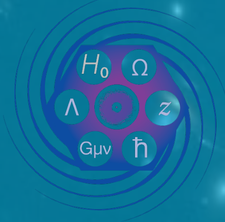
LECTURE 10:
UV-VISIBLE ISM / GALAXY STUDIES

Danielle A. Berg (she/her), Neurodivergent, Bisexual, Assistant Professor



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- UNDERSTAND HOW UV–MIR SPECTROSCOPY IS USED TO PROBE THE ISM IN GALAXIES
- DESCRIBE KEY DIAGNOSTICS OF CHEMICAL ABUNDANCES, DEPLETIONS, AND DUST ATTENUATION
- EVALUATE THE CONTRIBUTIONS OF INTEGRAL FIELD UNITS (E.G., MUSE) TO OUR UNDERSTANDING OF NEARBY GALAXIES
- RECOGNIZE THE LIMITATIONS OF CURRENT OBSERVATORIES AND THE SCIENCE DRIVERS FOR FUTURE IFM SYNERGIES (E.G., HWO+MUSE+MIR)

ISM BASICS

ISM BASICS

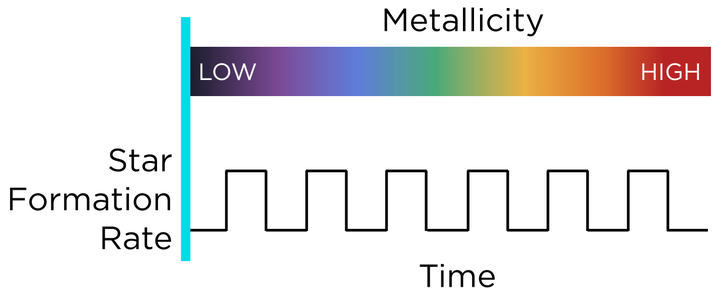
Massive star formation in a gas cloud

The first stars synthesized the first heavy elements

The death of these stars **enriched** the surrounding **interstellar medium**

The **metallicity continues to increase** monotonically with each successive **generation of stars***

*For a close box with instantaneous recycling



Observations of the ISM trace the cumulative evolution of a galaxy

Chemical evolution is directly shaped by star formation

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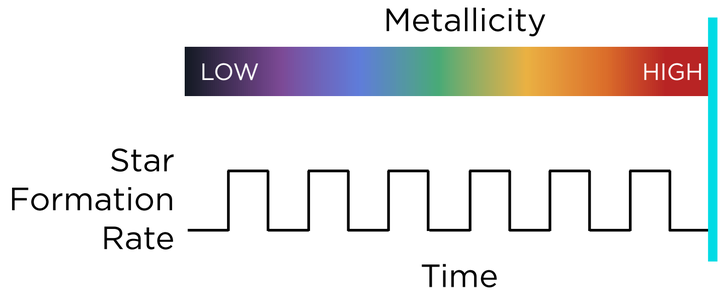
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ISM

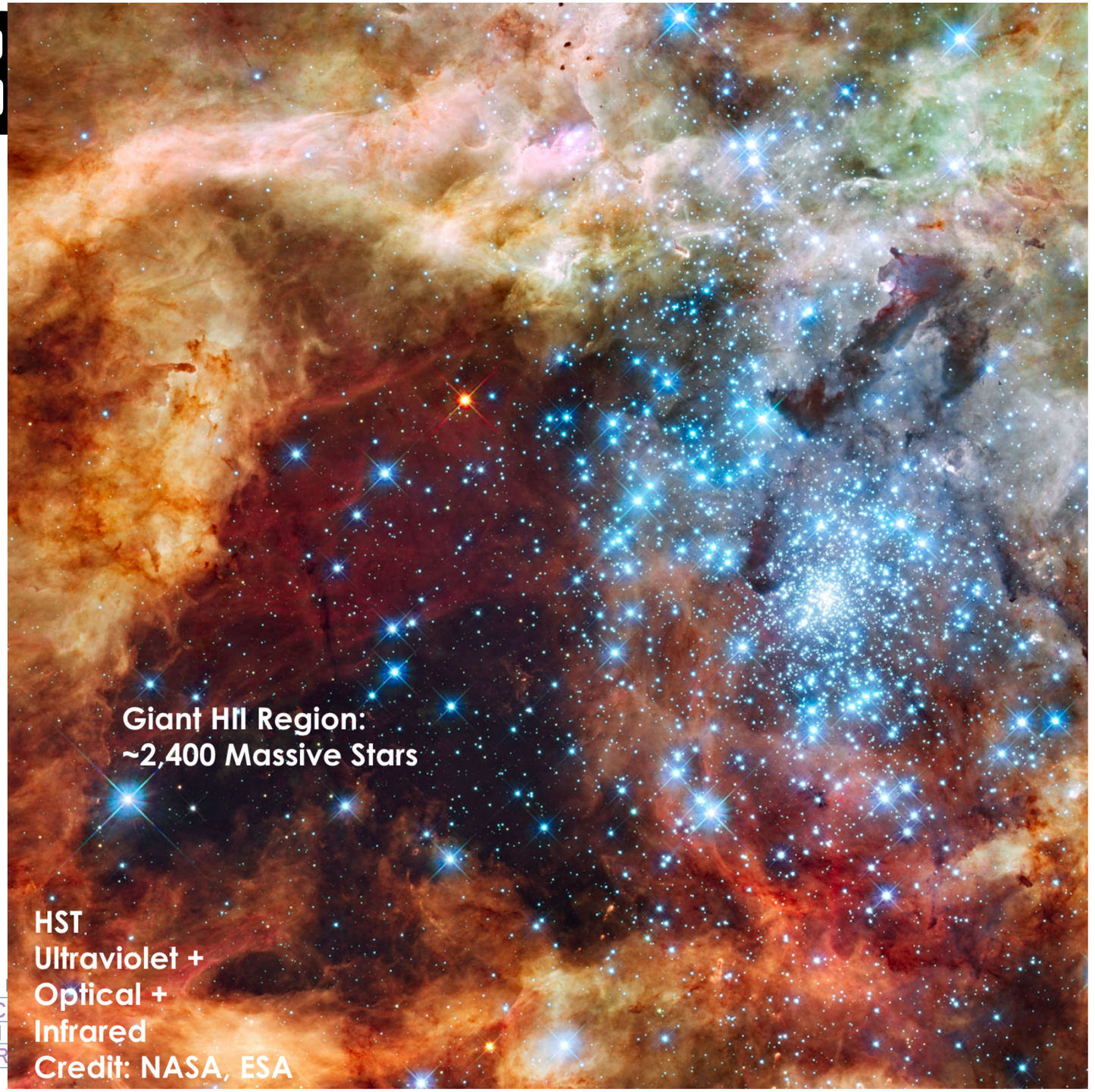


THE IMPORTANCE OF ISM EVOLUTION

Observations of the ISM trace the cumulative evolution of a galaxy

Chemical evolution is directly shaped by star formation

ISM B



Observations of the ISM trace the cumulative evolution of a galaxy

Stars ionize gas …

ISM BASICS

Volumetric Recombination Rate:

$$\frac{dn_{\rm HII}}{dt}\left(\frac{\#}{\rm s\ cm^3}\right) = n_e n_p \alpha(\rm H^0, T)$$

Total Recombination Coefficient

Recombination Time:

Assume gas with $T_e = 10^4$ K and $n_e = 10^2$ cm^{-3}, where $\alpha_B \approx 2.6 \times 10^{-13}$ cm^3 s^{-1}:

$$t_{\rm rec.} \approx \frac{1}{n_e \alpha}$$

$$= \frac{1}{(10^2\ \rm cm^{-3}) \times (2.6 \times 10^{-13}\ cm^3\ s^{-1})}$$

$$= 3.8 \times 10^{11}\ \rm s = 1.20 \times 10^4\ yr$$

Volumetric Photoionization Rate:

$$\frac{dn_{\rm HII}}{dt}\left(\frac{\#}{\rm s\ cm^3}\right) = n_{\rm H^0}\zeta_{\rm pho.} = F_\nu \sigma_{\rm pho.}(\nu) d\nu$$

Rate of ionizing photons

Photoionization cross section

Ionization Time:

Assume O star with $Q_{\rm pho.} = 10^{49}$ photons s^{-1} cm^{-2}, $\sigma_{\rm pho.} = 6.3 \times 10^{-18}$ cm^2, and ionizations occurring at a radius of 0.1 pc from the star:

$$t_{\rm pho.} = \frac{1}{\zeta_{\rm pho.}} = \frac{1}{F_{\rm pho.}\sigma_{\rm pho.}} = \frac{4\pi r^2}{Q_{\rm pho.}\sigma_{\rm pho.}}$$

$$= \frac{4\pi(0.1 \times 3.086 \times 10^{18}\ \rm cm)^2}{(10^{49}\ \rm photons\ s^{-1}) \times (6.3 \times 10^{-18}\ cm^2)}$$

$$= 1.9 \times 10^5\ \rm s = 5.2\ hr$$

Recombination time **decreases** with **increasing density**

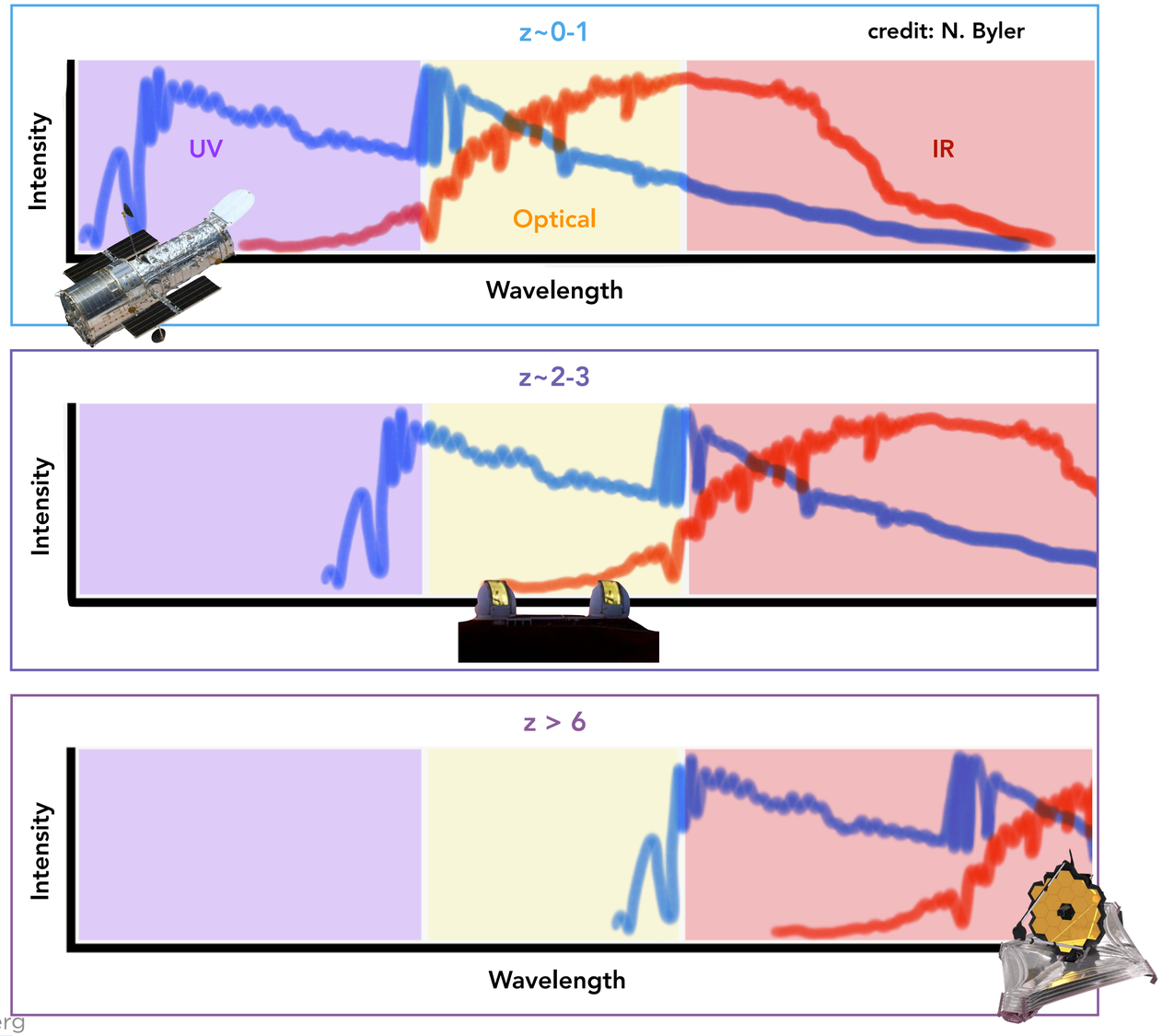
decreases with **increasing ionization fraction**

decreases with **increasing temperature** $\alpha_B(\rm H^0, T) \sim T^{-1}$

Ionization time really only depends on **ionizing photon flux**

Even after stars "turn off", gas stays ionized for ~10^4 yr

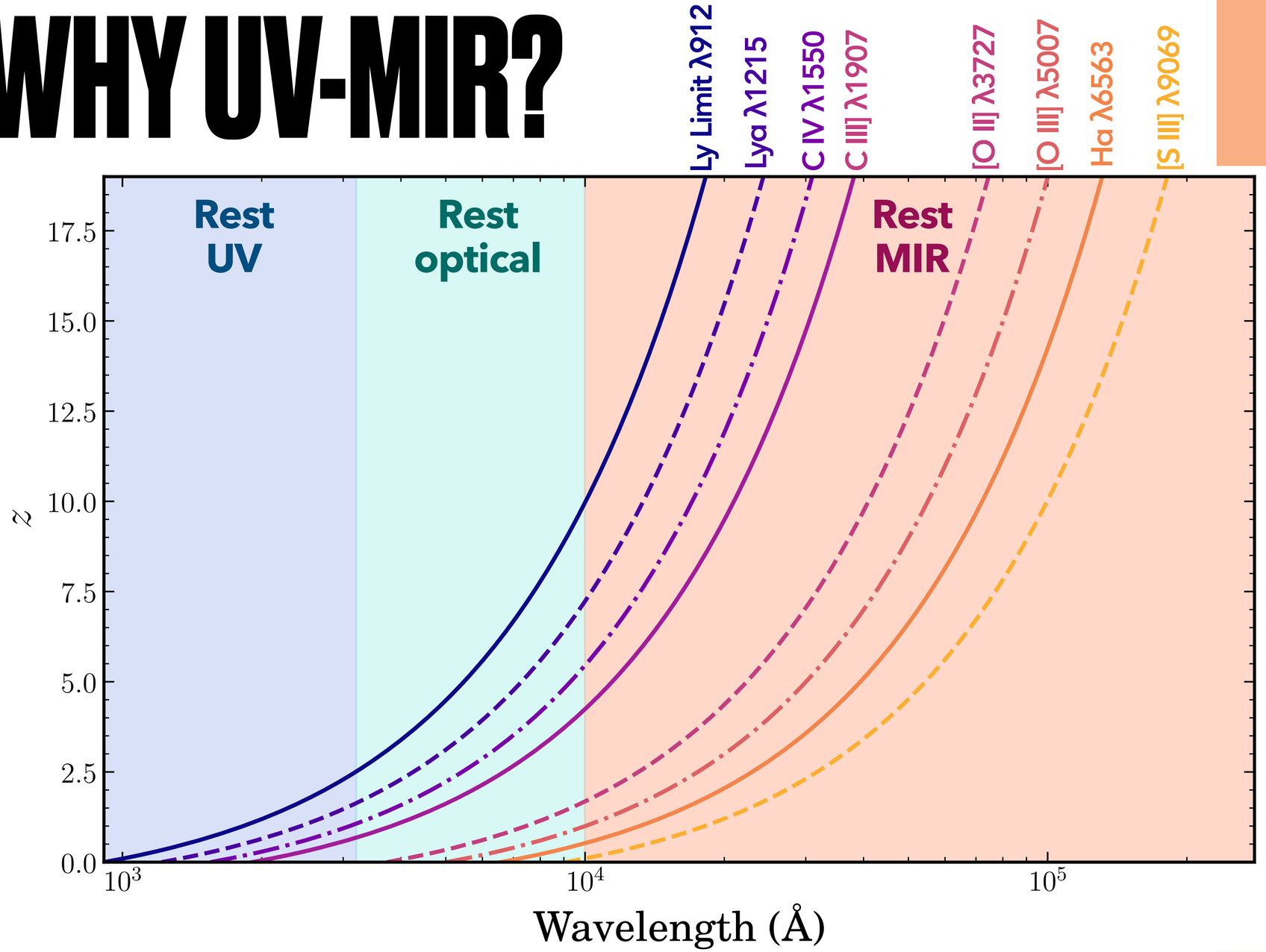
WHY UV-MIR?



Can study the rest-frame UV+optical+MIR of galaxies across cosmic time

Rest FUV: 912 – 2000 Å
Rest NUV: 2000 – 3200 Å
Rest Optical: 3200 – 10,000 Å
Rest NIR: 1 – 5 μm
Rest MIR: 5 – 28 μm

WHY UV-MIR?



Can study the rest-frame UV-optical of galaxies across cosmic time

Rest FUV: $912 - 2000$ Å
Rest NUV: $2000 - 3200$ Å
Rest Optical: $3200 - 10{,}000$ Å
Rest NIR: $1 - 5$ μm
Rest MIR: $5 - 28$ μm

Can probe all components of the ISM with UV+optical+MIR

Molecular gas (H_2): MIR (and EUV)
Neutral gas (H^0; H I): FUV
Ionized gas (H^+; H II): FUV+optical+MIR
Dust: FUV+optical+MIR

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METALLICITY MEASUREMENTS

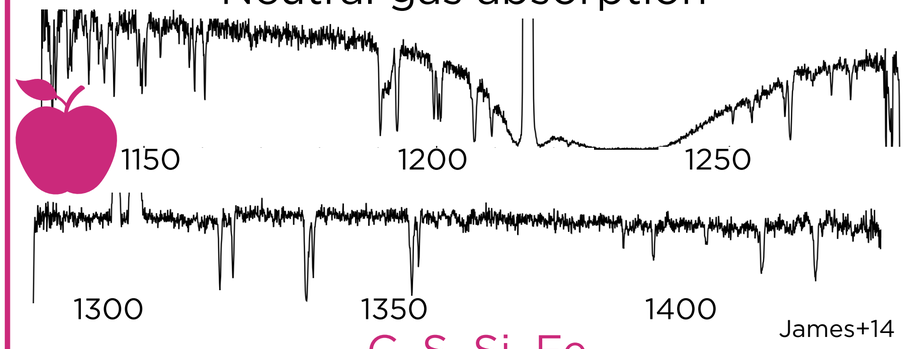
Abundances: How do we robustly measure chemical abundances?



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METALLICITY MEASUREMENTS

Neutral gas absorption

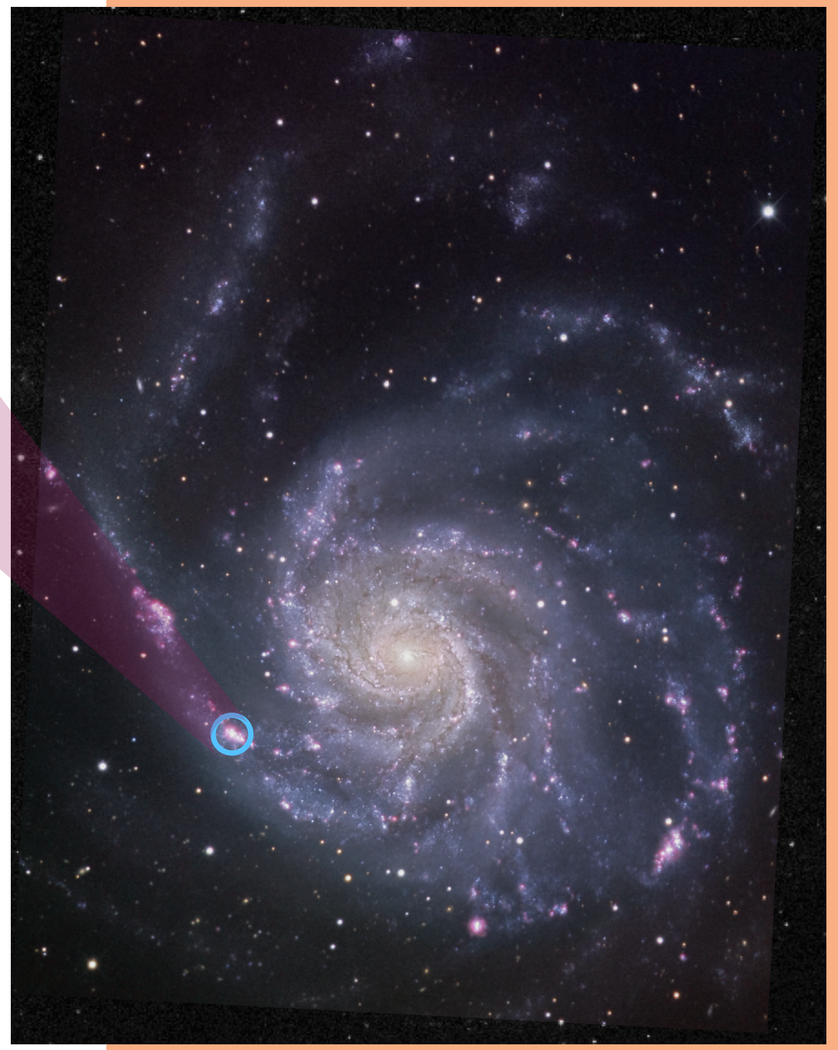


C, S, Si, Fe

Abundances: How do we robustly measure chemical abundances?

A fruit basket of abundance measurement methods

Are we comparing *apples to apples?*



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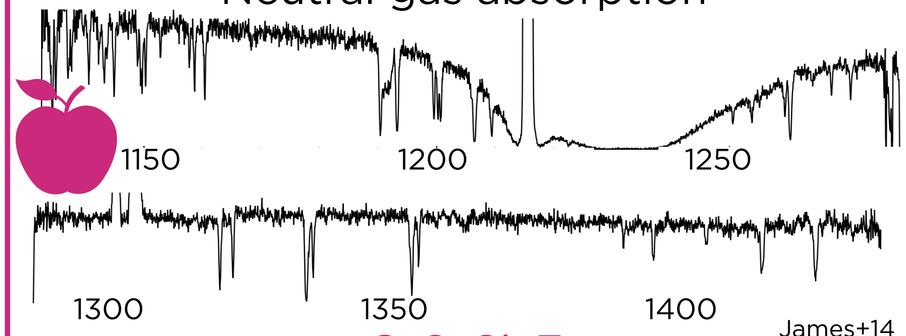
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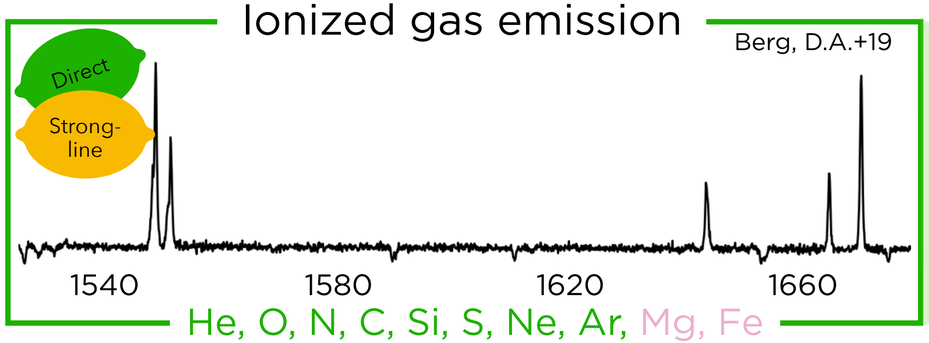
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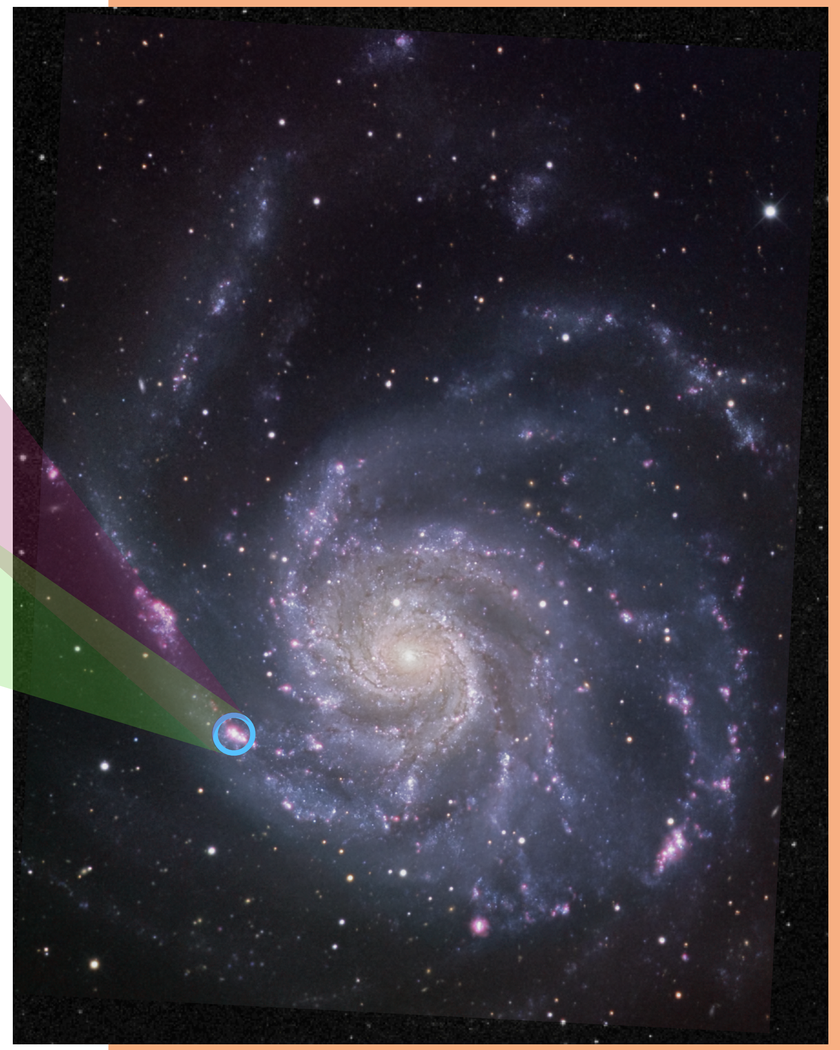


C, S, Si, Fe

Ionized gas emission



He, O, N, C, Si, S, Ne, Ar, Mg, Fe



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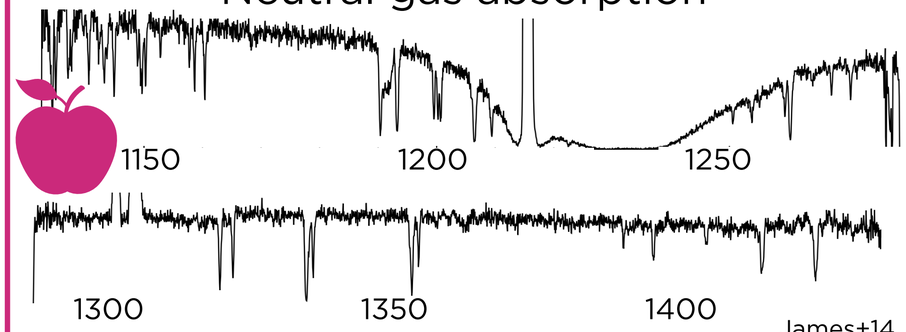
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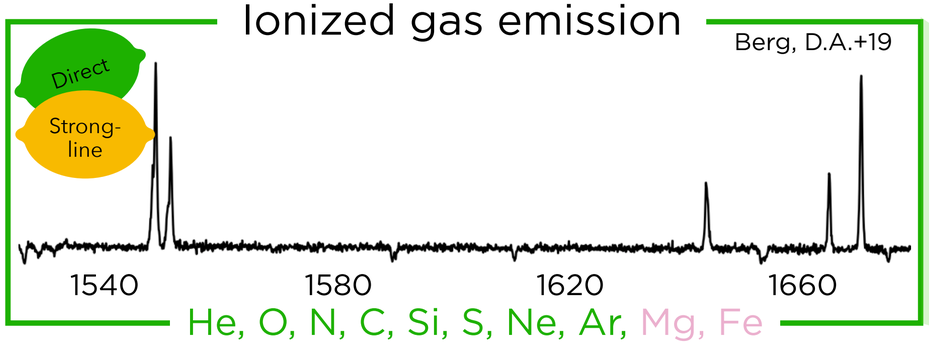
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Neutral gas absorption



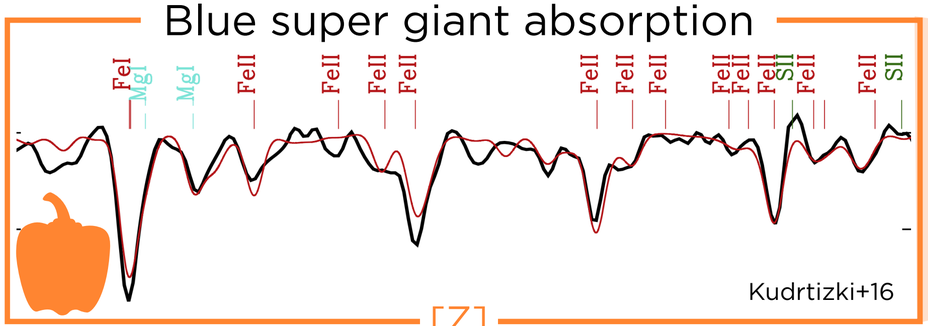
C, S, Si, Fe

Ionized gas emission



He, O, N, C, Si, S, Ne, Ar, Mg, Fe

Blue super giant absorption



[Z]



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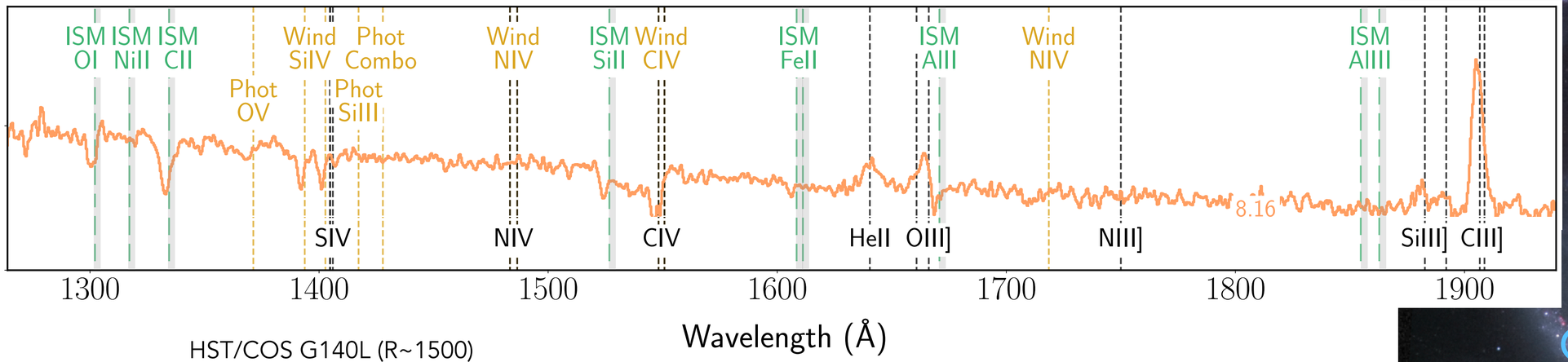
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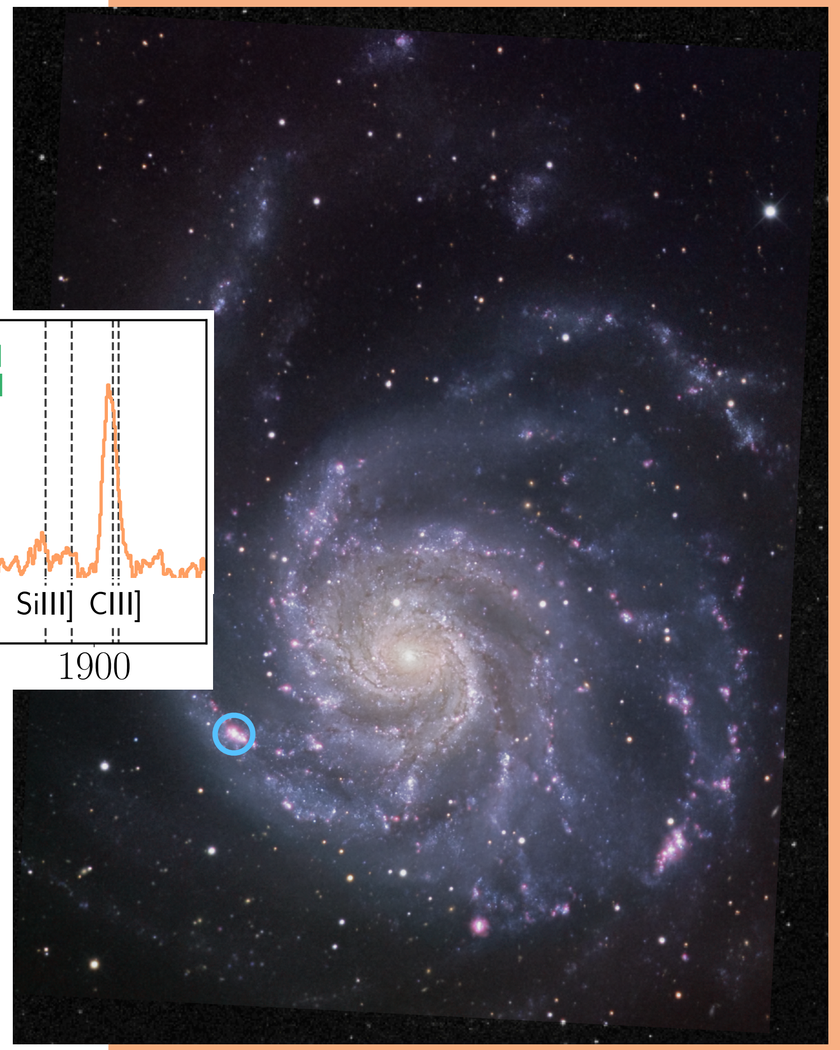
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Extragalactic H II region **UV spectra** are rich with abundance-dependent features:

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HST/COS G140L (R~1500)
HII Region in M101
Berg+2024



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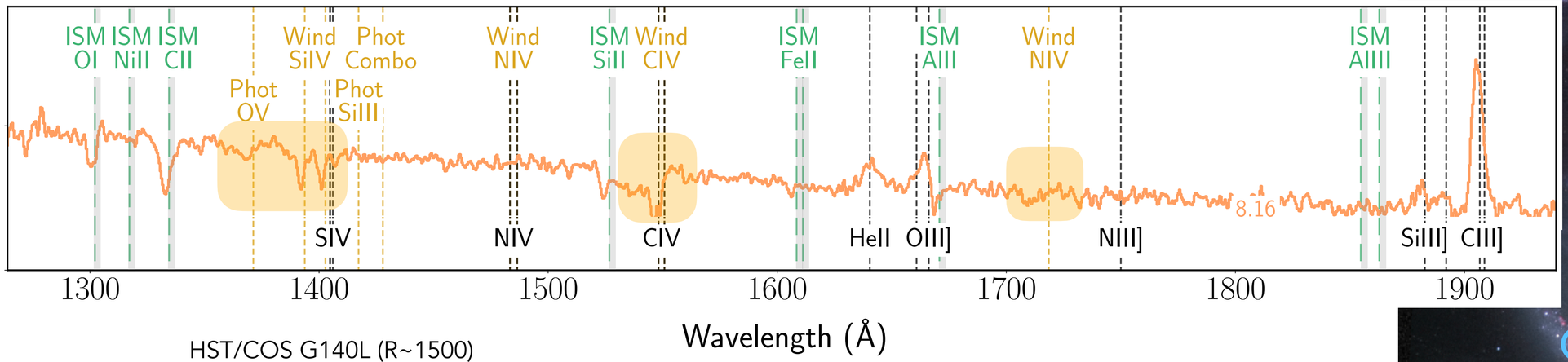
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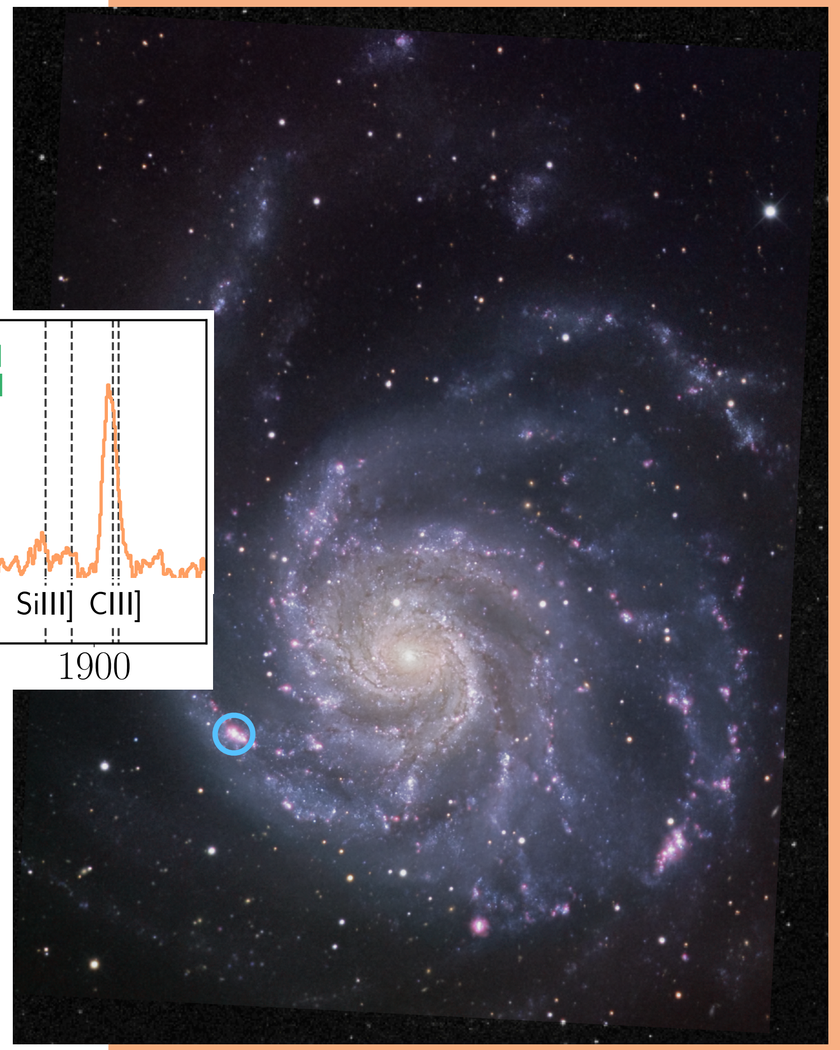
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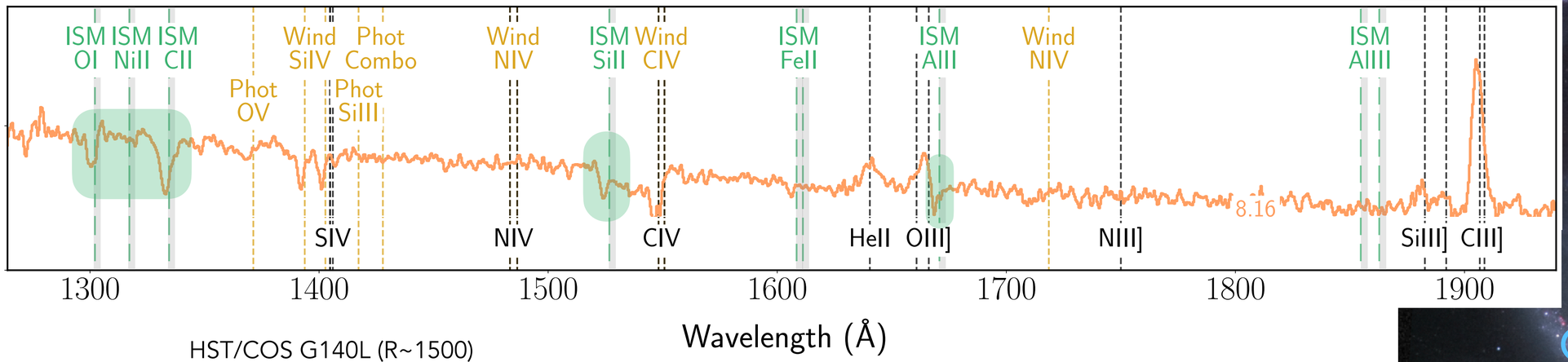
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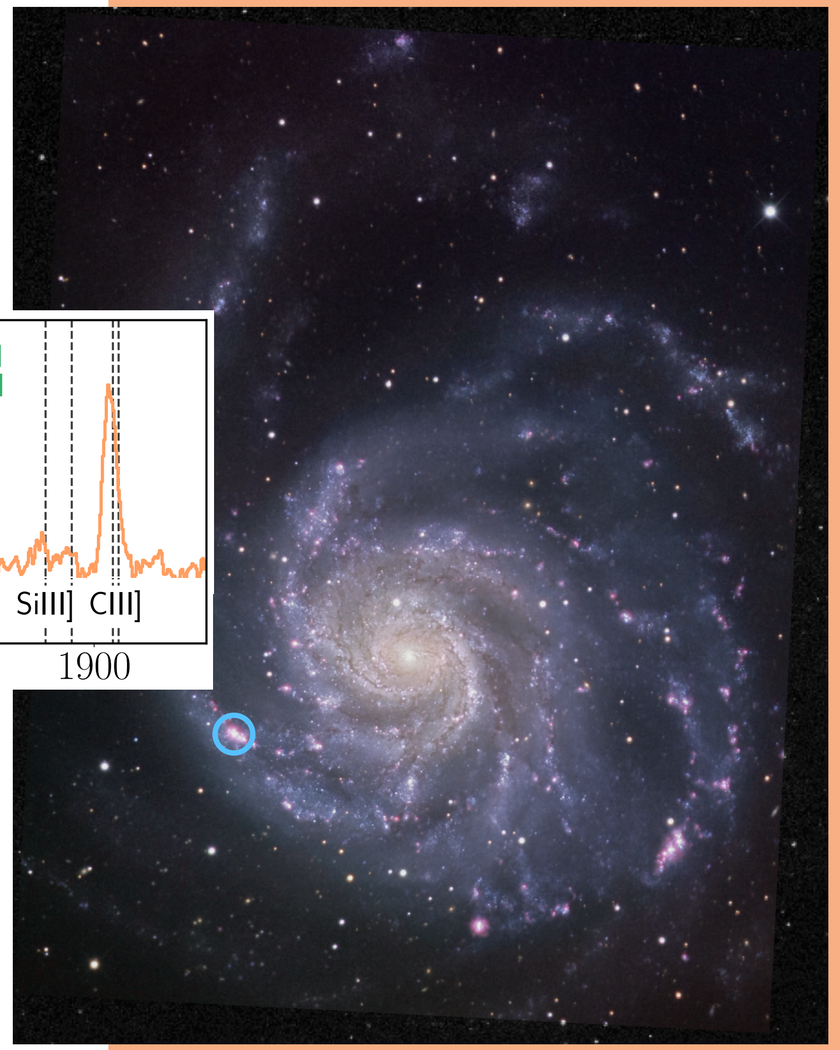
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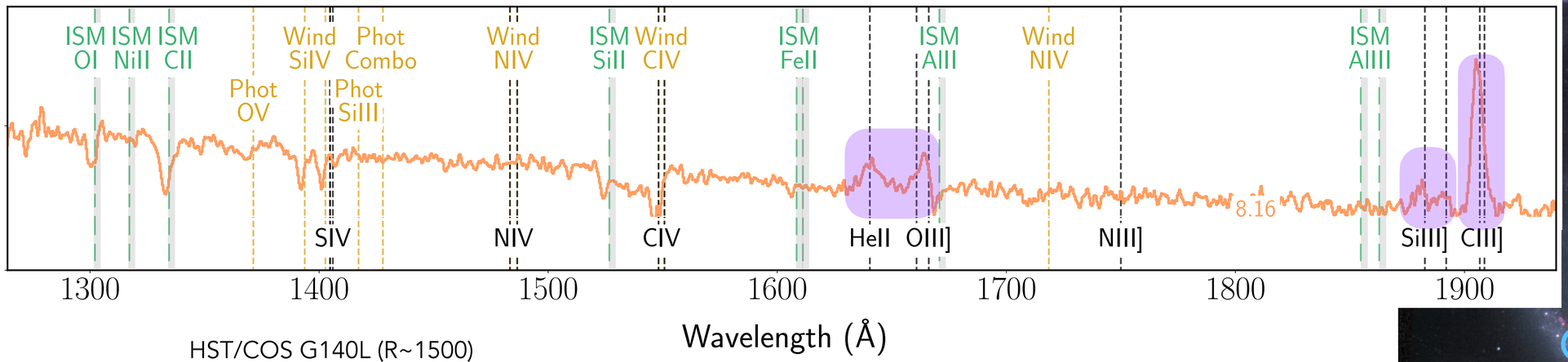
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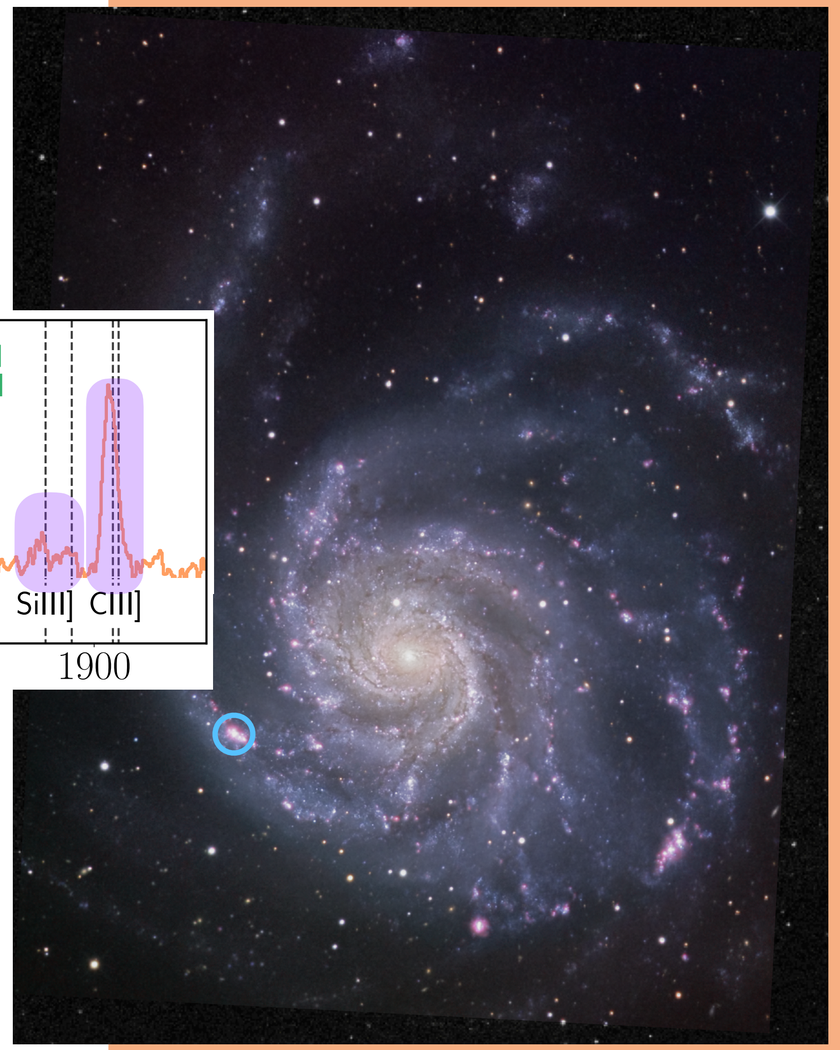
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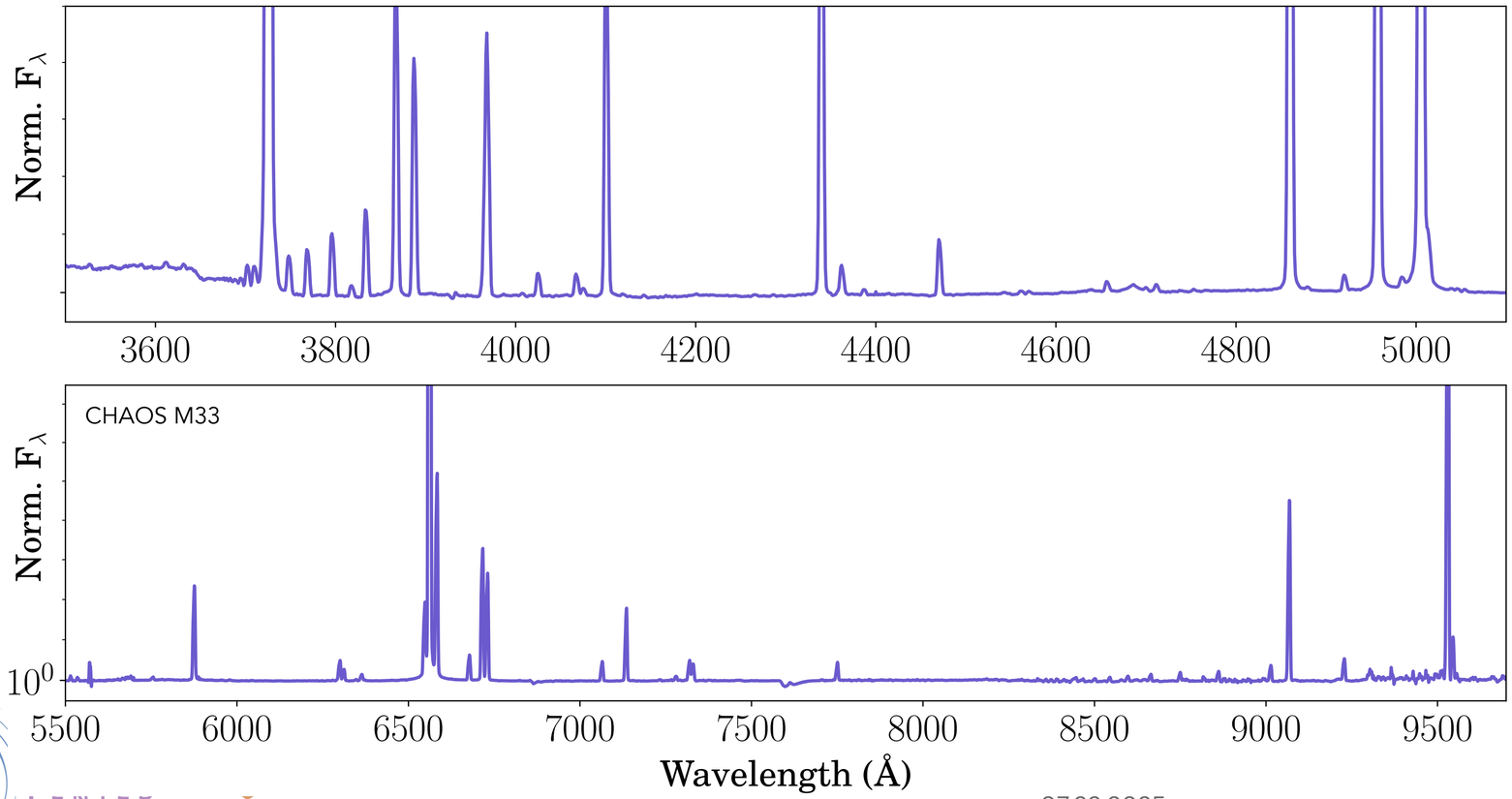
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METALLICITY MEASUREMENTS

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Abundances: How do we robustly measure chemical abundances?

