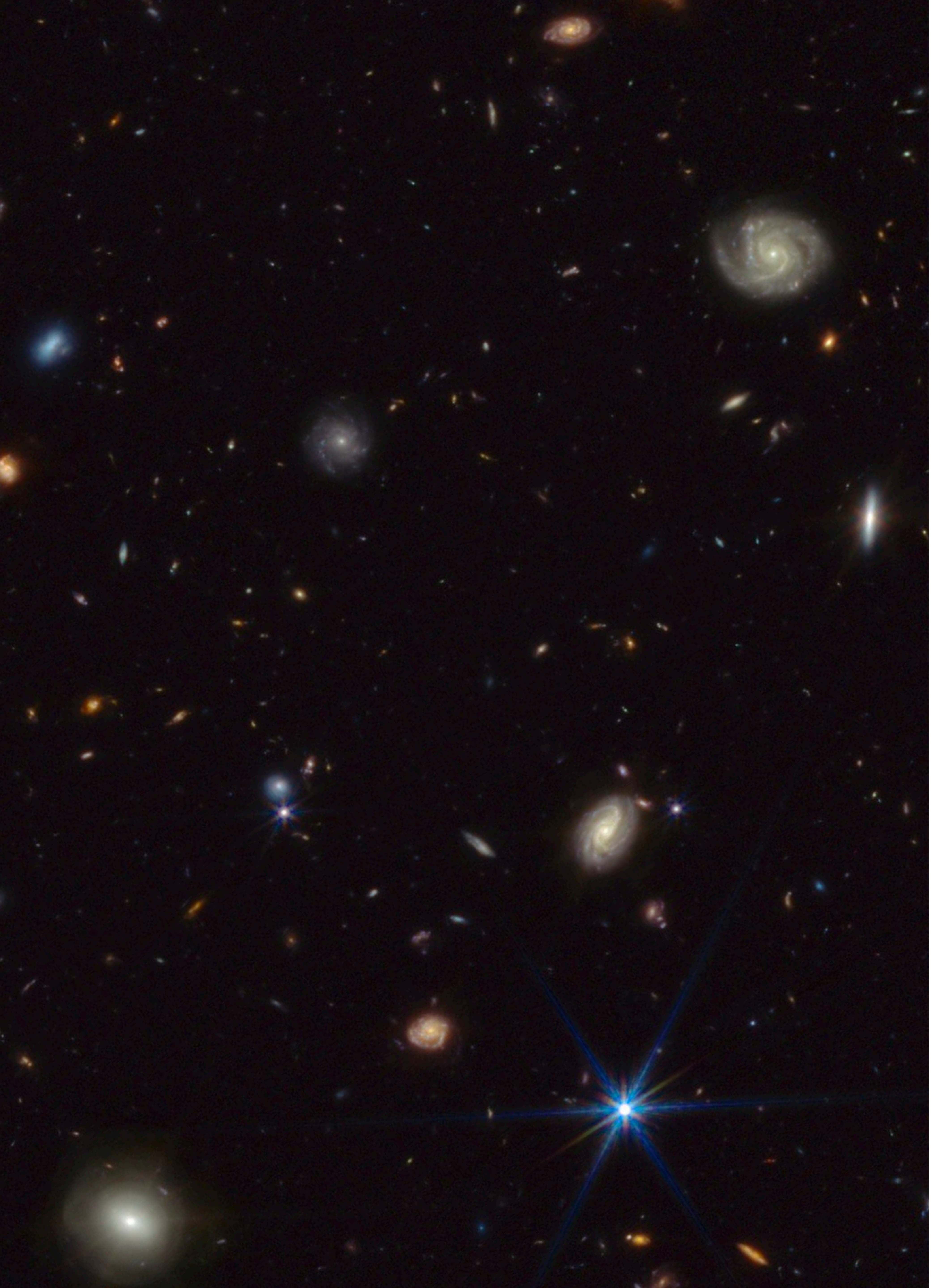


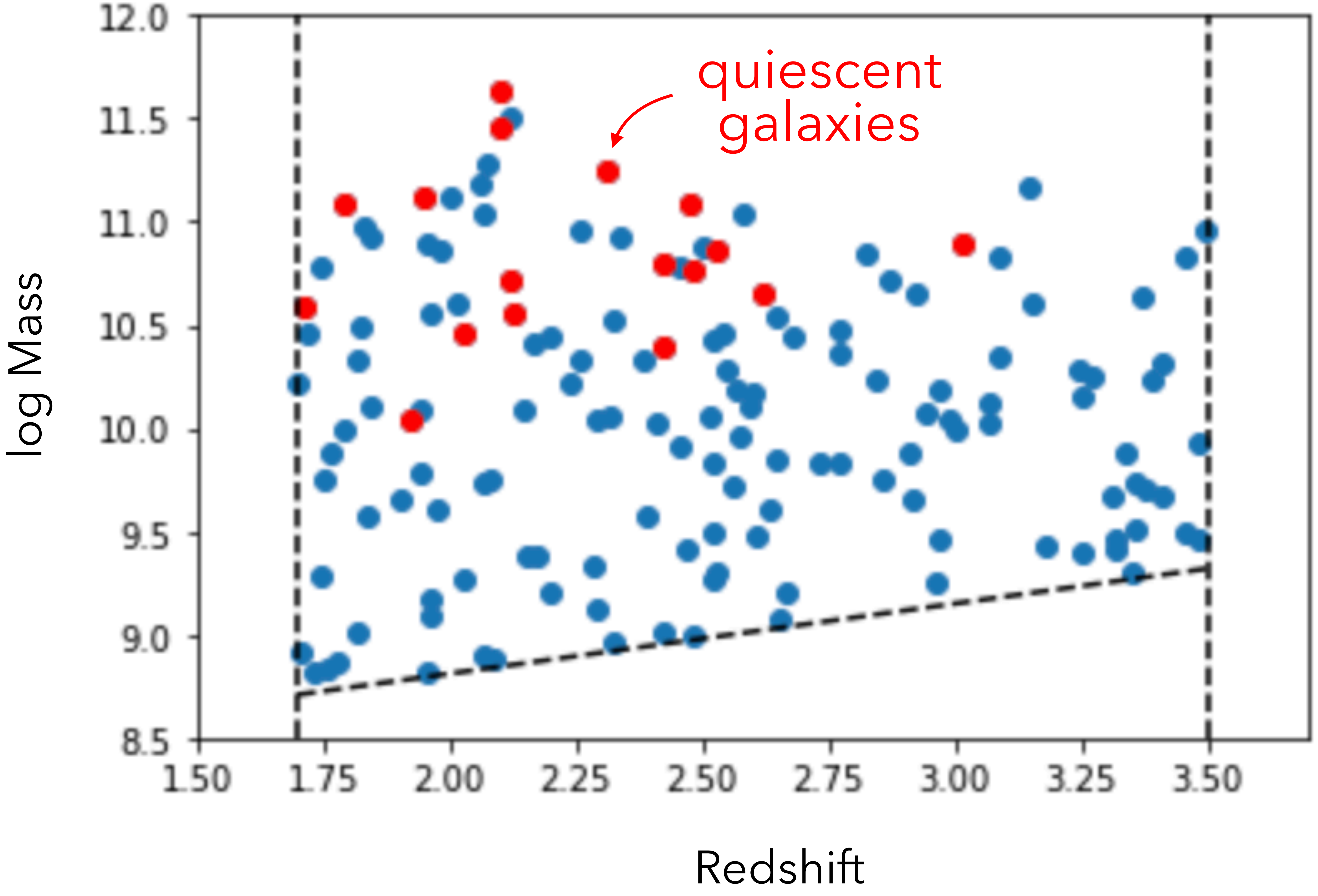
Observing Neutral Outflows in High-Redshift Galaxies with JWST

Sirio Belli

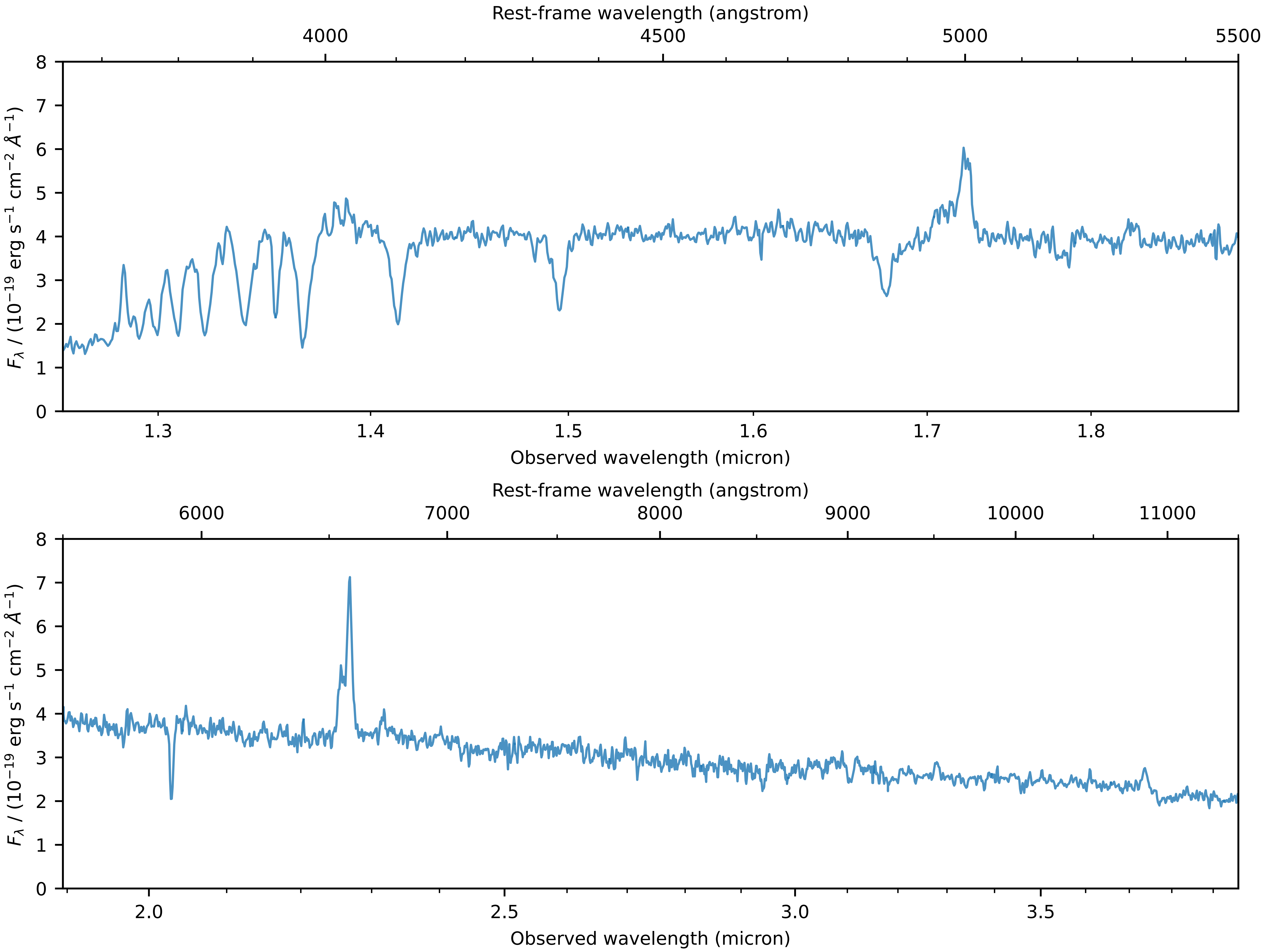
Università di Bologna

with Minjung Park, Rebecca Davies, Letizia Bugiani, Caterina Liboni, Lorenzo Moretti, Drew Newman, Gwen Rudie, Amir Khoram, and the Blue Jay team

Blue Jay



- Cycle-1 medium program with JWST/NIRSpec
- Representative sample of 150 galaxies at Cosmic Noon
- Full 1-5 um coverage, R~1000, ~18 hrs per mask



COSMOS-11142

z = 2.45

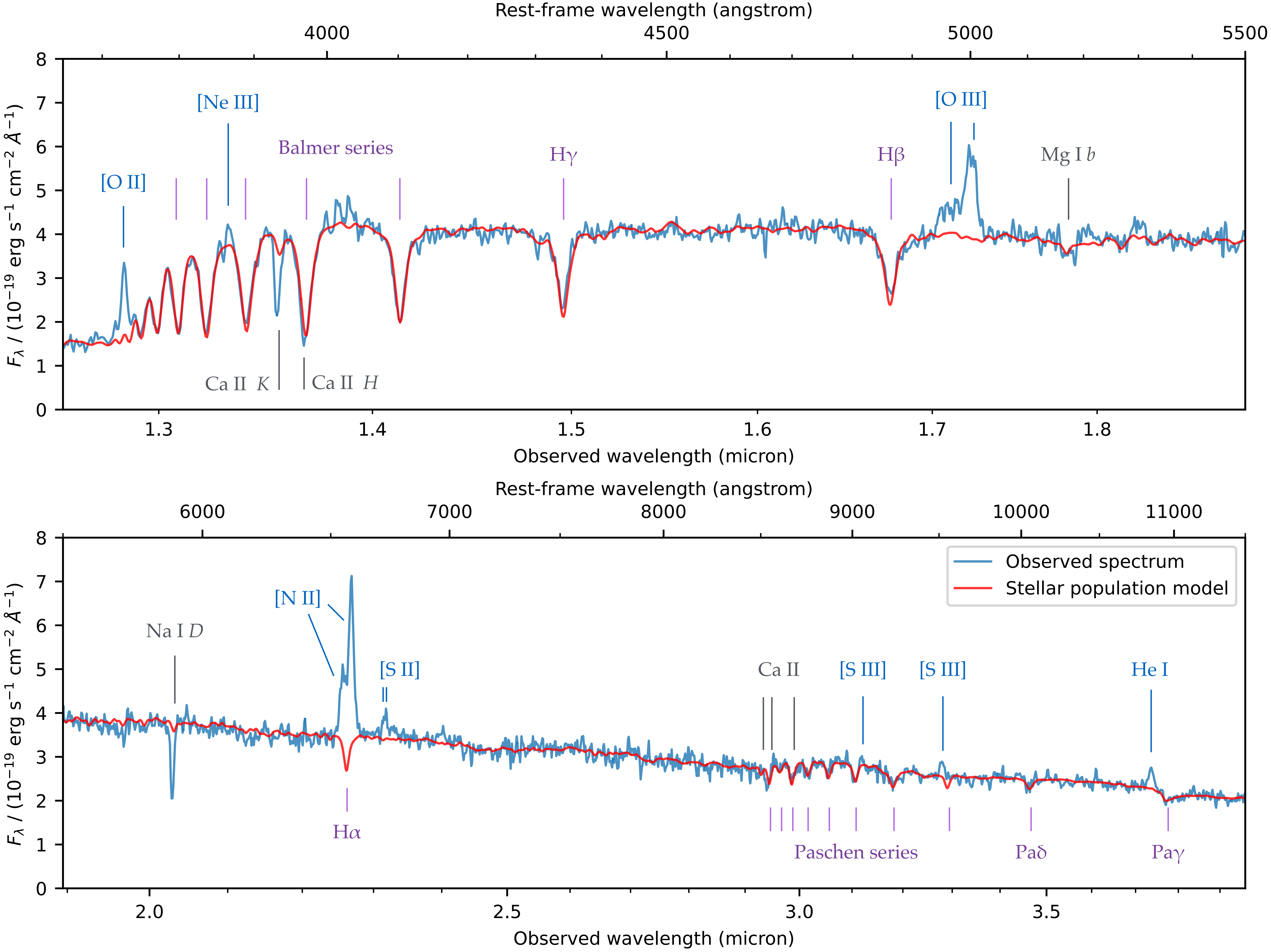
log $M_\star/M_\odot$ = 10.9

Blue Jay spectrum

JWST/NIRSpec

G140M + G235M + G395M

Belli et al. (2024)



