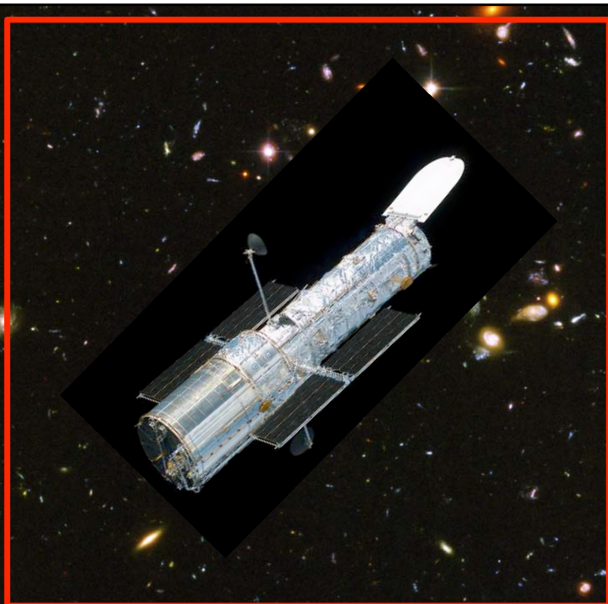
UT   March 2010   Austin, TX

First Stars and Galaxies



constraints on galaxies in the first billion years: the HST HUDF09 program

Garth Illingworth

(UCO/Lick Obs & University of California, Santa Cruz)

Thanks to Rychard Bouwens and the HUDF09 team

the HUDF09 team

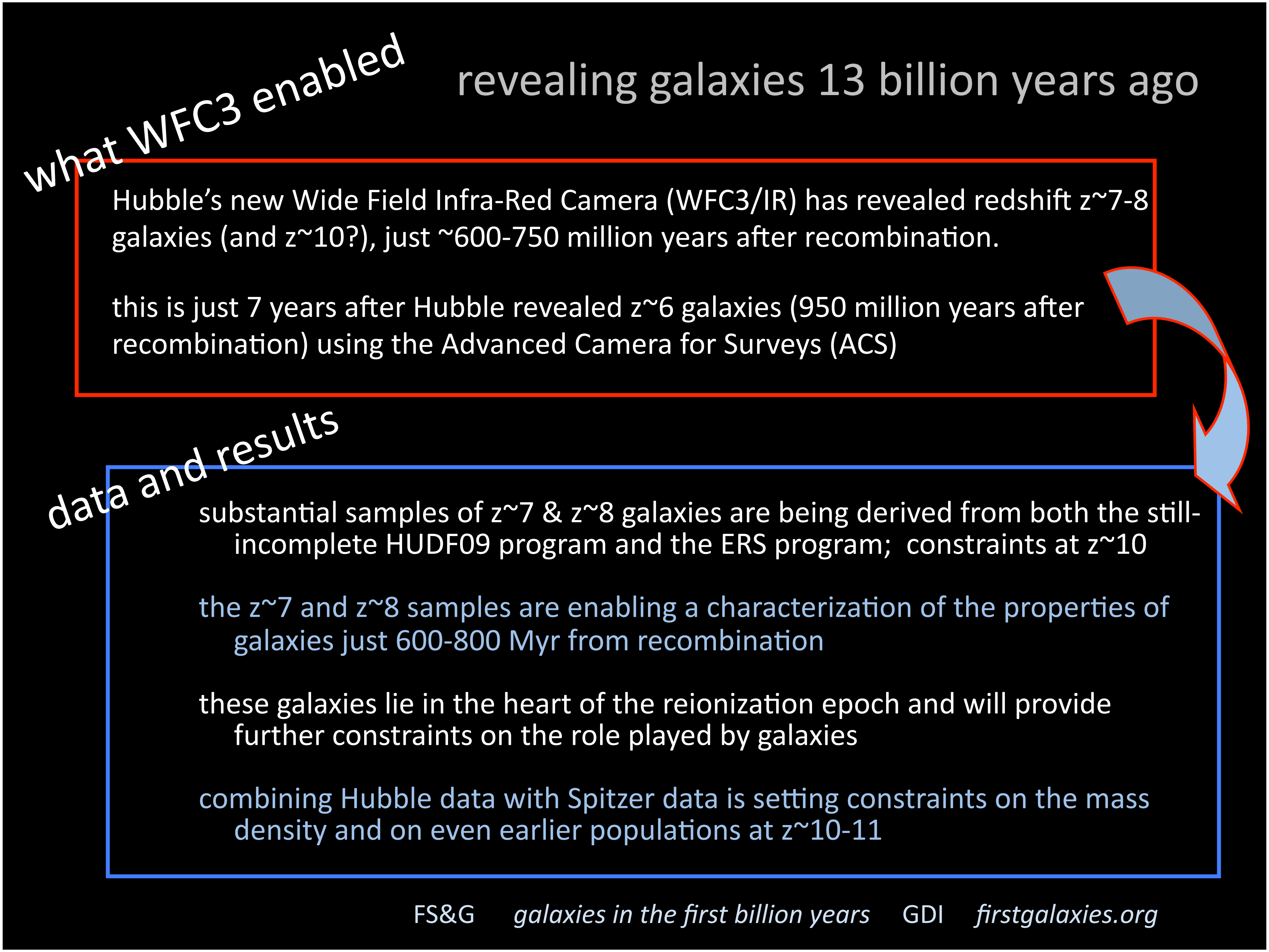
TEAM

these results are based on data from the original HUDF and the WFC3/IR and ACS cameras as proposed under GO11563 by the HUDF09 team:

G. Illingworth (UCO/Lick Observatory; University of California, Santa Cruz)
R. Bouwens (UCO/Lick Observatory and Leiden University)
M. Carollo (Swiss Federal Institute of Technology, Zurich)
M. Franx (Leiden University)
I. Labbe (Carnegie Institution of Washington)
D. Magee (University of California, Santa Cruz)
P. Oesch (Swiss Federal Institute of Technology, Zurich)
M. Stiavelli (STScI)
M. Trenti (University of Colorado, Boulder)
P. van Dokkum (Yale University)

a resource for high-redshift galaxies see:
firstgalaxies.org
http://firstgalaxies.org

for astro-ph links to papers see:
http://firstgalaxies.org/hudf09
firstgalaxies.org/hudf09

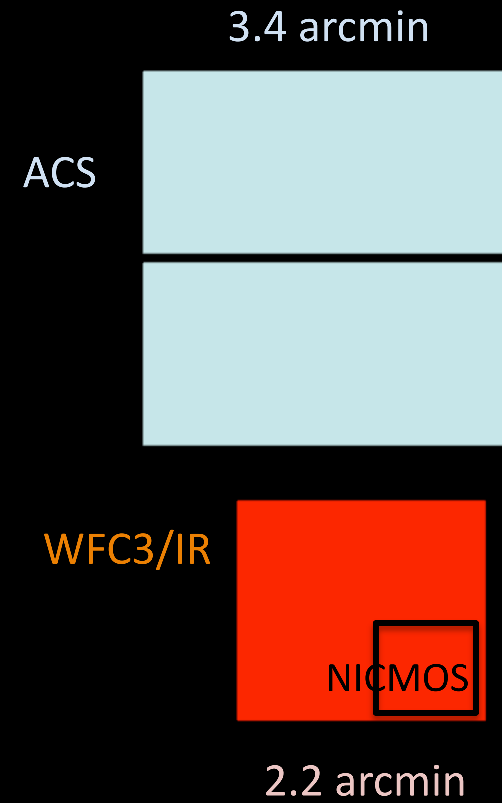

revealing galaxies 13 billion years ago
what WFC3 enabled
Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed redshift z~7-8 galaxies (and z~10?), just ~600-750 million years after recombination.
this is just 7 years after Hubble revealed z~6 galaxies (950 million years after recombination) using the Advanced Camera for Surveys (ACS)
data and results
substantial samples of z~7 & z~8 galaxies are being derived from both the still-incomplete HUDF09 program and the ERS program; constraints at z~10
the z~7 and z~8 samples are enabling a characterization of the properties of galaxies just 600-800 Myr from recombination
these galaxies lie in the heart of the reionization epoch and will provide further constraints on the role played by galaxies
combining Hubble data with Spitzer data is setting constraints on the mass density and on even earlier populations at z~10-11
FS&G galaxies in the first billion years GDI firstgalaxies.org

WFC3/IR *vs* NICMOS

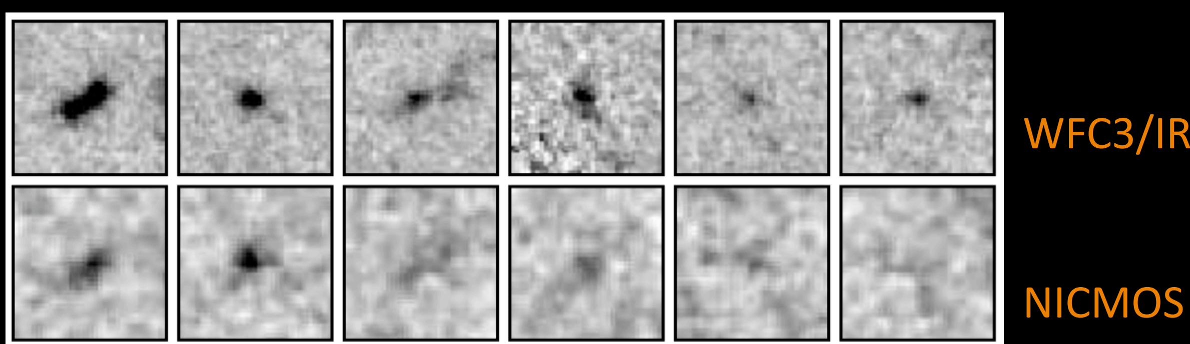
to find a z~7 galaxy took ~100 orbits with NICMOS – with WFC3/IR it takes a few orbits

