*science with the hubble space telescope – III*
*venice 2010*

# *revealing galaxies in the first billion years: HST's central role*


*garth illingworth*
*uco/lick obs & university of california, santa cruz*


**Science with the Hubble Space Telescope - III**
**two decades and counting**

**In honour of Bob Fosbury**

**October 11-14, 2010**

**Palazzo Cavalli-Franchetti, Venice, Italy**

After an initial agreement between NASA and ESA in 1977 and following Hubble's more than twenty years in space and 110,000 orbits of the Earth, the aim of this conference is to celebrate the huge contributions made by the Hubble observatory to our knowledge and understanding of the Universe. It is an opportunity to present its current performance following the successful servicing mission in May 2009 (SM4) and is a platform for showing early scientific results arising from the first year of operation of the new and repaired instruments. The meeting will provide a forum to consider the future usage of Hubble and to discuss the contributions that the observatory will make in the context of new space and groundbased facilities.

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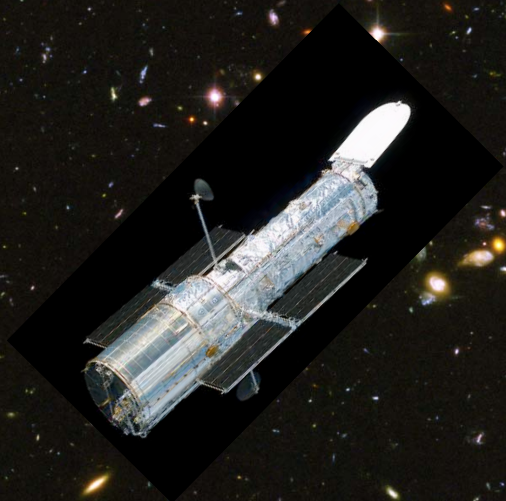

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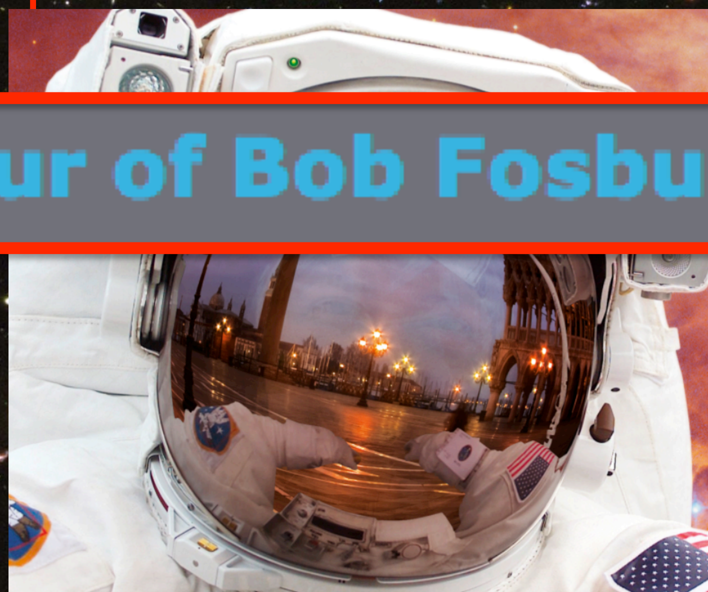


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our appreciation to all those who have brought us this remarkable Observatory

“acknowledgements” in a recent paper:

“We deeply appreciate all those at NASA, its astronauts and its contractors, ESA, 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.”

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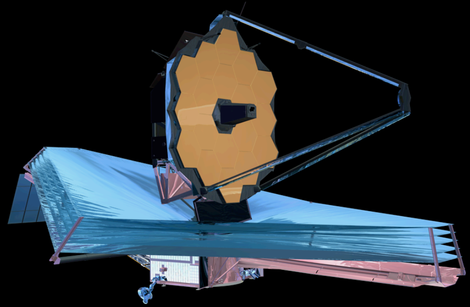

**let's make JWST just as great!!**

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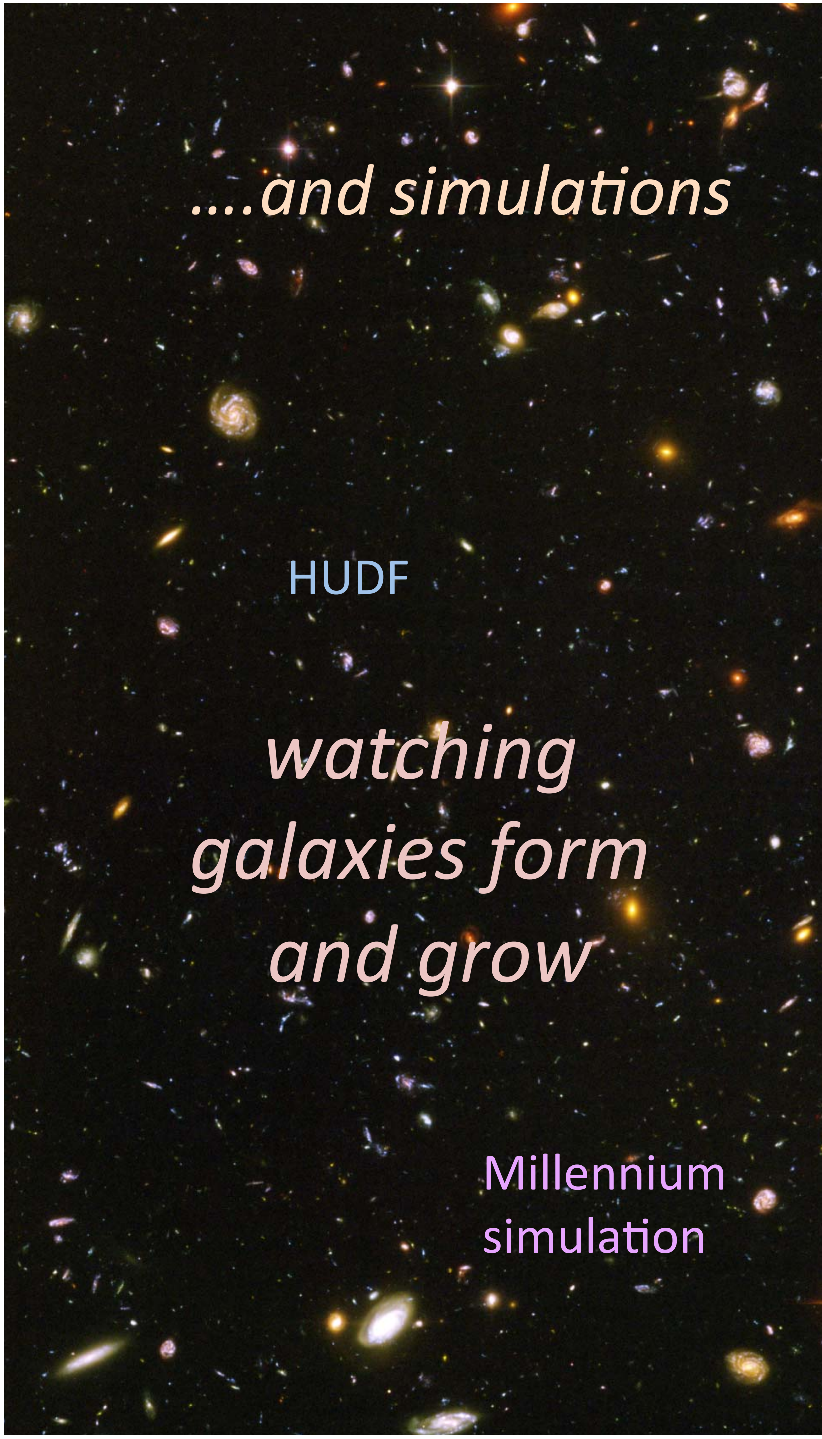
*remembering John Huchra*

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

*HST and Spitzer*


*ground 8-10 m telescopes*

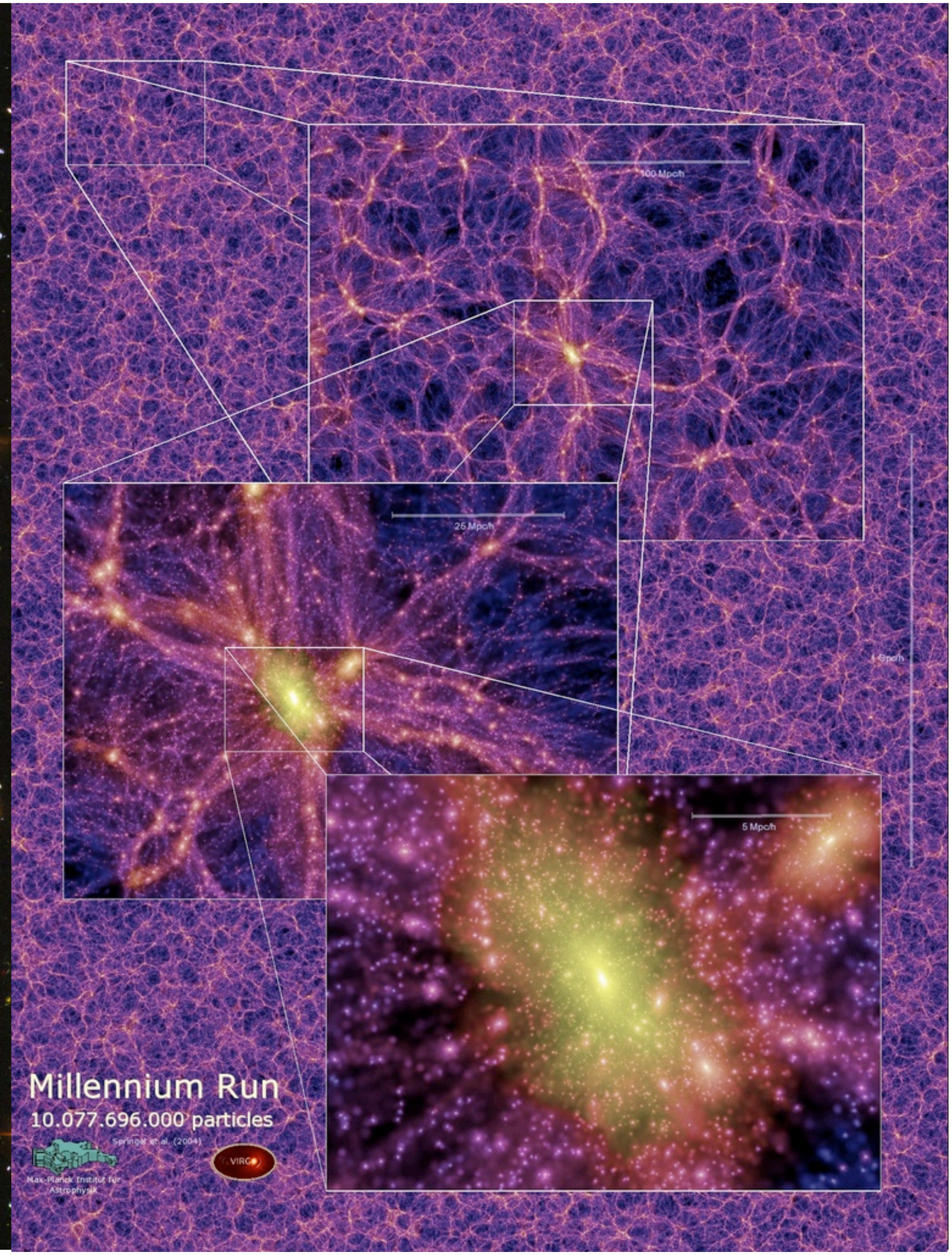
*....and simulations*



HUDF

*watching galaxies form and grow*

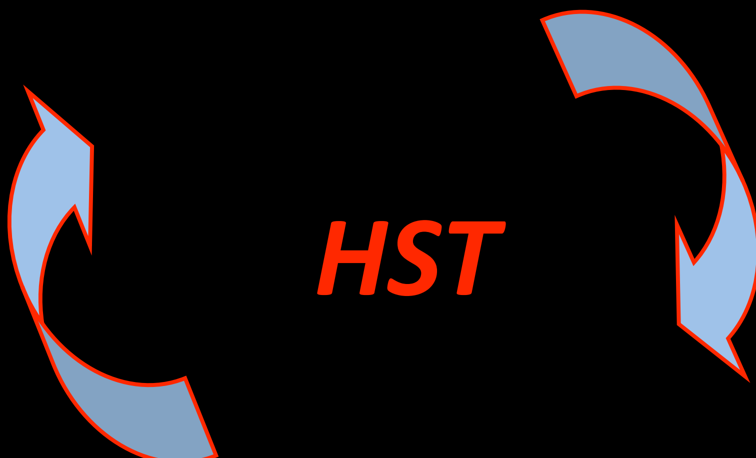
Millennium simulation



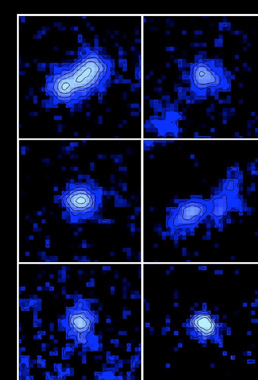
*understanding galaxy formation and evolution……*

*galactic archaeology*

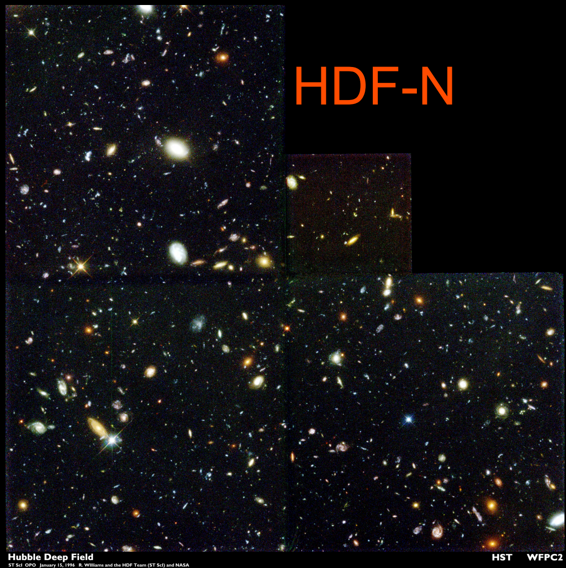
*we are remarkably fortunate to have two such powerful complementary approaches*




*direct observation*



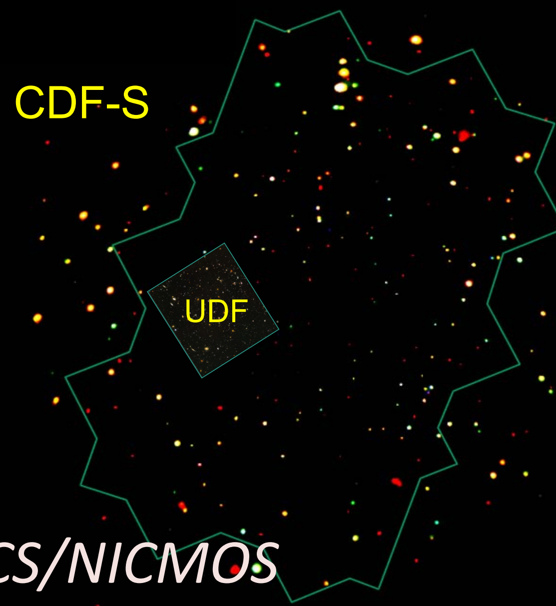
# *Hubble's remarkable track record in opening up the distant universe*




