From Classic to Realistic: Connecting SFH, Color Evolutions and SED-fitting Behaviors of $0.5<z<2.5$ Galaxies in CANDELS

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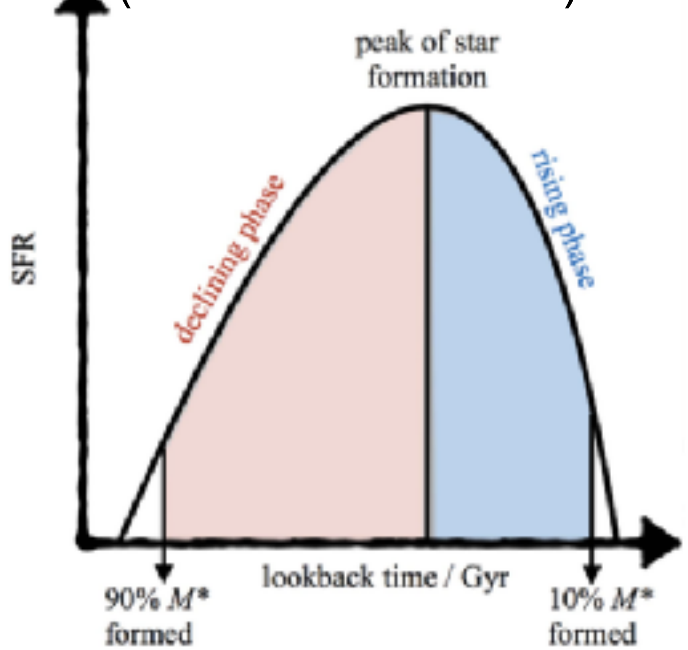
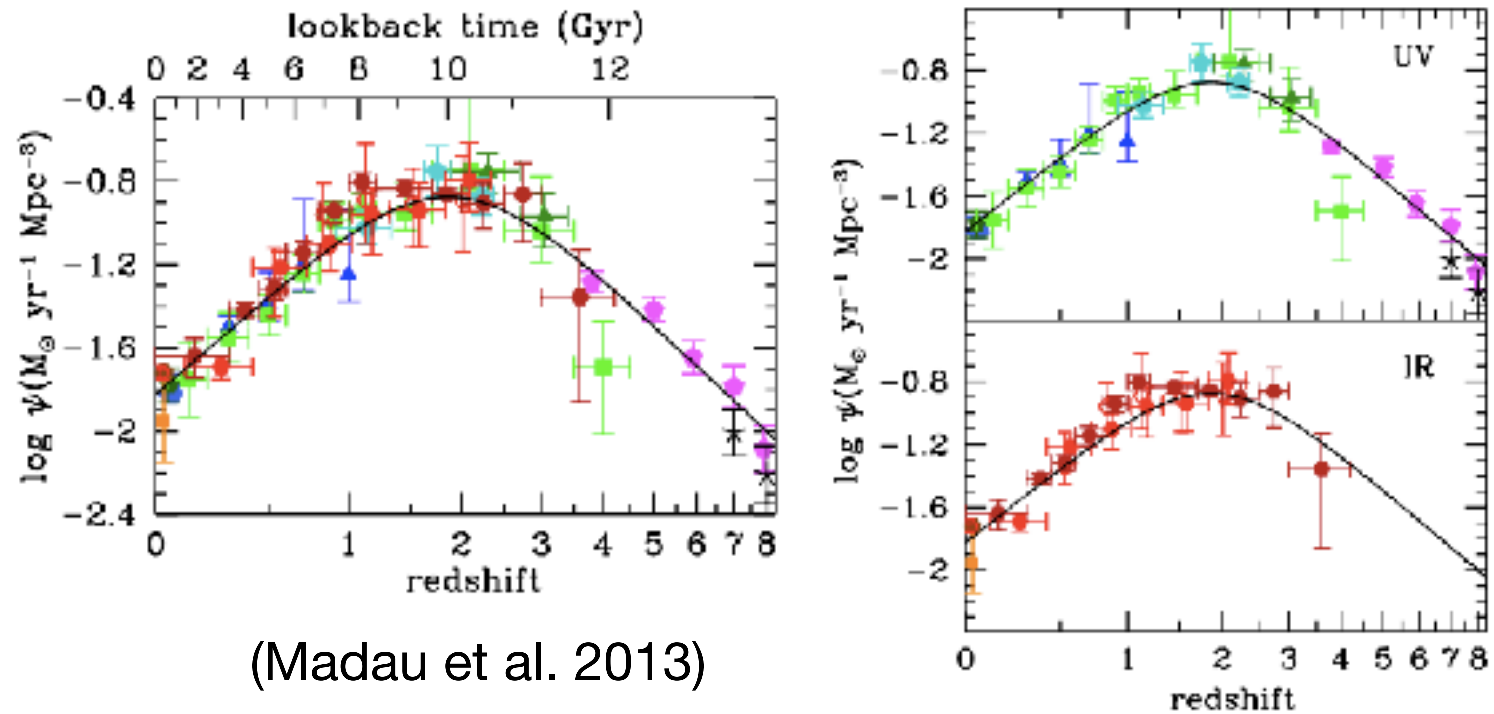
1. Introduction

■ Star Formation History (SFH) : the way how galaxies ***grow their mass***

(Pacifici et al. 2016)



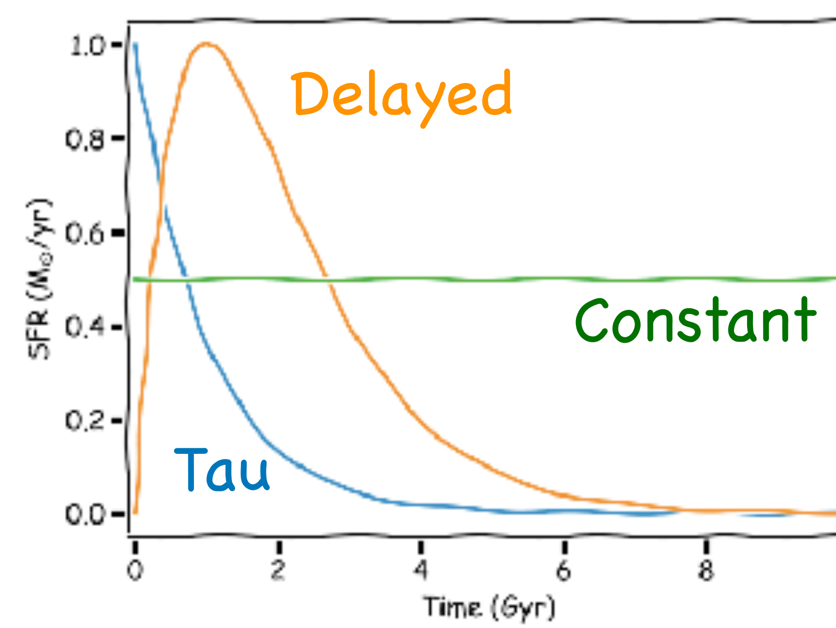


(Madau et al. 2013)

In simple and most popular cases, people use assumption of simple SFH models:

- Exponential tau Model $\mathrm{SFH}(t) \propto e^{-\frac{t}{\tau}}$
- Delayed tau Model $\mathrm{SFH}(t) \propto te^{-\frac{t}{\tau}}$
- Constant Model $\mathrm{SFH}(t) = const.$

Prior, Analytic, Hypothetical —— **'Classical'**



Many studies are based on results from **SED-fitting** with simple assumptions:

~95% Tau

~5% Delayed

However, some previous work have shown that:

Tau models are not PANACEA

E.g. Maraston et al. (2010): SED results for such models do not account well for the observed colors of z~2 galaxies for 96 GOODS-S sample.

Now we have recent CANDELS data ——

full GOODS-S: 34,930 objects + UDS: 35,932 objects

To check models on our own:

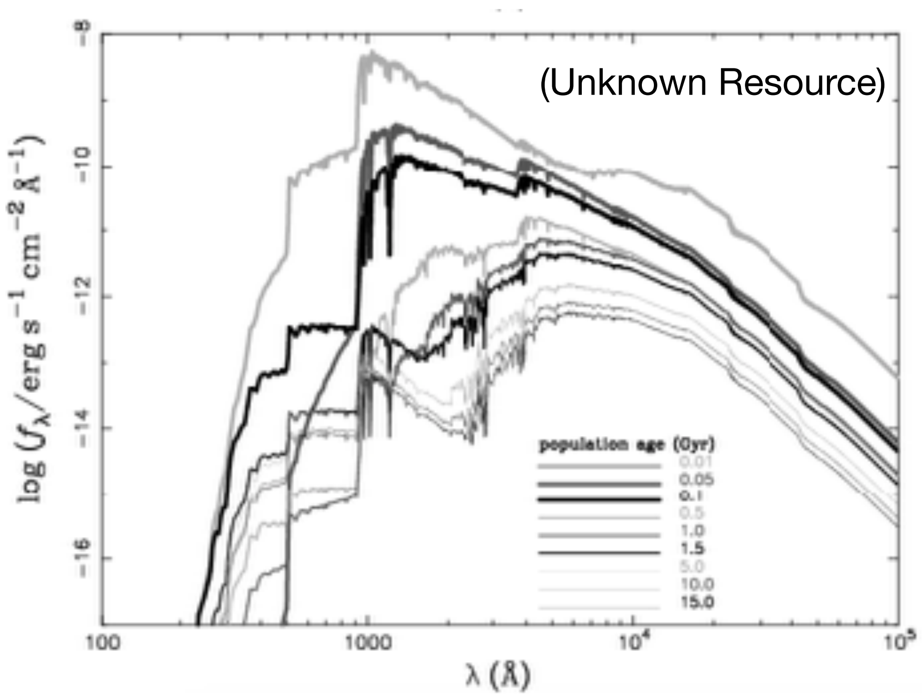
Q1: Can models explain real data?

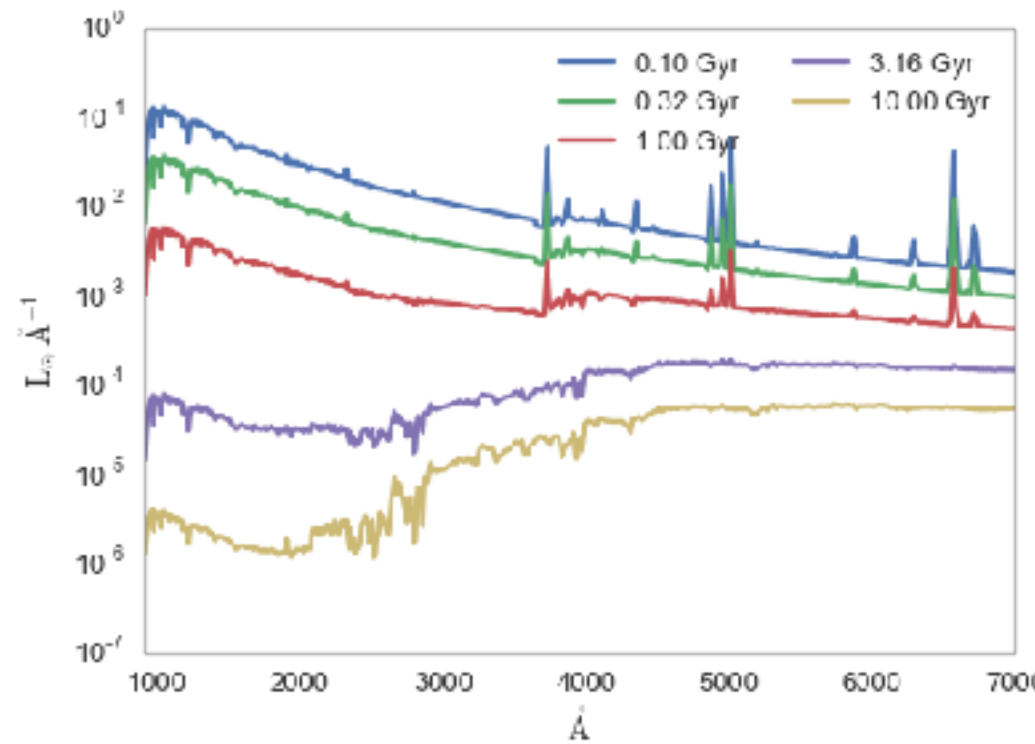
Q2: Can SED-fitting return correct estimation?

Use BC03 (Bruzual & Charlot, 2003) + astro-smpy (K. Duncan) to get synthetic SED from the models and then put them into FAST.

SED: Spectral Energy Distribution

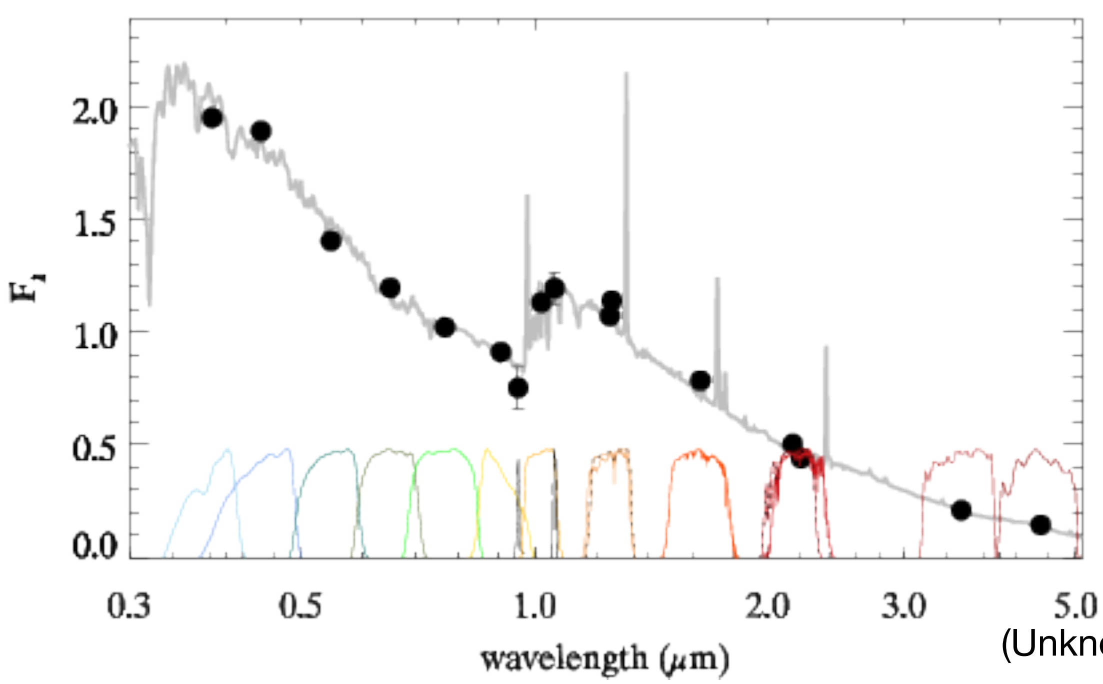
- **Synthetic SED : galaxy spectra following evolution models**





- **FAST (Fitting and Assessment of Synthetic Templates) : Standard SED-fitting Tool**

Kriek et al. 2007



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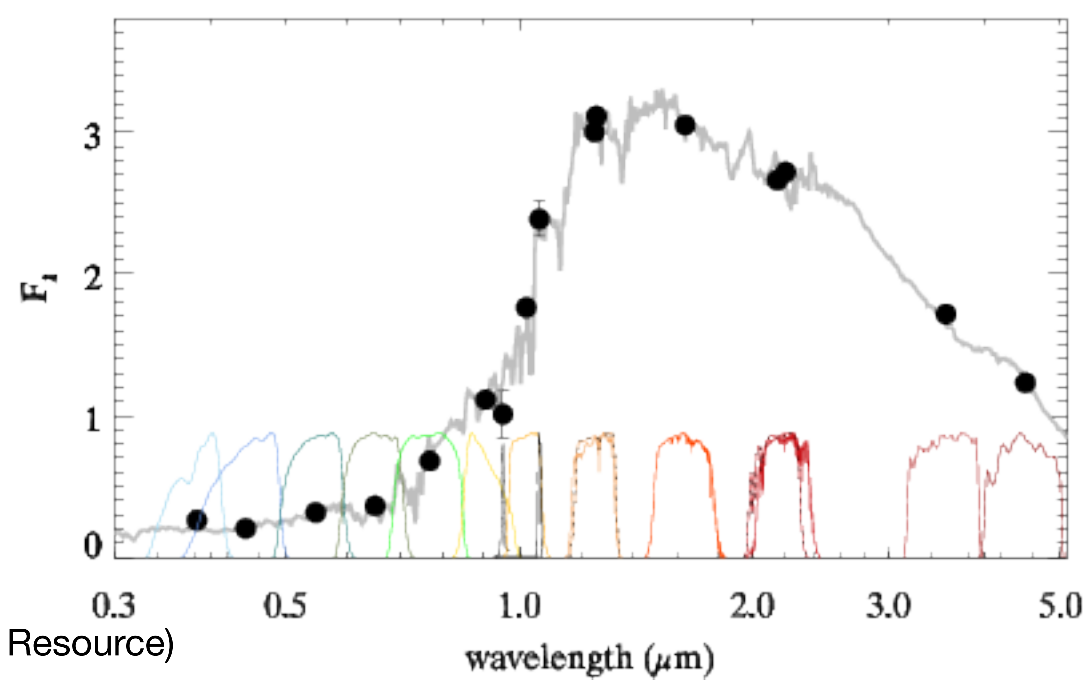


2. Data & Methods

2.1 CANDELS data

Cosmic Assembly Near-infrared and Deep Extragalactic Legacy Survey

Table 1. Sample Selection Cuts

Cut	GOODS-S	UDS	Combined
Full catalog	34,930 (100%)	35,932 (100%)	70,862 (100%)
F160W < 24.5	9,904 (28.4%)	12,223 (34.0%)	22,127 (31.2%)
SE flag = 0	9,607 (27.5%)	11,392 (31.7%)	20,999 (29.6%)
CLASS STAR < 0.9	9,376 (26.8%)	11,090 (30.9%)	20,466 (28.9%)
$0.2 < z < 2.5$	7,656 (21.9%)	9,534 (26.5%)	17,190 (24.3%)
$\log M_* < 11.0$	7,585 (21.7%)	9,445 (26.3%)	17,030 (24.0%)
$9.0 < \log M_* < 11.0$	4,683 (13.4%)	5,810 (16.2%)	10,493 (14.2%)
GALFIT flag = 0	4,028 (11.5%)	5,107 (14.2%)	9,135 (12.9%)
Star-forming	3,581 (10.3%)	4,479 (12.5%)	8,060 (11.4%)
Quiescent	447 (1.3%)	628 (1.7%)	1,075 (1.5%)

High-quality data to help us understand the formation and evolution of galaxies

We use the same sample and catalog in Fang+ 2017 (UVJ paper)

2.2 Stellar population Synthesis

- SSP Library: BC03
- Chabrier IMF
- Calzetti Attenuation: Av = 1
- No Emission Lines
- Solar Metallicity

2.3 SED-fitting: FAST

- Tau / Delayed Model Templates
- Chabrier IMF
- Calzetti Law
- Solar Metallicity
- 1% hypothetical error
- FUV, NUV, U, B, V, R, I, J, H, K

The parameters we are concerning about are:

M*, SSFR and Av

M*: Stellar Mass

sSFR: Specific Star Formation Rate

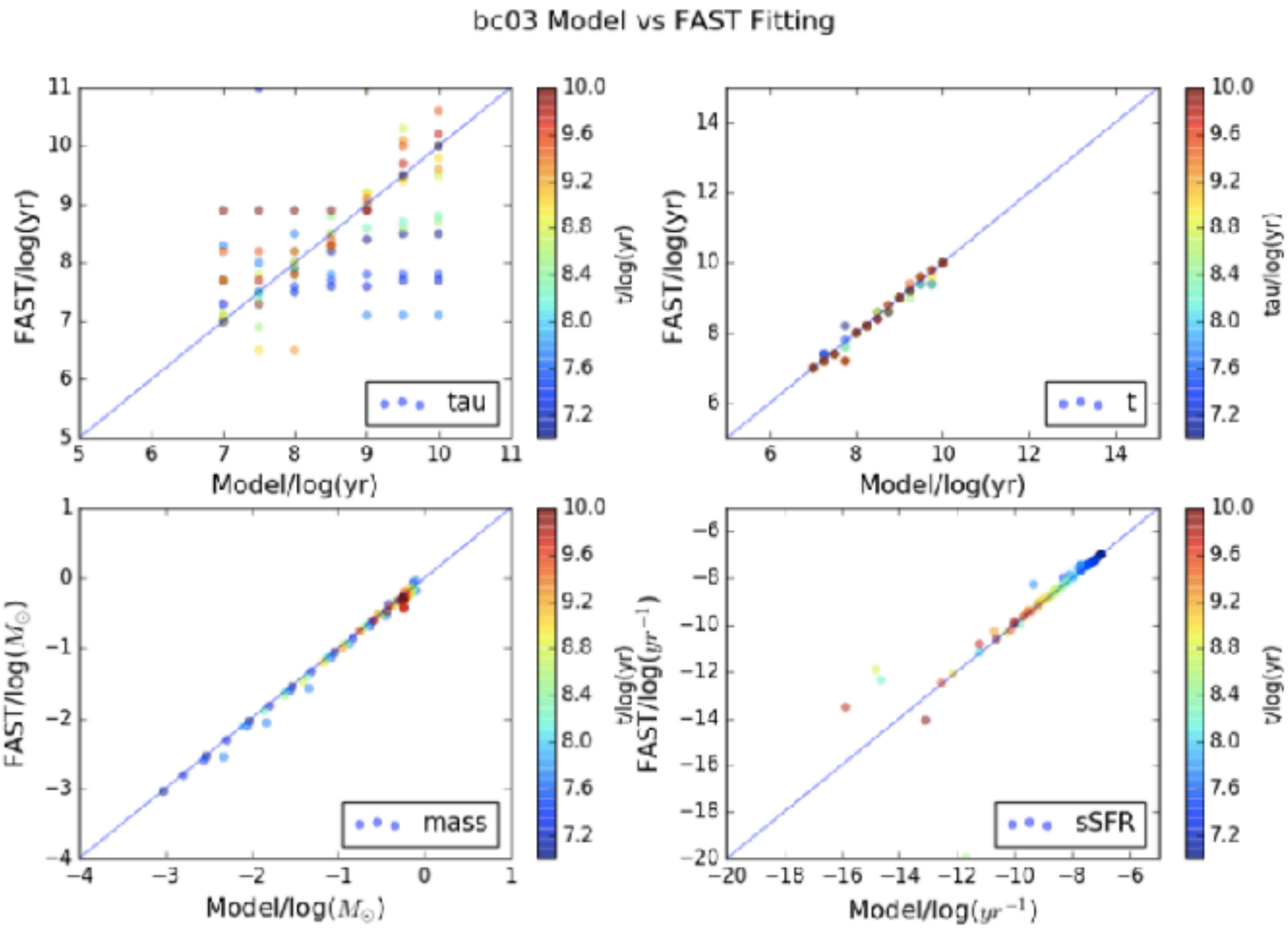


Fig 1: Comparisons of parameters which are input and FAST returns

Inputs (exponential tau model)

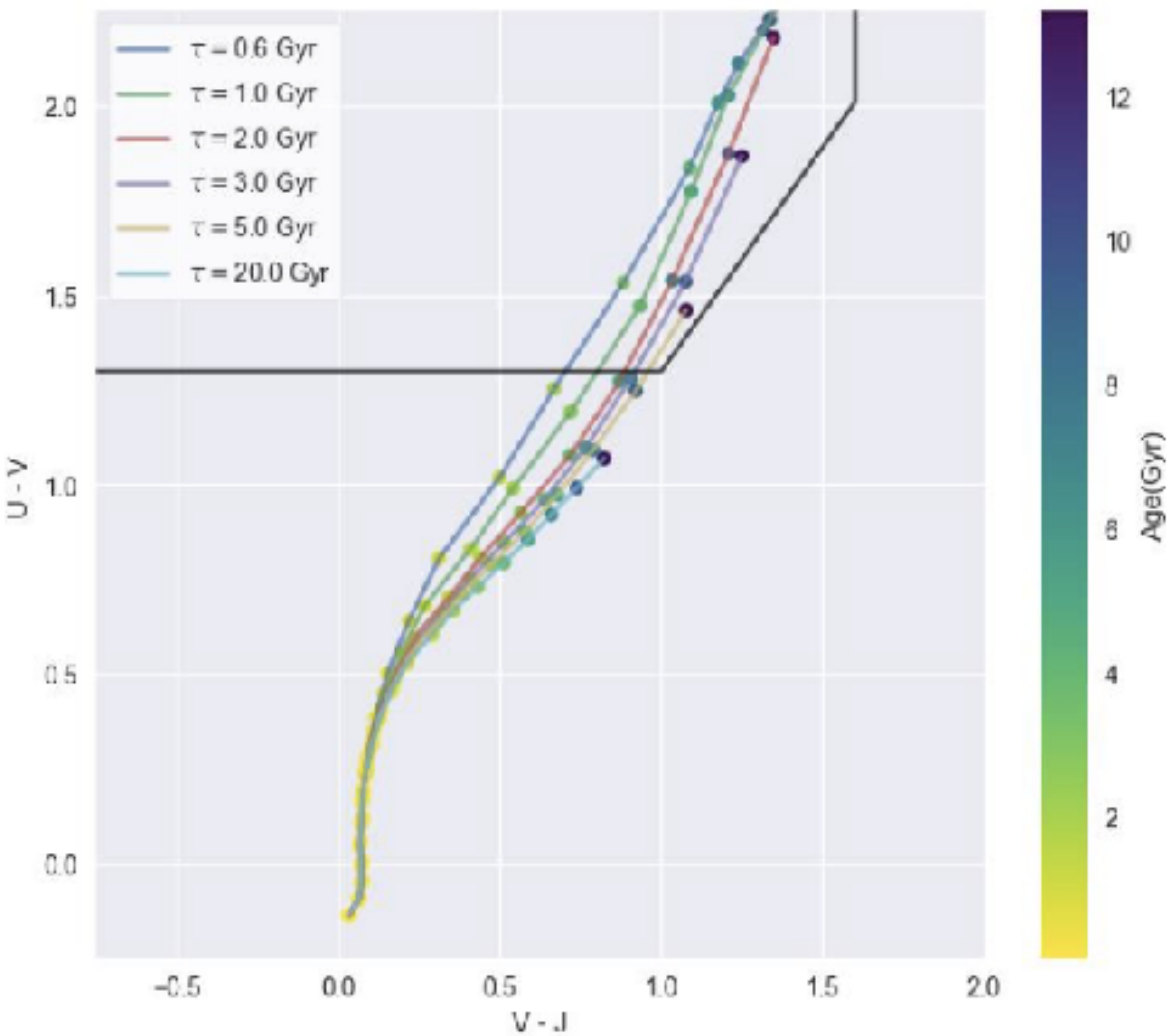
- Fit with tau templates
- SEDs with different taus and ages
- No dust
- Solar metallicity
- 1% photometric error

Outputs

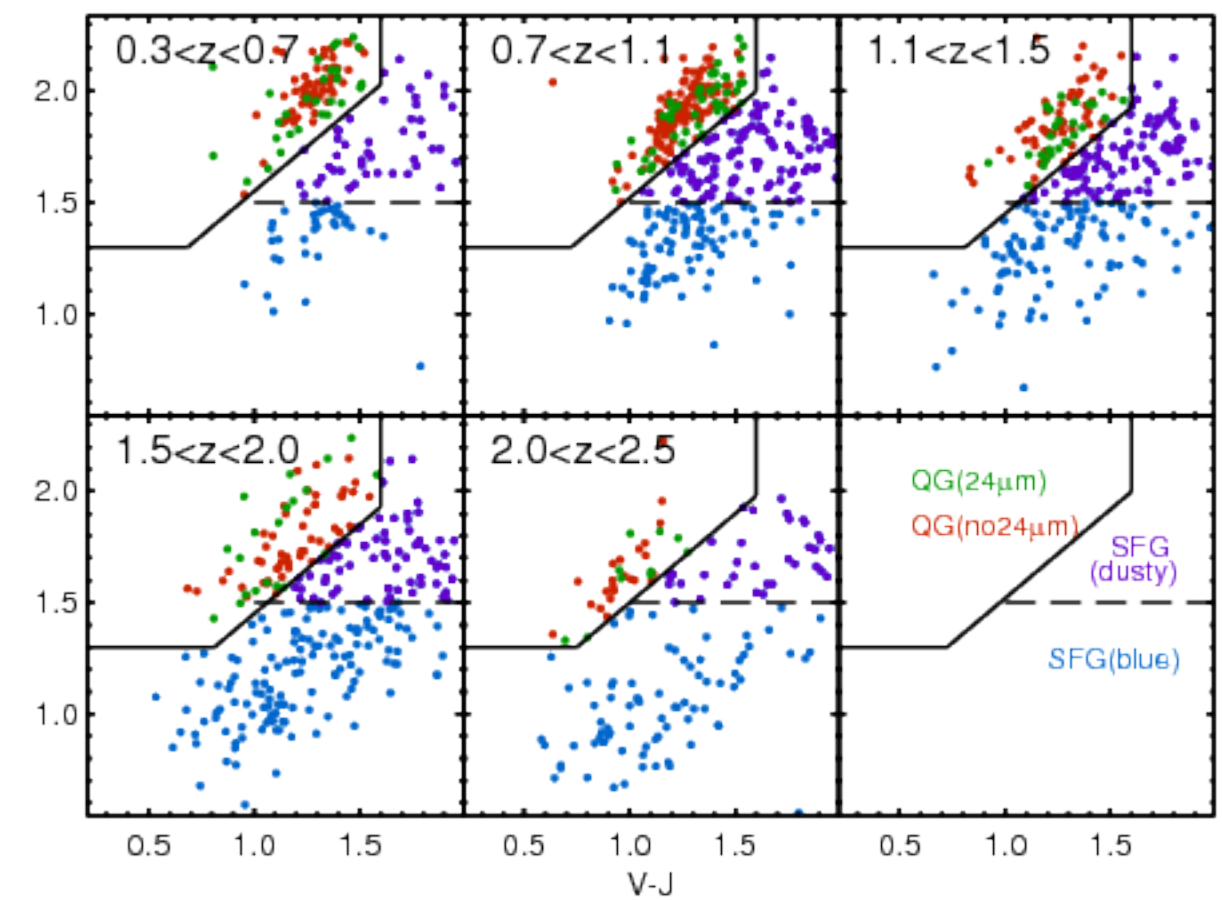
- Age, stellar mass, sSFR are relatively good
- Tau with large scatter