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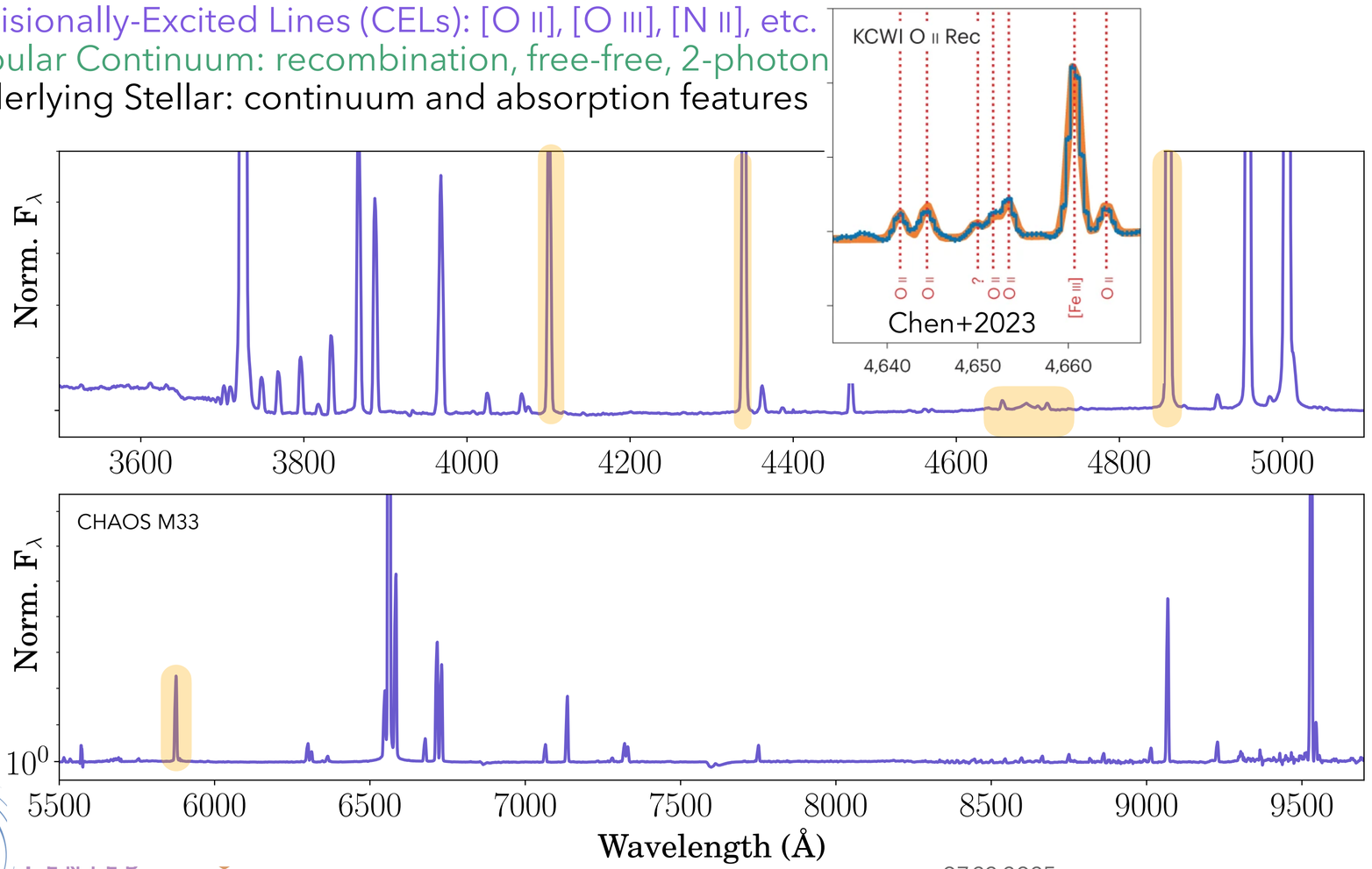
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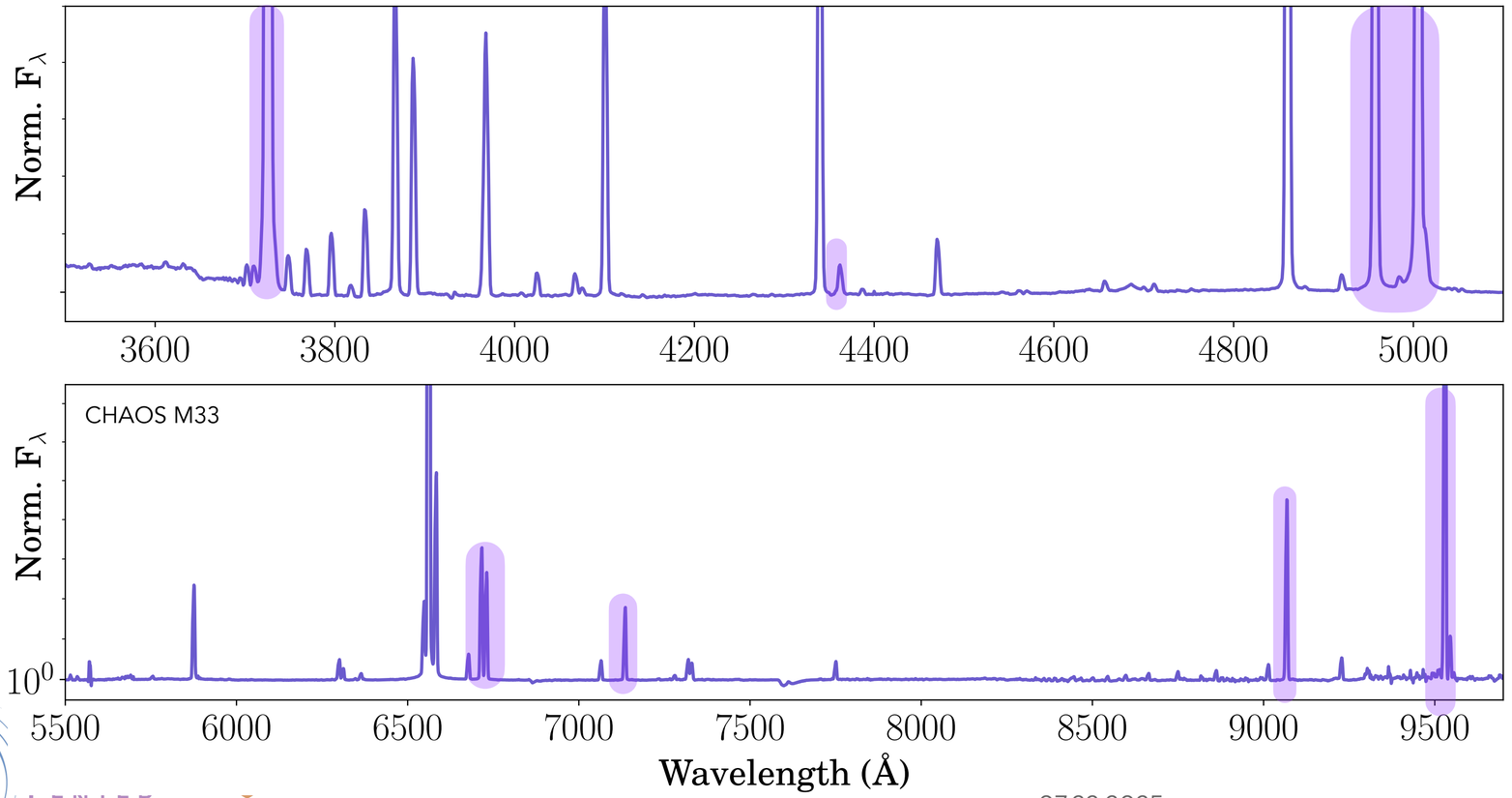
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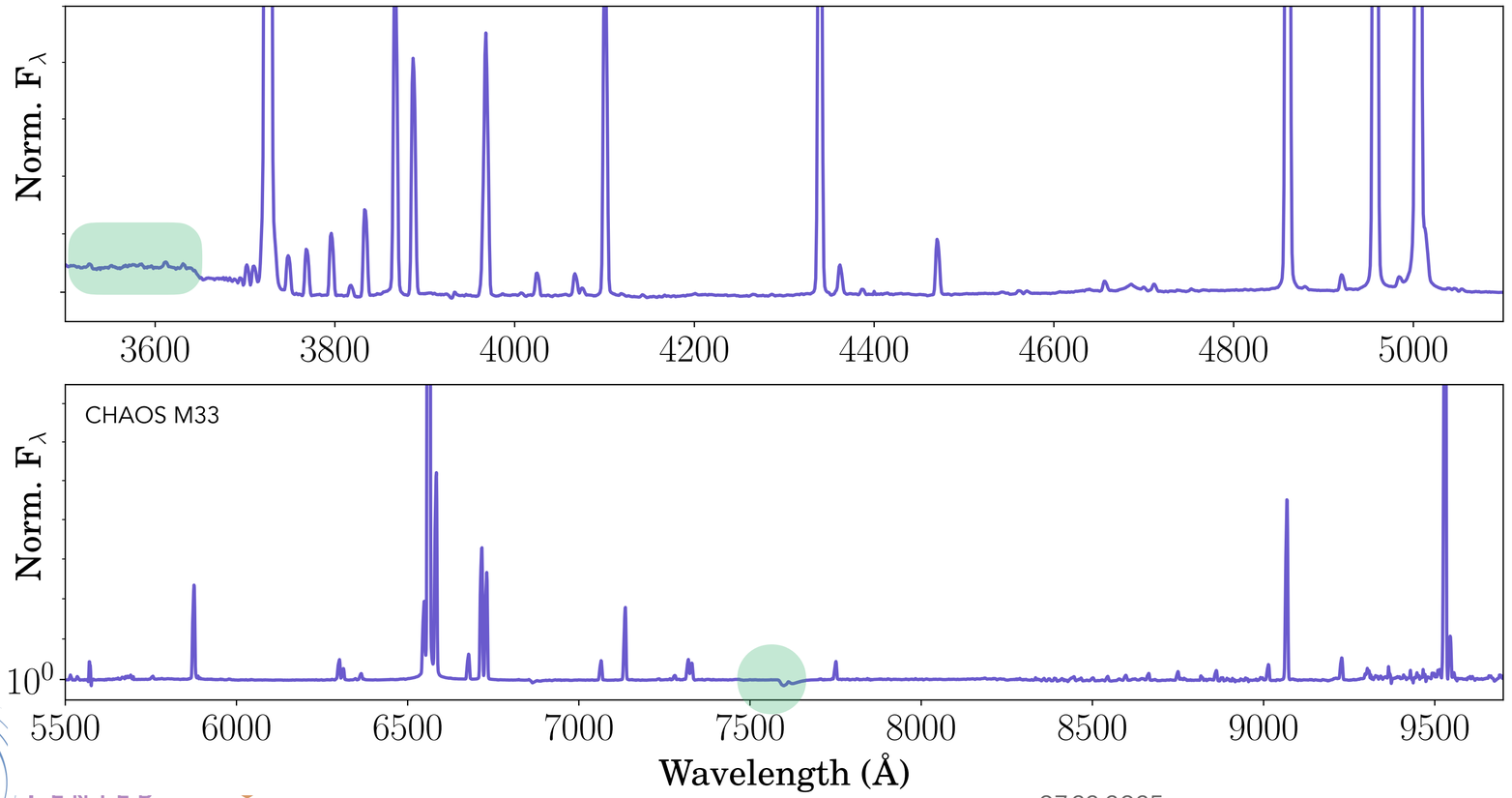
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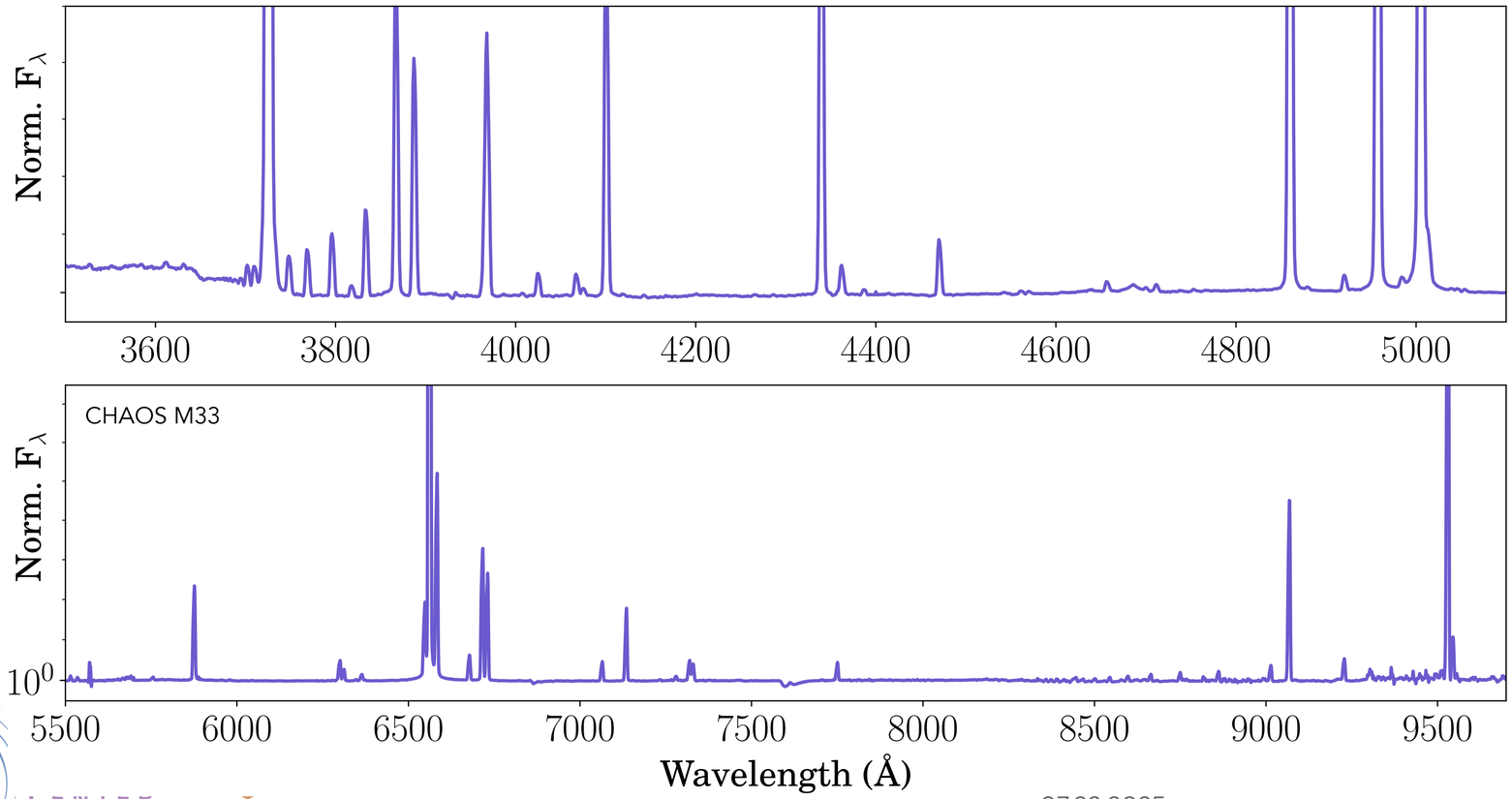
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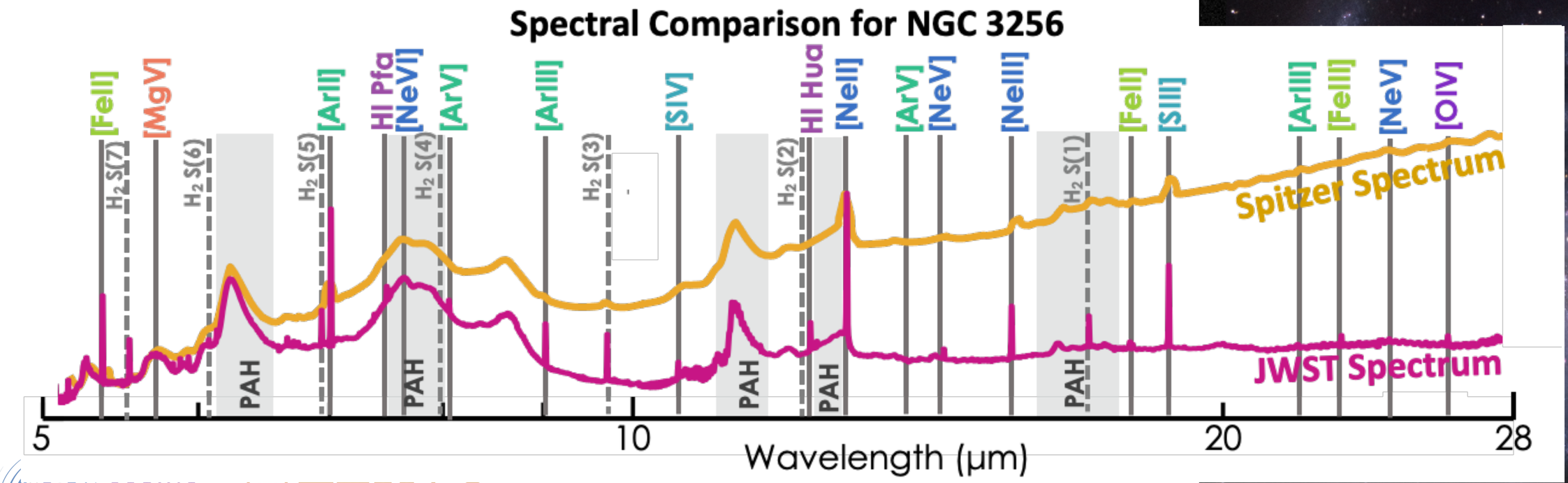
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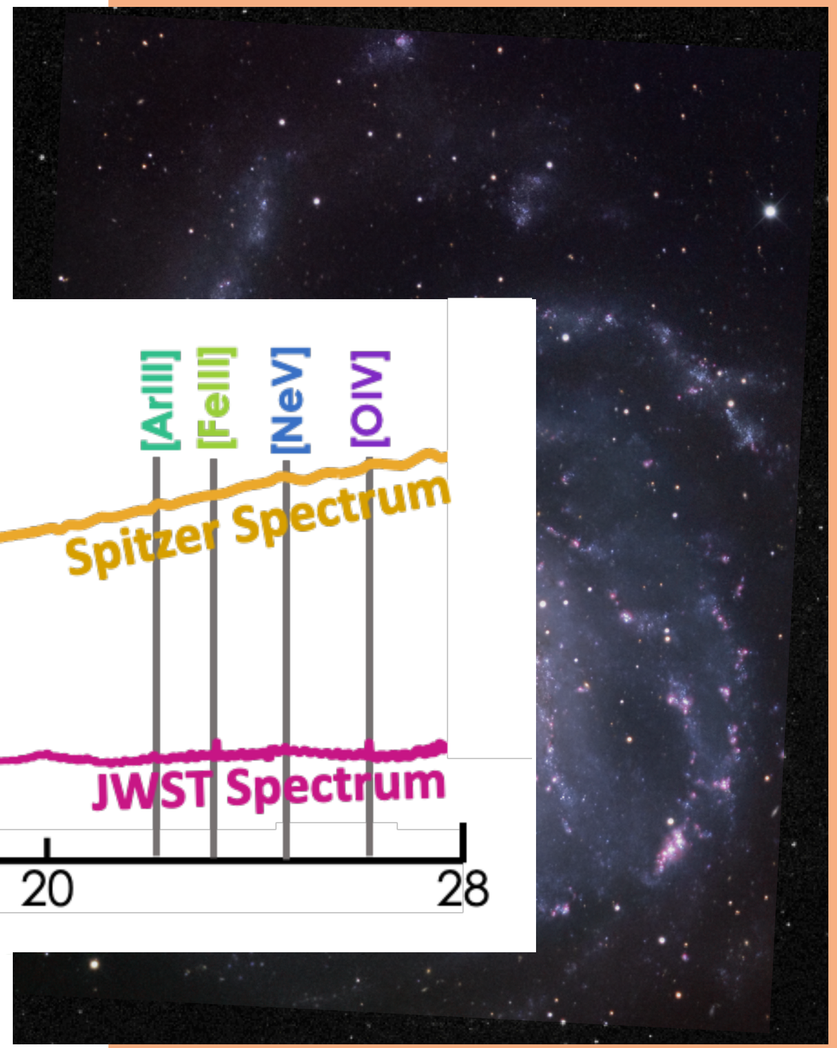
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Extragalactic H II region **MIR spectra** are rich with abundance-dependent features:

- PAH features
- Warm Molecular H lines: H_2 rovibrational lines
- Nebular CELs: [Ar II], [Ar III], [Ar V], [Ne II], [Ne III], [Ne V], [O IV], etc.





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Spitzer/IRS spectrum - Brandl et al. 2006

MIRI/MRS spectrum - GOALS ERS1328: PI Armis

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METALLICITY MEASUREMENTS

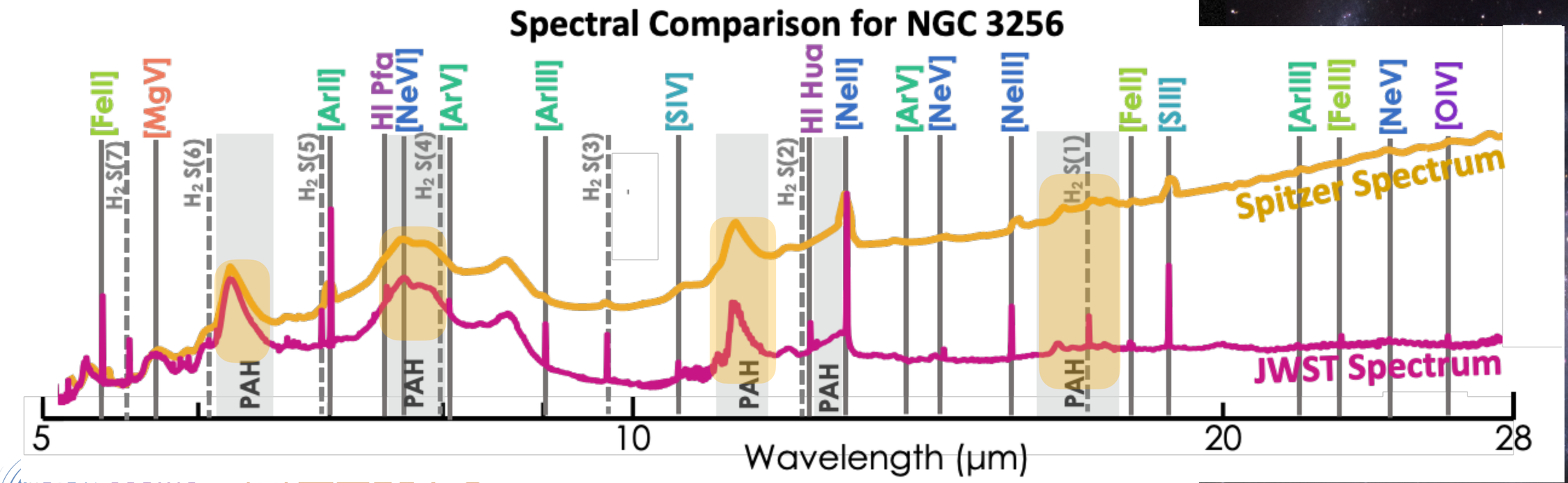
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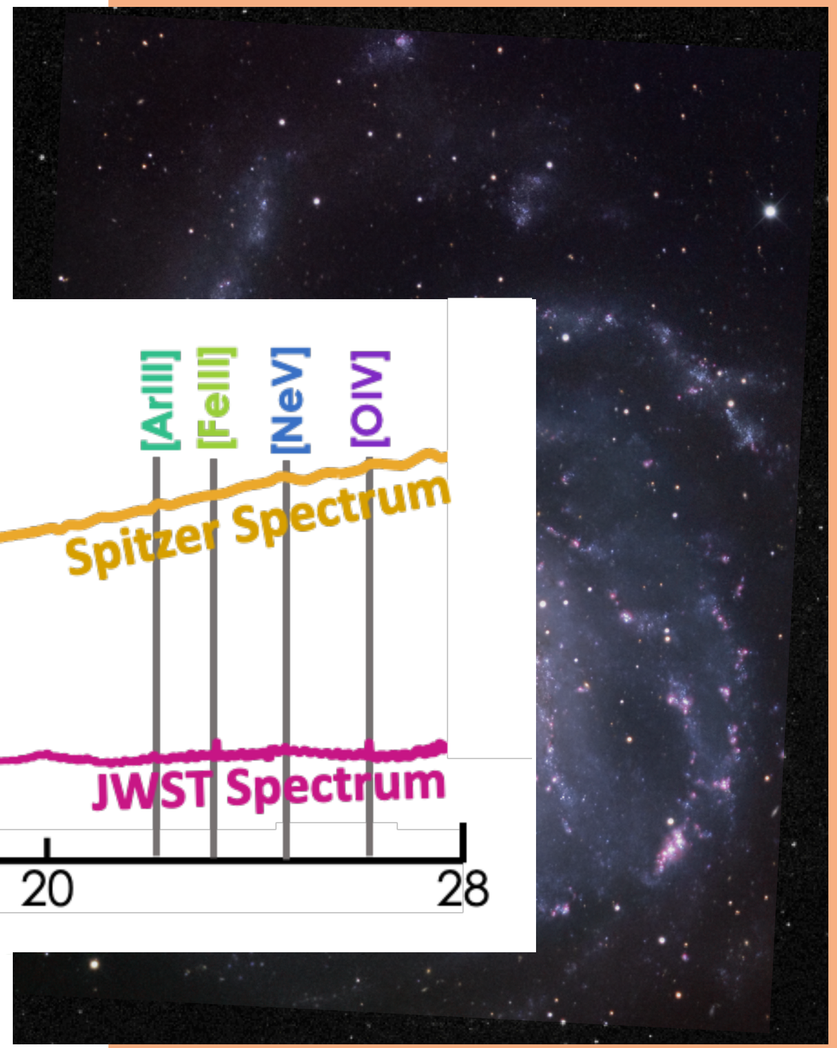
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- Nebular CELs: [Ar II], [Ar III], [Ar V], [Ne II], [Ne III], [Ne V], [O IV], etc.





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Spitzer/IRS spectrum - Brandl et al. 2006

MIRI/MRS spectrum - GOALS ERS1328: PI Armis

07.22.2025

METALLICITY MEASUREMENTS

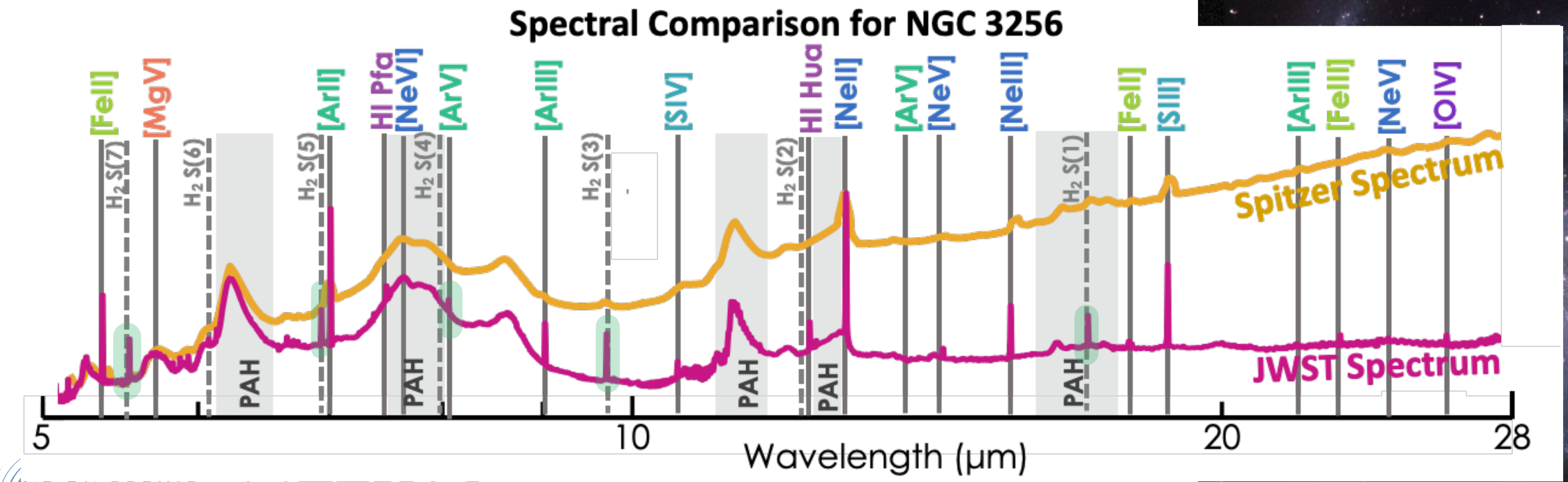
Abundances: How do we robustly measure chemical abundances?

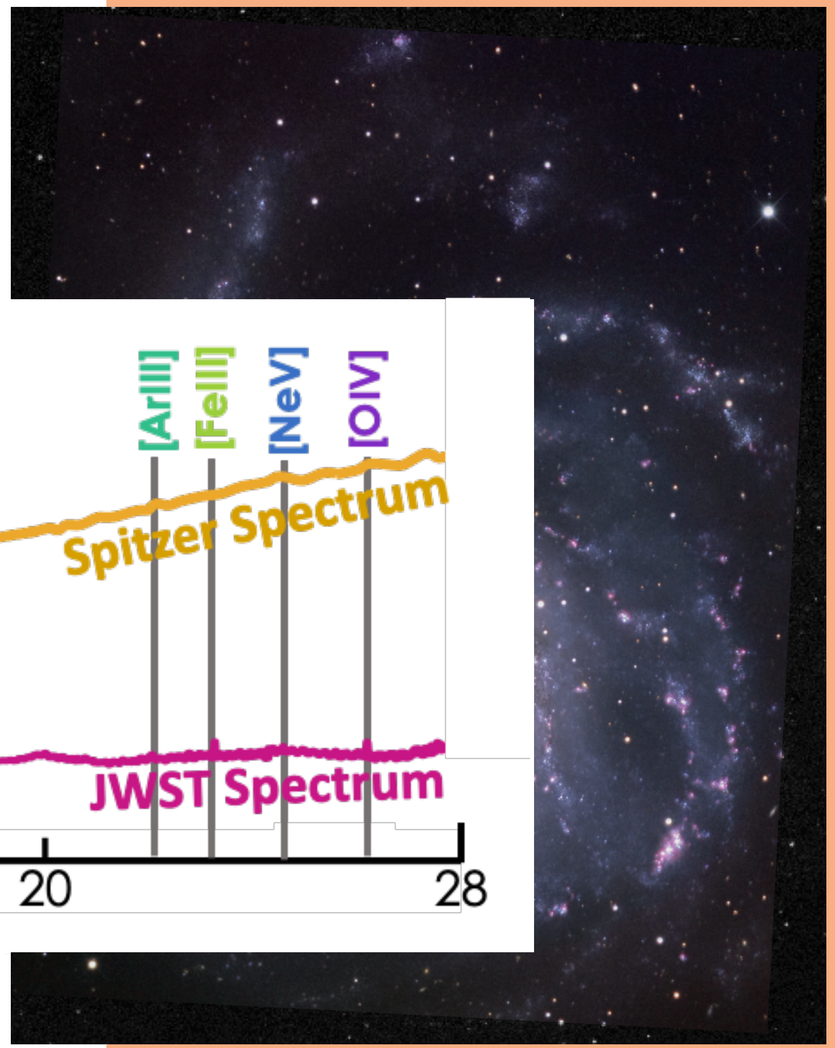
A fruit basket of abundance measurement methods

Are we comparing *apples to apples?*

Extragalactic H II region **MIR spectra** are rich with abundance-dependent features:

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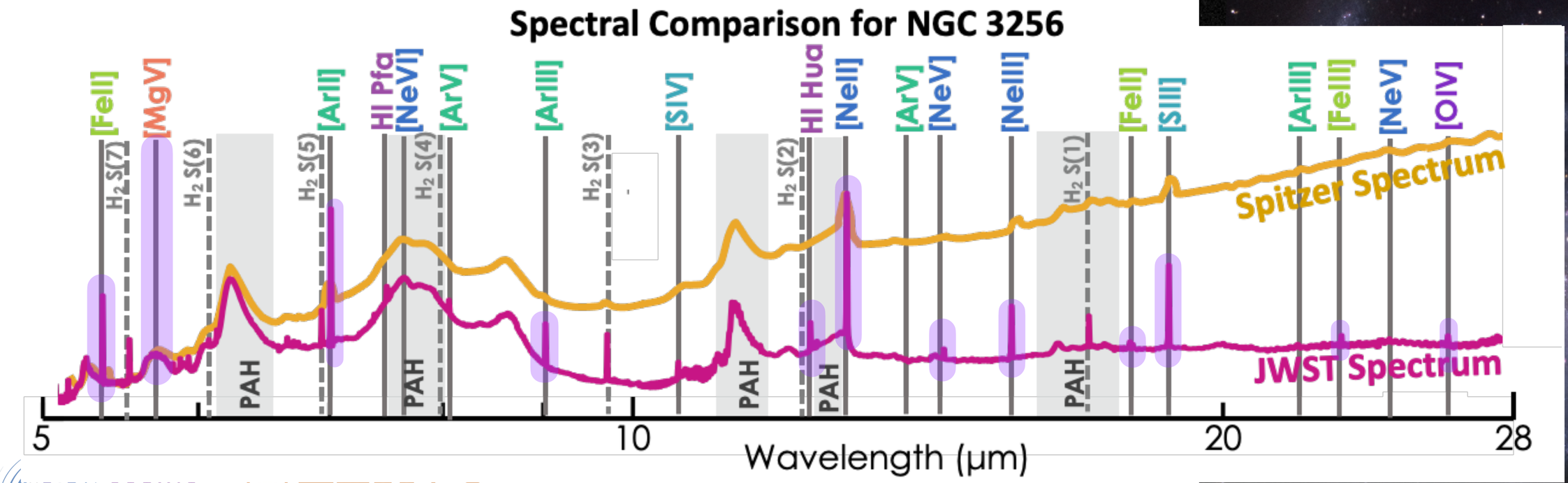
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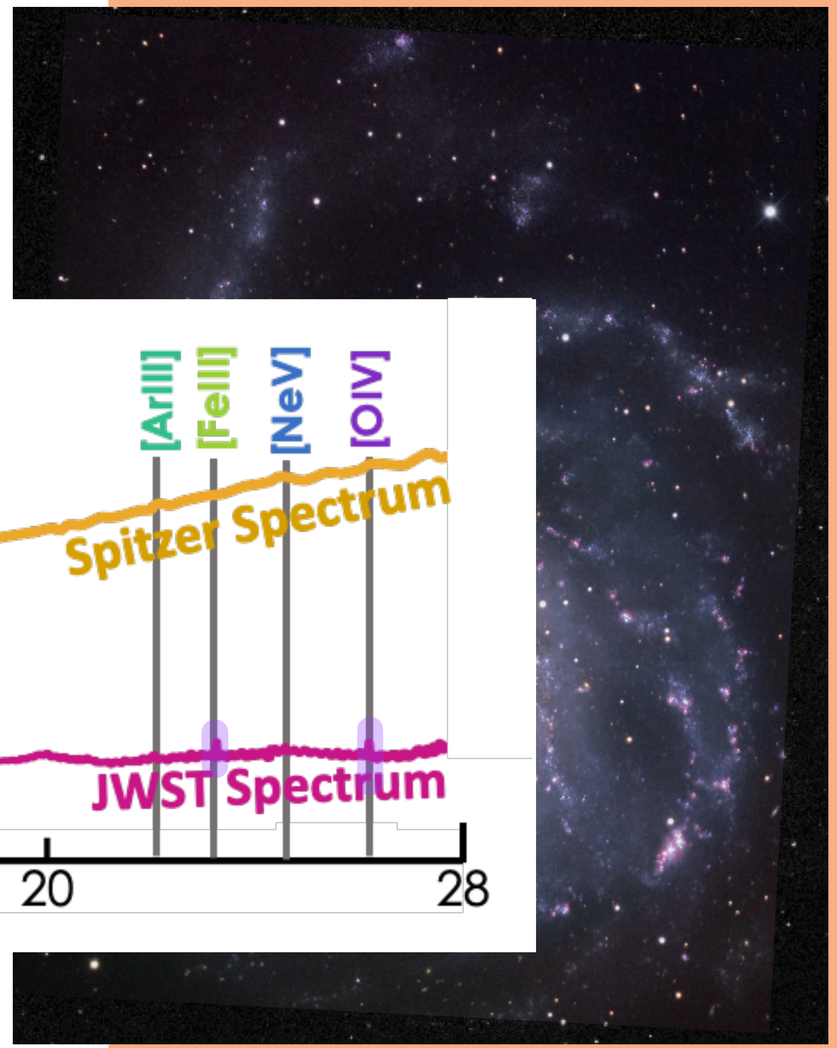
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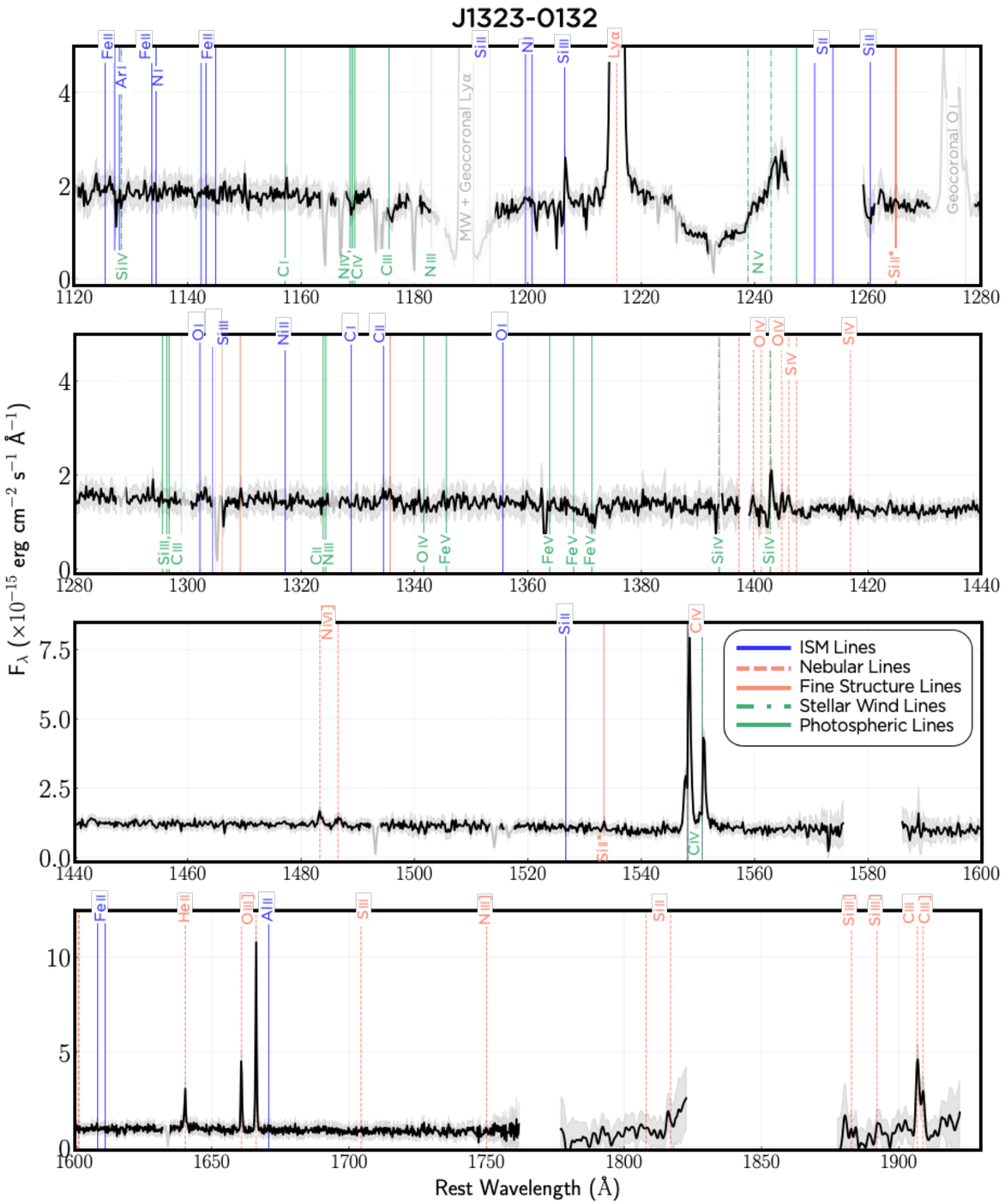
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METALTS

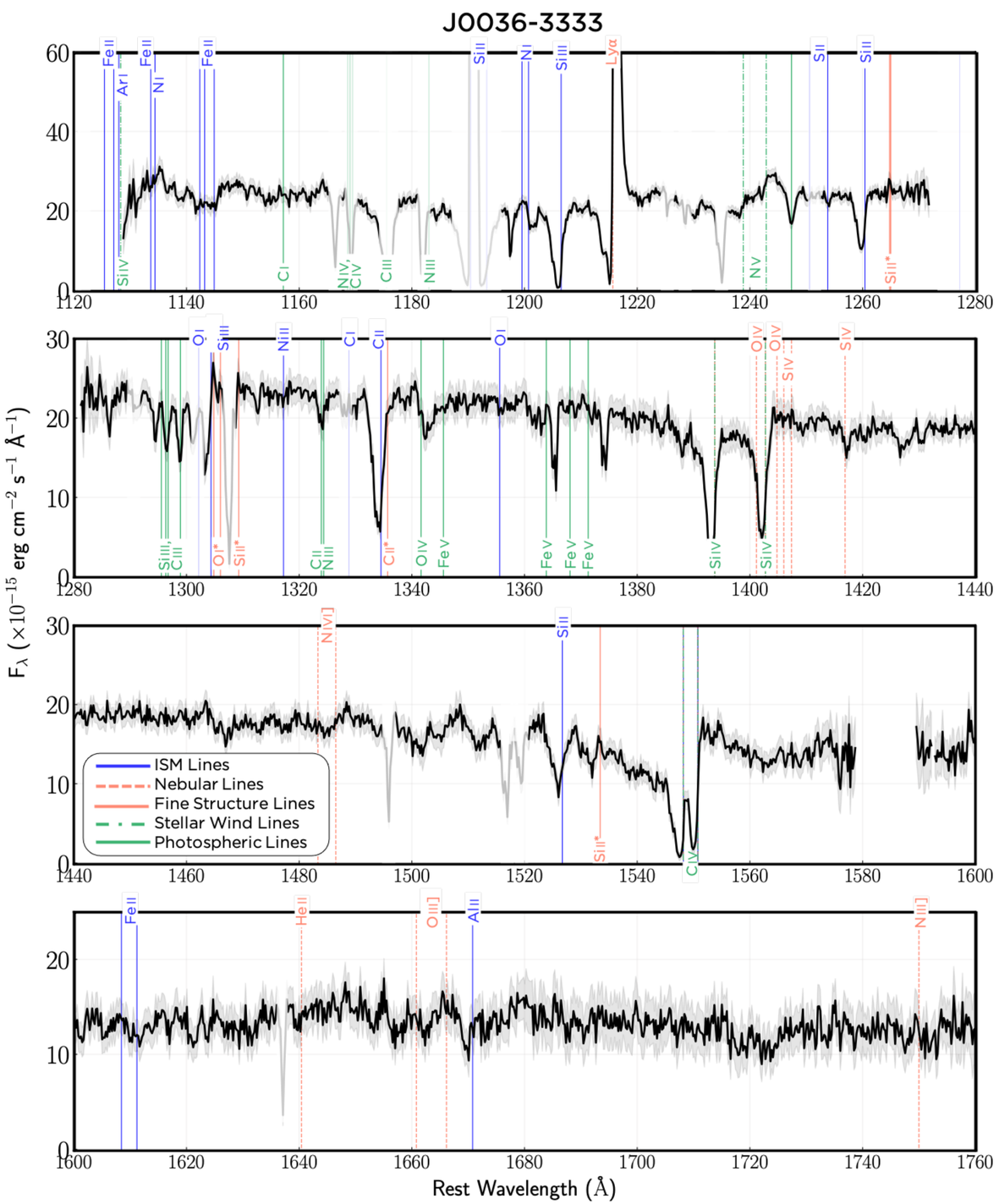


Abundances: How do we robustly measure chemical abundances?

UV spectra of **low-metallicity** galaxies are rich with ISM absorption lines, **nebular emission lines**, fine structure lines, stellar wind features, and stellar photospheric lines

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METALTS



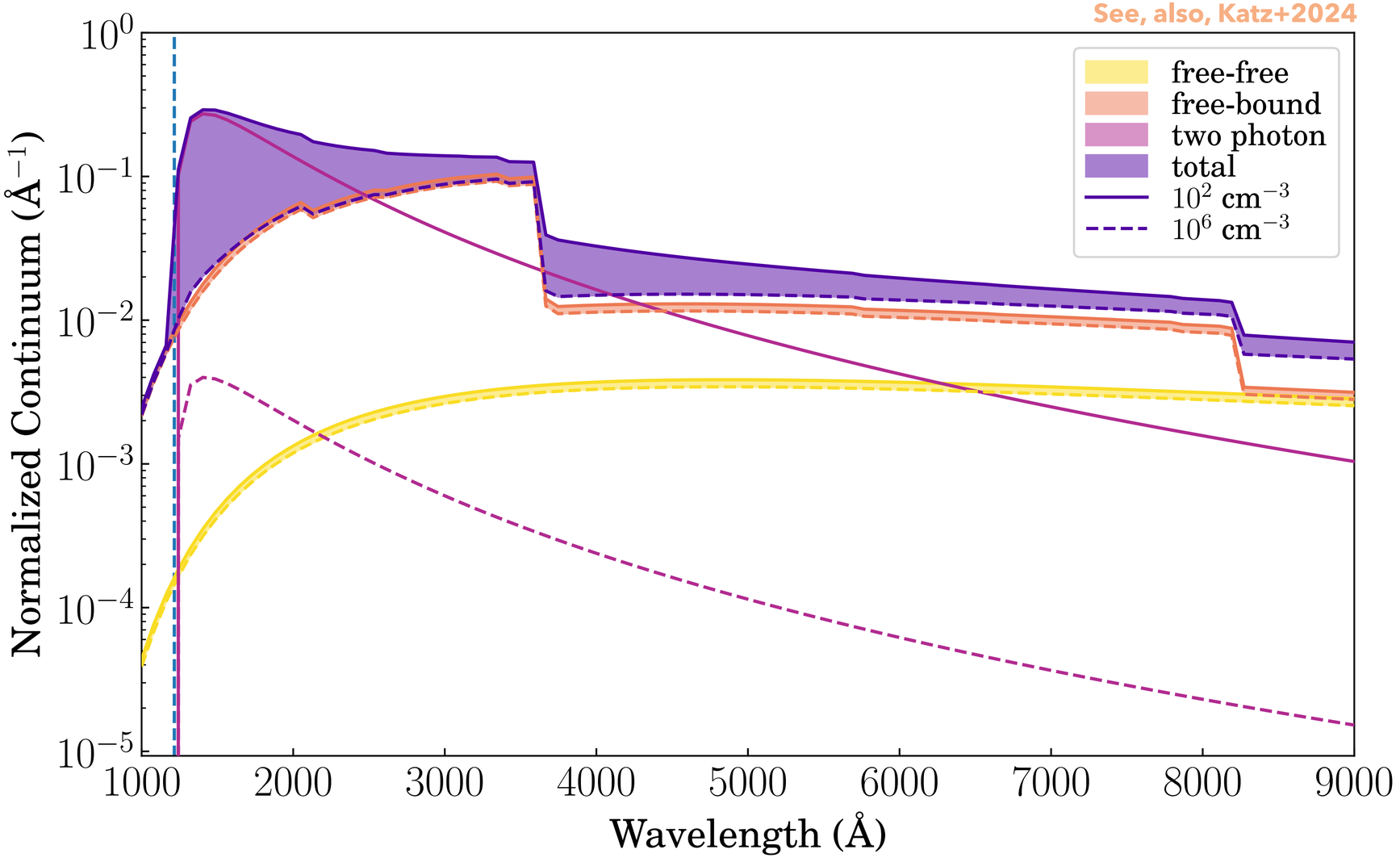
Abundances: How do we robustly measure chemical abundances?

