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

Rychard J. Bouwens

Leiden University

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

Heidelberg, Germany — June 28, 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 (UV continuum inventory) x $\xi_{ion}$ (conversion factor from UV-continuum to ionizing photons) x $f_{esc}$ (fraction of ionizing photons which escape)

Ionizing Emissivity

# Do Galaxies Reionize the Universe?

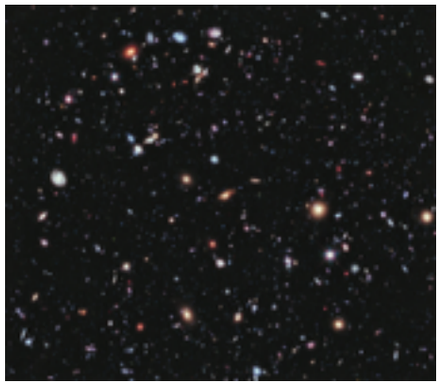
Counting the Ionizing Photons Galaxies Produce

UV luminosity density (UV continuum inventory) x $\xi_{ion}$ (conversion factor from UV-continuum to ionizing photons) x $f_{esc}$ (fraction of ionizing photons which escape)

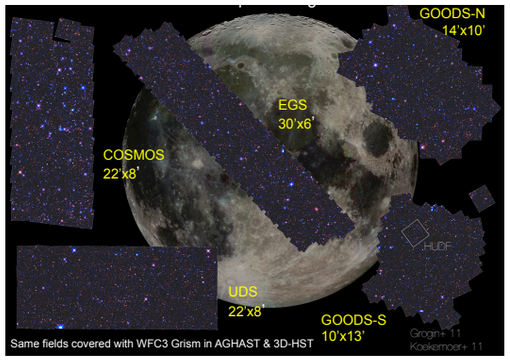
Ionizing Emissivity

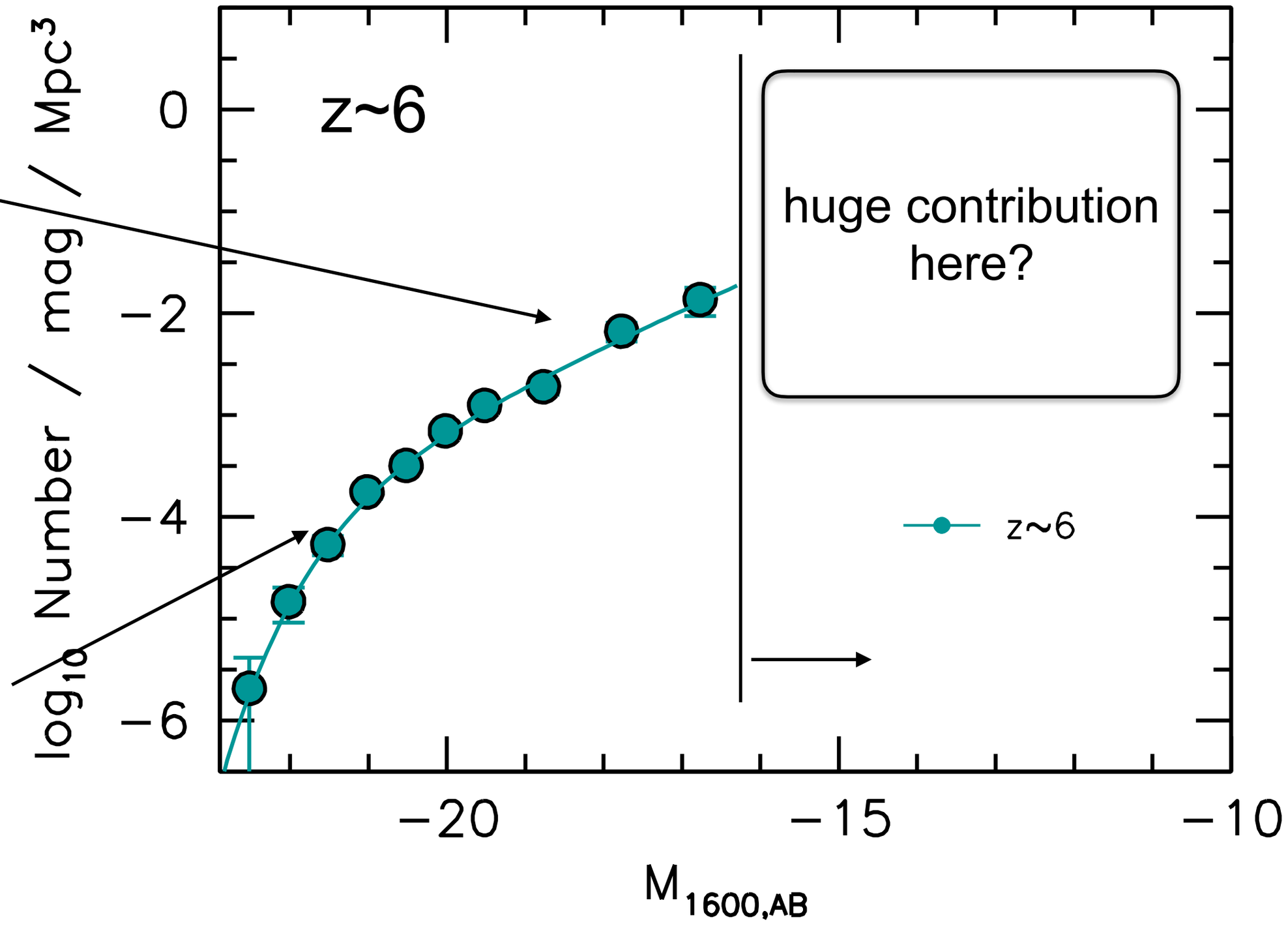
# How many UV-continuum photons do galaxies produce?

HUDF



CANDELS
(or better yet
UltraVISTA/UDS)



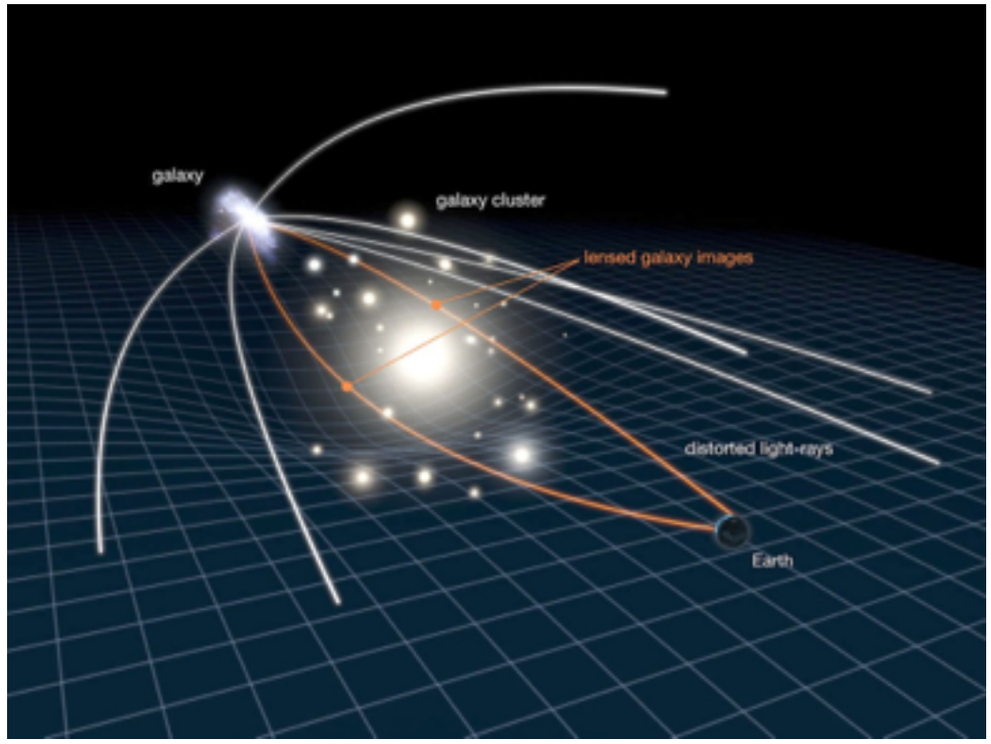




Bouwens+2015; see also McLure+2013; Bowler+2015; Finkelstein+2015

# 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

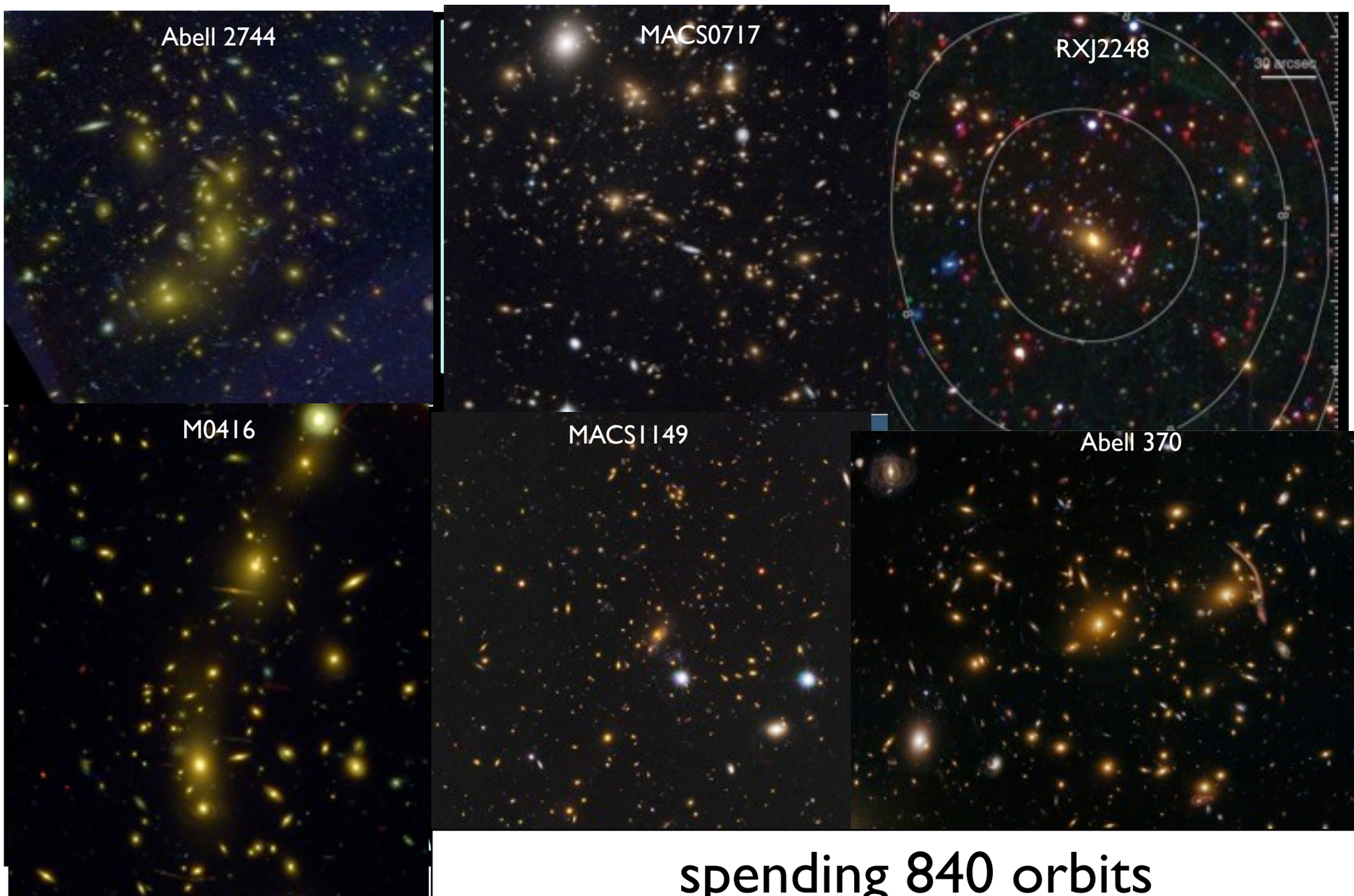

Integrate for 140 orbits with Hubble

70 orbits in the optical

70 orbits in the near-IR

# What is the trick to try to push fainter?

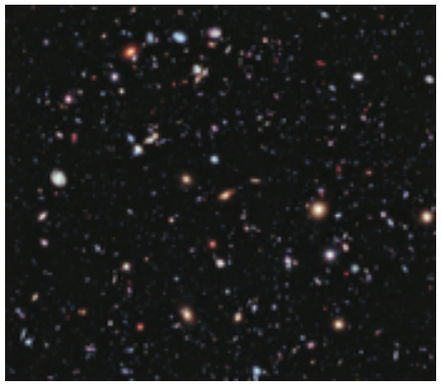
3. Repeat this trick over six massive clusters to improve the statistics and control for cosmic variance



