# Prospects for JWST Science: Beyond the Peak of Cosmic Star-Formation Activity (z<3)

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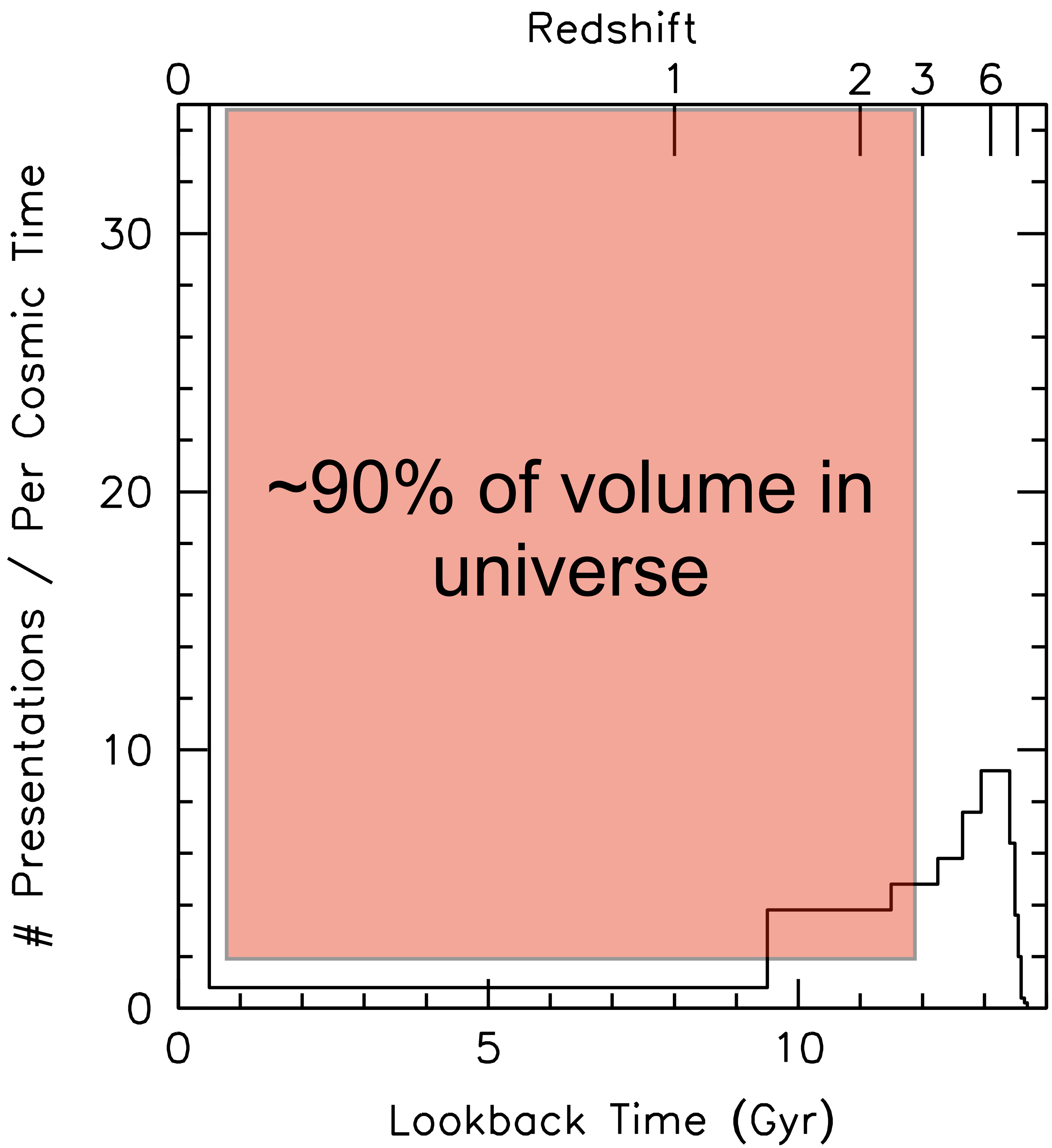
Leiden University

ESTEC -- October 16, 2015

# 0.1 < z < 3 -- Representation at this meeting



# Why Be Interested in z<3?

Late-Epoch Mass Build-up

In general, each of these science areas will be able to benefit from

extending to even lower masses / lower luminosities

JWST's higher spatial resolution

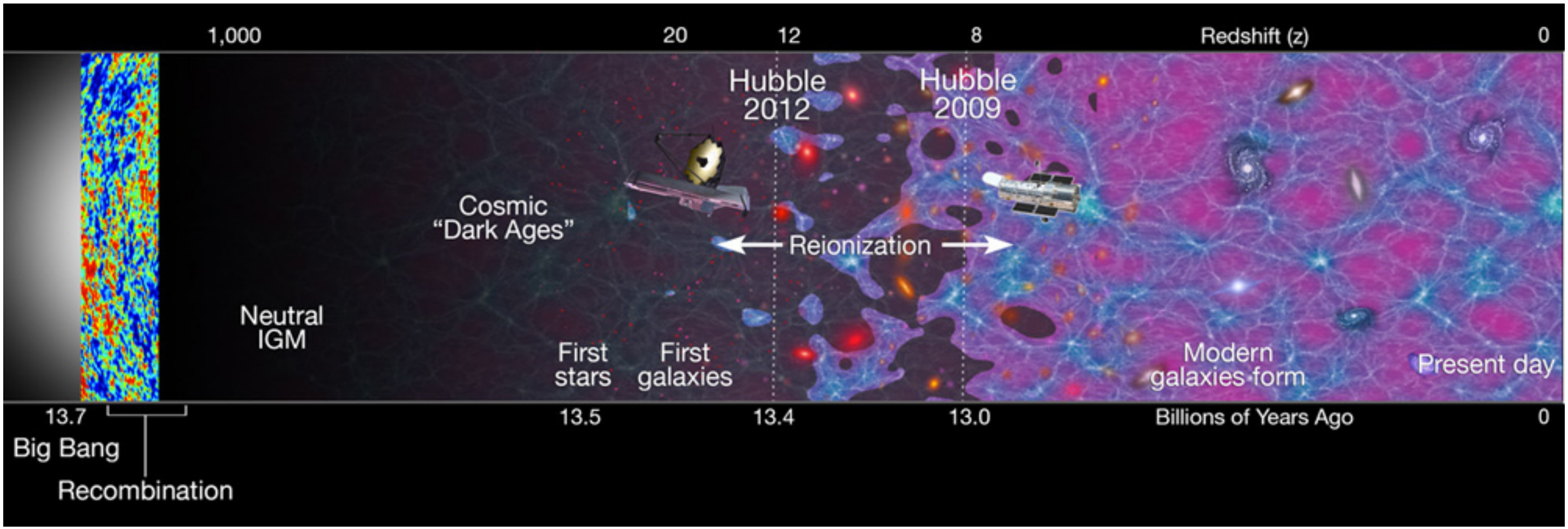
JWST's superior spectral sensitivity and wavelength coverage

Growth and Evolution of Galaxy Clusters

# What can z<3 galaxies teach us about the formation and evolution of the faintest, lowest-mass galaxies in the universe?

***(High-Redshift Galaxies are my primary focus of research, so this focus might be expected)***

# Primary science interest from JWST revolves around cosmic reionization and determining what reionizes the universe




## This keys an interest in ultra-faint, low-mass galaxies...

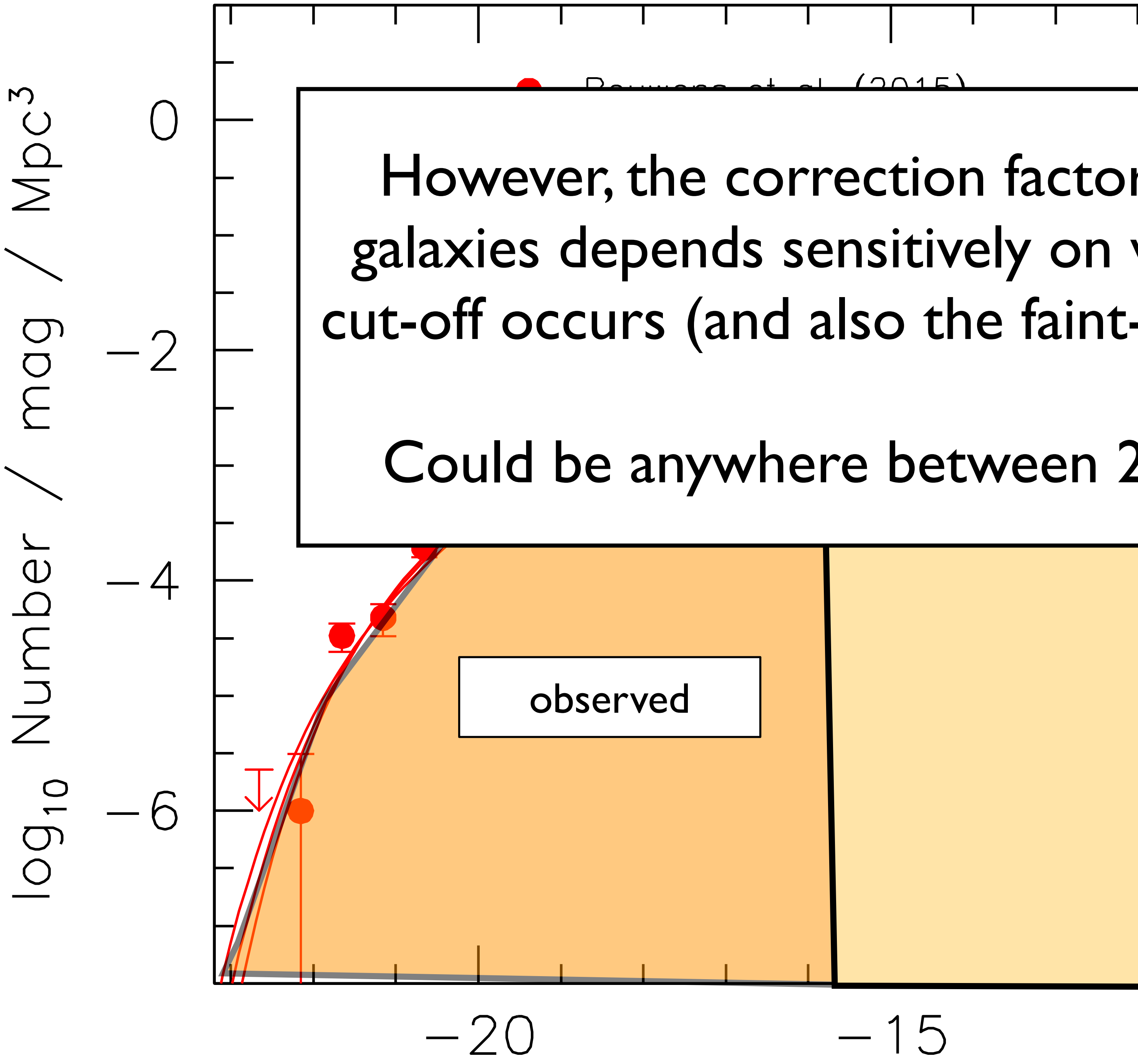
# Which galaxies contribute ionizing photons?

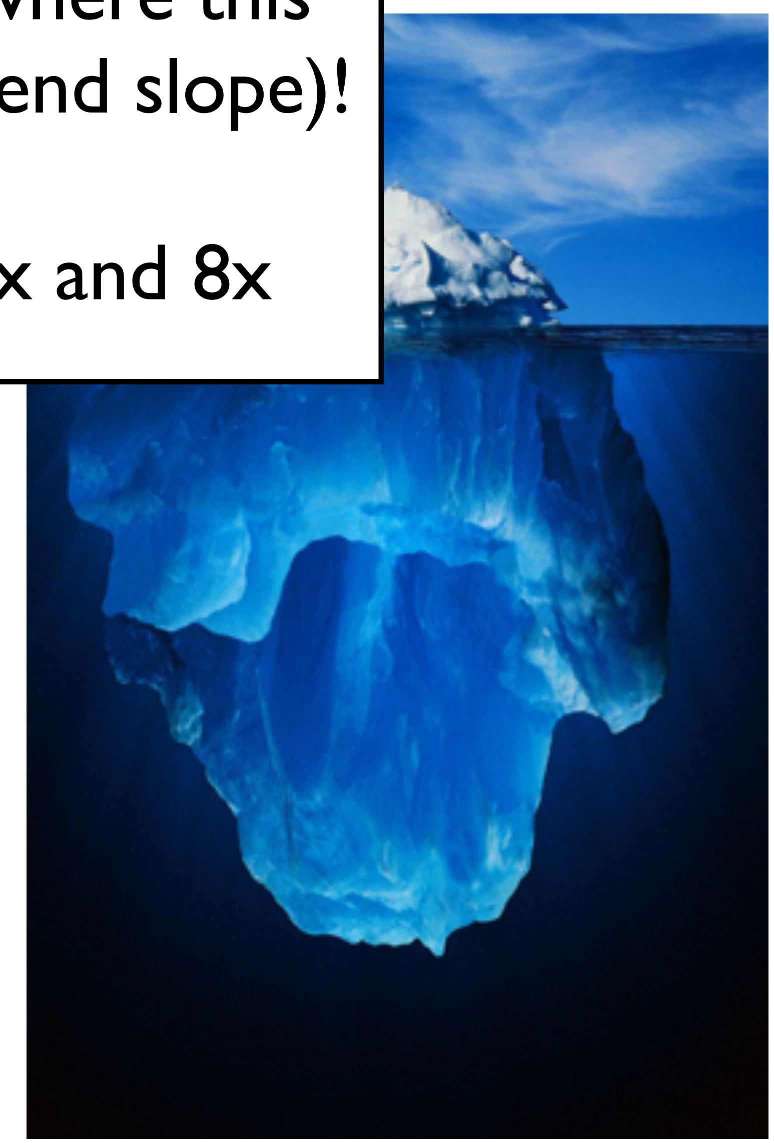
## *How faint do we need to consider?*

most photons appear to come from galaxies ...e observed ...mit

However, the correction factor for faint galaxies depends sensitively on where this cut-off occurs (and also the faint-end slope)!

Could be anywhere between 2x and 8x



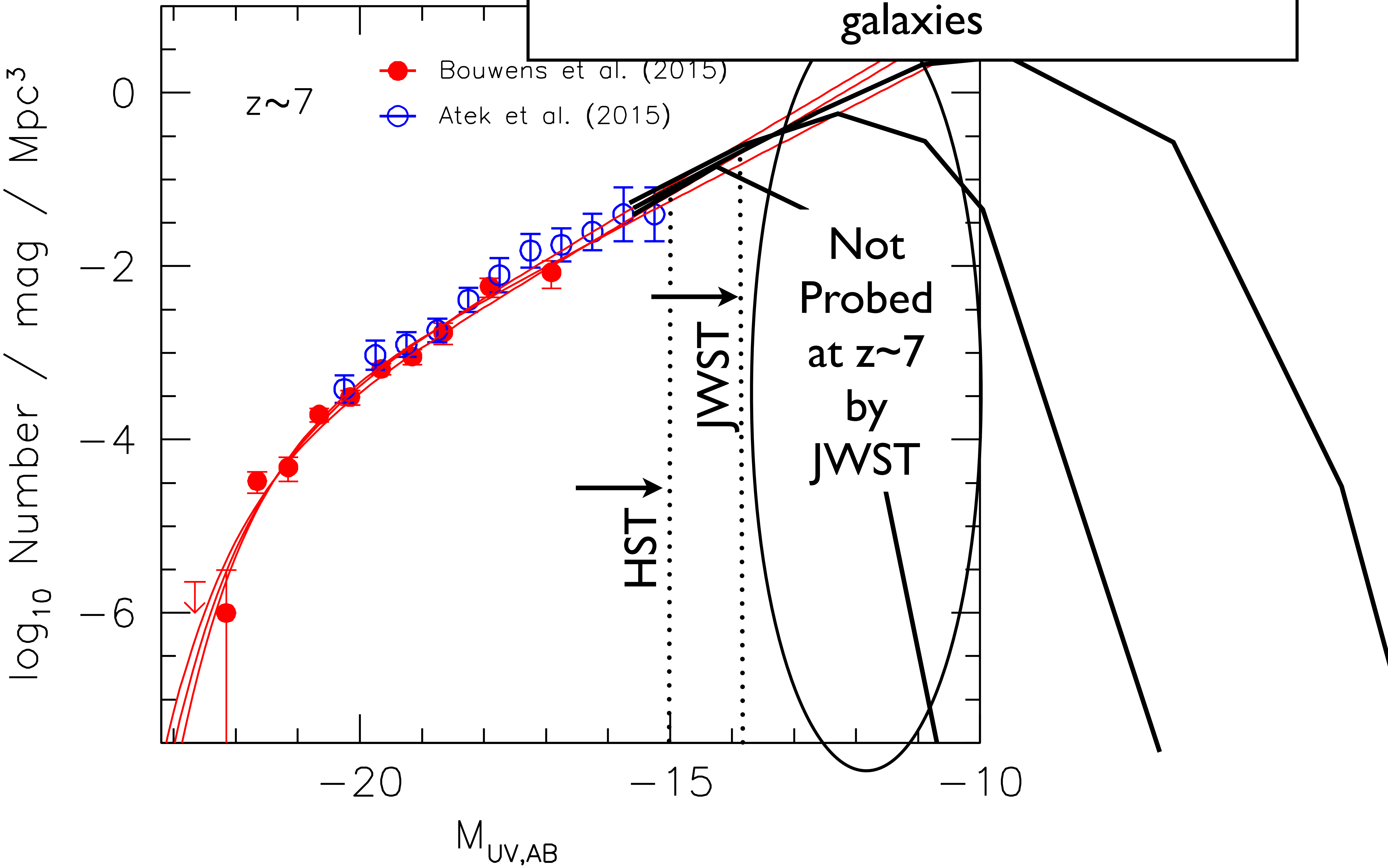
BRIGHT

FAINT

# Which galaxies ca

***How faint will***

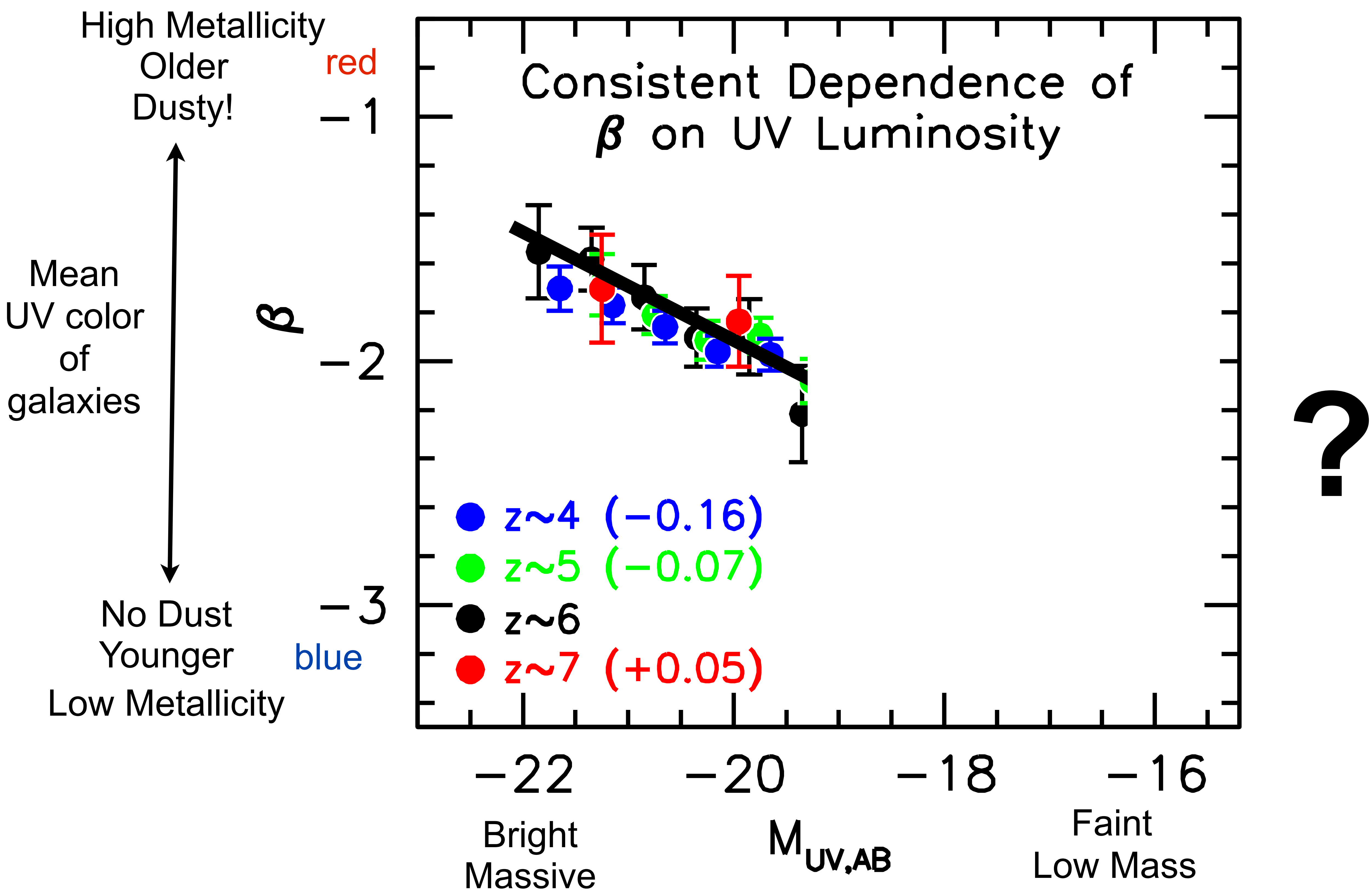
For full census of ionizing photons, we would like to understand these galaxies



## One question is about the prevalence of faint galaxies (and the cut-off of the LF)

## What are the physical properties of ultra low-mass galaxies?

# Dustiness vs. Luminosity *(proxy for Mass)*




Bouwens+2014; see also Bouwens+2009, 2012; Rogers+2014; Finkelstein+2012

Can we break this degeneracy between dustiness, age, and metallicity for the ultra-faint galaxies?

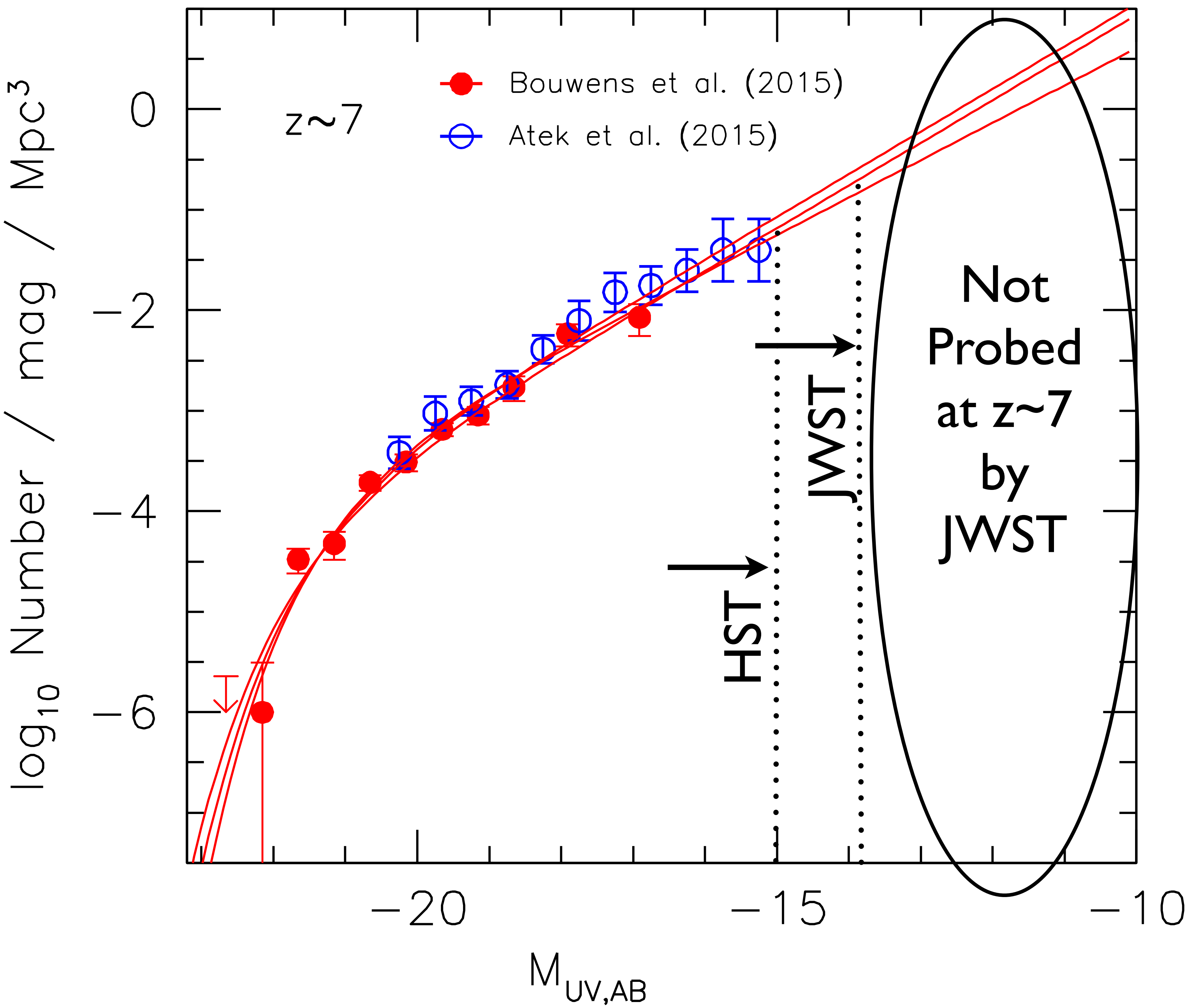
What are the masses (M/L ratios) of ultra-faint galaxies?

How strong are various emission lines in ultra-faint galaxies and what does this tell us about their gaseous nebula?

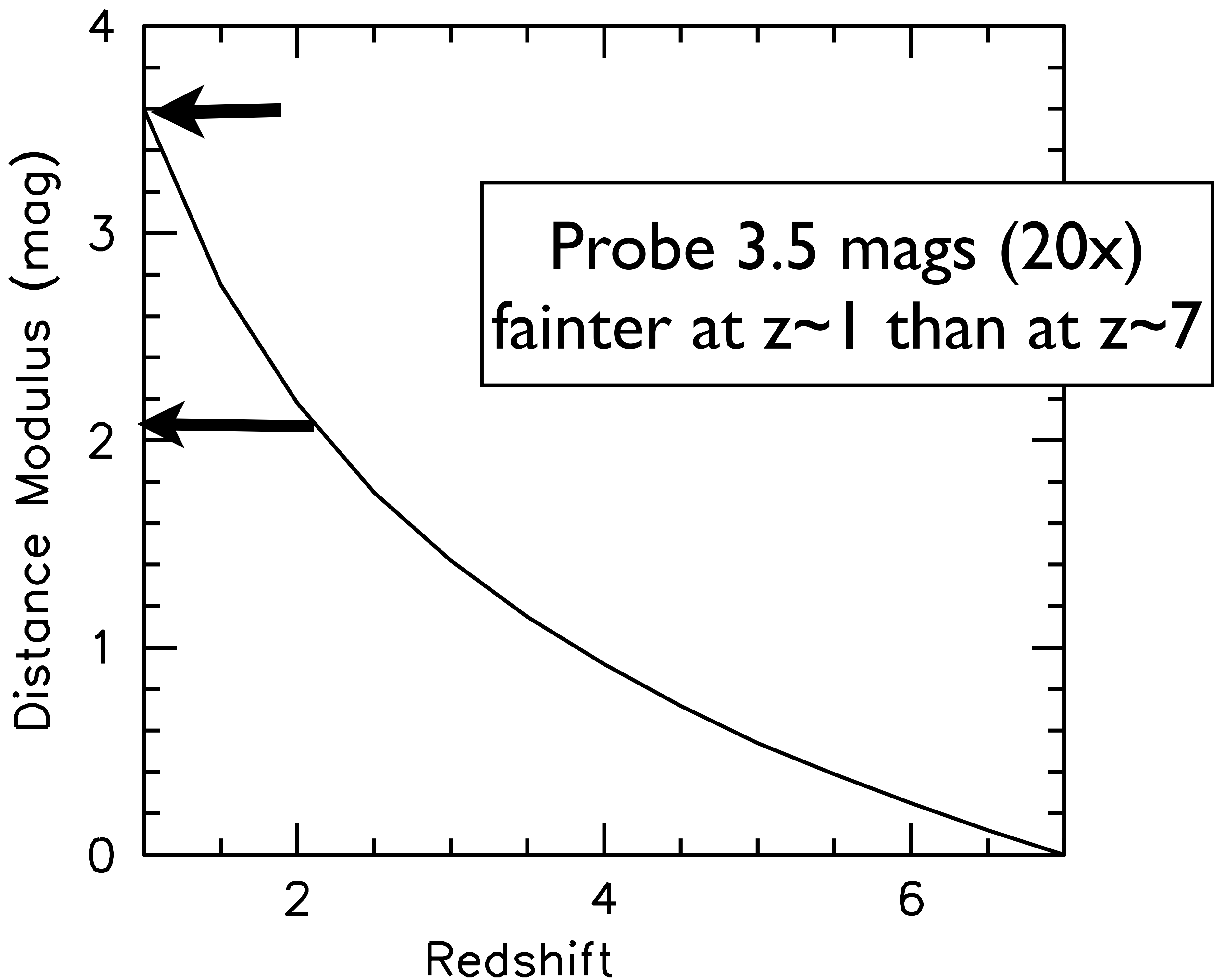
Can we measure the gas masses in ultra low-mass z~7-10 galaxies?