WFC3/IR has a discovery efficiency ~40X NICMOS

WFC3/IR is ~6X larger in area than NICMOS and much better matches ACS



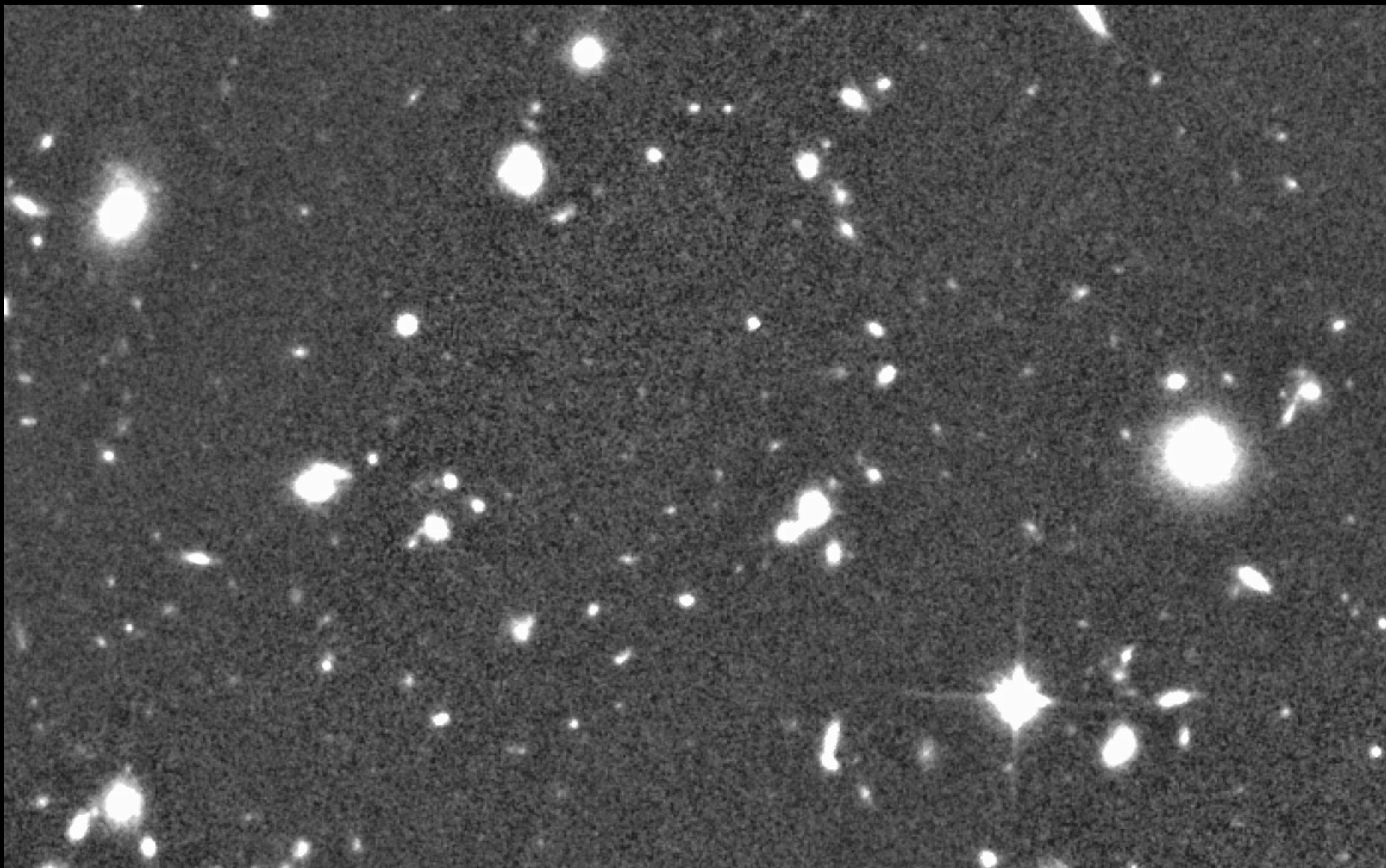
comparing the old and new Hubble infrared cameras