Csed = 0.82(U-V) - 0.57(V-J)

⬇ UVJ tracks of different exponential models



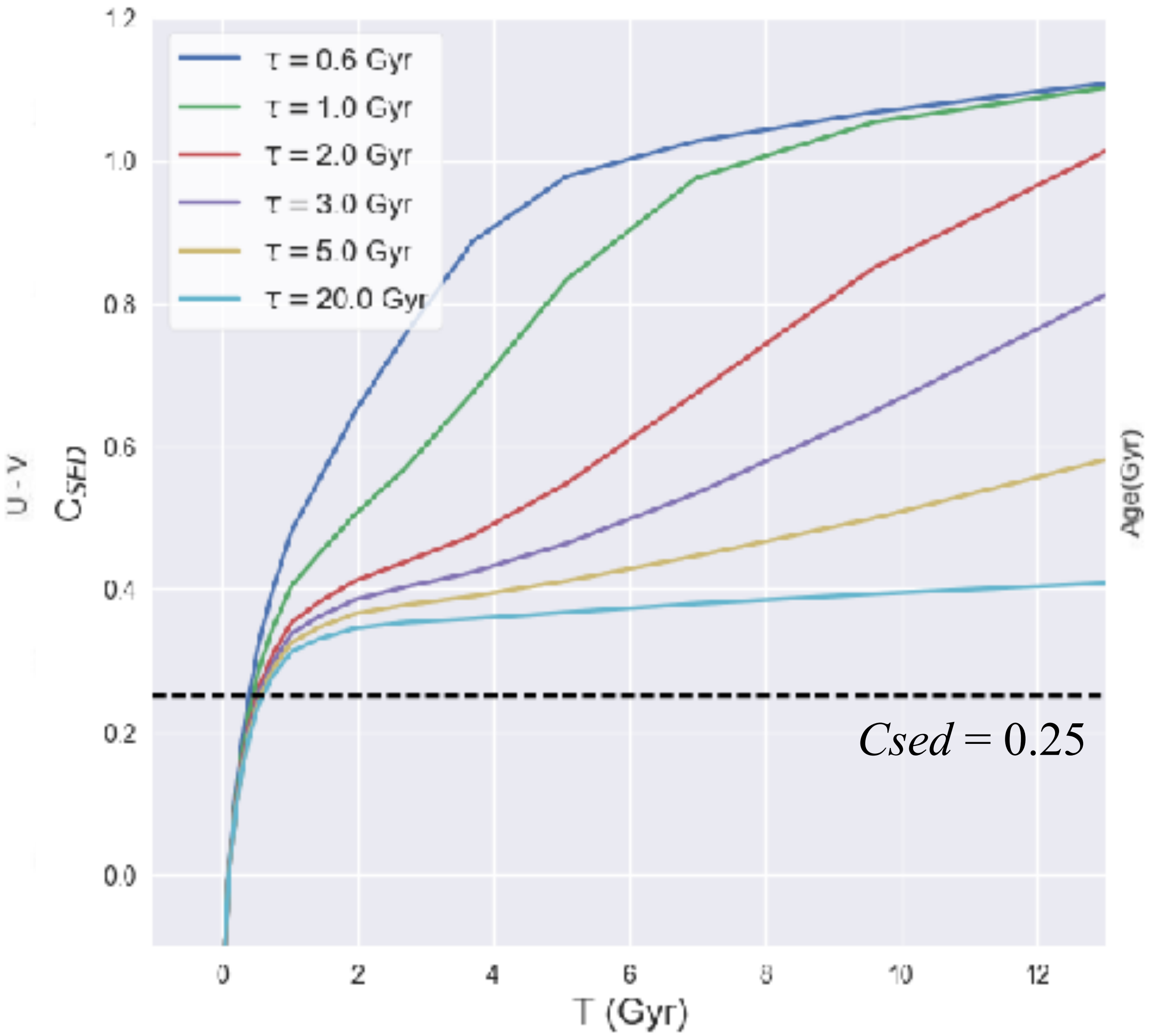
(Fumagalli+ 2014)

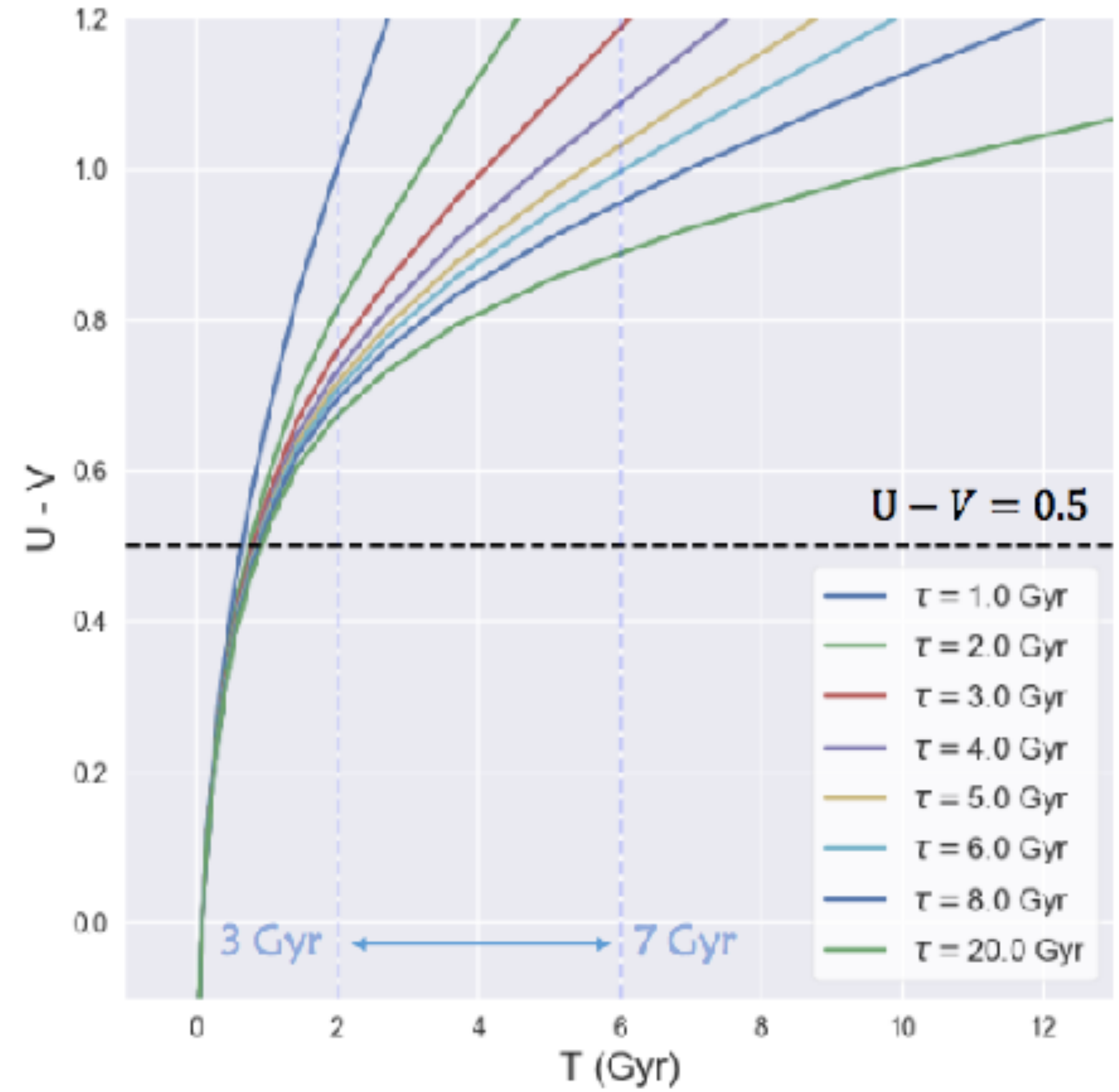


U-V evolution of different exponential models ⬆

Csed = 0.82(U-V) - 0.57(V-J)

Csed evolution of different exponential models

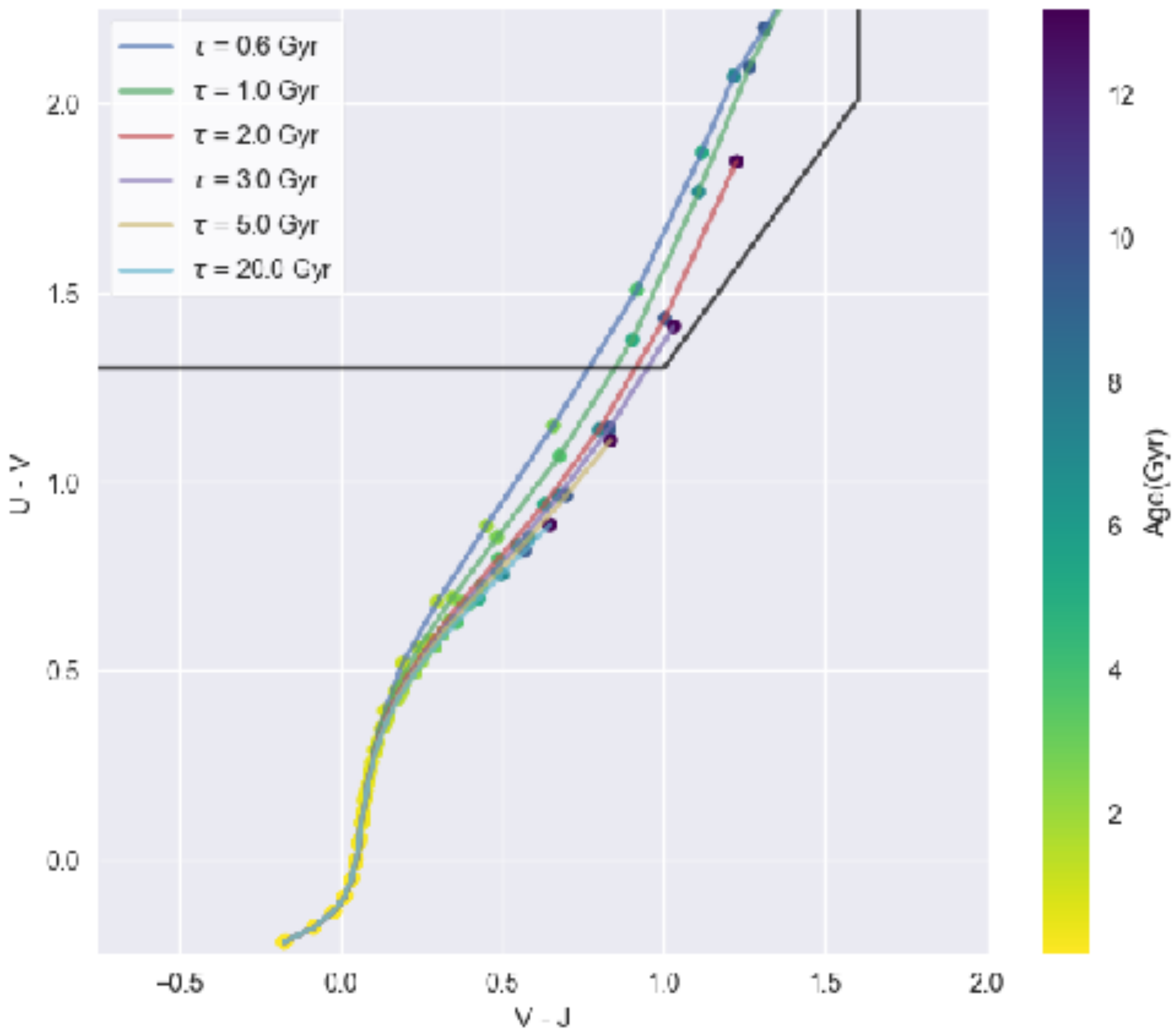


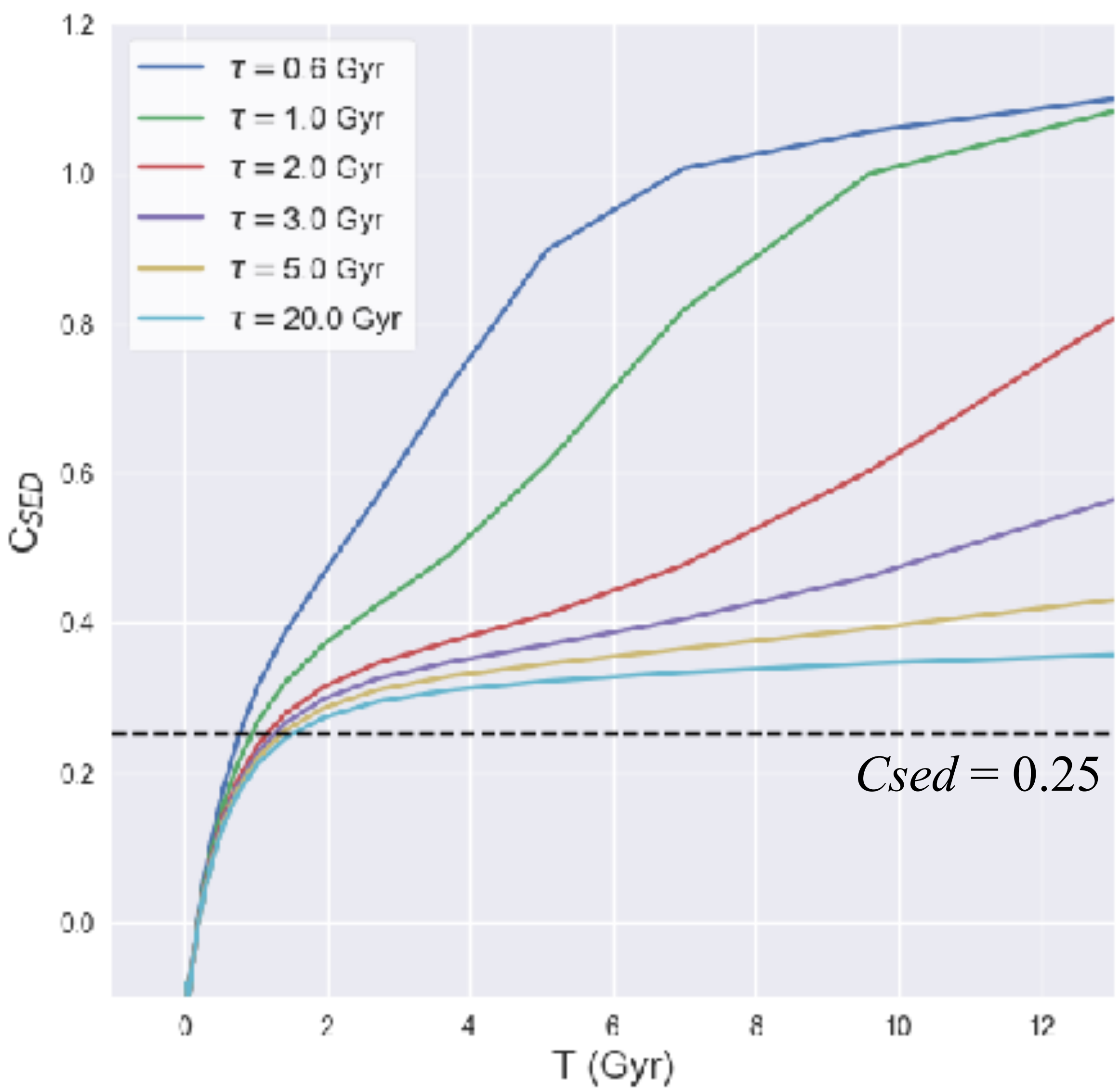


U-V evolution of different exponential models

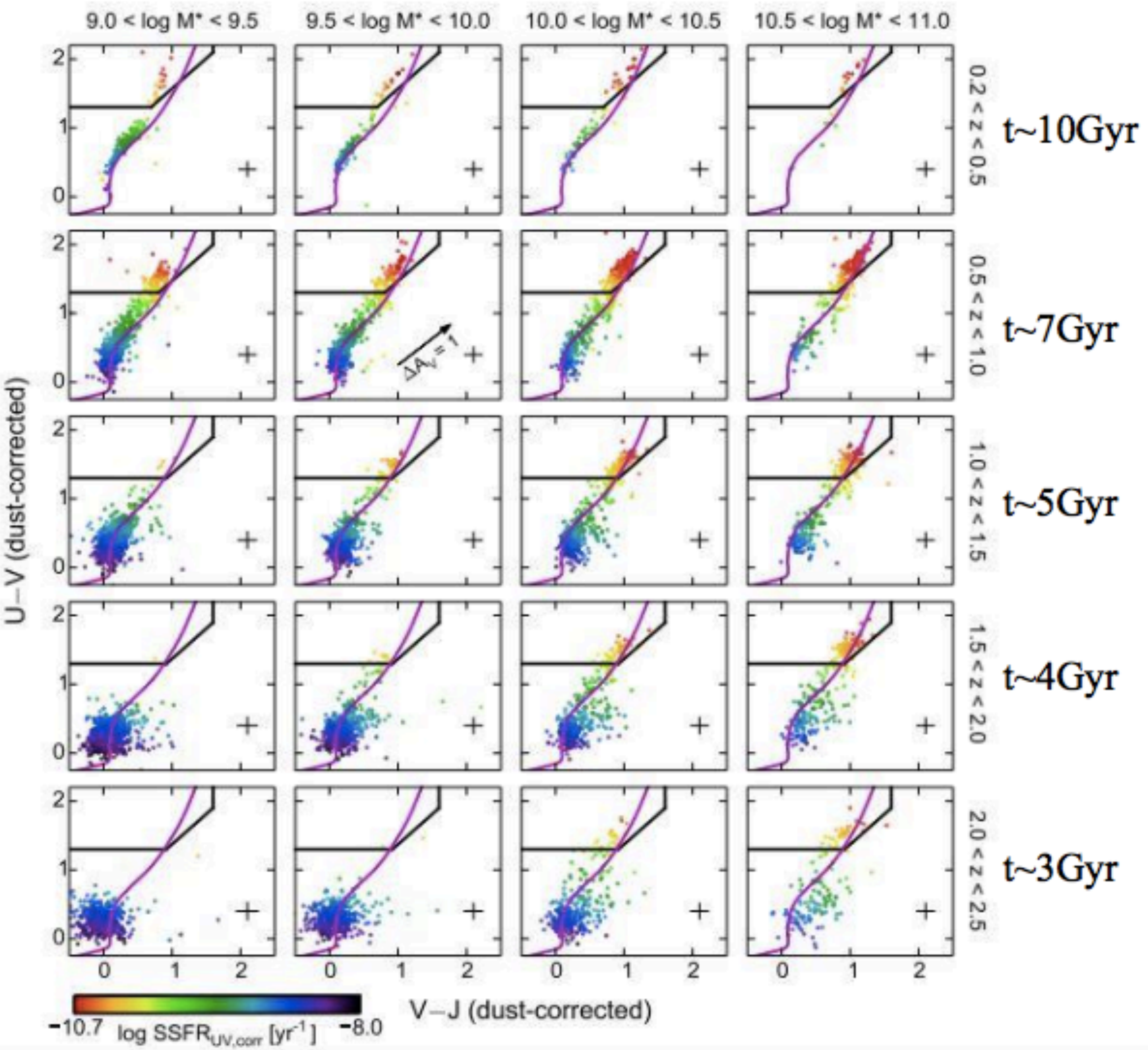
Galaxies following Tau models faded rapidly within 1 Gyr

What if
Delayed models?



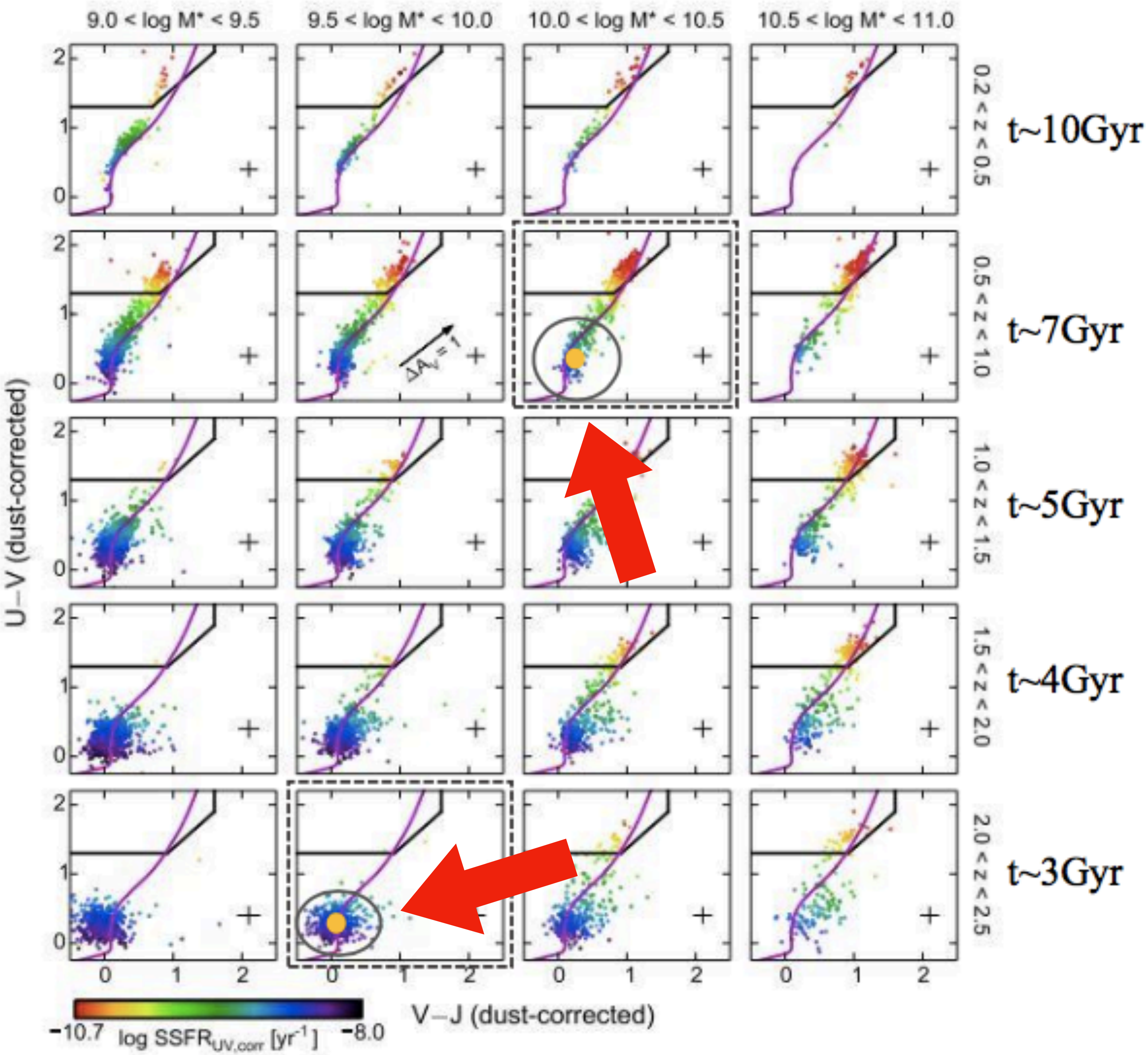


Delayed models
faded within
2 Gyrs as well



(Fang+2017) CANDELS data with different M* and z bins

- It seems that CANDELS data do follow the tau model UVJ track.
- **BUT** a large group of strong SFGs survive until 7 Gyrs.

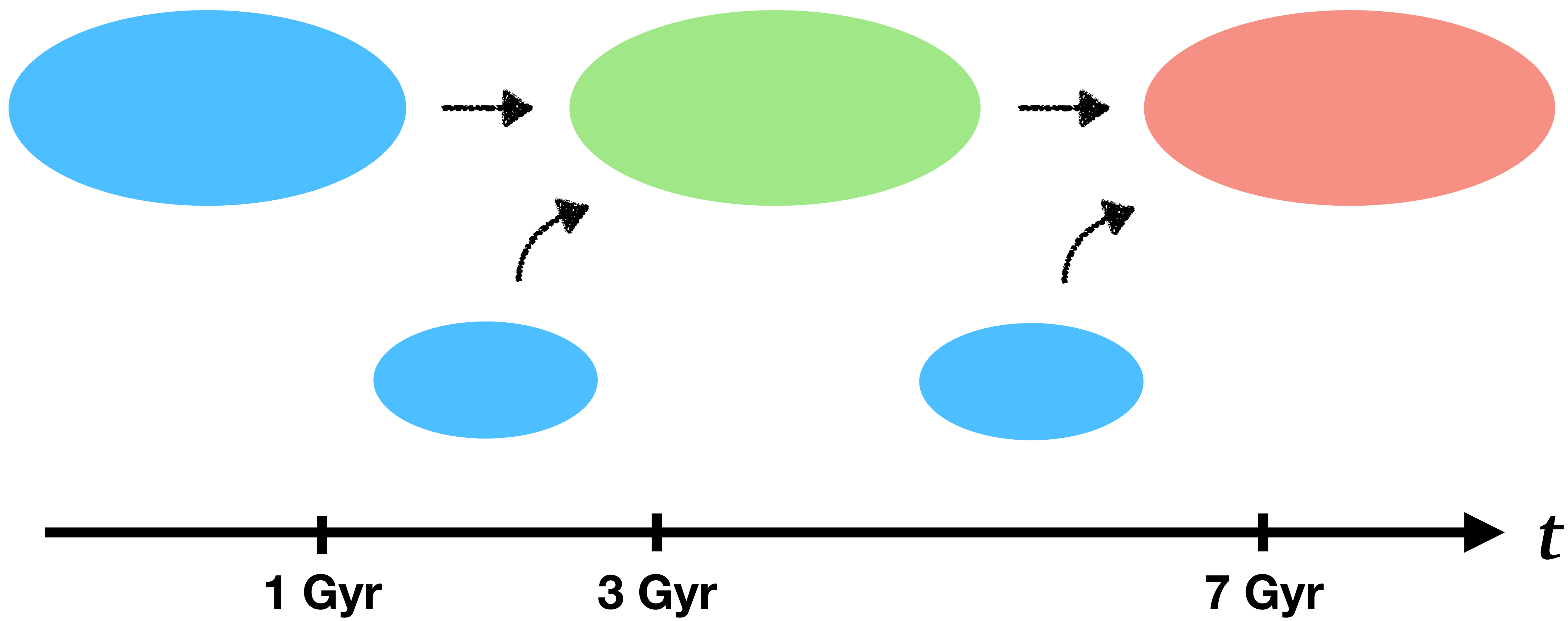


(Fang+2017) CANDELS data with different M* and z bins

- It seems that CANDELS data do follow the tau model UVJ track.
- **BUT** a large group of strong SFGs survive until 7 Gyrs.

Real Galaxies stay blue longer than what classic models predict.

Classical SFHs cannot well match the color evolution of galaxies.



Up-till-now it cannot reject such (although unrealistic) explanation:

Galaxies continuously born over a time span > 4 Gyr

However we are now helped by having actual evolution tracks based on **Abundance Matching**.

Abundance Matching would tell us: most galaxies seen at z ~ 2 are going to become their descendants at later times.

