STScI May 2010 Baltimore
Stellar Populations
in the Cosmological Context

galaxy buildup in the first gyr: the nature of galaxies in the epoch of reionization

Garth Illingworth

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

Rychard Bouwens and the HUDF09 team

the HUDF09 team

TEAM

results based on data from the HUDF using the WFC3/IR and ACS cameras

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

our appreciation to all those who have brought us this remarkable Observatory

"acknowledgements" in a recent paper:

"We deeply appreciate all those at NASA, its astronauts and its contractors, STScI and throughout the community who have worked so diligently to make Hubble the remarkable observatory that it is today. The servicing missions, like the recent SM4, have rejuvenated Hubble and made it an extraordinarily productive scientific facility time and time again. We greatly appreciate the support of policymakers, and all those at NASA in the flight and servicing programs who contributed to the repeated successes of the HST servicing missions."

what WFC3 enabled

revealing galaxies 13 billion years ago

SM4 + WFC3/IR => z~8 galaxies & lots of z~7 (z~10?) (~500-800 Myr)

just 7 years after SM3b and ACS => z~6 galaxies (950 Myr)

data and results

>100 z~7 and z~8 galaxies

properties: sizes, UV colors, deep luminosity functions

at ages 500-800 Myr => in the heart of the reionization epoch

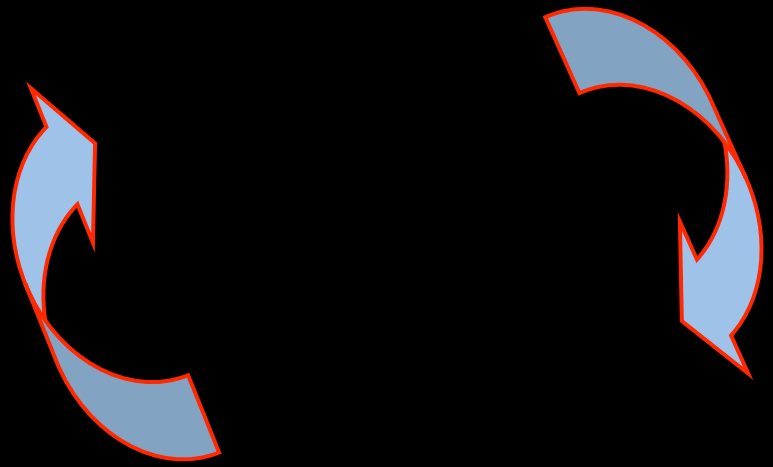
HST + Spitzer: SEDs, masses, mass density, ages

LBGs and the star forming population

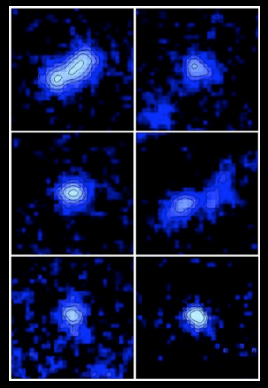
understanding galaxy formation and evolution……

galactic archaeology

we are remarkably fortunate to have two such powerful complementary approaches



direct observation

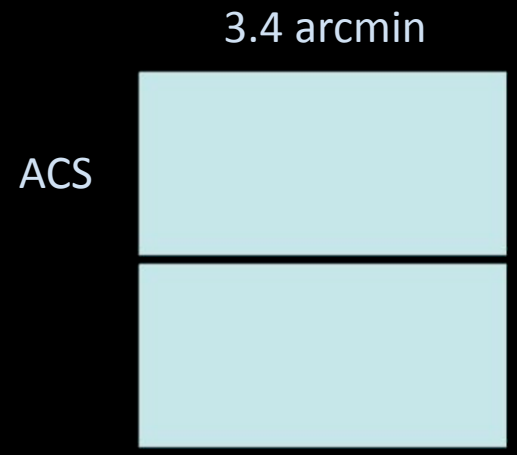


WFC3/IR *vs* NICMOS

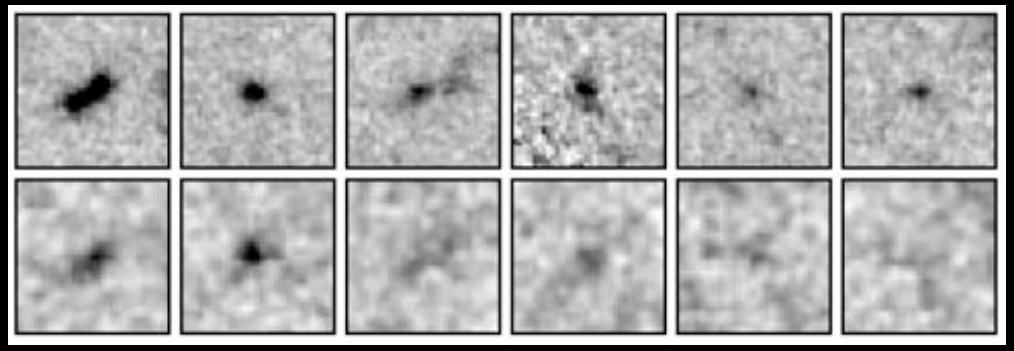
to find a z~7 galaxy took ~100 orbits with NICMOS
– with WFC3/IR it takes a few orbits