UV spectra of **high-metallicity** galaxies are rich with **ISM absorption lines**, nebular emission lines, fine structure lines, **stellar wind features**, and **stellar photospheric lines**

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HIGH DENSITIES BIAS EWs

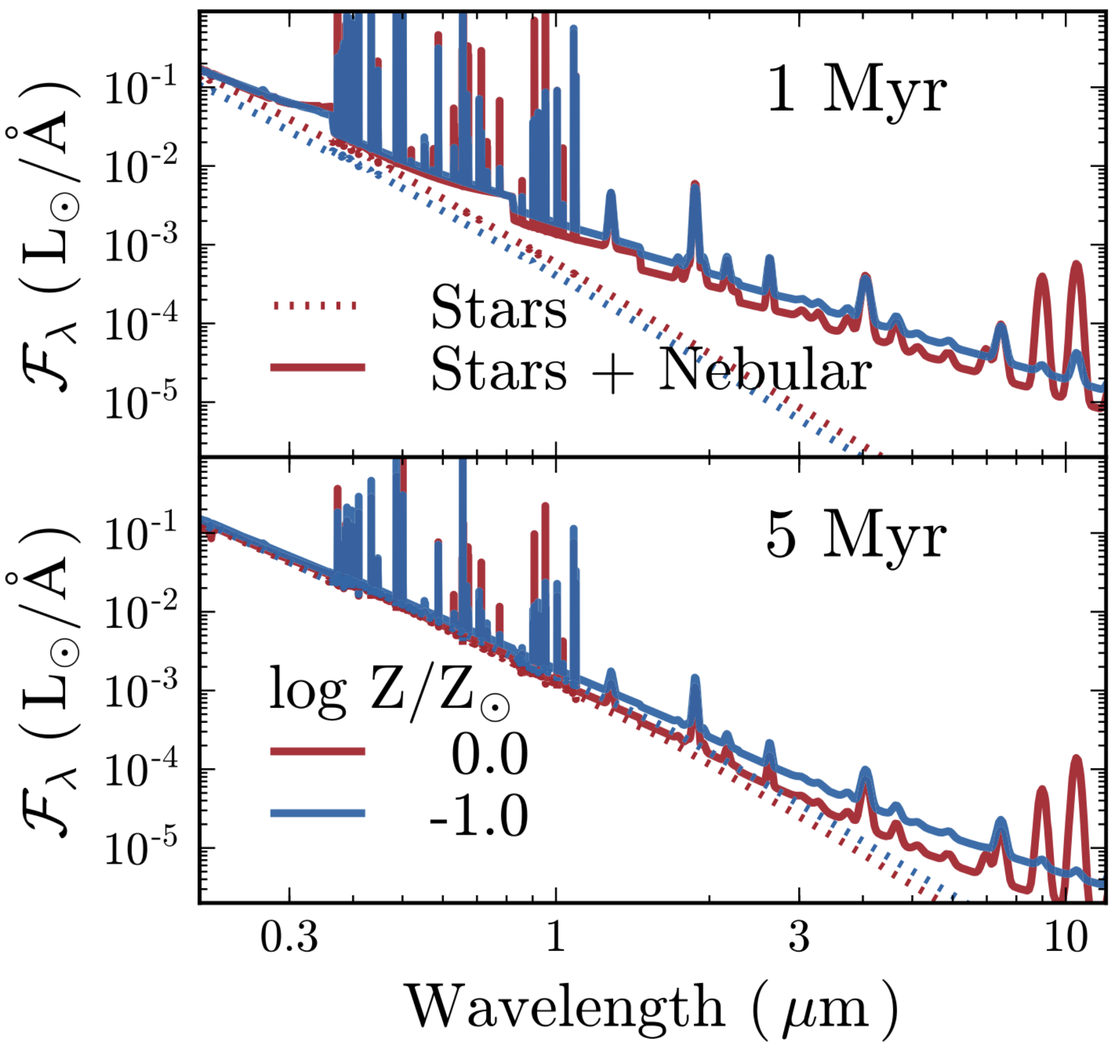
See, also, Katz+2024



Need to know nebular conditions to interpret the continuum correctly

ISM BASICS

Byler+2017



Younger stars+HII regions produce **more nebular line** and **continuum emission** than older ones.

THE DIRECT METHOD

Requires gas-phase **temperature** and **density** measurements in **each** relevant ionization **zone**

Photoionized nebular gas has spectra characterized by strong emission lines resulting from:

1. **RLs:** Recombination cascades in H and He (and to a lesser degree in metal ions).

2. **CELs:** Electron-ion impact excitation of low-lying levels in metal ions.

CELs dominate the cooling of the nebula, and can often have an integrated luminosity >> RLs of H and He.

$$I_{RL} \sim n_e n_i \alpha_{u\ell}^{\text{eff}} h\nu \sim T_e^{-1}$$

$$I_{CEL} \sim n_e n_i \frac{h\nu}{\sqrt{T_e}} \Omega_{\ell u} e^{-E_{u\ell}/kT_e}$$

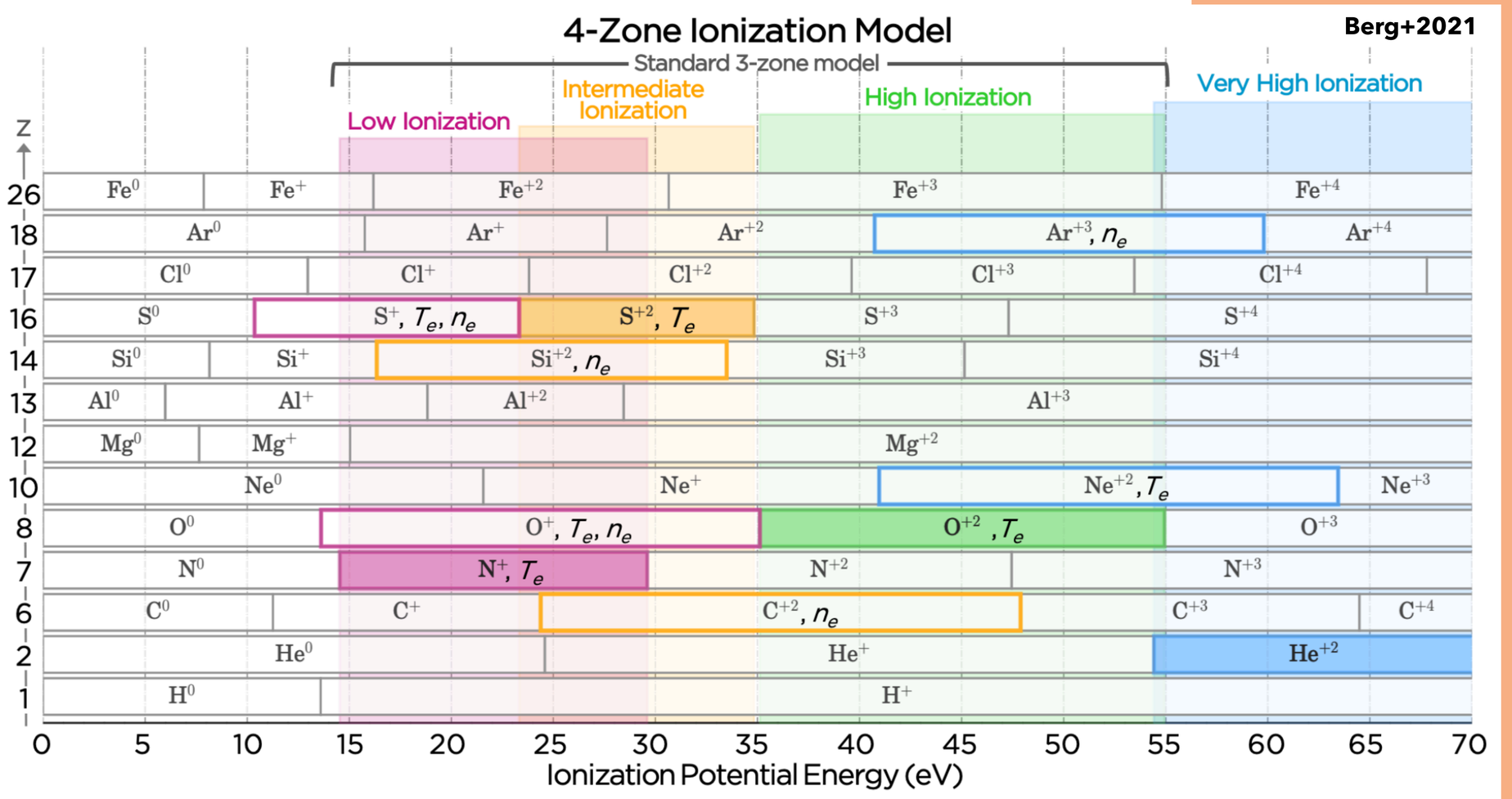
n_e = electron density
n_i = ion density
Ω = collision strength
$e^{-E_{u\ell}/kT_e}$ = exponential Boltzmann term
Mean velocity of electrons scles as $\langle v \rangle \propto \sqrt{T}$

THE DIRECT METHOD

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$$12 + \log\left(\frac{O}{H}\right) = \frac{O^0}{H^+} + \frac{O^+}{H^+} + \frac{O^{+2}}{H^+} + \frac{O^{+3}}{H^+}$$

How do we robustly measure chemical abundances?

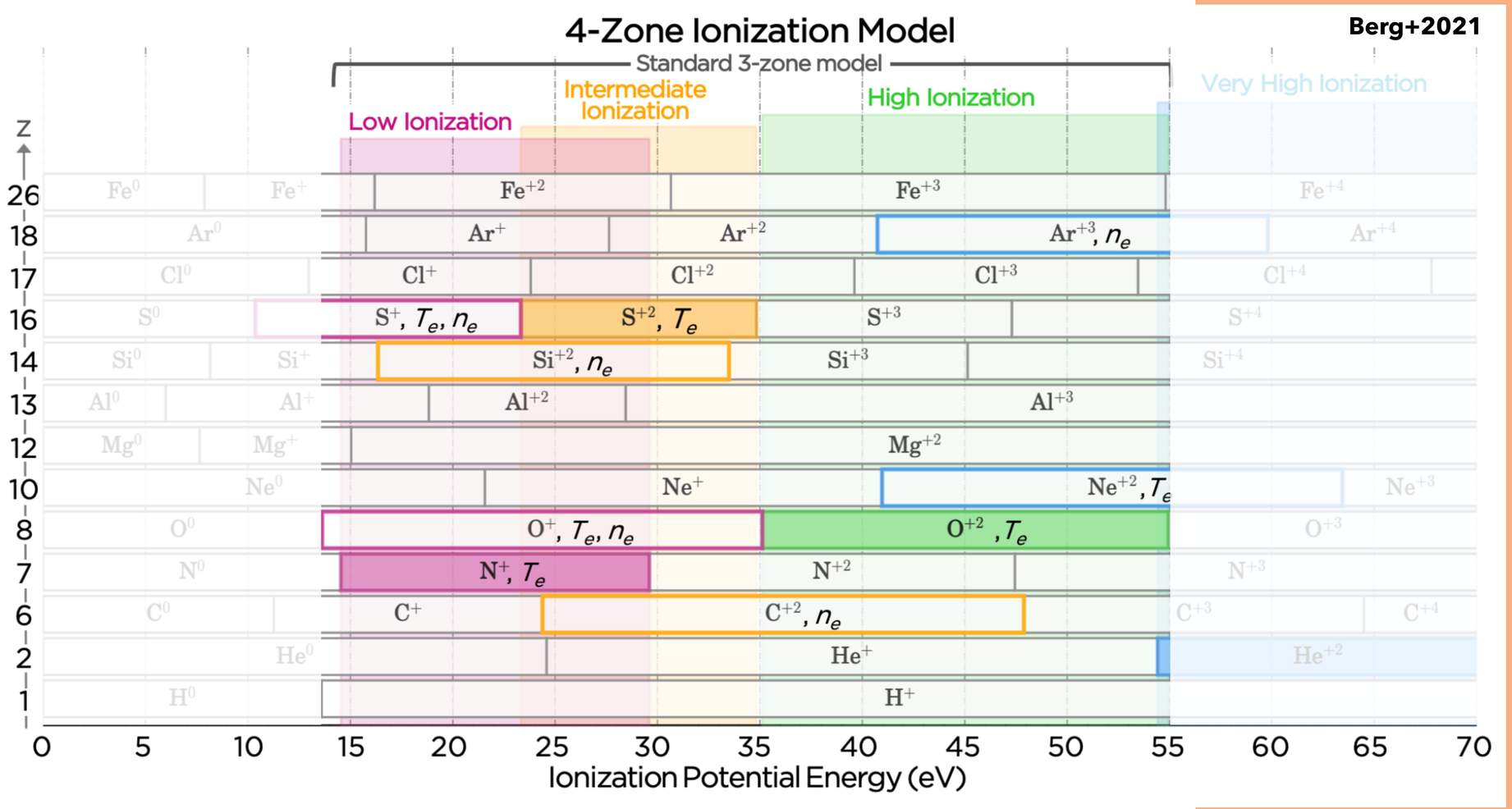


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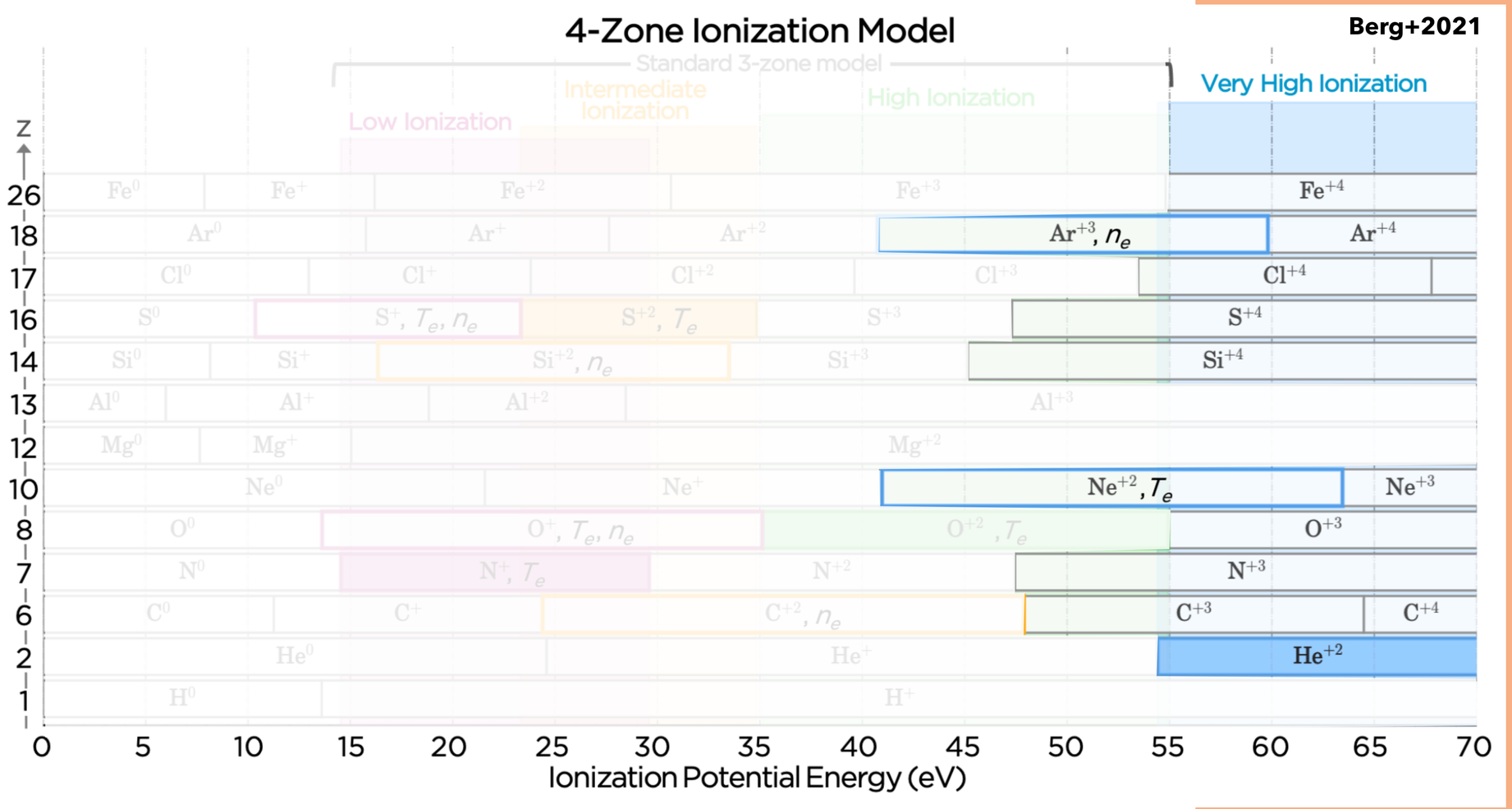
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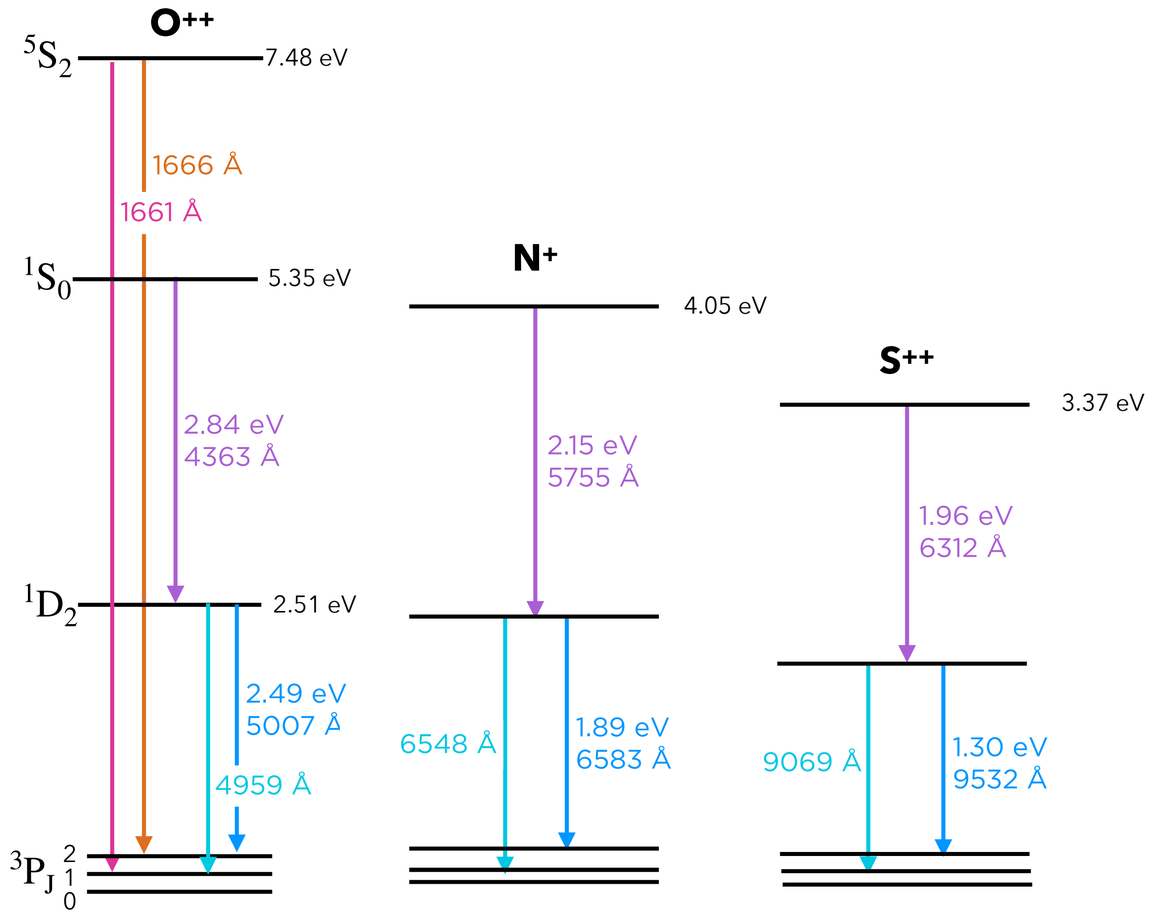
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How do we robustly measure chemical abundances?

Temperature Diagnostics:
any combination of lines from a single ion from different energy levels

$$I_{CEL} \sim T_e^{-0.5} e^{-E_{ul}/kT_e}$$





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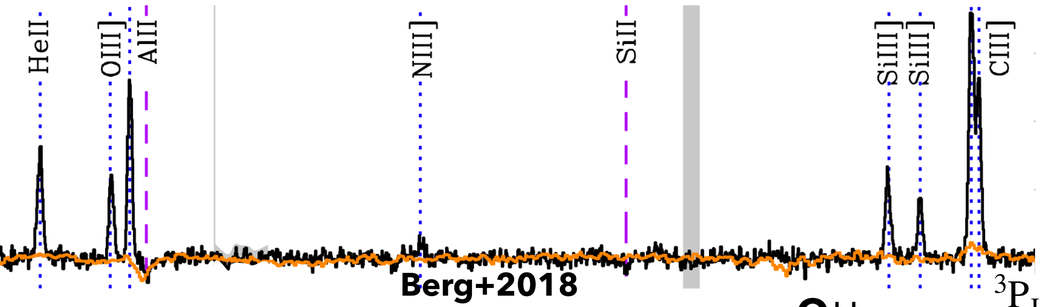
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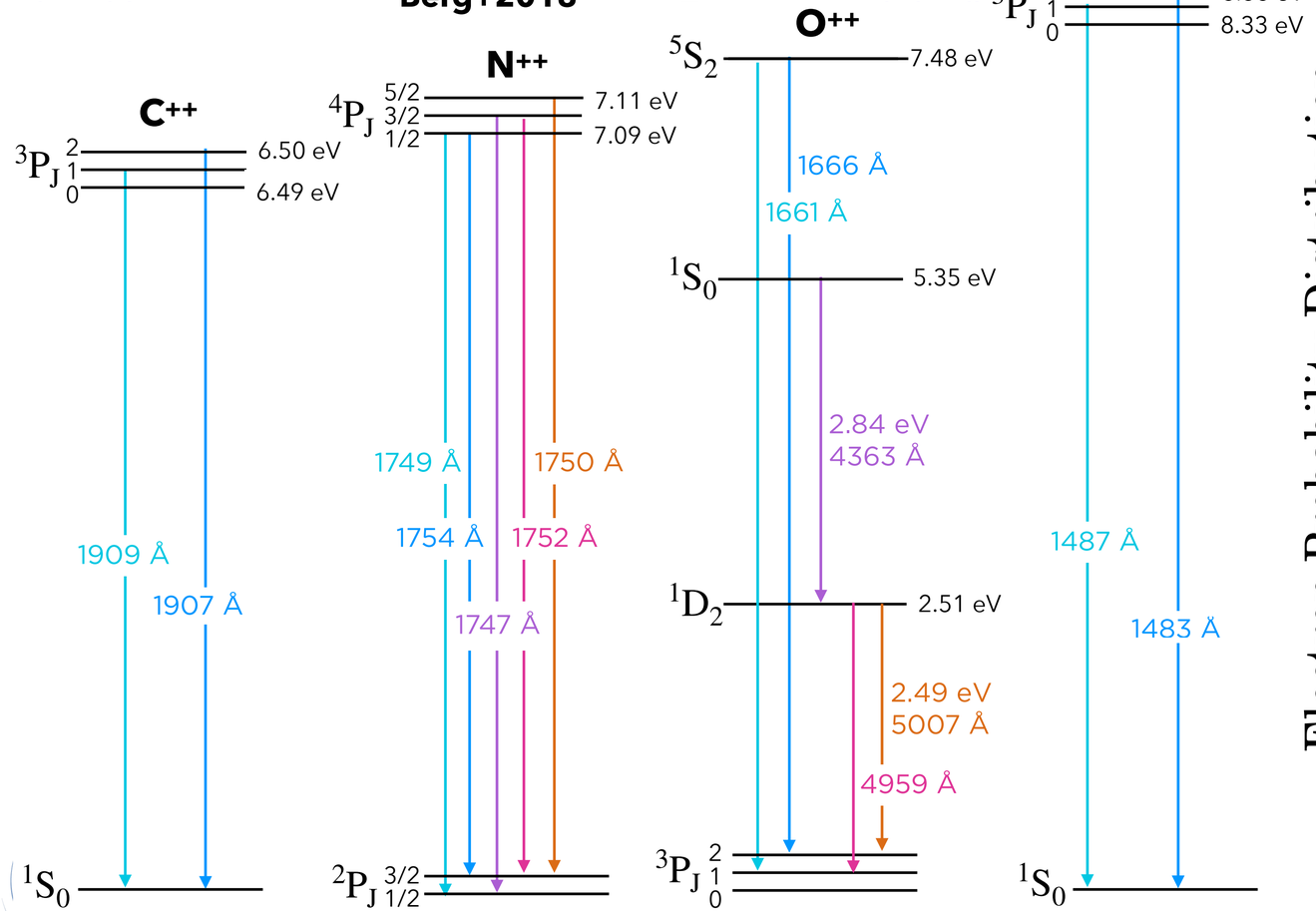
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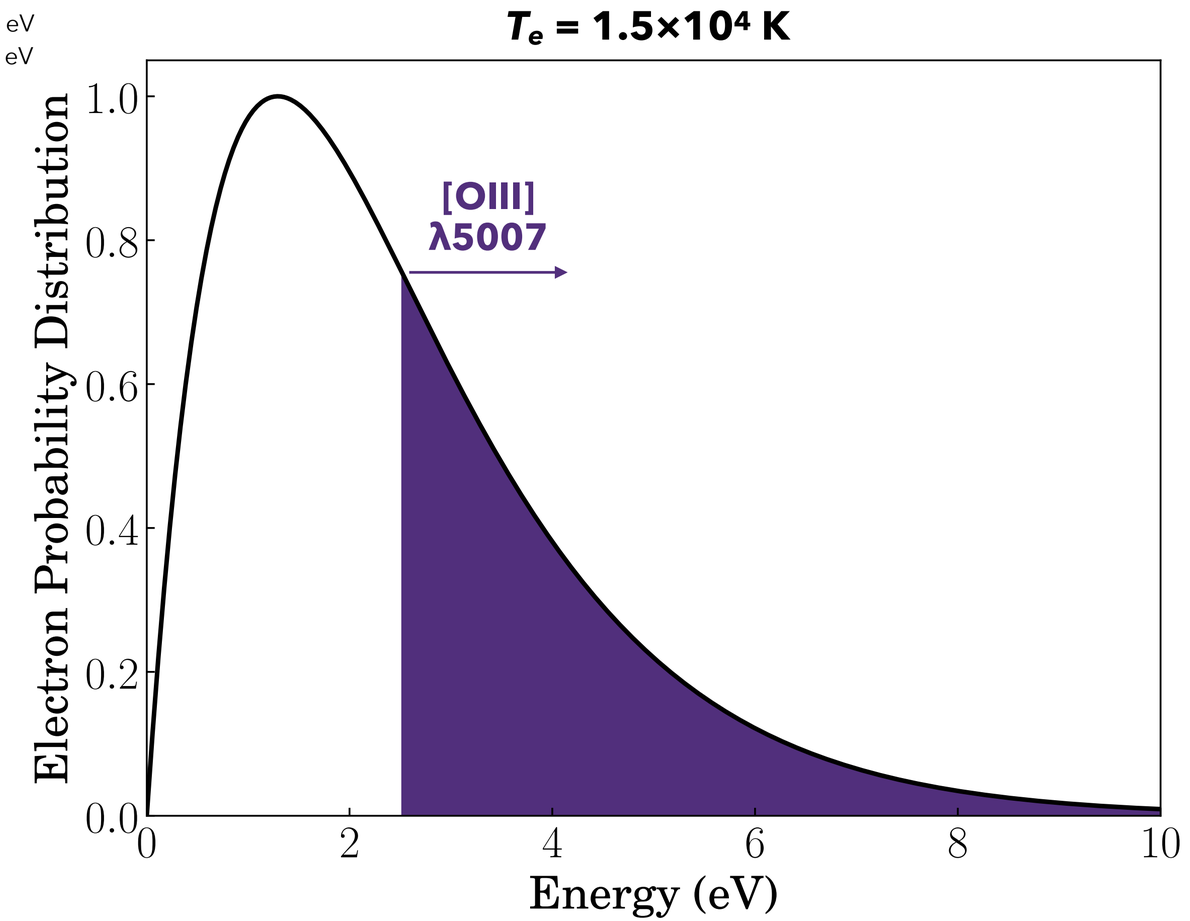
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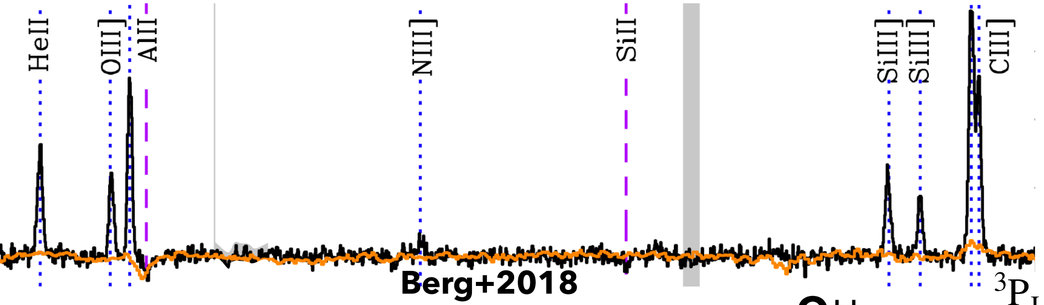


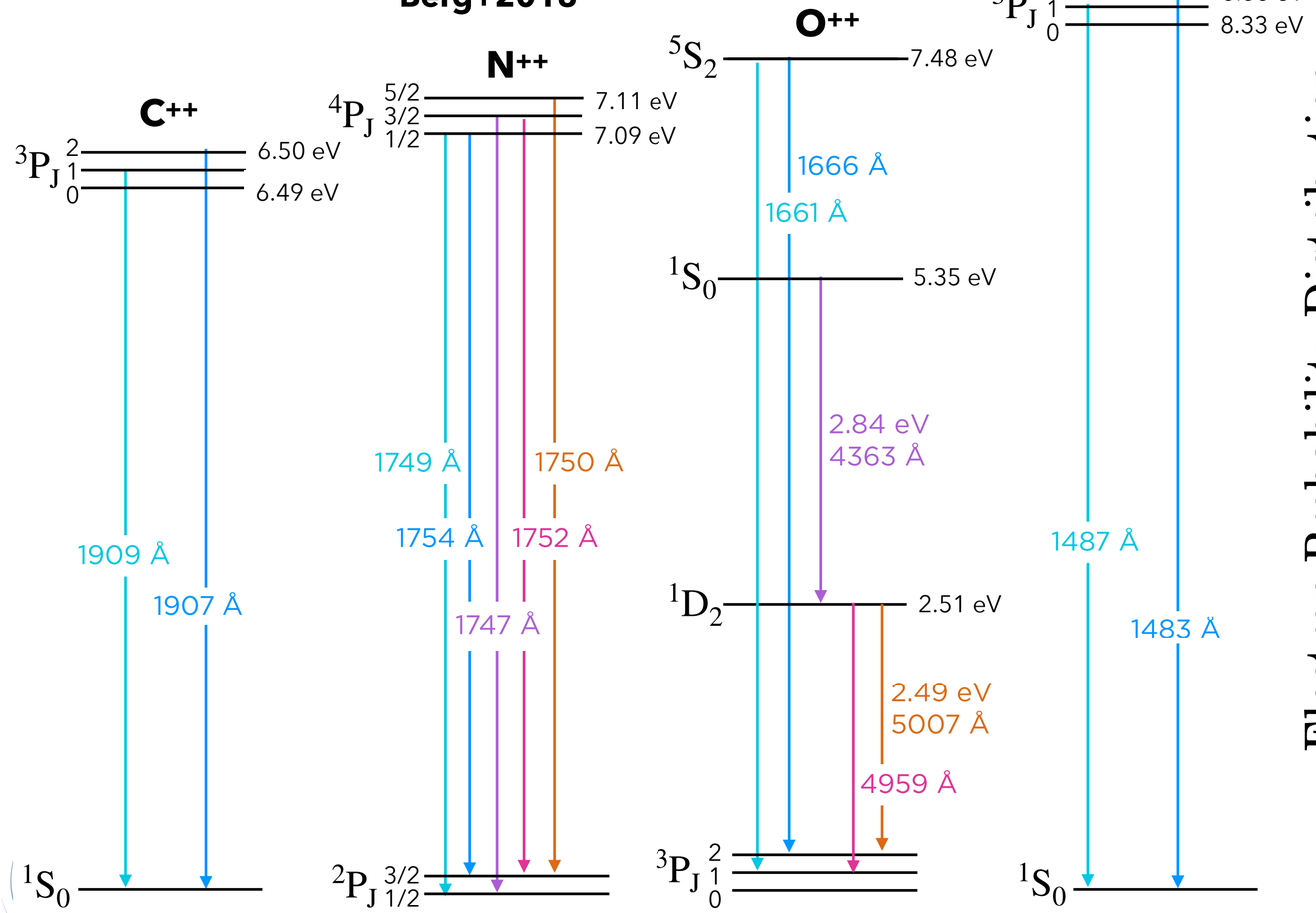
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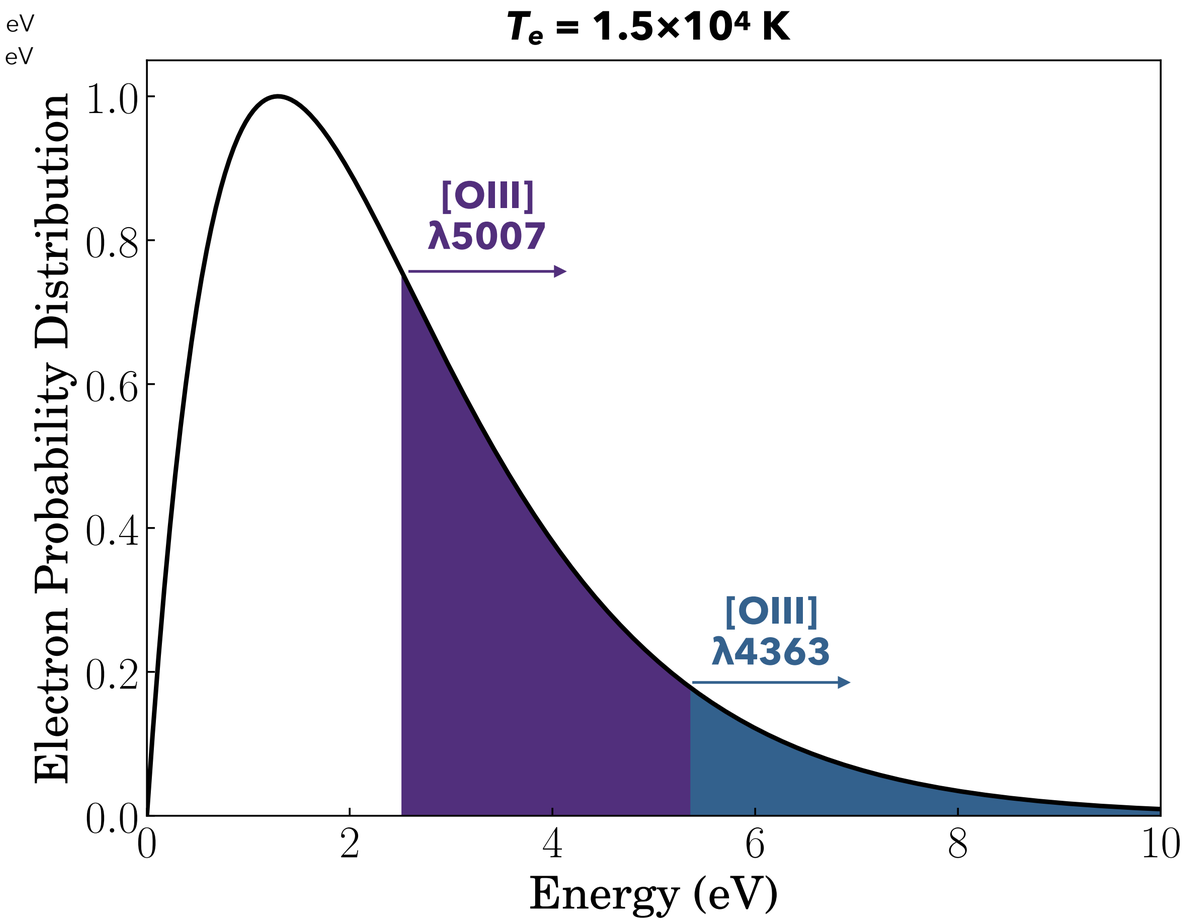
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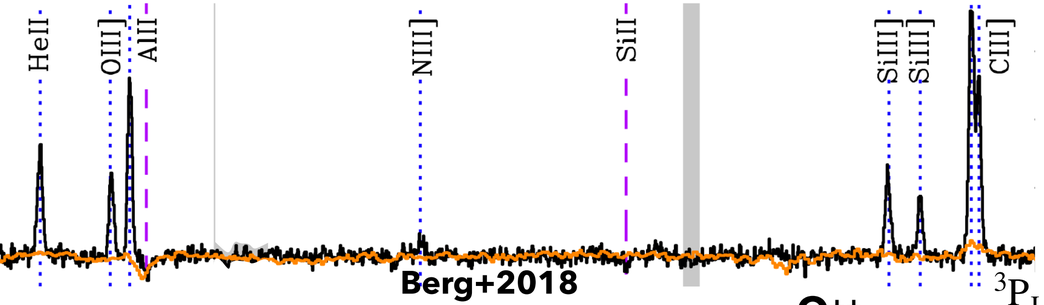


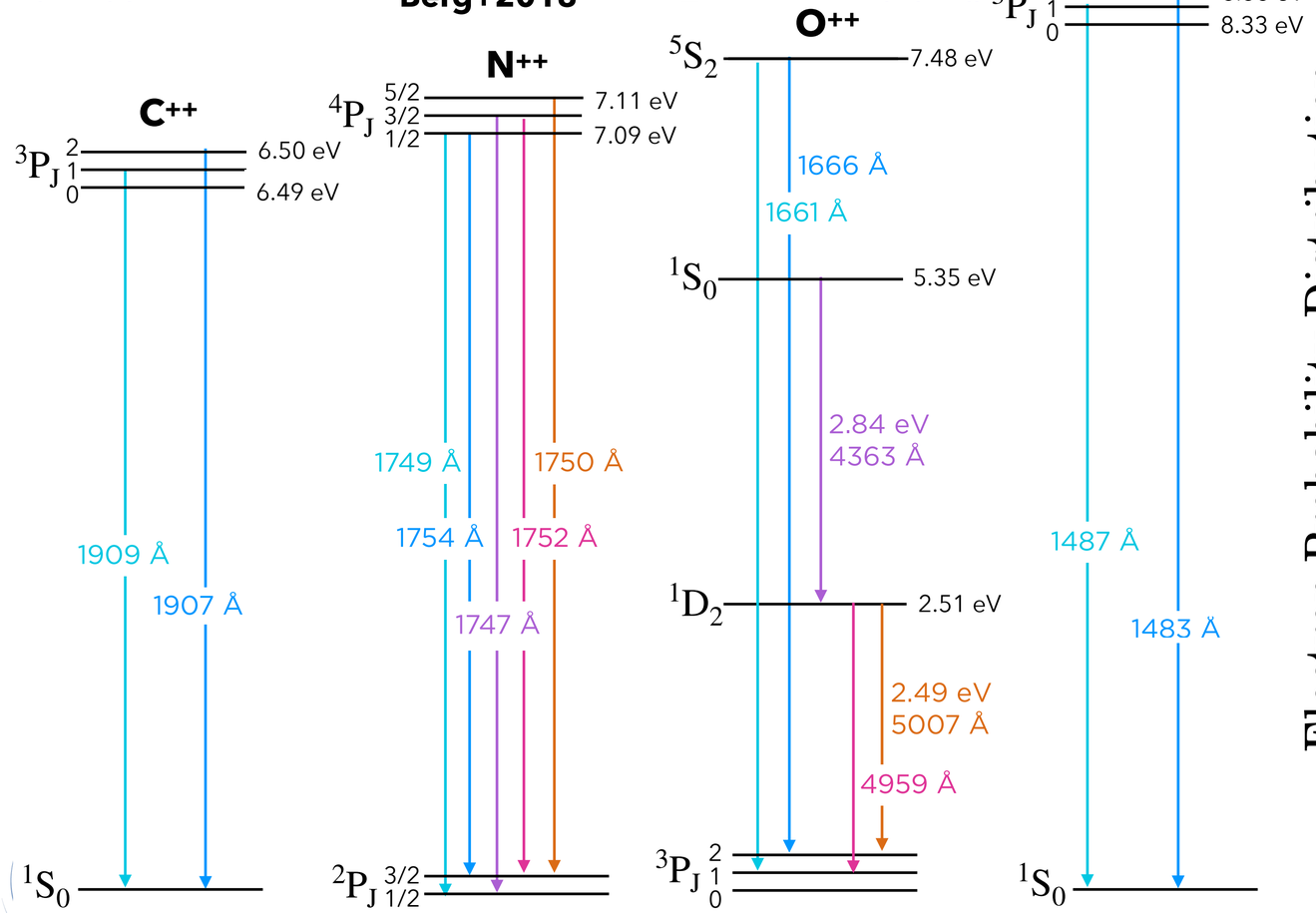
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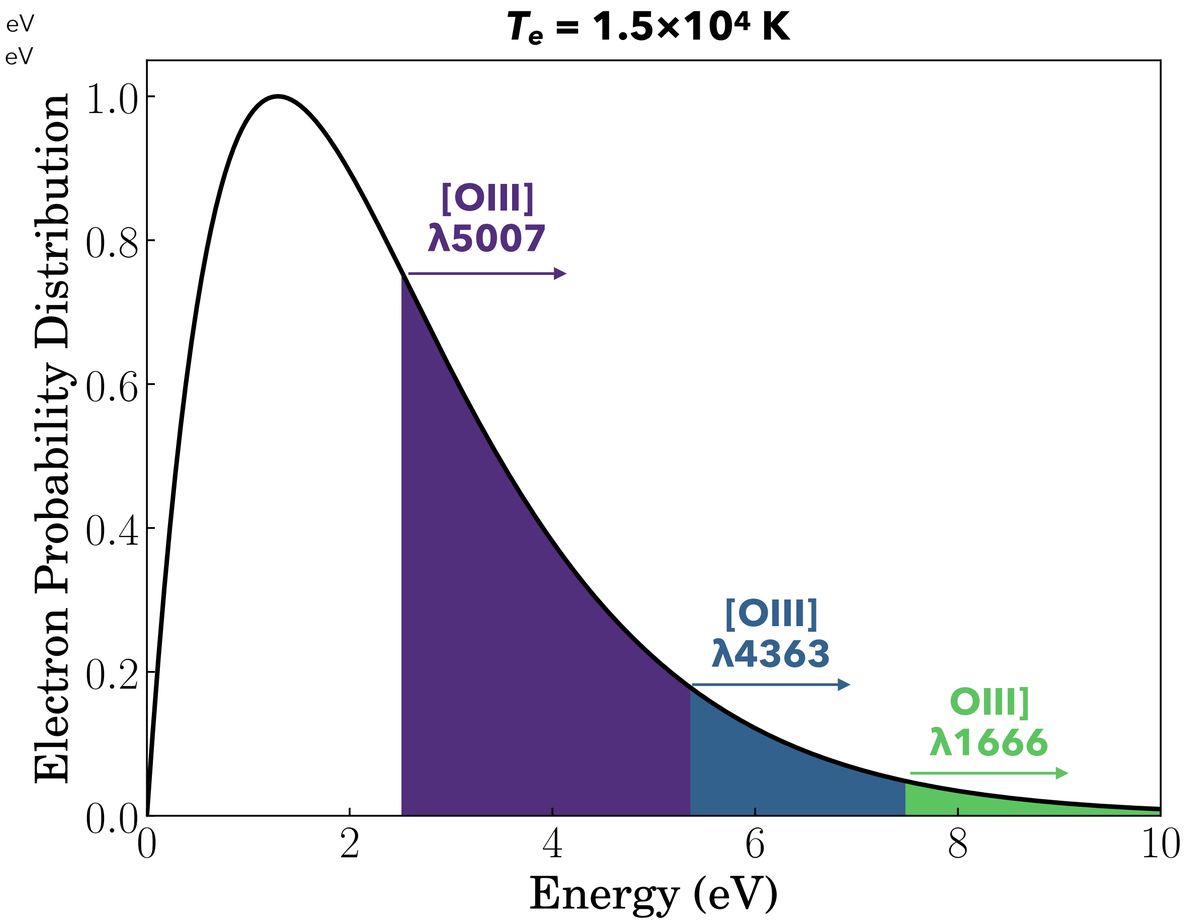
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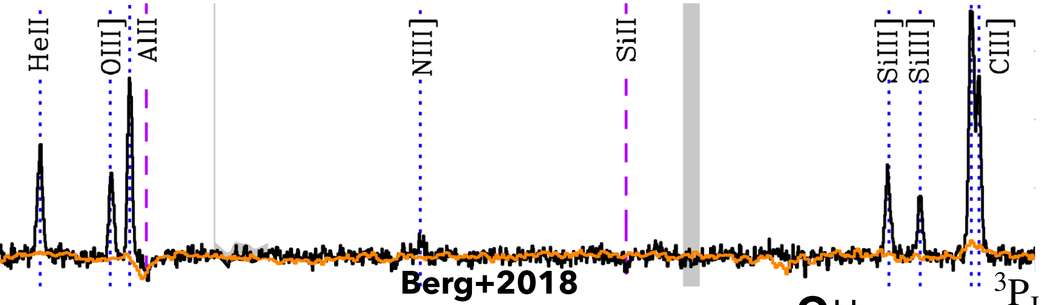


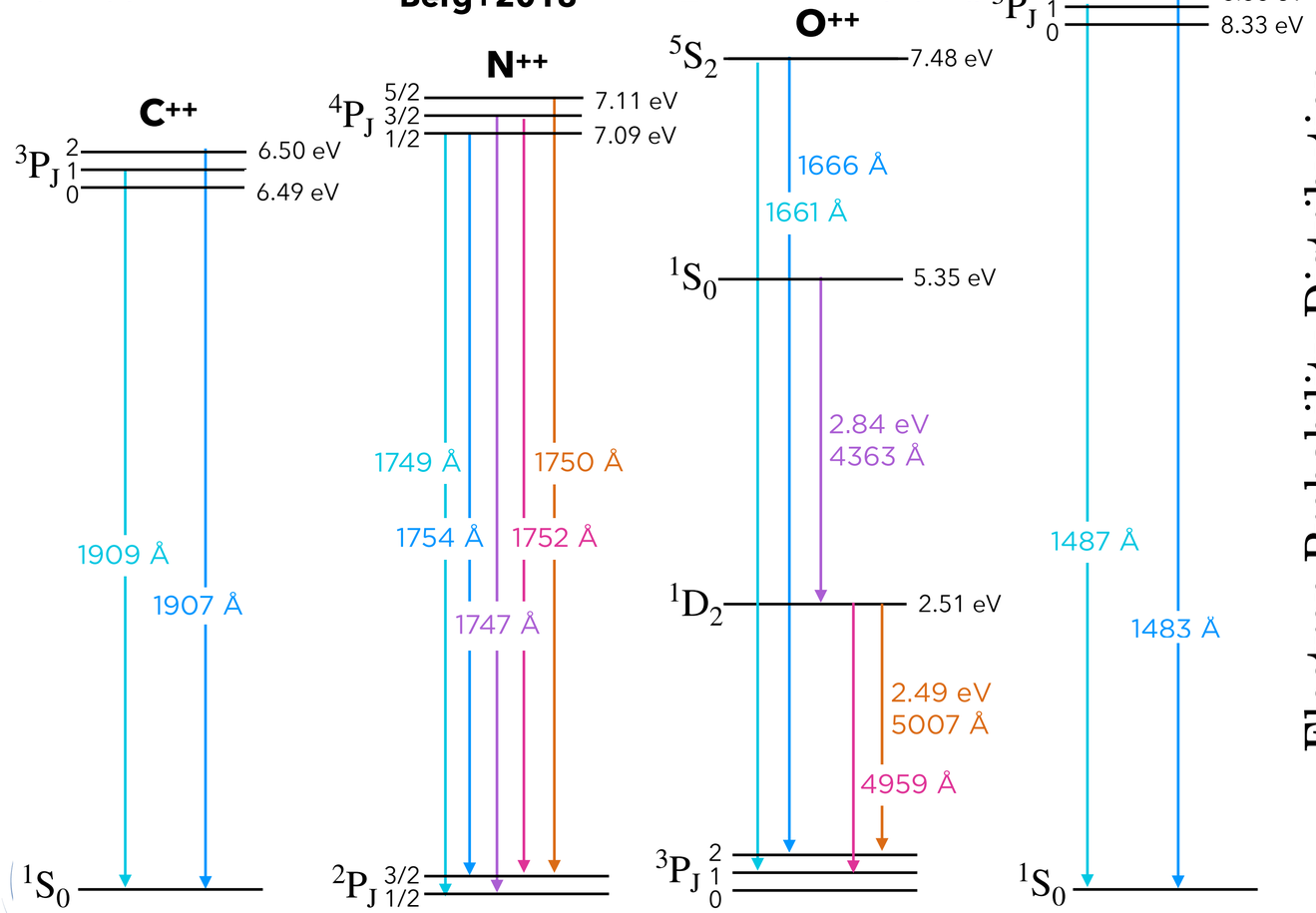
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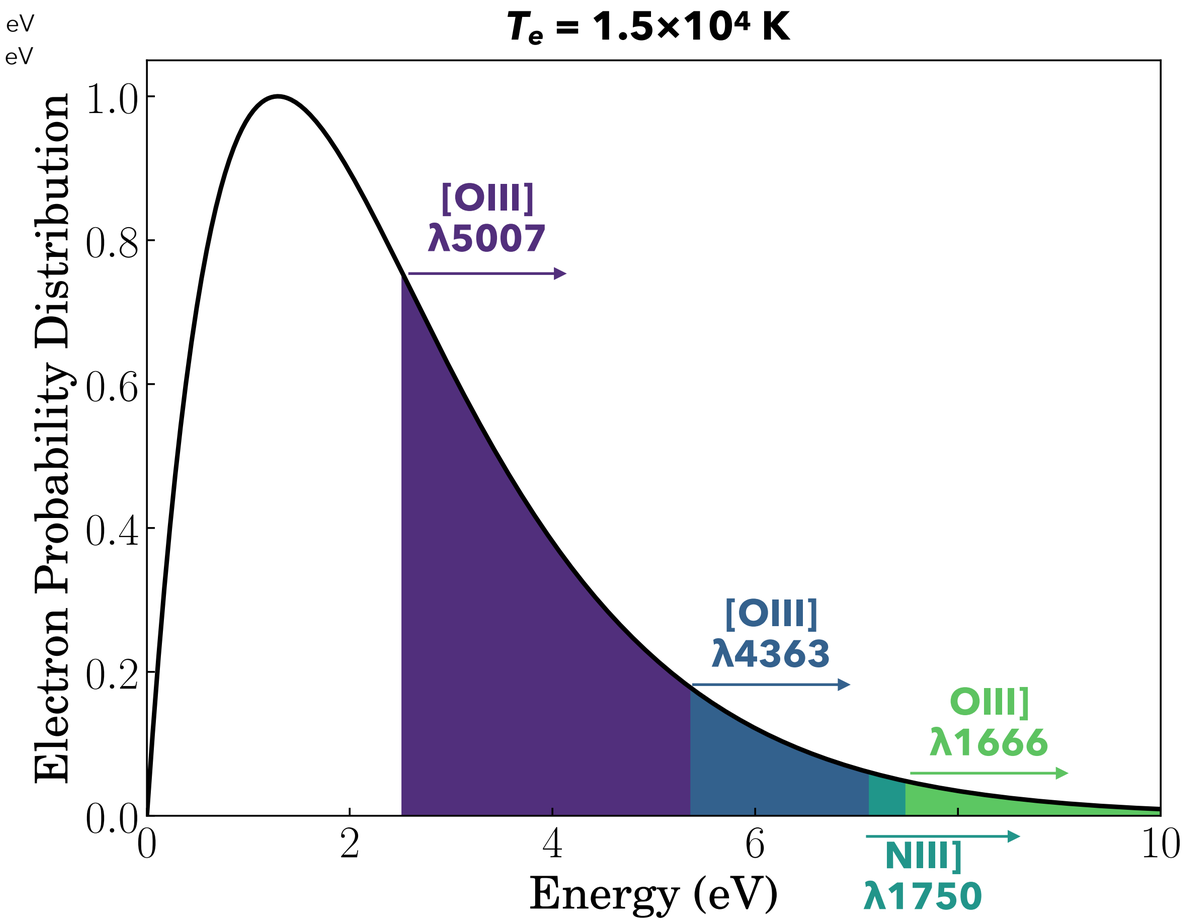
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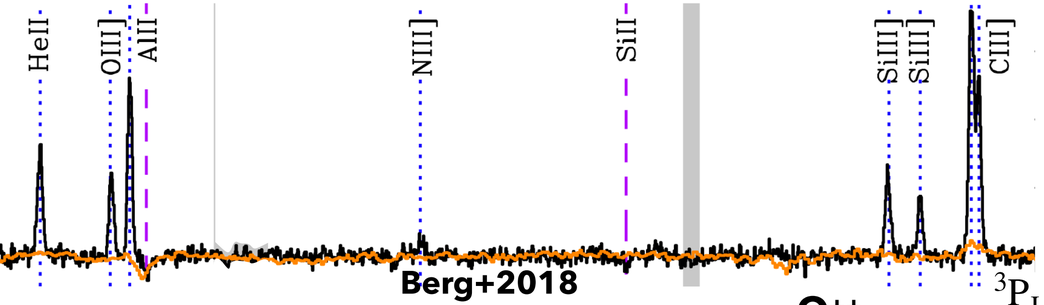