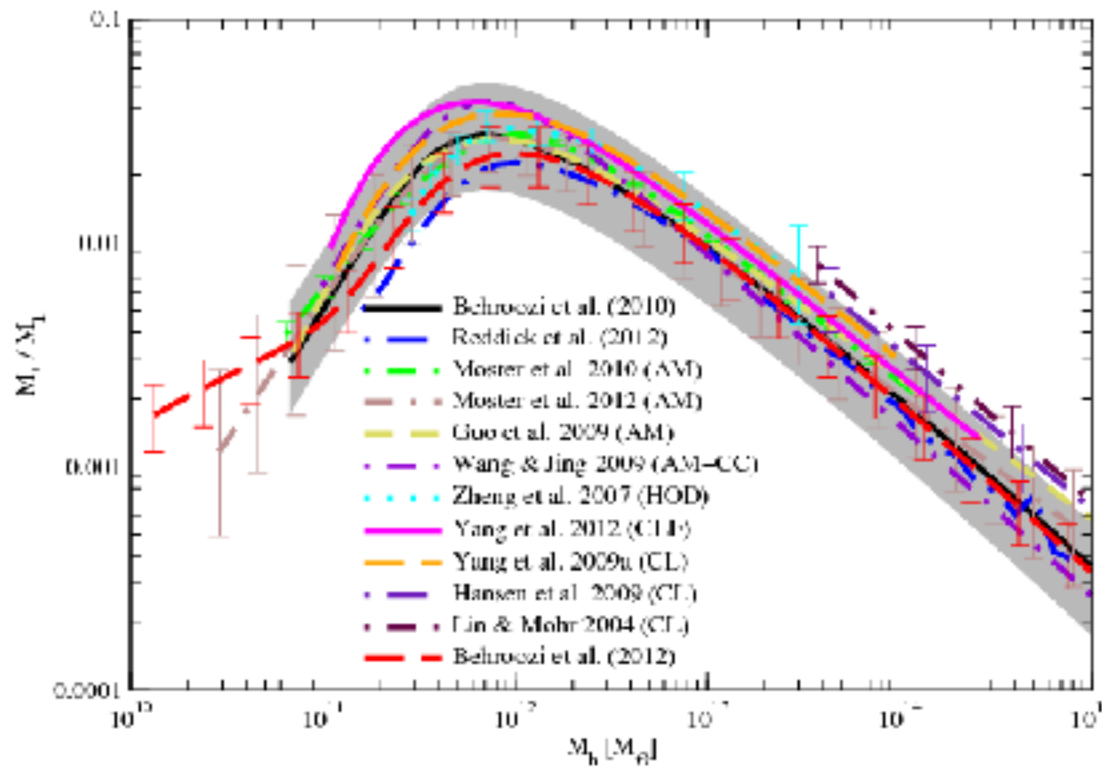
Galaxy-Halo Connection

Fundamental to Understand Galaxy Evolution

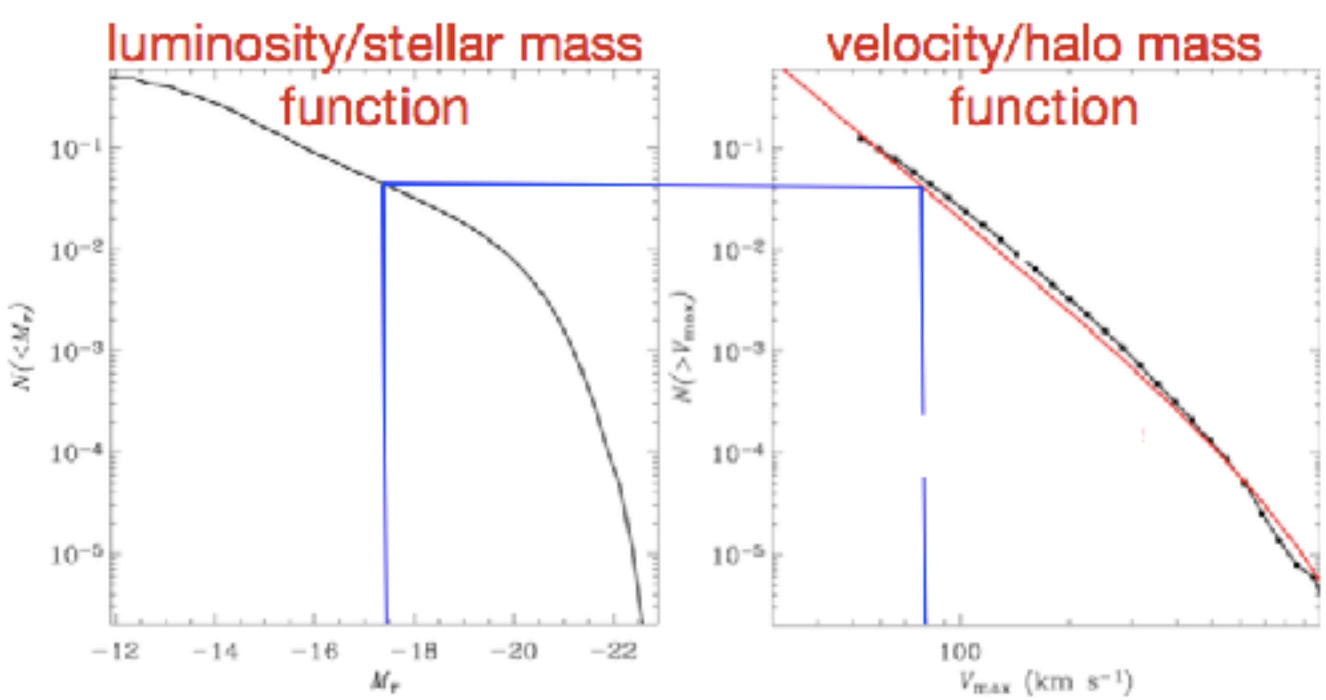
Bolshoi Simulation: Klypin, Trujillo-Gomez & Primack 2011

(from Aldo Rodriguez-Puébla 's talk)

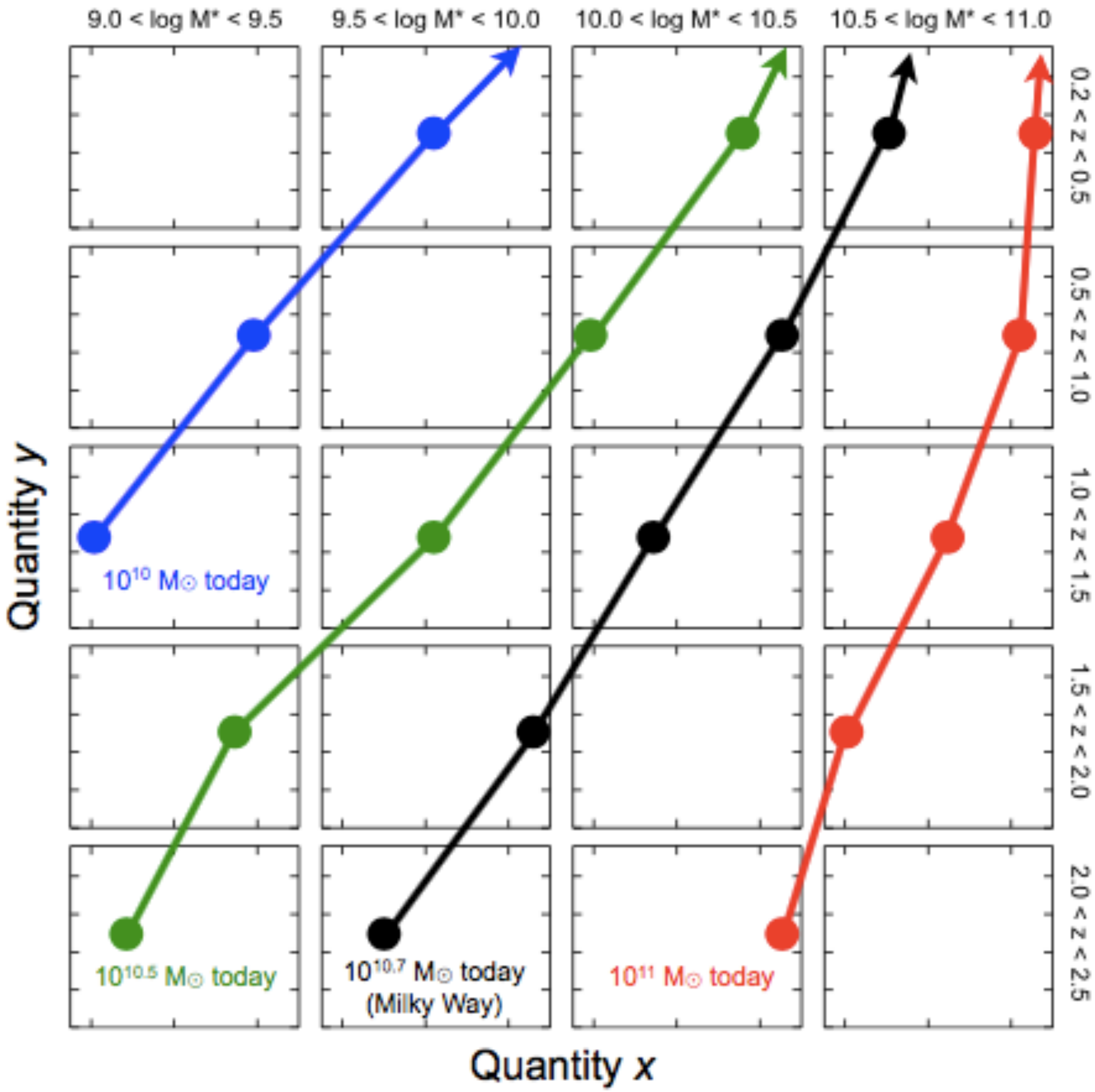
■ Abundance Matching: connecting galaxy property to halo property



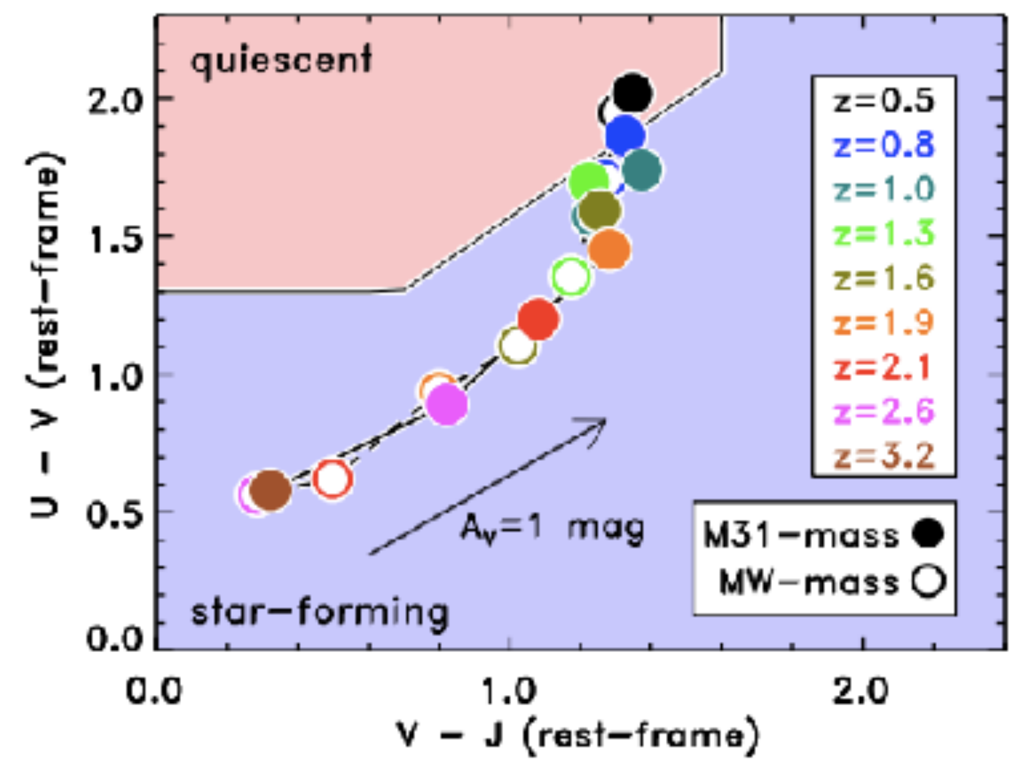
Stellar-to-Halo Mass Relation (Behroozi+2013)



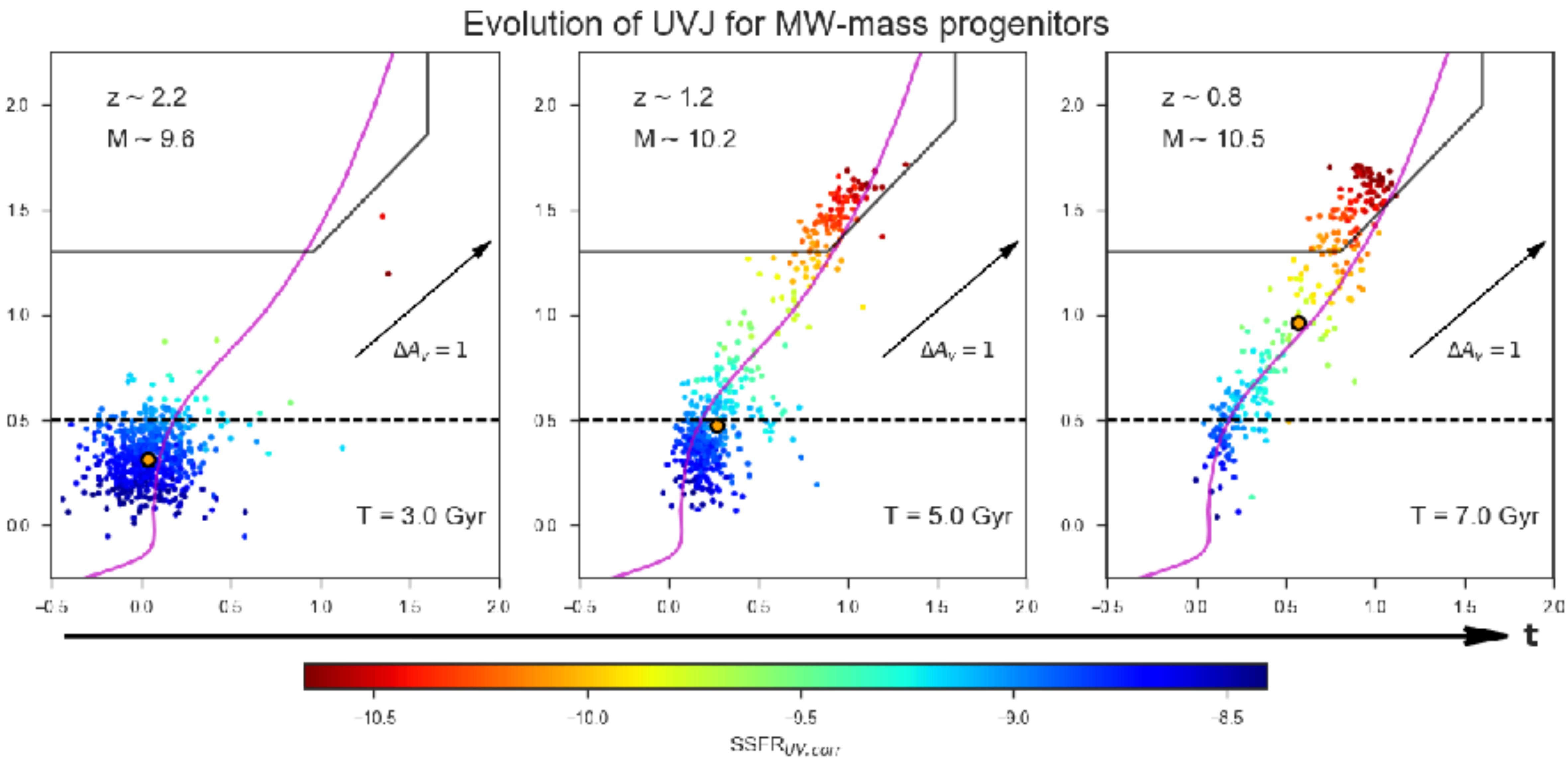
Abundance Matching Techniques (from Welcher 's talk)



(Fang+2017) Growth tracks for galaxy progenitors today



(Papovich+2015) UVJ evolution of MW & M31 Mass progenitors



1. Galaxies were evolving along the evolutionary tracks, turning from blue star-forming, up through the green valley (GV), into red quiescent galaxies.

2. It takes **>4 Gyr** for MW progenitors to evolve from the bluest end of the star-forming population into the GV, crossing a characteristic critical color, **0.5**

'Age-color' Problem: invalidity of classical SFH models to explain color evolution

3. Solutions to the 'Age-color' Problem based on SED-fitting Tests

3.1 Approach I : A Frosting of Young Stars

A small fraction of newly born very young stars is likely to keep galaxies blue.

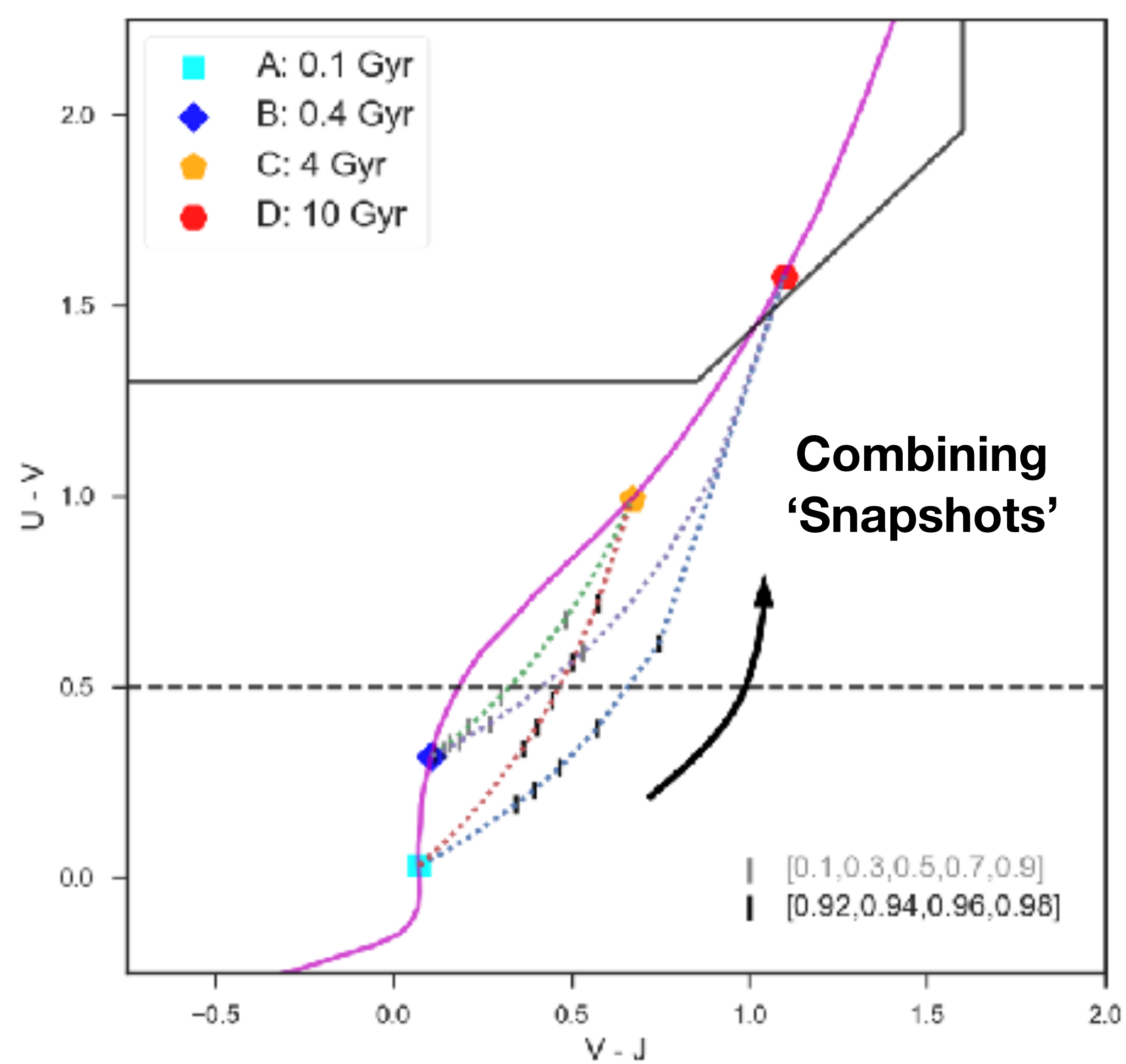
We will construct such populations, which are mixes of old and young populations—— we call them **"composite (tau) models"**

To simplify, consider a combination of two SSP:

a. an old evolved population across the GV

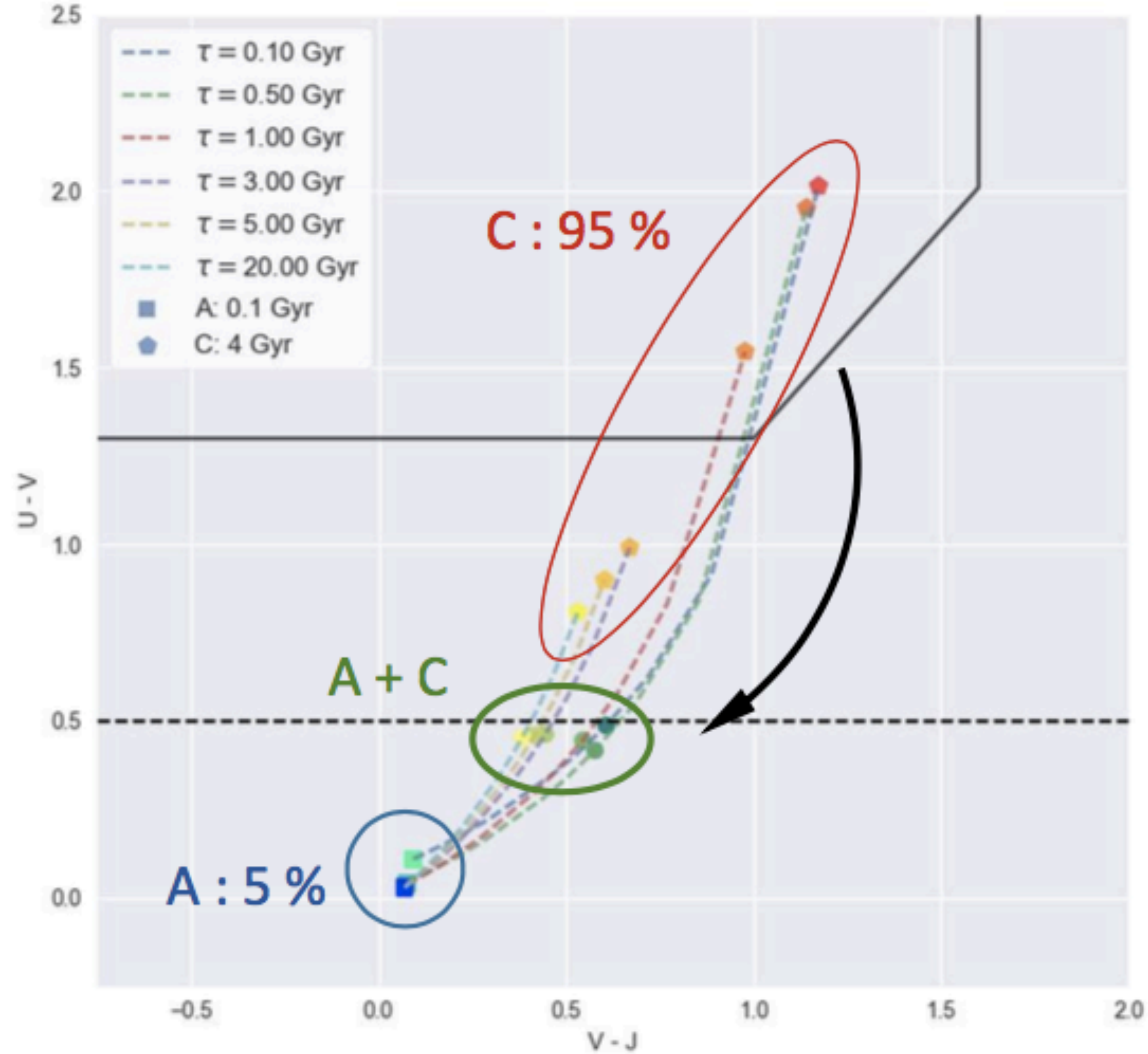
b. a newly- born group of very blue stars

- Old pop: 4/10 Gyr (above critical color)
- Young pop: 0.1/0.4 Gyr (below critical color)
- Mass weighted fraction from 0 to 1
- Both following exponential SFHs



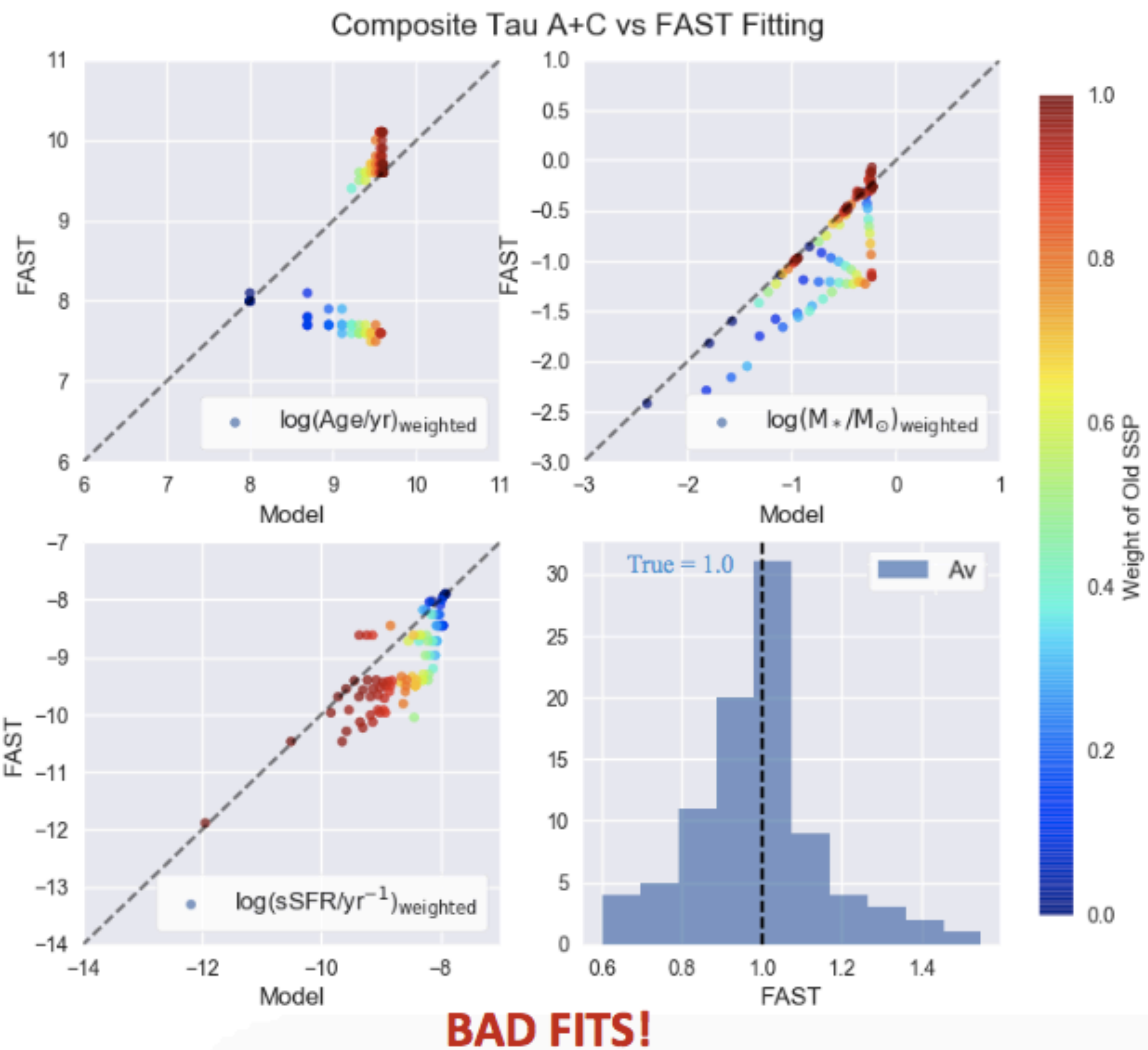
-What fraction of the blue population do we need to keep galaxies blue?

-Does FAST (when assuming classic templates) return correct values when applied to these models?



(A physical interpretation could be another burst happened *just before* we observe, e.g. *minor major*)

Given a certain fraction of young stars, galaxies could be blue again.



Q : Can FAST figure out these composite models and return reasonable results?