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Blue Jay spectrum

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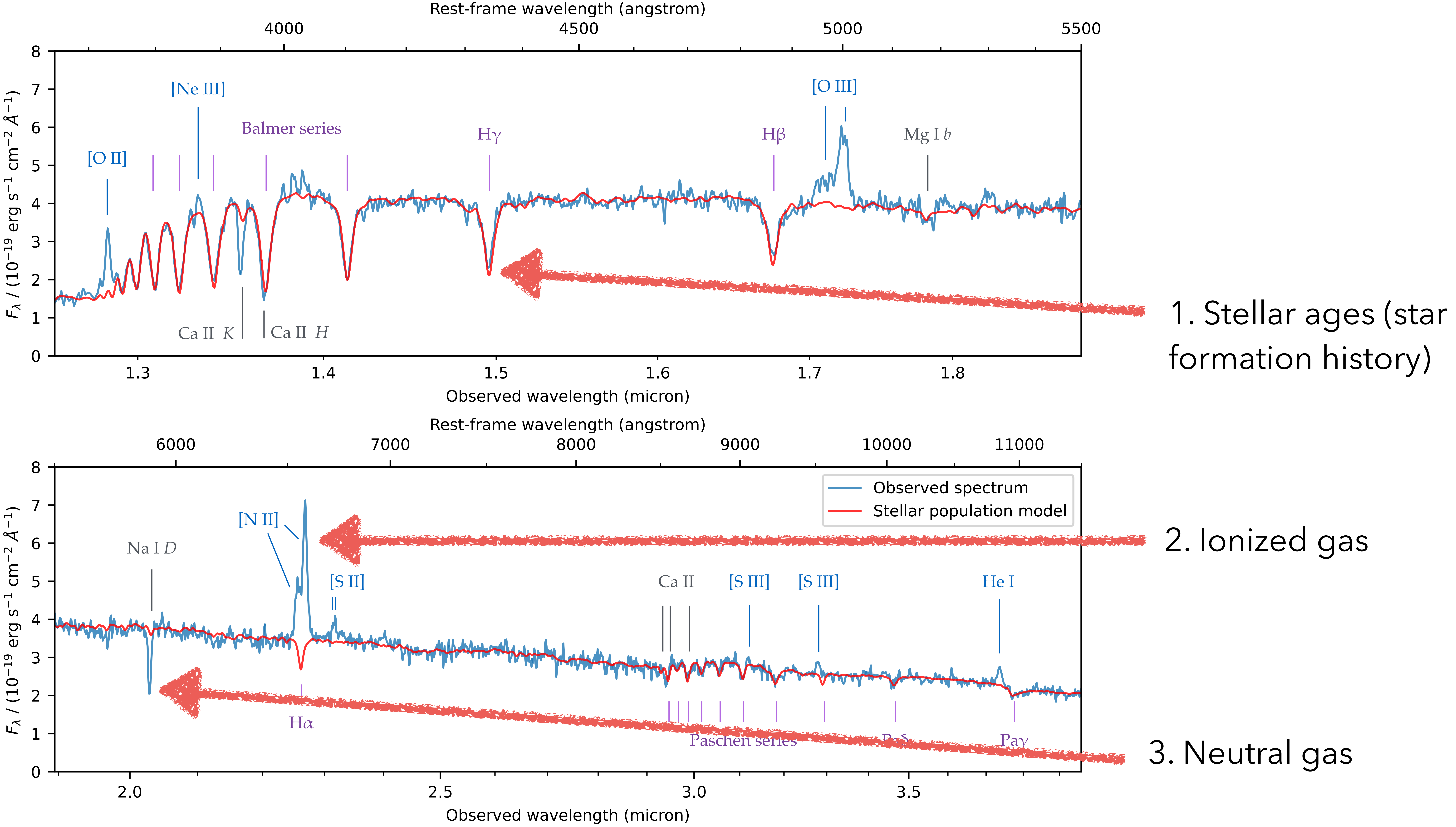
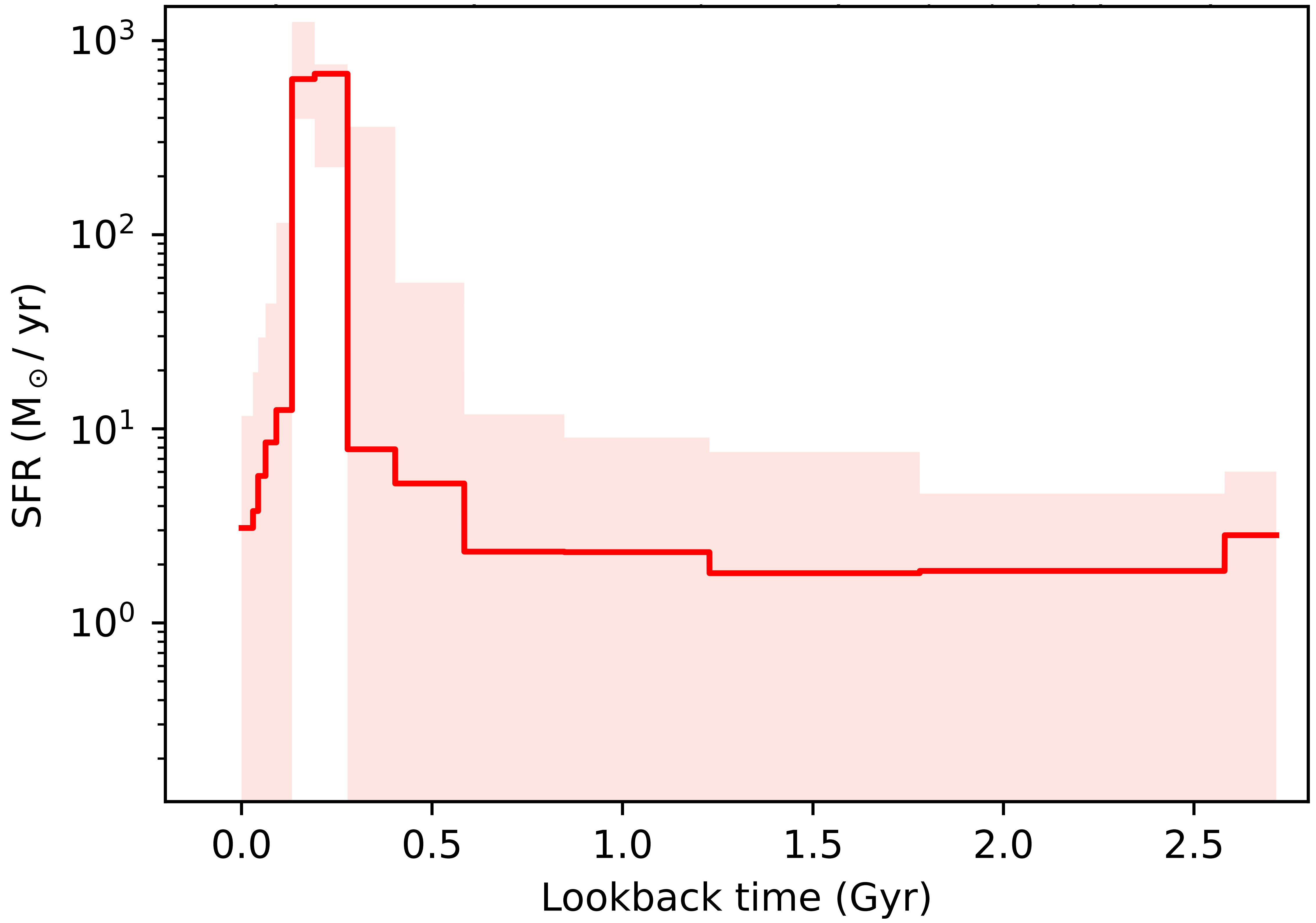


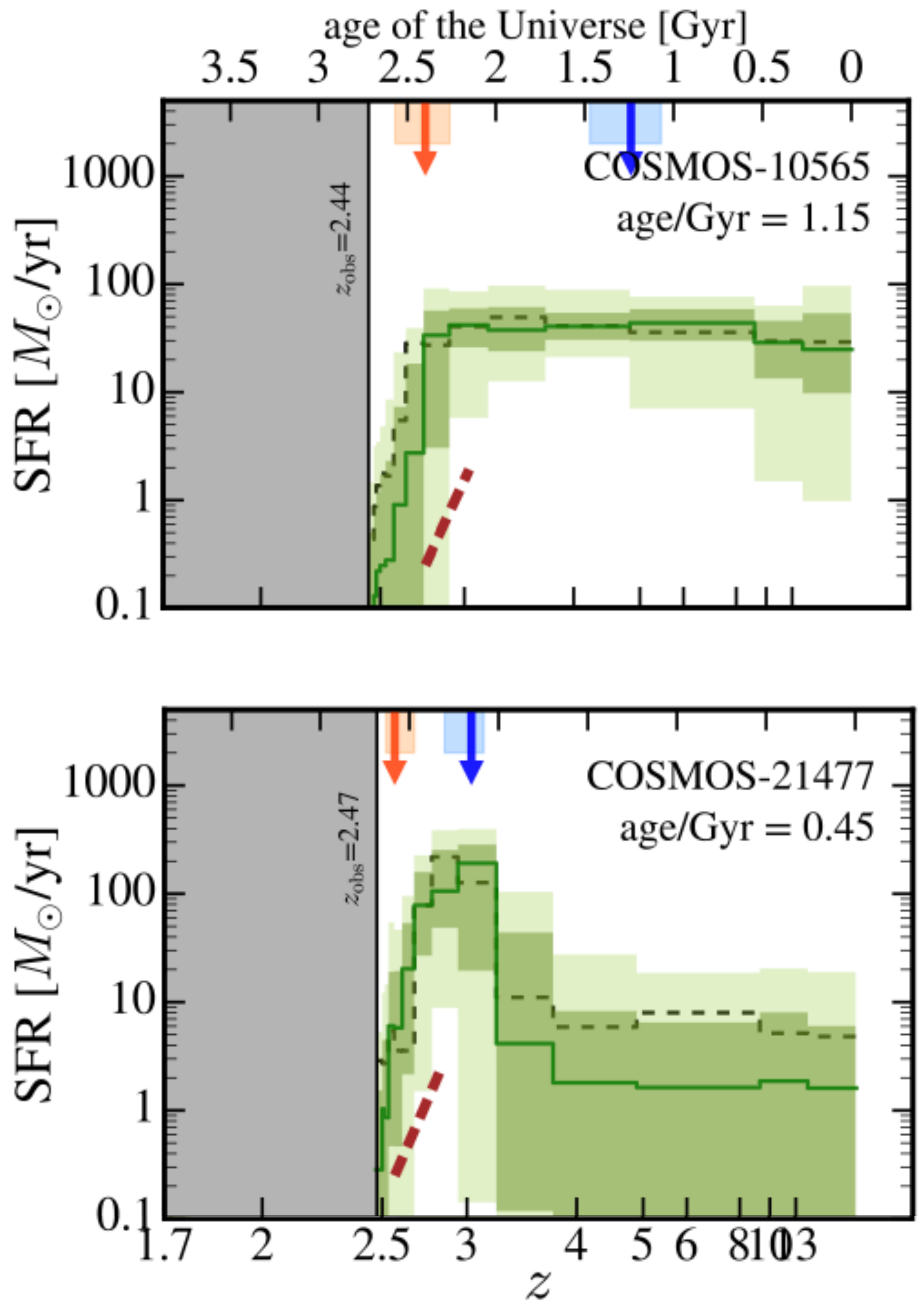
Belli et al. (2024)