Bob Williams and Steve Beckwith

*HDF – WFPC2*

***z~2-3-4***

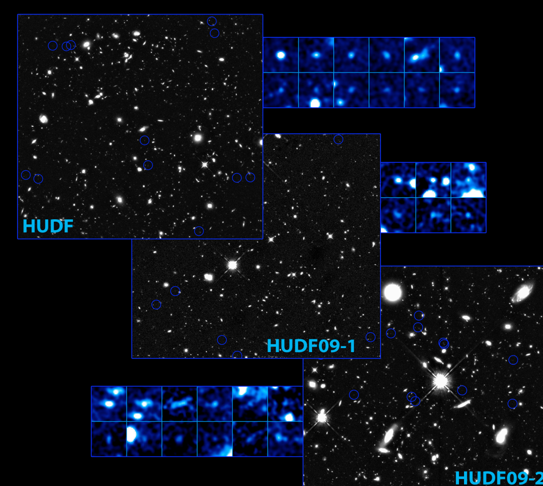



*HUDF & GOODS – ACS/NICMOS*

***z~4-6***

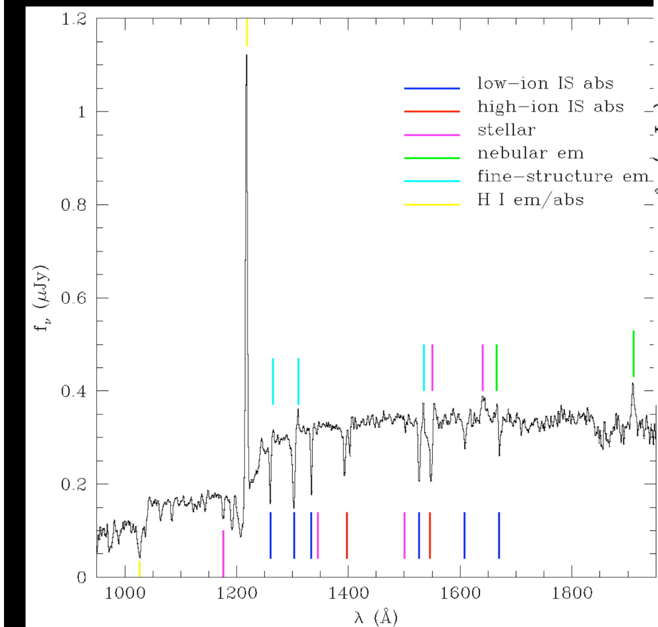
***z~7-8***

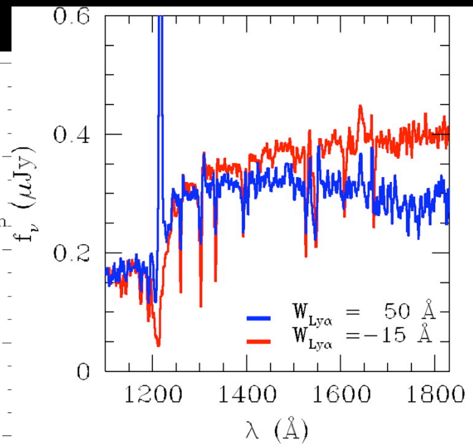
*HUDF09 & ERS – WFC3/IR*




**HUDF09 HST WFC3/IR z~8 Galaxies**

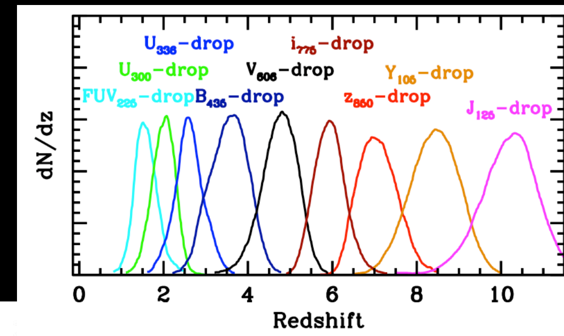
# *large samples of high redshift galaxies*

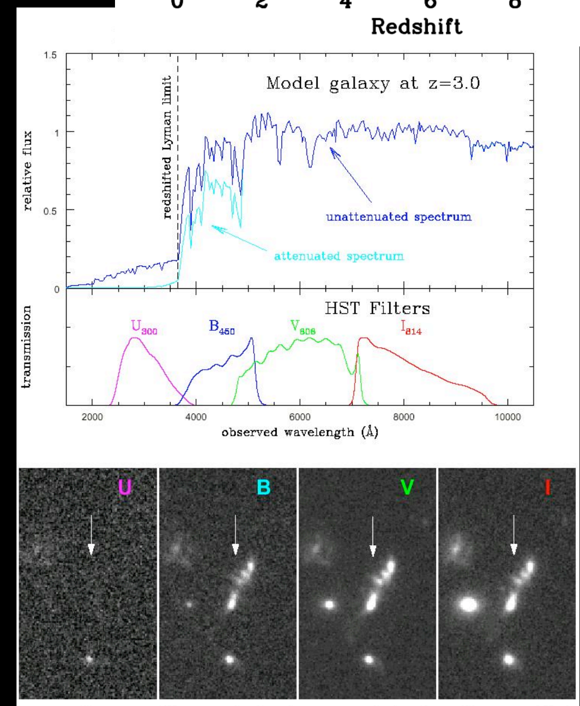



LAEs

*Lyman α emitters*




| | Field Surveys | Lensed (clusters) |
|---|---|---|
| z~4 | 20k+ | ~200 |
| z~5 | 8k+ | ~70 |
| z~6 | ~1000 | ~20 |
| z~7 | > ~70 | ~6 |
| z~8 | > ~30 | 1 |

LBGs

*dropouts/photometric redshifts*

*recent results from HST –*
*the new WFC3/IR camera*

TEAM

# *the HUDF09 team*

results based on data from the HUDF09 using the WFC3/IR and ACS cameras

G. Illingworth (UCO/Lick Observatory; University of California, Santa Cruz)
R. Bouwens (Leiden University and UCO/Lick Observatory)
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

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

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

### data and results

>110 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

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**"blob-ology"**

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

LBGs and the star forming population

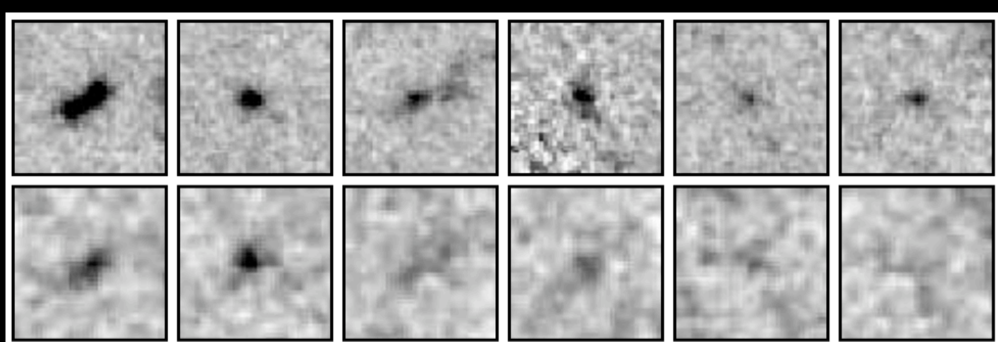
**science**

# *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**

comparing the old and new Hubble infrared cameras



WFC3/IR

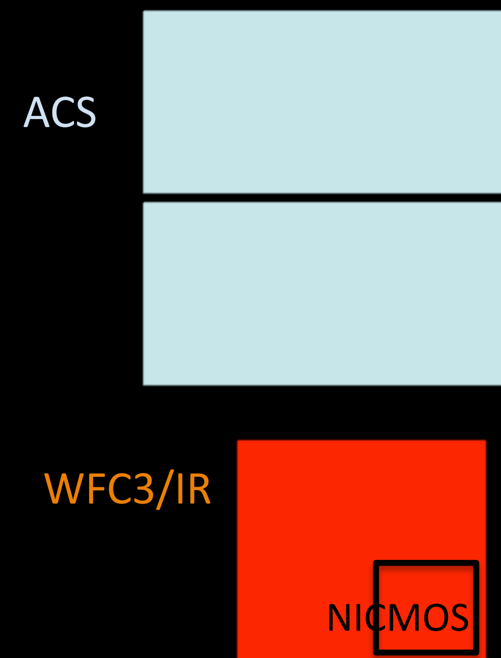
NICMOS

z~7 galaxies 2.2" x 2.2"

Oesch et al

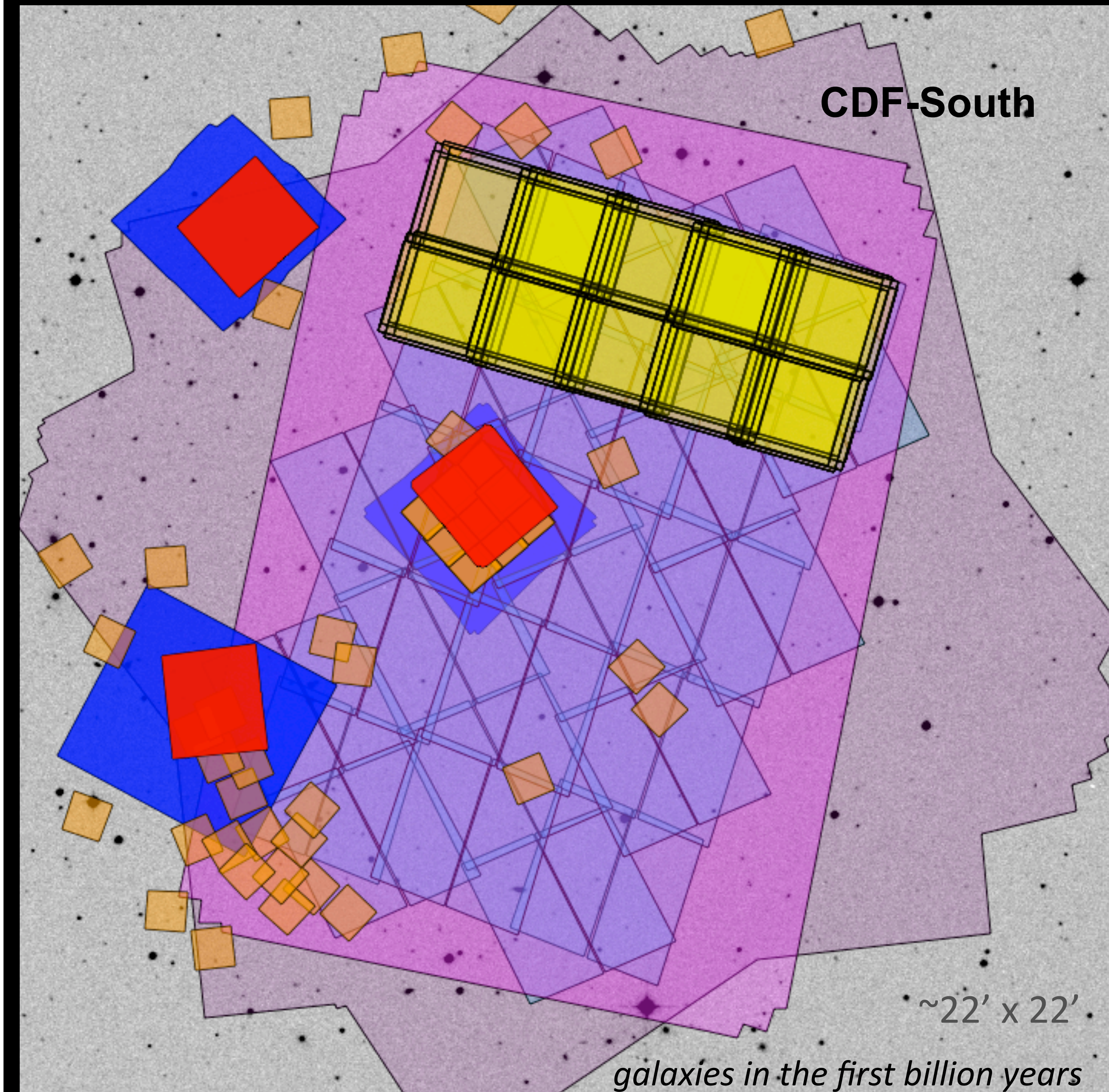
WFC3/IR is ~6X larger in area than NICMOS and much better matches ACS

3.4 arcmin




2.2 arcmin

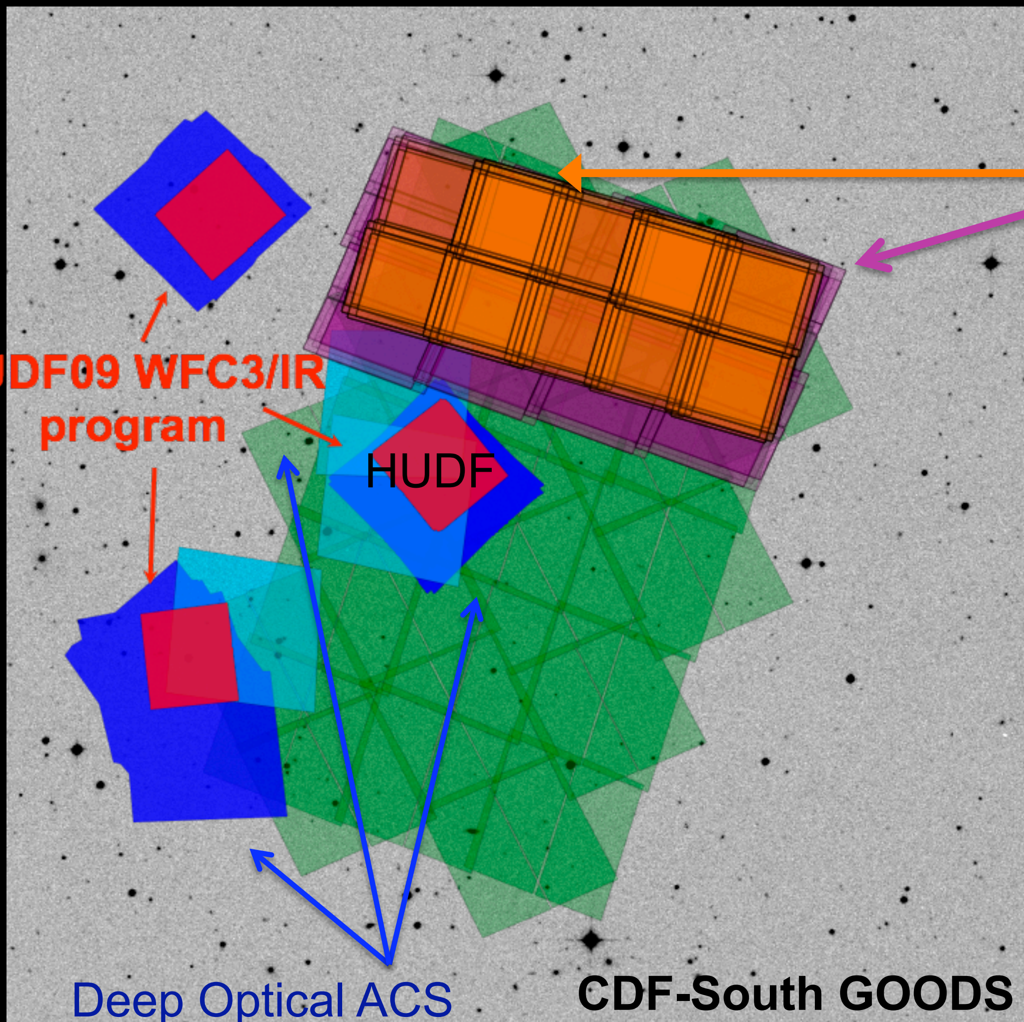
# *CDF-S region is rich in data (HST, Spitzer, Chandra, etc)*




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 community resource"*

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




~20' x 20'

Early Release Science (ERS) data taken

90% of HUDF09 data taken:

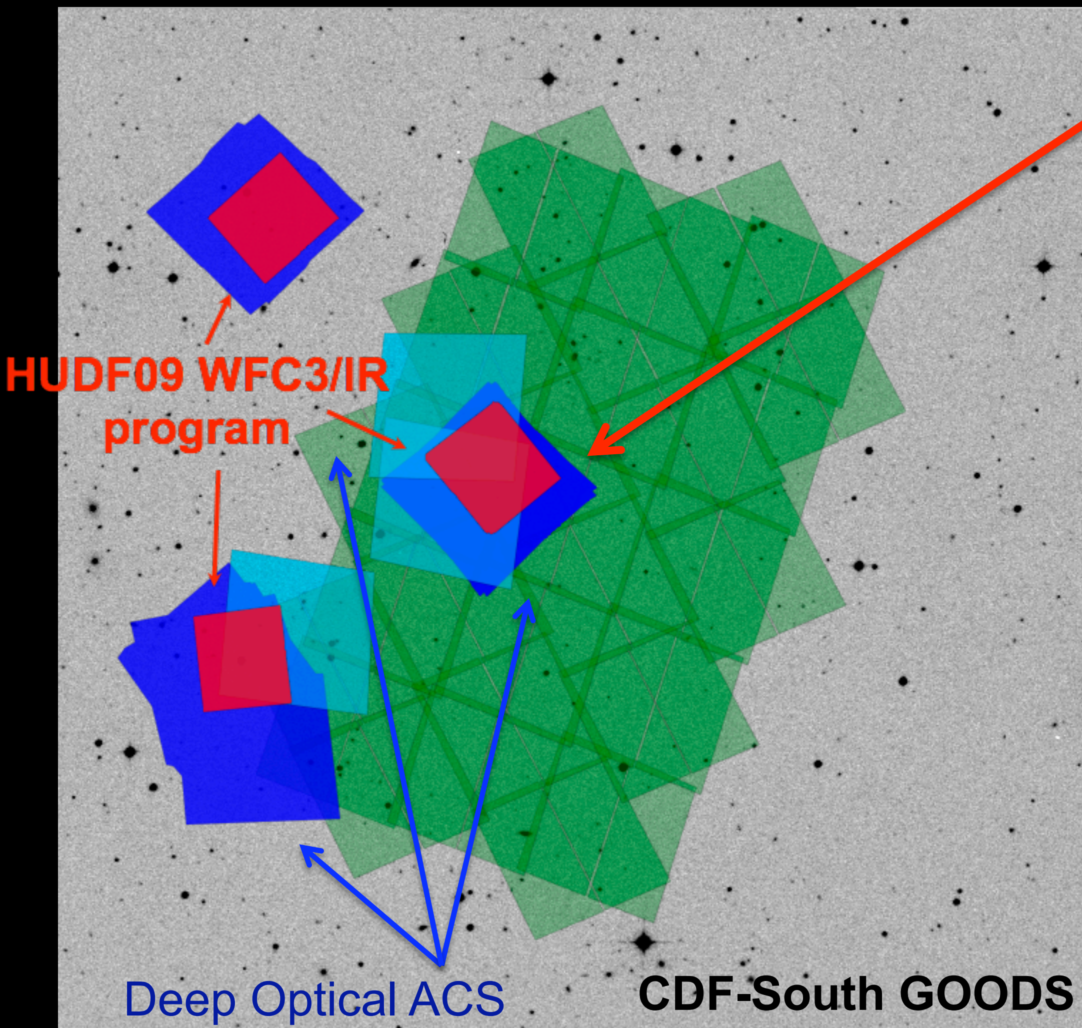
HUDF09 in aug 2009/10

HUDF09-1 in nov 2009/10

HUDF09-2 in feb 2010/11

All HUDF data taken

# *searches for z~7-8 objects in HUDF09*




First HUDF09 WFC3/IR data taken in late August 2009

very competitive area!

