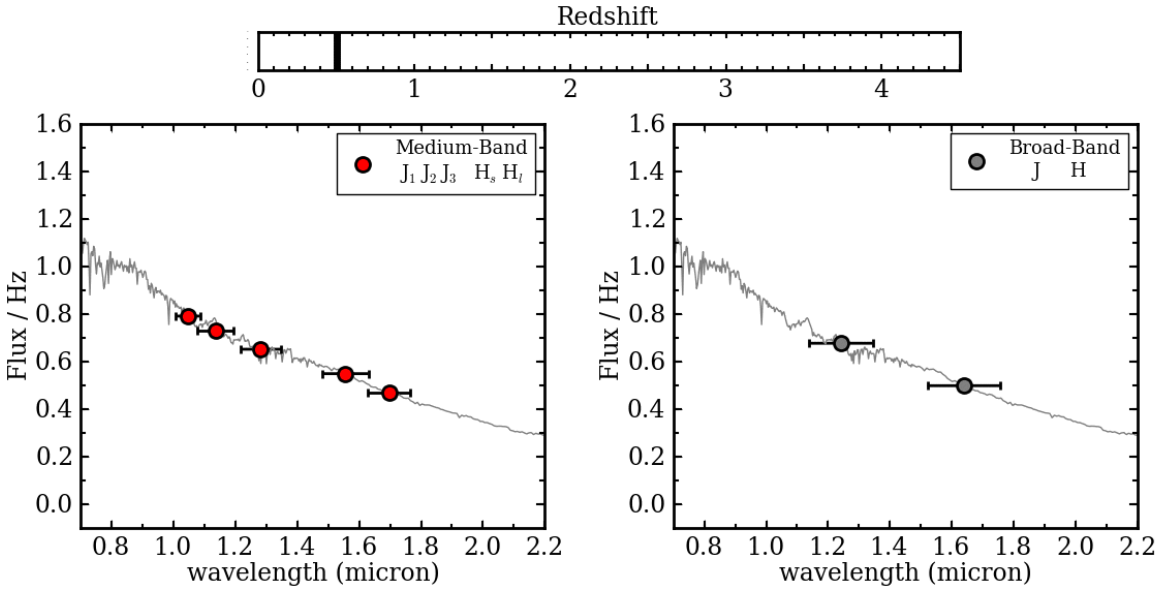
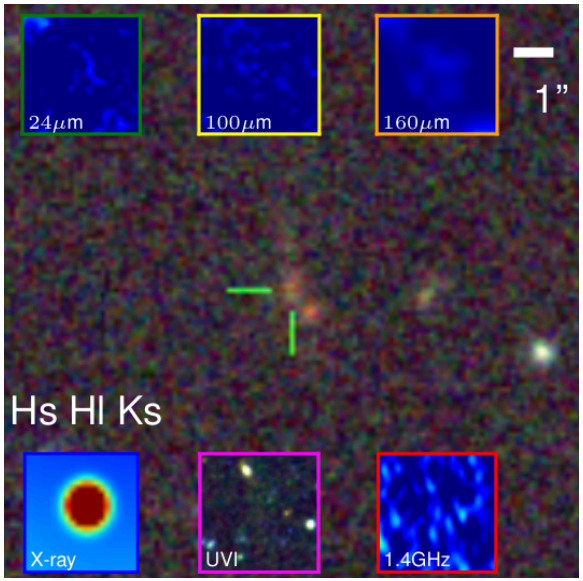




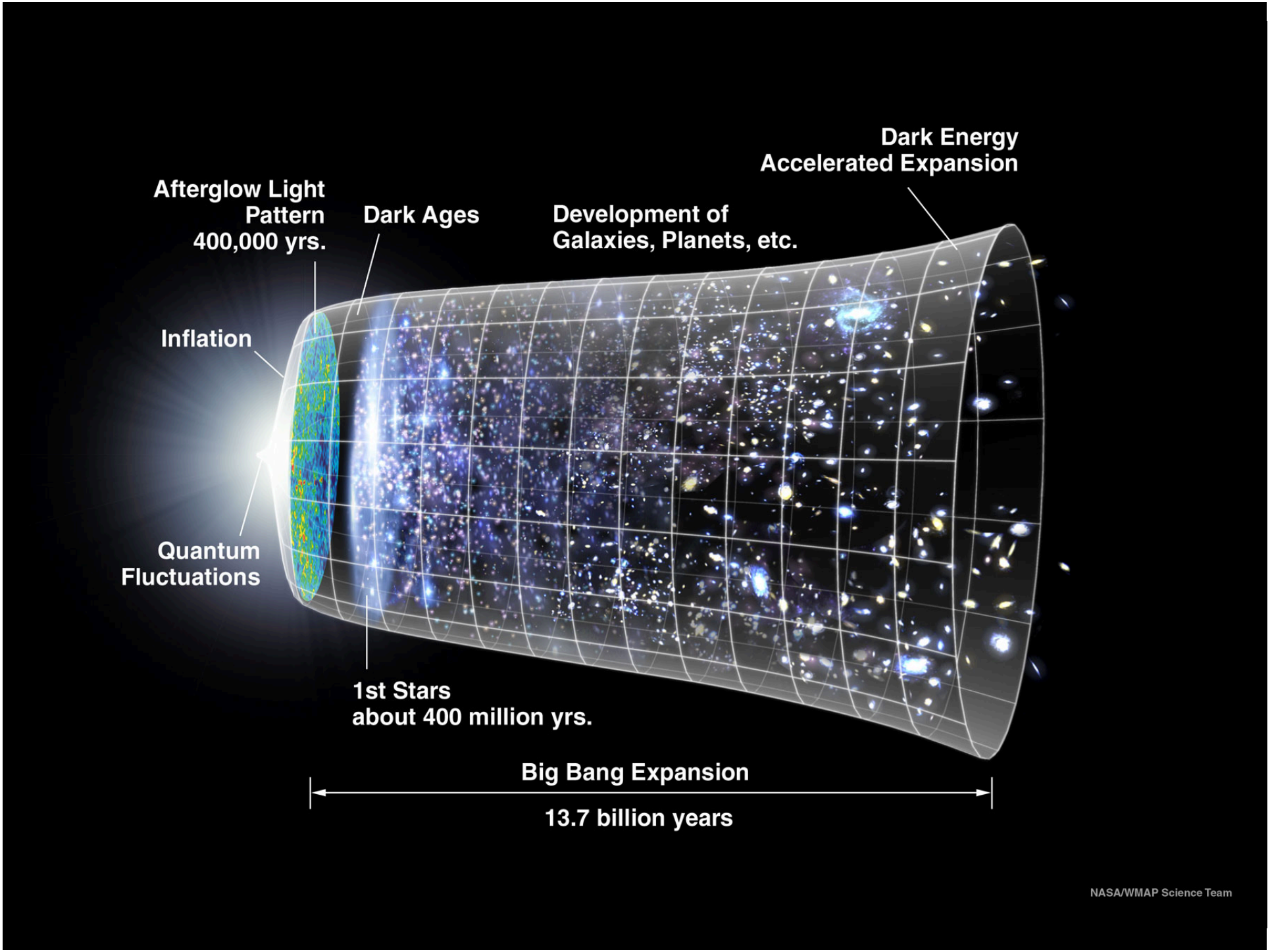
The ZFOURGE survey

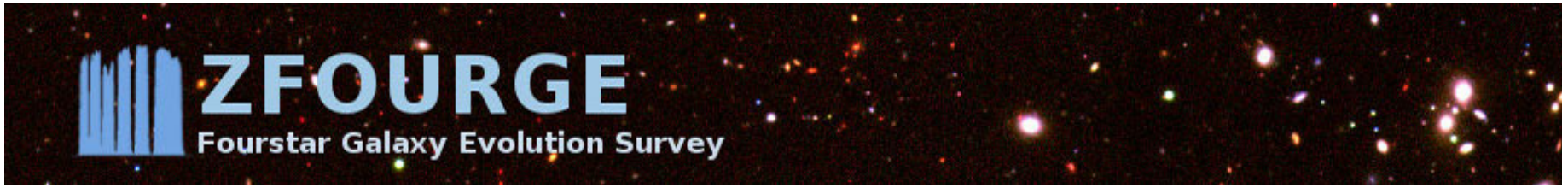
Lee Spitler

Australian Government
Department of Industry and Science

AAO

MACQUARIE University
SYDNEY·AUSTRALIA


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team



Australian Government Department of Industry | AAO

MACQUARIE University SYDNEY·AUSTRALIA

CARNEGIE INSTITUTION FOR SCIENCE

Sterrewacht Leiden

	Rebecca Allen	Swinburne	Casey Papovich	TAMU	
	Michael Cowley	Macquarie	Eric Persson	Carnegie	
	Karl Glazebrook	Swinburne	Ryan Quadri	TAMU	
	Glenn Kacprzak	Swinburne	Glen Rees	Macquarie/CASS	
	Nancy Kawinwanichakij	TAMU	Lee Spitler	Macquarie/AAO	Data lead
	Daniel Kelson	Carnegie	Caroline Straatman	Leiden	Catalog lead
PI	Ivo Labbe	Leiden	Vithal Tilvi	TAMU	
	Patrick McCarthy	Carnegie	Adam Tomczak	TAMU	
	Nicola Mehrtens	TAMU	Kim-Vy Tran	TAMU	
	Andrew Monson	Carnegie	Pieter van Dokkum	Yale	
	Themiya Nanayakkara	Swinburne			

MITCHELL INSTITUTE TEXAS A&M UNIVERSITY

SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

http://zfourge.tamu.edu/

ZFOURGE

Fourstar Galaxy Evolution Survey

What:

~45 nights Magellan/ FourStar near-IR camera

Data:

5 medium-band filters

Ks broadband

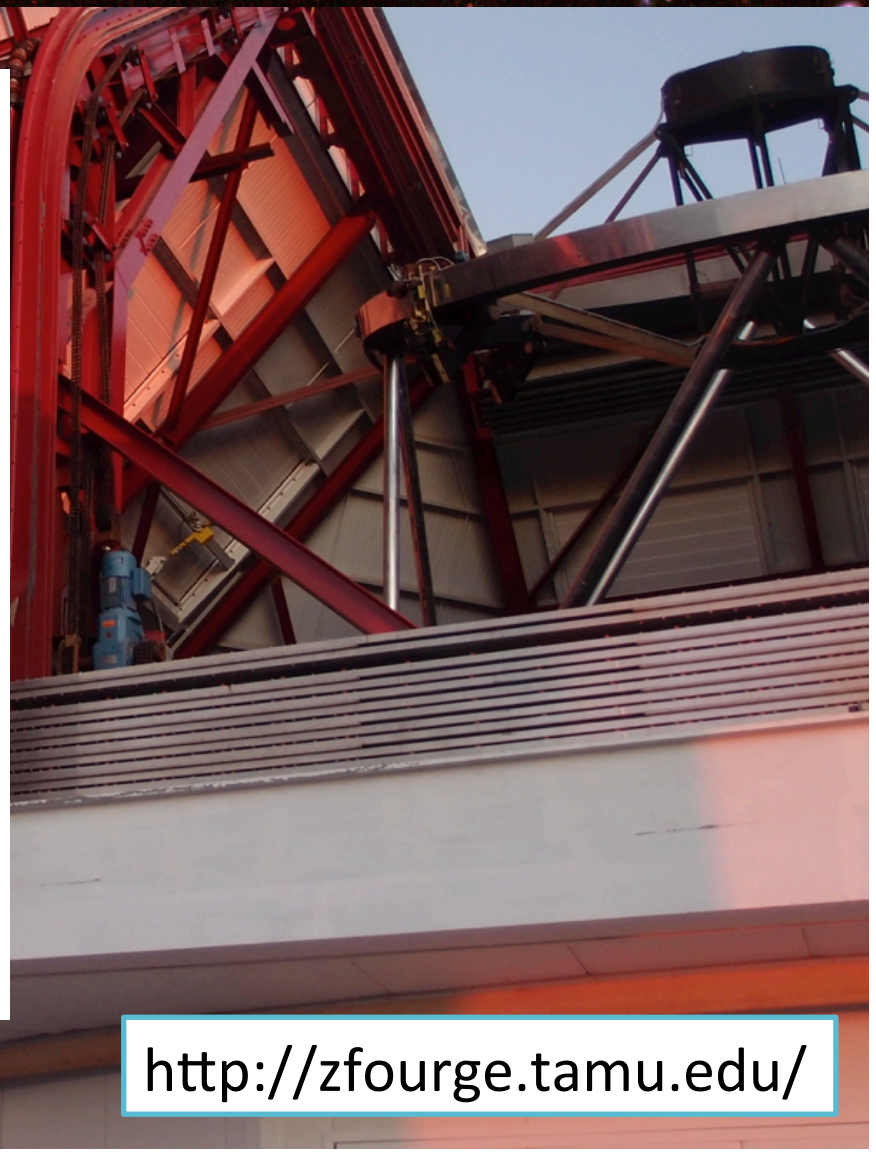
Primary goal:

Accurate photometric redshifts: 1-2% @ z=1.5-4

3 legacy fields:

COSMOS, GOODS-S, UDS

11x11 arcmin^2 each



http://zfourge.tamu.edu/

ZFOURGE
Fourstar Galaxy Evolution Survey

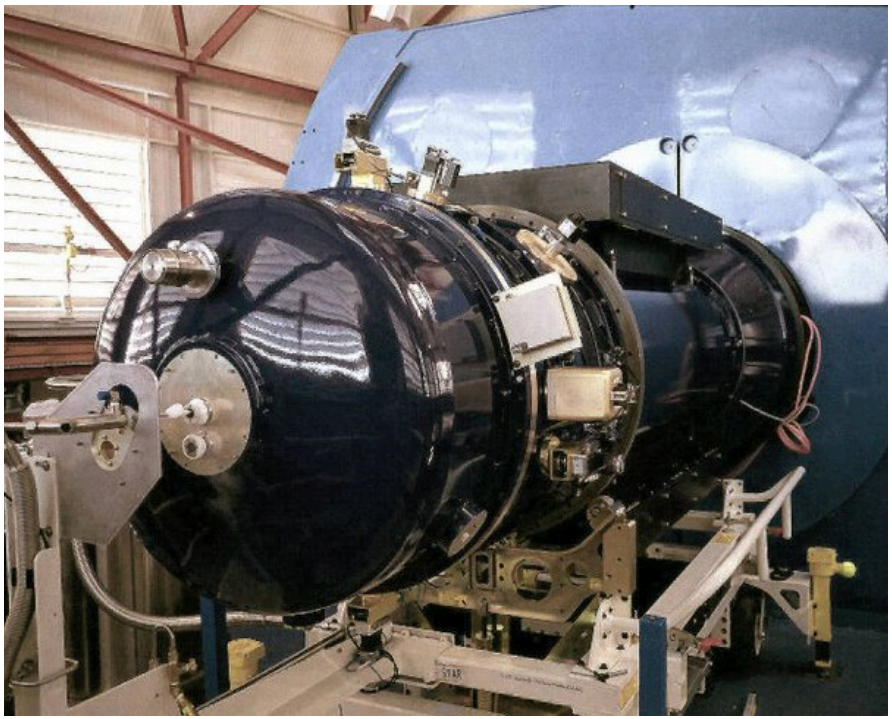
The FourStar camera

0.16” per pixel

11’x11’ FOV

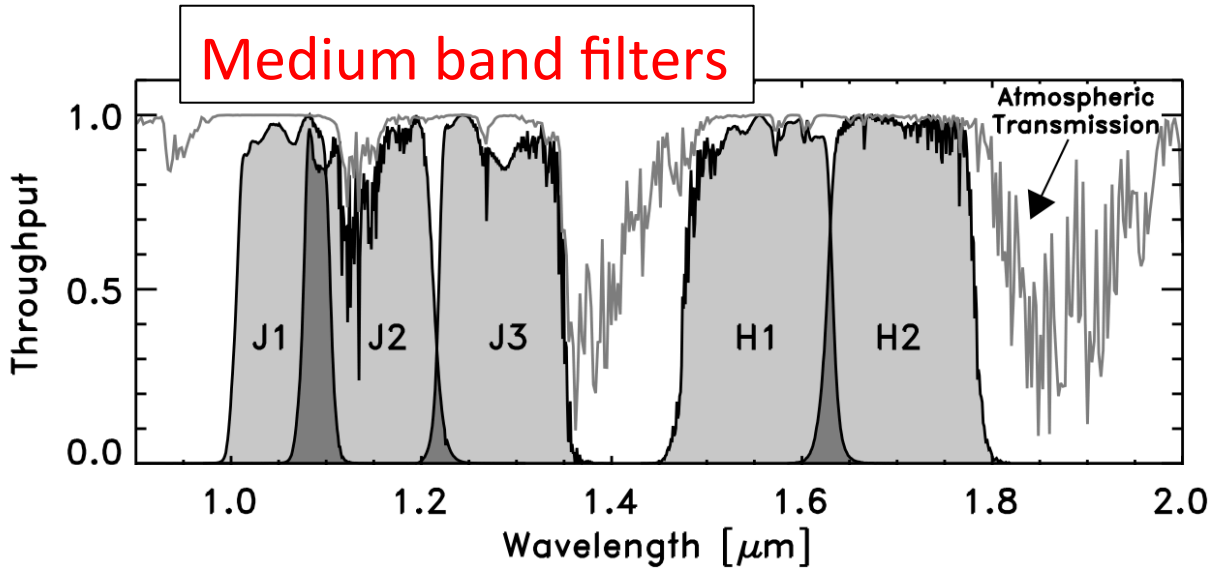
4x2048x2048 Hawaii-2RGs

PI: Eric Persson (Carnegie)



