Lyman-Continuum Photon Production Efficiency of z~5 Galaxies and the Reionization of the Universe

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Credit to collaborators: Renske Smit, Ivo Labbe, Manuel Aravena, Fabian Walter, Roberto Decarli, Pascal Oesch, Marijn Franx, and Garth Illingworth

Institut d'Astrophysique Paris — Cosmic Dawn of Galaxy Formation: Linking Observations and Theory with New-Generation Spectral Models: June 20, 2016

Which Sources drive the Reionization of the Universe?

Quasars

Key Question:
Could quasars still be abundant at z~6-7?

Galaxies

Key Questions:
Are faint galaxies still abundant?

Is the escape fraction moderately large?

Do Galaxies Reionize the Universe?

Counting the Ionizing Photons Galaxies Produce

UV luminosity density x ξ_{ion} x f_{esc}

(UV continuum inventory)

(conversion factor from UV-continuum to ionizing photons)

(fraction of ionizing photons which escape)

Ionizing Emissivity

Do Galaxies Reionize the Universe?

Counting the Ionizing Photons Galaxies Produce

UV luminosity density × ξ_{ion} × f_{esc}

(UV continuum inventory)

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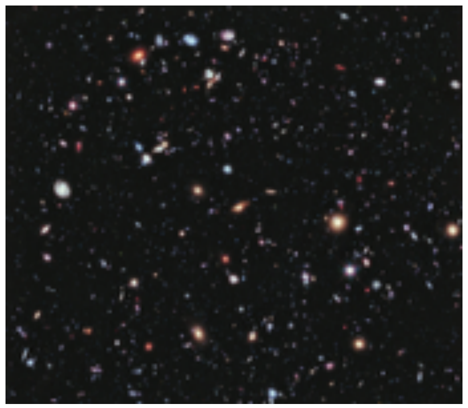
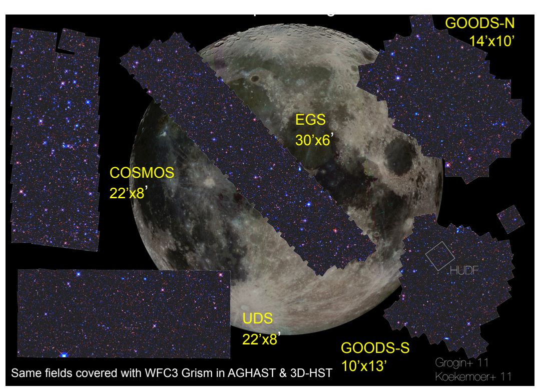
Ionizing Emissivity

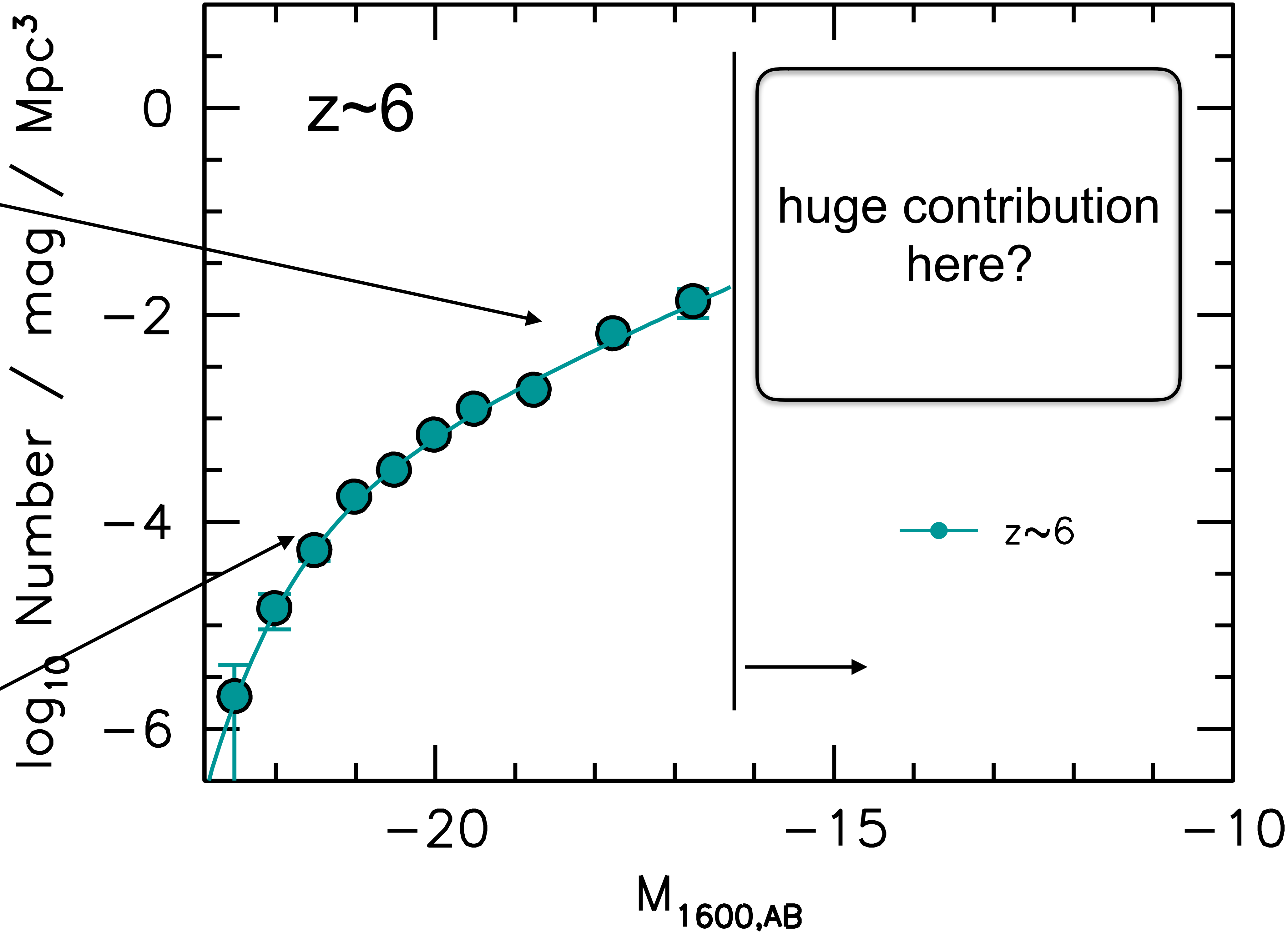
How many UV-continuum photons do galaxies produce?

HUDF



CANDELS
(or better yet
UltraVISTA/UDS)

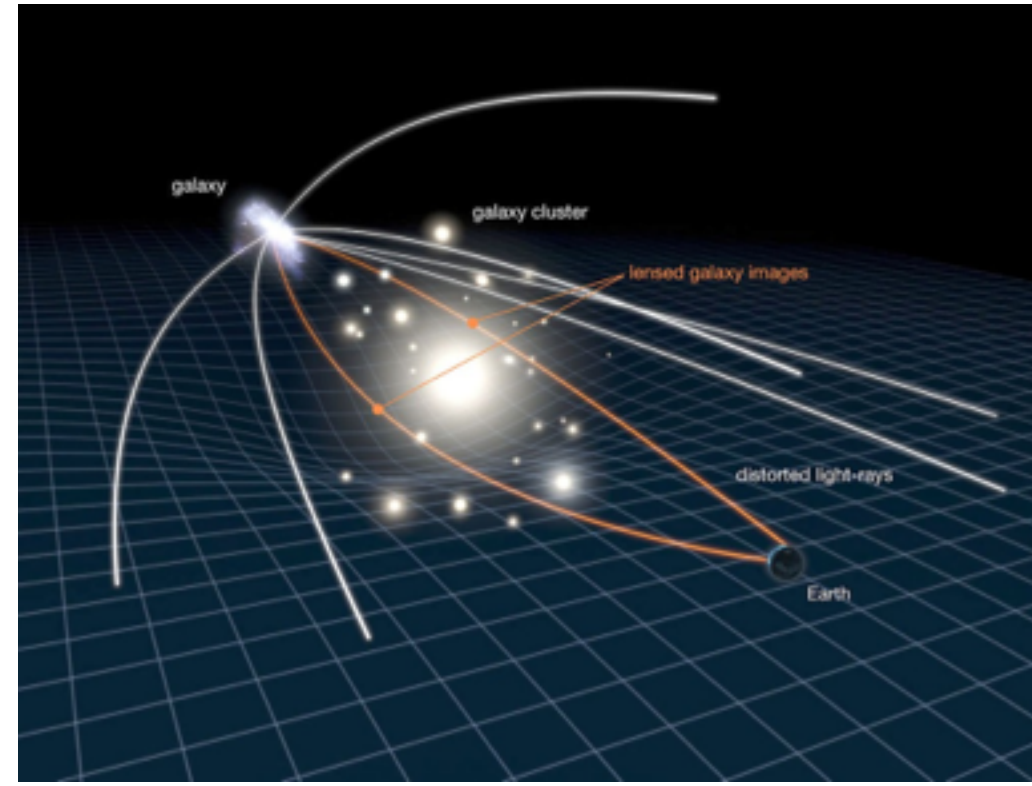




Bouwens+2015; see also McLure+2013; Bowler+2015; Finkelstein+2015

What is the trick to try to push fainter?

1. Find a Massive Object that magnifies a significant volume of the universe



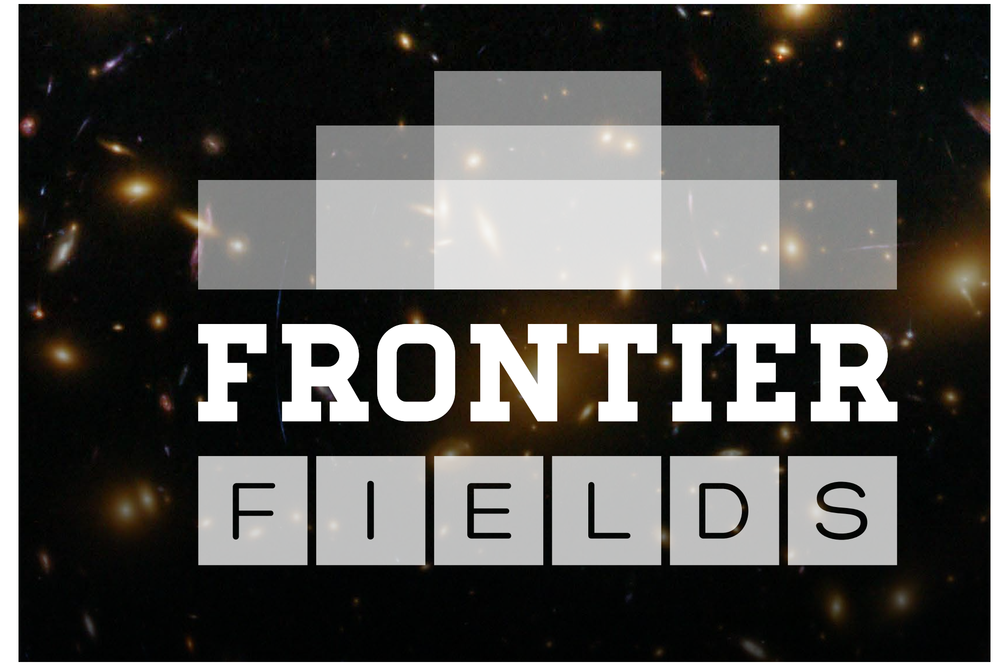
Massive Galaxy Cluster

Increase Sensitivity

Decrease Volume

What is the trick to try to push fainter?

2. Target that region of the sky with very deep observations with Hubble and other powerful telescopes



Massive Galaxy Cluster

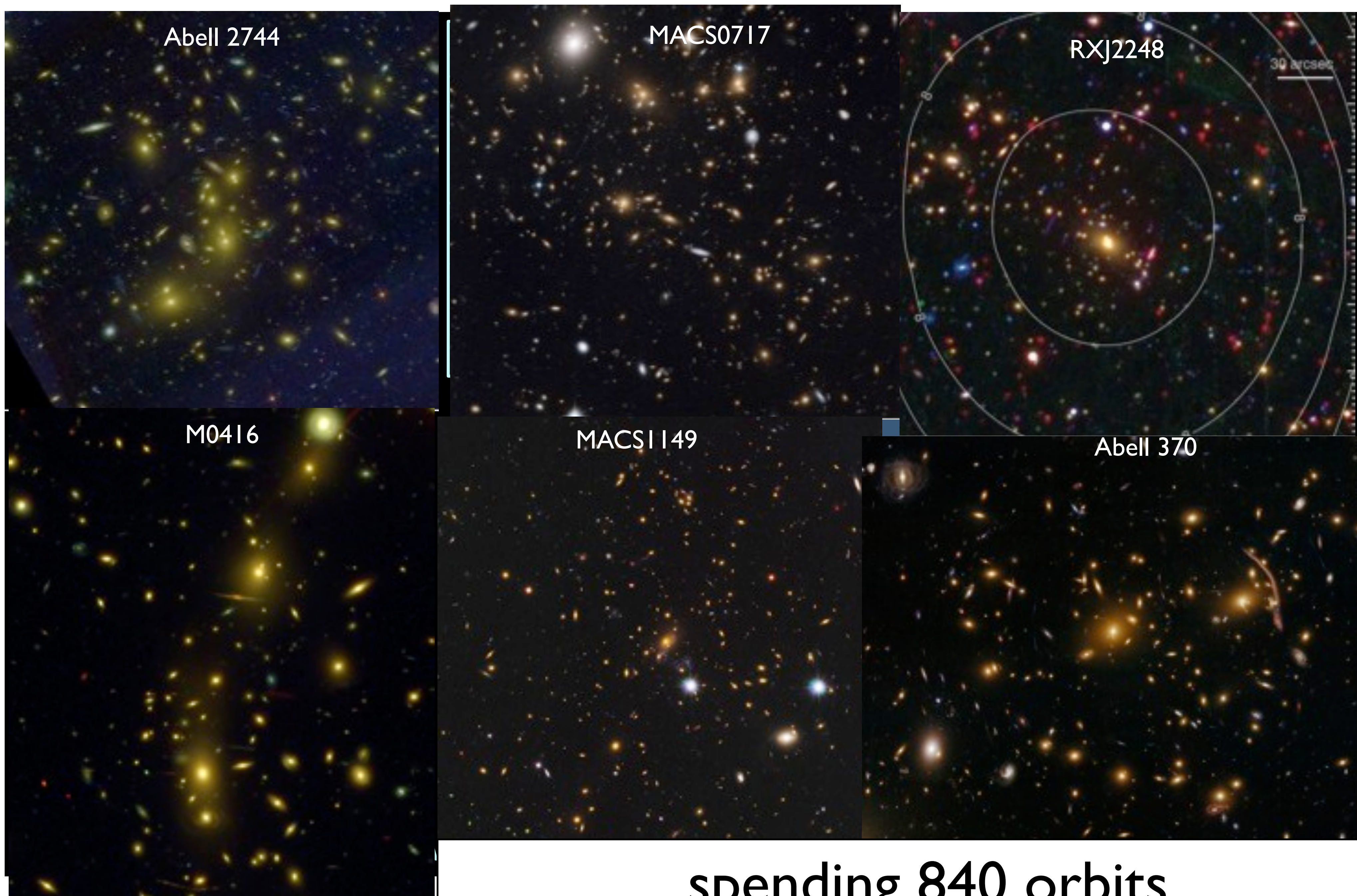
Integrate for 140 orbits with Hubble

70 orbits in the optical

70 orbits in the near-IR

What is the trick to try to push fainter?

