The diversity of building up the quiescent sequence at z~1

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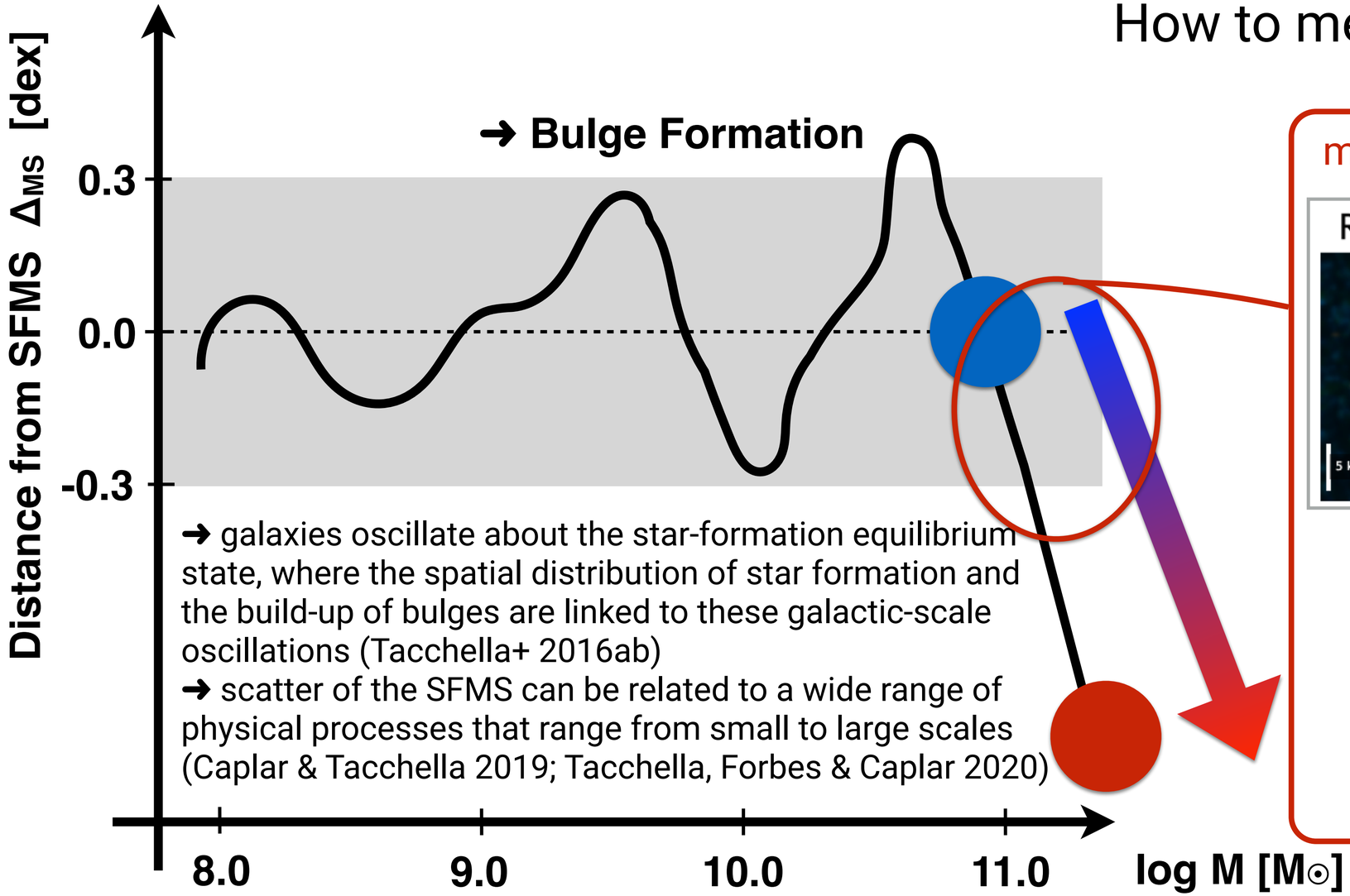
in collaboration with
C. Conroy, S. Faber, B. Johnson, J. Leja, et al.

Self-regulated growth and the cessation of star formation

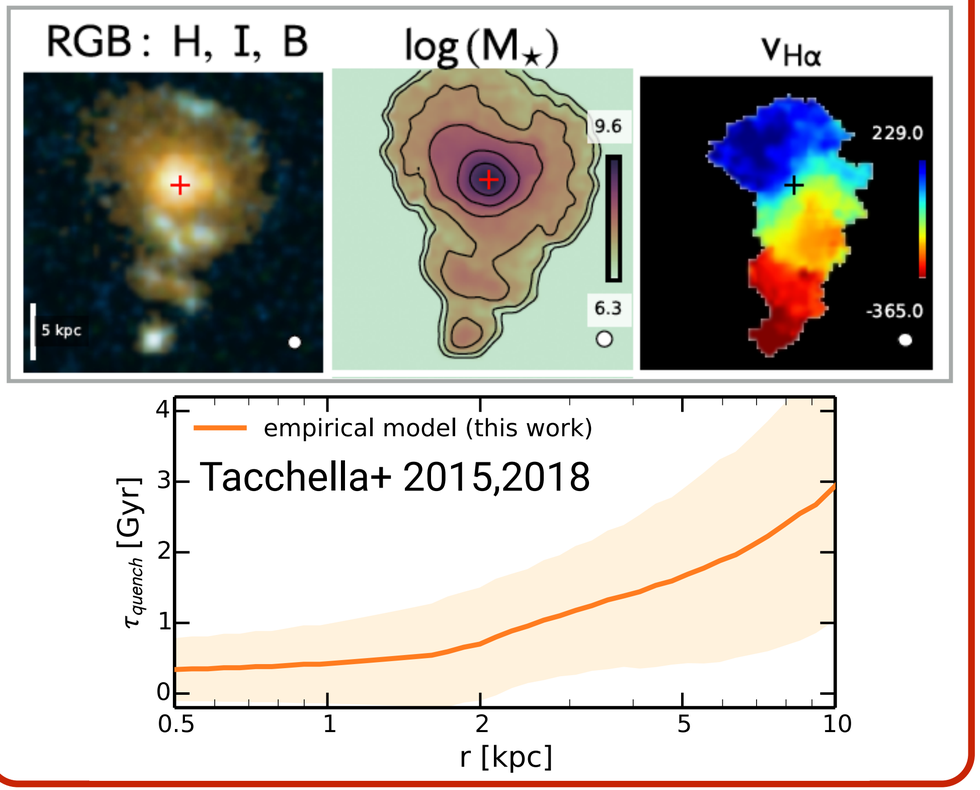


➜ galaxies oscillate about the star-formation equilibrium state, where the spatial distribution of star formation and the build-up of bulges are linked to these galactic-scale oscillations (Tacchella+ 2016ab)

➜ scatter of the SFMS can be related to a wide range of physical processes that range from small to large scales (Caplar & Tacchella 2019; Tacchella, Forbes & Caplar 2020)

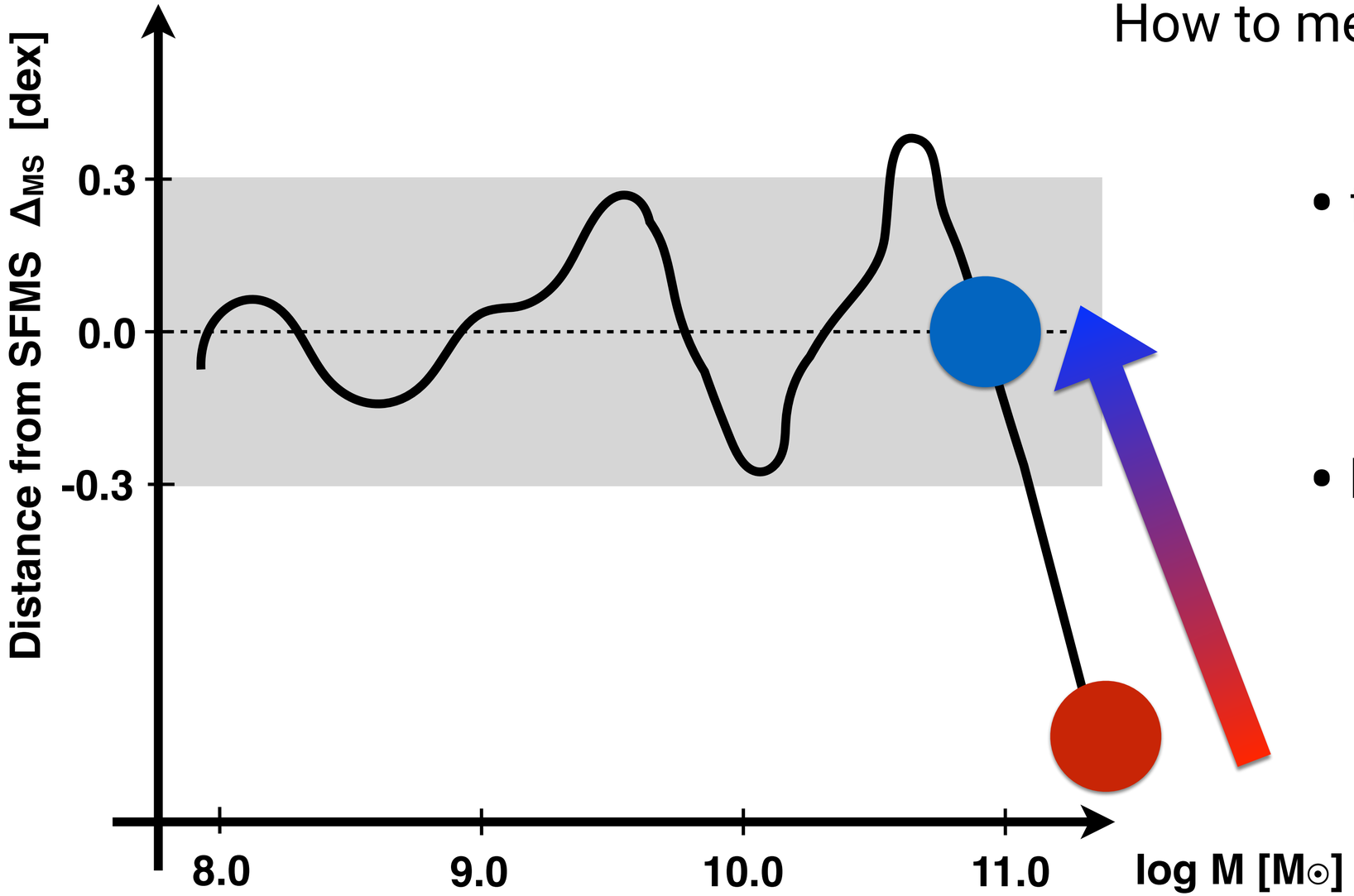
How to measure quenching timescale?

massive, z~2-3 galaxies quench inside-out



see also Nelson+ 2016; Morselli+ 2019
z~0: Belfiore+2017; Ellison+ 2018

Is the SF variability related to quenching timescales?