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

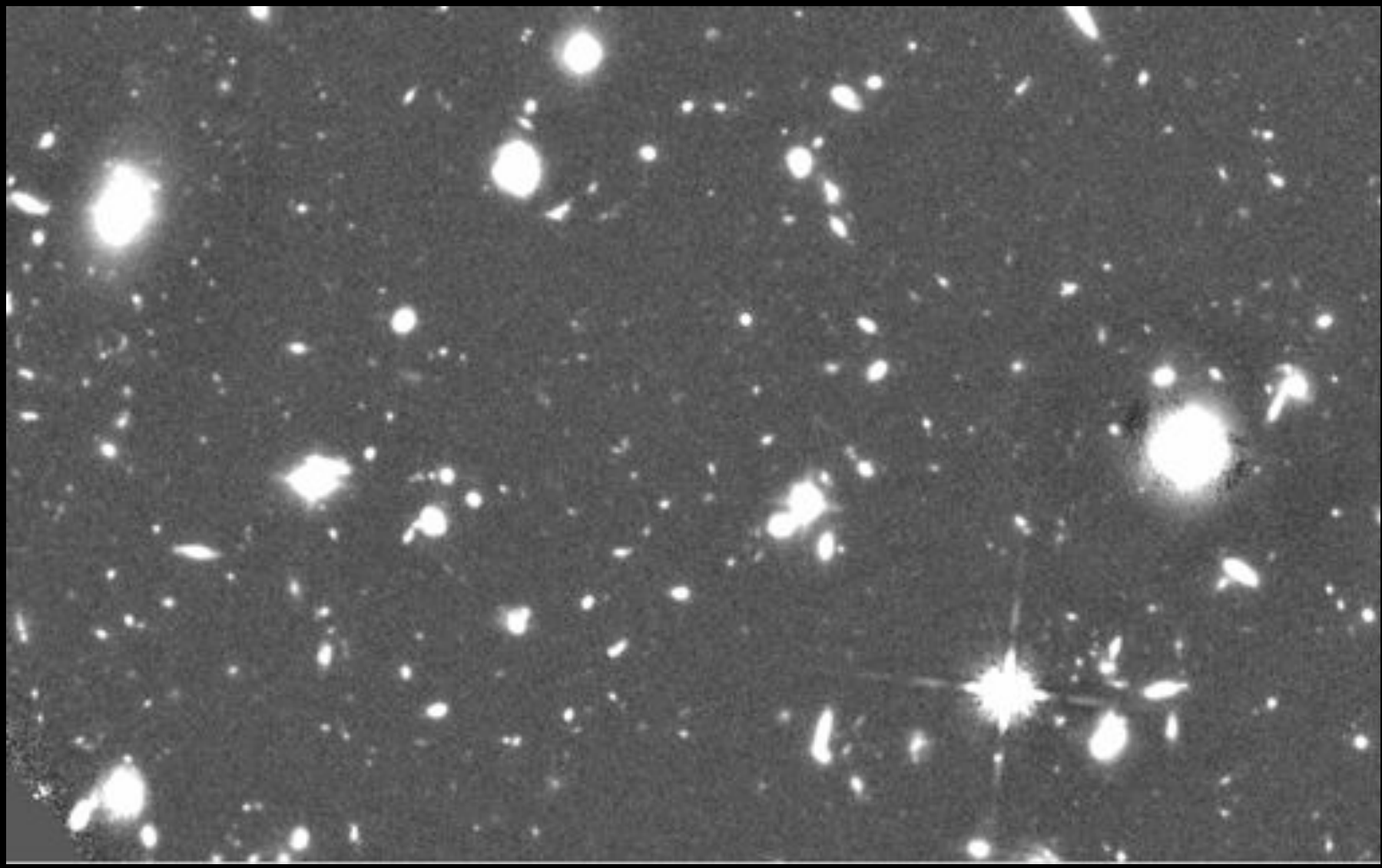


z~7 galaxies 2.2″ x 2.2″

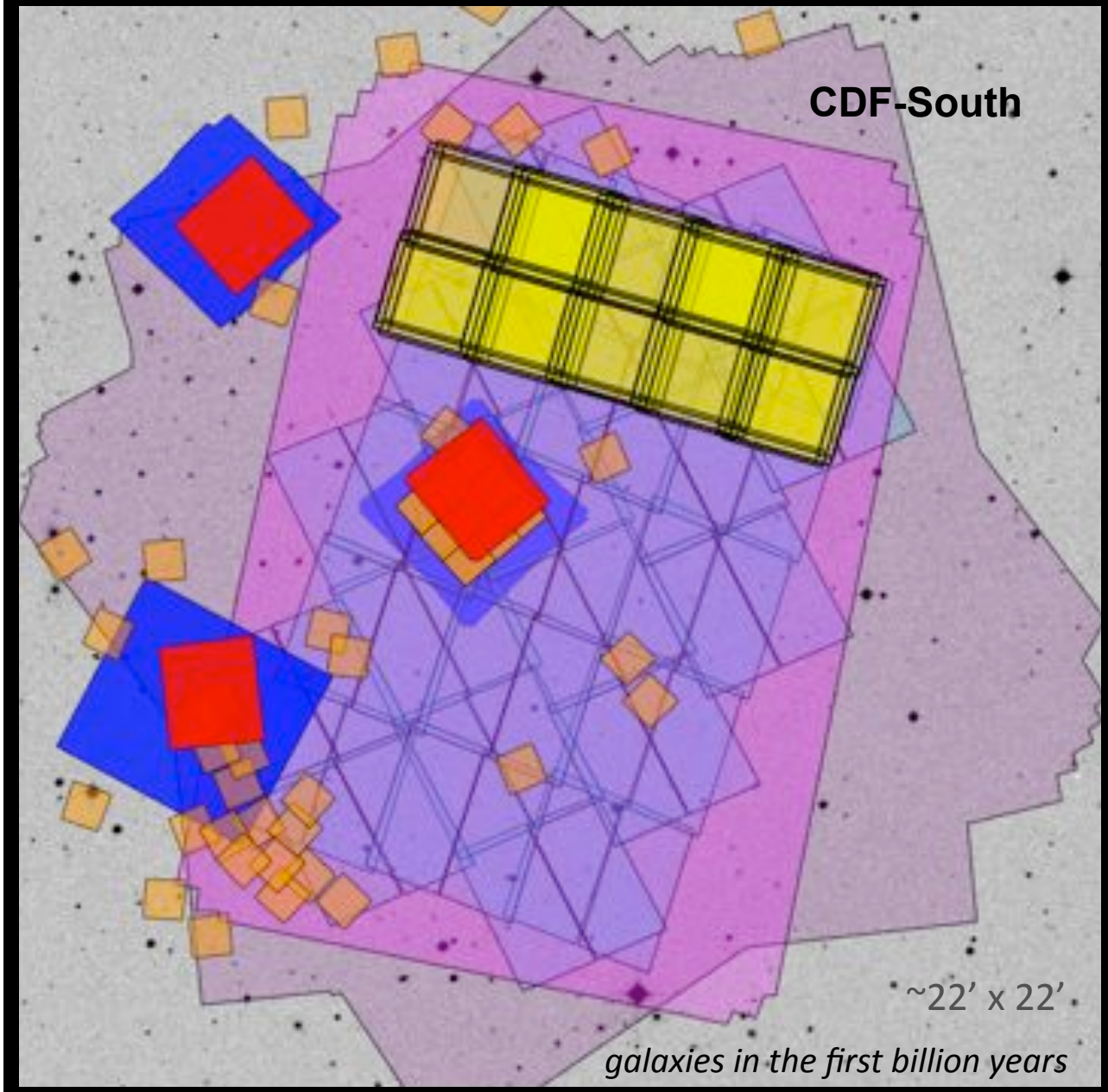
Oesch et al

NICMOS – 72 orbits

WFC3/IR – 16 orbits



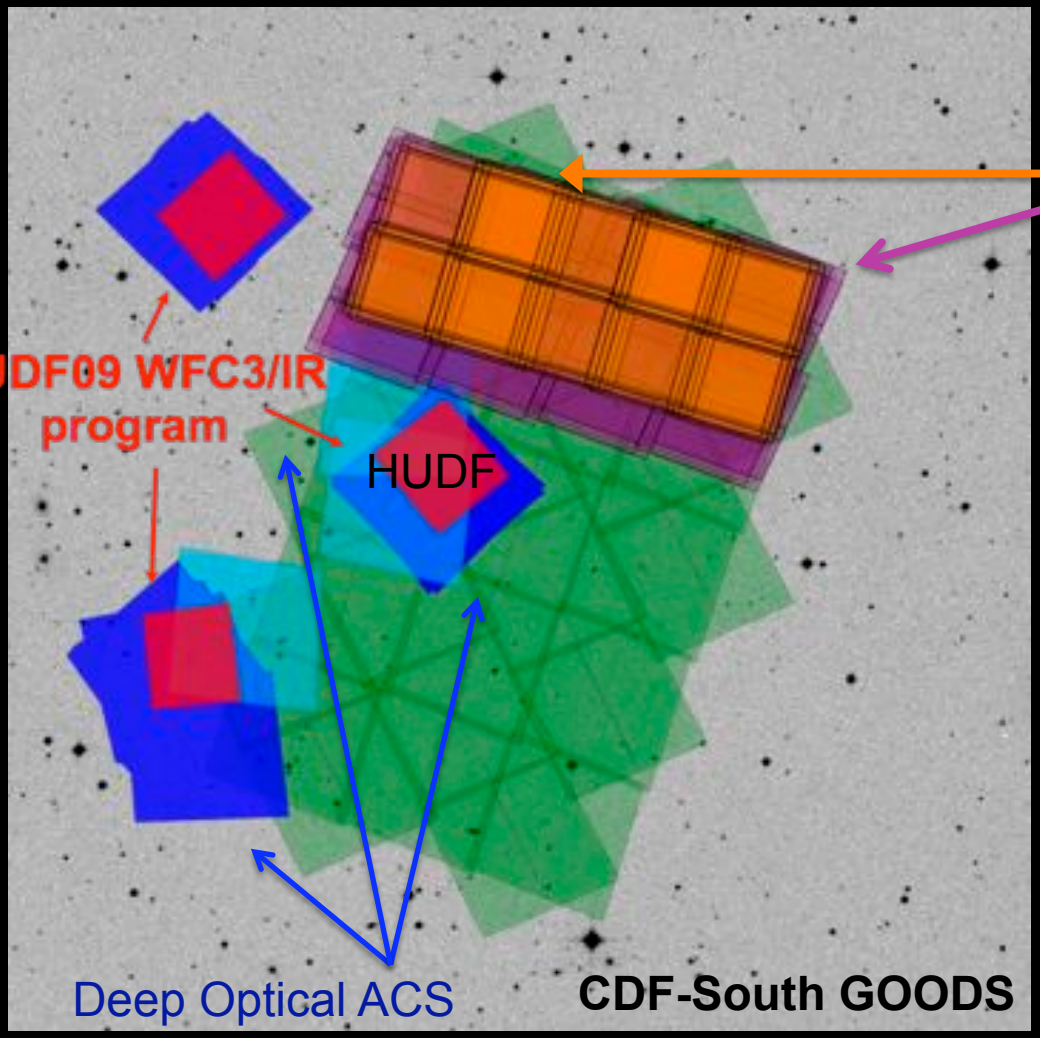
CDF-S region is rich in data (HST, Spitzer, Chandra, etc)



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
2010-2011 Chandra 4Ms
2010-2012 CANDELS

an “astronomy public commons”

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



~20’ x 20’

Early Release Science (ERS) data taken

~65% of HUDF09 data taken:

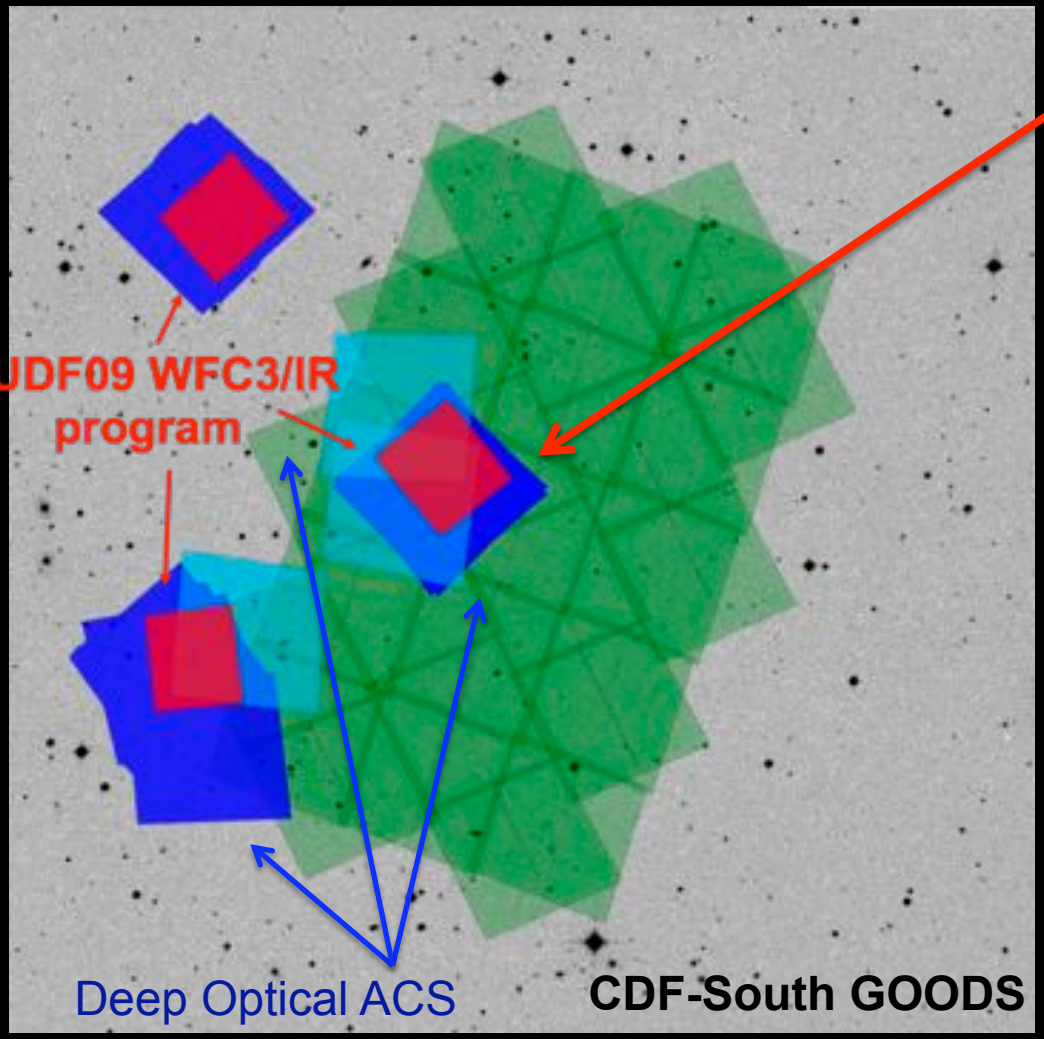
HUDF09 in aug 2009

HUDF09-1 in nov 2009

HUDF09-2 in feb 2010

remaining data to be taken later in 2010

searches for z~7-8 objects in HUDF09



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

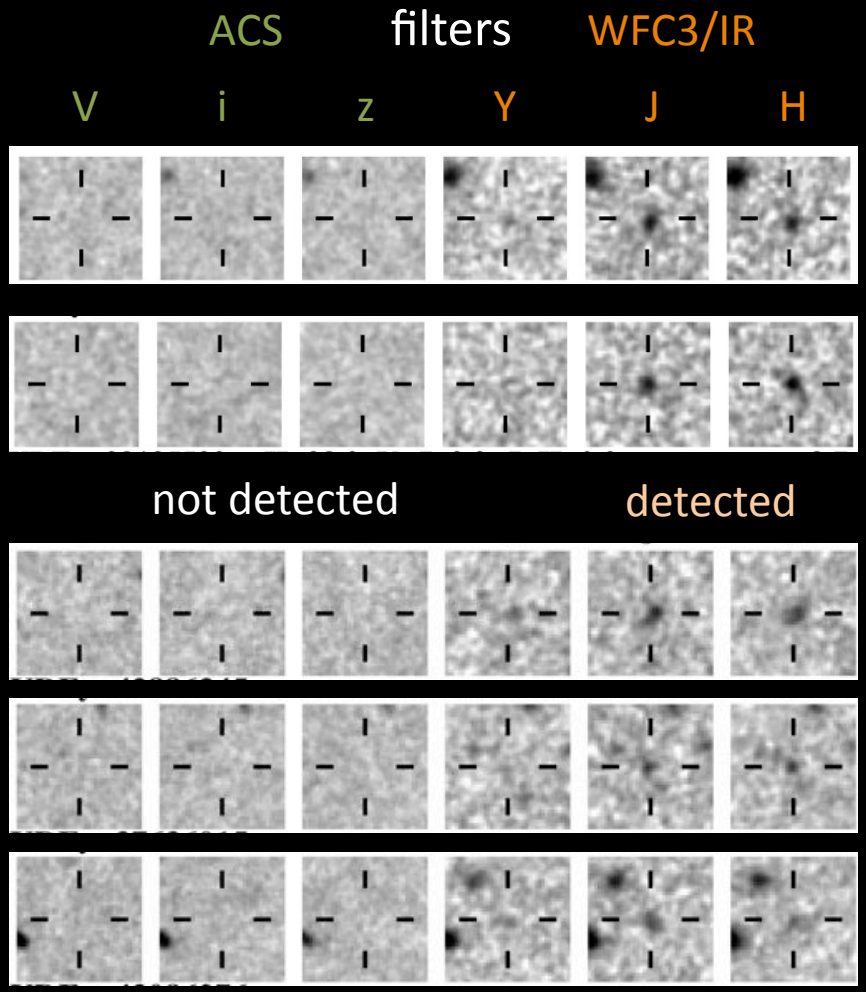
Yan et al

Finkelstein et al

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

first galaxies at z~8 from WFC3/IR

the two highest redshift z~8 galaxies



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

the other three z~8 galaxies

all are H~28-29 mag sources!

