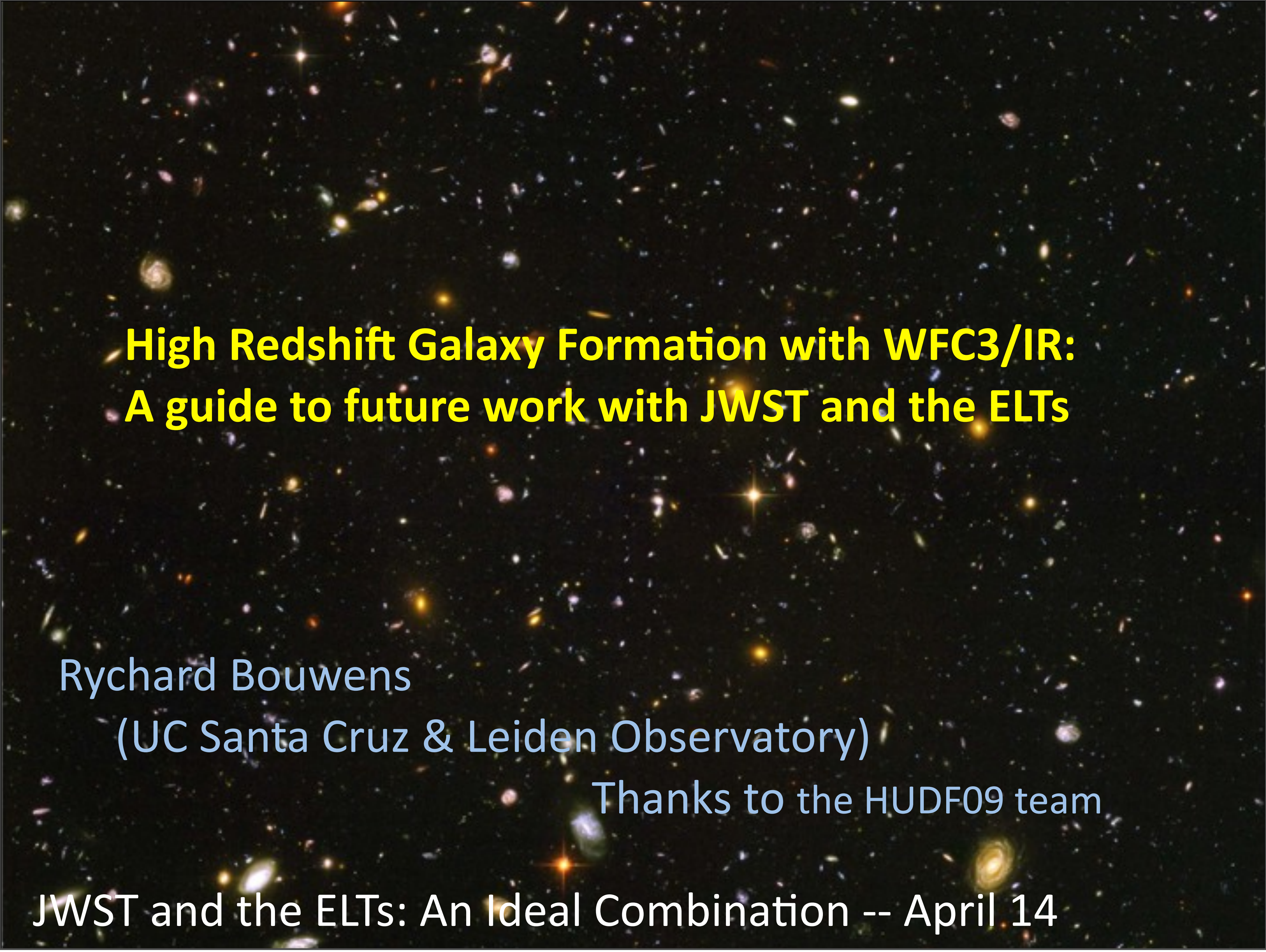


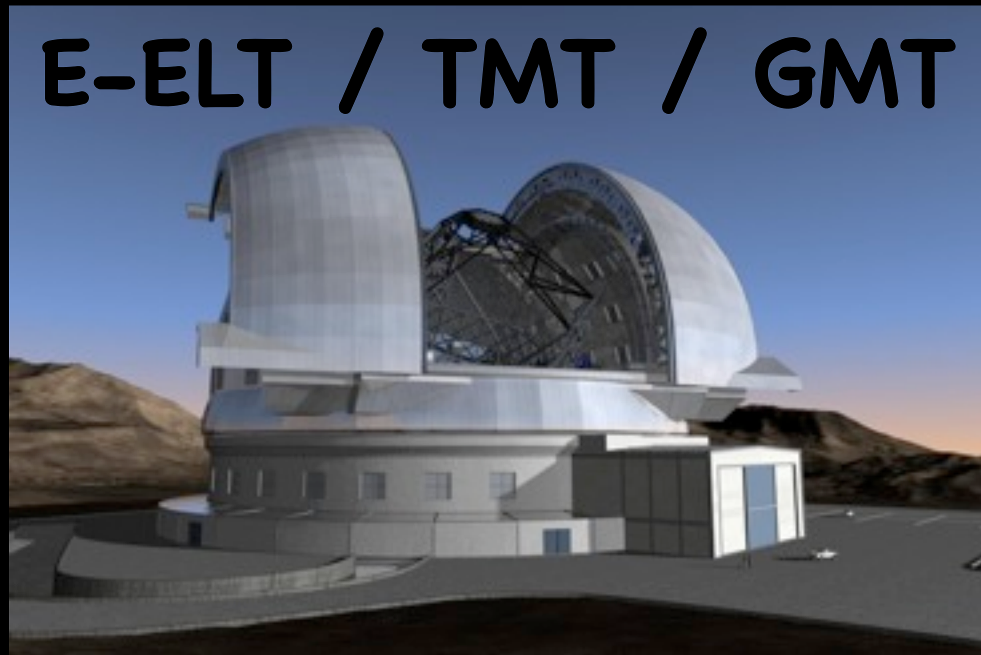
High Redshift Galaxy Formation with WFC3/IR: A guide to future work with JWST and the ELTs

Rychard Bouwens
(UC Santa Cruz & Leiden Observatory)

Thanks to the HUDF09 team

JWST and the ELTs: An Ideal Combination -- April 14

Long Anticipated Telescopes



These telescopes promise to answer many key questions:

- How do galaxies initially build up and evolve?

  -- exciting question at z>6 since we expect the halos of L* and sub-L* galaxies to be built up during this time period

- How do the stellar population in galaxies change due to the build-up in metals?

  -- looking for possible signatures of pop III stars, change in IMF or dust properties

- Which sources reionized the universe and when/how did this occur?

How will we answer these questions with future facilities like JWST and the ELTs?

Current WFC3/IR results provide us with some guidance...

WFC3/IR serves as an essential pathfinder (at <2μ)

HST
NICMOS
(1998-2008)

0.8 arcmin

40x
Improvement

(6x area,
3x sensitivity
2x resolution)

HST
WFC3/IR
(2009-)

2.2 arcmin

40x
Improvement

(2x area,
7x sensitivity,
1.5-2x resolution,
duplexing)

JWST
NIRCAM
(2014-)

2.2 arcmin

Spitzer IRAC Pathfinder at 2-5μ

Spitzer
IRAC
(2004-)

5.2 arcmin

>1000x

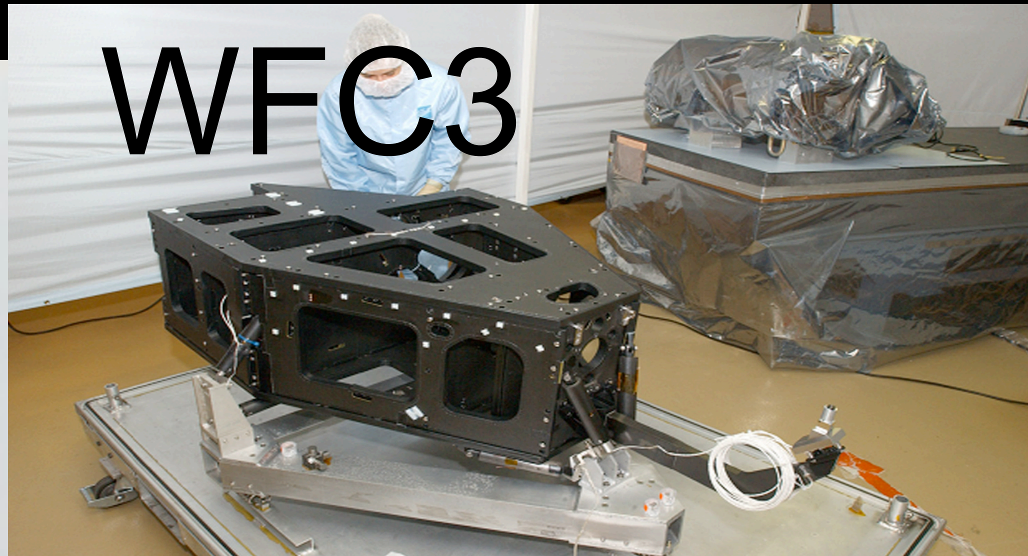
Improvement and few confusion issues

(70x sensitivity,
10x resolution,
0.35x area)

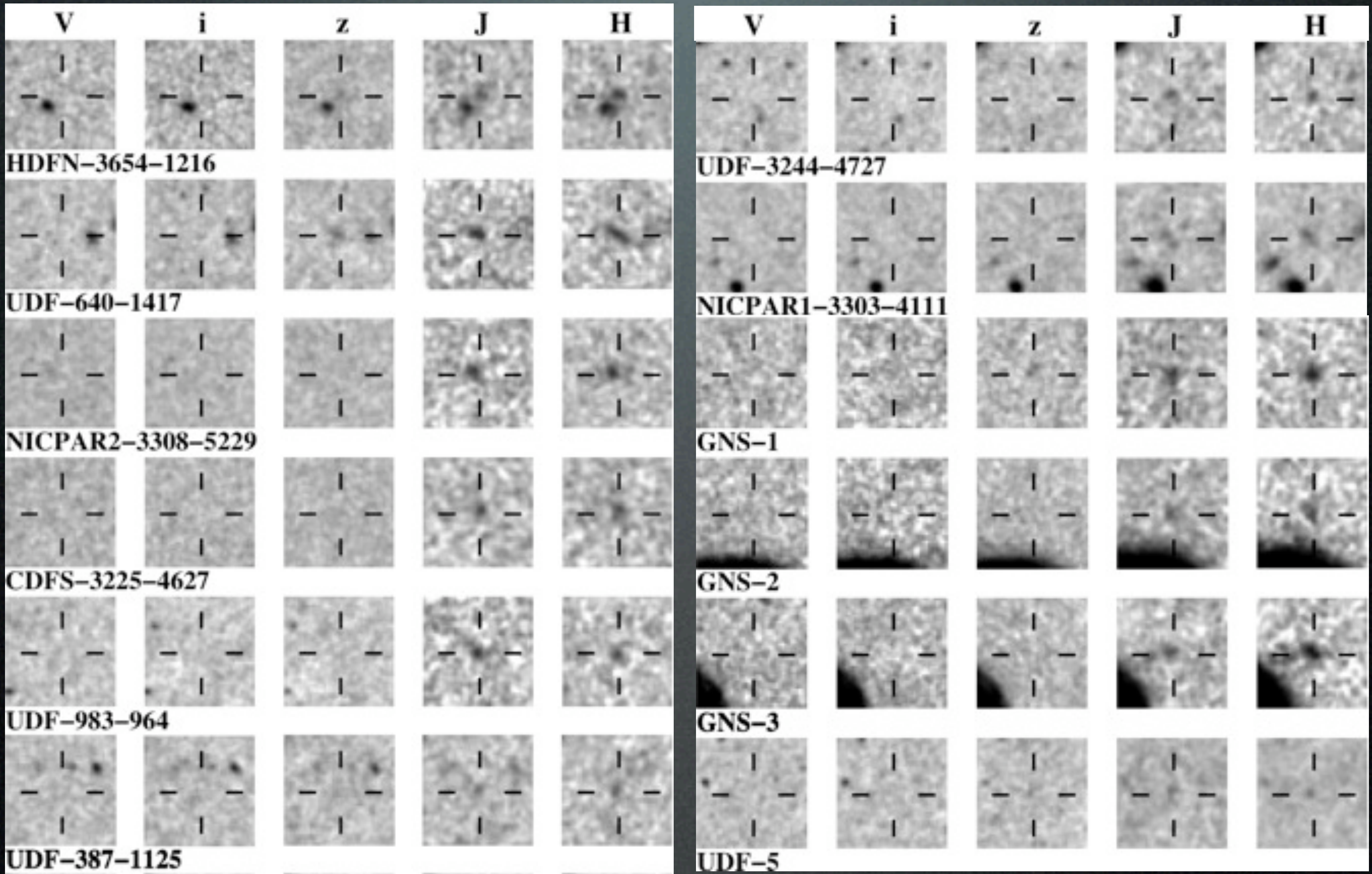
JWST
NIRCAM
(2014-)