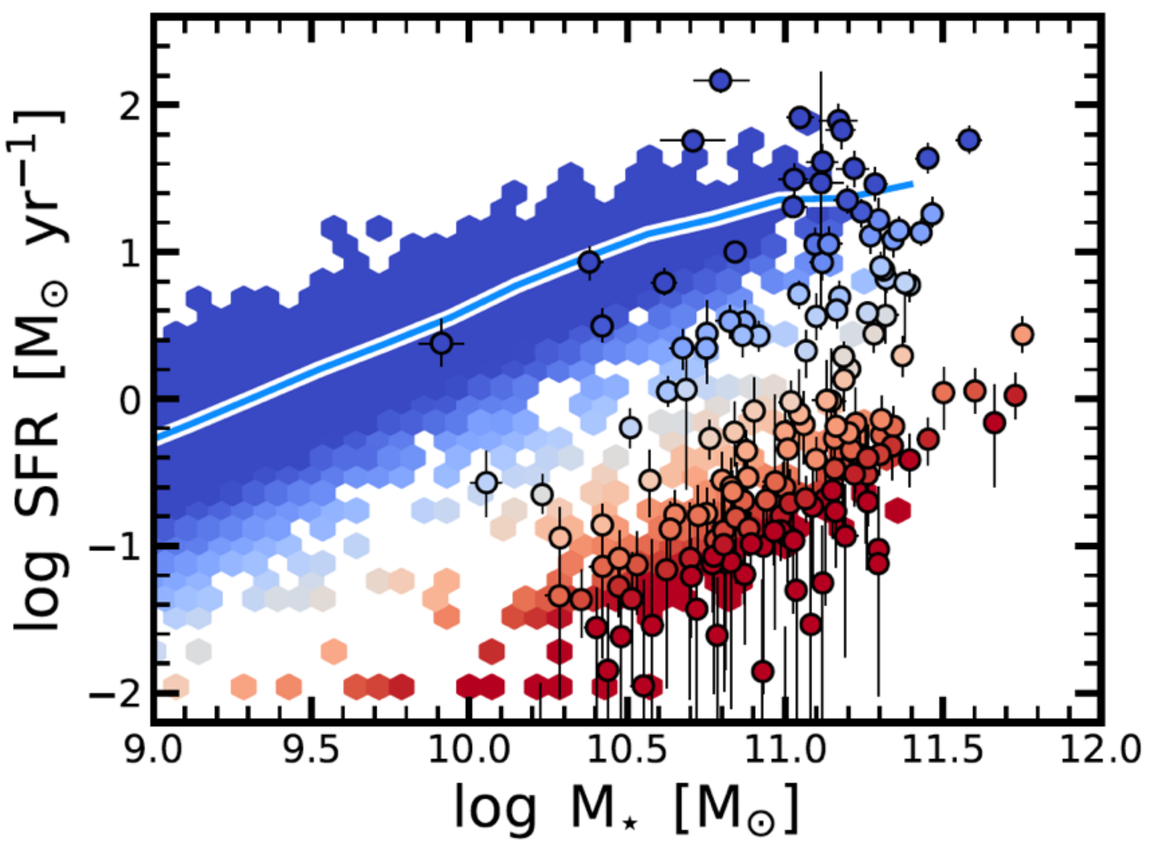
How to measure quenching timescale?

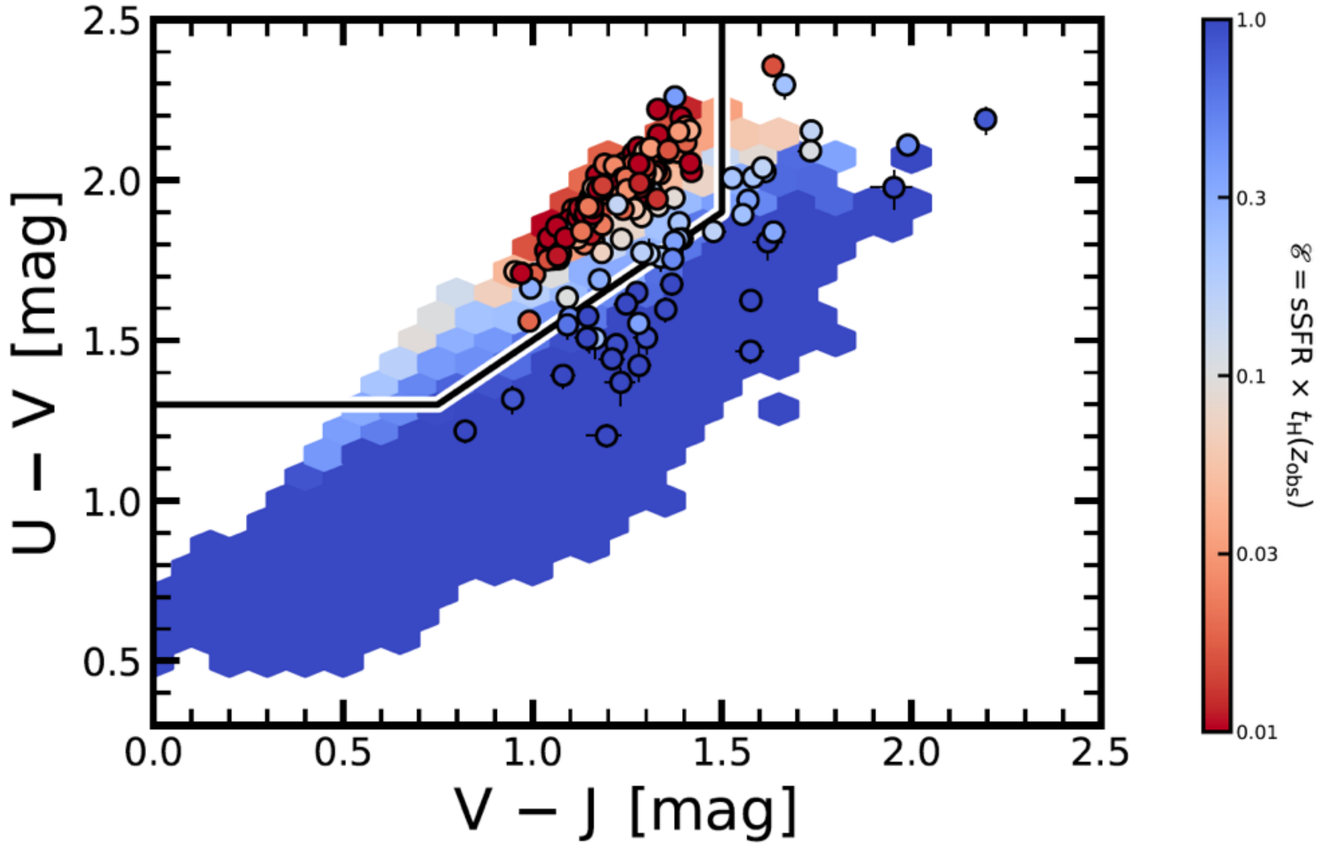
- forward approach:
  + quenching in action
  − predicting future is difficult (ensemble vs individuals)
- lookback approach:
  + quenching happened
  − in-situ / ex-situ mixing

Sample: HALO7D

in collaboration with Conroy, Johnson, Leja, et al.

