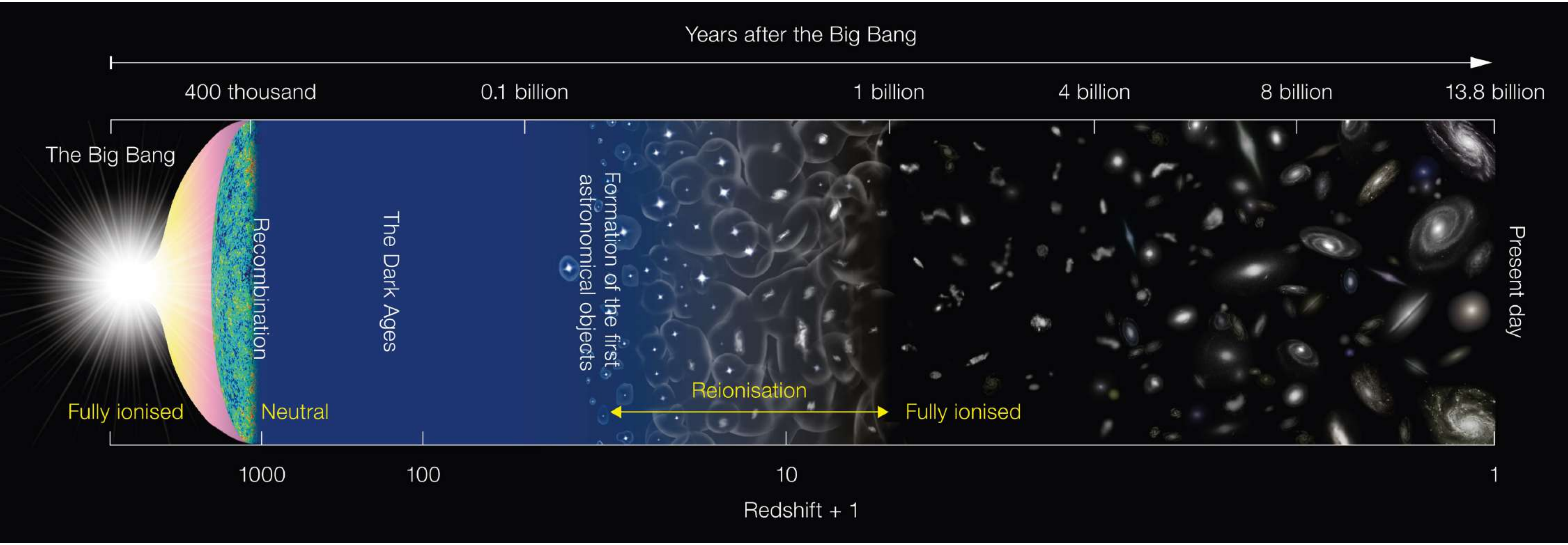
First galaxies: observations
Lecture 1

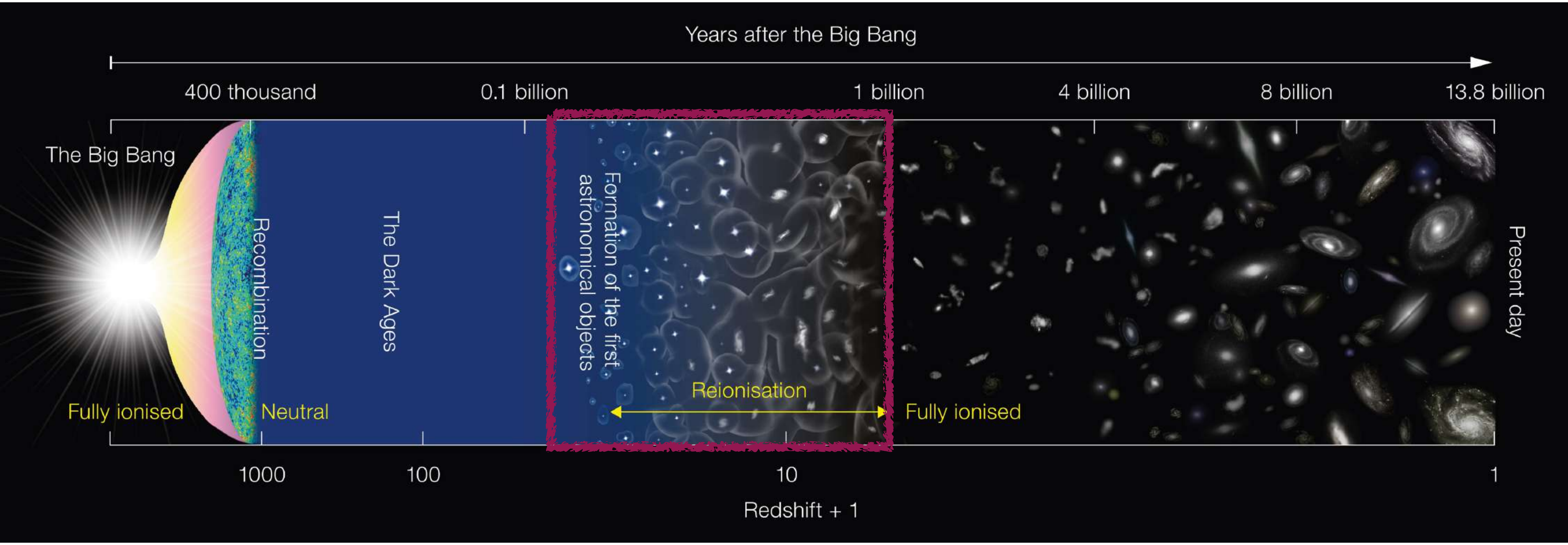
Renske Smit
Newton-Kavli fellow - University of Cambridge

Motivation



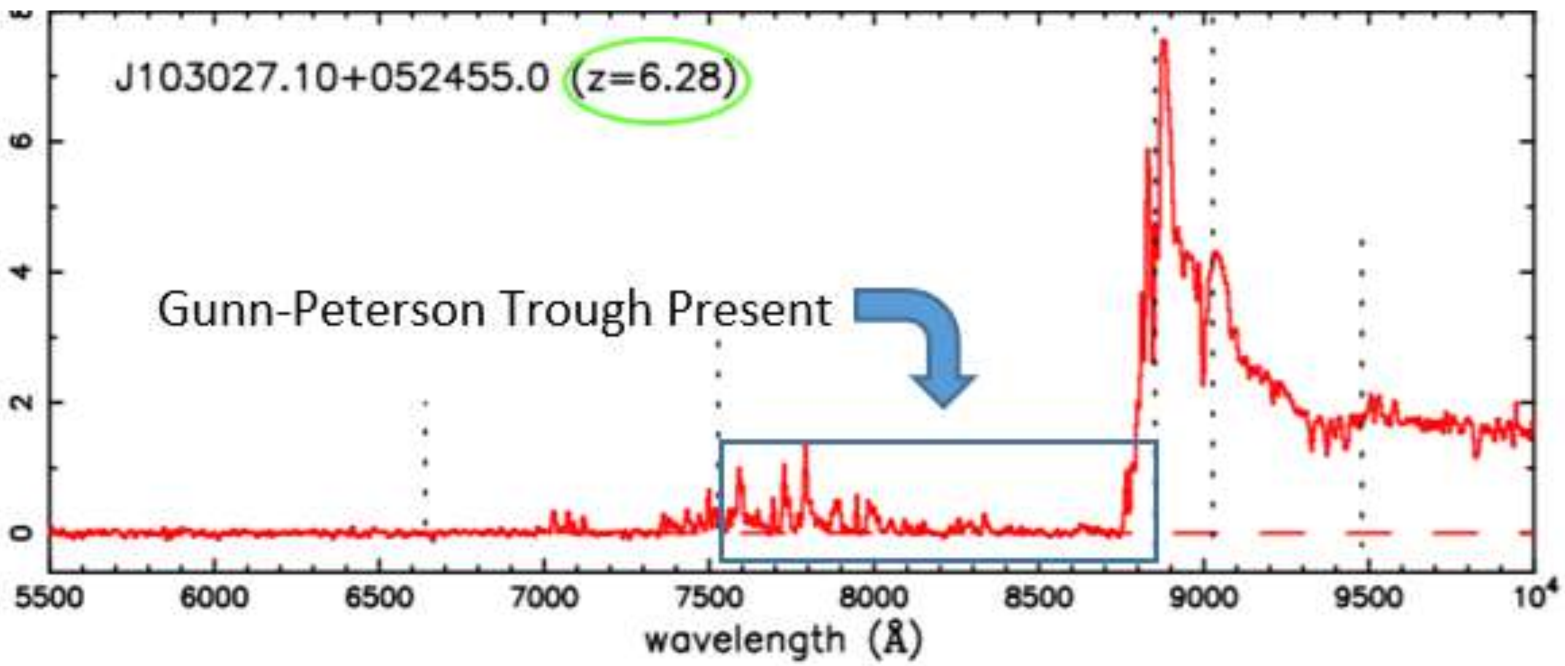
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1

Motivation



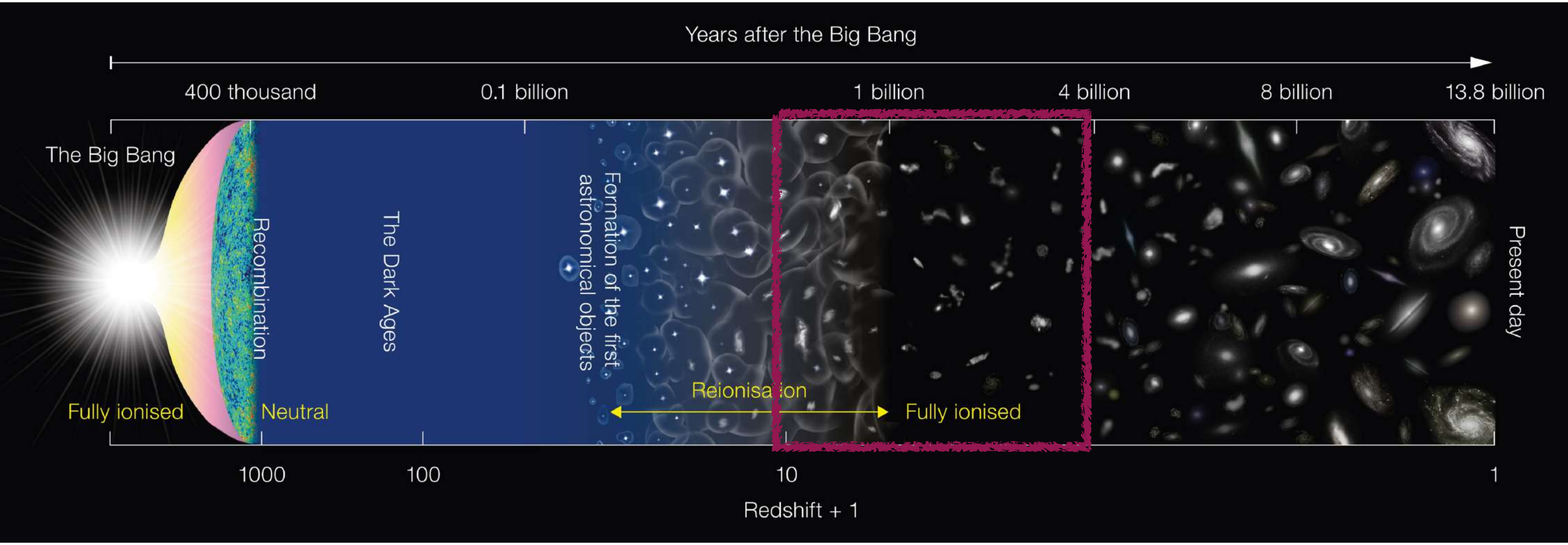
Reionisation ends

z ~ 6 or t = 1 Gyr



Becker et al. 2001

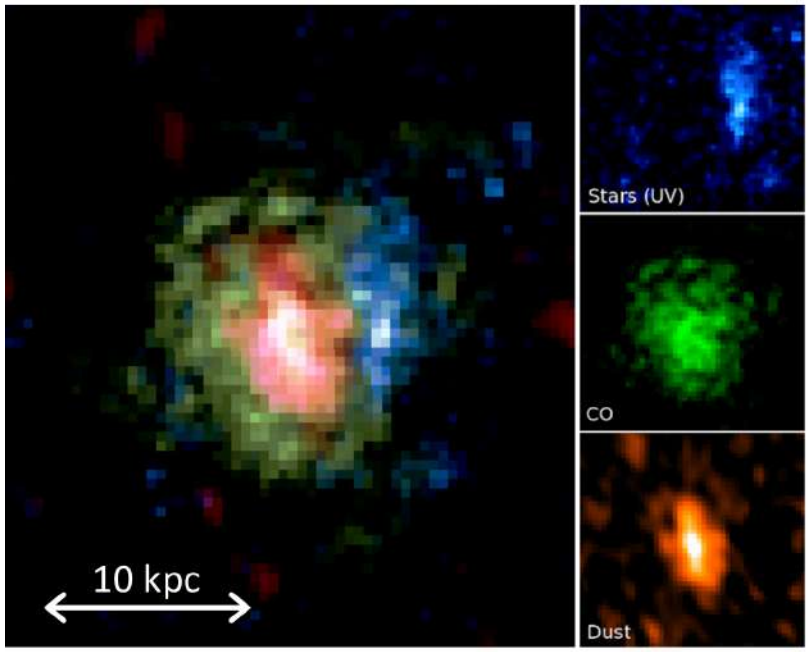
Motivation



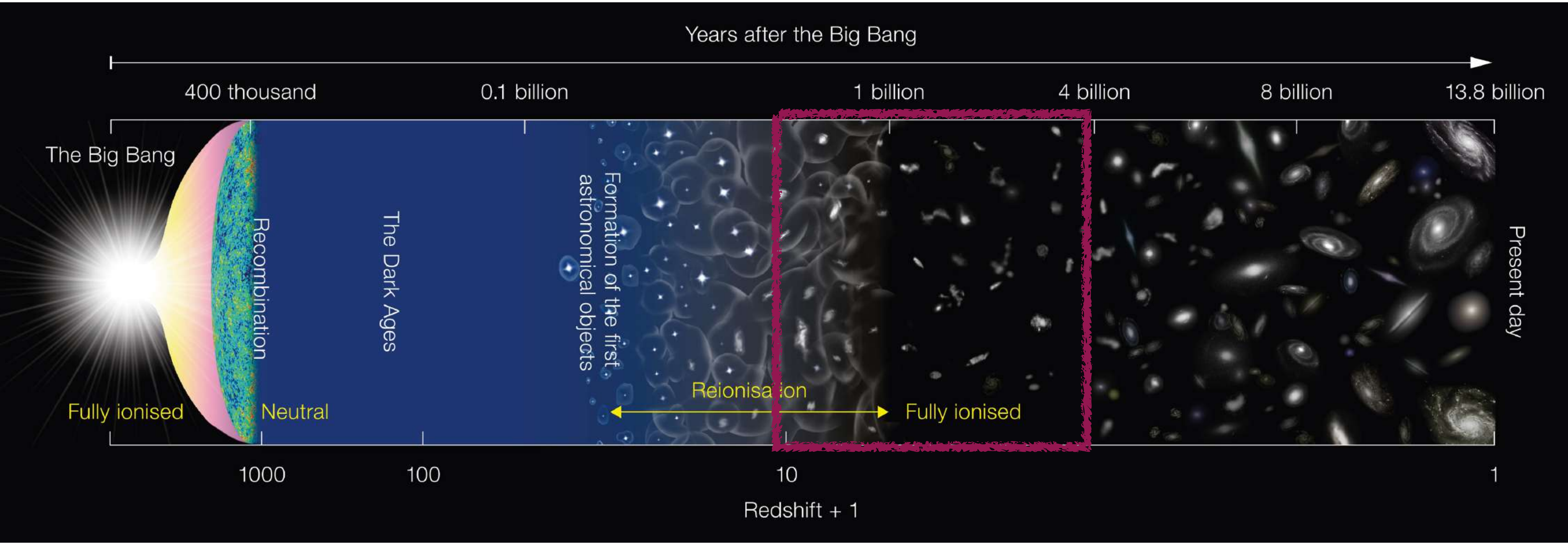
First ultra IR luminous galaxies
z ~ 5-3 or
t = 1-2 Gyr

GN20
z=4
SFR>3000M☉/yr

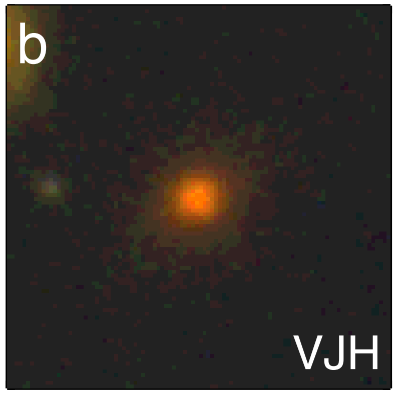
Hodge et al. 2015

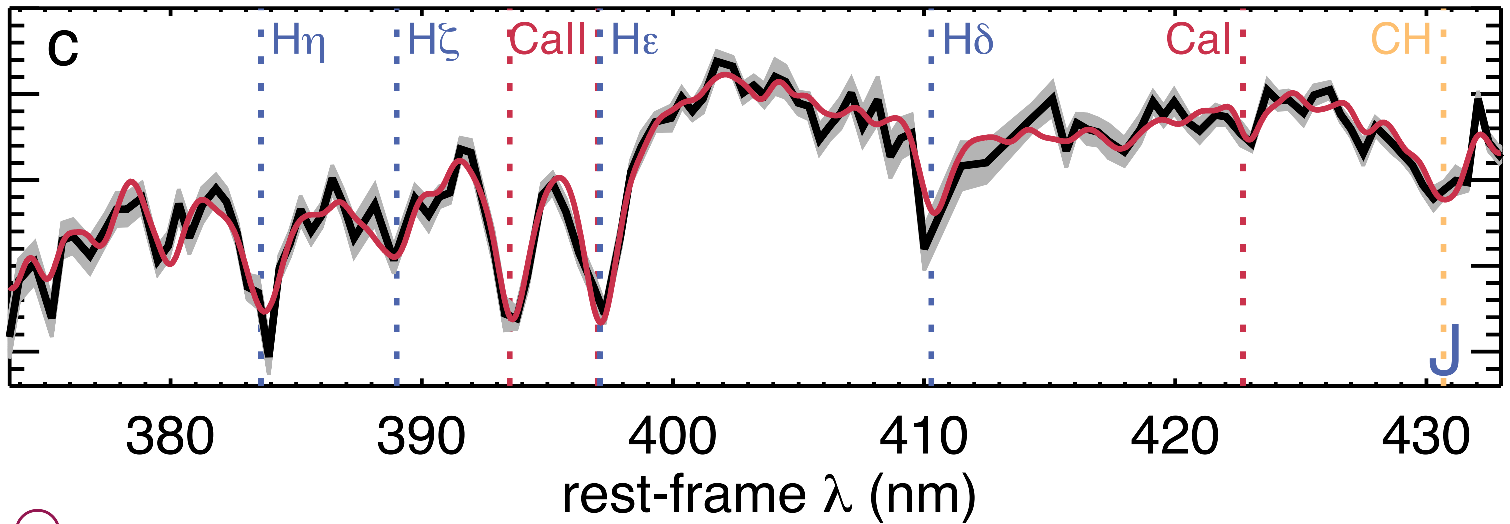


Motivation



First ultra-massive galaxies $z \sim 3\text{-}2$ or $t = 2\text{-}3$ Gyr





$M_{\star} > 10^{11} M_{\odot}$

Kriek et al. 2016

Overview

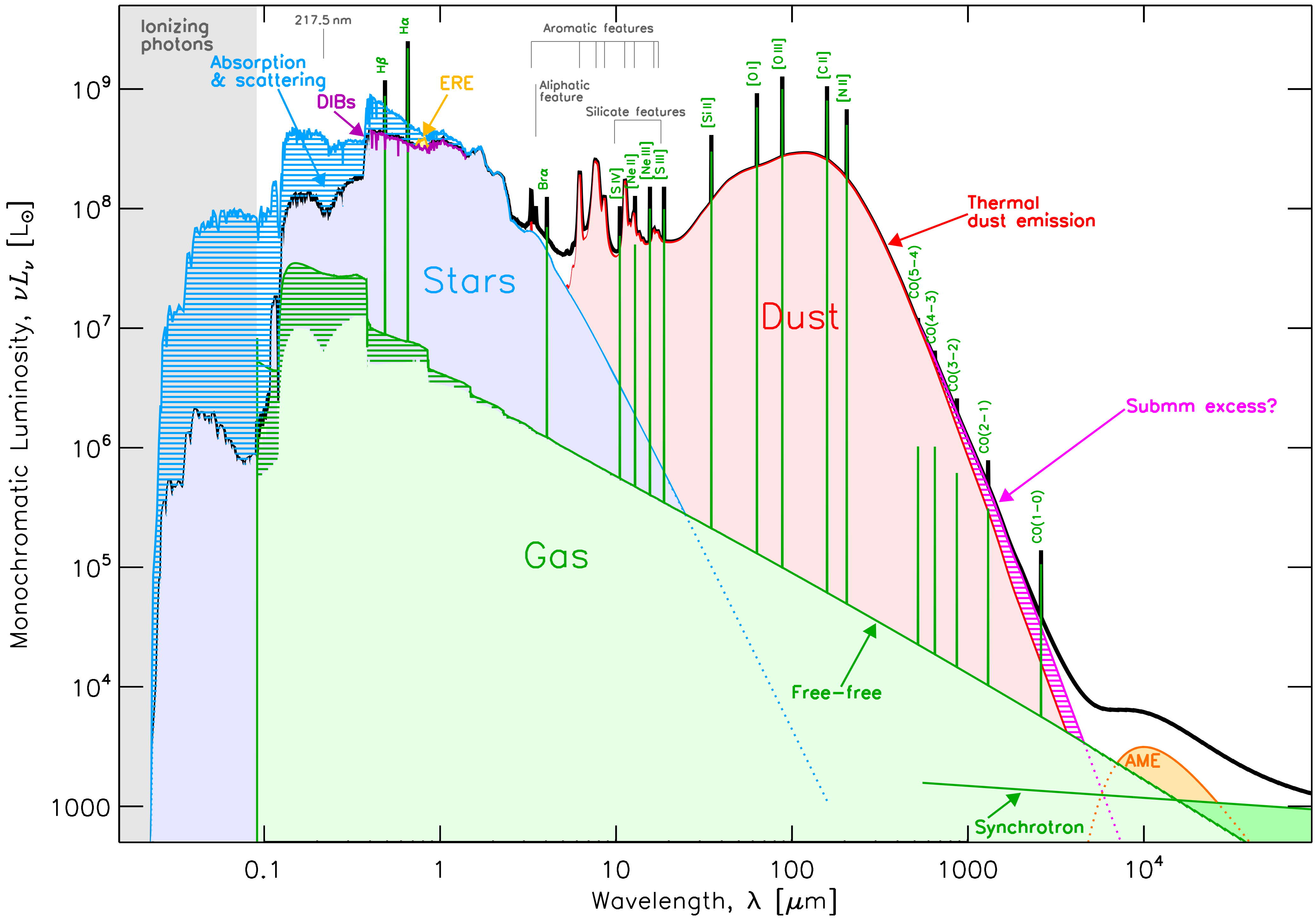
Lecture 1: Detection methods and the galaxy census

- The Lyman break technique
- Deep surveys: a short history
- The UV luminosity function
- Outstanding debates on the galaxy census
- Lyman alpha and dust continuum selections

Lecture 2: Dust and stellar mass

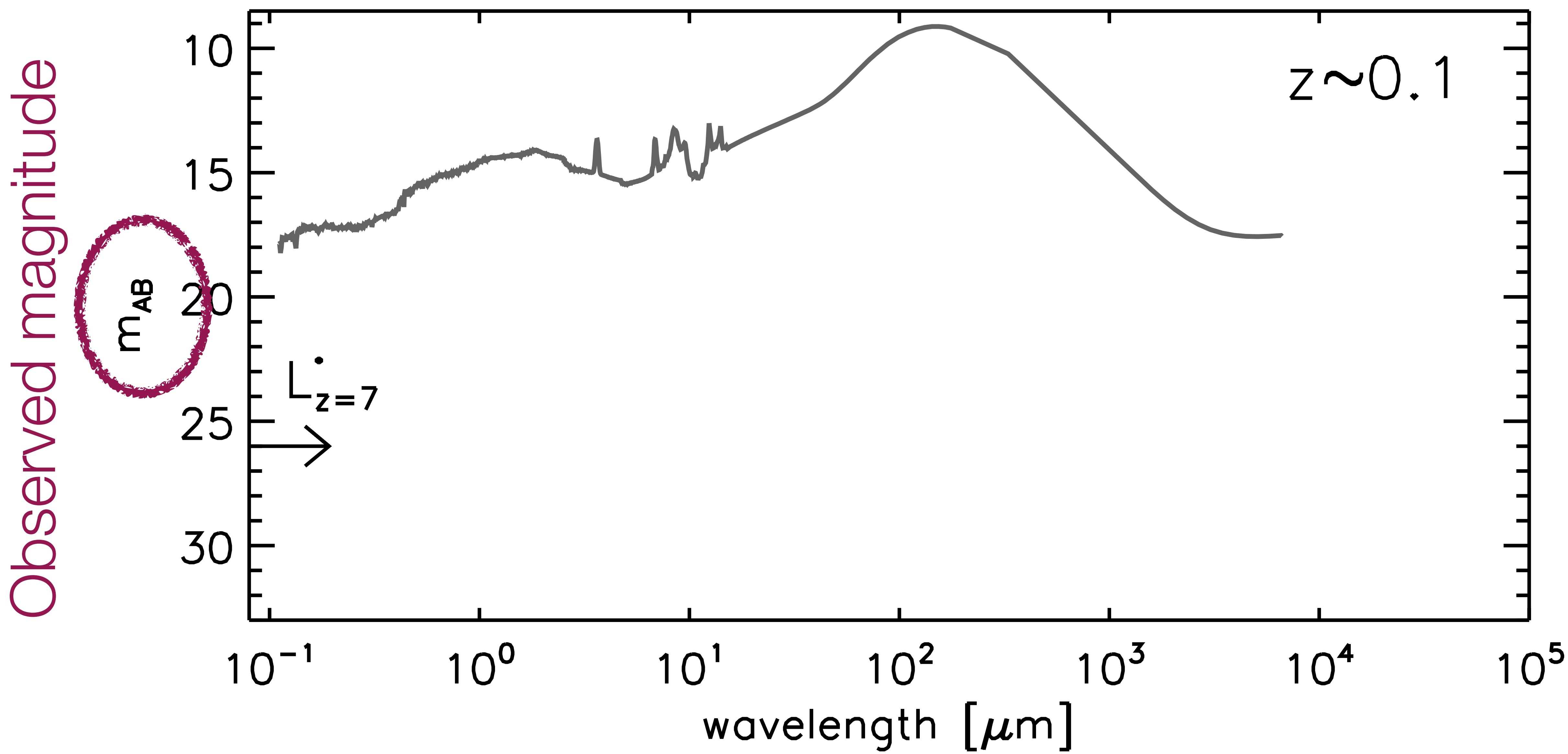
Lecture 3: Optical and sub-mm spectroscopy

The spectral energy distribution



Adapted from Galliano et al. 2018

The spectral energy distribution



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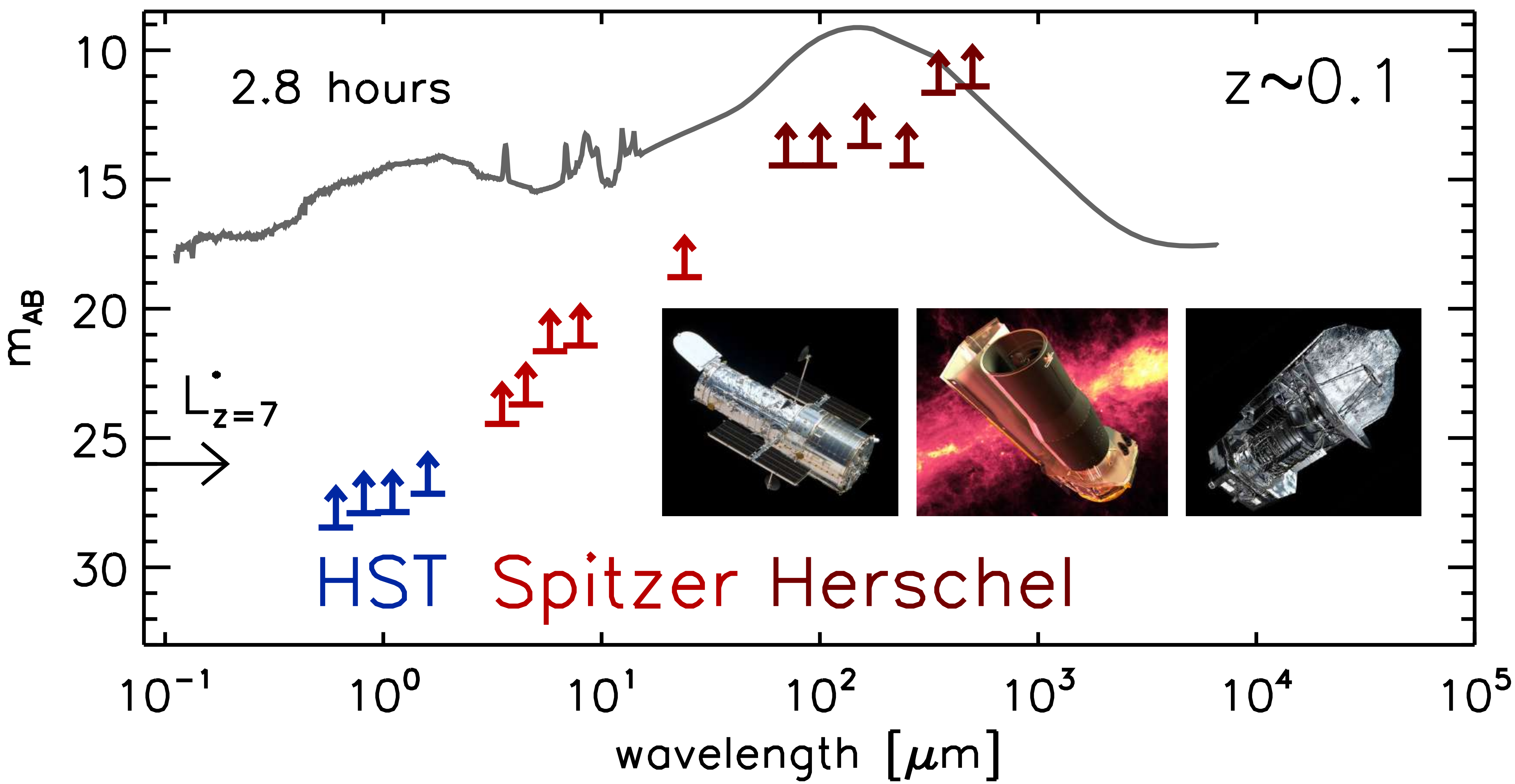

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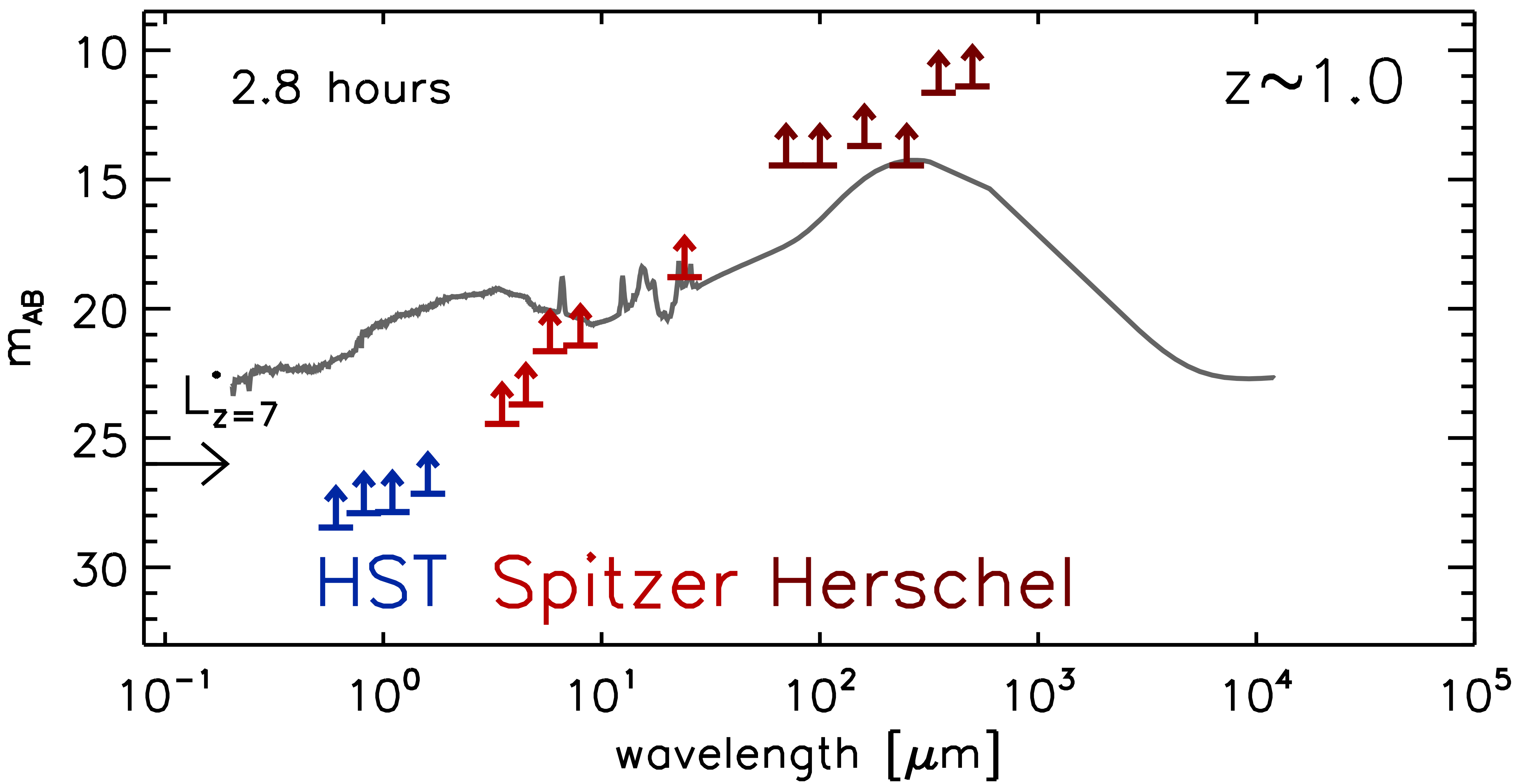

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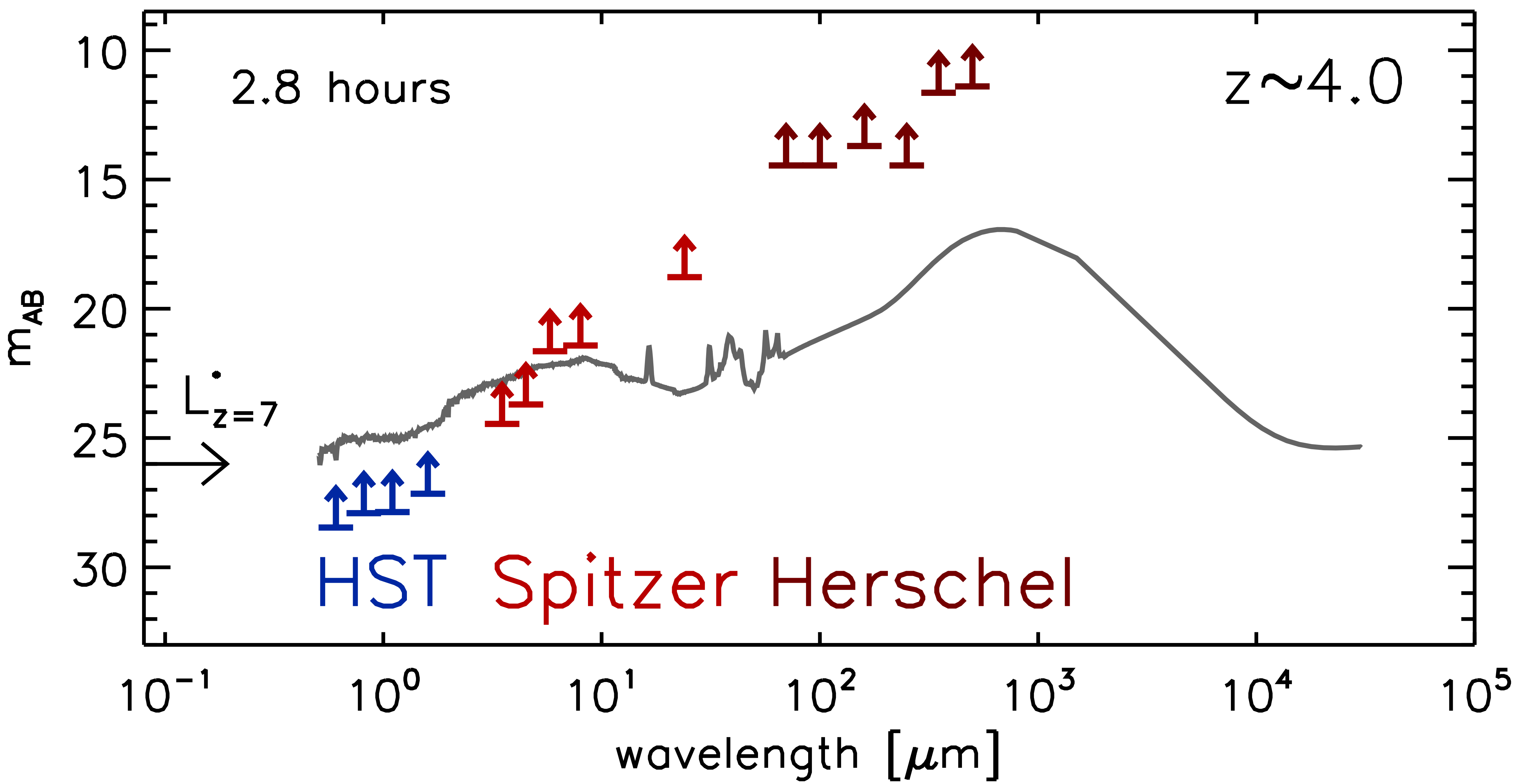

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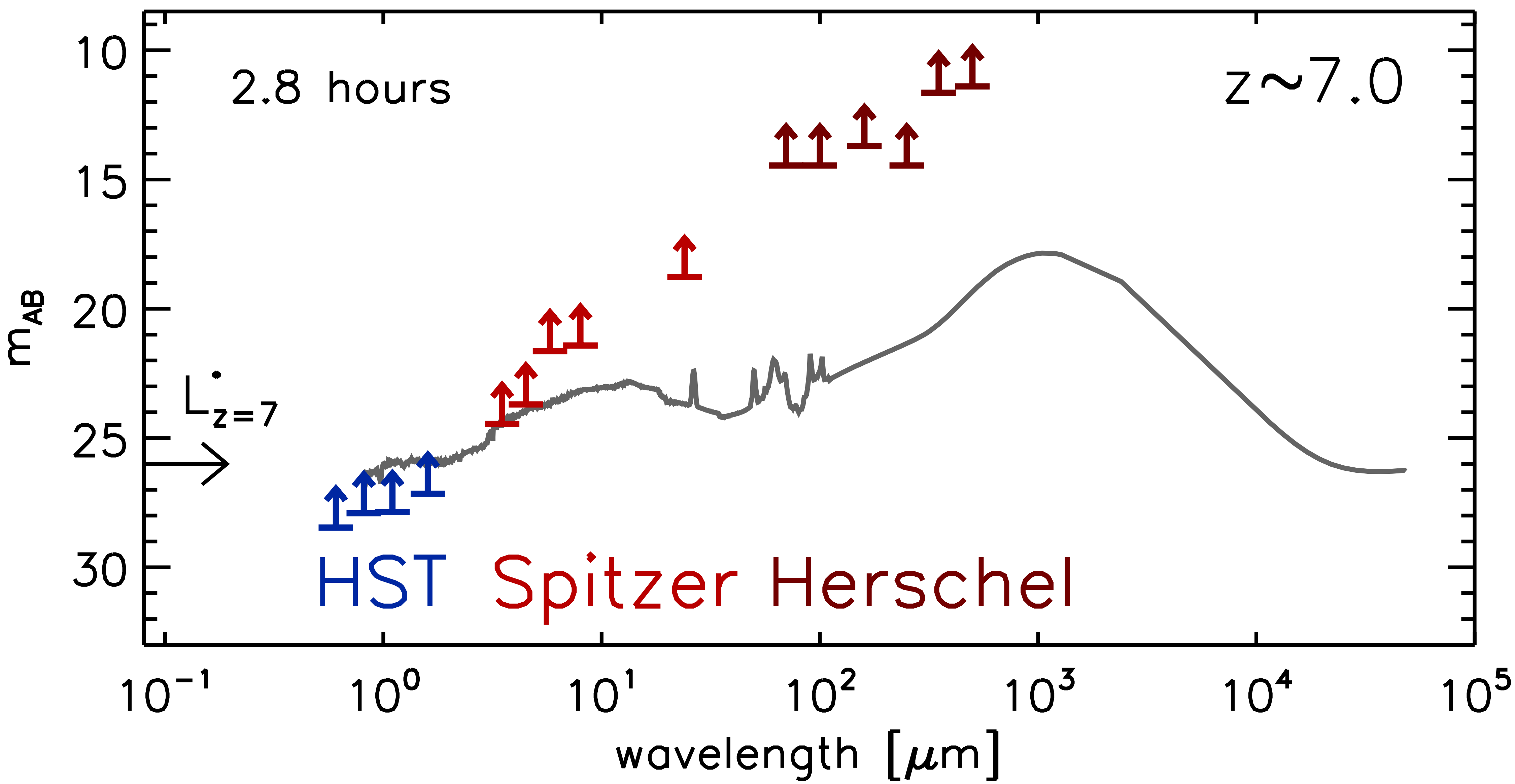