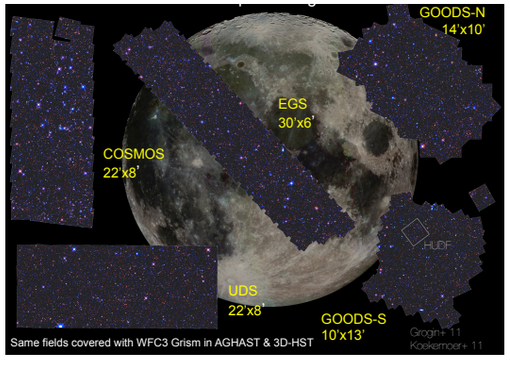

spending 840 orbits

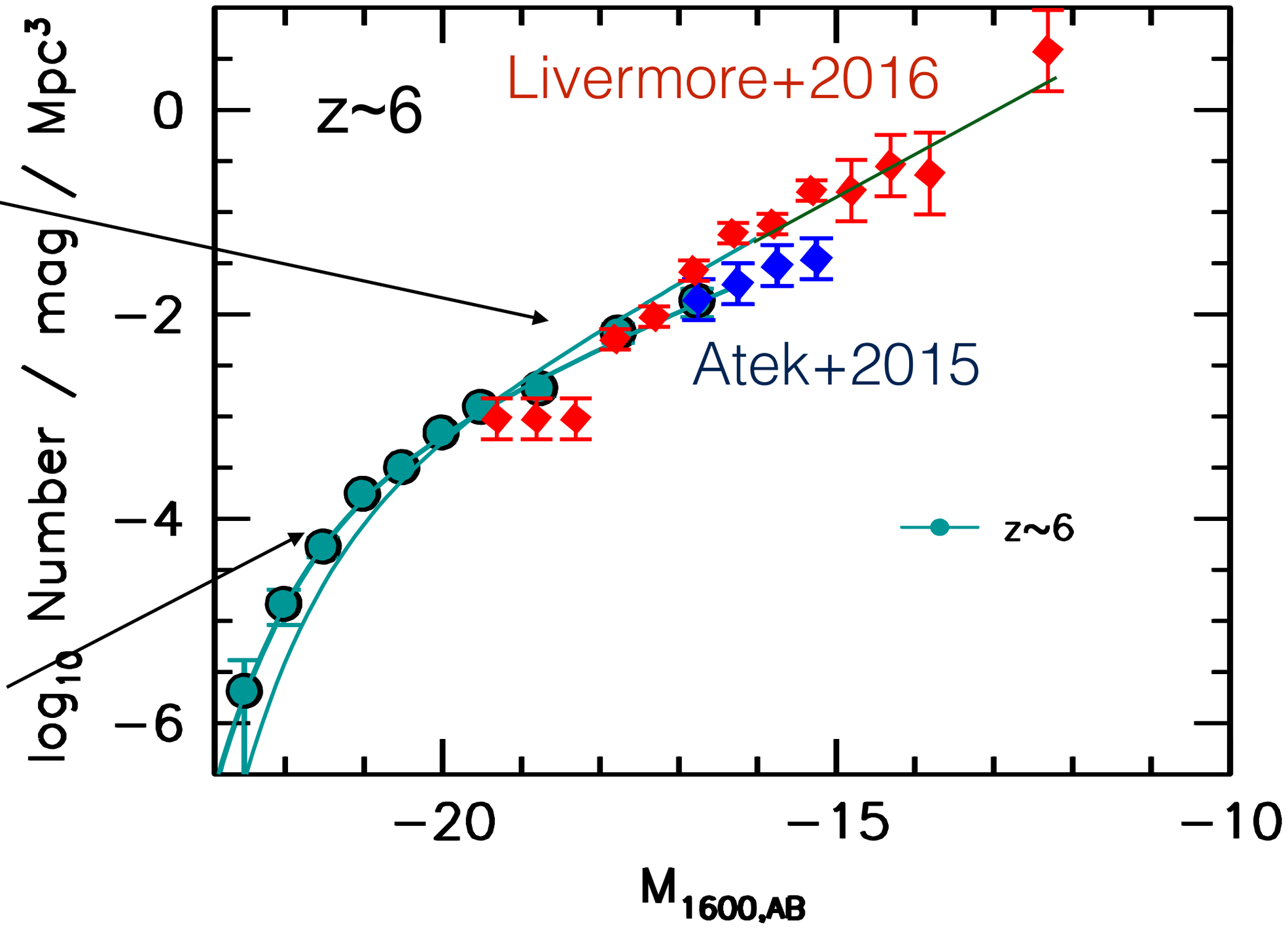
# How many UV-continuum photons do galaxies produce?

HUDF



CANDELS
(or better yet
UltraVISTA/UDS)




Bouwens+2015

# Do Galaxies Reionize the Universe?

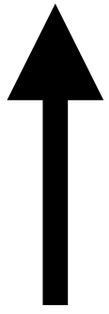
Counting the Ionizing Photons Galaxies Produce

UV luminosity density x $\xi_{ion}$ x $f_{esc}$

(UV continuum inventory)

(conversion factor from UV to ionizing photons)

(fraction of ionizing photons which escape)



# Measuring $\xi_{ion}$ (# 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)

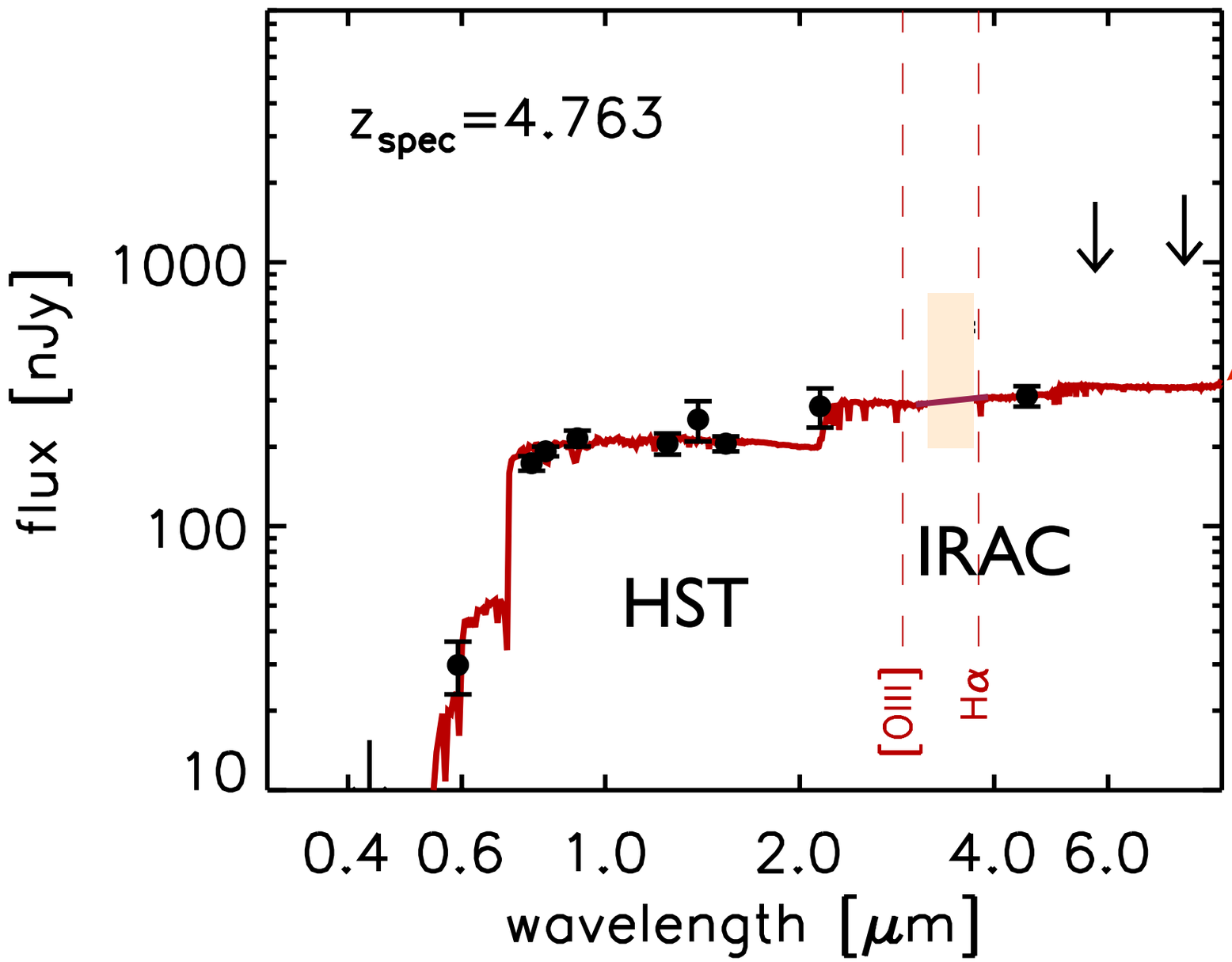
How can we measure the total UV-continuum luminosity for stars in a galaxy?

