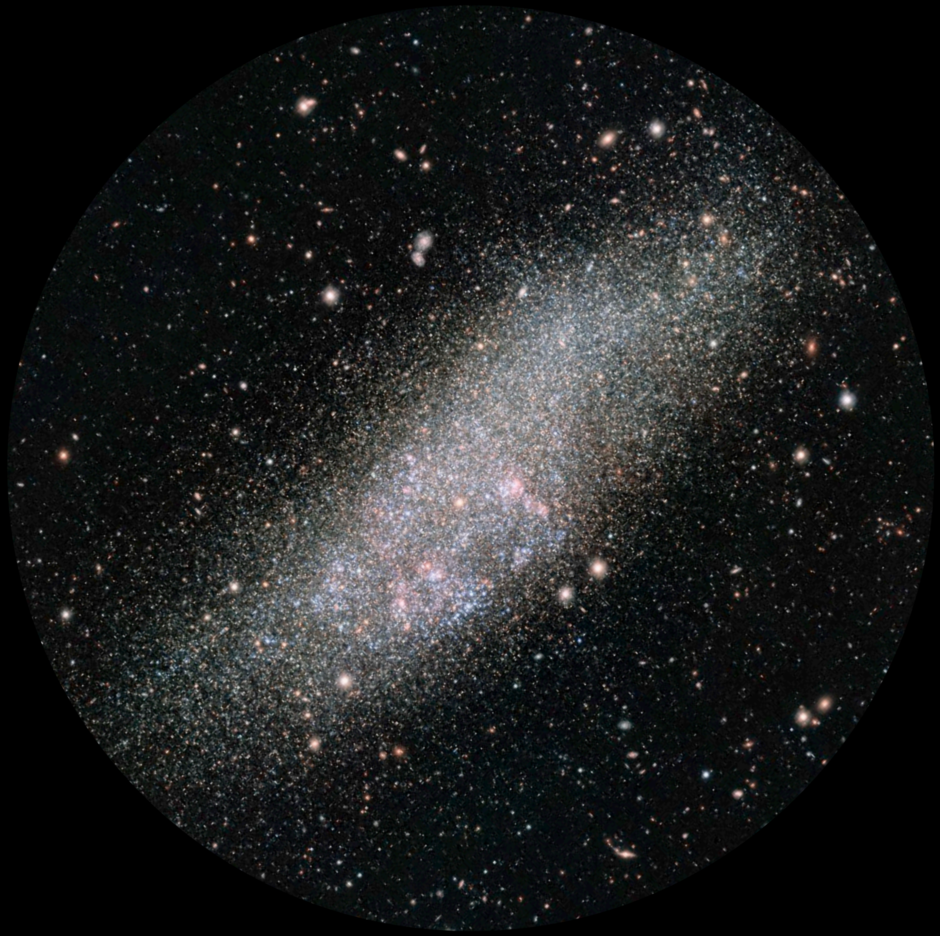
Local clues to understanding stellar feedback and ionizing photon production in the early Universe



Peter Senchyna (Carnegie Fellow, OCIW)

Lyman 2023 — 20 April 2023

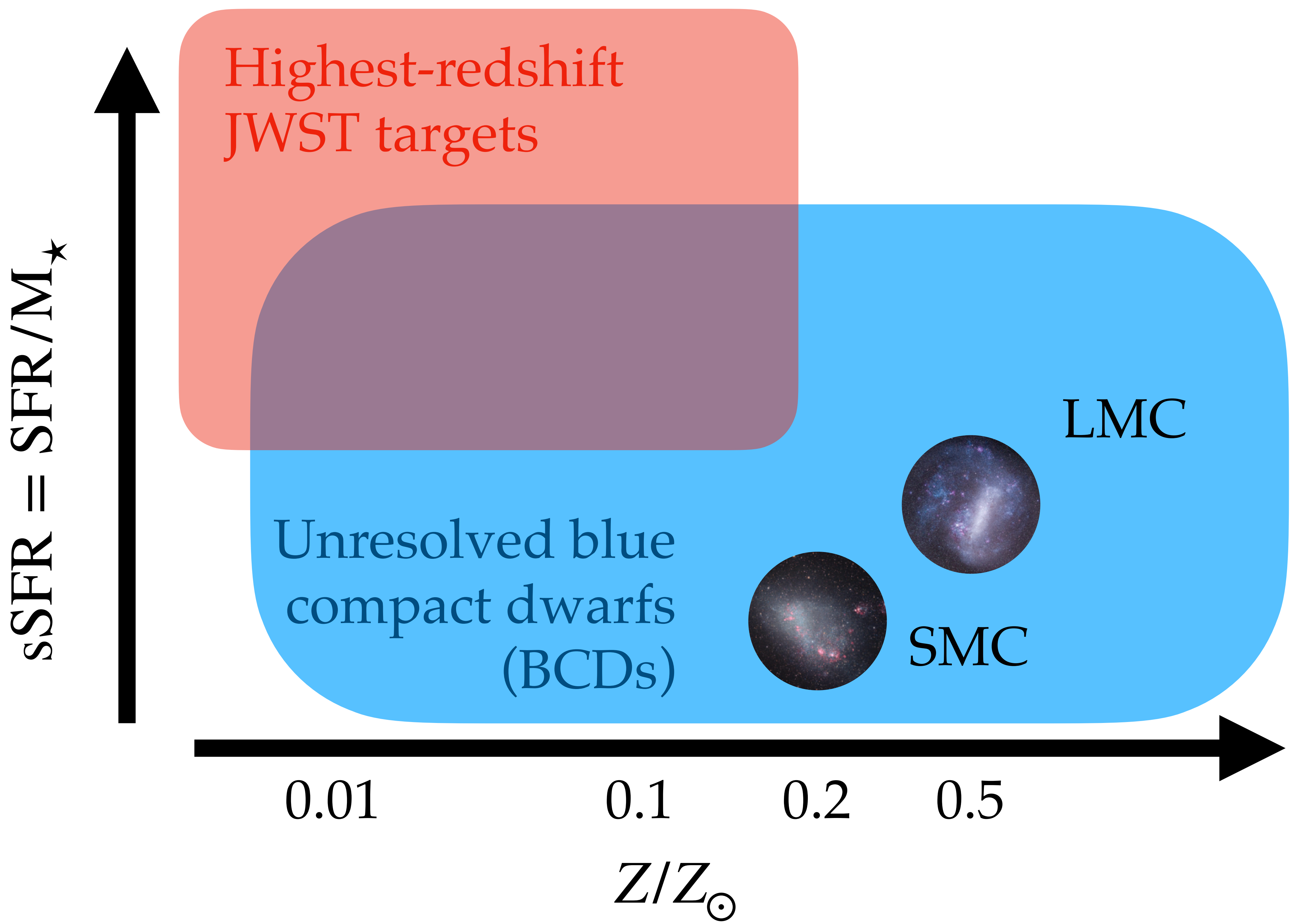
with Ylva Götberg, Maude Gull, Adele Plat,
Dan Stark, Dan Weisz, Nathan Smith, Maria Drout, Gwen Rudie, Drew Newman,
Stephane Charlot, Matilde Mingozzi, Bethan James, Danielle Berg, John Chisholm

A new era of quantitative spectroscopy at the highest redshifts:

Rest UV-optical JWST spectra promise to reveal:

- physical conditions of gas and star formation
- star formation and mass assembly histories
- feedback (shaping galaxies & the IGM)

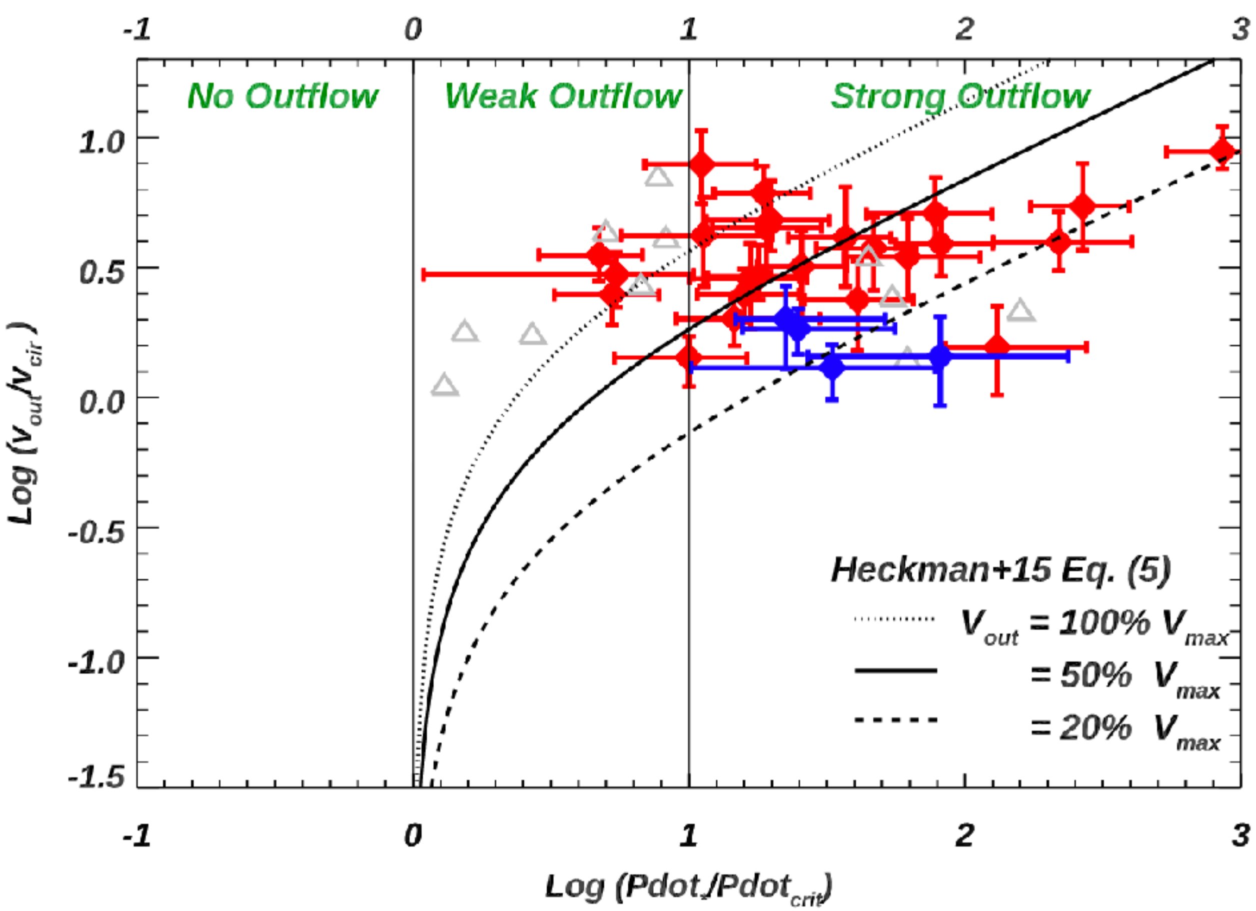
Work at high-*z* is *always* in conversation with what we know at $z \sim 0$

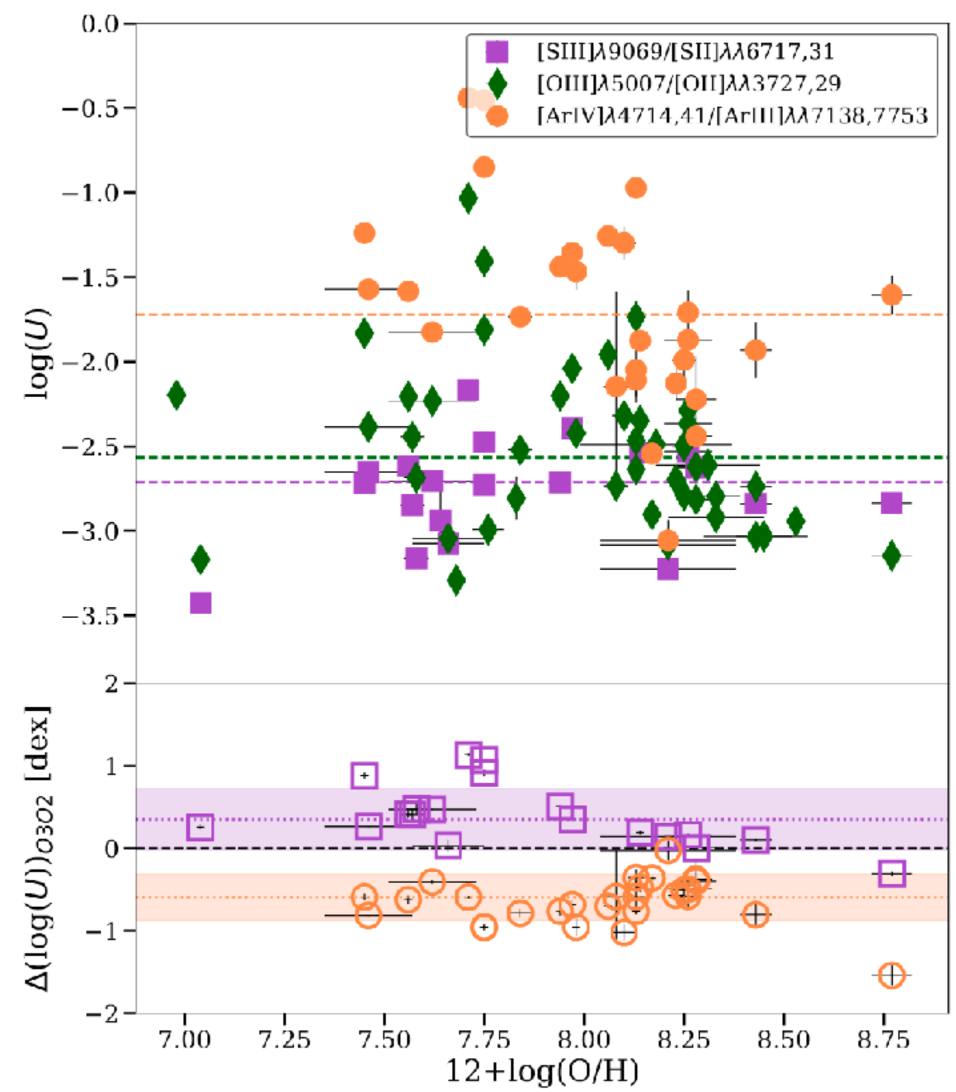


And what we know about massive stars and the galaxies they dominate is *incomplete*, especially at very low-metallicity

HST / COS observations of local BCDs have shed light on a wide range of physics in these systems:

- Lyα + LyC escape (e.g. Izotov+16,18, Jaskot+19, Flury+22a,b, Saldana-Lopez+22)
- Feedback & outflows (e.g. Chisholm+17, **Xu+22**,23)
- Highly-ionized nebular gas conditions (e.g. Berg+21, **Mingozzi+22**)

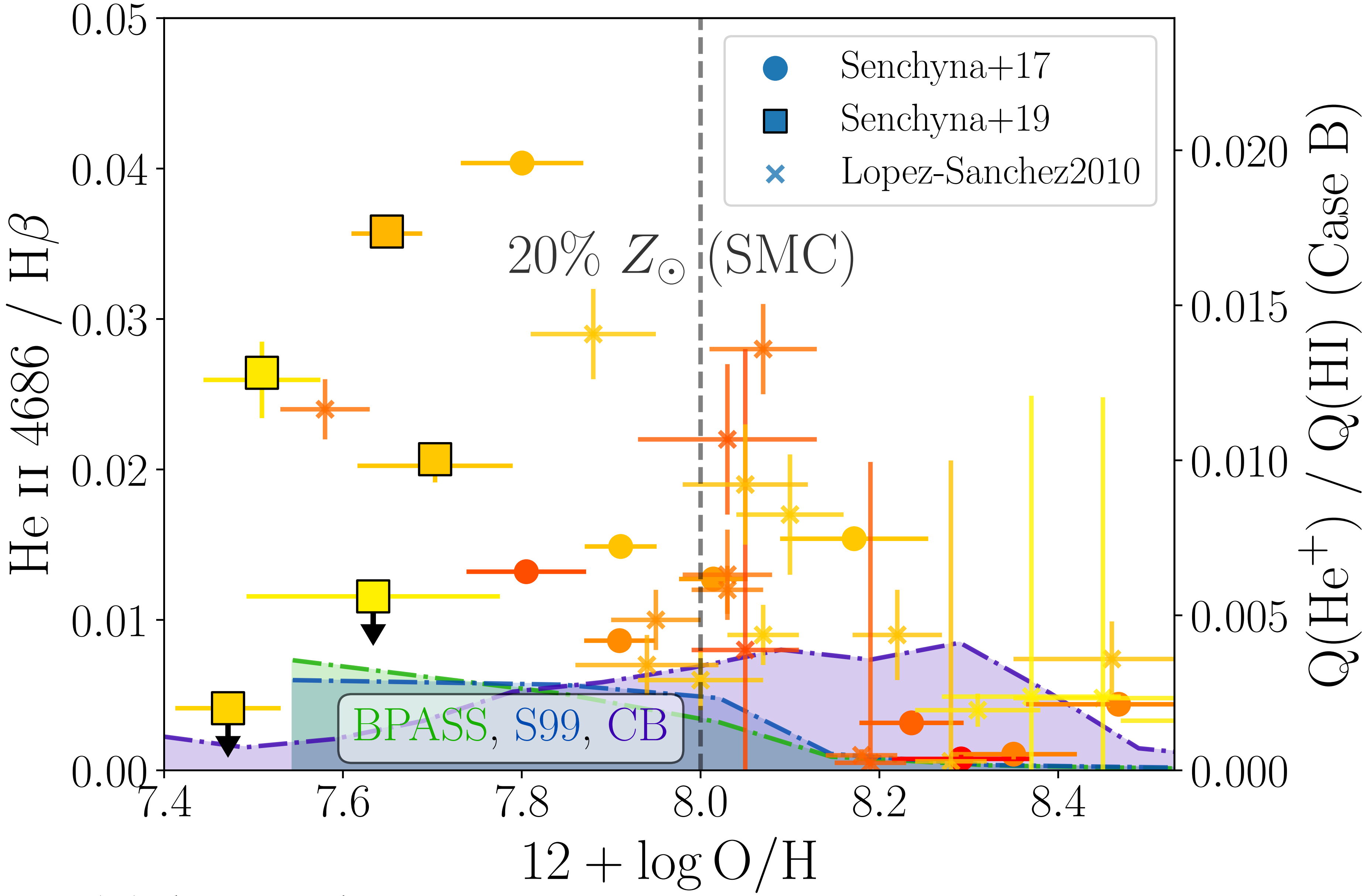




And: key insight onto **massive star properties + feedback at low-*Z***

And: key insight onto massive star properties + feedback at low-Z

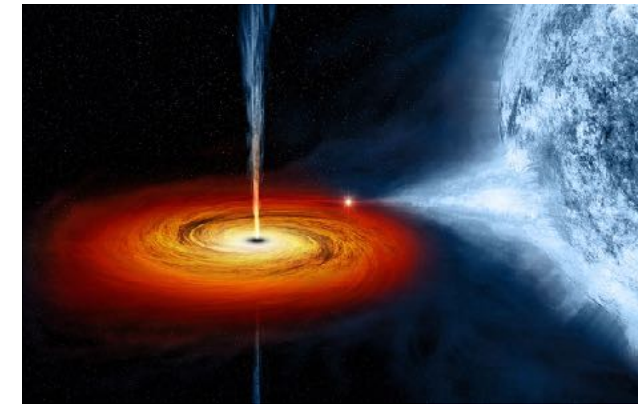
Two notable results:



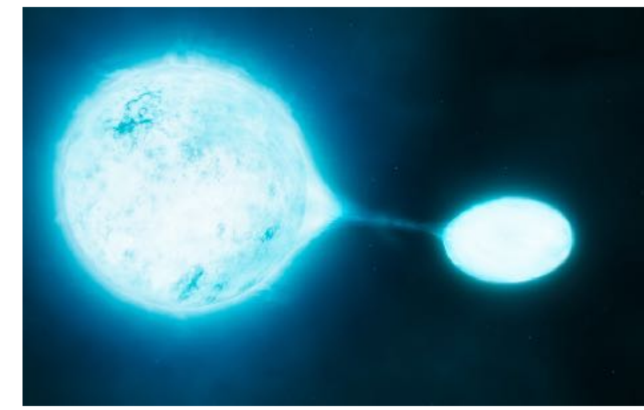
e.g. Garnett+1991, Izotov+2012(…), Shirazi&Brinchmann 2012, Kehrig+2015, 2019, Schaerer+2019, Gray+2019, Berg+2021, Simmonds+2021, **Senchyna**+2017, **2019**, 2022a

Result I: Nebular He II (+ other high-ionization line detections) -> some source(s) of hard ionizing radiation are **missing/not-correctly-reproduced** in our best models

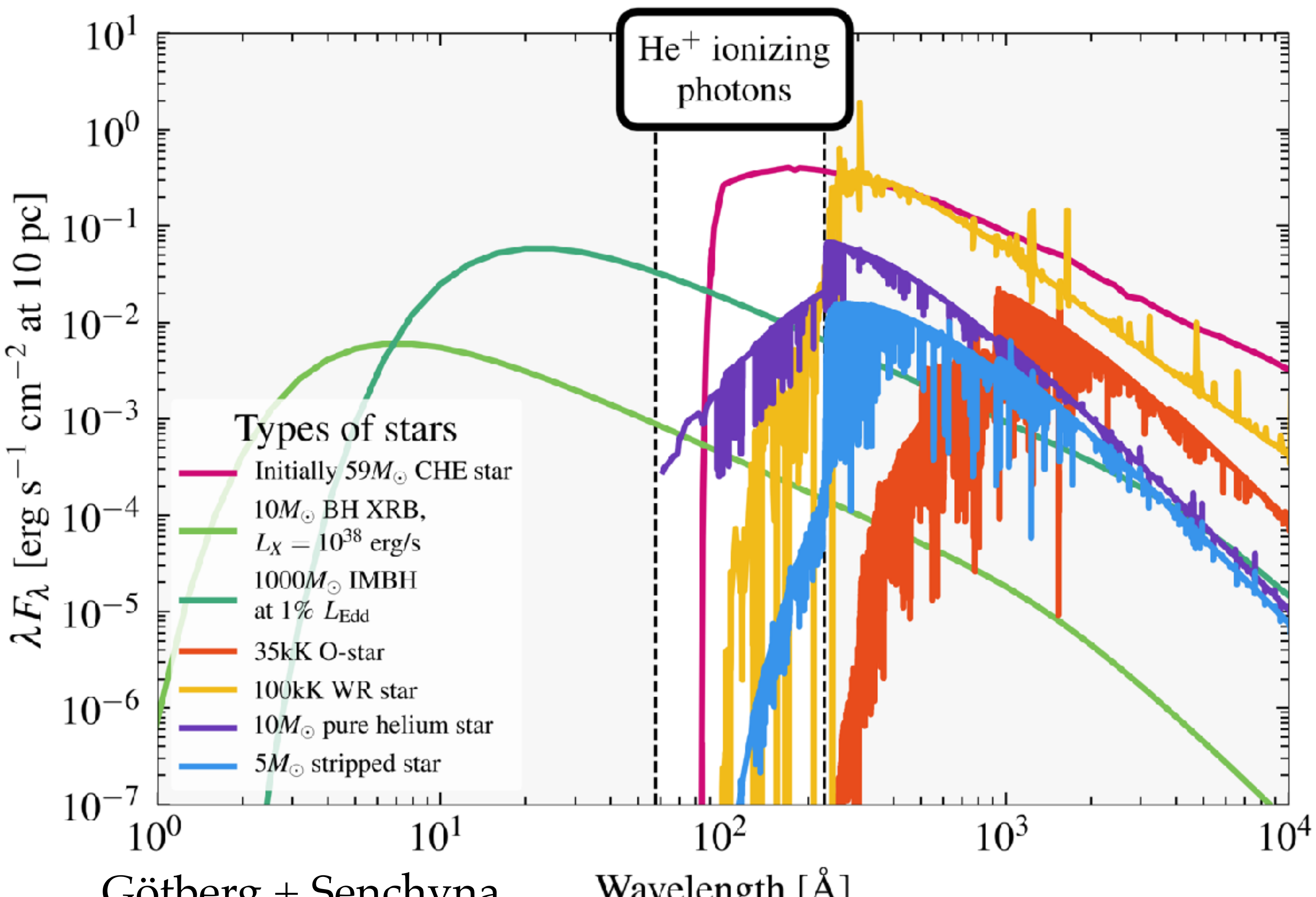
Many candidate sources; several linked to uncertain **binary evolution**:



- accretion onto compact objects in **X-ray binaries**?
  [e.g. Schaerer+19, Simmonds+21, but see **Senchyna+20**, Saxena+20, Kovlakas+22]



- stars **stripped or spun-up** by binary mass transfer?
  [e.g. Szécsi+15, Götberg+17,19, Stanway+2020]

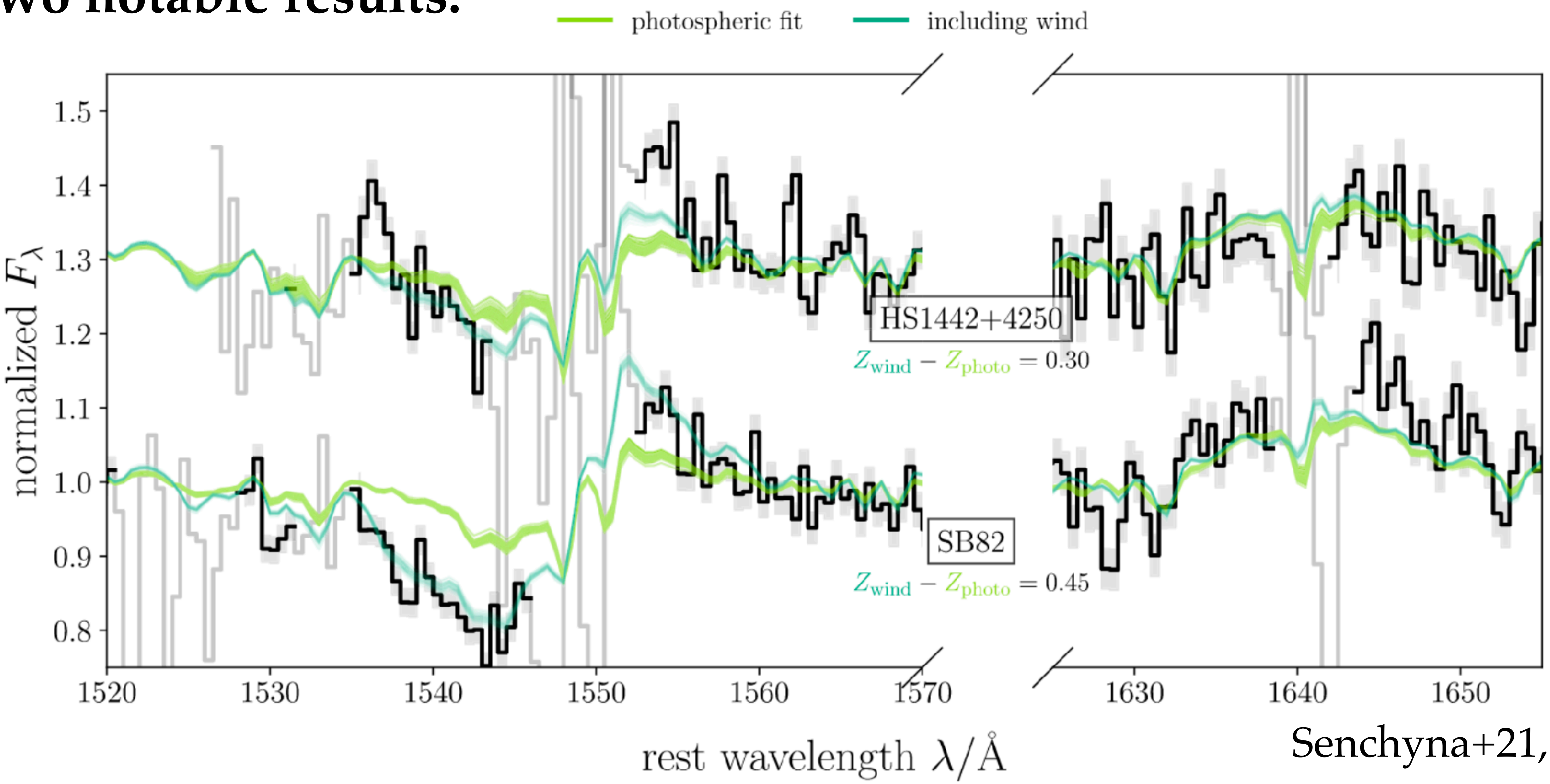


Götberg + Senchyna

Both are generally missing from pop synth models; but could have wide-ranging impacts at high-z: from biasing results of **nebular-only analyses**, to potentially driving **IGM heating** and **reionization**

And: key insight onto massive star properties + feedback at low-Z

Two notable results:

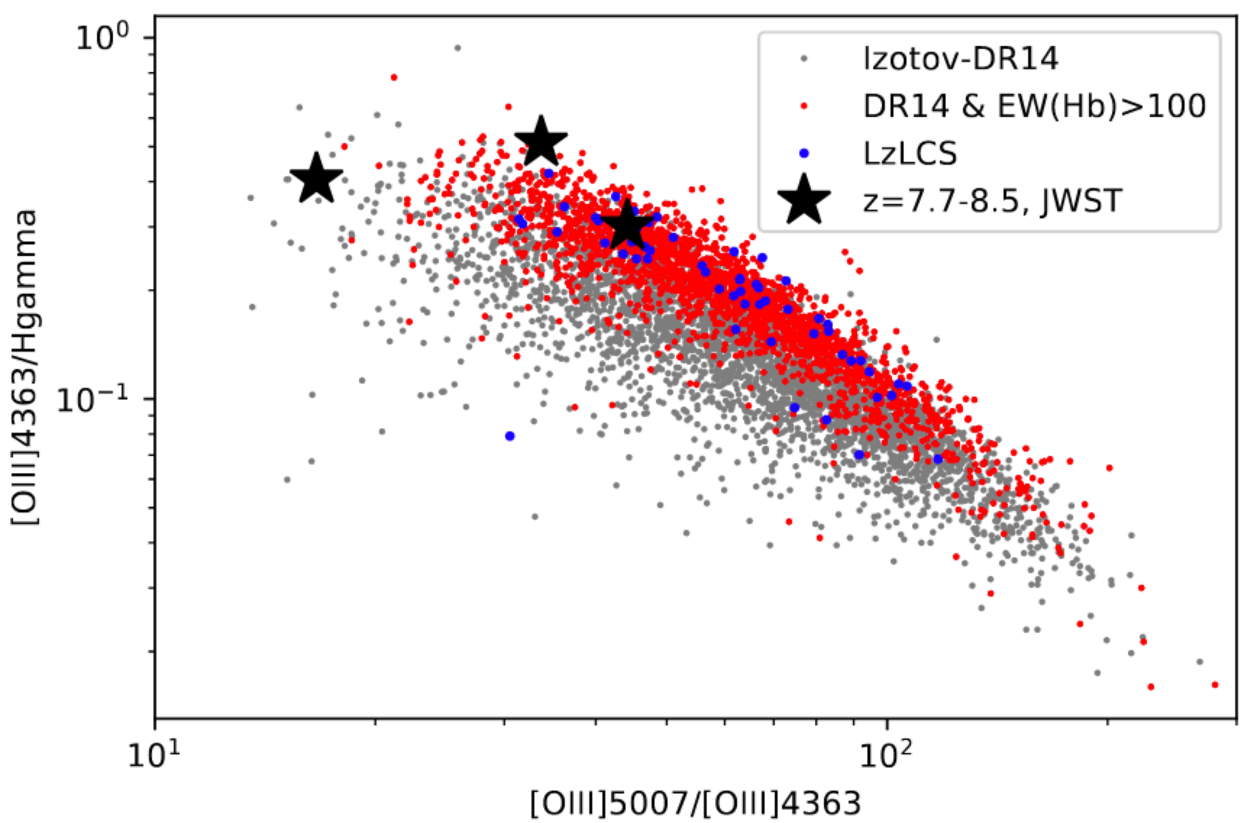


Senchyna+21, **22**

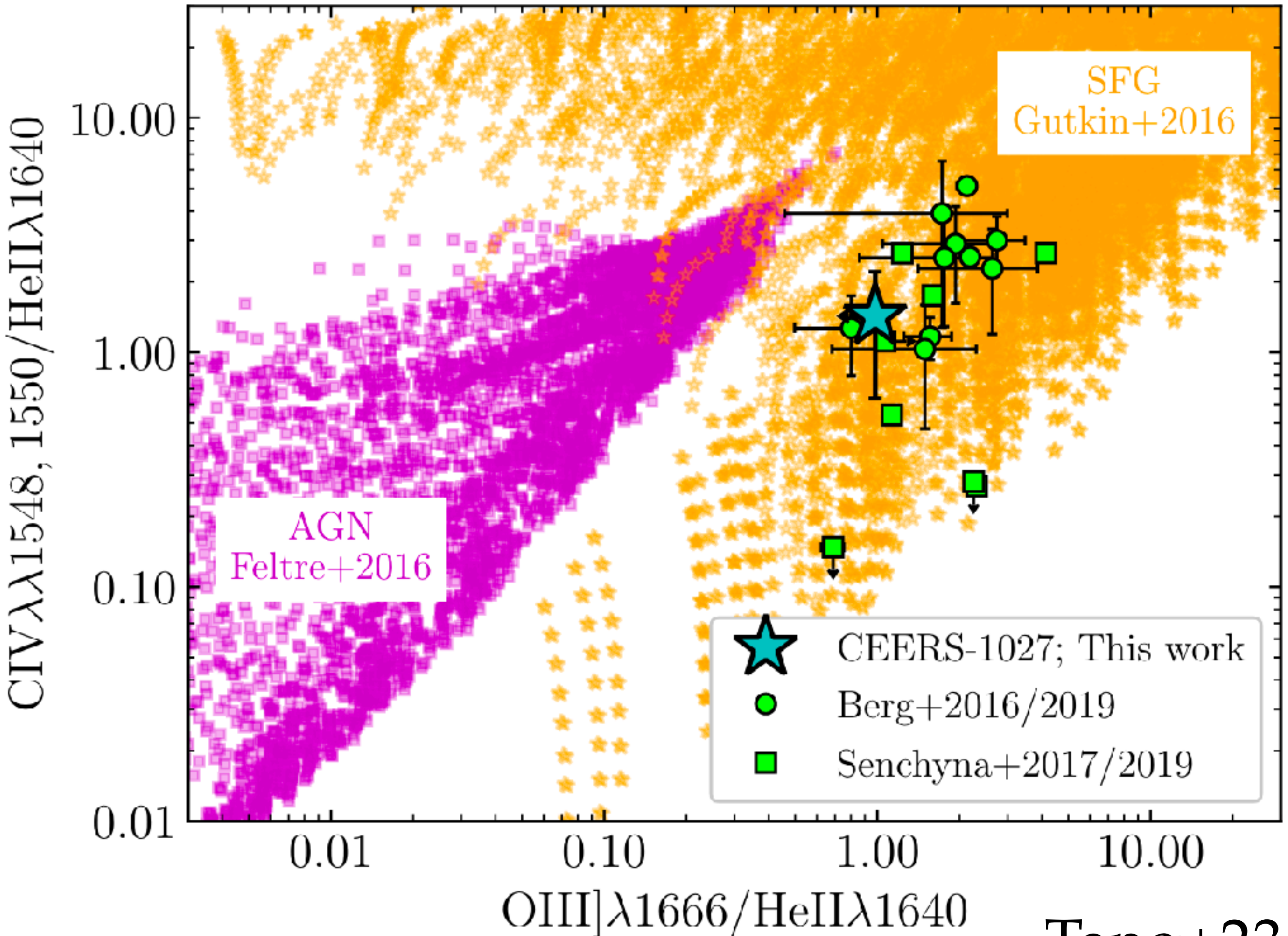
Deepest direct view of $Z/Z_\odot < 10\,\%$ very massive star atmospheres

Result II: Simultaneous modeling of nebular emission + the underlying massive star continuum reveals discrepancies; **missing luminous stars**, or **mis-modeled stellar winds**?

At minimum, these $z \sim 0$ galaxies provide a useful empirical reference point to high-z observations: **how well do they do in this role?**



Schaerer+22

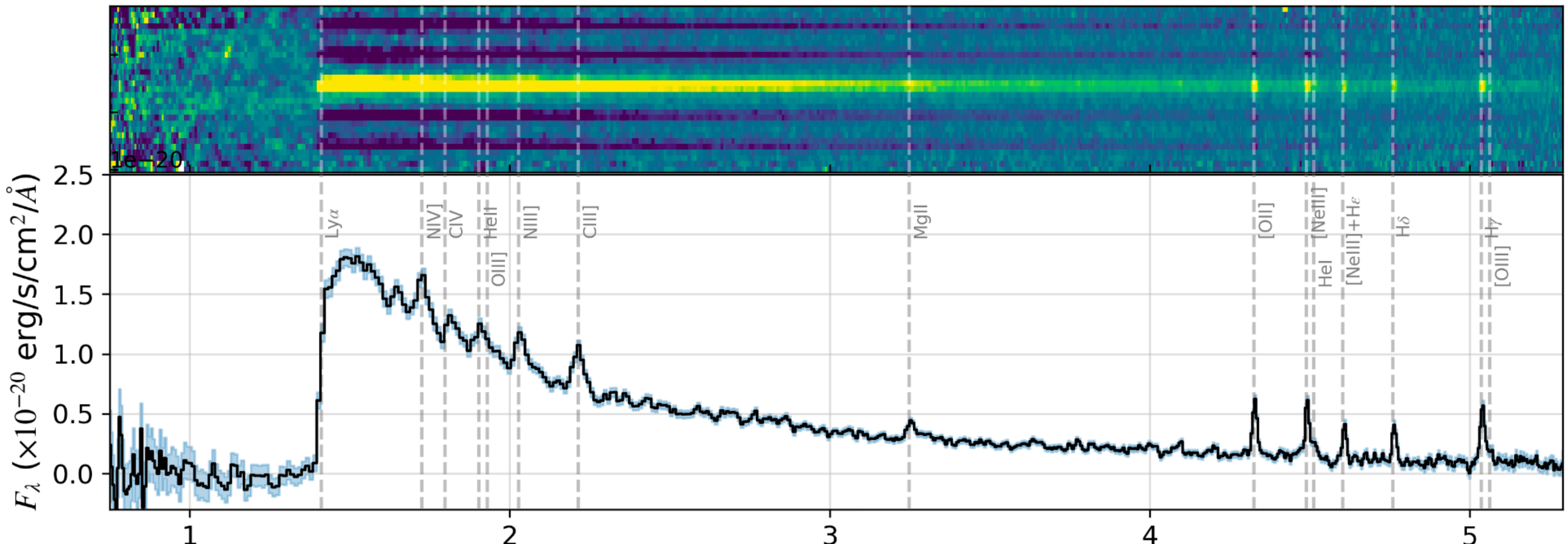


Tang+23

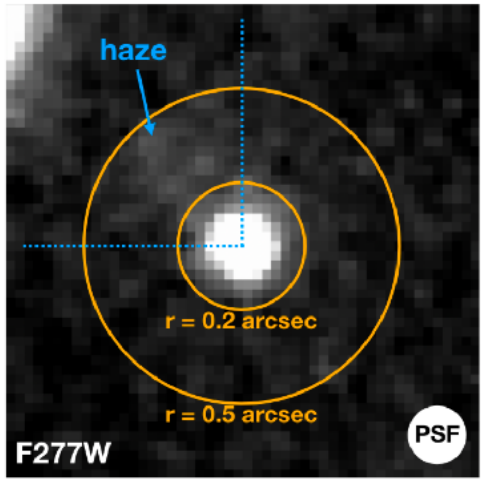
These galaxies are **highly-ionized** and host to **hot, metal-poor gas;** broadly similar to $z \sim 0$ BCDs dominated by metal-poor young stars

