STAR FORMATION HISTORIES OF MASSIVE QUIESCENT GALAXIES AT Z > 1

Linea Webinar • 25th May 2017

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OUTLINE

I. State of the art & Goals

- Main Sequence & Mass Function
- Compaction & Quenching
- Stellar Populations

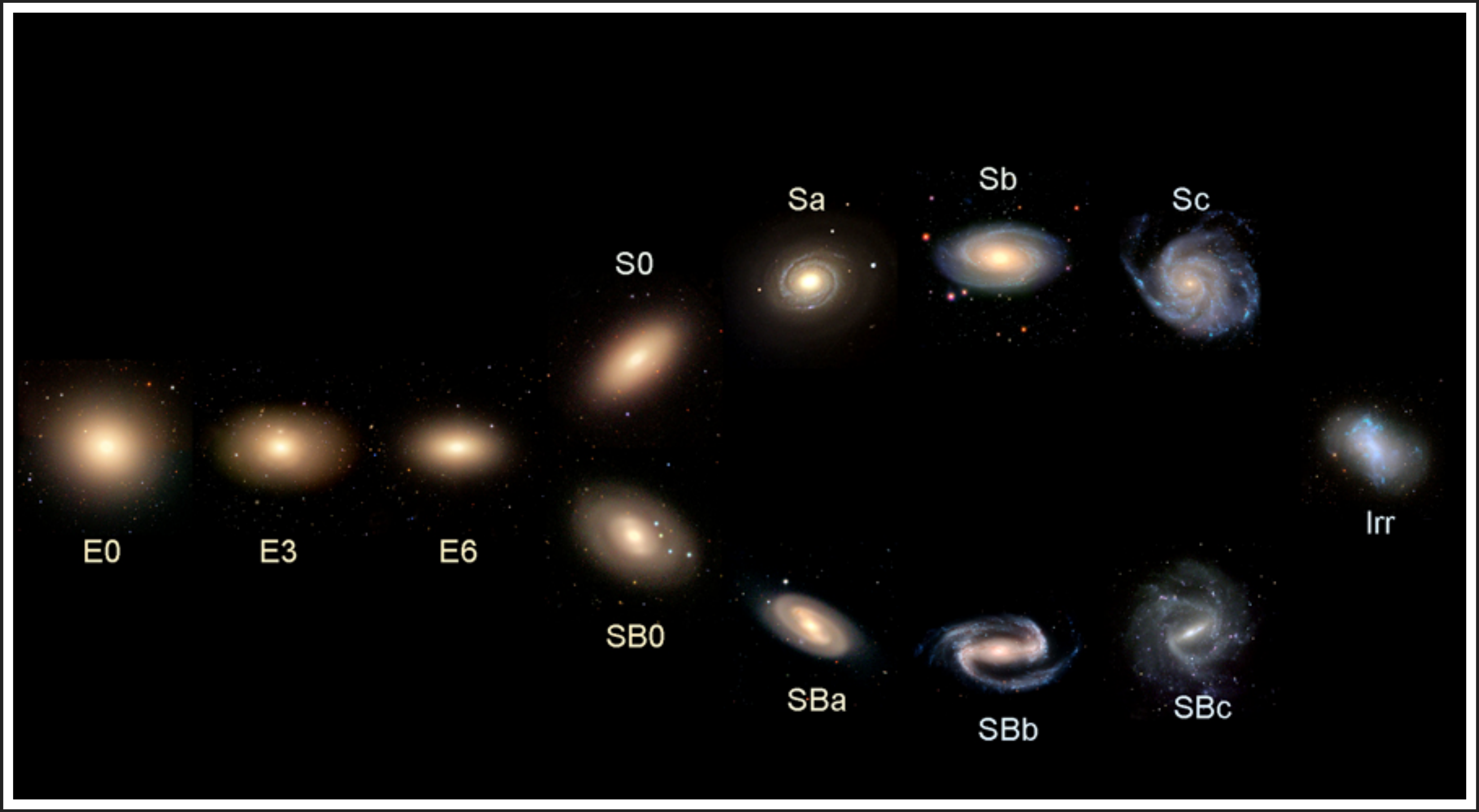
II. SFH of MQGs

- SHARDS survey
- Methods
- Results

III. On going projects

- Morphology of MQGs
- MANGA
- Deep learning

HUBBLE GALAXY CLASSIFICATION



SPIRAL

- Star Formation in spiral arms
- Young stellar populations
- Less massive

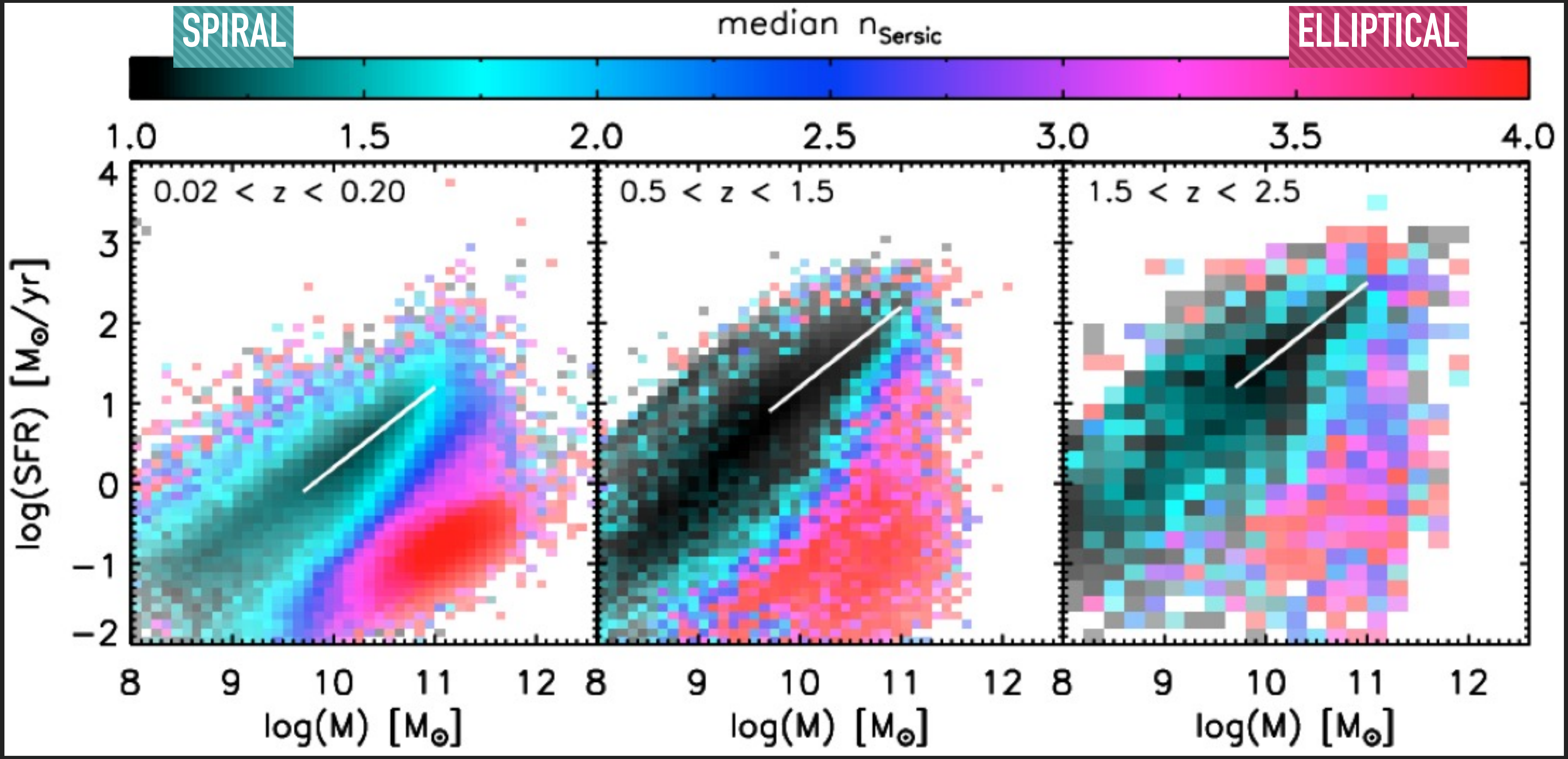
ELLIPTICAL

- Red colors
- Old stellar populations
- More massive

REDSHIFT EVOLUTION: MASS-SFR

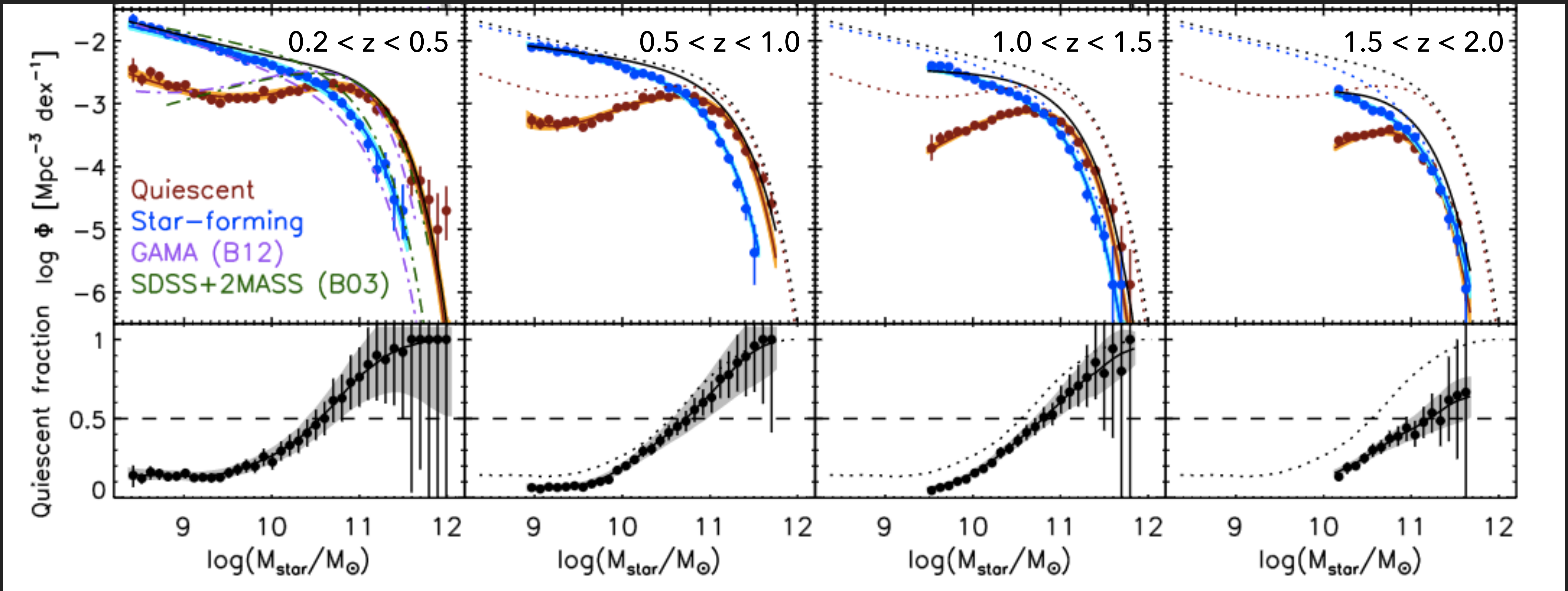
Main Sequence

Wyuts et al. (2011a)



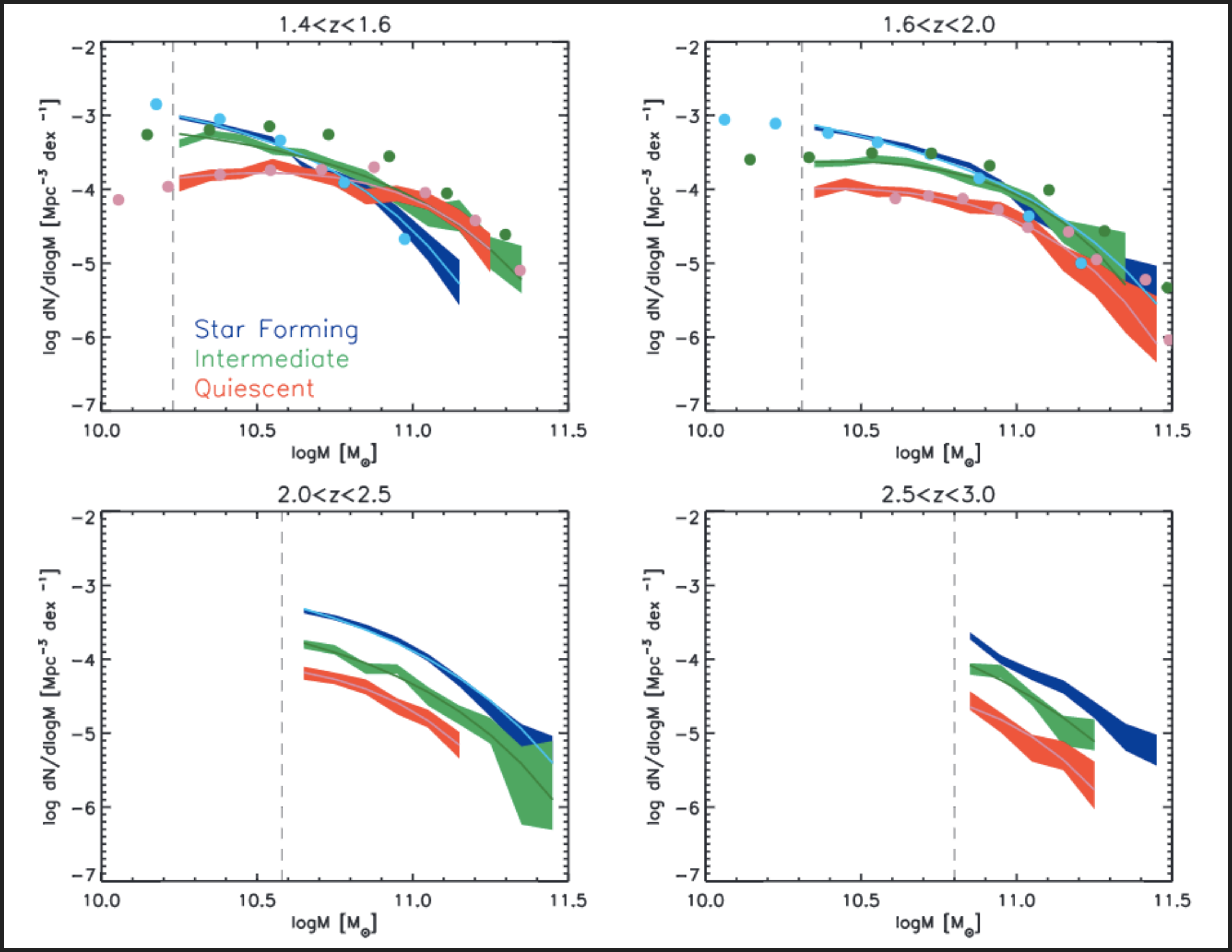
REDSHIFT EVOLUTION: MASS FUNCTION

Muzzin et al. (2013)



REDSHIFT EVOLUTION: WHY Z= 1.0-1.5?

Domínguez Sánchez et al. (2011)

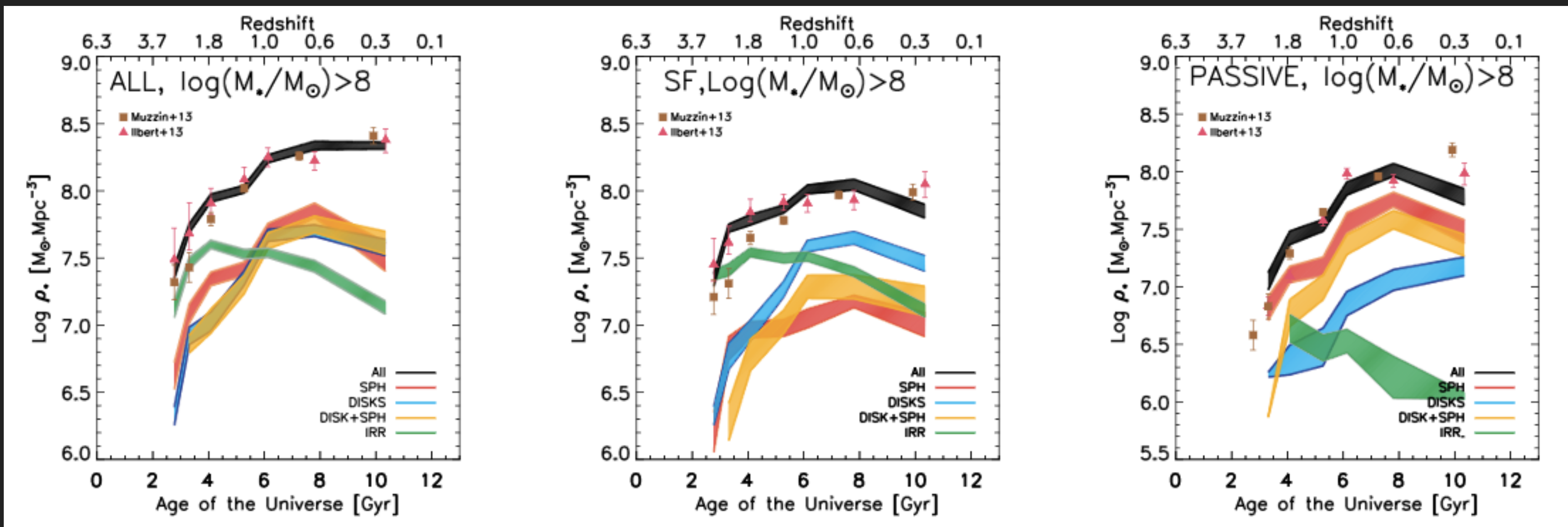


- Peak of SFR density (Bowens et al. 2013)
- Epoch of transition:

  at higher z MF dominated by SF galaxies at all masses

REDSHIFT EVOLUTION: MORPHOLOGY

Huertas-Company et al. (2016)



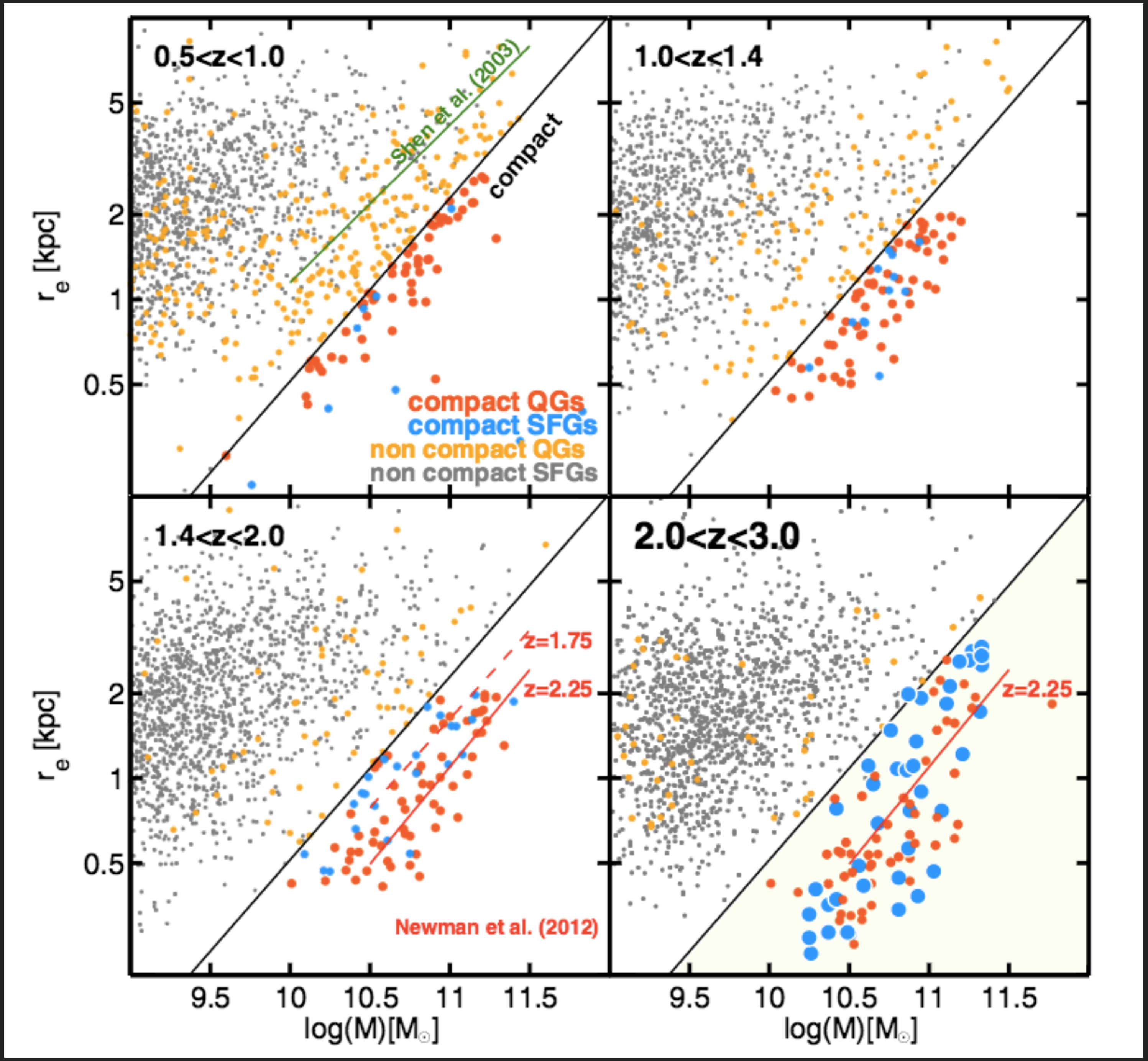
STAR FORMING

- **z > 2:** 80% of stellar mass density in Irr
- gradual transformation to disks at **z ~ 1.0**

QUIESCENT

- z > 2 : compact spheroids
- 1 < z < 2: disk+ bulge (inside out quenching)

REDSHIFT EVOLUTION: MASS-SIZE



- Steady increase of the radii of quiescent population

  (Daddi+05, Trujillo+07, VanDokum+08, Buitrago+08, Cassata+11, etc.)

- z > 2 the majority of compact galaxies are SF

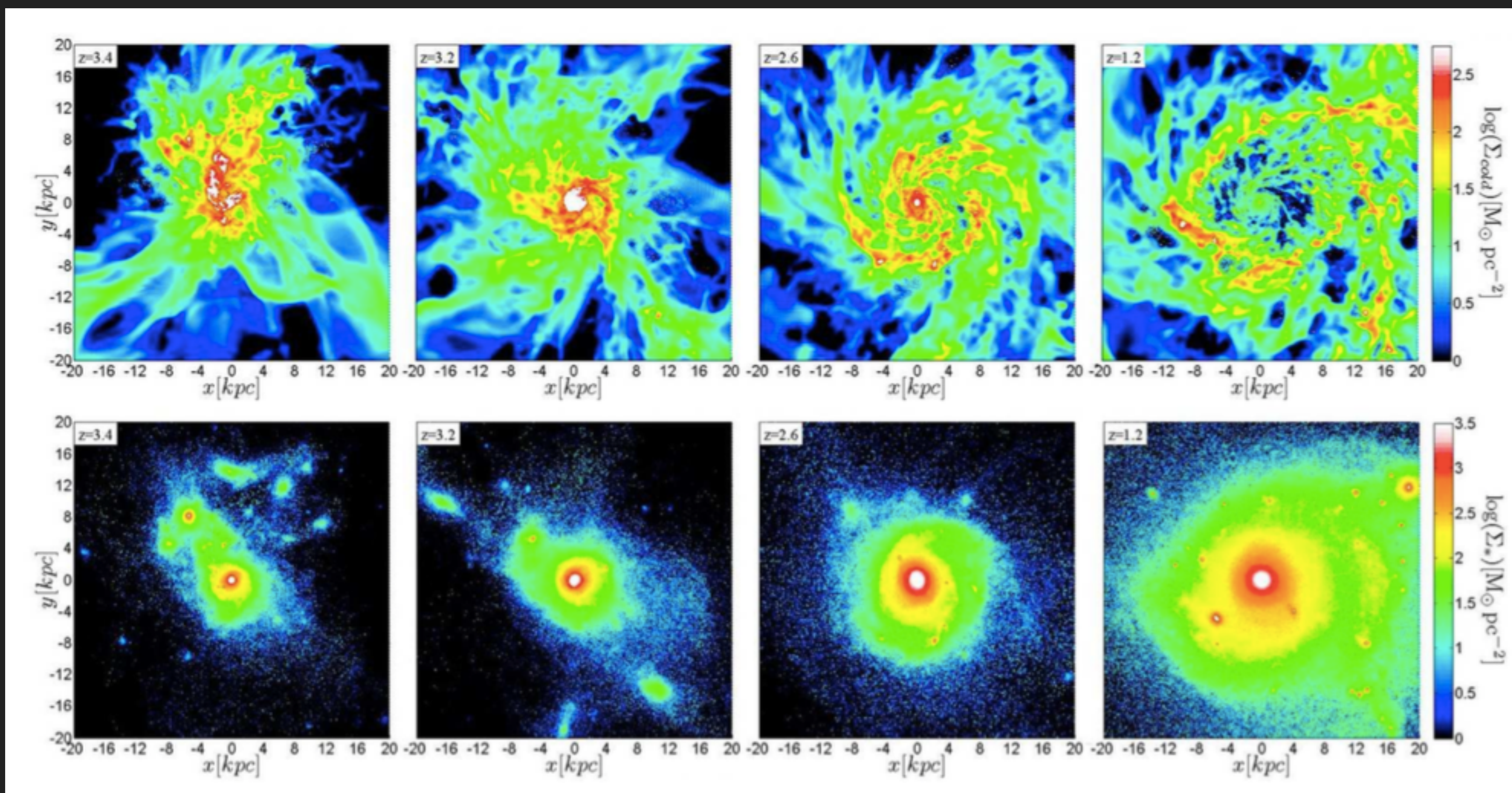
- Galaxies become more compact before quenching

Barro et al. (2014)

COMPACTION AND QUENCHING

Zolotov et al. (2015)

(A) PRIOR TO COMPACTION | (B) BLUE NUGGET | (C) GREEN NUGGET | (D) RED NUGGET



GAS + STARS < 100 MYR

STARS

COMPACTION AND QUENCHING

<u>See also:</u>
Van Dokkum et al. 2015
Tachella et al. 2016
Barro et al. 2014, etc.

