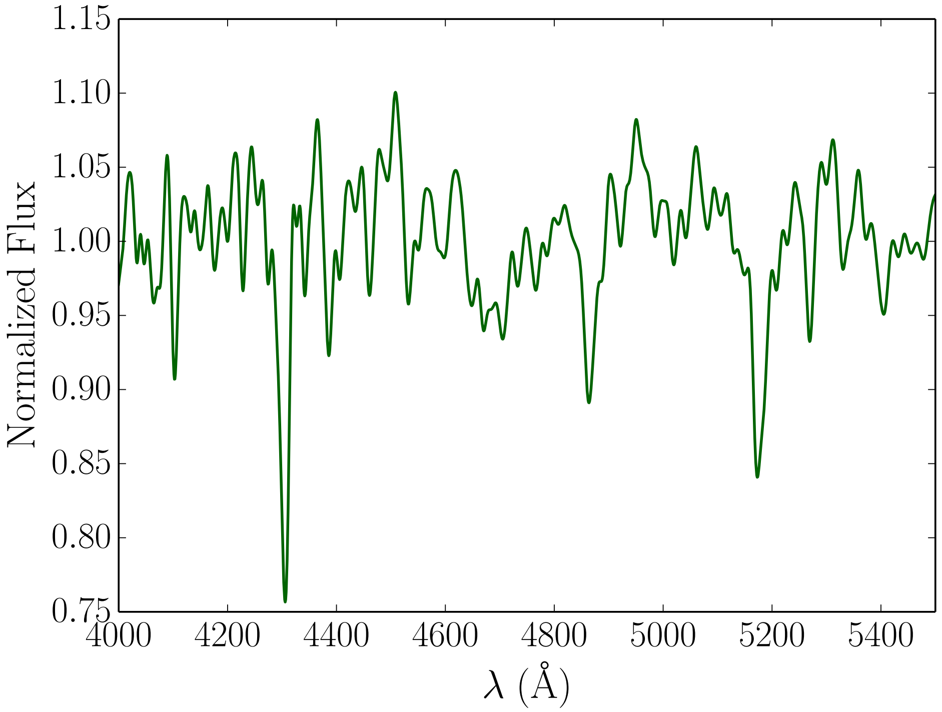
The Assembly Histories of Quiescent Galaxies Since z = 0.7

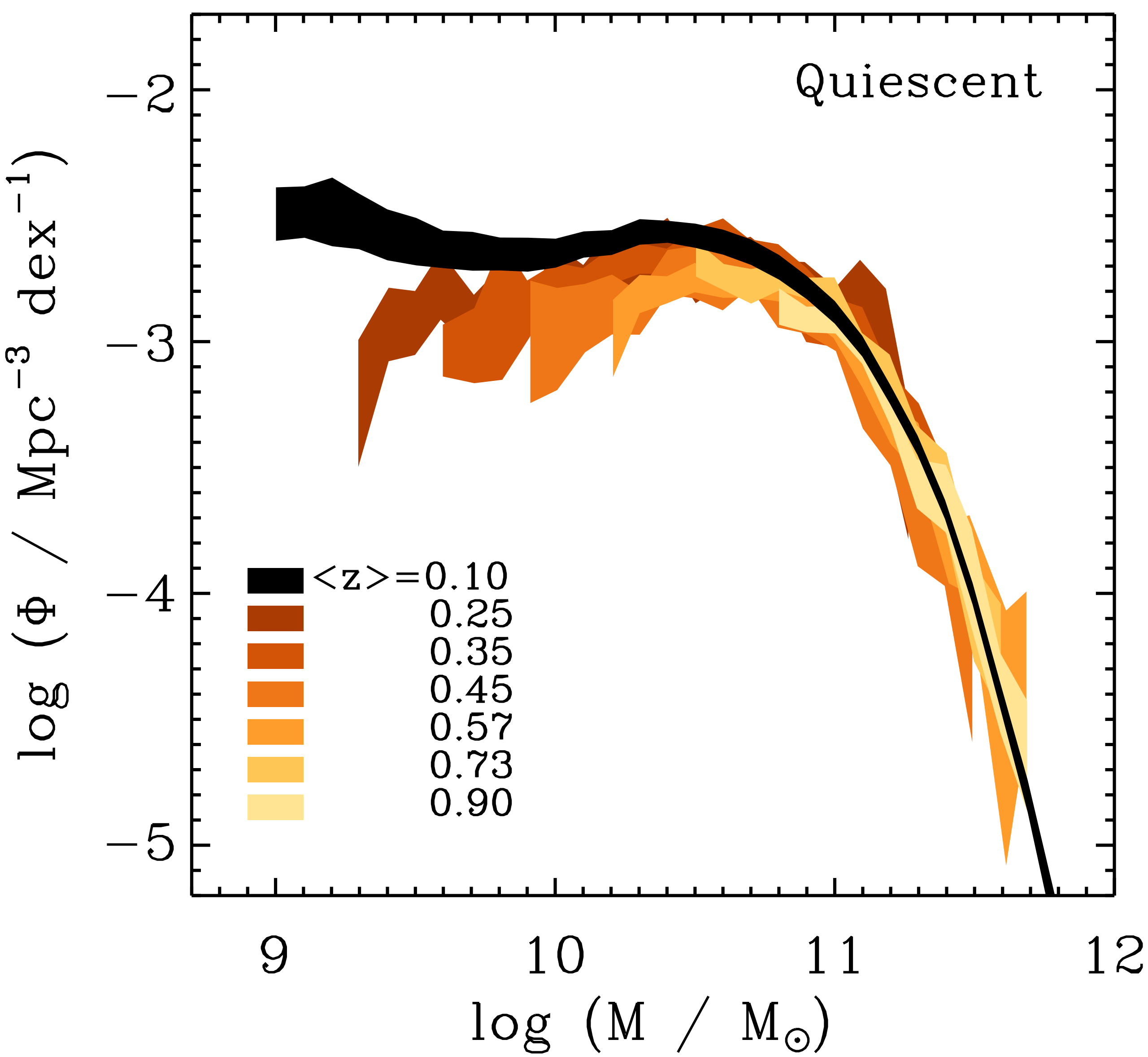


Jieun Choi

Harvard/CfA
University of California, Santa Cruz

Charlie Conroy
John Moustakas
Genevieve Graves
Brad Holden
Mark Brodwin
Michael Brown
Pieter van Dokkum

massive quiescent galaxies appear to be mostly assembled by z~1 then passively evolve to z~0

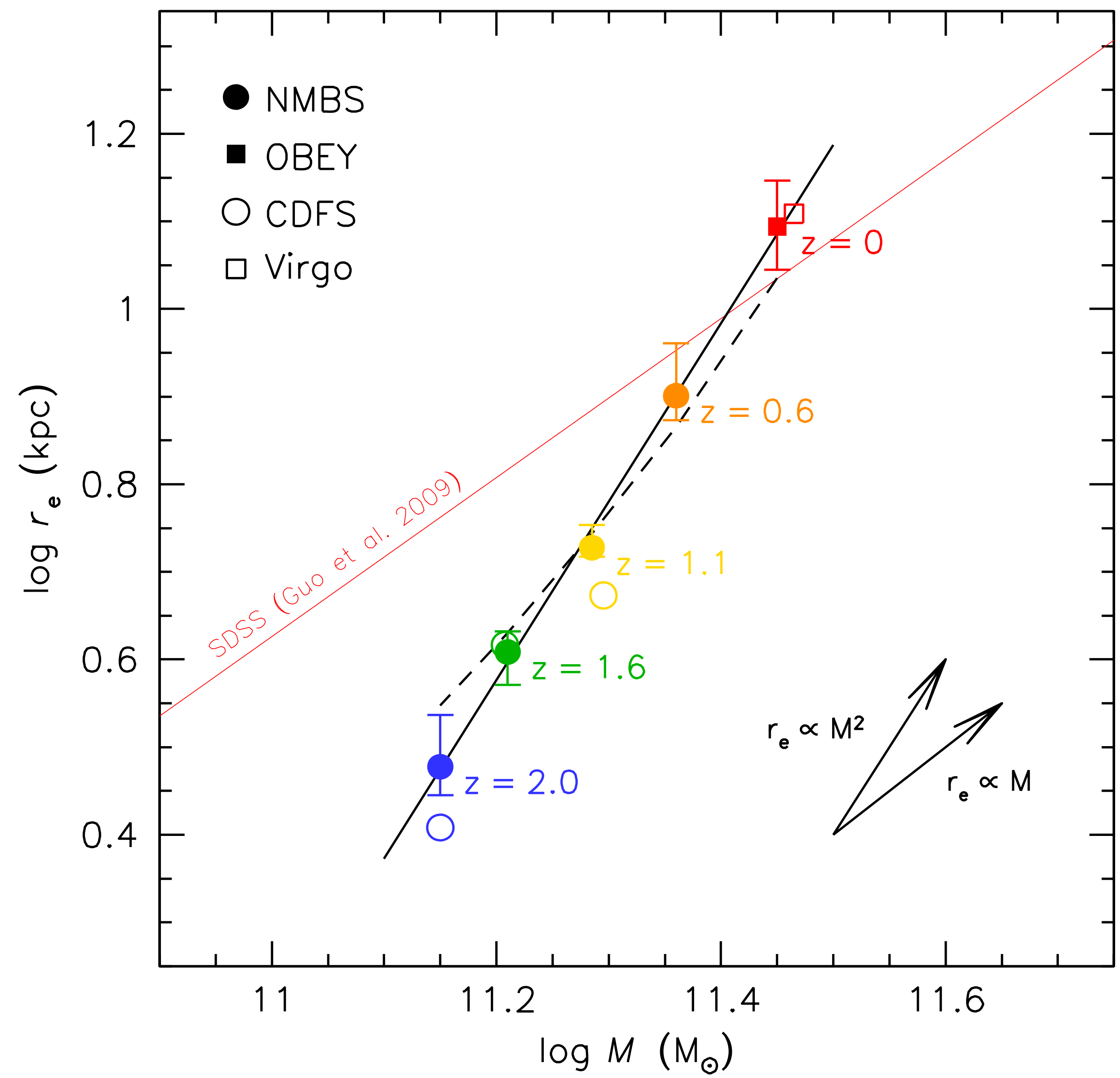


Moustakas+ 2013

e.g., Bundy+ 2006; Renzini 2006; Cirasuolo+ 2007; Vergani+ 2008; Marchesini+ 2009; Banerji+ 2010; Moustakas+ 2013; Muzzin+ 2013

quiescent galaxies appear to grow inside-out

van Dokkum+ 2010

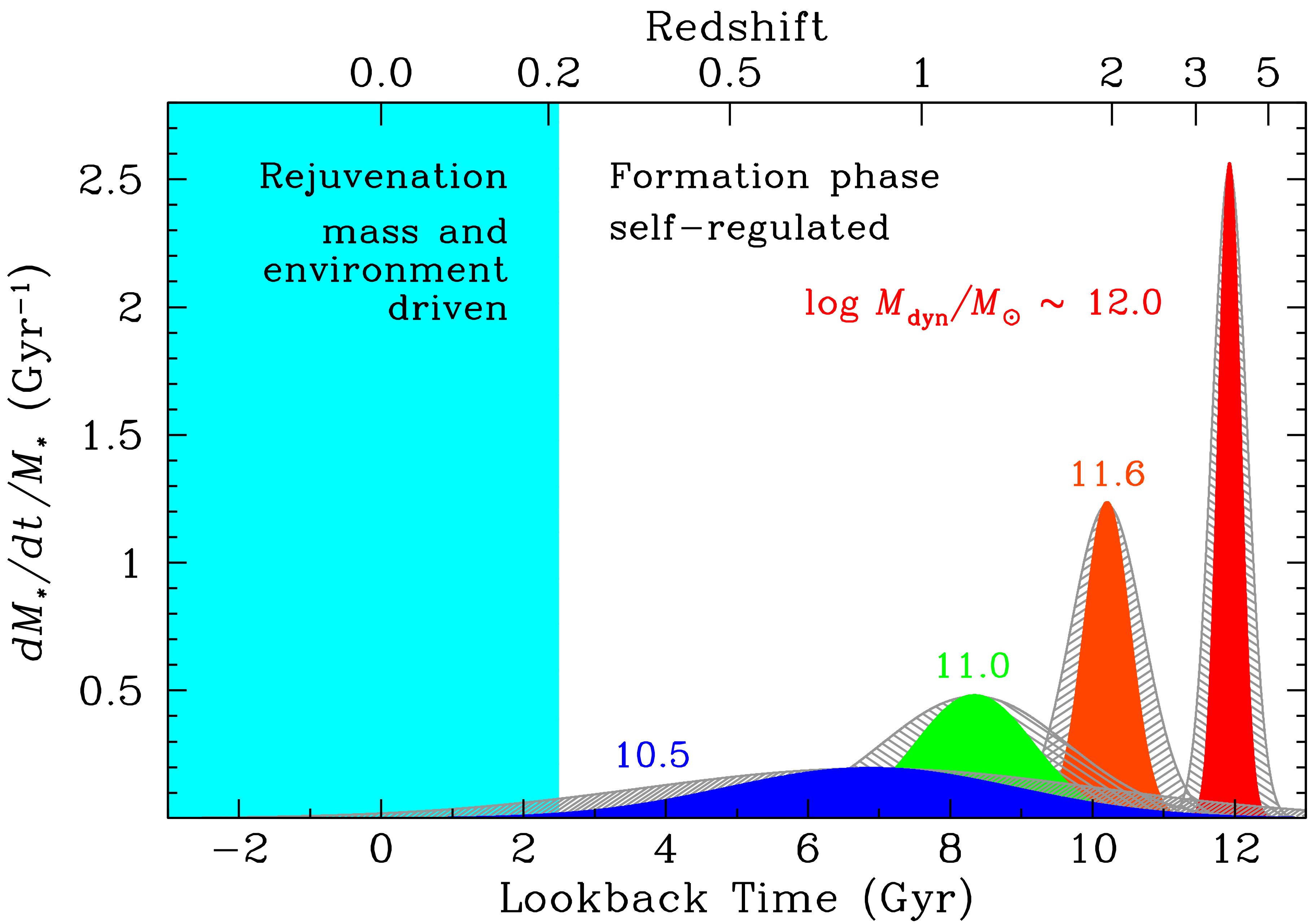


x4 size growth

x2 mass growth

e.g., Daddi+ 2005; Trujillo+ 2006; van Dokkum+ 2008; van der Wel+ 2008; Cimatti+ 2008; Bezanson+ 2009; Damjanov+ 2009; Williams+ 2010; Cassata+ 2010; van Dokkum+ 2010; López-Sanjuan+ 2012; McLure+ 2013; Belli+ 2013

stellar pop. analysis offers another channel for studying galaxy evolution

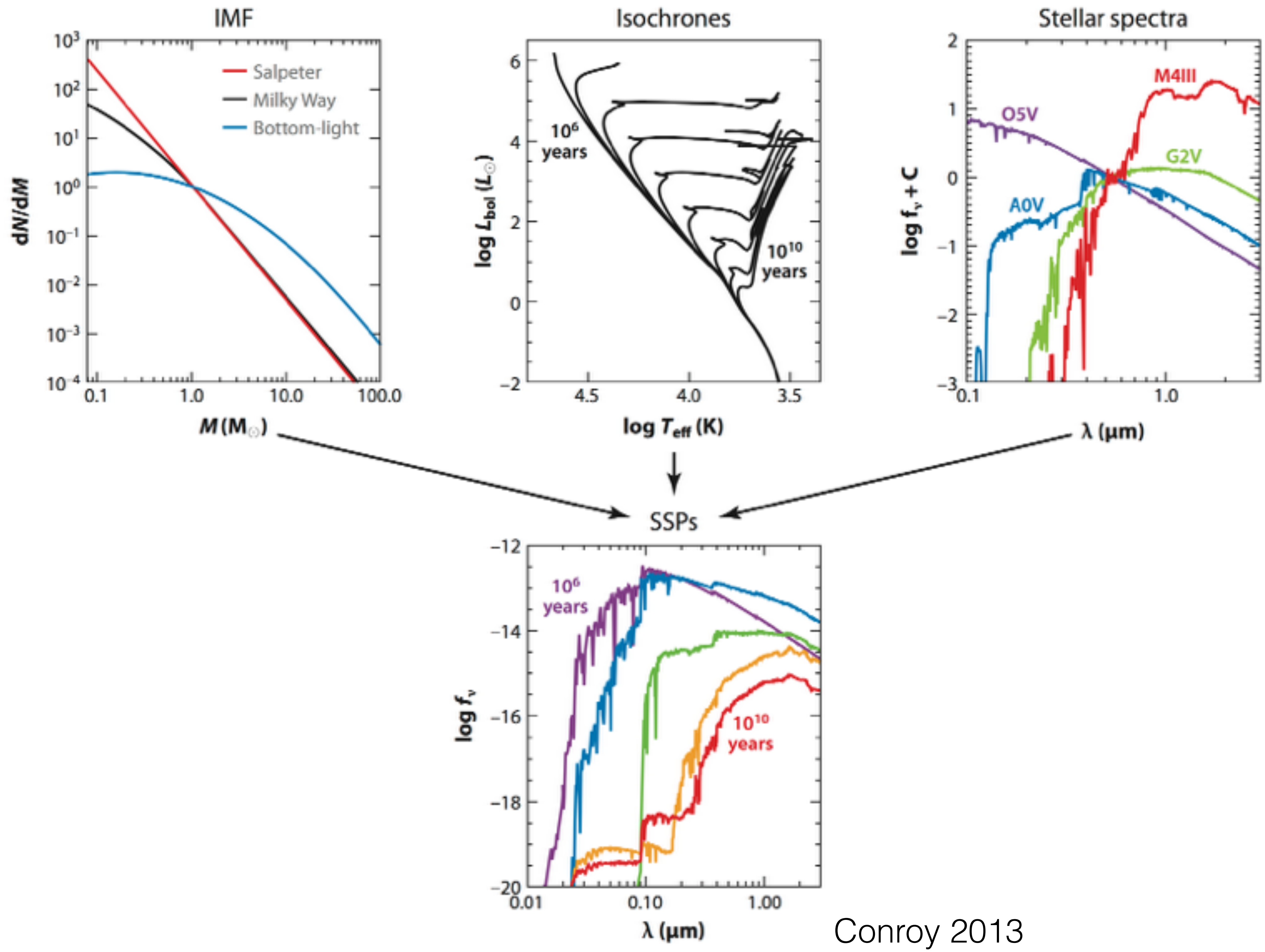


Thomas+ 2010

goal: to measure the
age and abundance ratios of
a mass-complete sample of
quiescent galaxies
as a function of $M_\star$ at $0.1<z<0.7$

our model uses
simple stellar populations

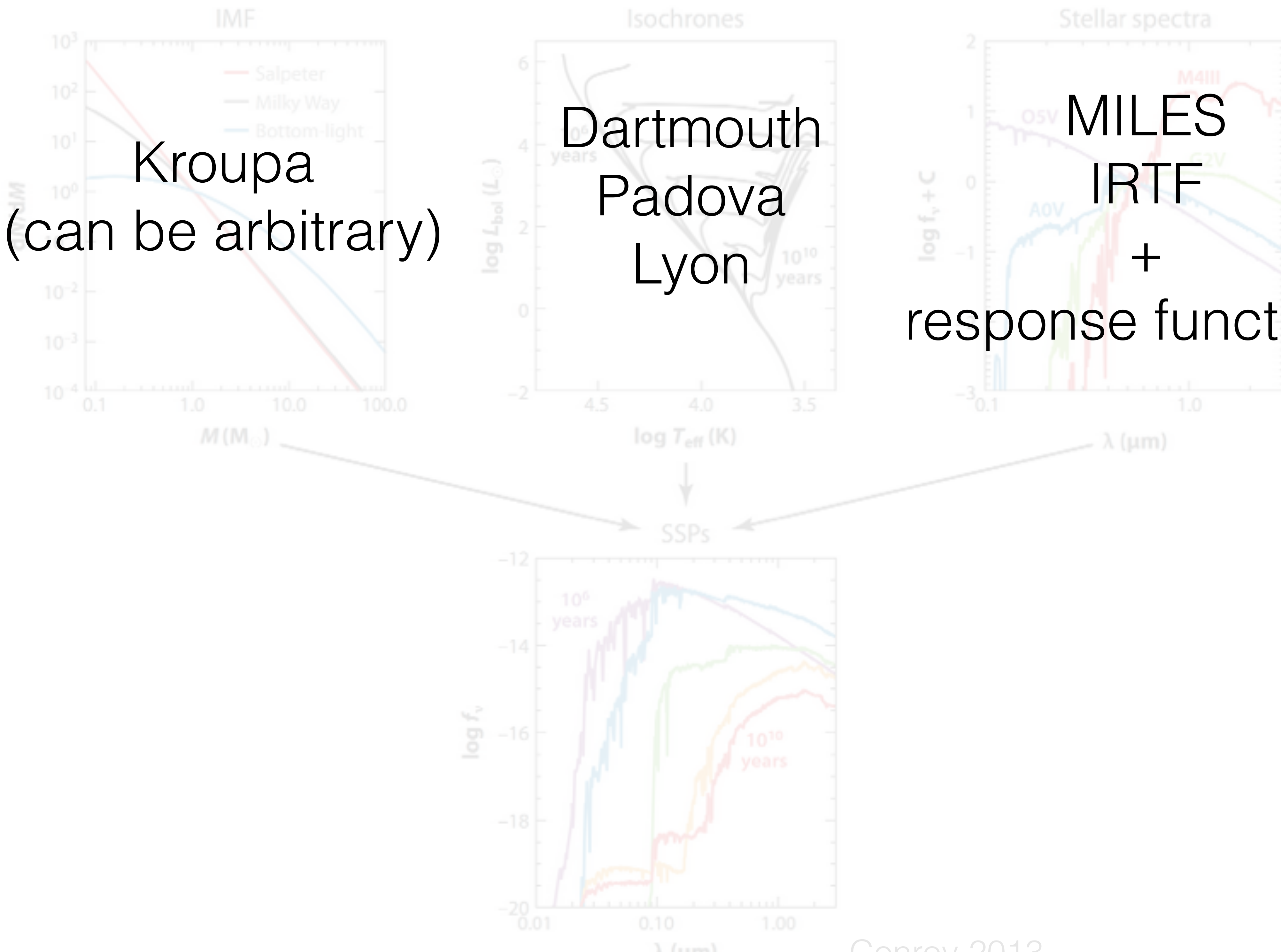
Conroy & van Dokkum+ 2012; Conroy+ 2014



Conroy 2013

our model uses
simple **s**tellar **p**opulations

Conroy & van Dokkum+ 2012; Conroy+ 2014



Kroupa
(can be arbitrary)