3. Repeat this trick over six massive clusters to improve the statistics and control for cosmic variance



spending 840 orbits

How many UV-continuum photons do galaxies produce?

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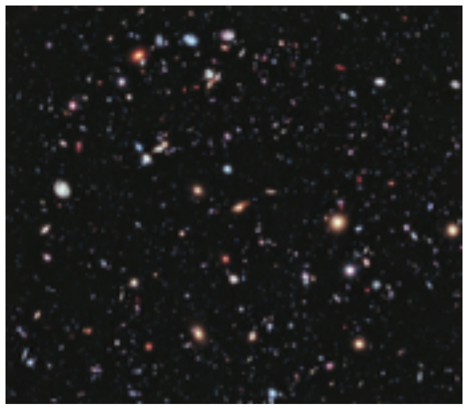

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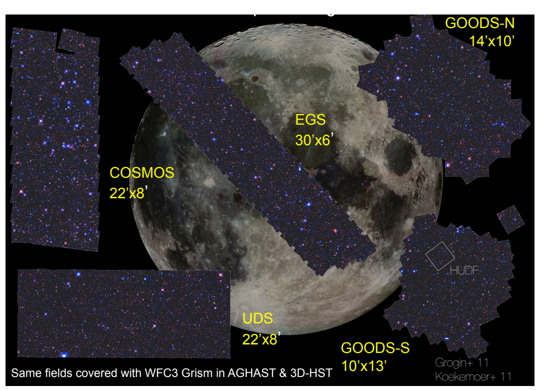
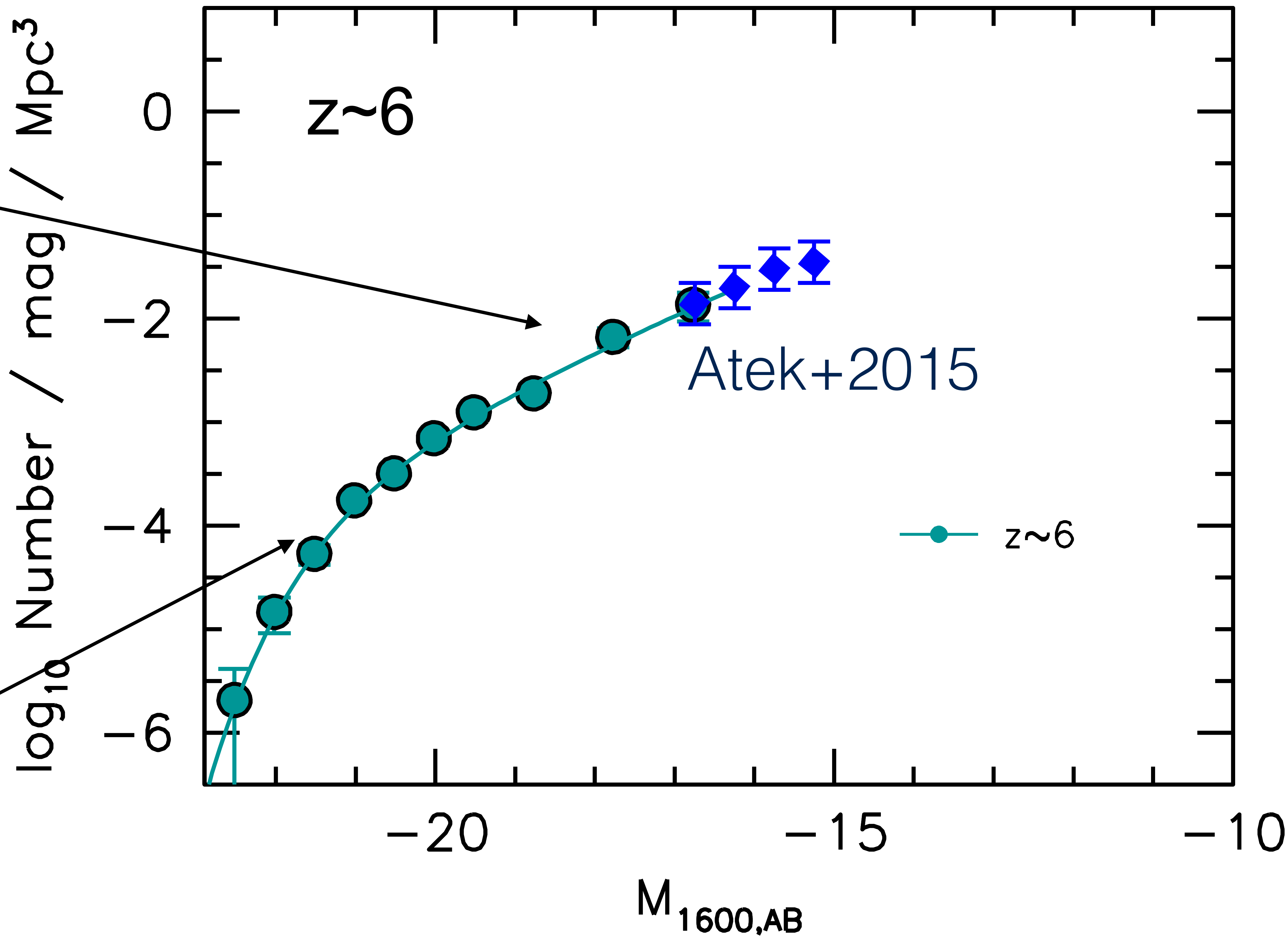
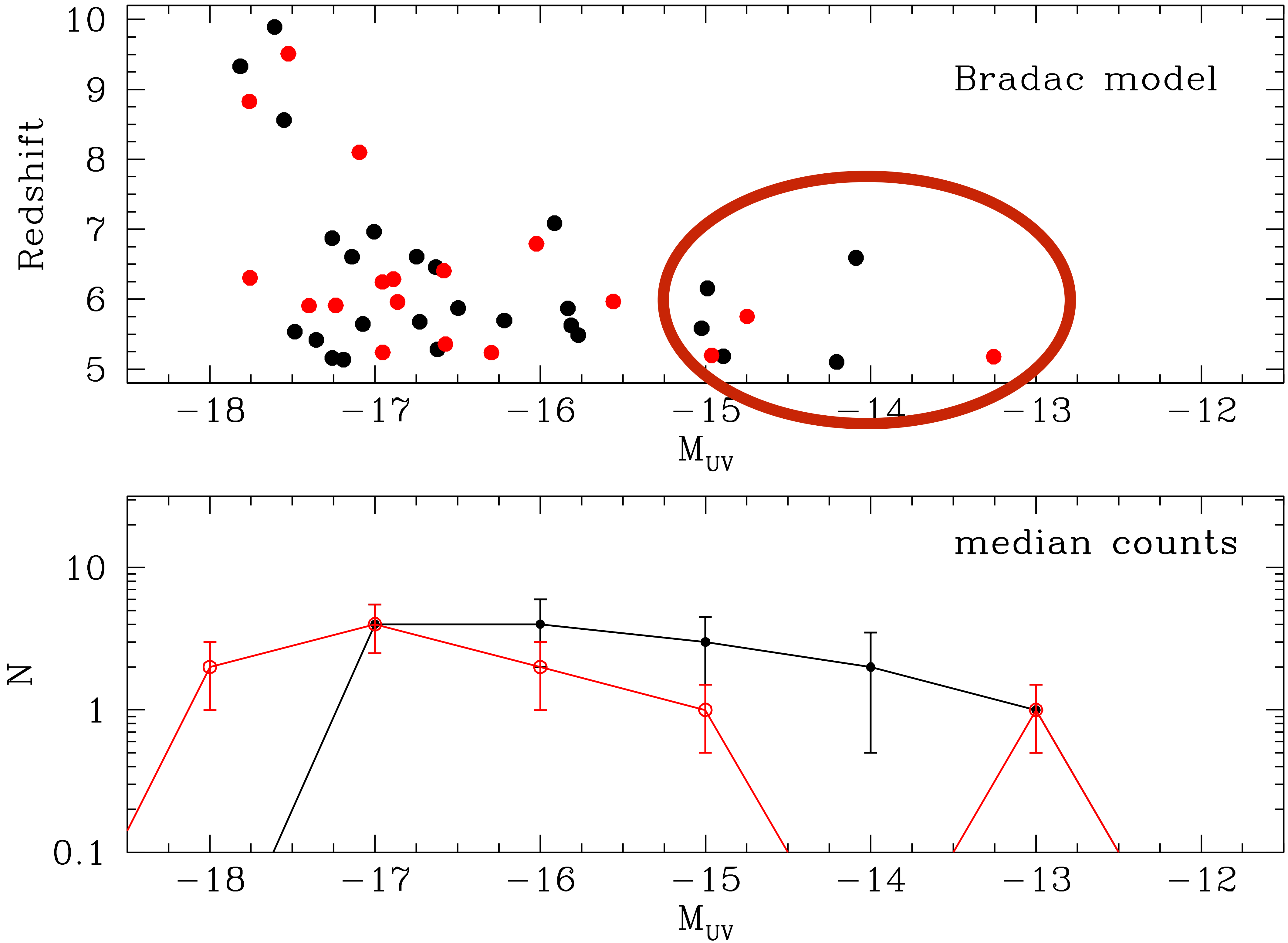




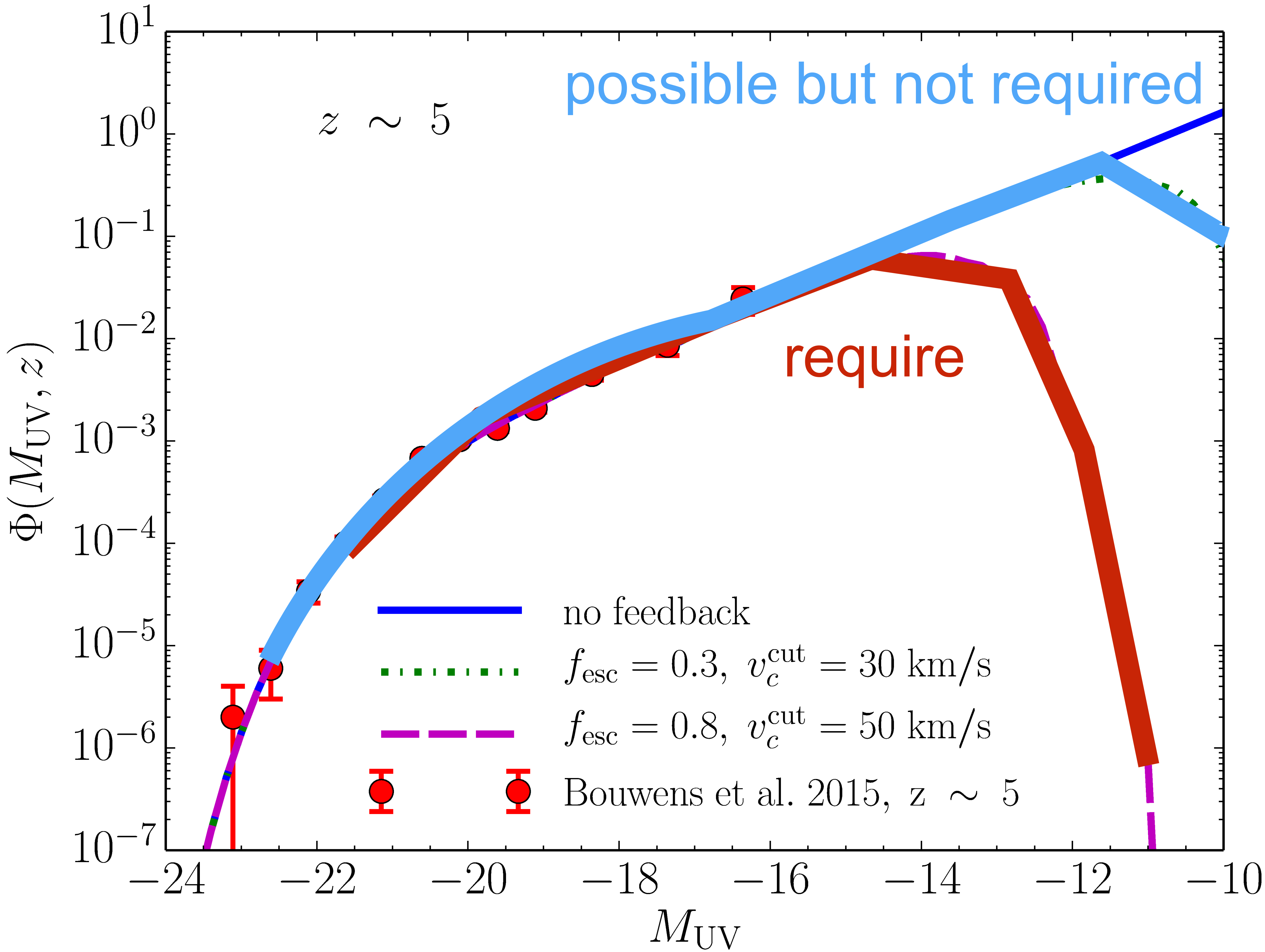
Bouwens+2015

Pushing to fainter galaxies in the Hubble Frontier Fields



Castellano+2016, in press

Which model LF does the data of Castellano+2016 require?



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How many UV-continuum photons do galaxies produce?

