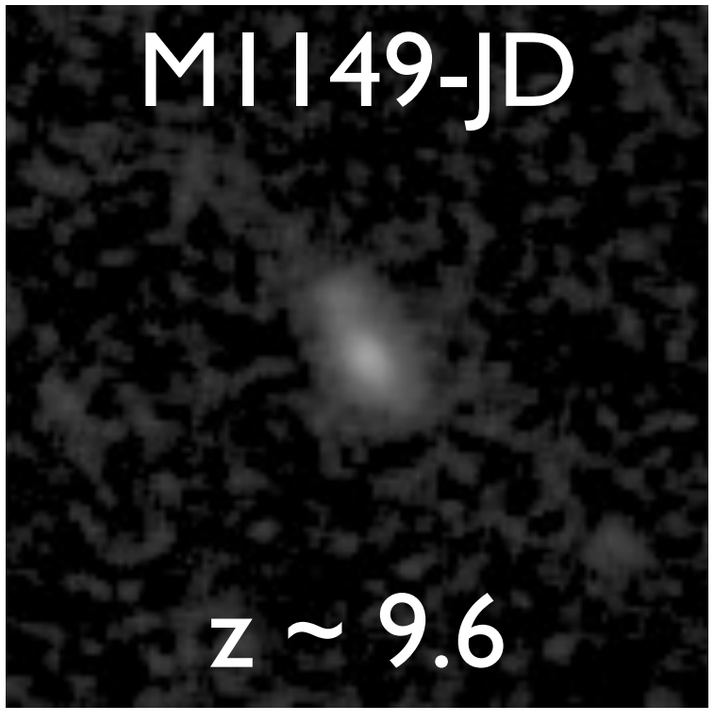
Observations of High-Redshift Galaxies



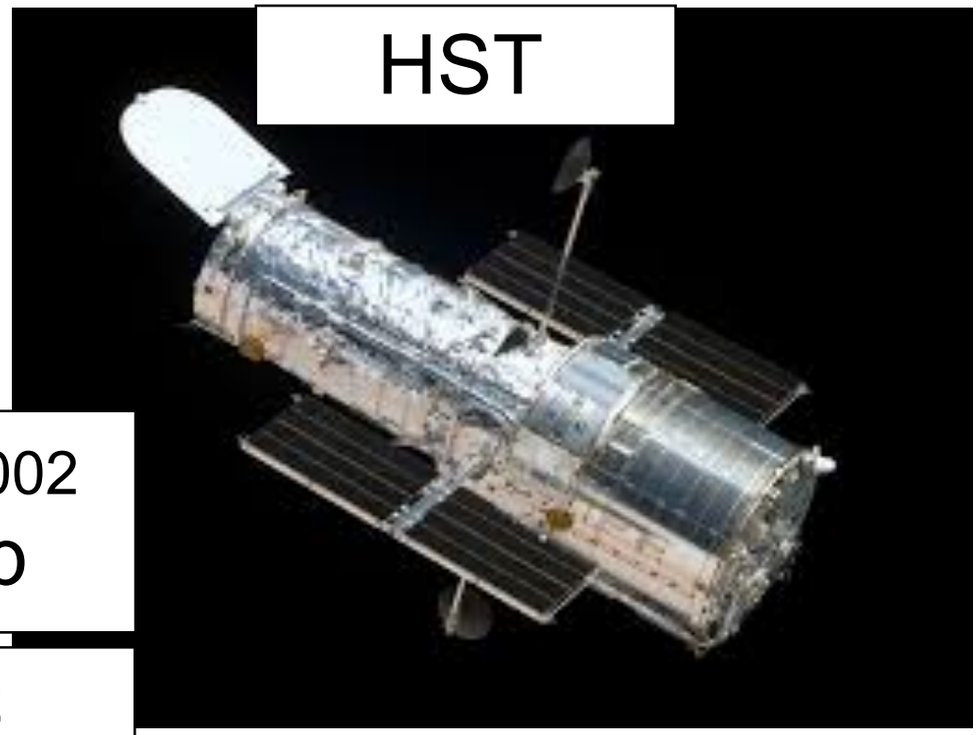
1.6 micron / 24 orbits /
~50σ

Rychard Bouwens
Leiden University

March 16, 2015
Sintra, Portugal: "Back At the Edge of the Universe"
"Latest Results from the Deepest Astronomical Surveys"

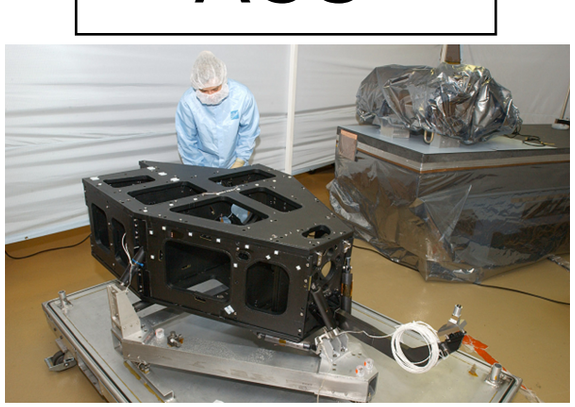
History and Legacy: “Edge of the Universe” Meetings in Sintra

HST



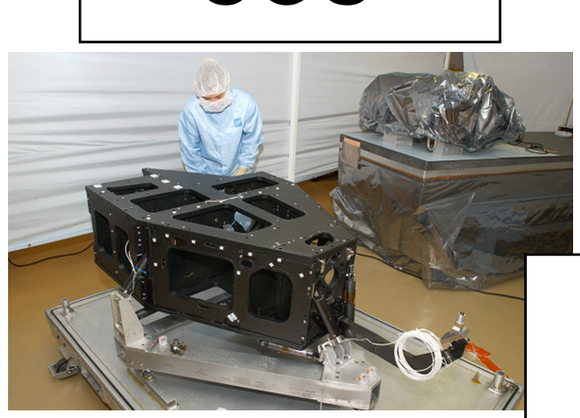
March 2002
SM3b

ACS

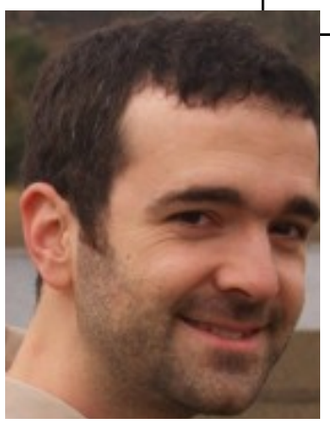


May 2009
SM4

WFC3 + COS



At the Edge of the Universe:
October 2006



Back At the Ed
the Universe
April 2015

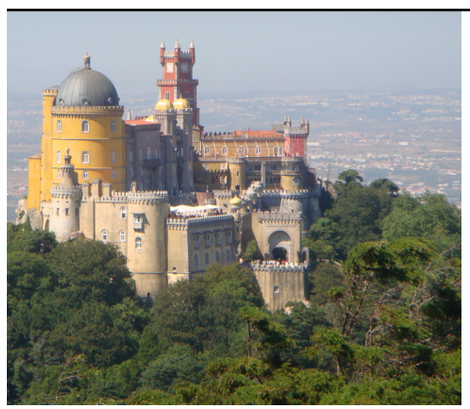
History and Legacy: "Edge of the Universe" Meetings in Sintra

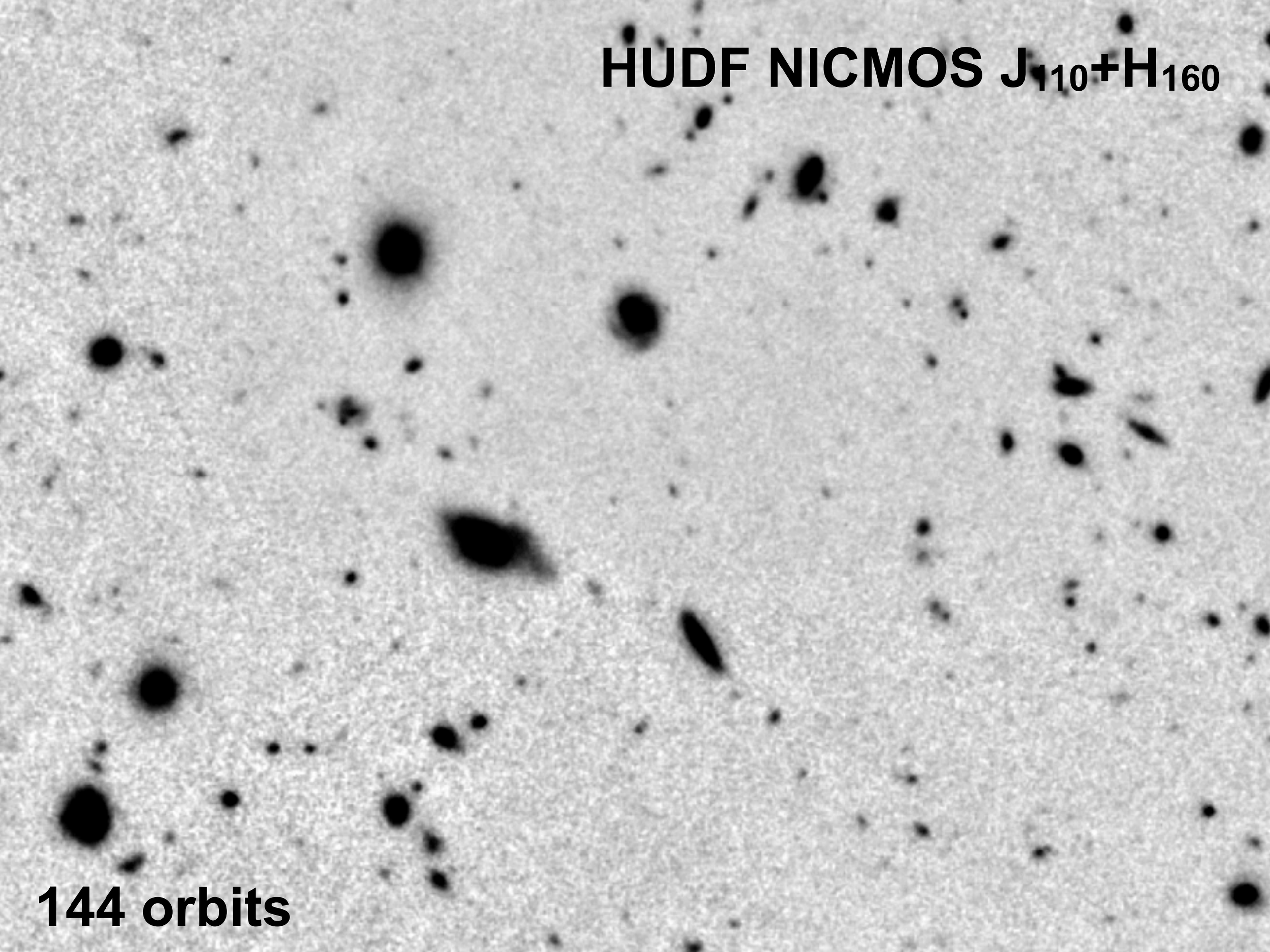
May 2009
SM4

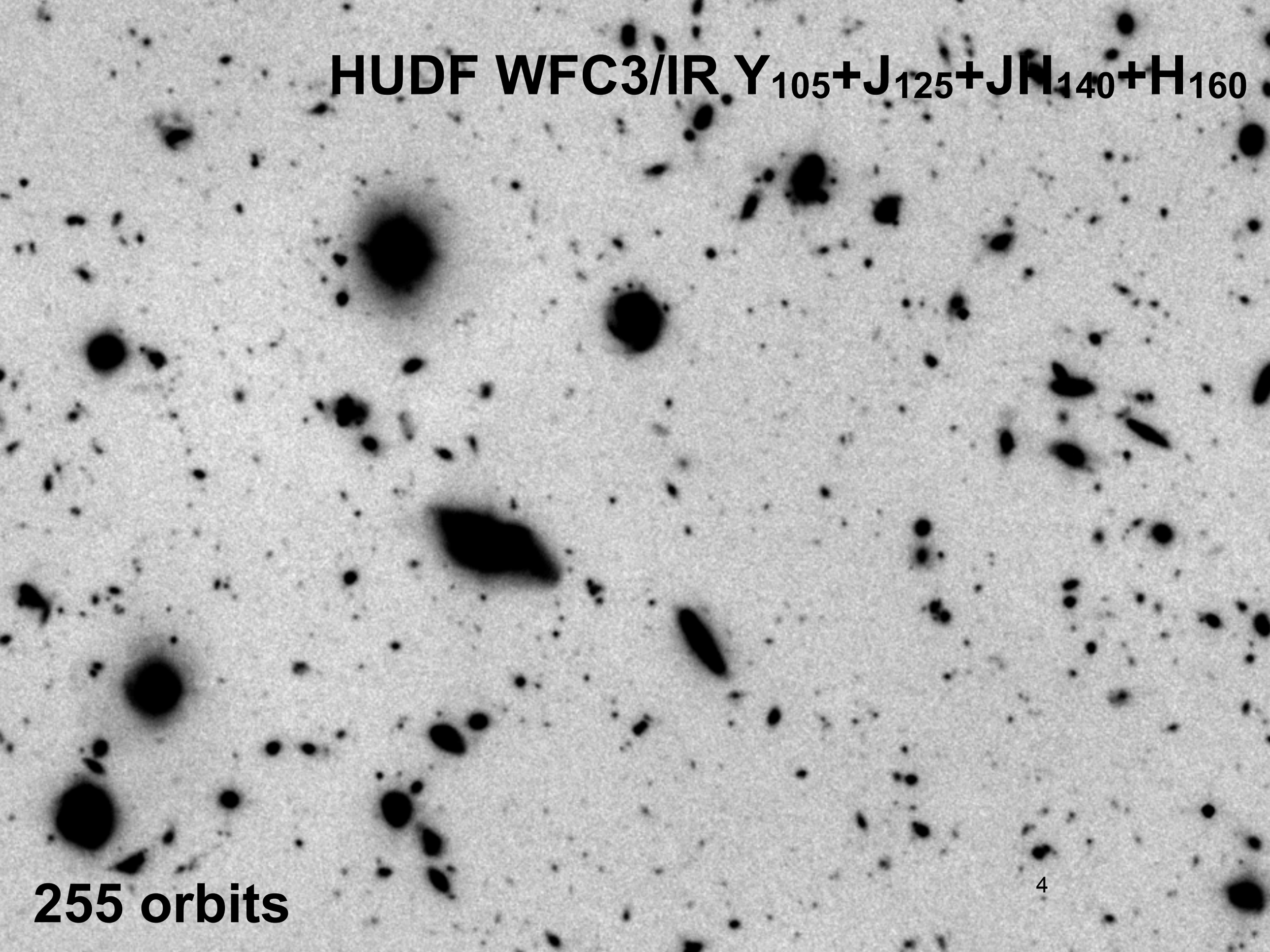
WFC3 +
COS

October
2018
JWST

Back At the Edge of
the Universe:
April 2015



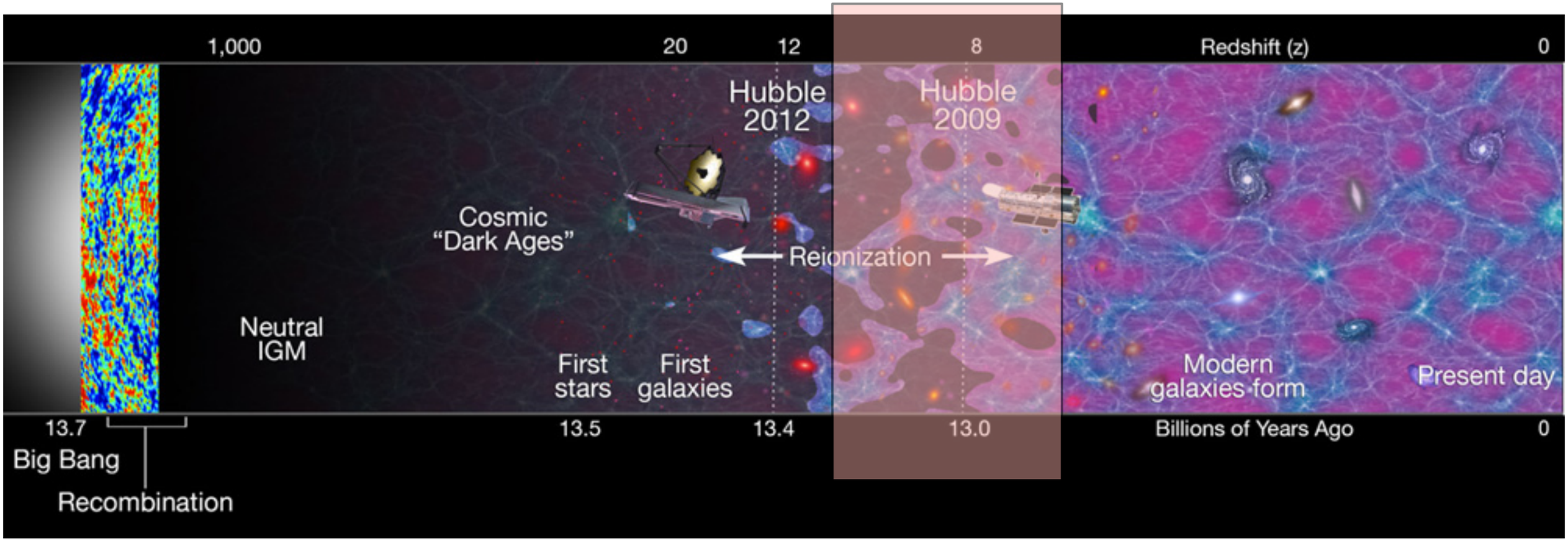

HUDF NICMOS J_{110}+H_{160}
144 orbits


HUDF WFC3/IR Y_{105}+J_{125}+JN_{140}+H_{160}
255 orbits

Studying Galaxies at the edge of the universe (‘high redshift’) is interesting!

-- when galaxies grew very rapidly!

Frontier!

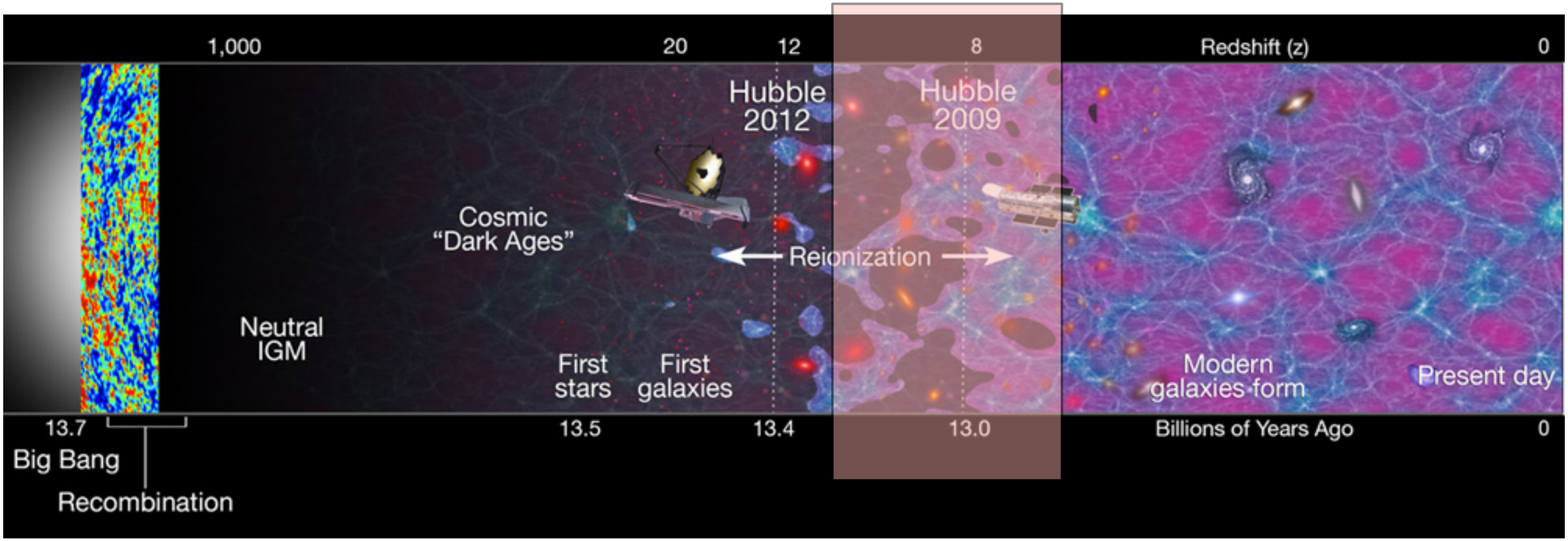


Studying Galaxies at the edge of the universe (‘high redshift’) is interesting!

-- when galaxies grew very rapidly!

-- when the universe is reionized
(did galaxies do it?)

Frontier!

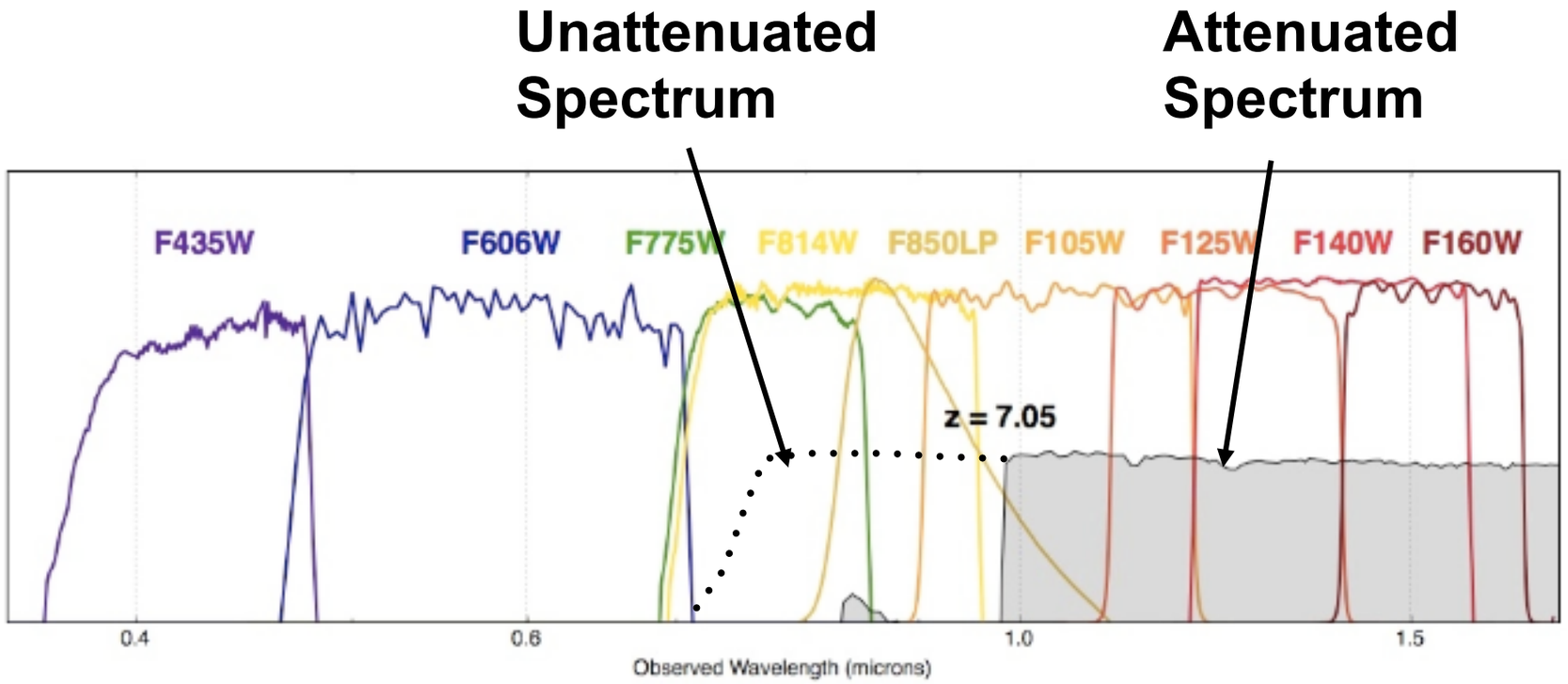


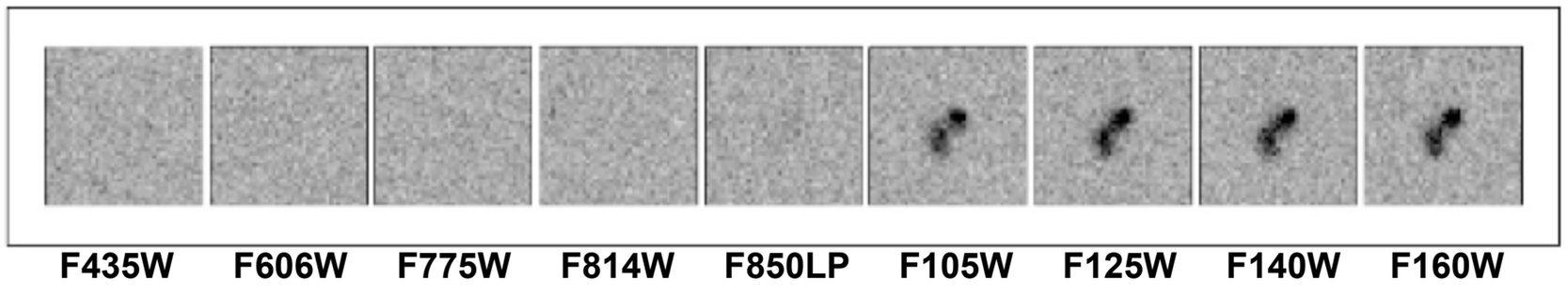
How do we identify galaxies in early universe?

Lyman Break Technique

Position of break tells us the redshift

Example z=7 galaxy

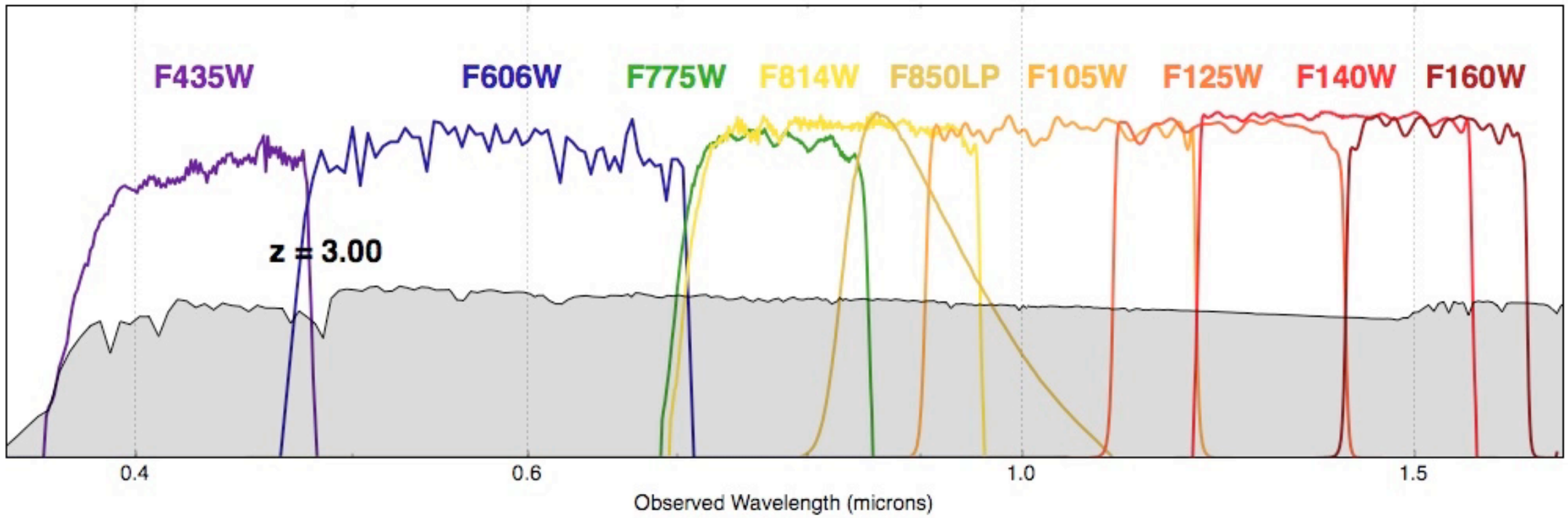


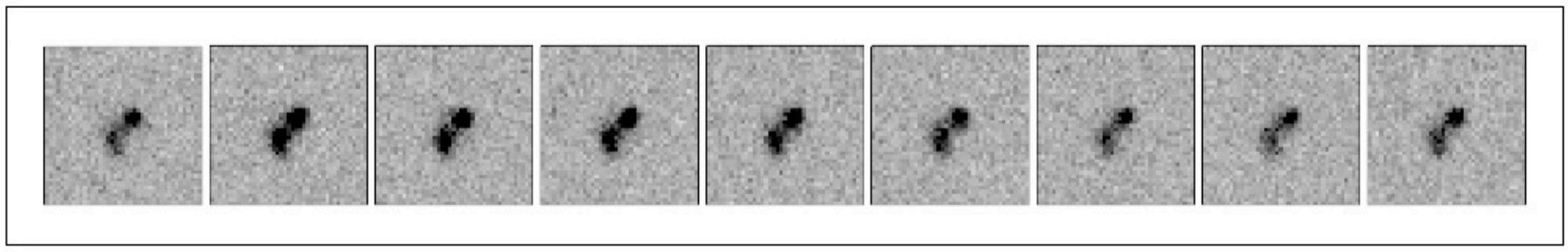


No Detection

Blue Continuum

How do we identify galaxies in early universe?