ZFOURGE

Fourstar Galaxy Evolution Survey



45 nights with FourStar/Magellan

5-sigma: J1 J2 J3 to 26 AB, H1 H2 to 25 AB, Ks to 25 AB

1-2% redshifts uncertainties, σ/(z+1), at 1.5 < z < 3.5

COSMOS, UDS, CDFS 11x11 arcmin^2 each

Full public release in 2015

ZFOURGE

Fourstar Galaxy Evolution Survey

TABLE 1
FourStar OBSERVATIONS

Cosmic field	Filter	Total integration time (hrs)	5σ depth (AB mag)
CDFS	J1	6.3	25.6
CDFS	J2	6.5	25.5
CDFS	J3	8.8	25.5
CDFS	Hs	12.2	24.9
CDFS	Hl	5.9	25.0
CDFS	Ks	5.0	24.8
COSMOS	J1	13.9	26.0
COSMOS	J2	16.0	26.0
COSMOS	J3	13.8	25.7
COSMOS	Hs	12.1	25.1
COSMOS	Hl	12.1	24.9
COSMOS	Ks	13.4	25.3
UDS	J1	7.9	25.6
UDS	J2	8.7	25.9
UDS	J3	9.3	25.6
UDS	Hs	11.0	25.1
UDS	Hl	10.4	25.2
UDS	Ks	3.9	24.7

26.5

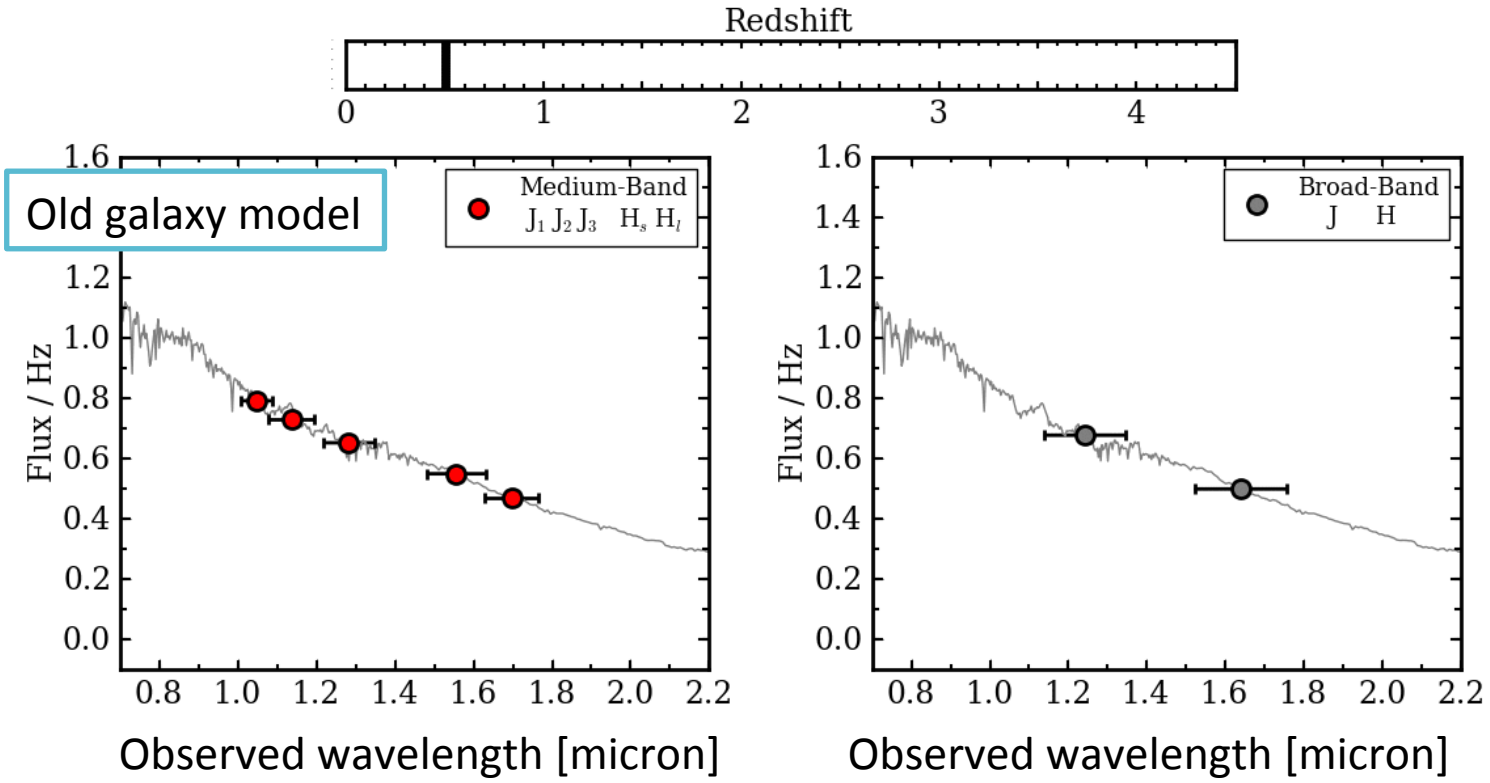
25.5

26.0

Straatman, Spitler, et al. submitted

ZFOURGE

Fourstar Galaxy Evolution Survey



ZFOURGE filters

Traditional filters

Depths

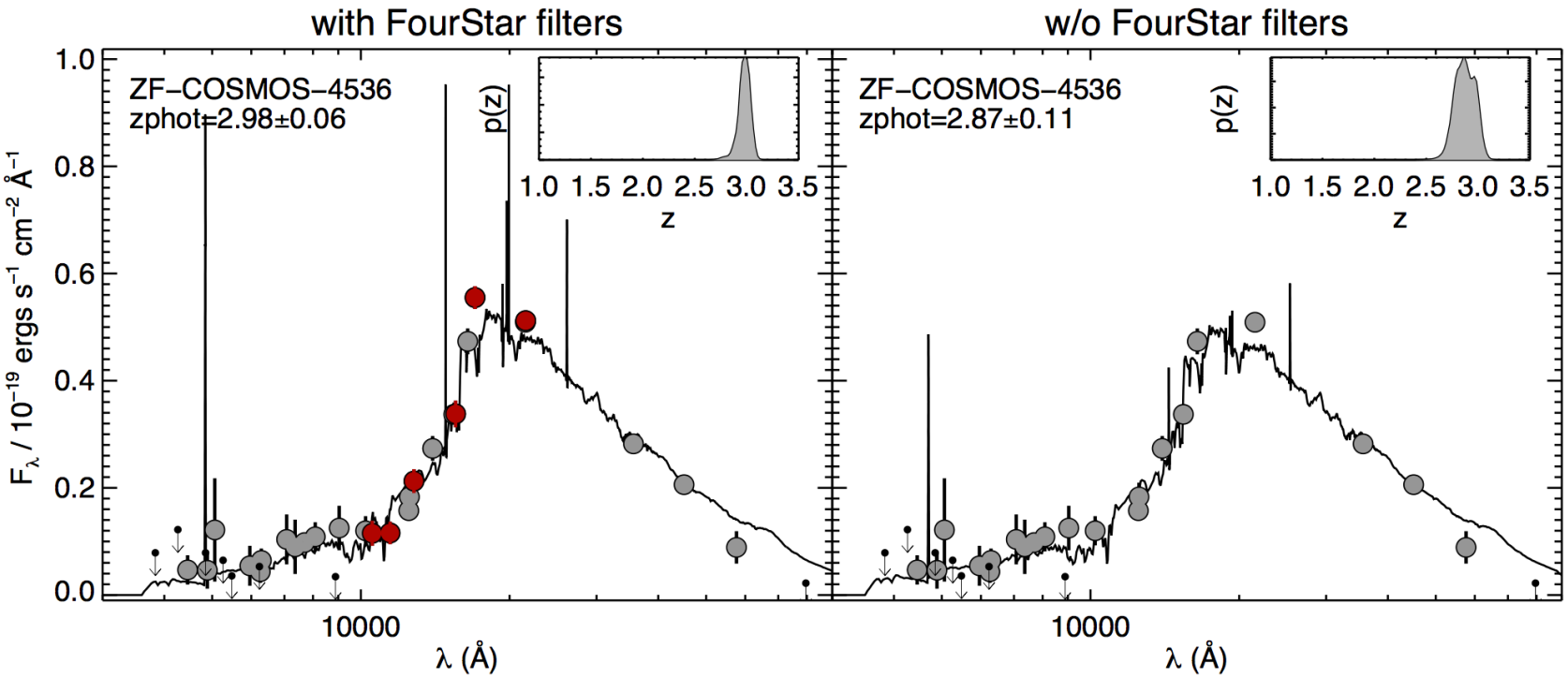
Hs, Hl & Ks ~ 25

J123 ~ 26

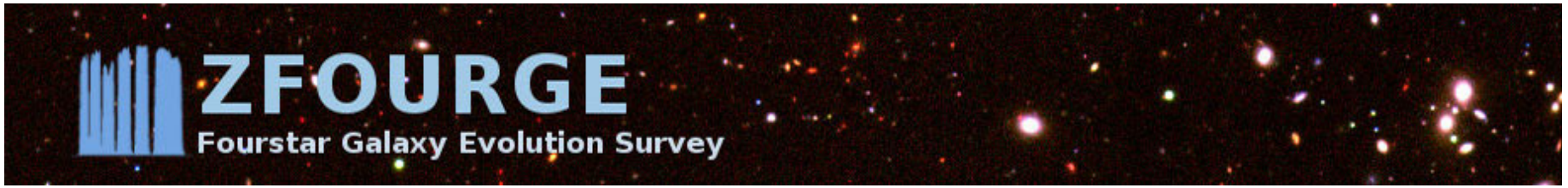
http://zfourge.tamu.edu/

Animation credit: Adam Tomczak

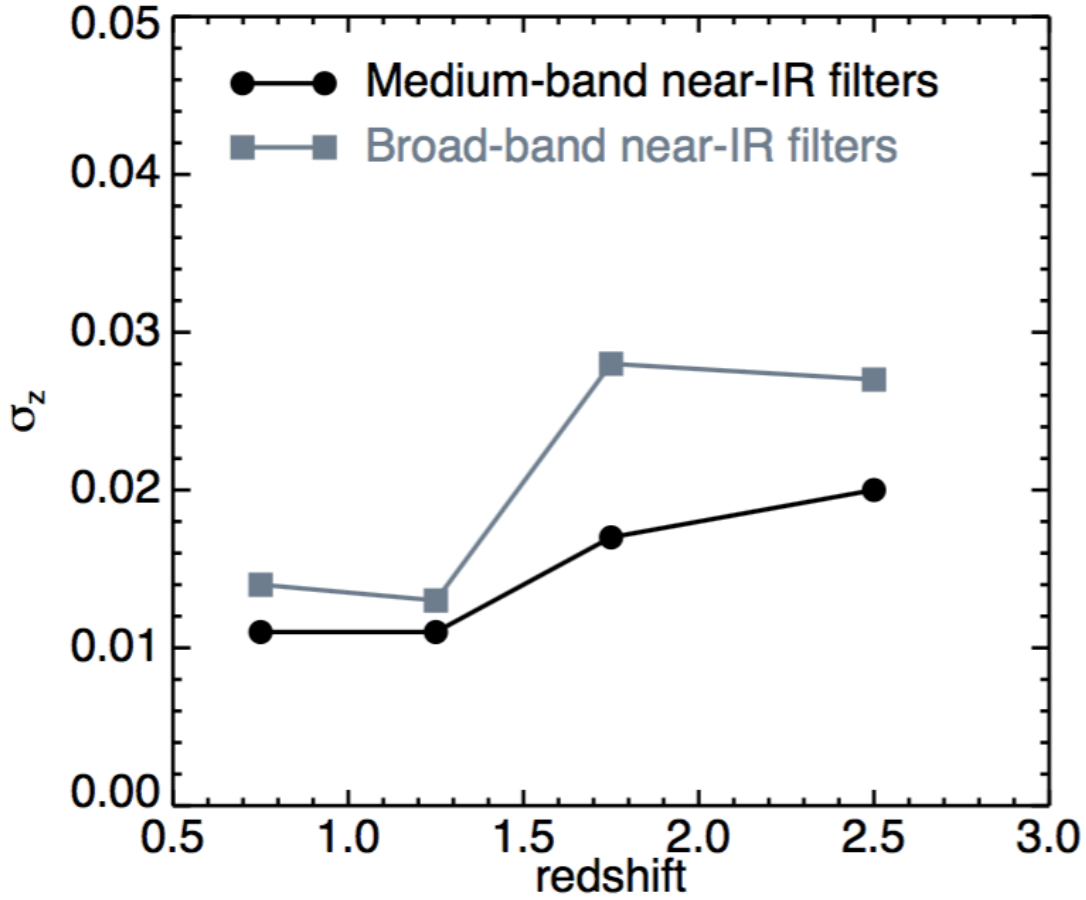
ZFOURGE
Fourstar Galaxy Evolution Survey



Straatman, Spitler, et al. submitted



Scatter in
Delta z / (1 + z)