- deep (10-20 hours per object) Keck/DEIMOS spectroscopic survey of z~0.8 galaxies
- 161 objects with S/N>5 per Å
- massive, mostly quiescent galaxies





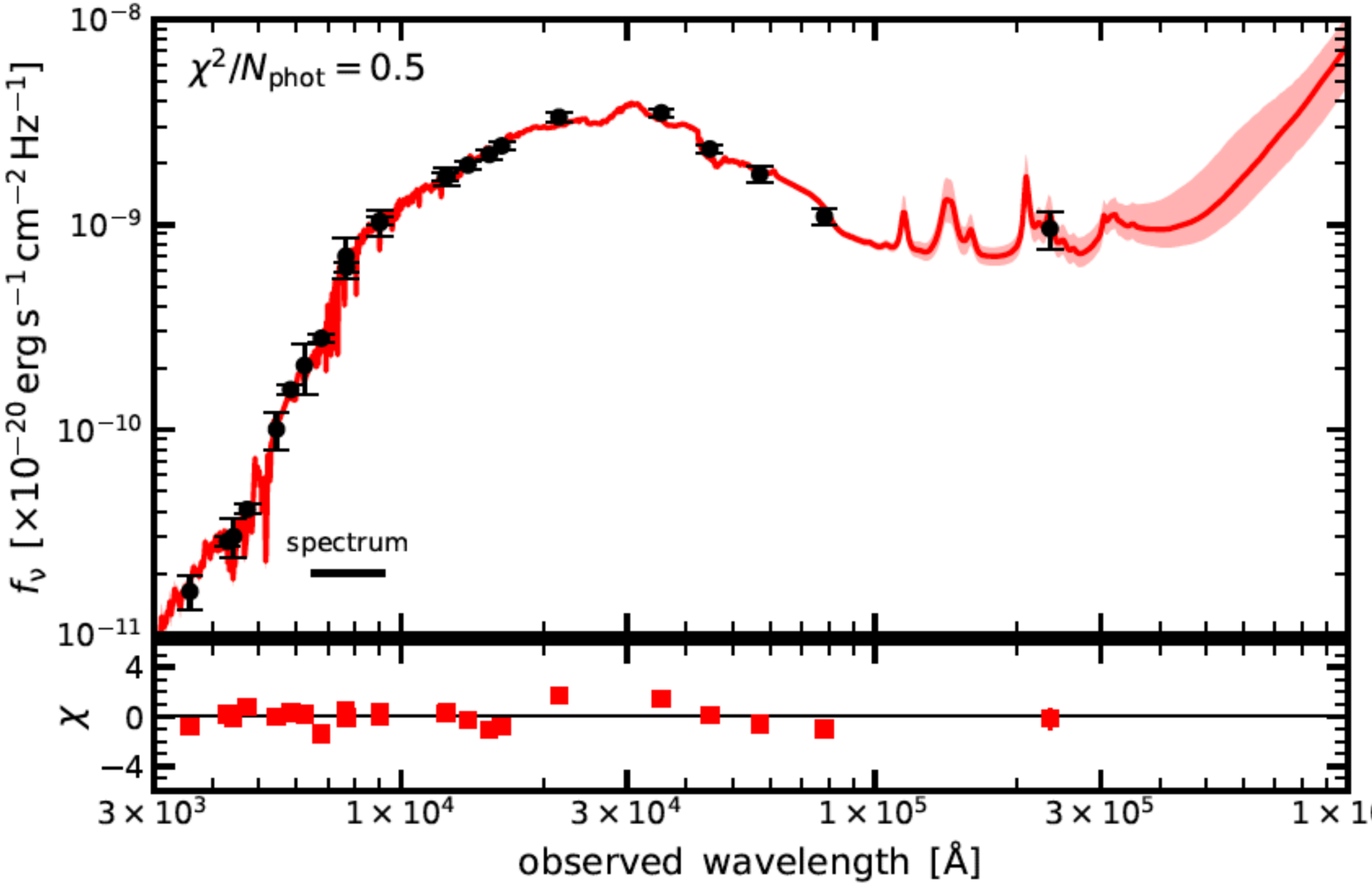
Modeling photometry + spectroscopy

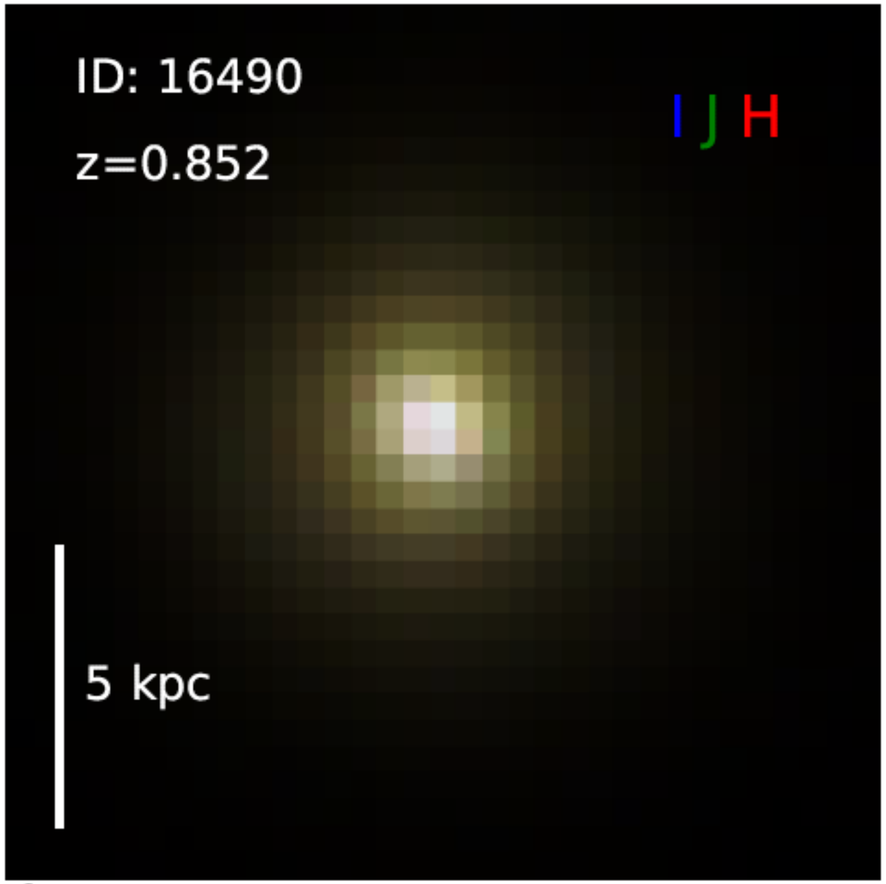
Prospector (Leja+ 2017, Johnson+ in prep.)
https://github.com/bd-j/prospector

- fully Bayesian package for inference of stellar population properties from photometric and/or spectroscopic data
- combine photometric and spectroscopic data rigorously using a spectroscopic calibration model

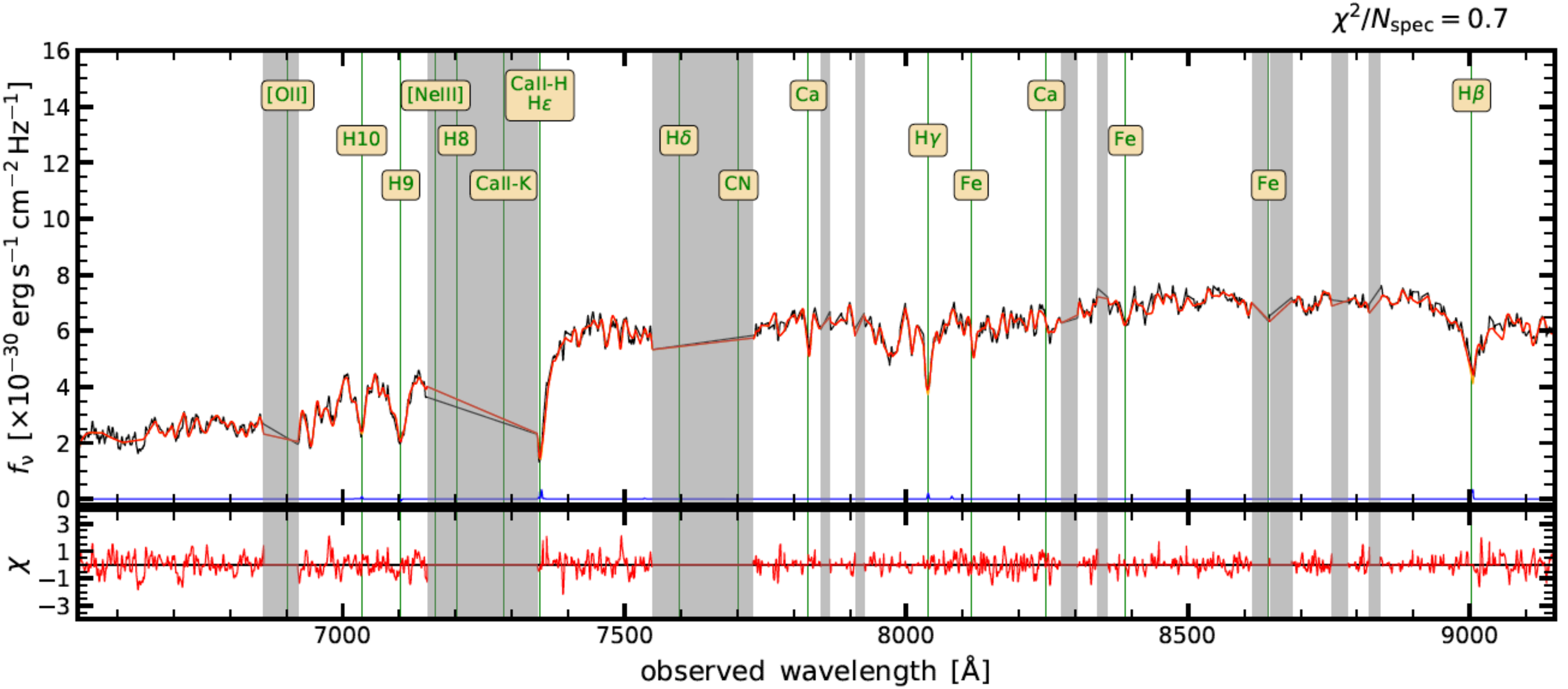
We model 20-30 parameters:
✤ standard: redshift, stellar mass, velocity dispersion, metallicity
✤ flexible dust attenuation model: A_V and multiplicative of Calzetti attenuation law
✤ dust emission: 3 parameters
✤ AGN emission in IR model: 2 parameters
✤ “non-parametric” SFH (10 bins in time)
✤ emission line model: fit for prominent emission lines
➜ fit for velocity dispersion, optimize out amplitude
✤ outlier model: skylines residuals, detector artifacts, data-model inconsistencies
➜ fraction of outlier pixels in spectrum