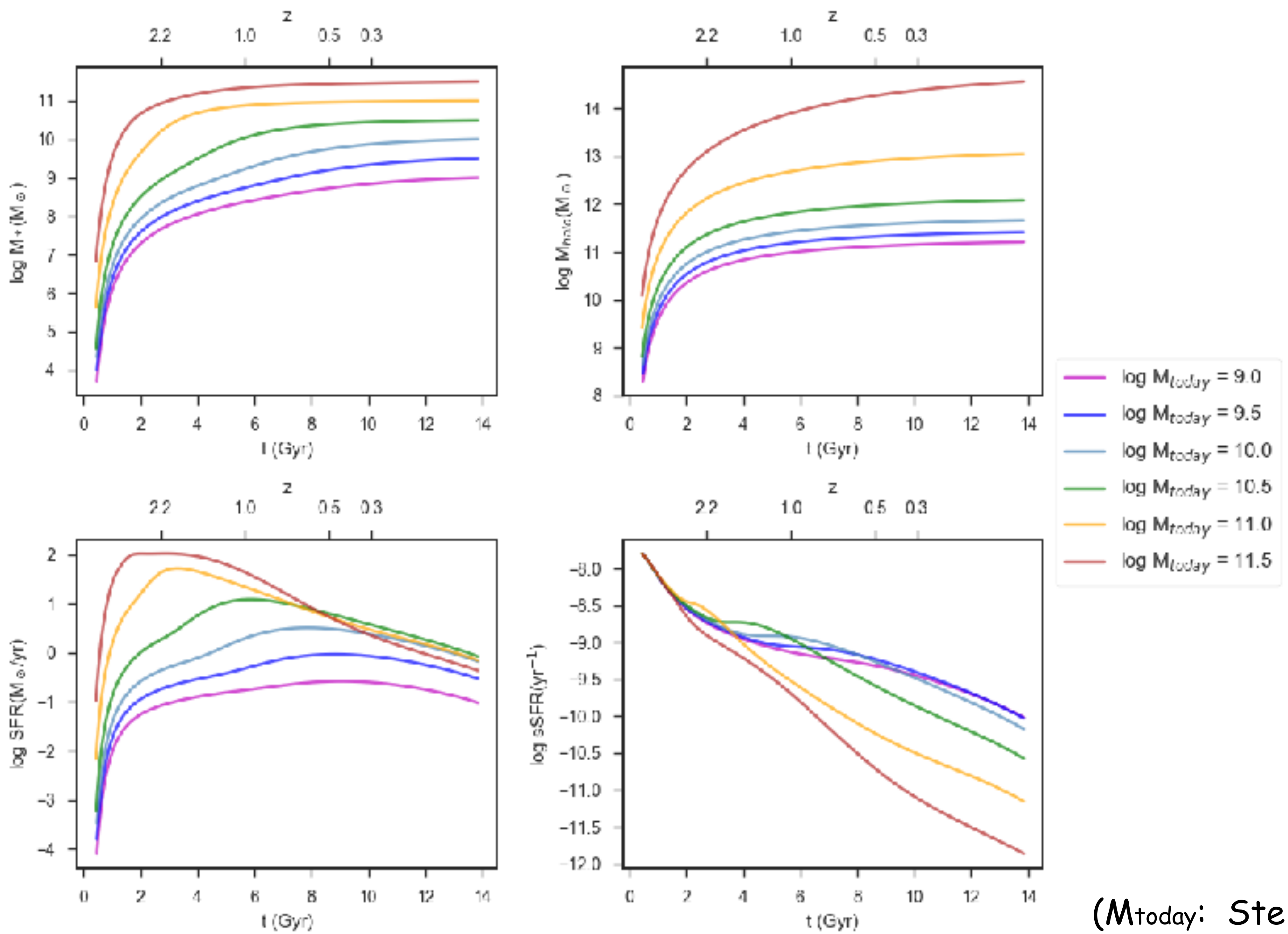
- **No.** FAST returns bad values for these composite stellar populations assuming tau / delayed templates.

Need more realistic SFHs!

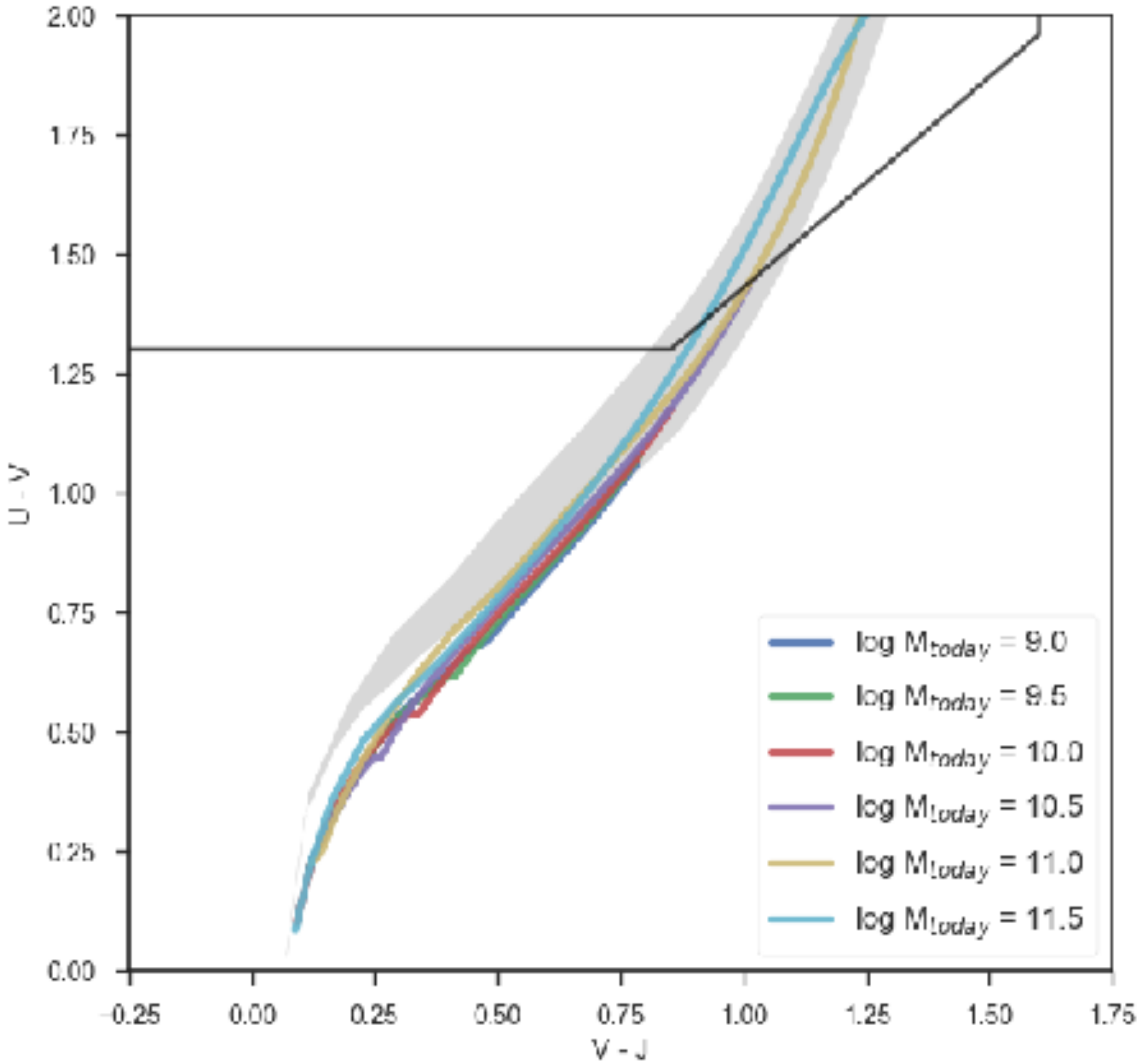
Furthermore, It is not plausible that *most* galaxies at late epochs have stayed blue via this mechanism.

3.2 Approach II : Abundance Matching Derived SFH (AM-SFH)

- Use more realistic SFH derived from abundance matching (Rodriguez-Puebla et al. 2017)
- Put them into BC03 and compute their UVJ tracks;
- Compare with tracks of tau / delayed models.

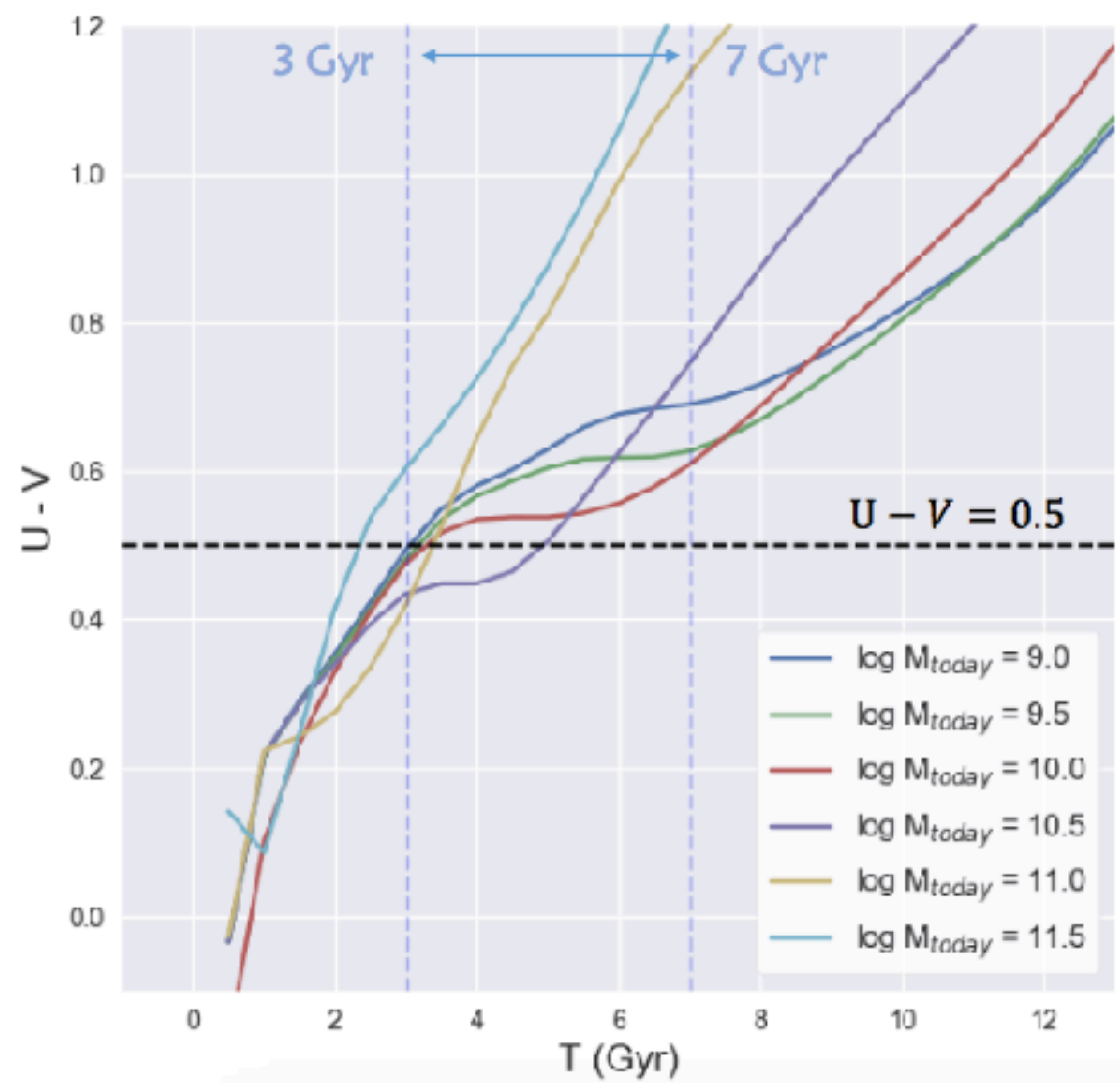


(M_{today}: Stellar Mass today)



UVJ tracks of AM-SFH models look quite similar to Tau (Delayed) models and to one another

Residence Time at the blue stage for AM-SFH models are much longer than Tau models

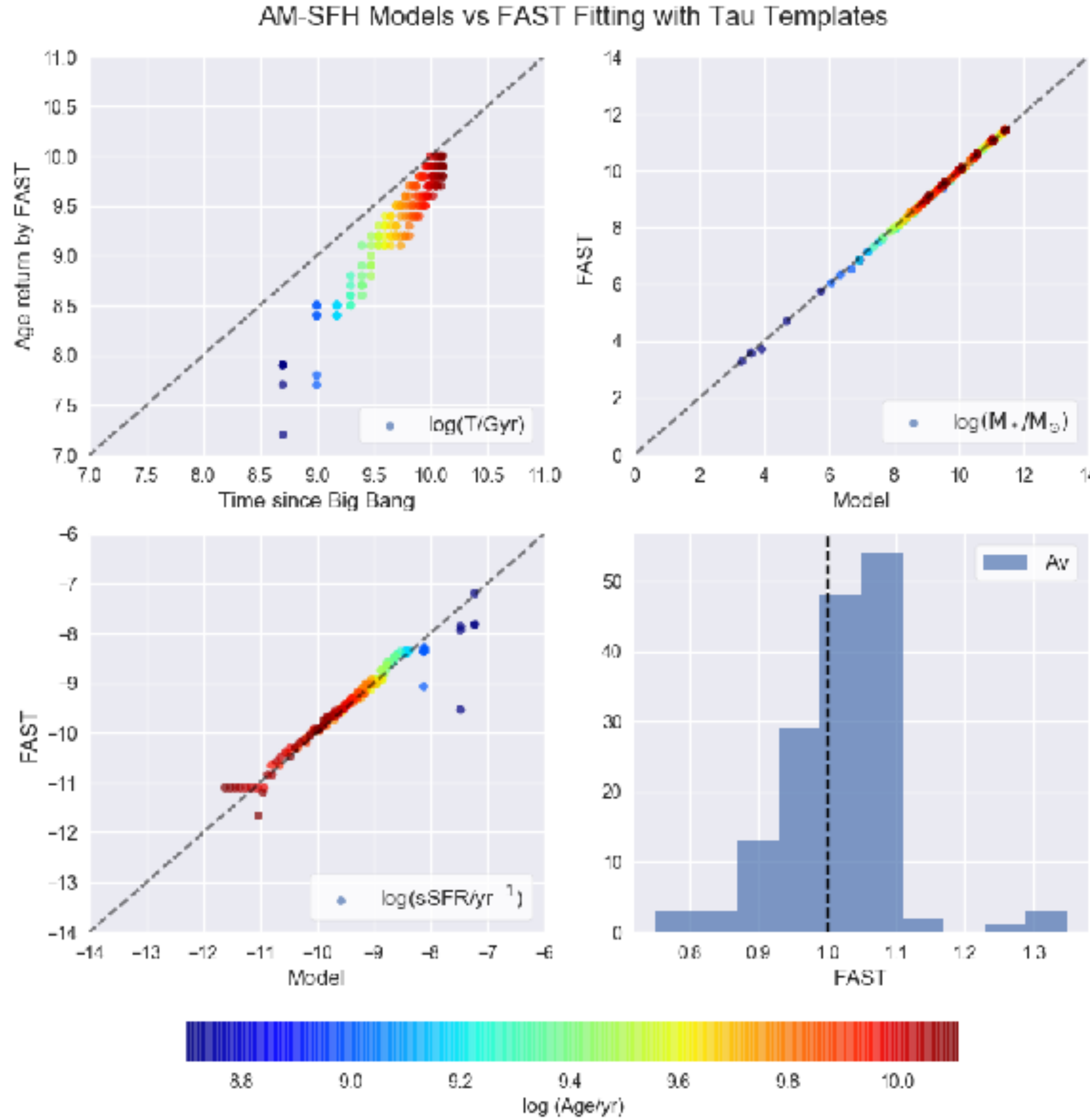


Q: Can FAST return the correct values of physical parameters for these AM-SFHs?

- **Yes.** FAST gives rather good estimates assuming Tau (Delayed) templates!

All Previous Results are not ***GARBAGE***

—— We are ***SAFE*** !



Even with oversimplified assumptions of unrealistic Tau / Delayed models, we can still retrieve the values of M*, SSFR and Av of galaxies following realistic SFHs.

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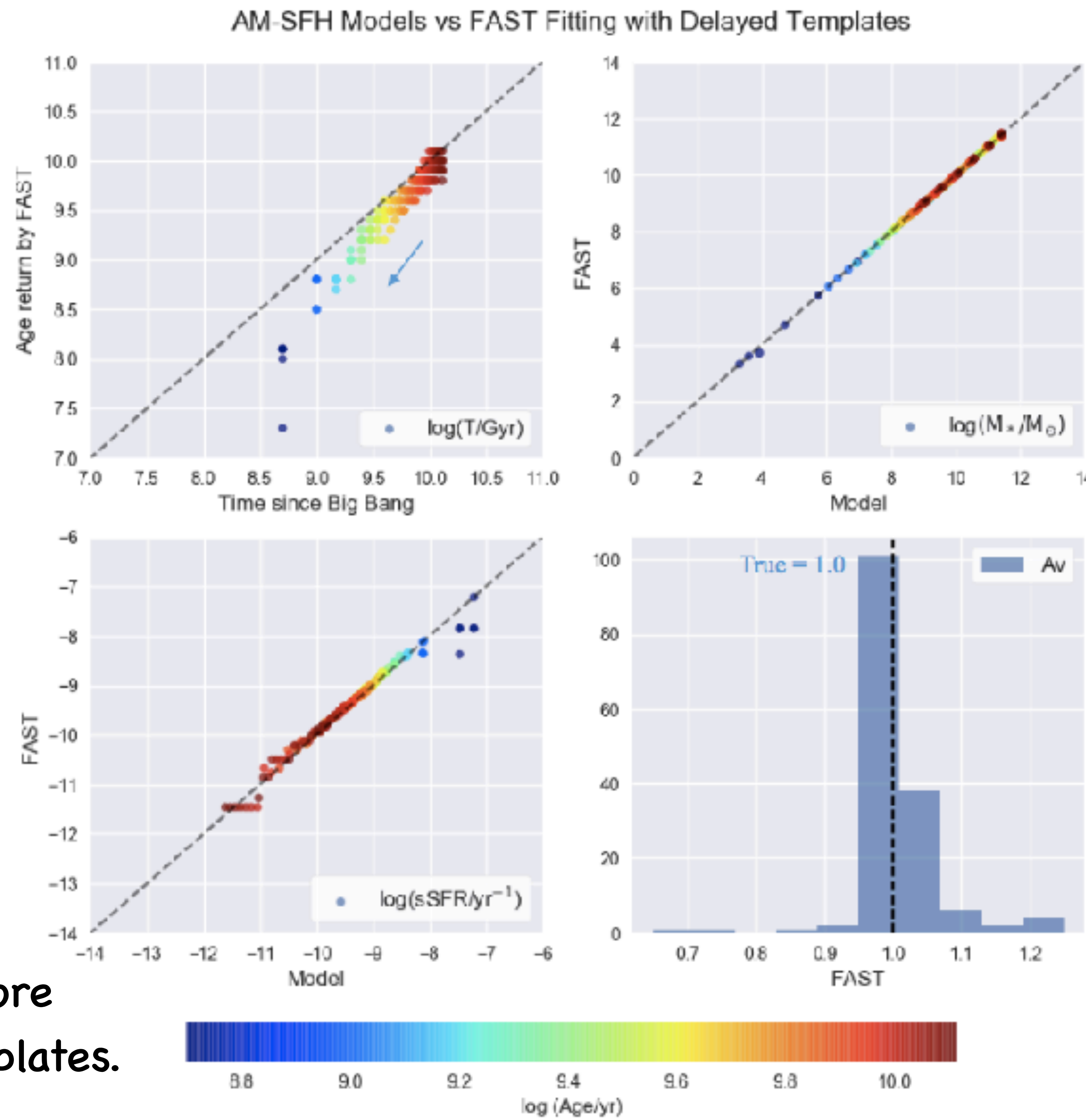
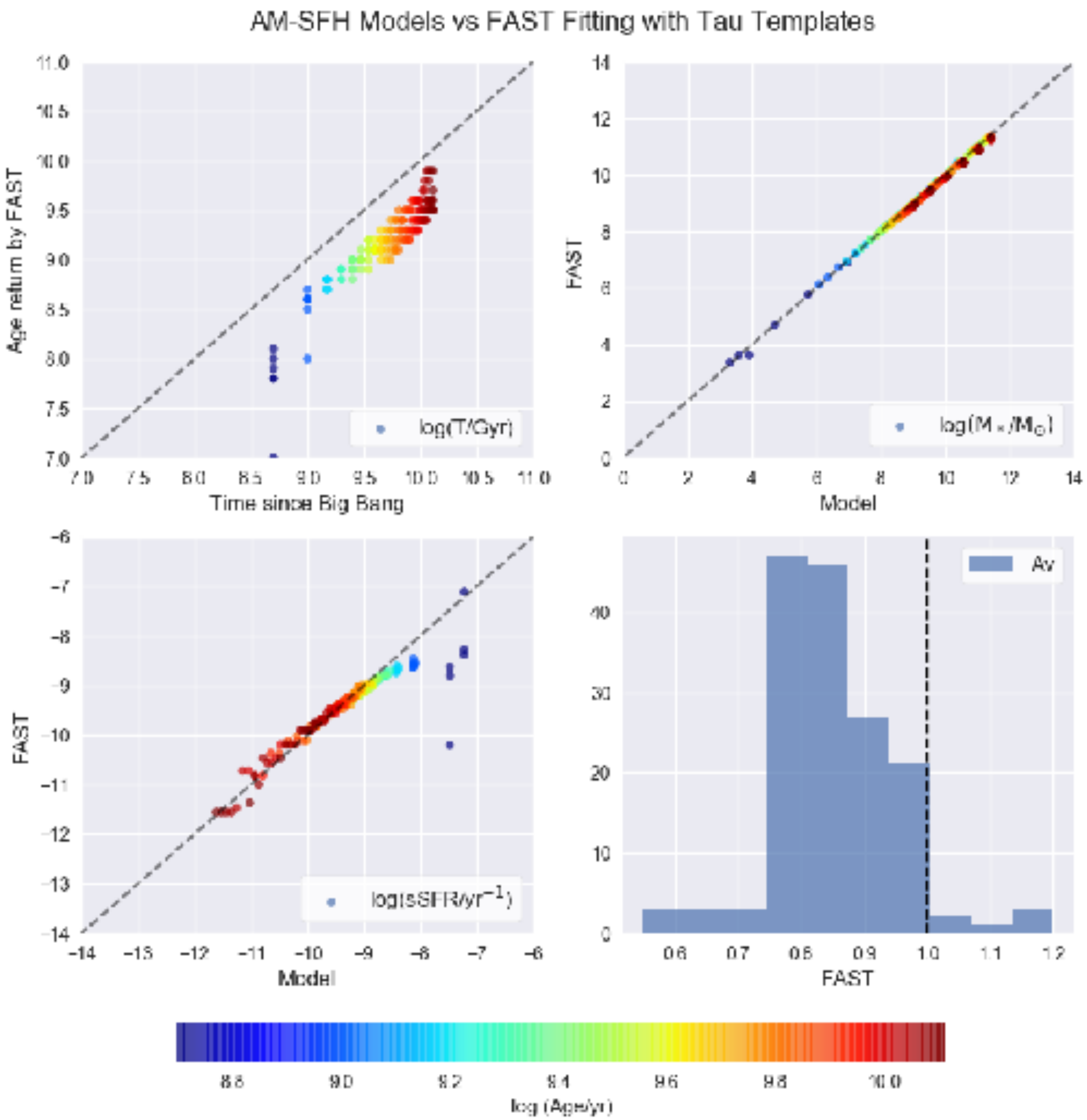
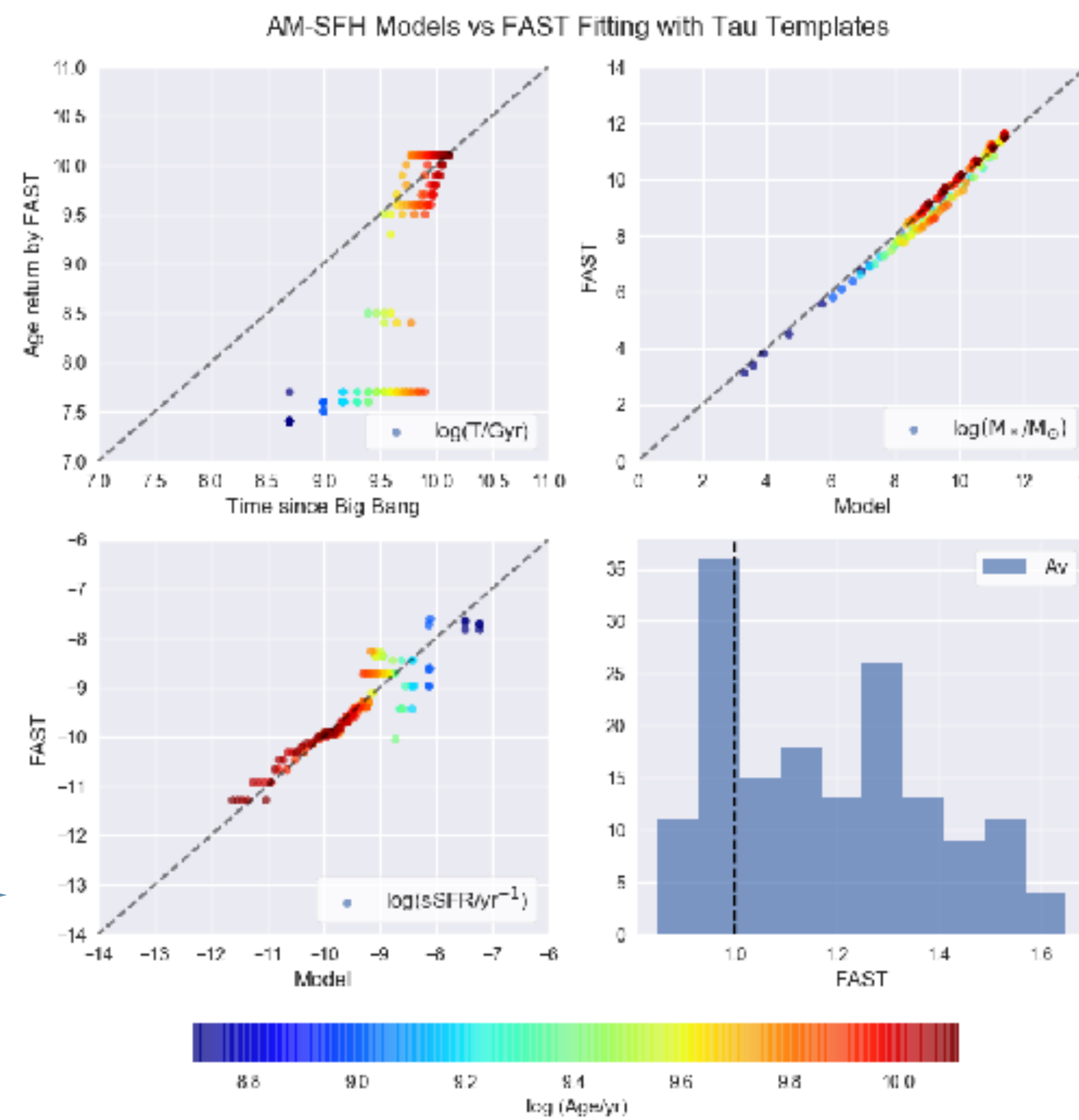


- Derivation of parameters is more precise when using delayed templates.

Even with oversimplified assumptions of unrealistic Tau / Delayed models, we can still retrieve the values of M*, SSFR and Av of galaxies following realistic SFHs.