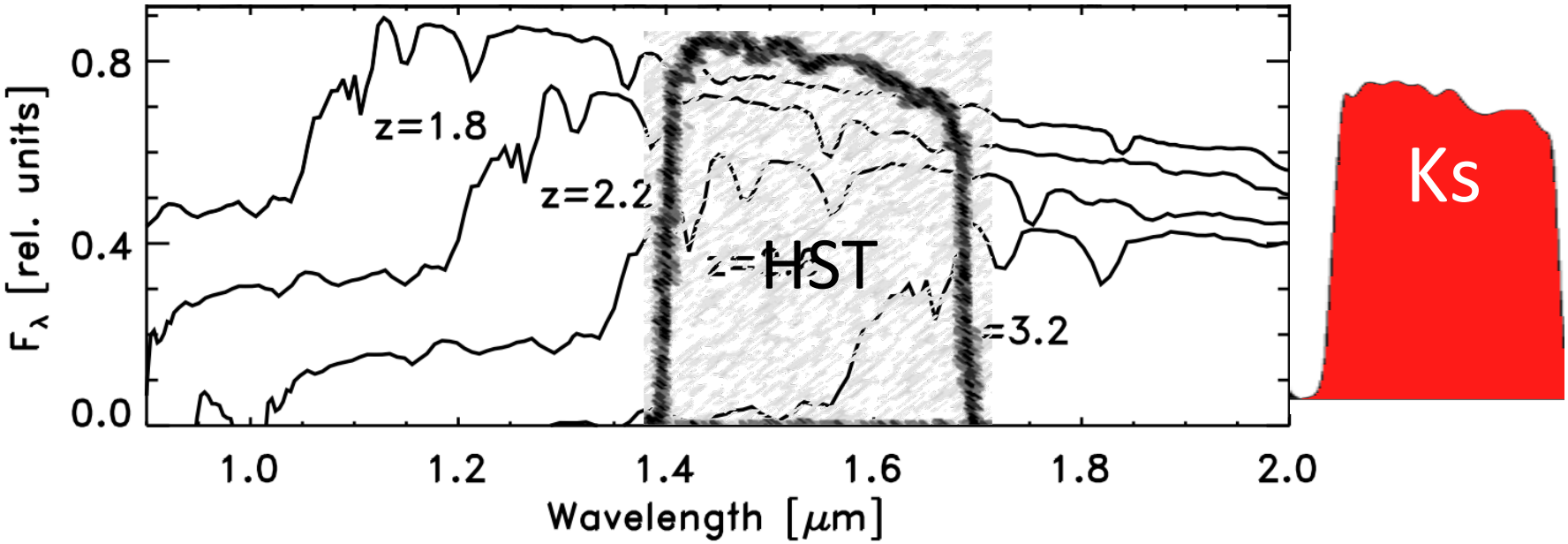
Derived using
galaxy pairs

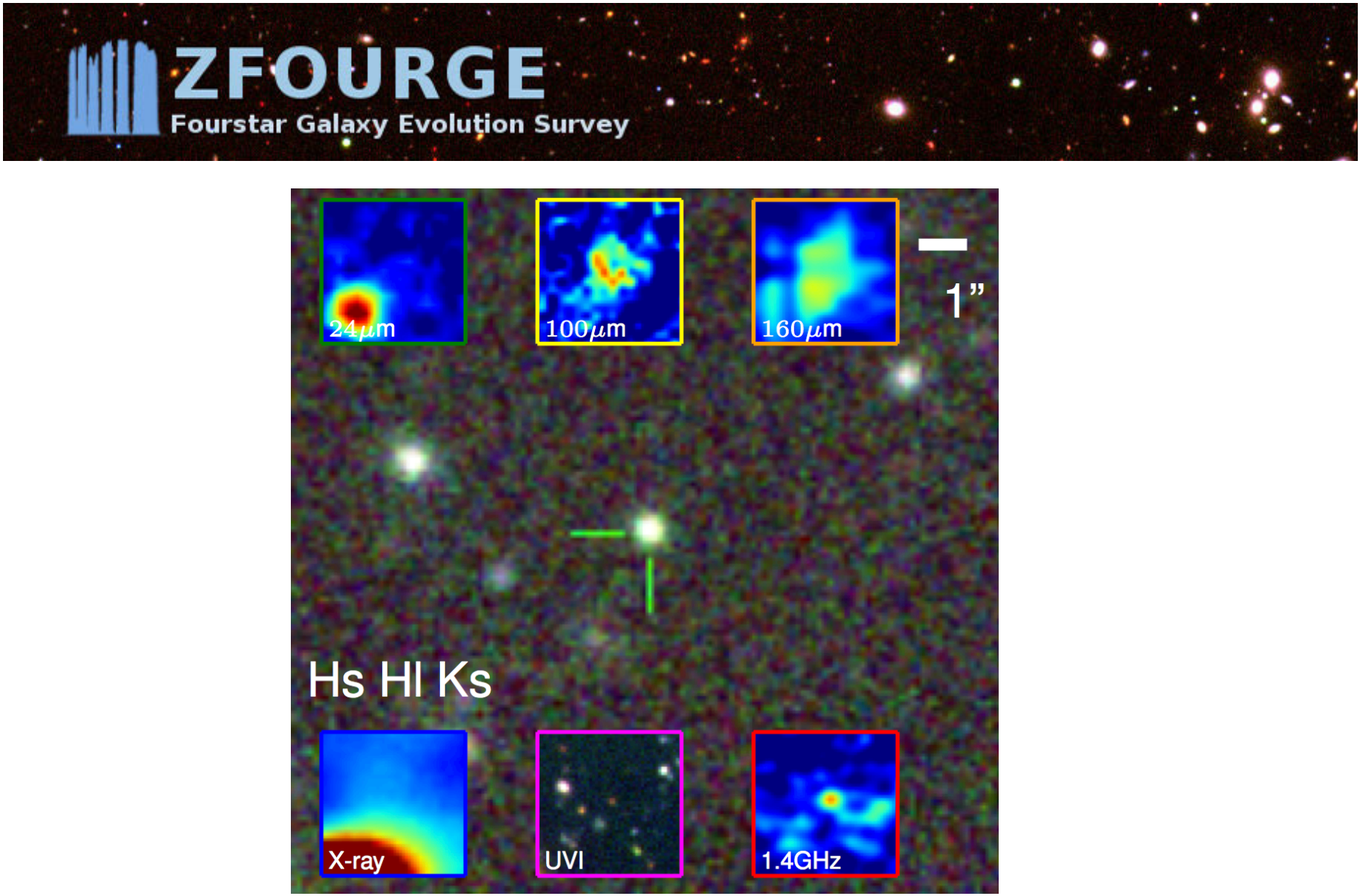
Straatman, Spitler, et al. submitted

ZFOURGE
Fourstar Galaxy Evolution Survey

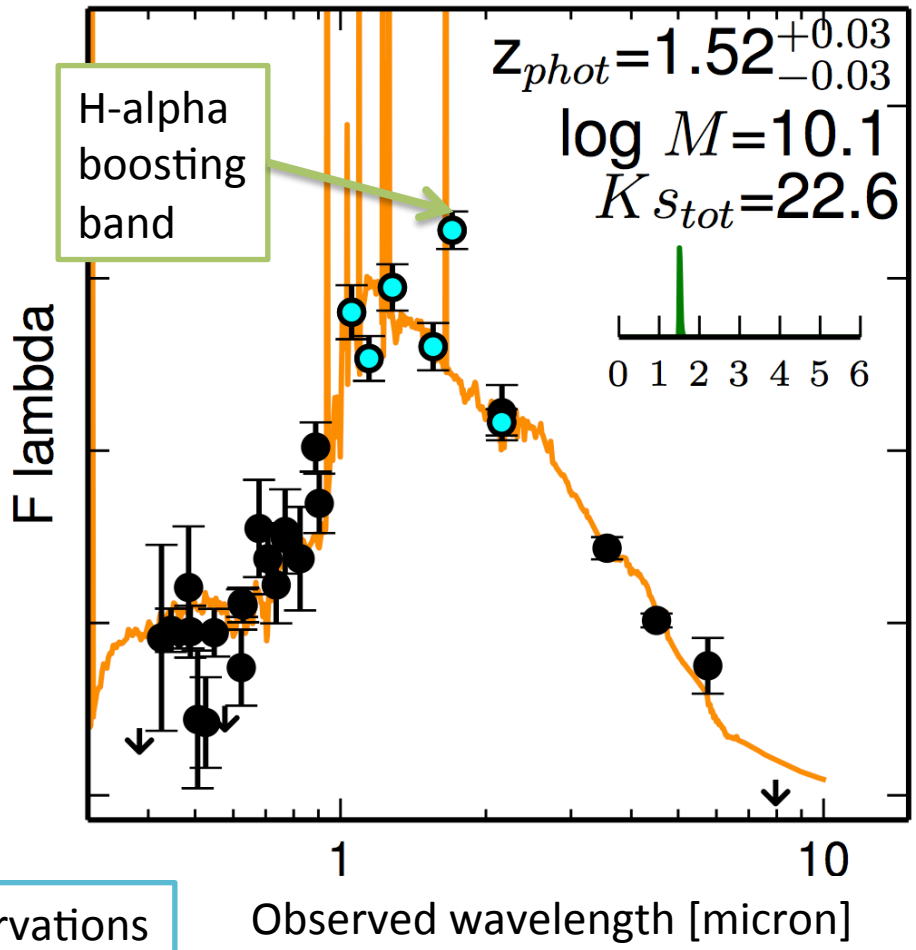
- Identify/select galaxies using evolved star light
  - Stellar mass-limited

    select galaxies with Ks-band: access older stars




ZFOURGE
Fourstar Galaxy Evolution Survey
24μm
100μm
160μm
1”
Hs Hl Ks
X-ray
UVI
1.4GHz

ZFOURGE
Fourstar Galaxy Evolution Survey

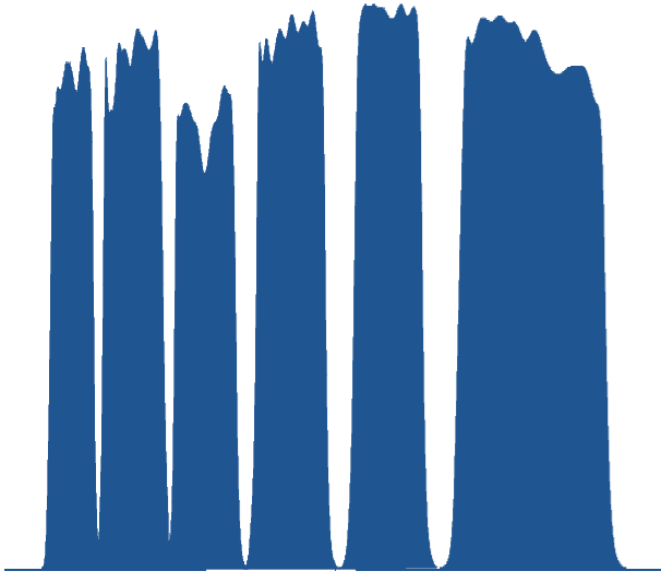


EAZY photo-z best-fit template

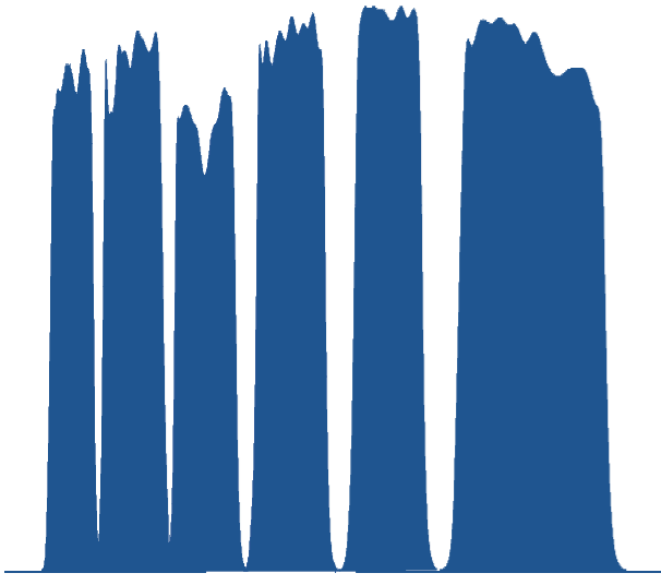
Cyan: ZFOURGE observations
Black: other observations

Highlights from ZFOURGE

Demonstrating the value of
a high-quality galaxy catalog

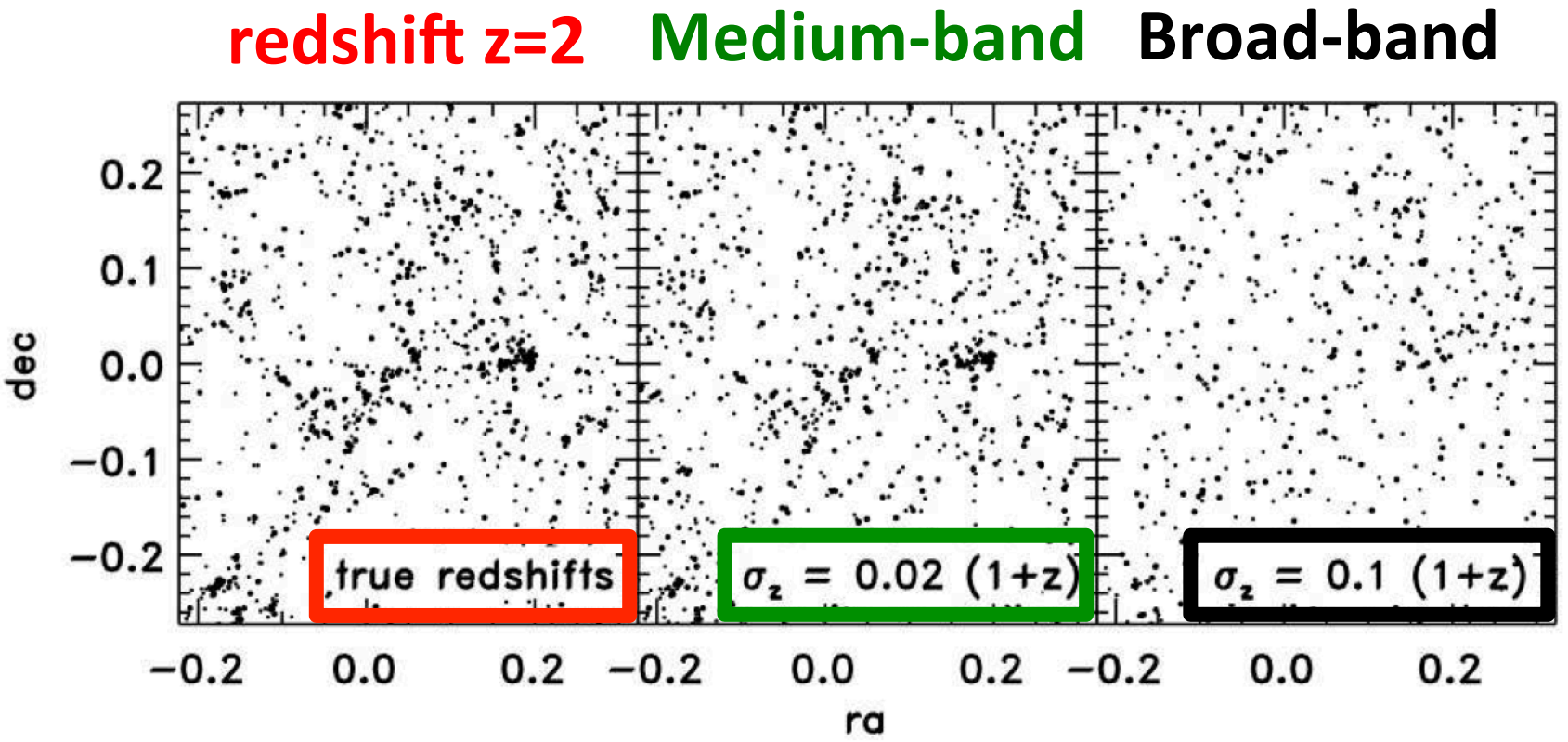


High-redshift cluster environments



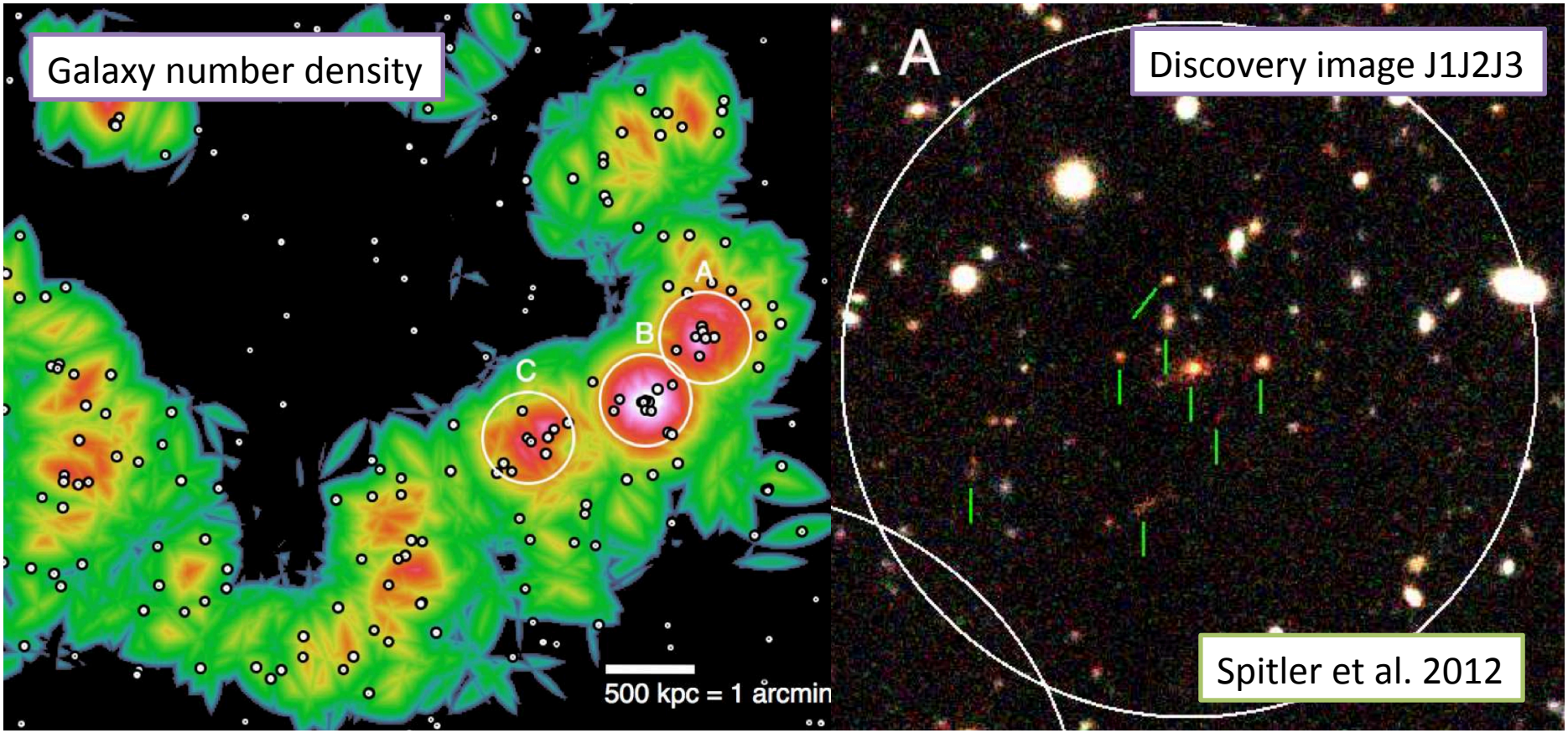
First results from ZFOURGE: Discovery of a candidate cluster at z=2.2 in COSMOS
Spitler et al. 2012
Keck/MOSFIRE Spectroscopic Confirmation of a Virgo-like cluster ancestor at z=2.095
Yuan et al. 2014