## 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

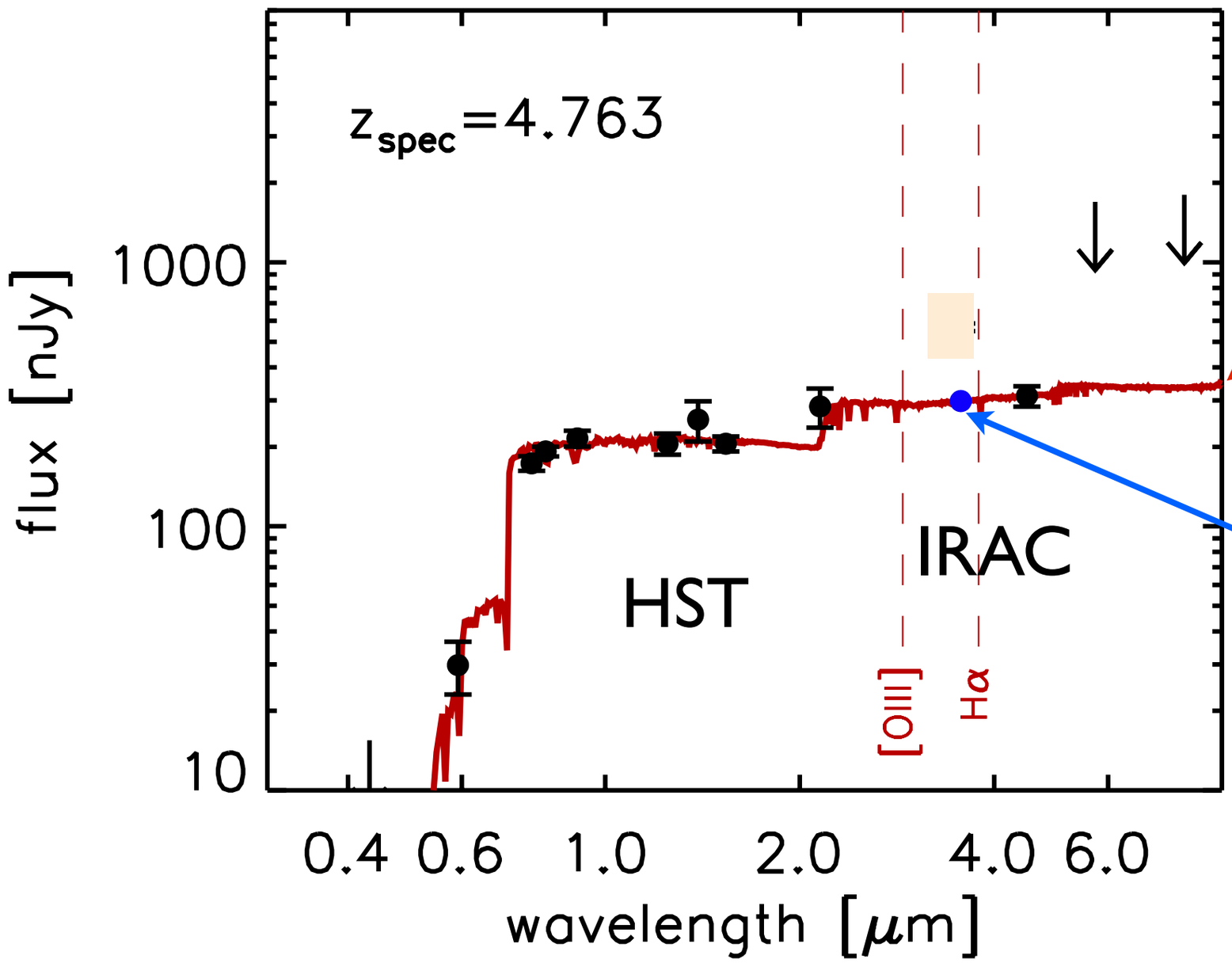



Fit to all bands but contaminated IRAC [3.6] band

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

# 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



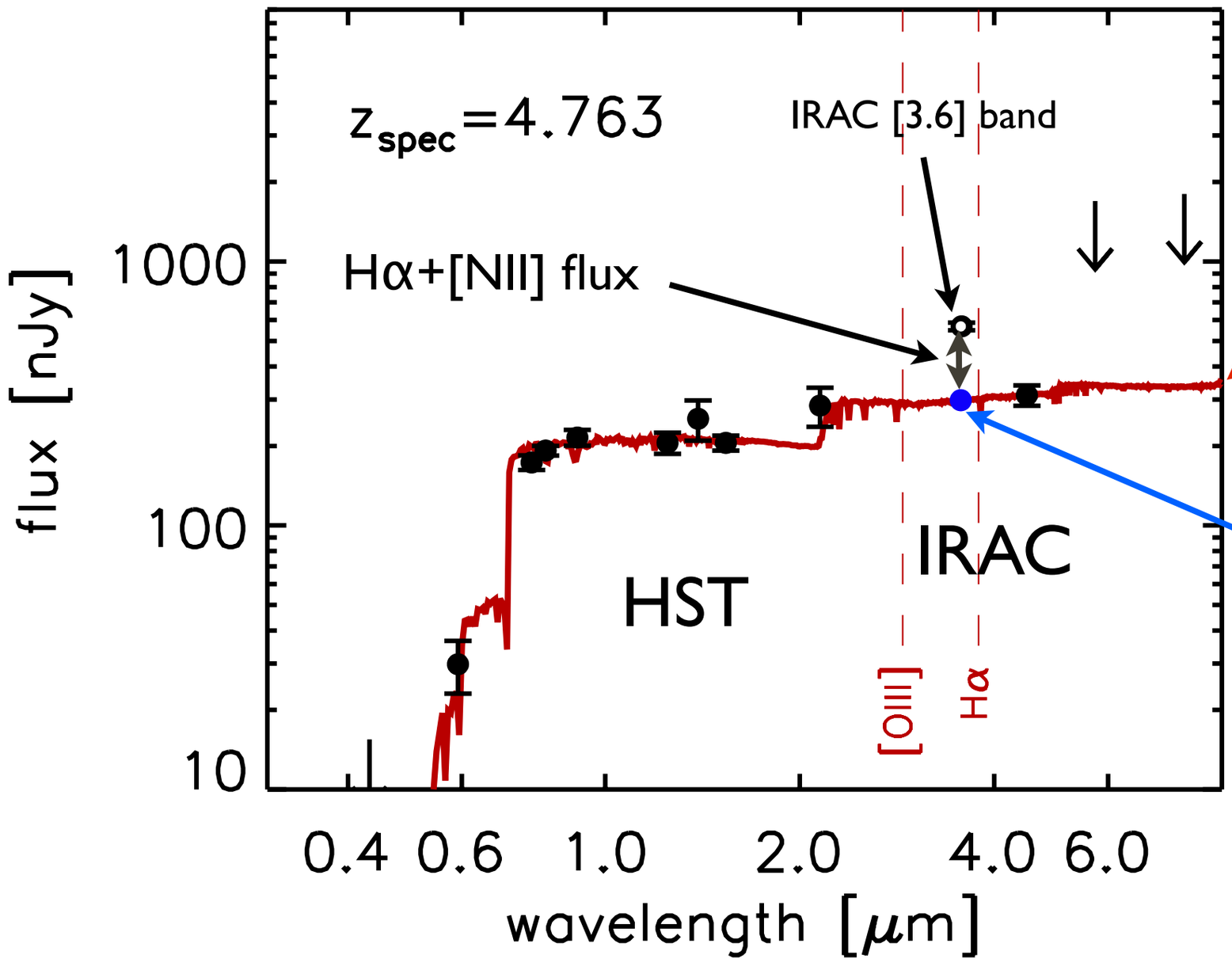

Fit to all bands but contaminated IRAC [3.6] band

Calculate Expected Model Continuum Flux without Hα contribution

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

# 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



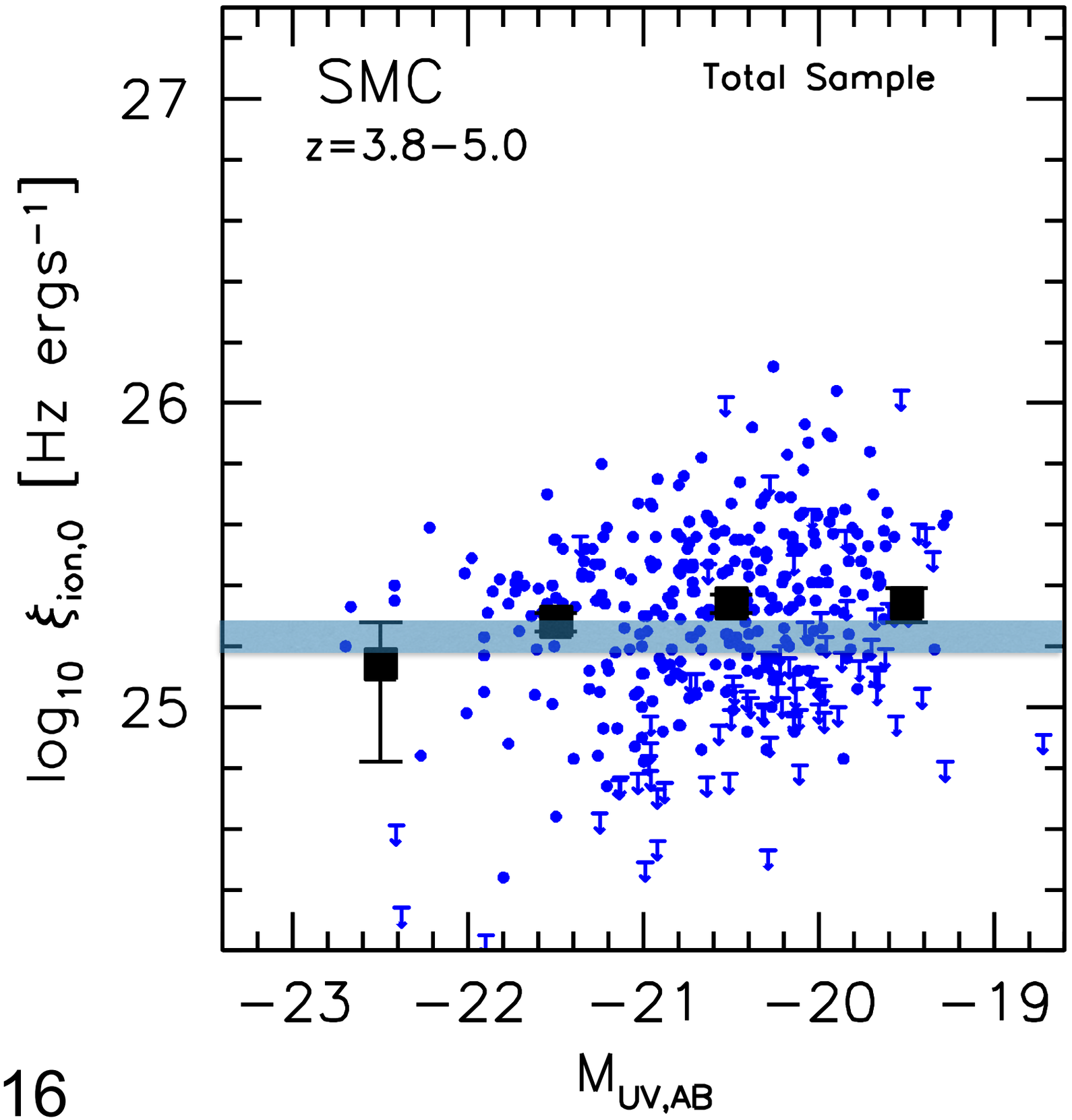

Fit to all bands but contaminated IRAC [3.6] band

Calculate Expected Model Continuum Flux without Hα contribution