Animation available at http://xdf.ucolick.org/

What can we do at present with HST and other state of the art telescopes?

What are the key data sets?

What are the key data sets?

Deep Survey for Faint Galaxies

HUDF/XDF

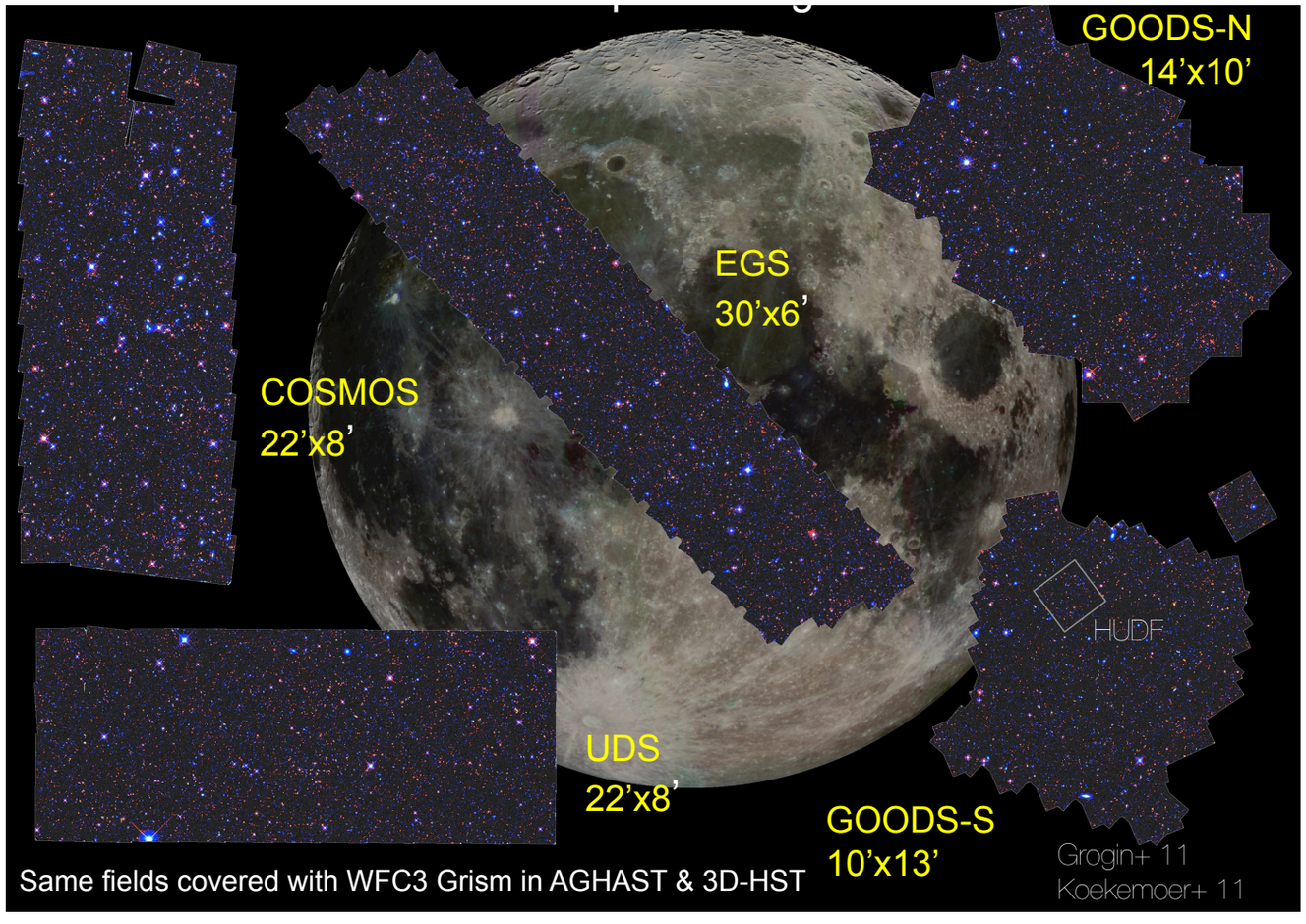
+ 2 Deep Parallel Fields
HUDF09-1 +
HUDF09-2

What are the key data sets?

Deep Survey for Faint Galaxies

+ 2 Deep Parallel Fields
HUDF09-1 +
HUDF09-2

Wide Surveys for Bright Galaxies

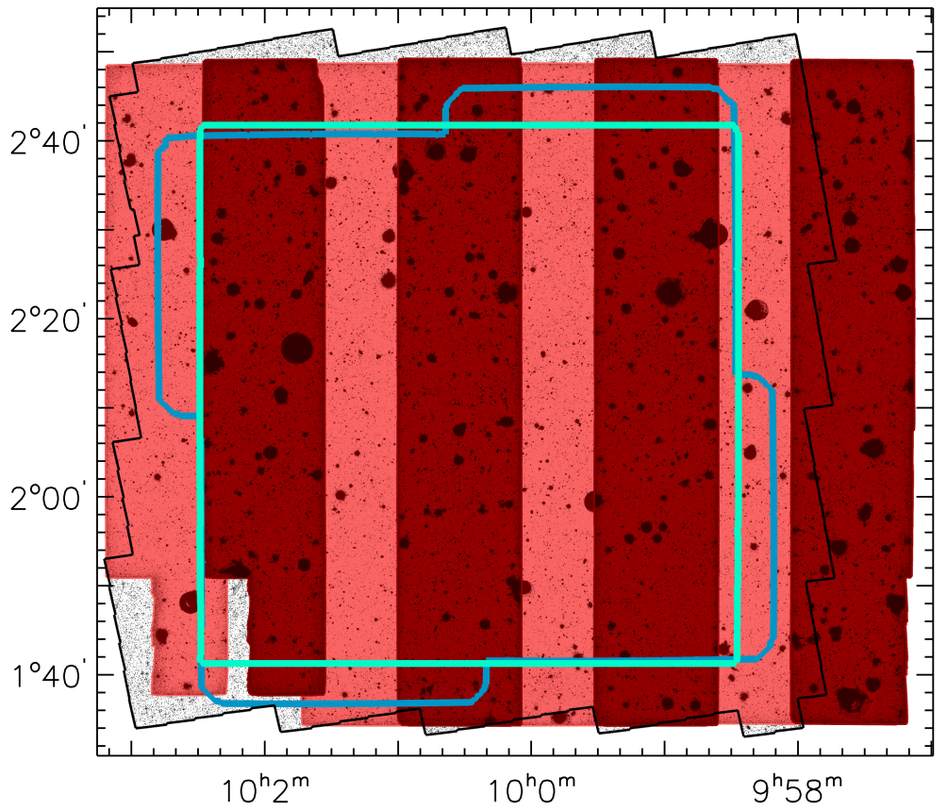


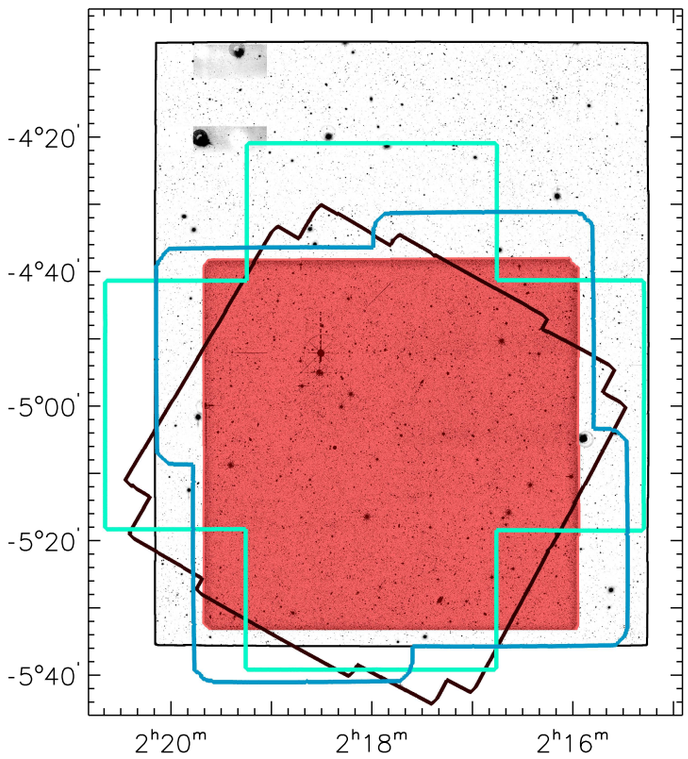
+ ERS + pure-parallel
BoRG/HIPPIES
program

What are the key data sets?

Wide-Area Ground-Based Probes

UltraVISTA (McCracken+2012)
1.5 sq. degree
Y ~ 25.8, J ~ 24.9, K ~ 25.0





UDS (Lawrence+2007)
0.74 deg^2
Y ~ 24.8, J ~ 25.7, K ~ 25.3

(see Bowler+2014/2015)

What are the key data sets?

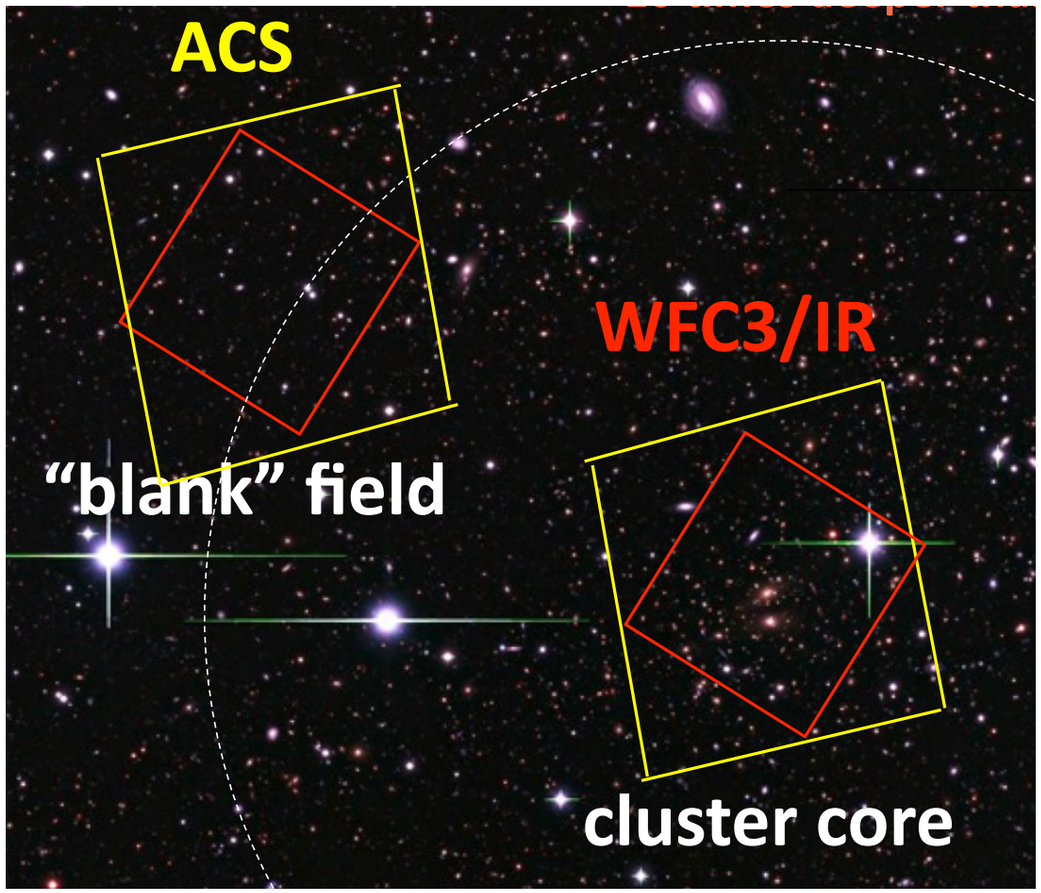
Frontier Fields Program

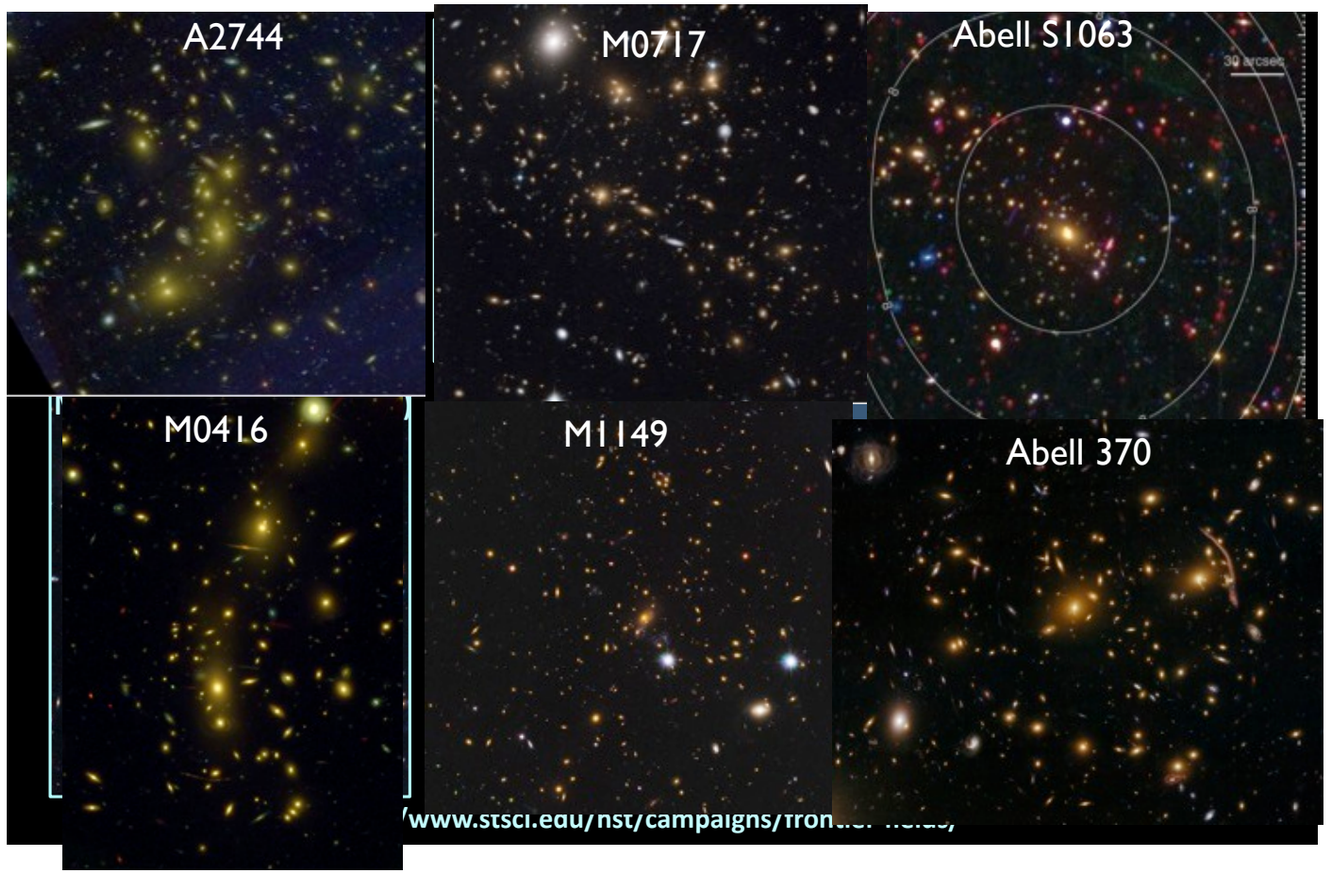
(Matt Mountain, Jennifer Lotz)

6 lensing cluster fields
6 deep "blank" fields
840-orbit program
(60 arcmin^2)

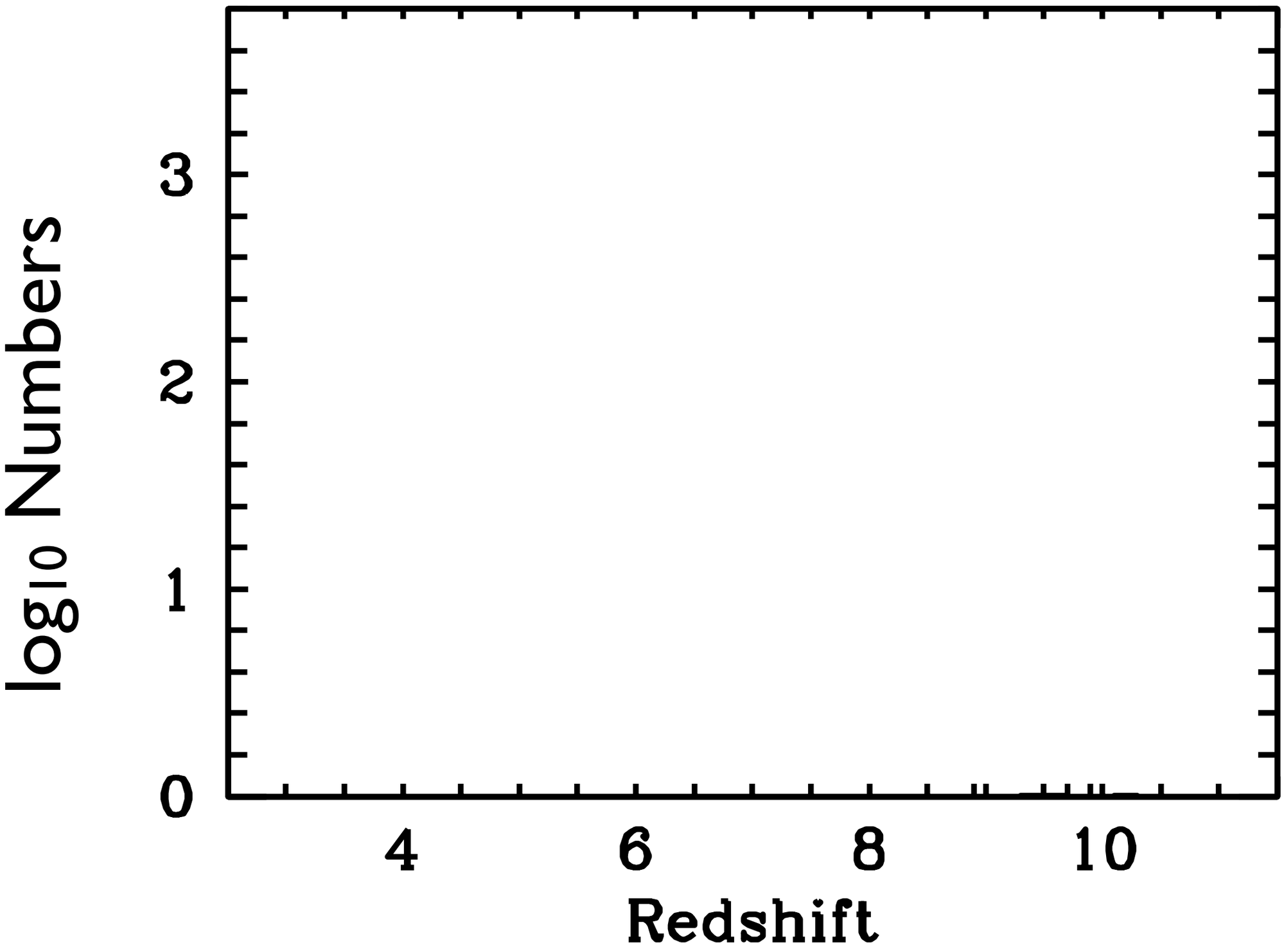
(28.7 mag, 5σ)

(~50% complete)





How many galaxies can we find at high redshifts?



(wide-area ground-based data adds more!)

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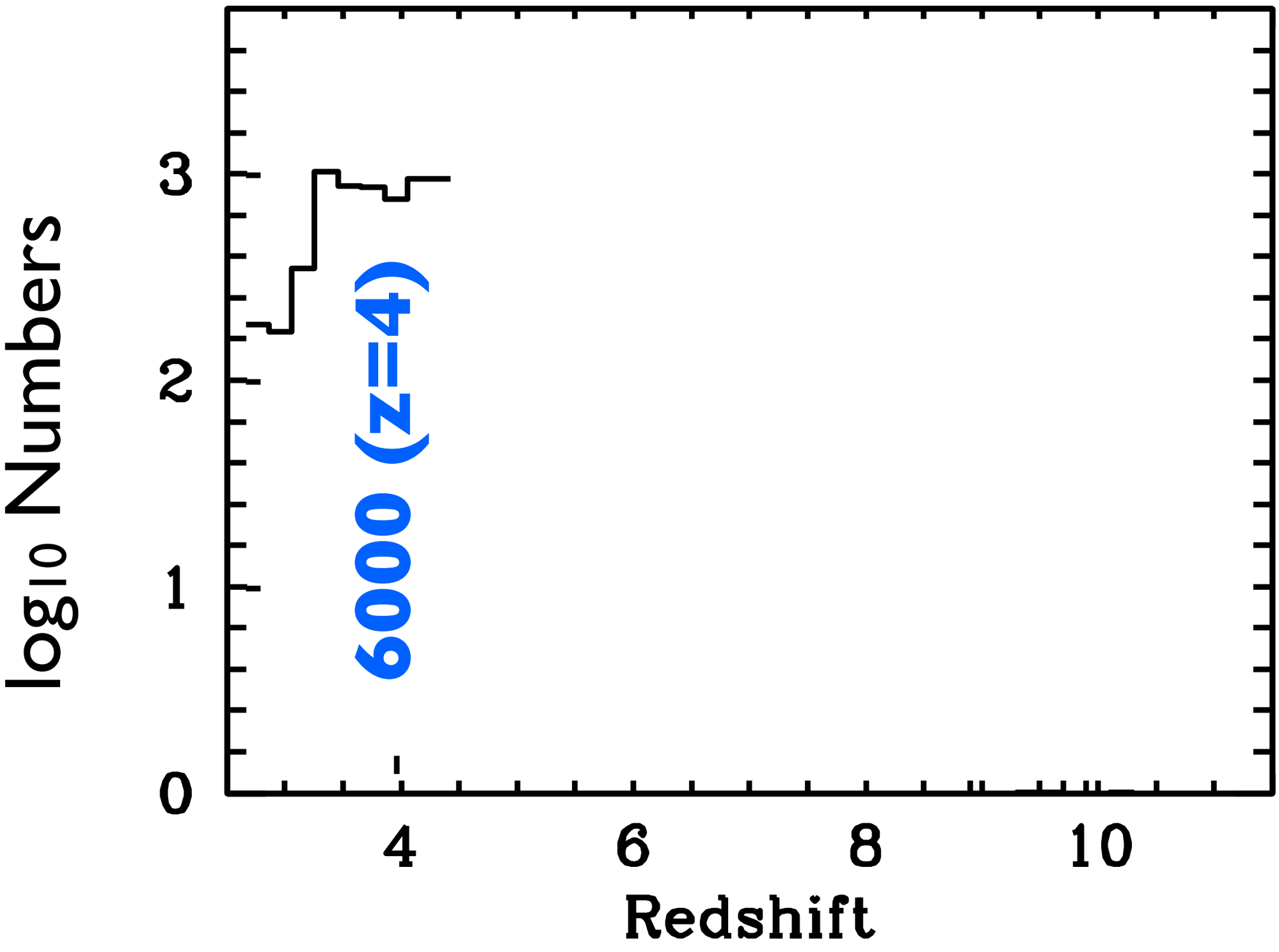

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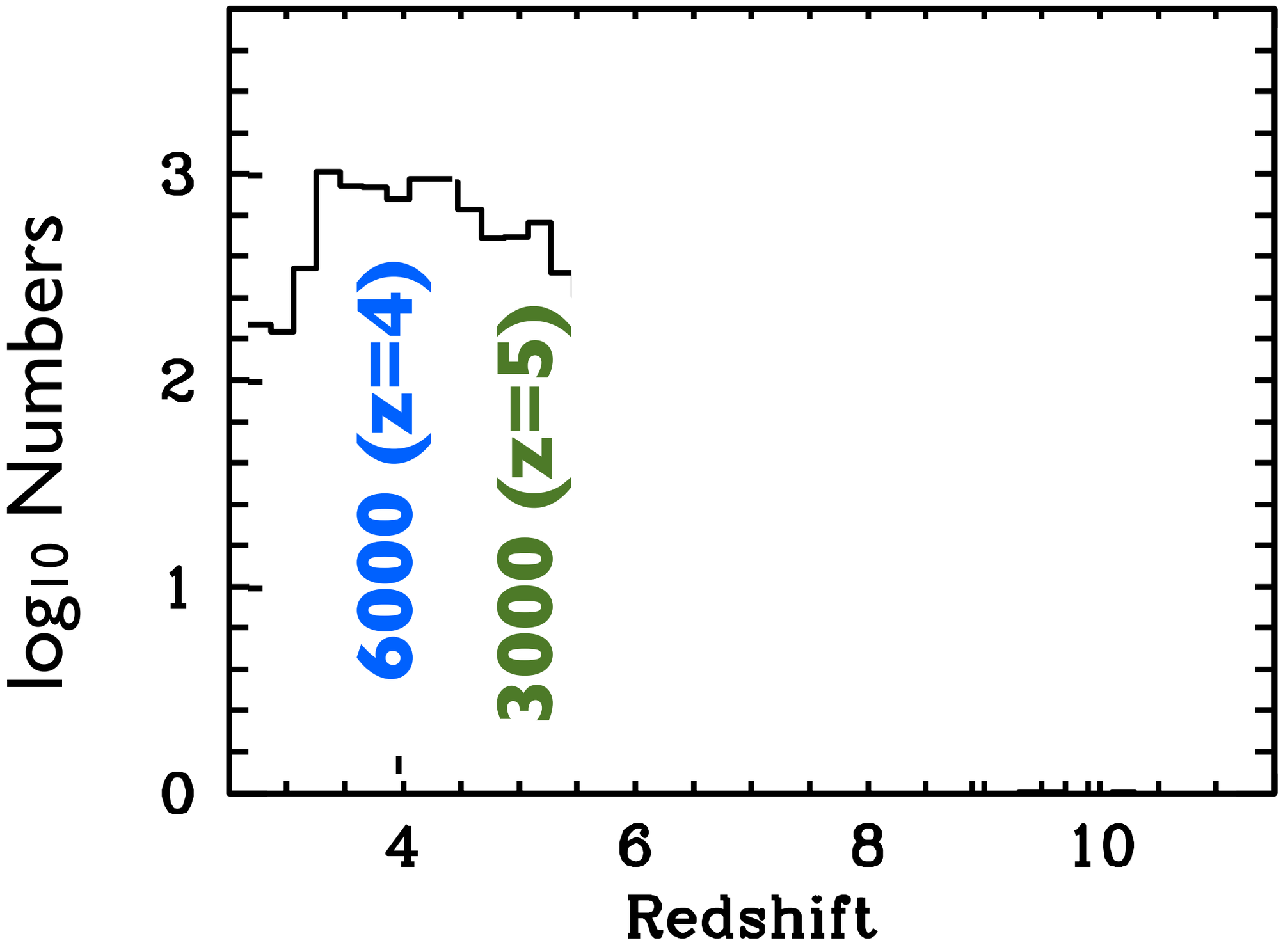

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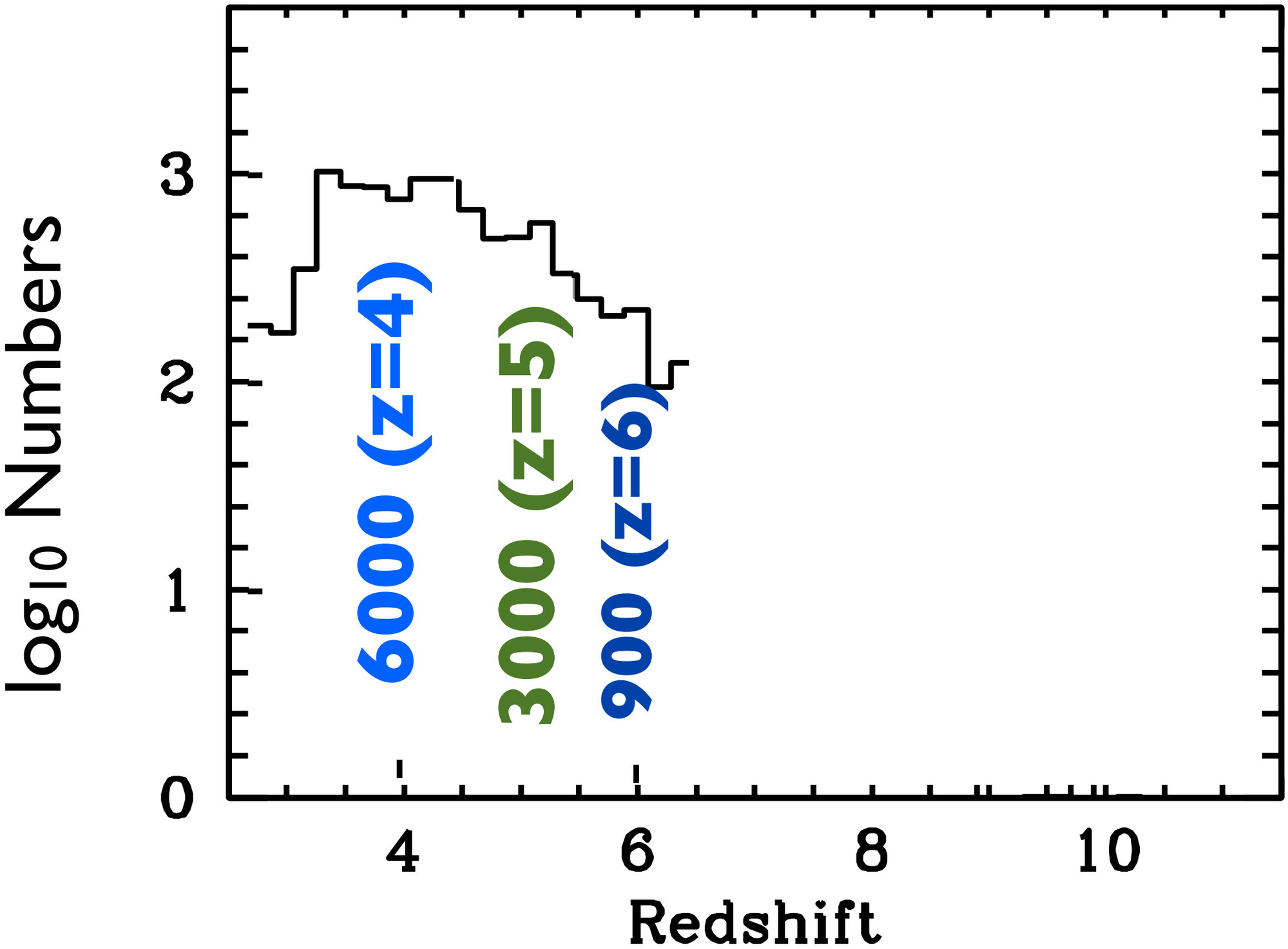

