

# Using Composite Spectral Energy Distributions to Characterize Galaxy Populations at $1 < z < 4$

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# Acknowledgements



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**MACQUARIE**  
University  
SYDNEY • AUSTRALIA



**CARNEGIE**  
INSTITUTION FOR  
**SCIENCE**



ZFOURGE data gathered at the  
Magellan Telescopes, Las  
Campanas Observatory.

# Outline

Motivation

Data and Methods

From Star-Forming to Quiescent

Extreme Emission Line Galaxies

Conclusions



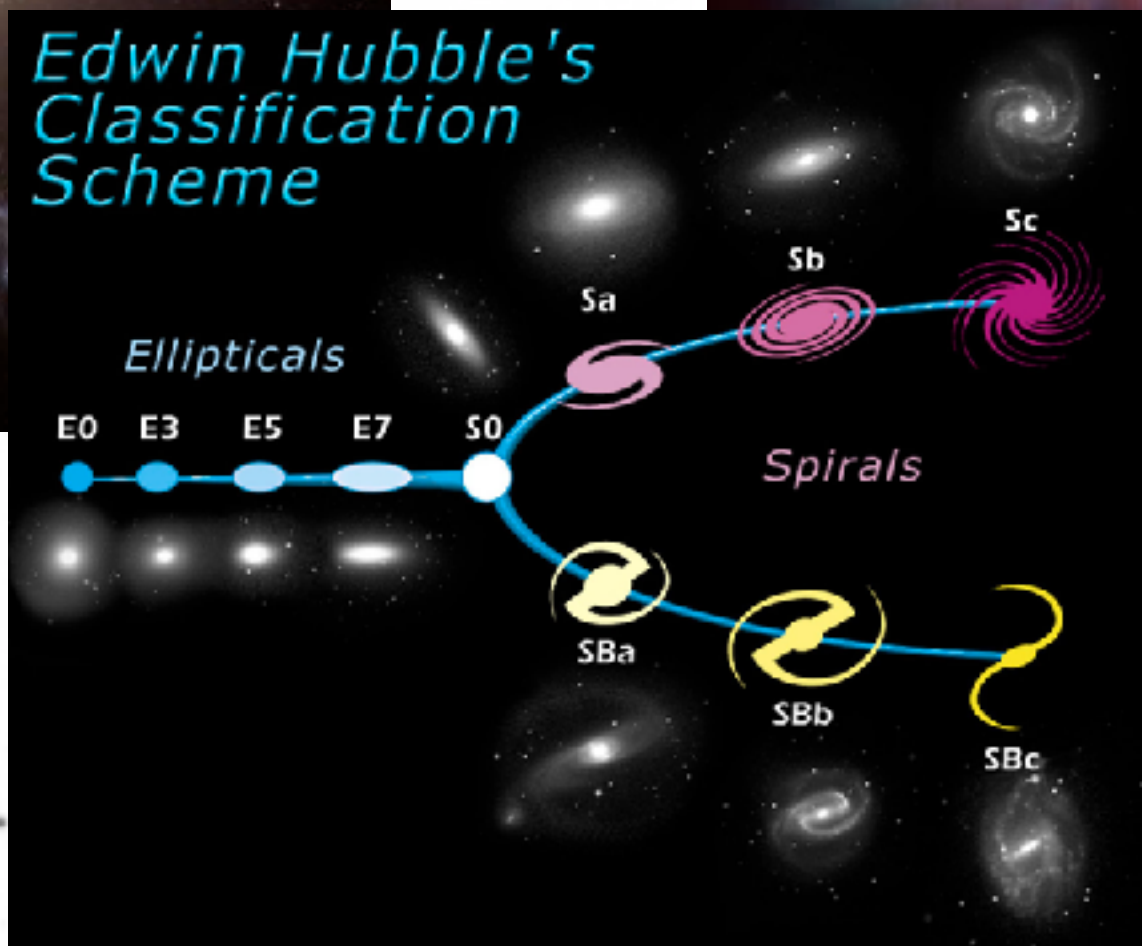
# The Life of Galaxies



ESO 325-G004; NASA



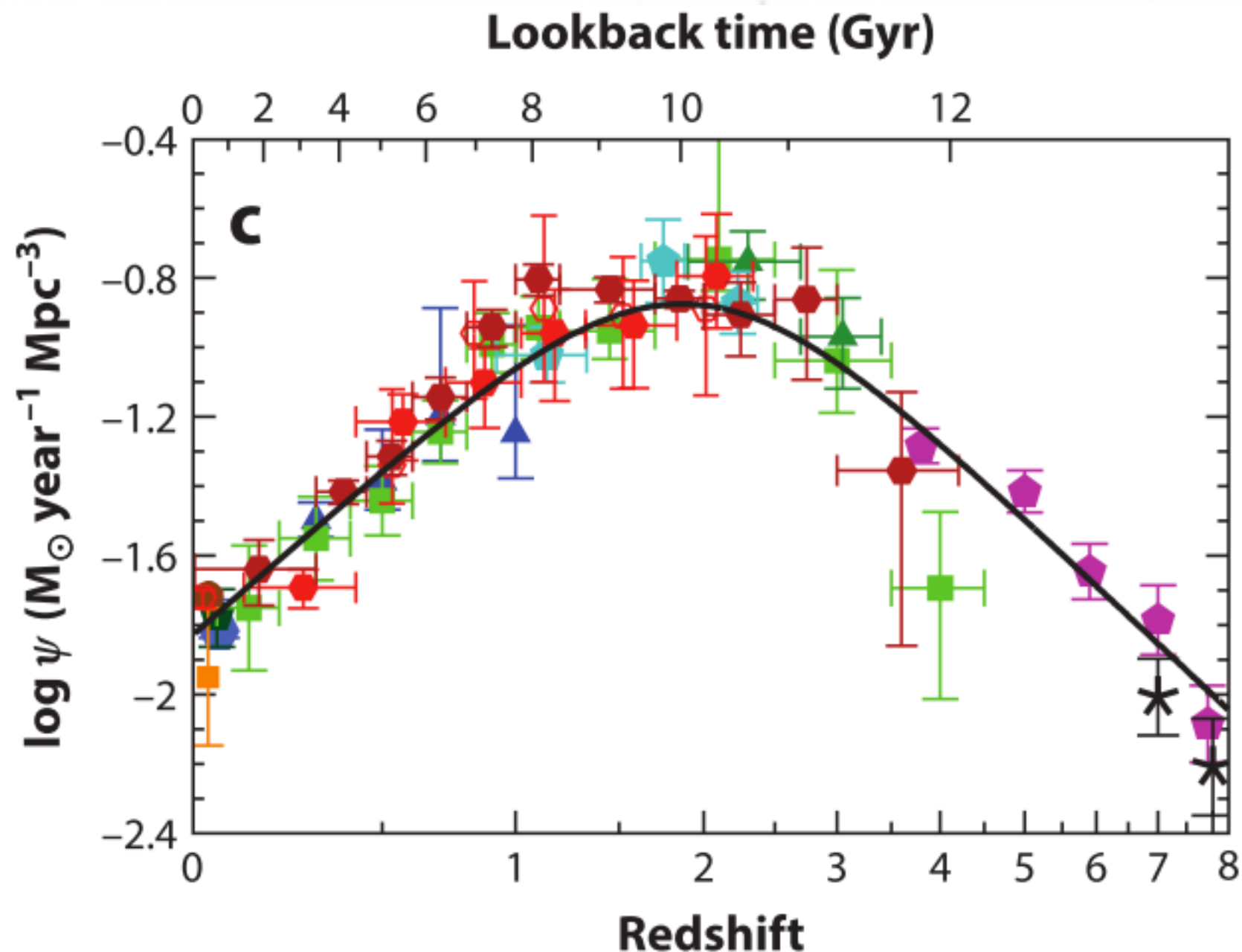
M82; NASA



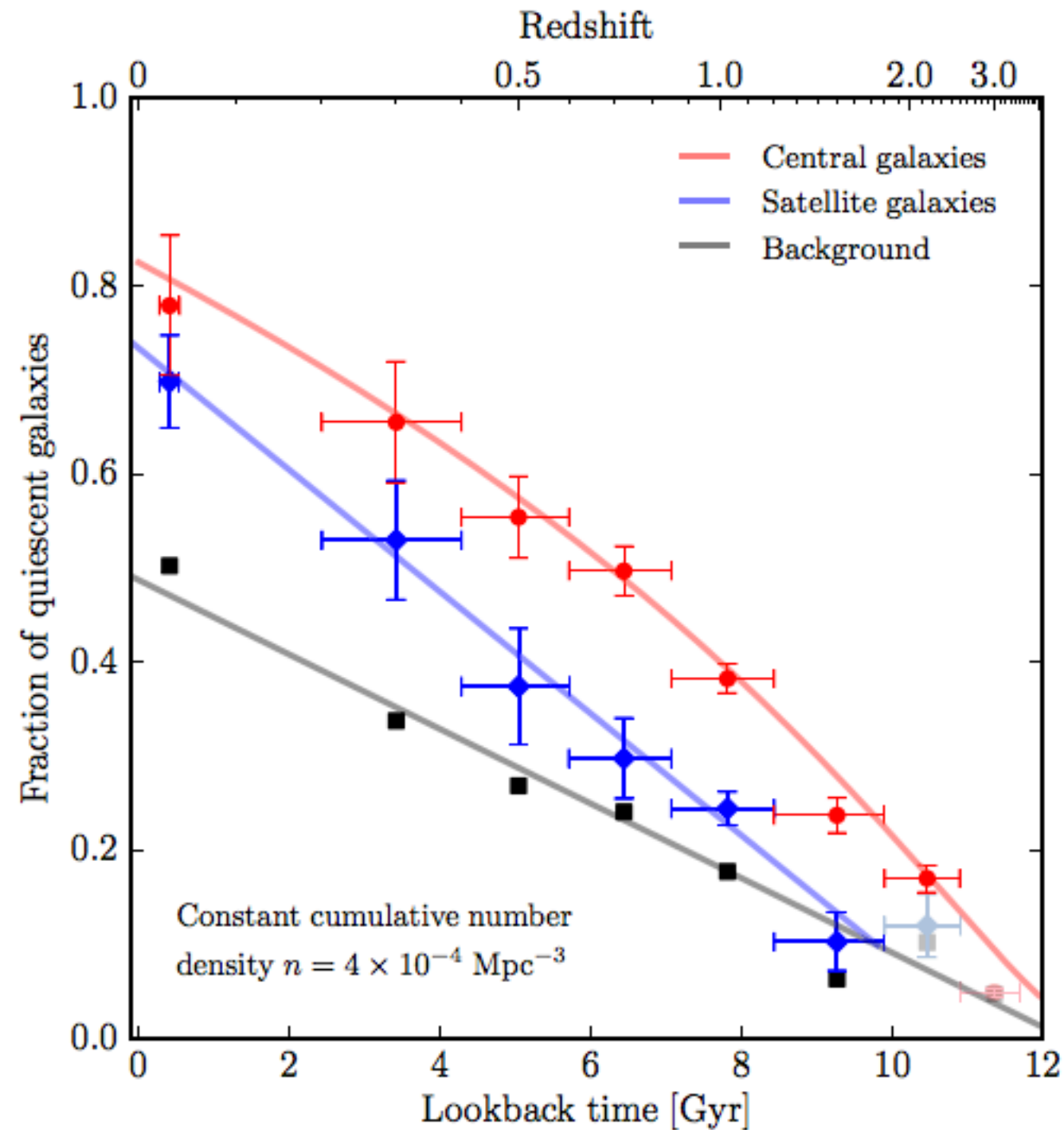
NGC 1232; ESO

STSCI