2.2 arcmin

Recent HST Servicing Mission and Installation of WFC3 on HST



Whereas ~15 candidate z~7 galaxies were found with NICMOS over ~10 years



Bouwens et al. 2010

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

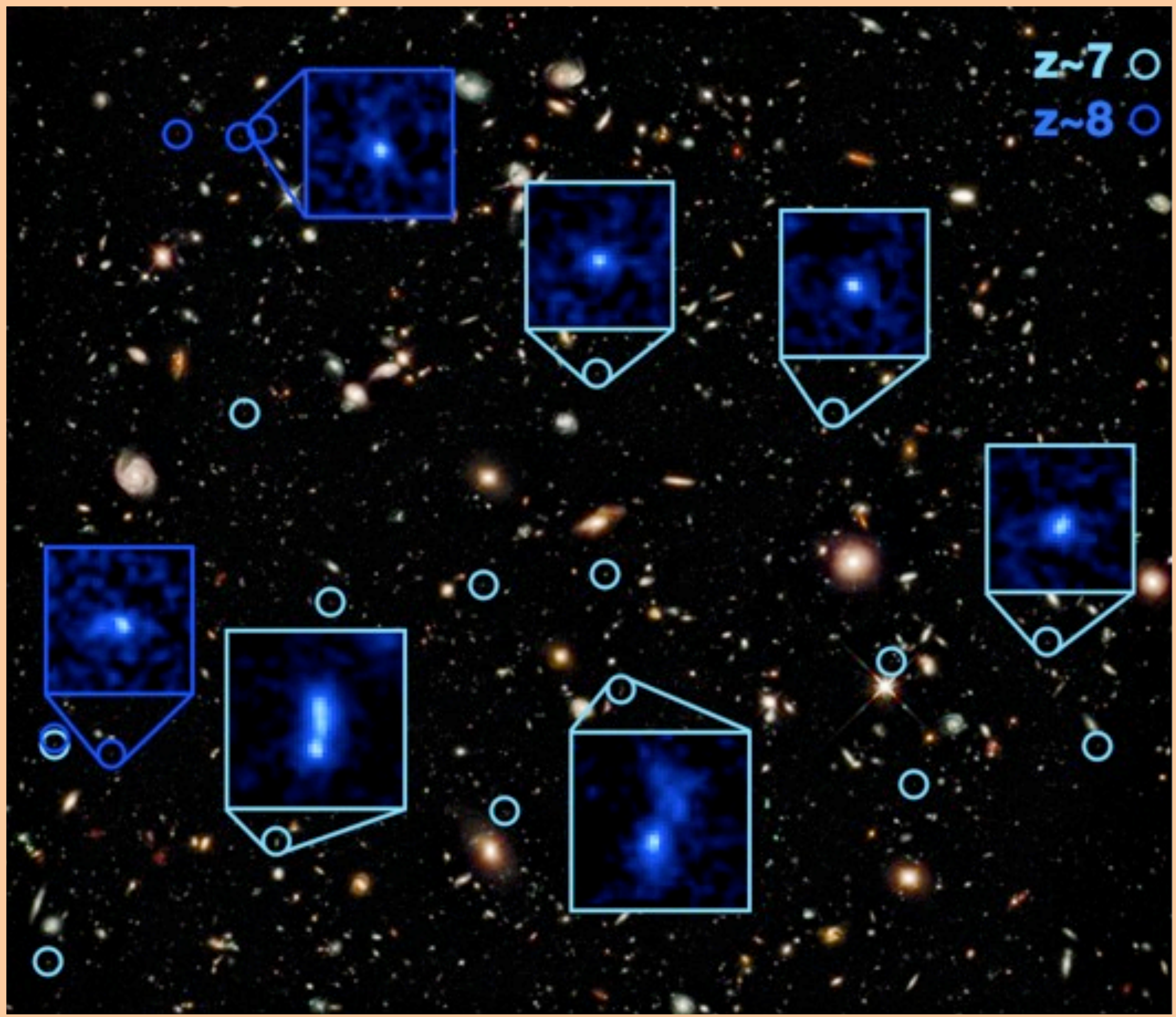
HUDF09
WFC3/IR

HUDF09
image ~2.2′

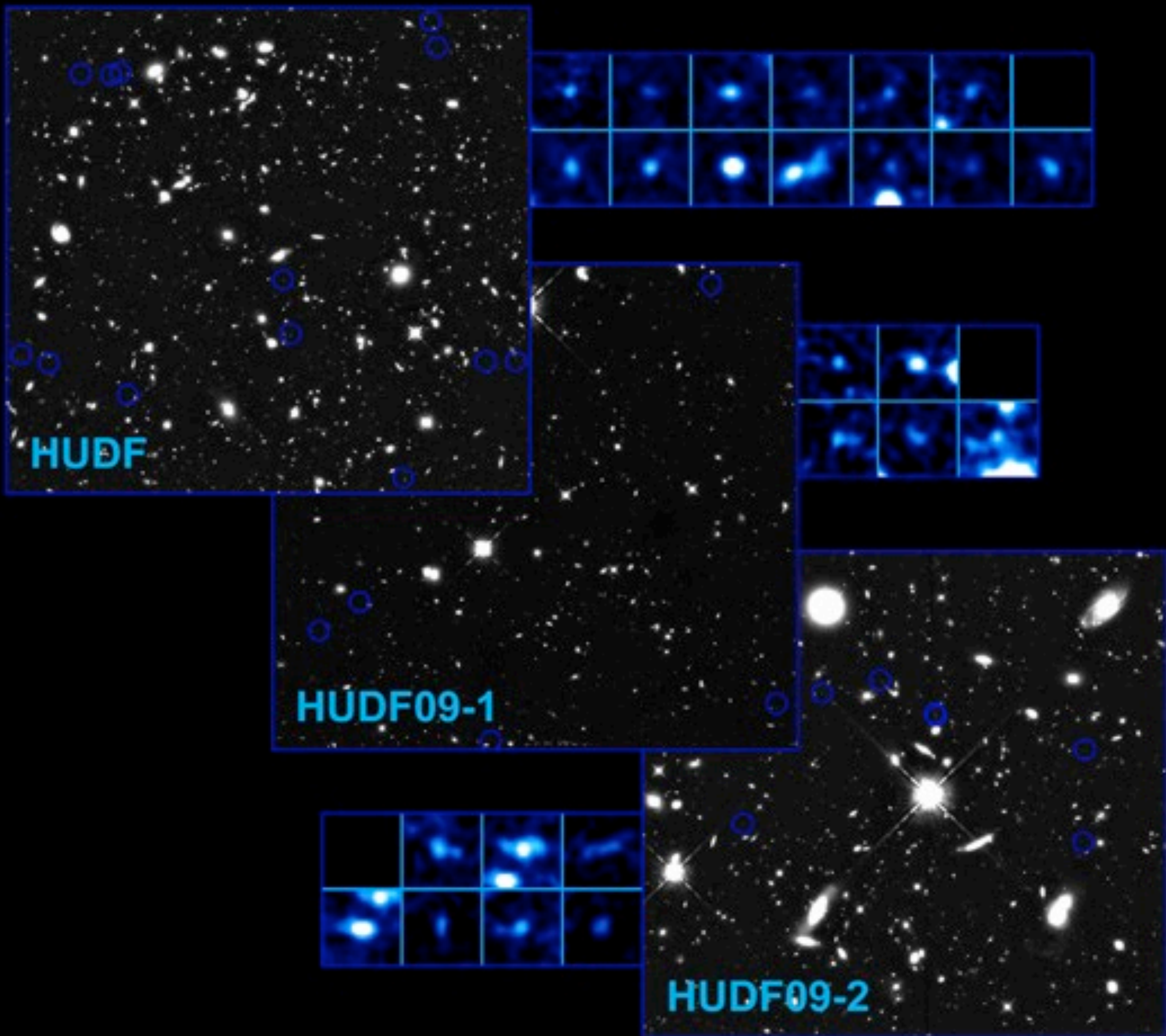
boxes ~2.5″

z~8
Bouwens et al

z~7
Oesch et al



>100 z~7-8 galaxies are now known (e.g., Bouwens et al. 2010)



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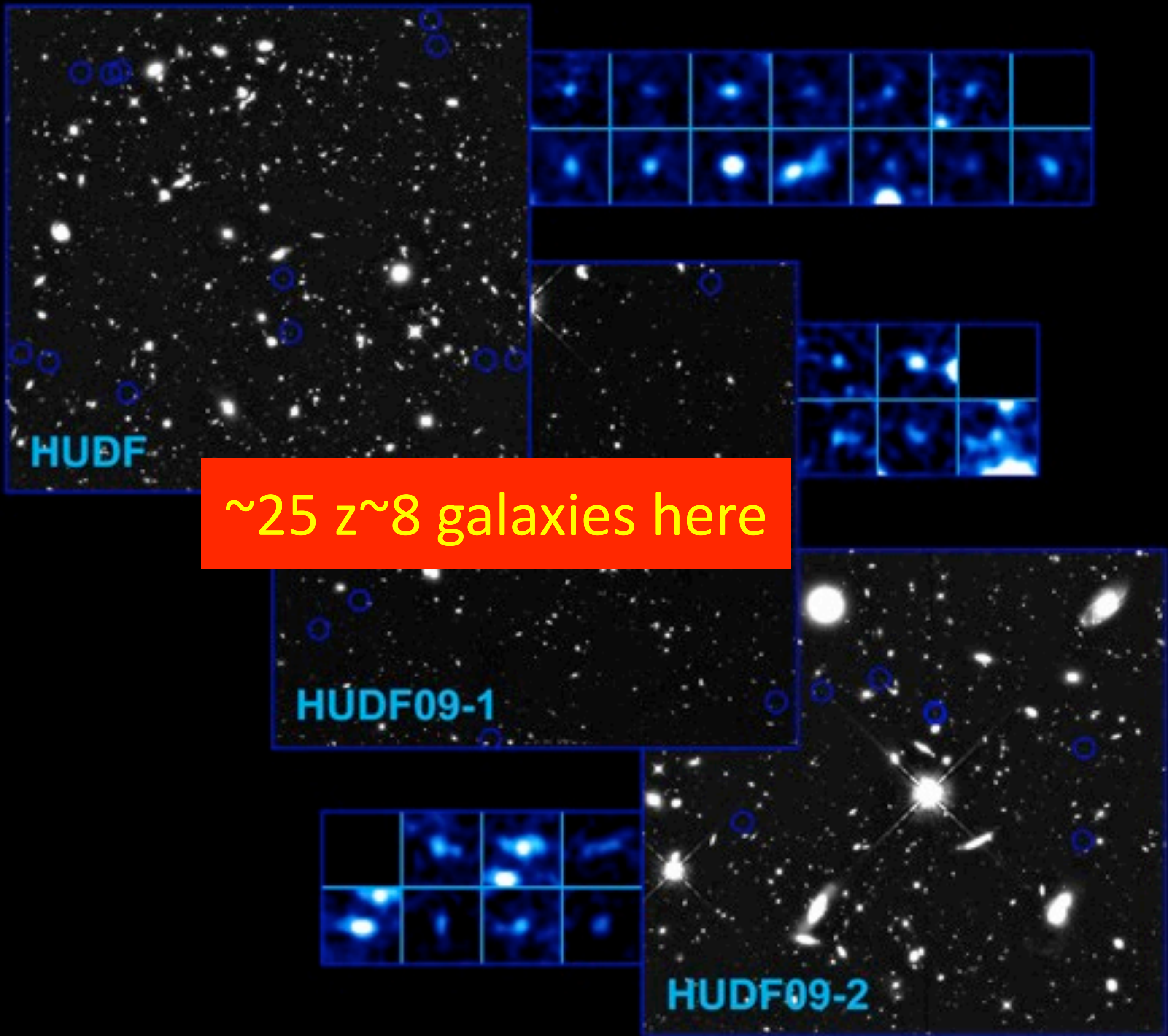

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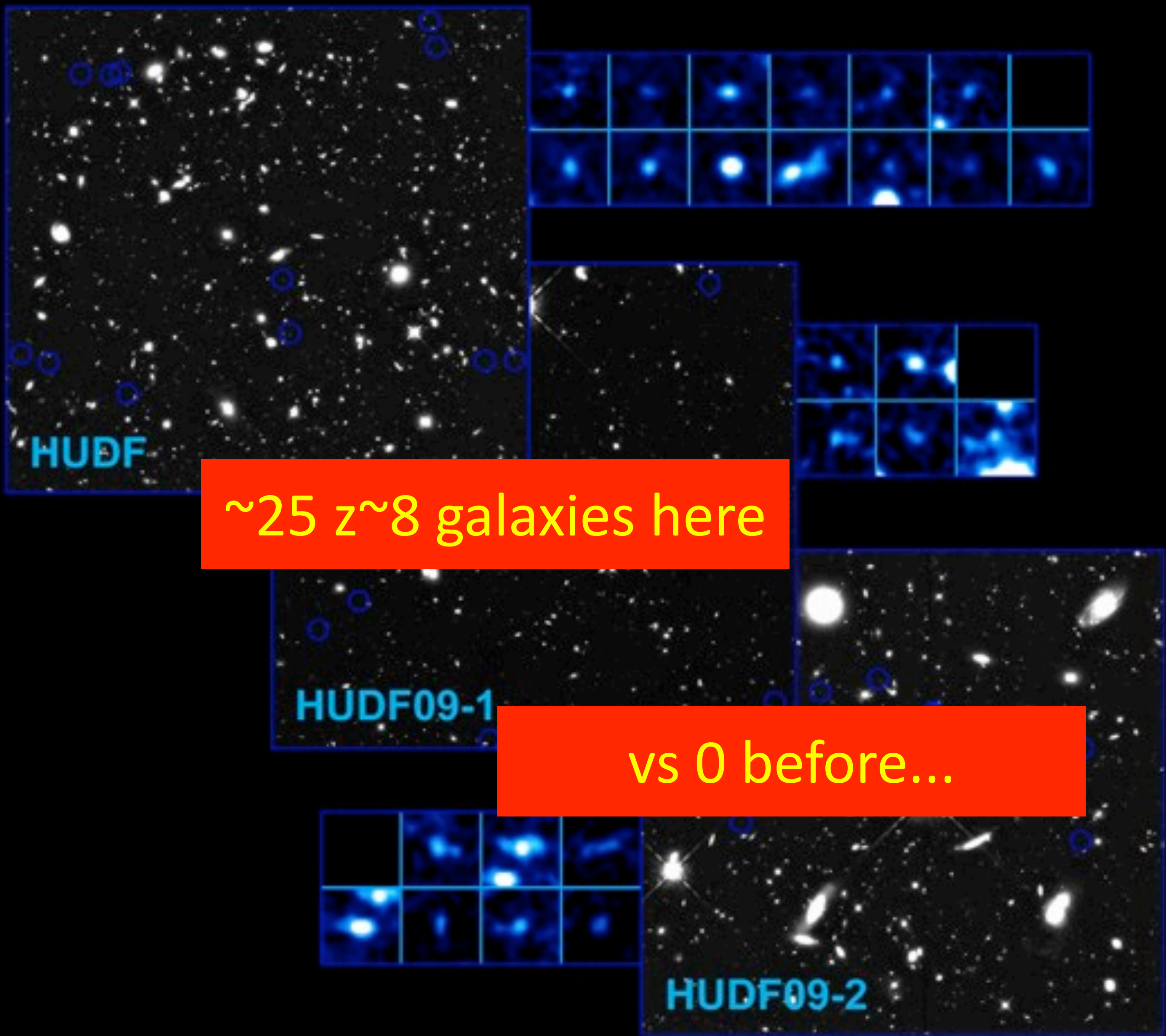


~25 z~8 galaxies here

vs 0 before...

TEAM

the HUDF09 team

many of the WFC3 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)

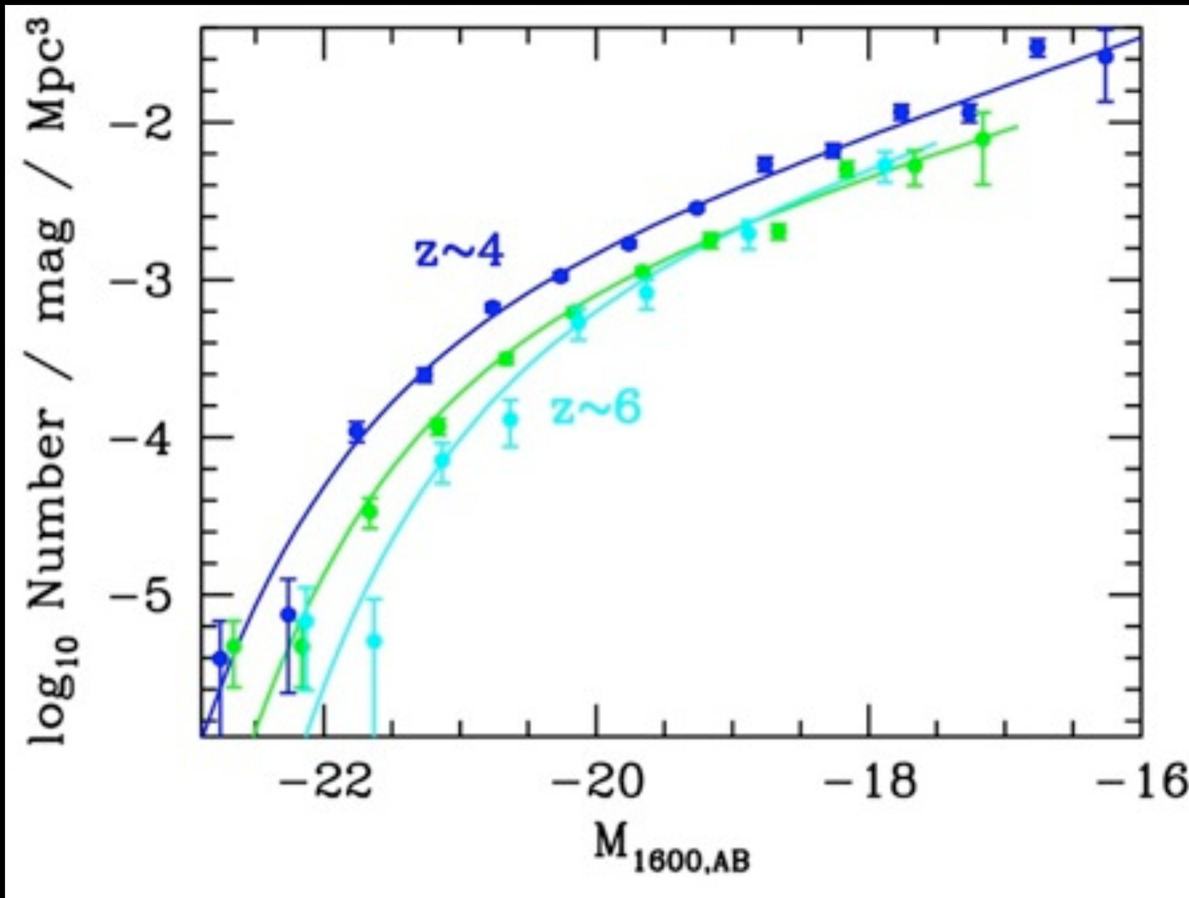
a resource for high-redshift galaxies see:
firstgalaxies.org
http://firstgalaxies.org

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

WFC3/IR results allow us to establish rate of evolution of galaxies back to early times...

UV Luminosity Functions

Log # mag^{-1} Mpc^{-3}



Bright Faint

Bouwens et al. 2010

WFC3/IR results allow us to establish rate of evolution of galaxies back to early times...