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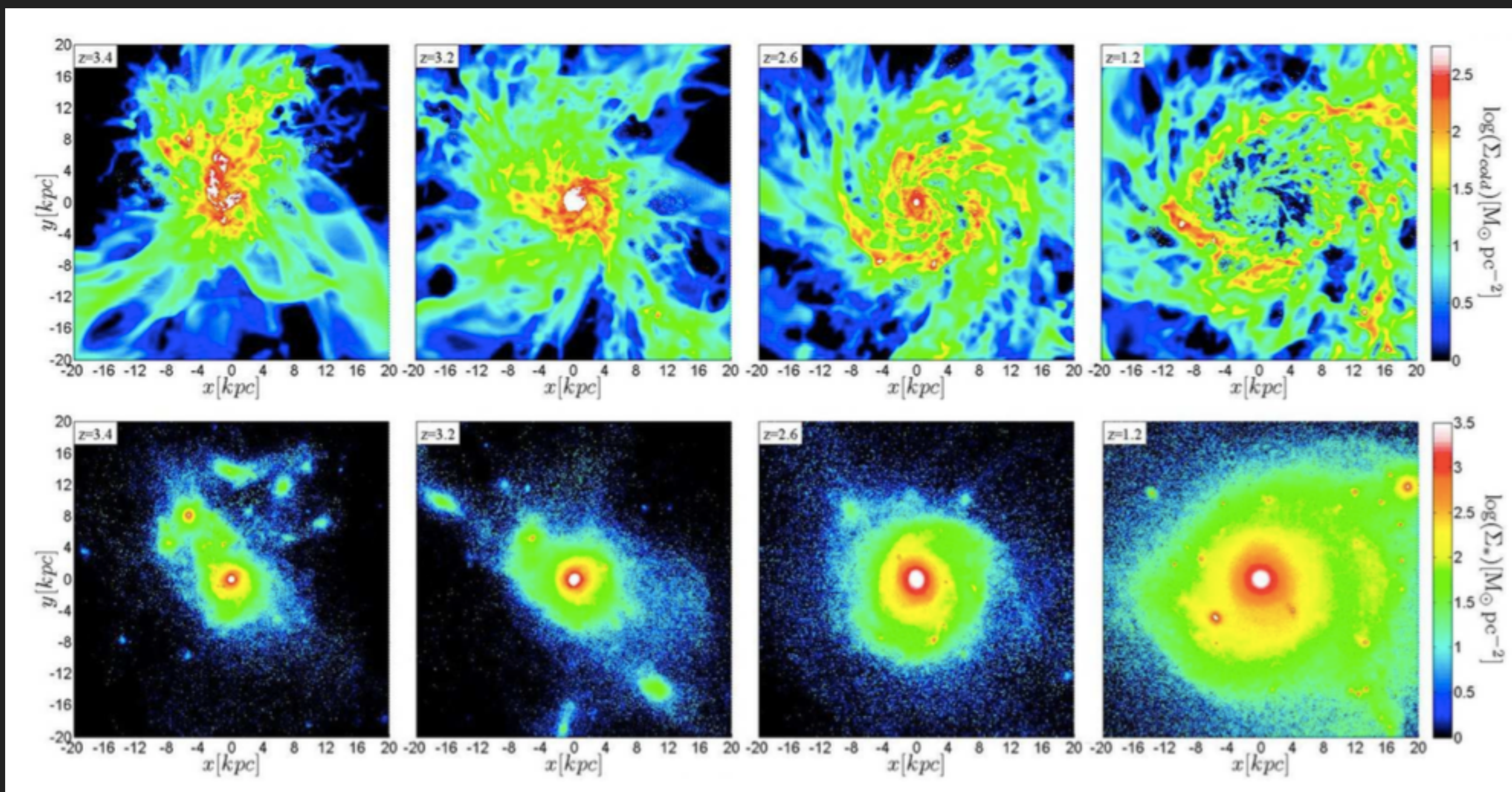

GAS + STARS
< 100 MYR

STARS

GALAXY CHARACTERIZATION

- ✓ Environment (e.g. Peng+2012)
- ✓ Morphology (Galaxy Zoo, Dielmann+2015, Huertas-Company+15)
- ✓ Mass (dynamical, photometric, 0.2 dex accuracy; e.g. Bernardi + 2017)
- ✓ Star Formation Rate (UV, nebular lines, IR, radio)
- ✓ Stellar populations (age, dust extinction, metallicity, SF-timescale)

GALAXY CHARACTERIZATION: SFR

- ★ UV emission: massive young stars are bright in the UV; direct probe of young stellar population
- ★ Nebular lines: zones of ionized gas around young star clusters that still contain OB stars; Hα is the brightest
- ★ Far-IR emission: light absorbed by dust and re-emitted at longer wavelengths
- ★ Radio, CO, SEDs…

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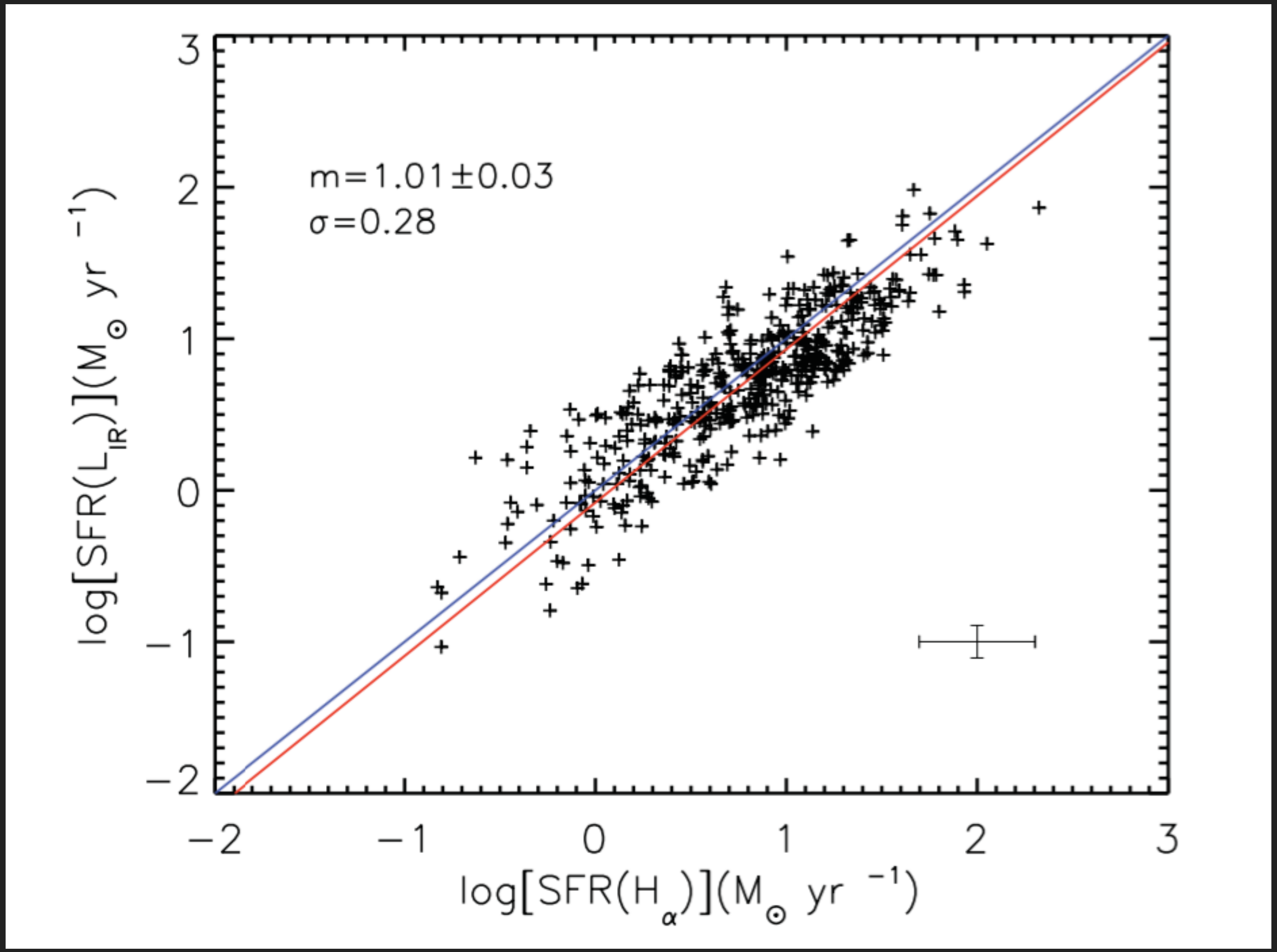

Domínguez Sánchez et al. (2012, 14)

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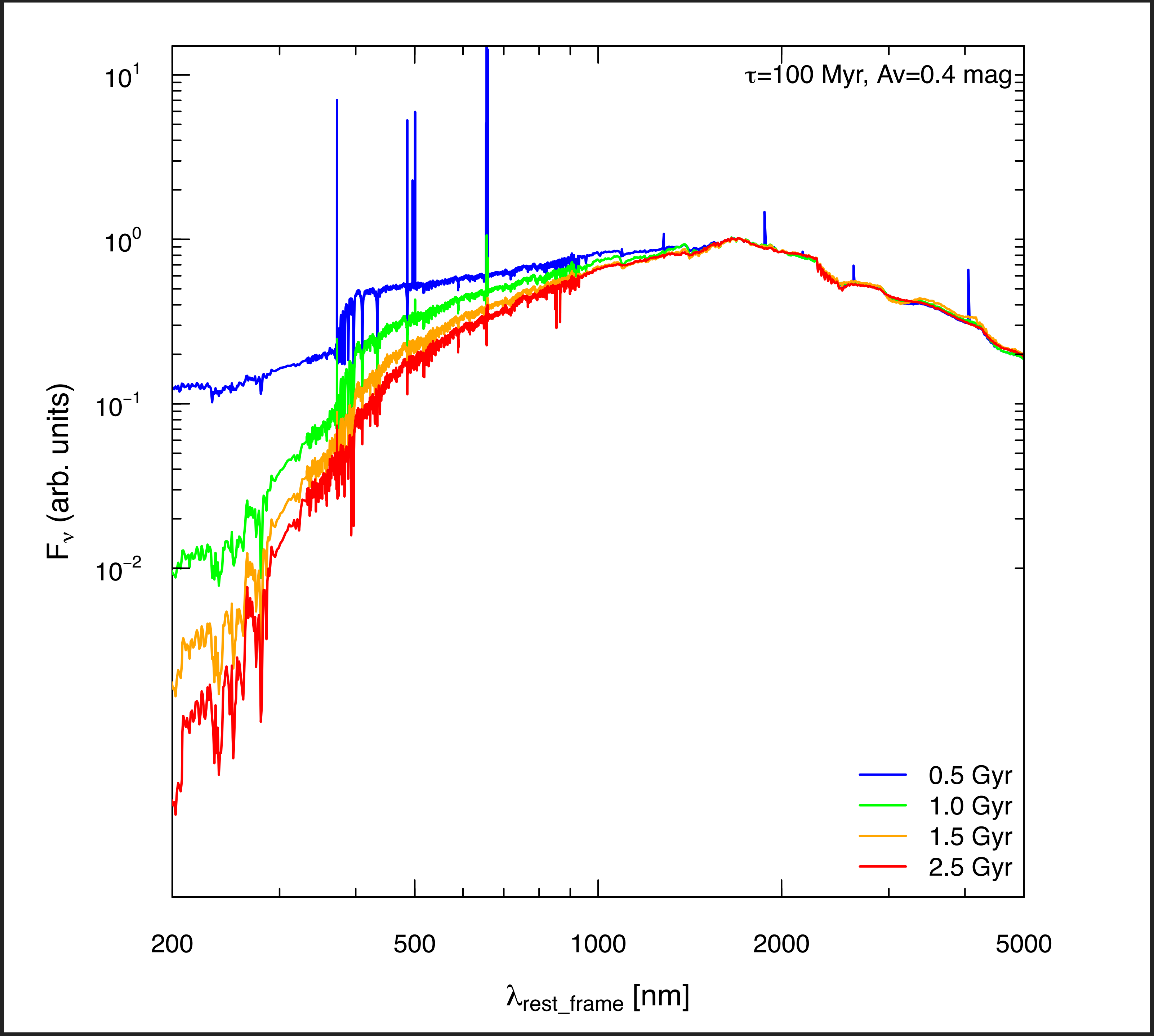
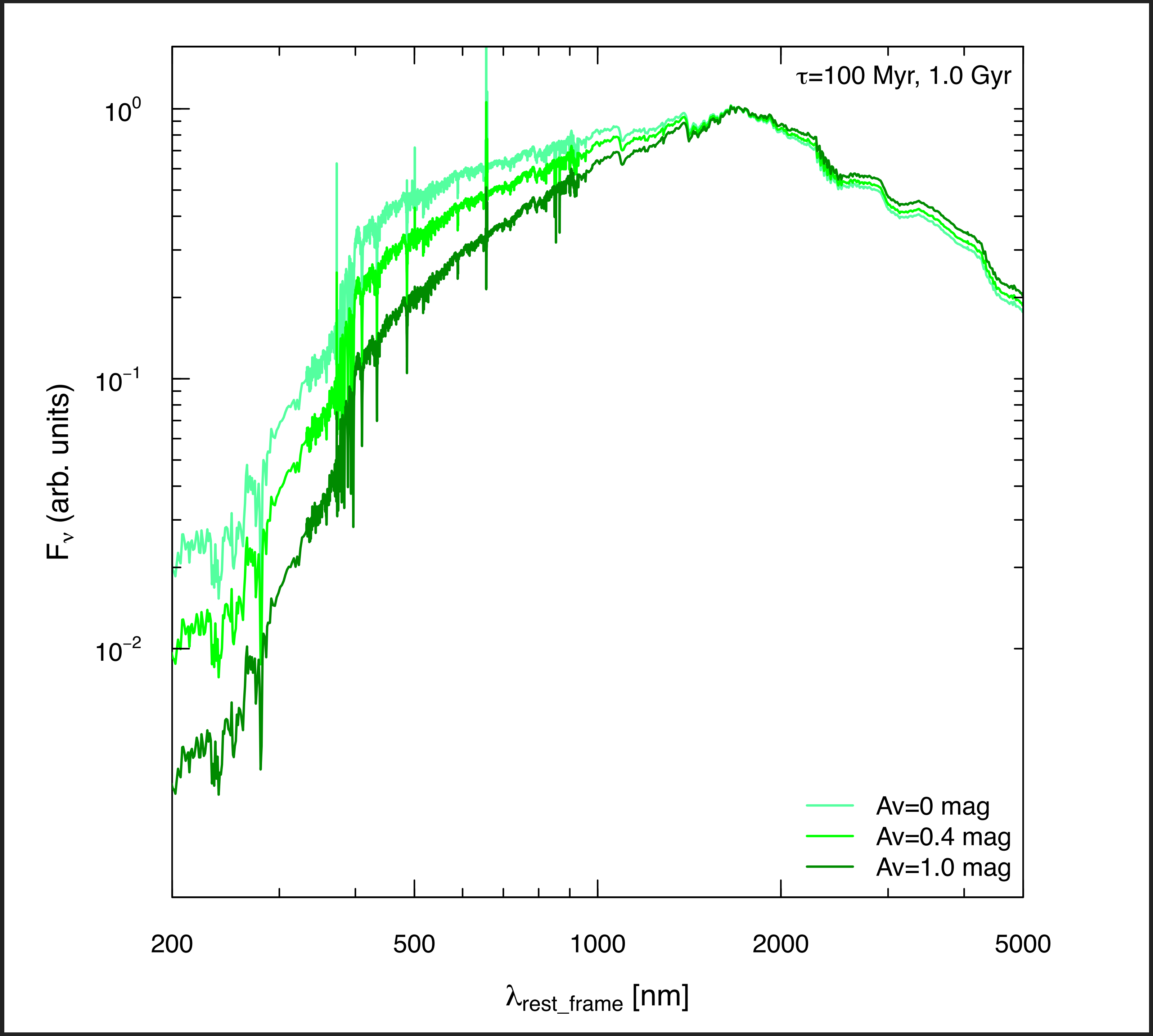
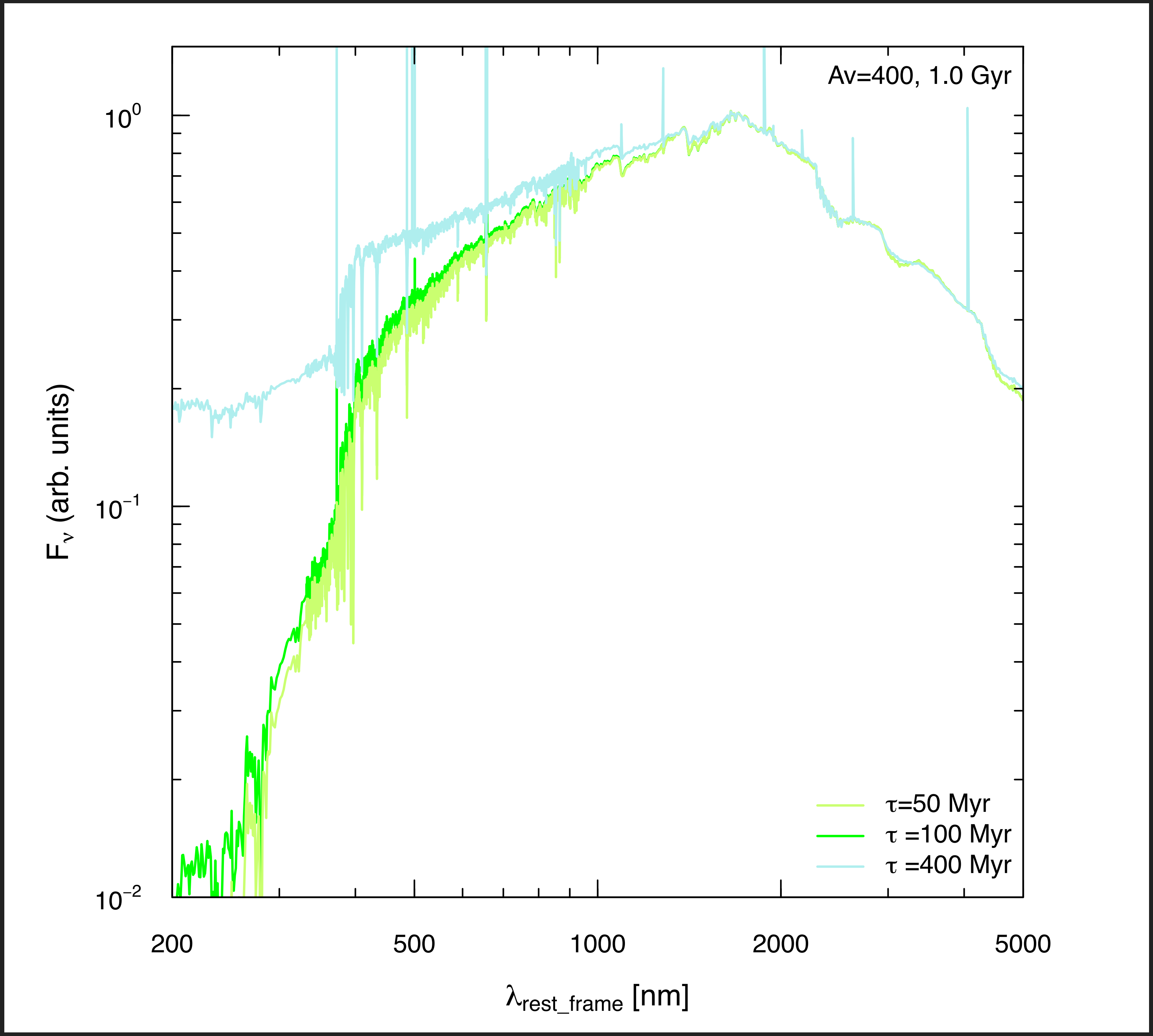
GALAXY CHARACTERIZATION: AGE