Example

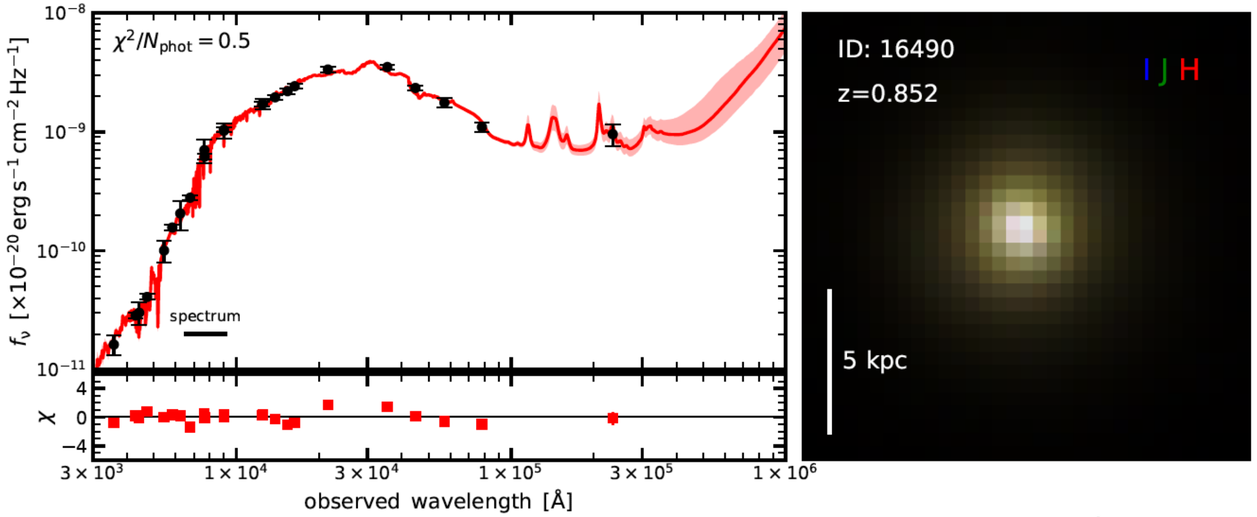

$\chi^2/N_{\rm phot} = 0.5$
spectrum
f_ν [$\times 10^{-20}$ erg s^{-1} cm^{-2} Hz^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
χ
4
0
−4
3×10^3
1×10^4
3×10^4
1×10^5
3×10^5
1×10^6
observed wavelength [Å]


ID: 16490
z=0.852
I J H
5 kpc

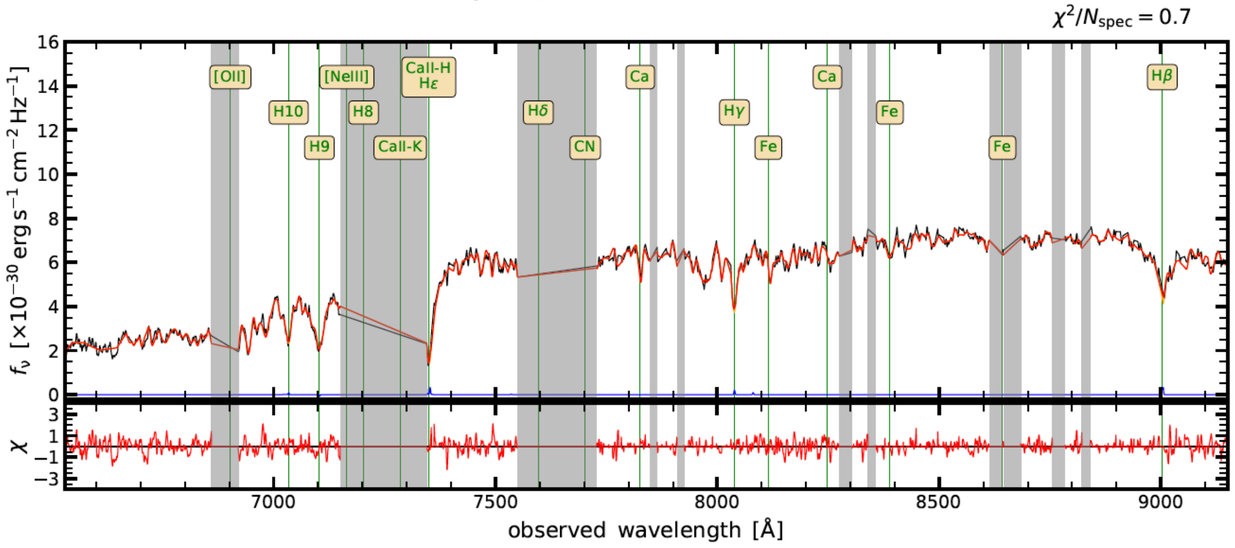
Example

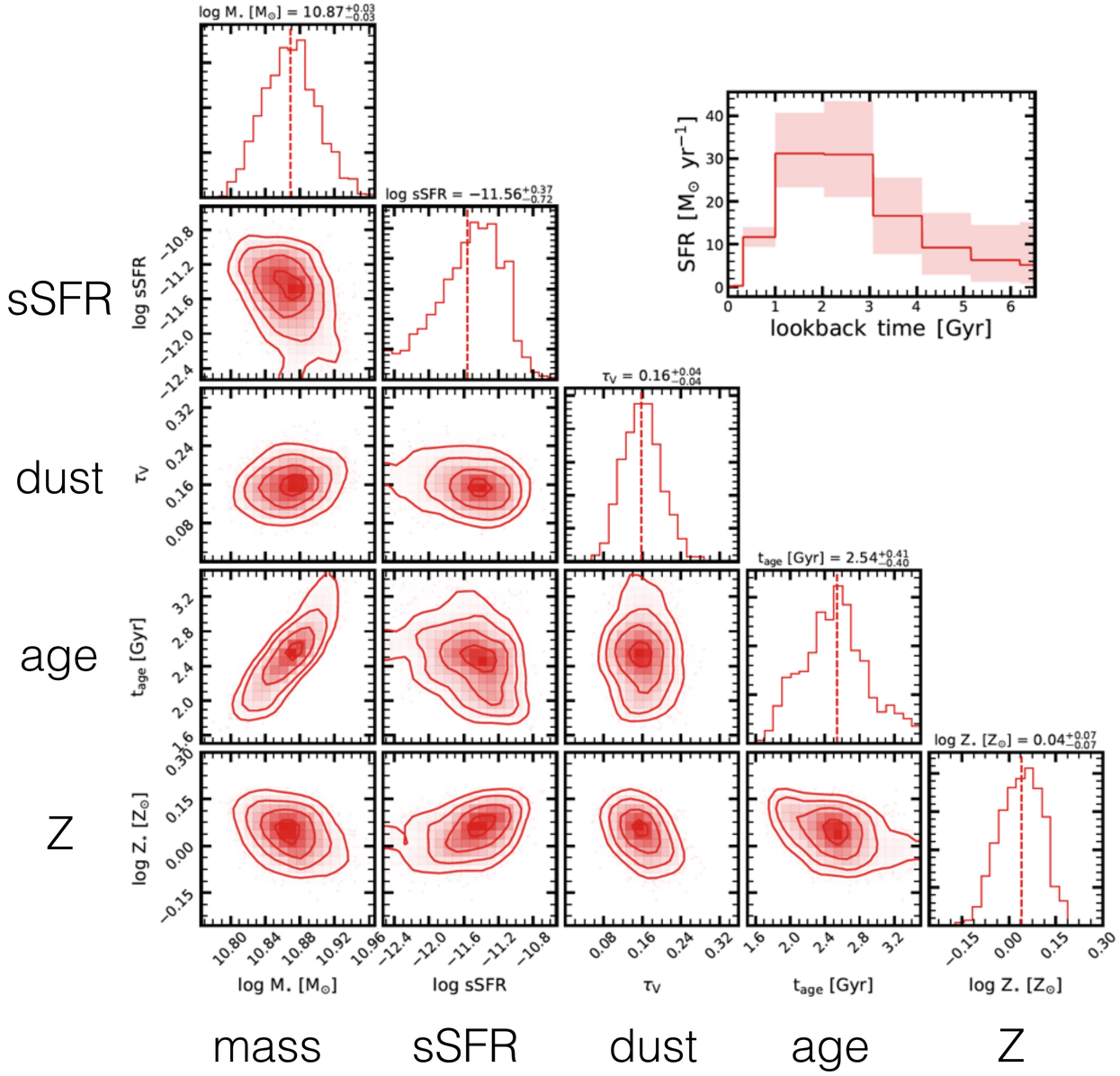

$\chi^2/N_{\rm spec} = 0.7$
[OII]
H10
H9
[NeIII]
H8
CaII-K
CaII-H
Hε
Hδ
CN
Ca
Hγ
Fe
Ca
Fe
Fe
Hβ
f_ν [$\times 10^{-30}$ erg s^{-1} cm^{-2} Hz^{-1}]
χ
observed wavelength [Å]