within 1-2 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

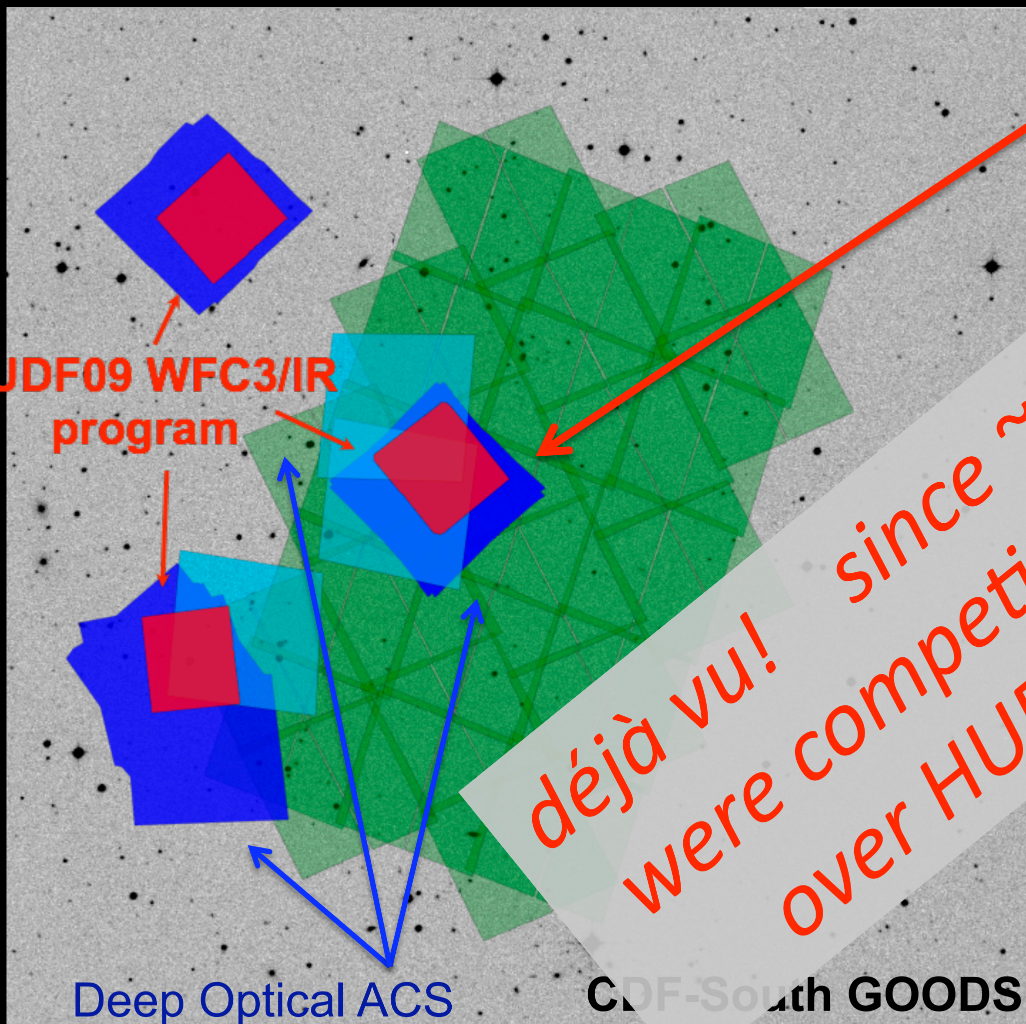
McLure et al

Yan et al

Finkelstein et al

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

## *searches for z~7-8 objects in HUDF09*

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Bouwens et al   Oesch et al

Bunker et al

McLure et al

Yan et al

Finkelstein et al

déjà vu! since ~same groups were competing in 2003-4-5 over HUDF and GOODS

# *first galaxies at z~8 from WFC3/IR*

the two highest redshift z~8 galaxies

ACS filters WFC3/IR

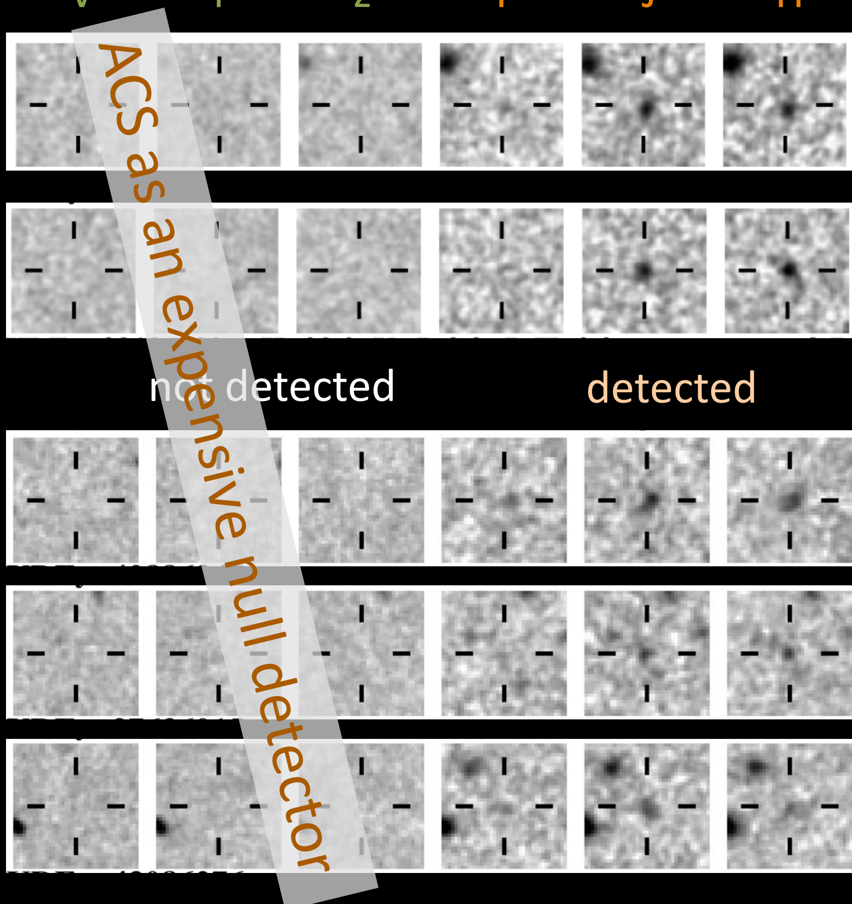
V i z Y J H

redshift

z~8.4

z~8.7

not detected detected




2.4″ x 2.4″

the other three z~8 galaxies

all are H~28-29 mag sources!

Bouwens, Illingworth et al 2010a

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

# *examples of z~7 and z~8 galaxies*

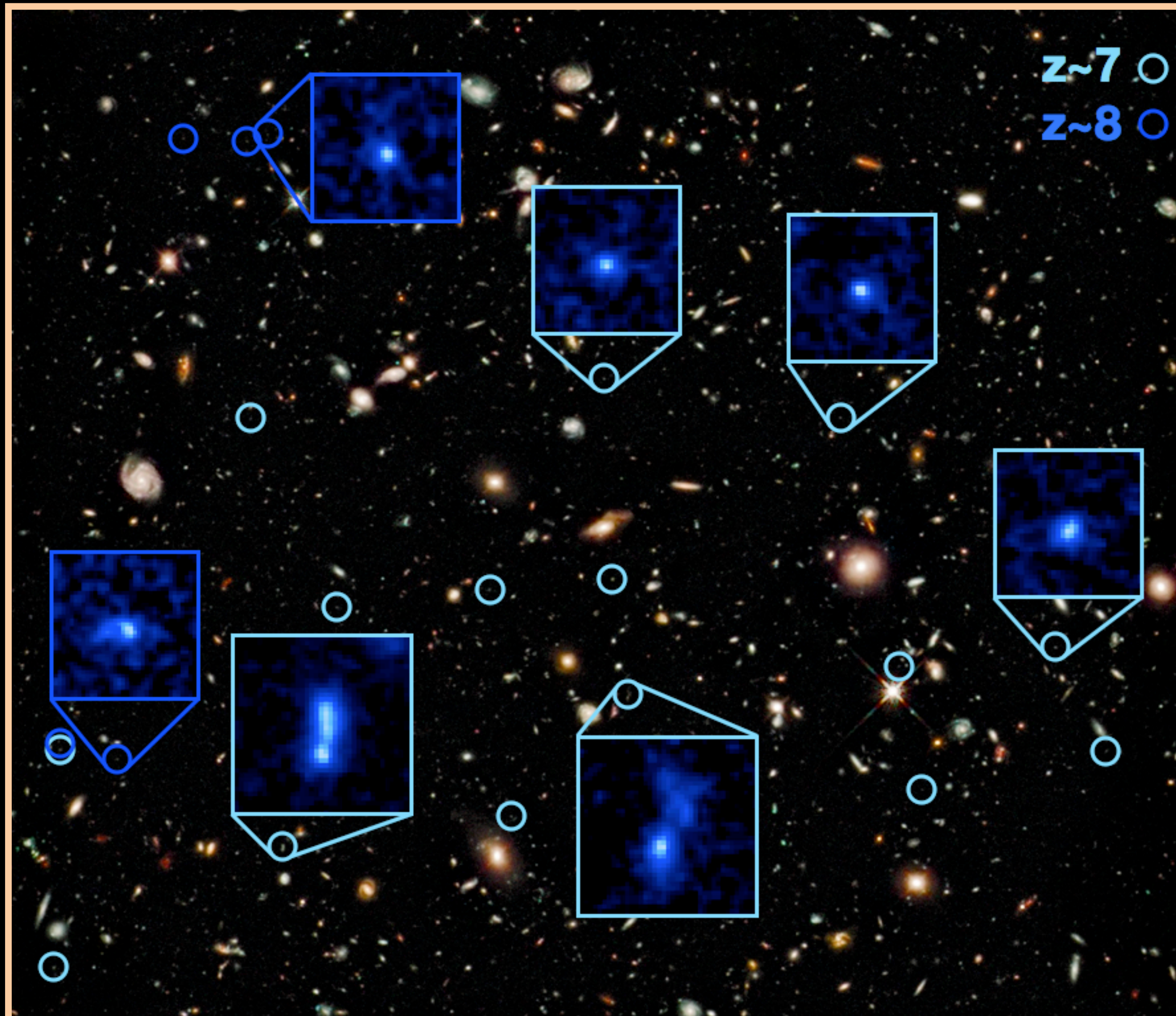
HUDF09
WFC3/IR

HUDF09
image ~2.2′

boxes ~2.5″

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

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




*galaxies in the first billion years* GDI *firstgalaxies.org*

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HUDF09
WFC3/IR

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2010a

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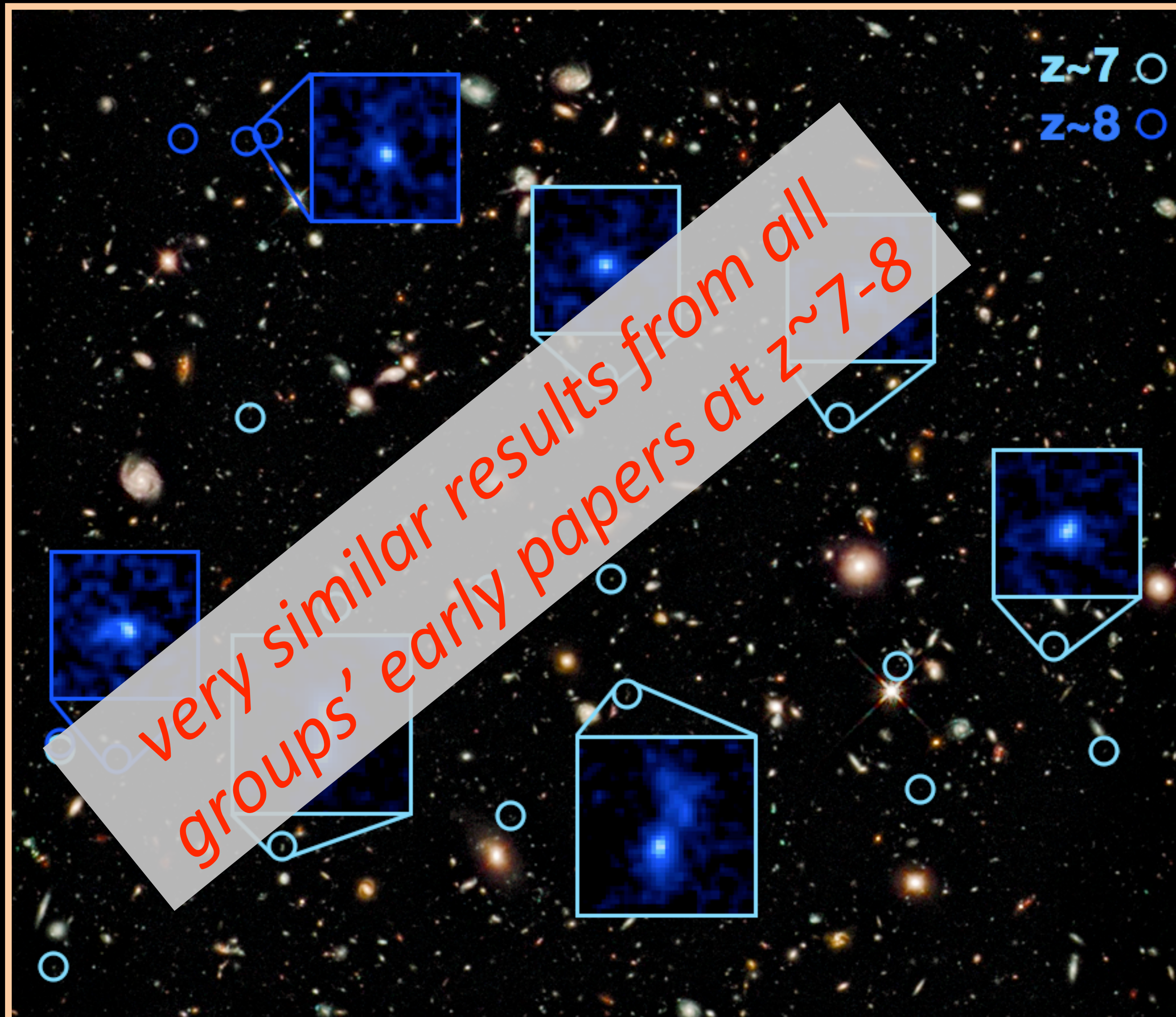
Oesch et al
2010a

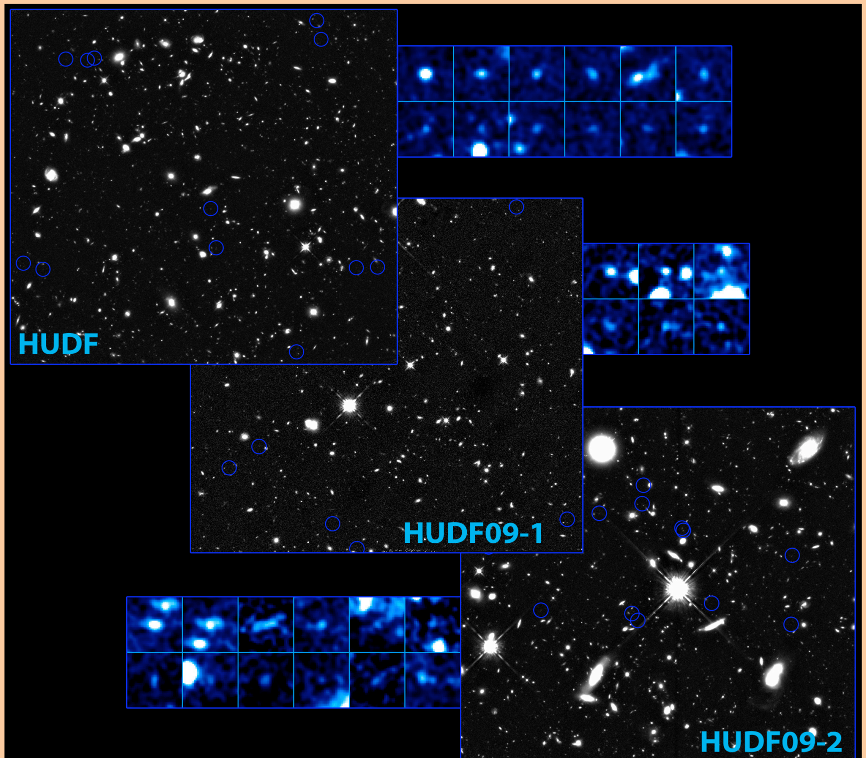


# *number of z~7 & z~8 galaxies is increasing quickly*

recent results: >100 z~7 & z~8 galaxies from ERS + HUDF09 fields

Bouwens et al (2010d)