# The Star-Forming History of the Universe

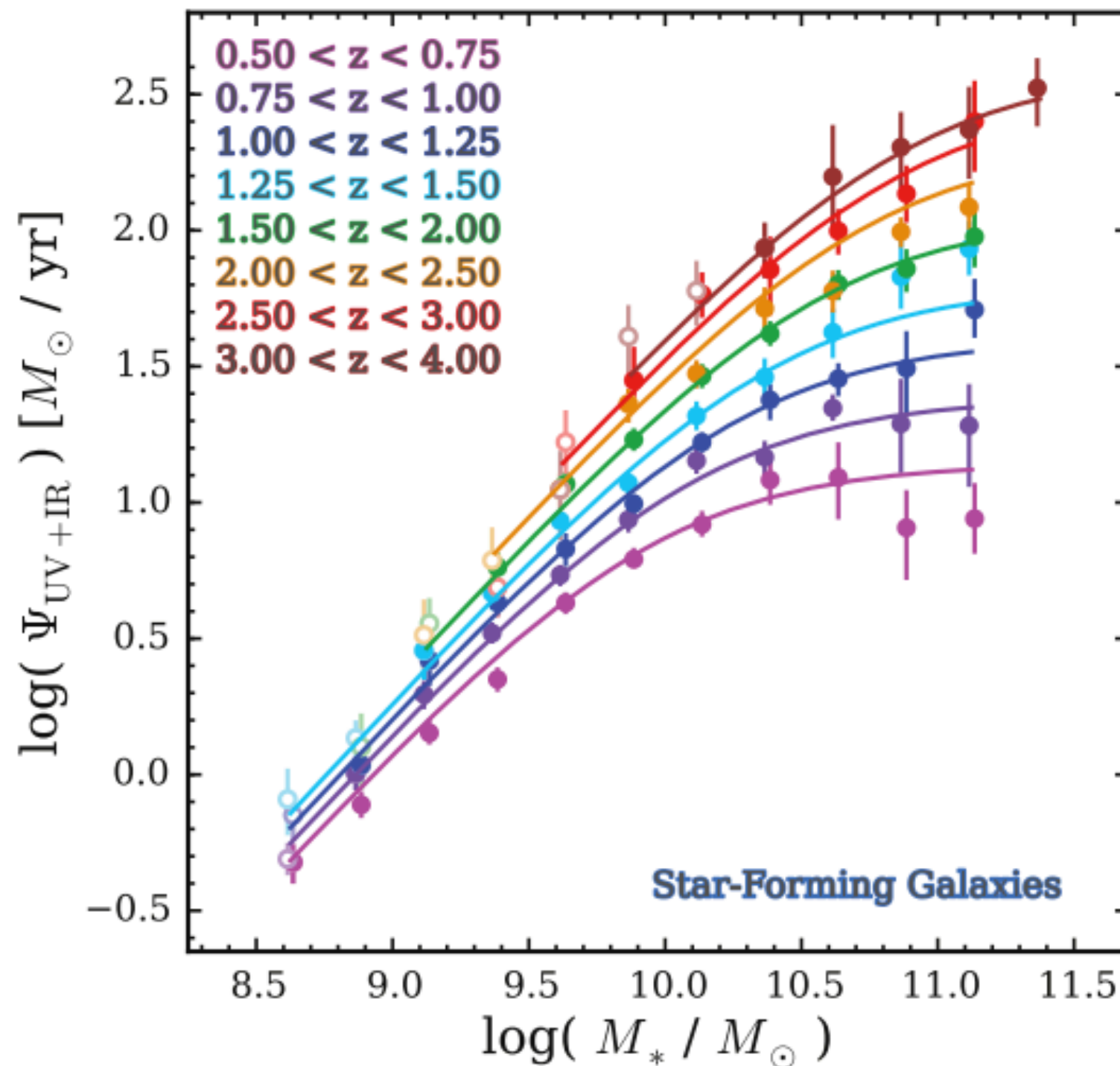


# Galaxies are Quenching

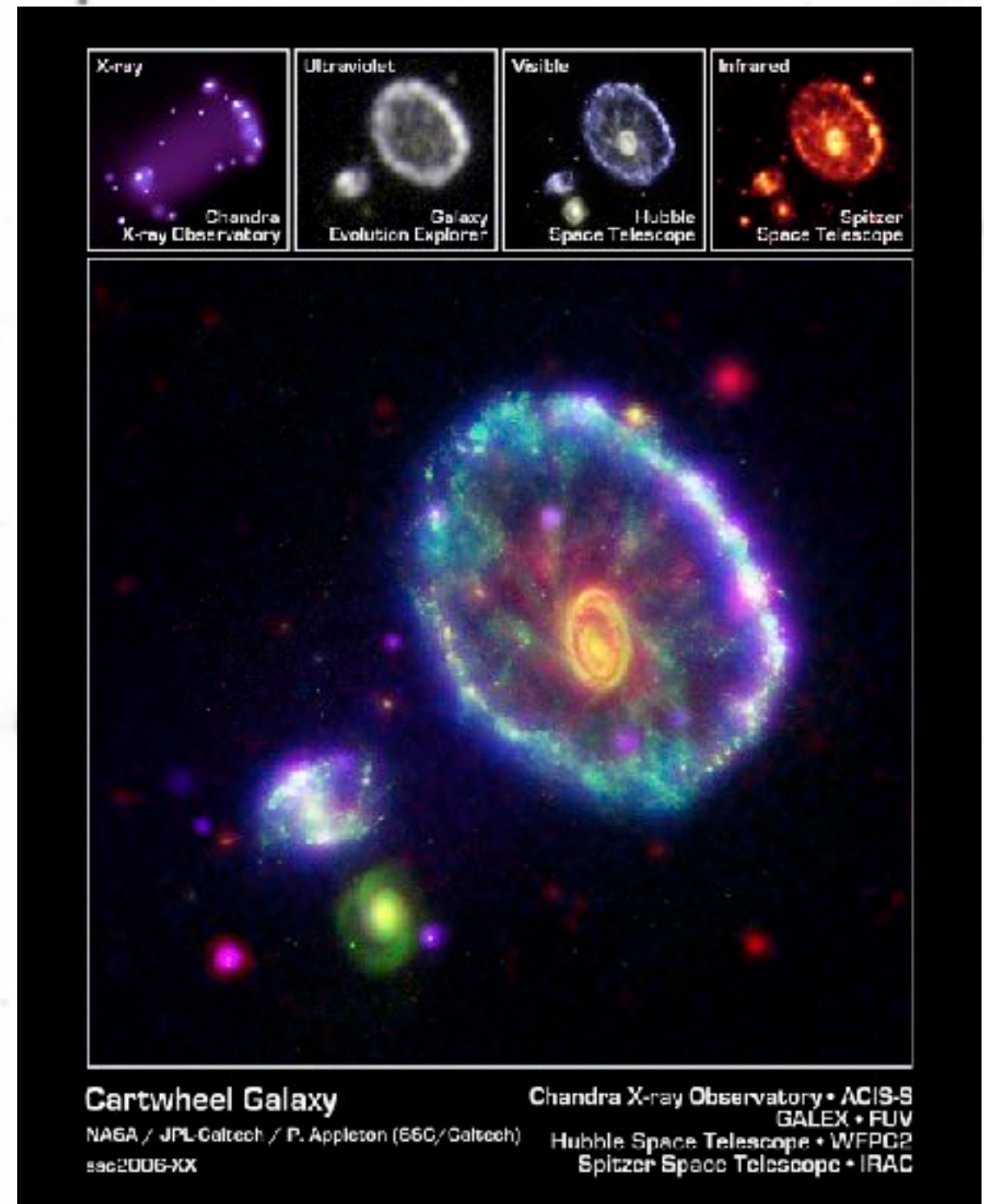




# The Star Formation - Stellar Mass Relation

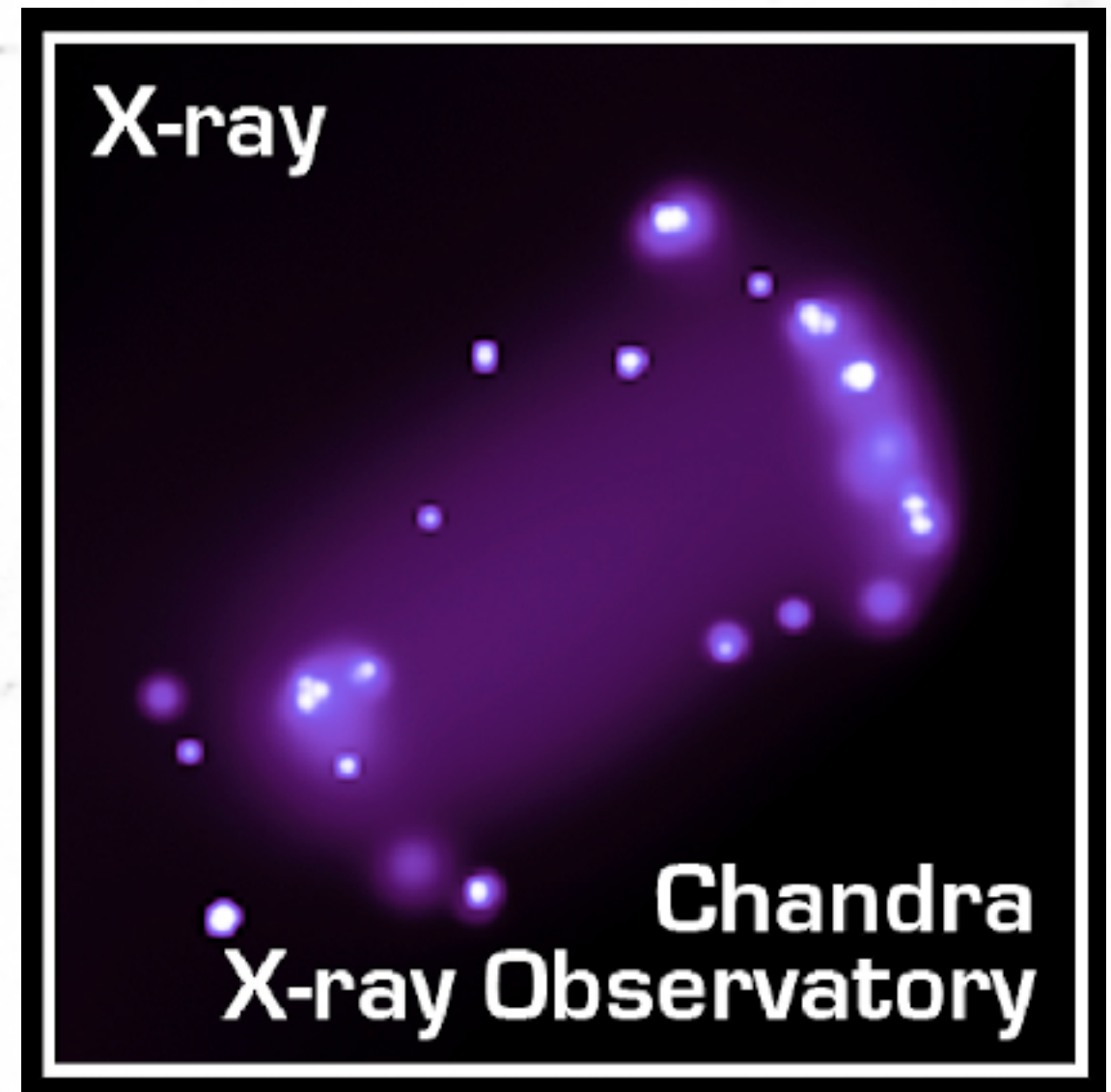
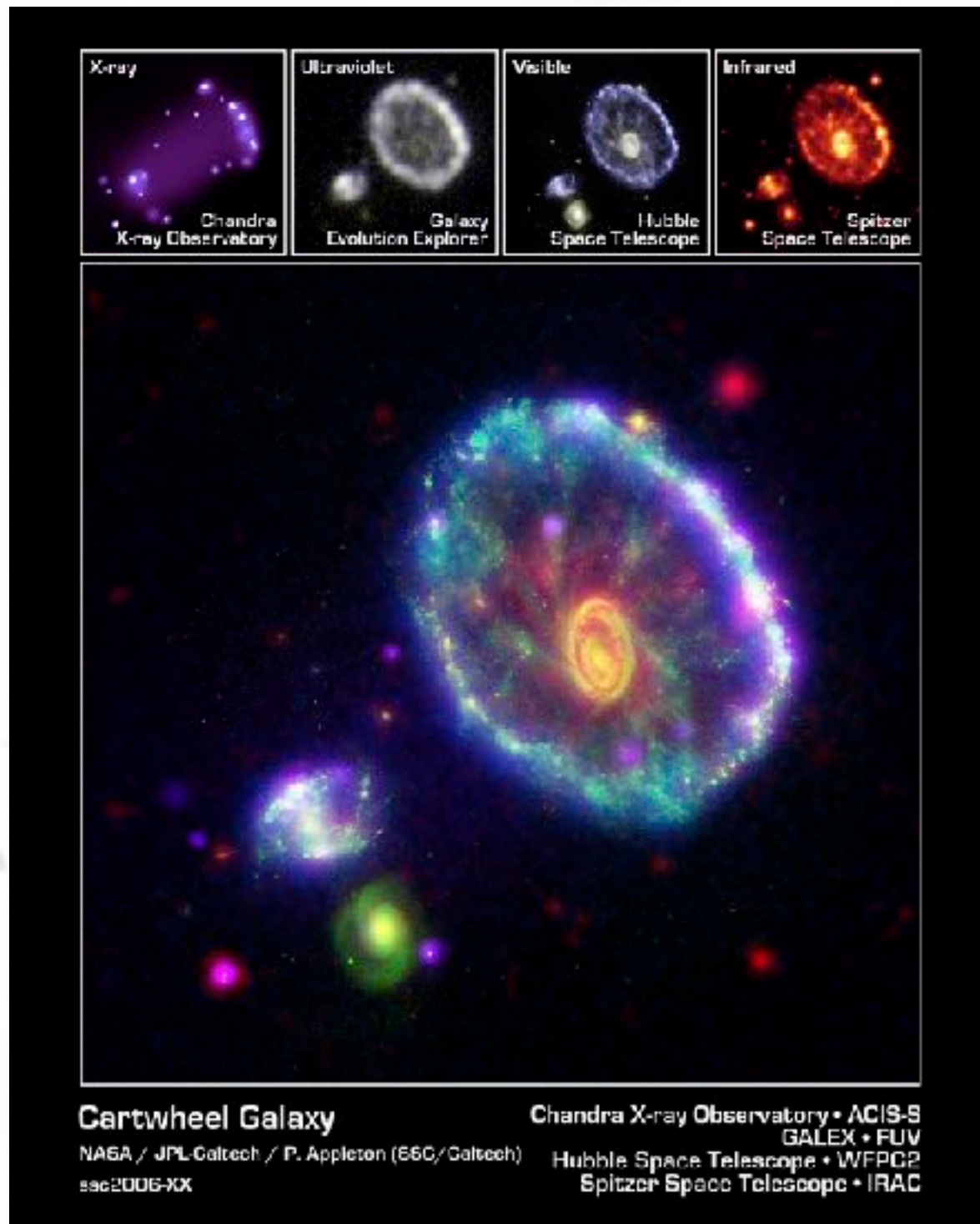


# Galaxy-Galaxy Interactions

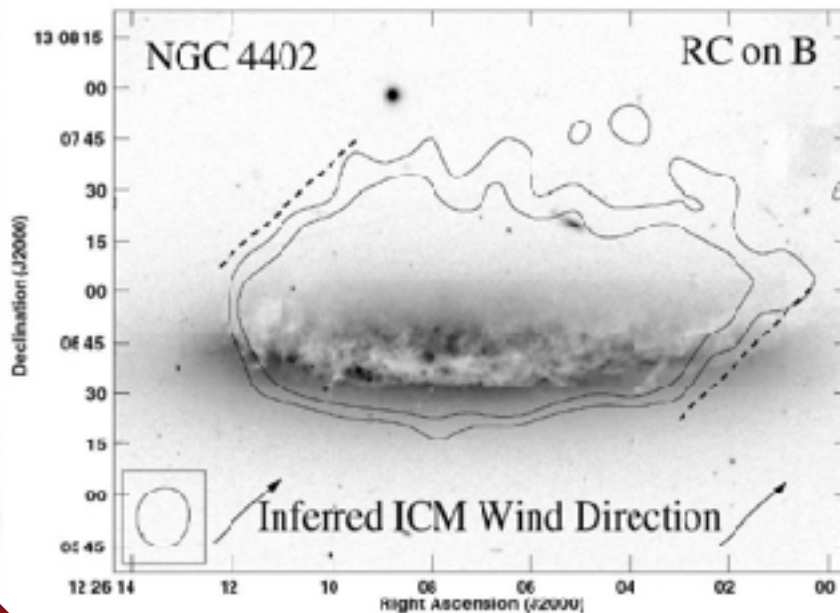
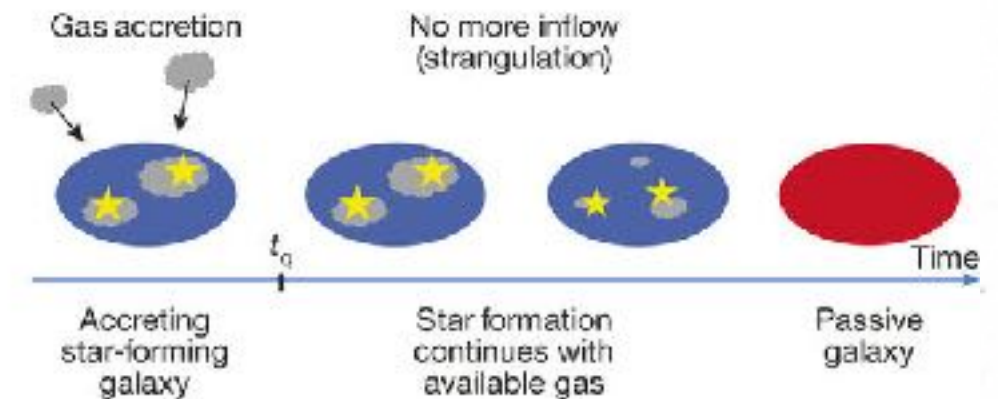
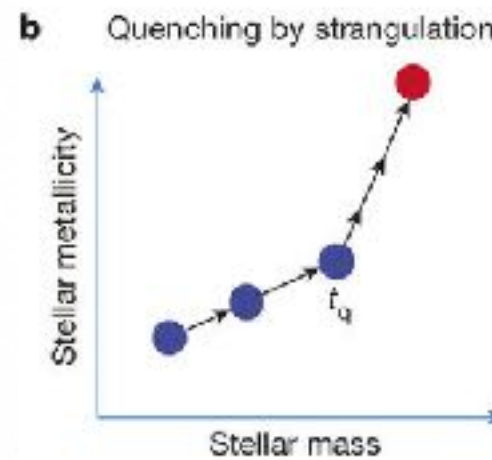
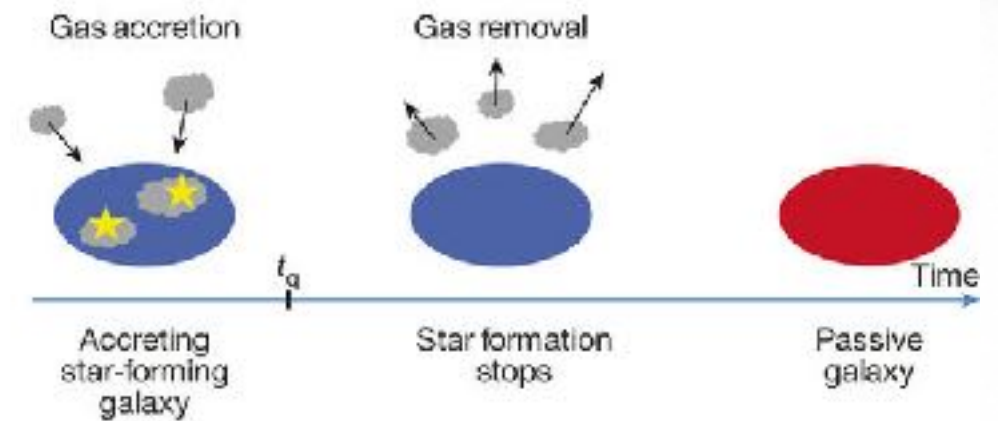
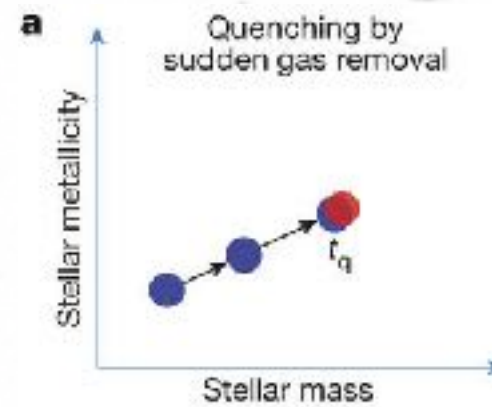




# Galaxy-Galaxy Interactions

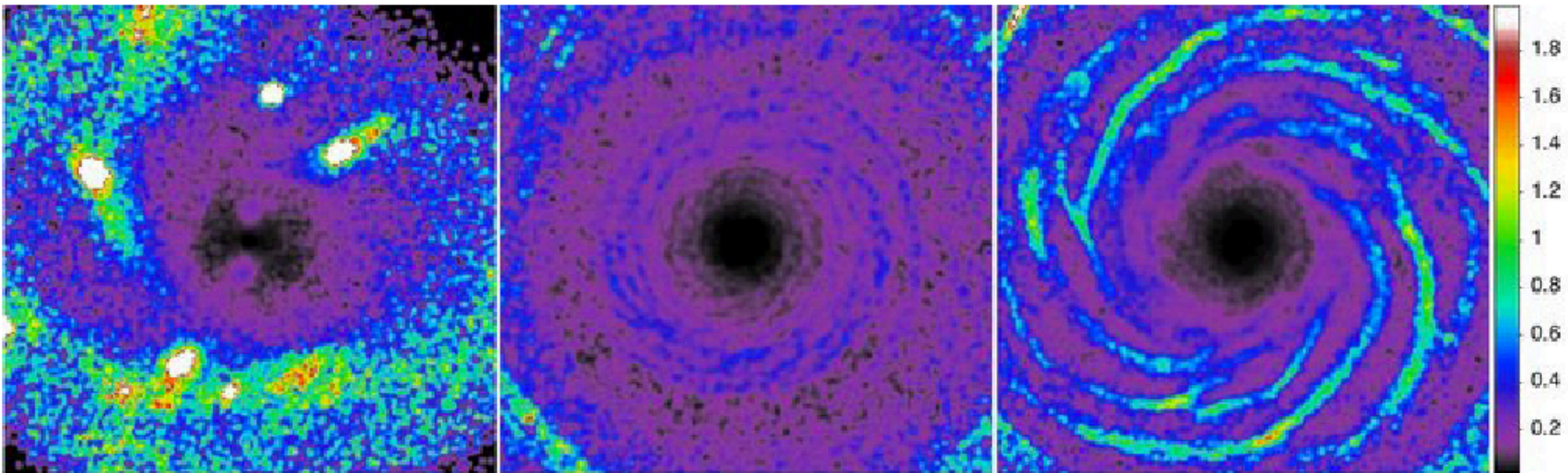


# Galaxy-Cluster Interactions





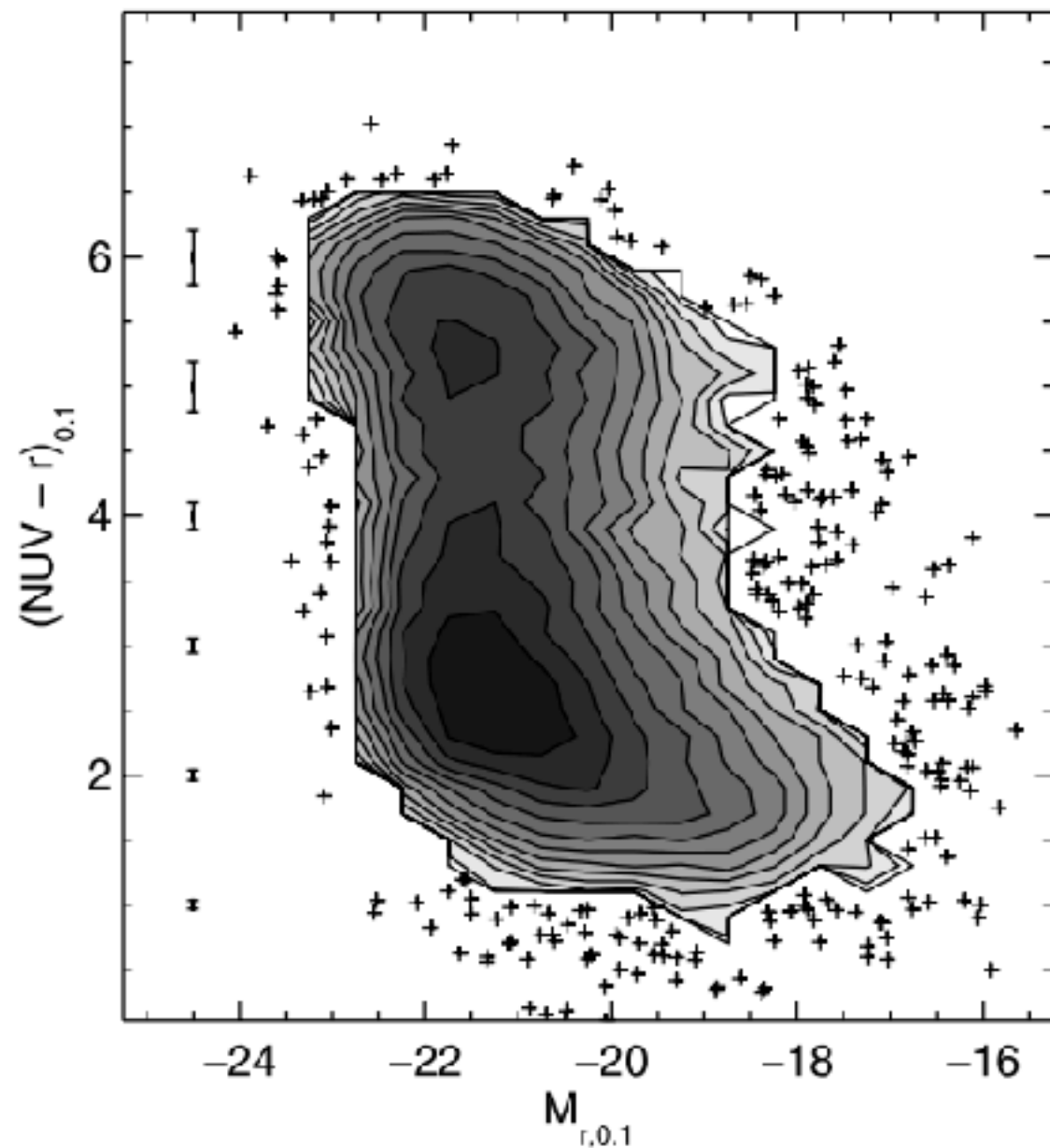
# Morphological Quenching



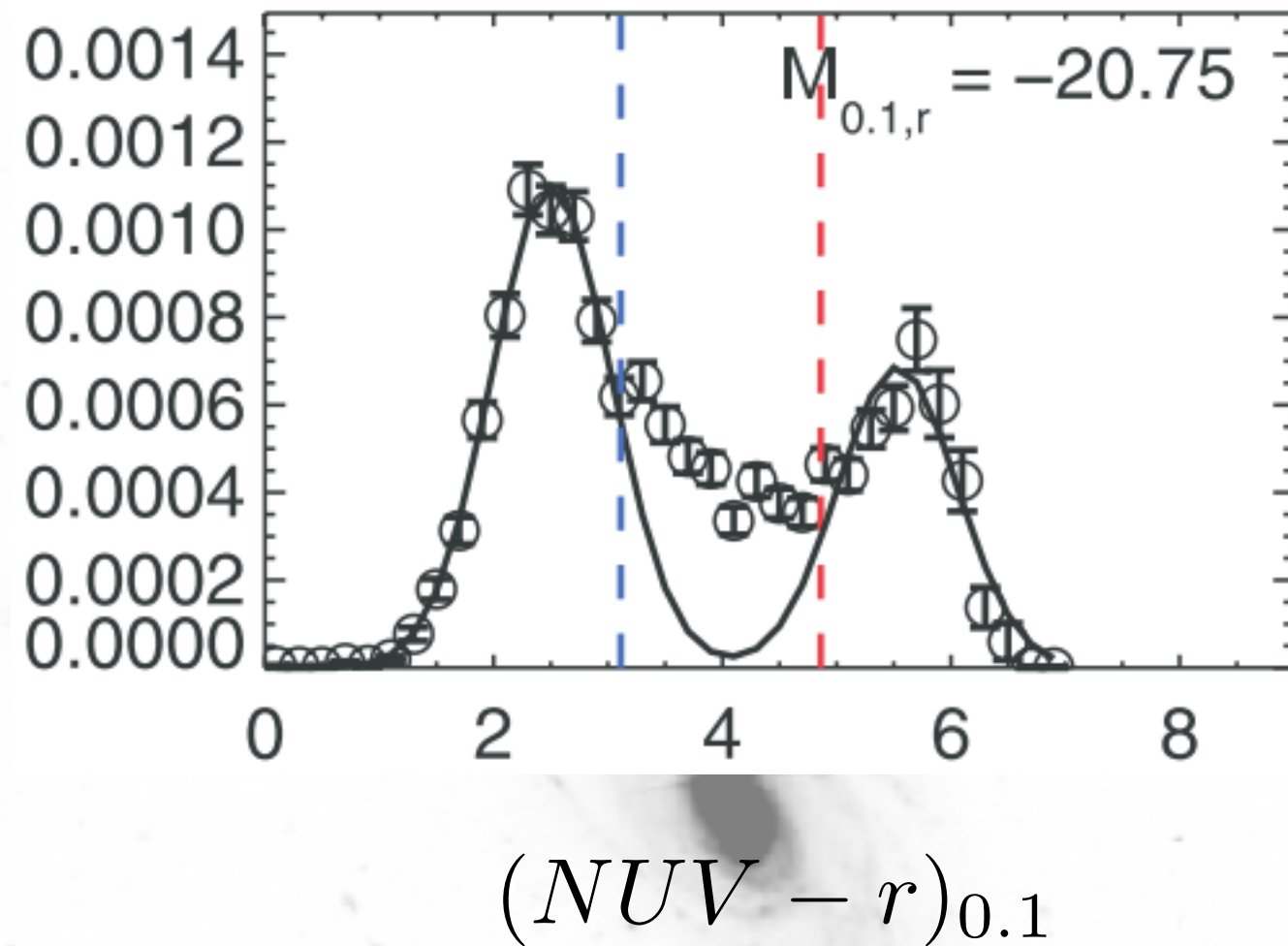
Colored by ratio of gas density to tidal density



