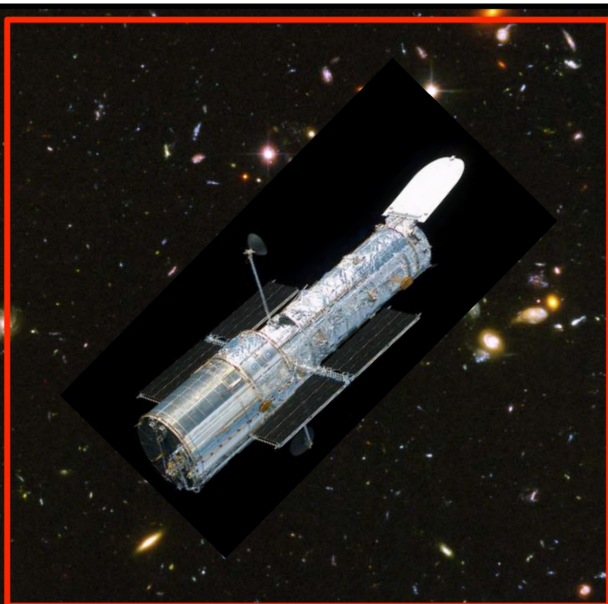
2011 Santa Cruz Galaxy Workshop
August 08, 2011

HIPACC



David's Day

galaxy buildup in the first billion years: galaxies in the epoch of reionization:

Garth Illingworth

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

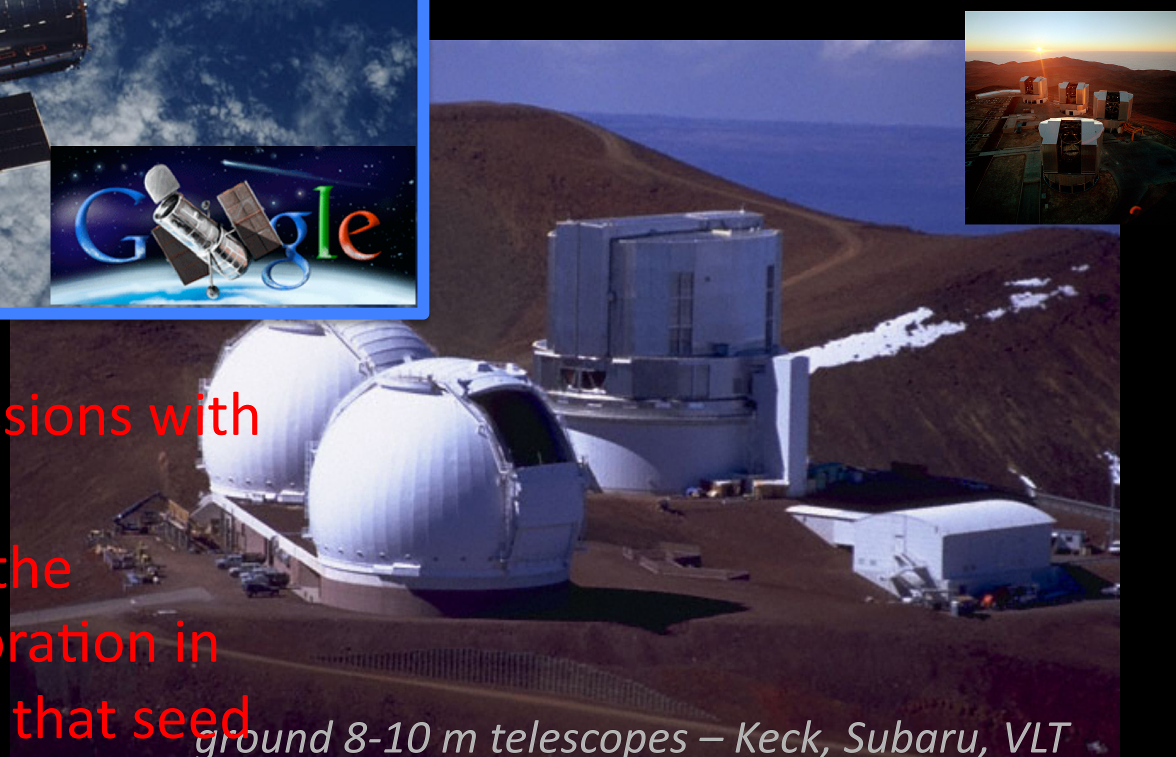
HUDF09 Project

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

HST and Spitzer

ground 8-10 m telescopes – Keck, Subaru, VLT *the first billion years of galaxies: brought to you by some remarkable observatories*

HST and Spitzer



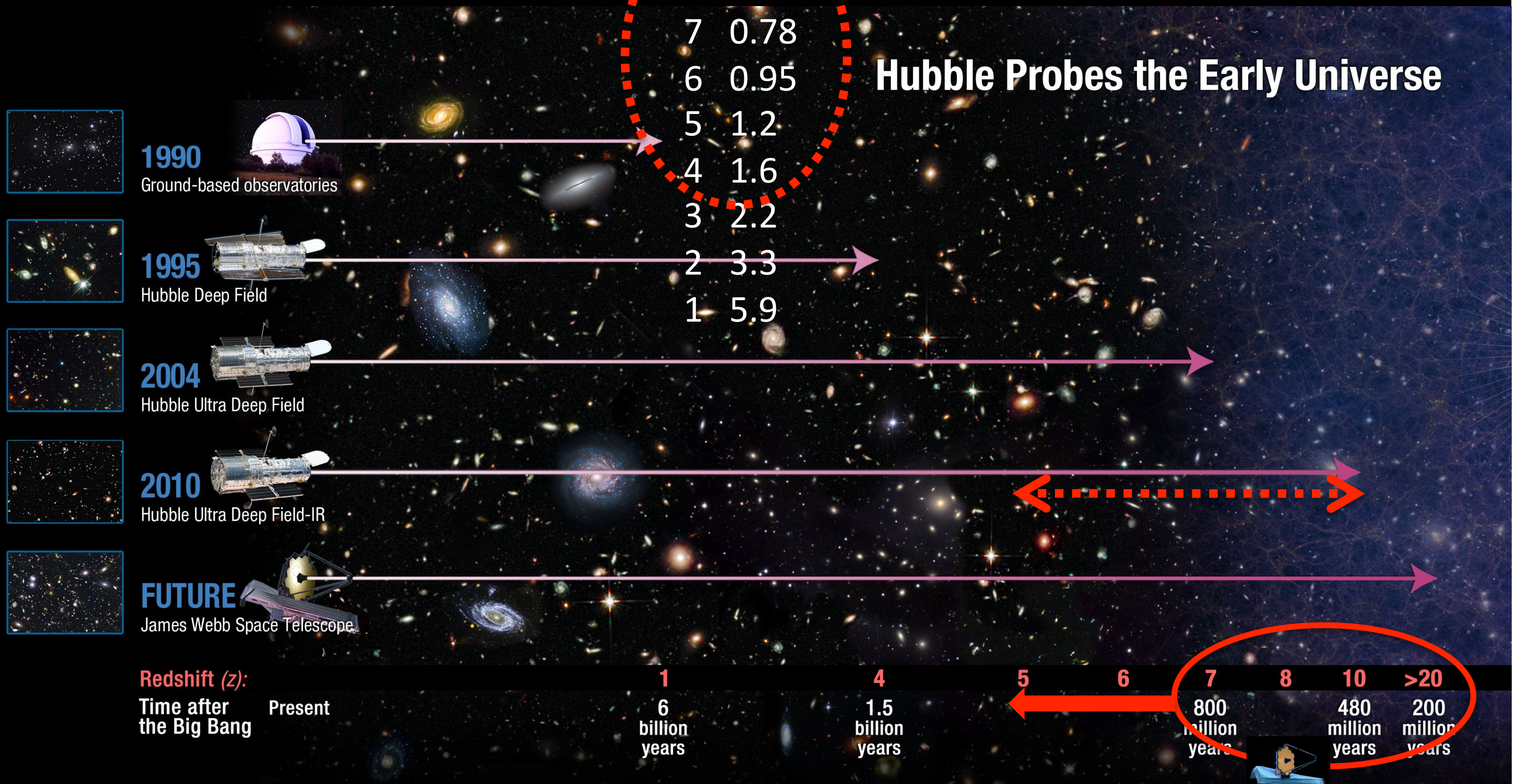
ground 8-10 m telescopes – Keck, Subaru, VLT

DEIMOS began in discussions with CfPA at UCB….
David Koo first realized the opportunity of a collaboration in the early 1990s => from that seed grew DEIMOS!

time vs redshift z

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

The universe age is
13.75 ± 0.11 billion years



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

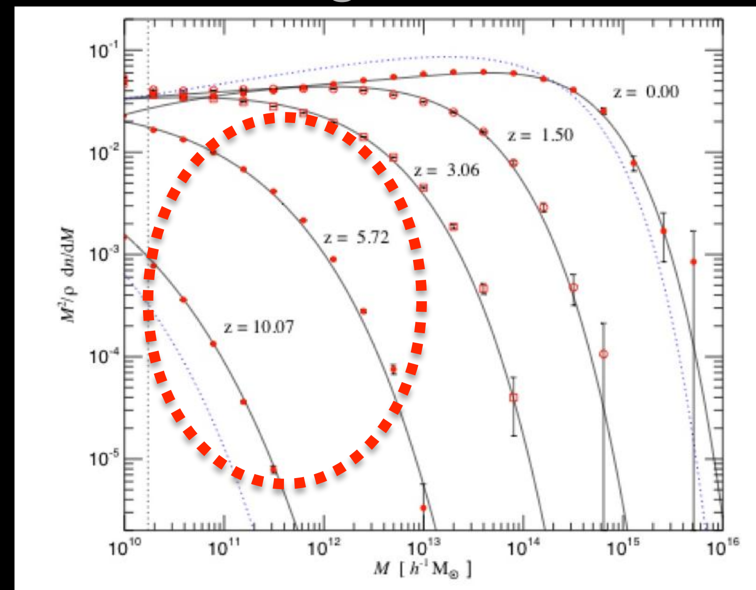
what are the key issues?
why is this first billion year period interesting?

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

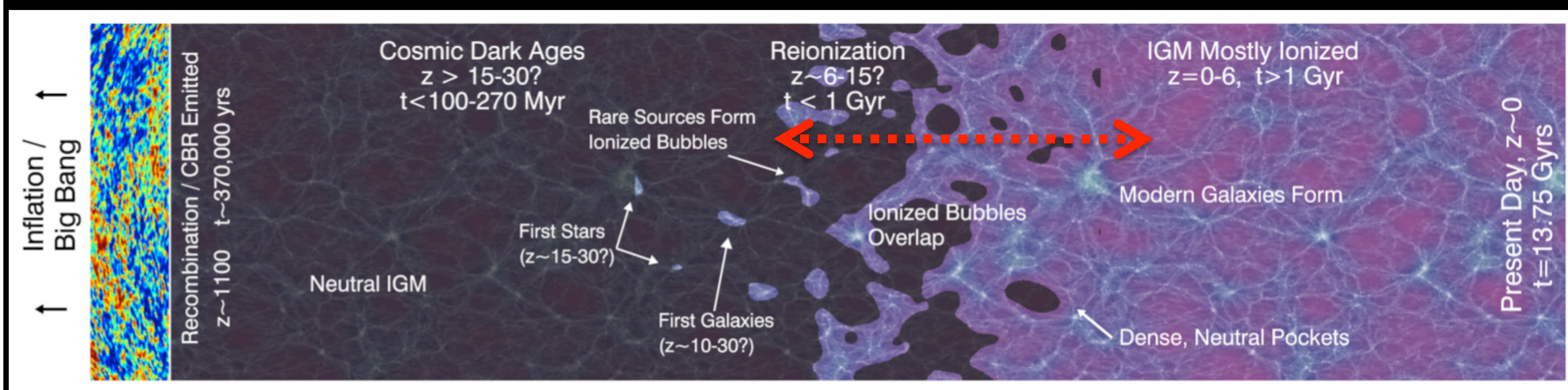
when the dark matter halos of massive (L*) galaxies first form...

when significant metals first form...

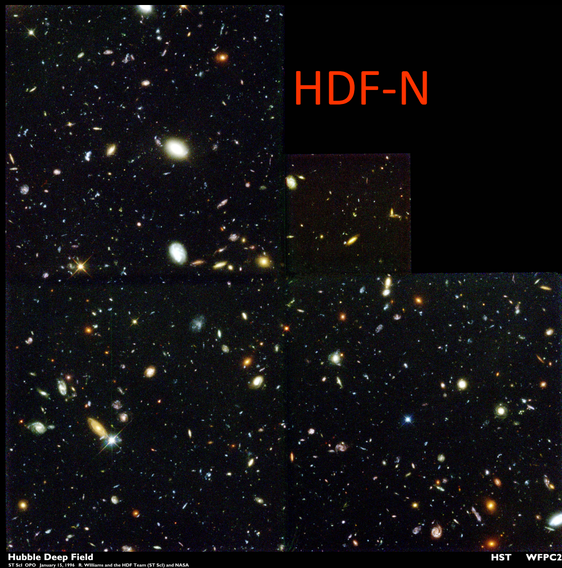
when the universe was reionized...



time of rapid growth in galaxy masses ....



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

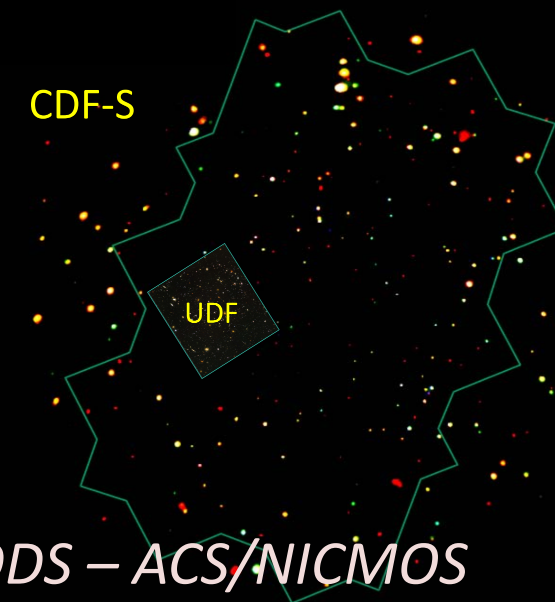


HDF-N

1995 – HDF – WFPC2

z~2-3-4

CDF-S



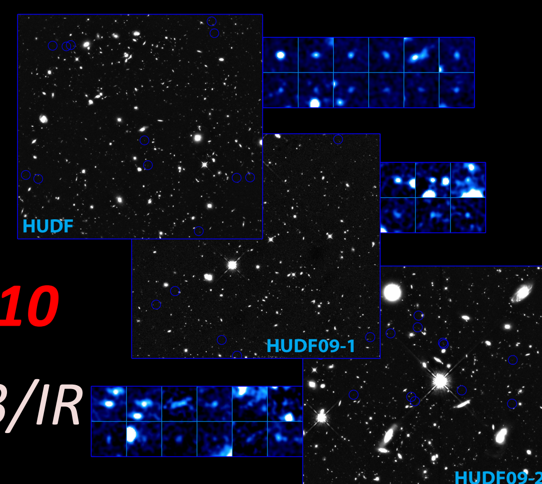
2003 – HUDF & GOODS – ACS/NICMOS

z~4-6

Thanks to STScI directors:

Bob Williams
Steve Beckwith
Matt Mountain

for these remarkable public datasets



HUDF09 HST WFC3/IR z~8 Galaxies

z~7-8-10

2009+ – HUDF09, ERS, CANDELS – WFC3/IR

the HUDF09 team

TEAM

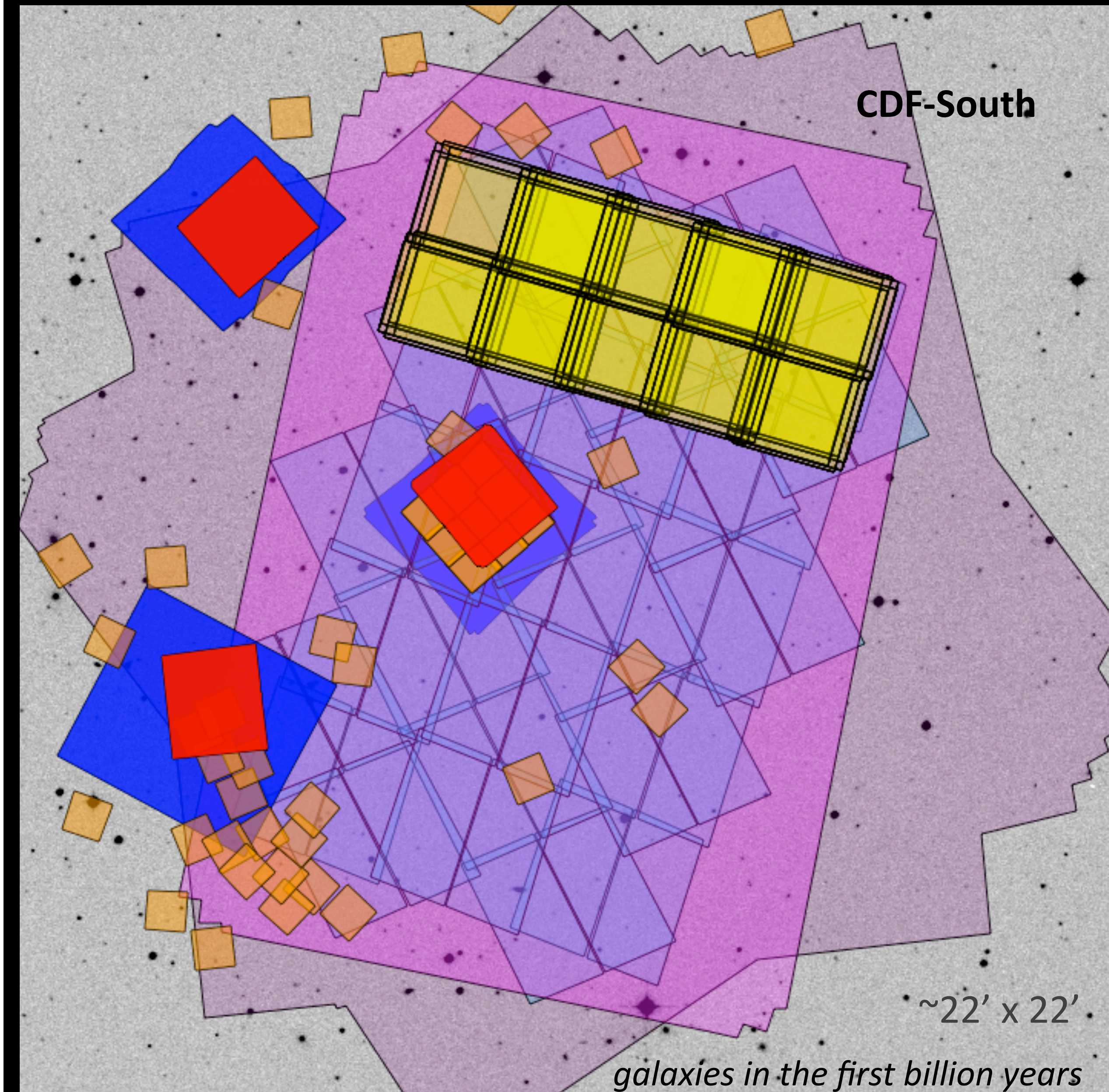
results based on data from the HUDF using the WFC3/IR and ACS cameras

G. Illingworth (UCO/Lick Observatory; University of California, Santa Cruz)
R. Bouwens (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 (UCO/Lick/UCSC; Swiss Federal Institute of Technology, Zurich)
M. Stiavelli (STScI)
M. Trenti (University of Colorado, Boulder)
P. van Dokkum (Yale University)
V. Gonzalez (UCSC)

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

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



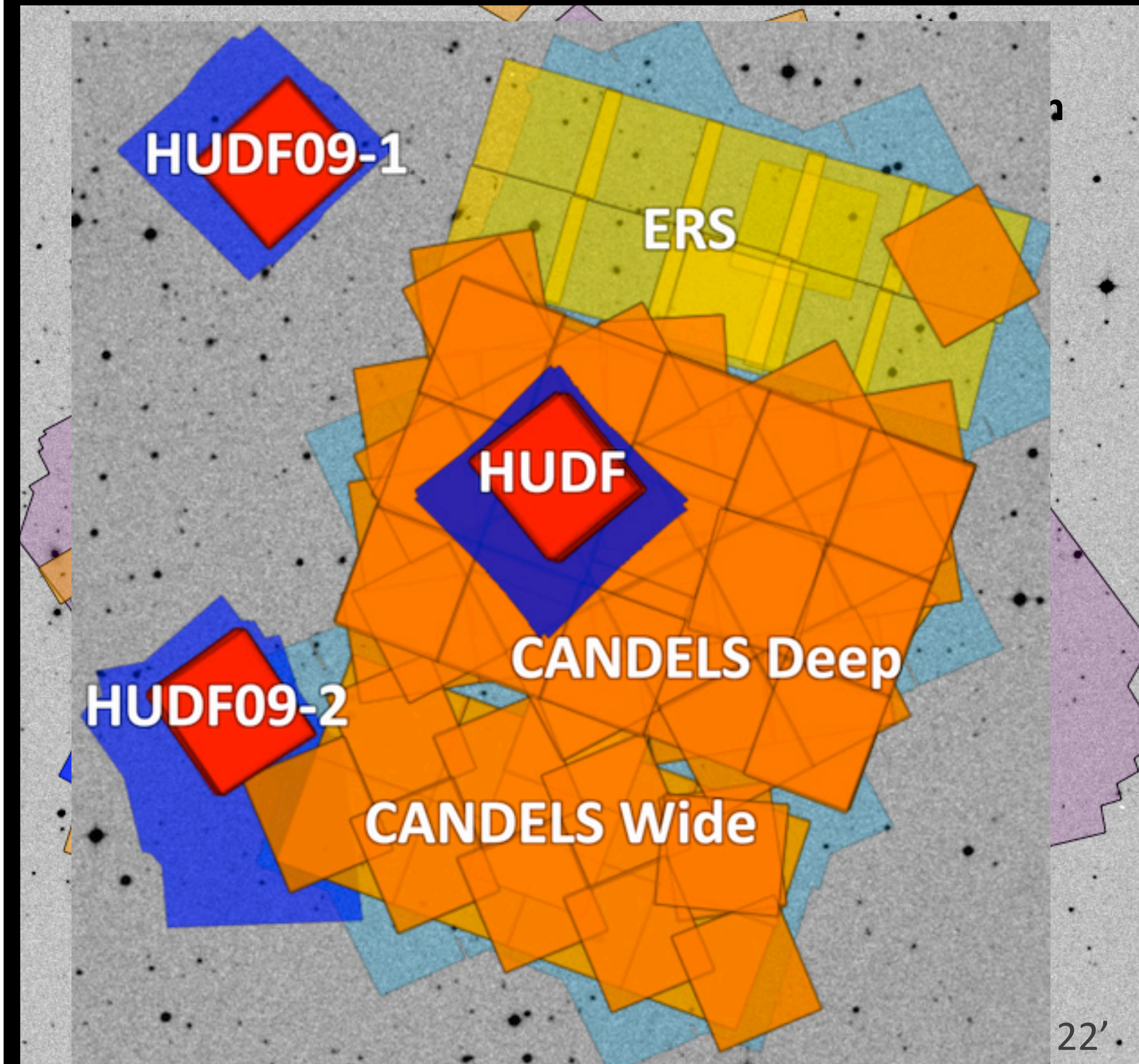
Chandra Deep Field-South

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

ALL PUBLIC DATA

GDI *firstgalaxies.org*

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



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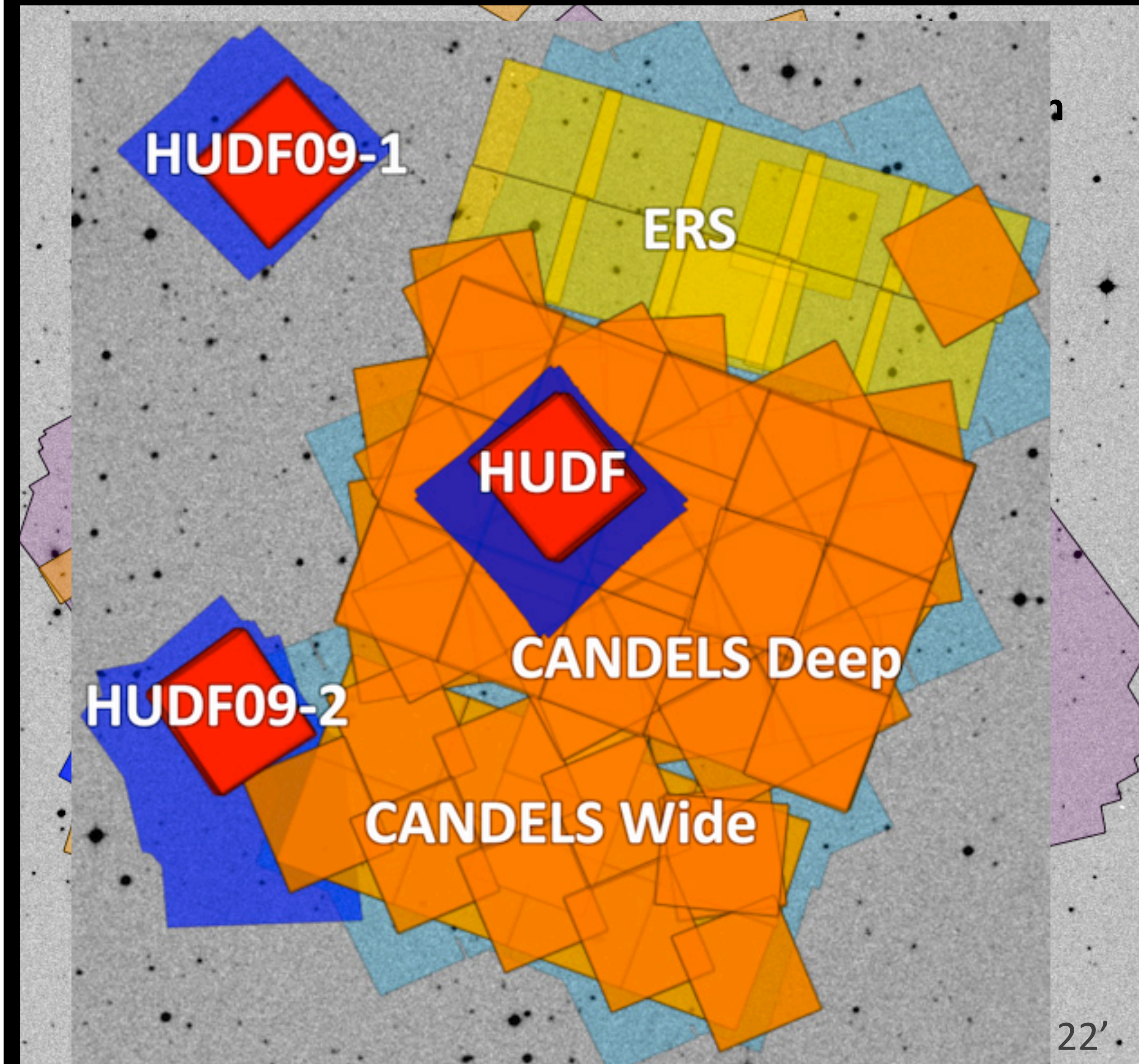

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2010-2012 CANDELS
2010-2012 3D-HST
2010-2011 Spitzer IUDF10
2011-2012 Spitzer Deep
2011-2012 HUDF UVIS

~2/3 yr of Hubble data and 1/3 yr ea on Chandra and Spitzer!

>$400M spent on the CDF-S fields.

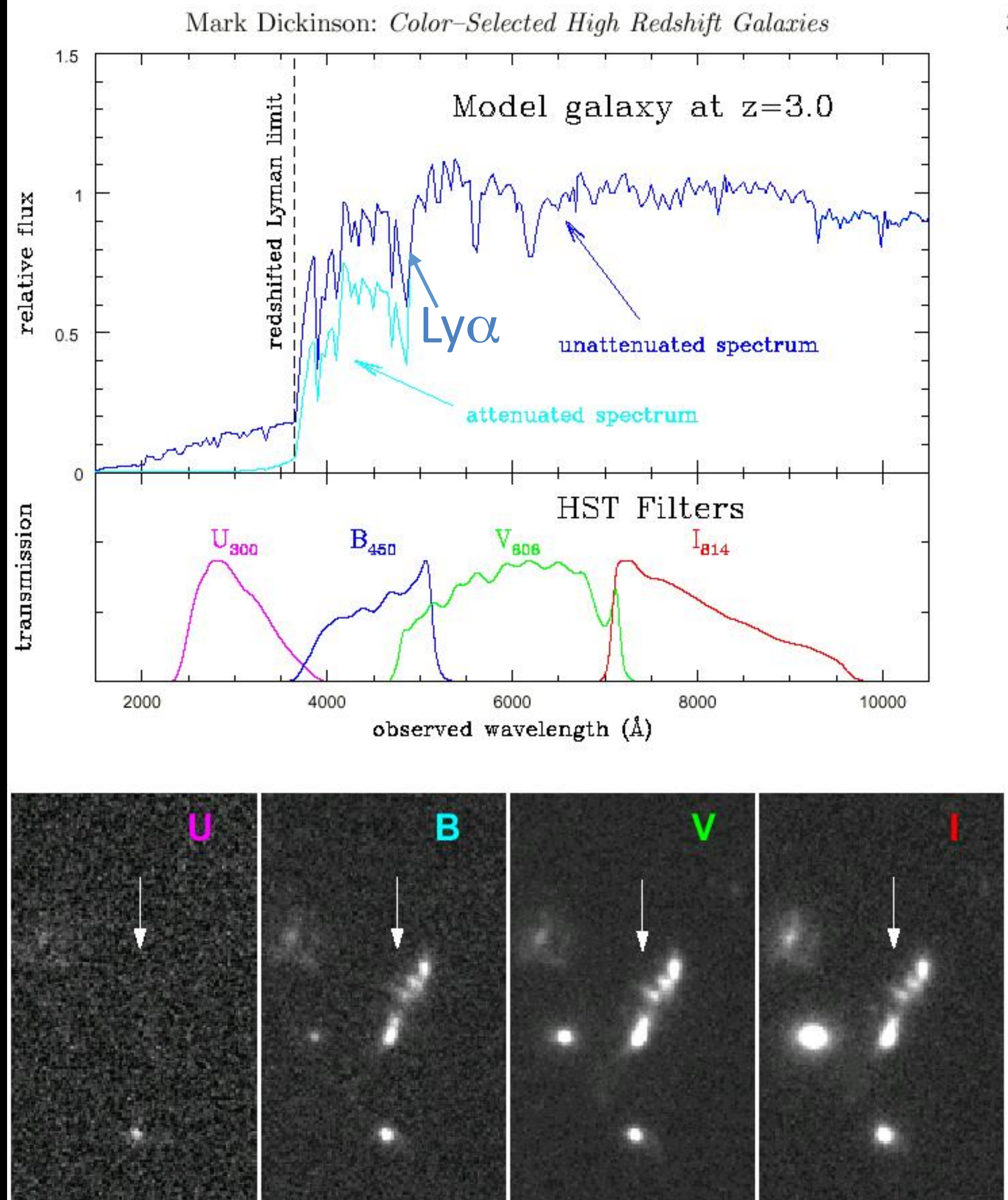
Amazing scientific returns justify investment of taxpayer funding on one tiny patch of sky!

finding high-redshift galaxies

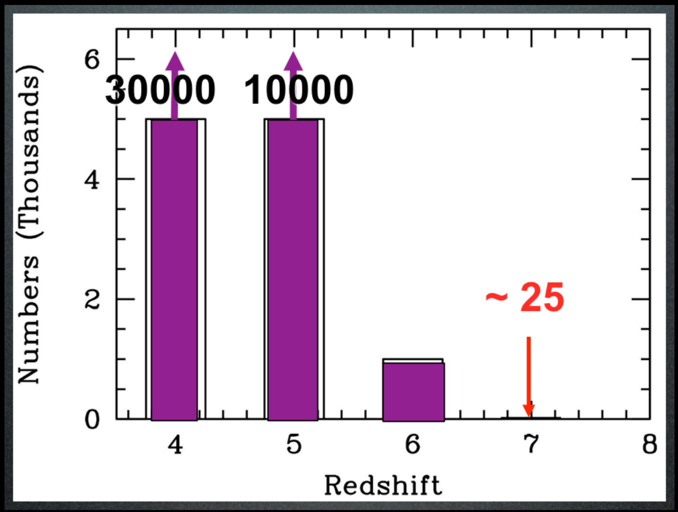
the "Lyman Break" technique – using the break at the Lyman limit and at Lyα

use data below the Lyman Break break with a χ^2_{opt} weighting to eliminate contamination – deep images below the break are *equally as important* as the detection bands

distant galaxy selection by the "Lyman-Break" technique – a 'U-dropout' in this case (Dickinson 1999)