Bouwens, Illingworth et al 2010a

our first results: HUDF09 team's 16 z~7 and 5 z~8 galaxies

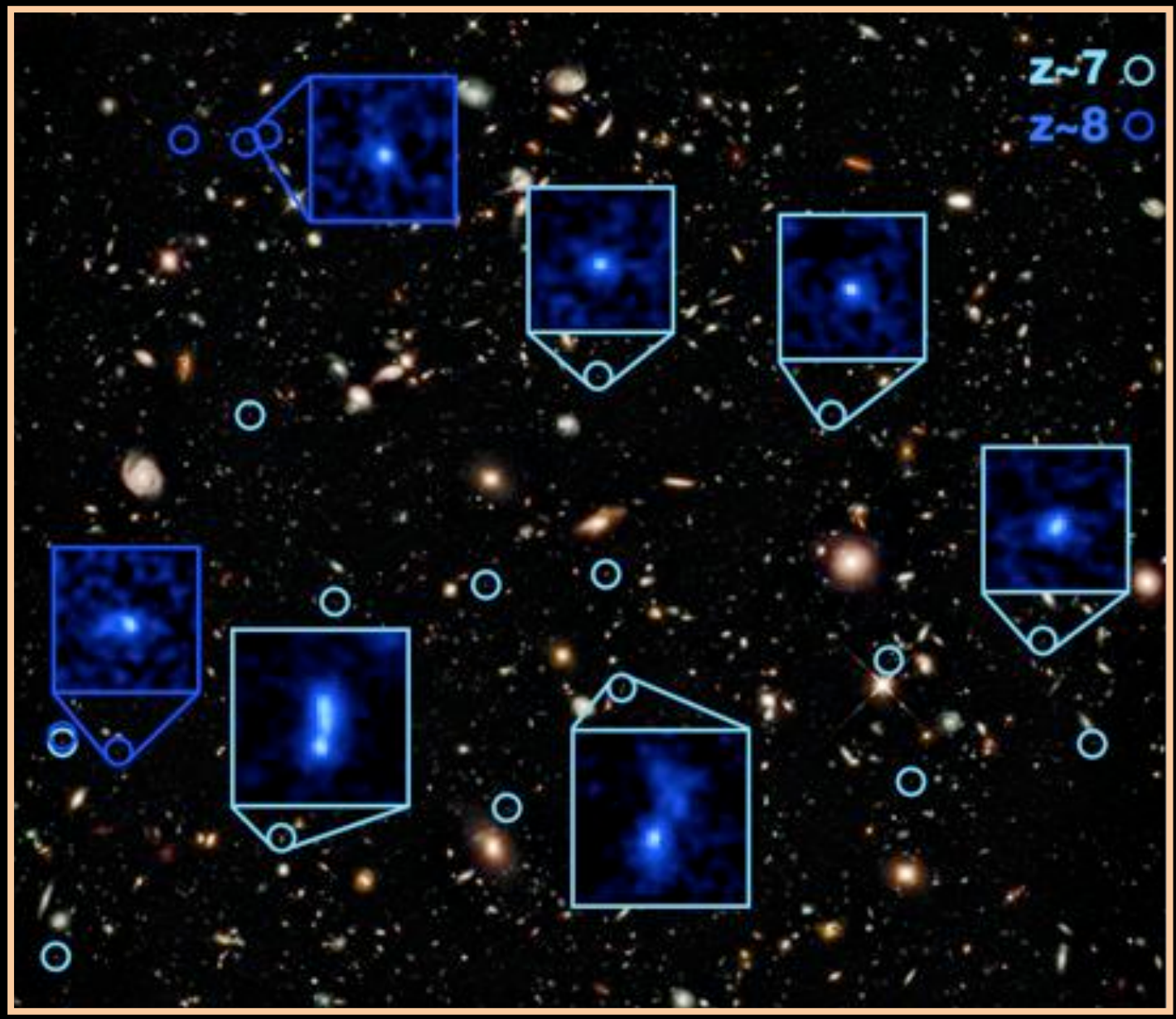
HUDF09
WFC3/IR

HUDF09
image ~2.2′

boxes ~2.5″

z~8 (650 Myr)
Bouwens et al
2010a

z~7 (800 Myr)
Oesch et al
2010a



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

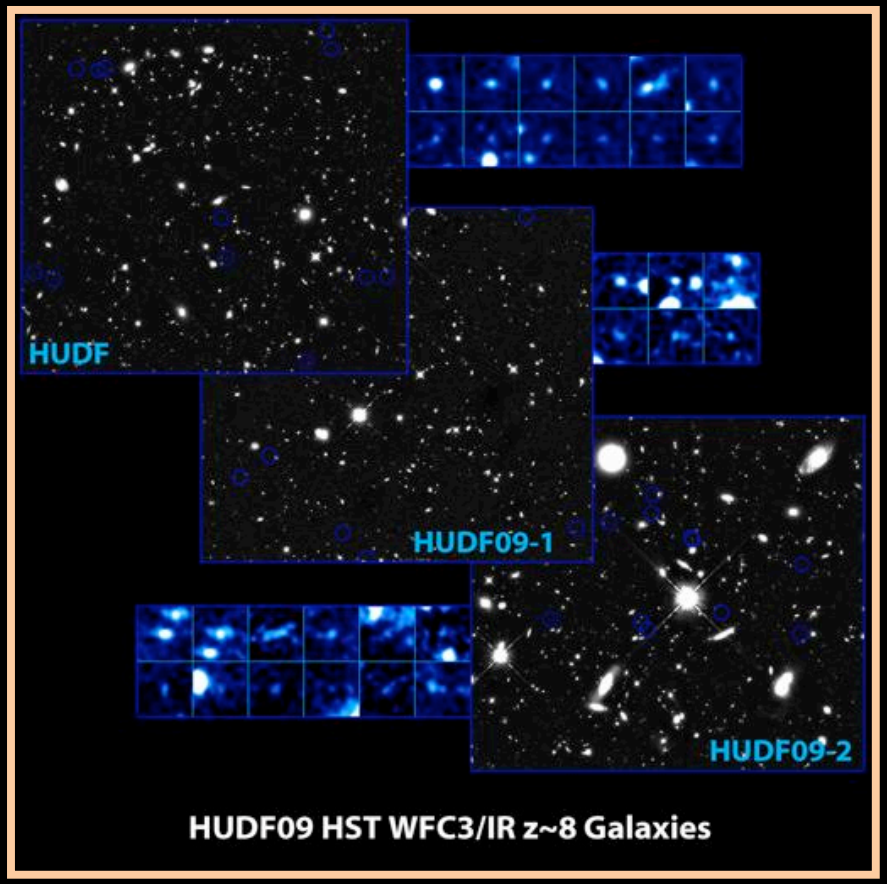
our current results: 101 z~7 & z~8 galaxies from ERS + HUDF09 fields

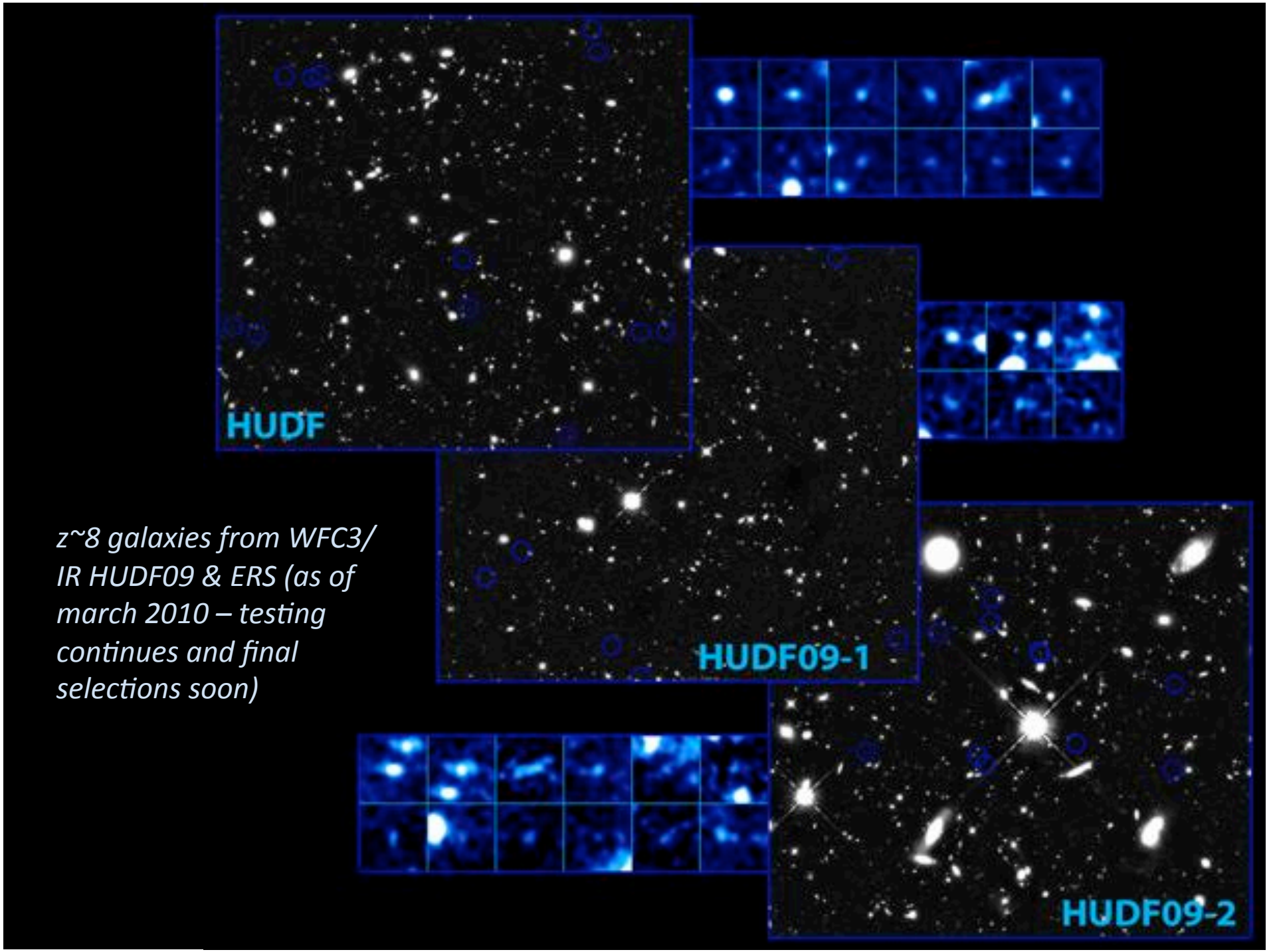
# of z~7 & 8 galaxies has increased by ~5x in 6 months – 9 months ago the only z~8 object was a GRB!

updated z~7 and z~8 sample is still being checked but will be coming to a server near you soon… Bouwens et al (2010d)

HUDF09 images: ~2.2′

HUDF09 fields WFC3/IR

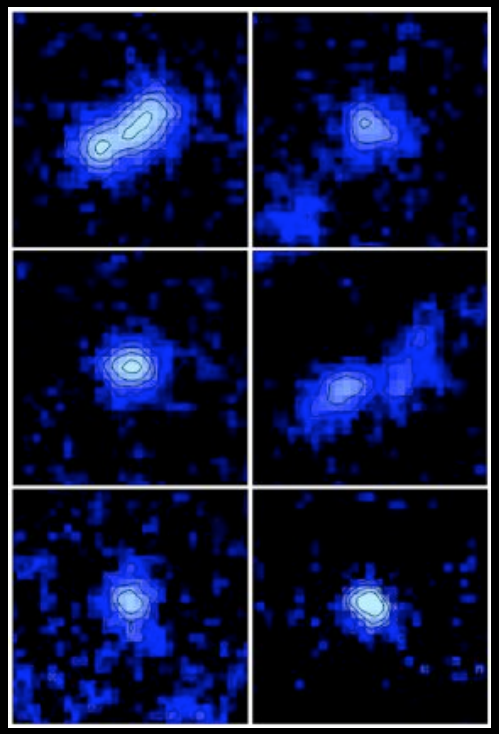




z~8 galaxies from WFC3/ IR HUDF09 & ERS (as of march 2010 – testing continues and final selections soon)

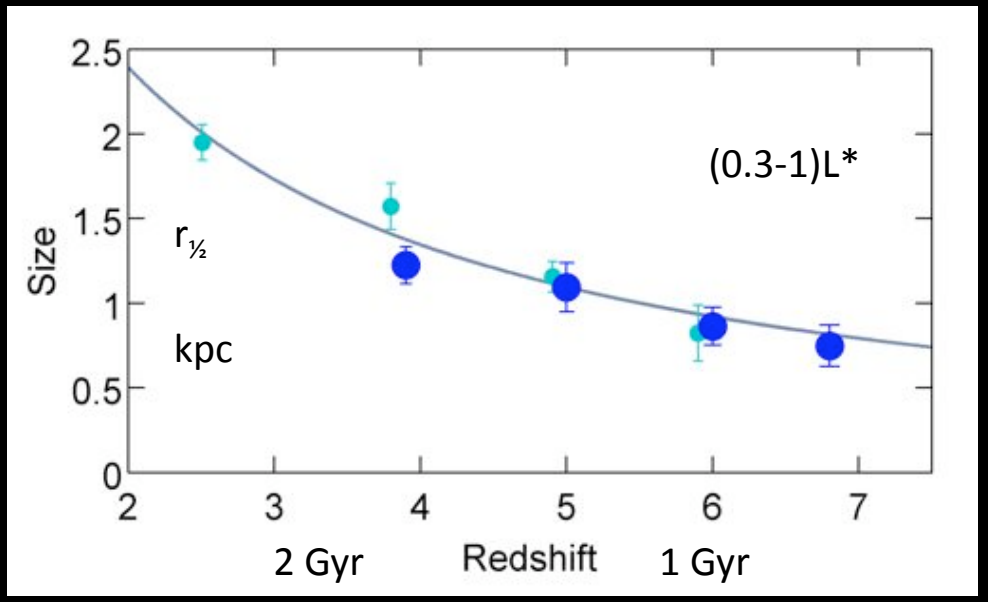
what have we learnt from the new HST data?

these early galaxies are small



1.8″ x 1.8″

Oesch/Carollo et al 2010b



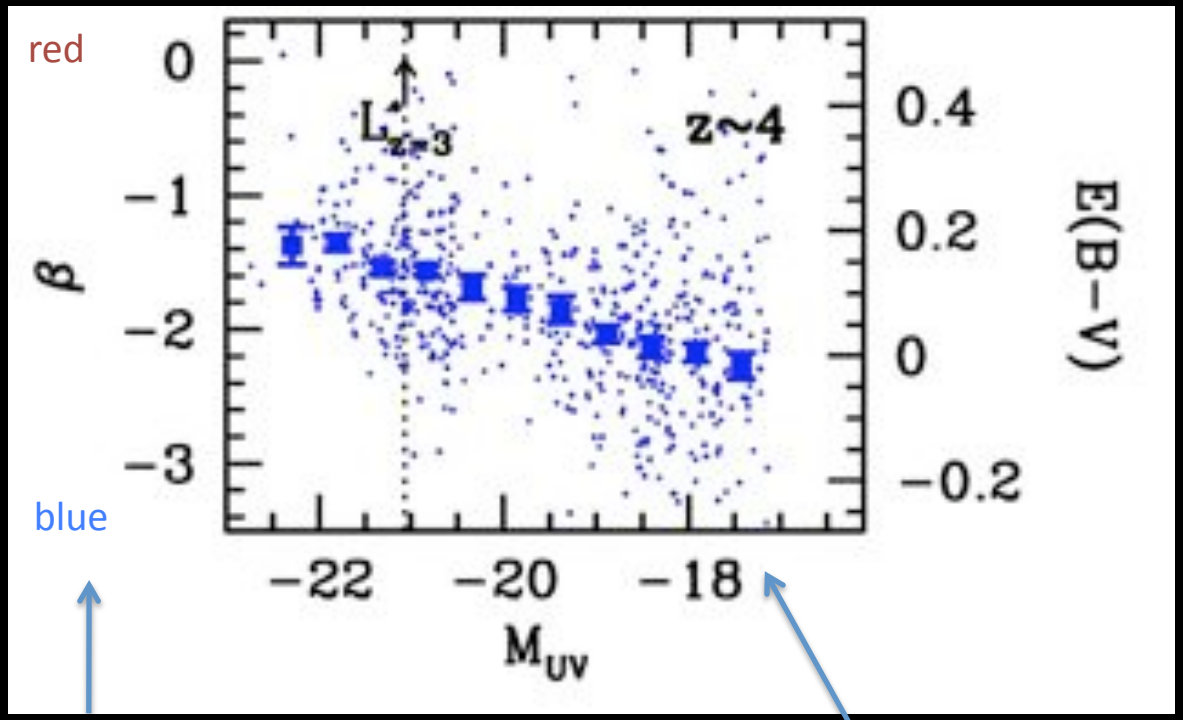
z~7 galaxies show considerable sub-structure