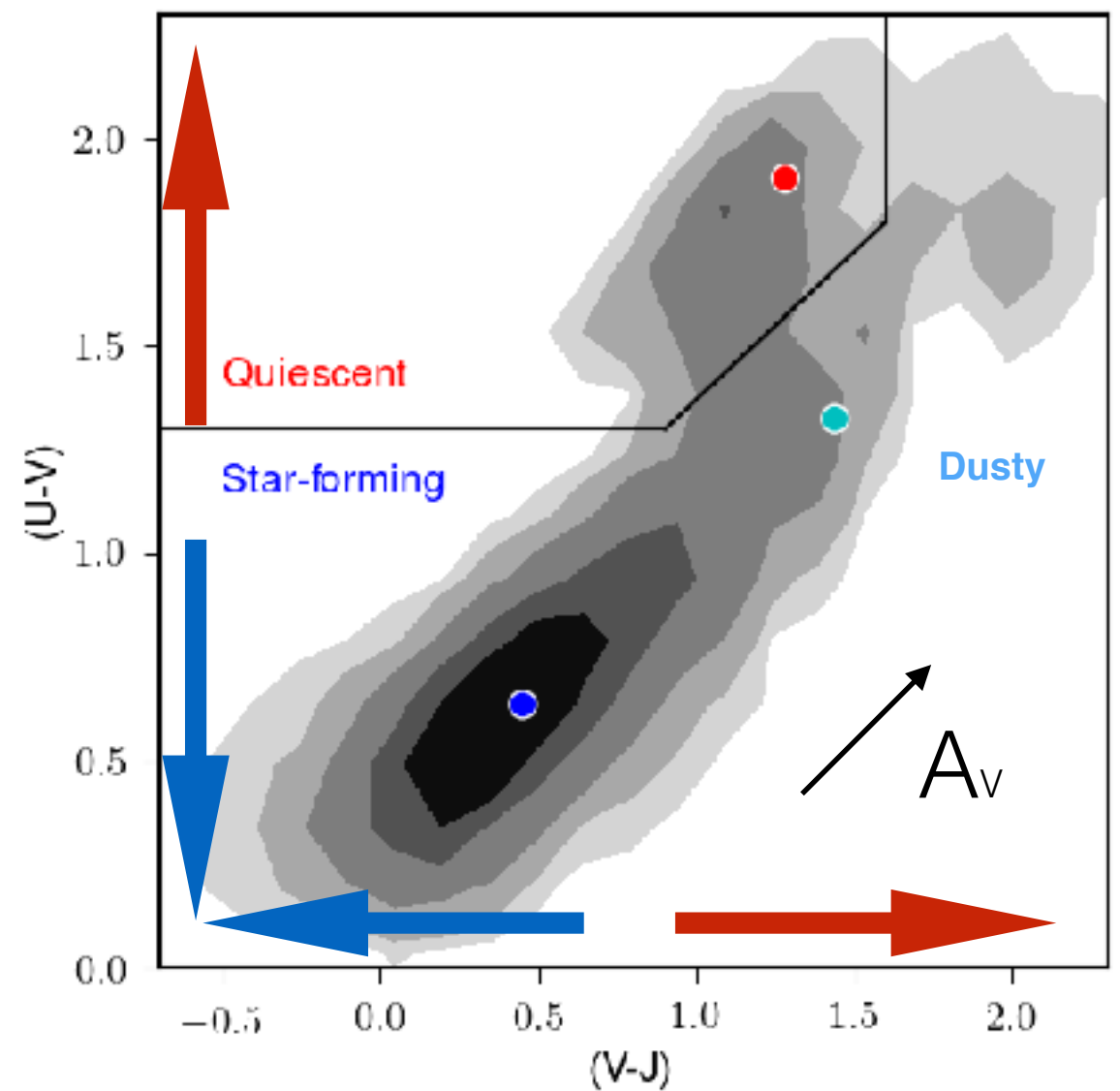
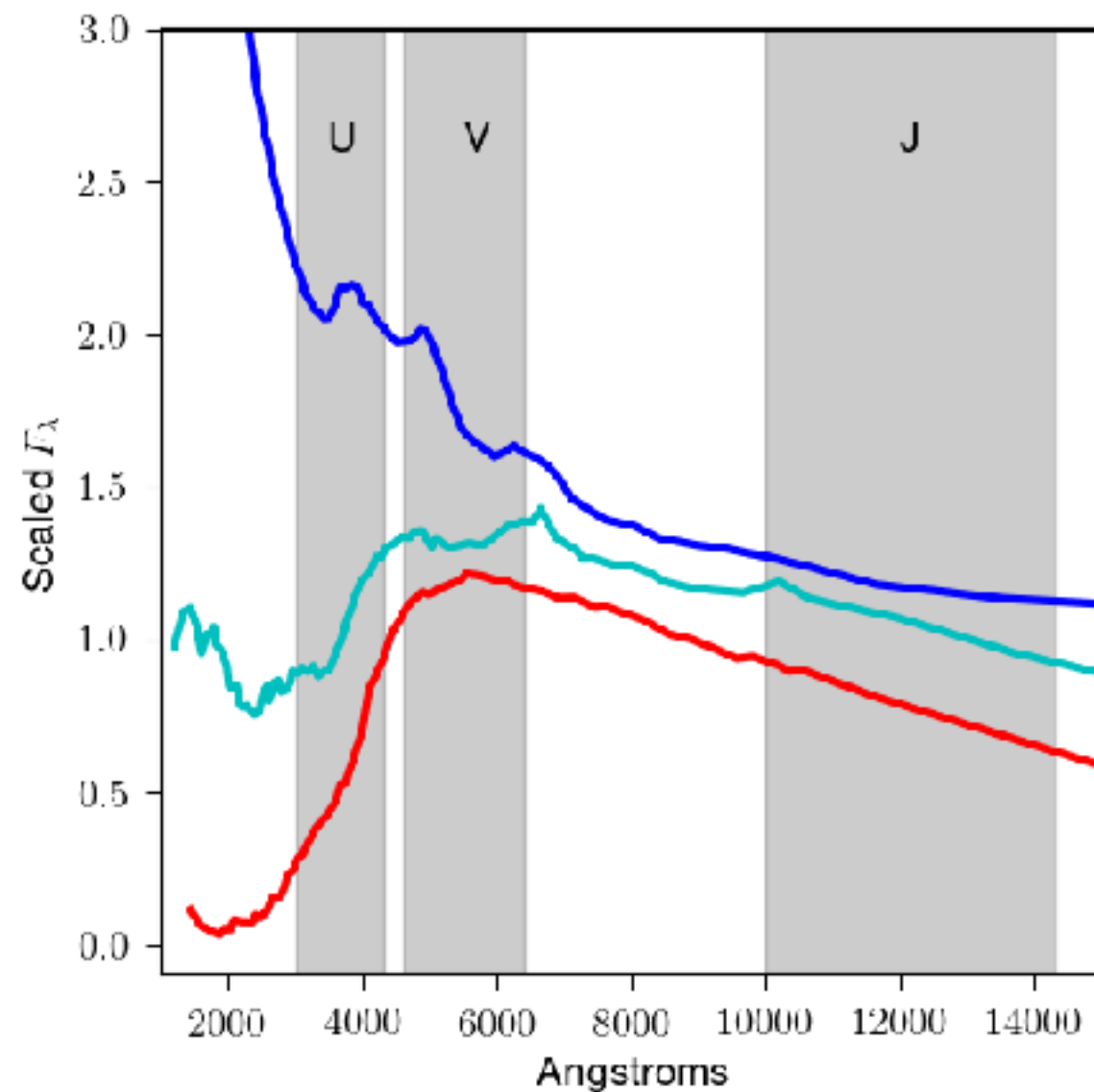
# The Green Valley