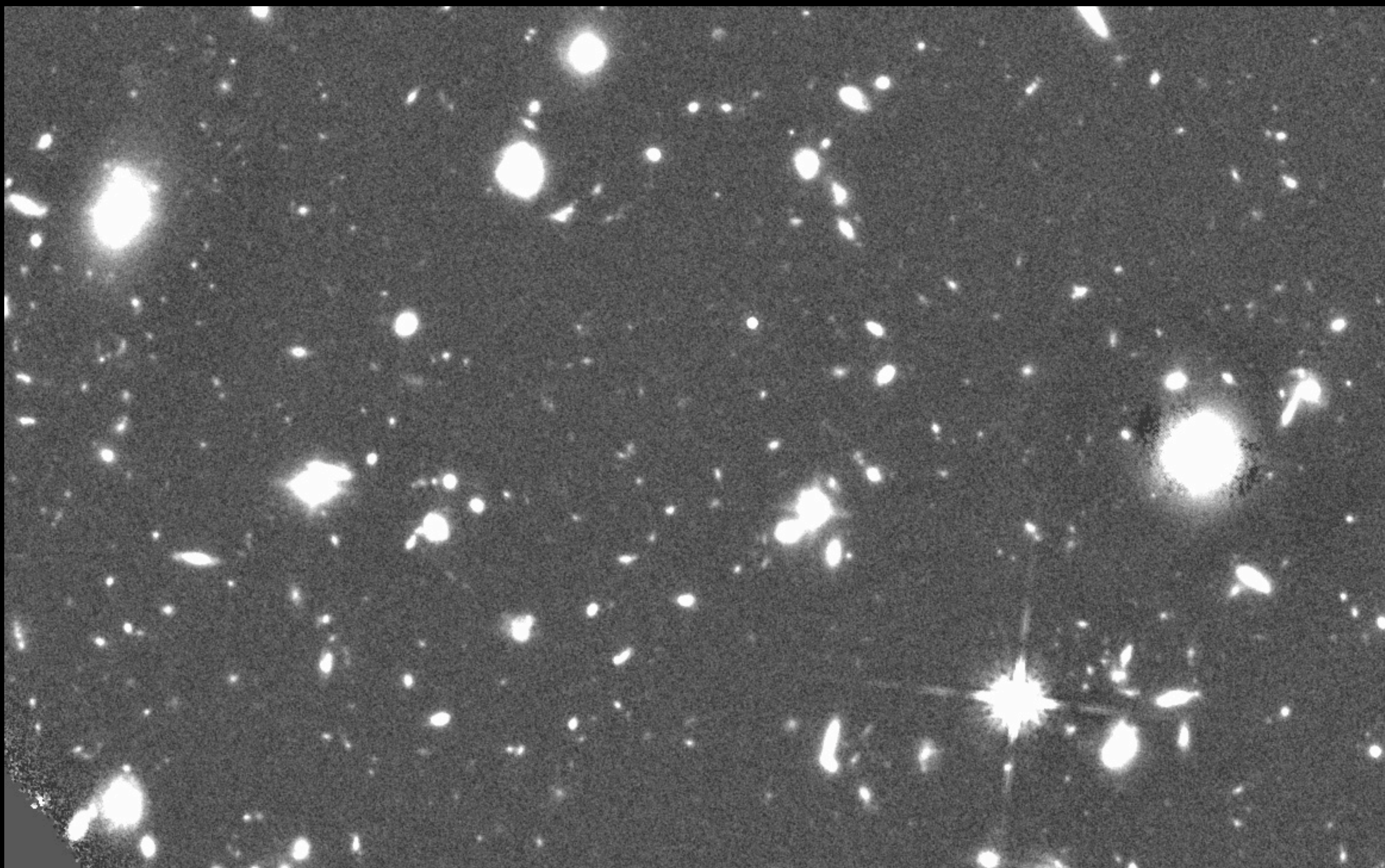
z~7 galaxies 2.2″ x 2.2″

Oesch et al

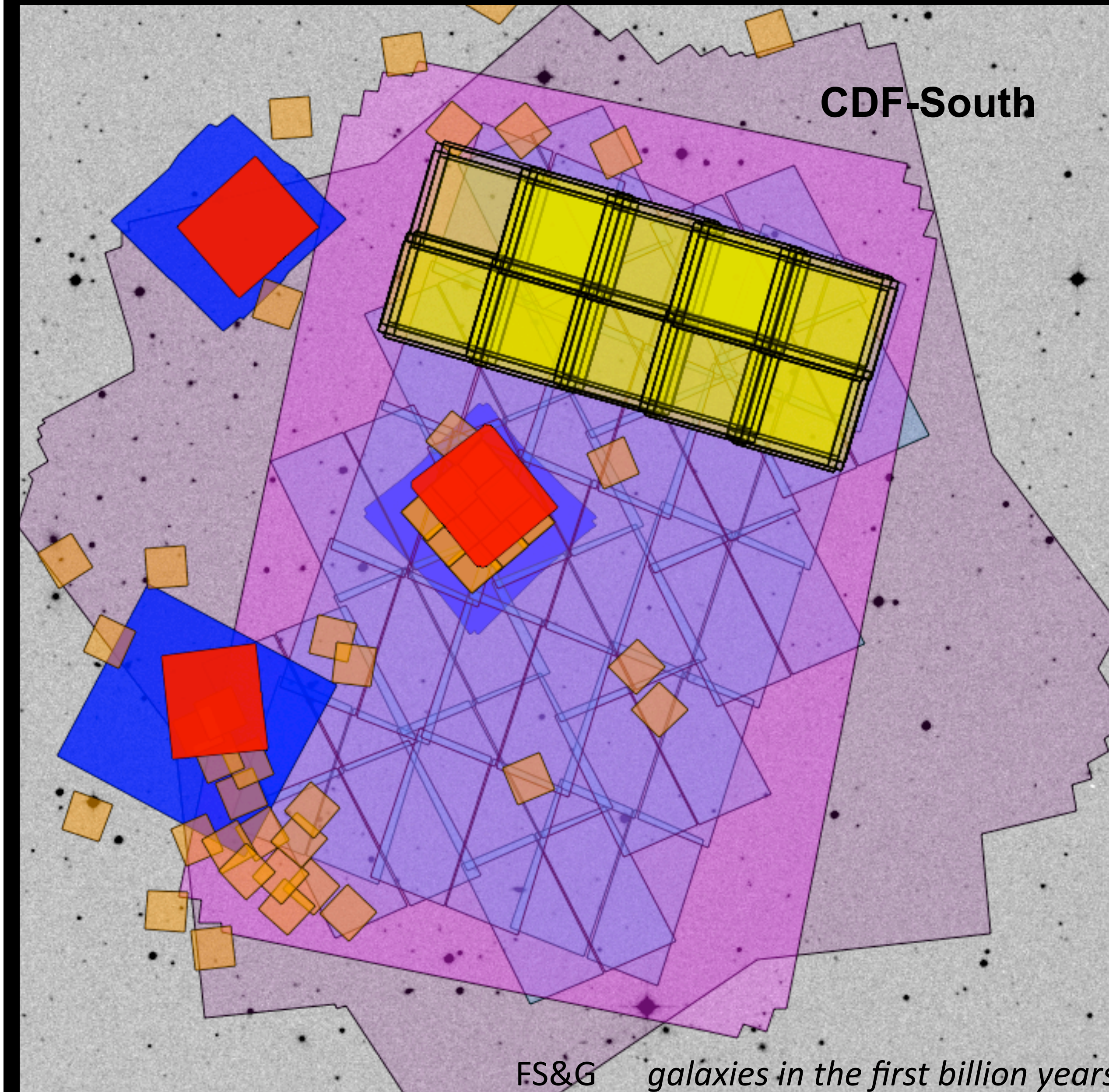
NICMOS – 72 orbits



WFC3/IR – 16 orbits



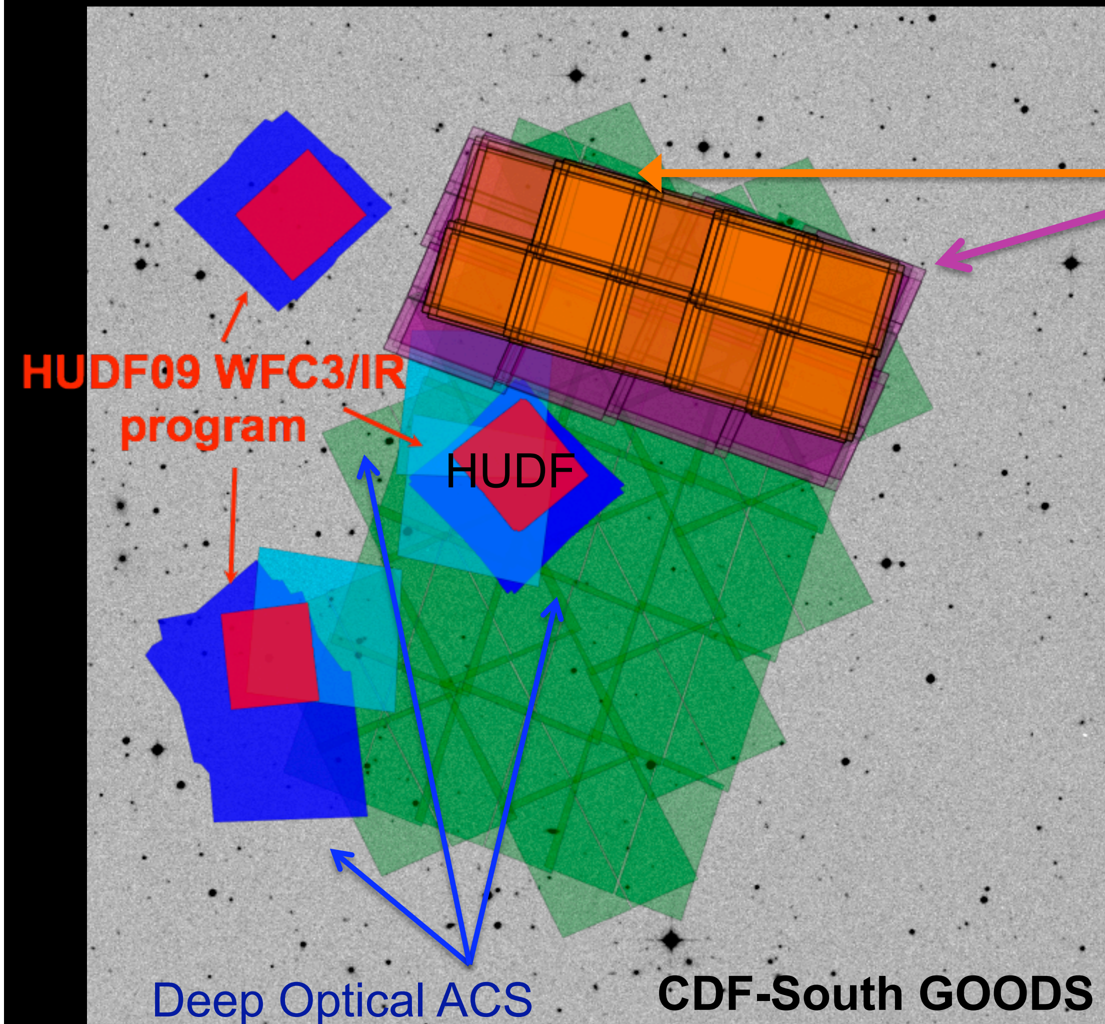
CDF-S region is rich in data (HST, Spitzer, Chandra, etc)



1999-2000+ Chandra CDF-S
2002-2003 ACS GOODS
2003 ACS HUDF
2003 NICMOS HUDF
2004 Spitzer GOODS
2003-2007 NICMOS
2005 HUDF05
2009 ERS
2009-2010 HUDF09

~22 x 22 arcmin

CDF-S region is focus for HUDF09 & ERS (WFC3 and ACS)



ERS data taken

~70% of HUDF09 data taken:

HUDF in august 2009

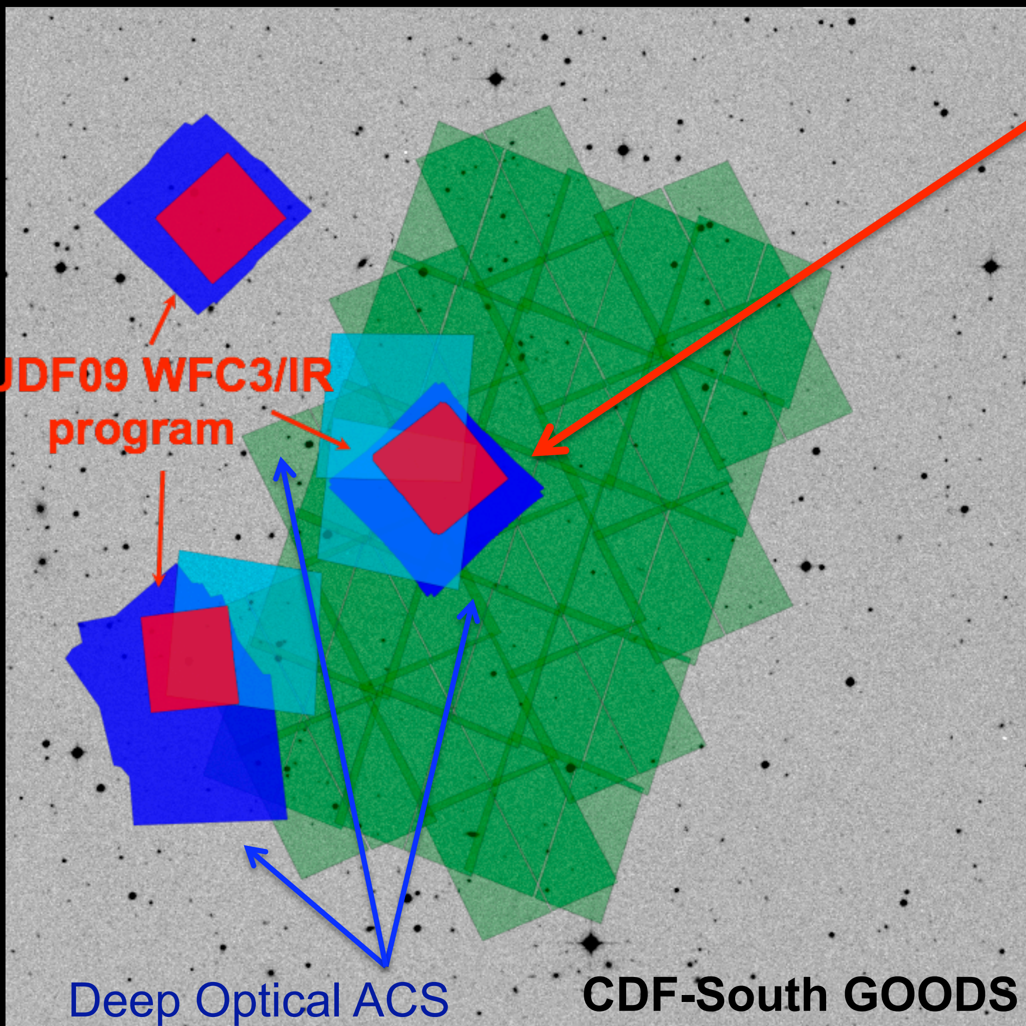
HUDF09-1 in nov 2009

HUDF09-2 in feb 2010

remaining data to be taken later in 2010

~20 x 20 arcmin

searches for z~7-8 objects in HUDF09



z~7-8 galaxies are just 600-800 million years from t=0

HUDF09 WFC3/IR data taken in late August 2009

very competitive area!

within two weeks three groups had submitted papers on z~7-8 galaxies, followed within a month by a fourth group, and then by a fifth group in Dec

Bouwens et al   Oesch et al

Bunker et al

McLure et al

Yan et al

Finkelstein et al

galaxies at z~8 from the HUDF09 team

the two highest redshift z~8 galaxies

ACS filters WFC3/IR

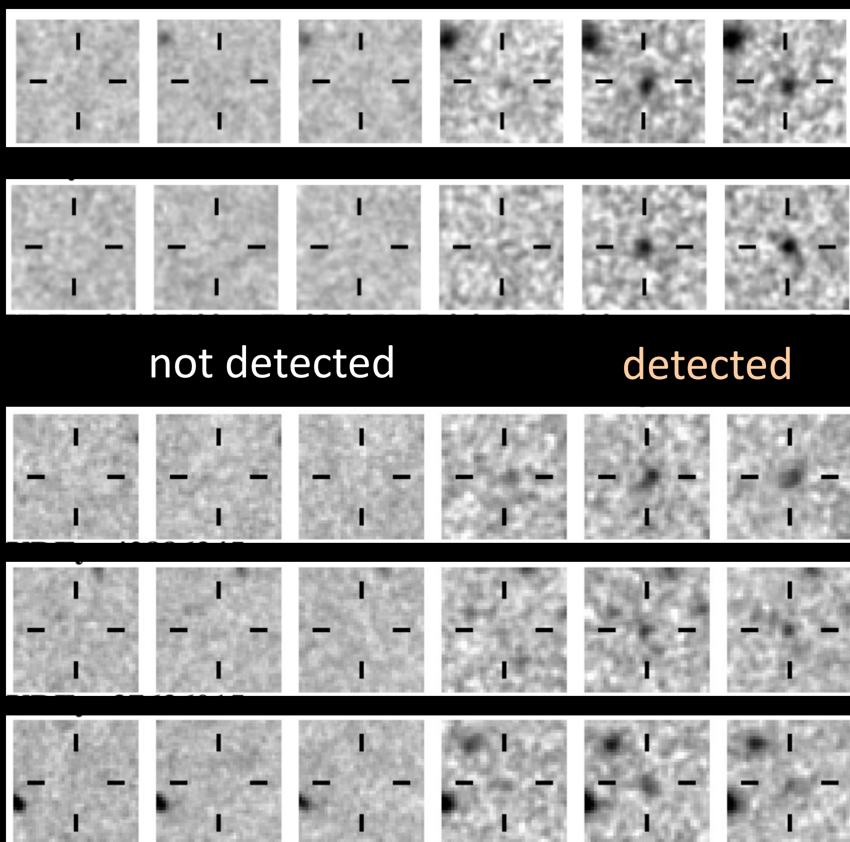
V i z Y J H

redshift

z~8.4

z~8.7

not detected detected



the other three z~8 galaxies

all are H~28-29 mag sources!

2.4" x 2.4"

searches conducted using the very robust and well-tested photometric "dropout" technique

Dropouts verified spectroscopically at z~2-6

extensive testing for contamination from photometric scatter, spurious sources, lower redshift sources….