But also, some striking differences:

GN-z11: a pre-JWST redshift record holder, and extremely luminous `Universe breaker'

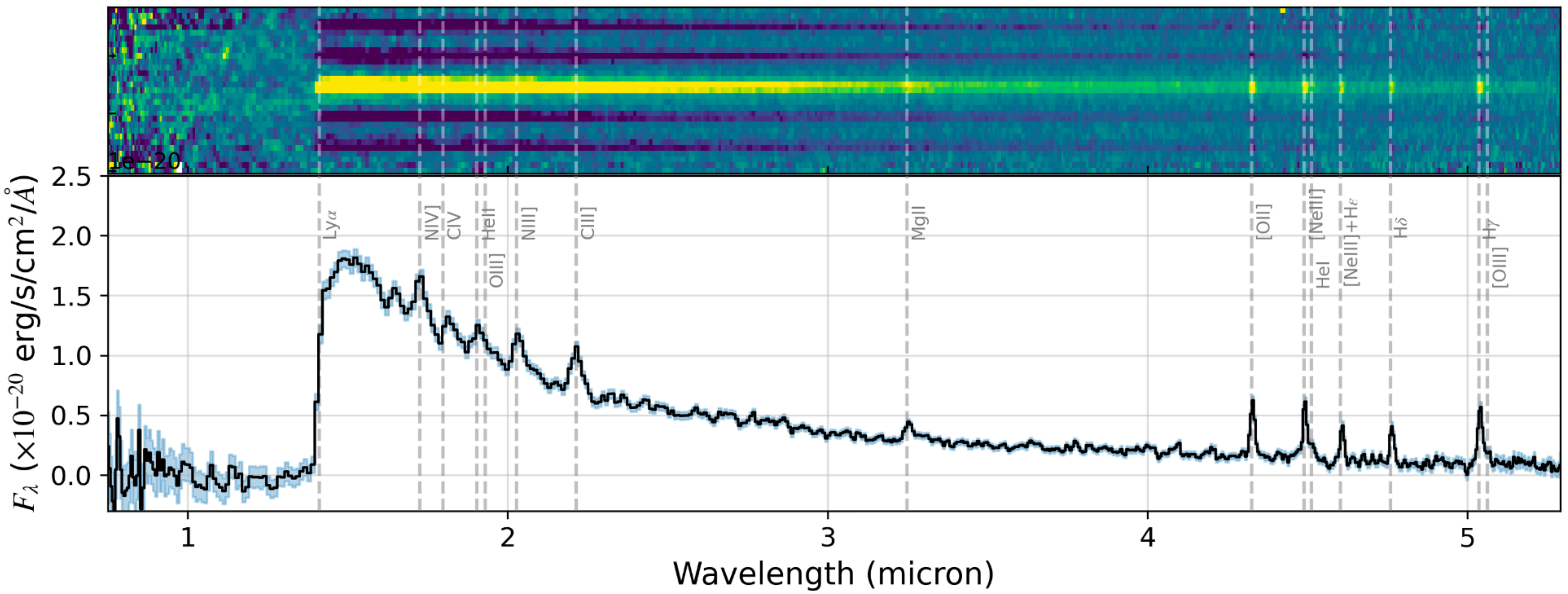


Bunker+23, Tacchella+23



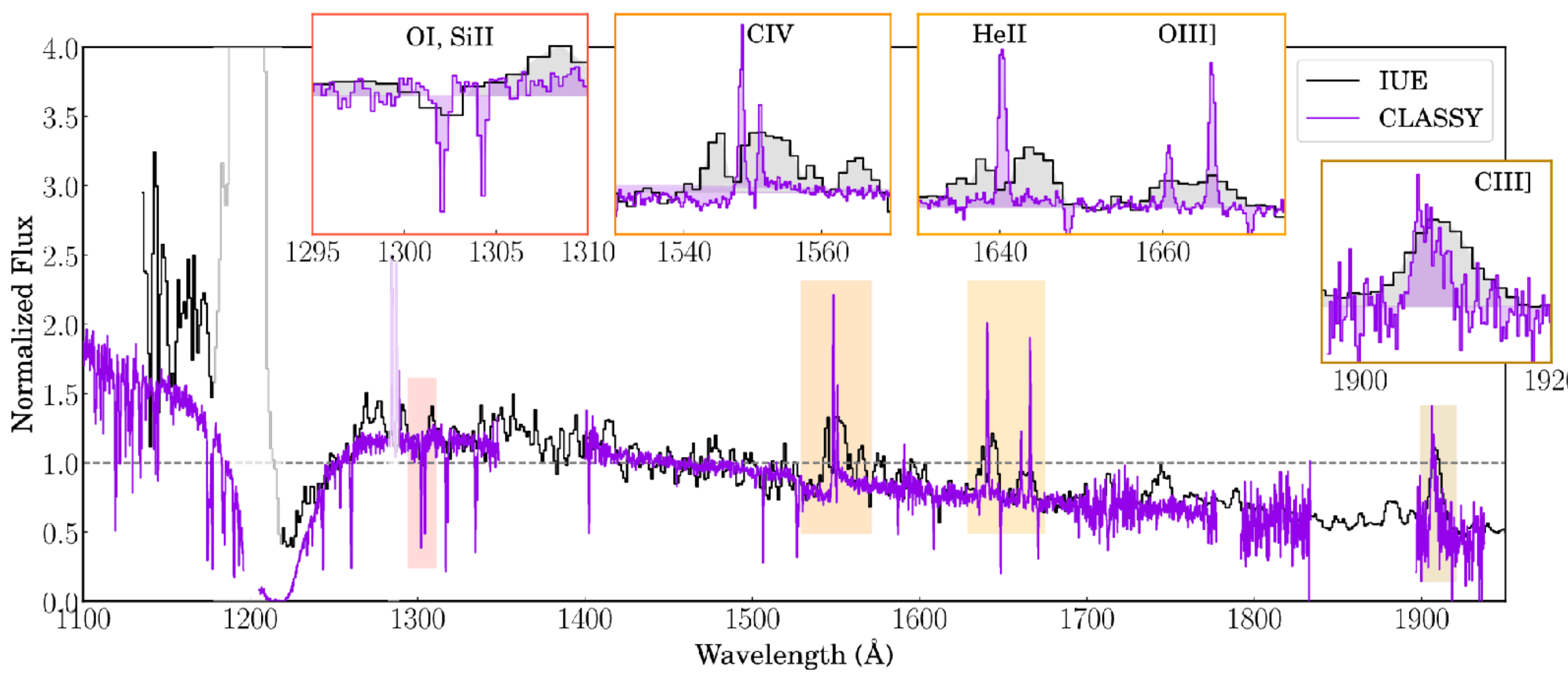
JWST/JADES confirms: essentially unresolved compact clump at $z = 10.603$; and reveals an **extremely weird** spectrum!

Most prominent lines are **N IV]**, **N III]**, and C III]



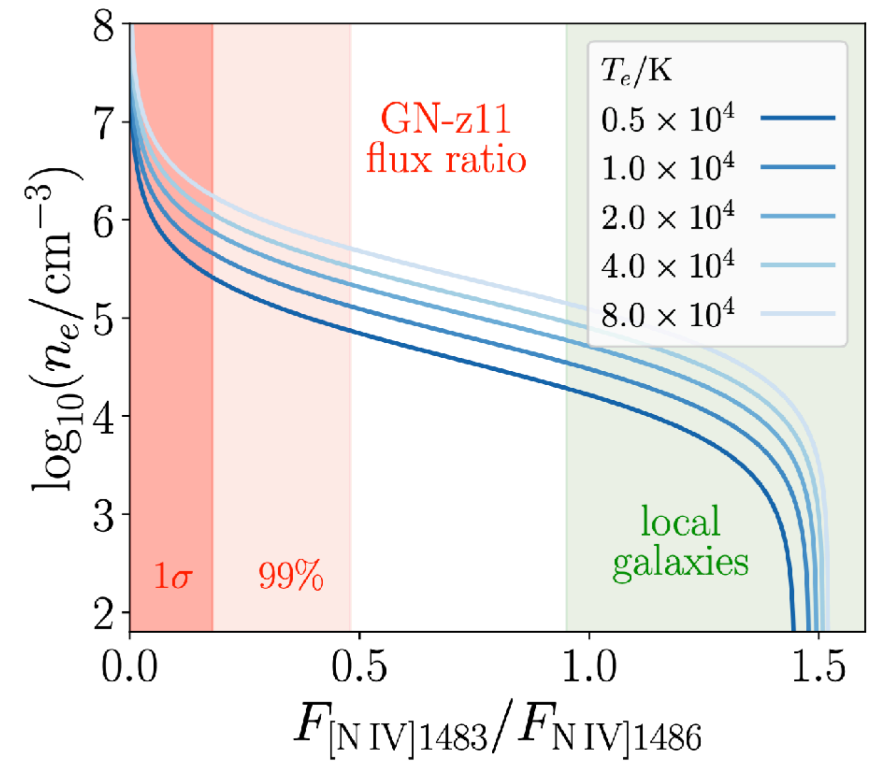
strong N IV], N III] are extremely rare—non-existent in local samples

Berg+22

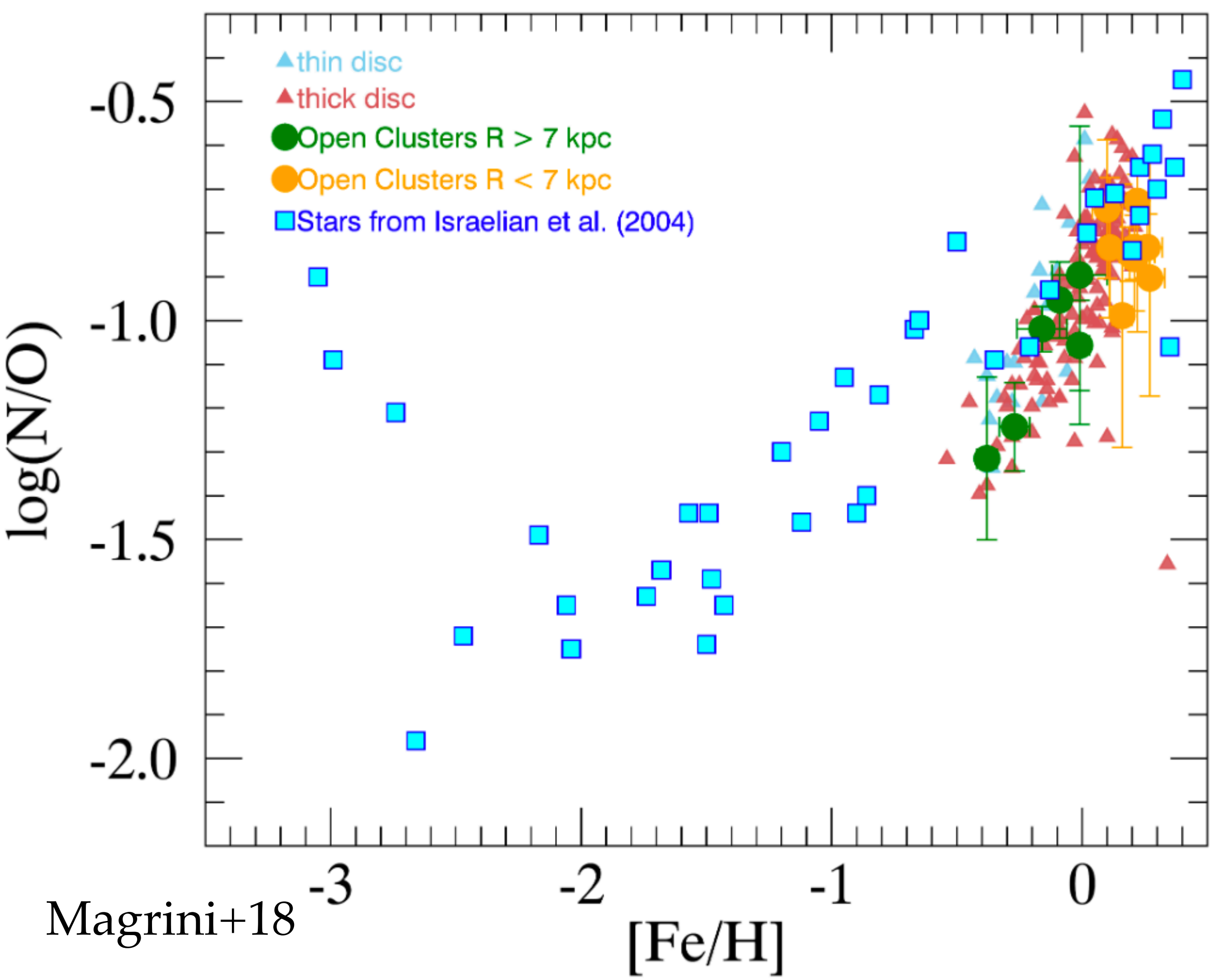


Detailed photoionization modeling confirms: this emission requires extremely **nitrogen-enriched** gas, with **[N/O]=+0.5**; and extremely **dense** gas, with $n_e \gtrsim 10^5$ cm^{-3}
- see Adele Plat's talk!

(Senchyna, Plat+23 submitted; see also Cameron+23)



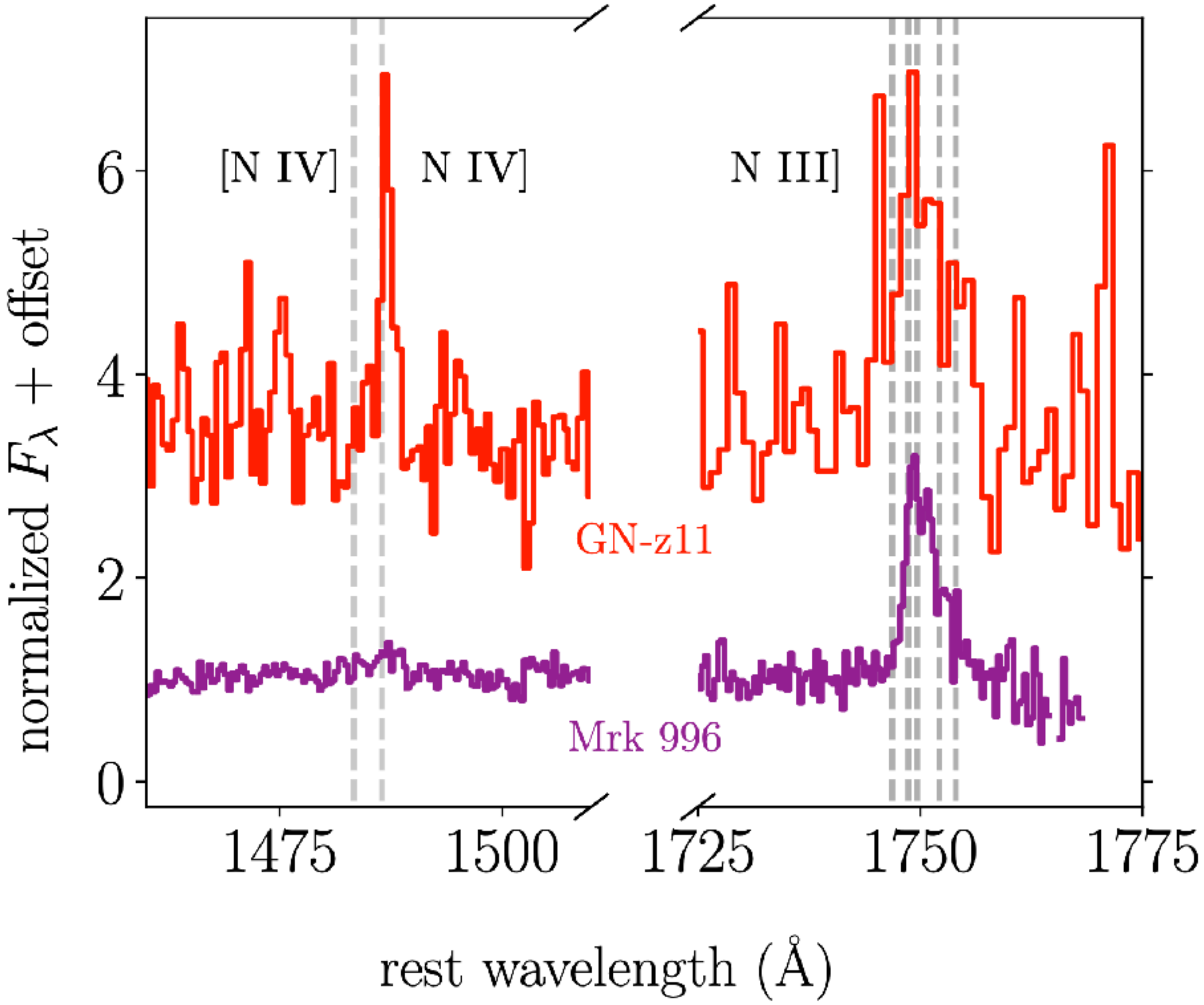
Why is this so surprising?



Magrini+18

Nitrogen follows a very tight correlation in the local Universe:

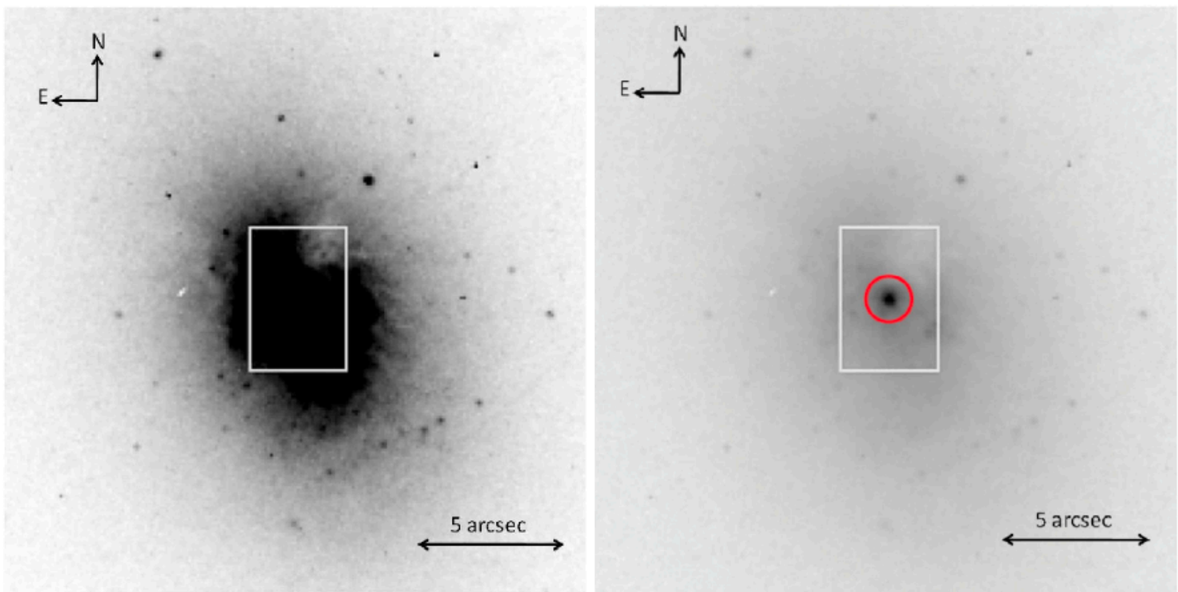
- low N/O at low-Z,
- increase in N/O only as O/H approaches solar
  - slow, secondary injection of CNO-processed material by AGB star winds



Senchyna, Plat+23

A single intriguing comparison point nearby: **Mrk 996**

Similar UV spectrum, though no N IV] (higher-metallicity stars?); similar N/O enhancement!