GALAXY CHARACTERIZATION: DUST EXTINCTION



GALAXY CHARACTERIZATION: SF-TIMESCALE



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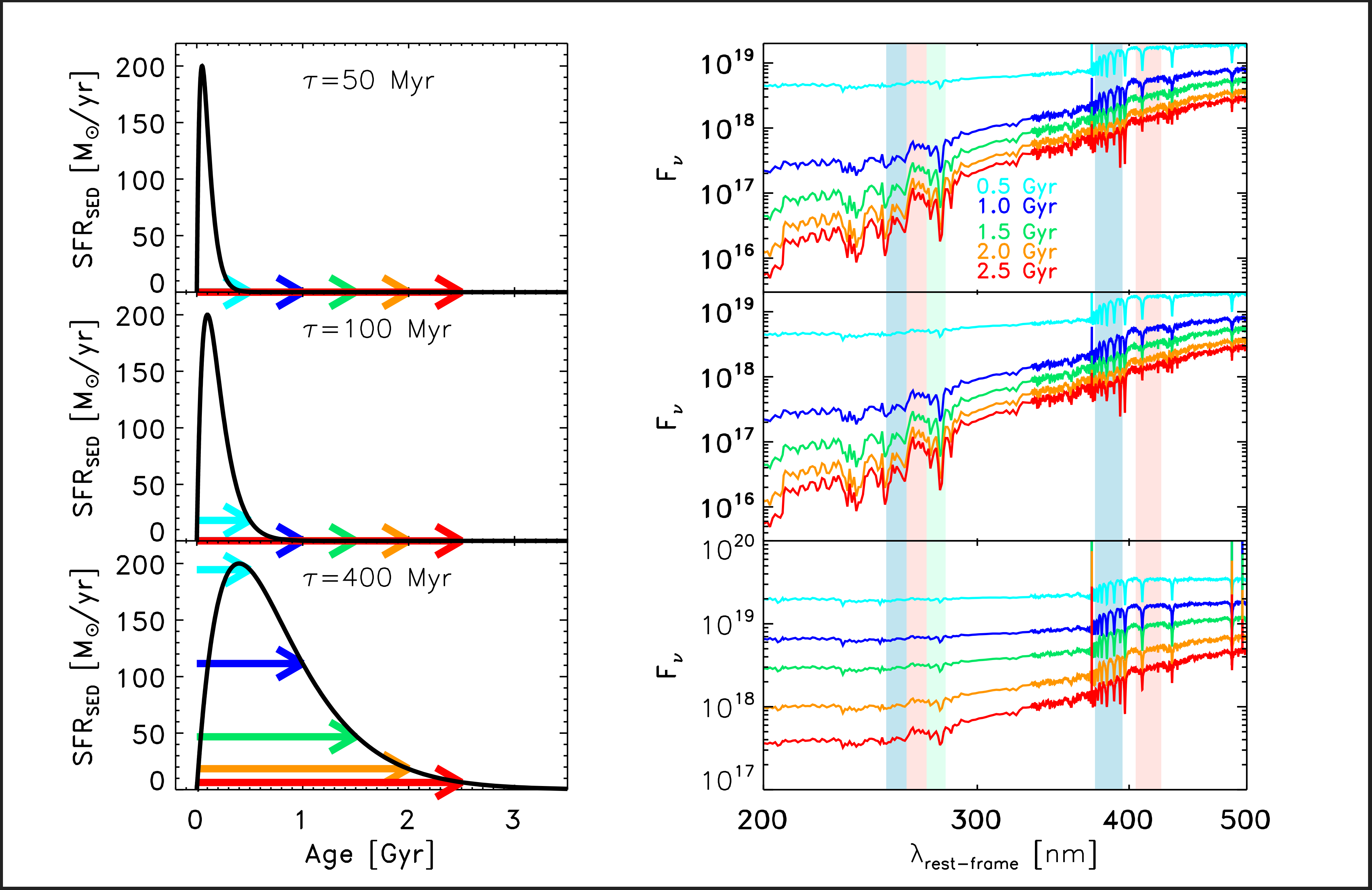
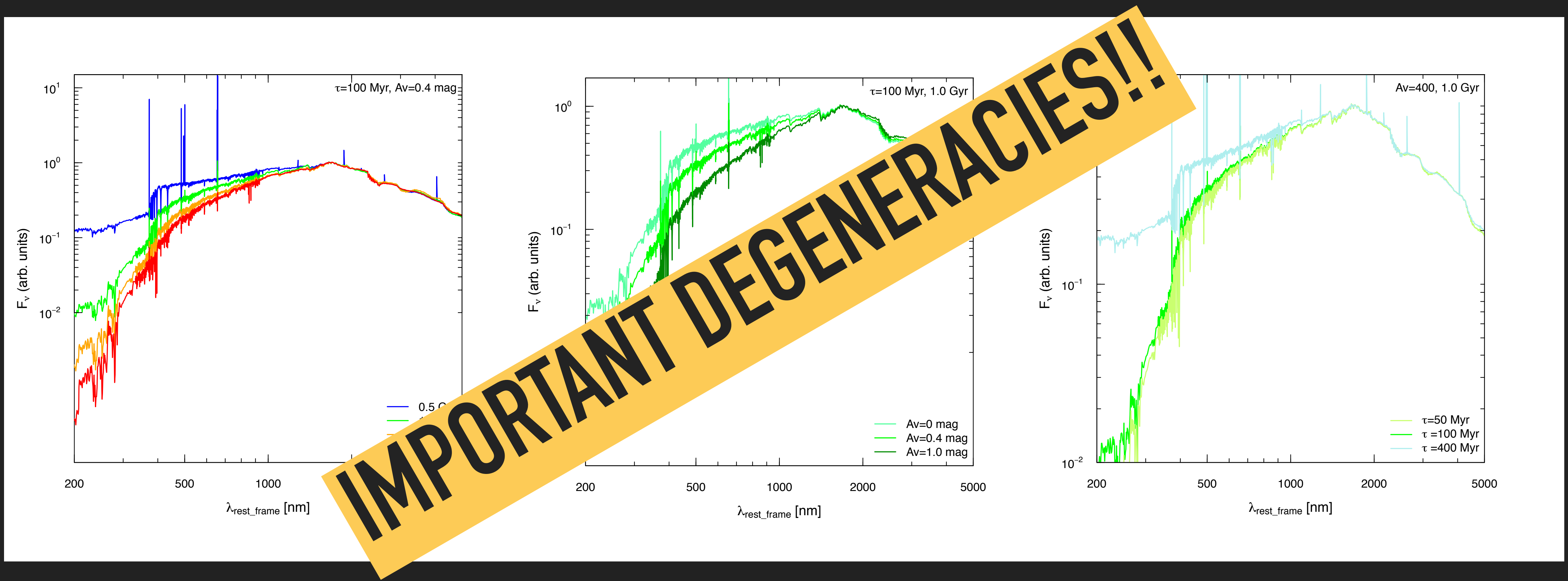


GALAXY CHARACTERIZATION: STELLAR POPULATIONS

- Age (t), star formation timescale (τ)
- Dust extinction (A_V), metallicity (Z)



WHAT?

Study the Star Formation Histories (SFH) of Massive Quiescent Galaxies (MQGs) at $z = 1.0\text{-}1.5$

Domínguez Sánchez et al. (2016)

WHY?

- ✓ **Quiescent galaxies dominate the massive end of the local MF**: fundamental in galaxy formation and evolution
- ✓ **z ~ 1.5** is an **epoch of transition** between star-forming and quiescence for MQGs
- ✓ Number density of massive quiescent galaxies at z >1 in **disagreement with theoretical expectations**
- ✓ MQGs at high-z are found to be much **more compact** than their local analogues: **mass-size evolution**
- ✓ **Challenge observations:** faint in the optical; important degeneracies using photometry (age-dust-metallicity); spectra very time consuming (~ 12 h per galaxy)
- ✓ Up to date works rely on **small samples or stacked spectra**
  - (Cimatti + 2008, Whitaker + 2013, Mendel + 2015, Belli + 2015)
- ✓ **SHARDS GTC data** especially designed to measure spectral features which help breaking degeneracies (MgUV, D4000)
- ✓ Wish to confirm existence of old passive population at high-z, **how were they formed (SFH)**?

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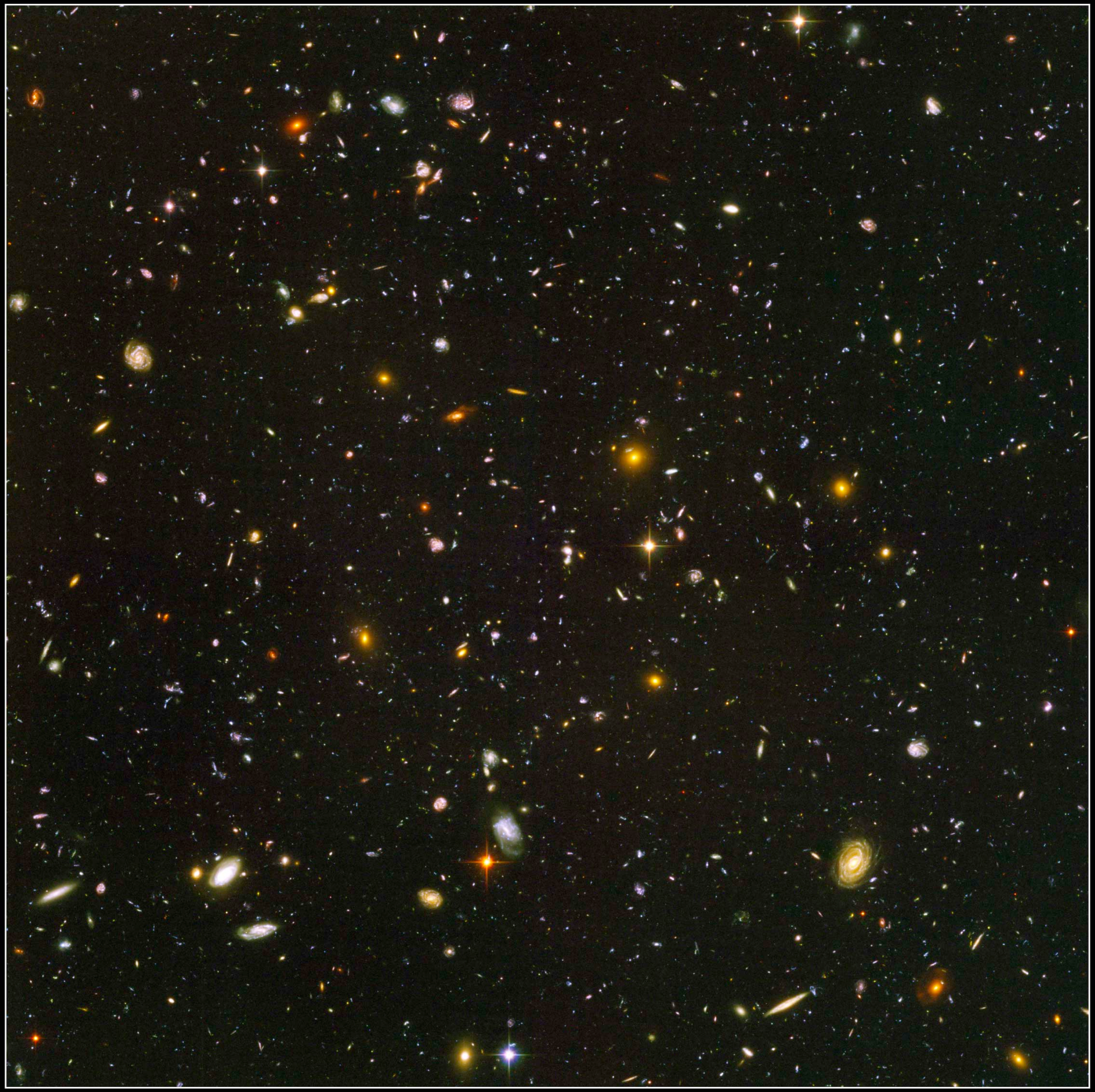

Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

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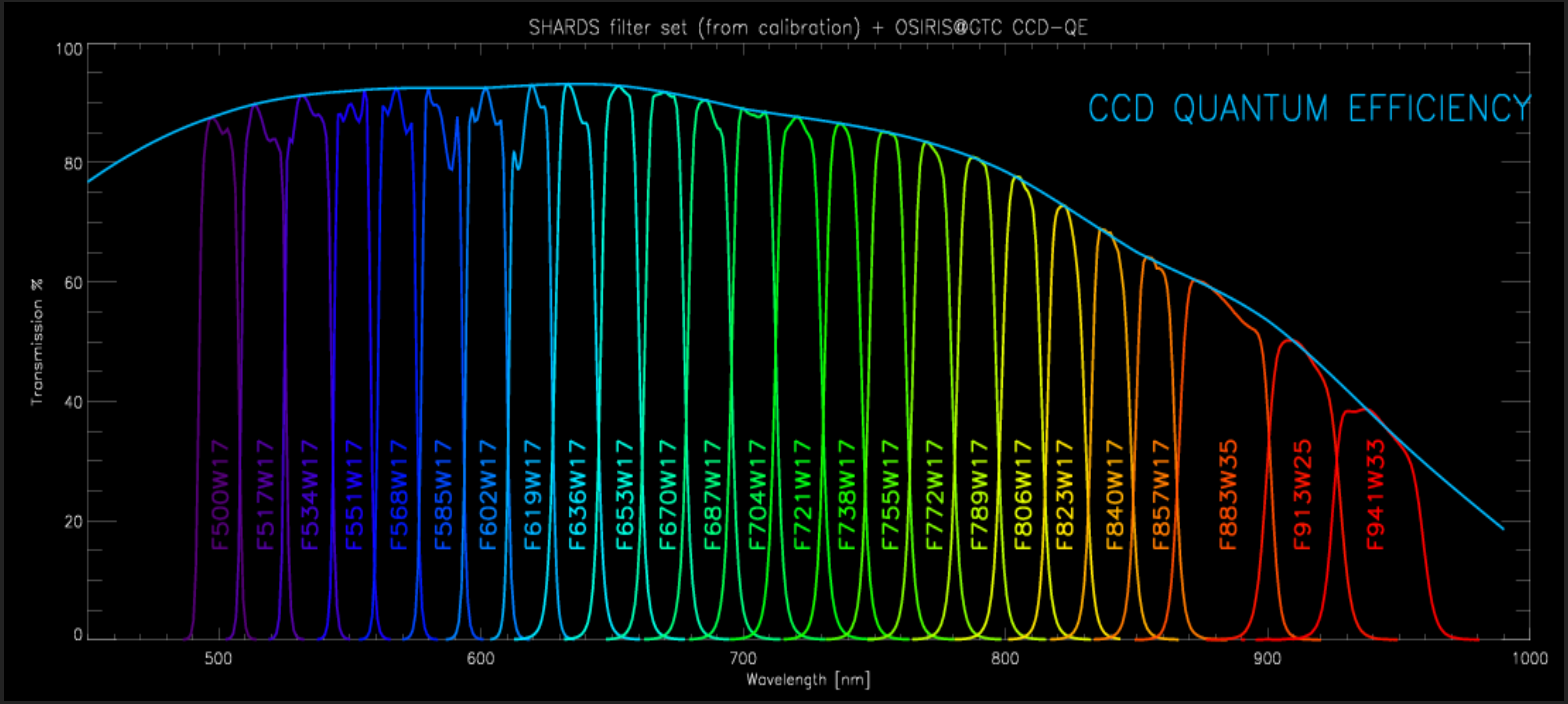
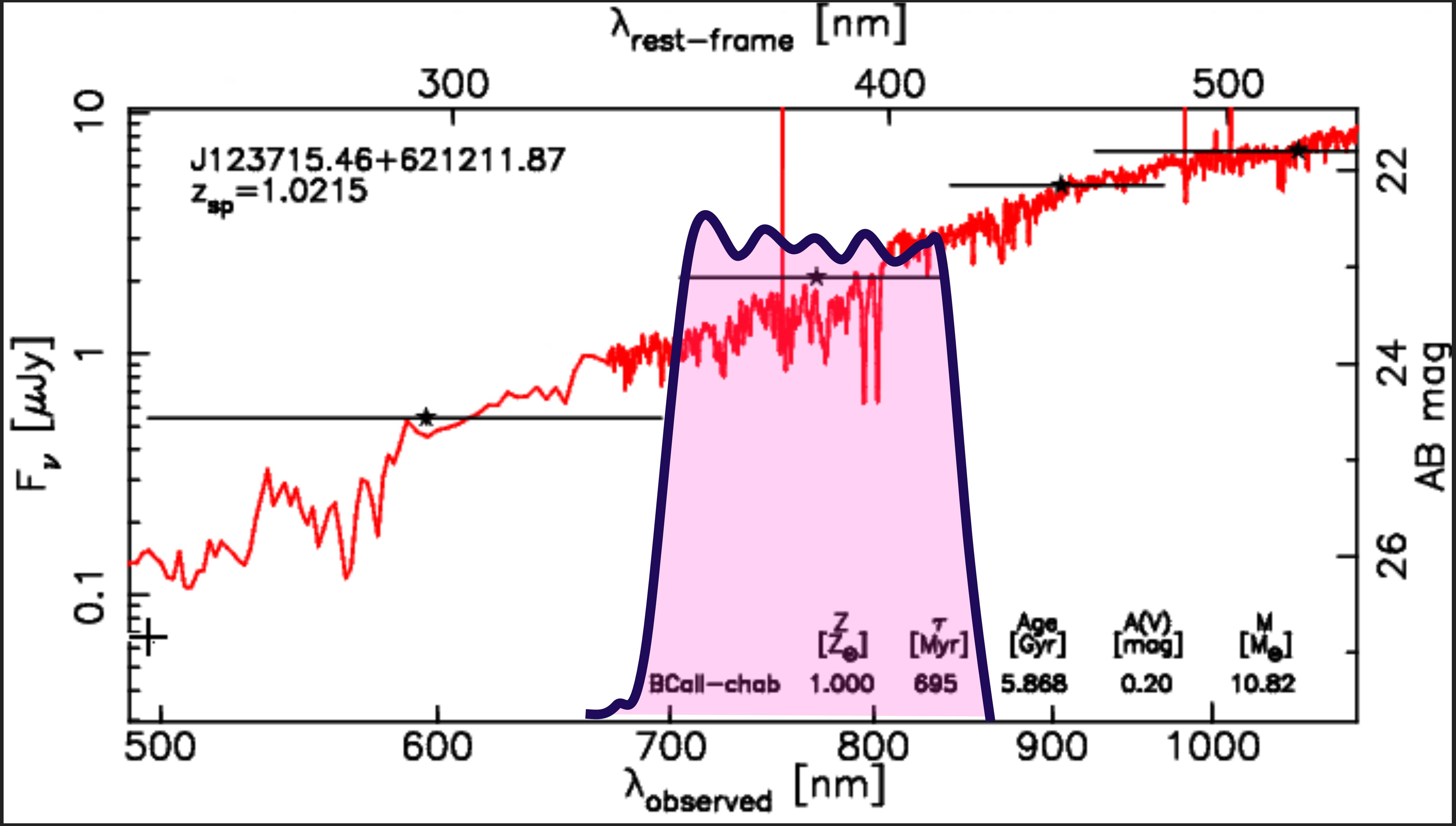
SHARDS SURVEY

Survey for High-z Absorption Red and Dead Sources

- PI: Pérez-González (et al. 2013)
- The **deepest medium band survey**
- ESO/GTC large program
- GOODS-N field, Hubble Frontier Fields (2 clusters)
- 25 filters, 500-950 nm, R~50, 26.5 mag 3σ



SHARDS SURVEY Beyond classic photometry



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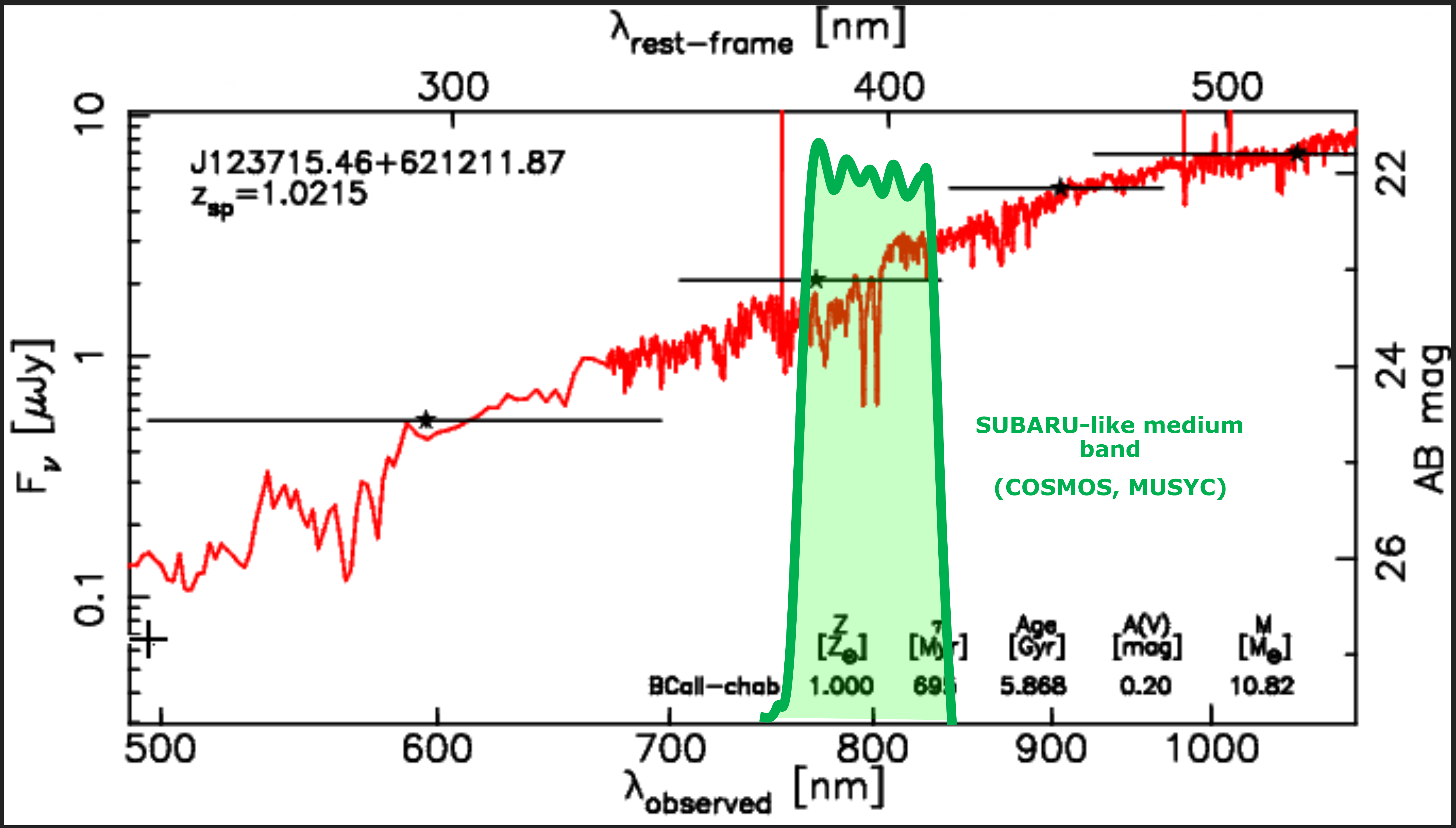

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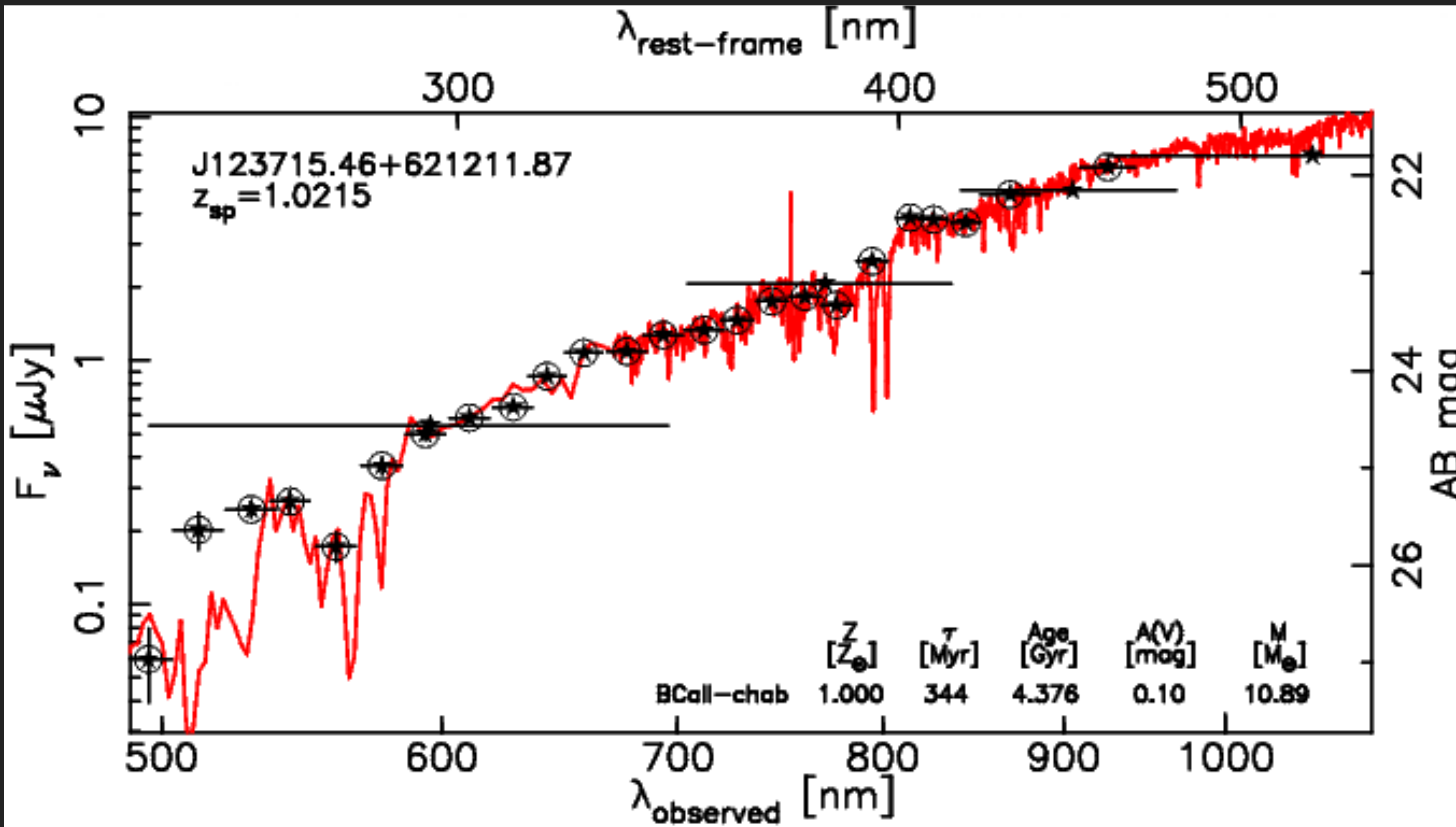