Galaxy environment with ZFOURGE



mock $H_{AB} < 25$ galaxies from the Millennium Simulation (Kitzbichler & White 2007)

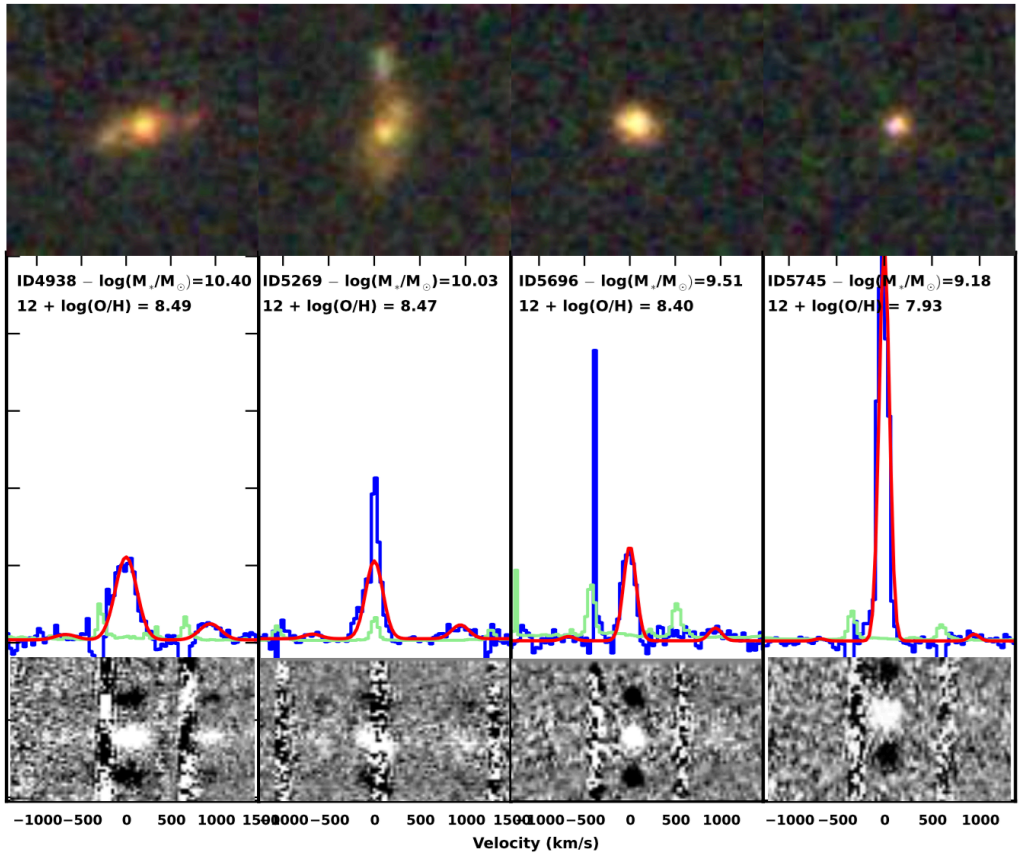
Environmental trends: detailed study of a z=2.09 galaxy cluster

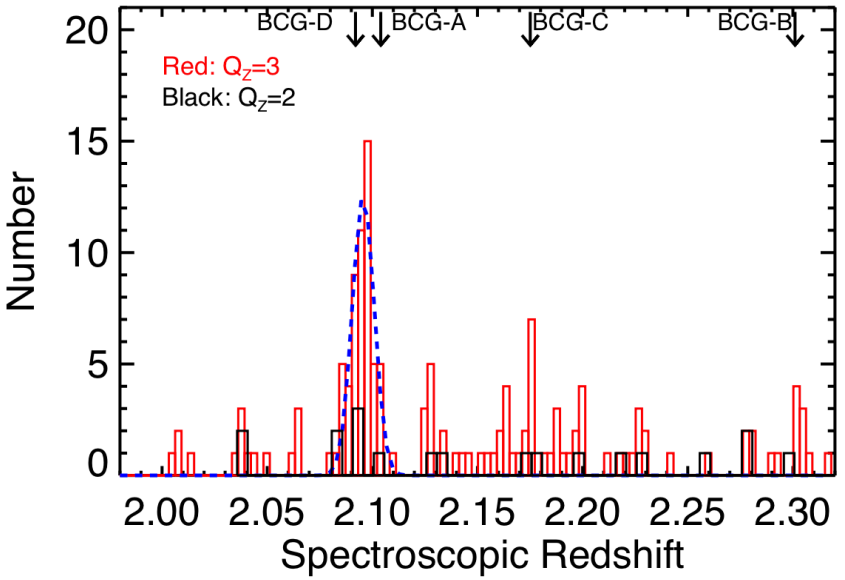


ZFOURGE + MOSFIRE

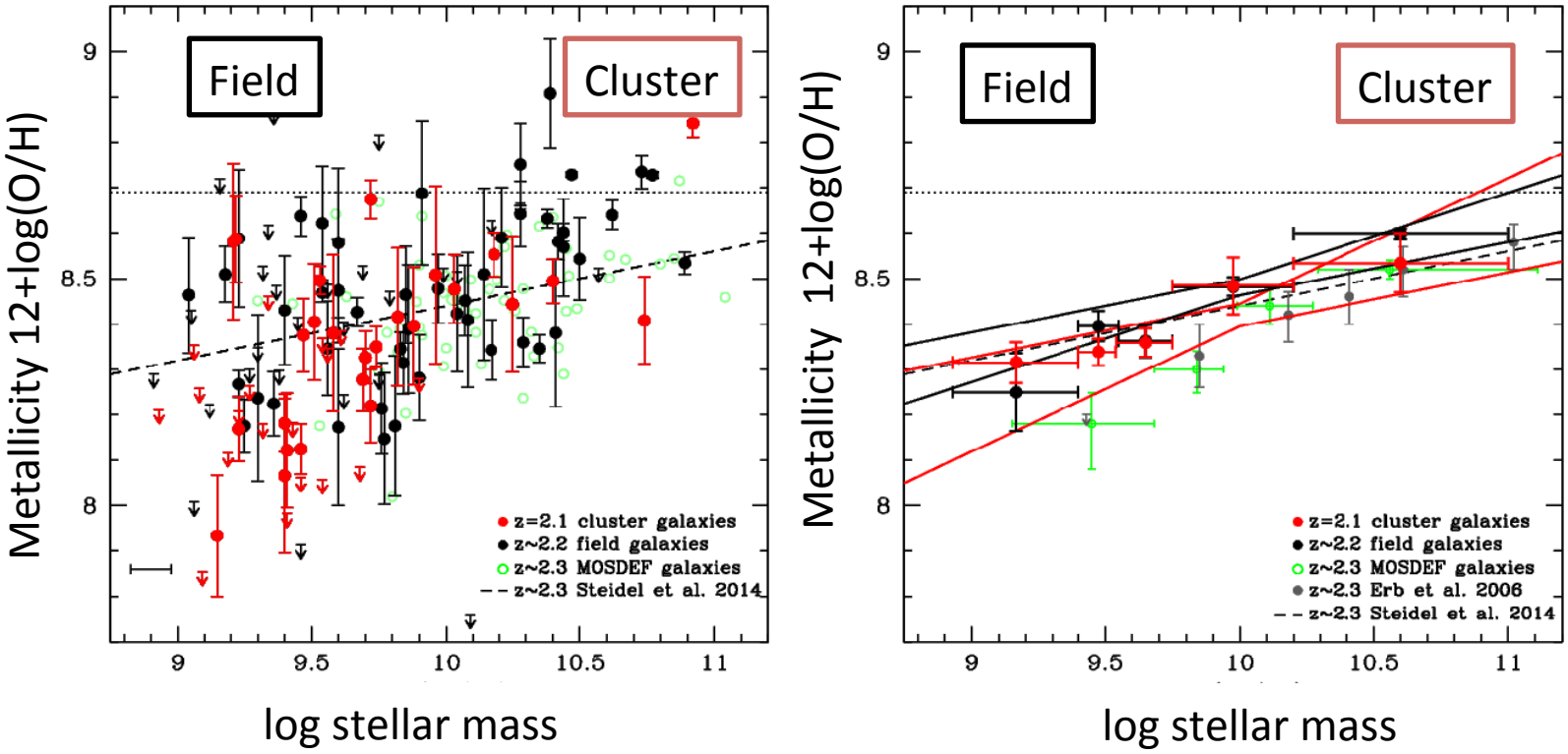
Tran, Glazebrook, Kewley
Yuan, Nanayakkara, Kacprzak
Spitler, Labbé, Straatman, Tomczak

57 confirmed cluster galaxies
at z=2.095 (Yuan et al., 2014)





Cluster/field mass-metallicity relation

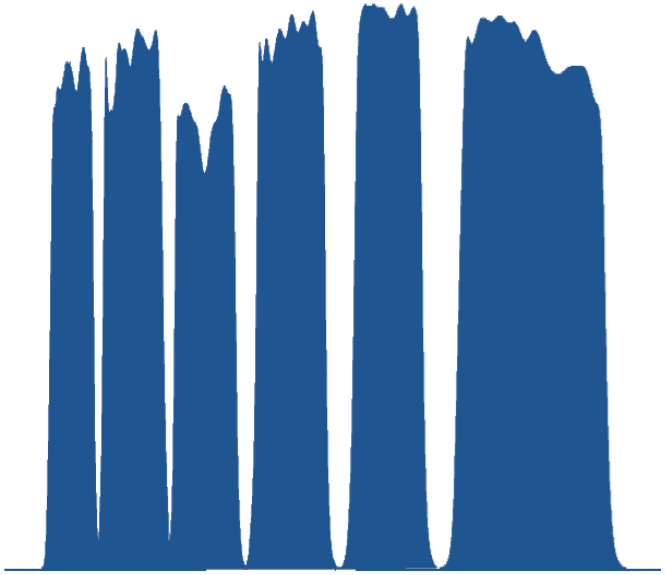


Kacprzak et a., 2015

A mass-limited census at z=3-4

Exploring the z=3-4 massive galaxy population with ZFOURGE: the prevalence of dusty and quiescent galaxies

Spitler et al. 2014

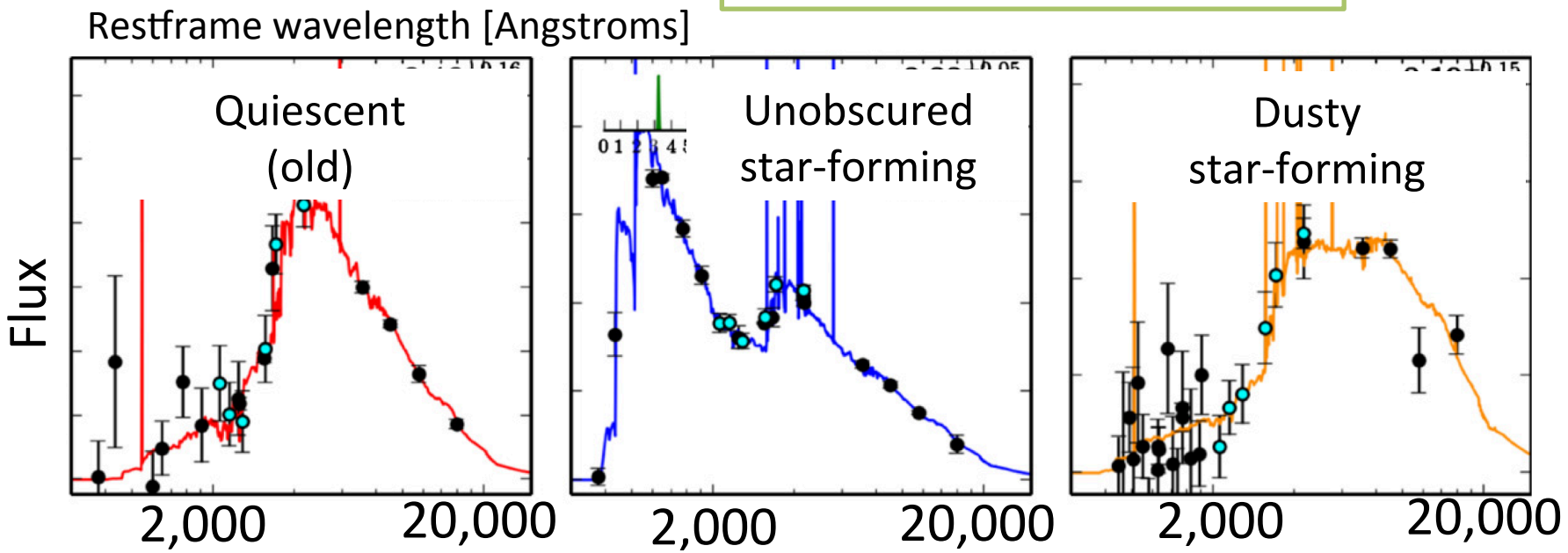


Motivation: high-redshift galaxy observations

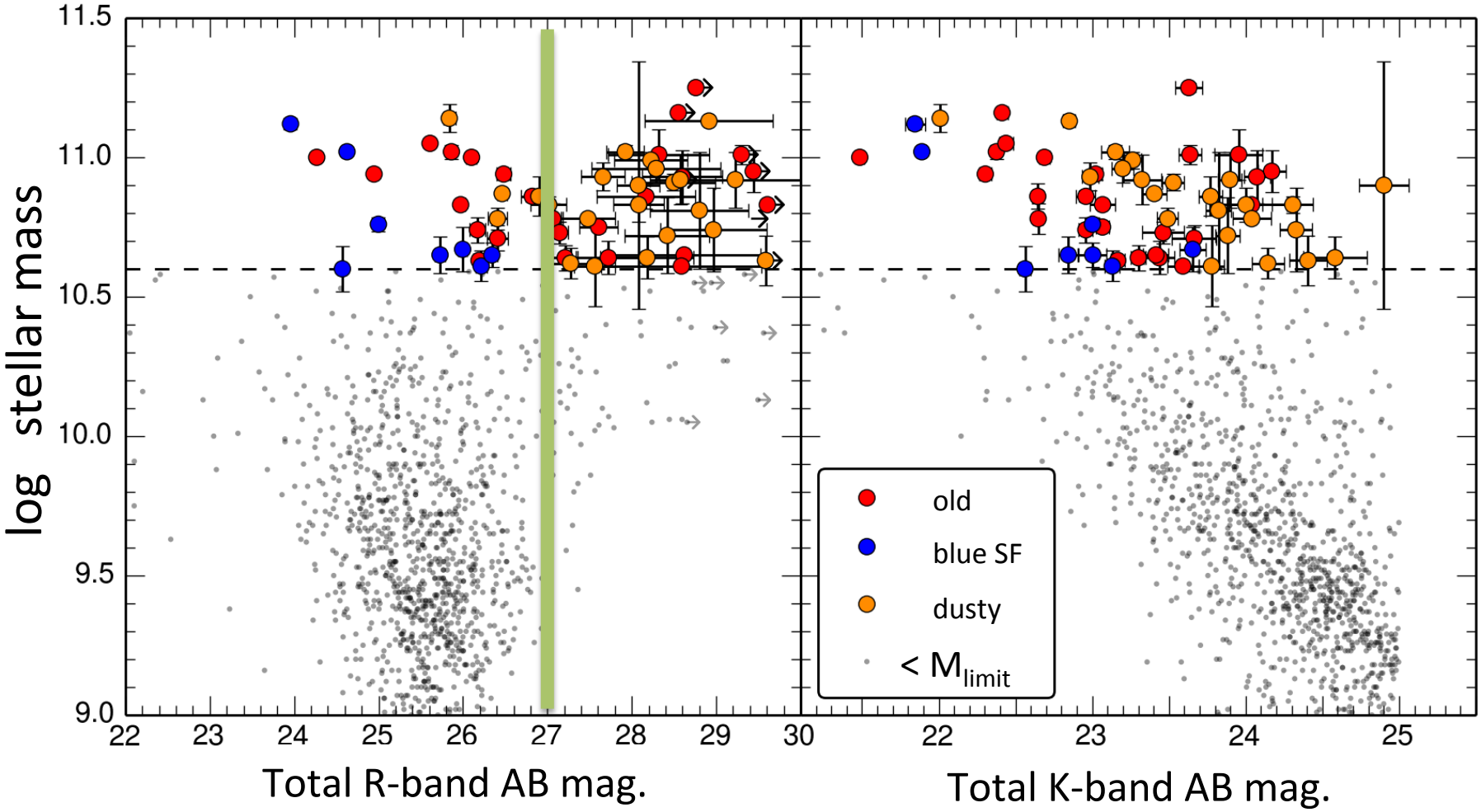
Current record redshift z = 11
~500Million years after Big bang

0 6 10 11.5 12 12.3 12.5 12.7 12.8 12.9 13 13.1 Gyrs
z=0 1 2 3 4 5 6 7 8 9 10 >11 Big bang