# Which galaxies can we probe at present?

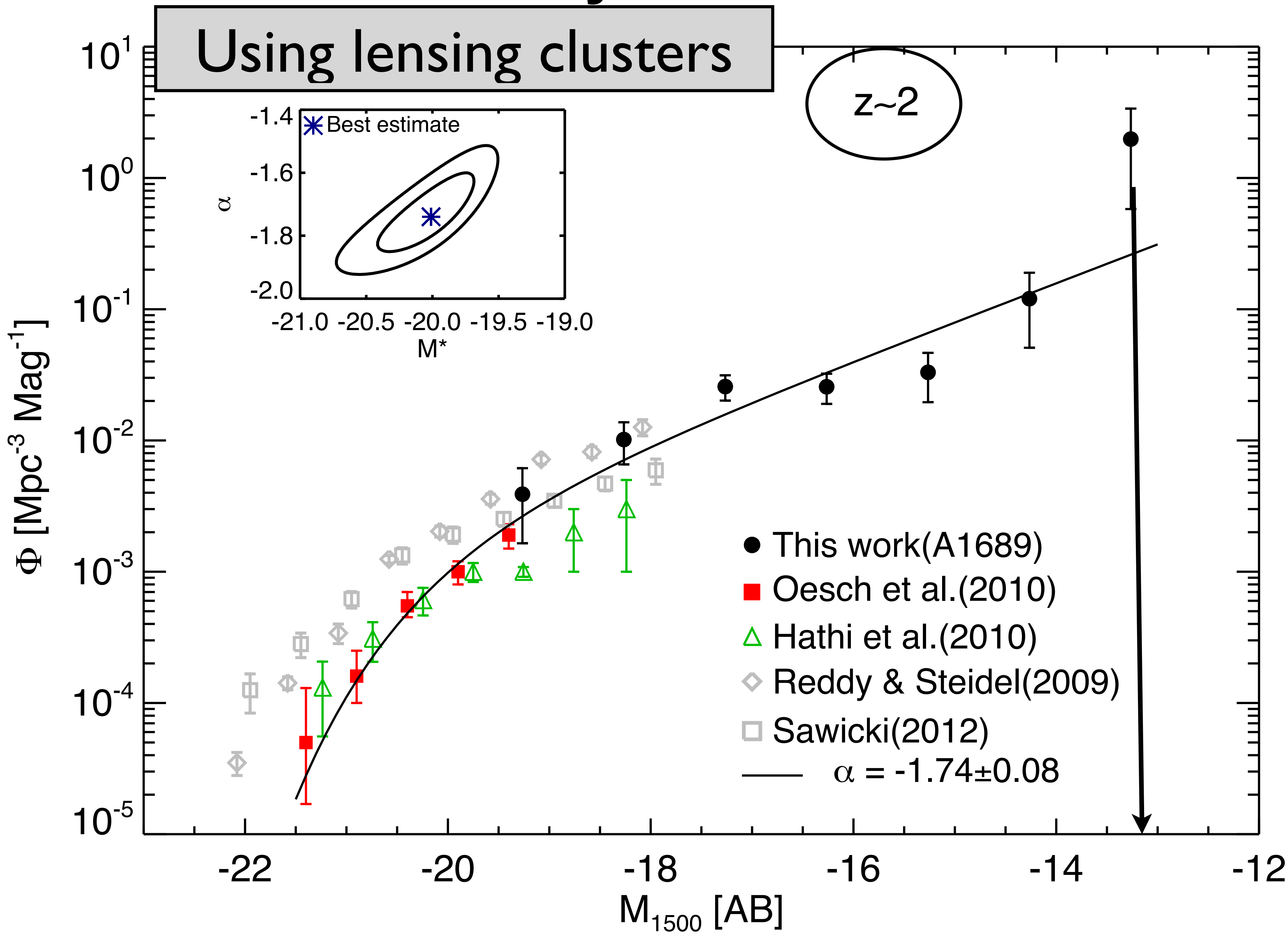
### *How faint will we probe with JWST?*



# Perhaps we can gain insight into what is going on by looking for similar galaxies at z<7...

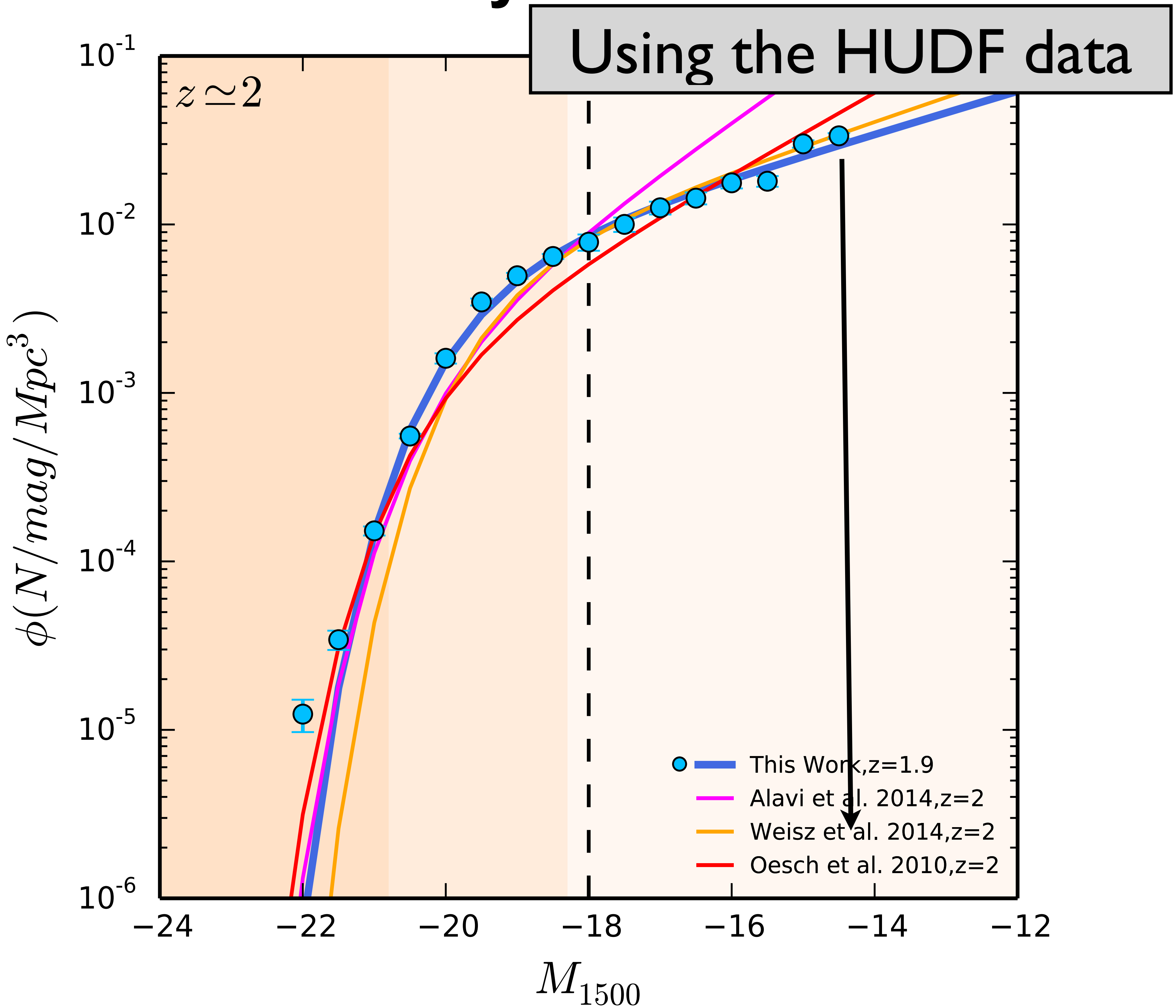


# This exercise already done with HST at z~2




Alavi+2014

# This exercise already done with HST at z~2




Parsa+2015

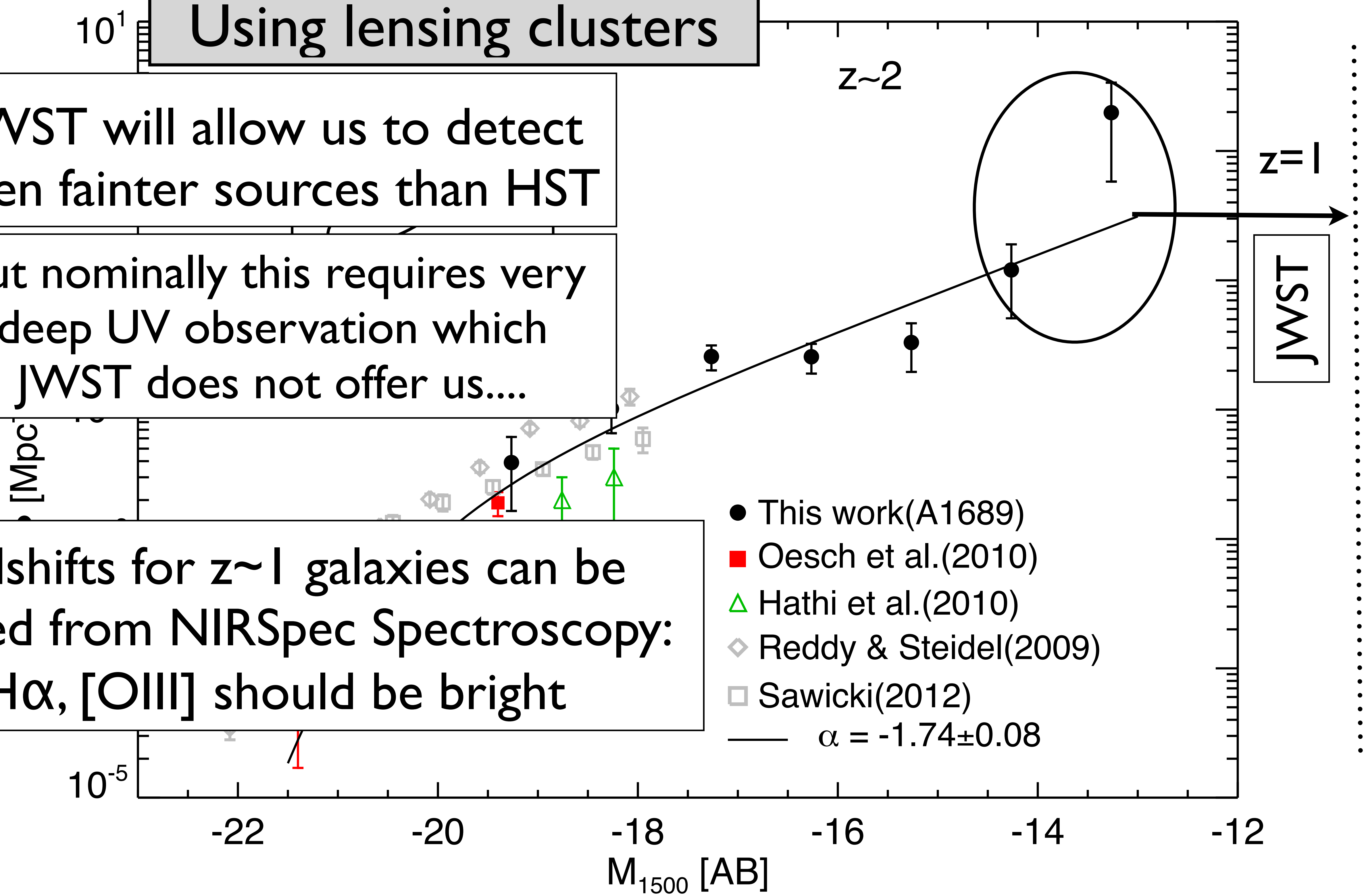
# How can we improve the HST exercise with JWST?

Using lensing clusters

JWST will allow us to detect even fainter sources than HST

But nominally this requires very deep UV observation which JWST does not offer us....

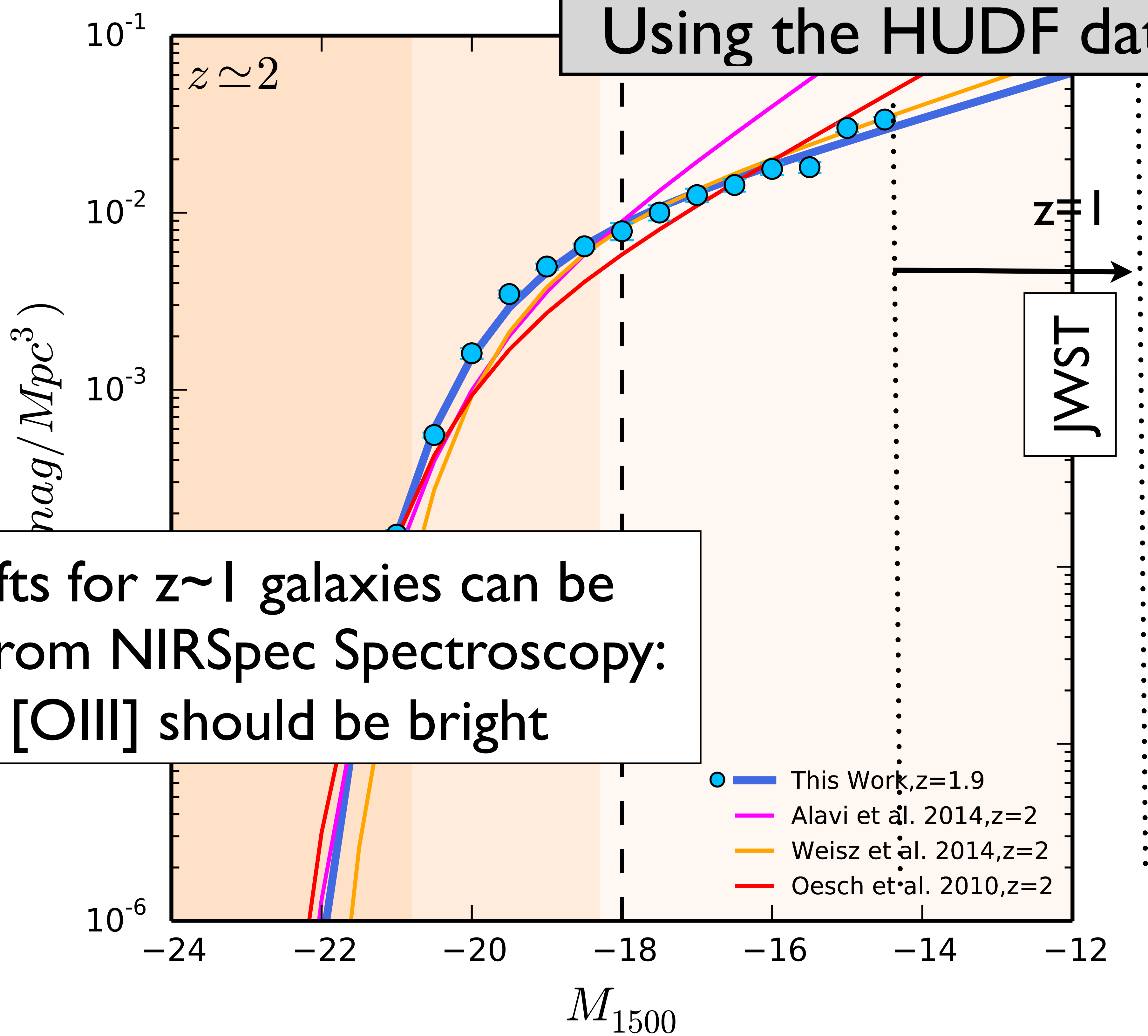
Redshifts for z~1 galaxies can be derived from NIRSpec Spectroscopy: Hα, [OIII] should be bright




Alavi+2014

# This exercise already done with HST at z~2

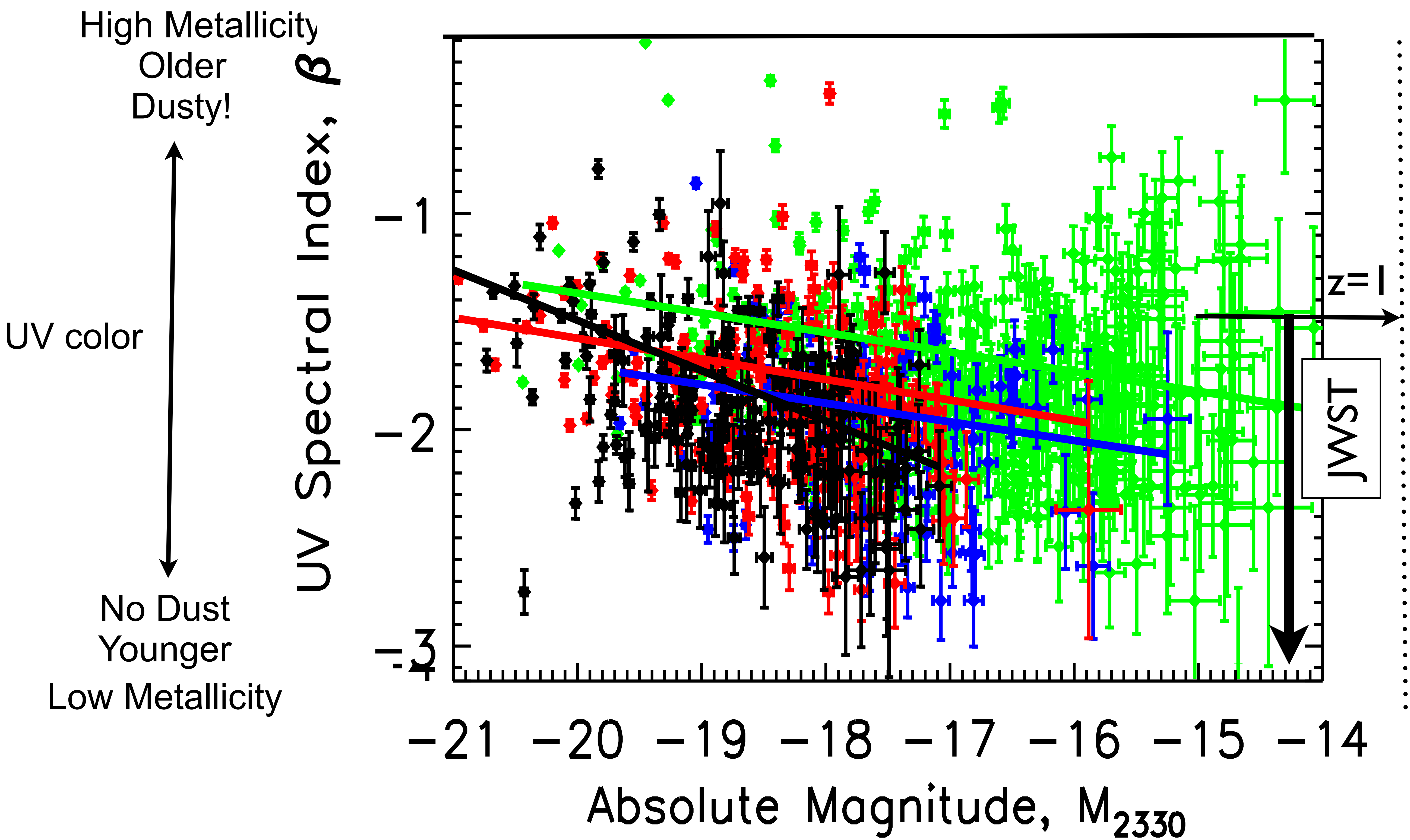
Using the HUDF data




Redshifts for z~1 galaxies can be derived from NIRSpec Spectroscopy: Hα, [OIII] should be bright

Parsa+2015

# Dustiness vs. Luminosity *(proxy for Mass)*

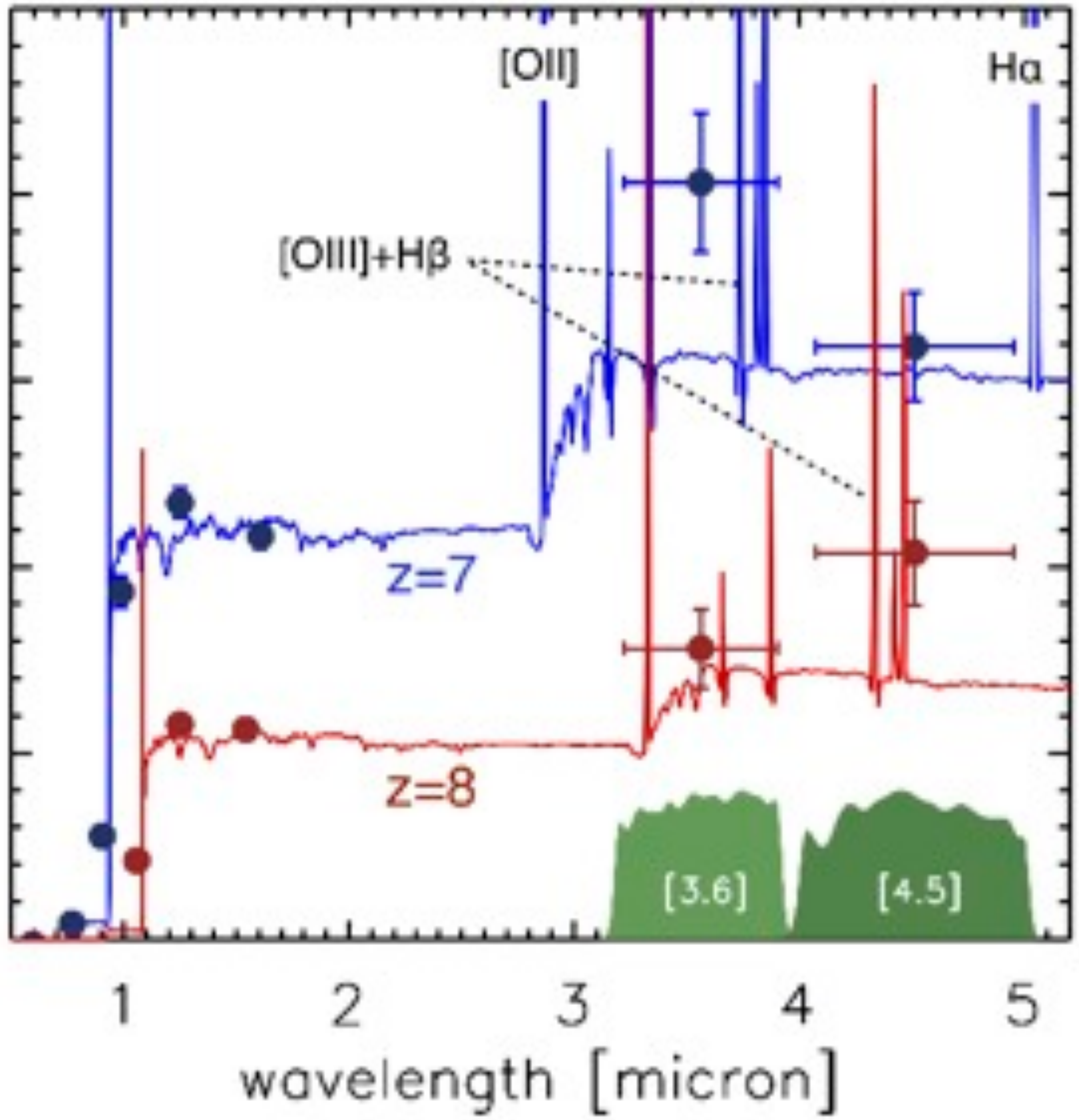



Kurczynski+2014

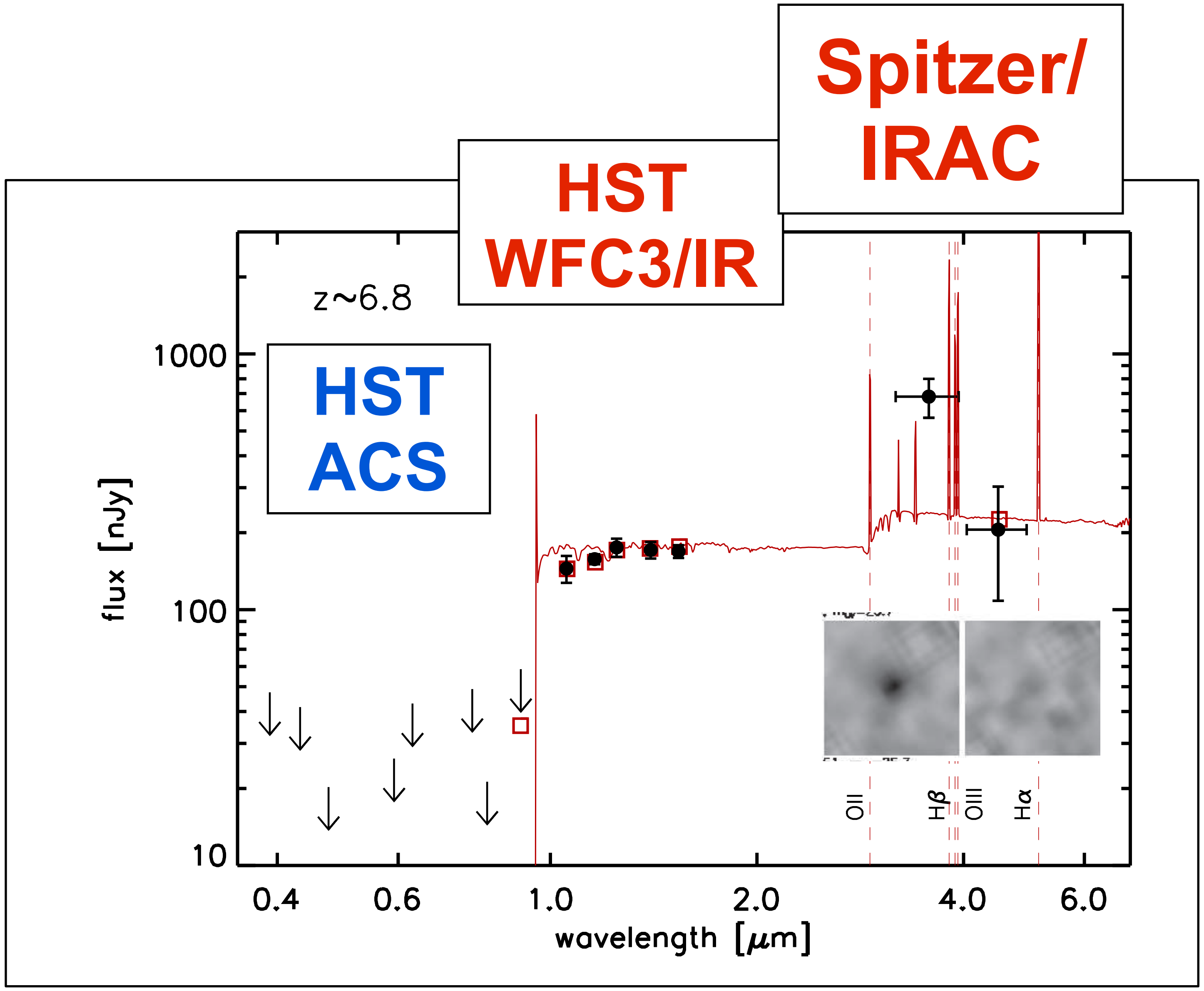
# How strong are emission lines in faintest z~7 galaxies?