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)

z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

the UV continuum slope is a powerful tool



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

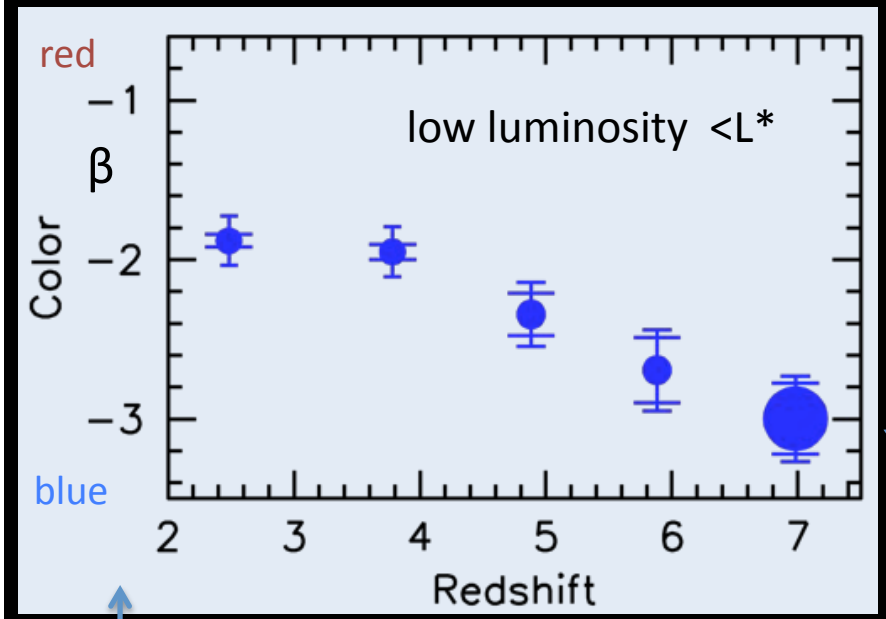
z~4 from ACS data in HUDF and GOODS

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

these early galaxies are very blue



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

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

but dust content of lower luminosity, z>5-6 galaxies is probably ➔ zero

so changes at z>5-6 must be due to other effects

low luminosity galaxies become very blue at early times – low metals?

dust free at β < ~-2.4

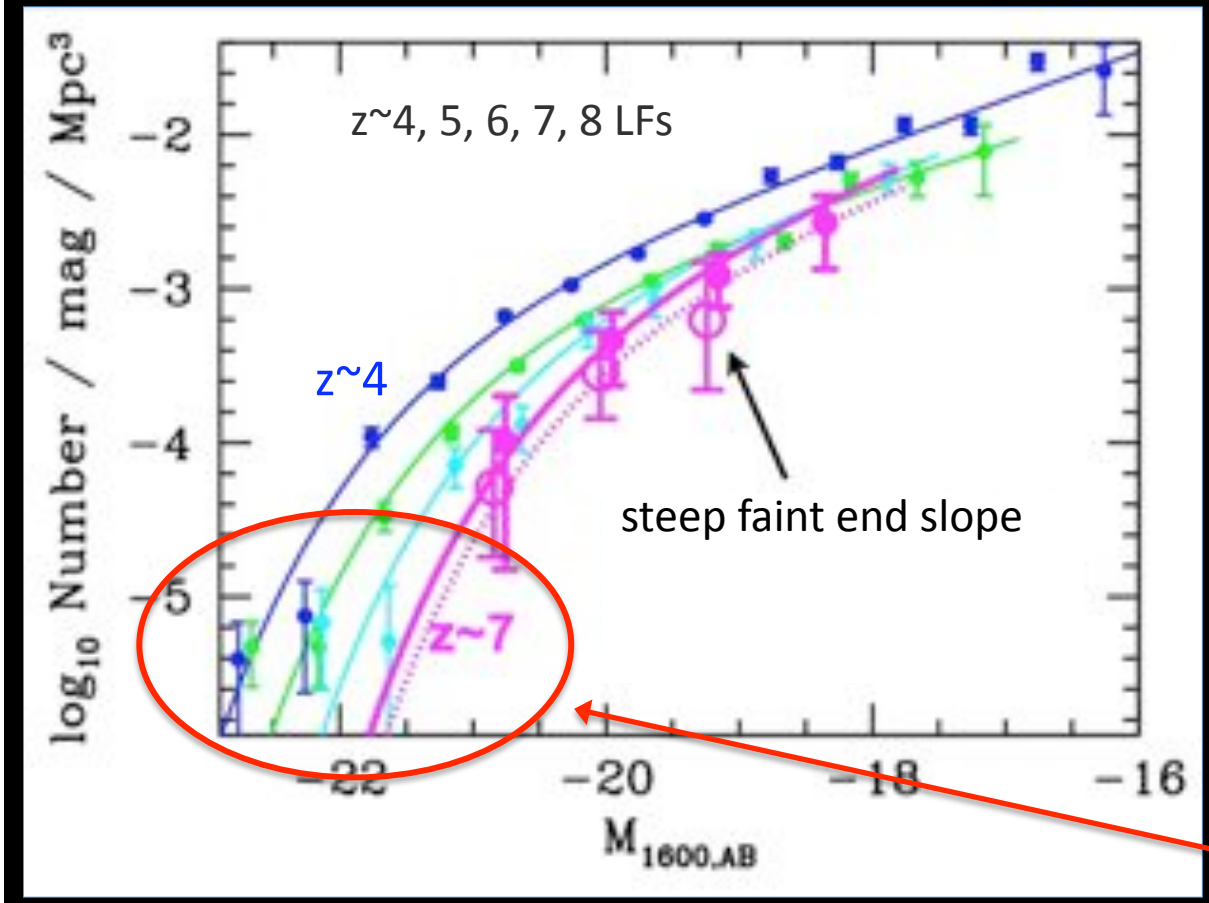
at β < ~-2.8 standard population models are challenged (even low metal abundance models) – need very low metallicity models?

Bouwens/Illingworth et al 2010b

z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5)

luminosity functions



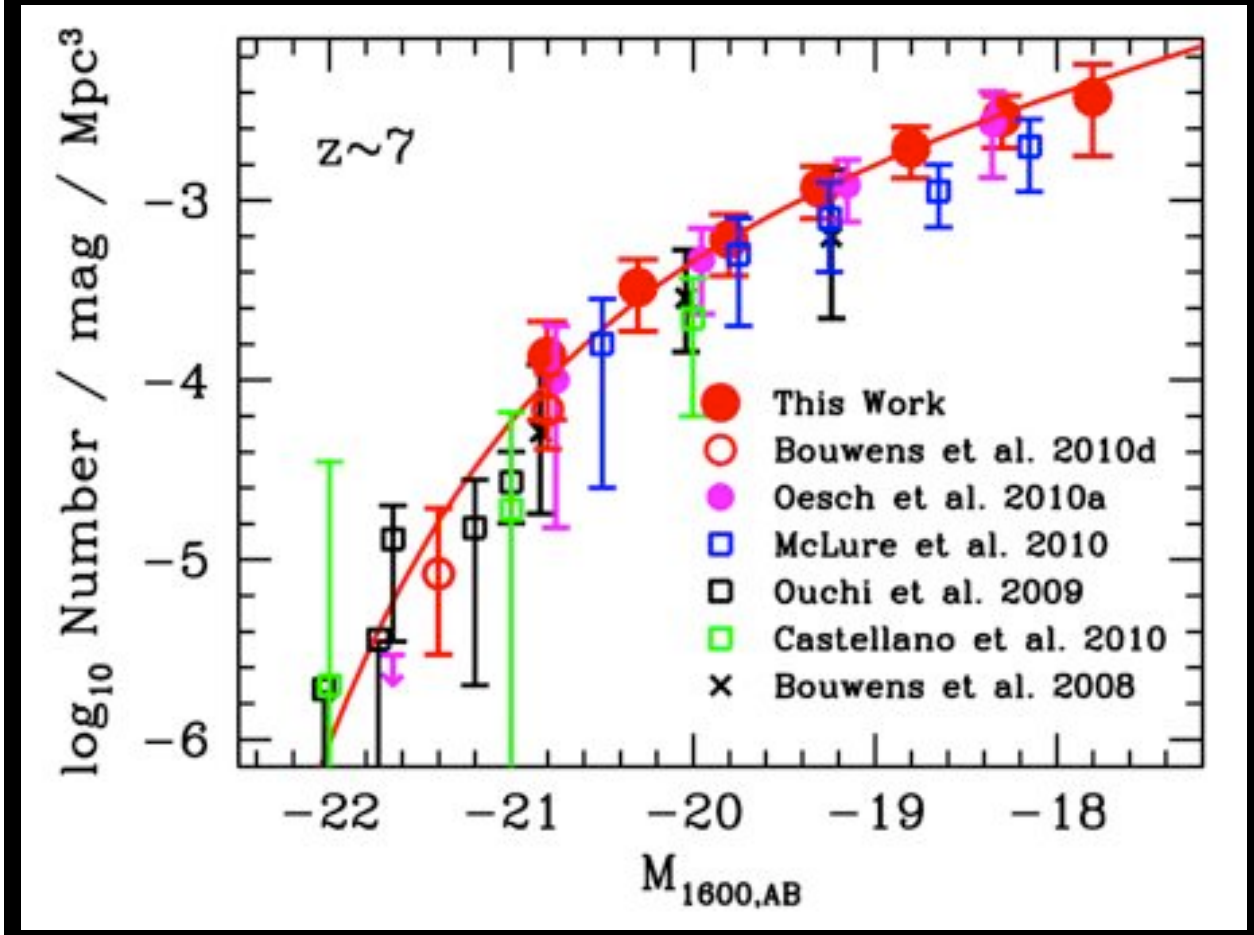
luminosity functions (LF) are key for determining the UV luminosity density and star formation rate densities

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

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

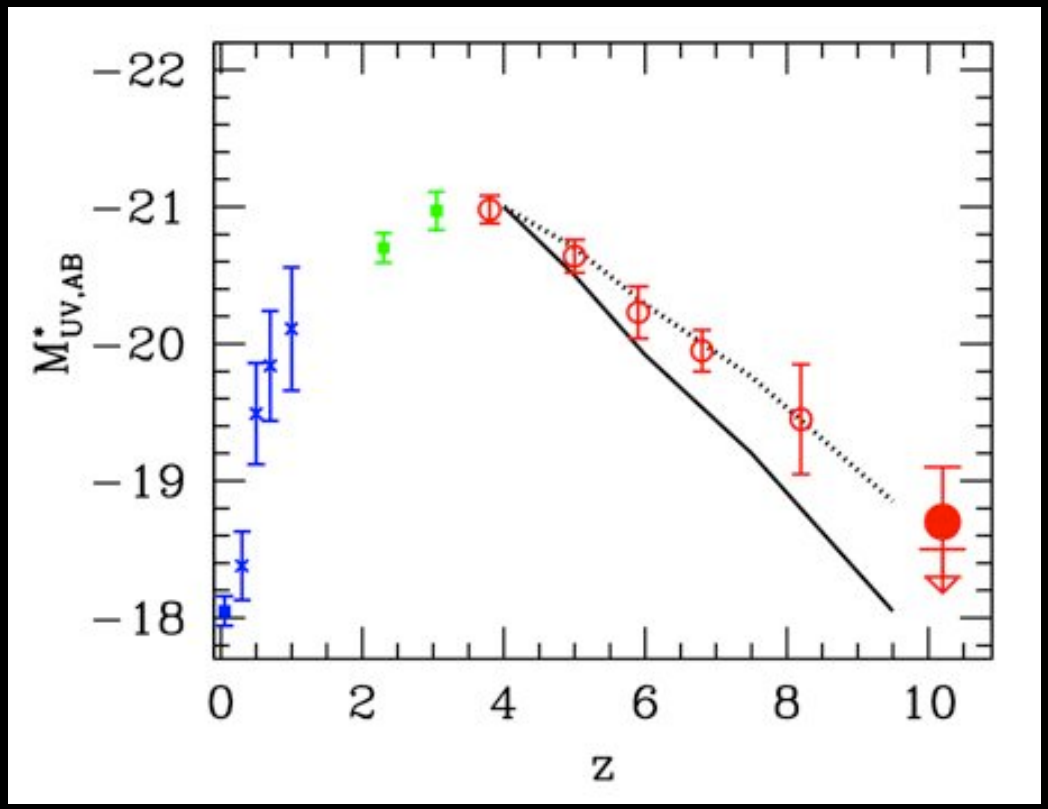


luminosity functions at z>7 are very important for establishing role of galaxies in reionization