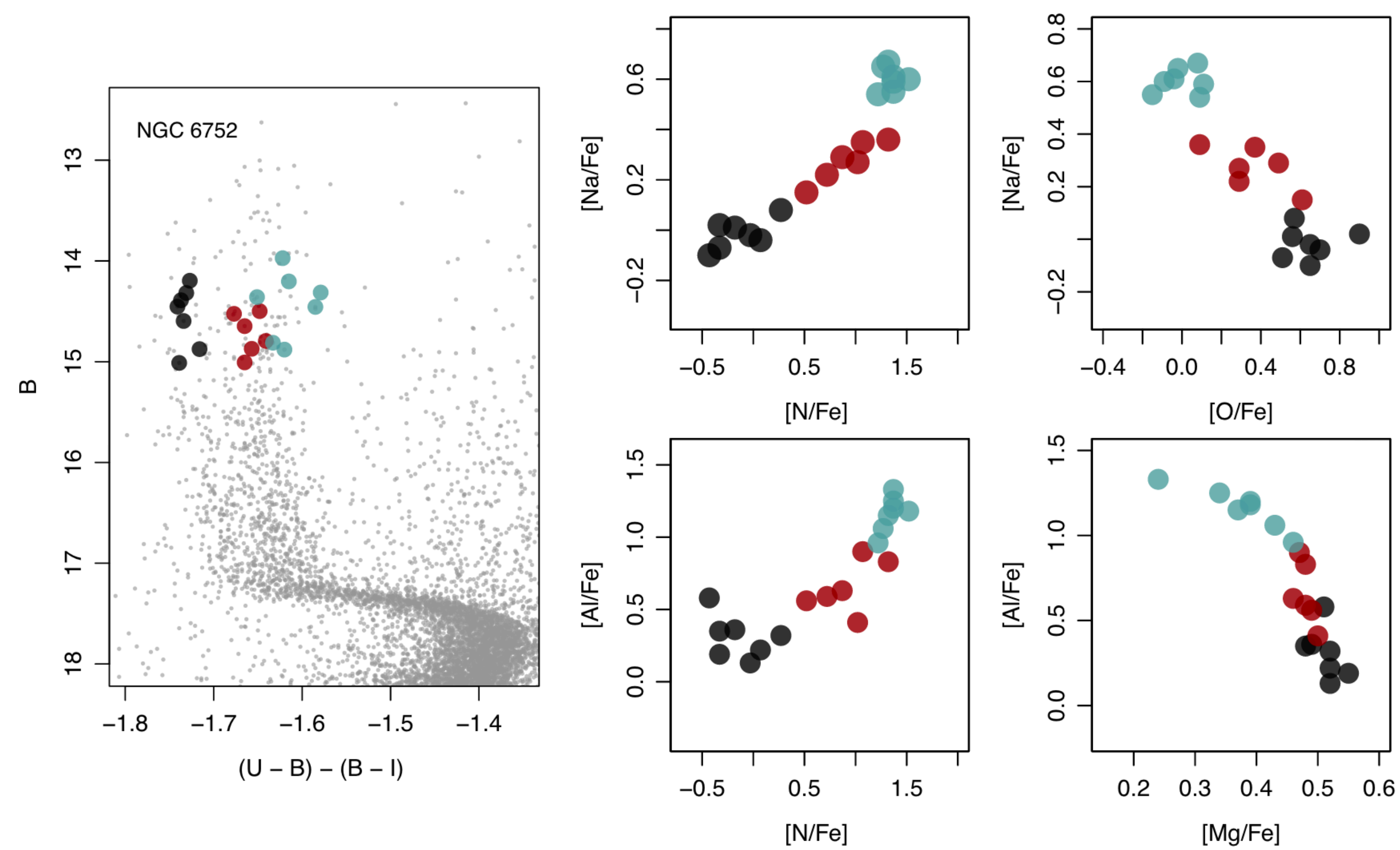
James+09, Telles+14

In this case, clearly produced by **huge concentration** of massive **Wolf-Rayet stars** (CNO-processed material from their winds)

- **Extremely high SFR concentration** (likely highly-clustered star formation)

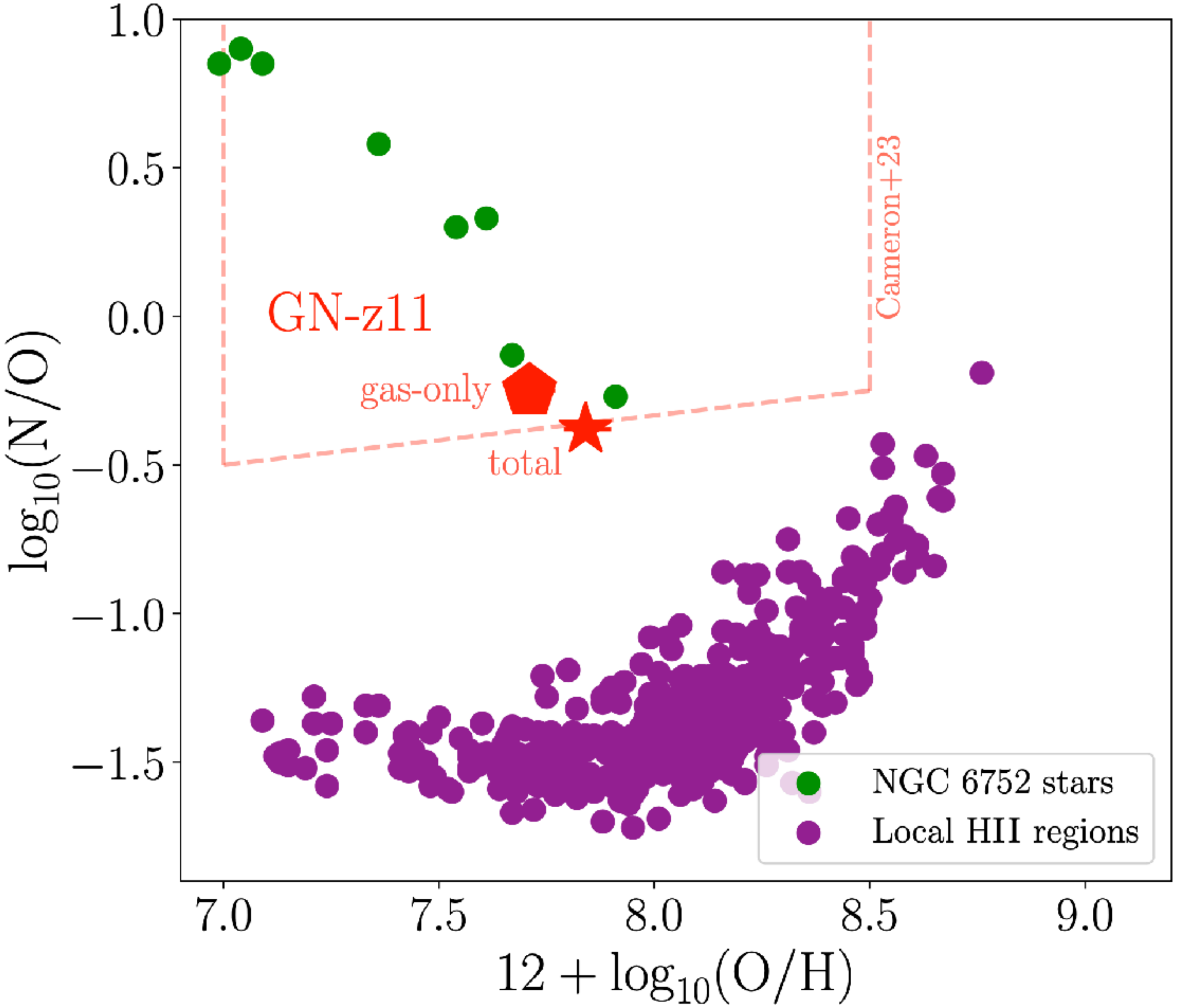
- Evidence of **extraordinarily high gas densities** (extremely compact clusters and gas)

- Gas shows evidence of **high temperature nuclear-processing** (CNO cycle)

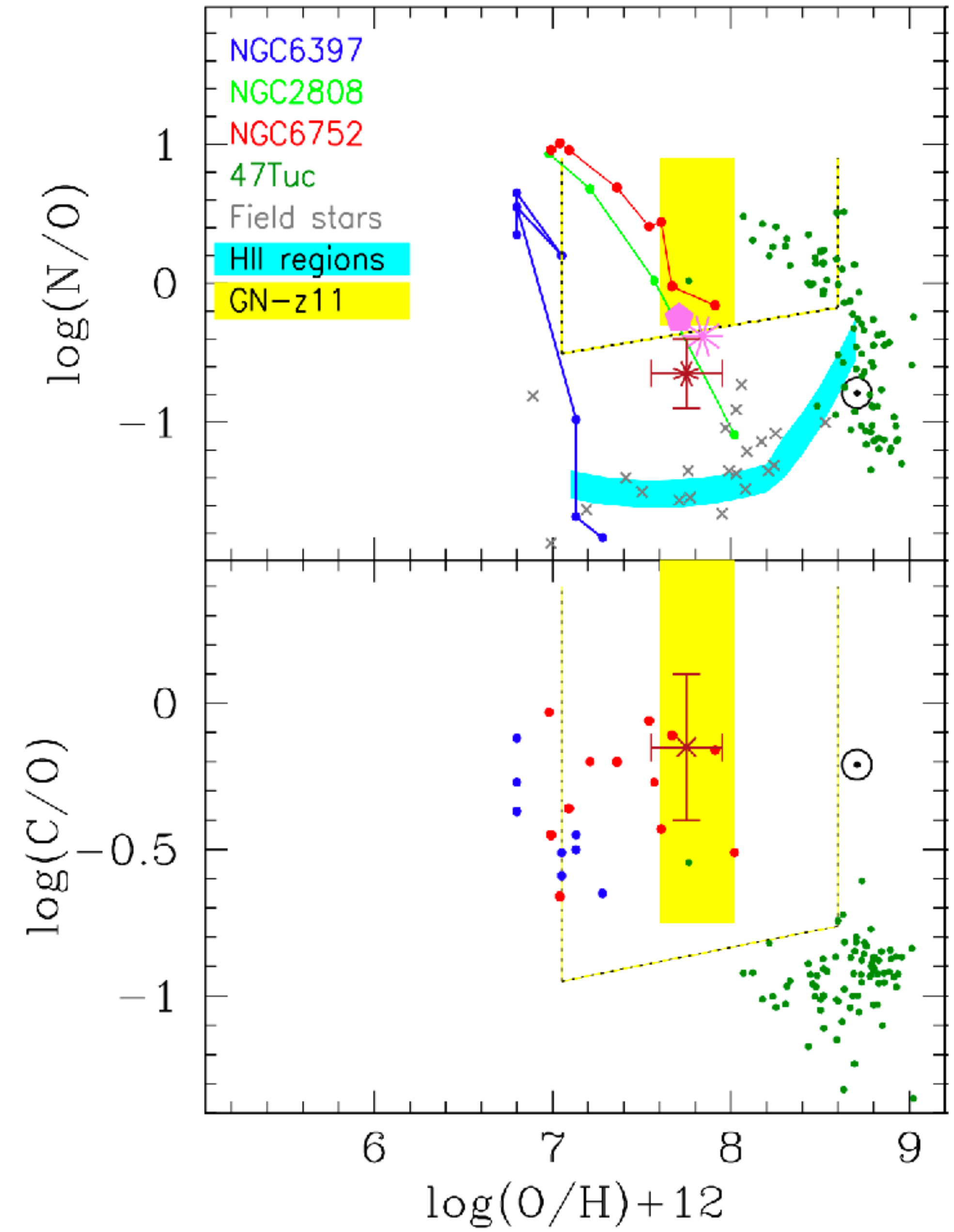


Gratton+12, Bastian&Lardo 18, …

evocative of globular cluster formation conditions



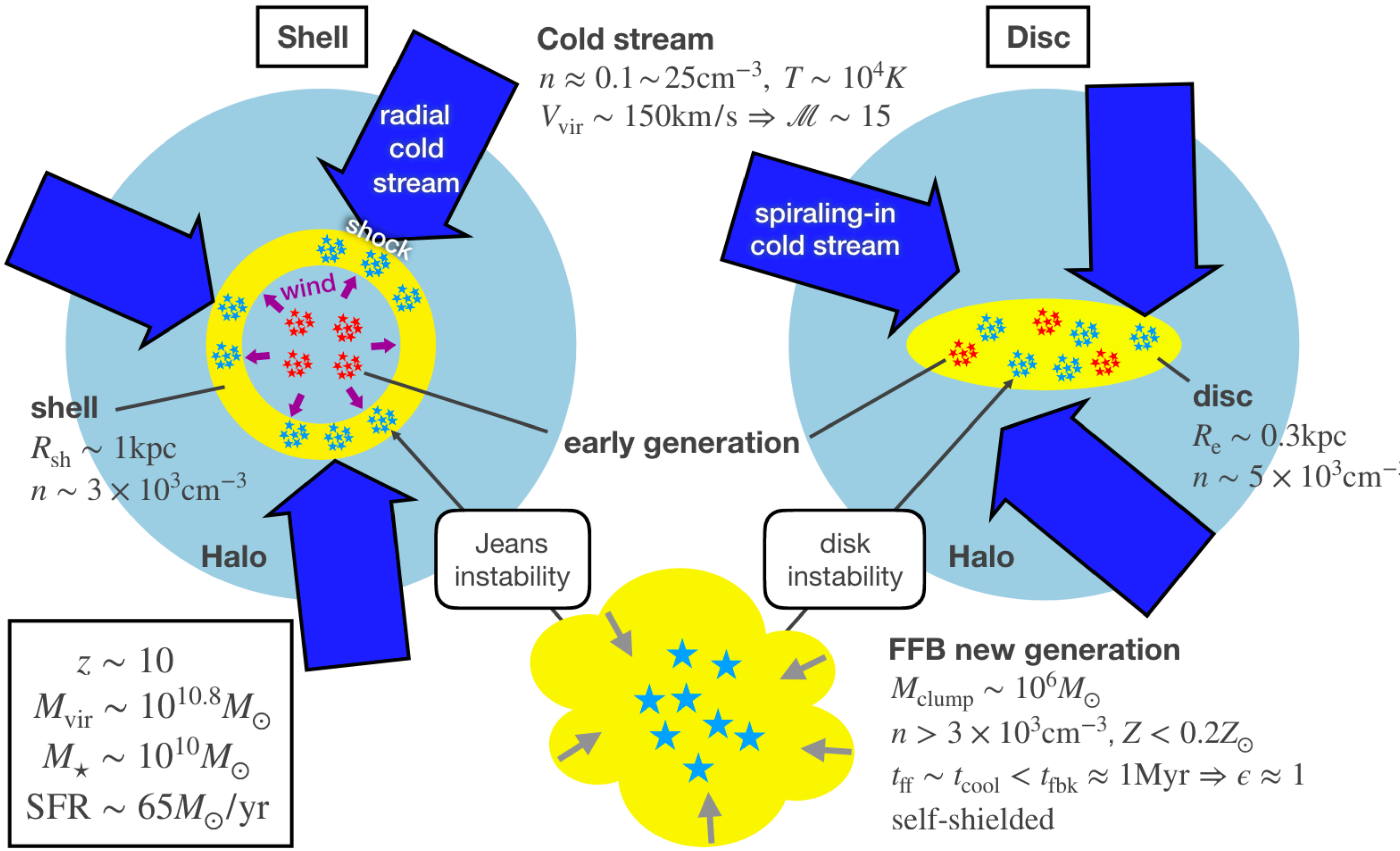
Senchyna, Plat+23



see also Charbonnel+23

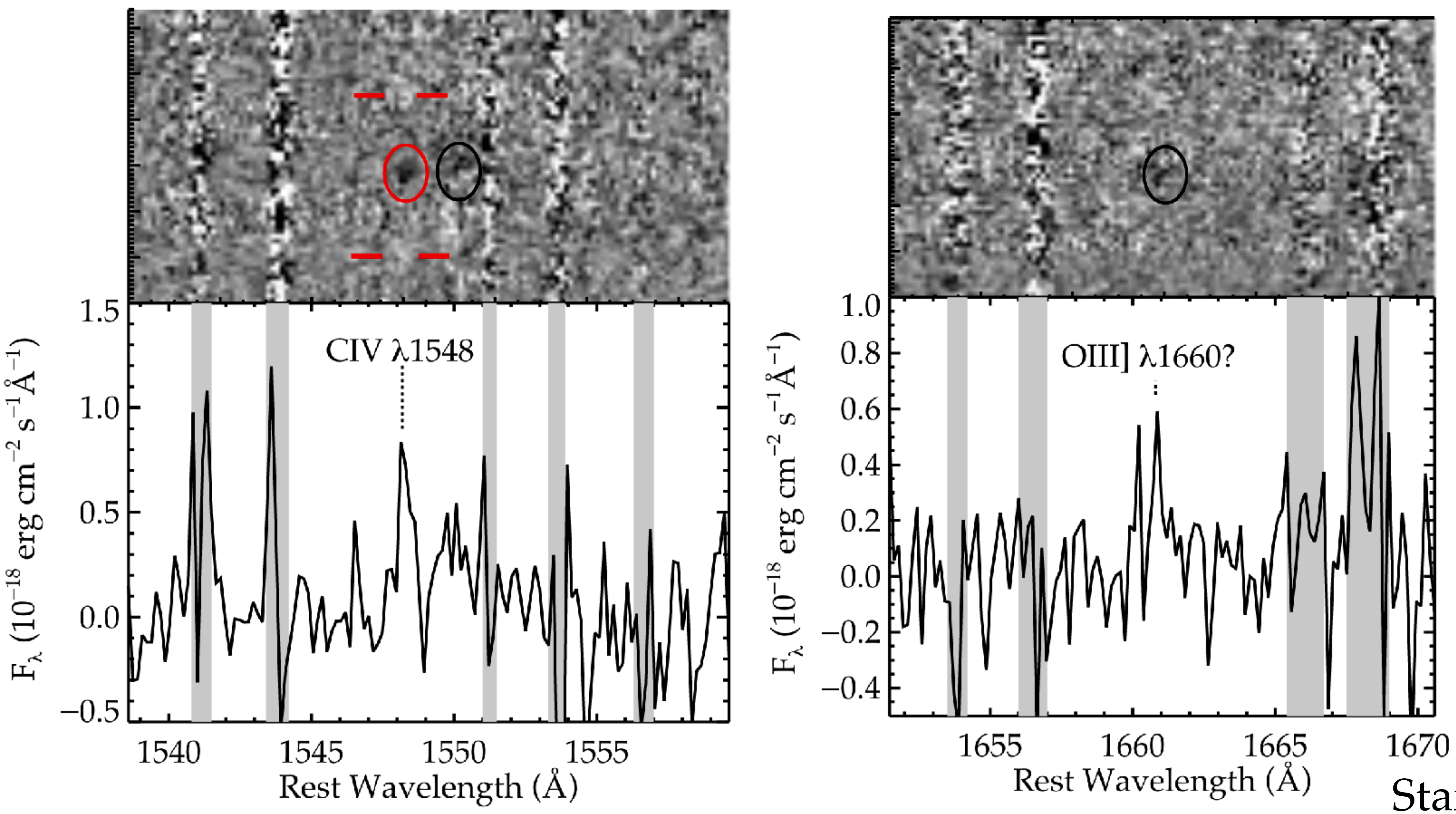
Suggests we may be directly observing a globular cluster precursor pollution event driven by metal-poor massive stars on a dramatic scale at $z = 10$

Suggestive of a mode of **extremely dense, highly-clustered star formation** rare at low-z, but linking globular clusters & anomalously luminous $z \gtrsim 10$ galaxies



Potentially related to extremely efficient *feedback-free* star formation?
$t_{ff} \lesssim 1$ Myr, overcoming SNe-dominated feedback (+enrichment);
Dekel+23

Is GN-z11 unique, or a glimpse of a new mold?

