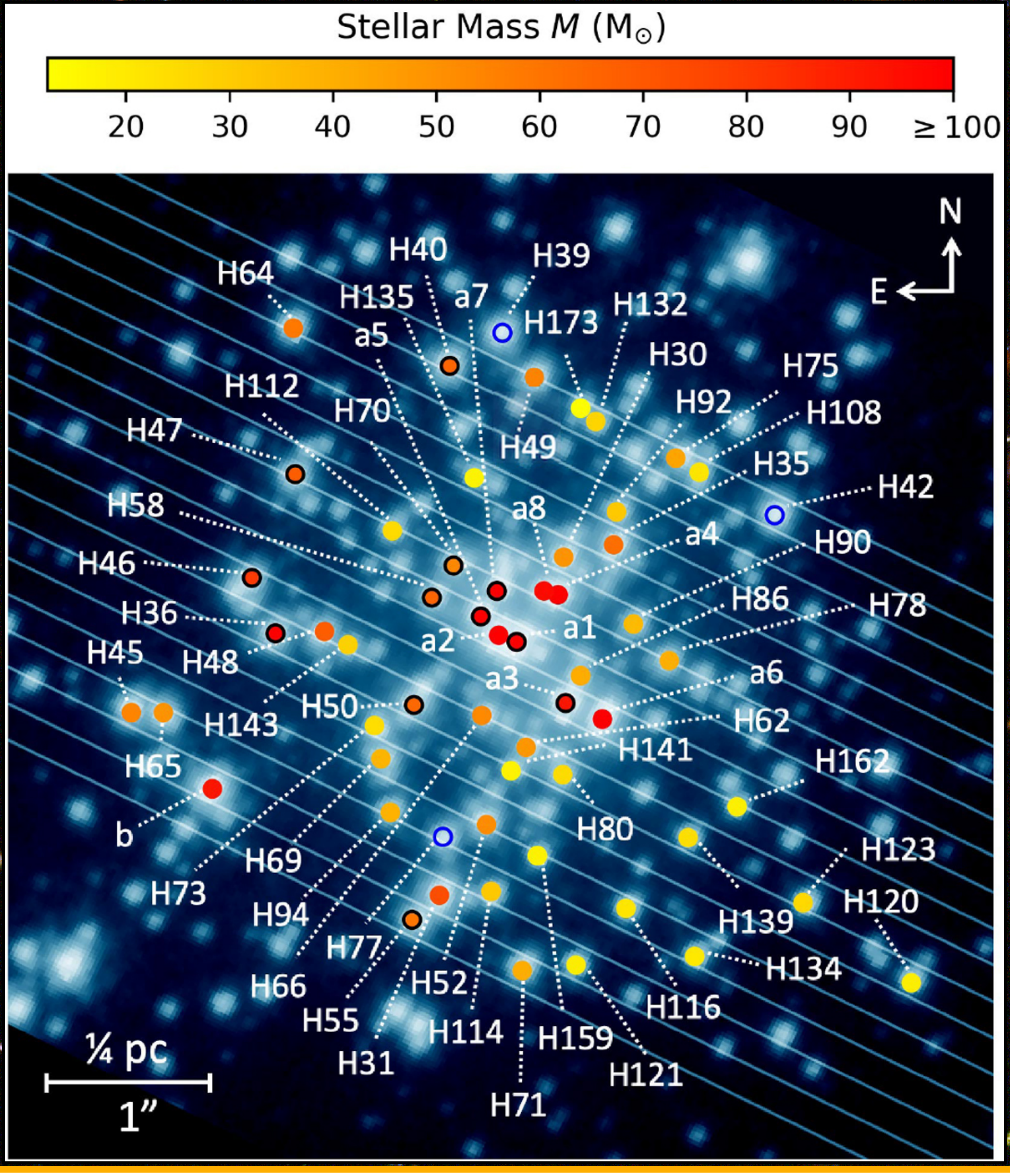
Evidence for Very Massive Stars (VMS) in Extremely UV-Bright Star-Forming Galaxies at z ~ 2.2–3.6



HST/WFC3 *F555W* image of VMS in the R136 cluster (Brands+ 2022, O'Connell+ 2010).

Upadhyaya, A. et al. 2024, A&A, 686, A185.

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Background: Hubble's Ultra Deep Field (NASA, ESA).

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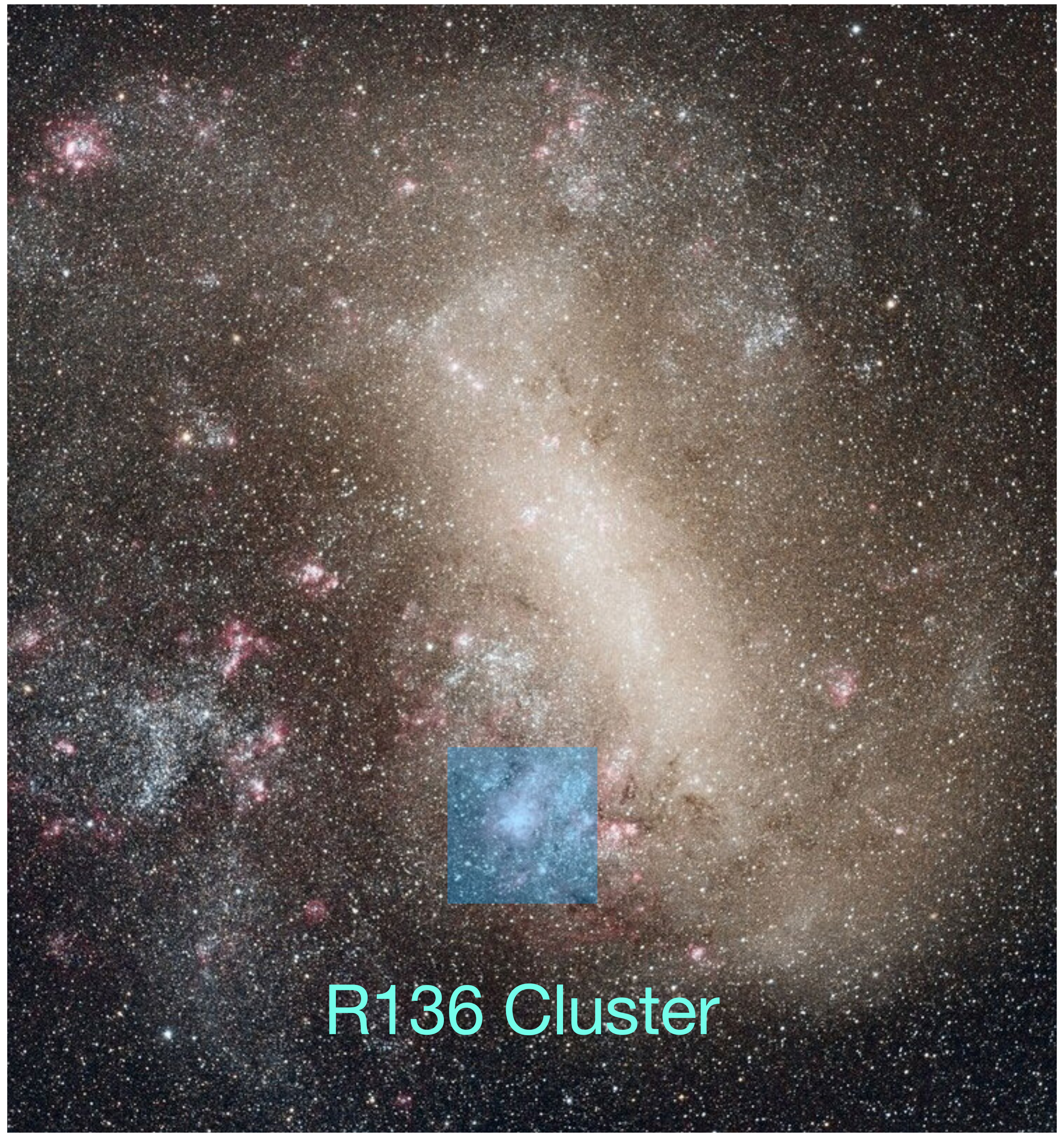
What are Very Massive Stars (VMS)?

- **Very Massive Stars (VMS)** are by definition stars with mass, **M ≈ 100** $M_\odot$ **to 1000** $M_\odot$.
- They are main sequence **H-burning** stars with very **strong stellar winds**.
- Locally, the **R136 cluster** in the LMC is known to host **VMS** and has been studied the most (Crowther+ 2010, 2016; Bestenlehner+ 2011, 2020; Hainich+ 2014; Brands+ 2022).



Large Magellanic Cloud taken by Andrew Lockwood

- At high z, presence of **VMS** are inferred by spectroscopic method; on e.g. is the LyC emitting gravitationally lensed **Sunburst Arc** at z = 2.37 (Meštrić+ 2023).

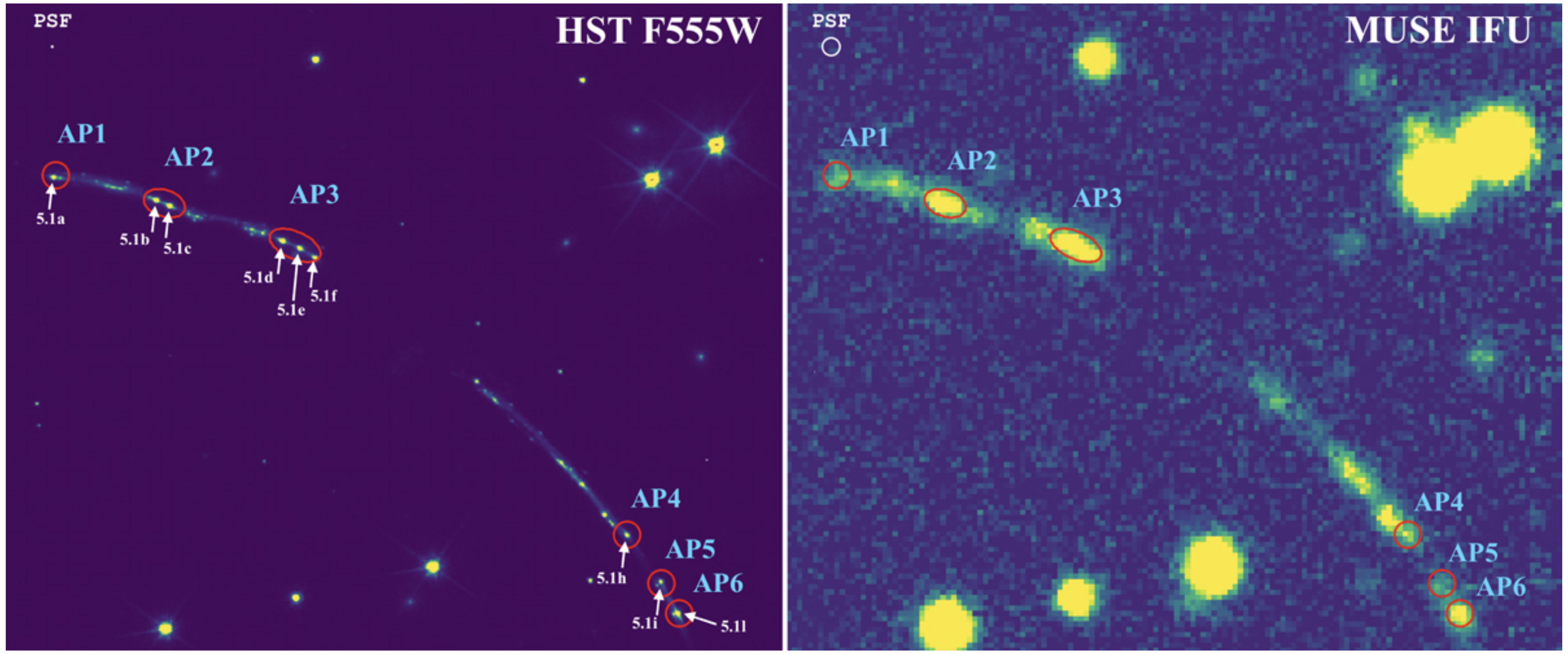


Fig: HST and MUSE imaging of **Sunburst Arc** (Meštrić+ 2023).