Dartmouth
Padova
Lyon

MILES
IRTF
+
response functions

Conroy 2013

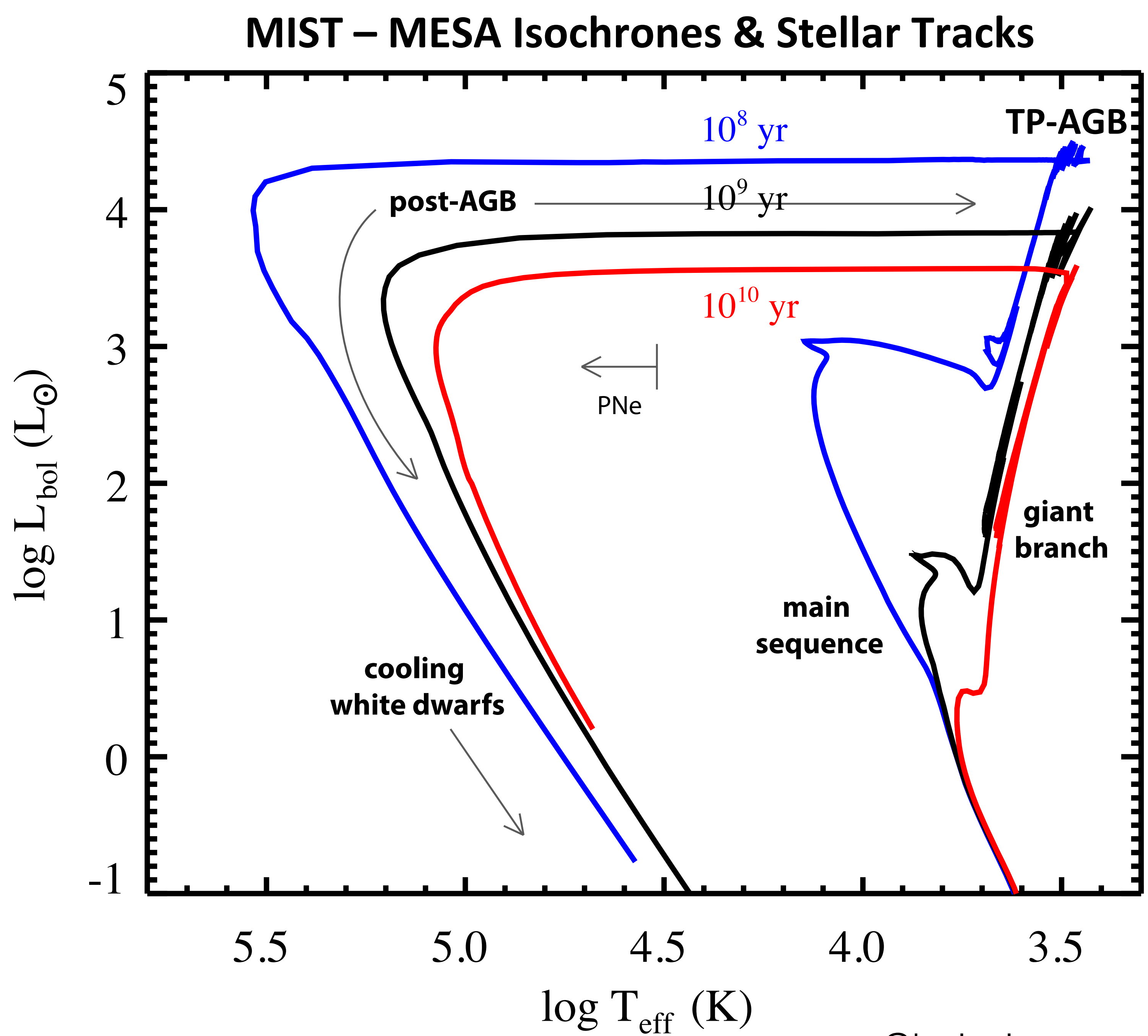
MESA Isochrones & Stellar Tracks coming soon!

Paxton+ 2011, 2013

0.08 – 150 $M_\odot$
many evolutionary phases
a variety of [Fe/H], [a/Fe]

in collaboration with:

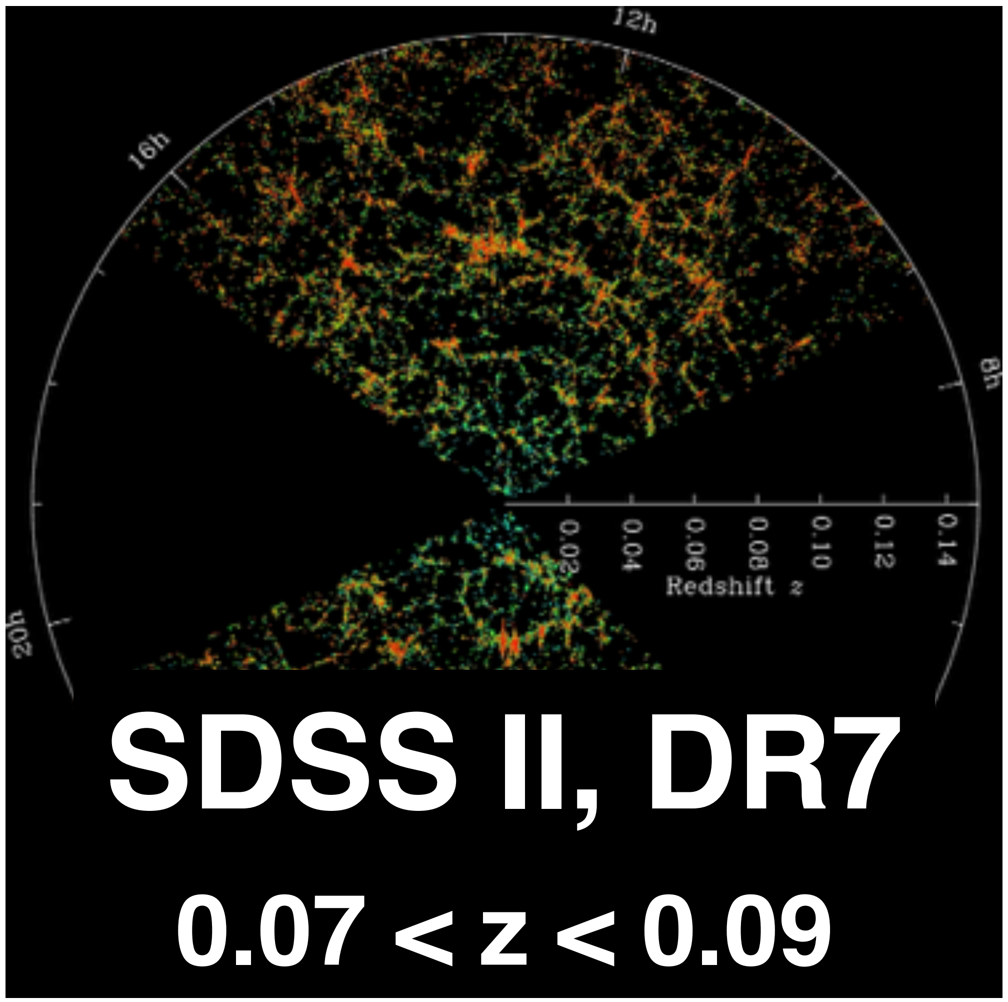
Charlie Conroy
Aaron Dotter
Matteo Cantiello



Choi+ in prep

the galaxy sample

sdss.org



Abazajian+ 2009

R ~ 2000
52,908 galaxies
14.5 < r < 17.6

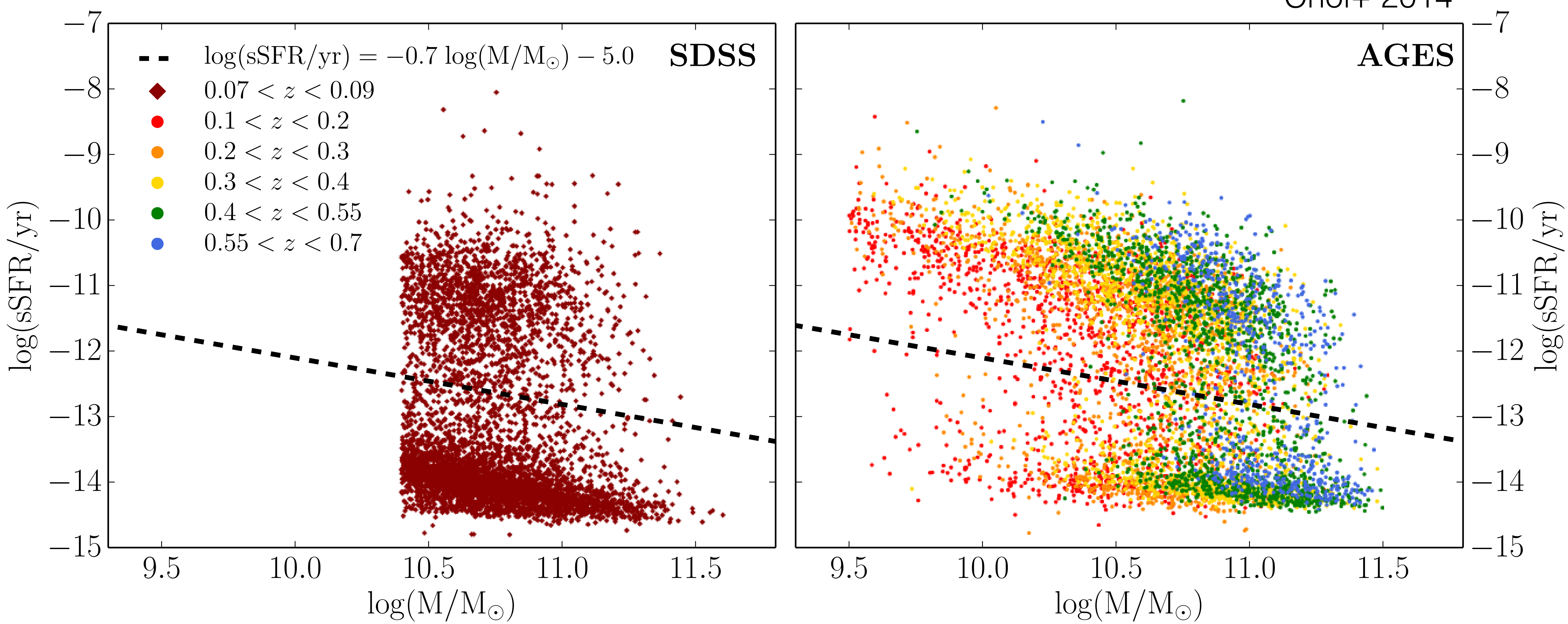
mmto.org

Jannuzi & Dey 1999; Kochanek+ 2012

R ~ 1000
10,839 galaxies
$15 < I_{Vega} < 20$

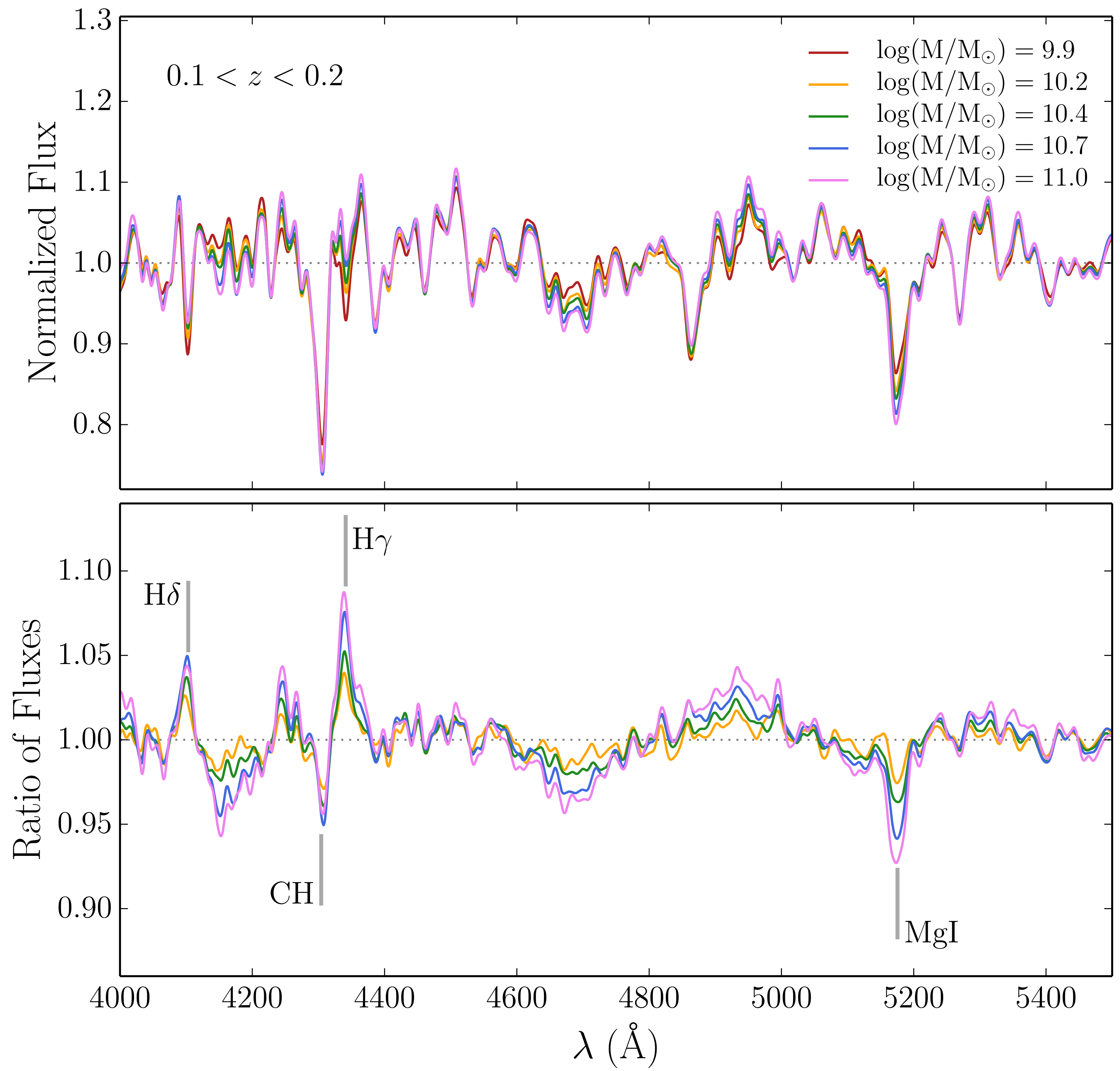
quiescence selection using specific SFR

Choi+ 2014



stellar mass and SFR estimates from iSEDfit Moustakas+ 2013

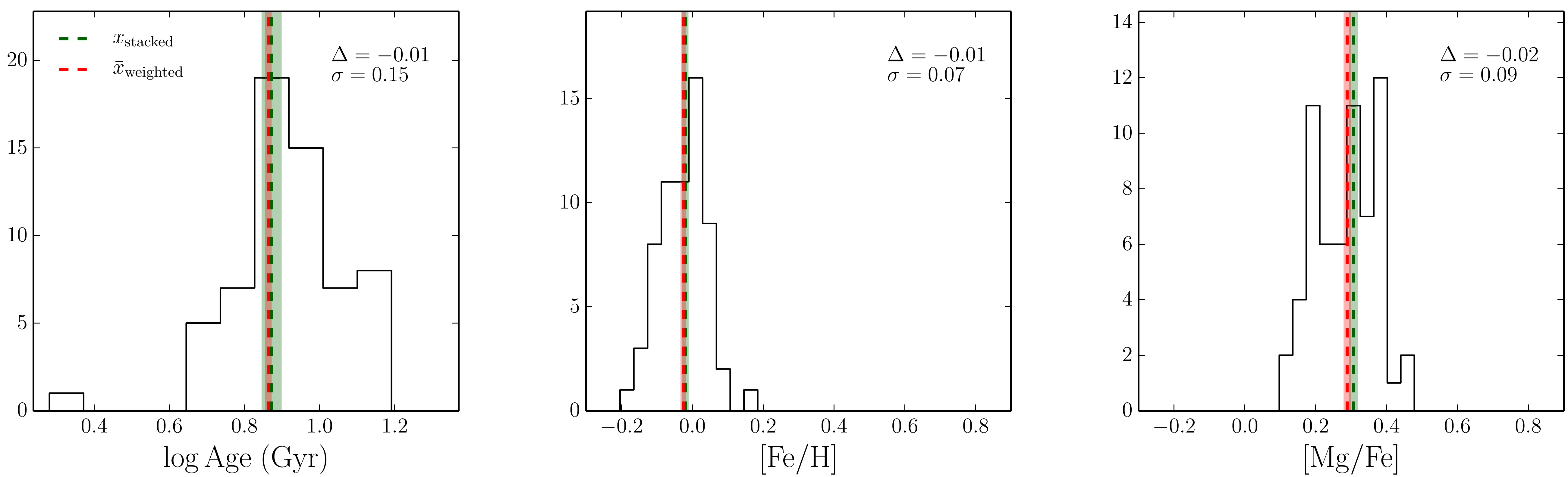
stacked spectra in bins of logM-z



Choi+ 2014

testing the stacking procedure

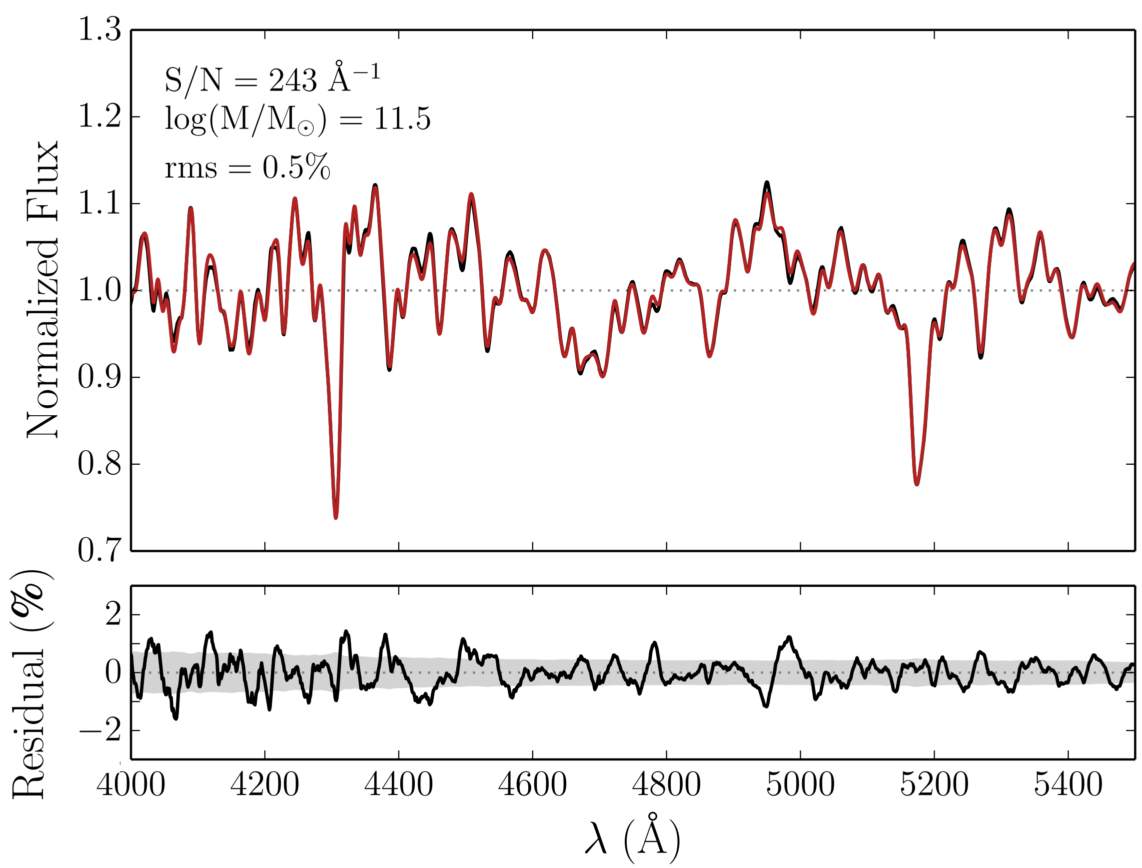
Choi+ 2014



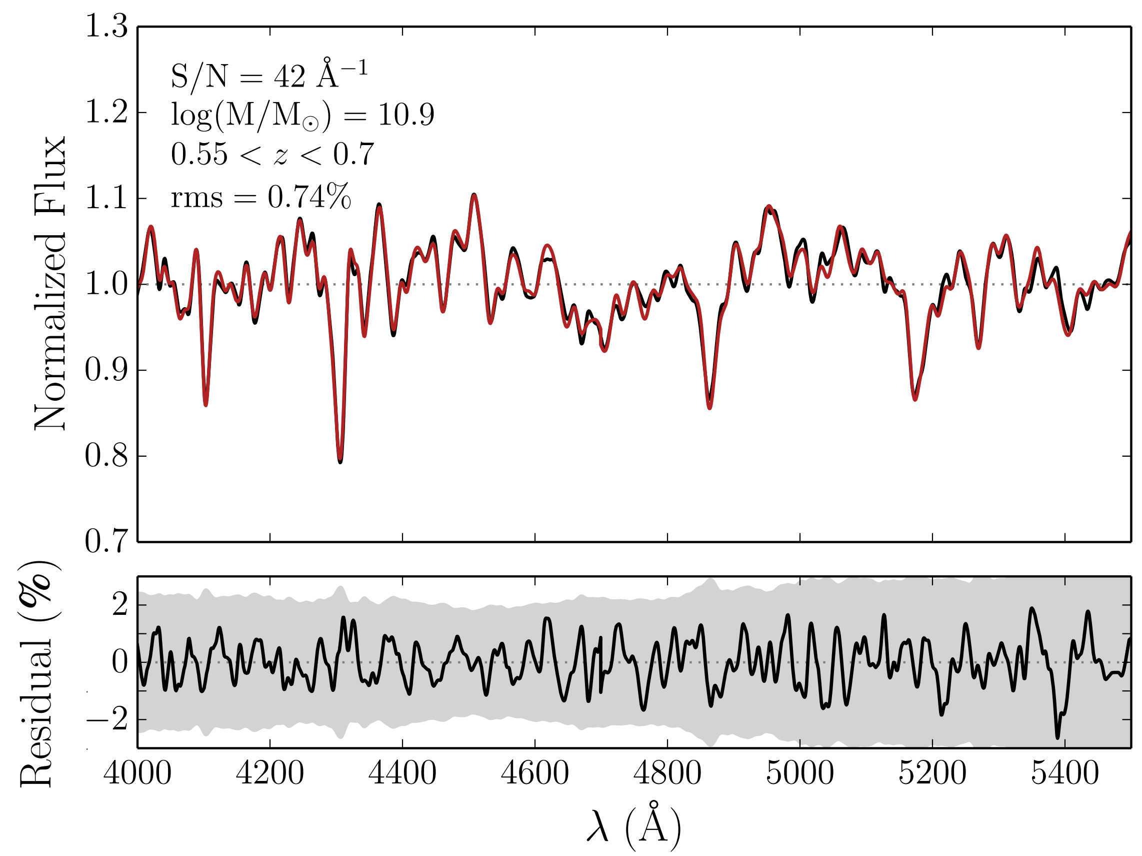
62 SDSS galaxies with $\log(M/M_\odot) \sim 11.5$