1. Star Formation History

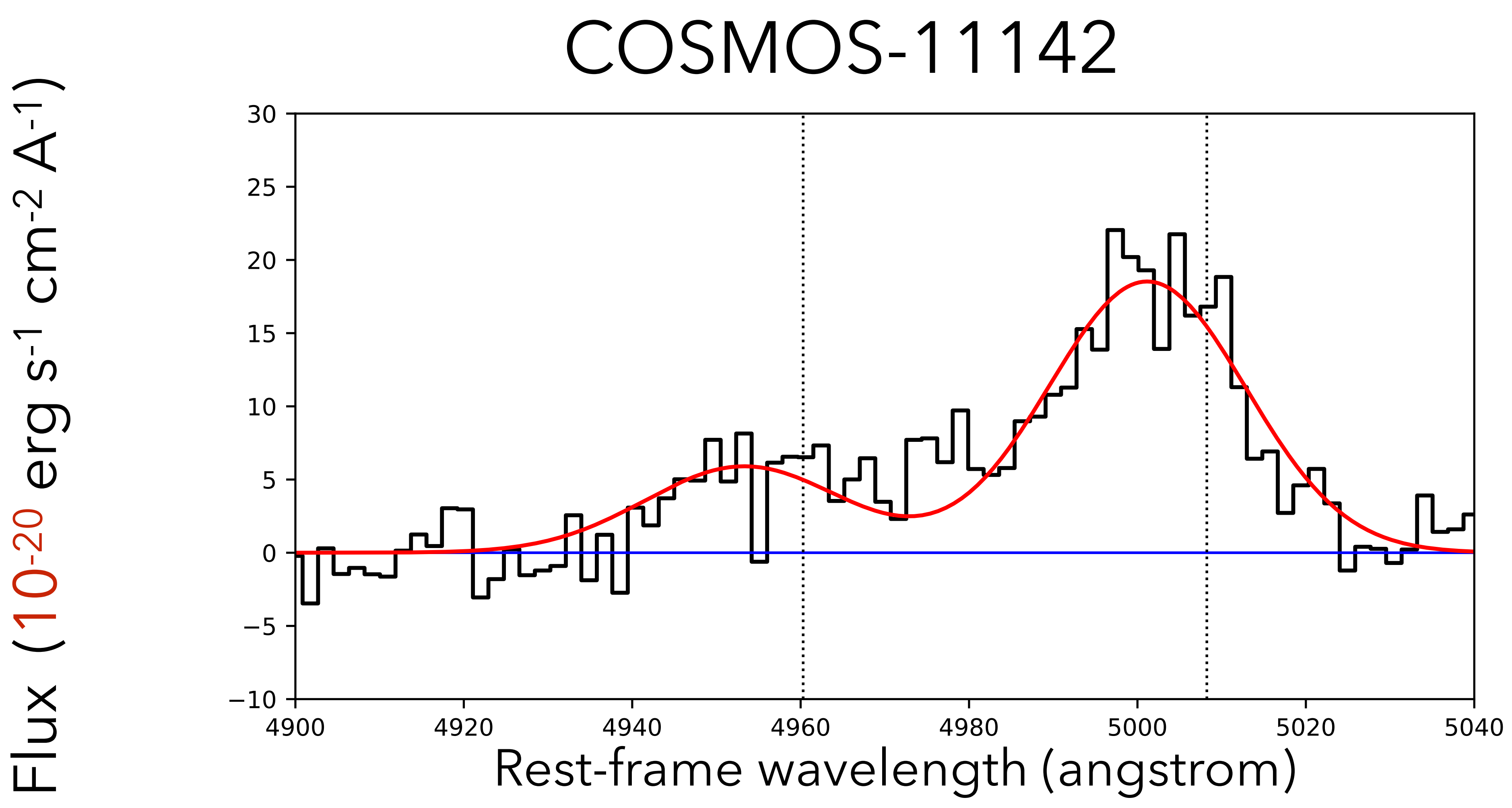
Most quiescent galaxies in Blue Jay are **quenched very rapidly**, with or without a starburst (Park et al. 2024)

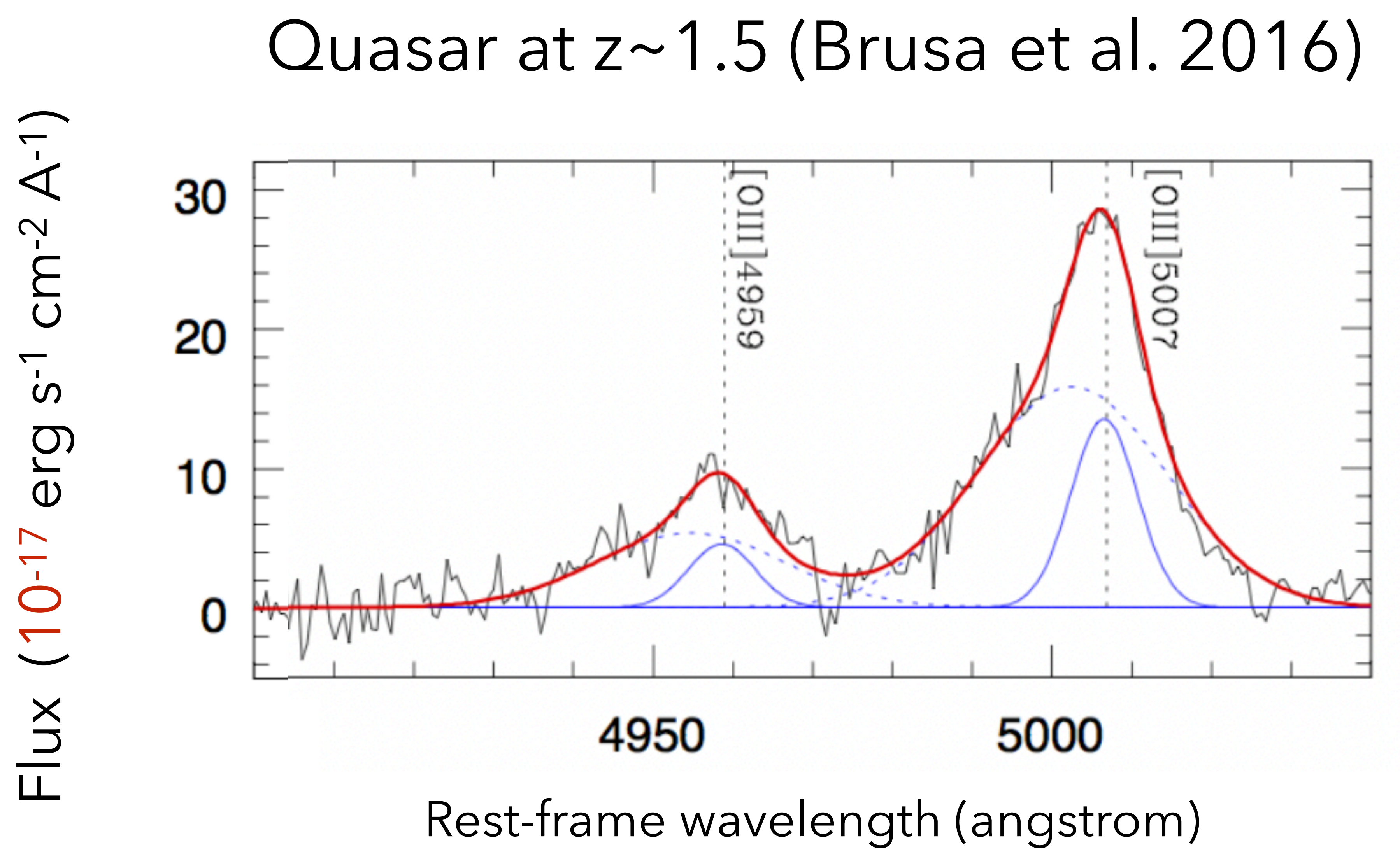
COSMOS-11142 experienced a strong starburst followed by rapid quenching





2. Ionized Gas





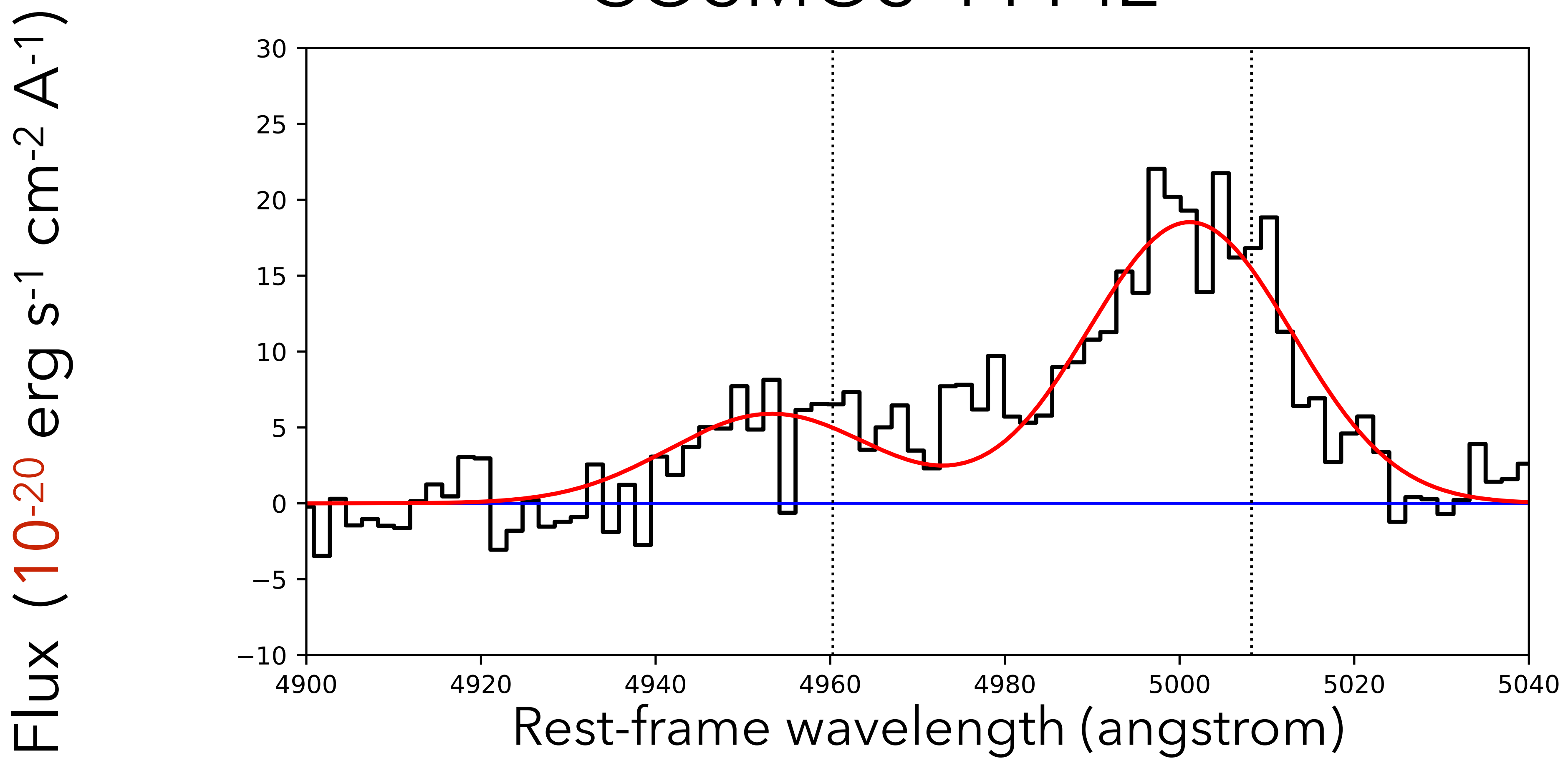
[O III] emission is broad and blueshifted

Ionized gas outflow

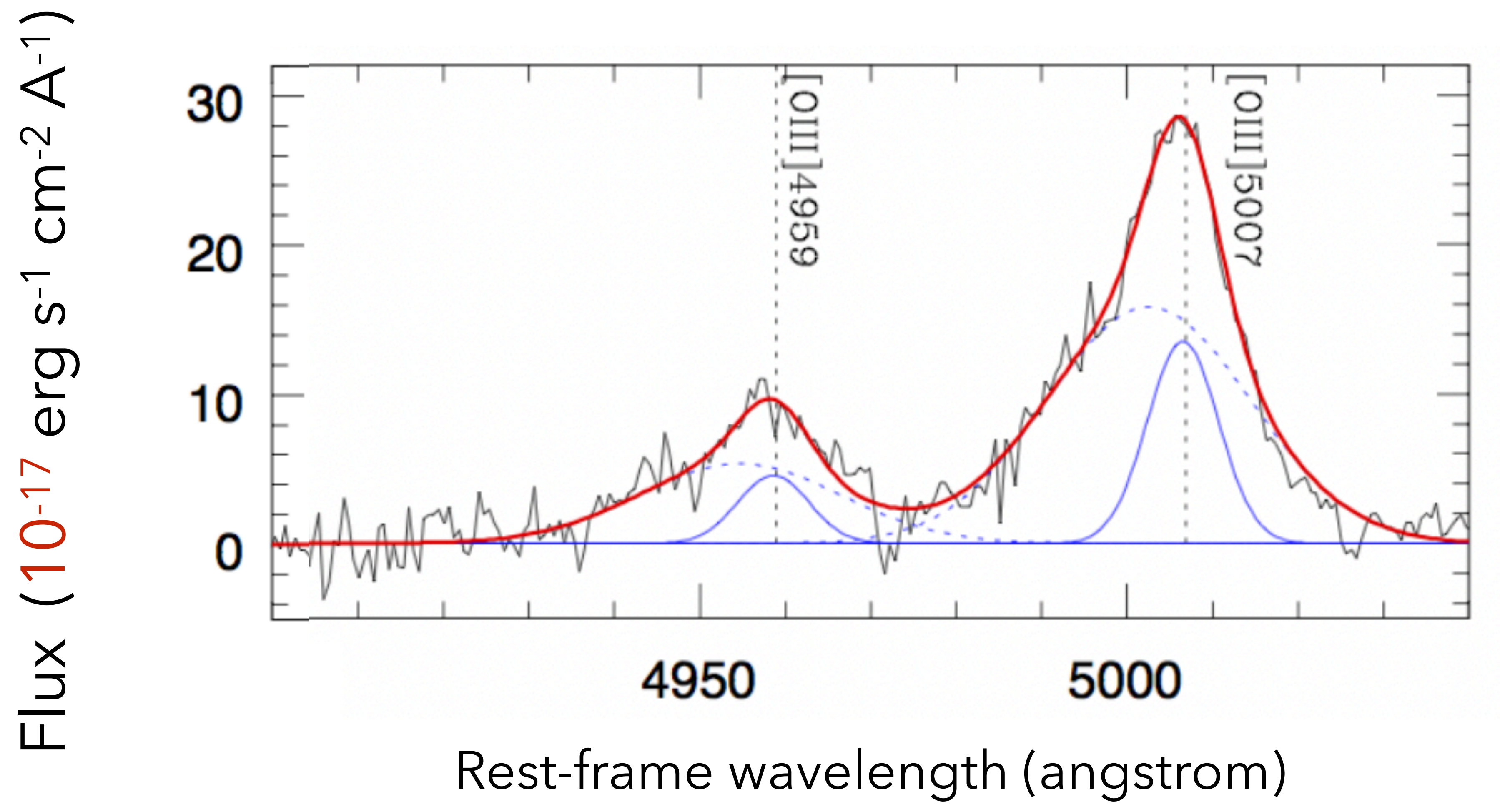
which is hundreds of times fainter than what we see in quasars

