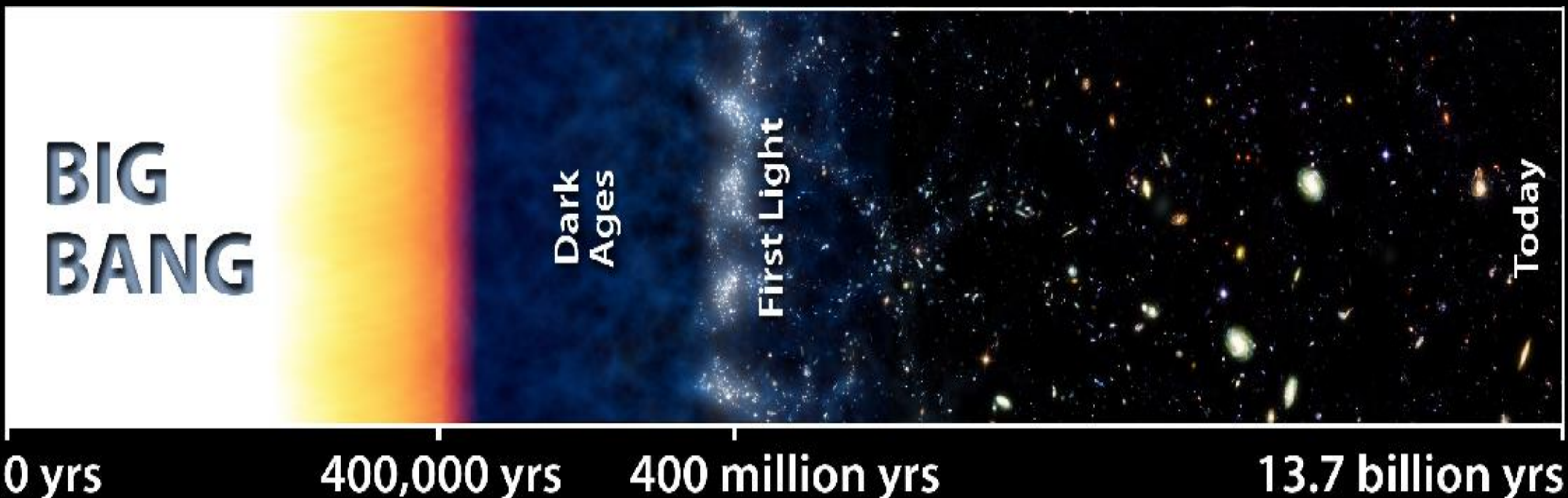
The Cosmic History of Star Formation



James Dunlop
Institute for Astronomy, University of Edinburgh

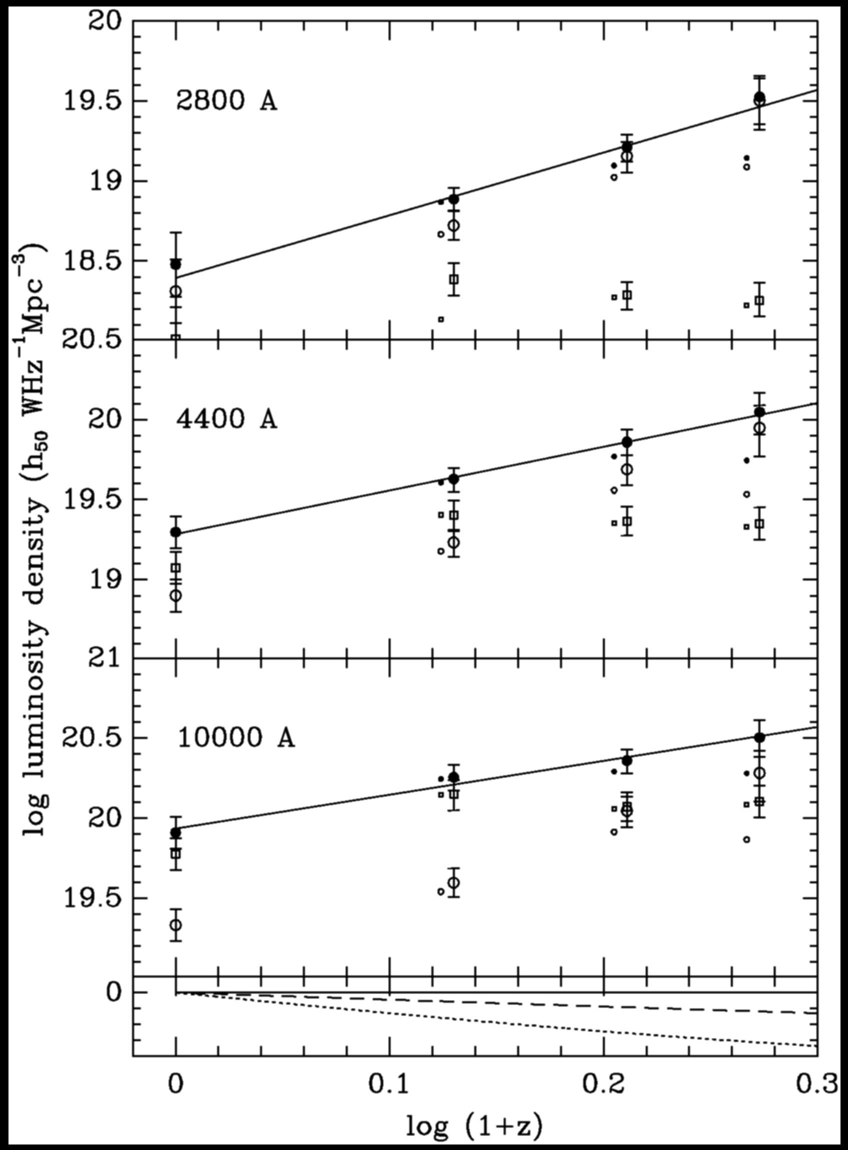
PLAN

1. Background
2. Star-formation rate (SFR) indicators
3. The last ~11 billion years: $0 < z < 3$
4. The first ~2 billion years: $3 < z < ?$ – HUDF12
5. A complete cosmic history of SFR density?
6. The growth of stellar mass - a consistent picture?
7. Summary, issues & future prospects – ALMA deep field

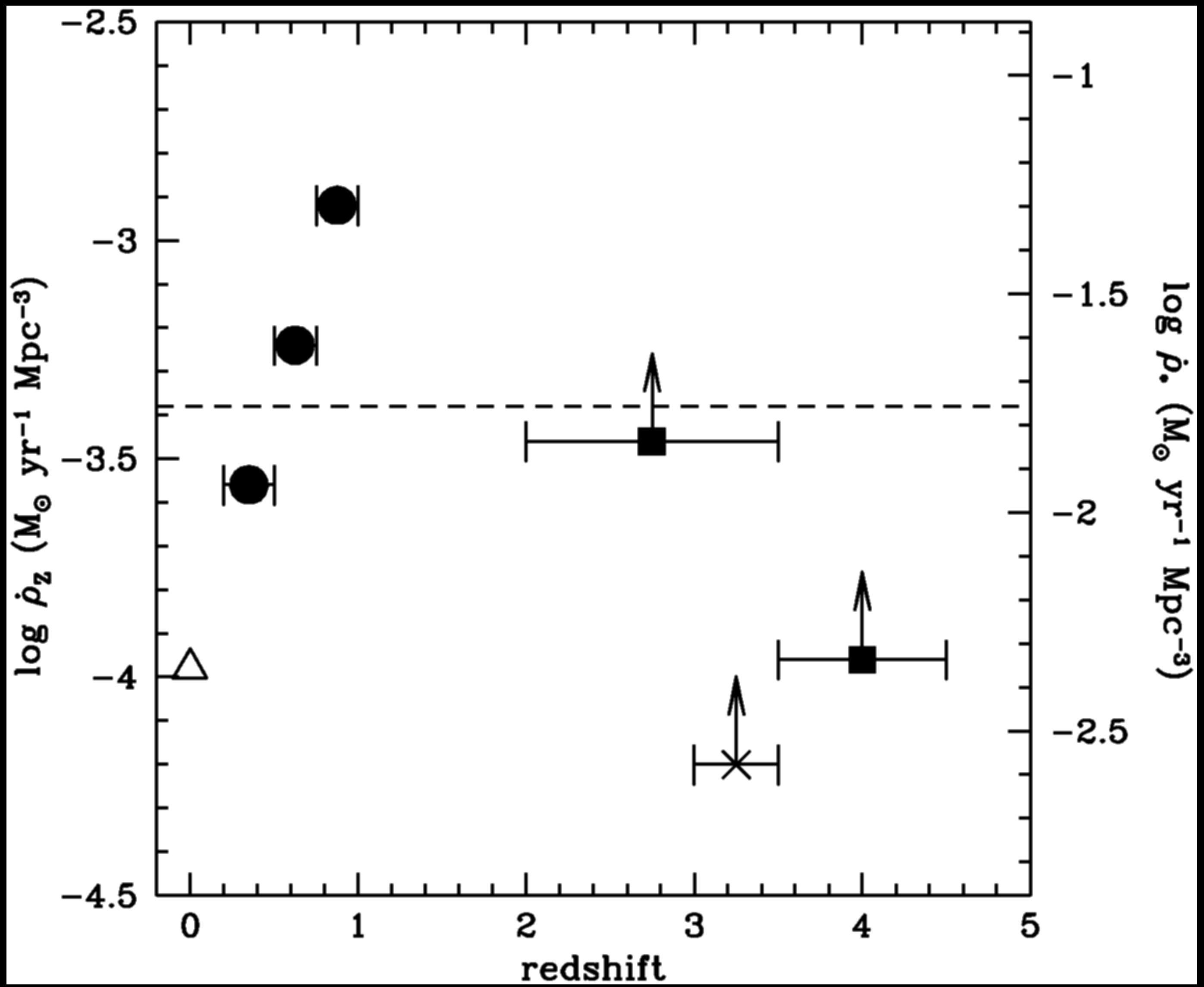
1. Background - 1996

Studies of cosmic evolution moved from AGN to starlight

UV luminosity density ⟶ evolution of star-formation rate density



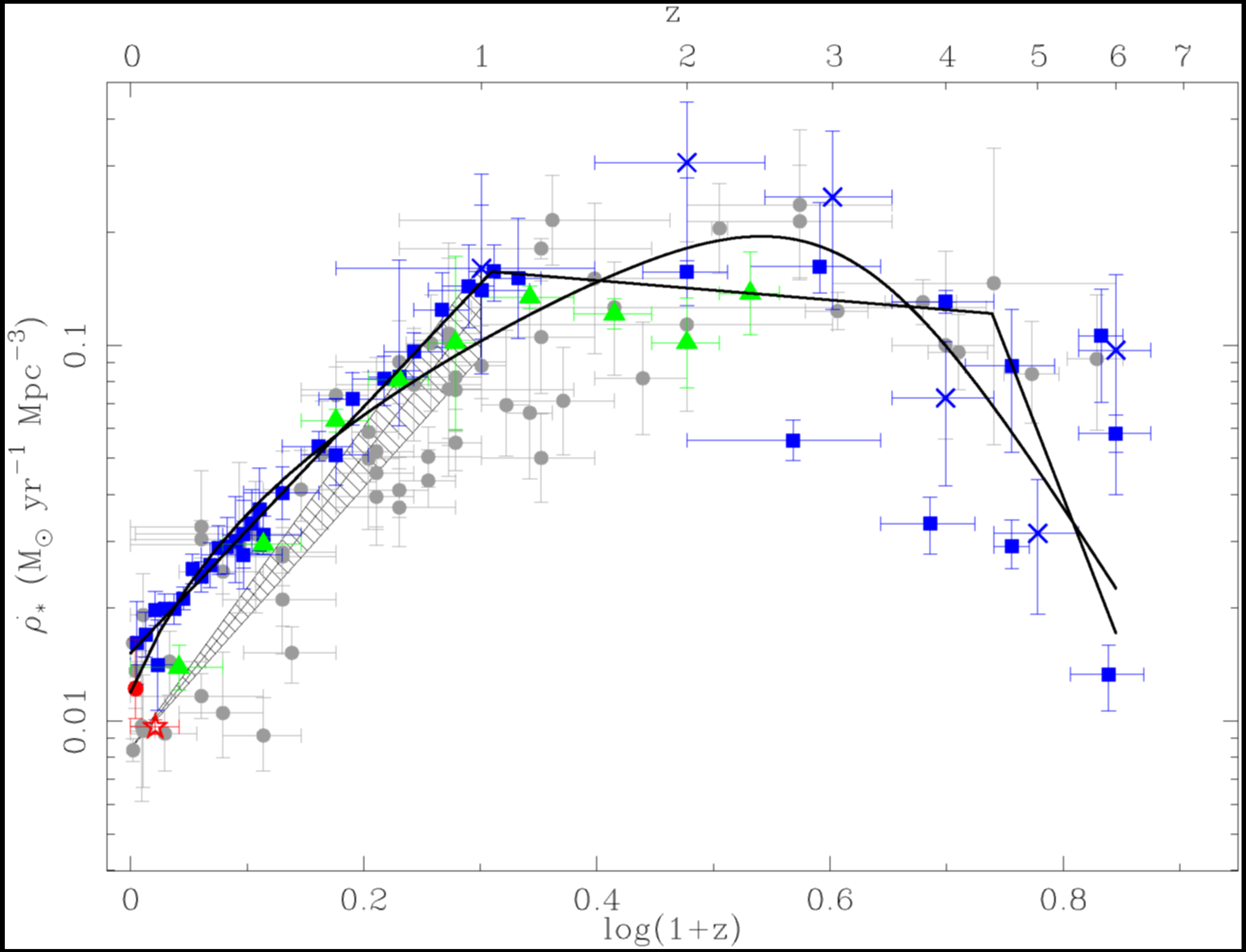
Lilly et al. 1996



Madau et al. 1996

1. Background - 2006

A decade of study: ground-based optical/near-IR/sub-mm
+ HST, Spitzer, ISO



Hopkins & Beacom 2006

1. Background

Issues in 2009 (i.e. pre HST WFC3/IR and Herschel)

Realization that most SF obscured by dust
(e.g. Hughes et al. 1998)
..but slow progress at far-IR/sub-mm wavelengths

Difficulty reconciling integrated SFR with stellar mass density
(e.g. Wilkins et al. 2008)

Extension of UV studies to z ~ 6.5, but higher z not possible
(e.g. Bouwens et al. 2007)

2. Star-formation rate indicators

Direct:	UV continuum
Reprocessed:	Hα emission Mid-IR (Spitzer 24 μm) Far-IR (Herschel PACS and SWIRE) (sub)-mm (SCUBA2 and ALMA)
Recent death:	Radio X-ray
Past history:	Differential of stellar mass growth – near-IR

2. Star-formation rate indicators

Updated conversions for Chabrier/Kroupa IMF

$$\log[(dM_*/dt)/(M_{sun}/yr)] = \log L_x - \log C_x$$

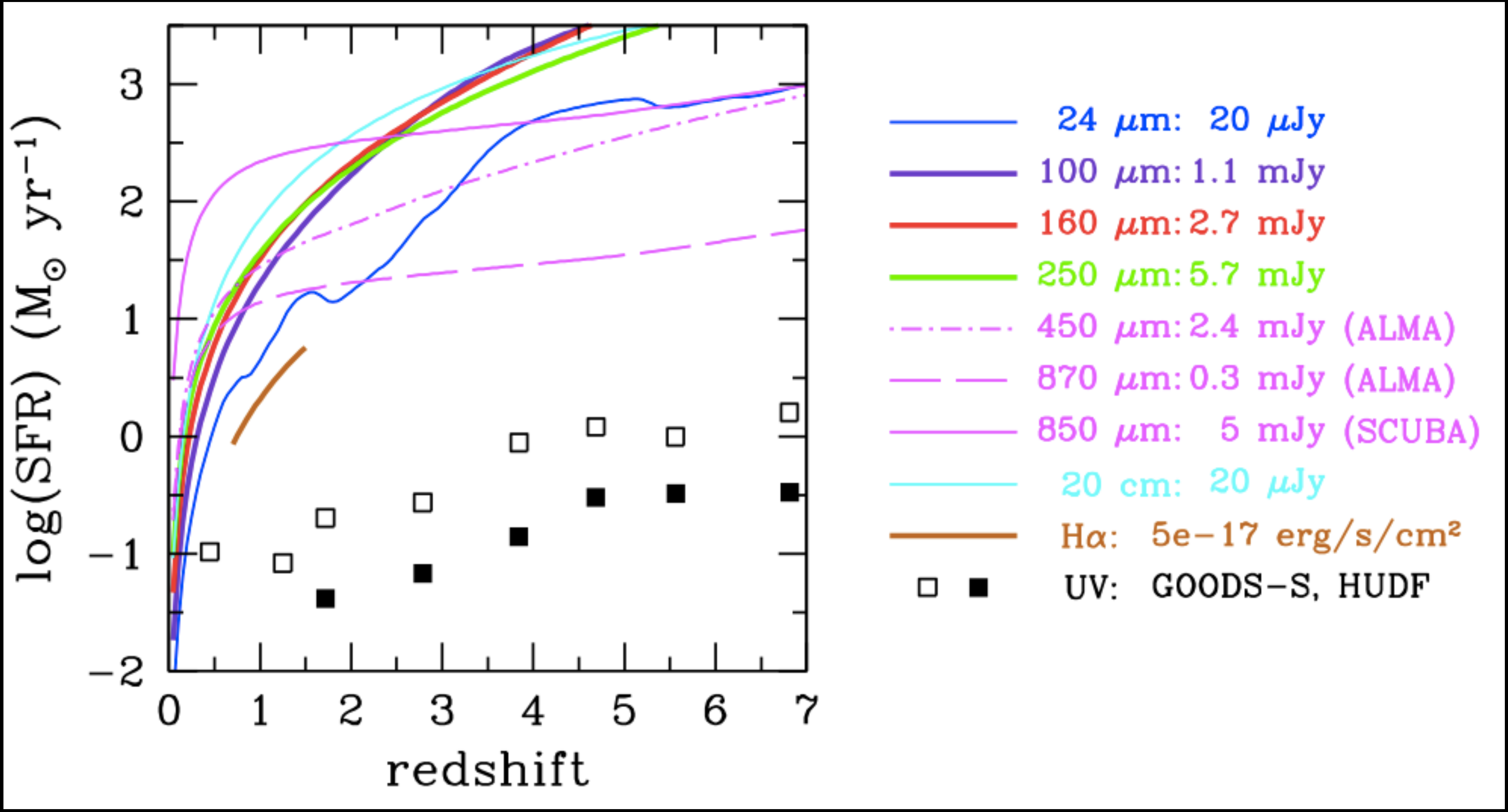
Table 1 Star-formation-rate calibrations

Band	Age range (Myr)[a]	L_x units	$\log C_x$[b]	$\dot{M}_* / \dot{M}_*(\mathrm{K98})$[c]	Reference(s)
FUV	0-10-100	ergs s^{-1} (νL_ν)	43.35	0.63	Hao et al. (2011), Murphy et al. (2011)
NUV	0-10-200	ergs s^{-1} (νL_ν)	43.17	0.64	Hao et al. (2011), Murphy et al. (2011)
Hα	0-3-10	ergs s^{-1}	41.27	0.68	Hao et al. (2011), Murphy et al. (2011)
TIR	0-5-100[d]	ergs s^{-1} (3–1100 μm)	43.41	0.86	Hao et al. (2011), Murphy et al. (2011)
24 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	42.69		Rieke et al. (2009)
70 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	43.23		Calzetti et al. (2010b)
1.4 GHz	0-100	ergs s^{-1} Hz^{-1}	28.20		Murphy et al. (2011)
2–10 keV	0-100	ergs s^{-1}	39.77	0.86	Ranalli et al. (2003)

Kennicutt & Evans 2012, ARAA, 50, 531

2. Star-formation rate indicators

Relative sensitivities of multi-wavelength probes



3. The last ~11 billion years: $0 < z < 3$

UV continuum measurements

+ve = direct obs of stars, few M_{sun}, 10-200 Myr
observations feasible at all redshifts
sensitive and unconfused – can detect $< 1\ M_{sun}\ yr^{-1}$ even at high z

-ve = very sensitive to dust extinction

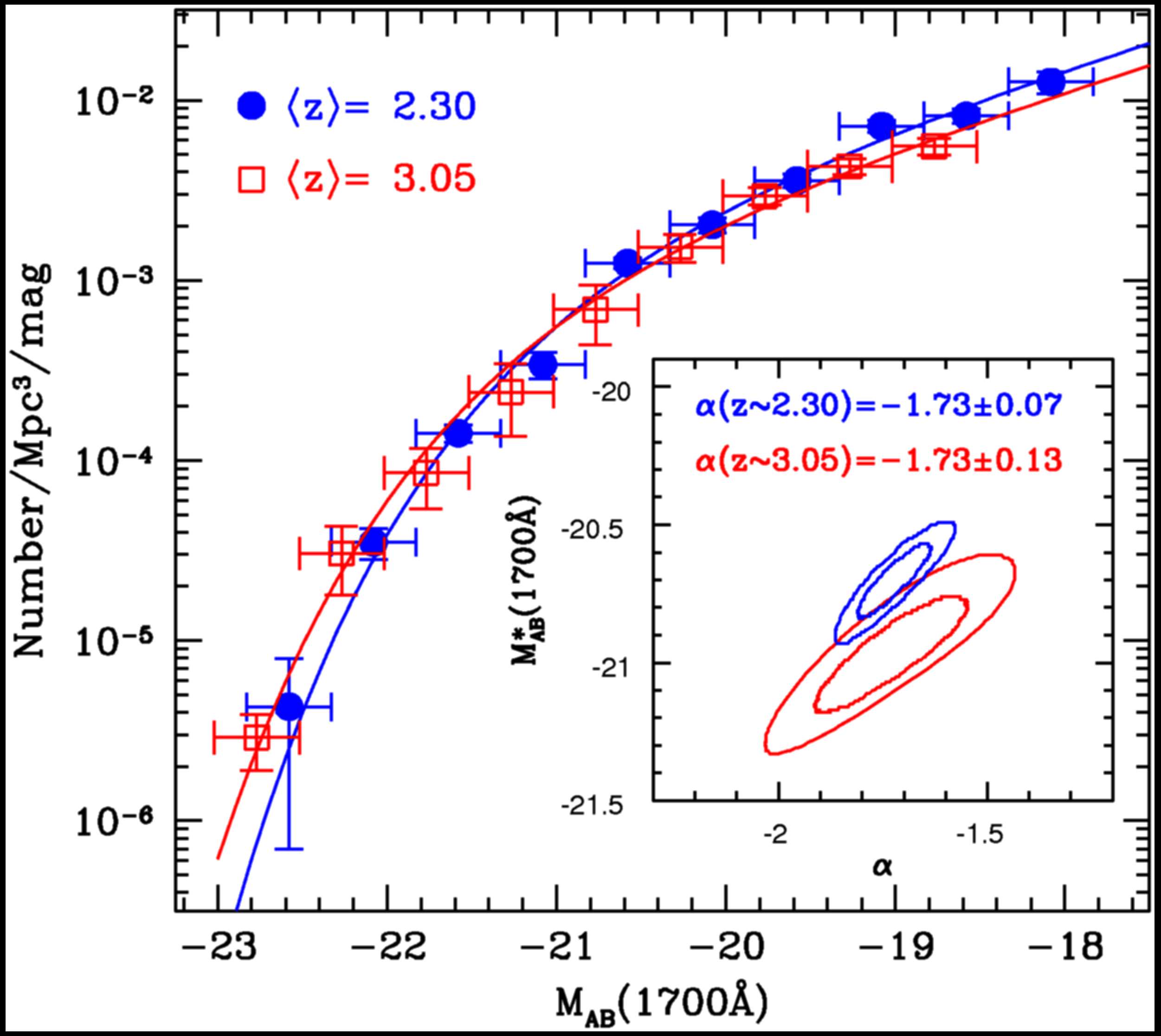
TASKS

- Make deep UV galaxy selection, estimate completeness/contamination
- Fit (Schechter) function to enable extrapolation to faint L_{gal}
- Make dust correction – luminosity dependent? redshift dependent?
- Integrate to zero dust-corrected galaxy luminosity to get luminosity density
- Adopt an IMF to convert to ρ_{SFR}
- Add anything completely missing from UV surveys

3. The last ~11 billion years: 0 < z < 3

UV continuum measurements

Discovery of steep faint end slope, and unchanged LF at z = 2 – 3



Reddy & Steidel, 2009, ApJ, 692, 778

Easy to integrate down LF but extinction a big issue e.g. poor correlation between β and L_{IR}/L_{UV} (Boquien et al. 2012)

Extinction correction involves multiplying observed L_{UV} by a factor ~ 4.5 at z ~ 2.5 (Reddy et al. 2012)

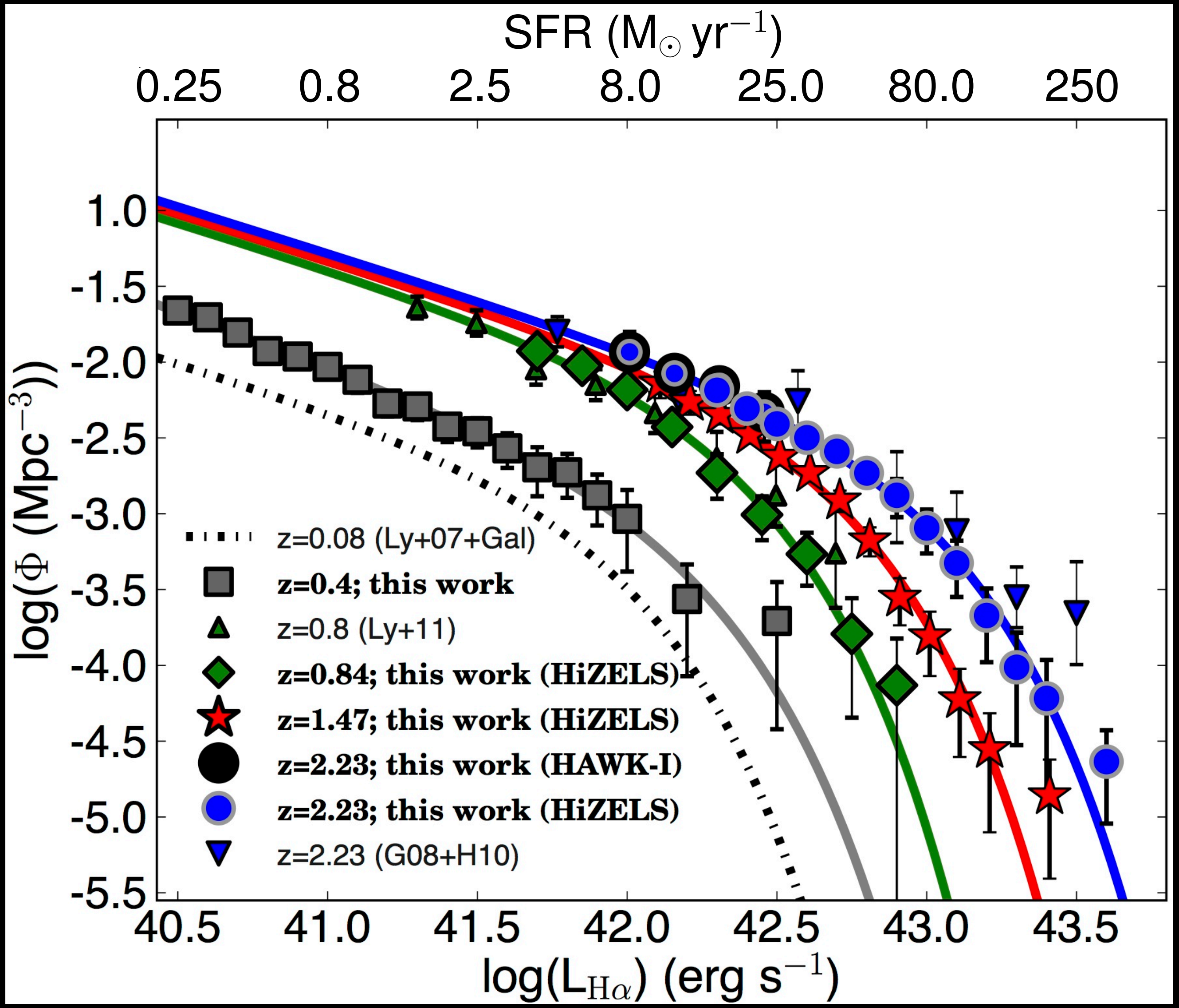
New measurements
Cucciati et al., 2013, A&A, 539, 31

3. The last ~11 billion years: 0 < z < 3

New Hα measurements

+ve = best line, ~30 M_{sun}, so 3-10 Myr, and extinction not too bad

-ve = very IMF sensitive since driven by very high mass stars



Hα luminosity functions

Conversion to SFR assumes 1 mag of extinction at Hα, recently validated by Ibar et al. (2013)

Sobral et al., 2013, MNRAS, 428, 1128

3. The last ~11 billion years: $0 < z < 3$

New mid-IR (Spitzer) and far-IR (Herschel) measurements

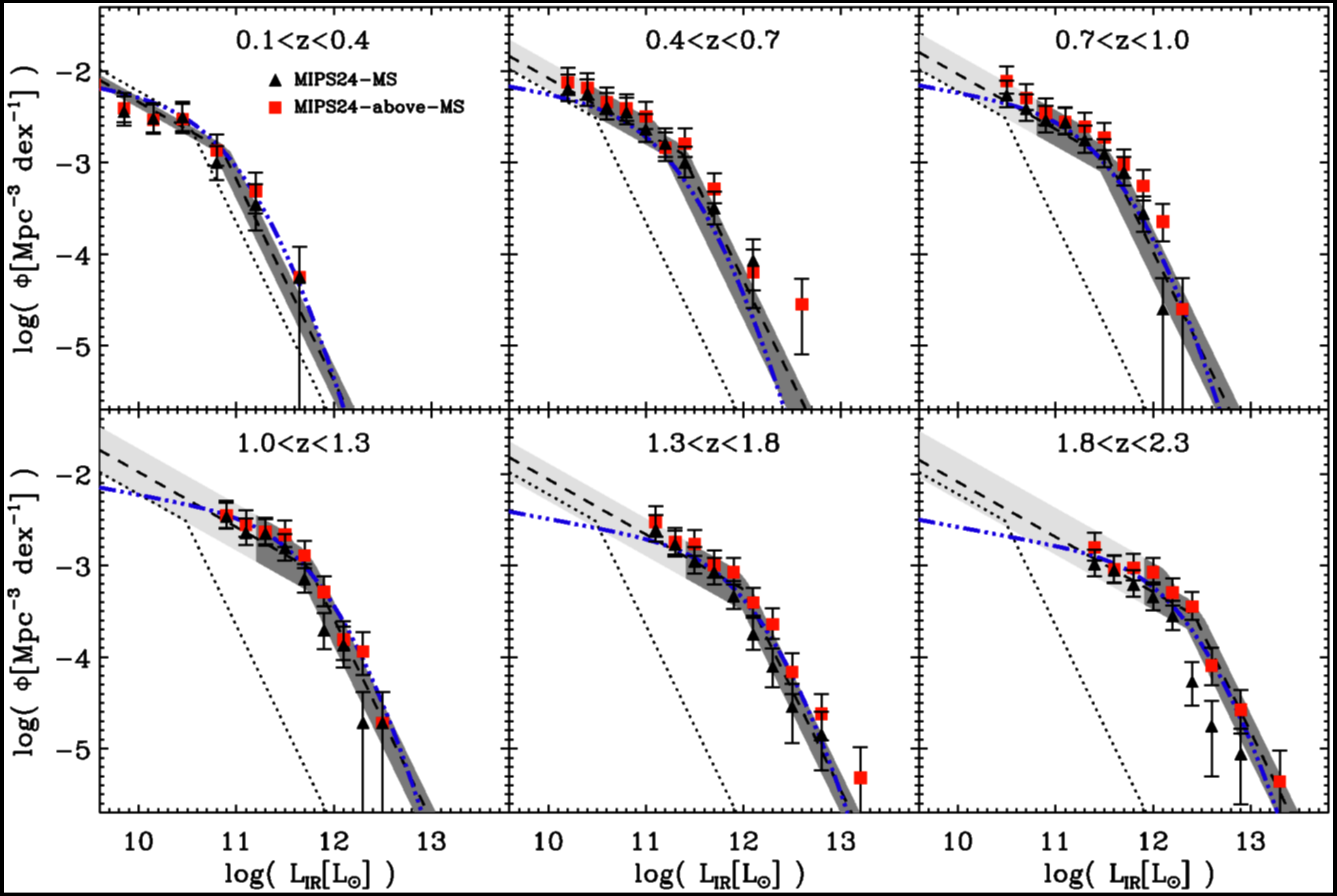
+ve = most SF obscured

-ve = misses unobscured + includes dust heated by older stars and AGN

Obvious route is to calculate total bolometric L_{IR} = TIR although hard to do with Herschel for SFR < 100 M_{sun} yr^{-1} and evidence that 24 μm is best indicator up to $z \sim 2$ (Elbaz et al. 2010)