- There have been only **a few** other recent studies that find **evidence** for **VMS** at high redshifts (e.g., Wofford+ 2023).

UV Bright Galaxies: Discovery and Properties

- **Rui Marques-Chaves** discovered 70 star-forming galaxies from the **eBOSS** survey of the **SDSS** (Eisenstein+ 2011).
- This work focuses on **follow up** observations performed for **13 sources** using the **OSIRIS** spectrograph of the **GTC**.
- Very high **SFR ~ 900-1000 $M_\odot$/yr** (Marques-Chaves+ 2020, 2021).
- Two sources studied are strong **LyC emitters** with one showing **90% f_{esc}** (Marques-Chaves+ 2021, 2022).
- One recently published source shows very **compact LyC & UV** morphology with half light radius, **r ~ 220 pc** (Marques-Chaves+ 2024) .
- Strong **He-II 1640 $\mathrm{\AA}$** emission.

He-II EW = 4.82 $\mathrm{\AA}$

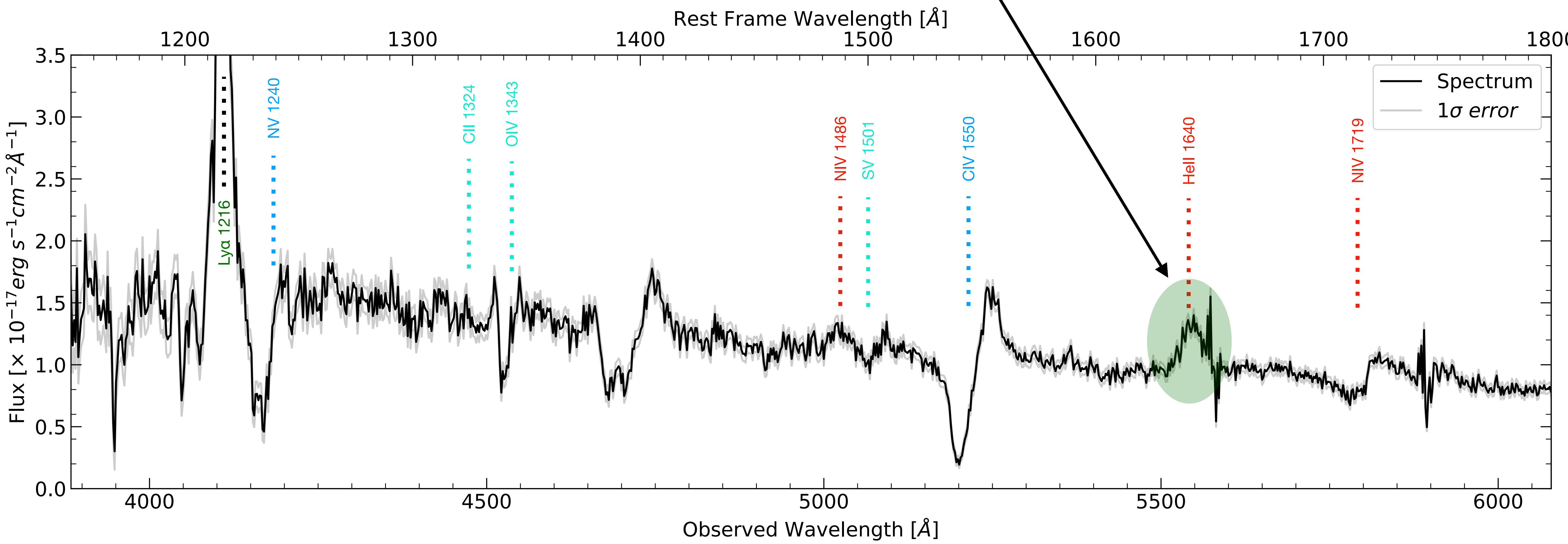


Fig: UV Spectrum of one of the sources. (Upadhyaya+ 2024).

Spectroscopic Appearance of UV Bright Galaxies

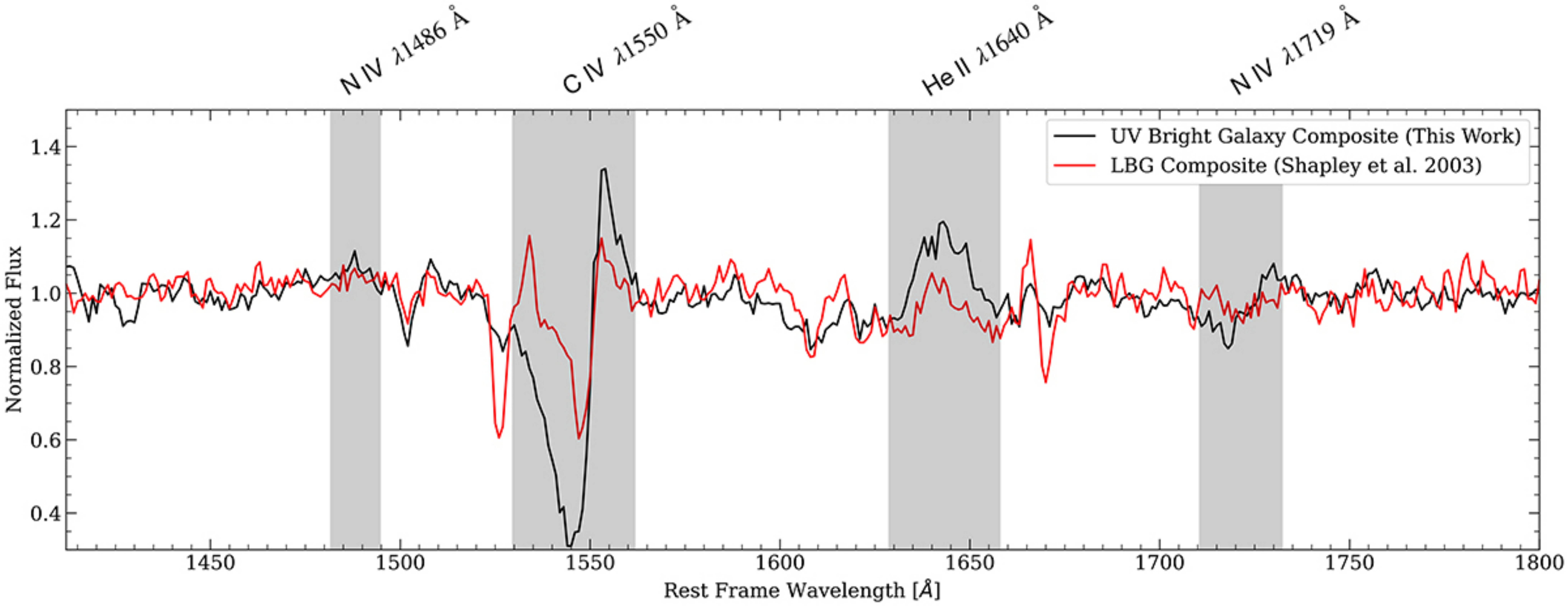
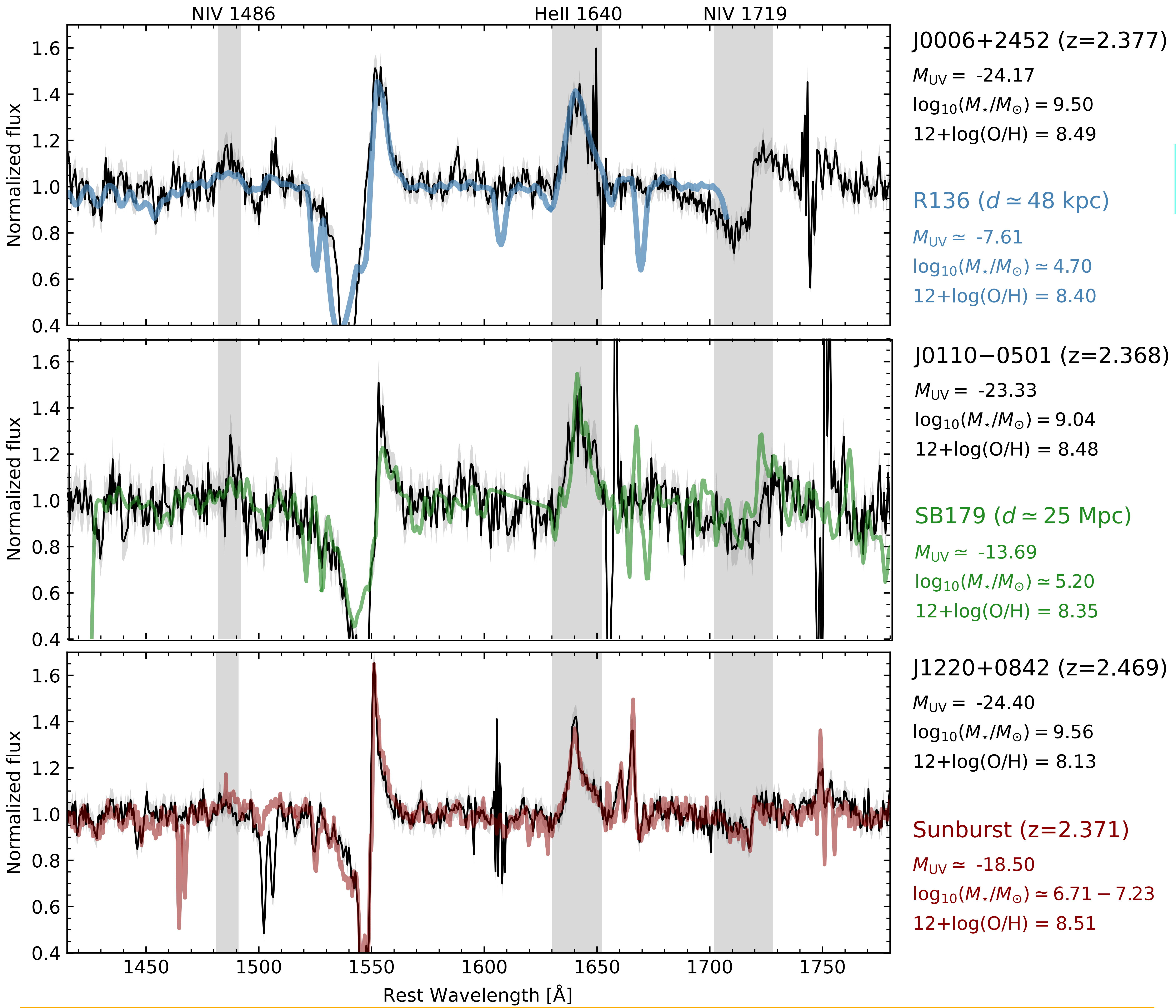


Fig: FUV spectral comparison of normal SFG and UV bright galaxy (Upadhyaya+ 2024).