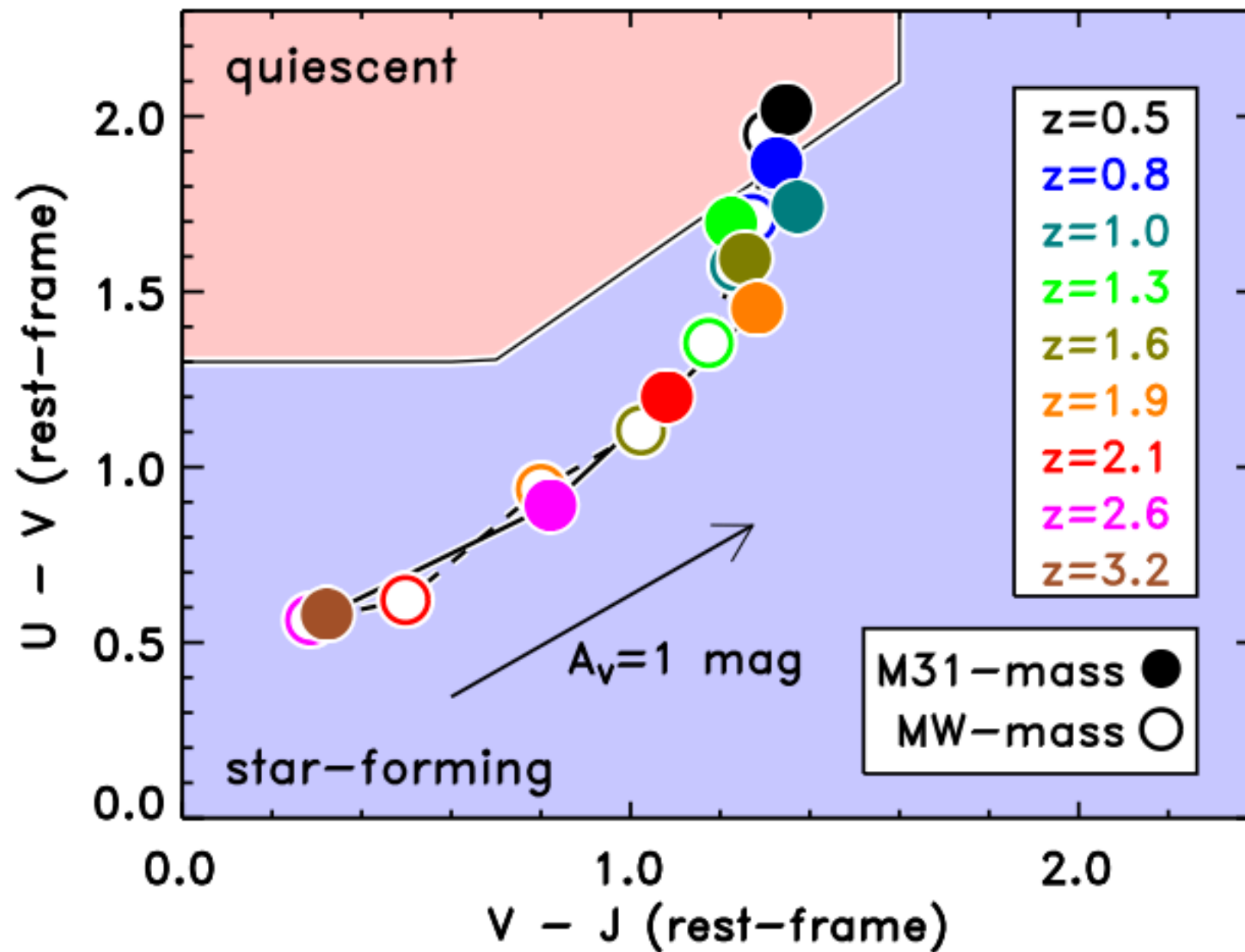
$N/Mpc^3$



# The UVJ Diagram

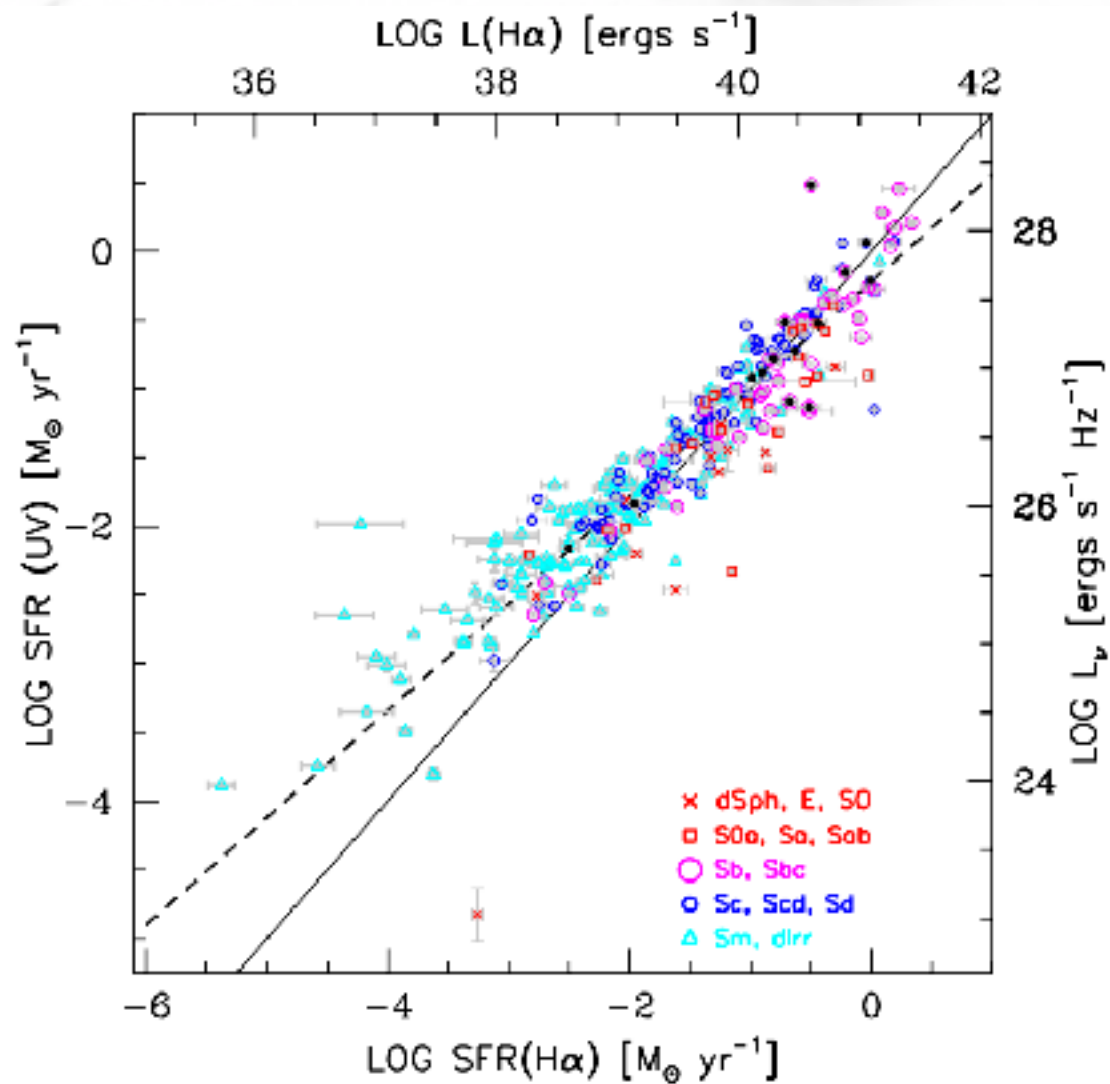


# The UVJ Diagram

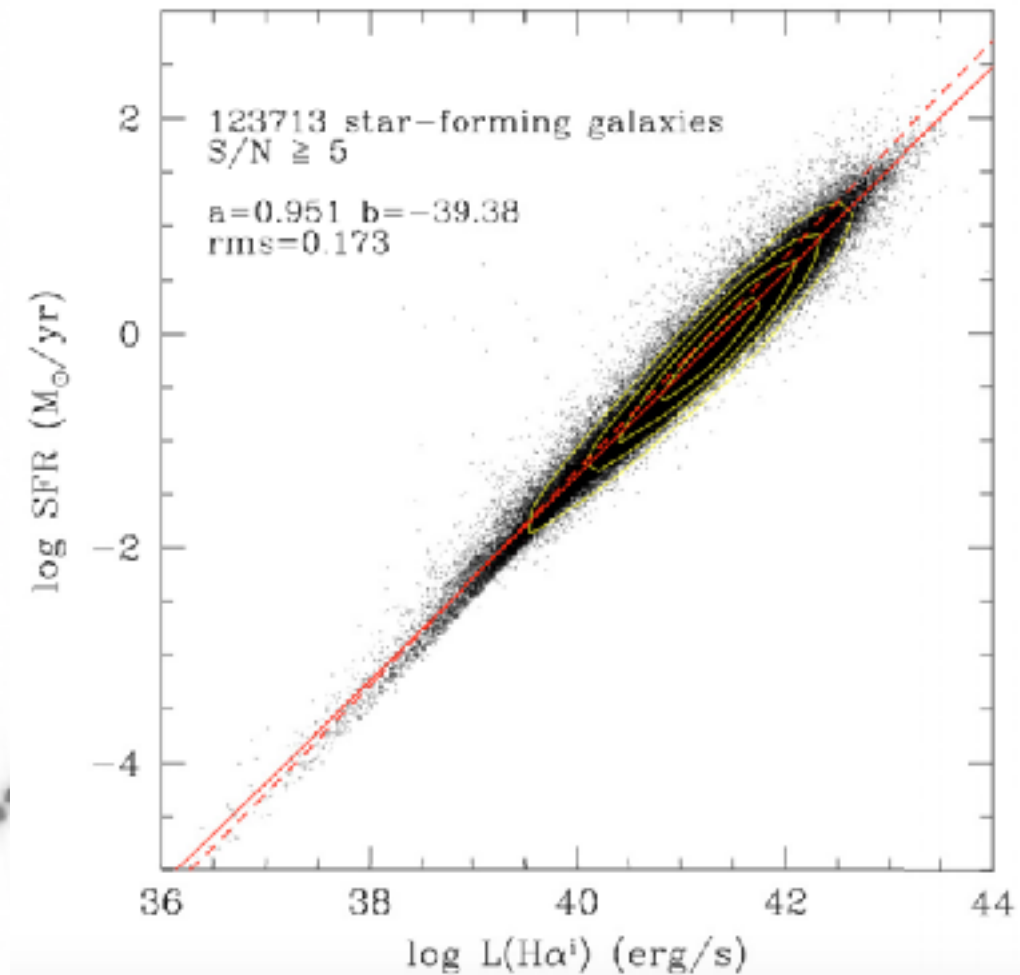




# H $\alpha$ Emission

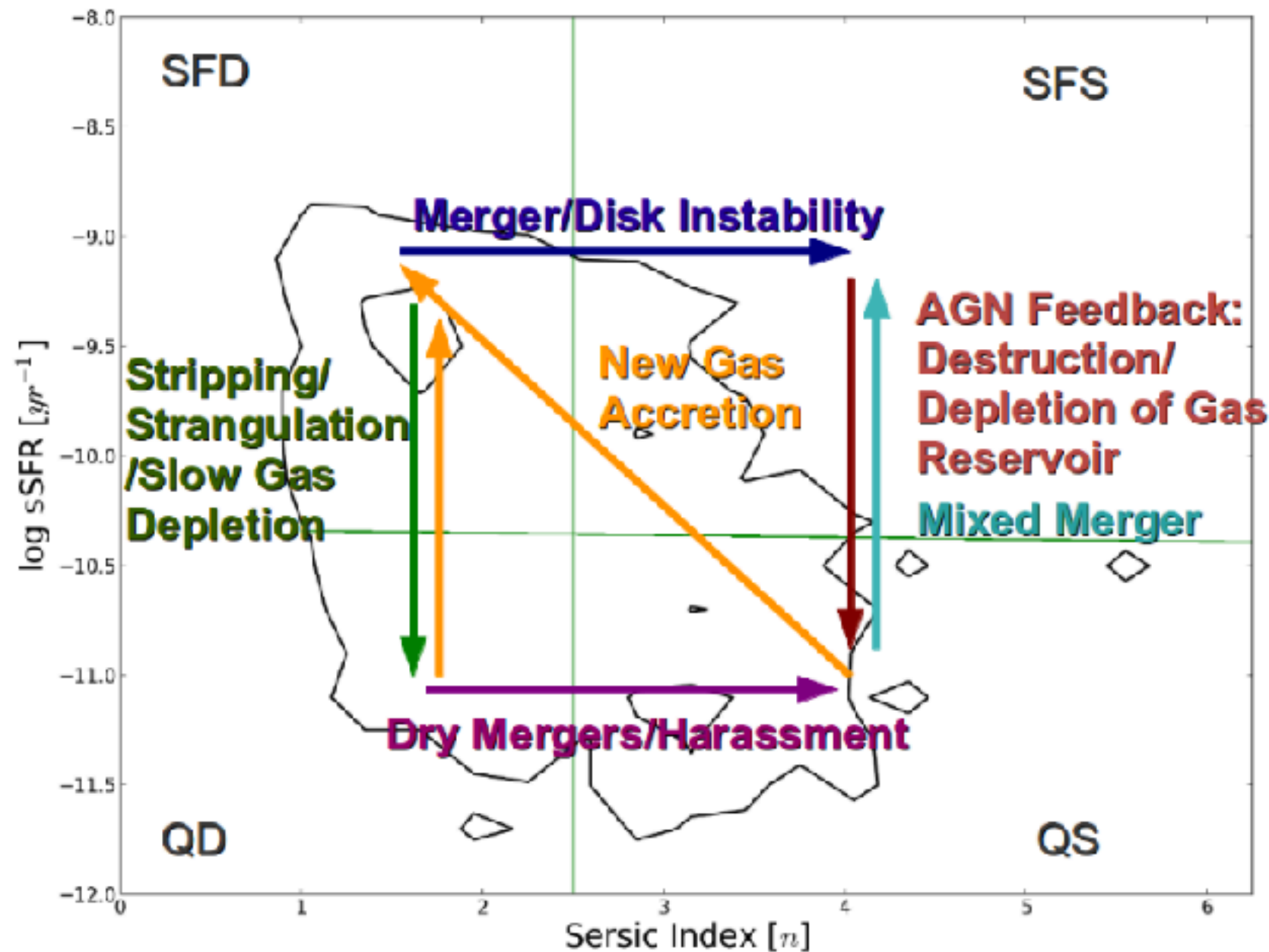


Lee+2009  
Local Dwarf Galaxies



Argence+2009  
SDSS

# Morphological Changes

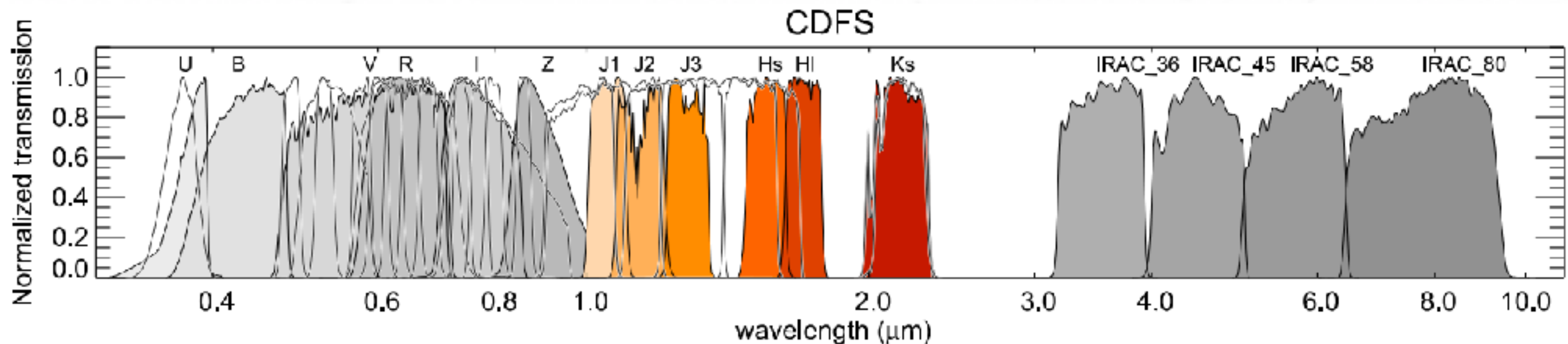


A grayscale astronomical image showing a field of galaxies. Several prominent galaxies are visible, including a large elliptical one in the upper left, a smaller one in the lower right, and a long, thin, edge-on galaxy in the upper right. The background is filled with numerous smaller, fainter galaxies. The word "Data" is centered in a large, black, sans-serif font. A solid dark red triangle is located in the bottom-left corner.

Data



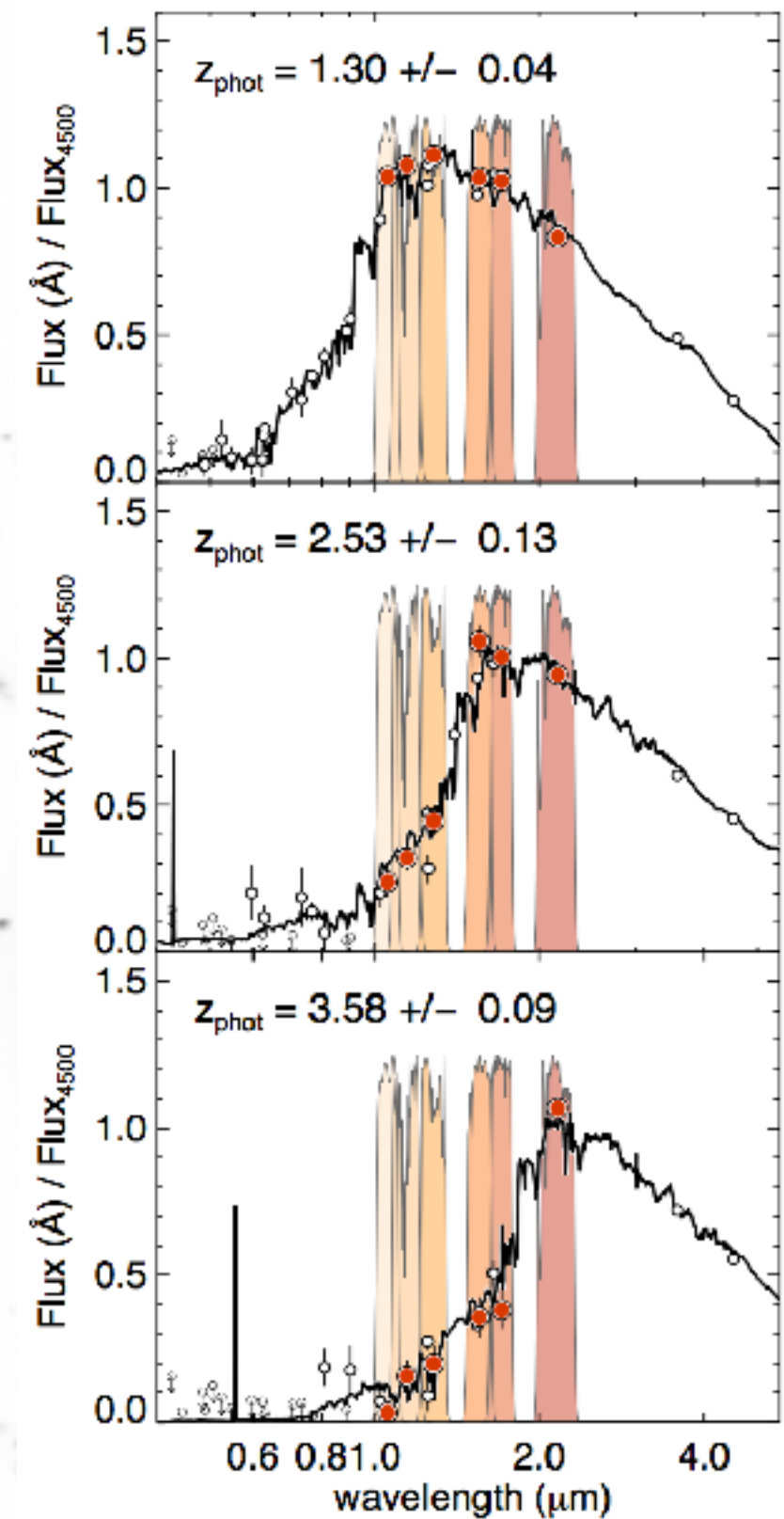
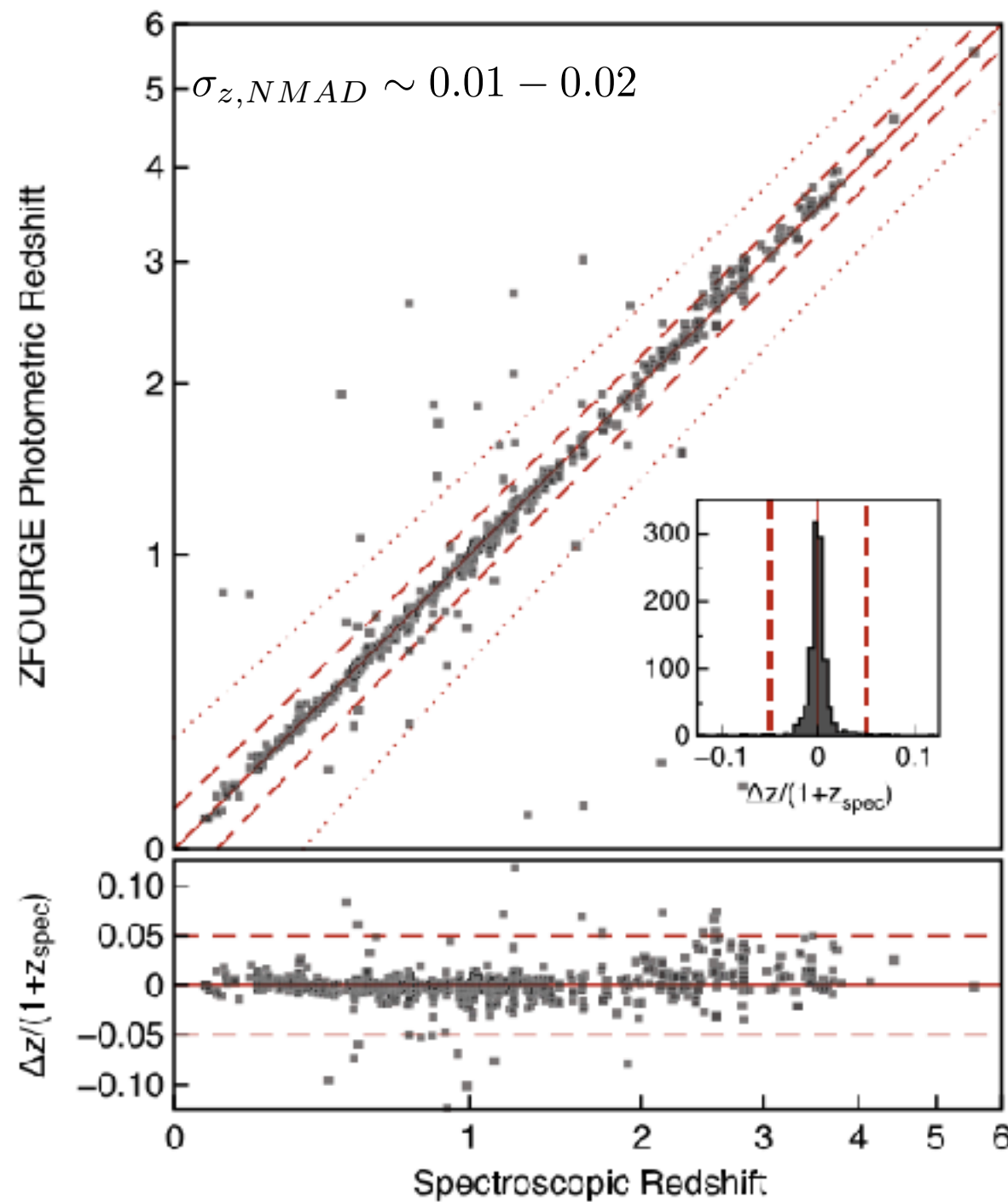
# THE FOURSTAR GALAXY EVOLUTION SURVEY (ZFOURGE)



~400 arcminutes in CDFS, COSMOS, and UDS  
80% completeness  $K_s \sim 26$   
Up to 40 photometric observations from 0.3-8 micron



# ZFOURGE



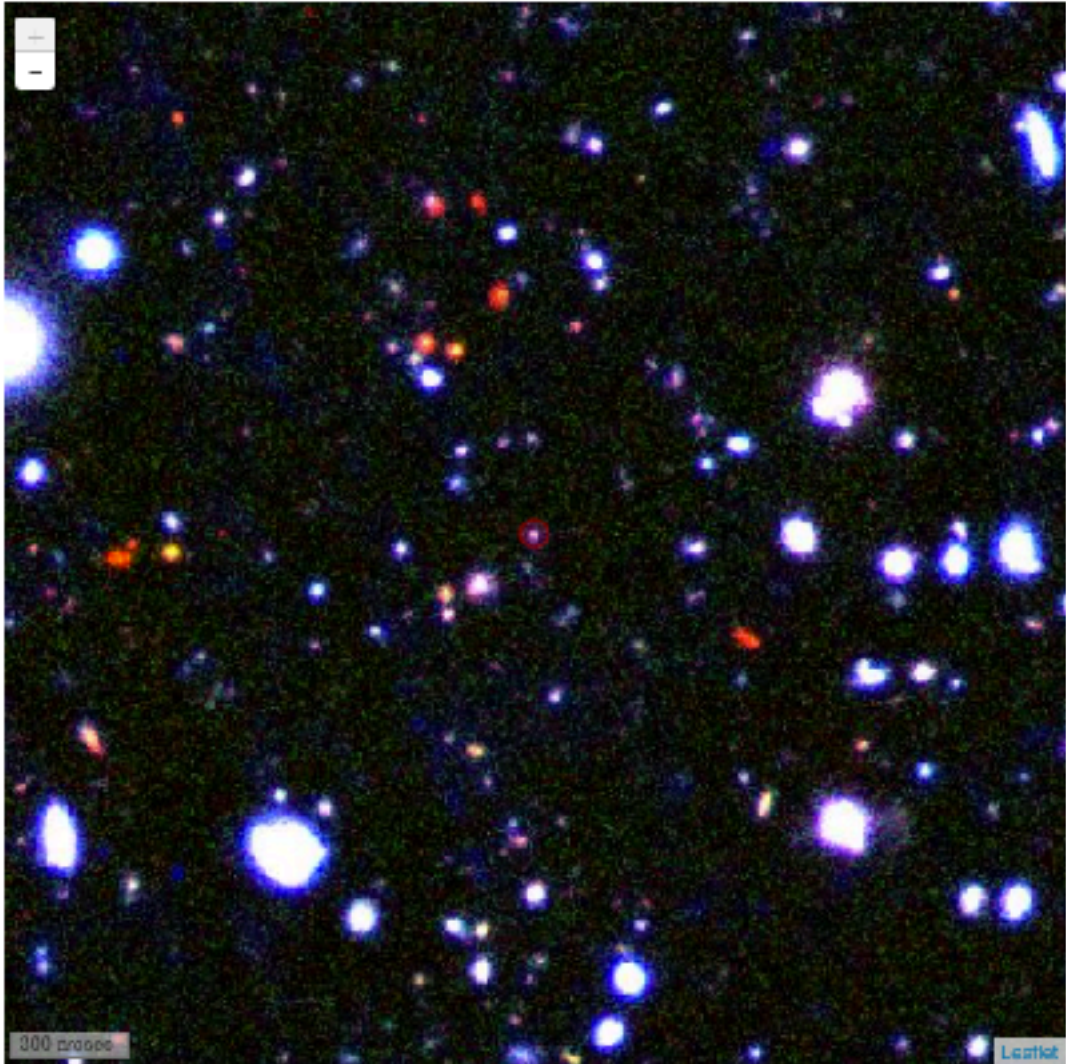


# ZFOURGE

CDFS

COSMOS

UDS



300 pixels

Leaflet

Filters for color image: **deep**, **Ks-band**, **combined J1, J2, and J3**, and **F814W**

Cursor Position:  
x, y: 3784, 7371  
RA, DEC: 53.11428, -27.66798

Selected Object:  
**Object: 14888**

x, y: 4262.1, 4011.0  
RA, DEC: 53.0914917, -27.0080635  
mag: 24.55  
Z<sub>phot</sub>: 2.35  
Z<sub>spec</sub>: No  
Star Flag: 0  
Use Flag: 1

Jump to Coordinates:  
RA (52.952787 to 53.232525):

DEC (-27.975388 to -27.625102):

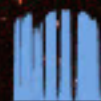
Zoom Level (0 to 4):

Go To

Jump to Object:  
Object Number (1 to 20911):

Zoom Level (0 to 4):