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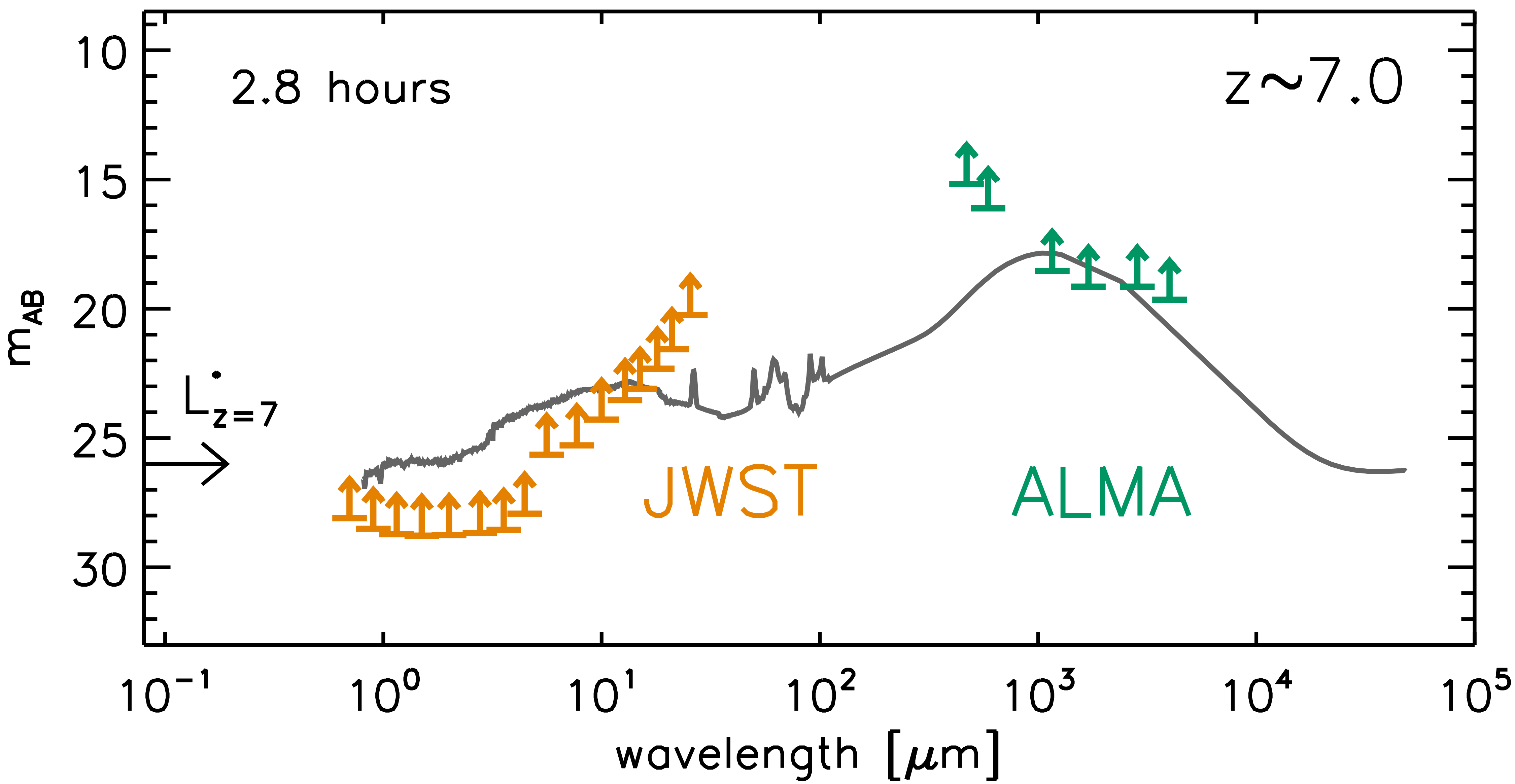

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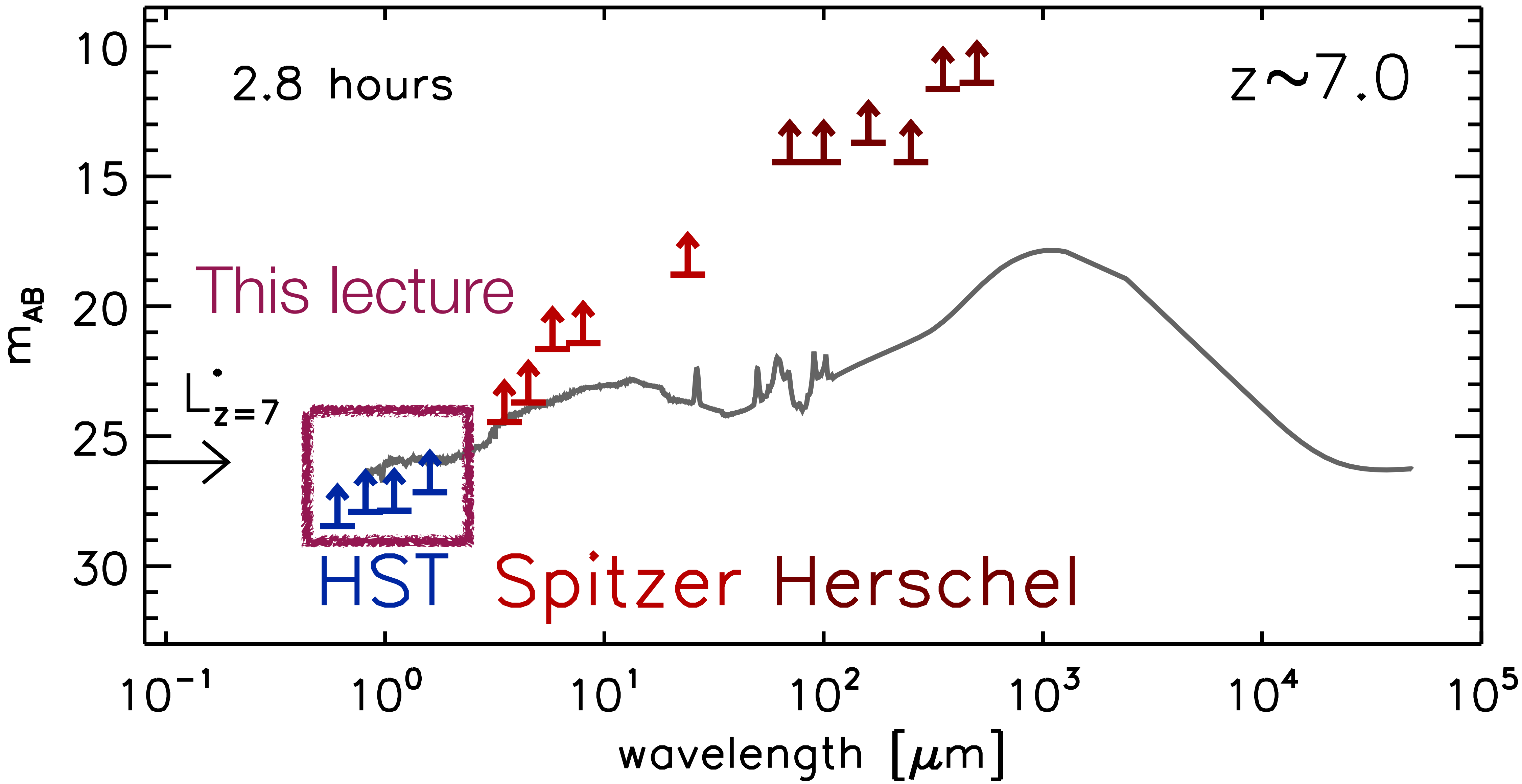
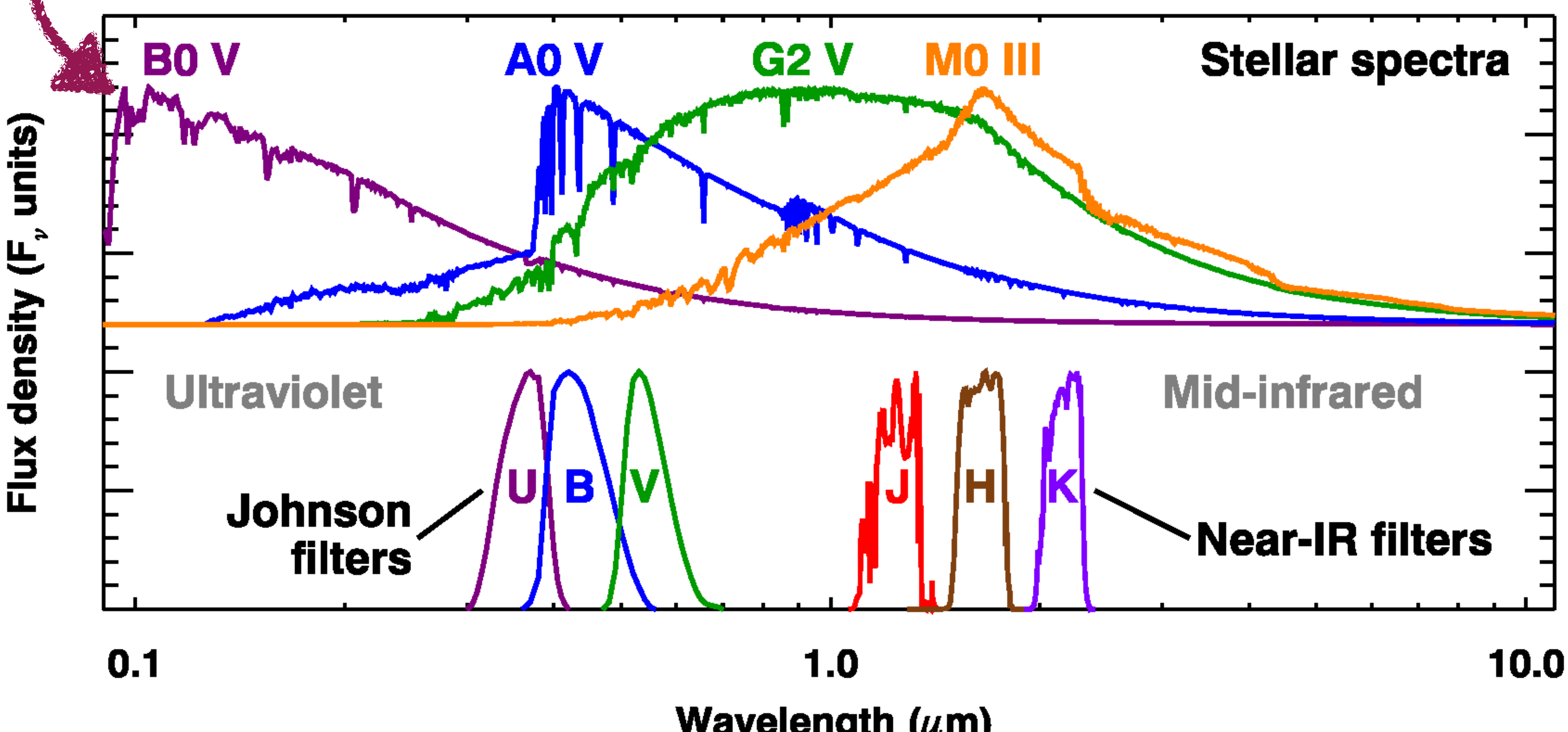


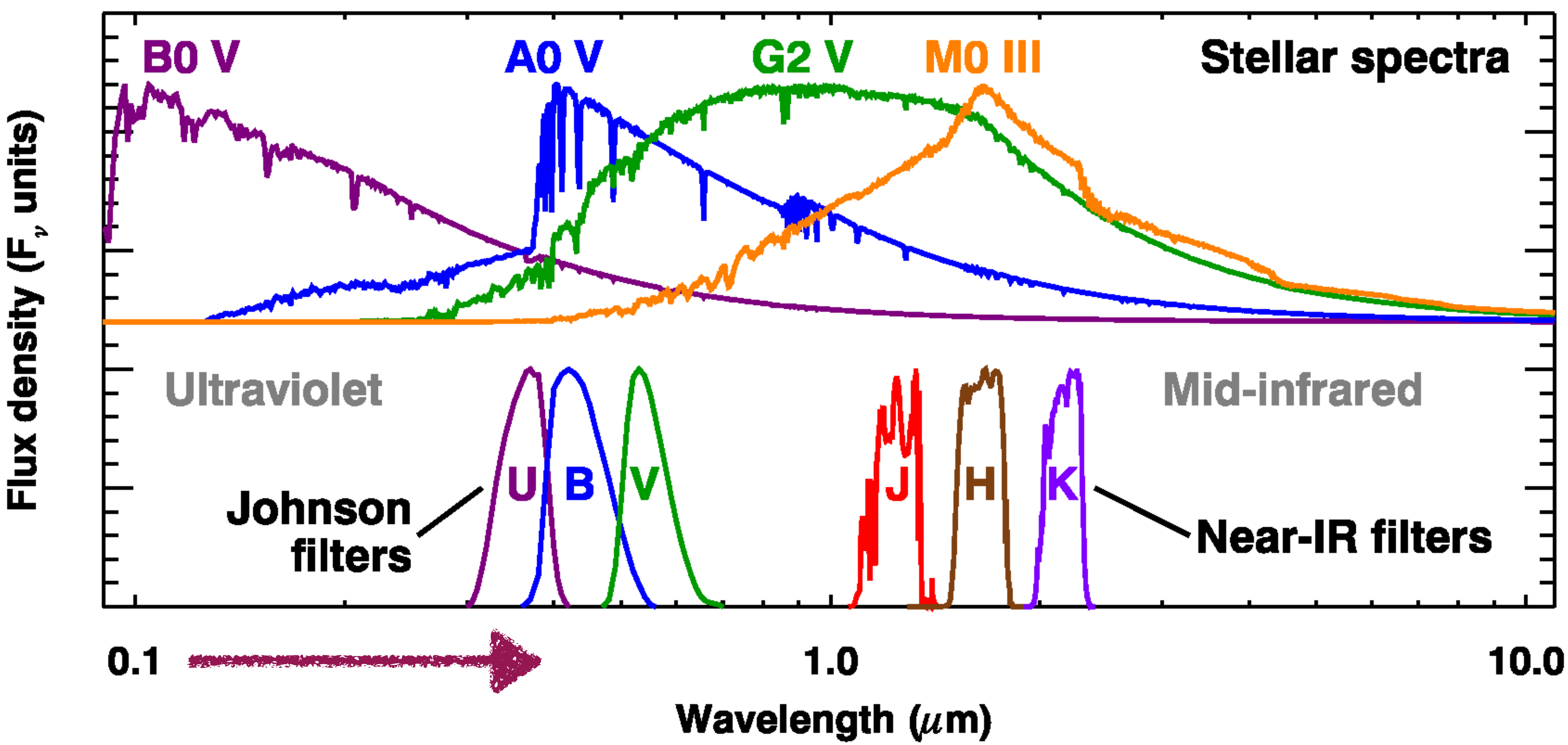
Looking back to the early Universe

Young galaxies are expected to be dominated by O and B type stars - bright in the UV

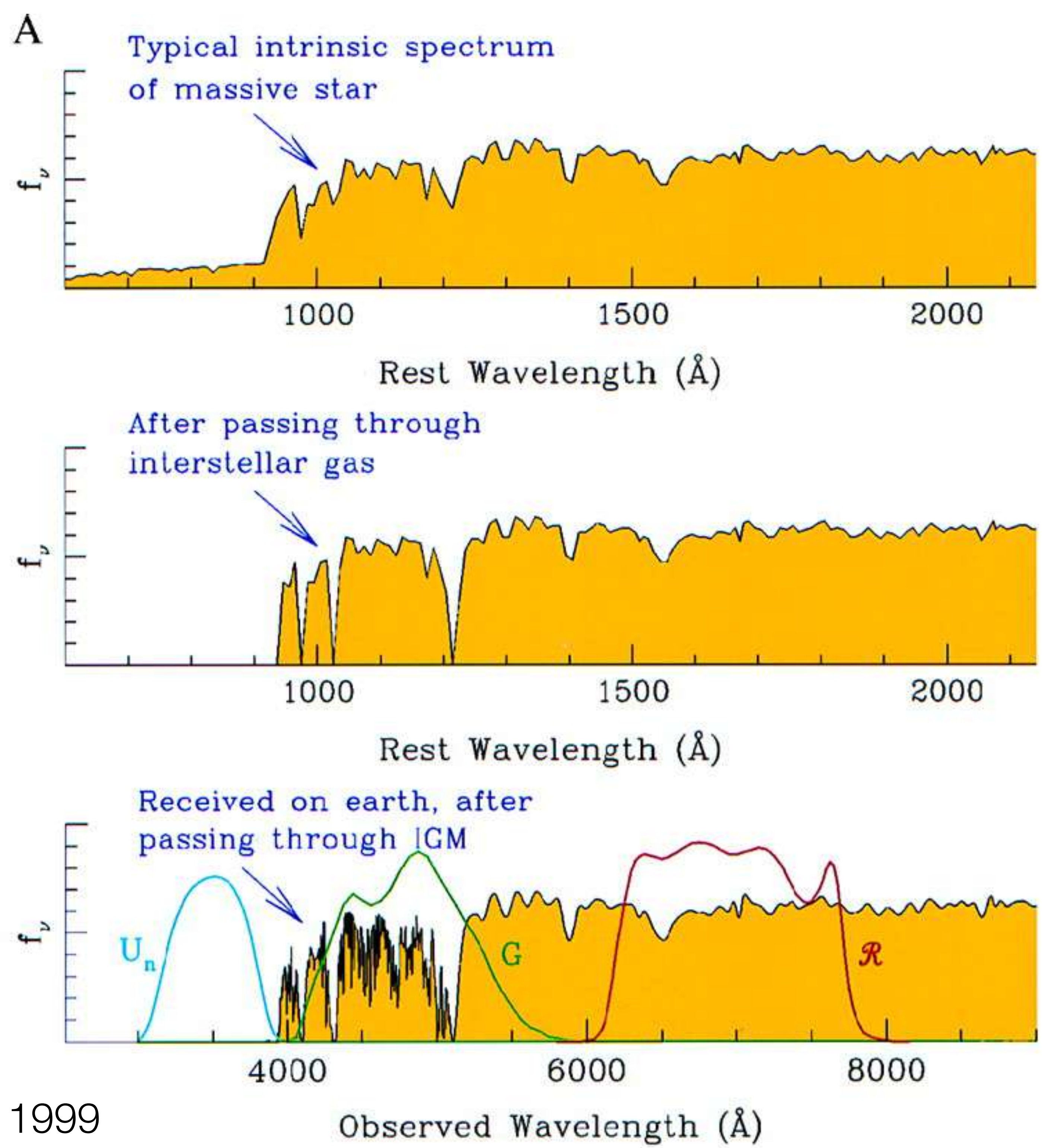


Looking back to the early Universe

Sharp feature around ~100 nm shifts to observable wavebands by redshift z=2-3

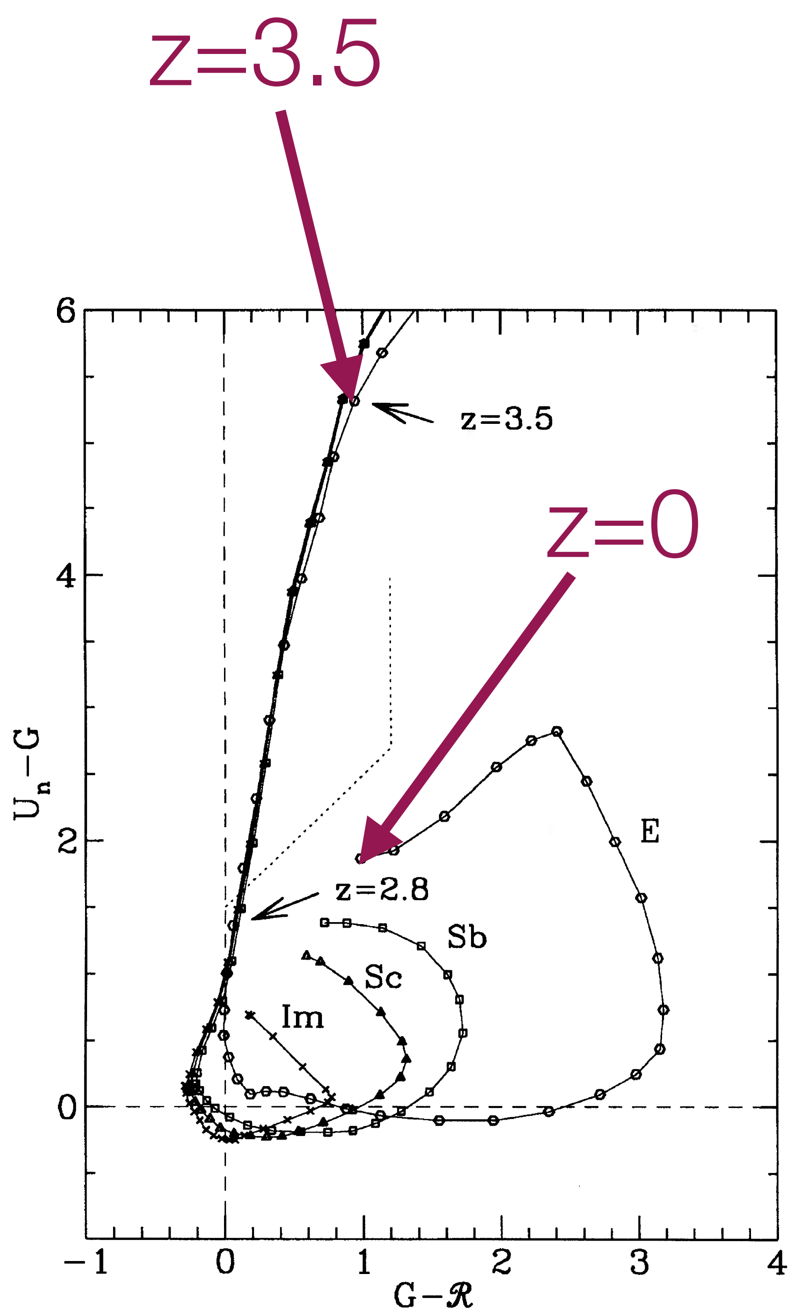


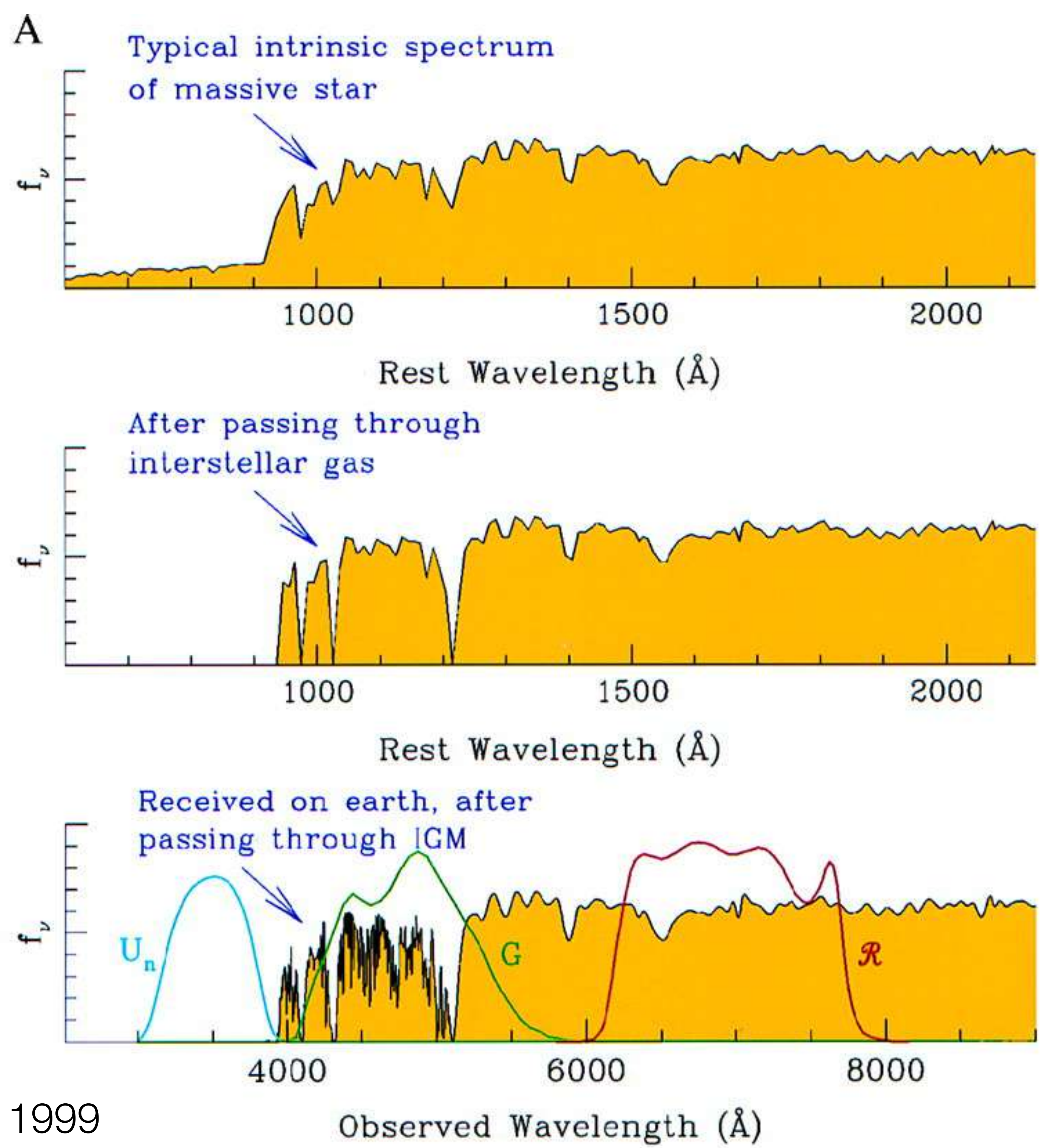
Lyman break technique



Steidel et al. 1999

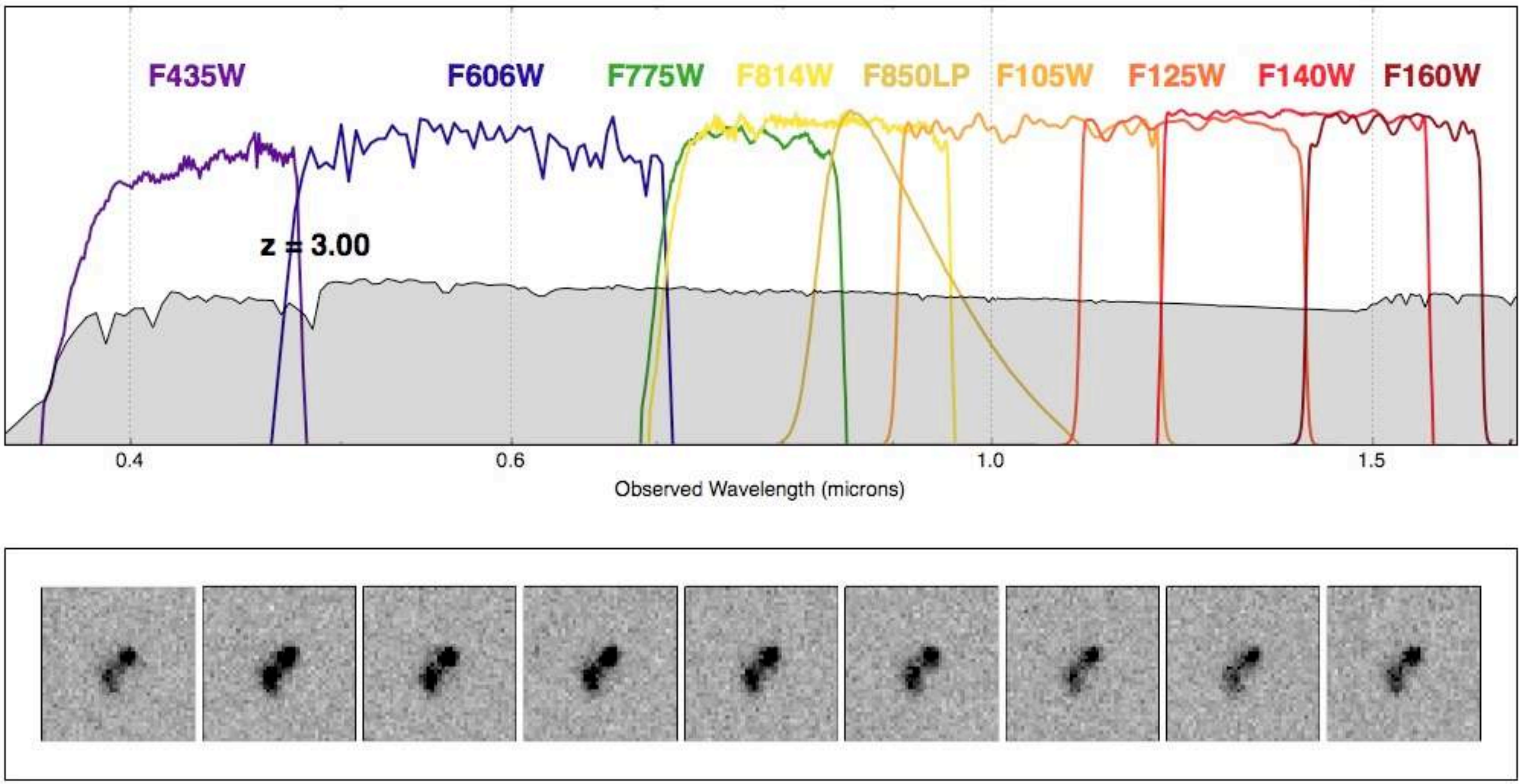
Lyman break technique





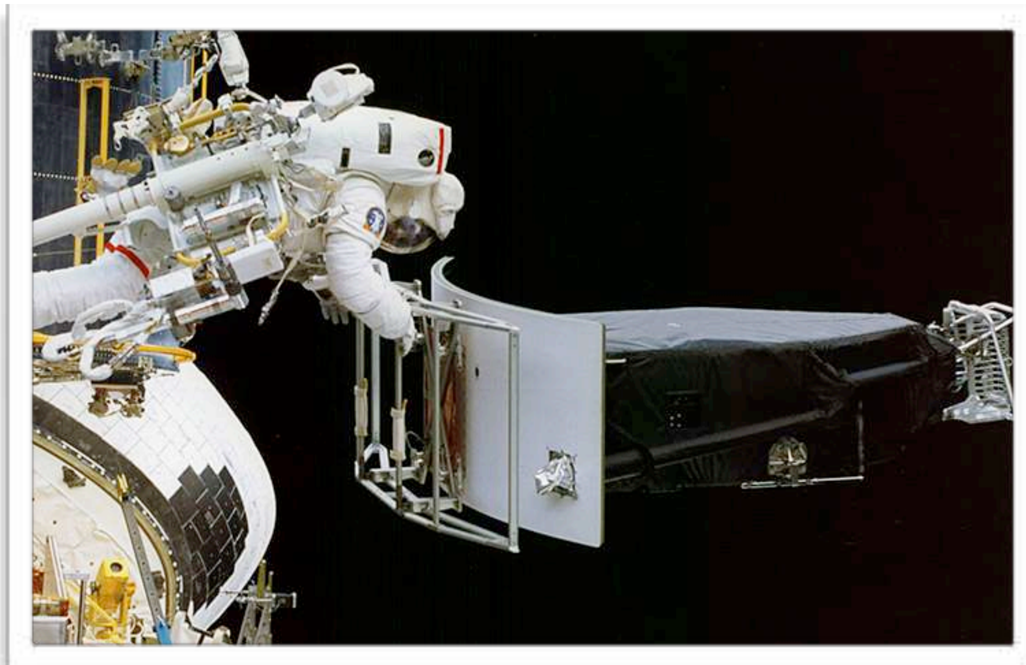
Steidel et al. 1999

Lyman break technique - ‘dropouts’

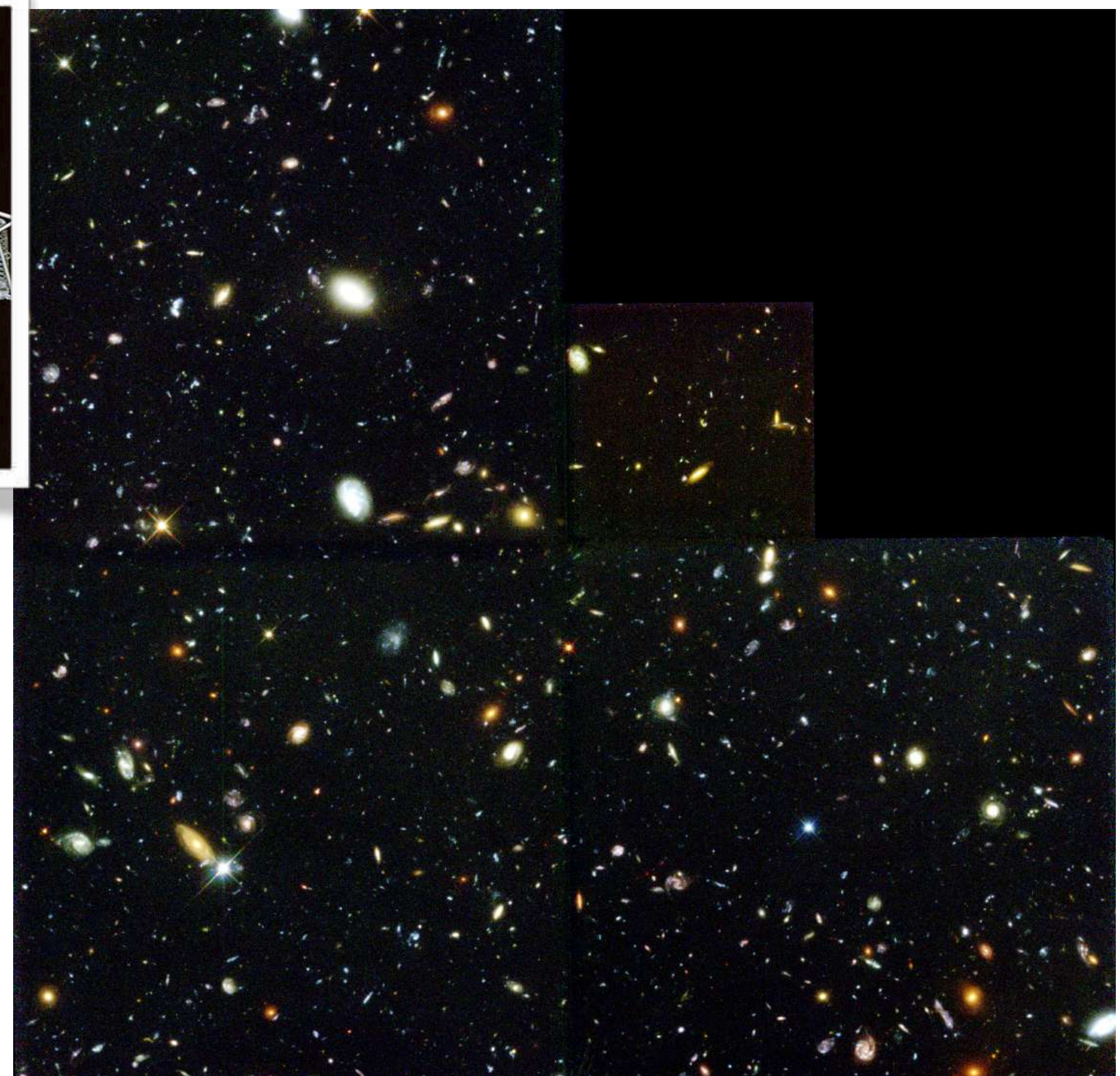


Credit: firstgalaxies.org

1995: Hubble Deep Field (HDF)



1993 Hubble mirror correction and installation of Wide Field and Planetary Camera 2 (WFPC2)

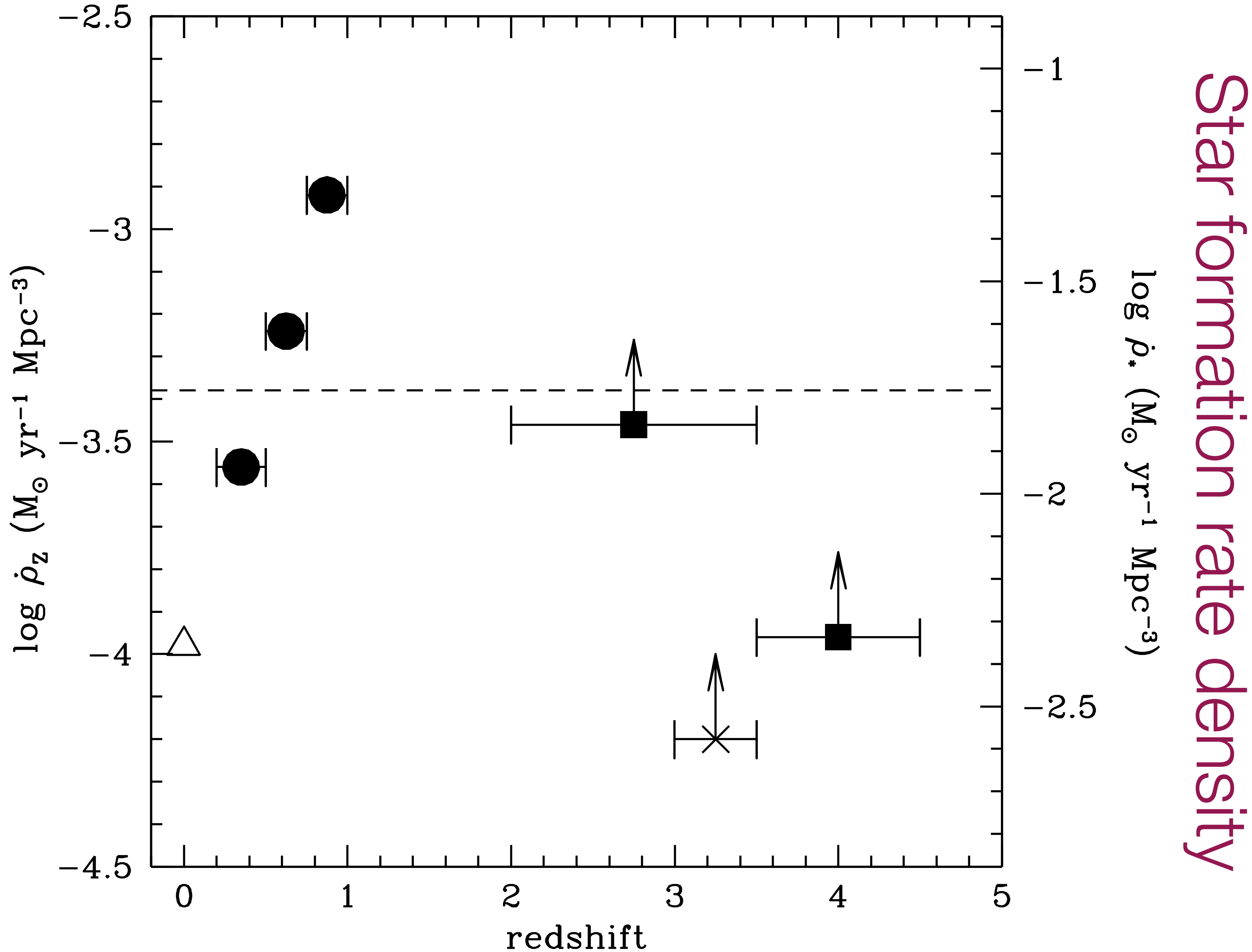


Census of star-formation in the Universe

UV luminosity to SFR conversion:

- Initial mass function (IMF; Salpeter)
- Age of the stellar population (100 Myr)
- Star-formation history (constant)
- Dust attenuation (assumed negligible)

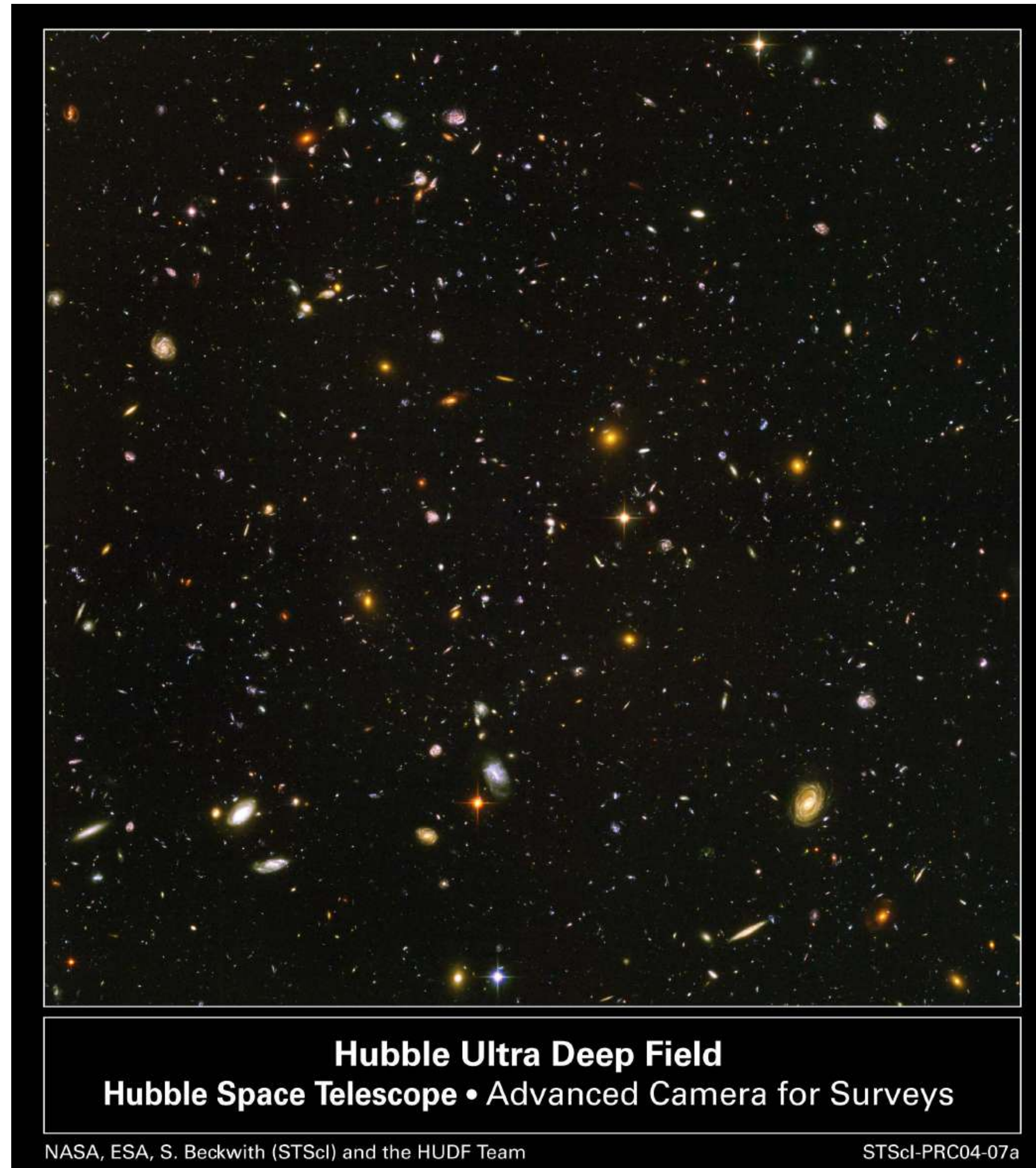
‘Lilly-Madau’ diagram



Lilly et al. 1996; Madau et al. 1996

2004: Hubble Ultra Deep Field (HUDF)