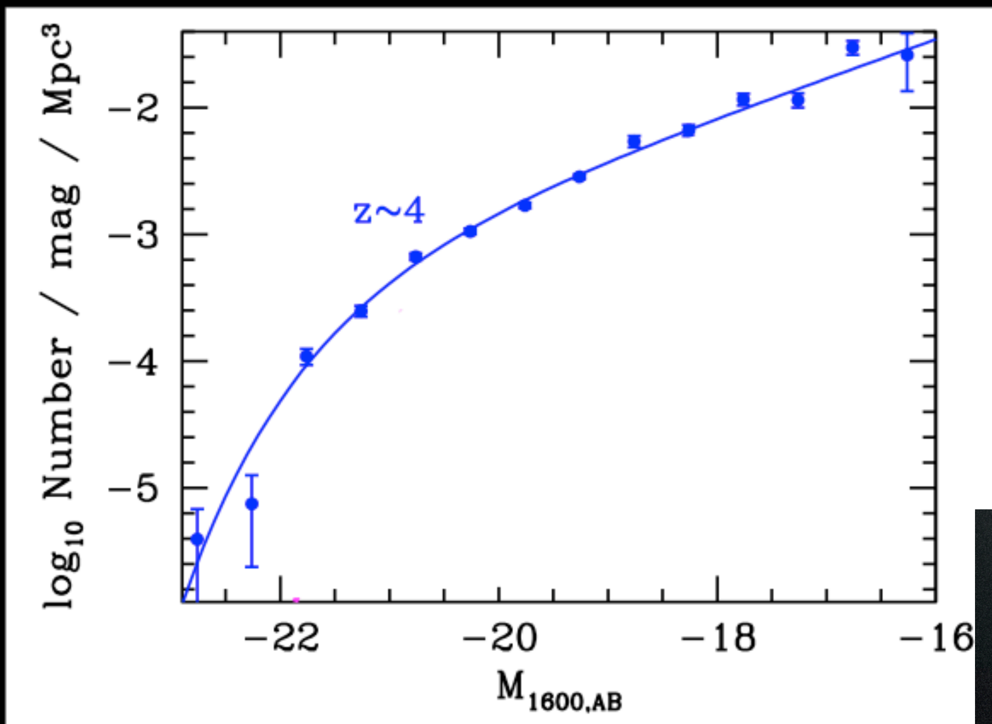


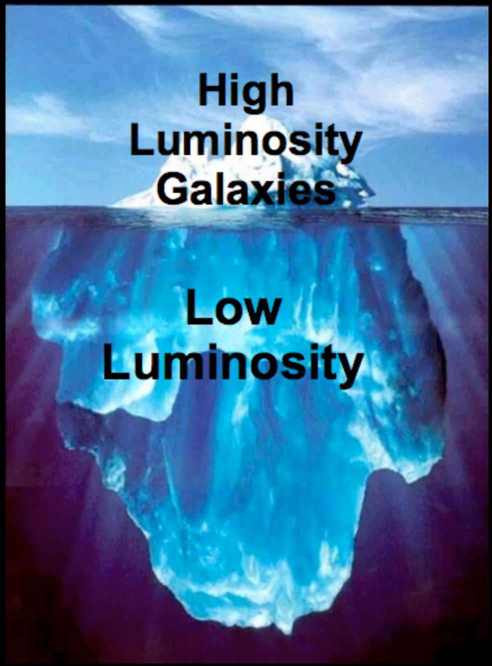
high-z galaxies from HST and ground-based telescopes

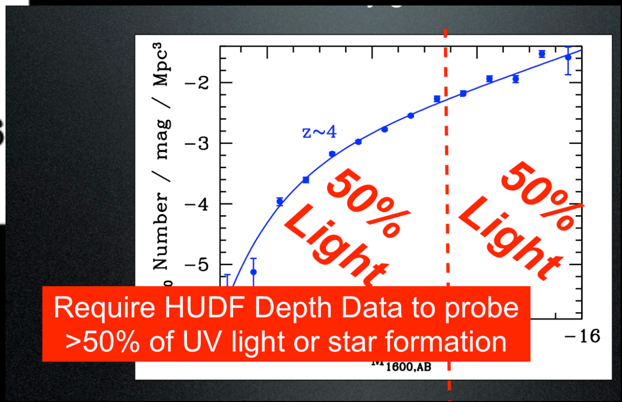


	Field Surveys	Lensed (clusters)
z~4	20k+	~200
z~5	8k+	~70
z~6	~1000	~20
z~7	> ~70	~6
z~8	> ~30	1

why is it important to go faint?



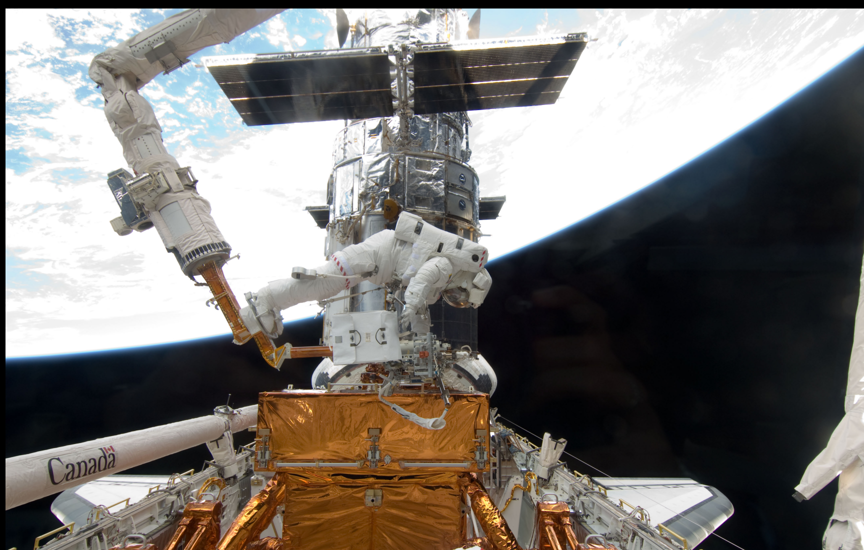




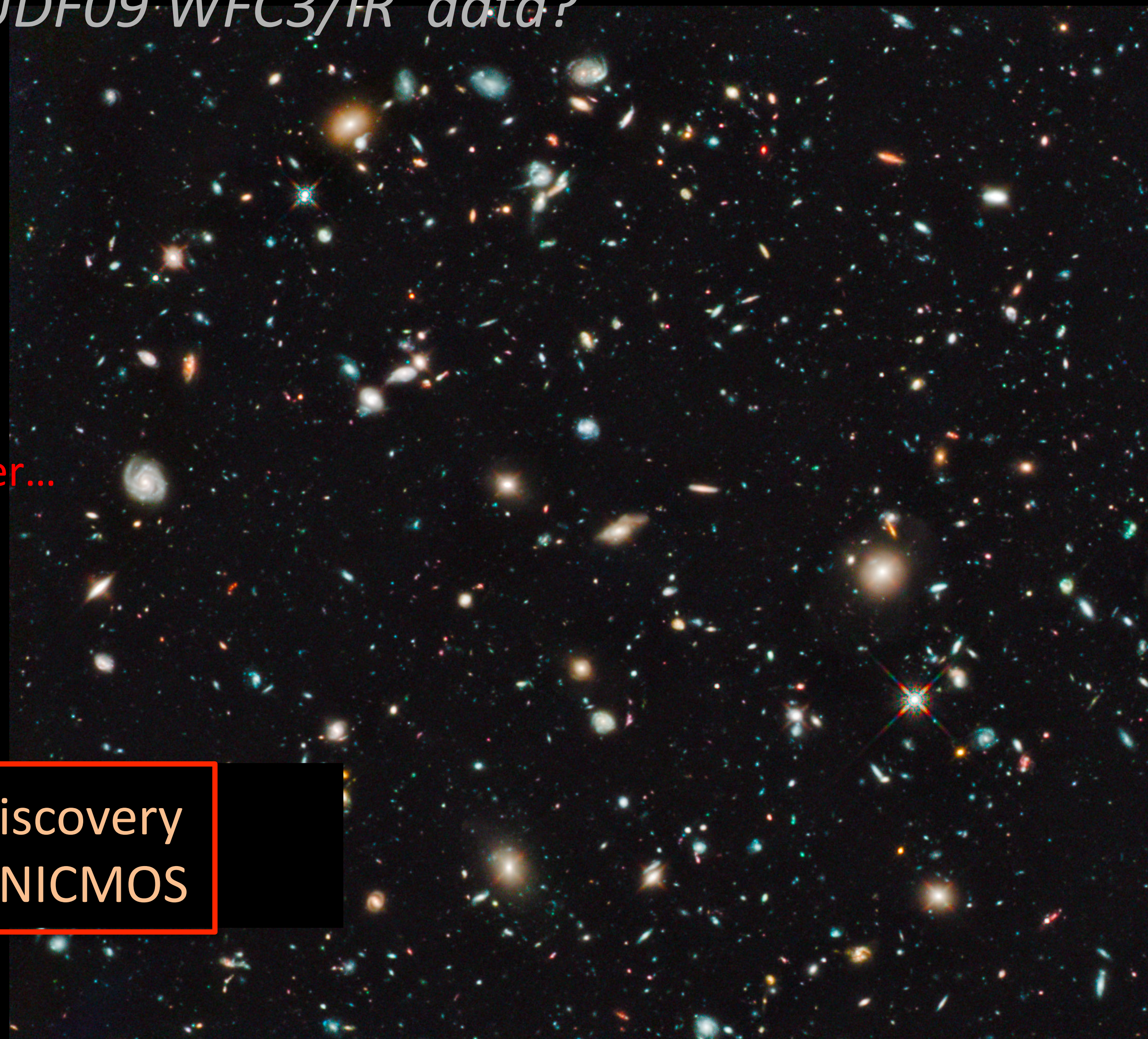
UV luminosity function

the new WFC3/IR camera

SM4
May 2009



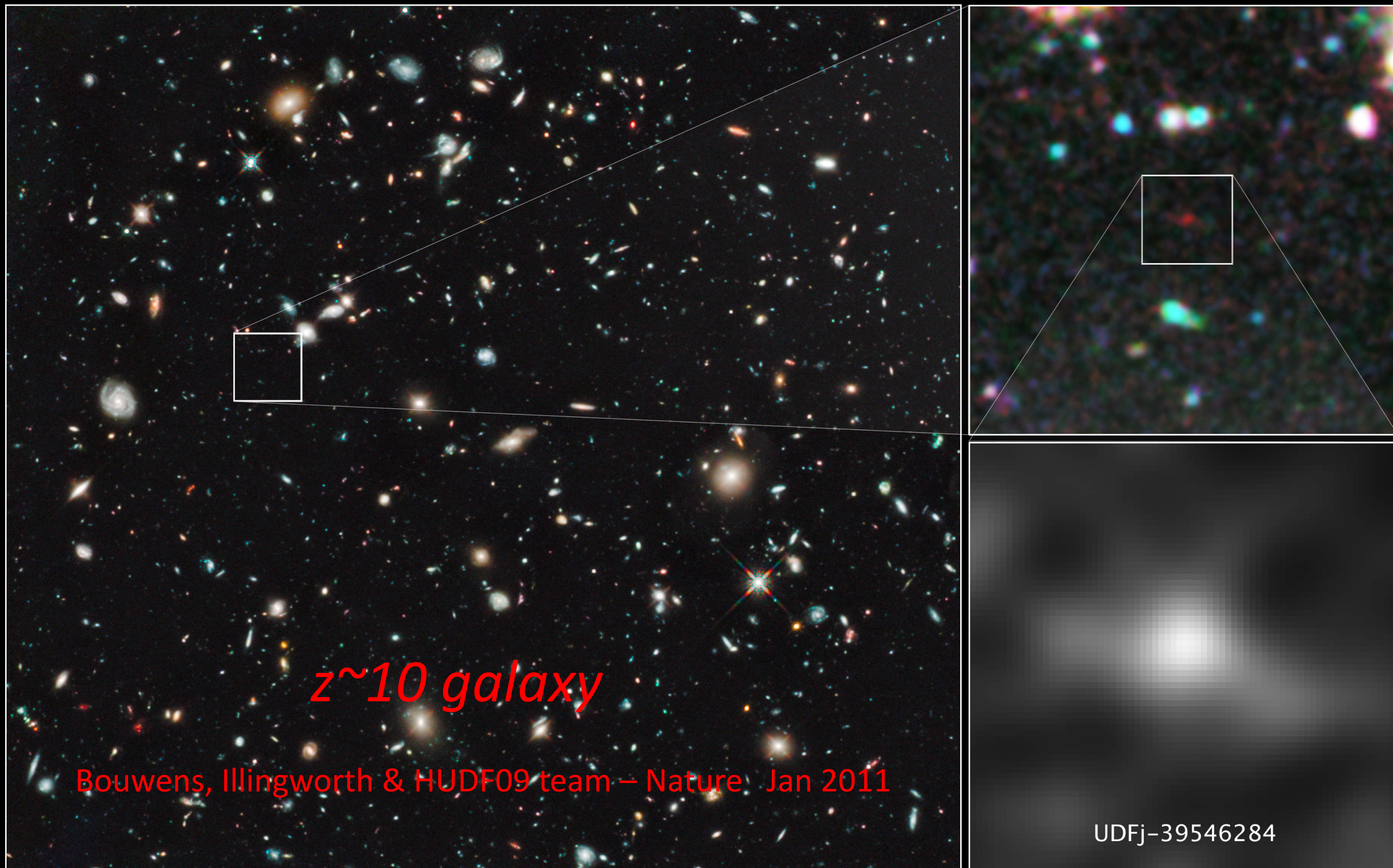
what have we learnt from the new HUDF09 WFC3/IR data?