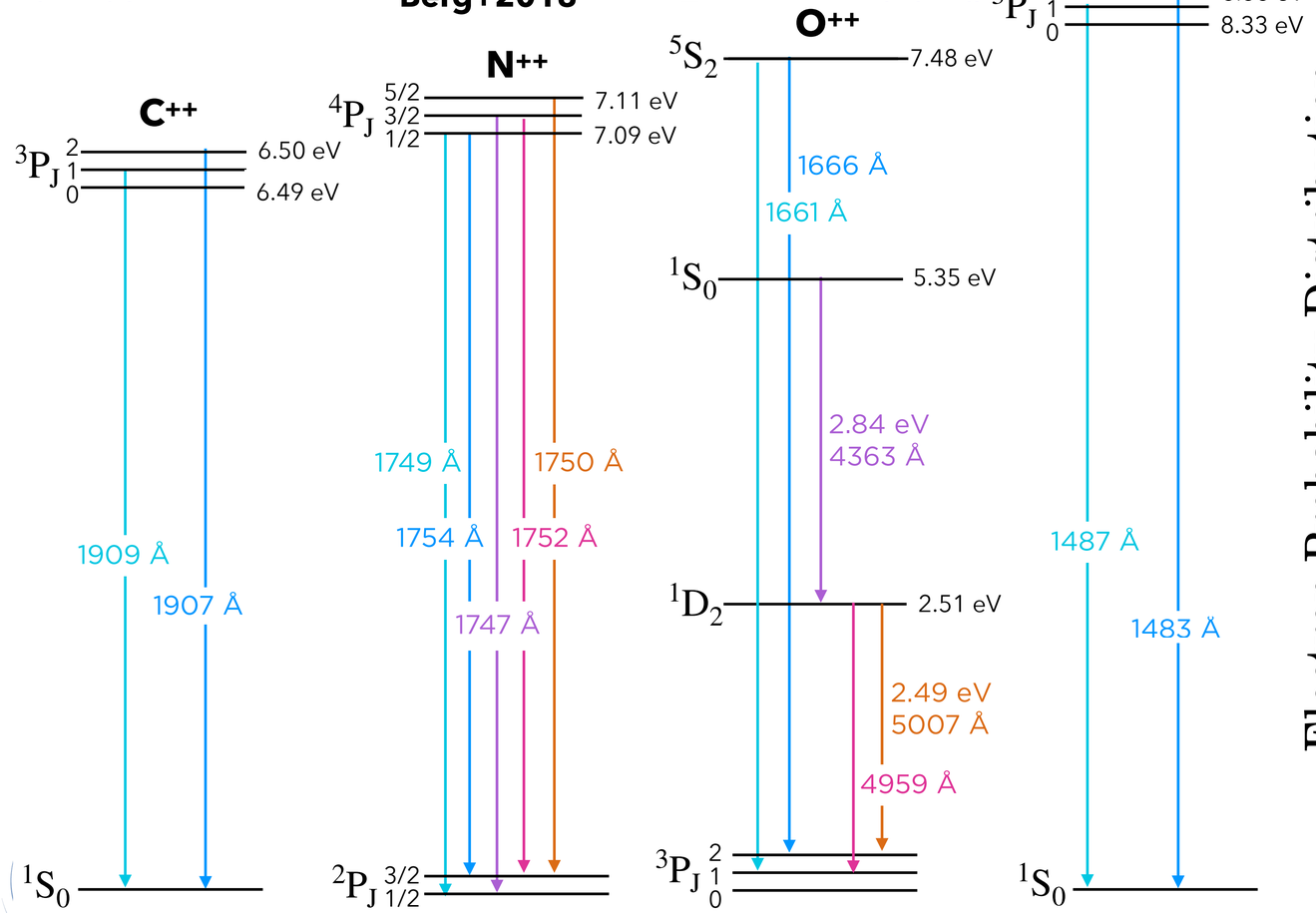
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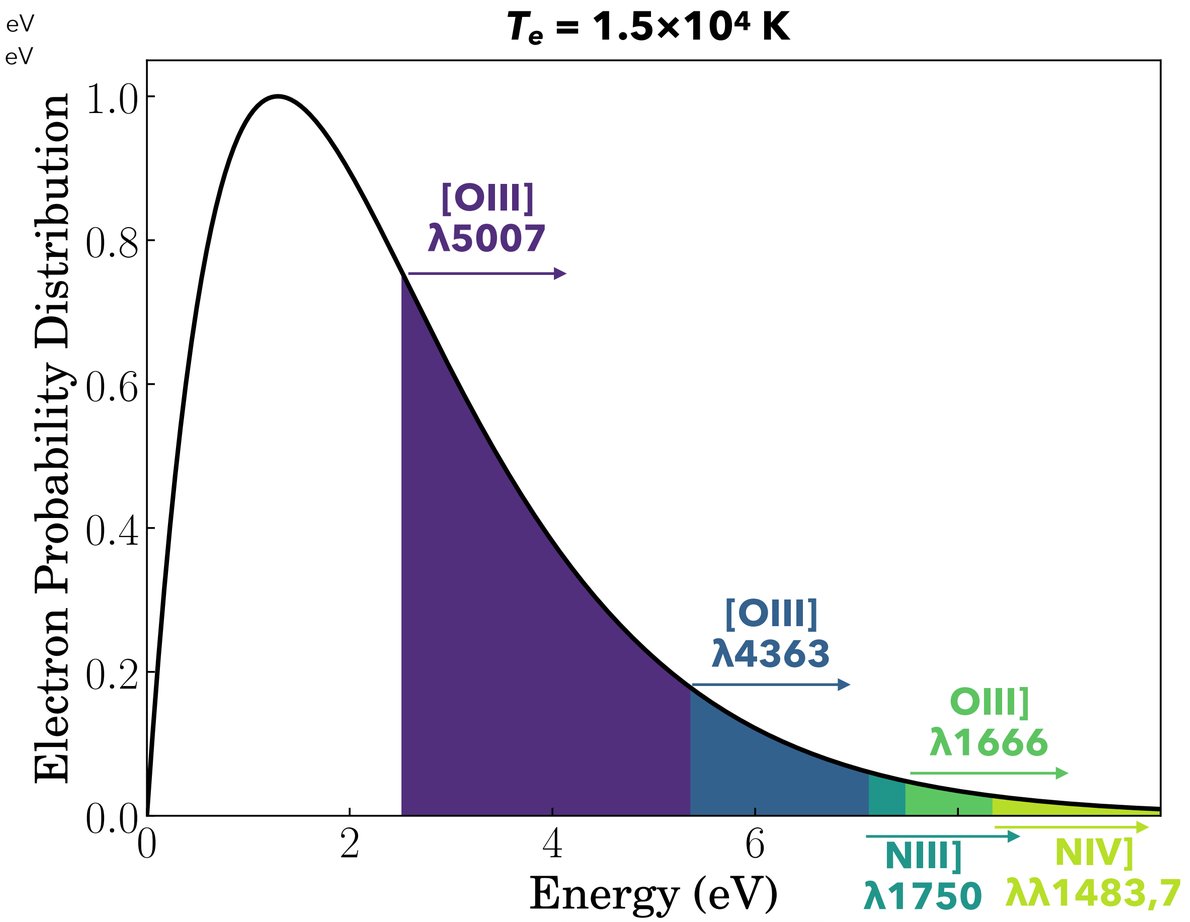
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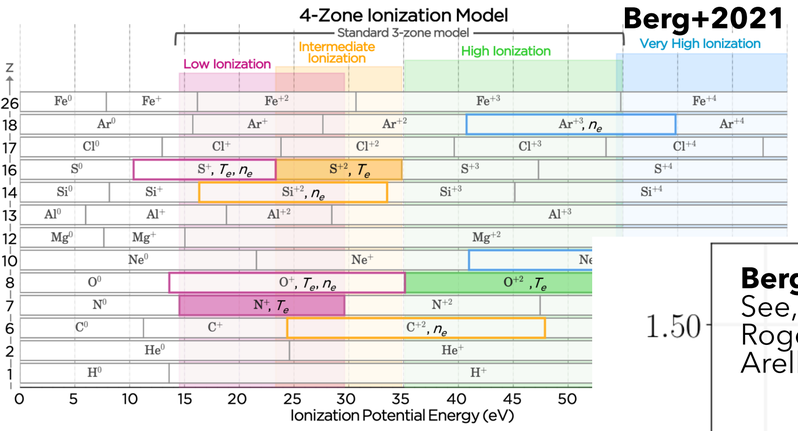


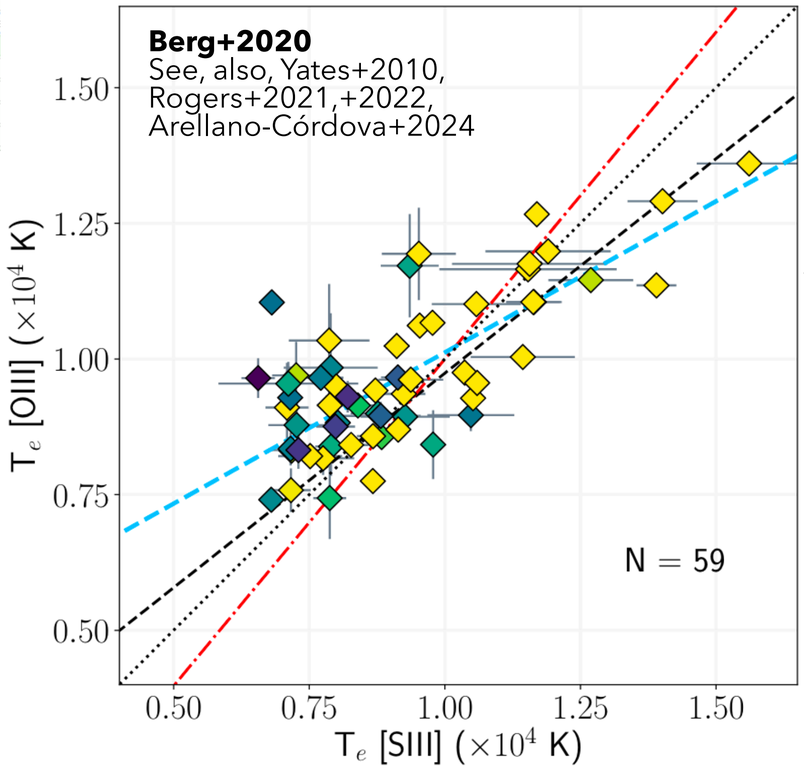
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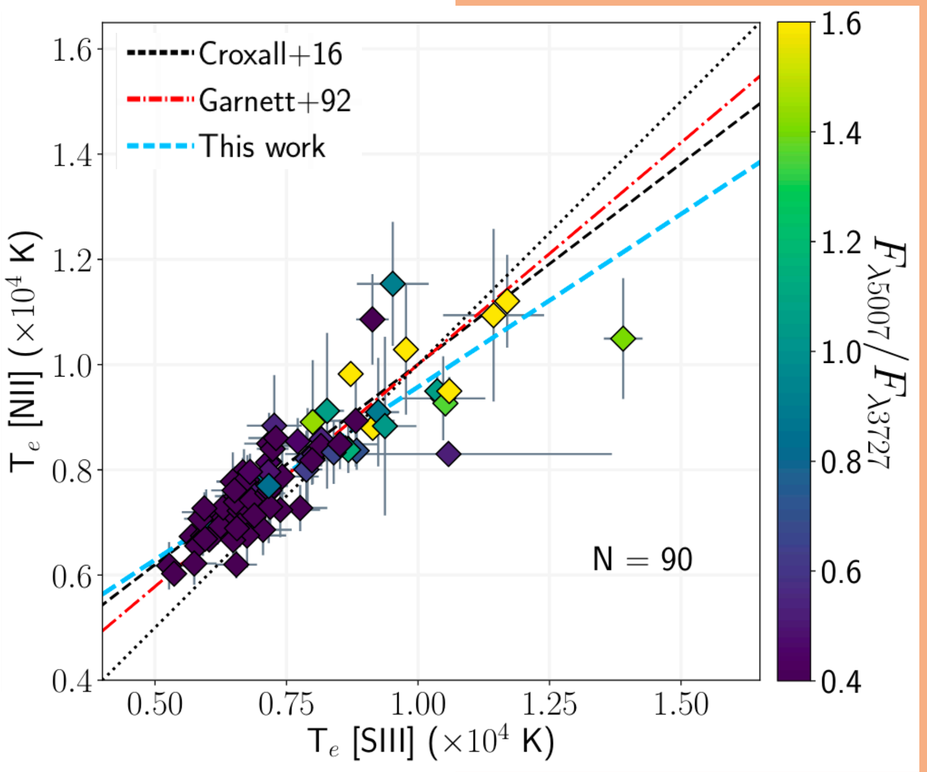
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How do we robustly measure chemical abundances?

Use T_e-T_e relations to get temperatures in zones without direct measurements







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THE DIRECT METHOD

Overall, the principal factors that influence the **nebular temperature** are:

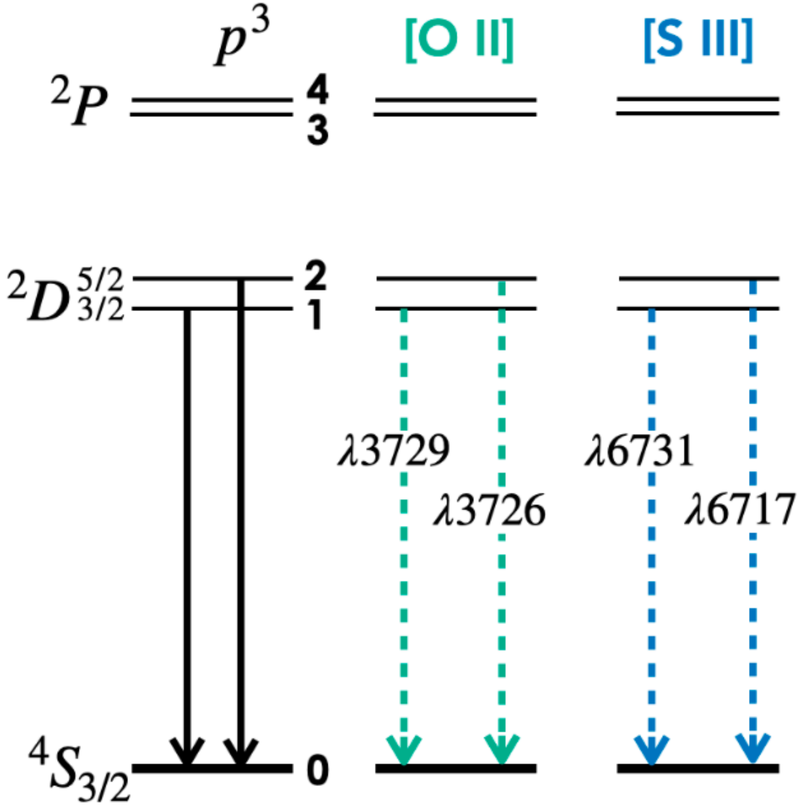
1. The **density** through critical density effects suppressing different cooling lines
2. The **ionizing radiation field** determines the input photoelectron energies and mix of ionic states present.
3. The **elemental abundances** determine amount of metal-line coolants present; lower metallicity → hotter nebulae.
4. **Dust** can modify the radiation field and cause other second-order effects.

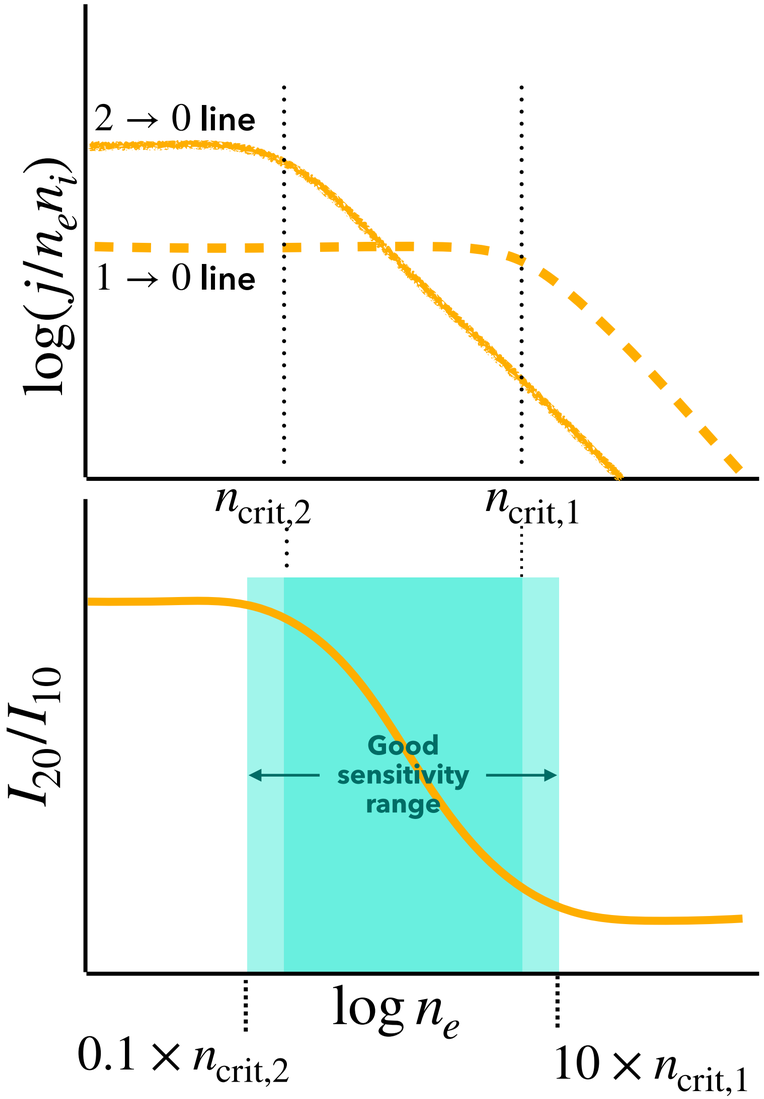
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THE DIRECT METHOD

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How do we robustly measure chemical abundances?



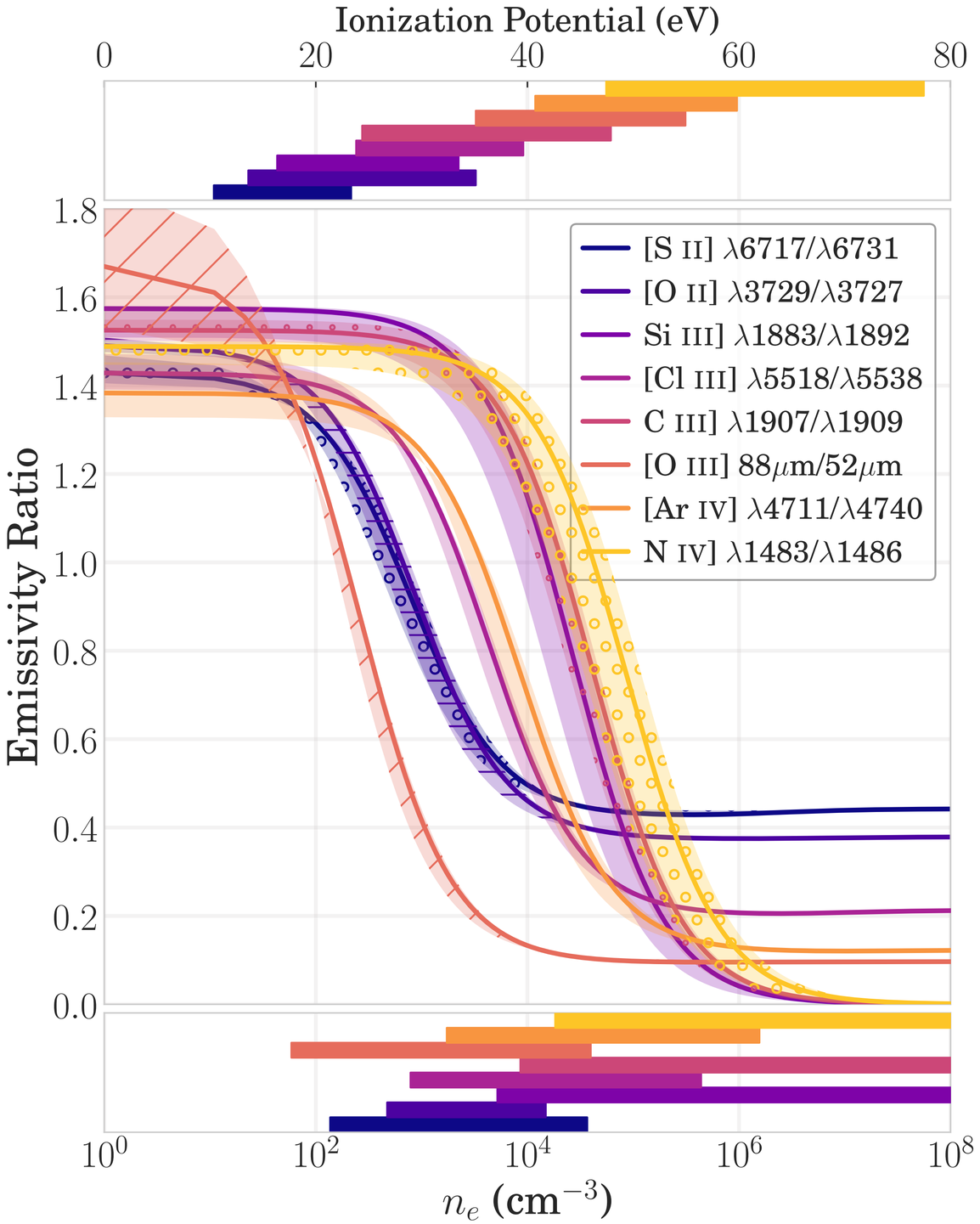




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THE DII

temperature
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tion **zone**

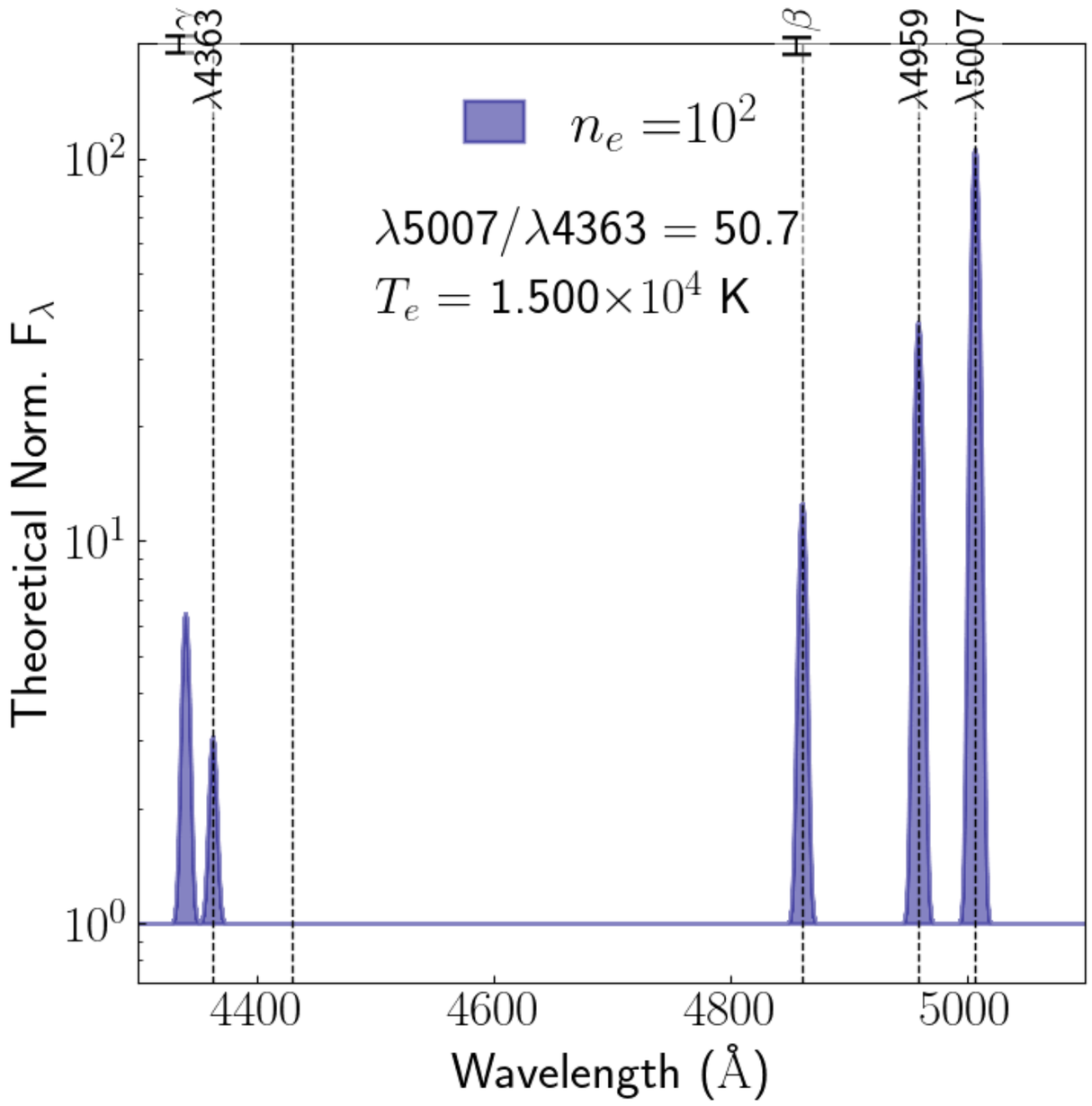


How do we robustly measure chemical abundances?



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HIGH DENSITIES AFFECT [OIII]



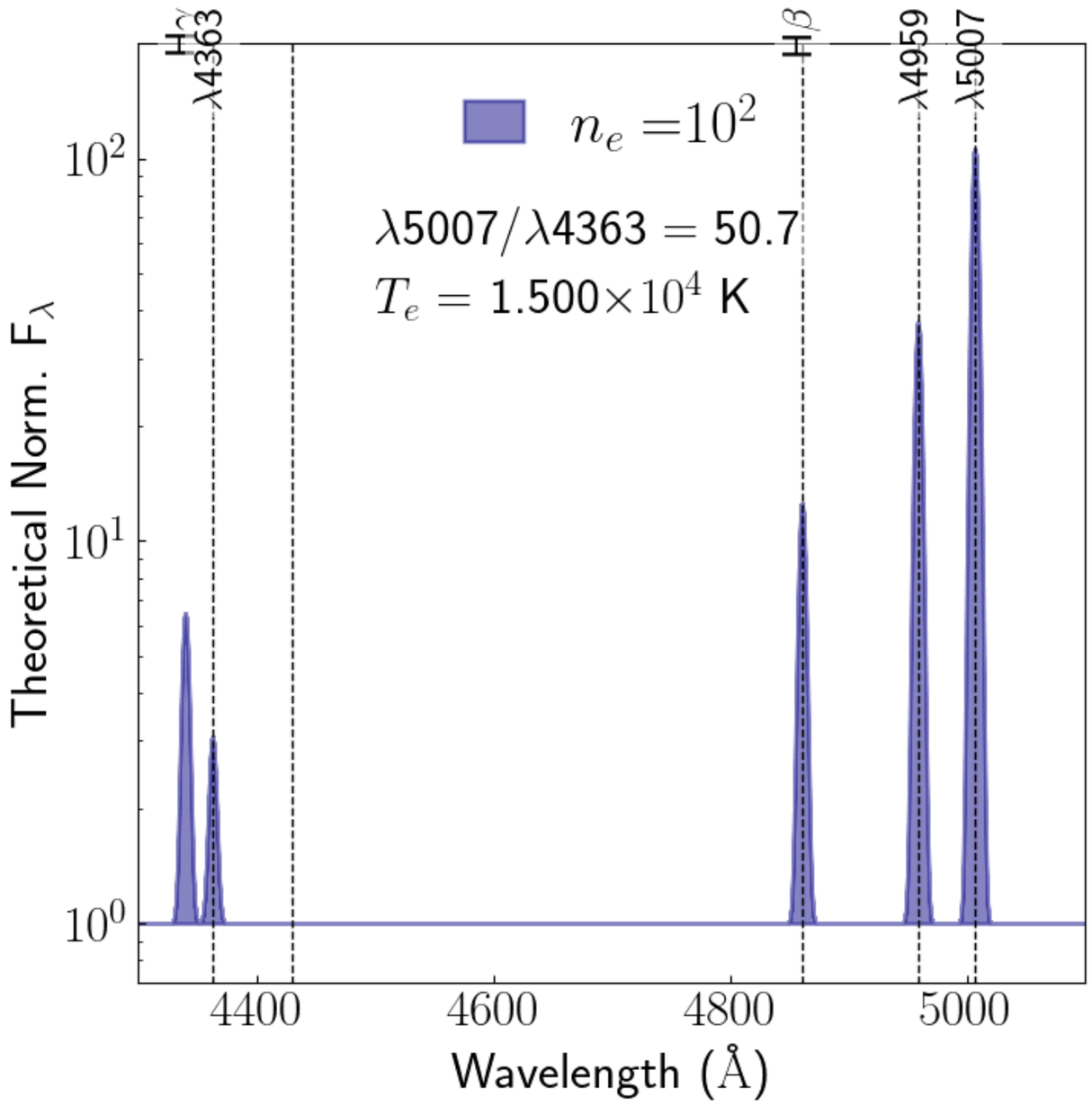
$n_{e,crit}$([OIII] λ5007) = 7.8×10⁵ cm⁻³

[OIII] starts to be **sensitive to collisional de-excitation** at **n_e > 10⁴ cm⁻³**

Possible path forward: Observing 3 or more ions from a given element with different critical densities to constrain density

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HIGH DENSITIES AFFECT [OIII]



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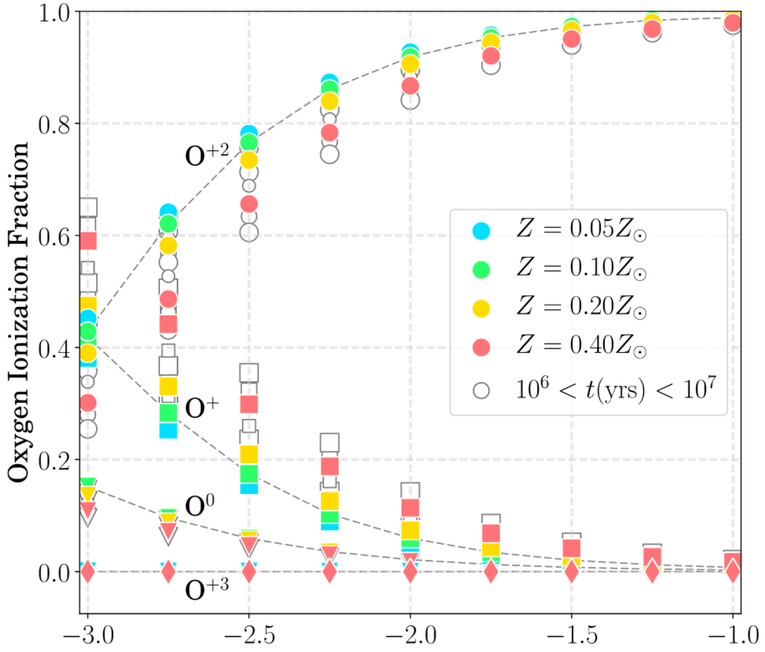
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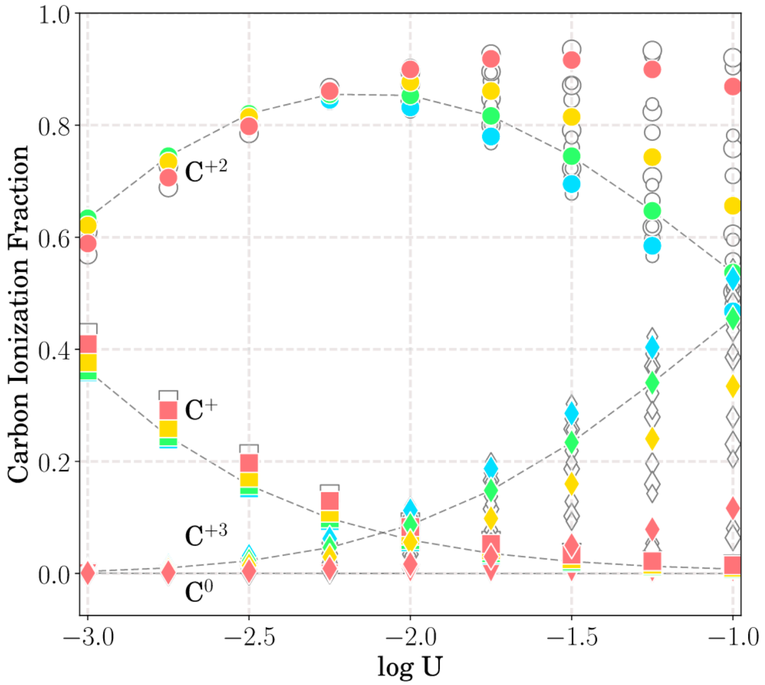
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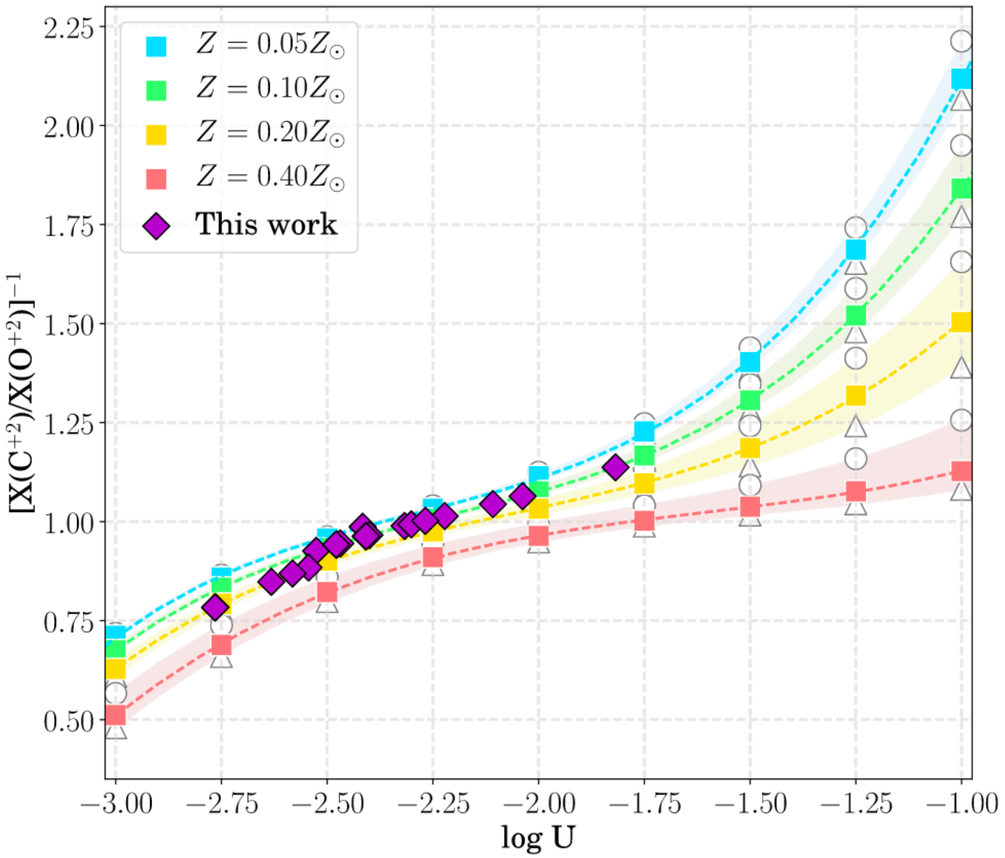
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THE DIRECT METHOD

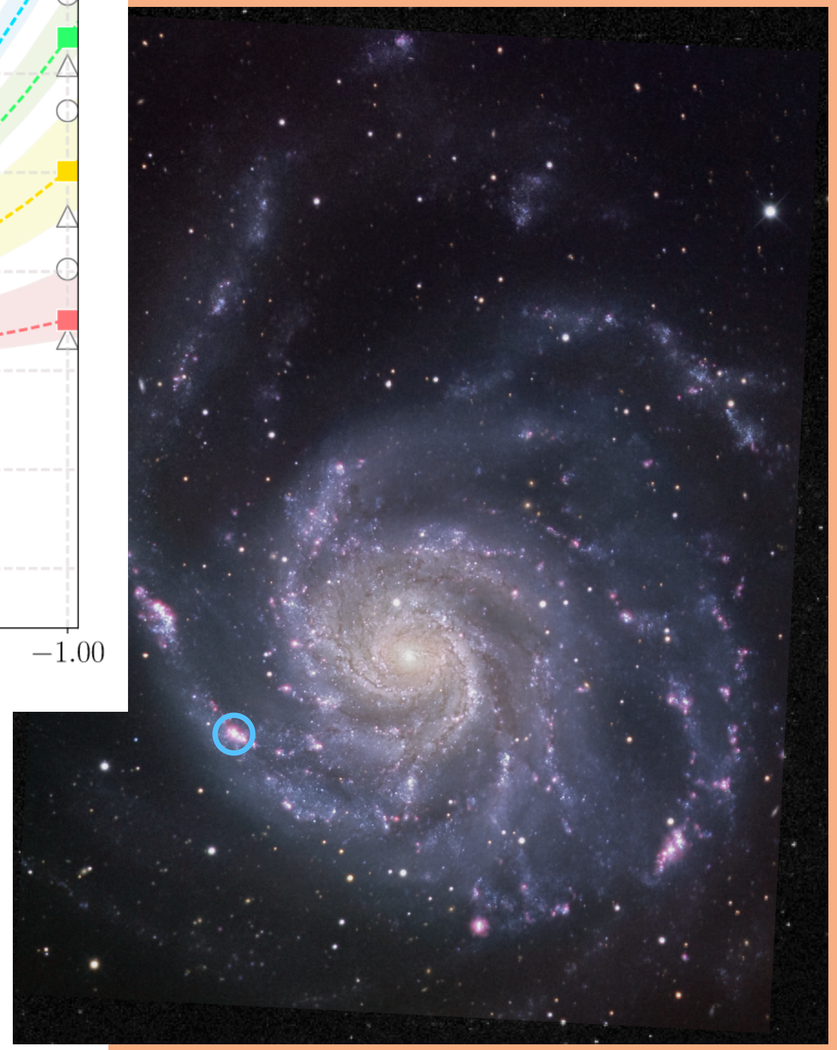
Requires ionization correction factor (**ICF**) if all relevant ions are not directly observed





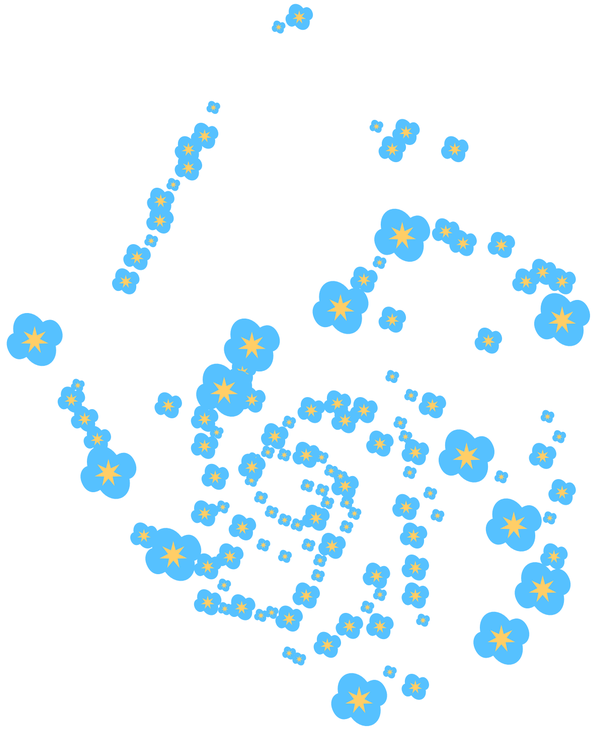


How do we robustly measure chemical abundances?



THIS COULD BE AN ENTIRE LECTURE ...

THE DIRECT METHOD



Spiral Galaxy



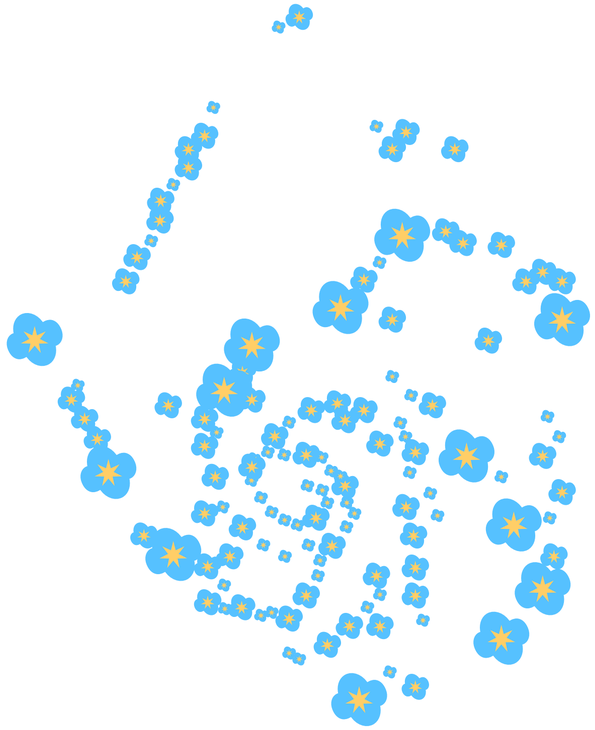
Dwarf Galaxy

How do we robustly measure chemical abundances?

The **metallicity** of a galaxy is **not** as **easily defined** as we often portray it to be.

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THE DIRECT METHOD



Spiral Galaxy

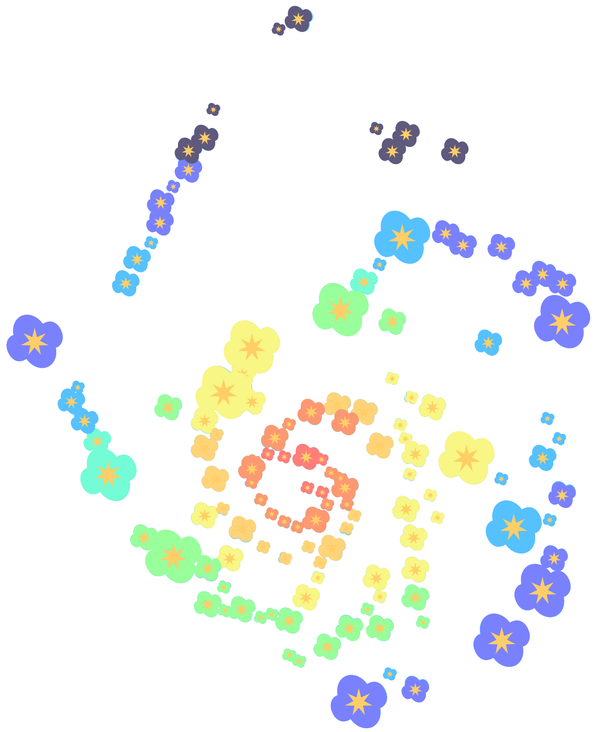


Dwarf Galaxy

How do we robustly measure chemical abundances?

The **metallicity** of a galaxy is **not** as **easily defined** as we often portray it to be.

THE DIRECT METHOD



Spiral Galaxy



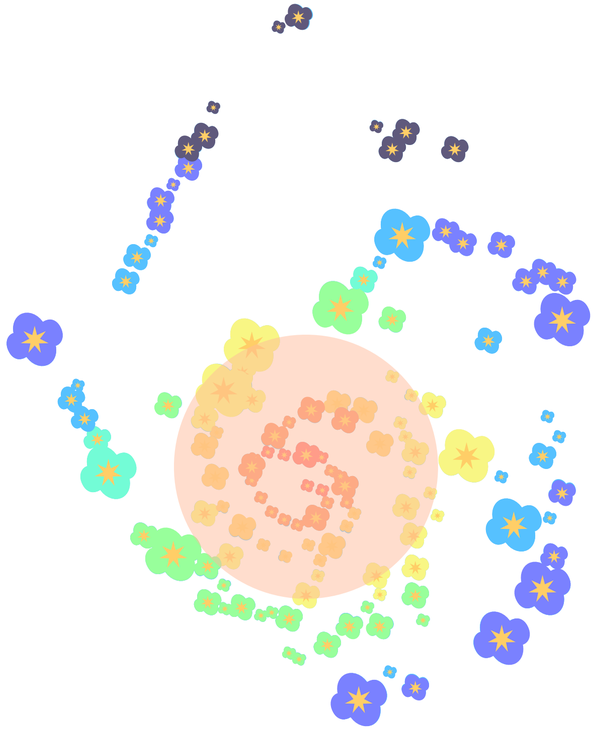
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TEXAS
The University of Texas at Austin

THE DIRECT METHOD



Spiral Galaxy



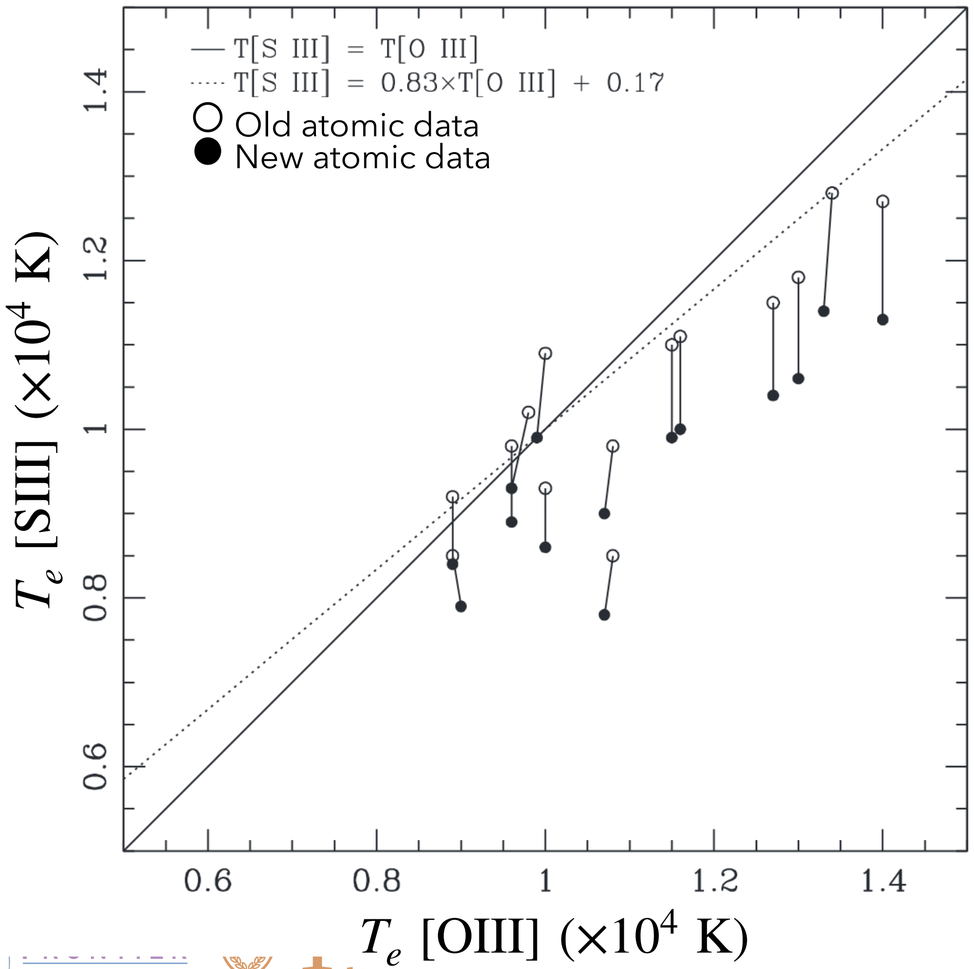
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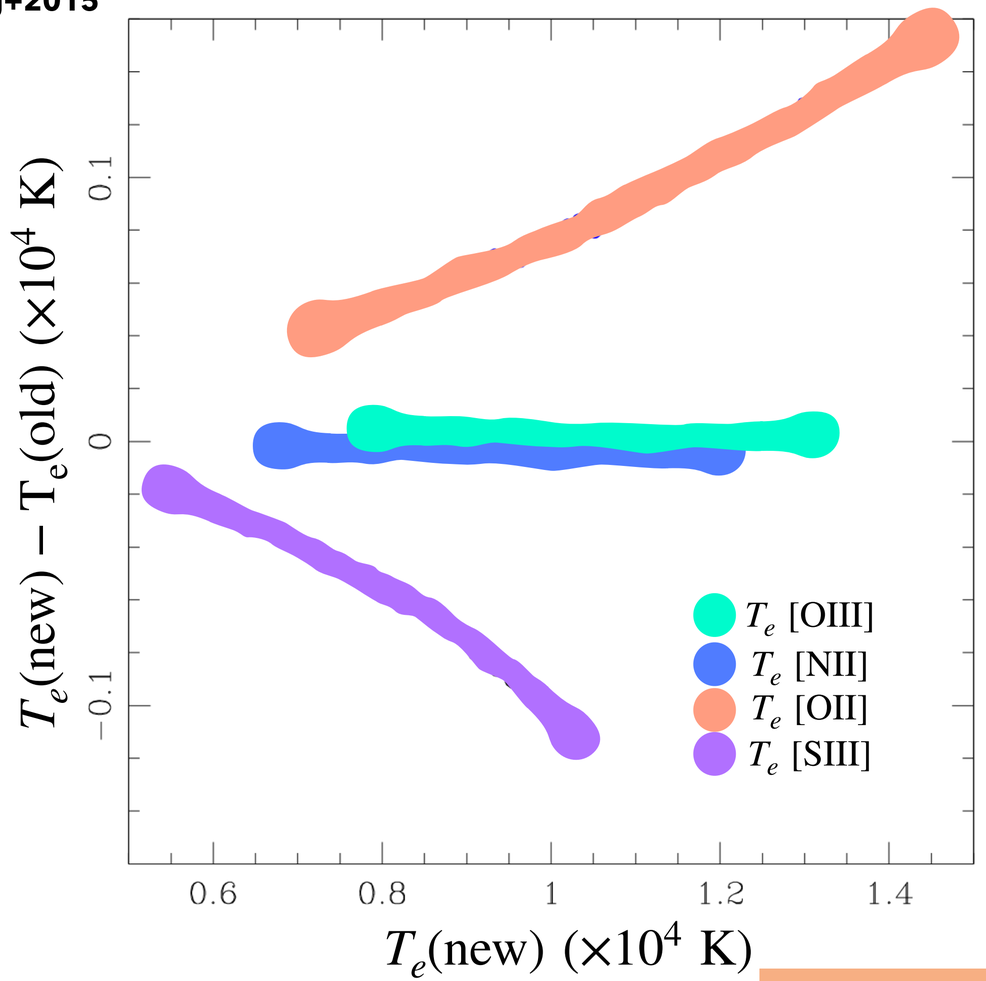
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CAVEAT: ATOMIC DATA

How do we robustly measure chemical abundances?