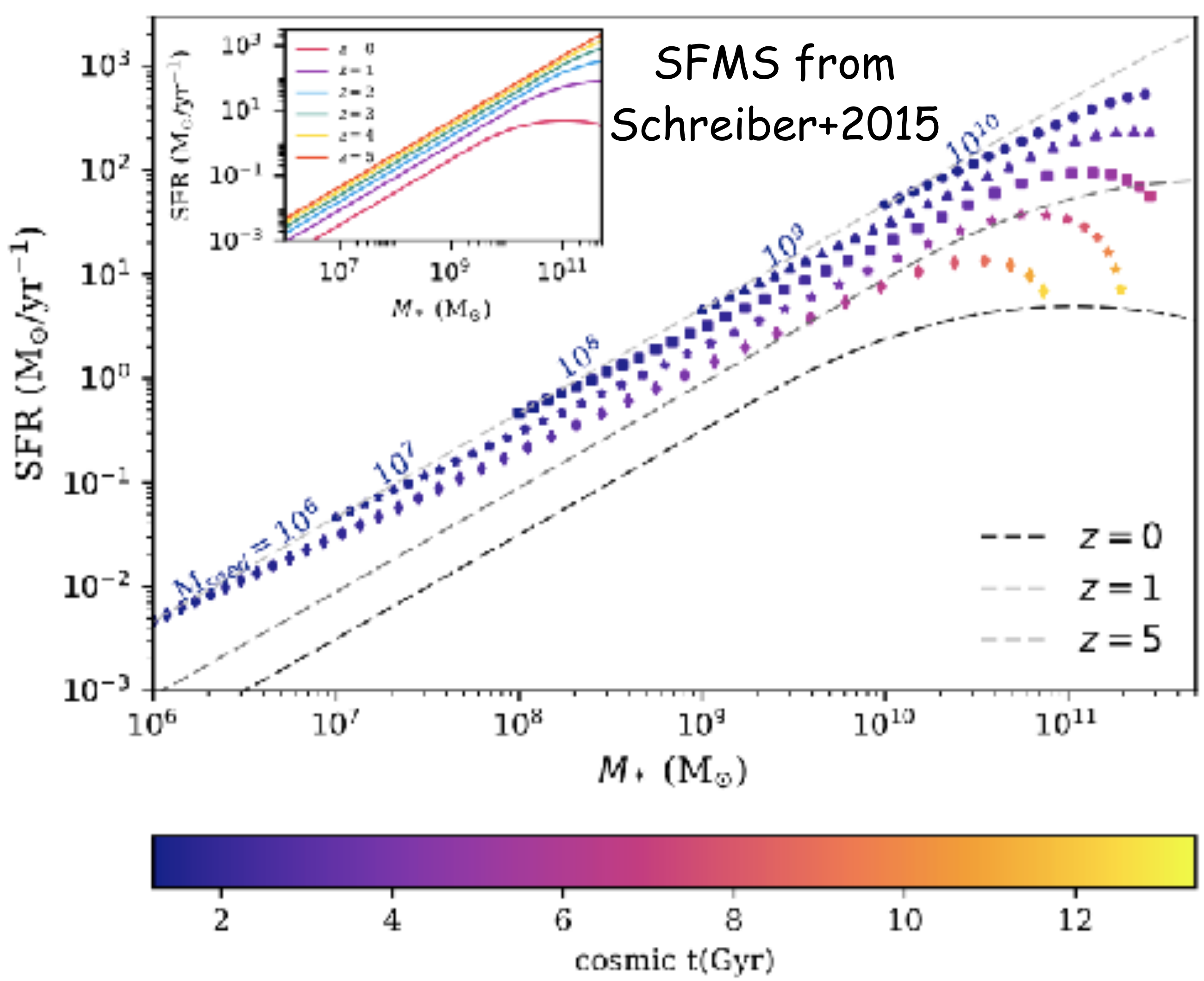


Sub-solar Metallicity (0.5 Z☉):
Under-estimate Av
Accurate Stellar Mass

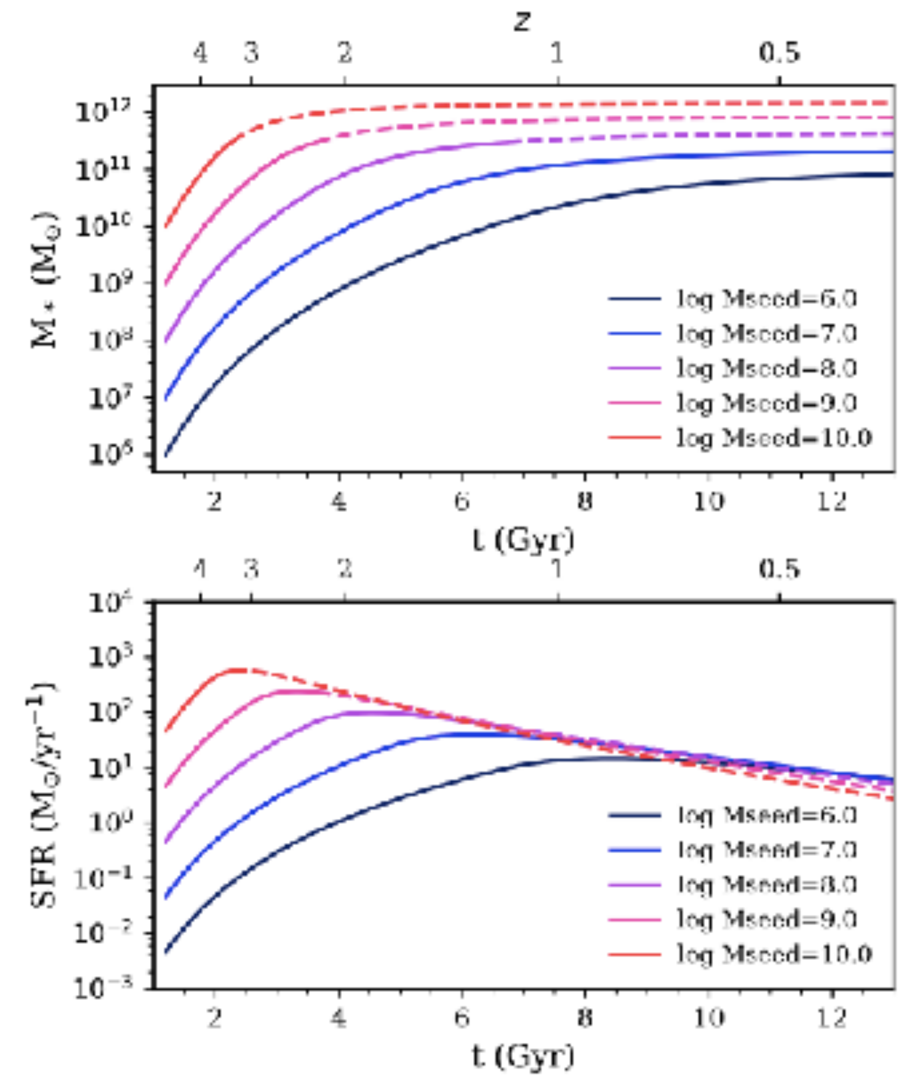


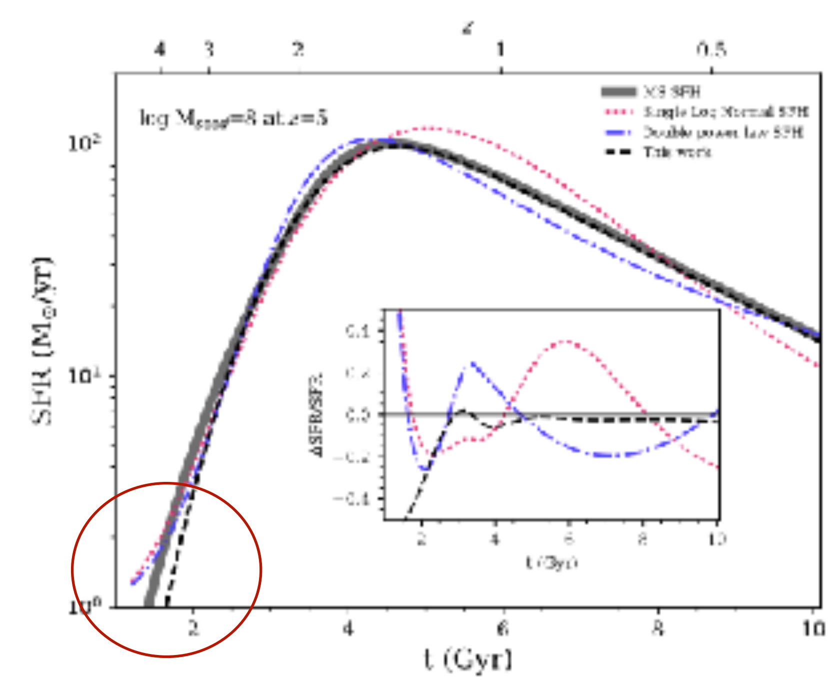
Super-solar Metallicity (2 Z☉):
Over-estimate Av
Larger Scatter in Stellar Mass

3.3 Approach III : Main Sequence Derived SFH (MS-SFH)



(Ciesla+2017) Evolution of Galaxies Recovered from SFMS



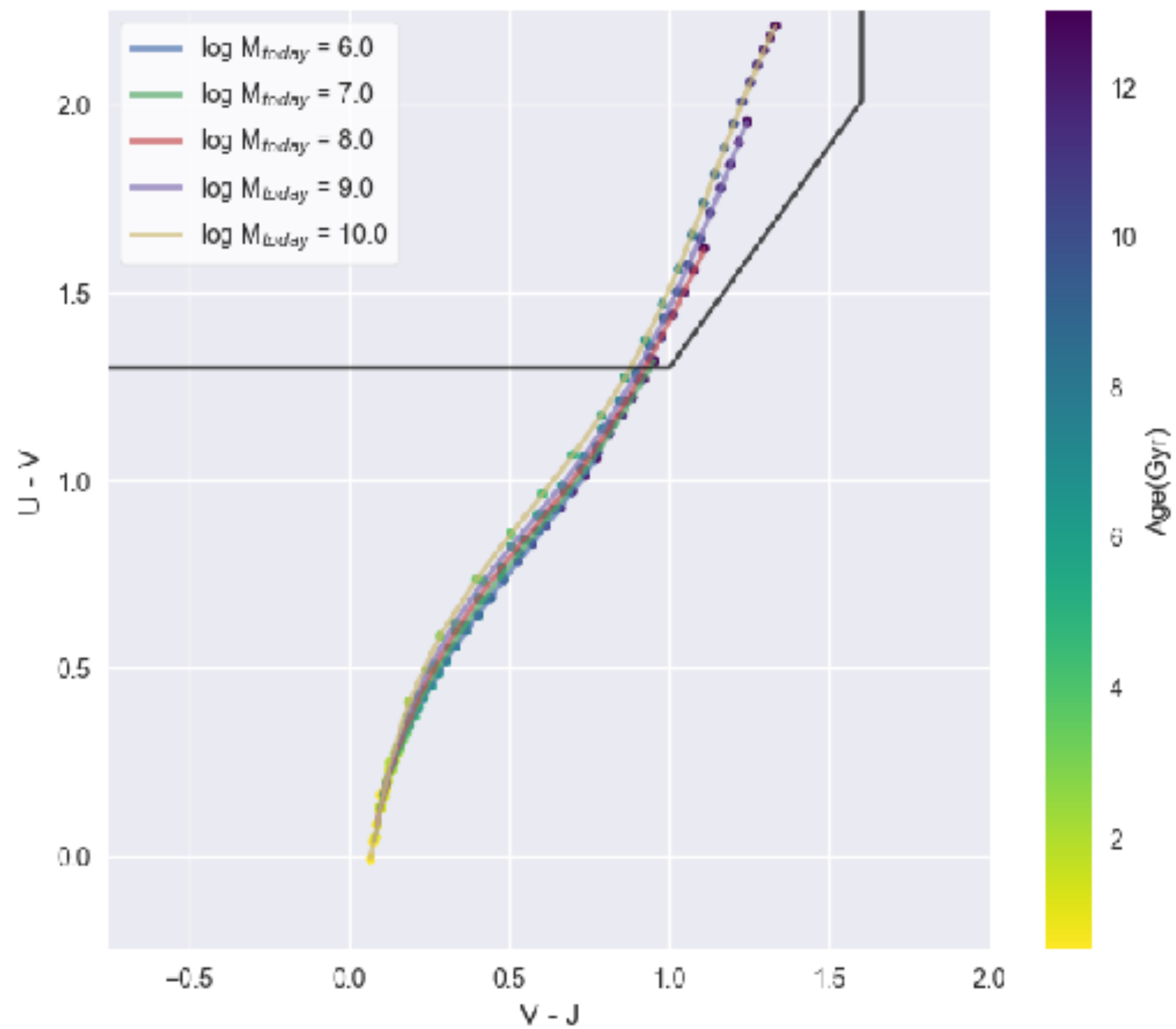


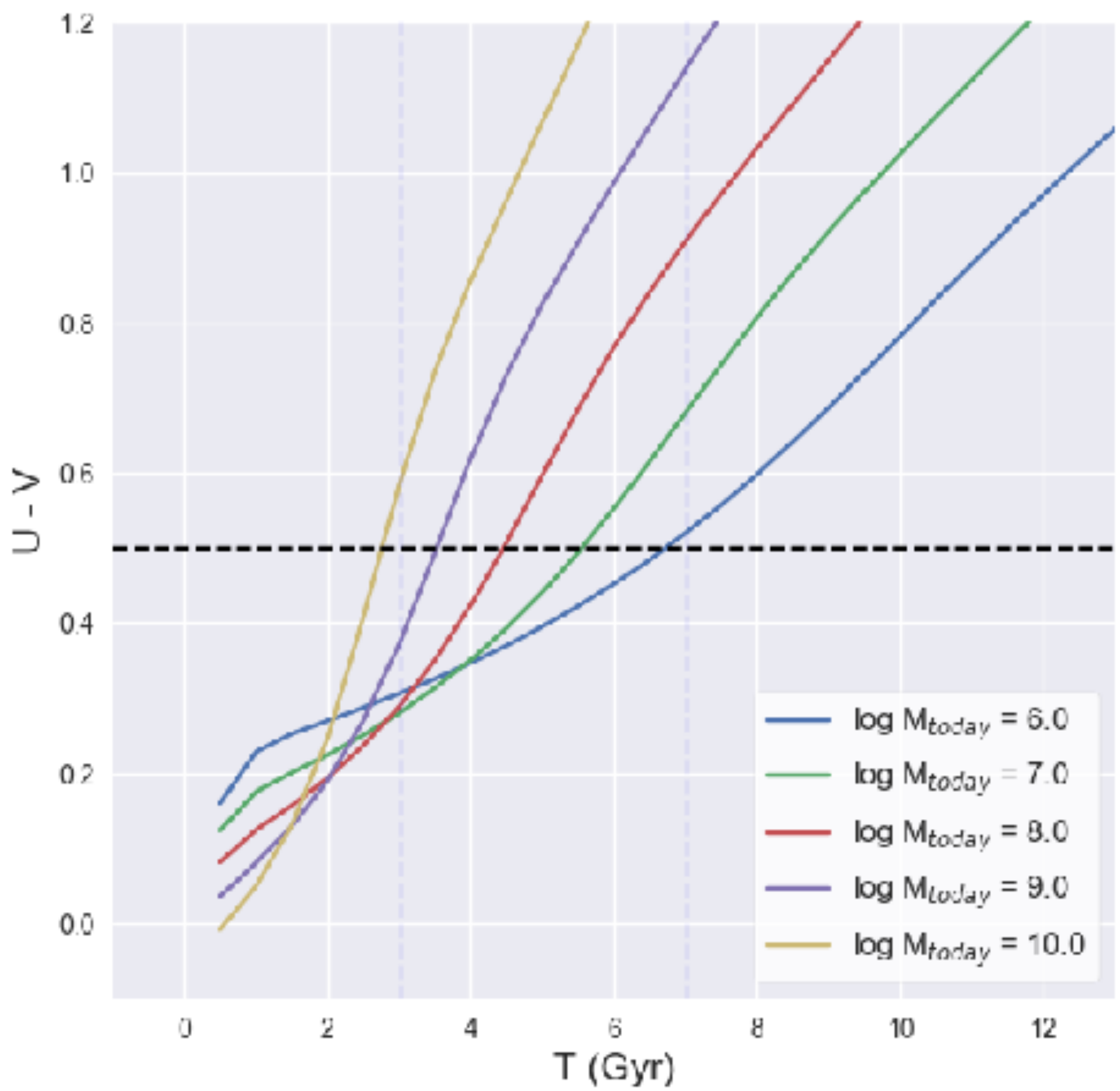
Right Skew Peak Skewed Gaussian (RSPSG):

$$\mathrm{SFR}(t, M_{seed}) = A\,\frac{\sqrt{\pi}}{2}\,\sigma\, e^{\left((\frac{\sigma}{2 r_S})^2 - \frac{t-\mu}{r_S}\right)}\,\mathrm{erfc}\left(\frac{\sigma}{2\,r_S} - \frac{t-\mu}{\sigma}\right),$$

(M_{seed}: Seed Mass at z = 5)

UVJ tracks of MS-SFH models also look like Tau/Delayed/ AM-SFH models and converge



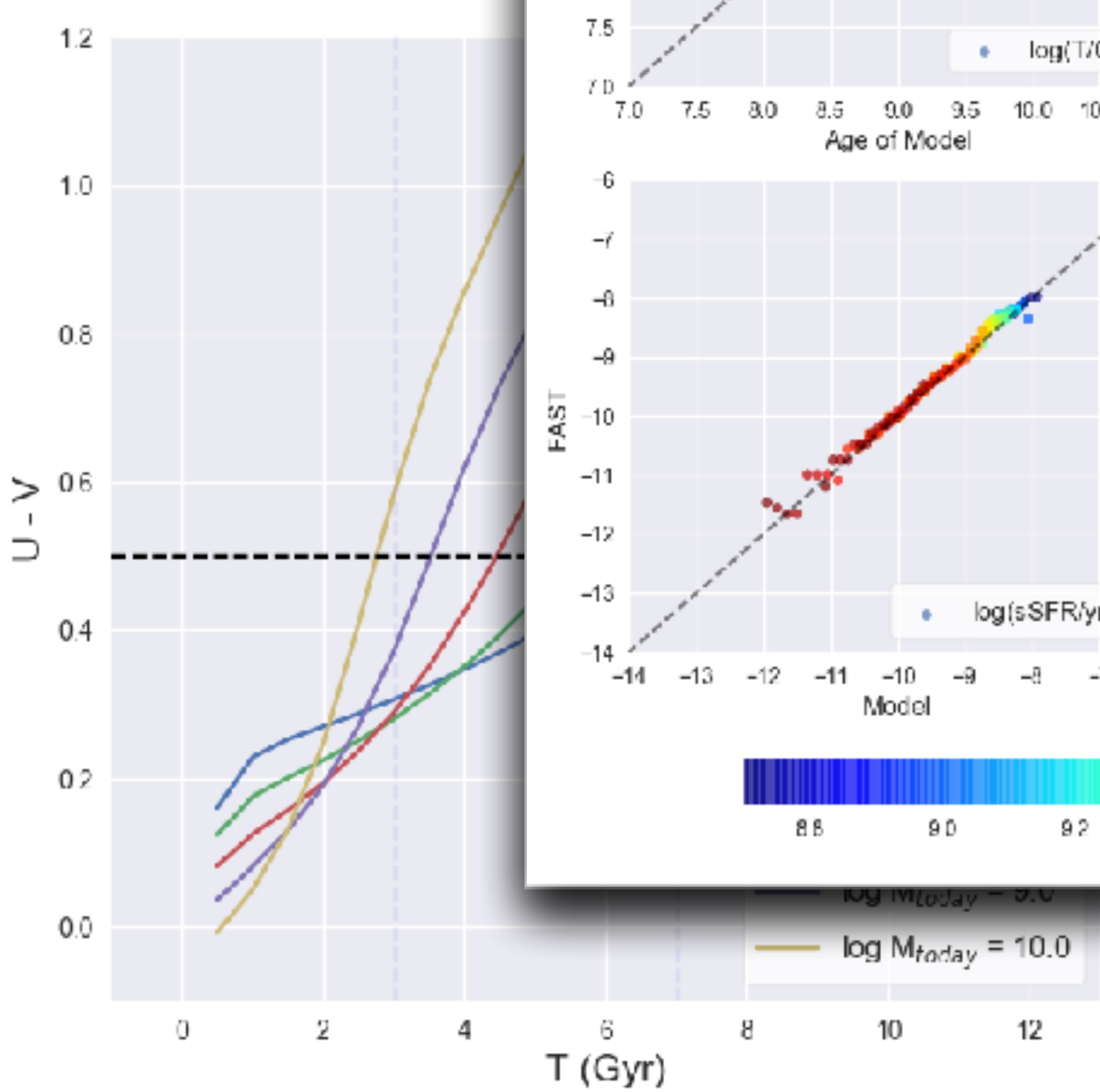


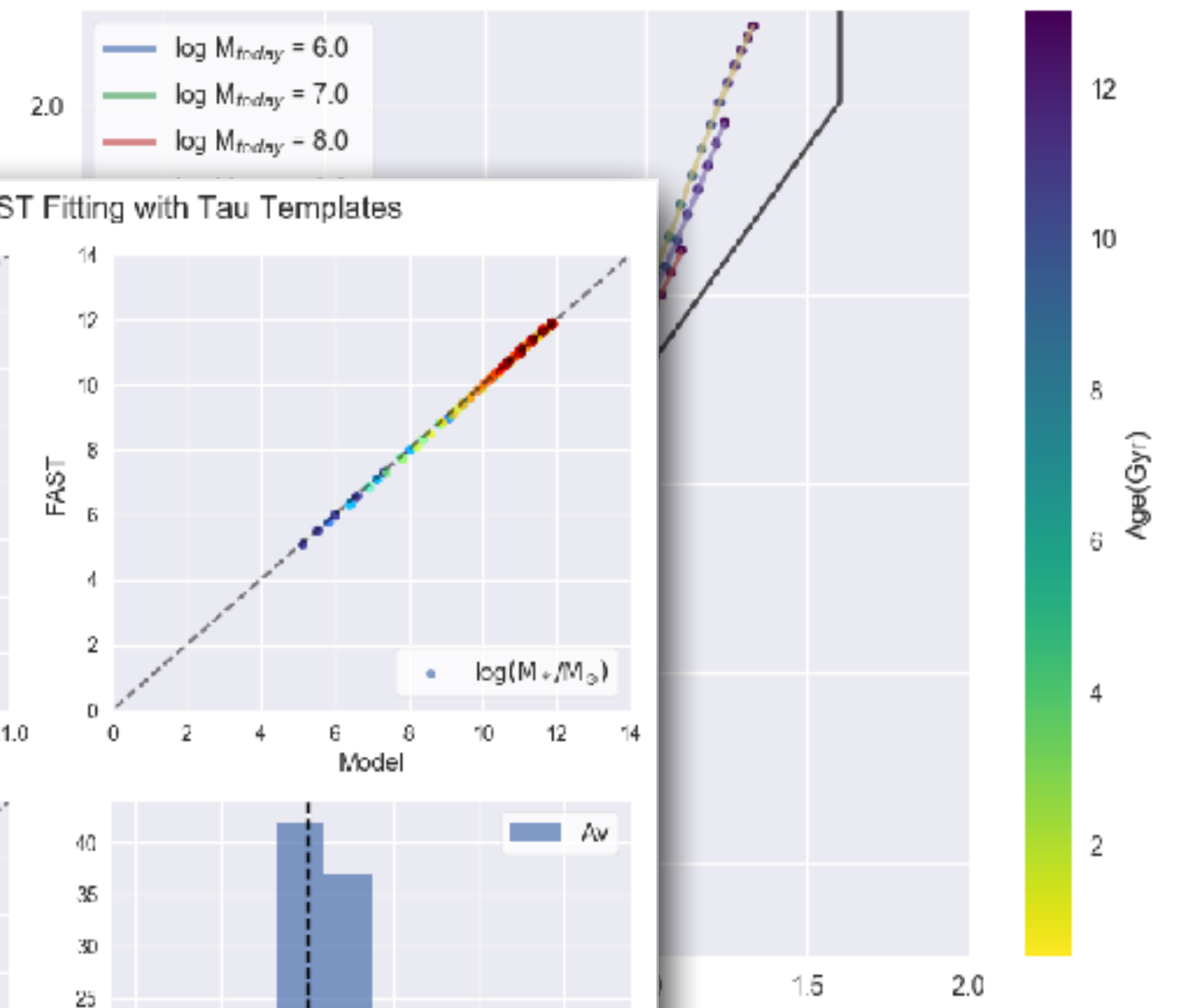
Residence Time at the blue stage for MS-SFH models extends longer than AM-SFH