3. The last ~11 billion years: 0 < z < 3

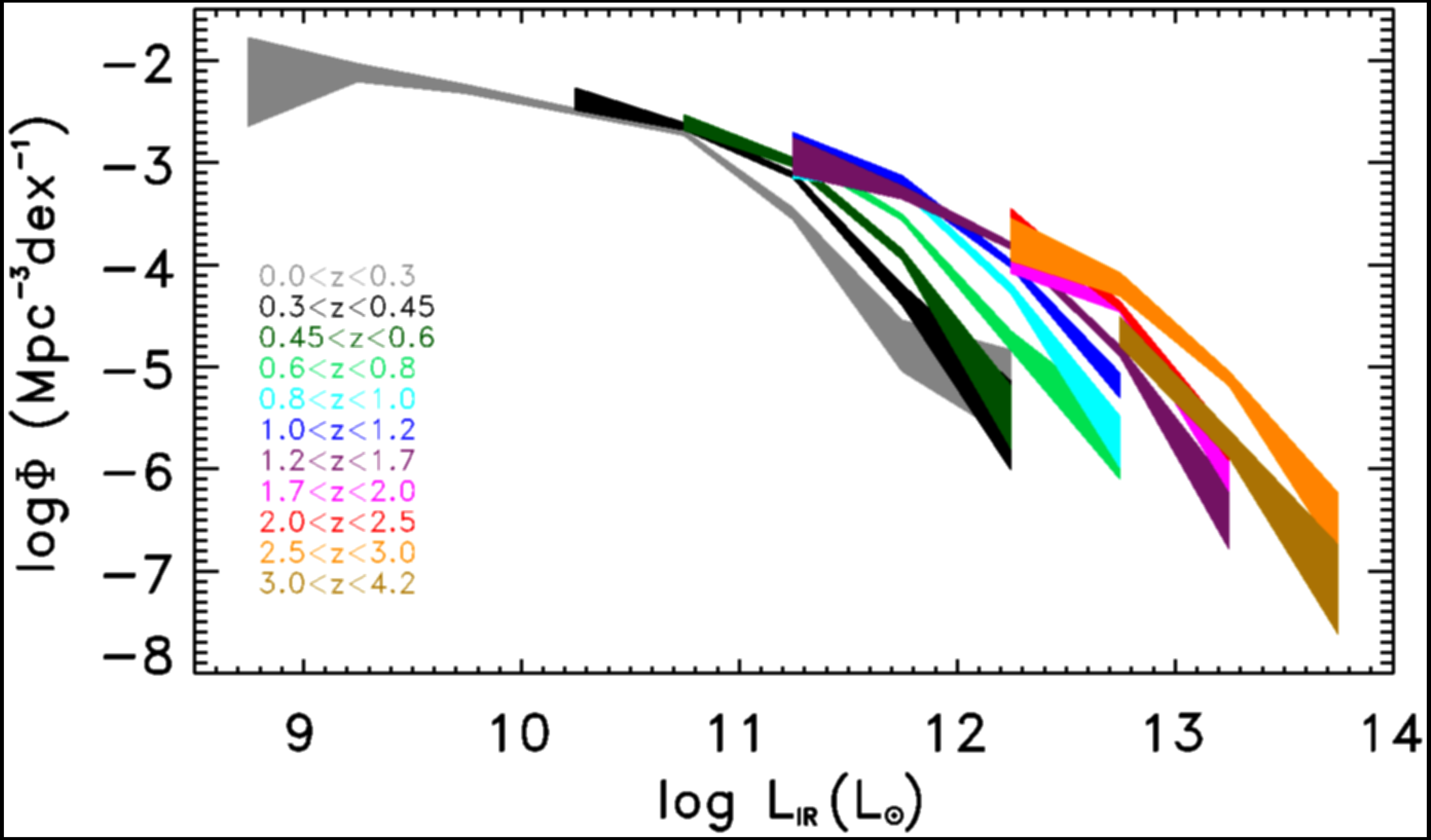
Mid and far-infrared LFs from MIPS & PEP GOODS



Magnelli et al. 2013, A&A, 553, 132

3. The last ~11 billion years: 0 < z < 3

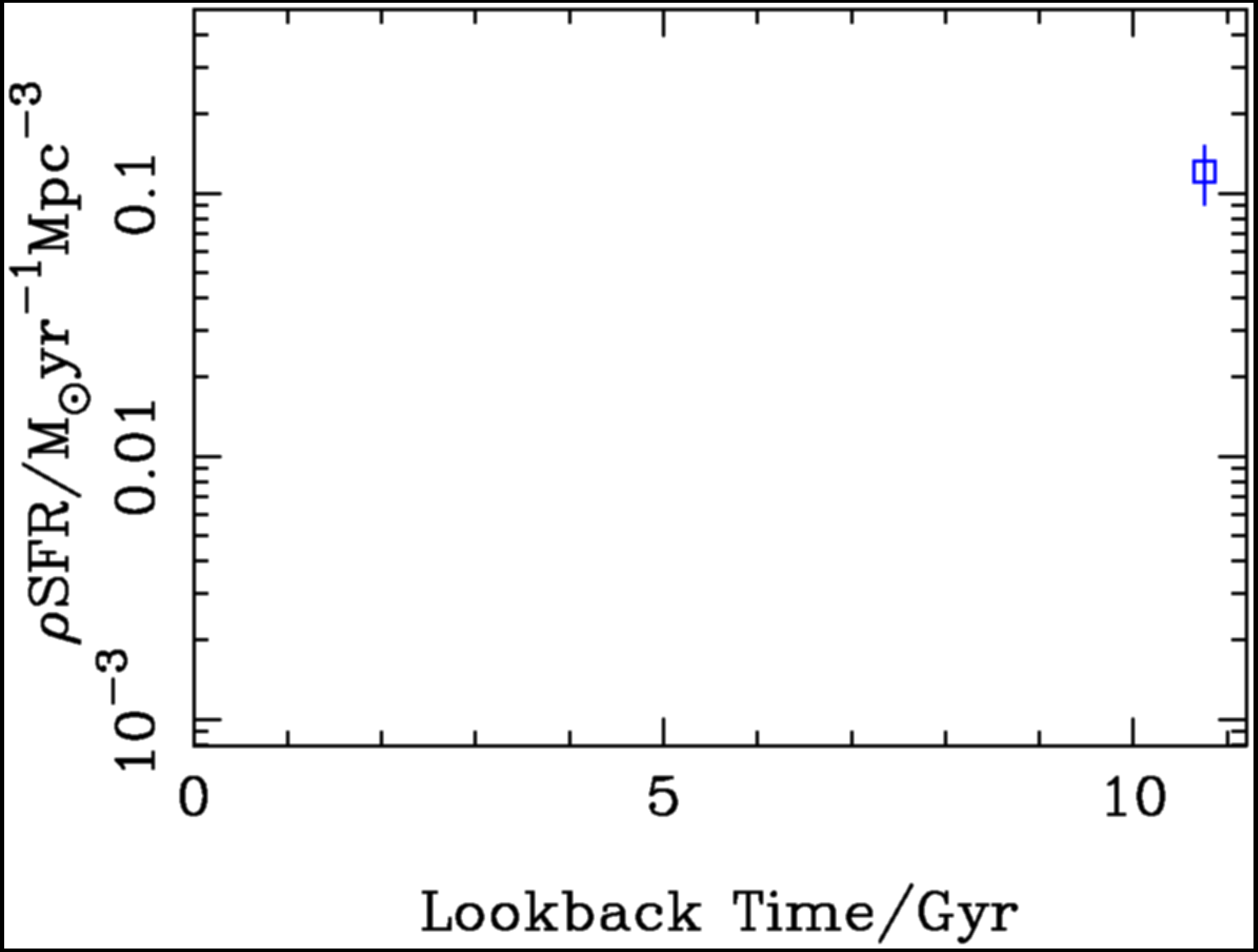
And from PEP-HERMES (brighter, but larger area)



Gruppioni et al. 2013, MNRAS, arXiv:1302.5209

3. The last ~11 billion years: 0 < z < 3

Agreement?



Reddy & Steidel 2009
dust corrected UV

3. The last ~11 billion years: 0 < z < 3

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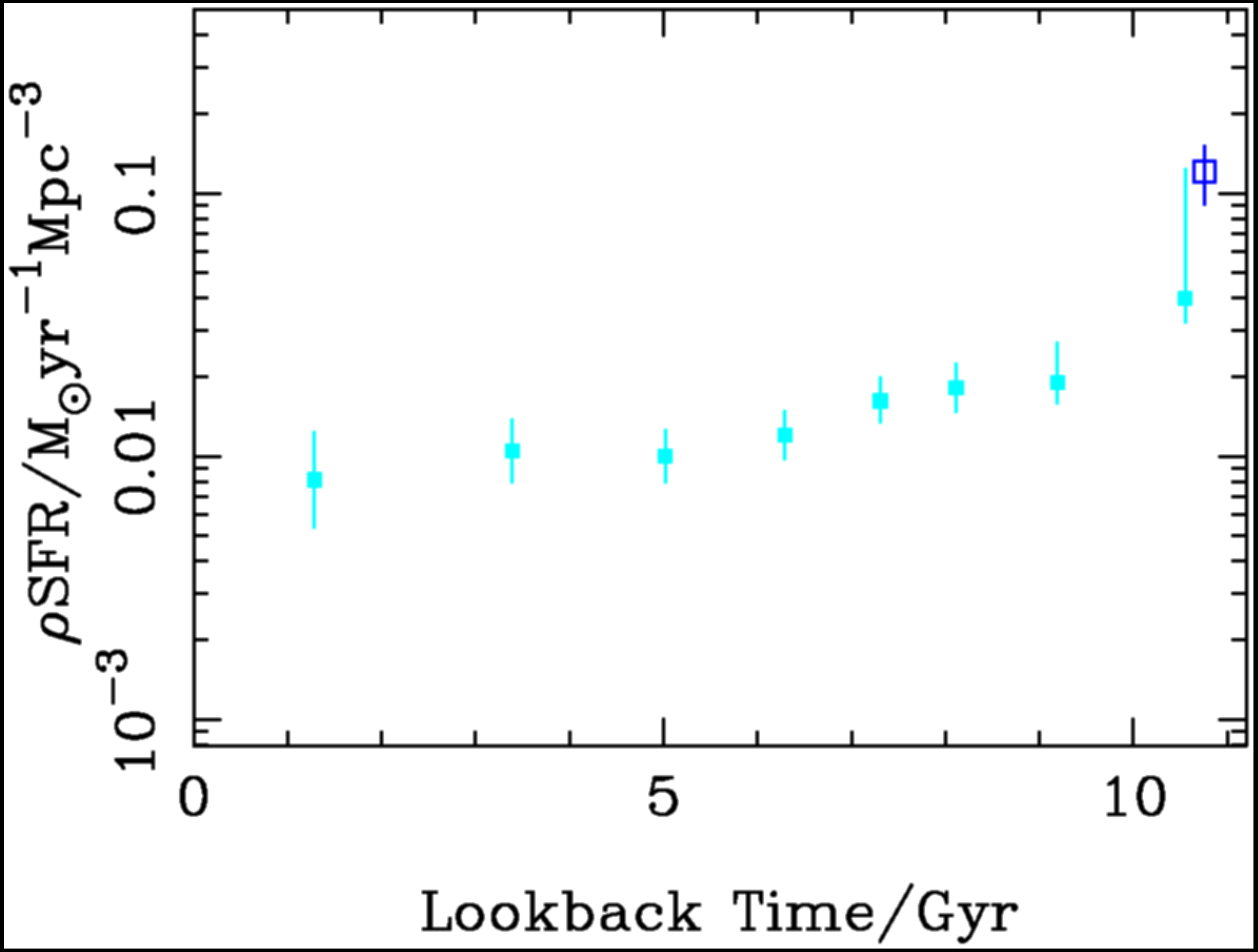

Reddy & Steidel 2009
dust corrected UV

Cucciati et al. 2013
raw UV

3. The last ~11 billion years: 0 < z < 3

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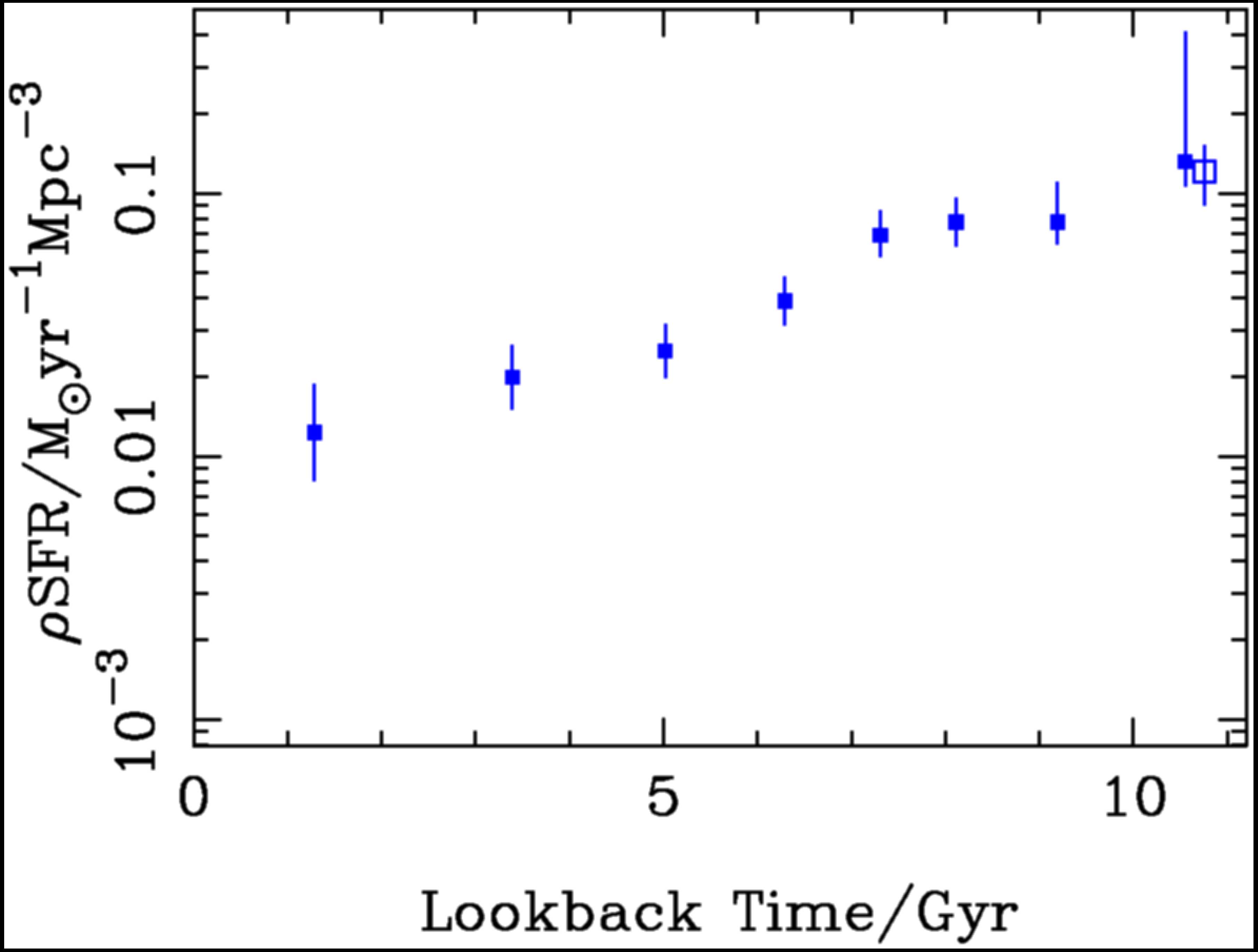

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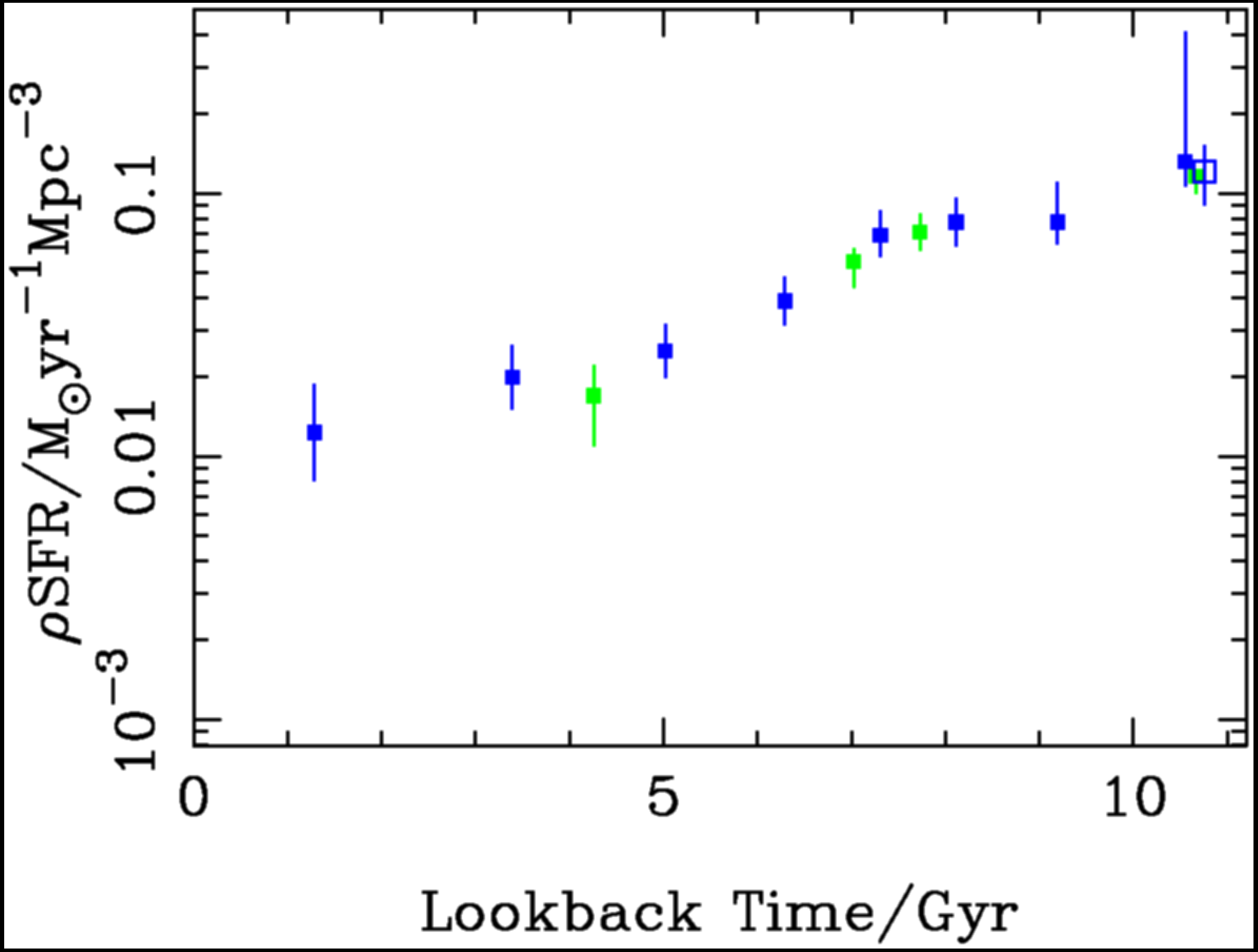

Reddy & Steidel 2009
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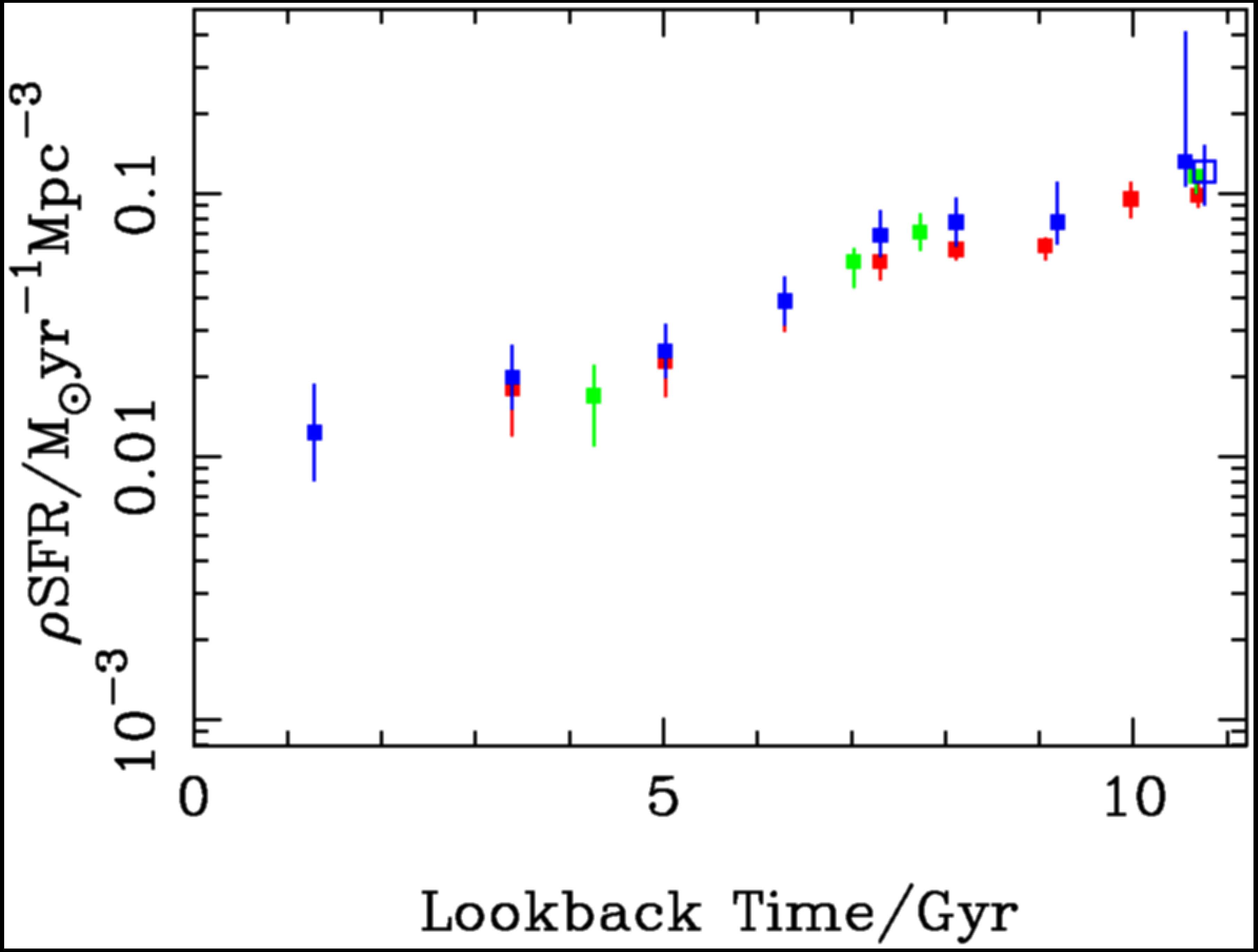
Cucciati et al. 2013
dust corrected UV

Sobral et al. 2013
dust corrected Hα

3. The last ~11 billion years: 0 < z < 3

Agreement?



Reddy & Steidel 2009
dust corrected UV

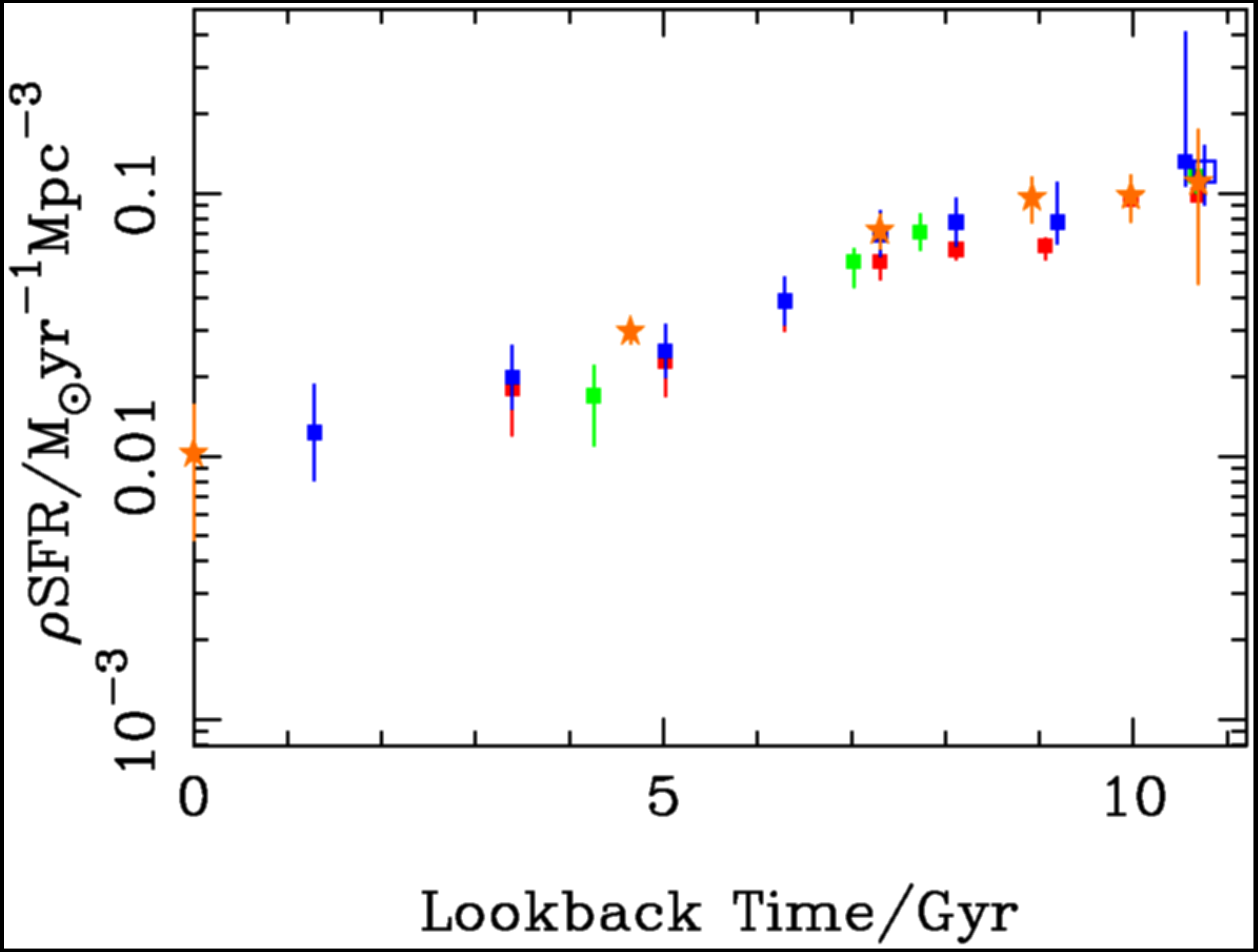
Cucciati et al. 2013
dust corrected UV

Sobral et al. 2013
dust corrected Hα

Karim et al. 2011
radio (1.4 GHz)

3. The last ~11 billion years: 0 < z < 3

Agreement – YES !