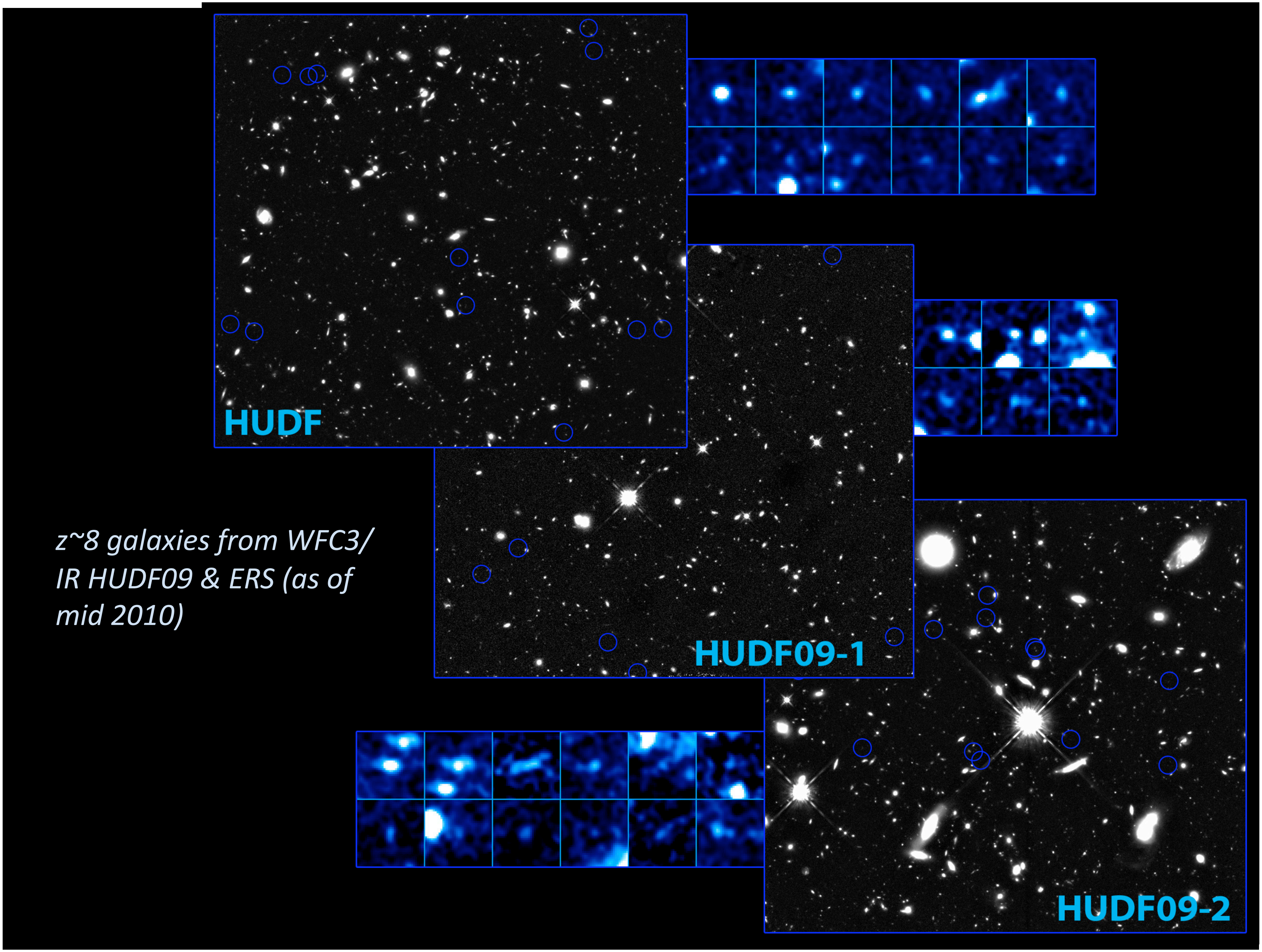
HUDF09 fields WFC3/IR




HUDF09 HST WFC3/IR z~8 Galaxies

# of z~7 & 8 galaxies has increased by >5-6x in the last year – 14 months ago the only z~8 object was a GRB!

HUDF09 images: ~2.2′


HUDF
HUDF09-1
HUDF09-2
z~8 galaxies from WFC3/
IR HUDF09 & ERS (as of
mid 2010)

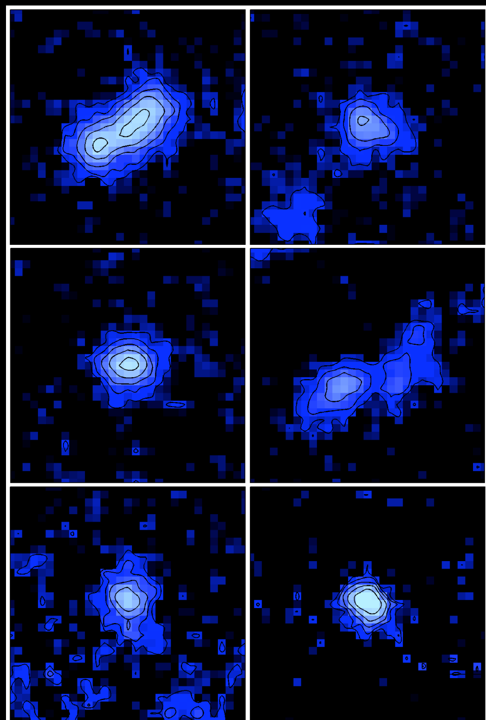
*what have we (really) learnt from the new HST data?*

*what have we (really) learnt from the new HST data?*

~~**“blobology”**~~

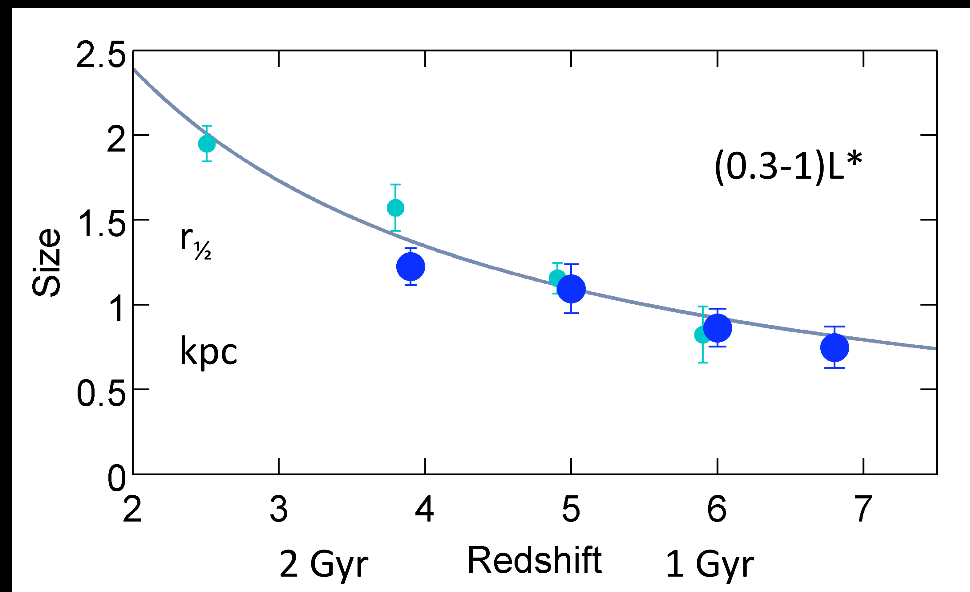
**science**

# *these early galaxies are small*



1.8″ x 1.8″

Oesch/Carollo et al 2010b



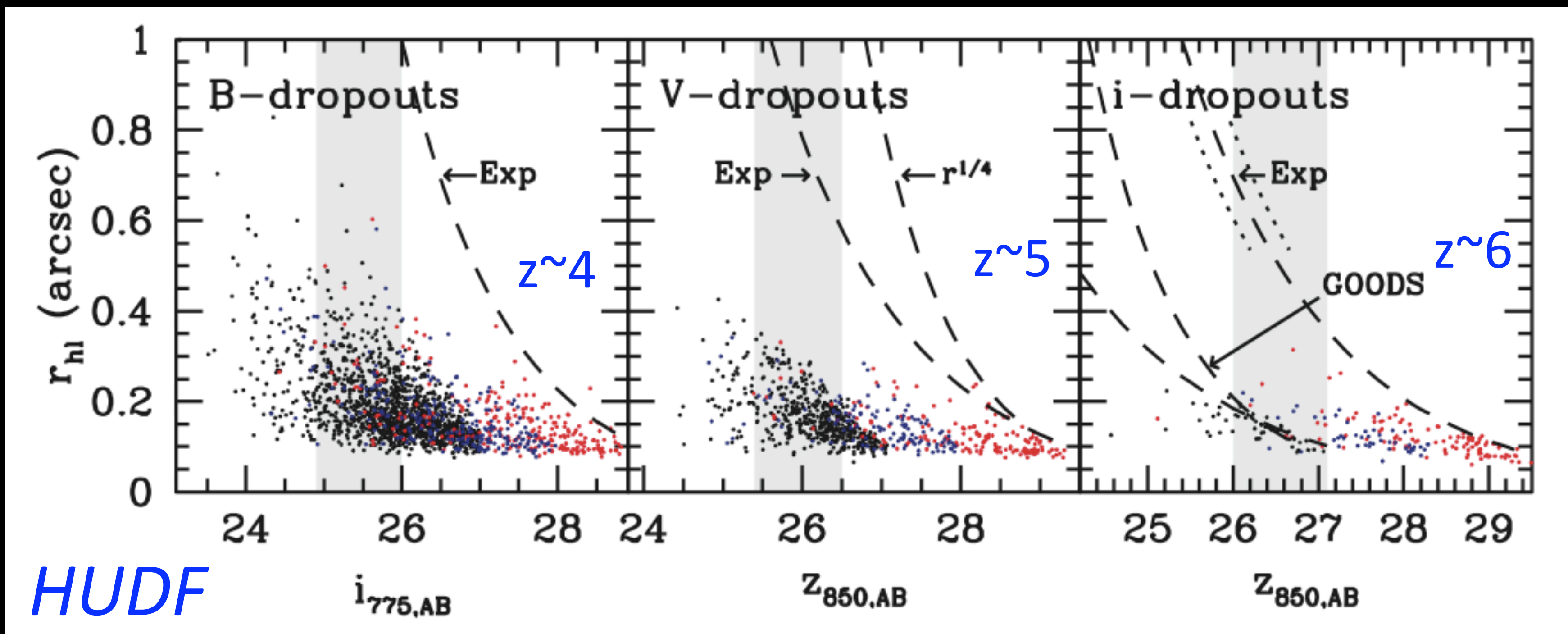

z~7 galaxies show considerable sub-structure

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)

# *low surface brightness high-z galaxies?*

low surface brightness sources could have been found in HUDF data




dashed lines are 50% completeness (10-90% is a small effect – see z~6 panel) for exponential profile – low surface brightness sources could have been found easily except at very low luminosities

Bouwens et al 2004

*indicates that size measurements are not biased by missing low SB sources*

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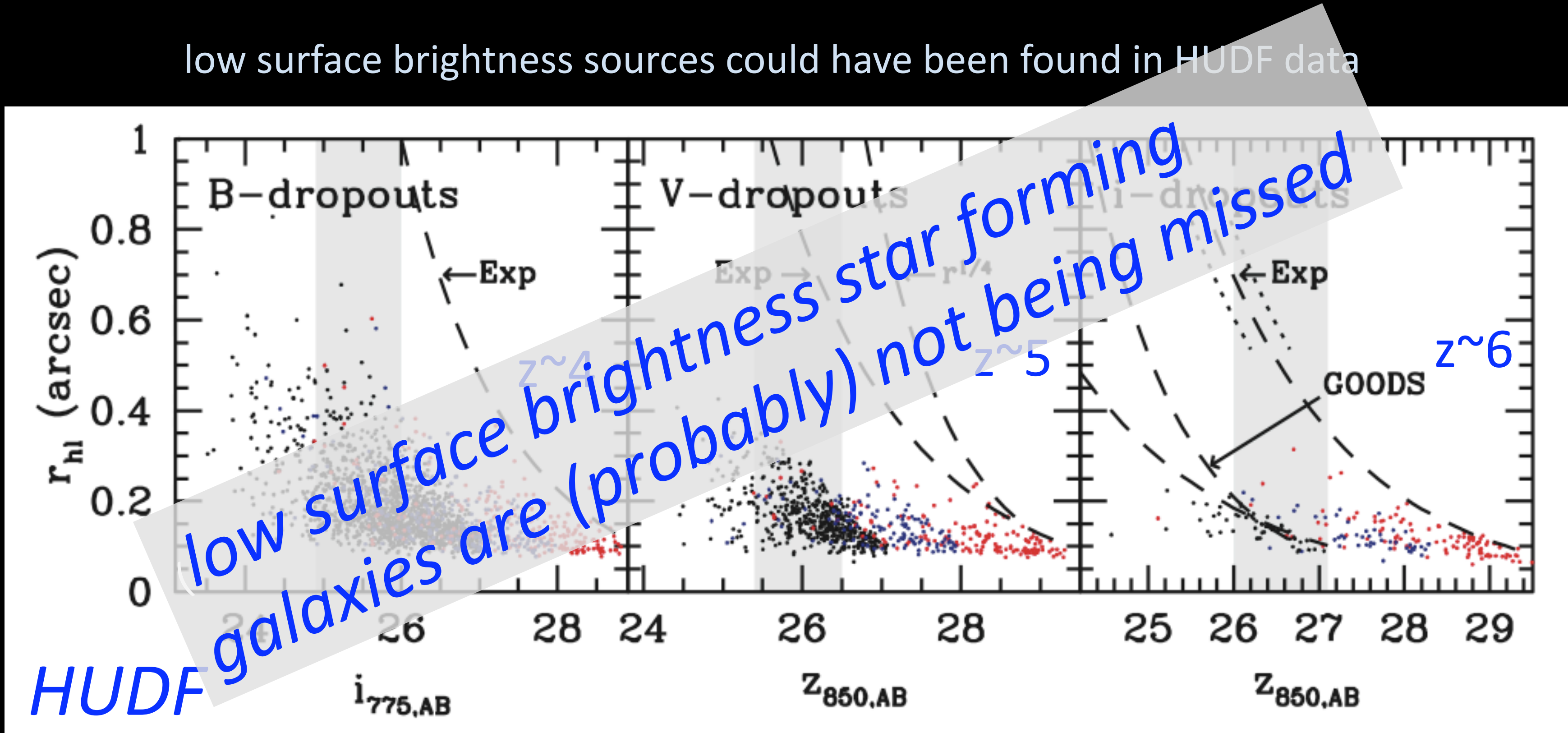