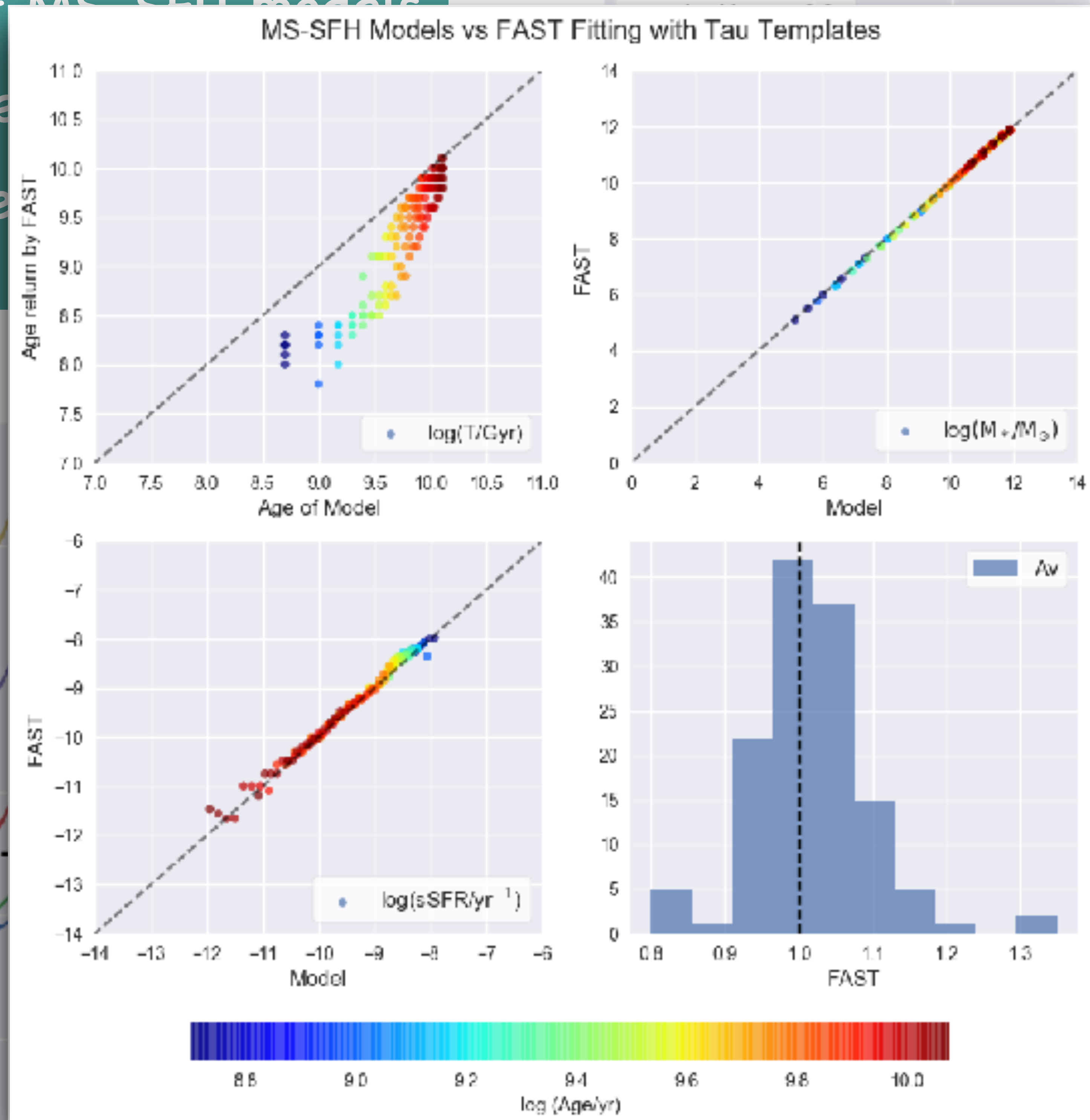
UVJ tracks of MS-SFH models

also look like

AM-SFH mode







at the blue

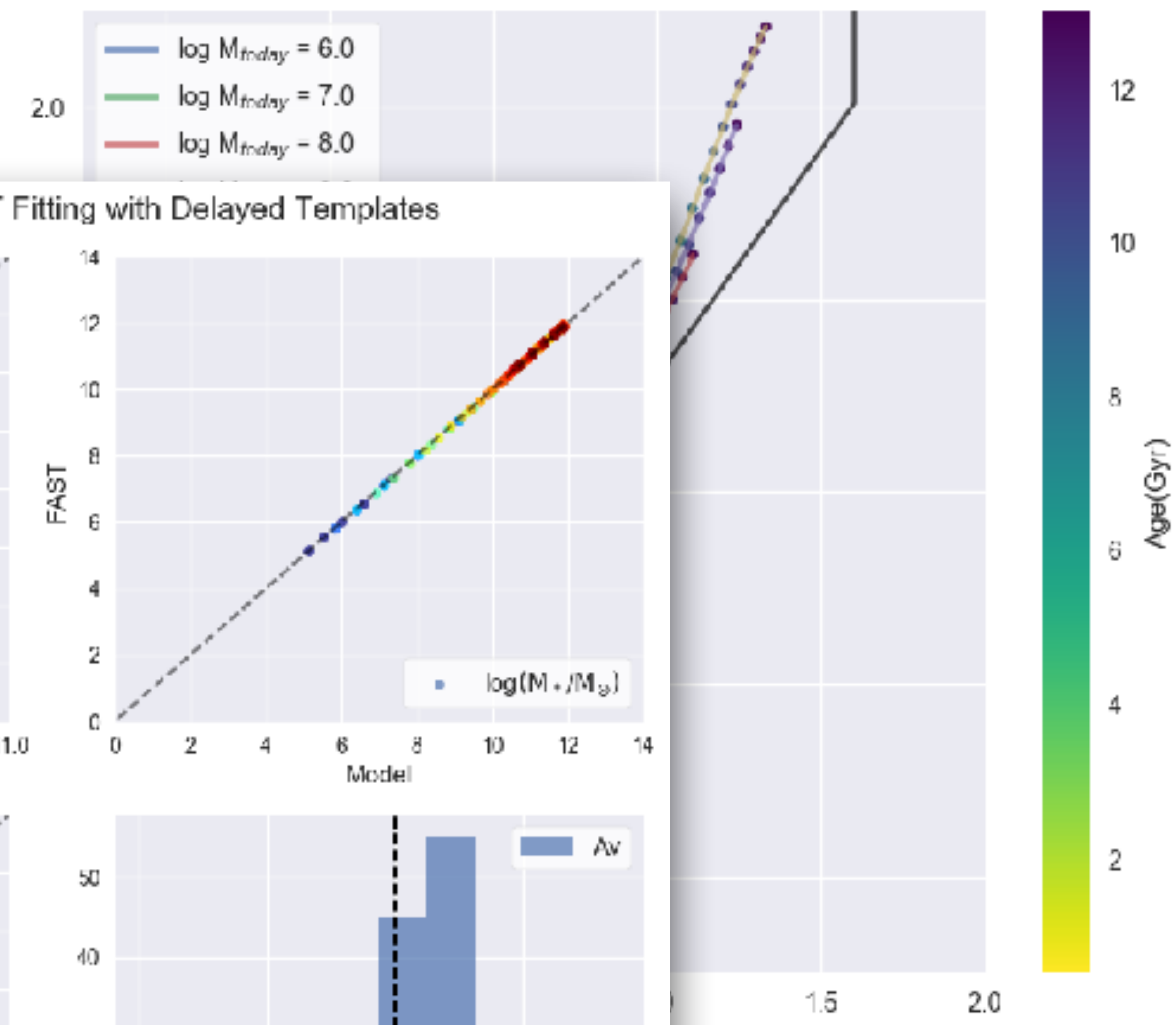
FH models

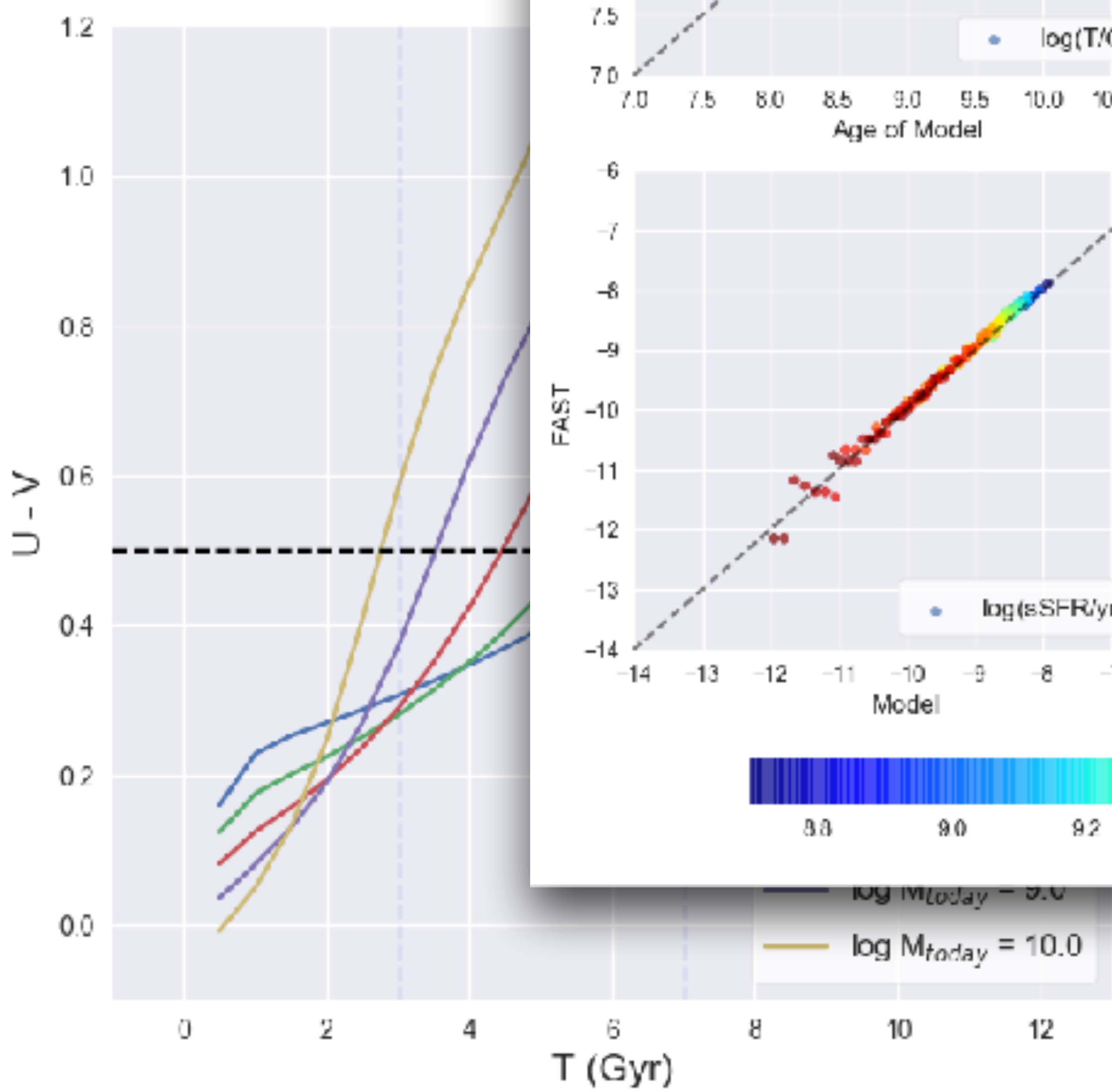
han AM-SFH

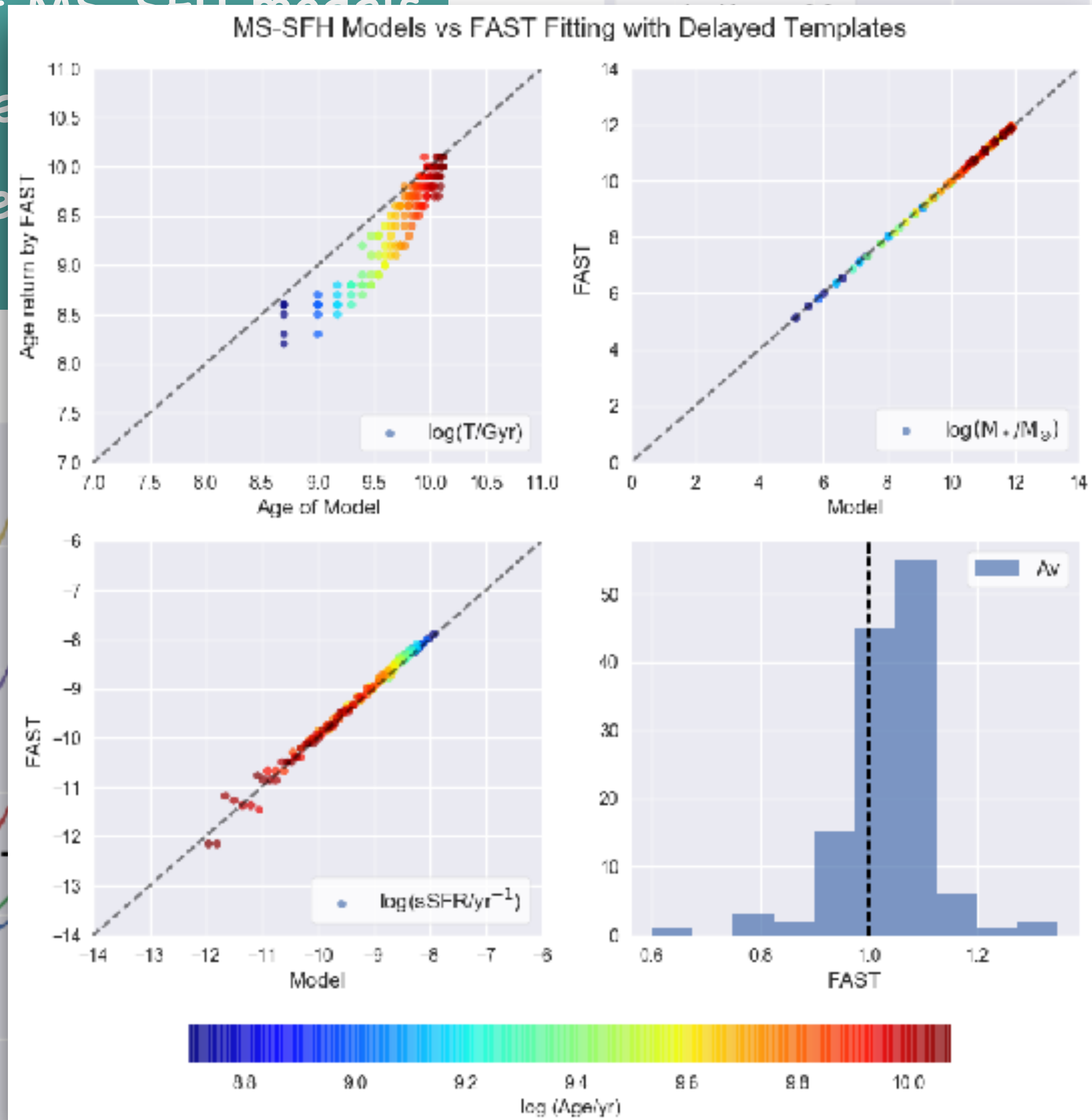
UVJ tracks of MS-SFH models

also look like

AM-SFH mode





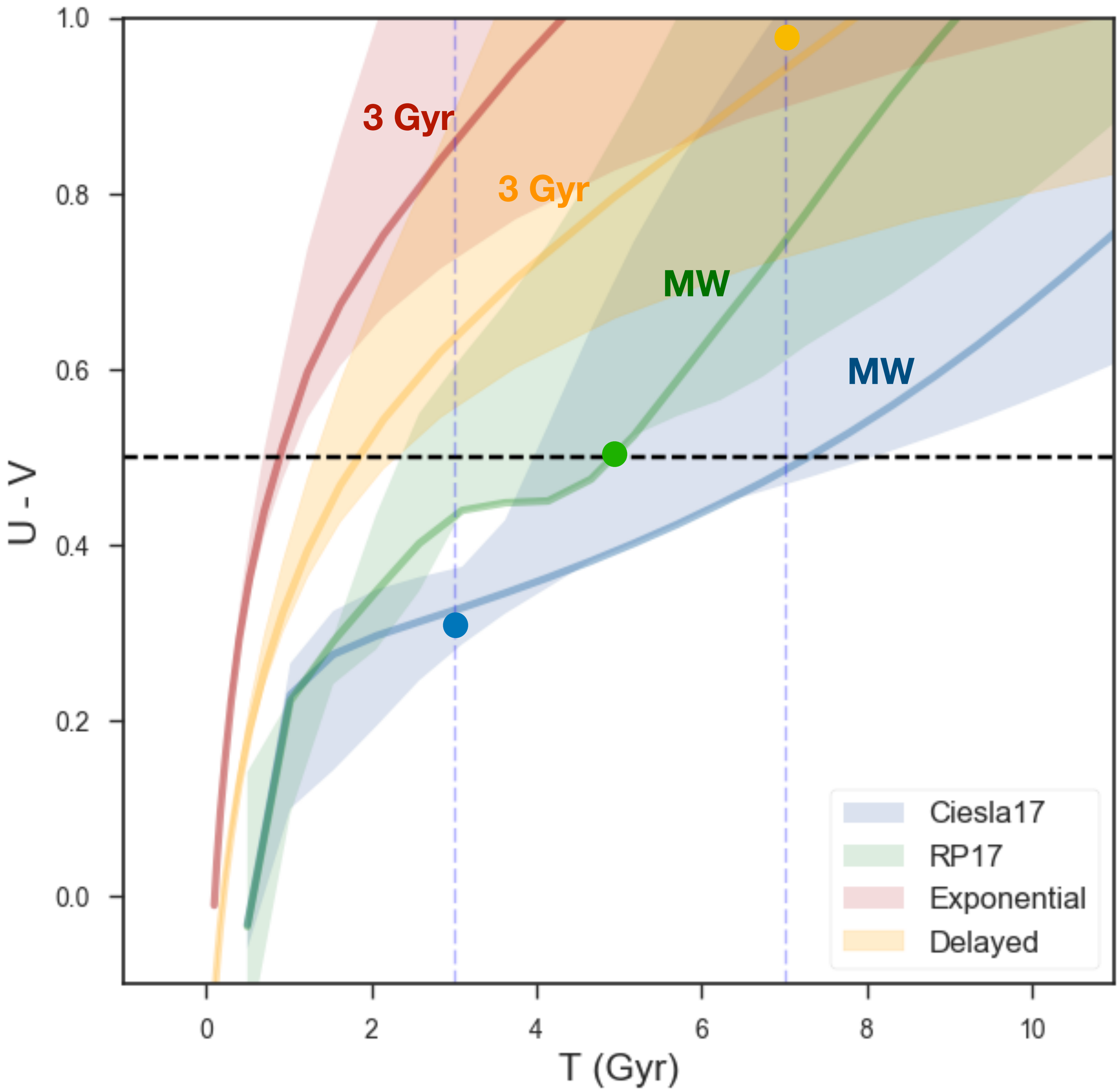


at the blue

FH models

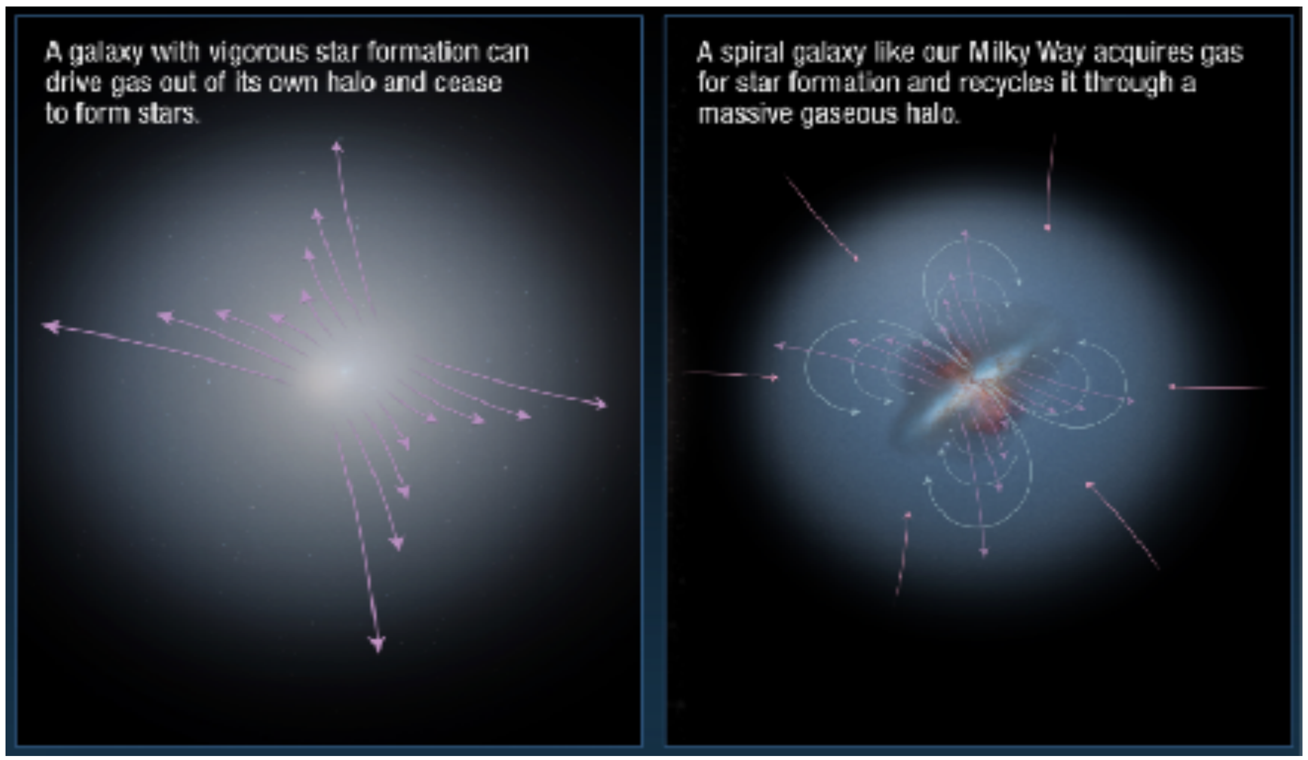
han AM-SFH

Color Evolution for Different SFH Models

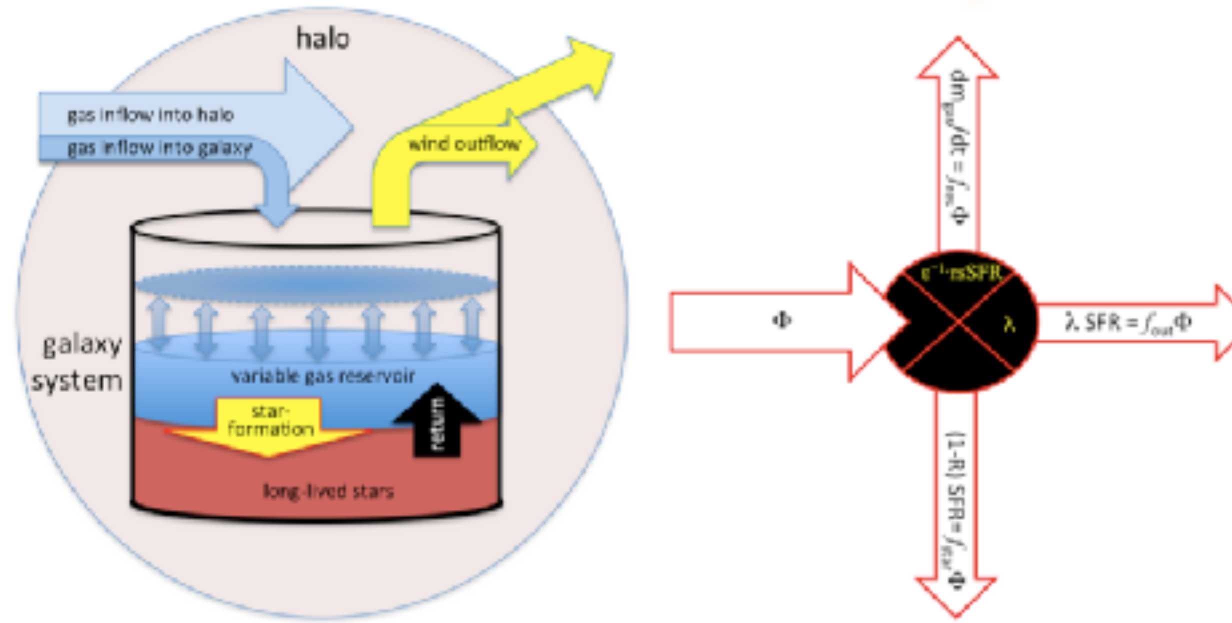


4. Fine-tuning on Realistic SFH Models: Fluctuations

- Real galaxies will not exactly follow ***smooth*** SFH. In the case of the sub-halo accretion (bathtub model), there should be fluctuations in SFH of galaxies.

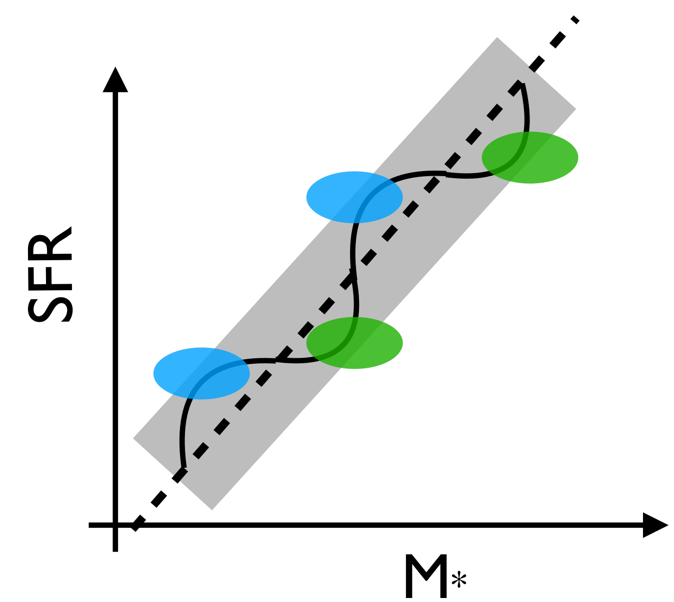


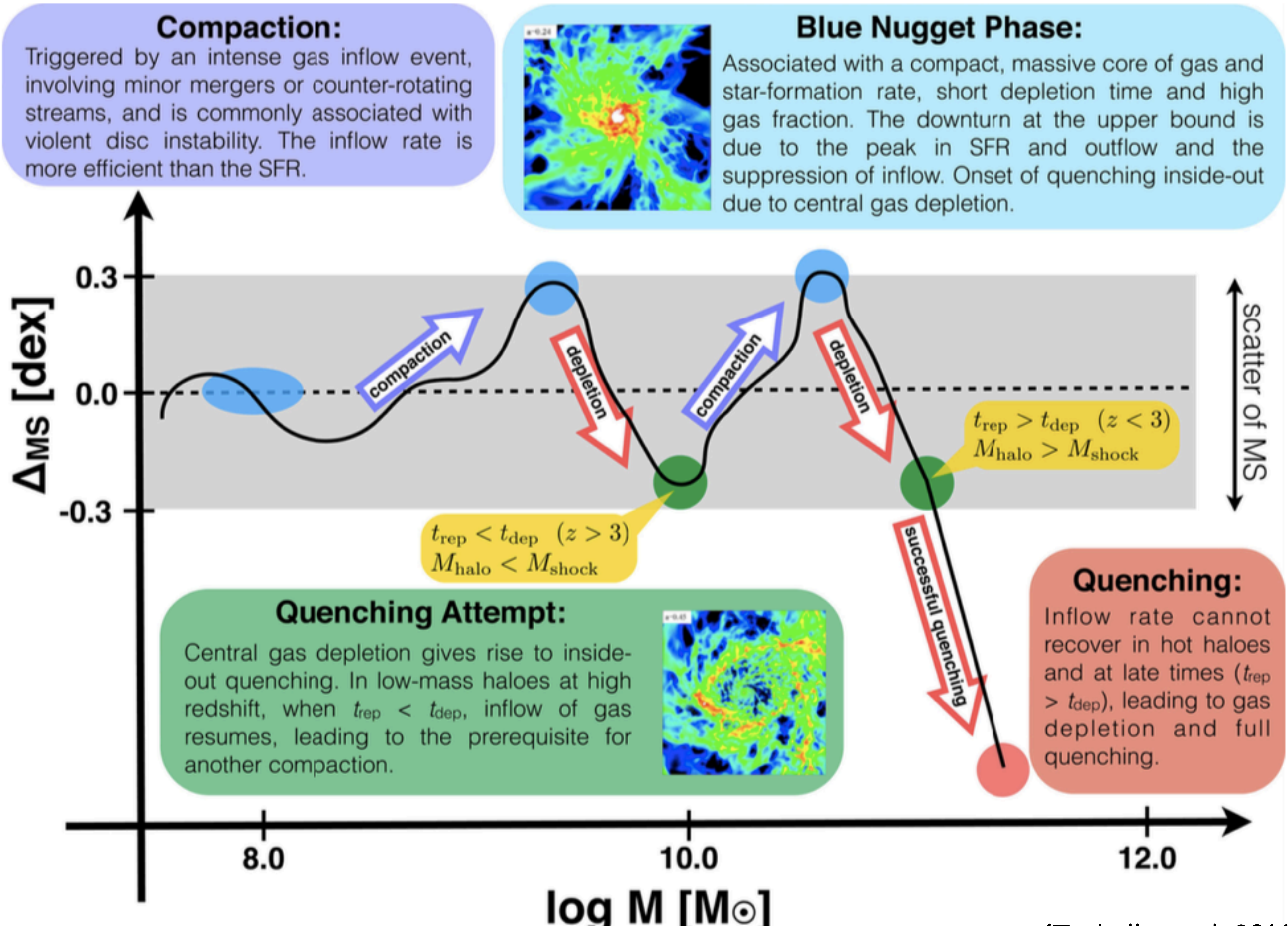
'Galaxy-Halo' Coevolution (Credit: NASA; ESA)



Galaxy Self-regulation (Lilly et al. 2013)

This means galaxies might ***go up and down*** on the SFMS during its mass assembled history, partially causing the scatter of MS.





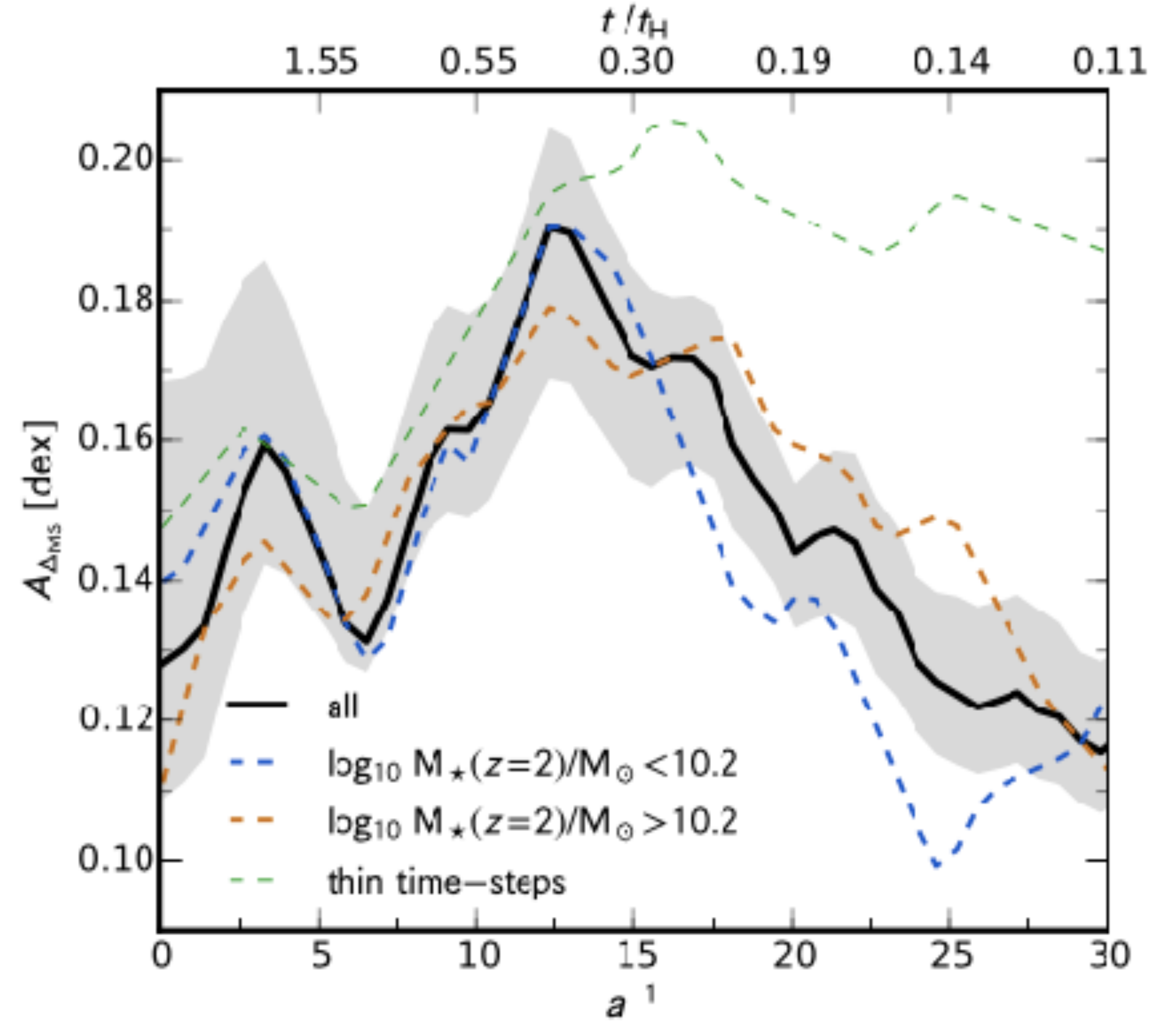
(Tachella et al. 2016)

Several questions can be asked:

- What's the largest *amplitude* we need to keep the variation of the galaxy within the MS scatter? (this test could help us restrain simulations)

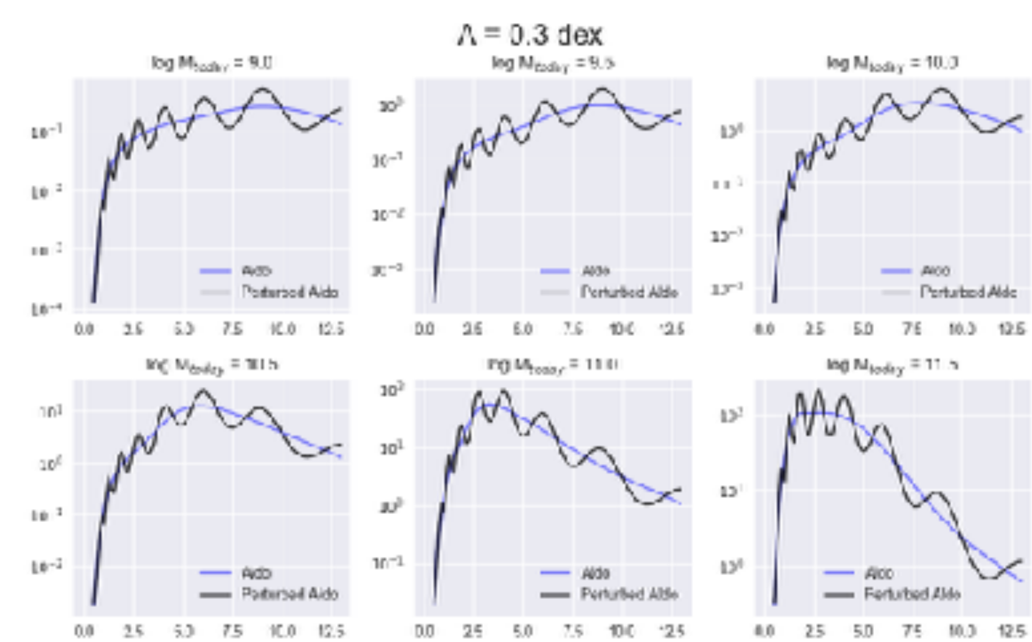
- How fluctuations influence the color evolution of the galaxy?