- Comparison with normal SFGs (Shapley+ 2003) show UV bright galaxies exhibit strong **He II 1640 Å** (EW > 3Å), **N IV 1719 Å, N IV 1486 Å** profiles.
- The **C IV 1550 Å** P-Cygni profile is also significantly **boosted** in comparison to normal SFGs at similar redshift.

Empirical Evidence for Very Massive Stars (VMS)



J0006+2452 comparison with **R136**

J0110-0501 comparison with **SB179**

J1220+0842 comparison with **Sunburst Cluster**

Fig: Empirical spectroscopic evidence for VMS (Upadhyaya+ 2024).

Signs of Different (!) IMF within UV Bright Galaxies?

- We have used **new** models of **VMS** from Martins & Palacios 2022 at 0.4 $Z_{\odot}$ metallicity that uses Grafener 2021 **mass loss** prescription for **stellar winds**.
- The new mass loss prescription leads to **higher mass loss** rates from **VMS** with **optically thicker winds**.
- We plotted **He II** 1640 Å emission and **N V** 1220 Å absorption **EW** for **sources** and **new VMS models** with **Salpeter IMF** slope of -2.35.
- We employ a **3 Å threshold** based on Schaerer & Vacca 1998 for WR stars only and classify in total **9 out of 13** UV bright galaxies to **host VMS**.

VMS models with different IMF upper mass M_{up} is required to predict the observed He II 1640 Å strength of the sources.

- Recently, Schaerer+ 2024 shows that models the **IMF** of **-2** slope can predict **He II EW** from **4 to 8** Å suggesting the **IMF slope** and **M_{up}** are **degenerate** at least for some sources.

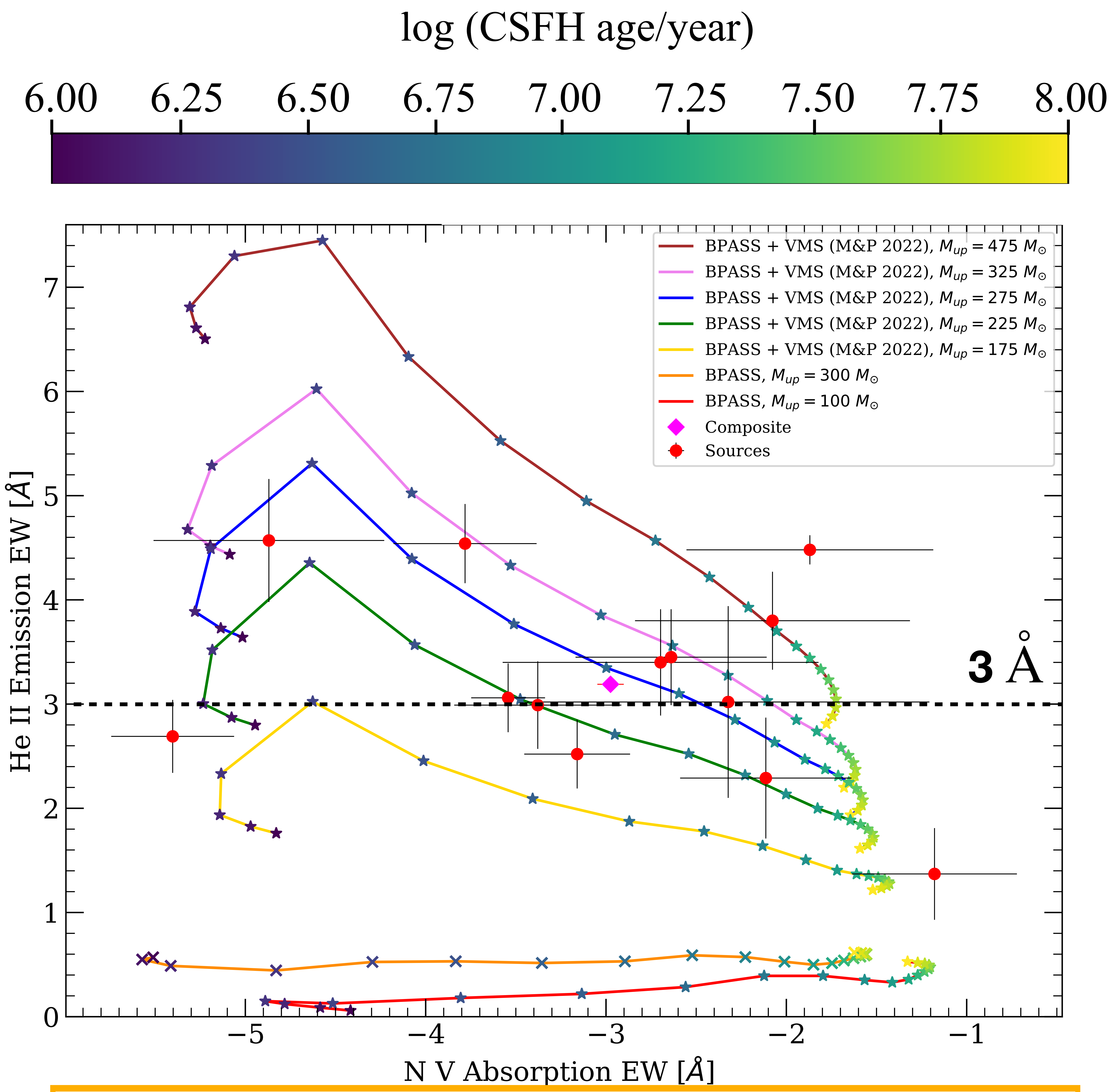


Fig: He II and NV EW for sources and different VMS models (Upadhyaya+ 2024).

Model Spectra Comparison and Incidence of VMS in Different Sources

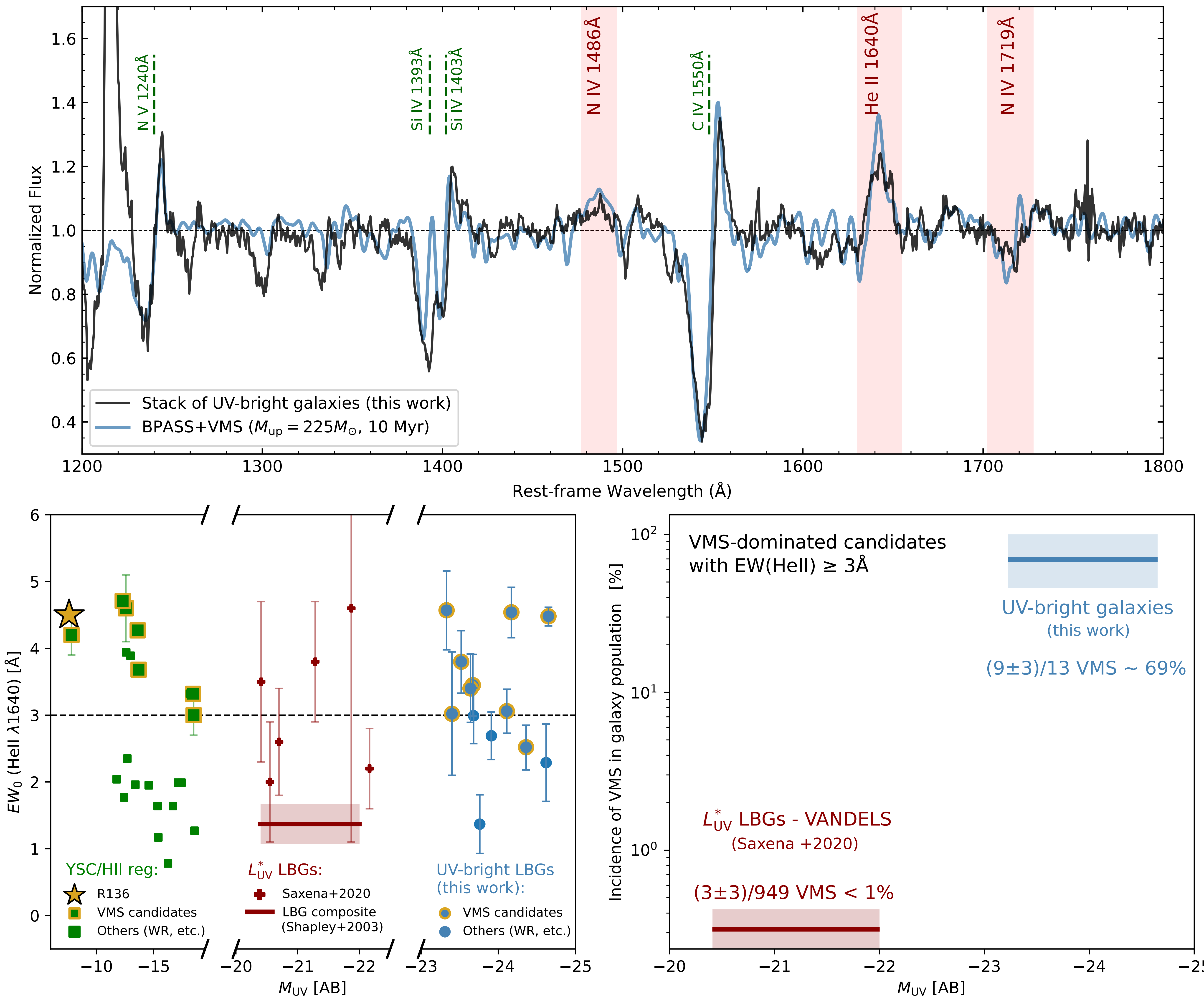


Fig: Comparison of model and source stack spectra along with incidence rates of VMS in different sources (Upadhyaya+ 2024).