WFC3/IR resolution helps separate galaxies from (rare) faint stars

Bouwens, Illingworth et al

HUDF09 team found 16 z~7 and 5 z~8 galaxies

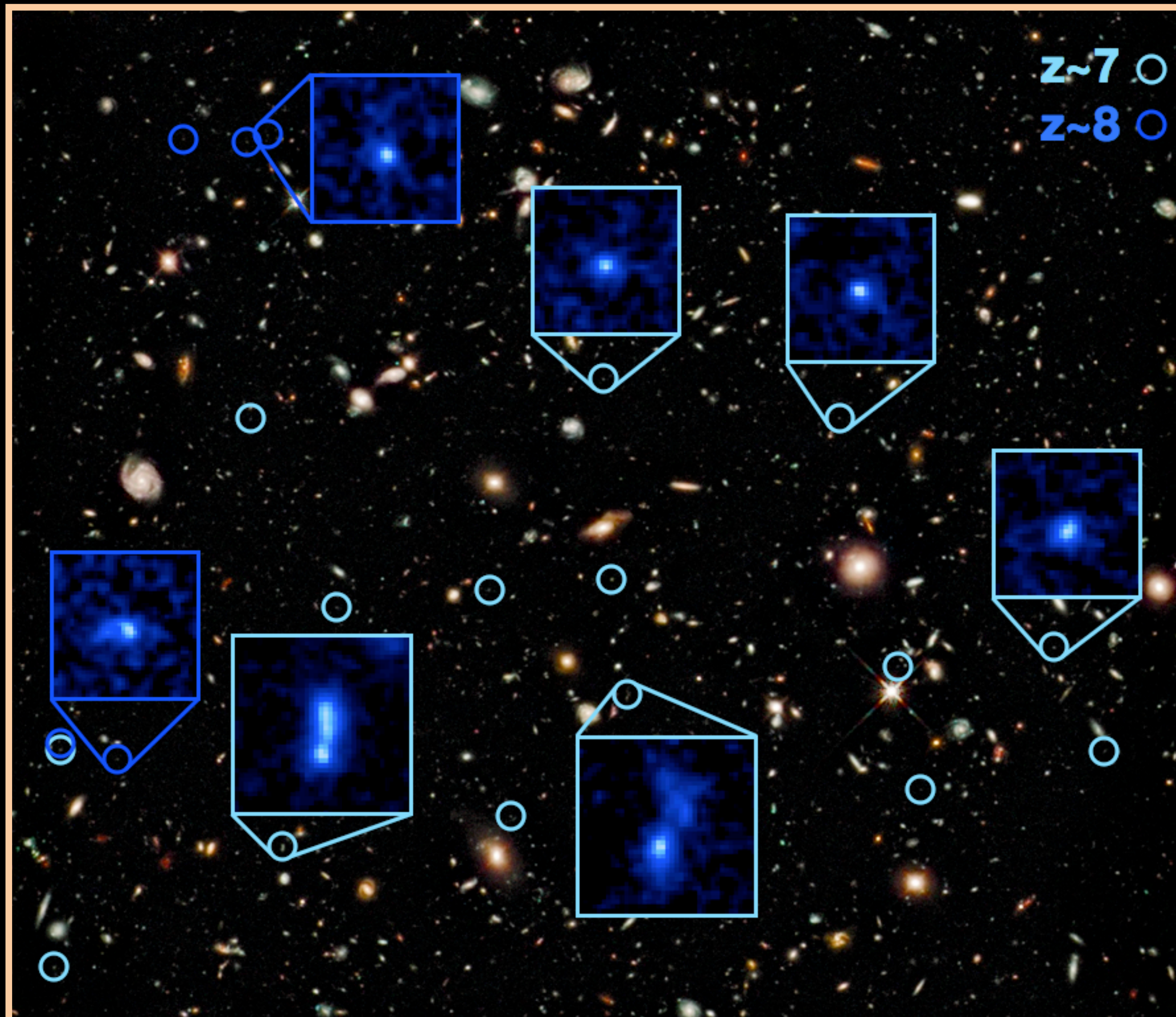
HUDF09
WFC3/IR

HUDF09
image ~2.2′

boxes ~2.5″

z~8
Bouwens et al

z~7
Oesch et al



FS&G *galaxies in the first billion years* GDI *firstgalaxies.org*

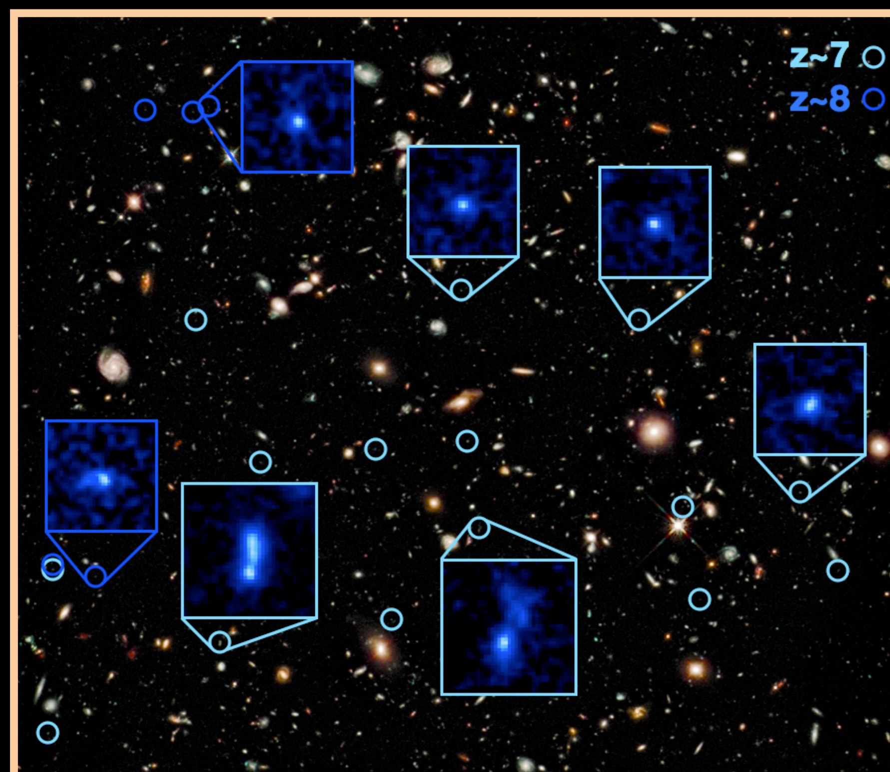
number of z~7 & z~8 galaxies is increasing quickly

using all current data (ERS and HUDF09) sample is now significantly larger. To date we have ~100 z~7 and z~8 galaxies from the combined ERS and HUDF09 observations

updated z~7 and z~8 sample in Bouwens et al (2010)

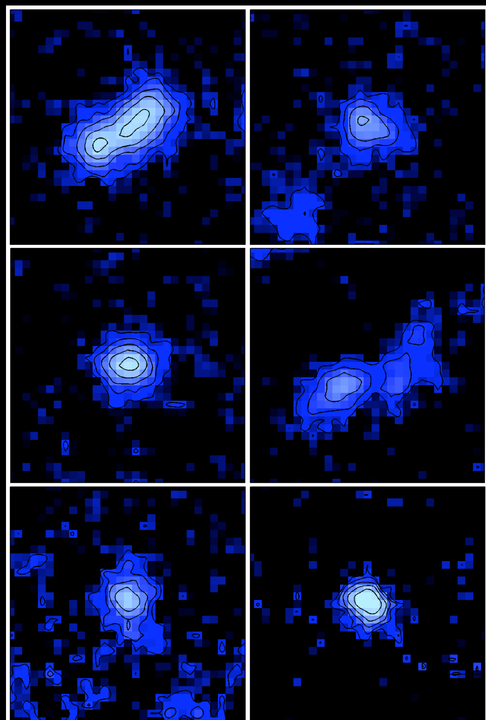
see Rychard's talk for new results from larger ERS/HUDF09 sample

HUDF09 WFC3/IR



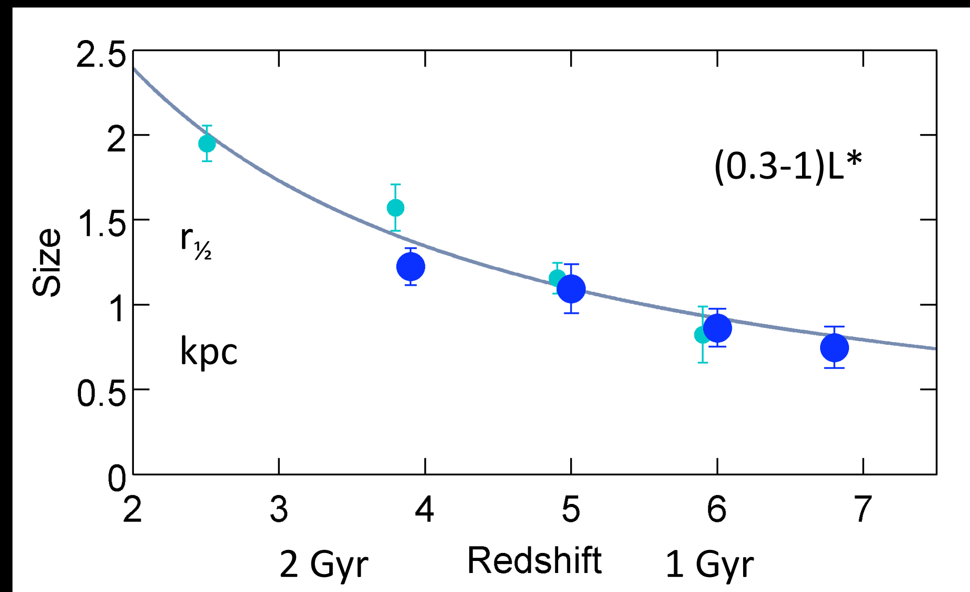
HUDF09 image ~2.2′

these early galaxies are small



1.8″ x 1.8″

Oesch/Carollo et al

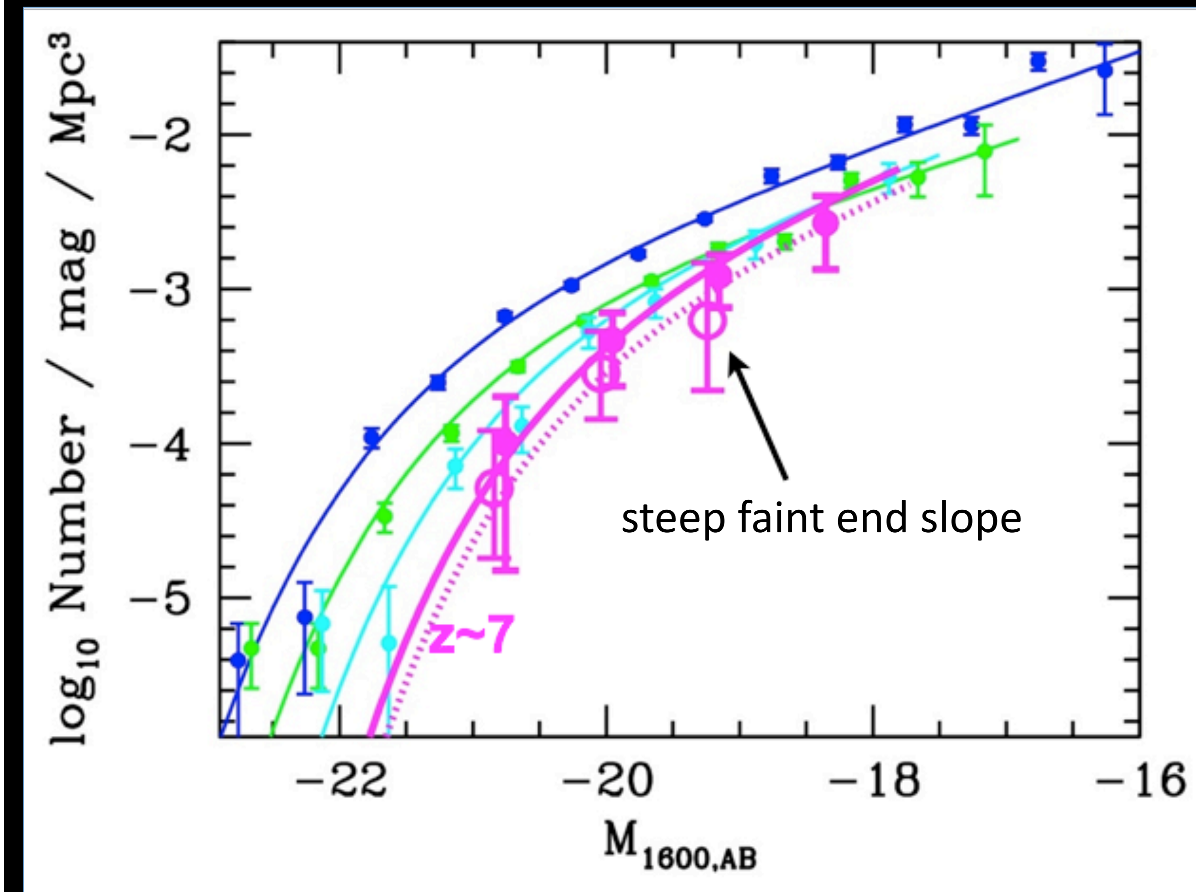


z~7 galaxies show considerable sub-structure

size scales as $(1+z)^{-m}$ where m = 1.12 ± 0.17

galaxies become very small at early times – does not appear to be a surface brightness effect (from simulations on lower redshift sources and stacking analysis)