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

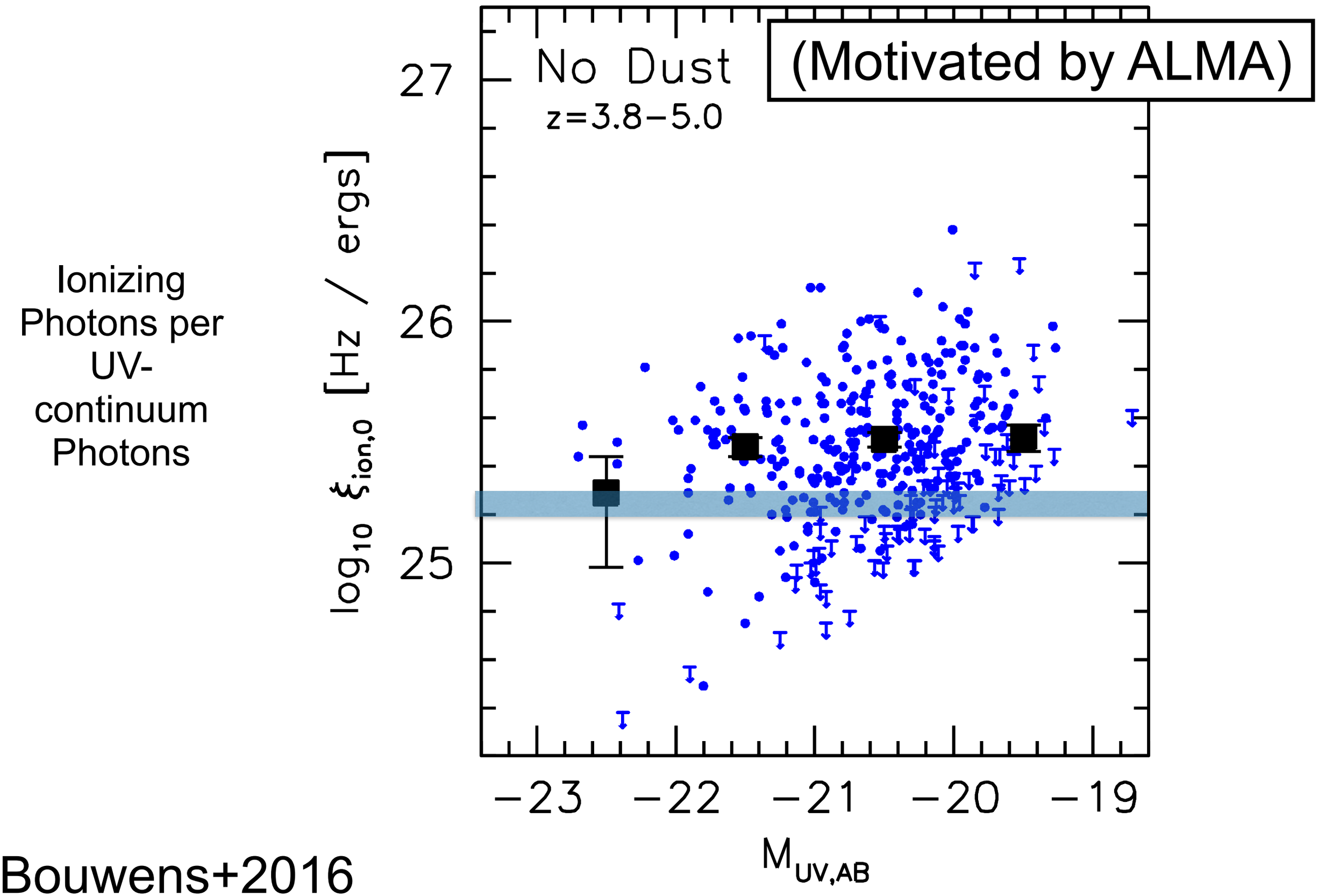
# Measured Values for $\xi_{ion}$

Ionizing Photons per UV-continuum Photons



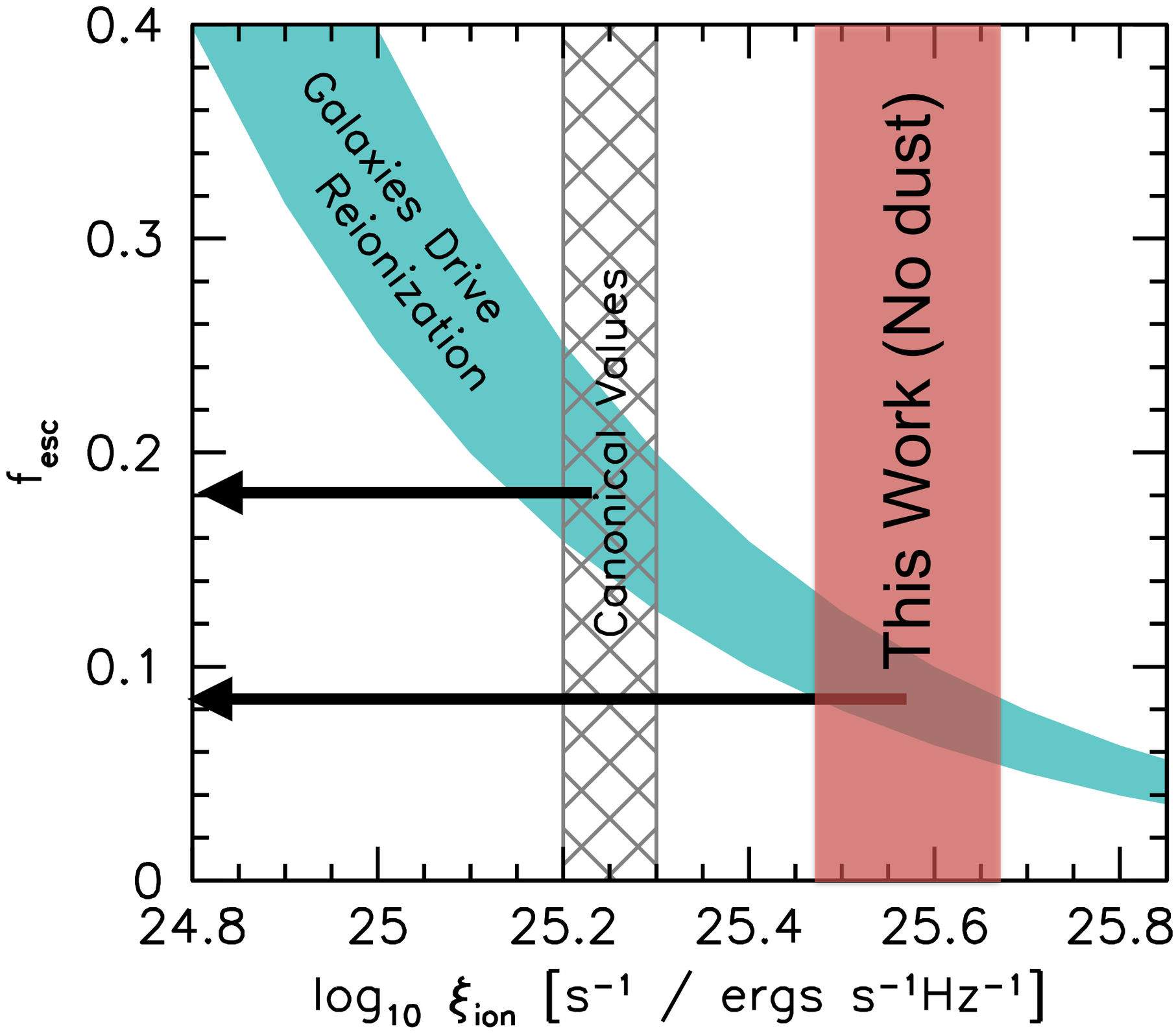

Bouwens+2016

# Measured Values for $\xi_{ion}$




Bouwens+2016

# Higher $\xi_{ion}$ 's Compatible with Lower $f_{esc}$




Bouwens+2016

# Do Galaxies Reionize the Universe?

**SOME PROGRESS** | **MEASUREABLE** | **VERY CHALLENGING**

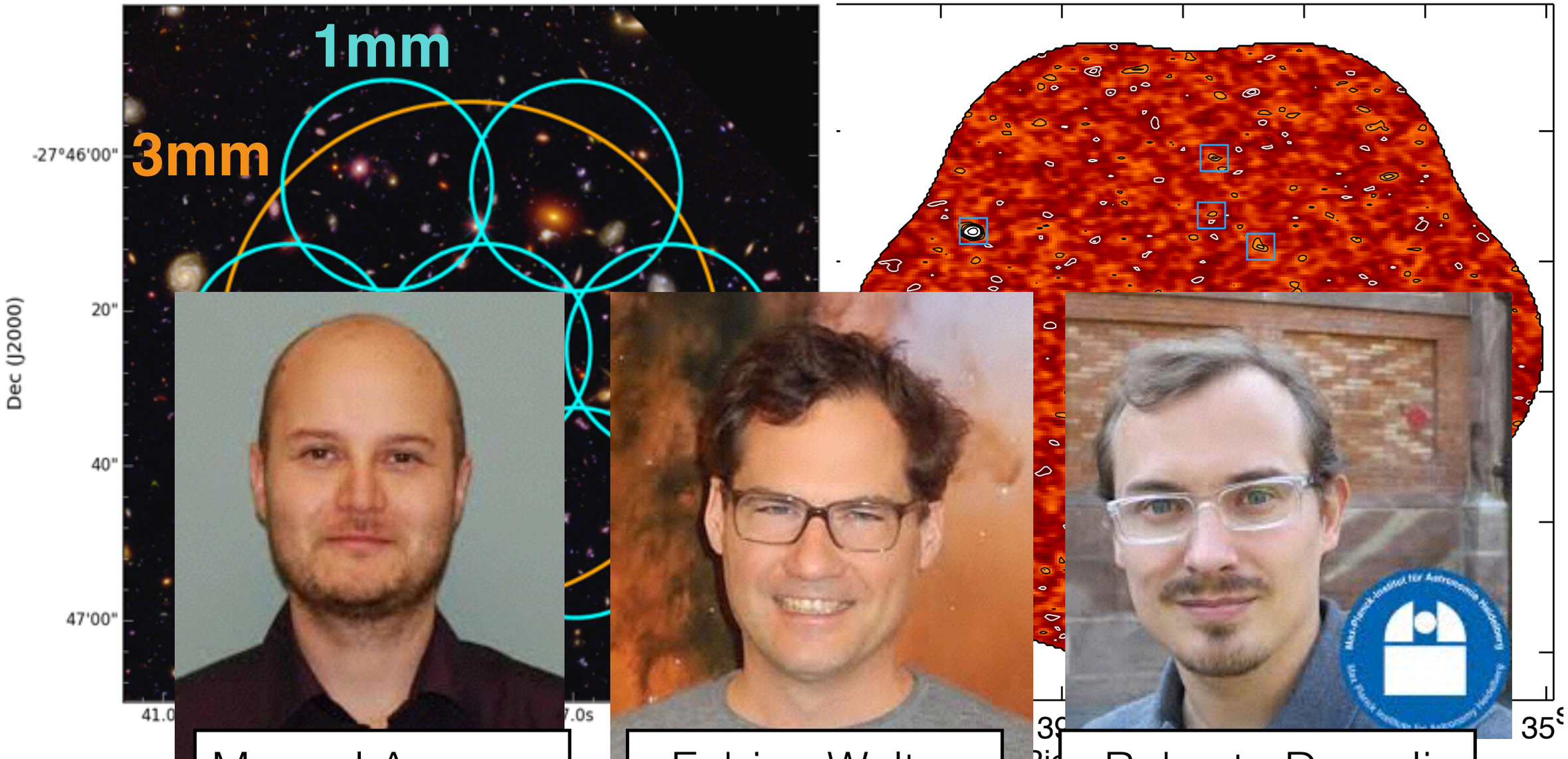
Counting the Ionizing Photons Galaxies Produce

UV luminosity density (UV continuum inventory) x $\xi_{ion}$ (conversion factor from UV to ionizing photons) x $f_{esc}$ (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)