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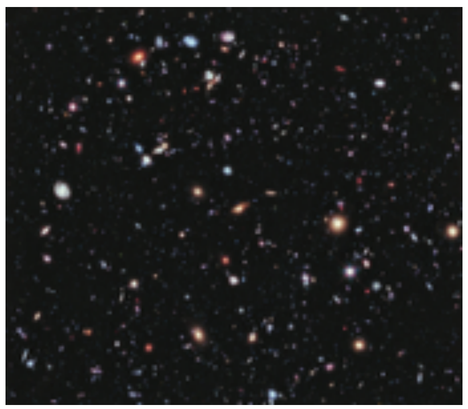

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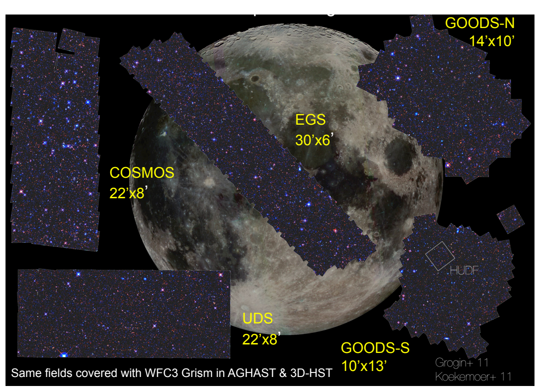

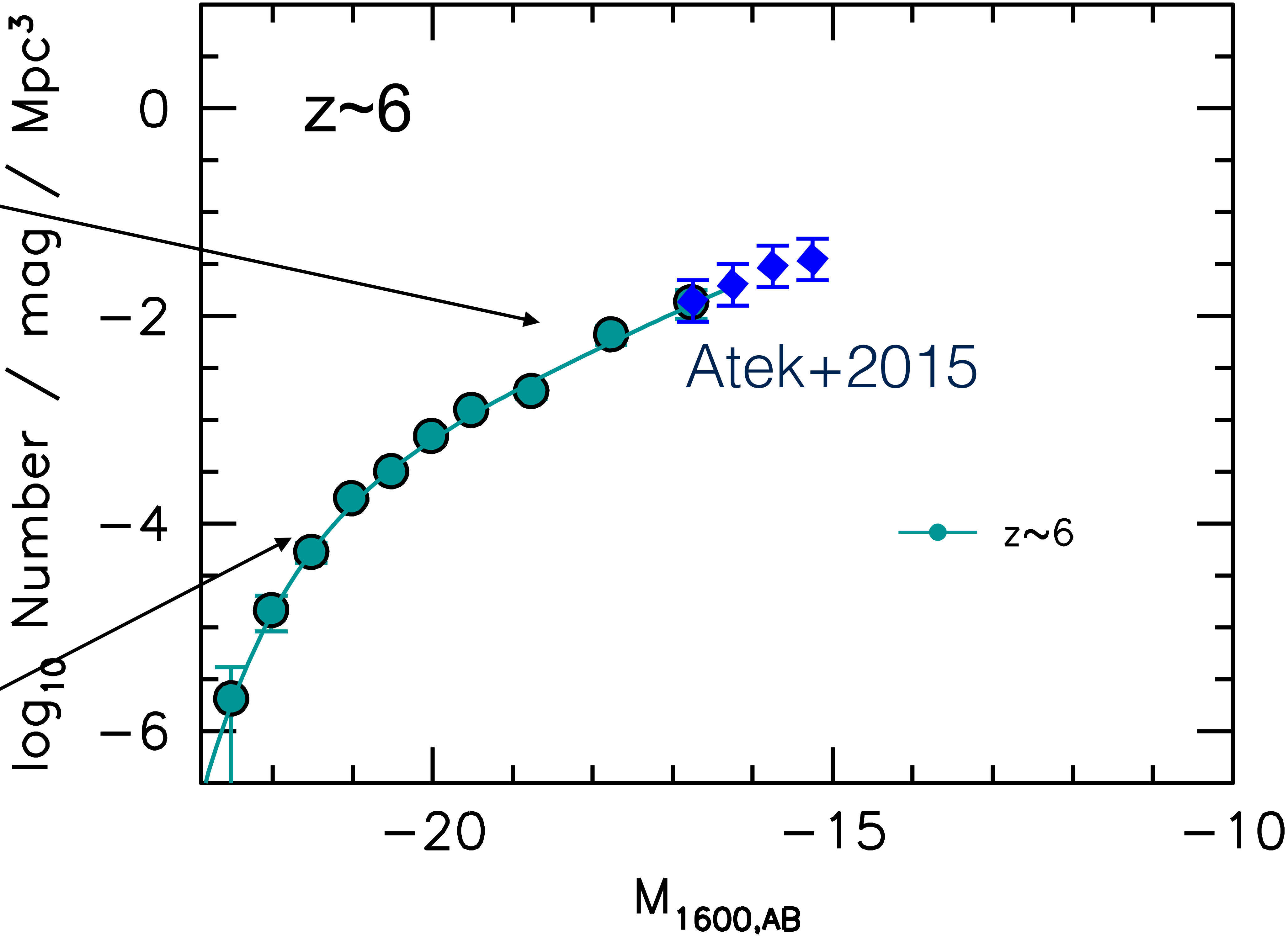

Bouwens+2015

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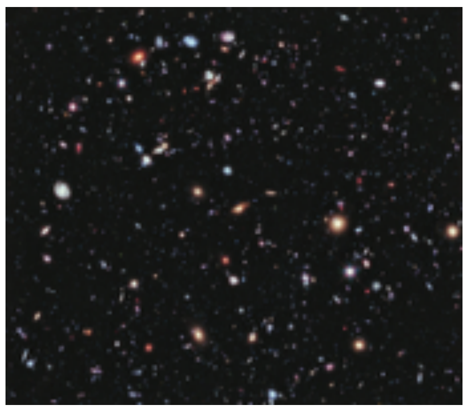

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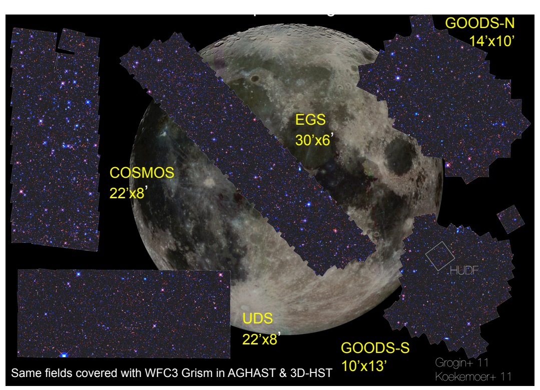
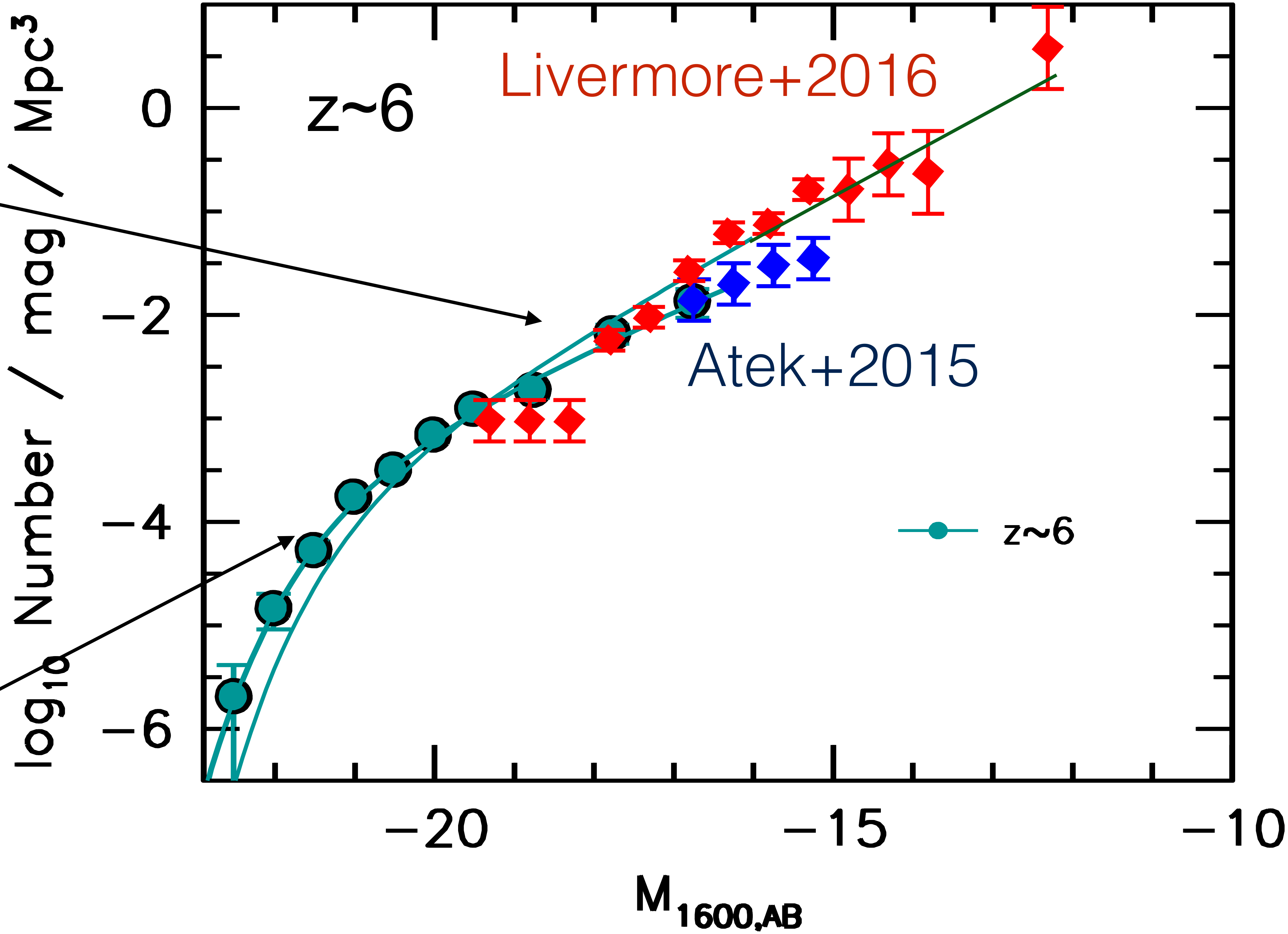




Bouwens+2015

Potential and Perils:

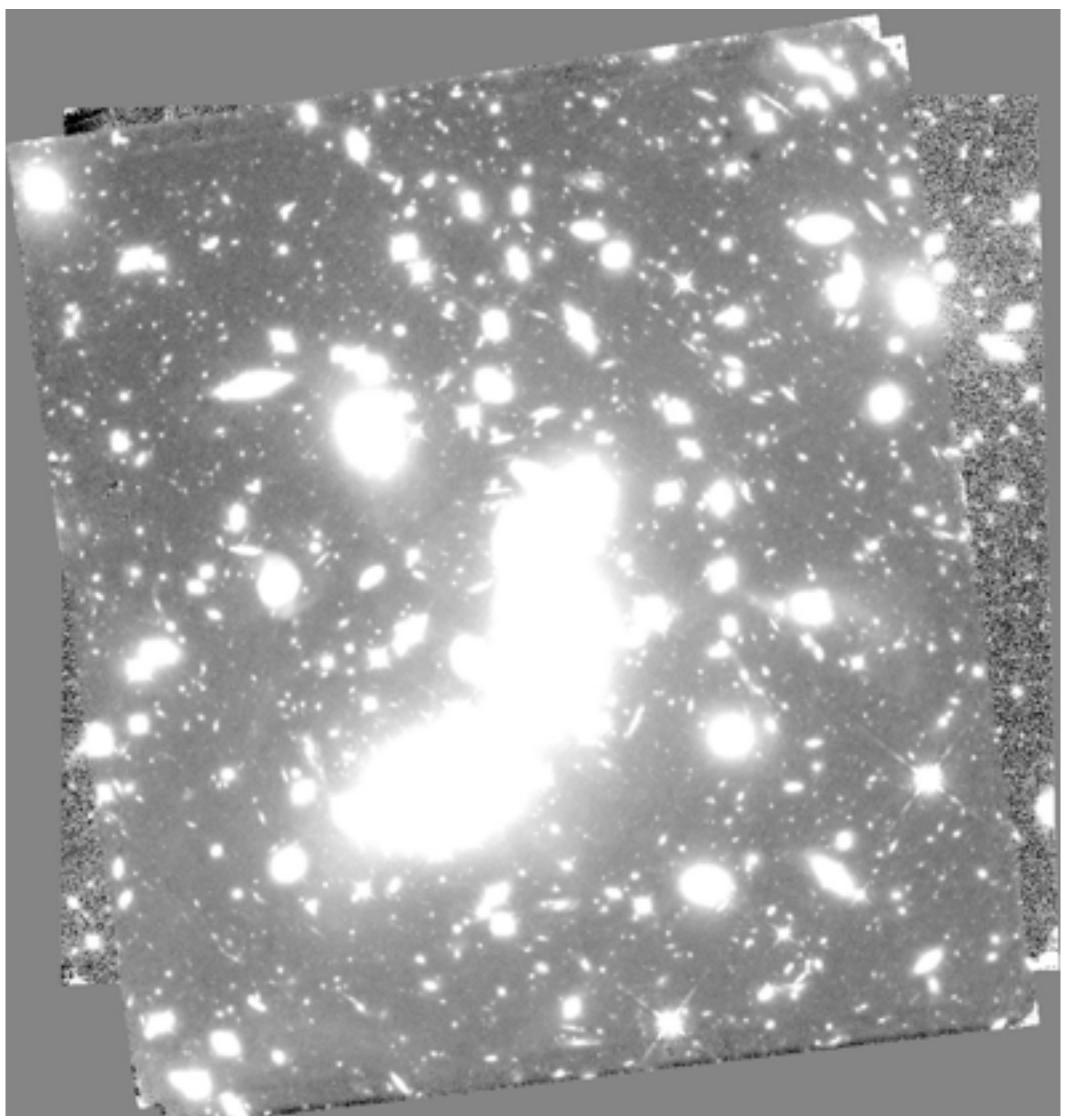
Deriving LFs from Lensing Clusters Has Great Potential but maybe things can go wrong….

Some Potential Gotchas…

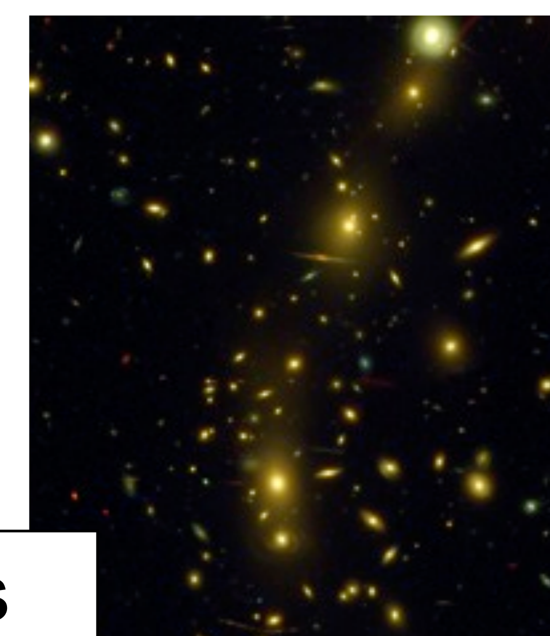
1. Rely on Gravitational Lensing Models
2. Cope with Foreground Cluster and Contamination
3. Other Possible Systematics…

Constraining the Faint-End of the LFs
(while worrying about what could go wrong)