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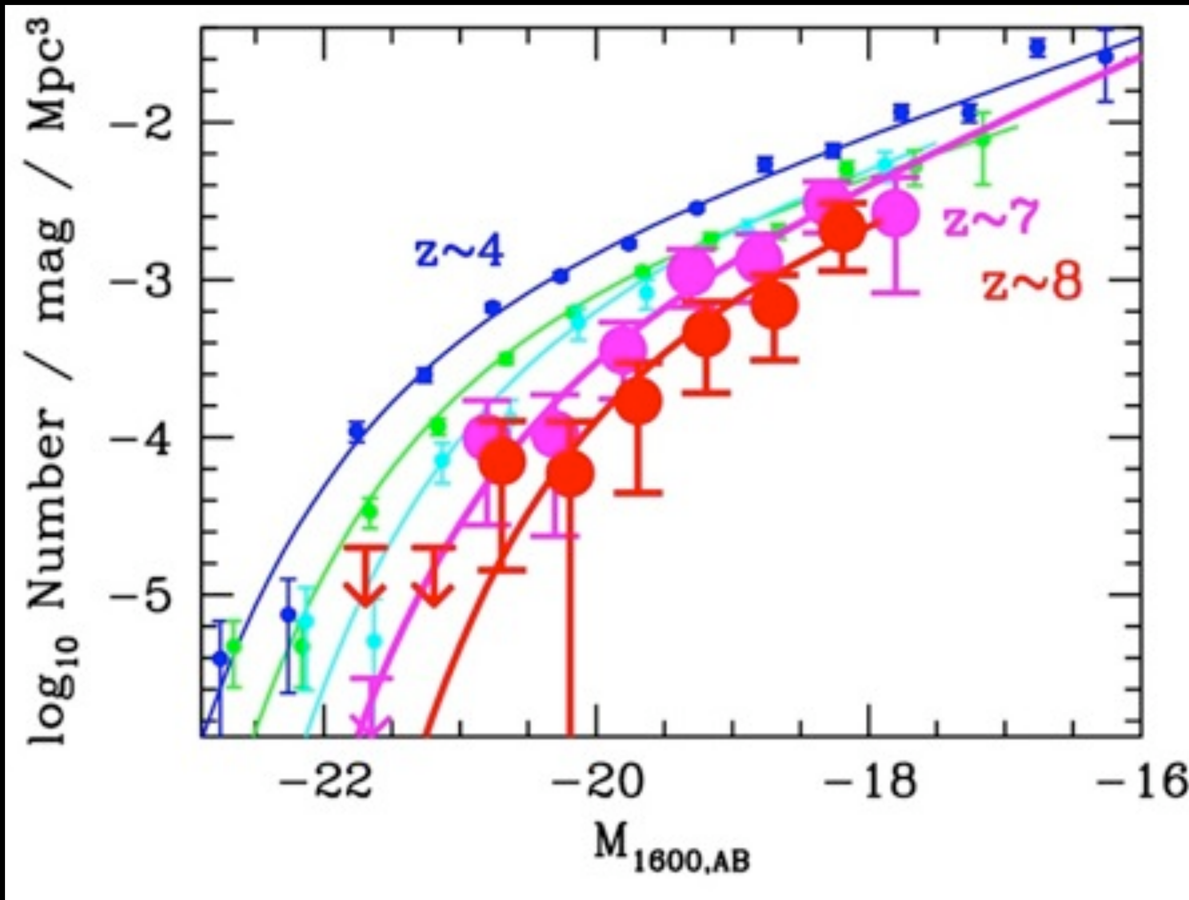

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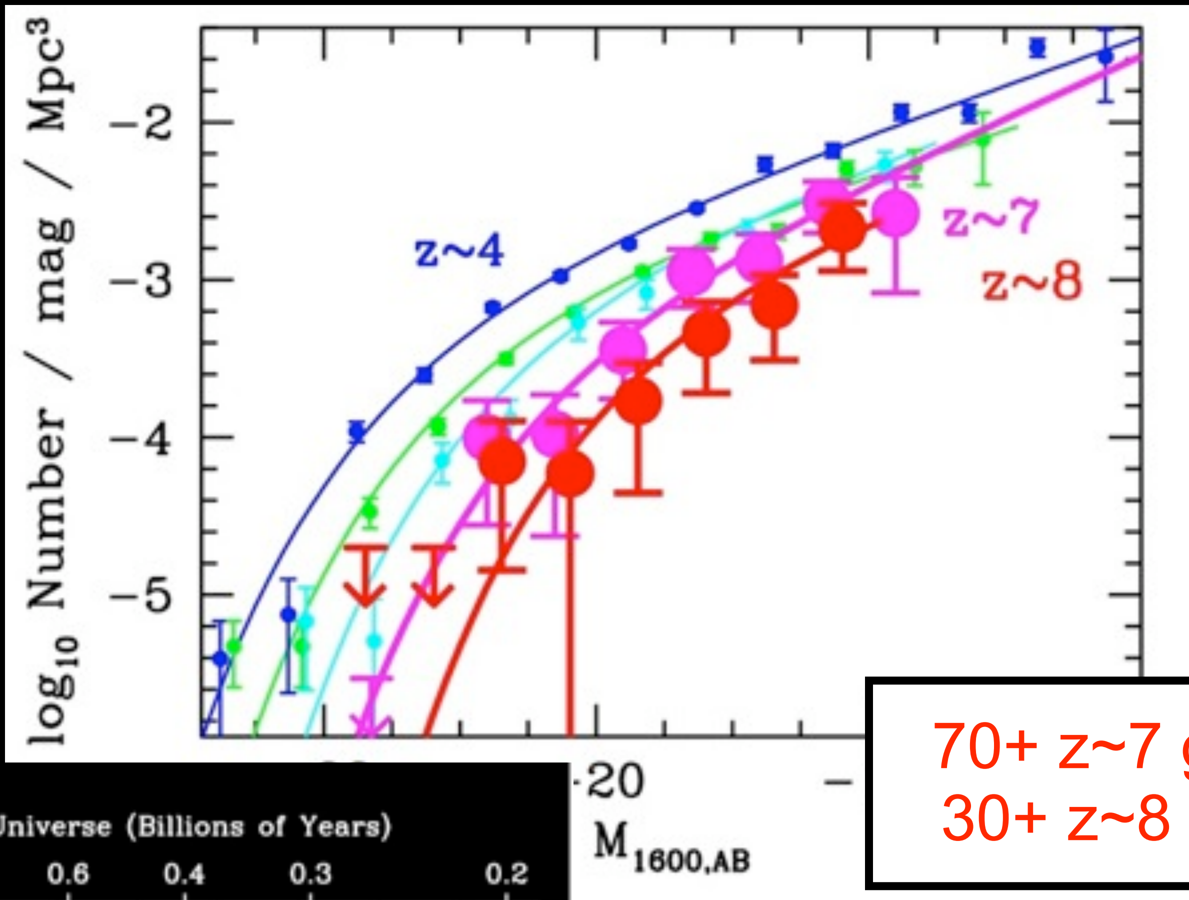
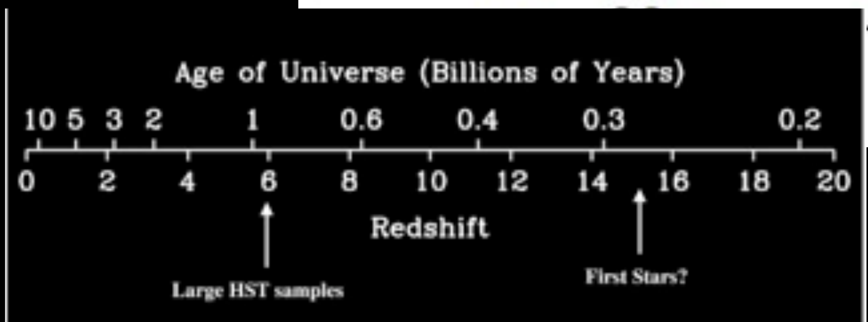
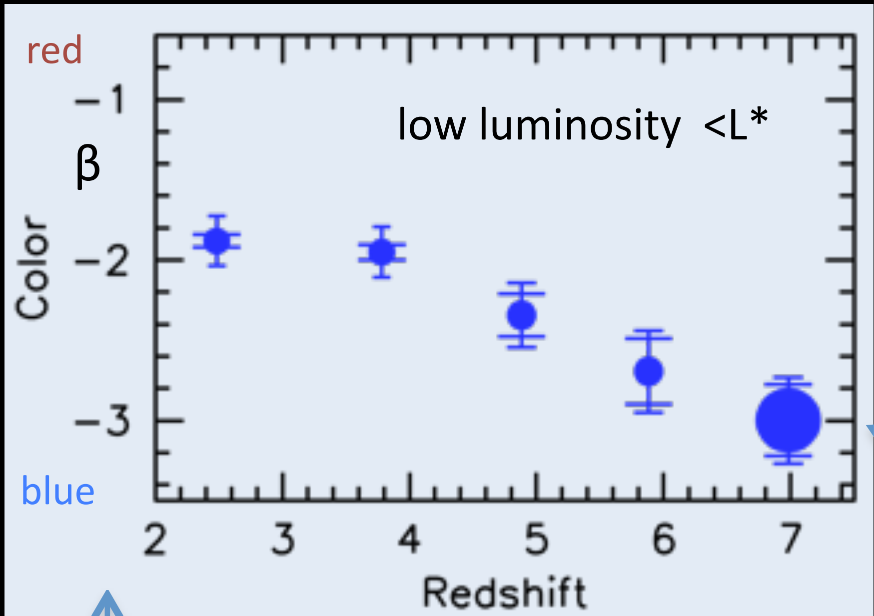


70+ z~7 galaxies,
30+ z~8 galaxies



Faint

galaxies at z>6 become very blue



UV-continuum slope β most sensitive to changes in dust content – but dust content of lower luminosity, z>6 galaxies is probably ➔ zero

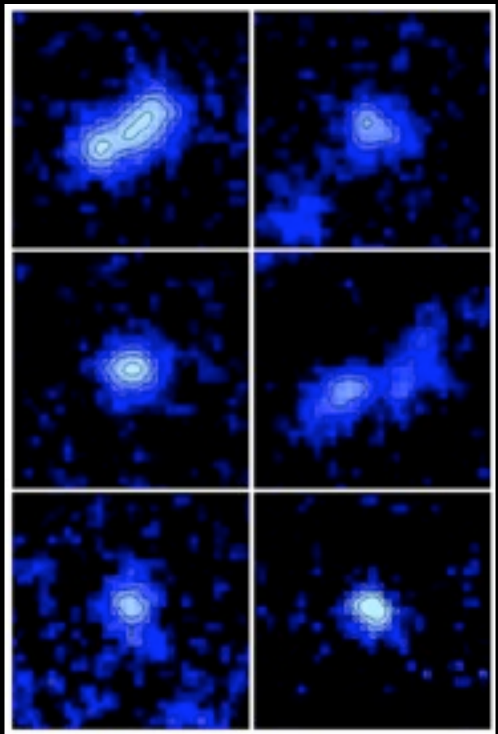
so changes at z>6 must be due to other effects

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

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

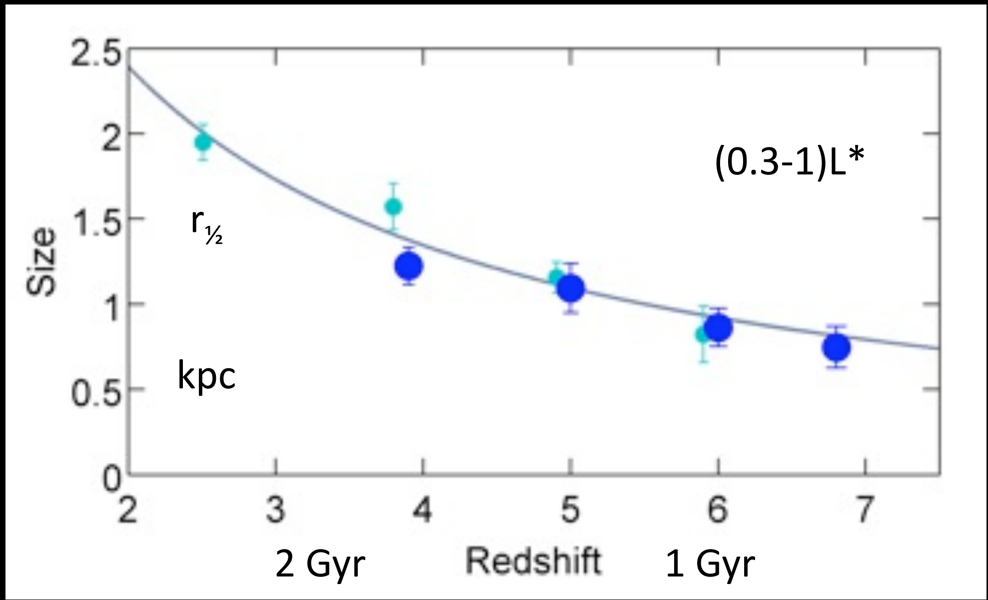
Bouwens/Illingworth et al

z~7 and z~8 galaxies are very small



1.8″ x 1.8″

Oesch/Carollo et al

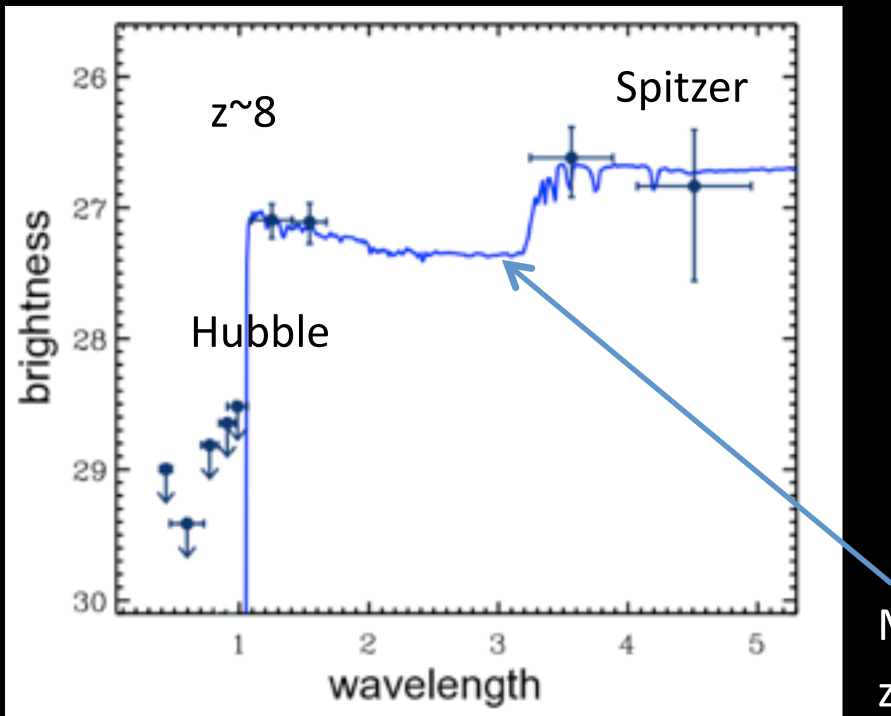


z~7 galaxies show considerable sub-structure

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

Star formation in z~8 galaxies is extended in time

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)



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)

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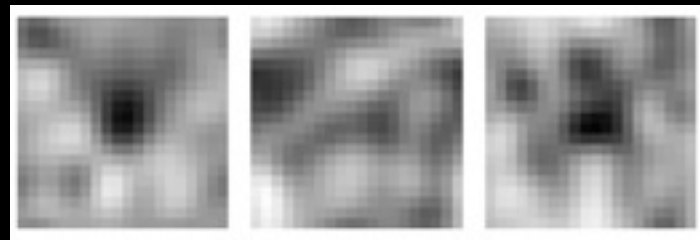
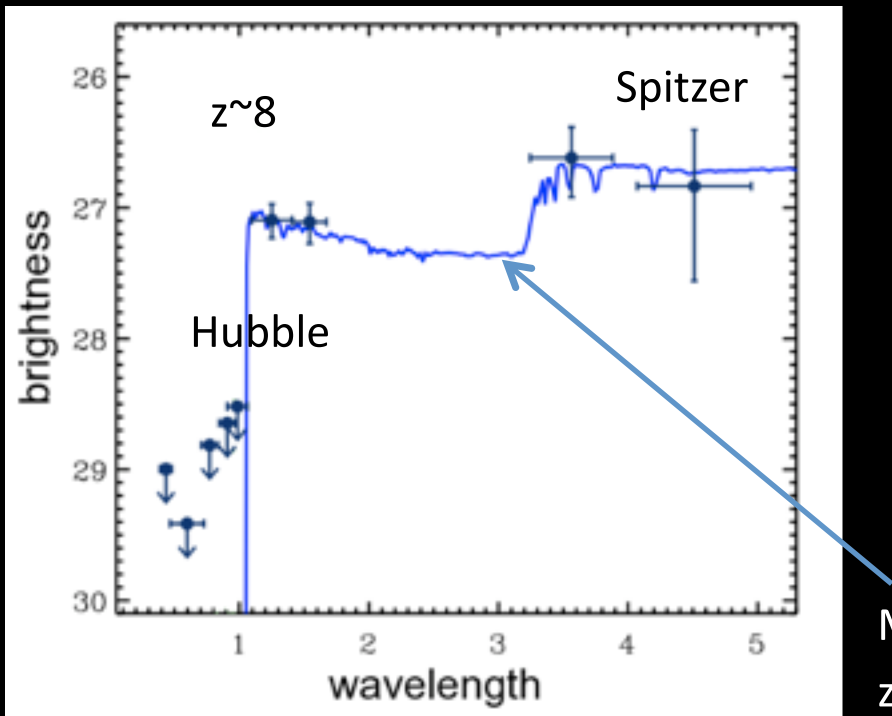
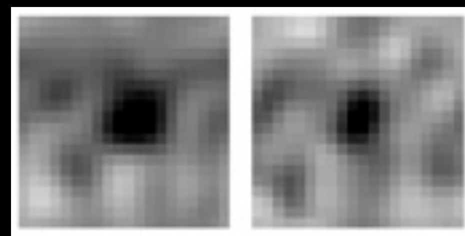
some individual z~8 Spitzer 3.6 μm images





z~8 summed Spitzer images



3.6 μm 4.5 μm

Labbé/Gonzalez et al

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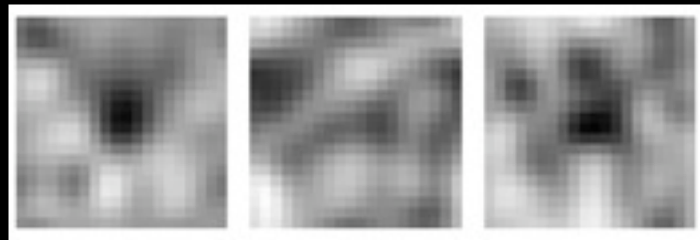