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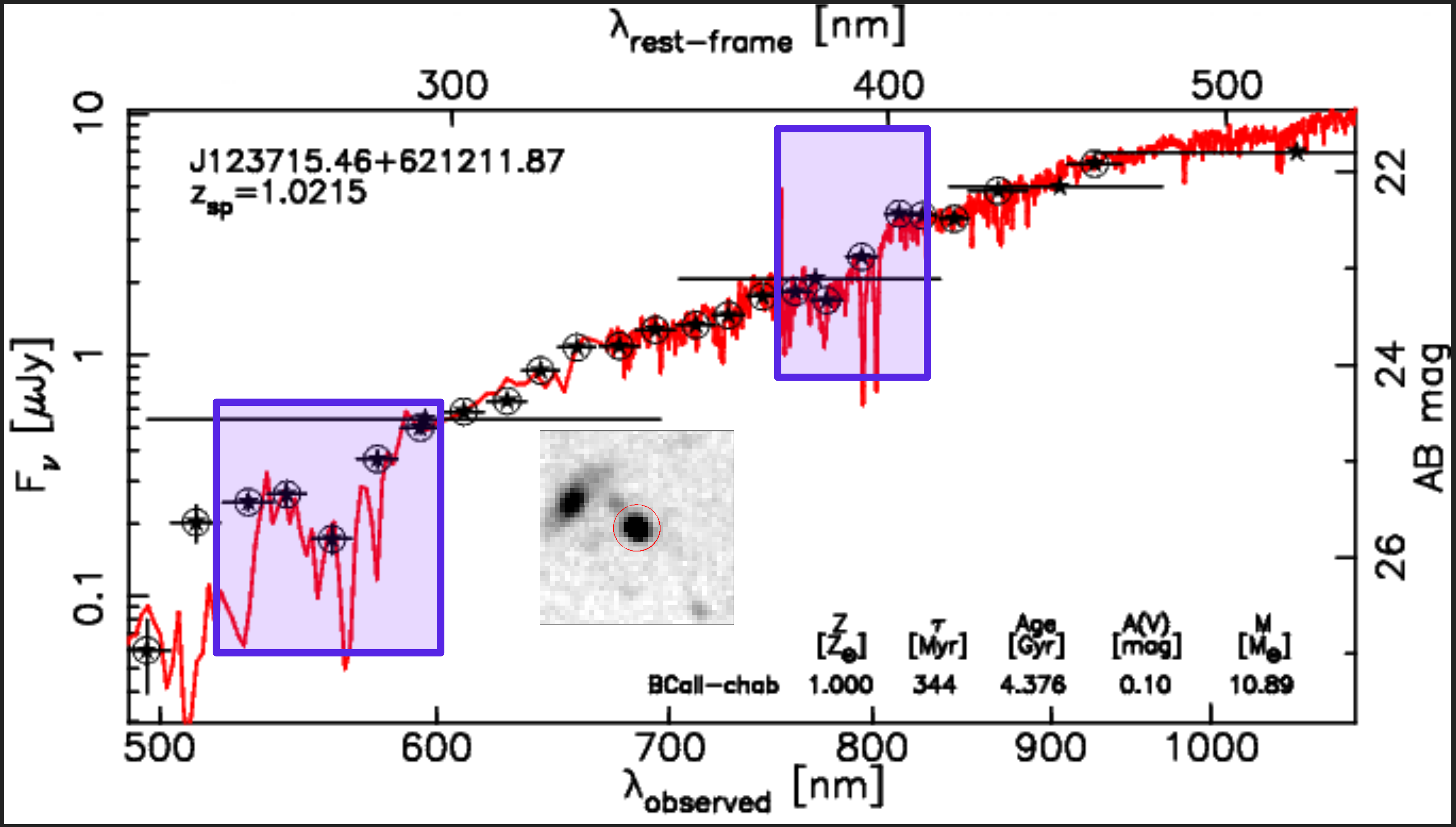
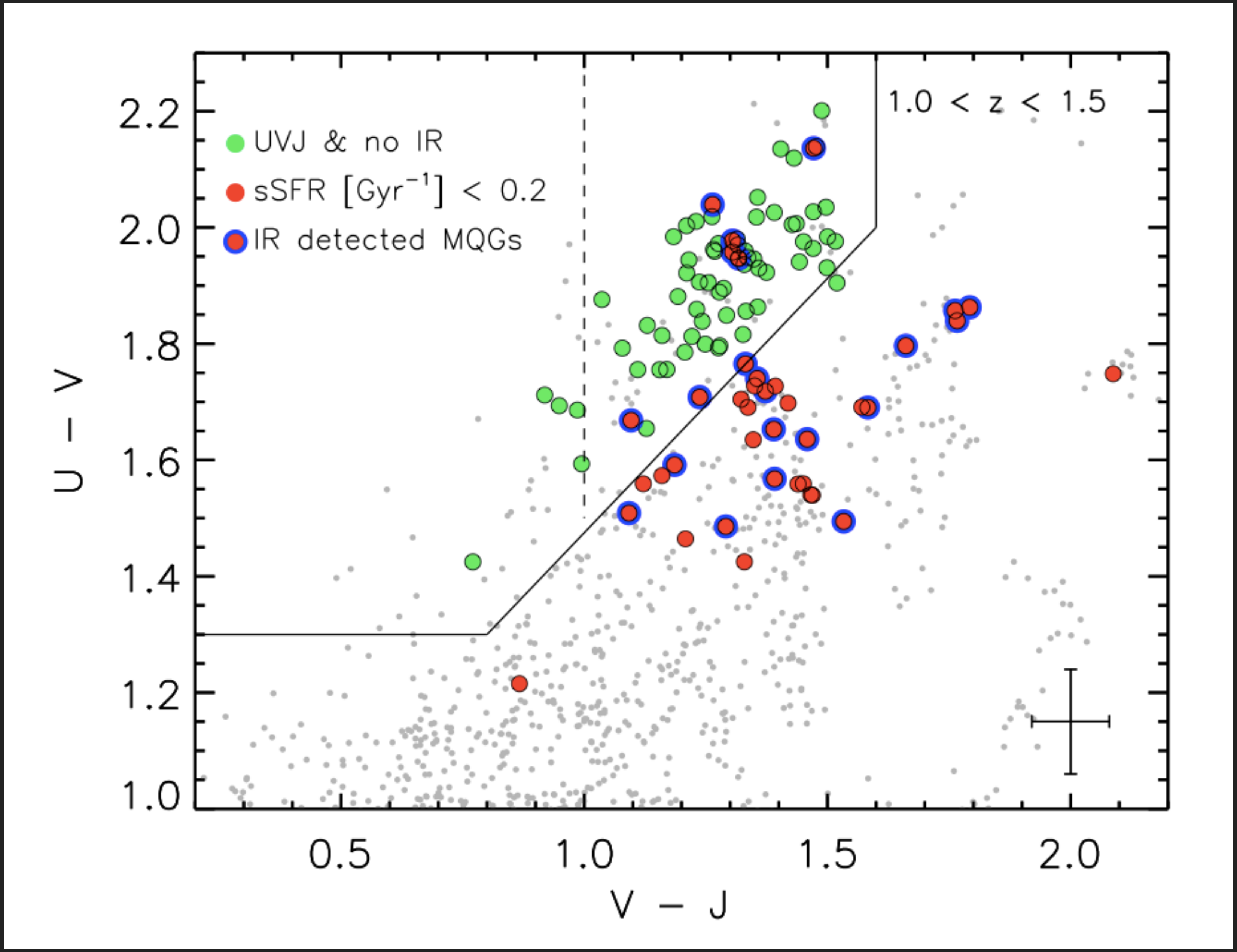


 Domínguez Sánchez et al. (2016)

SAMPLE SELECTION



- ✓ GOODS-N, z=1.0-1.5, log M > 10 $M_\odot$ (~ 500)
- ✓ UVJ quiescent region + No IR detection (65)
- ✓ sSFR < 0.2 Gyr $^{-1}$ if outside UVJ quiescent region (39)

sSFR=SFR/Mass

Domínguez Sánchez et al. (2016)

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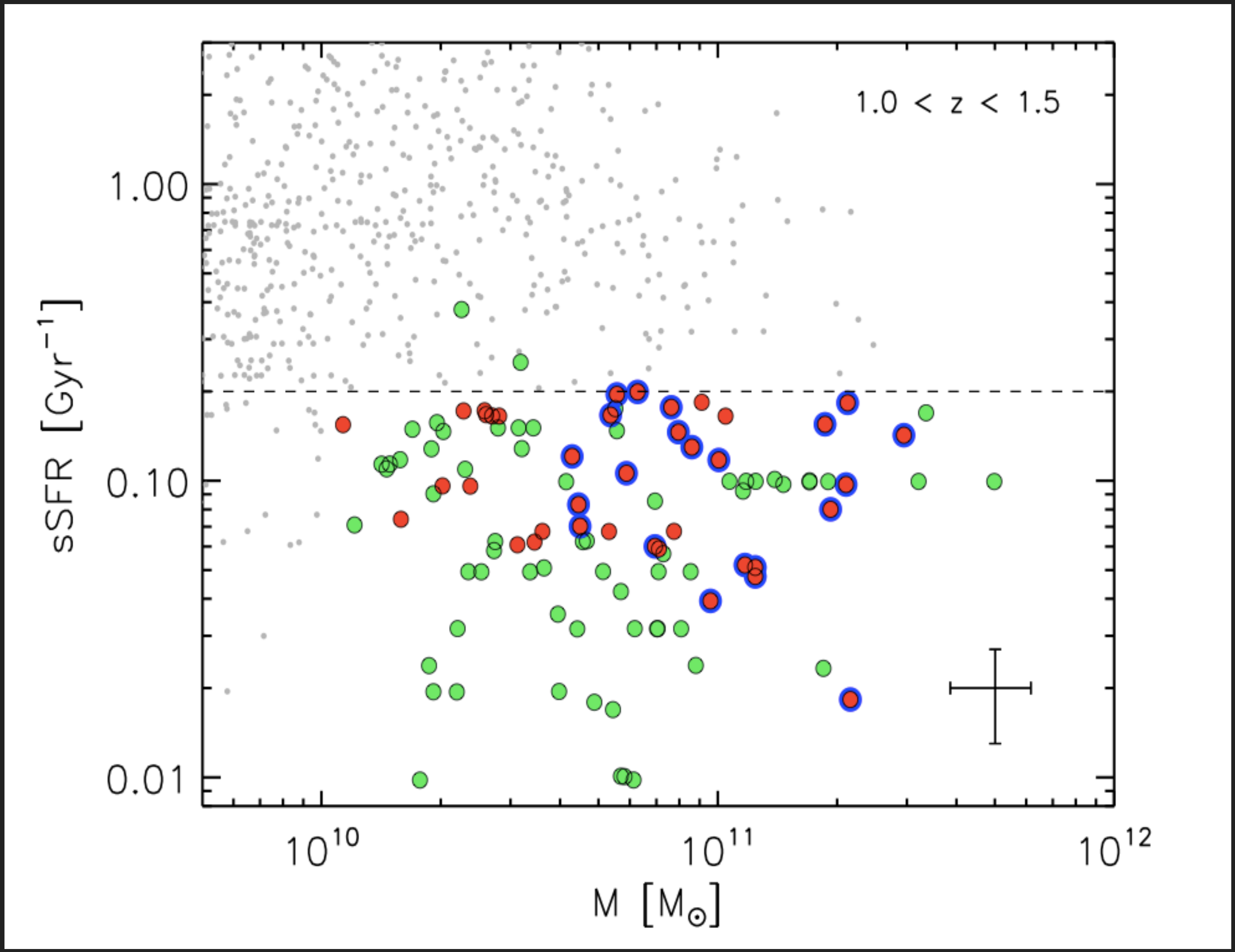

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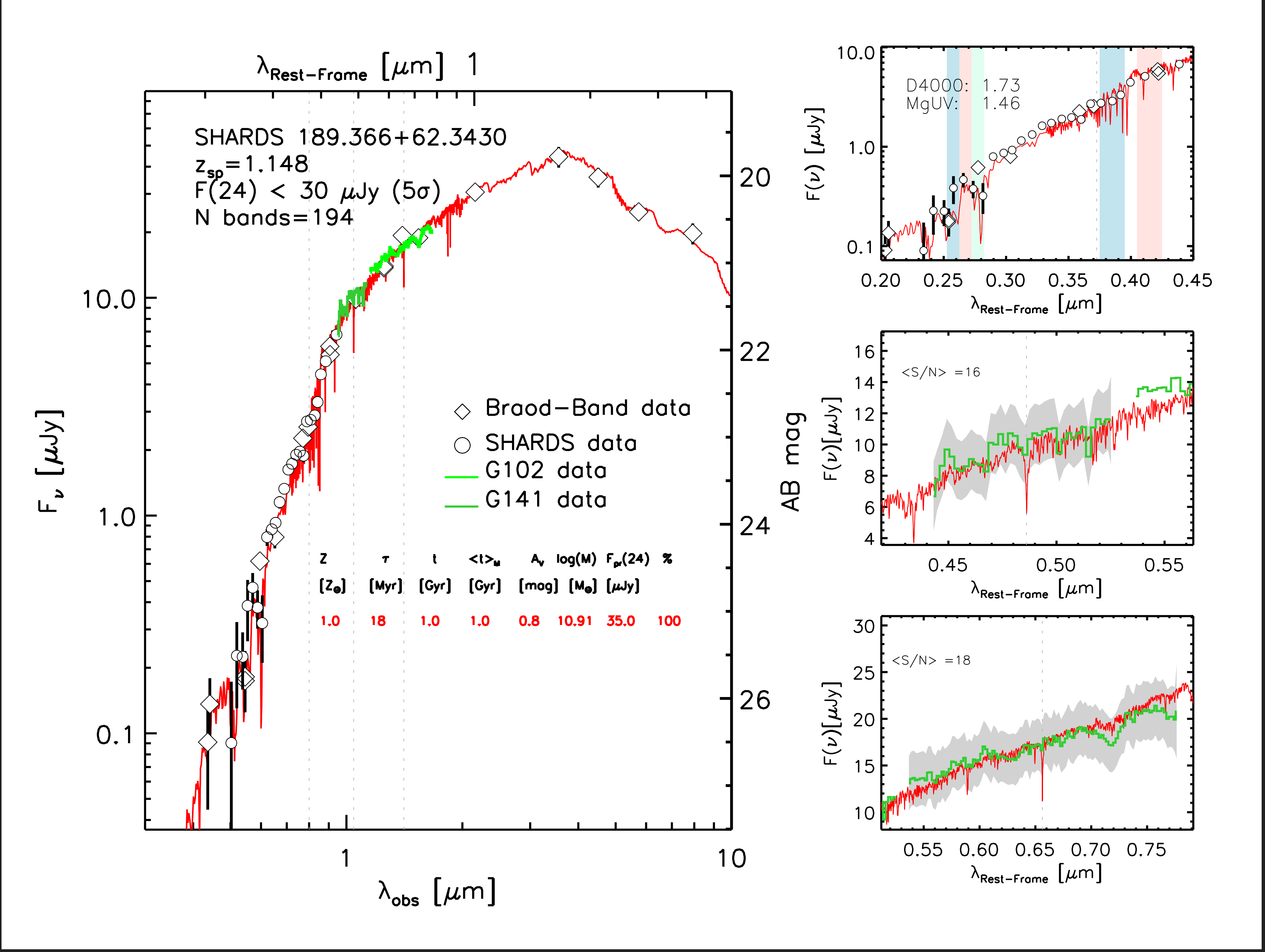
SAMPLE OF 104 GALAXIES

SED-FITTING

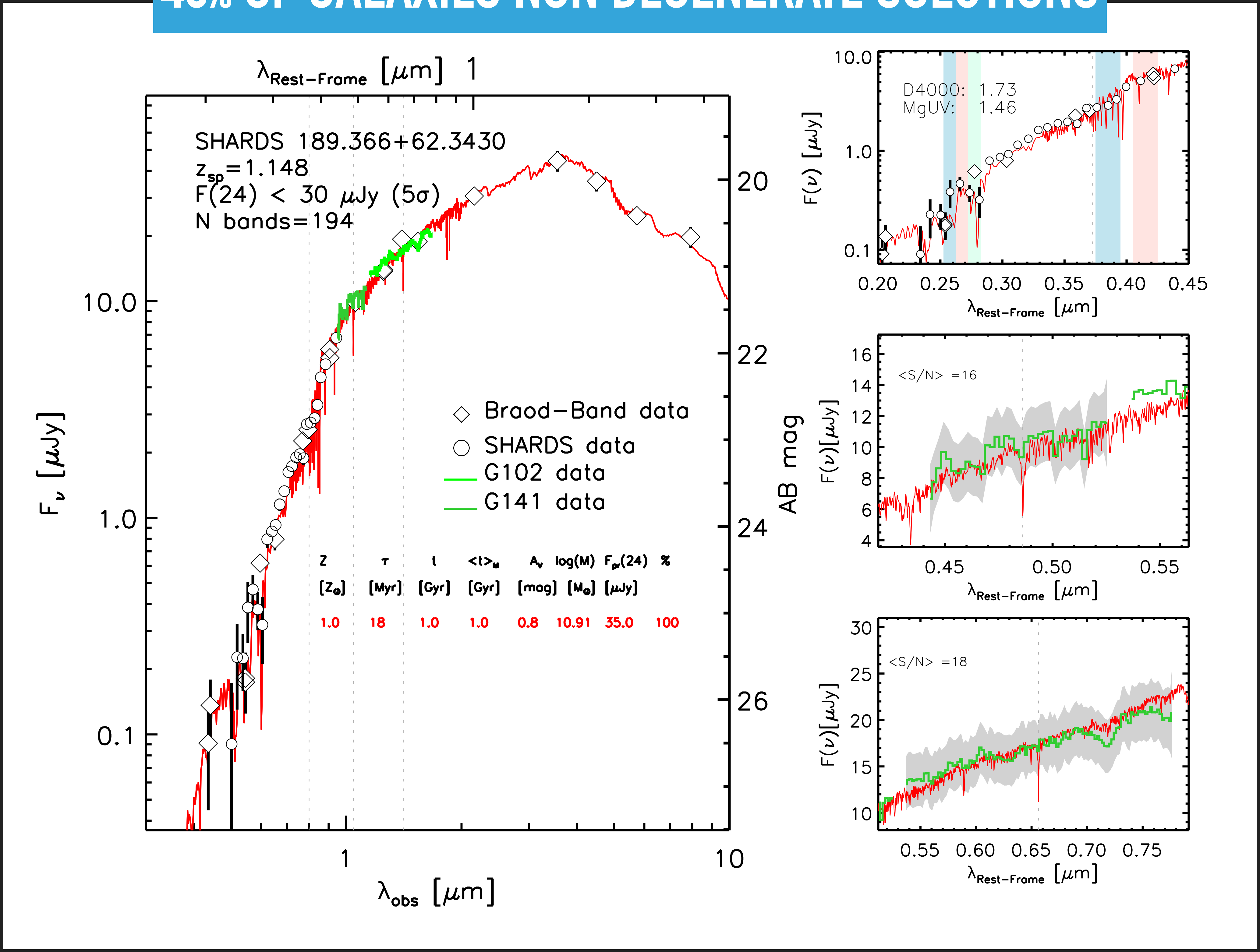
- ✓ Construct **best possible SEDs**:
- ✓ **SHARDS** (0.4-0.9 µm) + **WFC3/HST GRISM** (G102, 0.9-1.1 µm, 60%; G141, 1.1-1.6 µm, 70 %) + **Broad Band** (Rainbow-database)
- ✓ z-spec/z-phot from RB database ($\Delta z/(1+z)=0.0035$)
- ✓ **SFR(t) $\propto$ t exp (-t/τ)**
- ✓ **BC03 models**, Calzetti et al. 2000 ext. law, Krou IMF
- ✓ **Synthesizer code**: t (Gyr) =[0.04 - 6.3] (steps of 0.1 dex)
  τ (Myr) =[3 - 10000] (steps of 0.1 dex)
  A_V (mag) =[0 - 1.5] (step of 0.1 mag)
  $Z/Z_\odot$ = [0.4, 1.0, 2.5]
- ✓ 1**000 Montecarlo simulations** & **clusters** in t-τ parameter space with k-means method
- ✓ **Break degeneracies** with help of spectral indices (D4000, MgUV)

Domínguez Sánchez et al. (2016)



Domínguez Sánchez et al. (2016)

46% OF GALAXIES NON DEGENERATE SOLUTIONS



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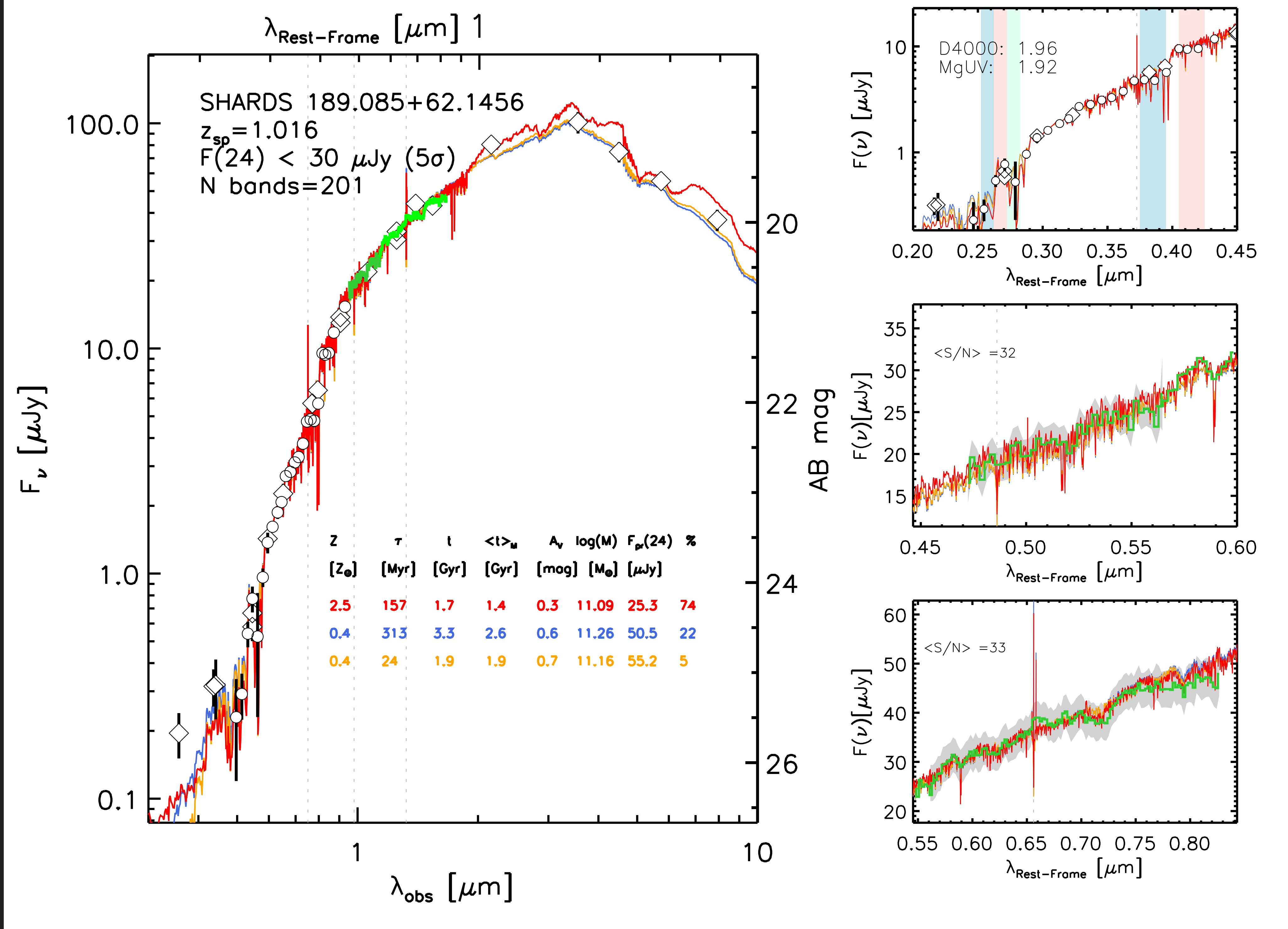