***What do the emission lines indicate?***

Bright [OIII] lines in z~7 galaxies from IRAC photometry




Labbe+2013




Smit+2014

## Emission Line Properties of Faint z~7 Galaxies Not Yet Clear

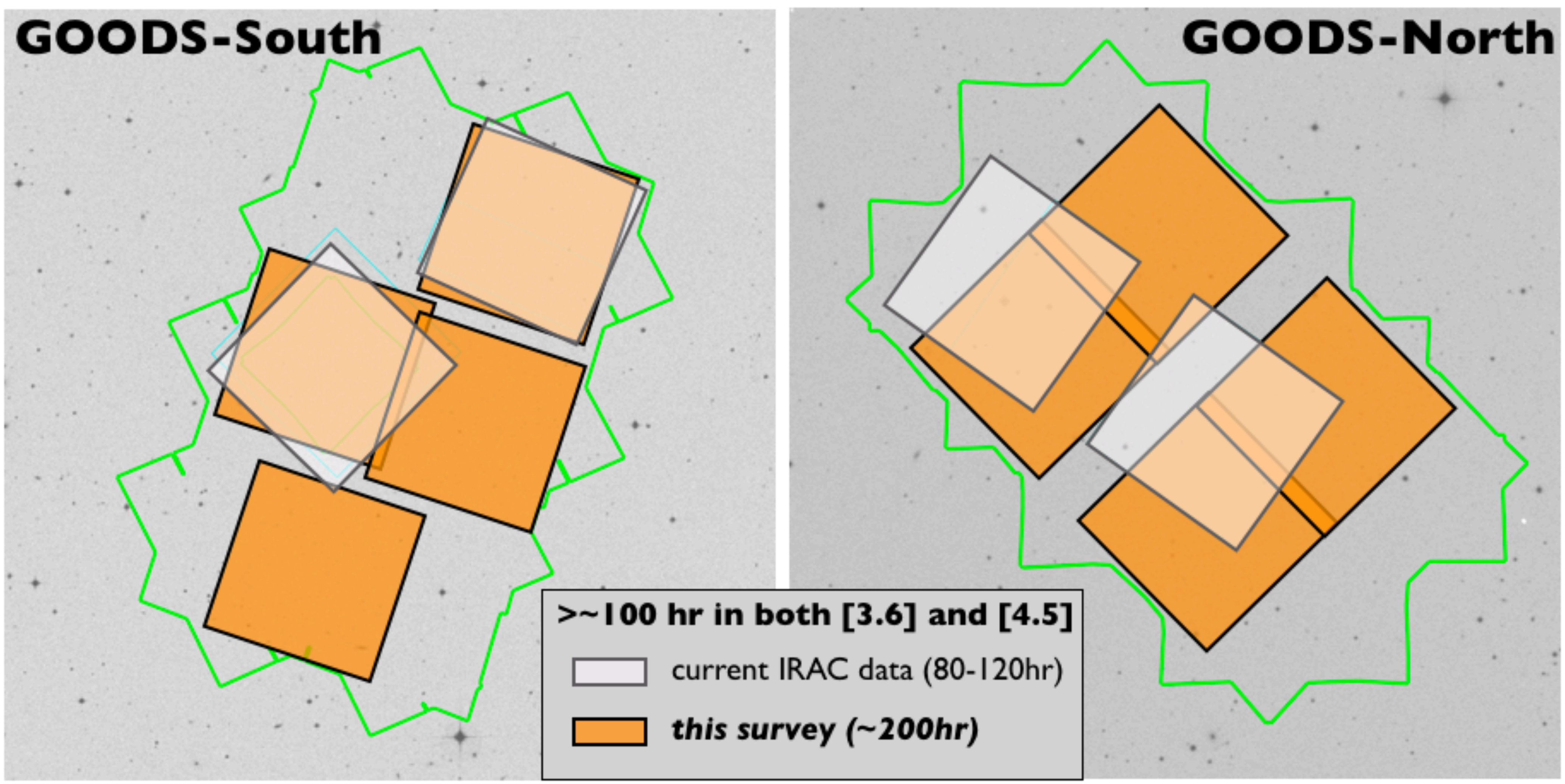
# GREATS program

(PI: Ivo Labbe)

200 hour depth IRAC data over 200 arcmin$^2$

26.7 mag at 5 sigma

Individual detections to 0.5 L* galaxies

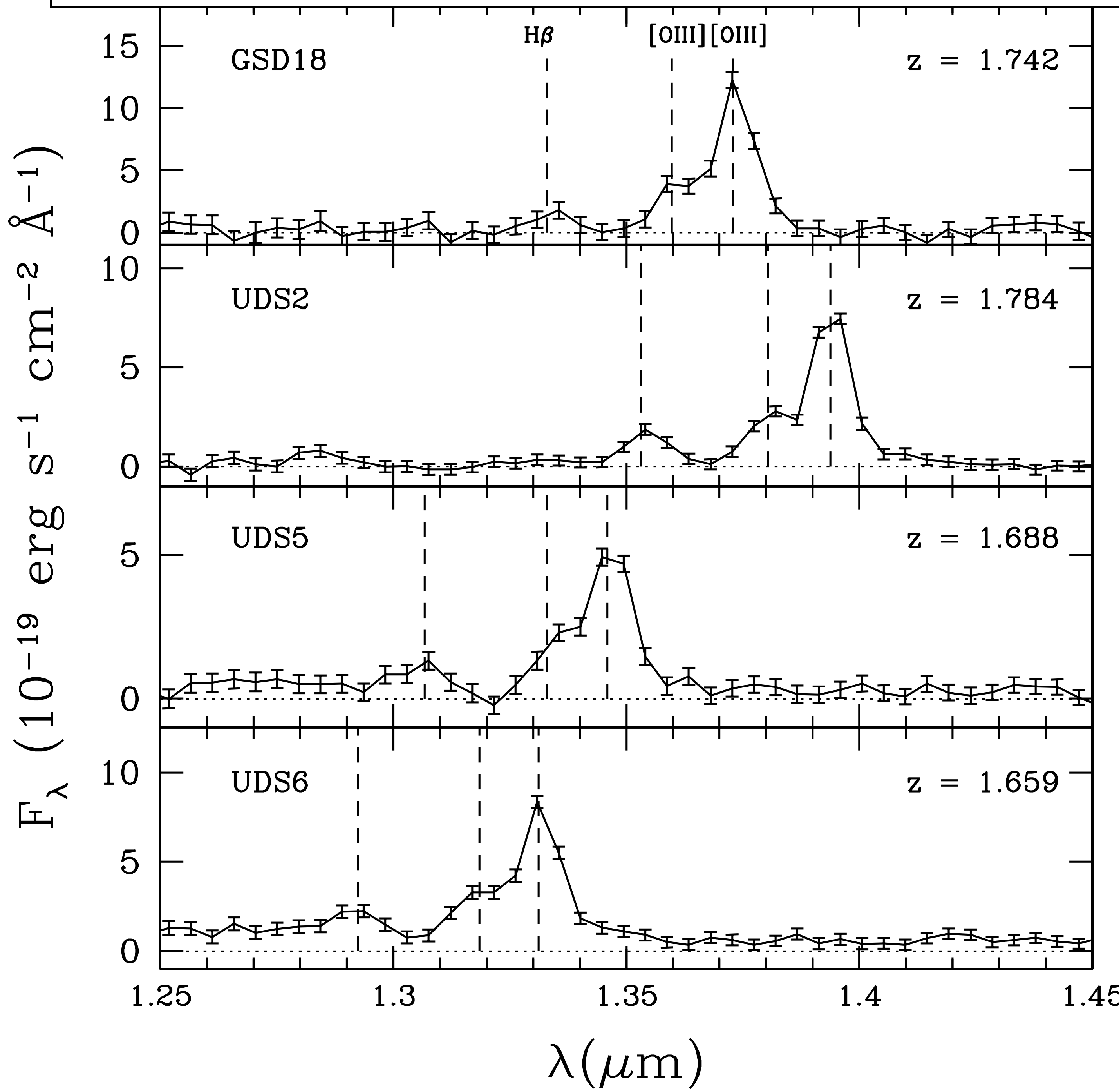


# Emission Line Properties of Faint z~7 Galaxies Not Yet Clear

## Let's go to z~1-3....

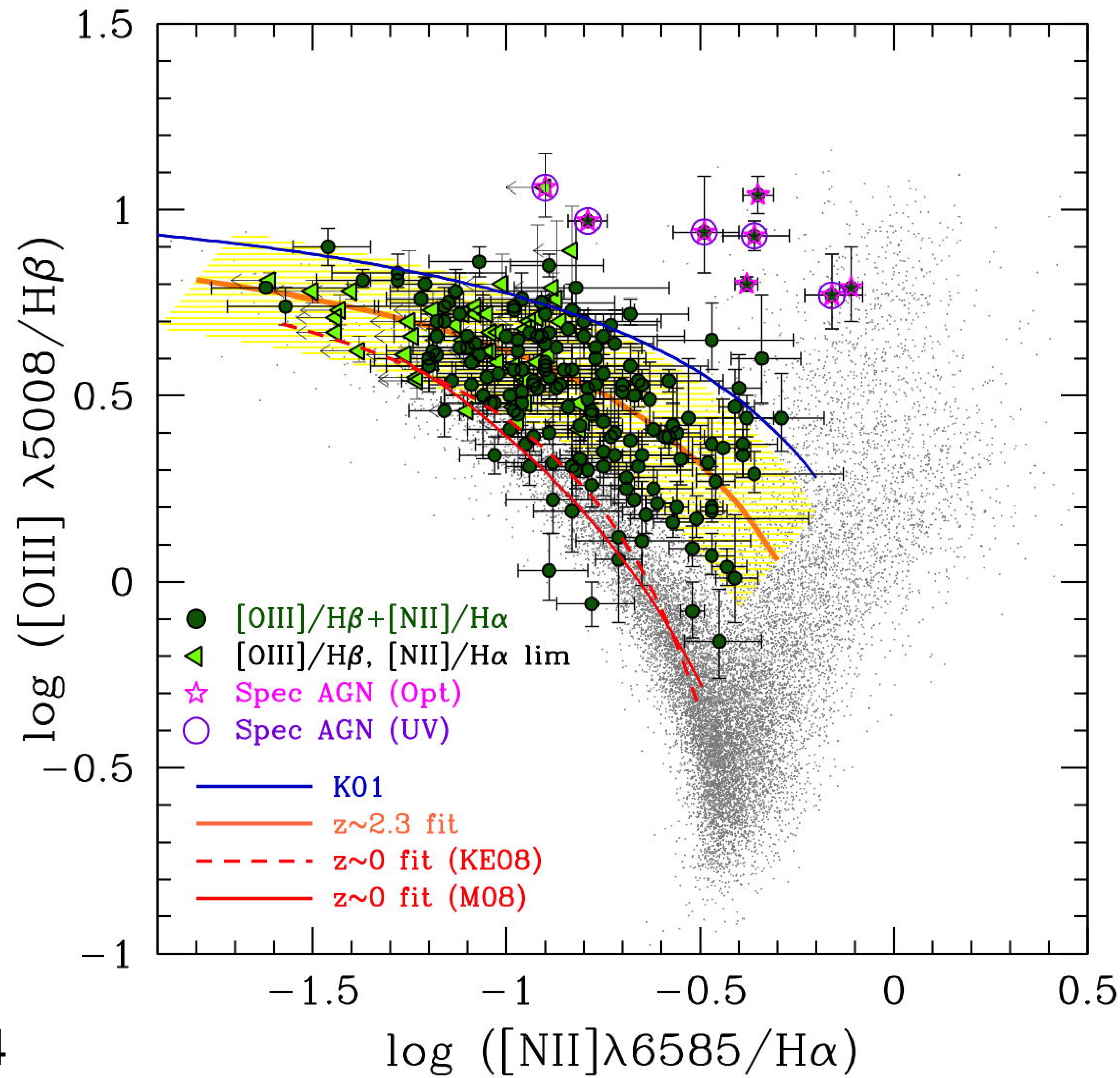
# Similar at z~7:
# [OIII] is elevated relative to Hβ at z~1-3

Evident from *direct spectroscopy:*



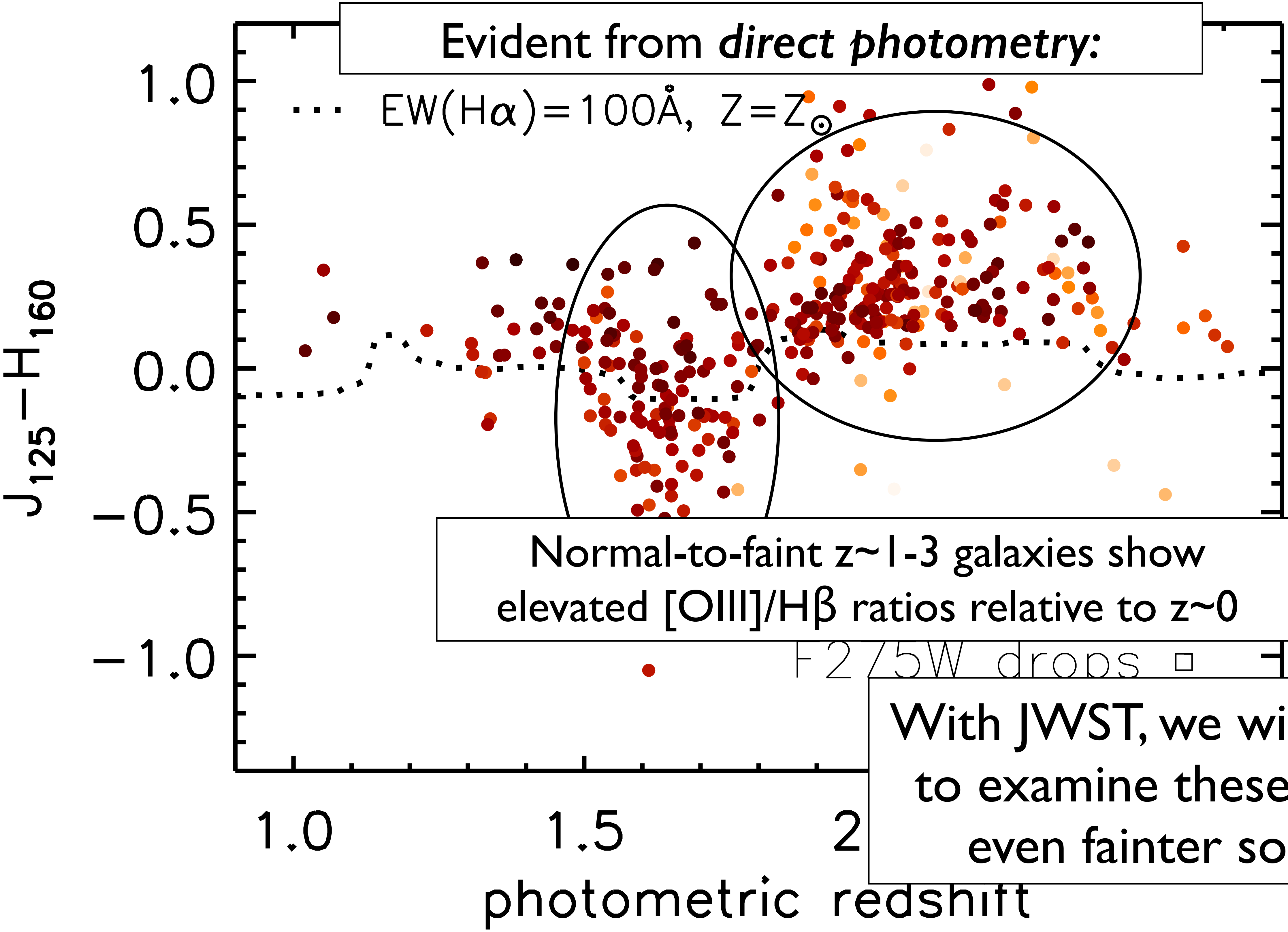

van der Wel+2011; see also Atek+2011; Brammer+2012

# Similar at z~7:
# [OIII] is elevated relative to Hβ at z~1-3




Steidel+2014

# Similar at z~7:
# [OIII] is elevated relative to Hβ at z~1-3

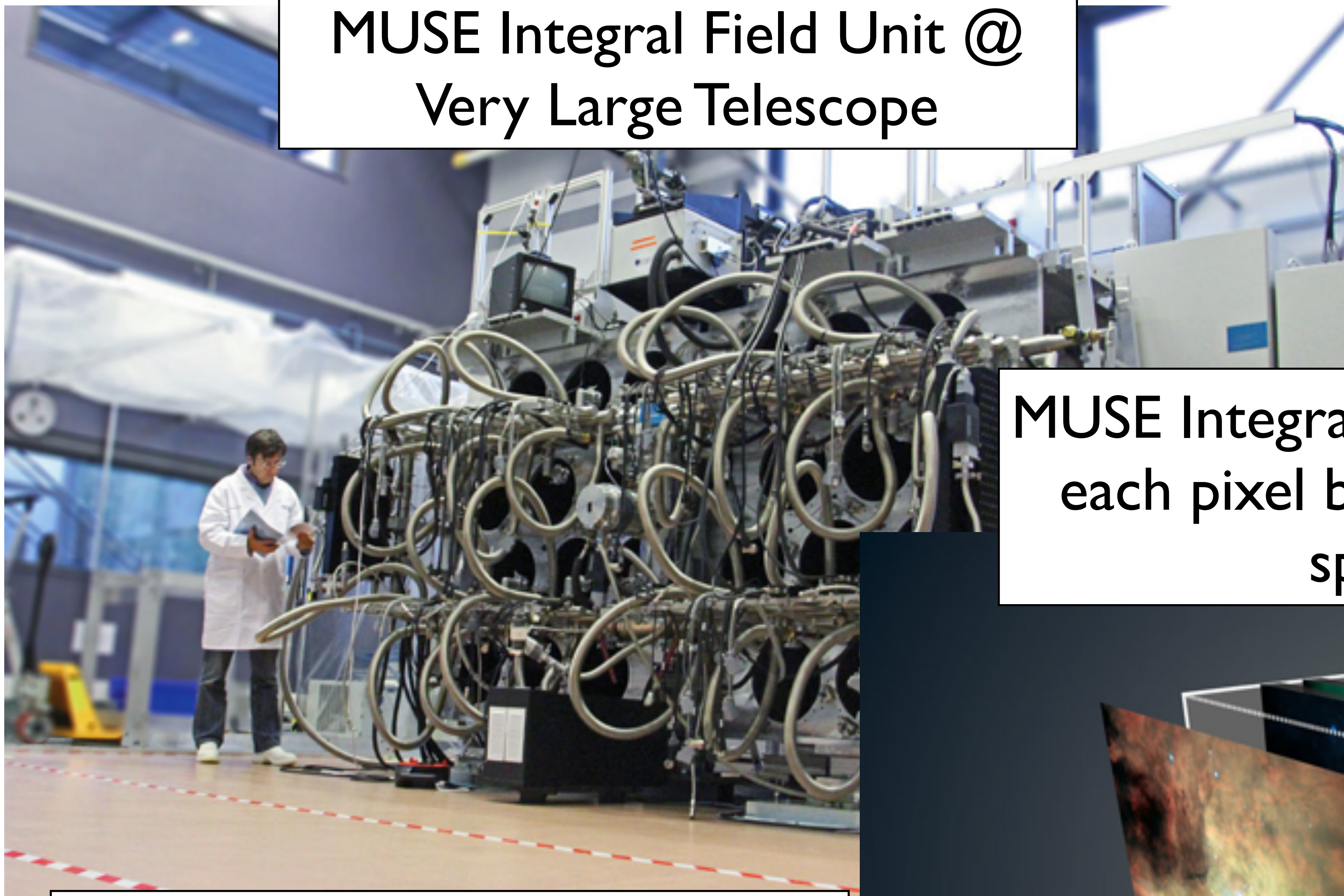



Normal-to-faint z~1-3 galaxies show elevated [OIII]/Hβ ratios relative to z~0

With JWST, we will be able to examine these lines in even fainter sources

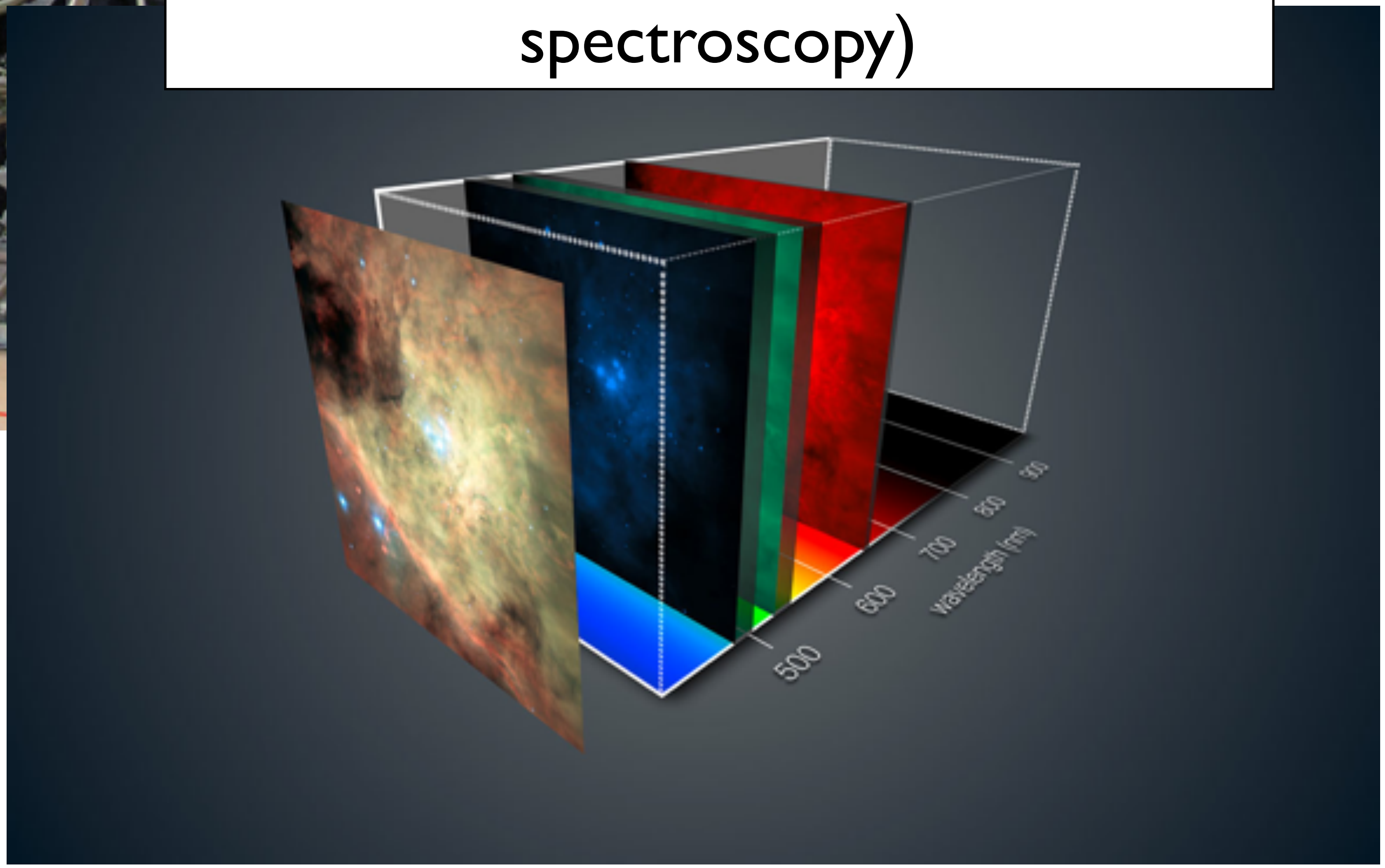
**How extreme can things look if we examine even fainter, lower mass z~2-4 galaxies?**

# MUSE Optical IFU on the VLT allows a first exploration of ultra-low-mass z~1-4 galaxies



MUSE Integral Field Unit @ Very Large Telescope

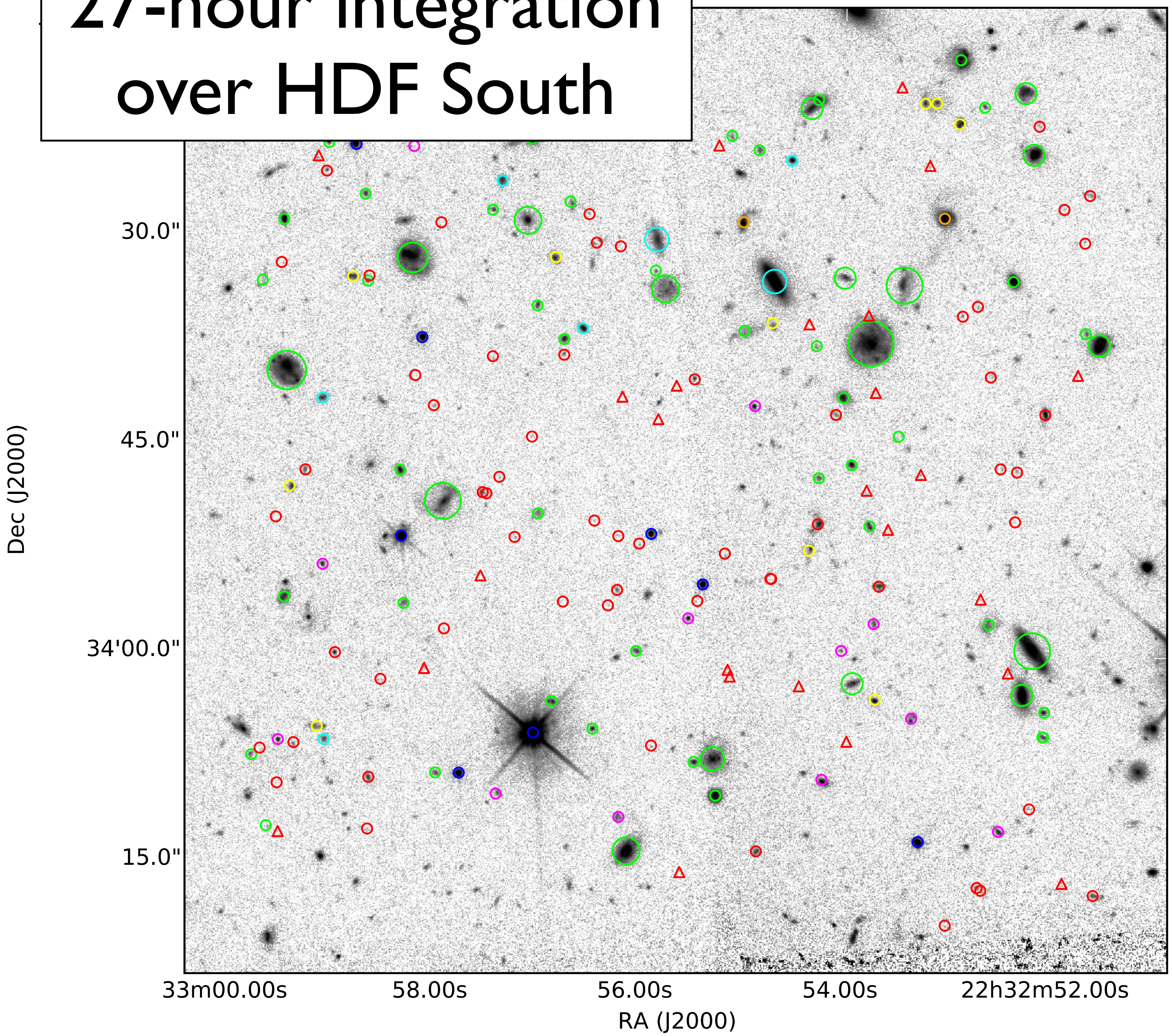
1 $arcmin^2$ field of view




MUSE Integral Field Unit decomposes each pixel by wavelength (R~3500 spectroscopy)