29.9 AB mag 5σ!

deepest IR image ever…

WFC3/IR has a “discovery efficiency” ~40X NICMOS



Hubble Ultra Deep Field 2009-2010

Hubble Space Telescope • WFC3/IR

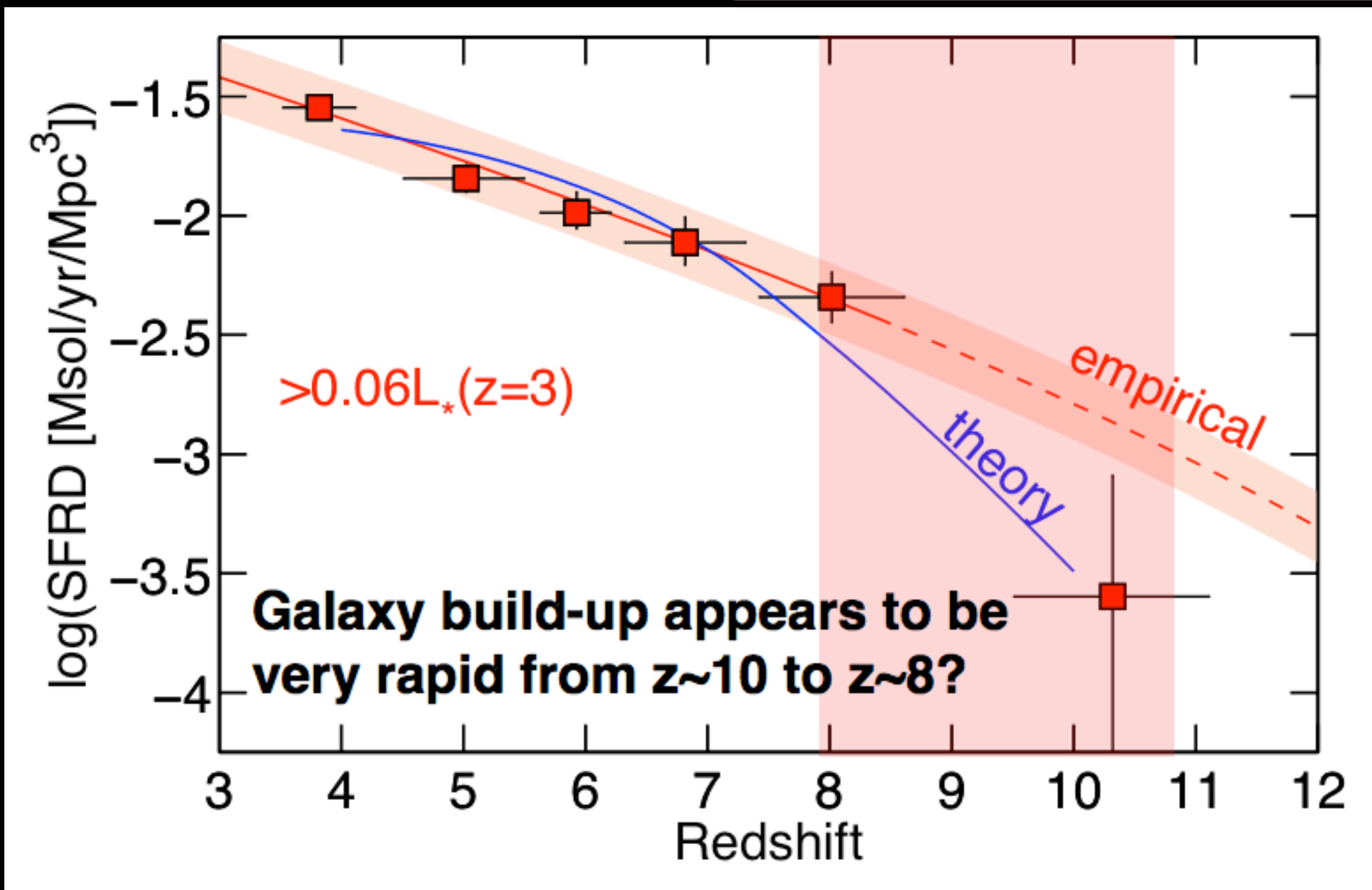
NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team

STScI-PRC11-05

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

is the global star formation rate changing rapidly from z~10 to z~8?

see Pascal's talk Wednesday



Oesch et al 2011

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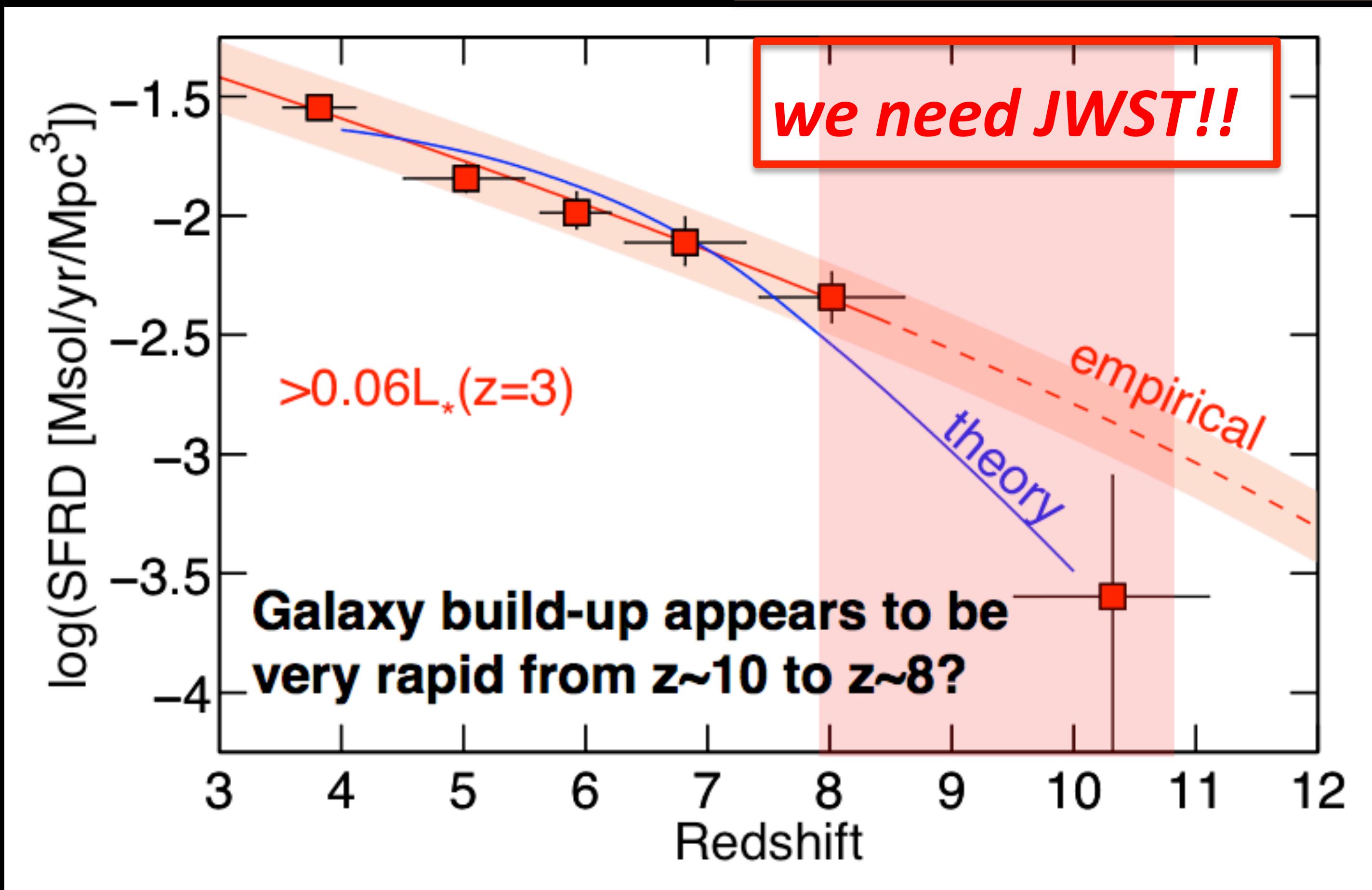
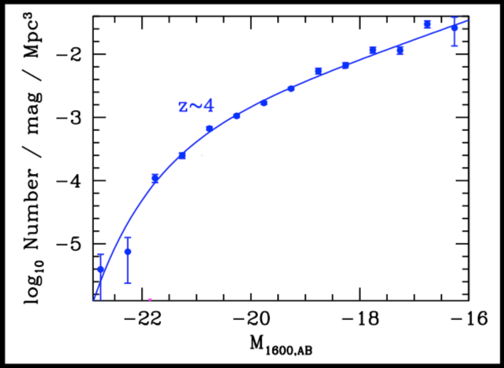


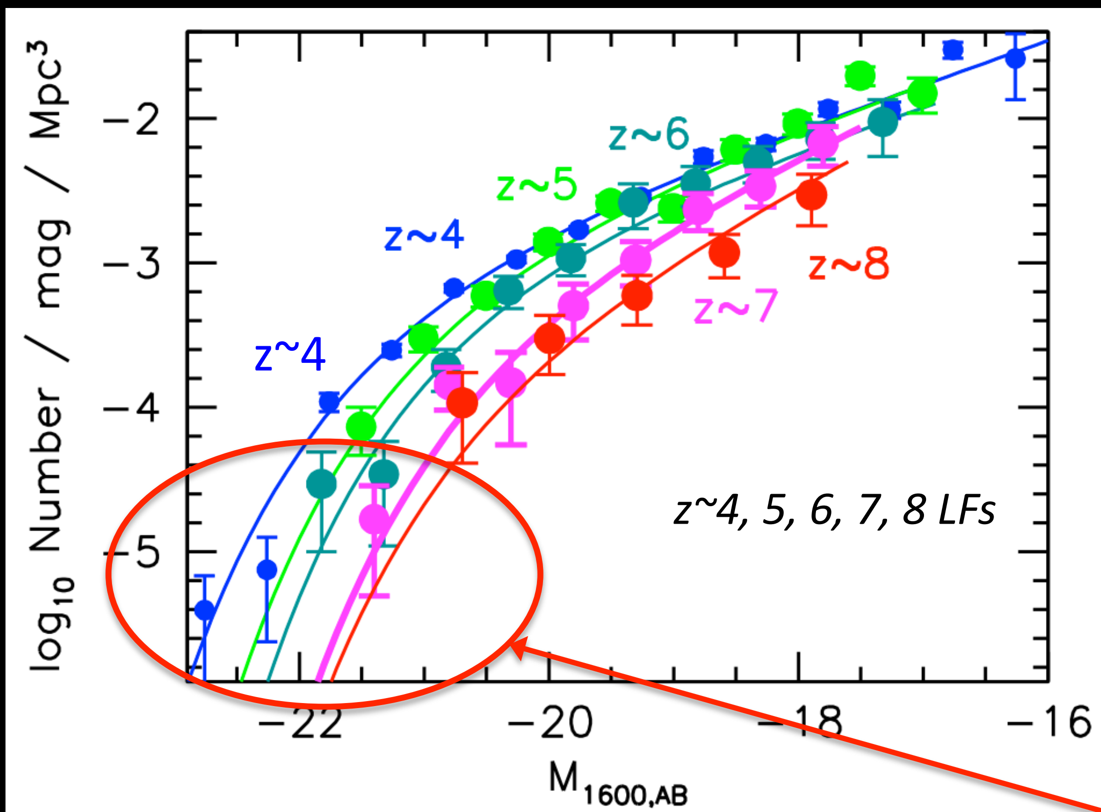
Oesch et al 2011

luminosity functions



key step in establishing properties of high redshift galaxies

luminosity functions
from all HUDF09, ERS and CANDELS data to 06/11



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

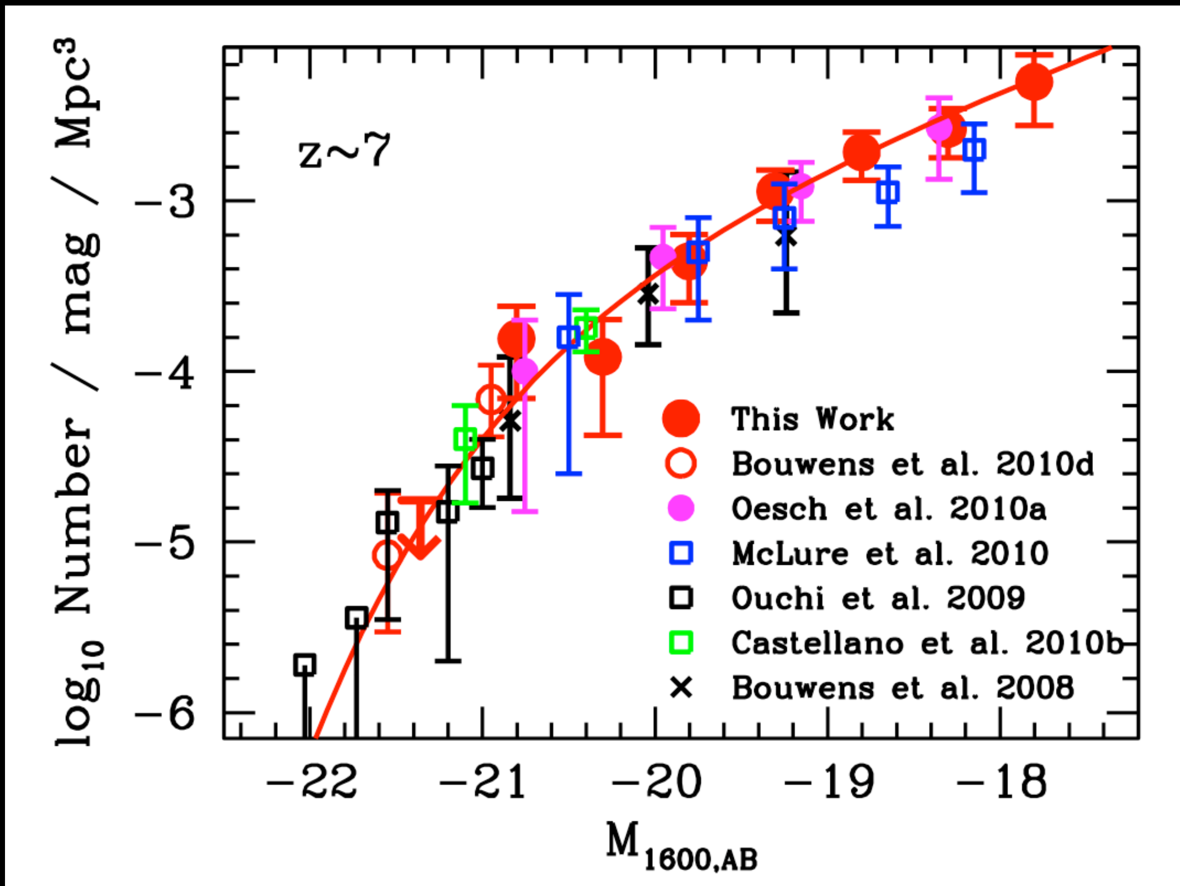
most of the integrated UV flux at high-redshift comes from sub-L* low luminosity galaxies

L* increases with time

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

Bouwens et al 2011b

luminosity functions – comparison



excellent agreement now between the several groups

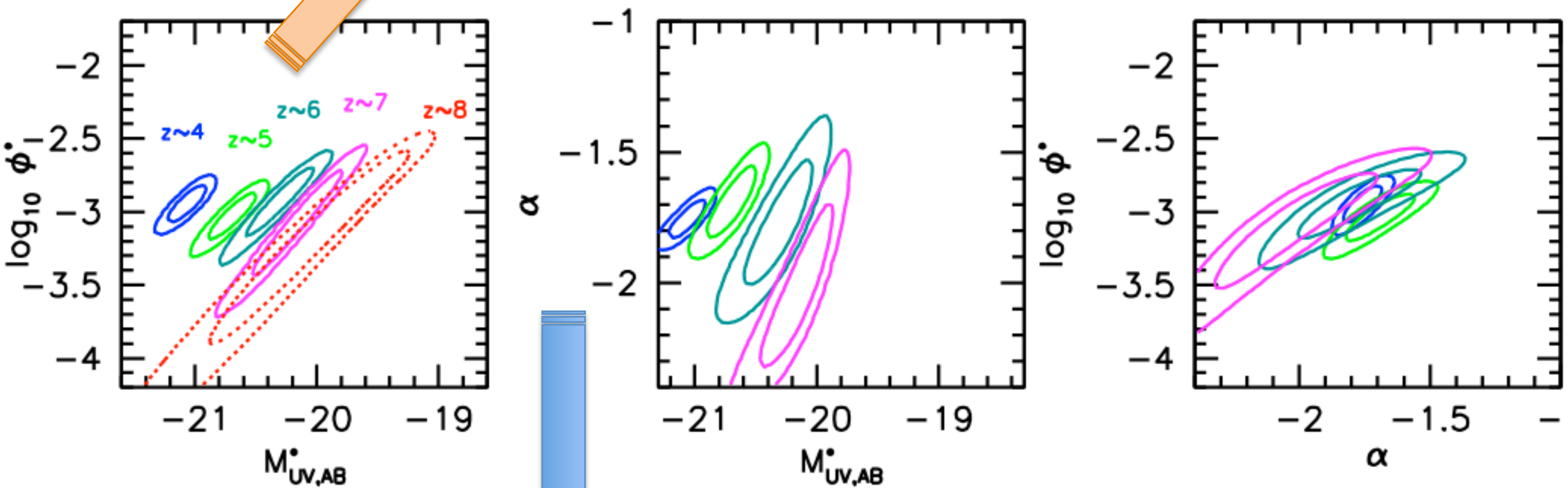
the very steep slope (α ~ -1.7) first seen at lower redshift persists to higher redshift