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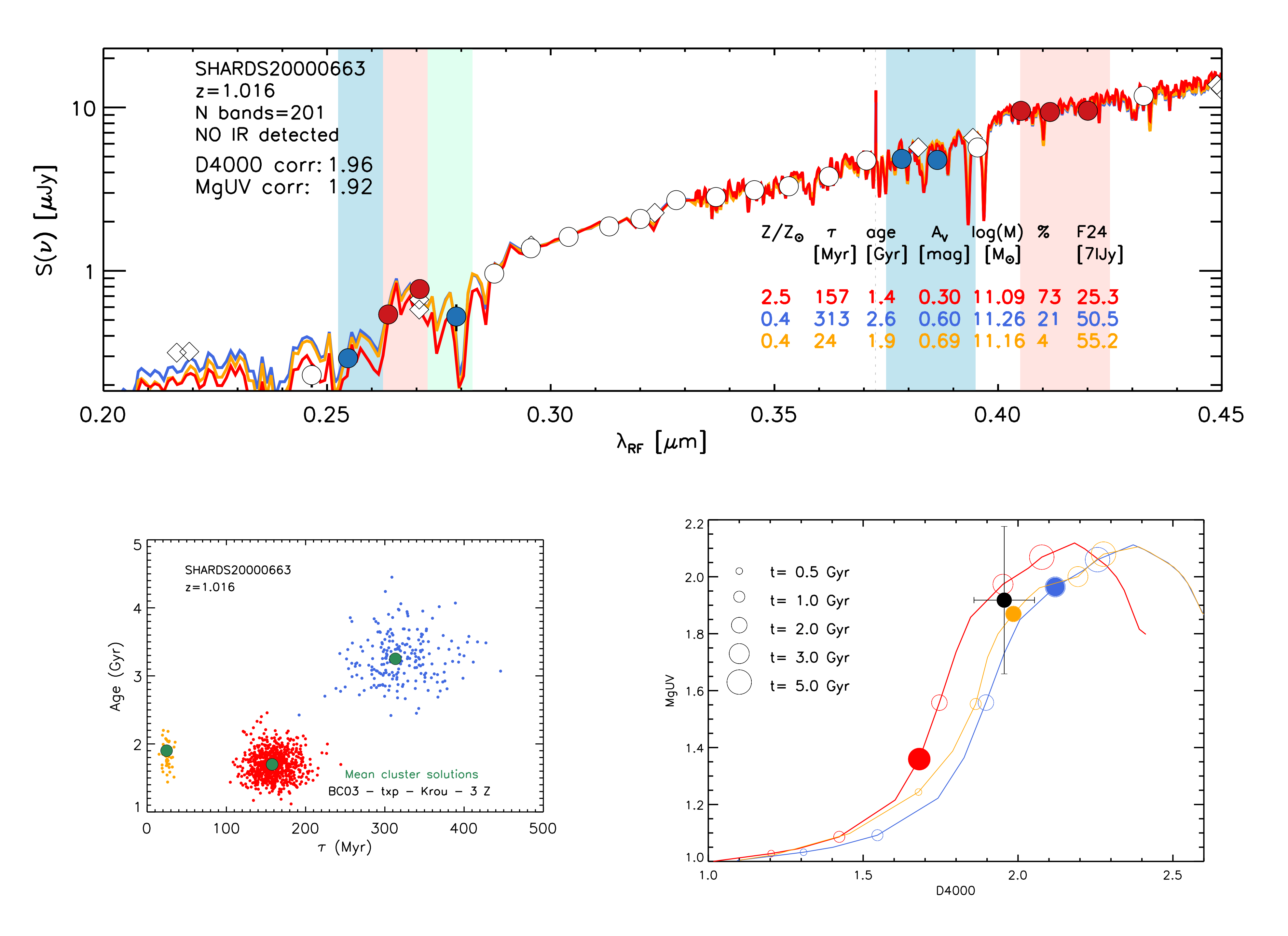
BREAKING DEGENERACIES



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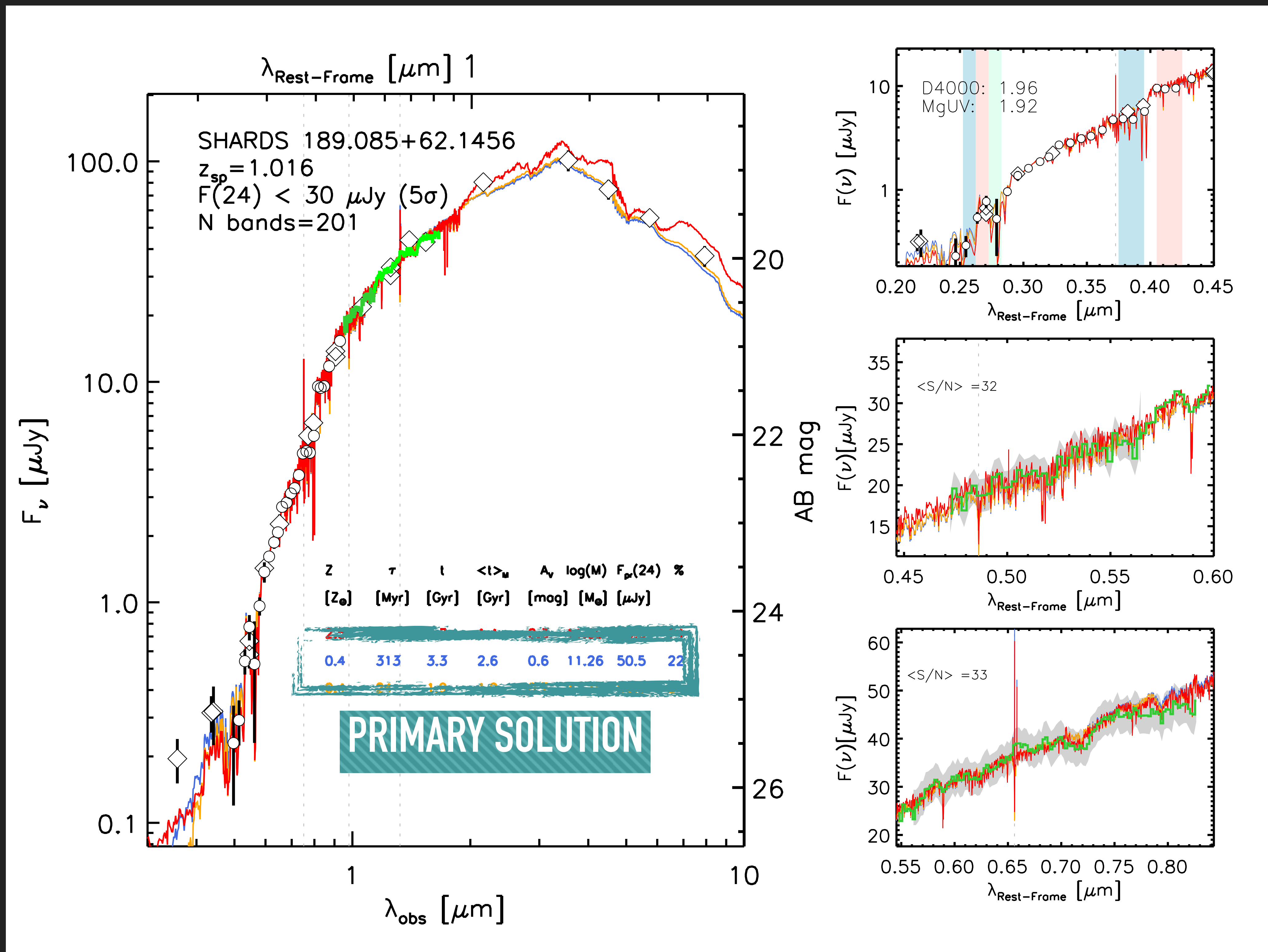
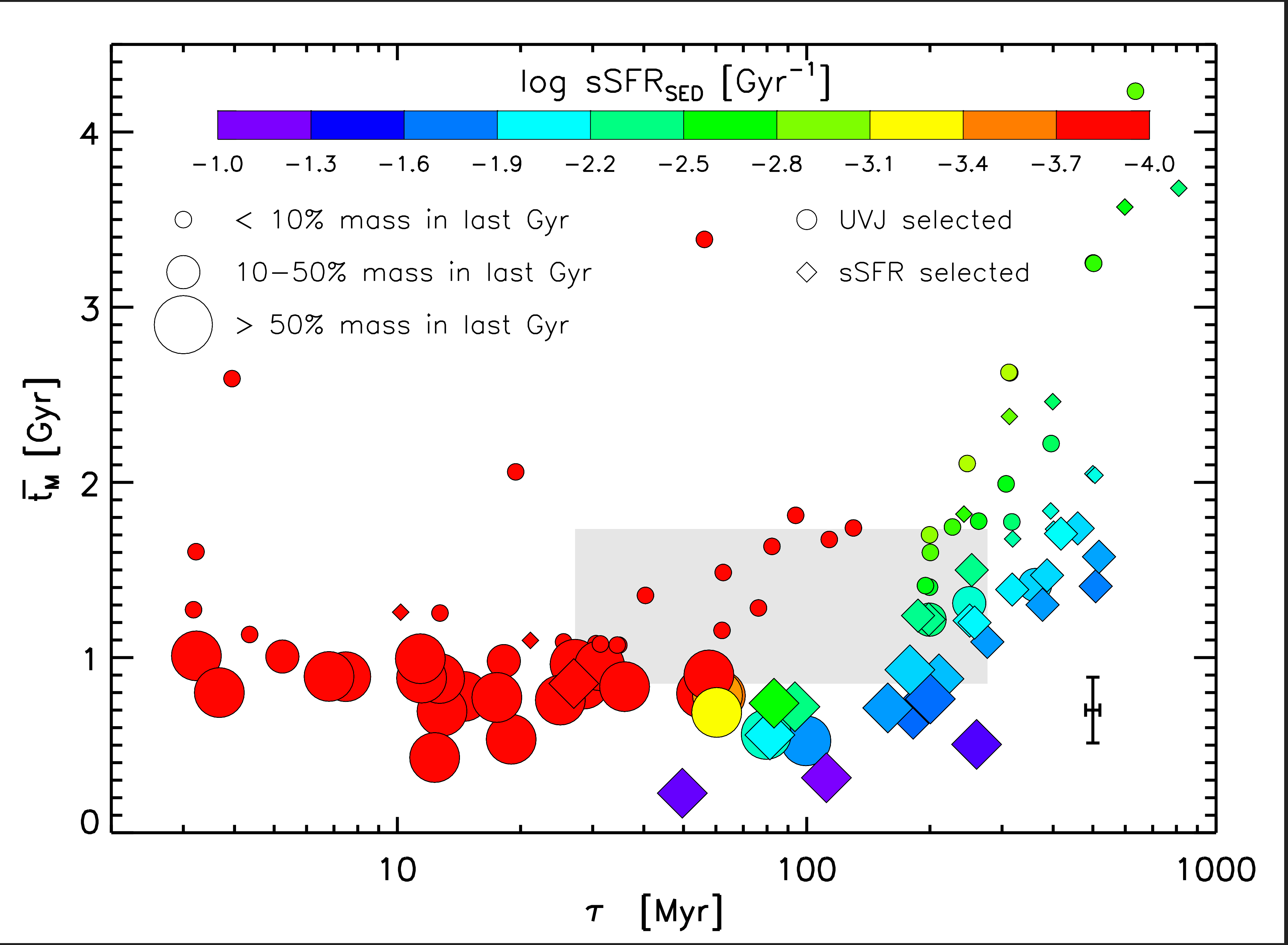
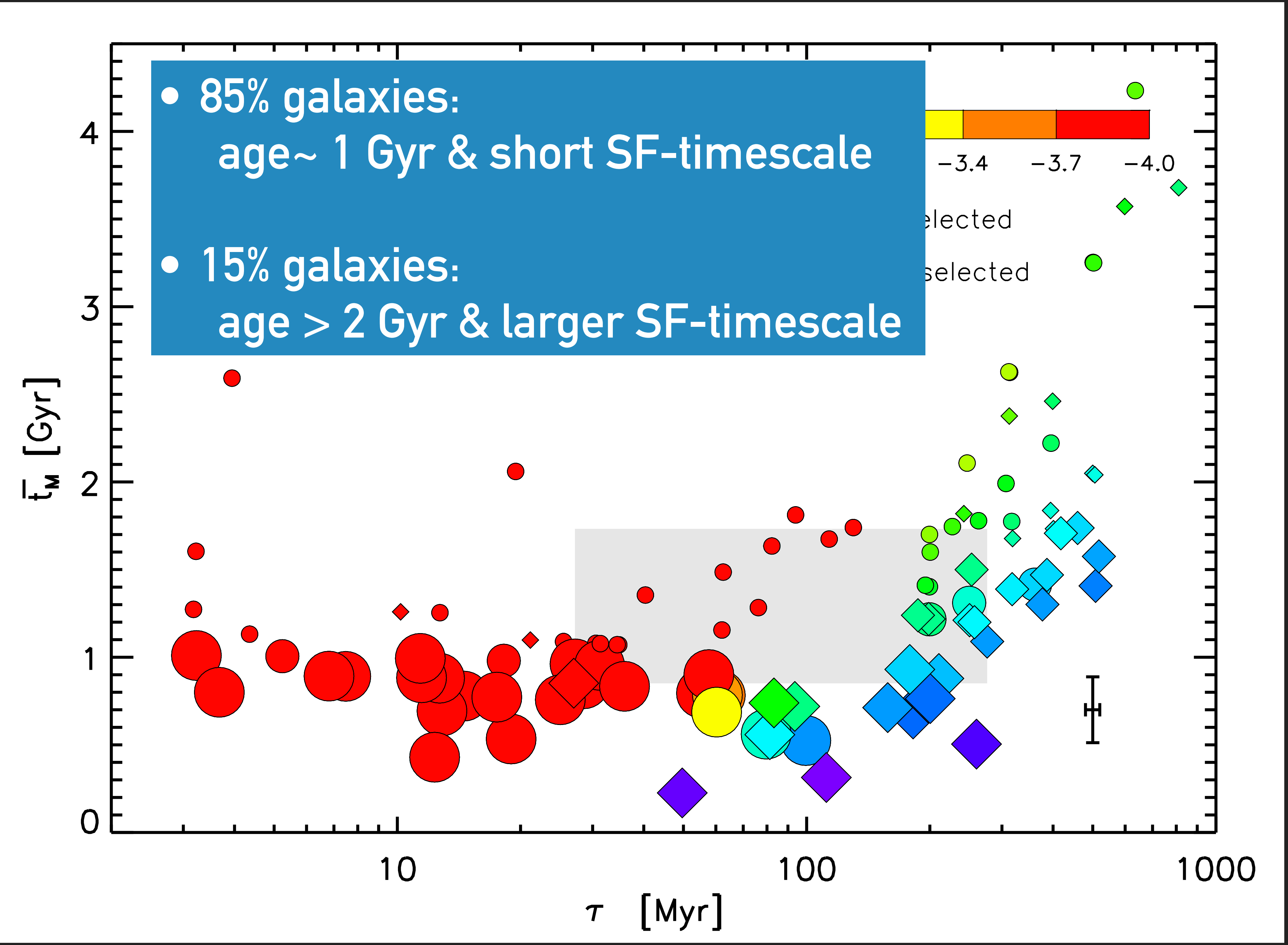
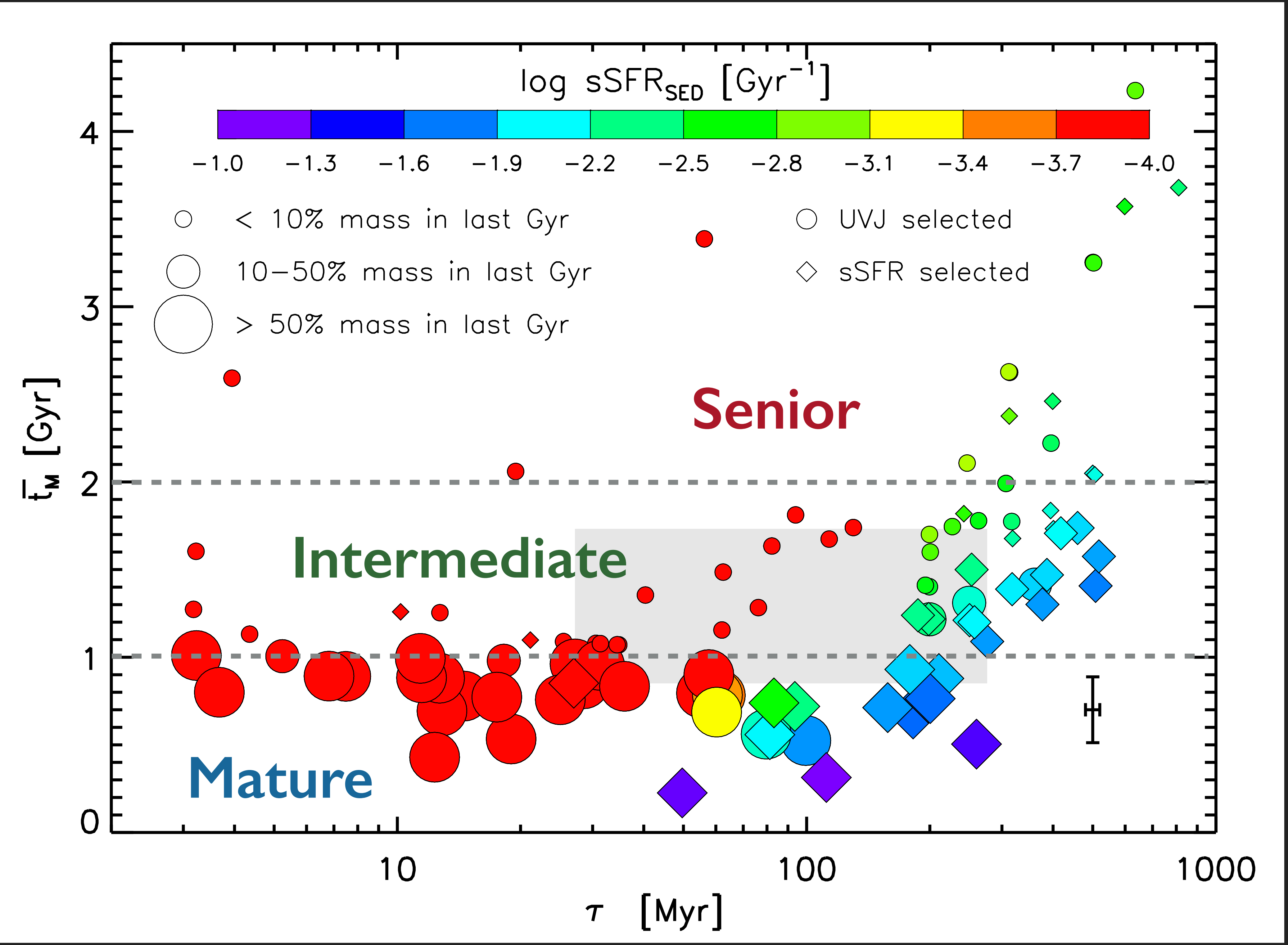


RESULTS


log sSFR$_{SED}$ [Gyr^{-1}]
−1.0 −1.3 −1.6 −1.9 −2.2 −2.5 −2.8 −3.1 −3.4 −3.7 −4.0
< 10% mass in last Gyr
10−50% mass in last Gyr
> 50% mass in last Gyr
UVJ selected
sSFR selected
$\bar{t}_M$ [Gyr]
0
1
2
3
4
10
100
1000
τ [Myr]


• 85% galaxies:
age~ 1 Gyr & short SF-timescale
• 15% galaxies:
age > 2 Gyr & larger SF-timescale
−3.4
−3.7
−4.0
elected
selected
4
3
2
1
0
$\bar{t}_M$ [Gyr]
10
100
1000
τ [Myr]

Domínguez Sánchez et al. (2016)



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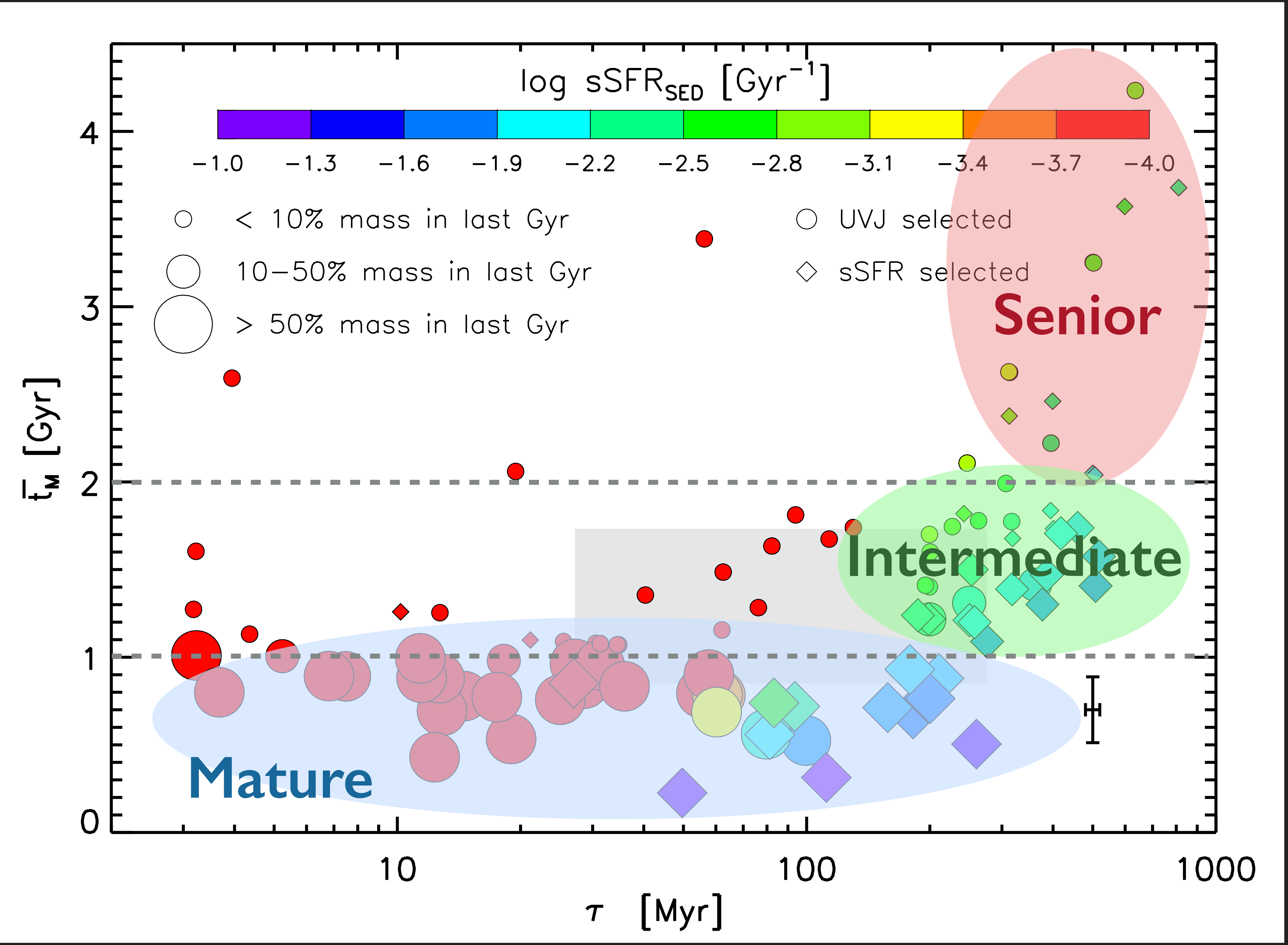