# MUSE Optical IFU on the VLT allows a first exploration of ultra-low-mass z~1-4 galaxies

27-hour integration over HDF South



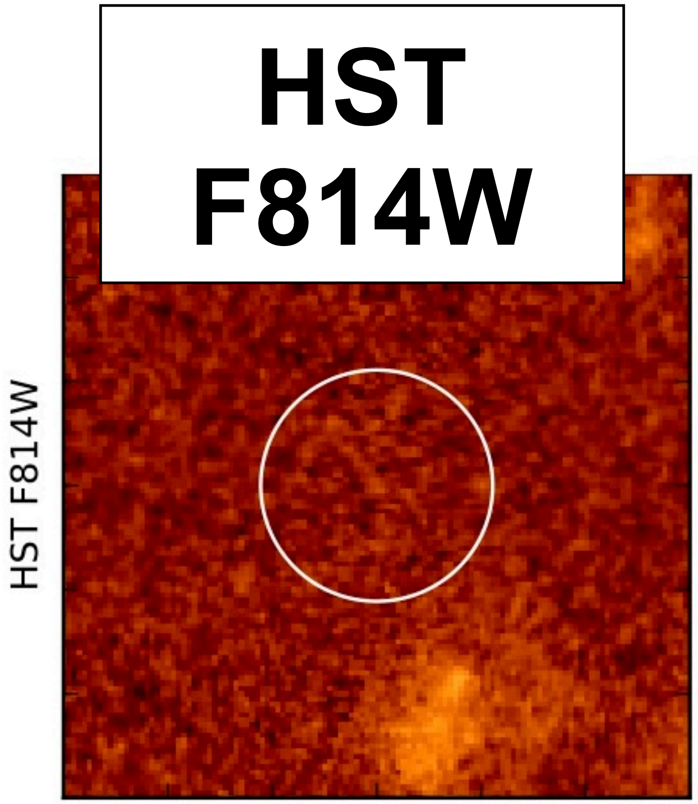

⇒ ~200 redshift measurements

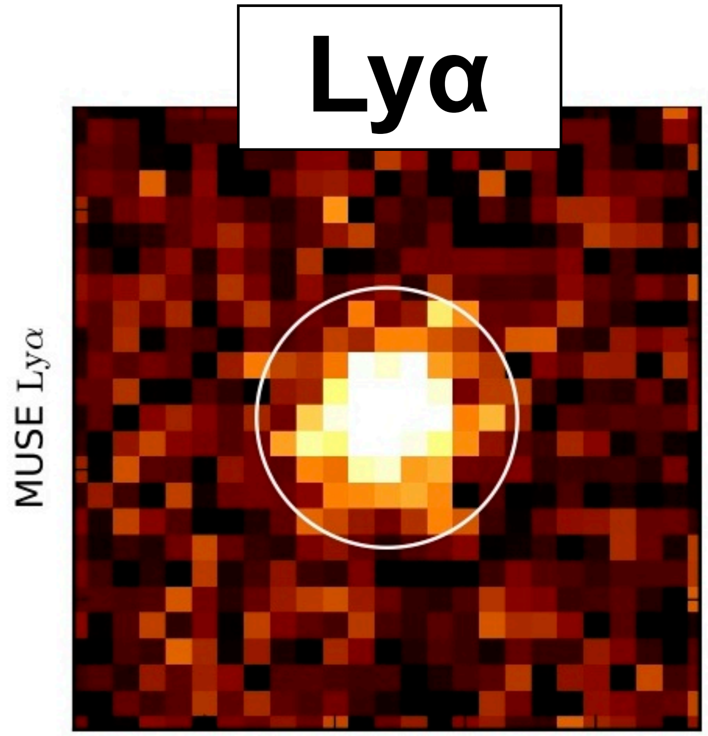
>10x more than before

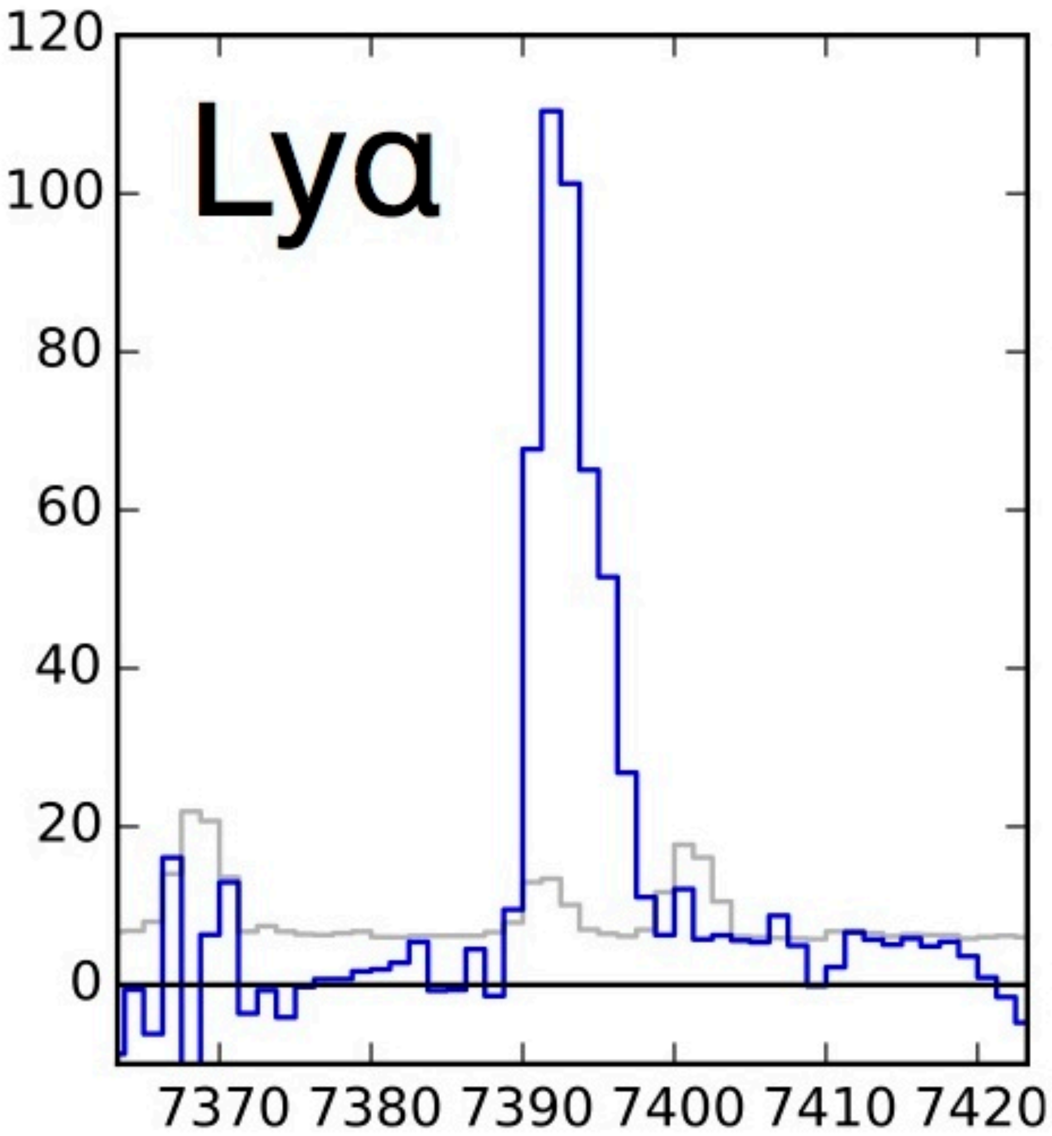
Reduced data publicly available for download

Bacon+2015

# MUSE reveals very high-EW Lyα-emitting Galaxies at z=3-6!



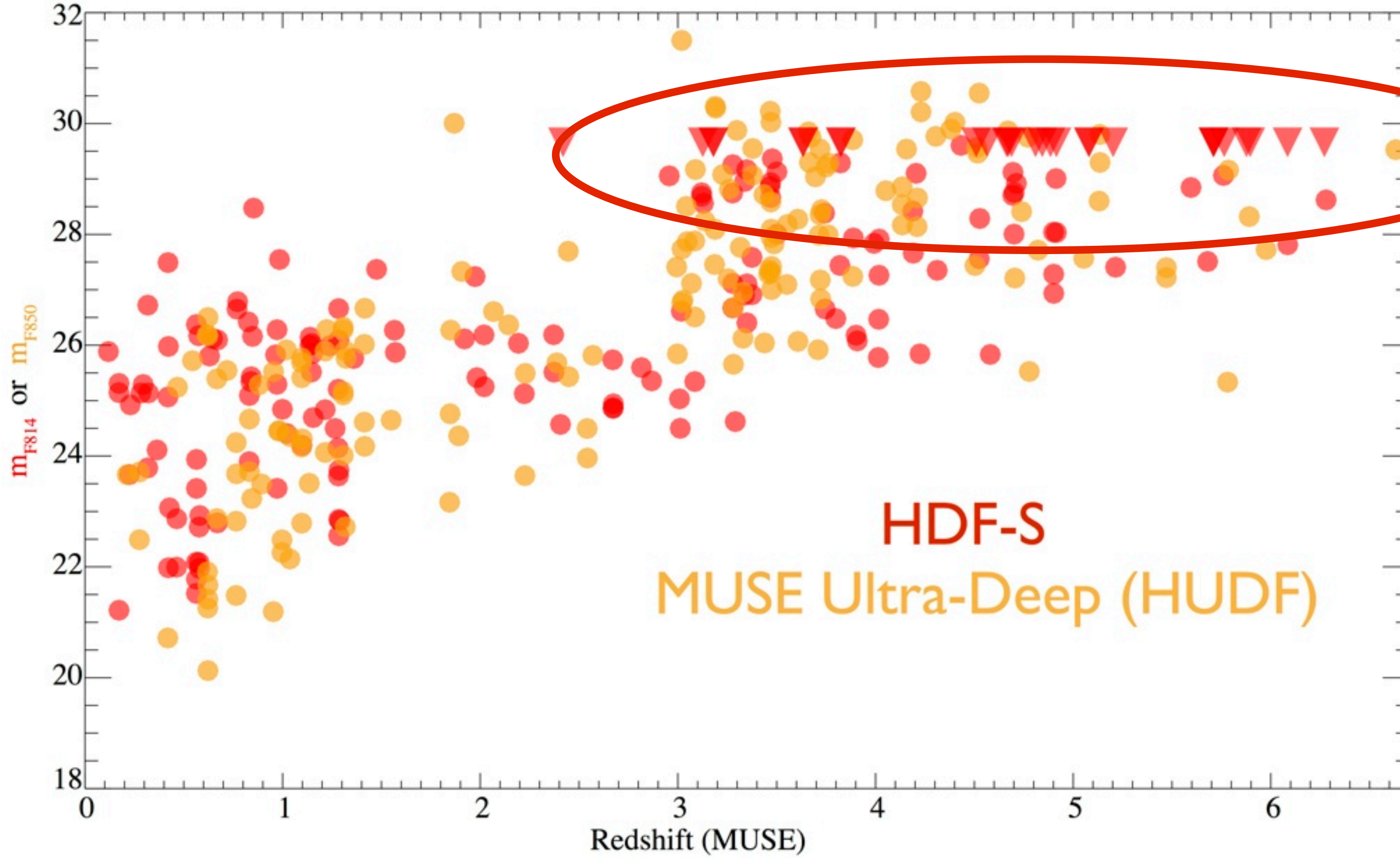




Ideal Sources to Target with JWST!

Lower Mass than Accessible z>7 Galaxies

Bacon+2015

# MUSE reveals very high-EW Lyα-emitting Galaxies at z=3-6!




Ideal Sources to Target with JWST!

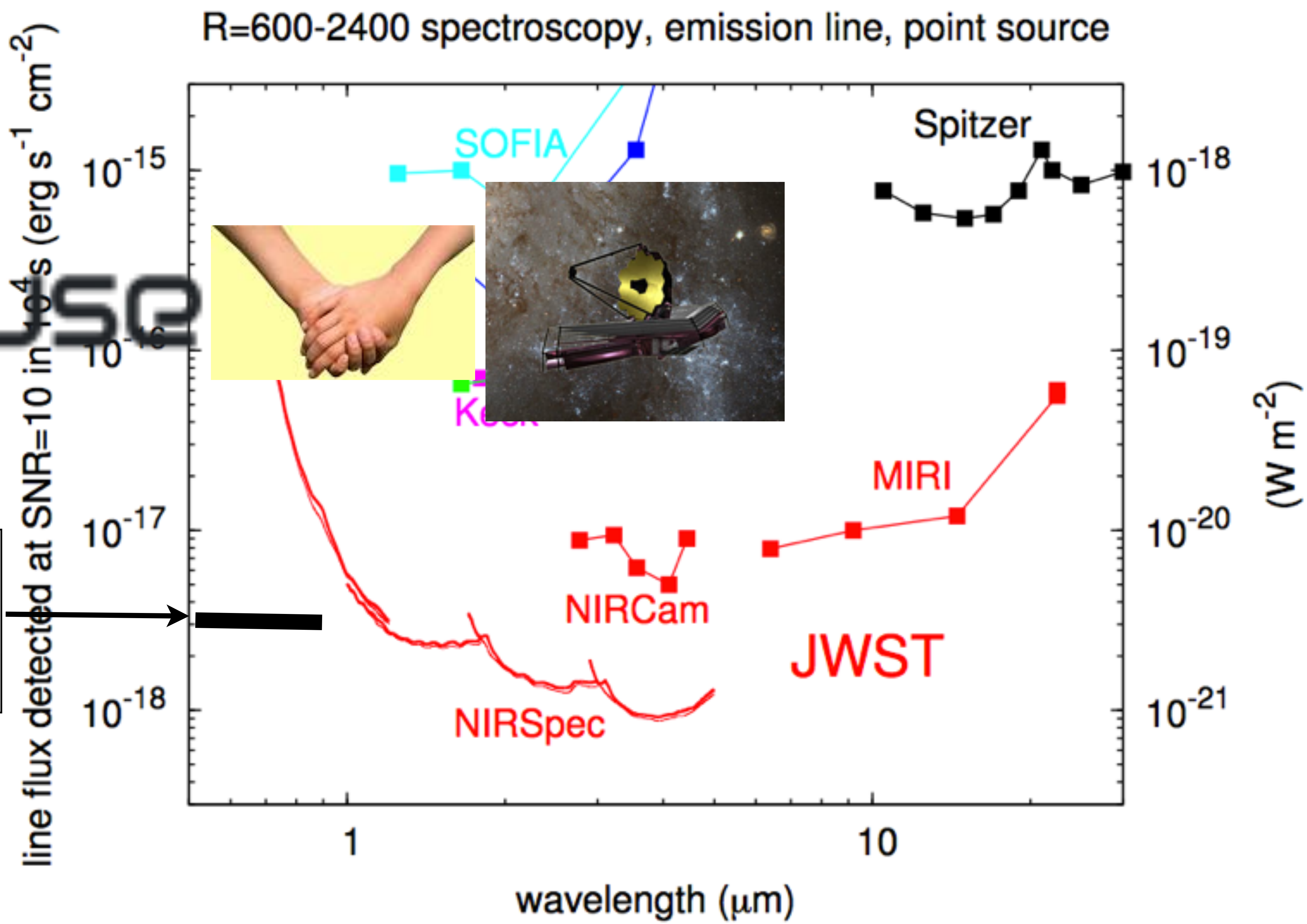
Lower Mass than Accessible z>7 Galaxies

Bacon+2015

# Optical IFUs (e.g. MUSE) highly complementary to JWST NIRSpec into the future

Lower-Redshift Sources with MUSE could be targeted...

**MUSE (AO enabled)**



# JWST will also allow us to probe the stellar masses and dynamical masses for the faintest z~1-3 galaxies.

The mass in stars will be computed both on the basis of the photometry (corrected for emission line contamination)

and on the basis of the IFU spectroscopy of sources

All of these activities can best be done on ultra-faint, low-mass z~1-3 galaxies -- where the sources are brighter and more accessible

# Faint z<3 Galaxies will give us high S/N measurements of unique spectral lines...

JWST will only provide especially high S/N spectroscopy over a limited range (1-5 microns)...

This becomes important if we want to model the nebular properties of the faintest galaxies accurately...

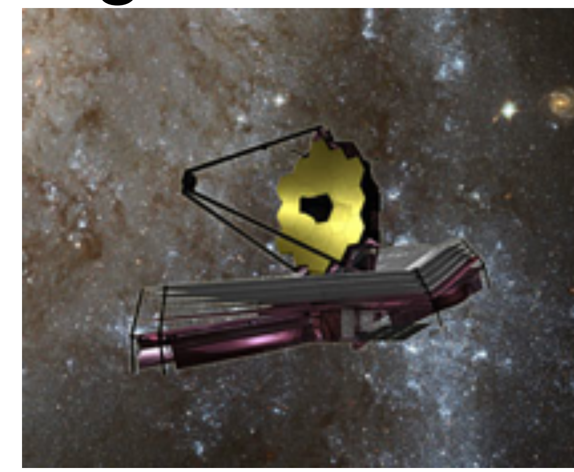
At z<3: we can measure the following lines (rest-frame 12000 Angstroms) at especially high S/N:

Paschen α, Brackett γ

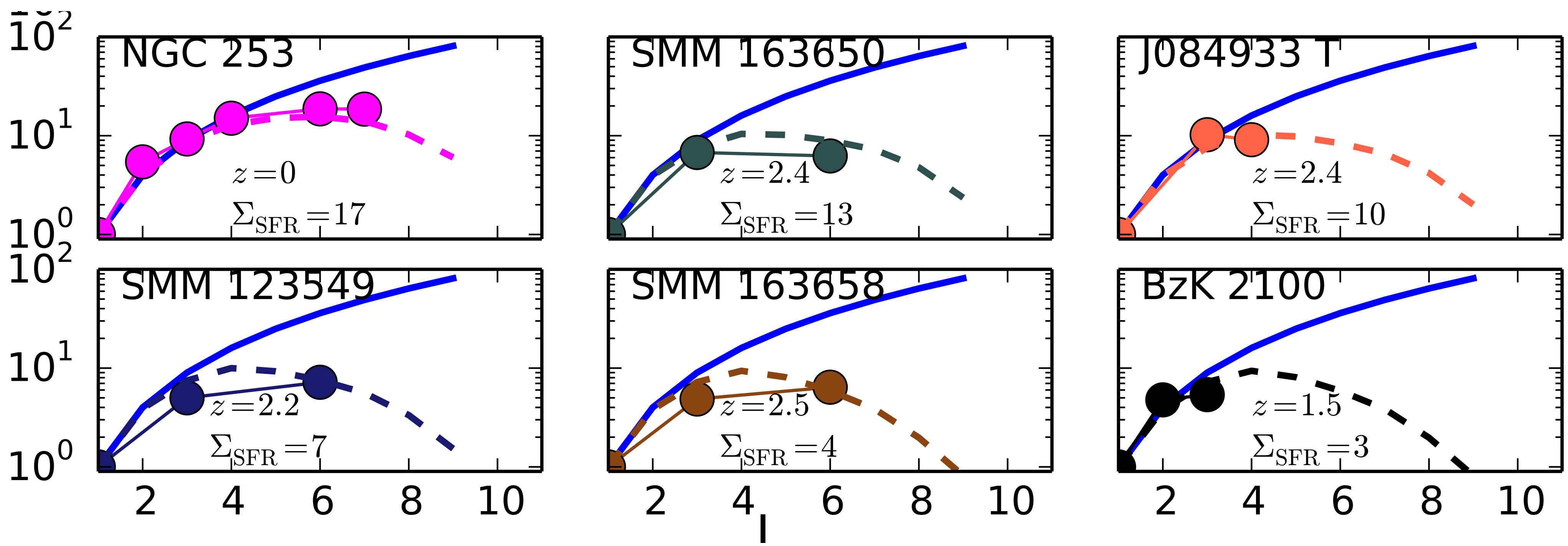
This should allow us to model the properties of nebulae in star-forming galaxies in low-mass galaxies very accurately. This provides insight into the physical conditions.

# How does gas fuel star formation in low-mass galaxies?

At z~1-5, the best information will be available on gas masses with JWST + ALMA....

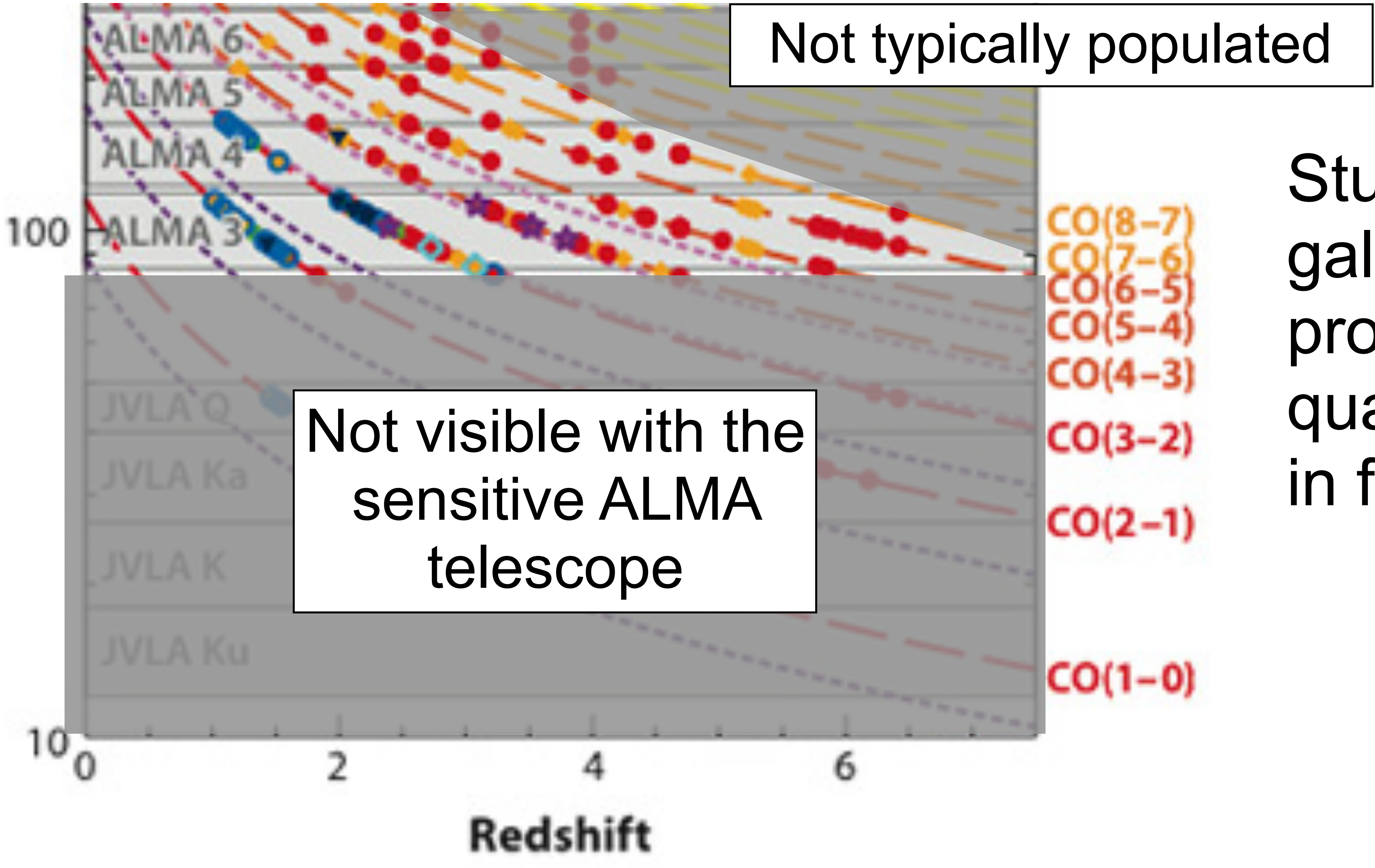
In the typical galaxy, only the lowest rotational states of CO tend to be populated.




Narayanan+2015

# How does gas fuel star formation in low-mass galaxies?

Direct measurements of the gas mass are difficult at z>5...




Study of lower-redshift galaxies more productive in terms of quantifying gas masses in faintest galaxies

JWST can help to further leverage ALMA data by providing measurements of the systemic redshifts to enable stacking of the CO lines

Carilli & Walter 2013

# What is the Lyman-continuum escape fraction in faint z~7 galaxies?

Difficult to probe directly, as any escaping Lyman-Continuum radiation at z~7 would need to redshift through Lyα forest.

Characterization Possible in faint z=1-3 galaxies (particularly those which are gravitationally lensed)

Combine

HST UV Images / Ground-Based UV IFU data (Keck Cosmic Web Imager)

with

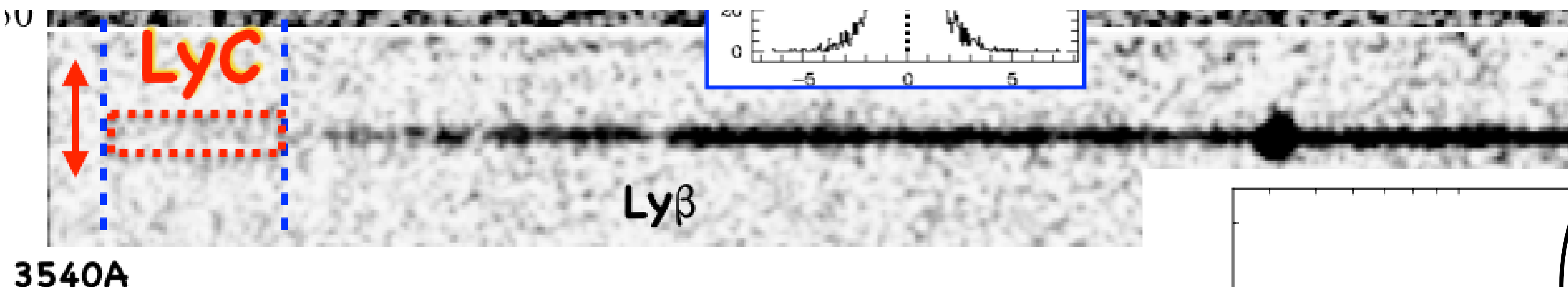
detailed spectral characterization possible with JWST

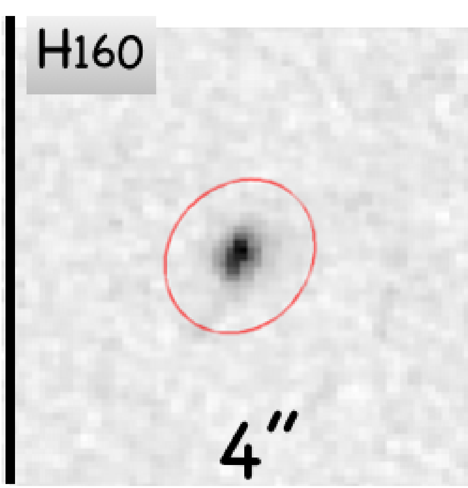
# What is the Lyman-continuum escape fraction in faint z~7 galaxies?

Characterization Useful given Evidence that only certain types of galaxies show substantial Lyman-Continuum Escape

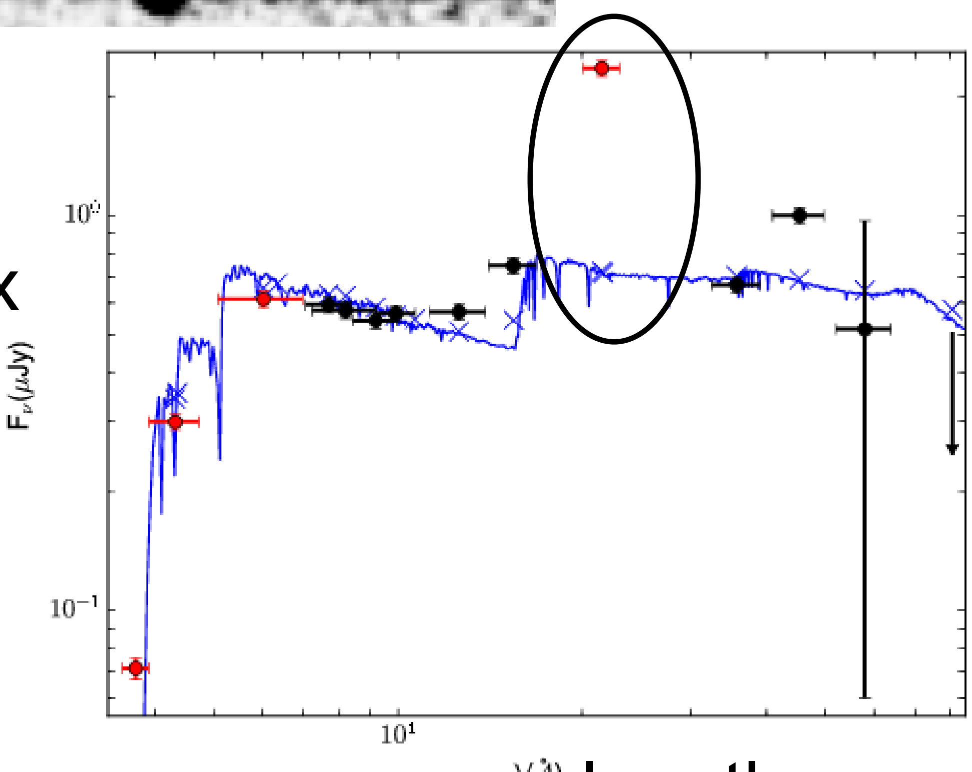
e.g. strong [OIII]-emitting galaxies (i.e. “green peas”) are claimed to show high escape fractions.

here is one example galaxy at z=3.2:




flux




wavelength

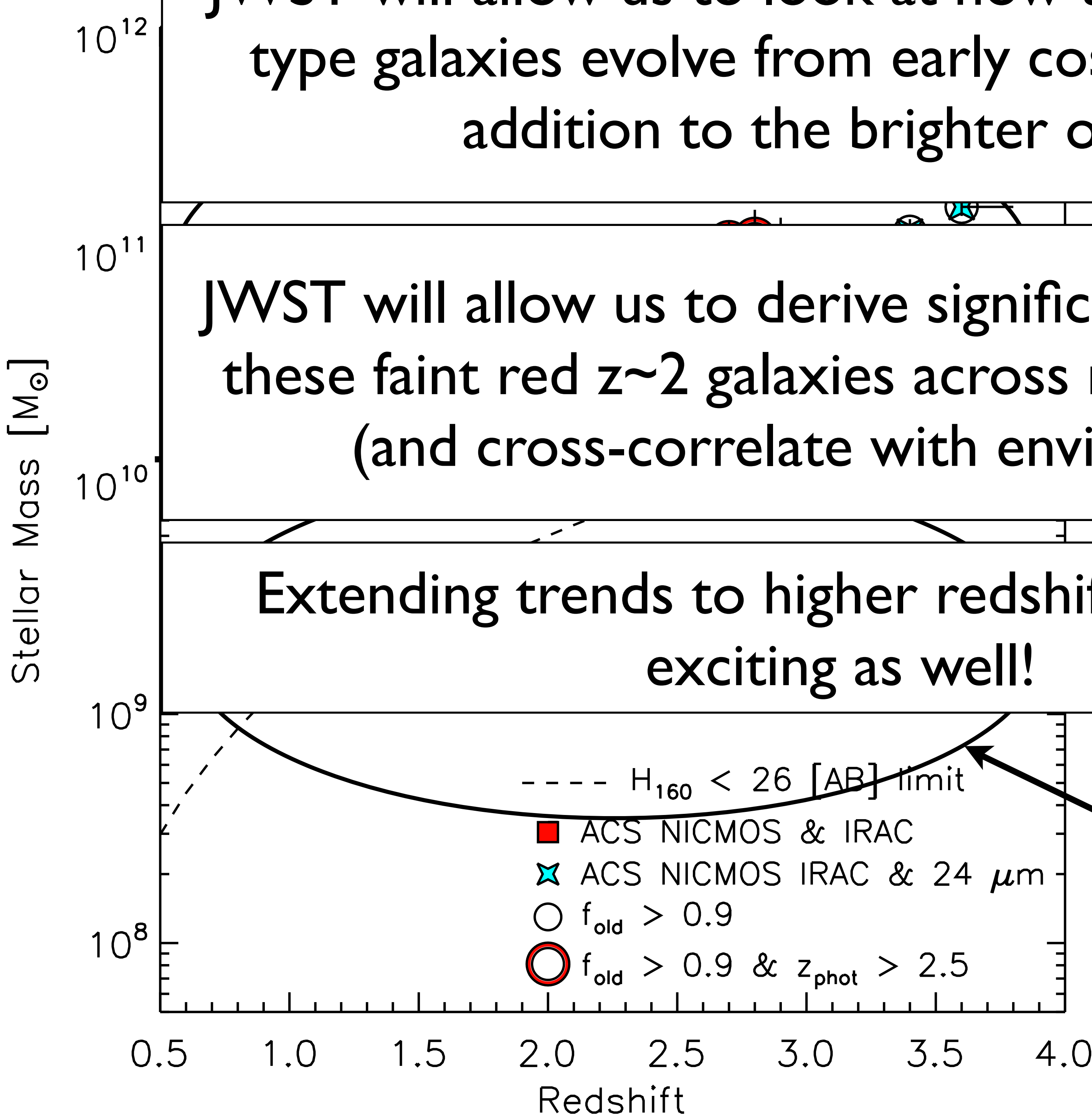
de Barros+2015

# What can JWST teach us about red z~2 galaxies that are ultra-faint?

JWST will allow us to look at how these faint early type galaxies evolve from early cosmic times (in addition to the brighter ones!)