Manuel Aravena
PI: Band-6

Fabian Walter
PI: Band-3

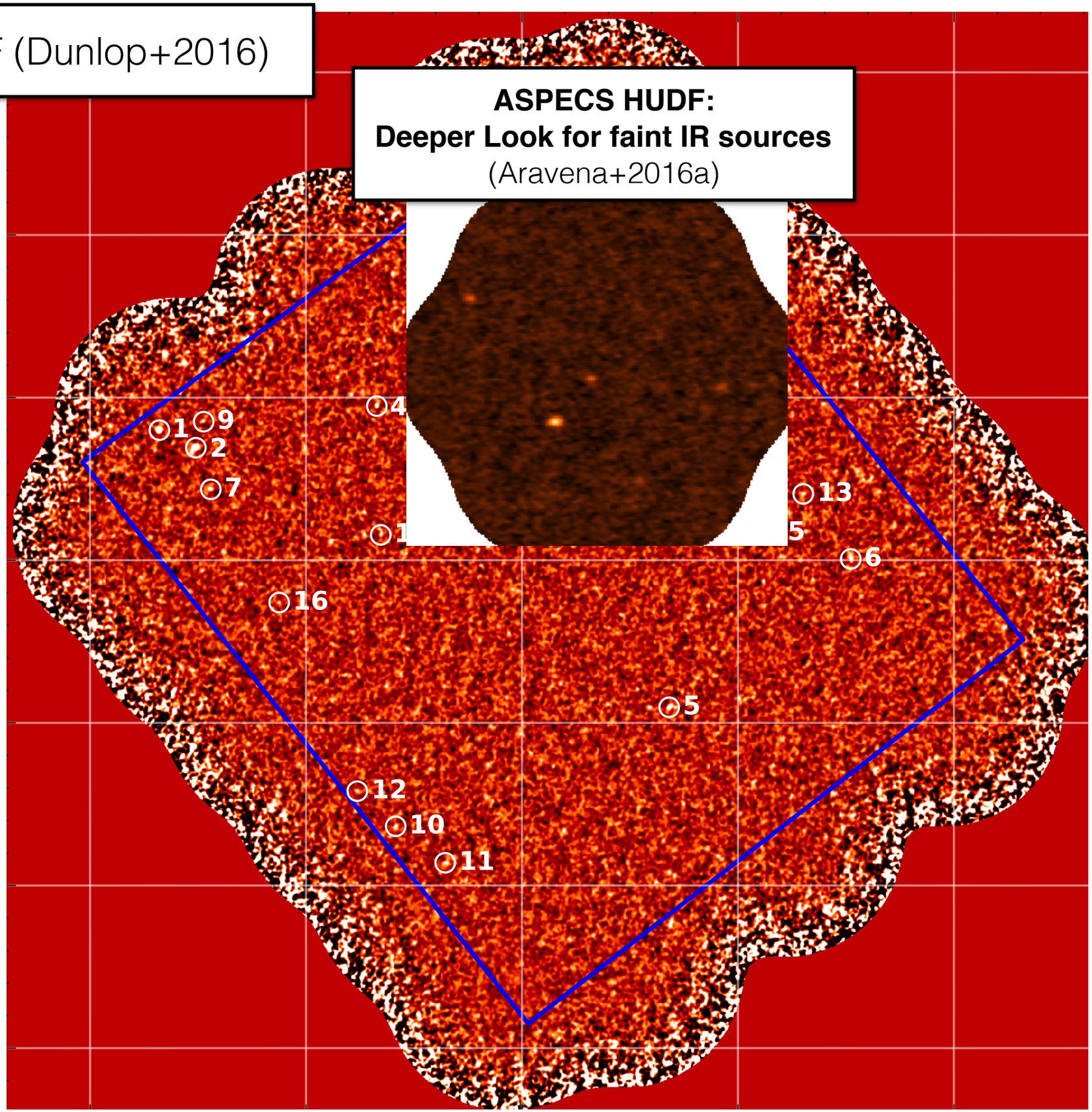
Roberto Decarli
Core co-I: Band-6

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

# ALMA UDF

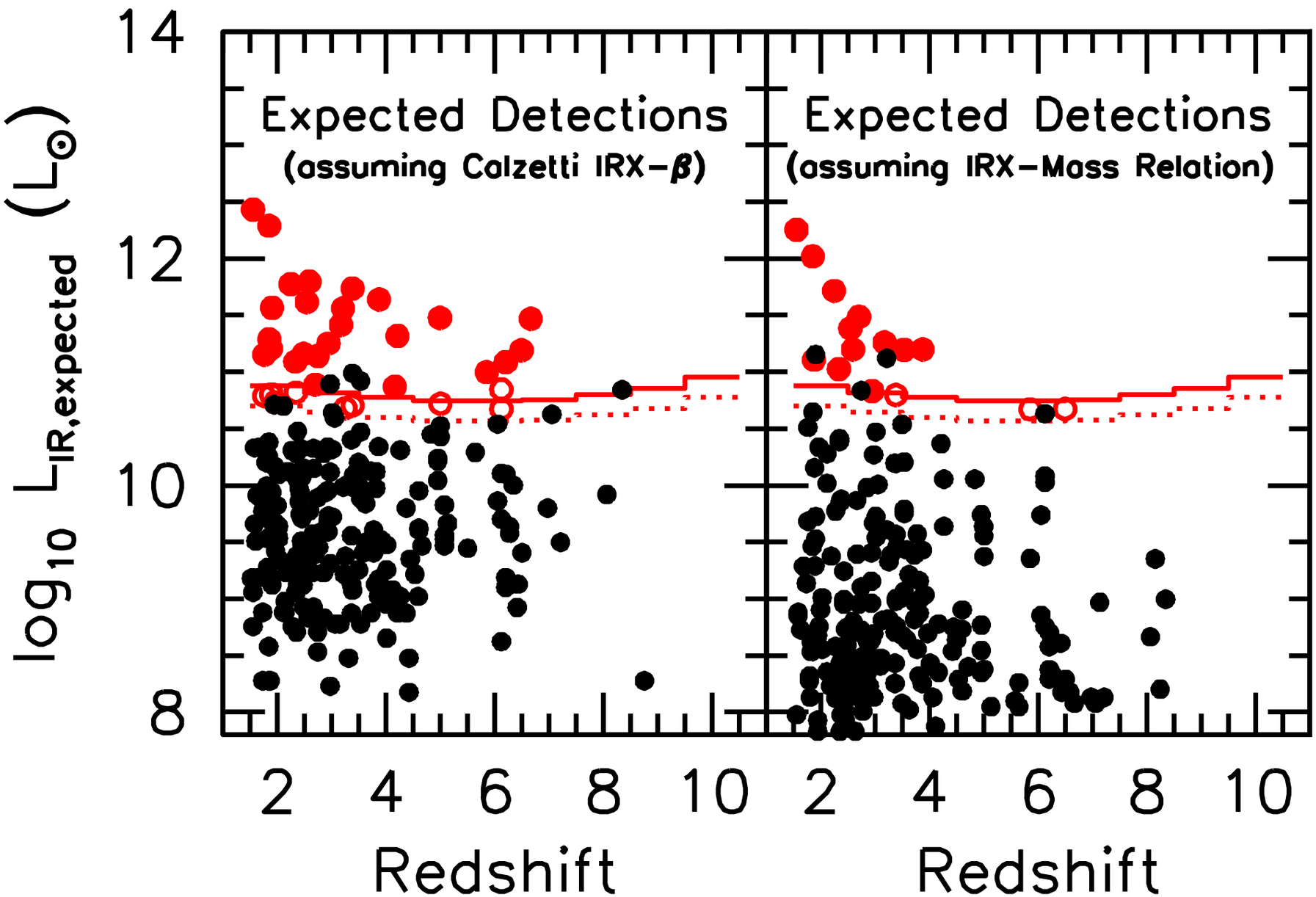
ALMA HUDF (Dunlop+2016)