example fits

SDSS

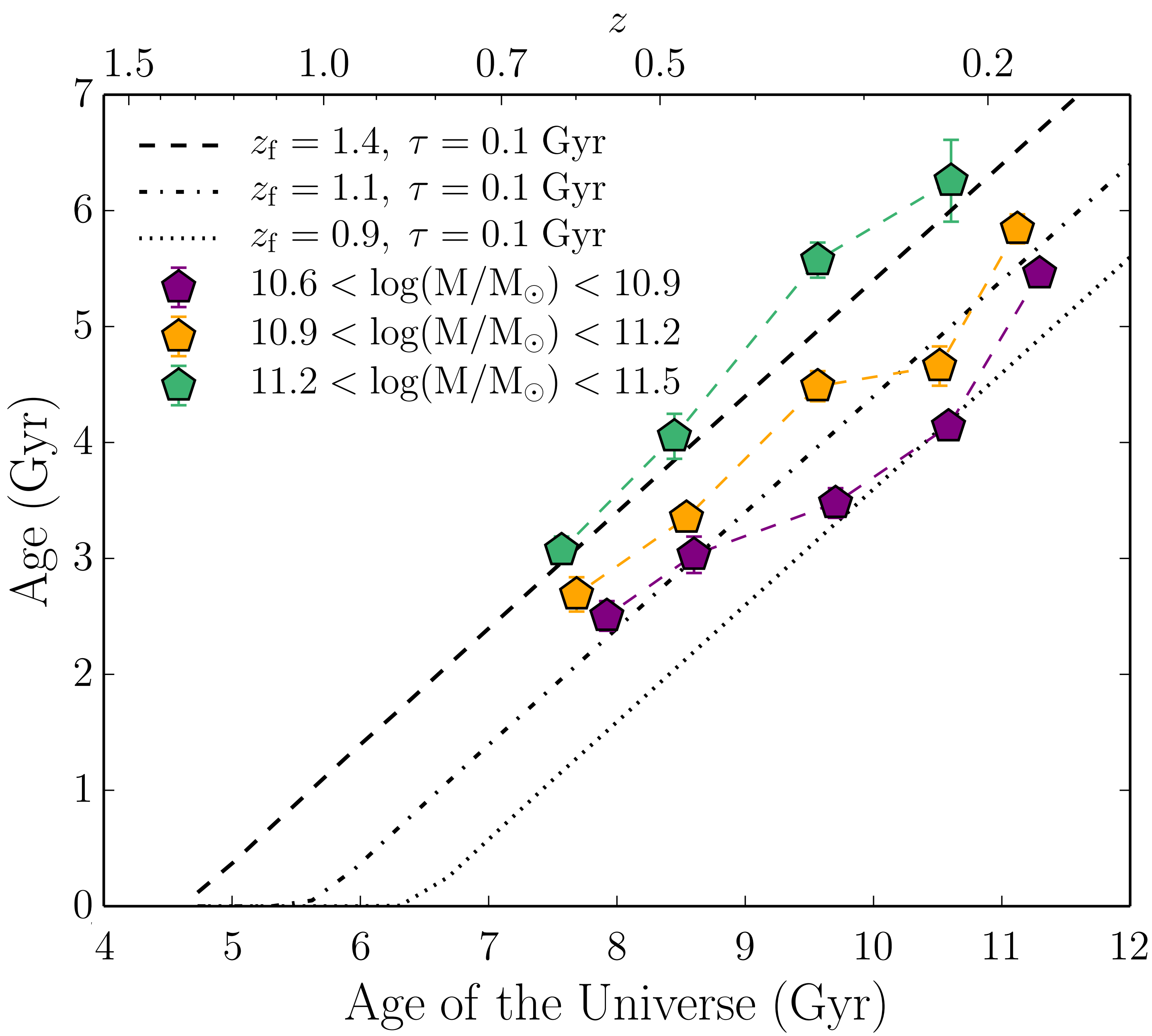


AGES



Choi+ 2014

Choi+ 2014



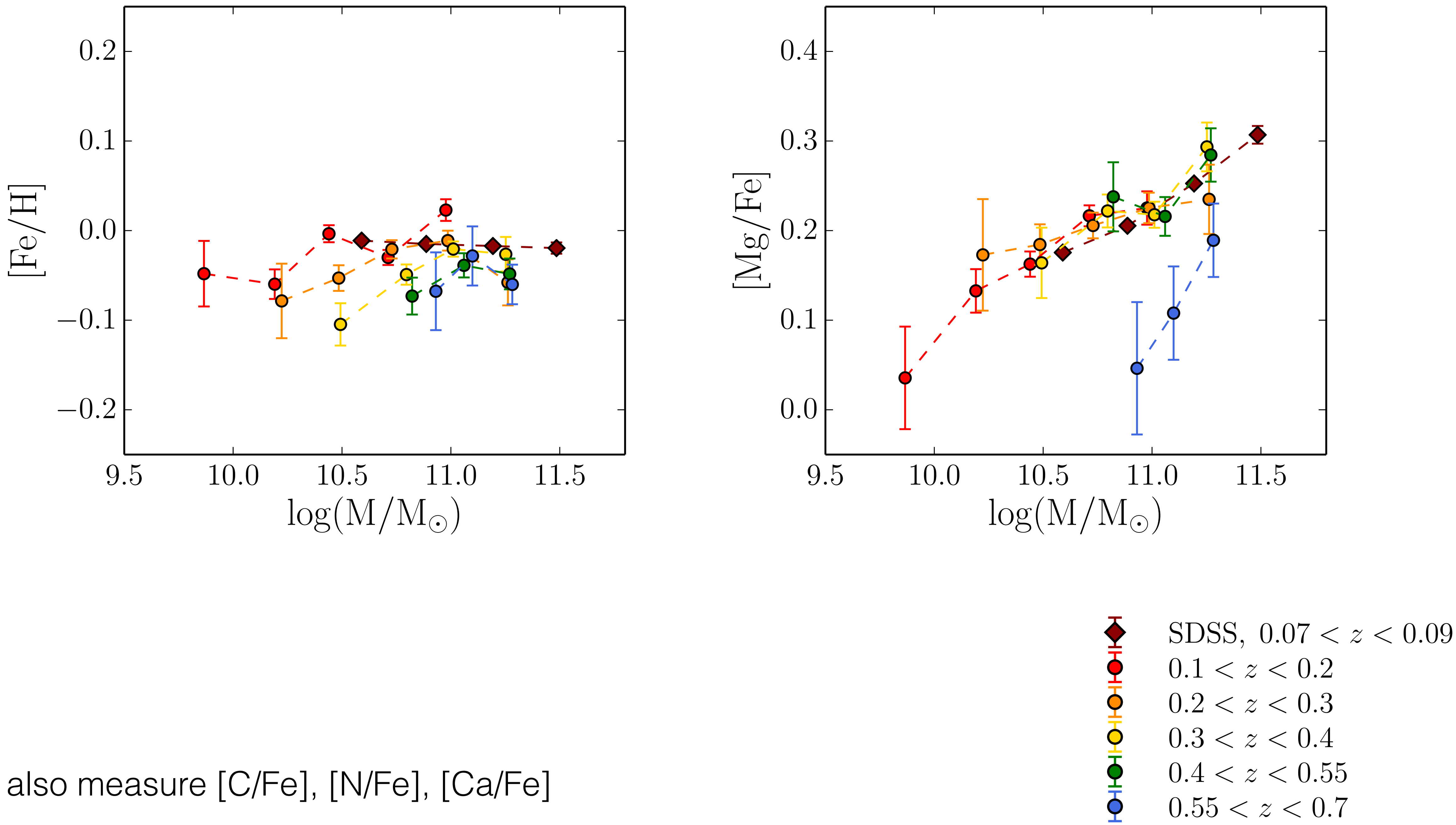
the ages of
massive quiescent galaxies
are consistent with
passive evolution

effective single-burst SF
at z < 1.5

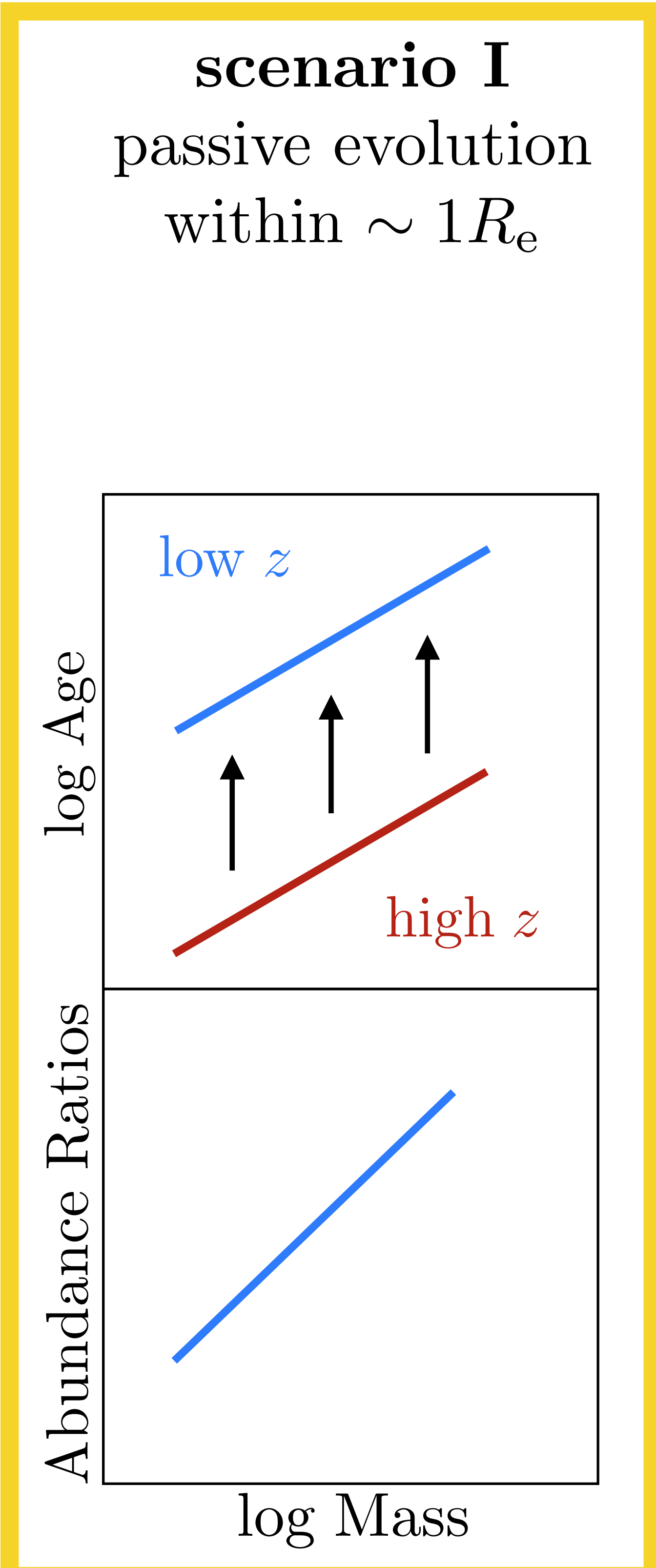
the addition of
newly quenched galaxies
at z > 0.7

the abundance ratios show no redshift evolution

Choi+ 2014



* we also measure [C/Fe], [N/Fe], [Ca/Fe]



Choi+ 2014

a comparison with toy models indicates that the inner regions (~0.3 – 3 R_e) of massive quiescent galaxies appear to be passively evolving since z~0.7

what's next?

ongoing survey at UCSC using Keck DEIMOS

~500 quiescent galaxies at <z>~0.7 with 8 - 36 hr exposures

http://www.astro.caltech.edu/

low S/N regime (~20 Å^{-1} with ~0.1 dex precision)

z ~ 1, e.g., MOSFIRE

radial gradient studies, e.g., MaNGA

summary

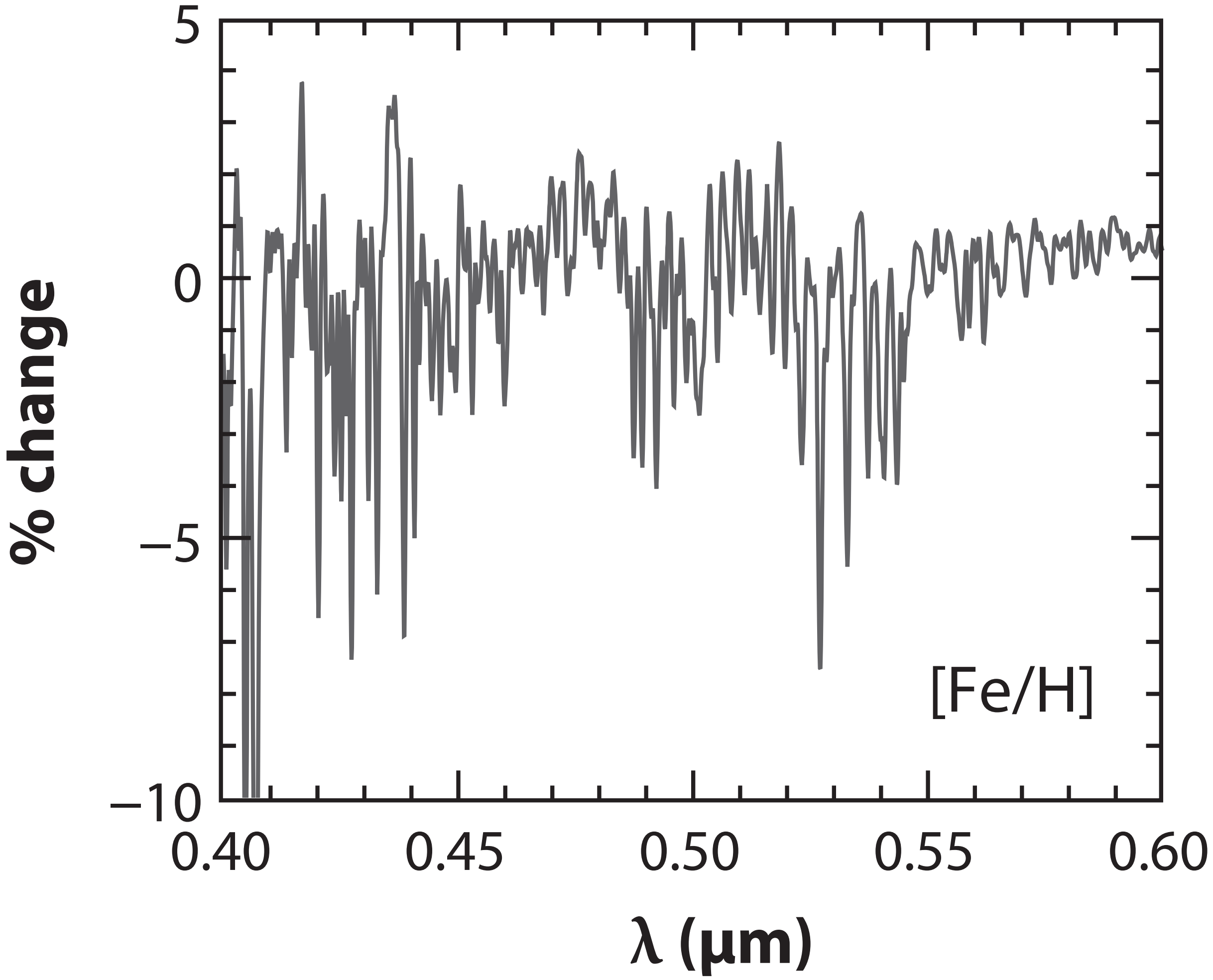
there is negligible evolution in abundances at fixed M over the last ~7 Gyr, consistent with passive evolution in the inner ~0.3 – 3 R_e

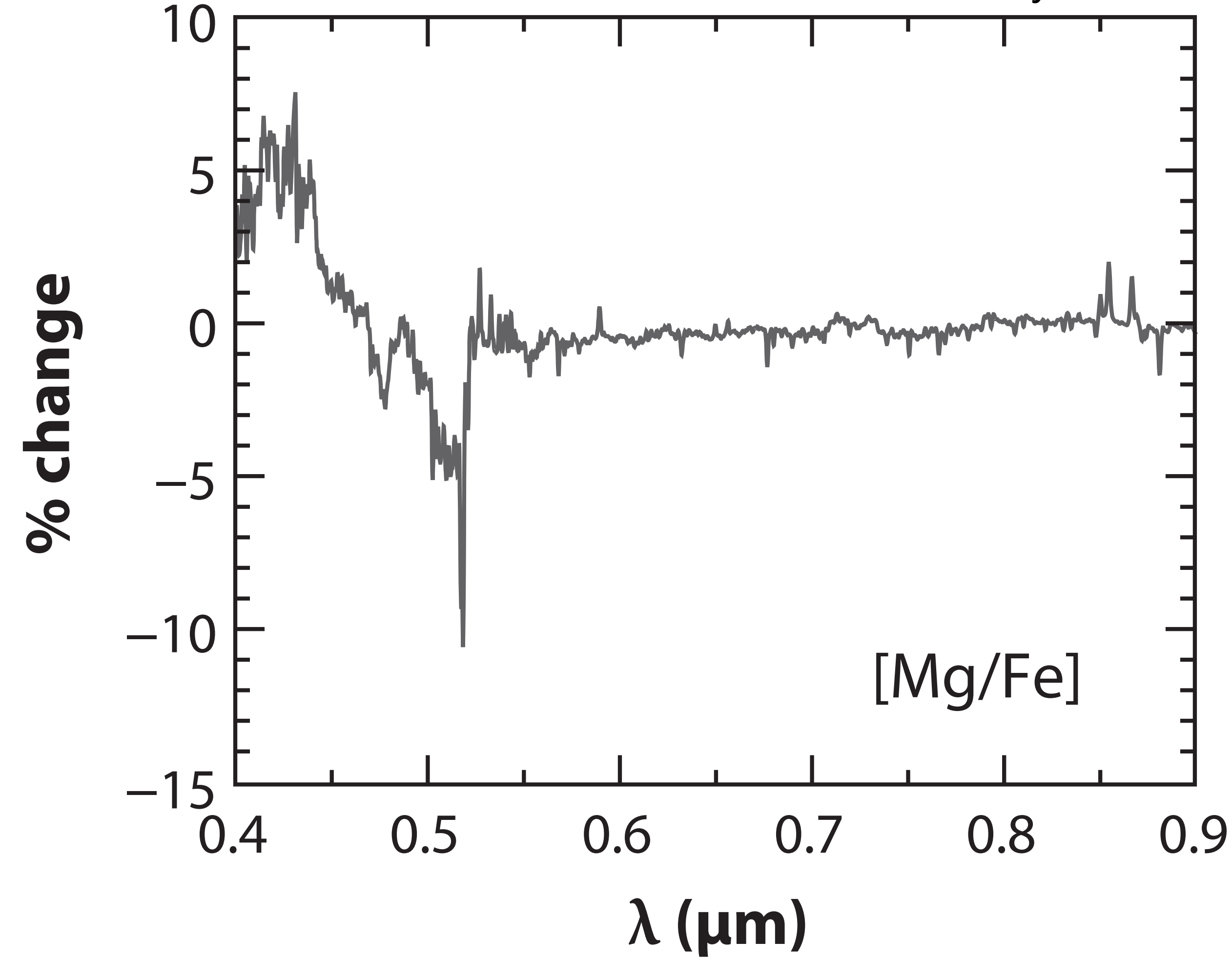
the young ages we observe & the existence of massive quiescent galaxies at $z > 1$ indicate the inhomogeneous nature of the $z<0.7$ quiescent population

the full-spectrum fitting technique opens the possibility to engage in stellar pop. analysis using low S/N data, e.g., $z>1$, galaxy outskirts