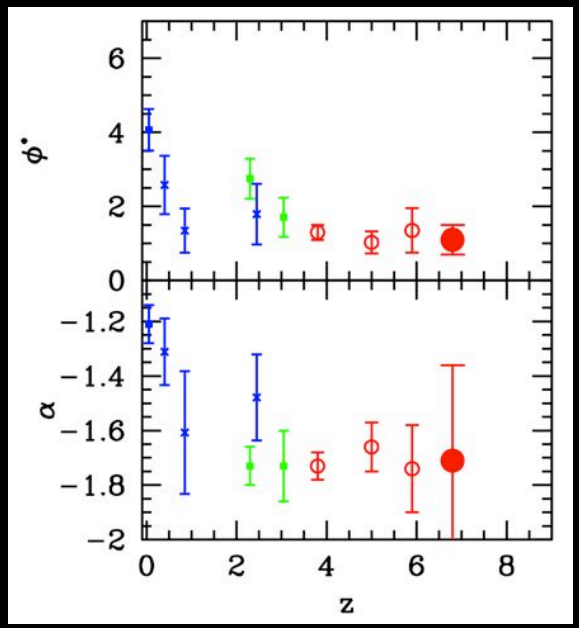
excellent agreement now between the several groups

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

luminosity functions – implications



dominant changes occur at bright, massive end



slope and density change very little

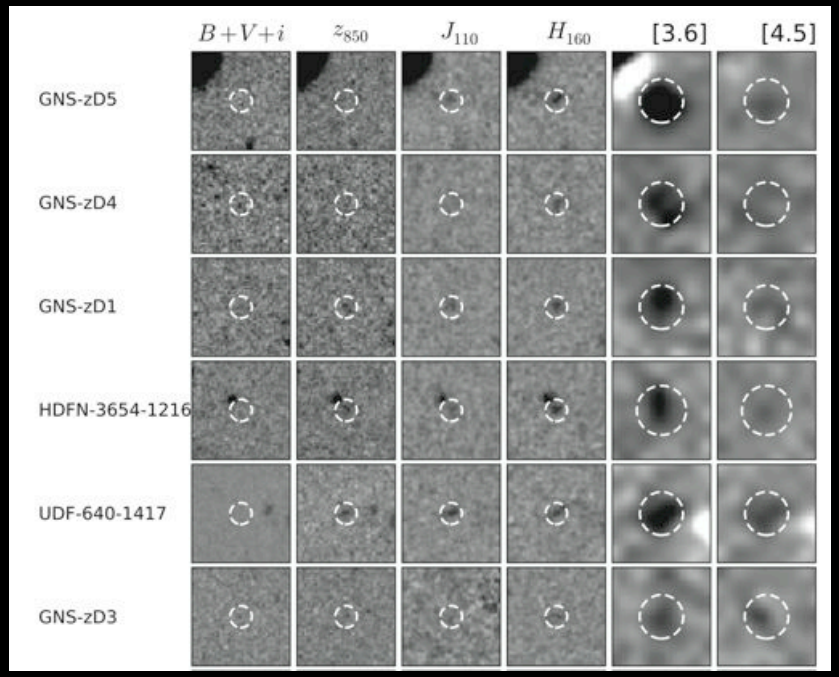
z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

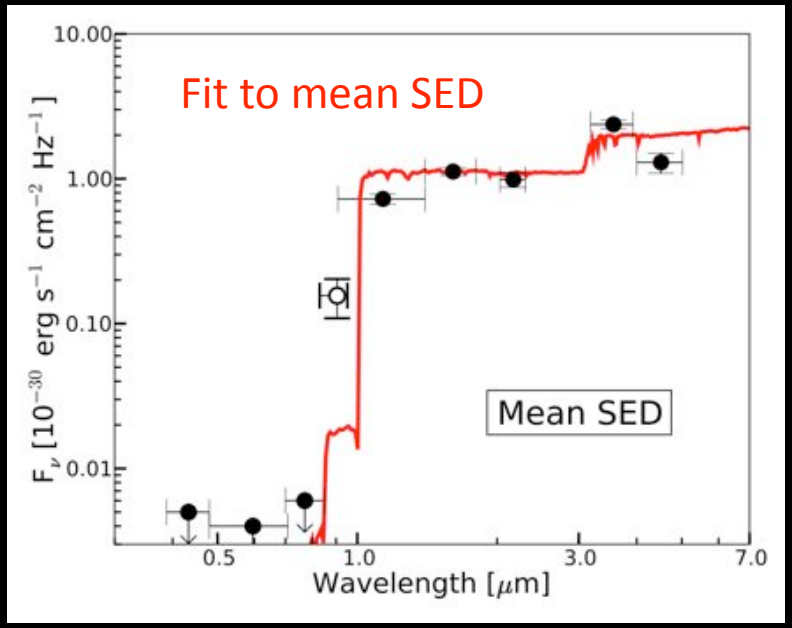
z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5)

the luminosity function at z>3 is very steep at α~1.7 => faint galaxies dominate the UV flux! changes are primarily at the bright end (>L*)

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 4.5×10^5 $M_\odot$ Mpc^{-3}

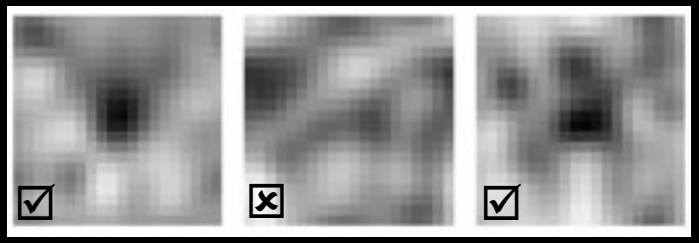
Gonzalez, Labbé et al 2010a

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

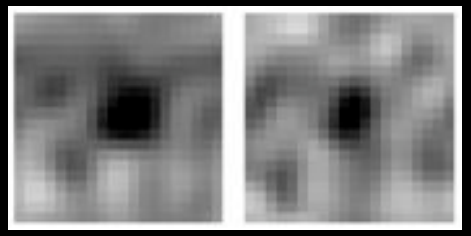
these galaxies probably formed stars much earlier

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)

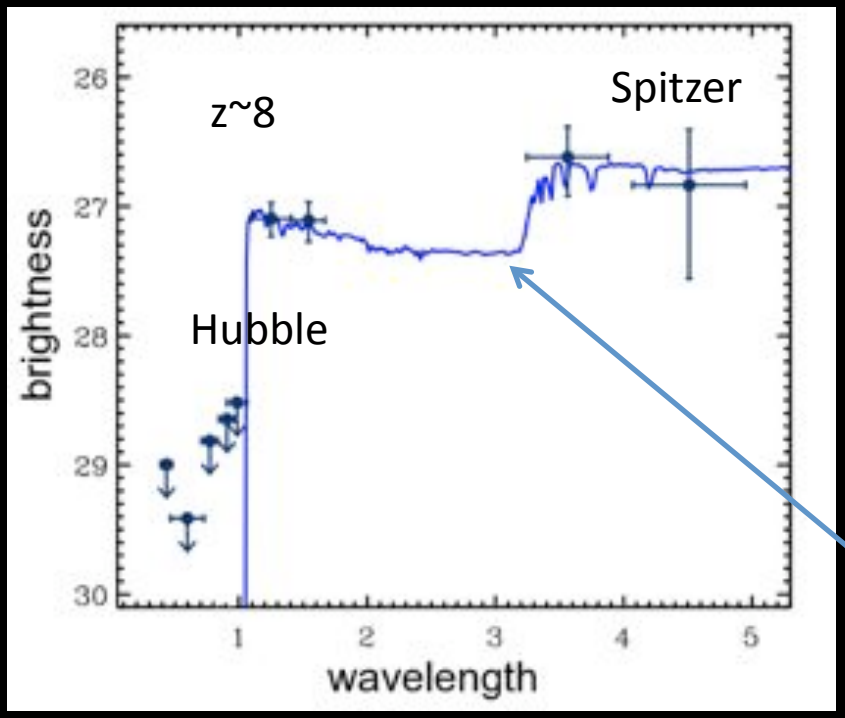
some individual z~8 Spitzer 3.6 µm images



z~8 stacked Spitzer images



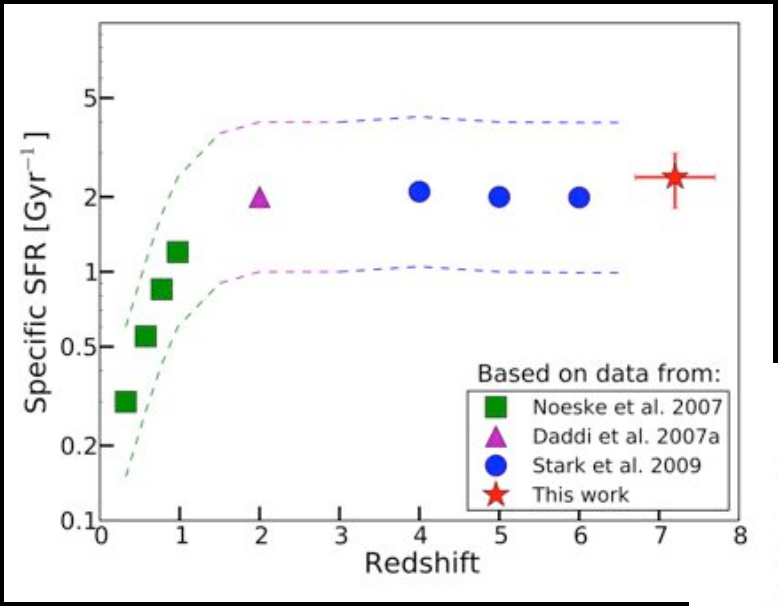
3.6 µm 4.5 µm



Labbé/Gonzalez et al 2010b

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

Spitzer + HST powerful combination



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

constant SSFR at z>2 – strikingly so….

effect of nebular emission lines on ages & SF history??

investigate with deep Spitzer IRAC data in 3.6 and 4.5

Gonzalez, Labbé, Bouwens, Illingworth et al 2010a

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

Quantity	Value
Redshifts	7.2 ± 0.5
Masses	$0.1\text{–}12 \times 10^9\ M_\odot$
M/L_{UV} ratio	$0.01\text{–}0.1\ M_\odot/L_\odot$
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)	$5.7 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$
Mass density (M/L of mean SED)	$4.5 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$
Mass density (random M/L)[b]	$6.6^{+5.4}_{-3.3} \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$
Predicted SFR density (at $z = 9$)	$0.0011\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$

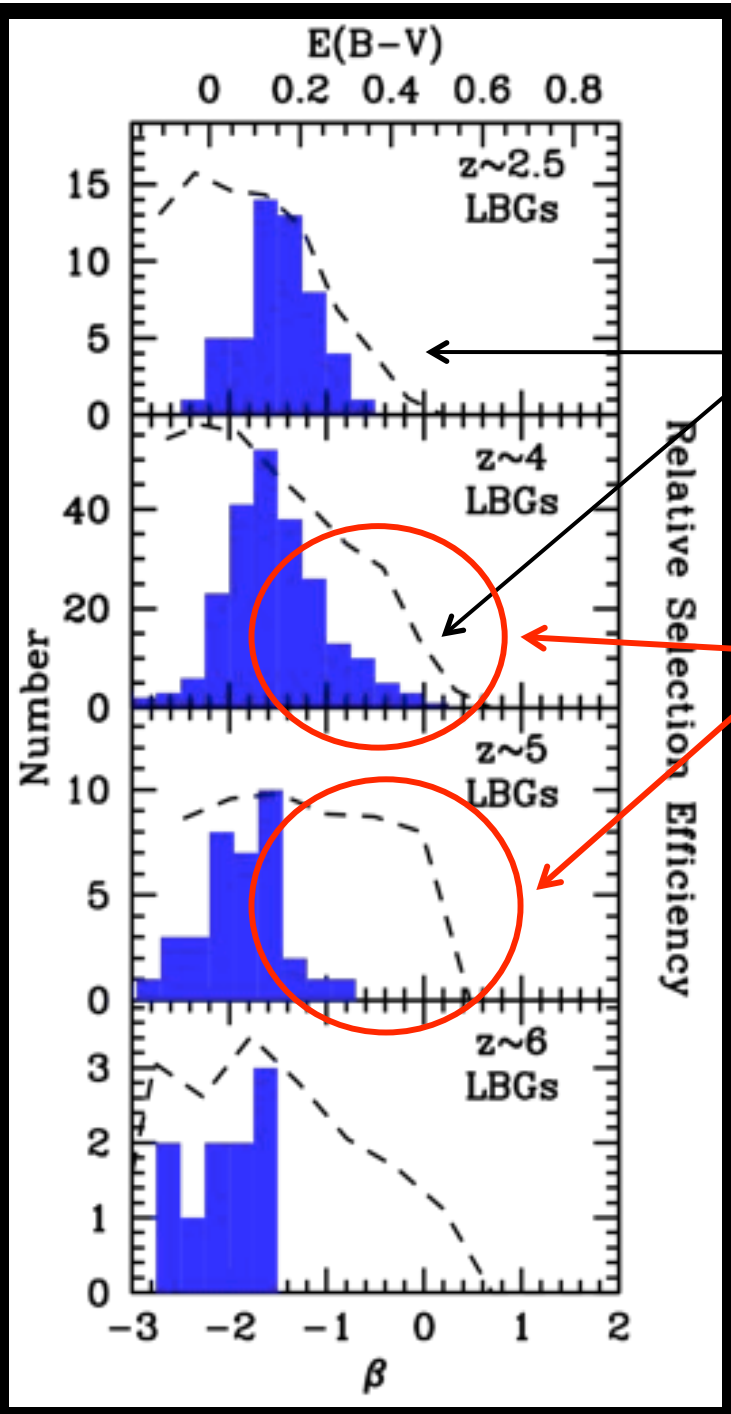
Notes.
[a] From single burst models.
[b] Our best estimate.