Bouwens et al 2011b

luminosity functions – implications

primary changes with time occur for bright (massive) galaxies

L* increases with time

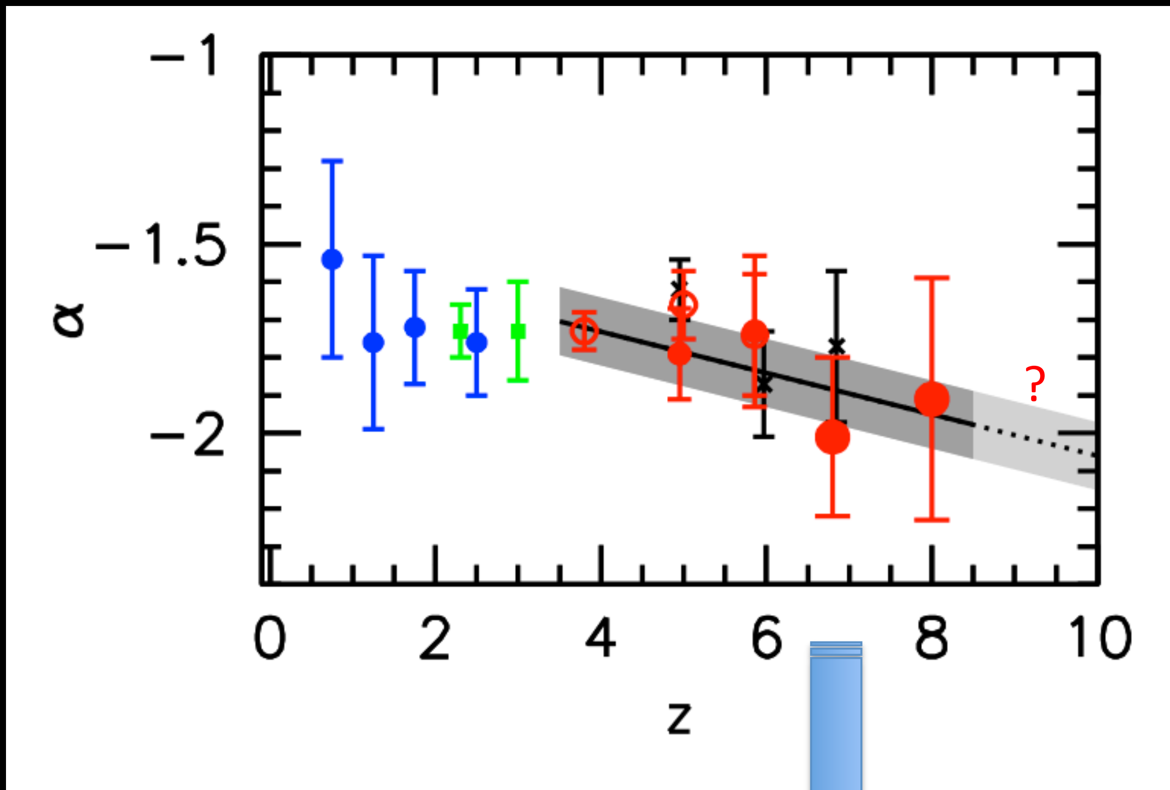


slope α is steep

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

Bouwens et al 2011b

luminosity functions – implications



(1) slope is very steep at z~7-8

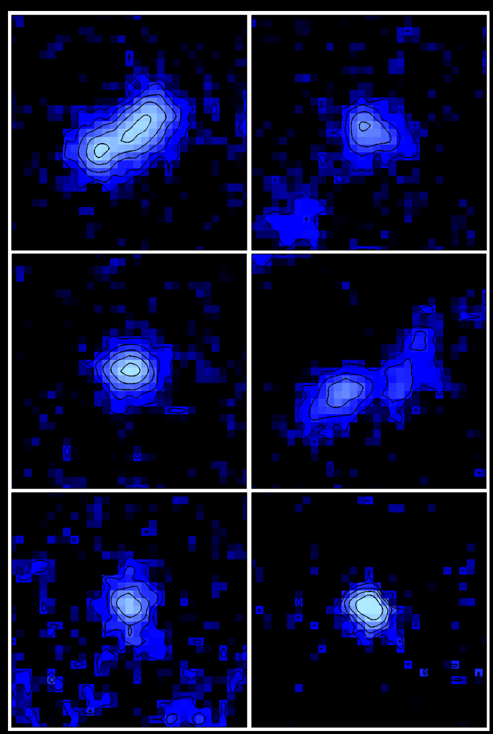
(2) weak evidence for trend to steeper slope at early times