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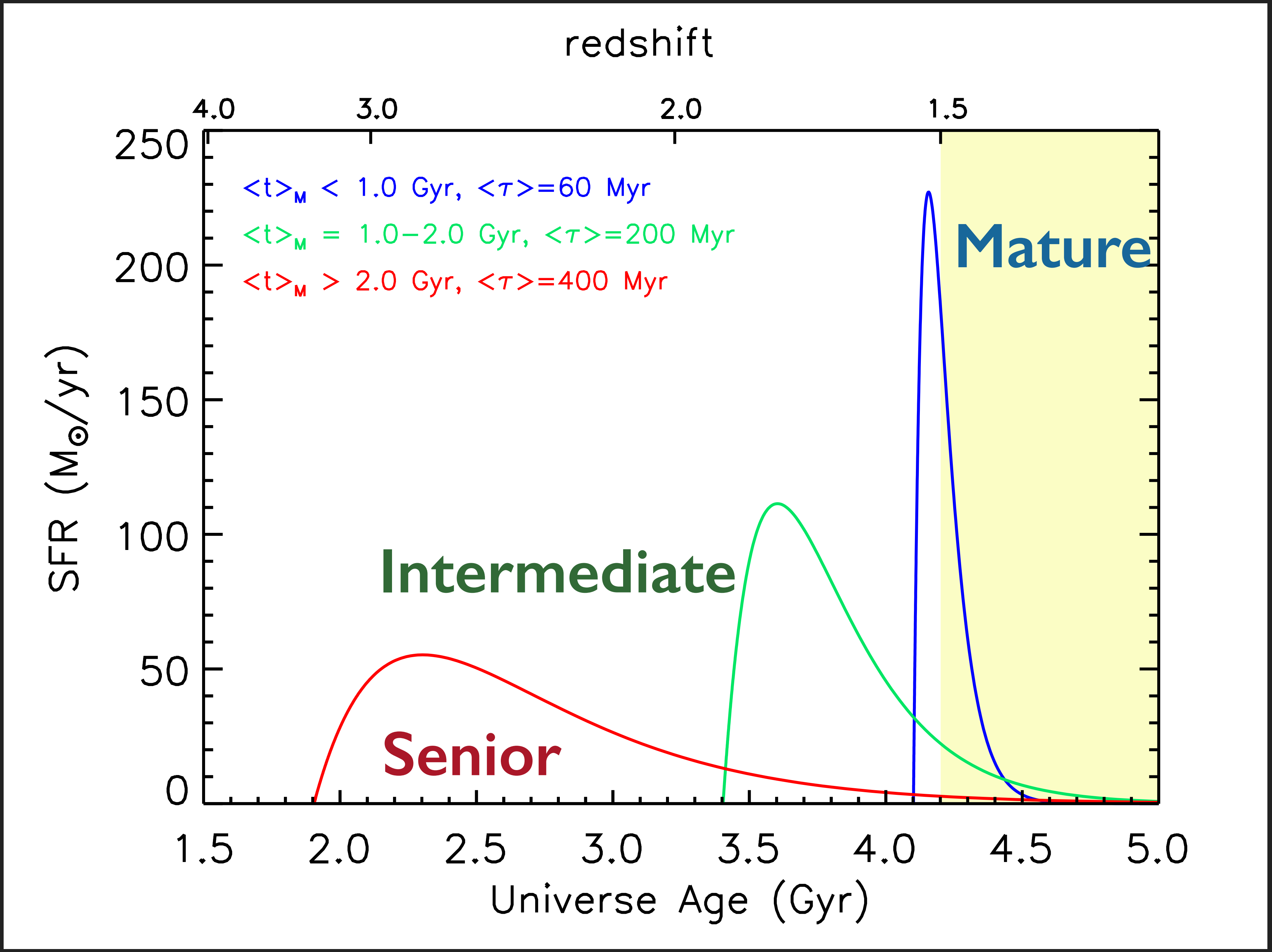
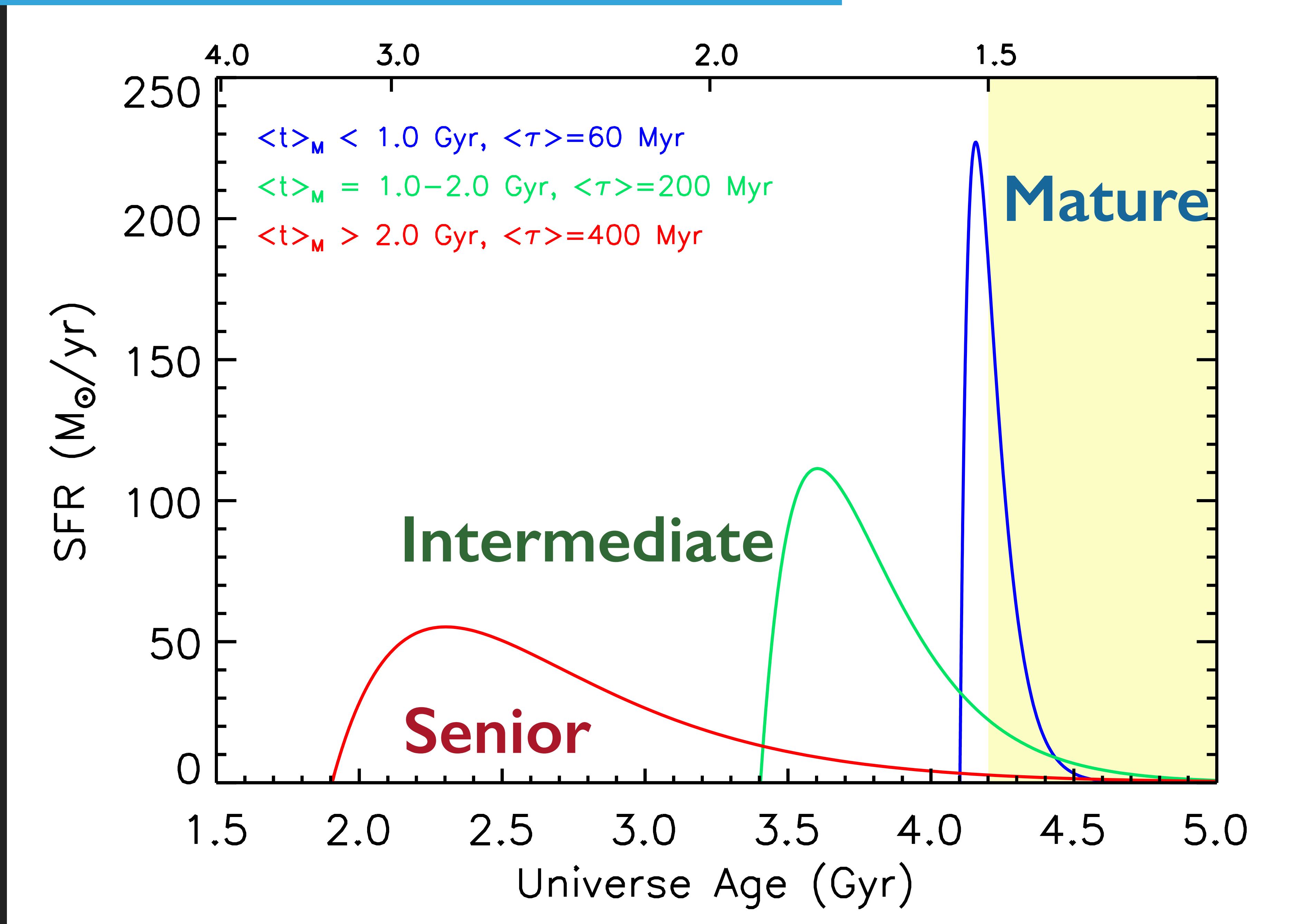
MEAN SFH BY OF AGE



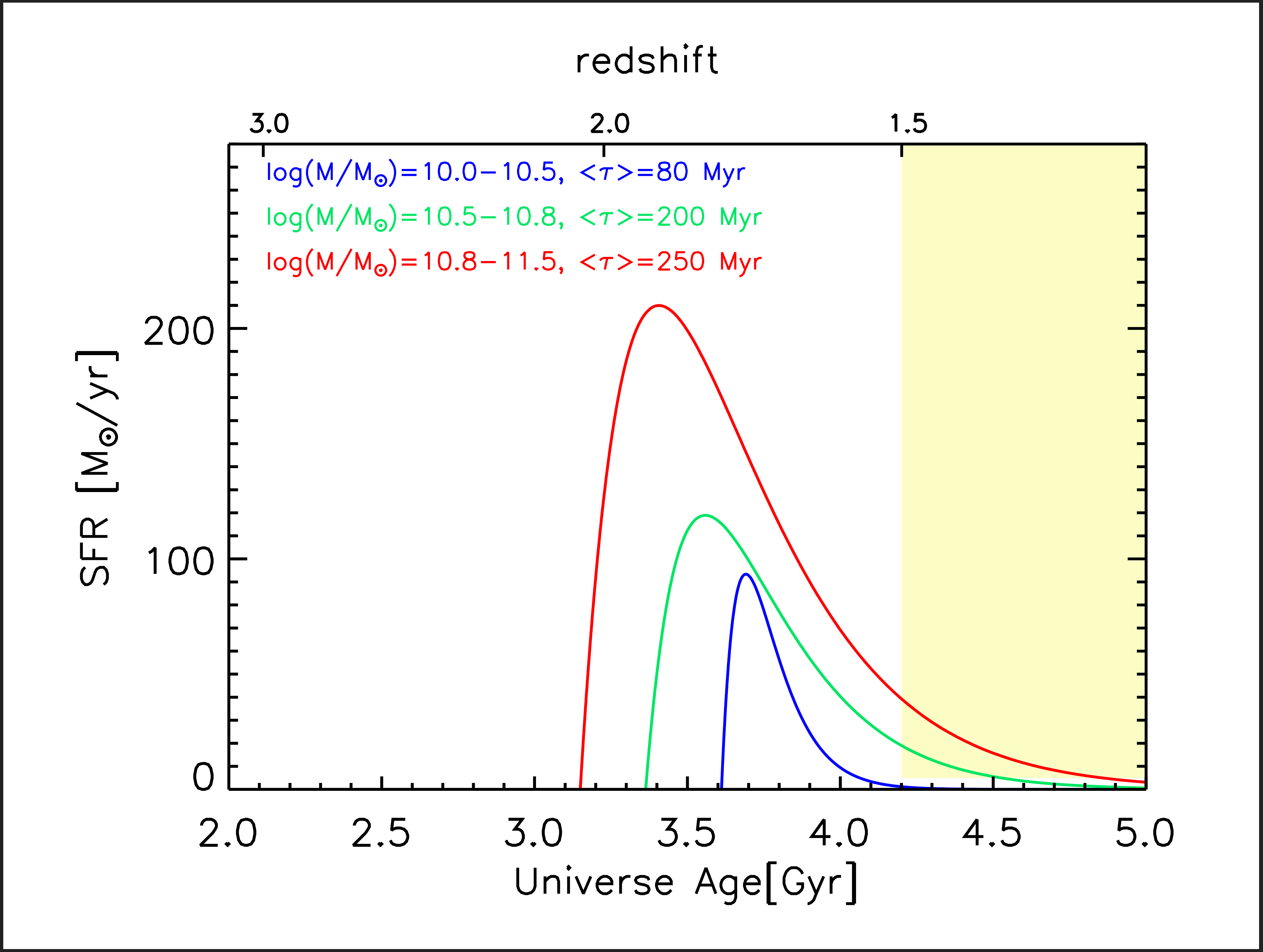
Domínguez Sánchez et al. (2016)

- Mature galaxies have low τ (selection effect)
- Senior galaxies lager τ:
  formed when Universe was ~2 Gyr old



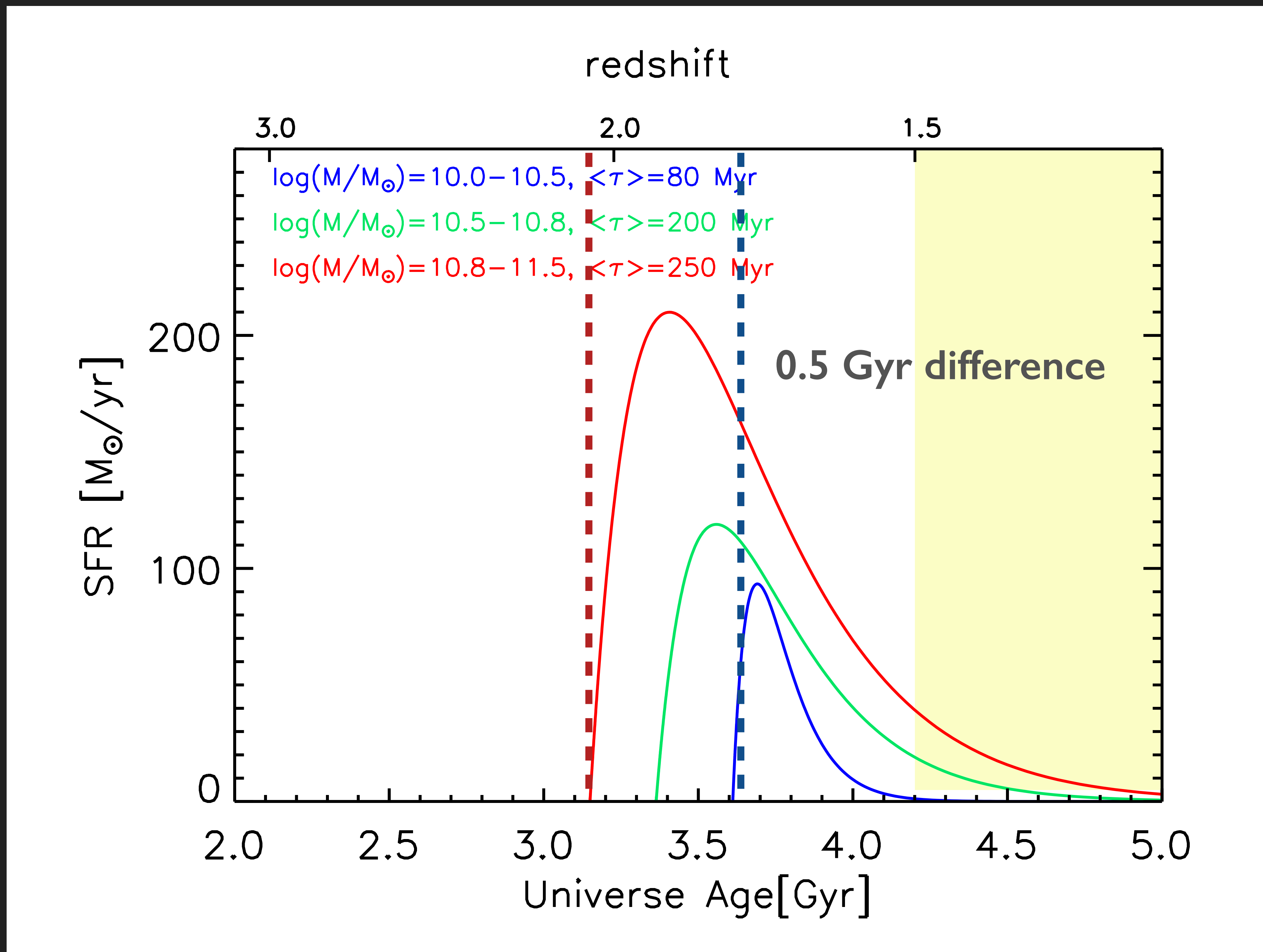
Domínguez Sánchez et al. (2016)

MEAN SFH BY OF MASS



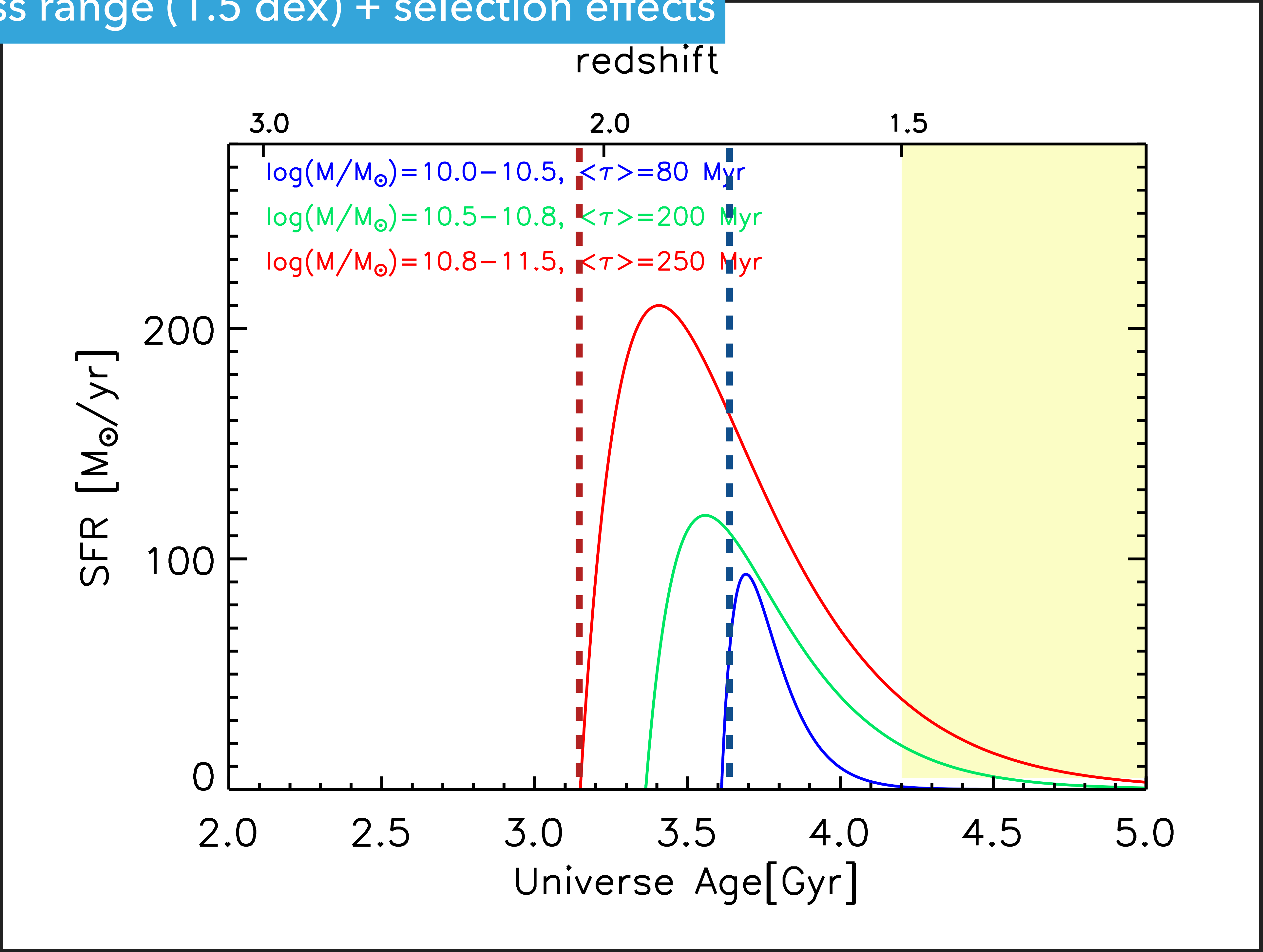
Domínguez Sánchez et al. (2016)

MEAN SFH BY OF MASS



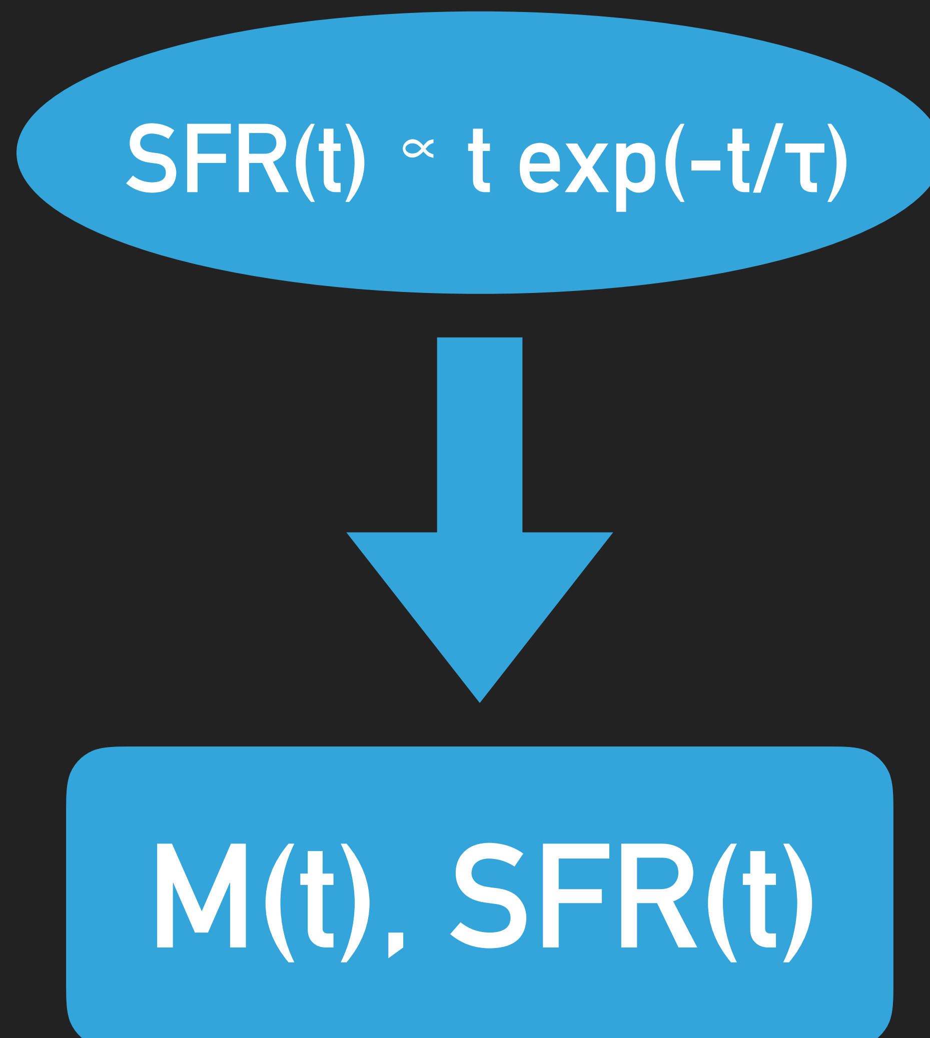
Domínguez Sánchez et al. (2016)

- Larger τ for high-M galaxies
- Disagreement with Thomas et al. (2005, 10)
- Low mass range (1.5 dex) + selection effects