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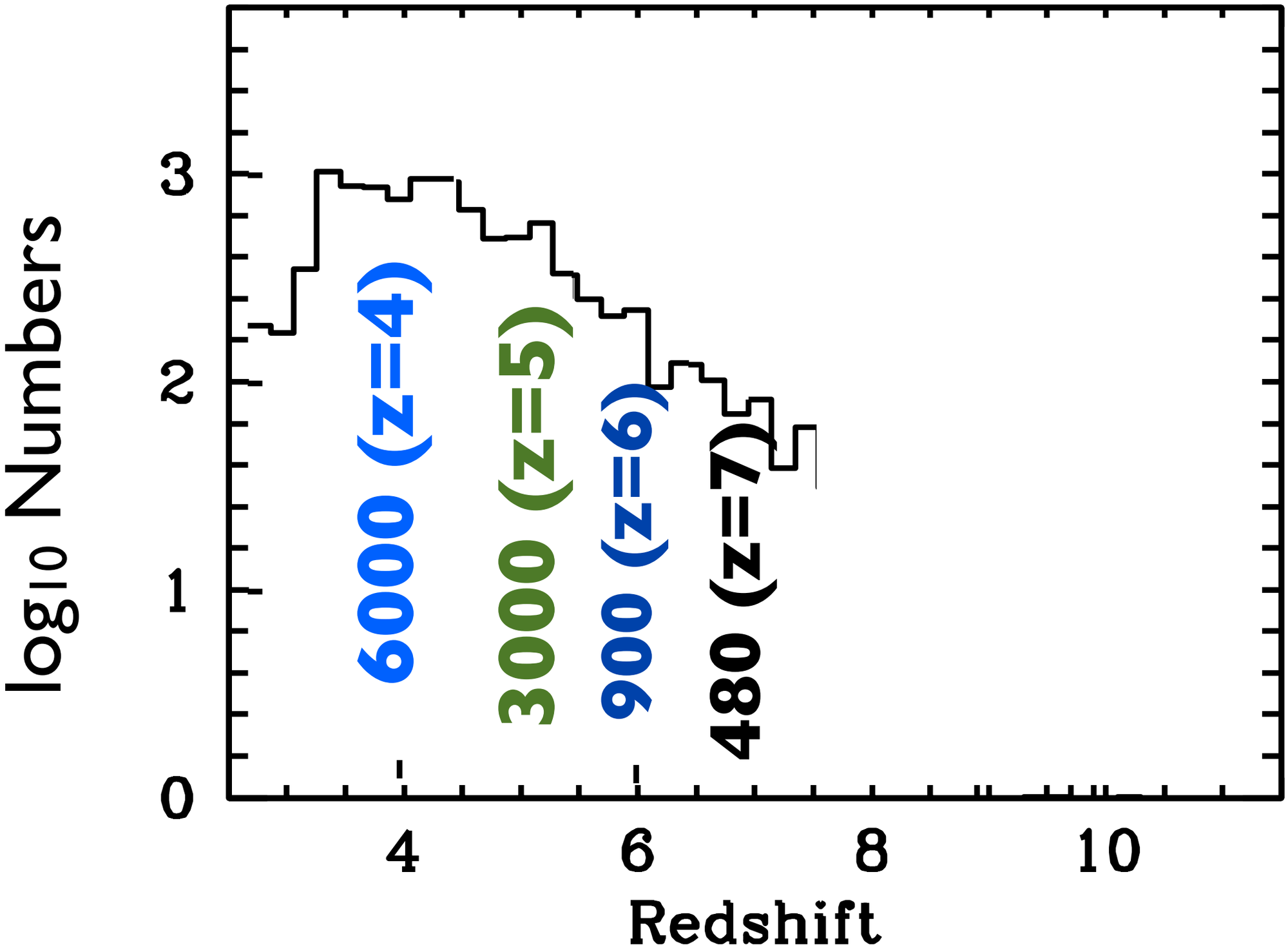

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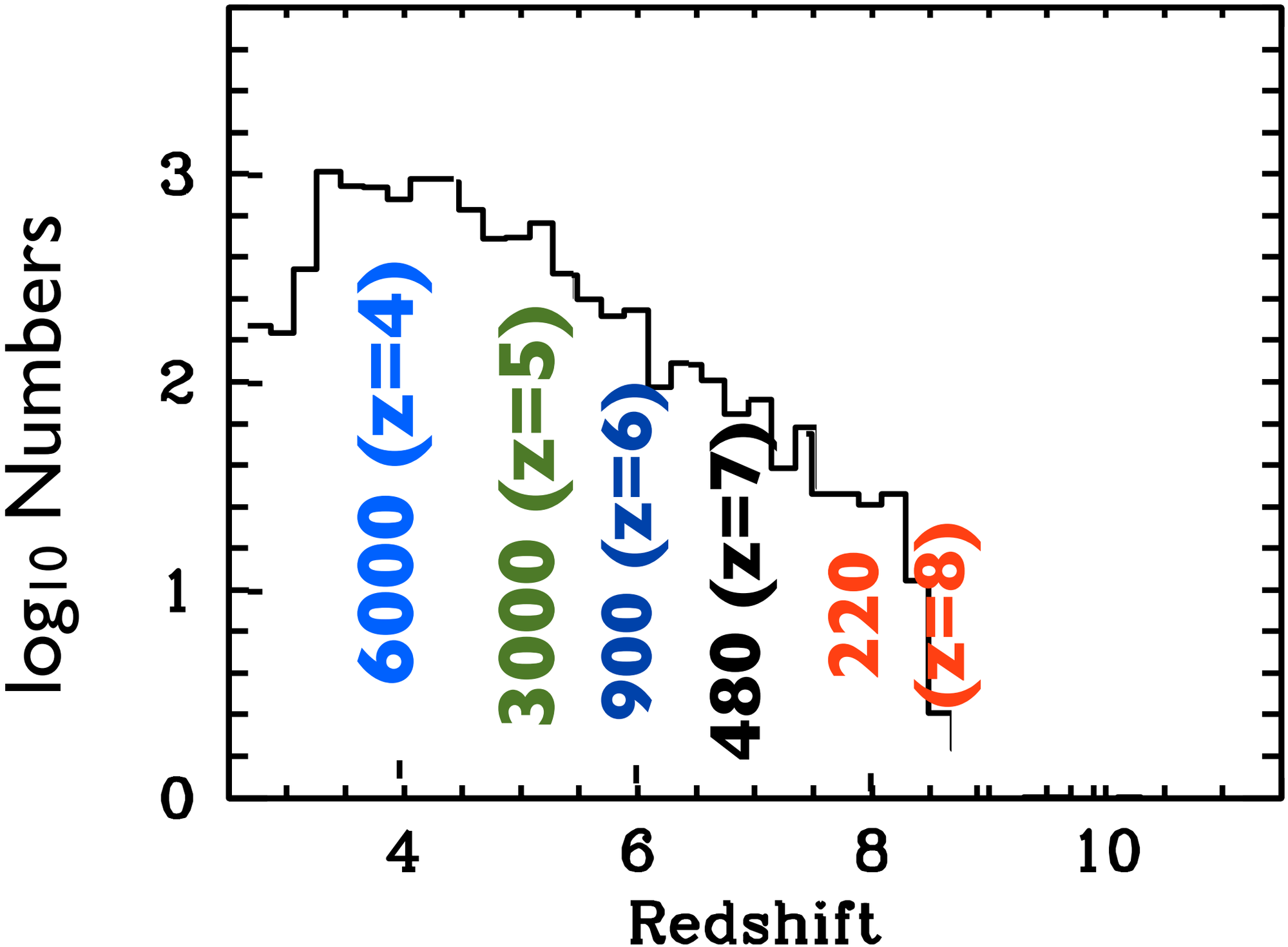

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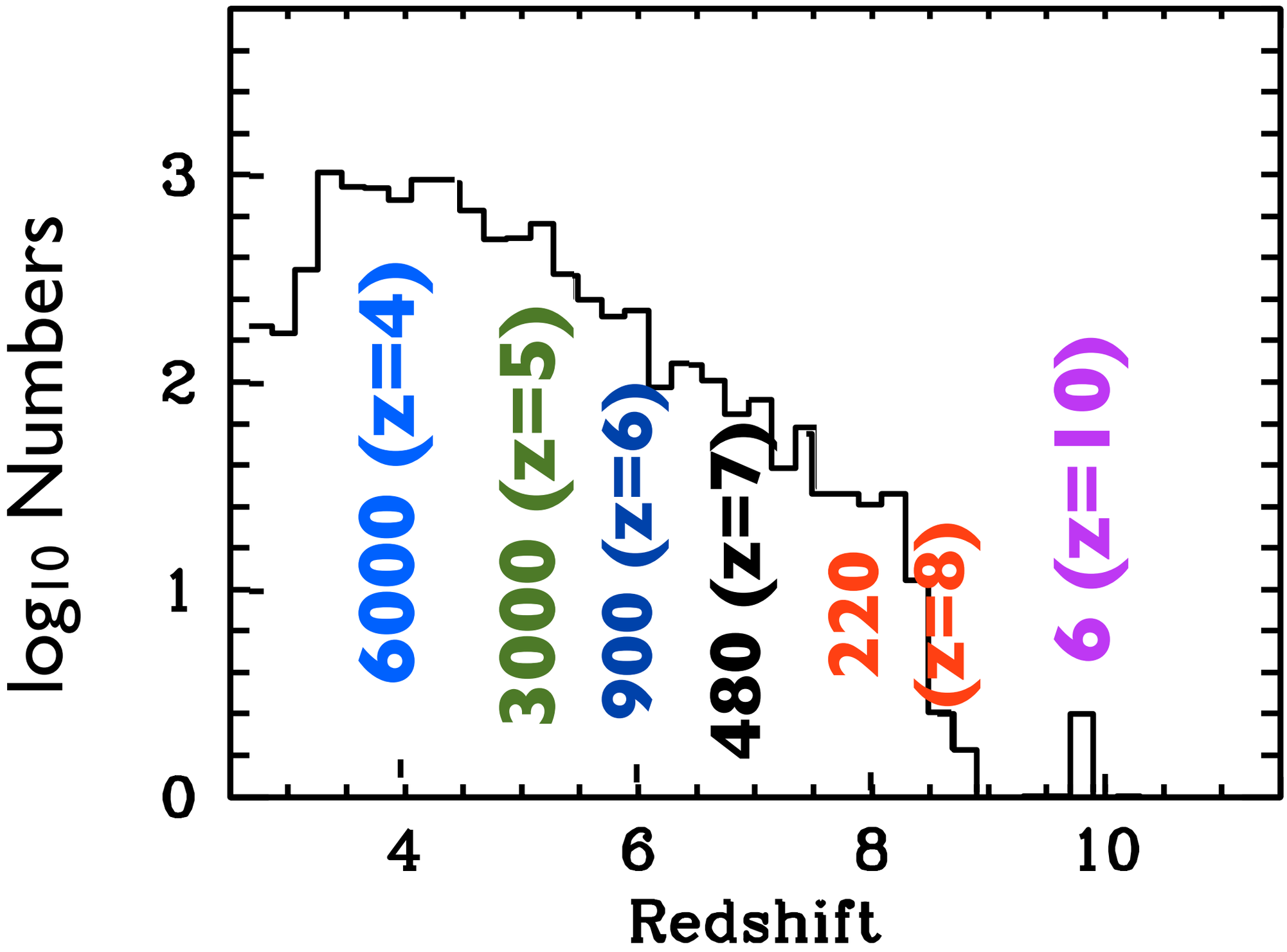

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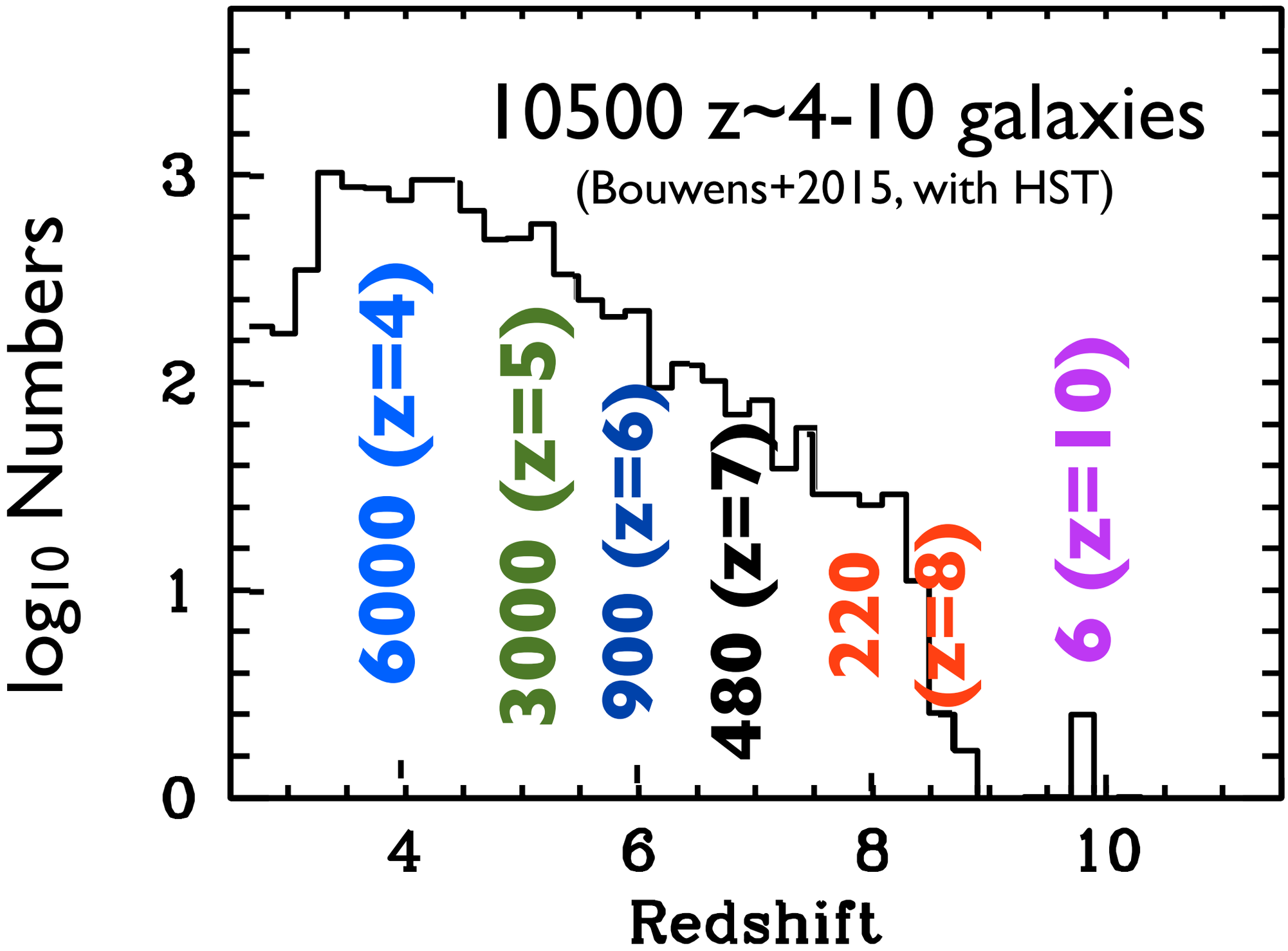

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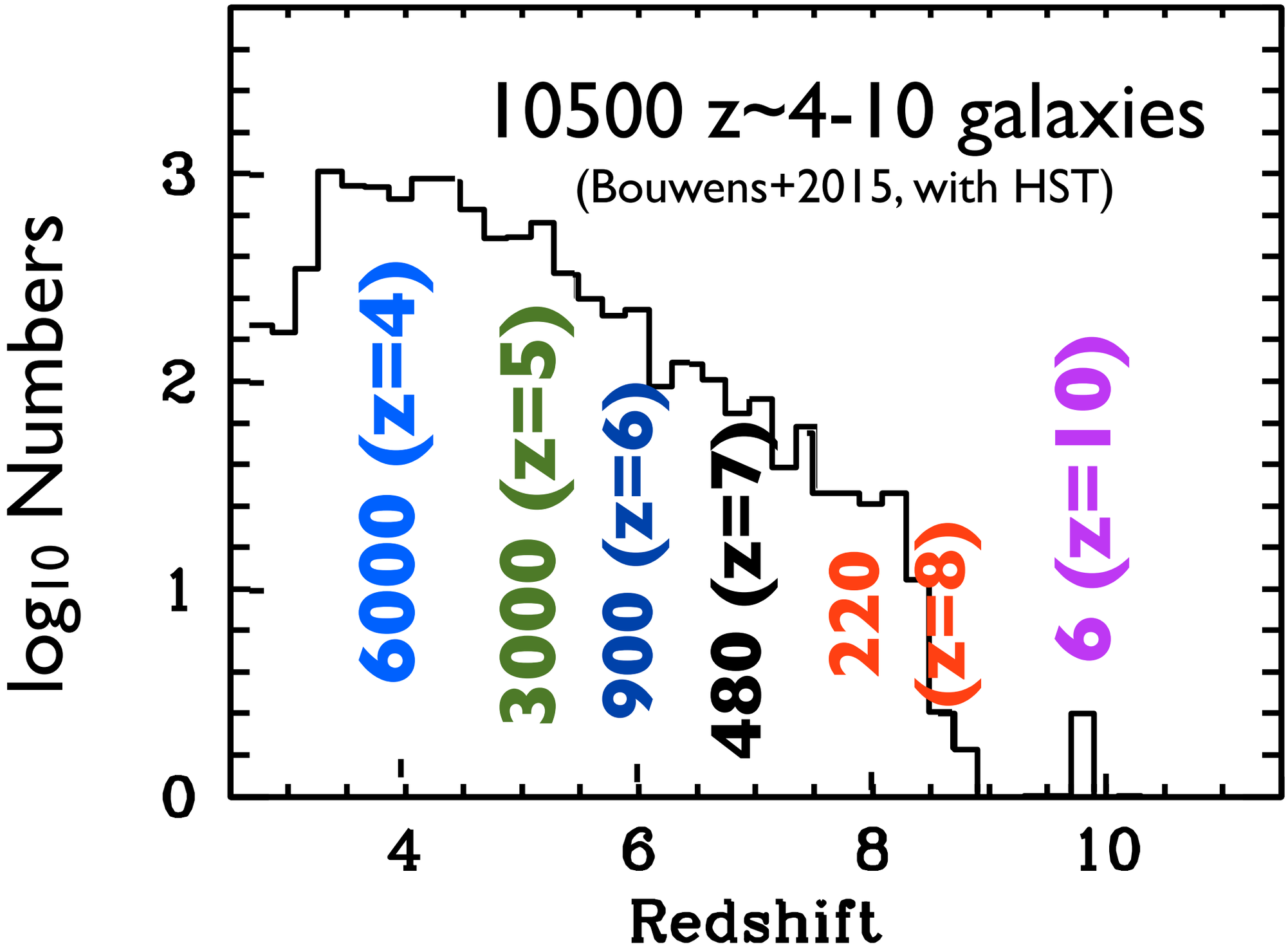
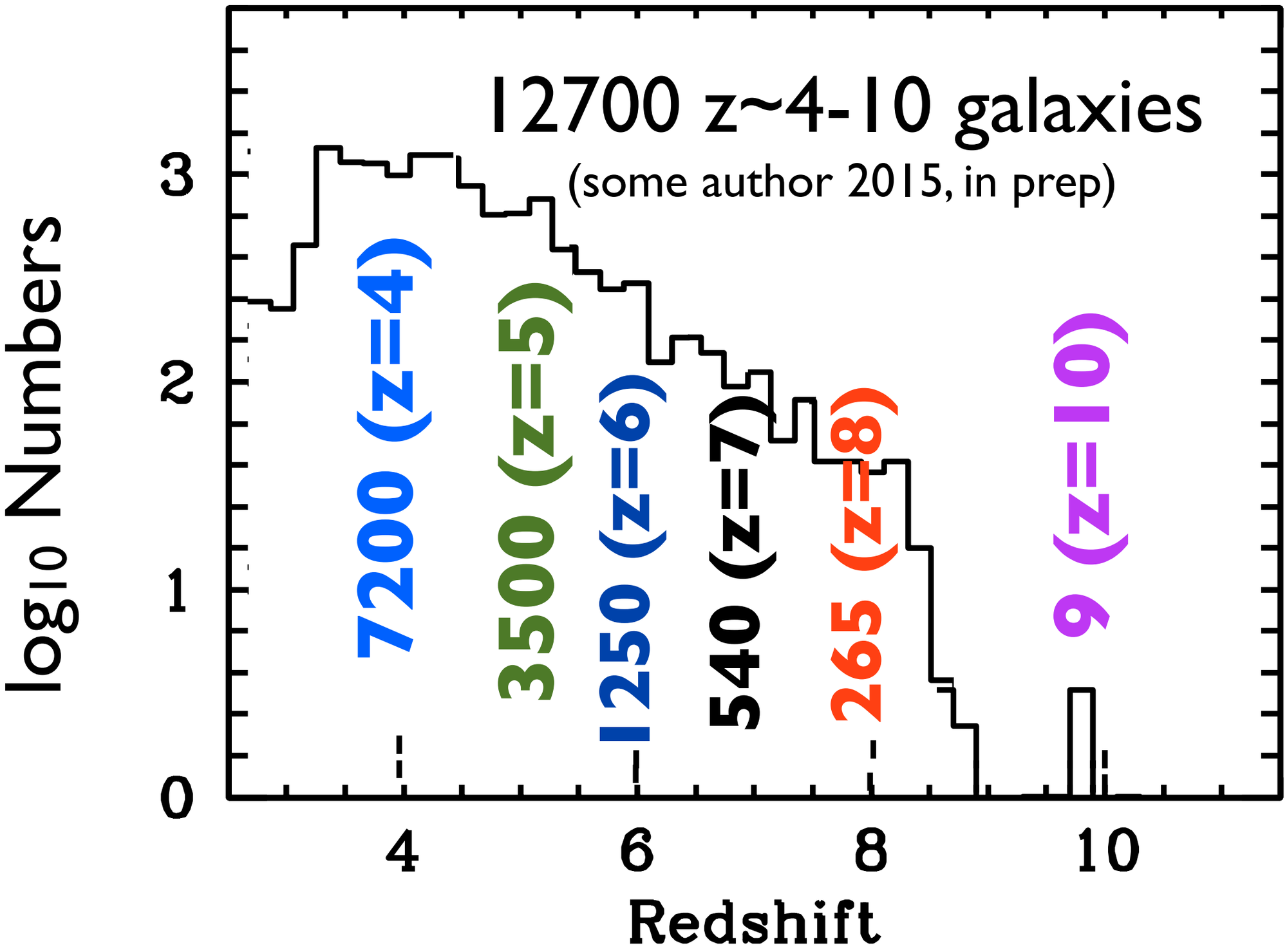


How many galaxies can we find at high redshifts?



Many Probable z = 9-10 Galaxies are Known

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
z~9.2 CLASH

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
z~9.2 CLASH

z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
z~11.9 HUDF(?)

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
z~9.2 CLASH

z~9.2 CANDELS
z~9.5 CANDELS
z~9.5 CANDELS
z~9.9 CANDELS
z~9.9 CANDELS
z~10.2 CANDELS

z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
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Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
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z~9.2 CANDELS
z~9.5 CANDELS
z~9.5 CANDELS
z~9.9 CANDELS
z~9.9 CANDELS
z~10.2 CANDELS

z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
z~11.9 HUDF(?)

z~9.1 CANDELS
z~9.0 CANDELS

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
z~9.2 CLASH

z~8.6 HUDF
z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
z~11.9 HUDF(?)

z~9.2 CANDELS
z~9.5 CANDELS
z~9.5 CANDELS
z~9.9 CANDELS
z~9.9 CANDELS
z~10.2 CANDELS

z~9.1 CANDELS
z~9.0 CANDELS

z~9.8 HFFs
z~8.4 HFFs
z~9.3 HFFs
z~8.9 HFFs
z~8.6 HFFs
z~8.5 HFFs
z~8.7 HFFs
z~8.5 HFFs
z~8.6 HFFs
z~8.7 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~8.4 HFFs

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

Many Probable z = 9-10 Galaxies are Known

z~9.6 CLASH
z~10.8 CLASH
z~9 CLASH
z~9.2 CLASH

z~9.2 CANDELS

30 z=9-10 galaxies

z~10.2 CANDELS

z~9.1 CANDELS
z~9.0 CANDELS

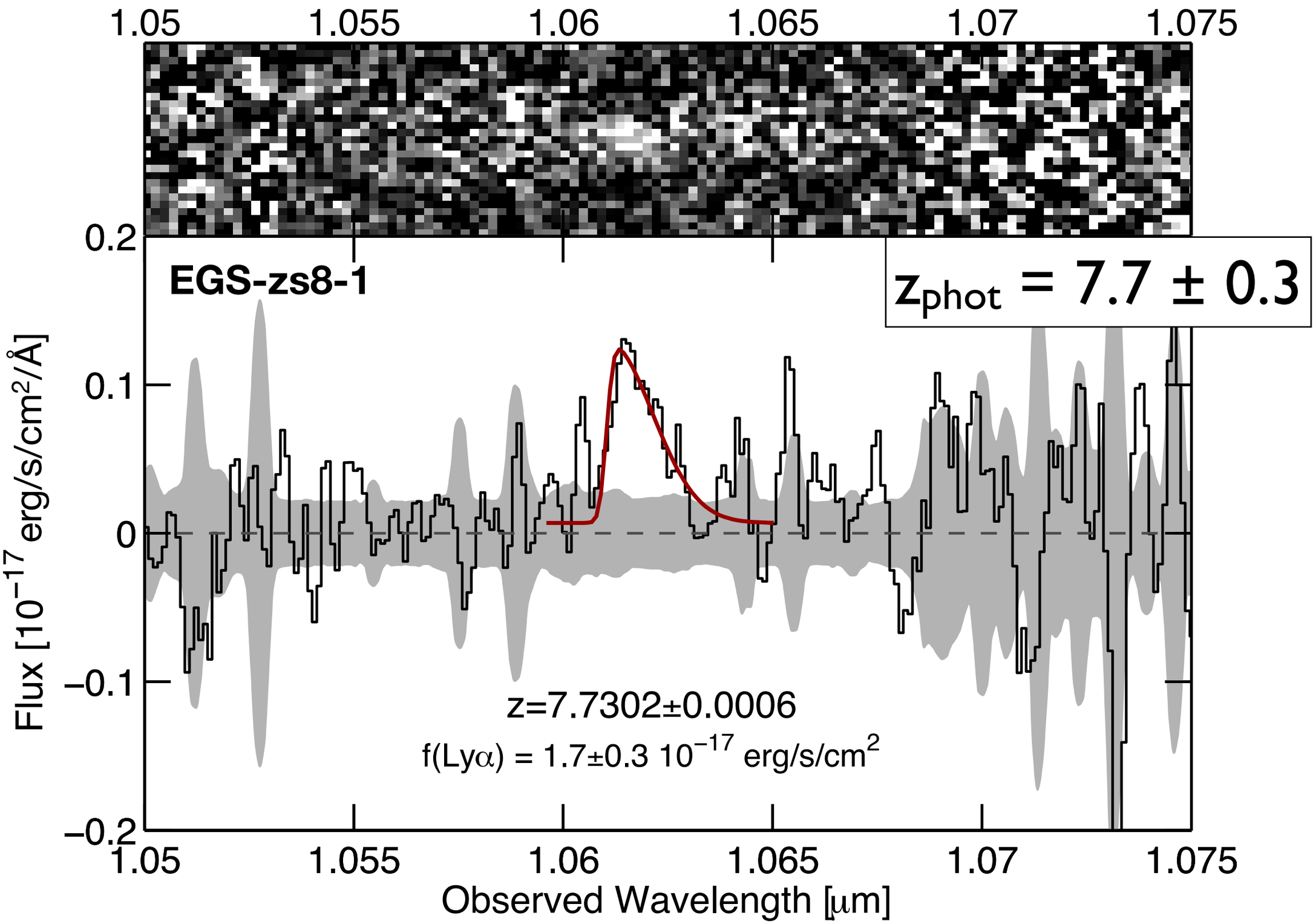
z~9.8 HFFs
z~8.4 HFFs
z~9.3 HFFs
z~8.9 HFFs
z~8.6 HFFs
z~8.5 HFFs
z~8.7 HFFs
z~8.5 HFFs
z~8.6 HFFs
z~8.7 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~9.0 HFFs
z~8.4 HFFs

z~8.6 HUDF
z~8.6 HUDF
z~8.8 HUDF
z~8.8 HUDF
z~8.9 HUDF
z~9.5 HUDF
z~9.8 HUDF
z~11.9 HUDF(?)