response functions allow us to measure variable abundances

Conroy 2013





13 Gyr simple stellar population

response functions allow us to measure variable abundances

response function

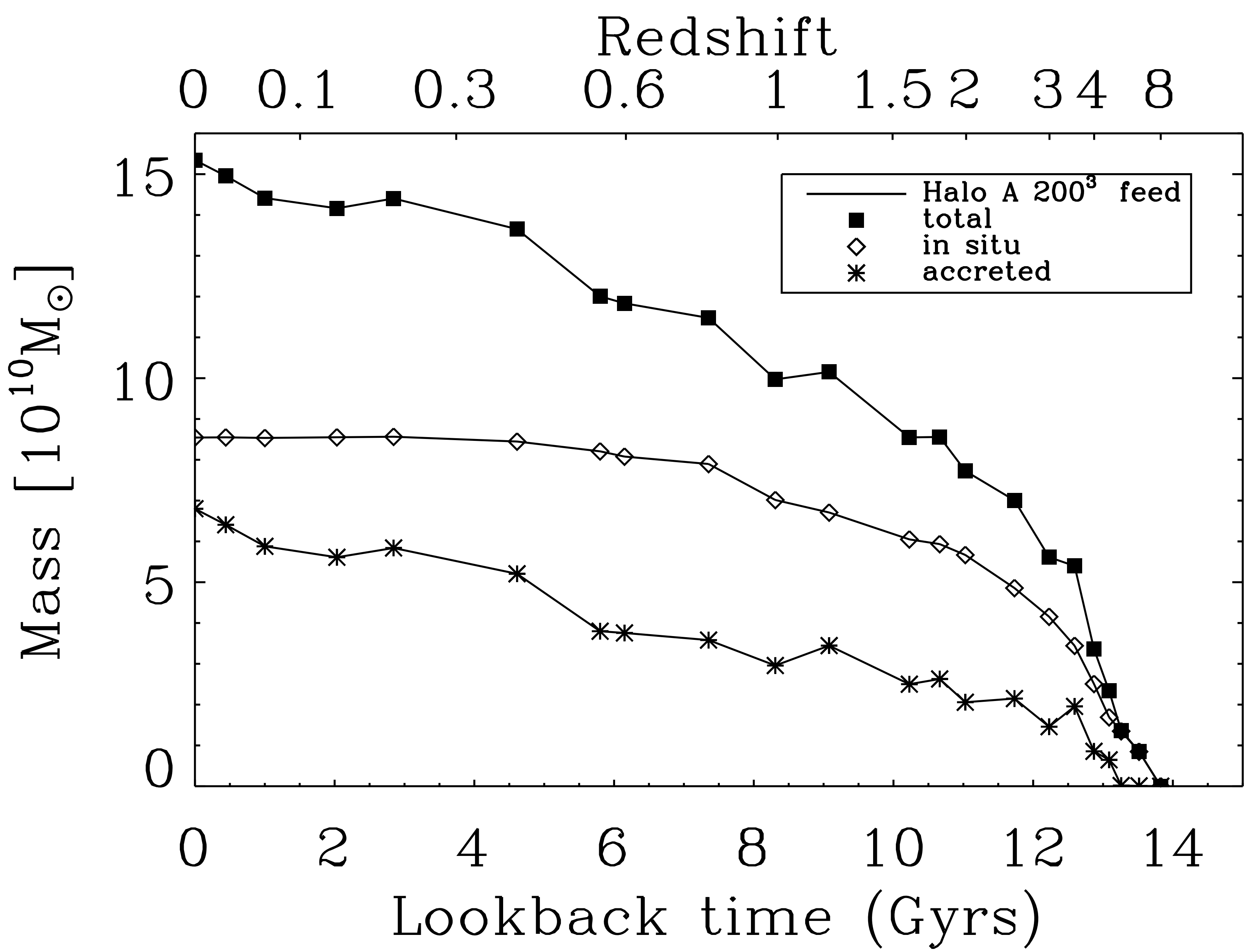
$$\mathbf{F_{\lambda,\,empirical}(non\text{-}solar)} = \frac{\mathbf{F_{\lambda,\,synthetic}(non\text{-}solar)}}{\mathbf{F_{\lambda,\,synthetic}(solar)}} \times \mathbf{F_{\lambda,\,empirical}(solar)}$$

what we fit to a galaxy spectrum
with non-solar abundances

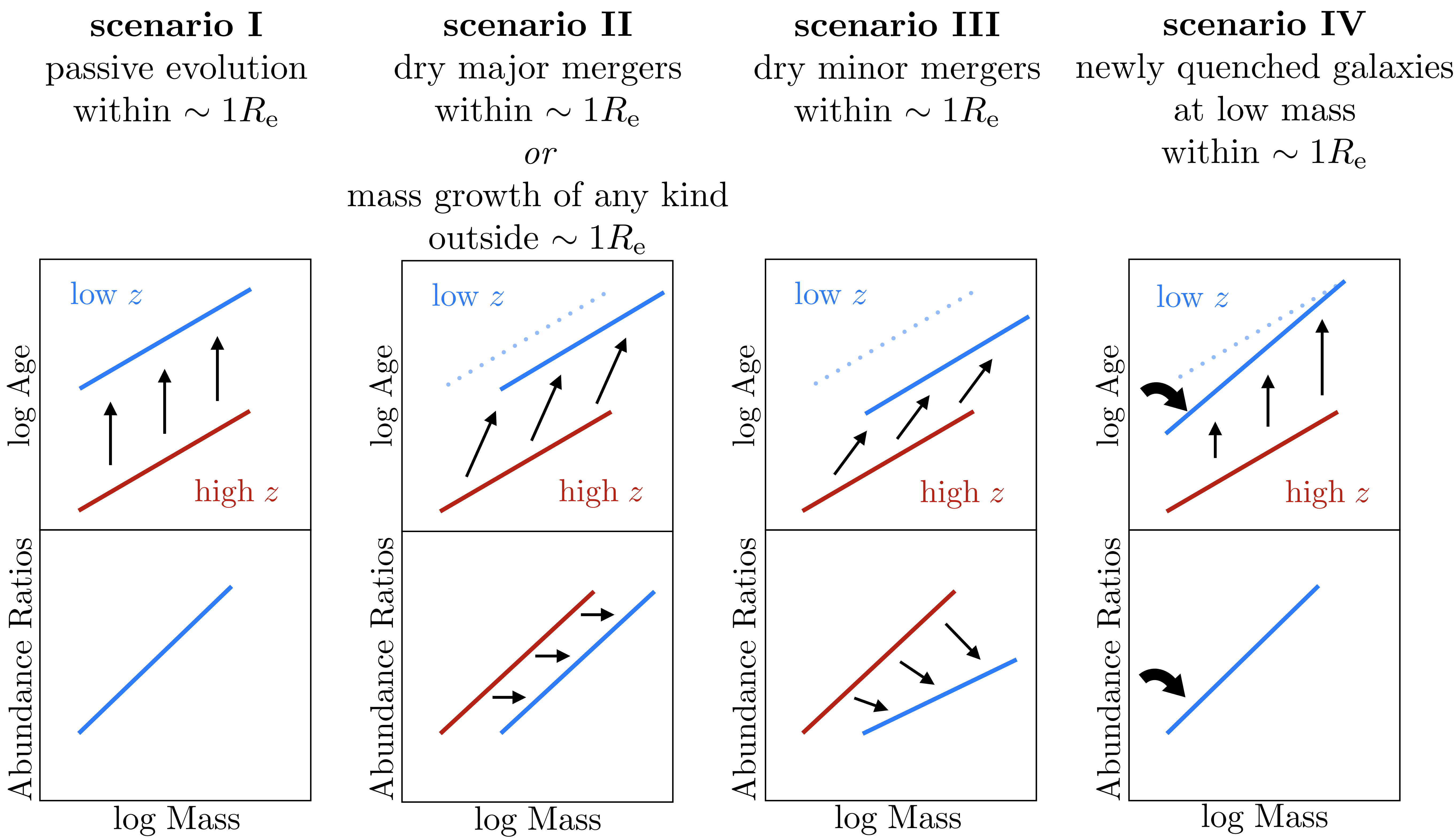
empirical spectrum

simulations suggest dry minor-mergers

Naab+ 2009

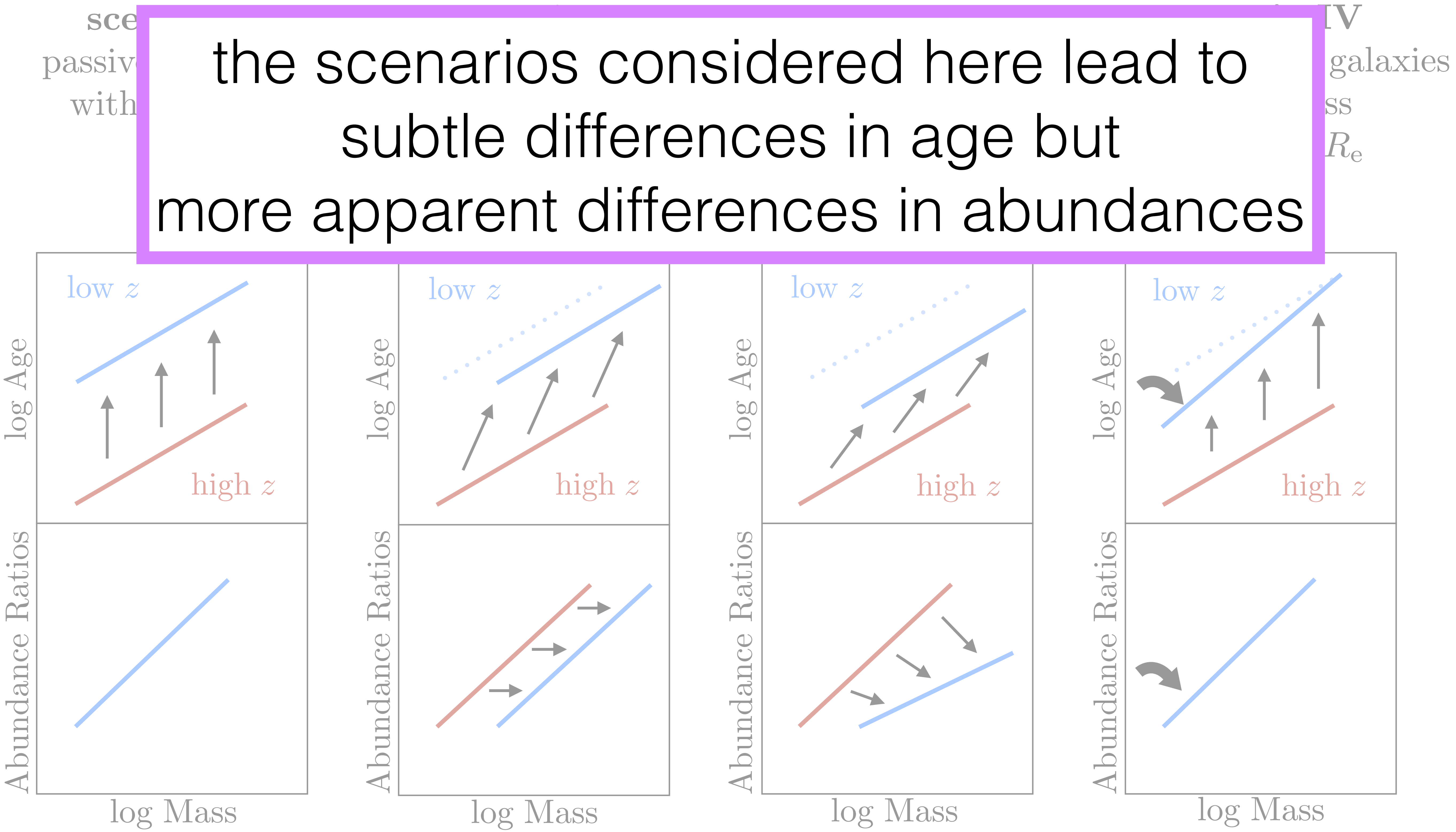


e.g., Naab+ 2007; Kereš+ 2009; Naab+ 2009; Hopkins+ 2009; Dekel+ 2009; Lackner+ 2012; Hilz+ 2013 *assuming the spectra are probing ~ 1 R_e



Choi+ 2014

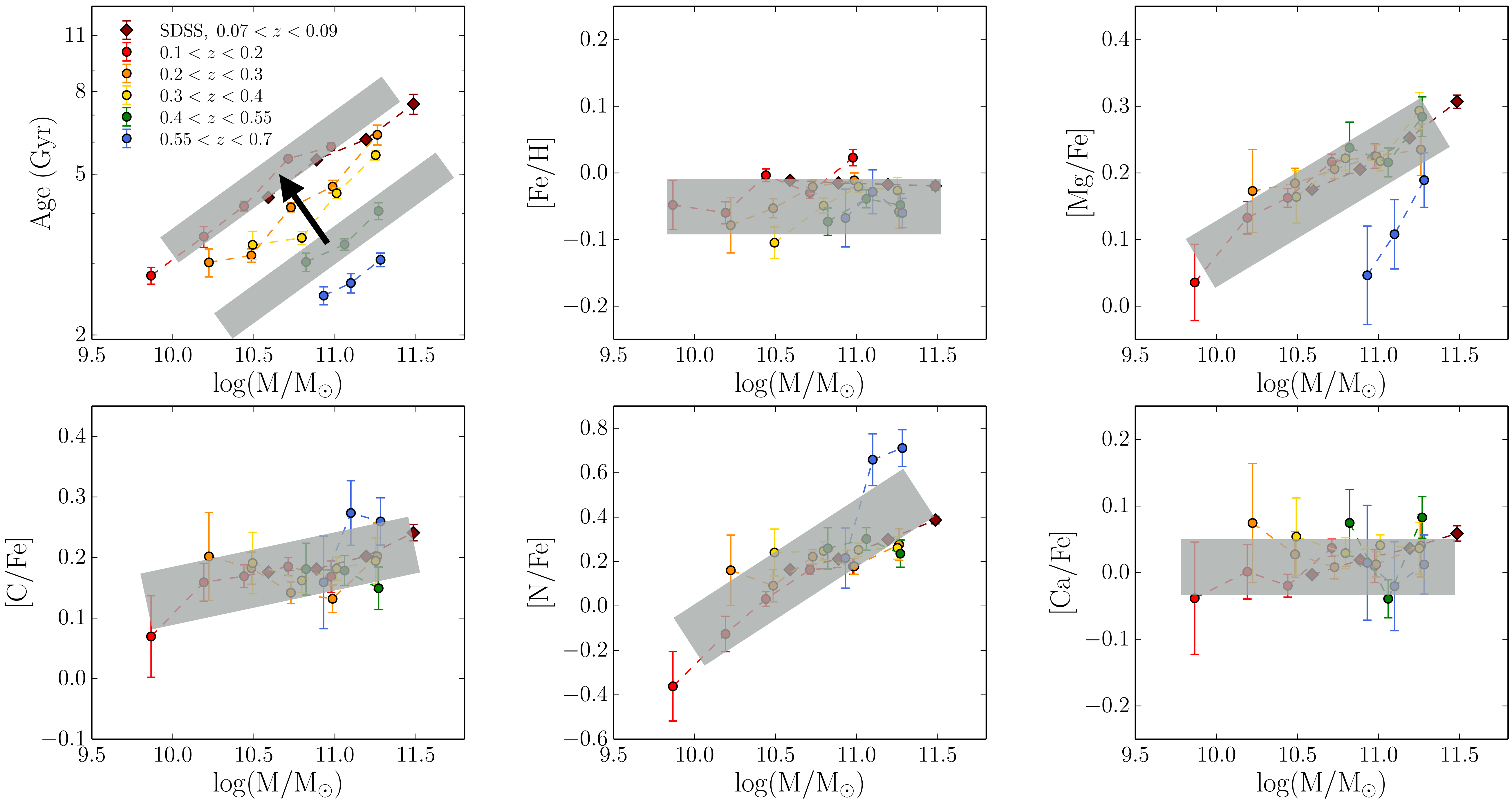
the scenarios considered here lead to subtle differences in age but more apparent differences in abundances



Choi+ 2014

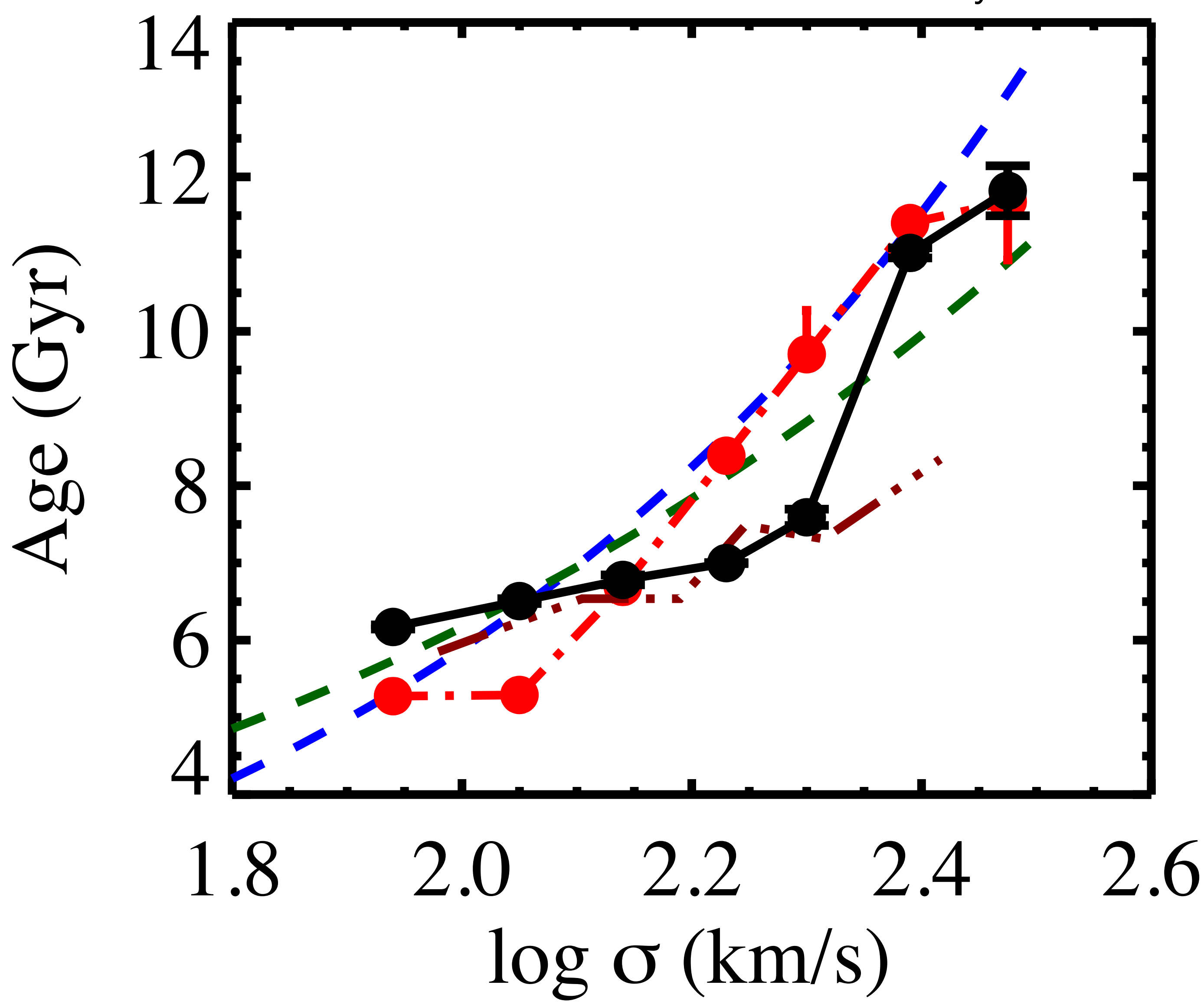
recall that the abundances show no redshift evolution

Choi+ 2014



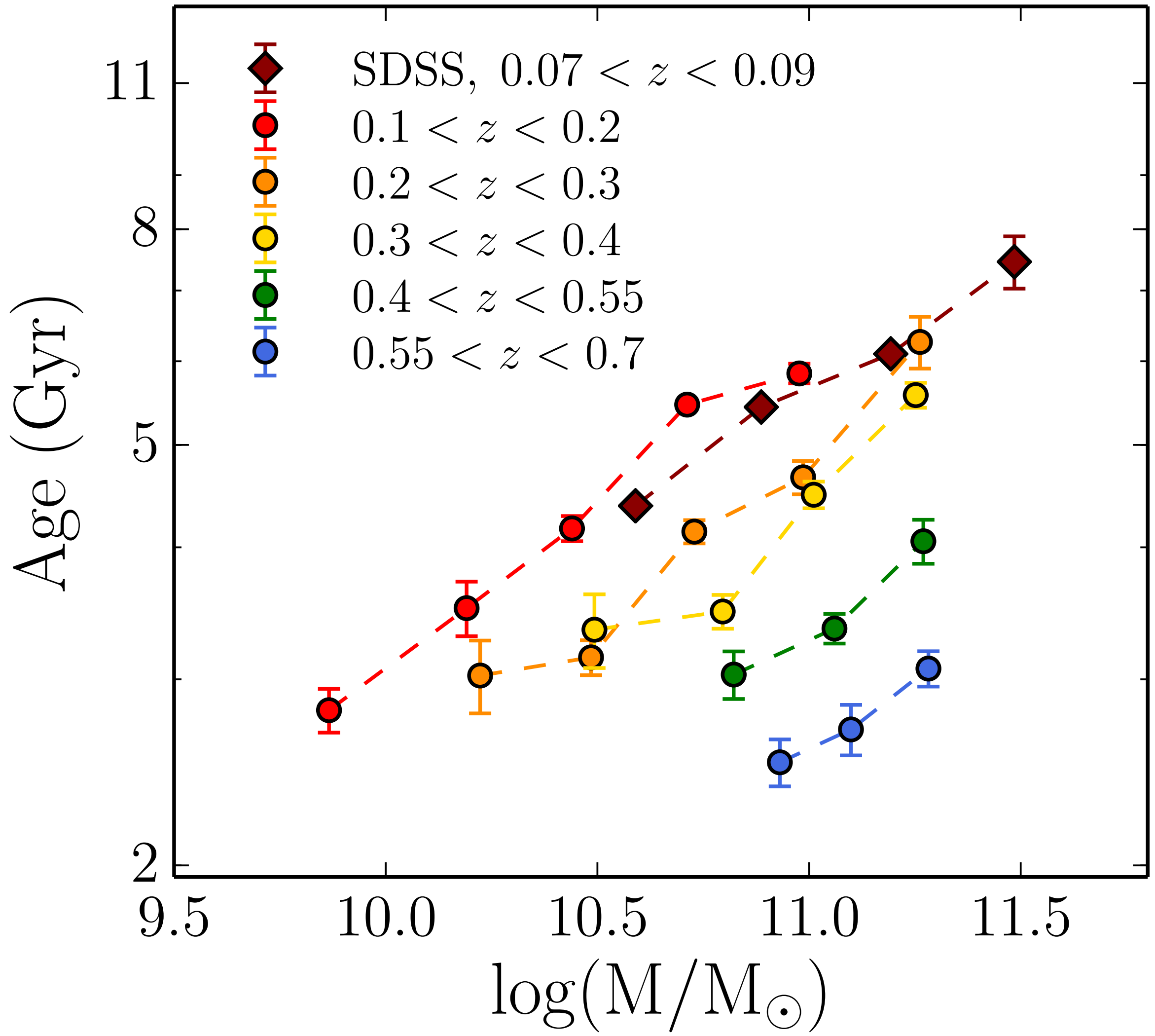
stars in massive quiescent galaxies are old