1. Subtract Diffuse Light from Cluster + Elliptical Galaxies



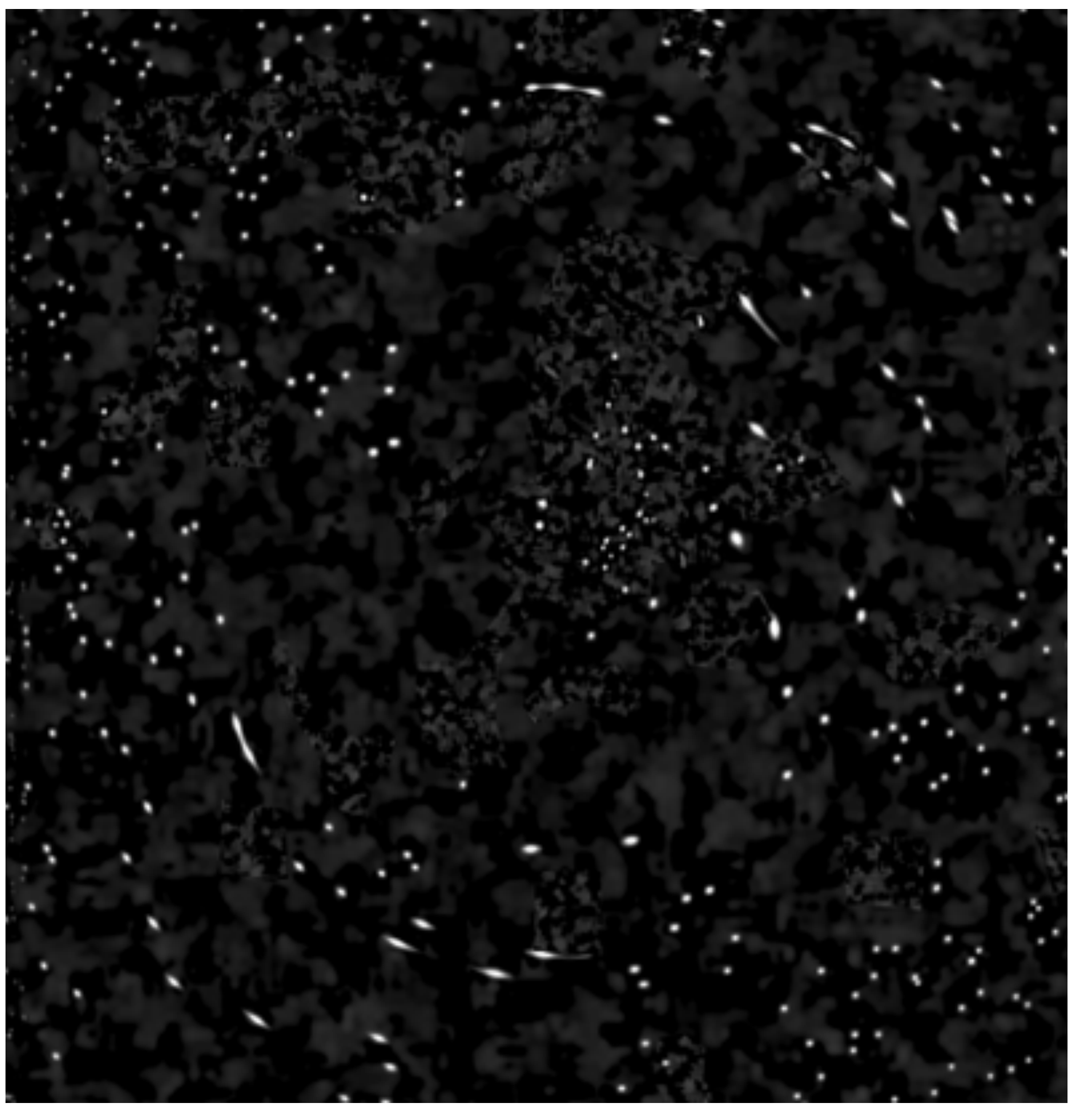
2. Construct catalogs of z~6 galaxies behind the HFF clusters



→ 200 z~6 galaxies

Constraining the Faint-End of the LFs
(while worrying about what could go wrong)

3. Determine How Easy it is to find the faint galaxies by running simulations…

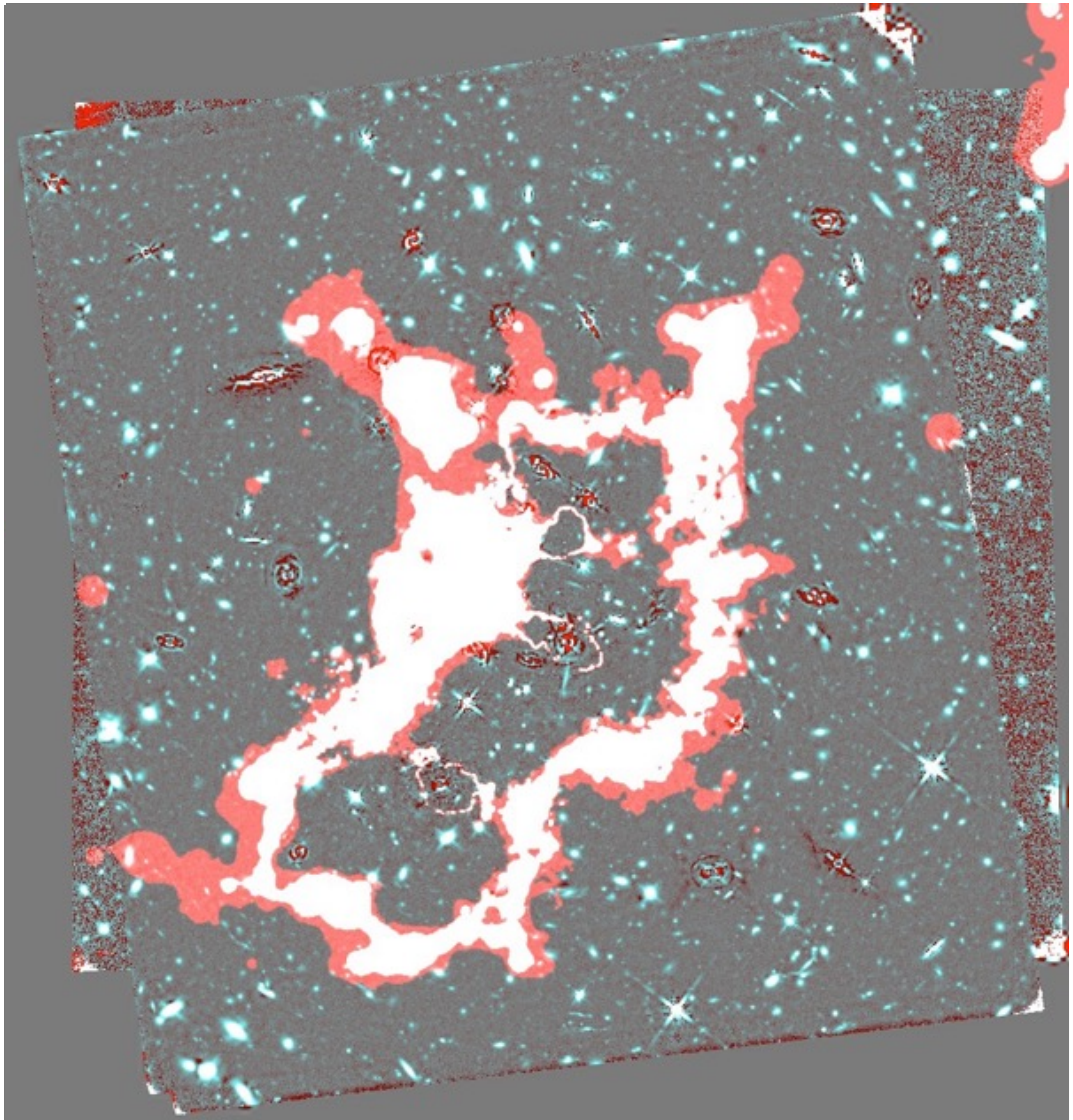


4. Put together all previous steps and calculate errors…

Set 100 as maximum magnification allowed in models..

Build in a number of systematic errors in the entire process..

Some Hubble Frontier Fields Lensing Models are Quite Different from other Models



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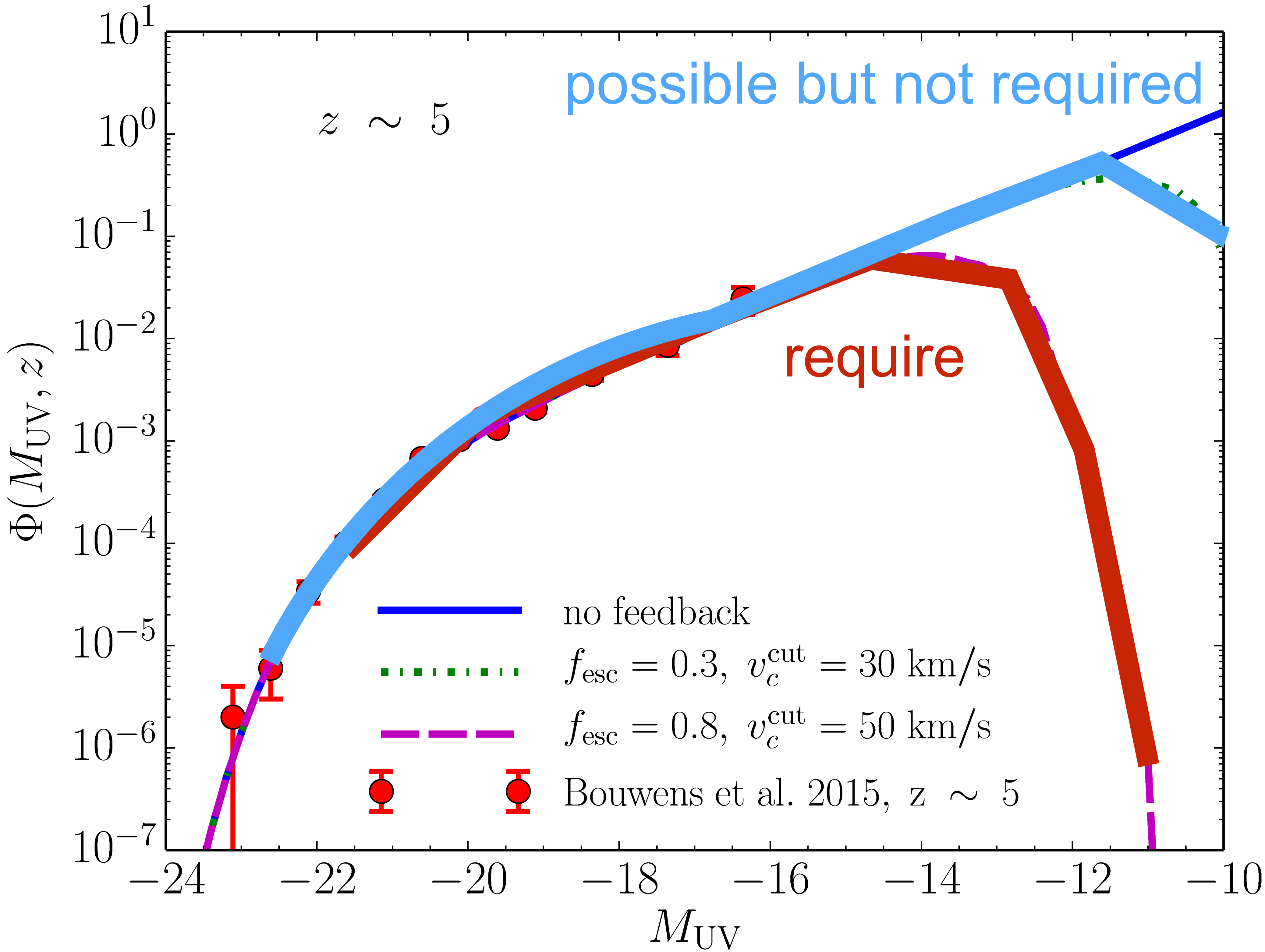


Castellano+2016

Do Galaxies Reionize the Universe?

$\boxed{\text{Counting the Ionizing Photons Galaxies Produce}}$

UV luminosity density x ξ_{ion} x f_{esc}

(UV continuum inventory)

(conversion factor from UV to ionizing photons)

(fraction of ionizing photons which escape)

Measuring ξ_{ion} (# of Ionizing Photons per UV continuum Luminosity)

How can we measure the # of ionizing photons produced by stars in a galaxy?

Using the Hα luminosity
(can be converted into Lyman-continuum photon production rate in almost model-independent way)

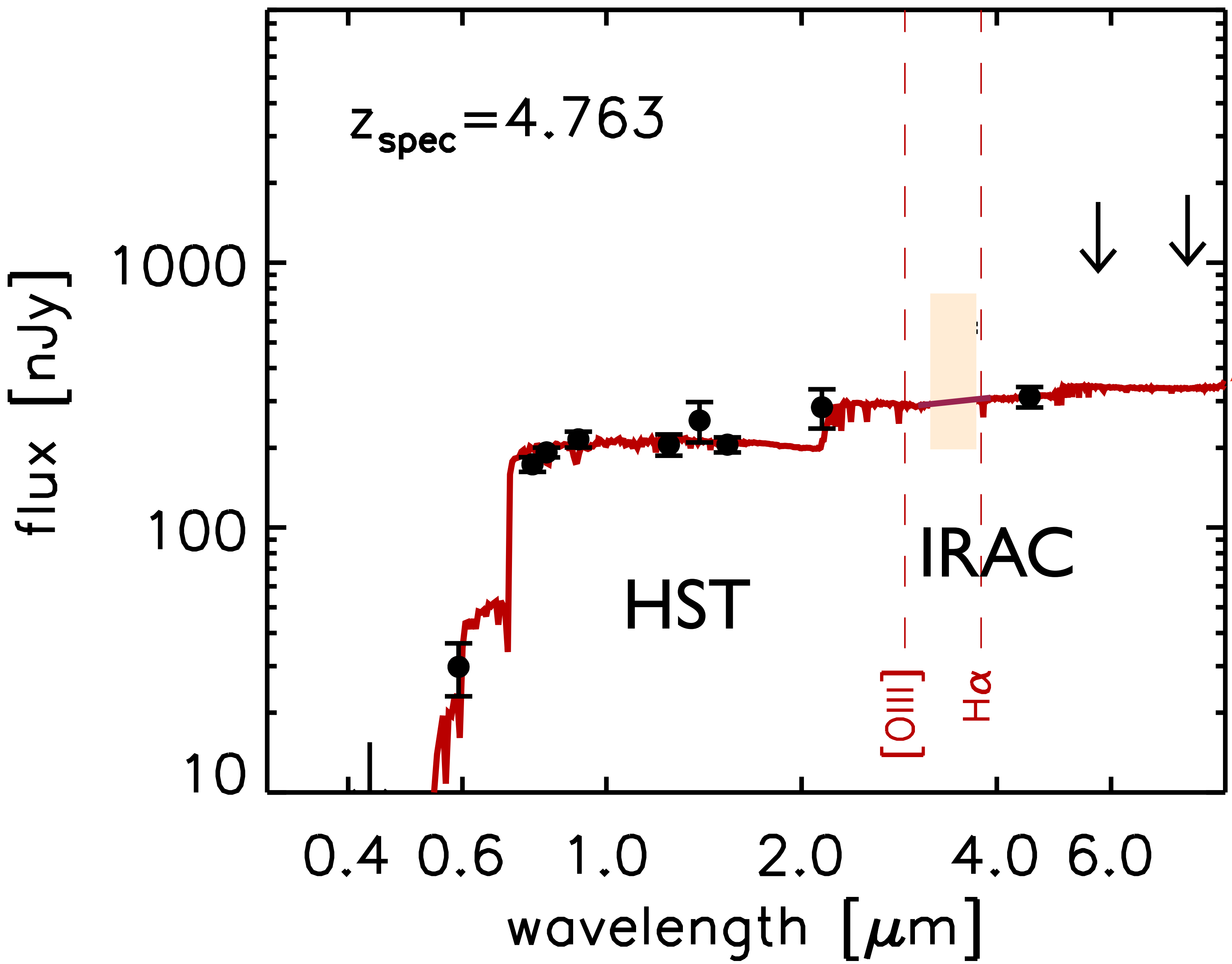
How can we measure the total UV-continuum luminosity for stars in a galaxy?