JWST will allow us to derive significant statistics on these faint red z~2 galaxies across many sightlines (and cross-correlate with environment)

Extending trends to higher redshift will be very exciting as well!




Understandable why rare...

Why do these form at all?

confirmed and extended by Sommariva+2014

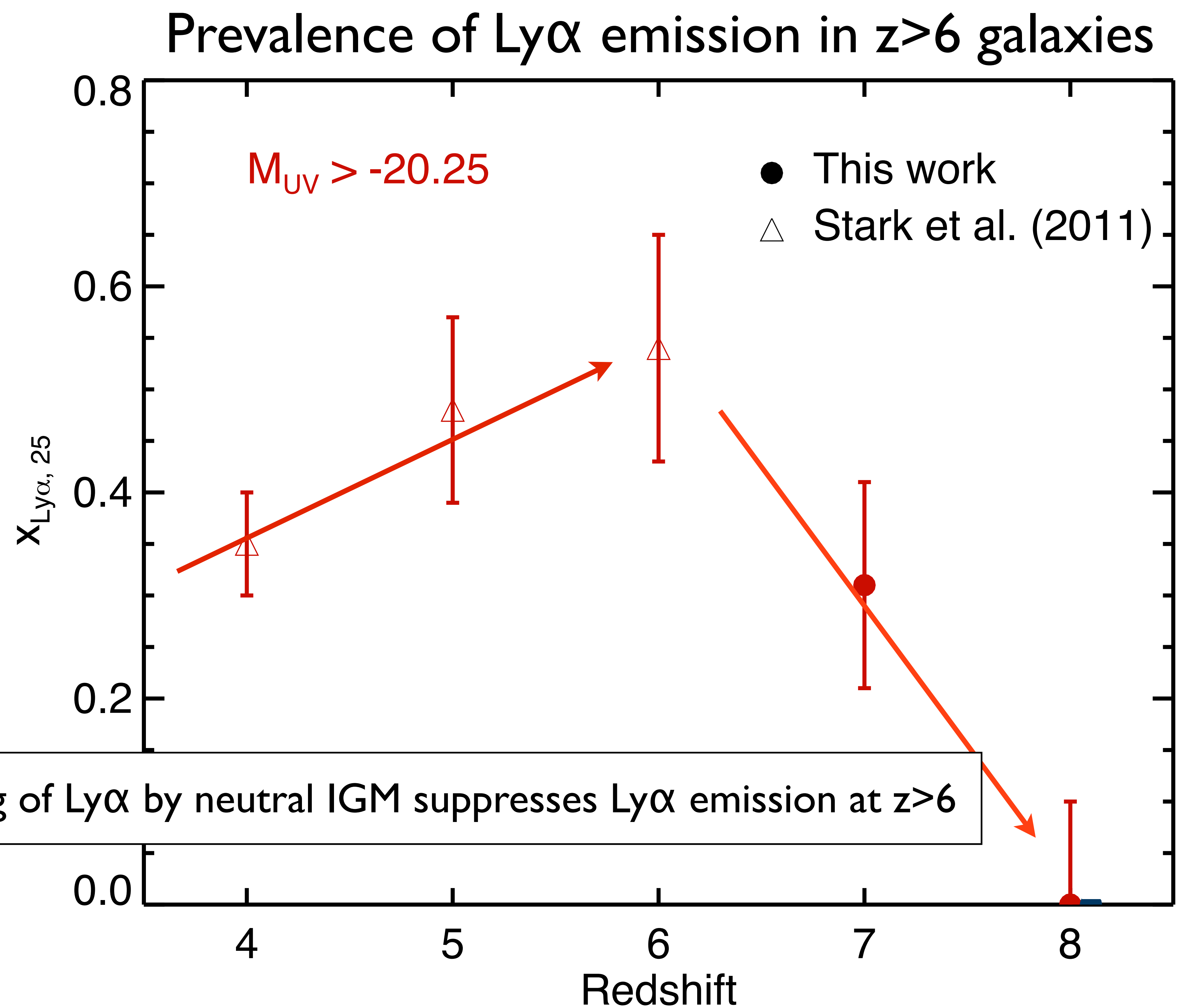
Stutz+2008; see also Sommariva+2014

**What can we learn from current and future JWST spectroscopy about the ionization state of the z>7 universe?**

# Spectroscopic Confirmation: Very Challenging!

**(Redshift Measurements)**

Fraction of galaxies with Lyα EW > 25 A




Resonant scattering of Lyα by neutral IGM suppresses Lyα emission at z>6

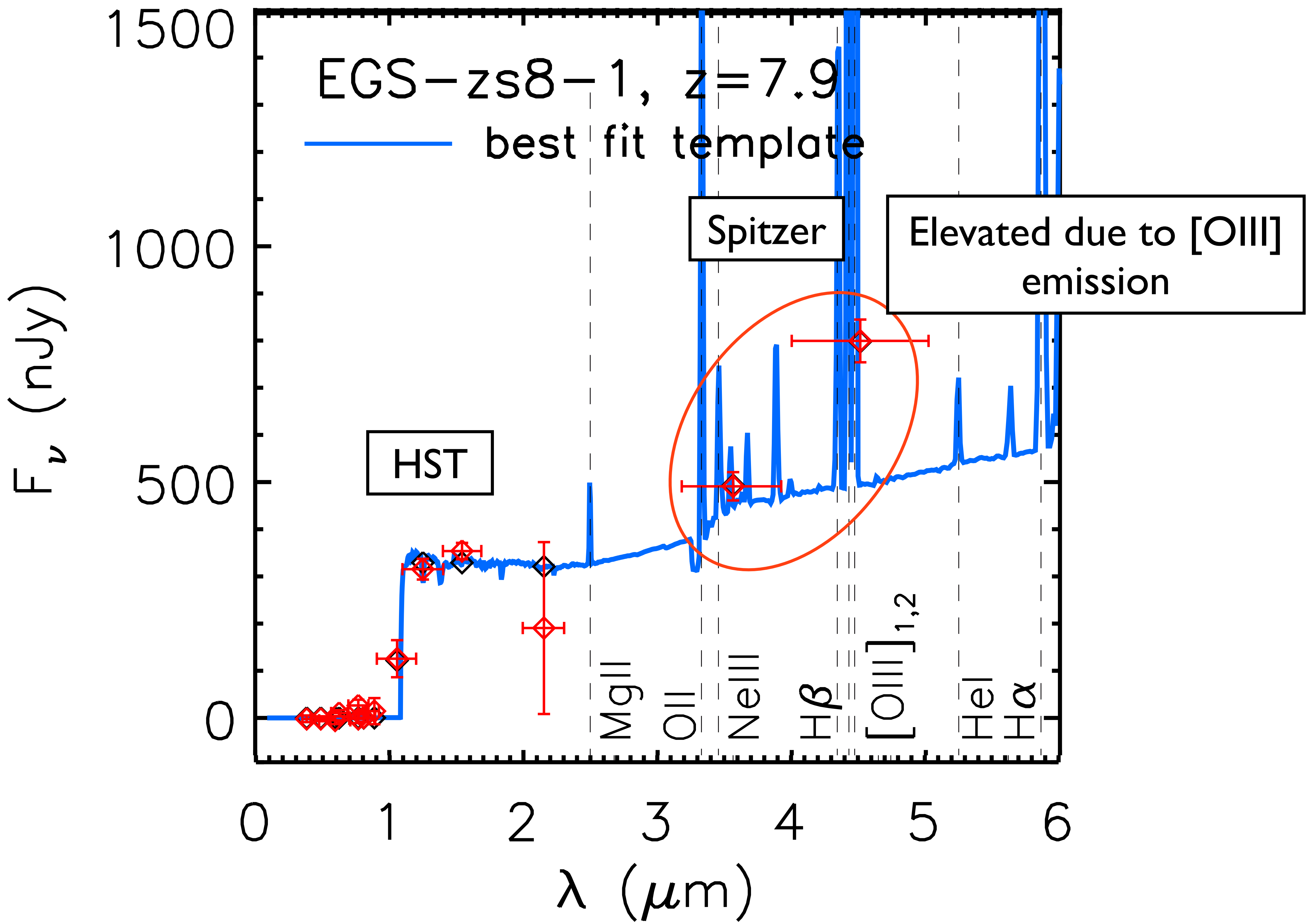
Schenker+2014; see also Pentericci+2014; Tilvi+2014; Treu+2013; Stark+2010; Fontana+2010; Caruana+2014; Ono+2012

**To search for probable Lyα emission from galaxies,**

**we should consider those galaxies which are the brightest**

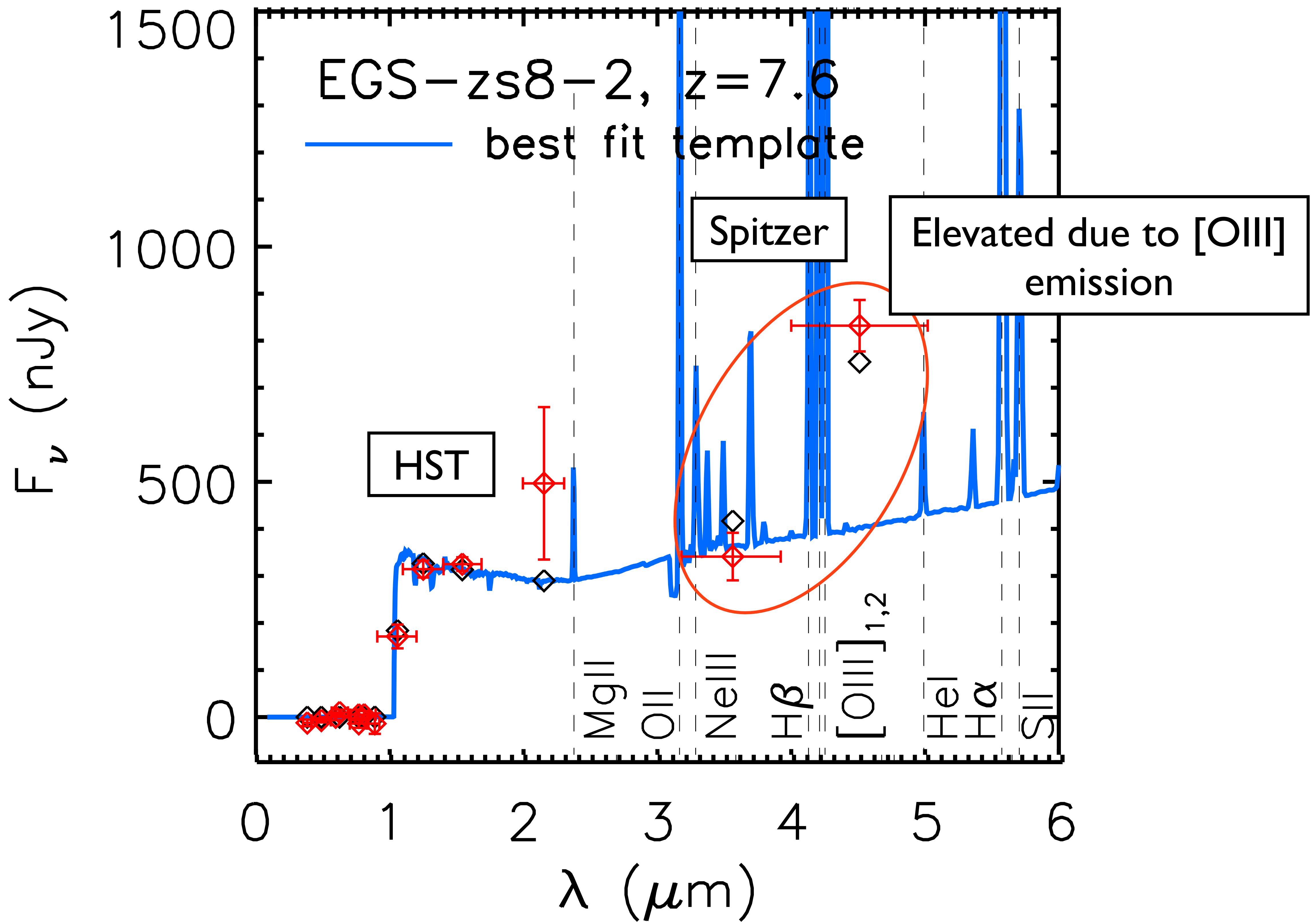
**and which are likely line dominated ([OIII])**

# Find Line-Dominated z>7 Galaxies Using Photometry



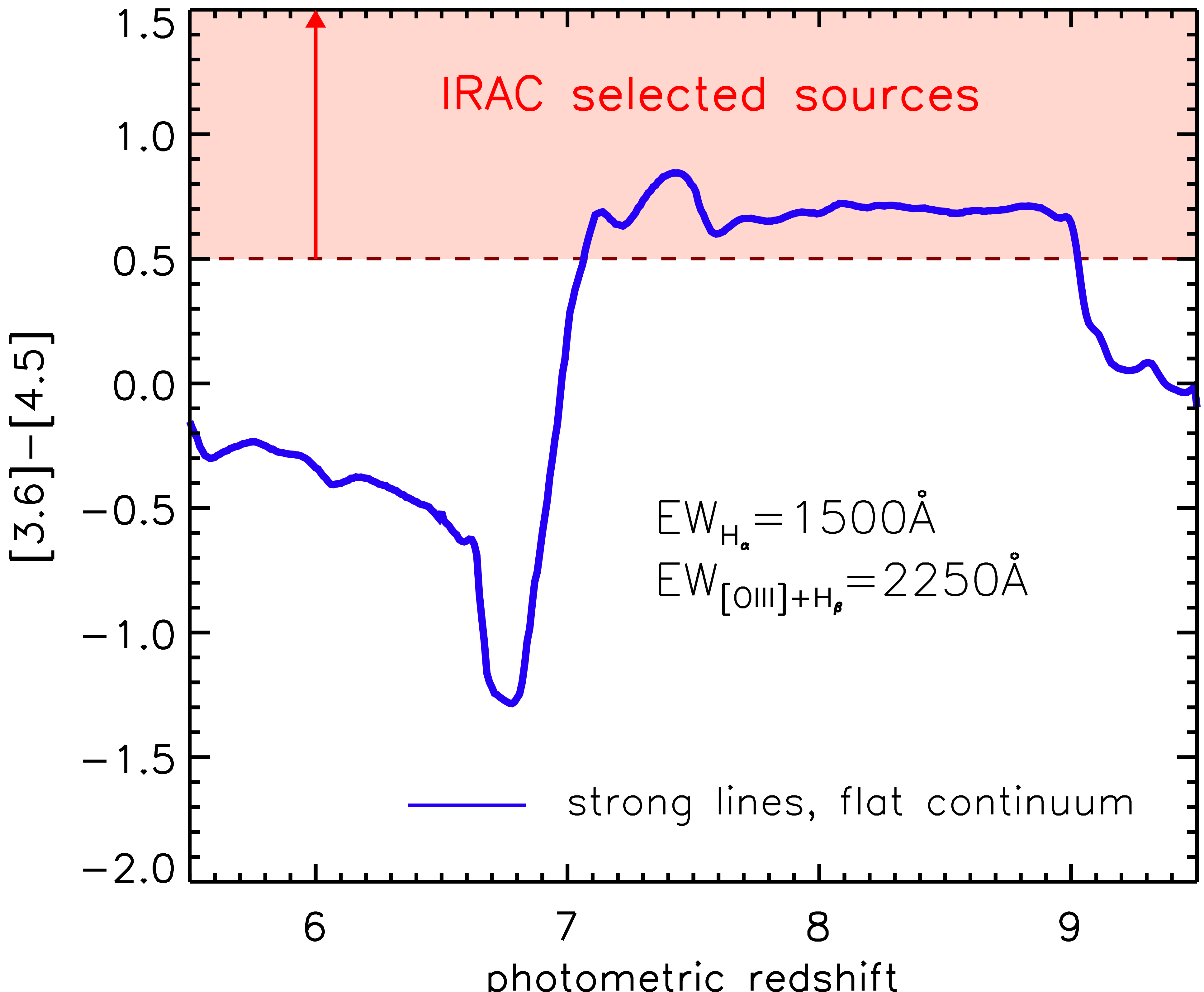

Roberts-Borsani, RJB + 2015

# Find Line-Dominated z>7 Galaxies Using Photometry




Roberts-Borsani, RJB + 2015

# Search for and Do Spectroscopy on very bright, Line-Dominated z>7 Galaxies




Roberts-Borsani, RJB + 2015

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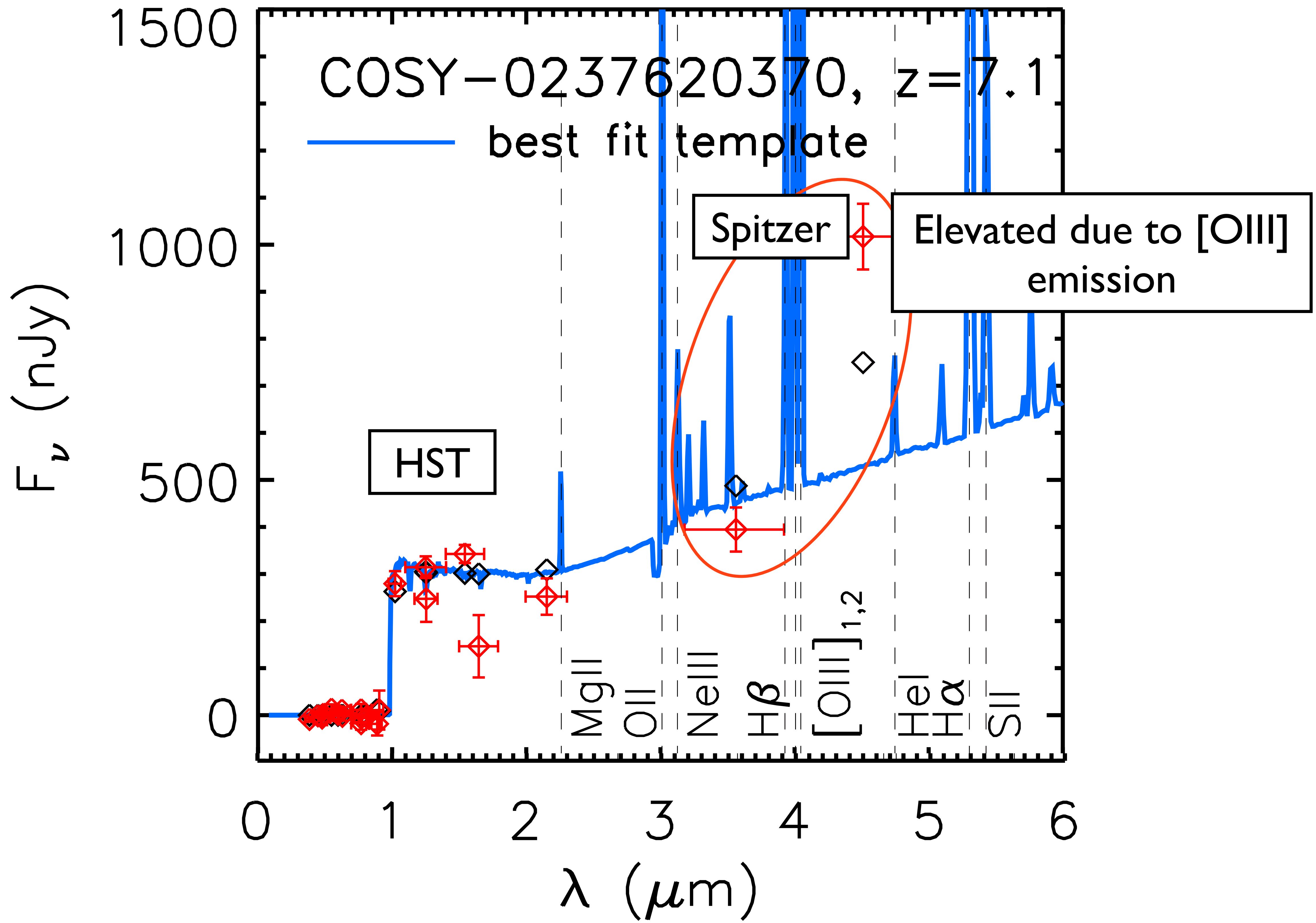


Roberts-Borsani, RJB + 2015

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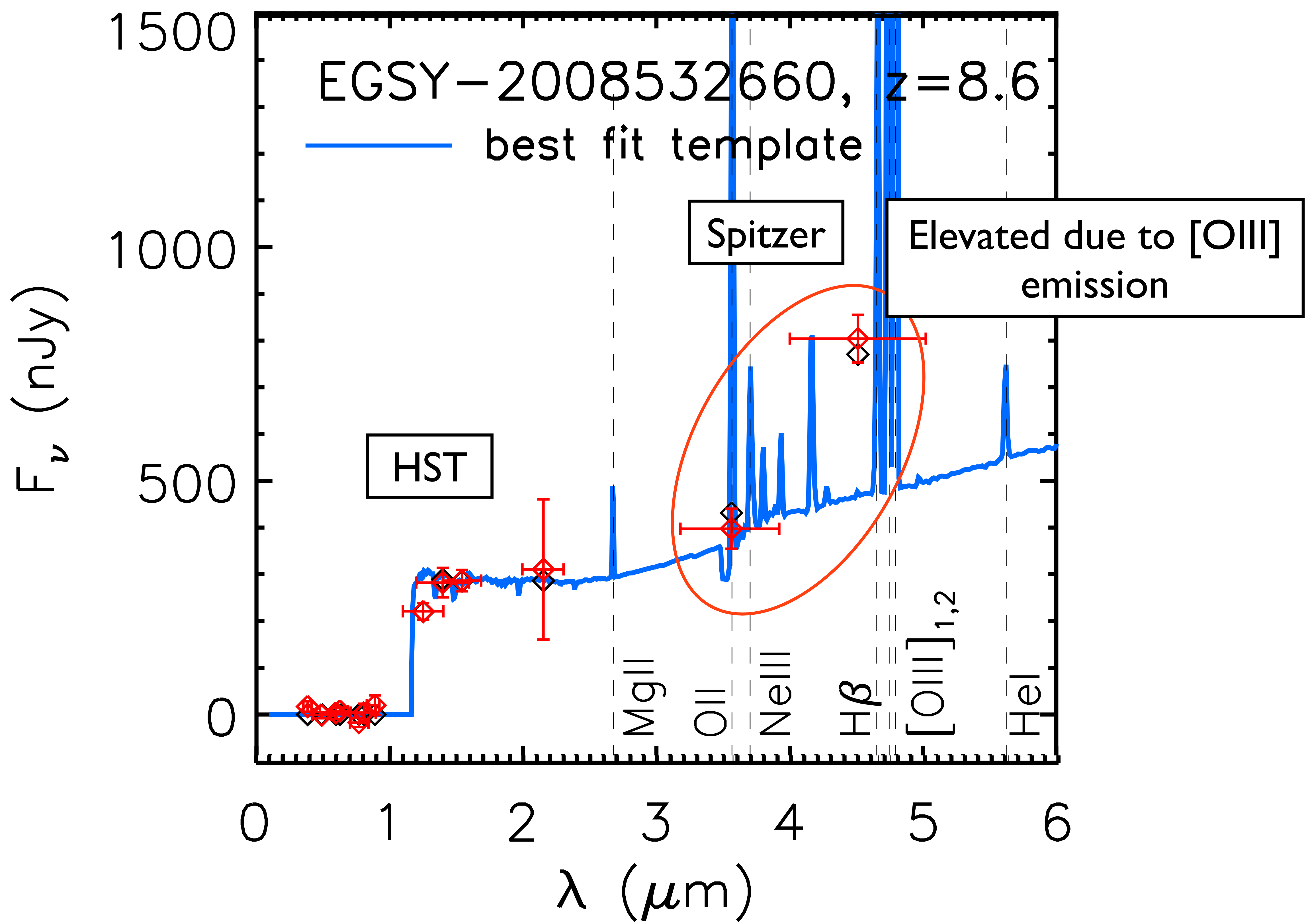
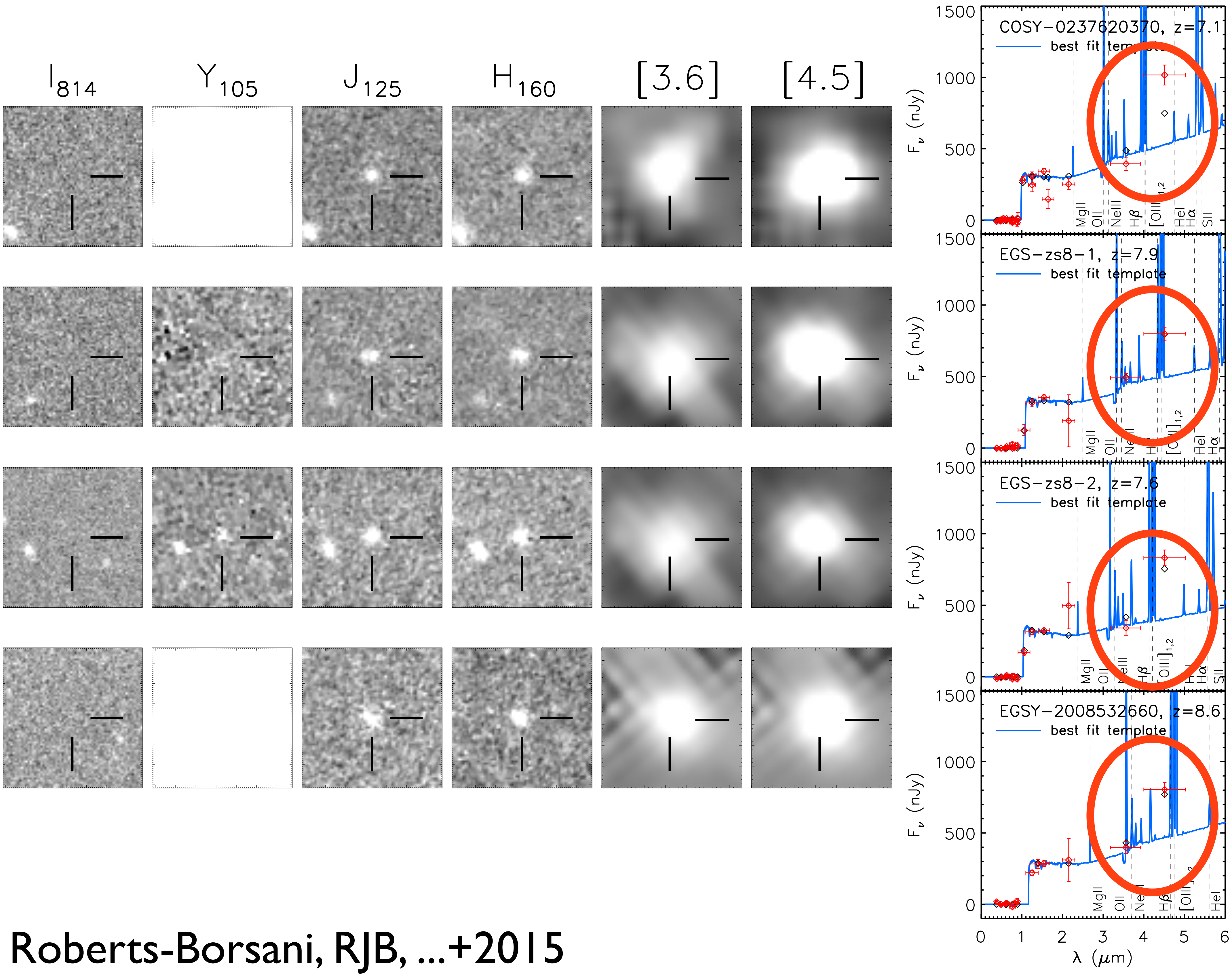