Bouwens+2011, 2015a,b; Ellis+2013; Oesch+2013, 2014, 2015; Zitrin+2014; Atek+2015; Ishigaki +2015; McLeod+2015

High-Redshift Record-Holder (From Spectroscopy)

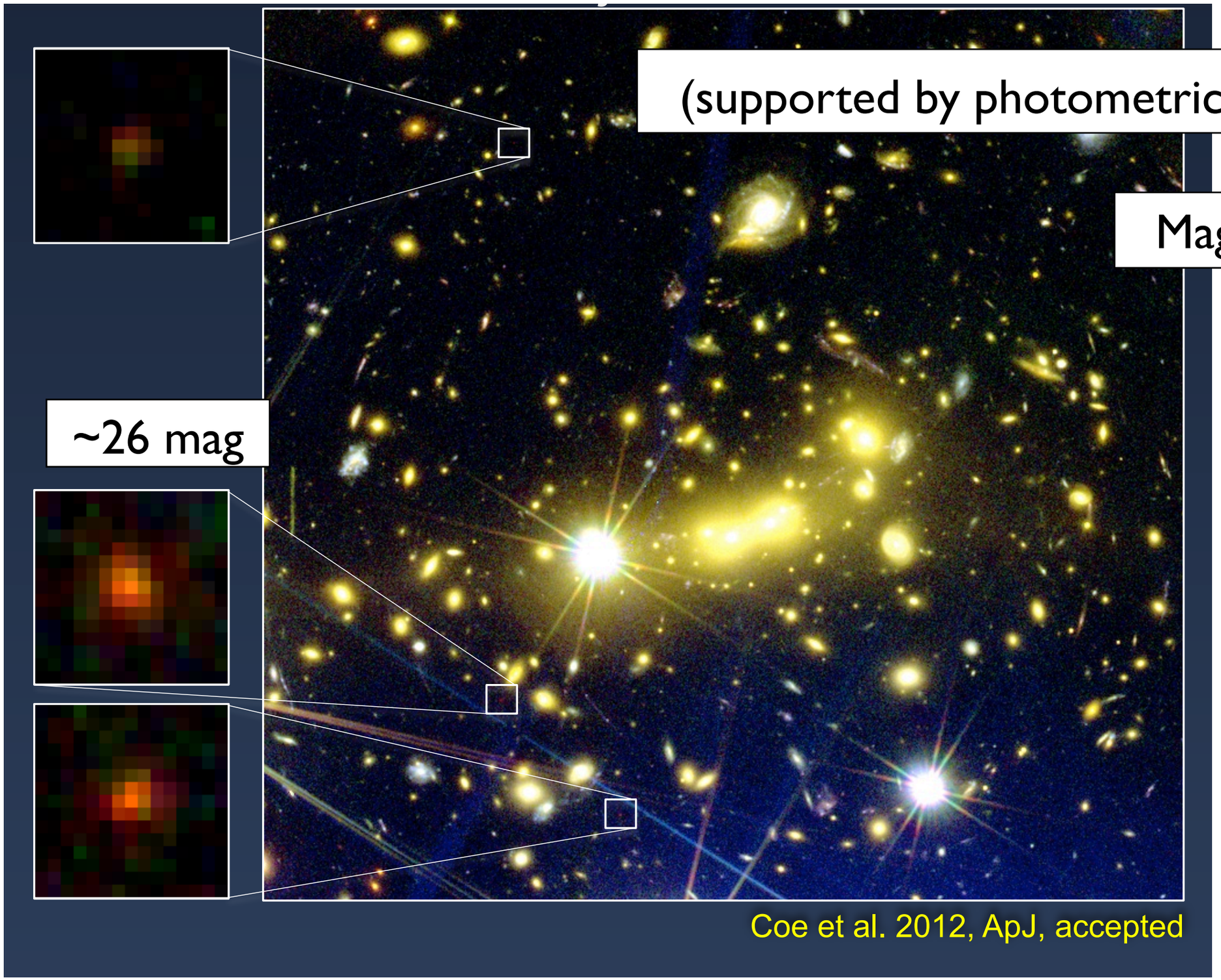
z = 7.7302 +/- 0.0006



Oesch+2015

High-Redshift Record-Holder (From Photometry)

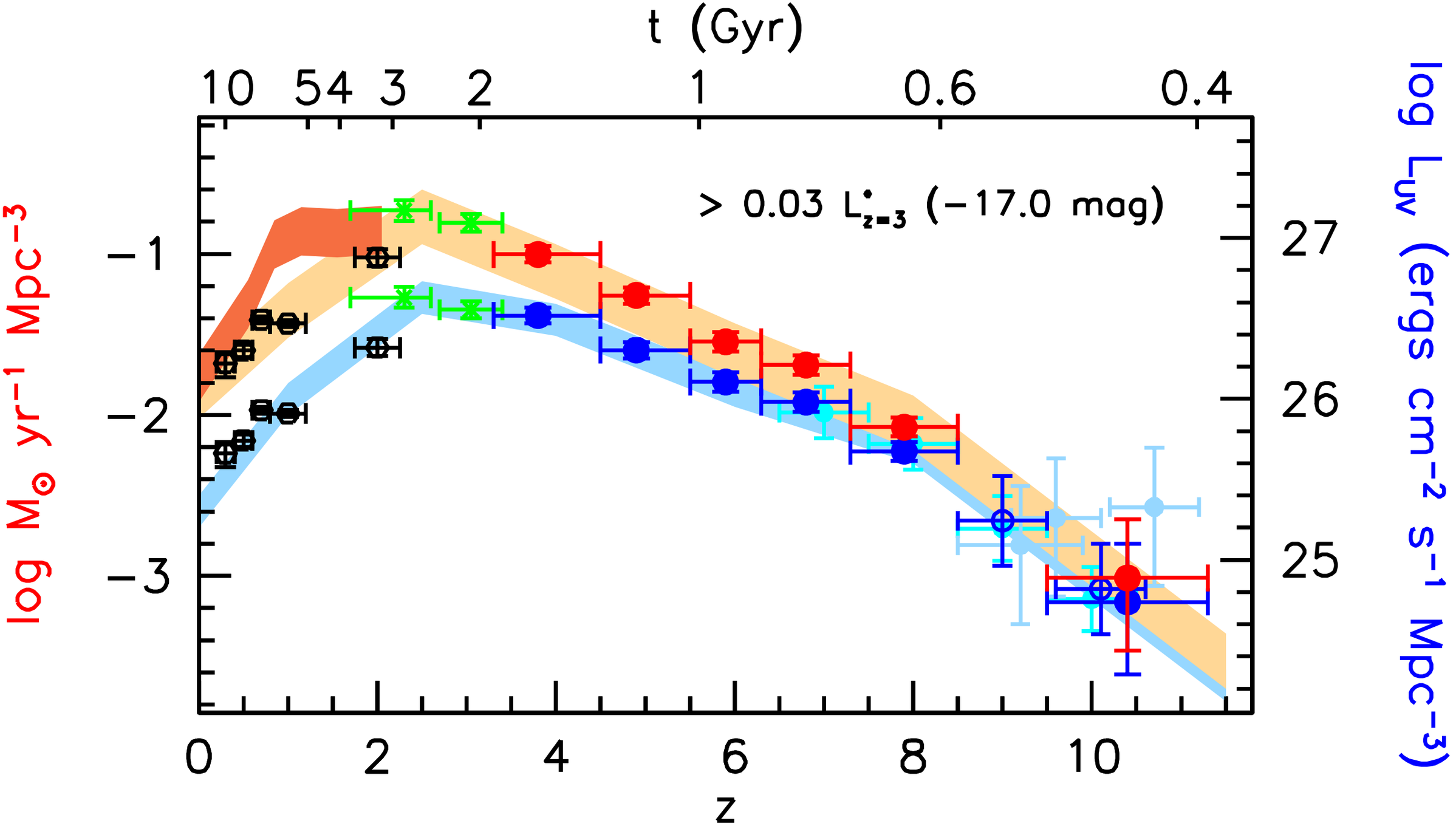
z~10.8 Galaxy Candidate behind MACS0647 (Triply Imaged)



Coe+2013; Pirzkal+2015

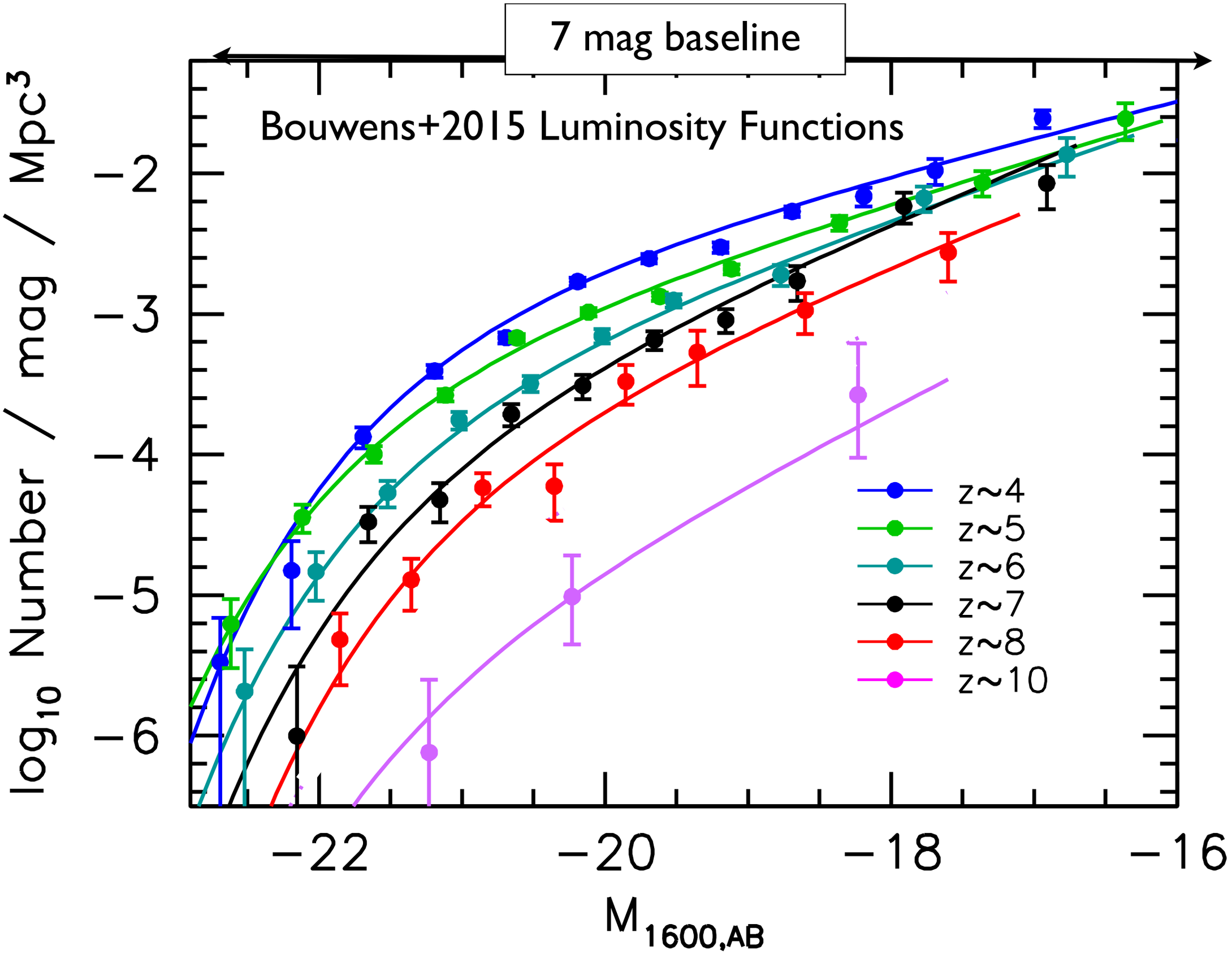
Build-up of Galaxies

Luminosity / Star Formation Rate Density



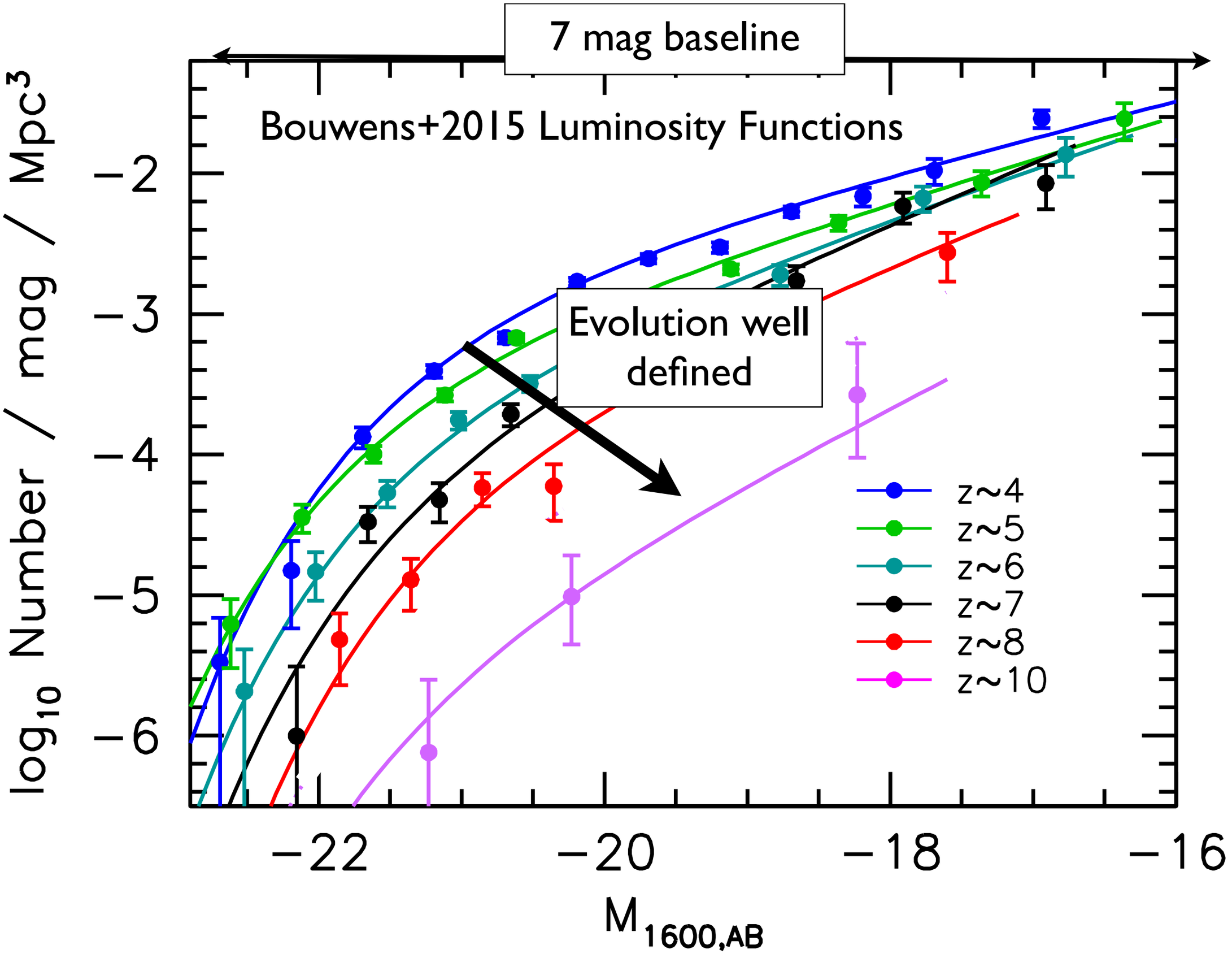
Bouwens+2015 (see also Madau + Dickinson 2015; McLure+2013; Bunker+2004)

Ultraviolet Luminosity Functions



Bouwens+2015; see also Bowler+2015; McLure+2013; Oesch+2012, 2013, 2014; Ishigaki+2014; Finkelstein+2015

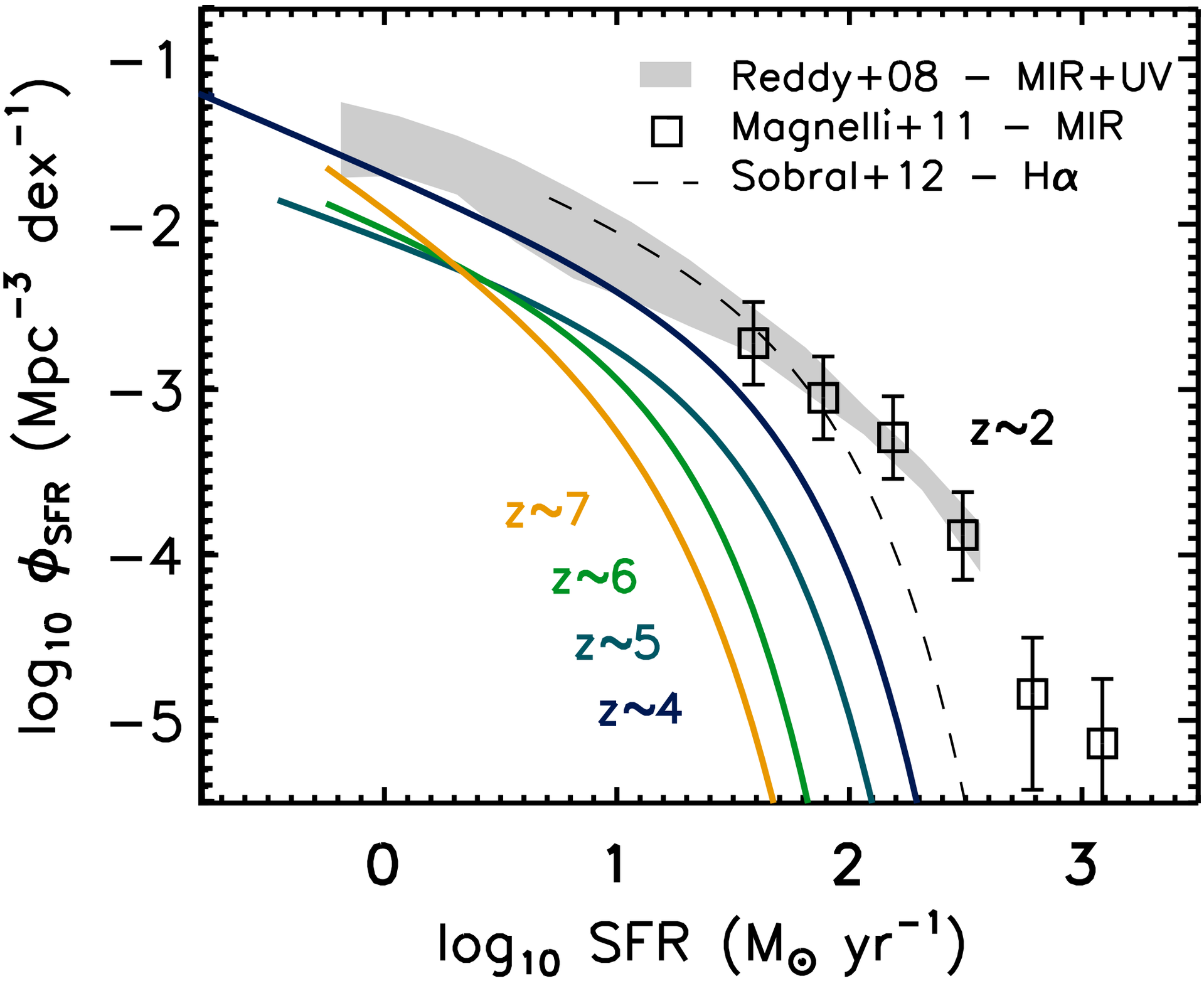
Ultraviolet Luminosity Functions



Bouwens+2015; see also Bowler+2015; McLure+2013; Oesch+2012, 2013, 2014; Ishigaki+2014; Finkelstein+2015

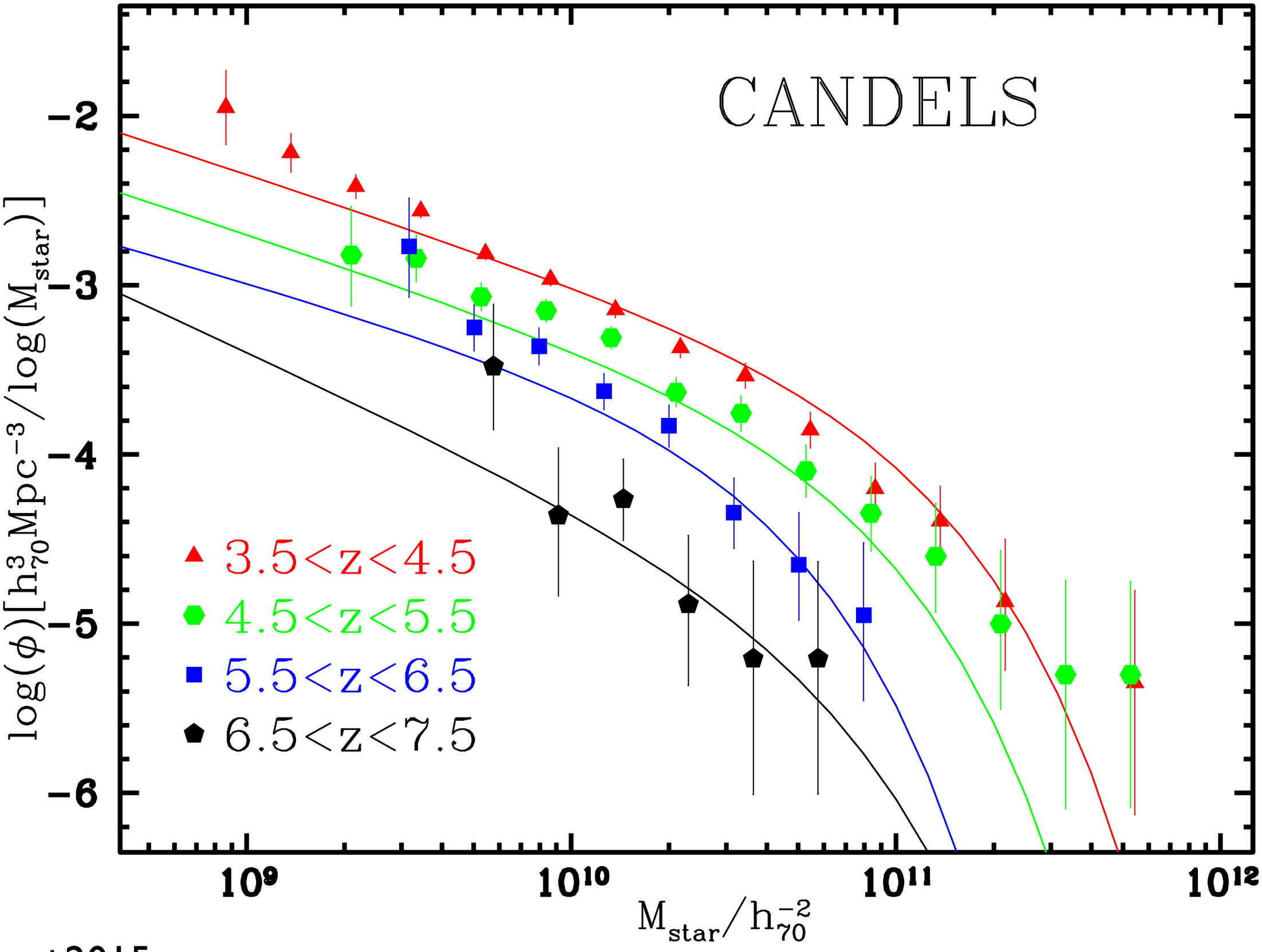
Star Formation Rate Functions

(i.e., dust corrected UV Luminosity Functions)



Smit+2012; see also Duncan+2014; Sobral+2014

Galaxy Stellar Mass Functions

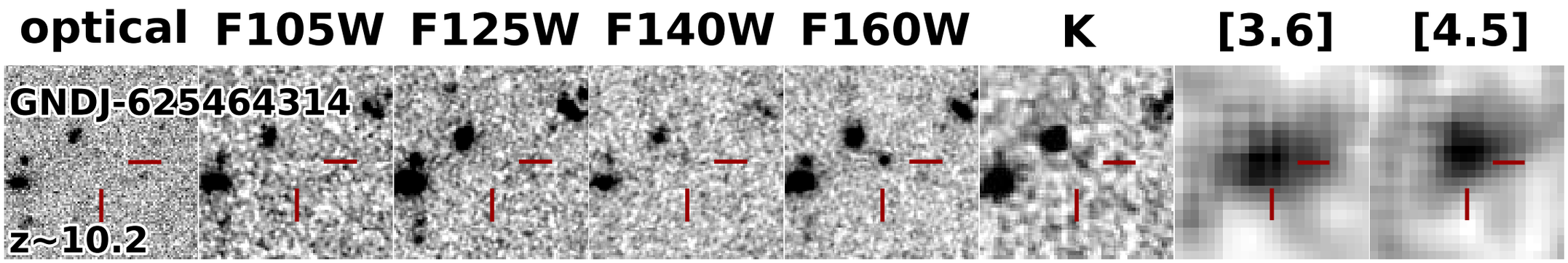


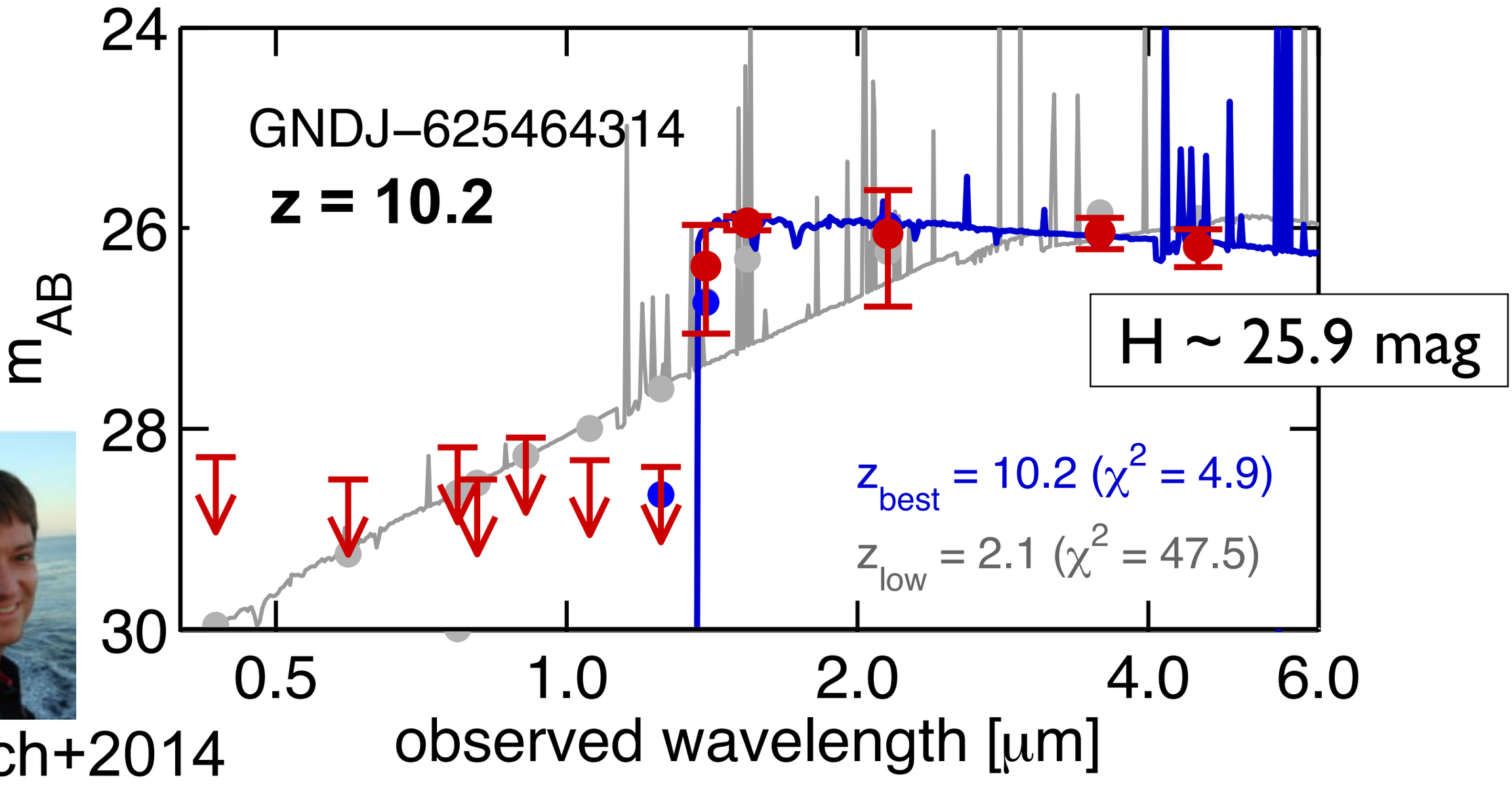
Grazian+2015 (see also Duncan+2014; Ilbert+2013; Muzzin+2013; Gonzalez+2011; Lee+2012)

Discovery of Many Very Luminous Galaxies at z~7-10

Especially Bright z=10.2 Galaxy Found over GOODS North

~1.5 L*(z=3)