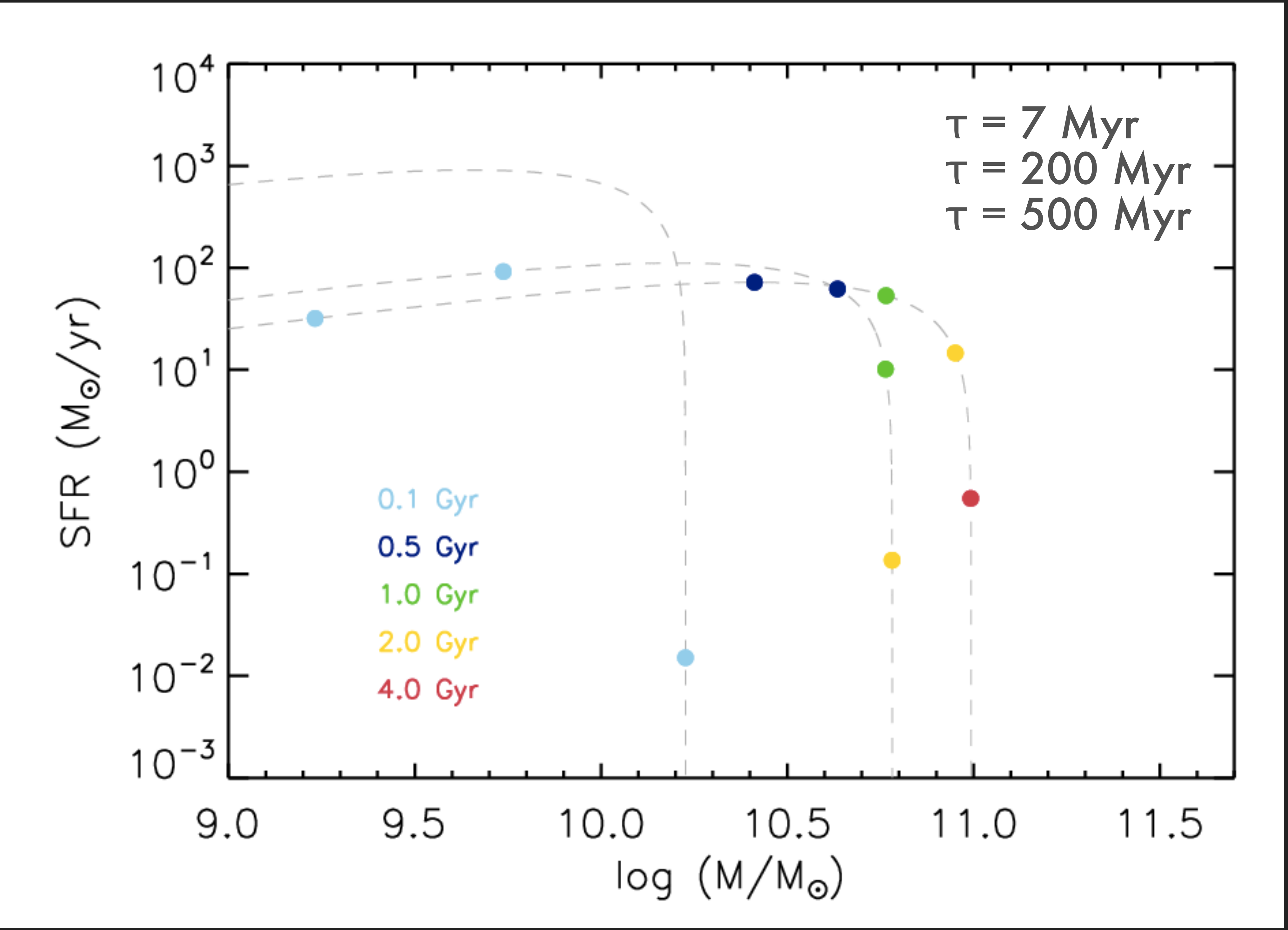


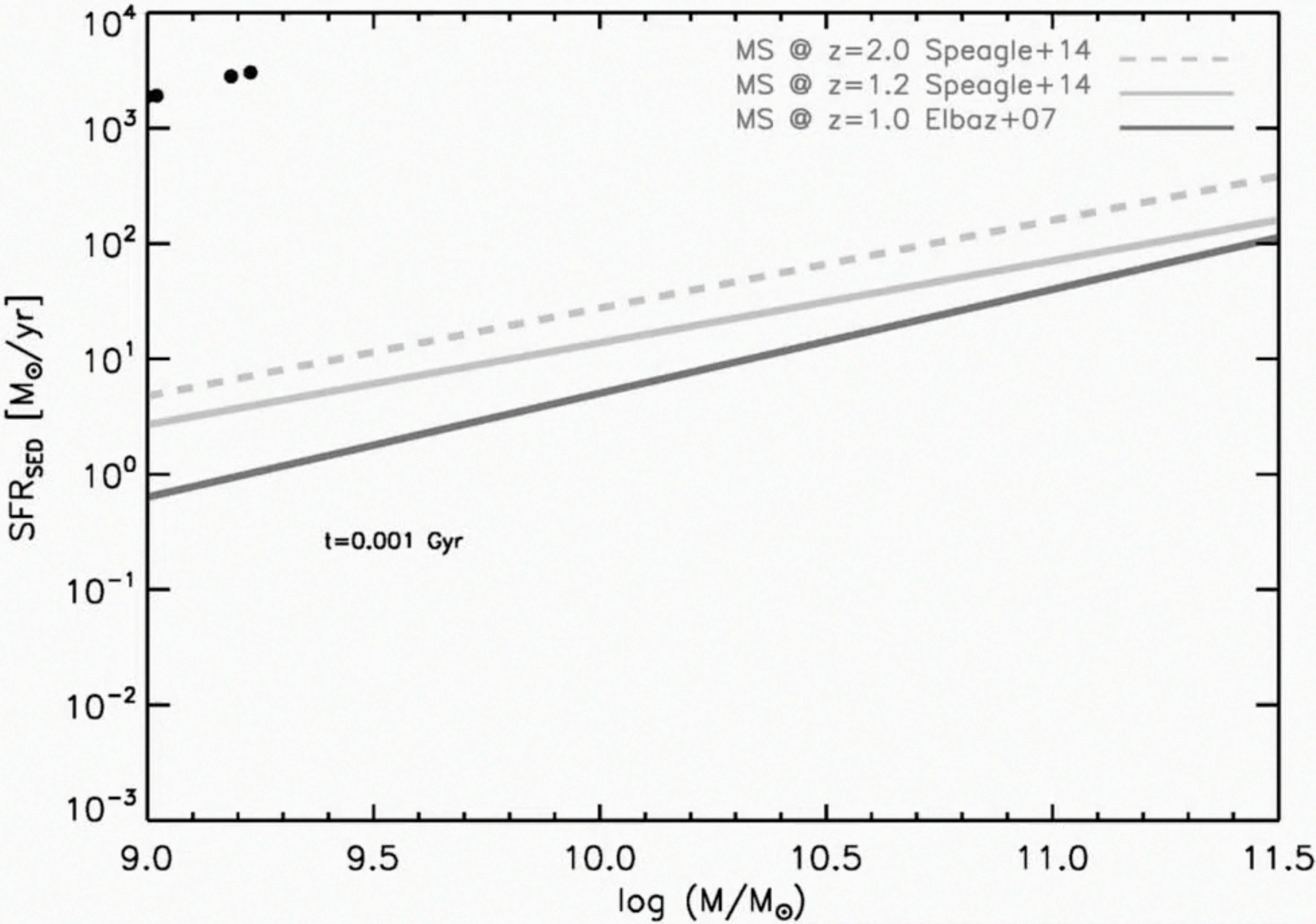
Domínguez Sánchez et al. (2016)

EVOLUTIONARY TRACKS



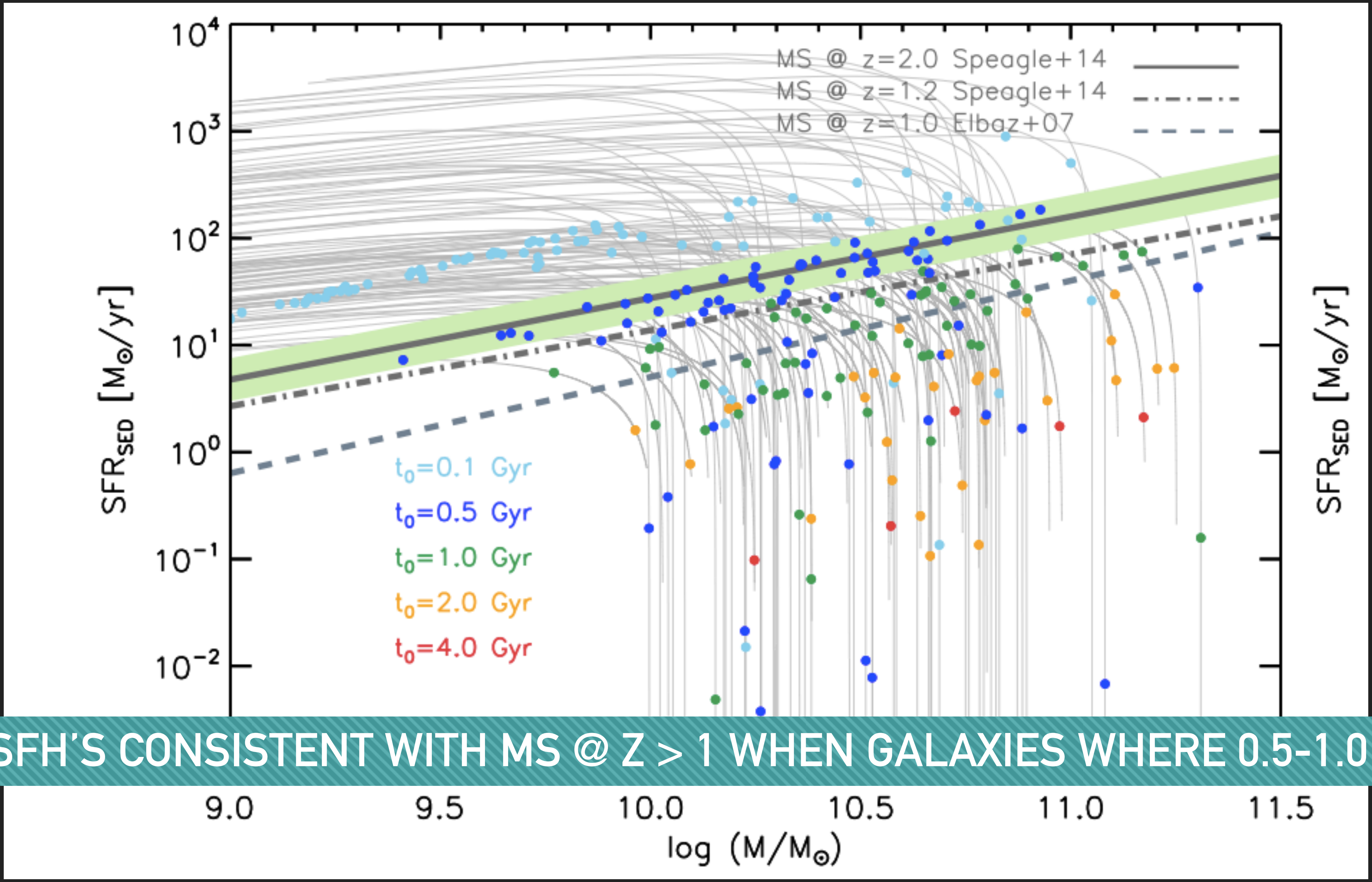
EVOLUTIONARY TRACKS





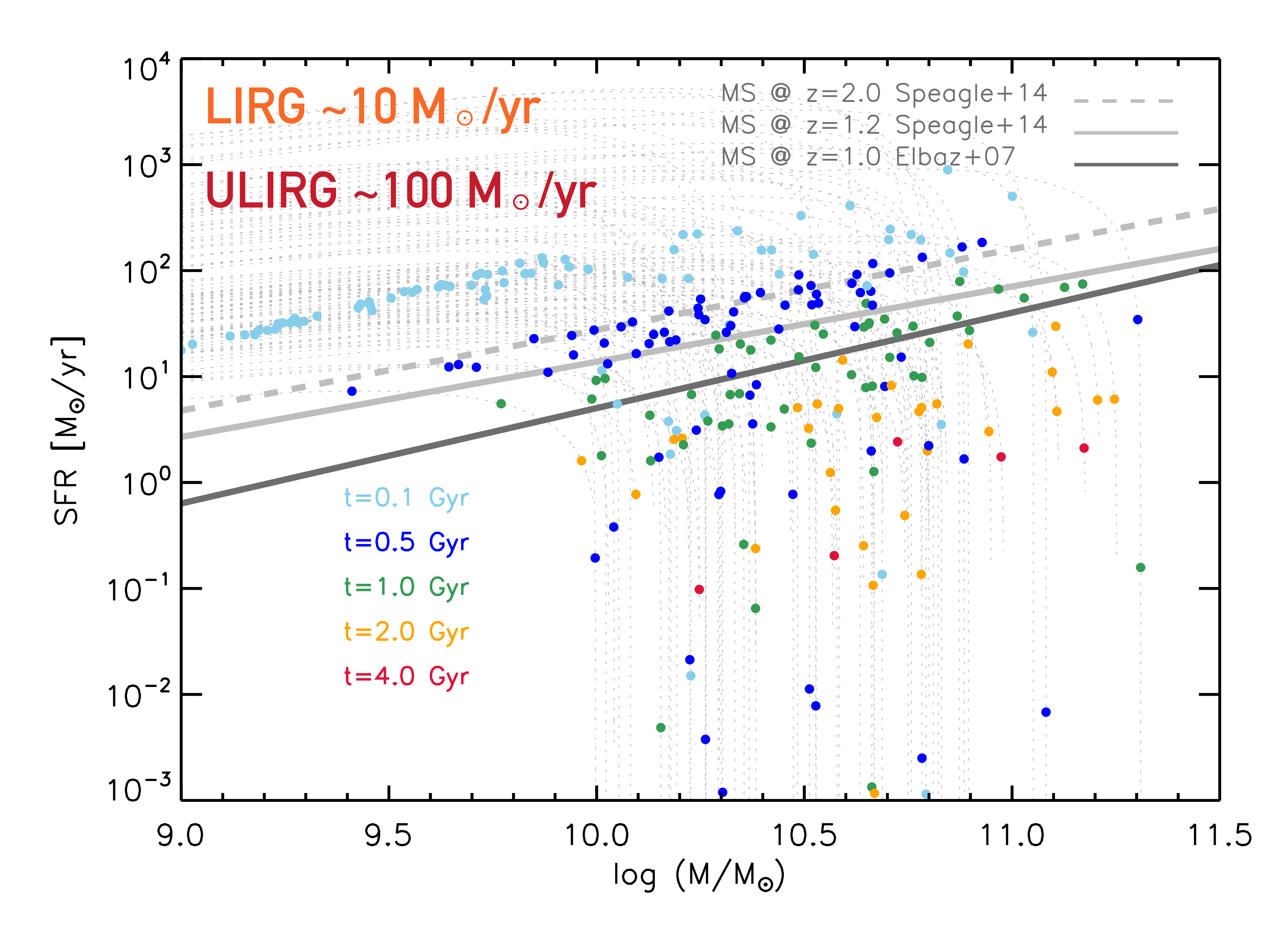
MS @ z=2.0 Speagle+14
MS @ z=1.2 Speagle+14
MS @ z=1.0 Elbaz+07
t=0.001 Gyr
SFR_{SED} $[M_\odot/yr]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
9.0
9.5
10.0
10.5
11.0
11.5
log $(M/M_\odot)$

EVOLUTIONARY TRACKS



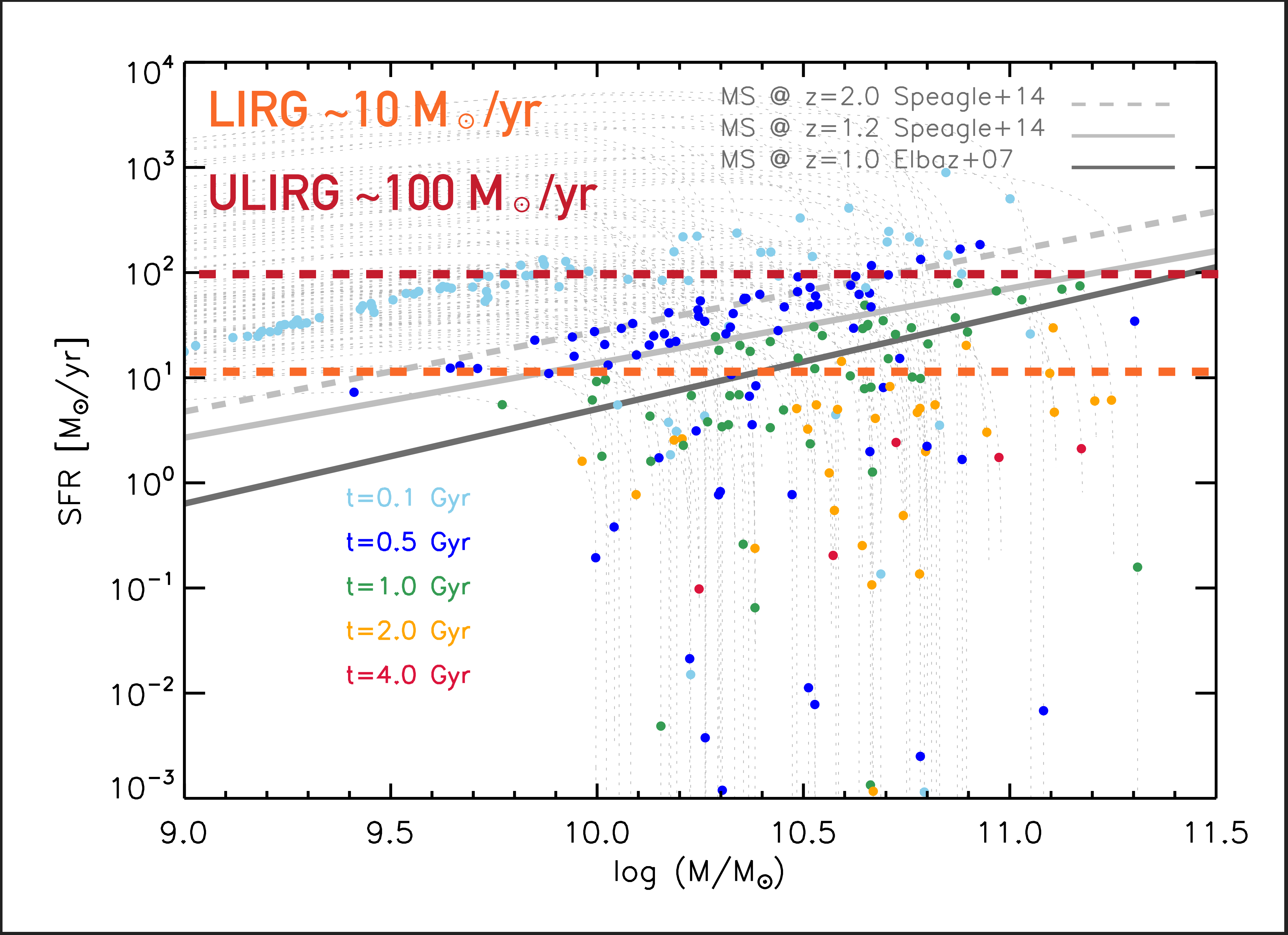
SFH'S CONSISTENT WITH MS @ Z > 1 WHEN GALAXIES WHERE 0.5-1.0 GYR

EVOLUTIONARY TRACKS



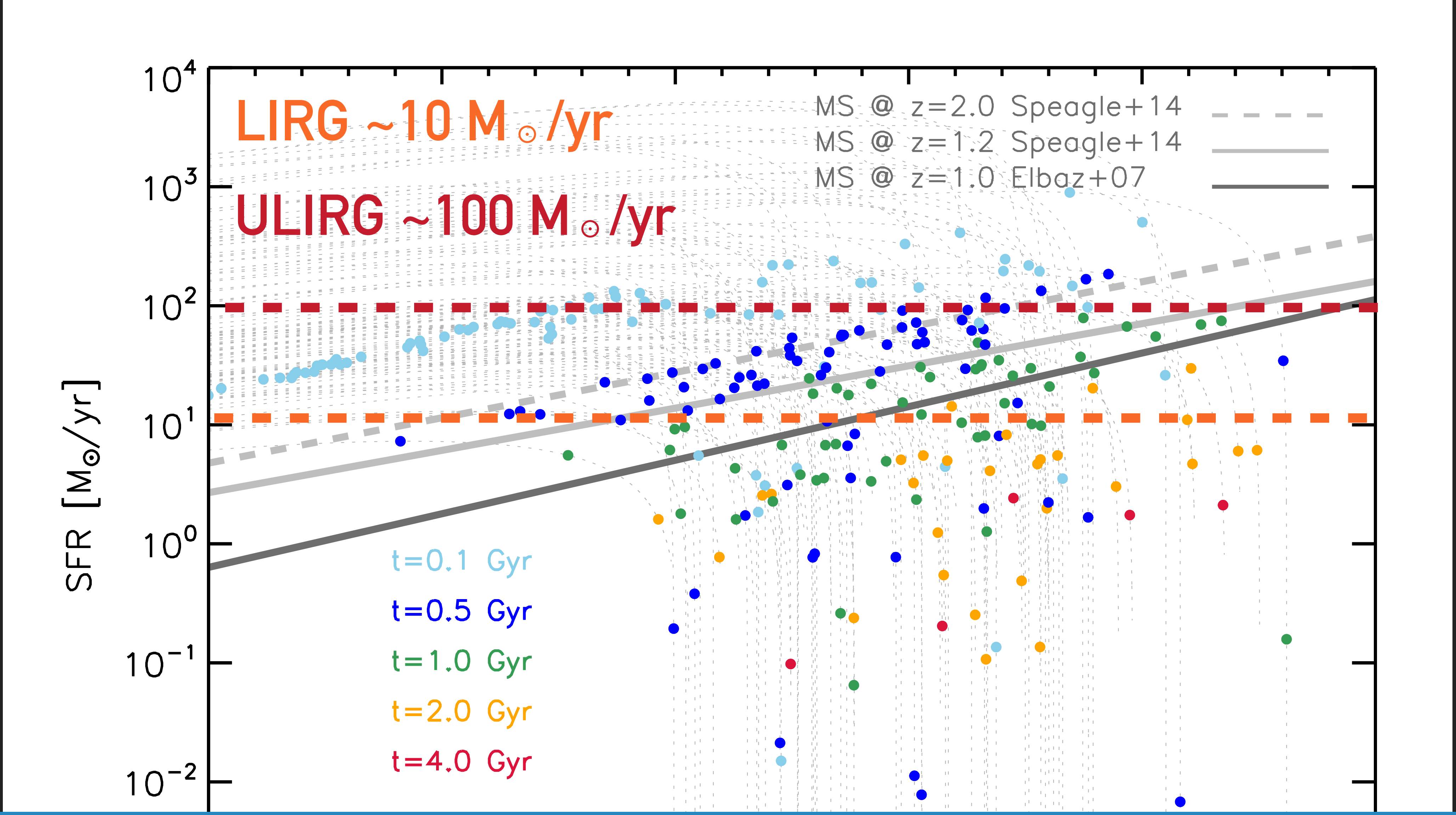
Domínguez Sánchez et al. (2016)

EVOLUTIONARY TRACKS



Domínguez Sánchez et al. (2016)

EVOLUTIONARY TRACKS



- All MQGs were LIRGs & 46 % were ULIRGs
- Time in LIRG/ULIRG phase ~500/100 Myr (32/8 % of their lives)
- 75 % of MQGs with log (M/M$_\odot$) > 11.0 were ULIRGs

OUTLINE

I. State of the art & Goals

- Main Sequence & Mass Function
- Compaction & Quenching
- Stellar Populations

II. SFH of MQGs

- SHARDS survey
- Methods
- Results

III. On going projects

- Morphology of MQGs
- MANGA
- Deep learning

OUTLINE

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WORK IN PROGRESS

- Morphology … QGs
- MANGA
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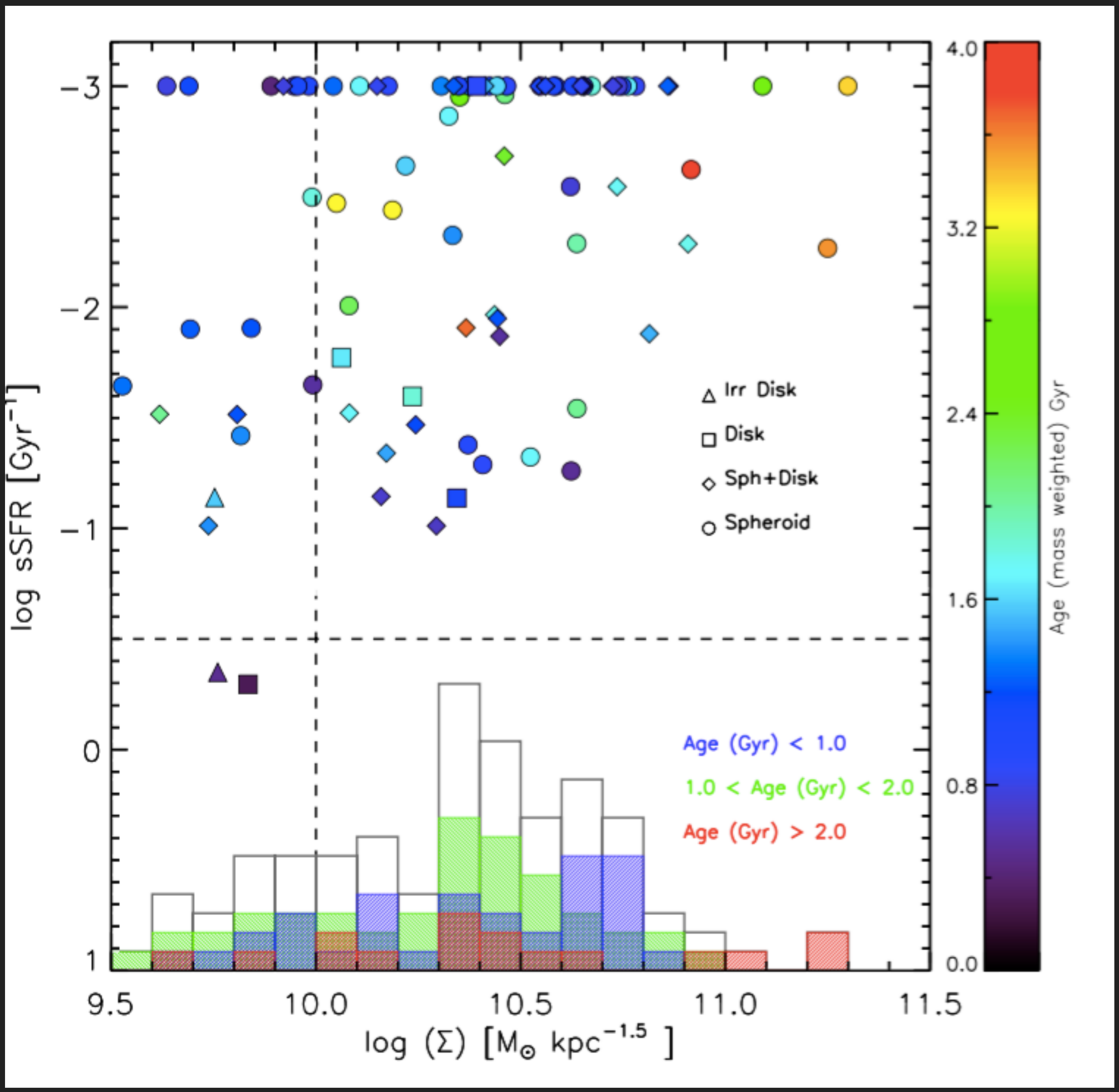
MORPHOLOGY OF MQGS



Correlation between SFH and structural properties?