From HST observations of UV-continuum luminosities

$$\xi_{ion} = \frac{\text{Number of Ionizing Photons}}{\text{Intrinsic UV Luminosity}}$$

Measuring the Hα flux (from IRAC data)

For z~4-5 Galaxies, can derive the Hα flux by fitting to all Passbands but Spitzer/IRAC band including Hα



Fit to all bands but contaminated IRAC [3.6] band

Shim+2011; Stark+2013; de Barros+2014; Smit+2015; Marmol-Queralto+2015

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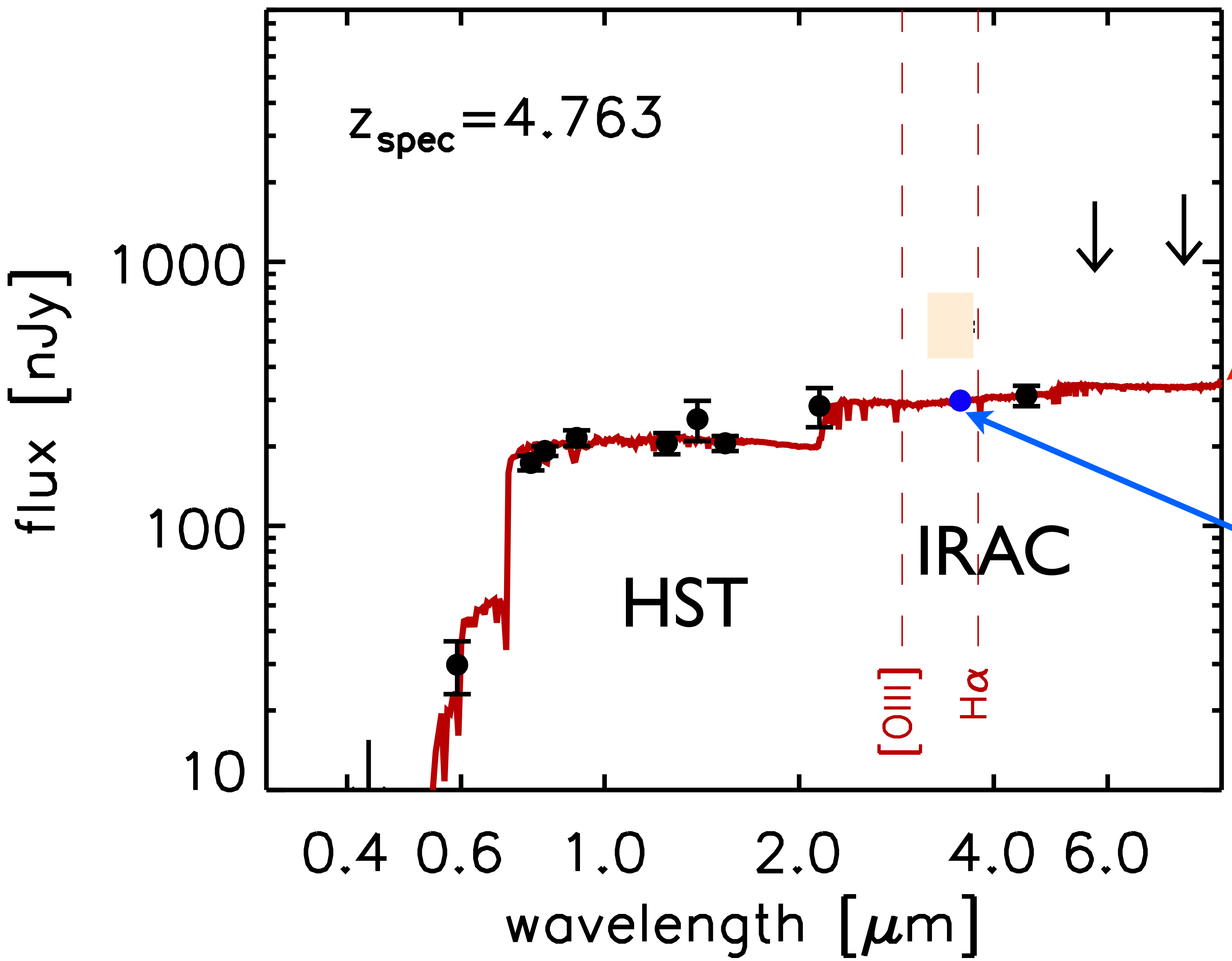

Fit to all bands but contaminated IRAC [3.6] band

Calculate Expected Model Continuum Flux without Hα contribution

Shim+2011; Stark+2013; de Barros+2014; Smit+2015; Marmol-Queralto+2015

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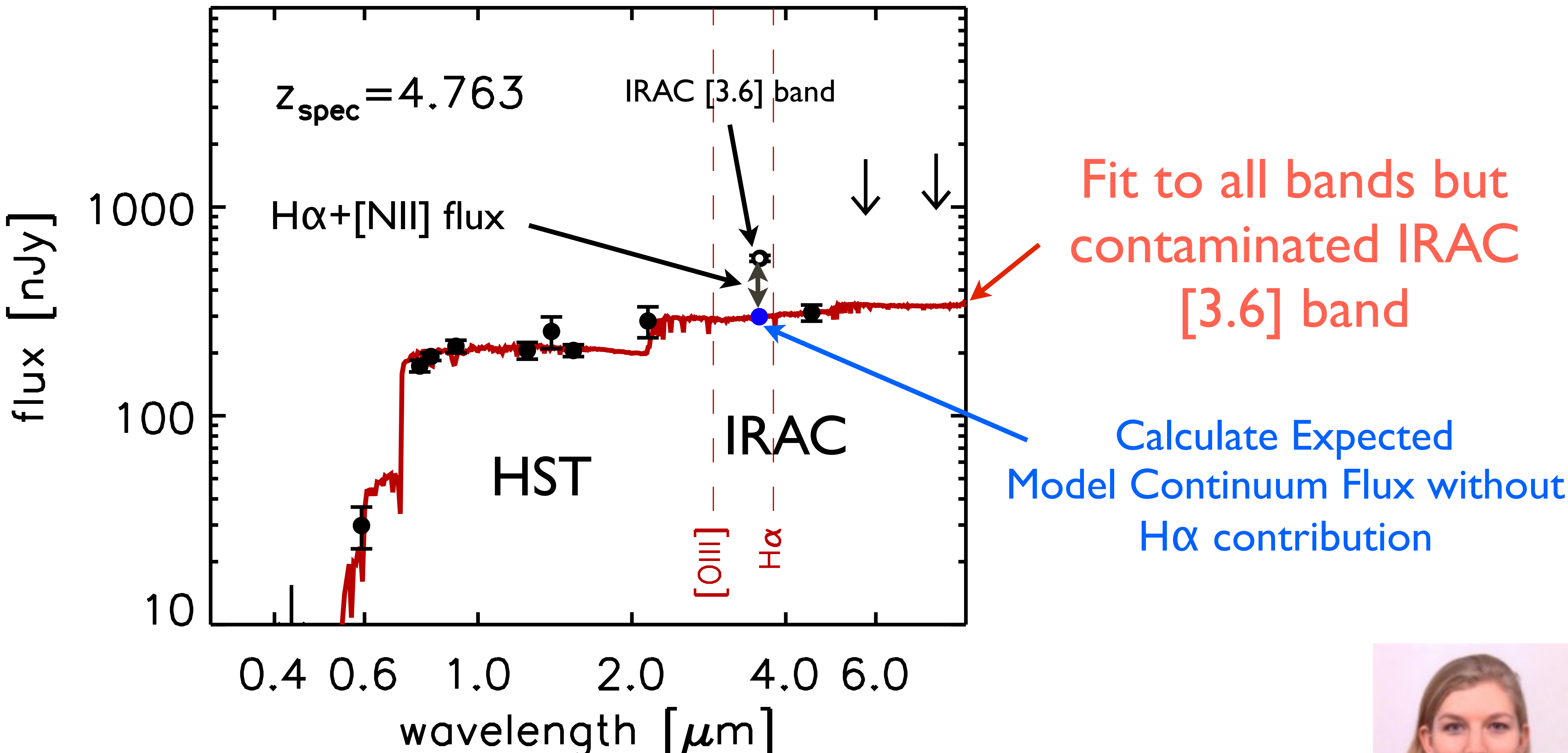

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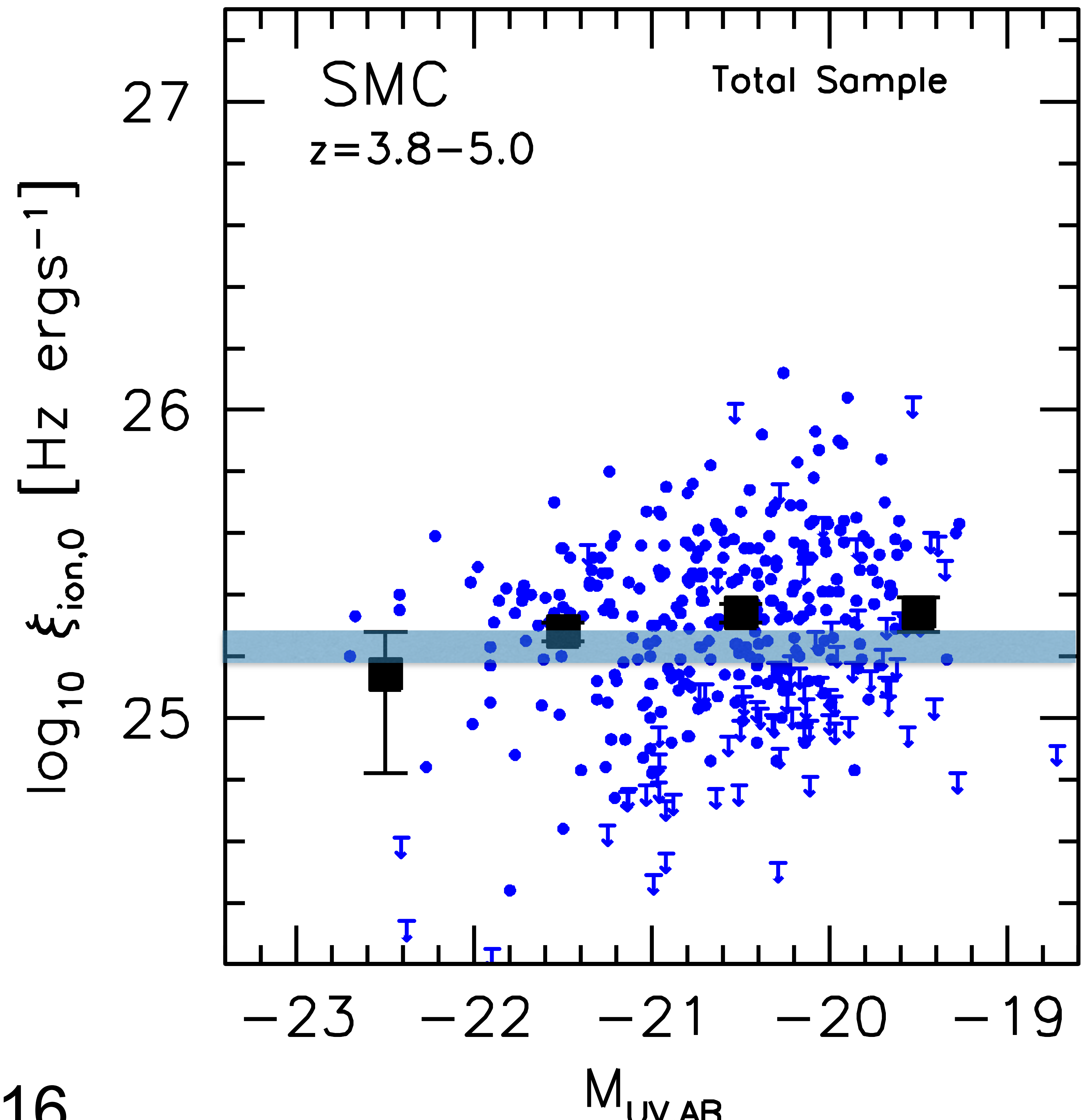
Measured Values for ξ_{ion}