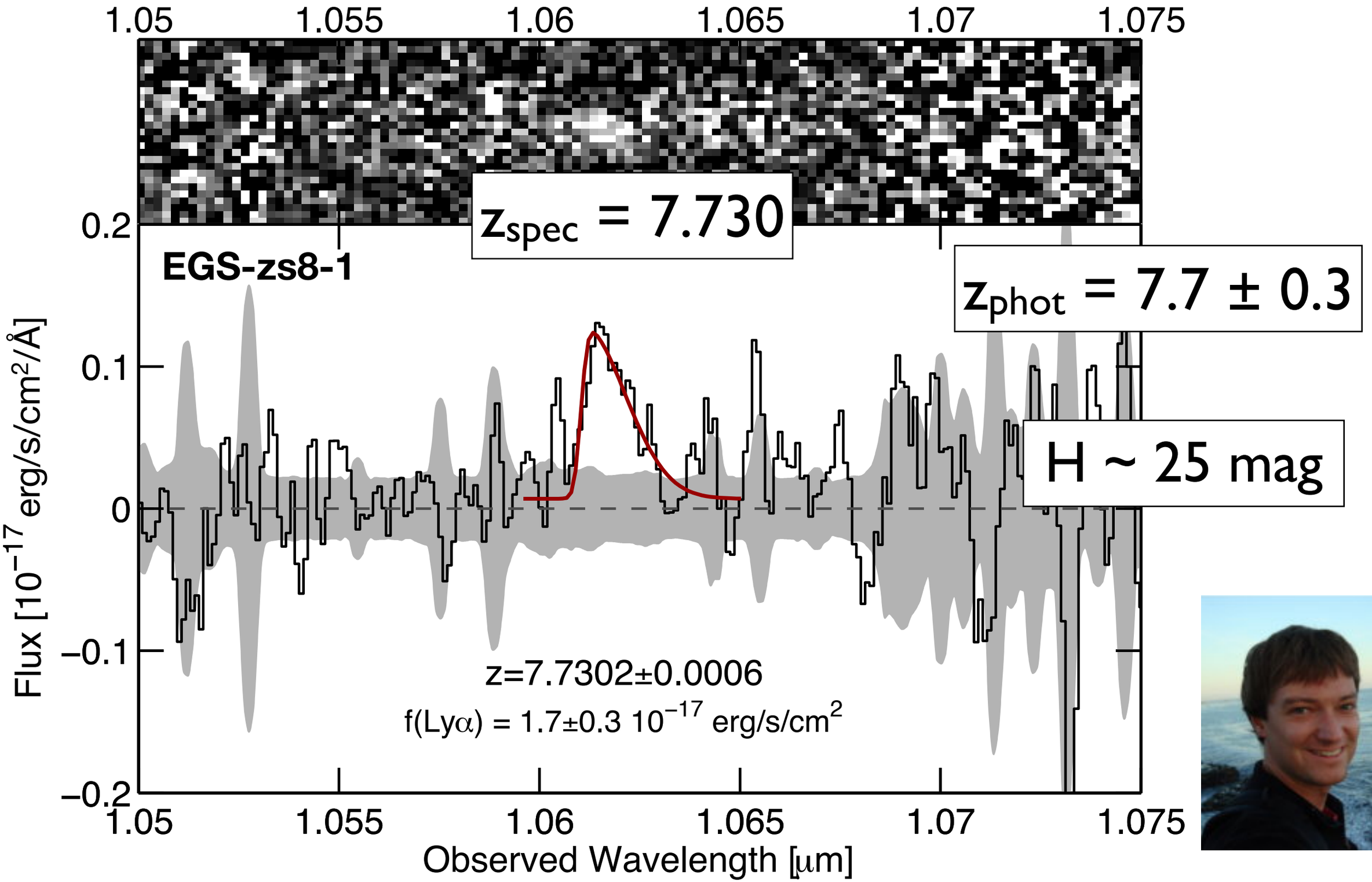




Oesch+2014

Especially Bright z~8 Galaxy Found over CANDELS EGS

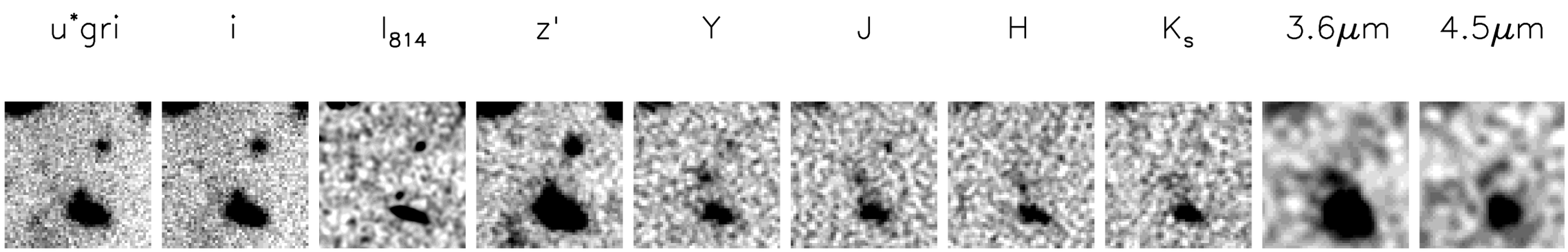
~ 3 L*(z=3)

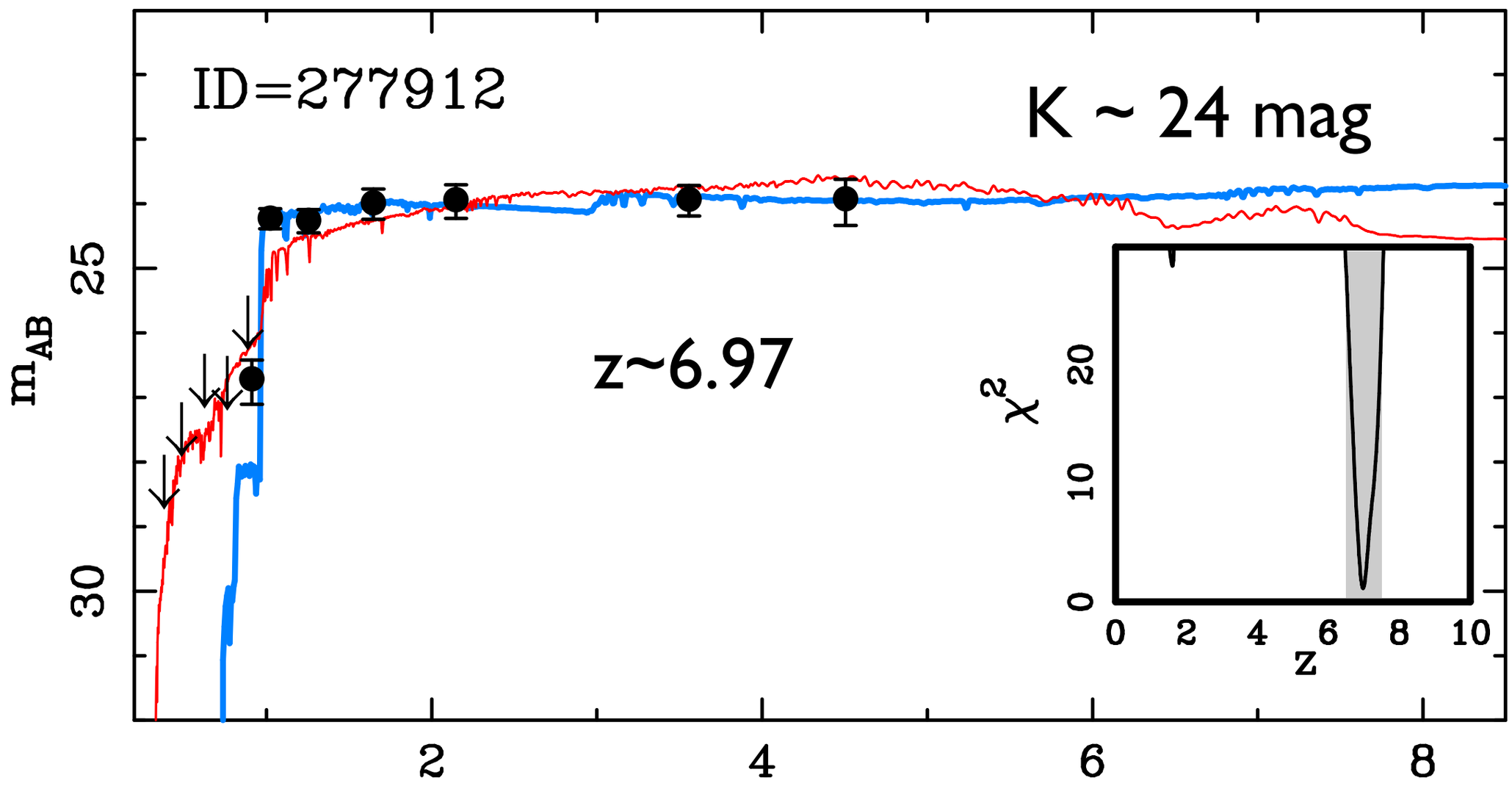


Oesch+2015

Especially Bright z~7 Galaxy Found over UltraVISTA

~ 6 L*(z=3)

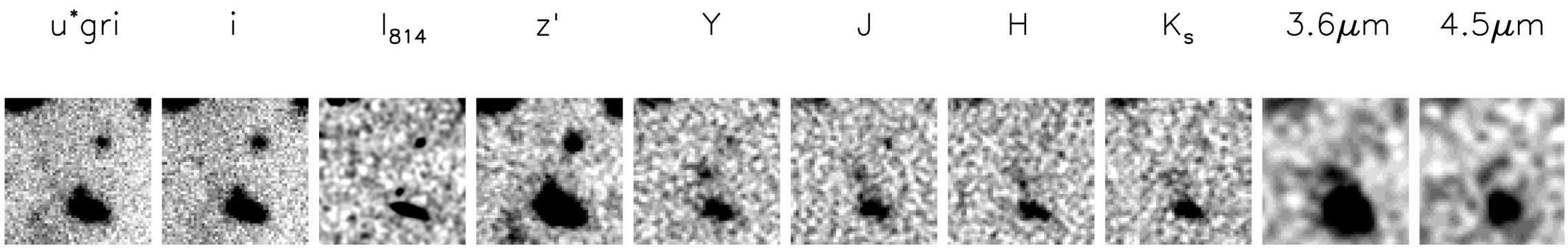




Bowler+2014

Especially Bright z~7 Galaxy Found over UltraVISTA

~ 6 L*(z=3)



Very Bright Galaxies are likely rare high-σ peaks from halo mass function

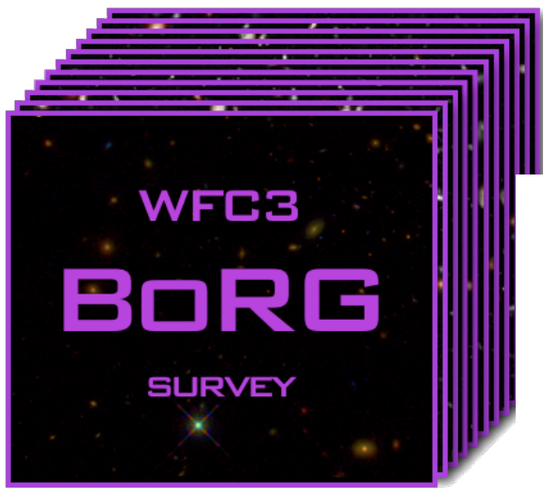
(no modulation by dust or quenching)

Bowler+2014

Finding More Bright z~8-10 Galaxies

Trenti+2015 BoRG$_{[z910]}$

(480 orbit program)

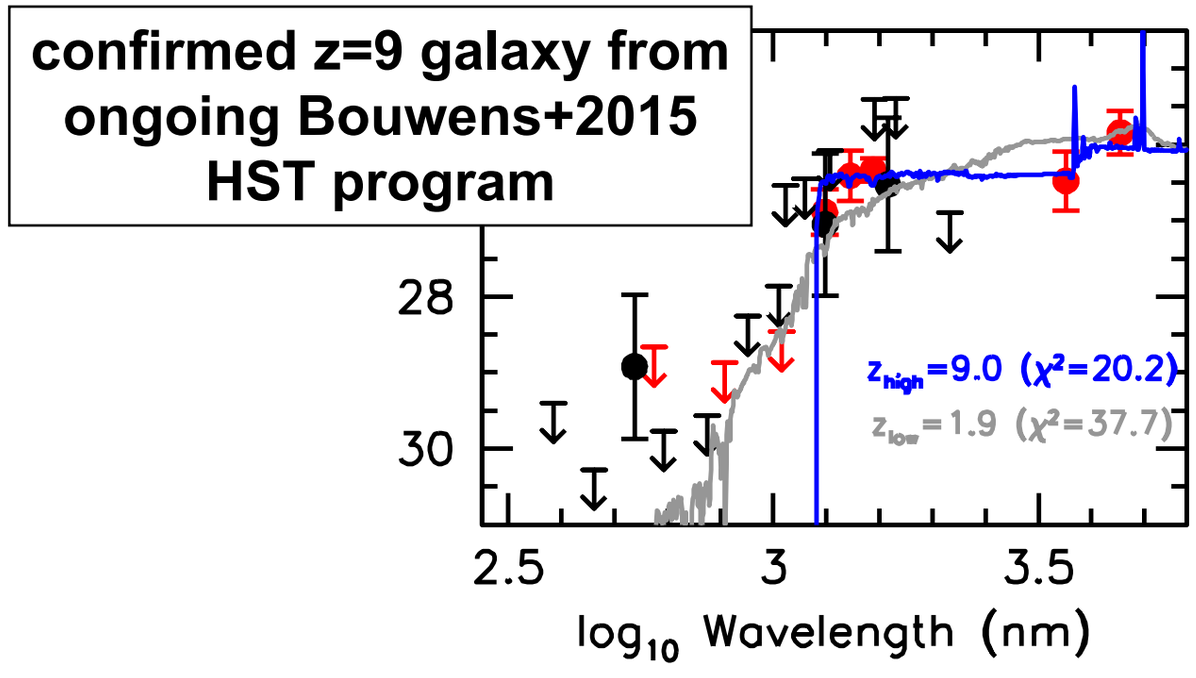


Bouwens+2015 CANDELS Follow-Up Program

(uses all ACS+WFC3 CANDELS area)

Leverages 1400 arcmin^2 search area (full CANDELS + 500 arcmin^2 in additional area)

6 bright z~9-10 galaxies (Oesch+2014)
-> 20 bright z~9-10 galaxies



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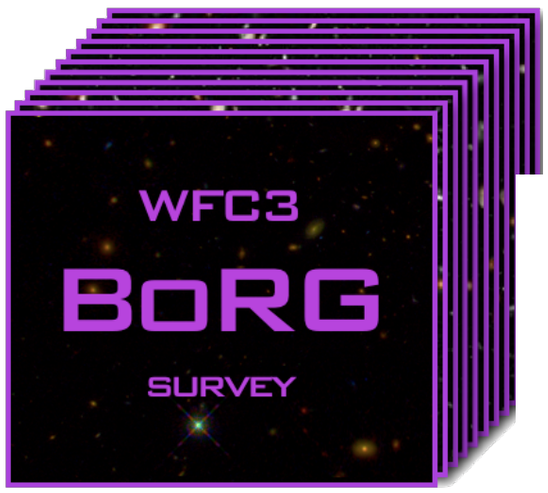

UltraVISTA + UDS + SPLASH + SMUVS

~1.7 deg^2 search area:
→ 26 mag

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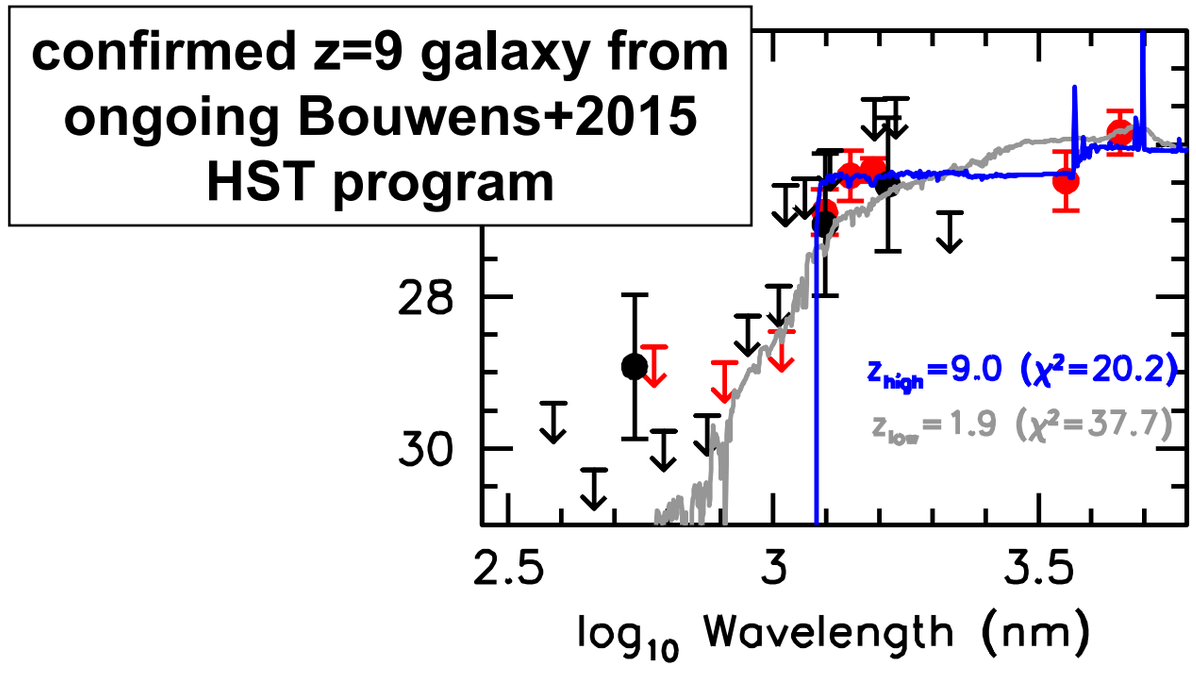
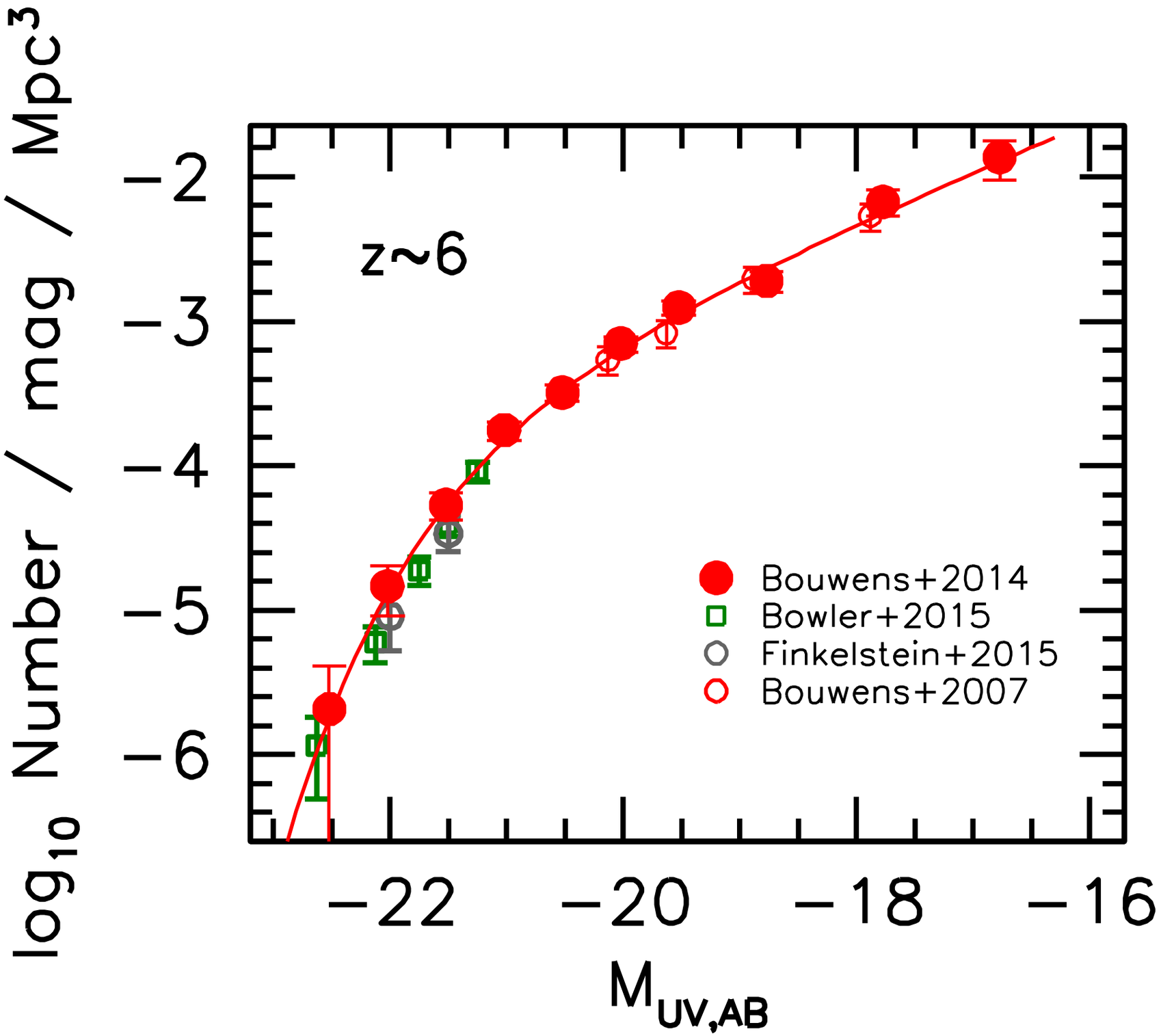


(Despite minor revolution in the # density for bright galaxies since 2013)

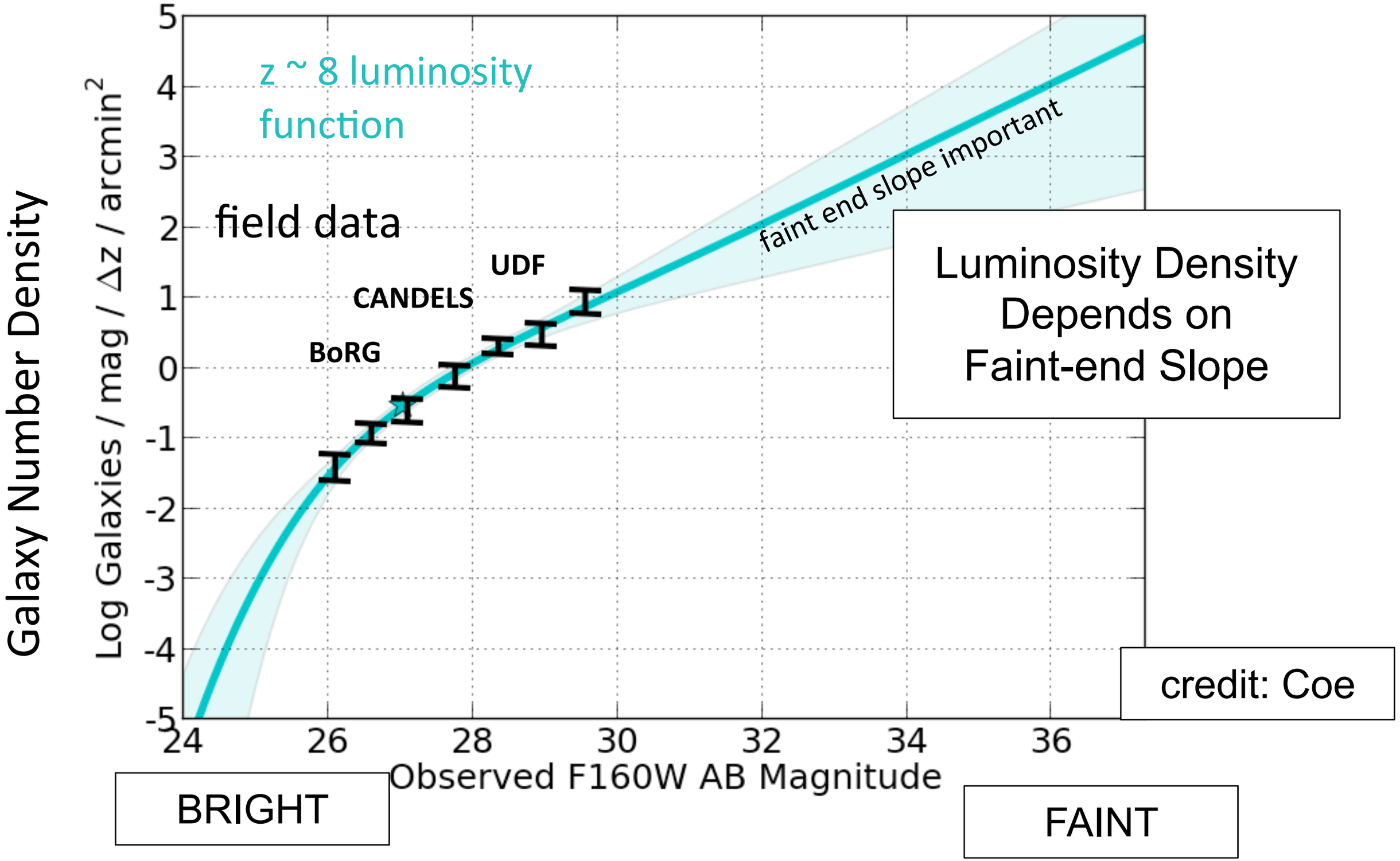
Excellent Agreement Found among 2015 Determinations



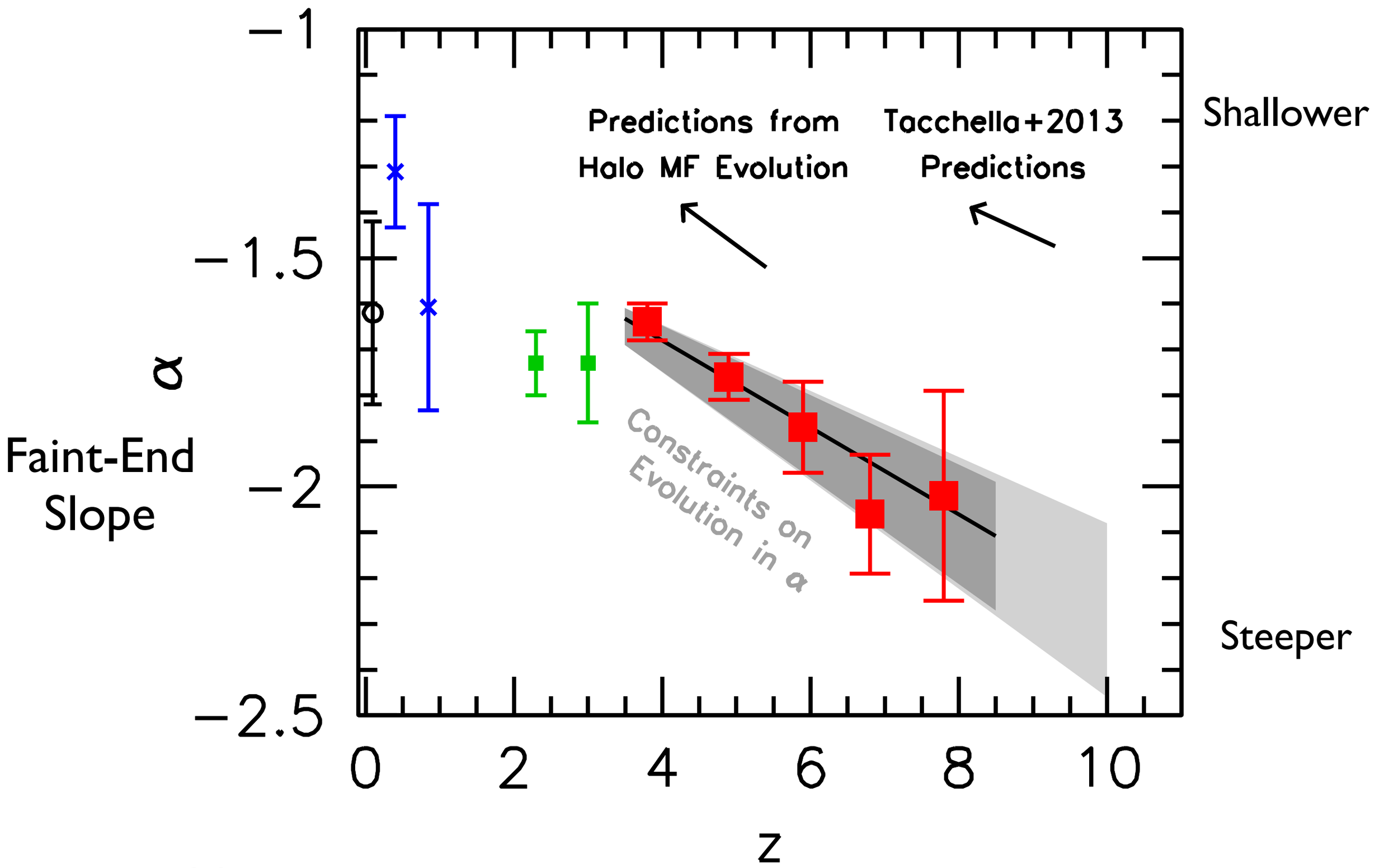
Bouwens+2015; Bowler+2015; Finkelstein+2015; Bouwens+2007