Conroy+ 2014



e.g., Trager+ 1998; Thomas+ 2005; Graves+ 2007; Schiavon 2007; Smith+ 2009; Zhu+ 2010; Thomas+ 2010; Johansson+ 2012; Worthey+ 2013; Conroy+ 2014

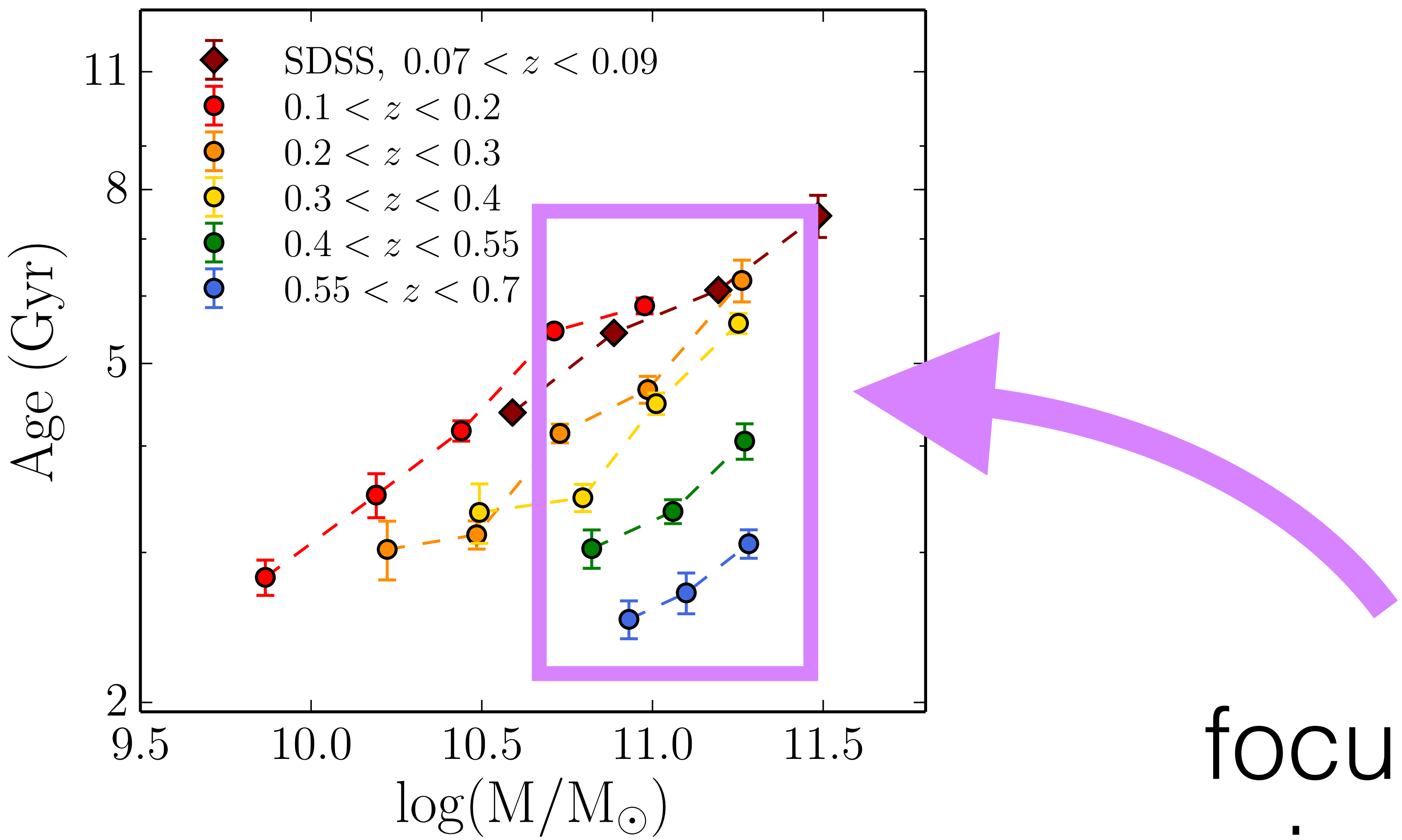
Choi+ 2014



galaxies become older
with decreasing z

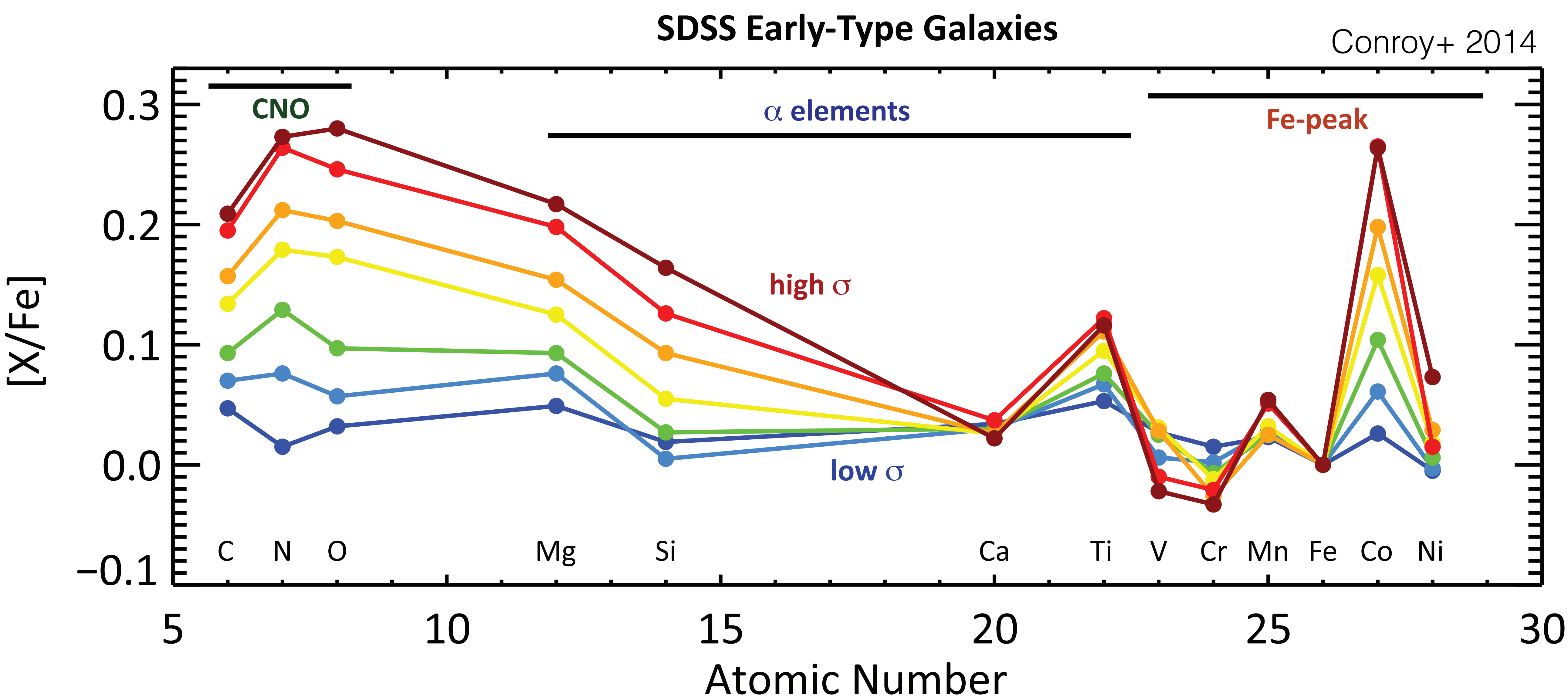
galaxies become older
with increasing mass

Choi+ 2014



focus on the massive end where we have good redshift coverage

… and enriched in elements like Mg and C



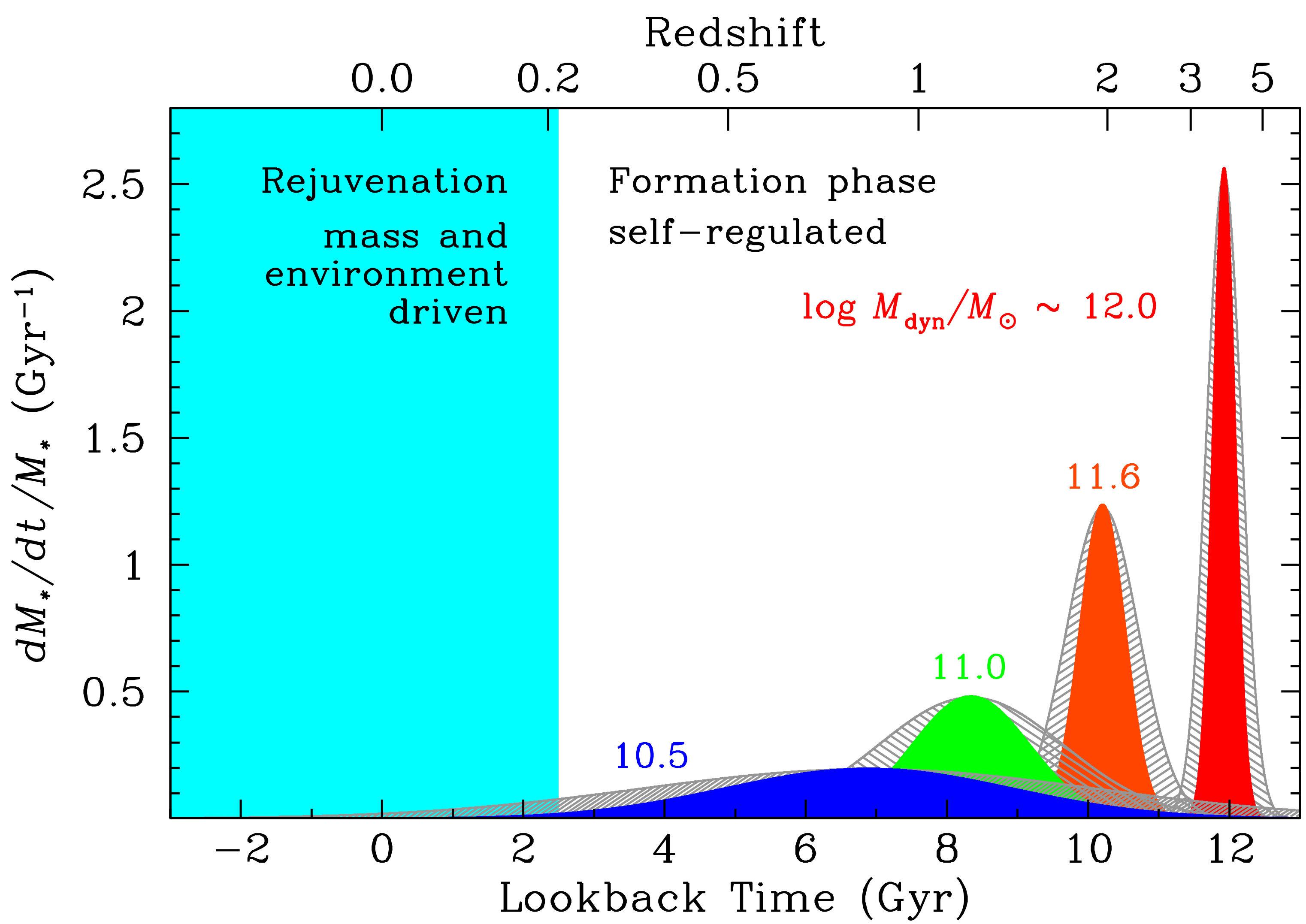
e.g., Trager+ 1998; Thomas+ 2005; Graves+ 2007; Schiavon 2007; Smith+ 2009; Zhu+ 2010; Thomas+ 2010; Johansson+ 2012; Worthey+ 2013; Conroy+ 2014

the abundance patterns provide clues about star formation processes

high [a/Fe]

=

short SF timescales



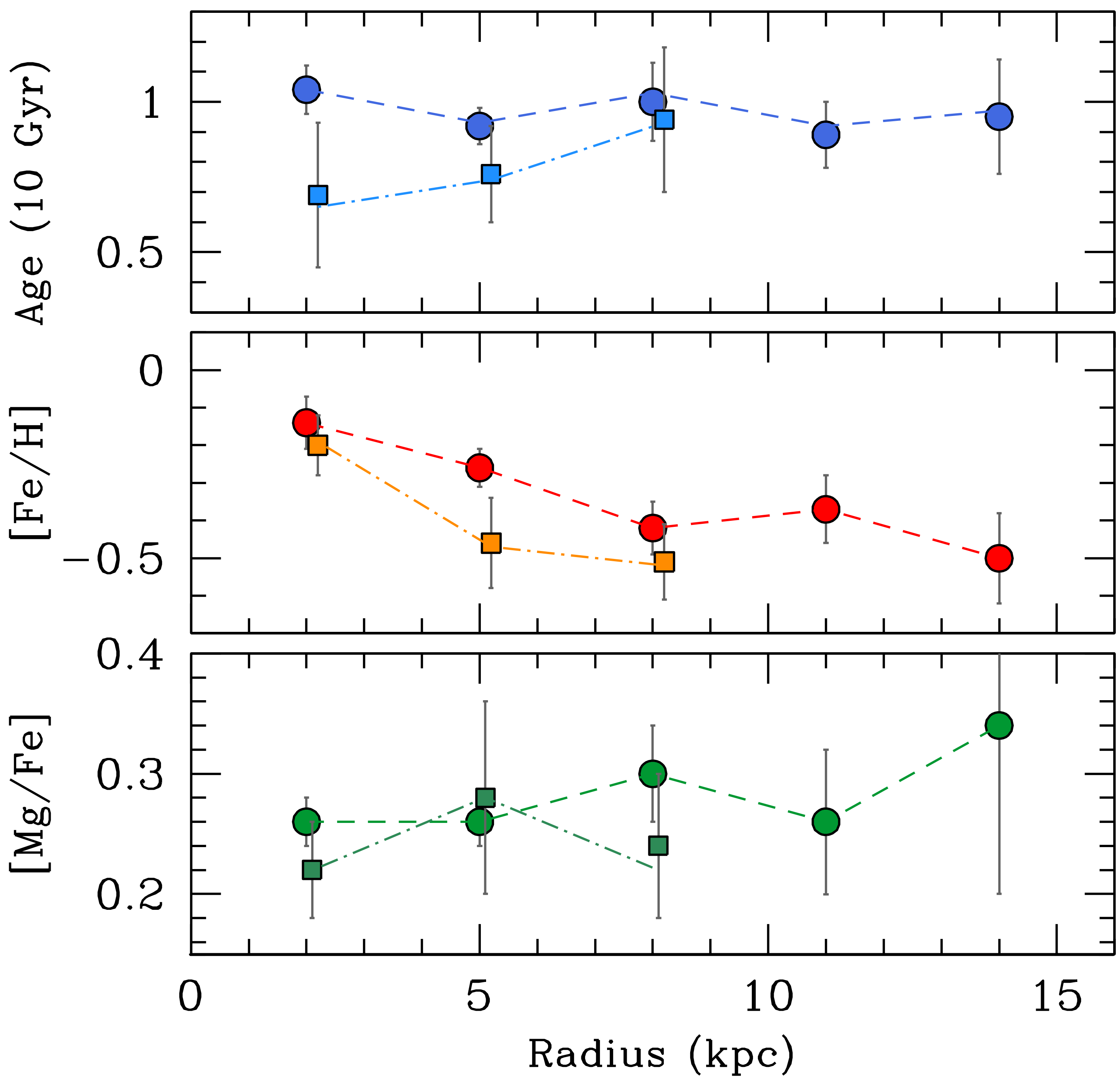
Thomas+ 2010

quiescent galaxies

=

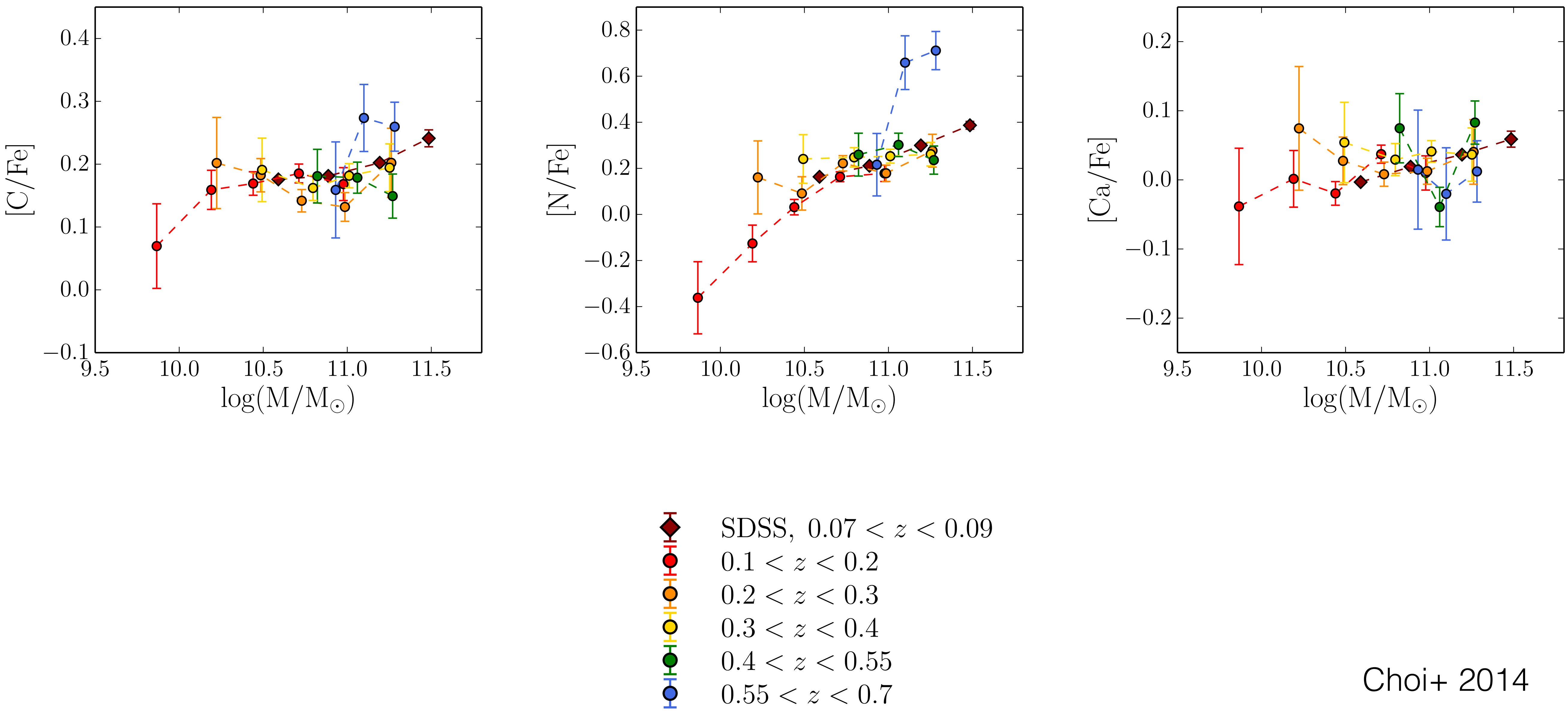
non-star-forming, red, and dead galaxies

radial gradients in stellar population properties support this story (maybe)



Greene+ 2013

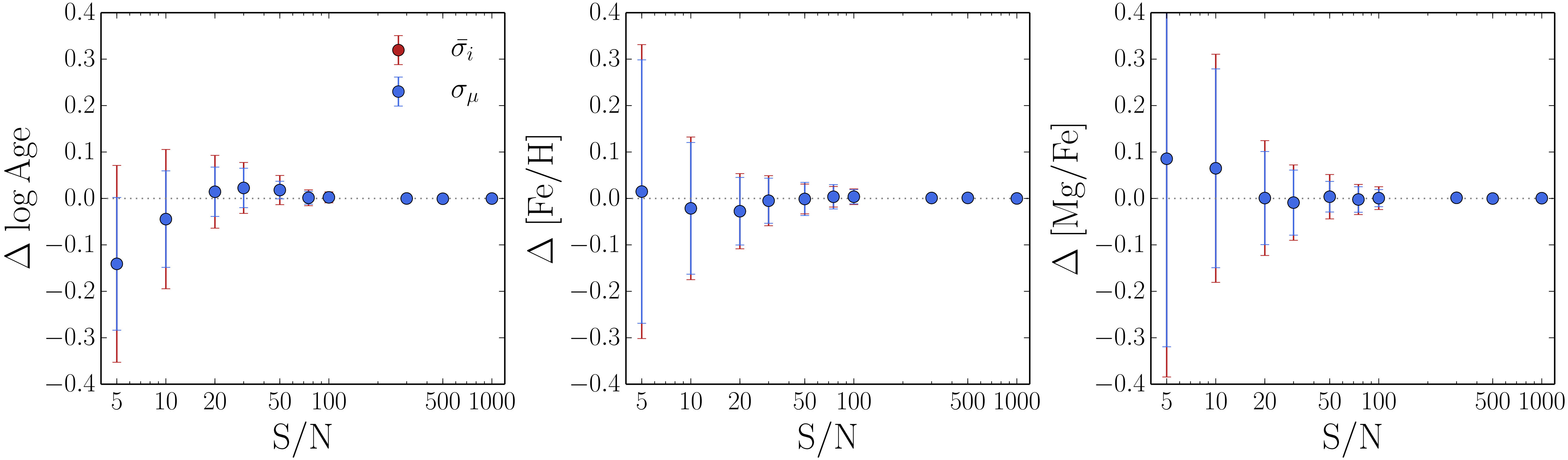
[C/Fe], [N/Fe], and [Ca/Fe] also show no redshift evolution