Ionizing Photons per UV-continuum Photons



Bouwens+2016

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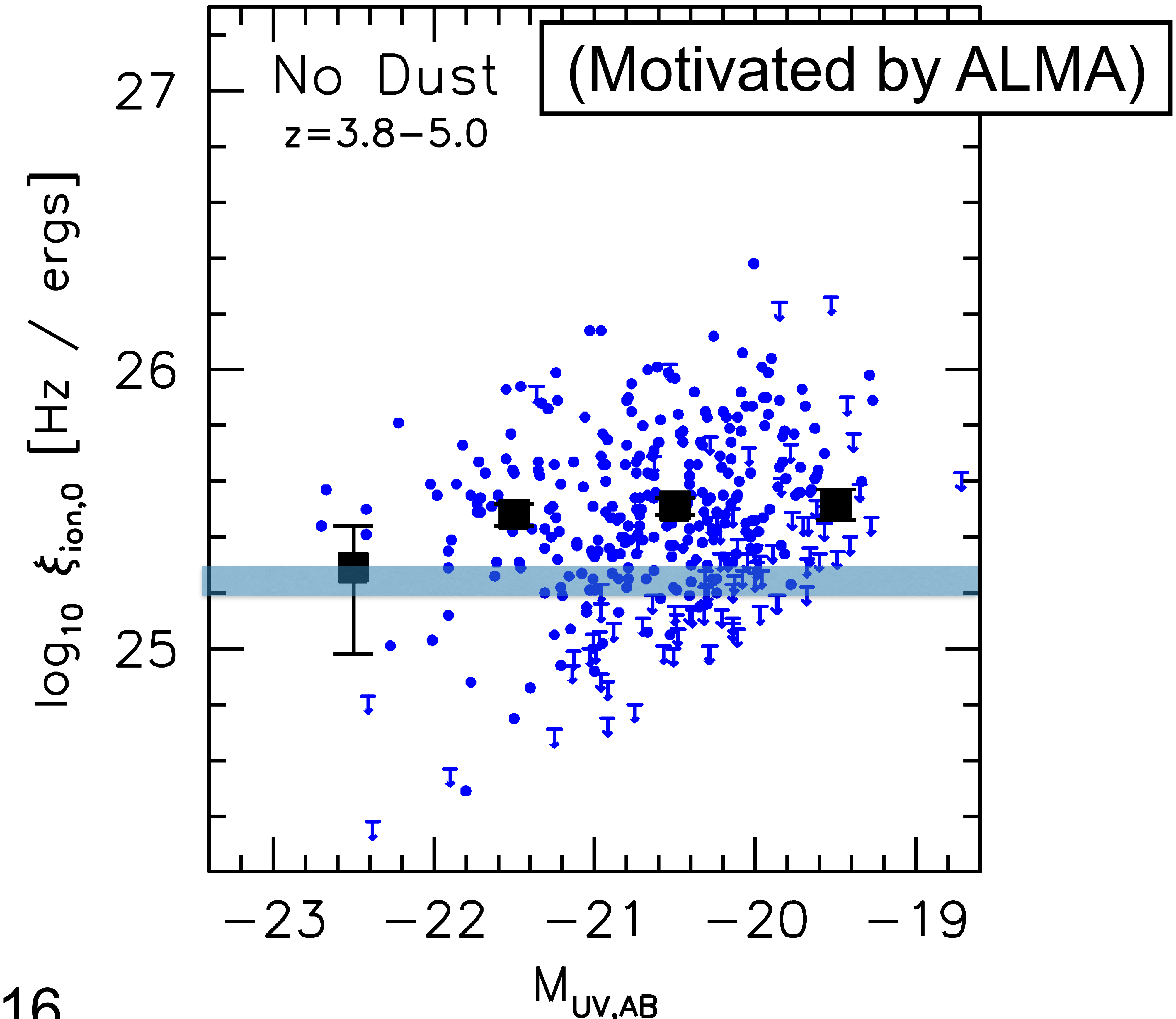
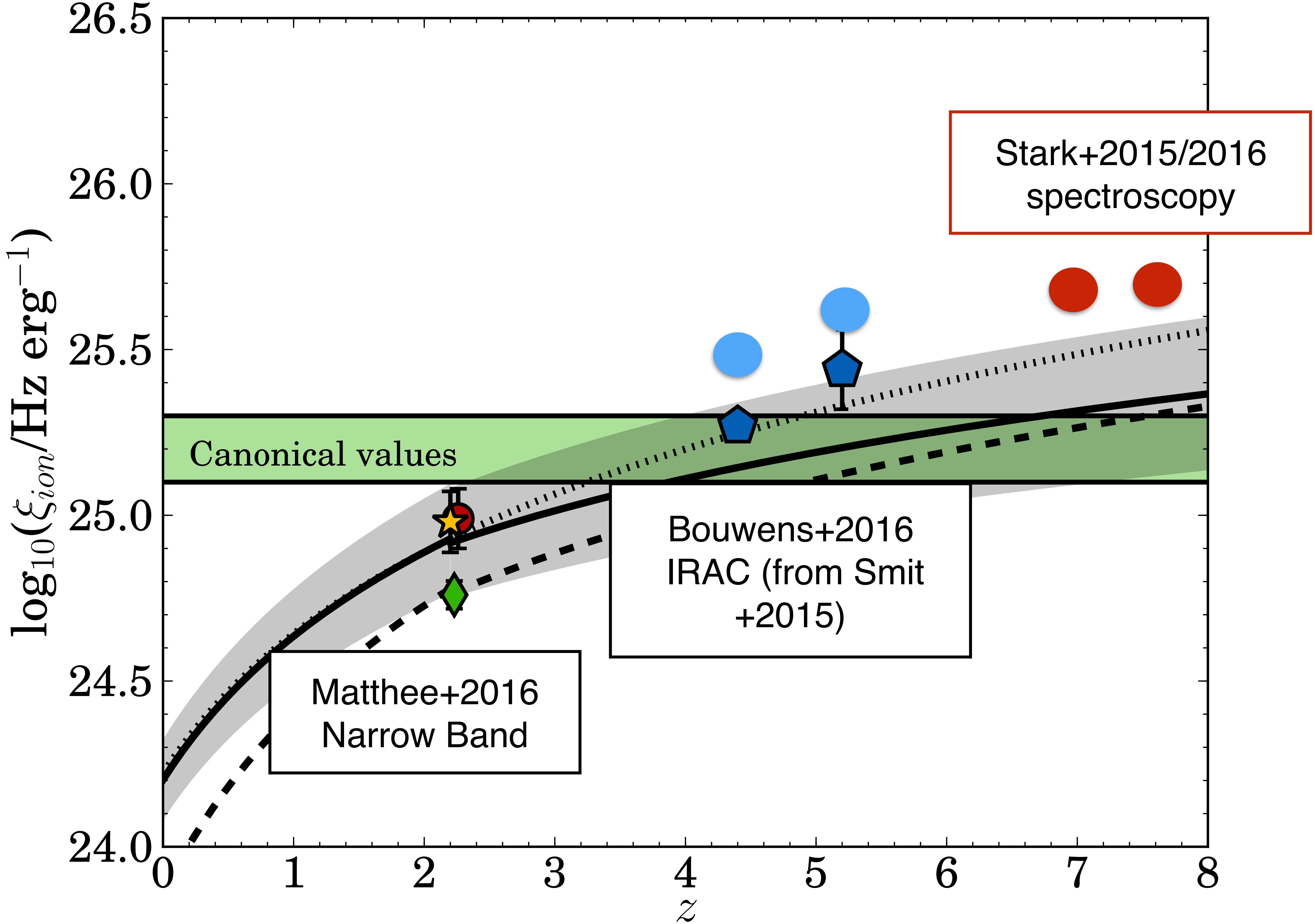


Ionizing Photons per UV-continuum Photons

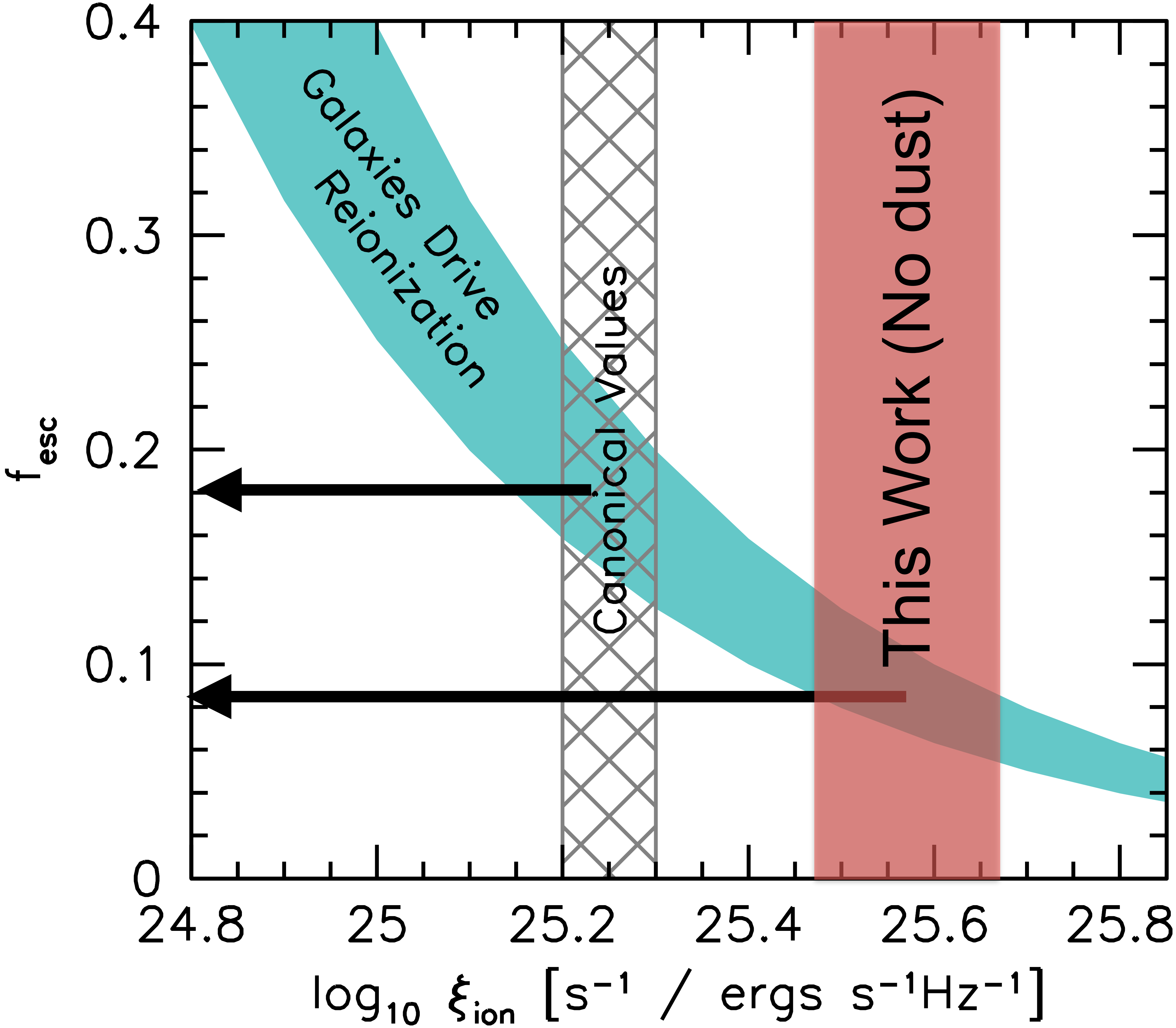
Bouwens+2016

Evolution of Lyman-Continuum Photon Production Efficiency



Stark+2015, 2016; Bouwens+2016; Matthee+2016

Higher ξ_{ion}'s Compatible with Lower f_{esc}



Bouwens+2016

Do Galaxies Reionize the Universe?

MEASUREABLE

VERY CHALLENGING

SOME PROGRESS

Counting the Ionizing Photons Galaxies Produce

UV luminosity density $\times$ ξ_{ion} $\times$ f_{esc}

(UV continuum inventory)

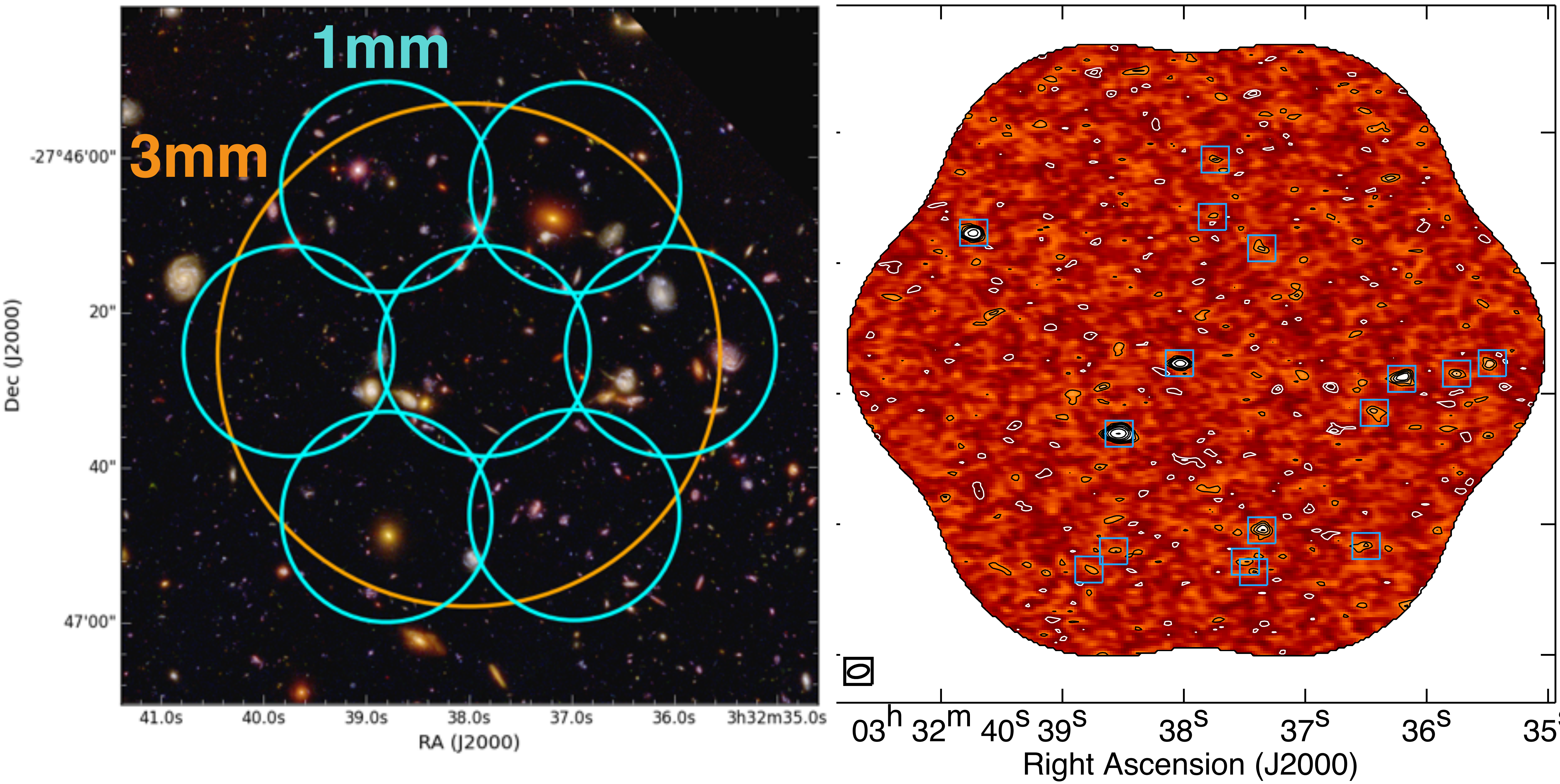
(conversion factor from UV to ionizing photons)

(fraction of ionizing photons which escape)

Why low dust?