steep slope important for reionization

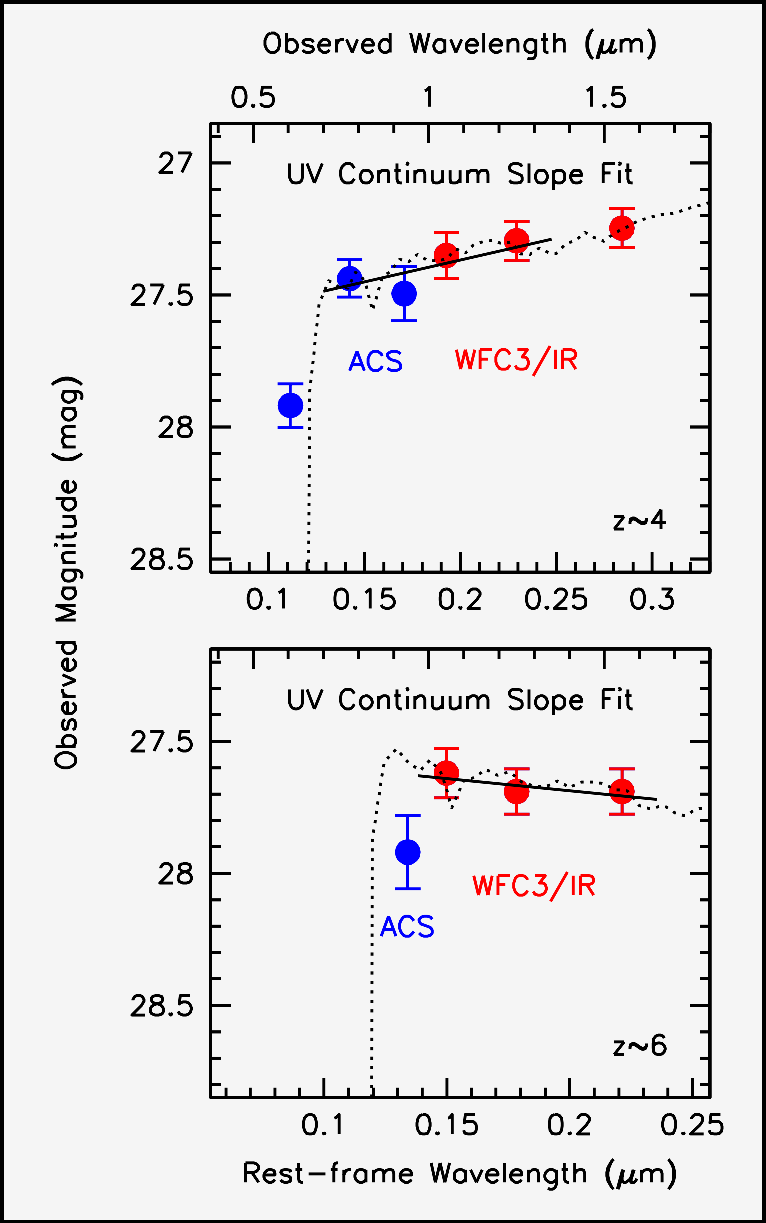
see Pascal's talk Wednesday

Bouwens et al 2011c

rest frame UV color:
a key diagnostic for high redshift galaxies



use UV slope β



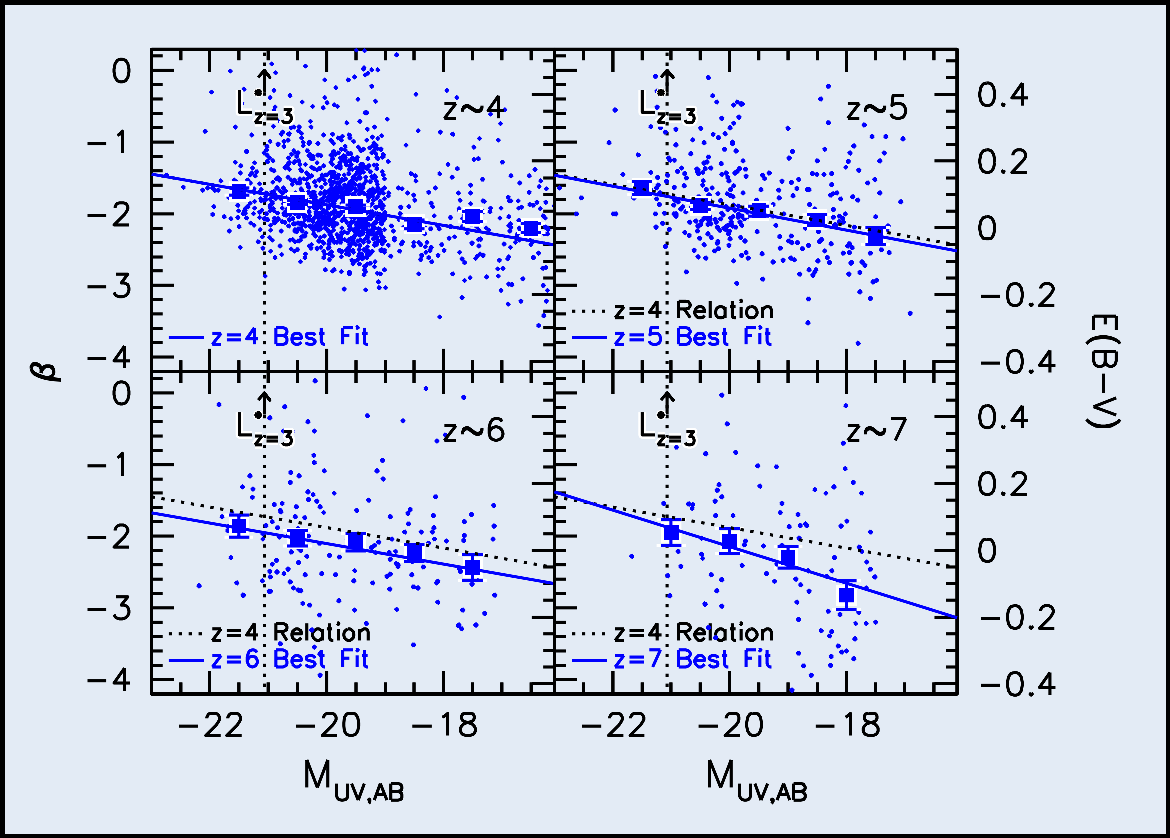
UV continuum slope

measure UV slope β excluding bands contaminated by Lyα and Balmer break

characterize as a function of luminosity and redshift

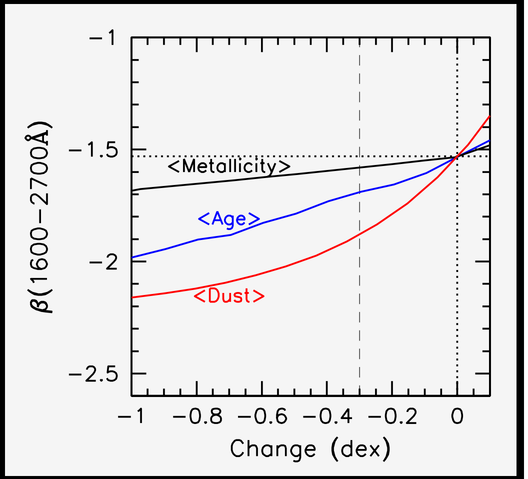
Bouwens et al 2011d

UV continuum slope results



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



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

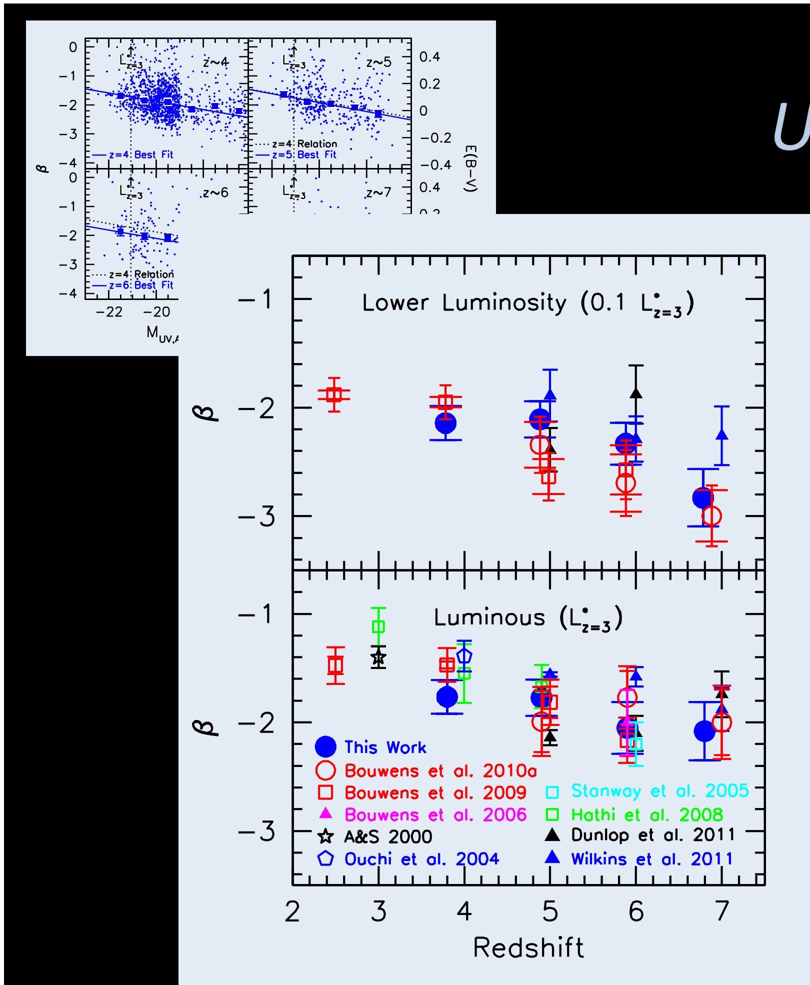
squares are bi-weight means

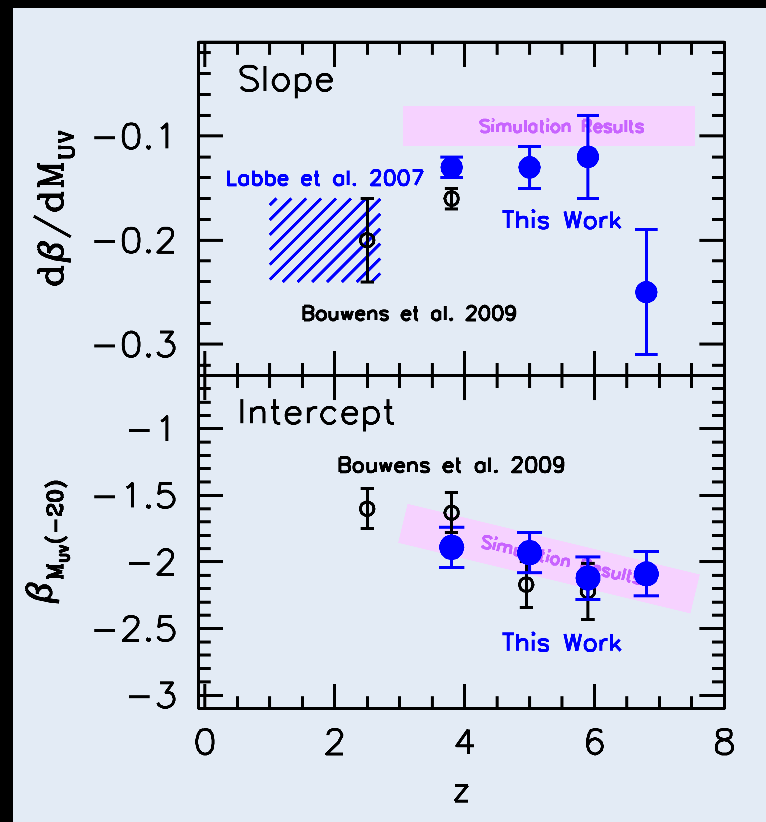
note trend with luminosity

Bouwens et al 2011d

UV continuum slope results

trends with redshift





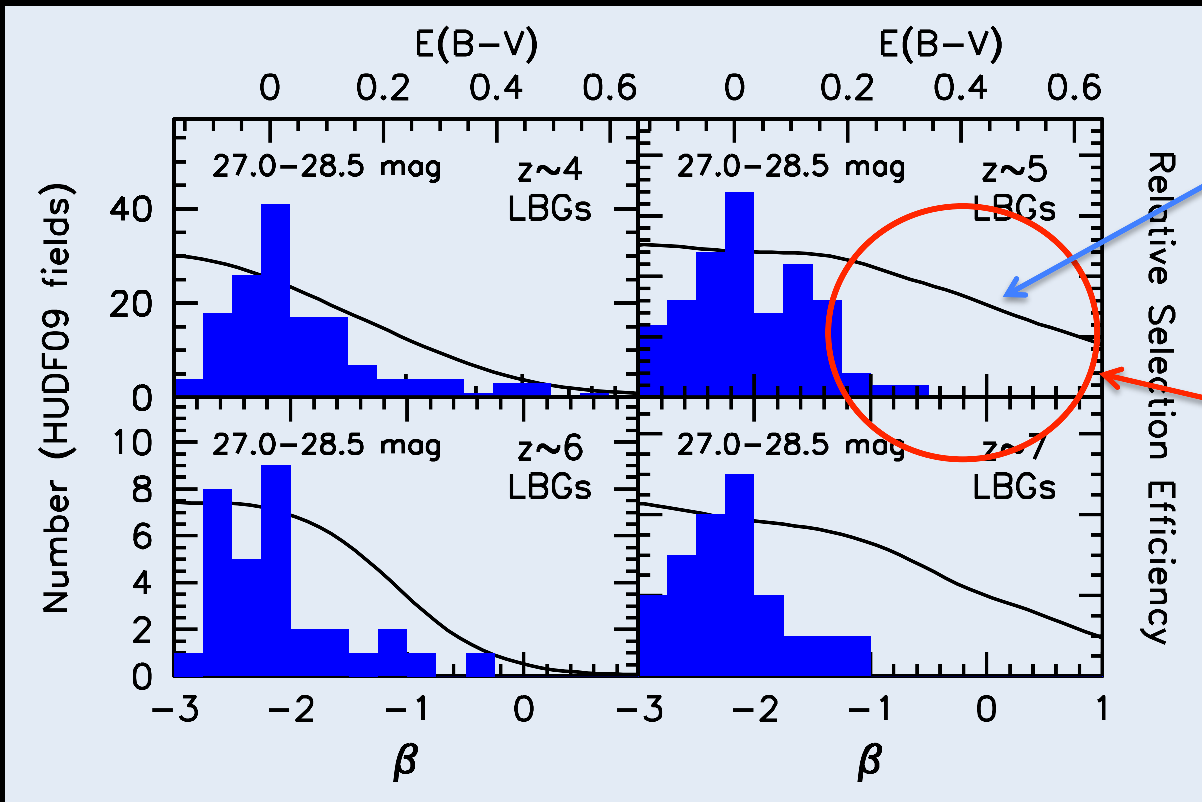
β still quite small at z~7
and low luminosity

simulations from work by Finlator, Dave and Oppenheimer

Bouwens et al 2011d

selection efficiency as a function of beta

biases are a serious concern



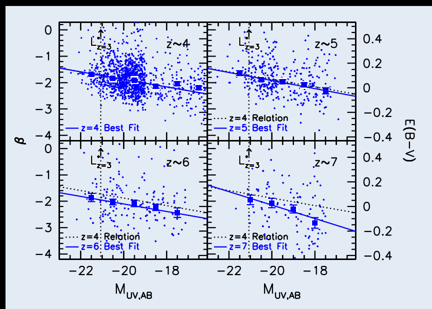
selection efficiency

"redder" sources not detected for ~0.2L* galaxies at z~4 – 7

redder slopes would be observable
(suggests that evolved galaxies are rare)

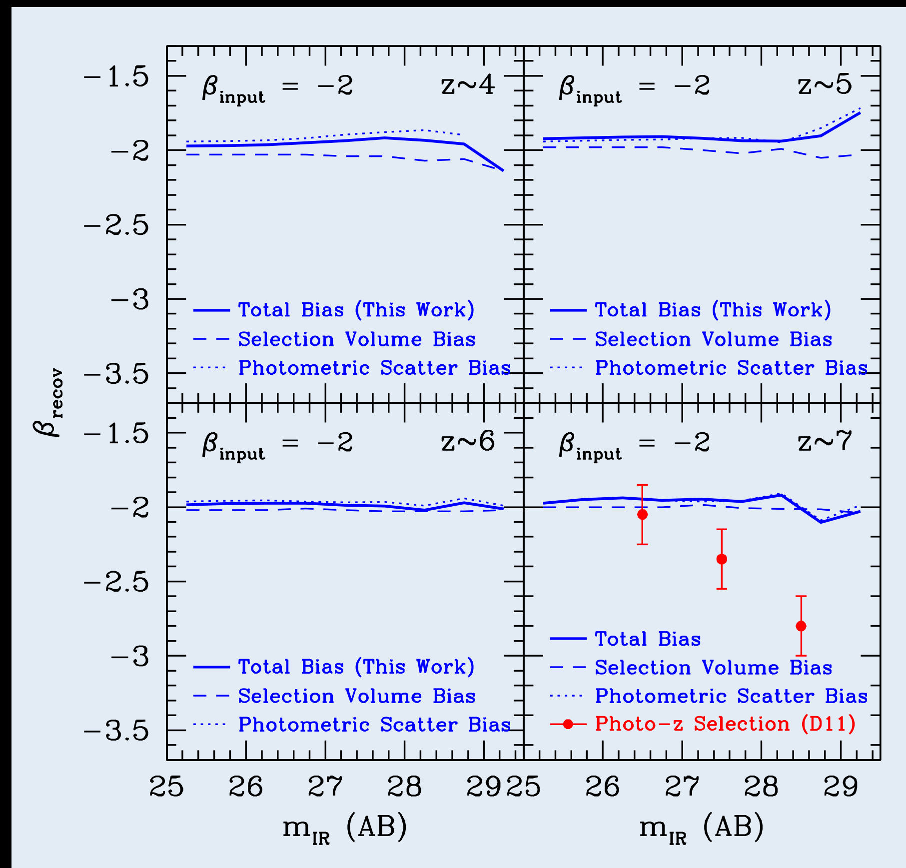
Bouwens et al 2011d;
(see also 2009 ApJ 705)

are the UV continuum slope results biased?



biases are a serious concern

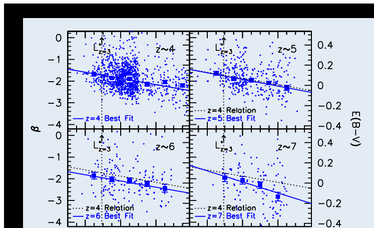
Dunlop et al 2011 showed significant biases from their simulations of their β measurements



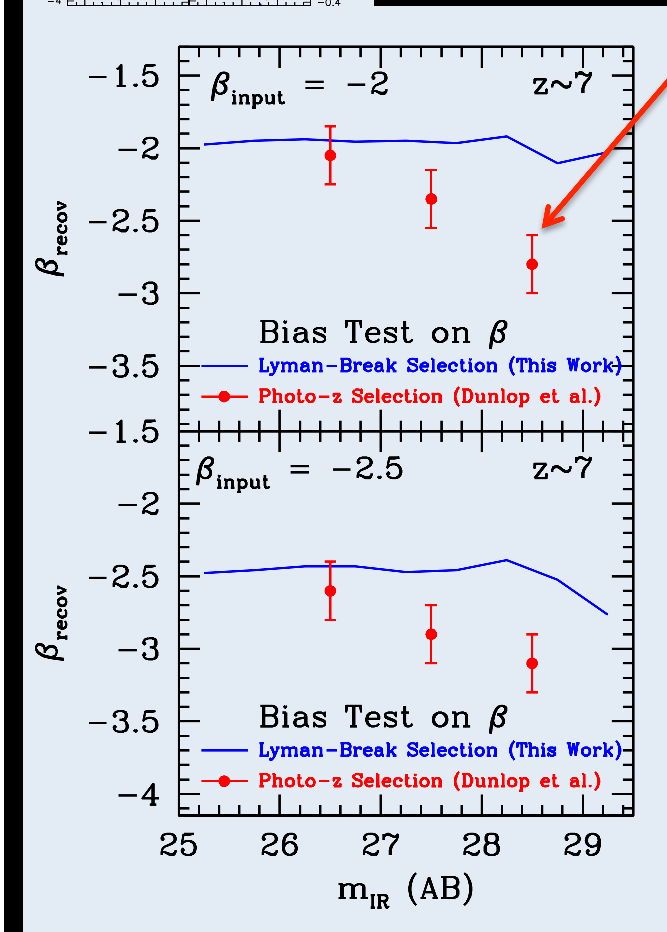
we carried out extensive simulations using real galaxies (10^5 galaxies!) with a variety of colors inserted into real datasets

our procedures have minimal bias

Bouwens et al 2011d

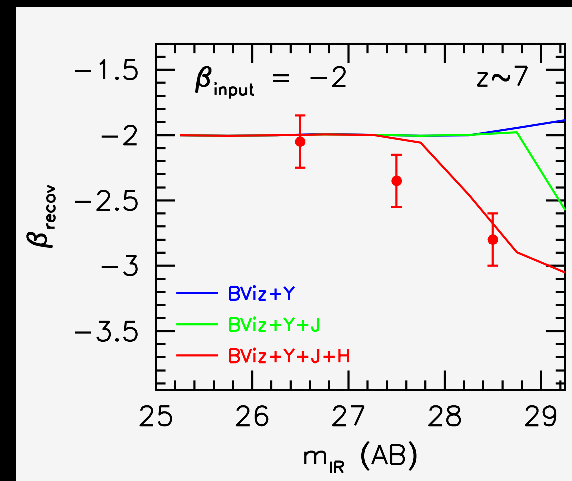


are the UV continuum slope results biased?



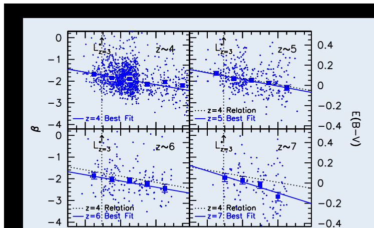
why does the Dunlop et al approach suffer such large biases?

we simulated the biases that would result by using Dunlop's photometric redshift selection technique and β measurement method



the primary reason is that the Dunlop et al bands used to measure β are also used to measure redshifts in their photometric redshift code – the coupling causes problems – our weighted Lyman-Break approach keeps the bands distinct

Bouwens et al 2011d



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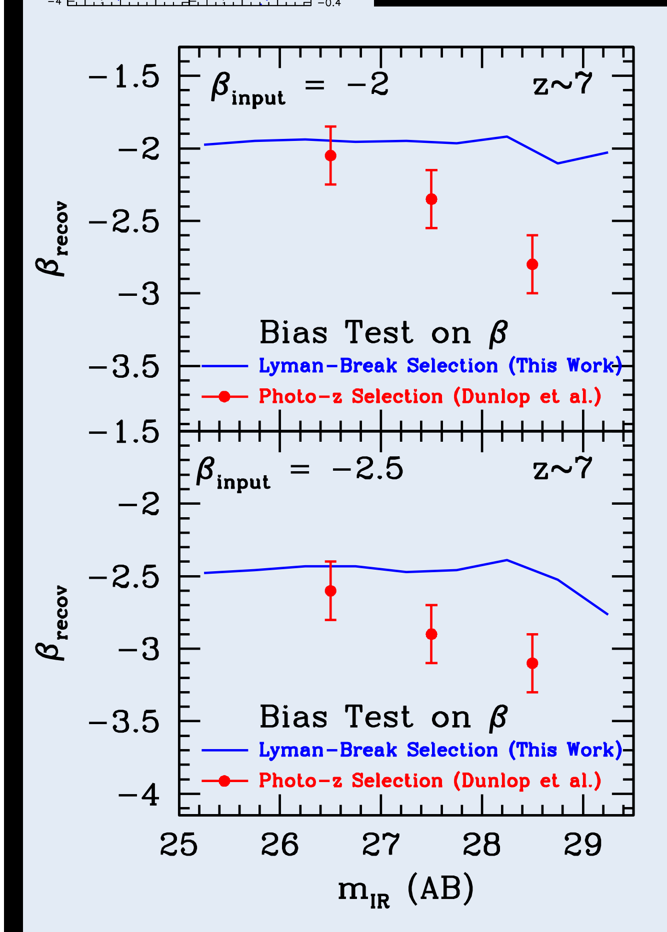
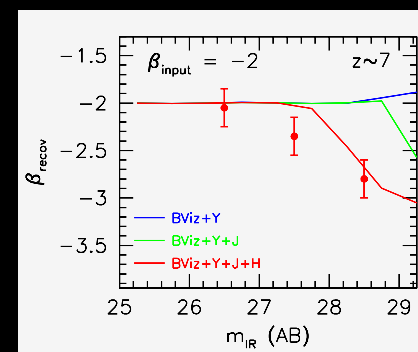


unfortunately in an attempt to compensate for this bias they throw out many galaxies that result in a small sample and also appear to do so in a way that limits their ability to detect a trend with luminosity



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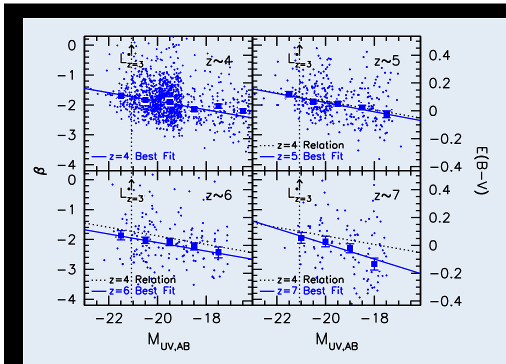
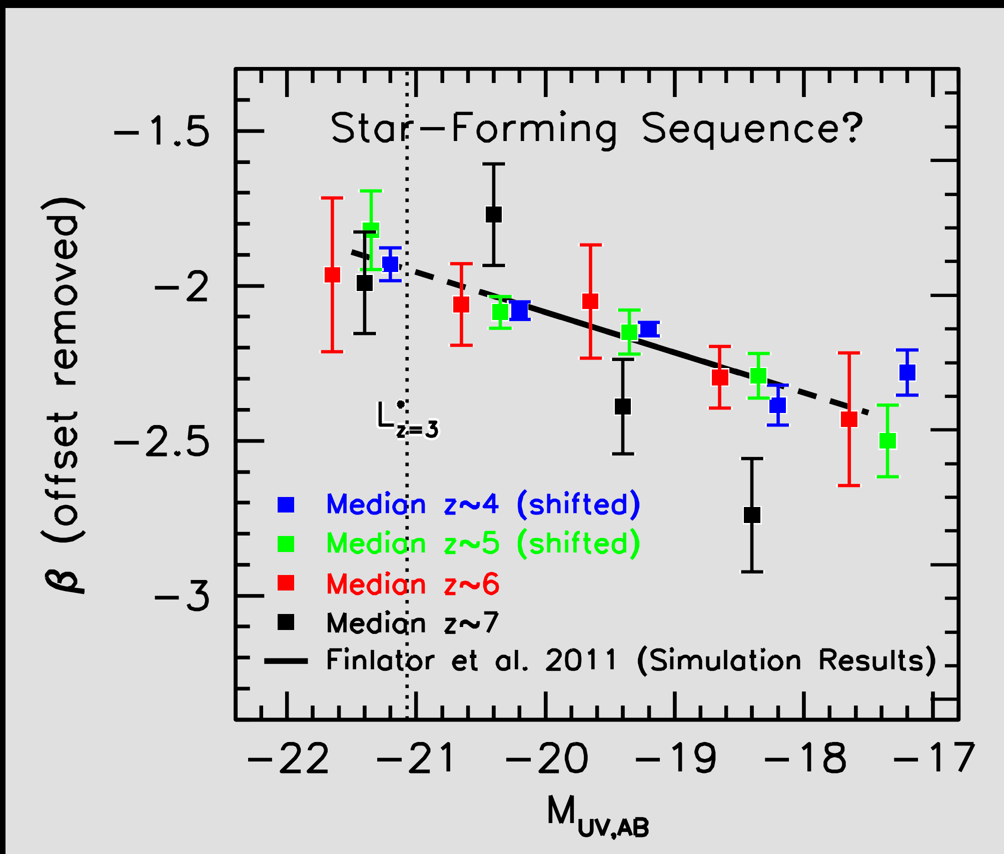
Bouwens et al 2011d