Choi+ 2014

advantages of full-spectrum fitting:
1. low S/N

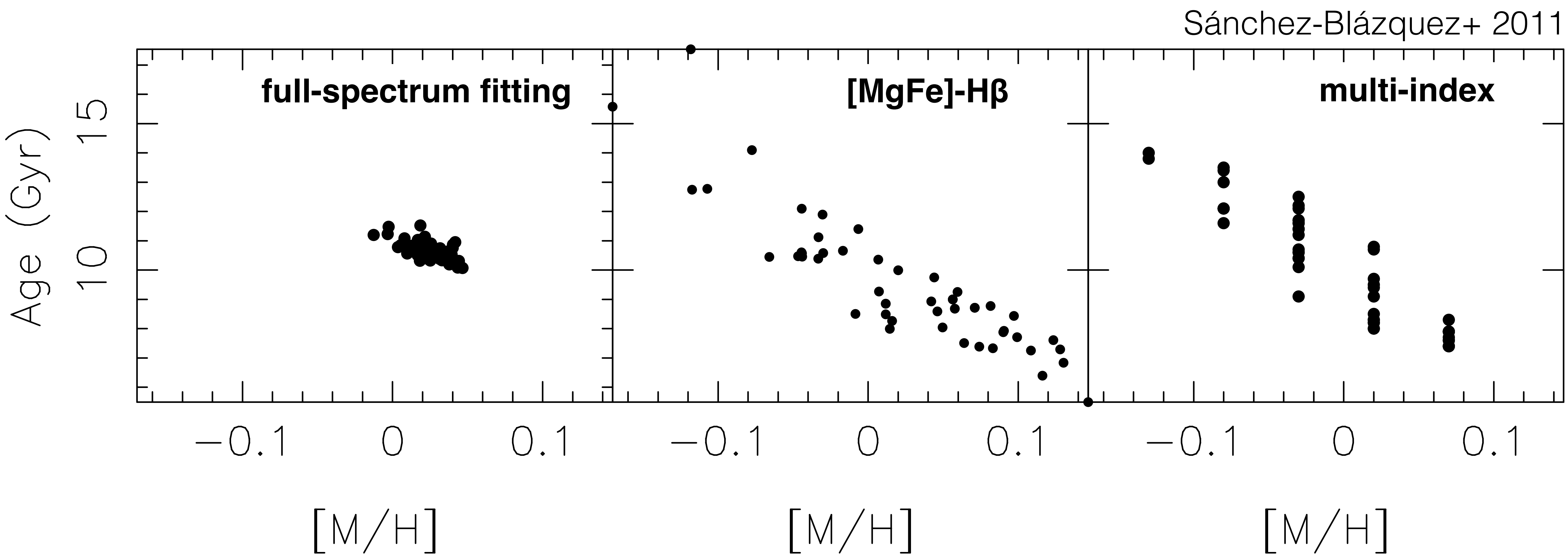
Choi+ 2014



x10 difference in S/N = **x100** difference in integration time!

full-spectrum fitting: see also, e.g., Walcher+ 2009, Ocvirk+ 2006a,b

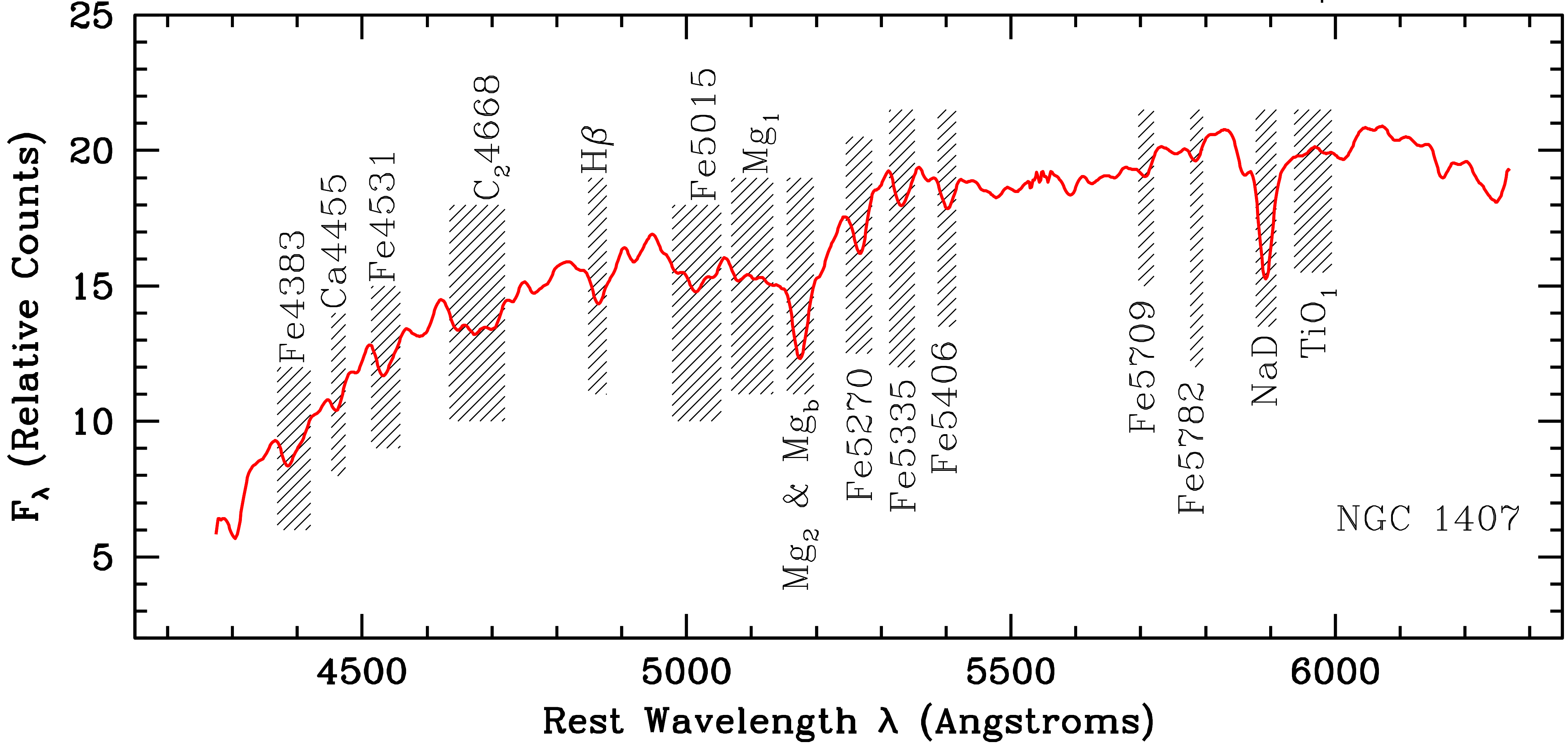
advantages of full-spectrum fitting:
2. age-metallicity degeneracy



a popular way to measure abundances is the Lick/IDS index system

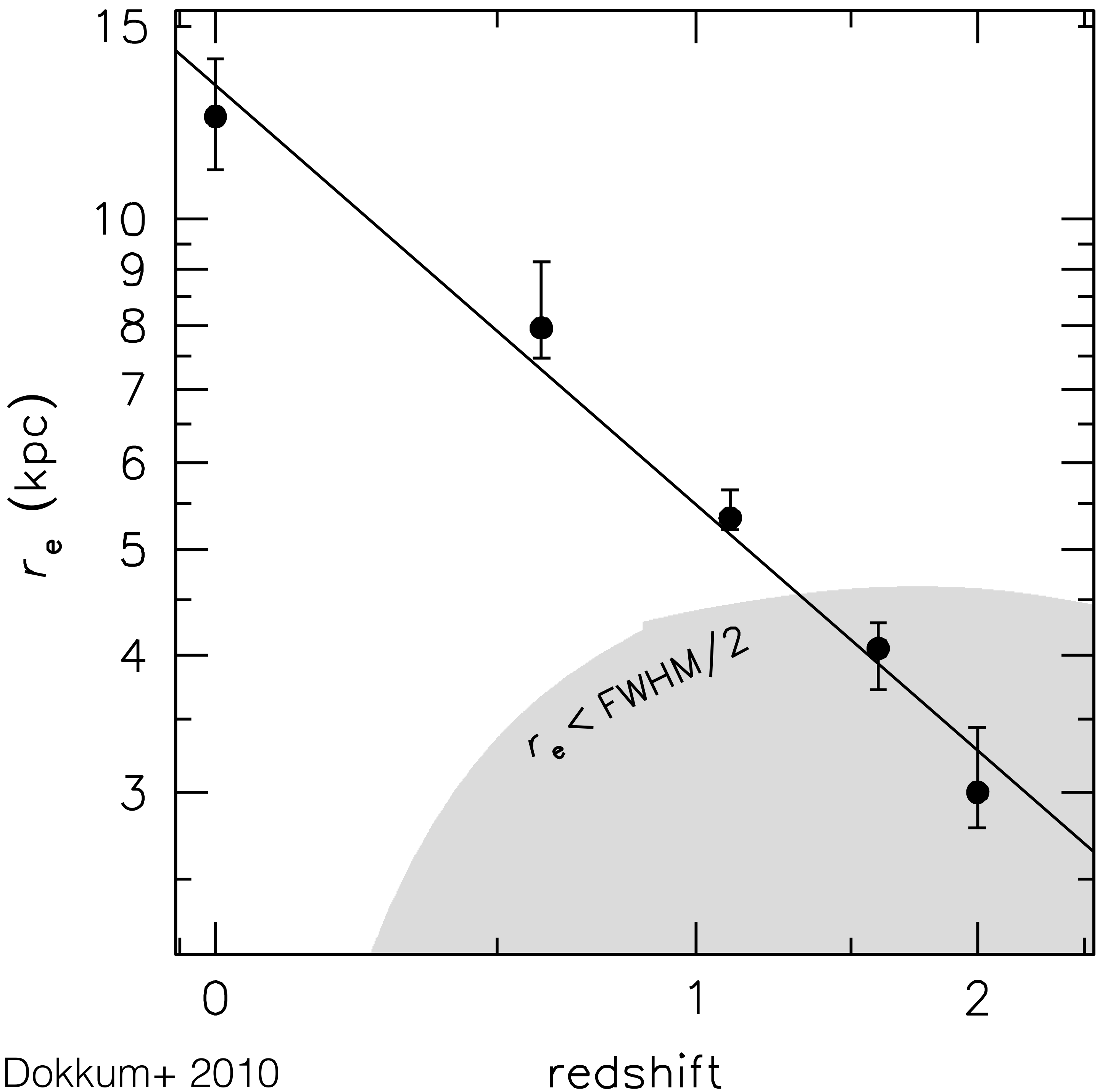
Burstein+ 1984; Worthey+ 1994

Spolaor+ 2007



requires S/N~100 per Angstrom

quiescent galaxies appear to grow inside-out

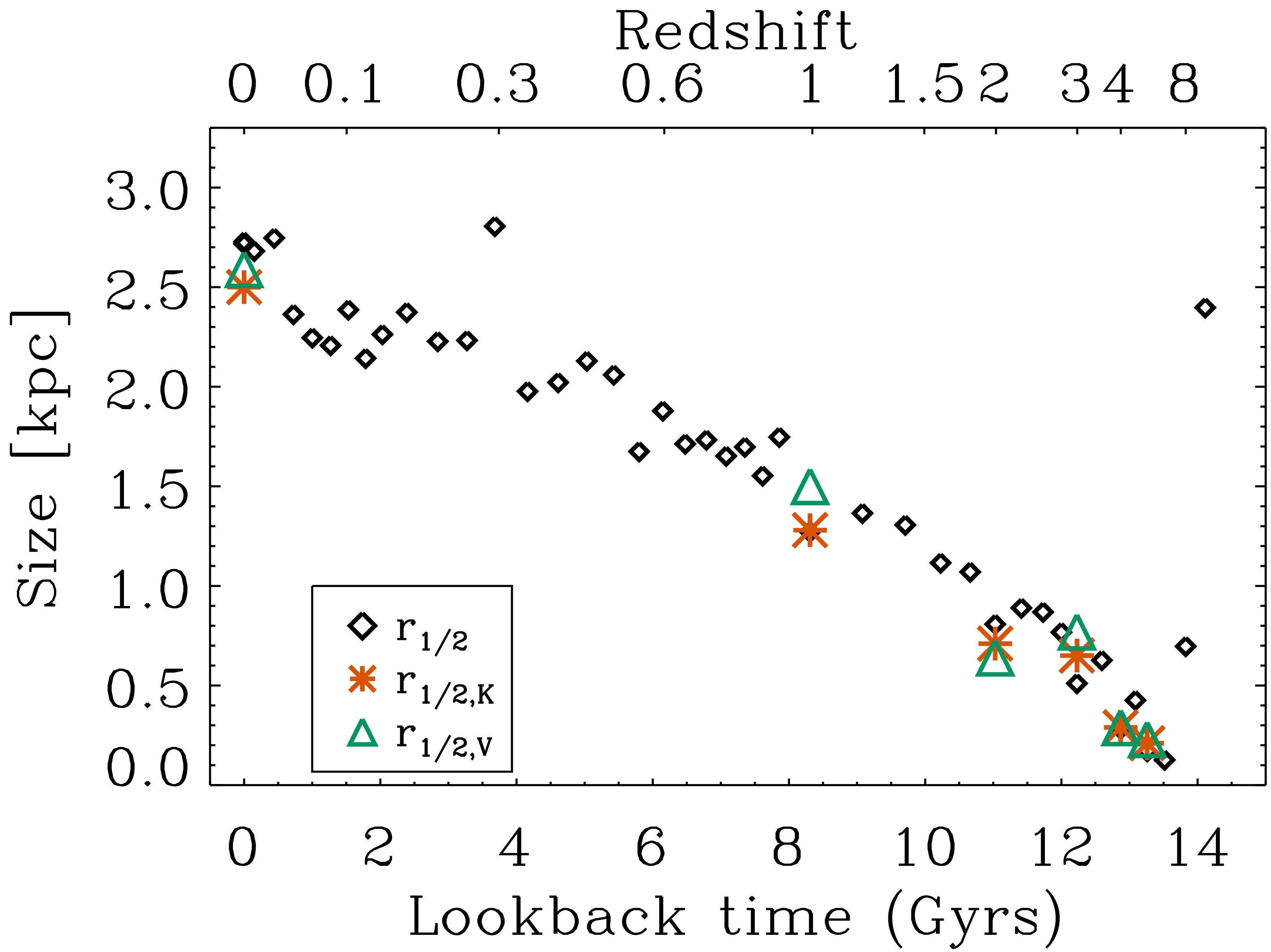


vanDokkum+ 2010

e.g., Daddi+ 2005; Trujillo+ 2006; vanDokkum+ 2008; vanderWel+ 2008; Cimatti+ 2008; Bezanson+ 2009; Damjanov+ 2009; Williams+ 2010; Cassata+ 2010; vanDokkum+ 2010; LópezSanjuan+ 2012; McLure+ 2013; Belli+ 2013

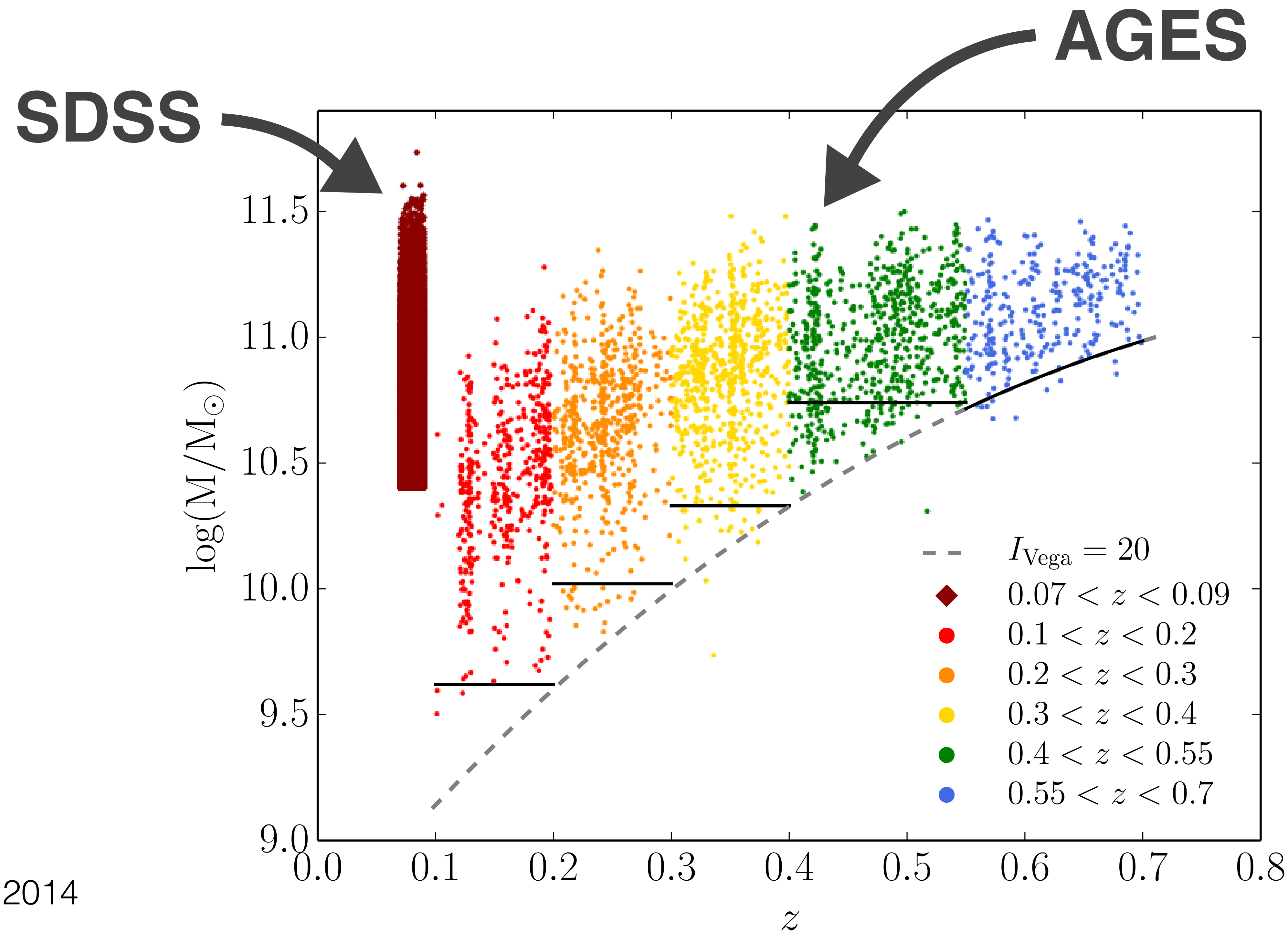
and simulations support this notion as well