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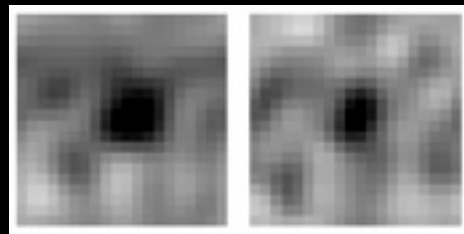
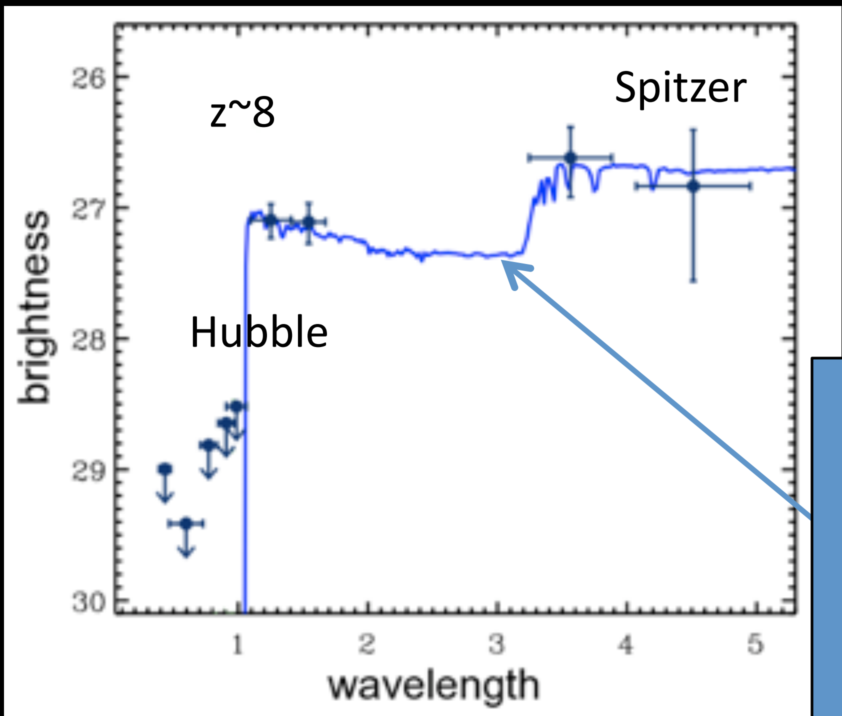
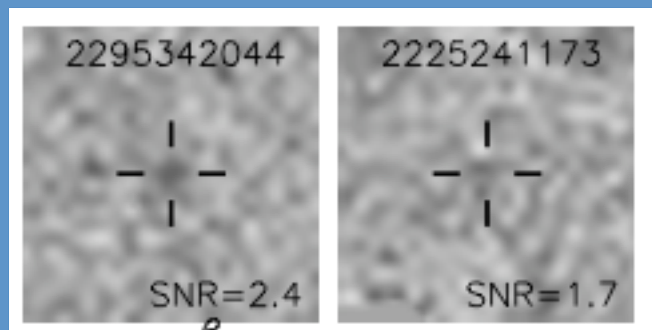
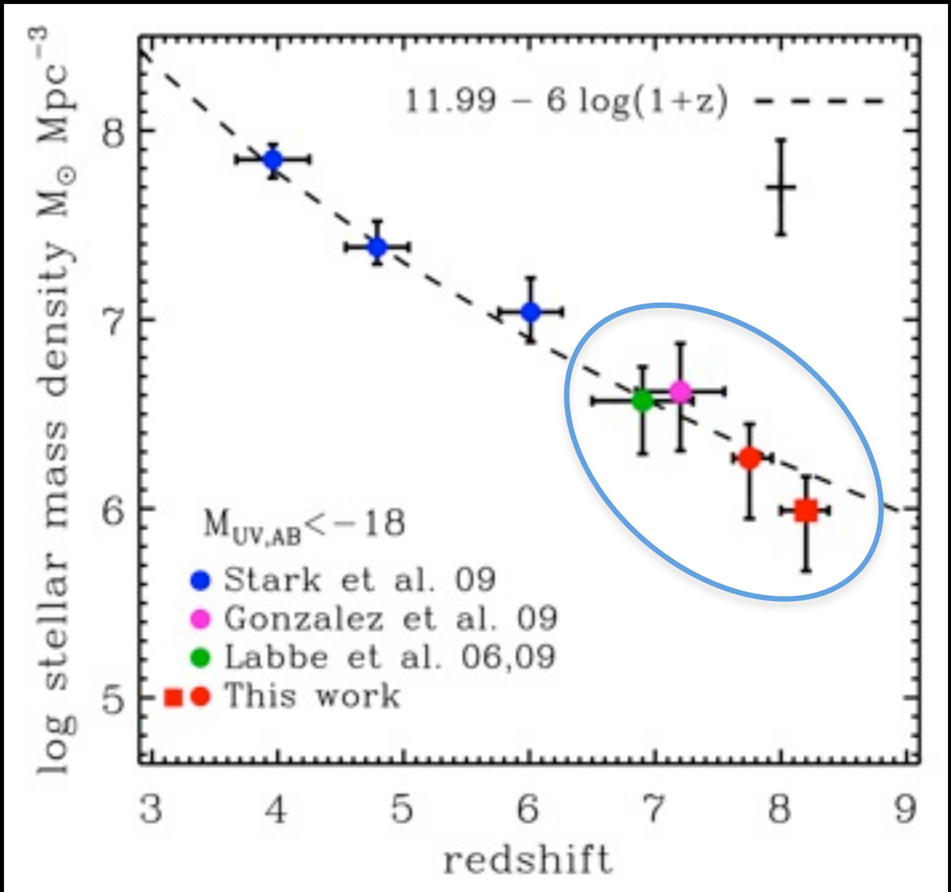




Very challenging measurement -- given low S/N of IRAC data and confusion



Stellar Mass Densities from IRAC + WFC3 Samples



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

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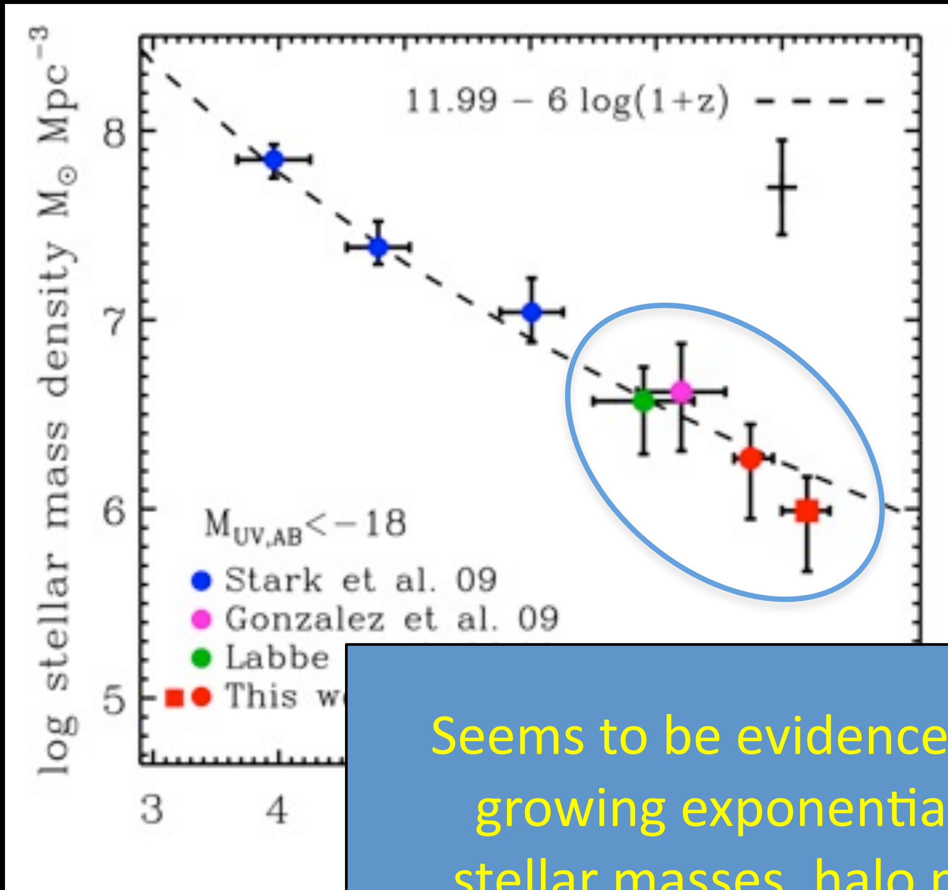

the Hubble and Spitzer data allow us to establish the evolution of the mass density at these early times

see papers by Gonzalez et al and Labbé et al

Seems to be evidence galaxies are growing exponentially in SFRs, stellar masses, halo masses, etc.

our new results

the history of the mass buildup in galaxies in the universe

Labbé/Gonzalez et al

WFC3/IR results allow us to establish rate of evolution of galaxies back to early times...

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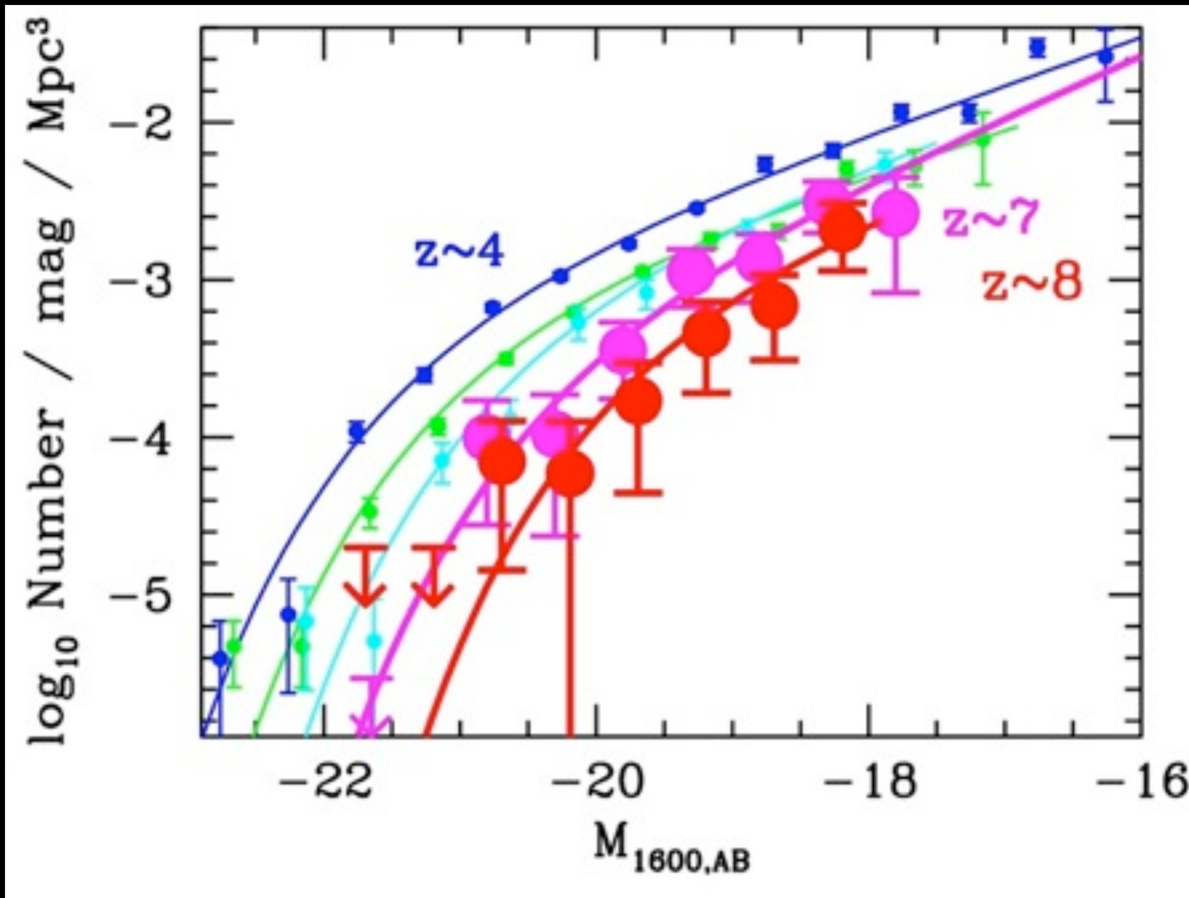