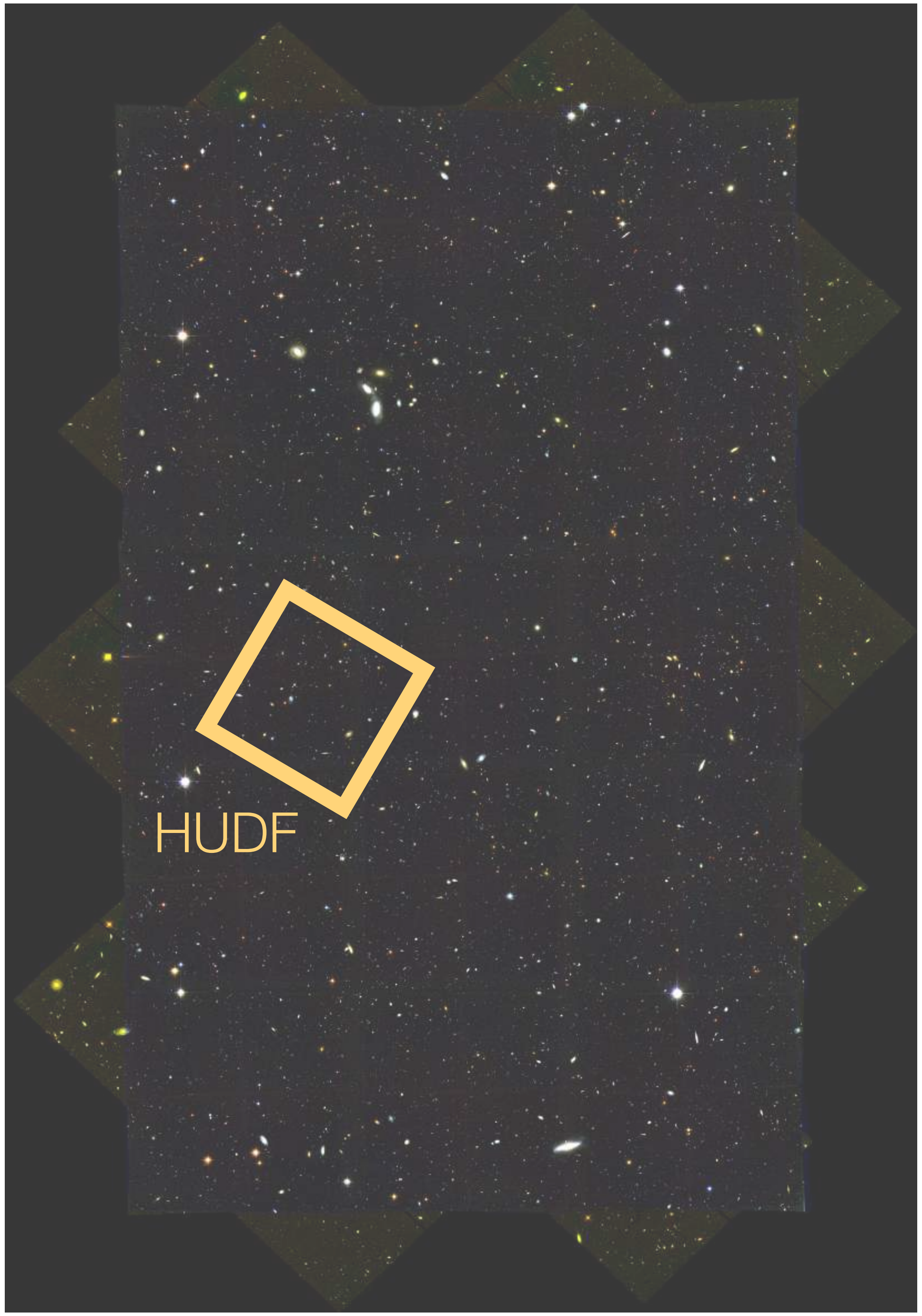
2002 Hubble upgrade with the Advanced Camera for Surveys (ACS)



GOODS fields

Great Observatories Origins Deep Survey (GOODS)

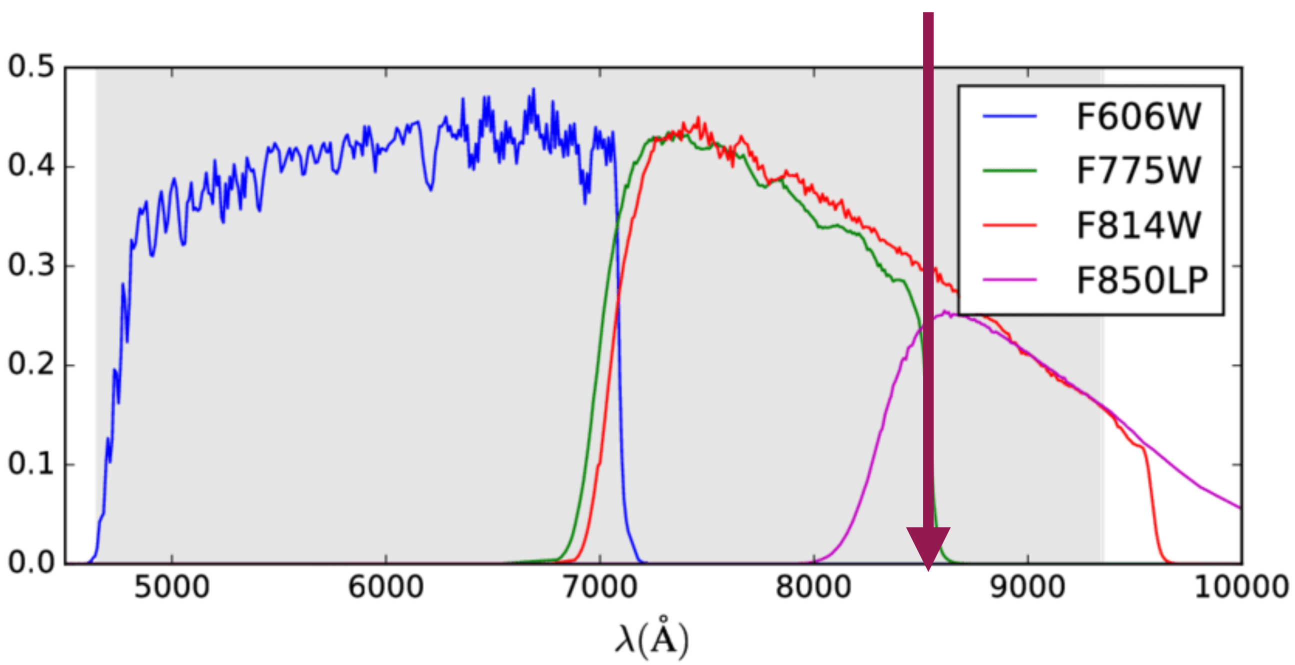
- Larger area survey detects brighter and more rare systems
- First statistical samples
- Start to obtain an actual census of the galaxy population out to z=6

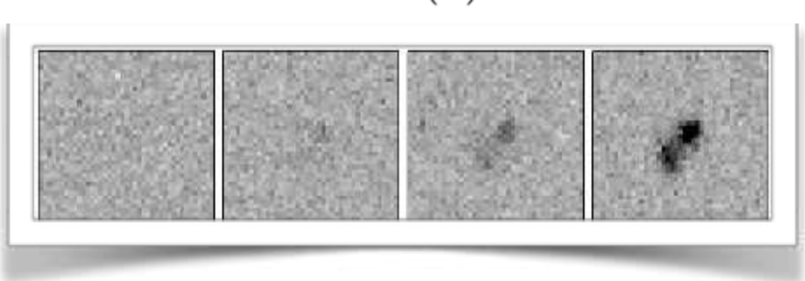


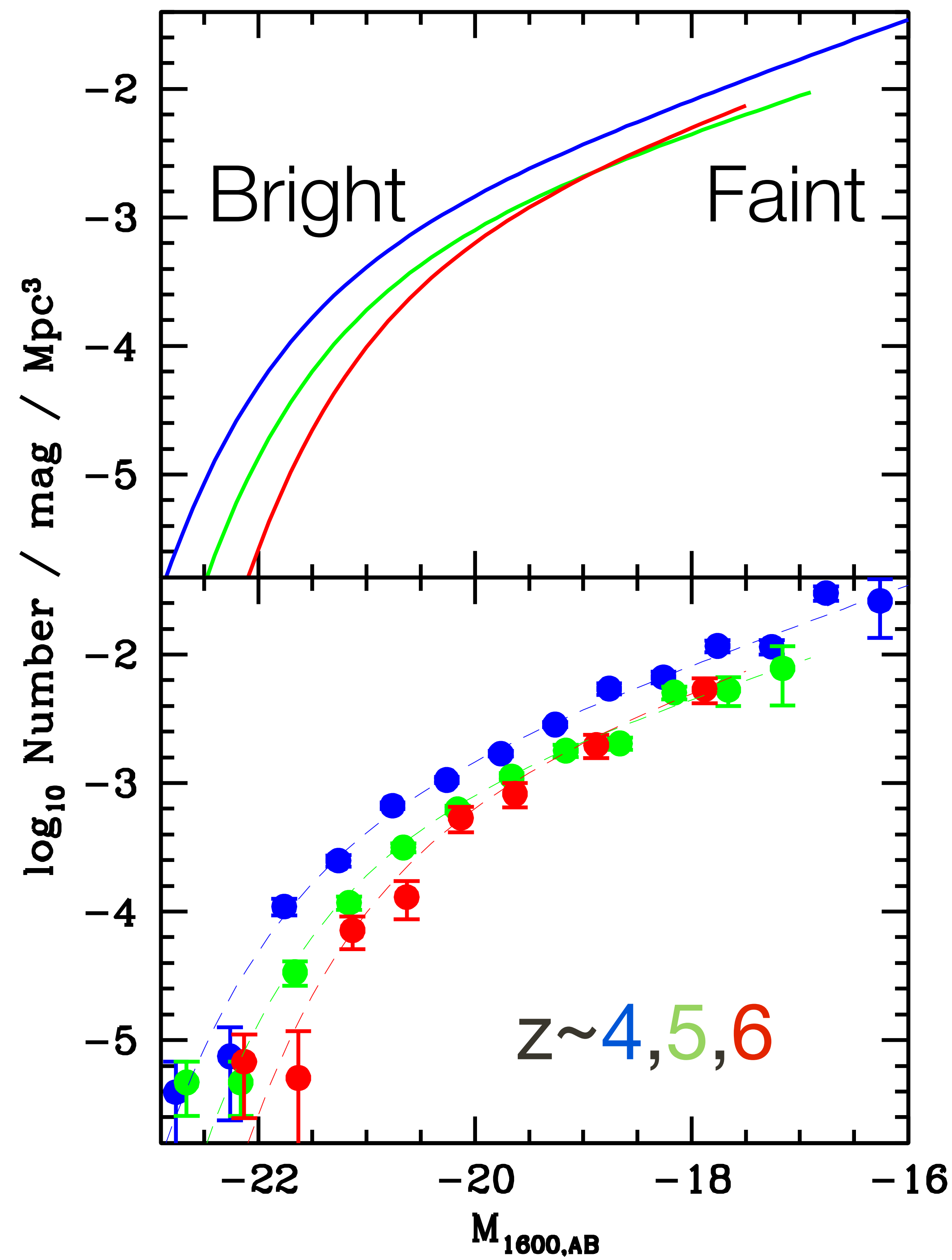
Giavalisco et al. 2004

UV luminosity function

At z=6 the Lyman break is shifted to ~8500Å

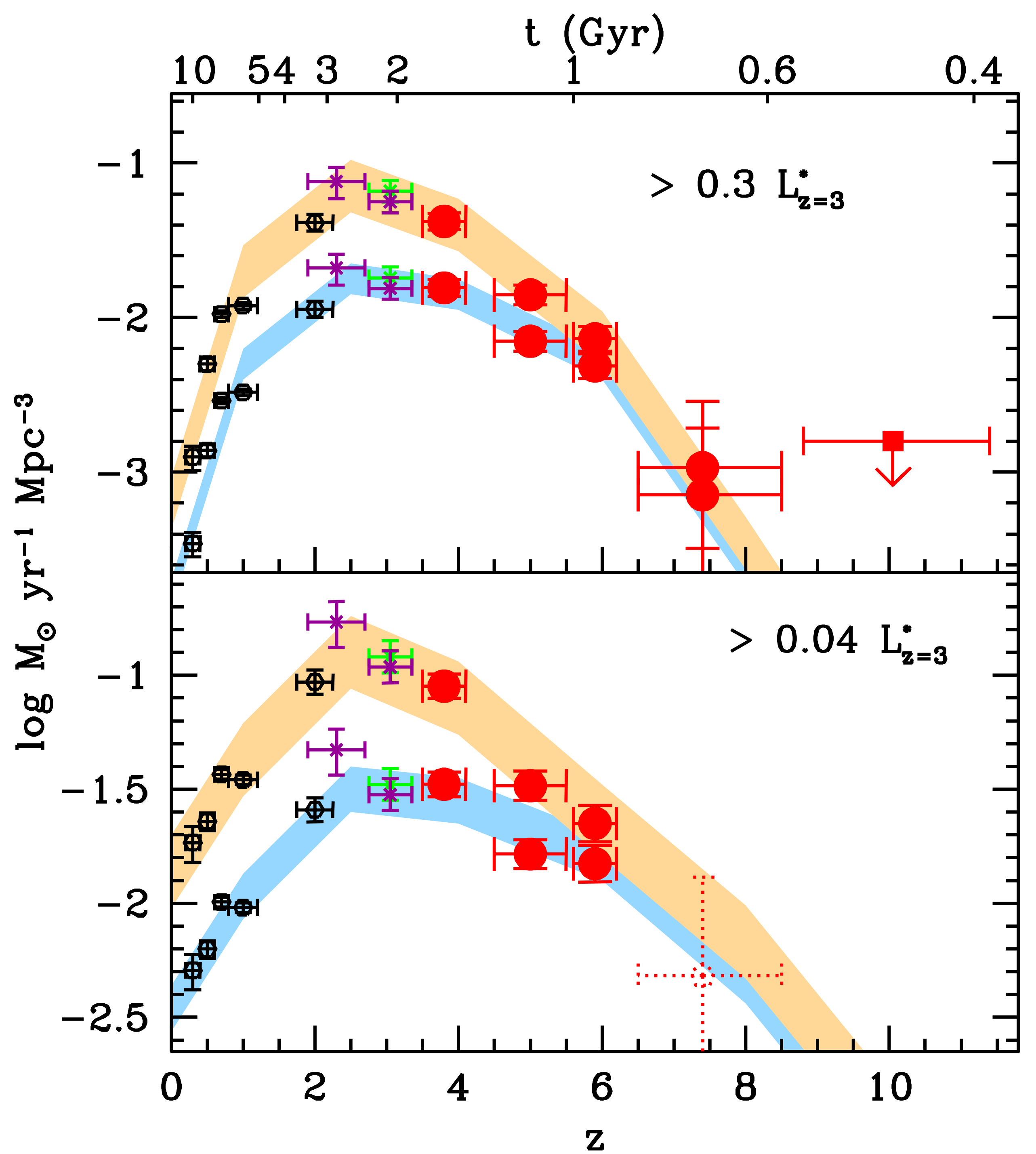




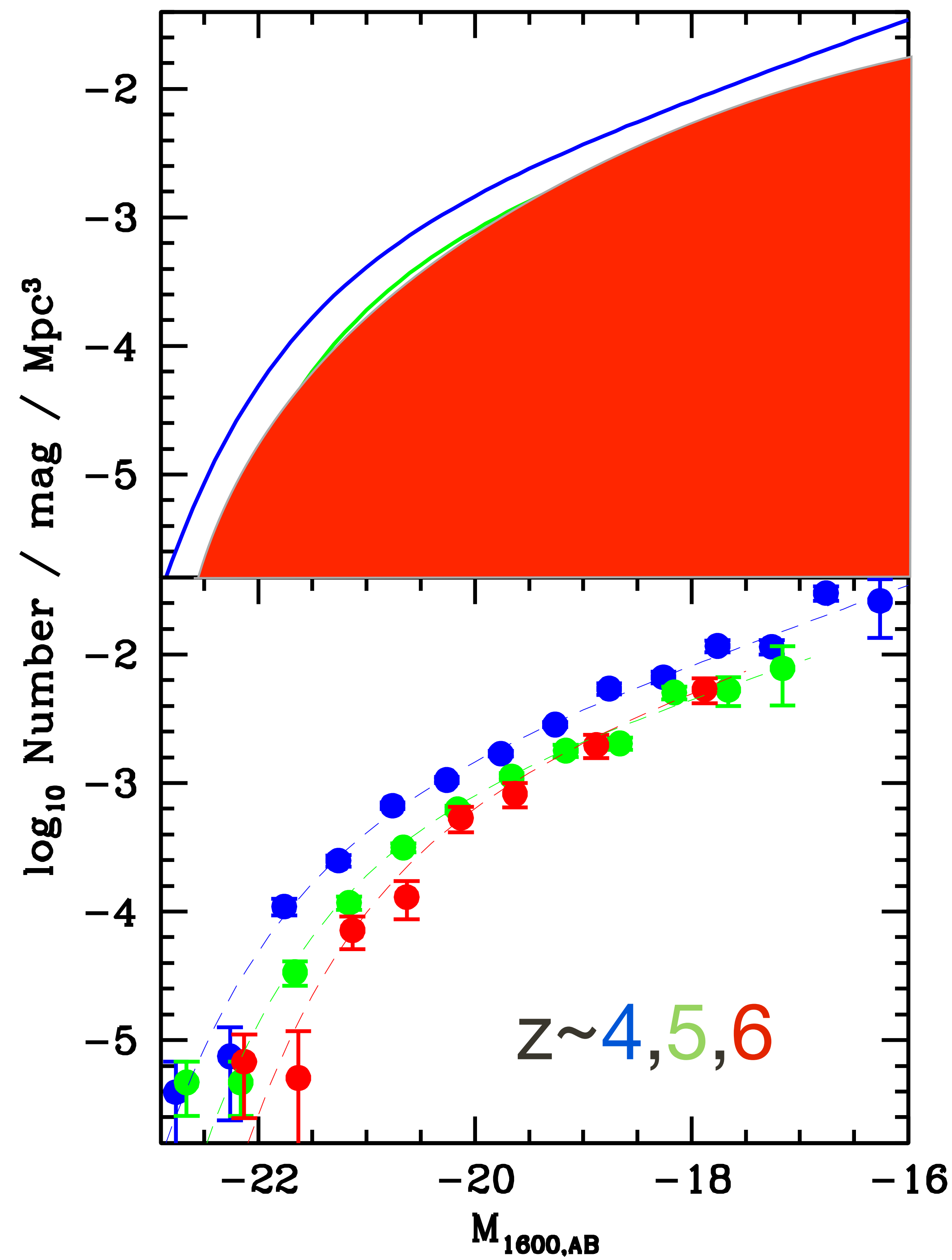


Bouwens et al. 2007

UV luminosity function

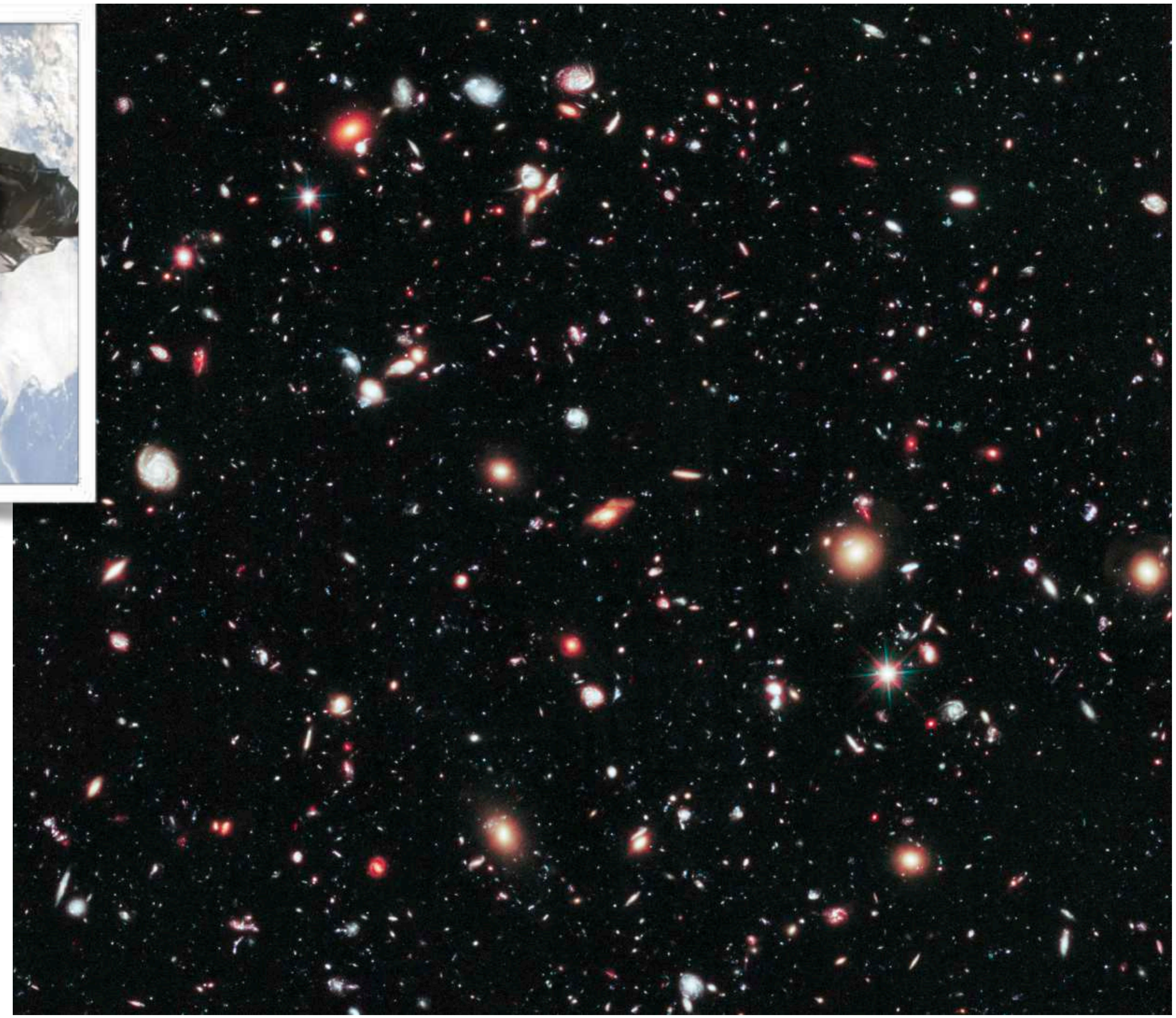


Bouwens et al. 2007



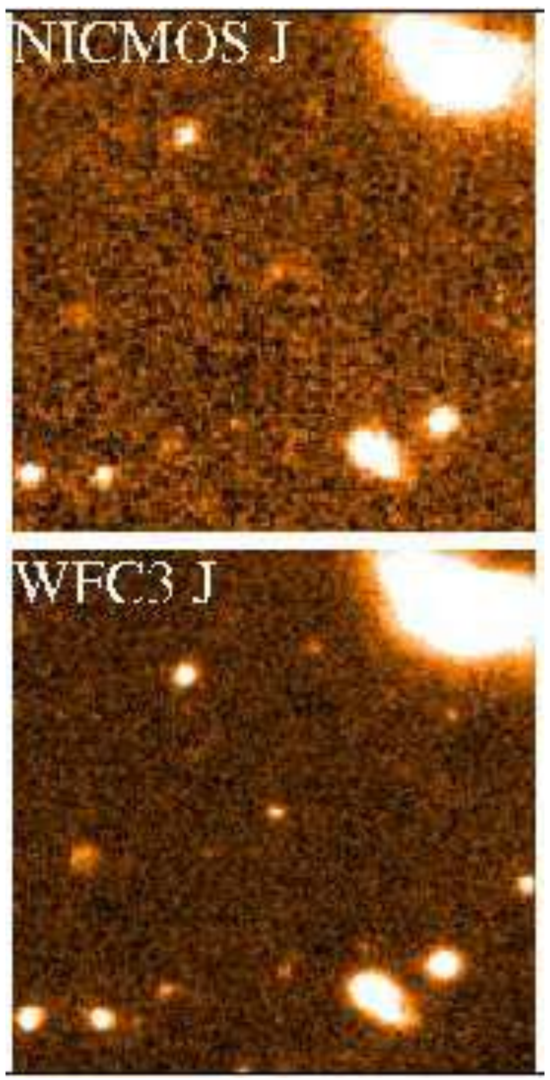
2012: eXtreme Deep Field (XDF)