Naab+ 2009

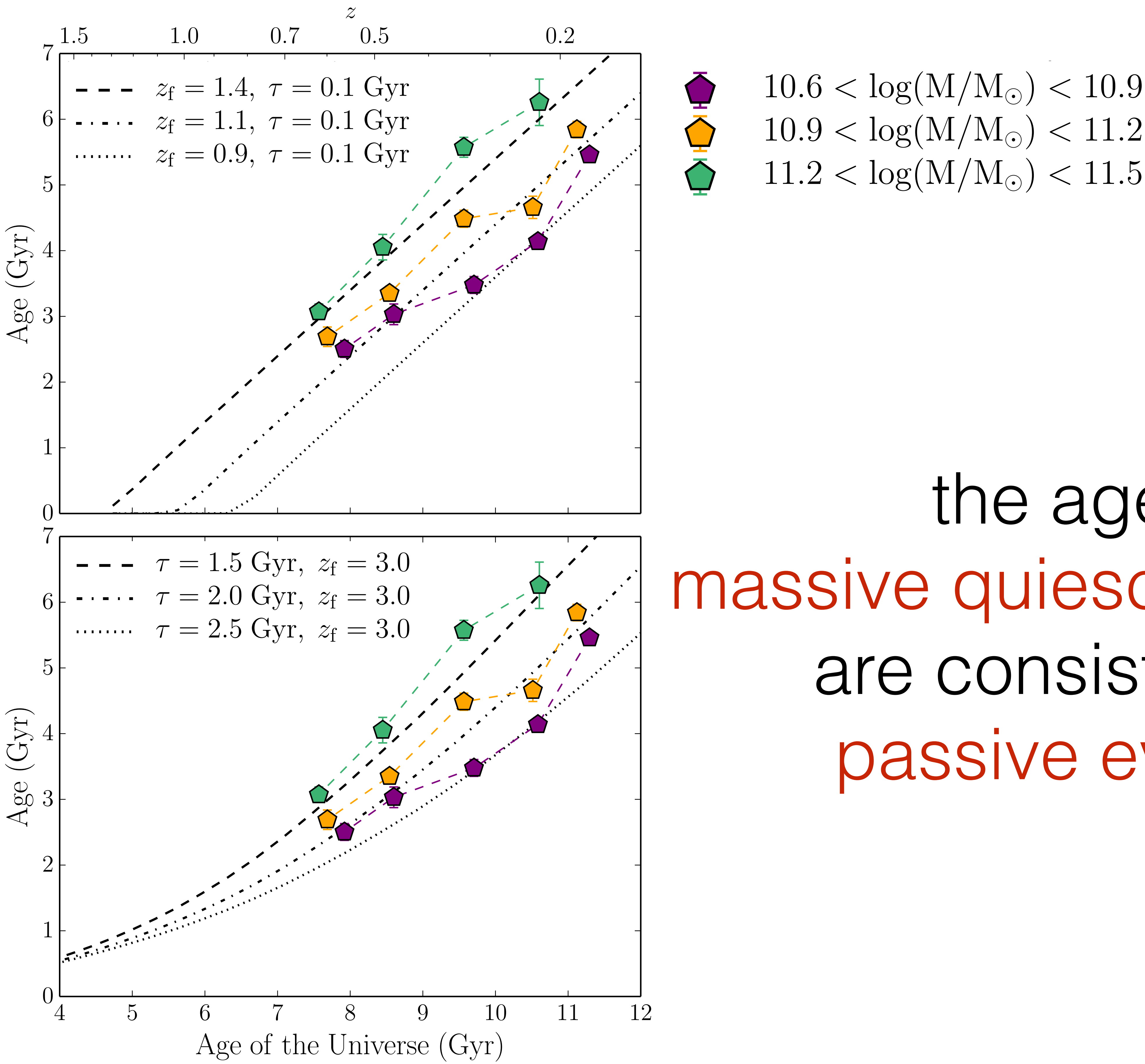


e.g., Naab+ 2007; Kereš+ 2009; Naab+ 2009; Hopkins+ 2009; Dekel+ 2009; Lackner+ 2012; Hilz+ 2013