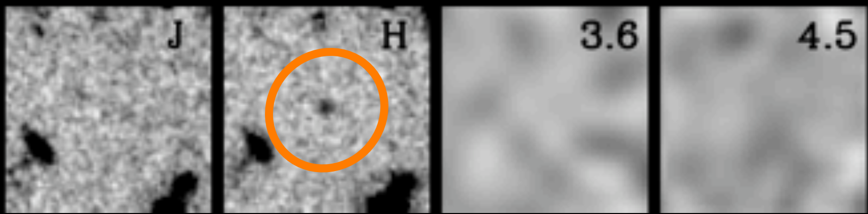
Bright Faint

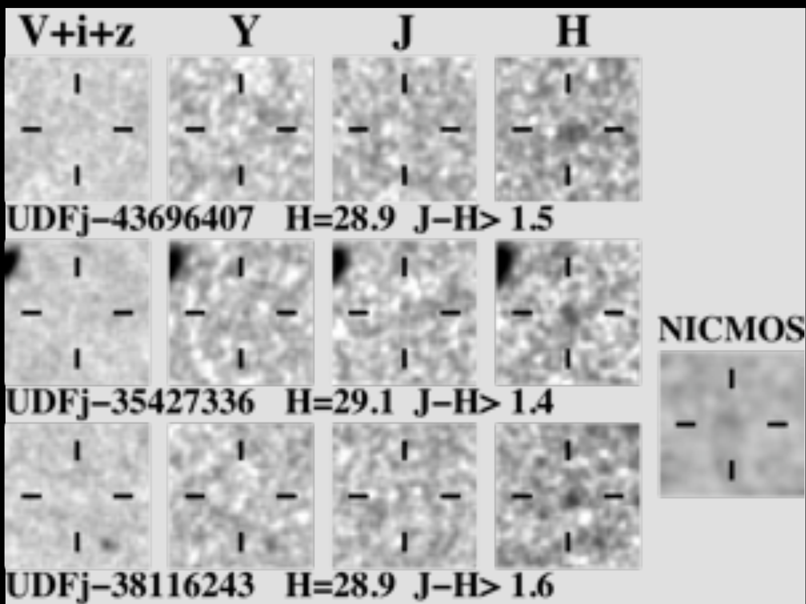
Bouwens et al. 2010

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

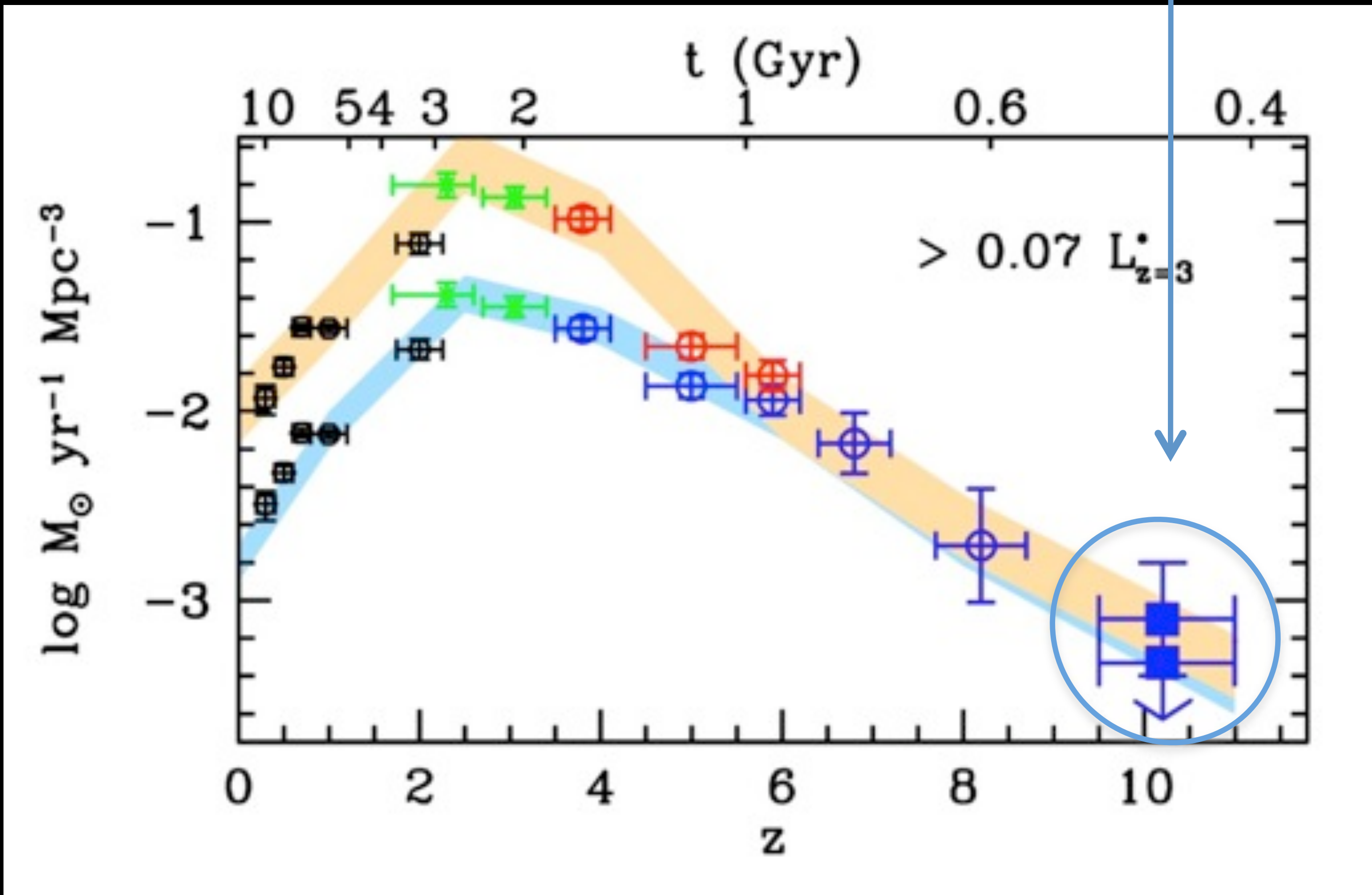
note detection in stack of two of three that are in earlier independent NICMOS data

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

Star Formation History and 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

WFC3/IR serves as an essential pathfinder (at <2μ)

HST
NICMOS
(1998-2008)

0.8 arcmin

40x
Improvement

(6x area,
3x sensitivity
2x resolution)

HST
WFC3/IR
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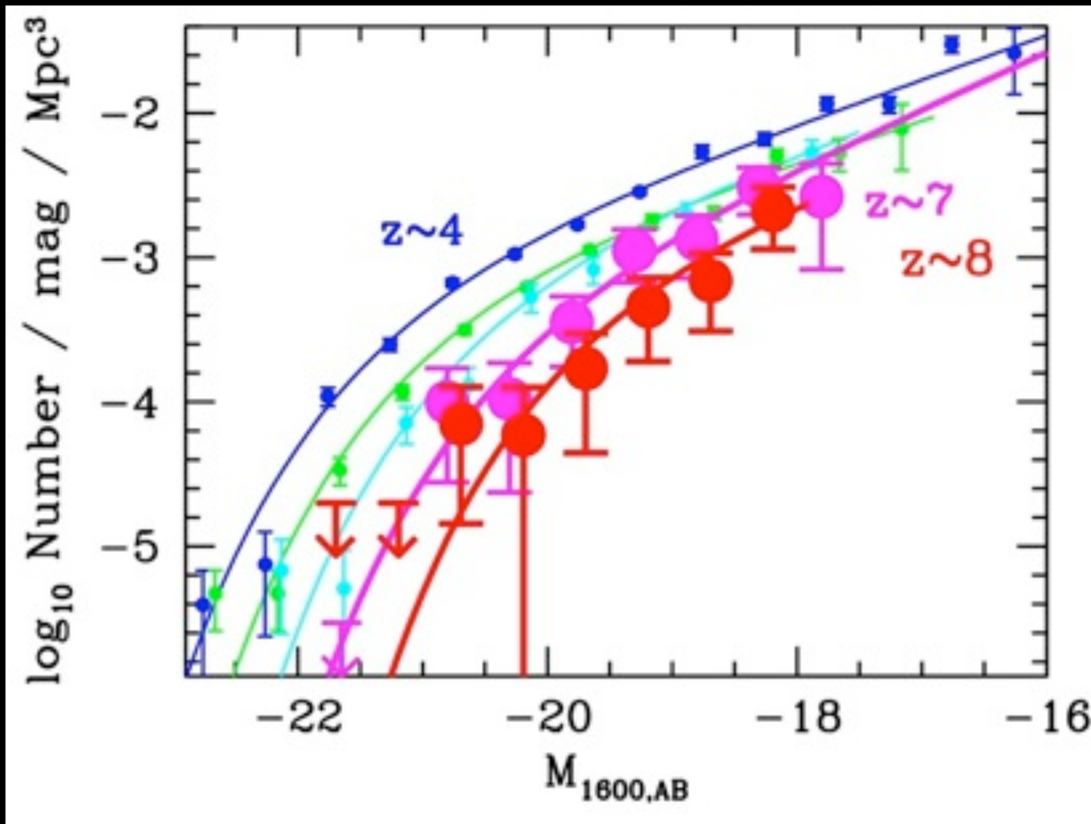
1.5-2x resolution,
duplexing)

JWST
NIRCAM
(2014-)

2.2 arcmin

What can we learn with JWST + ELTs?

How do galaxies initially build up and evolve?



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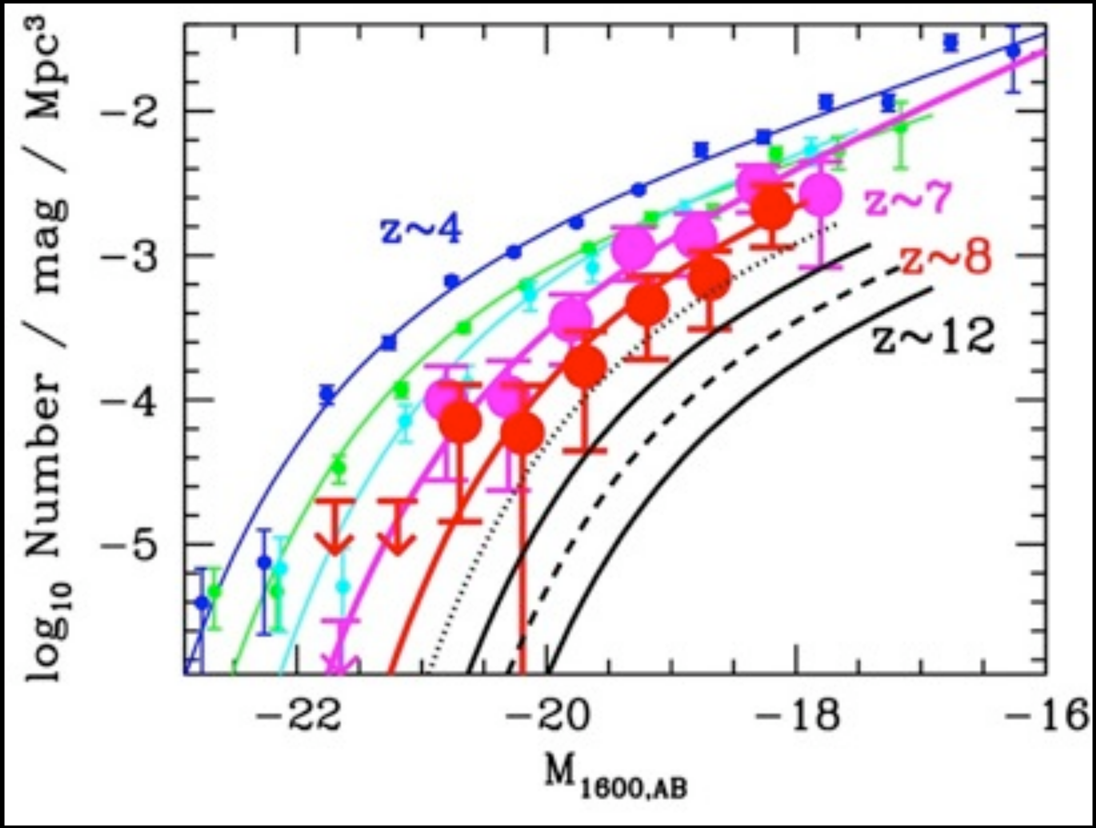

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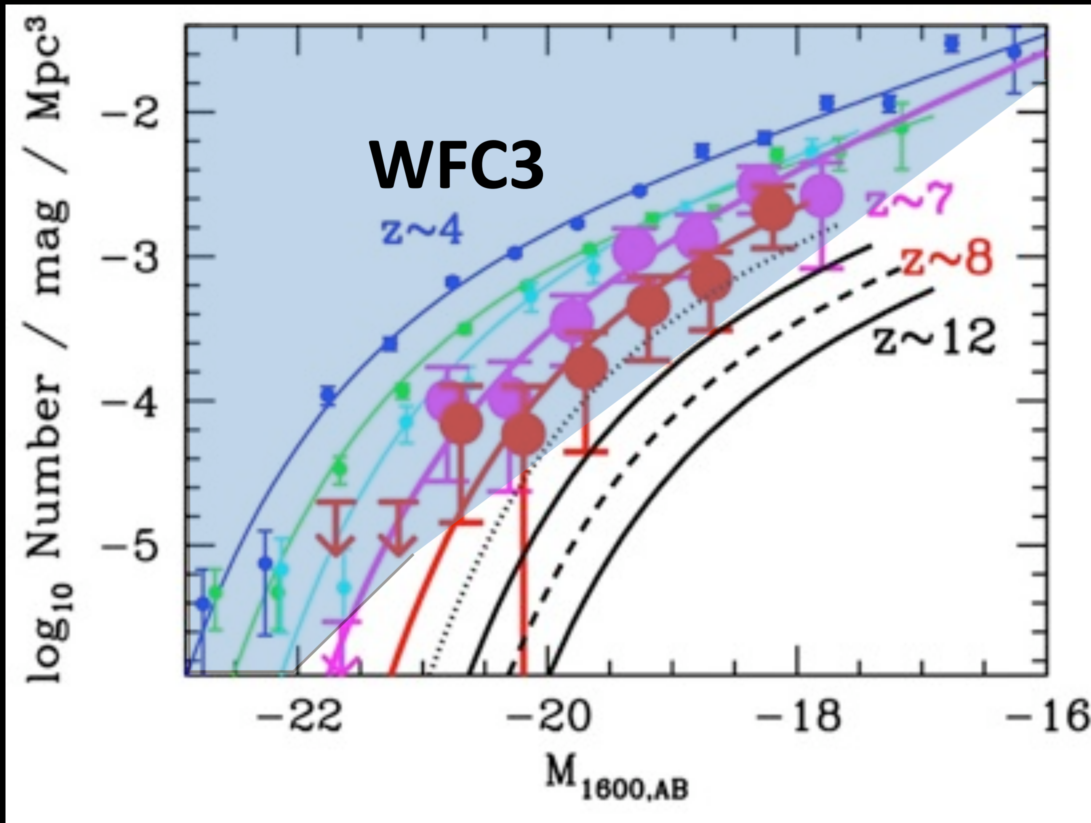

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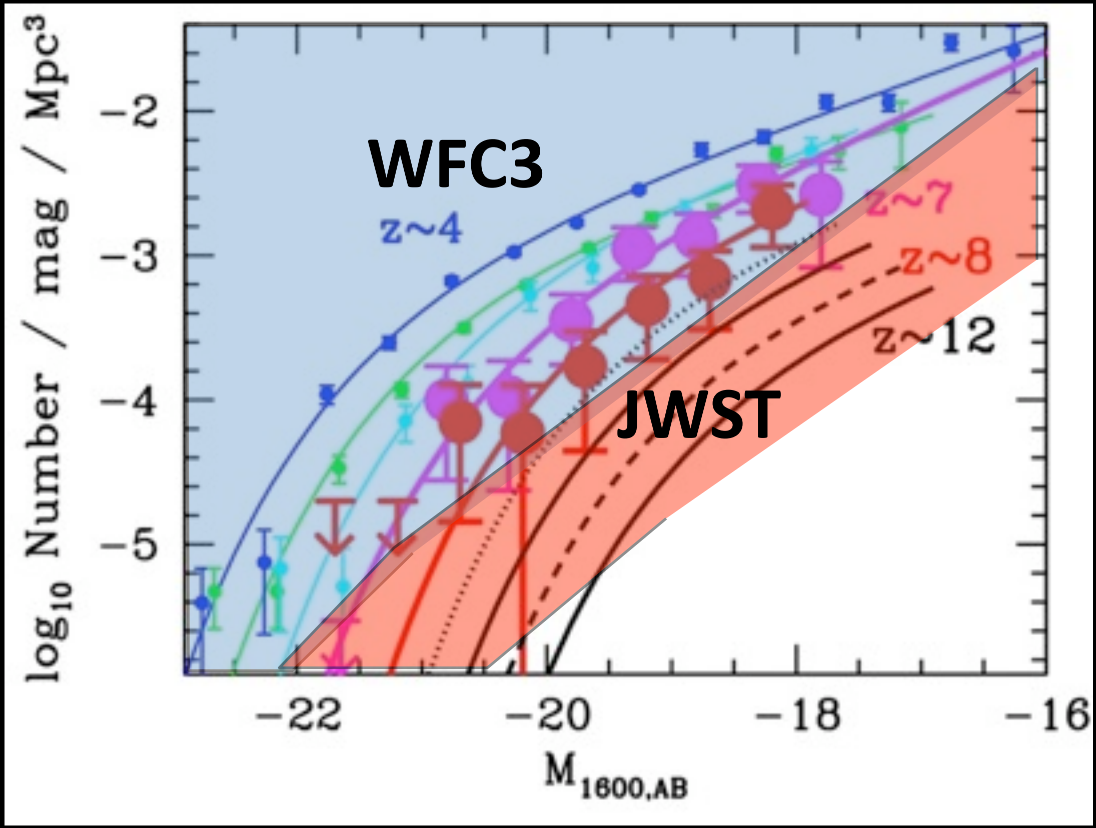

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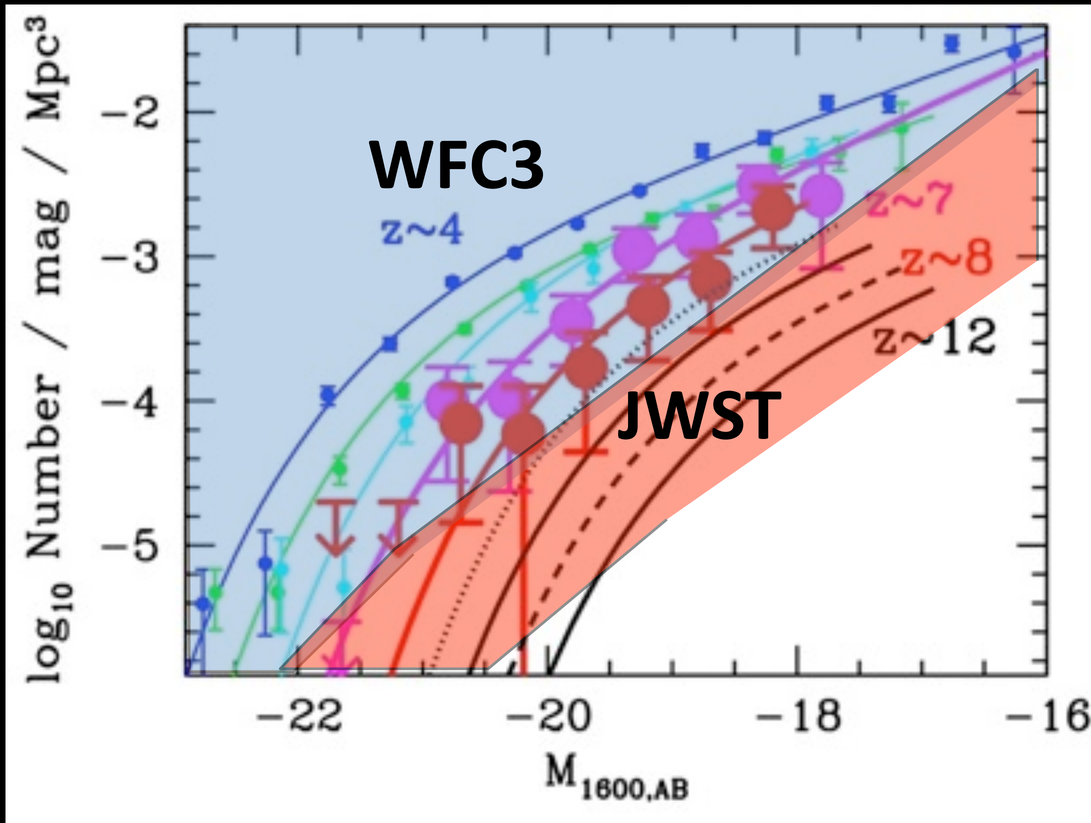


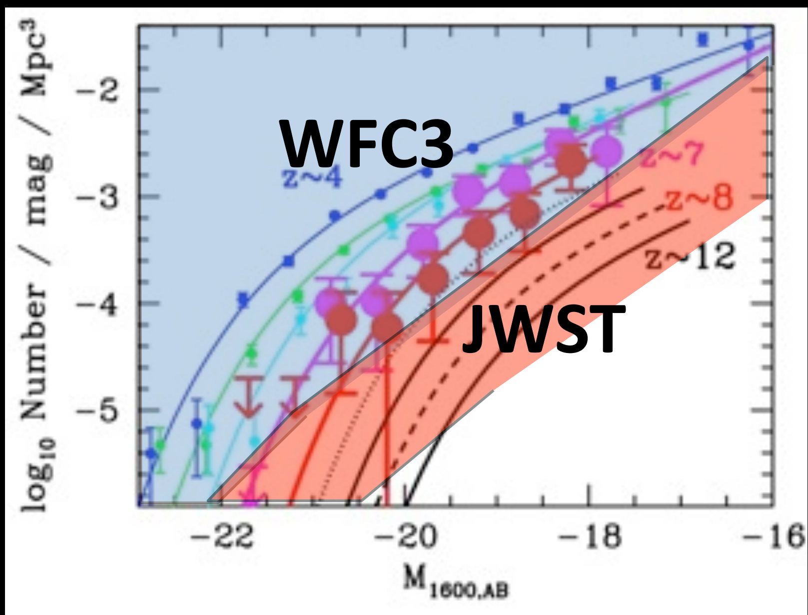
Push High-Redshift Frontier

z~6-7 → z~10-13

What can we learn with JWST + ELTs?