**ASPECS HUDF:**
**Deeper Look for faint IR sources**
(Aravena+2016a)



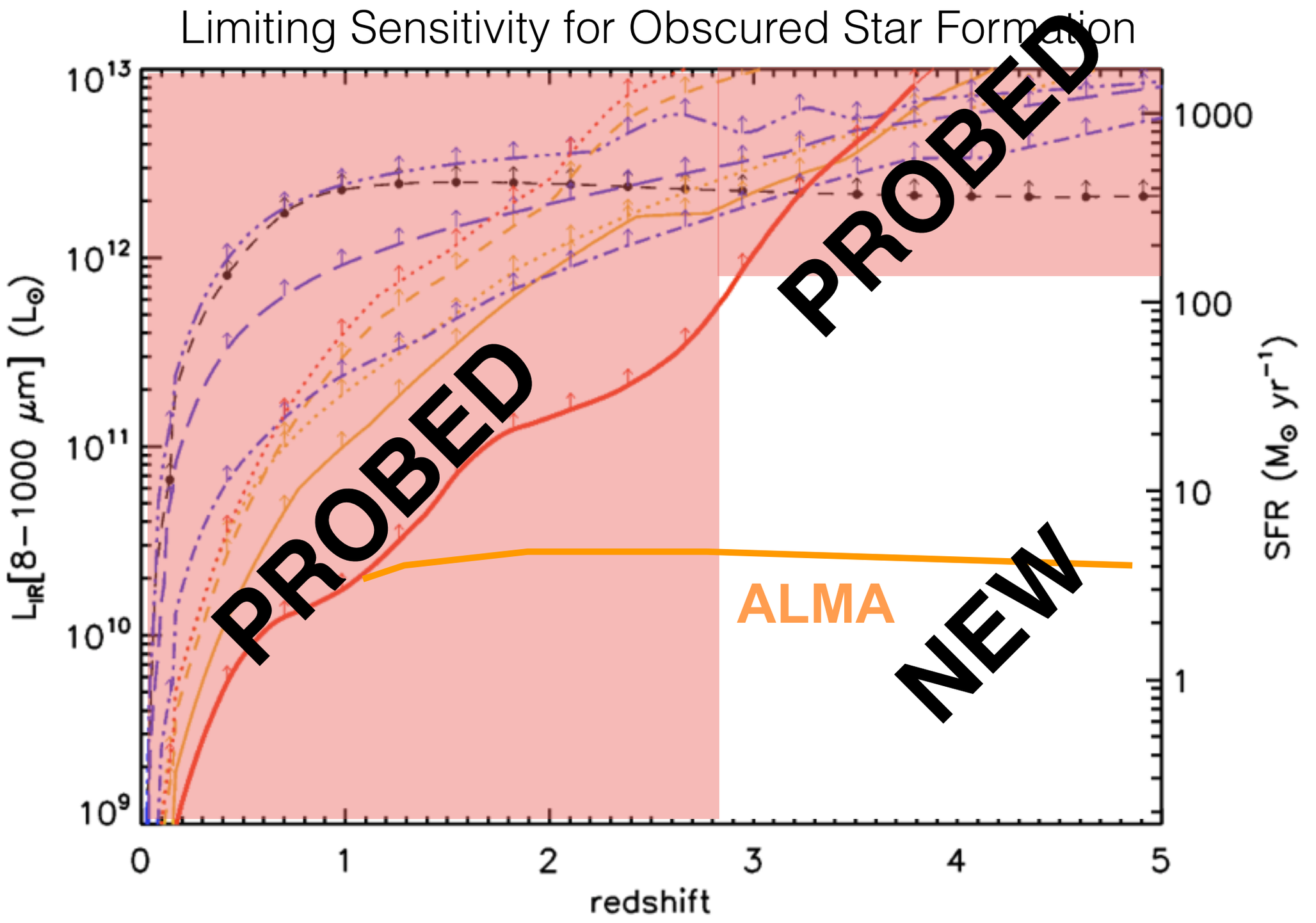
# ALMA UDF

## 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)

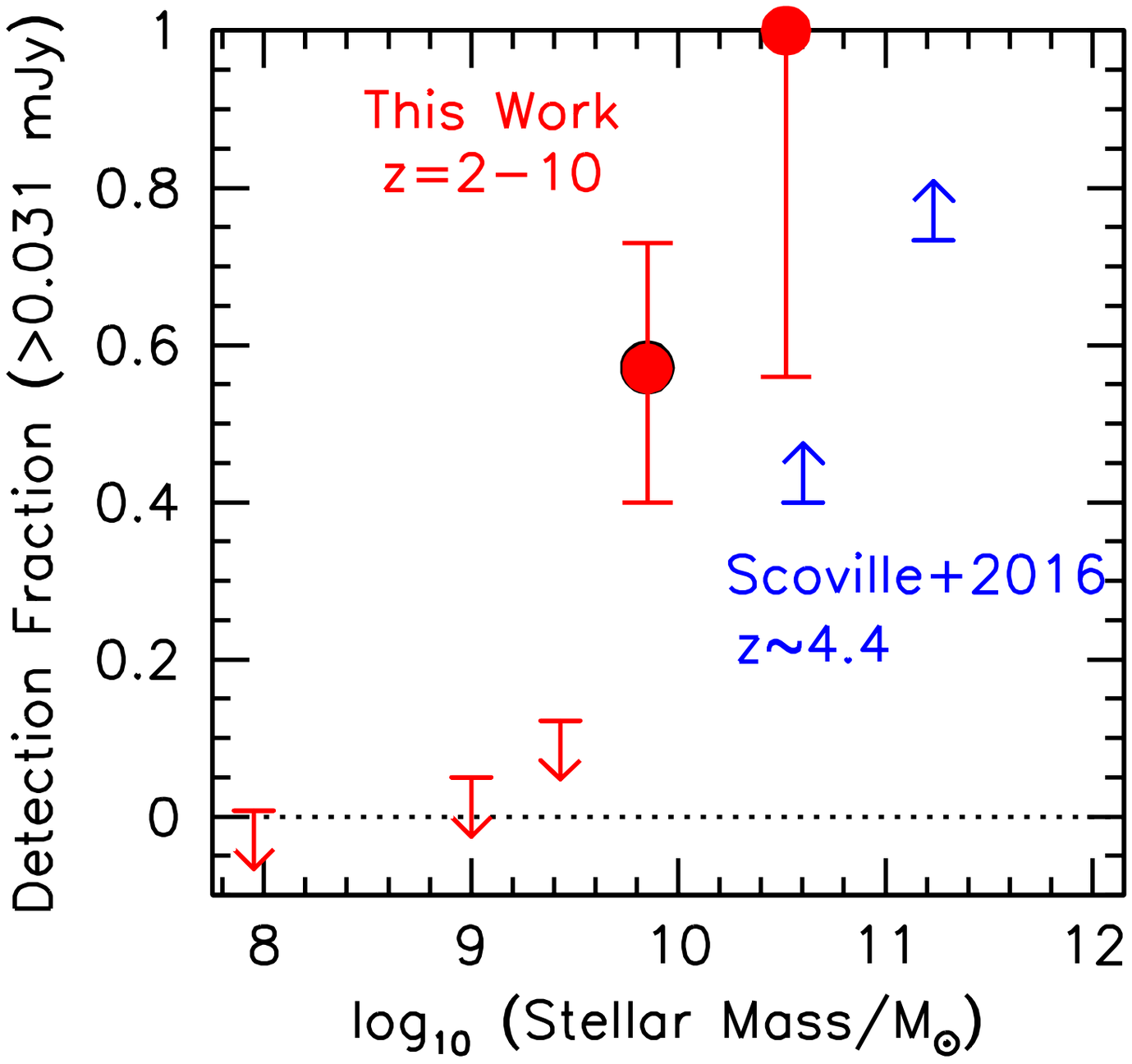
# ALMA UDF




Plot from David Elbaz

# ALMA UDF

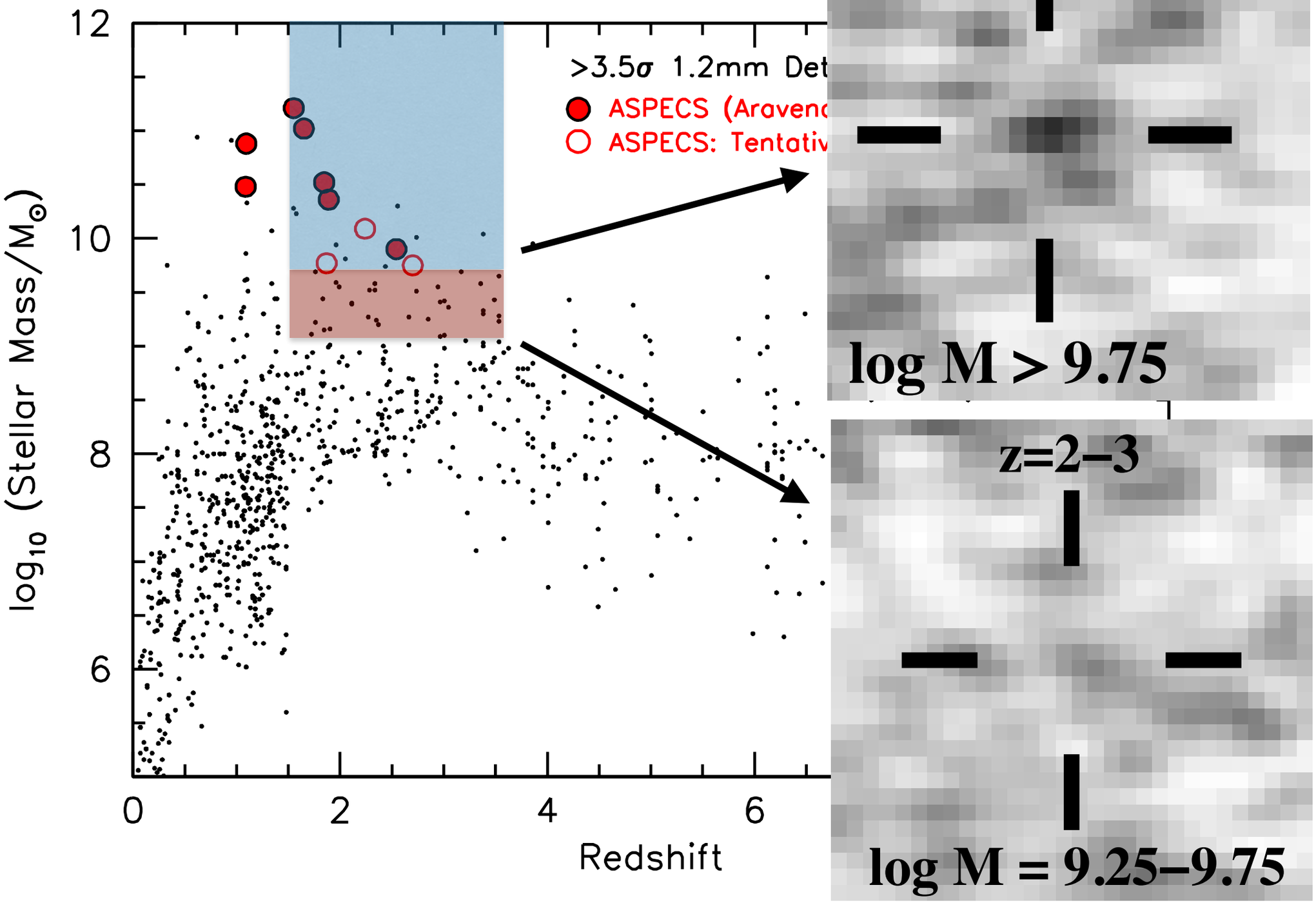
Only the highest-mass sources are individually detected!




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

# ALMA UDF

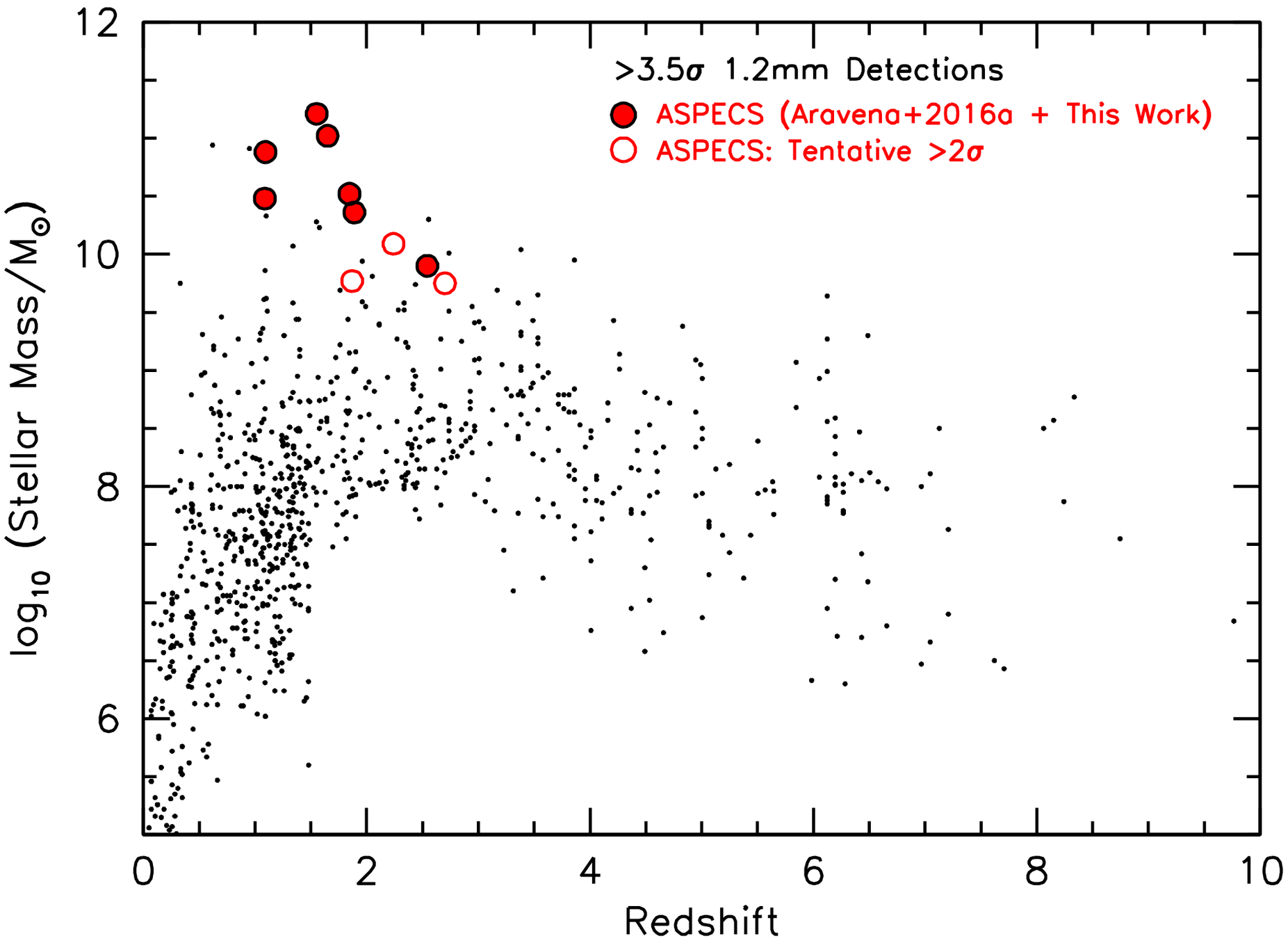
Only the highest-mass sources are in d!




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

# ALMA UDF

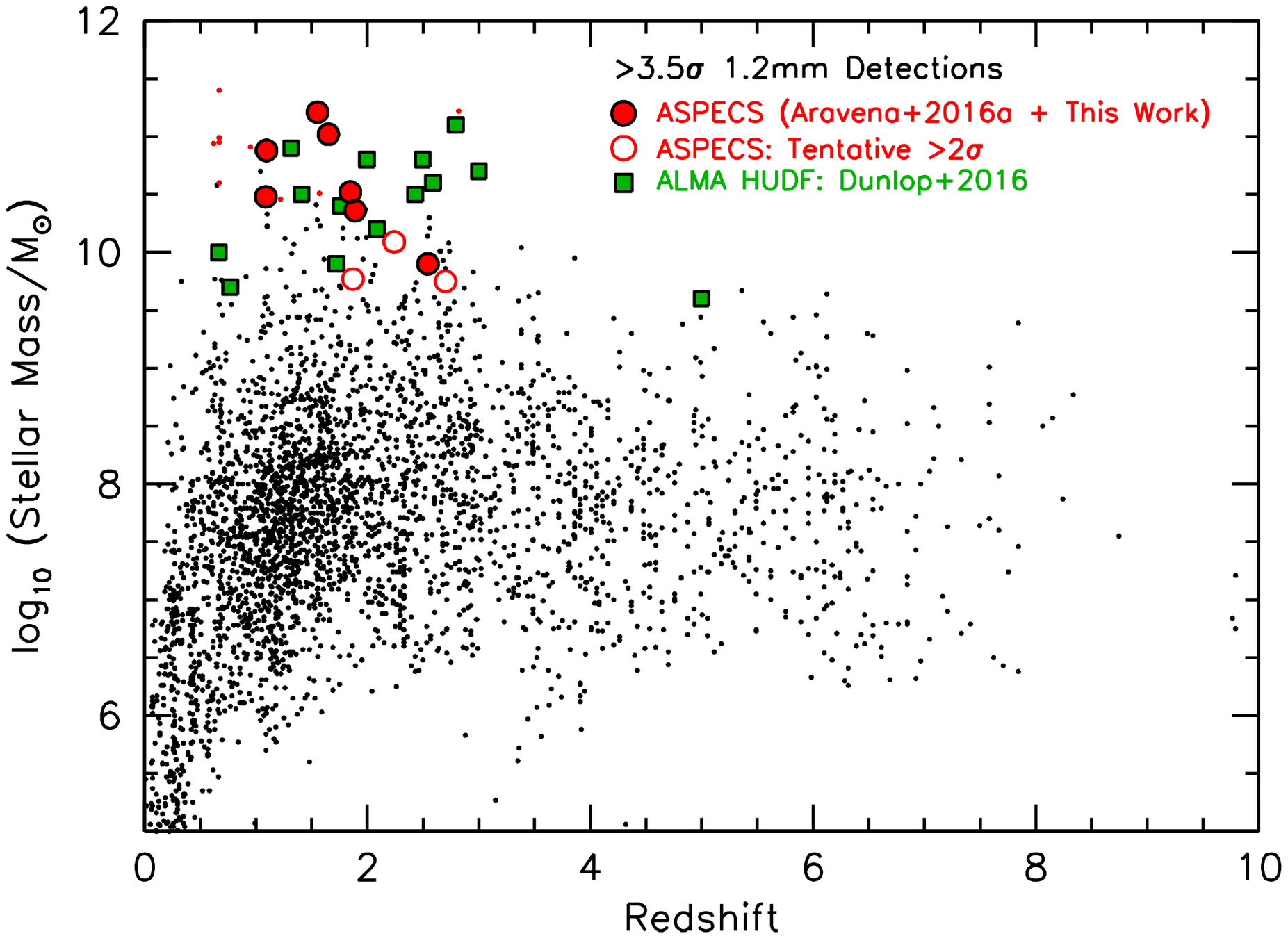
Only the highest-mass sources are individually detected!




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

# ALMA UDF

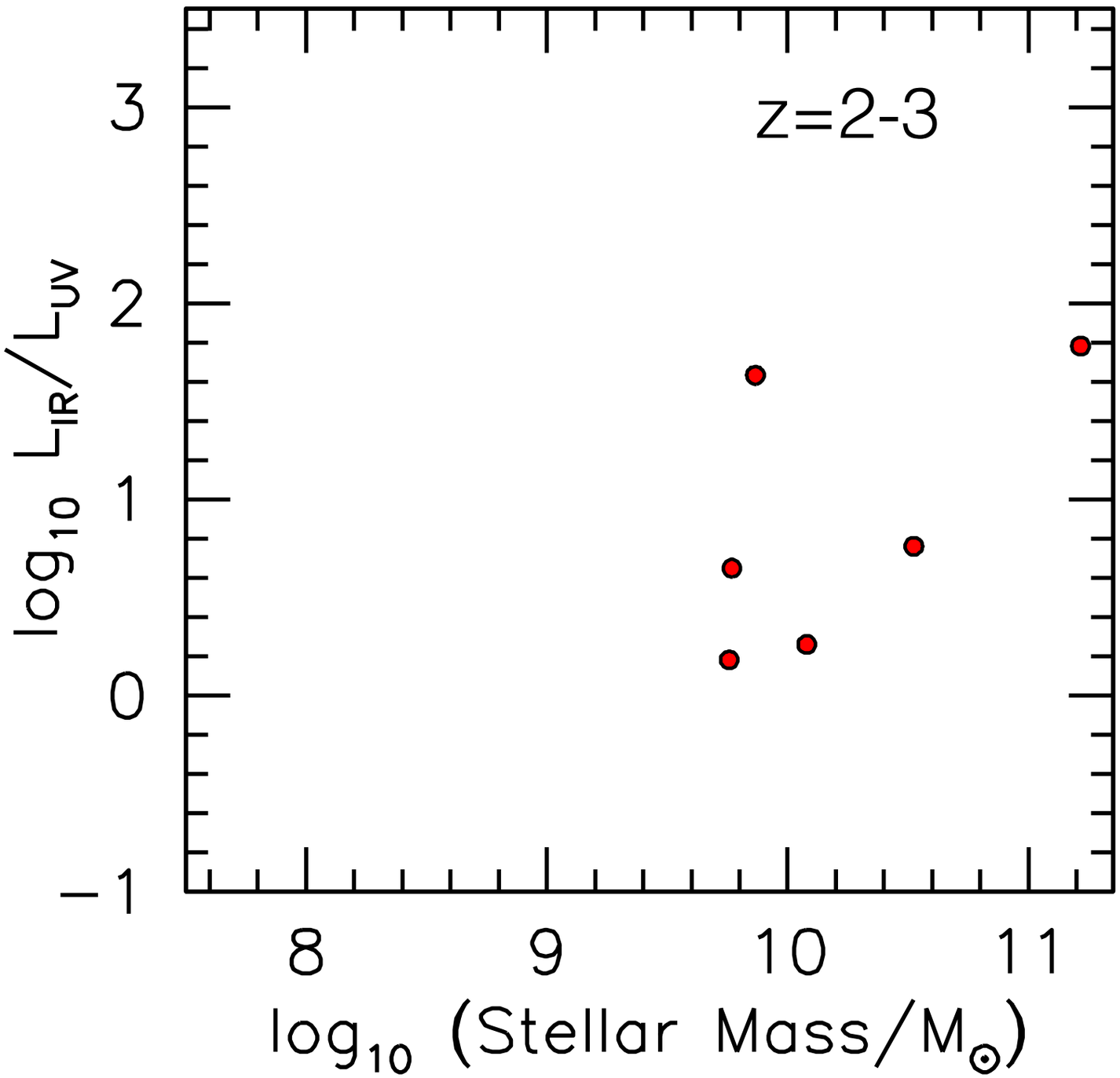
Only the highest-mass sources are individually detected!