Example

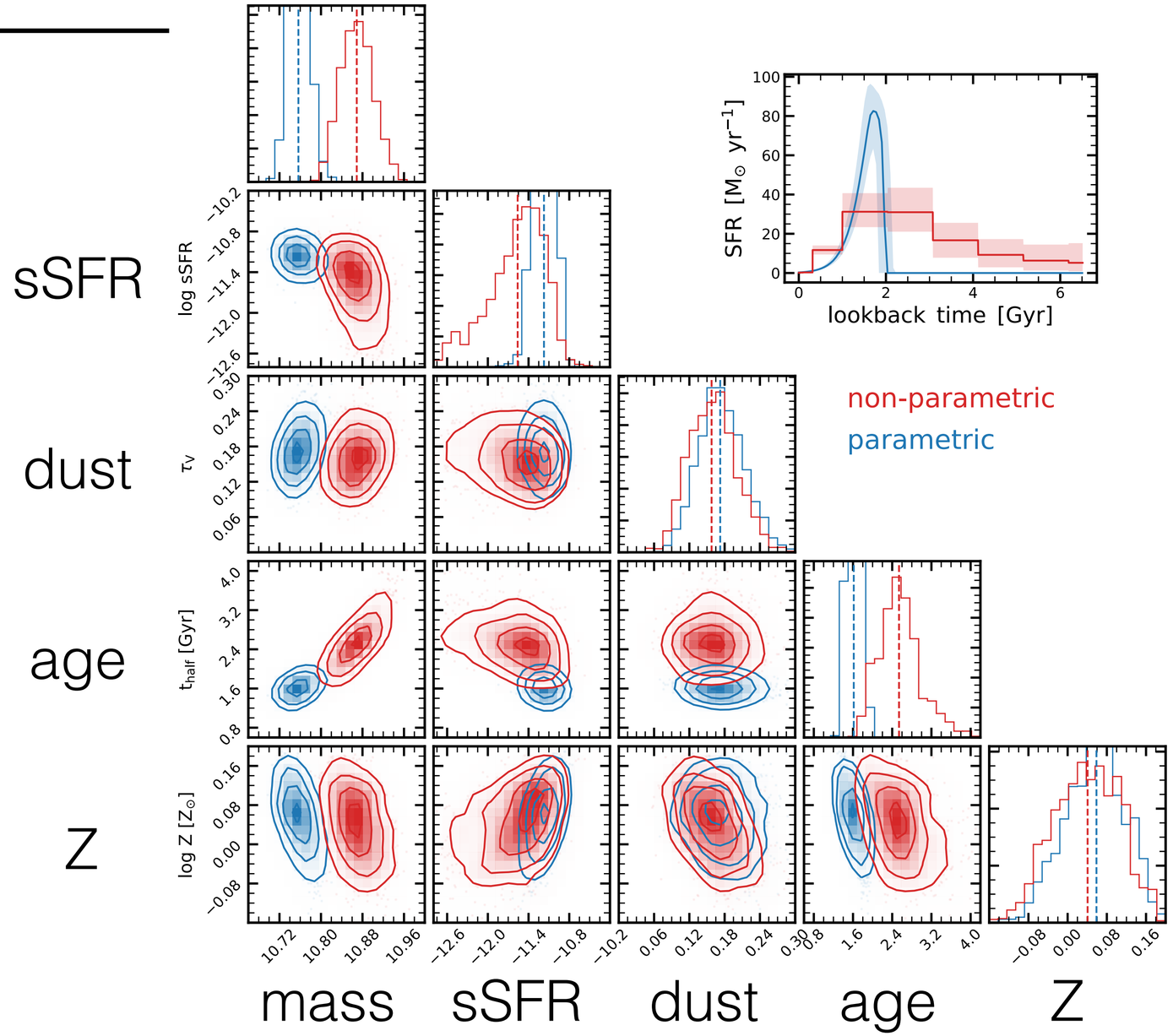

$\chi^2/N_{\rm phot} = 0.5$
spectrum
observed wavelength [Å]

ID: 16490
z=0.852
I J H
5 kpc

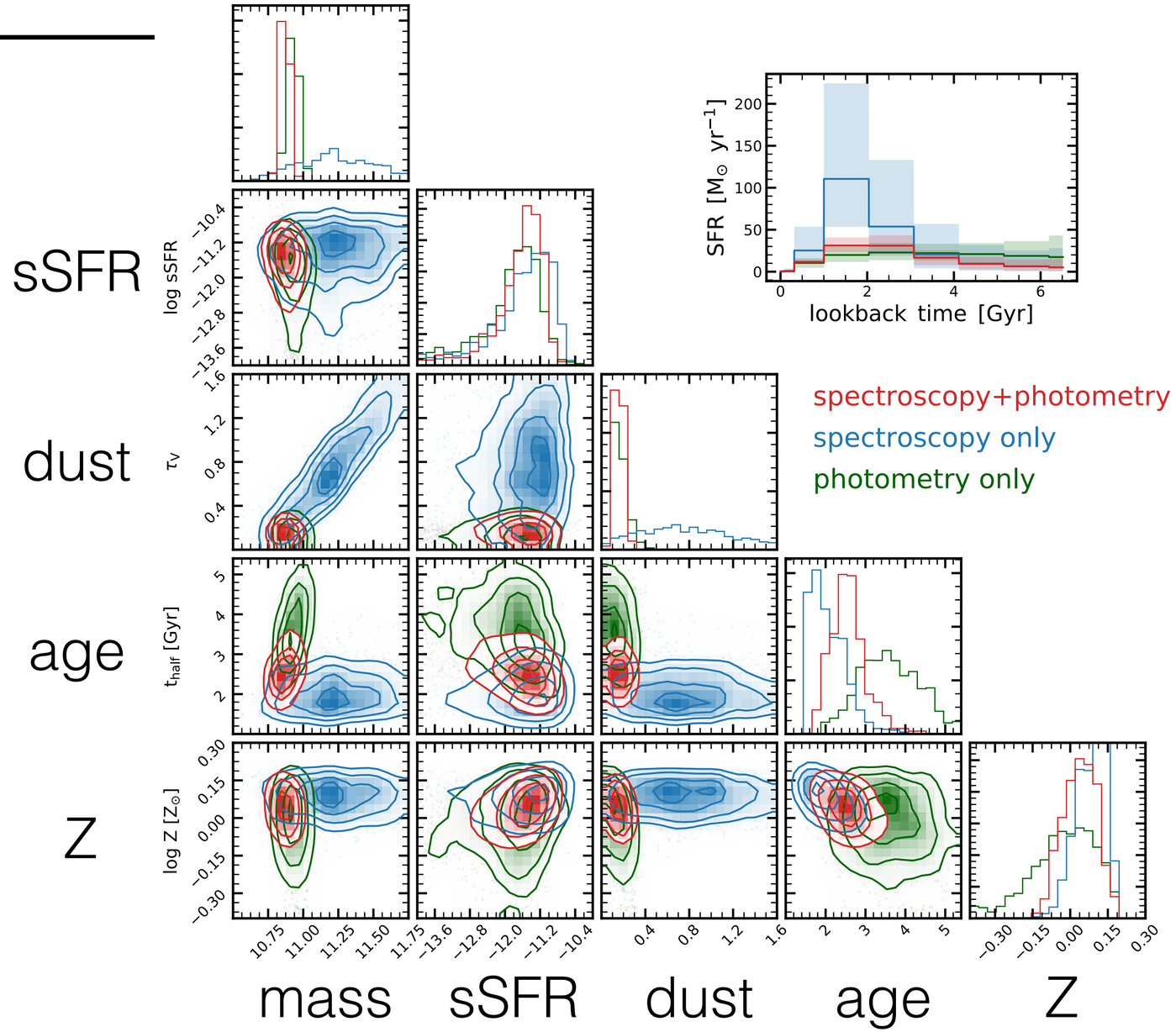

$\chi^2/N_{\rm spec} = 0.7$
[OII]
H10
H9
[NeIII]
H8
CaII-H Hε
CaII-K
Hδ
CN
Ca
Hγ
Fe
Ca
Fe
Fe
Hβ
observed wavelength [Å]