Are z>6 galaxies able to reionize the universe?

To answer this, we must have inventory -- which is challenging because most sources are extremely faint



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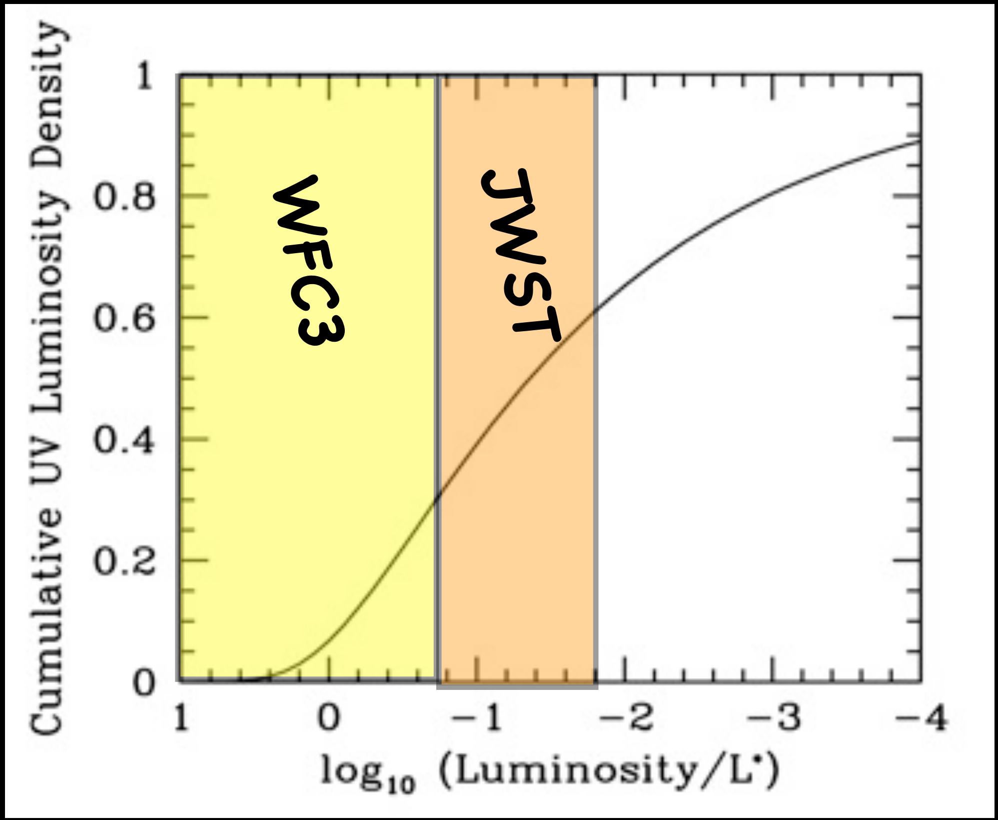
Fraction of rest-frame UV light in sources brighter than some luminosity at z~8



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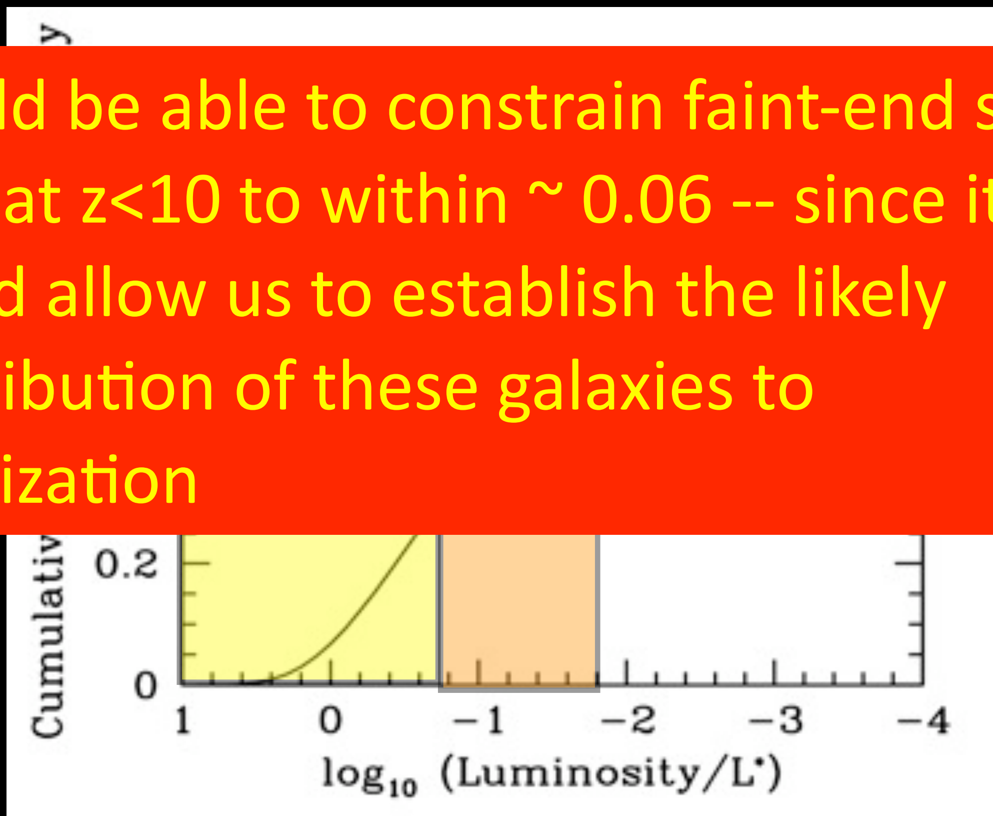


Should be able to constrain faint-end slope of LF at z<10 to within ~ 0.06 -- since it would allow us to establish the likely contribution of these galaxies to reionization

Two Key Points regarding advances with JWST

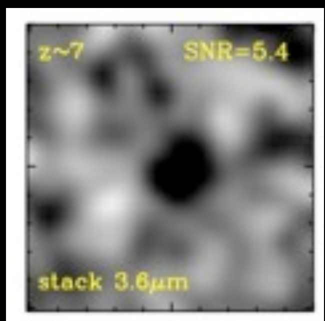
- One highly significant advance with JWST will be in the ability to do moderate resolution spectroscopy...

  * Able to do spectroscopy on most of the objects we are identifying with WFC3

- With superb sensitivities to ~5μ with NIRCAM, one of the most significant advances from JWST will be in extending rest-frame optical (i.e., stellar mass) studies to z~10...

Stack

Current Situation (Spitzer) where stacking is needed



vs.

Detection of individual faint z~10 galaxies in rest-frame optical

Two Key Points regarding advances with JWST

- One highly significant advance with JWST will be in the ability to do moderate resolution spectroscopy...

  * Able to do spectroscopy on most of the objects we are identifying with WFC3

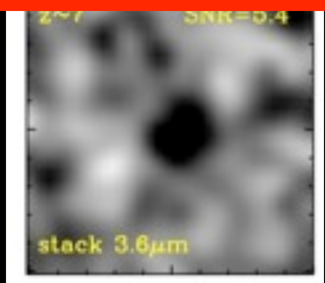
- With supe ne of the most signif tending rest-frame .

Rest-frame optical capabilities will allow us to extend our understanding of SF in galaxies even further into the past to z ~ 14

faint z~10

e optical

Current Situation (Spitzer) where stacking is needed



VS.

Spitzer IRAC Pathfinder at 2-5μ

Spitzer
IRAC
(2004-)

5.2 arcmin

>1000x

Improvement and few confusion issues

(70x sensitivity,
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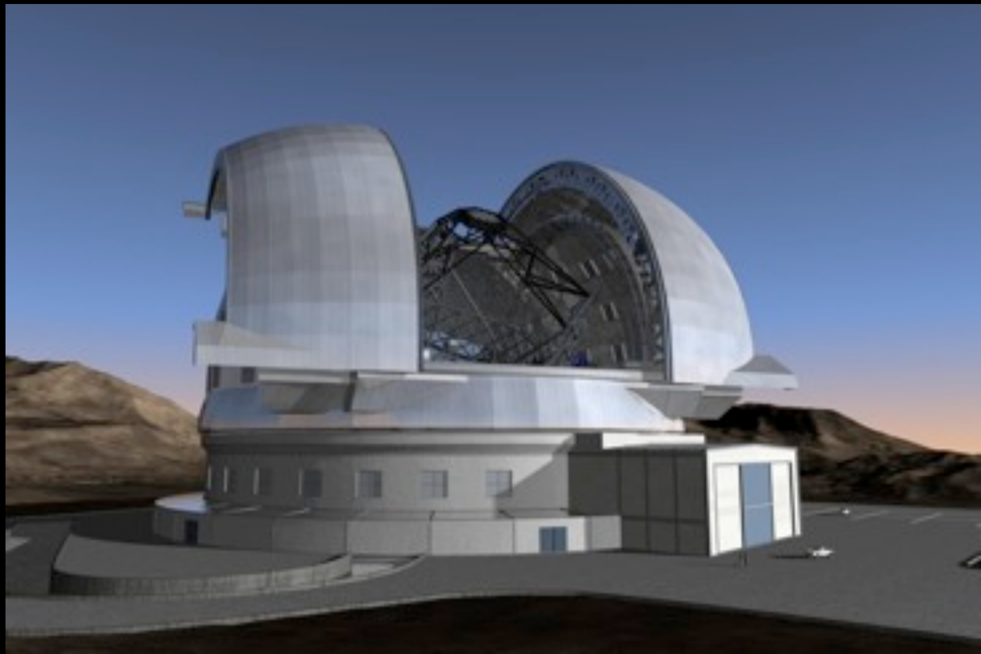
0.35x area)

JWST
NIRCAM
(2014-)

2.2 arcmin

Synergies with the ELTs



Many exciting first light instruments

TMT: IRIS, IRMS...

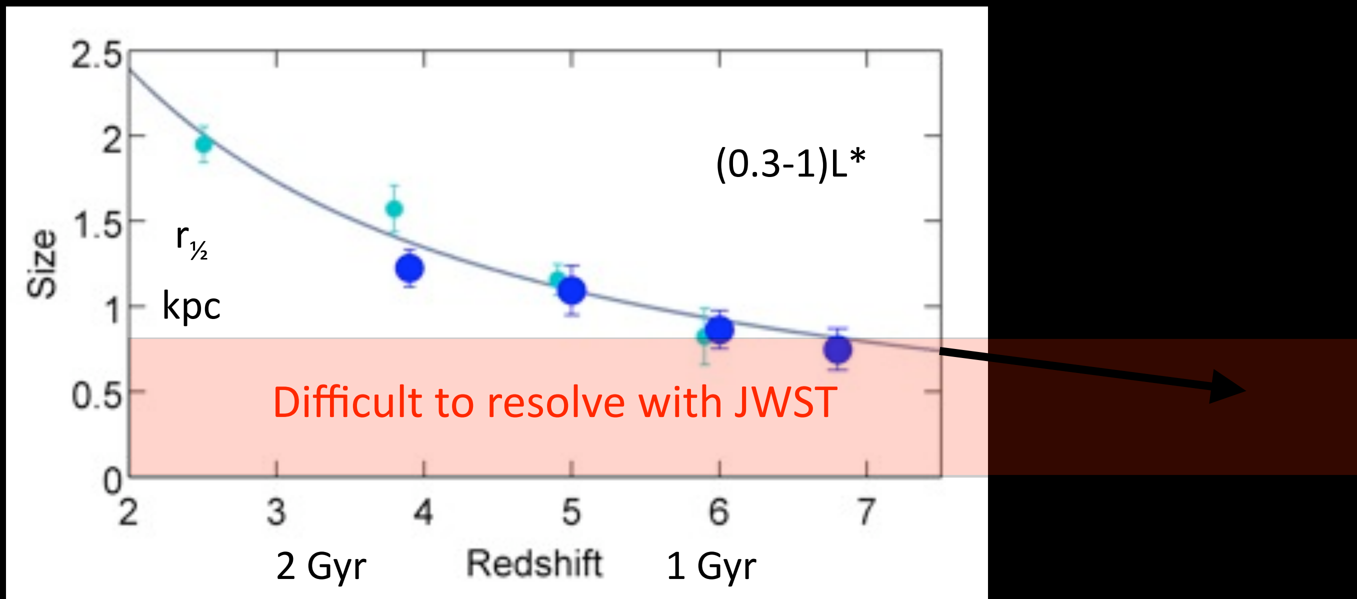
ELT: EAGLE, MICADO, METIS, ...

GMT: NIRMOS...

Small Sizes of high-redshift galaxies important opportunity for ELTs

At z>6, typical galaxies have sizes of <~0.1” and therefore unresolved with JWST

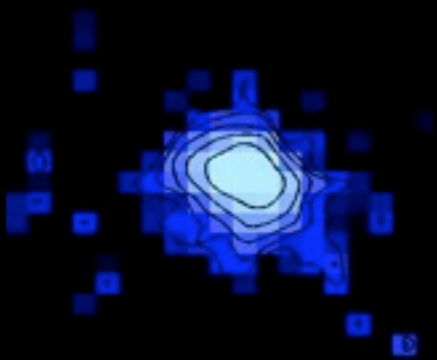
Oesch/Carollo et al

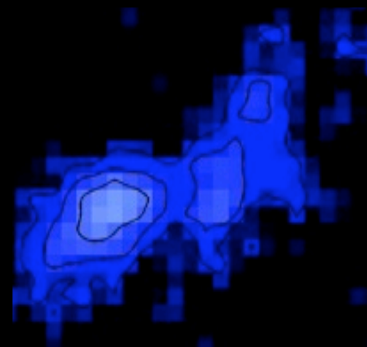


size scales as $(1+z)^{-m}$ where m = 1.12 ± 0.17

Small Sizes of high-redshift galaxies important opportunity for ELTs

Since the ELTs have apertures ~4-7x larger of JWST, the ELTs will easily be able to resolve high-redshift galaxies and hence study their structure...



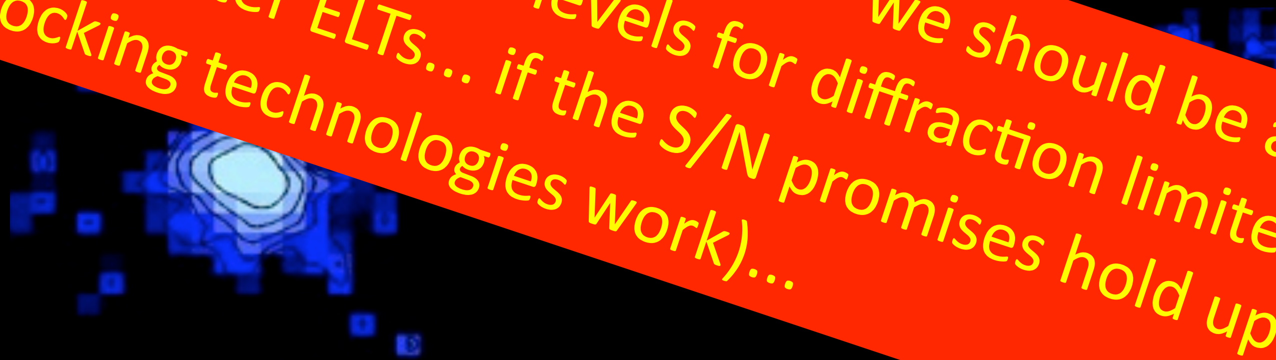


This should give us insight into how SF proceeds at early times, feedback processes, etc.