Current record for mass-limited sample of typical (L star) galaxies:
Redshifts z = 4
1.5 billion years after Big bang

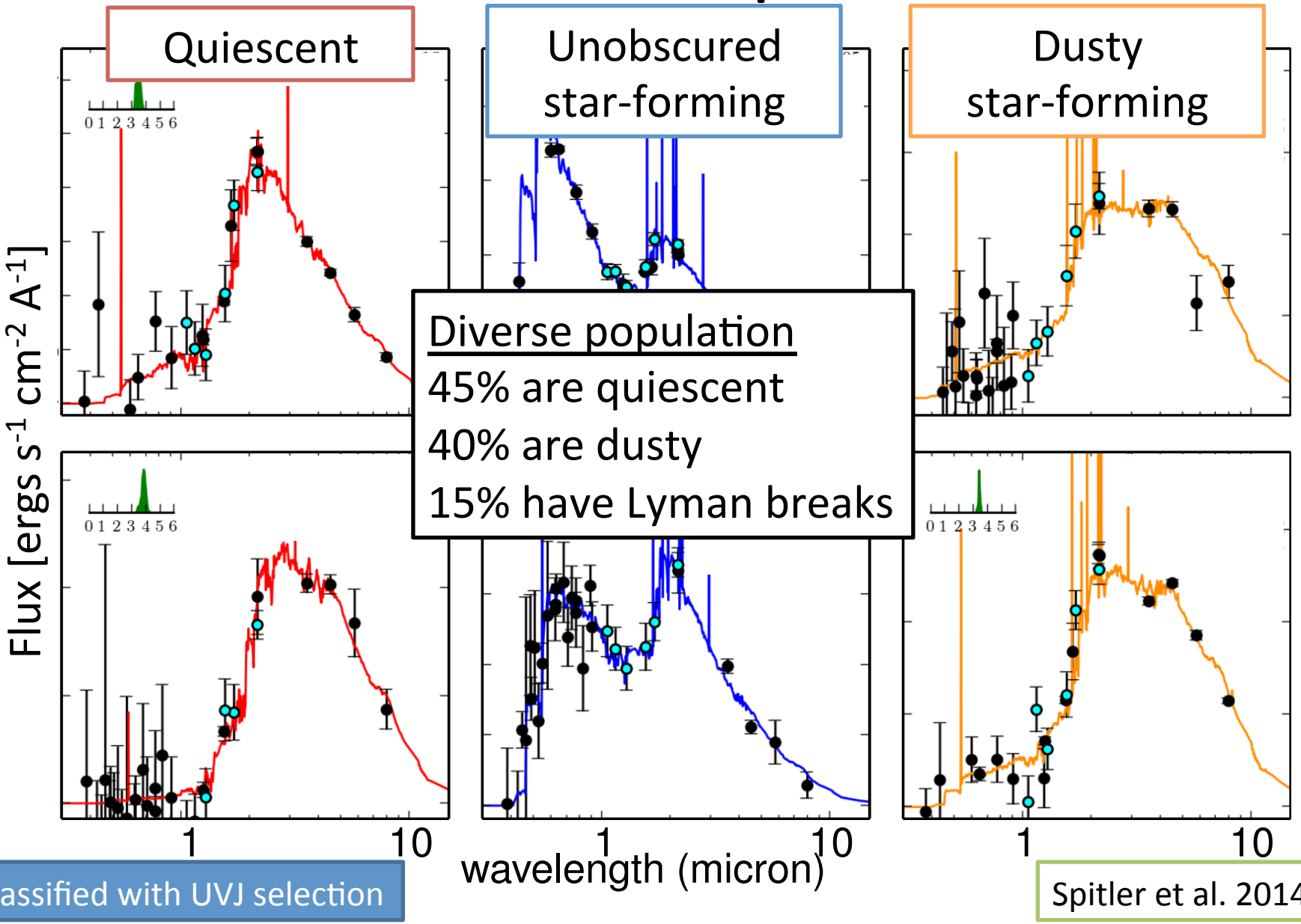


Massive z=3-4 galaxies are red



Spitler et al. 2014

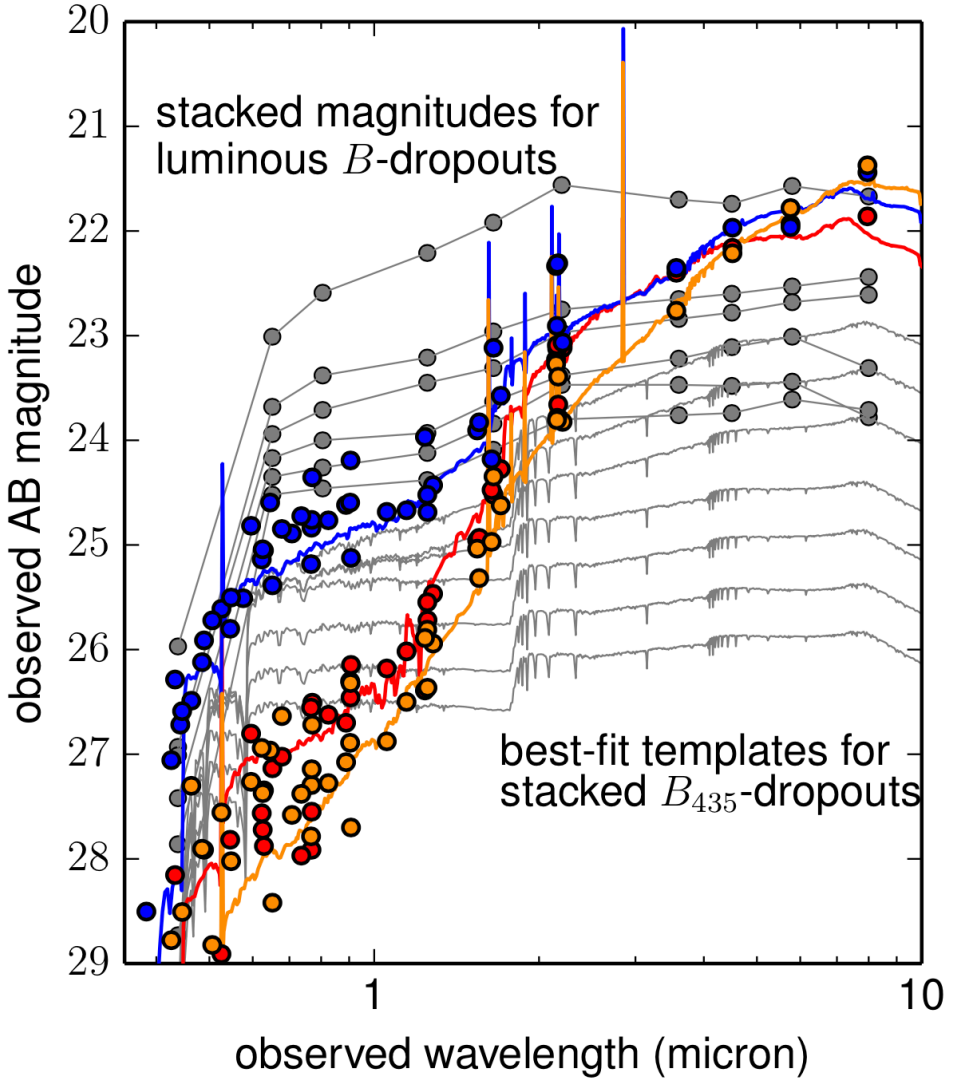
Mass-limited sample at z=3-4



Classified with UVJ selection

Spitler et al. 2014

Massive z=3-4 galaxies are red



old

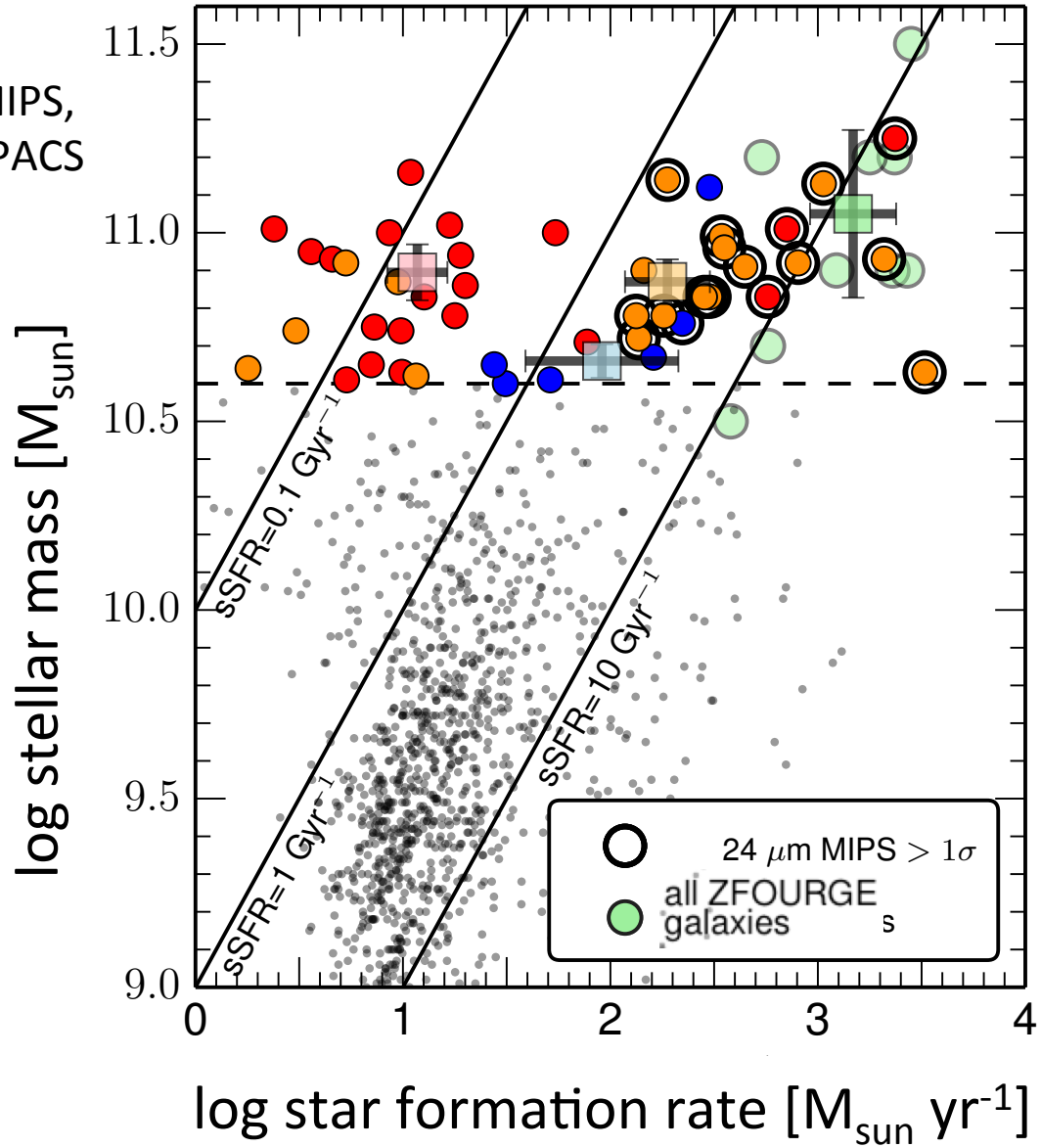
blue SF

dusty

median $M_{1700} = -18.05 \pm 0.42$

Spitler et al. 2014

SFRs from UV+MIPS,
confirmed with PACS



Submillimeter galaxy (SMG) sample from Toft et al., 2014

old

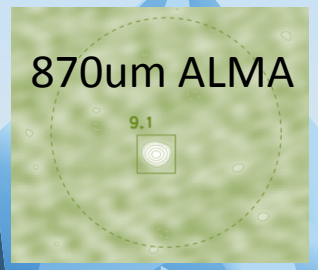
blue SF

dusty

Spitler et al. 2014

Tip of the iceberg

Rare submillimeter galaxies (SMGs) with star-formation rates SFRs > 1000 $M_{sun}yr^{-1}$



Karim et al. 2013

ZFOURGE results: the bulk below

Substantial population of massive **dusty** galaxies with SFRs ~ 200 $M_{sun}yr^{-1}$

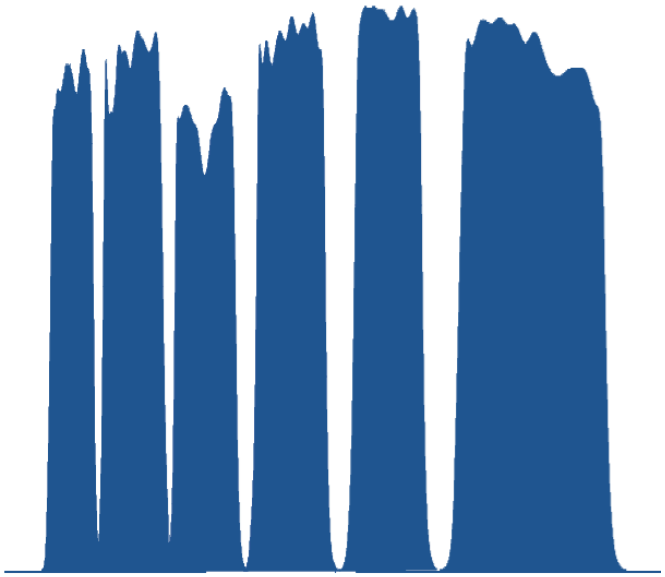
Typical mode of massive galaxy star-formation

- x5 more common than submillimeter galaxies
- Higher SFRs compared to Lyman breaks: massive end of star-forming main-sequence
- Is this how z=3-4 massive galaxies form stars?
- Simple scenario for old galaxies at z=3-4:

200 M_{sun}/year * 0.5 billion years = 10^{11} M_{sun}

started forming z~10 and finished at z~5.5

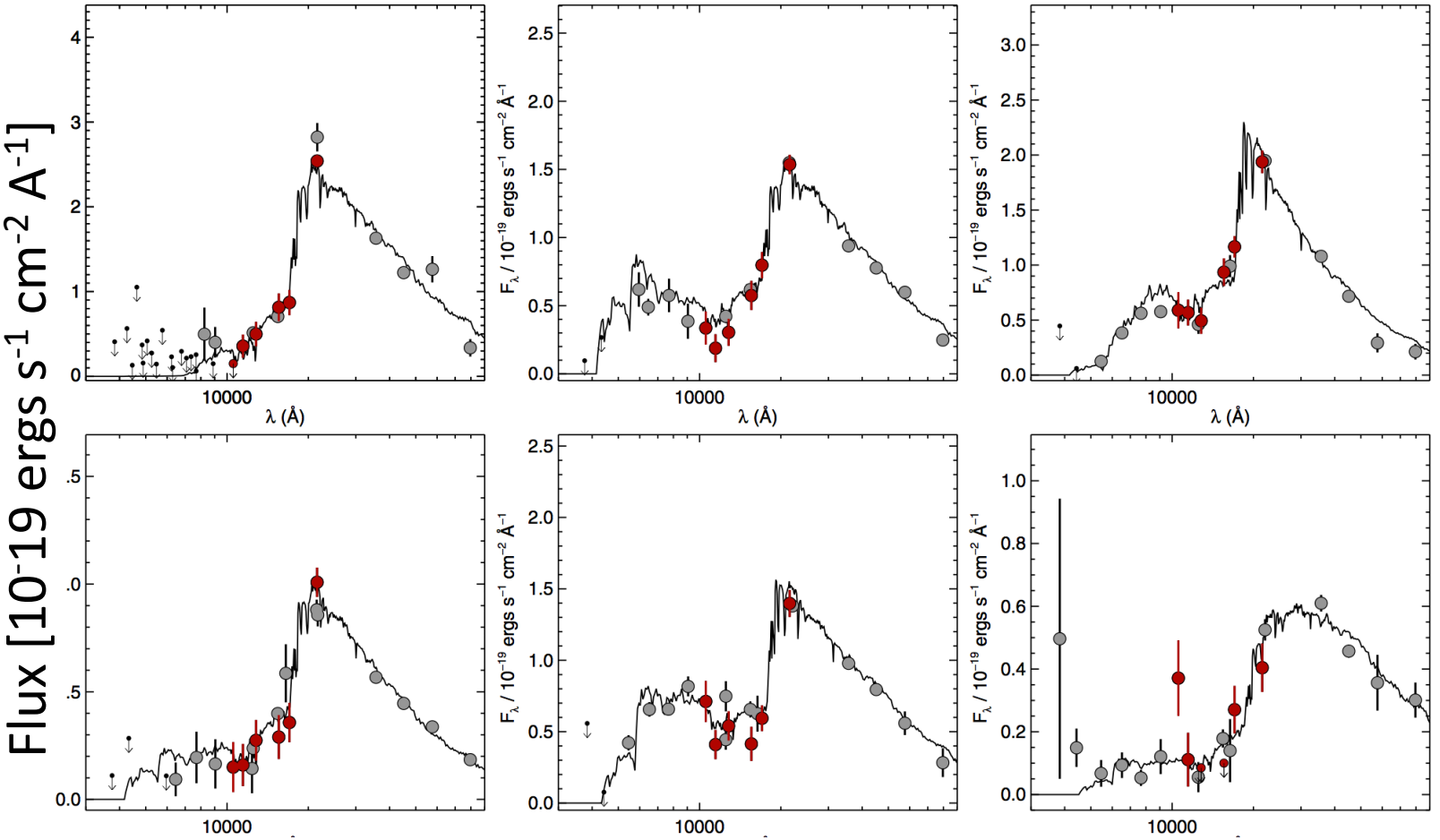
The First Quiescent Galaxies

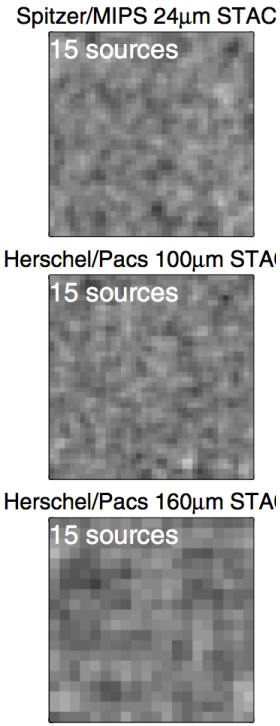


A substantial population of massive quiescent galaxies at z~4 from ZFOURGE
Straatman, Labbe, Spitler, et al. 2014