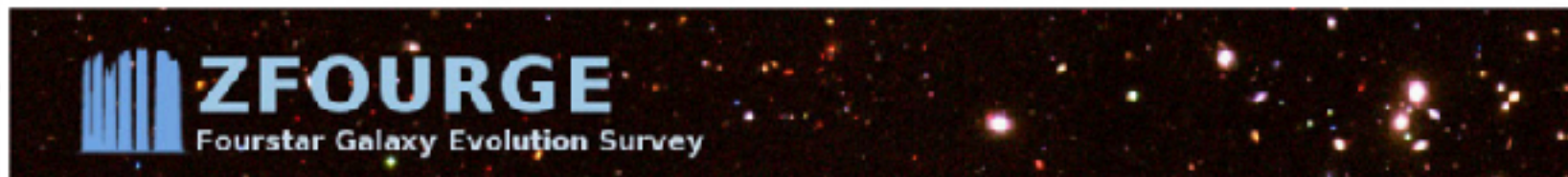
Go To



**ZFOURGE.TAMU.EDU**  
Fourstar Galaxy Evolution Survey



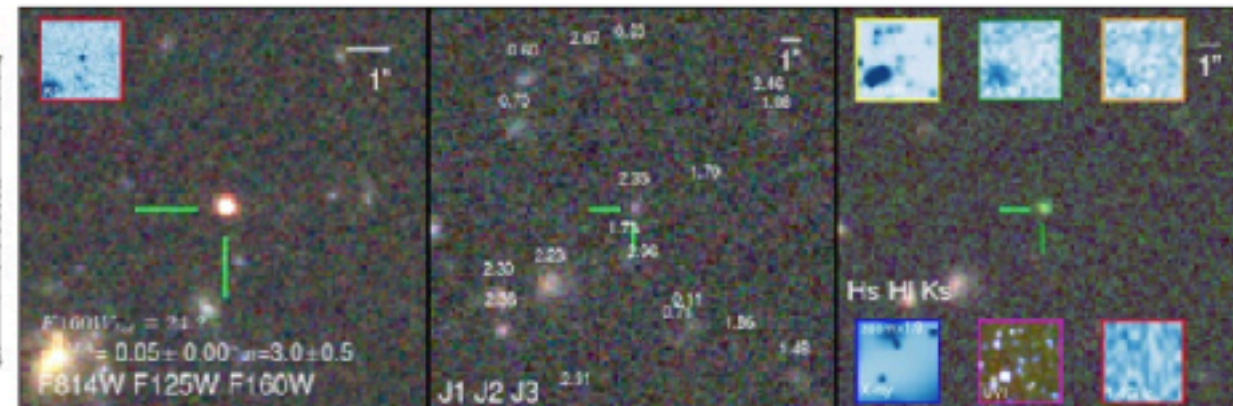
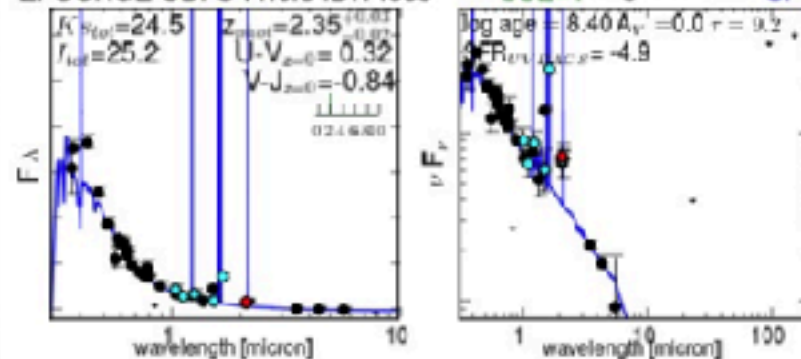
# ZFOURGE



CDFS Object ID: 14888

X (pixels)	4262.1	Y (pixels)	4011.0
RA (degree)	53.0914917	DEC (degree)	-27.8080635
mag <sub>K</sub>	24.55	mag <sub>J</sub>	25.21
z <sub>phot</sub>	2.35	z <sub>spec</sub>	No
Star flag	0	AGN flag	No
Use Flag	1	Log Stellar Mass ( $M_{\text{Sun}}$ )	8.85
SFR <sub>UV+IR</sub> ( $M_{\text{Sun}}$ /year)	-3.661	Log Specific Star Formation Rate	-99
(U-V) <sub>Rest</sub>	0.319	(V-J) <sub>Rest</sub>	-0.84

ZFOURGE CDFS v1.6.3 ID:14888



Warning: these values are for inspection only. If you would like to do actual science with these objects, please [download the catalogs](#).

A cosmic background image featuring various celestial objects. In the upper left, there is a bright, dark, circular galaxy. To its right, a long, thin, diagonal galaxy is visible. In the lower right, a large, prominent spiral galaxy with a dark core and distinct spiral arms is shown. The background is filled with numerous smaller, fainter galaxies and stars, some appearing as sharp points of light and others as diffuse clouds. A solid dark red triangle is located in the bottom-left corner of the image.

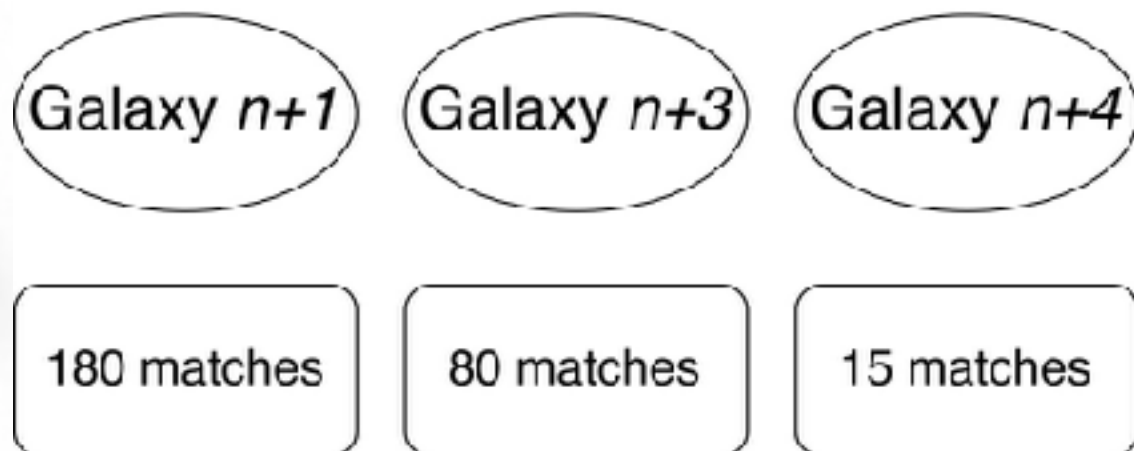
# Methods

# Grouping Galaxy SEDs

$$b_{12} = \sqrt{\frac{\Sigma(f_{\lambda}^{ob1} - a_{12}f_{\lambda}^{ob2})^2}{\Sigma(f_{\lambda}^{ob1})^2}}$$

$$a_{12} = \frac{\Sigma f_{\lambda}^{ob1} f_{\lambda}^{ob2}}{\Sigma(f_{\lambda}^{ob2})^2}$$

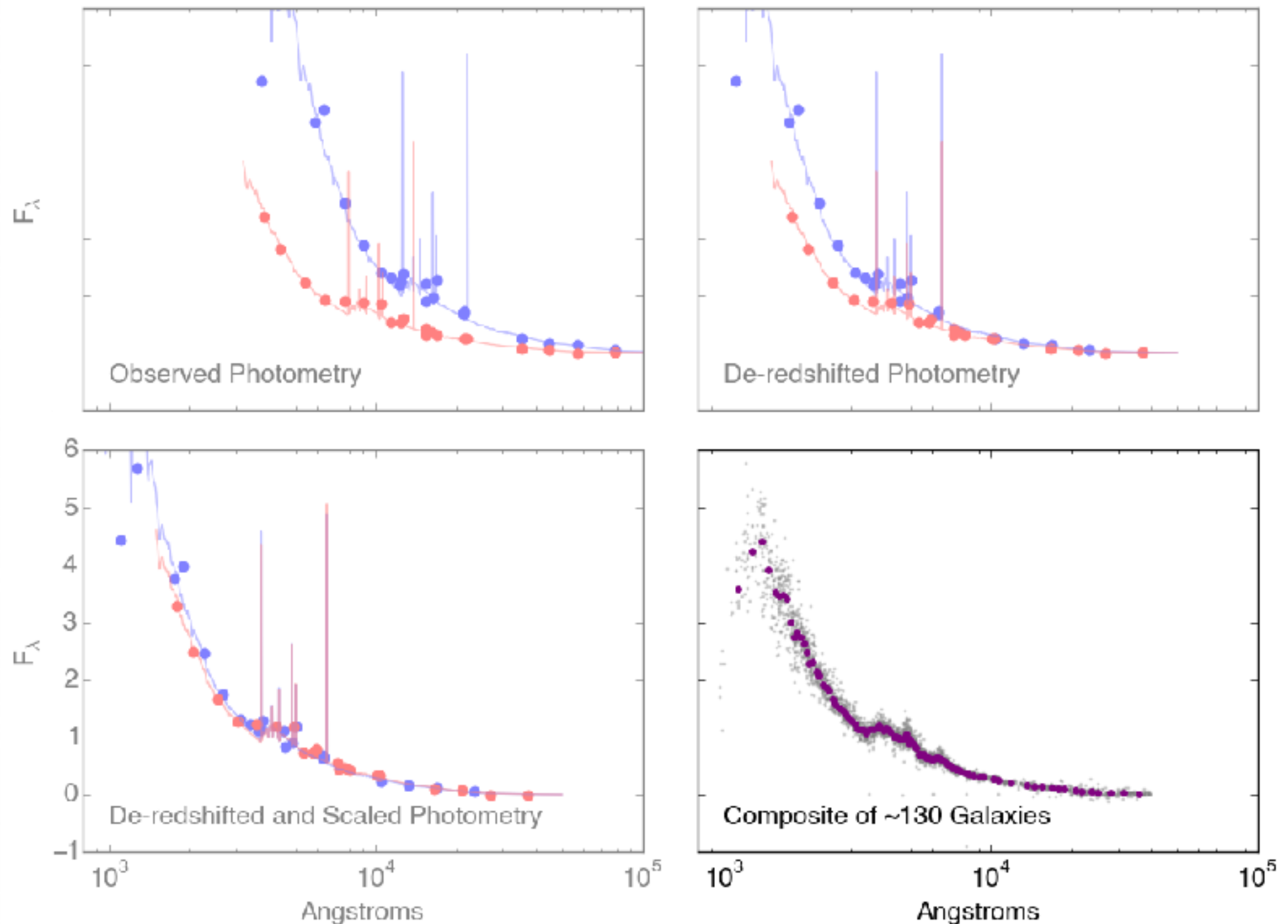
Method  
pioneered in  
Kriek, et al. 2011



- Compare rest-frame photometry of SNR>20 galaxies.
- The smaller the value of  $b$ , the more similar the photometry of the two SEDs.
- Galaxies are grouped according to which other galaxies they are the most similar.

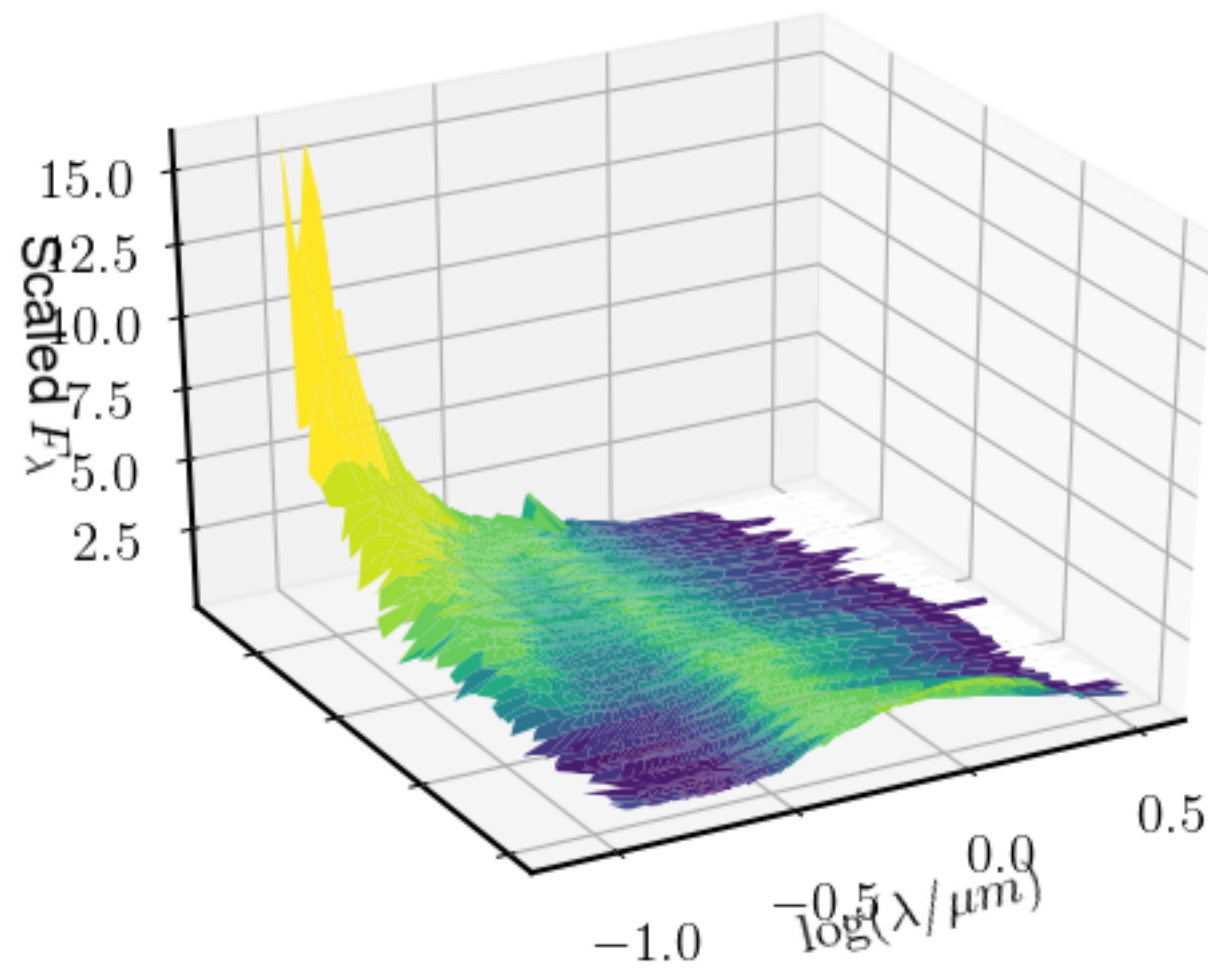


# Building Composite SEDs

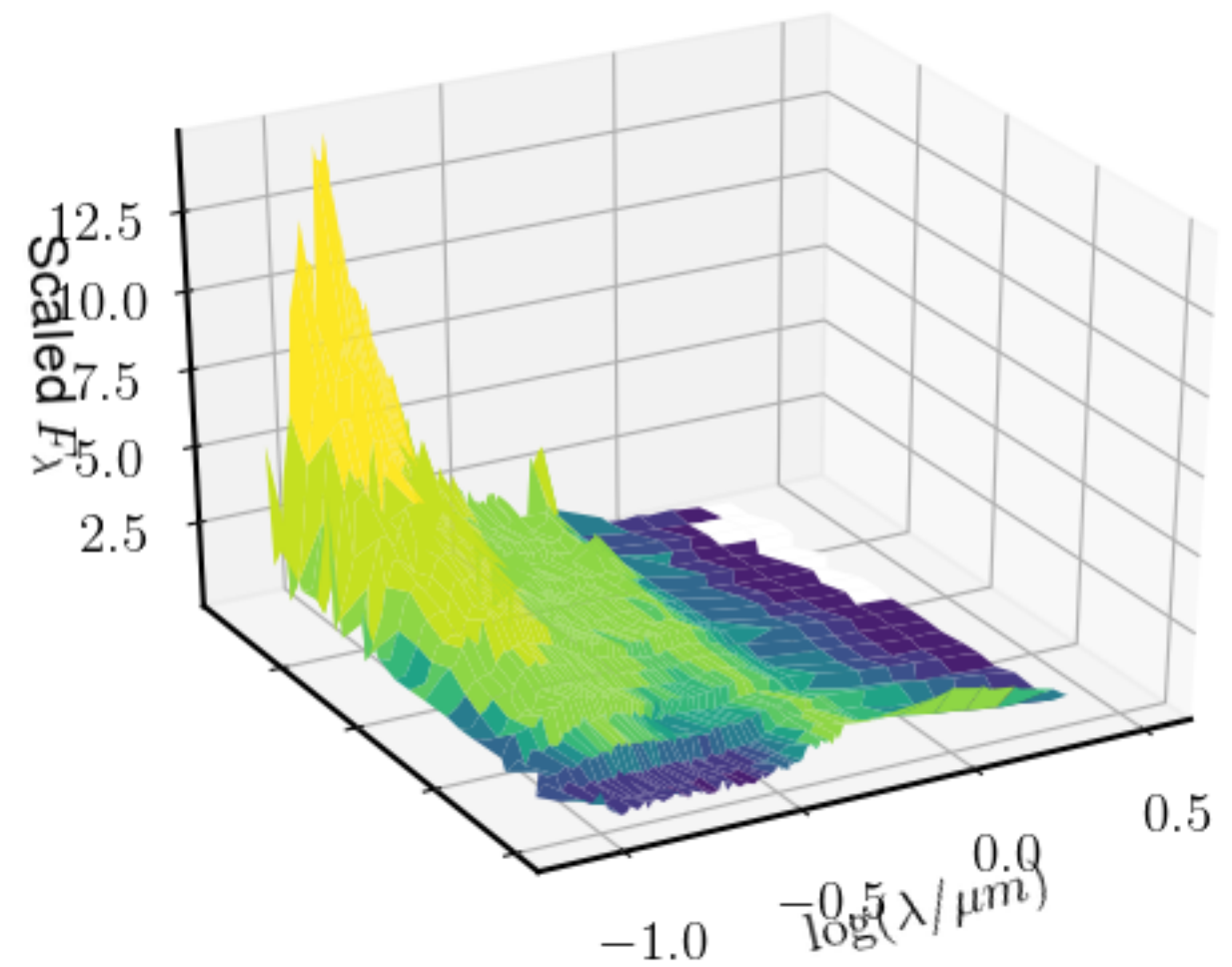


# Composite SEDs

$$1 < z < 3$$



$$2.5 < z < 4$$

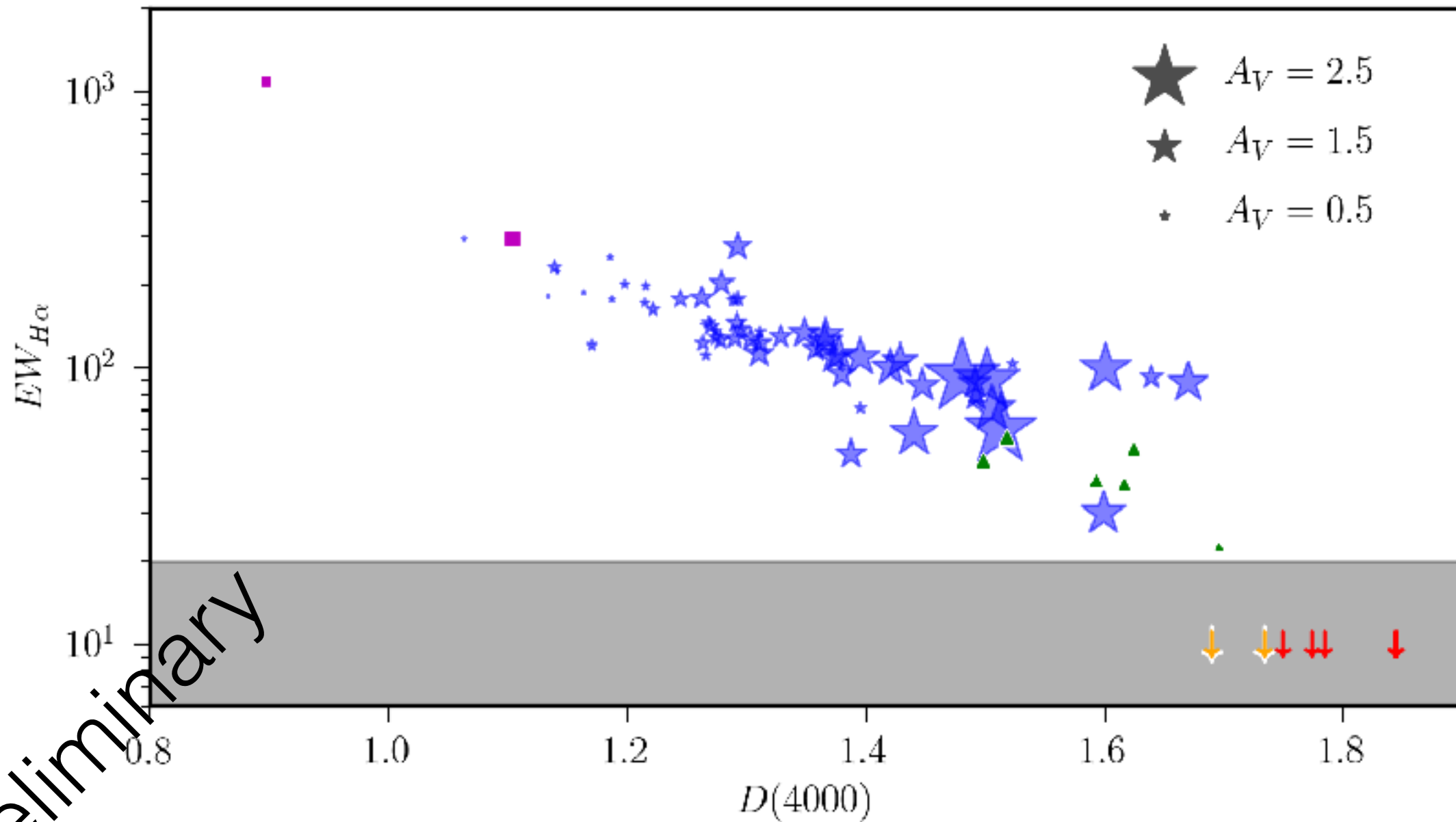


The background of the slide is a grayscale astronomical image showing a field of galaxies. Several galaxies are visible, including a prominent one in the upper left and another in the lower right. The text is centered over this image.