Adapted from Berg+2015





The COS Legacy Spectroscopic SurveY

THE LOCAL ADVANTAGE

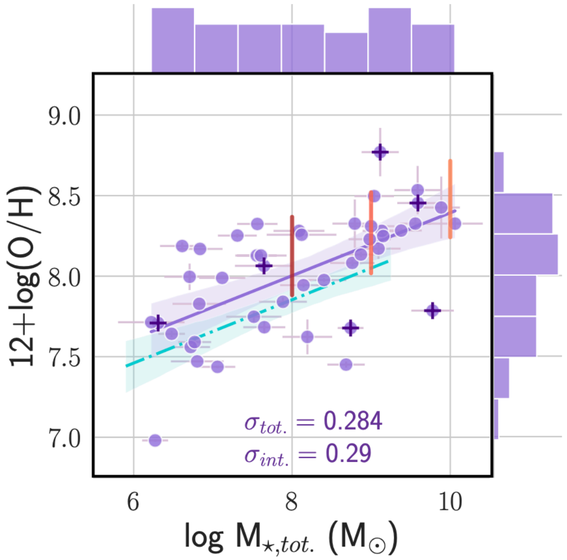
Unparalleled **S/N** and **spectral resolution**

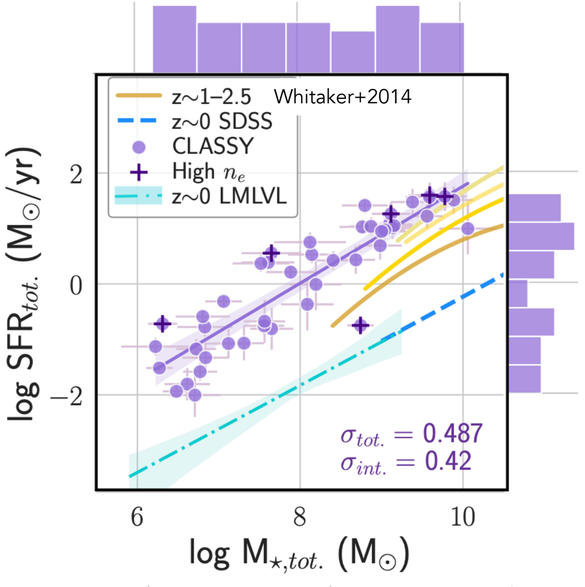
Berg & James and the CLASSY Team, 2022

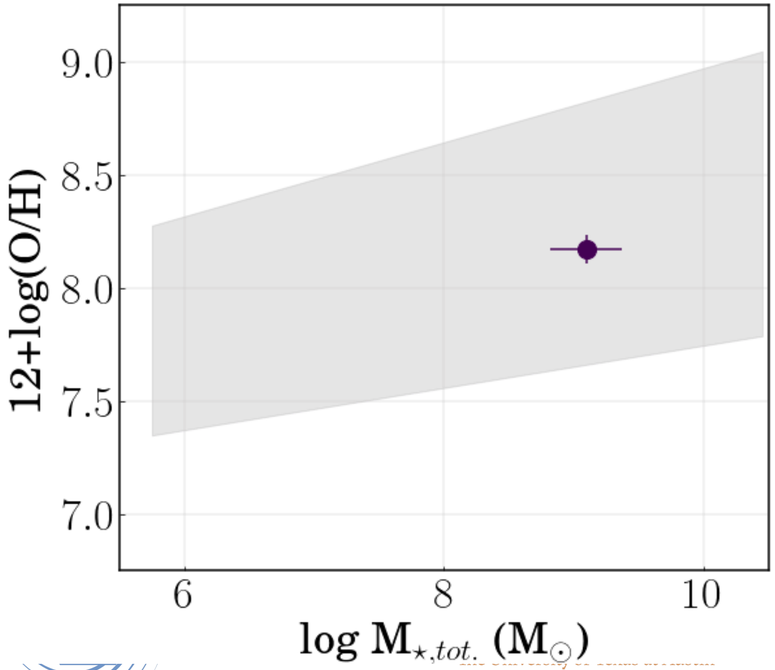
45 z~0 star-forming galaxies

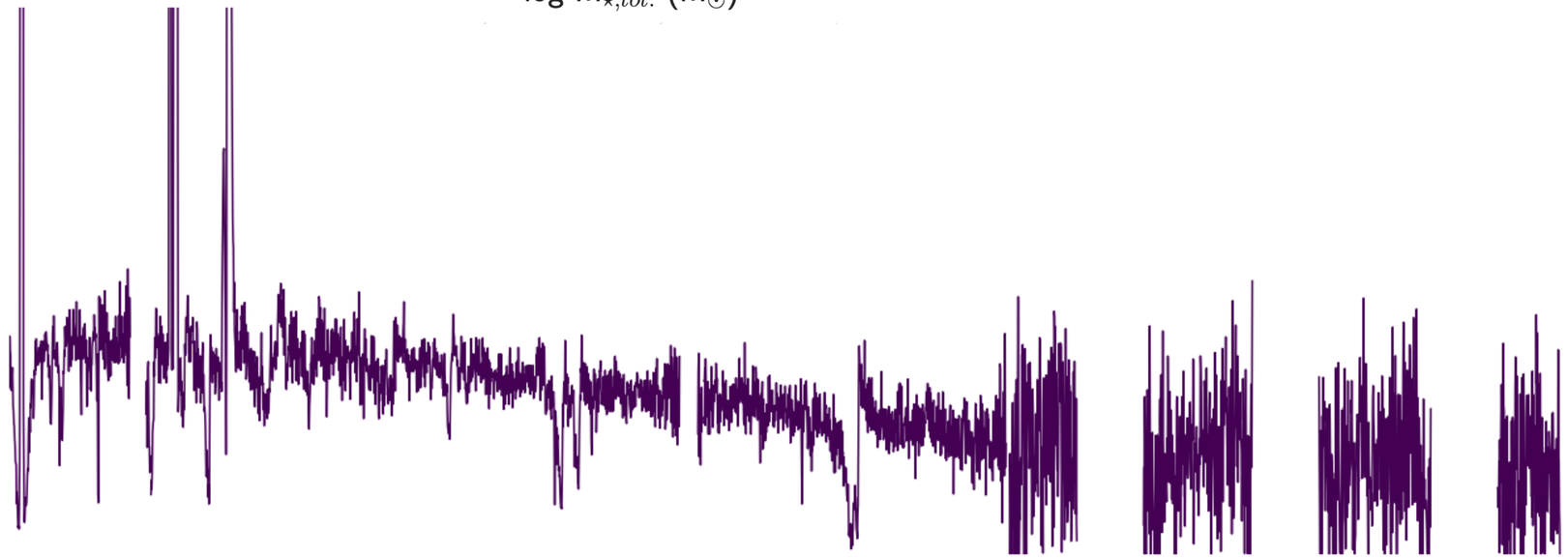
HST/COS R~15,000

FUV spectra 1200 - 2000 Å











The COS Legacy Spectroscopic SurveY

THE LOCAL ADVANTAGE

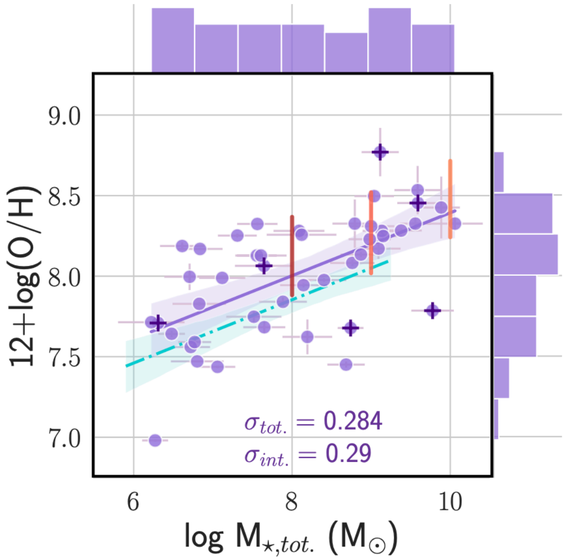
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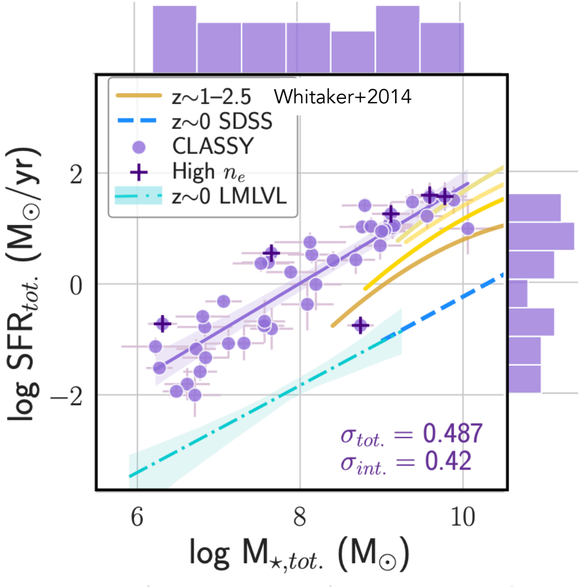
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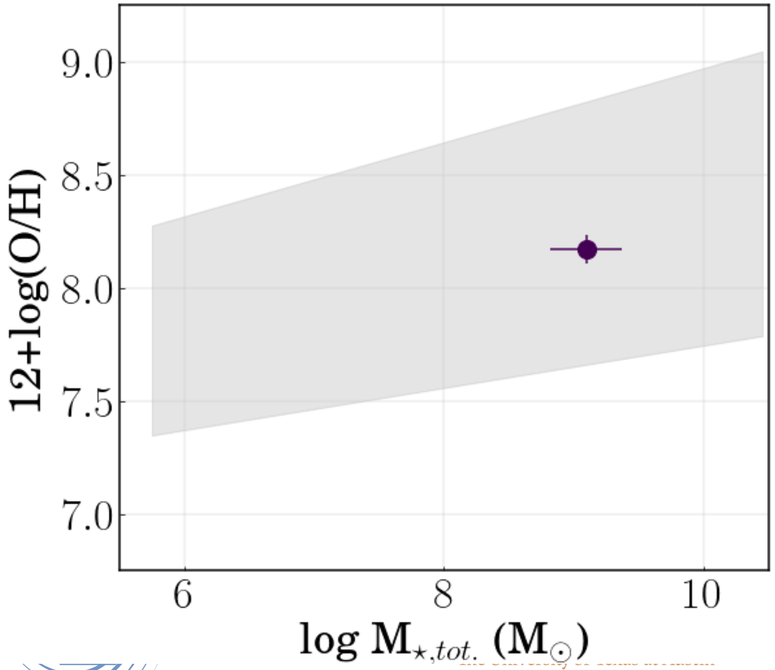
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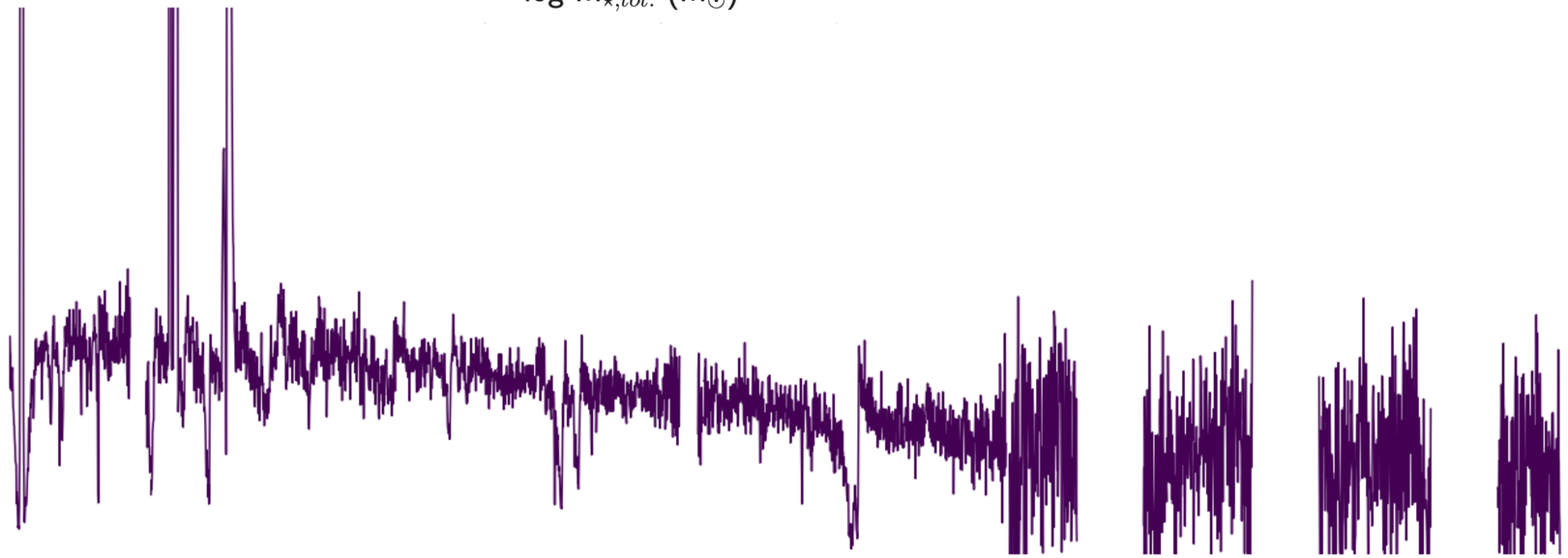
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The COS Legacy Spectroscopic SurveY

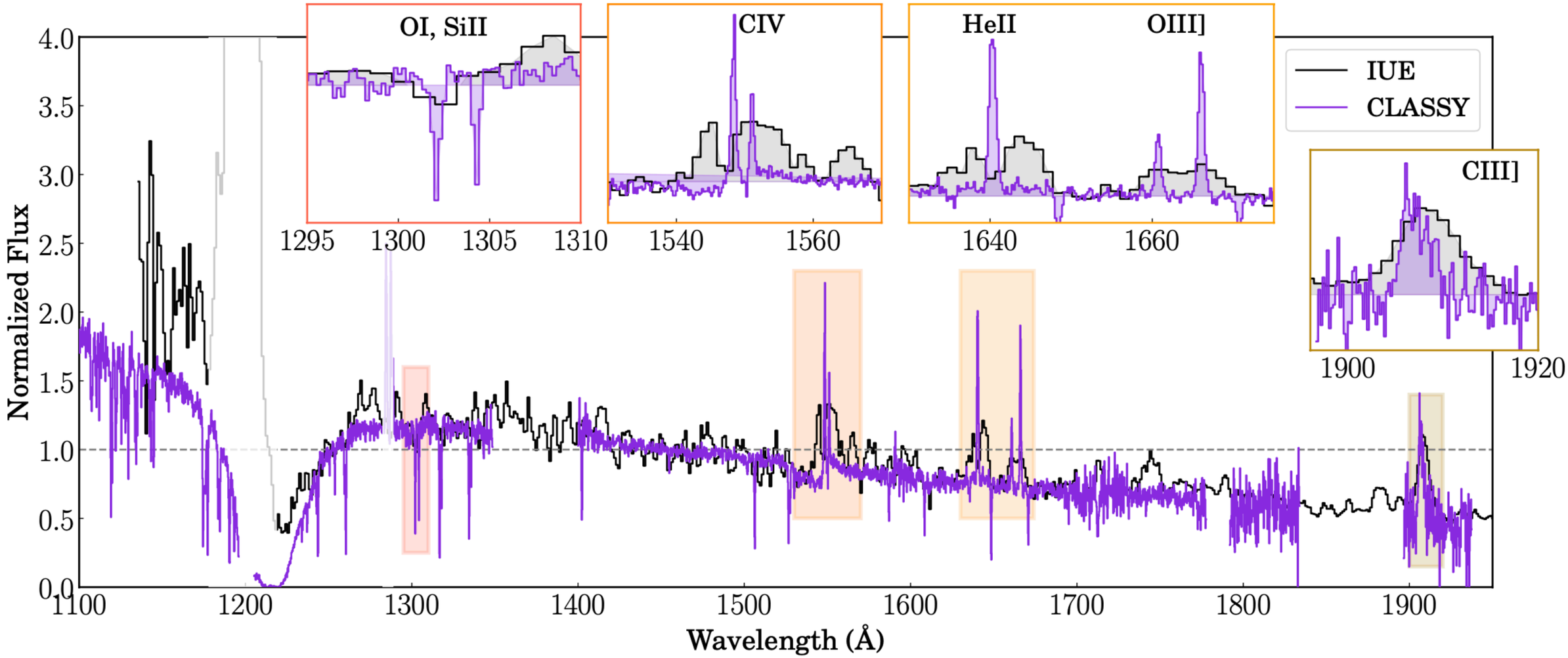
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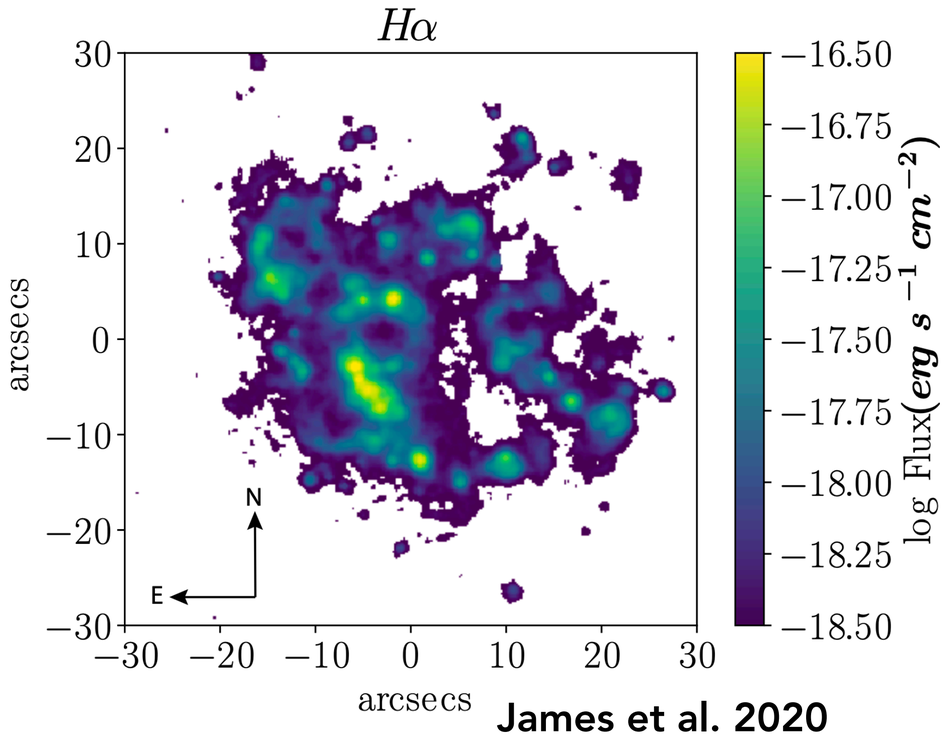
The COS Legacy Spectroscopic SurveY

THE LOCAL ADVANTAGE

Unparalleled
spatial resolution

James et al. 2020

Mapping the ISM in a local metal-poor ($z_{neb} \sim 0.08\ Z_\odot$) galaxy JKB 18 with MUSE



James et al. 2020

0th Moment: Integrated Intensity Map
Tells you surface brightness across the galaxy
e.g., spatial distribution

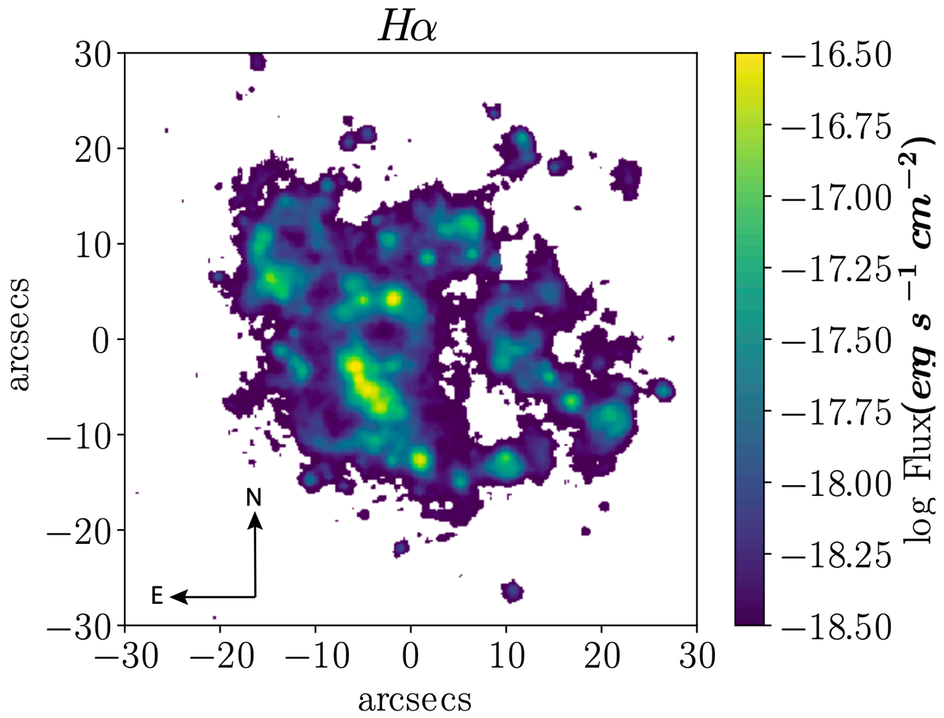
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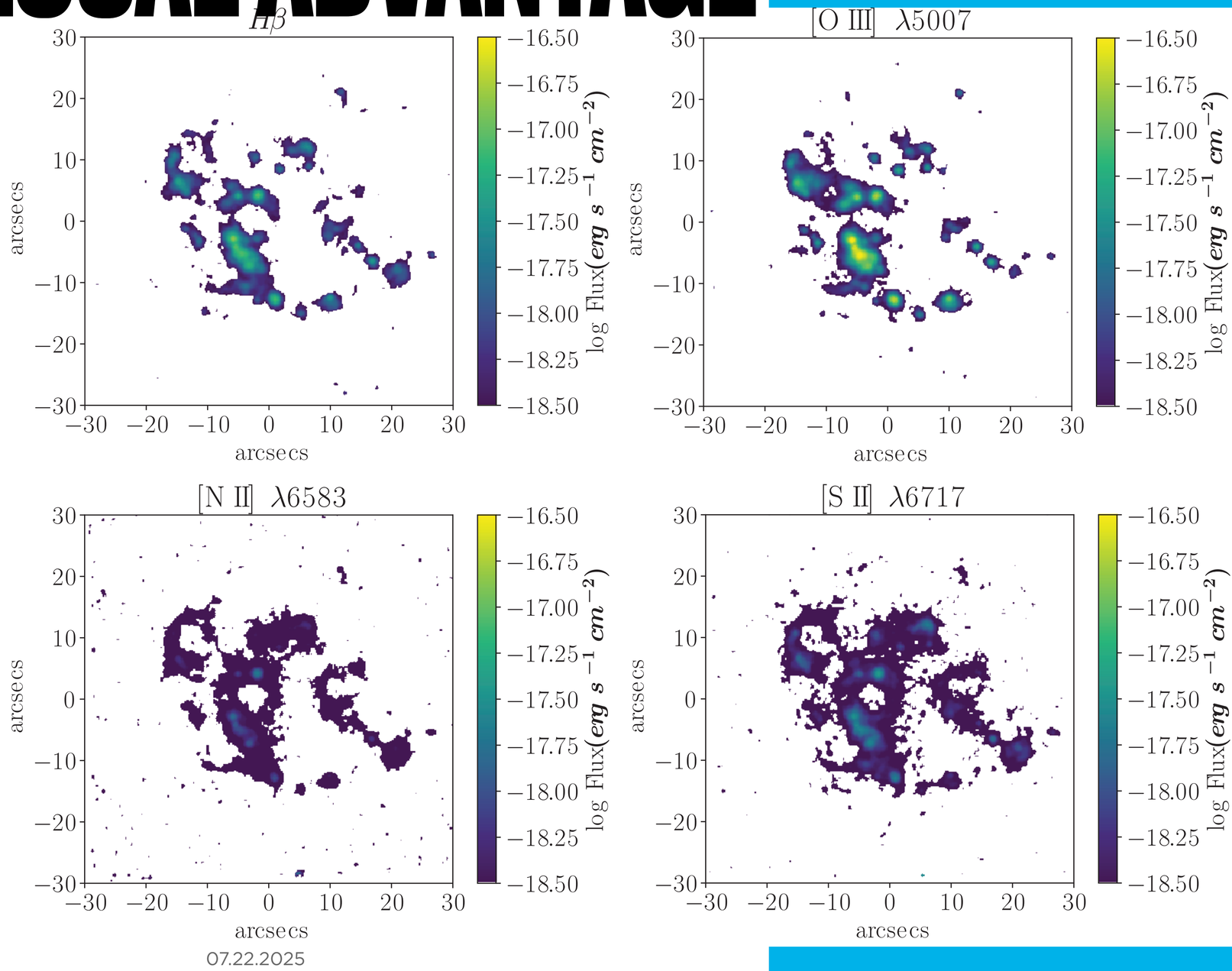
Mapping



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07.22.2025

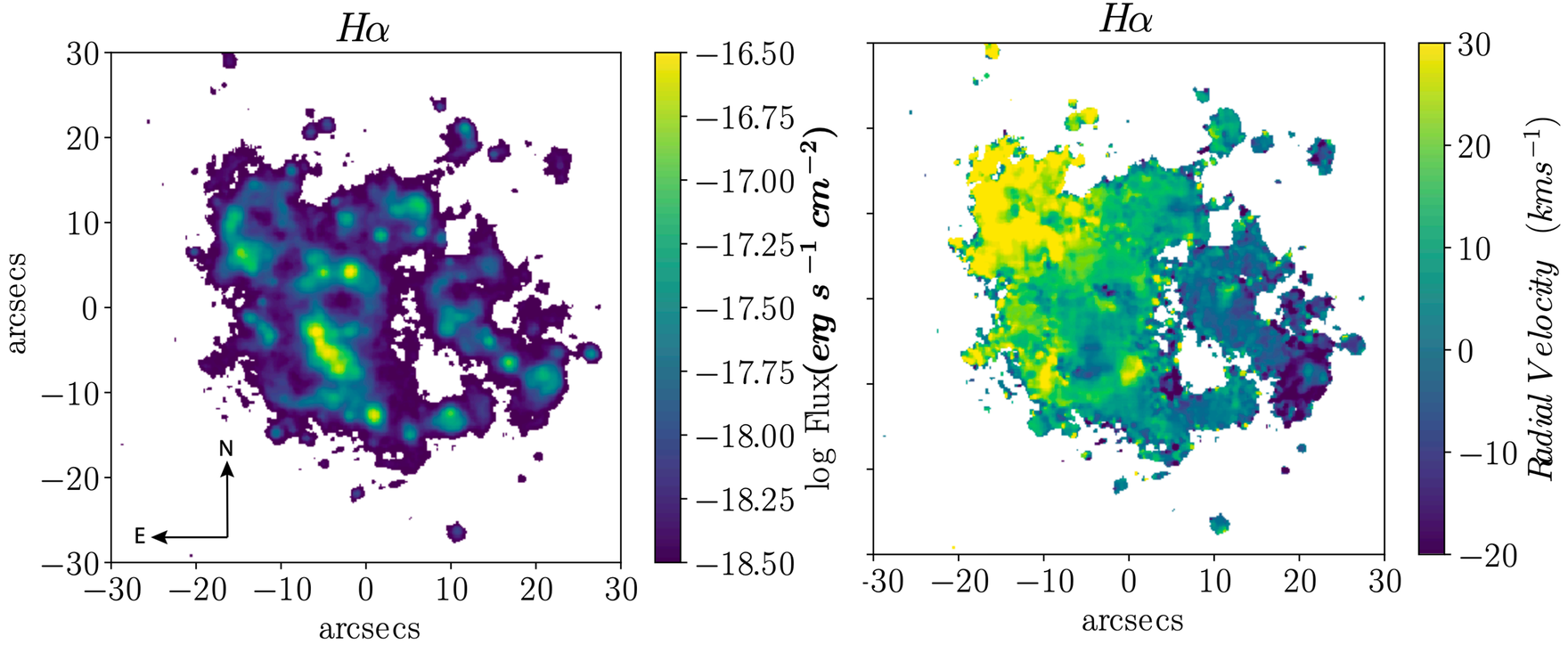
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1st Moment: Velocity Map

Tells you the line-of-sight velocity field,
i.e., bulk motion of the gas (flux-weighted)
Used to trace galactic rotation, outflows/ inflows, etc.

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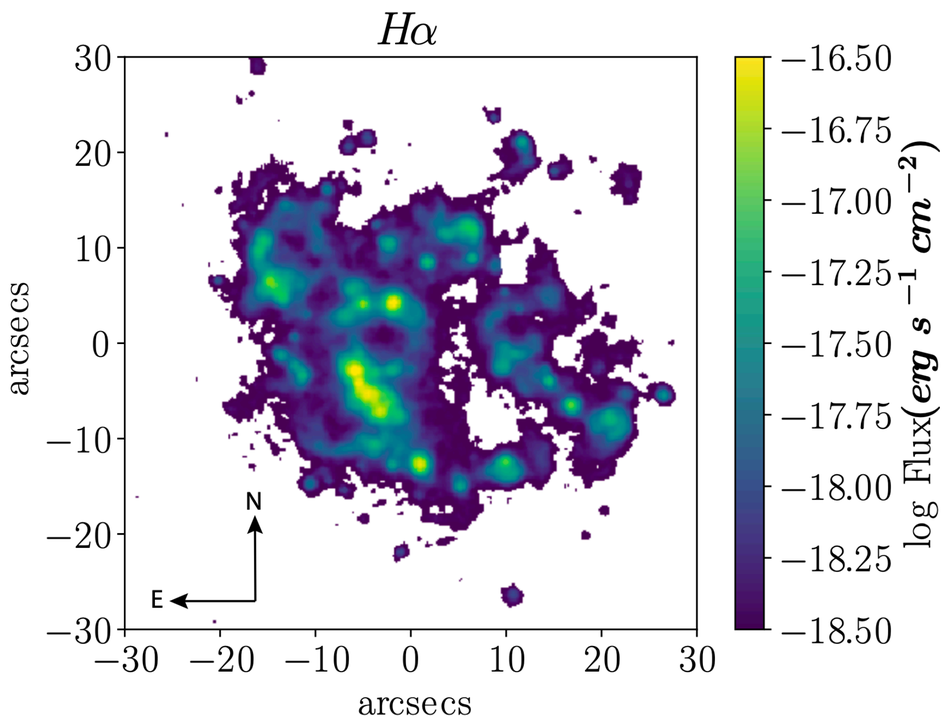
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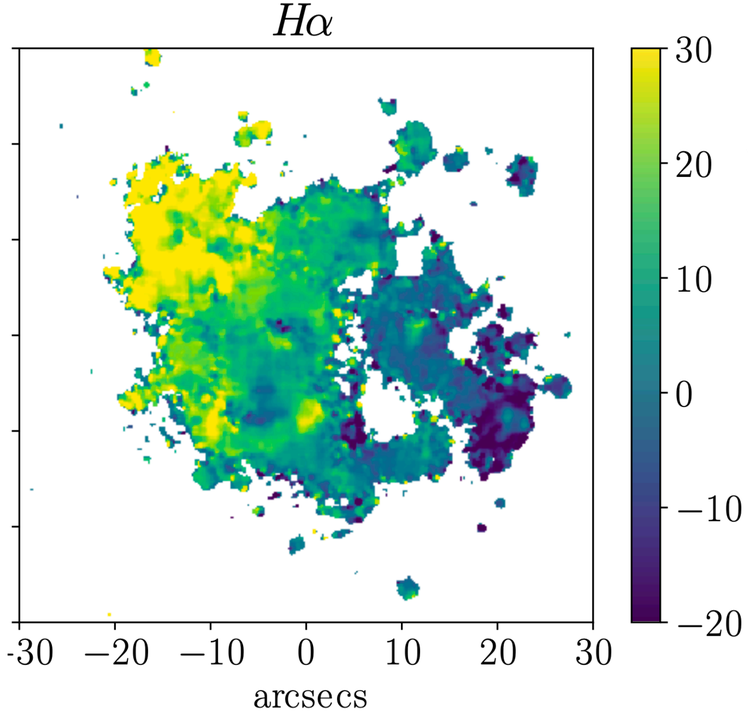
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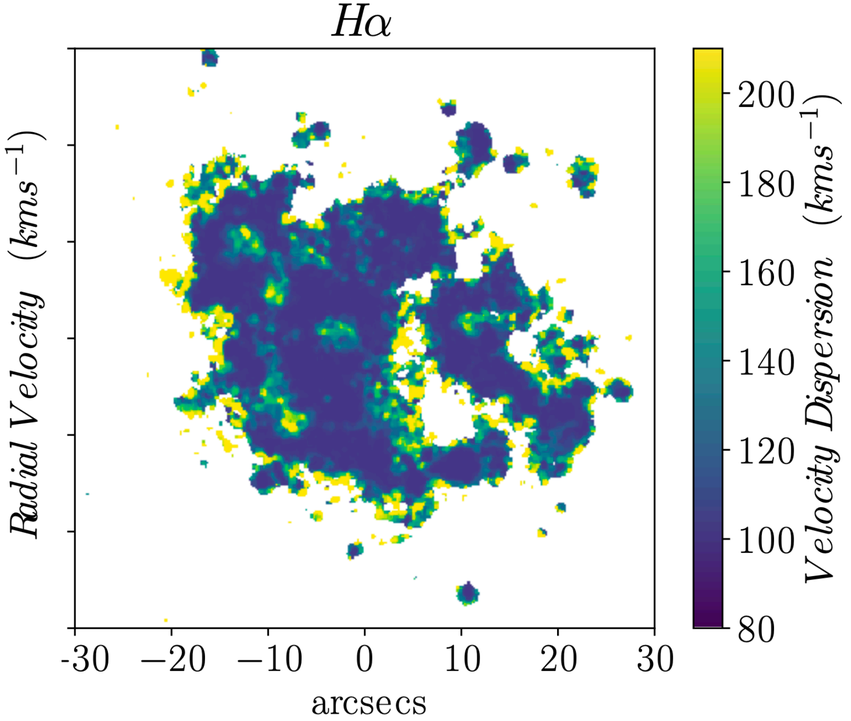
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2nd Moment: Velocity Dispersion Map

A measure of the width of the line or weighted velocity dispersion. Characterizes turbulence or non-thermal motions in the gas such due to, e.g., shocks.

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PART II:
ABUNDANCE & DEPLETION STUDIES

DIAGNOSTIC METHODS

UV Emission Lines

- Have **high** excitation **temps**.
- Have **high** critical **densities**
- Generally **higher ionization**
- **Very** sensitive to **dust**
- Sensitive to ionizing spectrum, gas temperature, radiative transfer effects (some lines)
- Utility: Radiation hardness, ionization, density, escape of ionizing radiation, relative abundances: C/O, N/O, Si/O

Optical Emission Lines

- Have **moderate** excitation **temps**.
- Have **moderate** critical **densities**
- **Span** full **ionization** range
- **Moderately** sensitive to **dust**
- Sensitive to ionizing spectrum, gas temperature, density, dust attenuation (moderate)
- Utility: ionization, temperature, density, dust attenuation, total and relative abundances: O, N, Ne, Ar, S, Fe

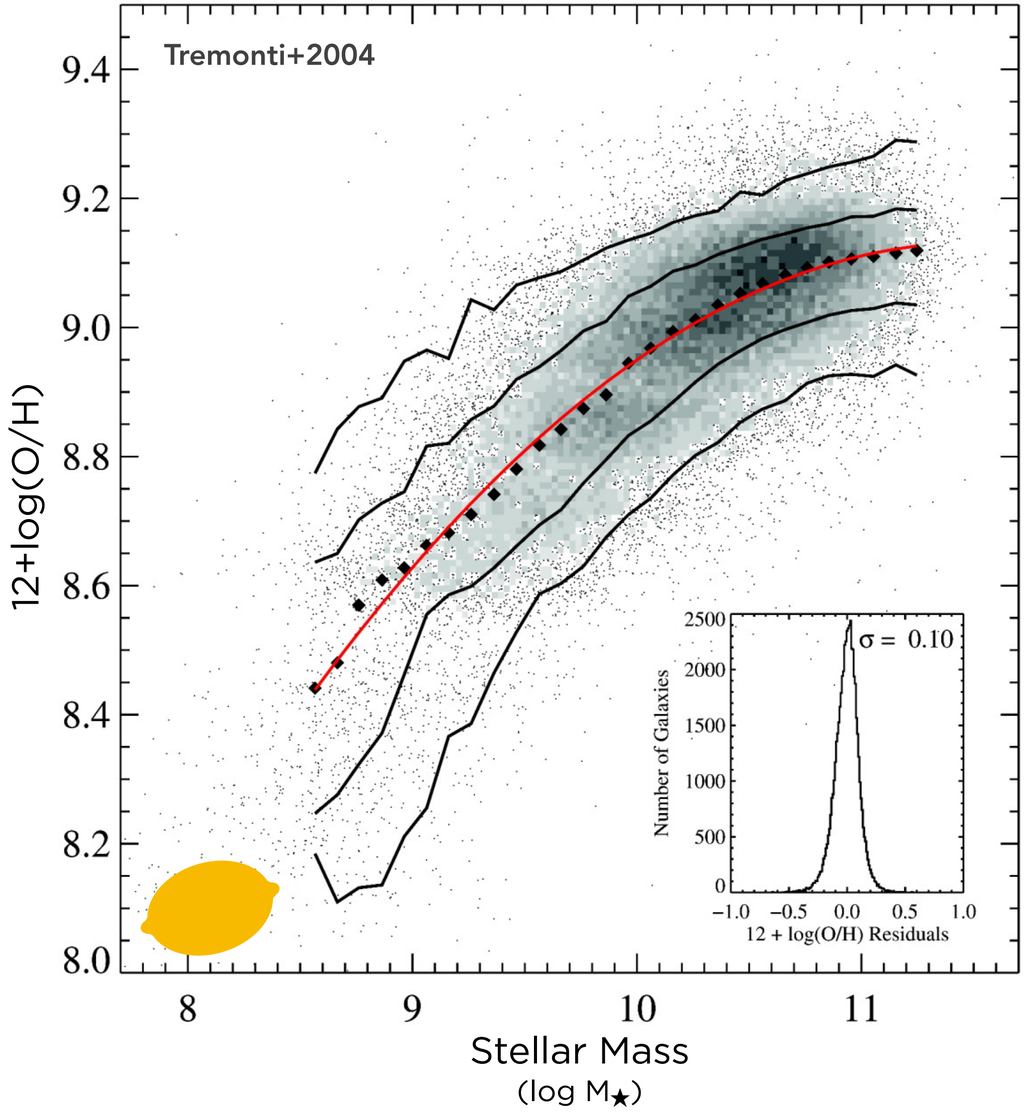
MIR Emission Lines

- Have **low** excitation **temps**.
- Have **low** critical **densities**
- **Span** full **ionization** range
- **Low** sensitivity to **dust**
- Sensitive to ionizing spectrum, gas temperature, density, dust attenuation (moderate)
- Utility: penetrates obscured regions, rarely observed low and high ionization species, traces warm molecular gas and PAHs

STRONG LINE ABUNDANCE METHODS

How does the ISM chemically enrich galaxies across cosmic time?

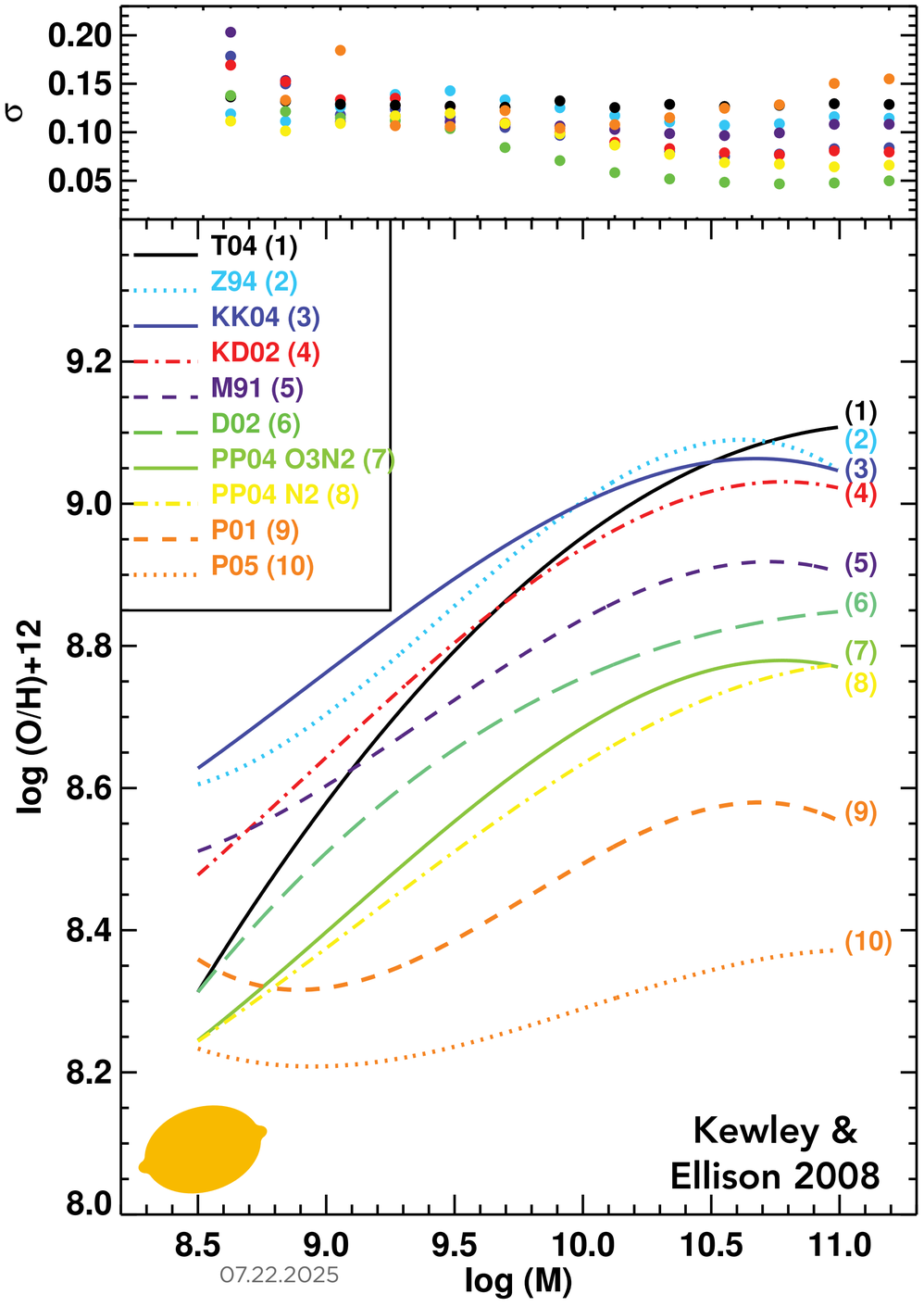
We can use **metallicity** to probe **galaxy evolution** on **global scales**



STRONG METHODS

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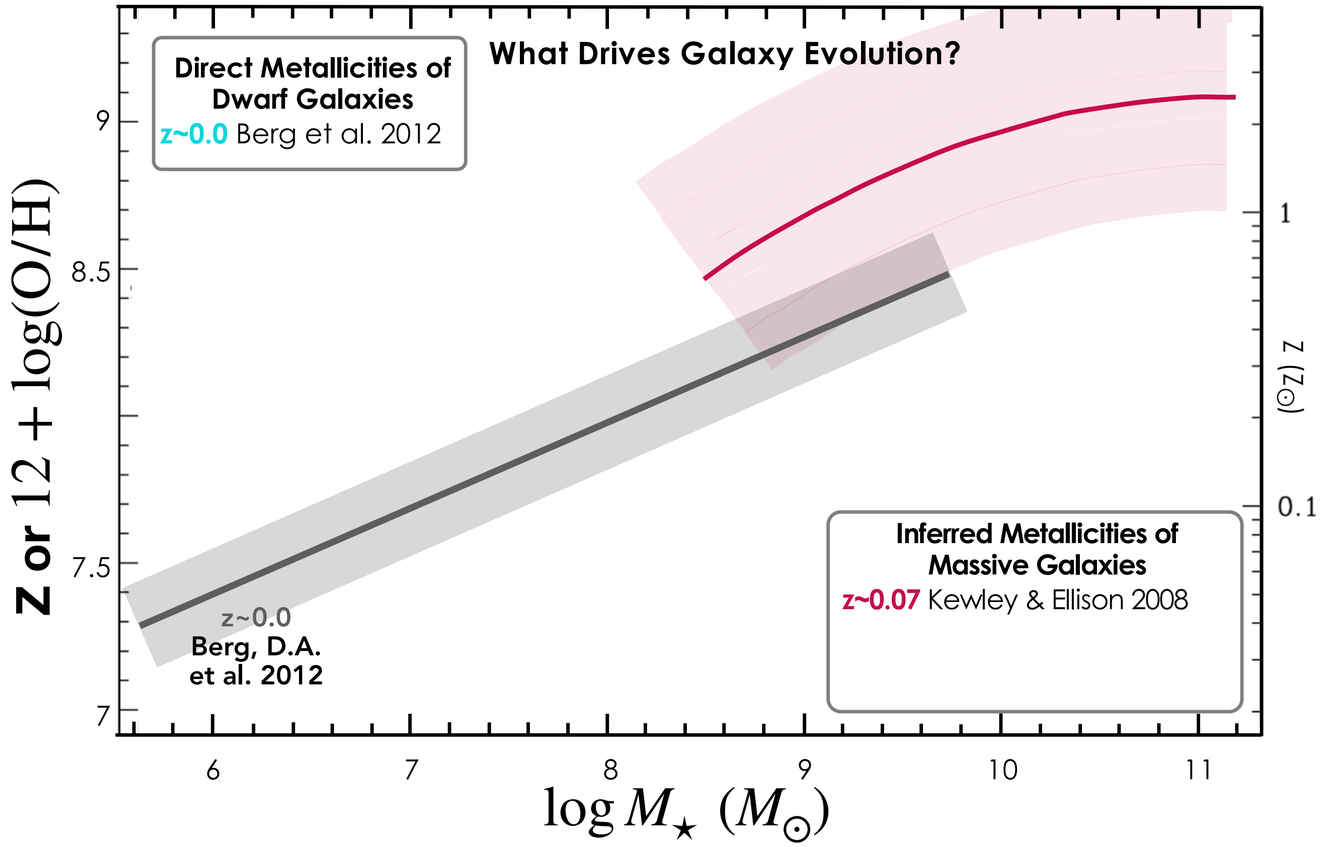
Can we trust strong-line calibrations?



THE MASS METALLICITY RELATIONSHIP

How does the ISM chemically enrich galaxies across cosmic time?