2. Ionized Gas

COSMOS-11142

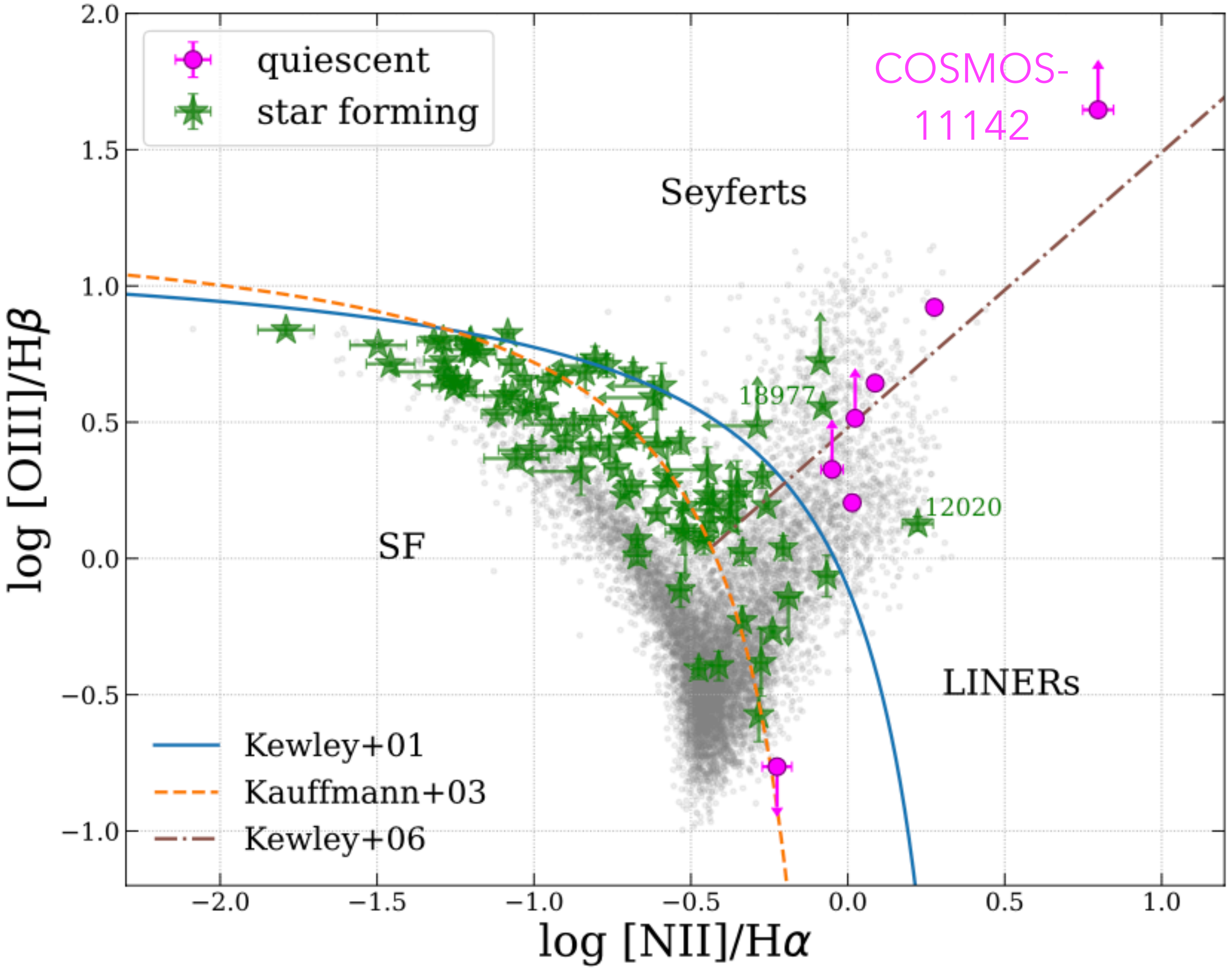


Quasar at z~1.5 (Brusa et al. 2016)

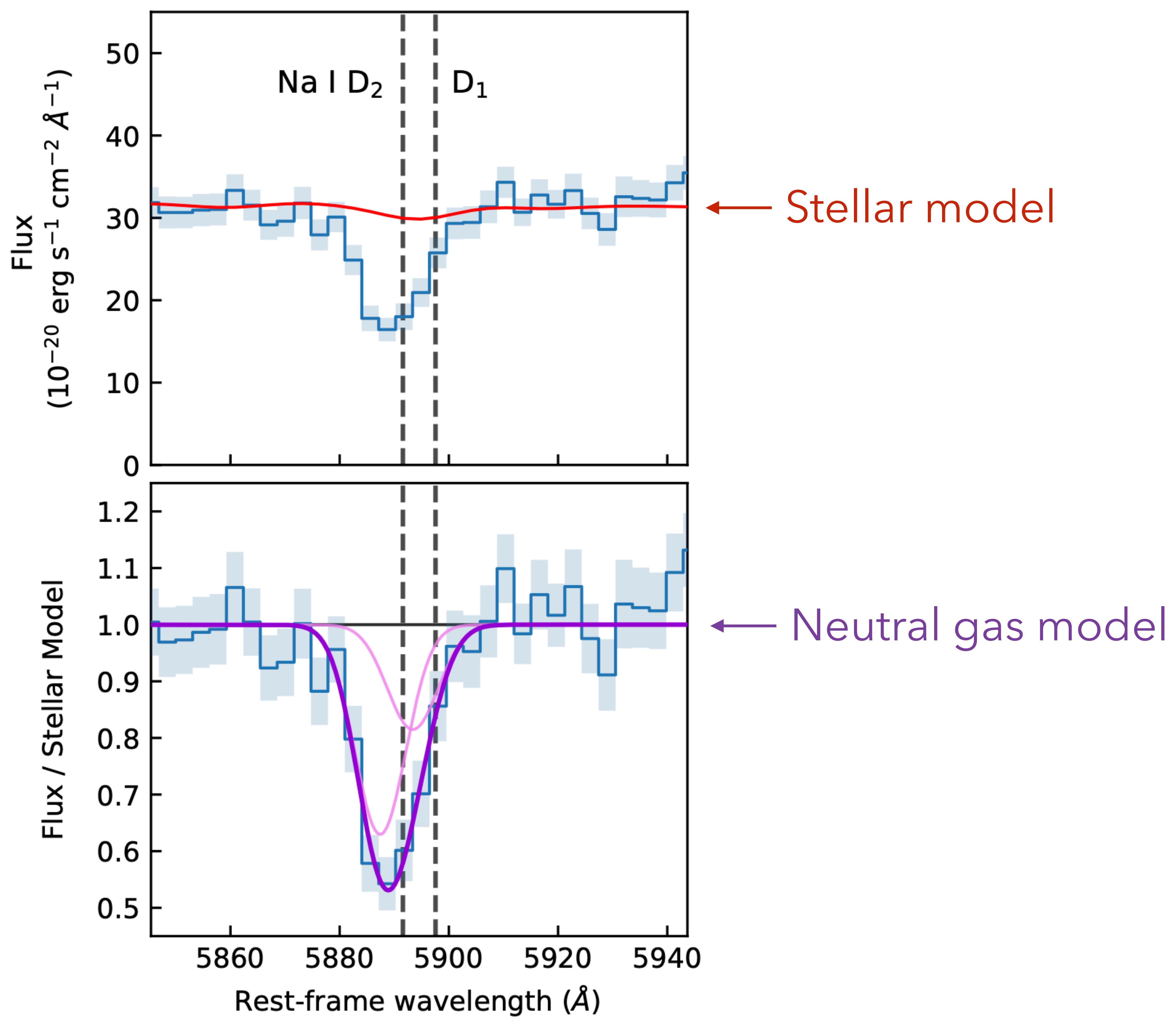


A large fraction of quiescent galaxies host **low-luminosity AGNs** (Bugiani et al. 2024)

Letizia Bugiani



3. Neutral Gas

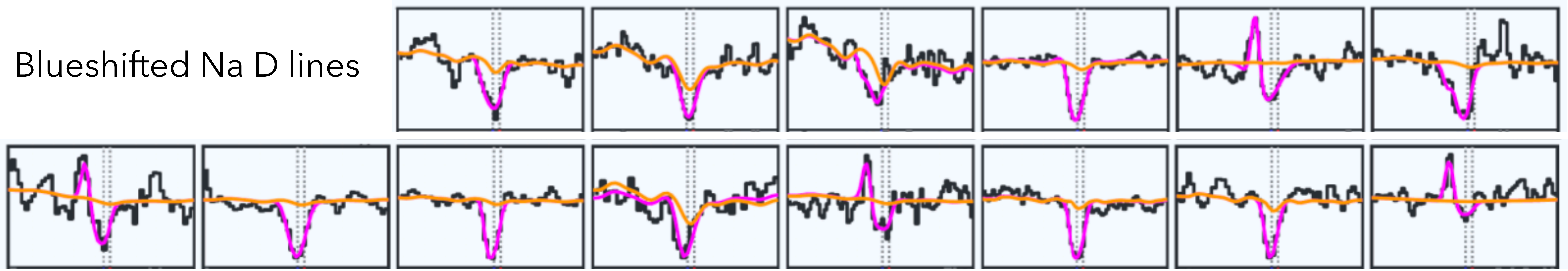


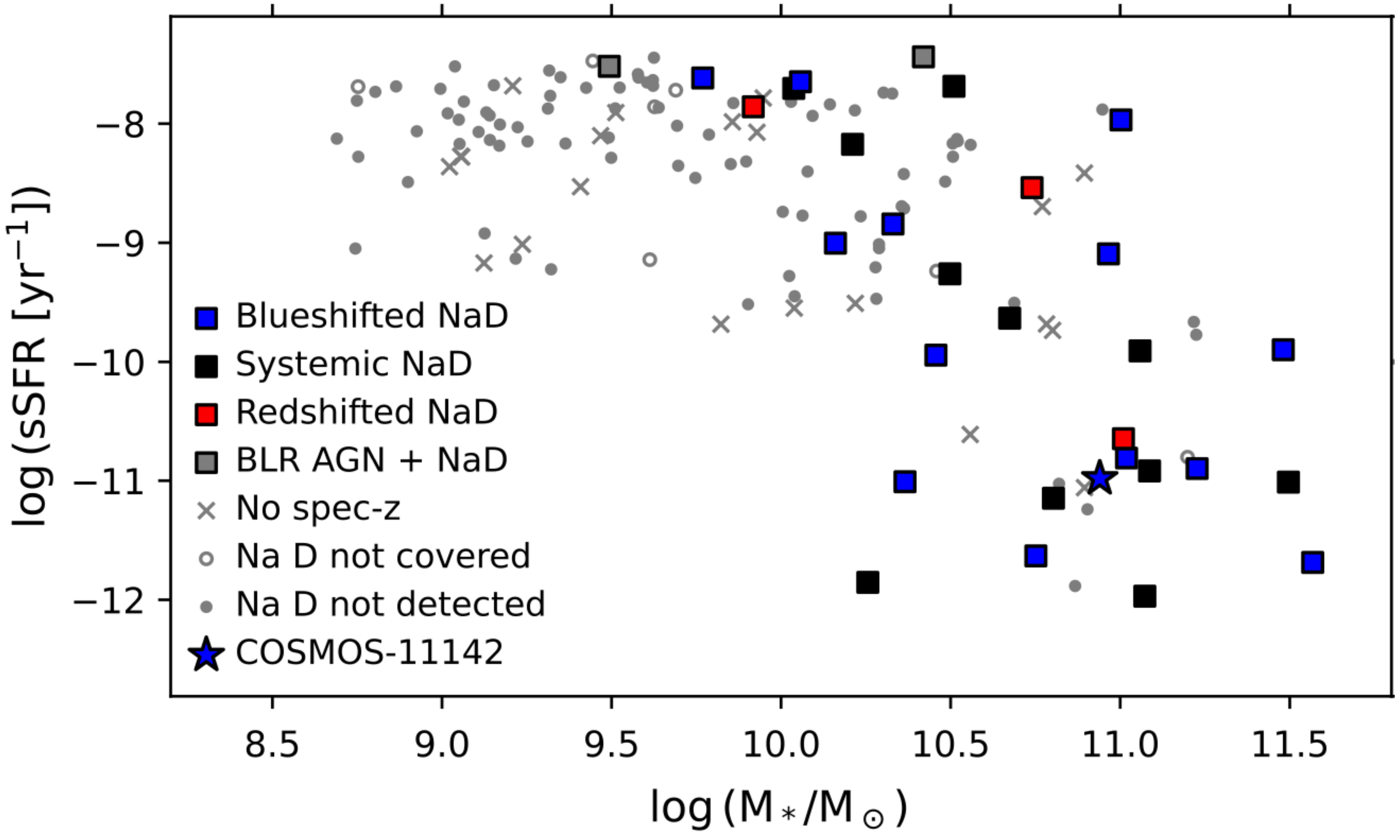
Neutral gas absorption lines are blueshifted