# From Star-Forming to Quiescent

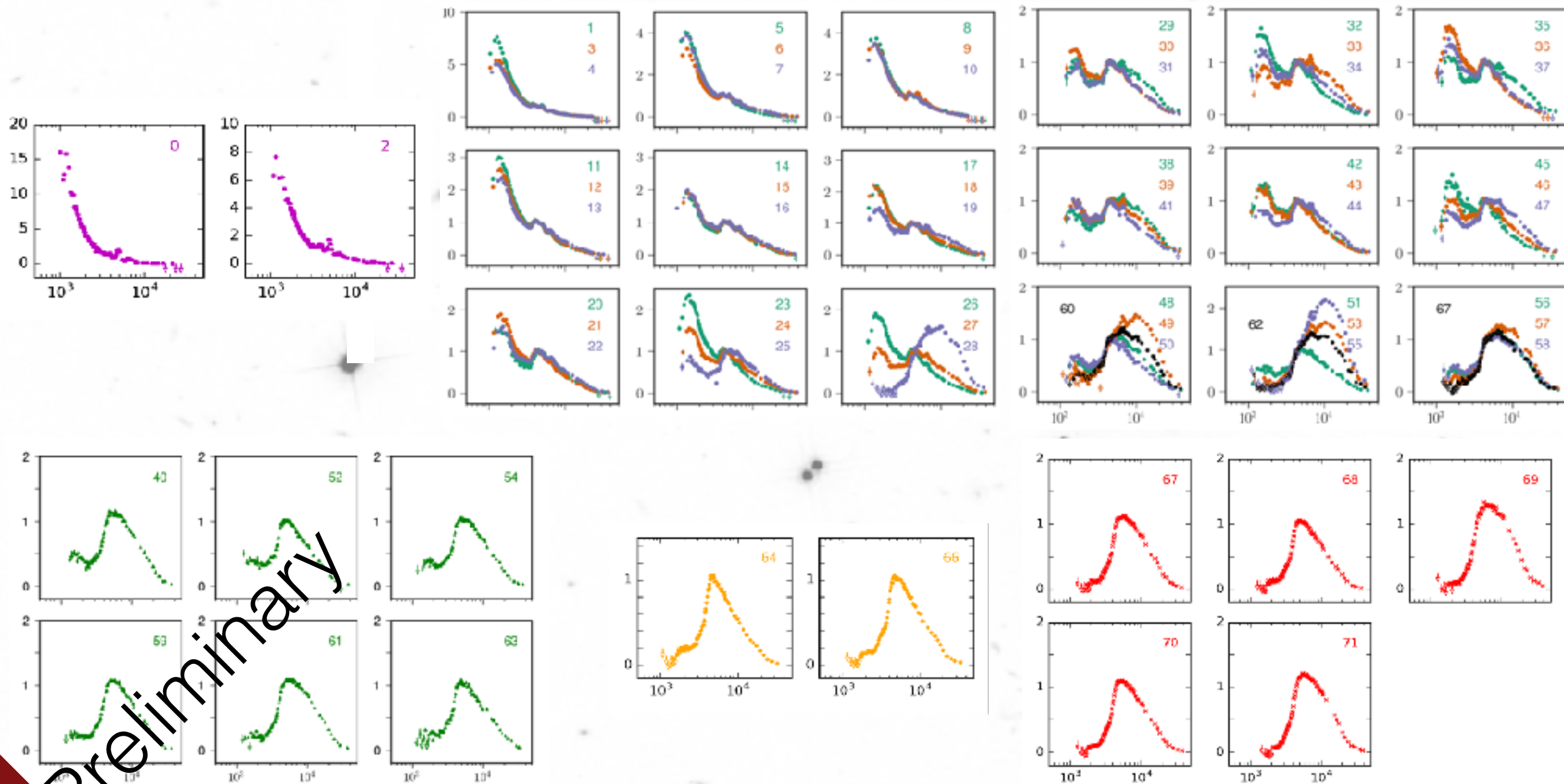


# Classification

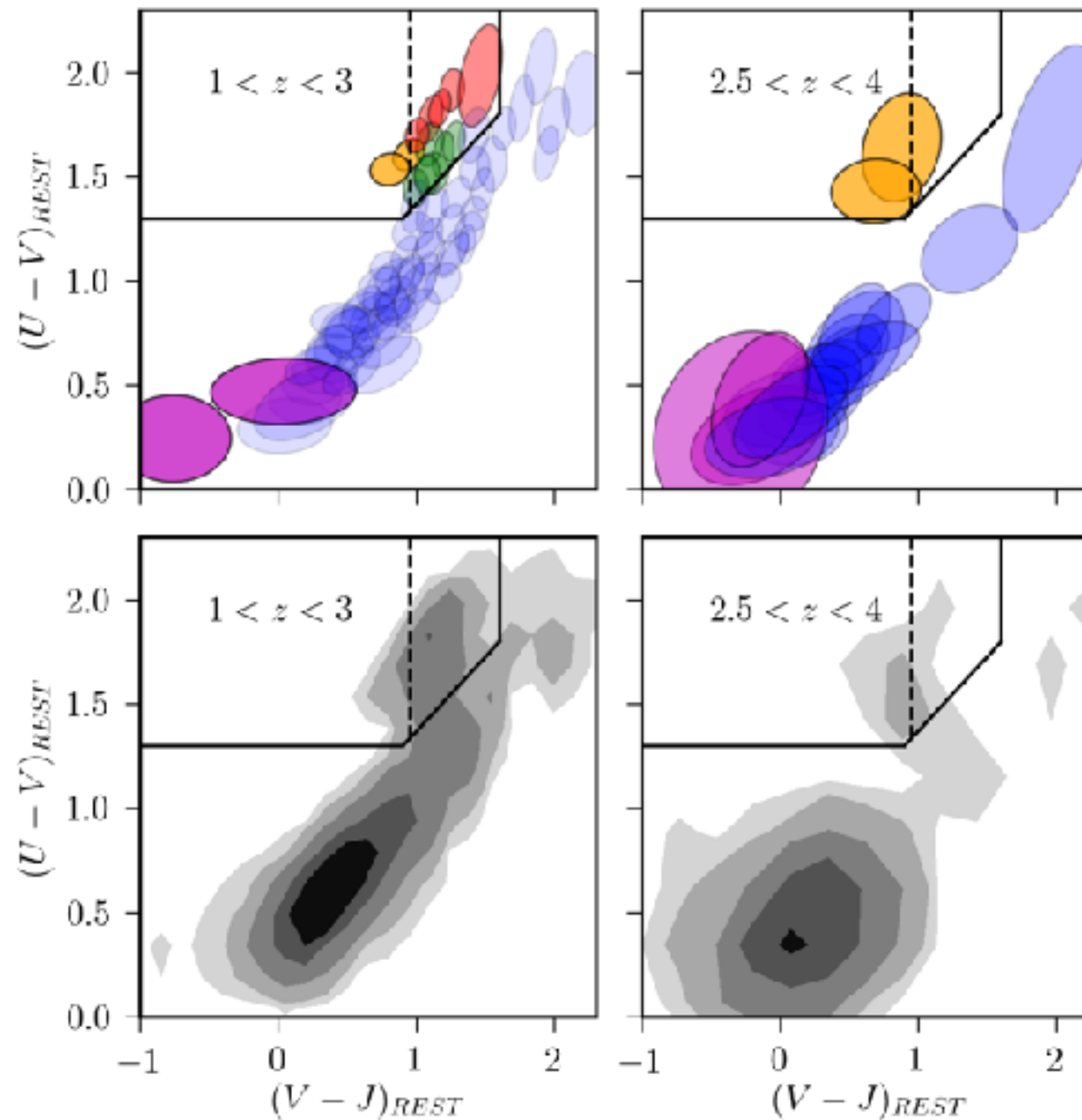


Preliminary

# Composite SEDs



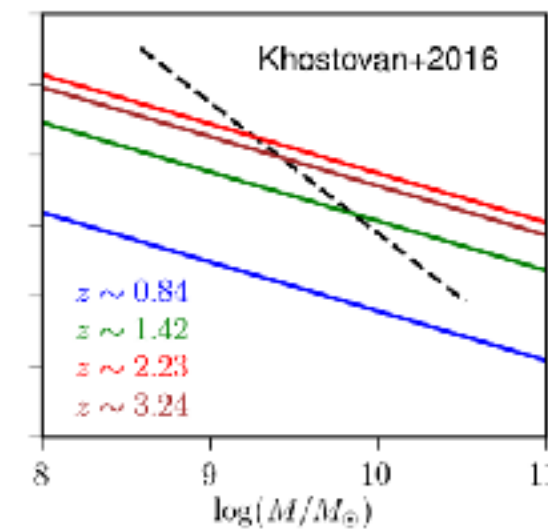
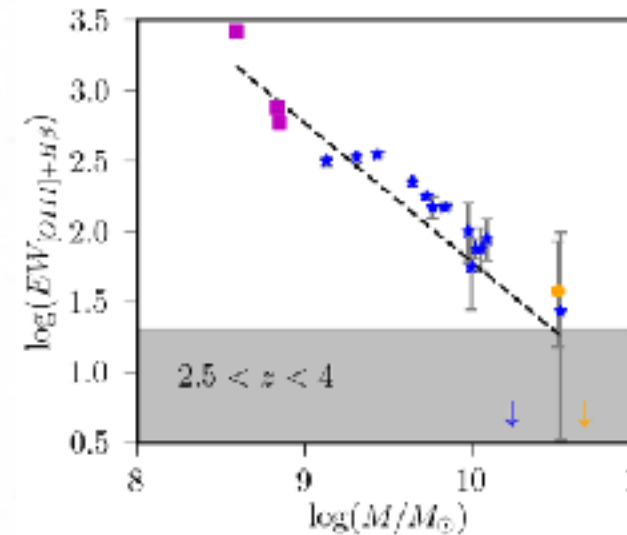
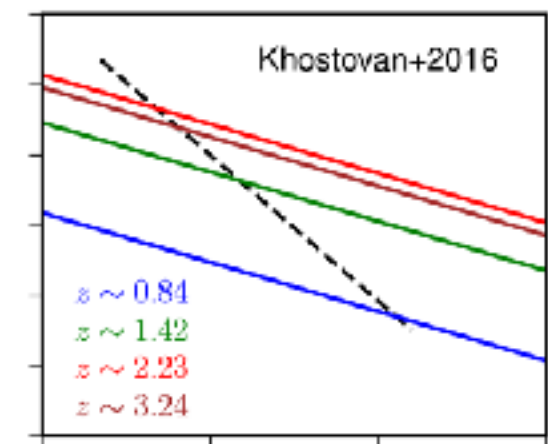
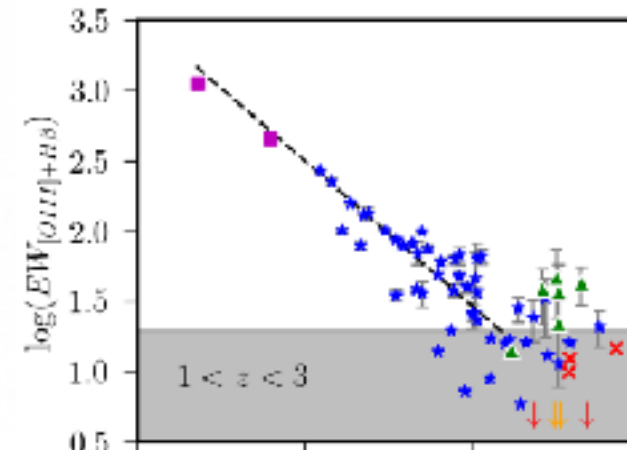
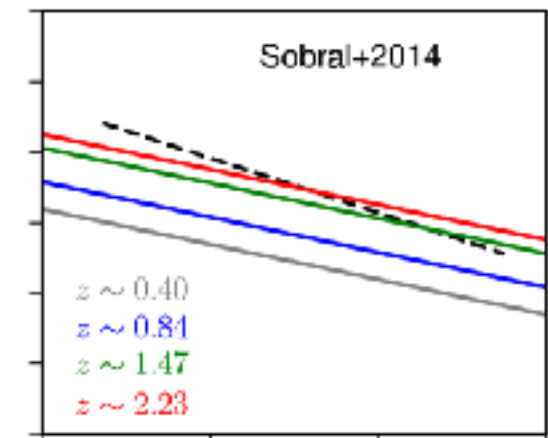
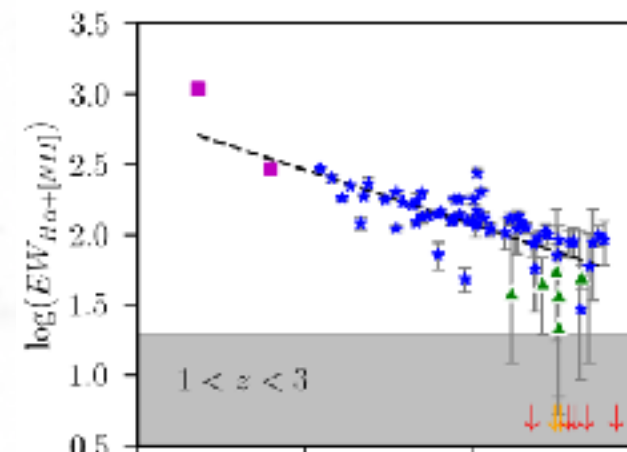
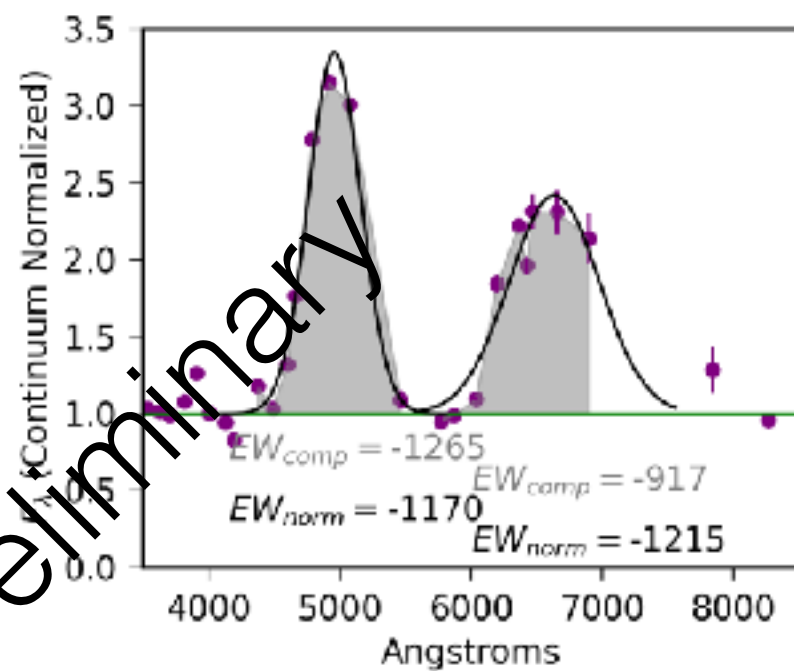
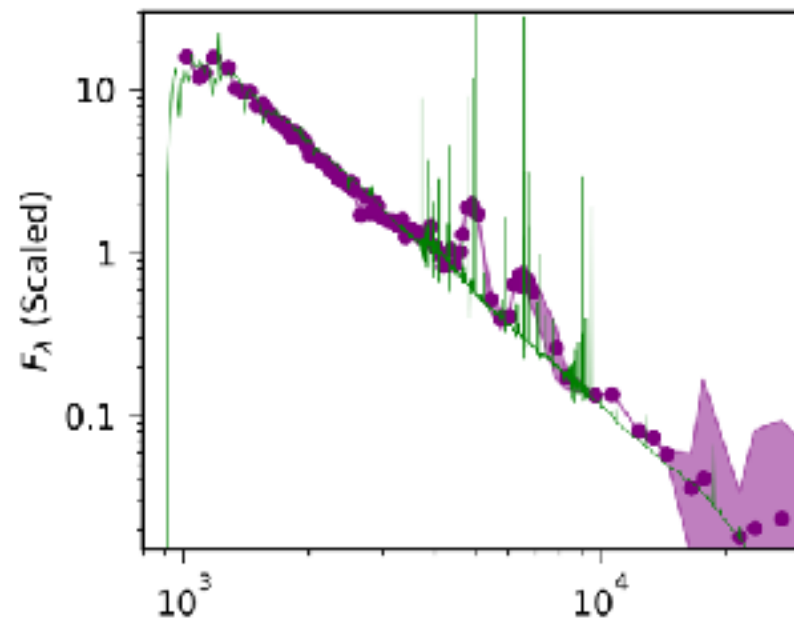
# Composite SED Colors