The sizes of massive quiescent and star forming galaxies at z~4 with ZFOURGE and CANDELS
Straatman, Labbe, Spitler, et al. 2015

Discovery of z=4 quiescent galaxies

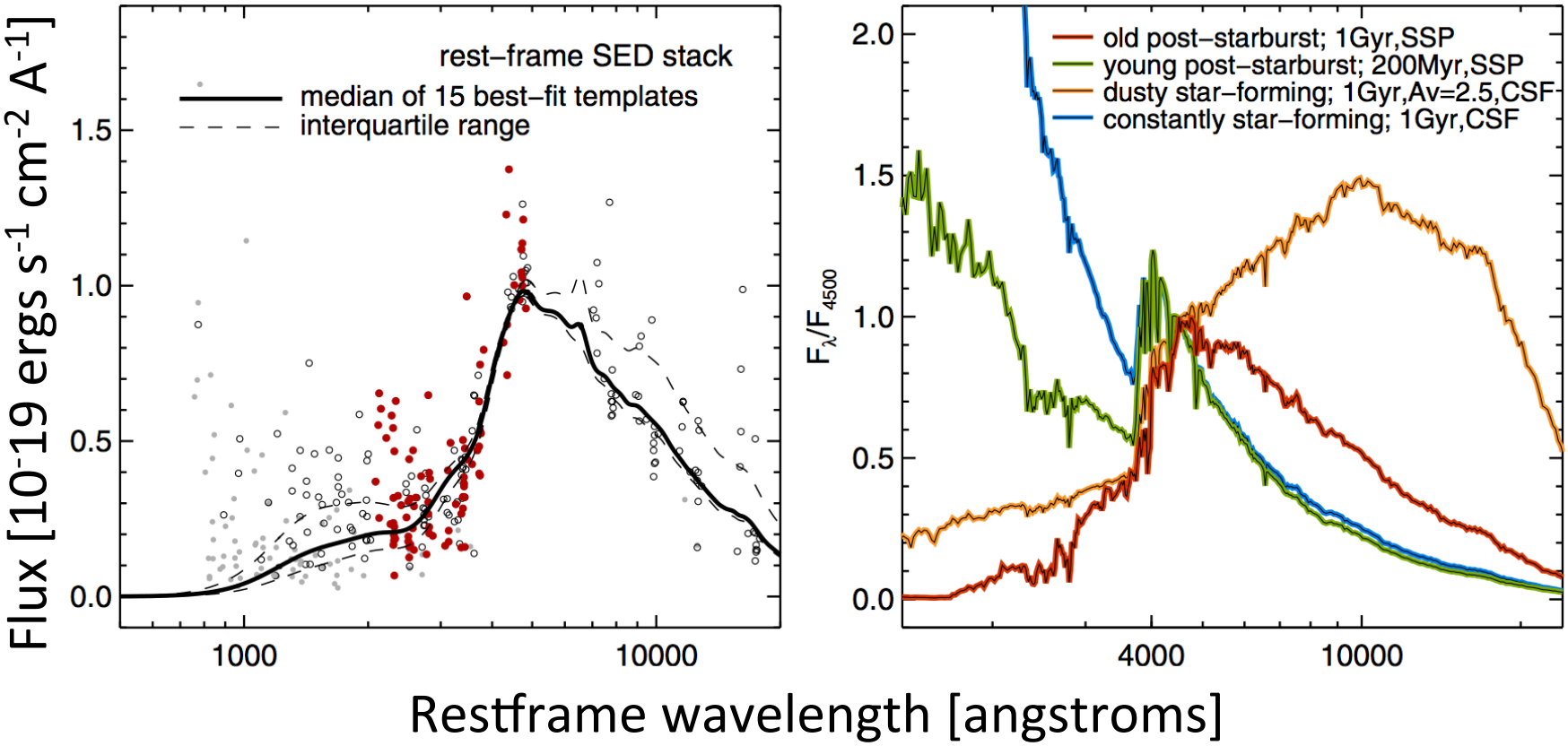




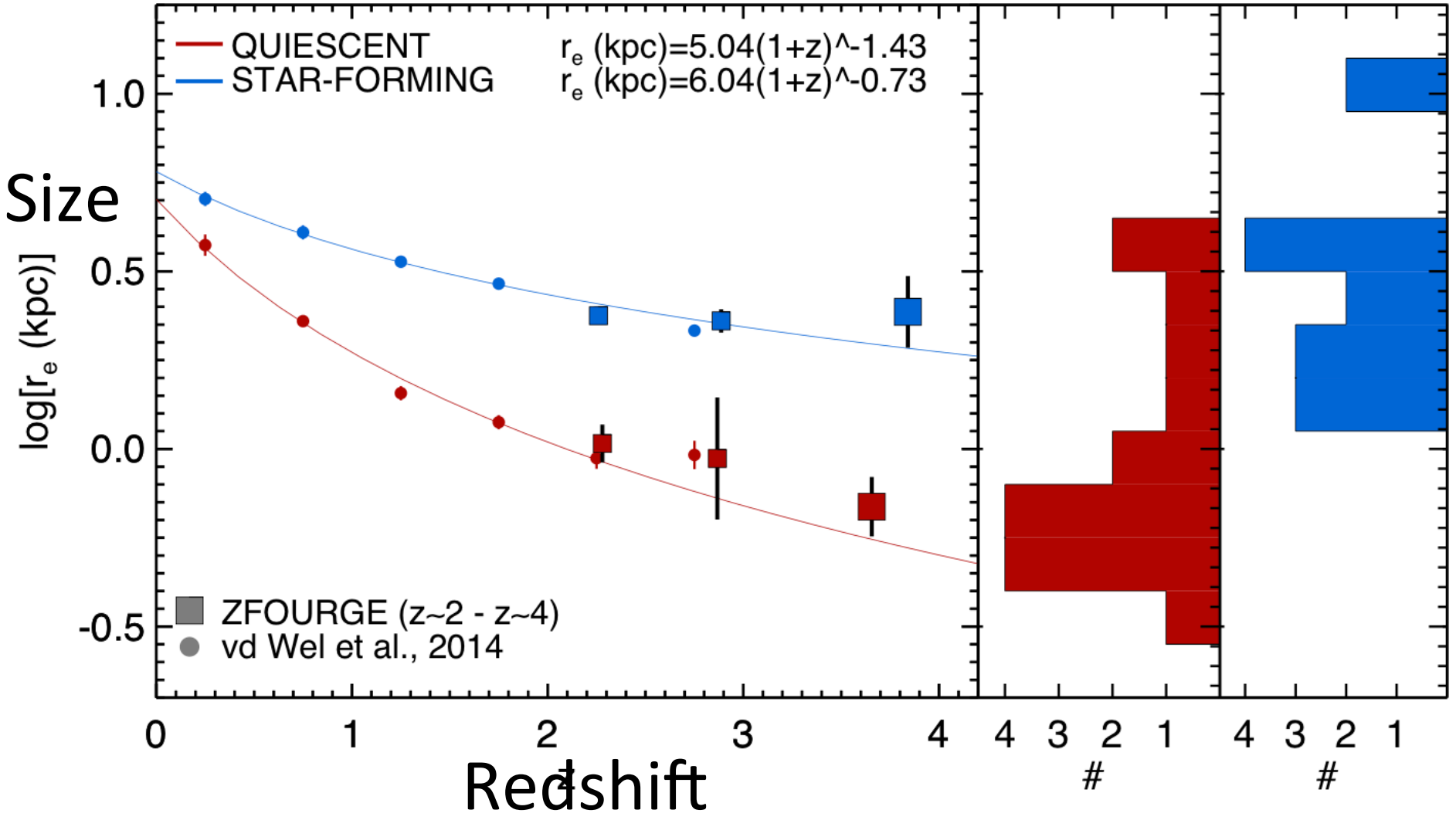
Observed wavelength [angstroms]

Straatman et al. 2014

Discovery of z=4 quiescent galaxies



Straatman et al. 2014

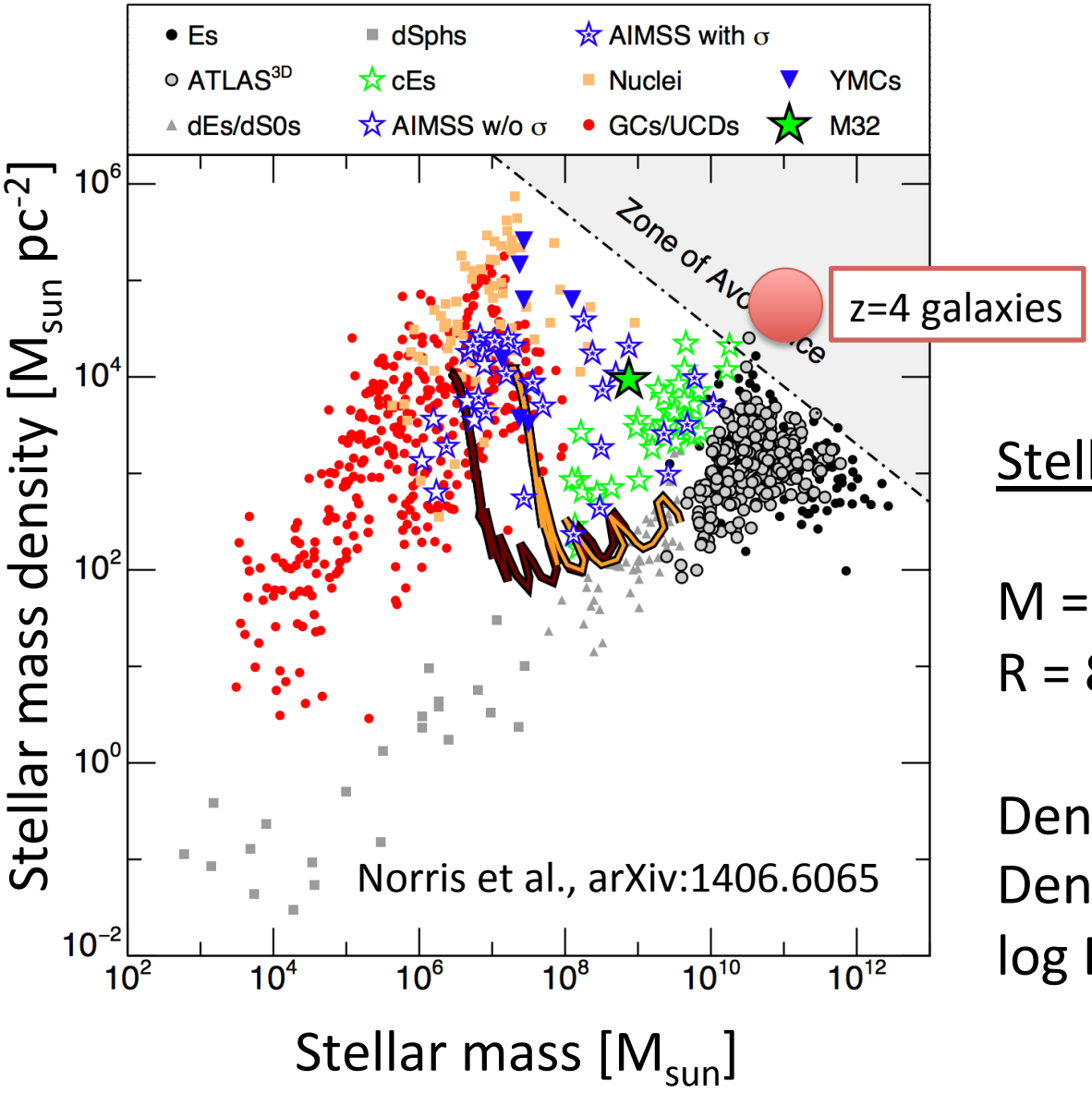


Size

Average age 0.8 Gyr

Formed 10^{11} M_{sun} worth of stars at z > 10

As dense as globular star clusters



Stellar density @ z=4

$M = 10^{11}\ M_{sun}$

R = 800 pc

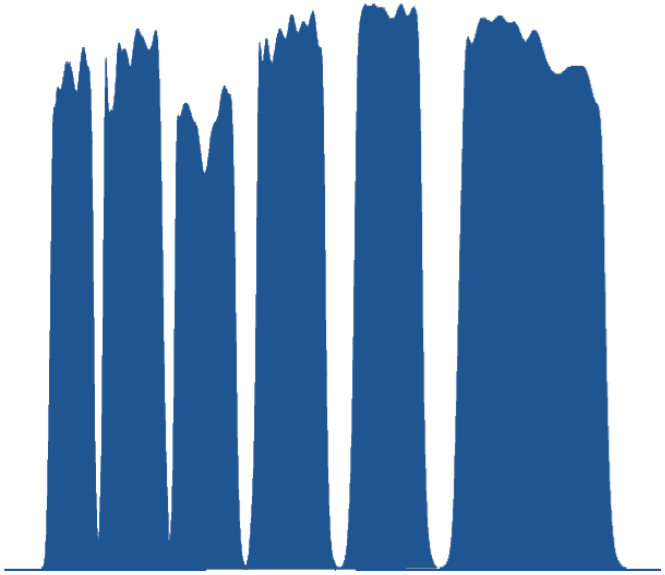
Density = M / (2 pi R^2)