The model spectrum can match the observed spectroscopic features of the source stack spectrum: see He II 1640 Å, N IV 1486 Å, N IV 1719 Å, C IV 1550 Å, and N V 1220 Å.

Incidence of VMS is around 70 % in UV bright galaxies compared to normal SFGs where VMS appear in less than 1 % sources.

Summary

- UV bright galaxies show strong **He II 1640** $\mathring{A}$, with **EW** between **1.4 to 4.8** $\mathring{A}$.
- We find 3 known **VMS host** whose spectra are **analogues** to 3 of the **UV-bright galaxies** and the comparison provides us with **empirical** evidence for **VMS** in UV bright galaxies.
- We use an empirical threshold of **EW (He II) = 3.0** $\mathring{A}$ to differentiate VMS or WR contributions, and we classify **9 out of 13** UV bright galaxies as VMS dominated sources.
- Our results suggest that UV bright galaxies have a **different IMF** with upper mass limits between $\mathbf{M_{up}}$ **= 175 – 475** $M_{\odot}$, assuming a Salpeter slope.
- **Incidence** of **VMS** in the UV bright galaxy population is **high**, around **≈70%**, compared to **normal SFGs** at similar redshifts (**<1%**).

Thank you!! Questions?

Thank you!!
Questions?

Signs of Different (?) IMF in UV Bright Galaxies?

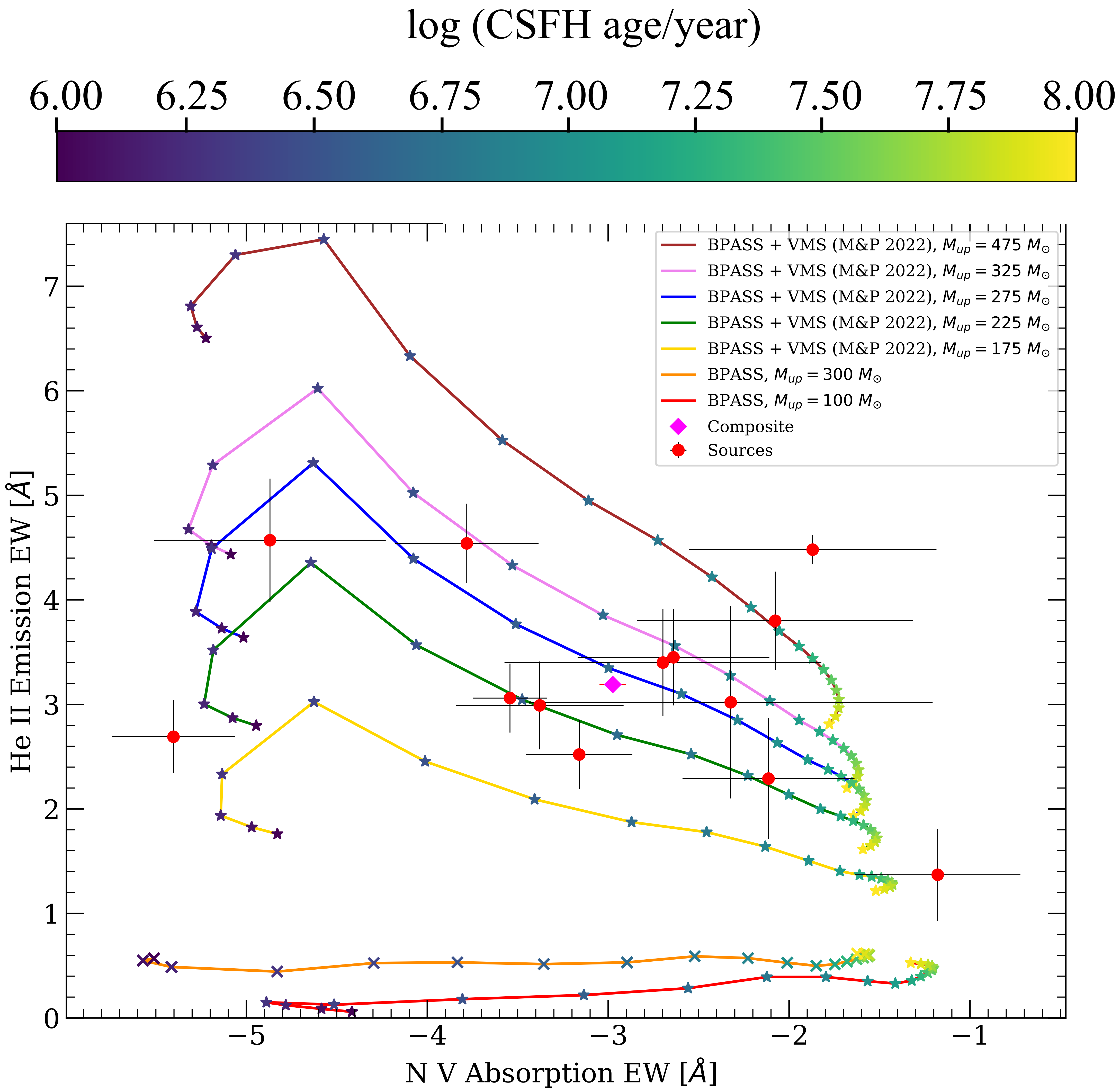


Fig: He II and NV EW for sources and different VMS models (Upadhyaya+ 2024).

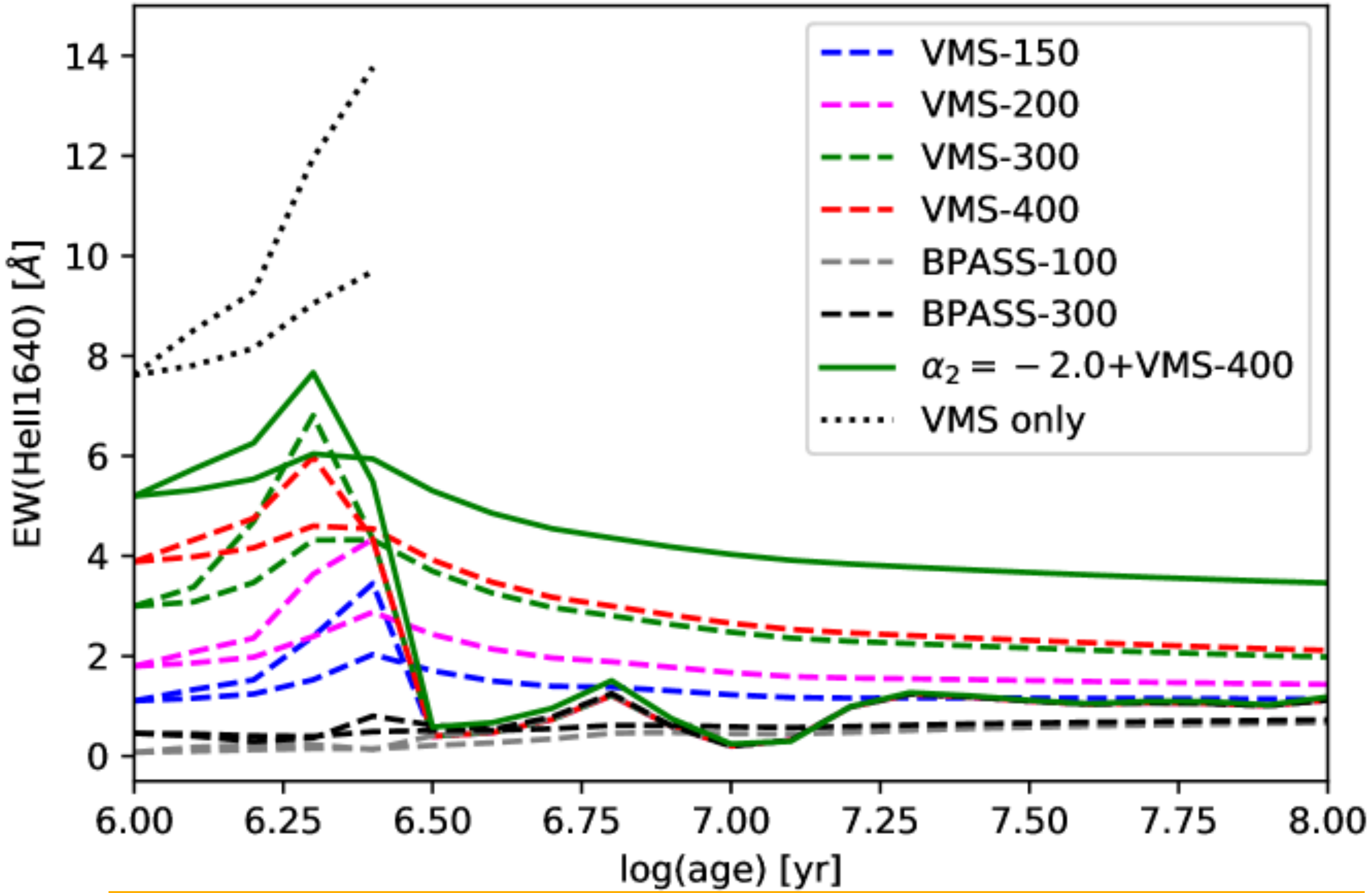


Fig: He II EW with age for different VMS models (Schaerer+ 2024).