2009 Hubble upgrade with the Wide Field Camera 3 (WFC3)



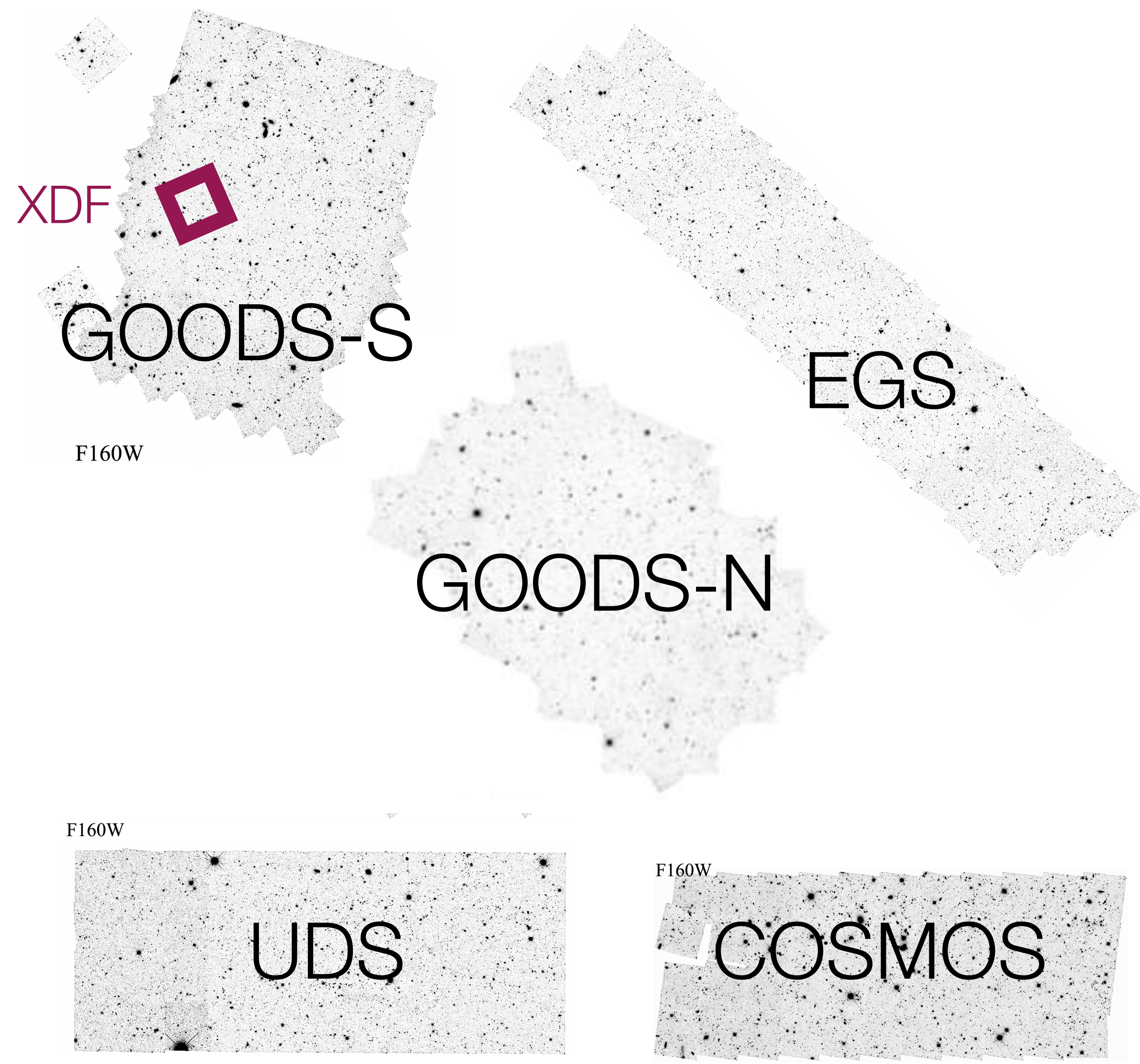
2012: eXtreme Deep Field

NICMOS vs WFC3

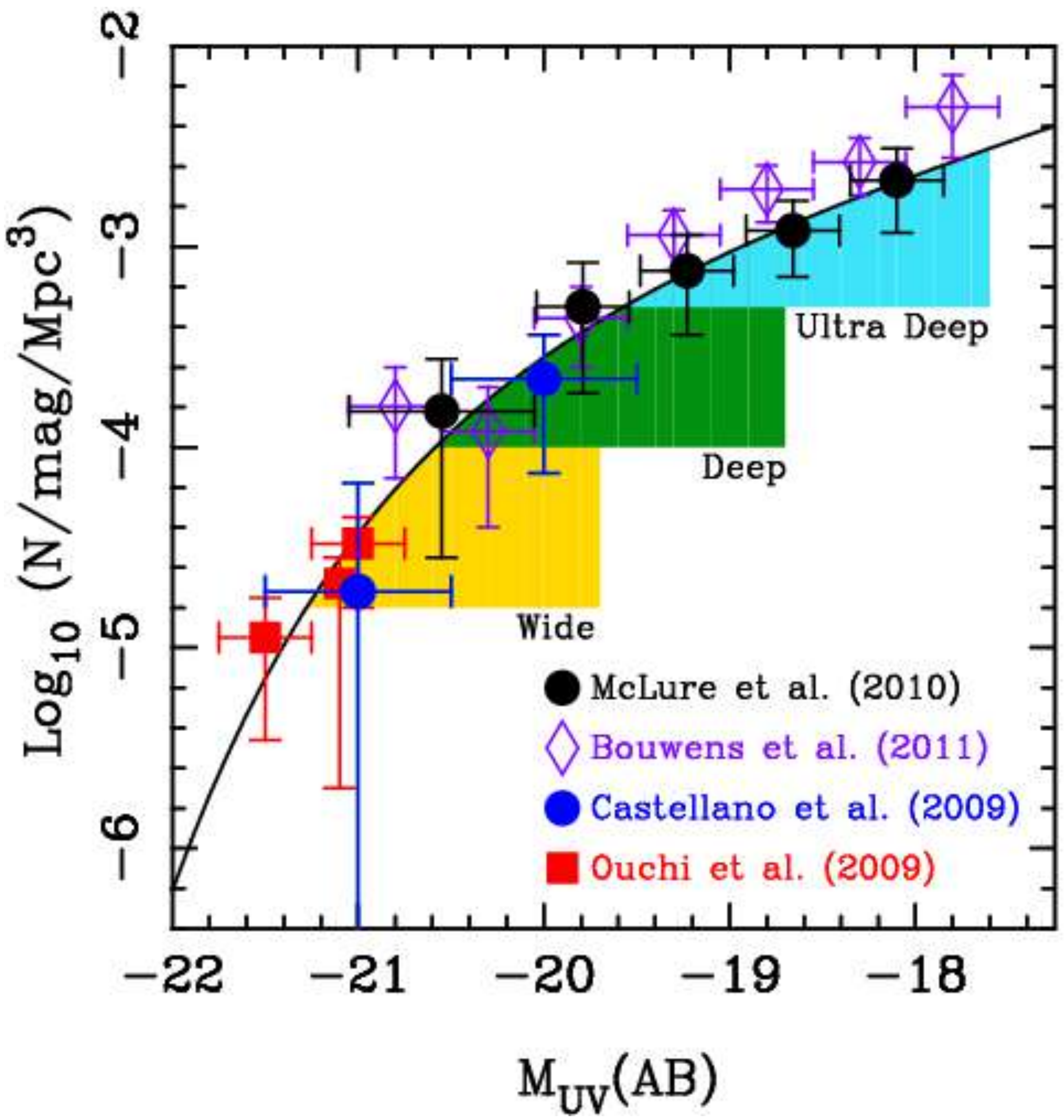


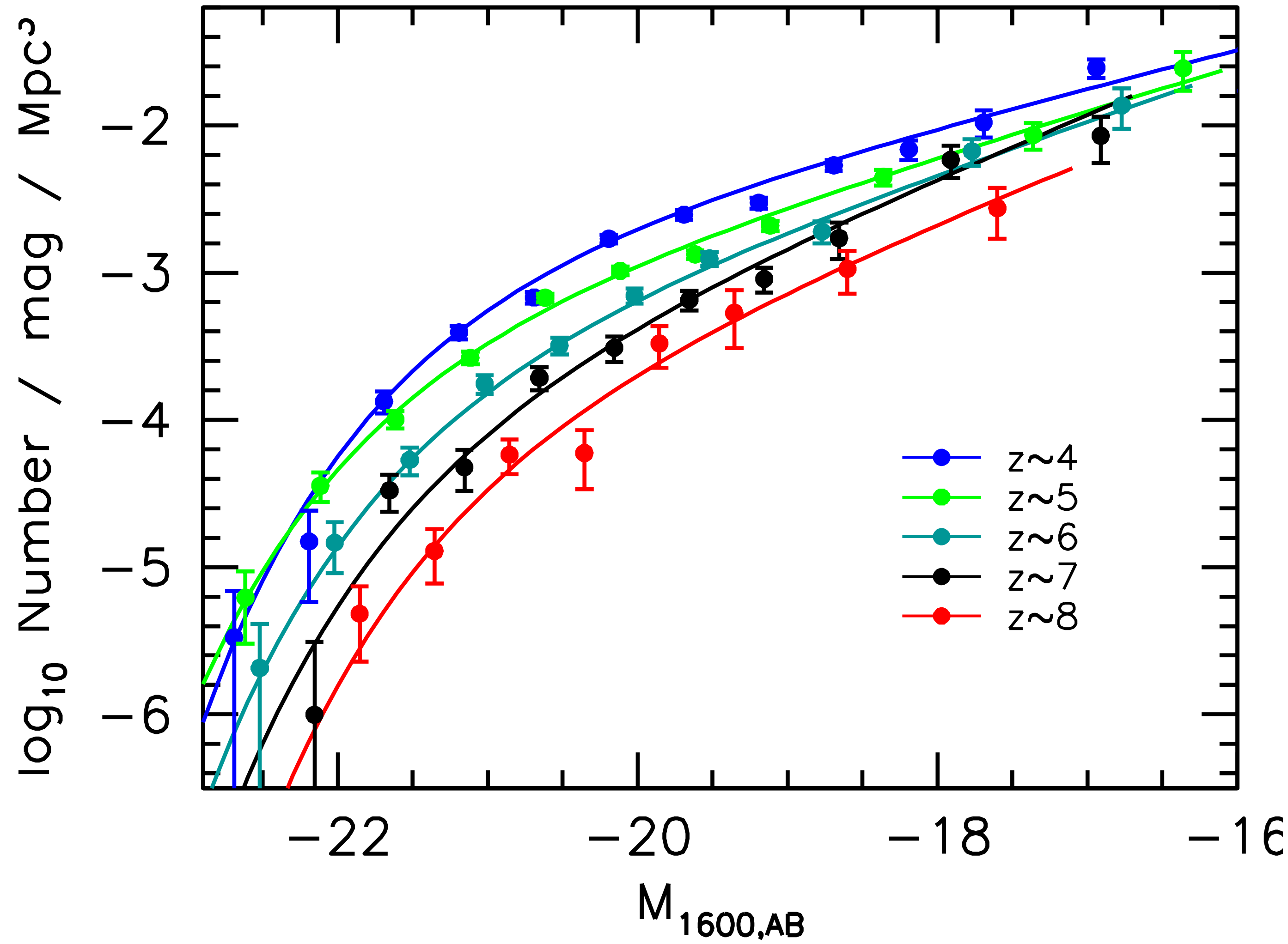
CANDELS

Cosmic Assembly Near-Infrared Deep Extragalactic Survey



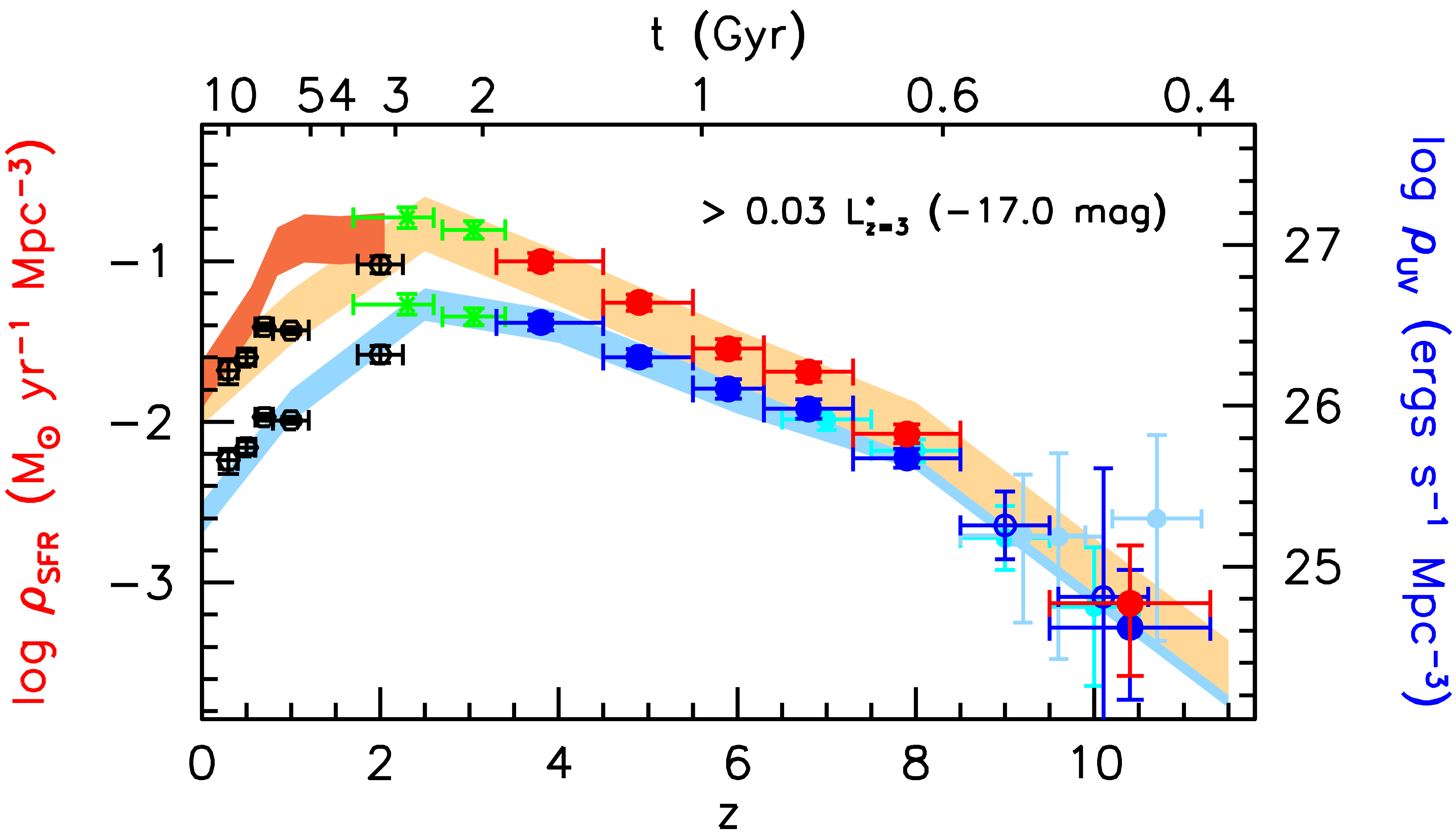
Wedding cake strategy





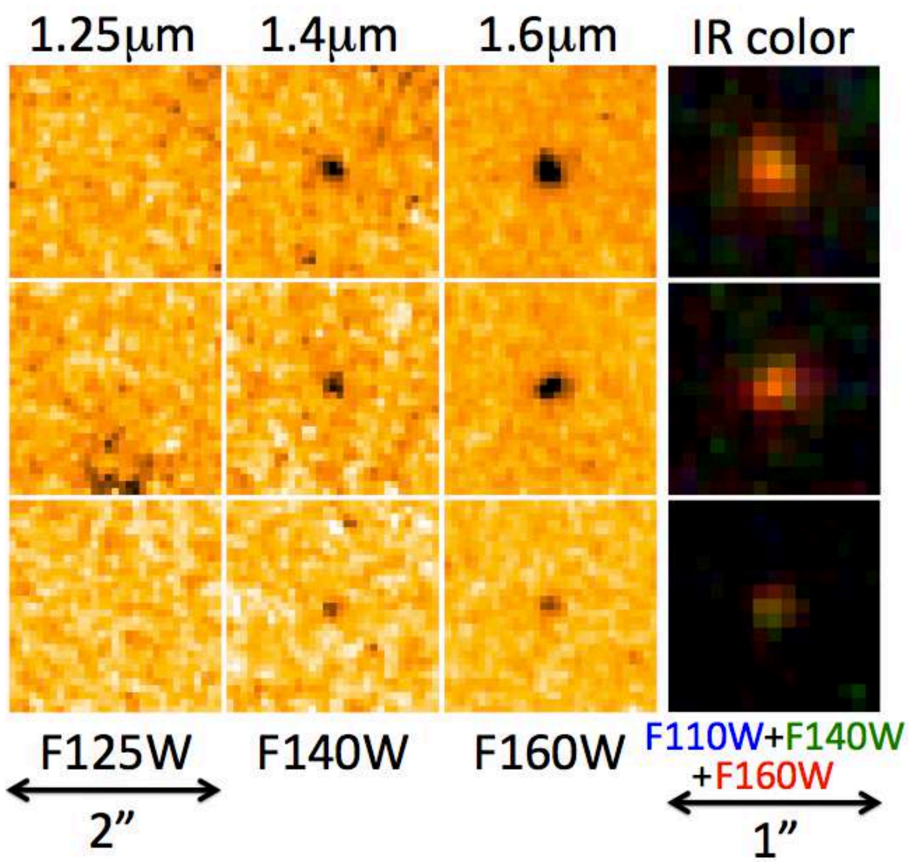
Grogin et al. 2011

Galaxy census out to the EoR



Bouwens et al. 2015

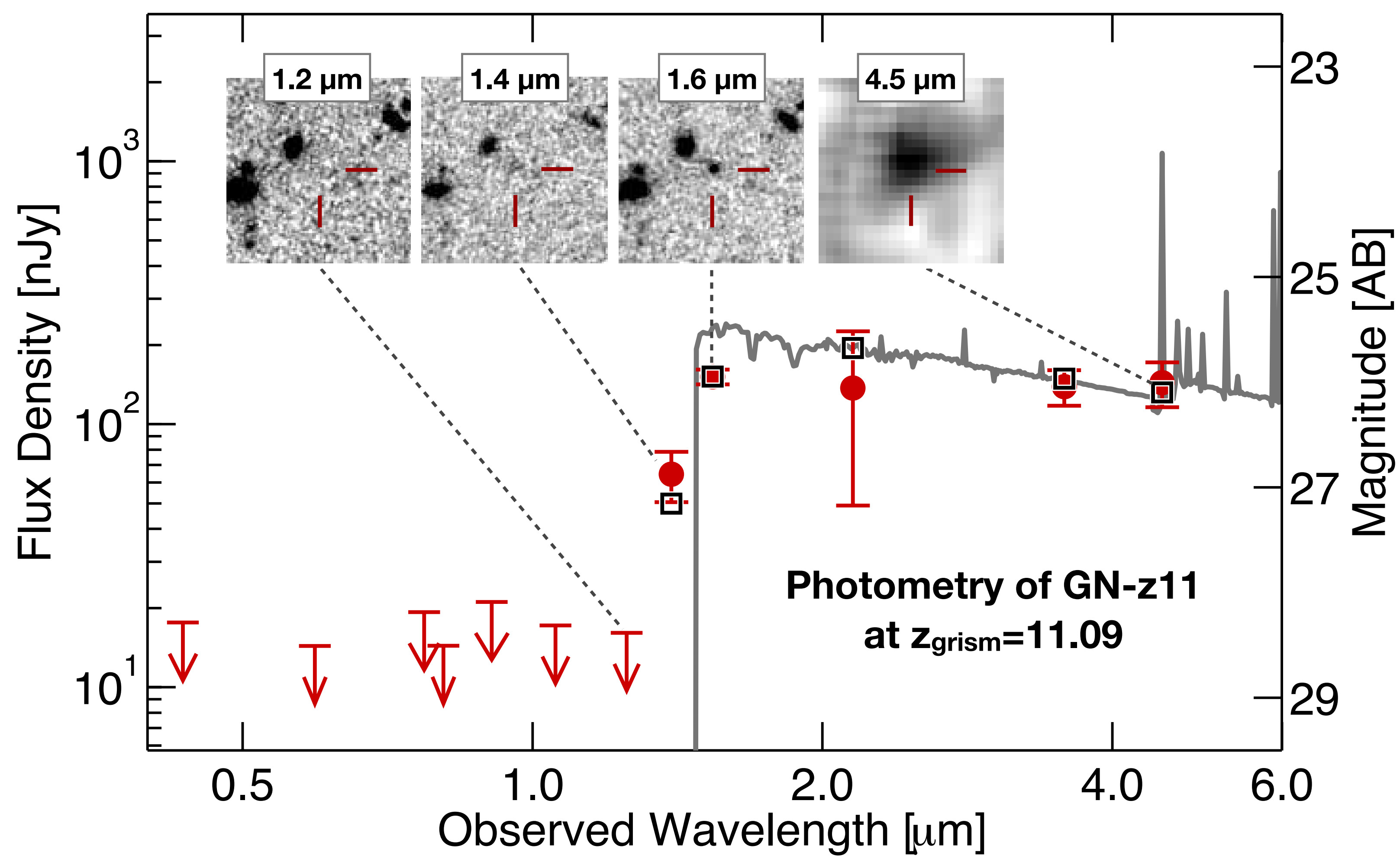
Redshift Frontier: z~11



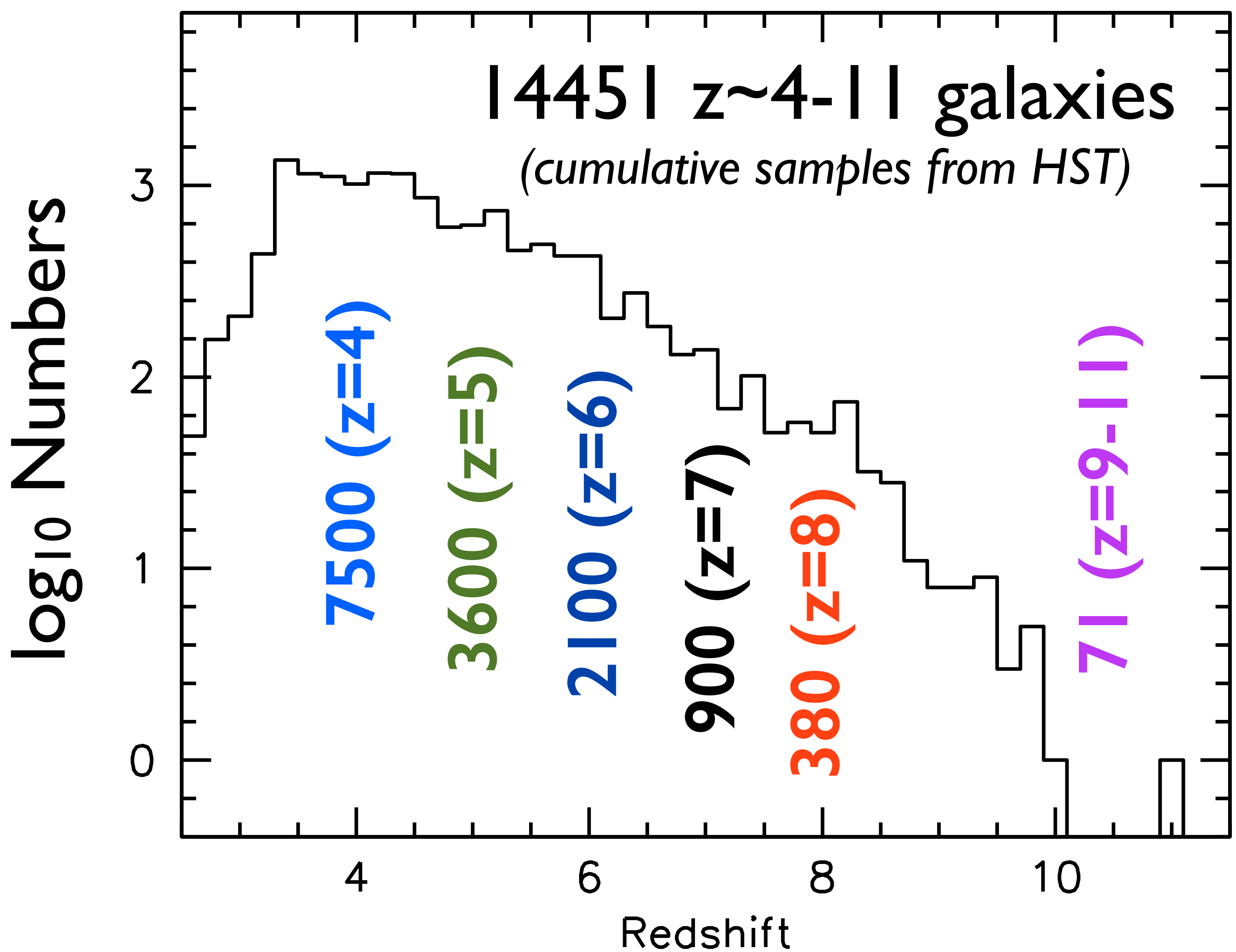
Coe et al. 2013

Only JWST will
push beyond z~11

Oesch et al. 2016

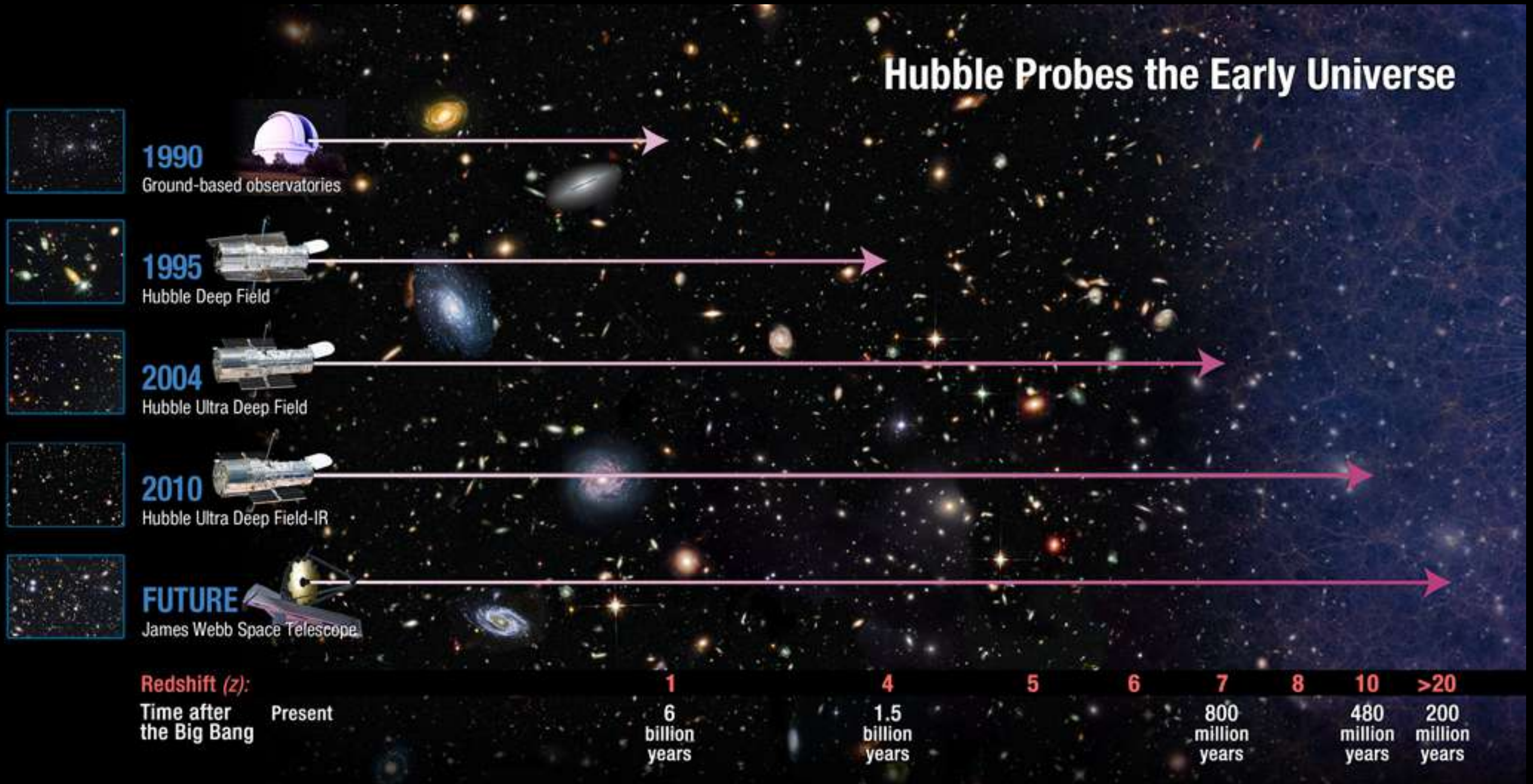


Statistical samples

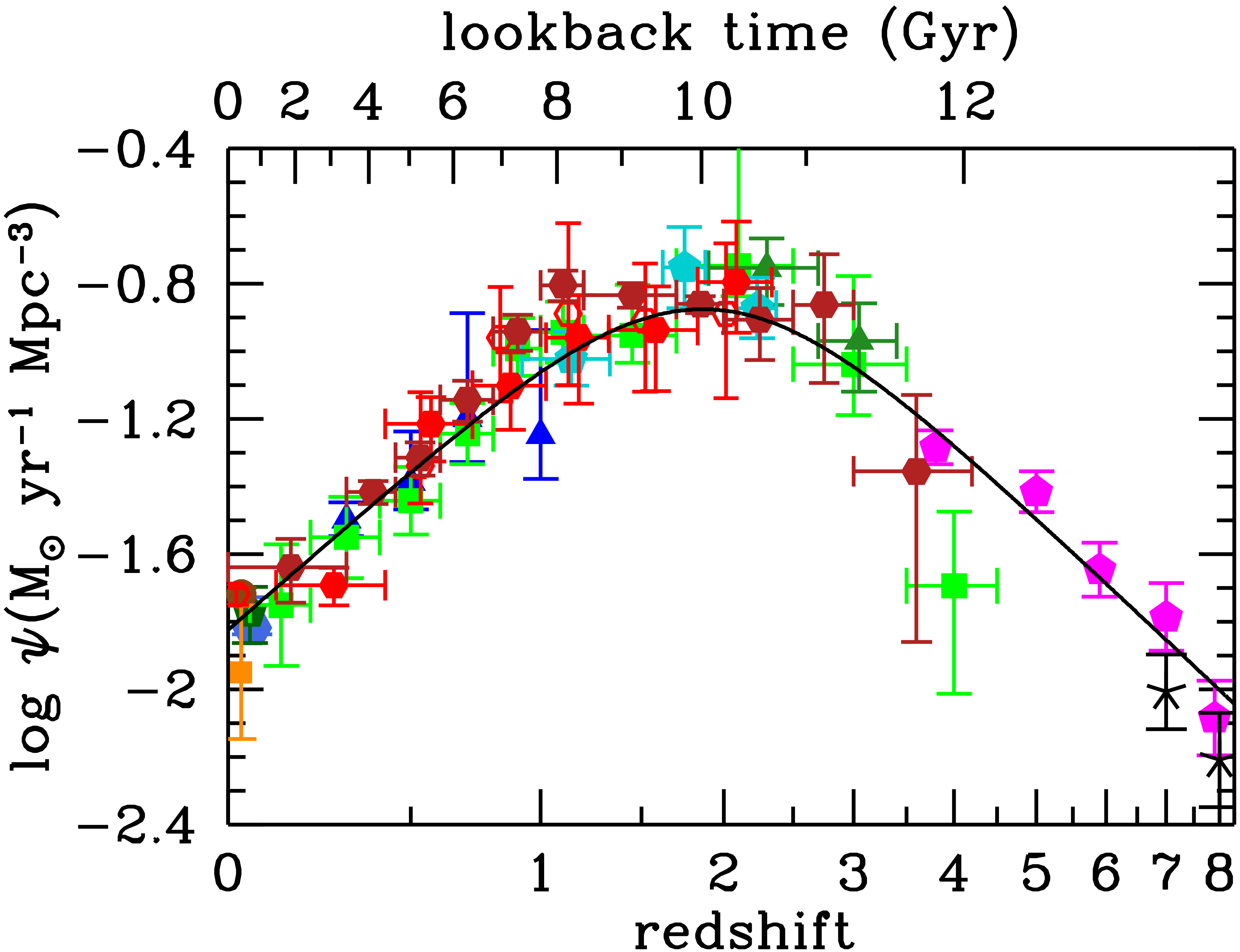


Oesch et al. 2016; Bouwens et al. 2015,2016

Redshift frontier

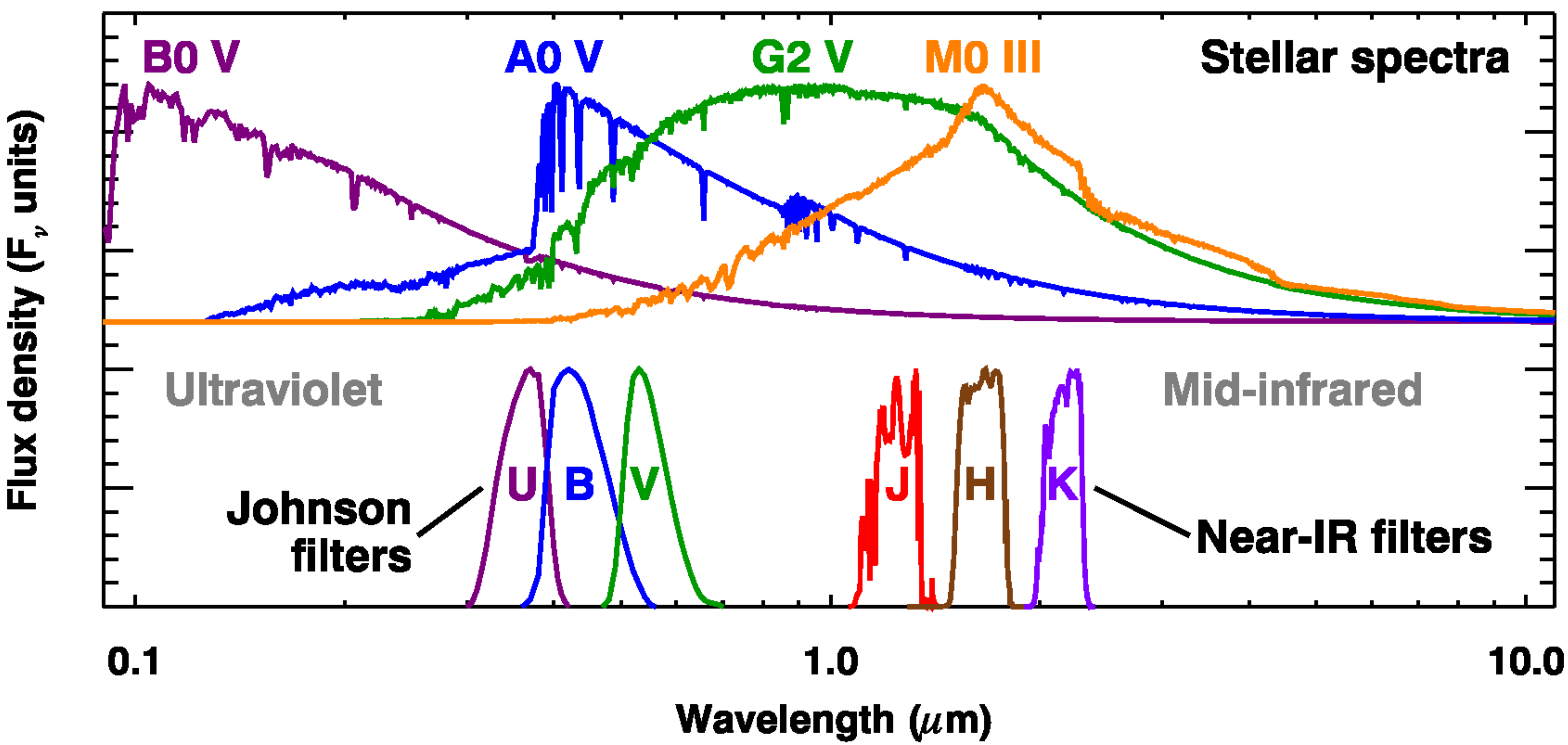


Obtaining a census of star-formation activity



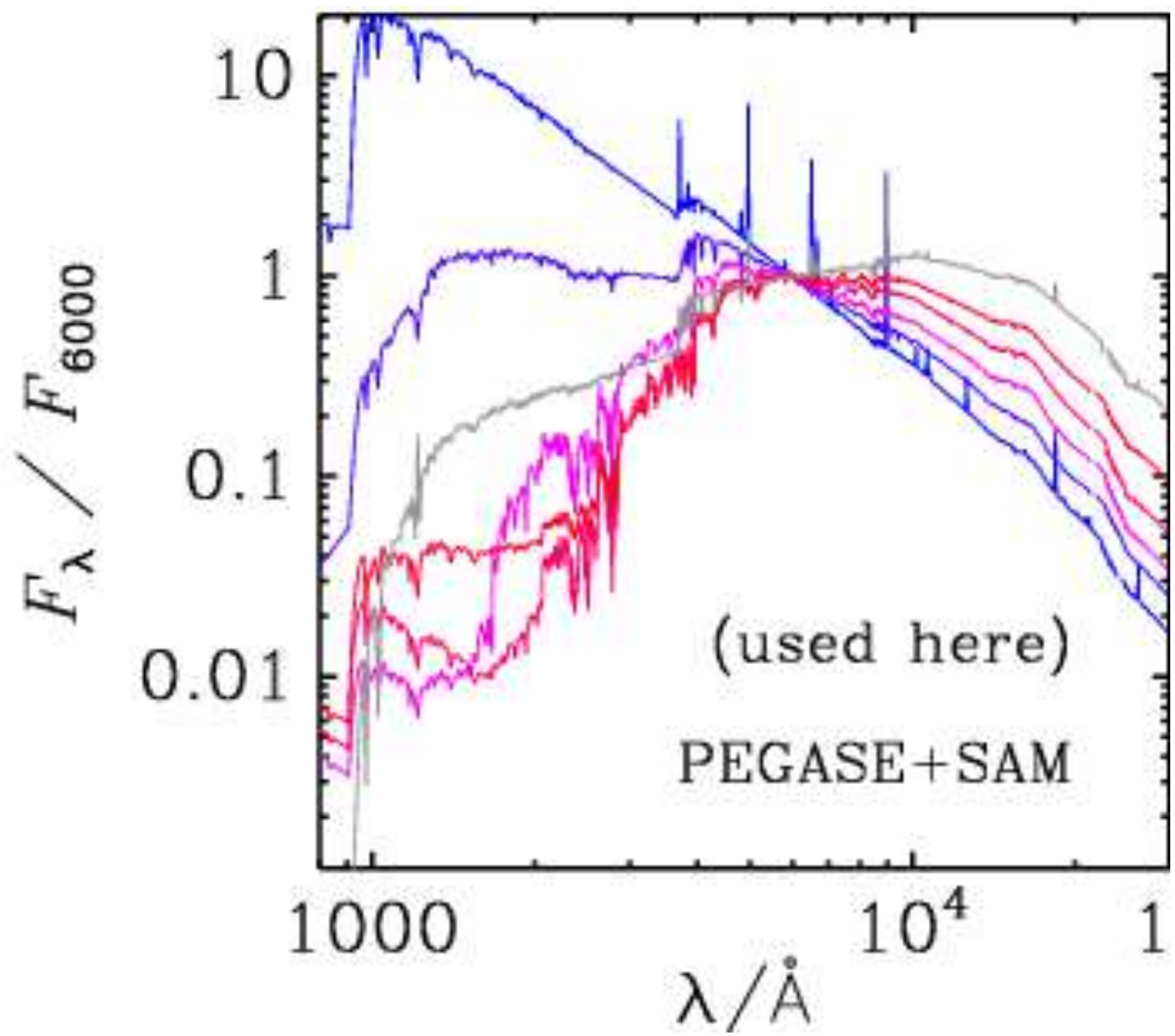
Madau & Dickenson 2017

Interlopers and selection bias



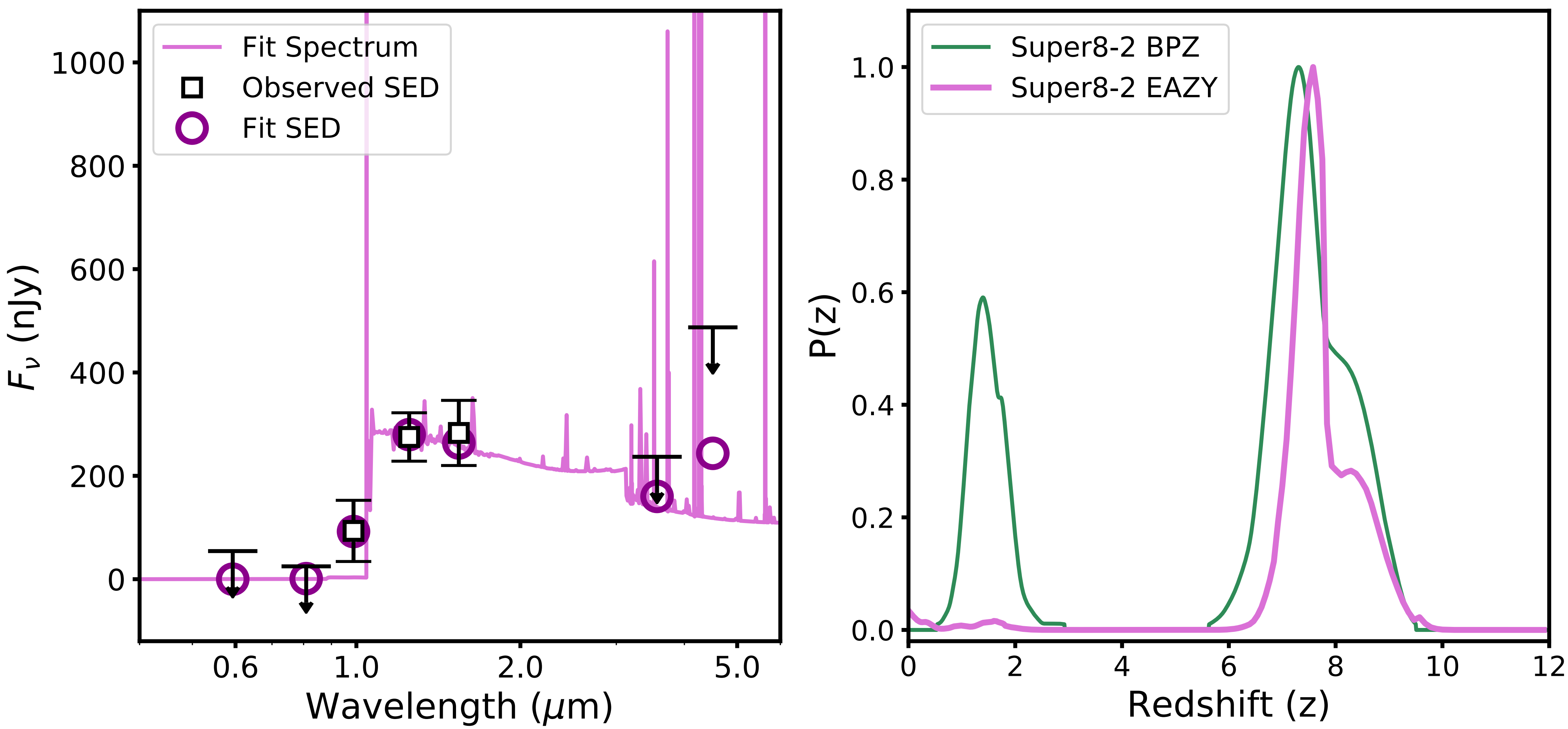
Photometric redshift fitting

- Take 5-10 ‘templates’ that cover the parameter space of galaxy spectra
- Take all possible linear combinations of the template set at every redshift with arbitrary normalisation
- Minimise X^2 for best fit redshift solution



Brammer et al. 2008

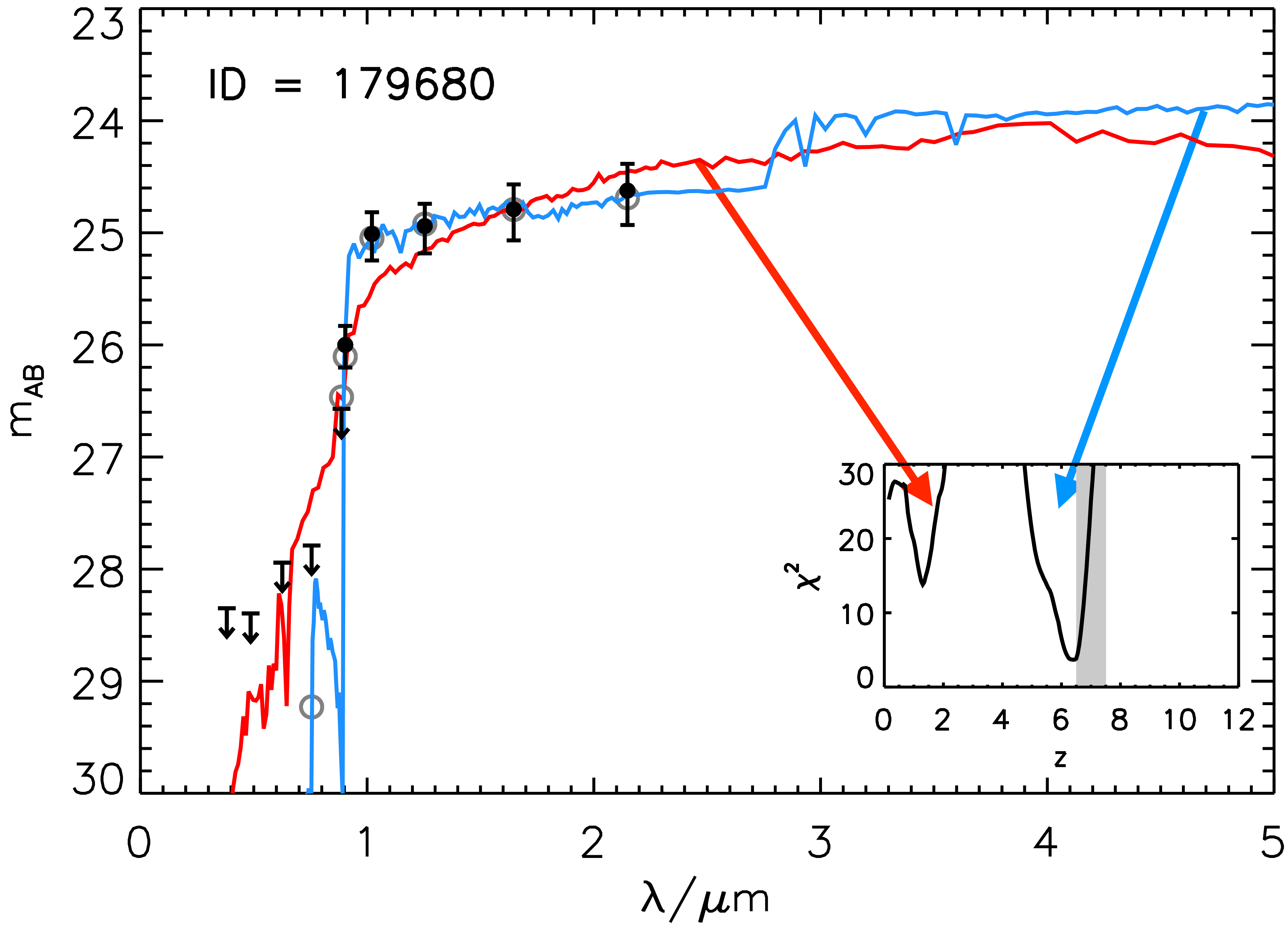
Photometric redshift fitting



Typical 'bimodal' solution

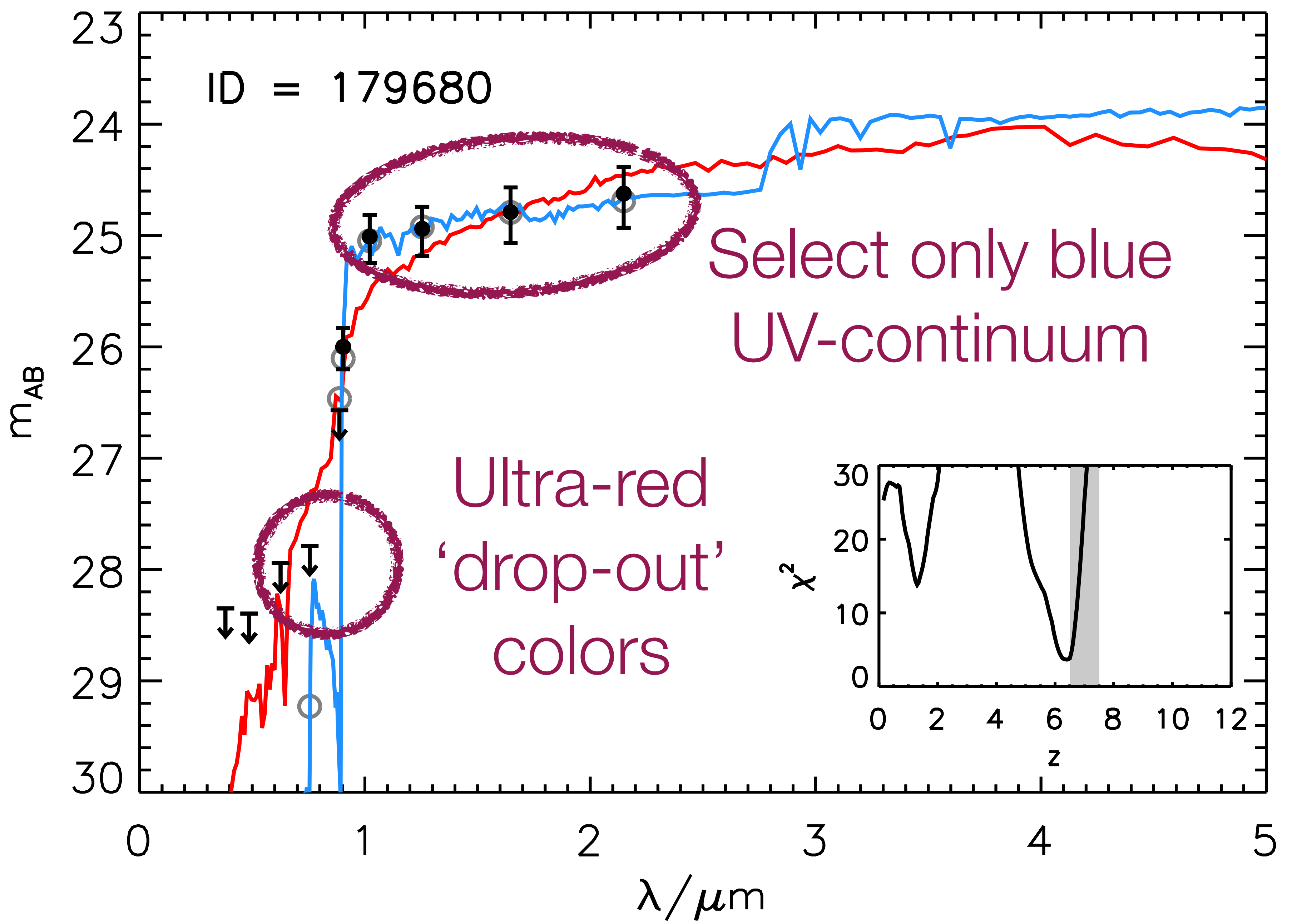
Bridge et al. 2019

Interlopers and selection bias



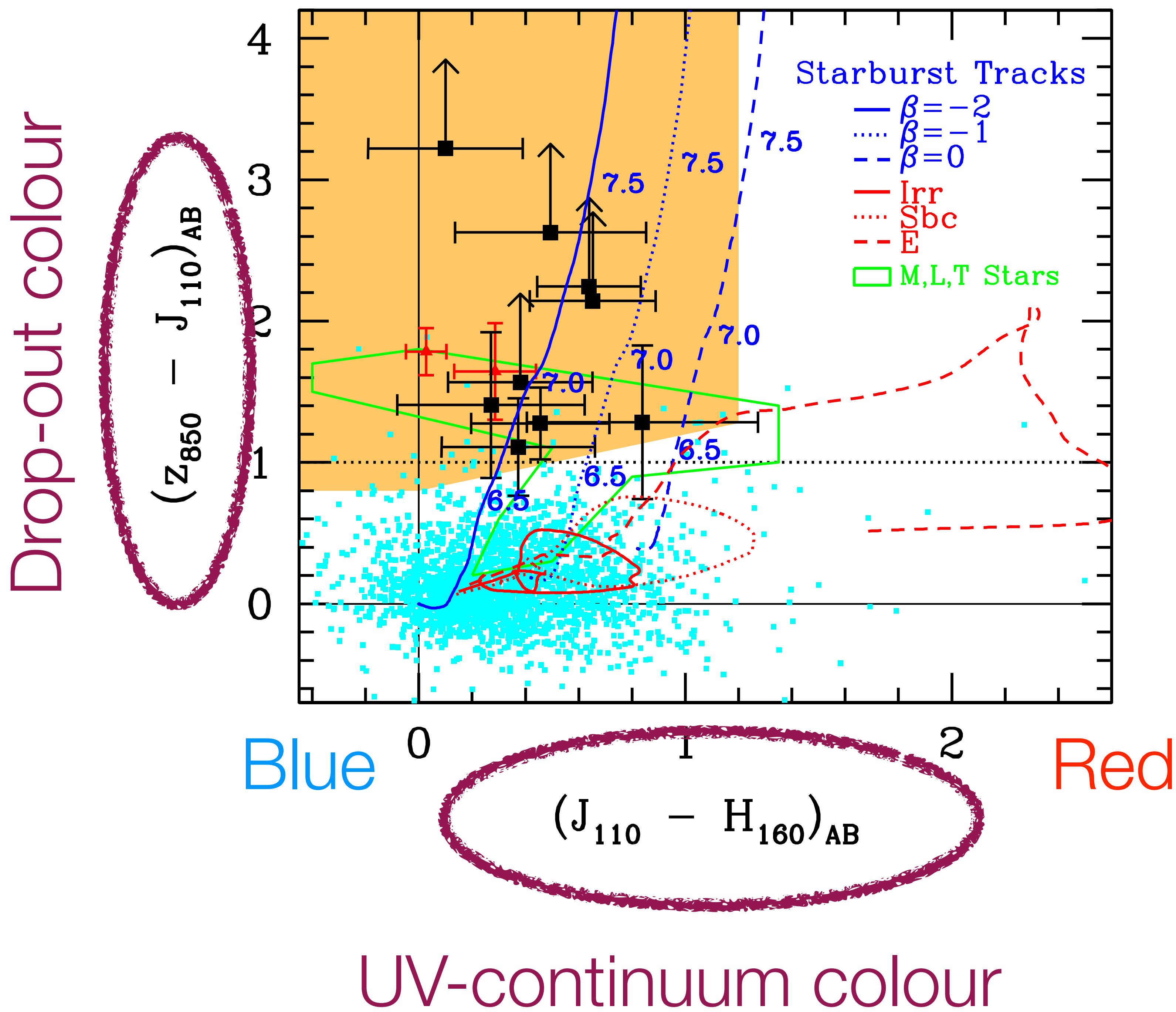
Bowler et al. 2014

Interlopers and selection bias

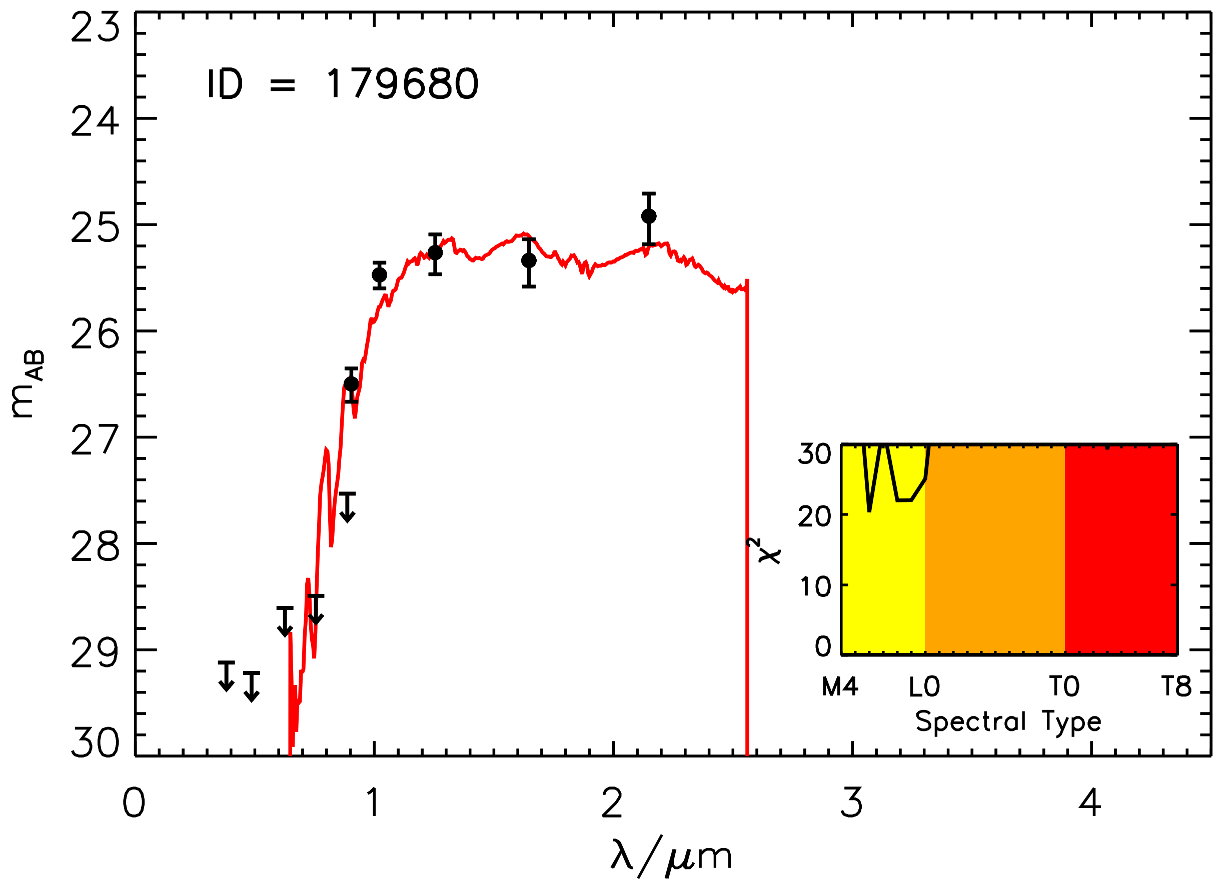


Bowler et al. 2014

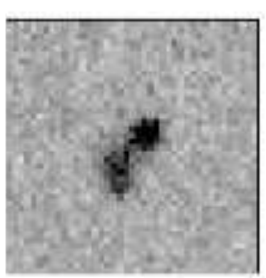
Colour-colour selection



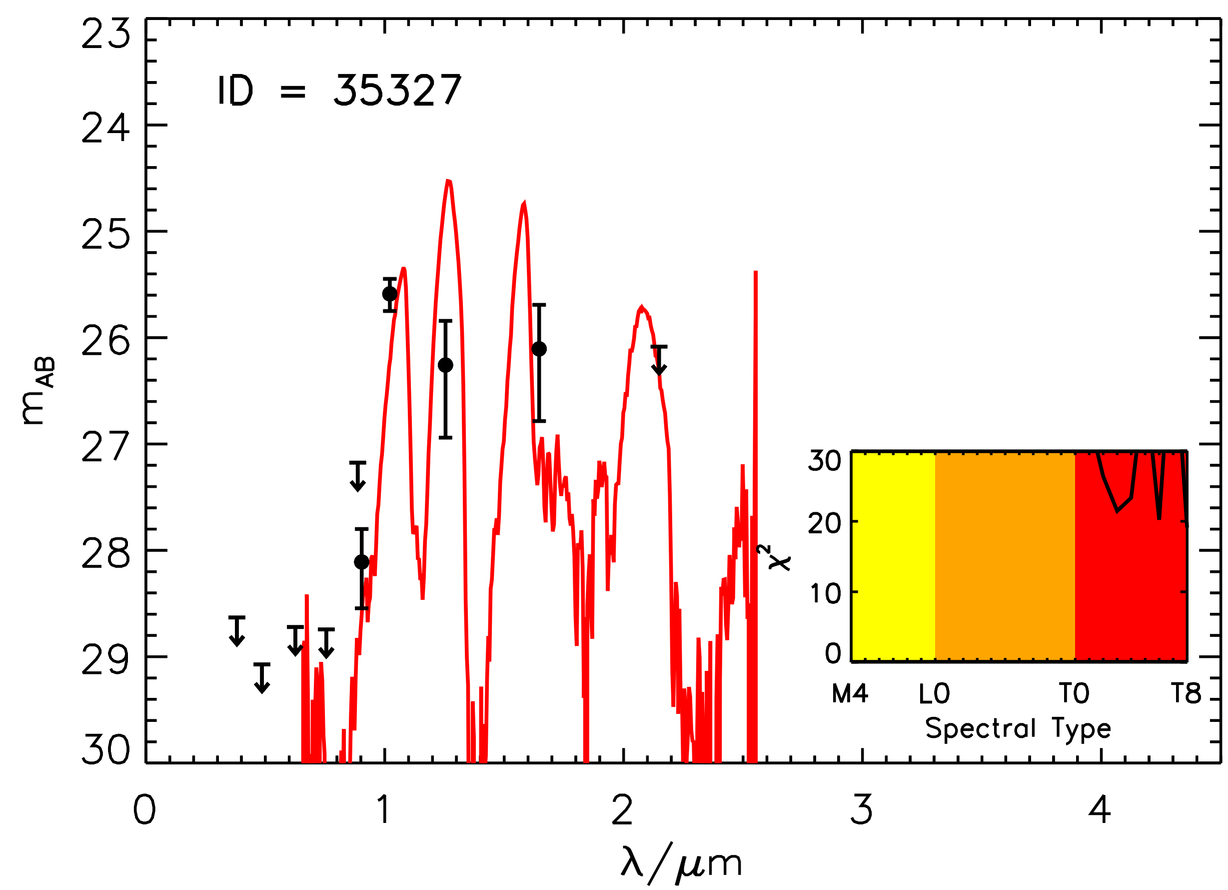
Interlopers and selection bias



Cool M, L & T dwarf stars also become problematic at z~7

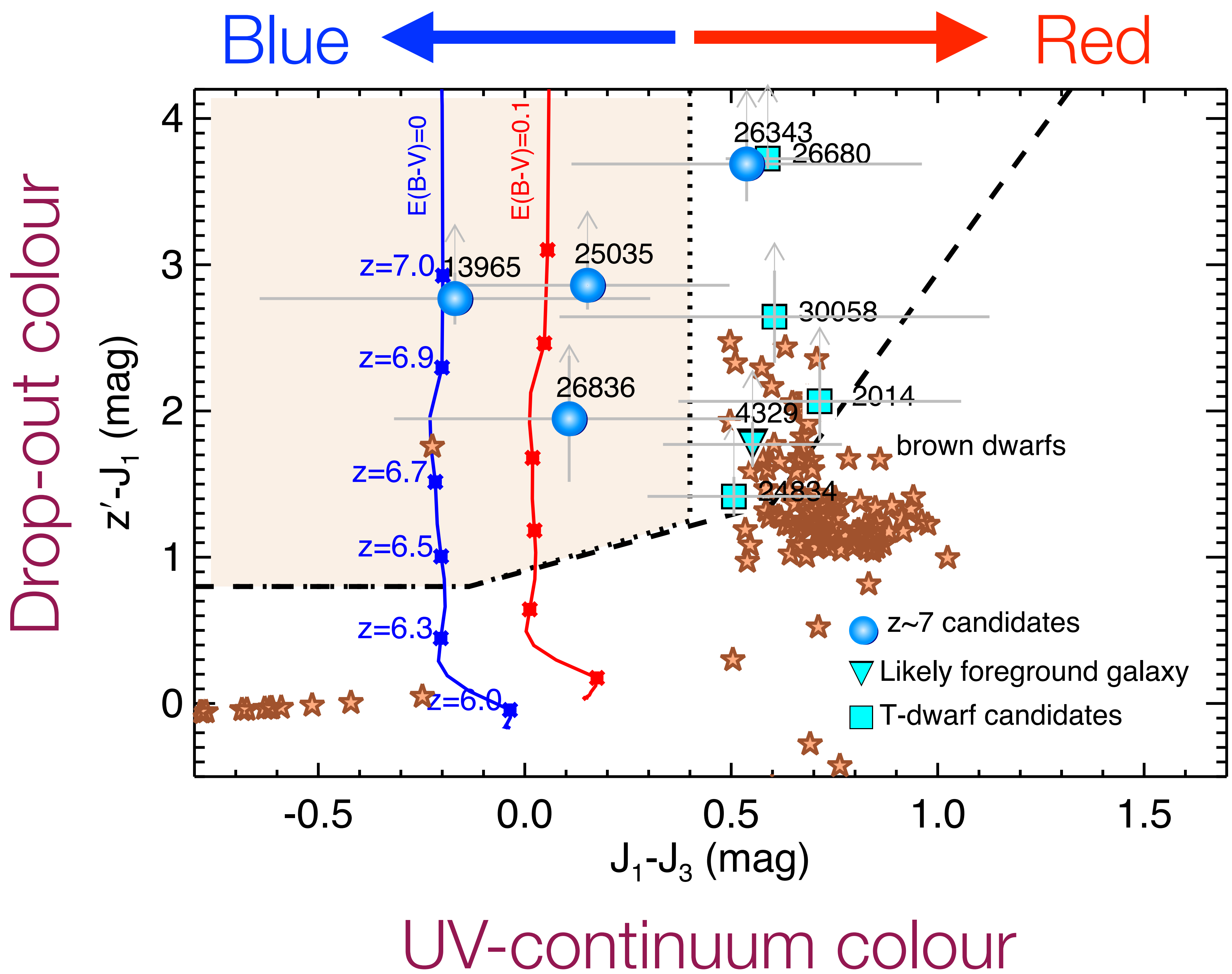


bright galaxies in Hubble can't be confused with stars - faint galaxies and ground based imaging are more problematic