- Morphology classification
- Bulge/Disk ratio
- Sersic index
- R_{eff} –> Surface density

CANDELS survey
Rainbow Navigator
https://arcoirix.fis.ucm.es/Rainbow_navigator

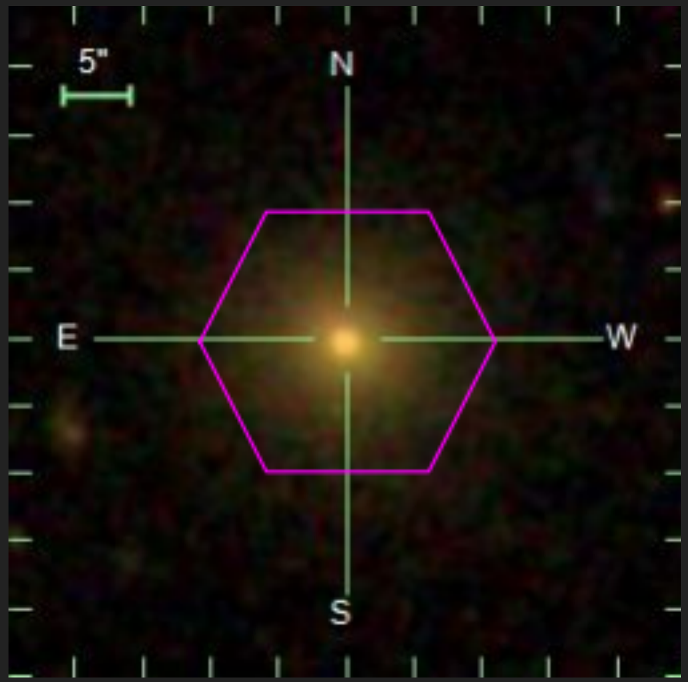
MaNGA survey: Mapping Nearby Galaxies at AP

- ✓ 17 IFUs per 7 deg^2 plate
- ✓ 360-1000 nm, R~2000
- ✓ 10,000 galaxies across ~2700 deg2, redshift z~0.03
- ✓ Spatial sampling of 1-2 kpc
- ✓ Per-fiber S/N=4-8 (per angstrom) at 1.5 Re

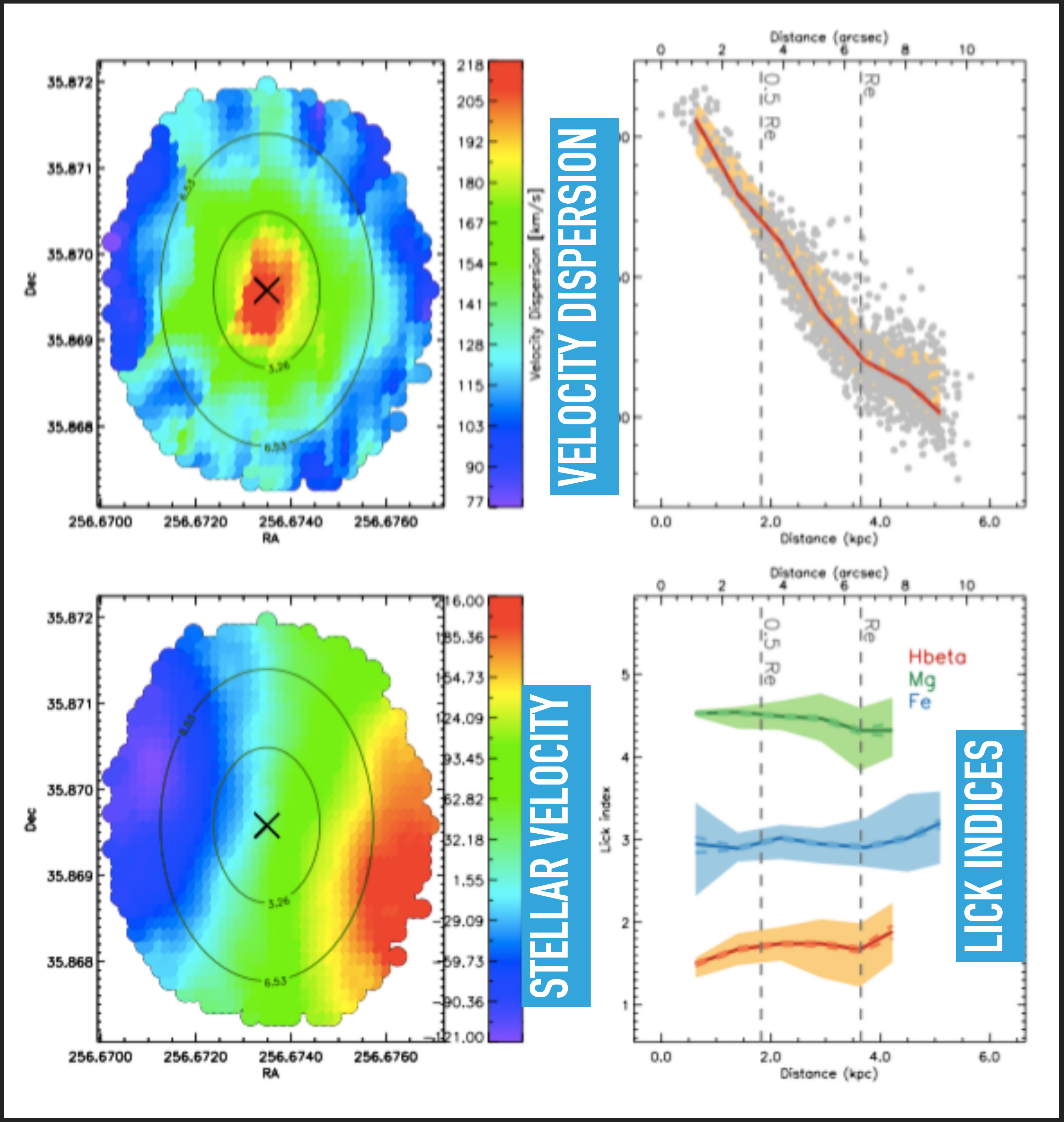
Signatures of major vs. minor mergers in Ell

Age and metallicity gradients:

- Photometric (colors+gradients)
- Spectra (vdisp, Lick indices)



MA. Bernardi, JL Fisher (UPenn)


VELOCITY DISPERSION
STELLAR VELOCITY
LICK INDICES
Velocity Dispersion [km/s]
Dec
RA
Distance (arcsec)
Distance (kpc)
0.5 Re
Re
Hbeta
Mg
Fe
Lick Index

DEEP LEARNING & MORPHOLOGY

M. Huertas-Company (OBSPM)

- ✓ Successful automated morphological classifications systems using convolutional neural networks (e.g., Galaxy Zoo, Dieleman+2015, CANDELS, Huertas-Company+2015)
- ✓ Future big-data surveys such as EUCLID or WFIRST include immense number galaxies
- ✓ How much of the knowledge acquired from an existing survey can be exported to a new dataset?
- ✓ Apply GZOO (SDSS, z~0.2) classification scheme to Dark Energy Survey
- ✓ DES: 5000 deg^2, 300 millions galaxies, Dark Energy Camera
- ✓ Morphology of galaxies up to z~0.4

DARK ENERGY SURVEY

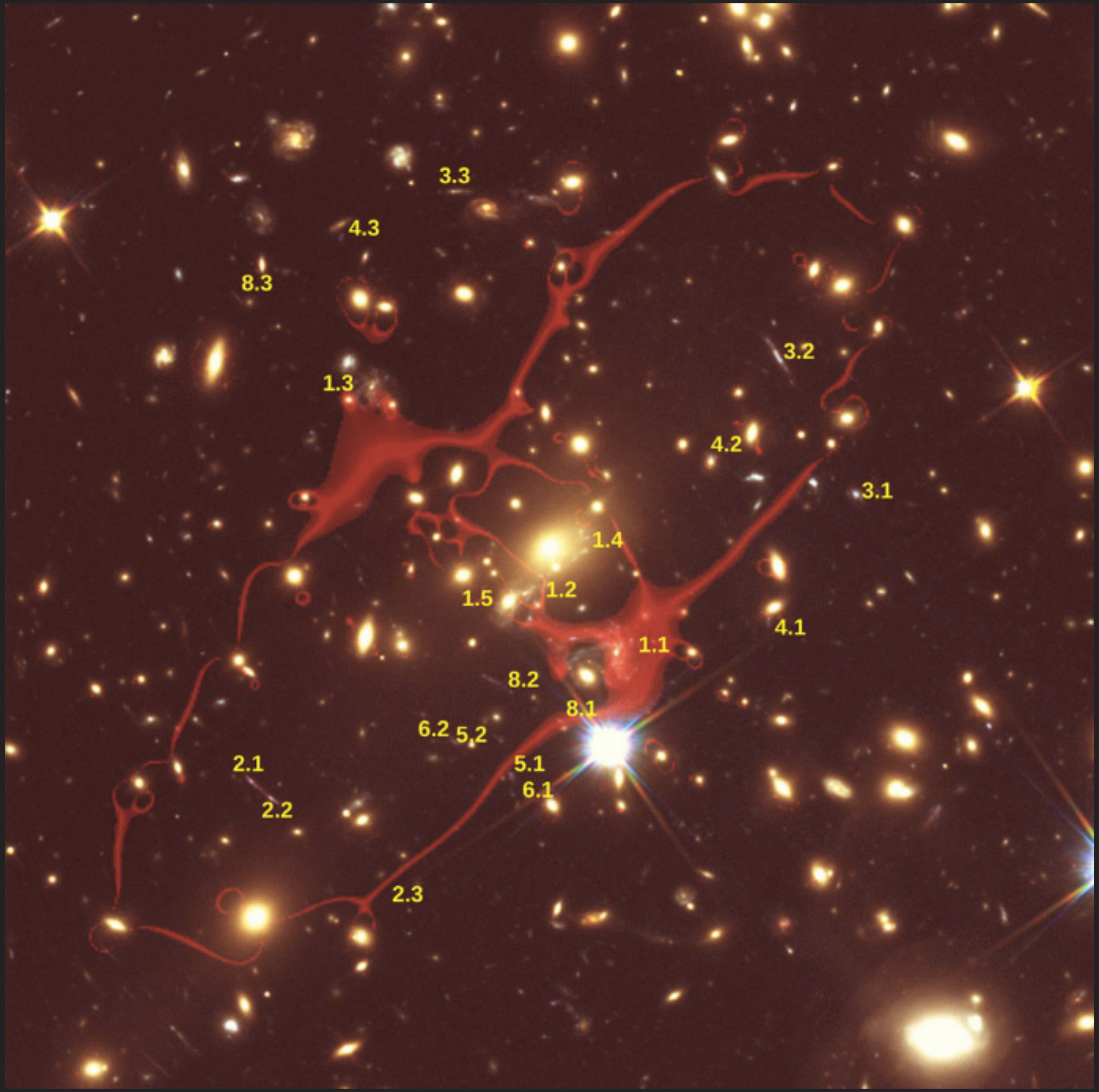
DEEP LEARNING & MORPHOLOGY

SPIRAL

ELLIPTICAL

MERGER

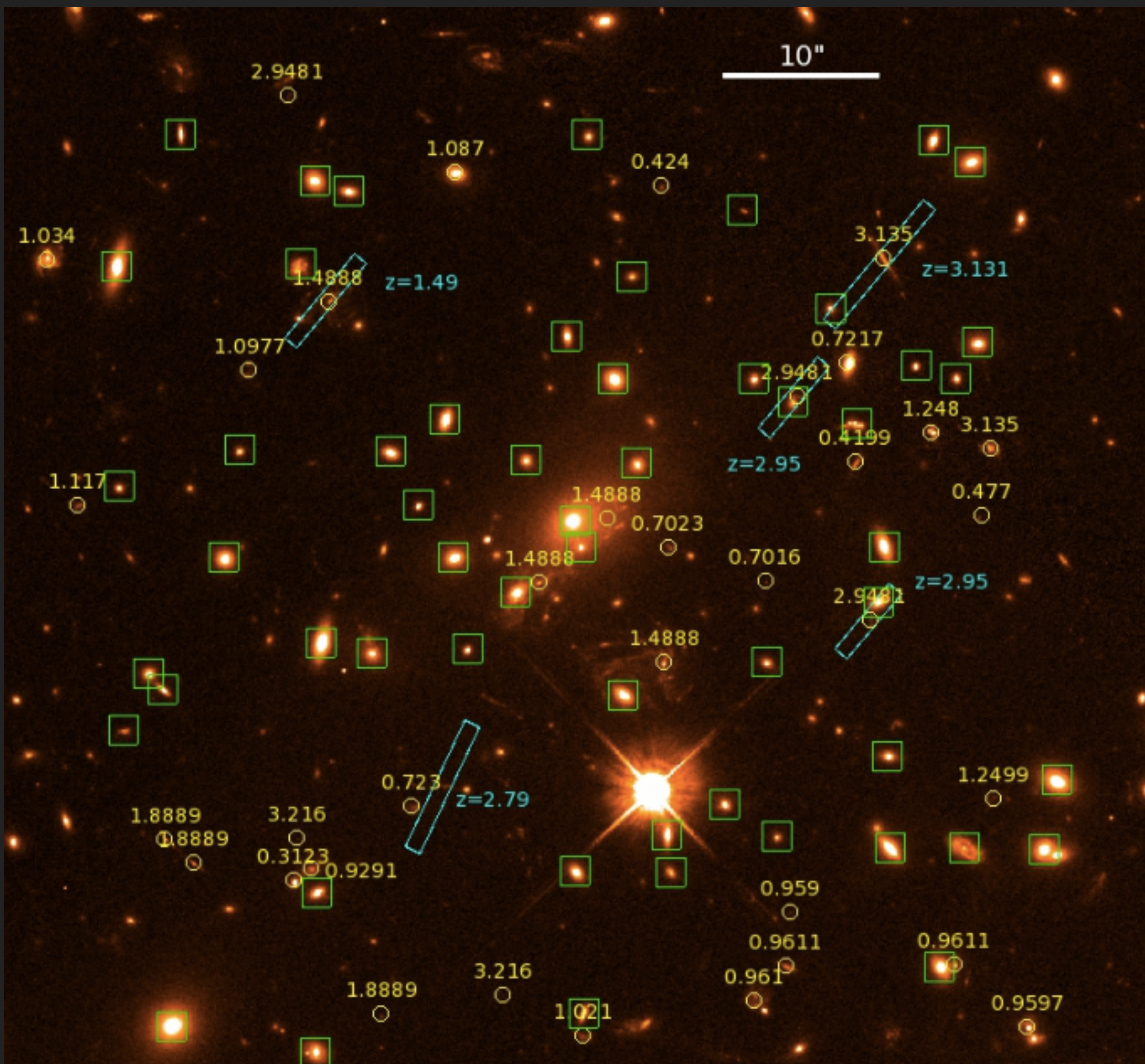
SHARDS+HUBBLE FRONTIER FIELDS



MACSJ1149
Abell 370

Diego et al. (2016)

SHARDS+HUBBLE FRONTIER FIELDS



MACSJ1149

- z=0.554
- 10’s of z~1 lensed galaxies
- Data release in early 2017

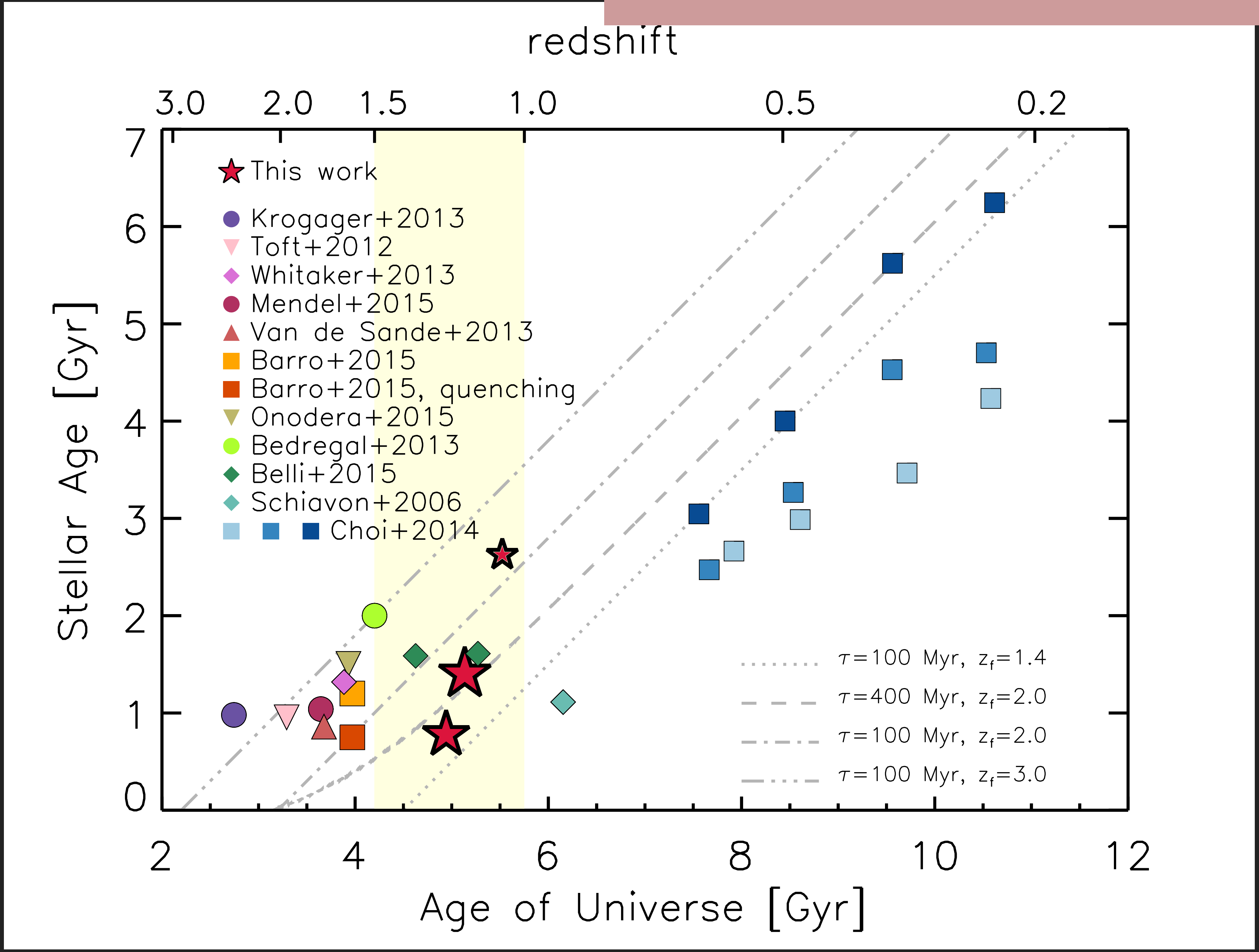
Diego et al. (2016)

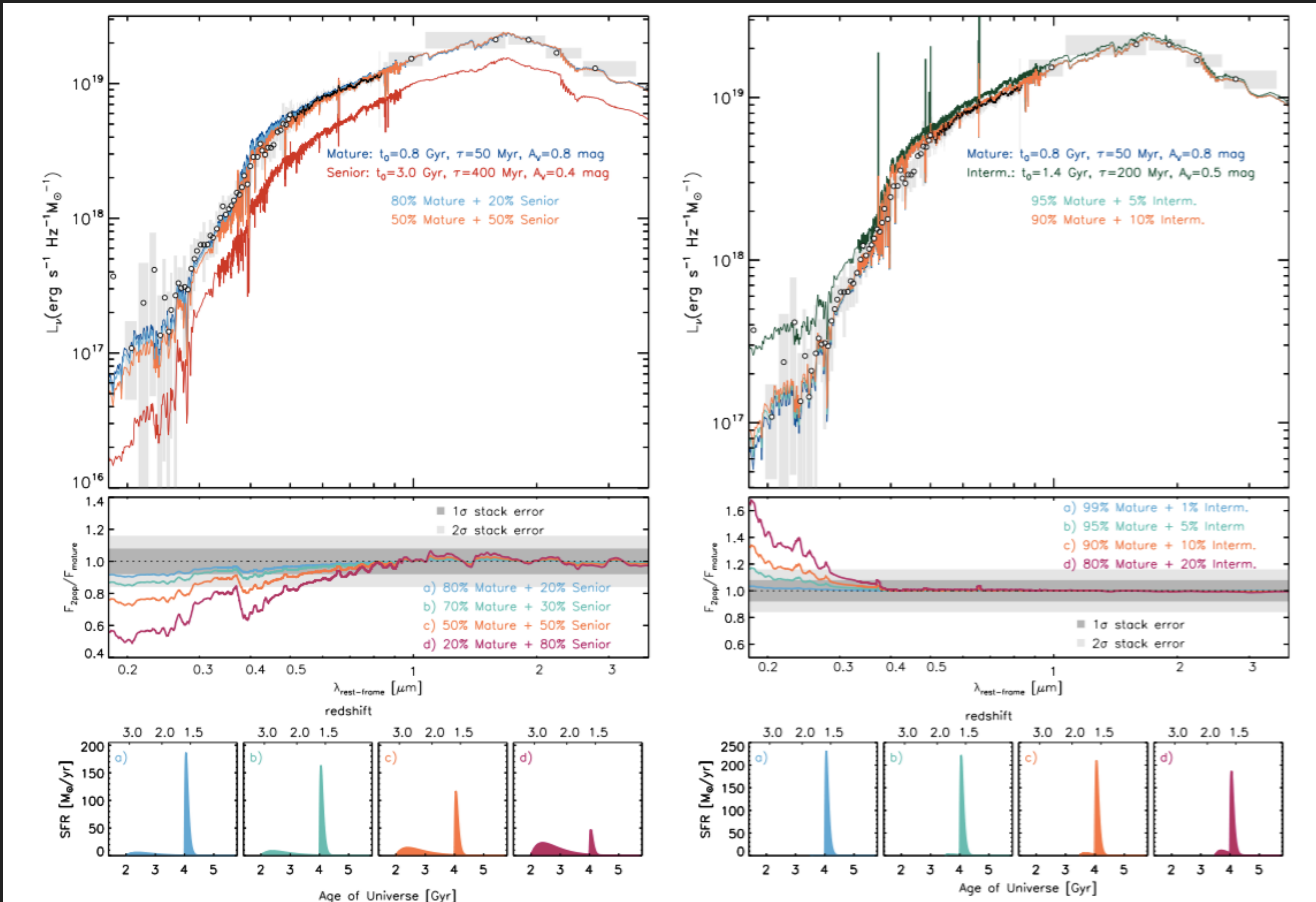
CONCLUSIONS

- ✓ With the combination of SHARDS + GRISM data we carried out the most comprehensive and reliable study (breaking and controlling the degeneracies) of SFH of MQGs @ z > 1.0
- ✓ Assuming $SFR(t) \propto t \exp(-t/\tau)$, SF timescales are 100-400 Myr
- ✓ MQGs live in the MS for 0.1-1.0 Gyr, reaching their top of SFR at (U)LIRGs levels, then aging rapidly out of it (dead in ~ 1.5-2.0 Gyr)
- ✓ Some MQGs @ 1.0-1.5 are quite old (> 2 Gyr, i.e., they were dead by z~2), but most are new arrivals (85%, < 2Gyr)
- ✓ No clear correlation between mass and SF timescale, but older galaxies present more extended SFH (care must be taken with selection bias + SFH parametrization)
- ✓ Most massive galaxies (log M > 10.8 $M_\odot$) were formed first (t_U ~ 3 Gyr) in very intense SF processes (> 200 $M_\odot$/yr)

AGE EVOLUTION OF MQGS

-Some rejuvenation needed for high-mass pop.
-Less massive pop. still forming stars at z~1




Mature: t_0=0.8 Gyr, τ=50 Myr, A_V=0.8 mag
Senior: t_0=3.0 Gyr, τ=400 Myr, A_V=0.4 mag
80% Mature + 20% Senior
50% Mature + 50% Senior
1σ stack error
2σ stack error
a) 80% Mature + 20% Senior
b) 70% Mature + 30% Senior
c) 50% Mature + 50% Senior
d) 20% Mature + 80% Senior
$\lambda_{rest-frame}$ [μm]
redshift
SFR [$M_\odot$/yr]
Age of Universe [Gyr]
Mature: t_0=0.8 Gyr, τ=50 Myr, A_V=0.8 mag
Interm.: t_0=1.4 Gyr, τ=200 Myr, A_V=0.5 mag
95% Mature + 5% Interm.
90% Mature + 10% Interm.
a) 99% Mature + 1% Interm.
b) 95% Mature + 5% Interm
c) 90% Mature + 10% Interm.
d) 80% Mature + 20% Interm.