Density = 2×10^4

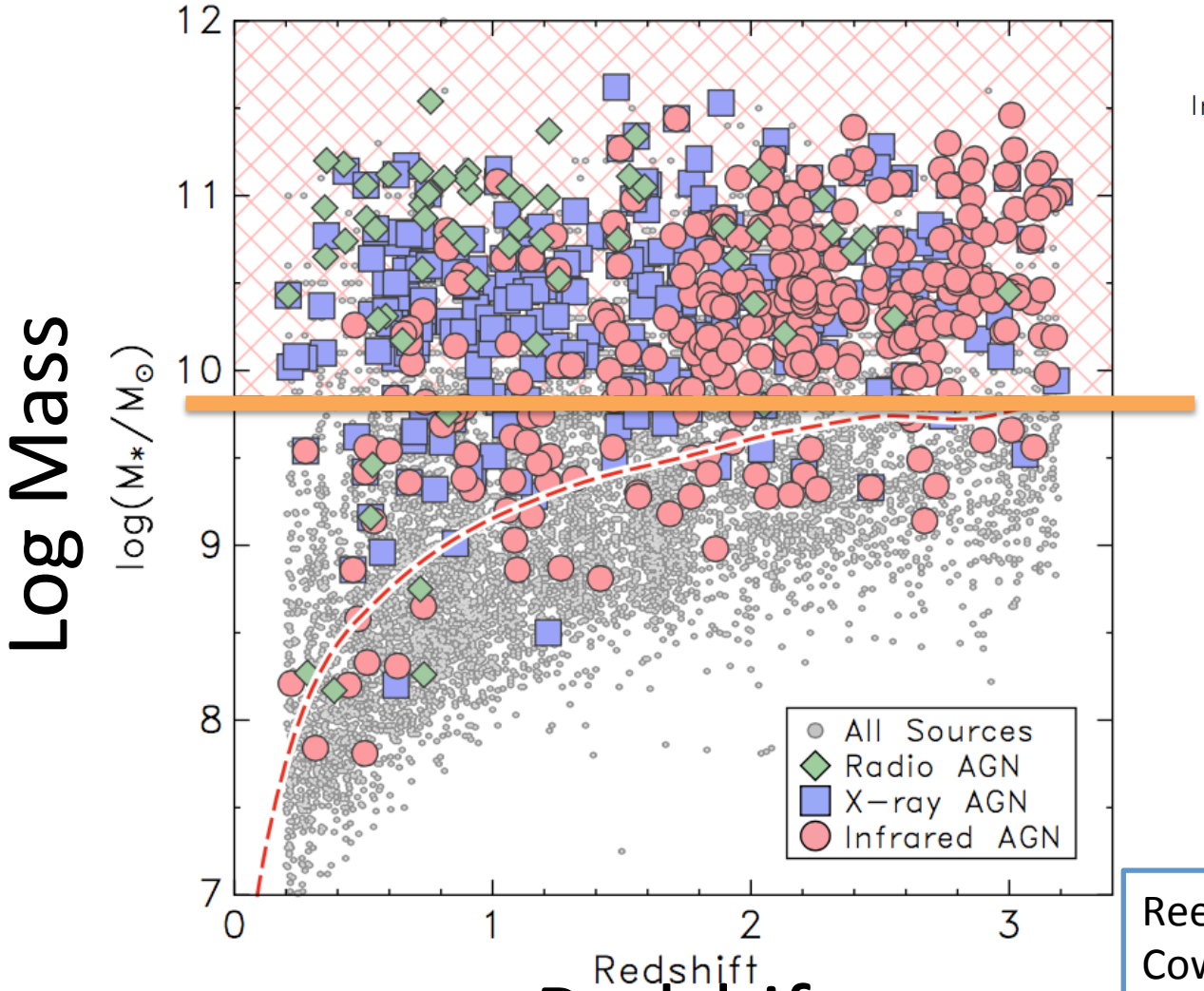
log Density = 4.4

Stellar populations of AGN hosts

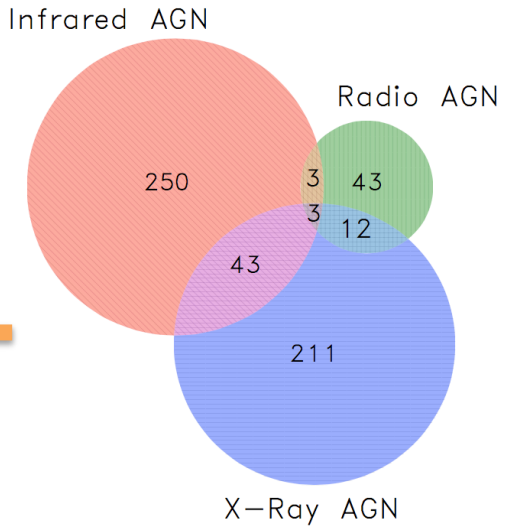
Rees, Spitler et al. submitted
Cowley, Spitler et al. submitted



Active Galactic Nuclei in ZFOURGE

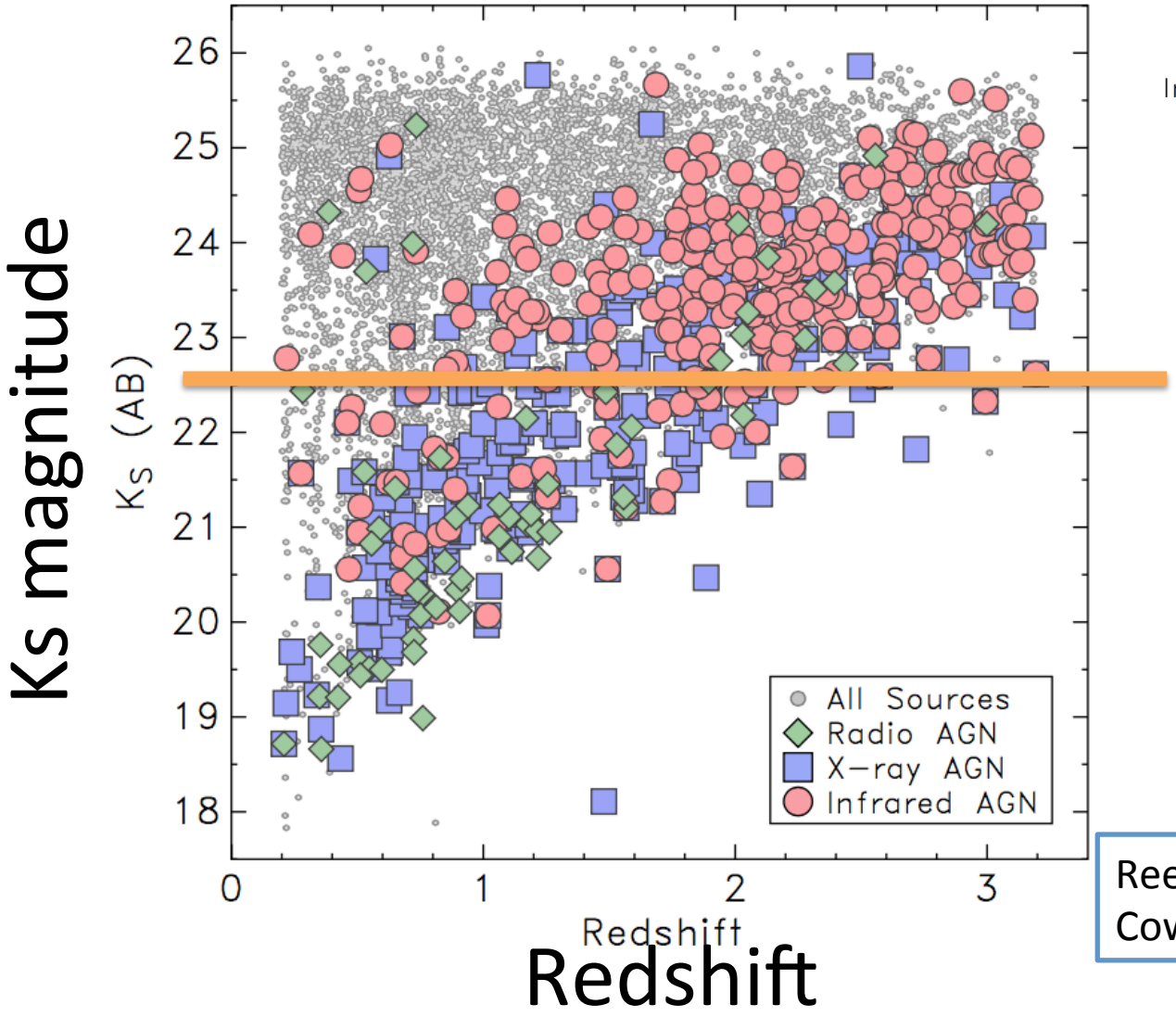


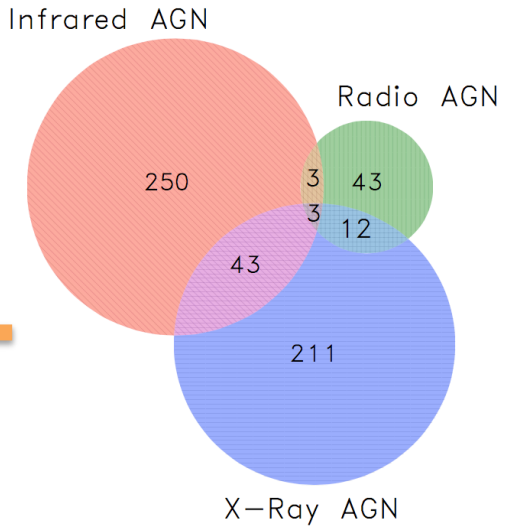
Redshift



Rees, Spitler et al., submitted
Cowley, Spitler et al., submitted

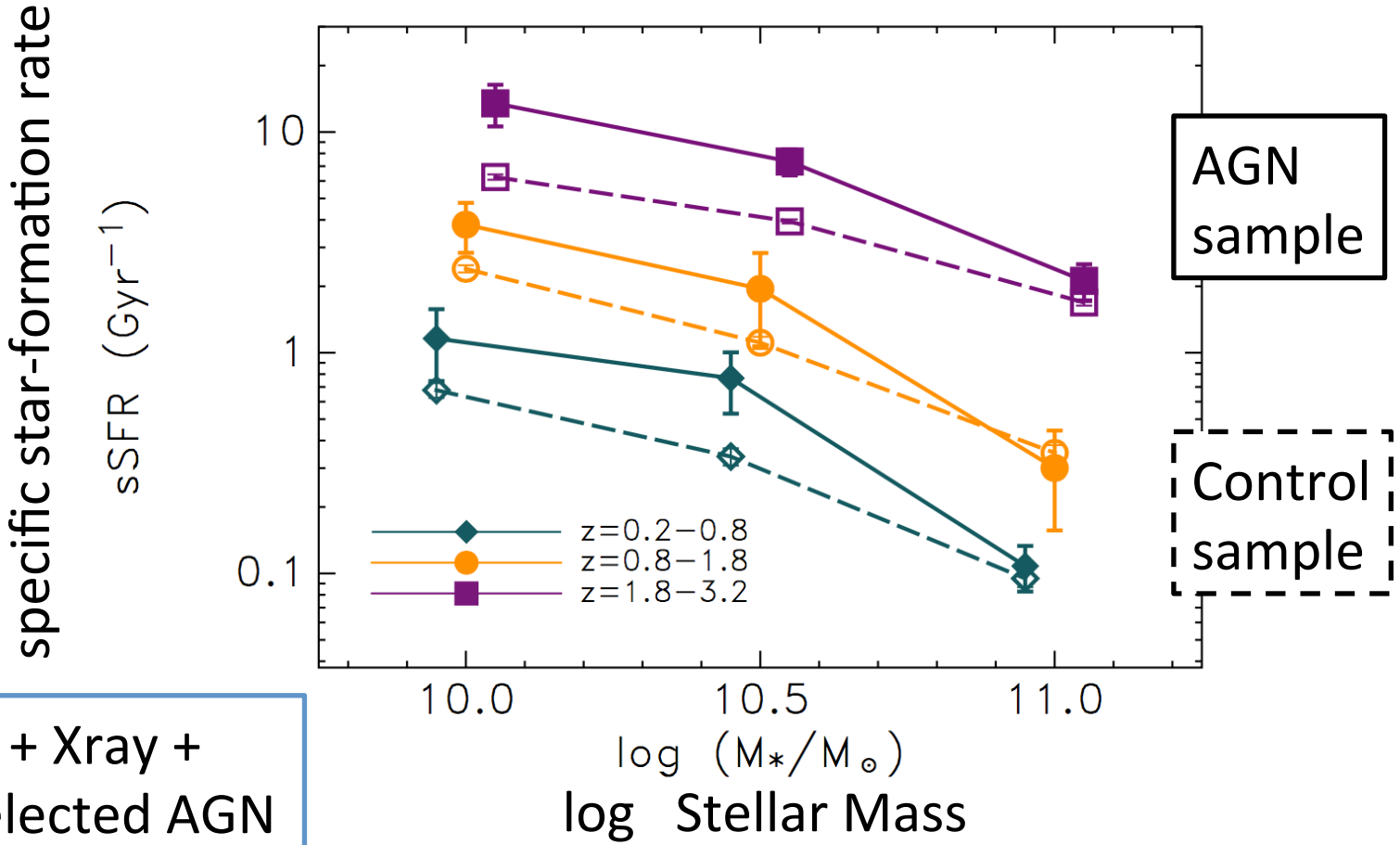
Active Galactic Nuclei in ZFOURGE





Rees, Spitler et al., submitted
Cowley, Spitler et al., submitted

AGN hosts tend to have higher star-formation rates



Infrared + Xray + Radio selected AGN

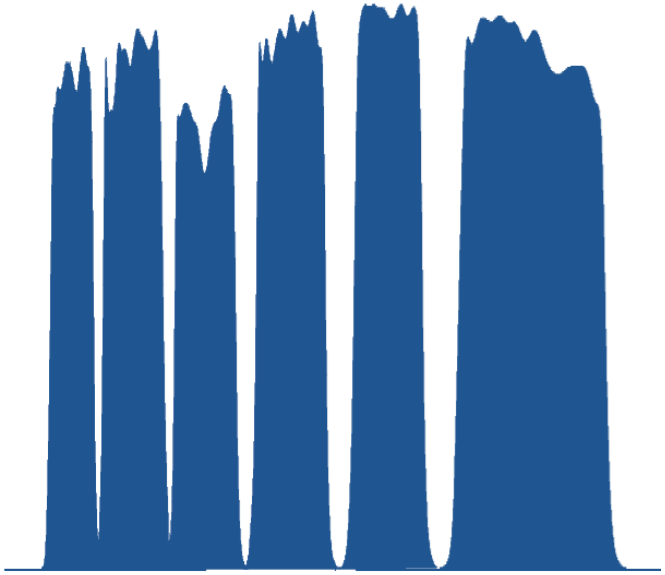
Herschel PACs SFRs

Cowley, Spitler et al., submitted

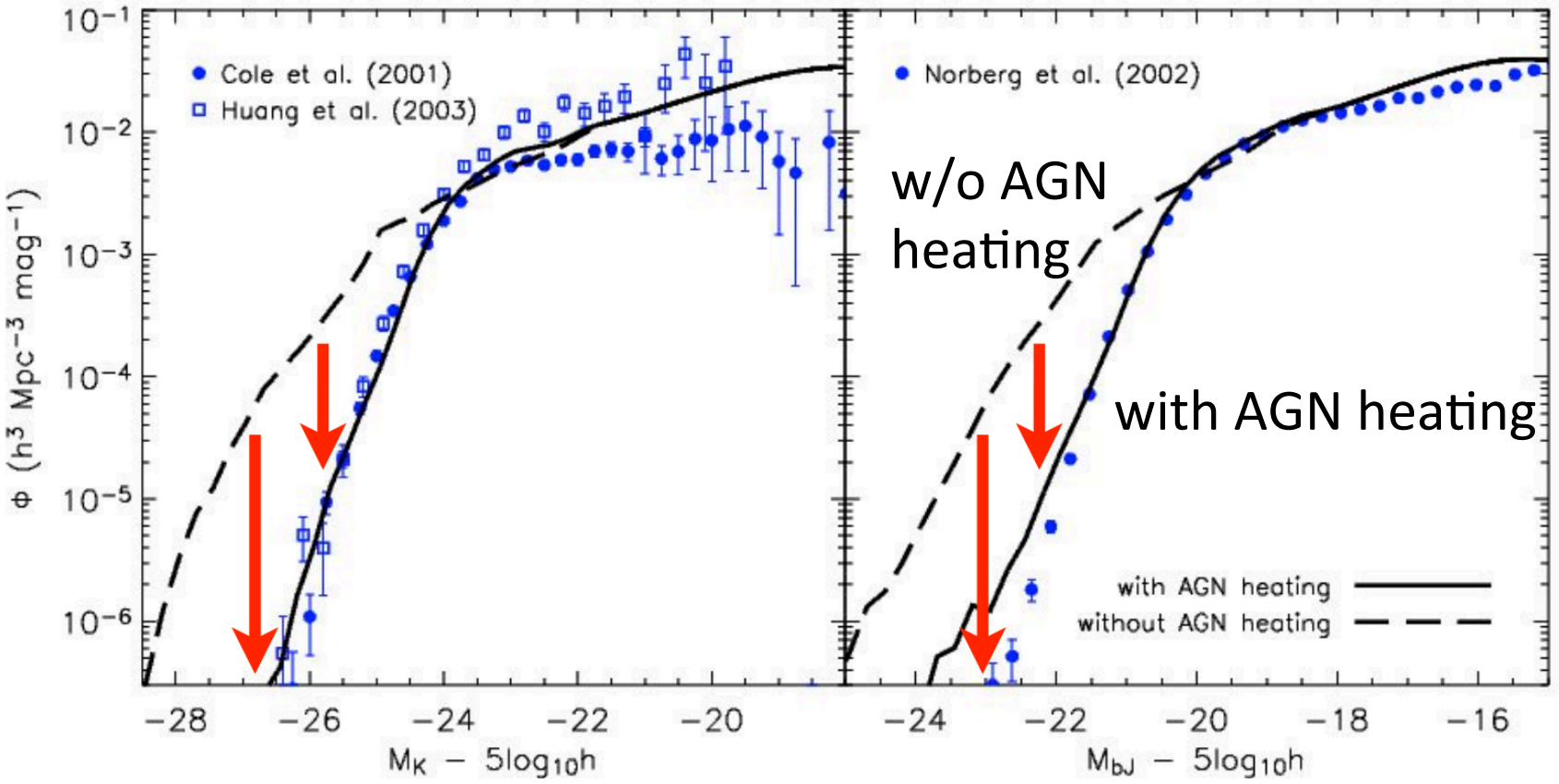
Evolution of the galaxy stellar mass function

Galaxy Stellar Mass Functions from ZFOURGE/CANDELS: An Excess of Low-Mass Galaxies Since z=2 and the Rapid Buildup of Quiescent Galaxies