Bowler et al. 2014

Interlopers and selection bias

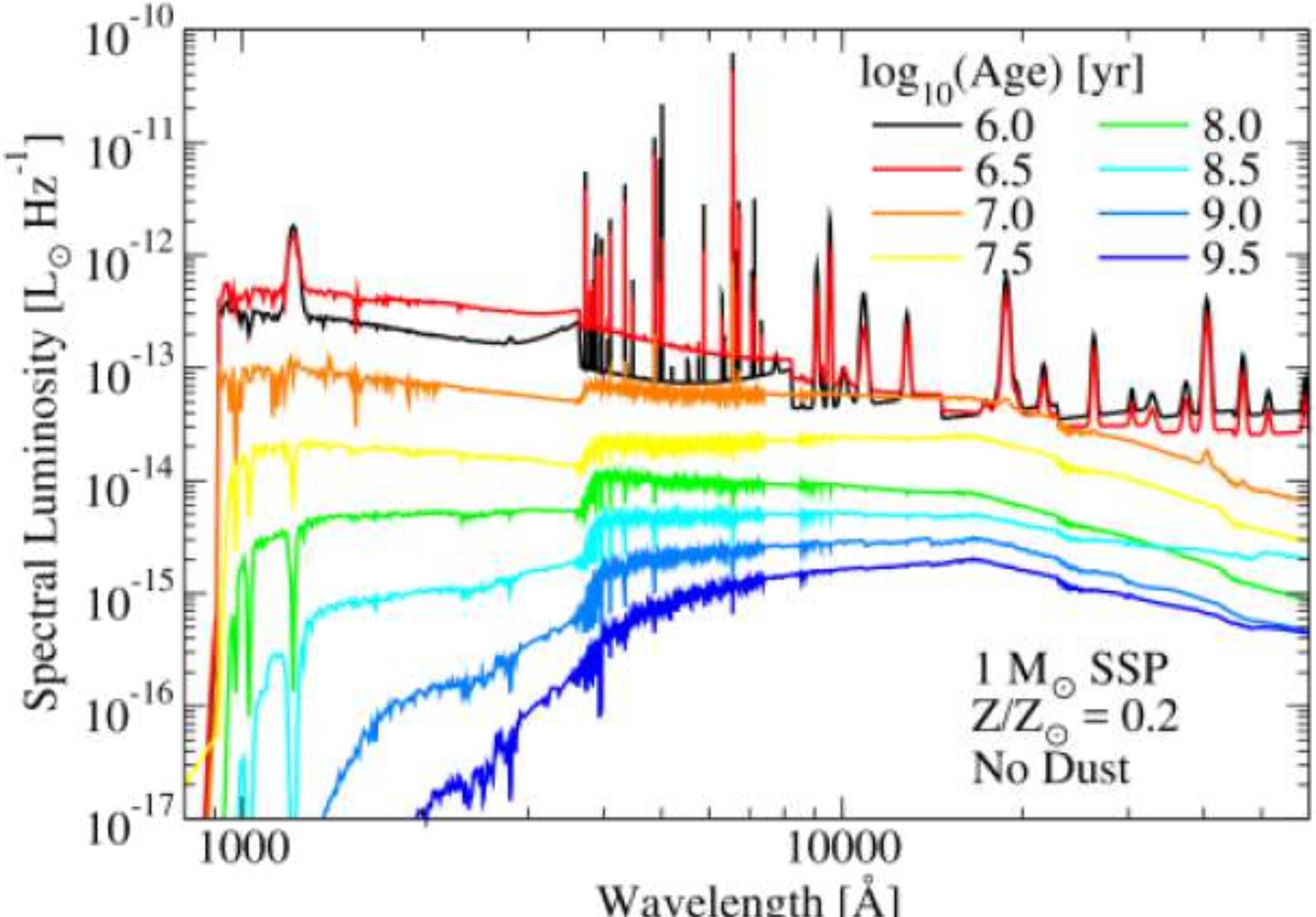


Tilvi et al. 2013

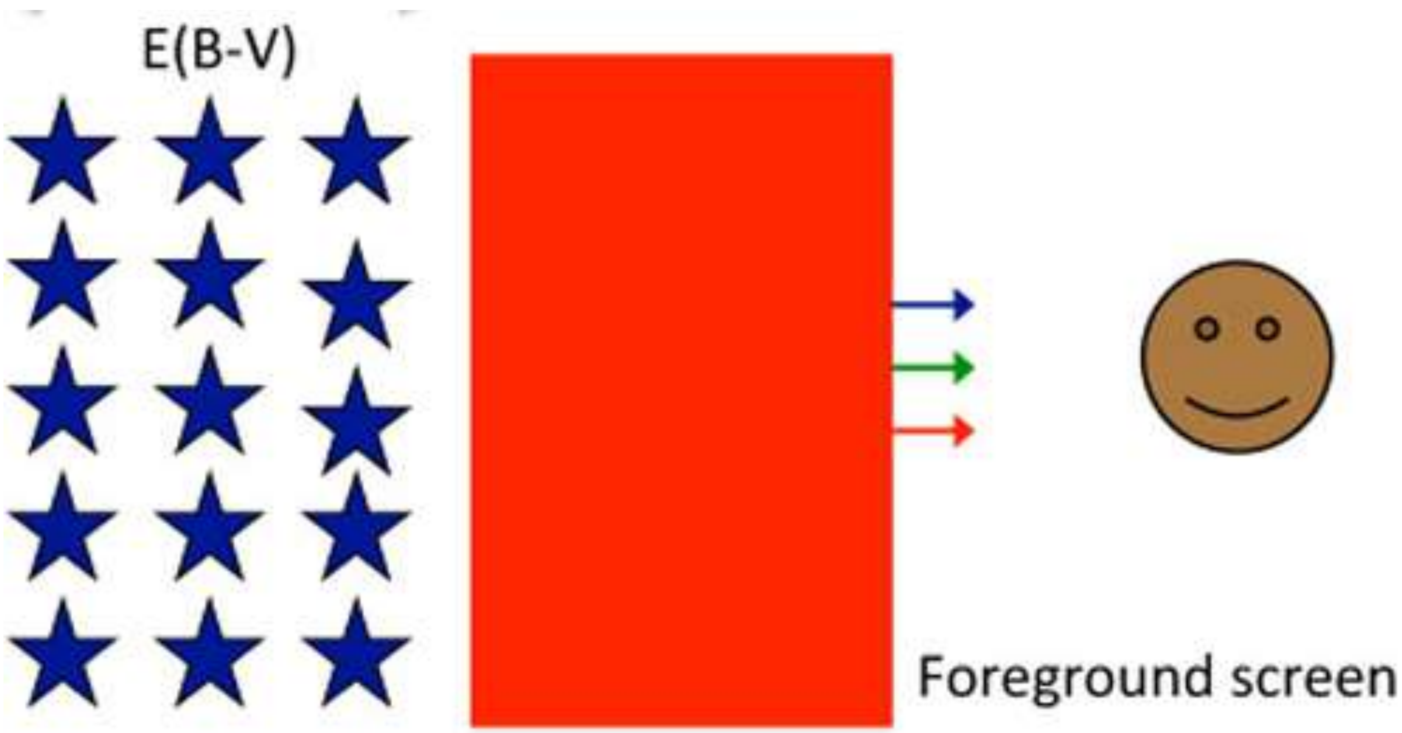
Selection bias: age

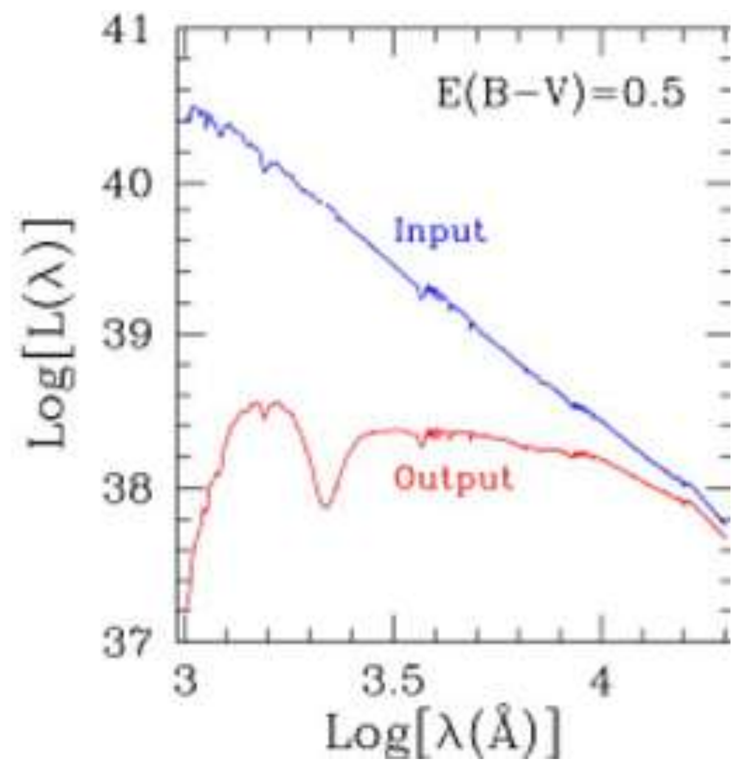
Easily selected

Difficult to distinguish from interlopers



Selection bias: dust



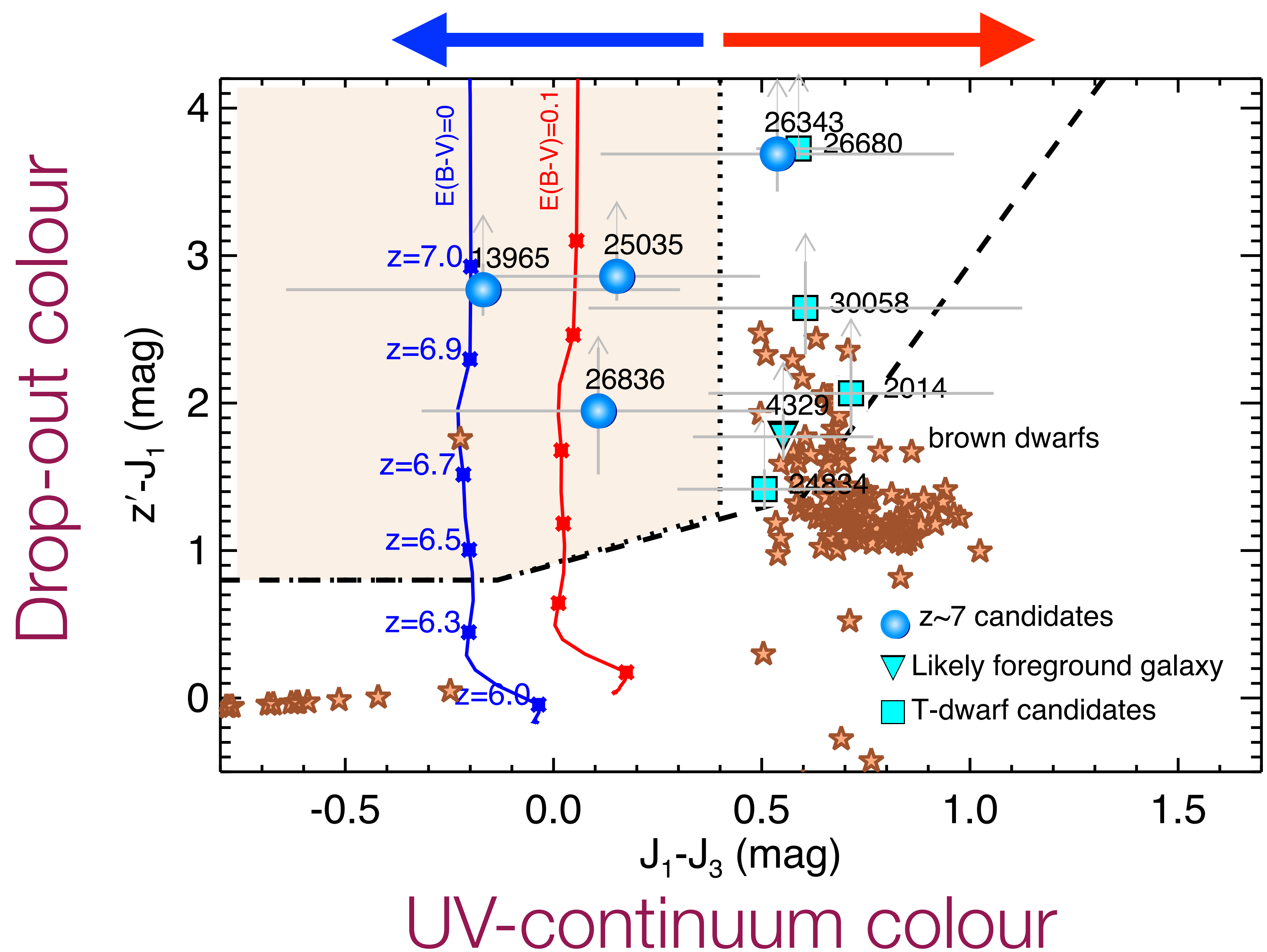


Dust-free galaxies are more easily distinguished form interlopers than dusty ones

Calzetti et al. 2001

Colour-colour selection

Stronger selection bias   More interlopers



Tilvi et al. 2013

UV luminosity function: open questions

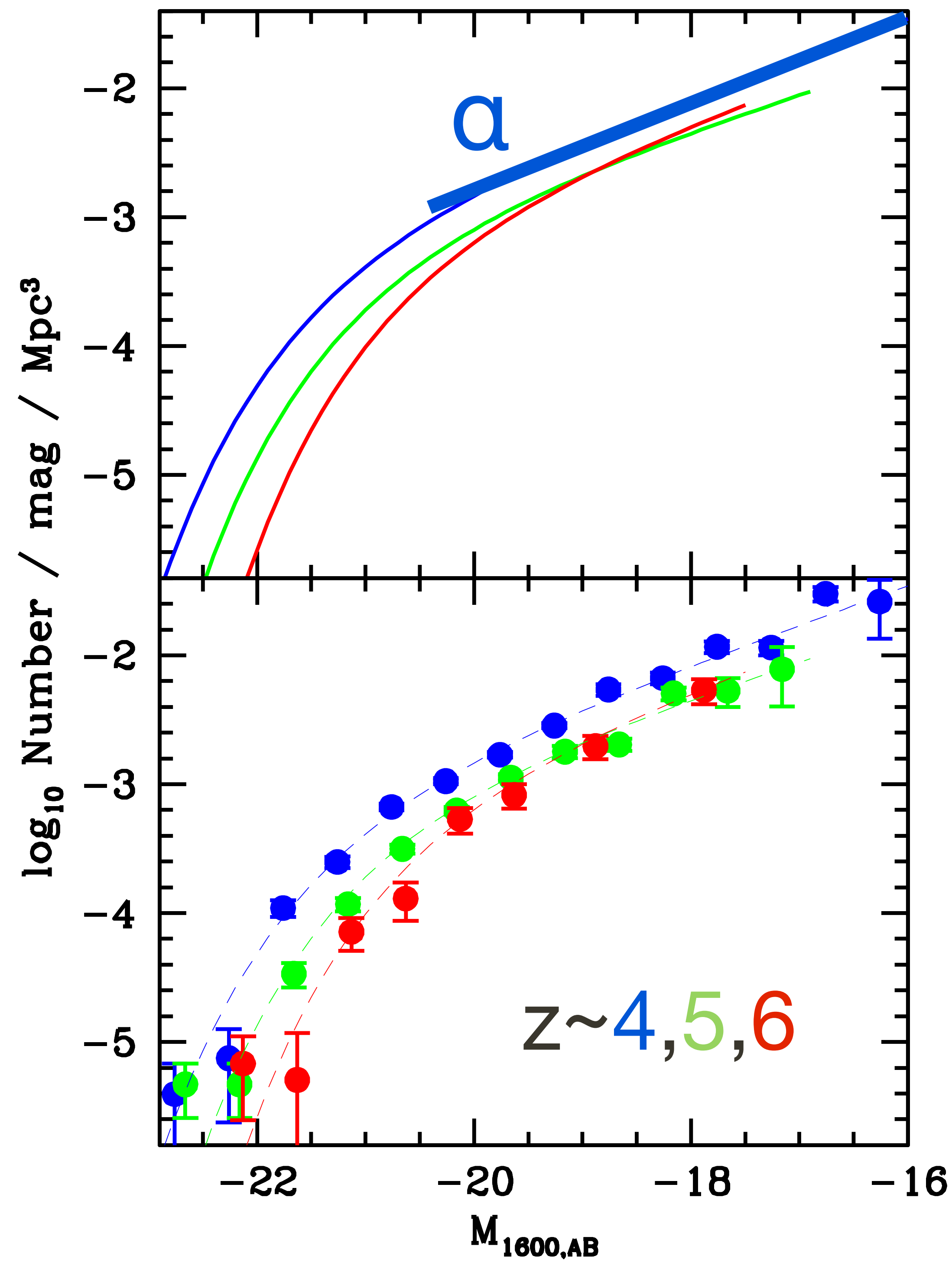
- Shape and evolution of the bright end of the UV LF: implications for (AGN) feedback
- Accelerated evolution at $z>8$: implications for the emergence of the very first galaxies
- Slope and turnover of the faint end of the UV LF: implications for cosmic Reionisation

Parametrisation of the UV LF

- Schechter function breaks evolution of galaxy populations down to 3 parameters: M_{UV}^*, ϕ^* and α

$$\frac{\mathrm{d}n}{\mathrm{d}L} = \phi(L) = \left(\frac{\phi^\star}{L^\star}\right)\left(\frac{L}{L^\star}\right)^\alpha \exp^{-L/L^\star}$$

$$\phi(M) = \frac{\ln 10}{2.5}\phi^\star(10^{0.4(M^\star-M)})^{(\alpha+1)}\exp[-10^{0.4(M^\star-M)}],$$



Bouwens et al. 2007

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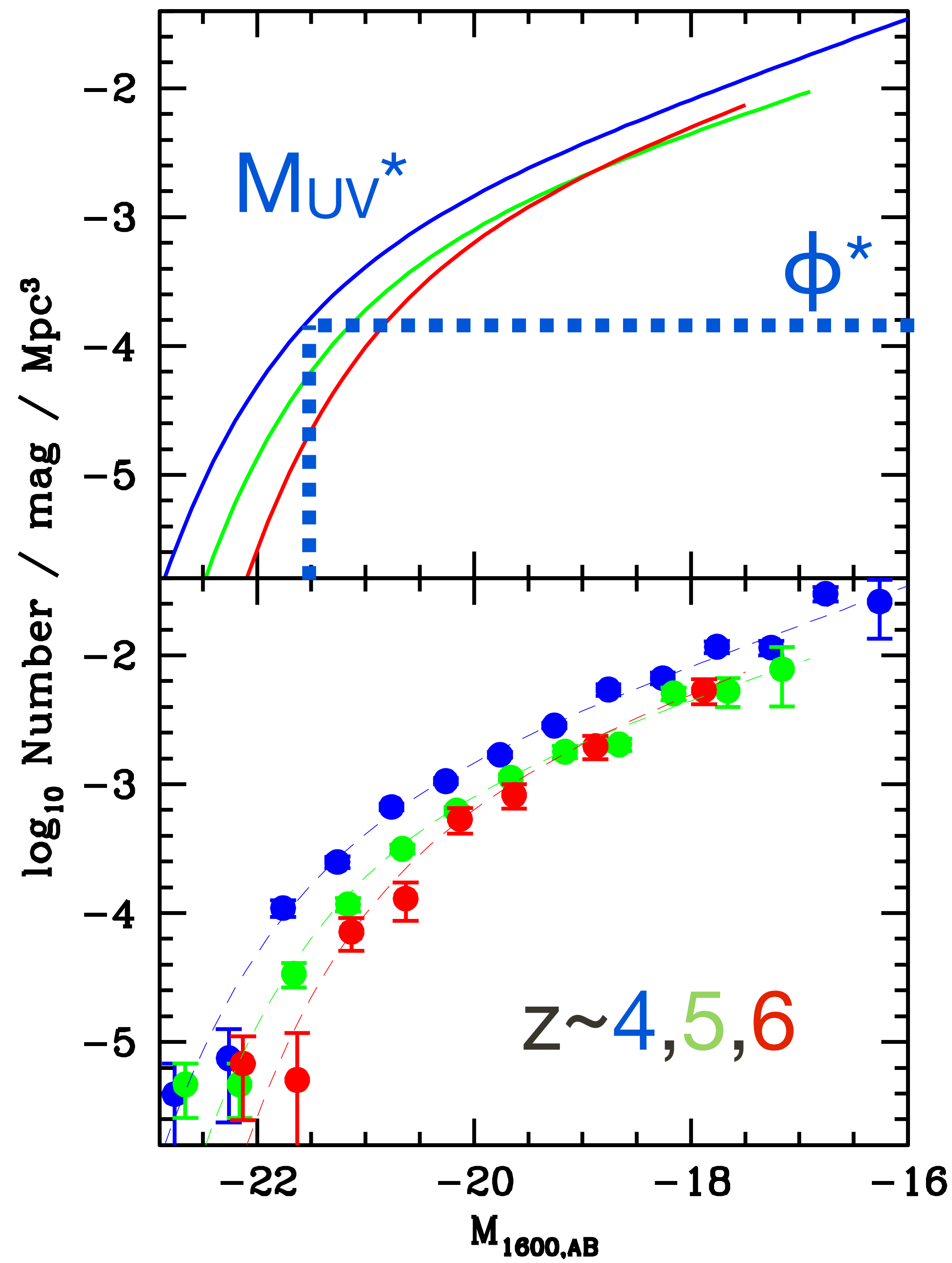
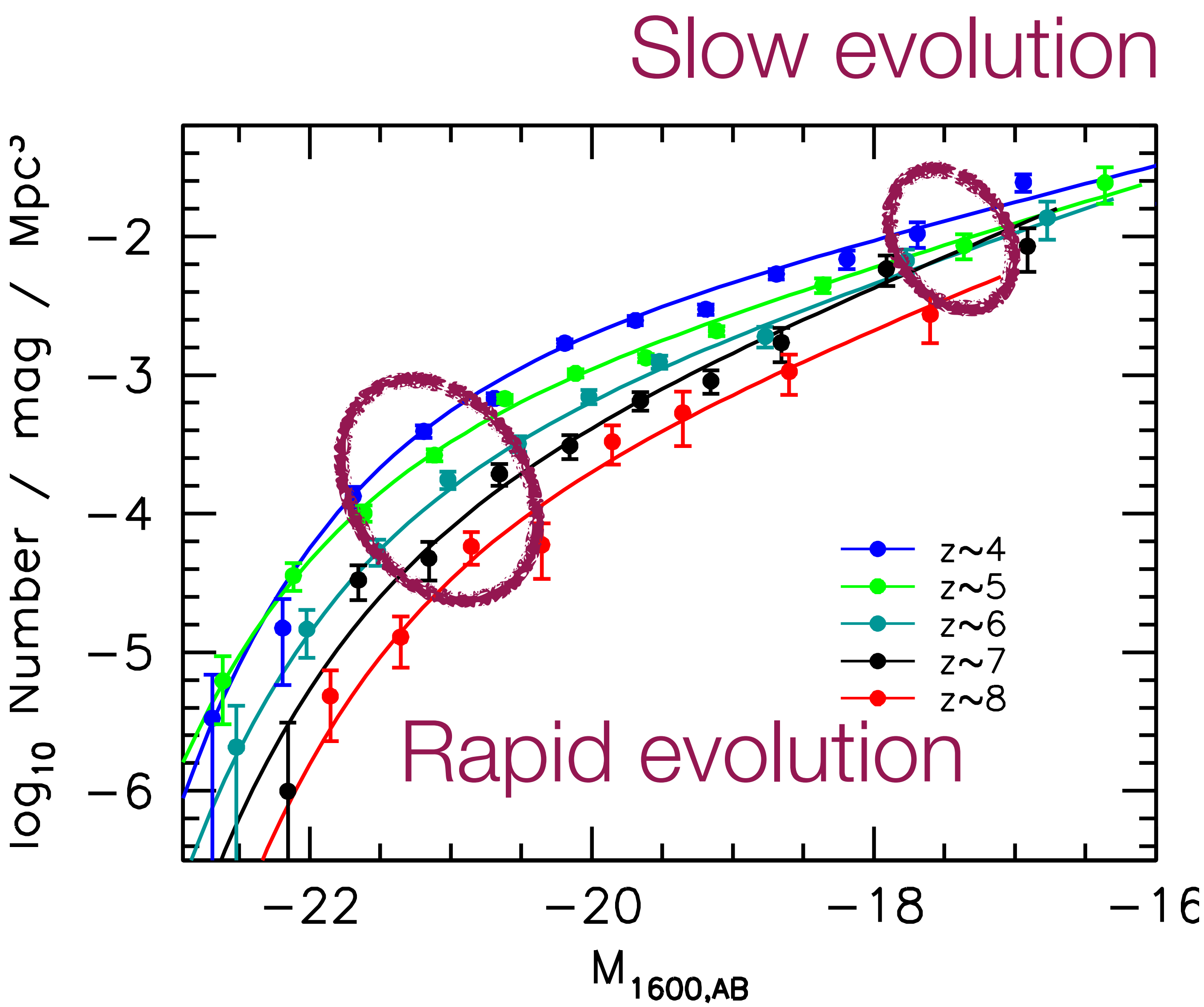
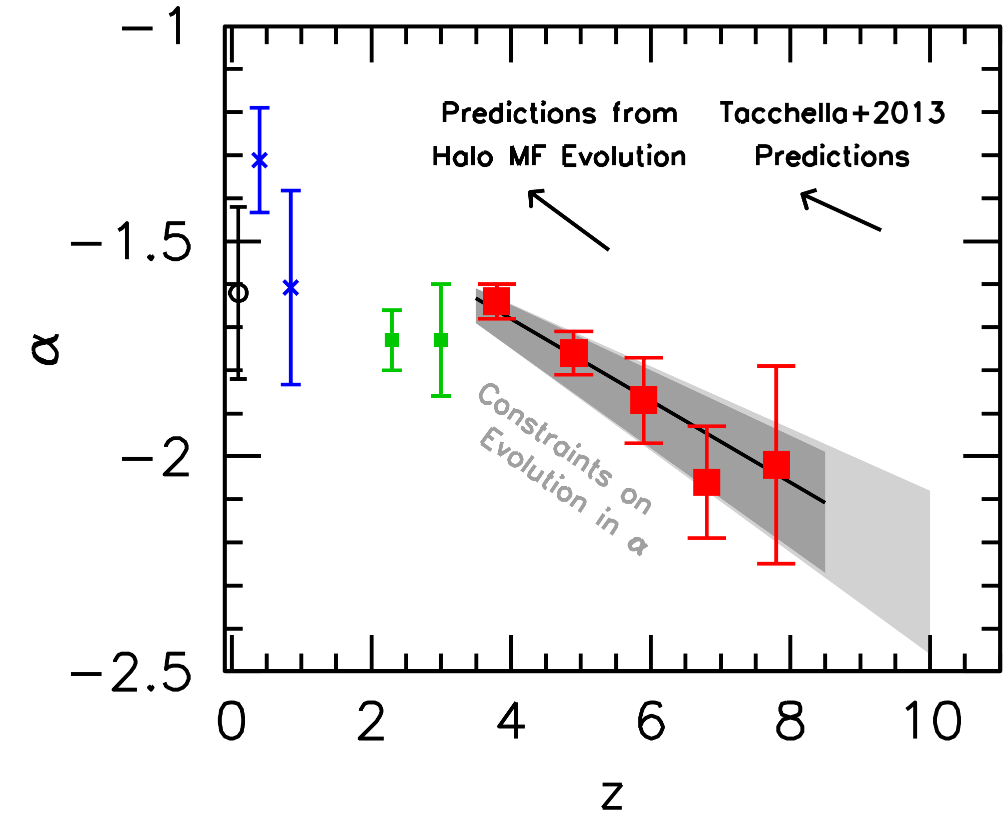
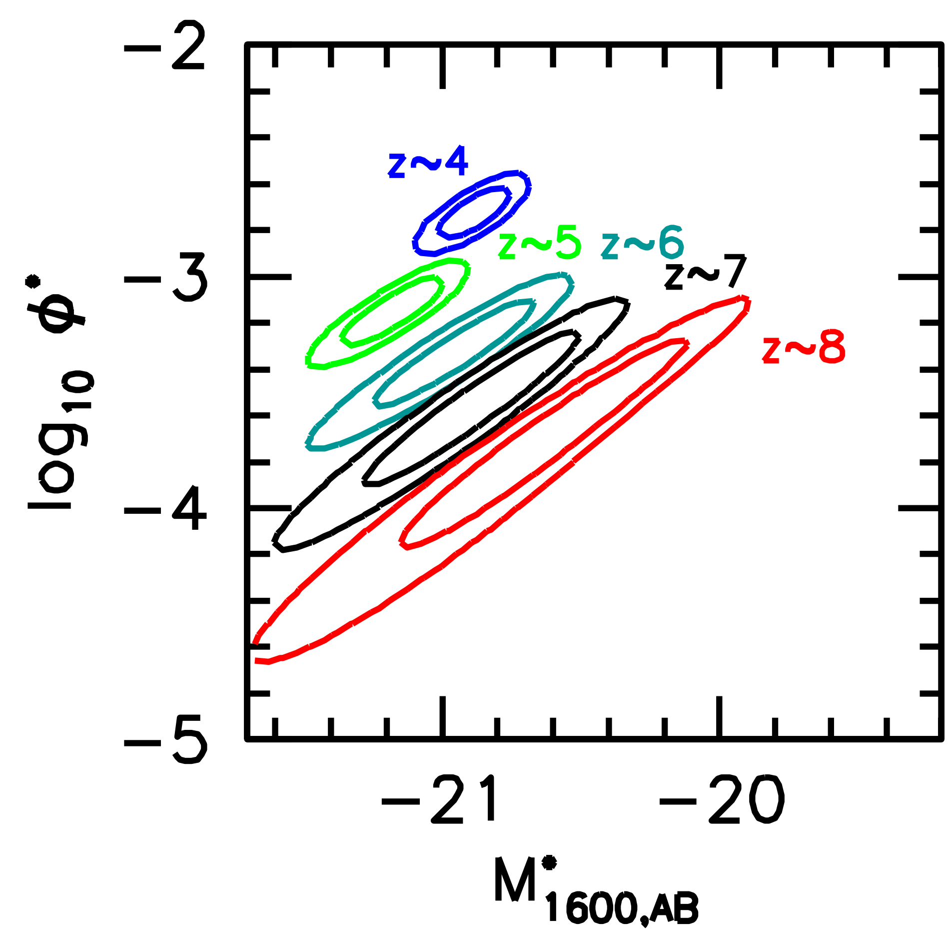