Preliminary

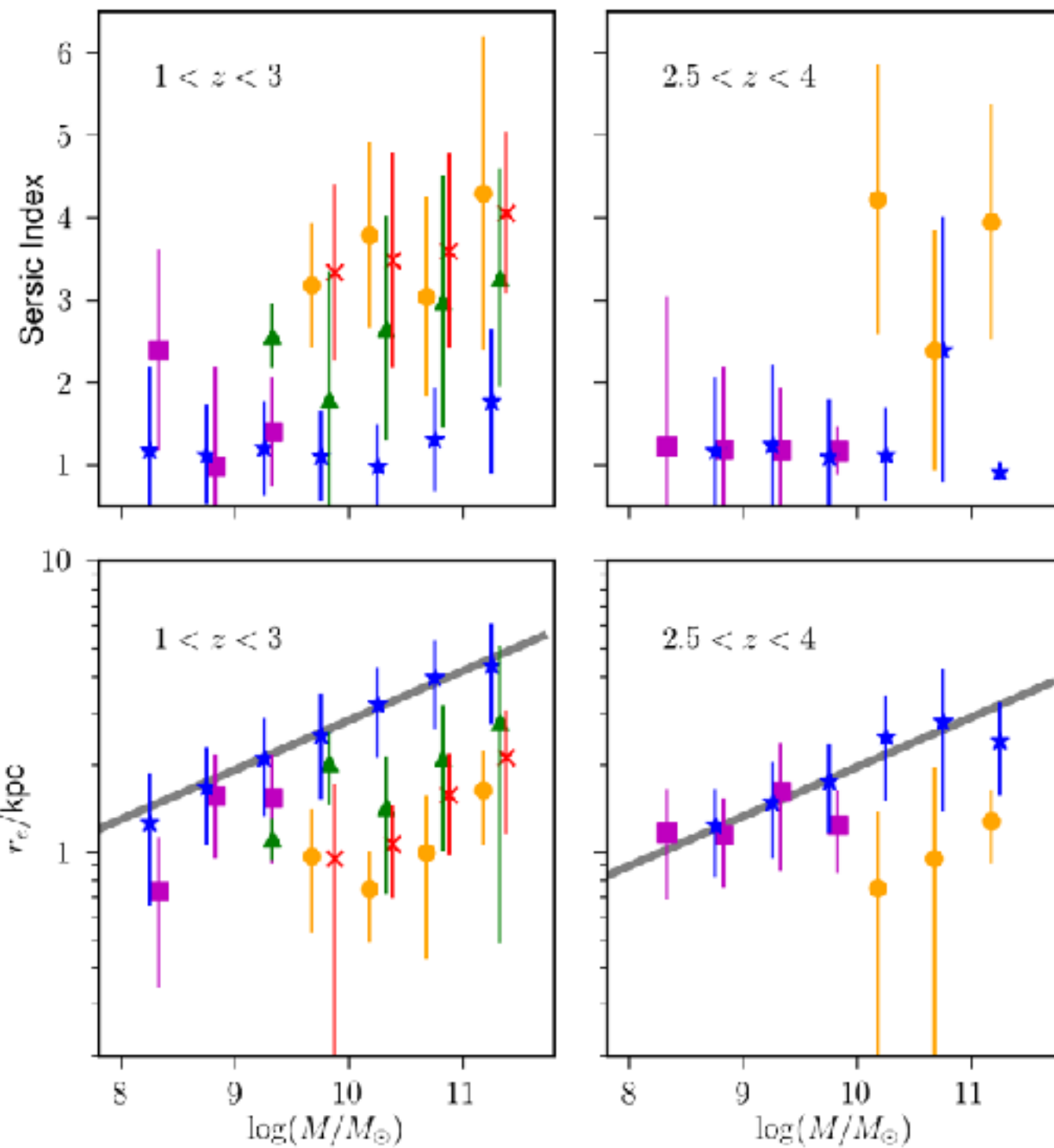


# Equivalent Widths



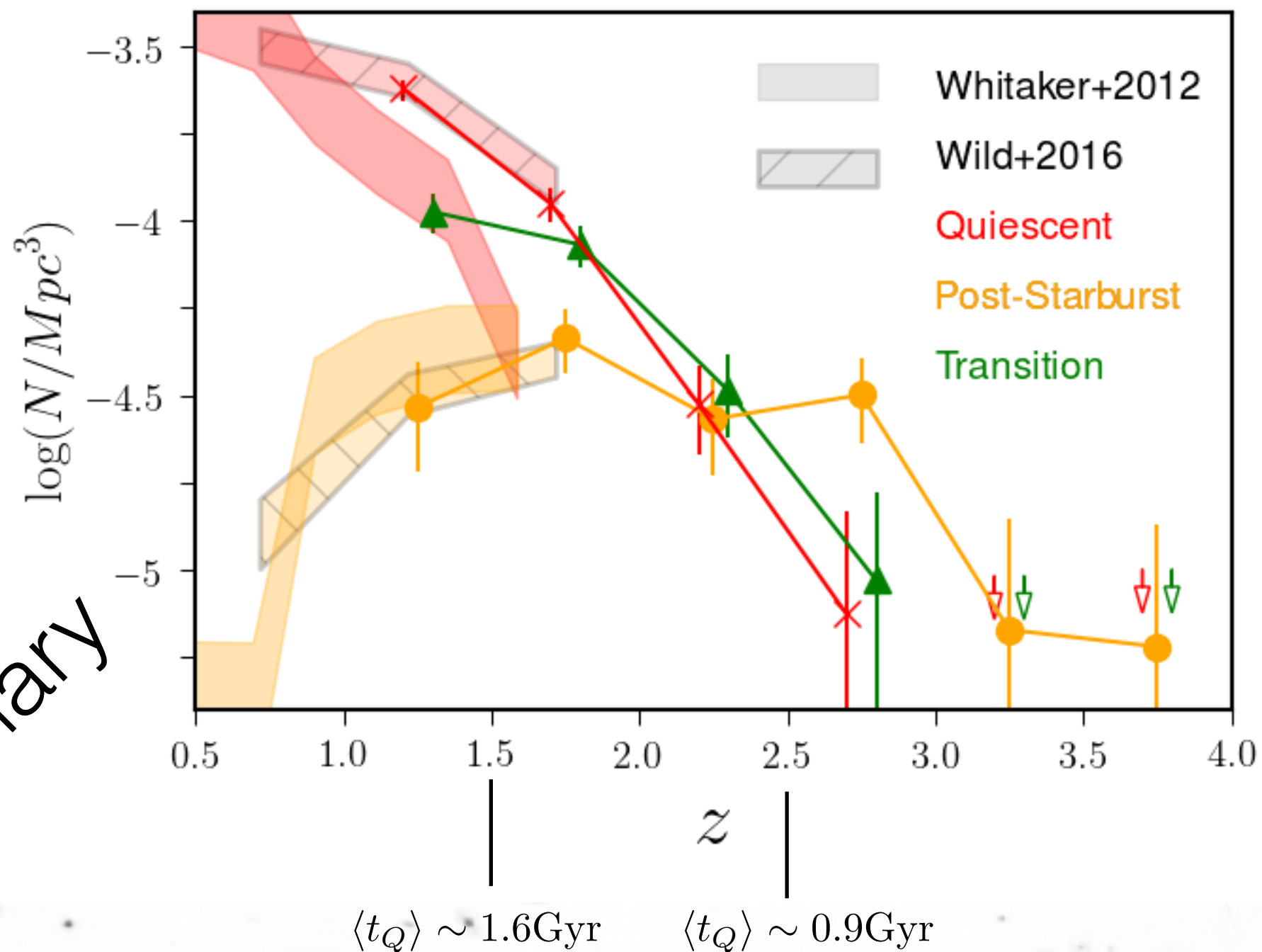
Preliminary

# Morphologies



Preliminary

# Number Density Evolution

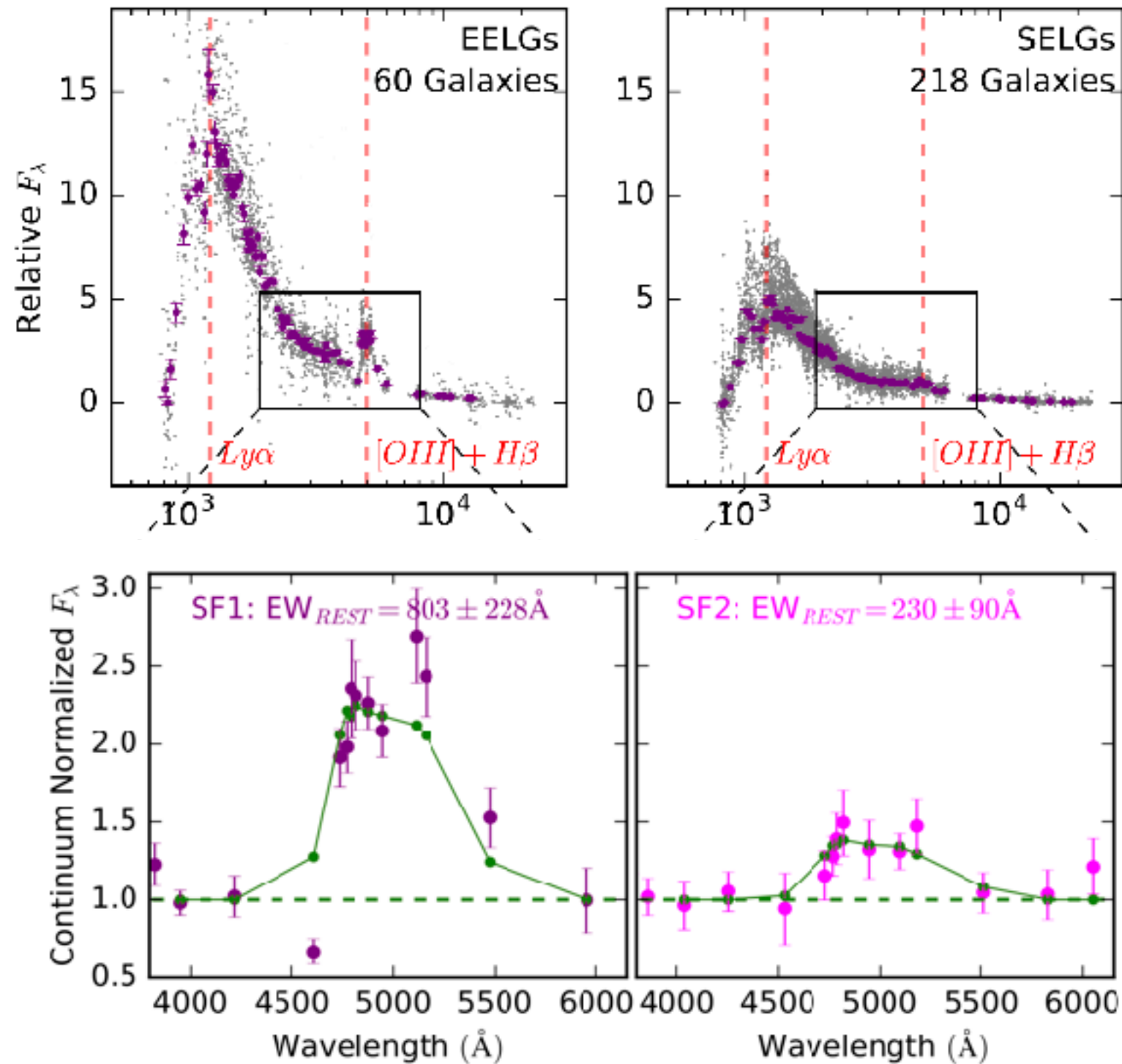


Preliminary

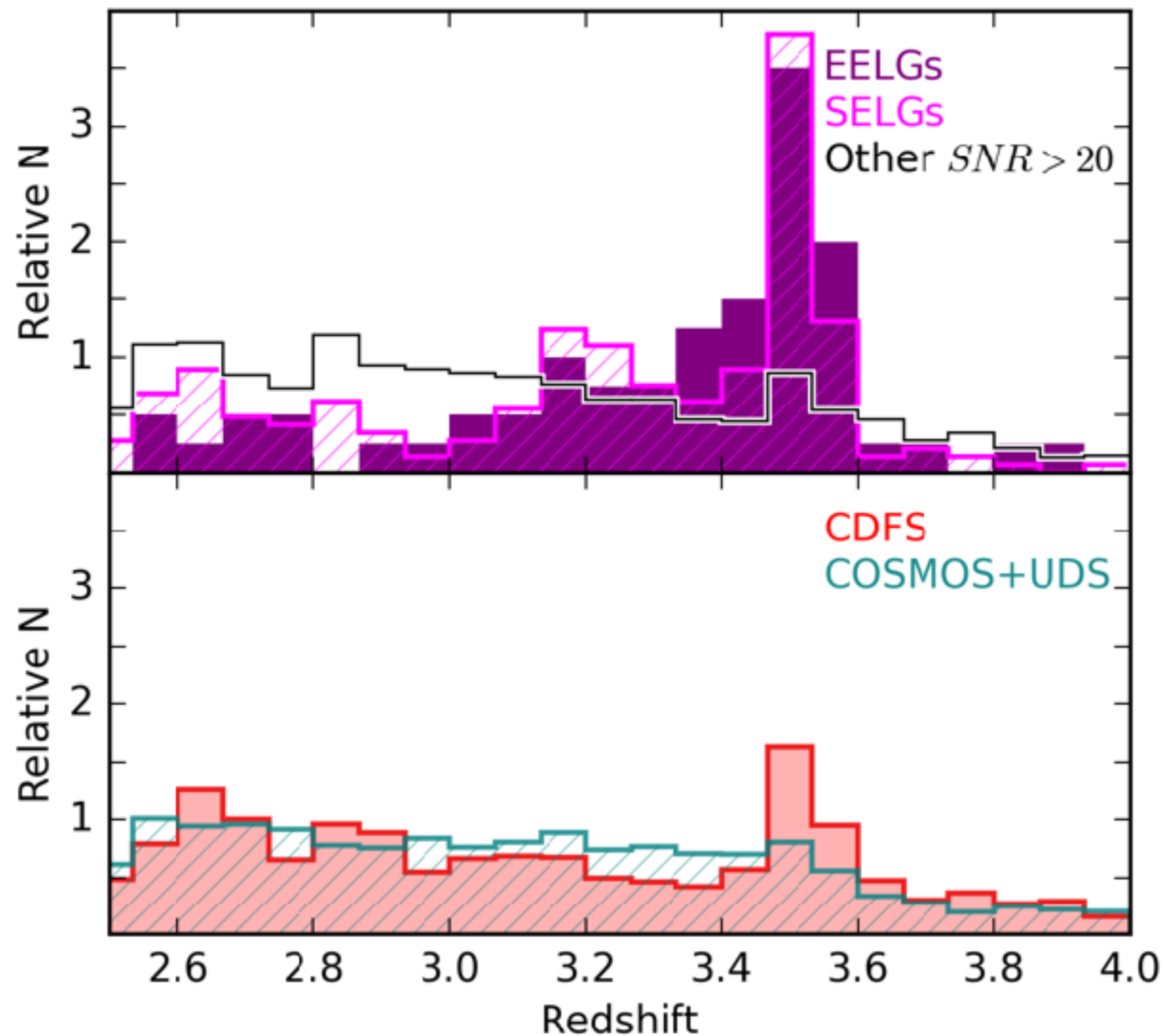


# Extreme Emission Line Galaxies

# Emission Lines

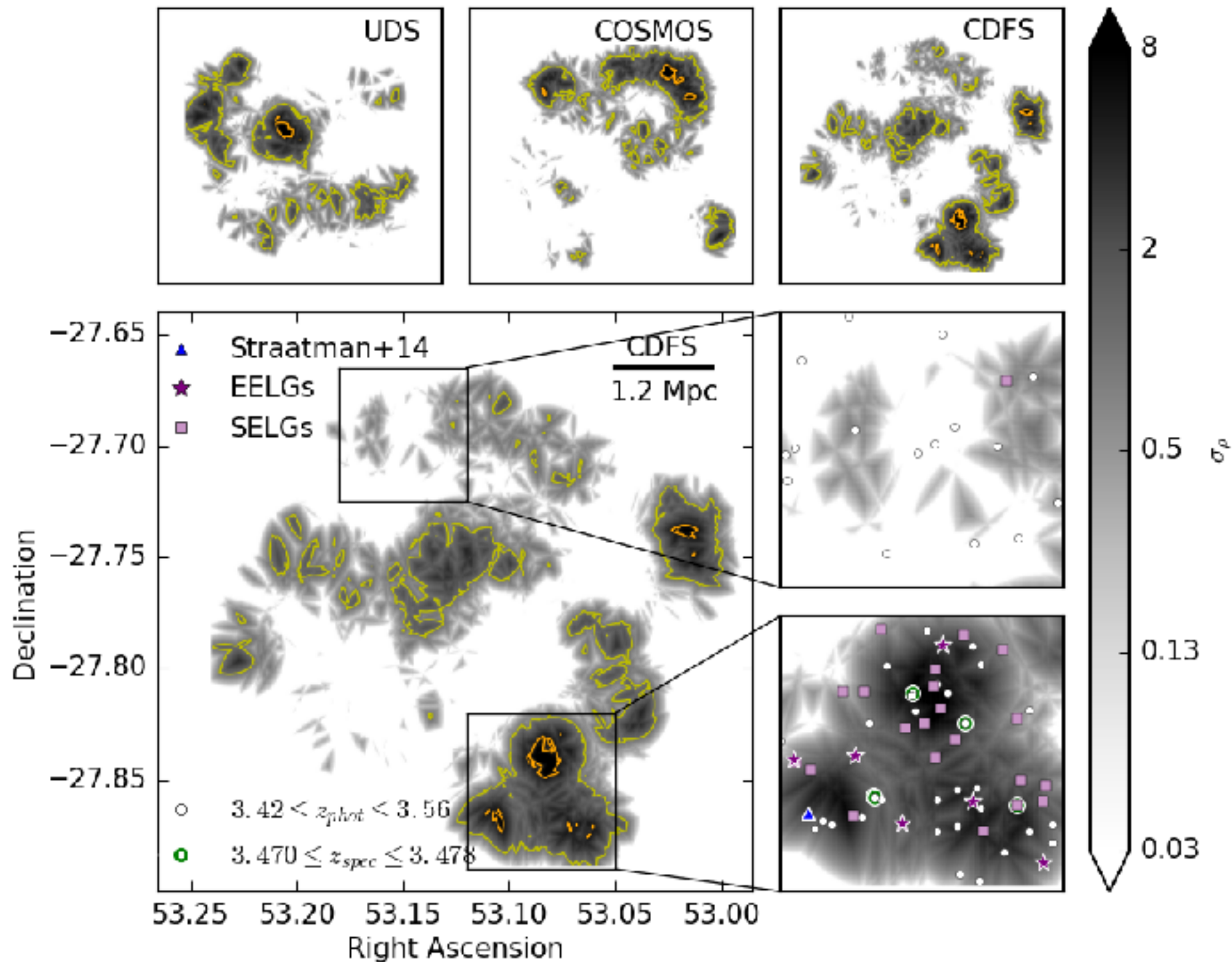


# Excessive Galaxies at $z \sim 3.5$



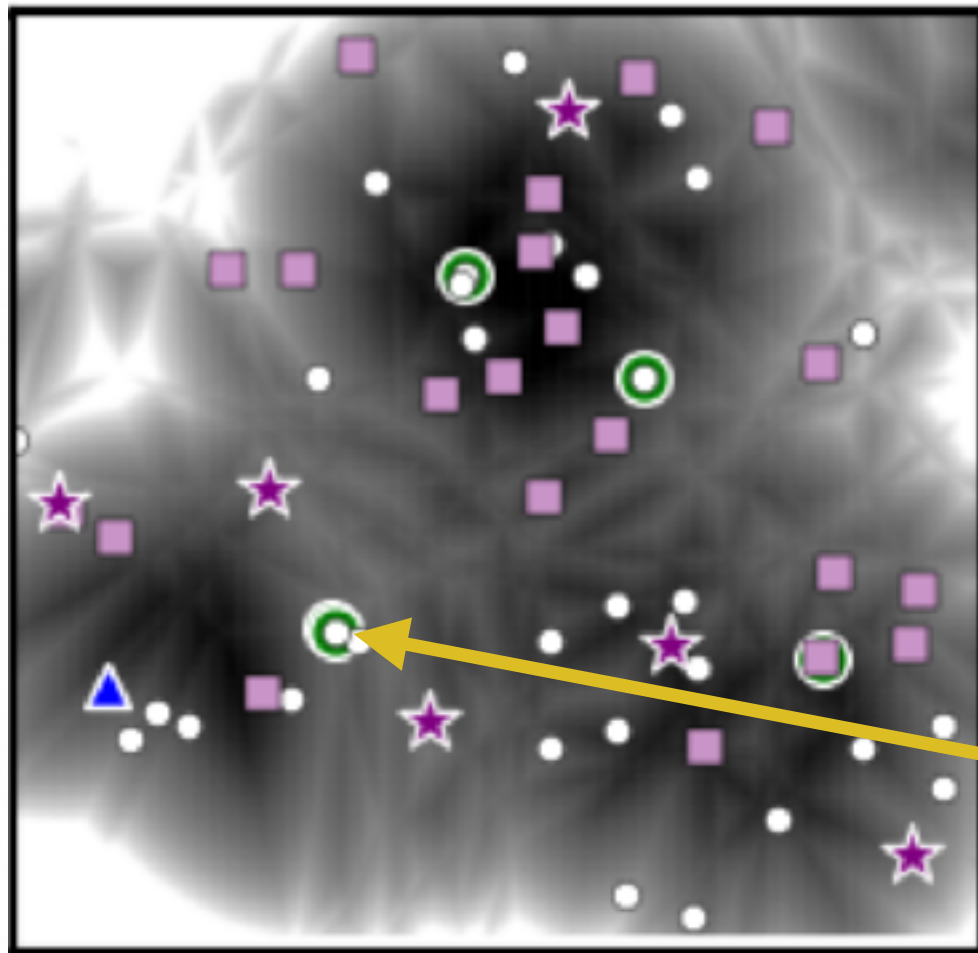


# Galaxy Overdensity

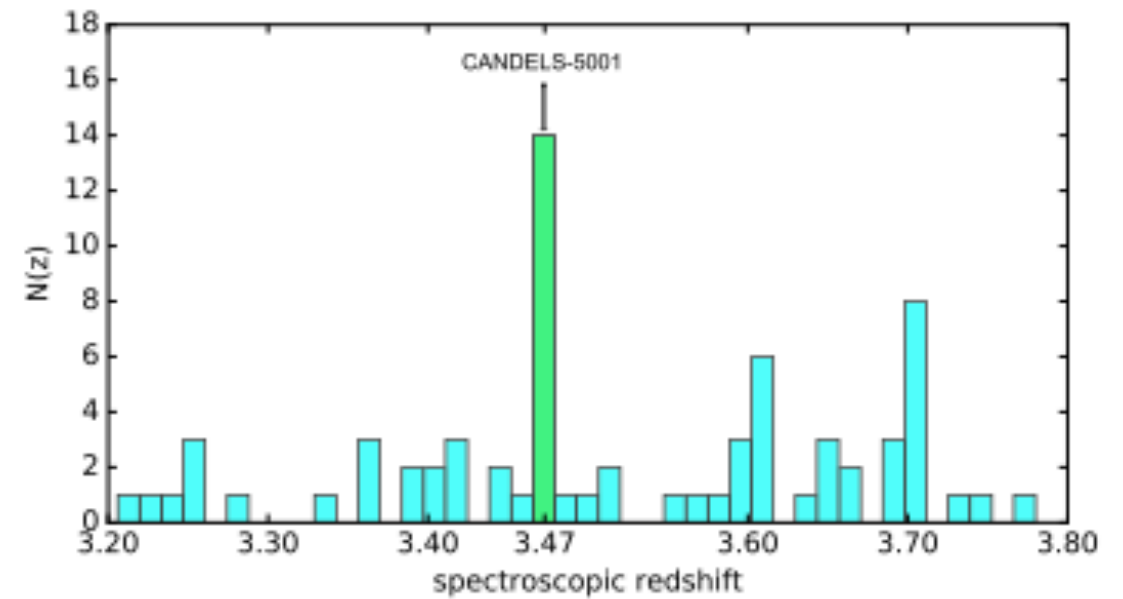


Forrest+2017

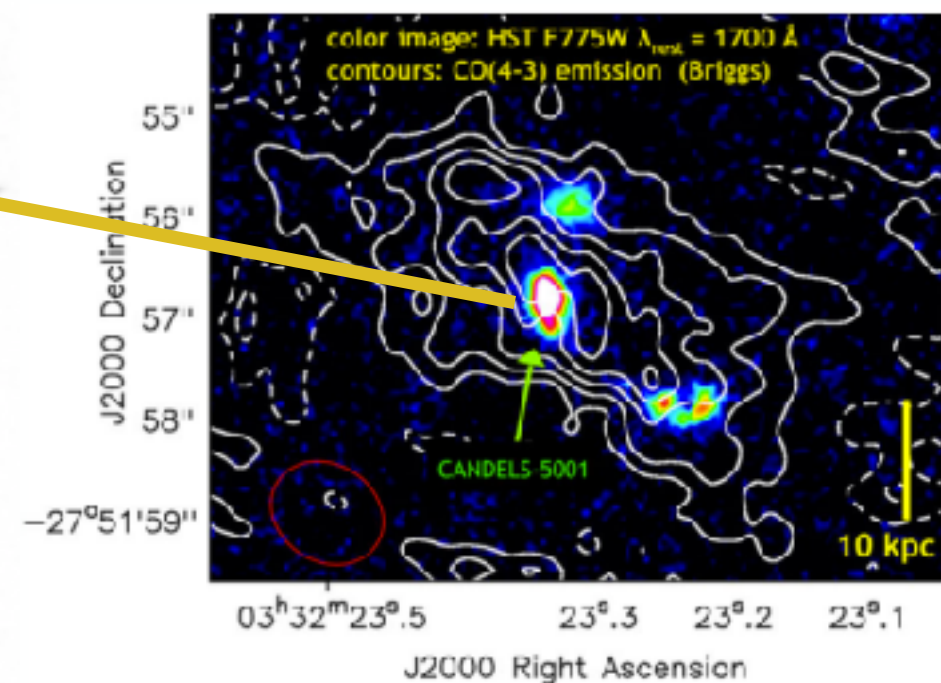
# Structure in CDFS at $z \sim 3.5$



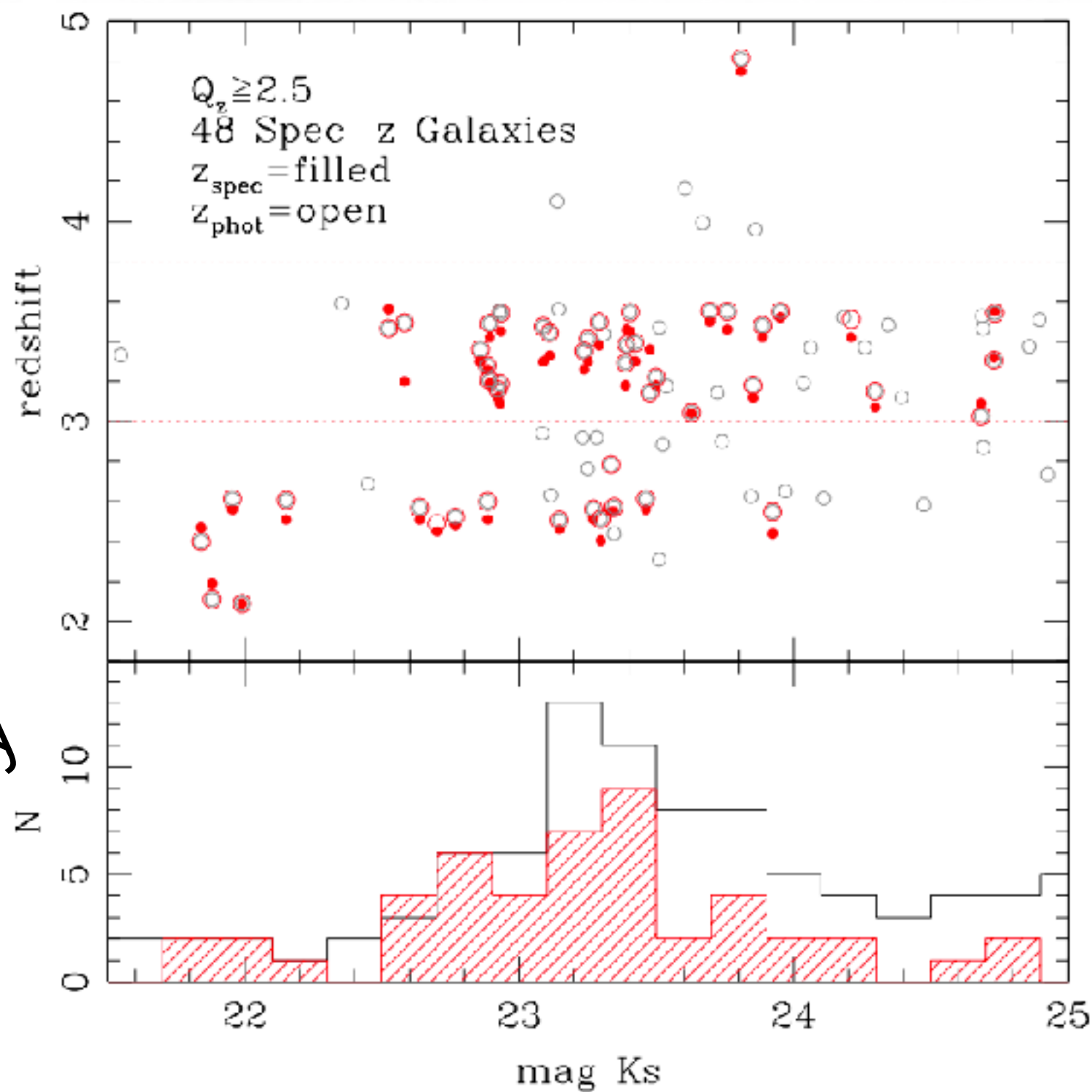
Forrest+17



Ginolfi+17



# Follow-Up: MOSEL

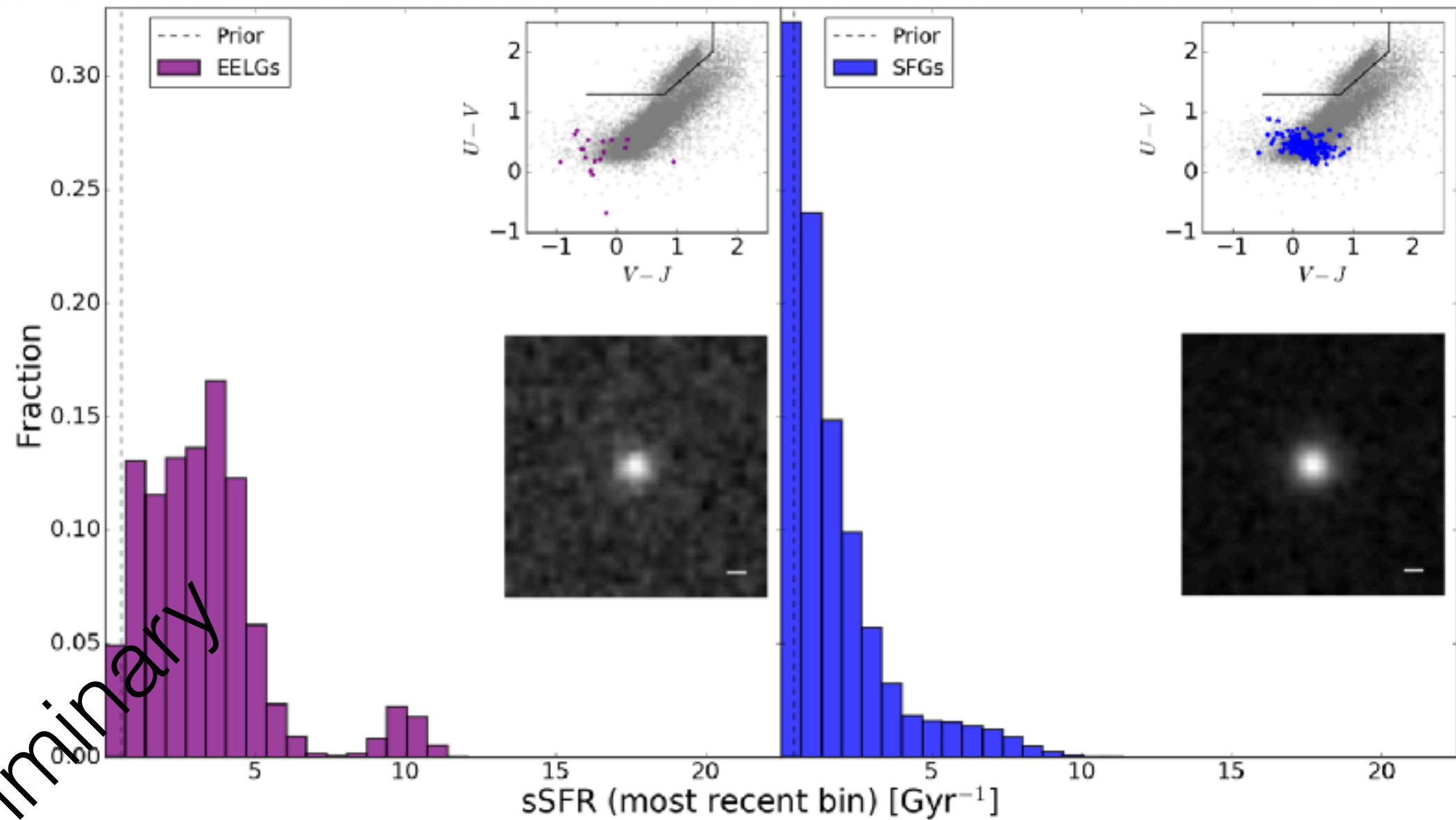


Tran, B.F.+, in prep

Preliminary