Growth and Build-up of Faint Galaxies

Ultra-Faint Galaxies Dominate UV Light Production at z~3-10

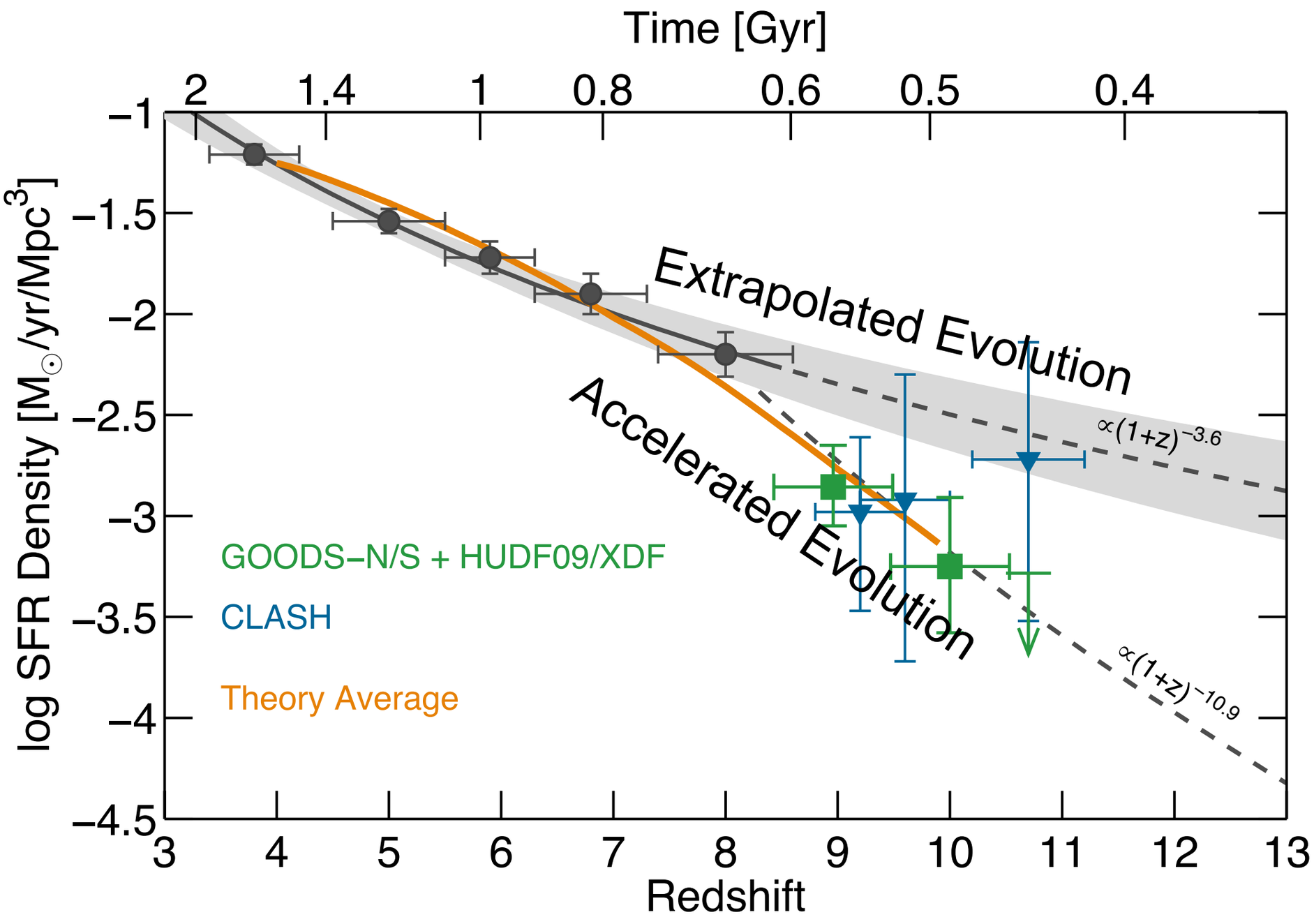


Luminosity Function Steeper at Early Times



Bouwens+2015; see also Bouwens+2011; Oesch+2010, 2012; Bradley+2012; McLure+2013; Schenker +2013; Schmidt+2014; Ishigaki+2014; Finkelstein+2015

Evolution of Luminosity Density to z = 8 → 10



Oesch+2014

Finding More Faint z~8-10 Galaxies

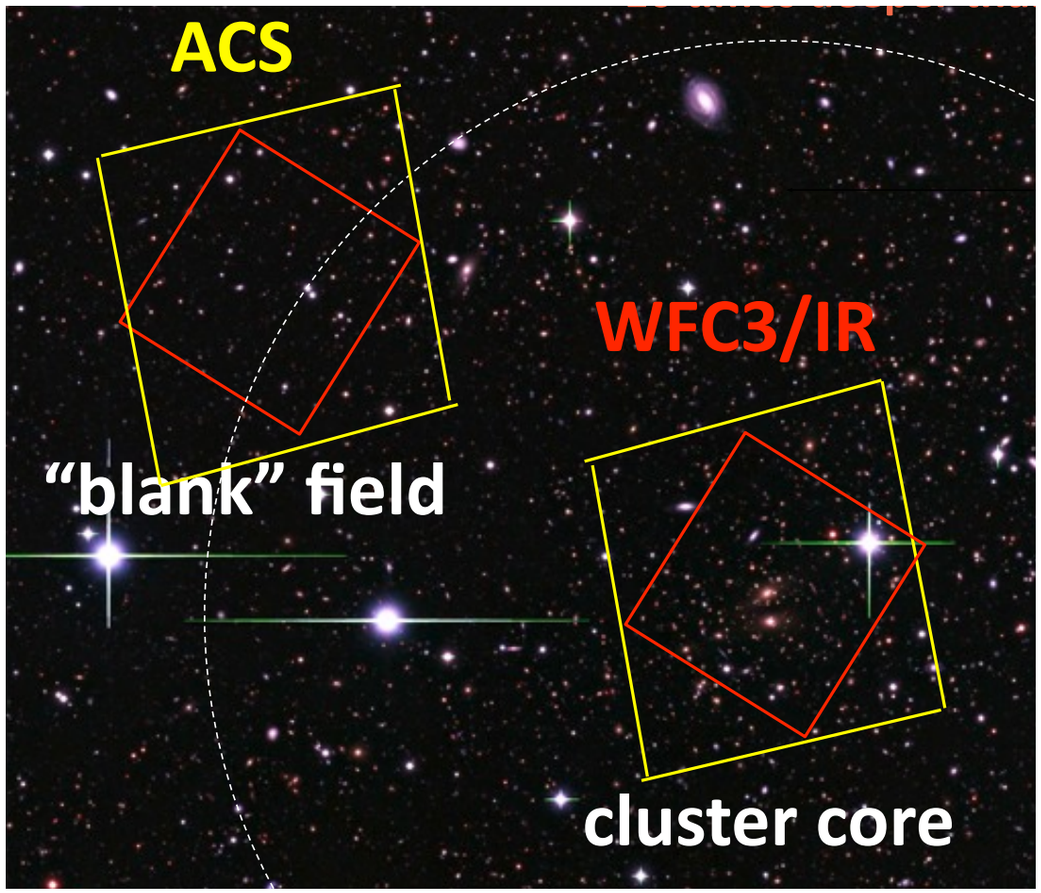
Frontier Fields Program

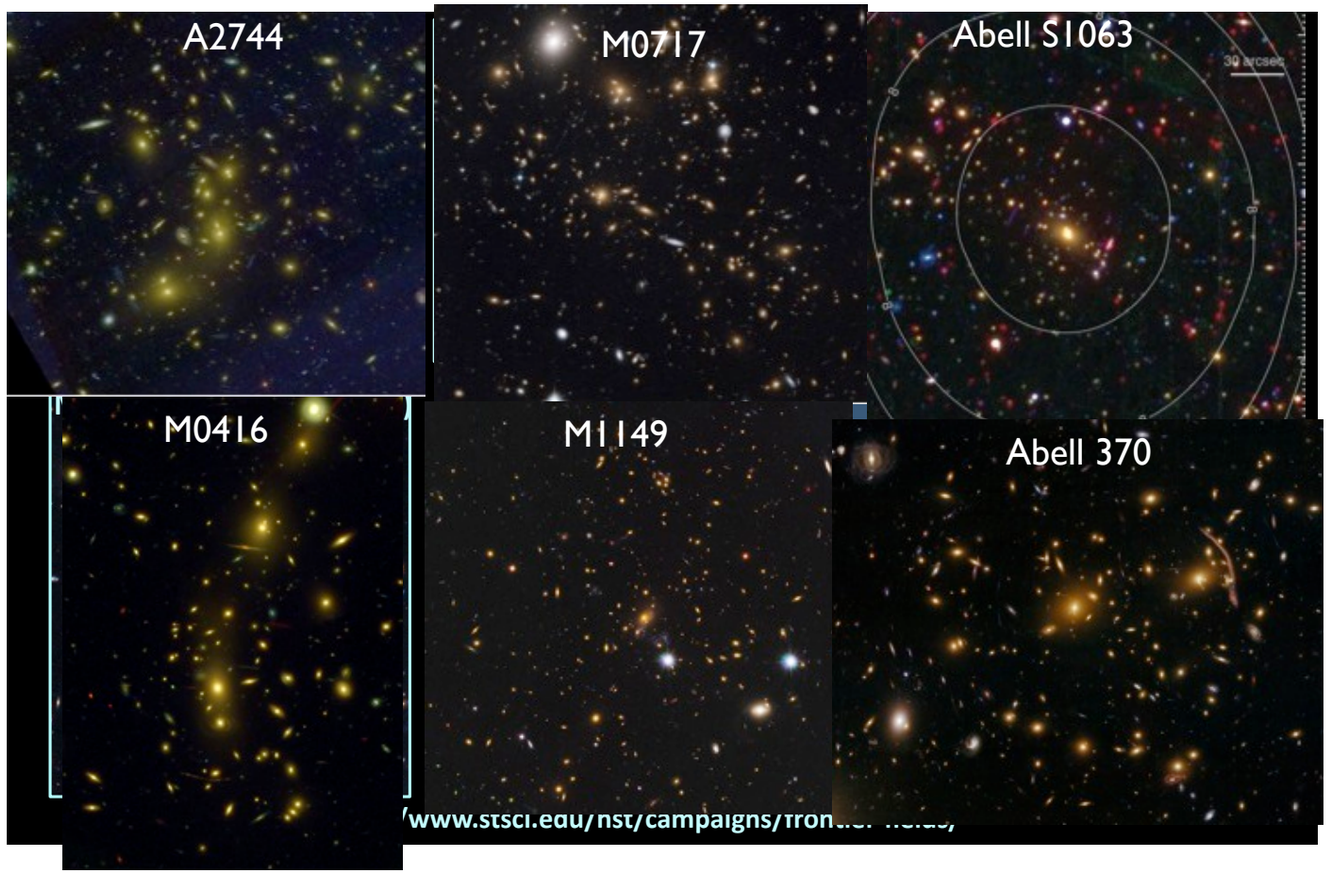
(Matt Mountain, Jennifer Lotz)

6 lensing cluster fields
6 deep "blank" fields
840-orbit program
(60 arcmin^2)

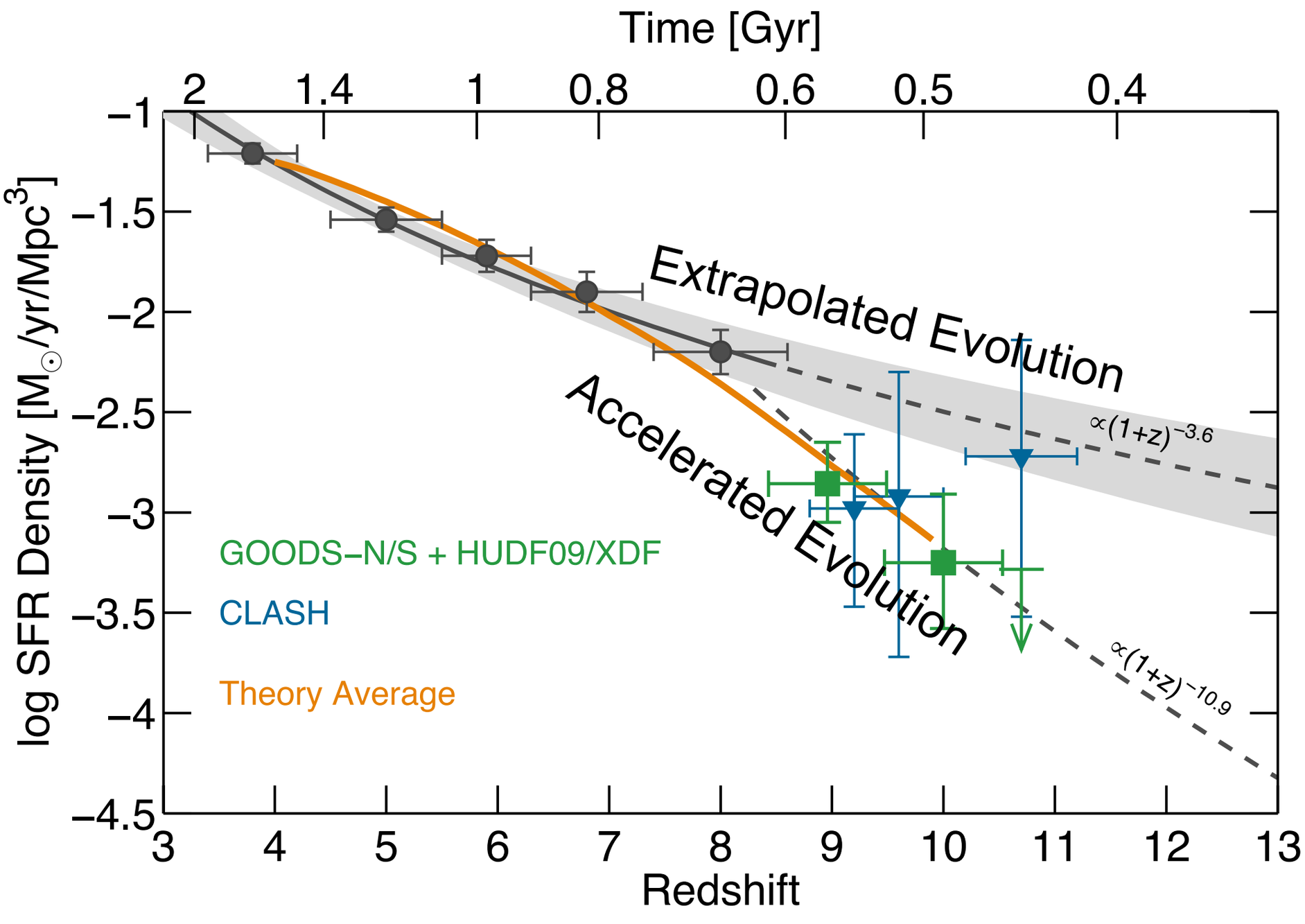
(28.7 mag, 5σ)

(~50% complete)





Evolution of Luminosity Density to z = 8 → 10



Oesch+2014; McLeod+2014; Ishigaki+2014

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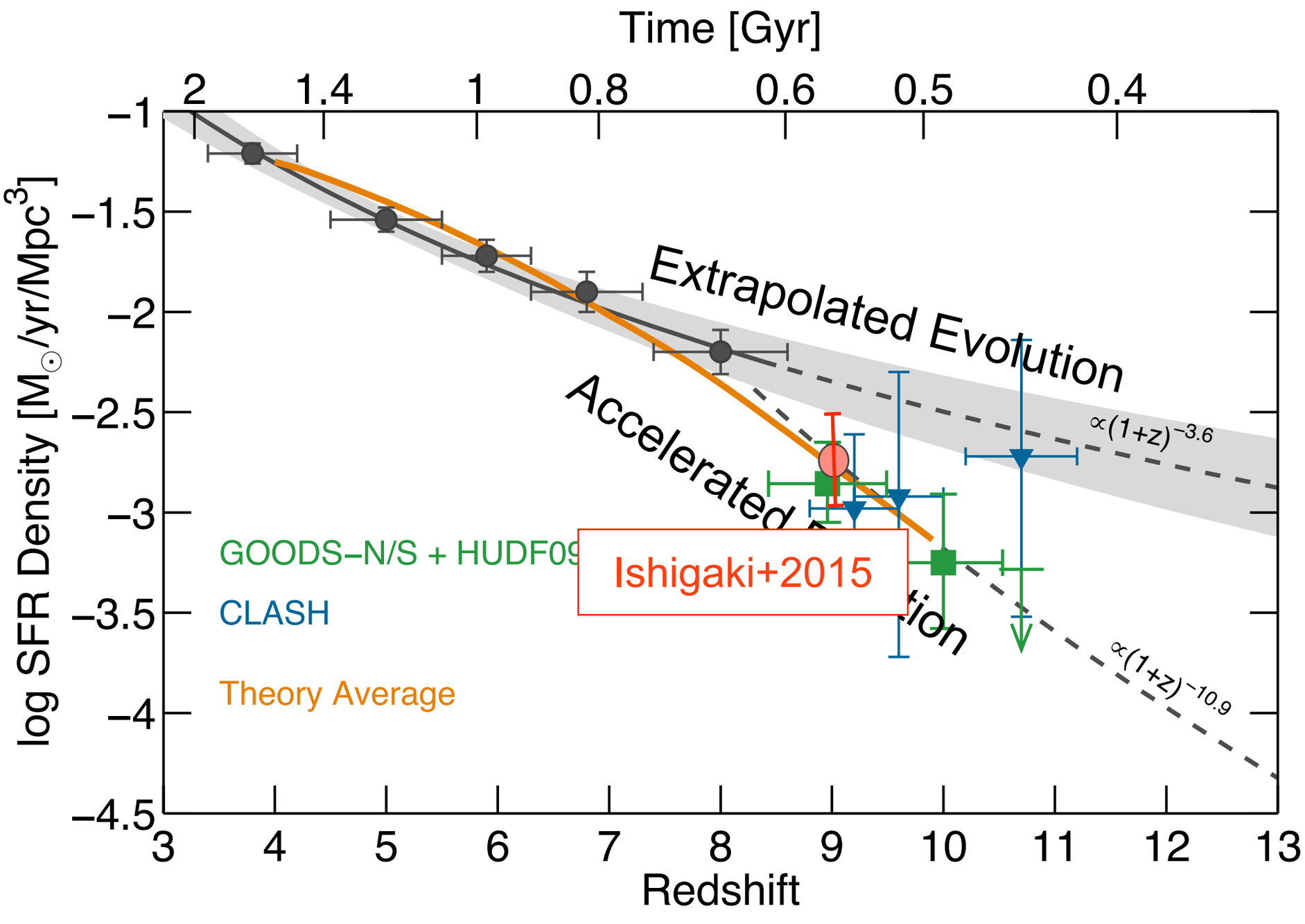

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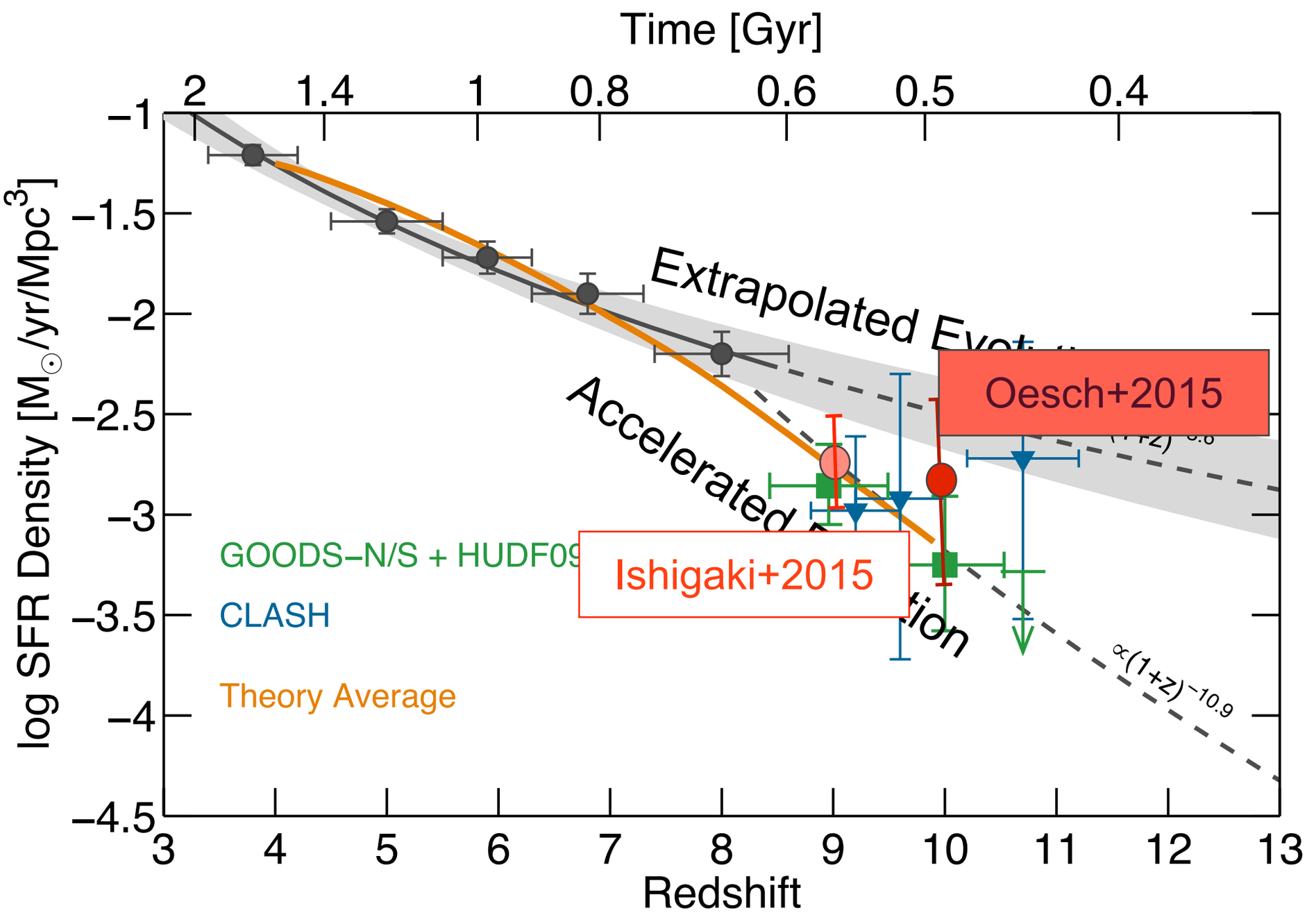

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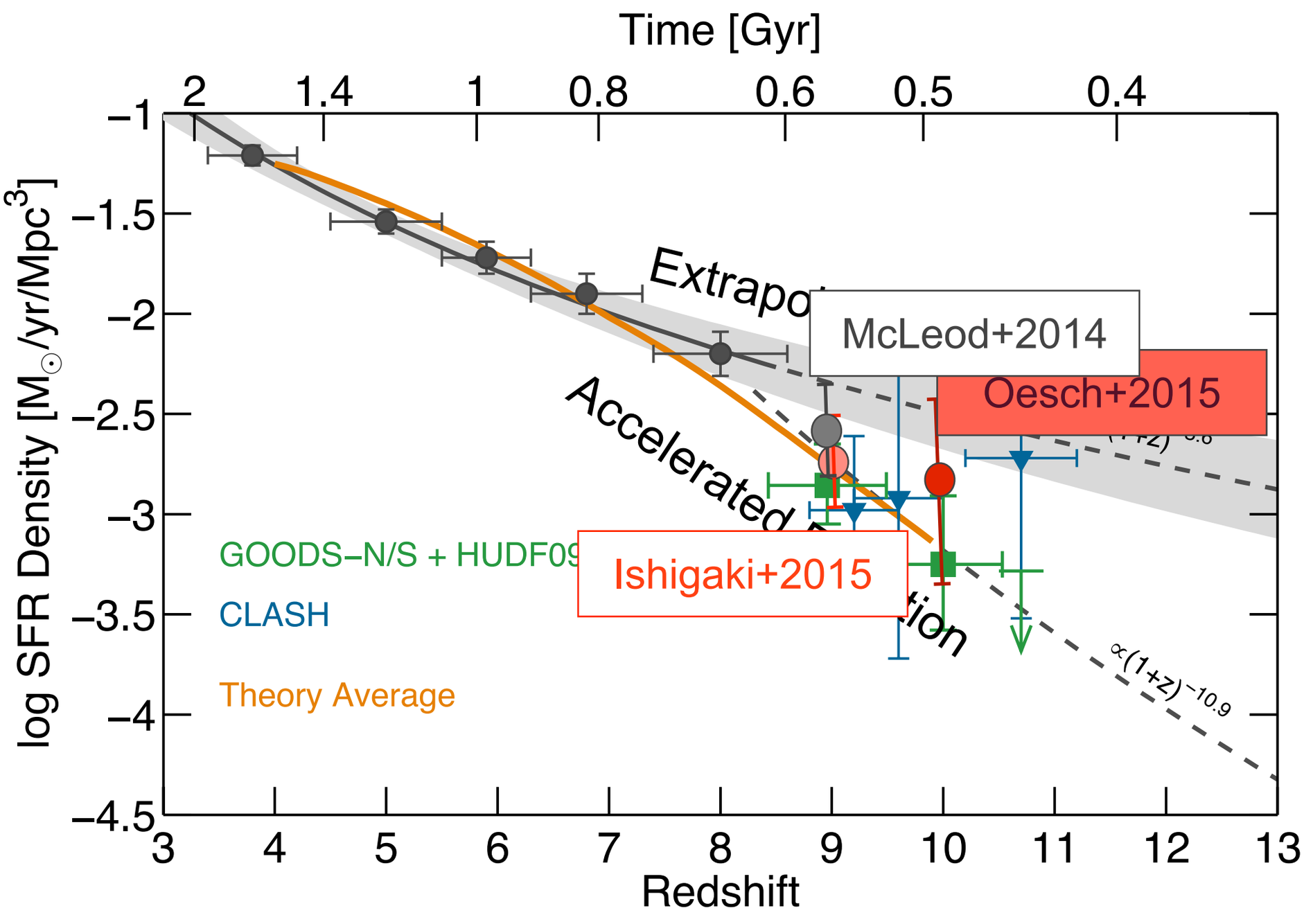