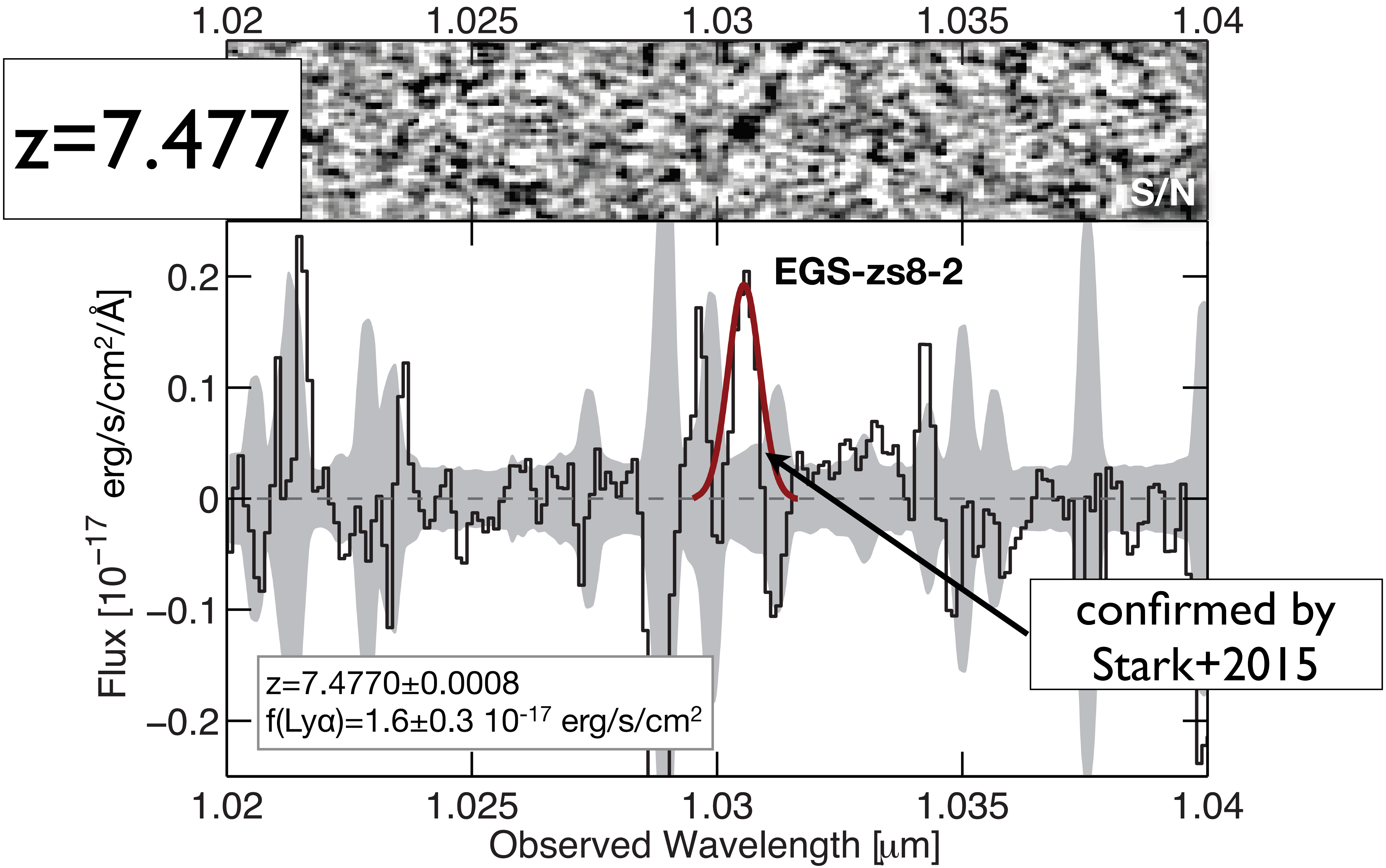

Roberts-Borsani, RJB + 2015

# Four Particularly Bright, [OIII]-Dominated z>7 Galaxy Candidates Identified



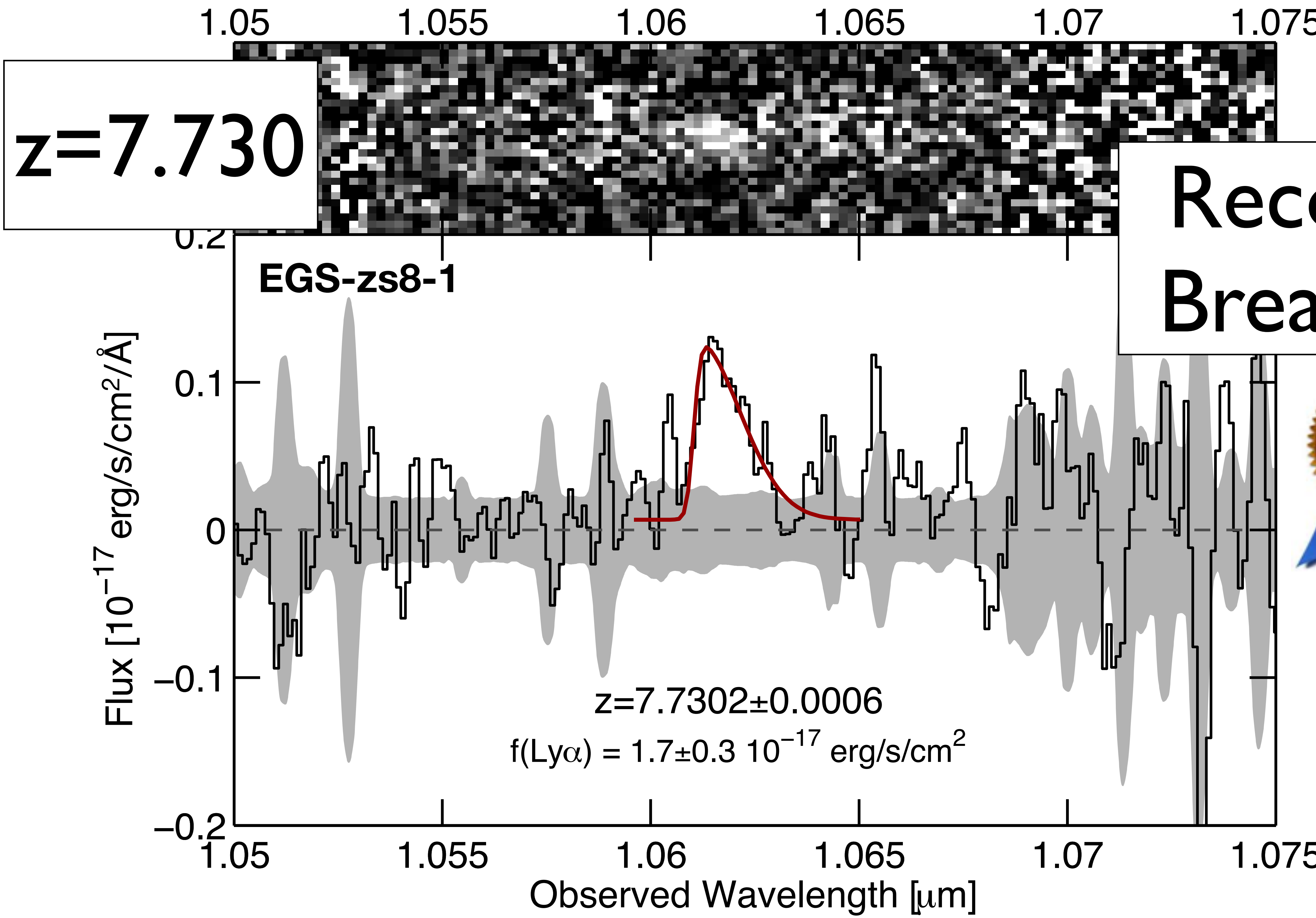

Roberts-Borsani, RJB, ...+2015

# Follow up with Keck/MOSFIRE Spectroscopy




Roberts-Borsani, RJB + 2015; Stark+2015, in prep

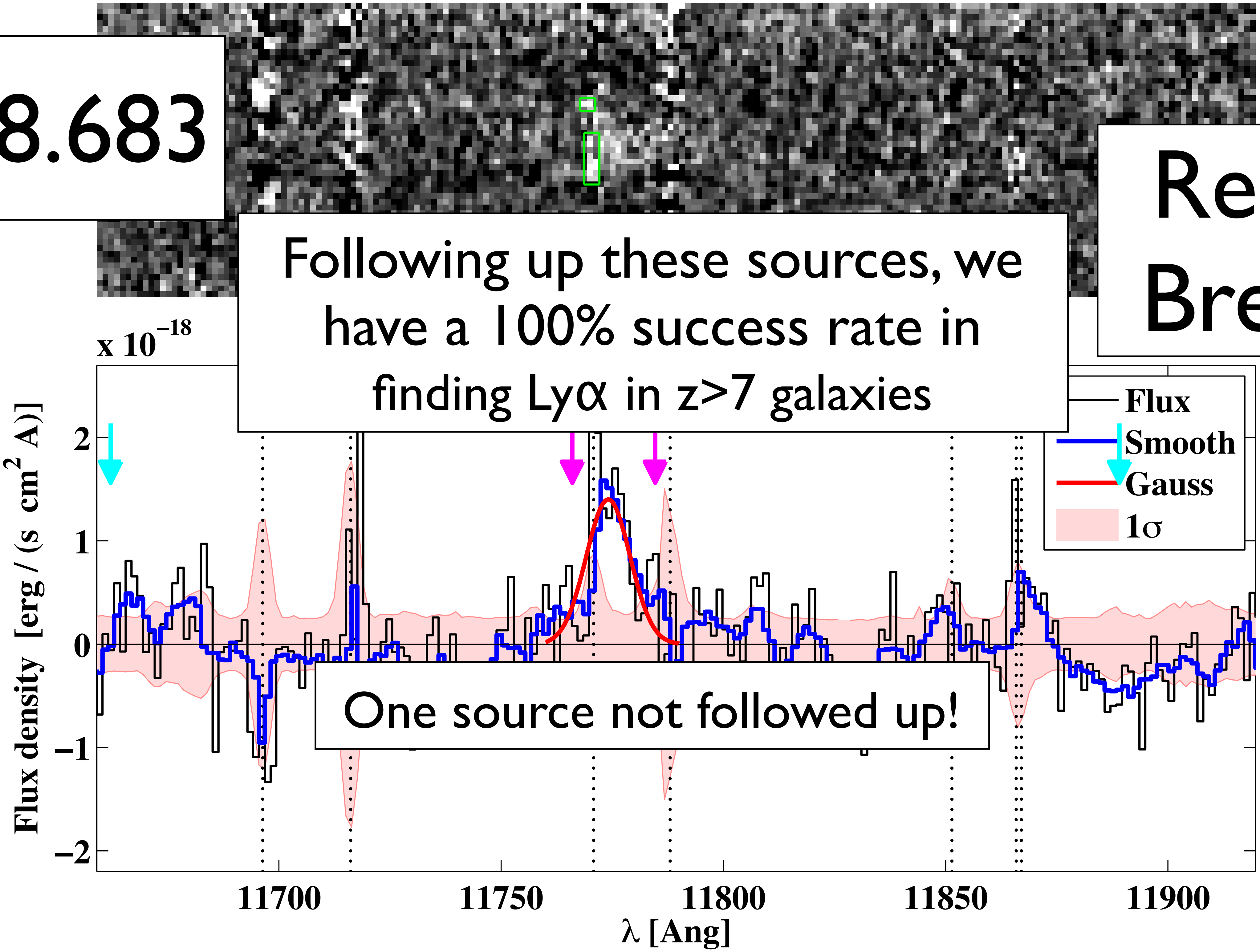
# Follow up with Keck/MOSFIRE Spectroscopy




Oesch, ..., RJB + 2015

# Follow up with Keck/MOSFIRE Spectroscopy

z=8.683




Following up these sources, we have a 100% success rate in finding Lyα in z>7 galaxies

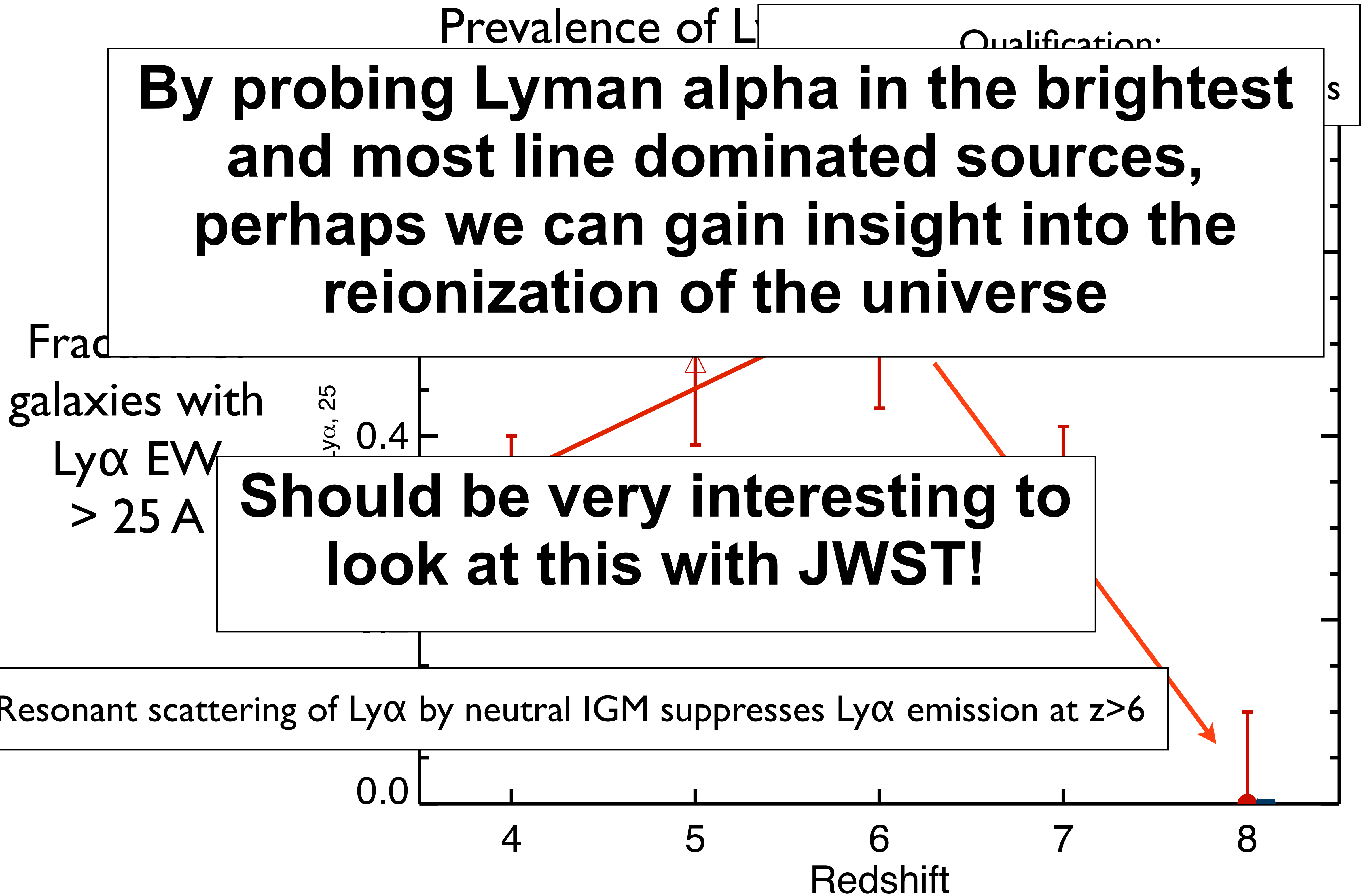
One source not followed up!

Record Breaker

Zitrin, ..., RJB + 2015

# Spectroscopic Confirmation: Very Challenging!

(Redshift Measurements)




**By probing Lyman alpha in the brightest and most line dominated sources, perhaps we can gain insight into the reionization of the universe**

**Should be very interesting to look at this with JWST!**

Resonant scattering of Lyα by neutral IGM suppresses Lyα emission at z>6

Schenker+2014; see also Pentericci+2014; Tilvi+2014; Treu+2013; Stark+2010; Fontana+2010; Caruana+2014; Ono+2012

# Beyond the Peak of Cosmic Star-Formation Activity (at $z<2$)

Most of the volume of the obserable universe lies between $z=0.5$ and $z=4.0$ and will be available for study with the James Webb Space Telescope.

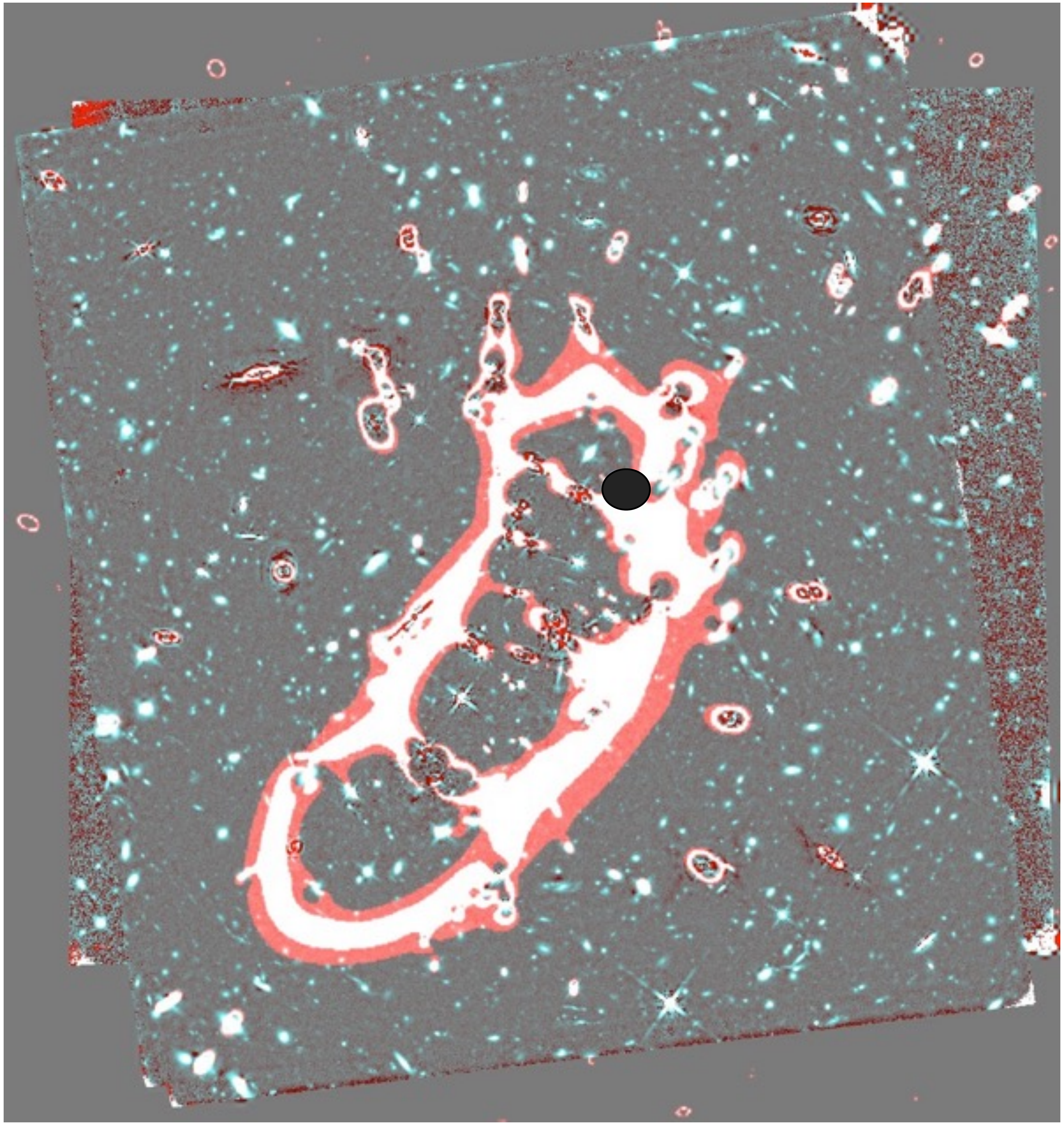
One of the most interesting frontiers at $z<2$-3 with JWST will involve characterization of the faintest and lowest-mass galaxies at these epochs (blue and red).

Study of the faintest $z=1$-2 galaxies with JWST should allow us to gain insight into both the possible cut-off of the LF at the faint end (since it seems unlikely to be robustly probed at $z\sim7$)

JWST should also give us our strongest leverage for looking at the properties of ultra low-mass star-forming galaxies (dust, age, metallicity, stellar / dynamic mass, gas masses, escape fraction)

JWST should also give us great insight into the mechanisms which guide the formation of ultra-faint, low-mass early time galaxies at $z>2$

# High Magnification Regions: Agreement?



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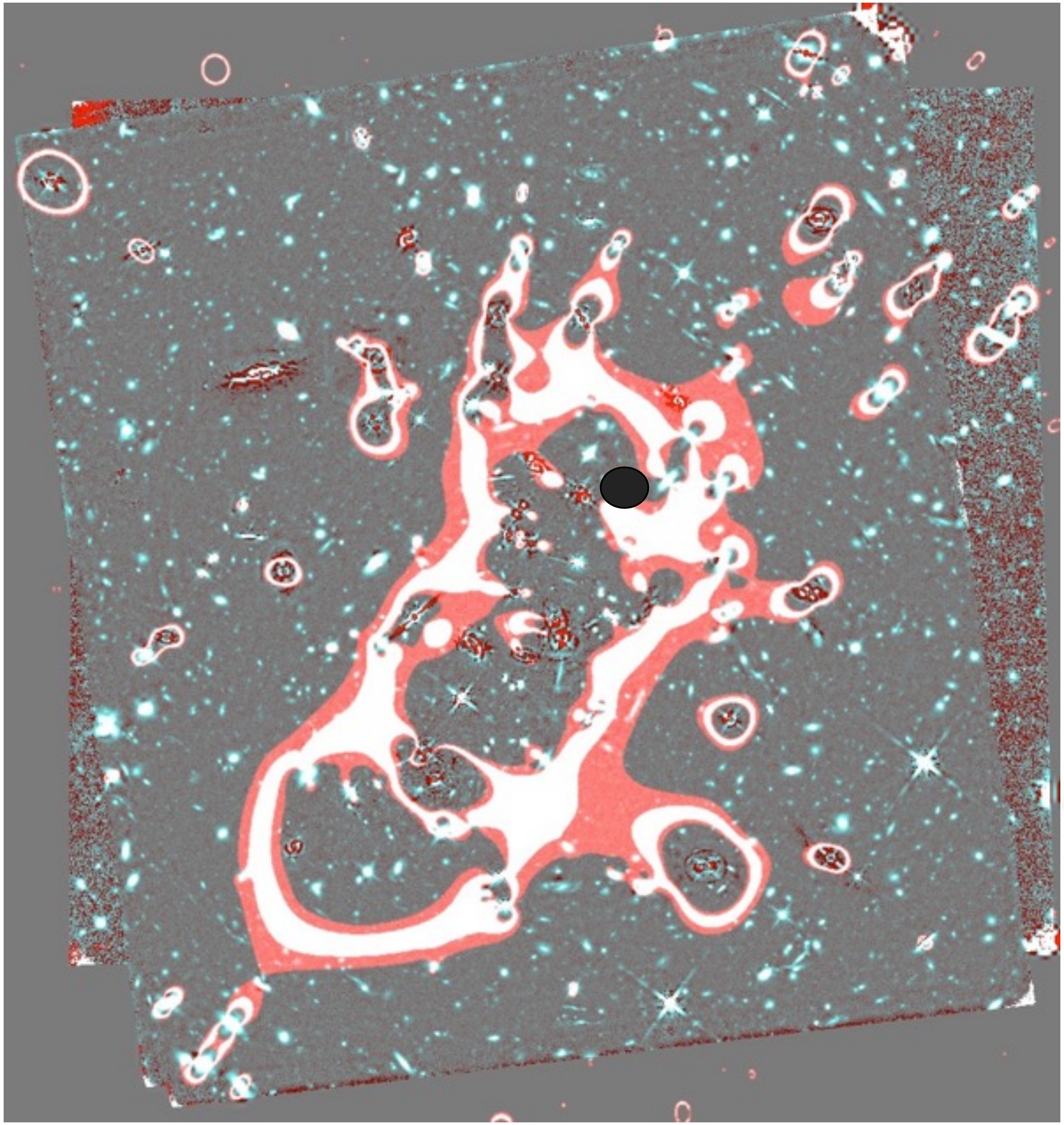

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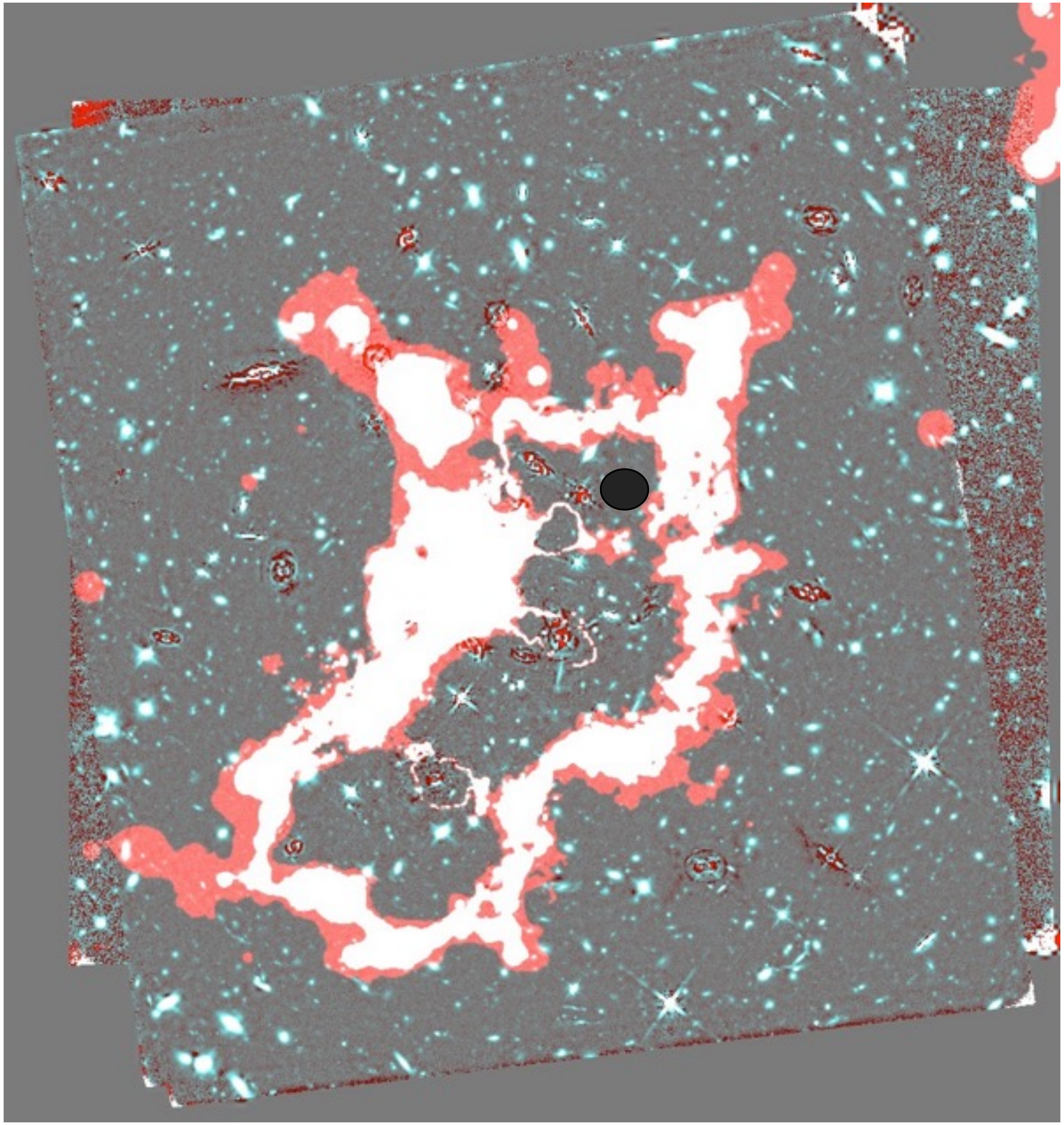