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Bouwens et al 2004

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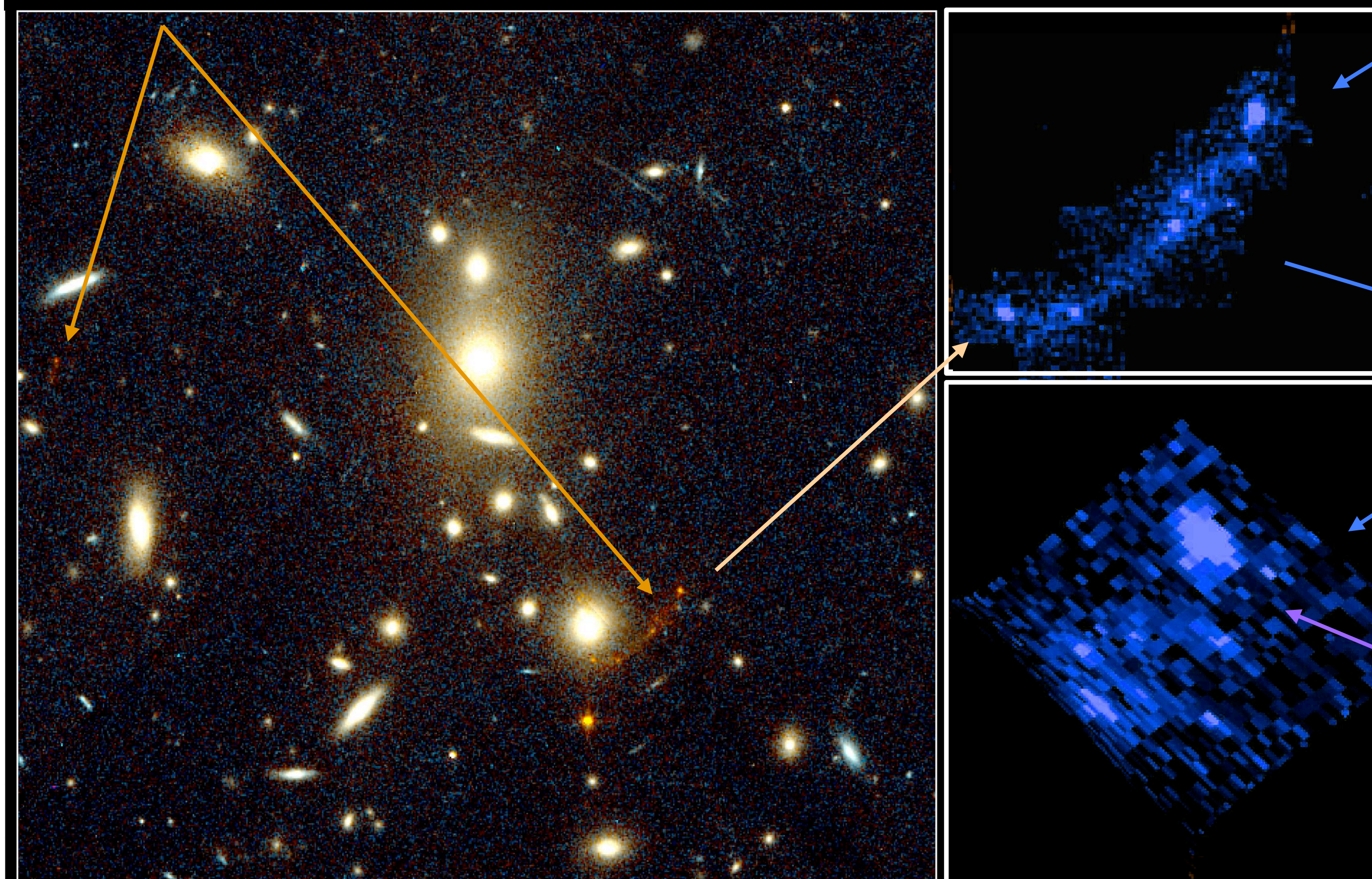
# *star formation occurs in compact regions*

Franx et al 1997

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

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

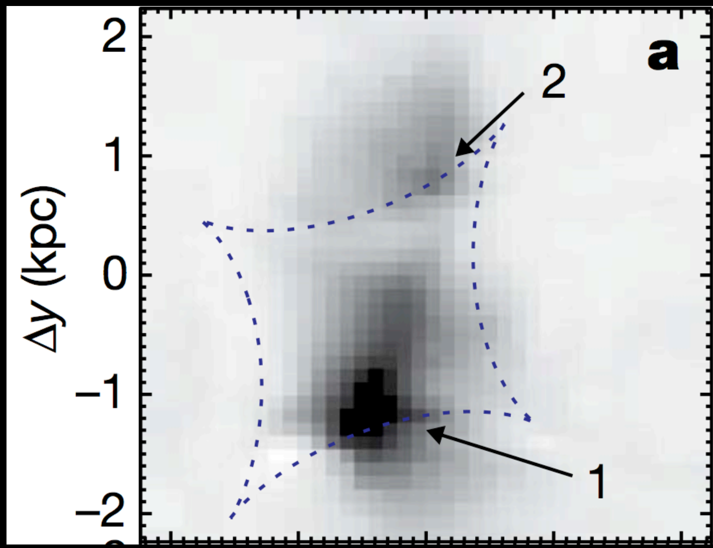
- *significant fraction of total star formation in "blob"*
- *just a few hundred pc in size*

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

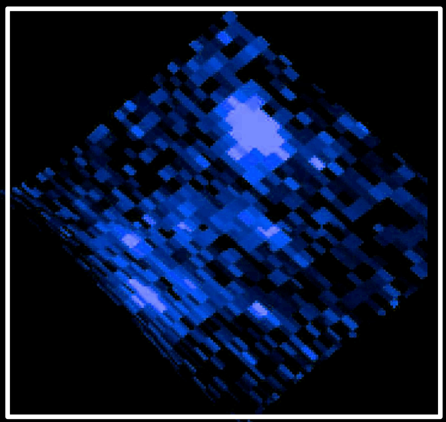
# *star formation occurs in compact regions*

*highly-lensed galaxies => give resolutions of ~100 pc or less – like 30-40 m telescope with AO*

but such highly-lensed galaxies are rare objects




Stark et al 2008

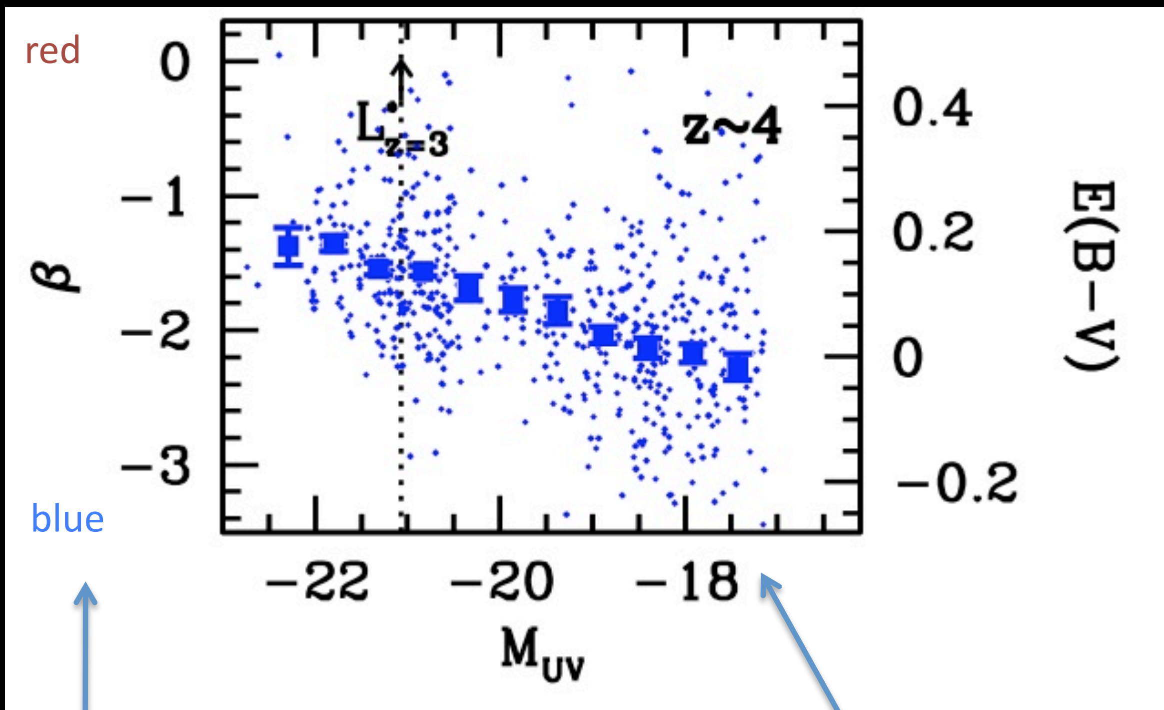


Franx et al 1997

- *these highly-magnified galaxies will continue to be important for assessing the nature of star forming regions at high redshift*

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

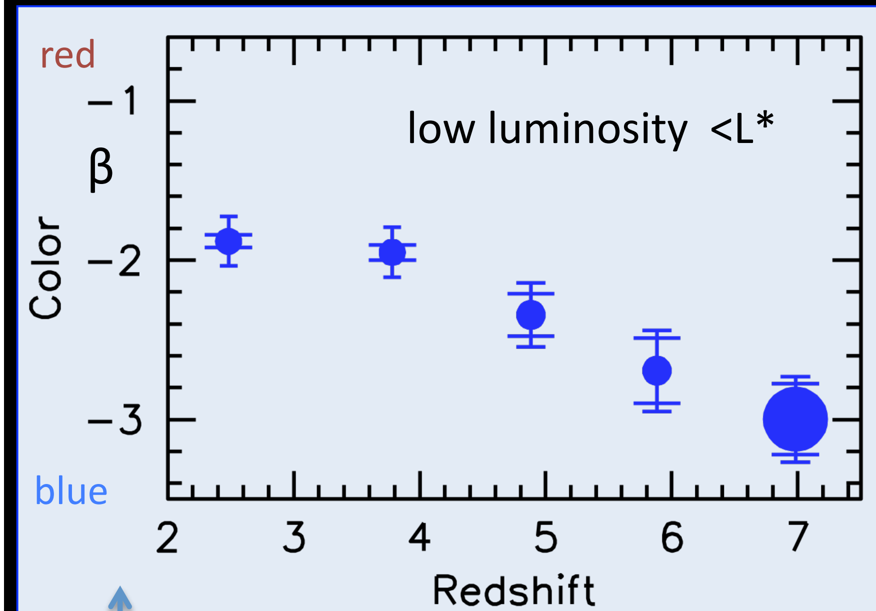
z~4 from ACS data in HUDF and GOODS

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*




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?

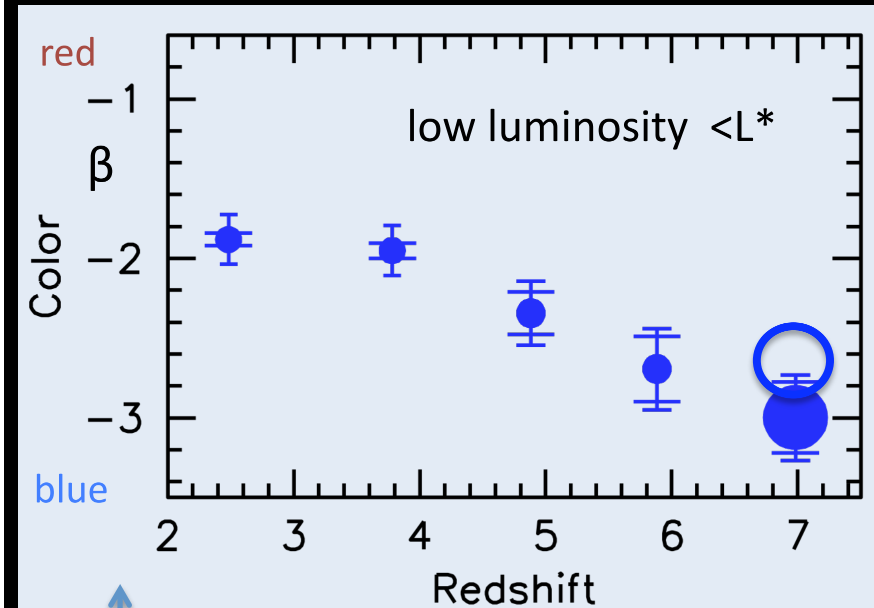
dust free at β < ~-2.4

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

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

Bouwens/Illingworth et al 2010b

*these early galaxies are very blue*




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

latest HUDF09 data suggest that β is => ~-2.6

dust free at β < ~-2.4

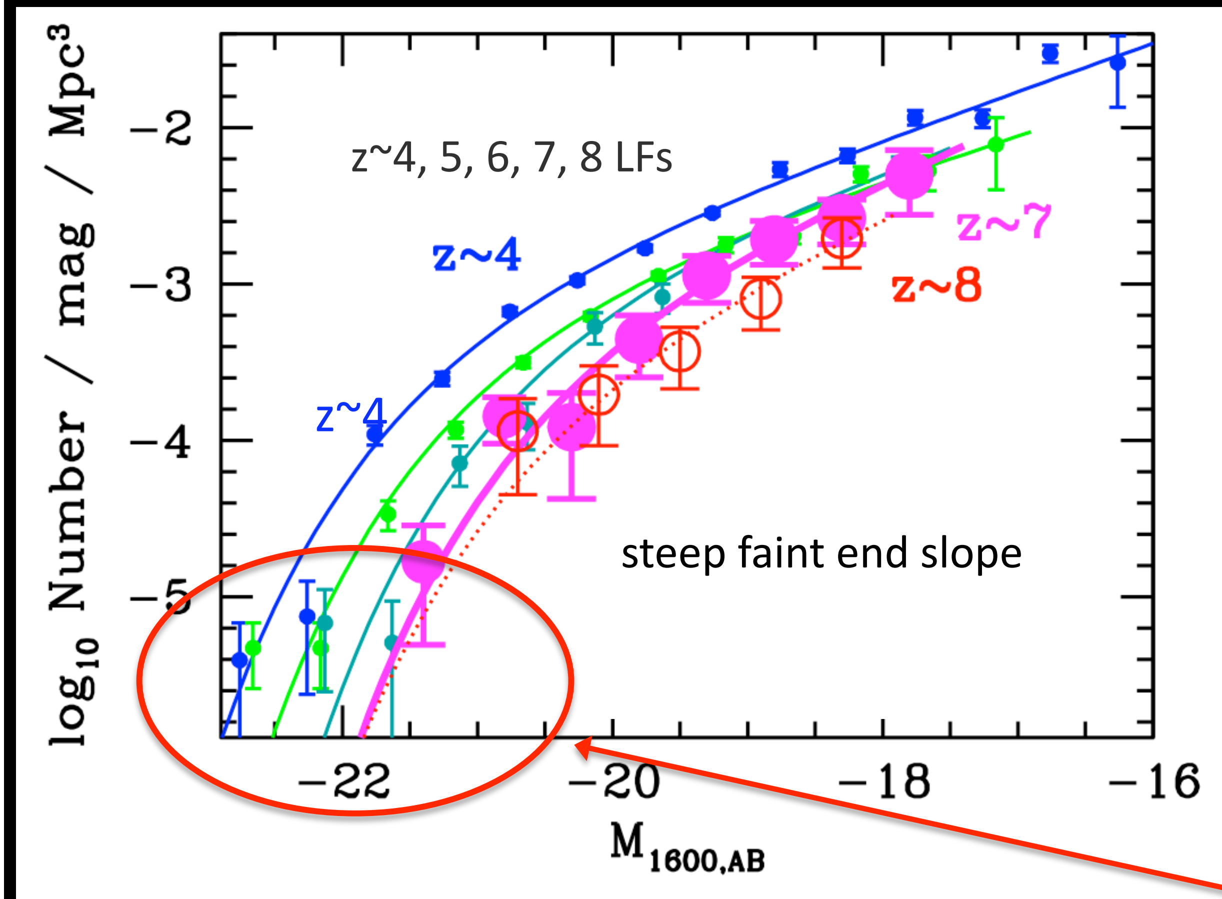
β is the power law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

Bouwens 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 in low luminosity galaxies)

# *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)

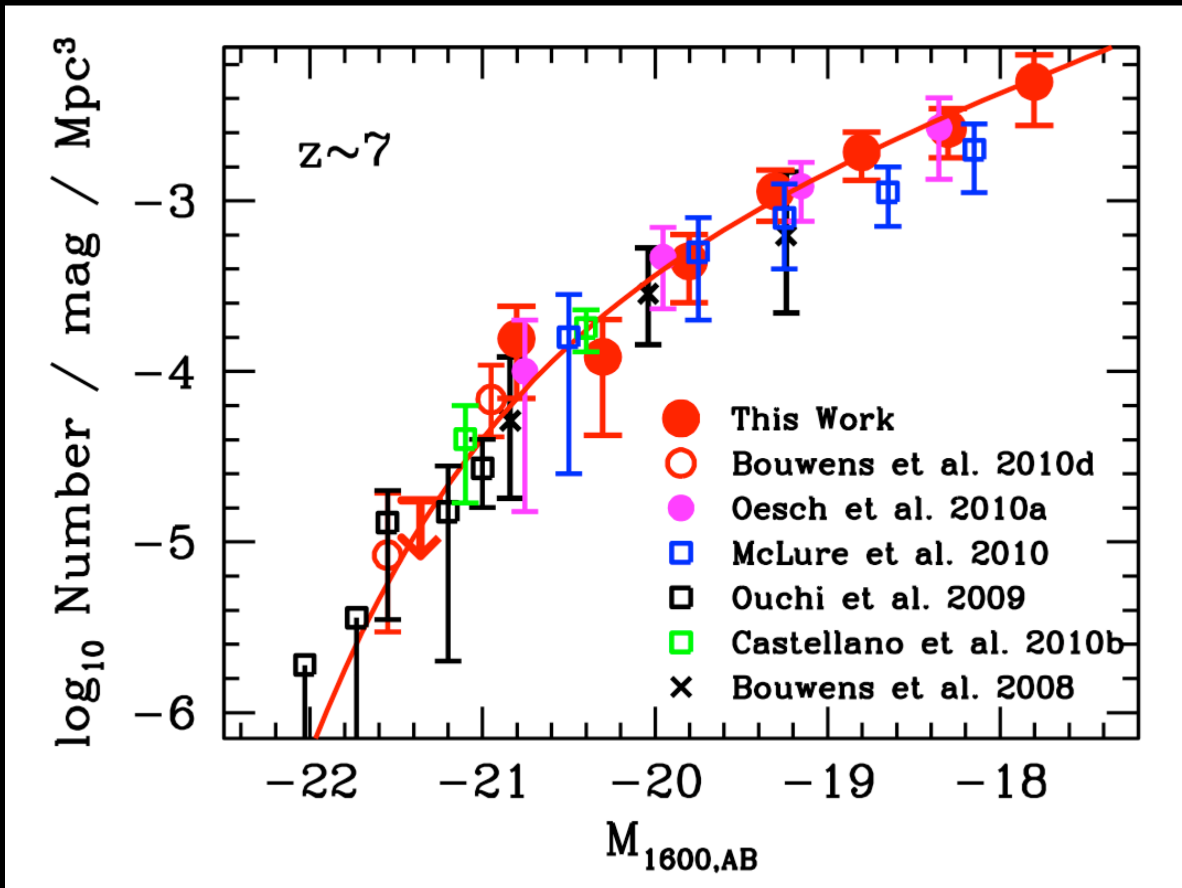
the bulk of the integrated UV flux at high-redshift comes from sub-L* low luminosity galaxies