Reddy & Steidel 2009
dust corrected UV

Cucciati et al. 2013
dust corrected UV

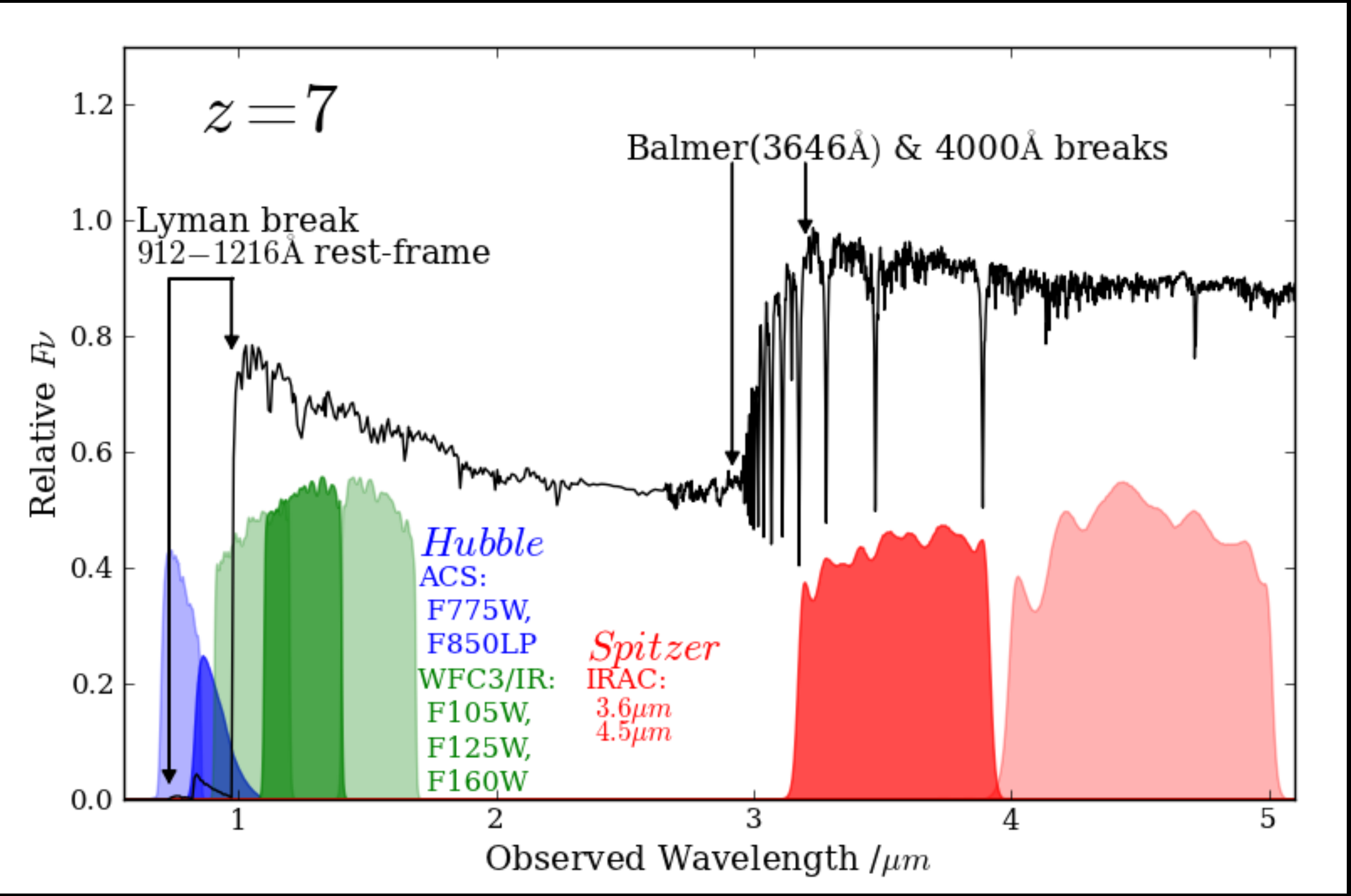
Sobral et al. 2013
dust corrected Hα

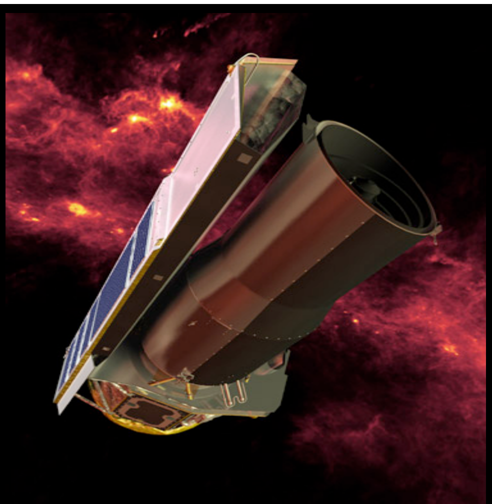
Karim et al. 2011
radio (1.4 GHz)

Burgarella et al. 2013
far-IR + raw UV

4. The first ~2 billion years: $3 < z < ?$

Observing a high-redshift Lyman-break galaxy





The Hubble Ultra Deep Field 2012

The deepest near-infrared image

UDF12: Observational details

Final depths (AB):

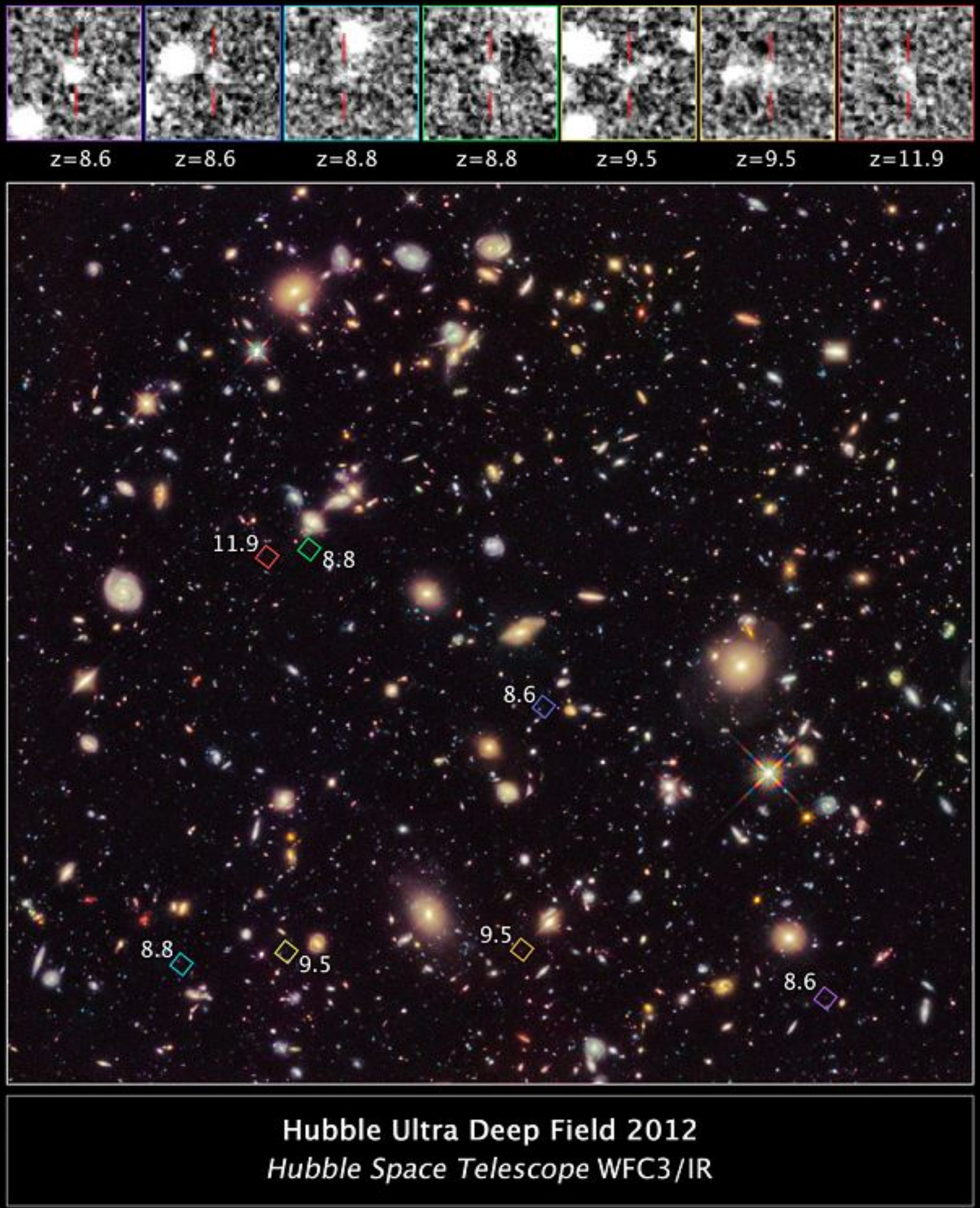
Y_{105} = 30.0

J_{125} = 29.5

J_{140} = 29.5

H_{160} = 29.5

Ellis, McLure, Dunlop et al., 2013, ApJ, 763, L7



First meaningful sample of galaxies at $z > 8.5$

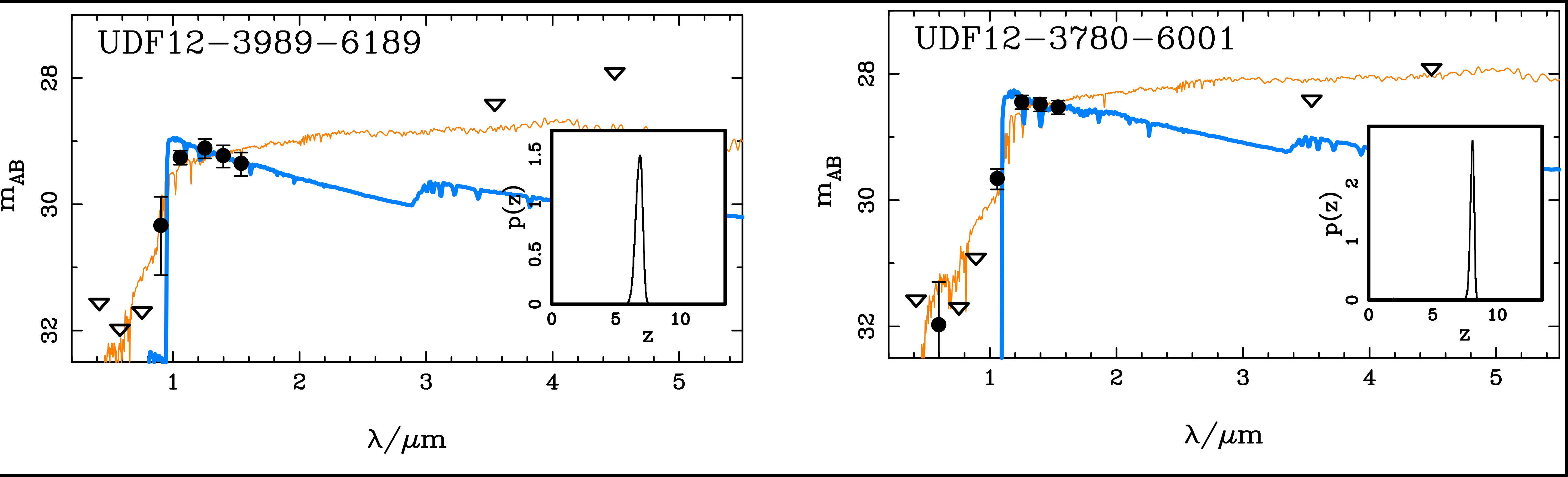
Ellis, McLure, Dunlop et al. (2013)

Now clear that galaxies exist and can be studied at $z \sim 10$ and beyond

The galaxy luminosity function at z=7 and z=8

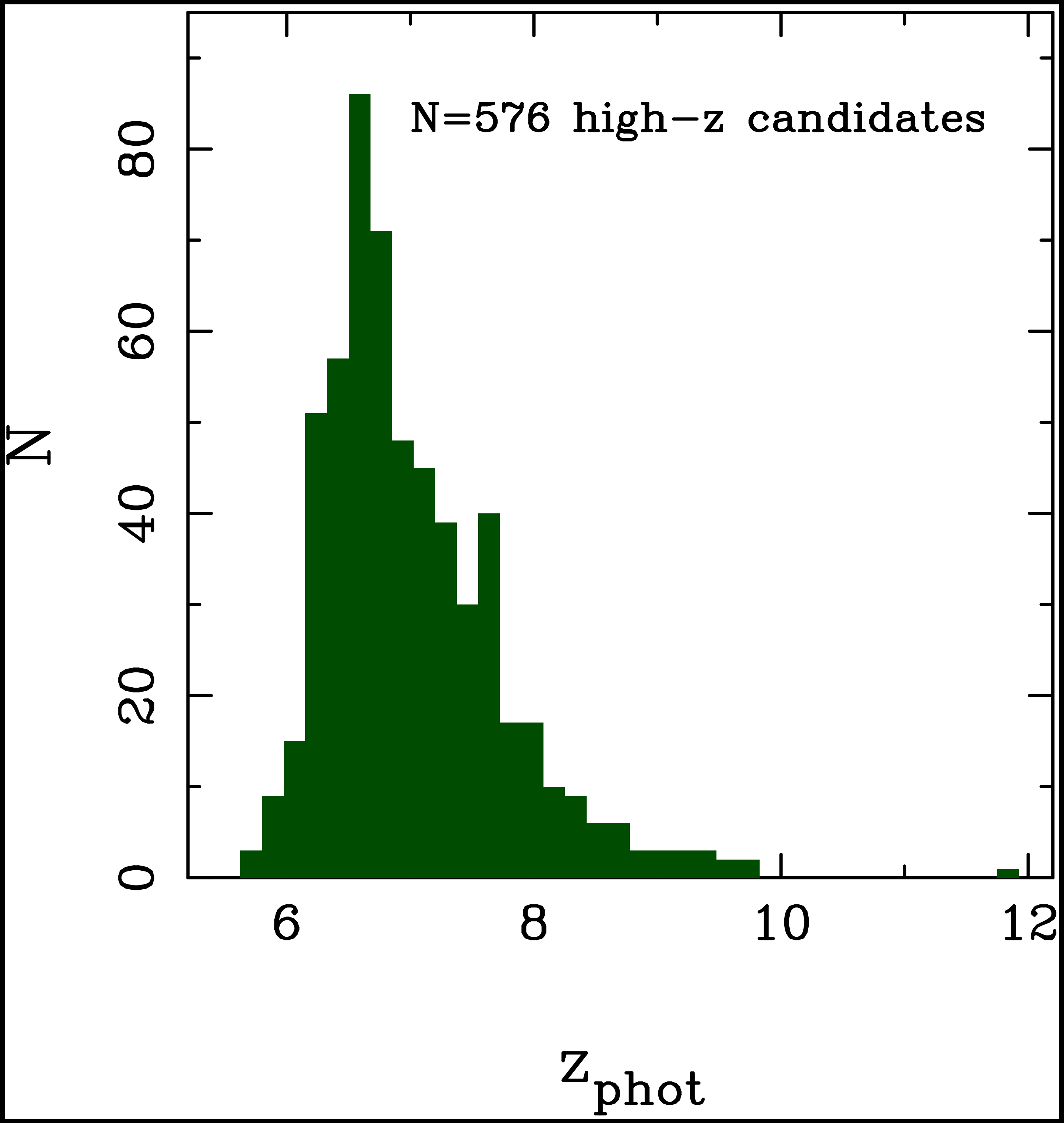
McLure, Dunlop et al. 2013, MNRAS, 432, 2696

- Photometric redshift selection of z > 6.5 galaxies (10-band SED fits)
- Nested structure of deep/shallow WFC3/IR imaging fields
- Incorporate p(z) into maximum likelihood LF fitting



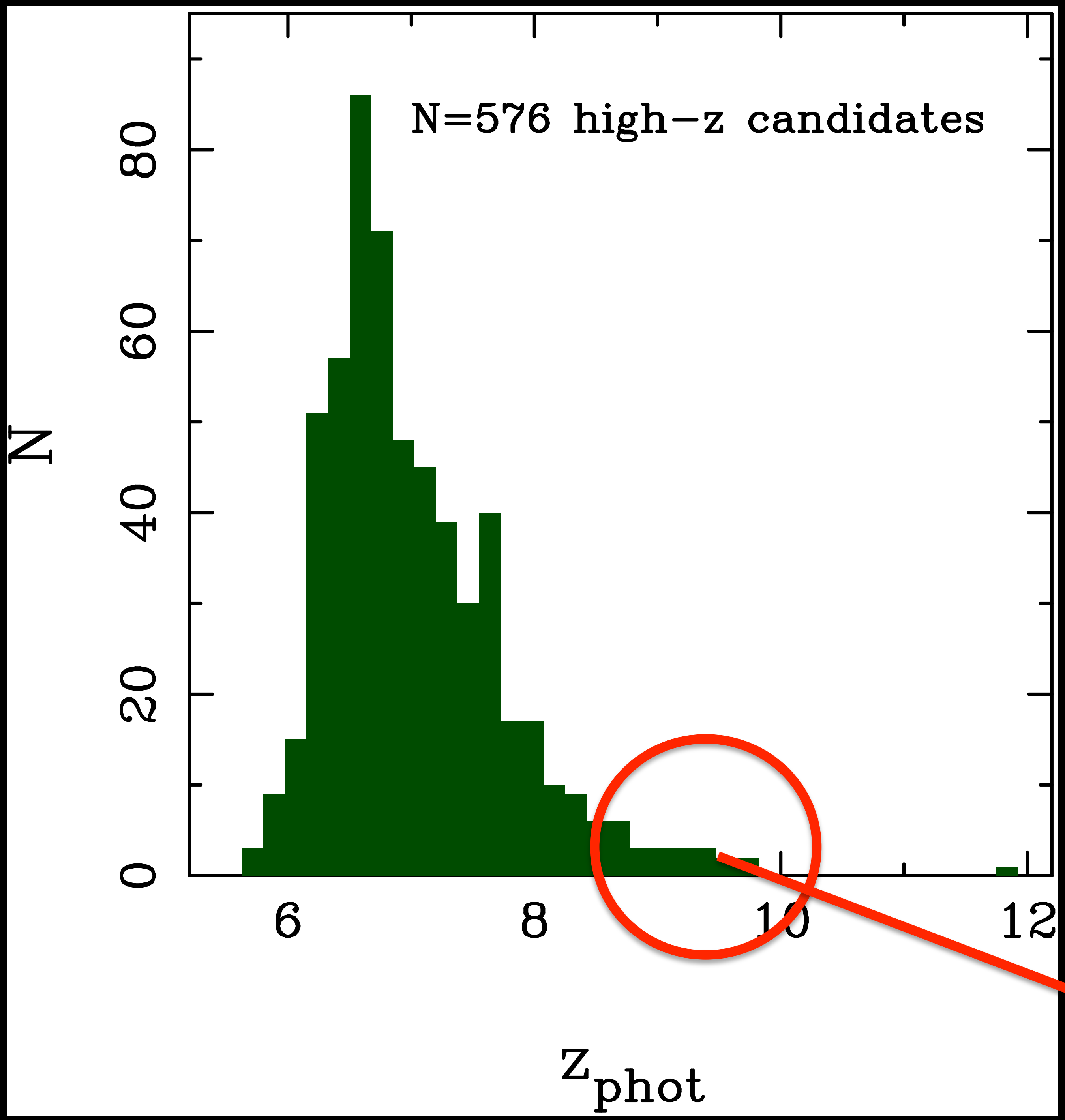
Example SED fits in UDF12 at z = 7 and z = 8

The galaxy luminosity function at z=7 and z=8



Final sample contains ~ 600 galaxies selected from 8 survey fields

The galaxy luminosity function at z=7 and z=8

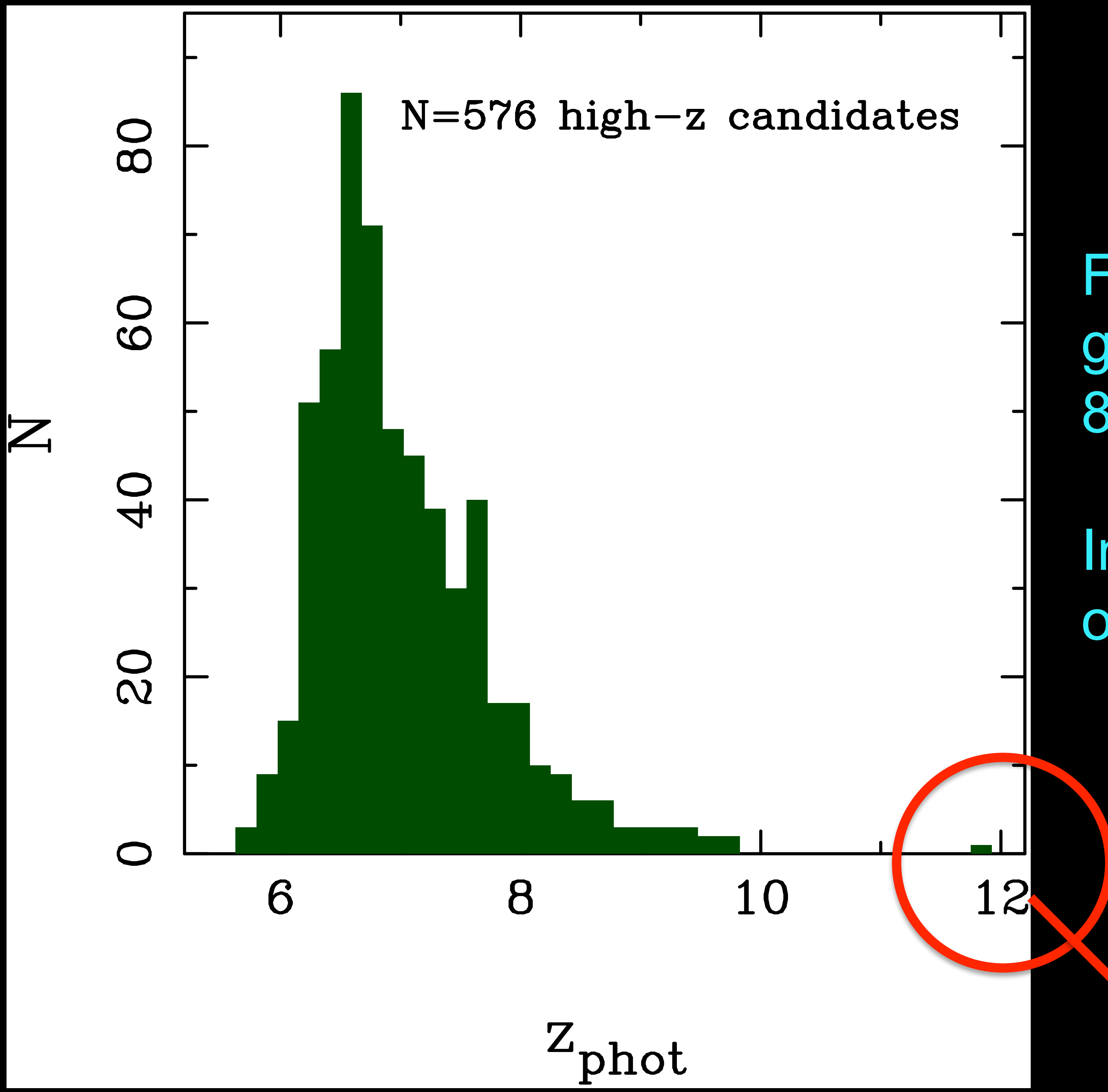


Final sample contains ~ 600 galaxies selected from 8 survey fields

Incorporates first robust sample of galaxies at z > 8.5

Ellis et al. (2013)

The galaxy luminosity function at z=7 and z=8



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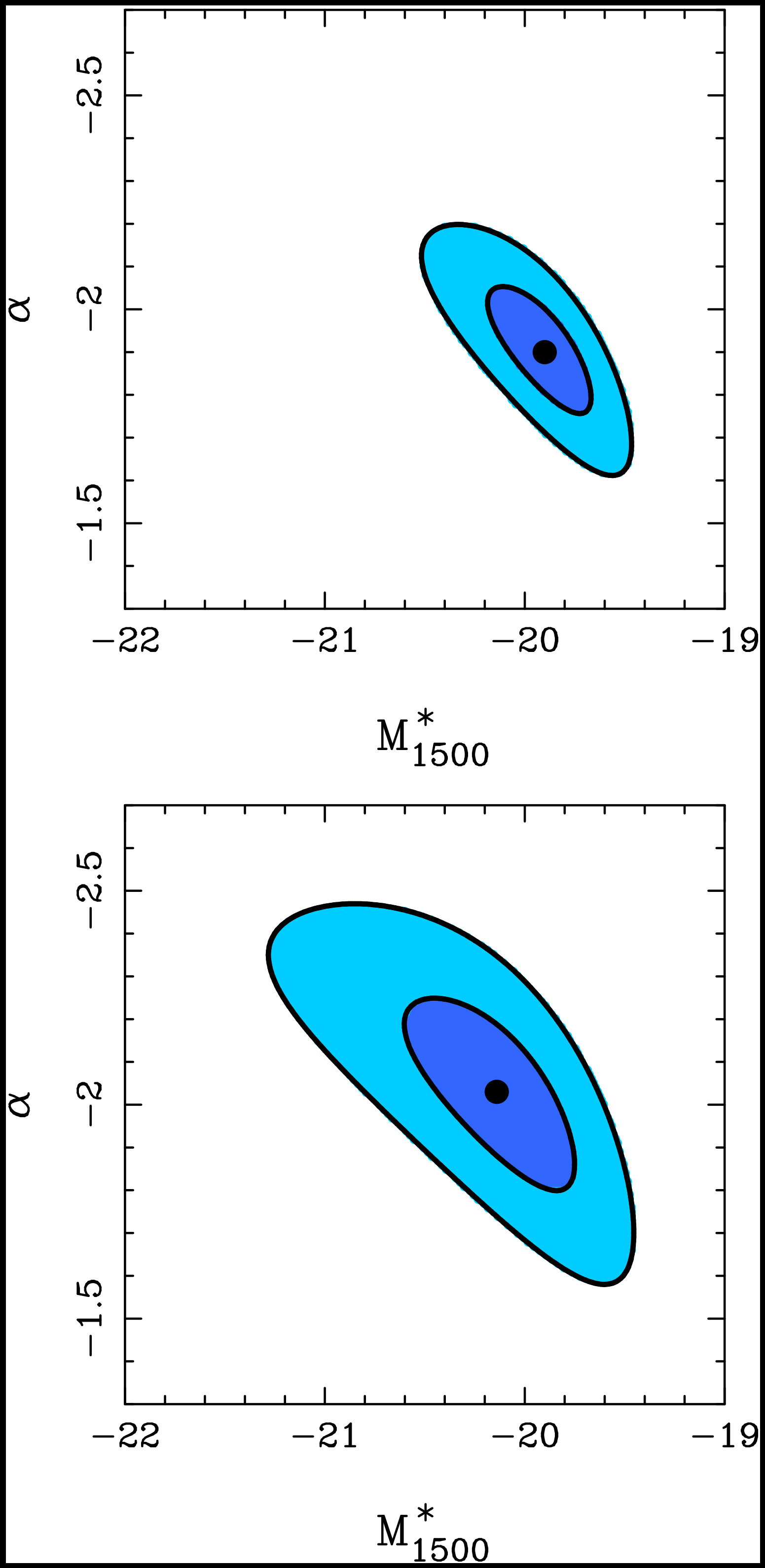
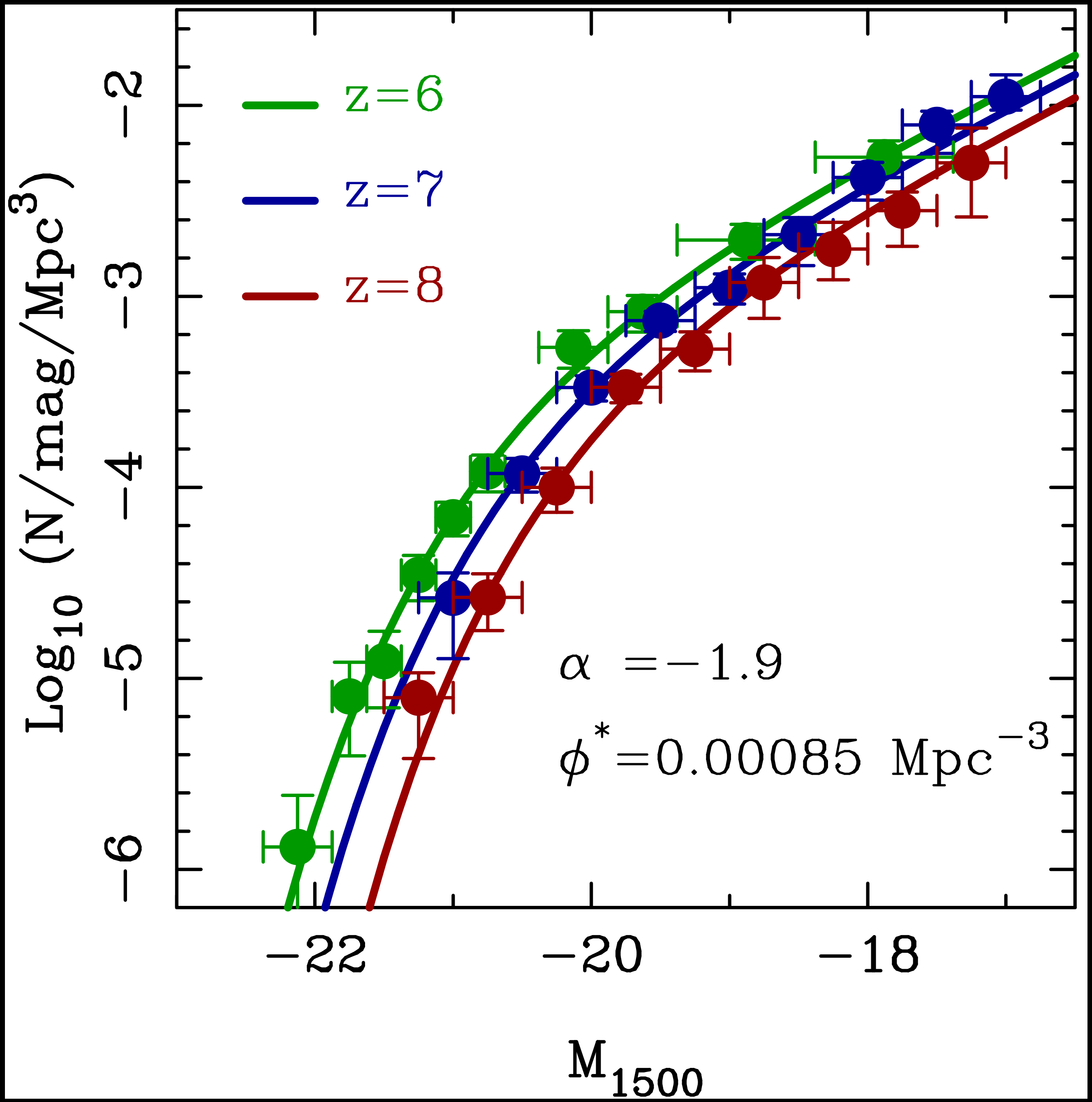
Redshift z=12 candidate?