Small Sizes of high-redshift galaxies important opportunity for ELTs

Since z>6 galaxies are so small -- we should be able to achieve very high S/N levels for diffraction limited large-diameter ELTs... if the S/N promises hold up (and OH blocking technologies work)...

Si... ELTs have apertures ~4-7x larger of JWST, the ... le to resolve high-redshift galaxies ... re...



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Summary

Current WFC3 results provide us with a useful guide as to what we might expect to find, as we anticipate observations with JWST and ELTs

>100 z~7 and z~8 candidate are known in current WFC3 observations -- permitting us to study galaxy evolution 600 Myr after the Big Bang

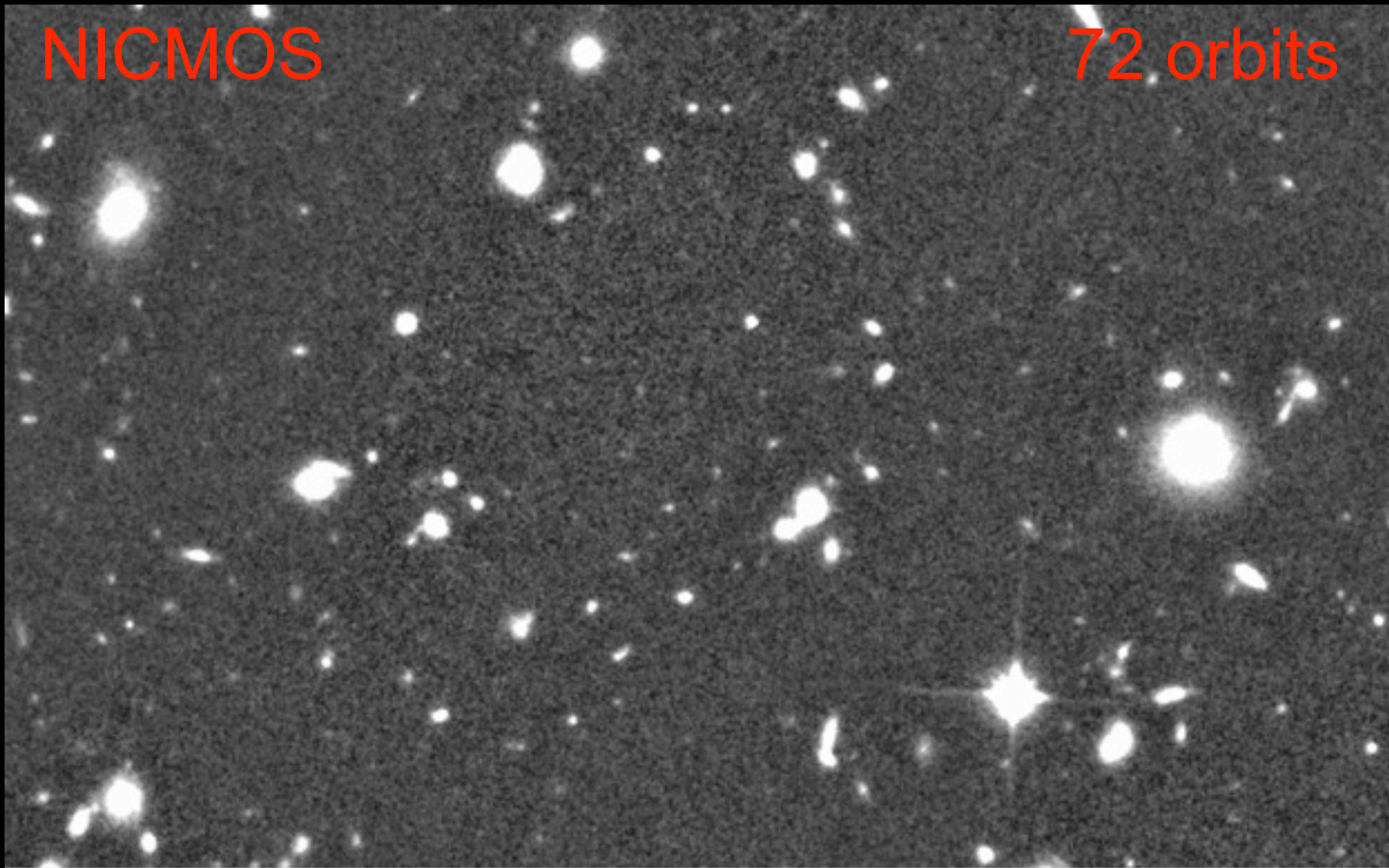
Current observations already permit us to quantify the SFR, stellar masses, ages, sizes, colors, dust properties of galaxies as early as z~8 and even possibly at earlier times

JWST + ELTs will allow us to push to z~11-13... allowing for accurate SFR and stellar mass estimates to limits of searches...

Key advances will be in spectroscopy and in rest-frame optical studies (for stellar masses) of z~8-10 galaxies -- reaching 100x fainter than possible now

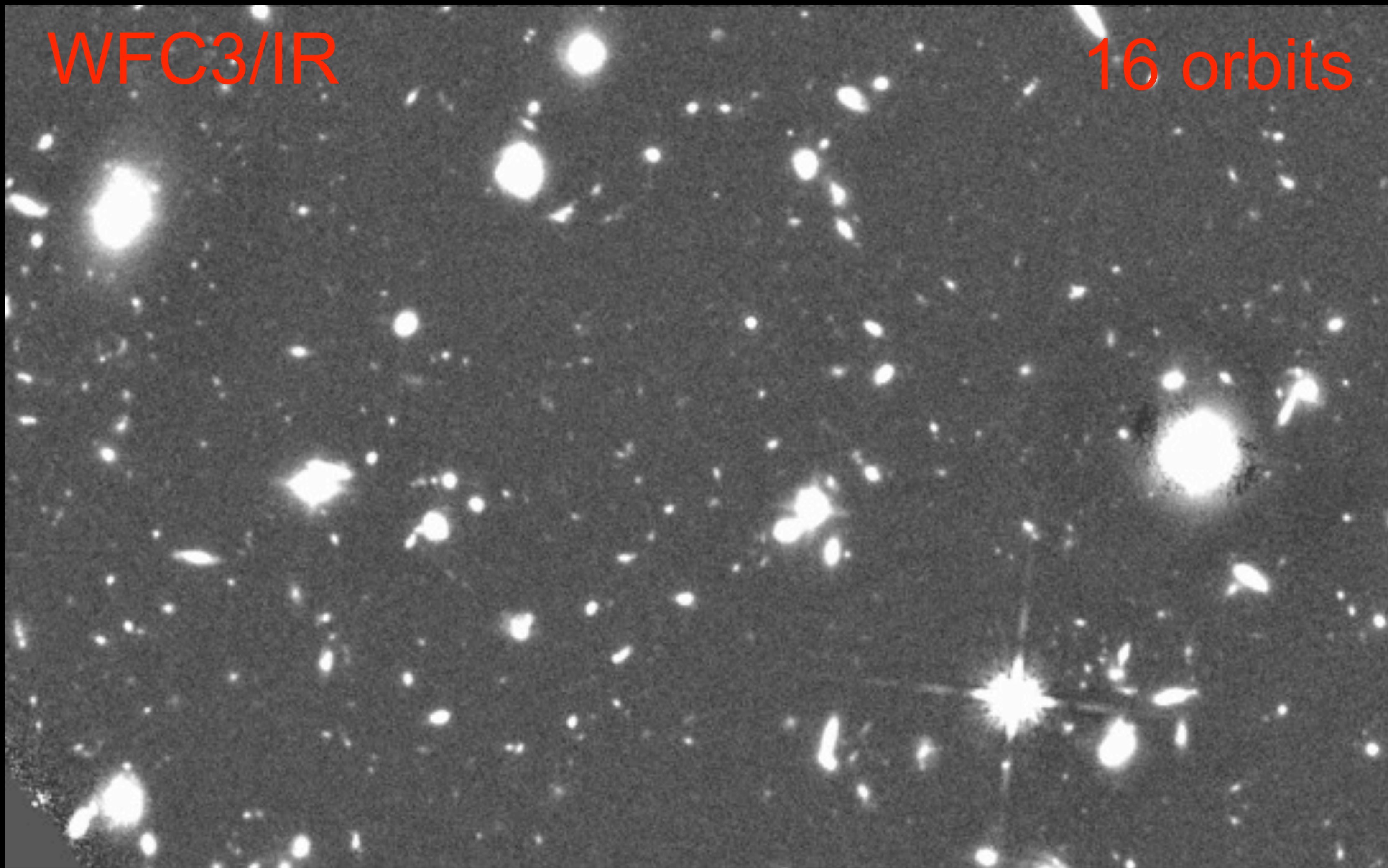
The ELTs will have a >6x resolution advantage over JWST which is important for studying z>~8 galaxies (largely unresolved with JWST)

Gains with JWST should mirror those achieved with WFC3



Region of the HUDF

Gains with JWST should mirror those achieved with WFC3



Region of the HUDF

Gains with JWST should mirror those achieved with WFC3

Region of the HUDF

TEAM

the HUDF09 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)
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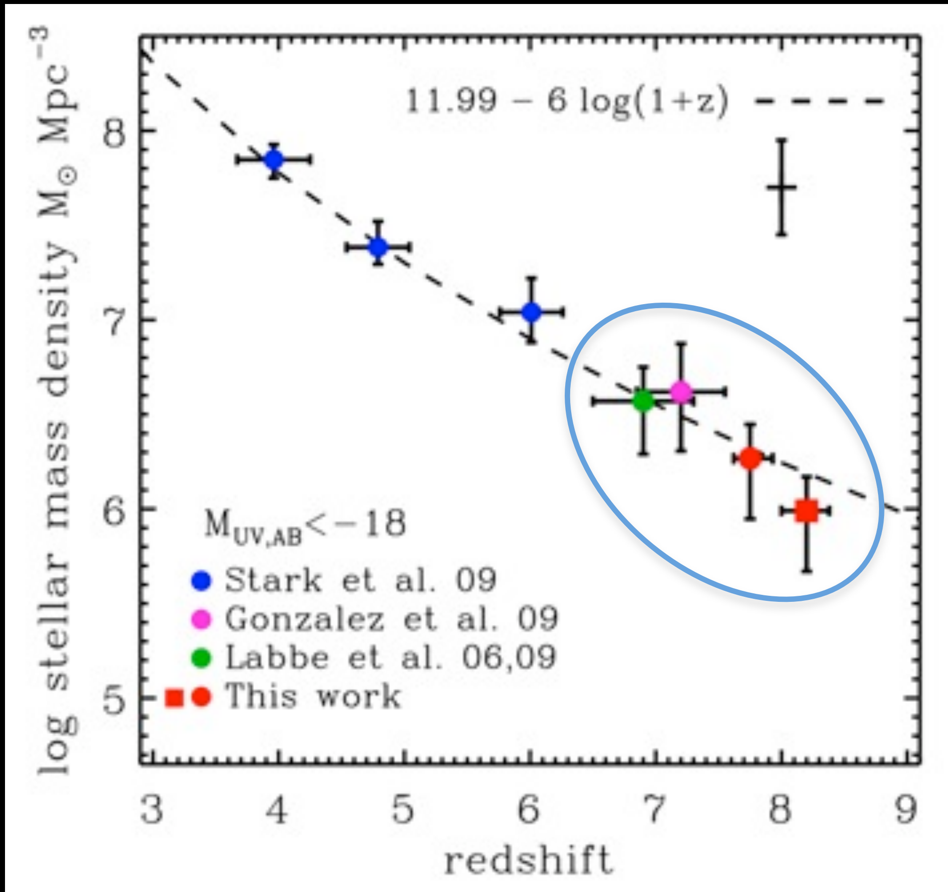
P. Oesch (Swiss Federal Institute of Technology, Zurich)
M. Stiavelli (STScI)
M. Trenti (University of Colorado, Boulder)
P. van Dokkum (Yale University)

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

mass buildup over time



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

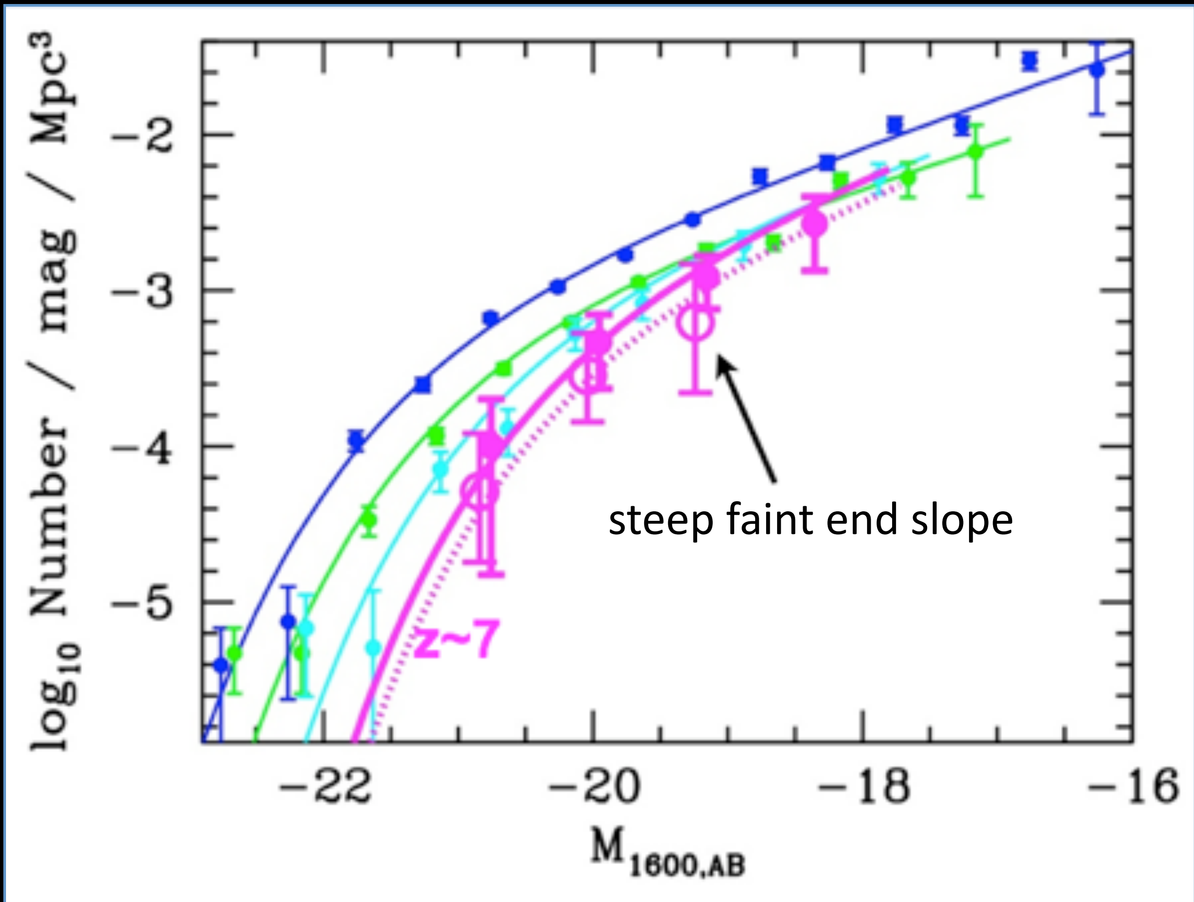
see papers by Gonzalez et al and Labbé et al