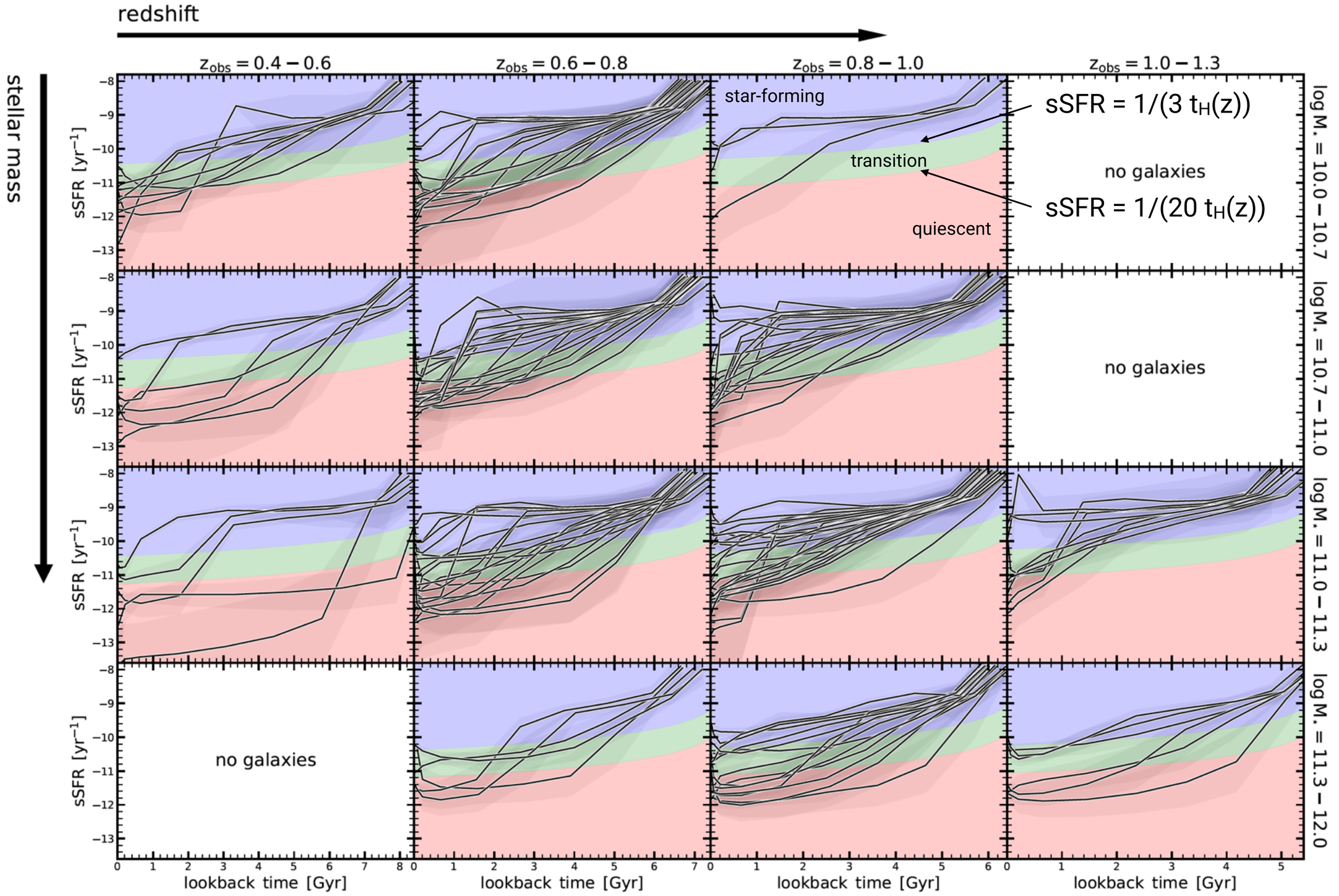

sSFR
dust
age
Z
log M. [M⊙] = 10.87$^{+0.03}_{-0.03}$
log sSFR = −11.56$^{+0.37}_{-0.72}$
τ_V = 0.16$^{+0.04}_{-0.04}$
t_{age} [Gyr] = 2.54$^{+0.41}_{-0.40}$
log Z. [Z⊙] = 0.04$^{+0.07}_{-0.07}$
SFR [M⊙ yr^{-1}]
lookback time [Gyr]
log M. [M⊙]
log sSFR
τ_V
t_{age} [Gyr]
log Z. [Z⊙]
mass
sSFR
dust
age
Z

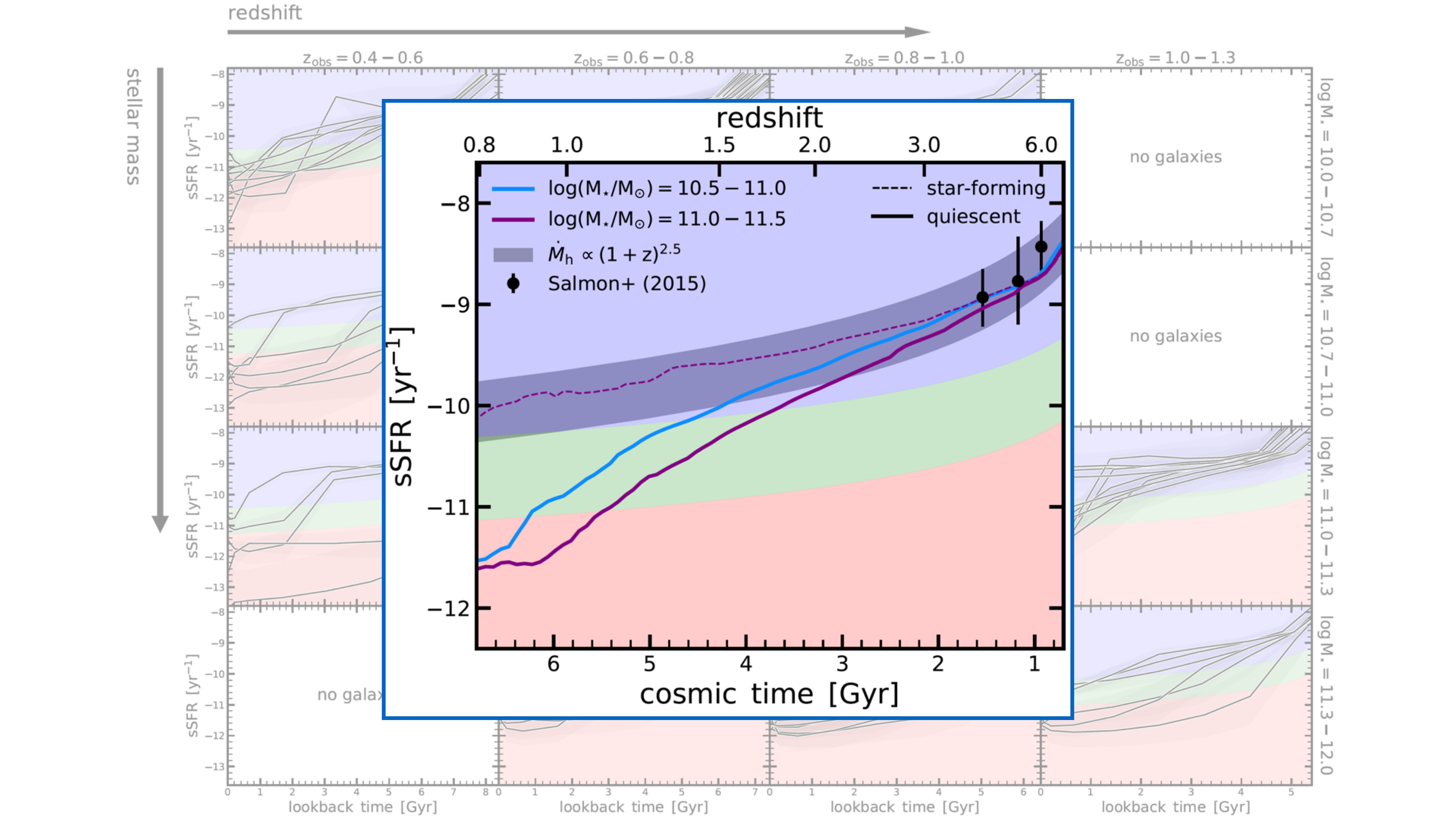
Fitting results: parametric versus non-parametric



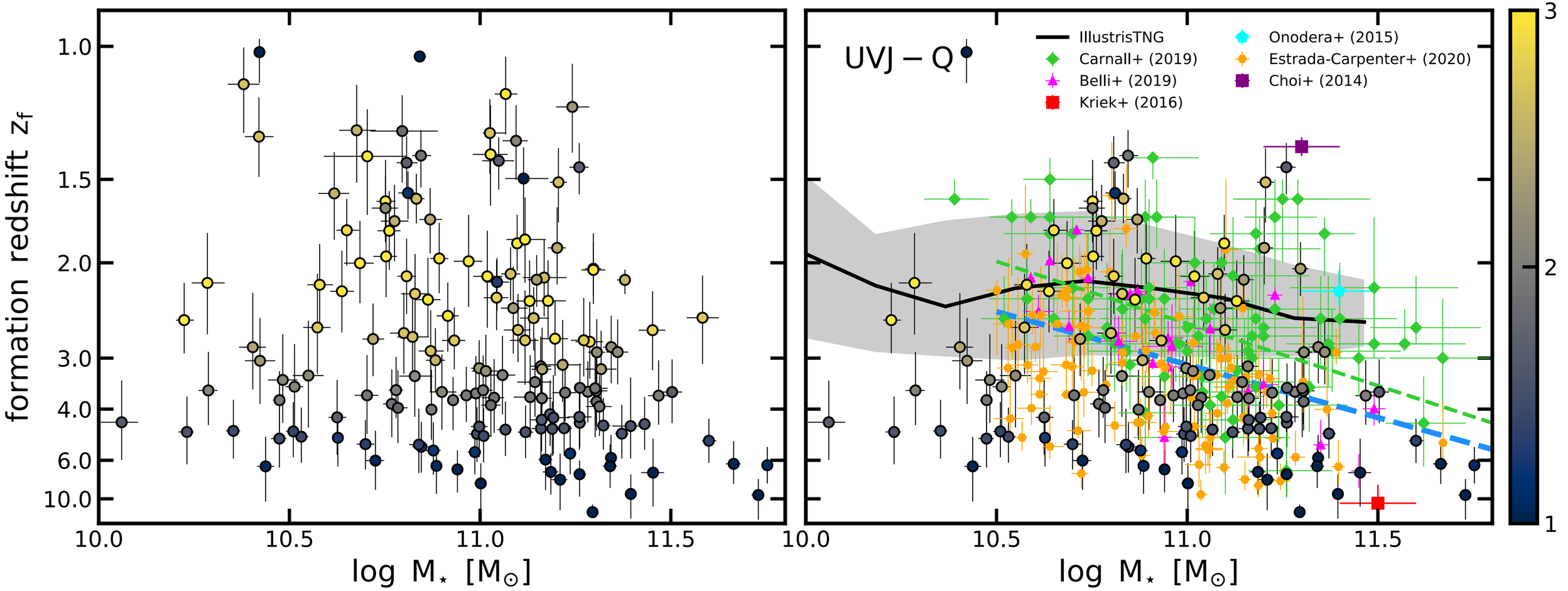
Fitting results: with and without spectroscopic data




redshift
stellar mass
$z_{obs} = 0.4 - 0.6$
$z_{obs} = 0.6 - 0.8$
$z_{obs} = 0.8 - 1.0$
$z_{obs} = 1.0 - 1.3$
star-forming
transition
quiescent
sSFR = 1/(3 $t_H(z)$)
sSFR = 1/(20 $t_H(z)$)
no galaxies
$\log M_* = 10.0 - 10.7$
$\log M_* = 10.7 - 11.0$
$\log M_* = 11.0 - 11.3$
$\log M_* = 11.3 - 12.0$
sSFR [yr^{-1}]
lookback time [Gyr]


redshift
stellar mass
$z_{obs} = 0.4 - 0.6$
$z_{obs} = 0.6 - 0.8$
$z_{obs} = 0.8 - 1.0$
$z_{obs} = 1.0 - 1.3$
$\log M_\star = 10.0 - 10.7$
$\log M_\star = 10.7 - 11.0$
$\log M_\star = 11.0 - 11.3$
$\log M_\star = 11.3 - 12.0$
sSFR [yr^{-1}]
lookback time [Gyr]
no galaxies
redshift
0.8
1.0
1.5
2.0
3.0
6.0
$\log(M_\star/M_\odot) = 10.5 - 11.0$
$\log(M_\star/M_\odot) = 11.0 - 11.5$
$\dot{M}_h \propto (1+z)^{2.5}$
Salmon+ (2015)
star-forming
quiescent
sSFR [yr^{-1}]
cosmic time [Gyr]