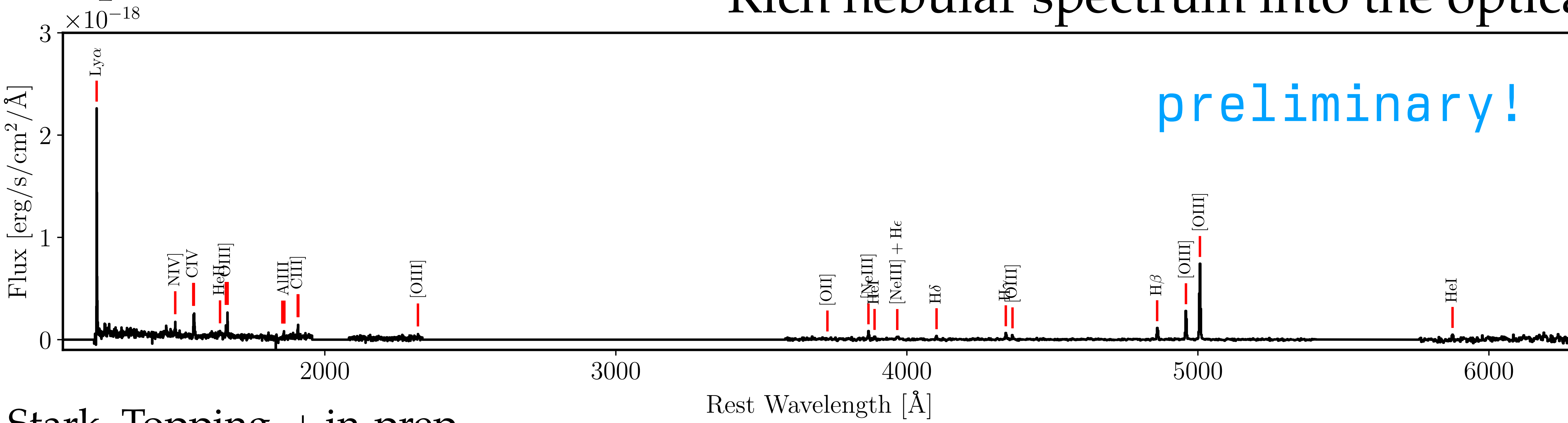


Stark+15

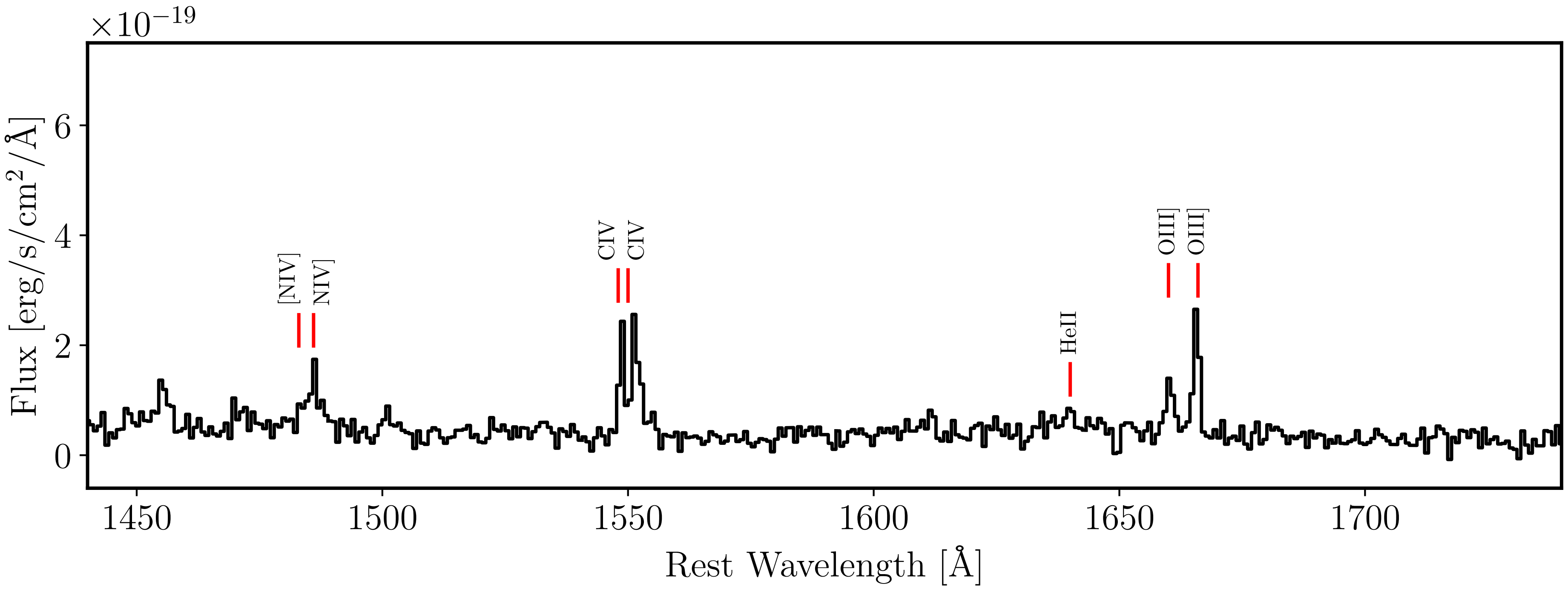
Sneak preview: NIRSpec follow-up of Keck-identified lensed C IV emitter at $z = 7.0$ behind Abell 1703

NIRSpec GO, PI: Stark

Rich nebular spectrum into the optical



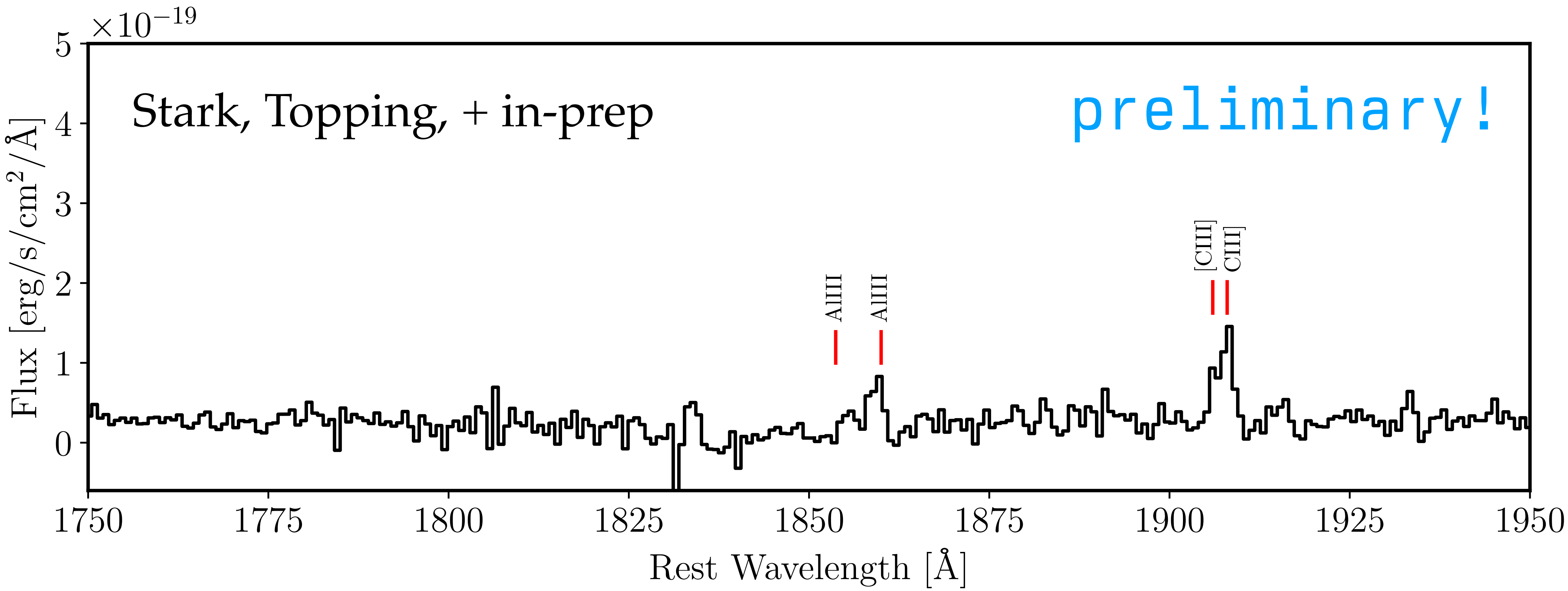
Stark, Topping, + in-prep



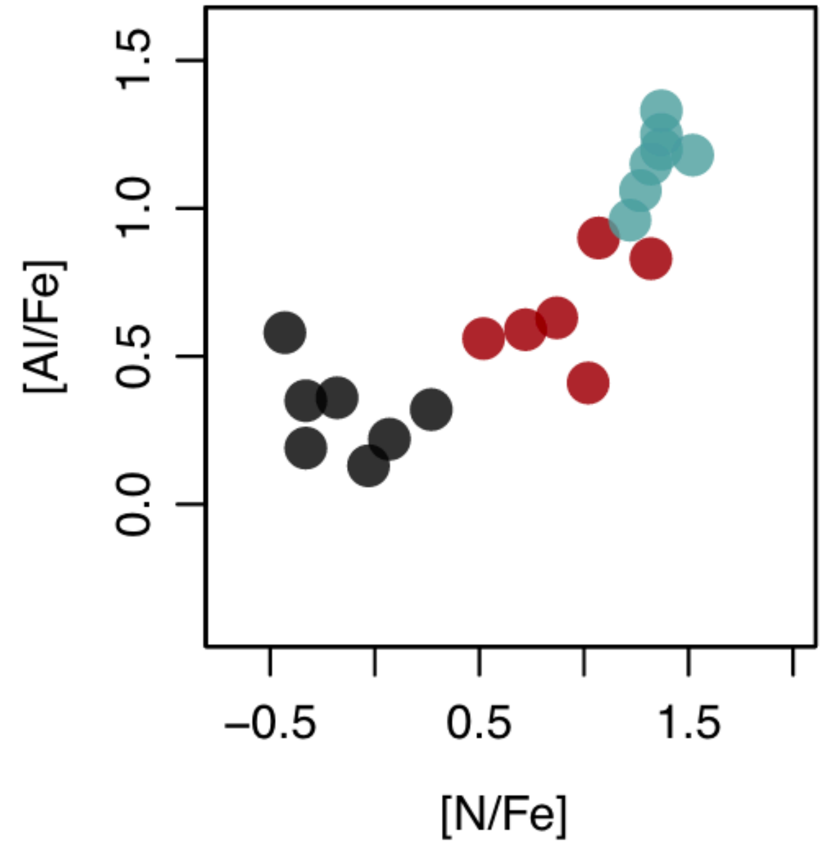
C IV is real and very prominent!

And alongside it: clear N IV] 1486 again! High-density N-enhanced gas

and alongside CIII]: possible **Al III 1854,1862** emission
- extremely rare - almost exclusively seen in ISM absorption alone



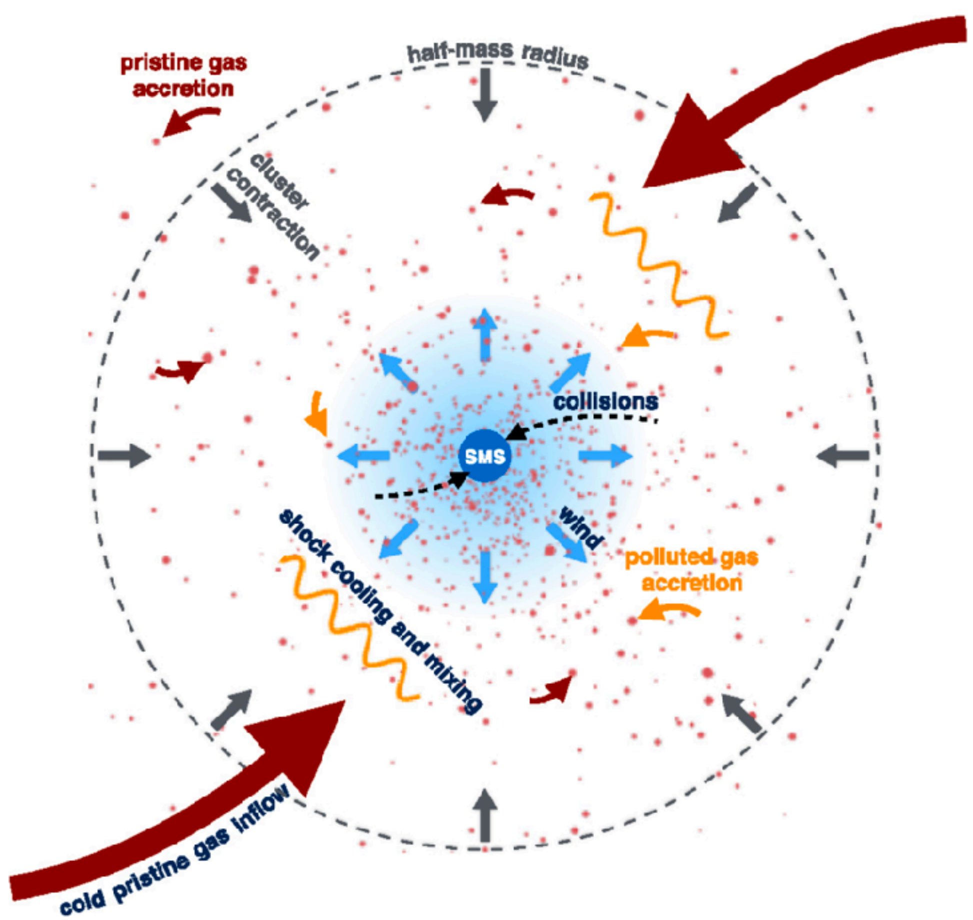
Overabundant Al? This is another key property of globular cluster stars, and evidence of even hotter nuclear burning (*p*-process, Mg->Al)

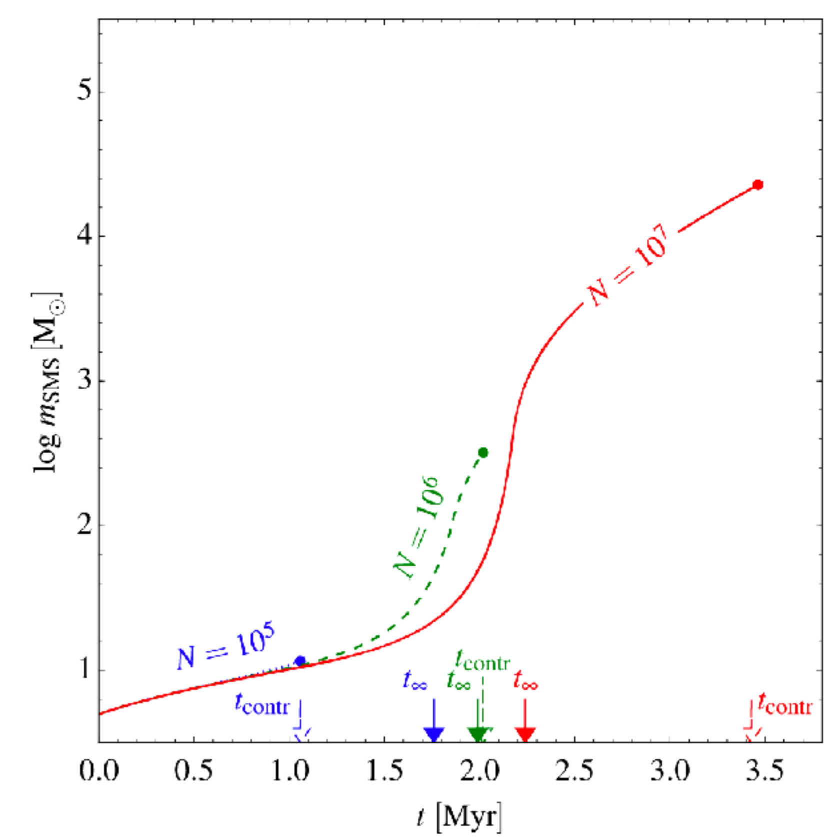


Where did this enriched material come from?