The UV Spectra of a 200 $M_\odot$ VMS Model

VMS signature features:

1. He-II 1640 Å emission.
2. N-IV 1720 Å P-Cygni Profile.
3. N-IV 1486 Å emission.

VMS Models Upper Mass:

1. M1 with 175 $M_\odot$
2. M2 with 225 $M_\odot$
3. M3 with 275 $M_\odot$
4. M4 with 300 $M_\odot$
5. ISFH $\longrightarrow$ CSFH

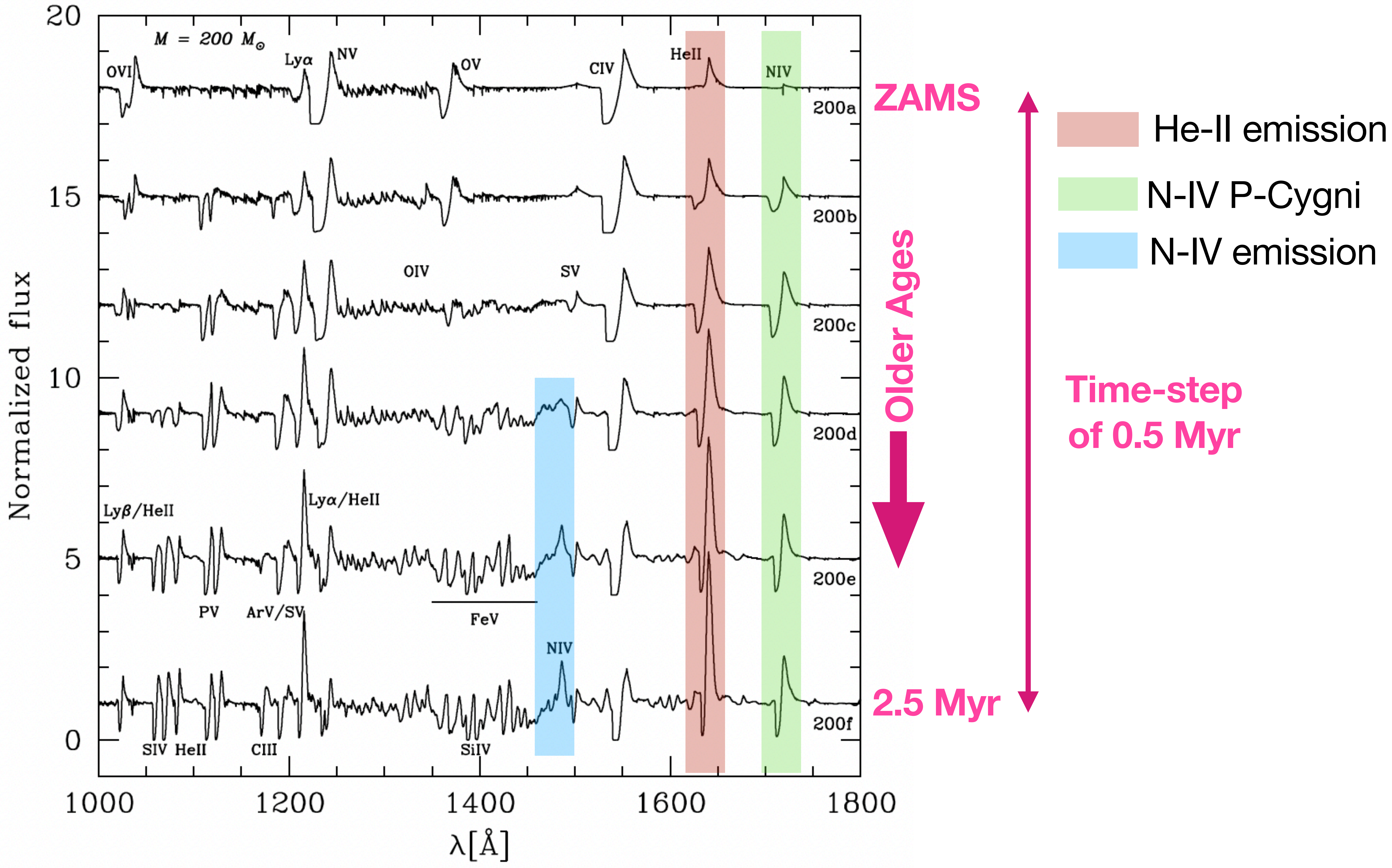


Figure: UV Spectra of 200 $M_\odot$ VMS (Martins & Palacios 2022).

Sources: Discarding as QSOs

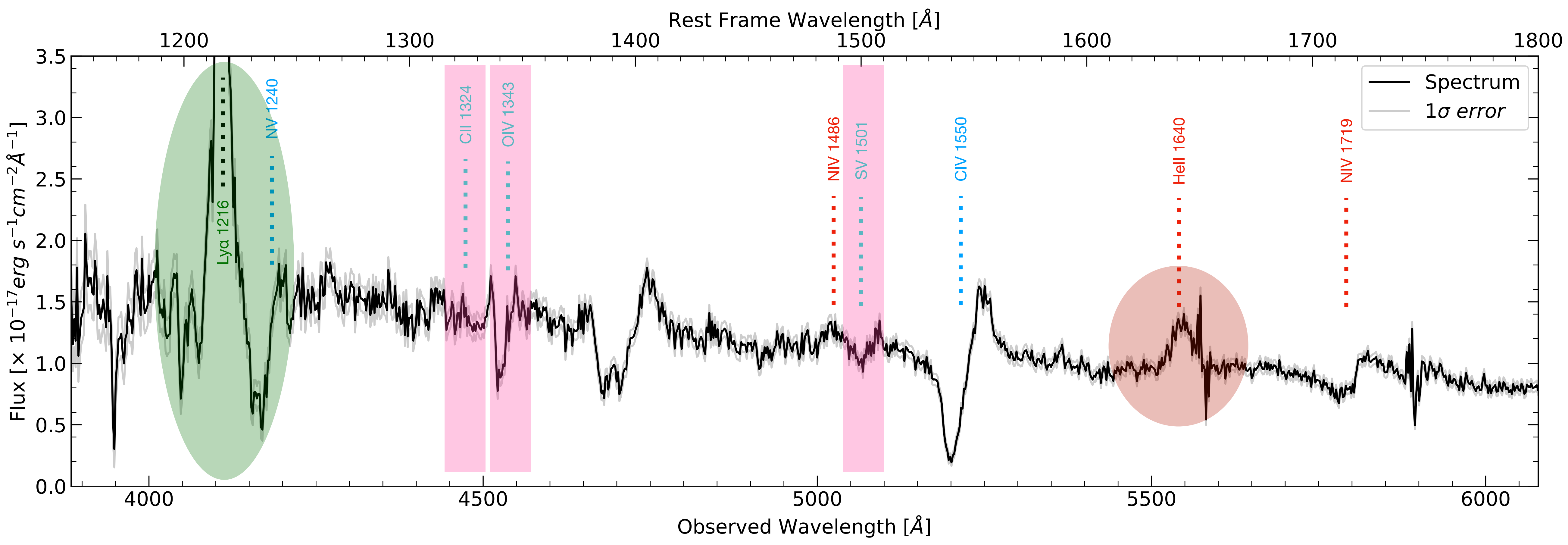


Figure: UV Spectrum narrow Lyα.

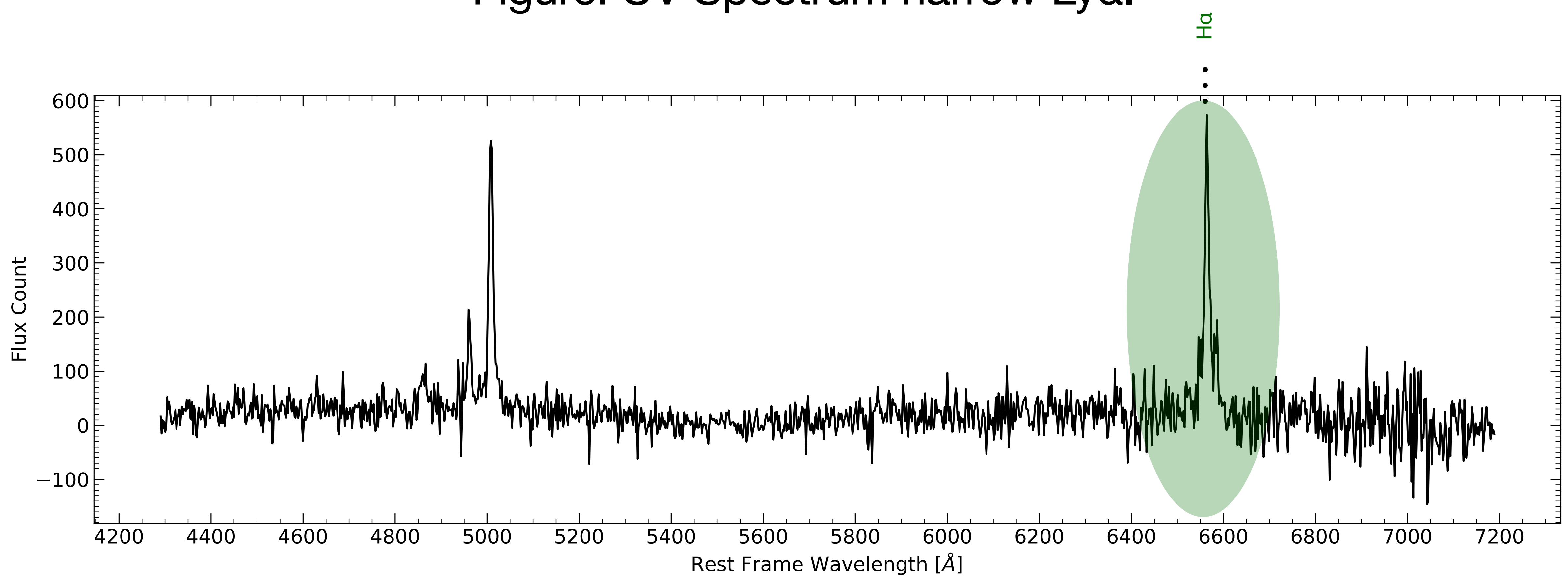
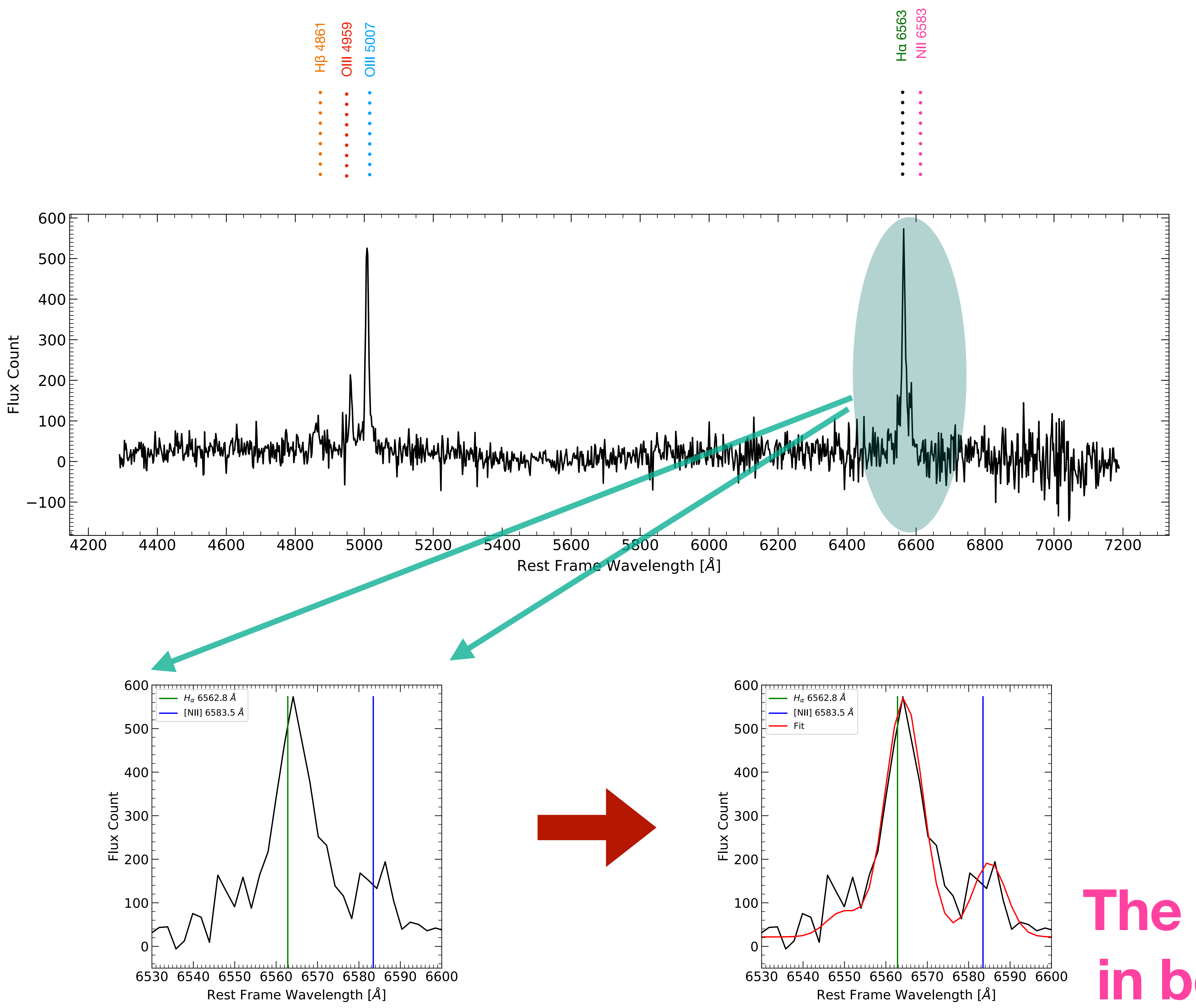