UV galaxy LFs out to z = 8 from UDF12

McLure et al. 2013, MNRAS, 432, 2696

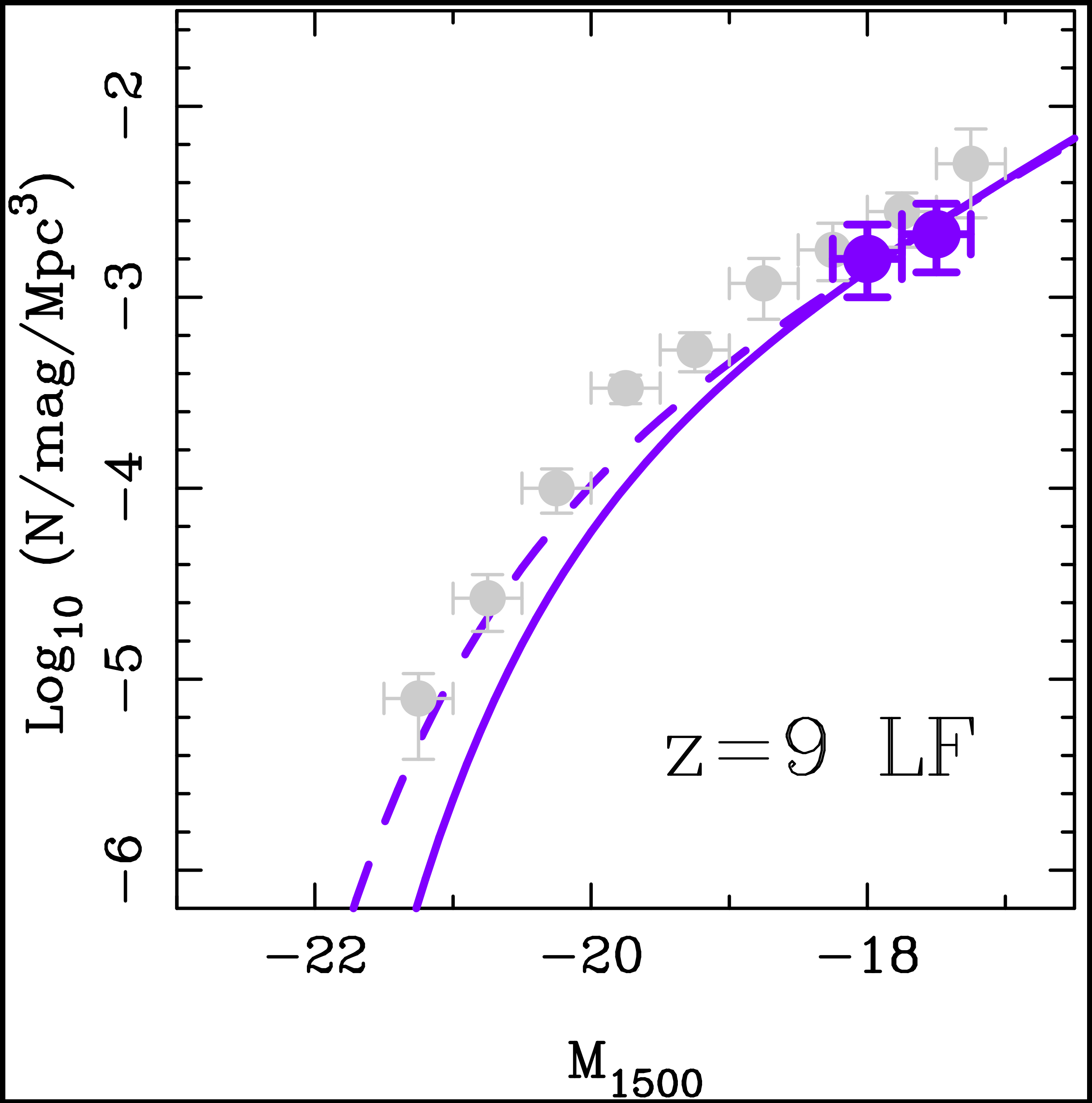




Luminosity evolution still looks okay:

α and ϕ^* fixed, M^* evolving: $\delta m = 0.3\delta z$

First look at the z=9 luminosity function



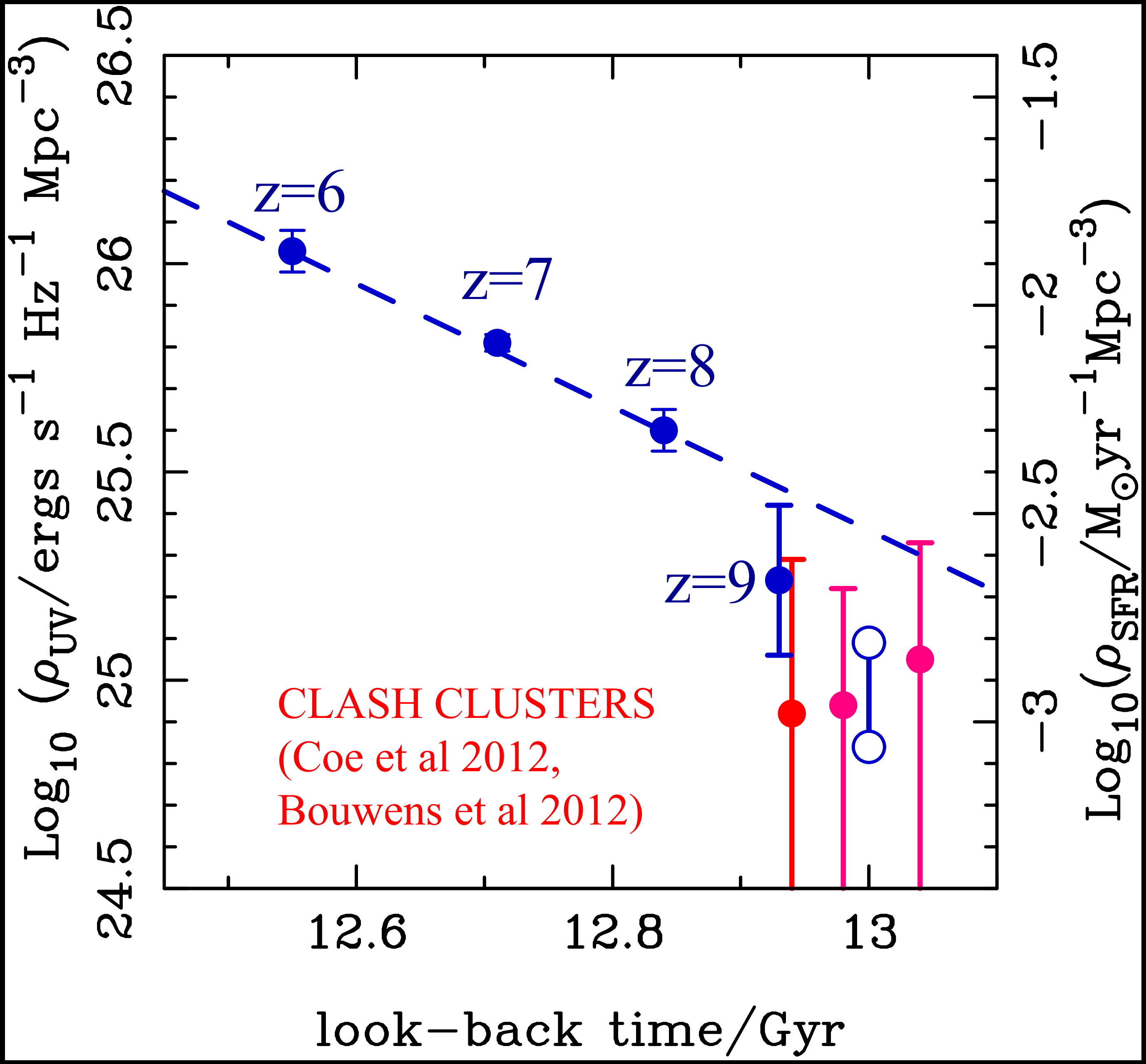
Purple data-points show two SWML bins at z=9

Solid/dashed lines show luminosity/density evolution from z=8 to z=9

Does at least allow an estimate of the star-formation rate density

High-z evolution of SFR density from UDF12 & CLASH

McLure, Dunlop et al. 2013, MNRAS, 432, 2696

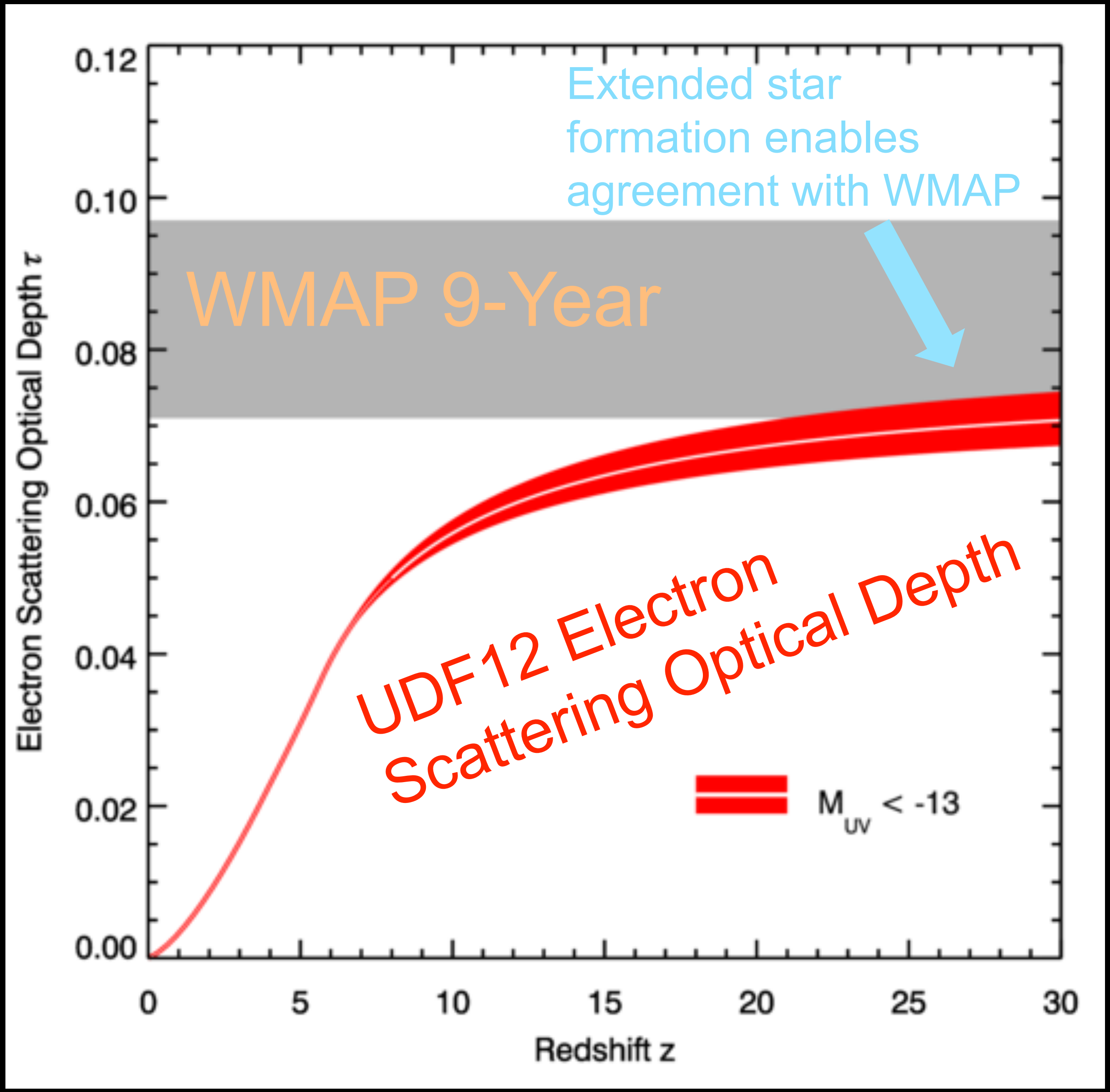


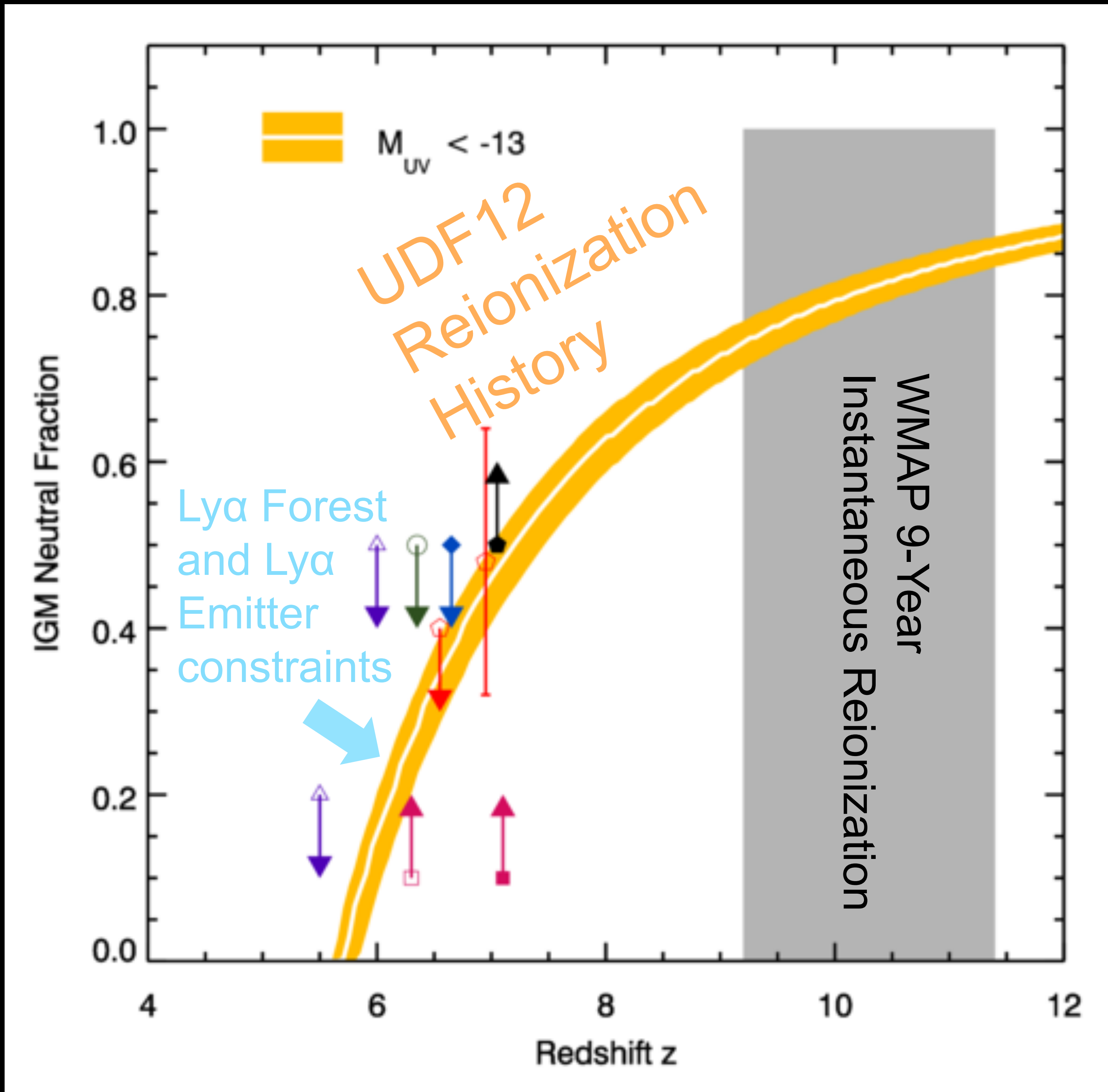
- Linear fall-off in log SF density with time in redshift interval $6 < z < 8$
- Evidence for steeper fall-off at $z > 8$?
- Important implications for reionization calculations

UDF12 Reionization Constraints:

Agrees with WMAP-9 and other probes if LF extended to $M_{uv} < -13$

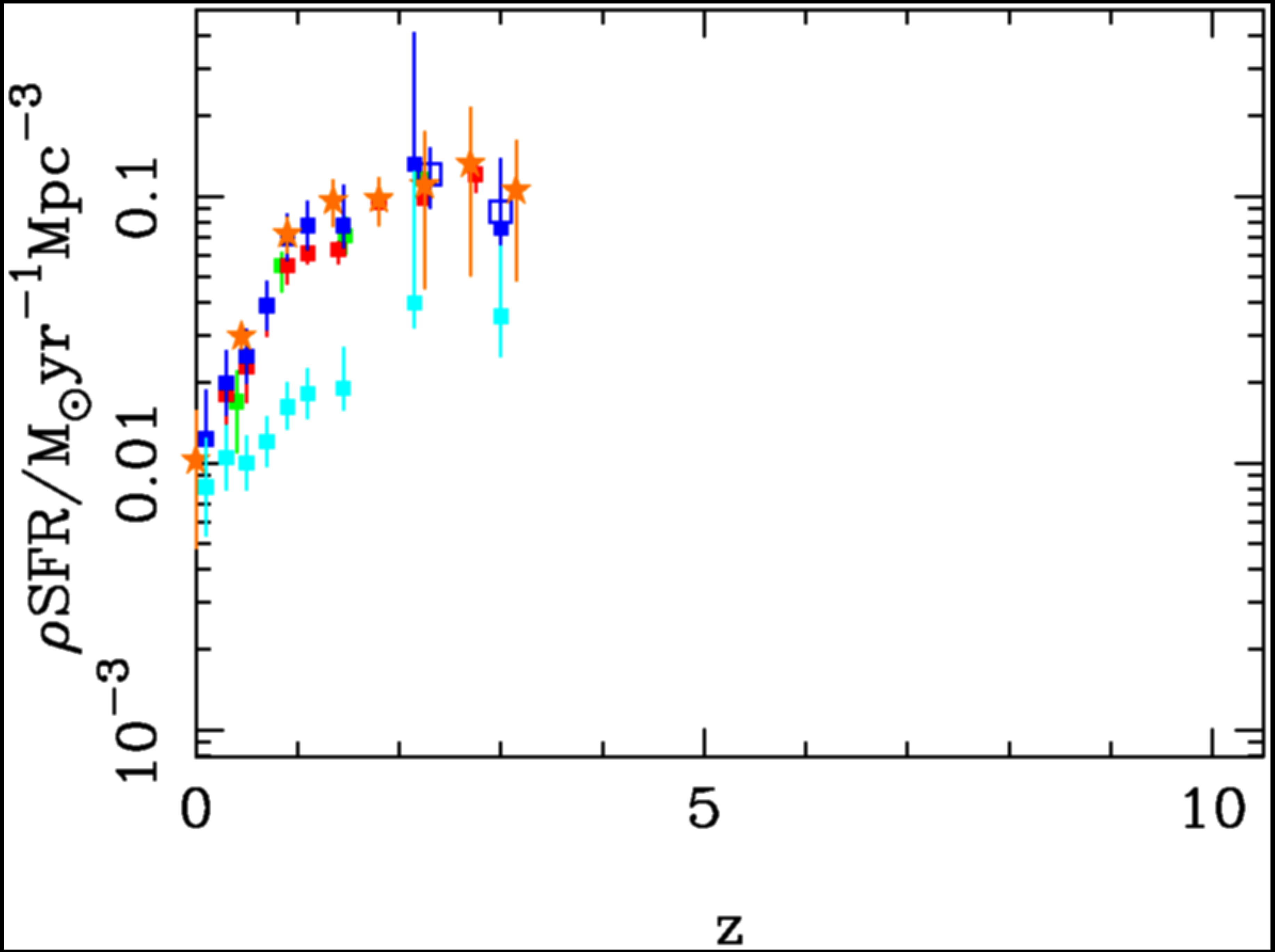
Robertson et al. 2013, ApJ, 768, 71





The reionization history implied by the high-redshift galaxy population discovered by UDF12 matches the constraints from *WMAP*, observations of the Lyman-α Forest, and the evolving fraction of Lyman-α emitting galaxies.

5. A complete cosmic history of SFR density?



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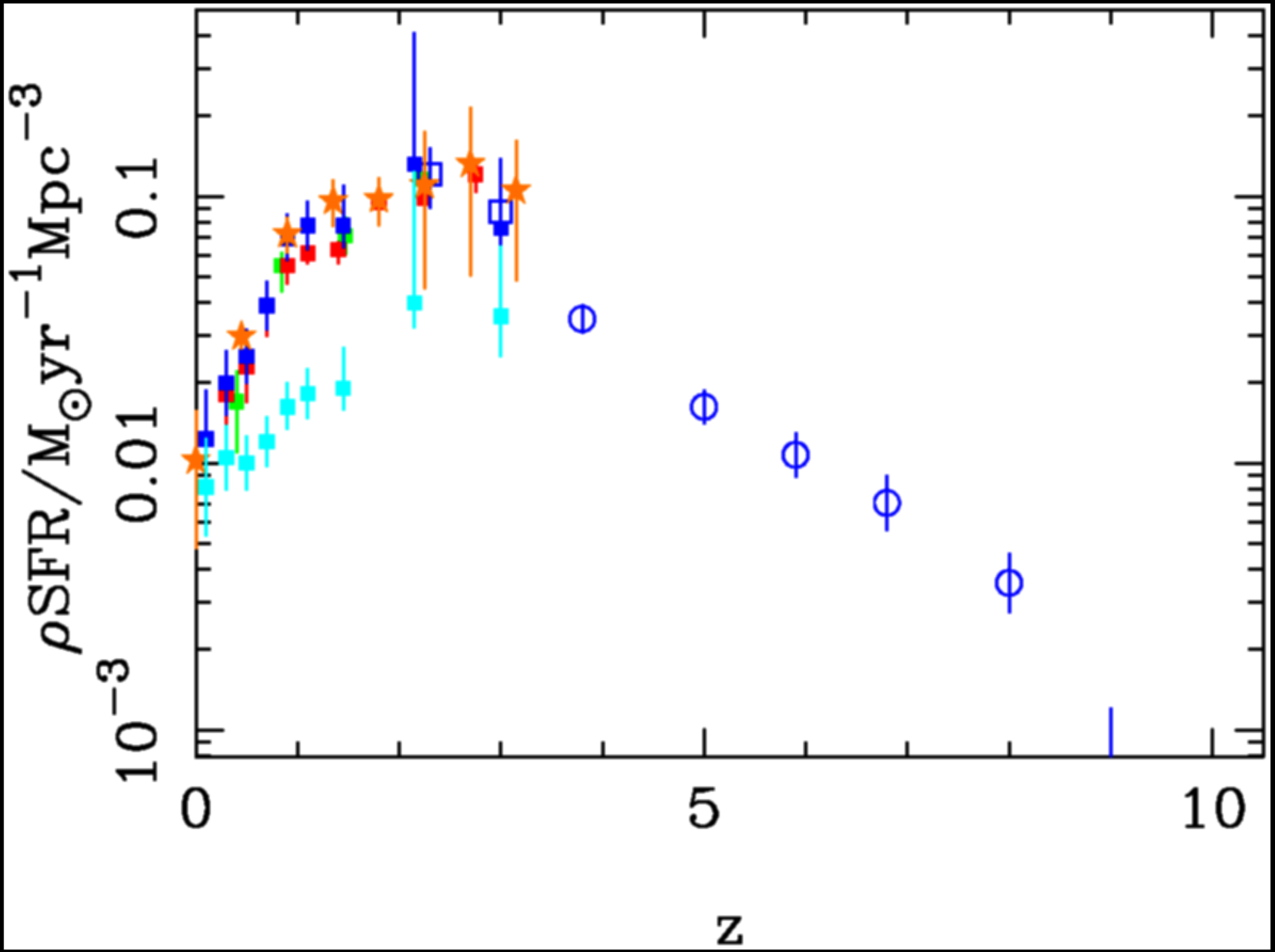

Bouwens et al. 2007
Bouwens et al. 2012
Oesch et al. 2013
- Dust corrected
- Chabrier IMF

Dunlop 2014

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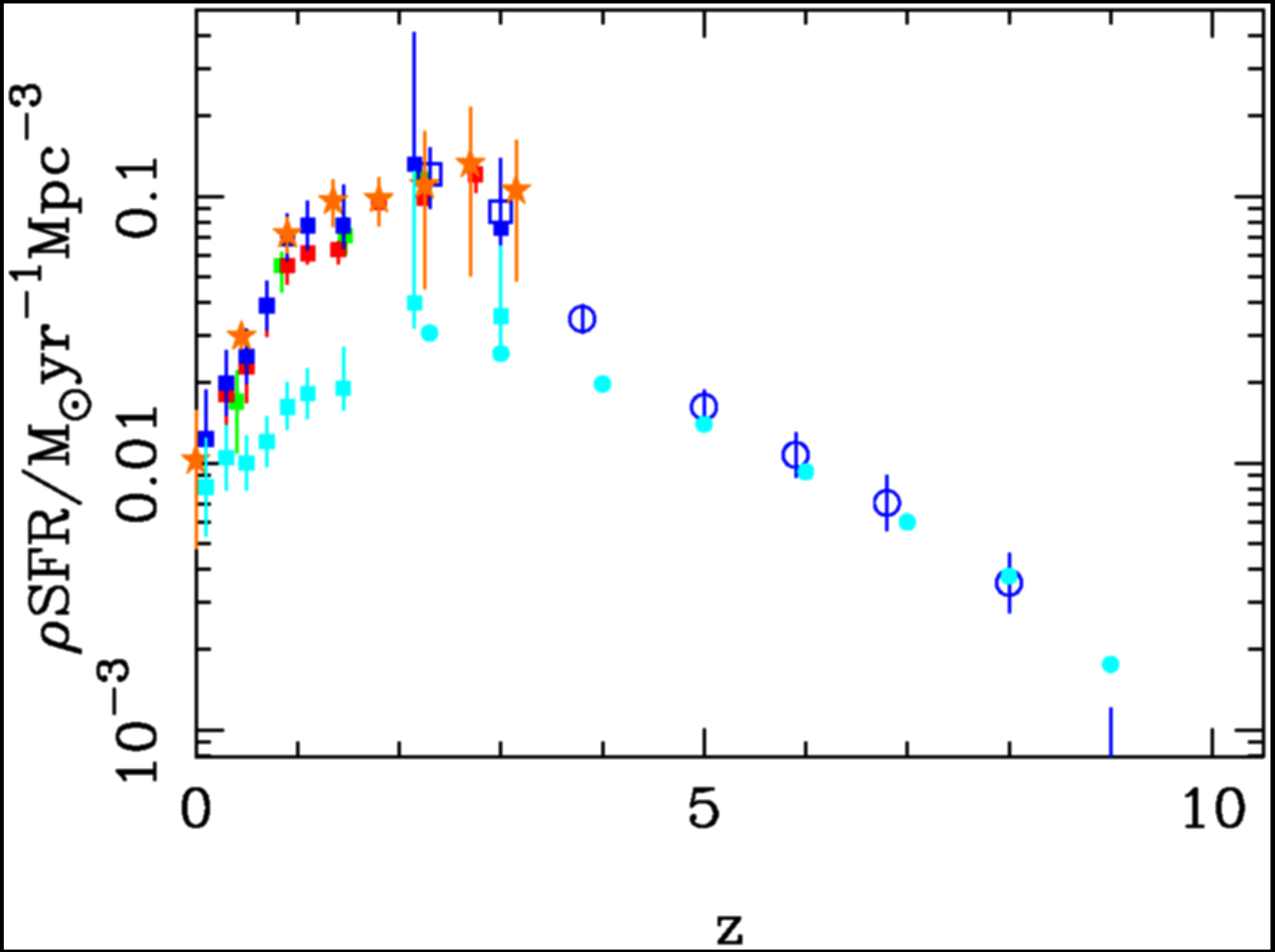

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McLure et al. 2013
Raw UV, to M = -17

Dunlop 2014

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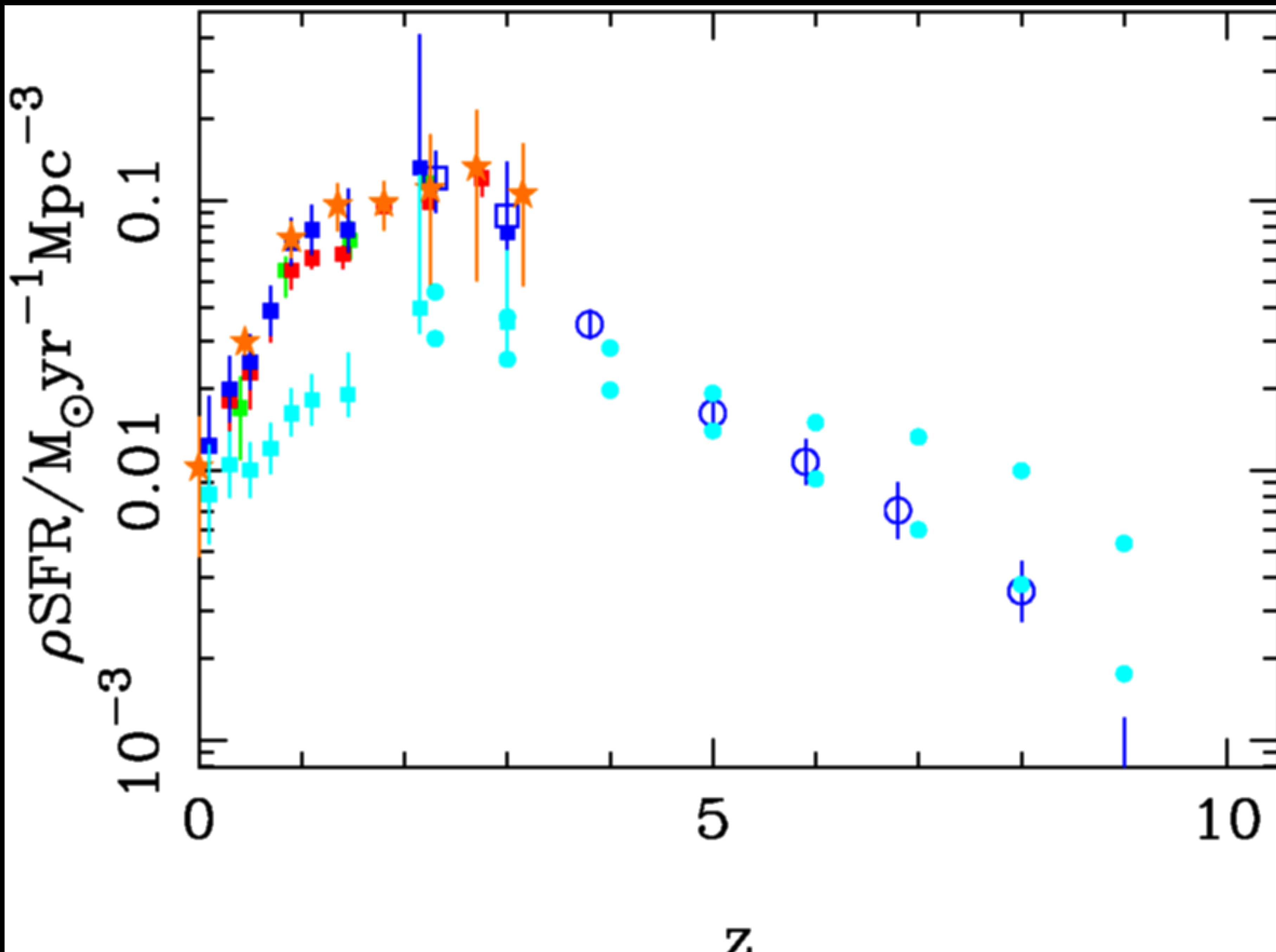

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Dunlop 2014

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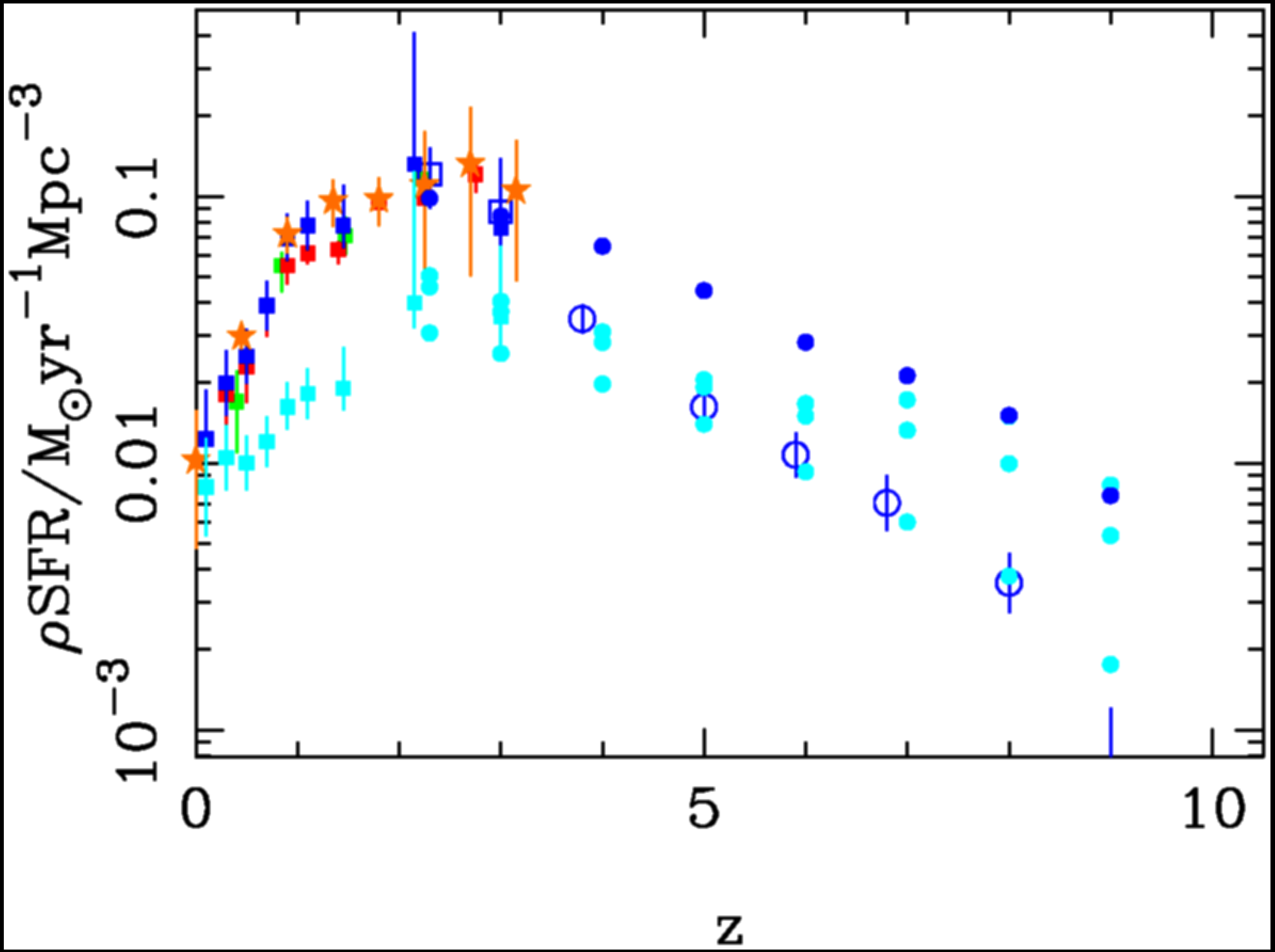