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

# ALMA UDF

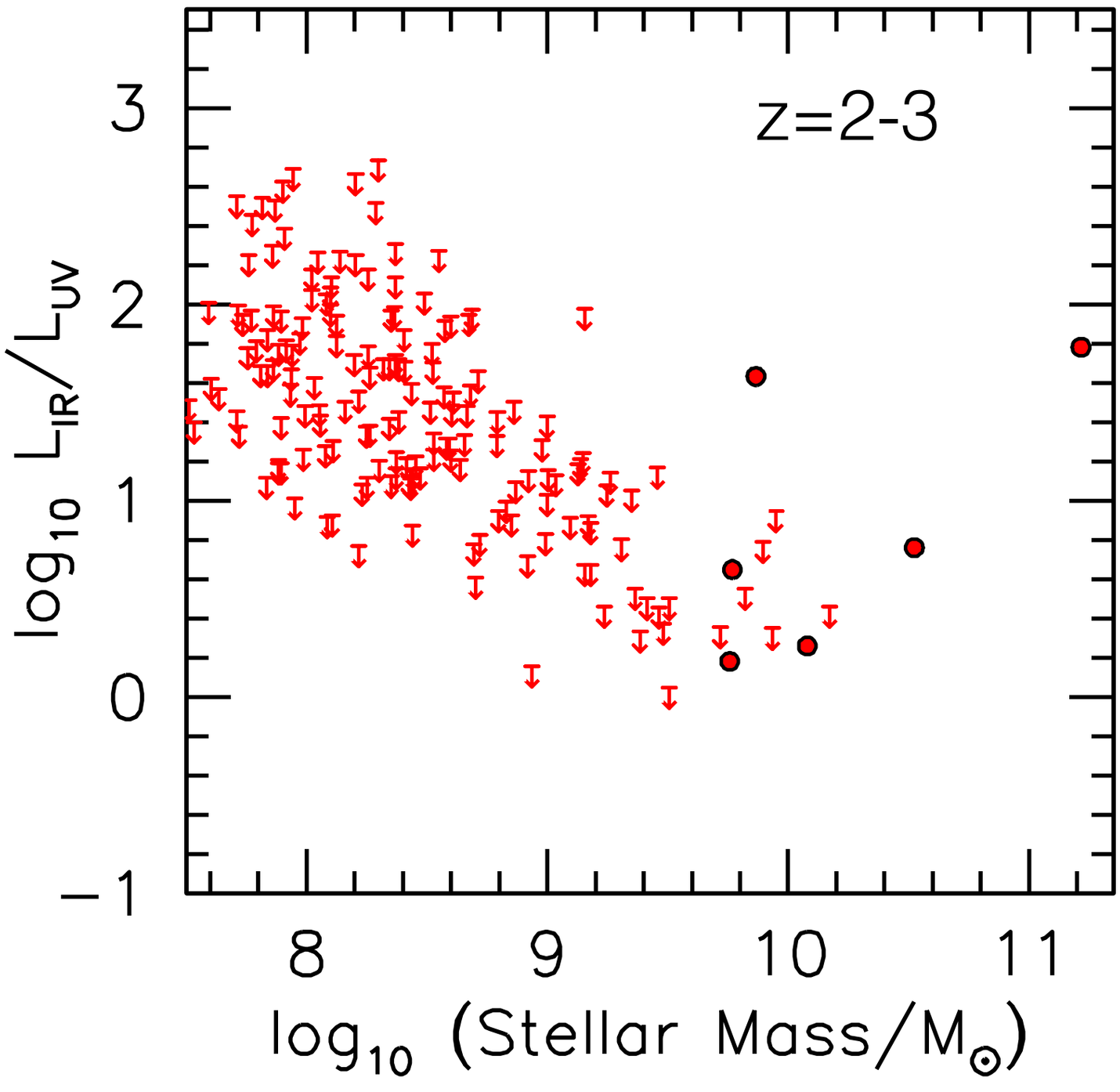
Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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

# ALMA UDF

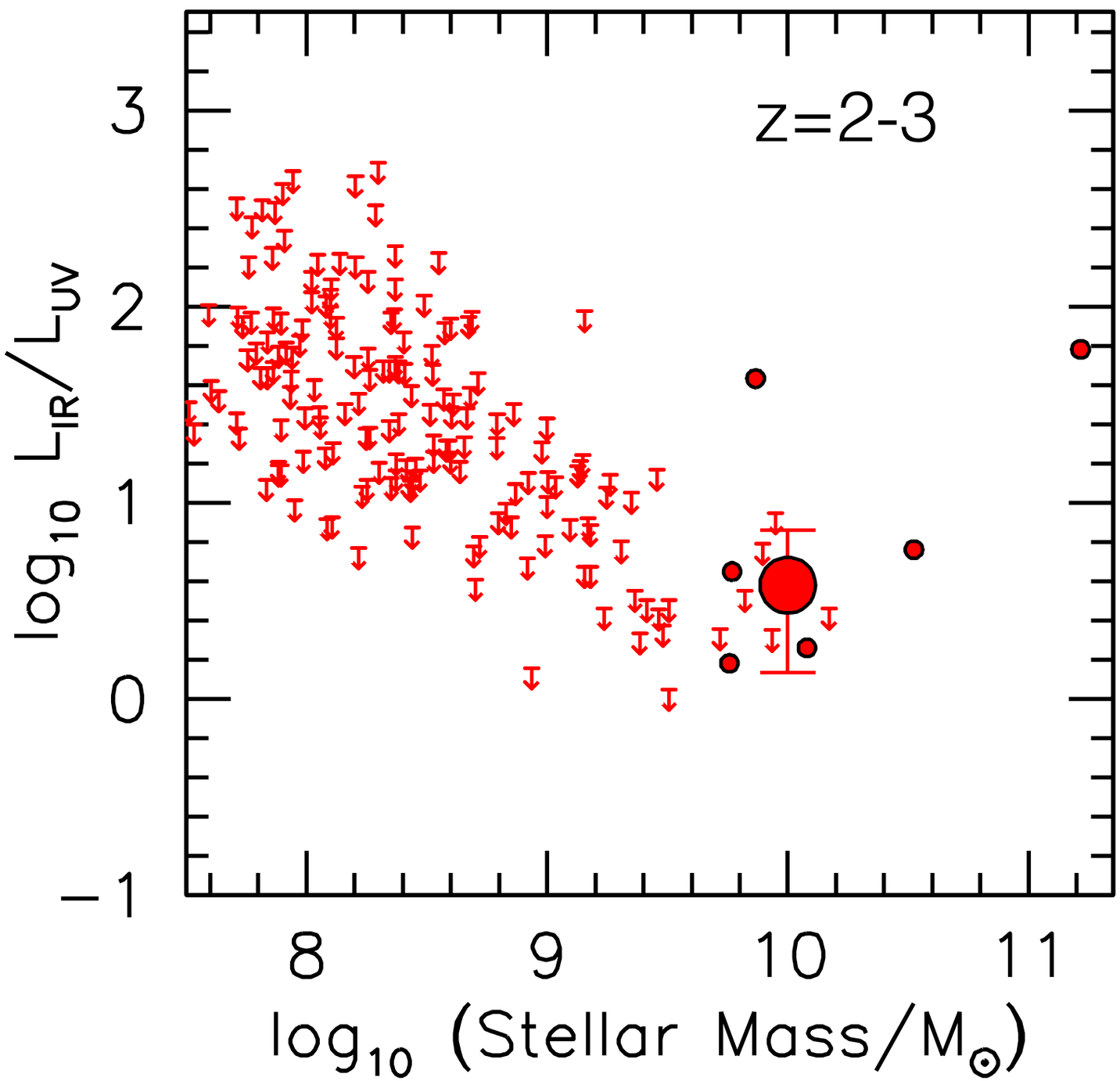
## Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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

# ALMA UDF

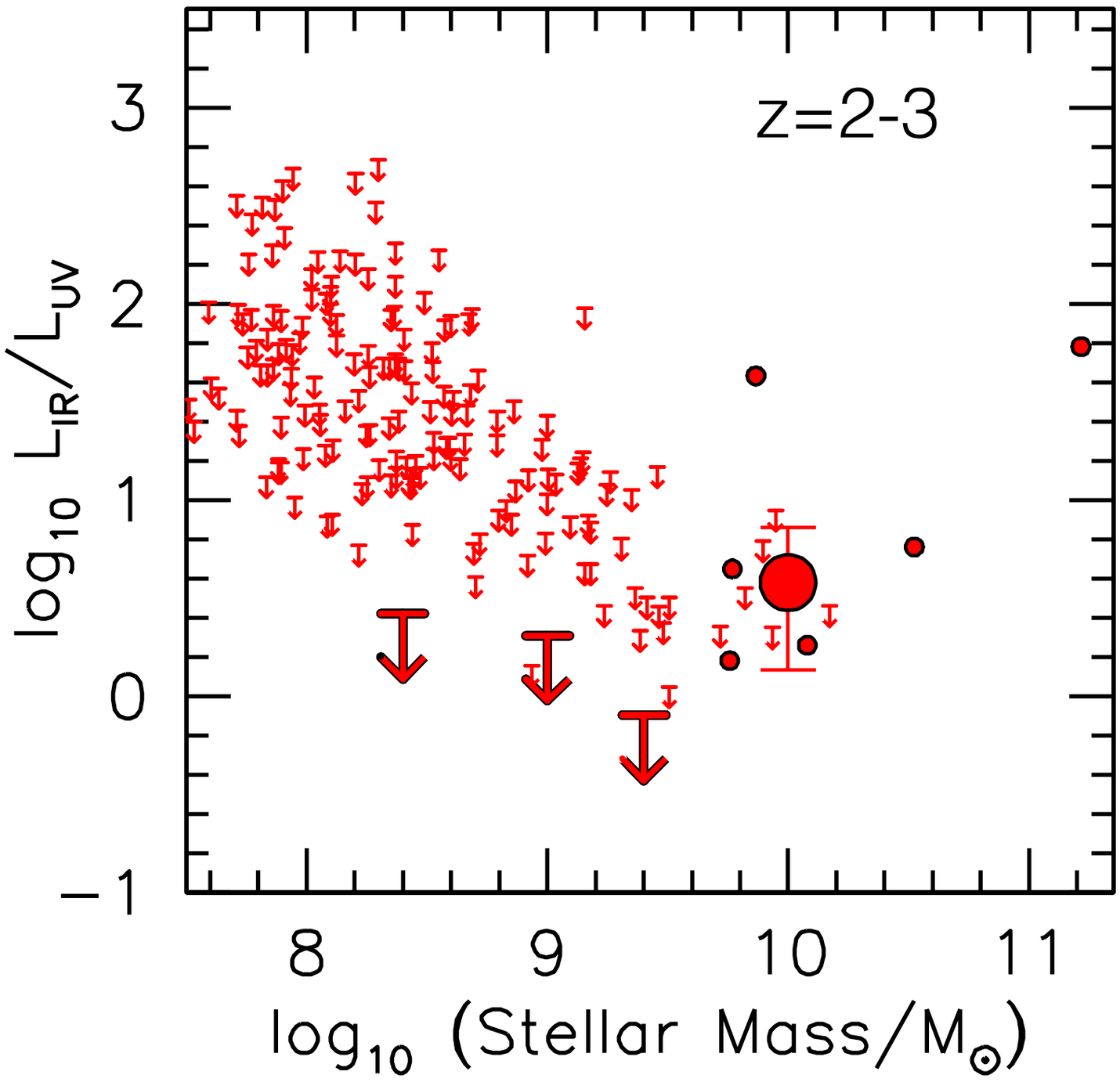
## Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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