Bouwens et al. 2007

Parametrisation of the UV LF

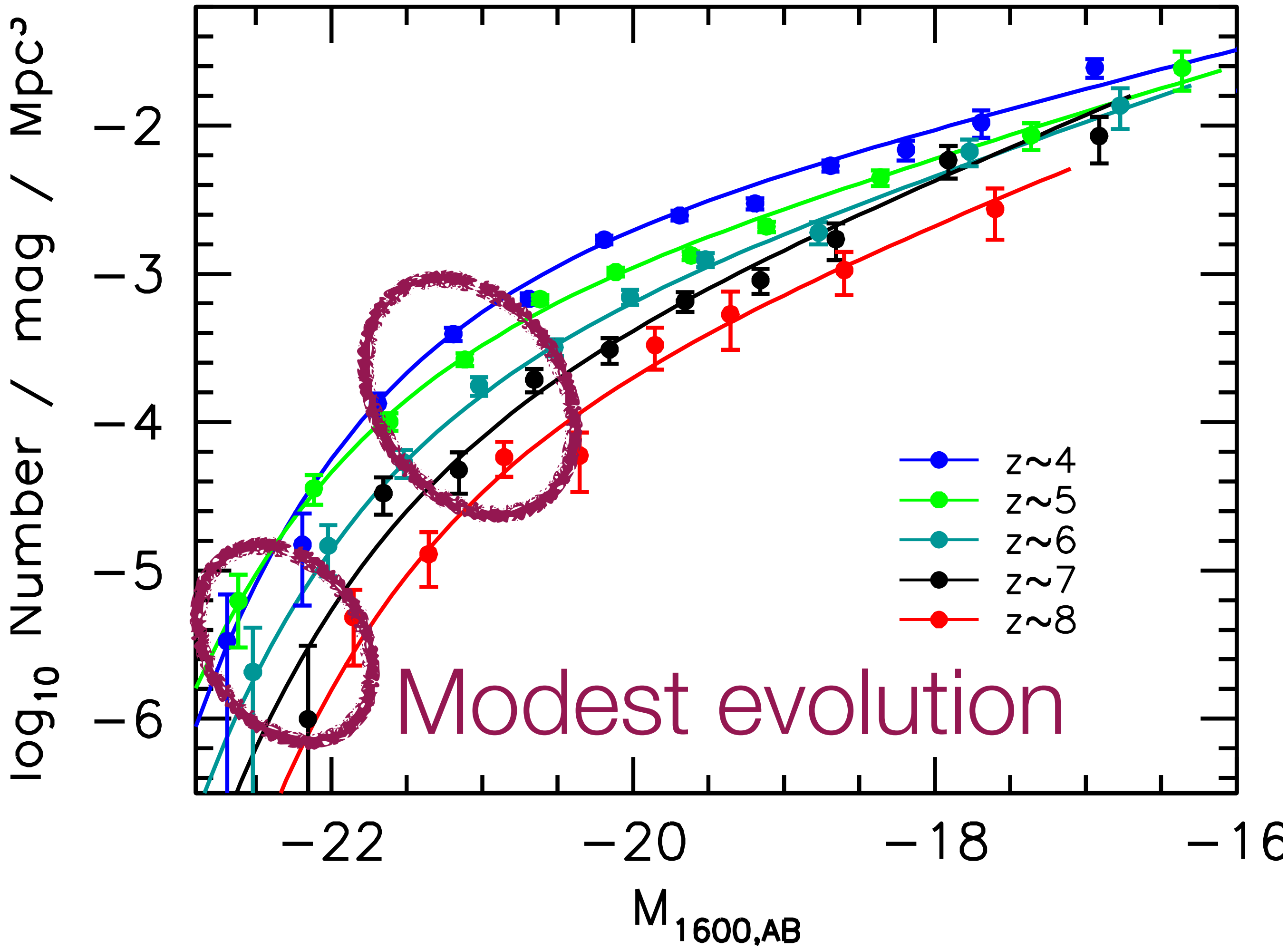


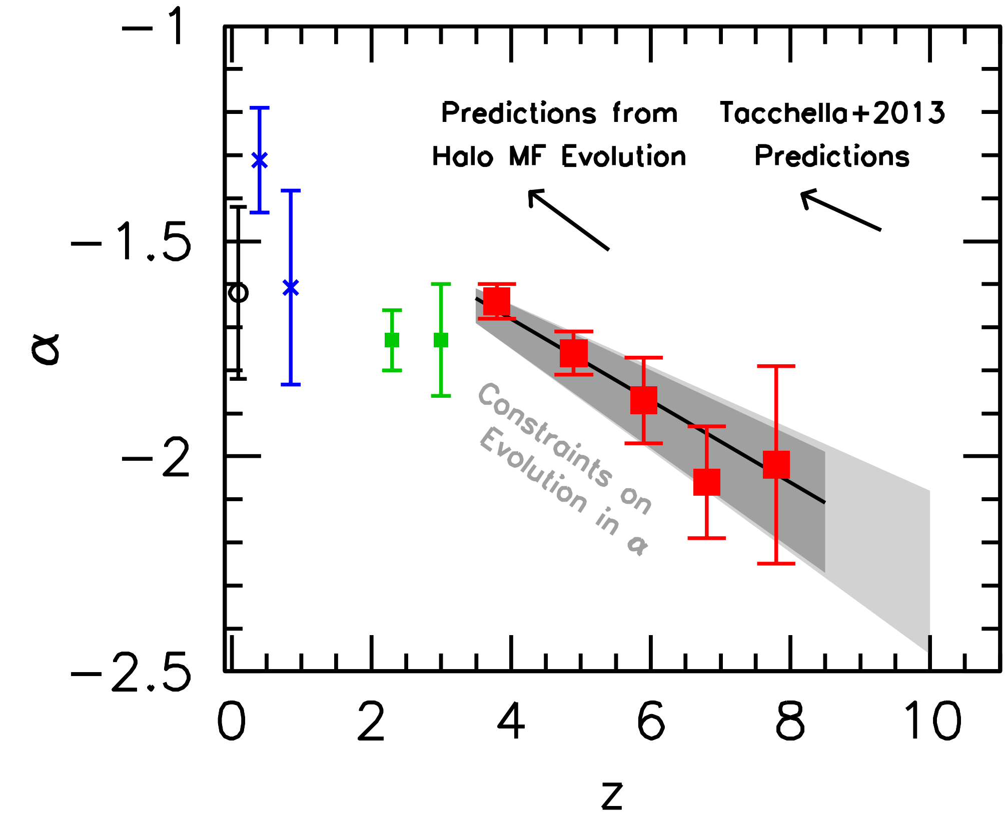




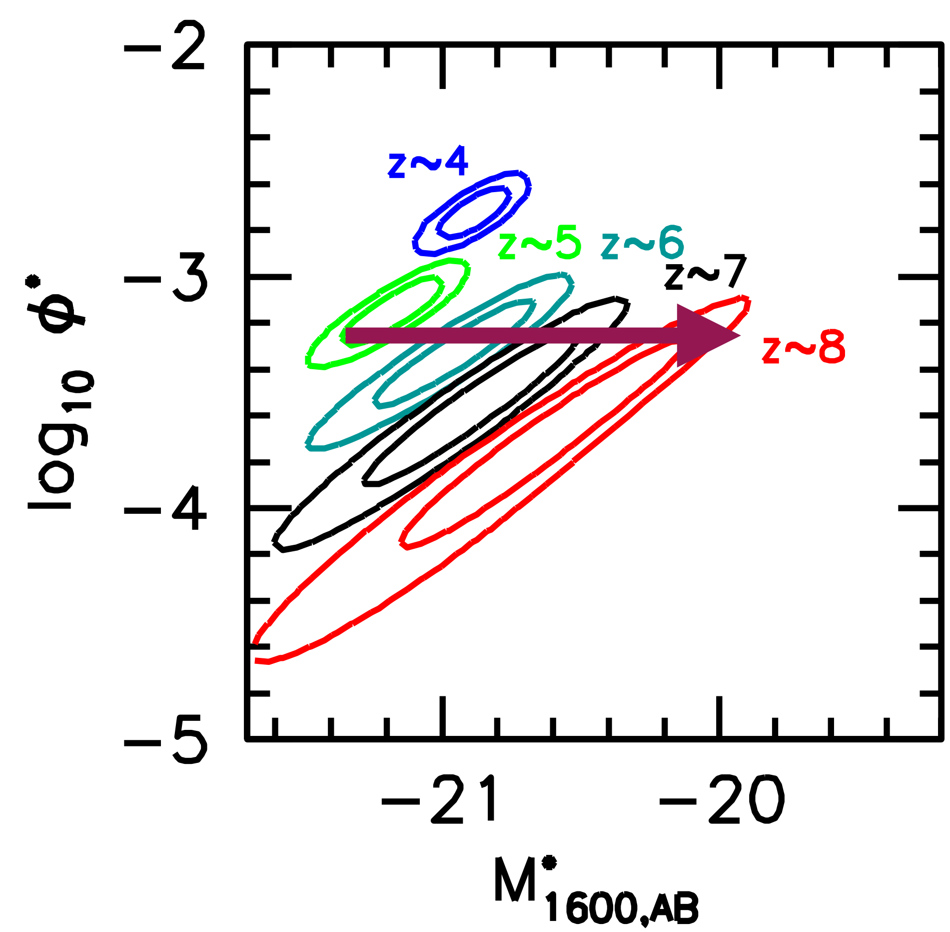
Bouwens et al. 2015

Parametrisation of the UV LF



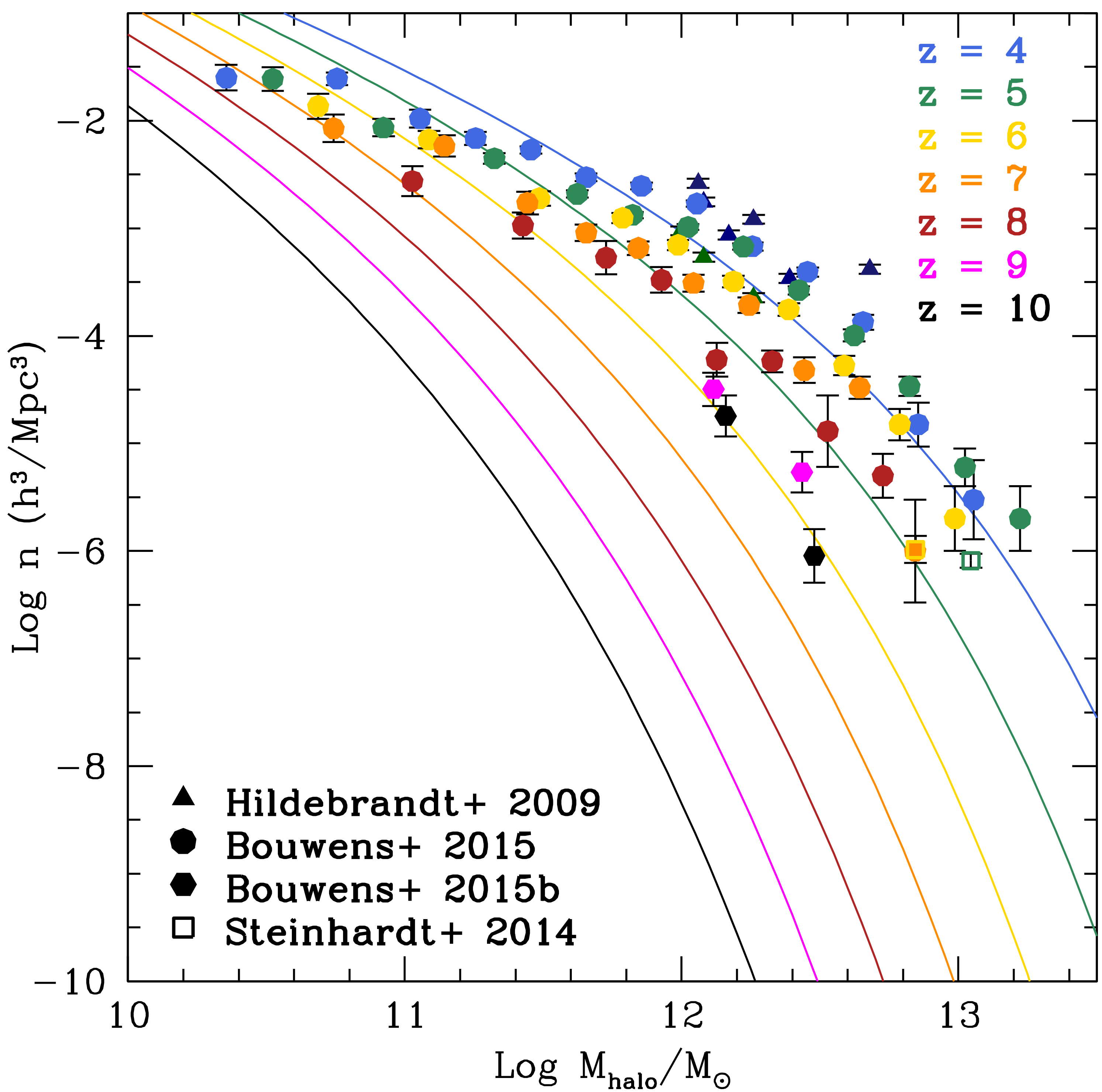


Evolution halo mass



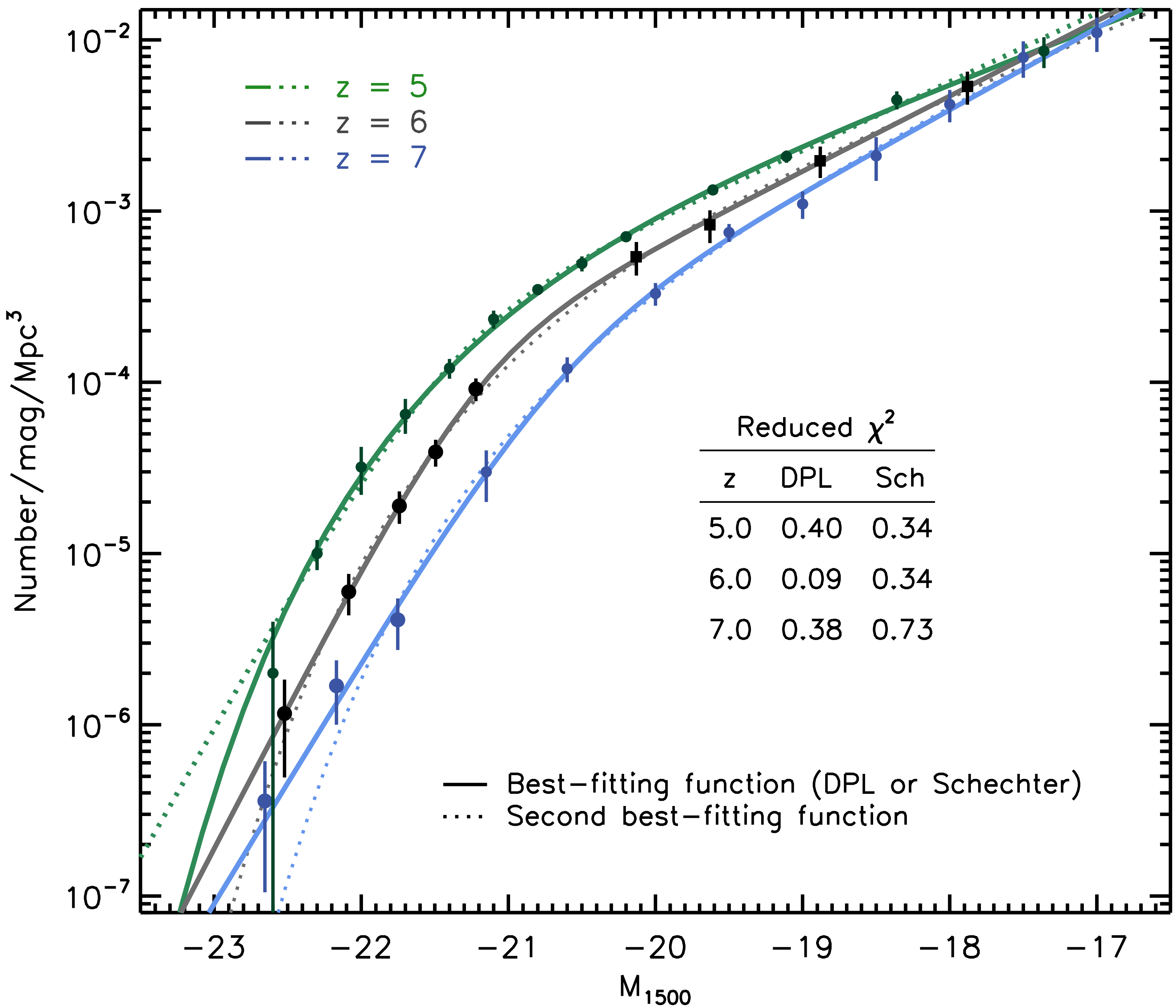
Bouwens et al. 2015

Halo mass evolution



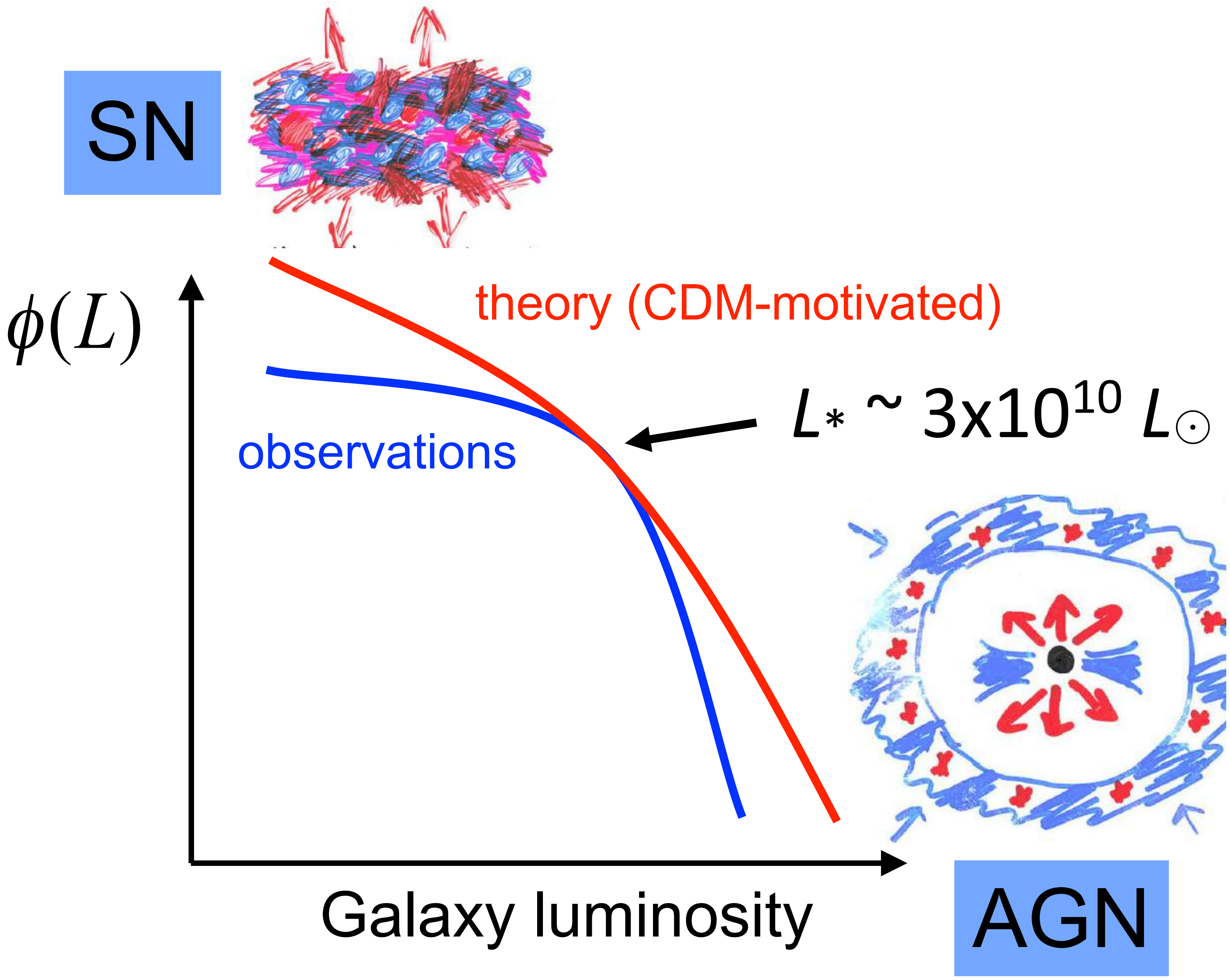
Steinhardt et al. 2016

Shape and parametrisation of the UV LF

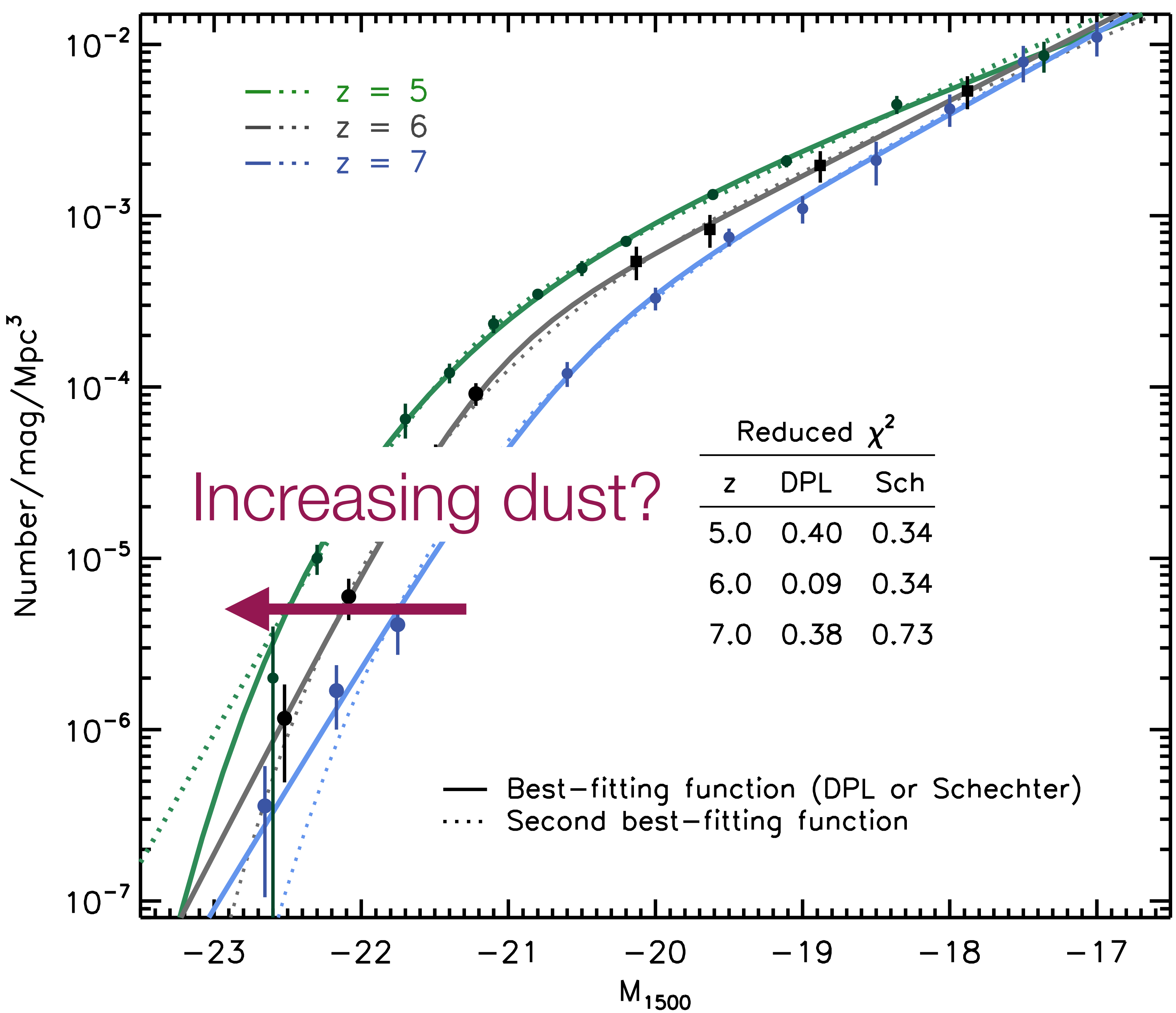


Bowler et al. 2014; 2015

Shape and parametrisation of the UV LF

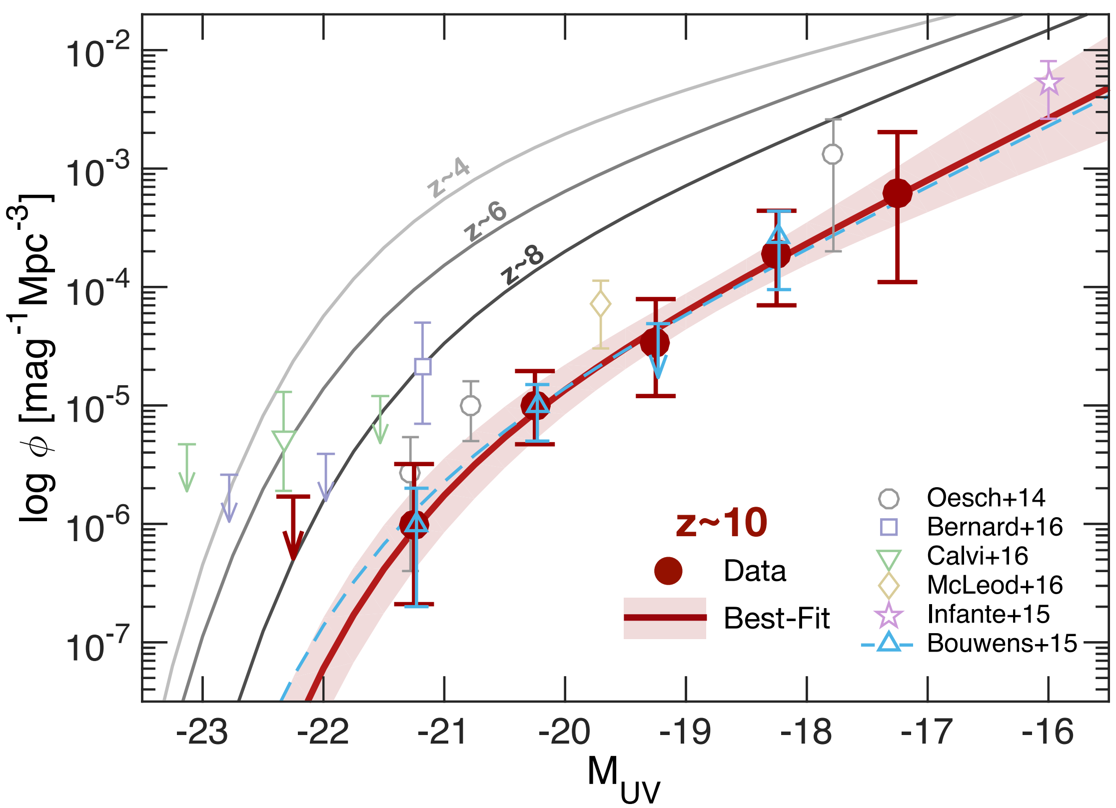


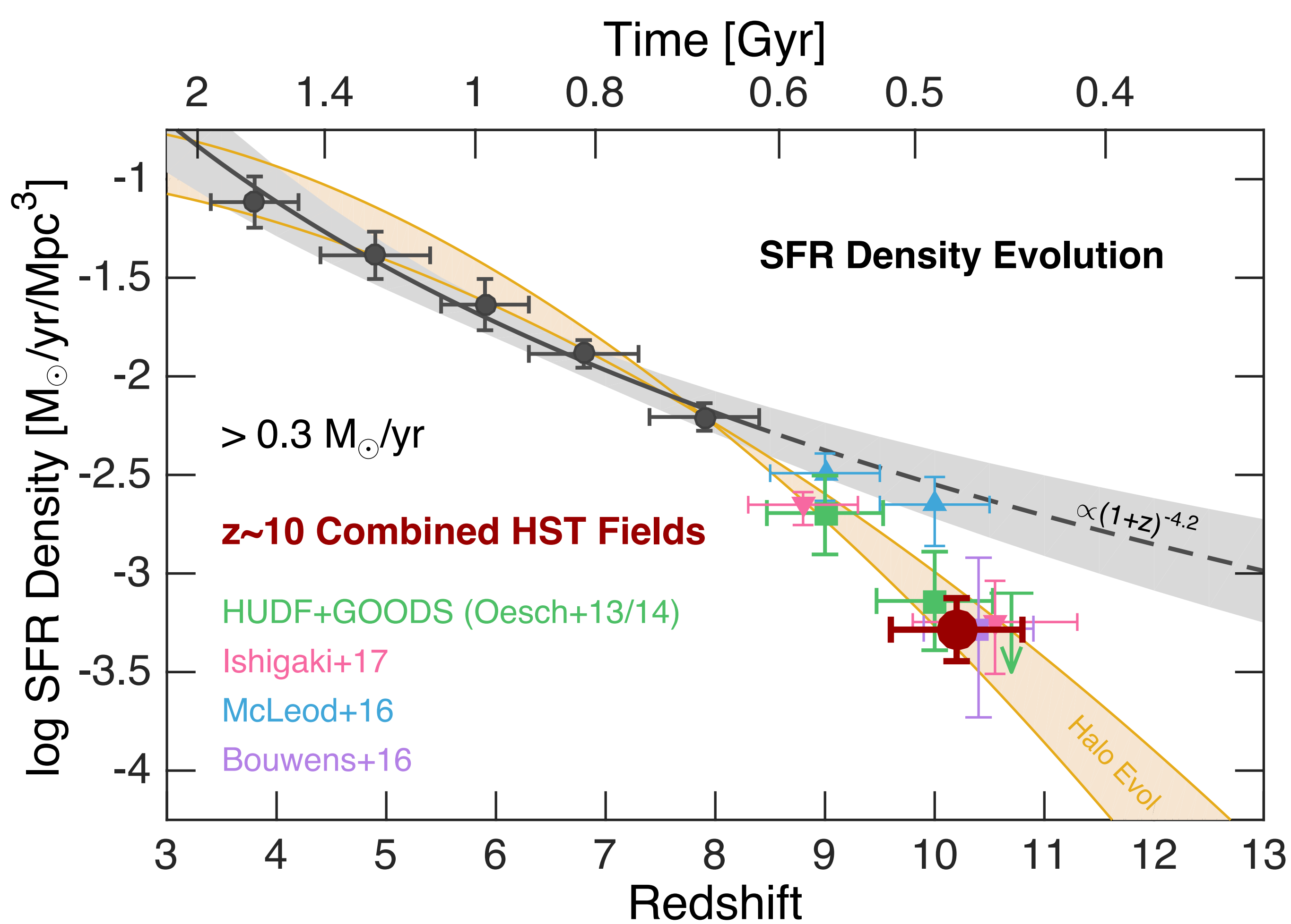
Shape and parametrisation of the UV LF



Bowler et al. 2014; 2015

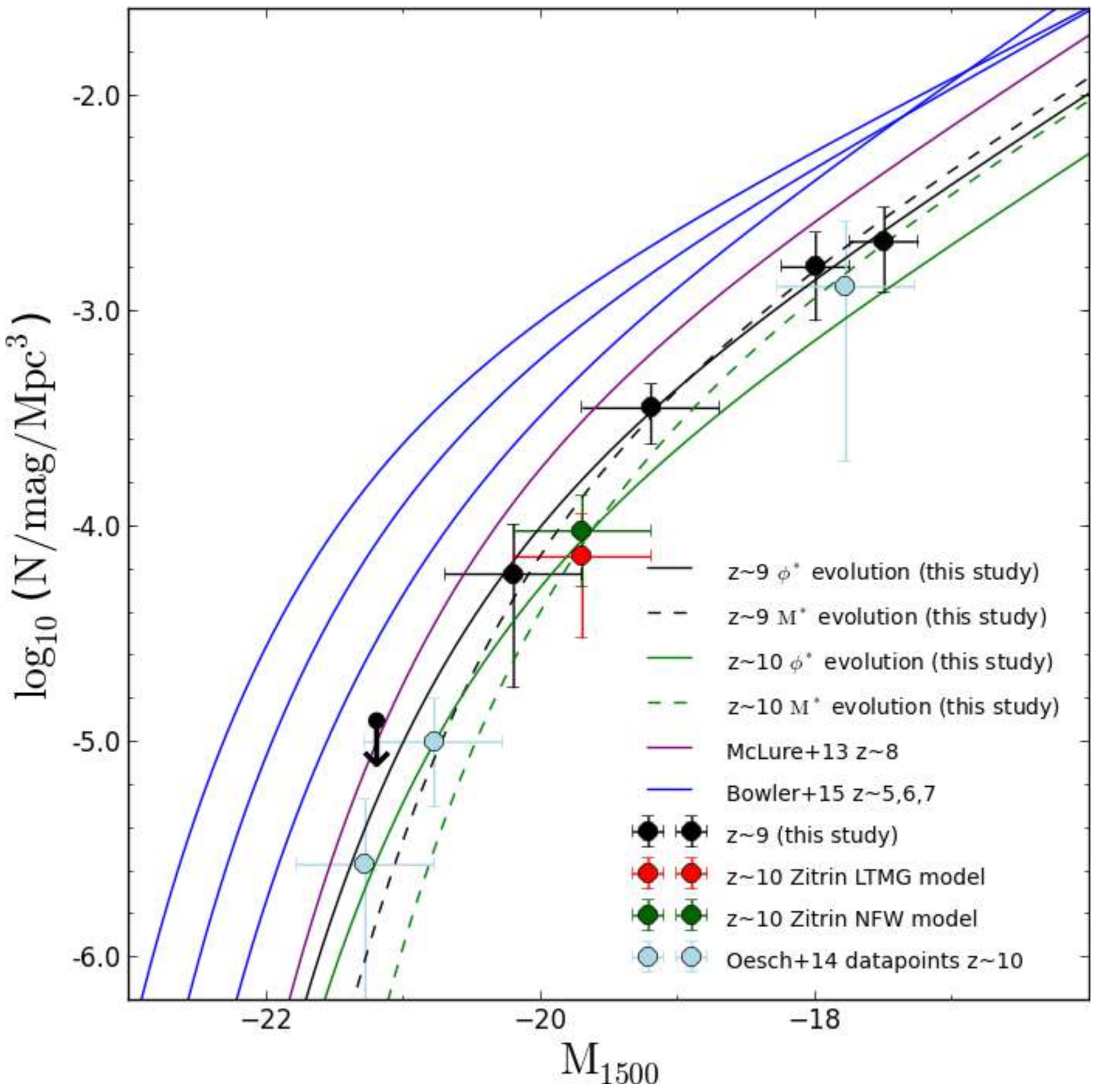
Accelerated evolution z>8?

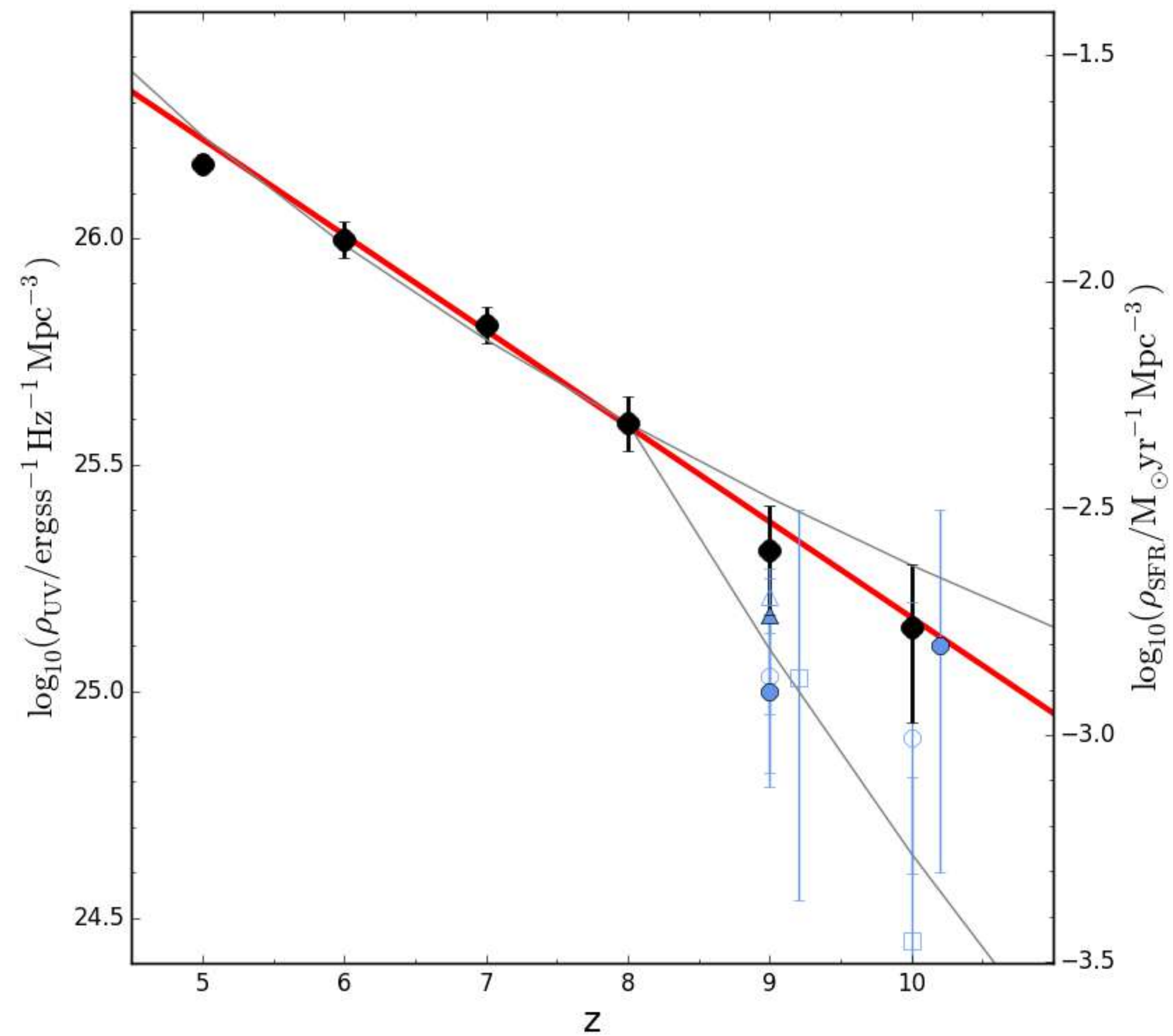




Oesch et al. 2018

Accelerated evolution z>8?