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McLure et al. 2013
Raw UV, to M = -13

McLure et al. 2013
Dust corrected UV
to M = -13
Redshift independent
dust obscuration

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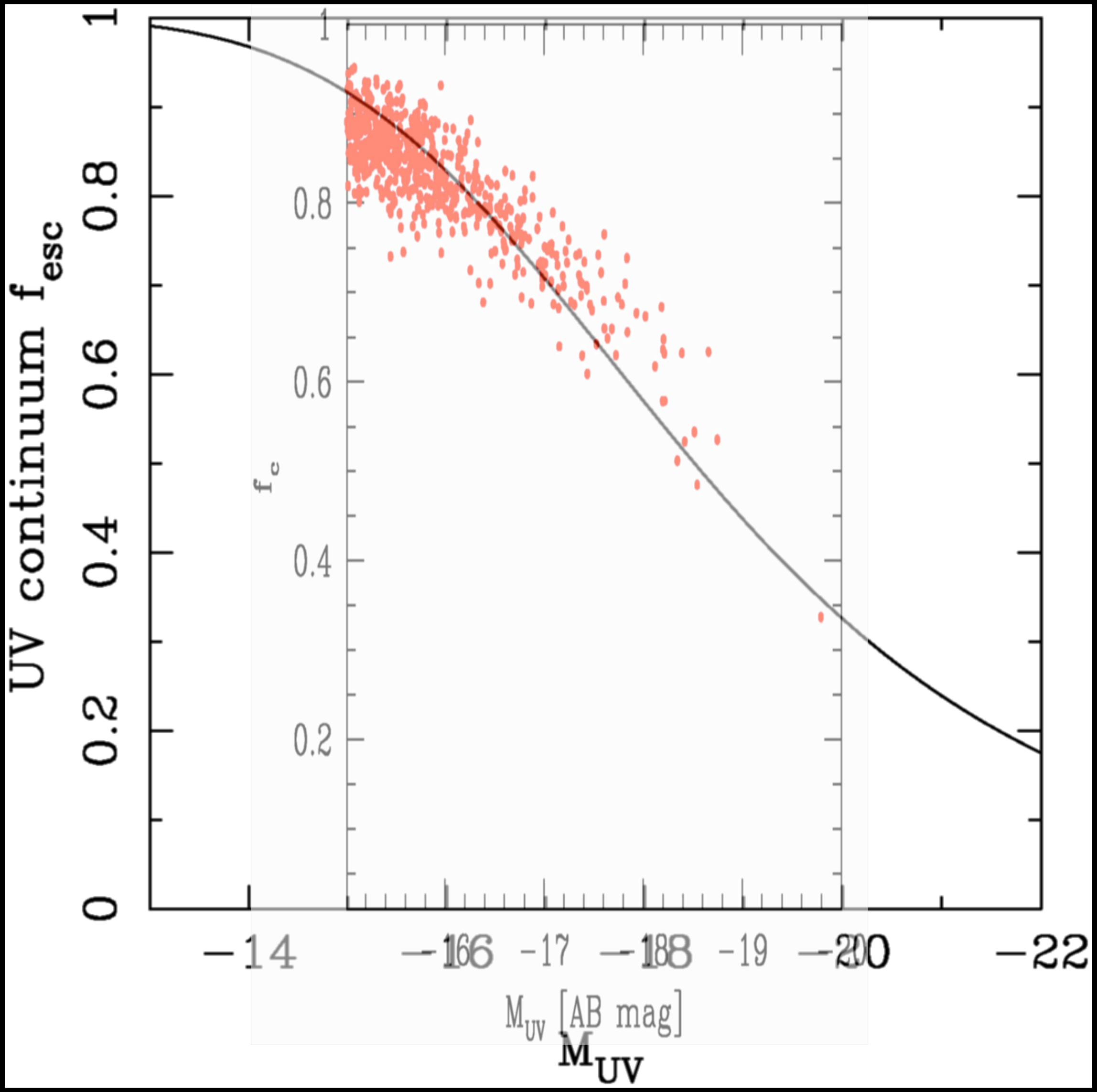
Extinction



UV continuum f_esc
0
0.2
0.4
0.6
0.8
1
−14
−16
−18
−20
−22
M_UV
f_c
0.2
0.4
0.6
0.8
1
−16
−17
−18
−19
−20
M_UV [AB mag]

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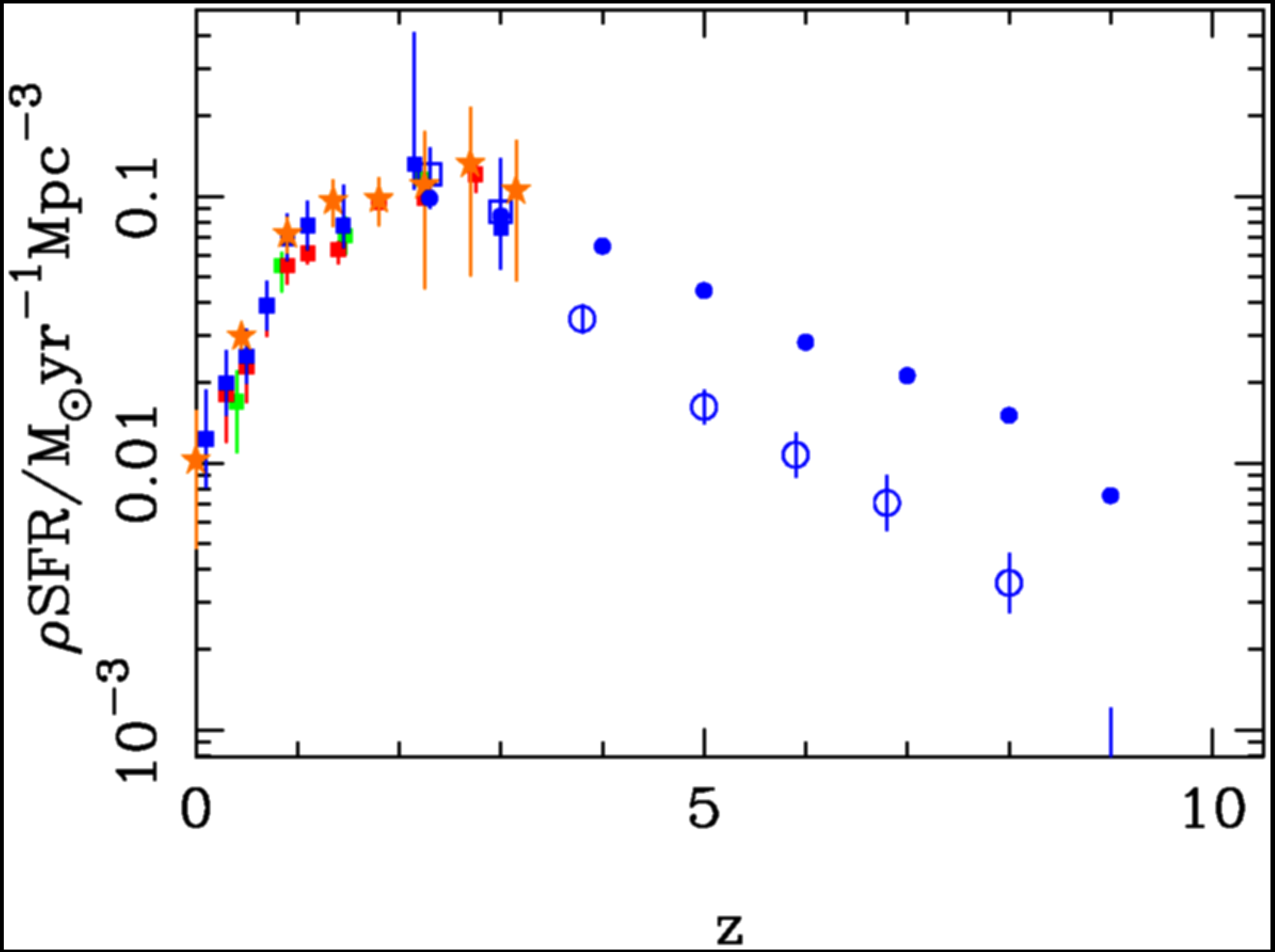

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McLure et al. 2013
Dust corrected UV
to M = -13
Redshift indep dust

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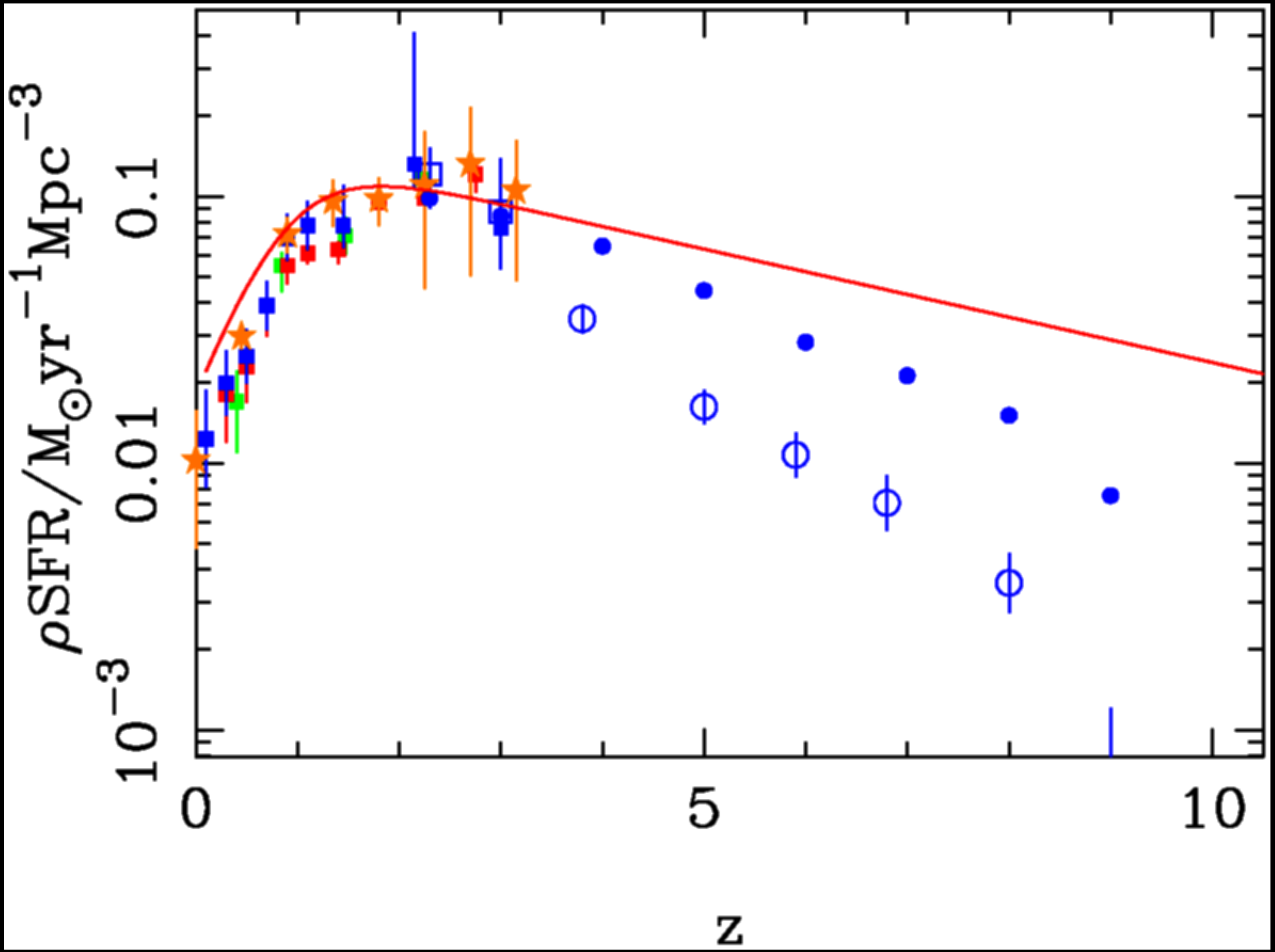

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Hopkins & Beacom

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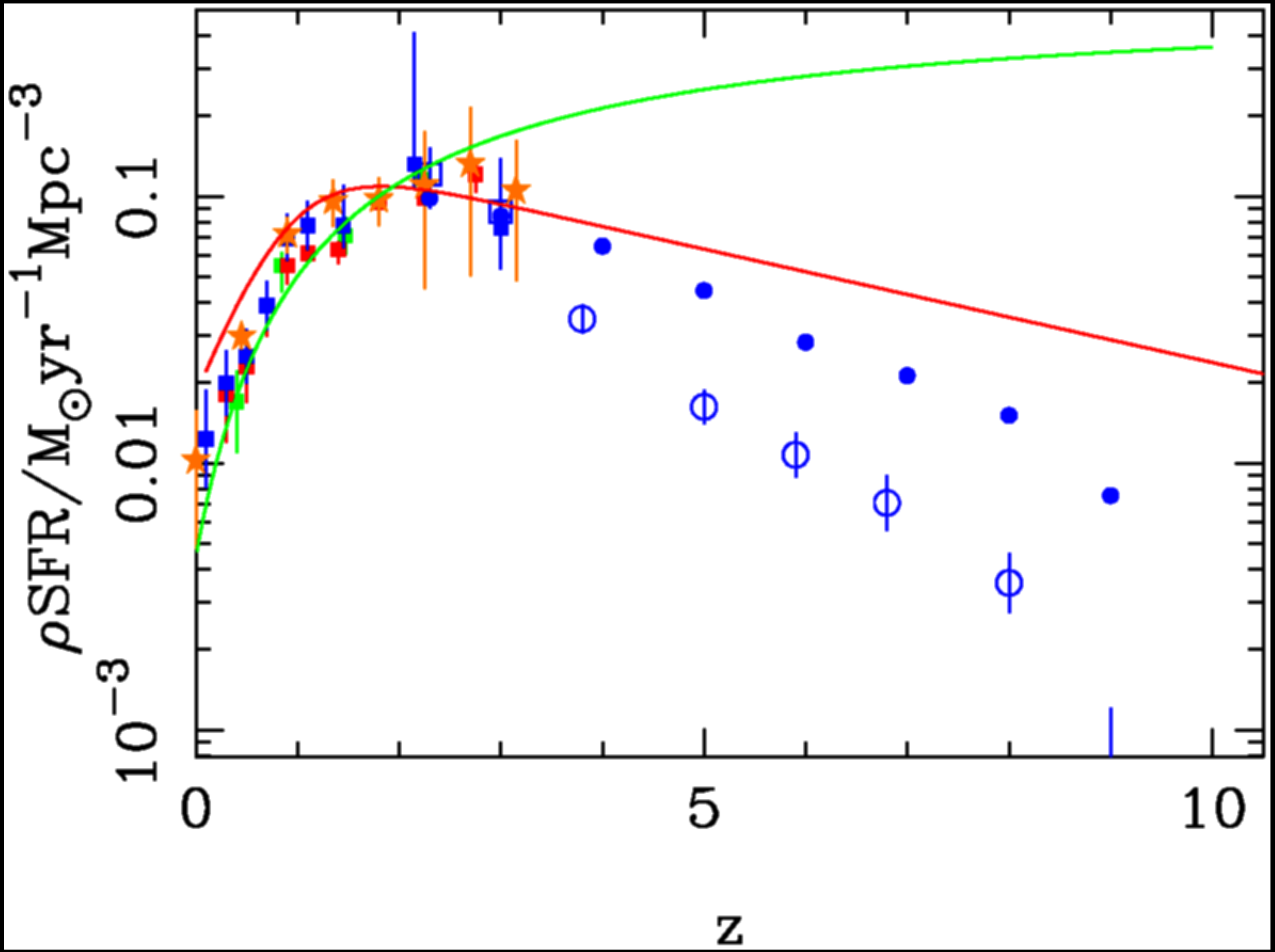

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Sobral et al.

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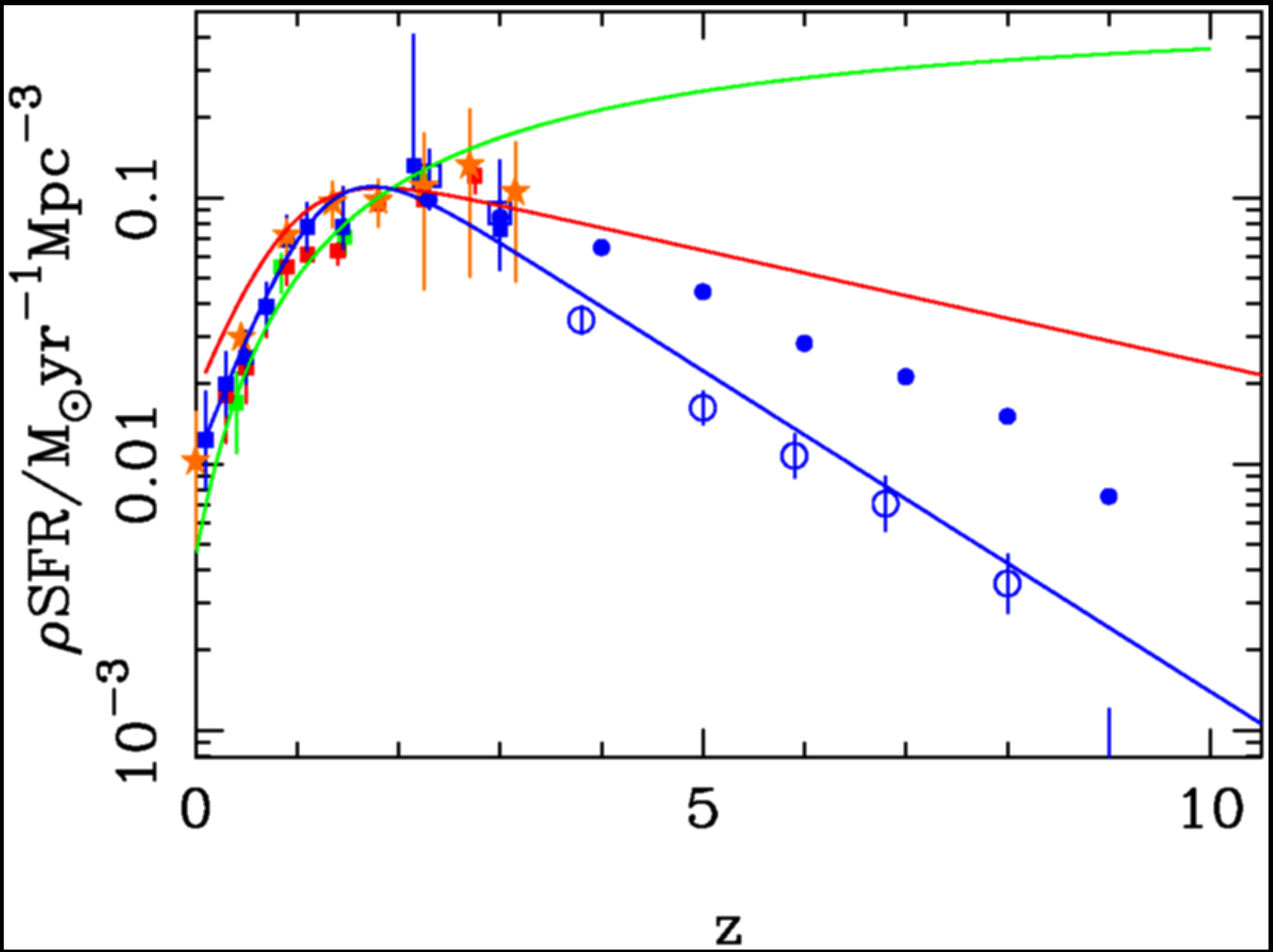

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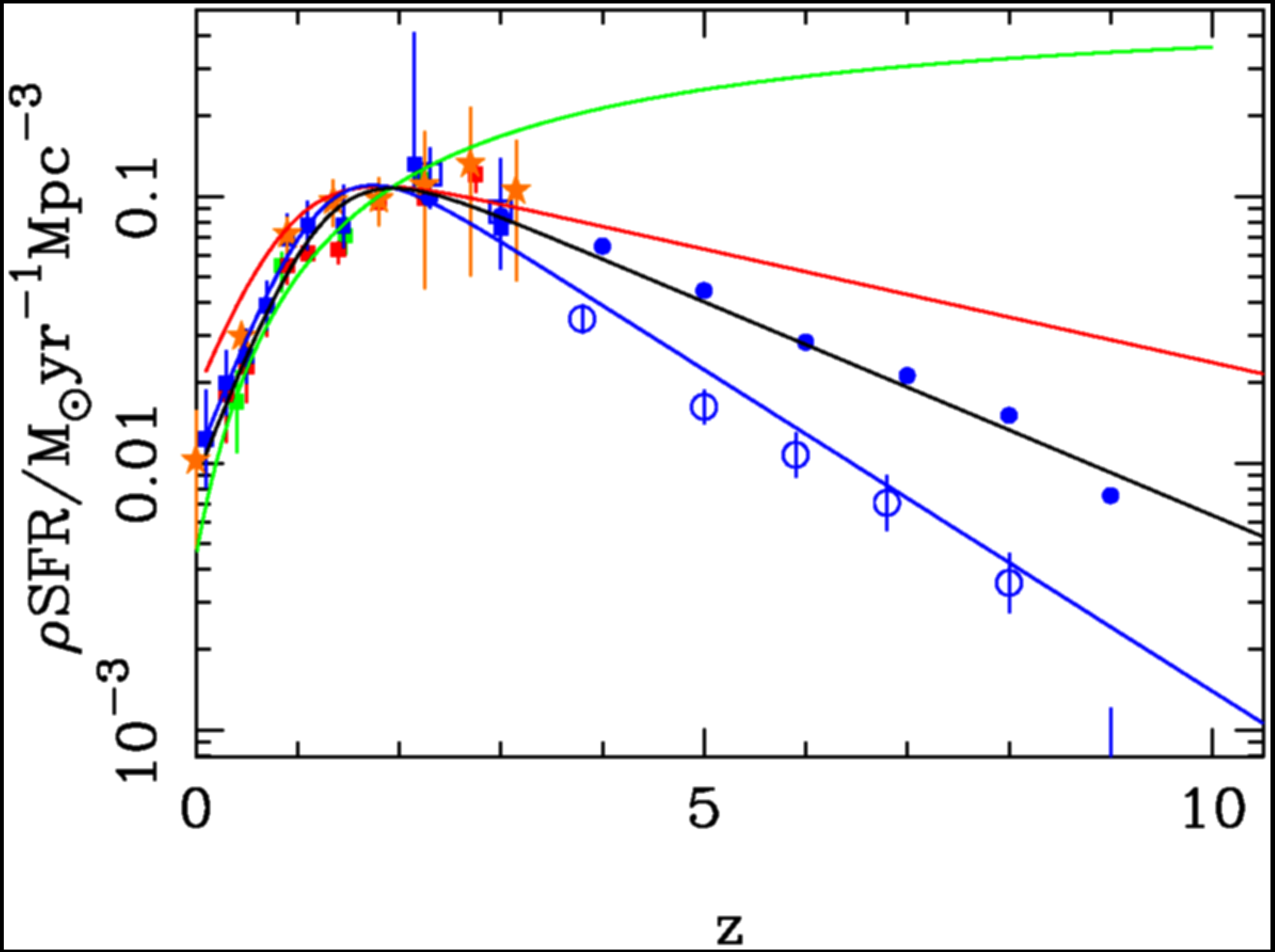

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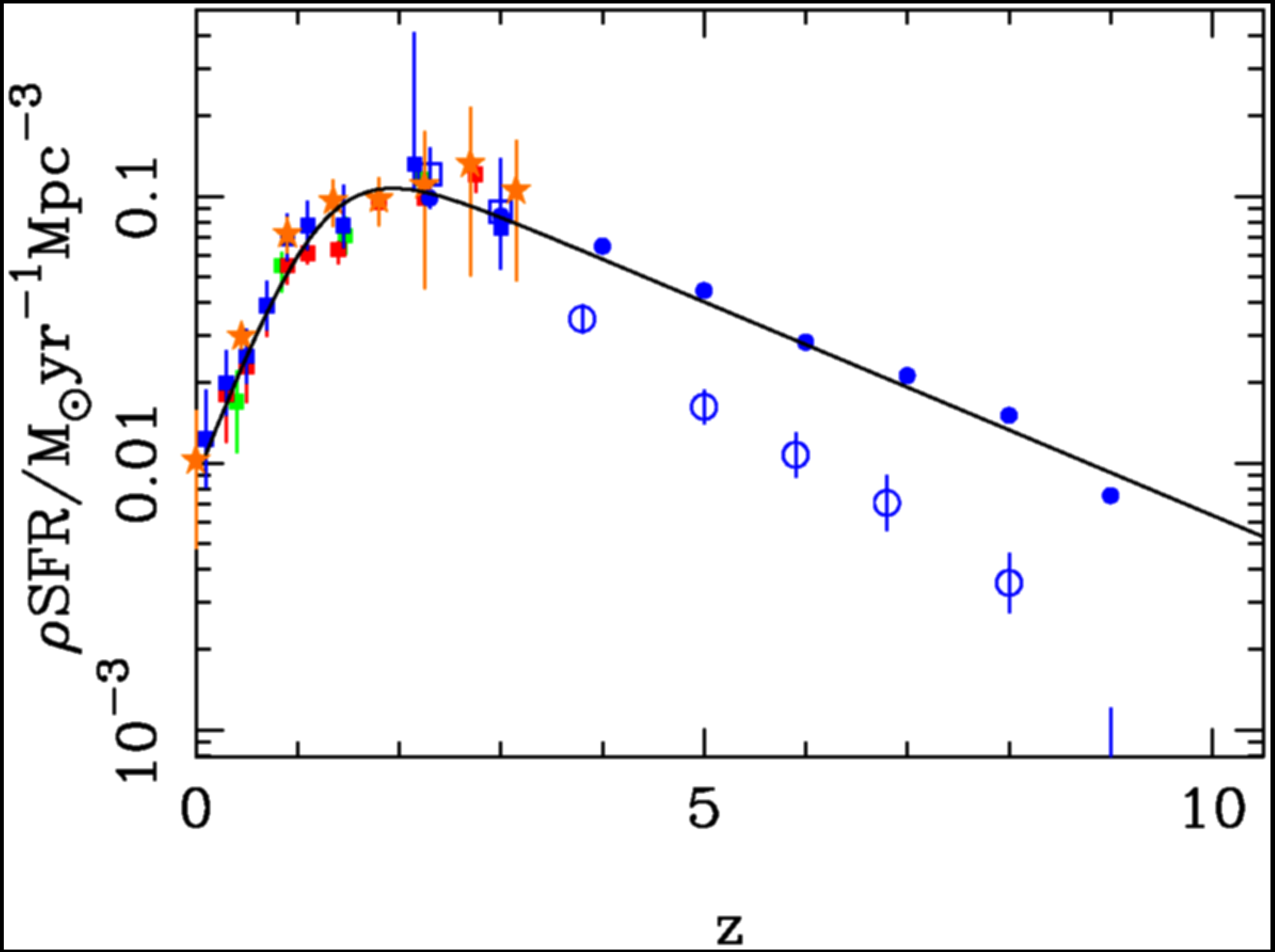

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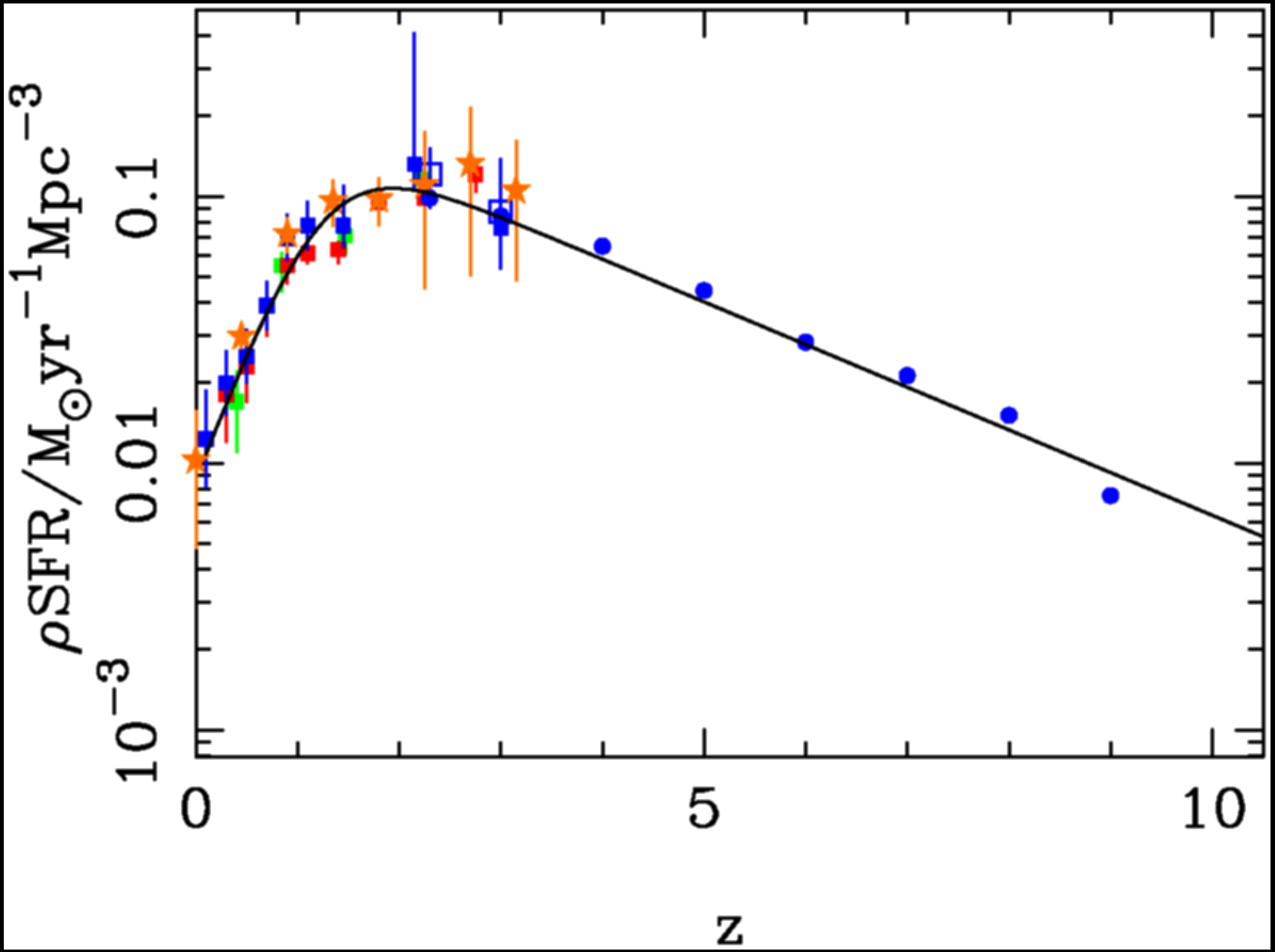

