ACS and WFC3/UVIS CCDs are being damaged by cosmic rays

thoughts for maximizing future advances at z>3

JWST is crucial for faint imaging and spectroscopy, and for the highest redshifts

new space facilities are expensive, limited life and need careful preparatory work to maximize their science return



additional HST deep fields (not lensing clusters) are crucial for further progress on galaxies at high redshift

such major datasets should be public – open access and competition is crucial for maximizing scientific return – proprietary data limits are increasingly anachronistic and not optimal for scientific progress

near-IR spectrographs on 8-10m-class telescopes will change the game on the ground for z>3 spectroscopy of bright objects

ultimately though, 30-m class telescopes are needed