z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5)

the luminosity function at z>3 is very steep α~1.7 => faint galaxies dominate the UV flux! changes are primarily at the bright end (>L*)

even at z~7-8 (650-800 Myr) indications of an "older" population (few hundred million years) => suggests some stars formed earlier at z>10



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

z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5)

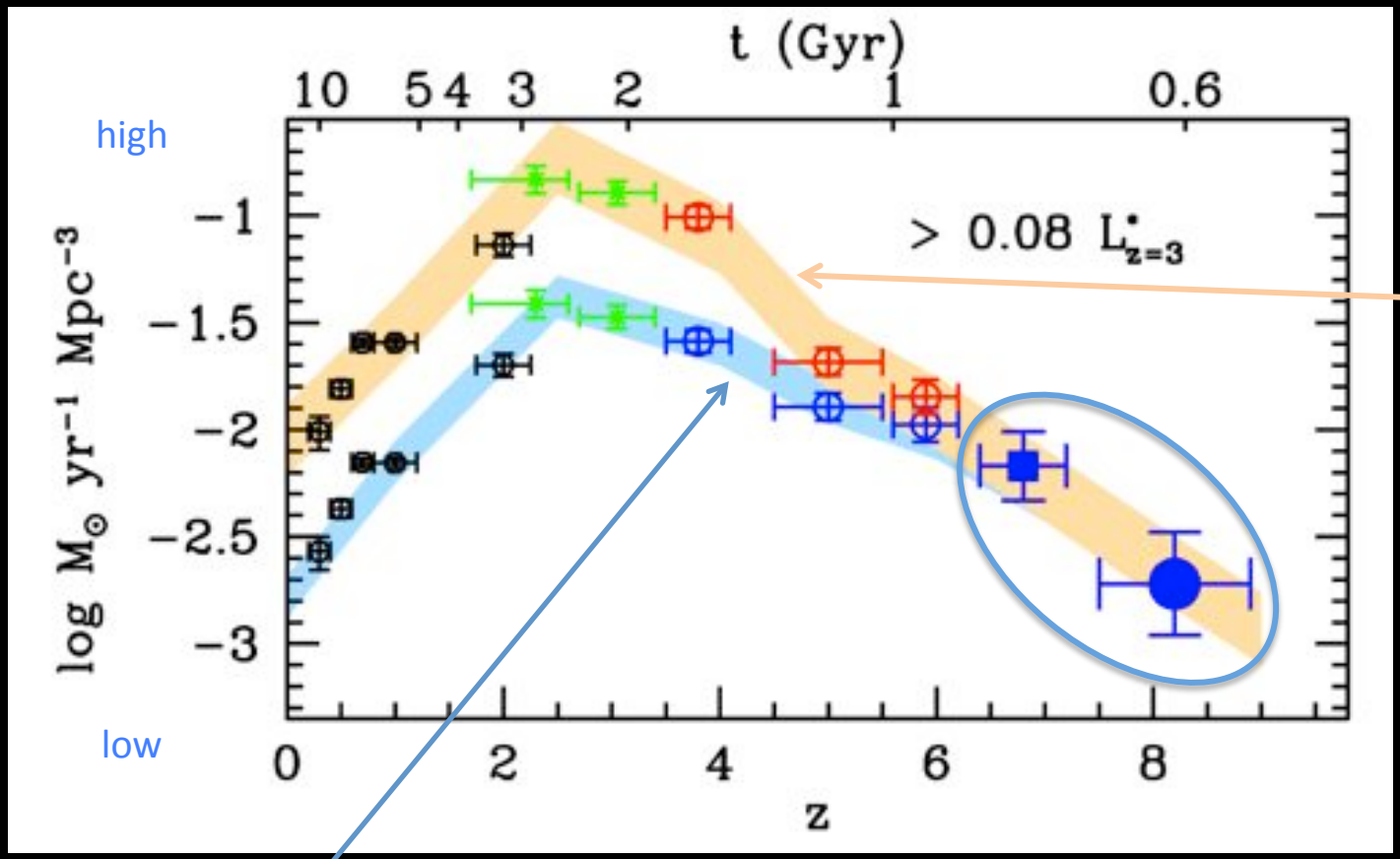
the luminosity function at z>3 is very steep α~1.7 => faint galaxies dominate the UV flux! changes are primarily at the bright end (>L*)

even at z~7-8 (650-800 Myr) indications of an "older" population (few hundred million years) => suggests some stars formed earlier at z>10

evolved galaxies appear to be rare at z>4 unless they have distinctly different characteristics (β is not continuous?)

integrated properties.....

the star formation rate density



dust-corrected SFR

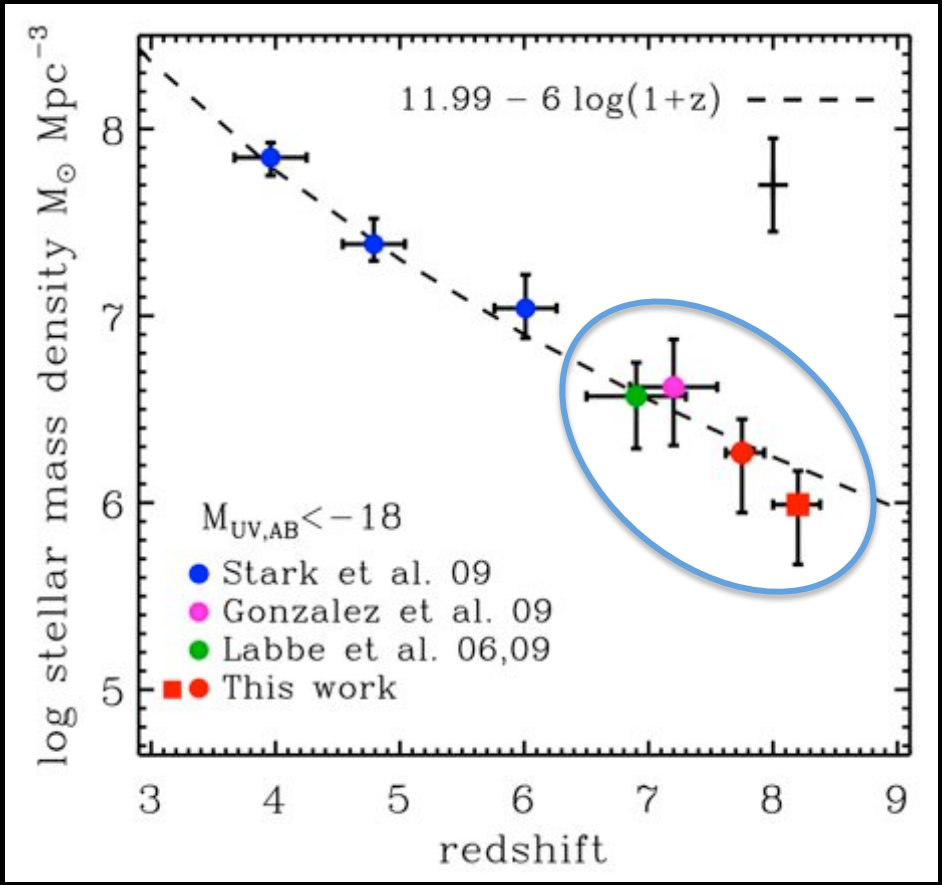
new results

UV luminosity density

Madau 1998 formulation with Salpeter IMF

Bouwens/Illingworth et al 2010d

mass buildup over time



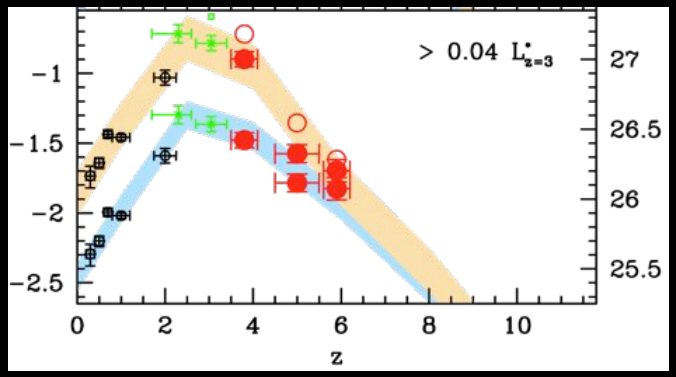
the Hubble and Spitzer data allow us to establish the evolution of the mass density at these early times

see papers by Gonzalez et al and Labbé et al

our new results

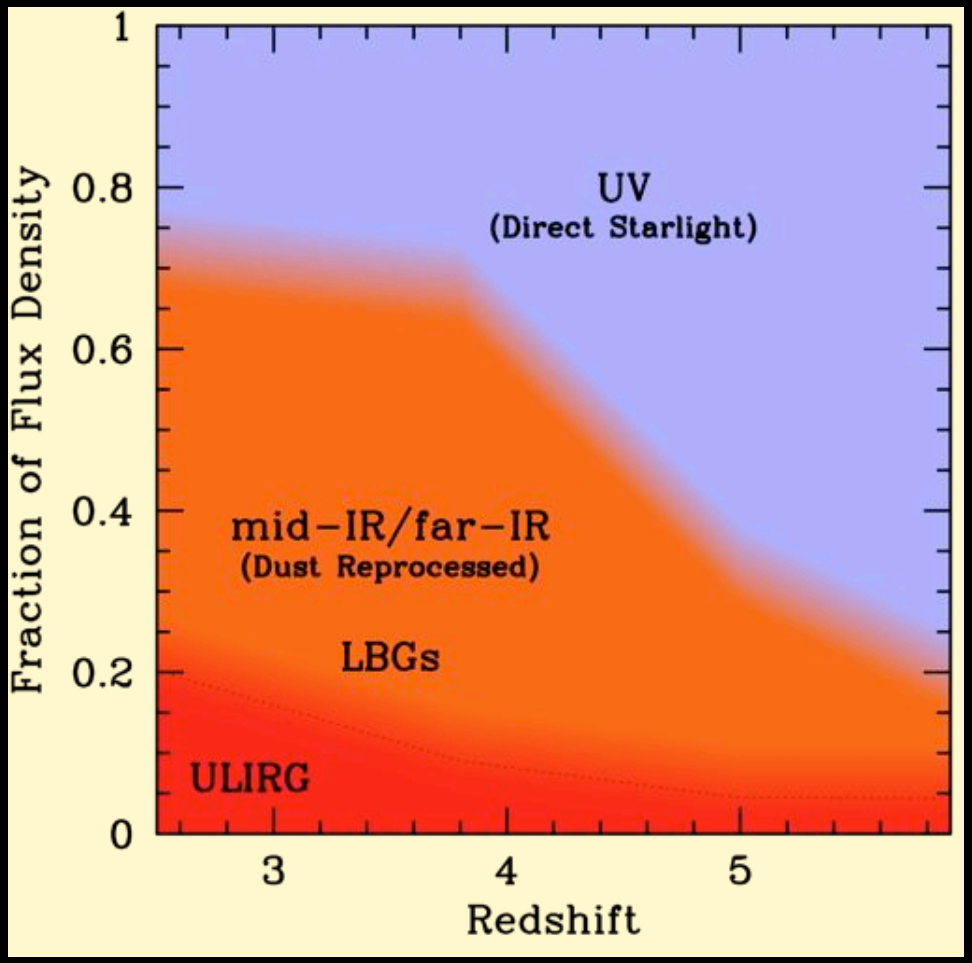
the history of the mass buildup in galaxies in the universe