The mass-metallicity relationship (**MZR**) **encodes** important **evolutionary processes**

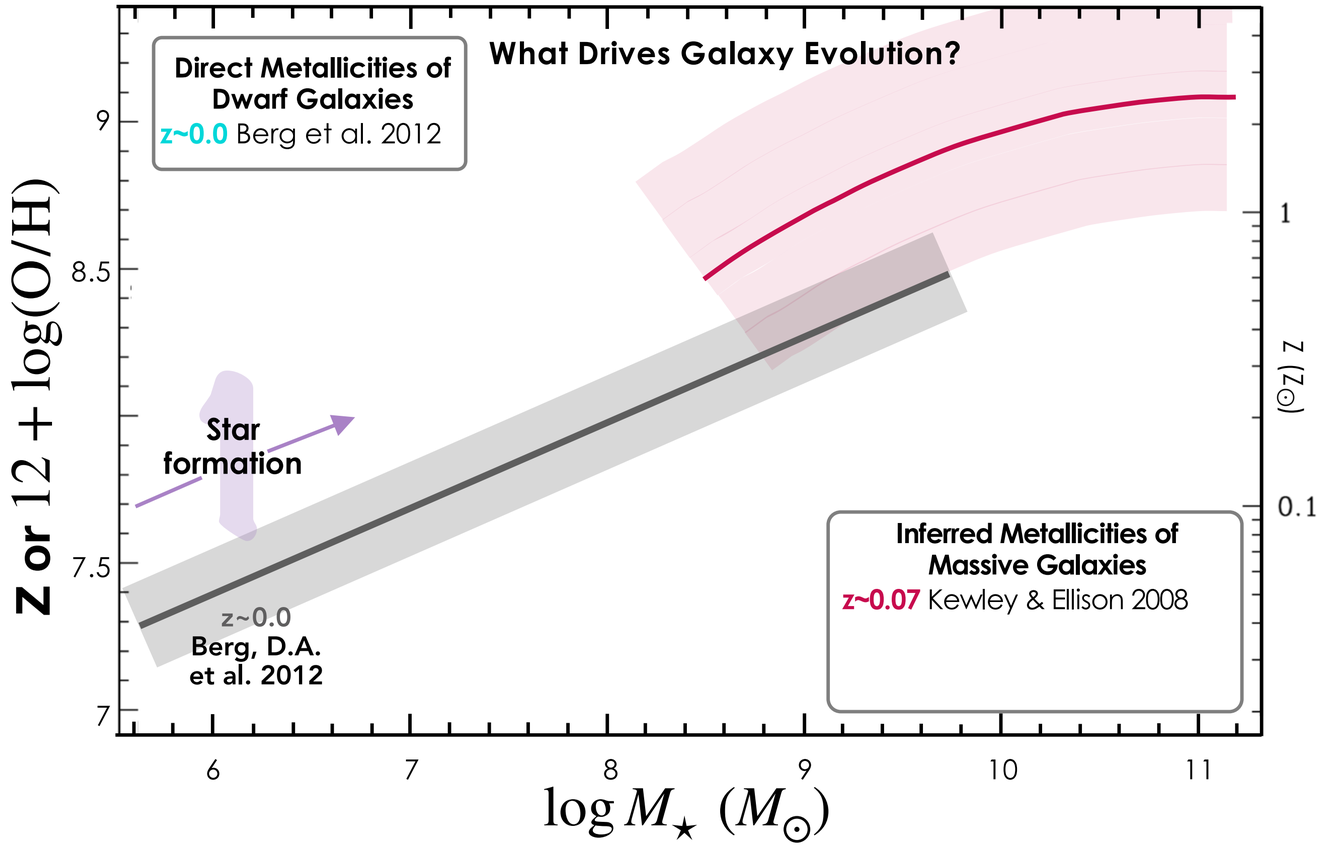




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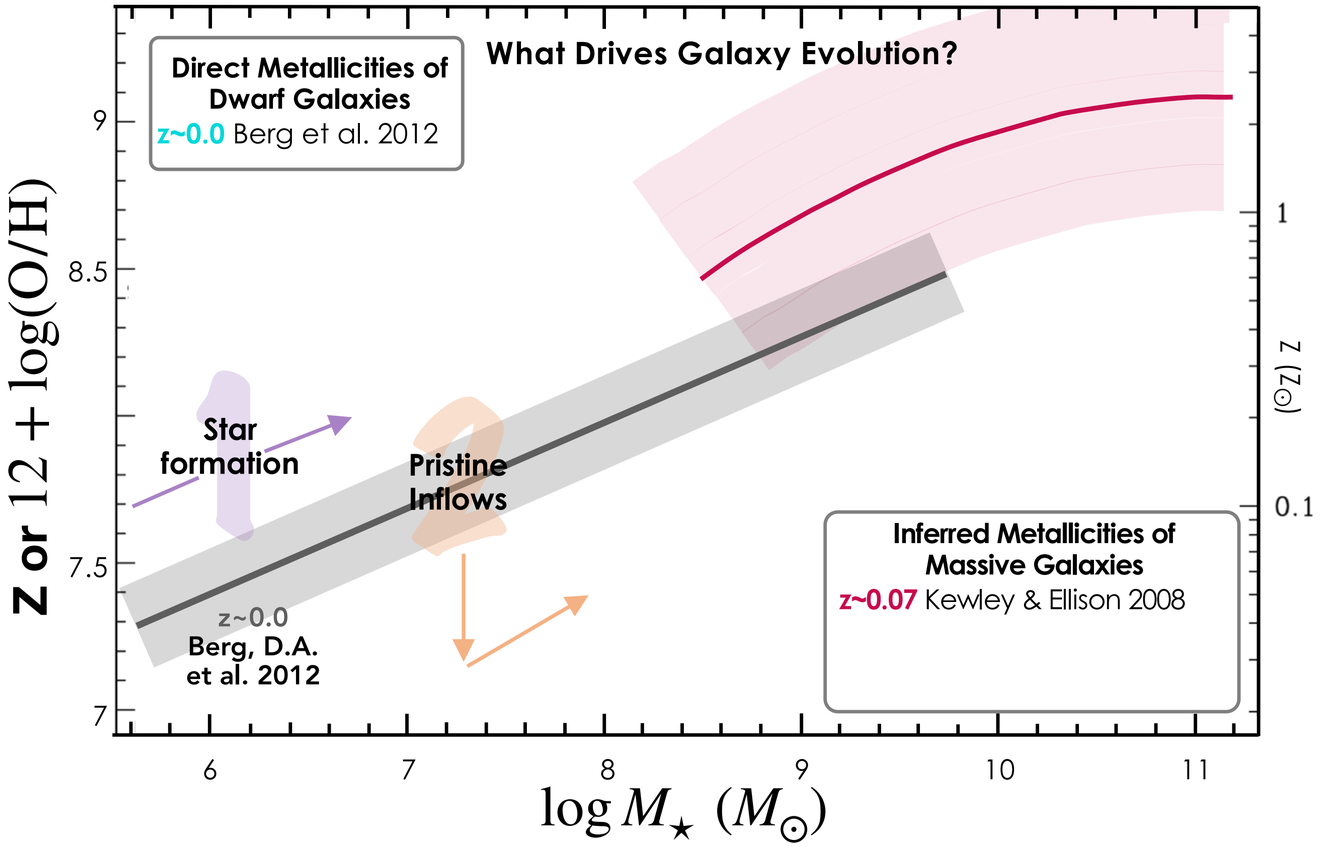




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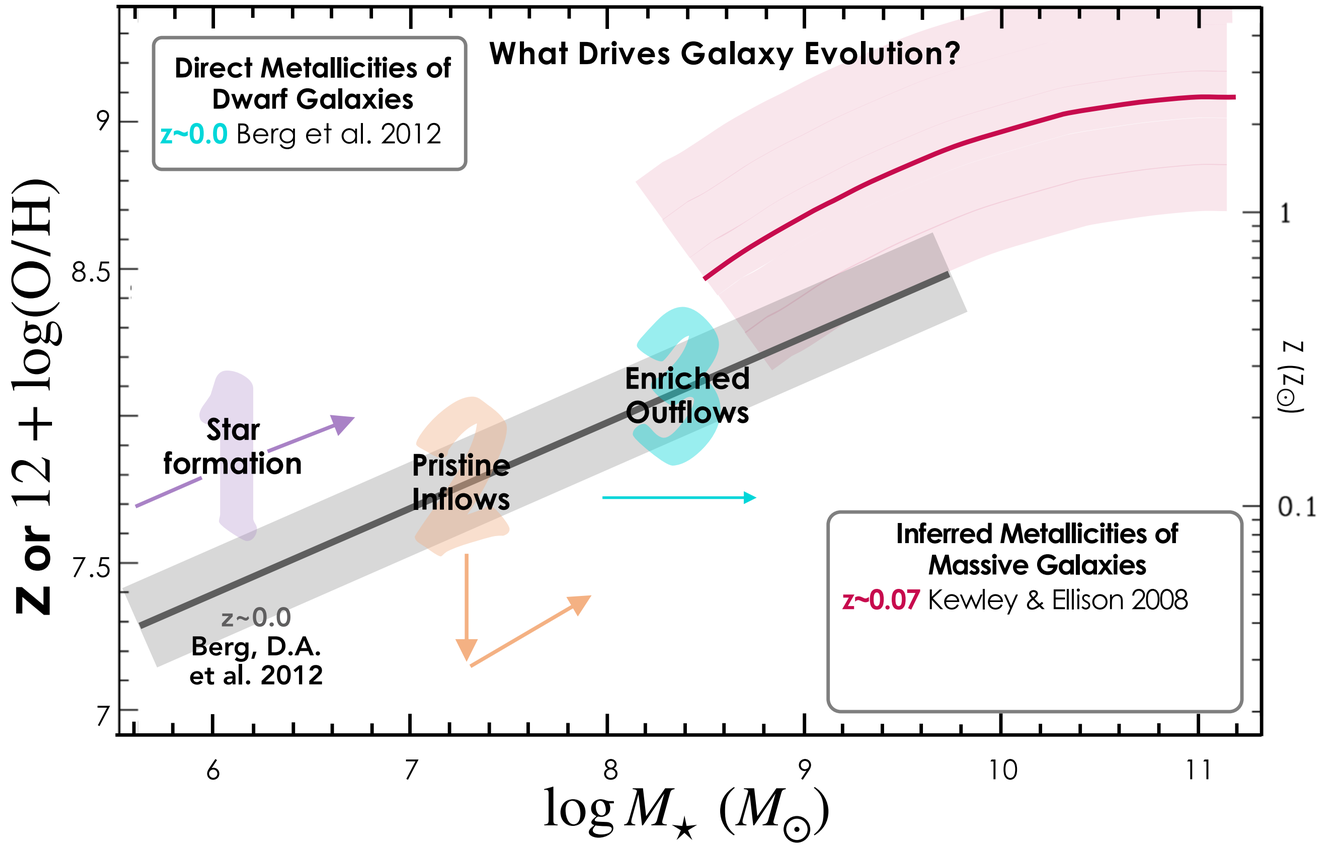





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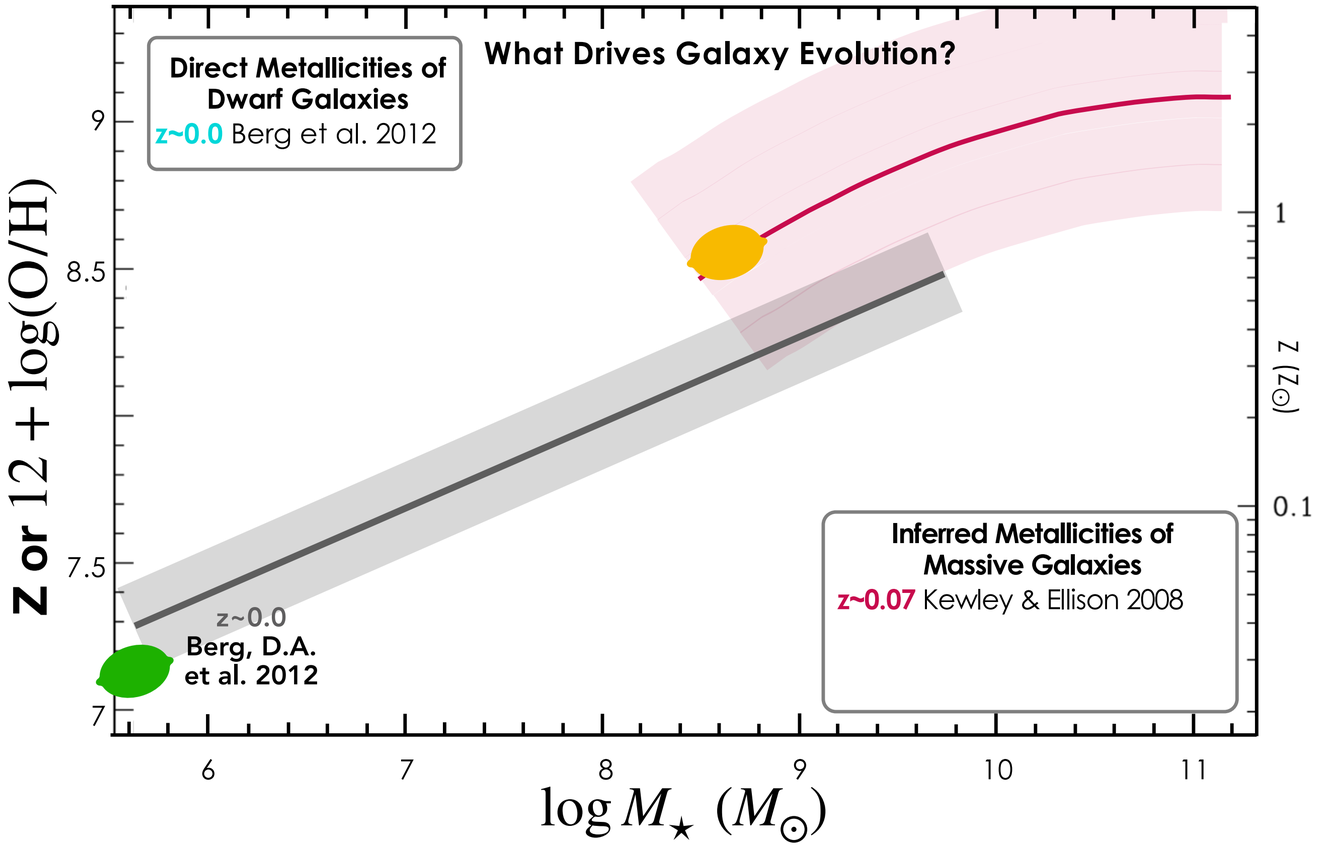

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No comparative direct-metallicity MZRs at z > 3.



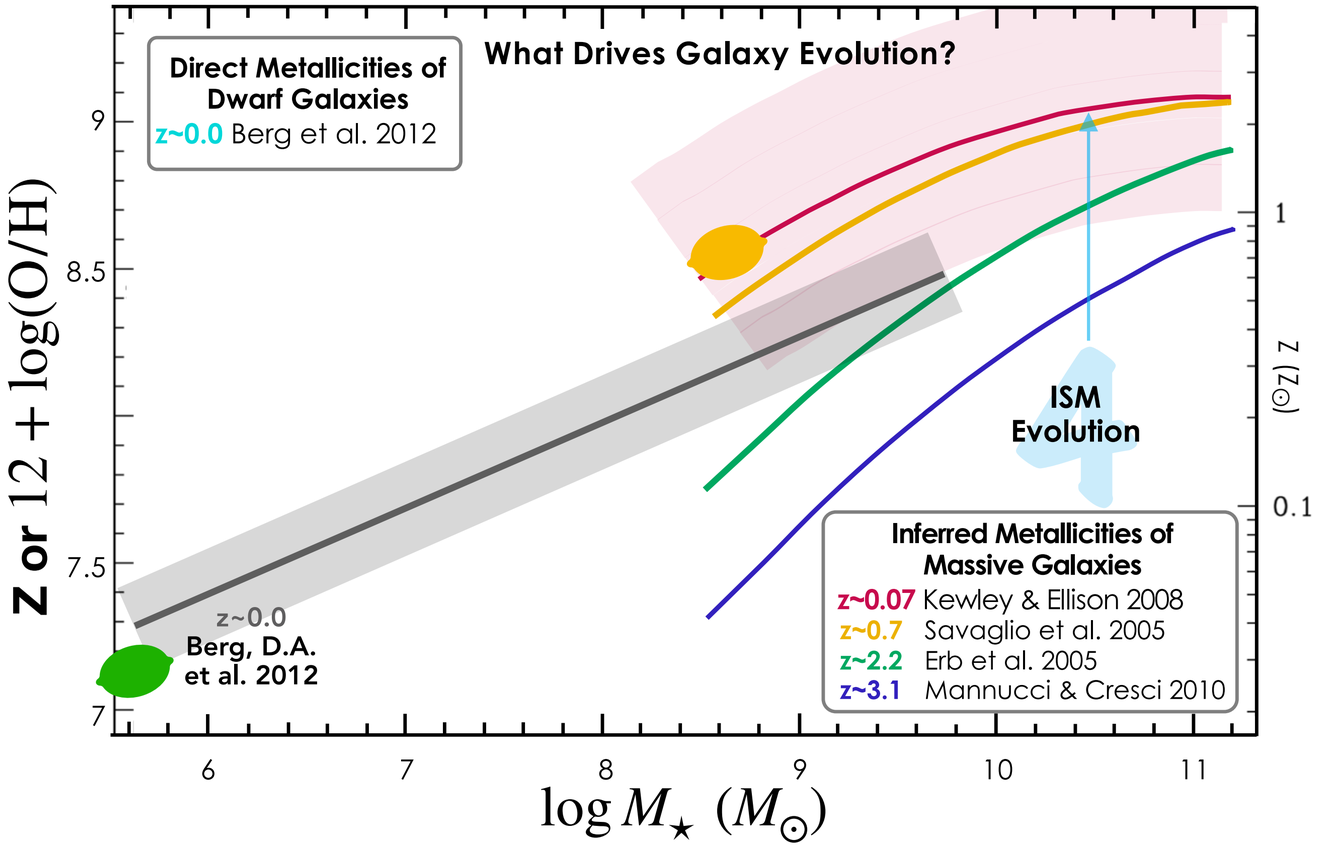
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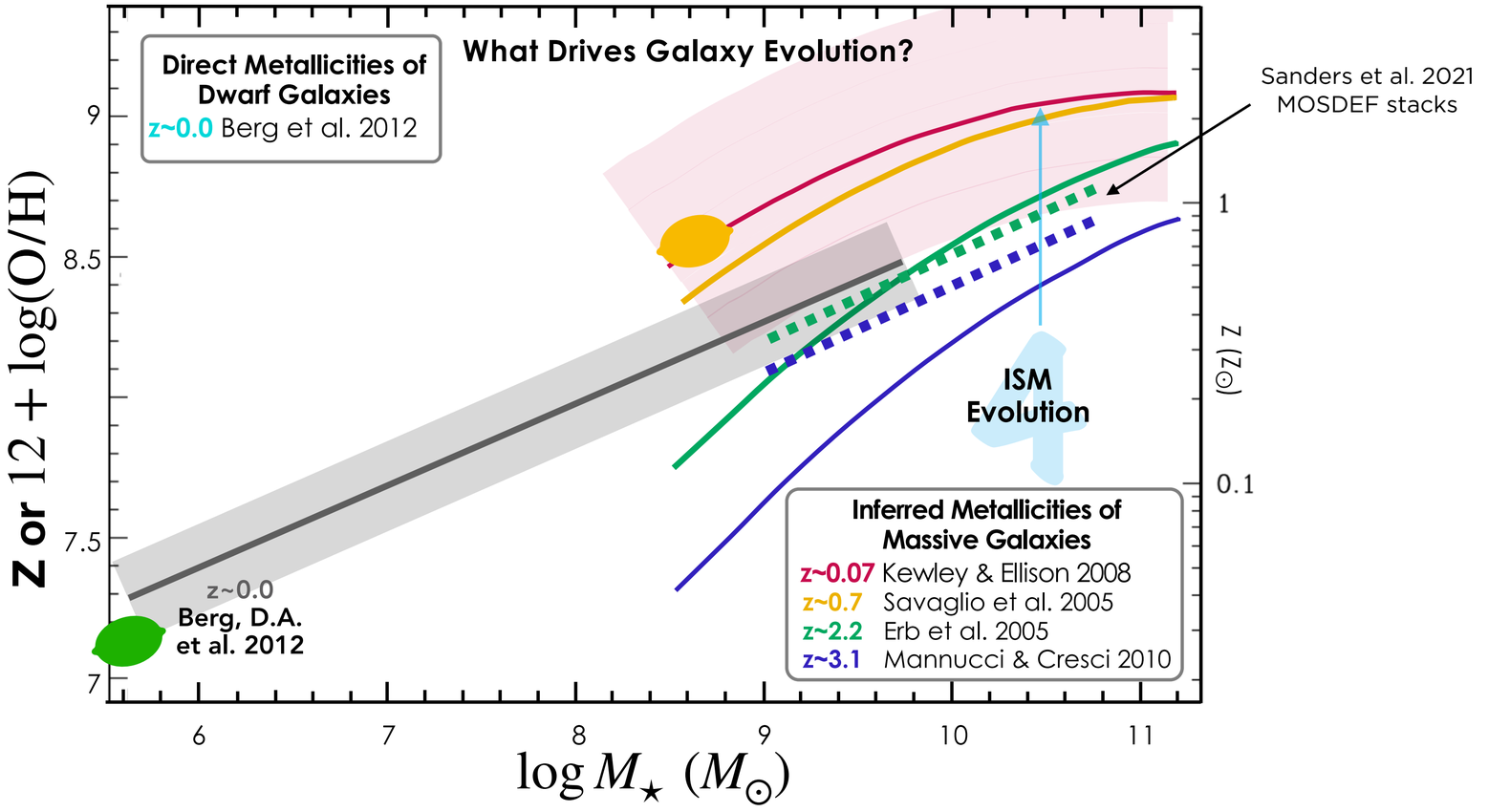
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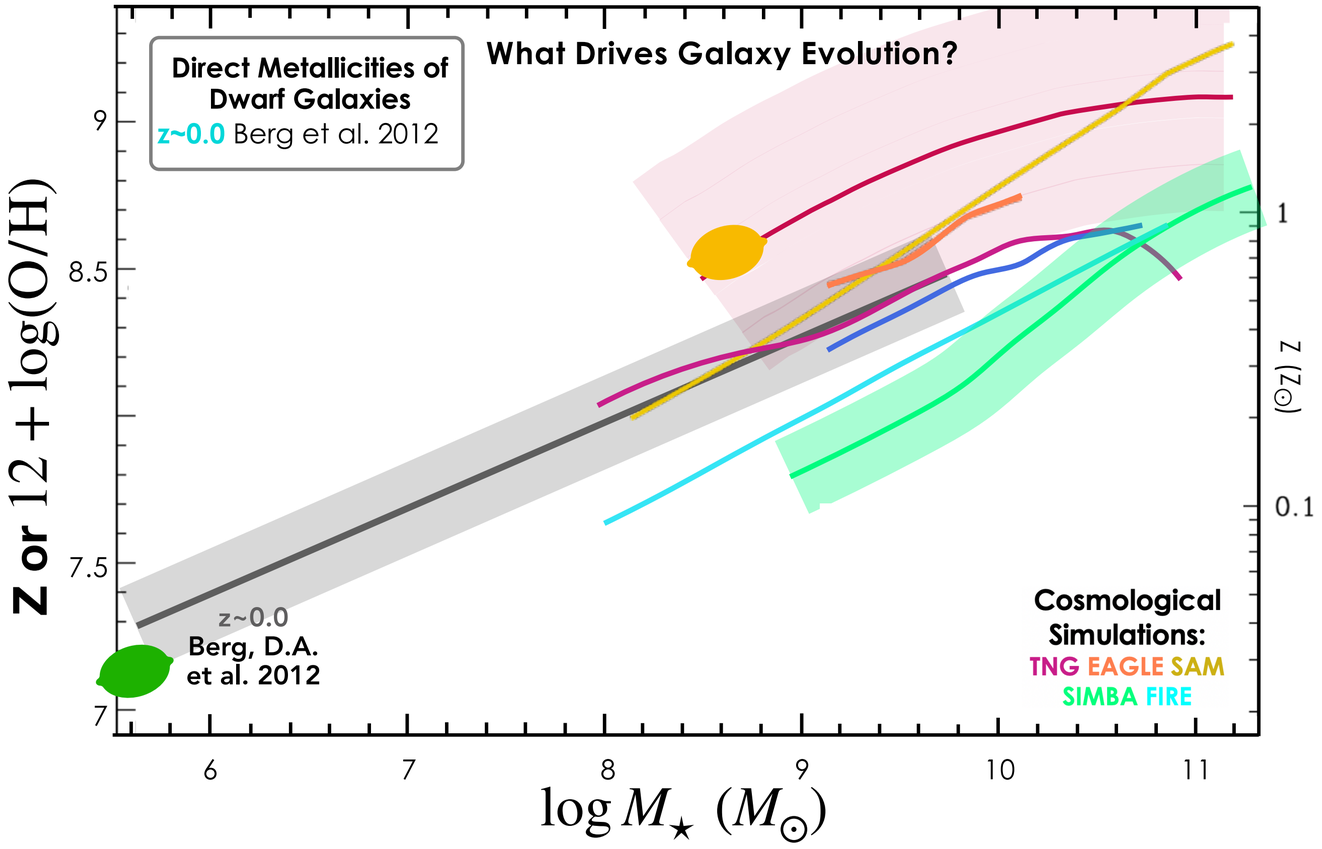
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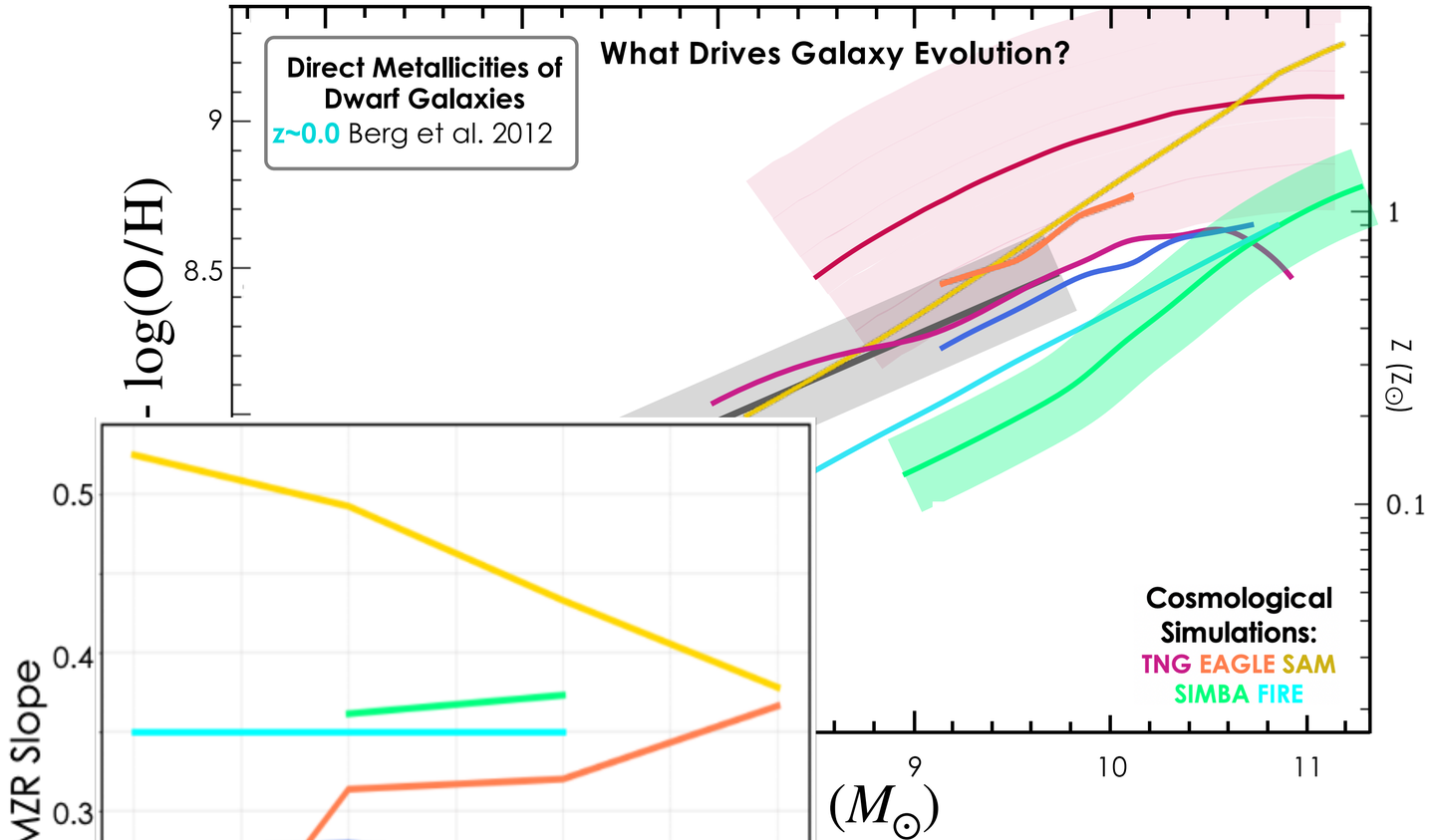


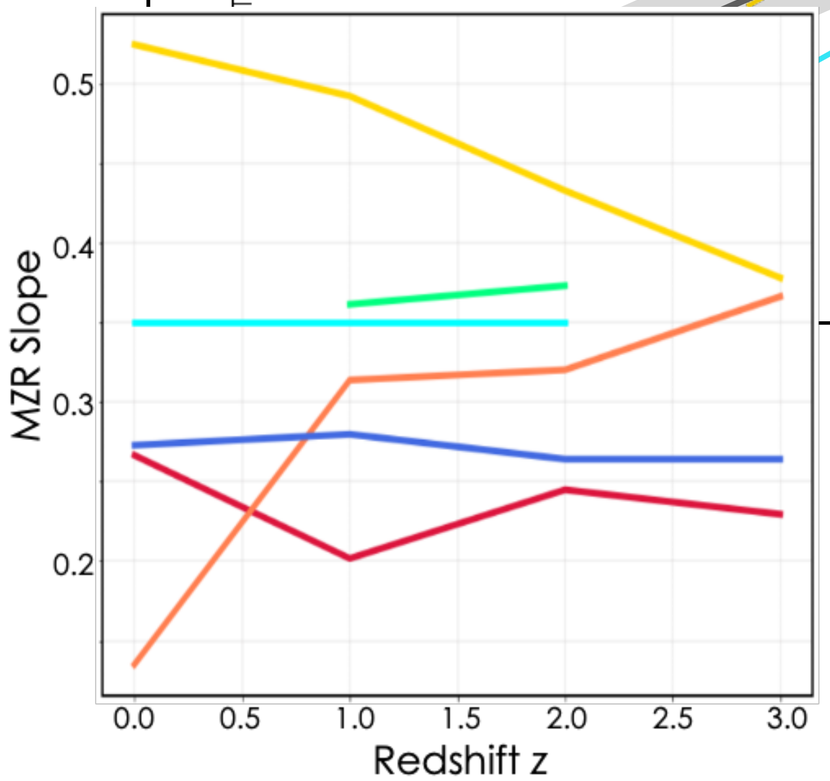
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JWST:
AURORA (PIs: R. Sanders & A. Shapley)
CECILIA (PIs: A. Strom & G. Rudie)
MARTA (PI: M. Curti)
NGDEEP (PIs: S. Finkelstein, C. Papovich, & N. Pirzkal)
PID 7729 (PI: G.Roberts-Borsani)





The **observed MZR slope** places tight constraints on the **type and strength of feedback** regulating the growth of galaxies

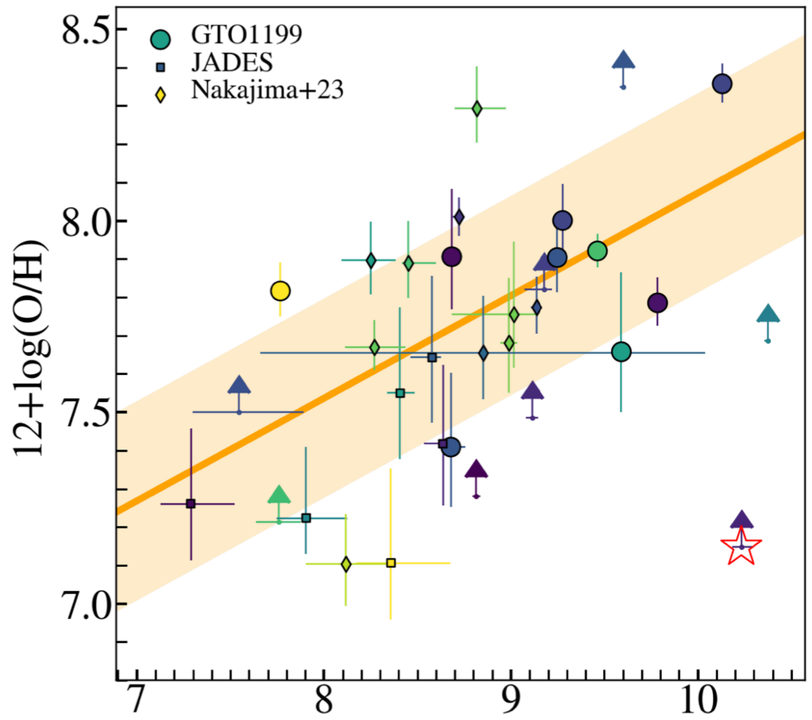
HIGH-Z

How does the ISM chemically enrich galaxies across cosmic time?

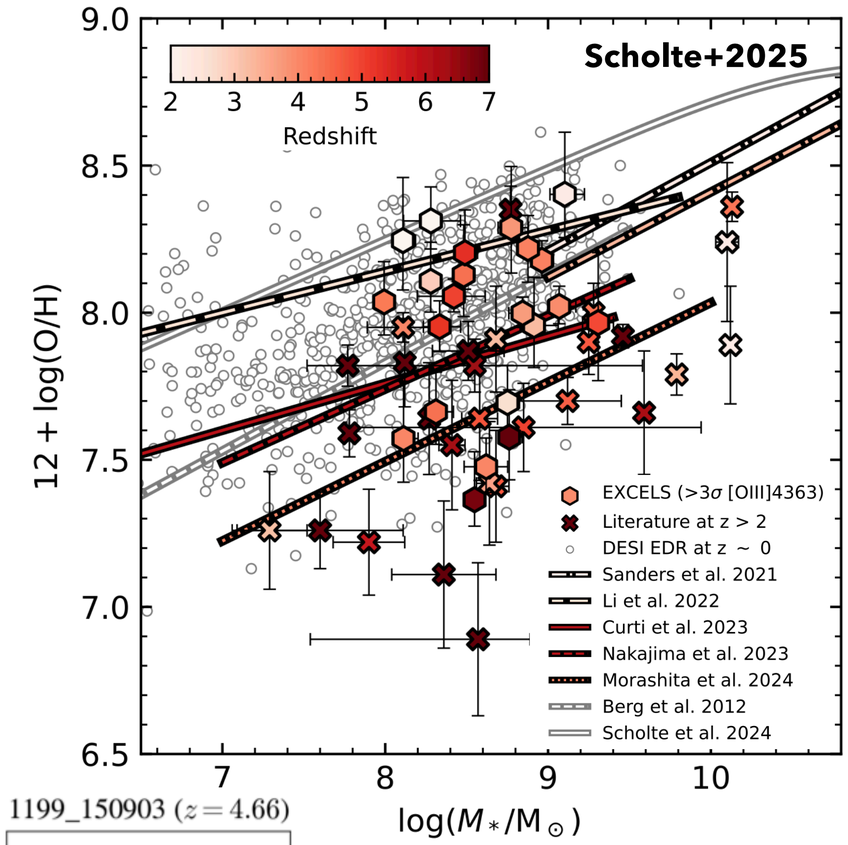
We now have a handful (~10) **direct-metallicity measurements at high-z** (z>6) with which to examine chemical evolution …

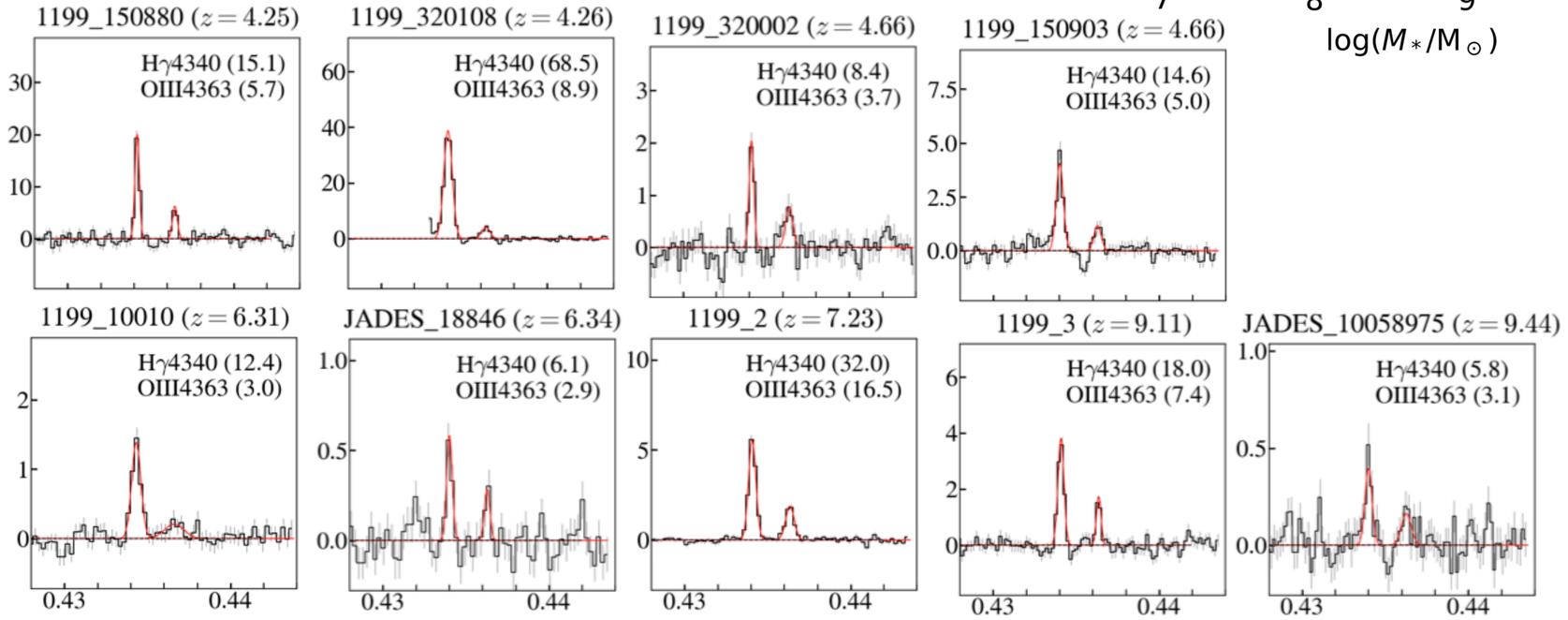
High-z is the chemical evolution frontier

See, also,
Chakraborty+2025,
Sanders+2024,
Arellano-Cordova+2023,
Langerood+2023



Morshita+2024

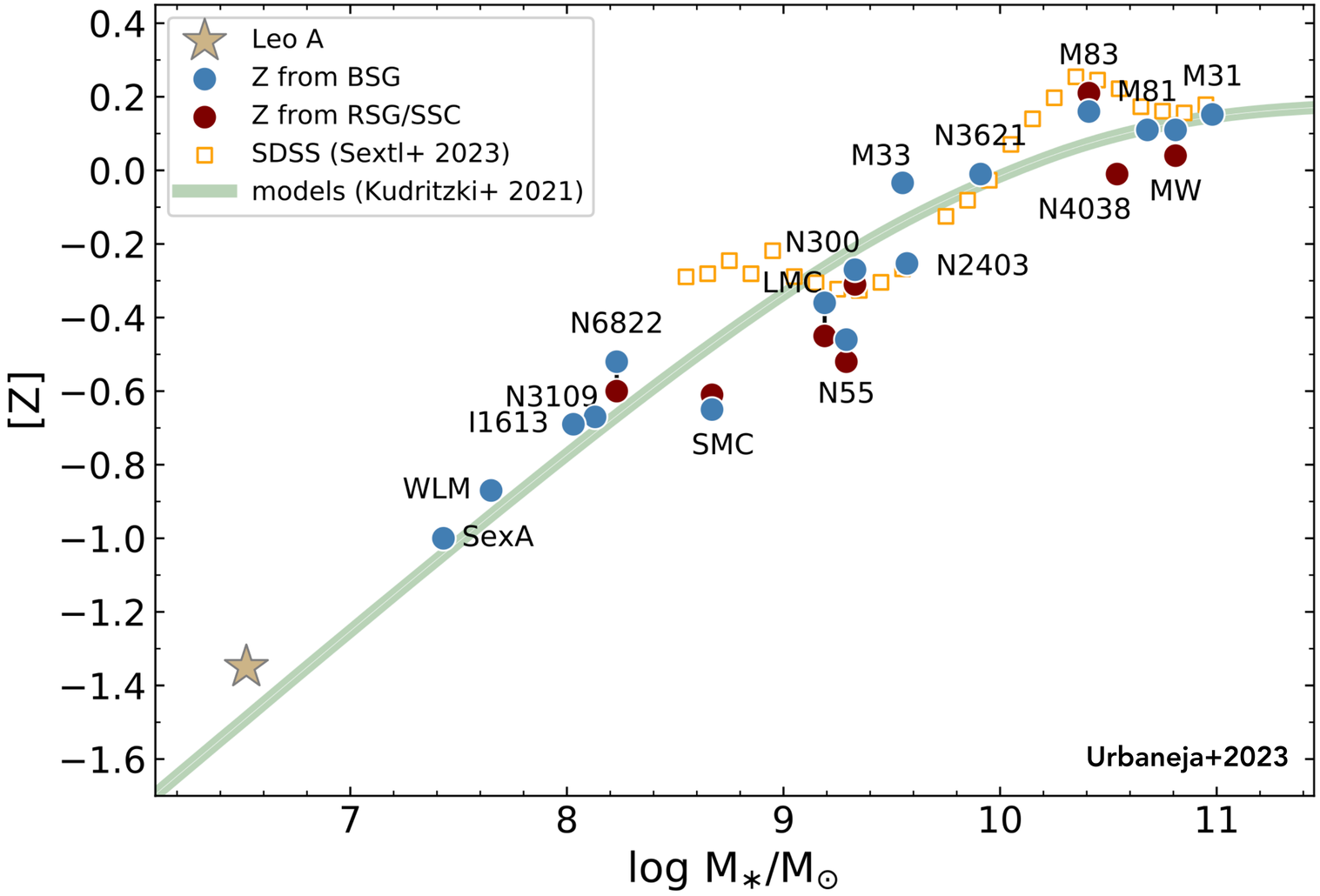




THE STELLAR MZR

How does the ISM chemically enrich galaxies across cosmic time?

There is a **good agreement between the massive-star and gas-phase MZR,** confirming a **universal MZR** in the **low-z** Universe**.**

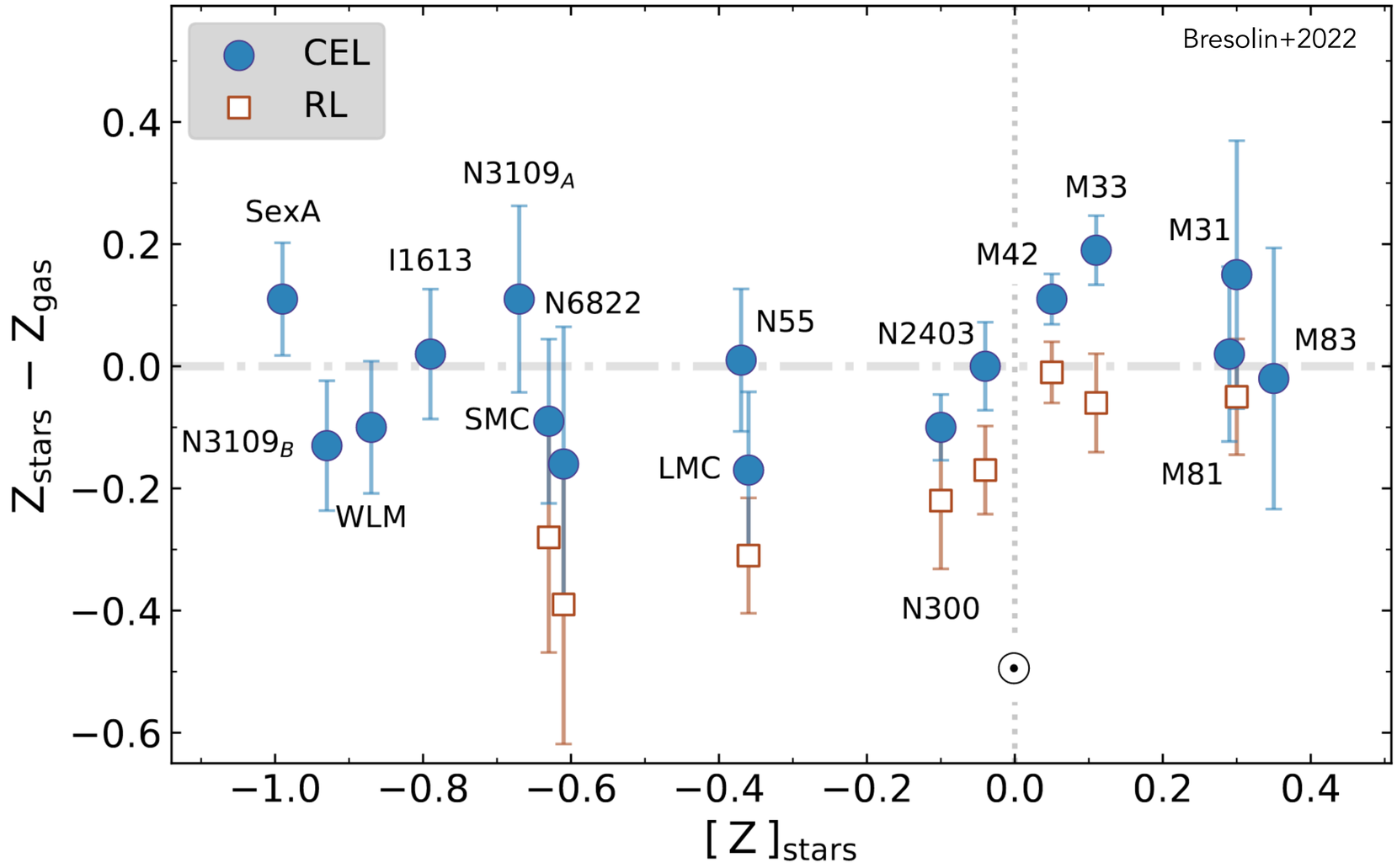


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CEL **direct-abundances agree well with stellar abundances** below solar.



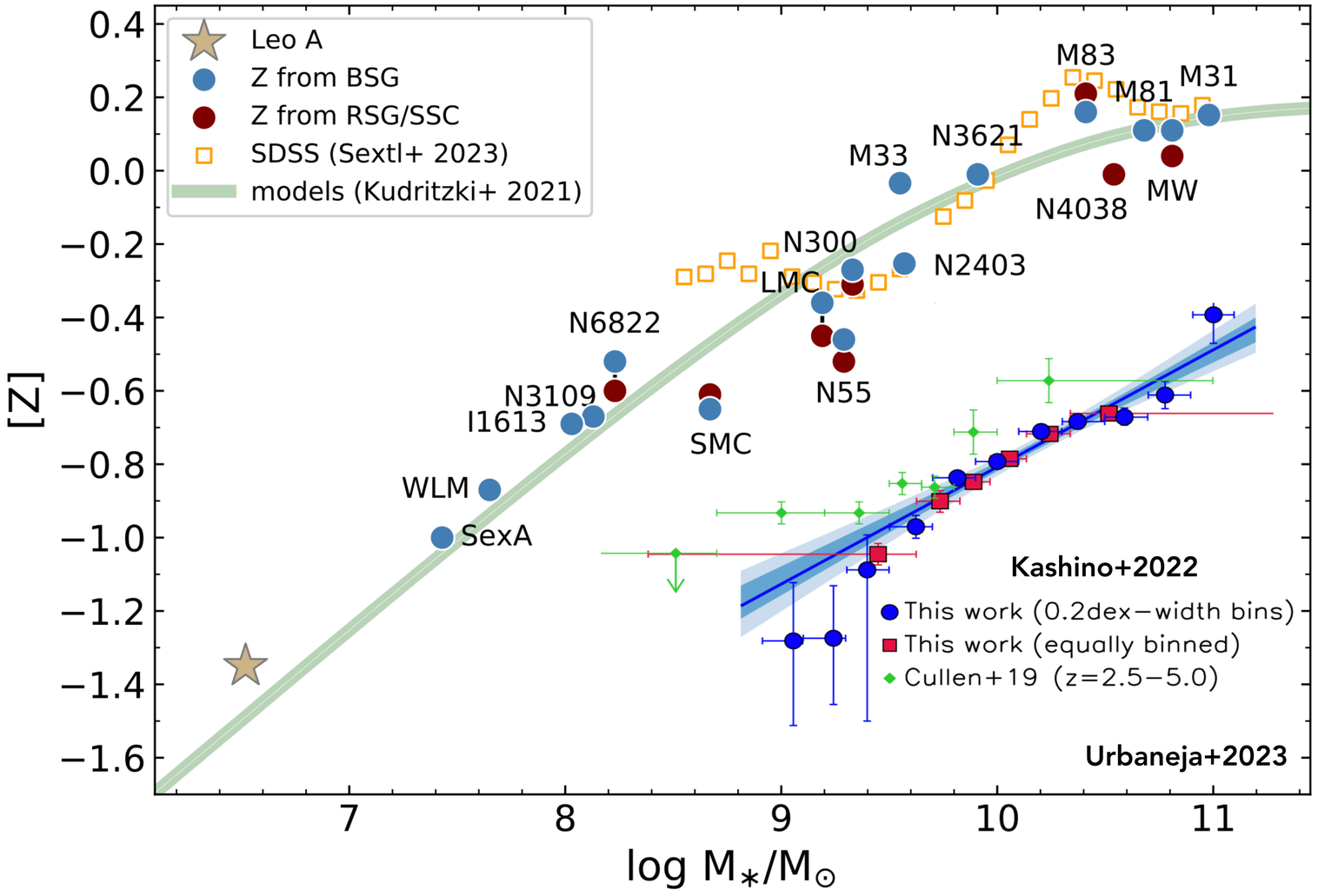
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There is **tension at cosmic noon** between stellar and gas abundances …

But **SFHs are very uncertain** and constant vs bursty SFHs give very different results



THE STELLAR VS NEBULAR MZR EVOLUTION?