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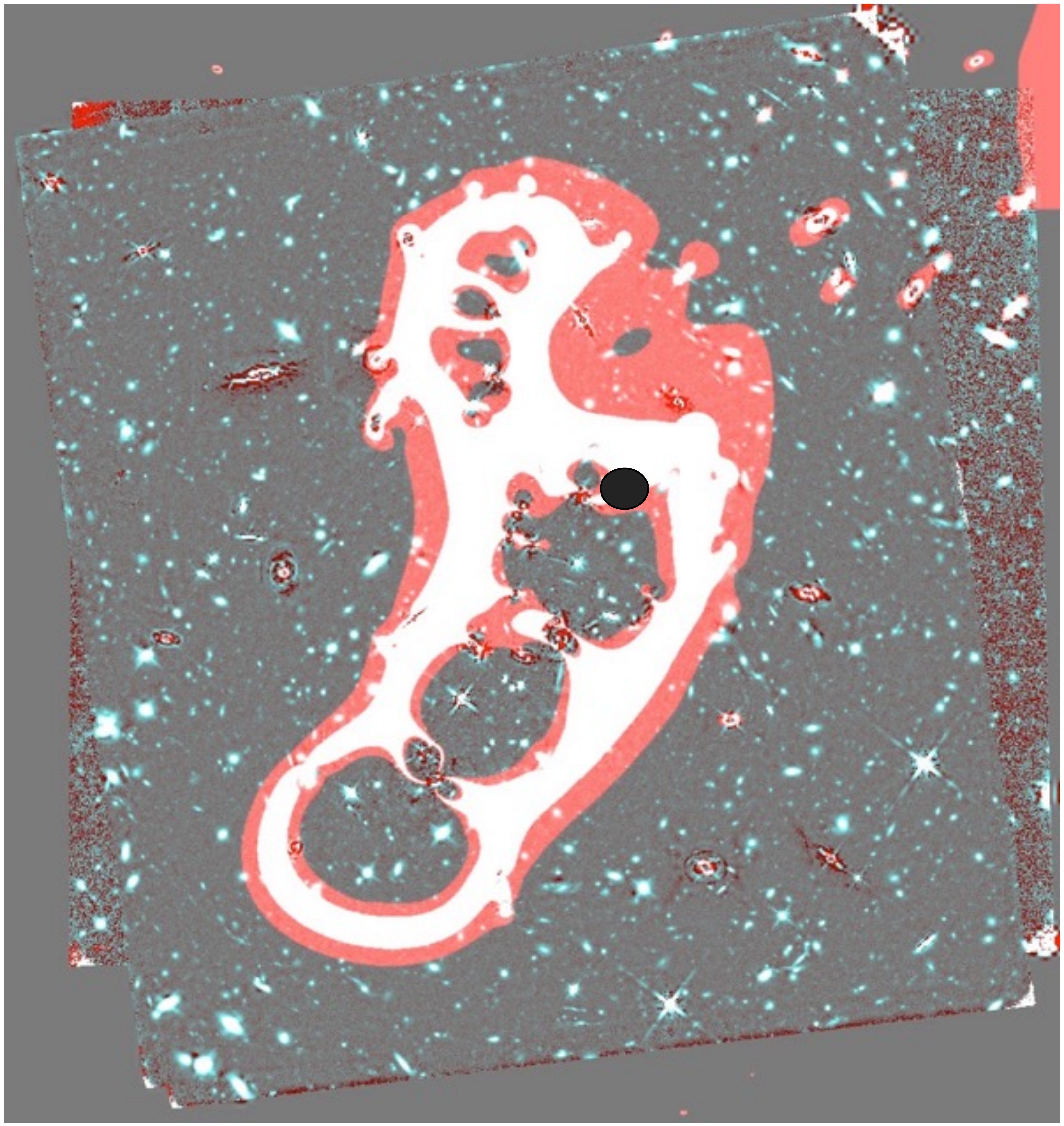
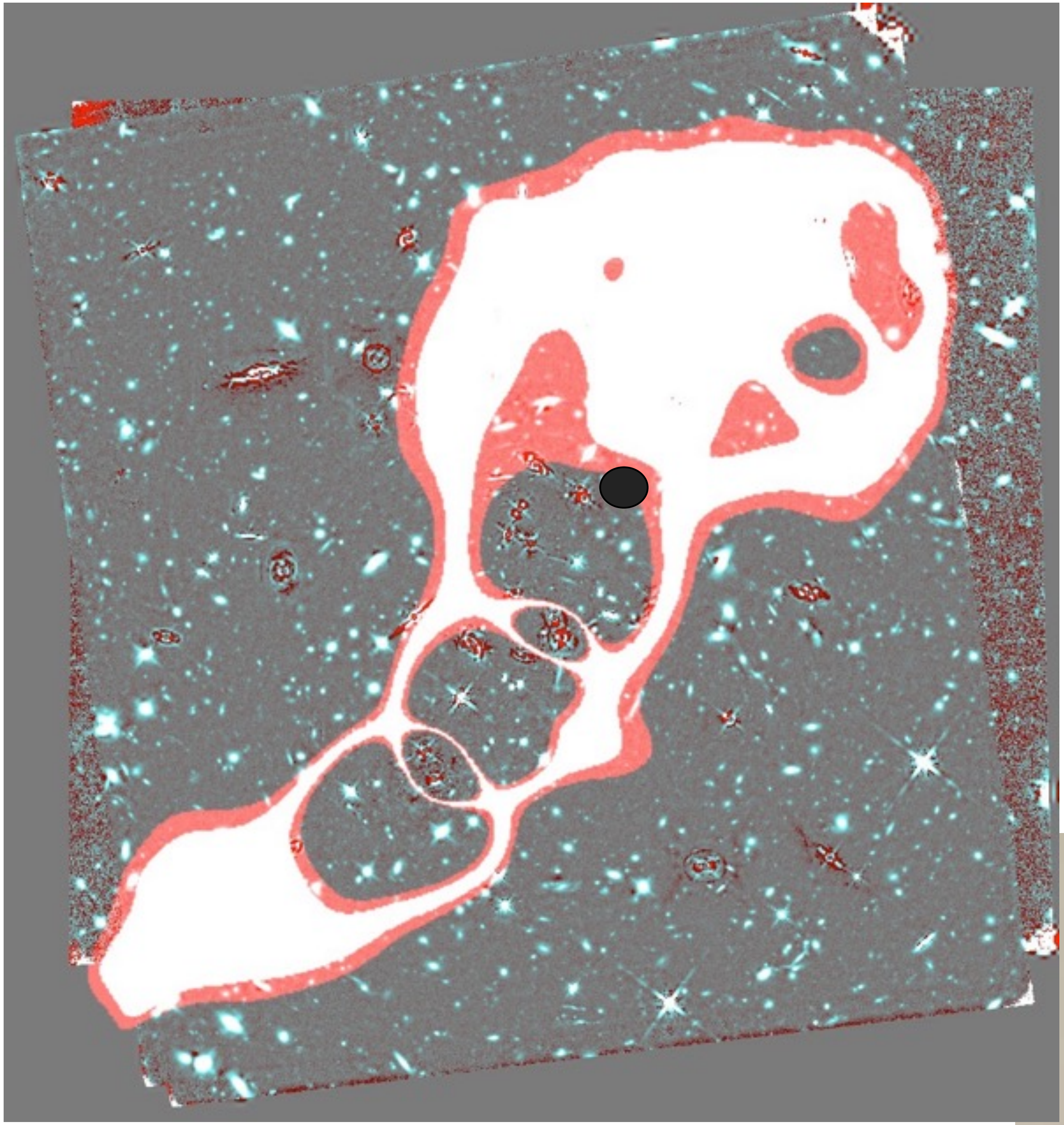
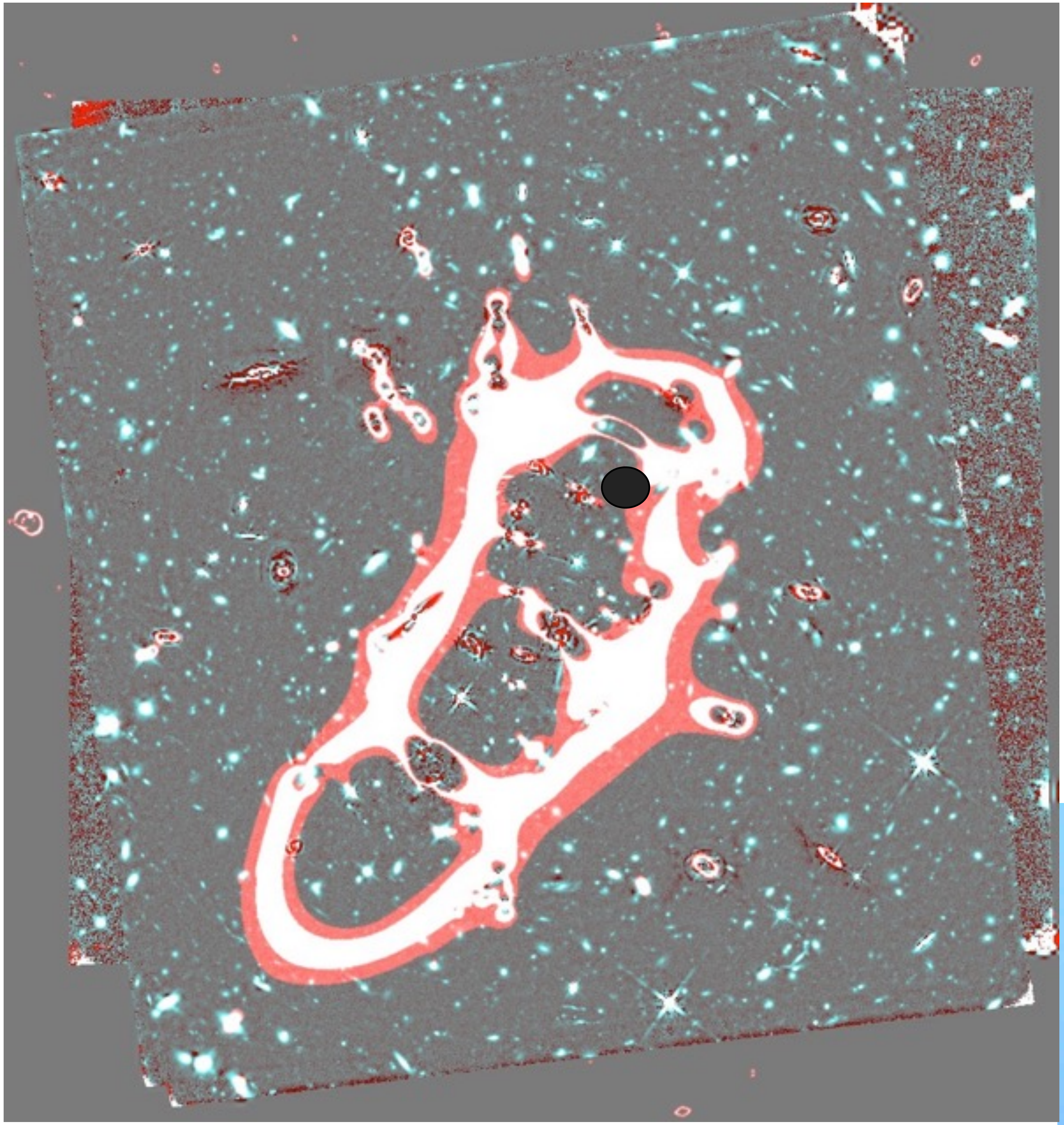


# High Magnification Regions: Agreement?



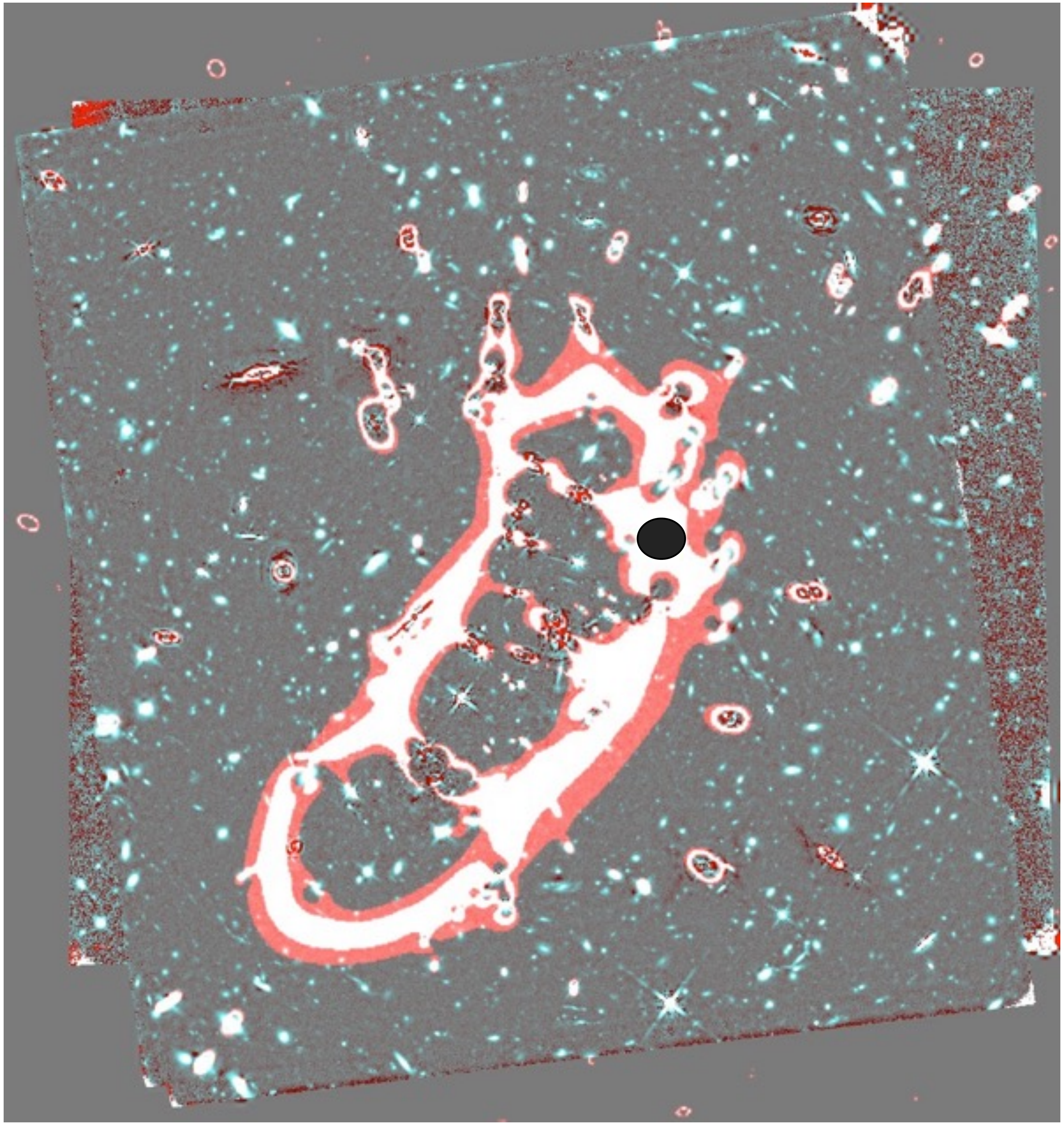
# High Magnification Regions: Agreement?



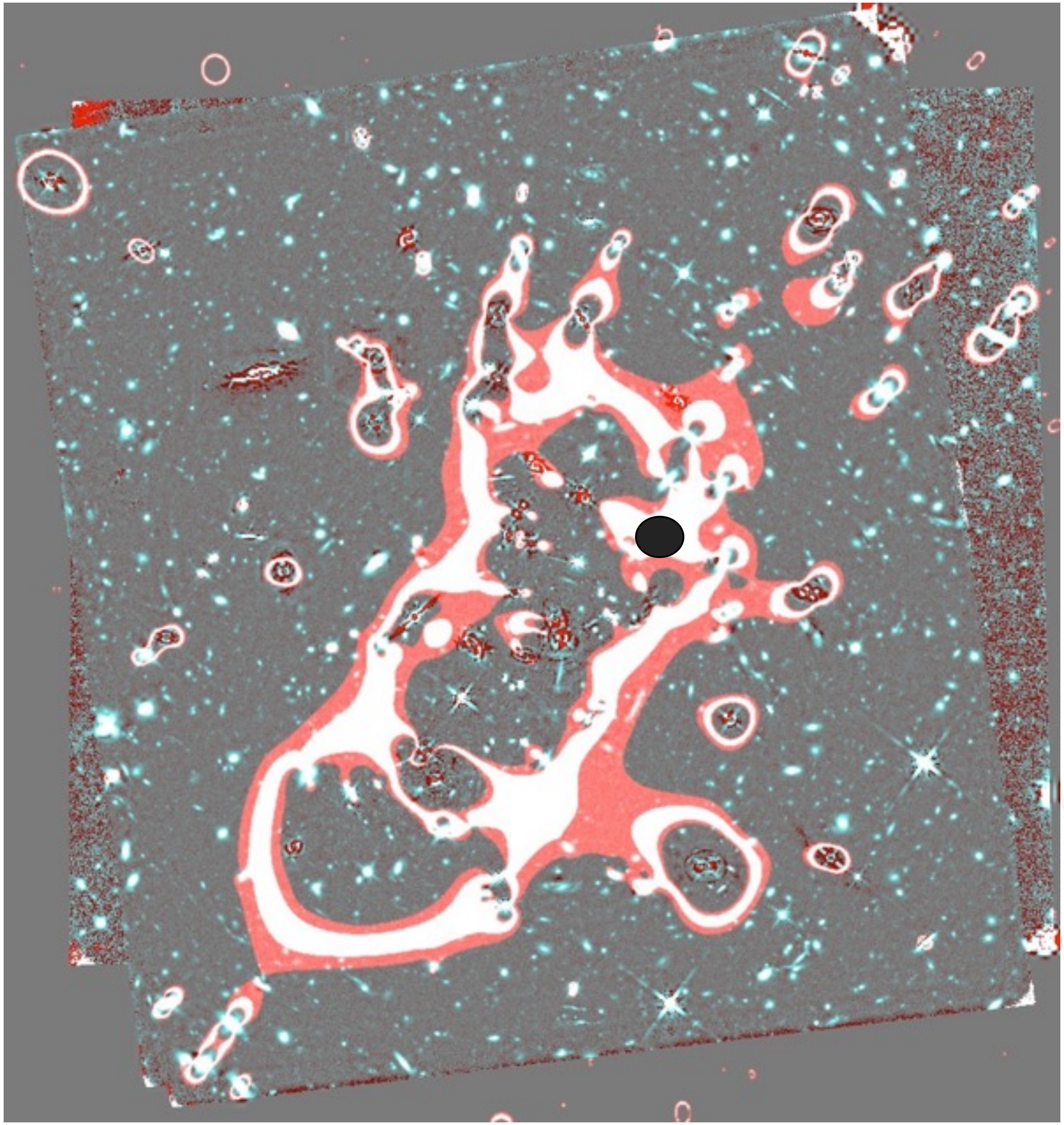
# High Magnification Regions: Agreement?

Let’s consider another possible high-magnification region in Abell 2744

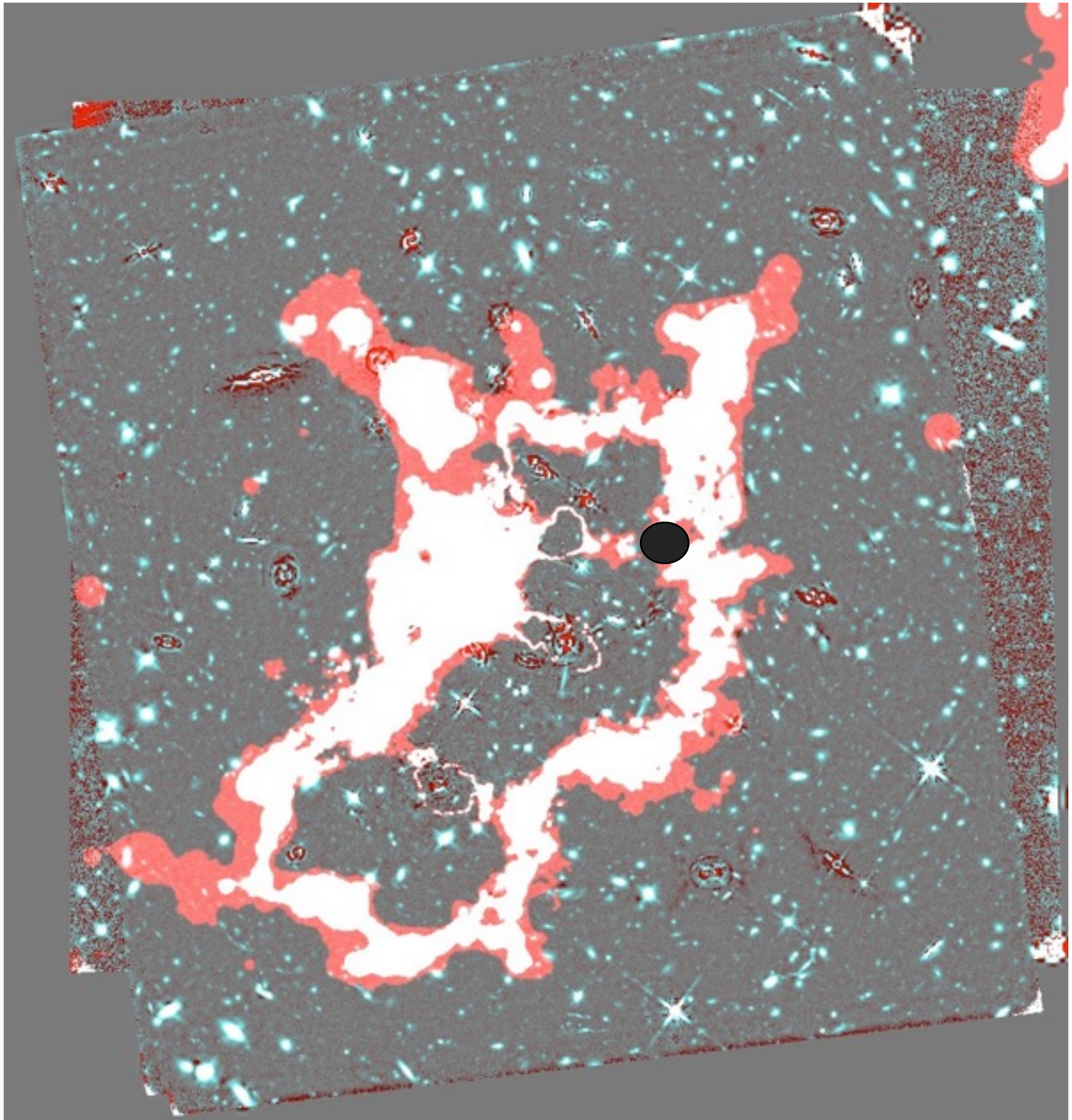
# High Magnification Regions: Agreement?



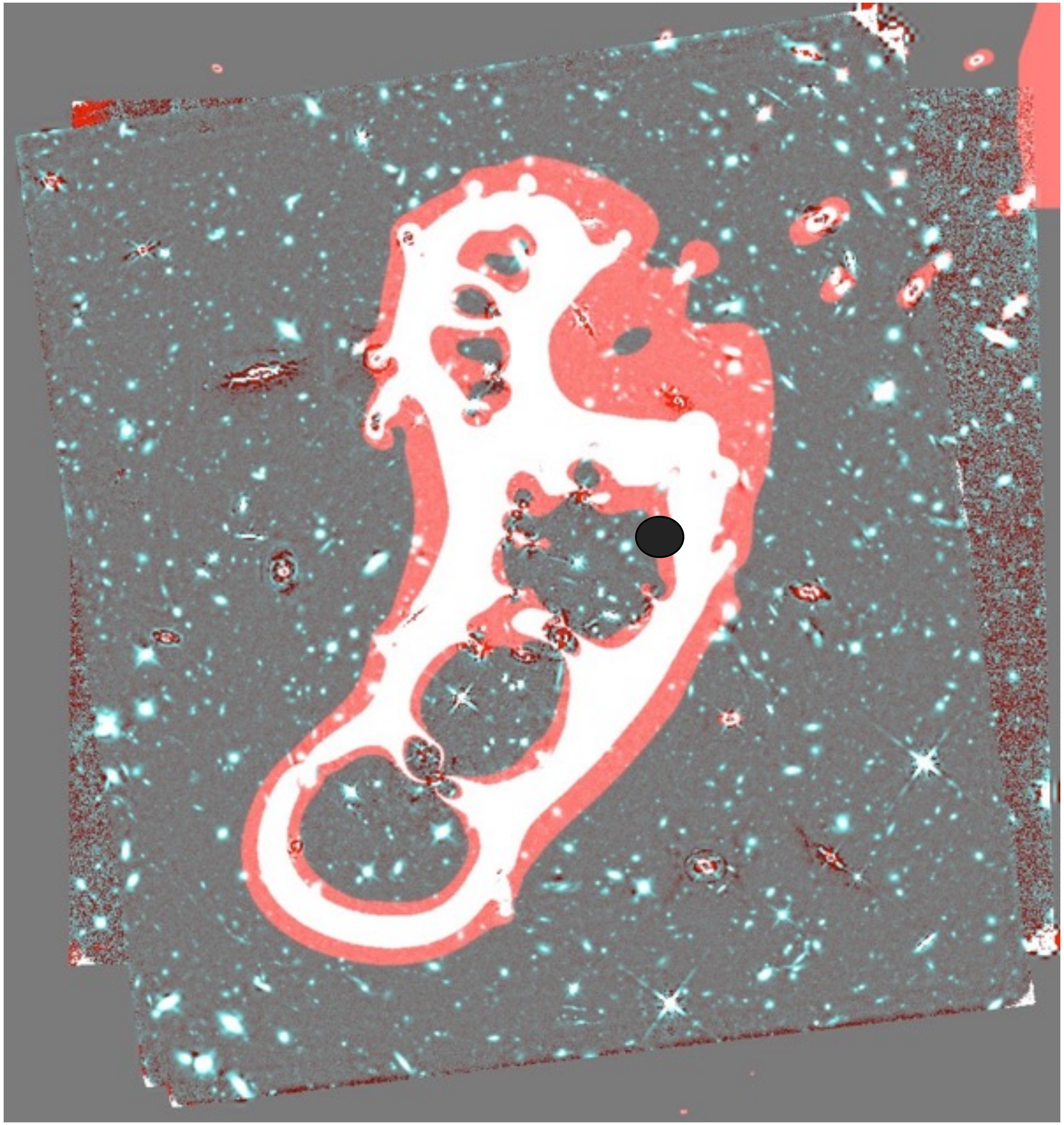
# High Magnification Regions: Agreement?



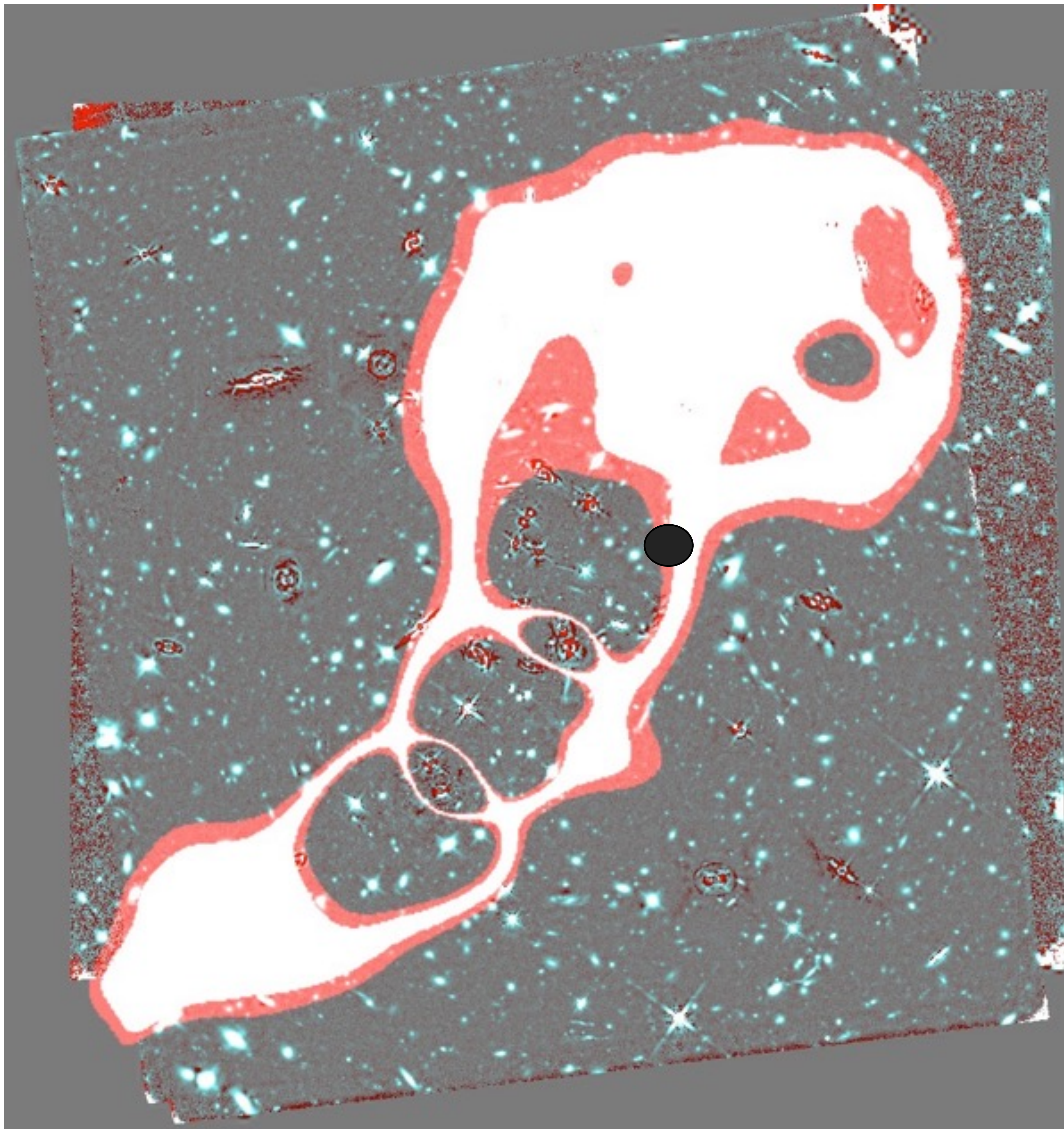
# High Magnification Regions: Agreement?