- Must be **massive star interiors** - only site where the necessary nuclear reactions take place

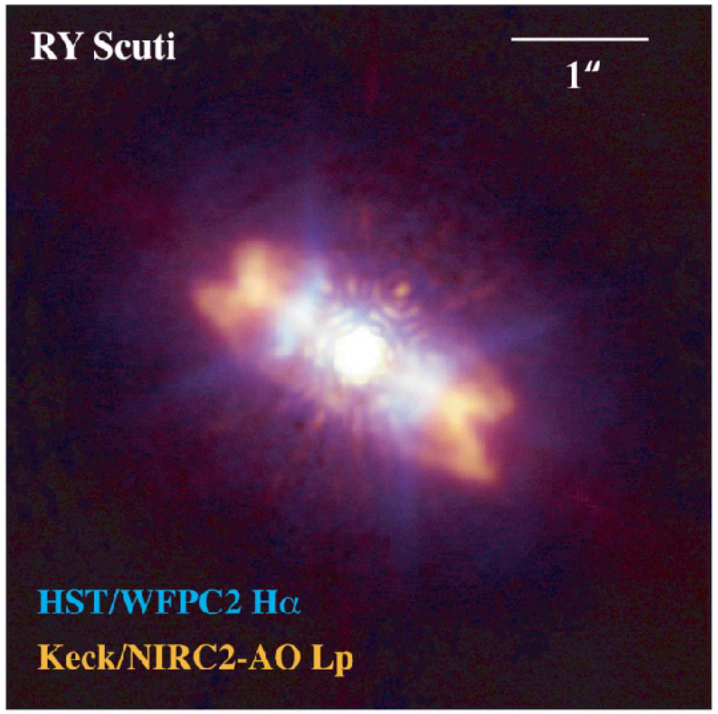
- **Can't be SNe** (low N/O) - either SNe haven't gone-off or their ejecta has not cooled into the ISM
- But (key point): **radiative line-driven winds** of massive stars will be **very weak at such low-*Z***



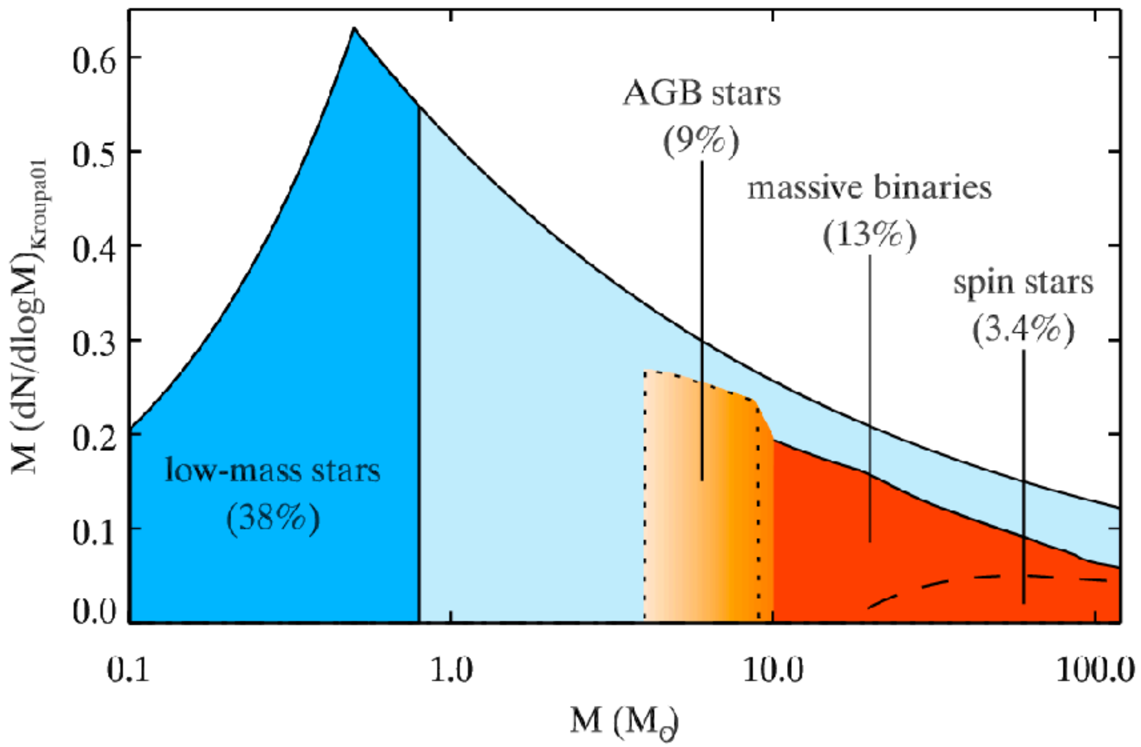


One solution: exotic supermassive stars (10^4 $M_\odot$) produced by runaway collisions (e.g. Gieles+18, Charbonnel+23)

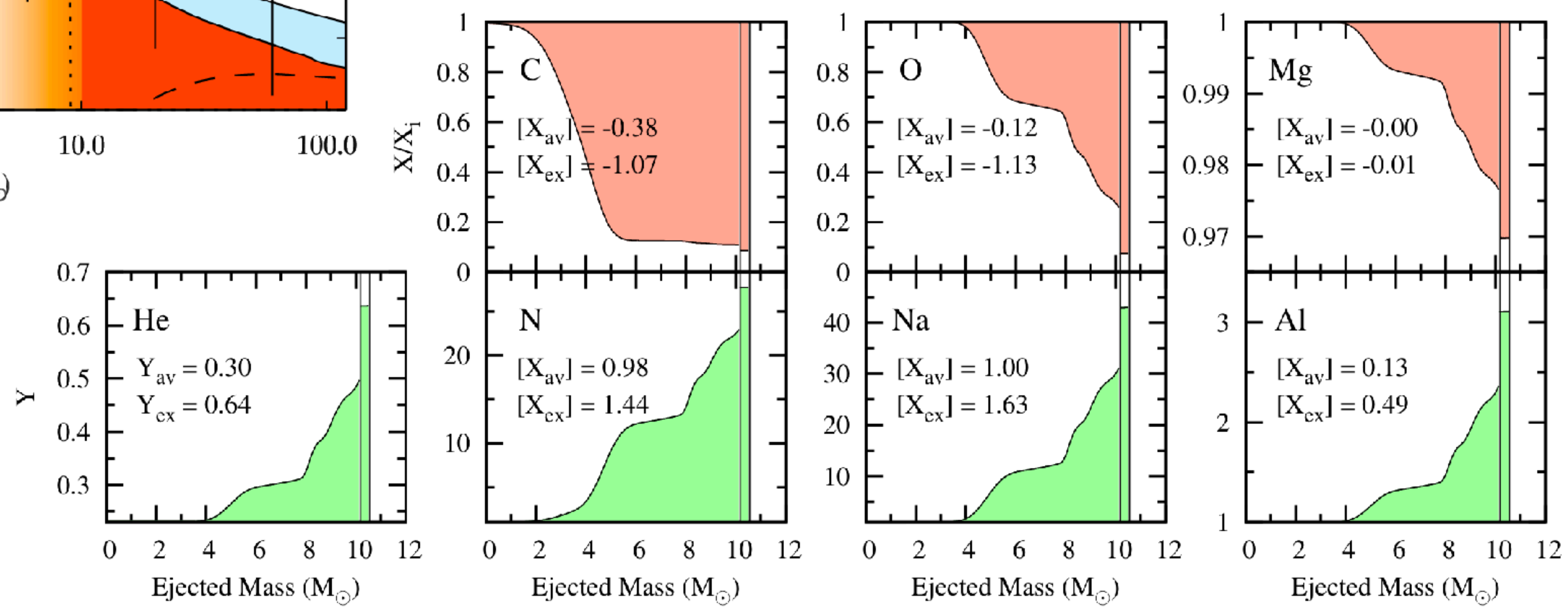
Another solution: **binary mass transfer!**



Smith+2011



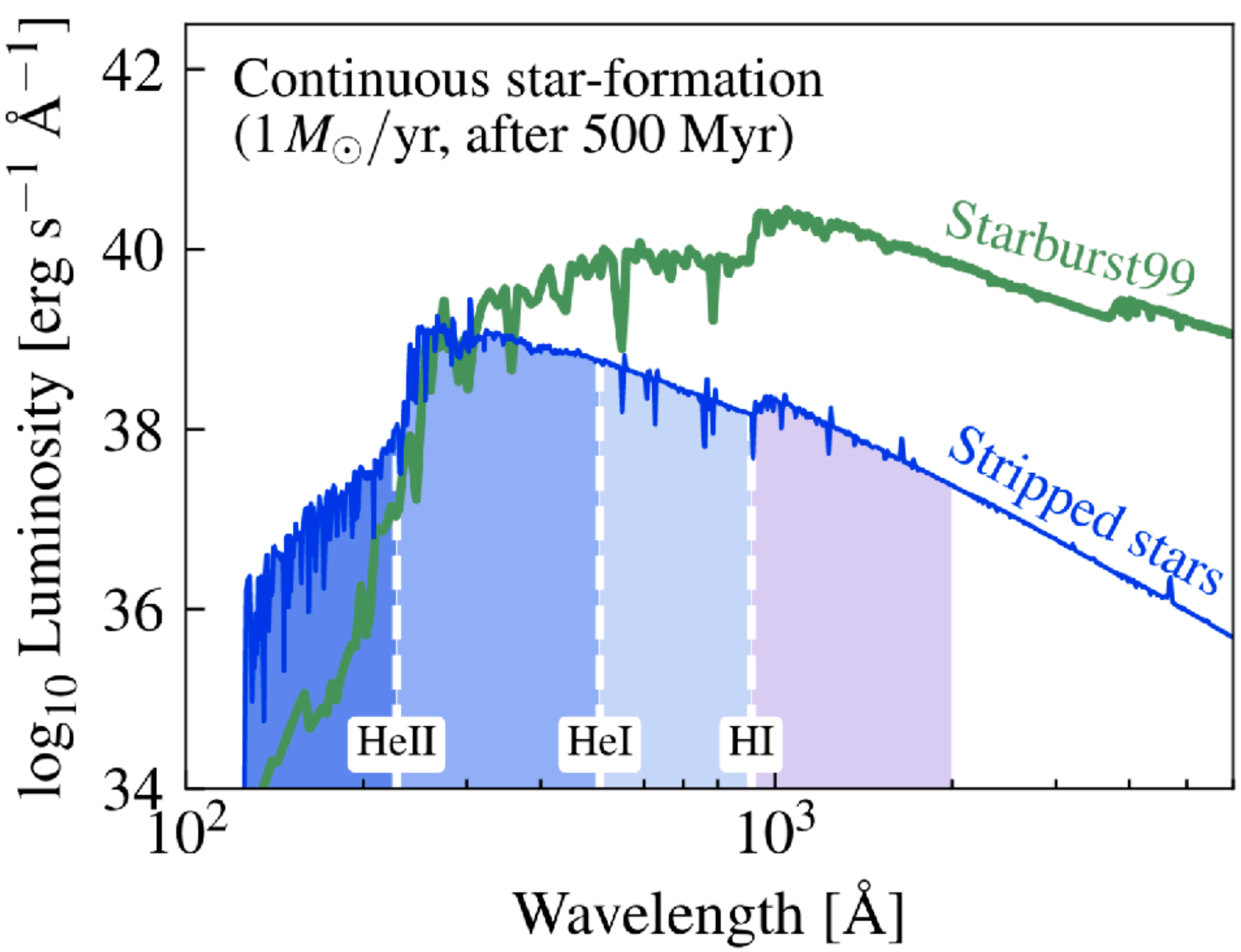
de Mink+2009

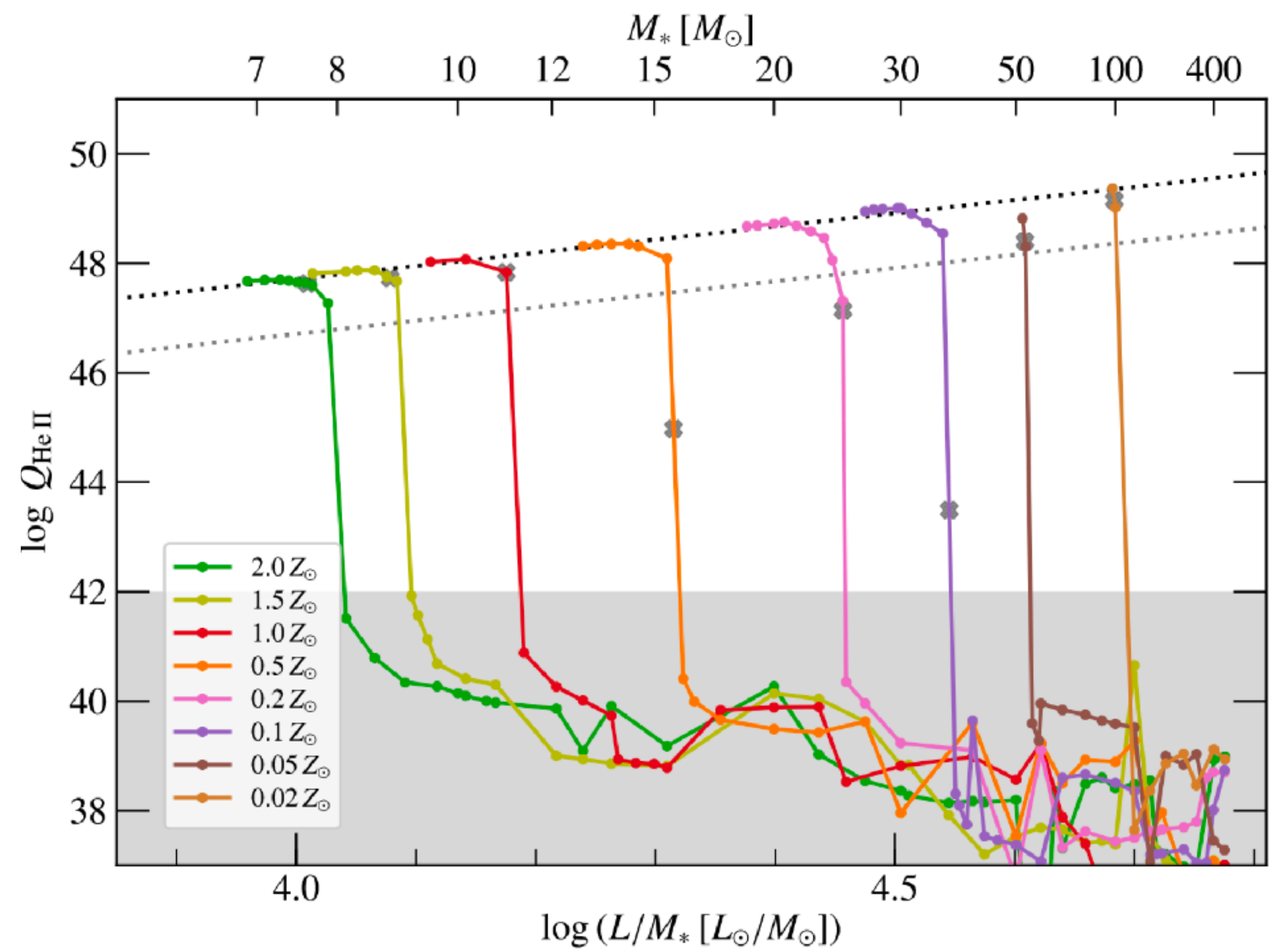


Huge amounts of such enriched material reside in stellar envelopes — and can be removed and ejected during stripping

Envelope stripping: potential solution both to peculiar high-z enrichment and missing hard ionizing photons

stars stripped by mass transfer could be **abundant at low-Z** and **extremely hot** [e.g. **Götberg+17,19**]





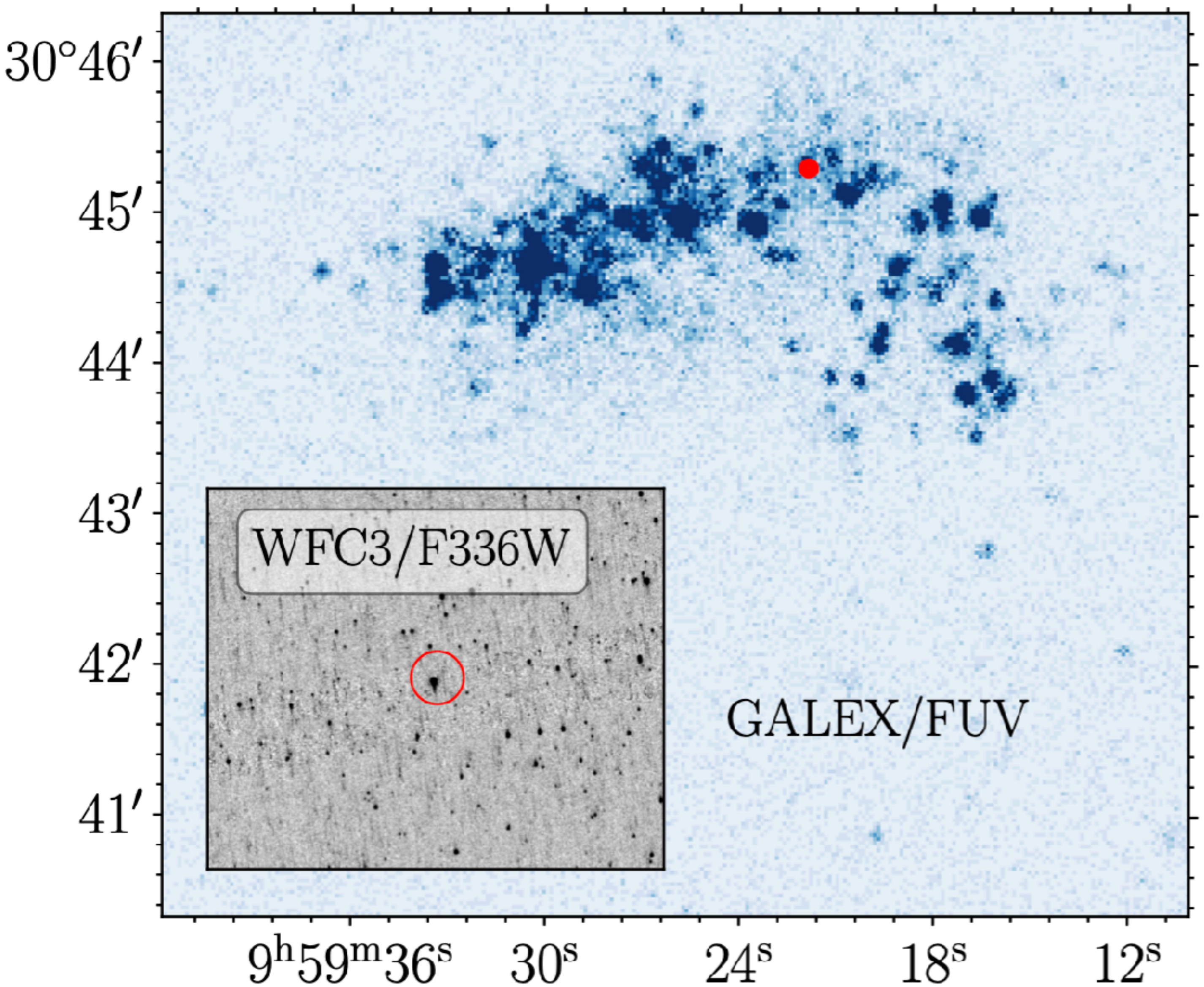
but depends in detail on their compactness during mass transfer and modeling of their winds

[e.g. **Sander&Vink 20**, Klencki+20,22]

And we haven't found (m)any in any environment (Andreas' talk)

(so hot they're usually outshined by companions in the optical)

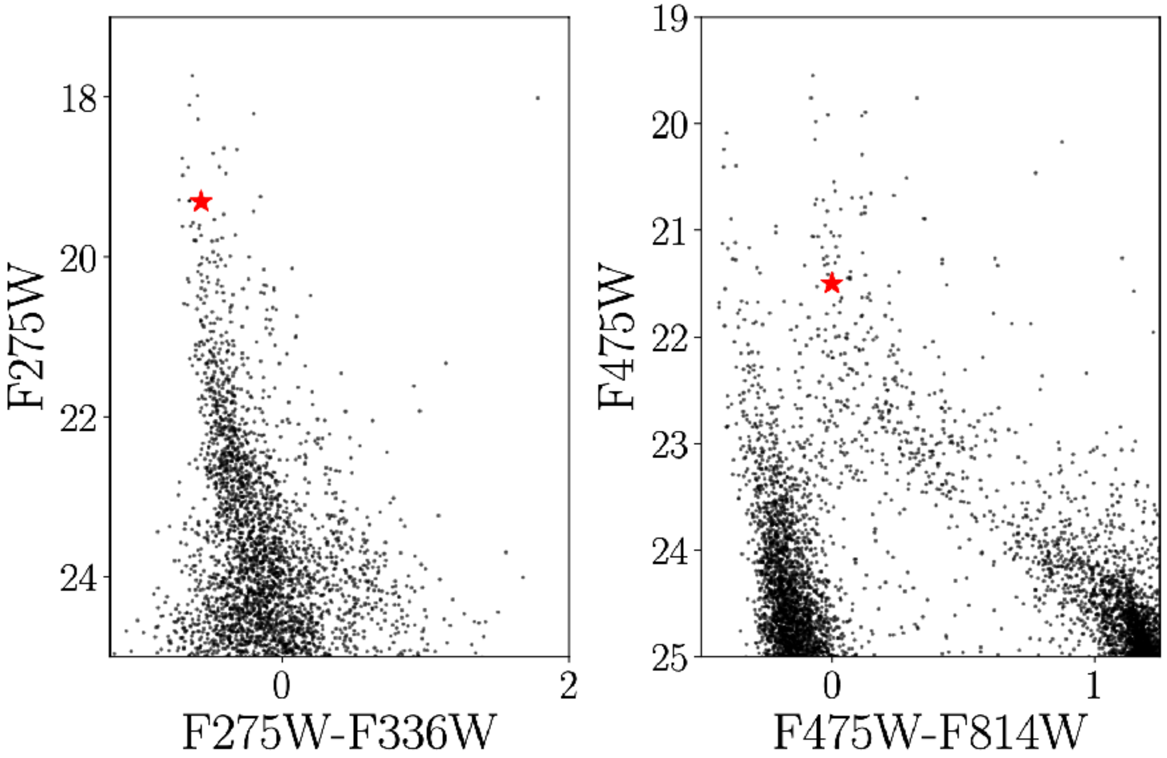
Need constraints at low-Z in particular:



Leo A:

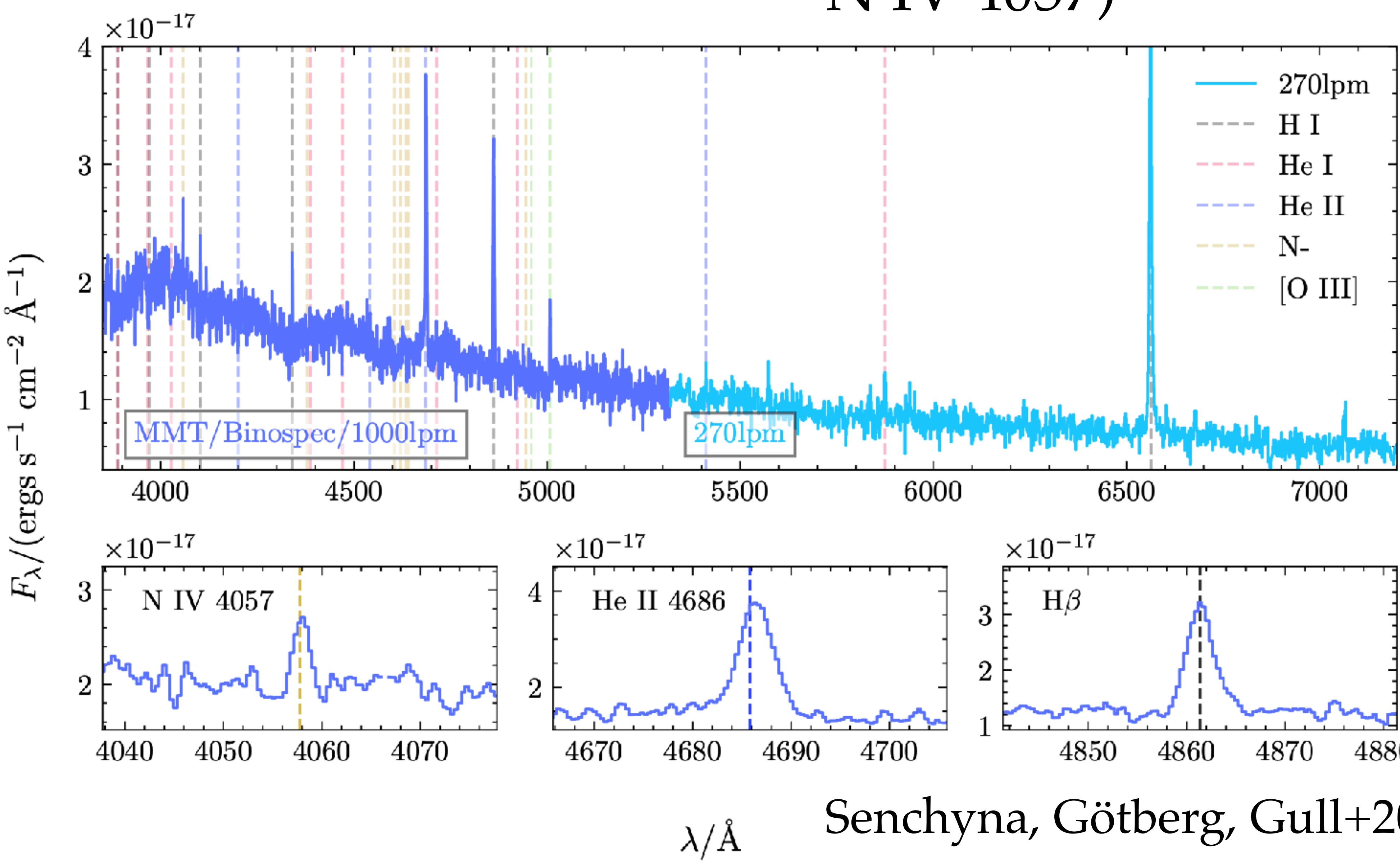
- sub-SMC: $\lesssim 0.1\,Z_\odot$
- resolved at the edge of the LG (760 Mpc)
- Host to recent ($\sim$ 10 Myr) star formation (host to late-O MS stars)
- Low MW extinction

  - Like Sextans A (Marta Lorenzo's talk), another crucial bastion for low-Z stellar studies
  - Target of ongoing optical+UV campaigns (see Gull, Wesiz, Senchyna+2022)



UV-bright, BHeB star?

But optical spectrum is strange: nearly blank, but **booming He II** emission (+Balmer nebular emission, N IV 4057)

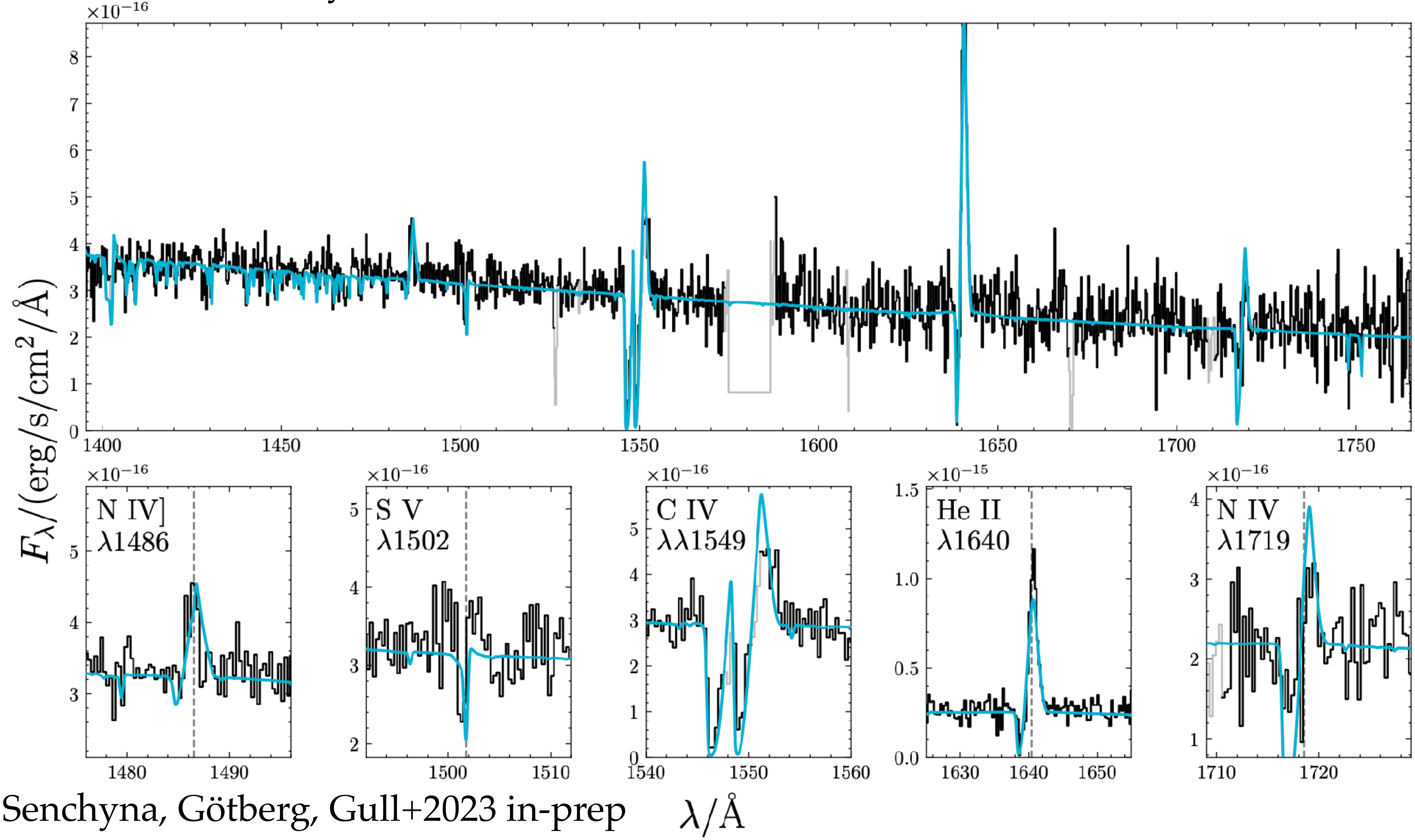


Suggests an extremely hot object is present

Senchyna, Götberg, Gull+2023 in-prep

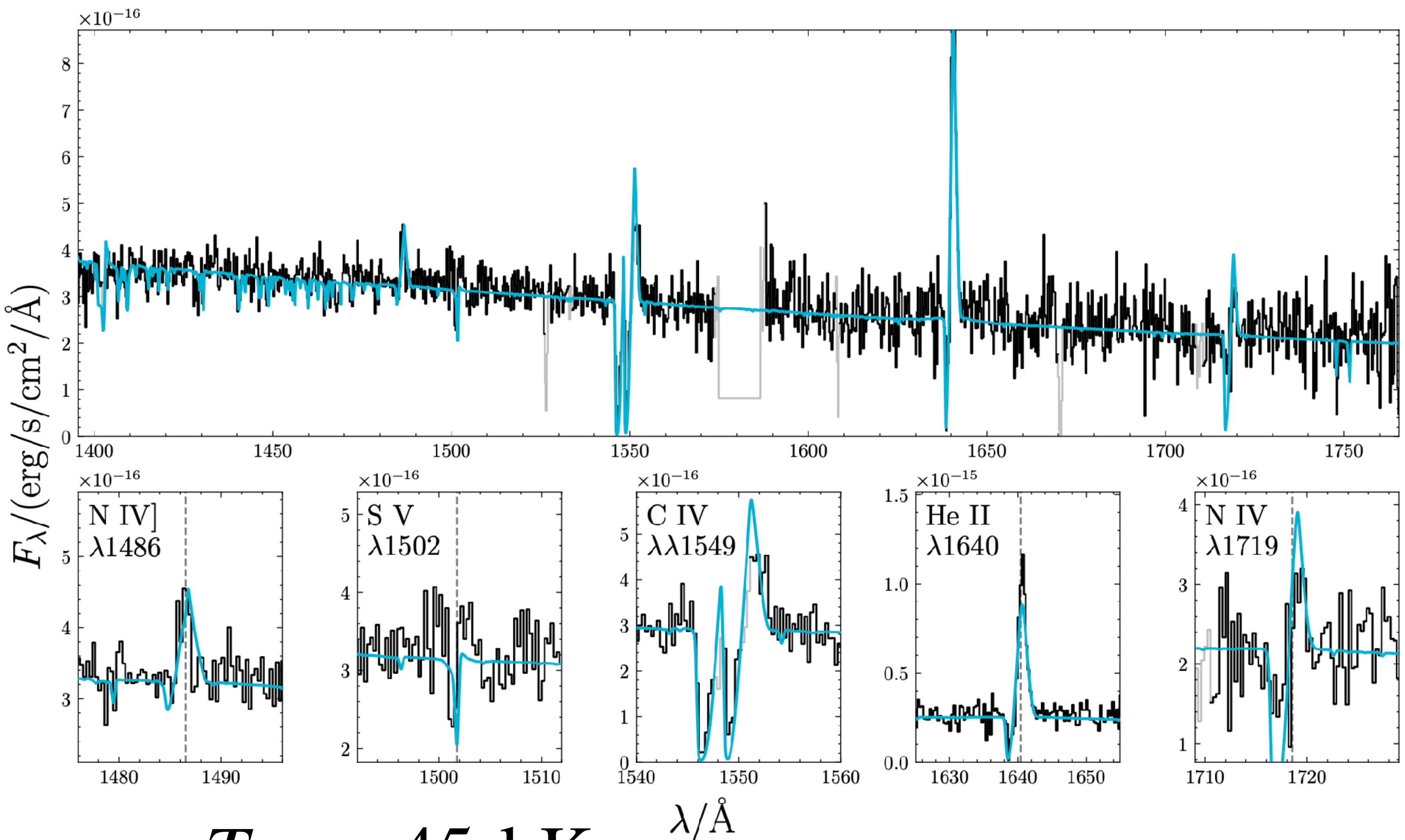
8 orbits of HST / COS follow-up spectroscopy in Cycle 29:

GO-16717, PI: Senchyna



Senchyna, Götberg, Gull+2023 in-prep

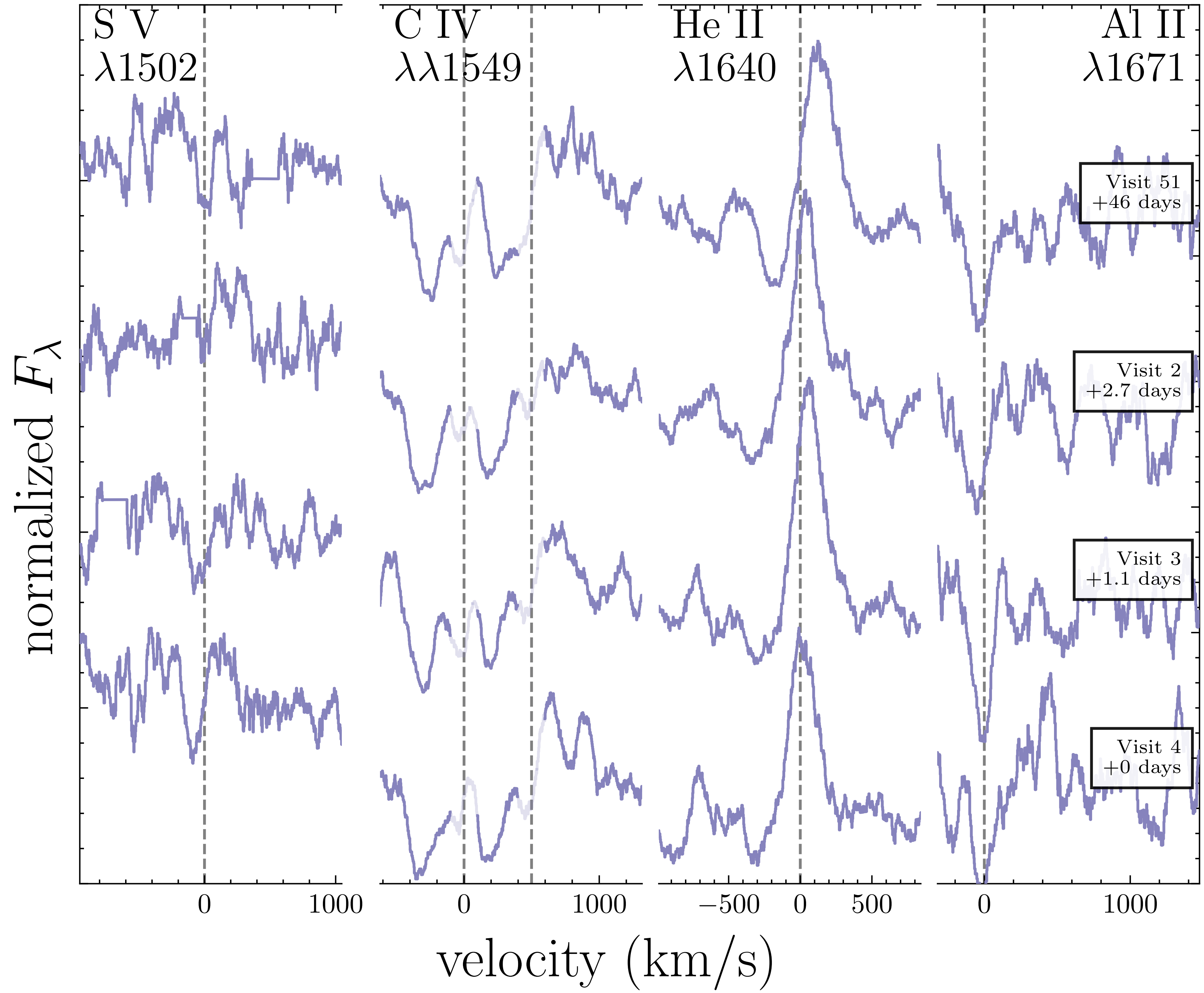
Confirms: looks like a hot (45 kK) WR-like atmosphere!



Tailored CMFGEN modeling readily reproduces the spectrum, with:

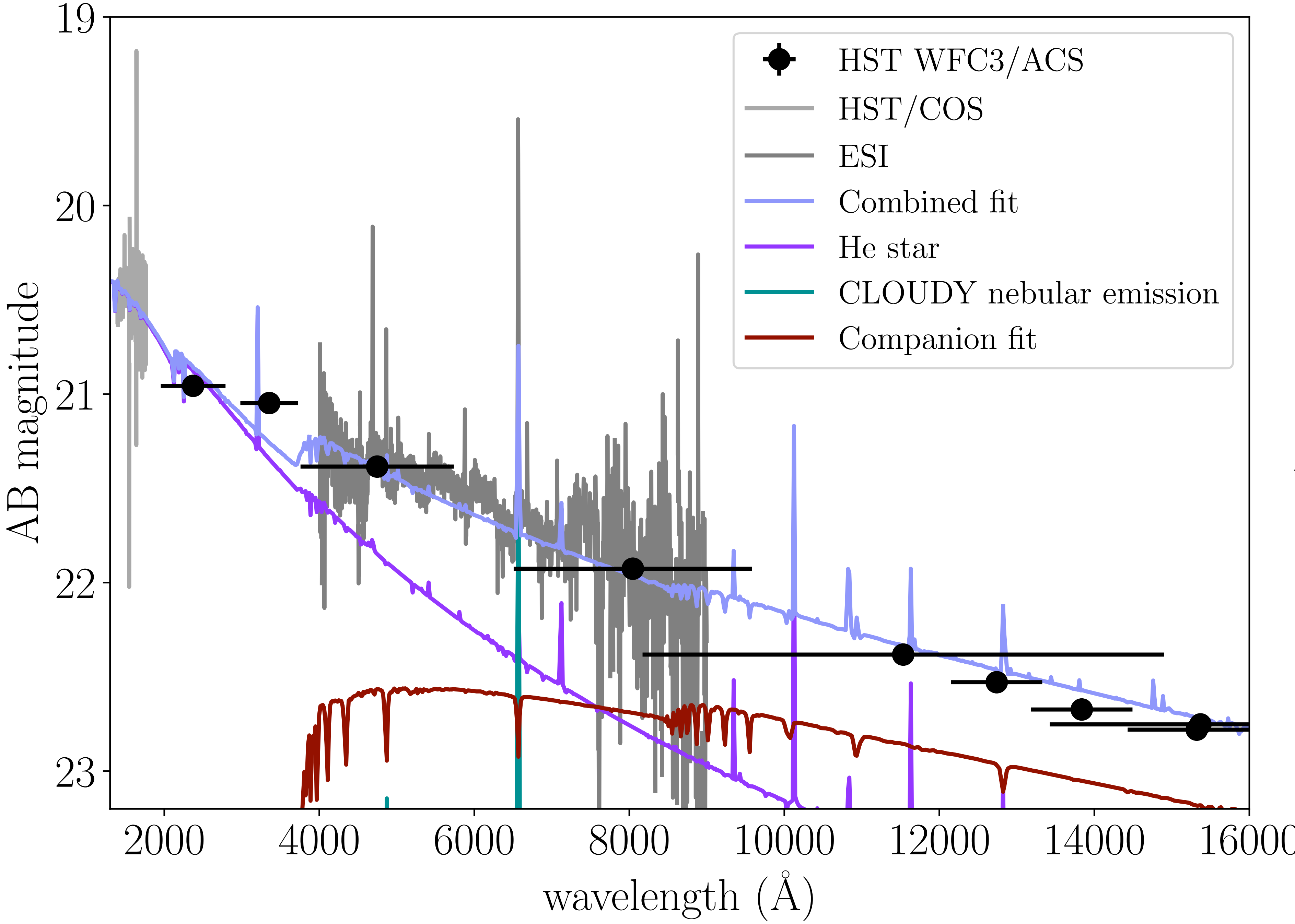
- $T_{\rm eff} = 45$ kK
- $L_{\rm bol} = 3 \times 10^4$ $L_\odot$
- $R_{\rm eff} = 2.9$ $R_\odot$
- mass? log g uncertain
  - but plausibly $\sim 5\ M_\odot$
- Consistent with [Fe/H] < -1 (extremely metal-poor!)
- Substantially N-enriched: [N/H] ~2.9
- Looks like a stripped star! How was its envelope removed?
  - too low in mass and Z to be wind-stripped…

We obtained 4 different epochs of HST data, including one delayed repeat observation:



Total shift relative to ISM lines over 46 days: ~103 km/s — consistent with orbital motion in a fairly close binary!