Figure: UV Spectrum narrow Hα.

1. Rest-frame UV and optical spectrum show very narrow Lyα and Hα nebular emission.
2. He-II emission is very broad not narrow, suggesting a stellar origin.
3. Presence of photospheric absorption lines like SV 1501 Å, OIV 1343 Å, CII 1324 Å.
4. The photospheric features originate from absorption in the stellar photosphere.
5. Narrow nebular lines and detection of photospheric features suggest that these are extreme SFG population.

No Significant AGN contribution !!

Metallicity



1. VMS models are constrained to a metallicity of 0.4 $Z_\odot$ so it is important to find metallicity of our sources.
2. The stellar metallicity calibrator like that from Calabro et al. 2021 are calibrated using S99 or BPASS model, won't work for VMS.
3. We have rest-frame optical spectra of 8 of the 13 sources.
4. We used the prescription from Marino et al. 2013 which uses the ratio of N-II and Hα to find nebular metallicity.

$$N2 = \log(\frac{NII}{H\alpha})$$

$$12 + \log(O/H) = 8.743[\pm 0.027] + 0.462[\pm 0.024] \times N2$$

The nebular metallicity of the sources is in between 8.16 to 8.55, all in sub-solar range.

Impact of Very Massive Stars (VMS)

UV Luminosity and Ionising Photon Production, and IMF Effect:

1. Schaerer+ 2024 uses BPASS + Martins & Palacios 2022 models of VMS to study impact of VMS on UV luminosity and ionising photo production.
2. Their study finds that the inclusion of VMS makes the ionizing photon production efficiency, $\boldsymbol{\xi}_{ion}$ to **increase** by 0.14 - 0.2 dex.
3. The study by Schaerer+ 2024 also finds that a change in the IMF slope from $\alpha_2 = -2.35$ to $\alpha_2 = -2$ **boosts** the UV luminosity by a factor of 2 to 8.

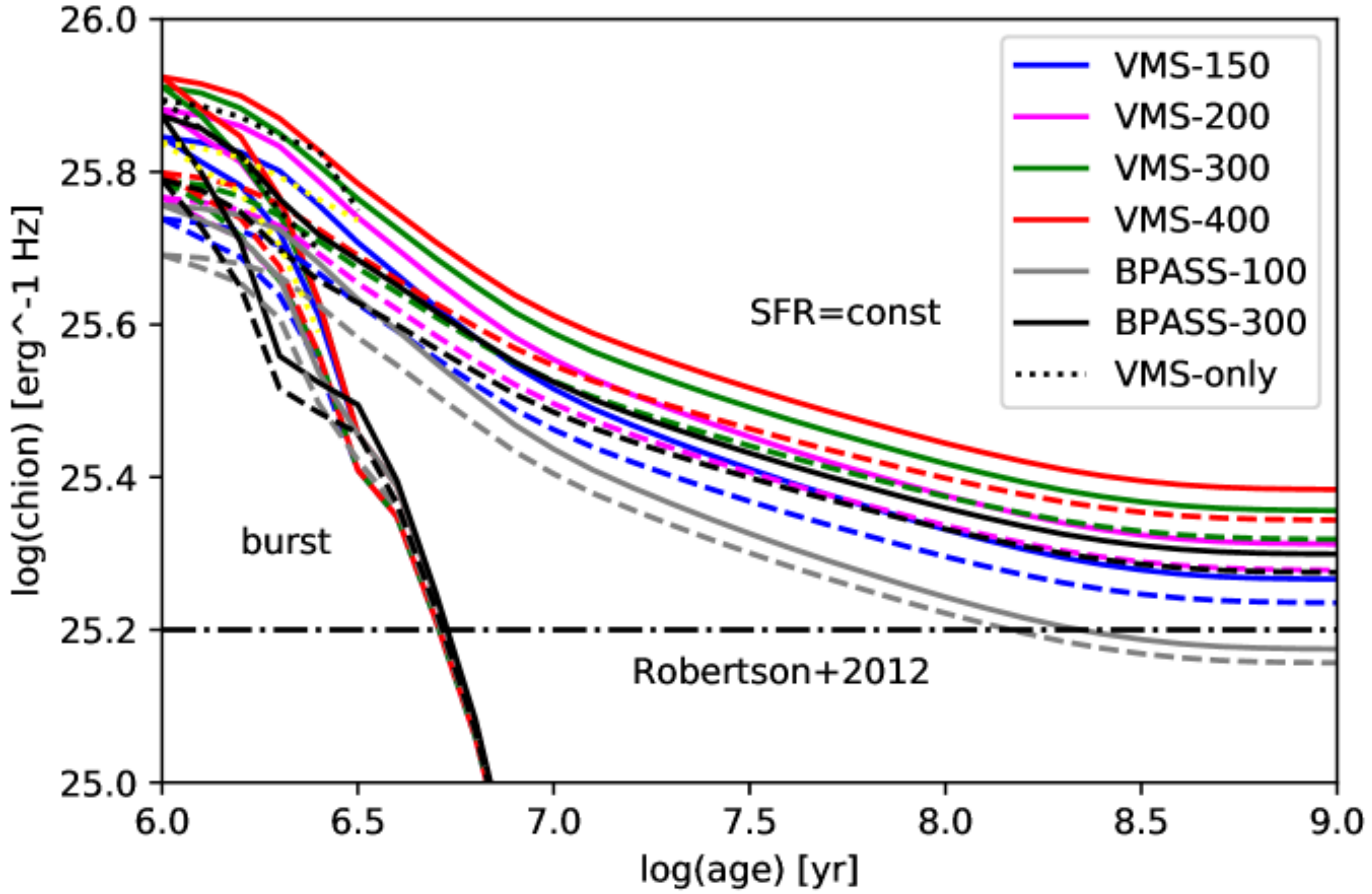


Fig: Spectra and ξ_{ion} for different models with VMS and non-VMS population (Schaerer+ 2024).

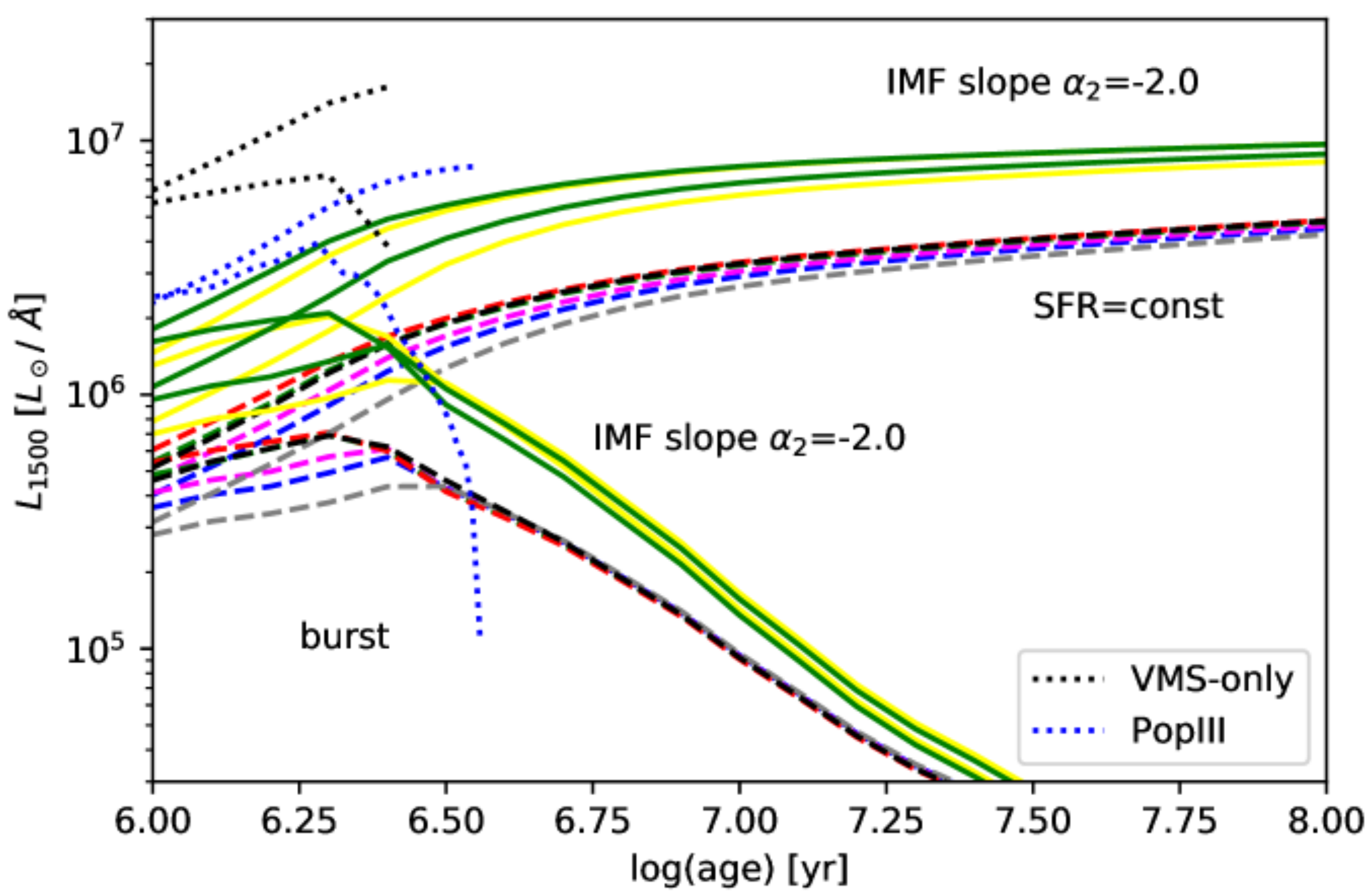


Fig: L_{1500} values for VMS models with IMF slopes of $\alpha_2 = -2.35$ and $\alpha_2 = -2$ (Schaerer+ 2024).