ALMA UDF

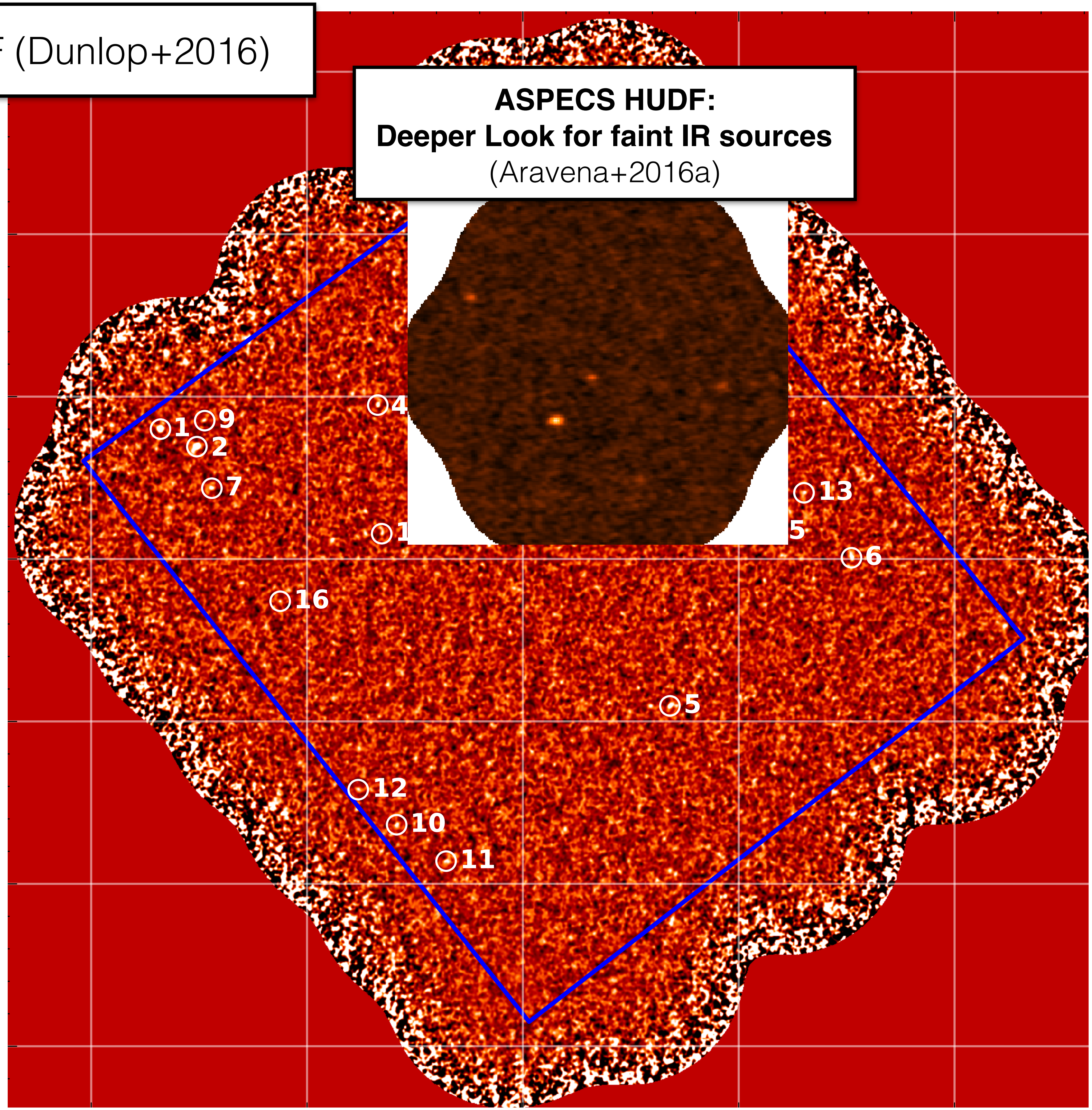
40h ALMA spectral scans of the UDF:
deepest maps so far (12.7 microJy rms)



Walter+, Aravena+, Decarli+, Bouwens+, Carilli+, submitted (May 2016)

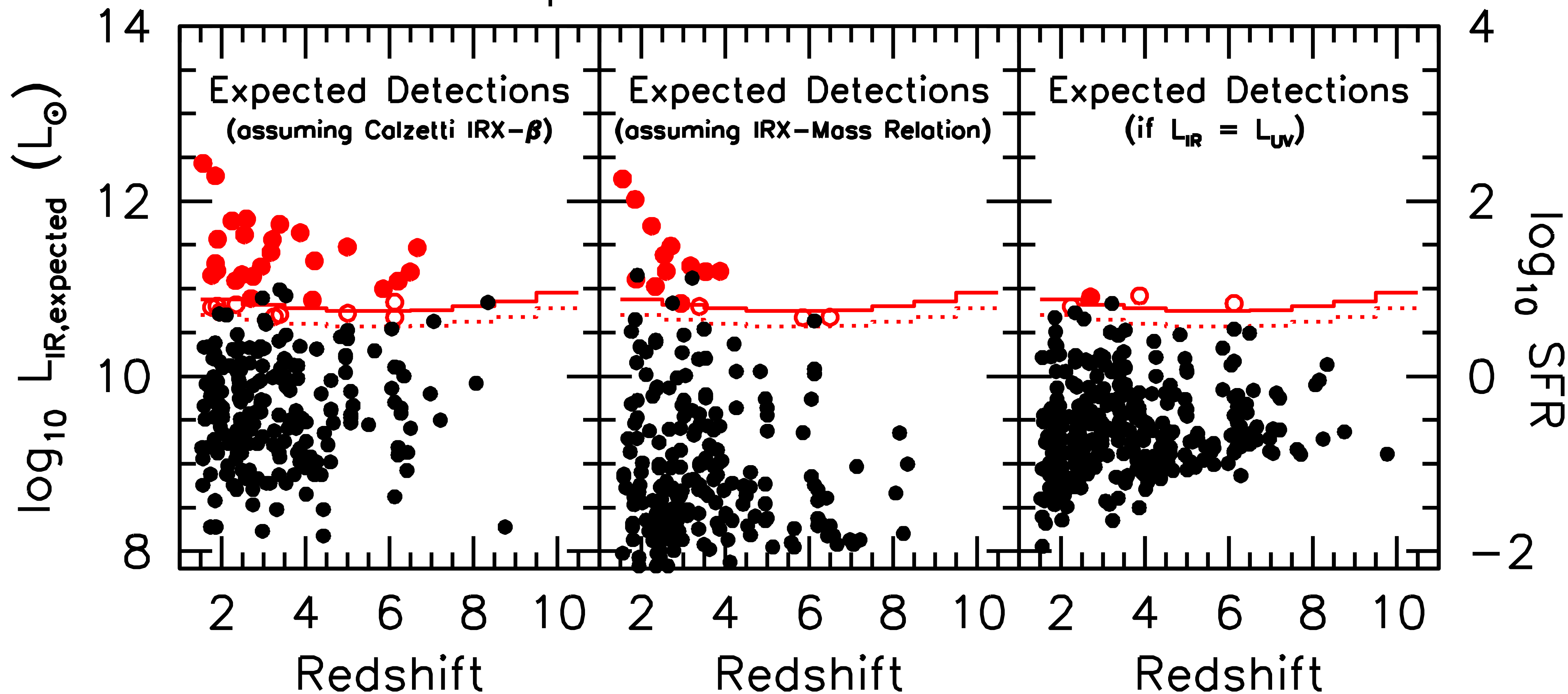
ALMA UDF

ALMA HUDF (Dunlop+2016)



ALMA UDF

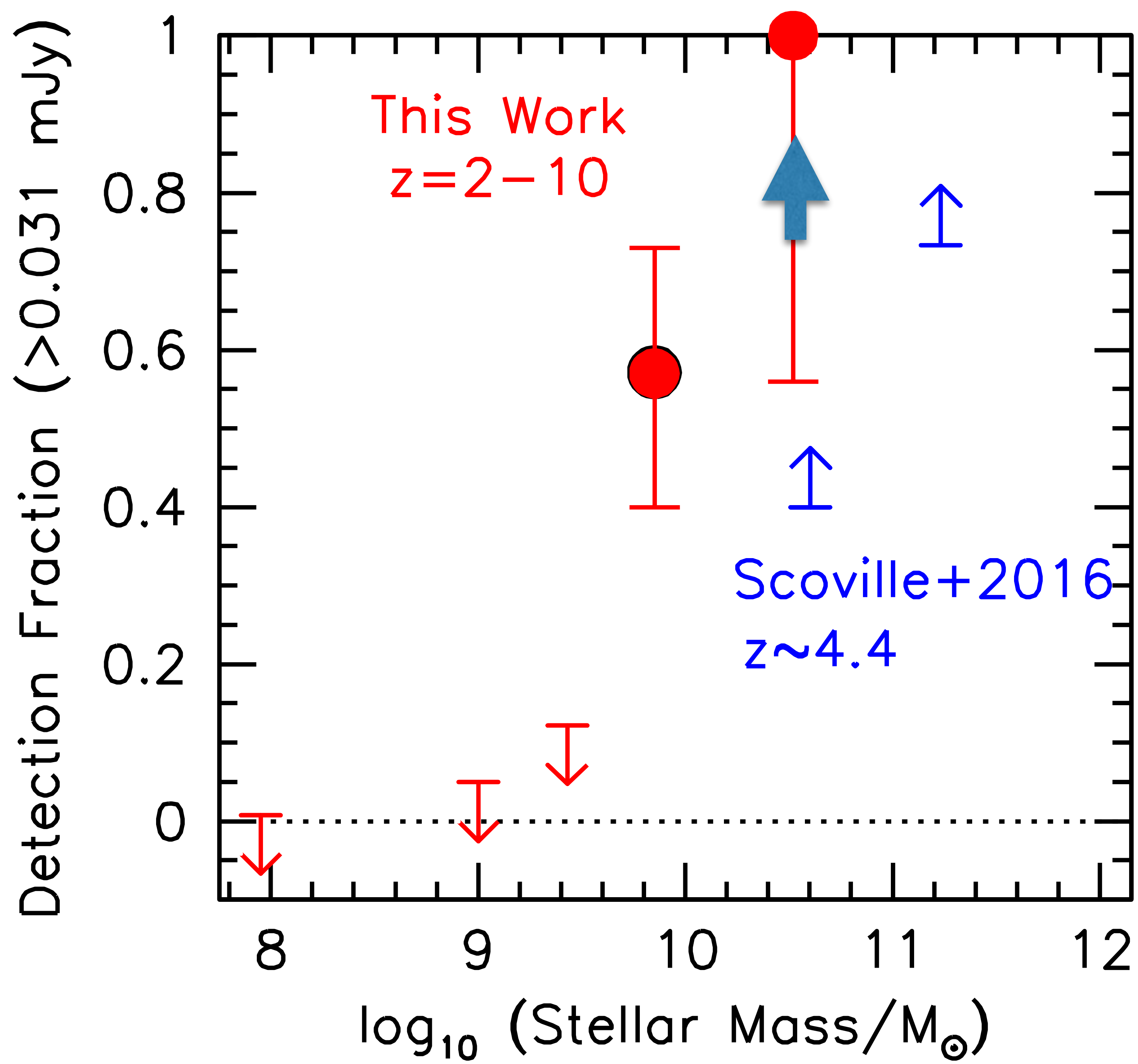
Many Dust-Continuum Detections Expected for HUDF samples of z=2-10 Galaxies



Bouwens et al., Walter et al., Aravena et al., Decarli et al., submitted (May 2016)

ALMA UDF

Only the highest-mass sources are individually detected!



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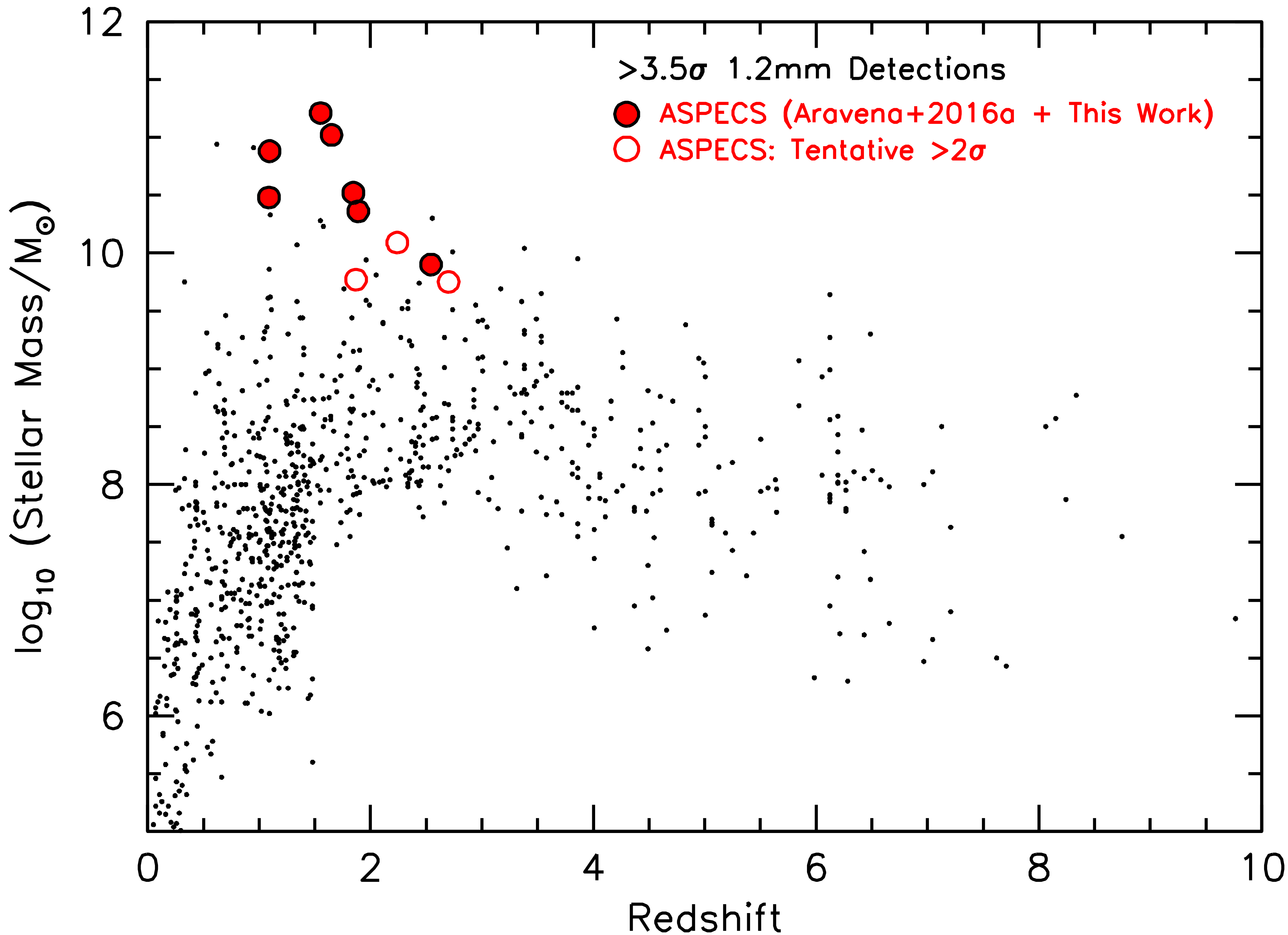