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

Bouwens et al 2010e

*need more at bright end: see Yan et al; Trenti et al*

# *luminosity functions*




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

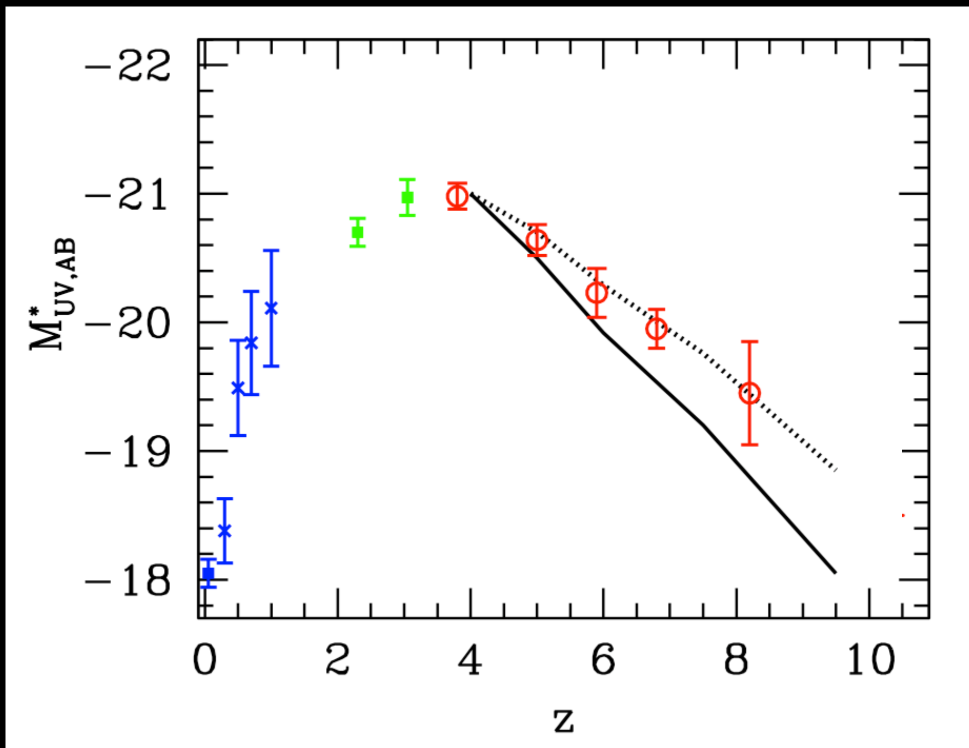
excellent agreement now between the several groups

*need more at bright end: see Yan et al; Trenti et al*

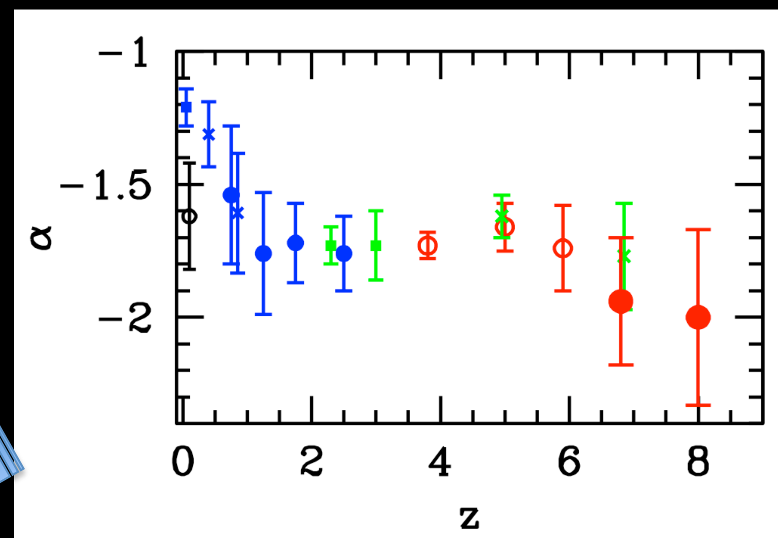
the new z~7 luminosity function indicates that the very steep slope (α ~ -1.75) seen at lower redshift persists to higher redshift

Bouwens et al 2010e

# *luminosity functions – implications*




dominant changes occur at bright, massive end




slope is steep and changes very little

*important for reionization:*
*galaxies are playing a substantial role at z~7-8 but still not definitive….*

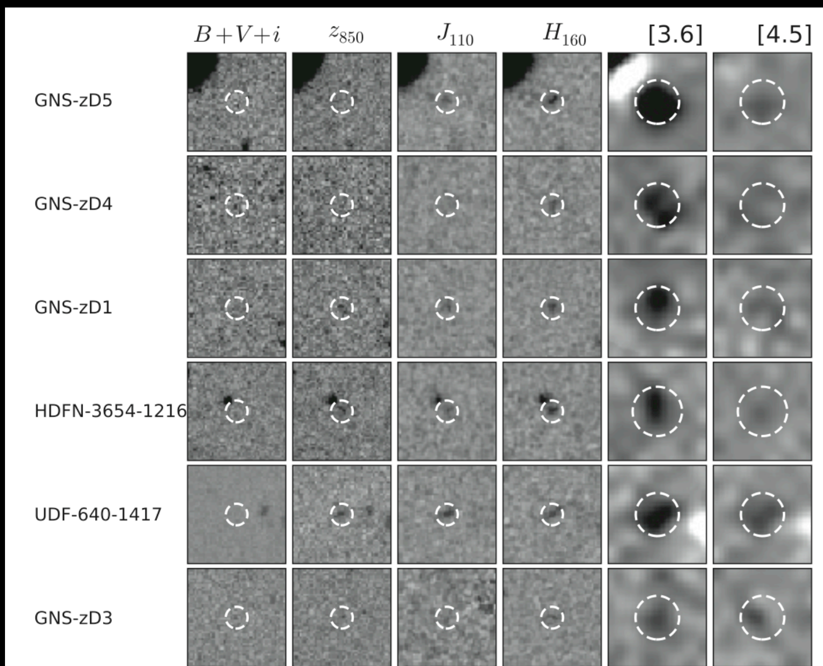
z>4 star-forming galaxies are very small, blobby objects ($r_{½}$ is sub-kpc)

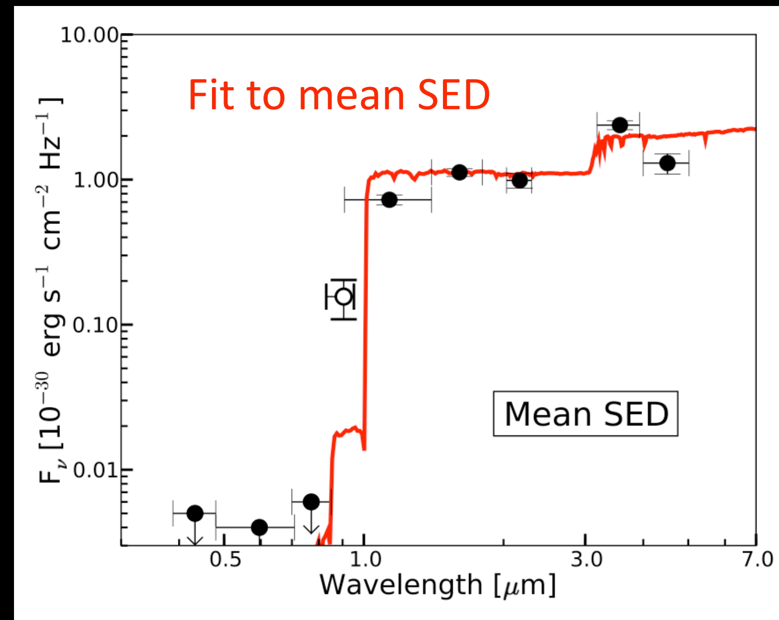
z>4 galaxies are very blue & fainter galaxies are even bluer
(little or no dust at z>5 in low luminosity galaxies)

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



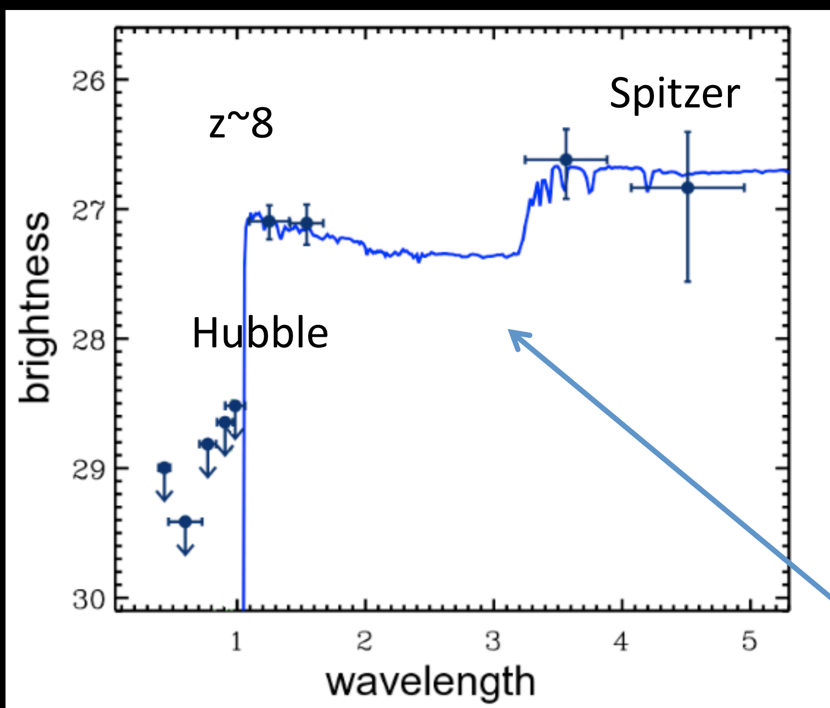

stellar mass density at z ~ 7 is 4.5 × $10^5$ $M_\odot$ $Mpc^{-3}$

Gonzalez, Labbé et al 2010a

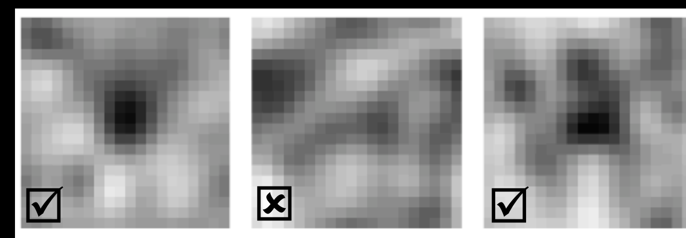
Model fits are BC03 CSF $0.2Z_\odot$ z~7 and ~300 Myr (SFH weighted age = t/2) with ~zero dust

# *these galaxies probably formed stars much earlier*

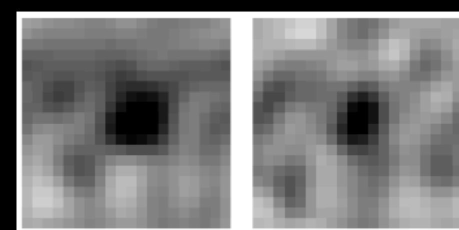
WFC3/IR Hubble and Spitzer results also combine to show us that z~8 galaxies could well have been forming stars two-three hundred million years earlier (at z>10-11)




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

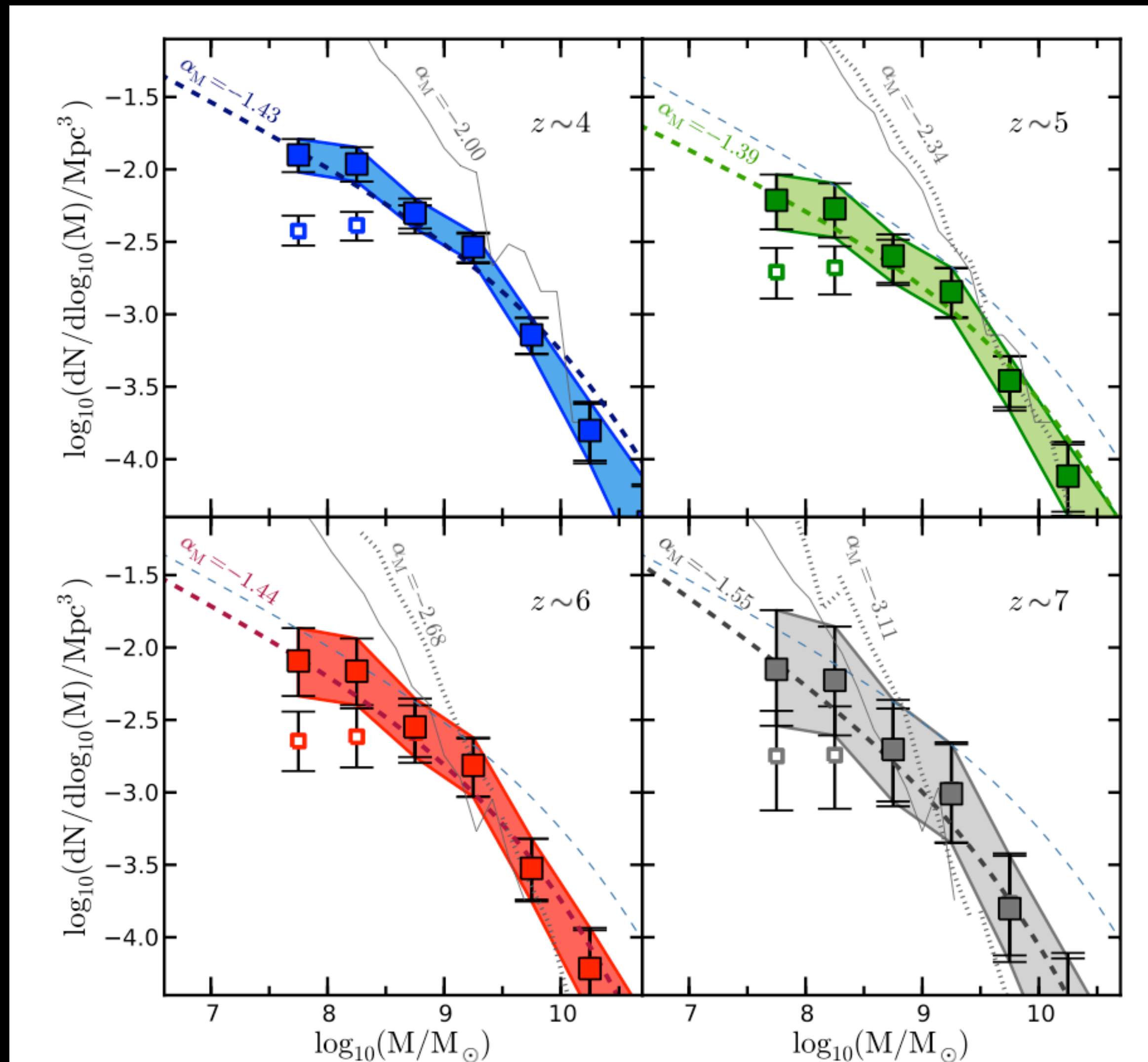
Model fit is BC03 CSF (?) $0.2Z_{\odot}$ log M = 9.3
z~7.7 and 300 Myr (SFH weighted age = t/2)

# *Spitzer + HST powerful combination*

Mass Functions

WFC3/IR ERS data + Spitzer IRAC data used to determine mass functions at z~4, 5, 6, 7 from SED fits, UV LFs and M_$L_{UV}$ relation – and completeness corrected