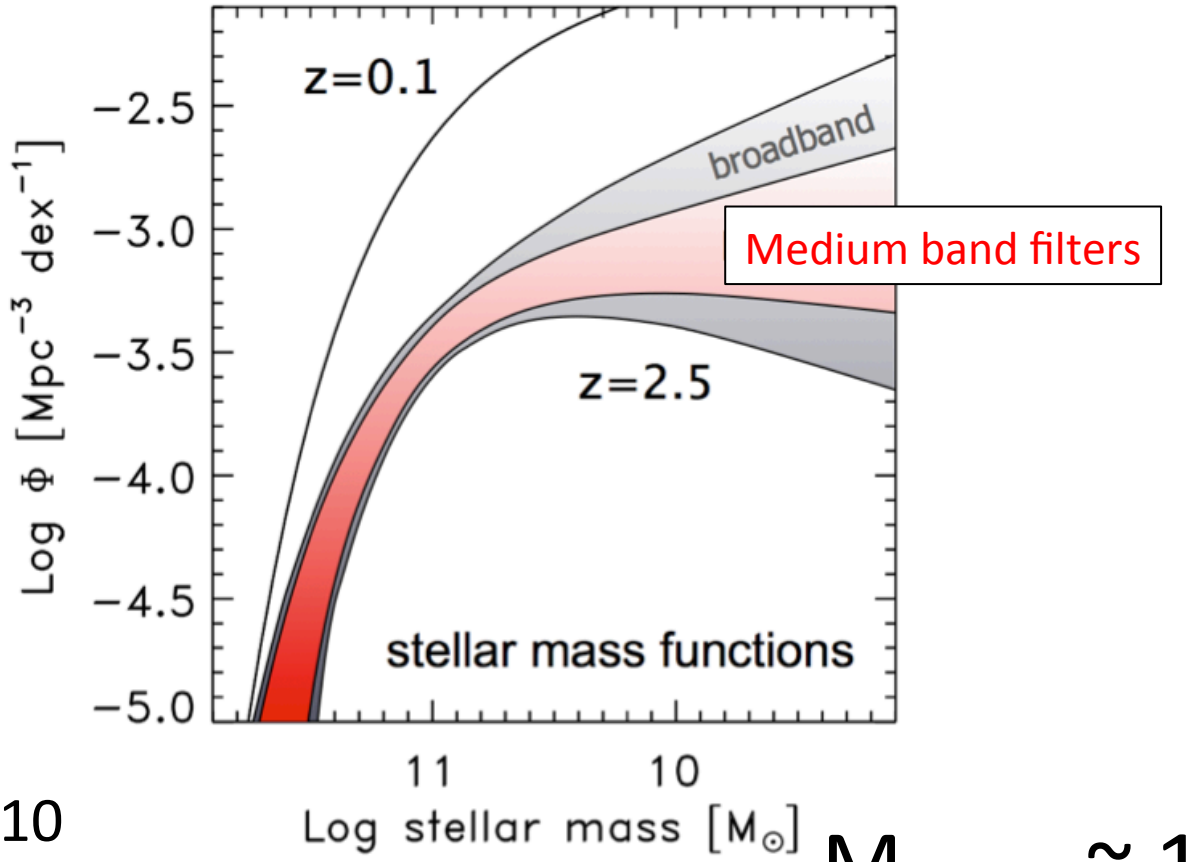
Tomczak et al. 2014



Galaxy mass/luminosity functions



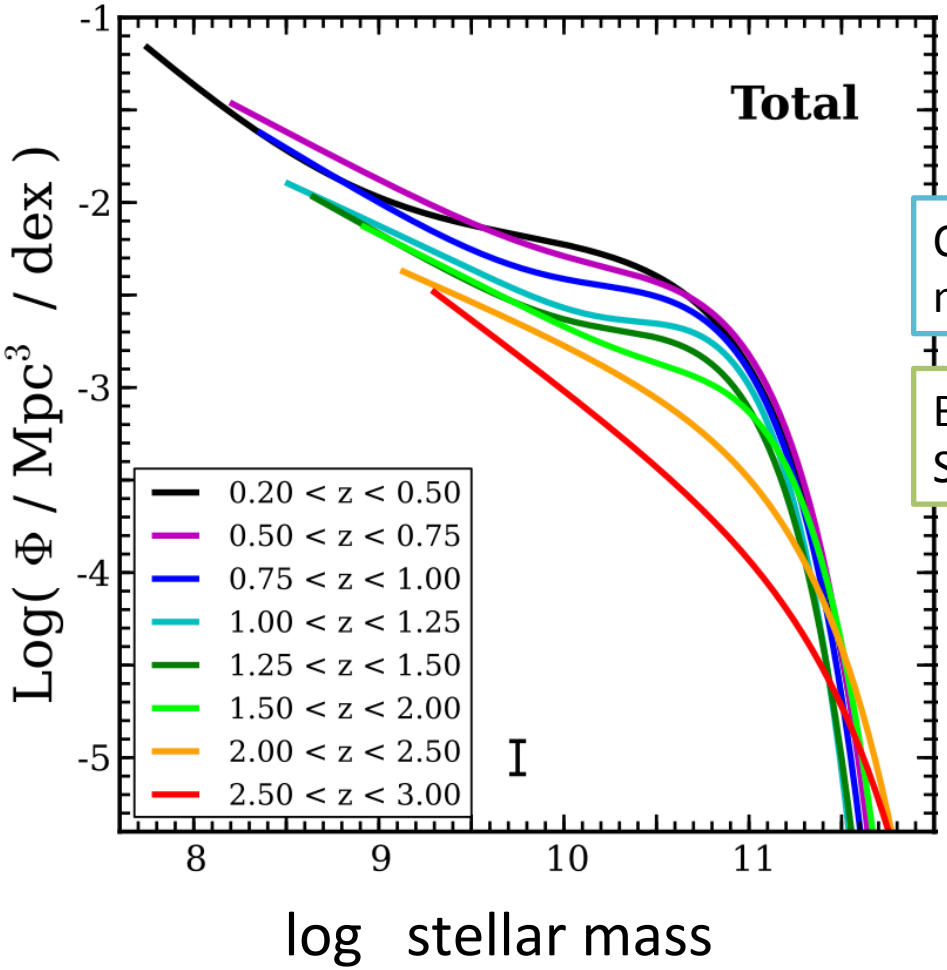
ZFOURGE mass functions to z=3



$M_{stellar} \sim 10^{10}$
for passive galaxies

$M_{stellar} \sim 10^{9}$
for SF-galaxies

ZFOURGE mass functions to z=3

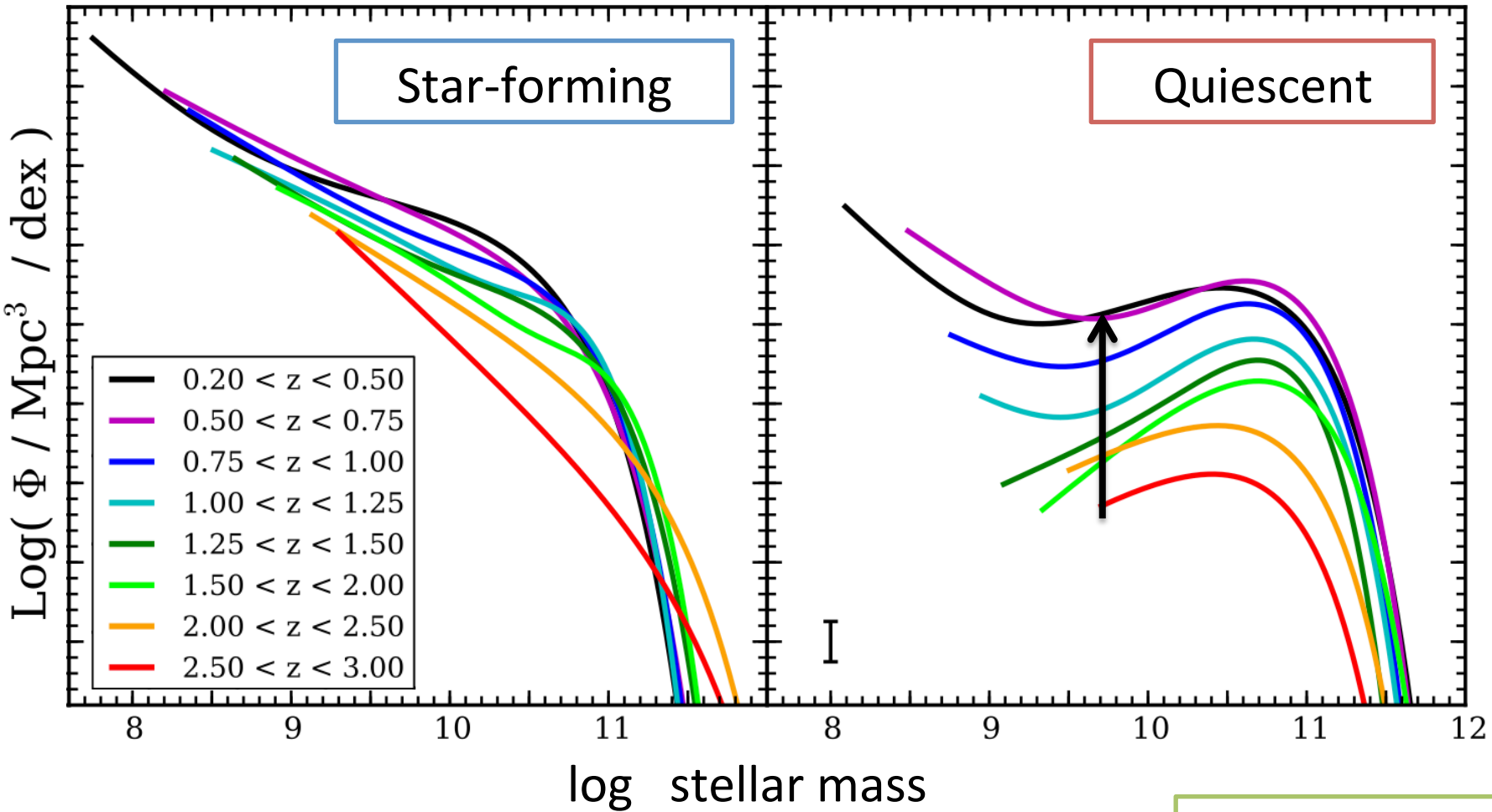


Confirm upturn at masses M > 10^{10}

Better fit by double-Schechter functions

Tomczak et al. 2014

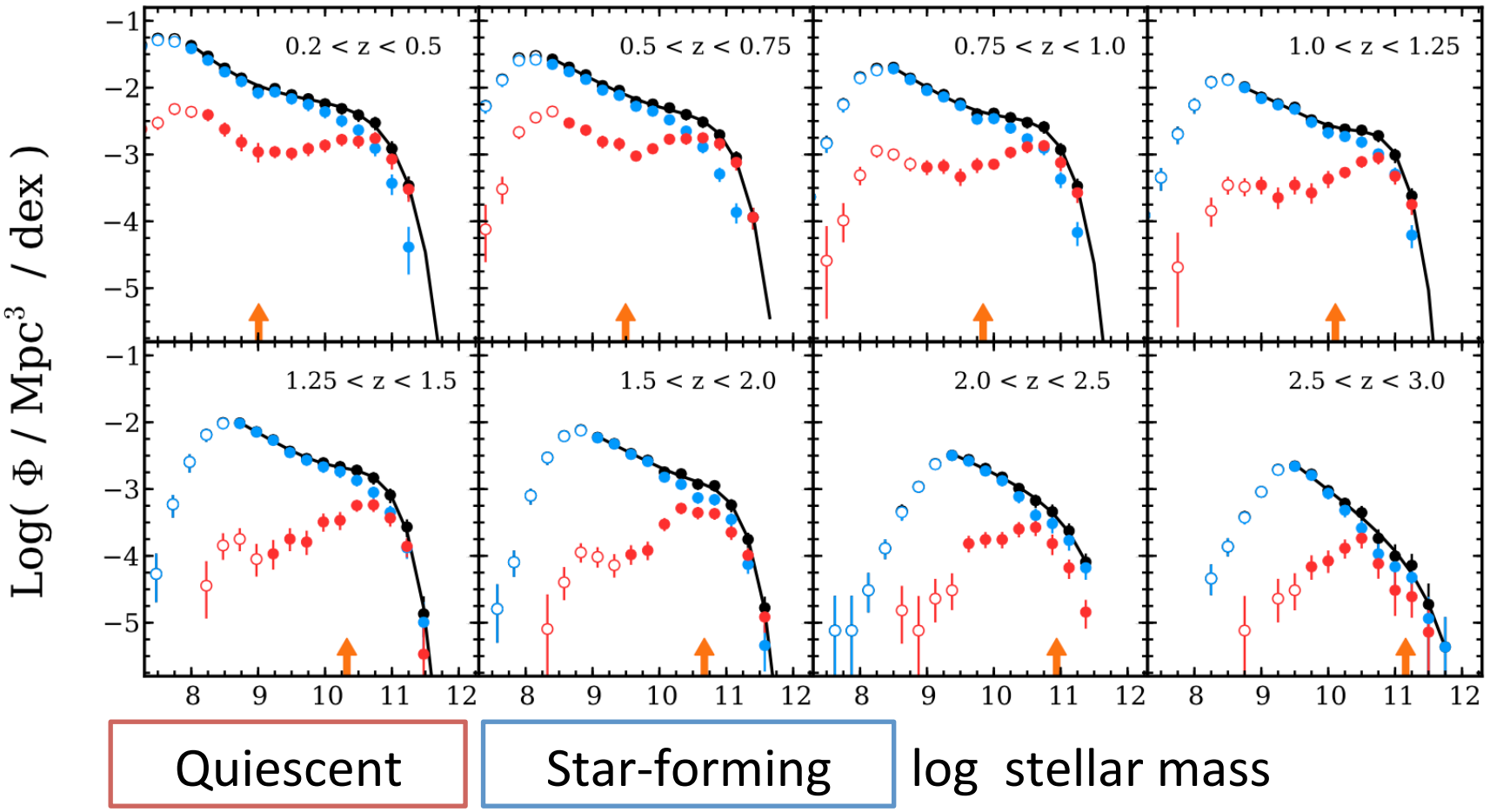
ZFOURGE mass functions to z=3



H_{160} selected + NMBS

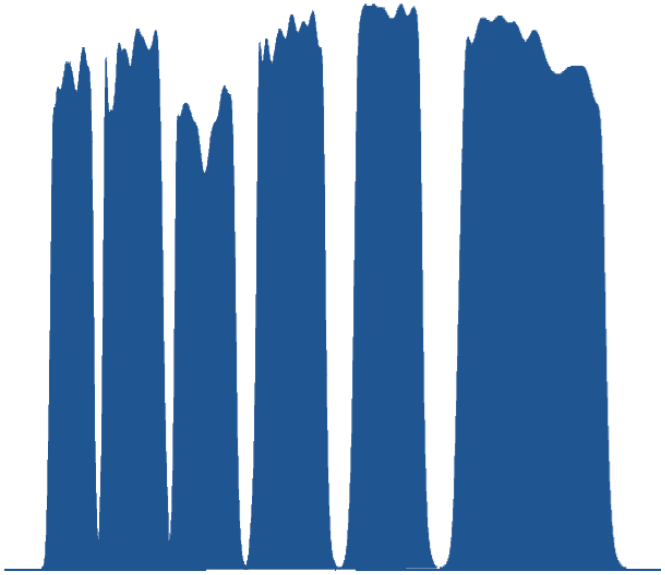
Tomczak et al. 2014

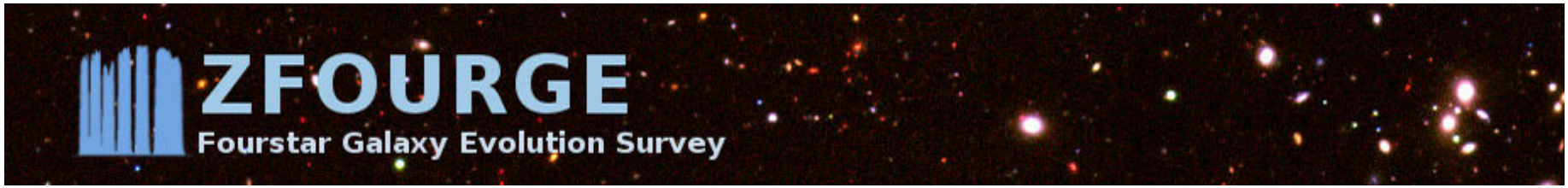
ZFOURGE mass functions to z=3



Tomczak et al. 2014

Summary





- Discovered distant galaxy protocluster
  - MOSFIRE follow-up program: ZFIRE
- Mass-limited census at z=3-4
  - Most are red, not like Lyman-break galaxies
  - 45% quiescent, 35% dusty, 15% blue star-forming
- Quiescent galaxies are very compact at z~4
- Host properties of AGNs
  - AGN hosts have higher star-formation rates
- Strong evolution in the quiescent galaxy mass function