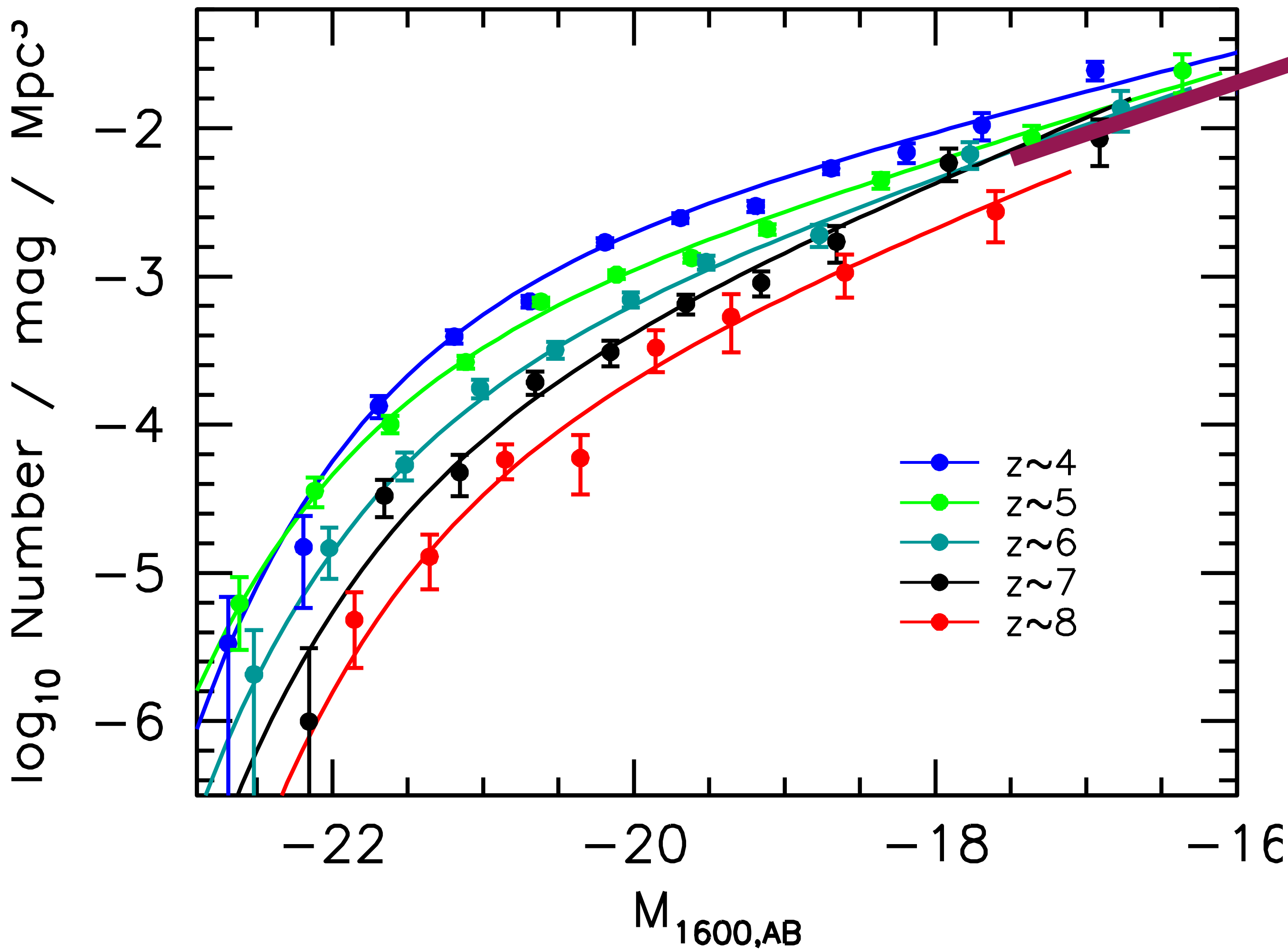


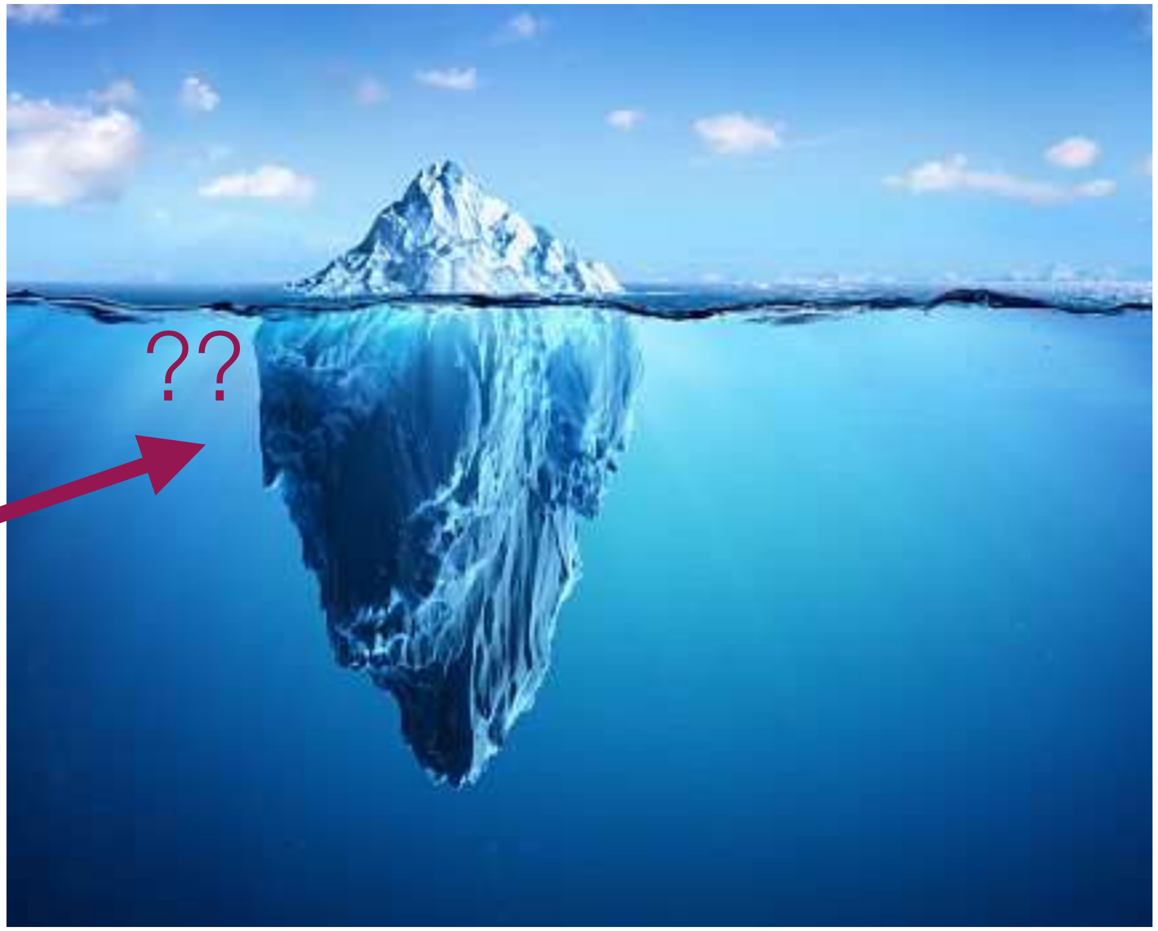


Mcleod et al. 2016

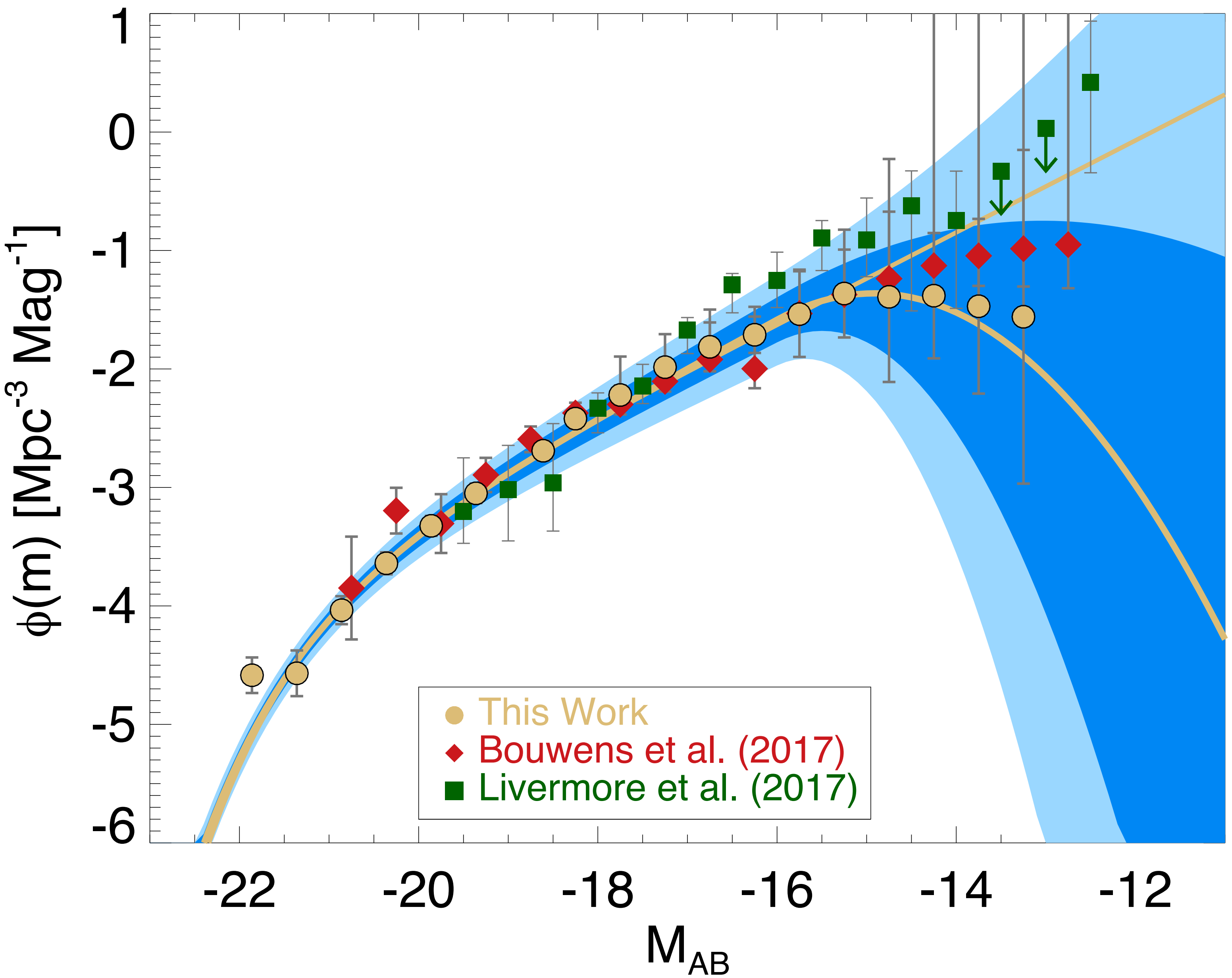
Faint end: below the tip of the iceberg

The galaxies that dominate the UV output are not observed in the HUDF

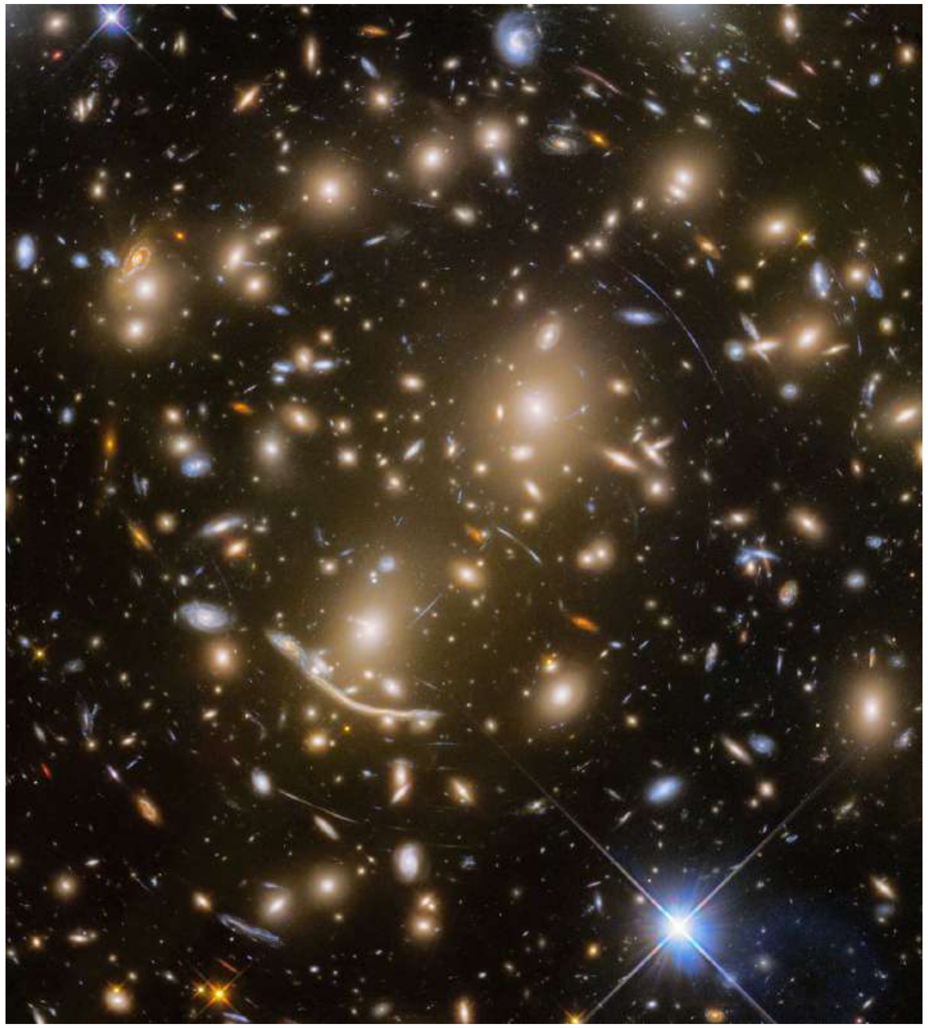




Faint end: below the tip of the iceberg

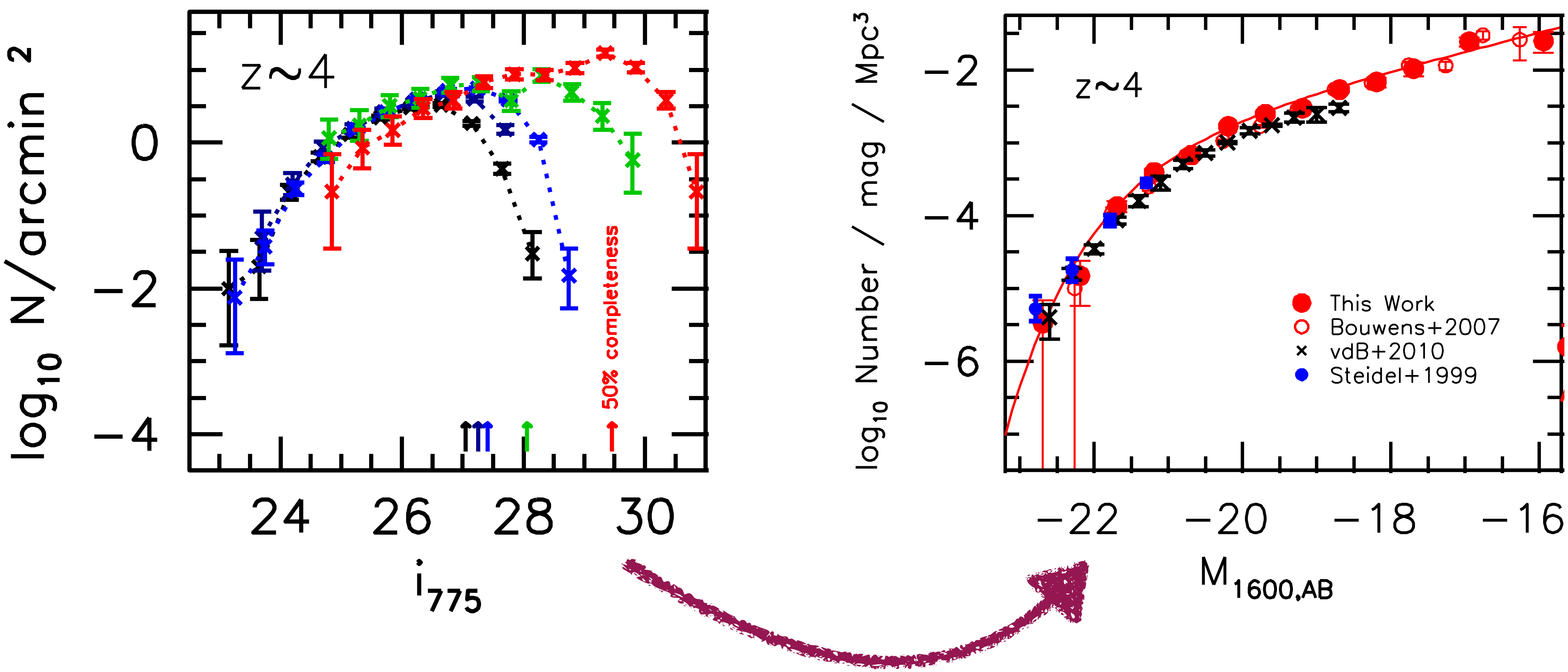


Frontier Fields



Atek et al. 2018

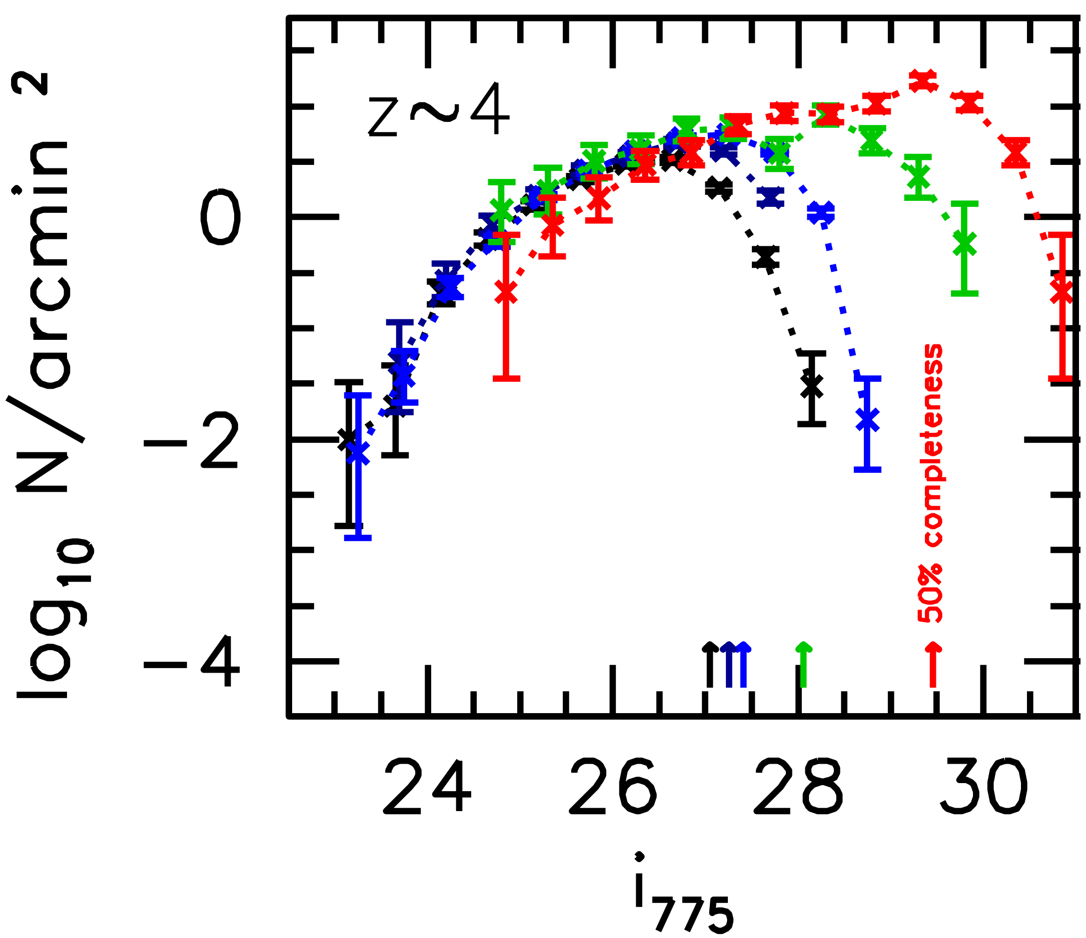
Faint end of the UV LF

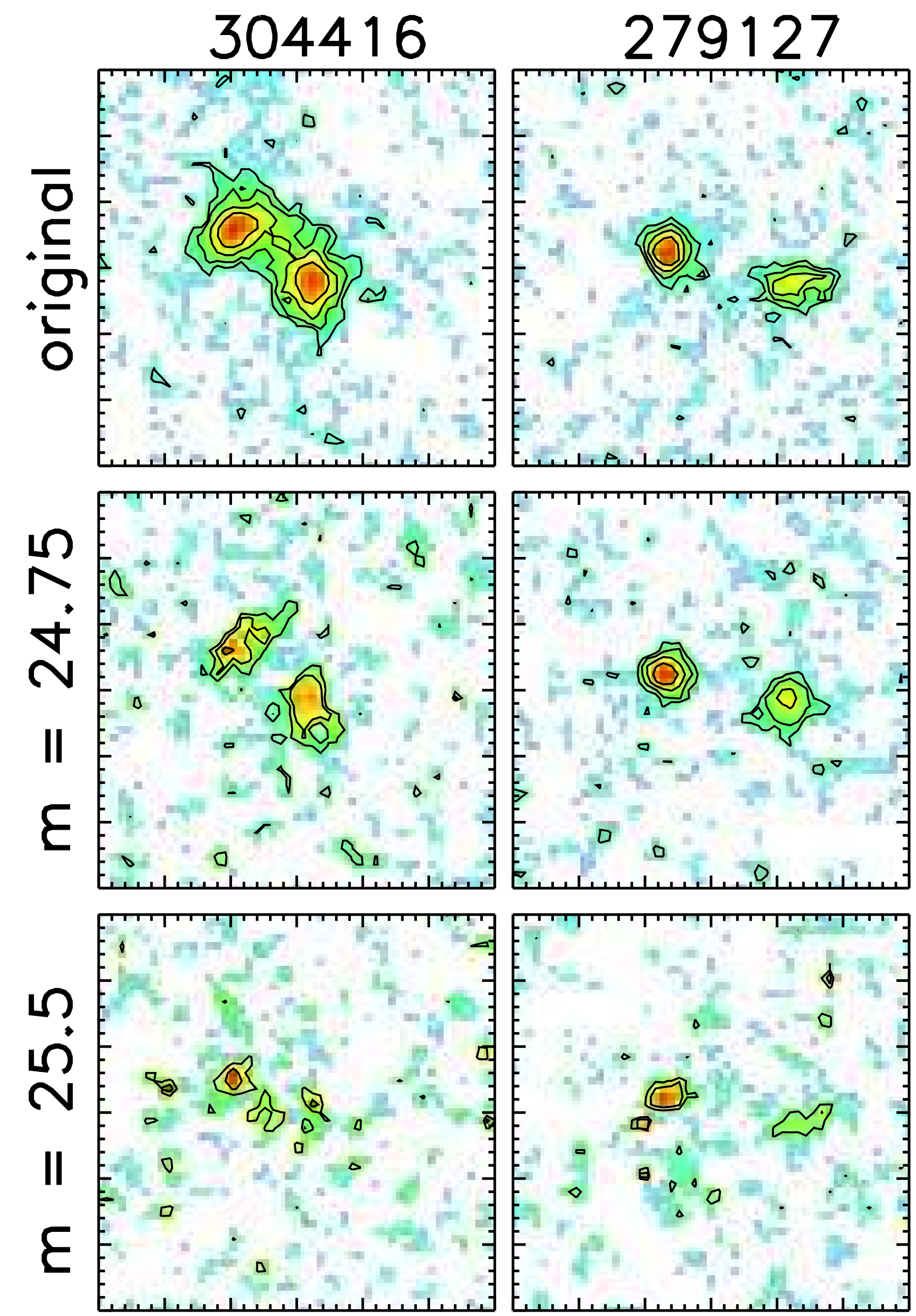


Incompleteness corrections!