luminosity functions



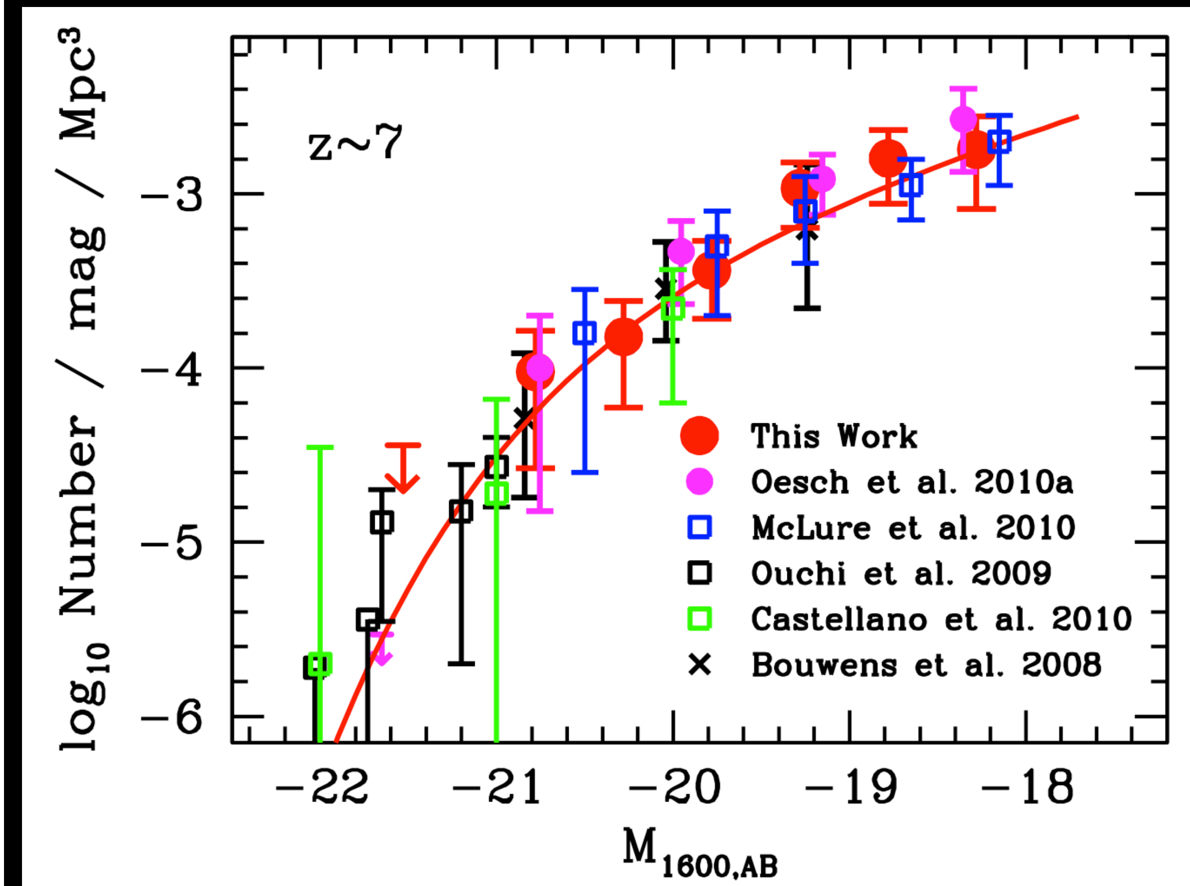
luminosity functions (LF) are key for determining the UV luminosity density and star formation rate densities

existing z~4-6 luminosity functions show that the slope is very steep at the faint end below L* (α ~ -1.75)

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

the changes in the LF with redshift are primarily at the bright end.

luminosity functions

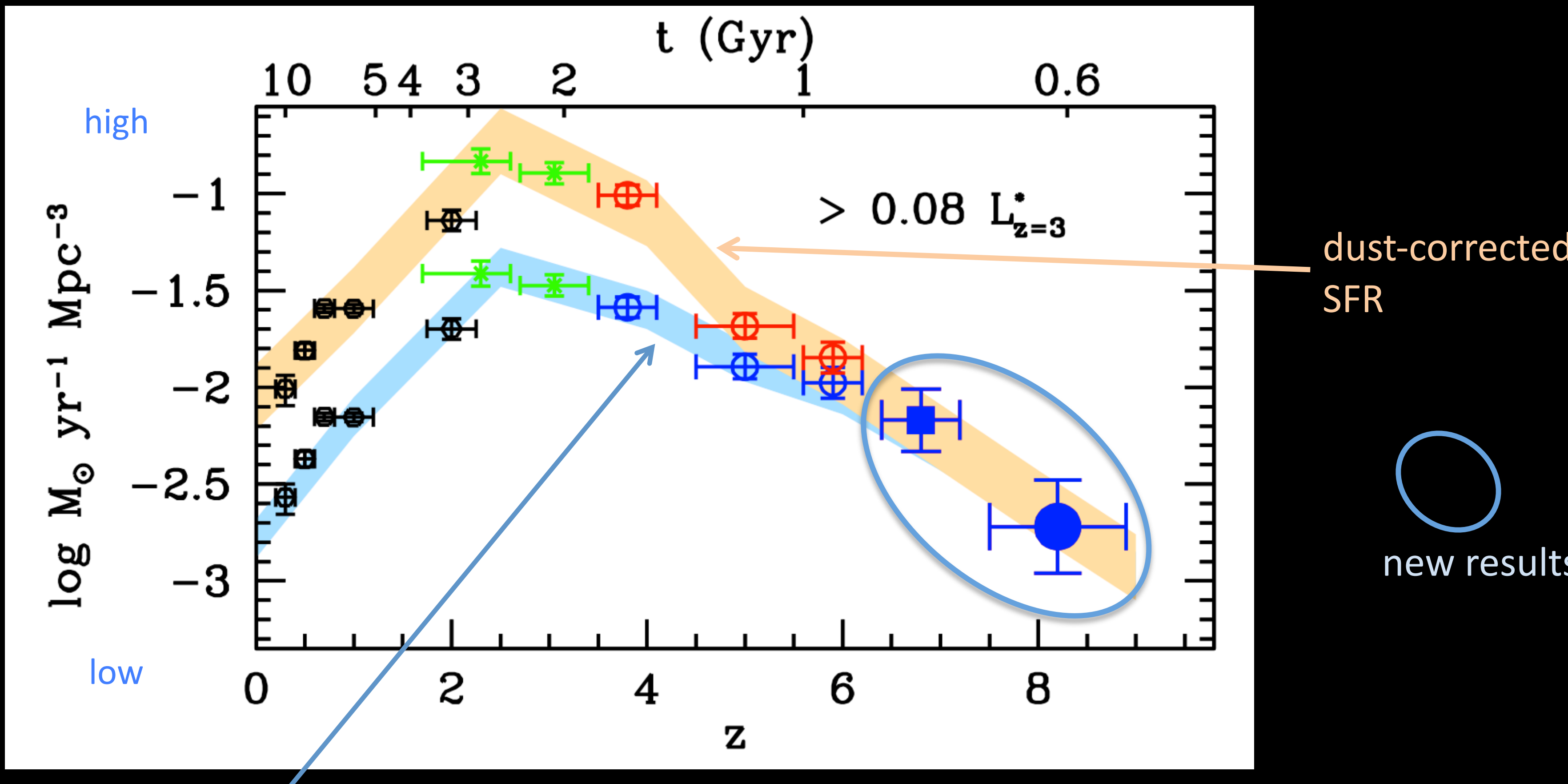


luminosity functions at z>7 are very important for establishing role of galaxies in reionization

excellent agreement now between the several groups

the new z~7 luminosity function indicates that the very steep slope (α ~ -1.75) seen at lower redshift persists to higher redshift

the star formation rate density

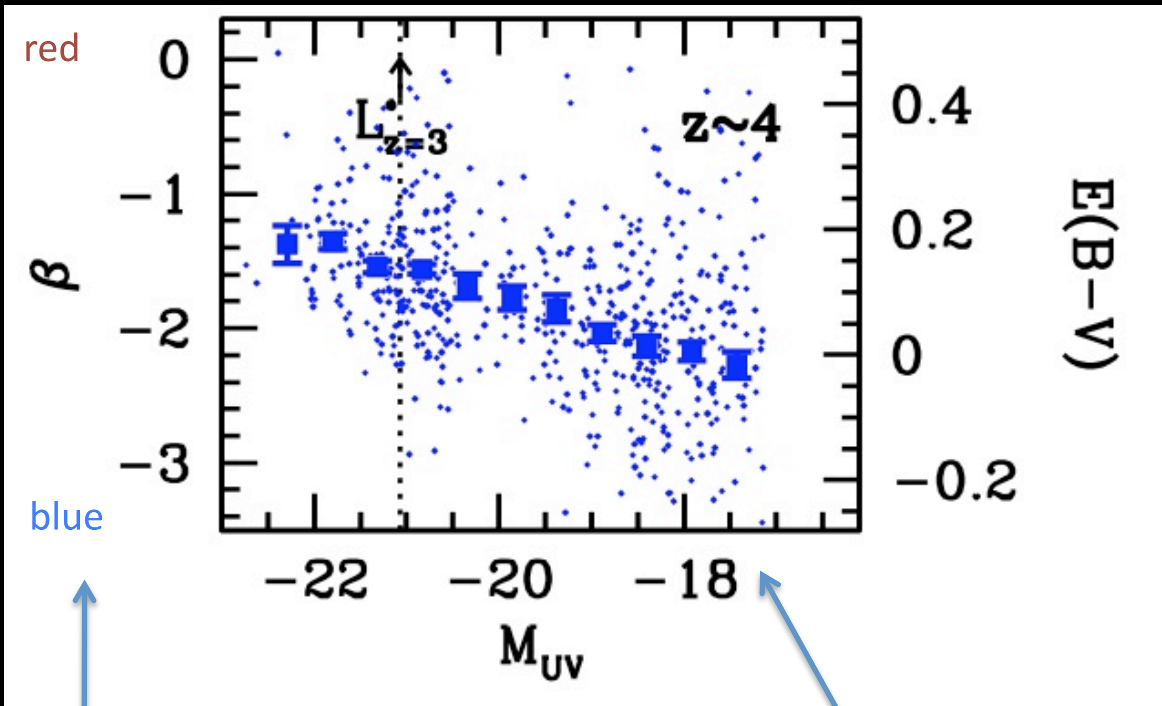


UV luminosity density

Bouwens/Illingworth et al

the history of star formation in galaxies in the universe

the UV continuum slope is a powerful tool



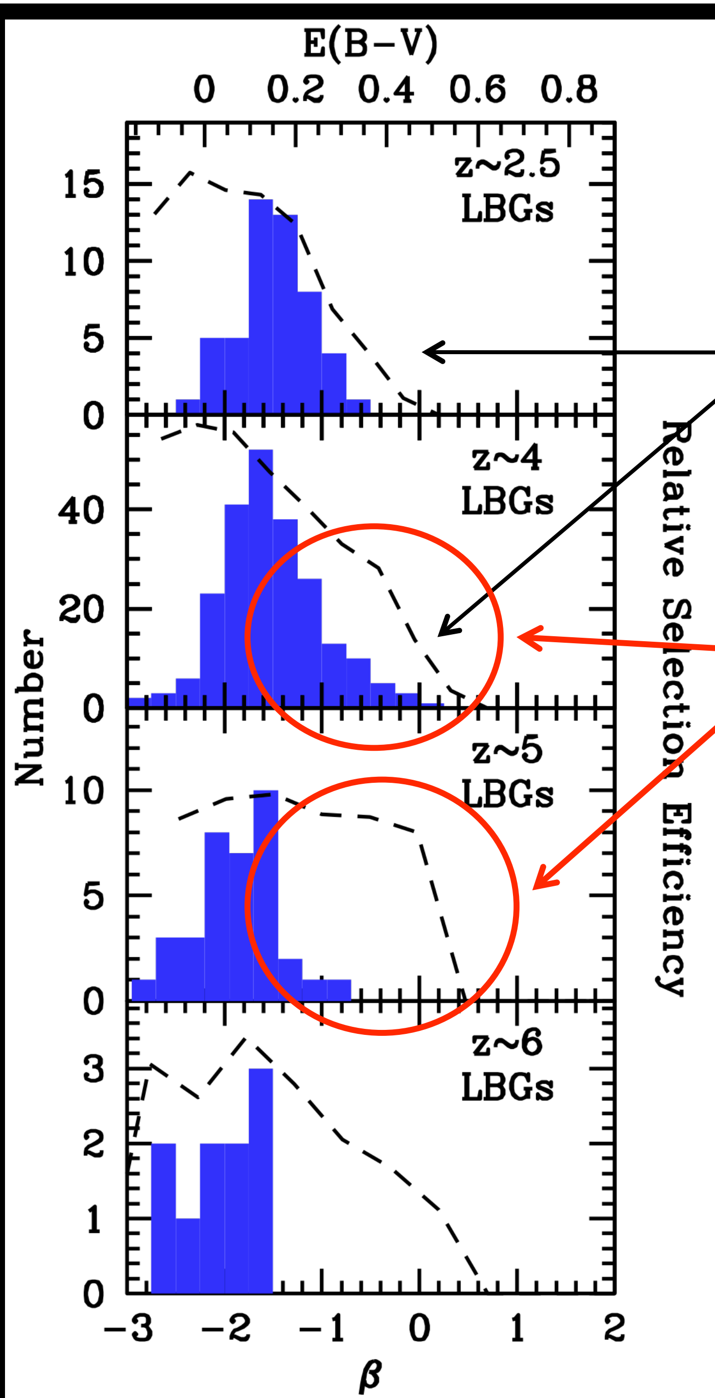
z~4-6 results last year built on ACS data in HUDF and GOODS