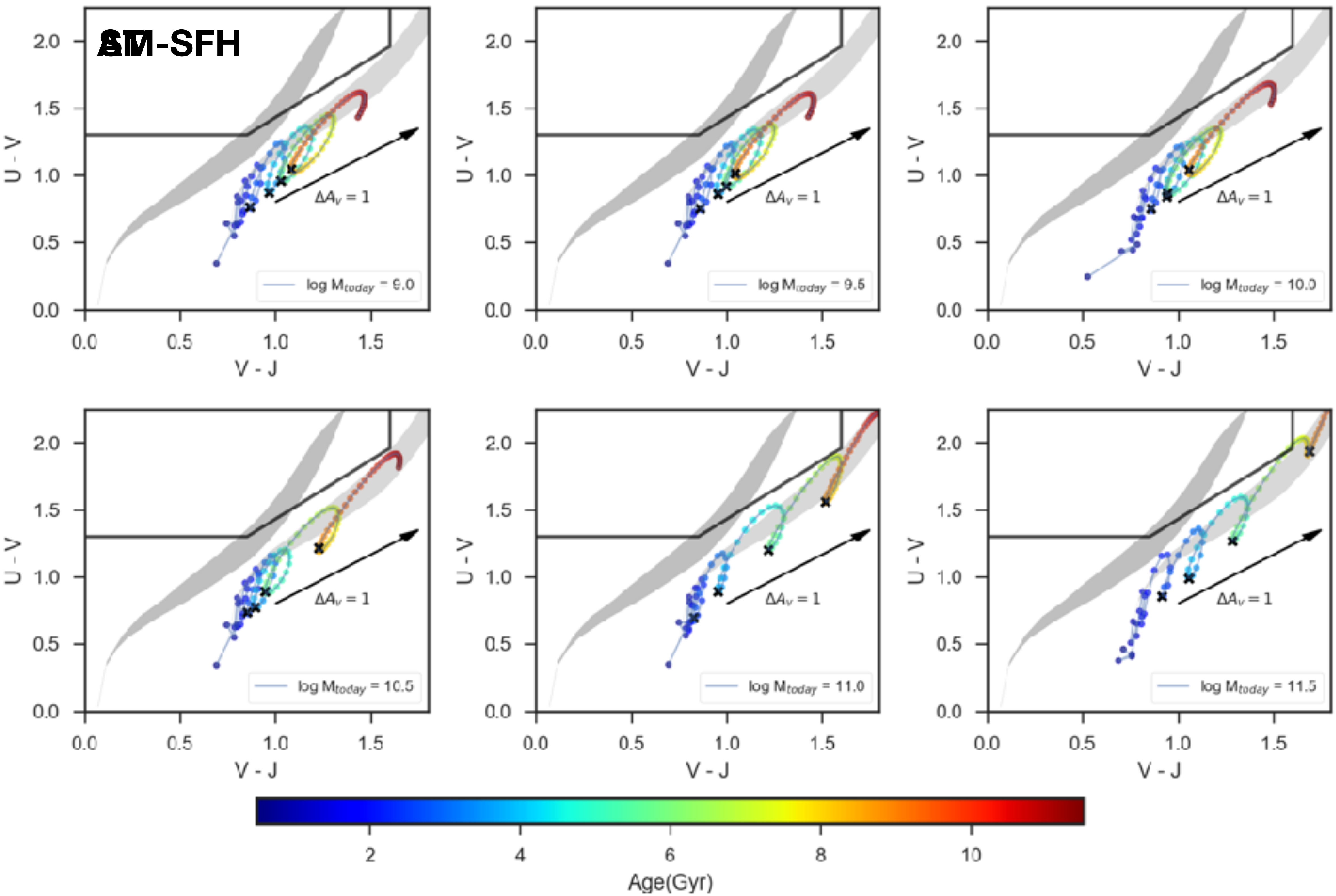
- To what degree can FAST return correct parameter values, in existence of fluctuations? Are there any perceptible effects in observations?

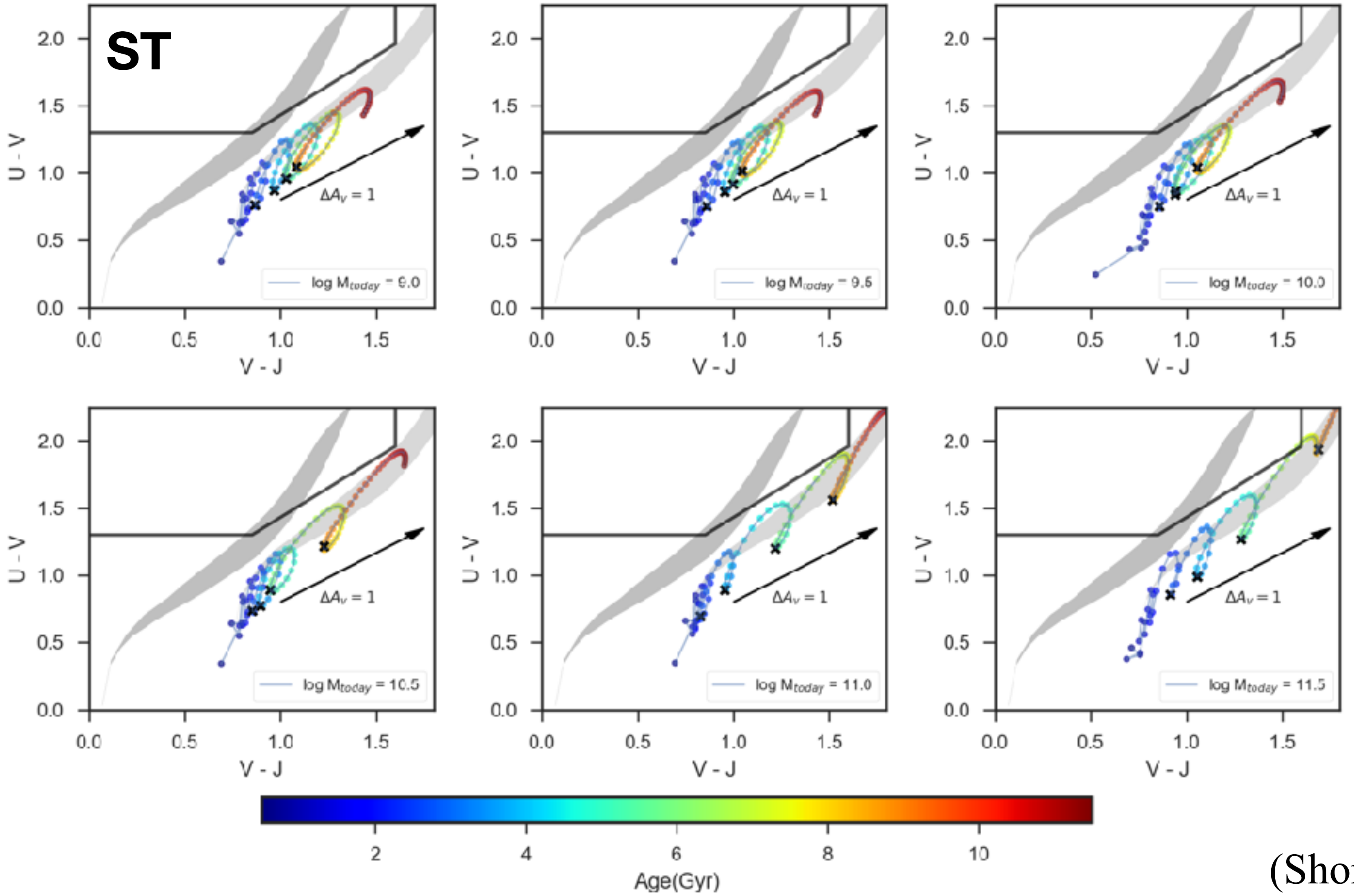


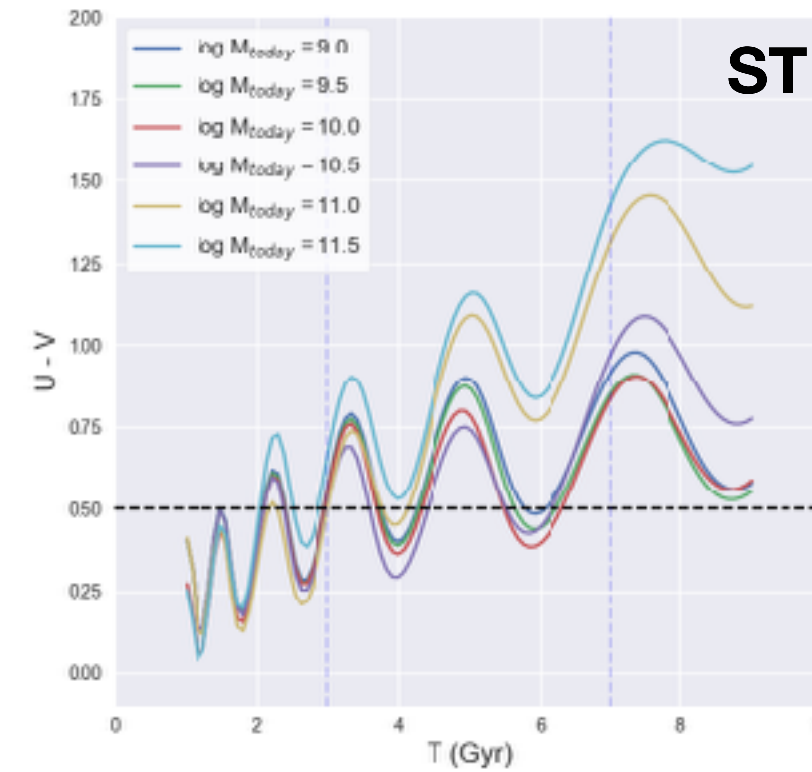
In Tachella et al. 2016, galaxies oscillate around the SFMS at a timescale ~ 0.4 t_H

We put 0.3dex sinusoidal fluctuation on our realistic SFH models on a time scale of Tachella et al. 2016 (**ST**) and a constant period of 2.5 (long) / 0.5 (short) Gyr.

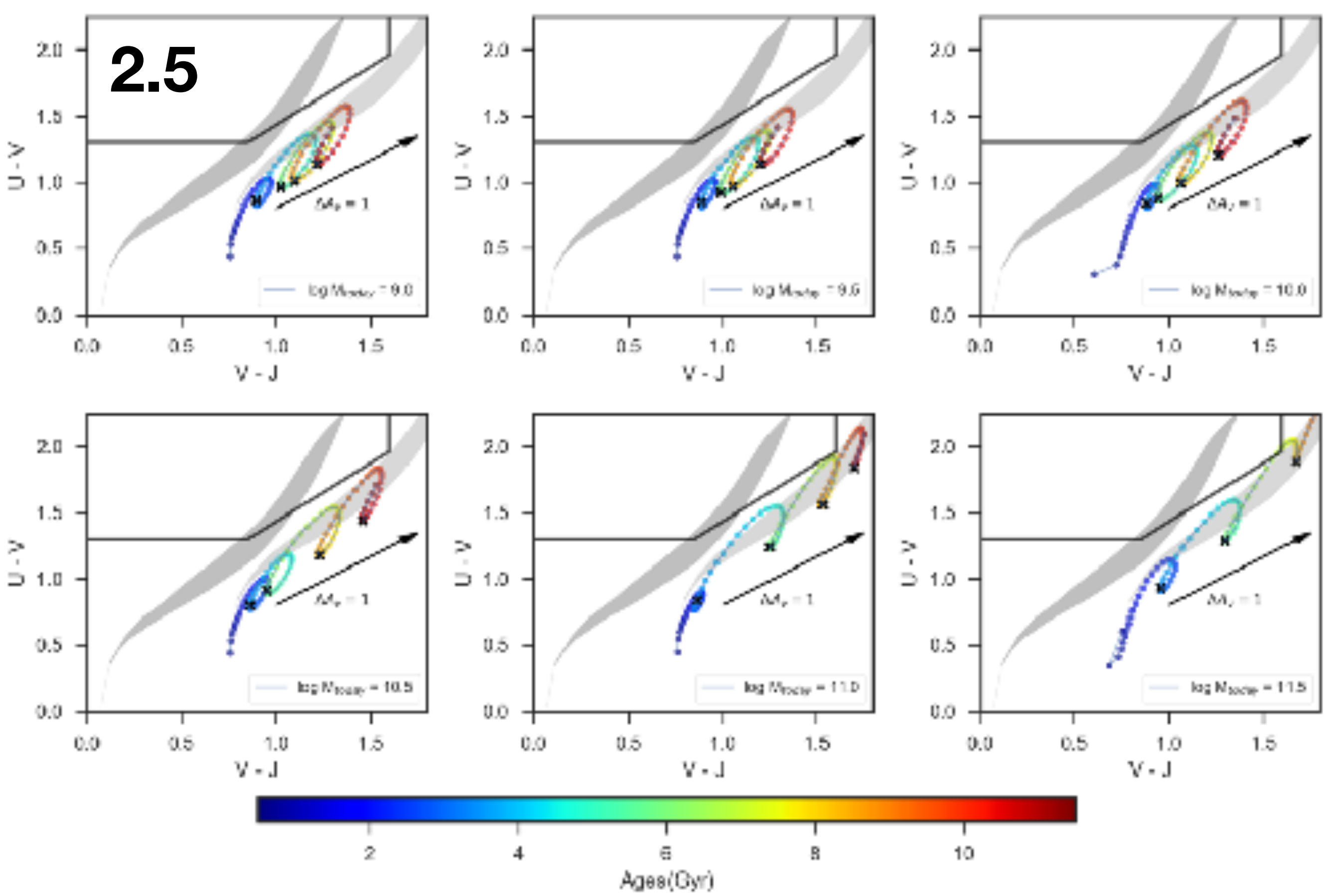


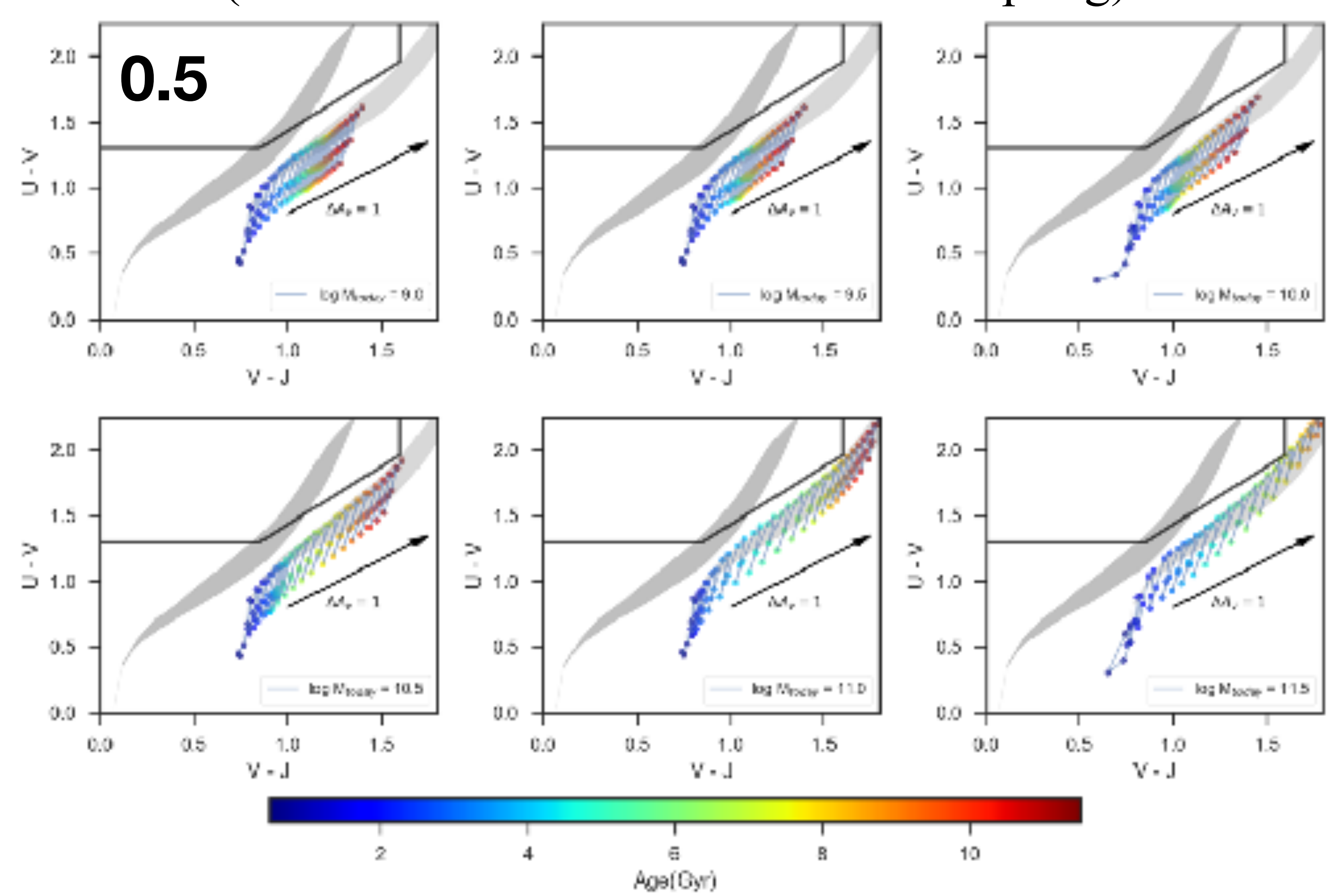

U - V
V - J
$\Delta A_v = 1$
log M_{today} = 9.0
log M_{today} = 9.5
log M_{today} = 10.0
log M_{today} = 10.5
log M_{today} = 11.0
log M_{today} = 11.5
Age(Gyr)

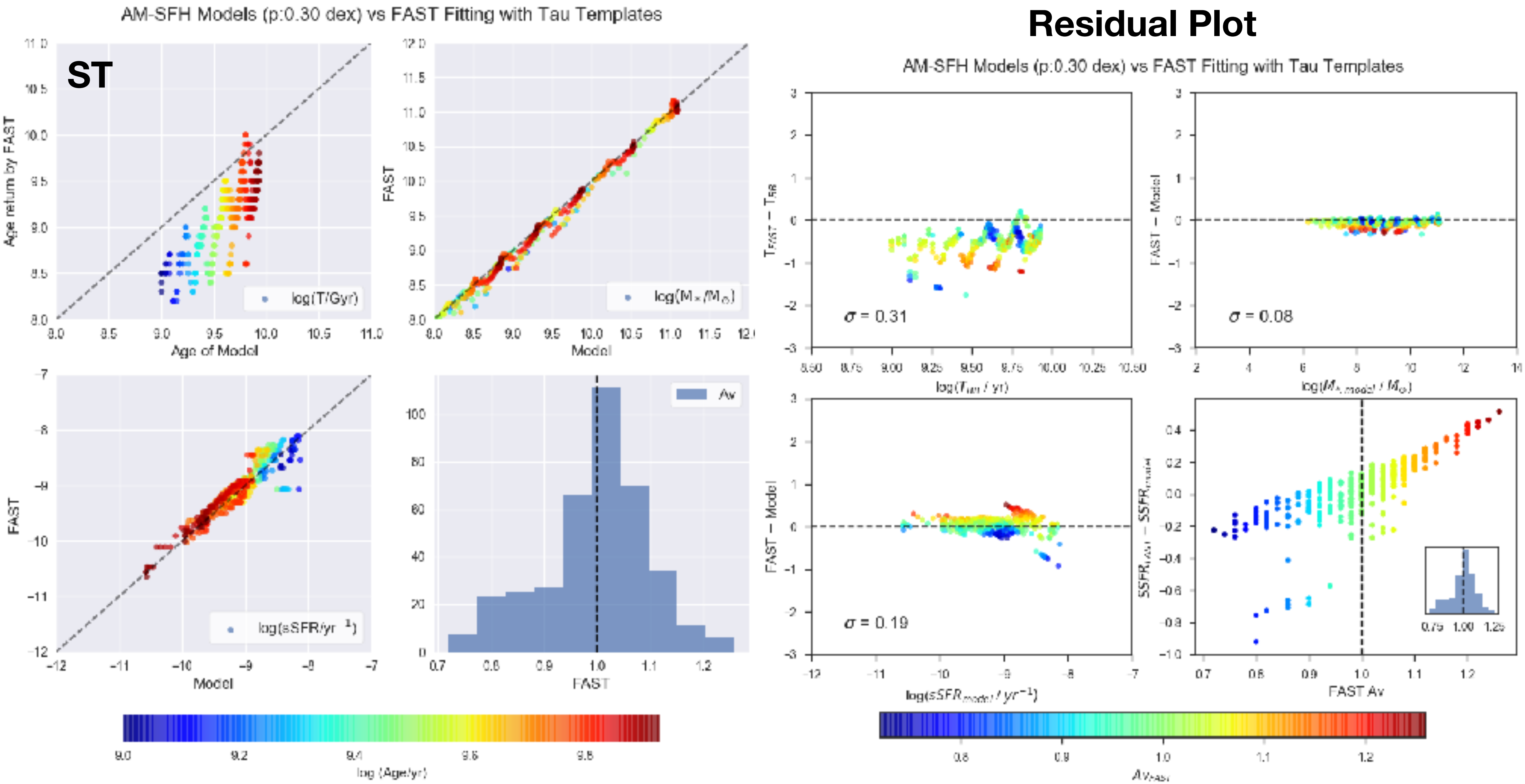




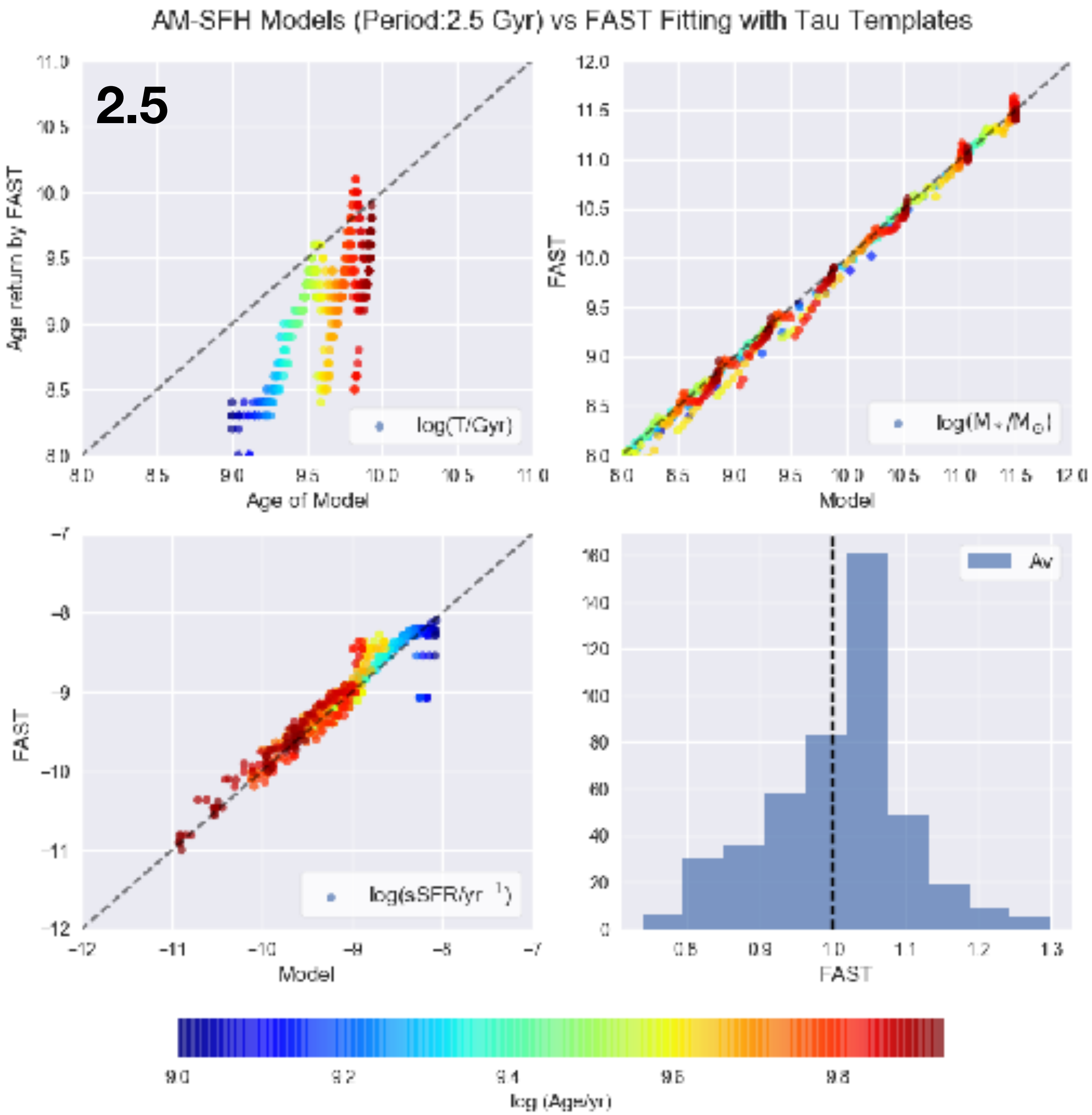
(Short Period suffer from Under-sampling)

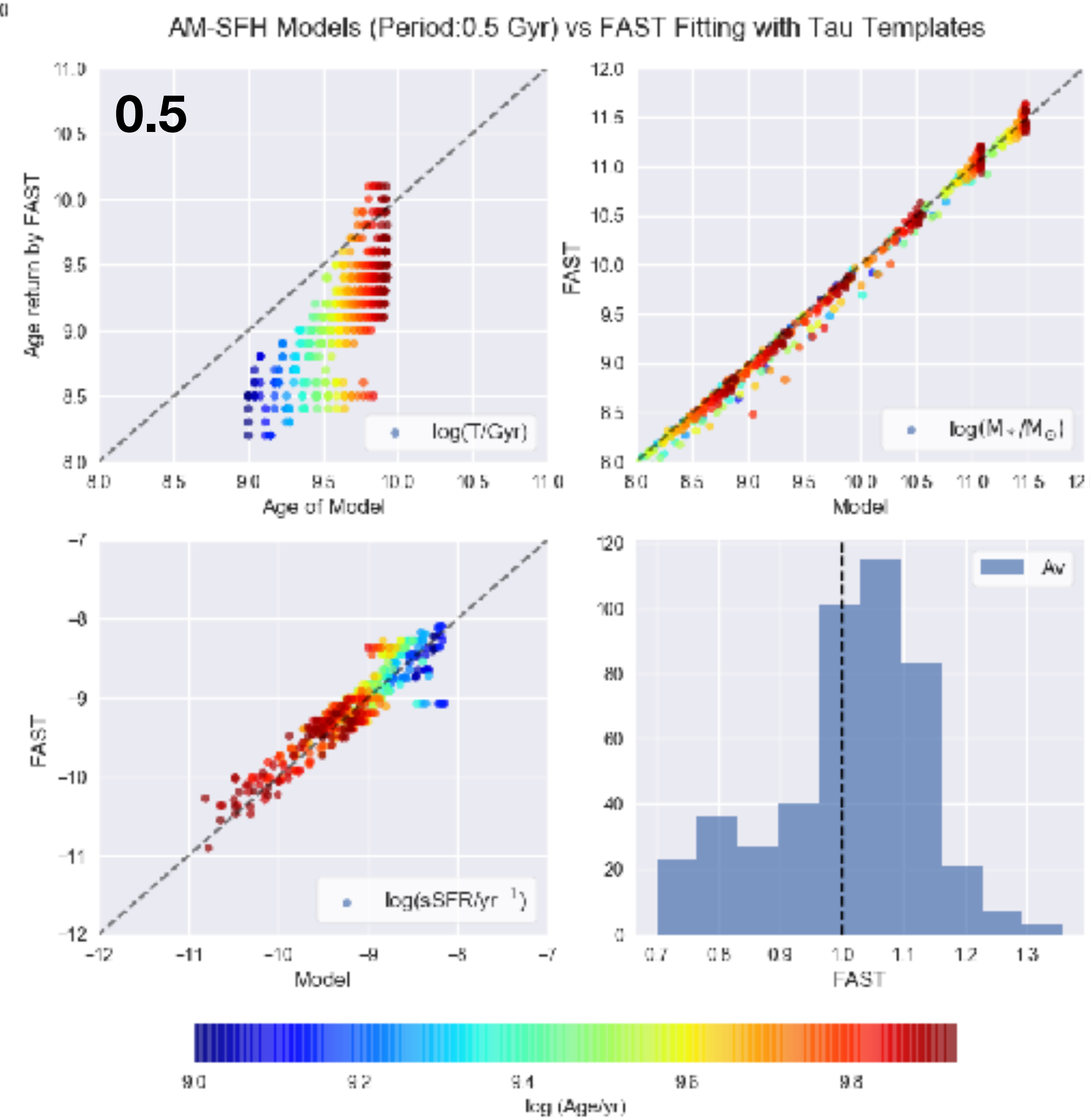






1. M* has smaller scatter (rather accurate) but under-estimated.
2. Fluctuations make galaxies stay blue longer.
3. Av-SSFR estimation correlate with *Phase.*
4. Little systematic scatter in SSFR.