# ALMA UDF

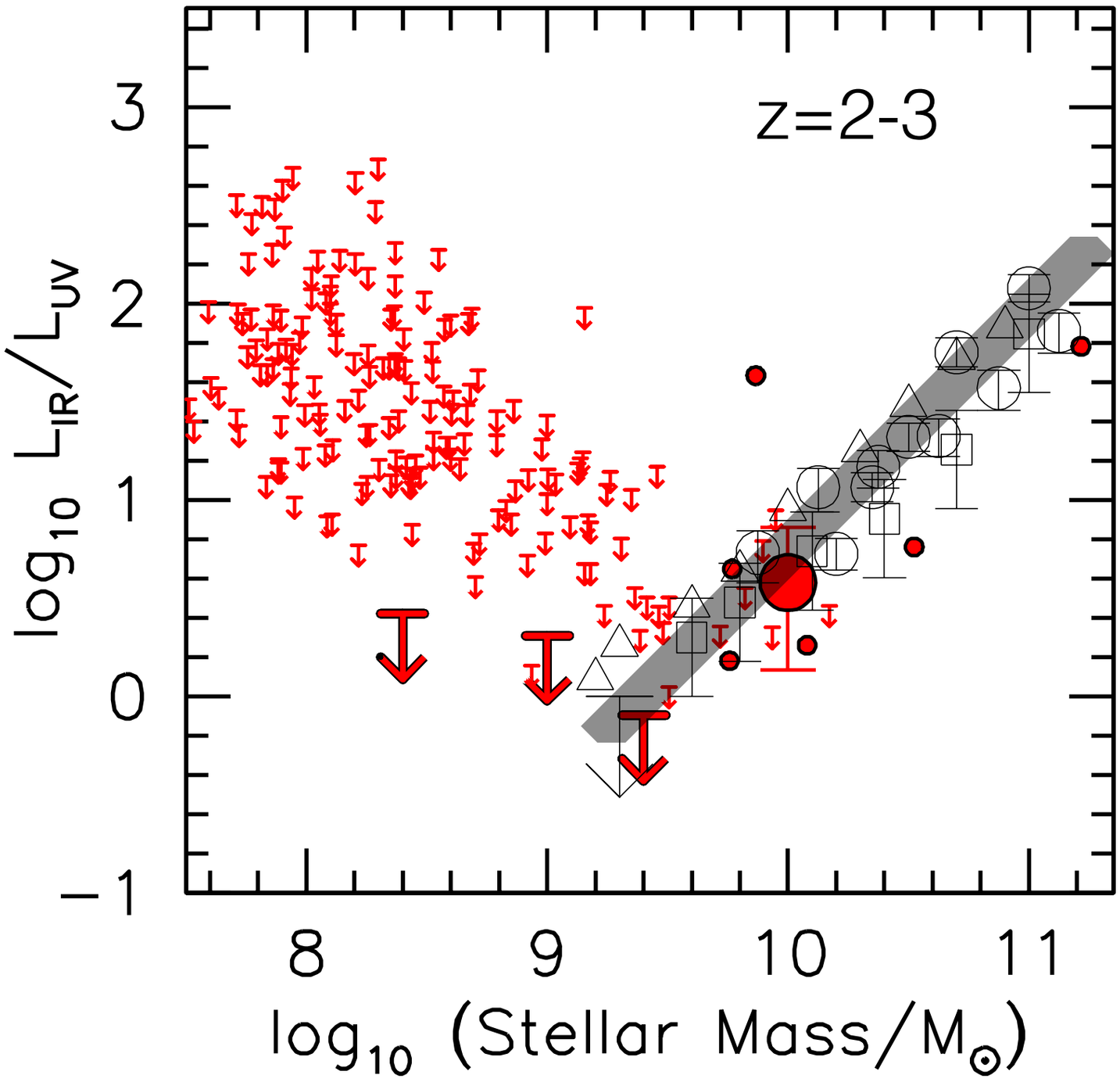
## Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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

# ALMA UDF

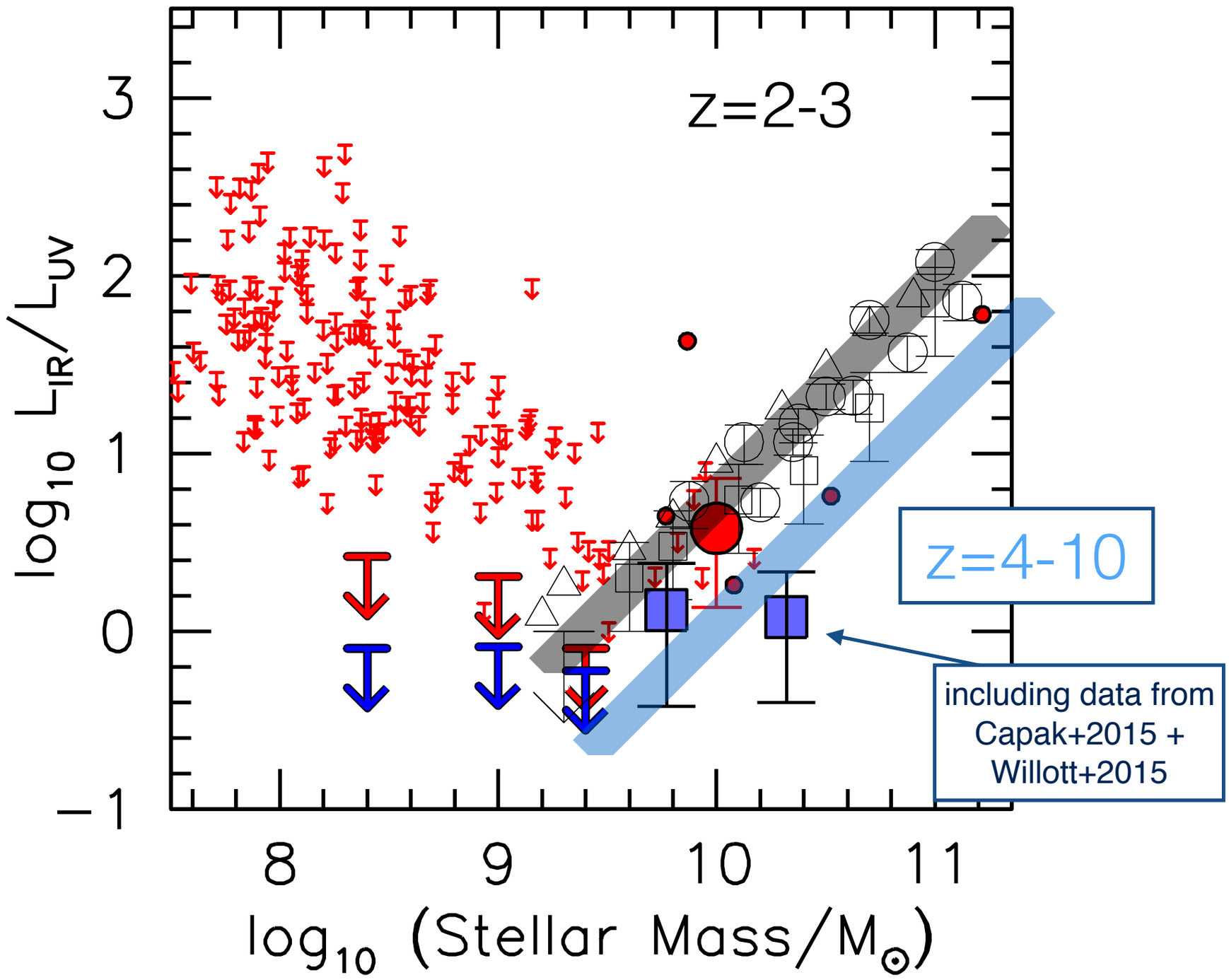
## Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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

# ALMA UDF

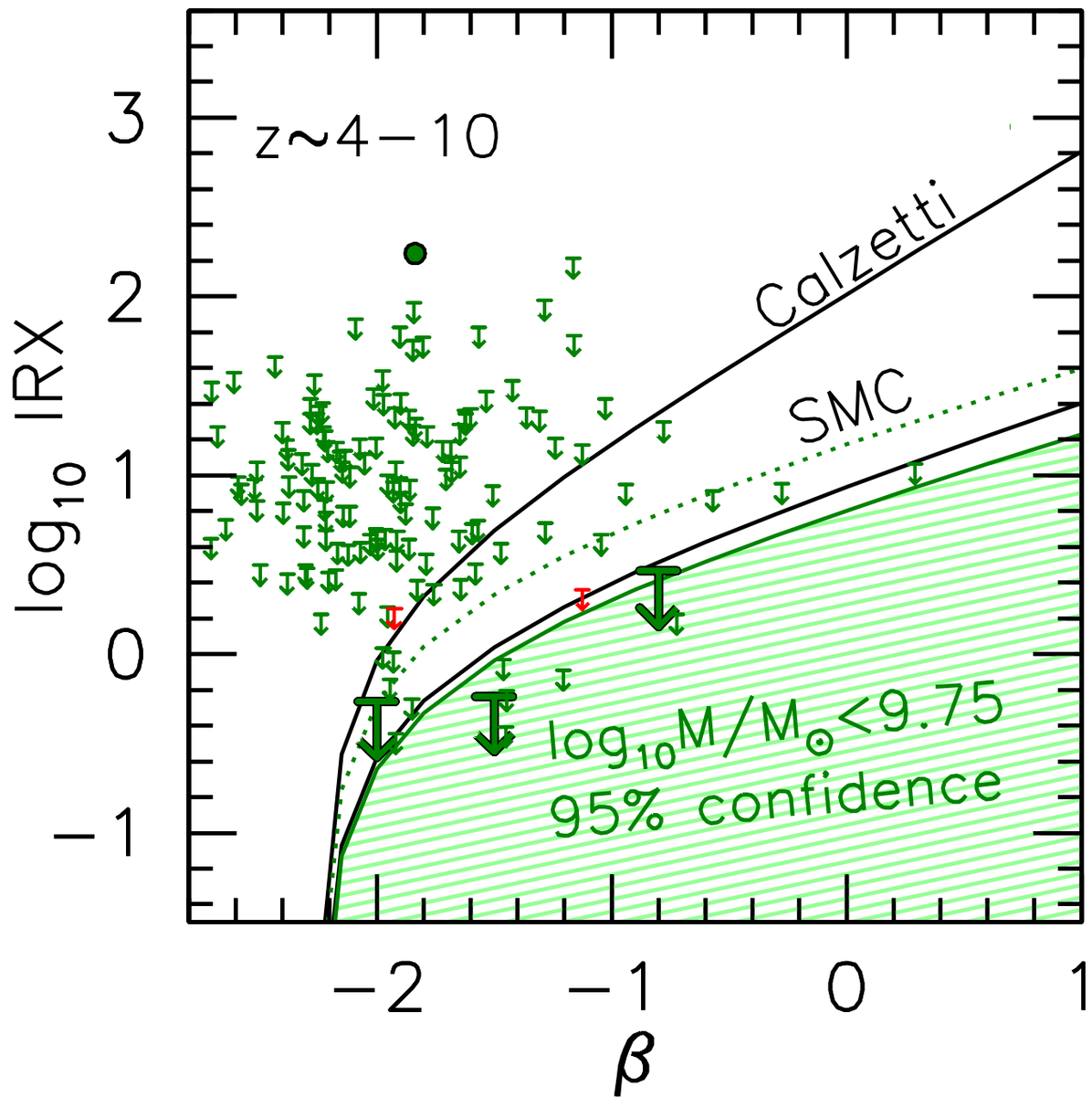
## Ratio of Obscured SFR to UV SFR vs. Stellar Mass




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. 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)

# 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