β is the power law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

low luminosity galaxies become quite blue, even at z~4

Bouwens/Illingworth et al 2009 ApJ 705

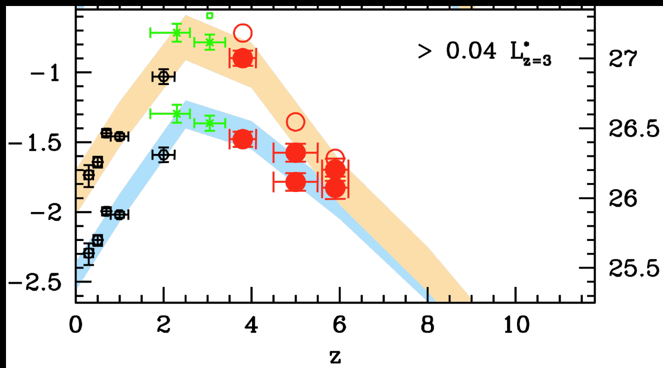
evolved galaxies not significant at z>4?



selection efficiency

"*redder*", evolved sources could be detected in these ~0.1L* to ~2L* samples at z~4 and z~5+

there is *NOT* a continuum of UV slopes: => if there are evolved galaxies or dusty galaxies at z>4 they must have *distinctly* different UV properties or be quite rare

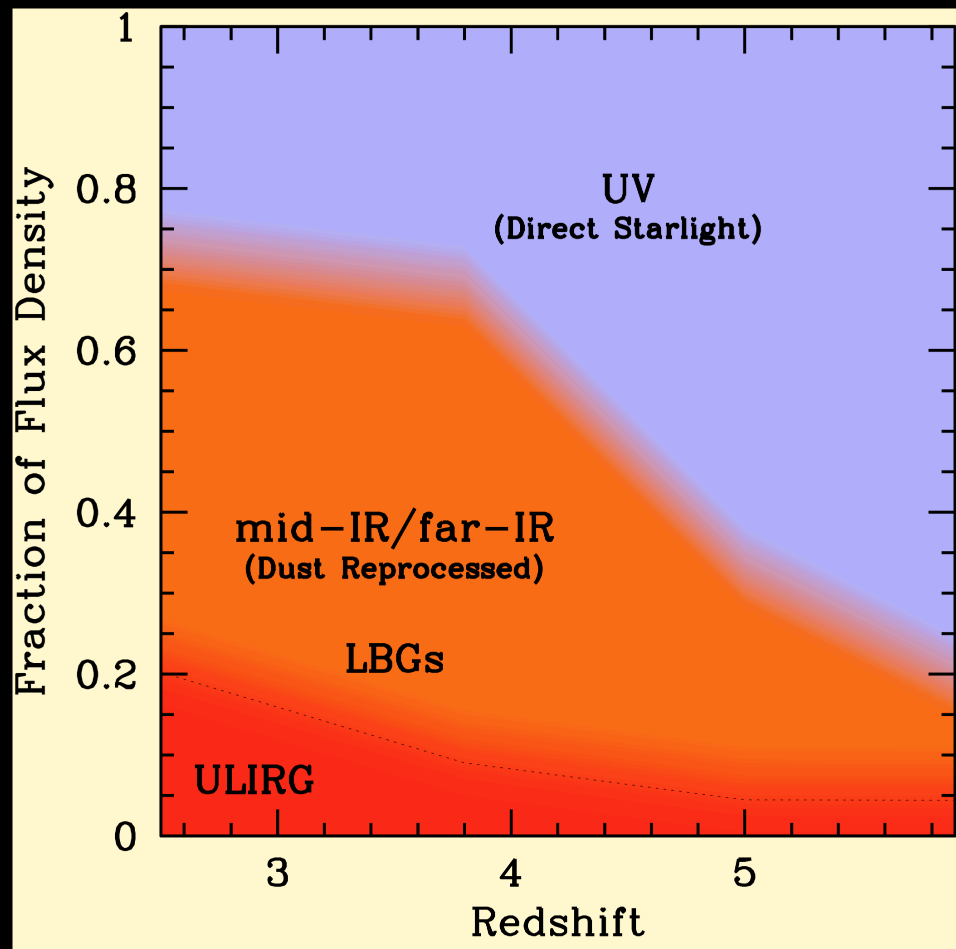


flux density in UV & IR

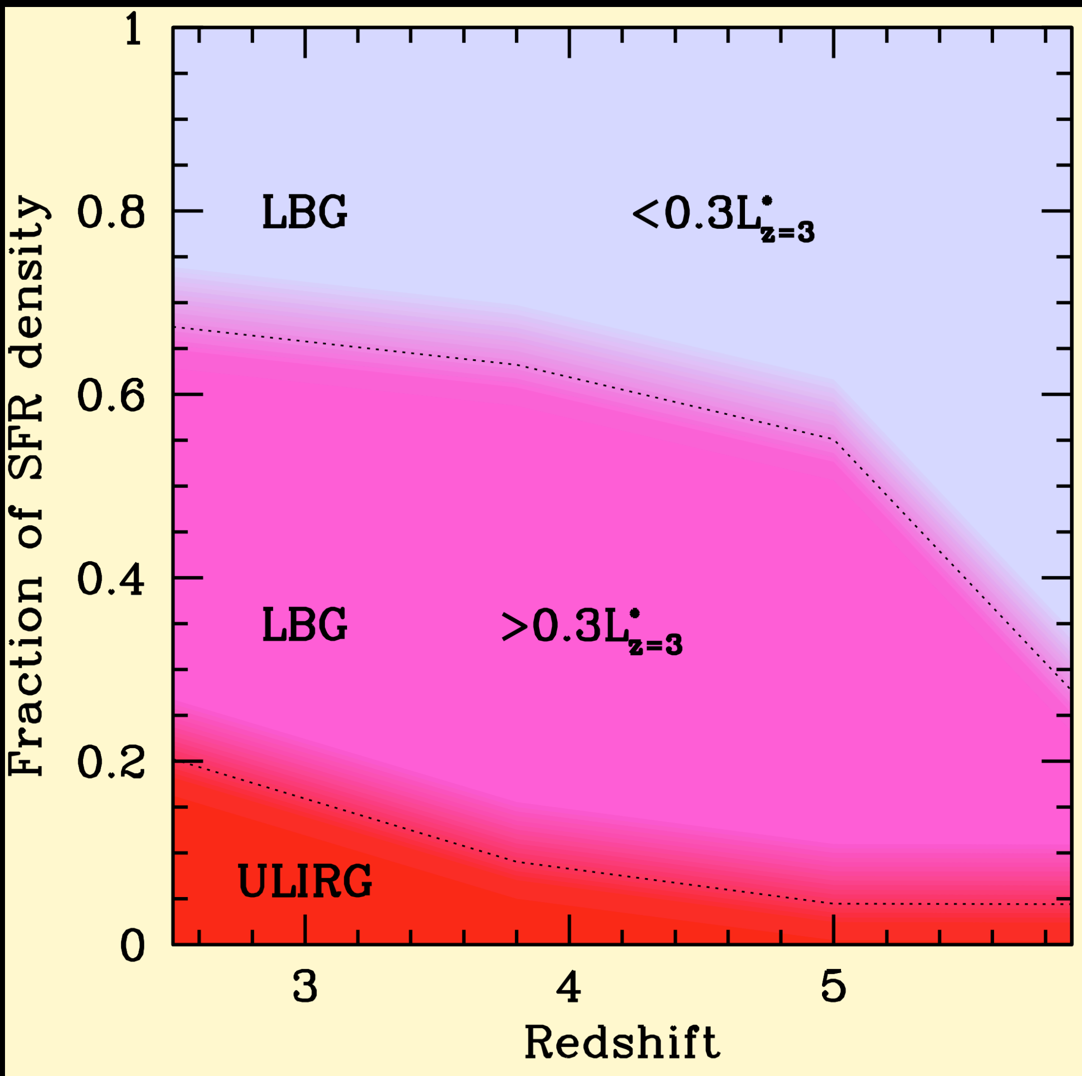
for star forming galaxies...

>80% of energy output in UV & IR at high redshift can be derived from UV detected sources

ULIRG estimate based on z~2 24 µm LF by Caputi et al. (2007: see Reddy and Steidel 2009) and from Daddi et al. (2009) sample at z~4



the star formation rate density from z~6 to z~2.5: LBGs and ULIRGs/SMGs



ULIRG estimate based on z~2 24 μm LF by Caputi et al. (2007: see Reddy and Steidel 2009) and from Daddi et al. (2009) sample at z~4

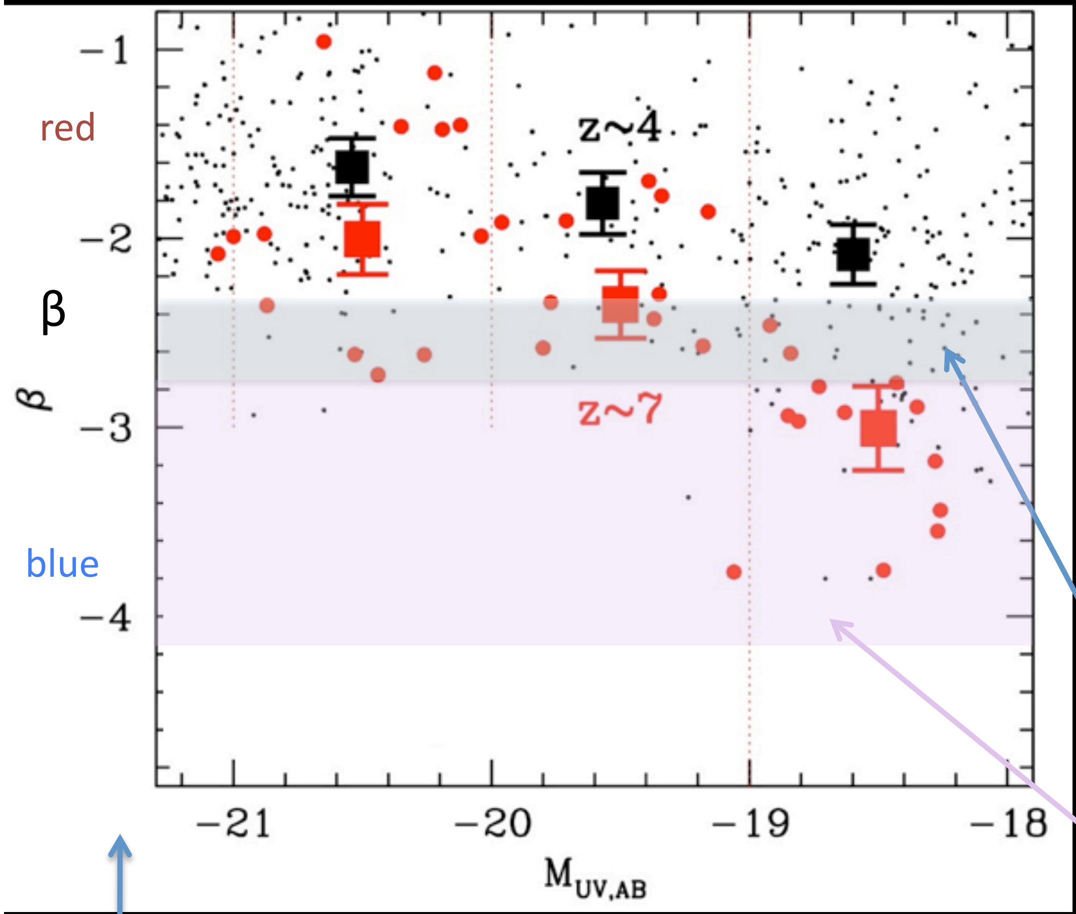
Faint LBGs

Bouwens/Illingworth et al 2009 ApJ 705

Luminous LBGs

ULIRGs/SMGs

z~7 galaxies are very blue at low luminosity



UV-continuum slope β depends upon the age, metallicity, and dust content of a star-forming population