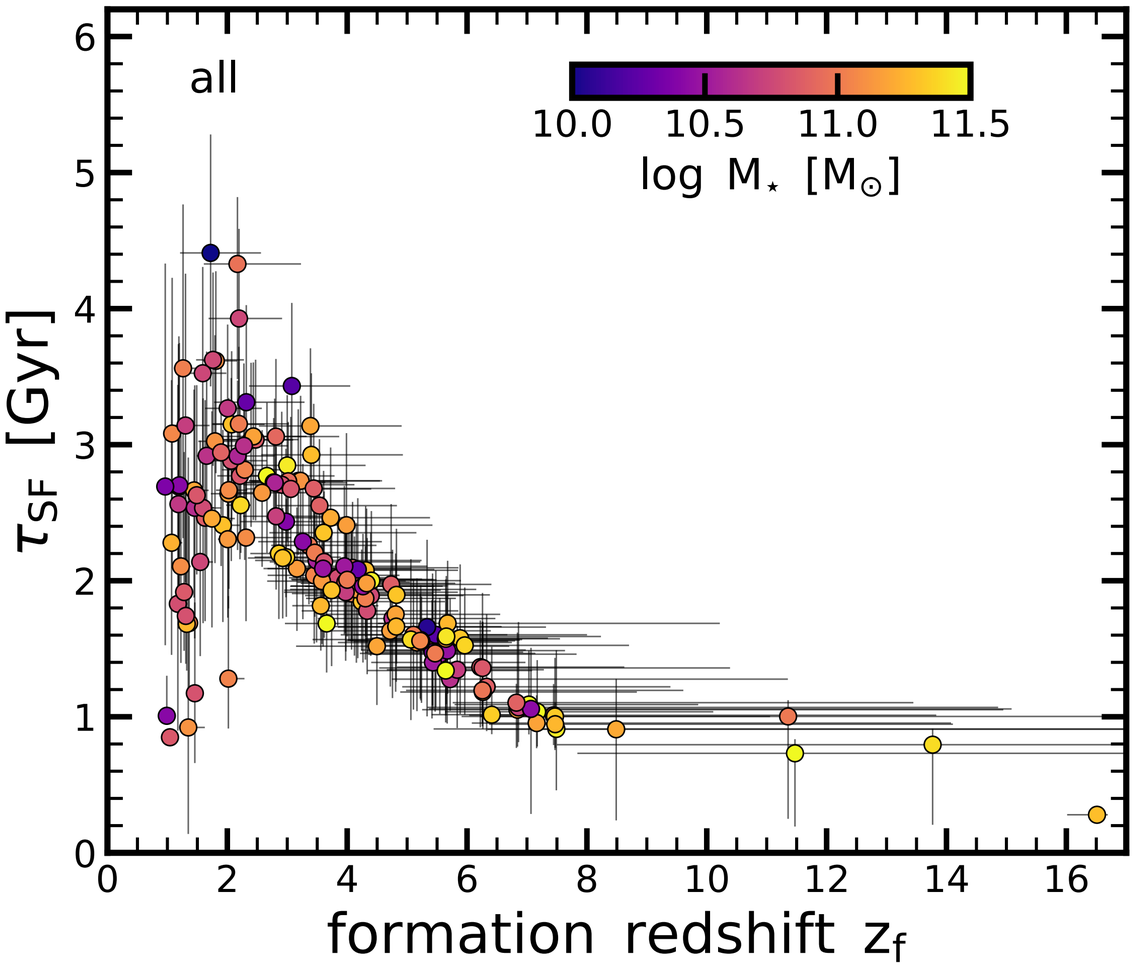
Redshift of formation and star-formation timescale



z_f: redshift of t_{50} (when 50% of the mass formed)

τ_{SF}: star-formation timescale (t_{20}-t_{80})

Redshift of formation and star-formation timescale

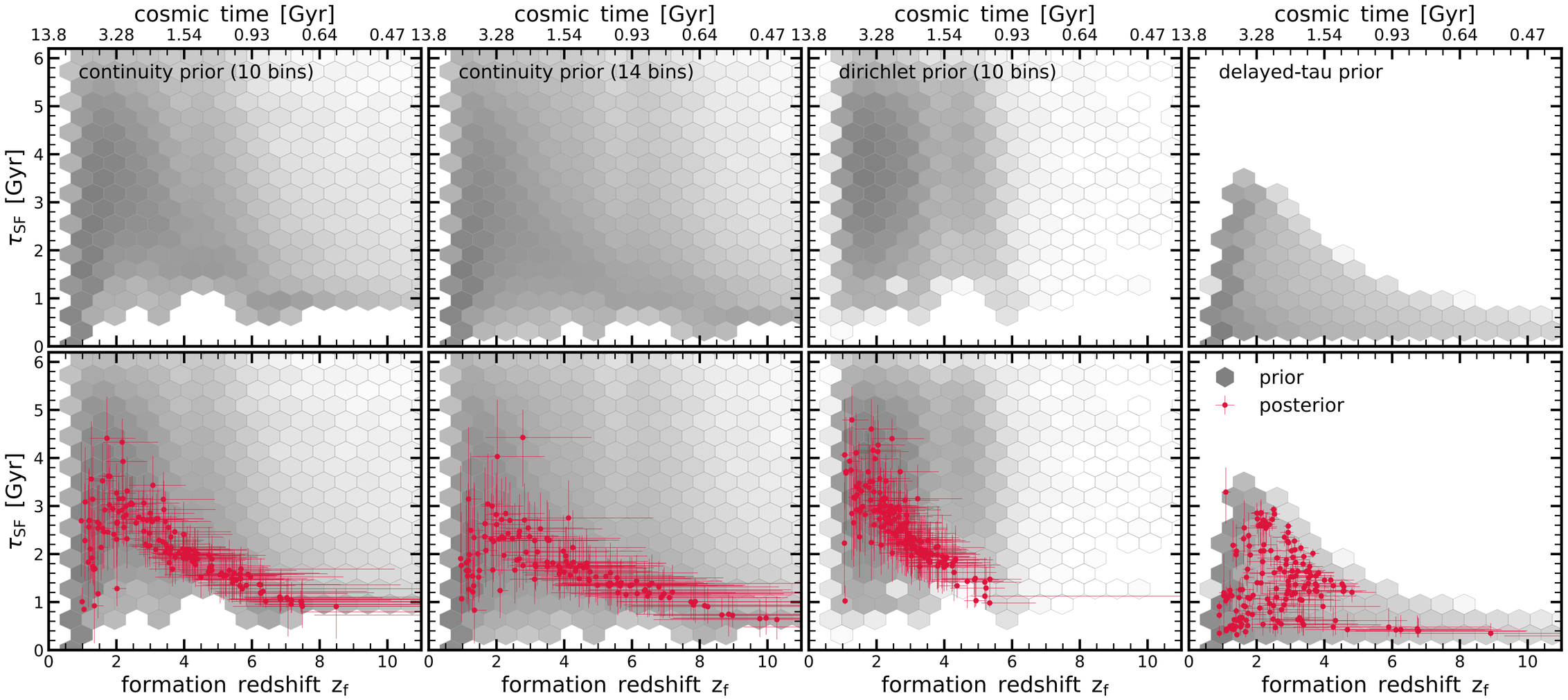


shorter star-formation timescale for more massive and early-forming galaxies

z_f: redshift of t_{50} (when 50% of the mass formed)
τ_{SF}: star-formation timescale (t_{20}-t_{80})

see also Carnall+ (2019), Leja+ (2019)