Impact of Very Massive Stars (VMS)

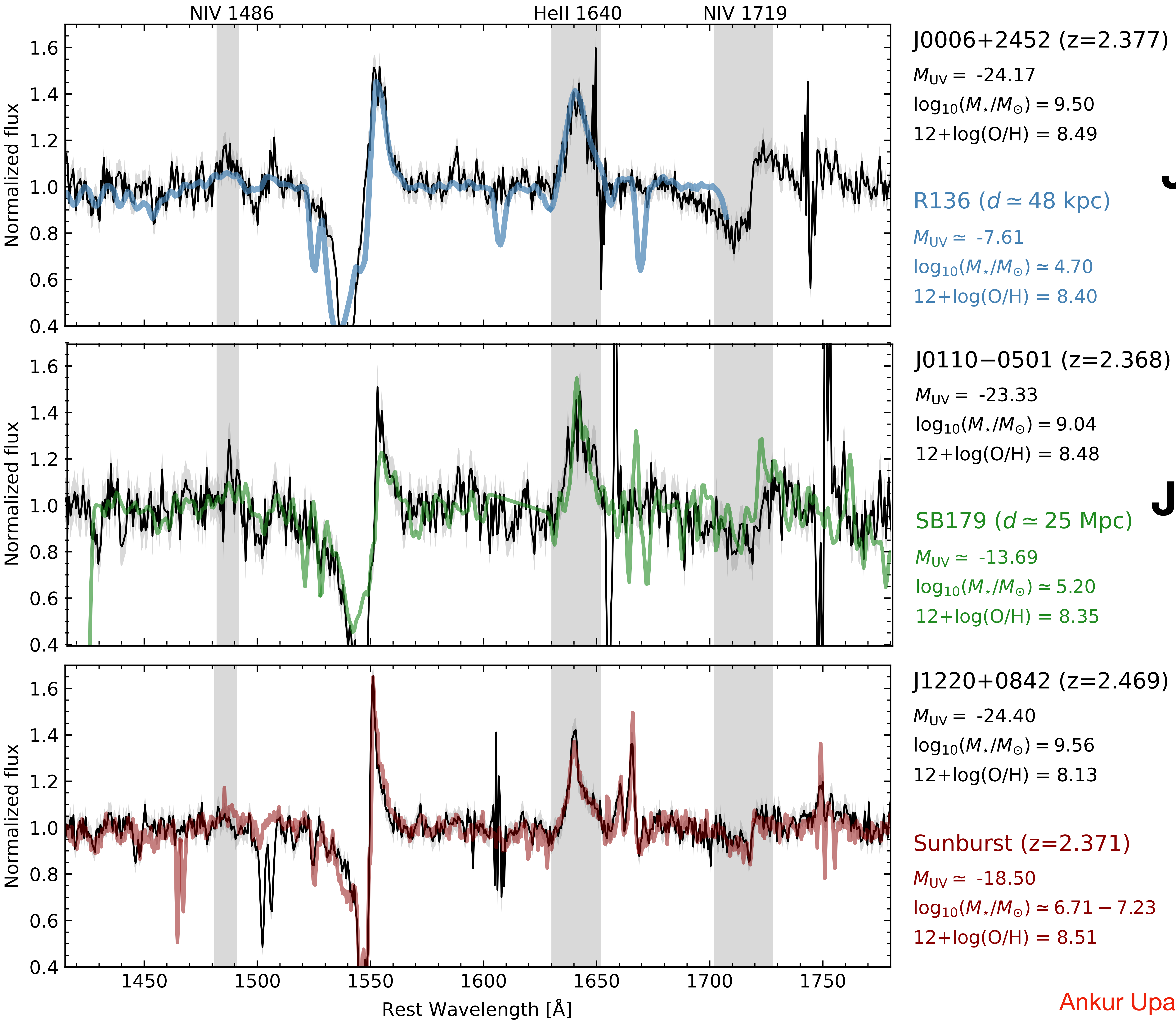
N-enhancement due to VMS:

1. With the help JWST we made many discoveries of UV bright nitrogen emitting galaxies like the **GNz11** (Bunker+ 2023, Castellano+ 2024, Schaerer+ 2024b, and others).
2. Vink 2023 argues that VMS are responsible for producing **N enhancement** in these galaxies as:
    - VMS mix the product of H burning very efficiently in its interior as they have huge **convective** cores.
    - Their strong stellar **winds** then brings out the nitrogen at later evolutionary stage.
3. The recent study by Sibony+ 2024 on **rotating** low metallicity VMS models shows evidence for nitrogen enhancement.

Other Important Aspects of VMS:

1. We don't know how the VMS die? Do they go pair instability supernovae or leave any seeds?
2. How much do they contribute to alpha enhancement?

Empirical Evidence for Very Massive Stars (VMS)



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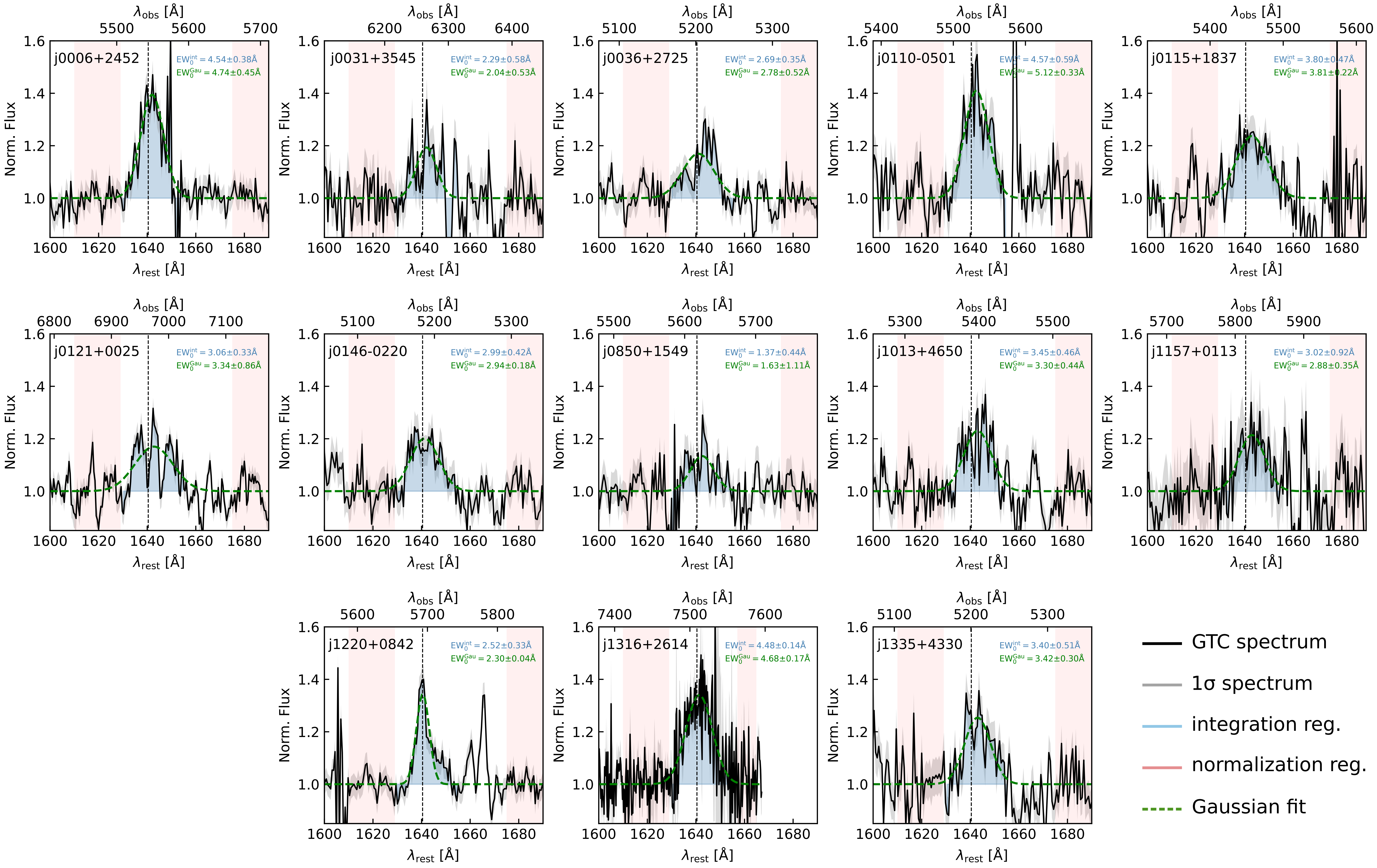