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6. The growth of stellar mass

Convergence at z = 0
Baldry et al. 2012

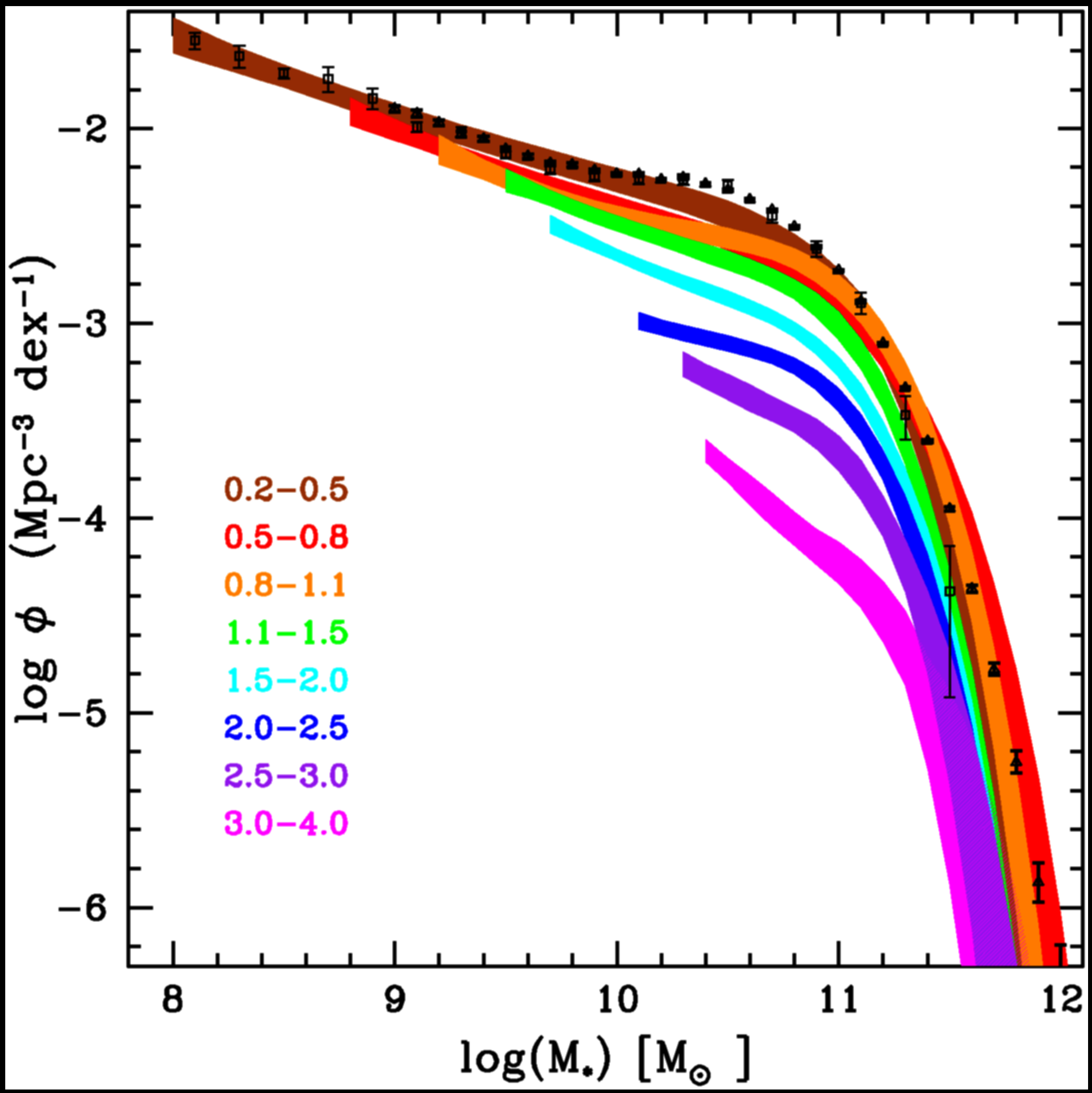
New results out to z = 3 from UltraVISTA DR1:
Ilbert et al. 2013; Muzzin et al. 2013

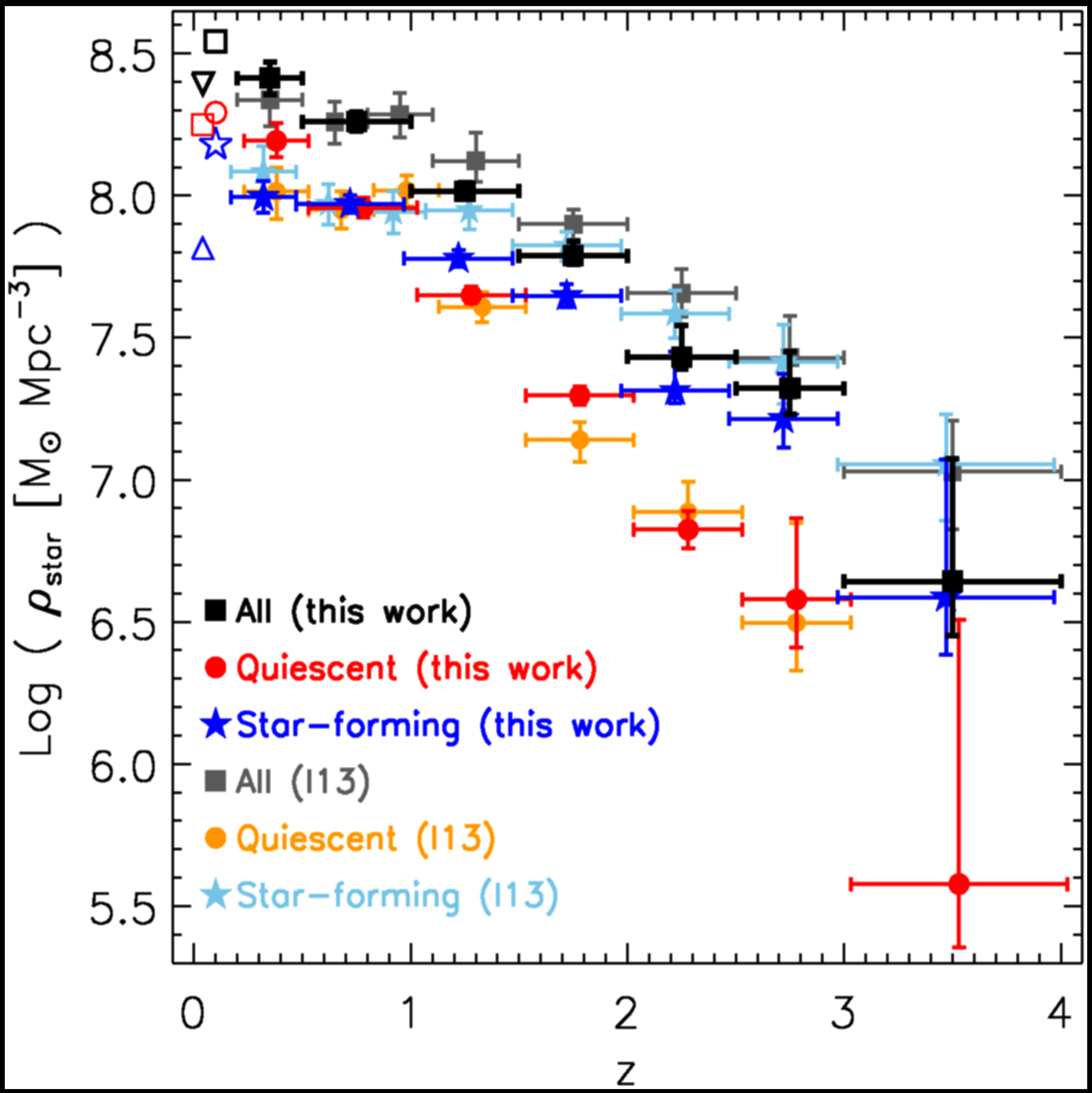
Evolving debate over contribution of emission lines at z = 5 – 7
Gonzalez et al. 2011; Stark et al. 2013; Labbe et al. 2013

6. The growth of stellar mass

Latest stellar mass functions from UltraVISTA

McCracken et al. 2012



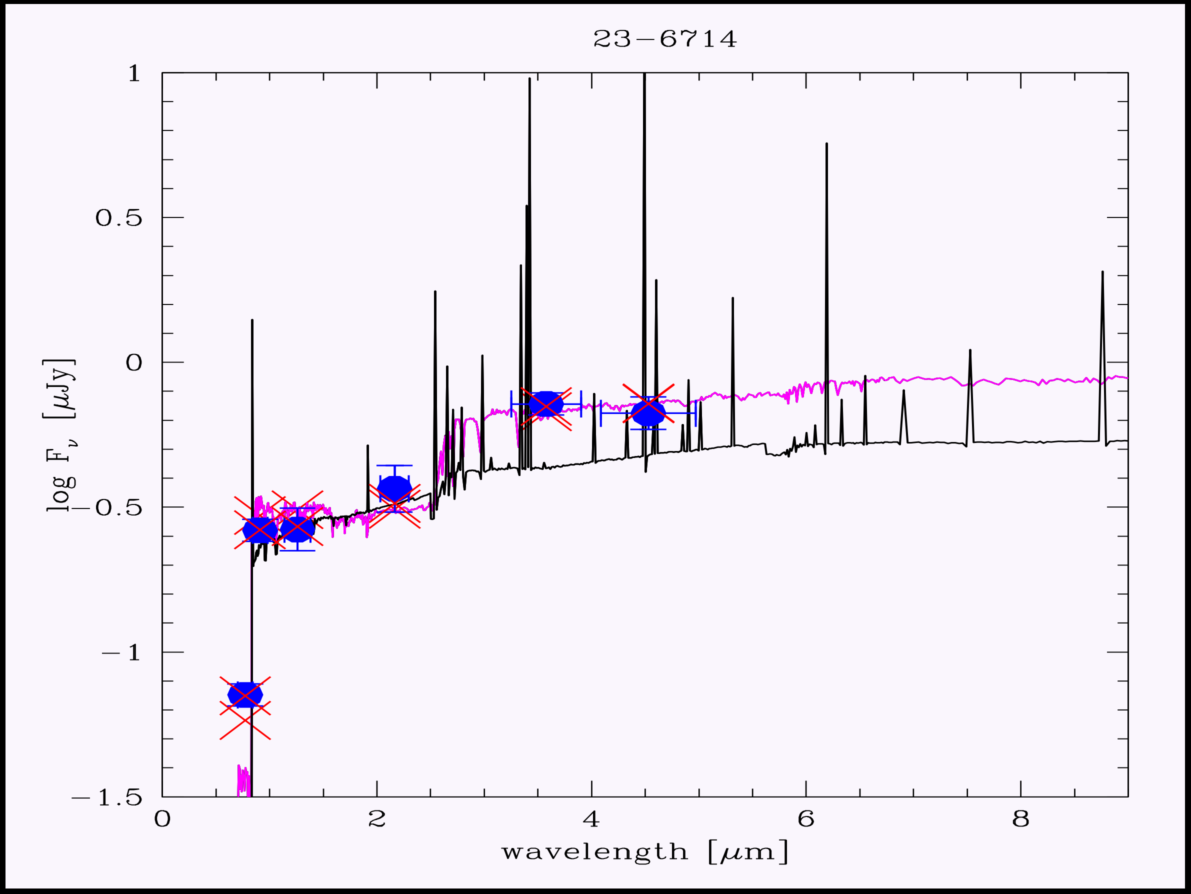


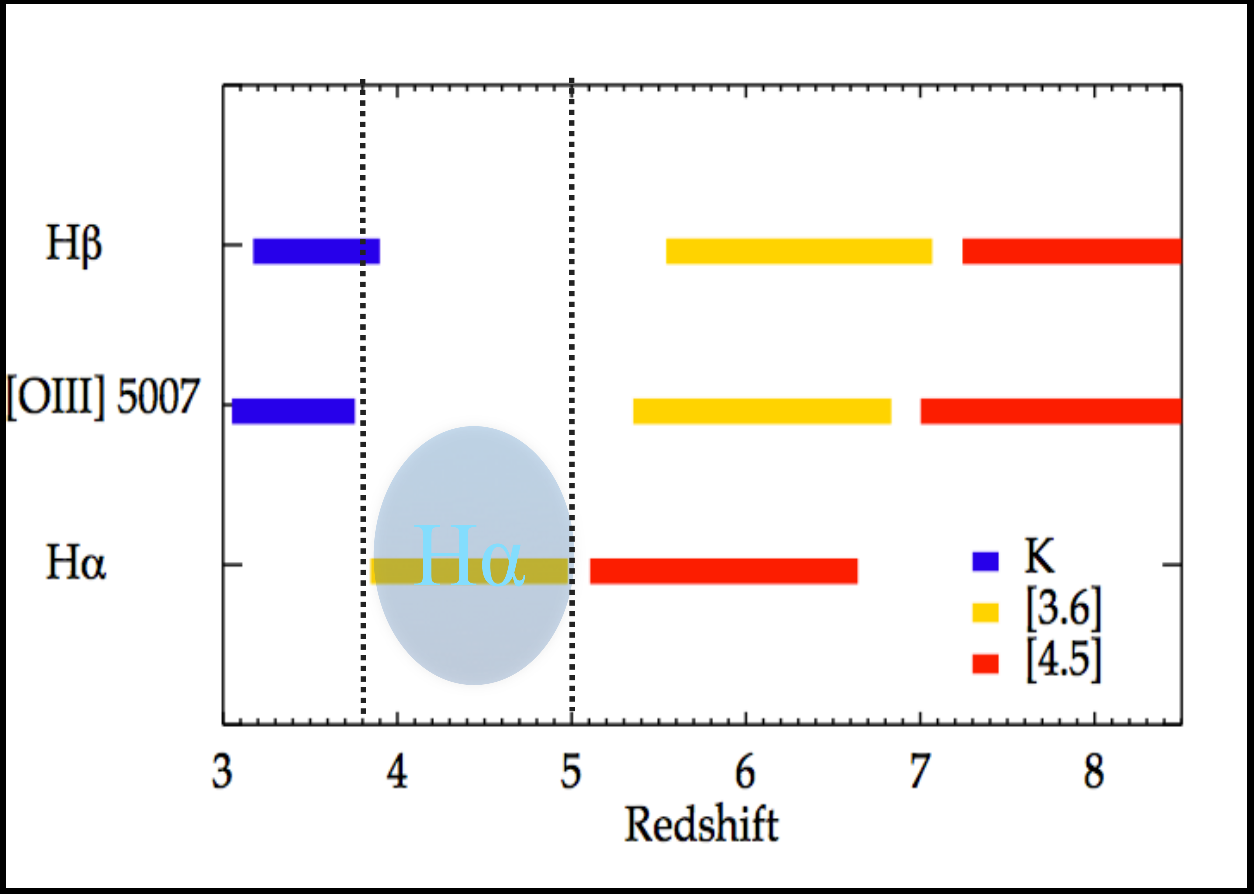
Ibert et al. 2013, A&A, 556, 55

Muzzin et al. 2013, arXiv:1303.4409

6. The growth of stellar mass

Debate over level of correction to IRAC fluxes at high z

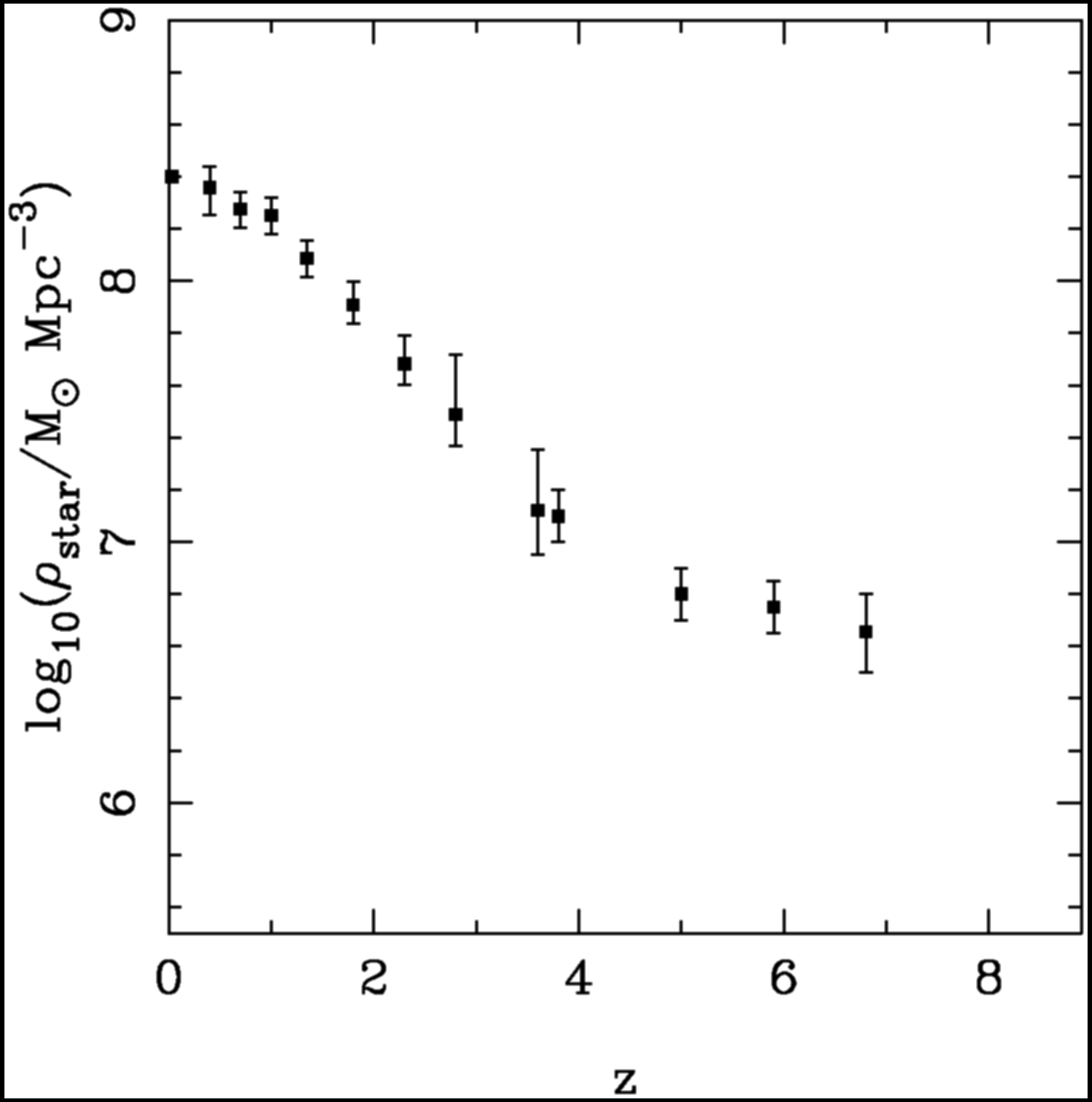




e.g. Schaerer & de Barros (2009)

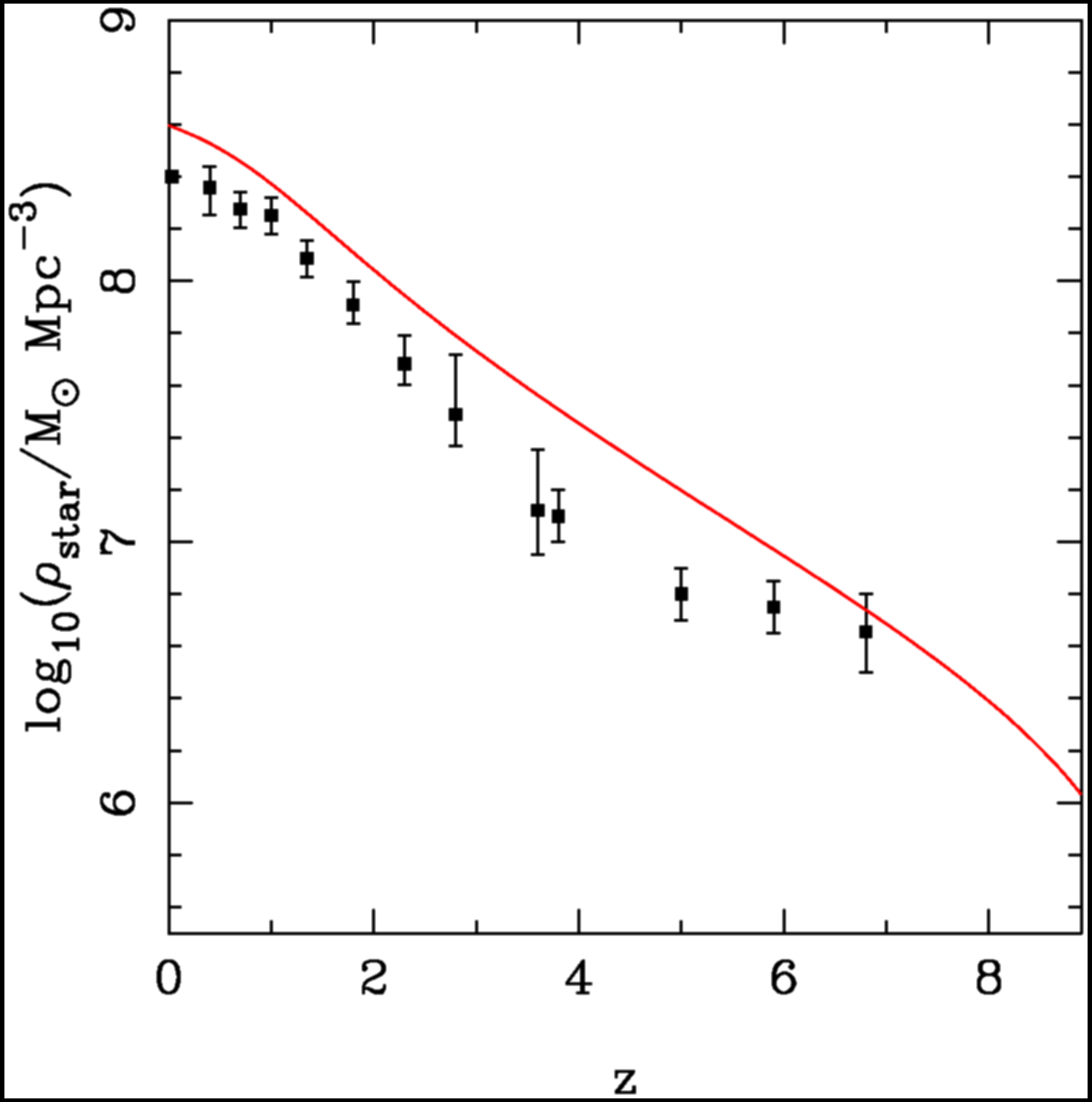
Stark et al. (2013) suggests stellar masses need to be reduced by factors of 1.1 at z = 4; 1.3 at z = 5; 1.6 at z = 6; 2.4 at z = 7

6. The growth of stellar mass



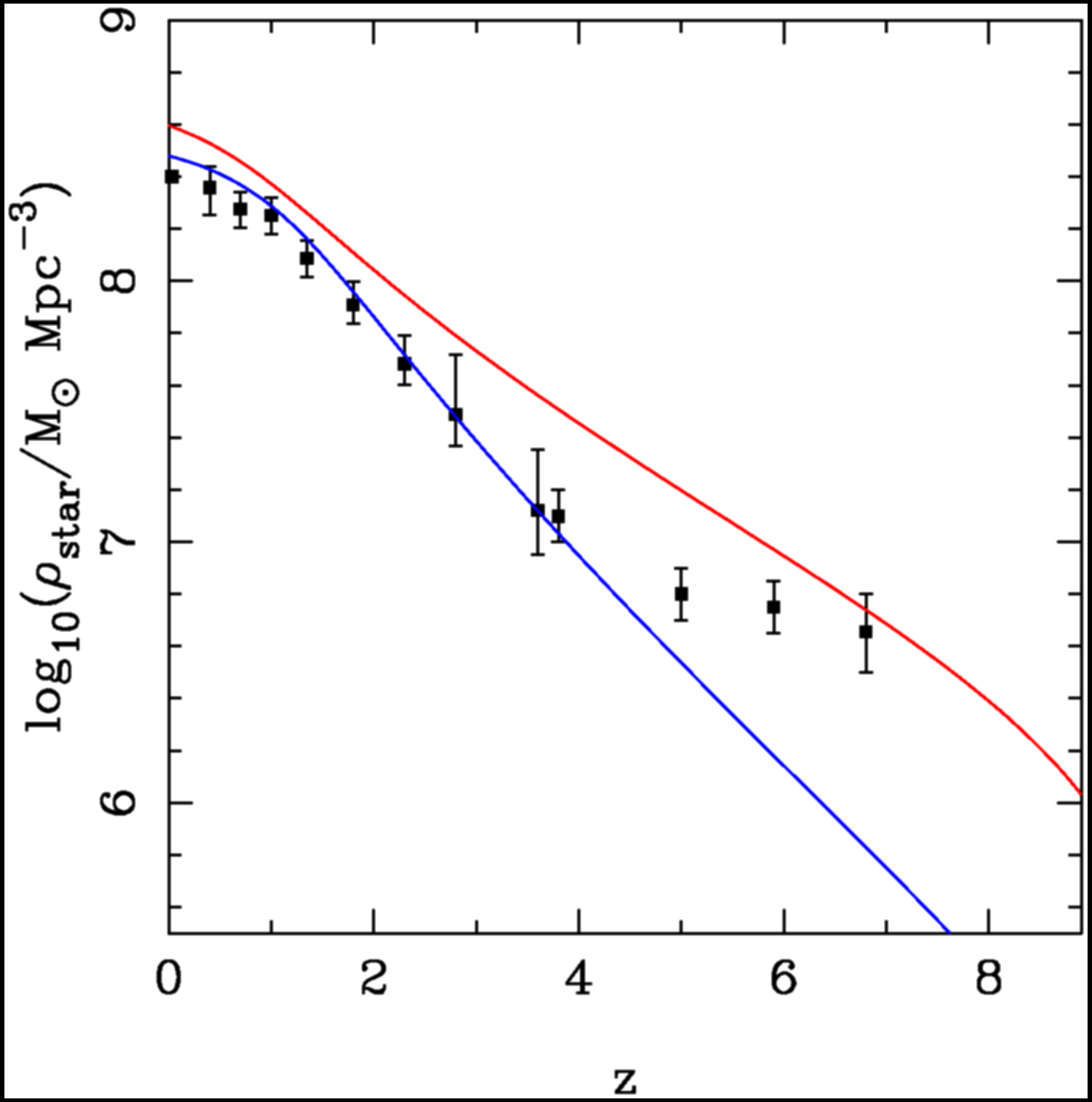
Data from Baldry et al. 2012, Ilbert et al. 2013, Gonzalez et al. 2011

6. The growth of stellar mass



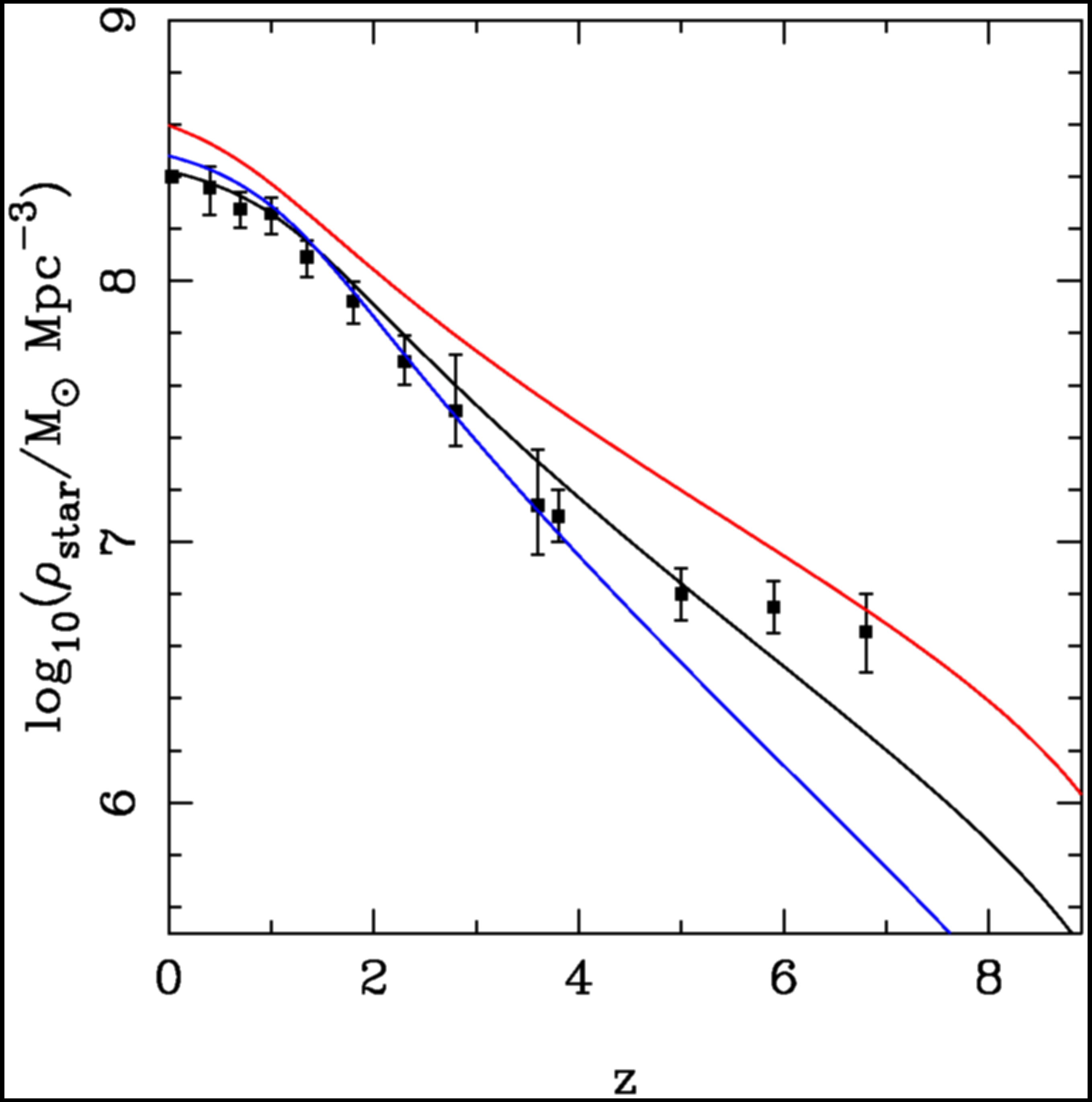
Data from Baldry et al. 2012, Ilbert et al. 2013, Gonzalez et al. 2011
+ Hopkins & Beacom 2006 prediction (converted to Chabrier IMF)