Labbé/Gonzalez et al 2010a, b



flux density in UV & IR

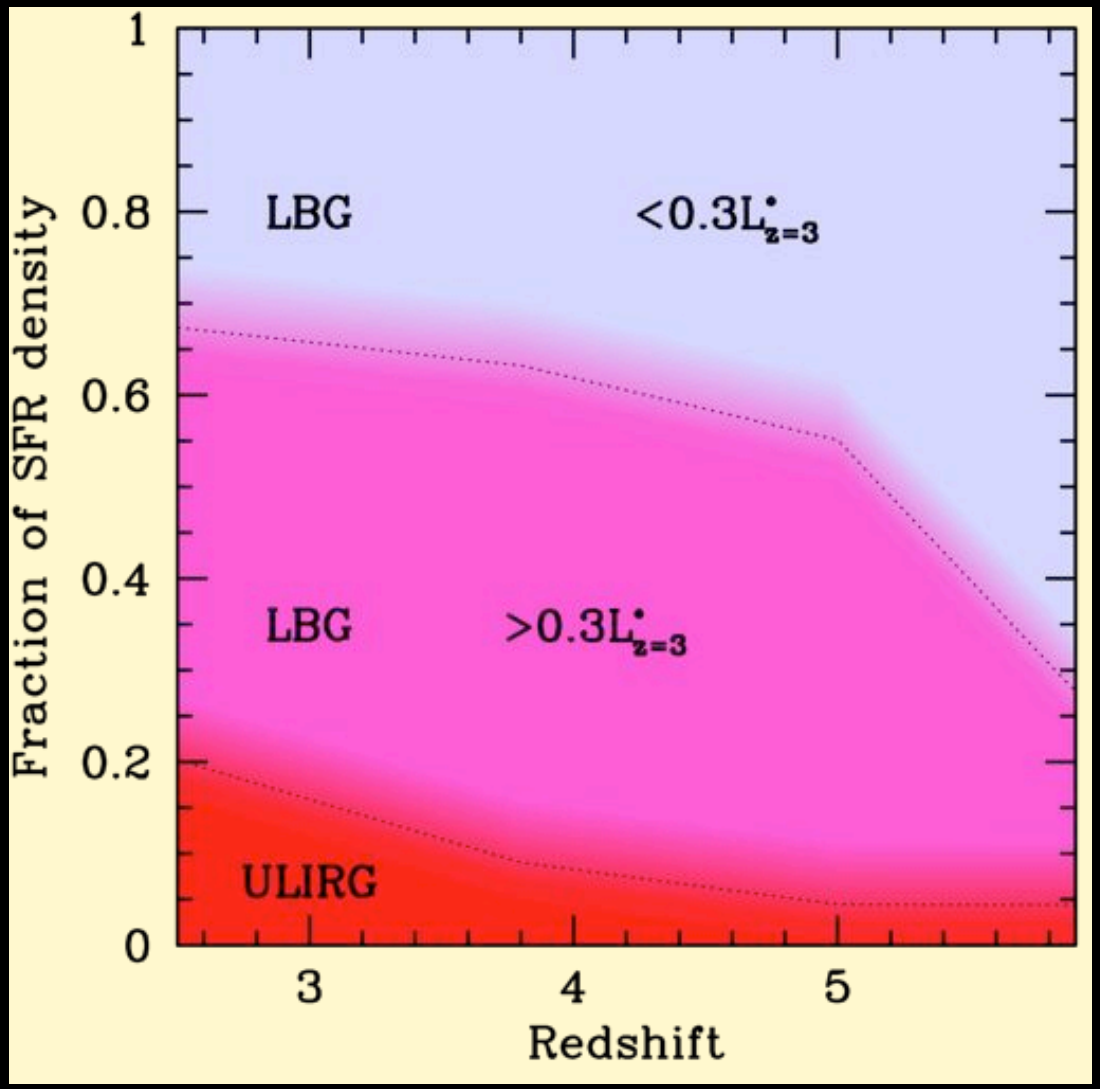
for star forming galaxies…



>80% of energy output in UV & IR at high redshift from star-forming galaxies 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>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5)

the luminosity function at z>3 is very steep α~1.7 => faint galaxies dominate the UV flux! changes are primarily at the bright end (>L*)

even at z~7-8 (650-800 Myr) indications of an "older" population (few hundred million years) => suggests some stars formed earlier at z>10

evolved galaxies appear to be rare at z>4 unless they have distinctly different characteristics (β is not continuous?)

the bulk of the star formation at z>3 is in the LBGs massive galaxies like SMGs/sub-mm galaxies do not appear to contribute significantly to SFR

lots of reasons to expect galaxies at z~10+

can we find galaxies at z~10?

can we find galaxies at z~10?

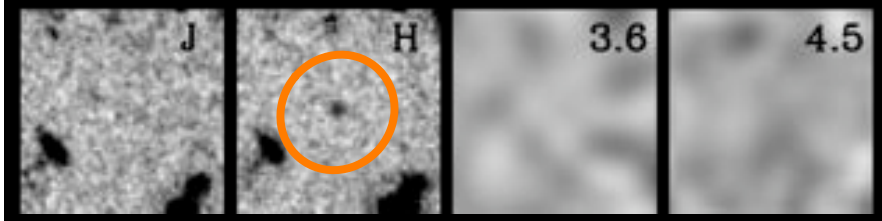
PROBABLY??

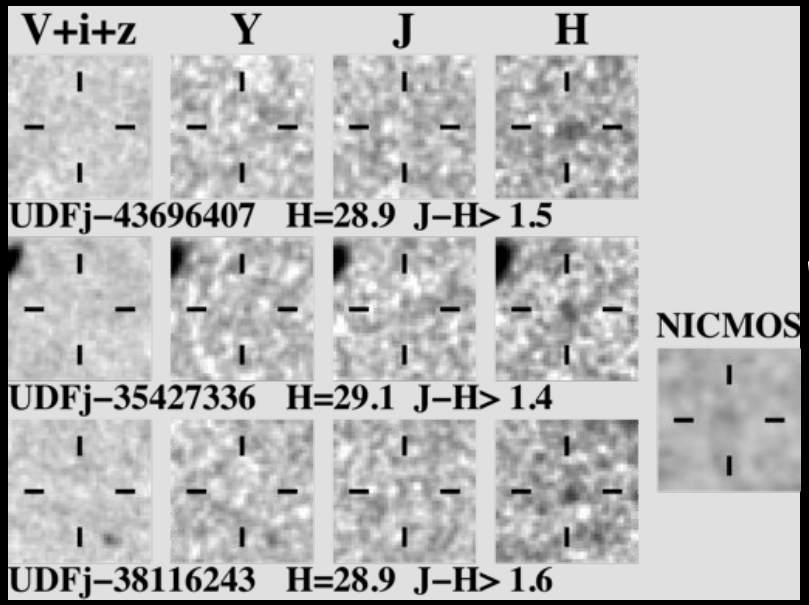
but, it is very challenging with the current dataset……

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

Bouwens, Illingworth & HUDF09 team

Stacked J & H image + Spitzer IRAC





detected three probable z~10 sources

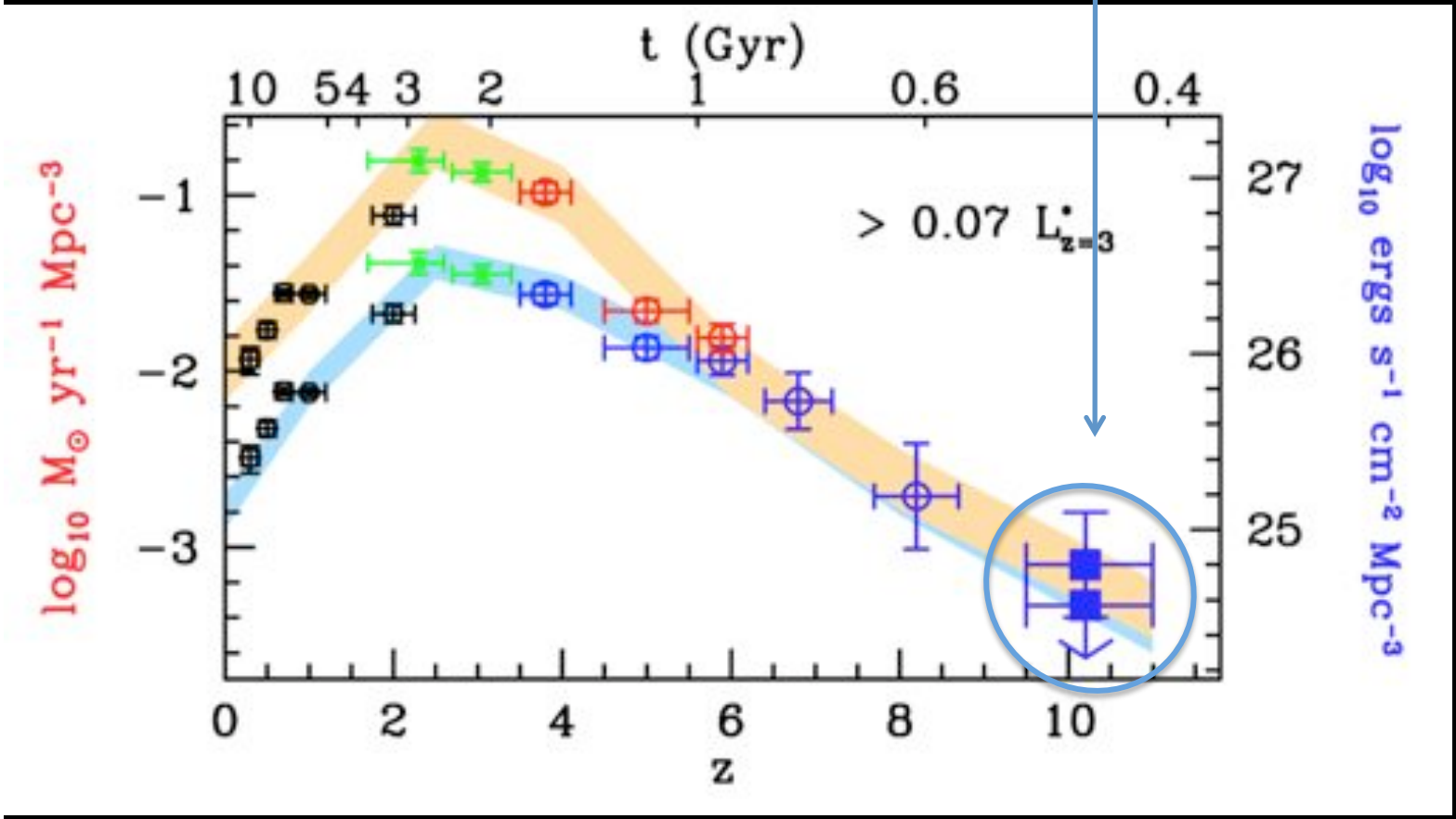
note detection in NICMOS stack at ~3σ of two of three that are in earlier independent NICMOS data

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, spurious sources, etc (~1.2 source), we derived constraints on the star formation rate density, and also set an upper limit from the current HUDF09 data

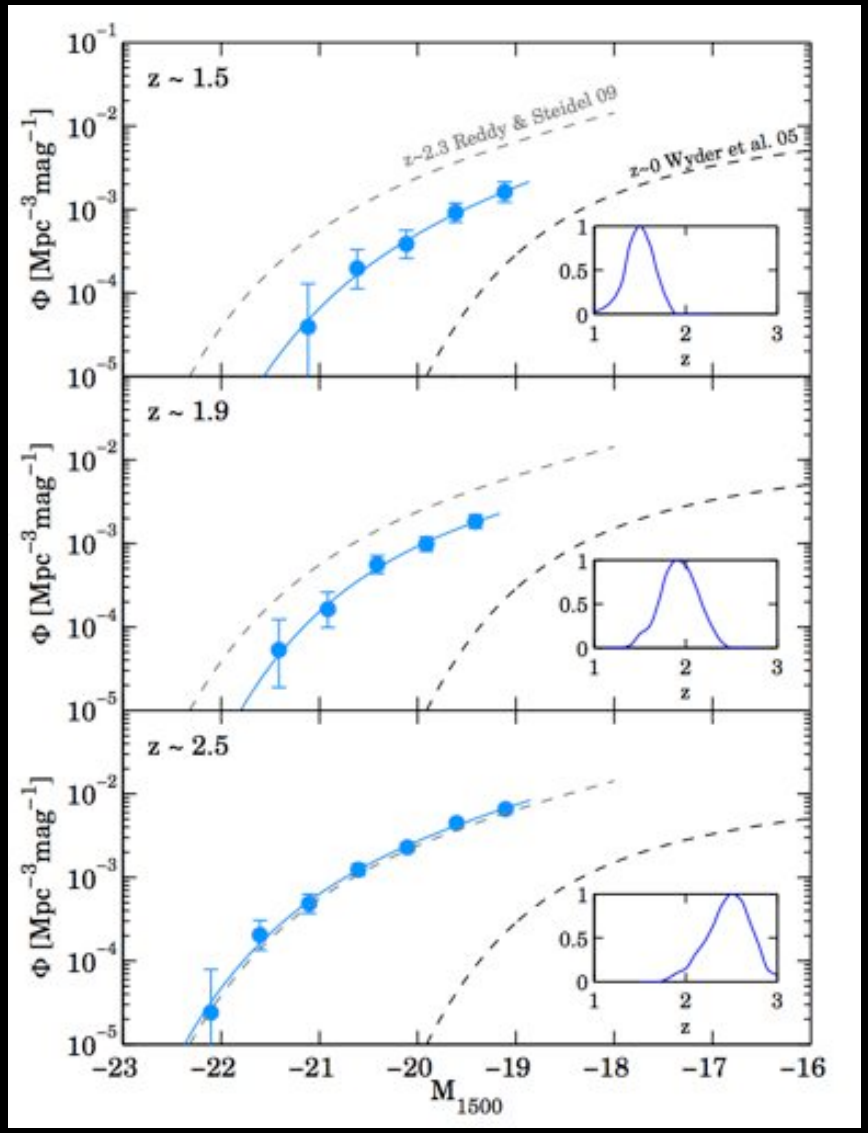


upper limit is very robust, even if detections are uncertain

Bouwens/Illingworth & HUDF09 team

WFC3/UVIS is also incredibly powerful but
that power has not yet been fully exploited

WFC3/UVIS results in the ERS field



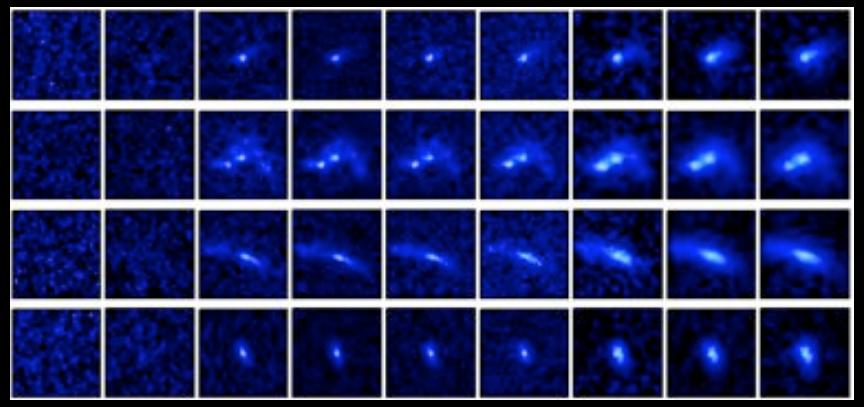
! usual competition !