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j0036+2725
j0110-0501
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j0121+0025
j0146-0220
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j1013+4650
j1157+0113
j1220+0842
j1316+2614
j1335+4330
λ_{obs} [Å]
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Norm. Flux
GTC spectrum
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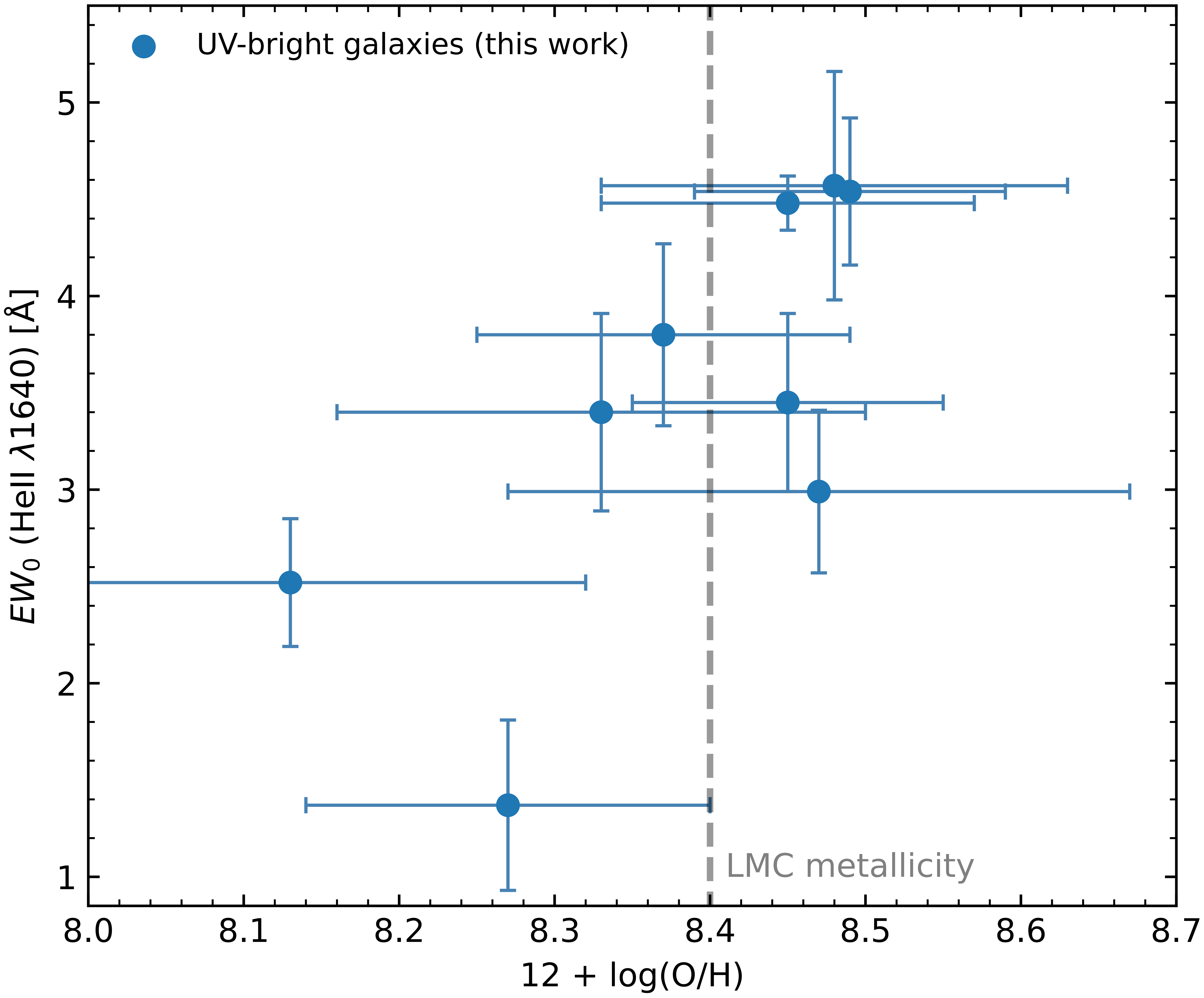
integration reg.
normalization reg.
Gaussian fit



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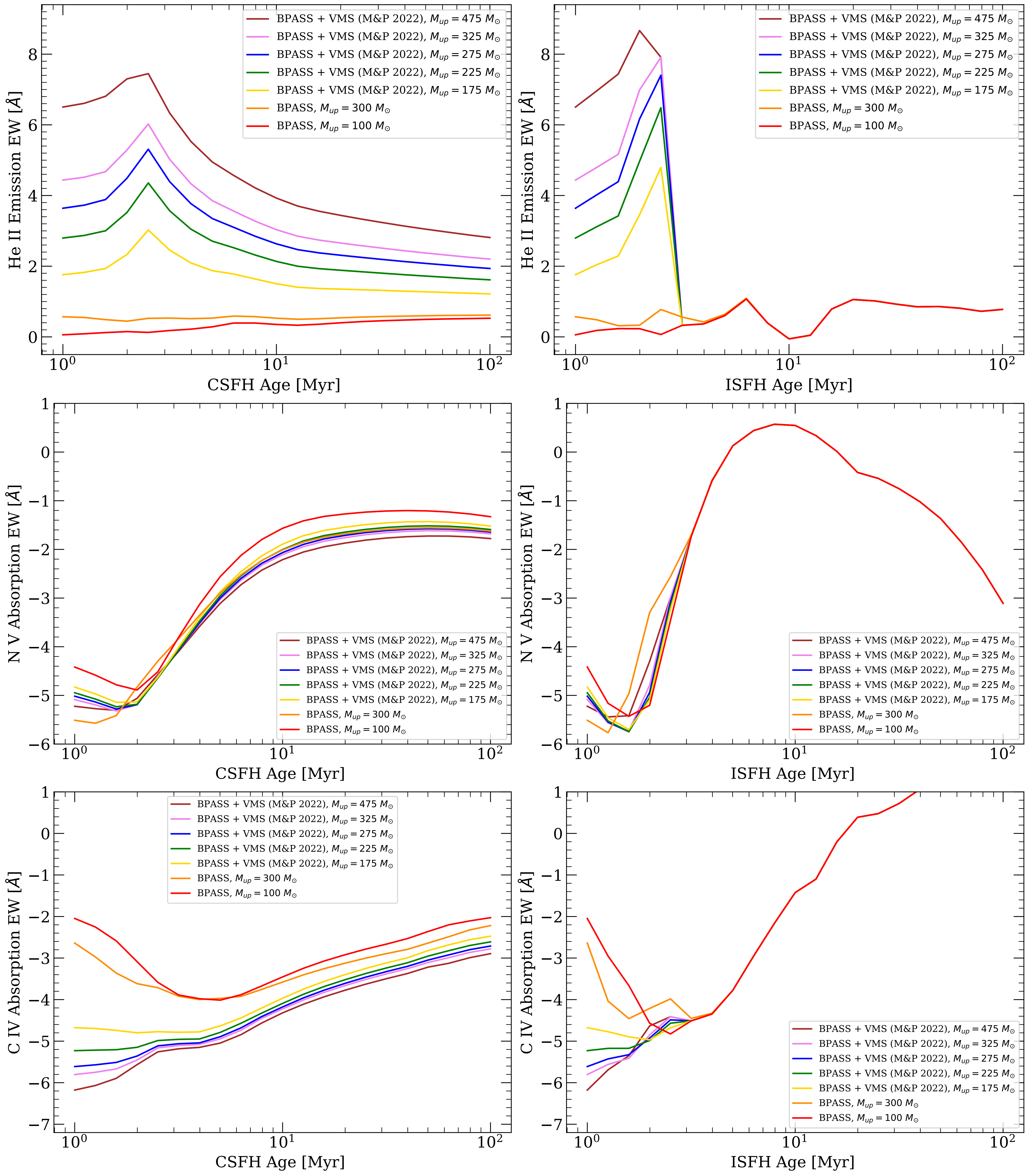

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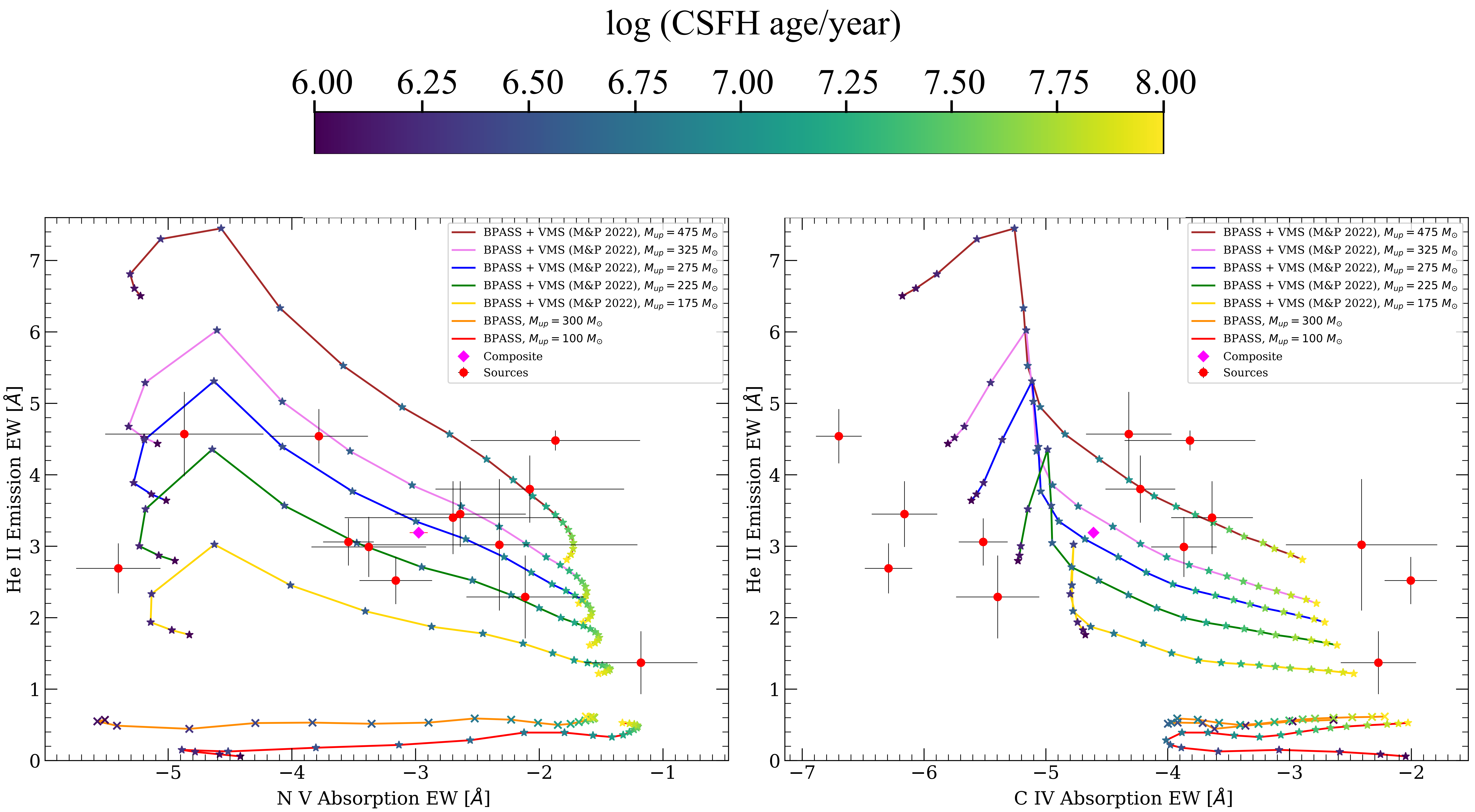

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