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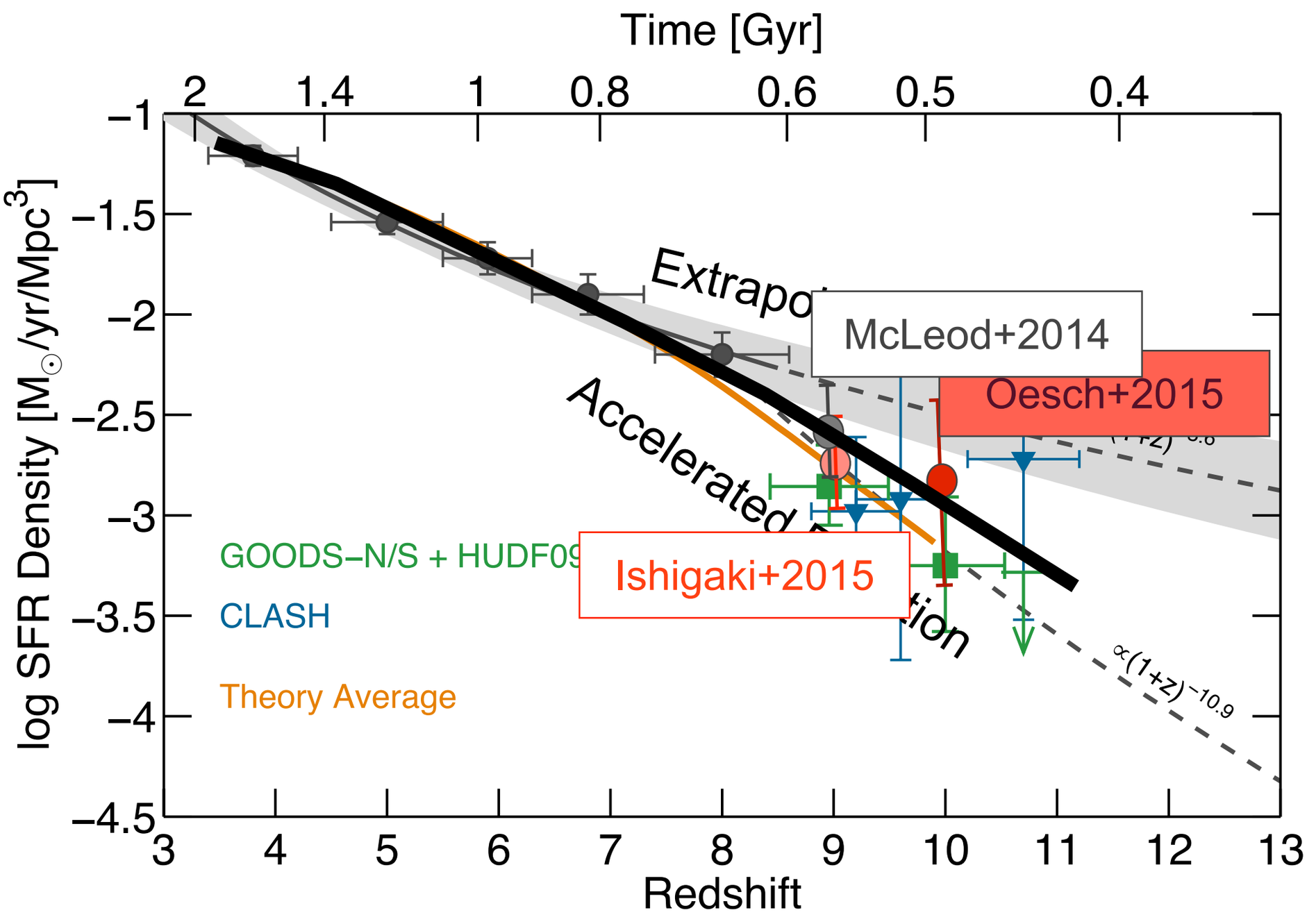
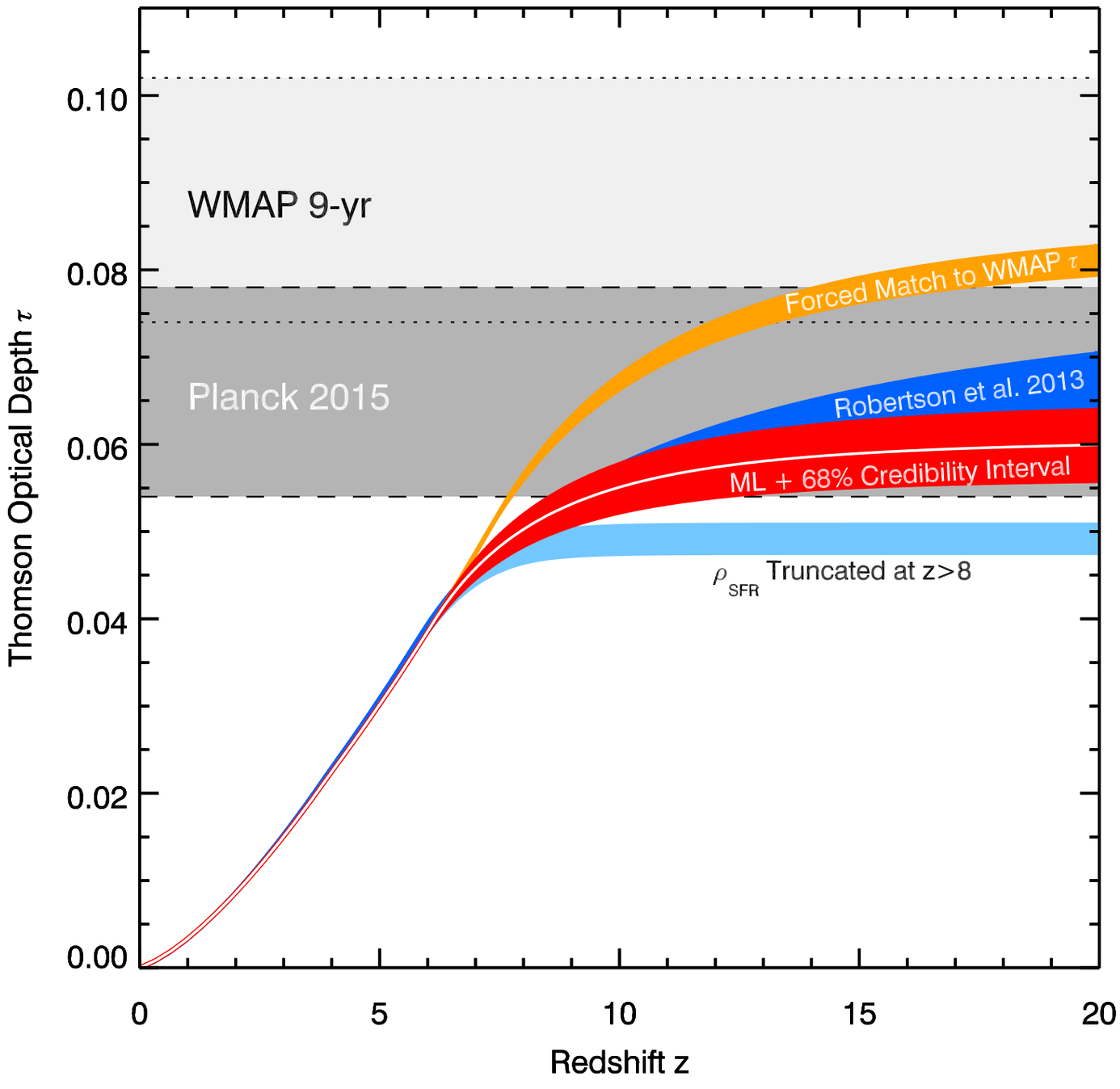
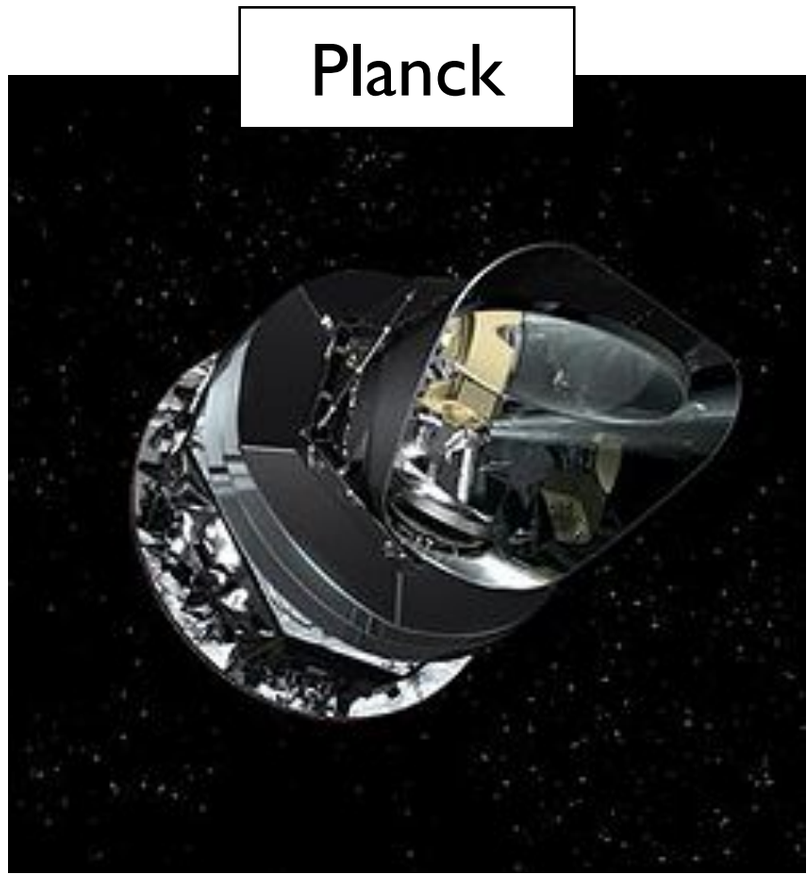


Oesch+2014; McLeod+2014; Ishigaki+2014

New Information on the Reionization of the Universe

New Planck results suggest a less Ionized Universe at z > 7 (τ consistent with UV LF evolution)





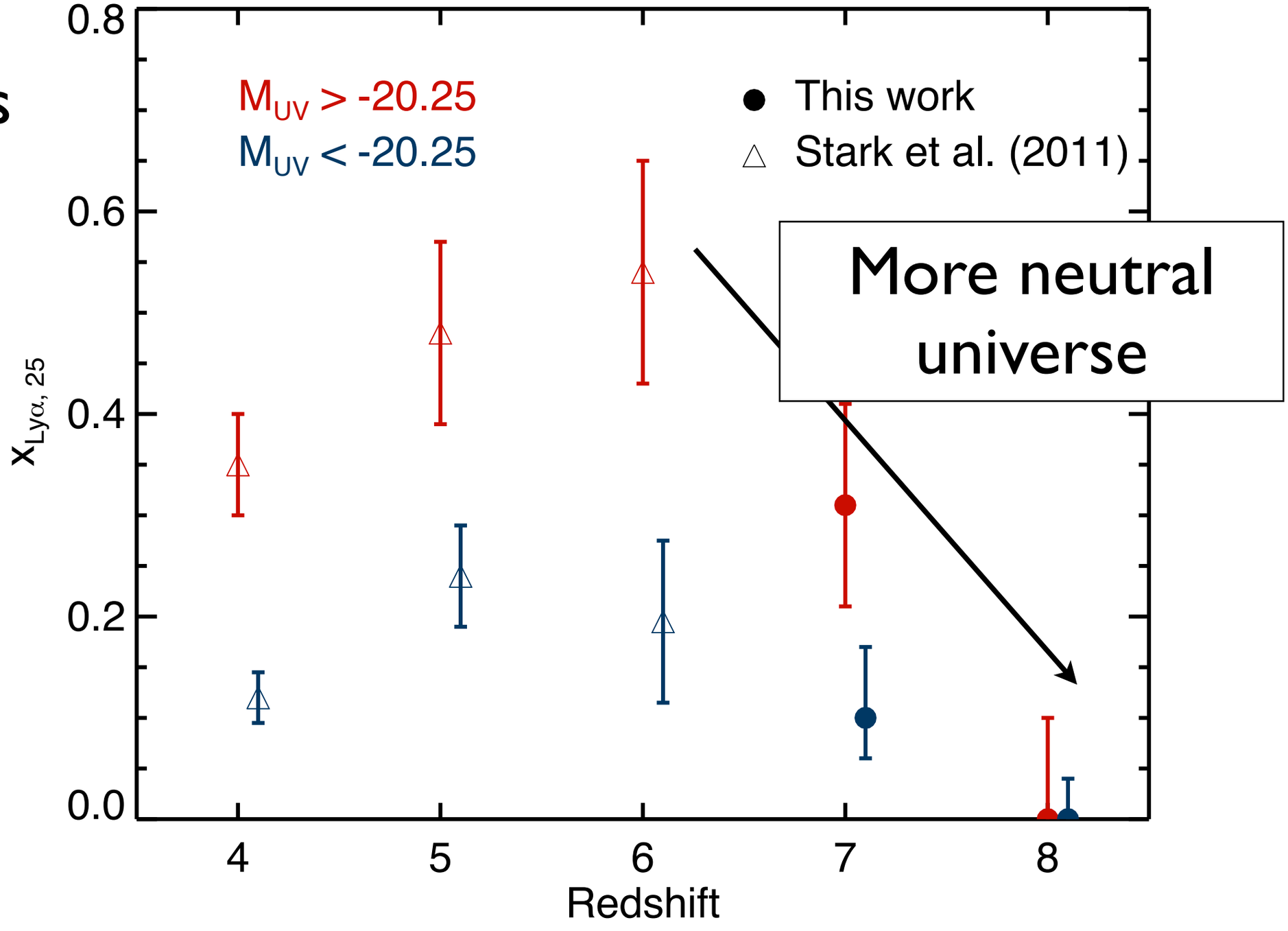
τ = 0.066 ± 0.012

Planck Consortium 2015; Robertson+2015; see also Choudhury+2015

Increasing Statistics Available on Prevalence of Lyα Emission in z=7-8 Galaxies

~ 100 sources well probed

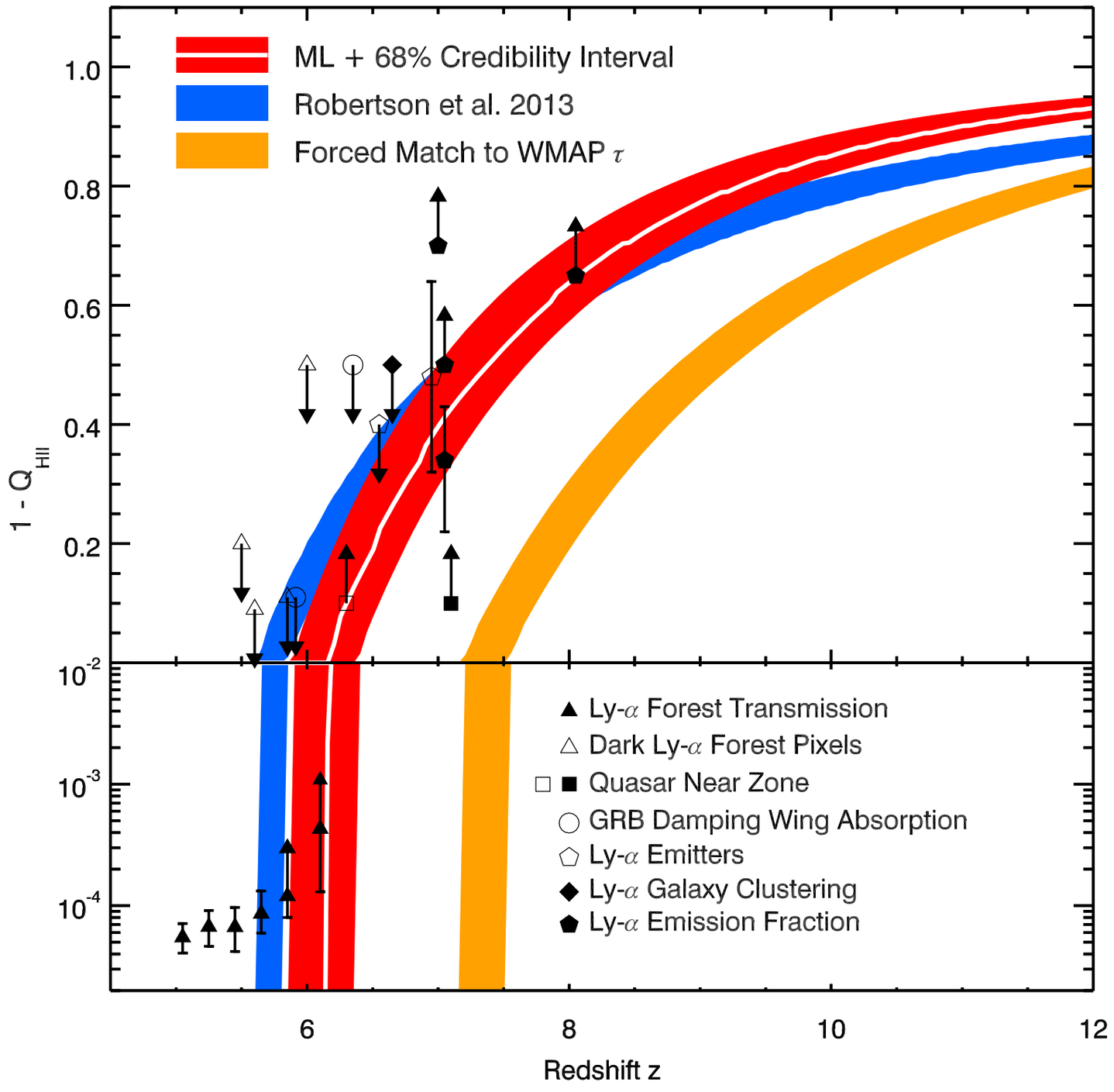
Fraction of Galaxies with Lyα EWs > 25 Angstroms



Schenker+2014; see also Pentericci+2011/2014; Tilvi+2014; Treu+2013; Stark +2010; Fontana+2010; Caruana+2012, 2014; Schenker et al. 2012; Ono+2012

Self-consistent Picture of Cosmic Reionization now available

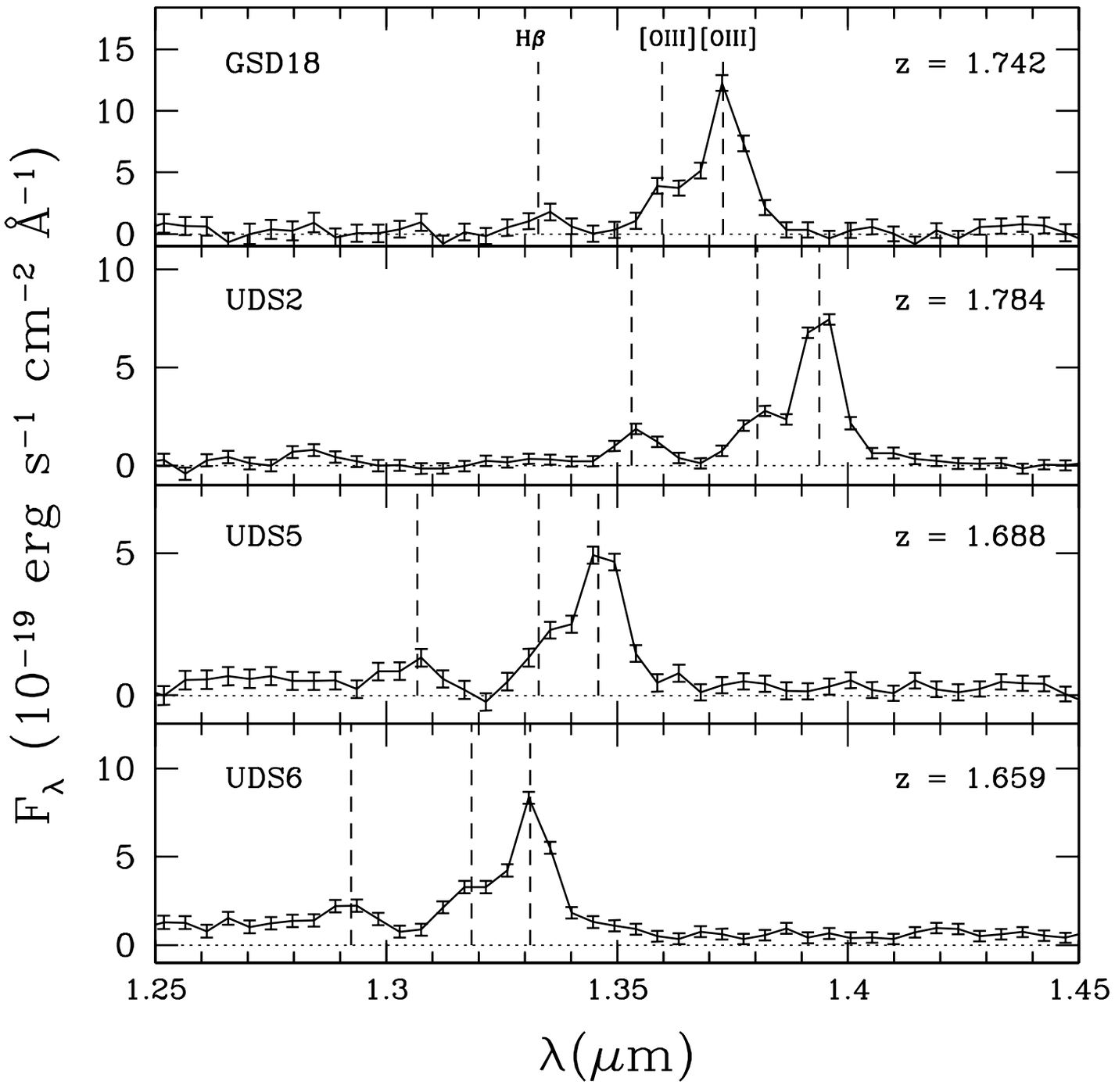
Filling Factor of Neutral Hydrogen



Robertson+2015

z~4-9 Galaxies Also Show Strong Nebular Line Emission: Hα + [OIII]

Nebular Emission lines ([OIII], Hα) Prominent in z>1 Galaxies

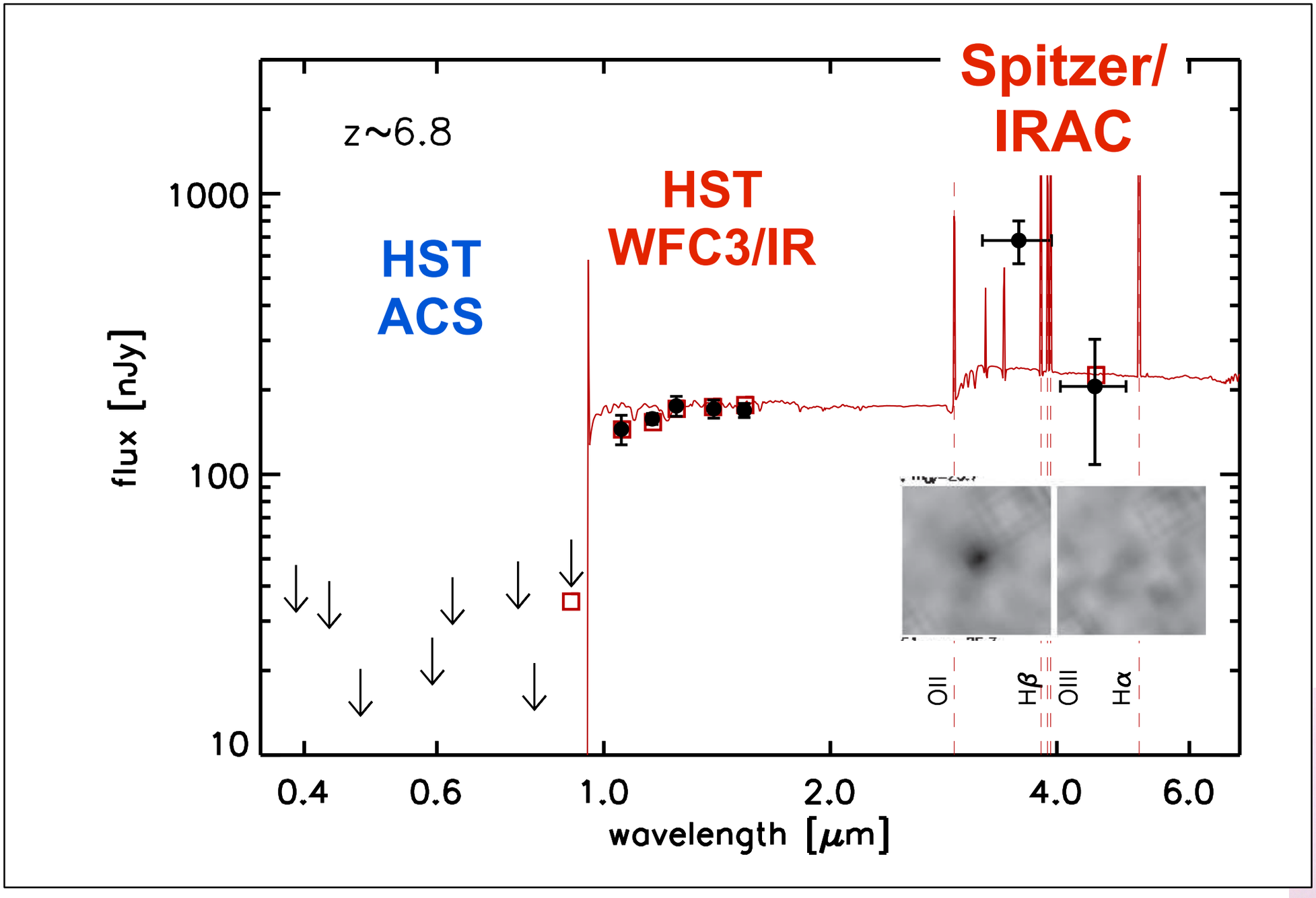


Rest-frame EWs ~ 1000 Angstroms

van der Wel+2011; see also Atek+2011; Brammer+2012

Nebular Emission Lines ([OIII], Hα) are Especially Bright at z~4-8

Example:



Smit+2014

Renske Smit

Strong Nebular Emission Lines allow for many scientific gains:

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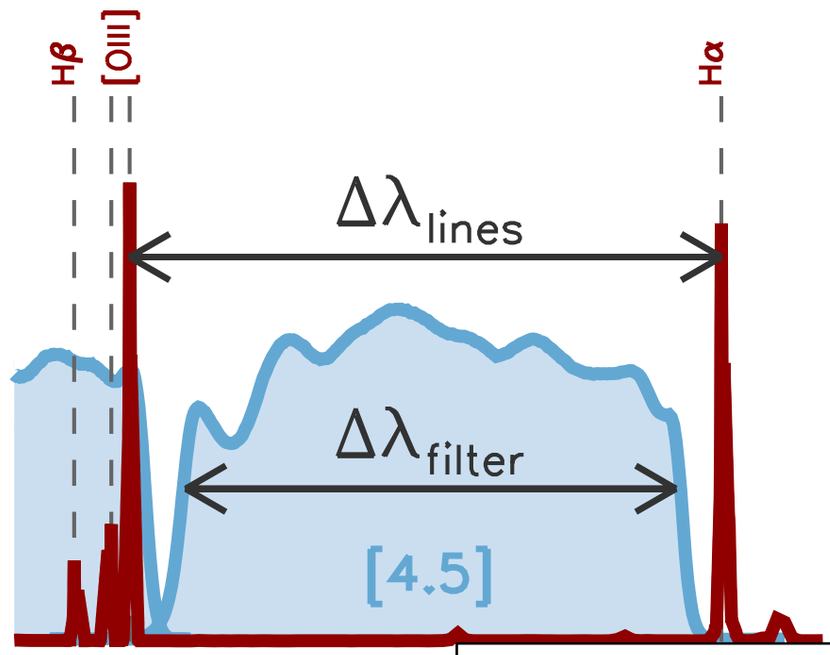
Substantially Improved Photometric Redshifts (useful for ALMA follow-up)

Narrow redshift window where [4.5] band misses [OIII]+Hα

(~30 sources identified with extreme colors)



credit: Smit+2015

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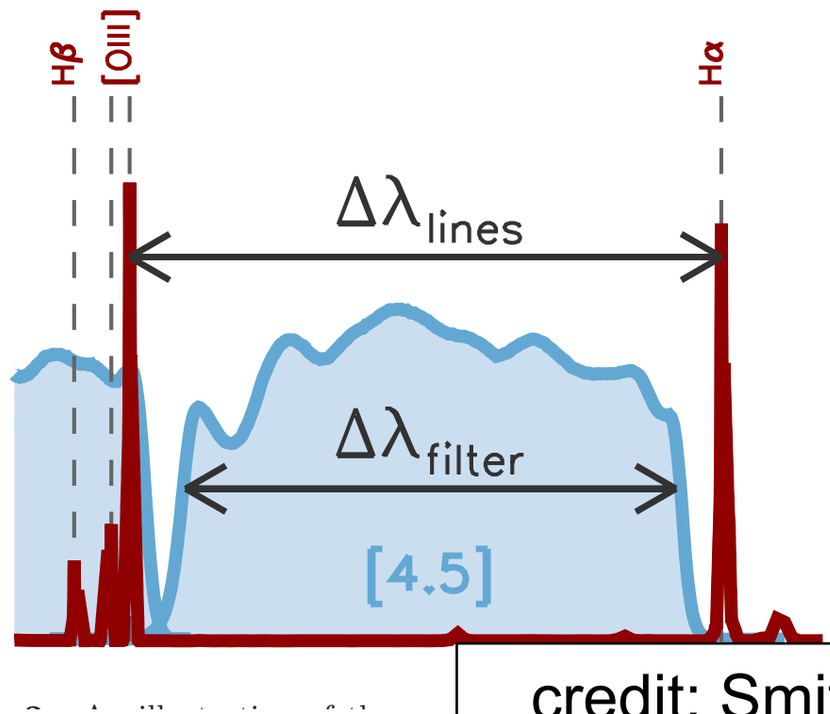

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Metallicity, SFR, or Ionization State

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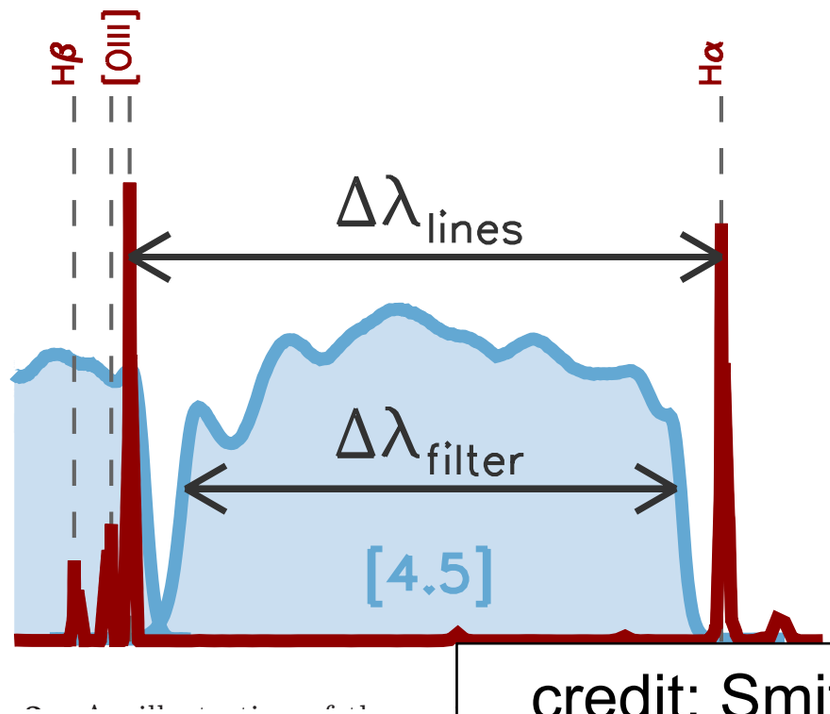


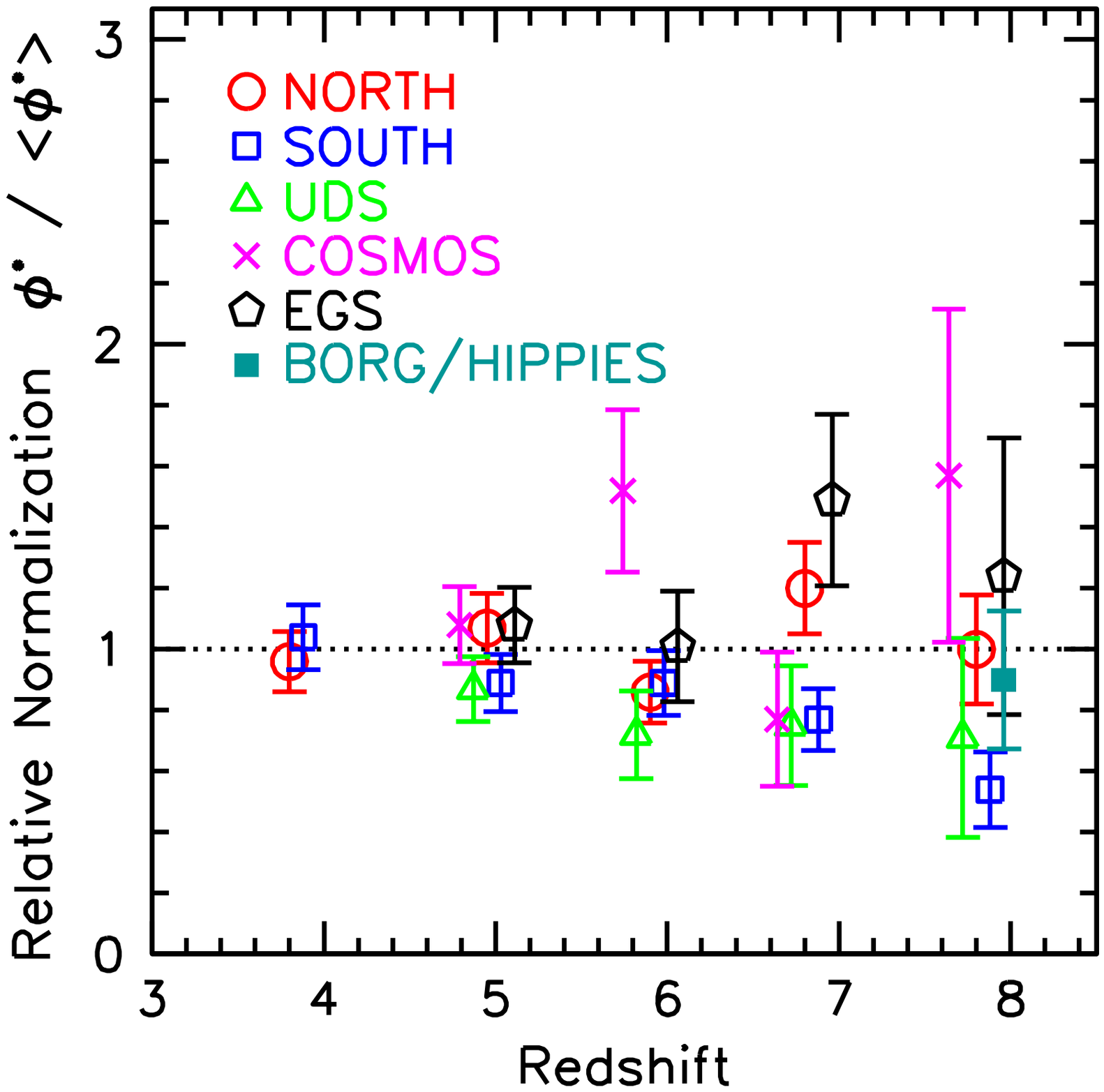
credit: Smit+2015

Metallicity, SFR, or Ionization State

Uncertain Stellar Mass Estimates (if improperly corrected)

Continuing Challenges....