Neutral gas outflow

in a quiescent galaxy at Cosmic Noon

Blueshifted Na D lines





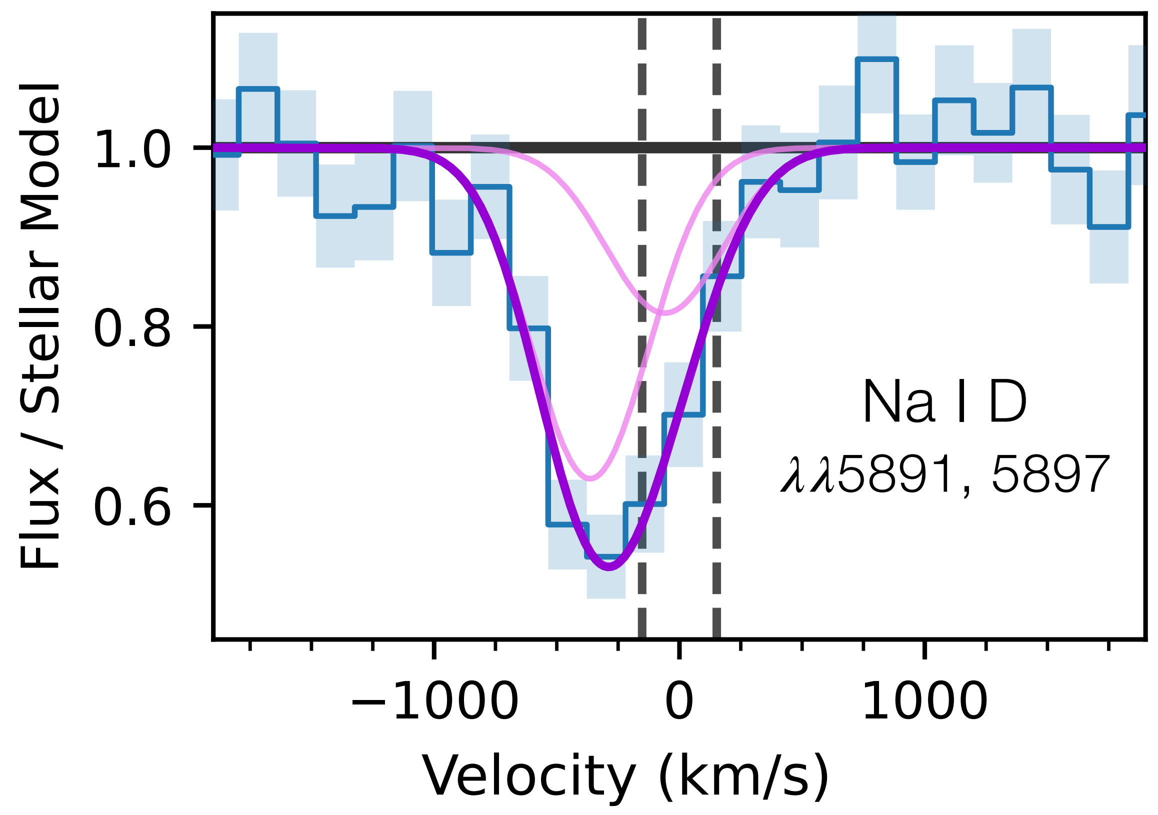
Neutral outflows are extremely common in massive galaxies!

(**Davies et al. 2024**)

Cycle-3 NIRSpec high-resolution follow-up to resolve the Na D doublet

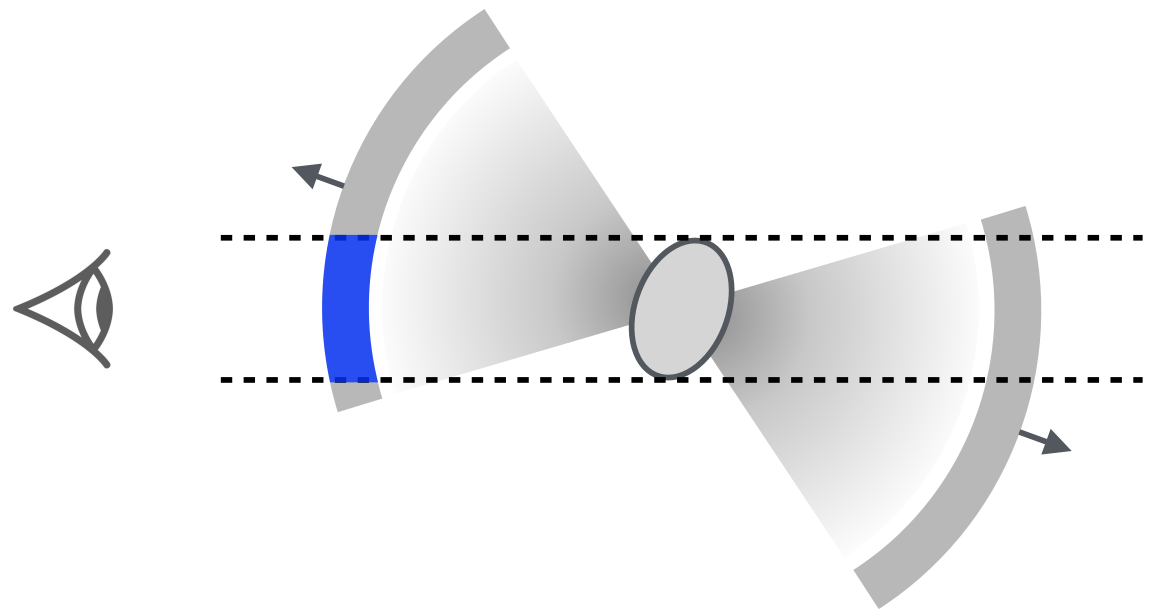
(**Davies et al. in prep.**)

Mass Outflow Rates



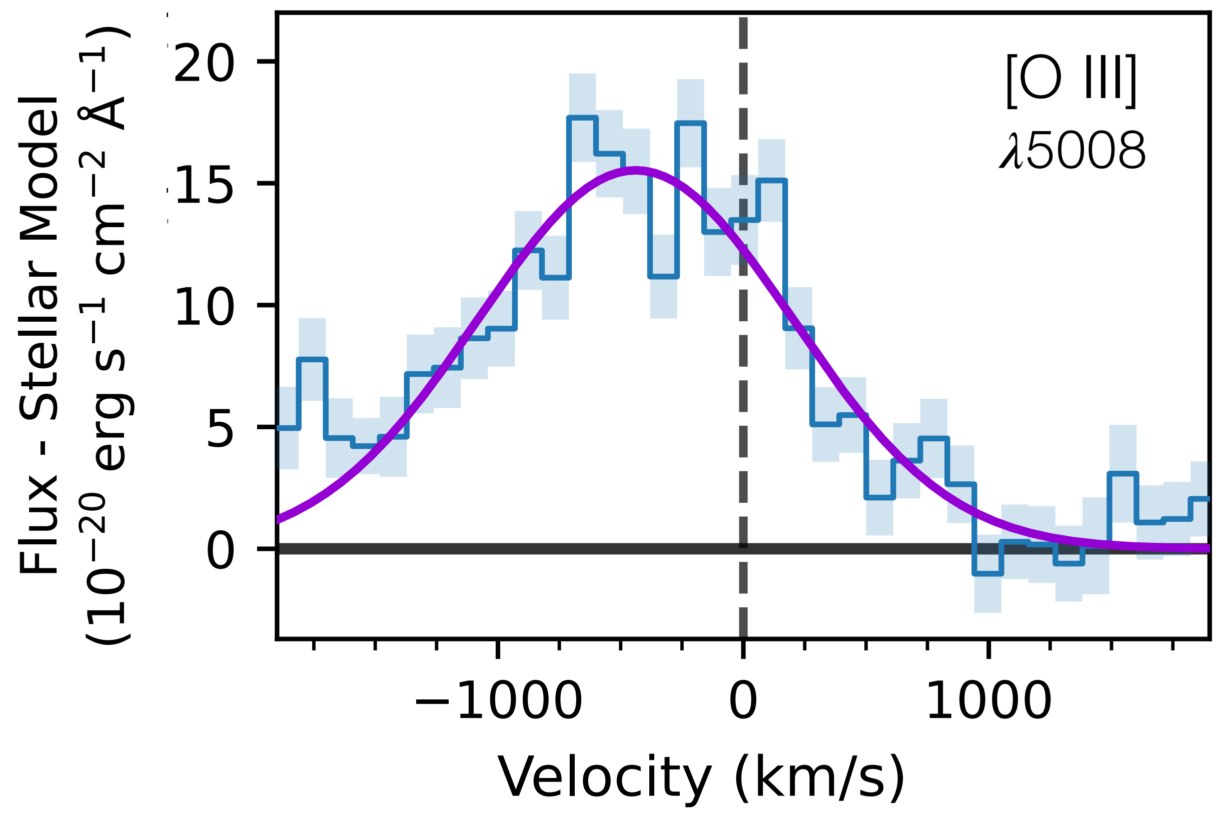
Neutral gas

blueshifted Na I absorption



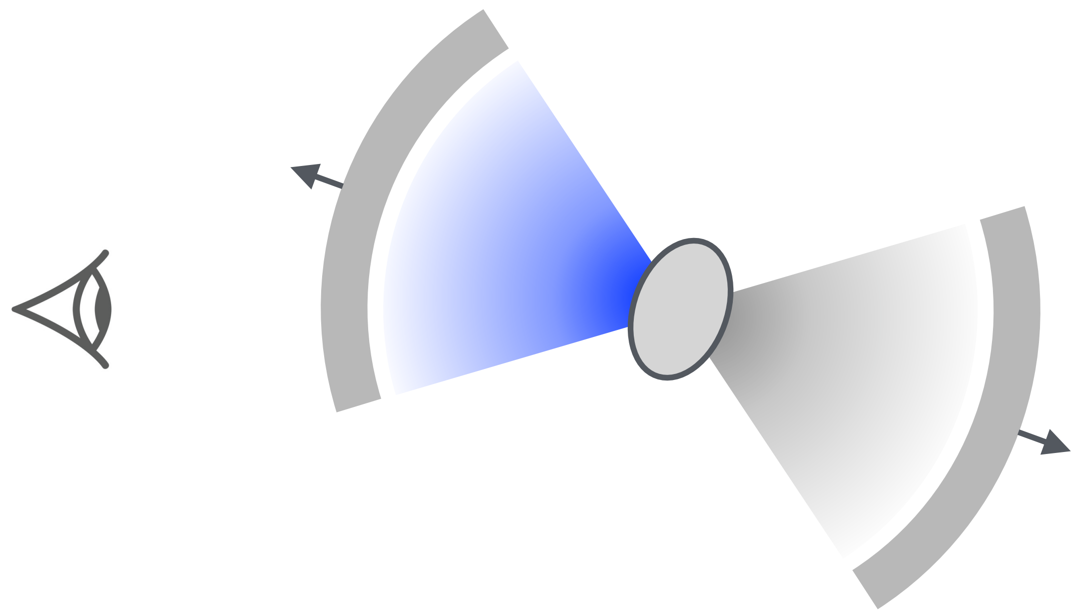
$$N_{\rm H\,I} = \frac{N_{\rm Na\,I}}{(1-y)\,10^{[\rm Na/H]}\,(n_{\rm Na}/n_{\rm H})_\odot\,10^{b}}$$

$$\dot{M}_{out} = 1.4 m_p \cdot 4\pi\, C_\Omega\, C_f\, N_{\rm H\,I}\, R_{out} v_{out}$$



Ionized gas

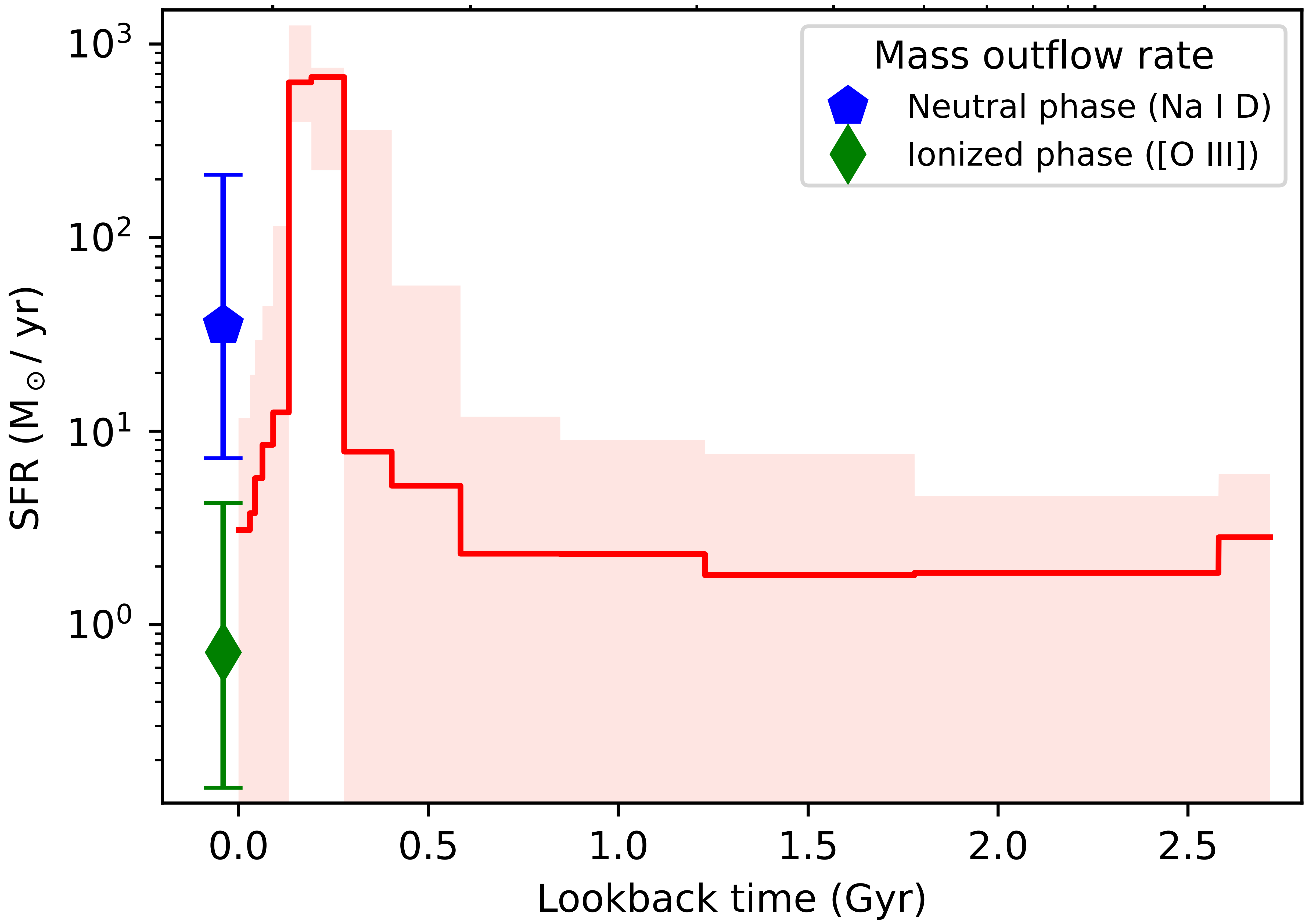
blueshifted [OIII] emission



$$M_{\rm out} = \frac{1.4\, m_{\rm p}\, L}{n_{\rm e}\, 10^{[\rm X/H]}\, (n_{\rm X}/n_{\rm H})_\odot\, j}$$

$$\dot{M}_{\rm out} = M_{\rm out}\, v_{\rm out}/R_{\rm out}$$

Belli et al. (2024)