4. The growth of stellar mass



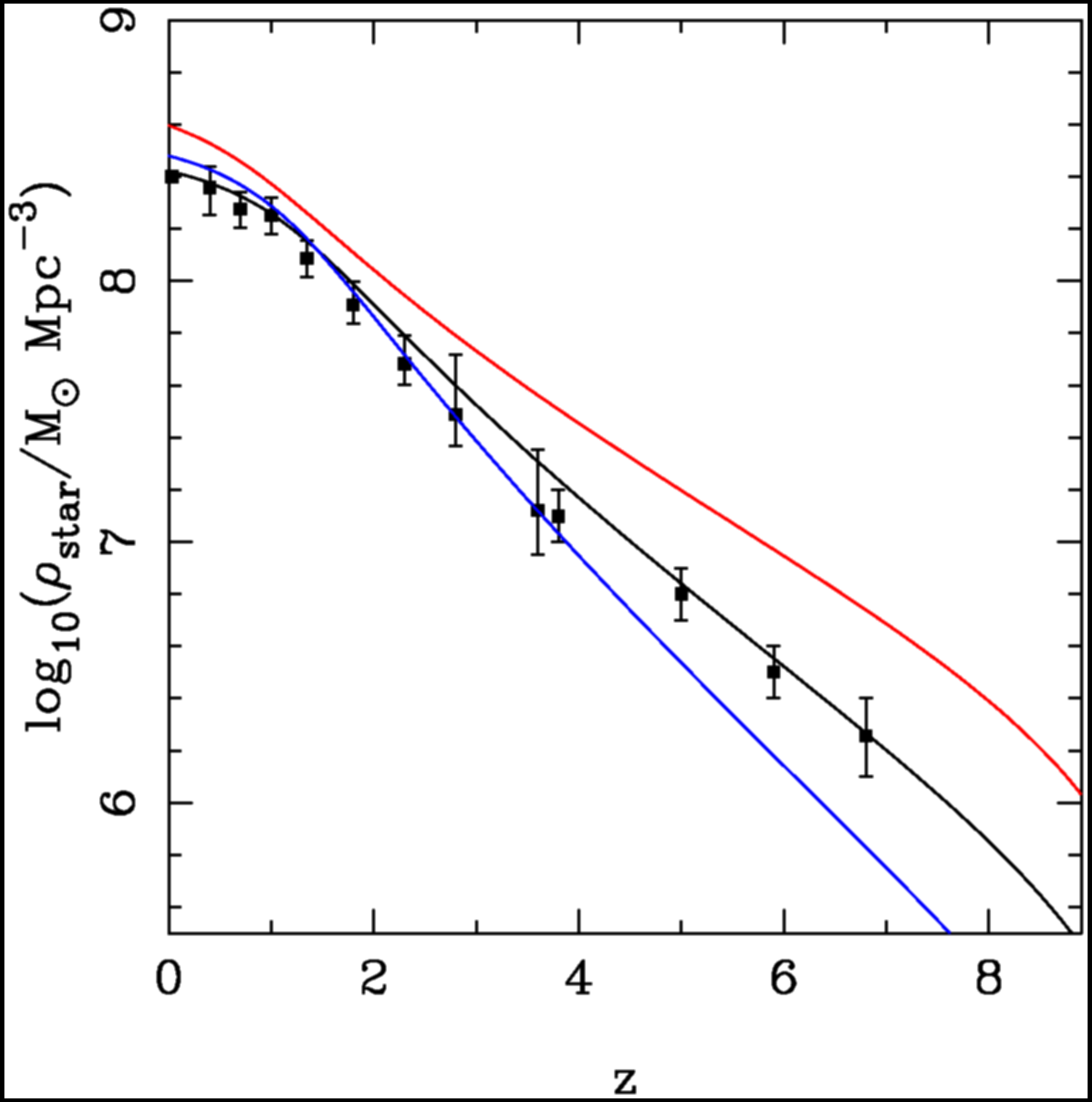
Data from Baldry et al. 2012, Ilbert et al. 2013, Gonzalez et al. 2011
+ Behroozi et al. 2013 prediction

6. The growth of stellar mass



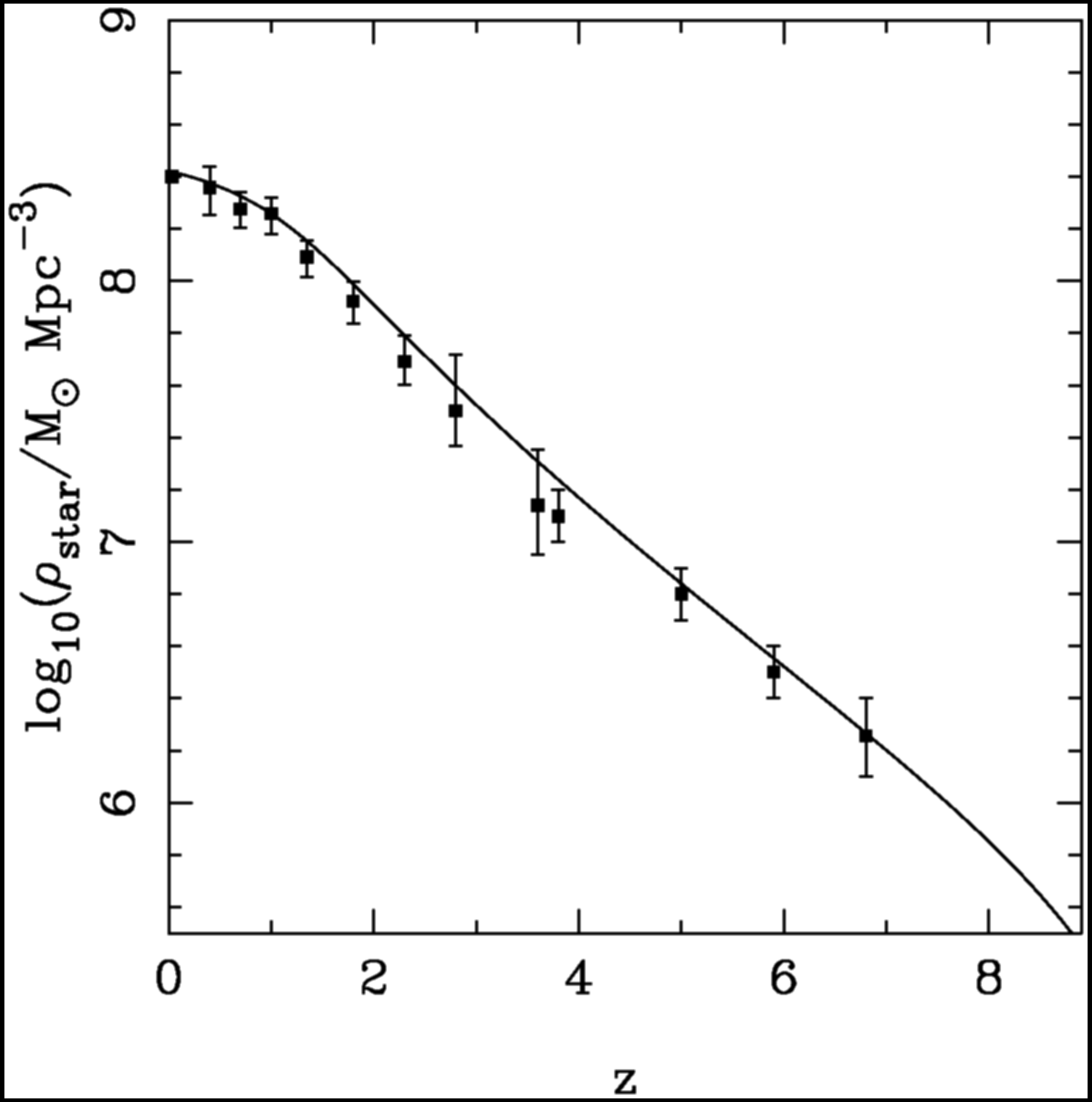
Data from Baldry et al. 2012, Ilbert et al. 2013, Gonzalez et al. 2011
+ Dunlop 2014 prediction

6. The growth of stellar mass



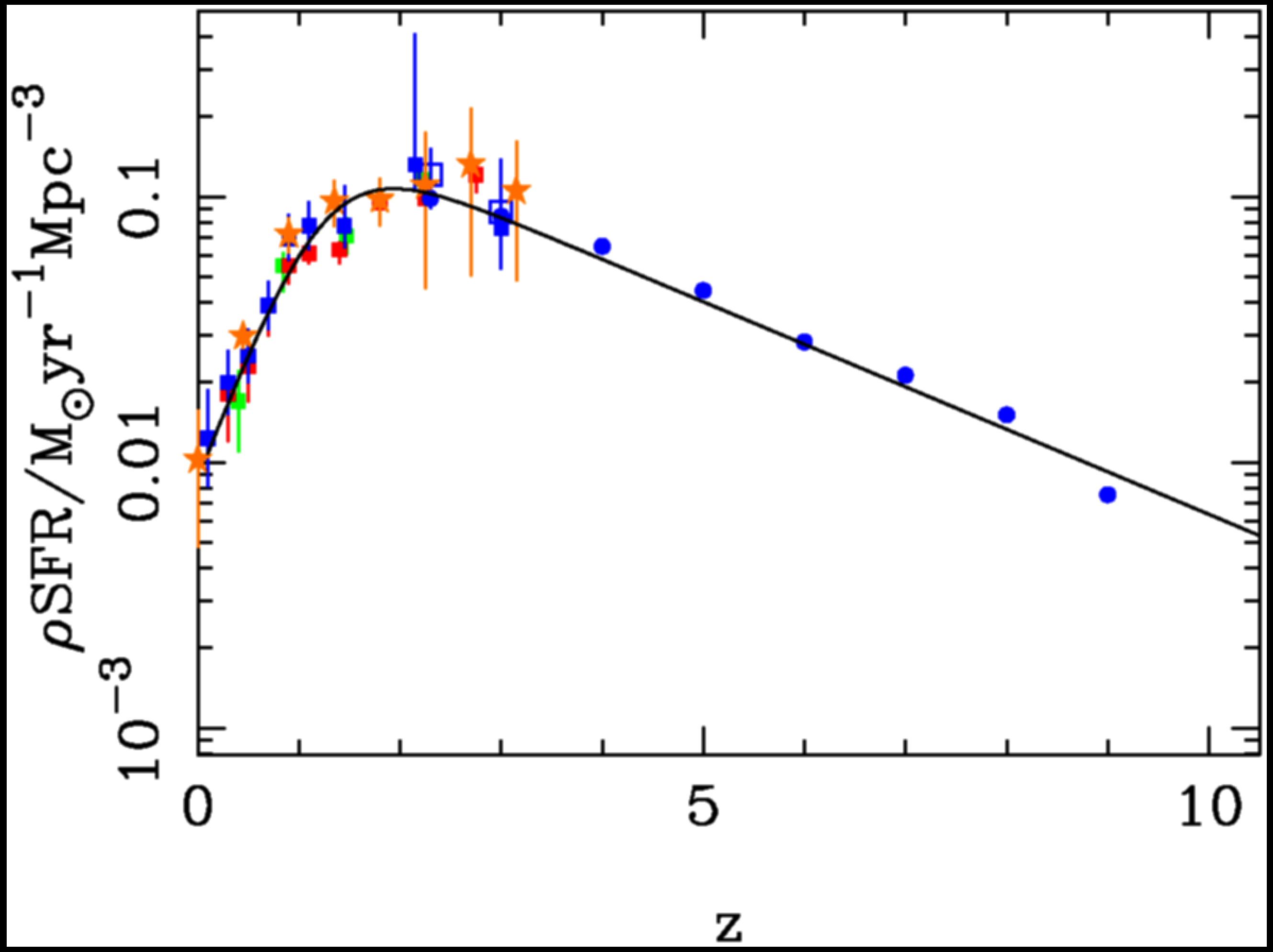
Data from Baldry et al. 2012, Ilbert et al. 2013, Gonzalez et al. 2011
with high-z masses now fixed to Stark et al. 2013 emission-line corrected

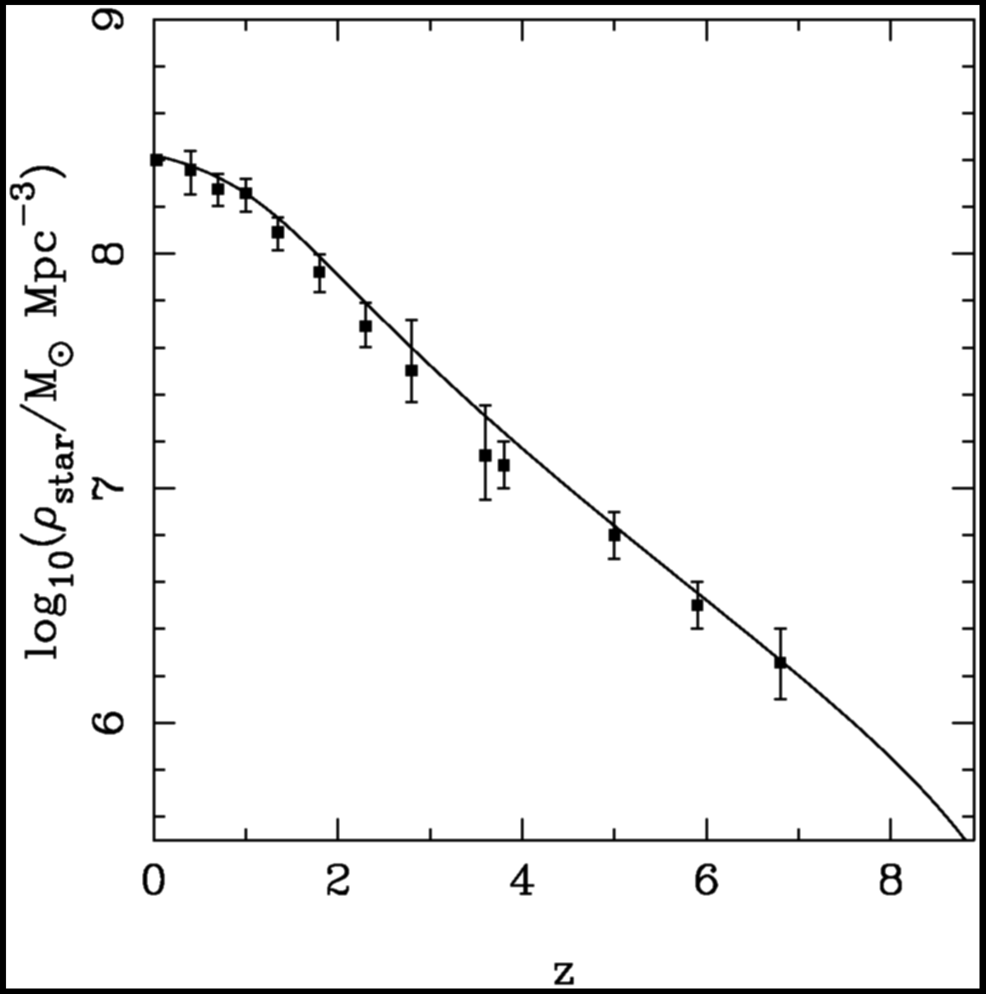
6. The growth of stellar mass



Data from Baldry et al. 2012, Ilbert et al. 2013 integrated to $M_* = 10^6\ M_{sun}$, Stark et al. 2013, and Dunlop 2014 prediction

7. Summary, issues & future prospects





Haven't had time to review :

- Cosmic SF history via galactic archaeology
- History of metals in the Universe

Issues

- Incompleteness and steepness of stellar mass functions at $z > 2$?
- Strength of emission-line contributions at high redshift ?
- Should UV LF be integrated down to $M_{UV} \sim -13$? Beyond $z \sim 12$?
- Gamma Ray bursts – any use ?
- Extinction as a function of mass/luminosity/redshift – dust at high z ?
- CII as a sub-mm star-formation tracer – any use ?
- What limits star formation at high redshift ?
- What is the physical mechanism for mass quenching ?
- Link to morphological transformations ?
- Impact of complex/stochastic SF histories, ?
- The IMF ?

And many more…..

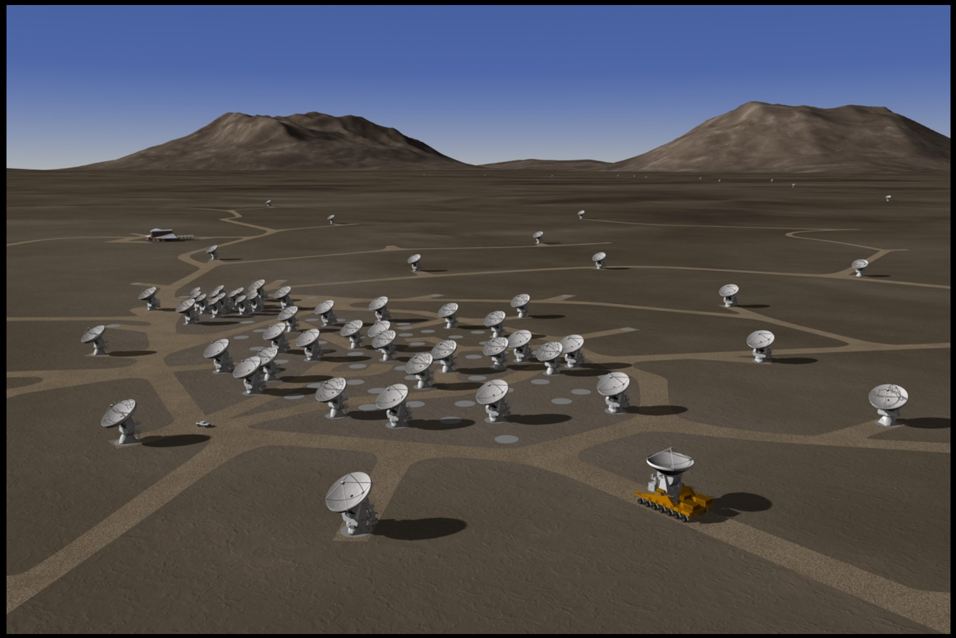
The Future – ALMA deep field

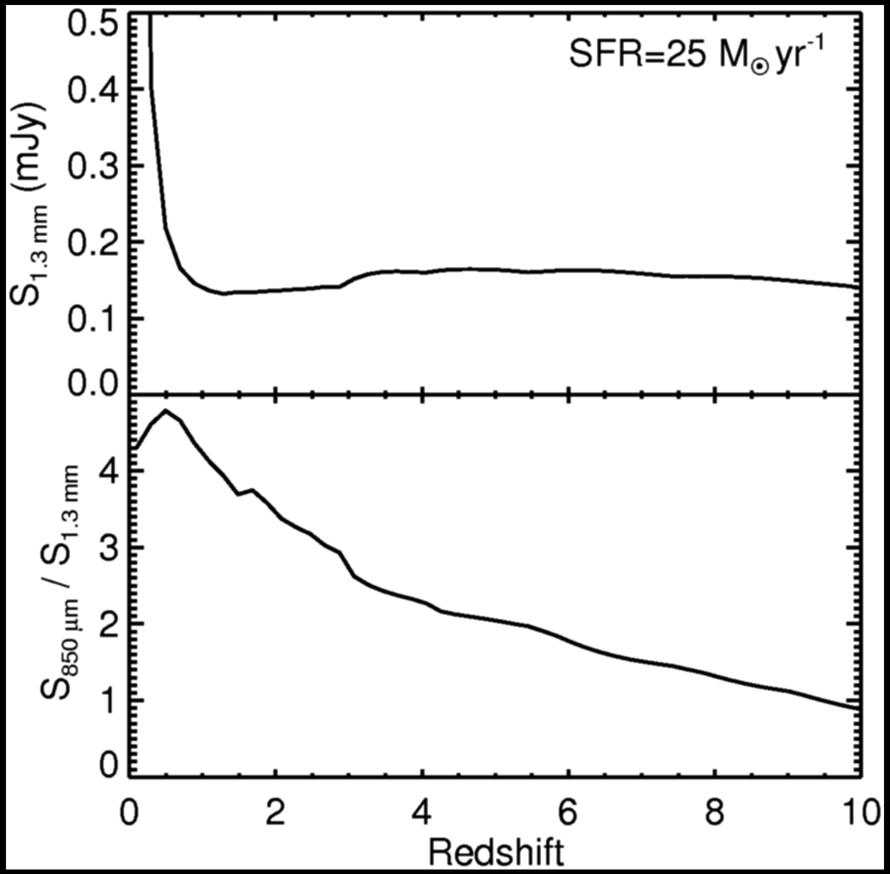
ALMA Deep Field

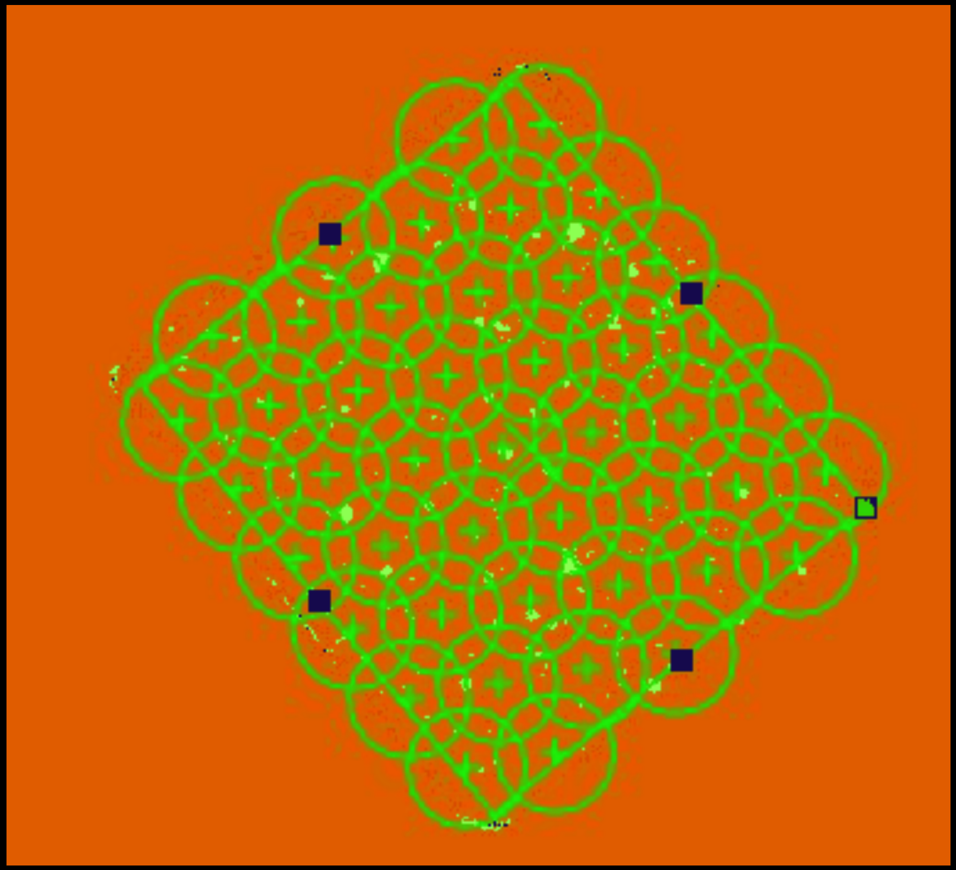
β measurements imply presence of dust in even highest z galaxies seen to date

Need to observe dust emission to complete picture of cosmic star-formation history

ALMA 1.3mm image of HUDF – awarded 20 hrs in Cycle 1







ALMA Deep Field

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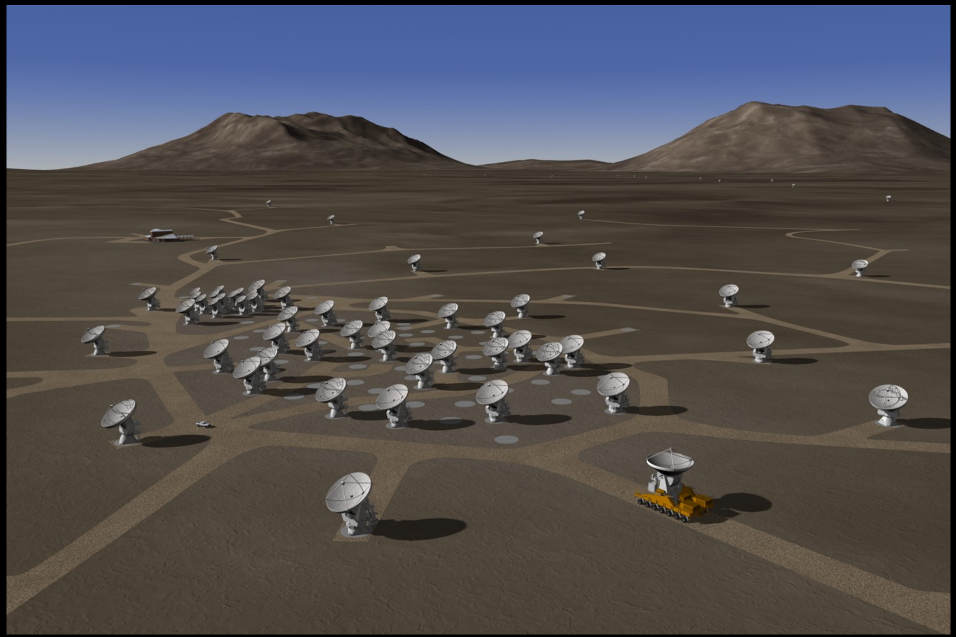
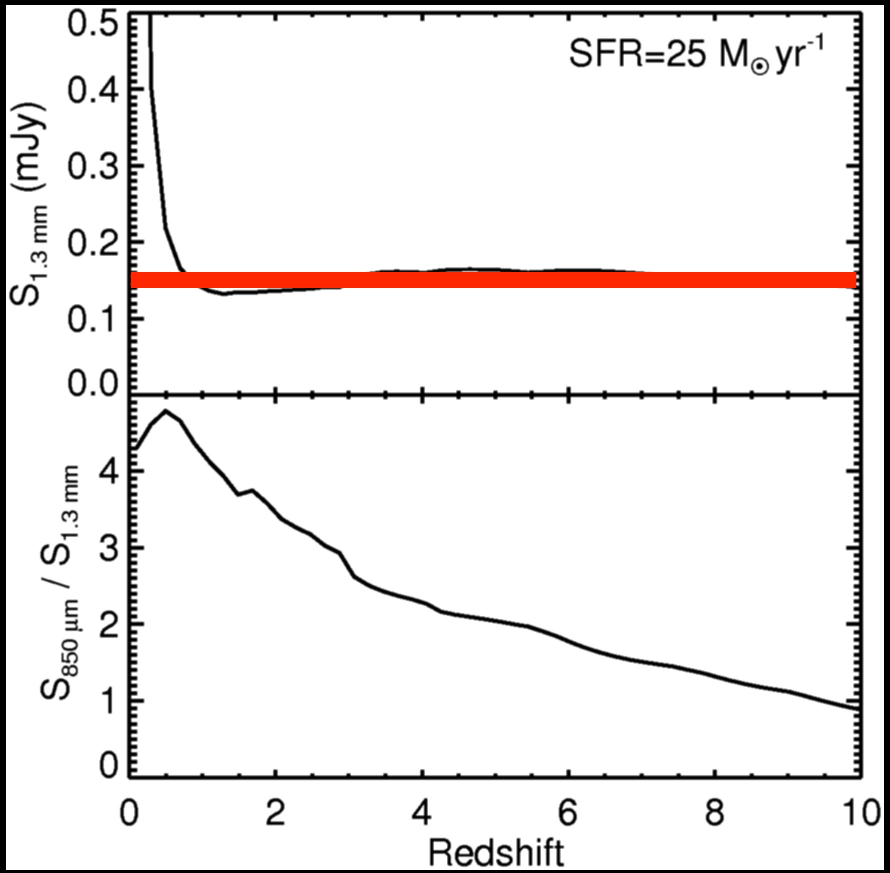
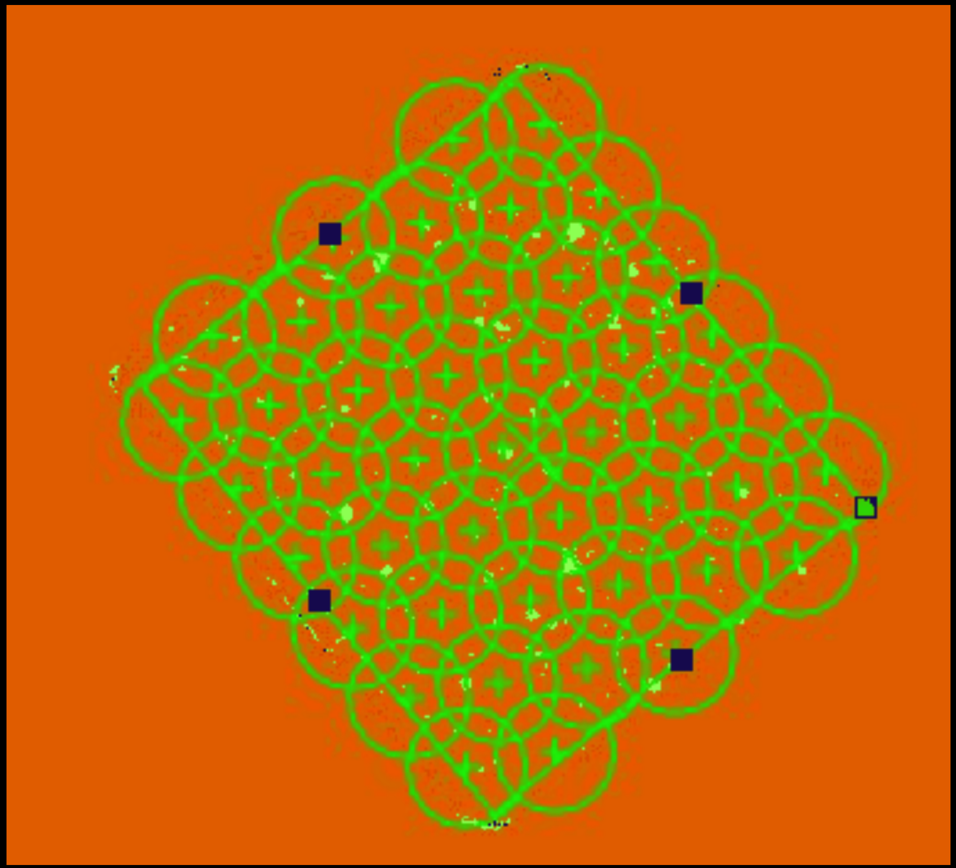
ALMA 1.3mm image of HUDF – awarded 20 hrs in Cycle 1