Gonzalez, Labbé, Bouwens, Illingworth et al 2010b




log mass

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

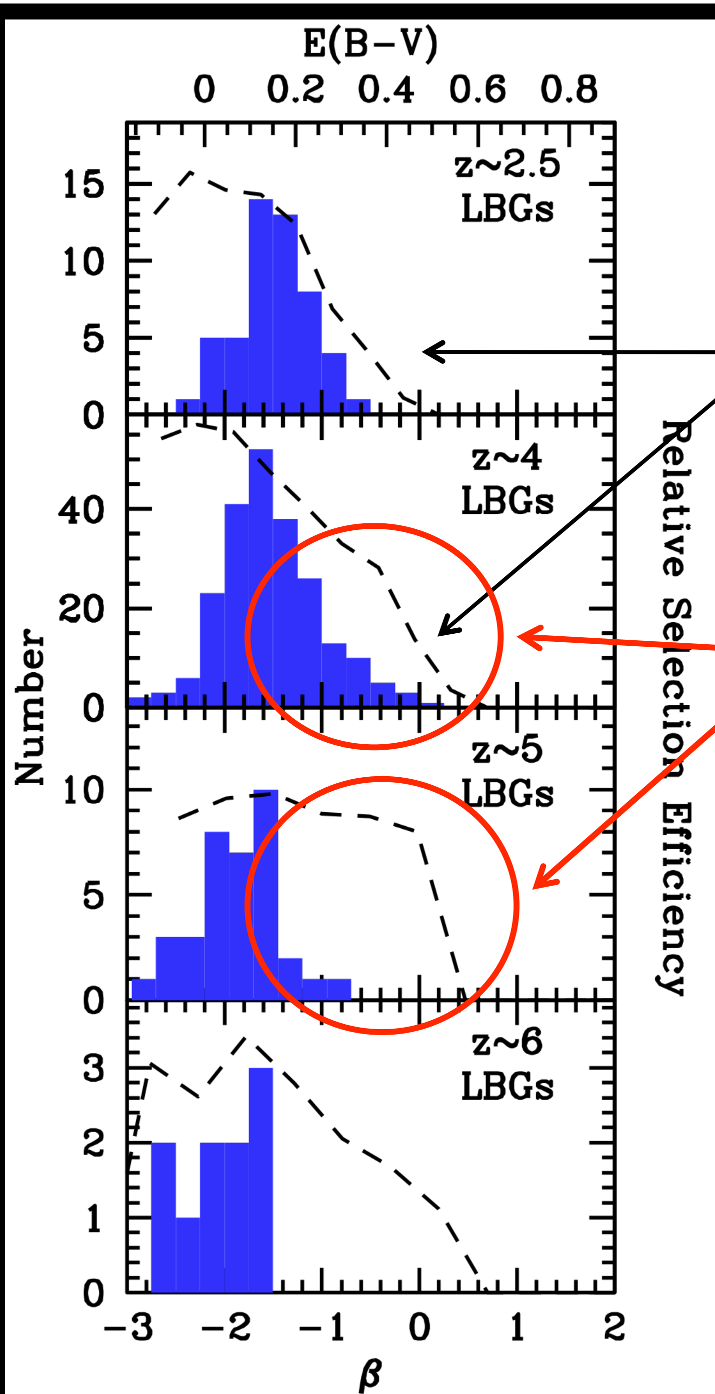
z>4 galaxies are very blue & fainter galaxies are even bluer

(little or no dust at z>5 in low luminosity galaxies)

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

relatively steep mass functions at early times




*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+

Bouwens/Illingworth et al 2009 ApJ 705

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 in low luminosity galaxies)

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
relatively steep mass functions at early times

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

lots of reasons to expect galaxies at z~10+

*can we find galaxies at z~10?*

*can we find galaxies at z~10?*

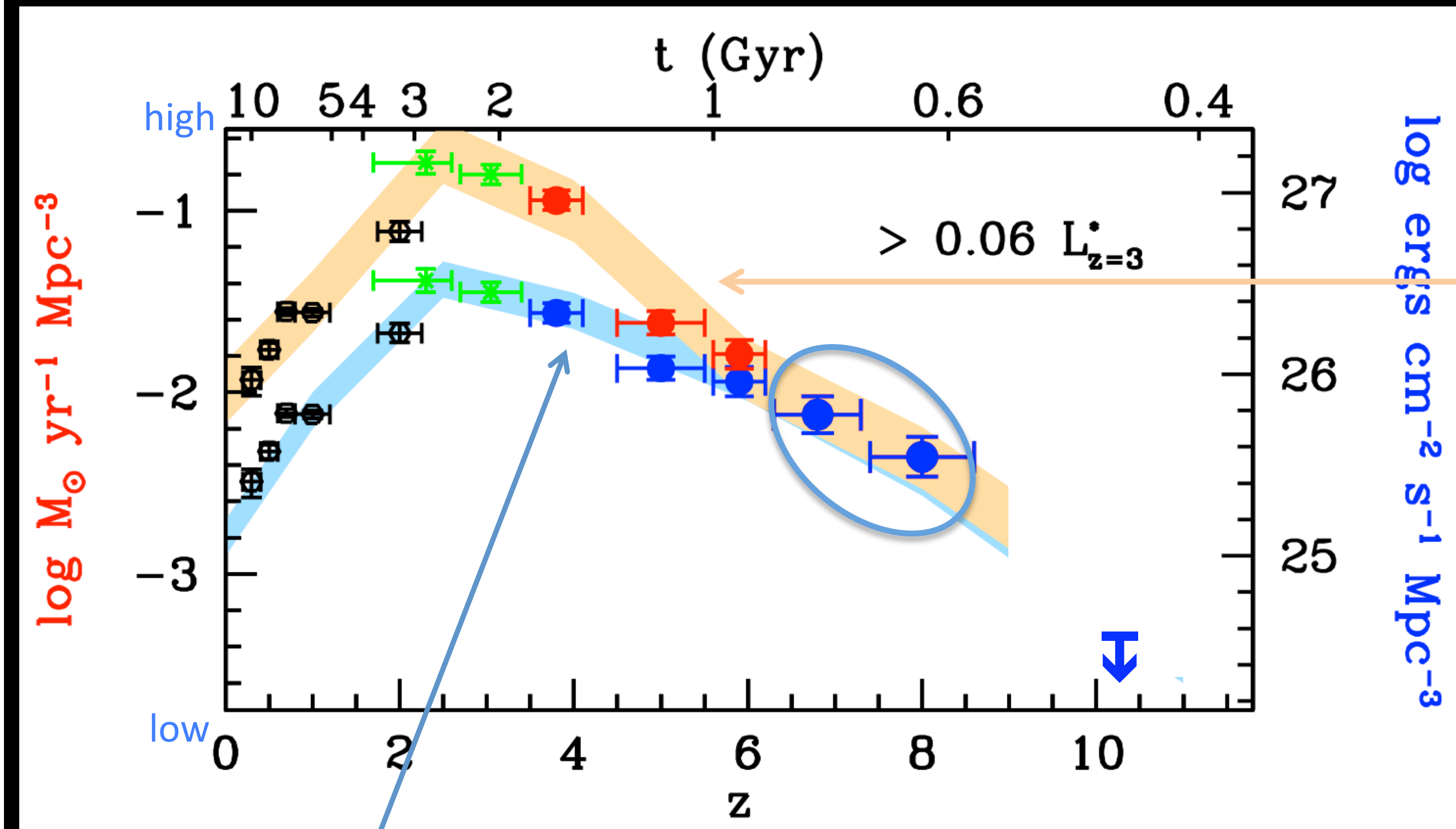
challenging with the current dataset……

With all 2009+2010 HUDF data, candidates from 2009 data now below acceptable detection limits (need S/N>5σ)

***most robust result is still upper limit***

*integrated properties…..*

*the star formation rate density*




dust-corrected SFR

new results

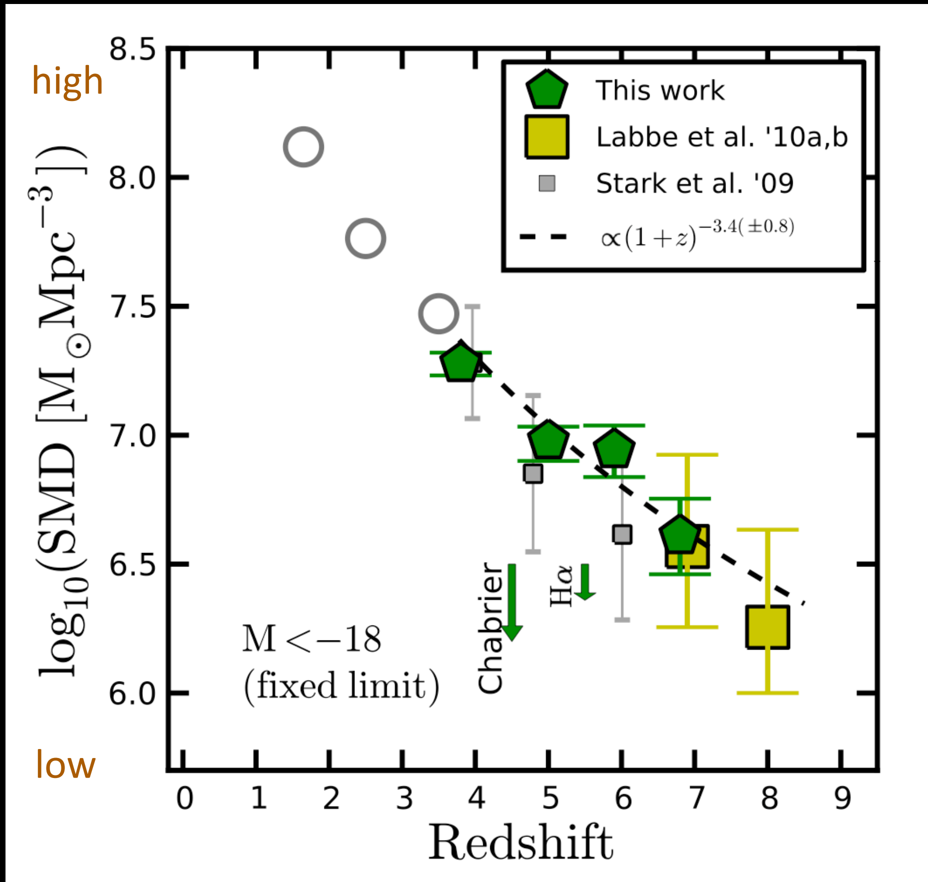
UV luminosity density

Madau 1998 formulation with Salpeter IMF

Bouwens/Illingworth et al 2010d

## *mass buildup over time*

Log M$_\odot$ Mpc$^{-3}$



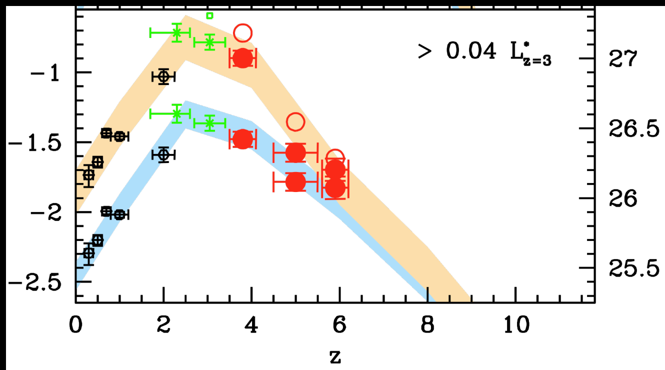

the Hubble and Spitzer data allow us to establish the evolution of the mass density at these early times

see papers by Gonzalez et al and Labbé et al

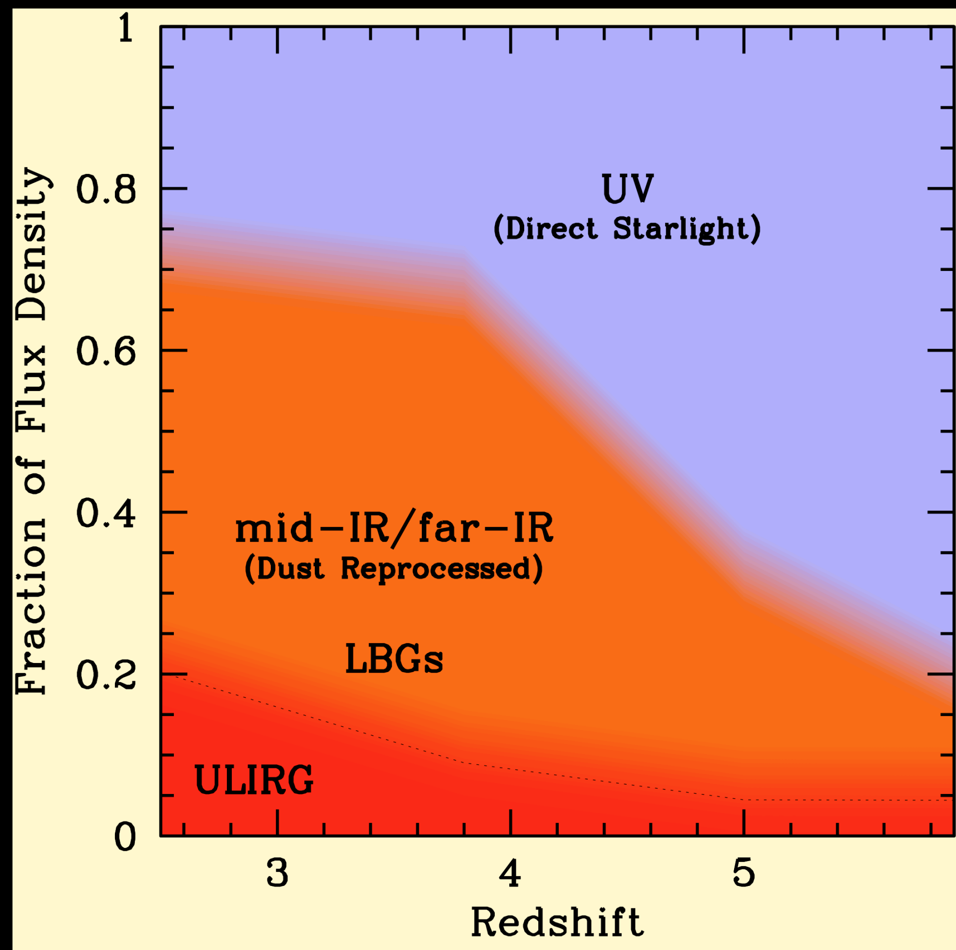
the history of the mass buildup in galaxies in the universe

Gonzalez/Labbé et al 2010

# *flux density in UV & IR*




for star forming galaxies!...

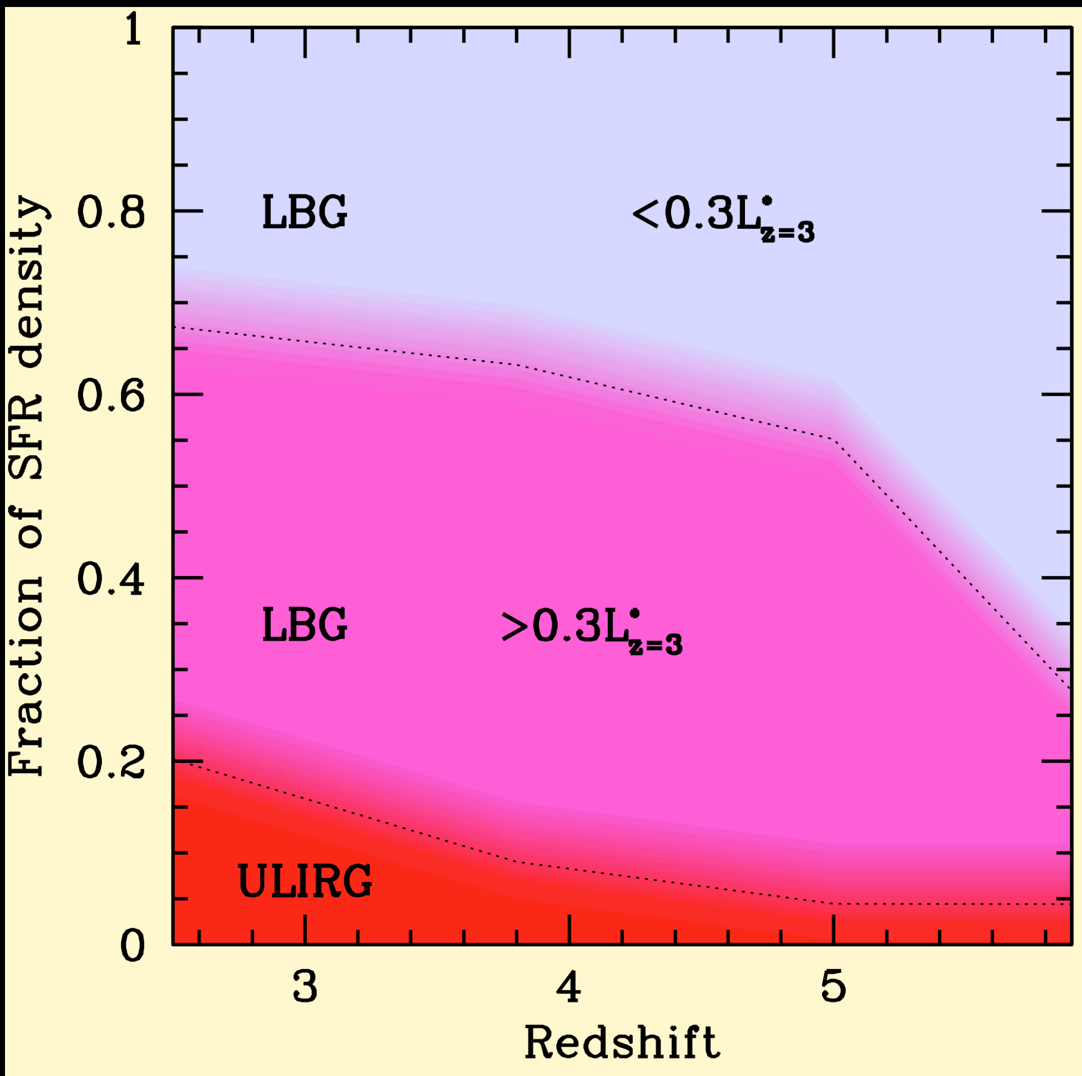



>80% of energy output in UV & IR at high redshift from star-forming galaxies can be derived from UV detected sources

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

Herschel?