Neutral outflow:
sufficient to quench the galaxy

Ionized outflow:
negligible

Quenching by gas ejection via multi-phase AGN-driven outflows

(see also D'Eugenio et al. 2024, Wu et al. 2025, Valentino et al. 2025)

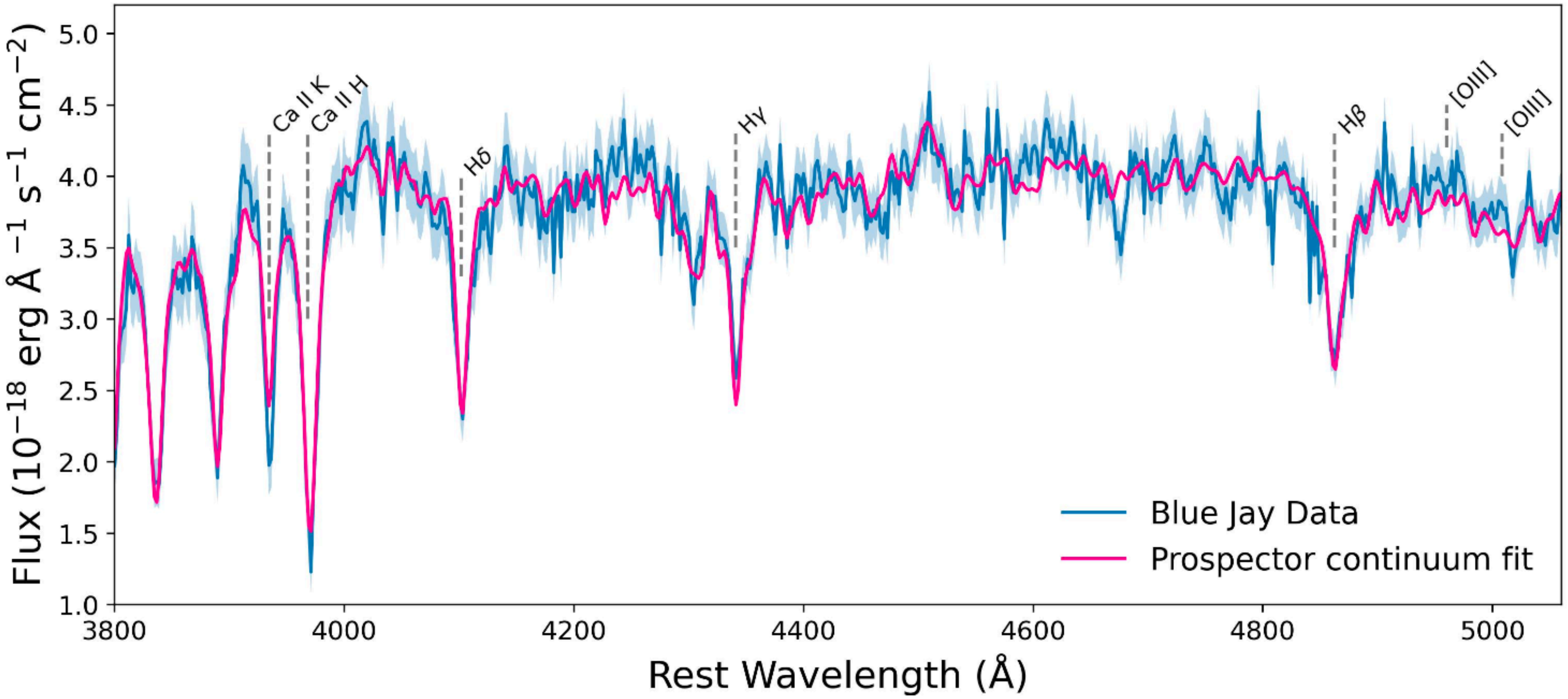
Probing neutral outflows in $z \sim 2$ galaxies using JWST observations of Ca II H and K absorption lines

Caterina Liboni[1], Sirio Belli[1], Letizia Bugiani[1,2], Rebecca Davies[3,4], Minjung Park[5], Charlie Conroy[5], Razieh Emami[5], Benjamin D. Johnson[5], Amir H. Khoram[1,2], Joel Leja[6,7,8], Gabriel Maheson[9,10], Matteo Sapori[1,2], Trevor Mendel[4,11], Sandro Tacchella[9,10], Rainer Weinberger[12]

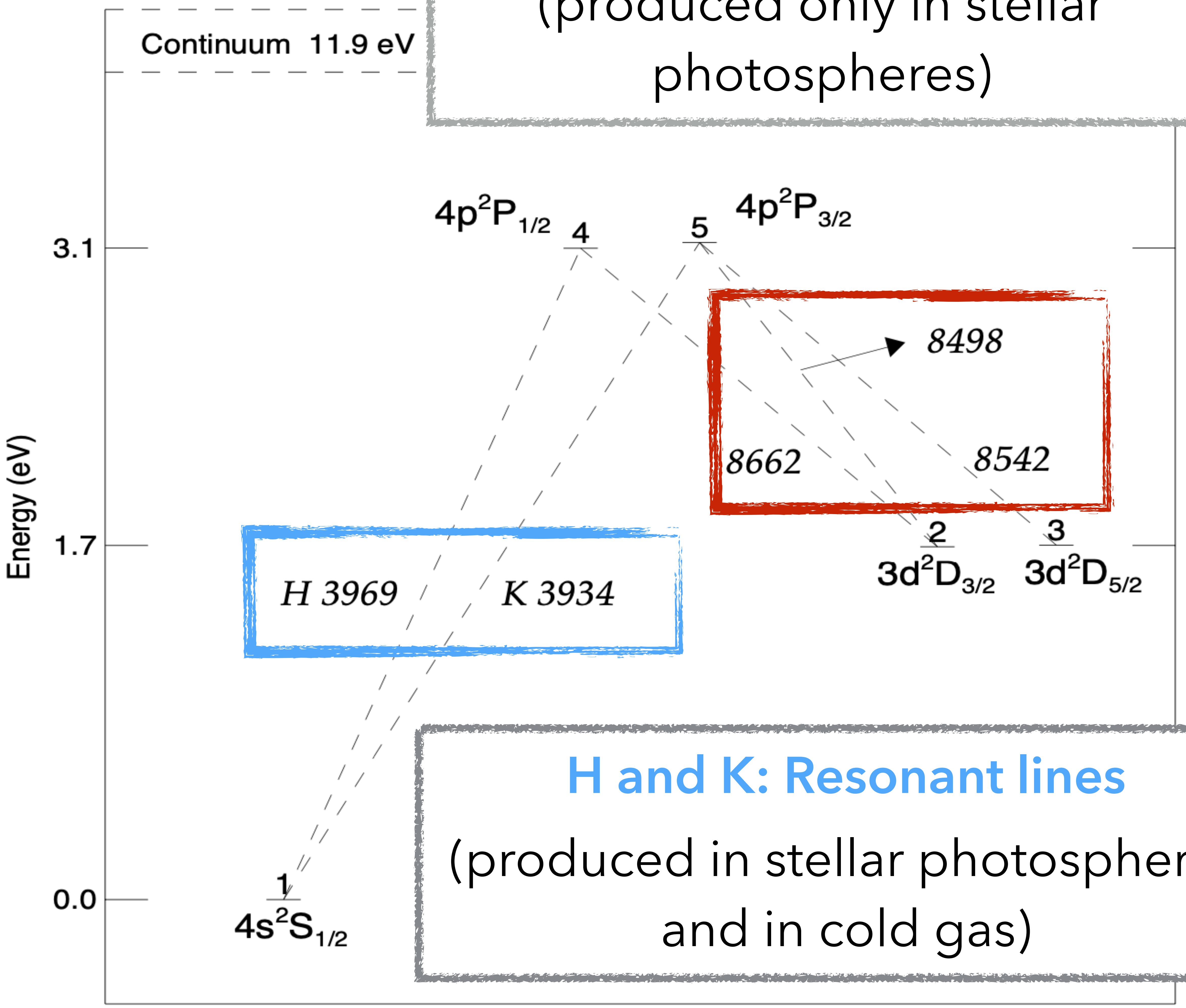
Caterina Liboni

Can we use the Ca II H and K lines to study neutral outflows?

We need to trust the stellar population template



Stellar pop. model can reproduce the Ca triplet!



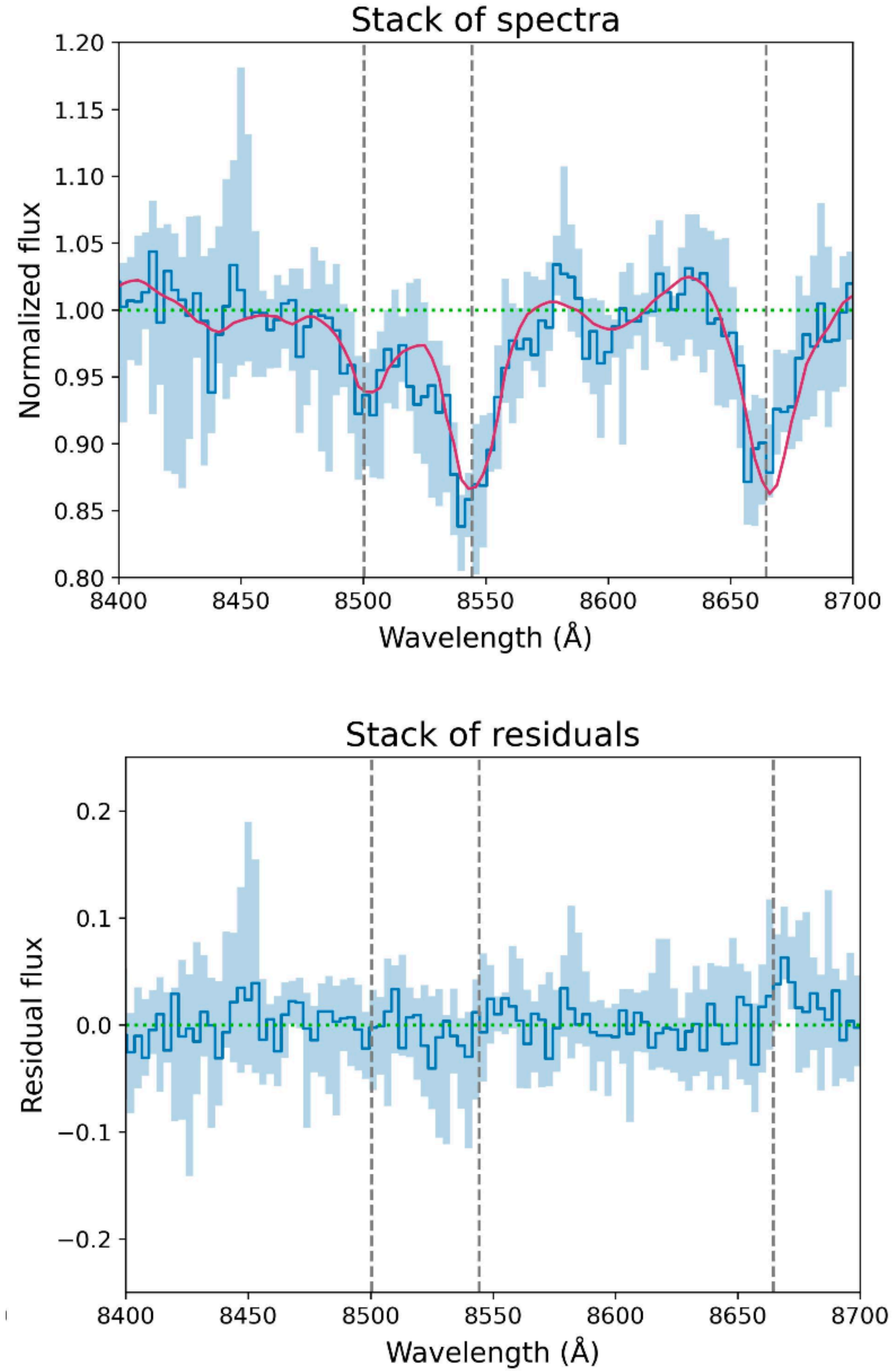
Ca triplet: non-resonant lines

(produced only in stellar photospheres)

H and K: Resonant lines

(produced in stellar photospheres and in cold gas)