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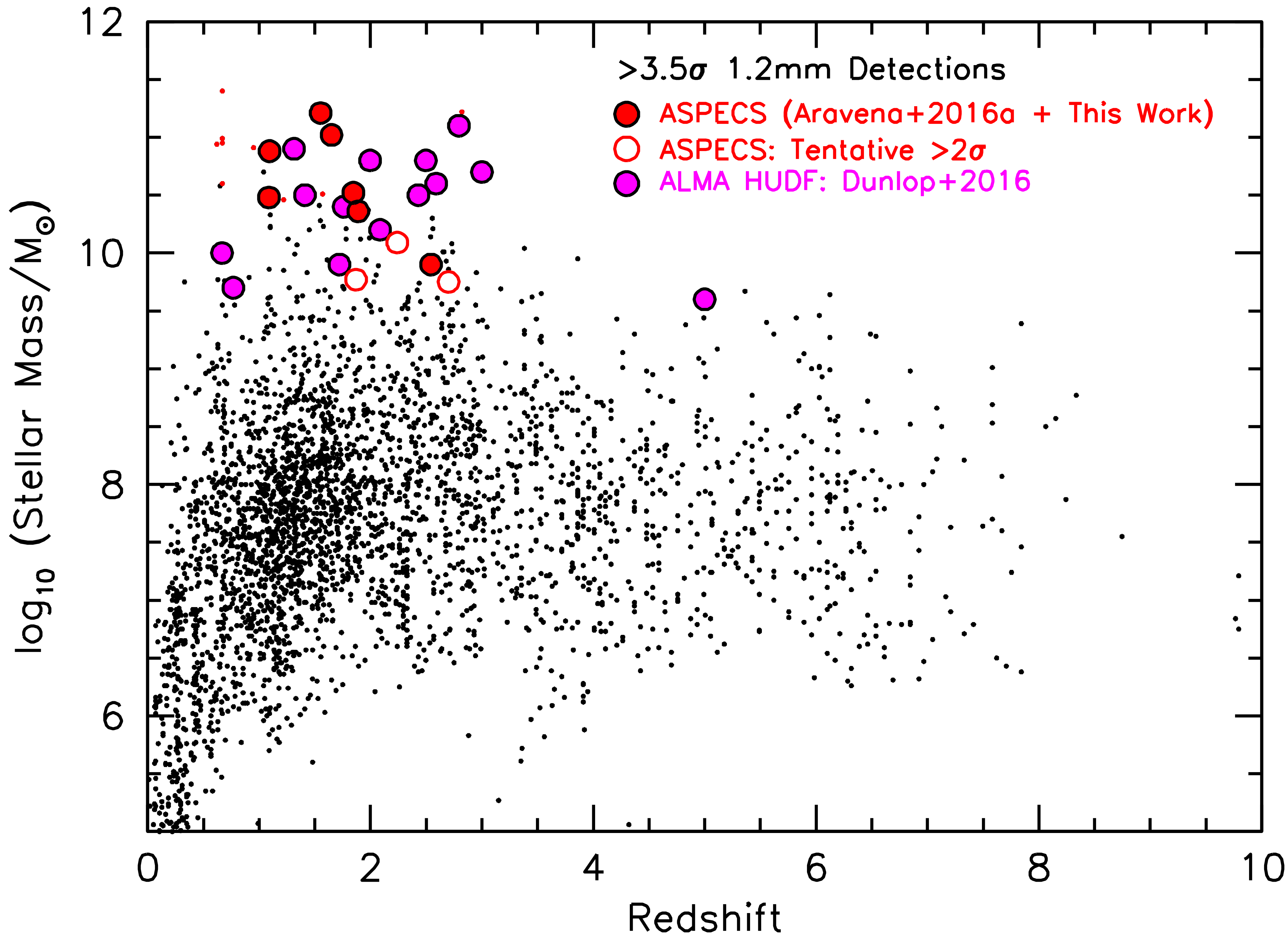
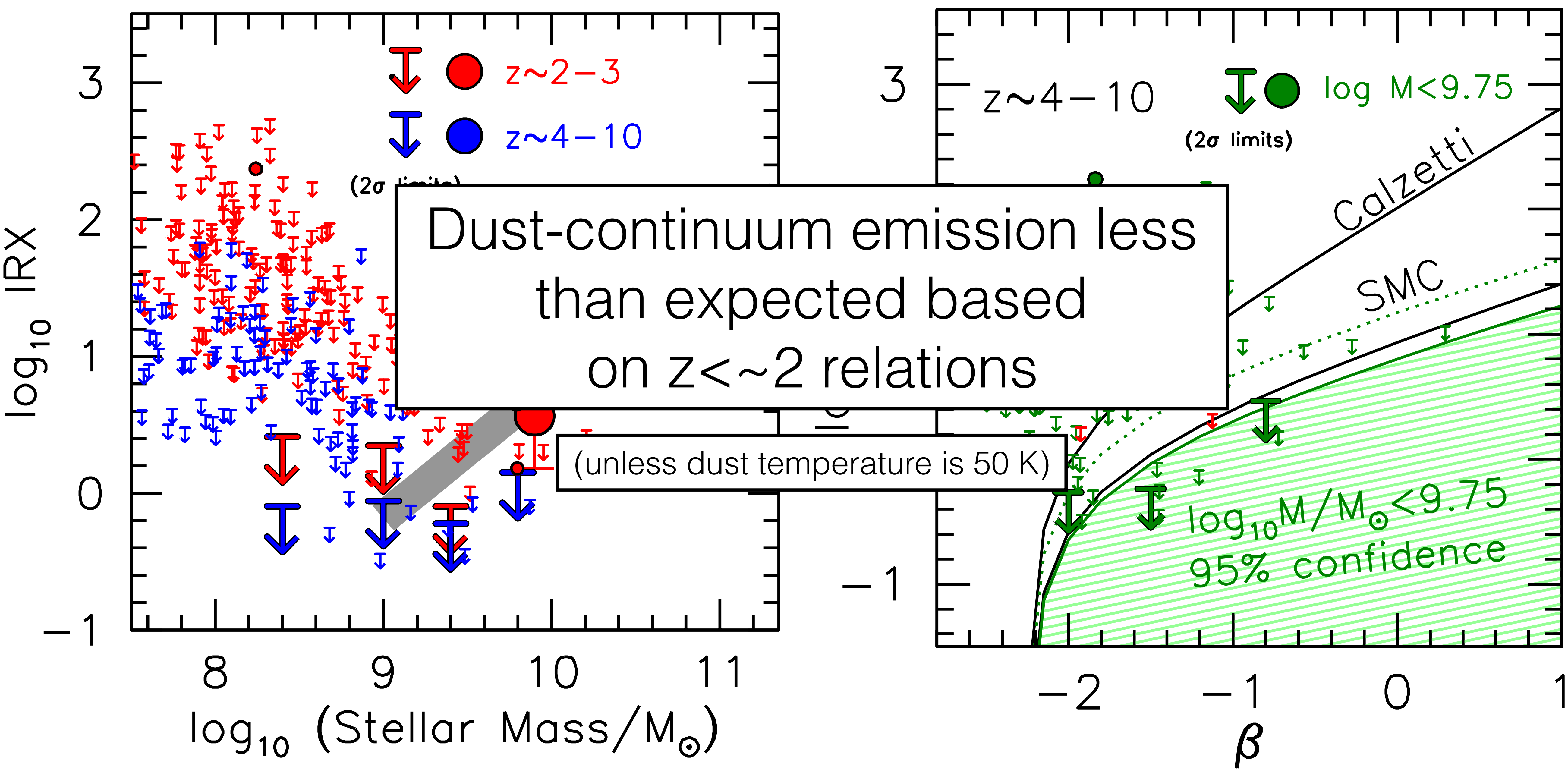


Bouwens et al., Walter et al., Aravena et al., Decarli et al., submitted (May 2016)

ALMA UDF

Stack sources to derive IRX (L_{IR}/L_{UV}) vs. stellar mass and beta



Bouwens et al., Walter et al., Aravena et al., Decarli et al., submitted (May 2016)

(IRX-Stellar Mass: Panella+2009, 2015; Reddy+2010; Whitaker+2014; Alvarez-Marquez+2016)

Putting it altogether

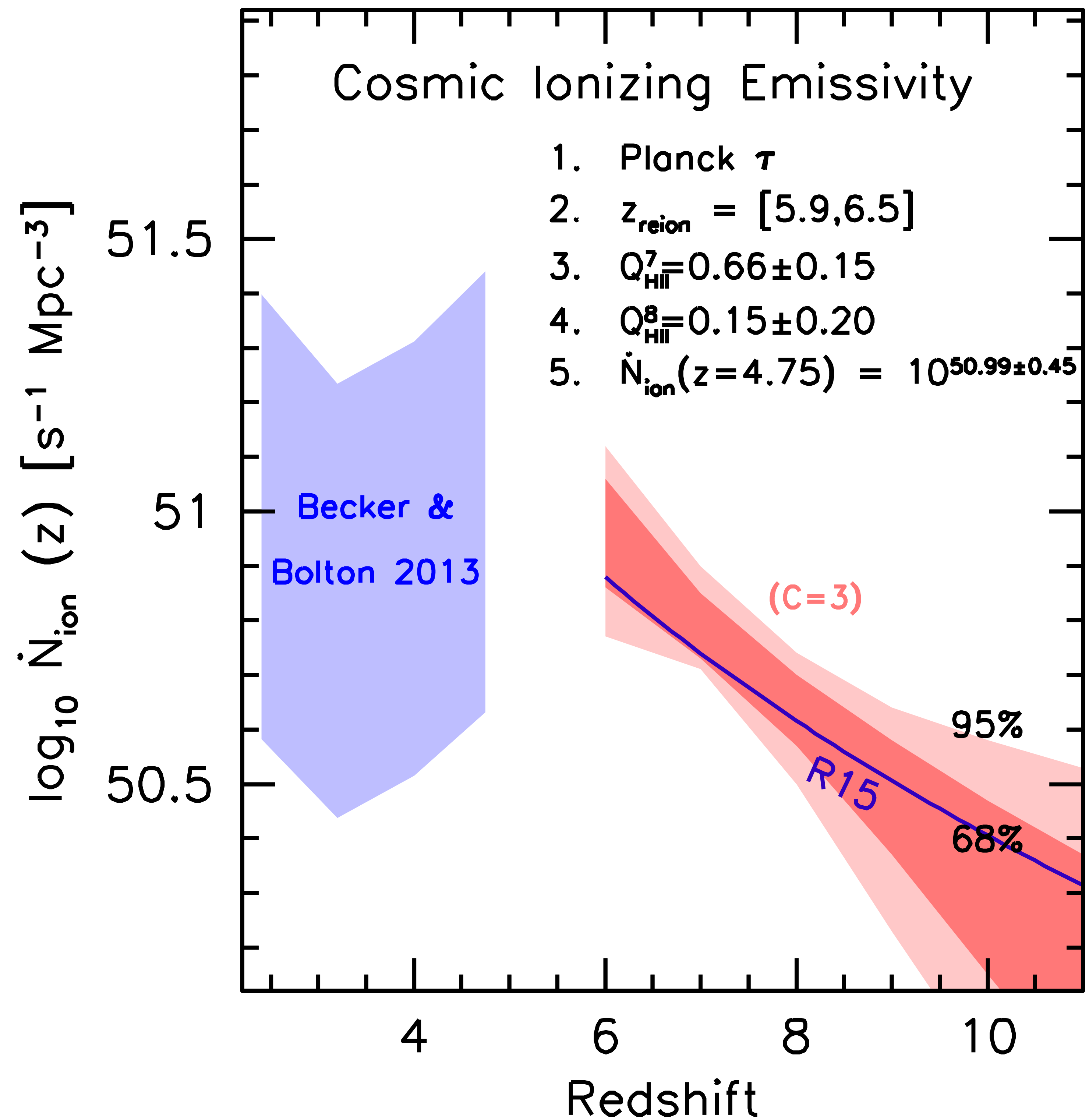
Do current constraints from galaxies agree with the inferred evolution on the ionizing emissivity?

Do current constraints from galaxies agree with the evolution on the ionizing emissivity?

We can infer the evolution regarding the evolution of the ionizing emissivity using a simple two parameter model and the following constraints:

1. Planck tau
2. Reionization finishes no later than z=5.9-6.5
3. Constraints from prevalence of Lyman alpha emitters
4. Continuity with constraints on ionizing background

Incorporate Planck 2016 constraints!



Bouwens et al. 2015; Bouwens et al., 2016, in prep; see also Mitra+2011, 2012, 2013, 2015, 2016

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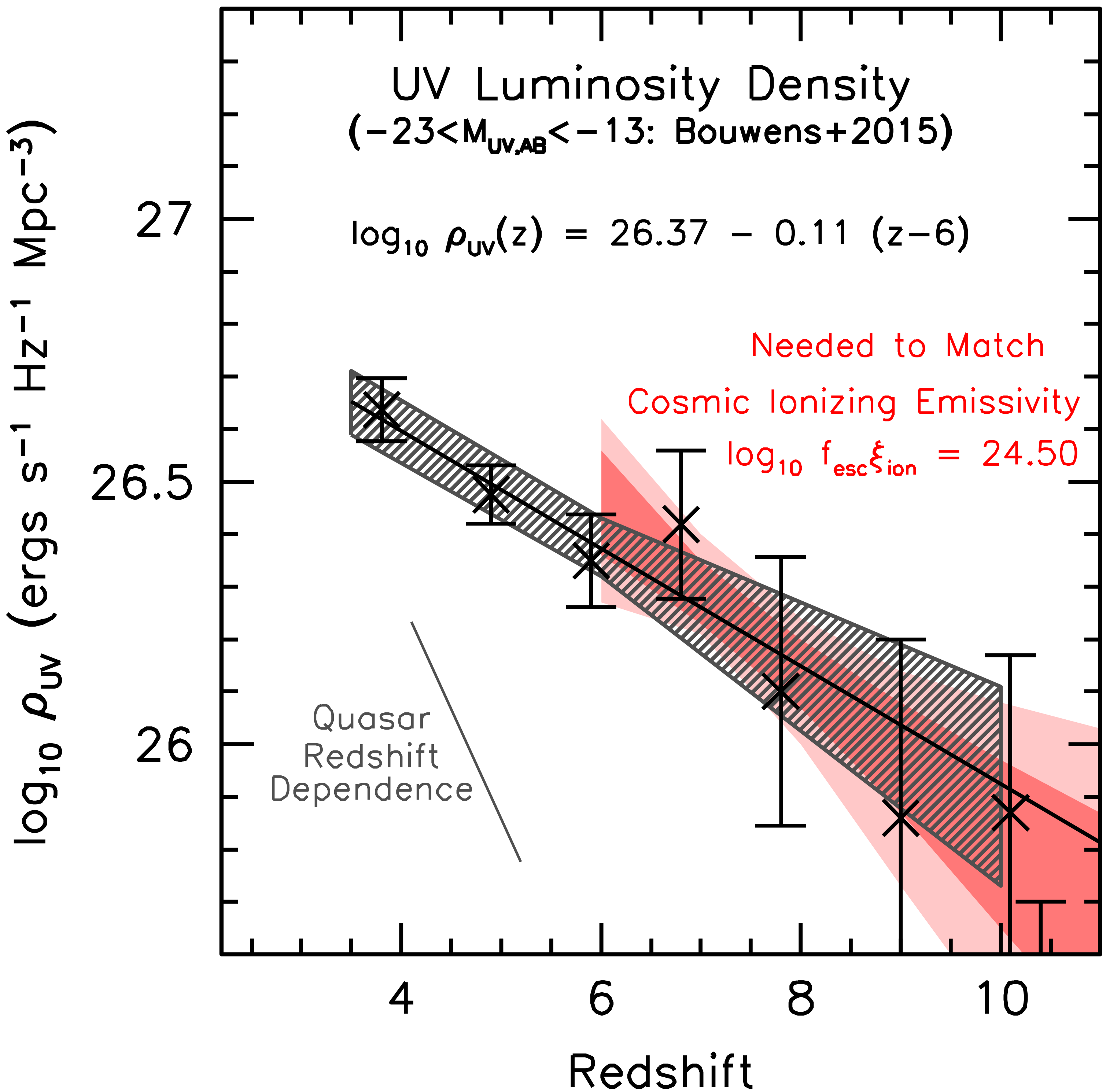

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Key Points

Lyman-Continuum Photon Production Efficiency:

Directly Measurable in z~4-5 Galaxies from IRAC

May be ~2x larger than typically assumed (if dust very low)

Ultra-Faint Extension to z~6 UV Luminosity Functions:

Hubble Frontier Fields Data Set can Potentially Probe Very Faint Galaxies

Uncertainties Very Large!, but current Samples suggestive of significant population of especially faint galaxies

Dust-continuum Emission from z=2-10 Galaxies

Stellar Mass is Particularly Useful Predictor of IR emission, almost all massive galaxies are detected with ALMA

IRX-β for typical low-mass galaxies at z>~2 is ~SMC or below