UV slope vs luminosity

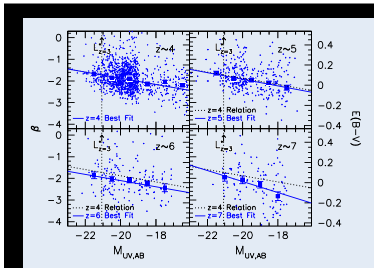
UV color-magnitude diagram



trend of color (β) with luminosity is largely redshift independent

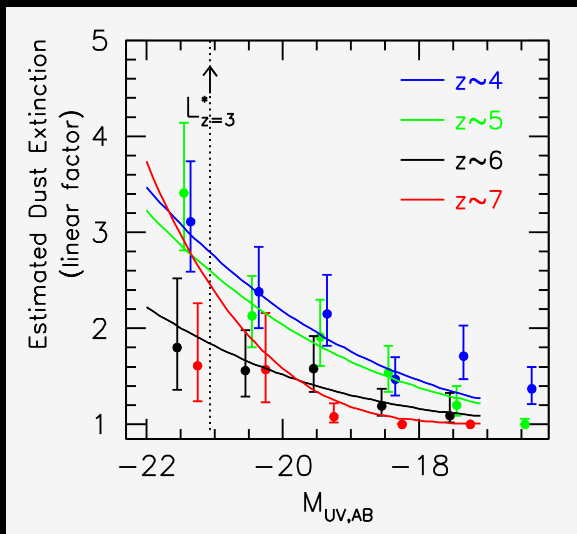
agreement with trends seen in recent simulations – e.g., Finlator et al…

Bouwens et al 2011d

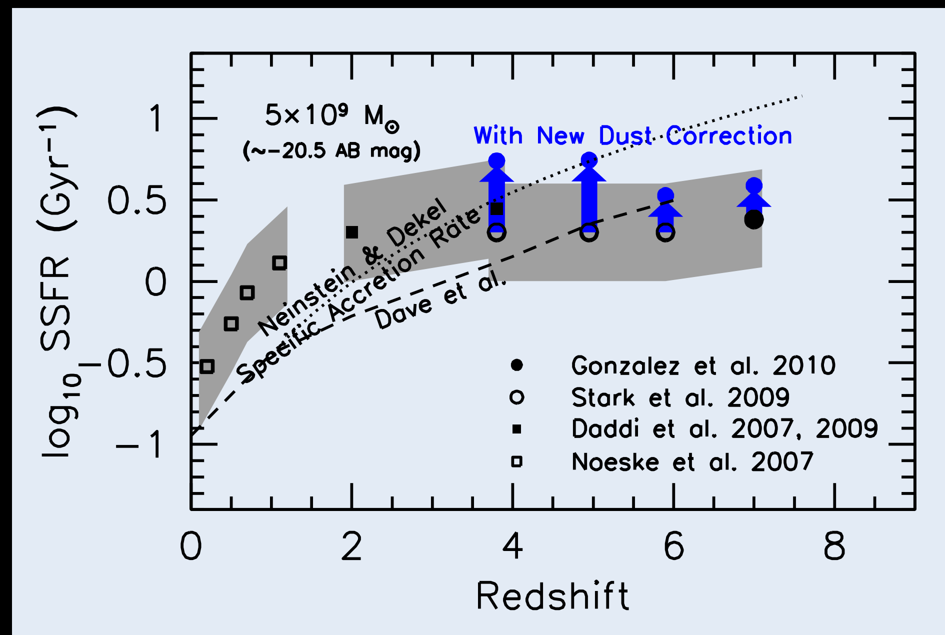


dust/extinction estimates

extinction larger for more luminous galaxies



dust corrections not included in prior estimates of SSFR – but clearly important

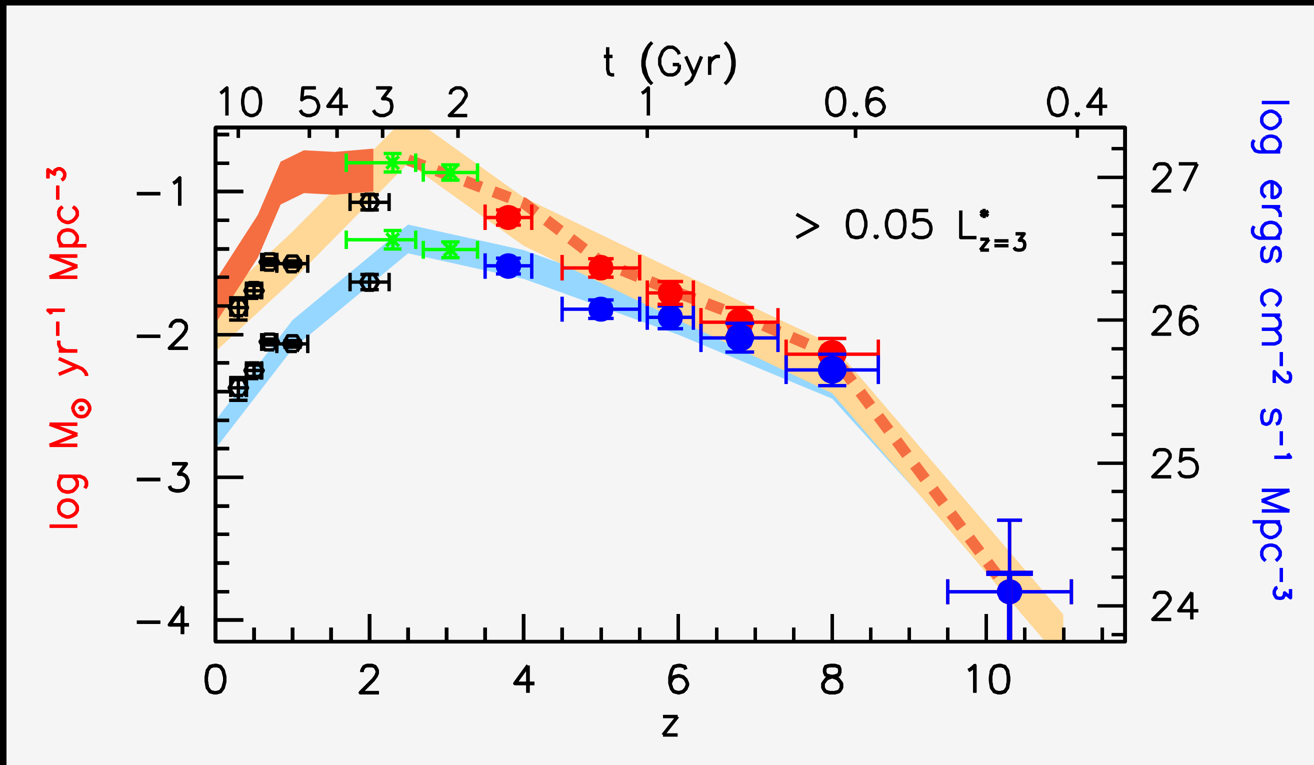


see Valentino's talk Wednesday

given difficulty of establishing SSFR, differences between z~6-7 and z~4-5 are well within uncertainty

Bouwens et al 2011d

luminosity density and SFR density vs redshift



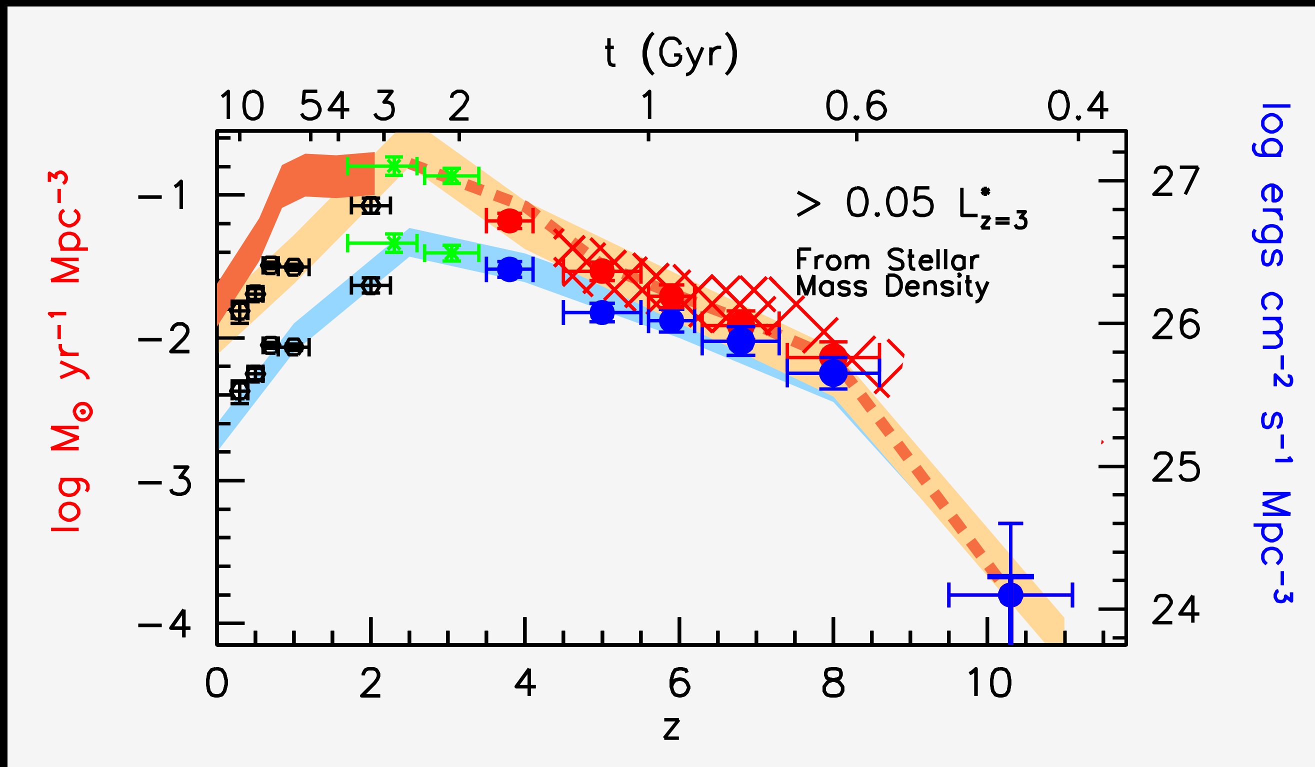
revised to account for slightly larger dust estimates in more luminous galaxies

dark orange line includes ULIRGS and similar very luminous galaxies

Bouwens et al 2011d

luminosity density and SFR density vs redshift

compared with SFR(z) from mass estimates



revised to account for slightly larger dust estimates in more luminous galaxies

dark orange line includes ULIRGS and similar very luminous galaxies

Bouwens et al 2011d

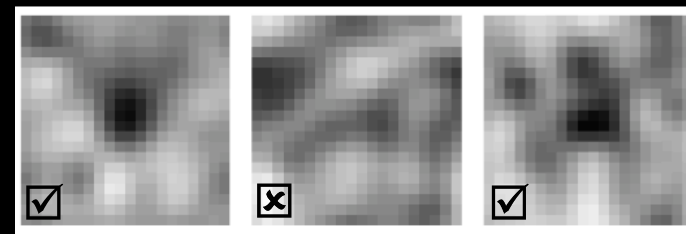
mass functions and mass densities

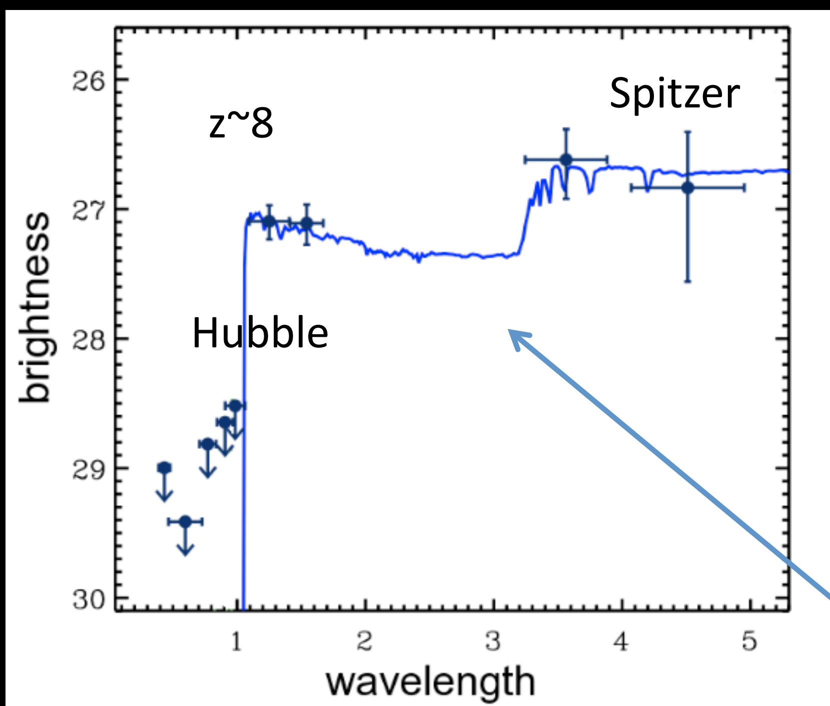
Spitzer + HST is a powerful combination

galaxies at z~8 from Spitzer IRAC

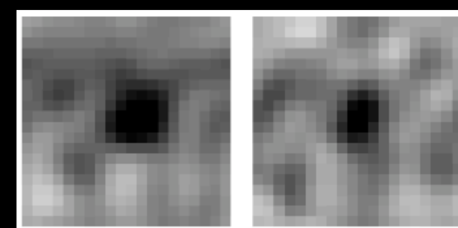
WFC3/IR Hubble and Spitzer results also combine to show us that z~8 galaxies could well have been forming stars two-three hundred million years earlier (at z>10-11)

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

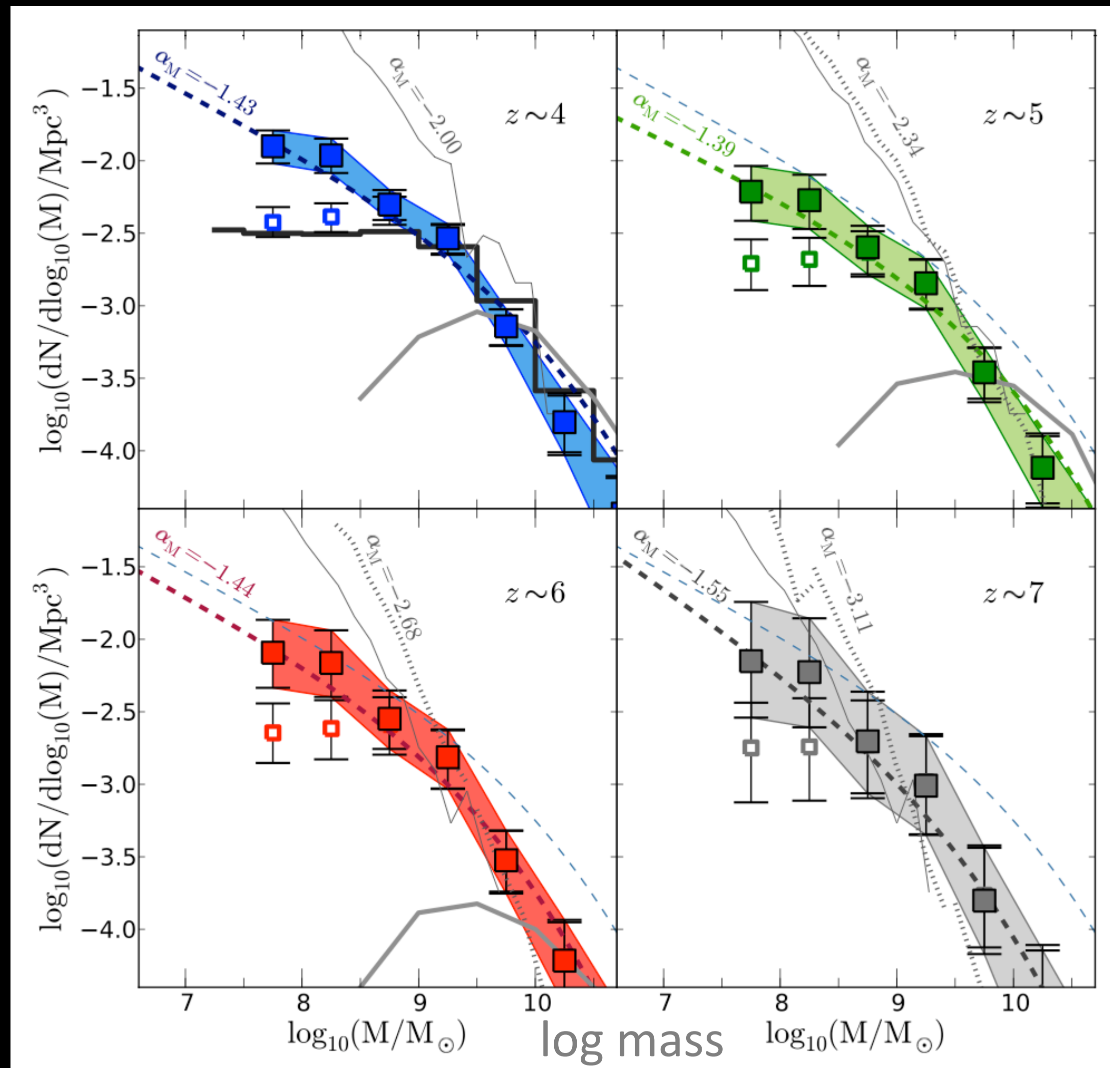
Model fit is BC03 CSF (?) $0.2Z_{\odot}$ log M = 9.3
z~7.7 and 300 Myr (SFH weighted age = t/2)