our new results

the history of the mass buildup in galaxies in the universe

Labbé/Gonzalez et al

luminosity functions



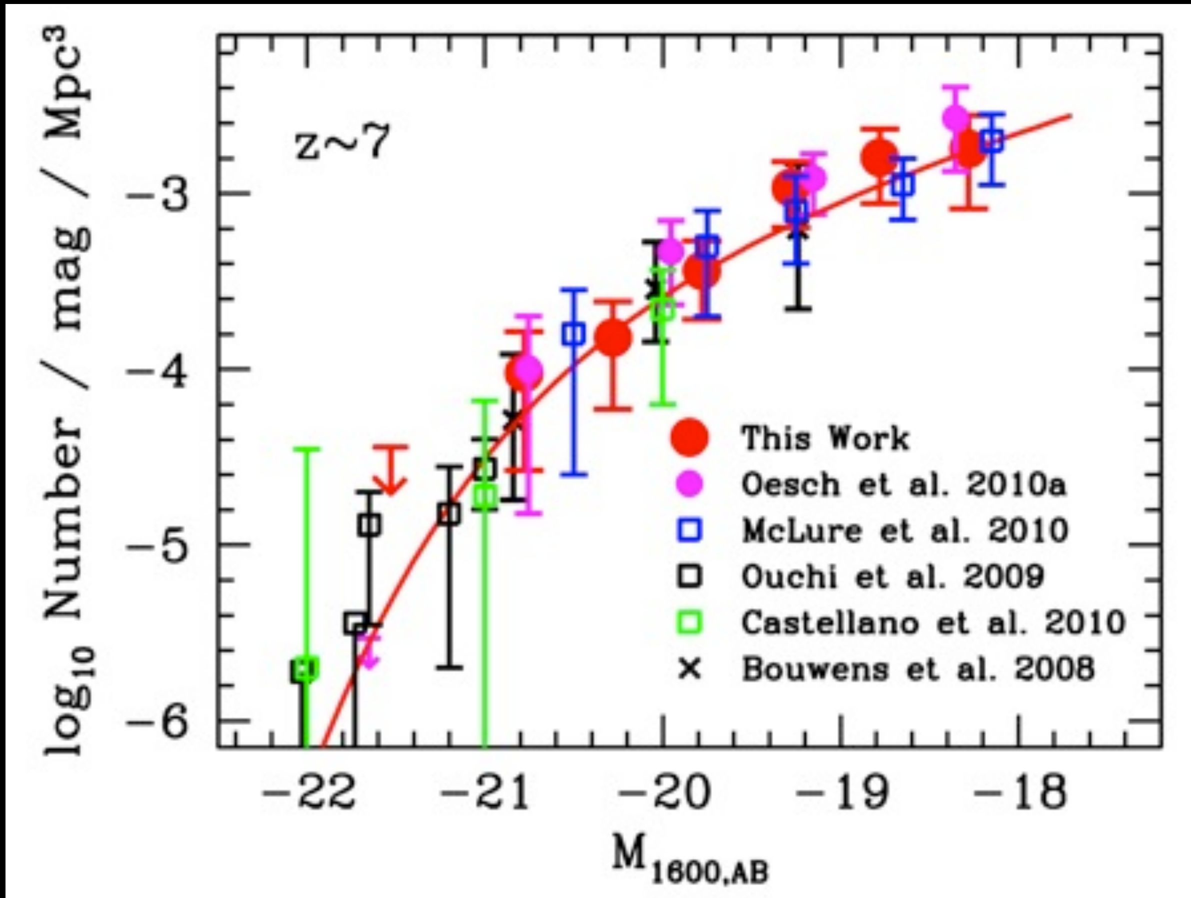
luminosity functions (LF) are key for determining the UV luminosity density and star formation rate densities

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

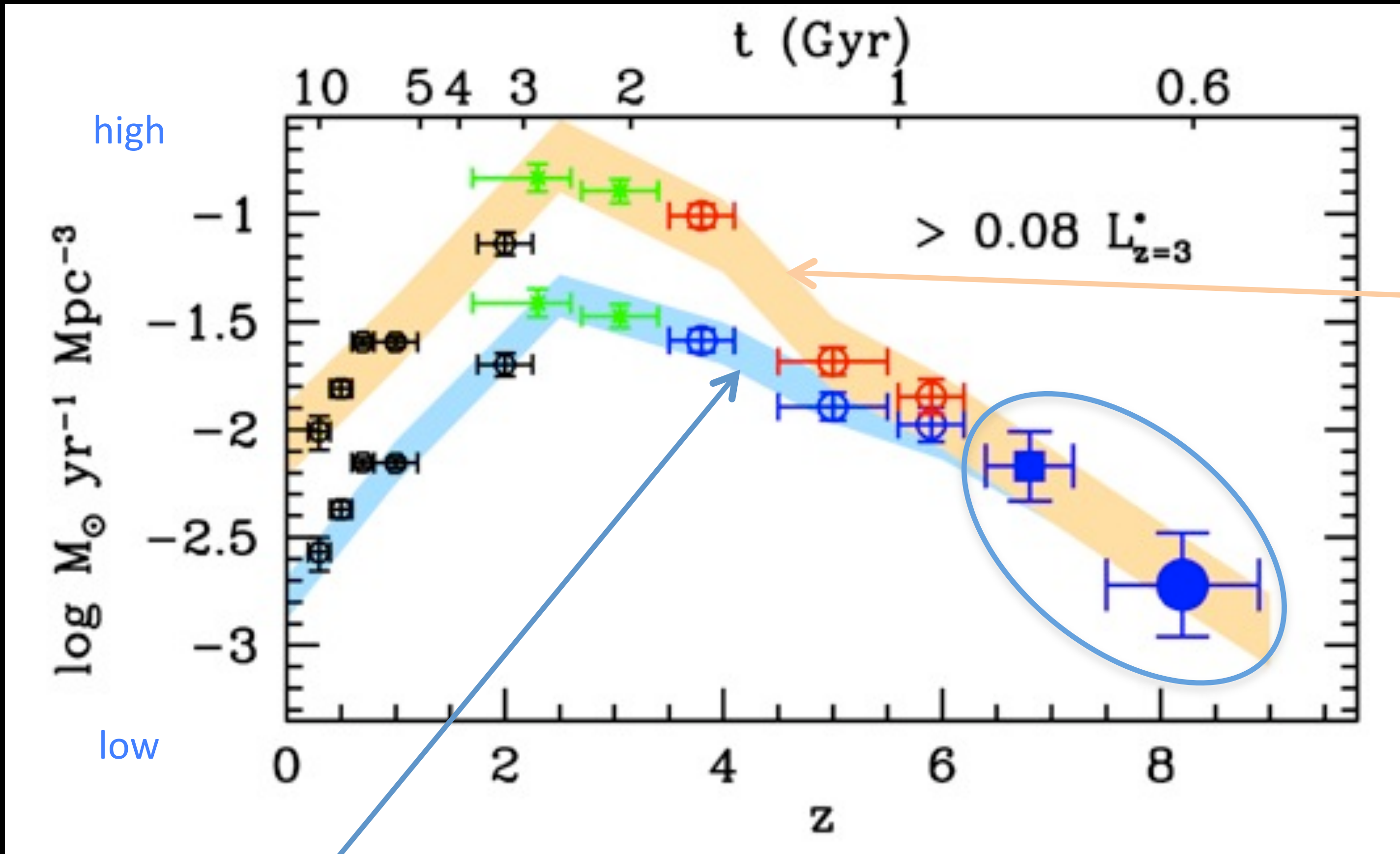


luminosity functions at z>7 are very important for establishing role of galaxies in reionization

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



high

low

dust-corrected SFR

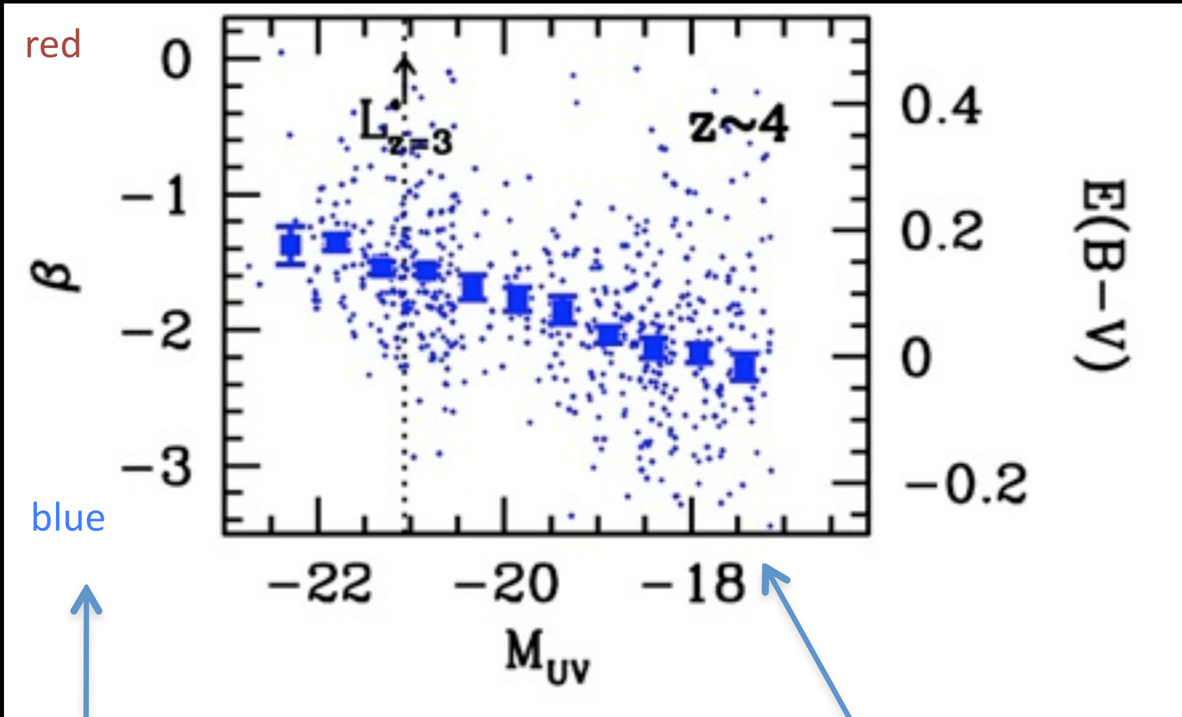
new results

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



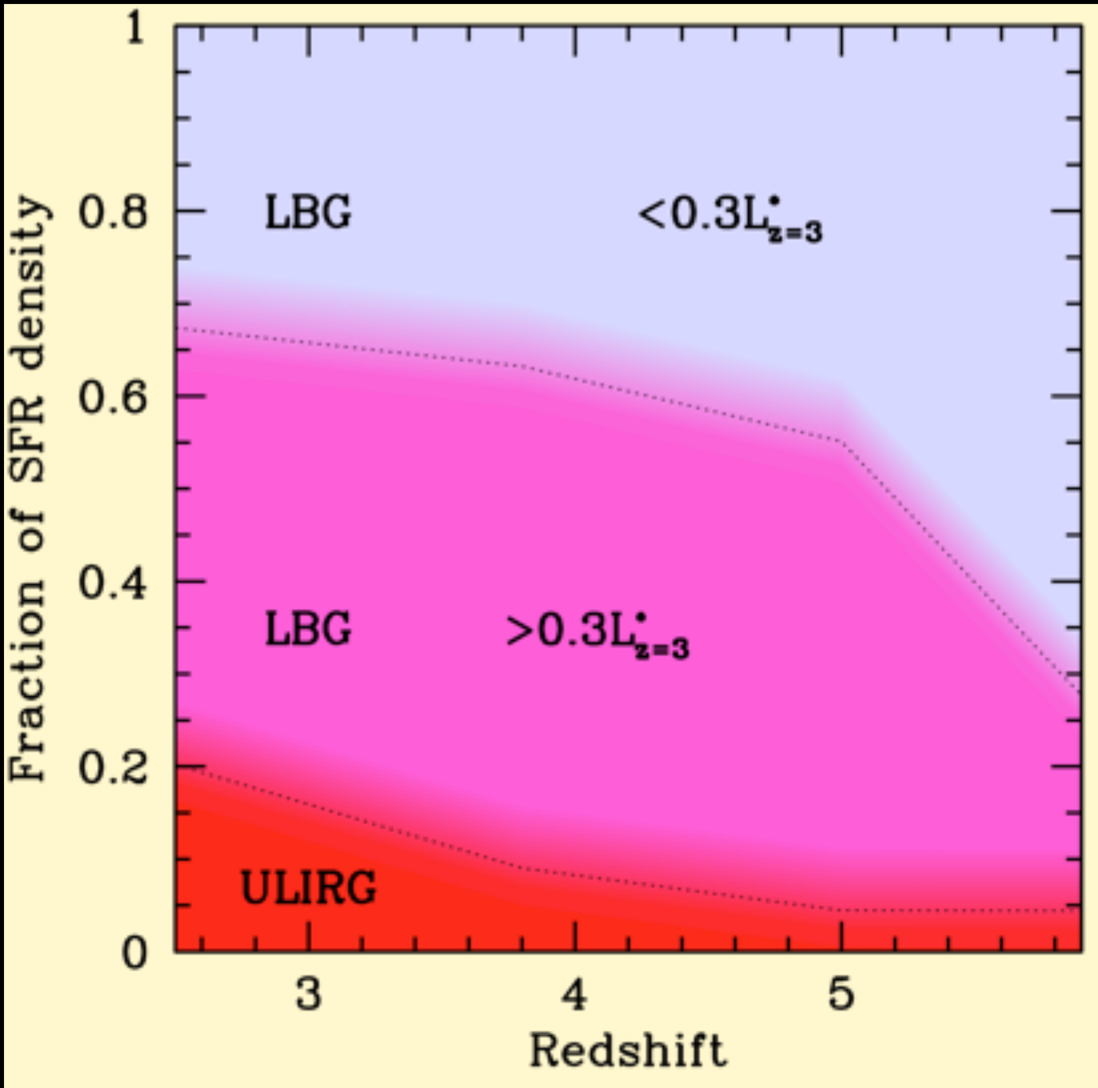
z~4-6 results last year built on ACS data in HUDF and GOODS

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

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

what these new observations tell us

SUMMARY

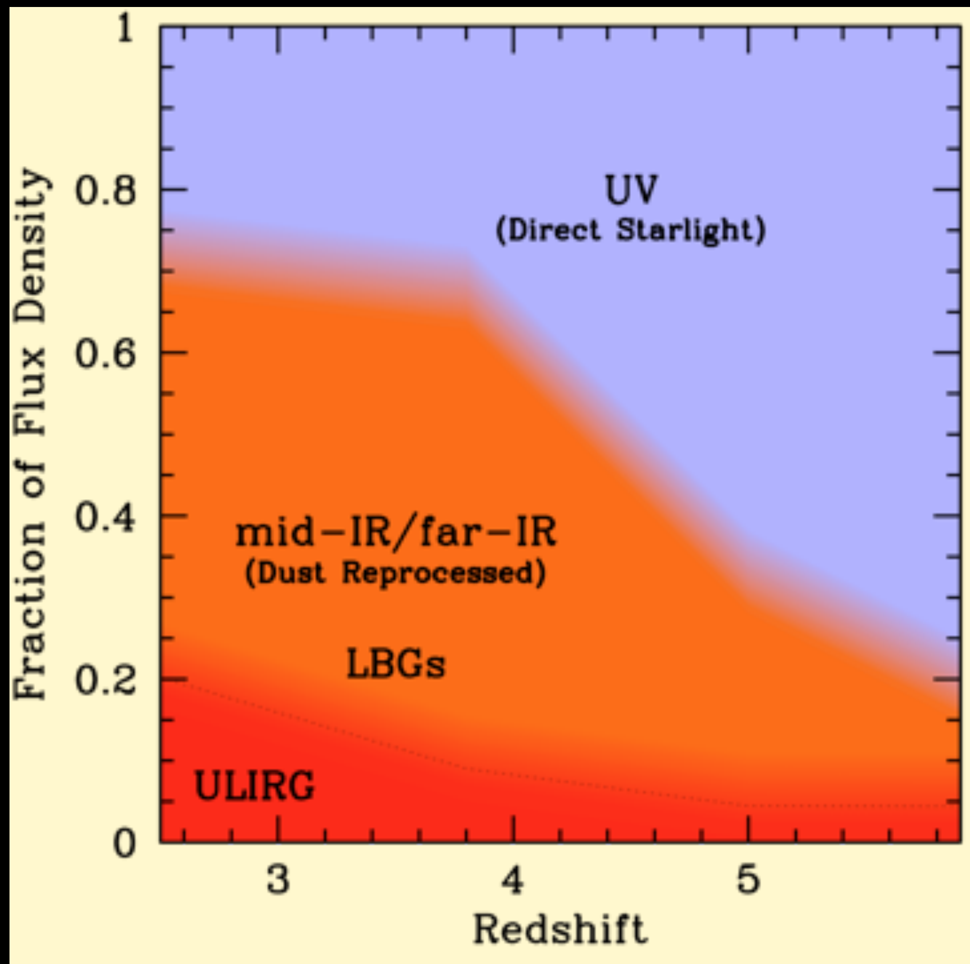
Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed many galaxies 13 billion years ago (at redshifts z~7 and z~8), just 600-800 million years from the big bang

- 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 ELT/TMT ALMA

Increasing fraction of energy coming out in UV at z>5

for star forming galaxies…



Bouwens/Illingworth et al 2009 ApJ 705

>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 new WFC3 Results are key

They allow us to accurately establish what we might expect to find with JWST/ELTs

They help to frame the questions that are likely to be important for the new facilities