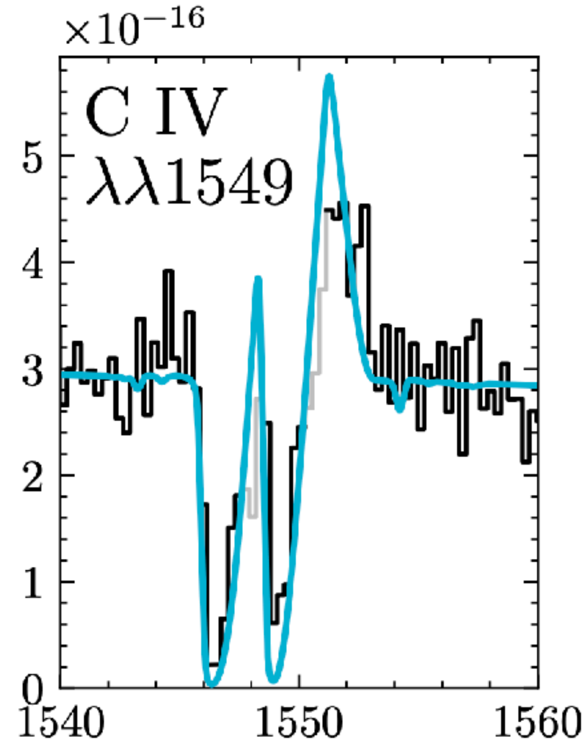
Broadband SED+optical spectrum also indicate contributions from a cooler companion

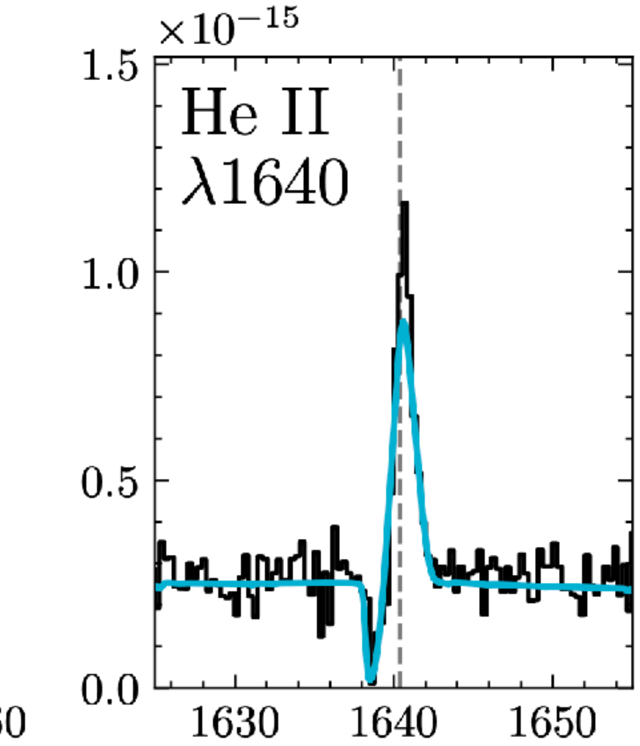


$T_{\rm eff} \sim 7000$ K, $L_{\rm bol}/L_{\odot} \sim 500$

Puffed-up mass-gainer? MESA modeling ongoing — but further evidence we are potentially viewing a product of interaction

But: the wind is peculiar!



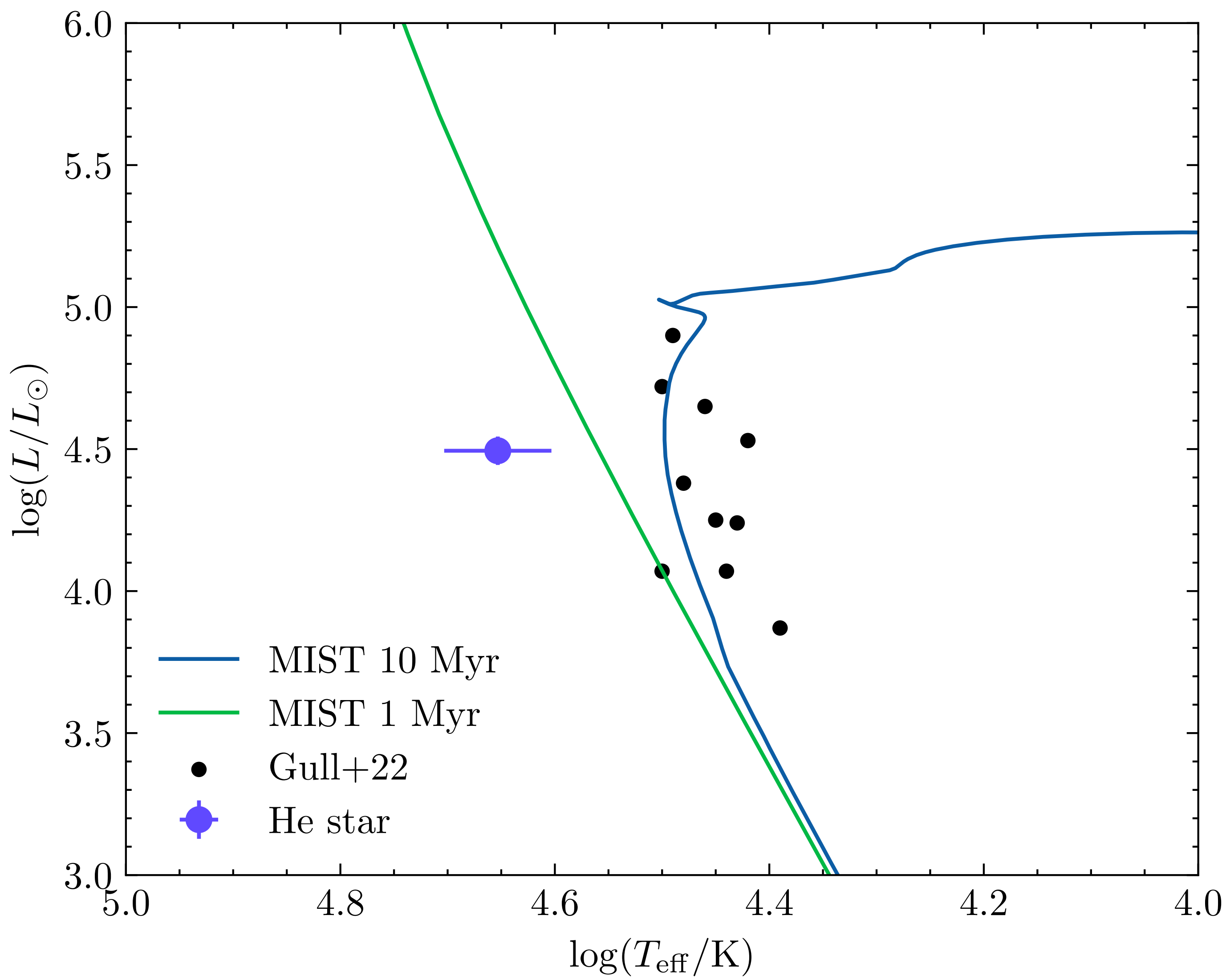


Significant mass loss rate for $Z, L/M$: $\dot{M} = 5 \times 10^{-7}\ \mathrm{M}_\odot/\mathrm{yr}$ and very slow terminal velocity: v_∞=350-400 km/s

- suggests v_∞/v_{esc} of-order unity or less
- sharp contrast to normal Wolf-Rayet winds, with $v_\infty/v_{esc} > 1.5$
- and with recent predictions that low-Z and low-$M_\odot$ He stars might drive even faster, low-density winds: Sander+Vink 2020

- Incomplete stripping?
- Different mode of mass loss?

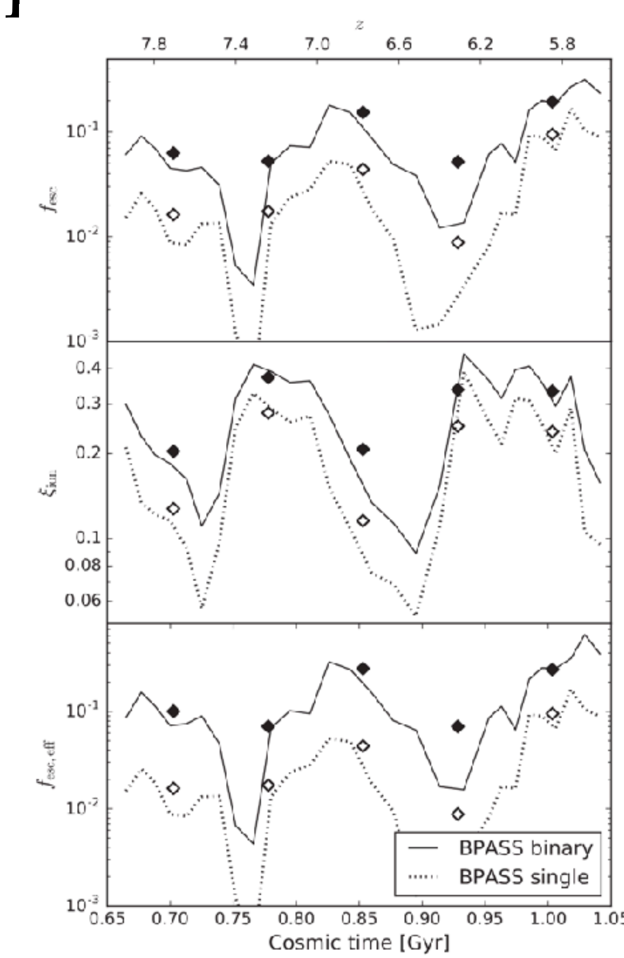
Implications for LyC production+escape:



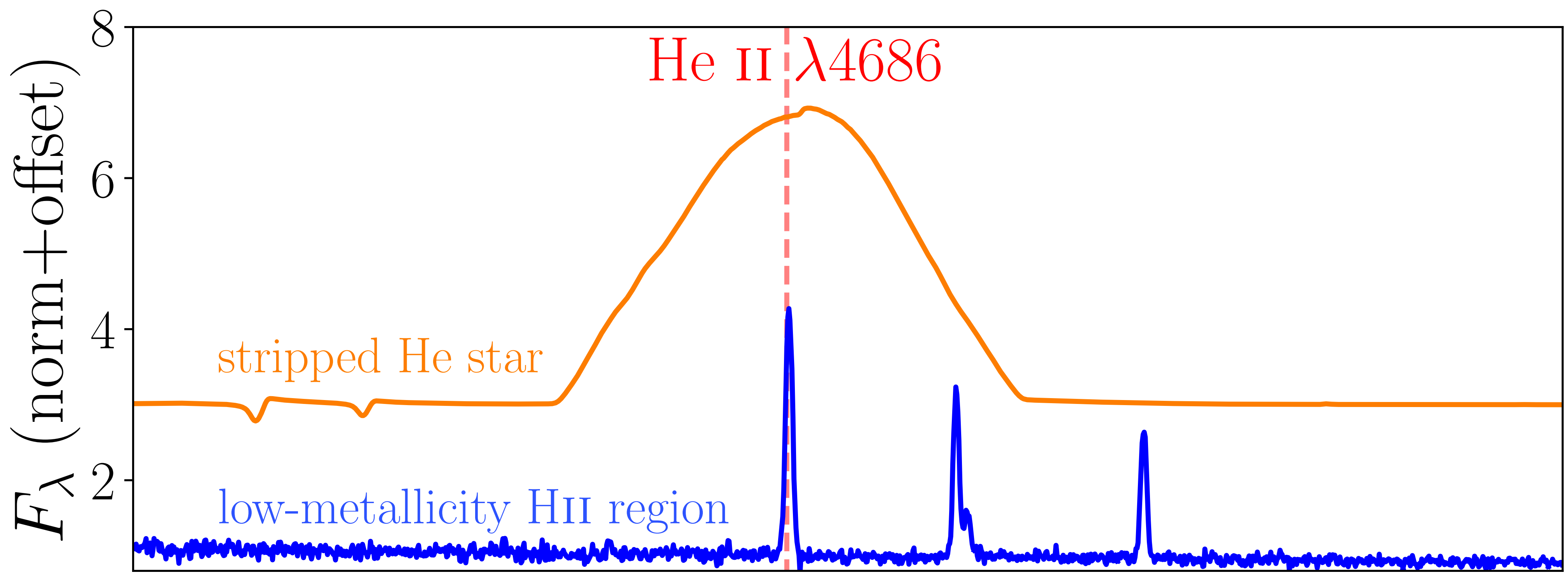
Extremely hot star for a population approximately ~10 Myr old — important! (see Jan Eldridge's talk)

Atmosphere analysis suggests: $Q(\text{H I}) = 1.8 \times 10^{48}$ (~O7 V): $\sim 10\times$ that of the earliest O dwarfs still present

In aggregate, could substantially affect total LyC escaping a galaxy: providing ionizing photons *after* SNe/other feedback has cleared-out channels
e.g. **Ma+2016**, Götberg+19



How do we find more stripped stars / other hot ionizing sources?
An efficient option: **deep narrowband imaging**

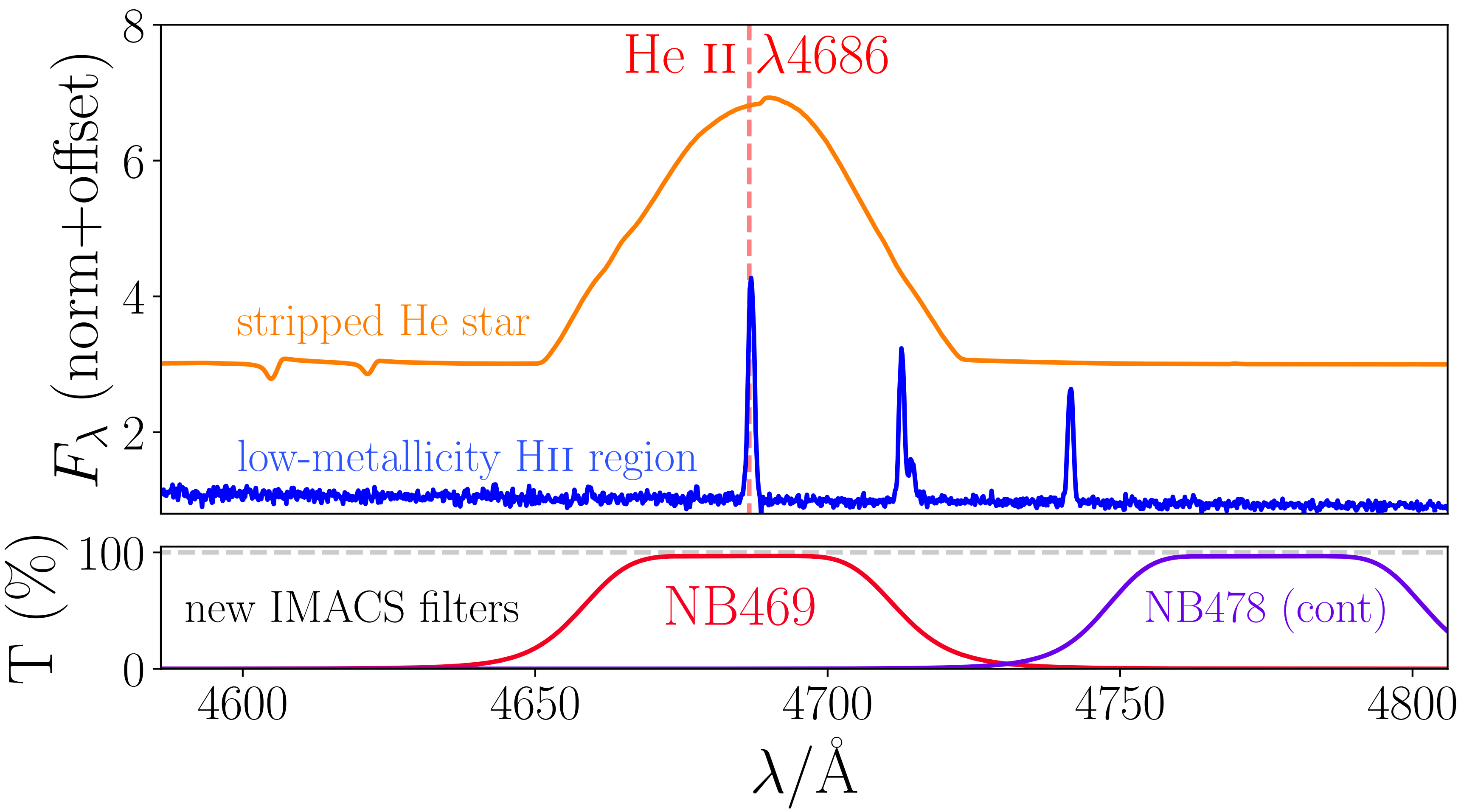


Stripped / spun-up stars are likely to either show:

- prominent **broad He II emission** formed in their winds
- in the weak-wind case, extended **narrow nebular He II emission** formed in surrounding gas they have ionized

(naturally, also useful for spatially-resolving any other potential sources)

Narrowband He II+cont filters (canonically used to find luminous classical WR stars: e.g. Wray&Corso 1972, Massey&Conti 1983, Massey+2014, Neugent+2018; though also see e.g. Kehrig+2011) should be extremely **efficient stripped-star finders**, if you can go deep enough

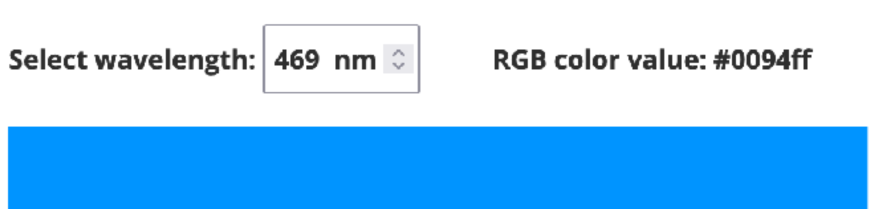


2 new narrowband interference filters for IMACS f/4 (Asahi Spectra)

HeII Emission in Local Galaxies with IMACS

Peter Senchyna, Ylva Götberg,
Gwen Rudie, Drew Newman, John Mulchaey
Carnegie Science

- Initial survey targeting $\sim 0.4 - 1$ Mpc LG dIrrs (NGC6822, WLM, IC 1613, …)
- Deep narrowband imaging + MOS follow-up
- **Link nebular (and stellar/wind) emission directly to its sources:** stripped stars, WR/CHE stars, X-ray binaries/ULXs/IMBHs, fast radiative shocks, …
- Rough 2022 weather, but data are now coming in!



Html Css Color HEX **#0094FF**

Dodger Blue

Summary:

- Massive star populations are at the core of LyC production and likely shaping its escape, but their evolution and properties especially at low-metallicities remain highly uncertain
- First spectra of luminous high-redshift galaxy GN-z11 reveal direct evidence of massive star pollution event on an galaxy-wide scale - a glimpse of an extreme (feedback-suppressed?) mode of dense clustered star formation antecedent to globular clusters?
- A peculiar star in Leo A looks to be the first extremely metal-poor massive binary-stripped star found; wind presents a significant challenge to our expectations, but confirms extremely hot sources can be produced by mass transfer at low-*Z* on longer timescales - implications for LyC escape!