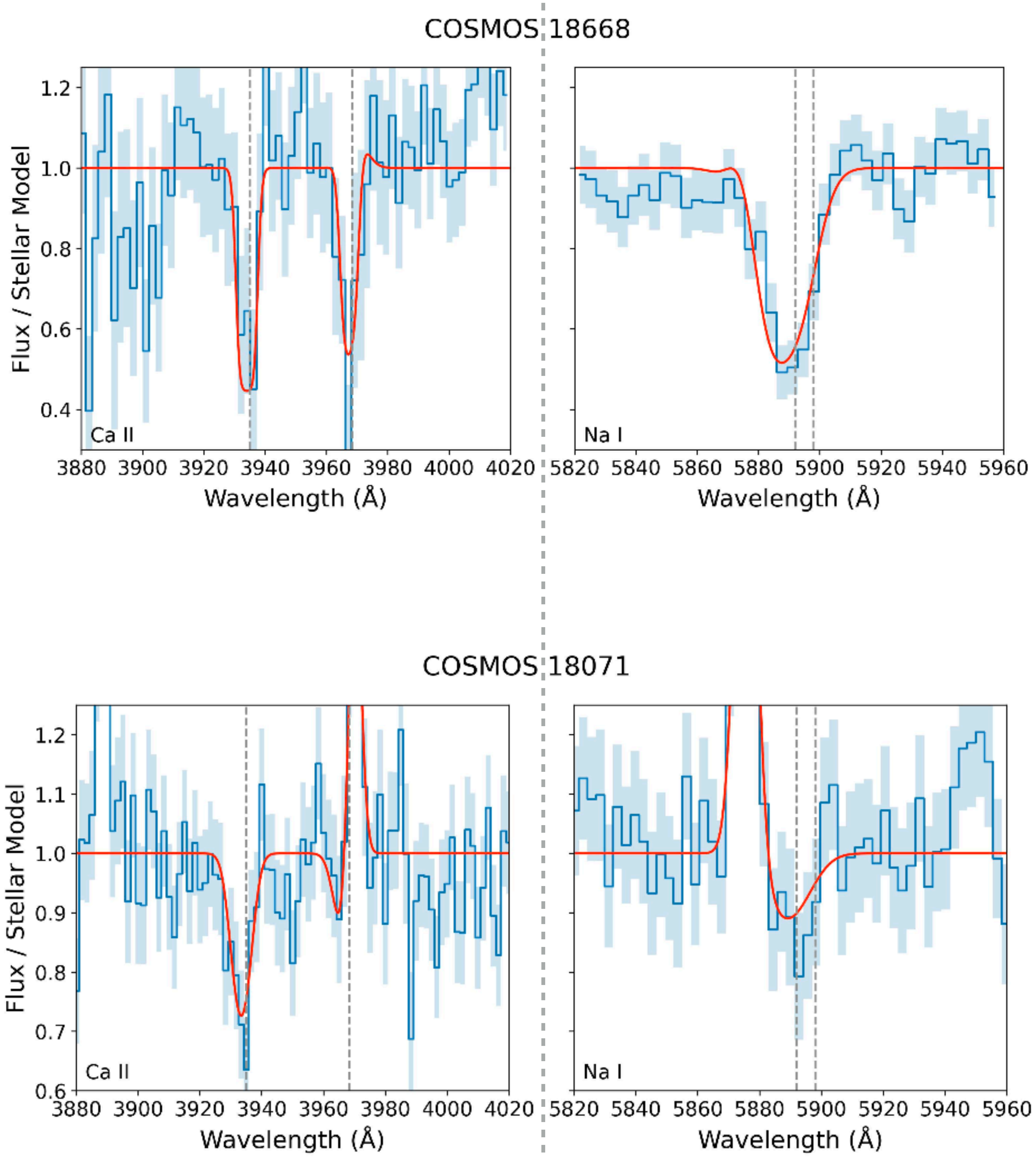
Azevedo et al. 2006



Liboni et al. 2025

Ca II H, K doublet

- Well resolved: easy to measure covering fraction
- Contaminated by Hε emission
- Poorly studied in the local universe (strong stellar absorption)

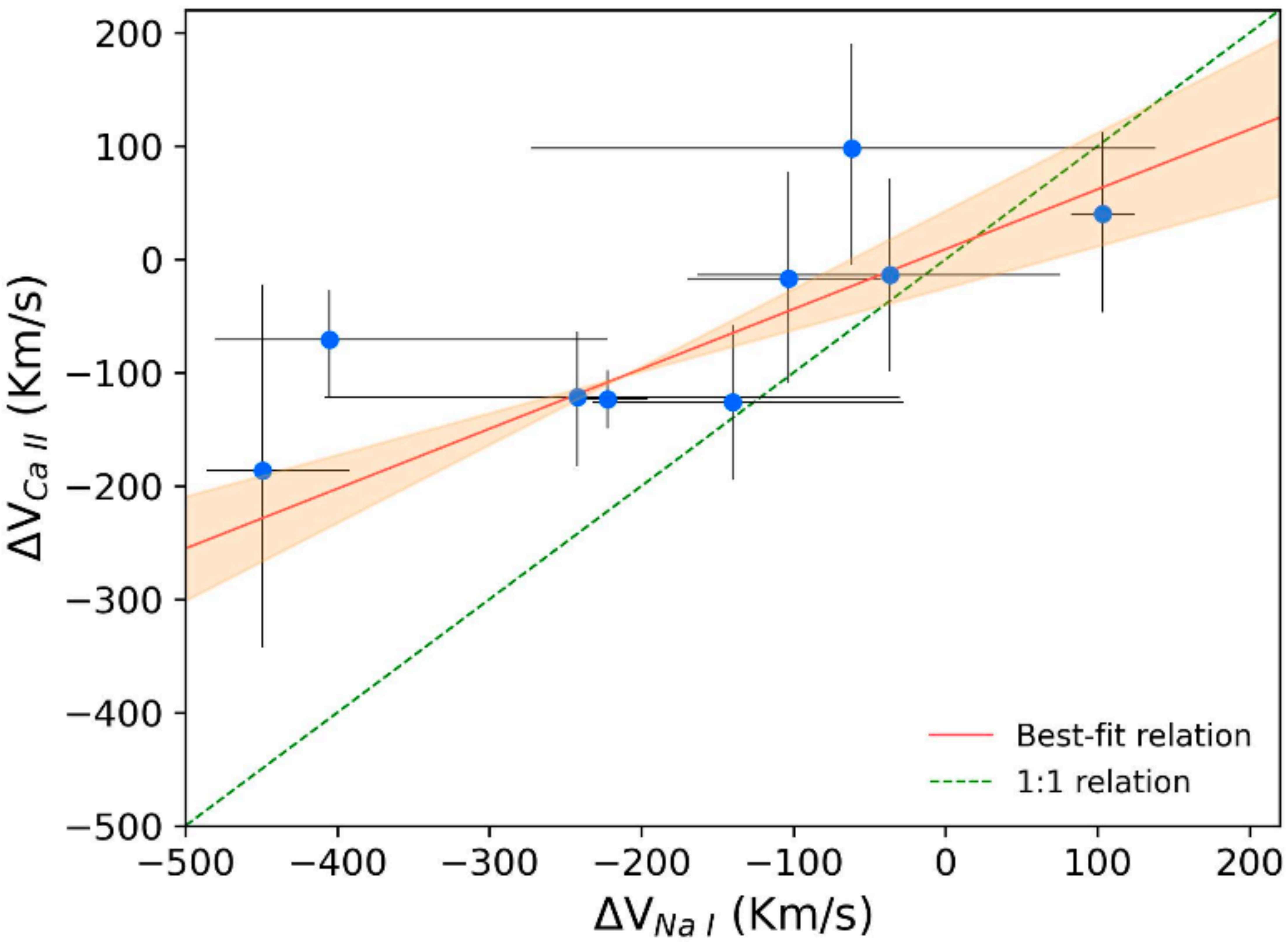


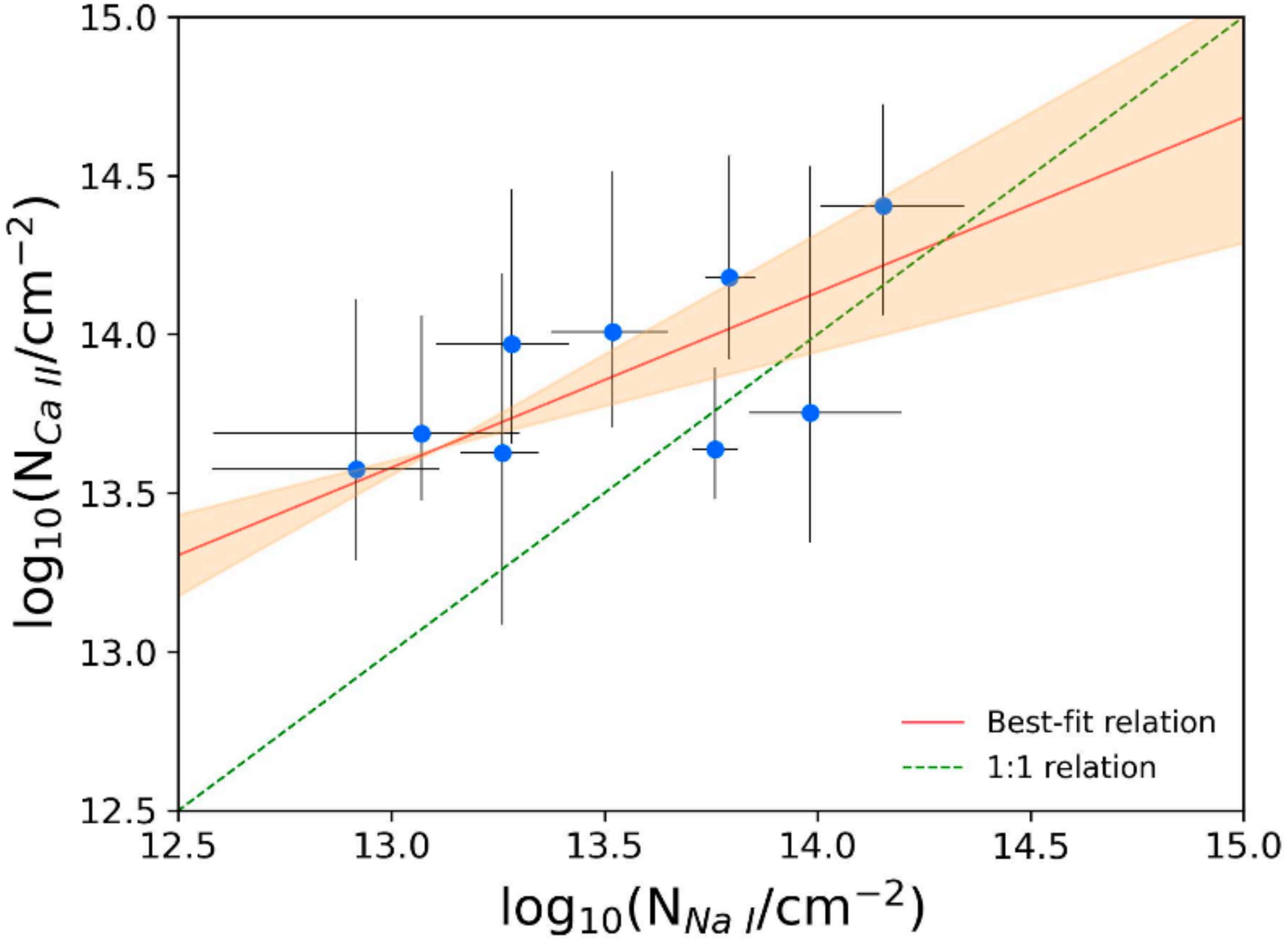
Na I D doublet

- Blended: hard to measure covering fraction
- Contaminated by He I emission
- Widely studied in the local universe

Liboni et al. 2025

Ca II H, K and Na I D trace similar gas





Liboni et al. 2025

However, we are still observing trace elements, representing <1 in a million atoms!

Most of the mass is here

But we can only measure this

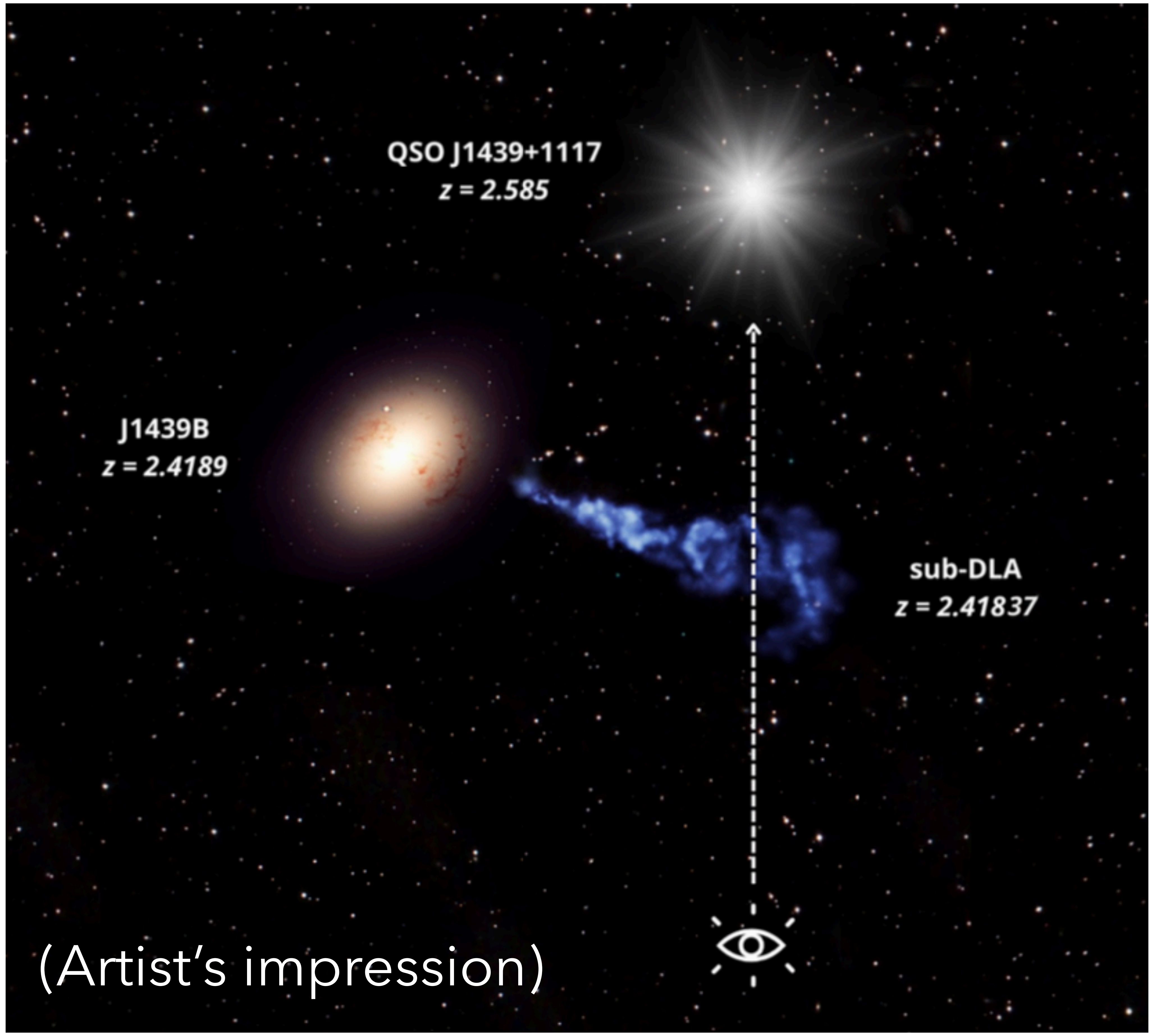
$$N_{\mathrm{H\,I}} = \frac{N_{\mathrm{Na\,I}}}{(1-y)\,10^{[\mathrm{Na/H}]}\,(n_{\mathrm{Na}}/n_{\mathrm{H}})_{\odot}\,10^{b}}$$

Lots of assumptions with huge uncertainties!