UV-continuum slope β most sensitive to changes in dust content

but recent studies have shown that the dust content of lower luminosity, z>6 galaxies must be essentially zero

dust free at β < ~-2.4

at β < ~-2.8 standard population models are challenged (even low metal abundance models)

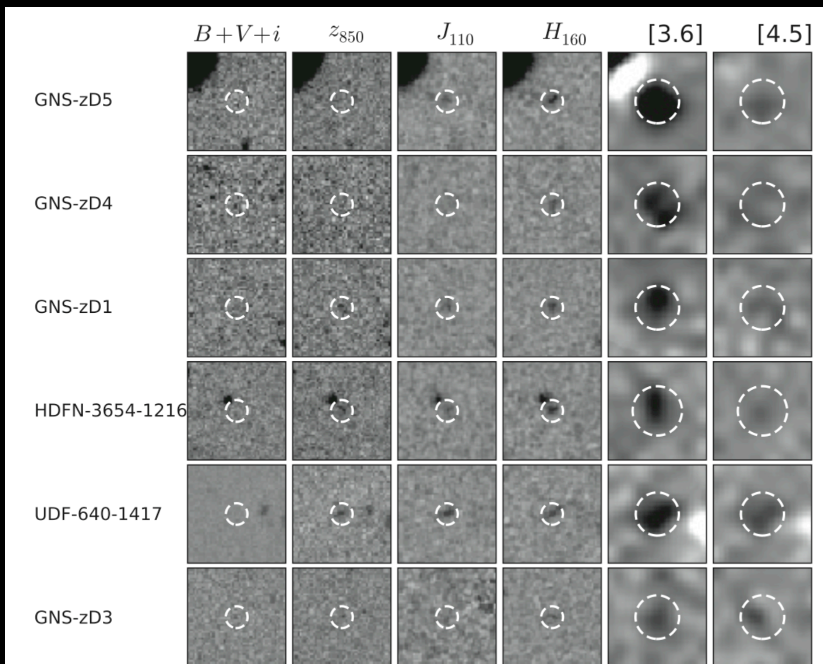
β is the power law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

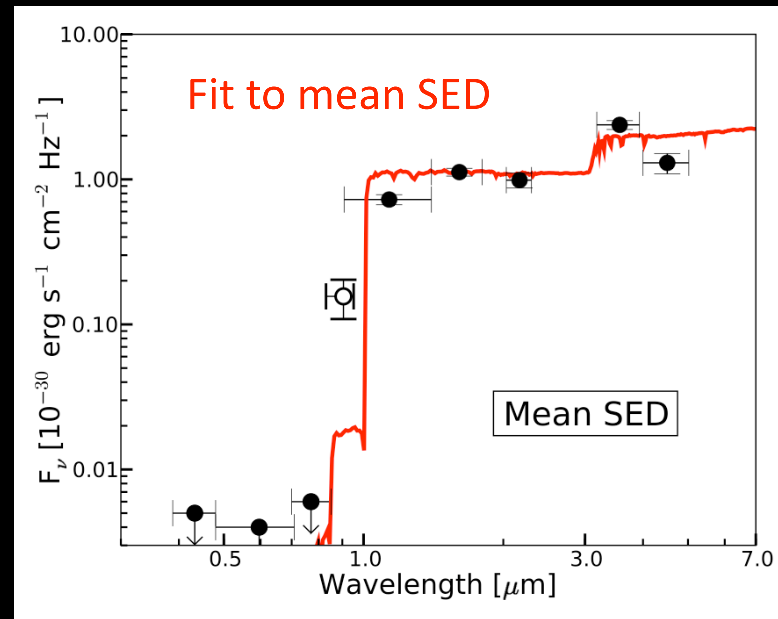
Bouwens/Illingworth et al

see Rychard's talk

striking results at z~7 from HST + Spitzer

HST NICMOS and Spitzer IRAC detections of 11 z~7 galaxies



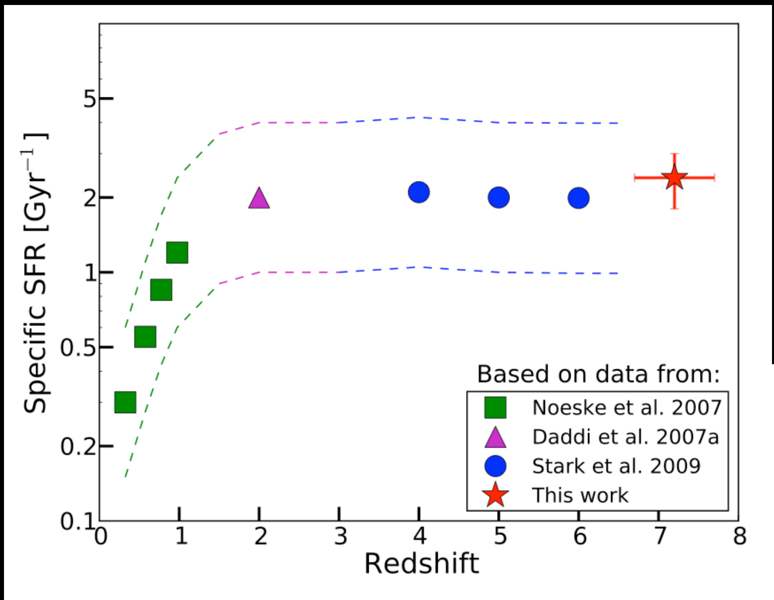


stellar mass density at z ~ 7 is $4.5 \times 10^5\ M_\odot\ Mpc^{-3}$

Gonzalez, Labbé, Bouwens, Illingworth et al

Model fits are BC03 CSF $0.2Z_\odot$ z~7 and ~300 Myr (SFH weighted age = t/2) with ~zero dust

these galaxies probably formed stars much earlier



Specific SFR (SFR/Mass) – derived from listed studies

average age is 300 Myr!

constant SSFR at z>2 – strikingly so

Gonzalez, Labbé, Bouwens, Illingworth et al

Table 4
Key Results Derived from $z \sim 7$ Sample

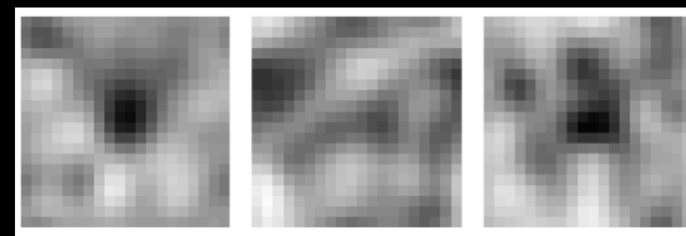
Quantity	Value
Redshifts	7.2 ± 0.5
Masses	$0.1–12 \times 10^9\ M_\odot$
M/L_{UV} ratio	$0.01–0.1\ M_\odot/L_\odot$
Minimum age[a]	80 Myr
Average age	300 Myr
UV-continuum slope β	-2.4 ± 0.4
SSFR	$2.4 \pm 0.6\ Gyr^{-1}$
Mass density (direct)	$5.7 \times 10^5\ M_\odot$ Mpc^{-3}
Mass density (M/L of mean SED)	$4.5 \times 10^5\ M_\odot$ Mpc^{-3}
Mass density (random M/L)[b]	$6.6^{+5.4}_{-3.3} \times 10^5\ M_\odot$ Mpc^{-3}
Predicted SFR density (at $z = 9$)	$0.0011\ M_\odot$ yr^{-1} Mpc^{-3}

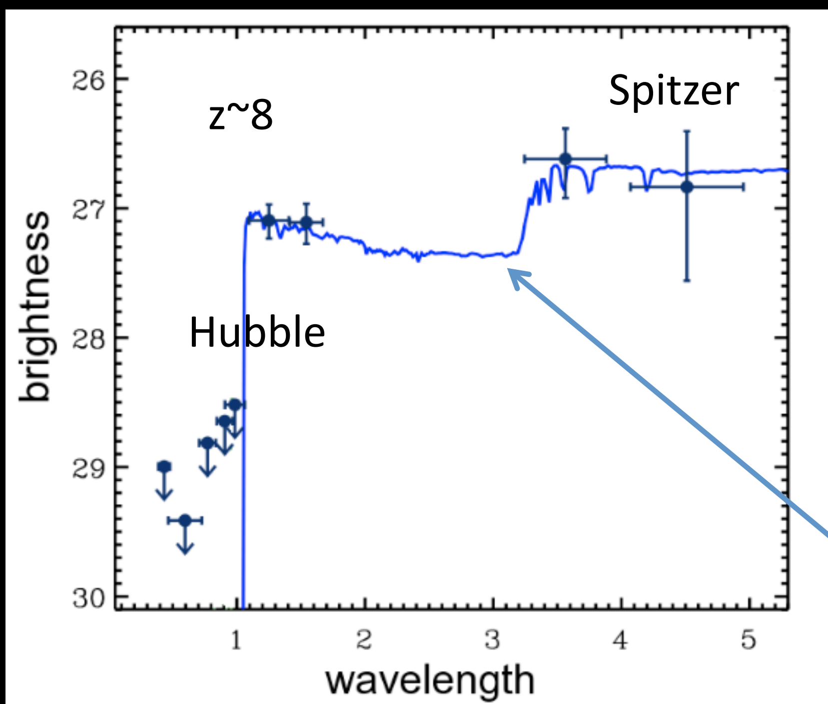
Notes.
[a] From single burst models.
[b] Our best estimate.