Bouwens et al. 2015

Faint end of the UV LF

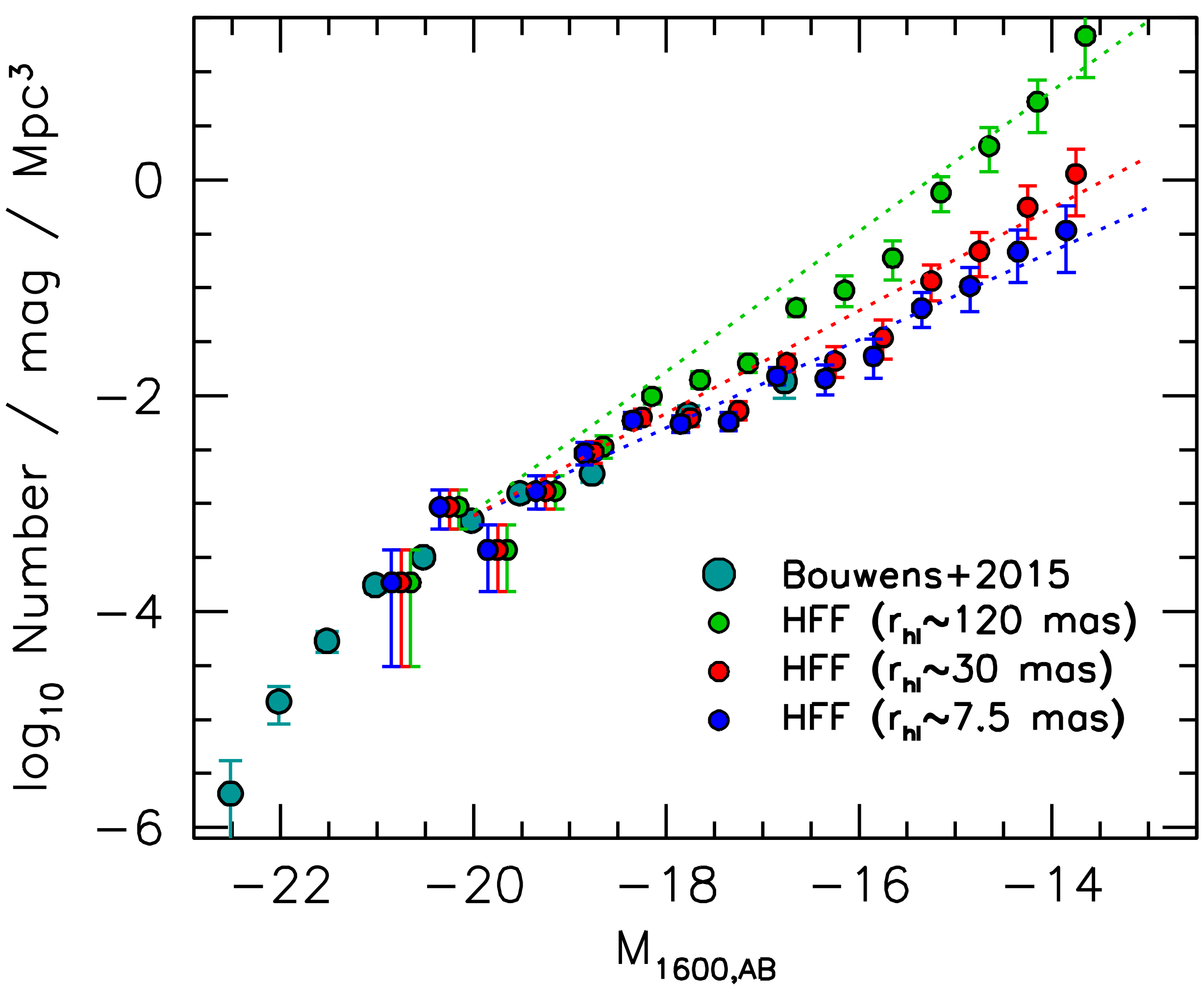


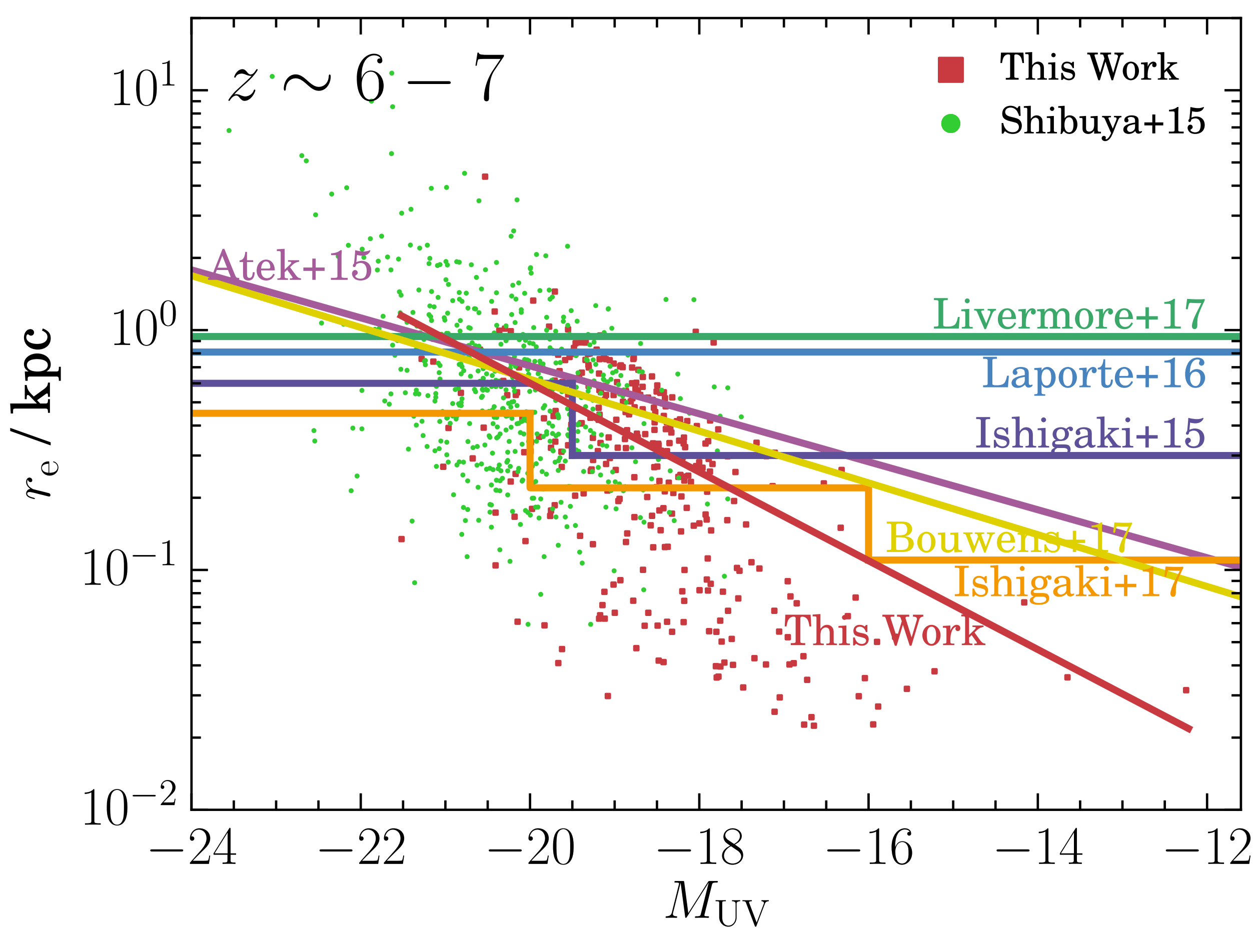


Bouwens et al. 2015

Bowler et al. 2017

Faint end of the UV LF: impact of size distribution

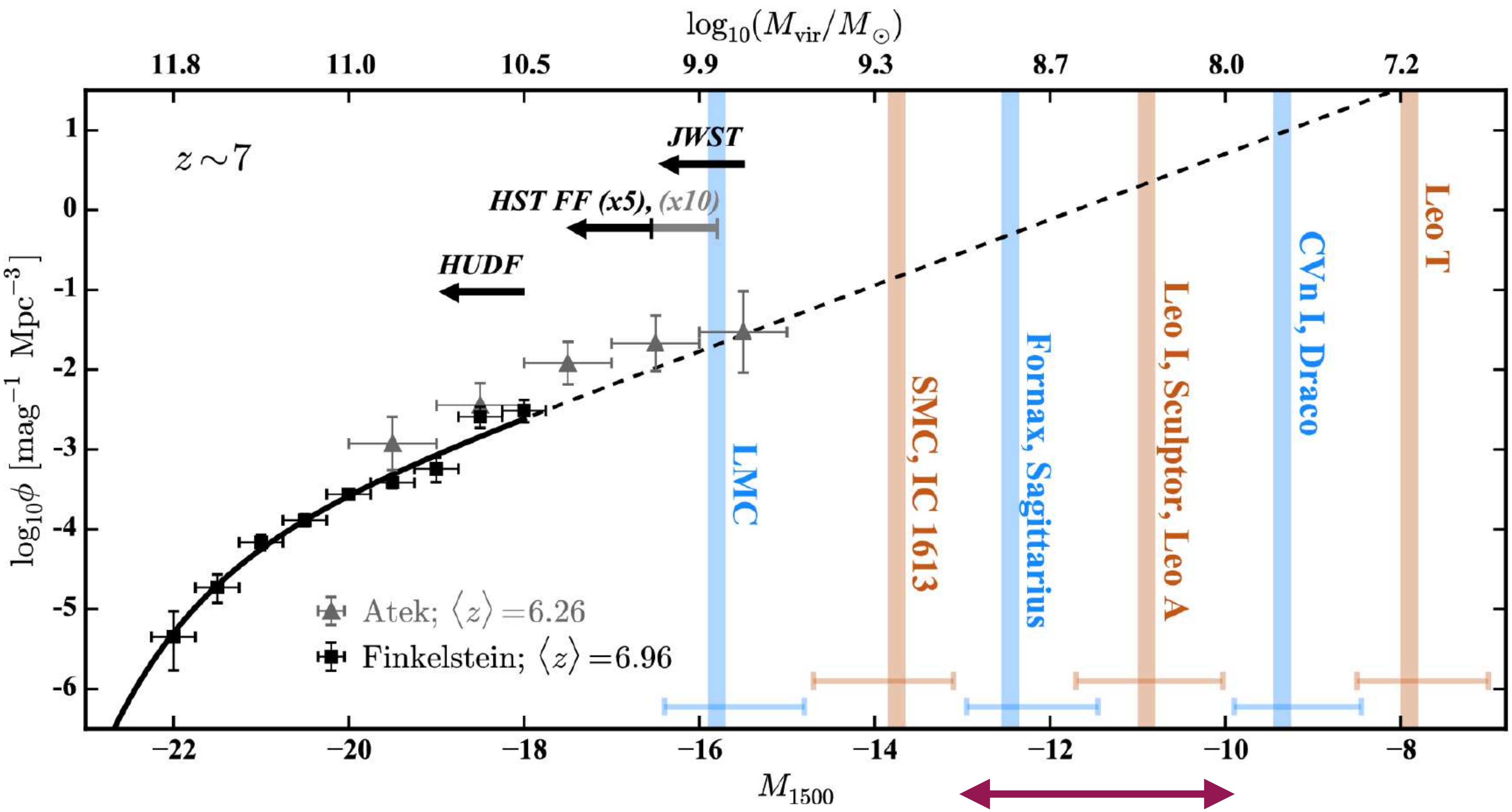




Bouwens et al. 2017

Kawamata et al. 2018

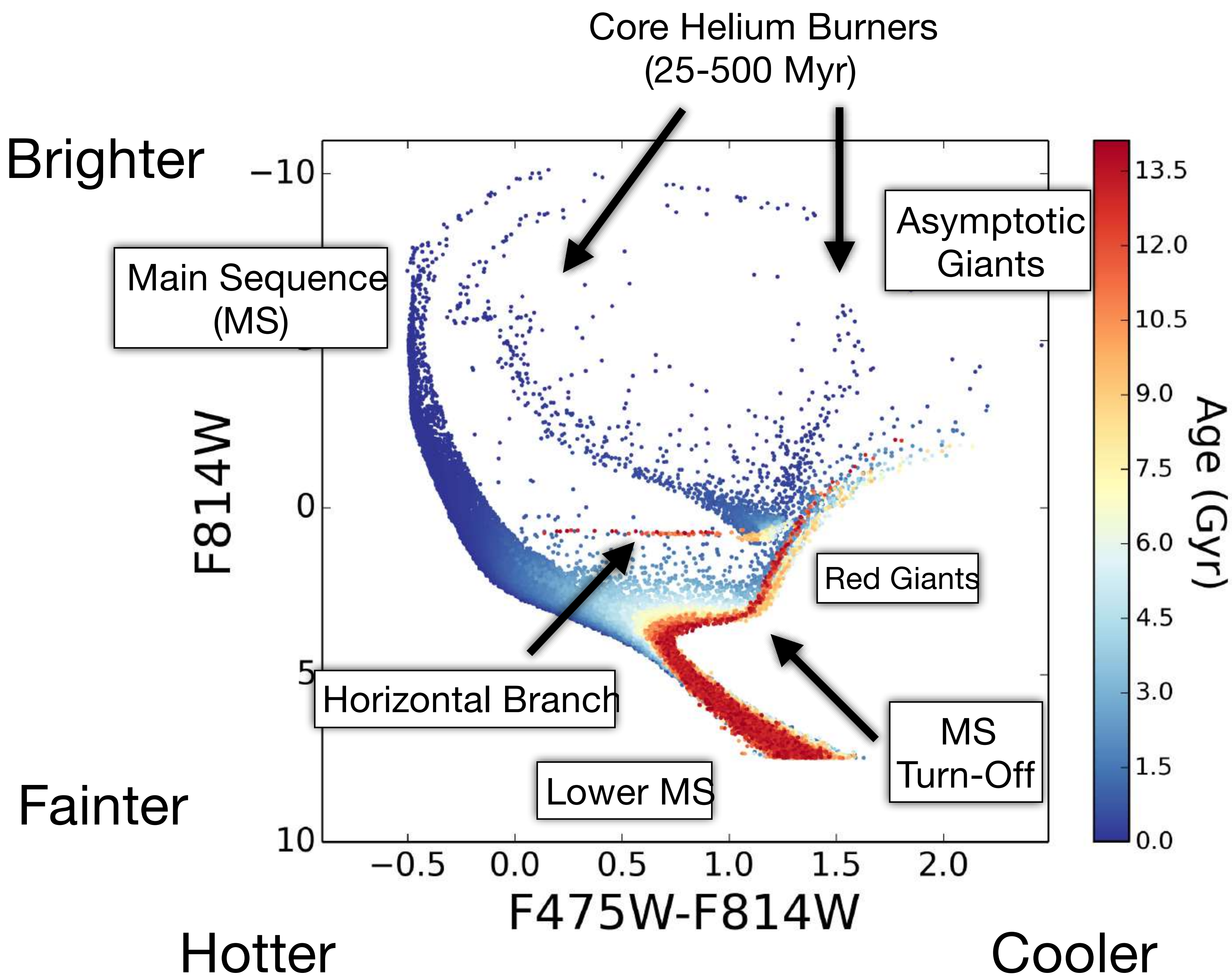
Faint end of the UV LF: local dwarfs



Needed for cosmic Reionisation

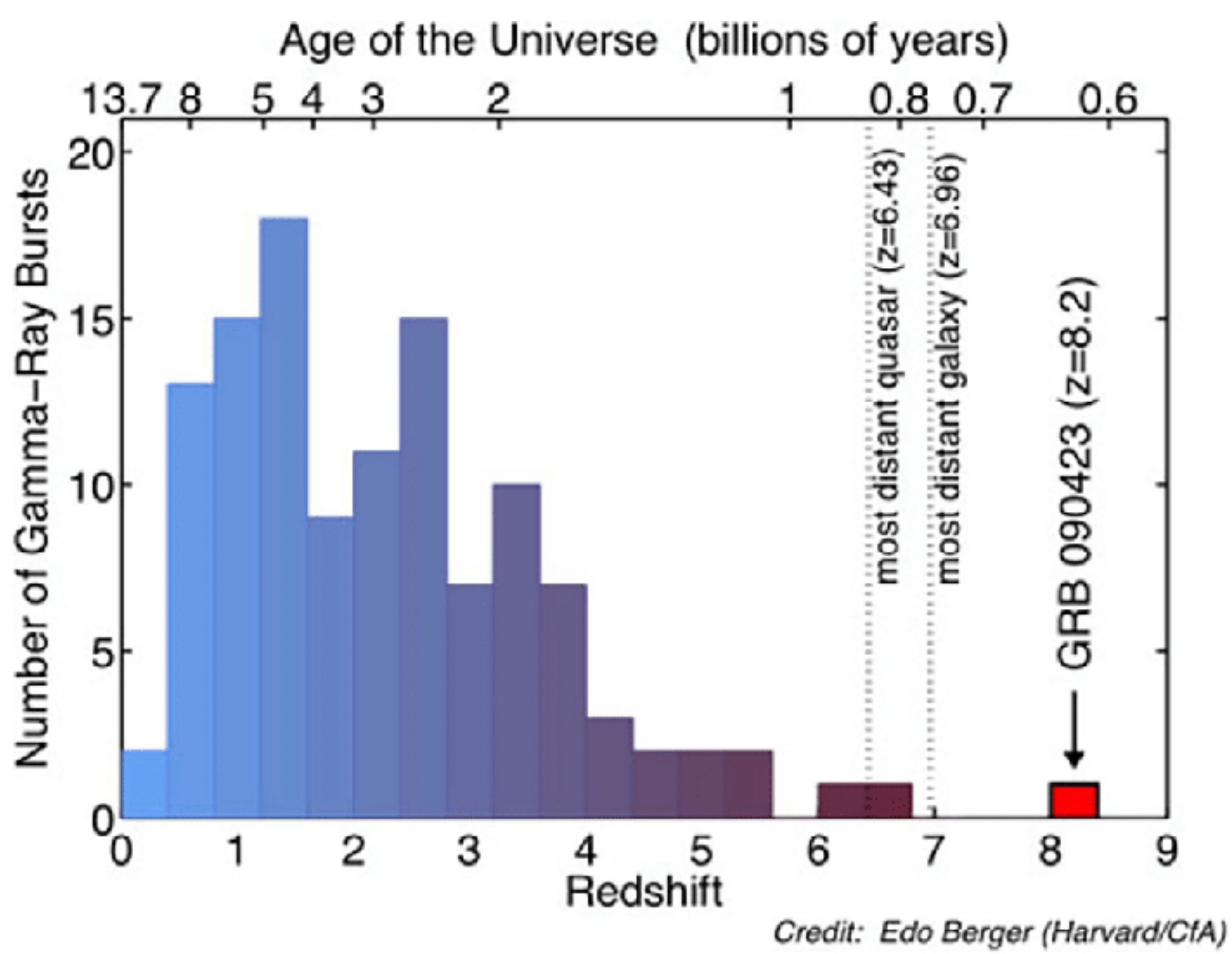
Boylan-Kolchin et al. 2015

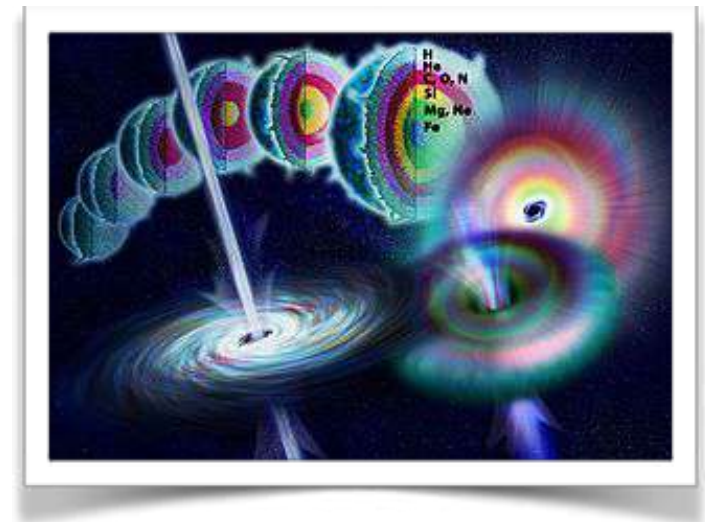
Faint end of the UV LF: local dwarfs

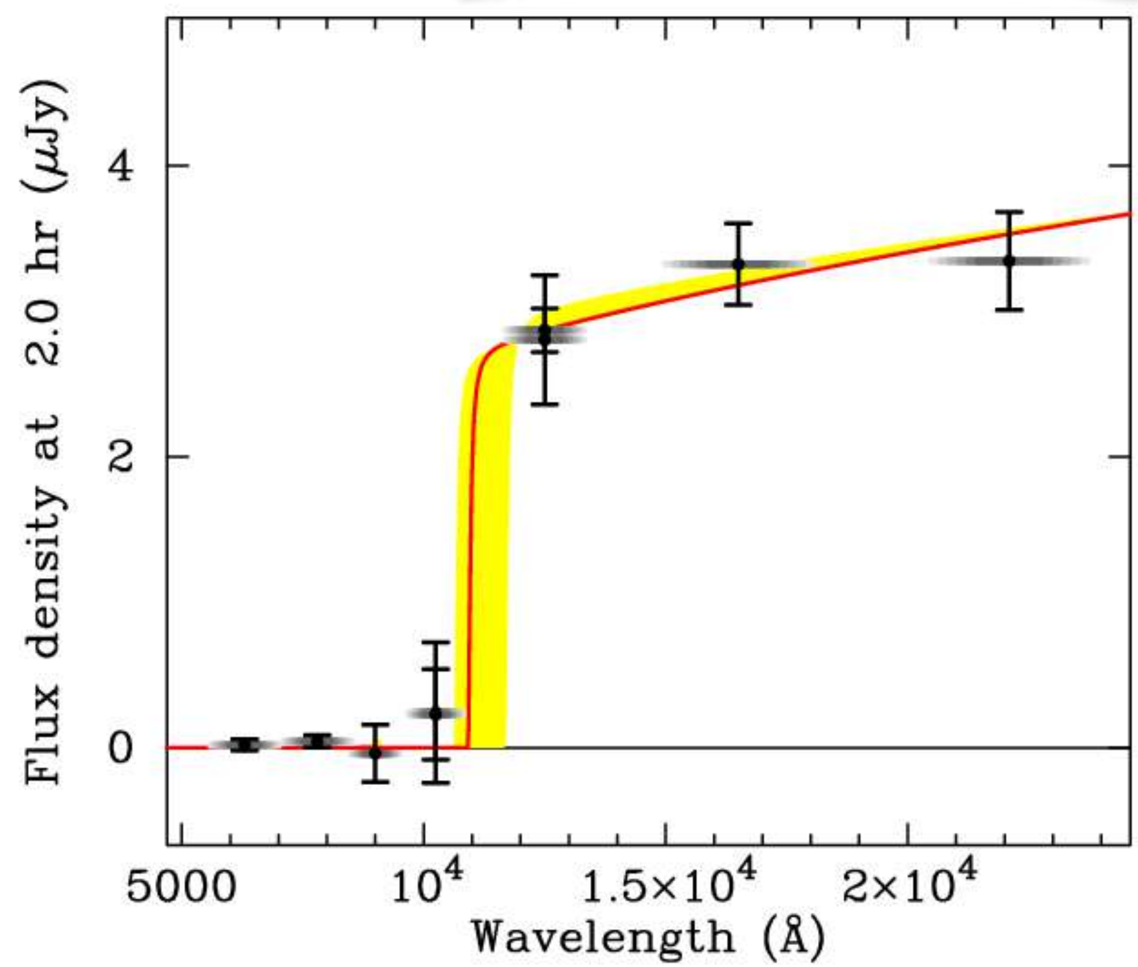


Credit: Dan Weisz

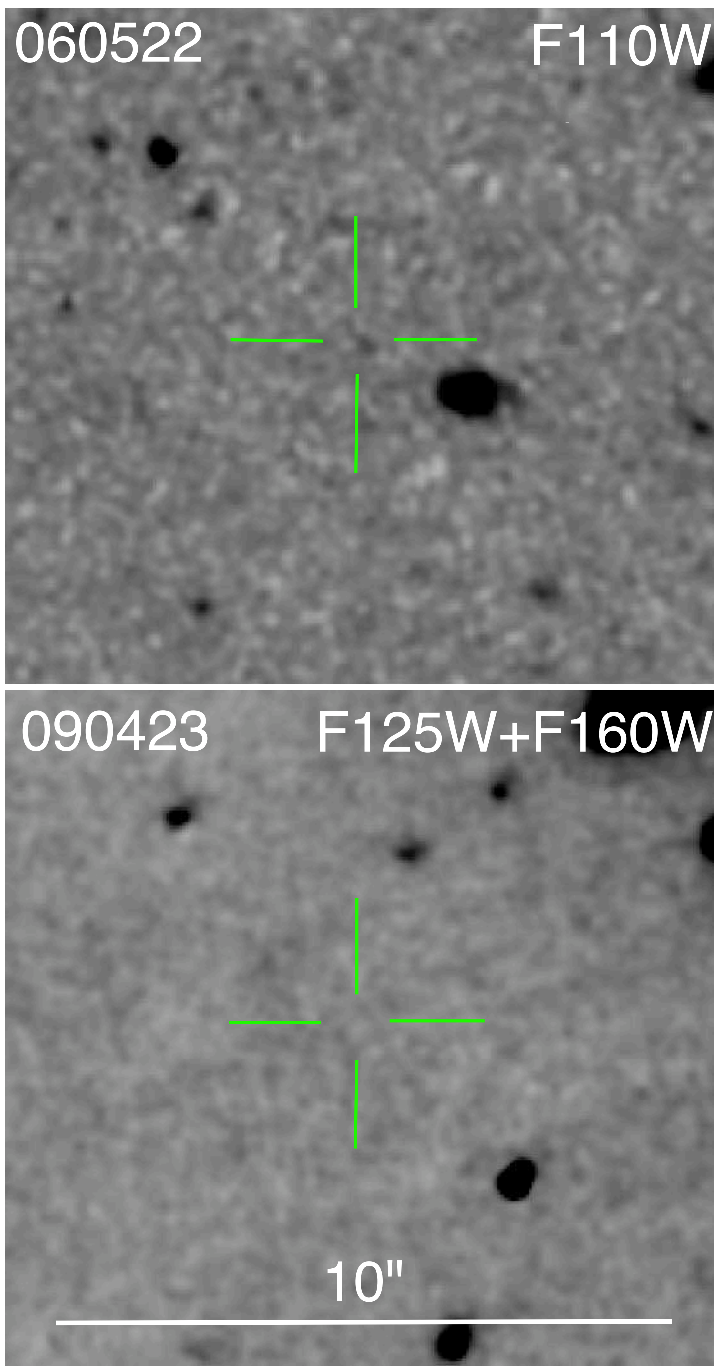
Faint end of the UV LF: GRBs

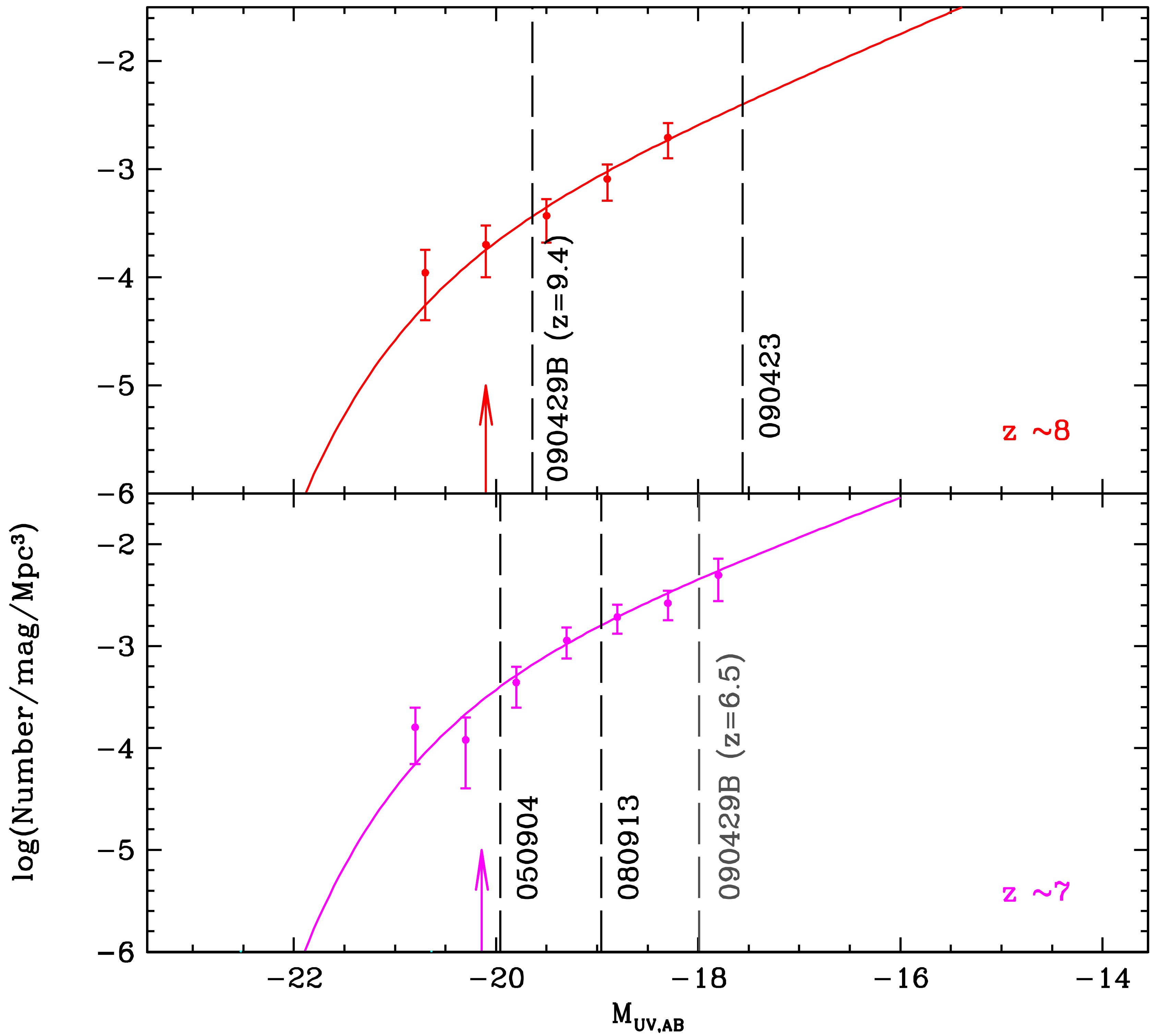






Faint end of the UV LF: GRBs





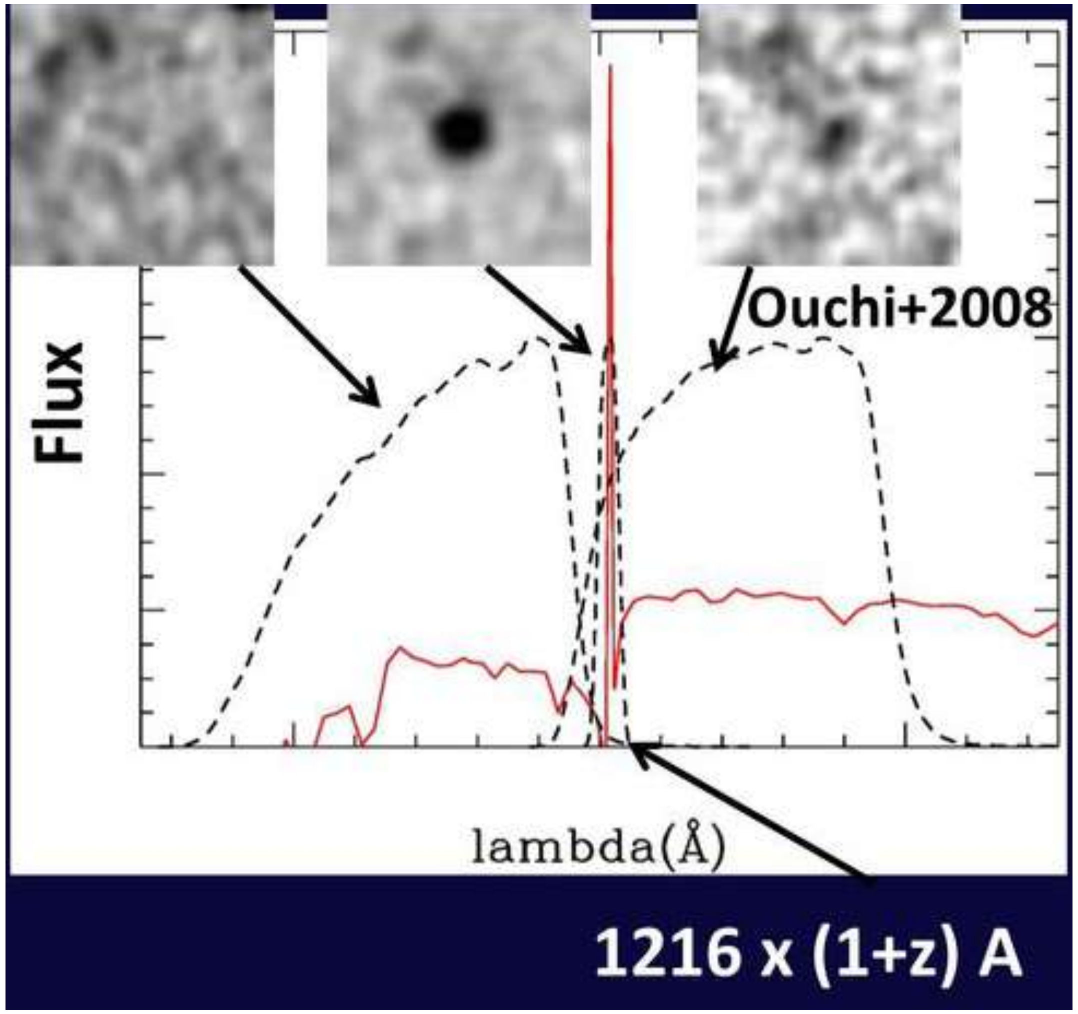
Tanvir et al. 2012

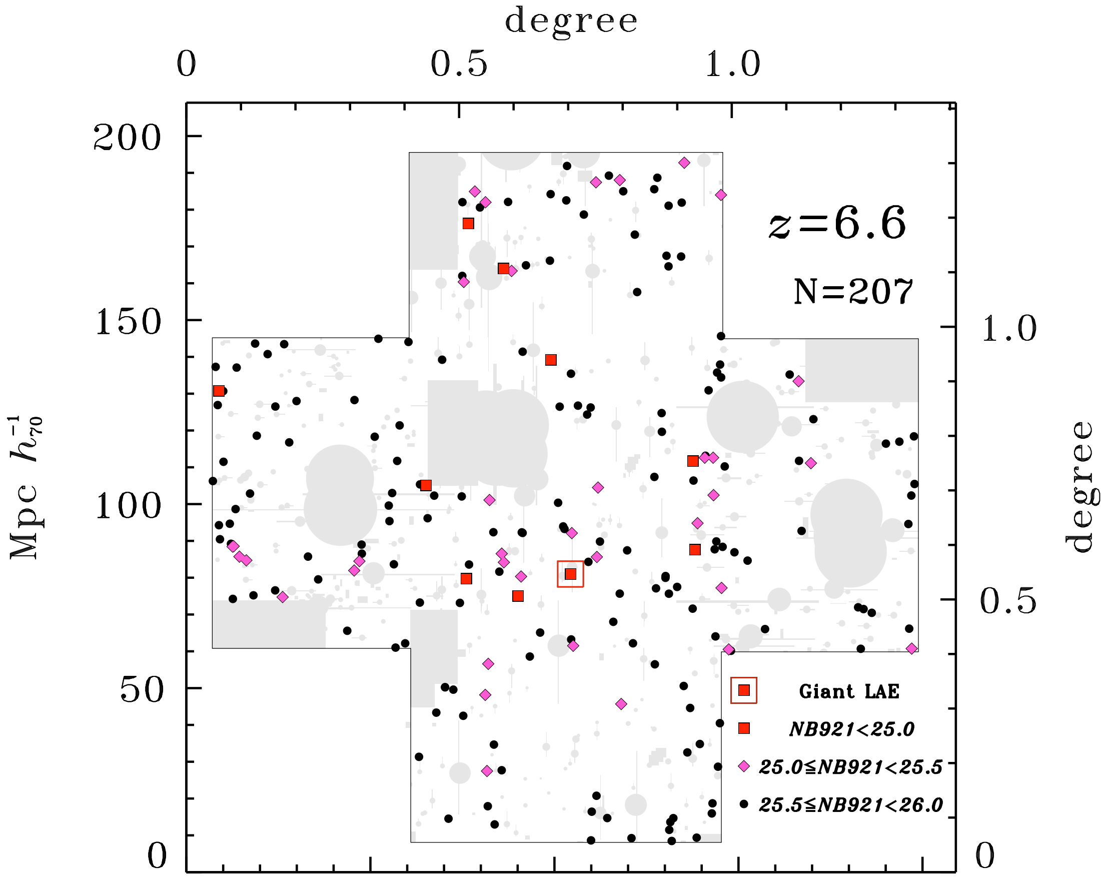
Alternative selection methods out to $z=7$

Alternative selections: Lya / LAEs

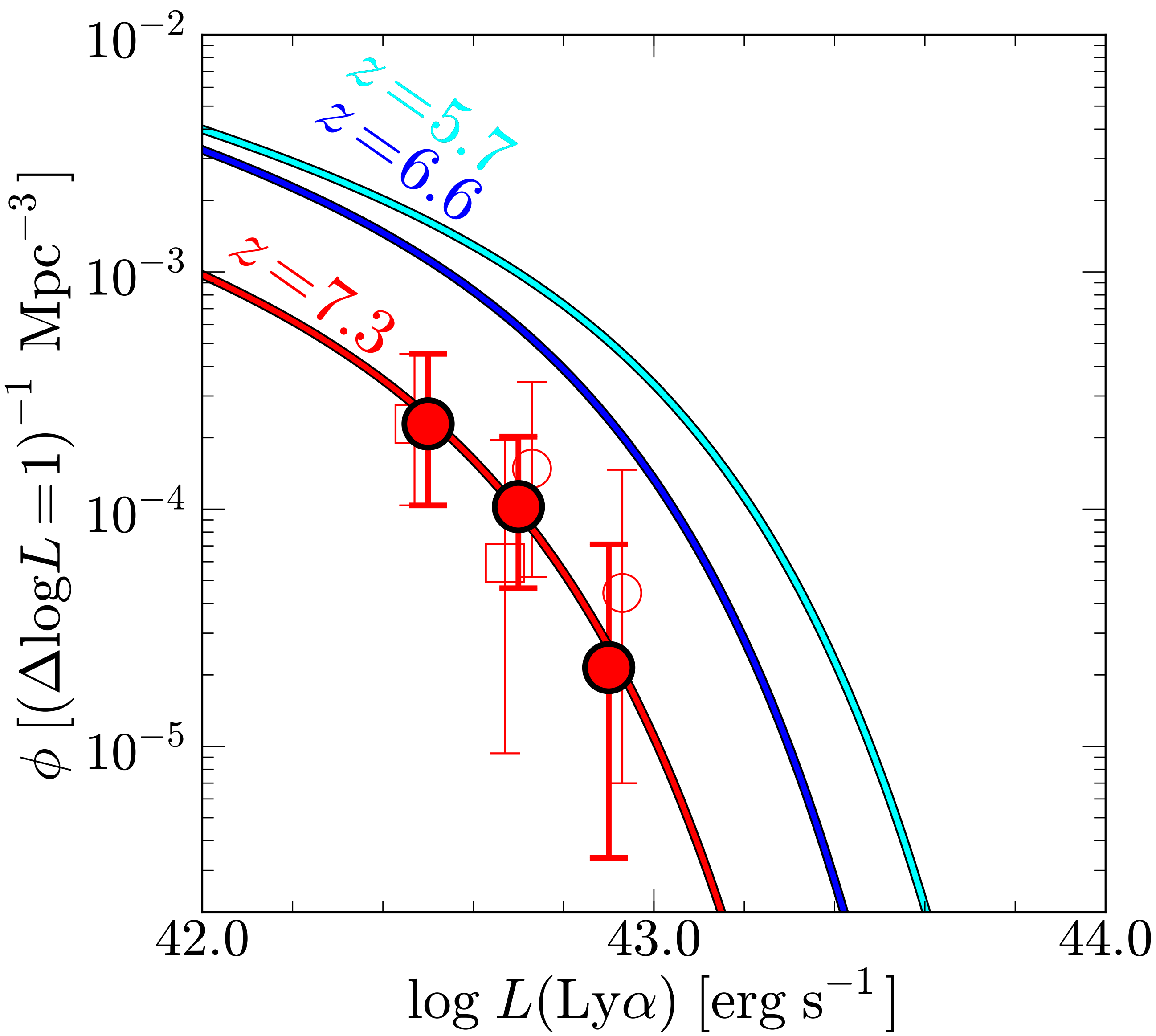
- Lyα at 1216Å is the intrinsically the brightest emission line in the spectrum of SF galaxies
- Due to resonant scattering the Lyα fraction goes down. Lyα is mainly observed in low-mass, low metallicity systems
- Ground based wide-field narrowband imaging (e.g. Subaru Hyper Supreme Cam) has selected statistical samples out to z=6.6

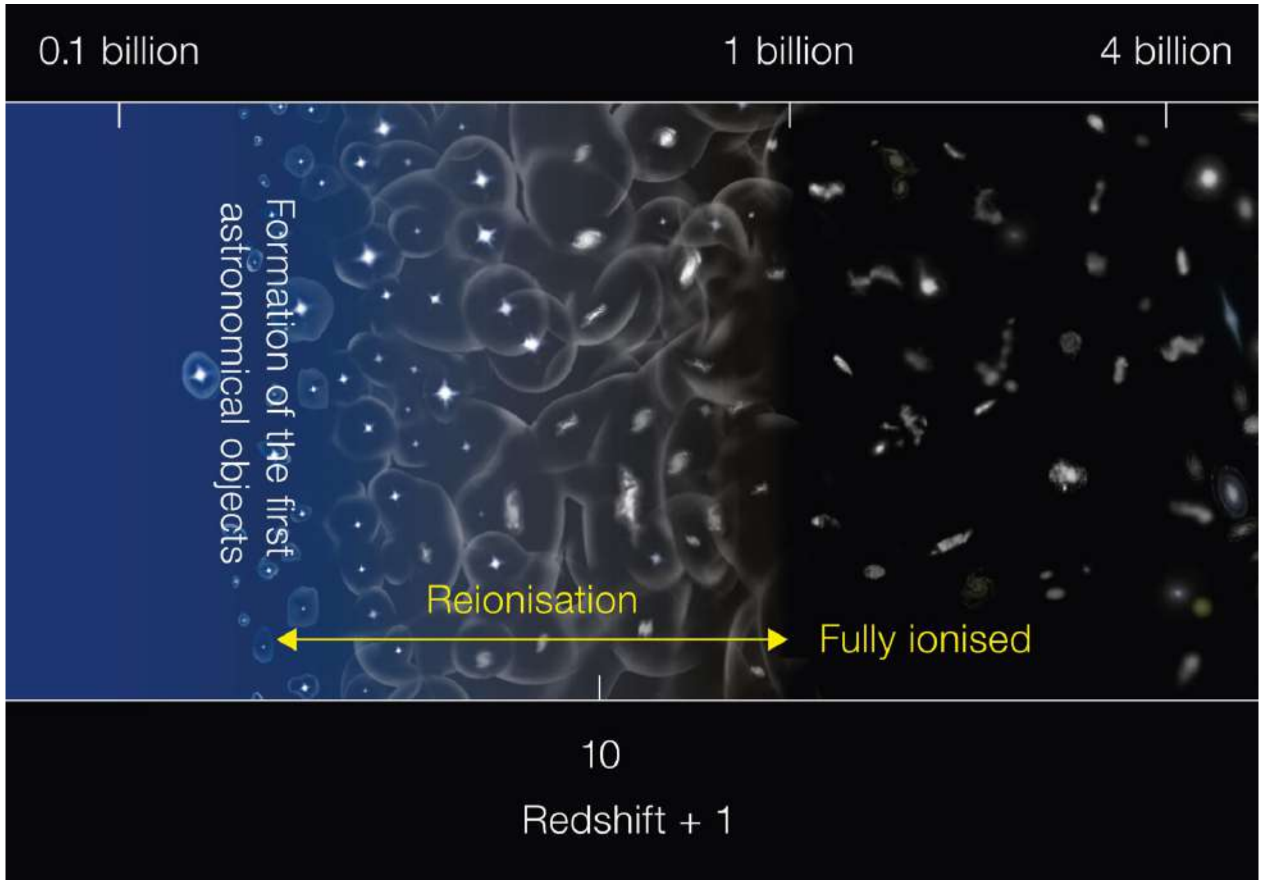
Ouchi et al. 2008





Alternative selections: Lya / LAEs

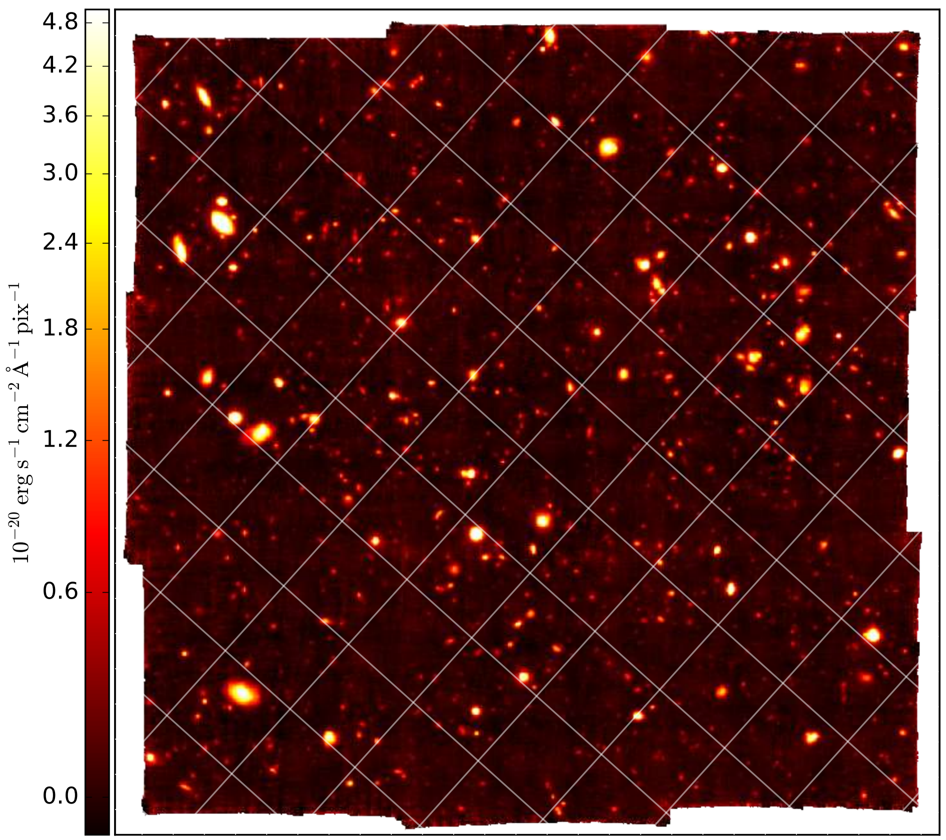




Above z>6.6 the neutral IGM in the EoR decreases the samples dramatically

Konno et al. 2014

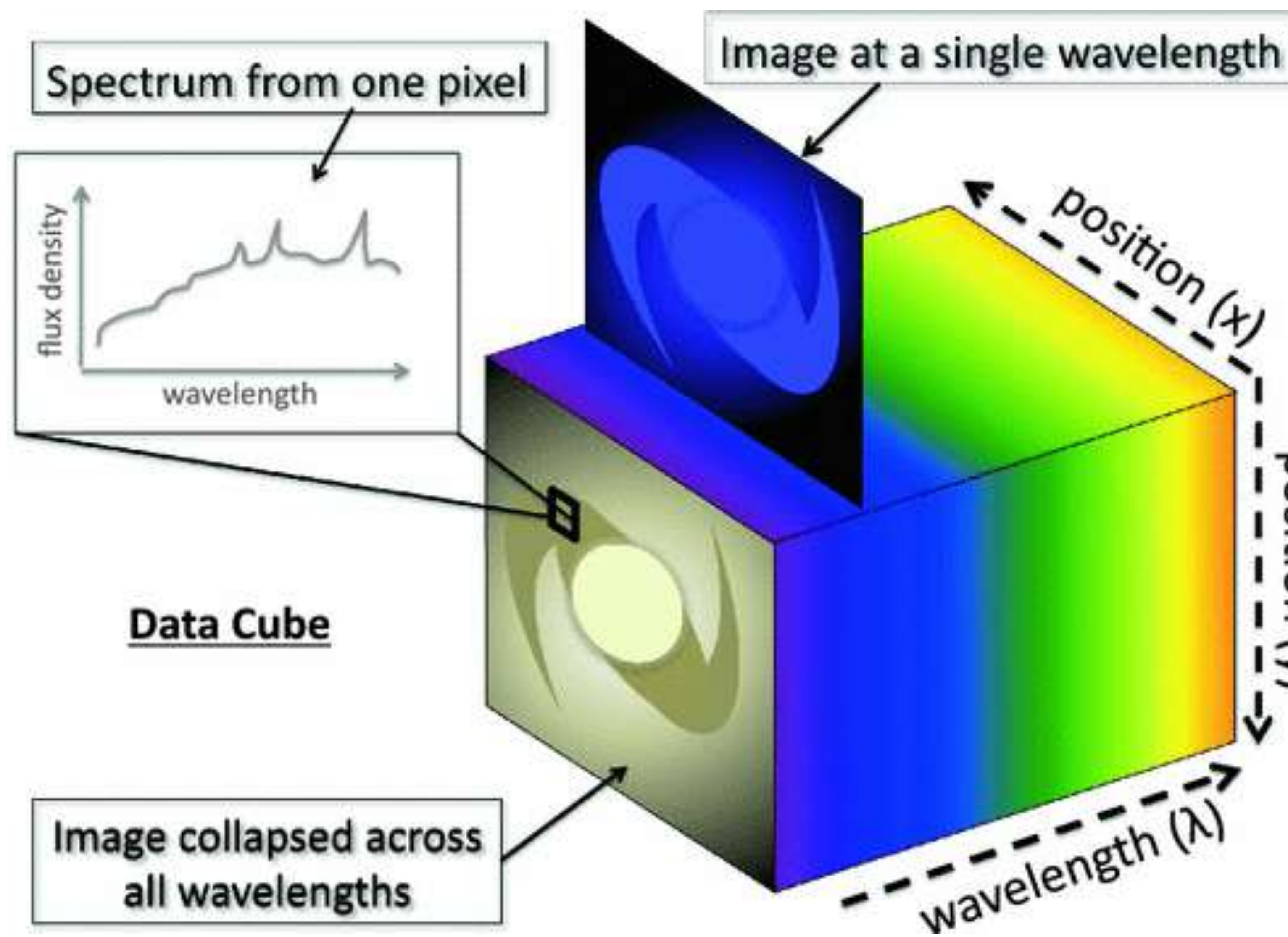
Alternative selections: Lya in IFU spectroscopy



VLT/MUSE

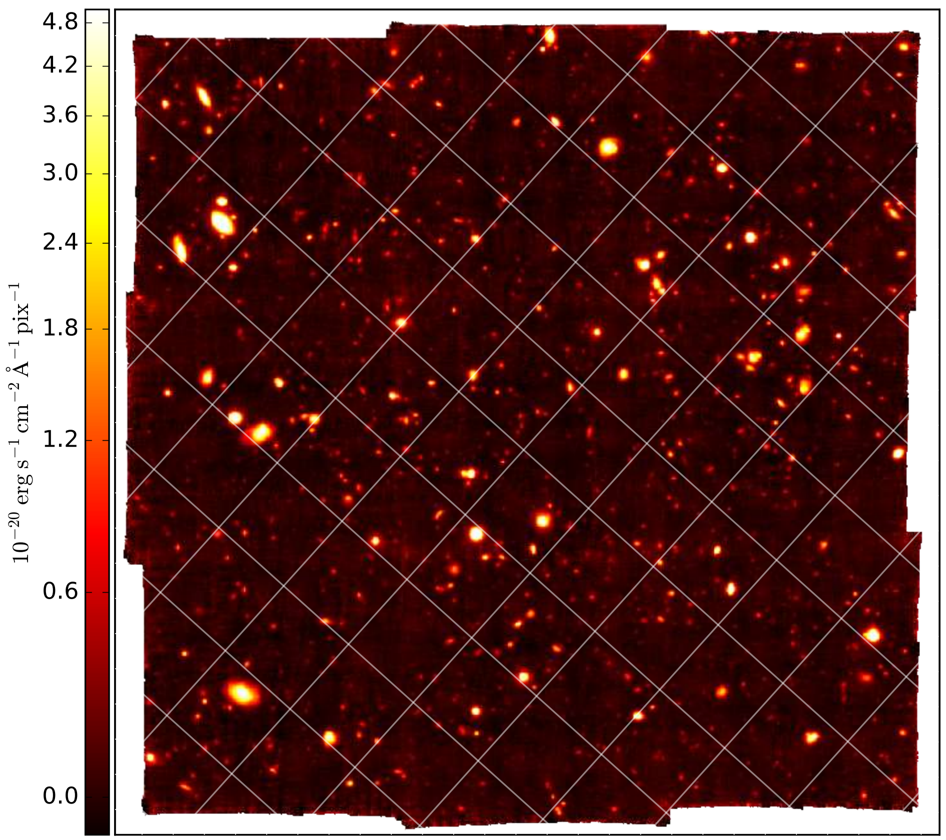
Bacon et al. 2017

Integral Field Unit (IFU)

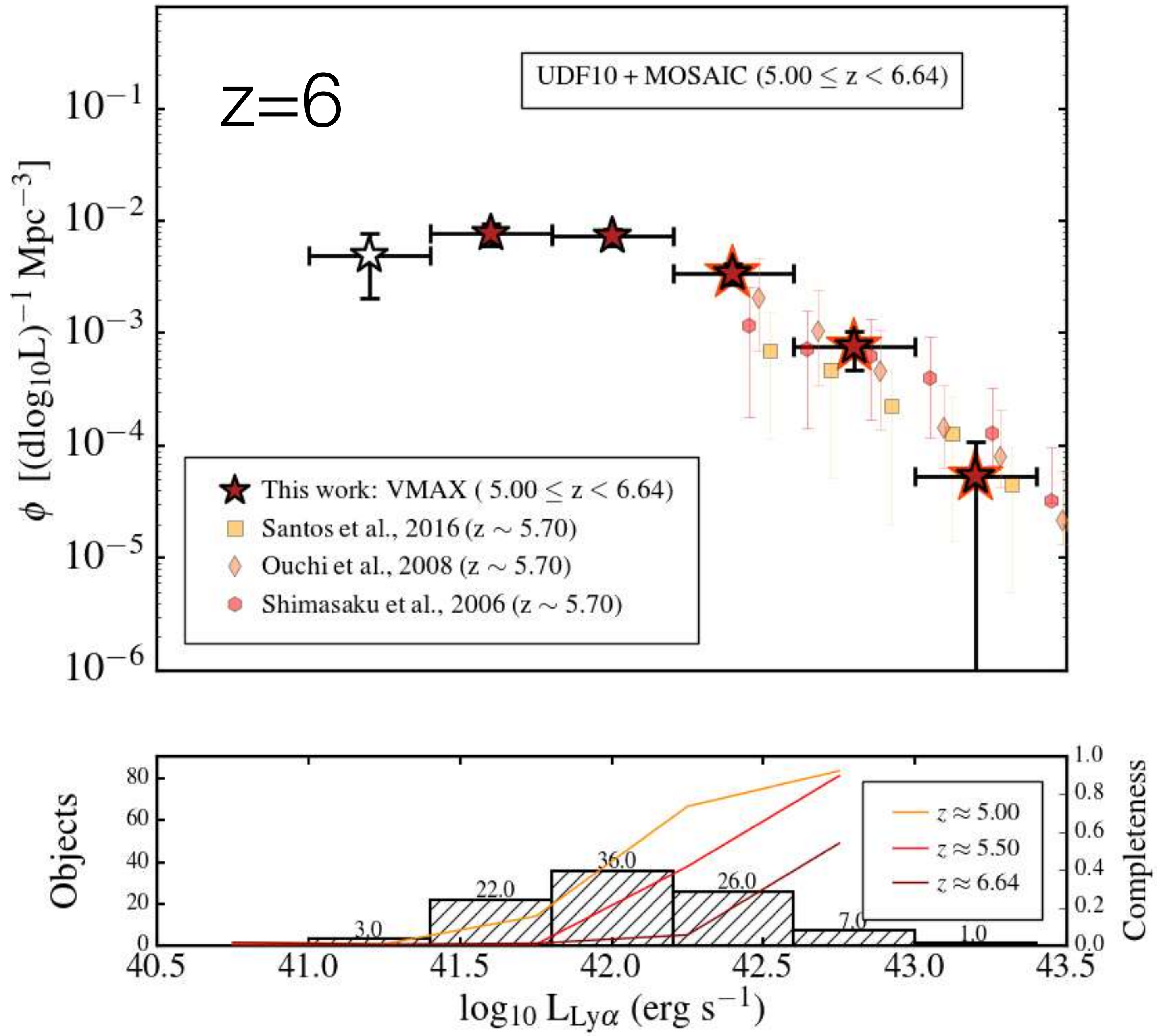


Credit: Chris Harrison

Alternative selections: Lya in IFU spectroscopy

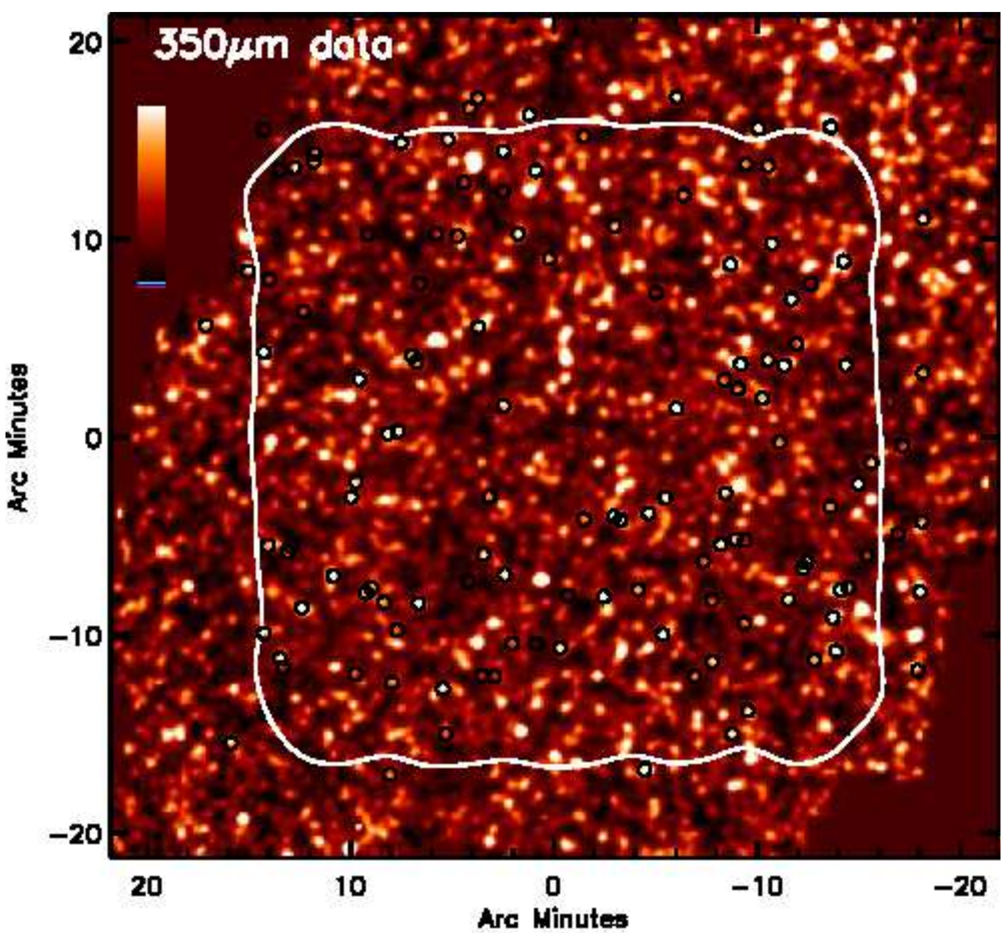


VLT/MUSE

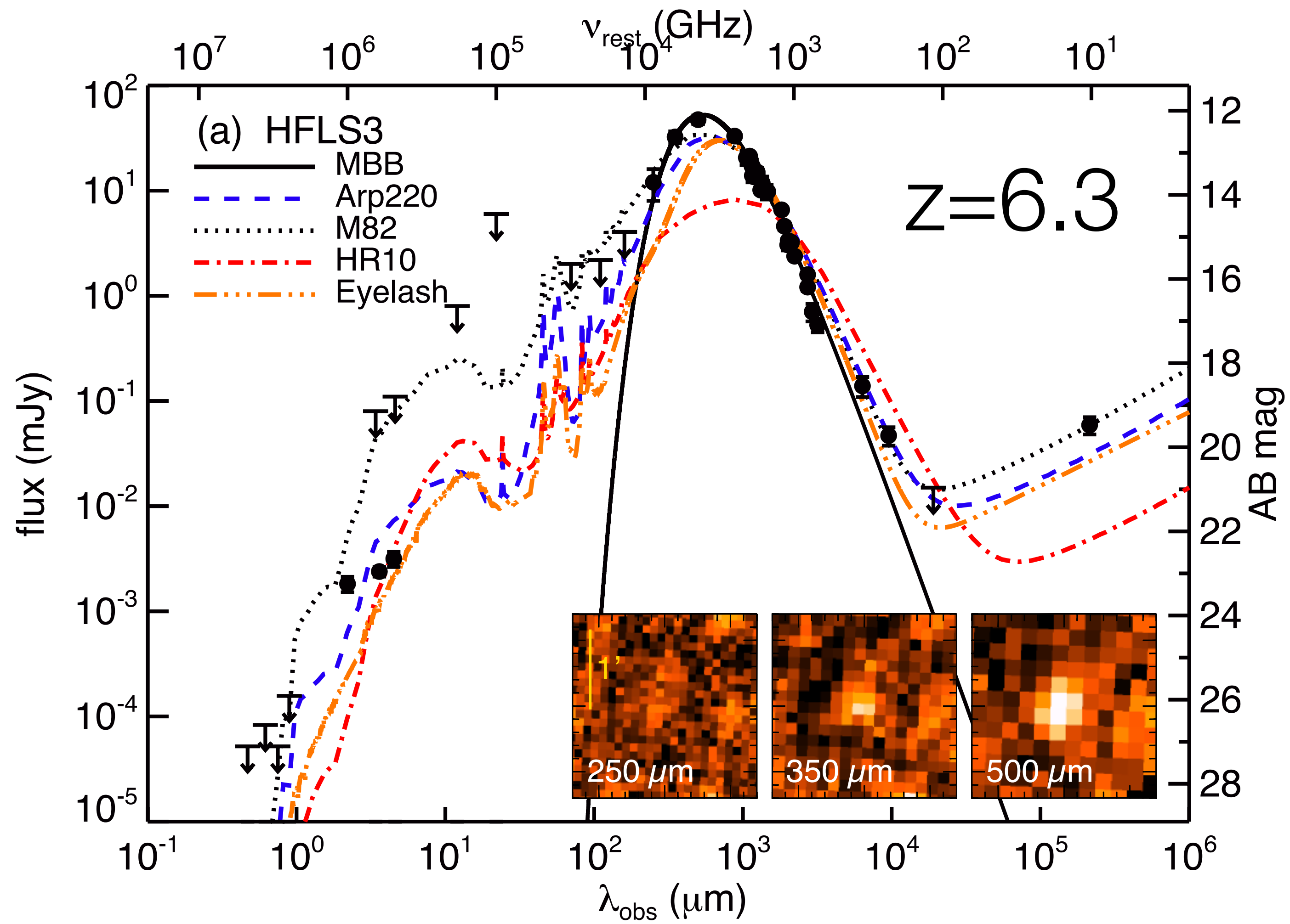


Drake et al. 2017

Alternative selections: IR/Sub-mm continuum



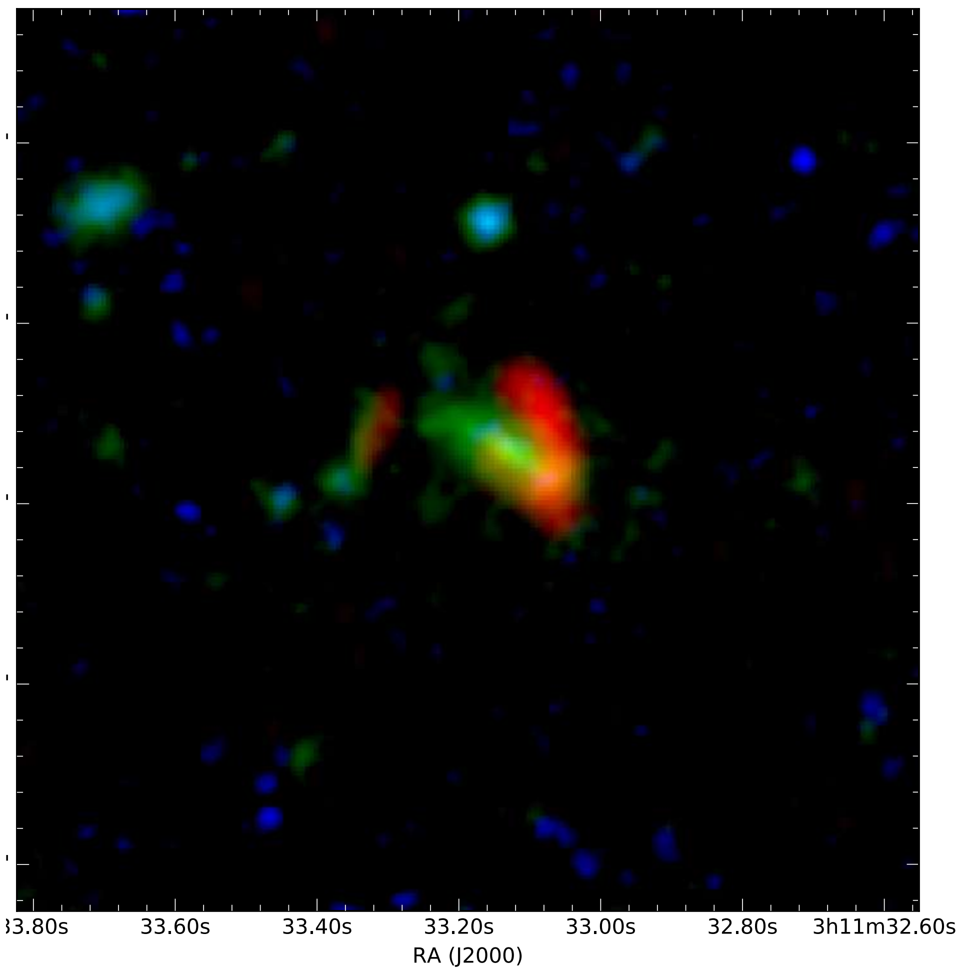
Herschel wide-field imaging



SFR=2900M$_\odot$/yr

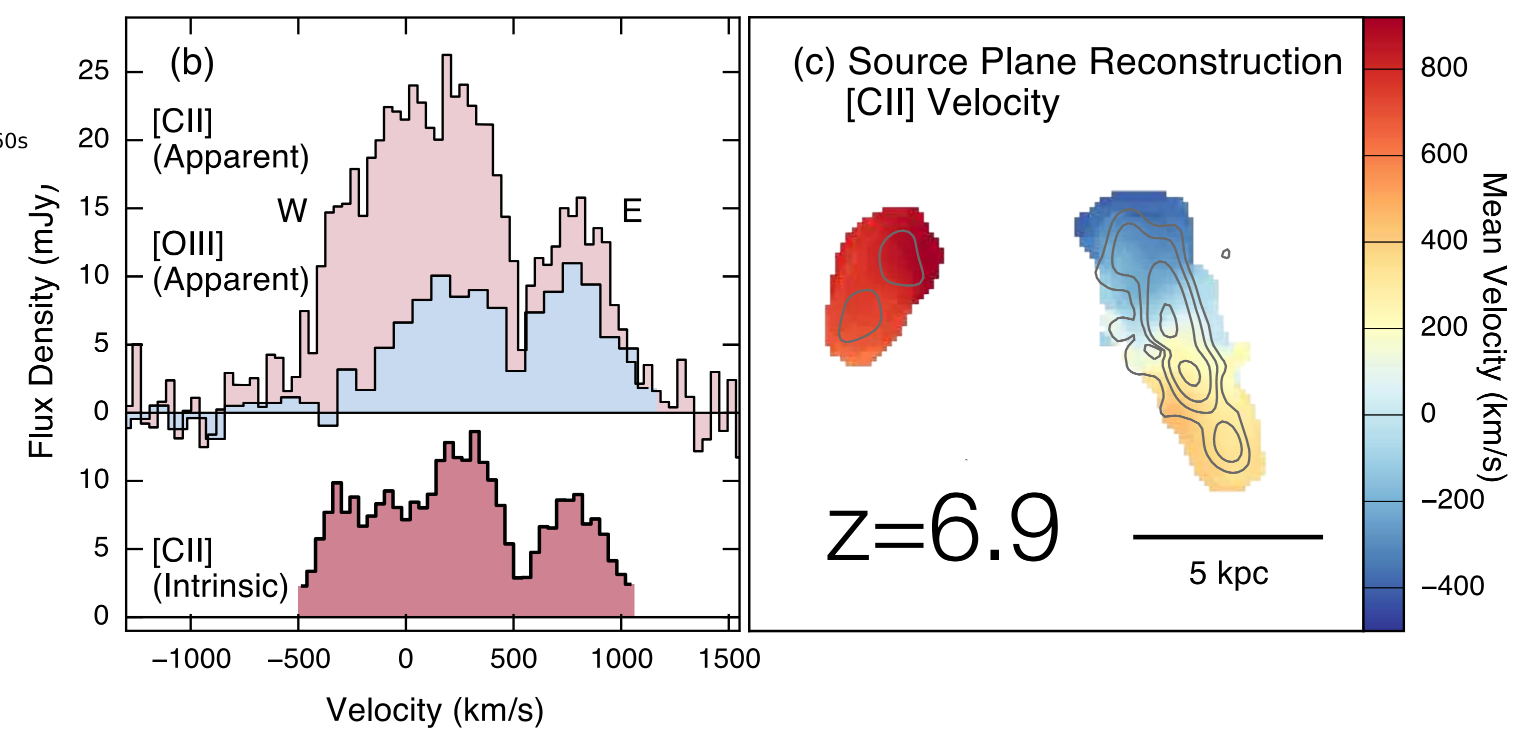
Riechers et al. 2013

Alternative selections: IR/Sub-mm continuum



- Current redshift record at for sub-millimetre selected source is z=6.9 - selected from South Pole Telescope point-source detections (lensed sub-millimetre galaxies)

SFR>3000M$_\odot$/yr



Marrone et al. 2017

Summary lecture 1

- Despite very limited information that is available on distant galaxies, the last ~20 years has seen incredible progress in detecting galaxies out to redshift z=10

- Some scepticism is justified as galaxy samples are always biased towards young & dust-free galaxies and interlopers of lower redshift quiescent galaxies and Milky Way stars are still often present

- Open questions on the galaxy census include
  1) understanding the evolution of the UV LF bright end with respect to halo mass evolution
  2) How steep is the UV LF faint end and when does it turn over?
  3) Is there evidence for accelerated evolution at z>8?