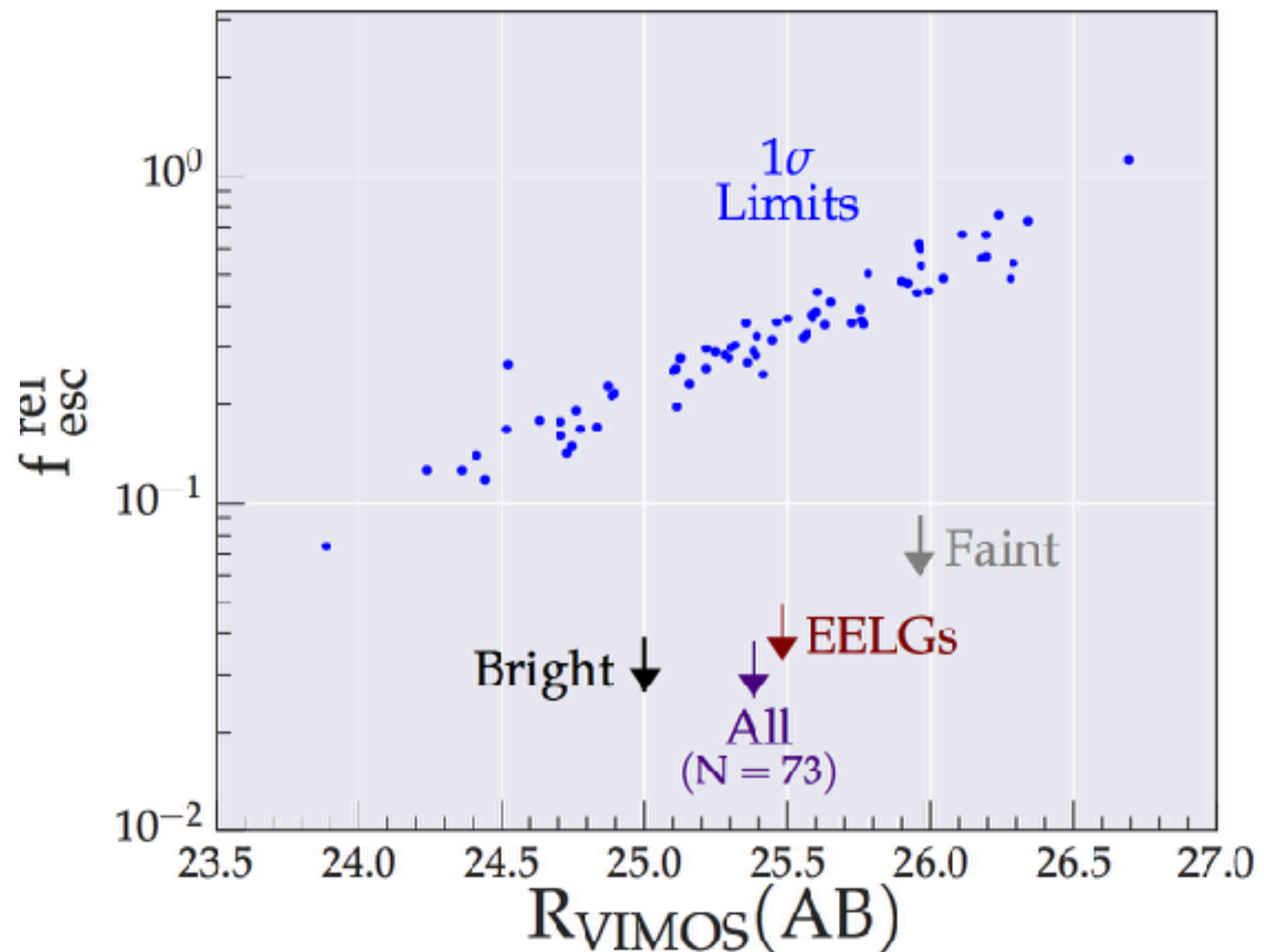
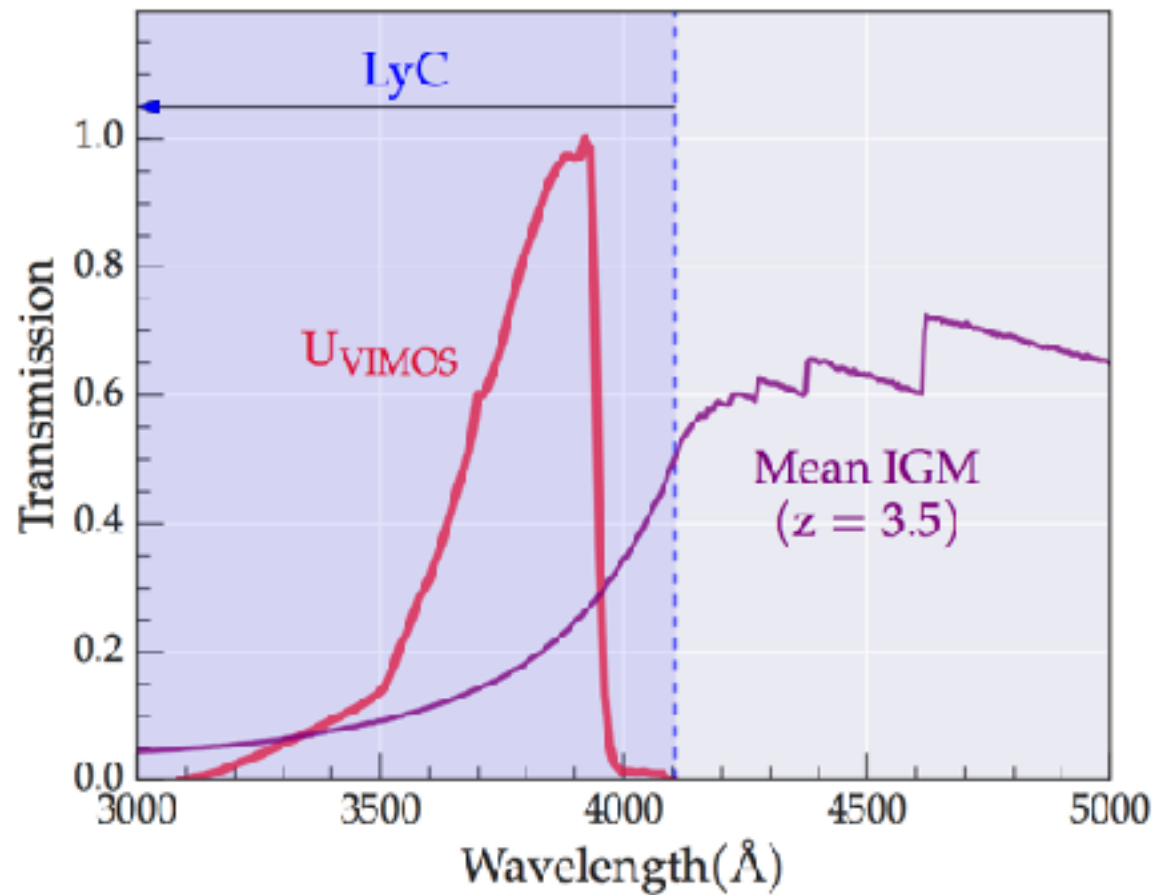


# Follow-Up: Prospector



Preliminary

# Follow-Up: Escape Fractions



Naidu, B.F.+, submitted

Preliminary

# Conclusions

- The average galaxy in the process of shutting off star formation has recently undergone a morphological change, consistent with mechanisms such as morphological quenching.
- These galaxies have become more common from  $z=4$  to  $z=1$ , in tandem with the number density of quenched galaxies.
- Galaxies with large amounts of nebular emission are increasingly common at high redshift.
  - \* The most extreme of these galaxies are likely undergoing their initial bursts of star formation.
  - \* Similar galaxies at higher redshifts will need larger escape fractions to contribute significantly to cosmic reionization.