Empirical Calibration of Na I D and Other Absorption Lines as Tracers of High-Redshift Neutral Outflows

Lorenzo Moretti[1], Sirio Belli[1], Gwen C. Rudie[2], Andrew B. Newman[2], Minjung Park[3], Amir H. Khoram[1,4], Nima Chartab[5], Darko Donevski[6,7]

Lorenzo Moretti



(Artist's impression)

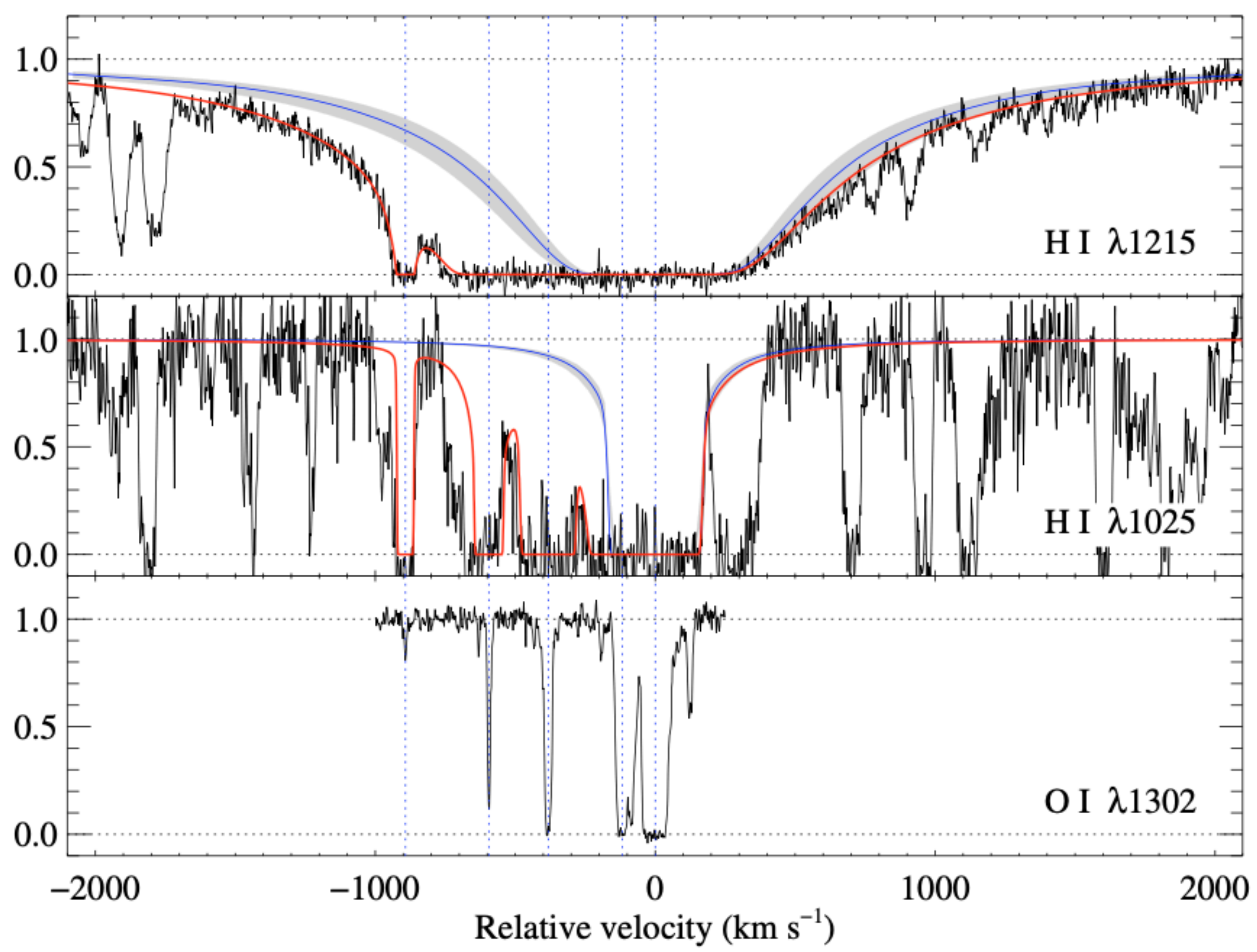
J1439: a unique system

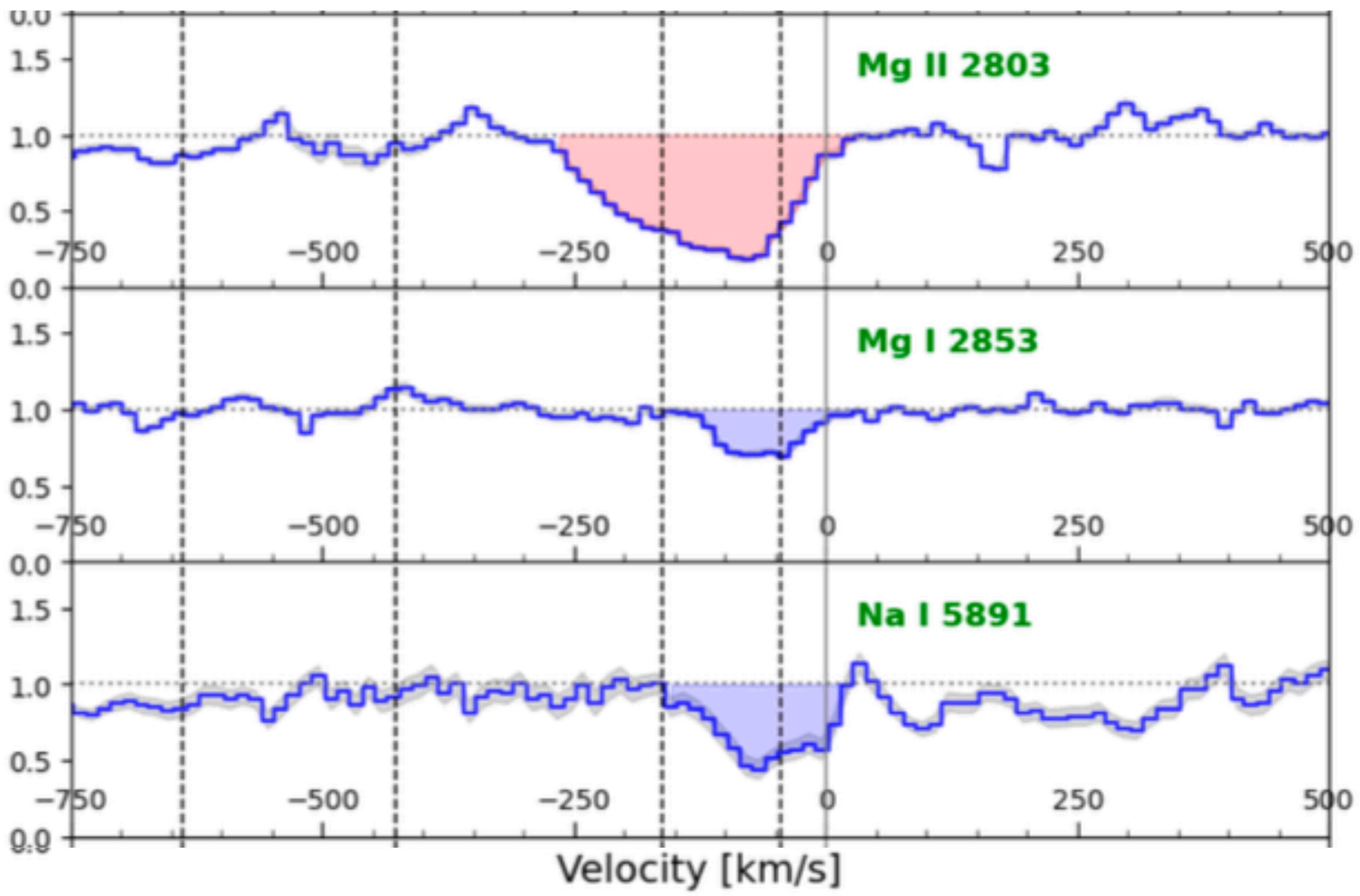
- **Chance alignment** between the outflow from a massive quiescent galaxy at z~2.4 and a background QSO (Srianand et al. 2008, Noterdaeme et al. 2008, Rudie et al. 2017)

- Bright UV background light makes it easy to detect Lyman absorption lines: **direct observation of hydrogen atoms**

VLT observations (Srianand et al. 2008)

New Magellan near-IR observations





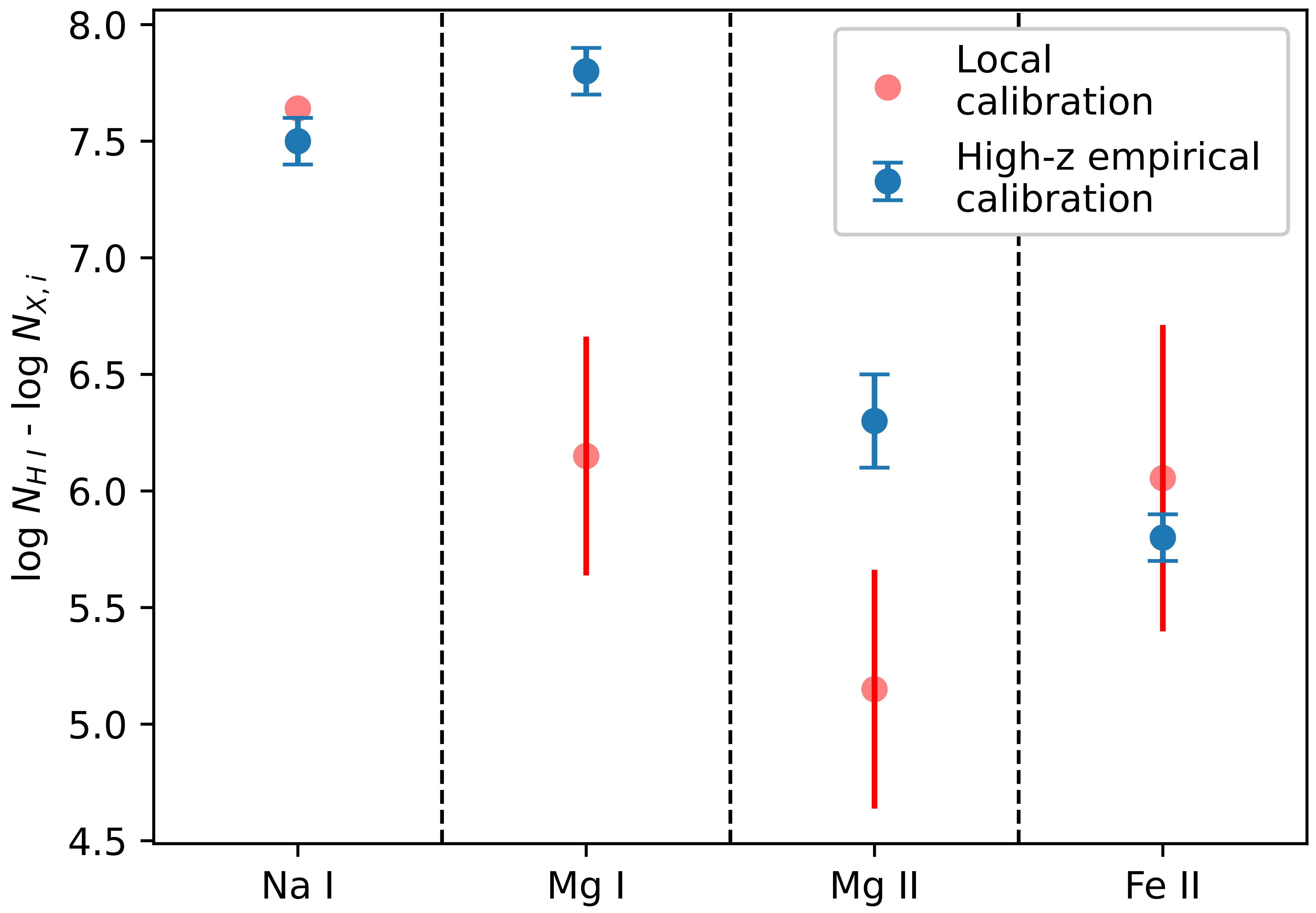
$\log(N_{\rm H\,I} / {\rm cm^{-2}}) = 20.1$

$\log(N_{\rm Na\,I} / {\rm cm^{-2}}) = 12.6$

$$\log N_{\rm H\,I} = \log N_{\rm Na\,I} + 7.5$$

Only 30% lower compared to the “nominal” assumptions!

Na I calibration is spot on, but for Mg II the nominal assumptions are off by a factor of 10! Possibly because of dust depletion pattern



Moretti et al. 2025

Conclusions

1. Neutral outflows are **common** and **important** in massive galaxies at high redshift

2. They are likely the main cause for **rapid quenching**

3. We still need a lot of work to understand **physical origin**, **geometry**, and **mass rates**