# *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 in low luminosity galaxies)

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*)

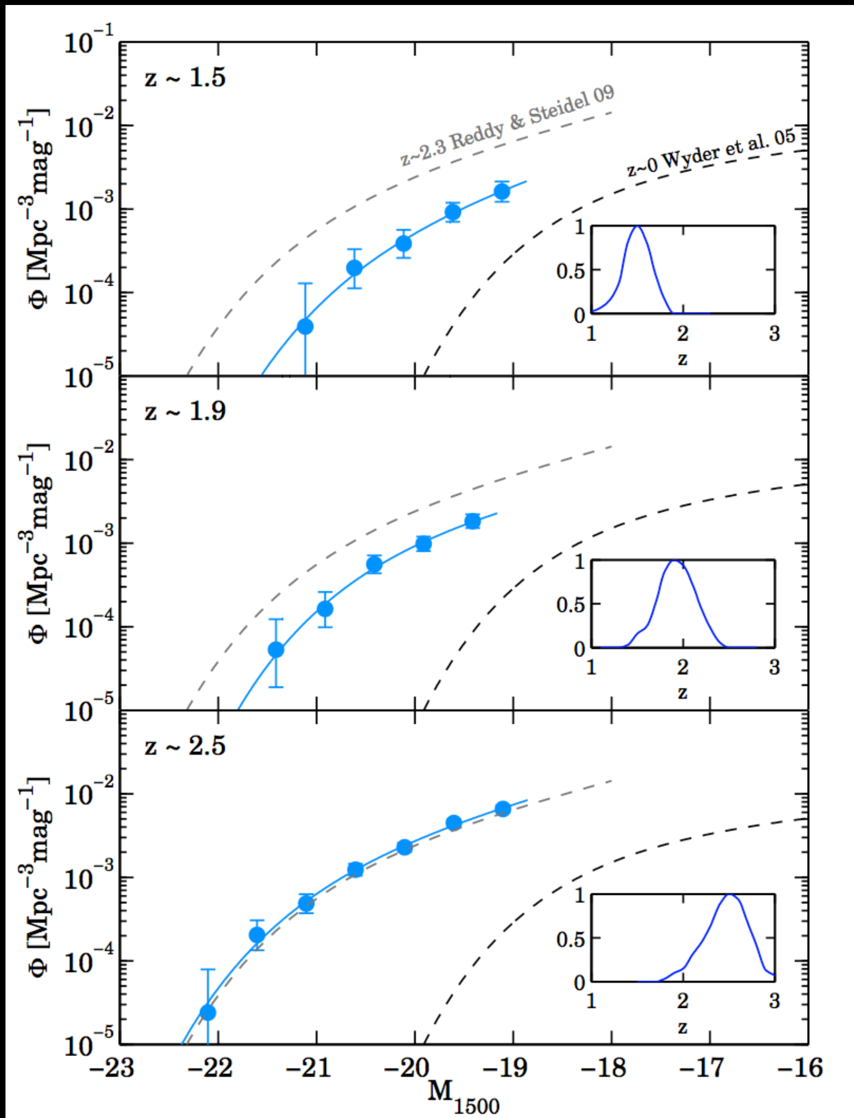
even at z~7-8 (650-800 Myr) indications of an "older" population (few hundred million years) => suggests some stars formed earlier at z>10
relatively steep mass functions at early times

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 the SFR density at z>3

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

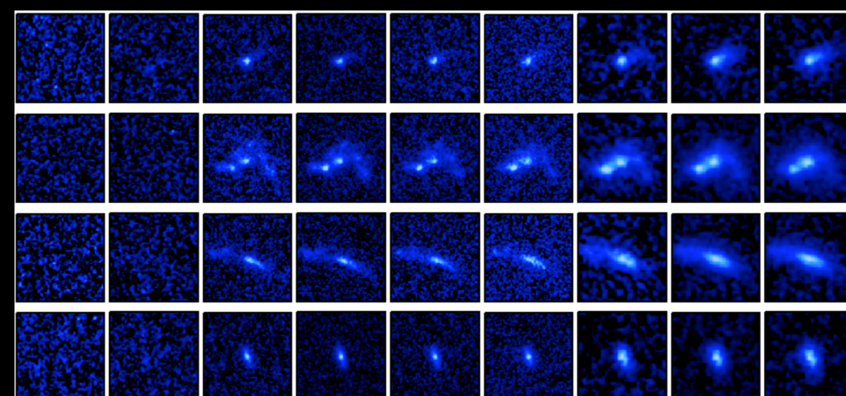
# WFC3/UVIS results in the ERS field




Hathi et al 2010
Oesch et al 2010

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

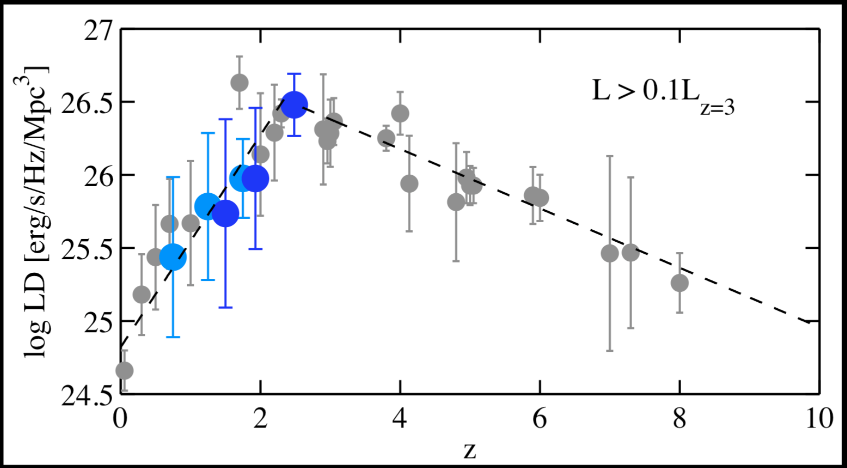
WFC3/UVIS dropouts



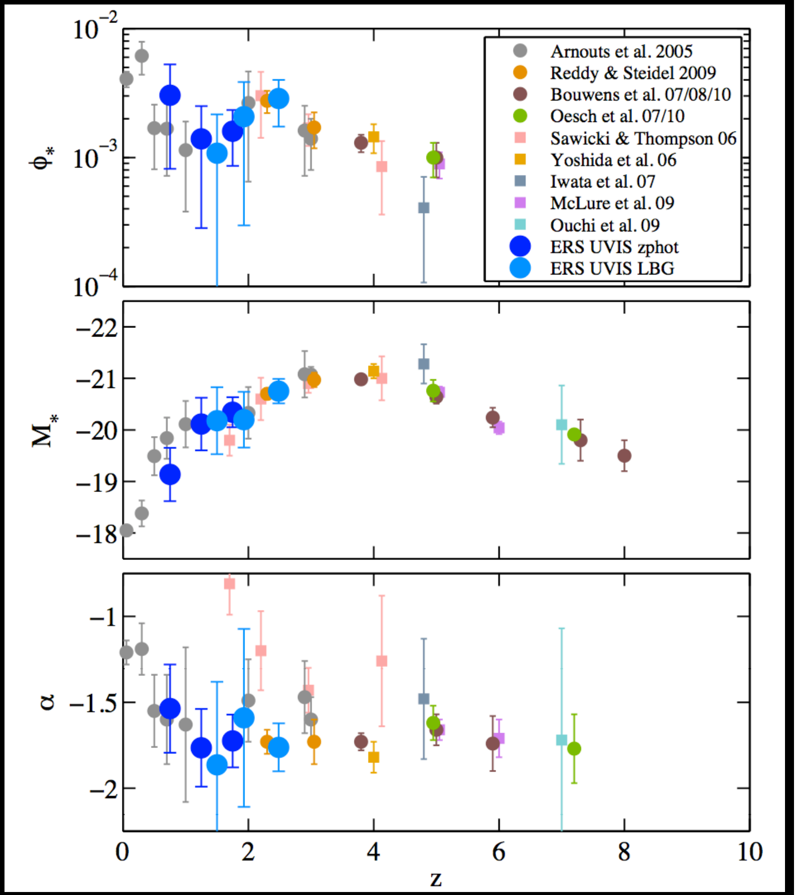
WFC3/UVIS ACS WFC3/IR

# *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


what we can look forward to using in the next decade
JWST
ELTs
HST
ALMA
galaxies in the first billion years
GDI
firstgalaxies.org

## *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)

low luminosity galaxies dominate the luminosity density and SFR density and are very blue in color (no dust- low metals?)

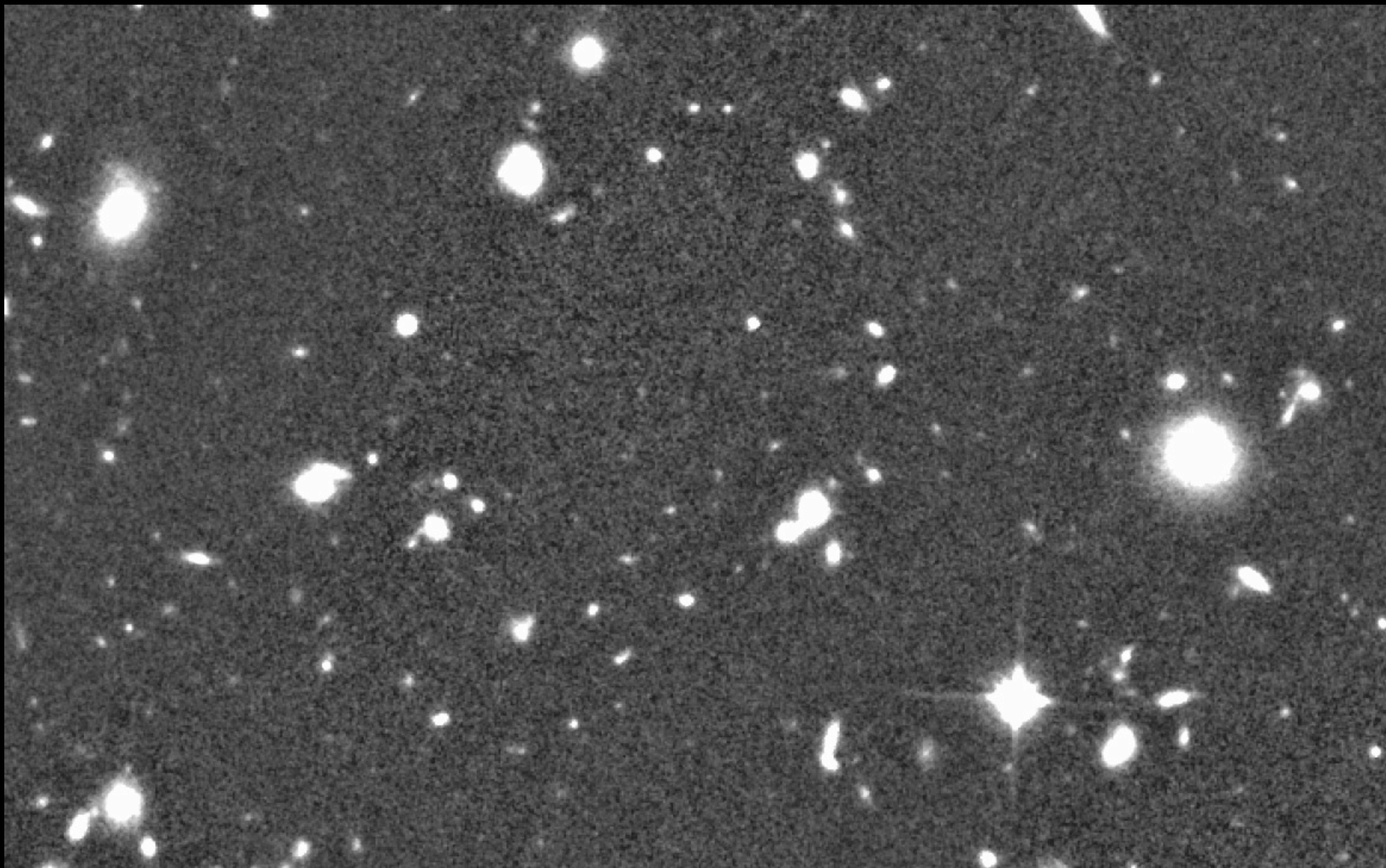
they give us estimates for the mass density and the star formation rate density that extends from the first ~5% of the age of the universe

combining these results with Spitzer data suggests that these galaxies were forming stars ~200-300 million years earlier, at z>10-11 (with strong limit at z~10)

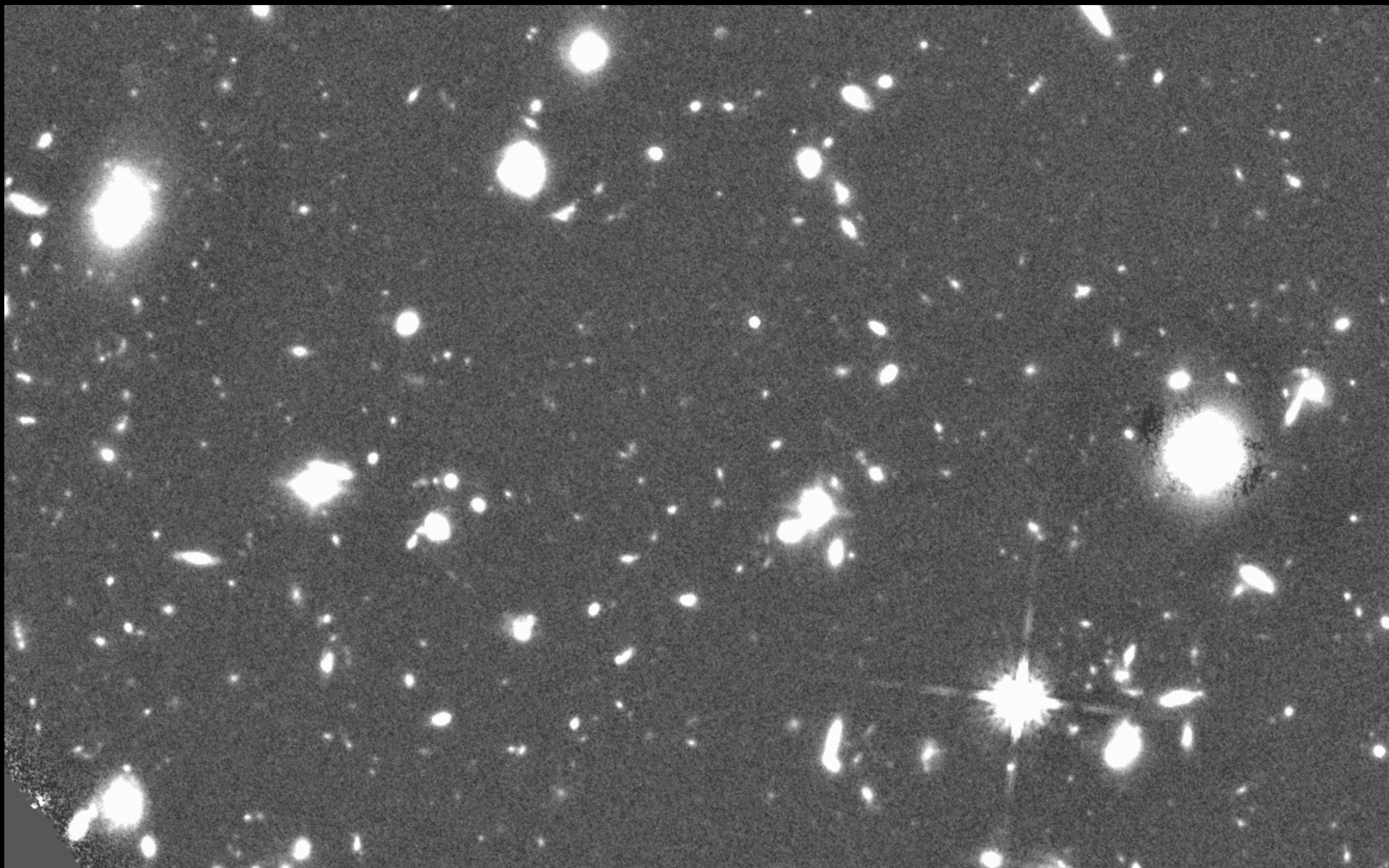
these galaxies fall in the heart of the "reionization" epoch, but our estimates are still somewhat low for the contribution of galaxies to reionization: we still don't know if galaxies could have reionized the universe!!

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

# NICMOS – 72 orbits



# WFC3/IR – 16 orbits



*galaxies in the first billion years* GDI *firstgalaxies.org*