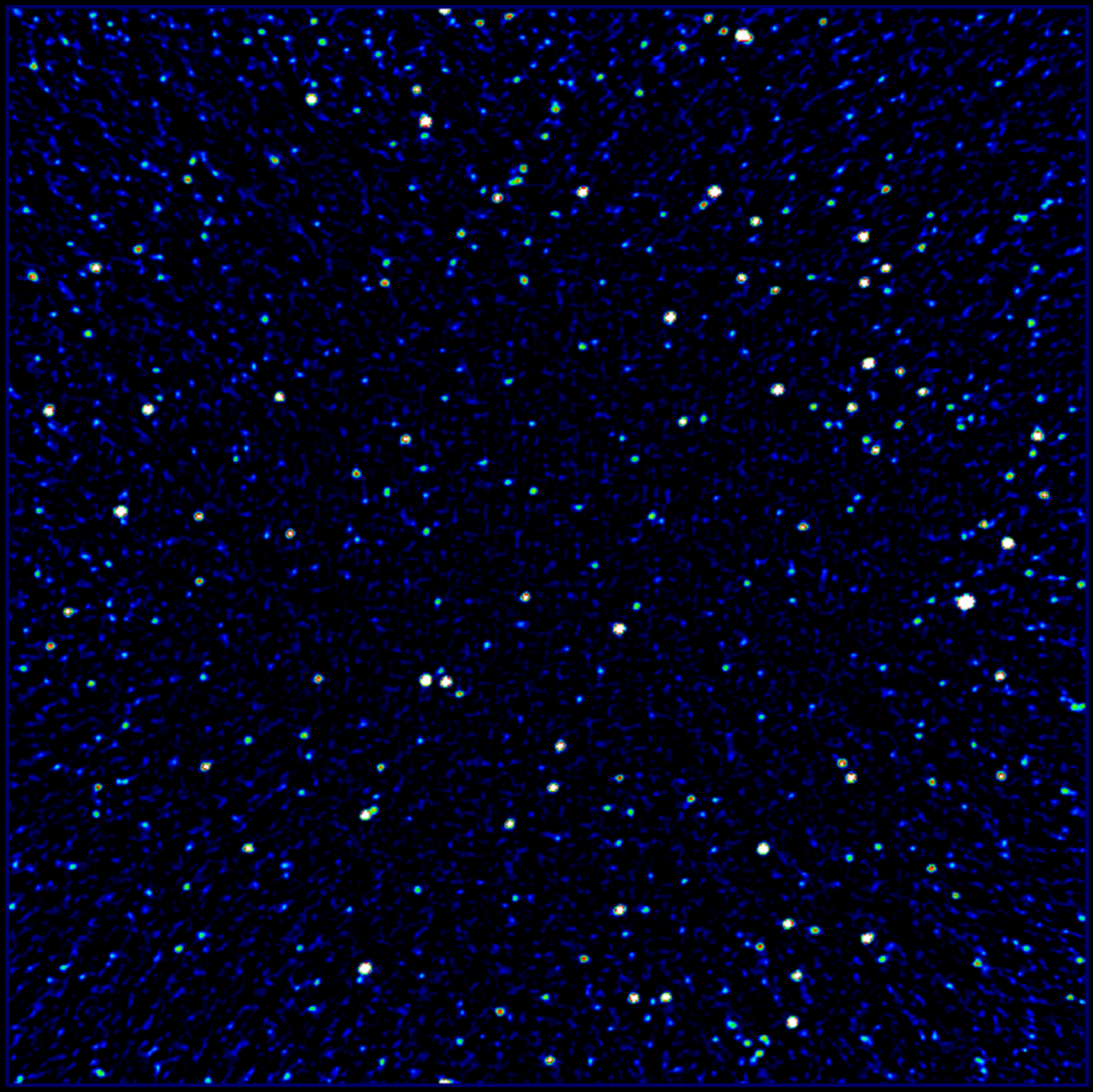


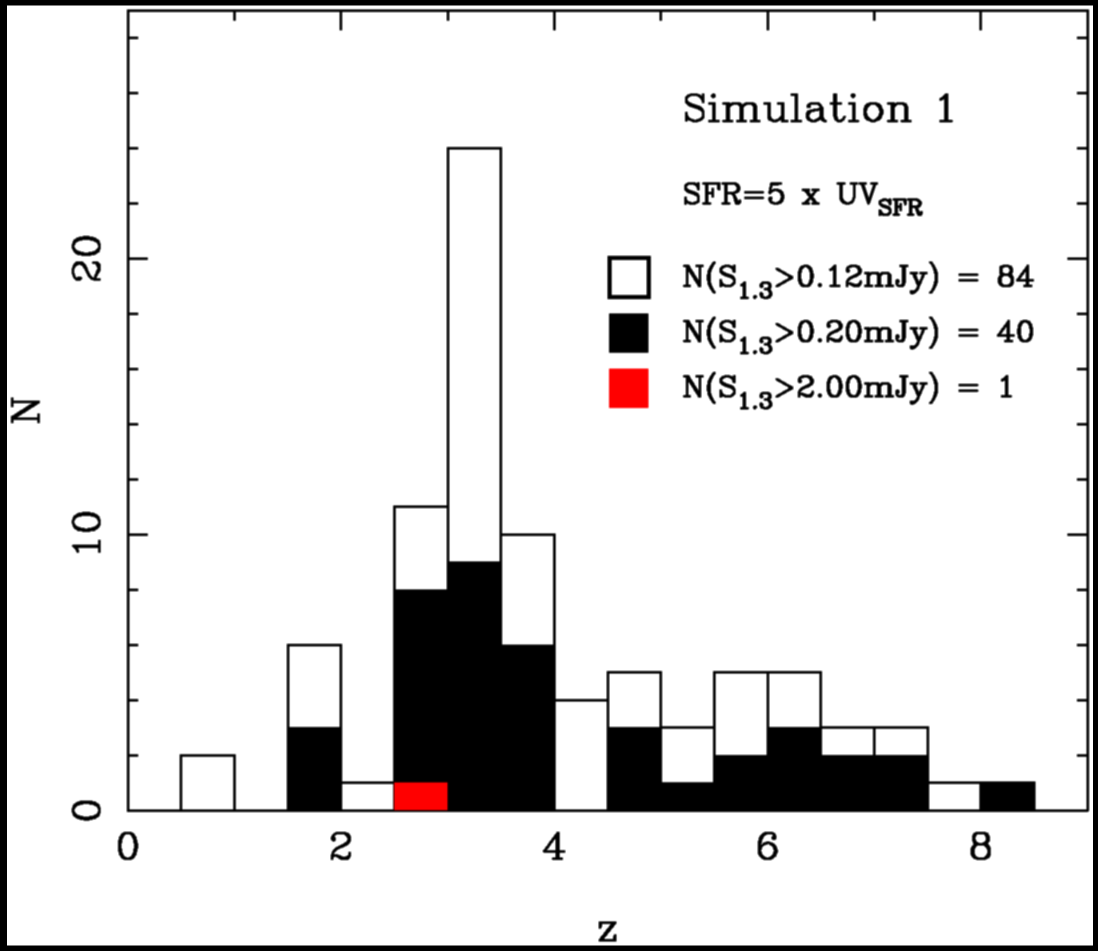
5-sigma detection limit is 0.15 mJy, spatial resolution of 0.7” FWHM

ALMA Deep Field

Alternative predictions based on > 2000 galaxies in the HST imaging

SFR = 5 x UV SFR

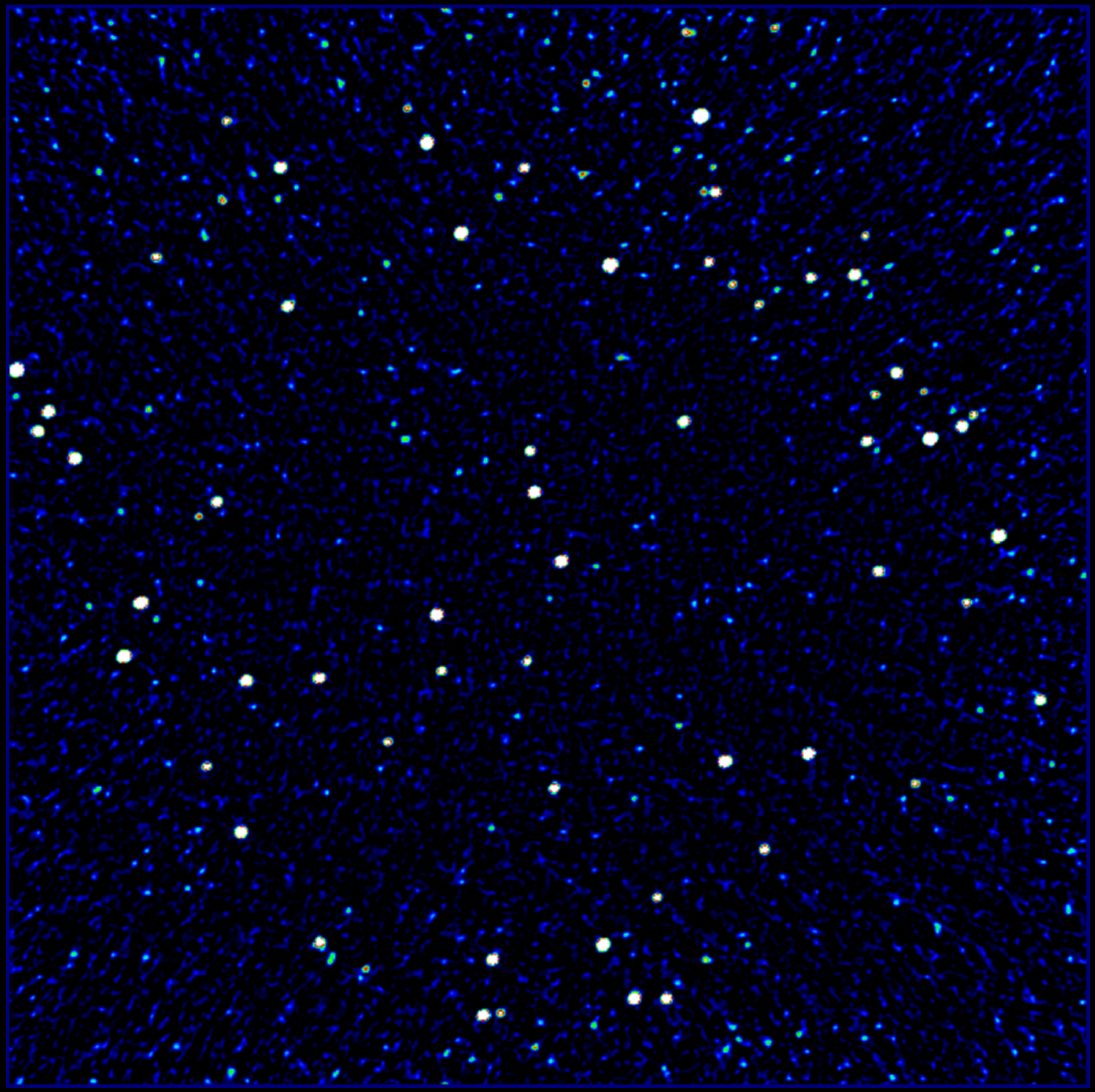


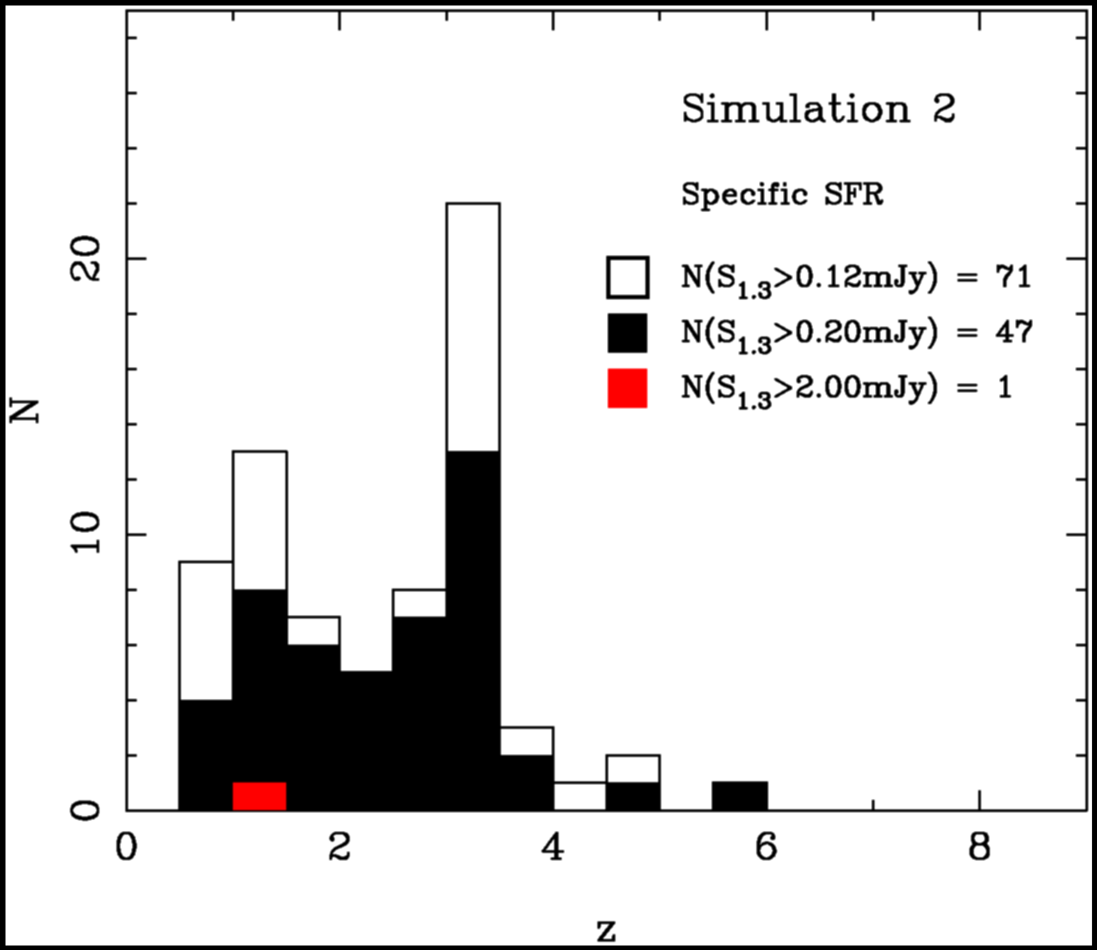


ALMA Deep Field

Alternative predictions based on > 2000 galaxies in the HST imaging

Specific SFR = 2/Gyr

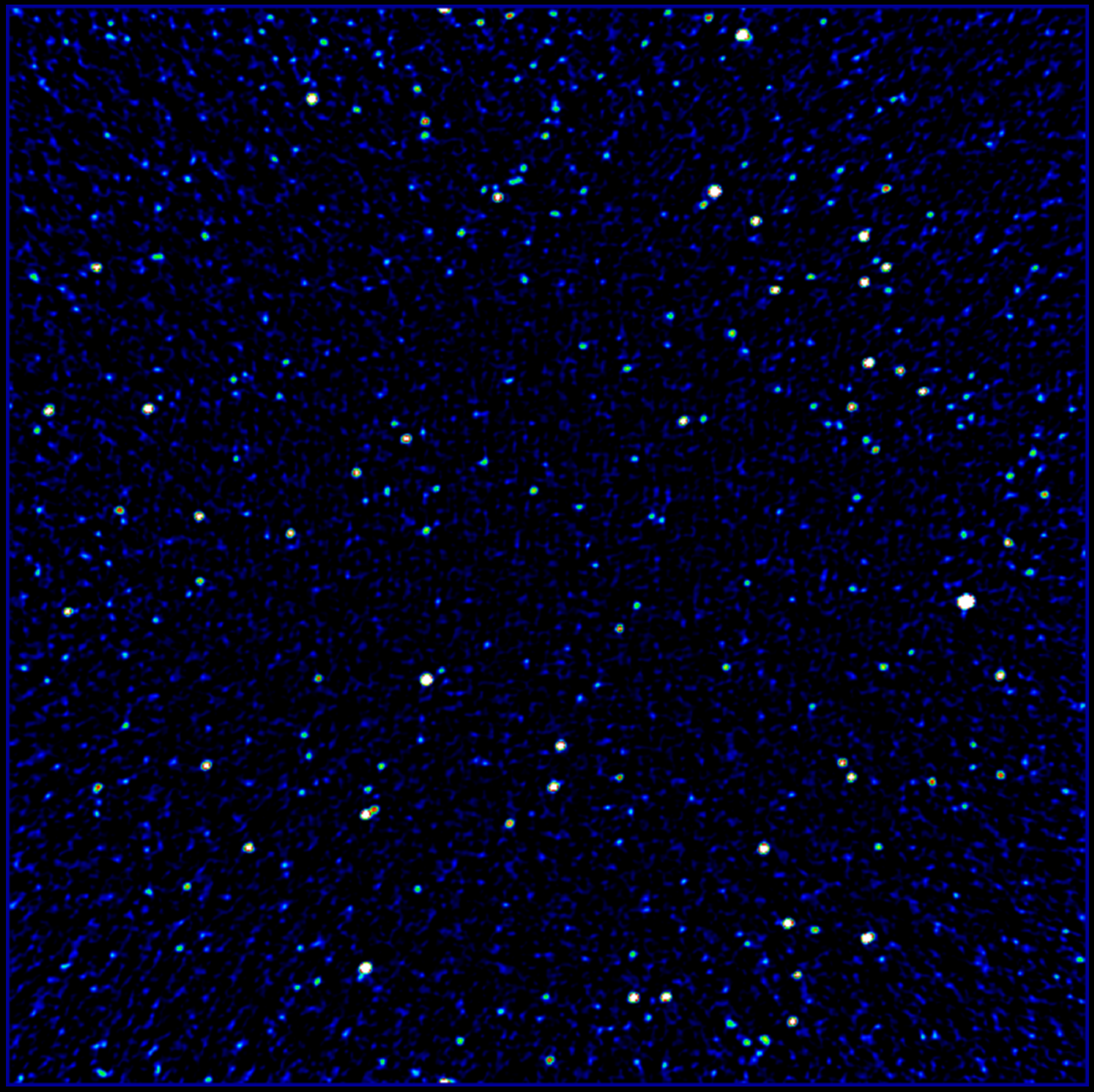


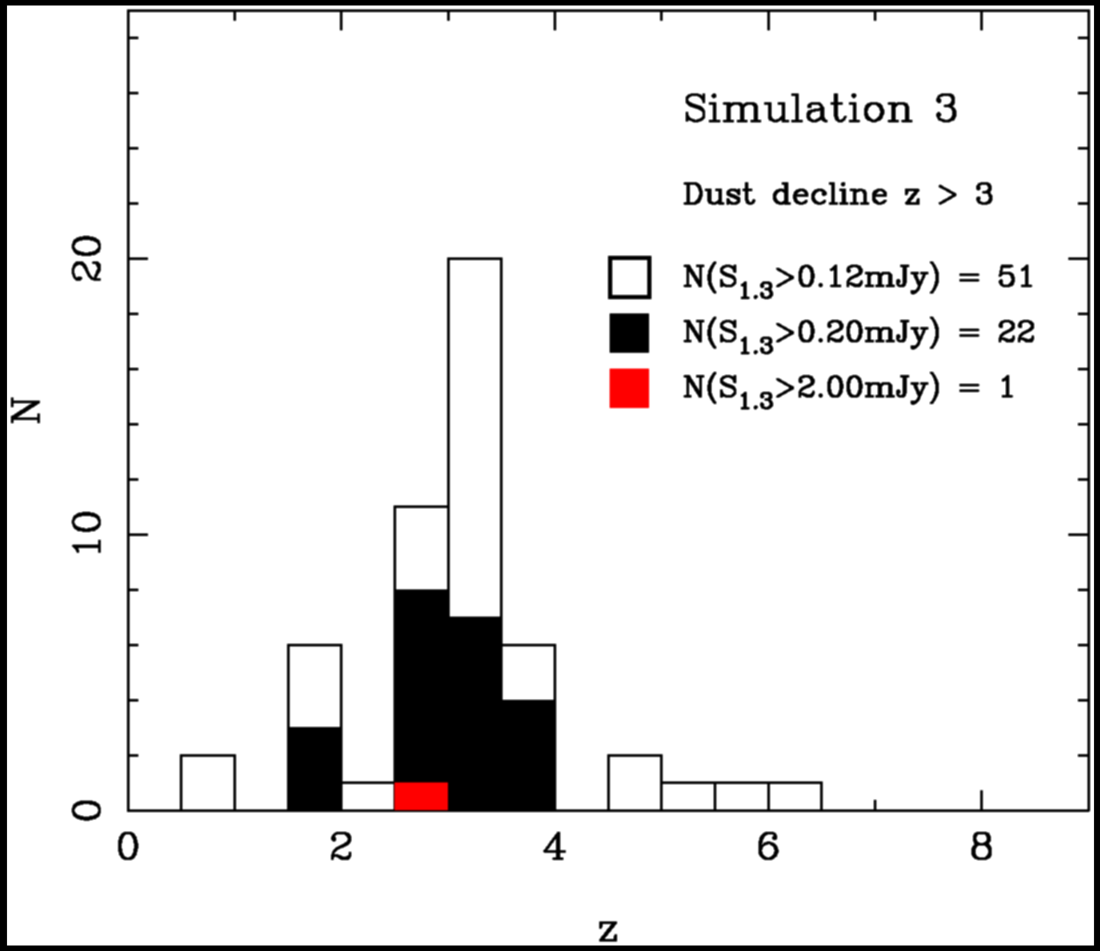


ALMA Deep Field

Alternative predictions based on > 2000 galaxies in the HST imaging

SFR = 5 x UV SFR plus /$(1+z)^2$ at z > 3





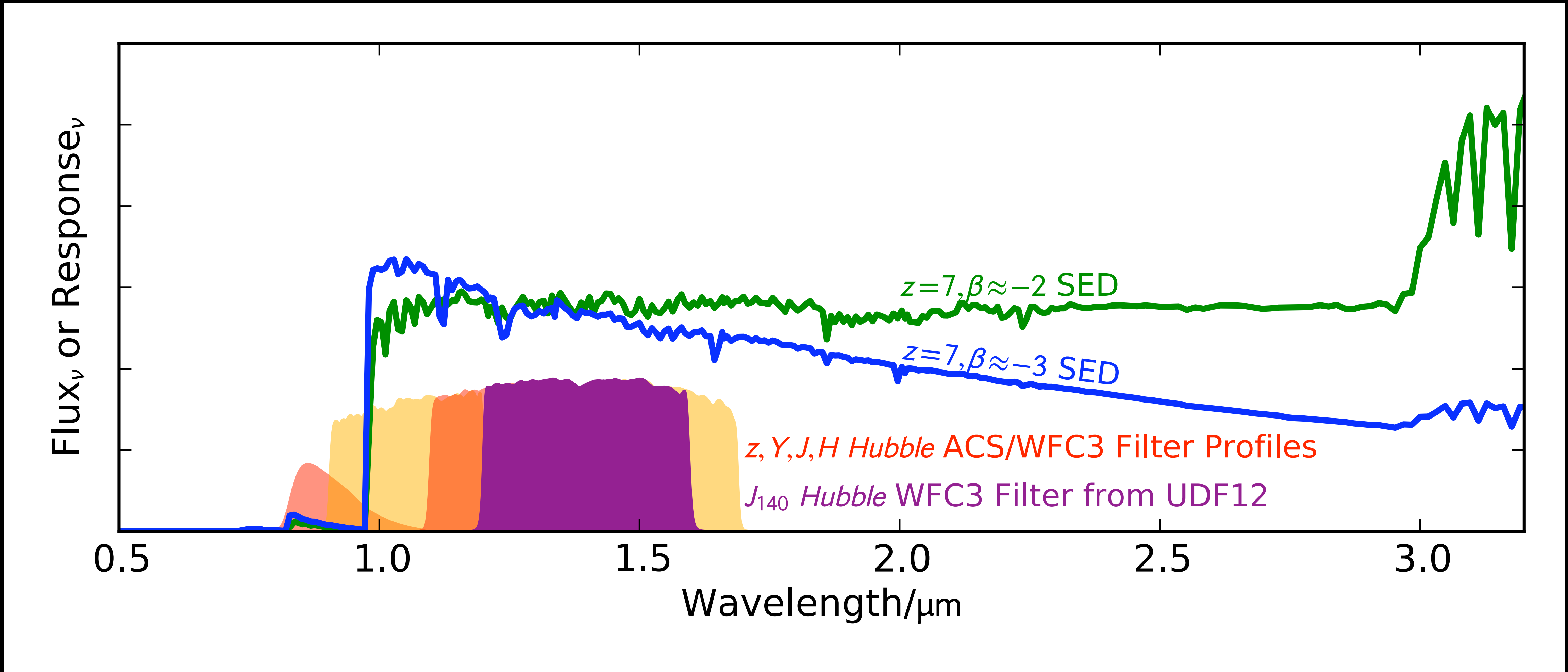
Answer late 2013?

Physical properties of faint z = 7 - 8 galaxies

Dunlop et al. 2013, MNRAS, 432, 3520

Can't measure much, but can make new unbiased measurement of UV continuum slope

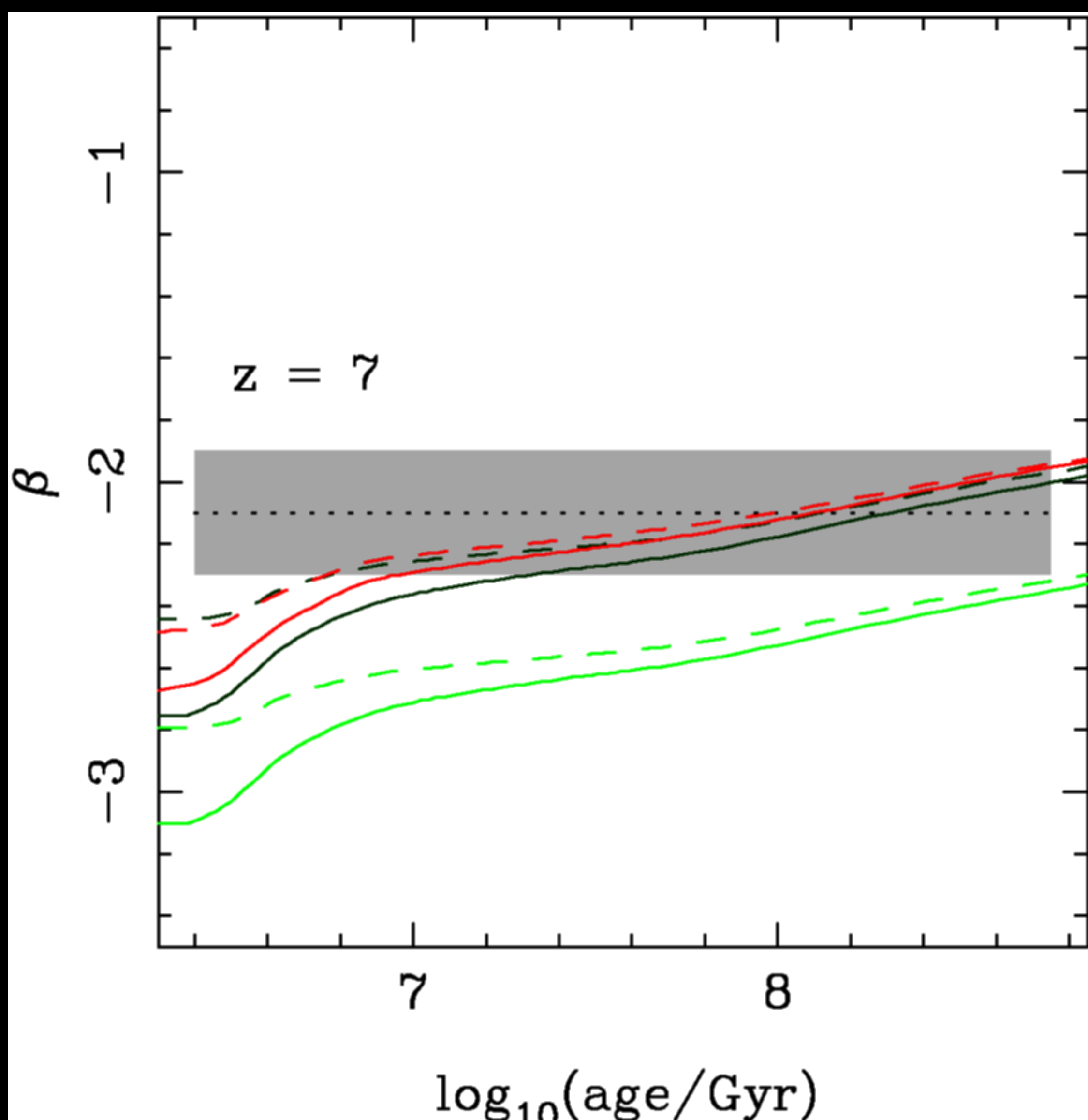
β, where F_λ = const x λ^β



Aided by selection in new J140W filter

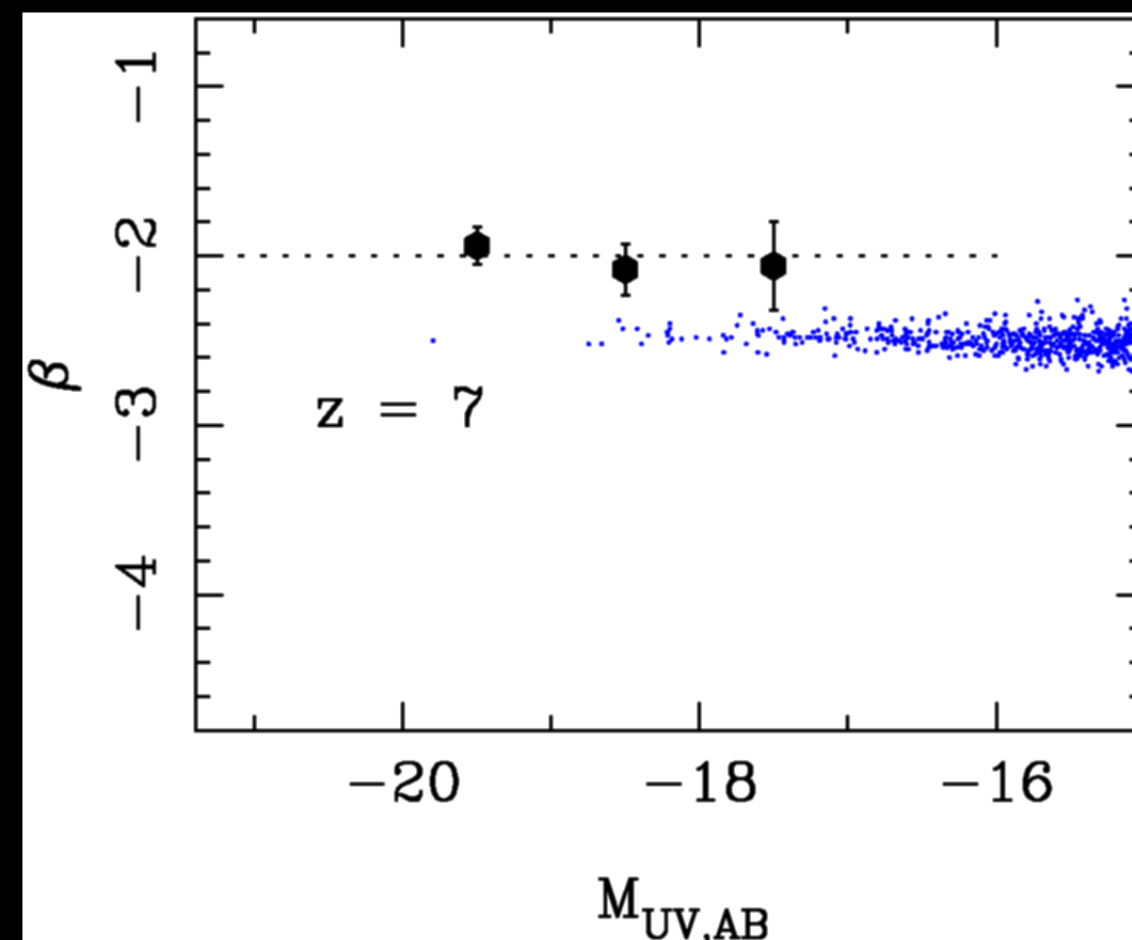
HUDF12 has enabled new, unbiased measure of average UV slope at z = 7 – 8

But what can this tell us?



Burst models for galaxies
Constant star-formation galaxies

solar, 0.2 solar, 0.02 solar metallicity
solar, 0.2 solar, 0.2 solar + dust



cf predictions from galaxy formation simulation (Dayal et al. 2013)