Hathi et al last week

Oesch et al next week

ERS observations in UV let us search for star-forming galaxies at z~1 => z~2.5

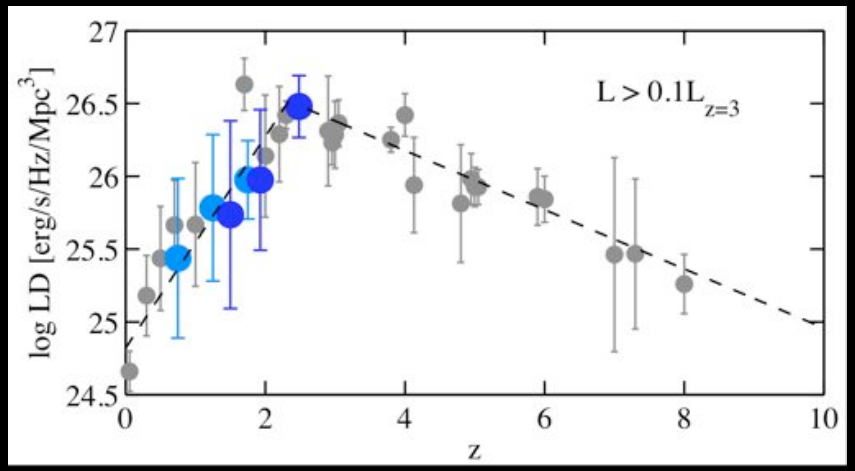
WFC3/UVIS dropouts



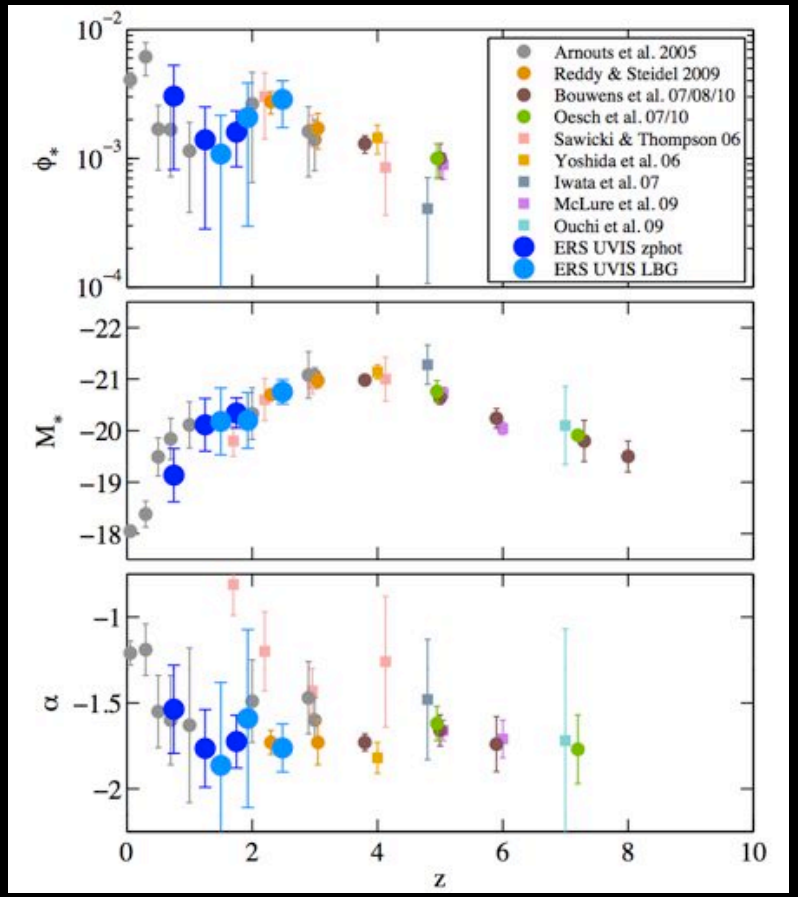
WFC3/UVIS ACS WFC3/IR

WFC3/UVIS results in the ERS field

transition to “downsizing”….



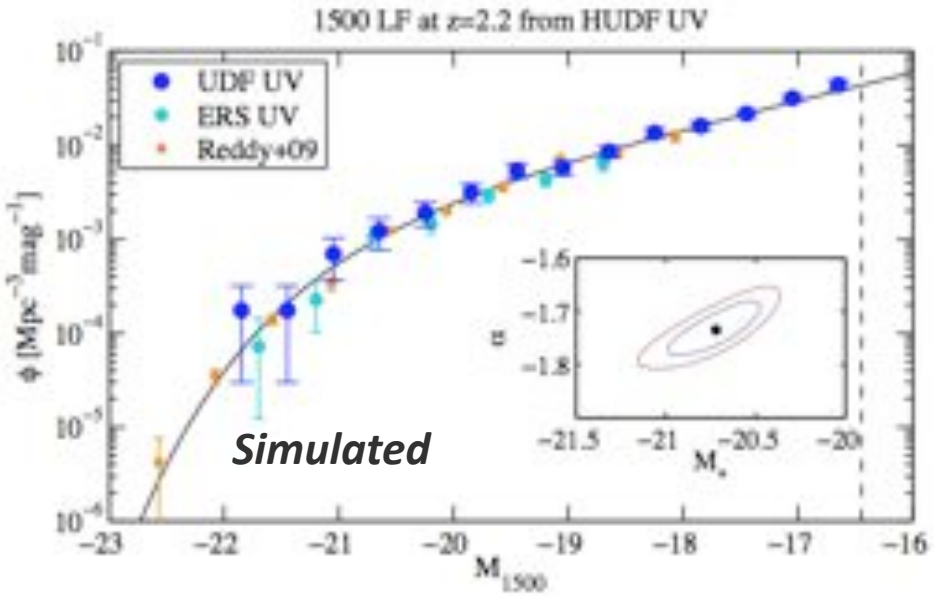
schechter luminosity function parameters

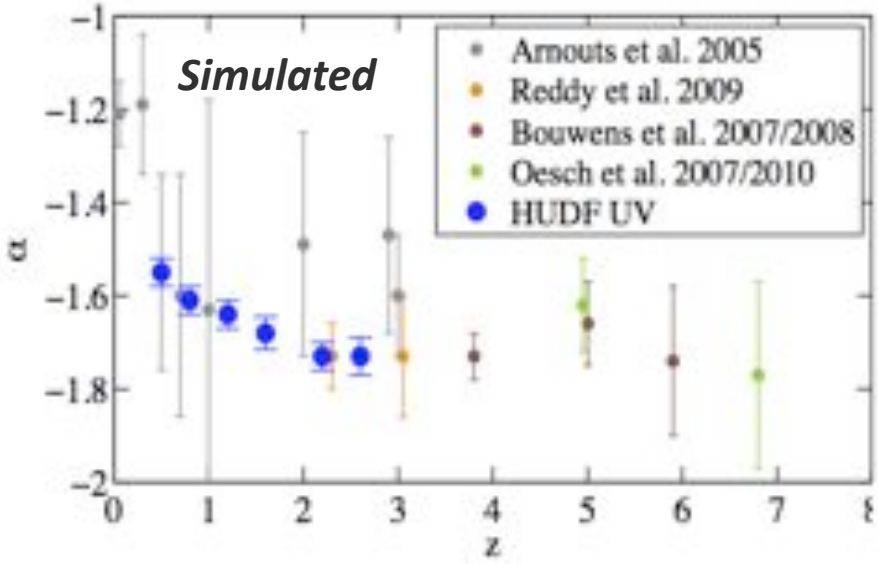


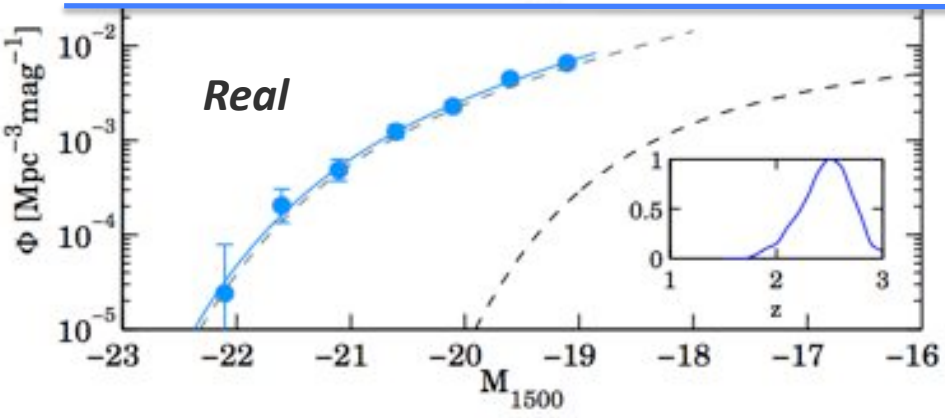
Current data is very shallow – deep WFC3/UVIS data would provide uniformly deep luminosity functions from z~1 to z~6 (ACS + WFC3/IR)

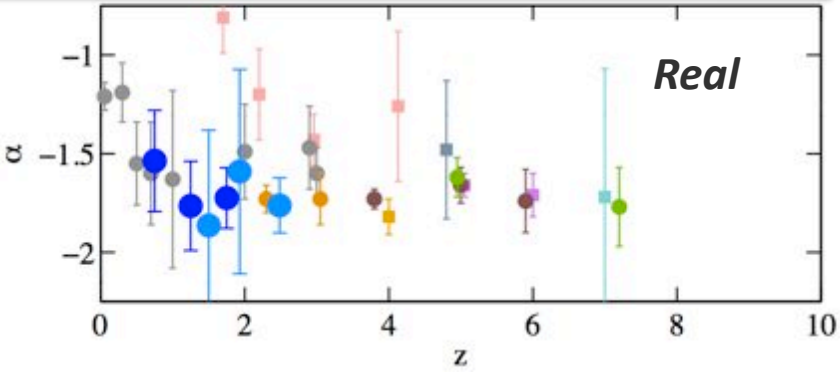
Oesch et al 2010c

WFC3/UVIS results in the ERS field



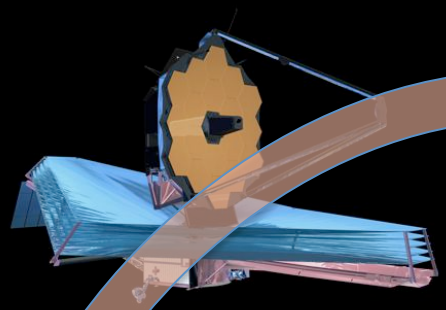


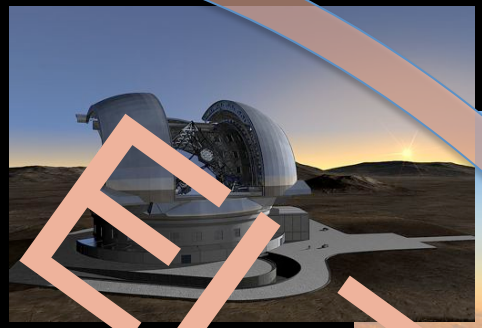




simulations show potential of deep WFC3/UVIS data

what we can look forward to using in the next decade





JWST

ELTs

HST

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!!

WFC3/UVIS has now revealed its potential at z~ 1-3, but not yet realized that potential