Field-to-Field Variations are Large!



Bouwens+2015

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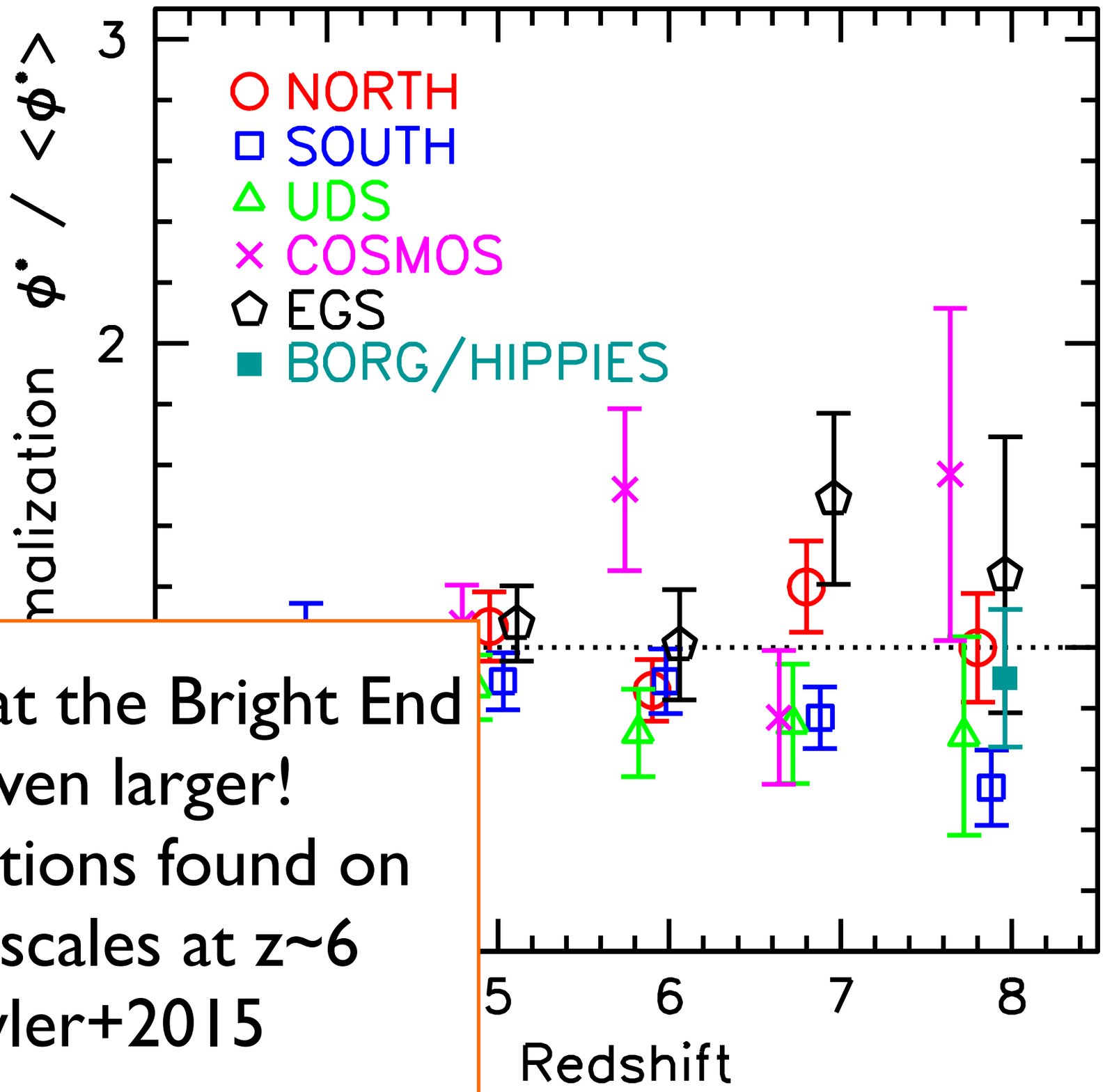

Variations at the Bright End are even larger!
~2x variations found on degree scales at z~6
Bowler+2015

Bouwens+2015

Clearer Physical Interpretation of Observations Needed!

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Deriving Physical Parameters (Masses, Metallicities,
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Part of the Answer = Deep Spectroscopy

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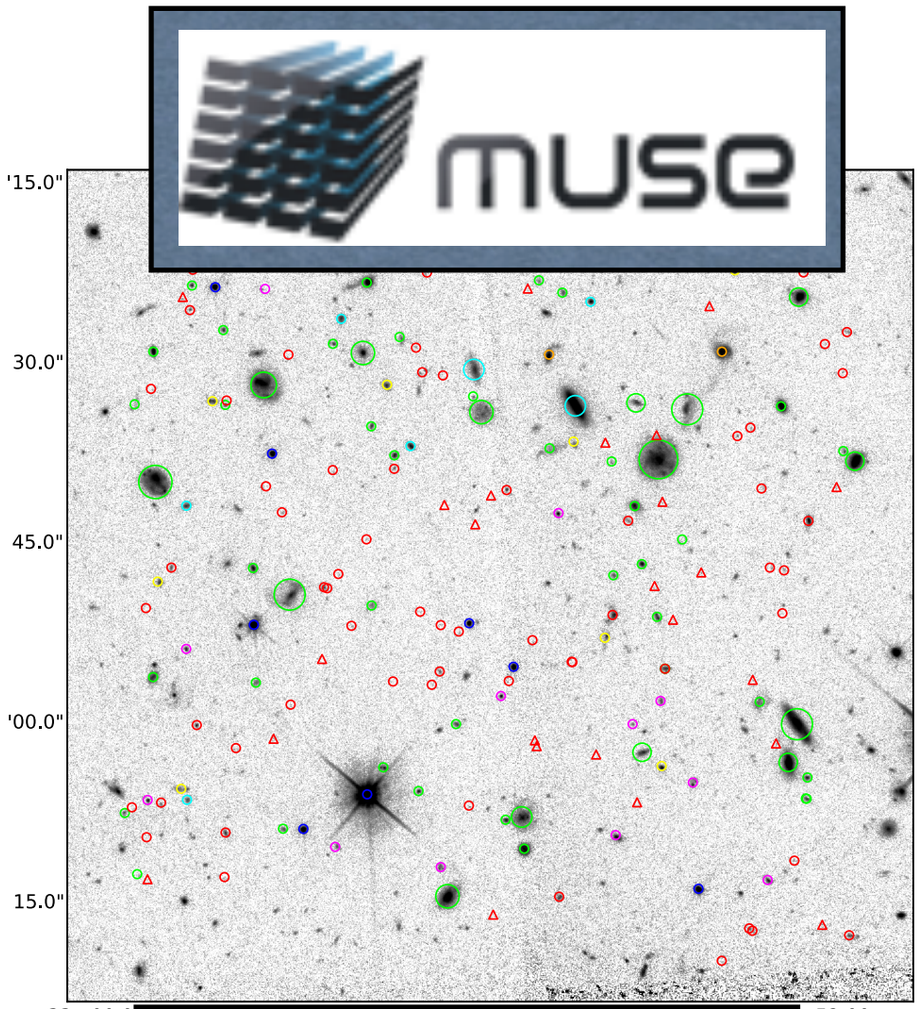

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~200 redshifts / arcmin^2

MUSE GTO: 260 nights

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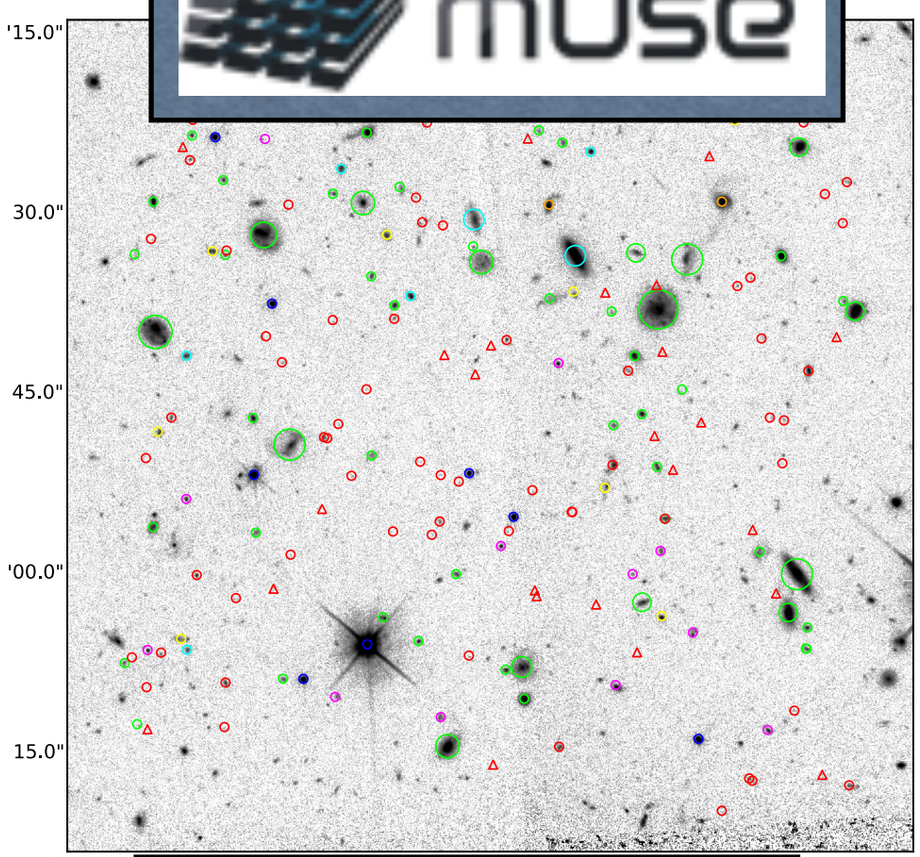

'arame

as Mas

~600 hour program / 2400 sources

A deep VIMOS survey of the CANDELS UDS and CDFS fields

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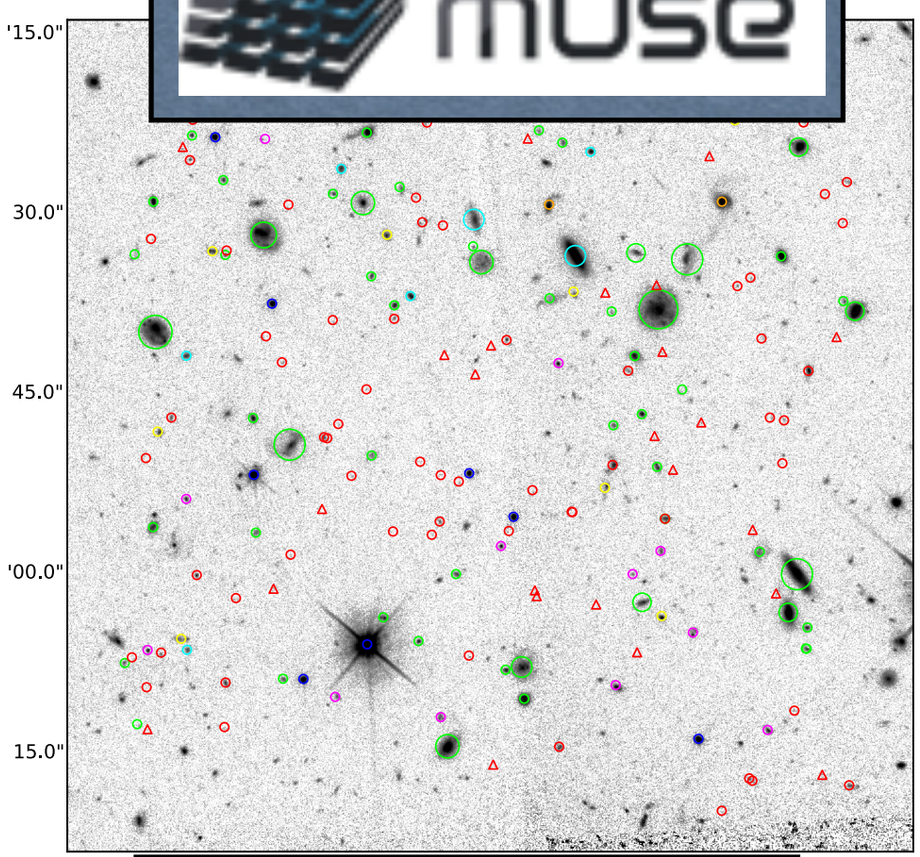

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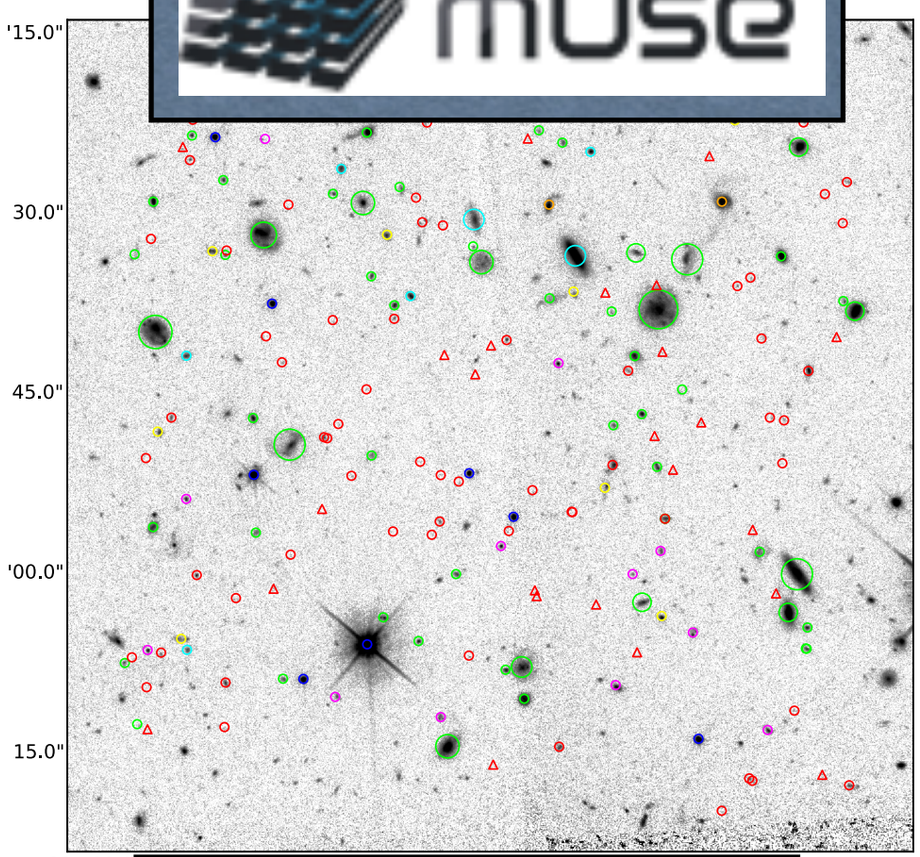

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Part of the Answer = Deep ALMA Observations

Dust Continuum

Gas Masses from CO lines

SFRs / Other Information from Cooling Lines

Interpretation of Strong Nebular Emission Lines at z>4?

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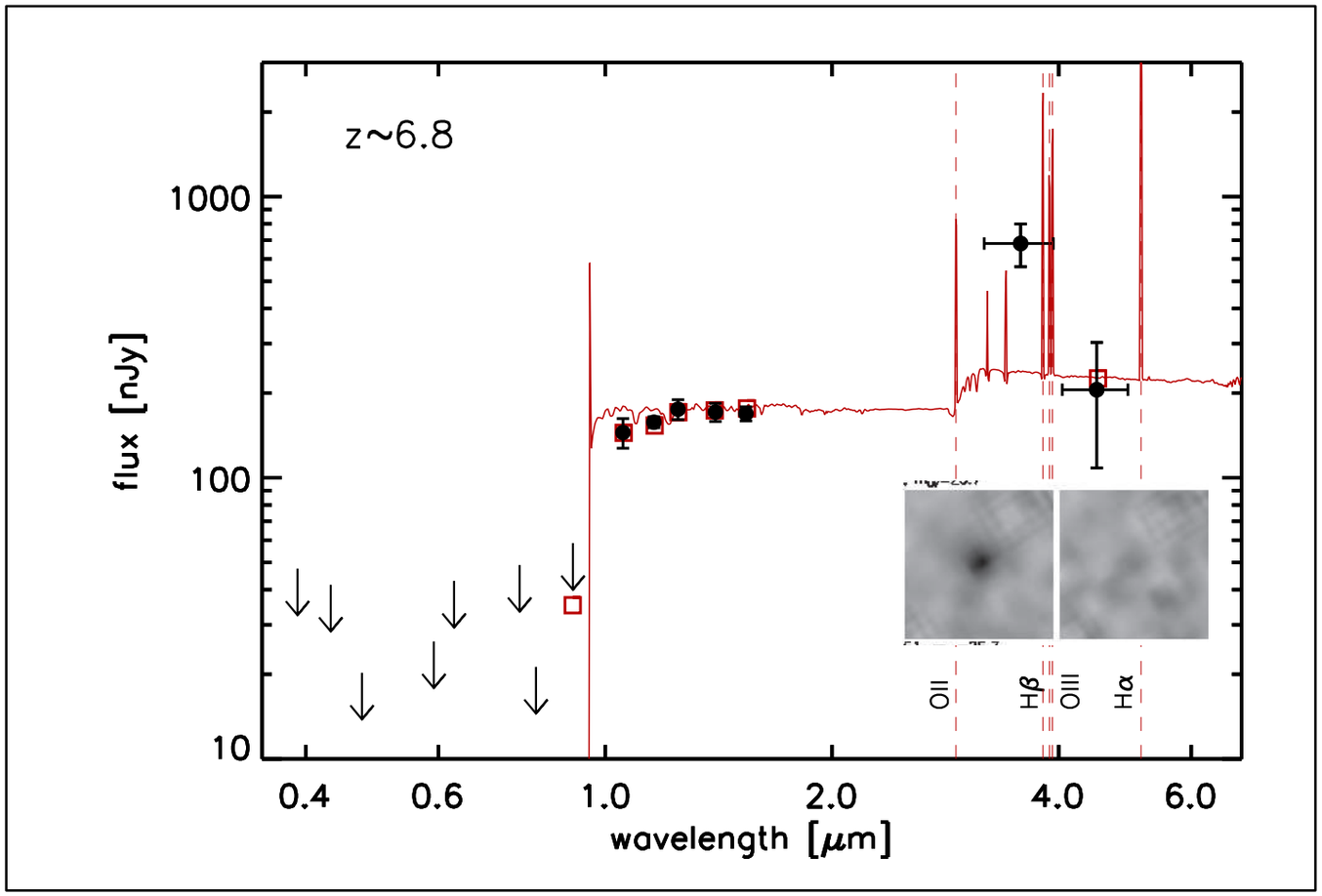
Objects like this appear to be typical



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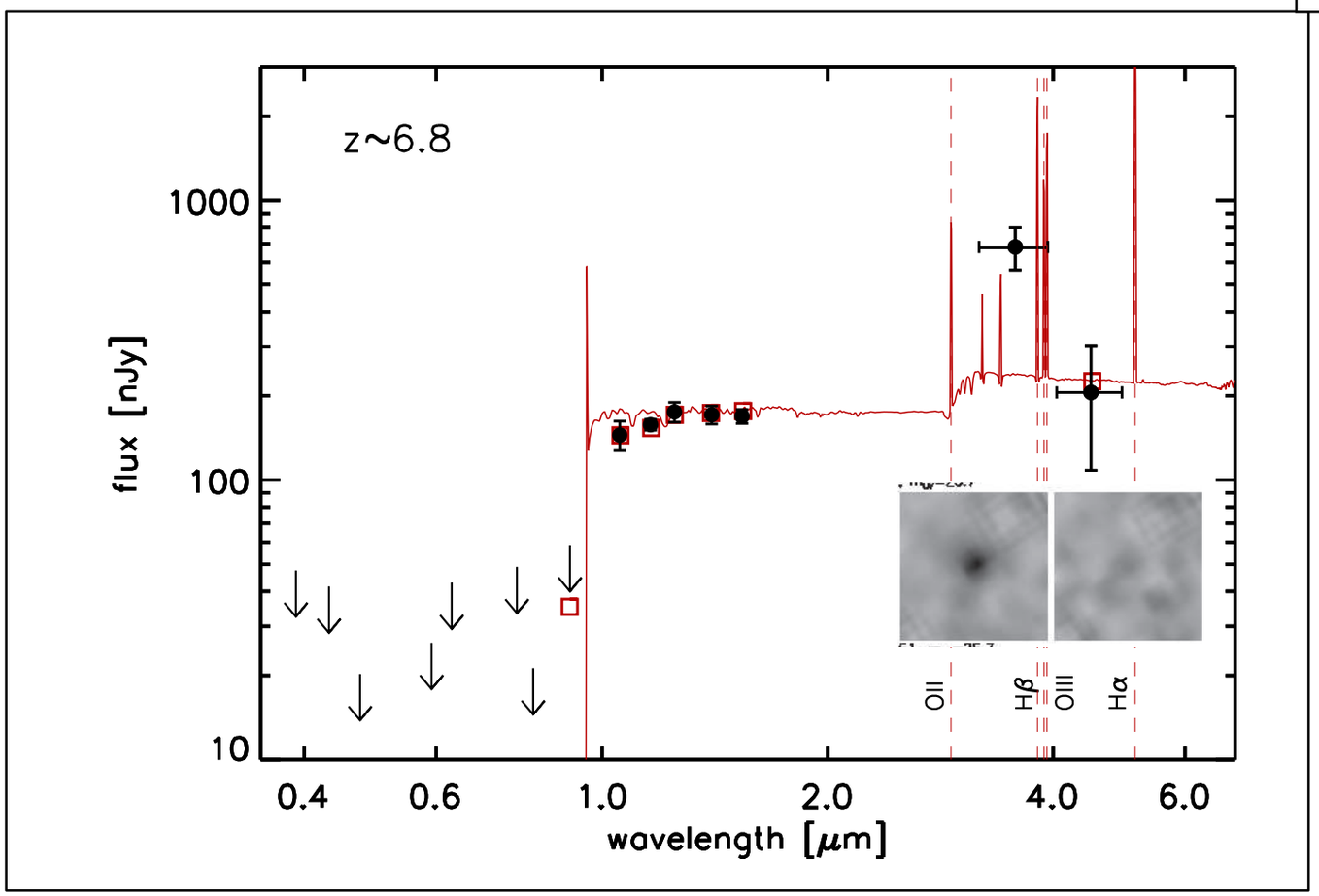

Conventional Models would require these sources to be extremely young

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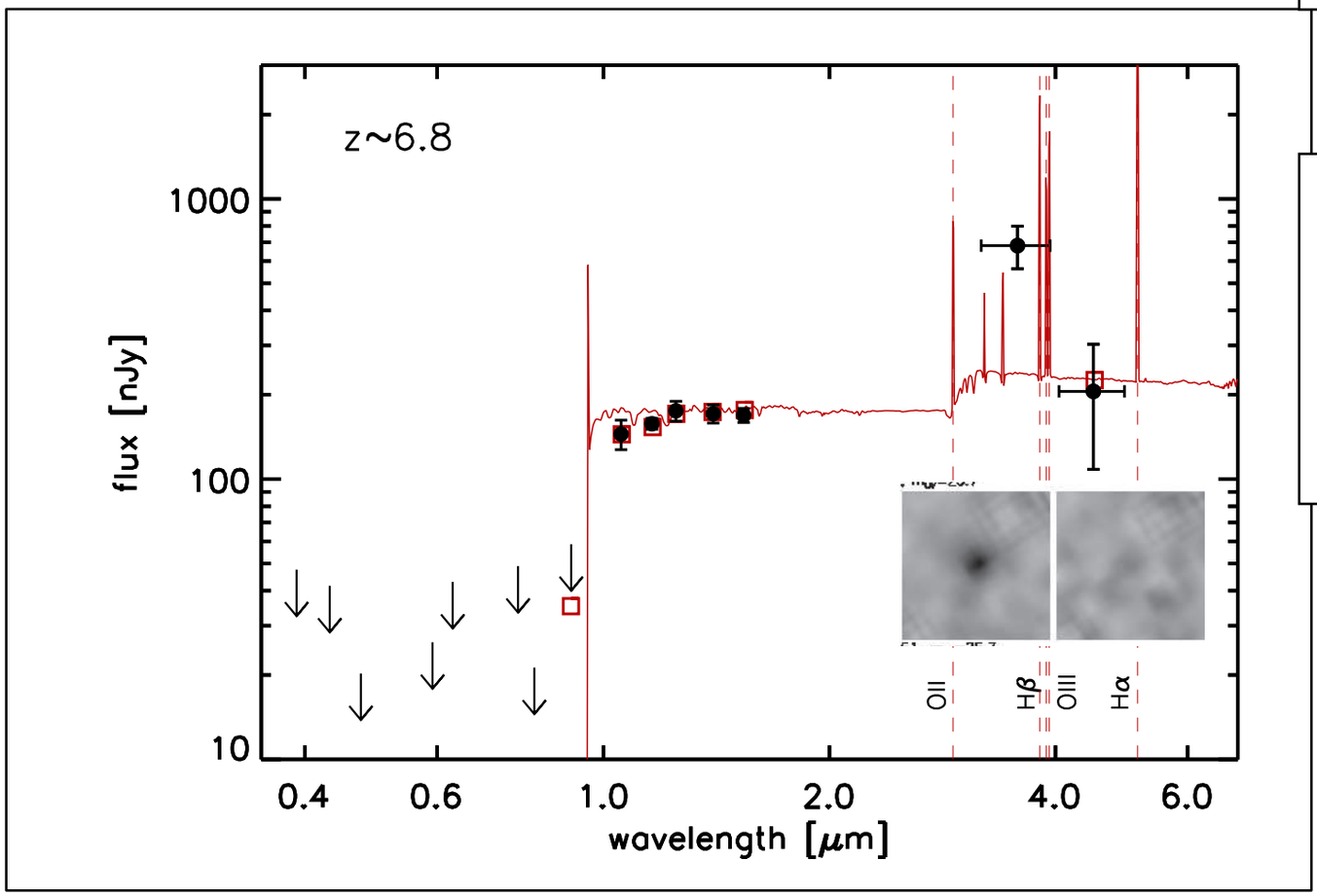

Conventional Models would require these sources to be extremely young

Yet such objects are ubiquitous!

Why?

Observations of the High-Redshift Universe: Summary

Current facilities (HST with ACS+WFC3/IR) are allowing for the selection of large $>10^4$-object samples of galaxies to z~11, with spectroscopic redshifts out as high as z=7.73.

Huge progress has been made in understanding galaxy growth with the Hubble Space Telescope... in terms of the UV luminosity density, UV LFs, and galaxy stellar mass functions.

Modest numbers of intrinsically highly luminous z~7-10 galaxies have been recently discovered. The existence of these objects suggest little impact of dust or quenching on UV luminosities of these rare, high-σ peaks

Current observations suggest the faint-end slope of the UV LF becomes increasingly steep at z>6. The UV luminosity density shows moderately smooth evolution to z~9, but may show faster evolution at z>9.

High-redshift EW nebular emission lines are particularly ubiquitous in z>8 galaxies.

Key challenges for progress in galaxy formation include achieving a more physical understanding of galaxies, coping with large field-to-field variance, and obtaining a better understanding of strong nebular emission at z>~2-8.