Spitzer + HST is a powerful combination

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

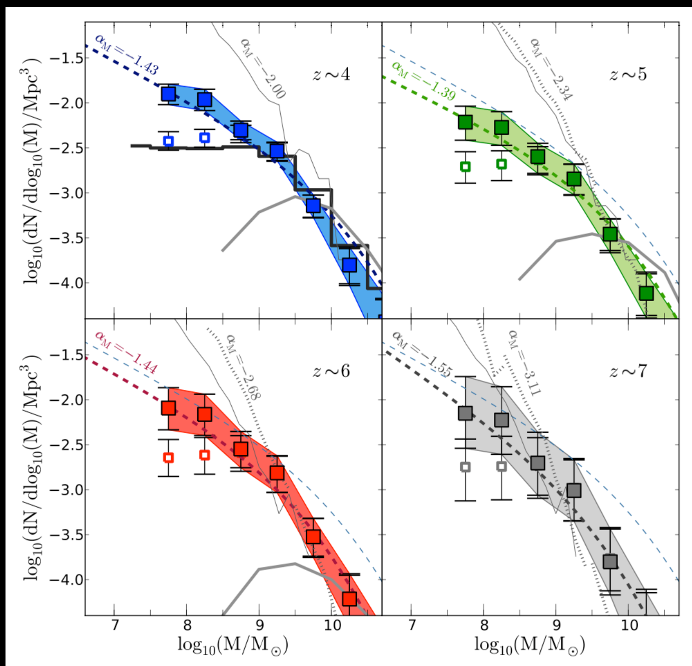
the completeness-corrected mass functions are steep

Gonzalez et al 2011a

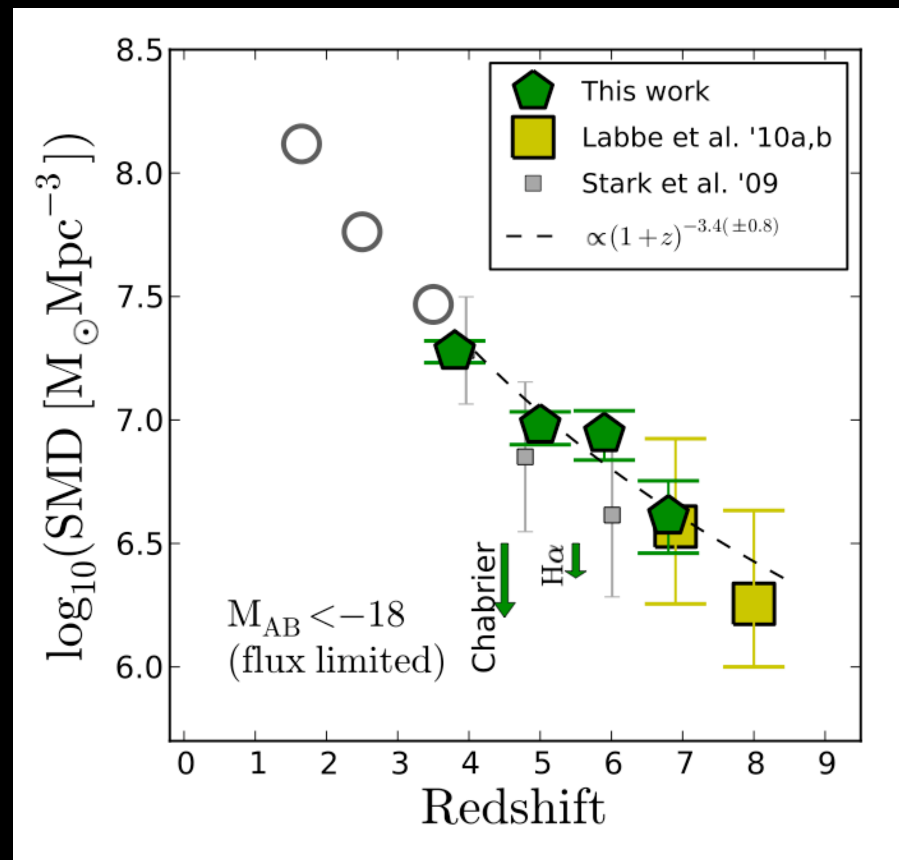


even completeness corrected results do *not* match models (Finlator; Choi & Nagamine)

mass densities at high redshift from the mass functions



Gonzalez et al 2011a



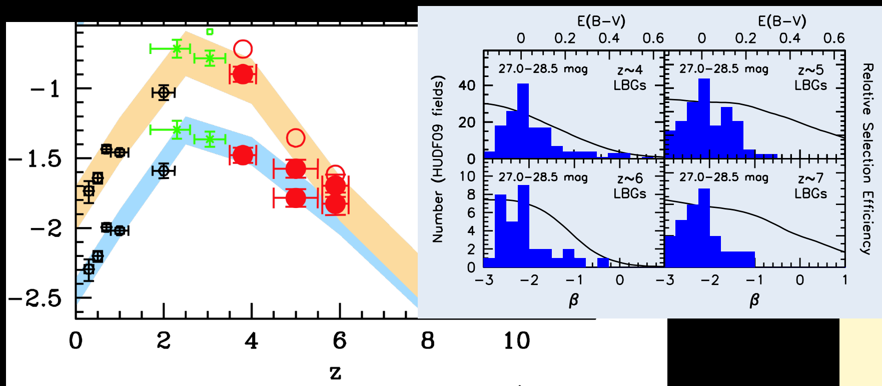
see Valentino's talk Wednesday

are our samples of star-forming galaxies representative of most of the mass?

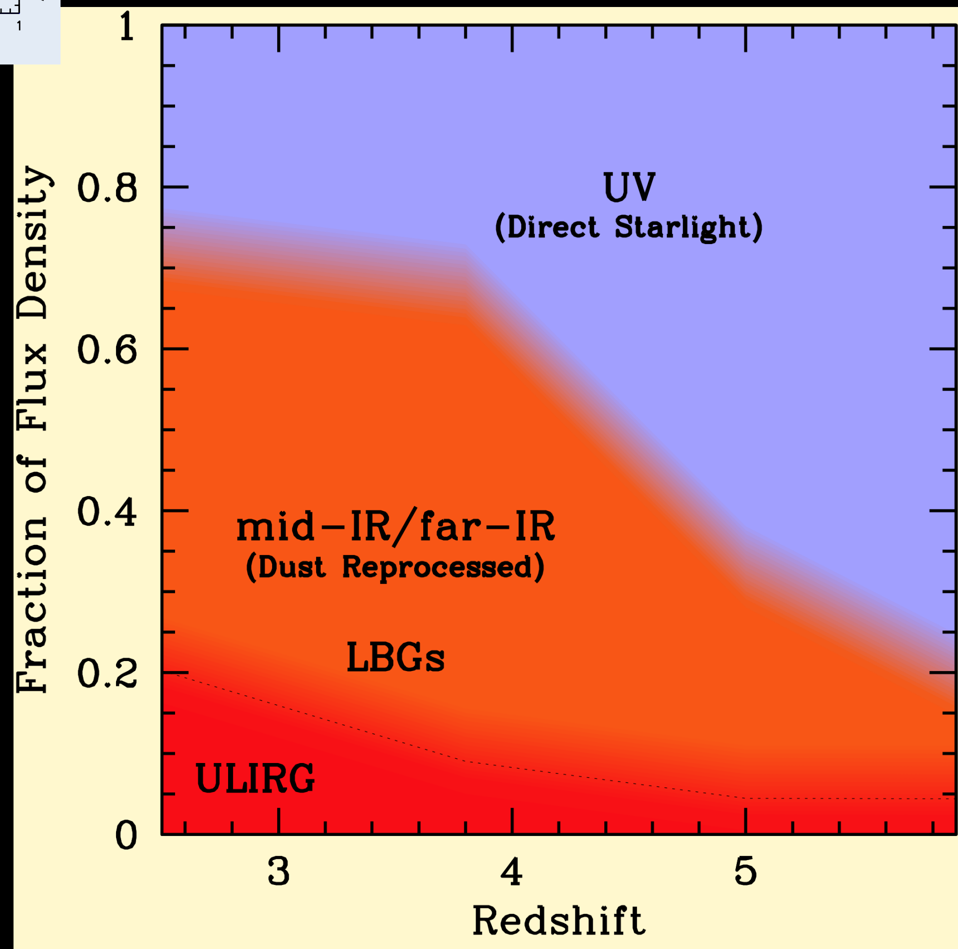
do evolved galaxies contribute significantly at z>4?

flux density in UV & IR

for star forming galaxies!...



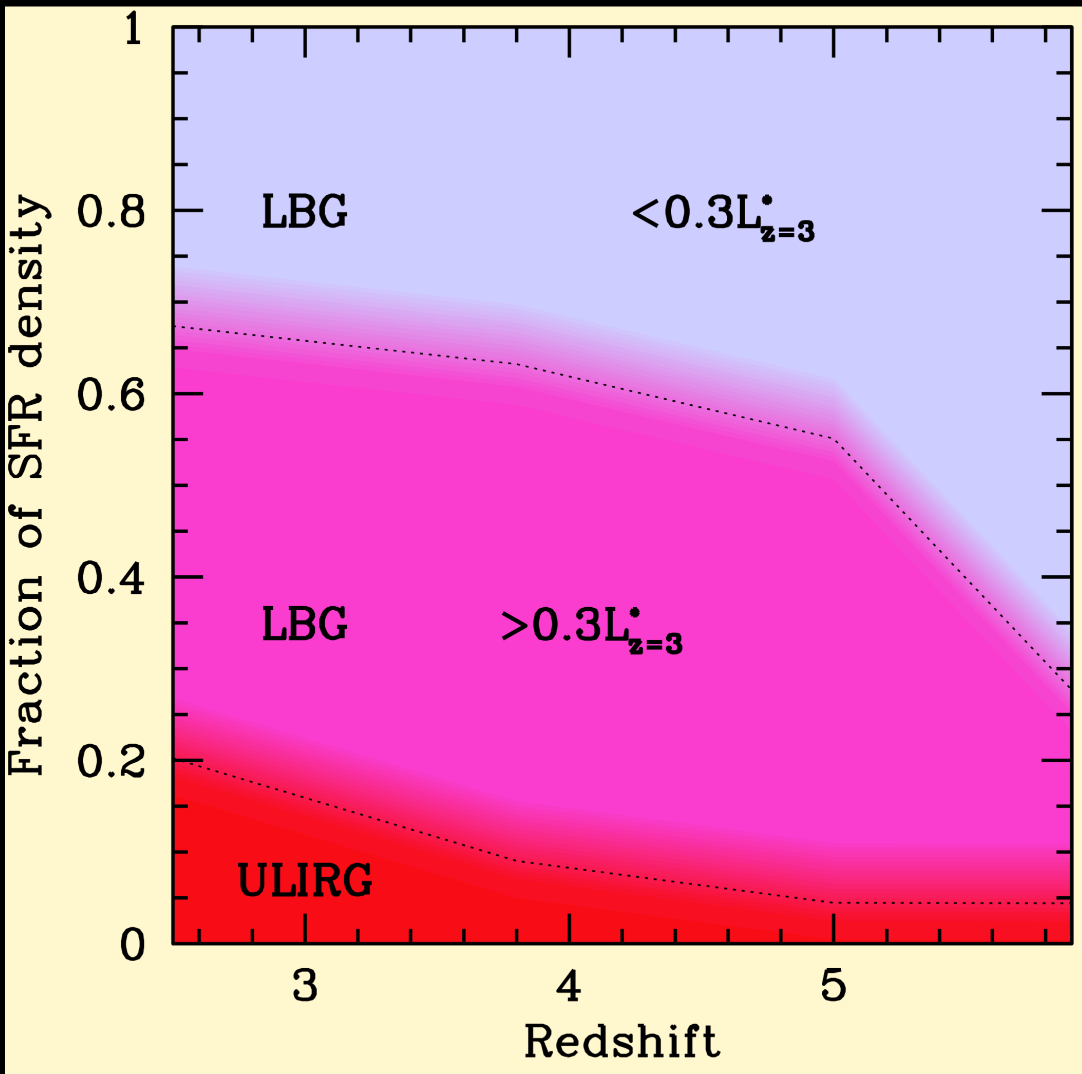
>80% of energy output in UV & IR at high redshift from star-forming galaxies can be derived from UV detected sources at z>4



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

Bouwens et al 2009

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



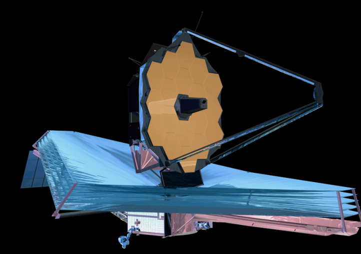
Herschel doesn't appear to indicate any major changes for z>4

Faint LBGs

Bouwens et al 2009

Luminous LBGs

ULIRGs/SMGs



Hubble and JWST…

tough to extend results at z>8 with HST

it is getting very hard to make large improvements with Hubble at z ~8-10 – and will not be possible at z >~10

new Ellis WFC3/IR 128 orbit program on HUDF

our simulations show that it can:

(a) improve high-z beta measurements by ~√2
(b) get ~1 extra z~10 candidate and 1-2 z~9 candidates
(c) improve faint-end slope of the LF at z~7 by ~30%
(d) help confirm highest redshift candidates

its getting tough – to do better with Hubble requires HUDF-like numbers of orbits with ACS and WFC3 *it is getting very hard to make large improvements with Hubble at z ~8-10 – and will not be possible at z >~10*

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its getting tough – to do better with Hubble requires HUDF-like numbers of orbits with ACS and WFC3

we need JWST!

JWST resolution and sensitivity will make a huge difference

(z~1)

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

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

Hubble is doing well at z~7 and at z~8 but
Hubble is approaching its limit at z~10-11

JWST is crucial if we are to explore and understand the fascinating buildup of the earliest galaxies at z~15 to z~8

the time before z~8 (~600 Myr) is JWST time!

SUMMARY

what these new observations tell us

Hubble's new Wide Field Infra-Red Camera (WFC3/IR) has revealed galaxies 13 billion years ago (at redshifts z~7 and z~8), at 600-800 million years, plus a likely z~10 galaxy and limits at z~10 (at 480 Myr)

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 at highest redshift - 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 (change in SFR from z~10 to z~8)

these galaxies fall in the heart of the "reionization" epoch, but our estimates remain uncertain for the contribution of galaxies to reionization: the steep LF slopes suggest that faint galaxies could have reionized the universe!!

z~10 is just possible with Hubble but JWST is really needed for the first 600 Myr