Prior on the star-formation history

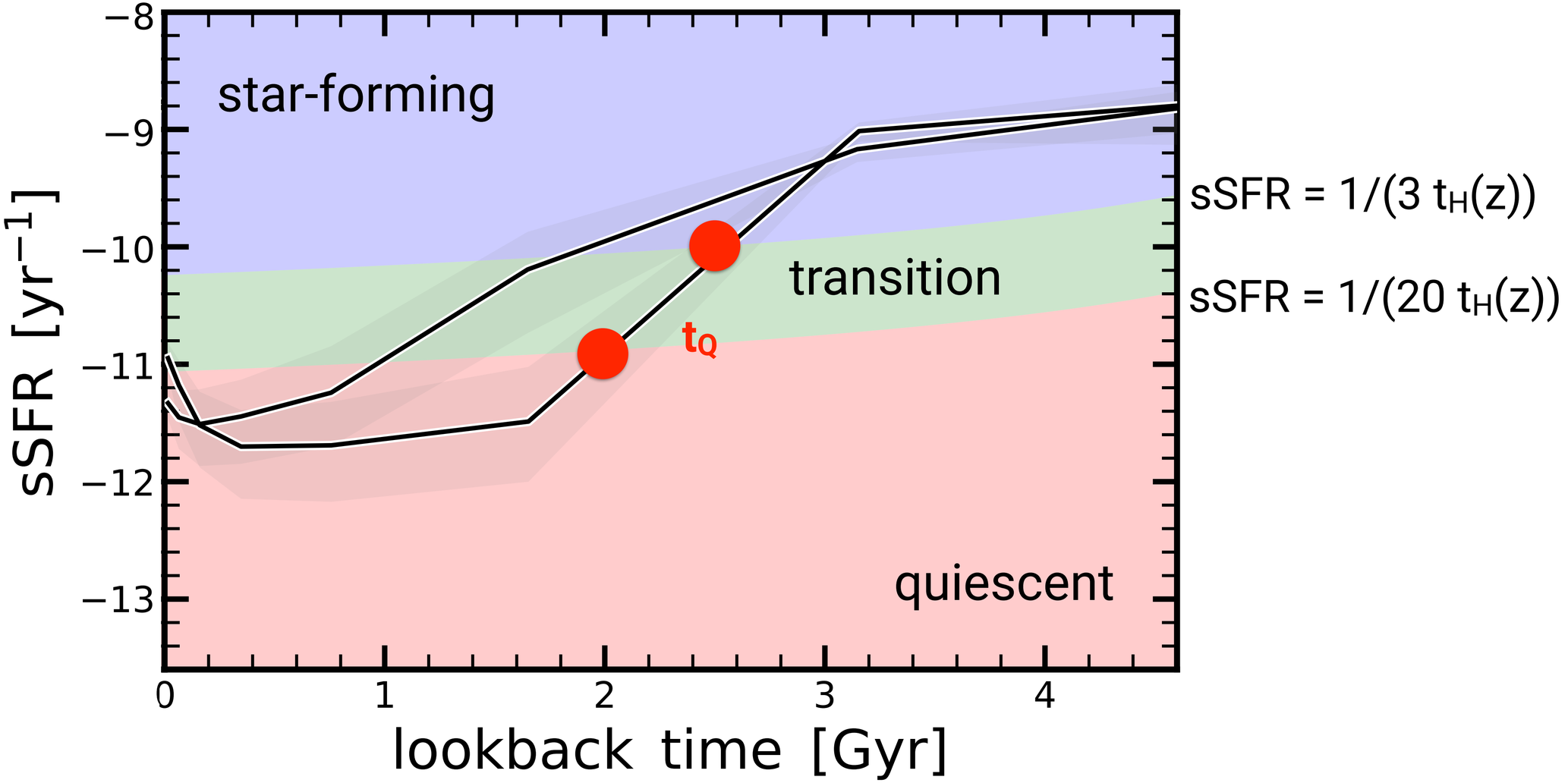


$$\mathcal{K} = \frac{\mathcal{Z}_{\rm np,14}}{\mathcal{Z}_{\rm np,10}} = 1.3$$

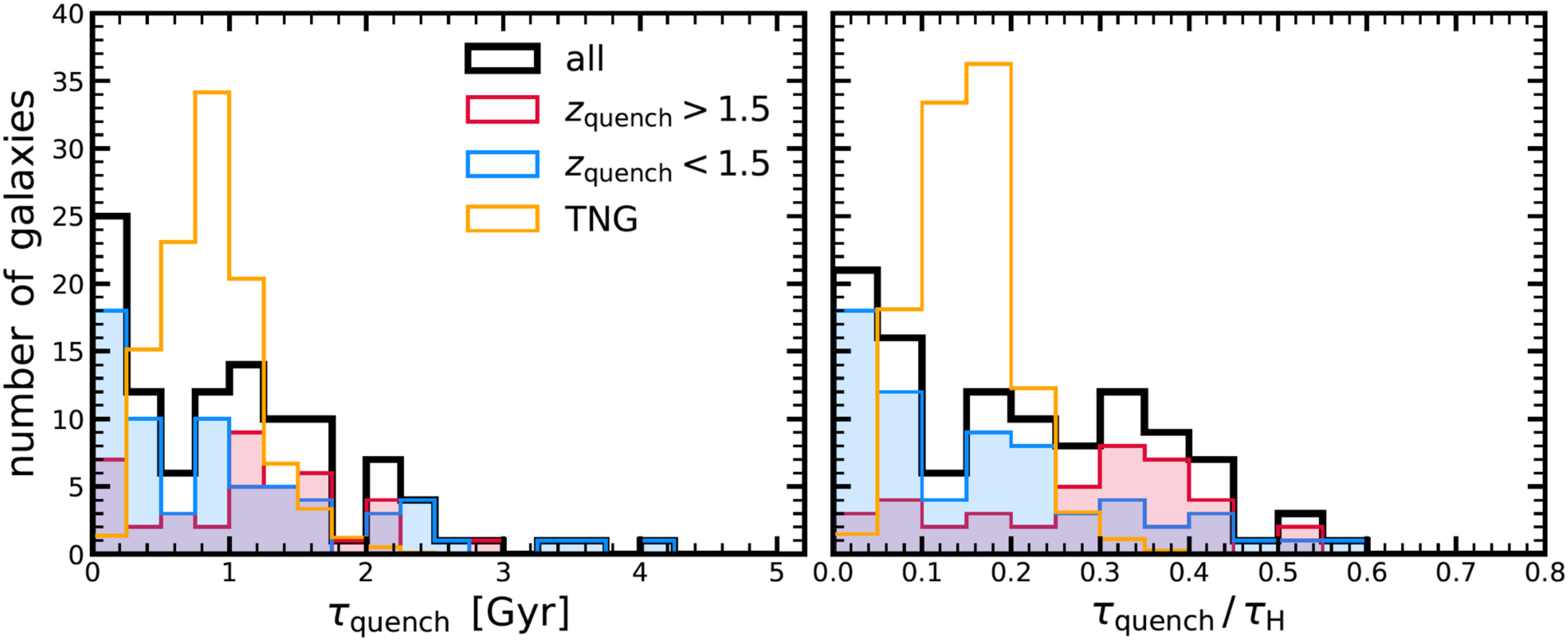
$$\mathcal{K} = \frac{\mathcal{Z}_{\rm np,dir}}{\mathcal{Z}_{\rm np,10}} = 6 \times 10^{-4}$$

$$\mathcal{K} = \frac{\mathcal{Z}_{\rm delayed-tau}}{\mathcal{Z}_{\rm np,10}} = 0.14$$

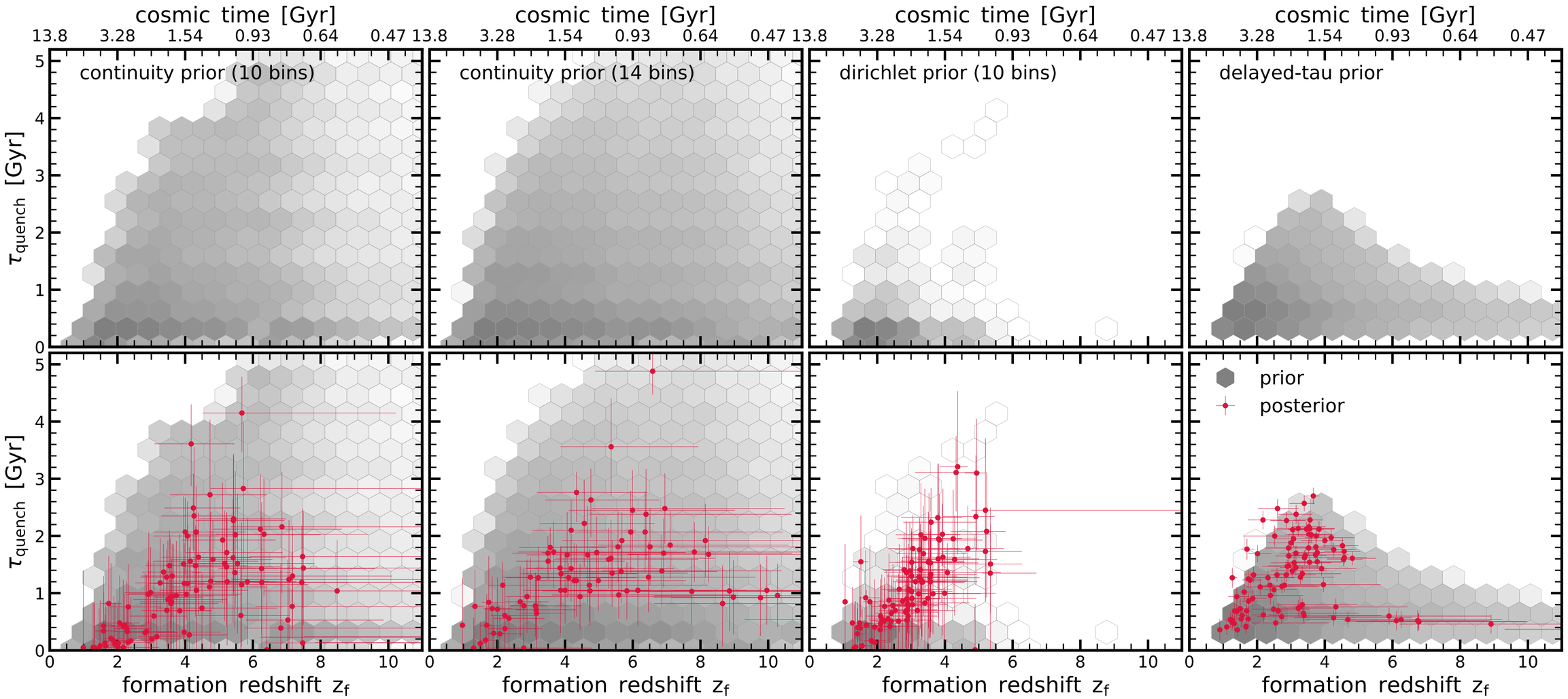
Definition of quenching timescale



Quenching timescales



Prior on the quenching timescale



Conclusions

- measuring quenching timescale for individual galaxies: forward vs lookback in time
- detailed modeling of spectroscopic + photometric data
- need both spectroscopic and photometric data in order to break age-dust-Z degeneracy
- understanding the imprint of the prior onto measurements is important
- large diversity of star-formation histories of galaxies at z~1:
  - some galaxies are extremely old with formation redshift of z~10 (➜ JWST)
  - star-formation timescale: shorter for more massive and early-forming galaxies
  - mergers have a non-trivial effect
  - large diversity of quenching timescale: few tens Myr to a few Gyr
  - do galaxy formation models predict this diversity?
- more about abundances and morphology