AM-SFH Models (Period:2.5 Gyr) vs FAST Fitting with Tau Templates
2.5
Age return by FAST
Age of Model
log(T/Gyr)
FAST
Model
log(M*/M☉)
log(sSFR/yr⁻¹)
Av
log (Age/yr)


AM-SFH Models (Period:0.5 Gyr) vs FAST Fitting with Tau Templates
0.5
Age return by FAST
Age of Model
log(T/Gyr)
FAST
Model
log(M*/M☉)
log(sSFR/yr⁻¹)
Av
log (Age/yr)

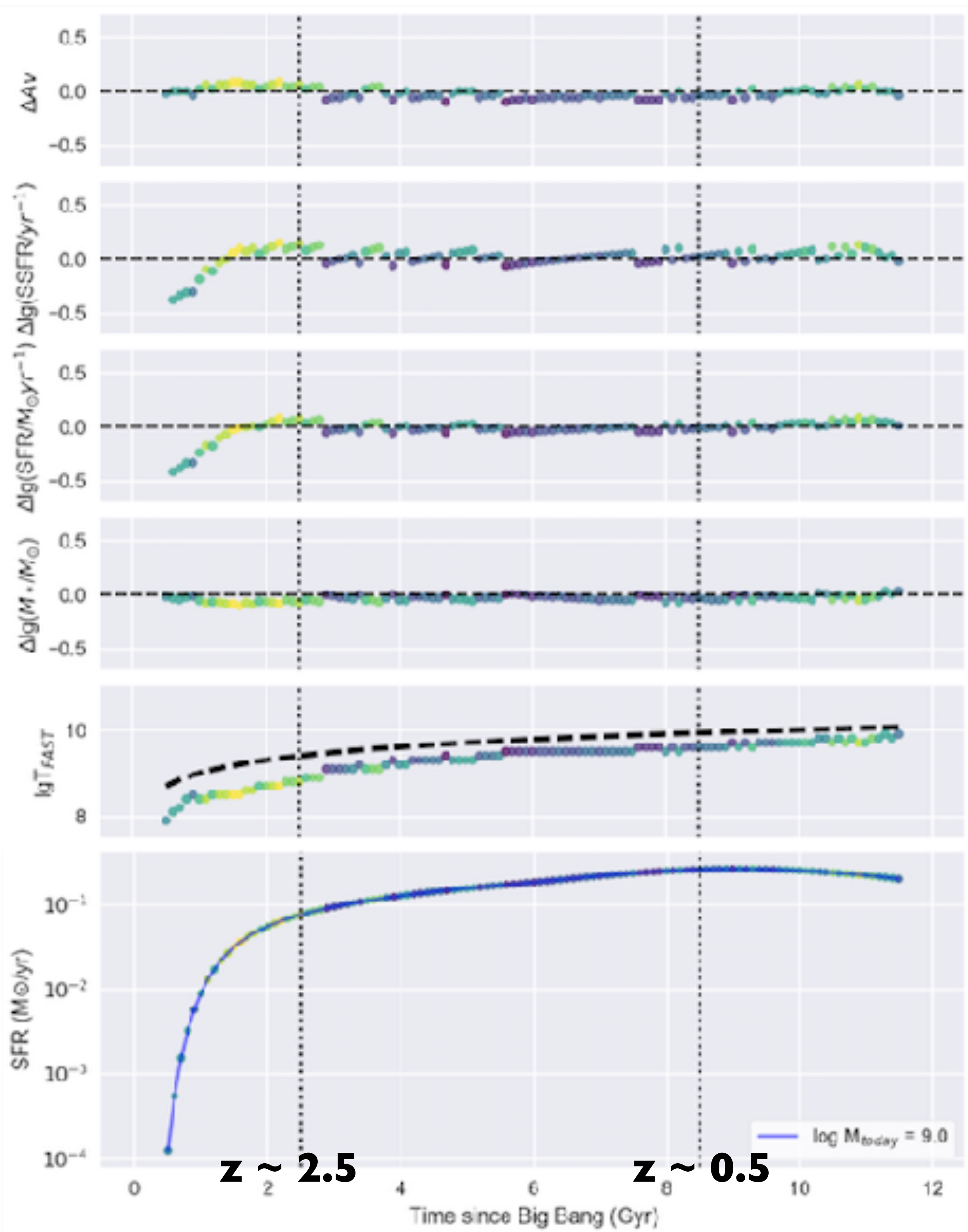
If unravel FAST estimation along time…

Δ = FAST - Model

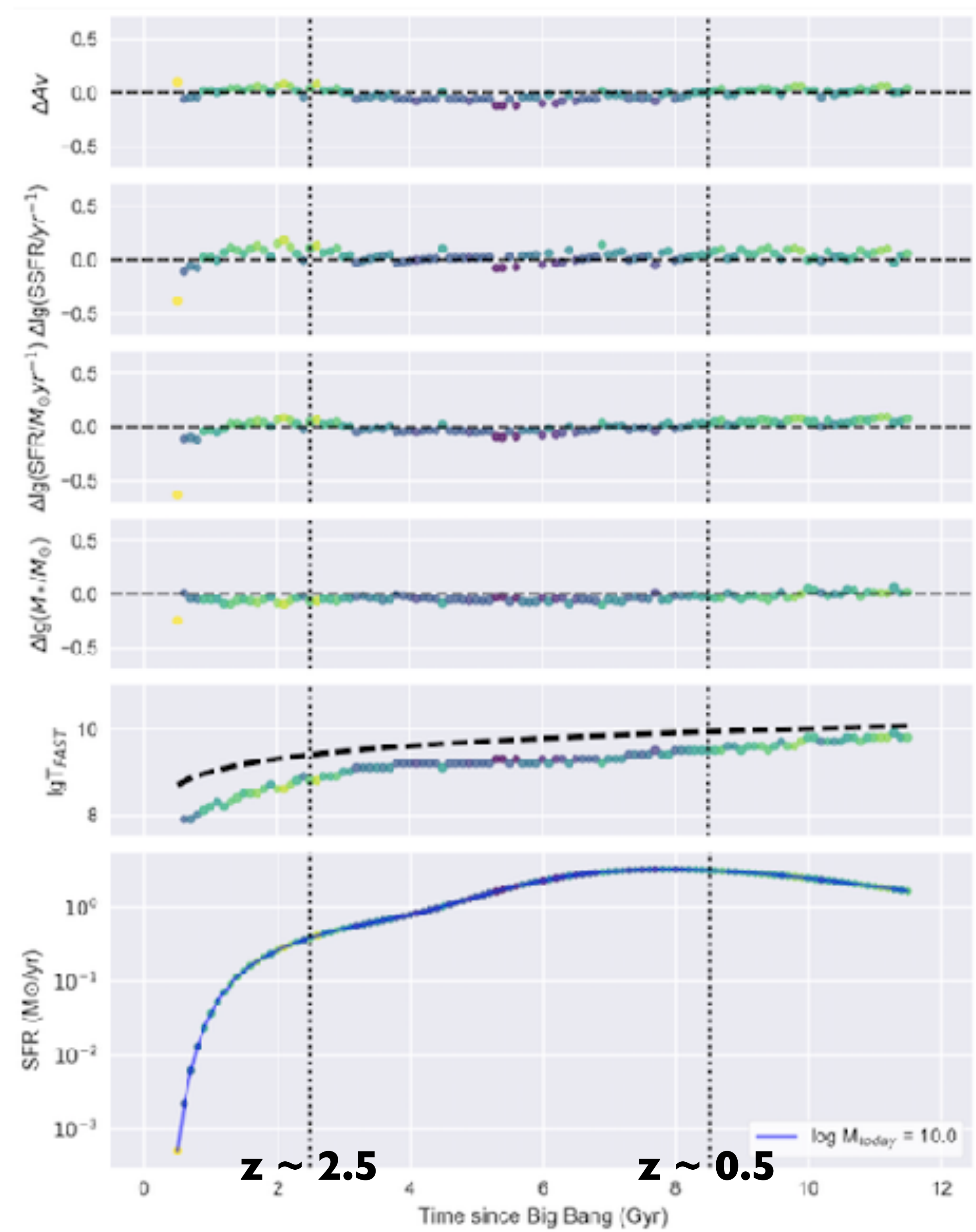
—— See how response of FAST change with growth of galaxies

AM-SFH (w/o Fluctuation)

log M_{Today} = 9



log M_{Today} = 10



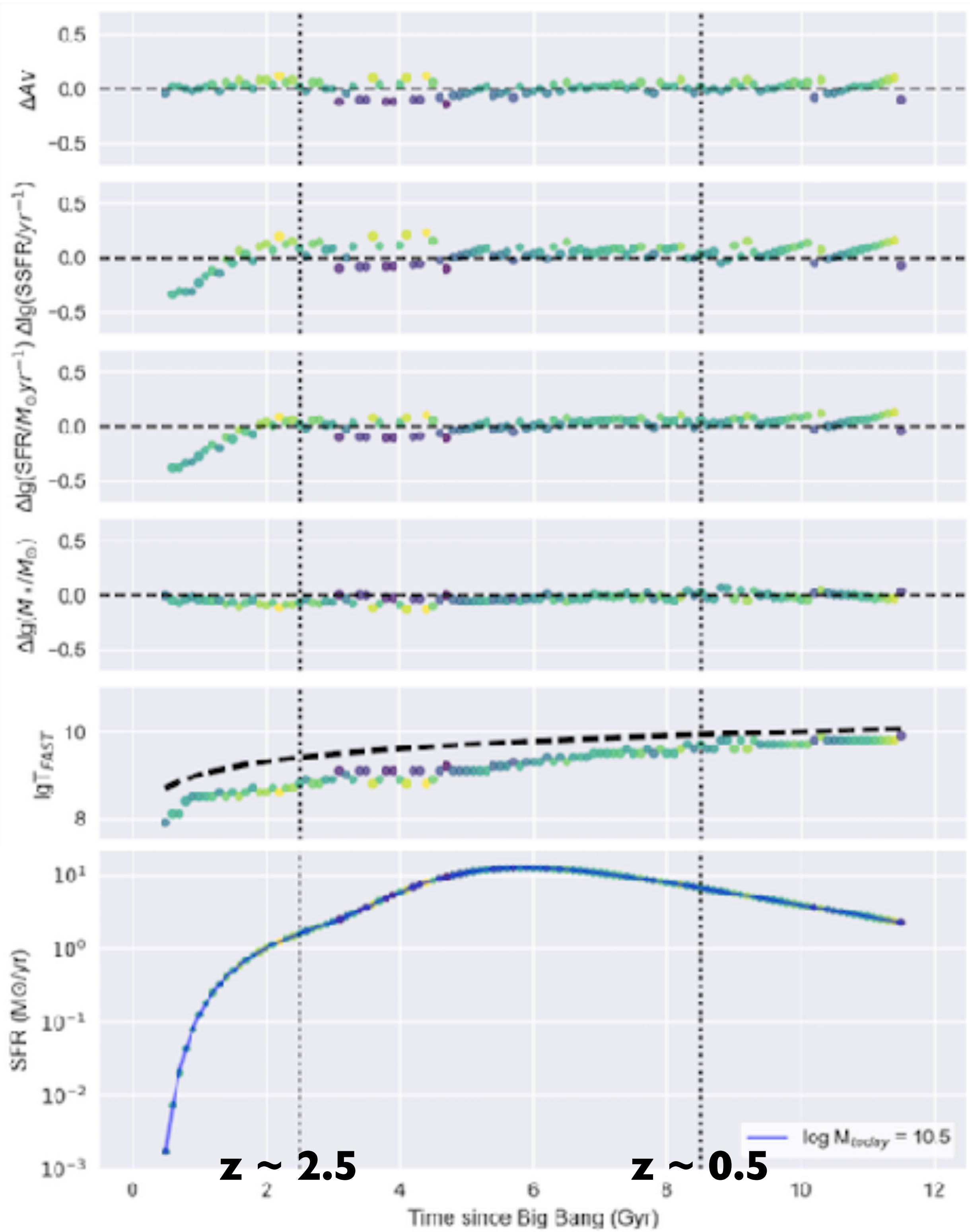
If unravel FAST estimation along time…

Δ = FAST - Model

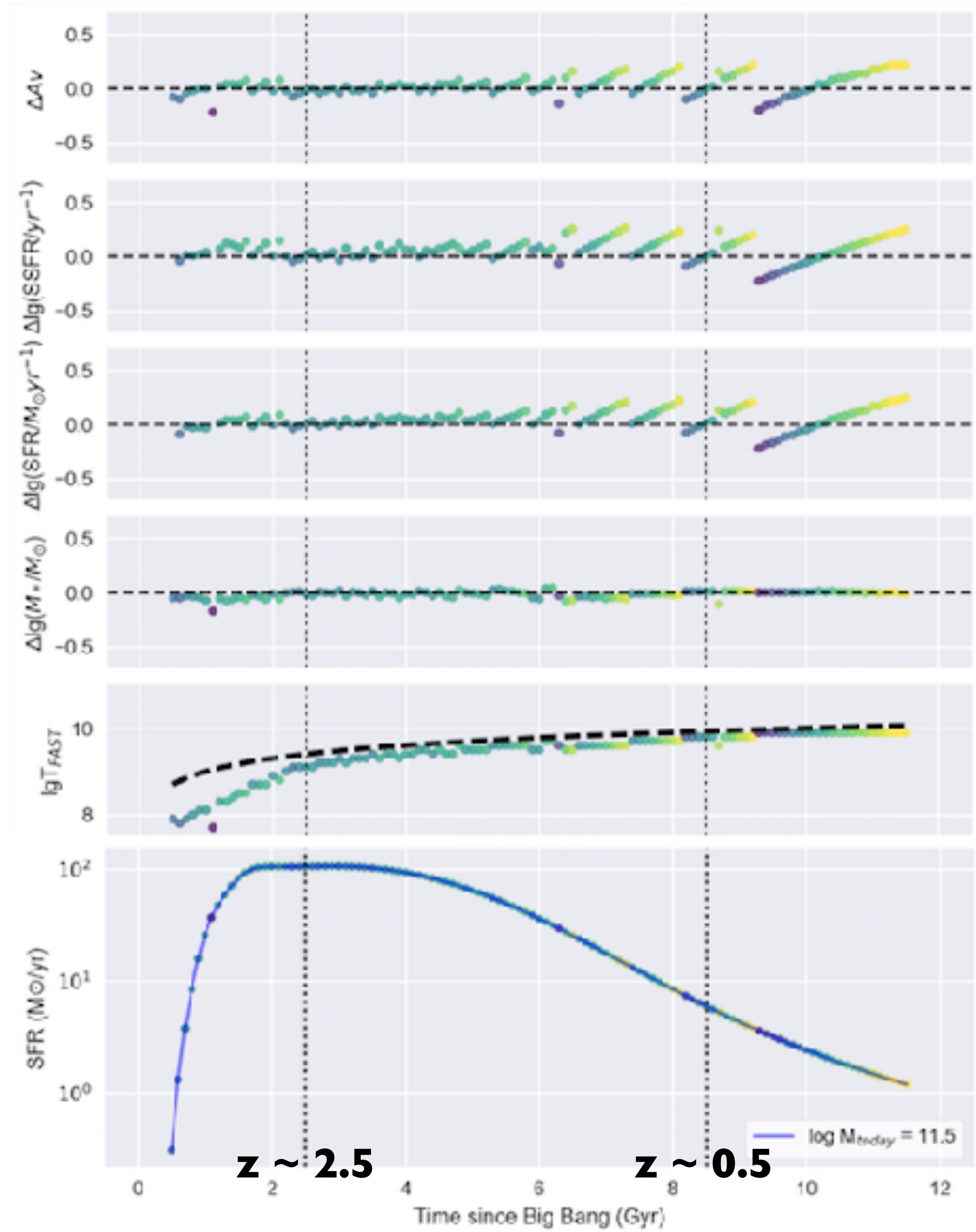
—— See how response of FAST change with growth of galaxies

AM-SFH (w/o Fluctuation)

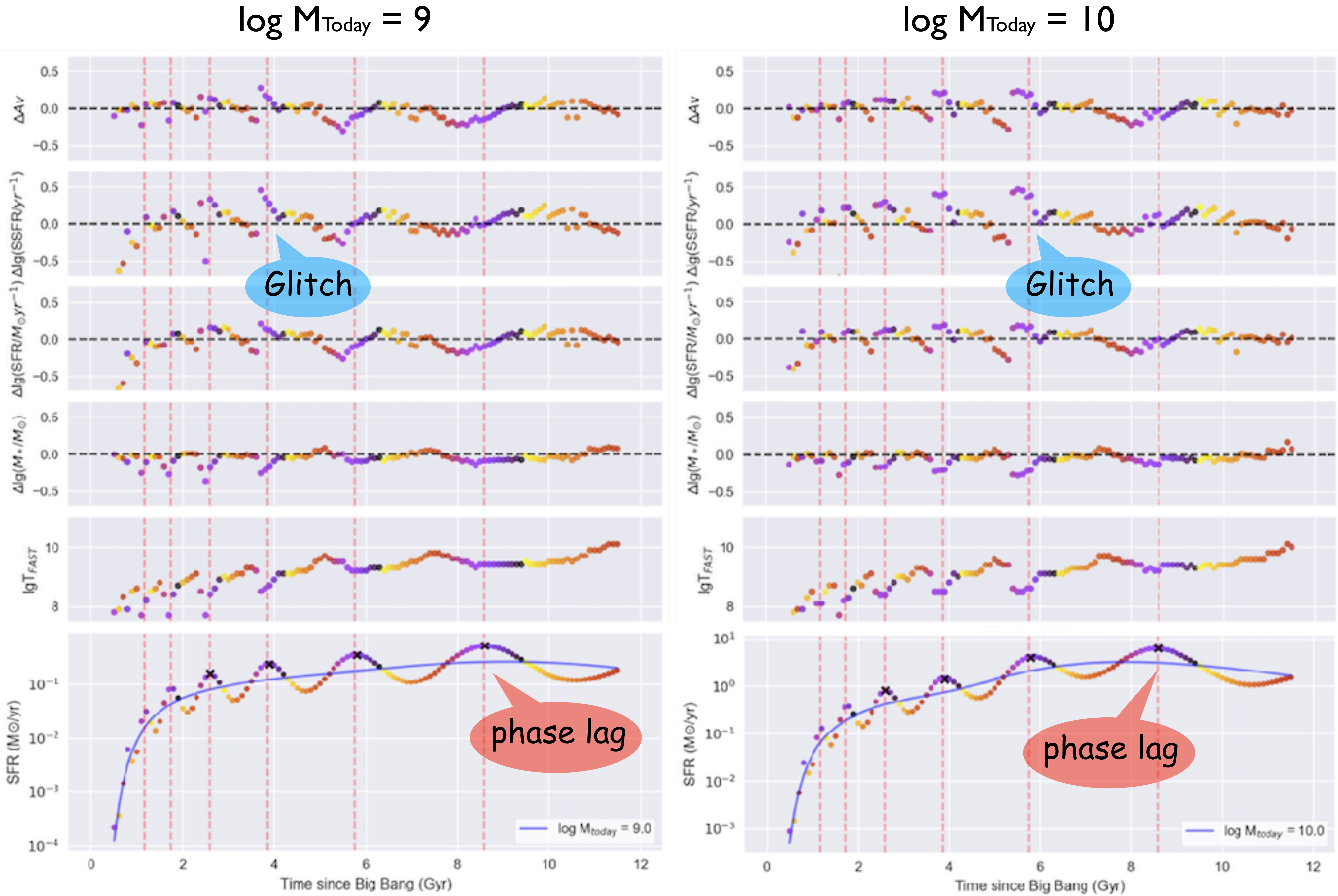
log M_{Today} = 10.5



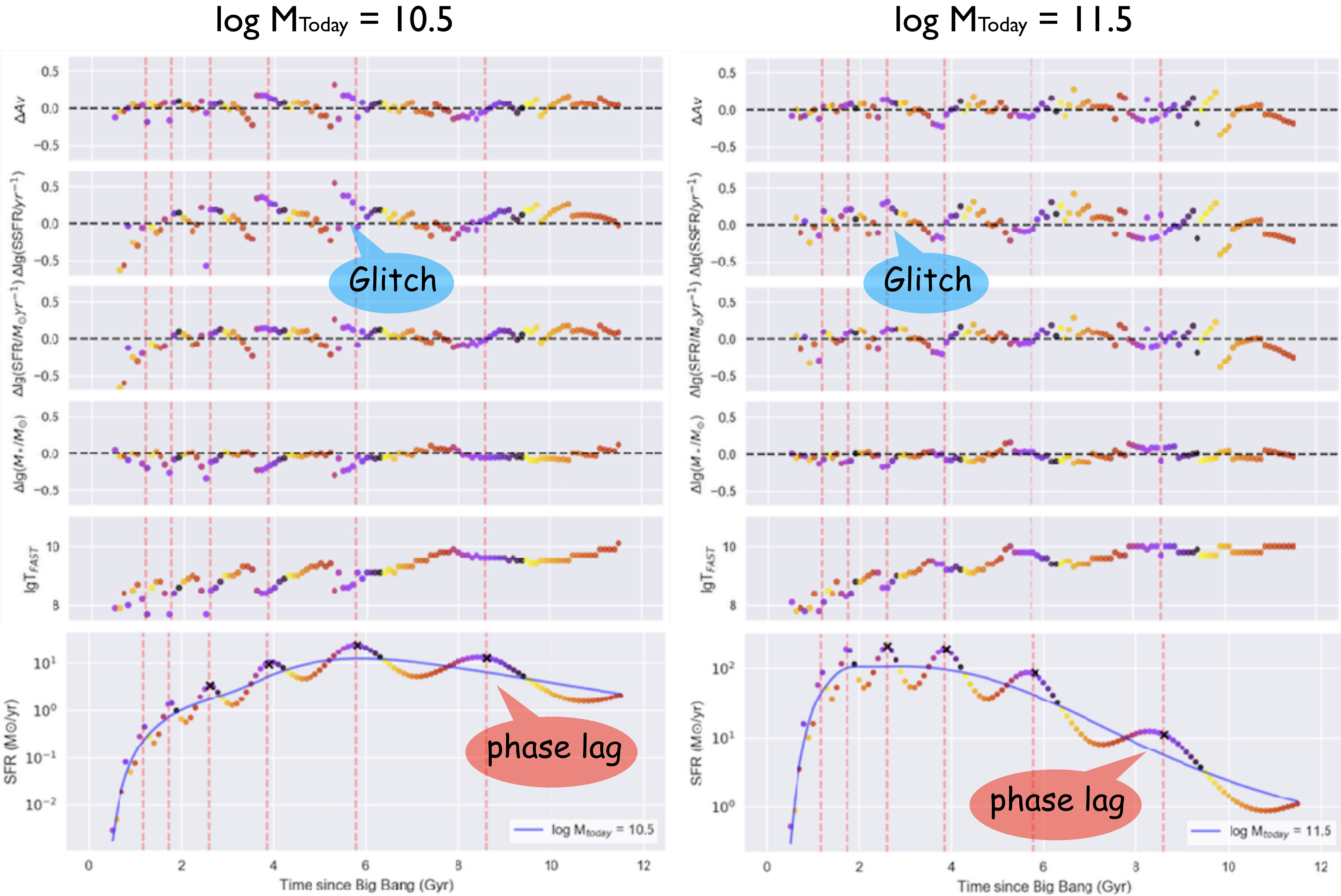
log M_{Today} = 11.5



AM-SFH + ST Fluctuation

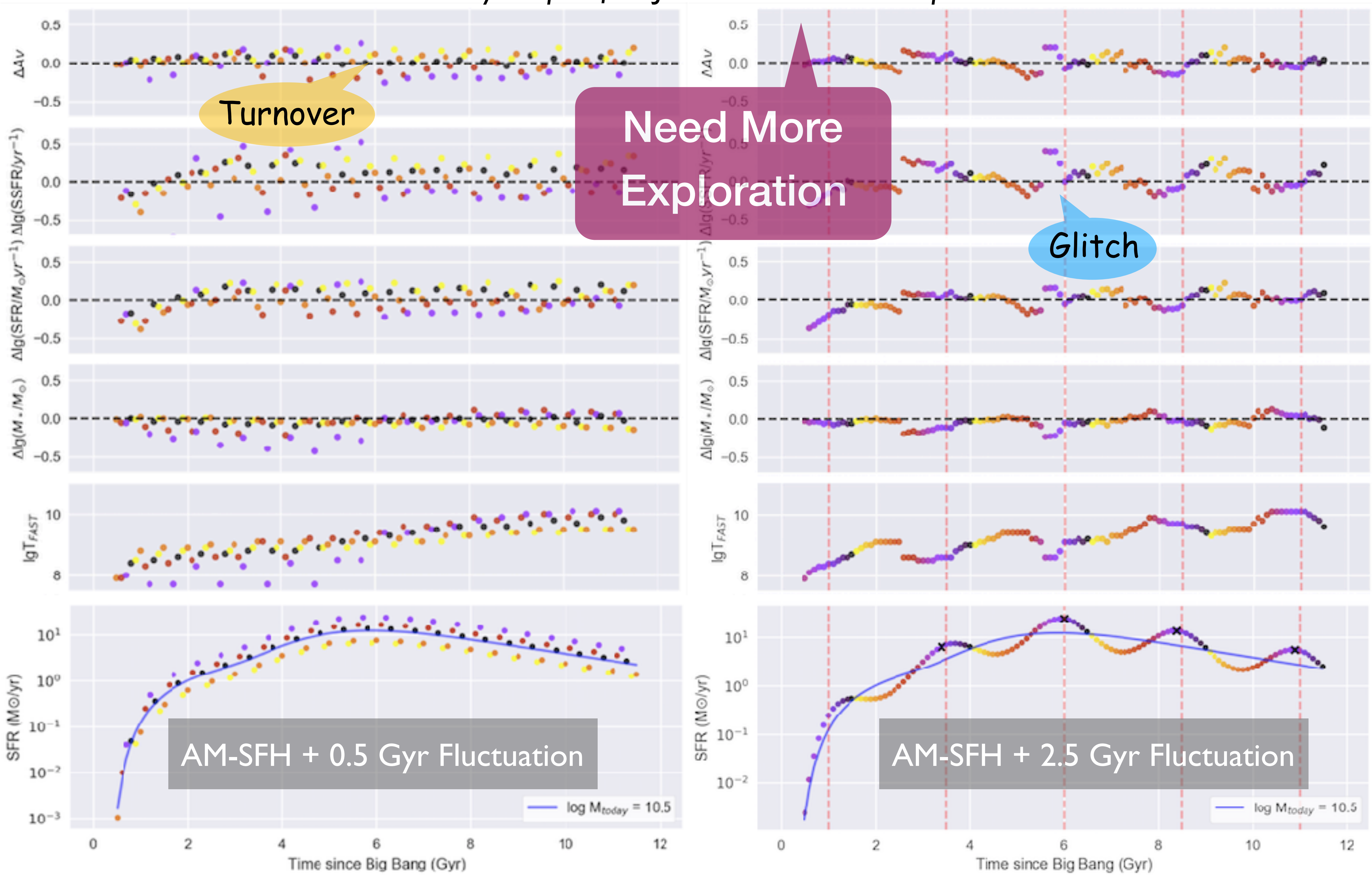


AM-SFH + ST Fluctuation



1. After a certain point Av turn over, no glitch any more, M* become accurate;
2. Glitches come with very young age => Does FAST 'compromise' in these points?

Decided by shape of UVJ tracks relative to templates!



Take-away Message:

1. Classical SFH models (Tau, Constant, Delayed) become too red too fast to represent real galaxy populations.
2. Realistic SFH models derived from Abundance Matching and Main Sequence would help solve the 'age-color' problem.
3. Their UVJ tracks are similar and multi-band SED-fitting return relatively accurate estimation for their M*, SFR and Av.
4. Peroidical fluctuations in SFH have influences in color evolution and SED-fitting behaviors.

Future Exploration:

1. Quantitative matching between models and CANDELS data;
2. Adding photometric errors in observations in SED-fitting;
3. Use less bands (e.g. remove FUV) to do SED-fitting;
4. Further exploring SED-fitting behaviors with fluctuation.