these galaxies probably formed stars much earlier

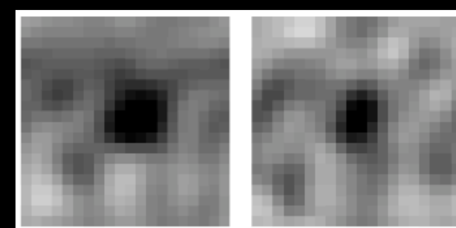
WFC3/IR Hubble and Spitzer results also combine to show us that z~8 galaxies could well have been forming stars two-three hundred million years earlier (at z>10-11)

some individual z~8 Spitzer 3.6 μm images





z~8 summed Spitzer images

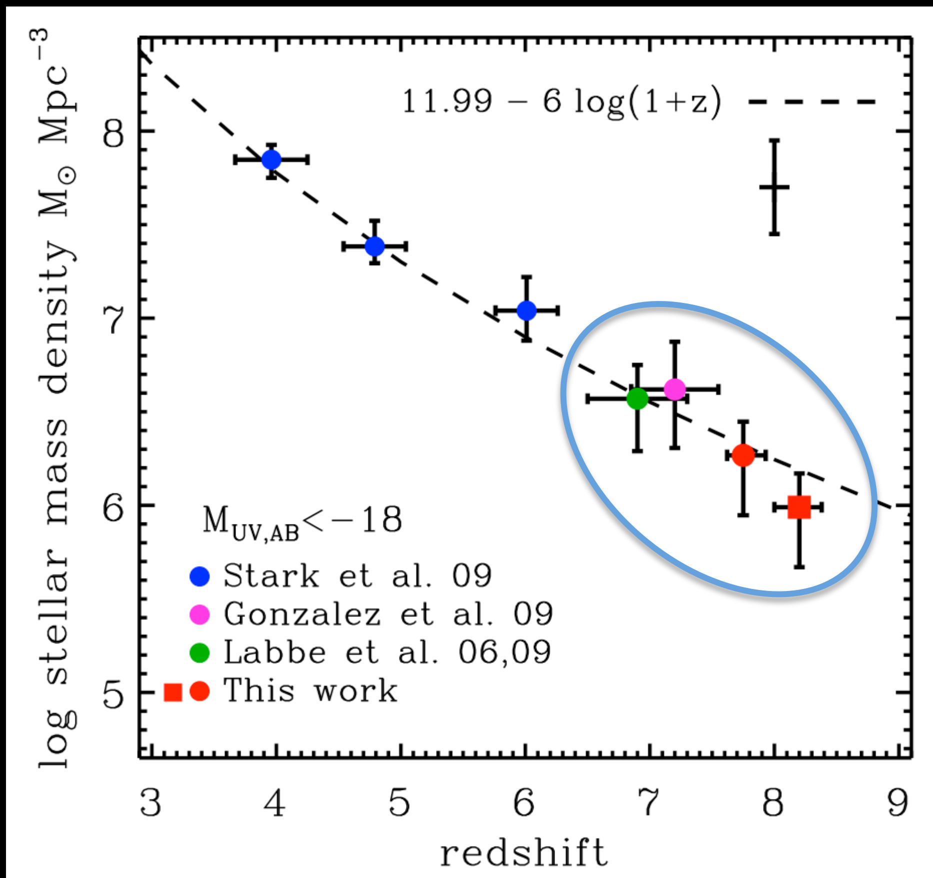


3.6 μm 4.5 μm

Labbé/Gonzalez et al

Model fit is BC03 CSF $0.2Z_{\odot}$ log M = 9.3
z~7.7 and 300 Myr (SFH weighted age = t/2)

mass buildup over time



the Hubble and Spitzer data allow us to establish the evolution of the mass density at these early times

see papers by Gonzalez et al and Labbé et al

our new results

the history of the mass buildup in galaxies in the universe

Labbé/Gonzalez et al

lots of reasons to expect galaxies at z~10+

can we find galaxies at z~10?

can we find galaxies at z~10?

the answer is an unequivocal ***MAYBE!***

can we find galaxies at z~10?

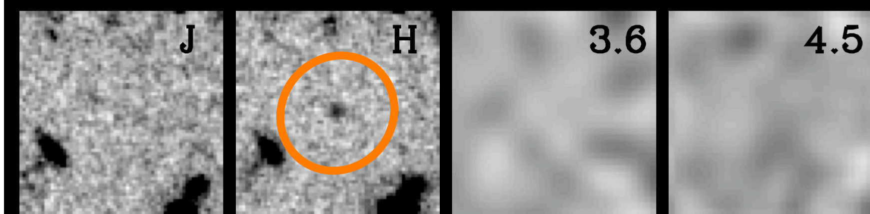
the answer is an unequivocal ***MAYBE!***

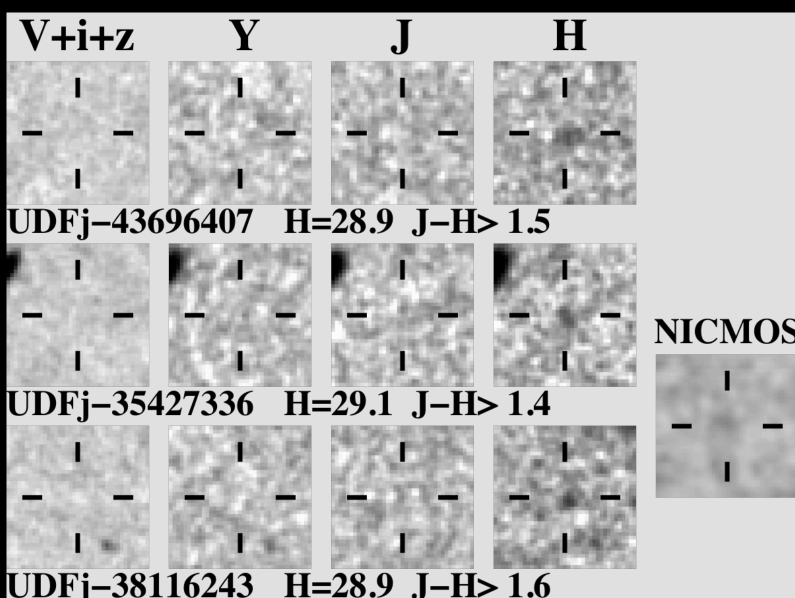
it is very challenging with the current dataset……

challenging or not – what do we see at z~10?

Bouwens/Illingworth & HUDF09 team

Stacked J & H image + Spitzer IRAC





recent results from Yan et al suggested that z~10 galaxies existed in large numbers – this appears not to be the case

we recently reported the possible detection of 3 z~10 sources

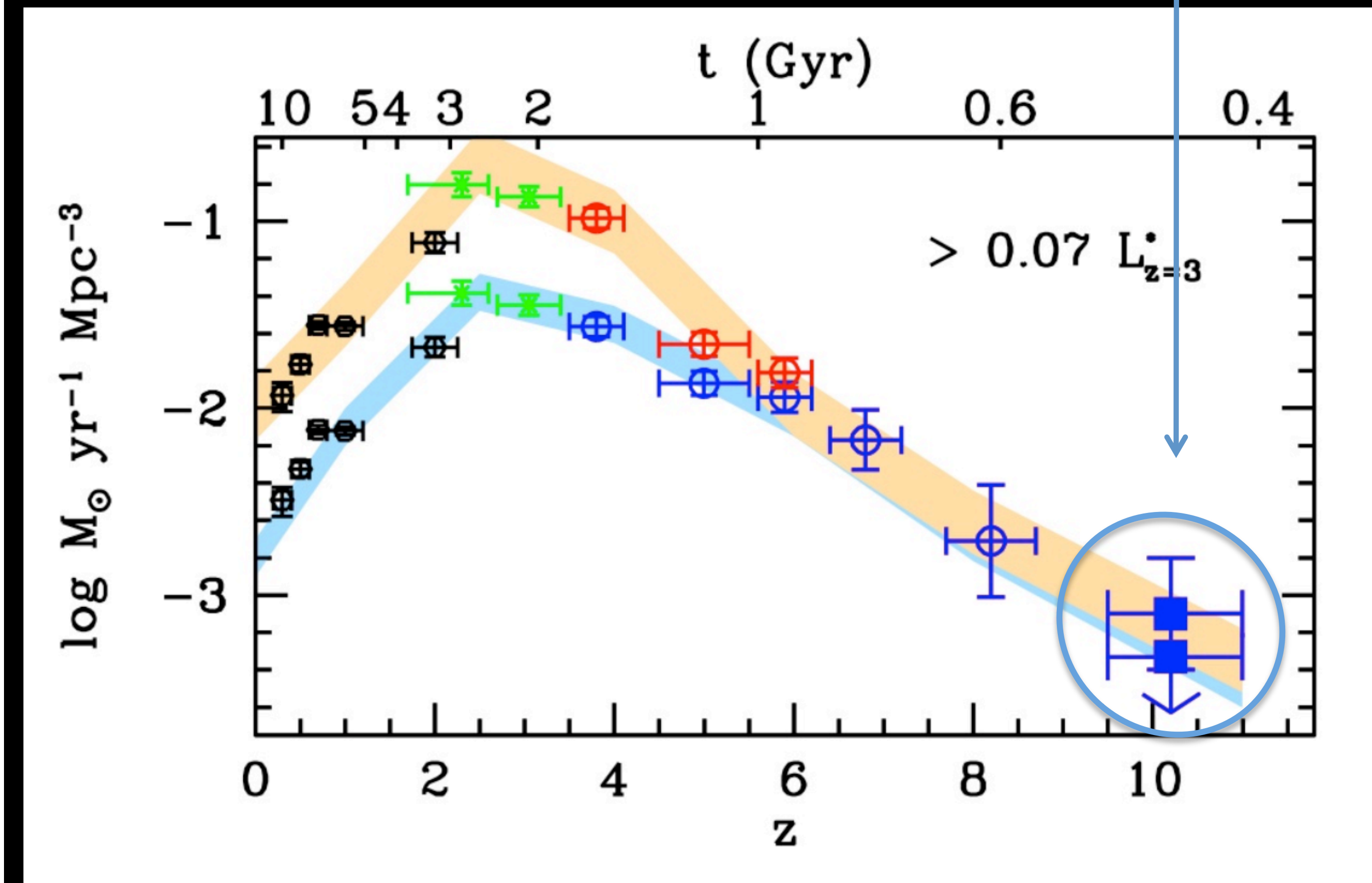
note detection in stack of two of three that are in earlier independent NICMOS data

these sources are detected at >5σ in the WFC3/IR H band – as a cross check we searched for similar, single-band >5σ sources in exactly the same way in just the WFC3/IR J-band: we found NONE

extensive testing for spurious sources, contamination, effects of noise… …looks OK, but "probably" is still the right answer

constraints at z~10

after correcting for our estimate of the contamination (~1.2 source), we derived constraints on the star formation rate density, and also set an upper limit from the current HUDF09 data



Bouwens/Illingworth & HUDF09 team

upper limit is very robust, even if detections are uncertain

what these new observations tell us

SUMMARY

Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed many galaxies 13 billion years ago (at redshifts z~7 and z~8), just 600-800 million years from the big bang

- these galaxies are small, low mass objects (half-light radii of just 0.7 kpc at z~7-8)
- they are extremely blue in color and are probably quite deficient in heavier elements
- they give us estimates for the mass density and the star formation rate density that extends from just ~5% of the age of the universe
- combining these results with Spitzer data suggests that these galaxies were forming stars ~200-300 million years earlier, at z>10-11 (with recent possible detections being found at z~10)
- these galaxies fall in the heart of the "reionization" epoch, but our estimates are still low for the contribution of galaxies to reionization: we still don't know if galaxies could have reionized the universe!!

JWST

TMT

ALMA

what these new observations tell us

SUMMARY

Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed many galaxies 13 billion years ago (at redshifts z~7 and z~8), just 600-800 million years from the big bang

these galaxies are small, low mass objects (half-light radii of just 0.7 kpc at z~7-8)

they are extremely blue in color and are probably quite deficient in heavier elements

they give us estimates for the mass density and the star formation rate density that extends from just ~5% of the age of the universe

combining these results with Spitzer data suggests that these galaxies were forming stars ~200-300 million years earlier, at z>10-11 (with recent possible detections being found at z~10)

these galaxies fall in the heart of the "reionization" epoch, but our estimates are still low for the contribution of galaxies to reionization: we still don't know if galaxies could have reionized the universe!!