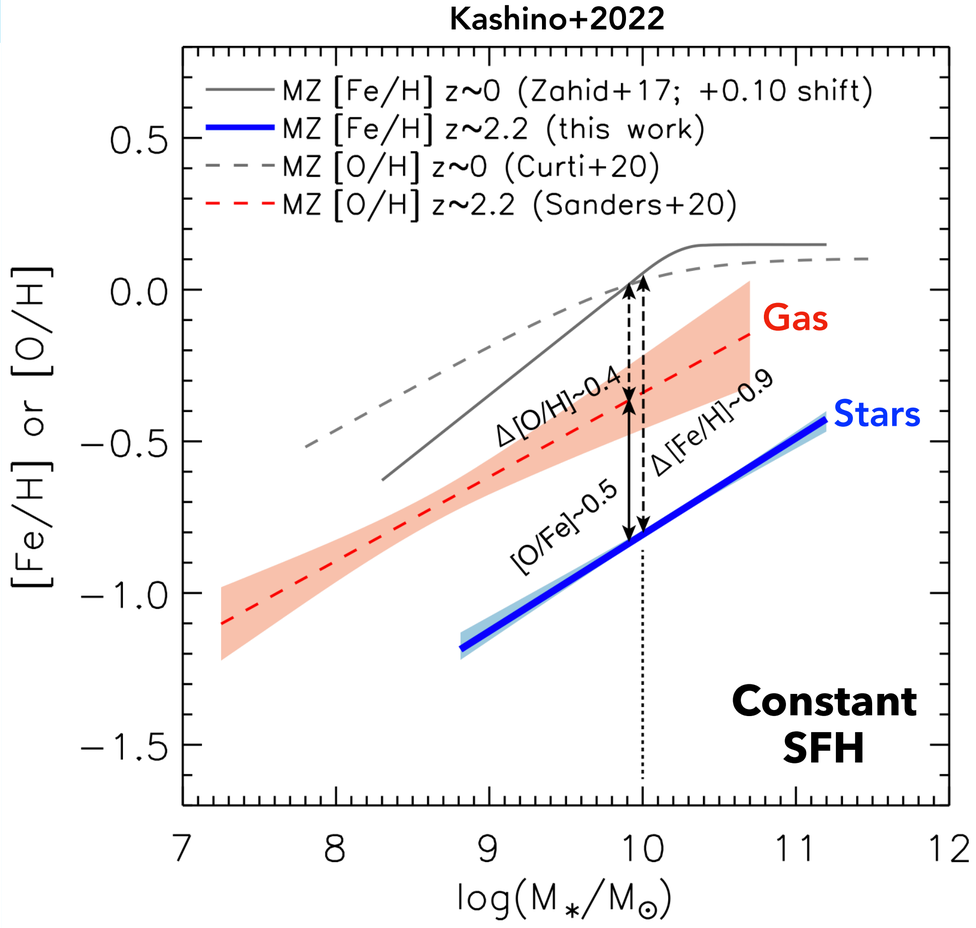
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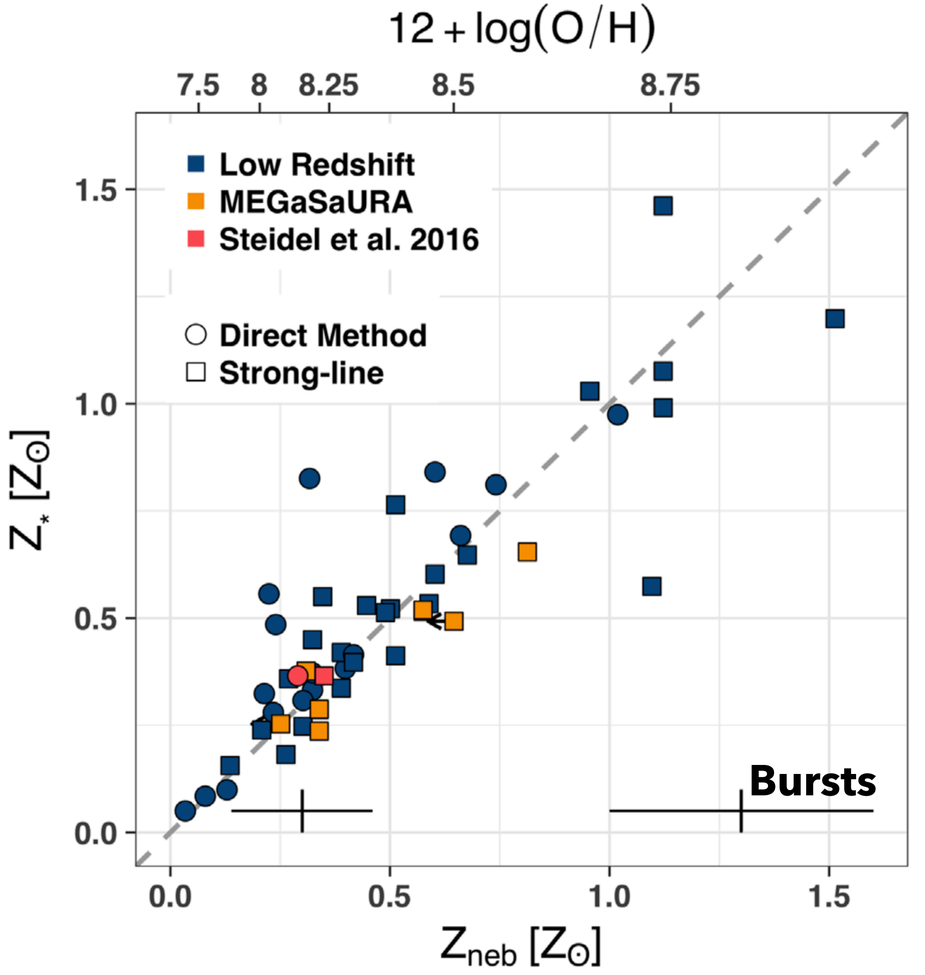
There is a **good agreement between the massive-star and gas-phase MZR,** confirming a **universal MZR** in the **low-z** Universe**.**

There is **tension at cosmic noon** between stellar and gas abundances …

But **SFHs are very uncertain** and constant vs bursty SFHs give very different results

Kashino+2022





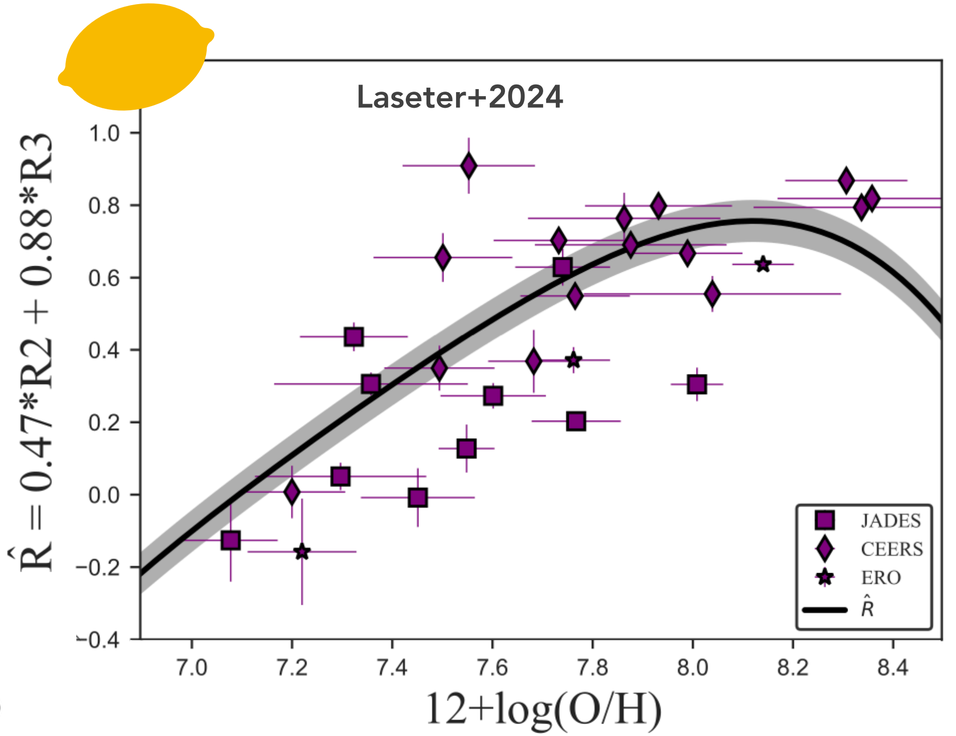
Chisholm+2019
(see, also, e.g. Cullen+2019)

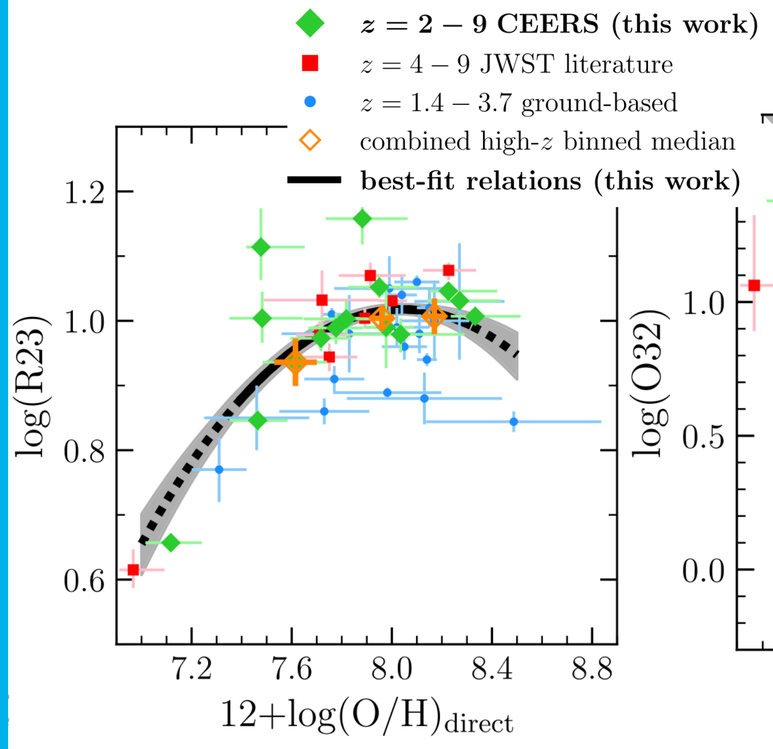
SL RATIO EVOLUTION

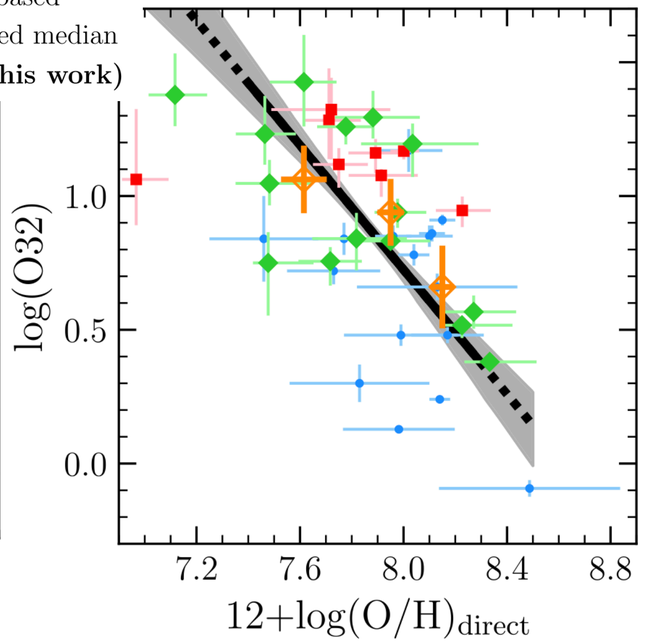
How does star formation chemically enrich the ISM across cosmic time?

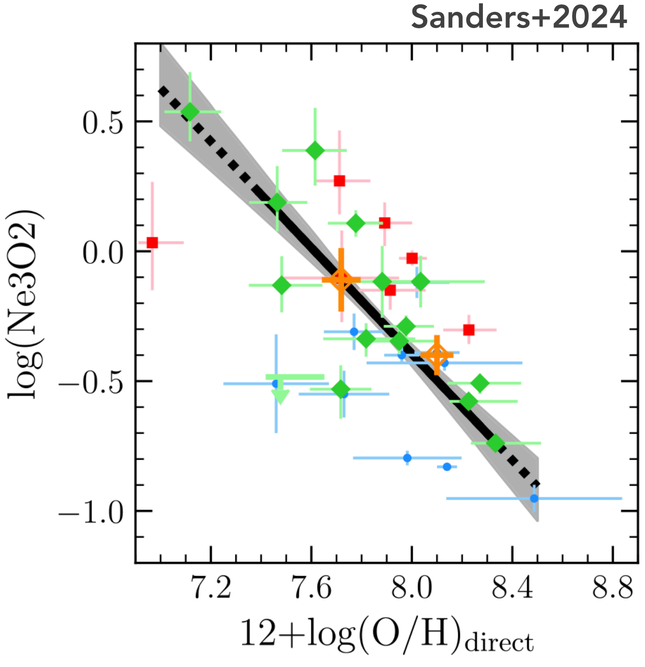
High-z metallicity diagnostics need to be recalibrated to appropriate conditions to probe galaxy evolution on global scales …

See, also, Nakajima+2023







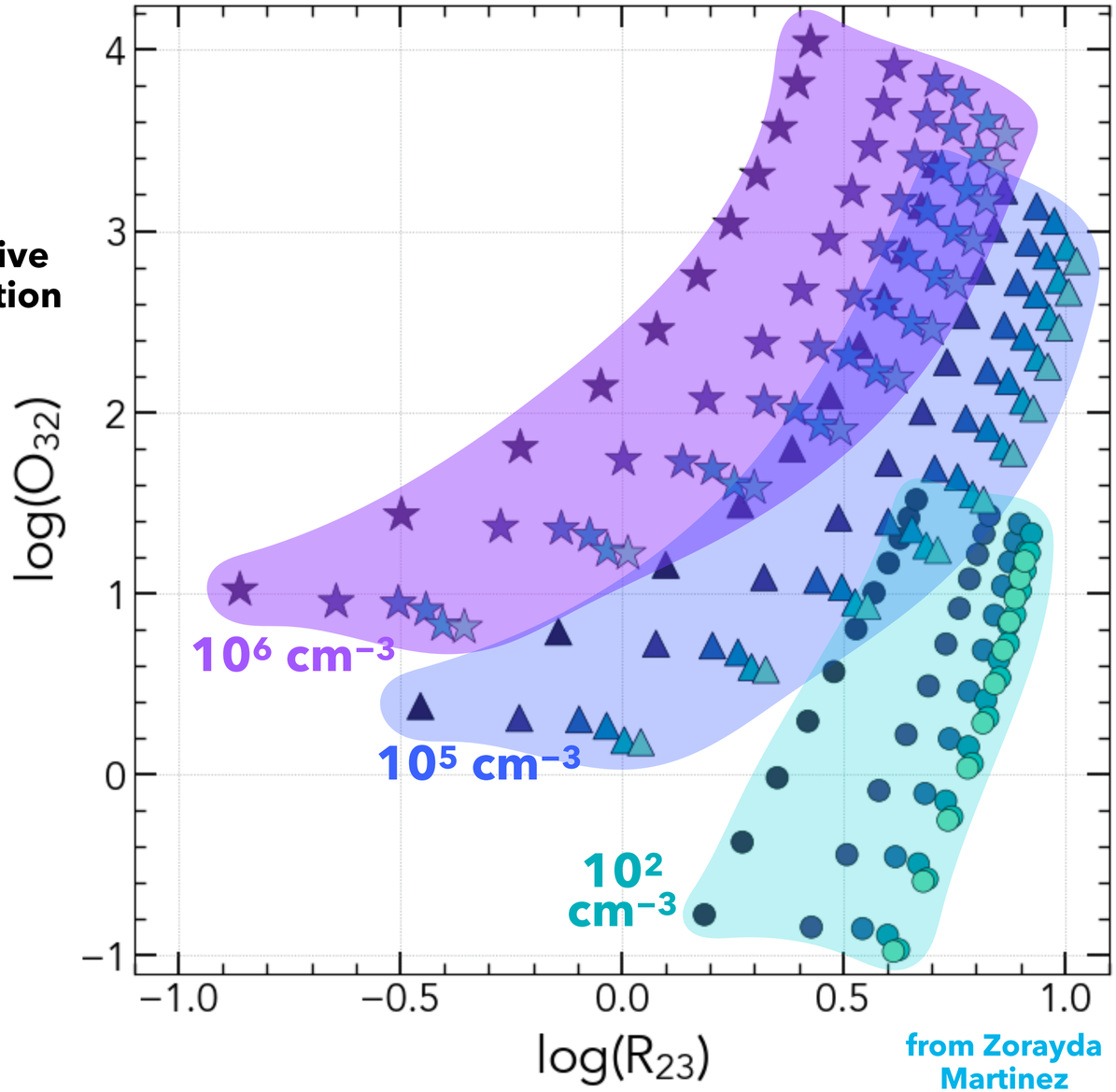


DENSITY EFFECTS ON ISM MEASUREMENTS

HIGH DENSITIES BIAS SL RATIOS

$n_{e,crit}$([OIII] λ5007) = 7.8×10^5 cm^{-3}

[OIII] starts to be **sensitive to collisional de-excitation** at $n_e > 10^4$ cm^{-3}



How does star formation chemically enrich the ISM across cosmic time?

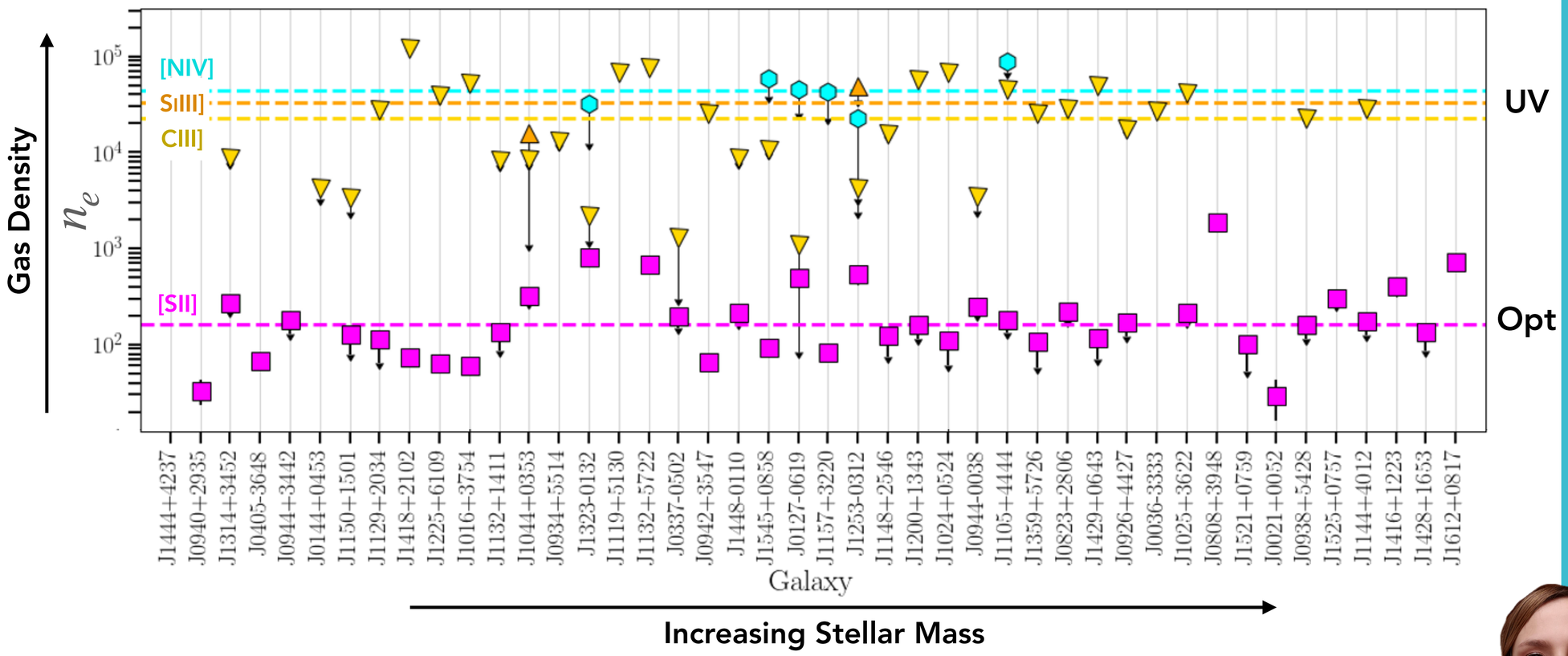
SL ratios are sensitive to high gas densities

High-z metallicity diagnostics need to be recalibrated to appropriate conditions to test whether we are seeing evolution on global scales …

The COS Legacy Spectroscopic SurveY

DENSITY STRATIFICATION

see, also, e.g., Hainline+09, Maseda+17, Berg+18, Berg+21



In the local universe:

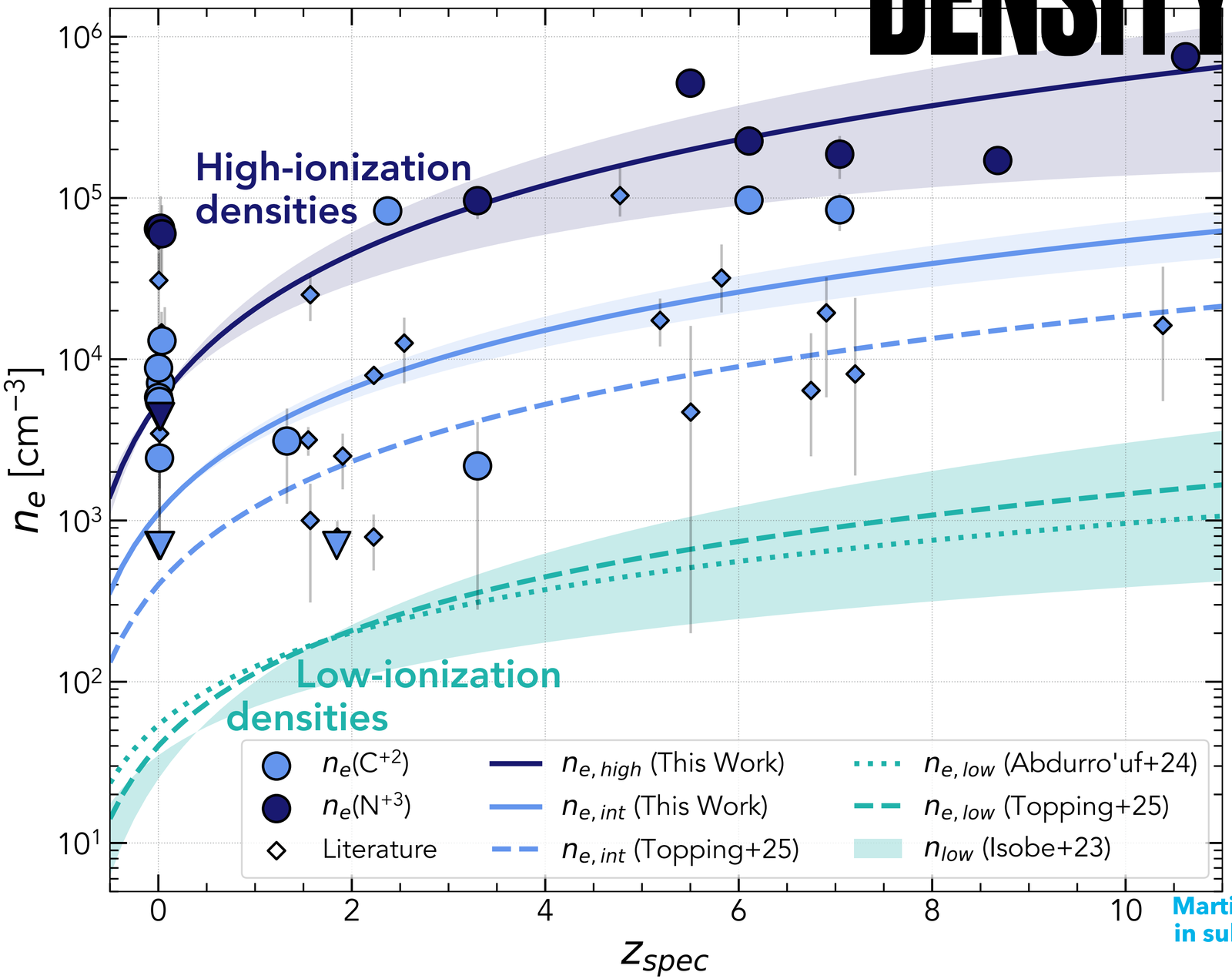
Gas densities in the **high-ionization zone** are **higher** than the **low-ionization zone** by 1-2 dex on average



Matilde Mingozzi
STScI Astronomer

Danielle A Berg
COSMIC FRONTIER CENTER
TEXAS
The University of Texas at Austin

DENSITY STRATIFICATION



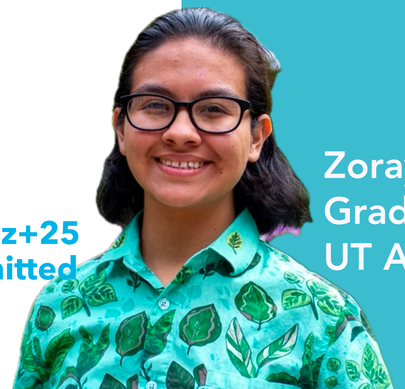
Gas densities in the **high-ionization zone** are **significantly higher** than the **low-ionization zone**

and

Gas densities are **higher** at **high-redshift**

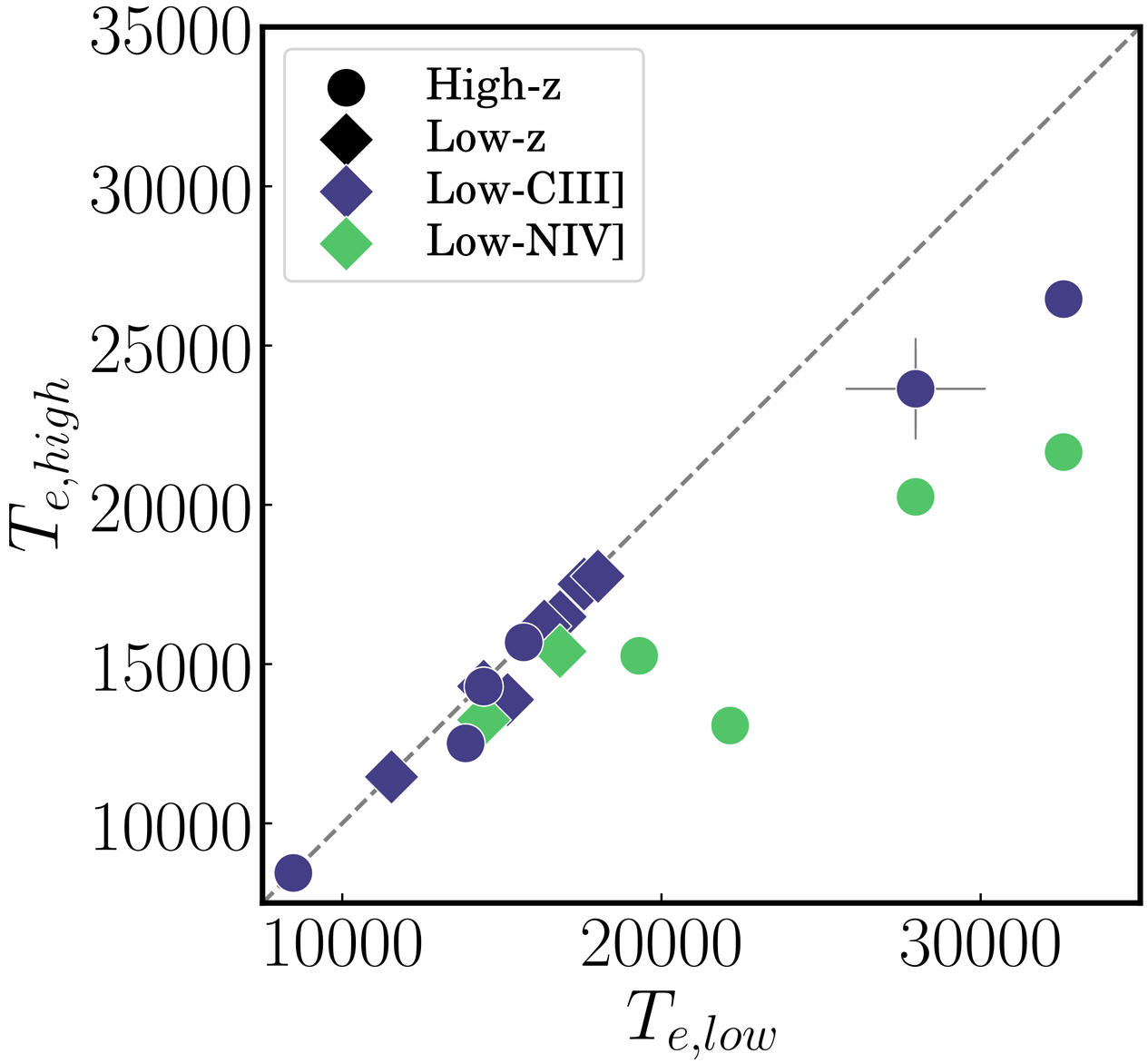
NIV] densities are >2x higher than CIII] densities

Martinez+25 in submitted



Zorayda Martinez
Graduate Student
UT Austin

HIGH DENSITIES BIAS TEMPERATURES

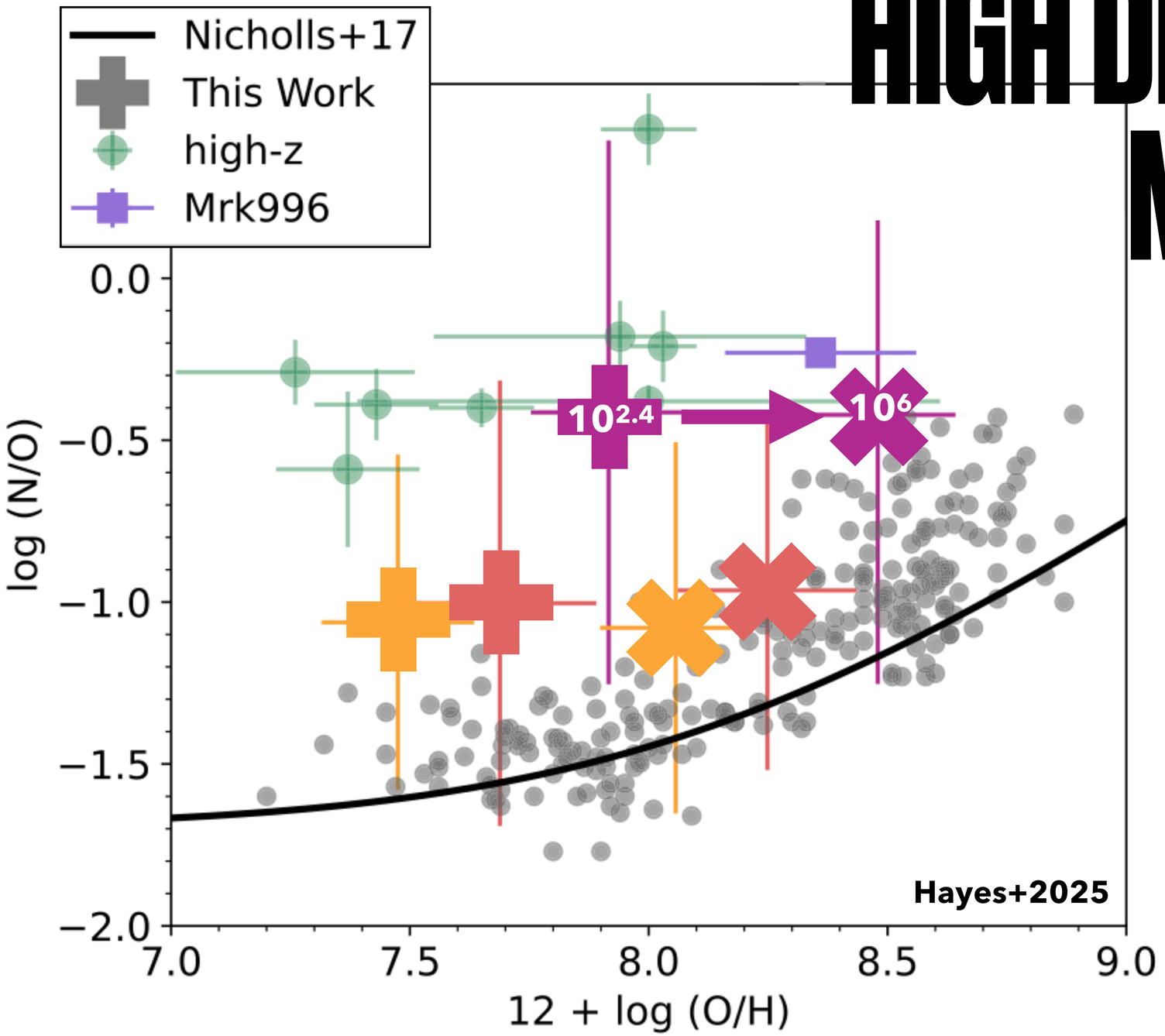


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COS
FRO
CEN

HIGH DENSITIES BIAS METALLICITIES



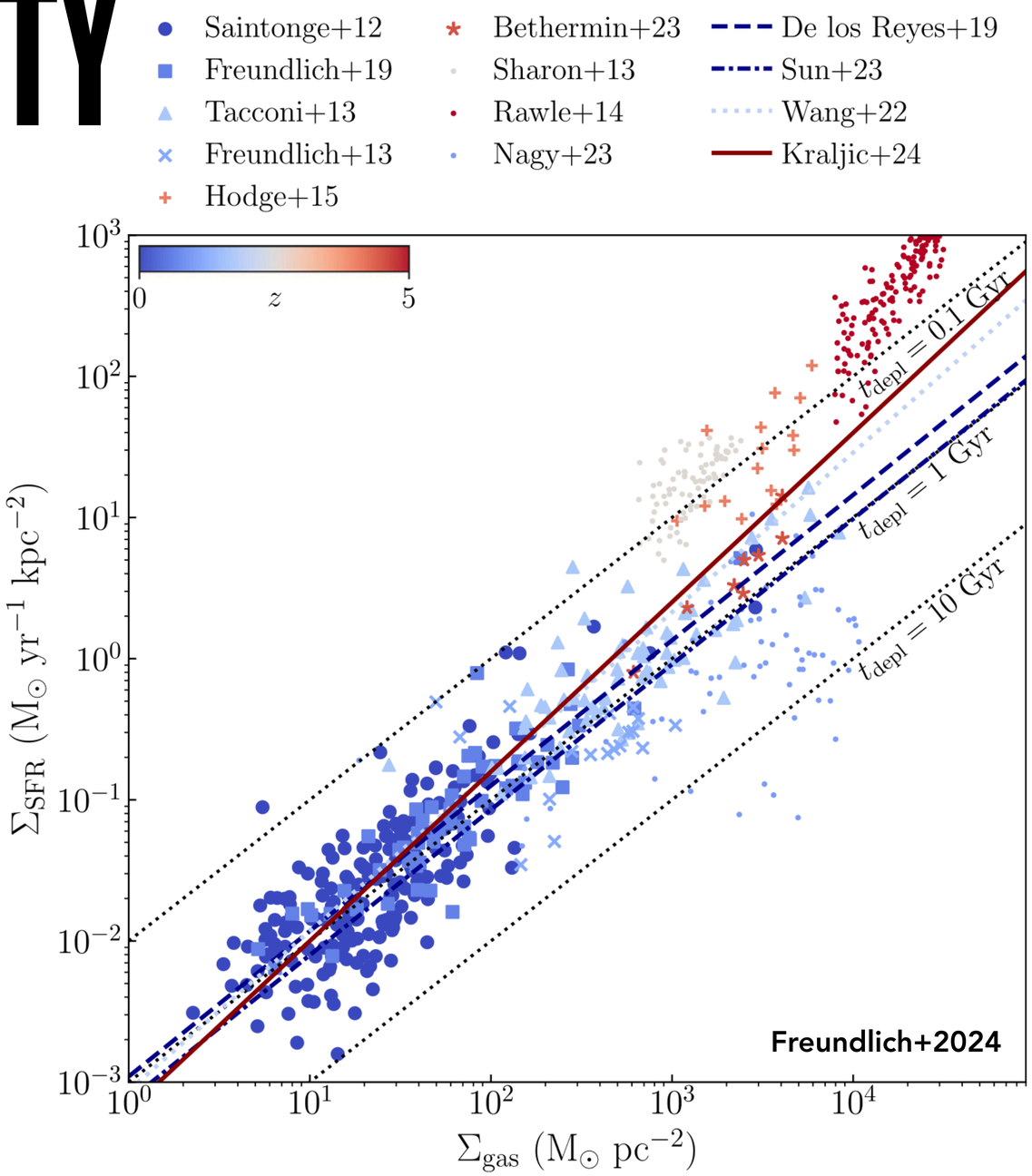
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GAS SURFACE DENSITY EVOLUTION

Gas conditions are evolving with significantly higher gas and SFR surface densities at z>5

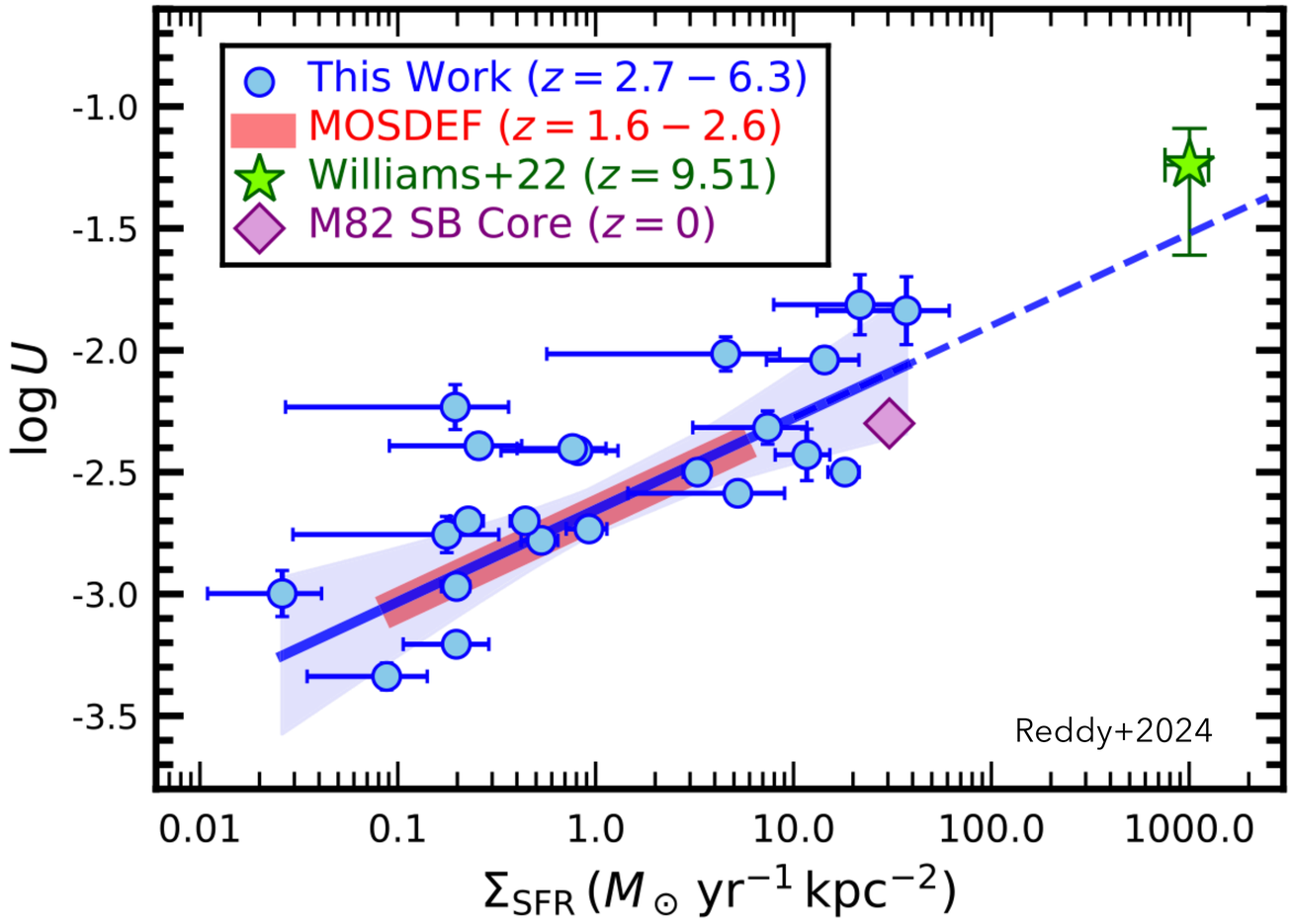
See, also, e.g., Nakajima & Ouchi 2014, Matthee+2022, Katz+2023, Sanders+2023, Trump+2023, Lu+2025



IONIZATION PARAMETER EVOLUTION

A **strong, redshift-invariant correlation** is found between **log U** and Σ_{SFR} from z ≈ 1.6 to 6.3 (and possibly to z ~ 9.5). Reddy+2024

Implies that **gas density** and **ISM pressure** are key in setting the ionization conditions in galaxies across cosmic time.



DUST IN THE ISM

DUST DEPLETION

Some **elements** can be **significantly locked up** in dust …

So understanding **dust depletion** is **important** for detailed **abundance determinations**

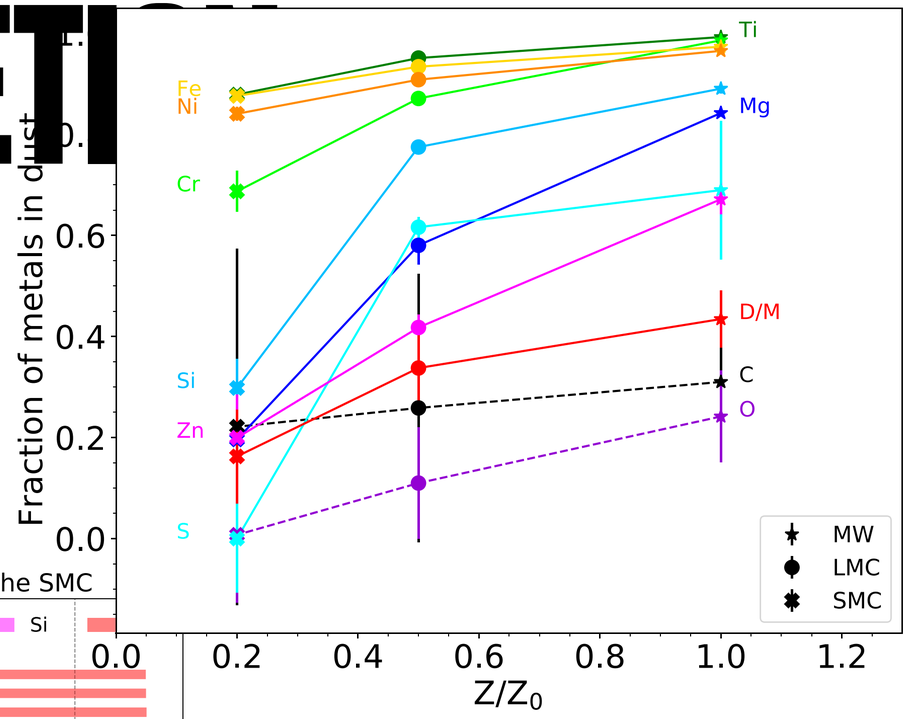
Jenkins et al. 2009 examined how gas-phase elemental depletions vary across different environments using UV absorption lines toward 243 sightlines, comparing observed gas-phase column densities to Solar reference abundances.

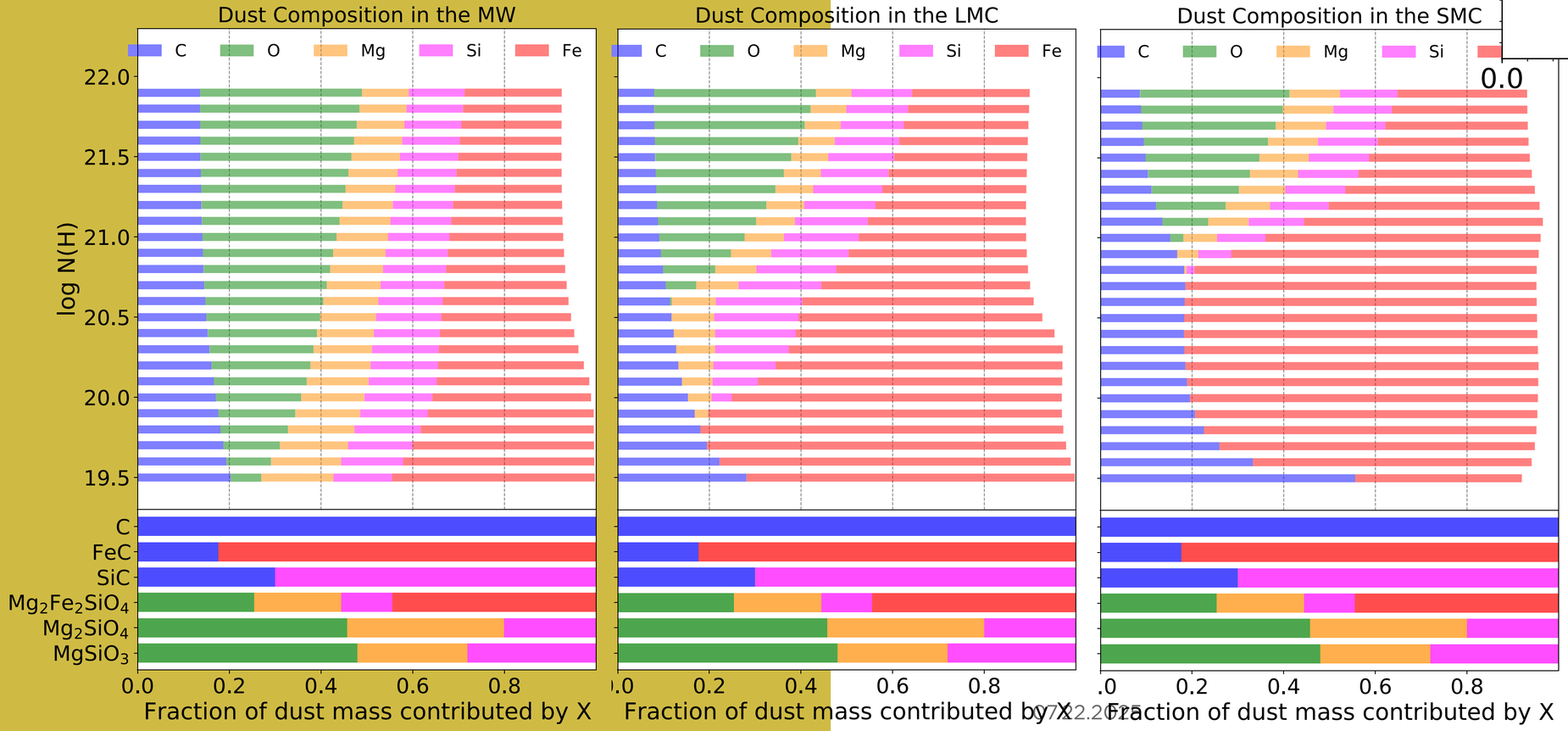
Found systematic depletion sequences across environments
Refractory elements (e.g., Fe, Ti) deplete more strongly than volatiles (e.g., N, S).
S and Zn, often assumed undepleted, but Jenkins+09 found mild depletion at high $F_\star$.

DUST DEPLETI

Roman-Duval el al. (2019, 2021) expanded upon the Jenkins work by studying the LMC ($Z = 0.5\ Z_\odot$) and SMC ($Z = 0.2\ Z_\odot$) to examine the effects of metallicity.

Elemental depletions and dust-to-metals ratio (D/M) are lower than in the Milky Way.





DUST DEPLETION

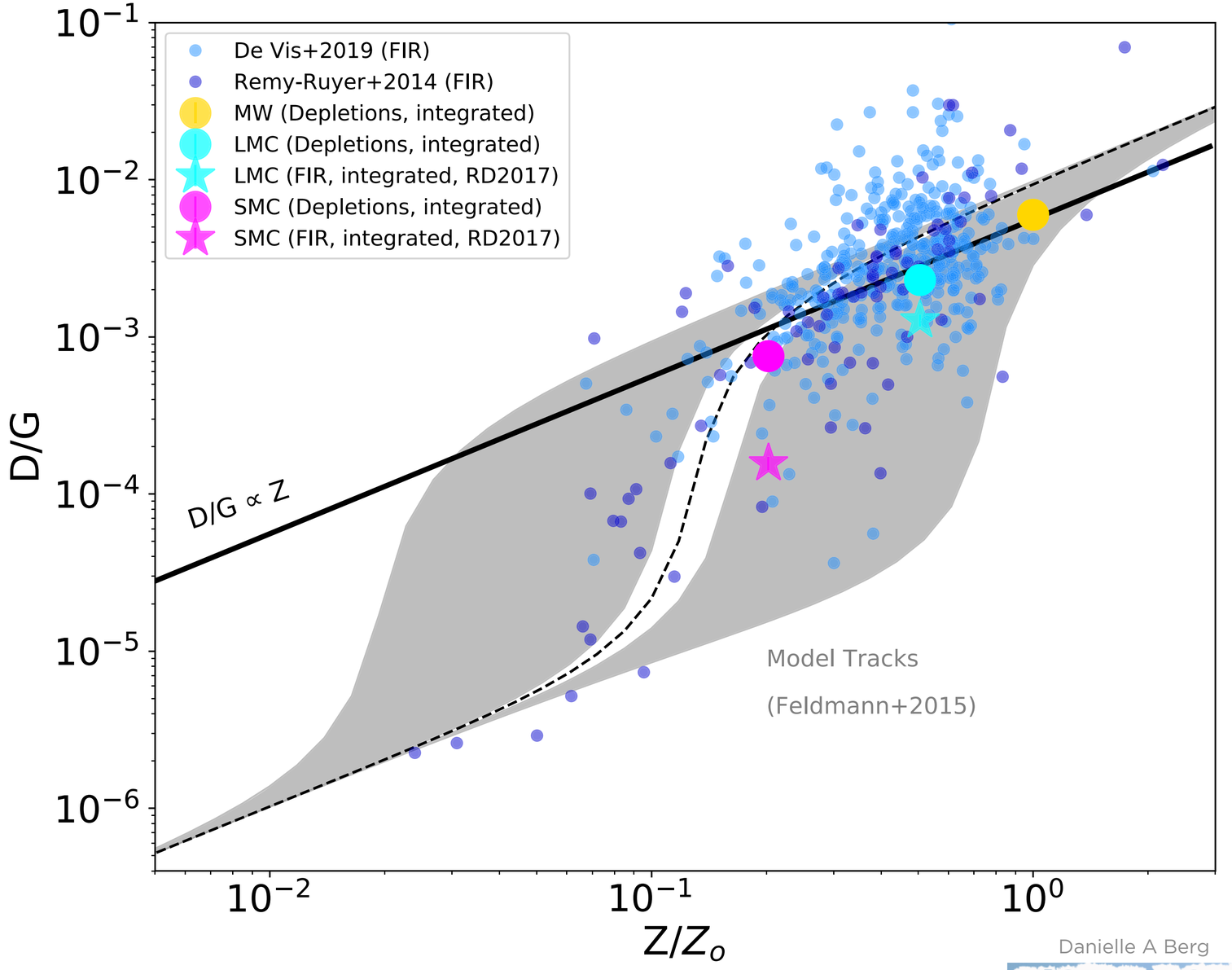
Roman-Duval el al. (2019, 2021) expanded upon the Jenkins work by studying the LMC ($Z = 0.5\ Z_\odot$) and SMC ($Z = 0.2\ Z_\odot$) to examine the effects of metallicity.

Elemental depletions and dust-to-metals ratio (D/M) are lower than in the Milky Way.

D/M scales non-linearly with metallicity: $D/M \propto Z^{1-2} \rightarrow$ grain growth less efficient at low Z.

Depletion sequences differ from MW: Shallower trends, different zero-points.