check that the sample is mass-complete then stack spectra in bins of logM-z



Choi+ 2014

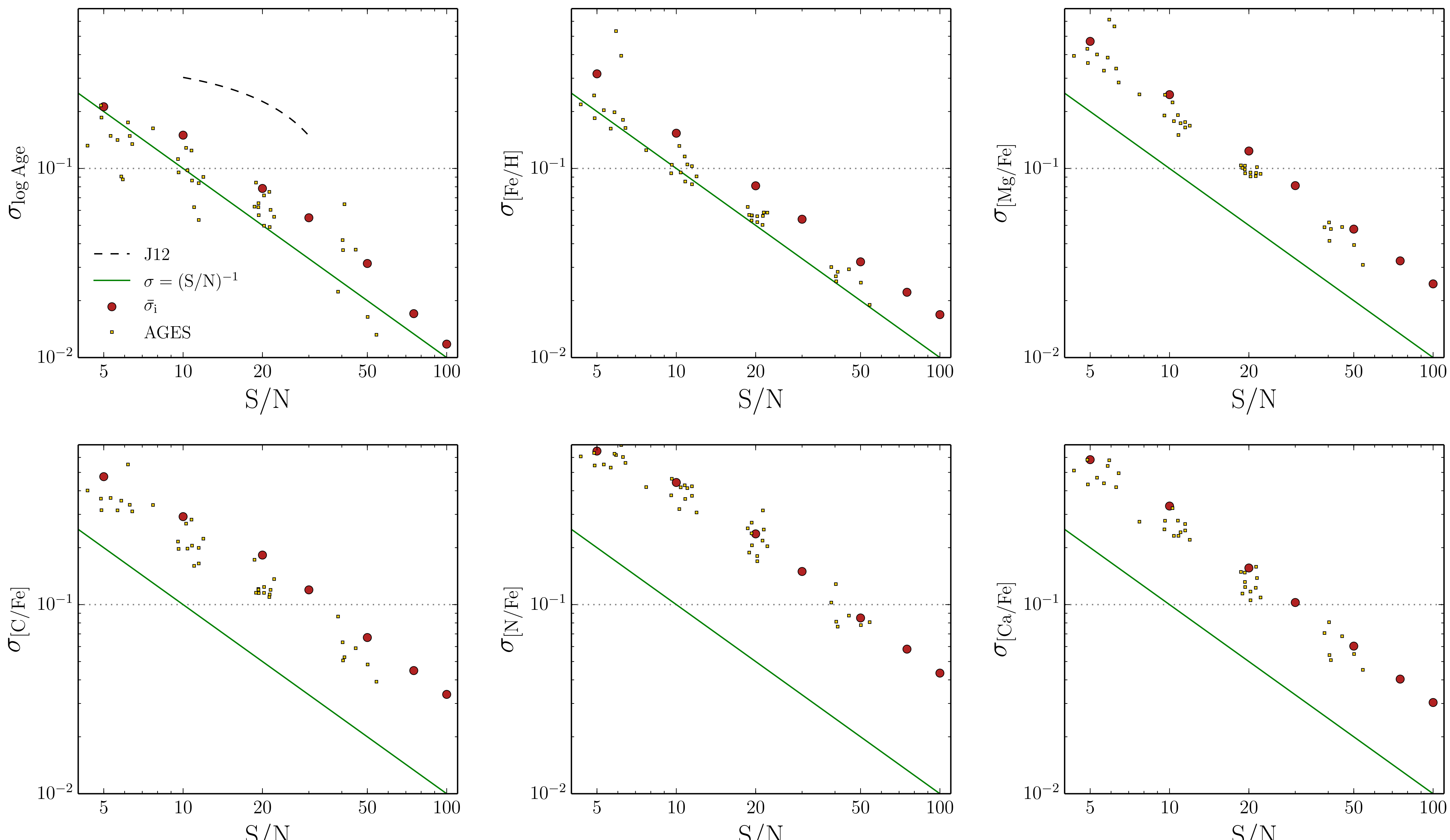


the ages of
massive quiescent galaxies
are consistent with
passive evolution

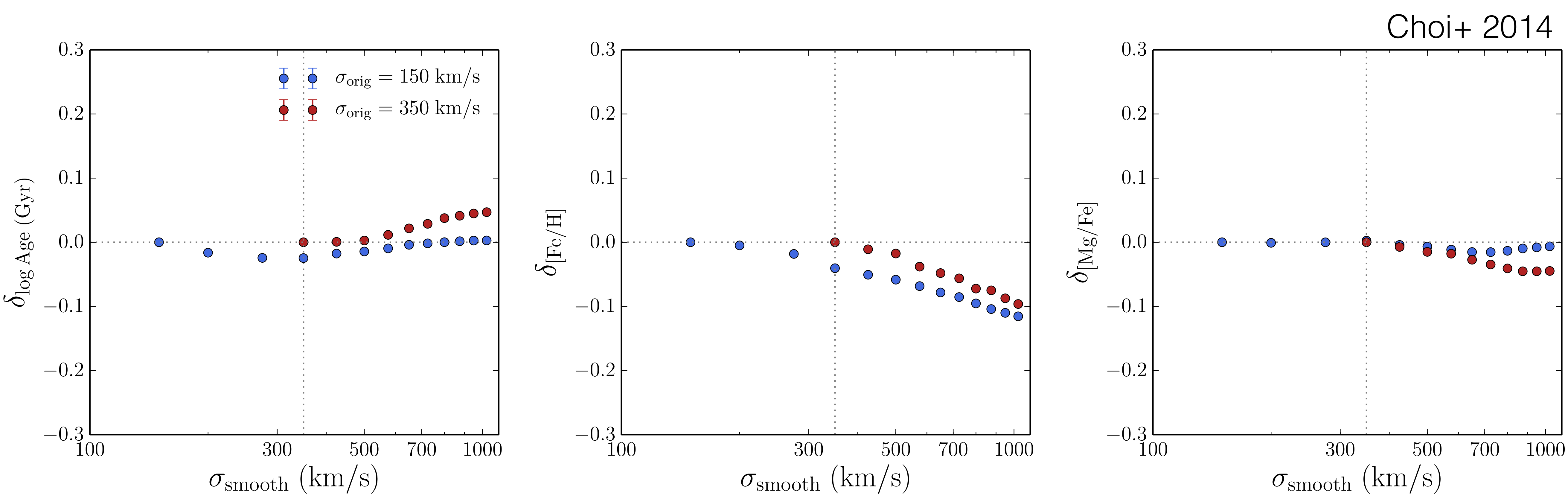
Choi+ 2014

uncertainties as a function of S/N

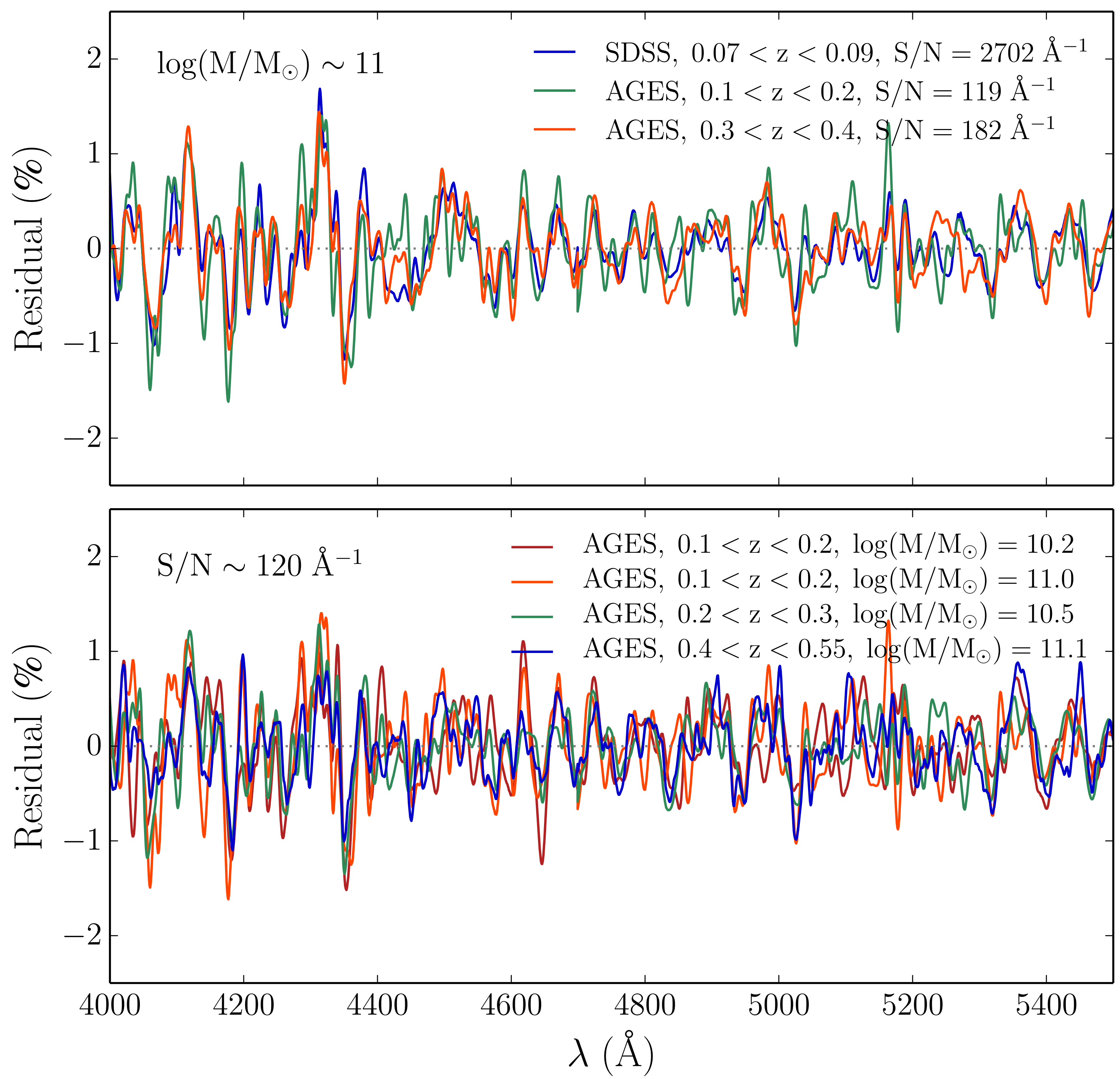
Choi+ 2014



there is no significant bias introduced due to artificial smoothing

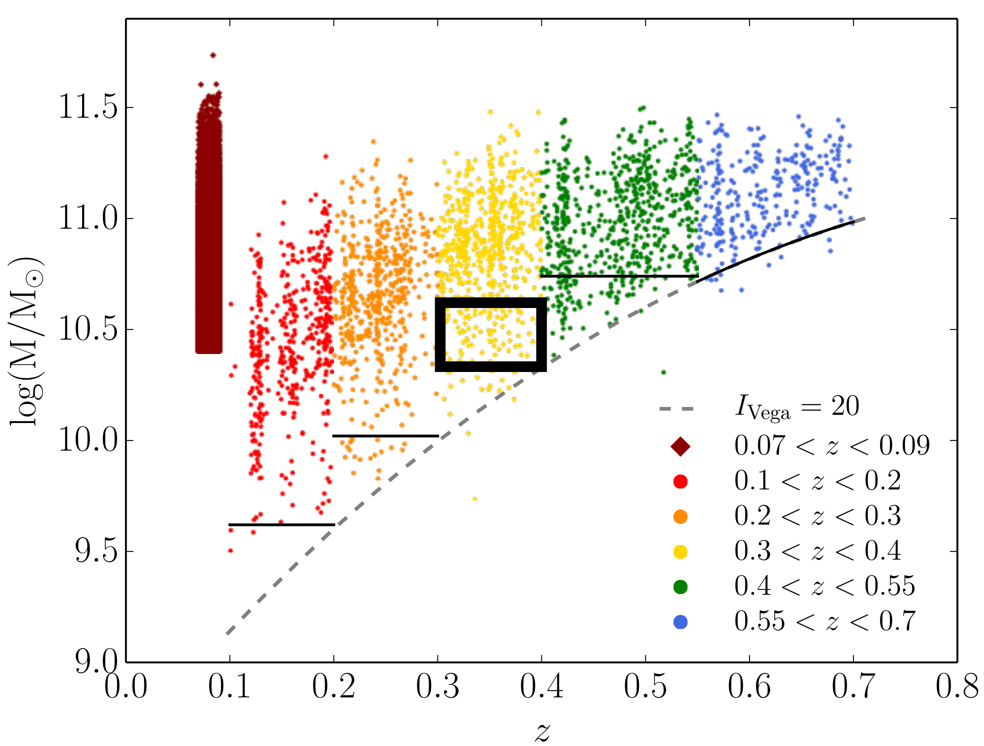


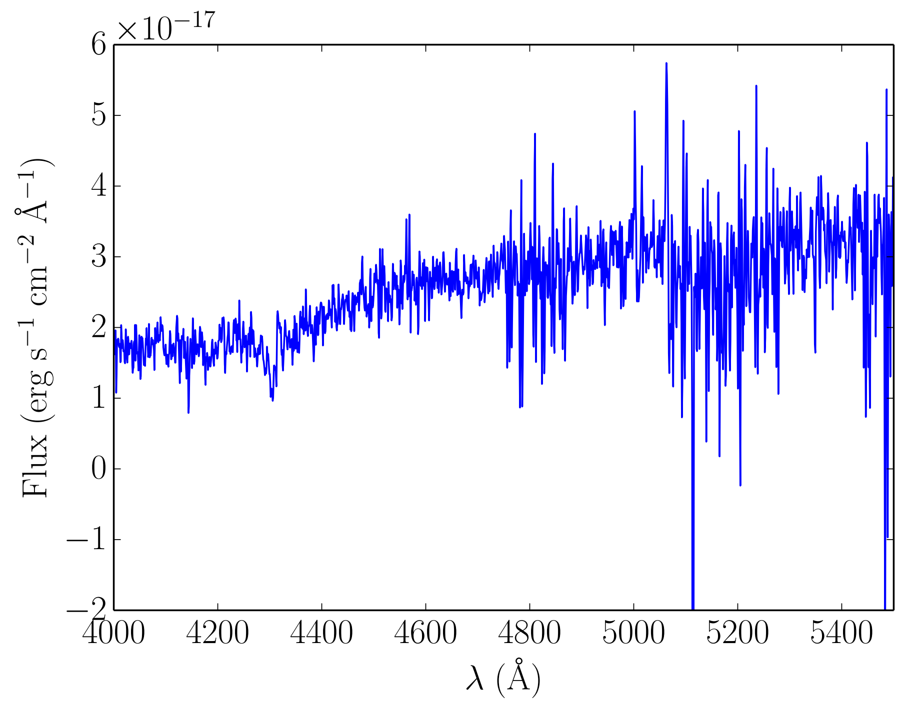
examining the residuals



Choi+ 2014

we create stacked spectra in bins of logM-z



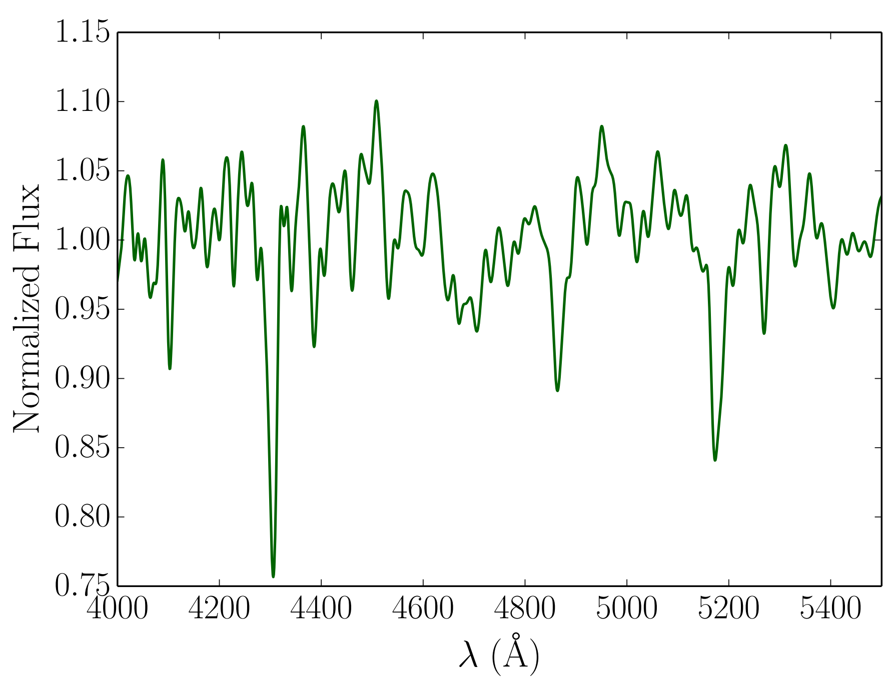


continuum-normalize

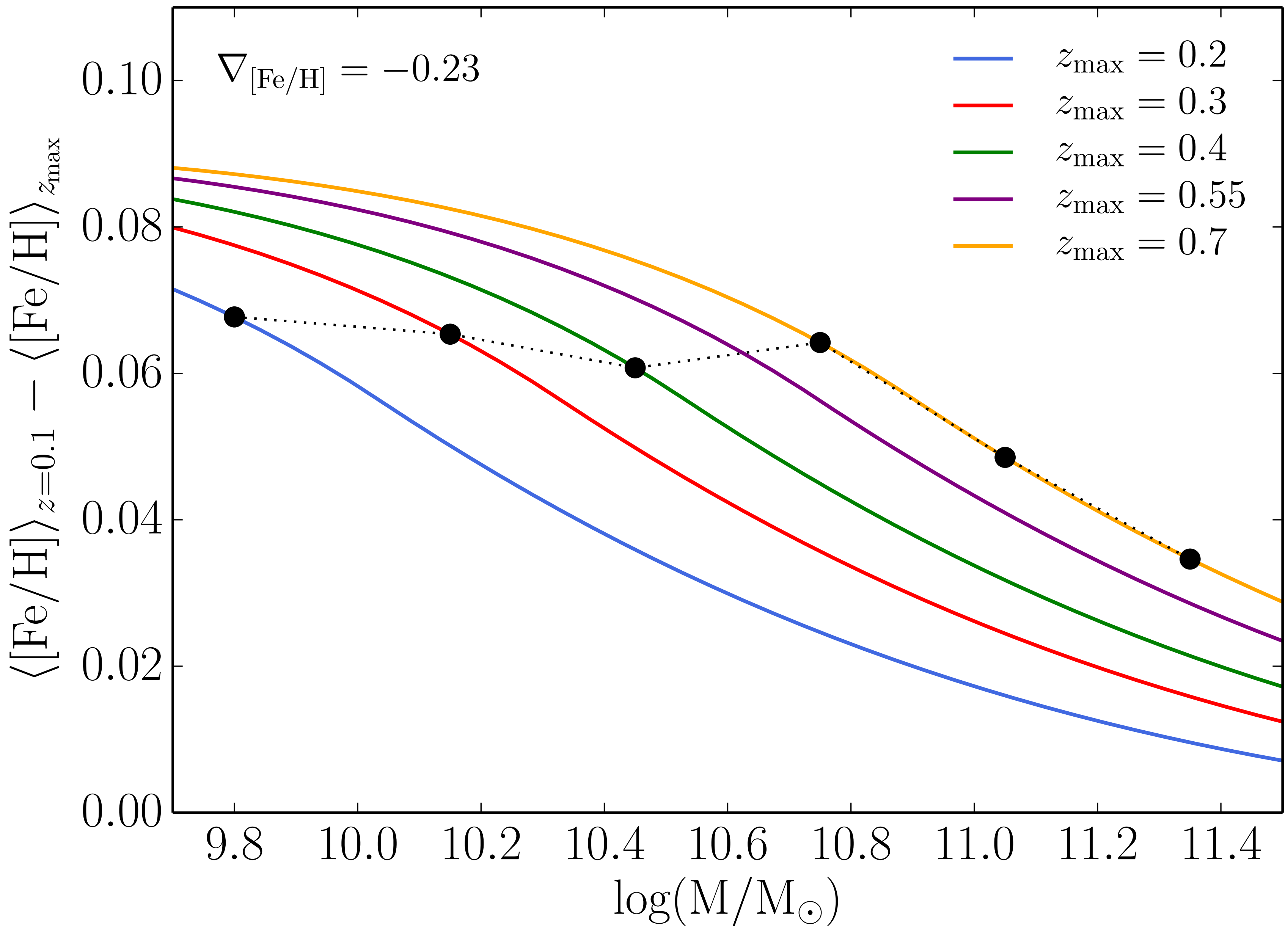
smooth with a Gaussian

coadd with

$$w_\lambda = \frac{1}{{\sigma_\lambda}^2}$$

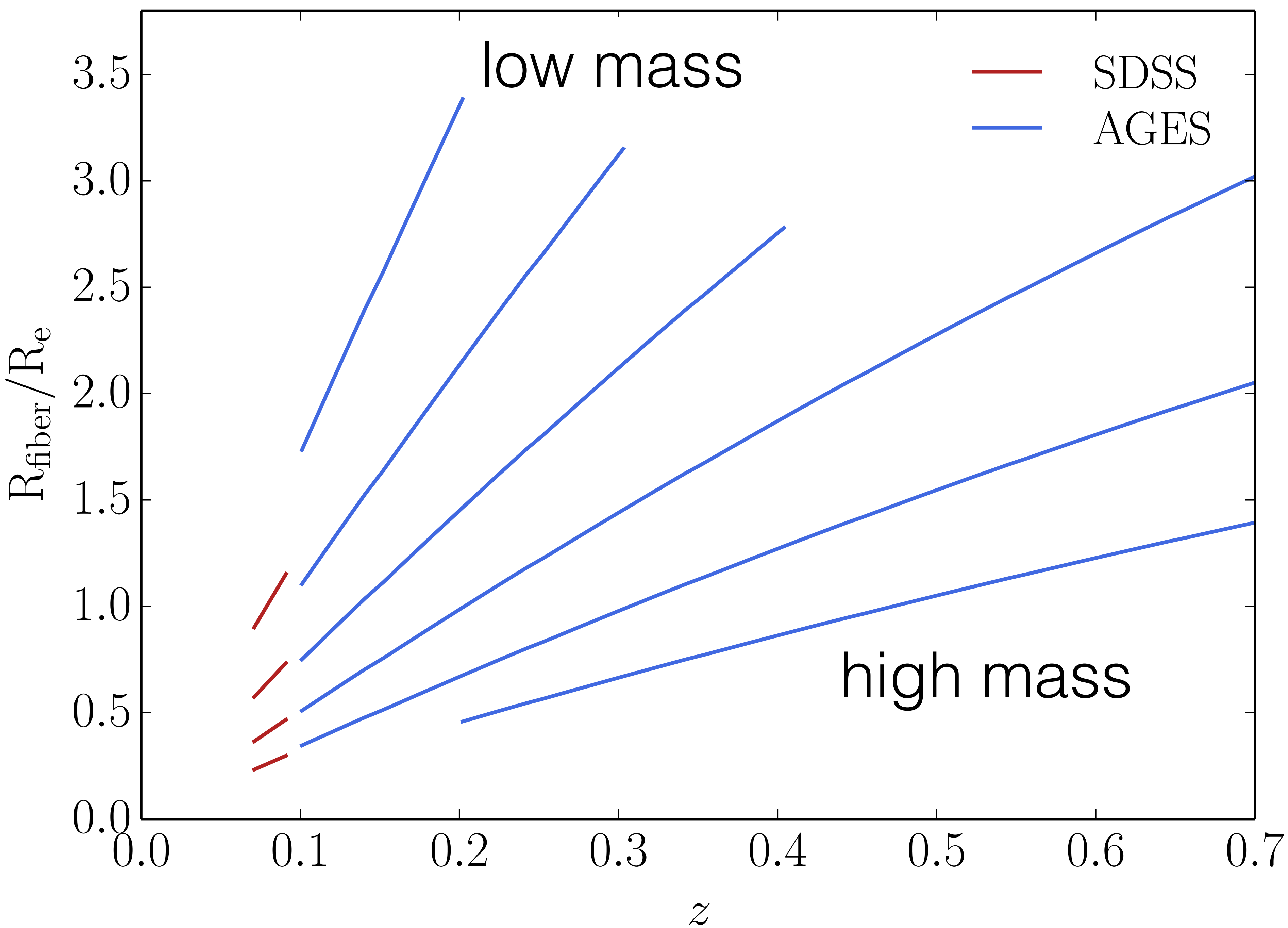


even in the presence of radial gradients (worst-case scenario), we expect negligible aperture bias



Choi+ 2014

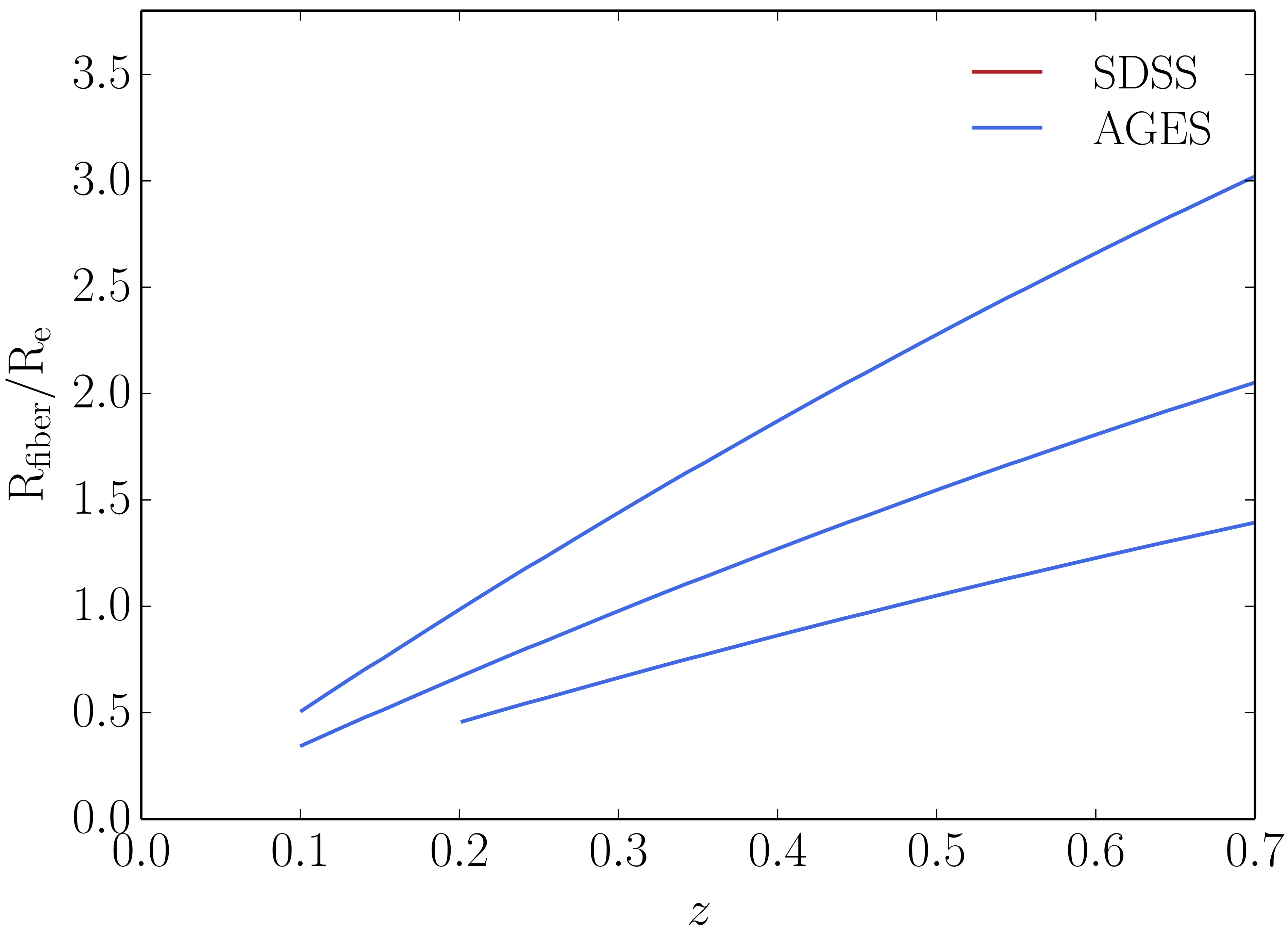
where is the light coming from?



SDSS: 3''
AGES: 1''.5

Choi+ 2014

where is the light coming from?



$\log(M/M_{\odot})$

10.6 - 10.9

10.9 - 11.2

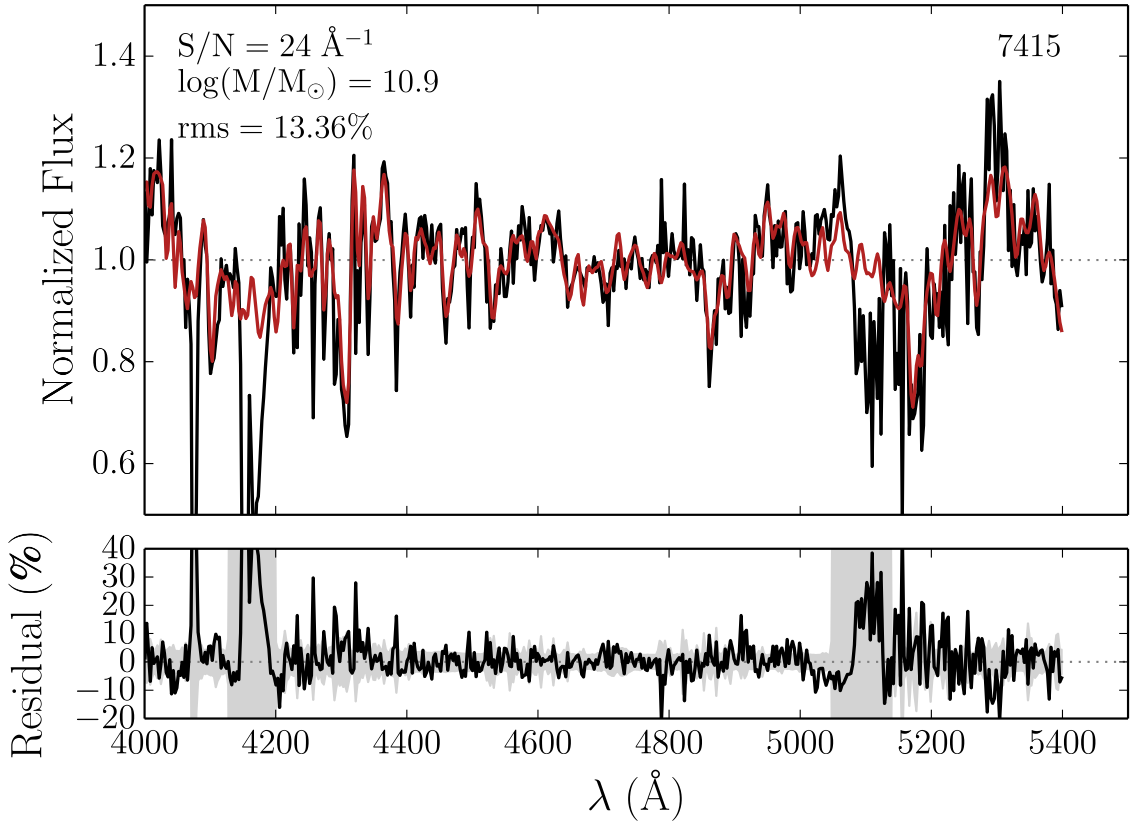
11.2 -11.5

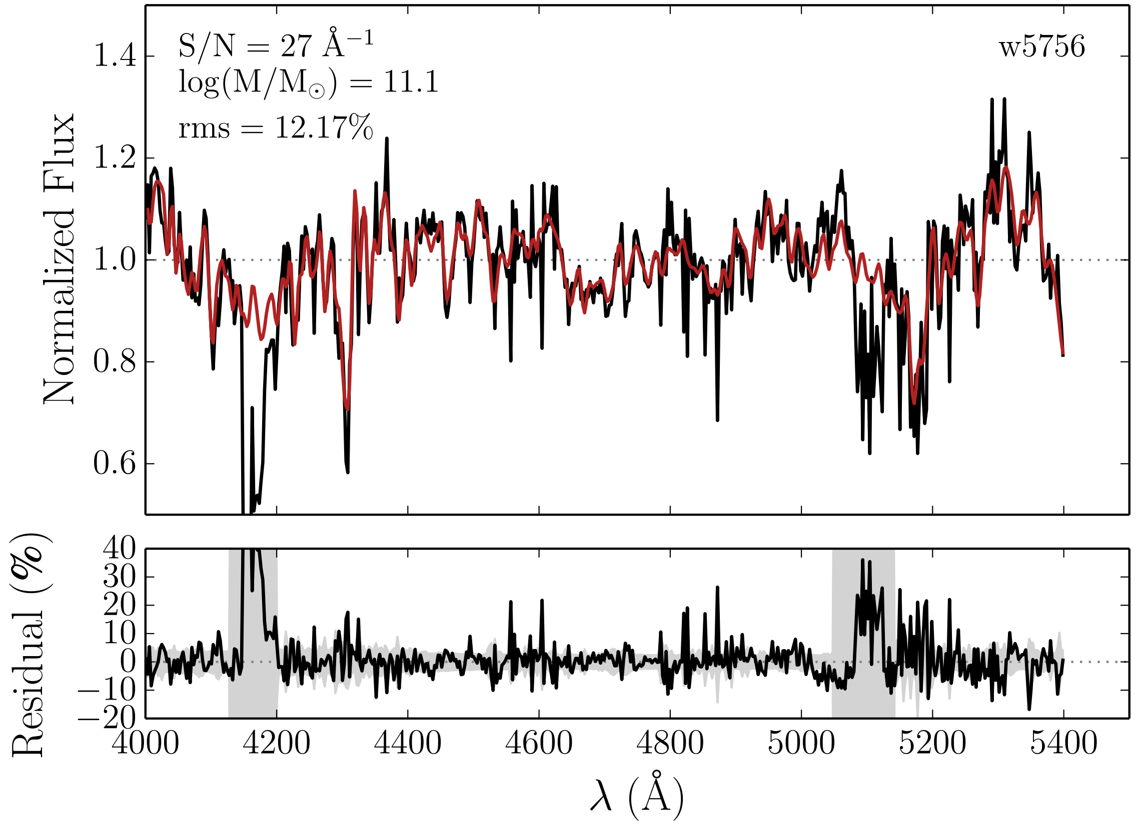
SDSS: 3''

AGES: 1''.5

Choi+ 2014

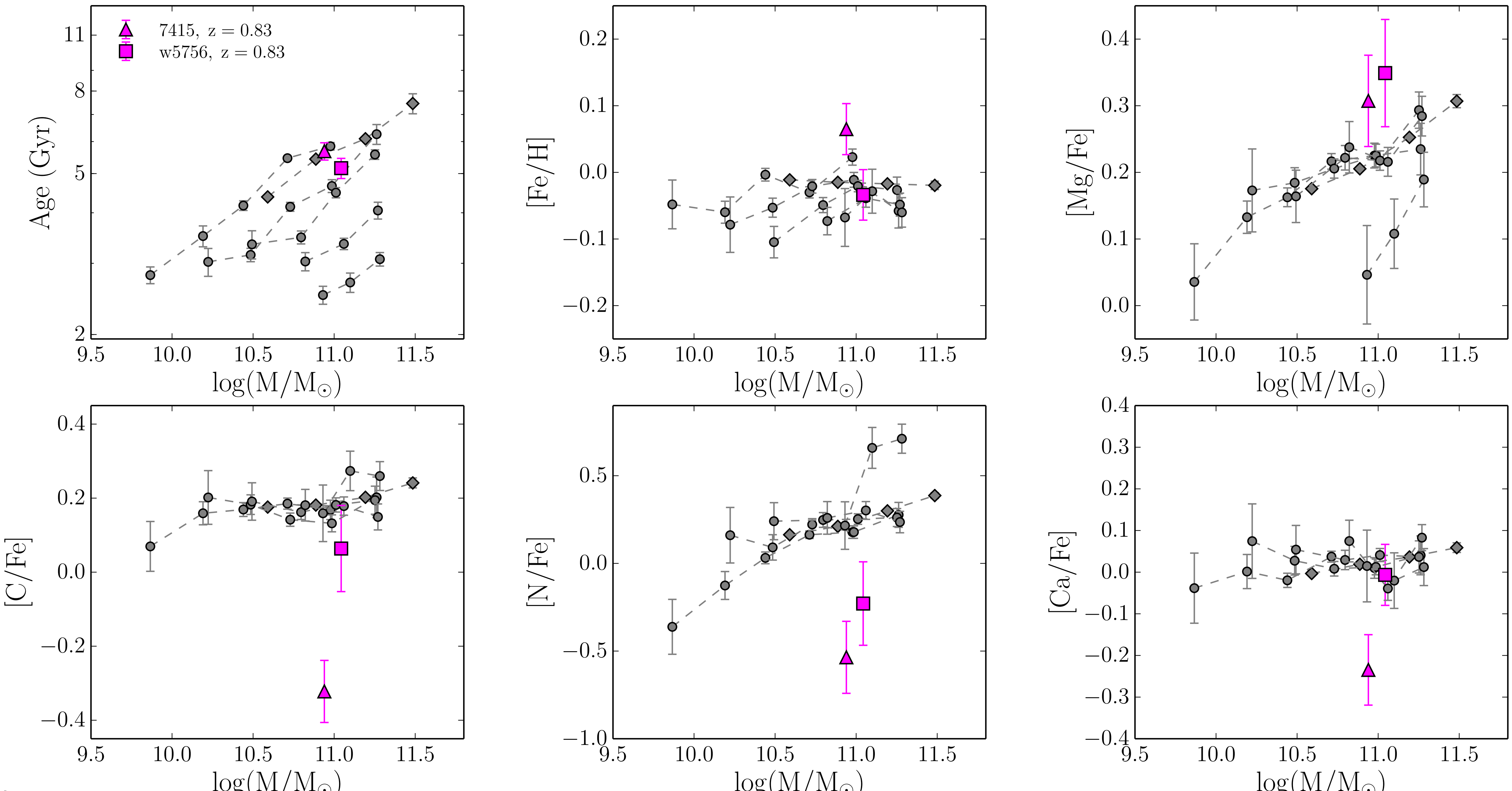
Keck DEIMOS spectra of two quiescent galaxies in a cluster at z = 0.83





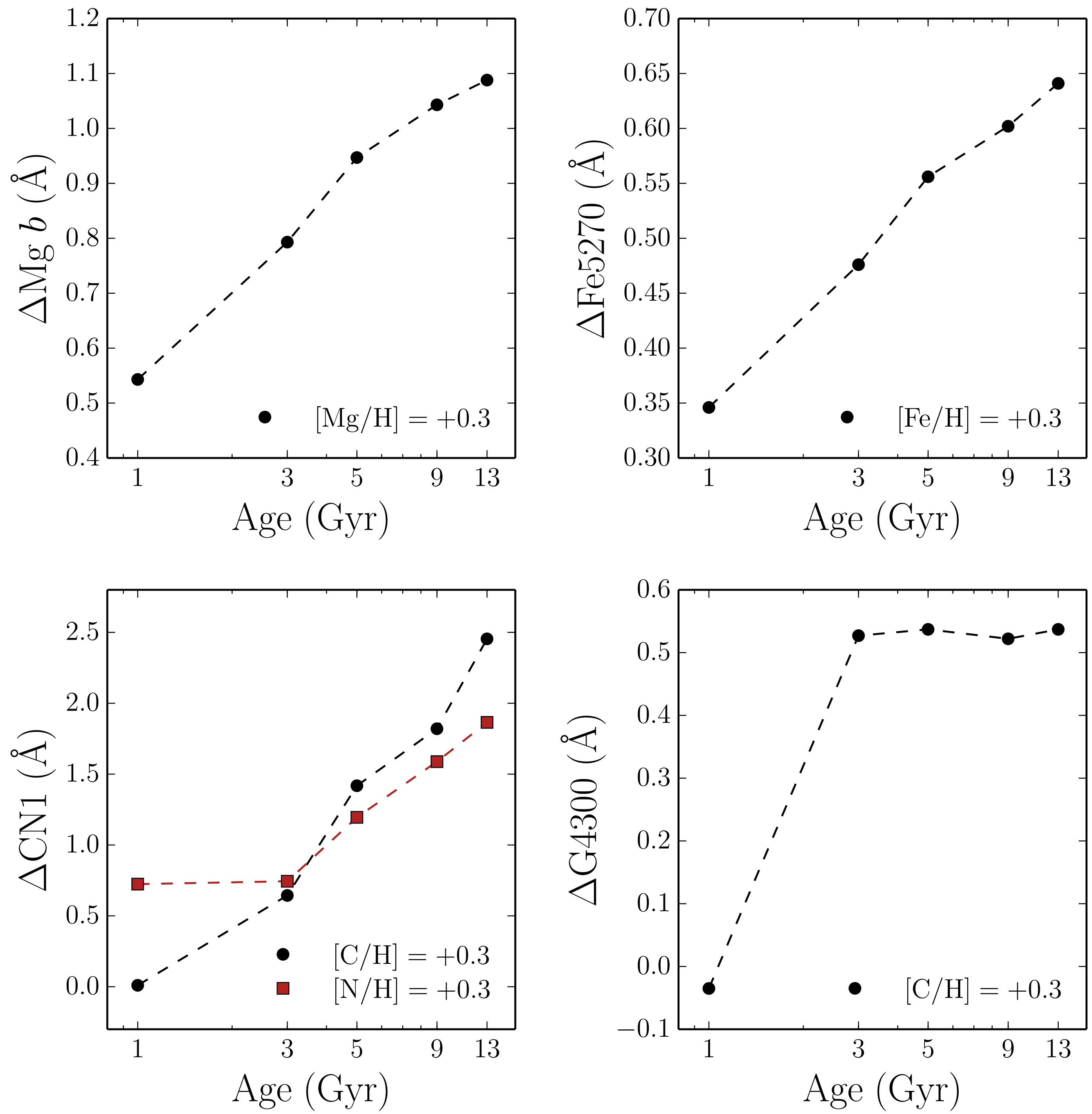
Choi+ 2014

tantalizing clues of the role of environment on stellar population properties



Choi+ 2014

age-dependent response functions



Choi+ 2014