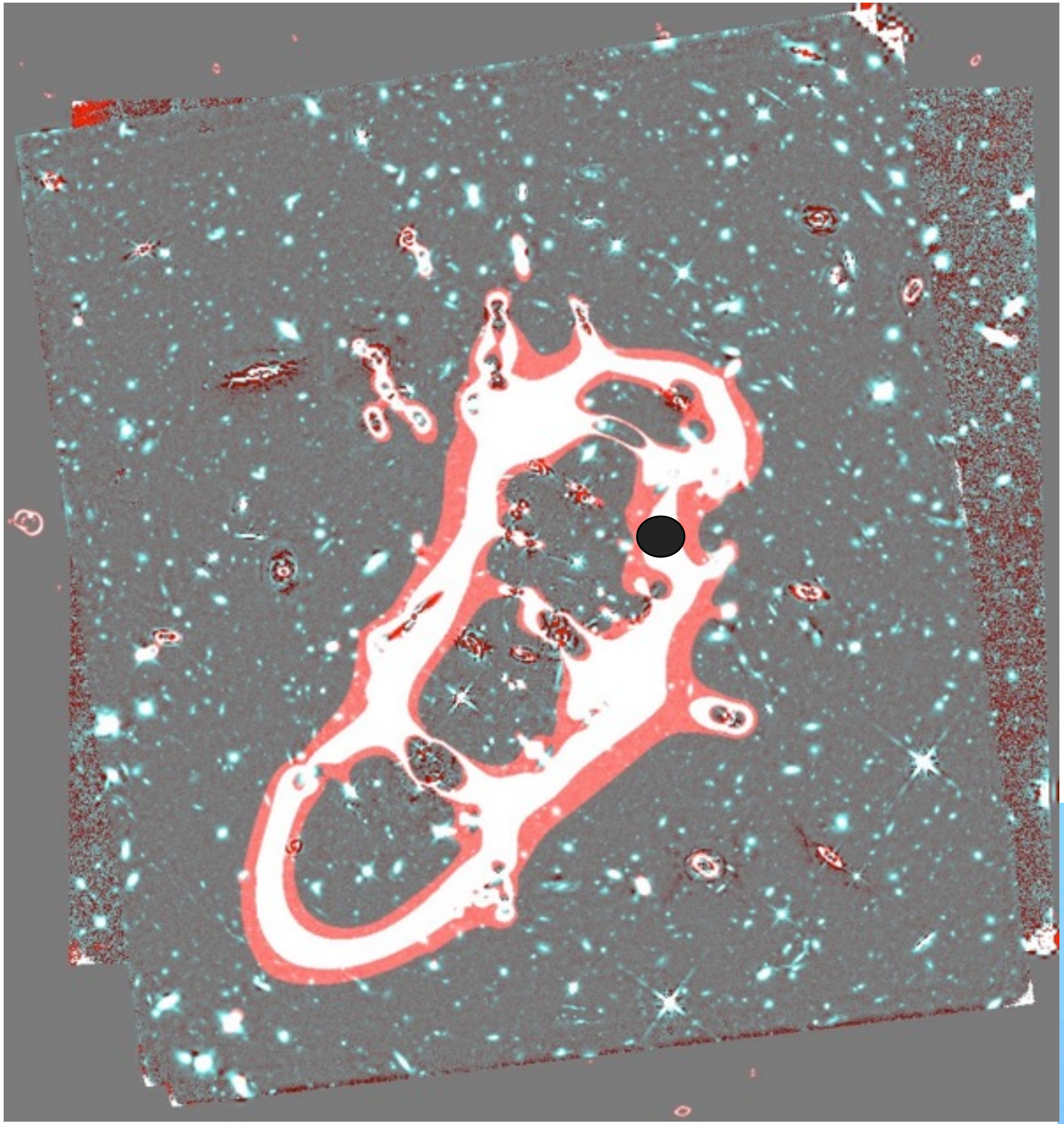
# High Magnification Regions: Agreement?



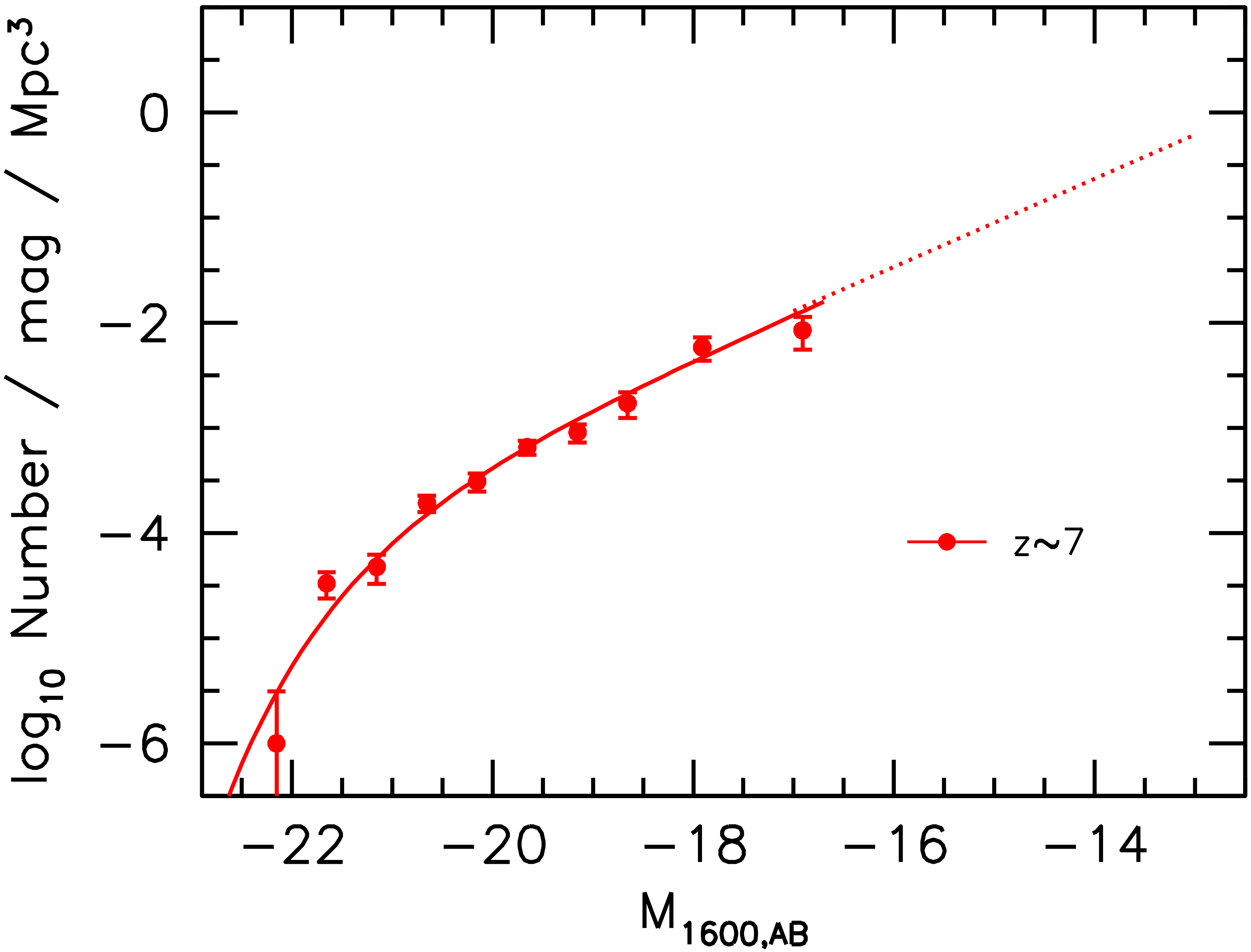
# High Magnification Regions: Agreement?



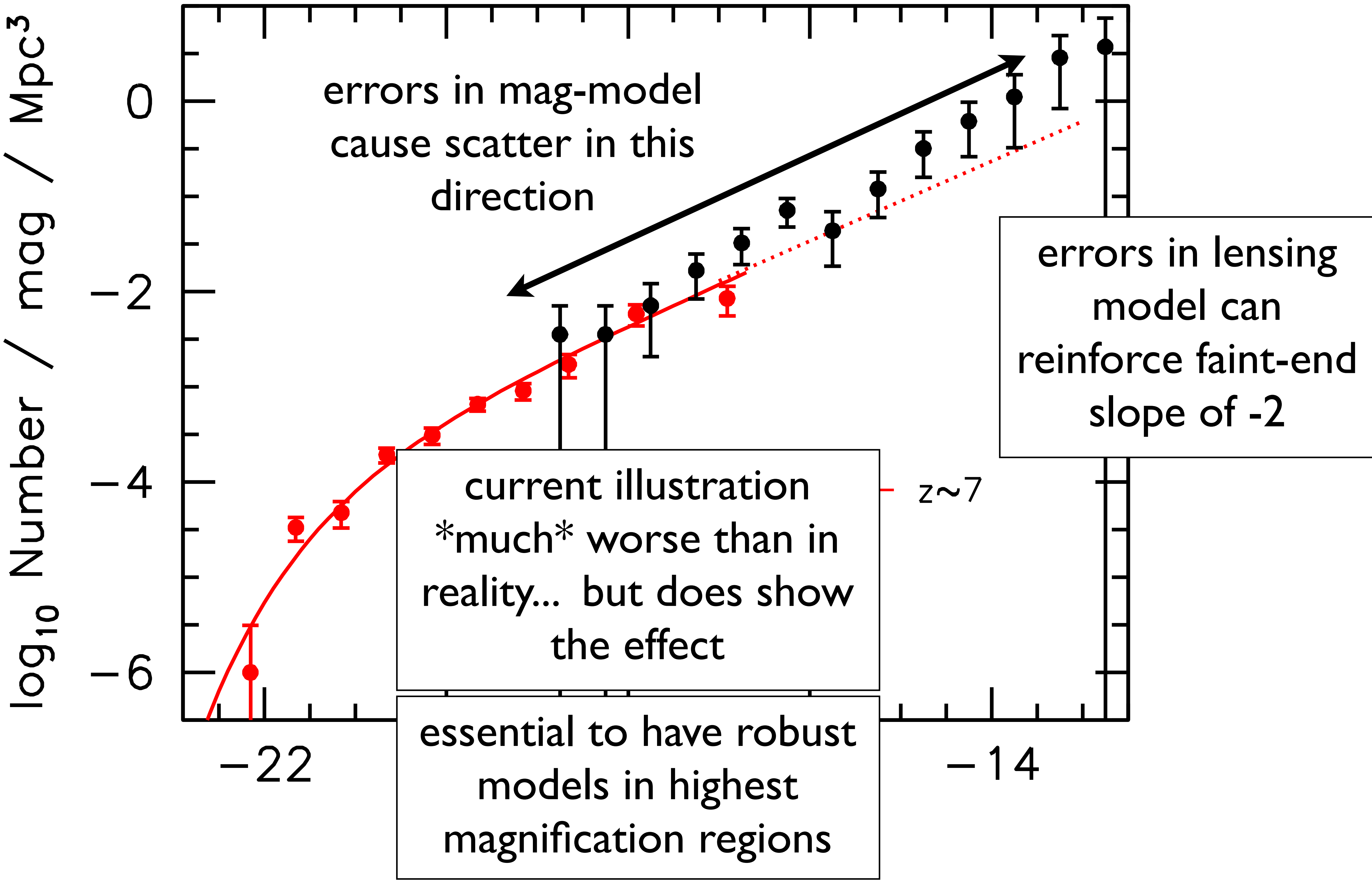
# High Magnification Regions: Agreement?



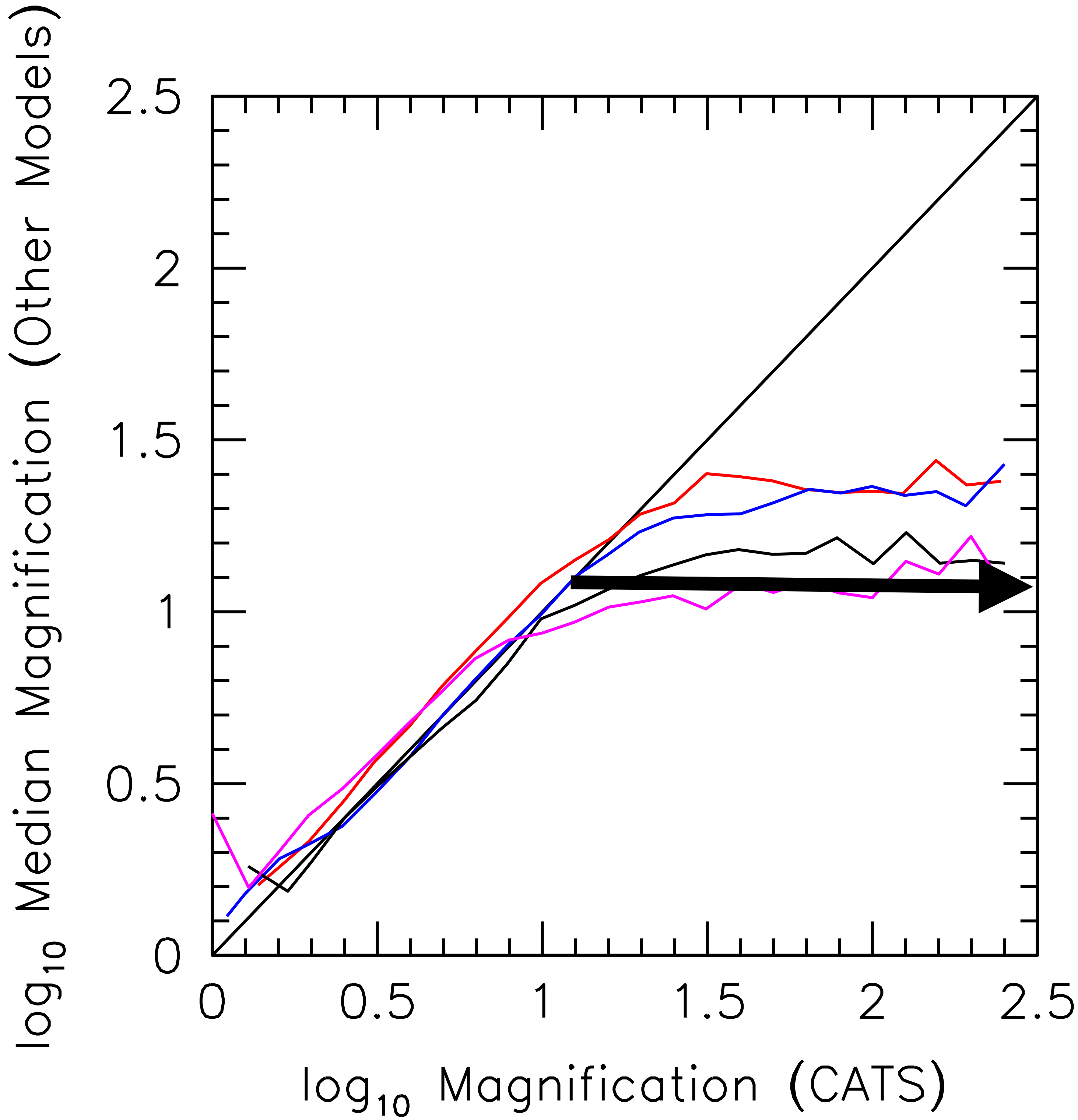
# What happens if you apply the MACS1149 model to the HUDF z~7 sample?



# What happens if you apply the MACS1149 model to the HUDF z~7 sample?



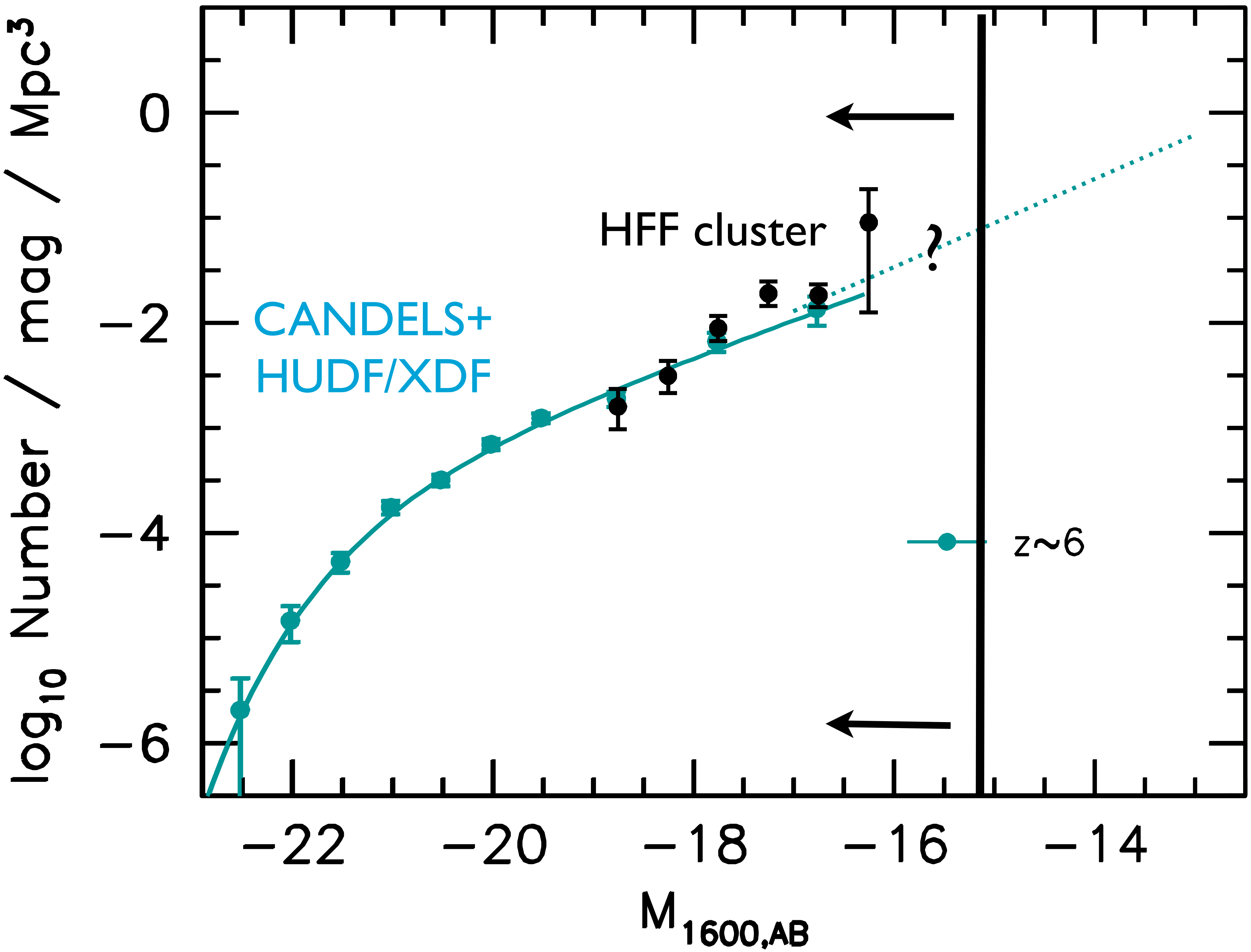
# To what magnification factor do current results seem reliable?



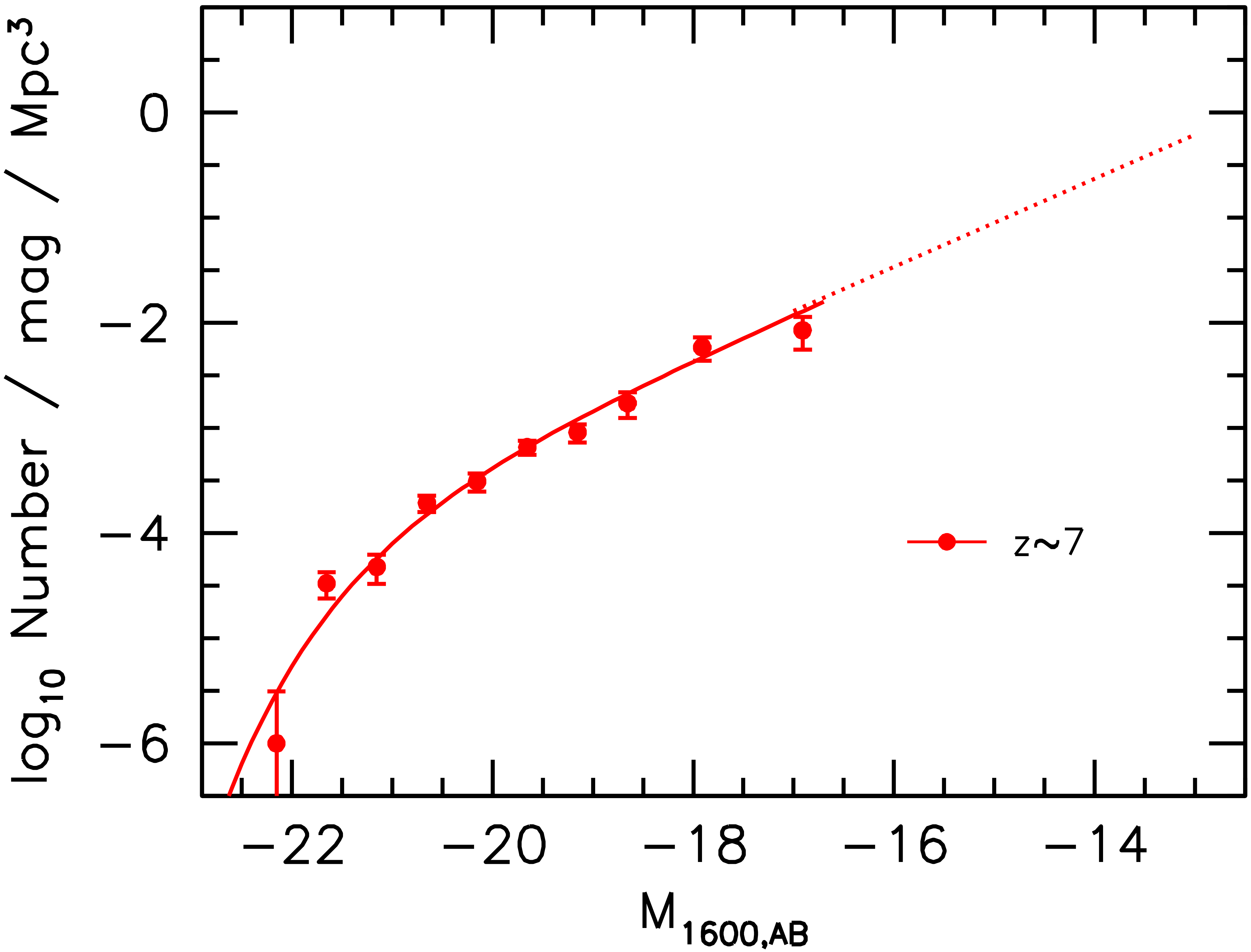

Magnification Factors of 10

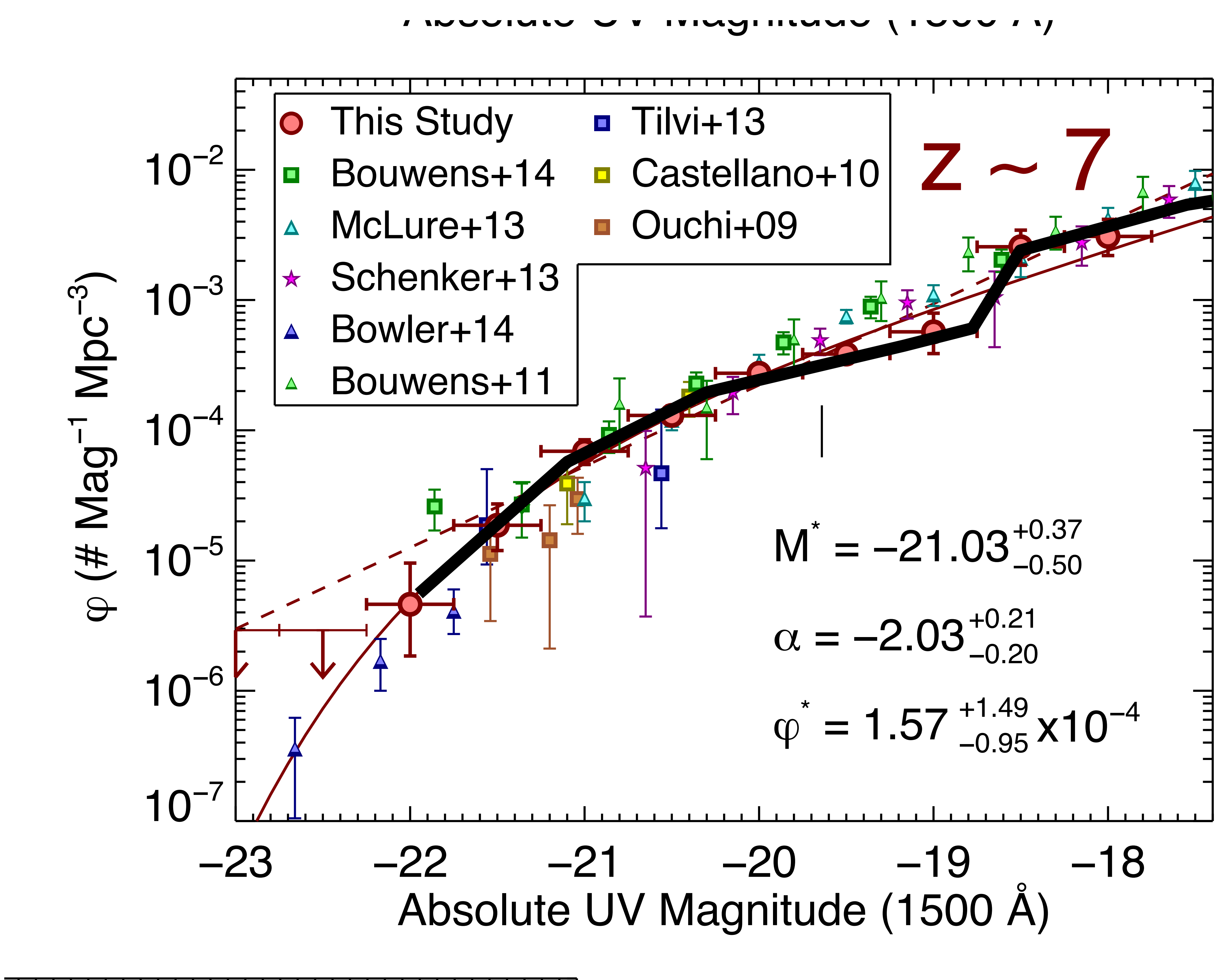
# z=6 LF Results:

## (CANDELS+XDF vs. HFF cluster [4-cluster] constraints)



# What happens if you apply the MACS1149 model to the HUDF z~7 sample?




Absolute UV Magnitude (1500 Å)
This Study
Bouwens+14
McLure+13
Schenker+13
Bowler+14
Bouwens+11
Tilvi+13
Castellano+10
Ouchi+09
z ~ 7
$M^* = -21.03^{+0.37}_{-0.50}$
$\alpha = -2.03^{+0.21}_{-0.20}$
$\varphi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$\varphi$ (# Mag$^{-1}$ Mpc$^{-3}$)
−23
−22
−21
−20
−19
−18
Absolute UV Magnitude (1500 Å)