Grain composition likely varies: Low-Z systems may favor carbon-rich grains over silicates.



DUST DEPLETION

Gas Implications for ISM Studies and Galaxy Evolution

Milky Way depletion corrections may not apply in low-metallicity environments.

Dust modeling in high-z galaxies requires metallicity-dependent depletion sequences.

Impact on ISM diagnostics:
Depletion affects observed gas-phase abundances → corrections are essential for accurate metallicity and C/O, N/O ratios, etc.

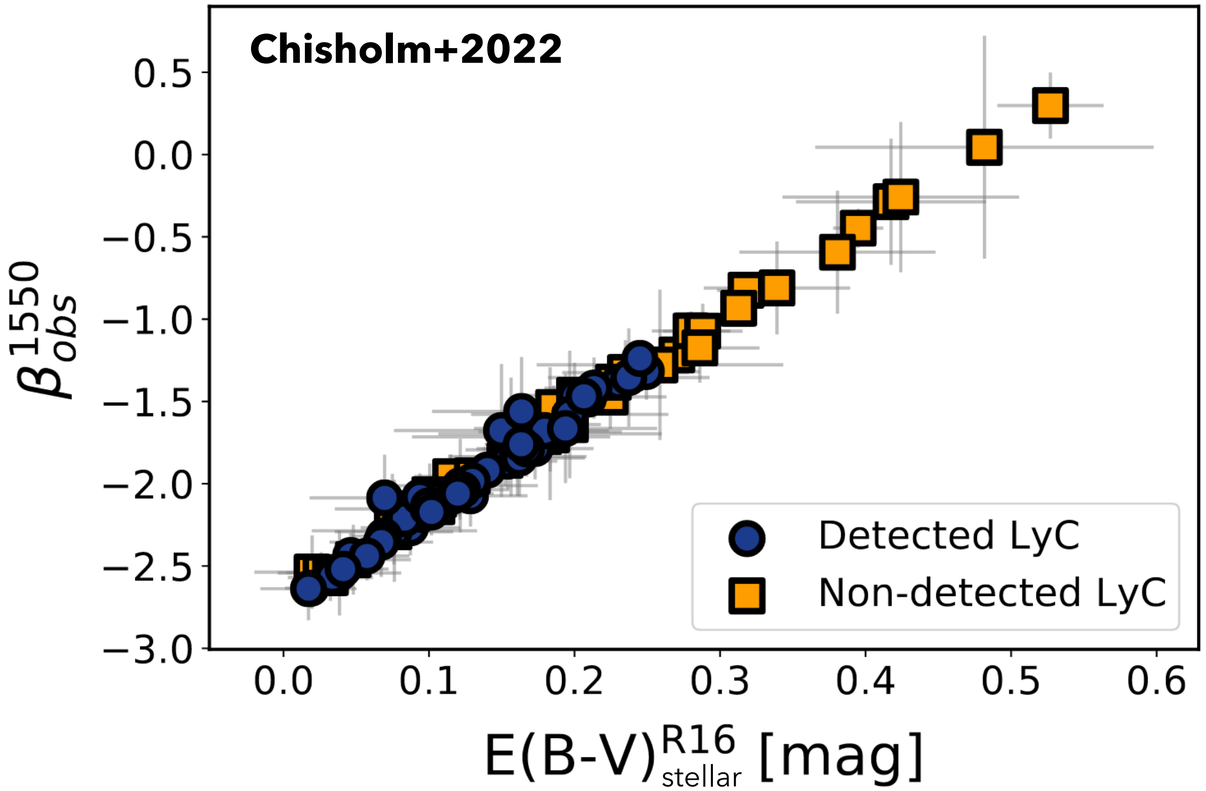
Dust composition evolution:
Changes in grain type and size impact extinction curves, dust SEDs, and ISM cooling.

Essential for interpreting JWST and future IR/UV missions (e.g., UVEX, HWO).

How do we measure dust reddening?

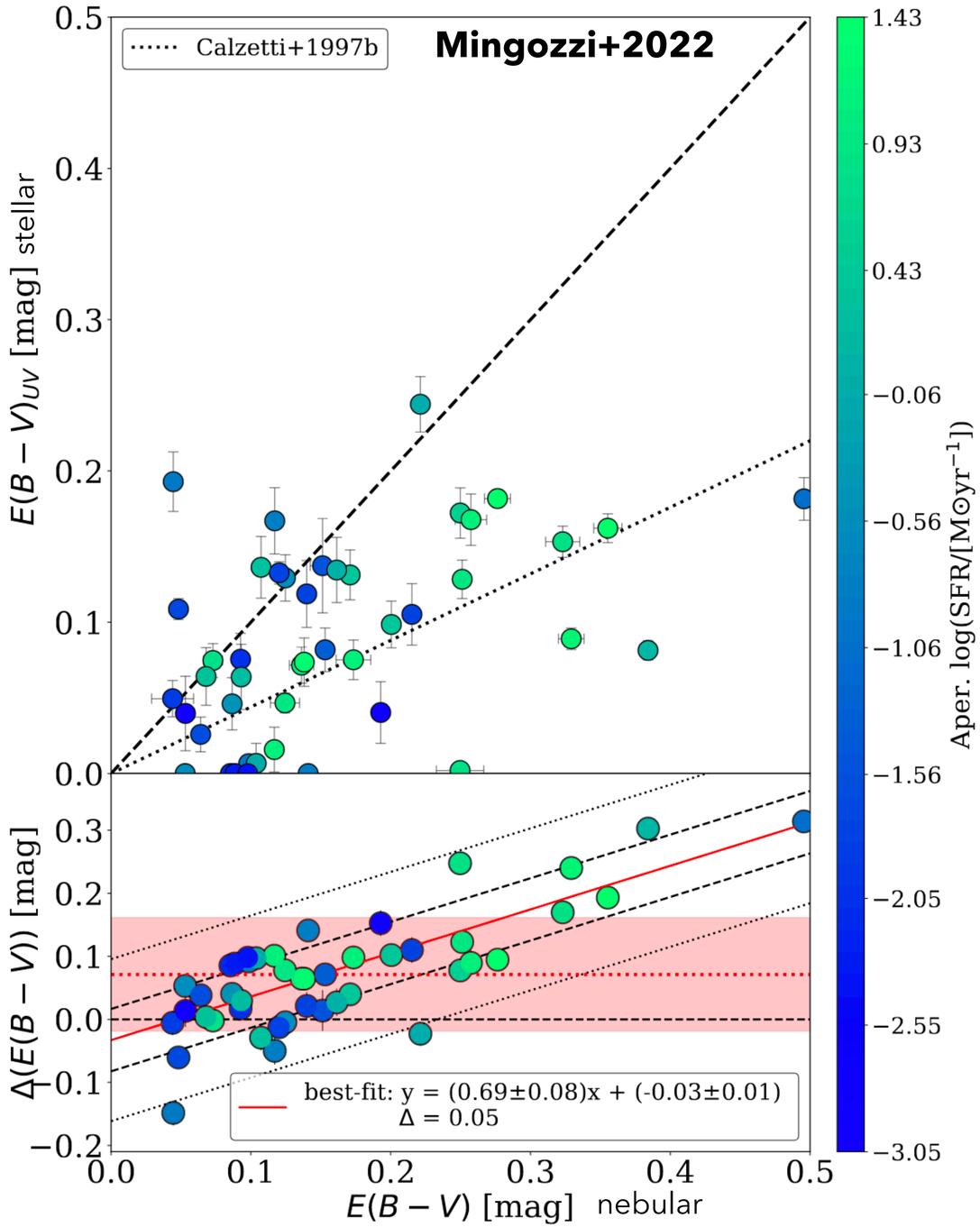
DUST REDDENING

Strong correlation between β-slope and *E(B-V)*



How do we measure dust reddening?

Tends to be greater dispersion between stellar and nebular reddening at higher reddening



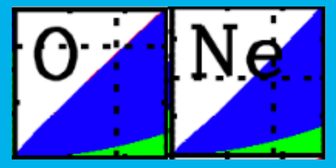
RELATIVE ABUNDANCES IN THE ISM

NE/O VARIATIONS

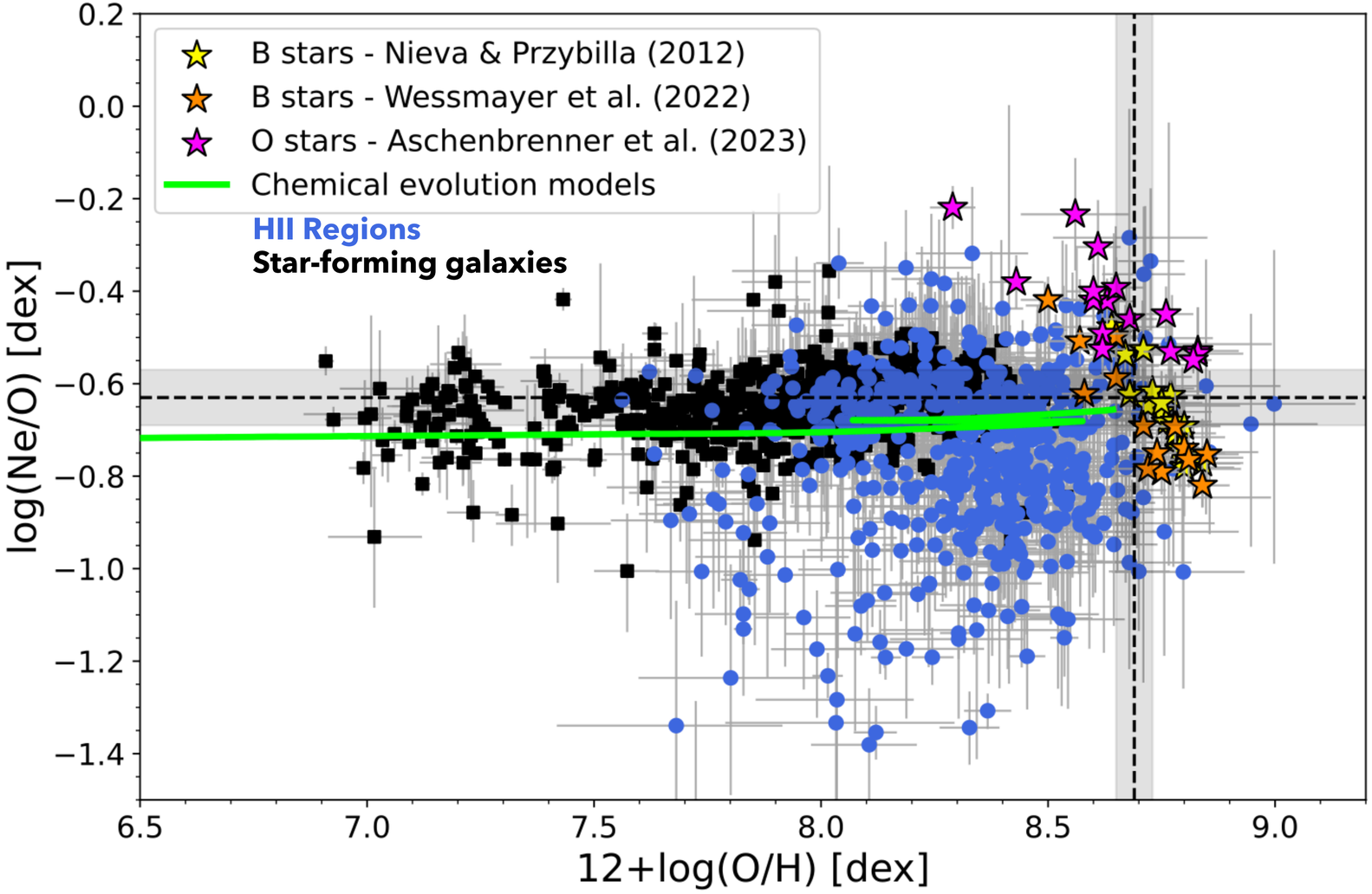
[NeIII]/[OIII] is a challenging line ratio diagnostic:

- Typically, only Ne^{+2}/O^{+2} is observed, so requires an ICF
- Large Ne/O deviations from assumed solar ratio

AGB Stars
CCSNe



Kobayashi+2020 (see, also, Kobayashi+2023, Kobayashi+2025)

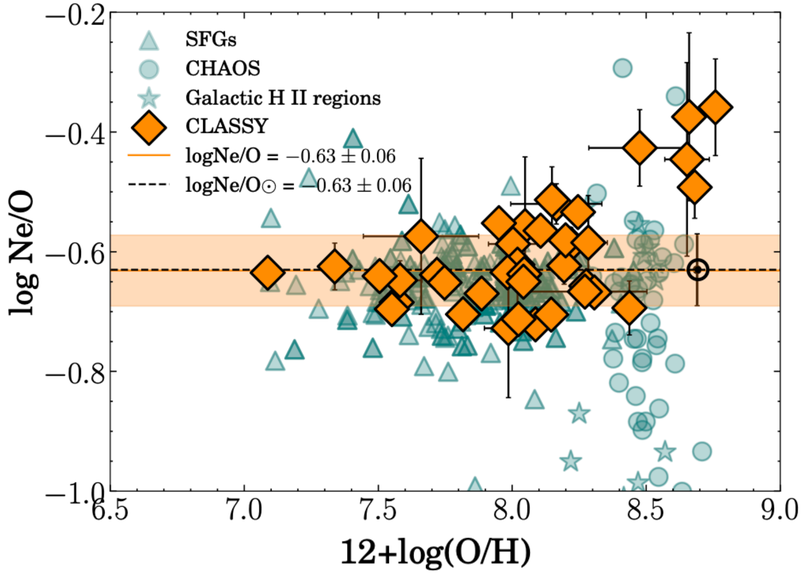


Esteban+2025

NE/O EVOLUTION

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Arellano-Cordova+24

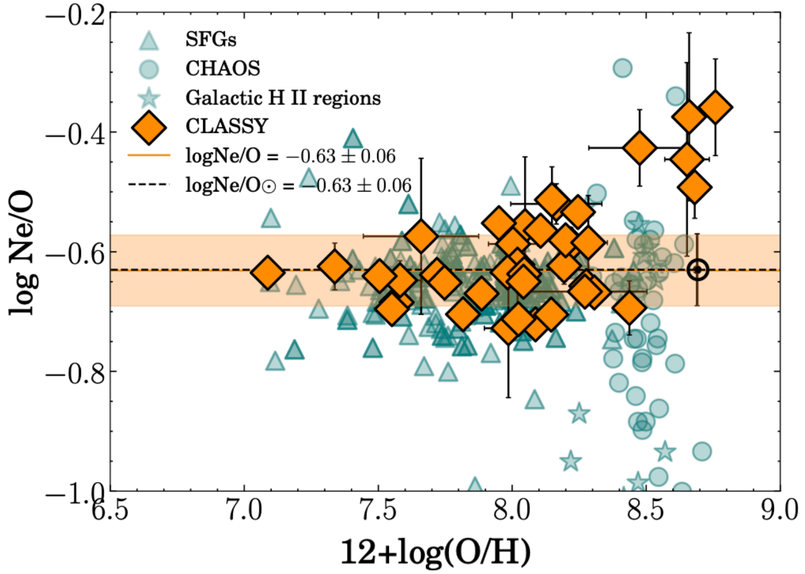


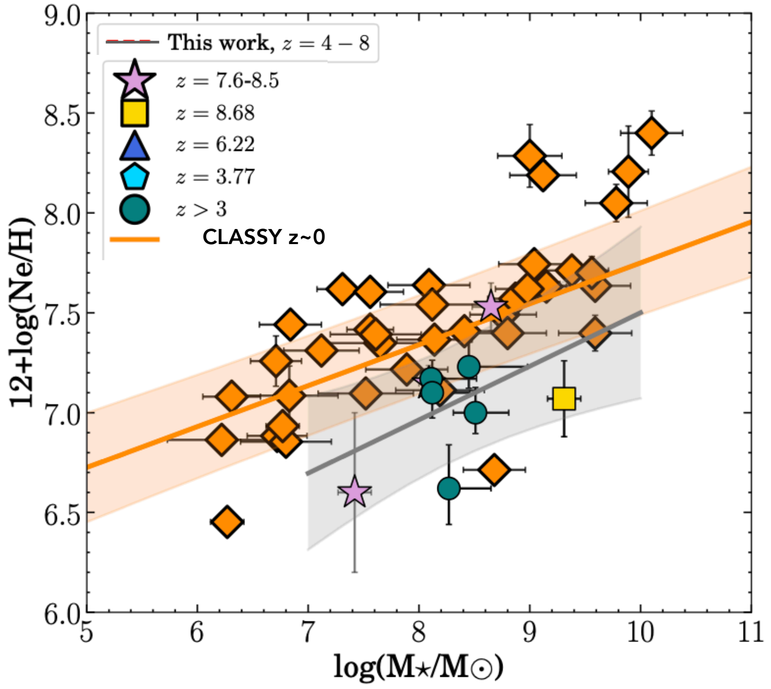
Karla Arellano-Córdova
Postdoc
University of Edinburgh

NE/O VARIATIONS

[NeIII]/[OIII] is a challenging line ratio diagnostic:

- Typically, only Ne^{+2}/O^{+2} is observed, so requires an ICF
- Large Ne/O deviations from assumed solar ratio





Also see strong Ne and O emission in z > 6 galaxies (e.g., Arellano-Cordova+22) suggesting rapid chemical enrichment from SNe.

Arellano-Cordova+24

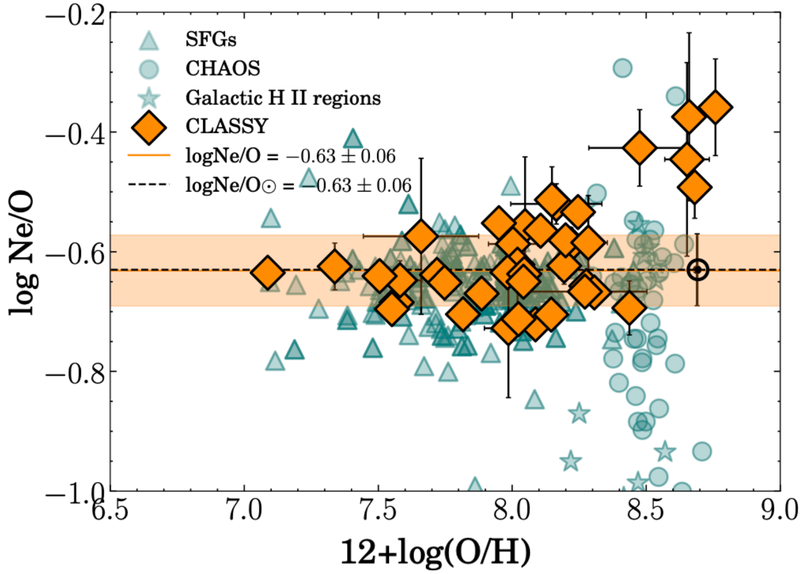


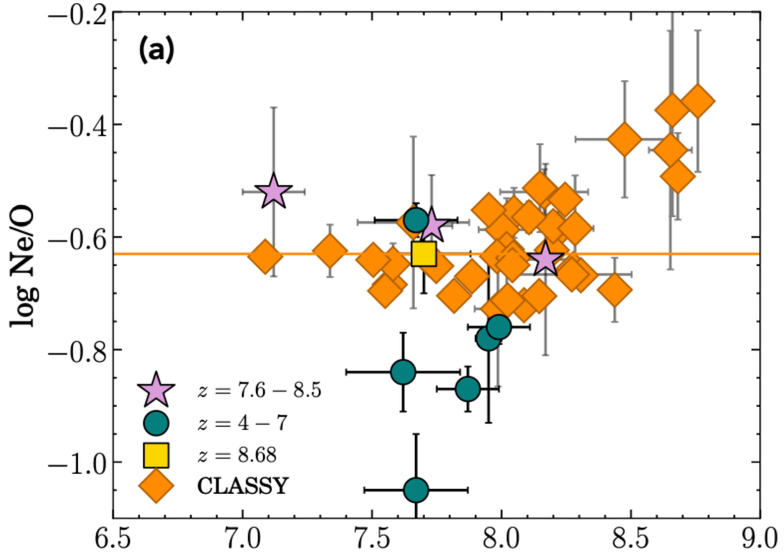
Karla
Poste
University of Edinburgh

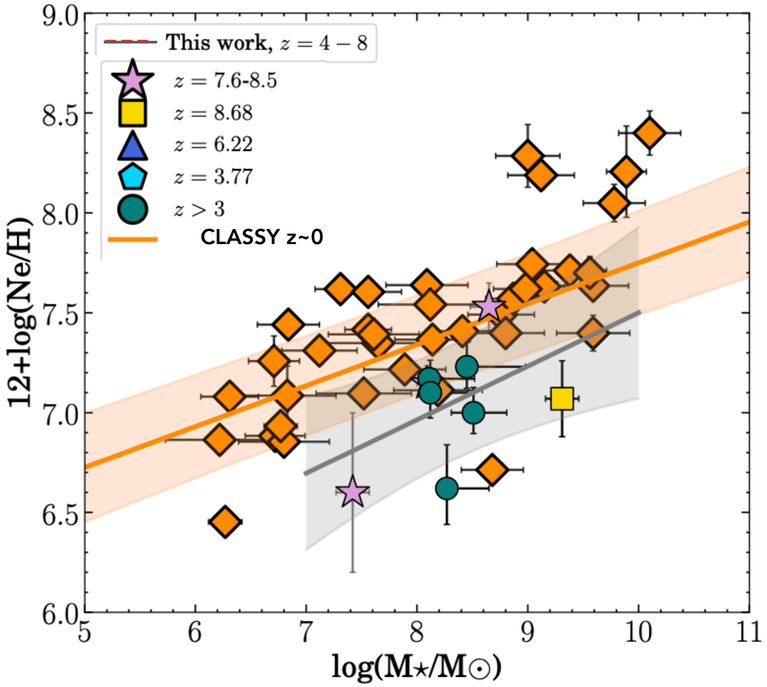
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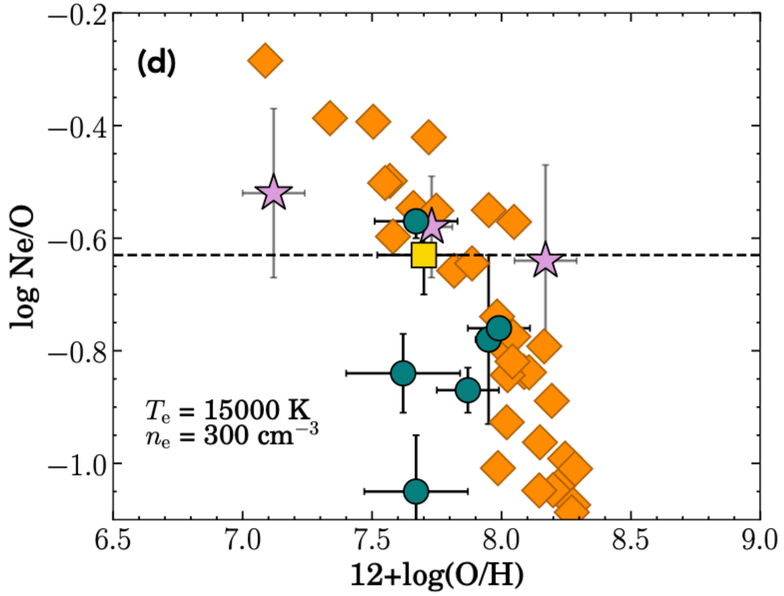
[NeIII]/[OIII] is a challenging line ratio diagnostic:

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- Large Ne/O deviations from assumed solar ratio
- There is possible evolution in the Mass-Ne/H relationship
- Ne/O ratio is very sensitive to the assumed nebular temperature









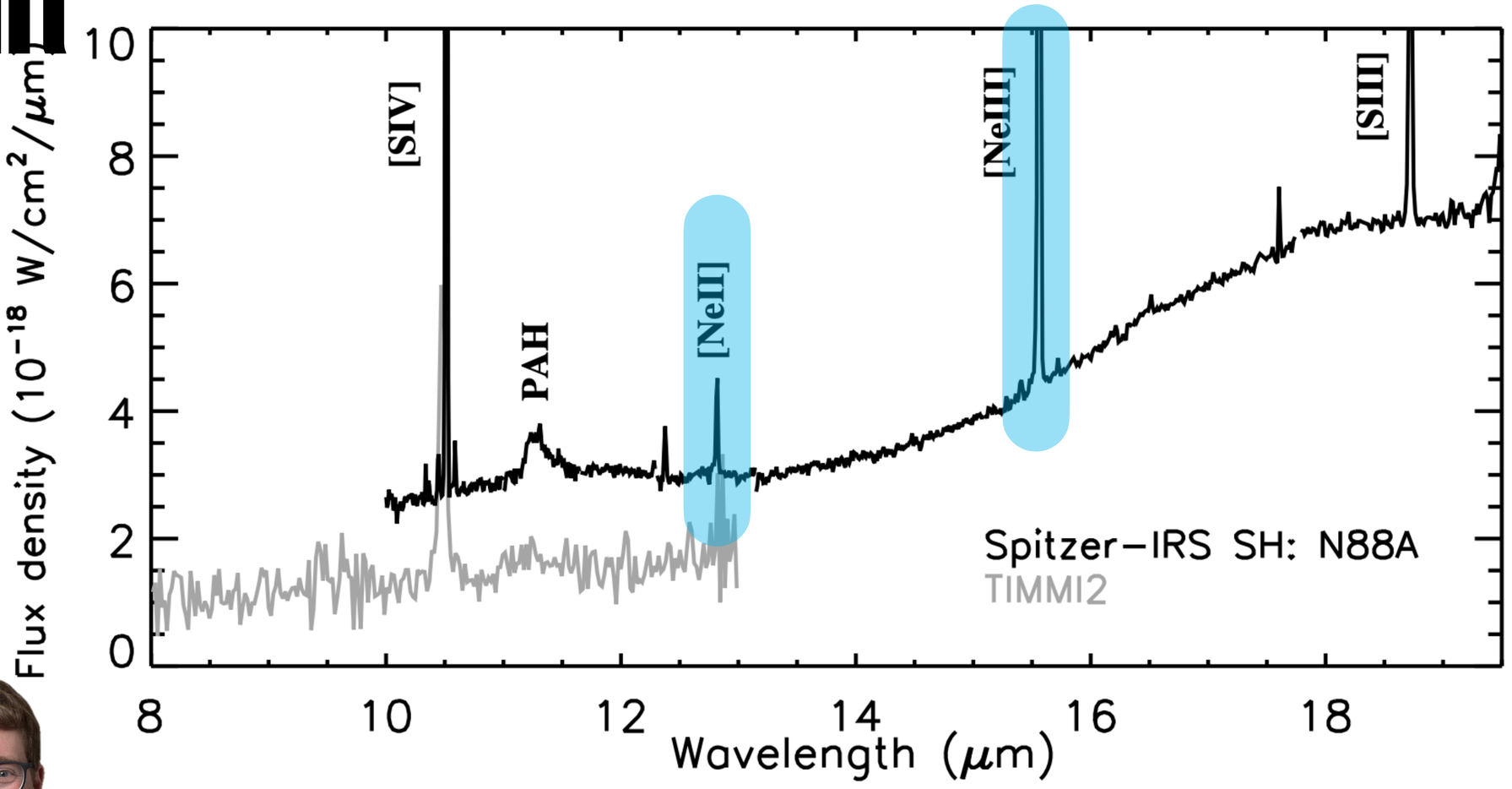
Arellano-Cordova+24



Karla
Poste
University of Edinburgh

NOVEL NE/O METHOD IN MIR

MIR [NeIII]/[OIII] line ratio diagnostic offers path forward:



Martín-Hernández+2008, Figure 3



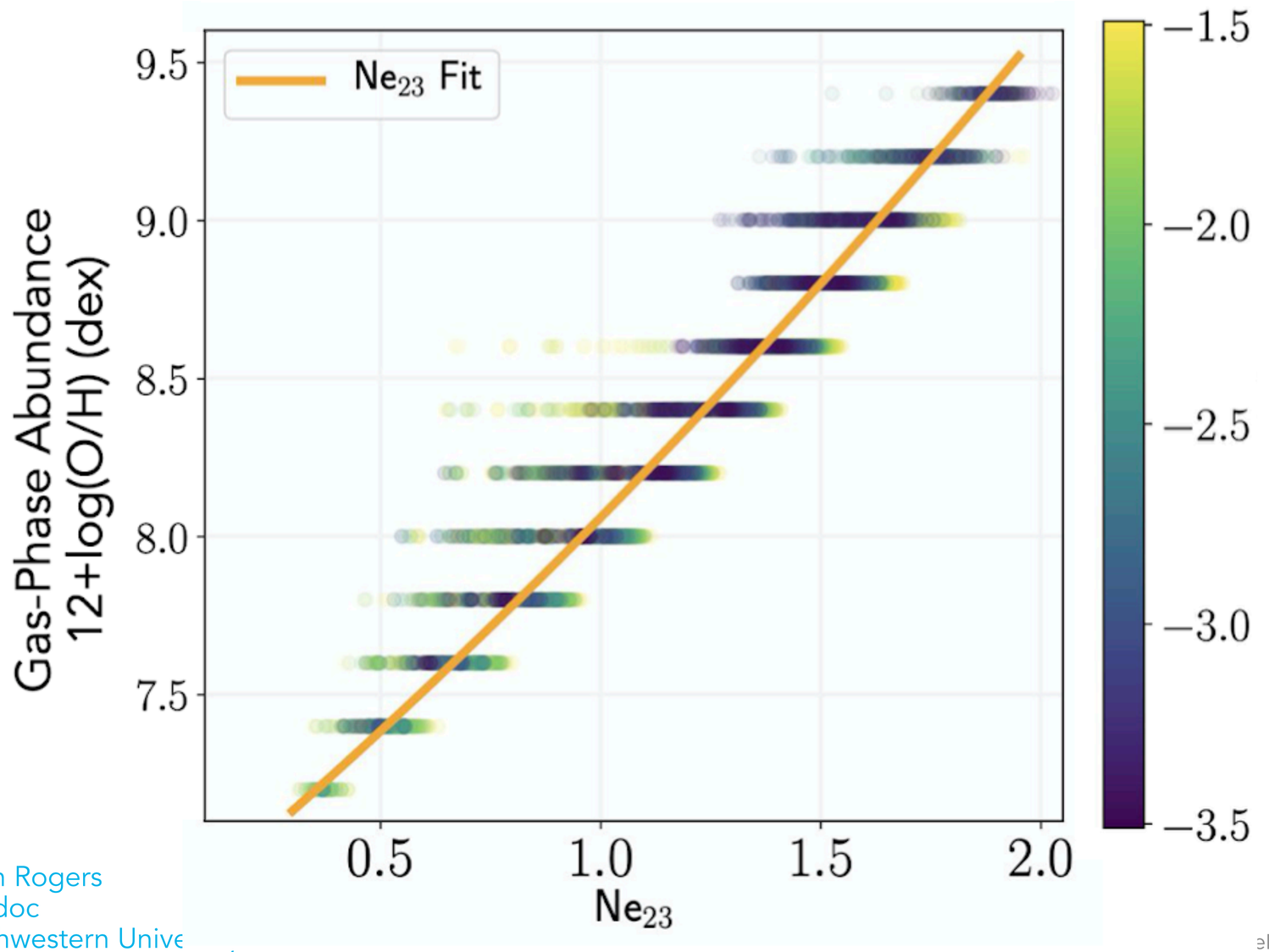
Noah Rogers
Postdoc
Northwestern University

NOVEL NE/O METHOD IN MIR

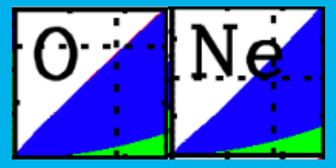
MIR [NeIII]/[OIII] line ratio diagnostic offers path forward:

- If Ne and O evolve in lock-step, Ne emission should trace the O abundance in the ISM

$$\mathrm{Ne_{23}} = \log_{10}\left[\frac{\mathrm{I([Ne\ II]12.8\mu m)} + \mathrm{I([Ne\ III]15.6\mu m)}}{\mathrm{I(Hu\alpha)}}\right]$$



AGB Stars
CCSNe



Kobayashi+2020 (see, also, Kobayashi+2023, Kobayashi+2025)

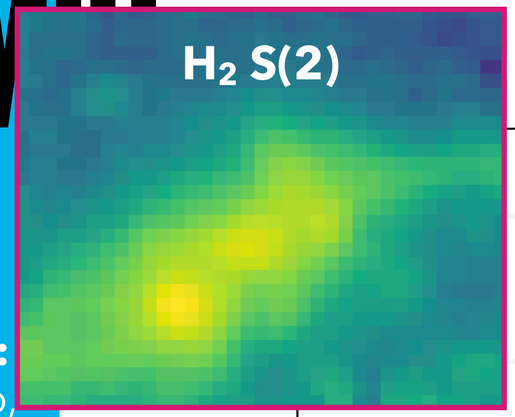


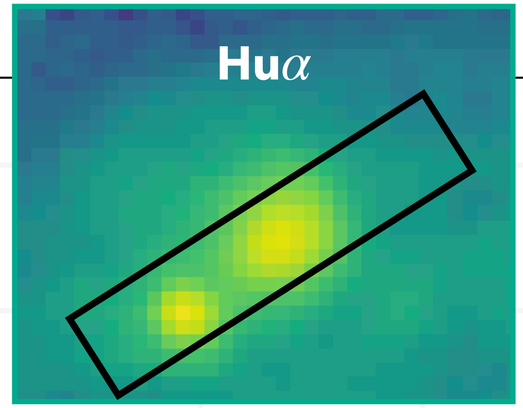
Noah Rogers
Postdoc
Northwestern Unive

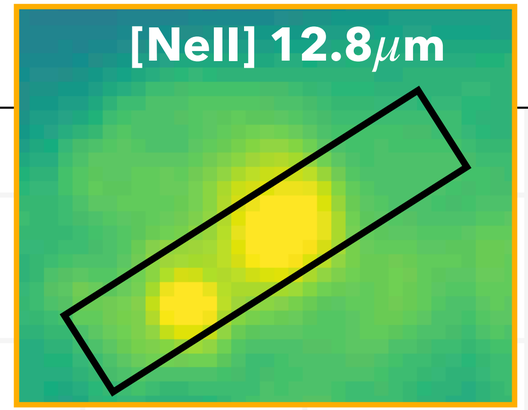
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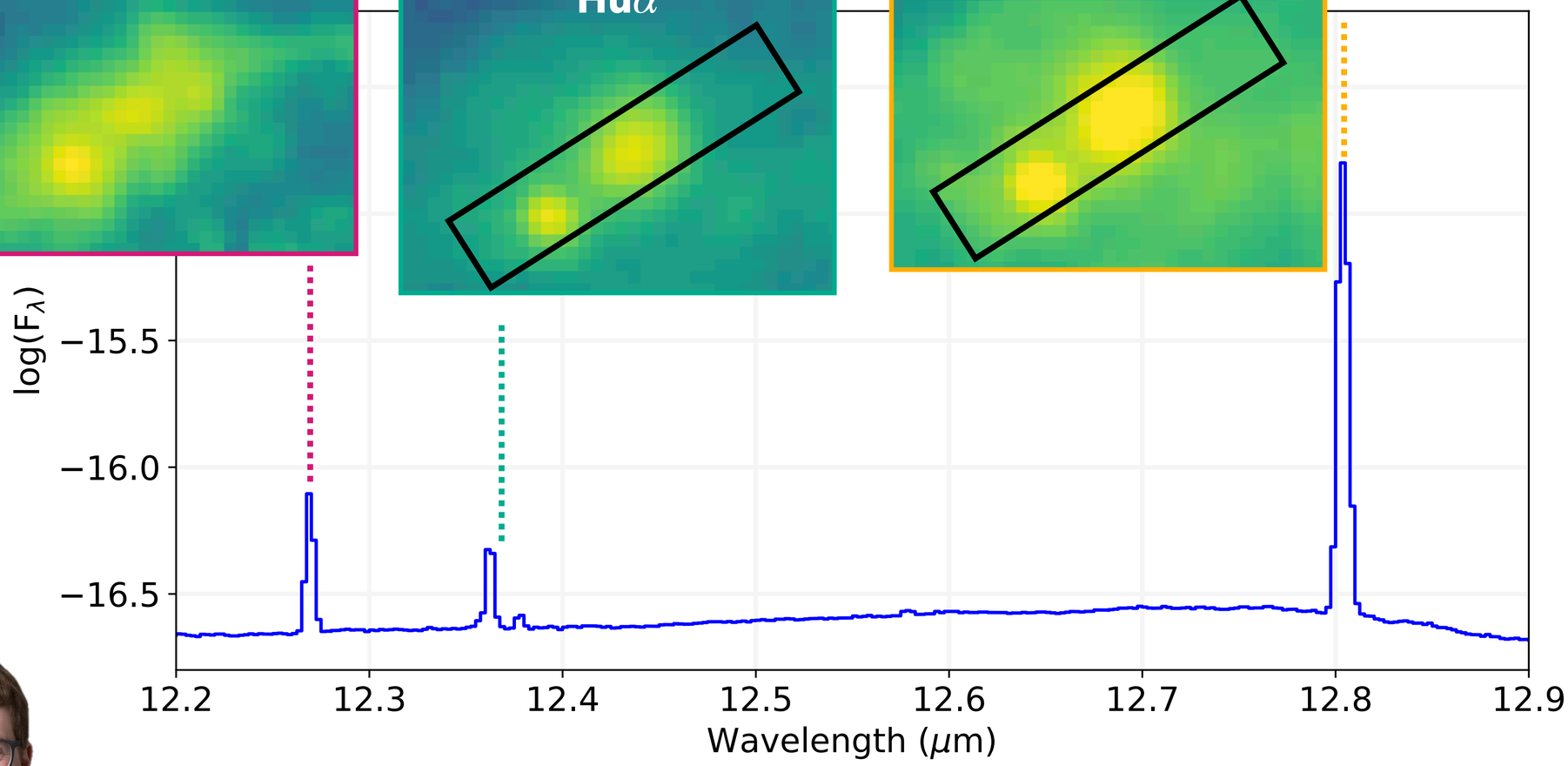
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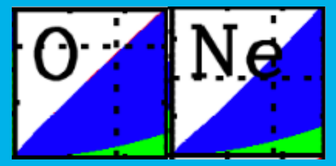




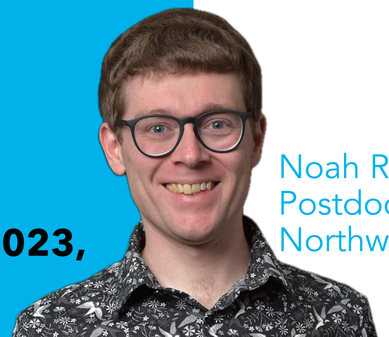




AGB Stars
CCSNe



Kobayashi+2020 (see, also, Kobayashi+2023, Kobayashi+2025)



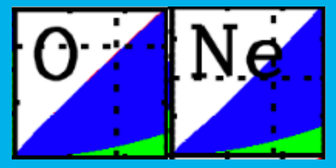
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NOVEL NE/O METHOD IN MIR

MIR [NeIII]/[OIII] line ratio diagnostic offers path forward:

- If Ne and O evolve in lock-step, Ne emission should trace the O abundance in the ISM
- O/H is correlated with Ne23, providing an abundance indicator that is insensitive to gas-phase physical conditions!

AGB Stars
CCSNe



Kobayashi+2020 (see, also, Kobayashi+2023, Kobayashi+2025)



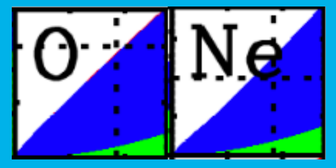
Rogers et al., in Prep, Low-Z Galaxies credited to PID2424 (PI A. Jaskot)

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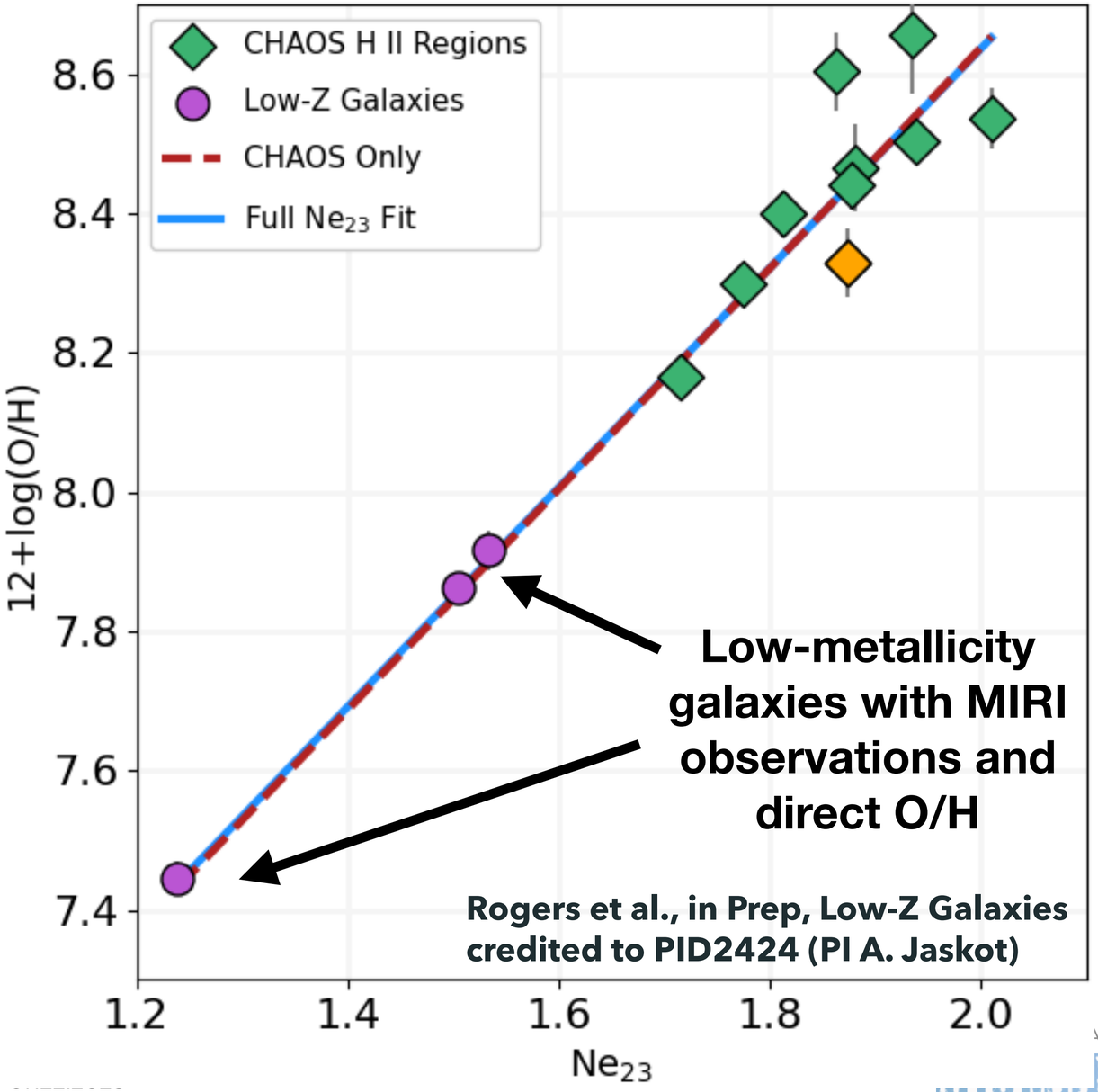
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AGB Stars
CCSNe

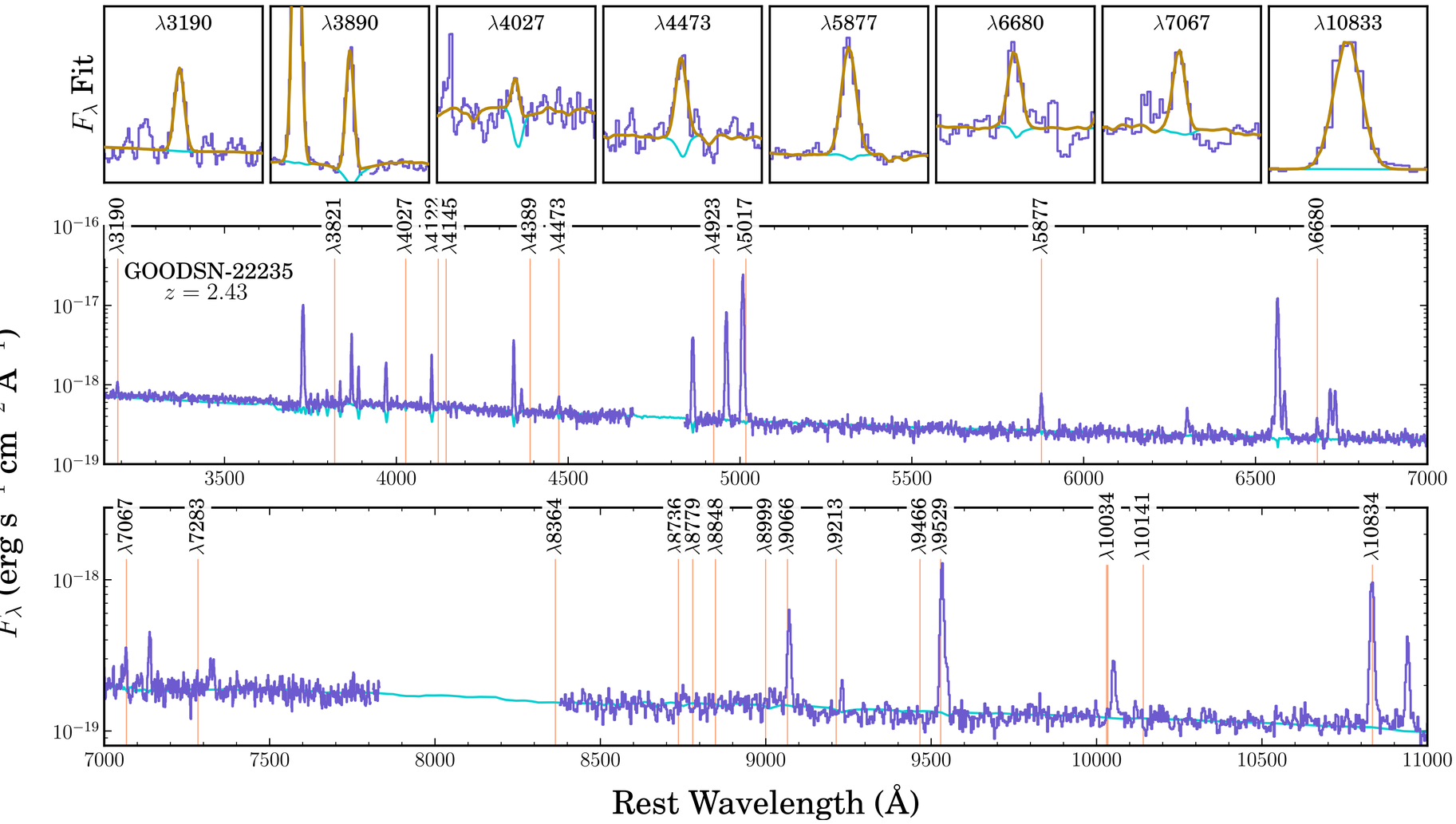


Kobayashi+2020 (see, also, Kobayashi+2023, Kobayashi+2025)





Berg, et al., 2025, on arxiv.



HE/H EVOLUTION

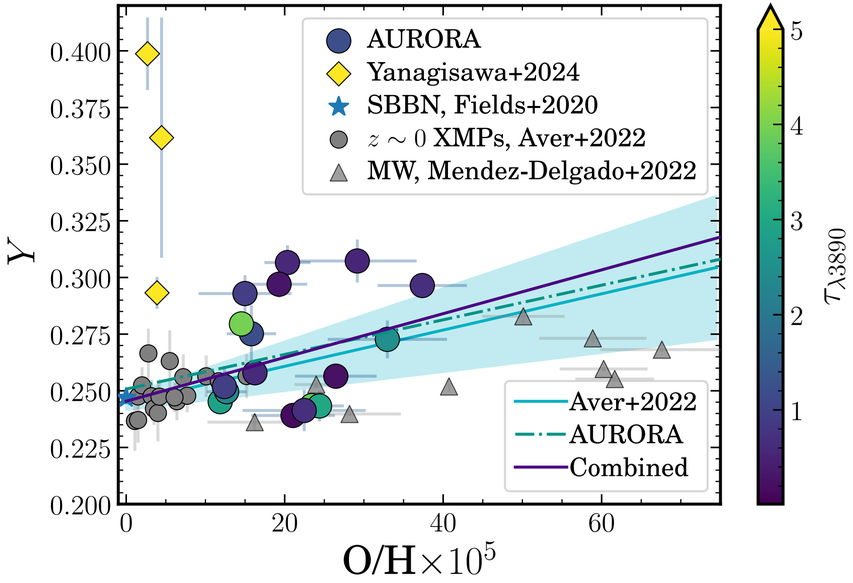
Multi-element abundance profiles provide better constraints on enrichment history

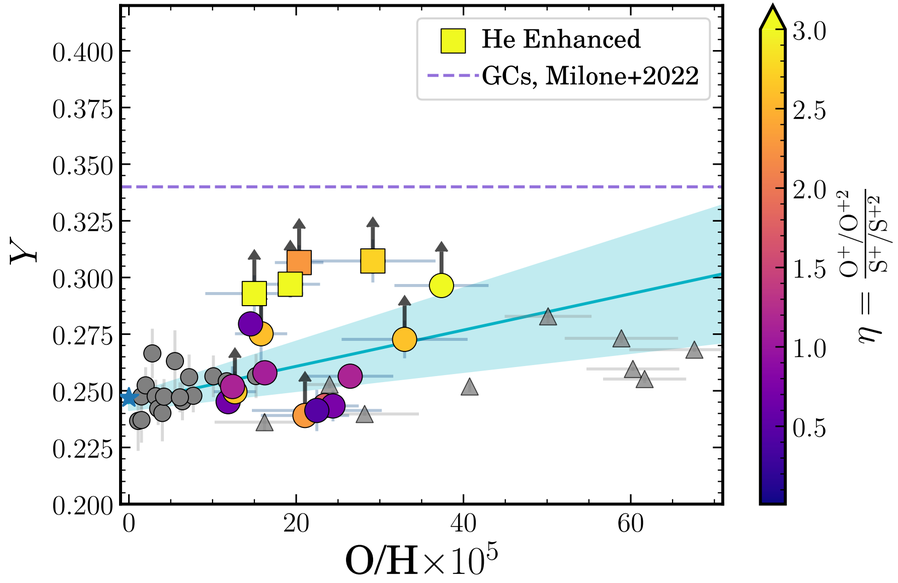
See, also, Yanagisawa+2024, Katz+2024

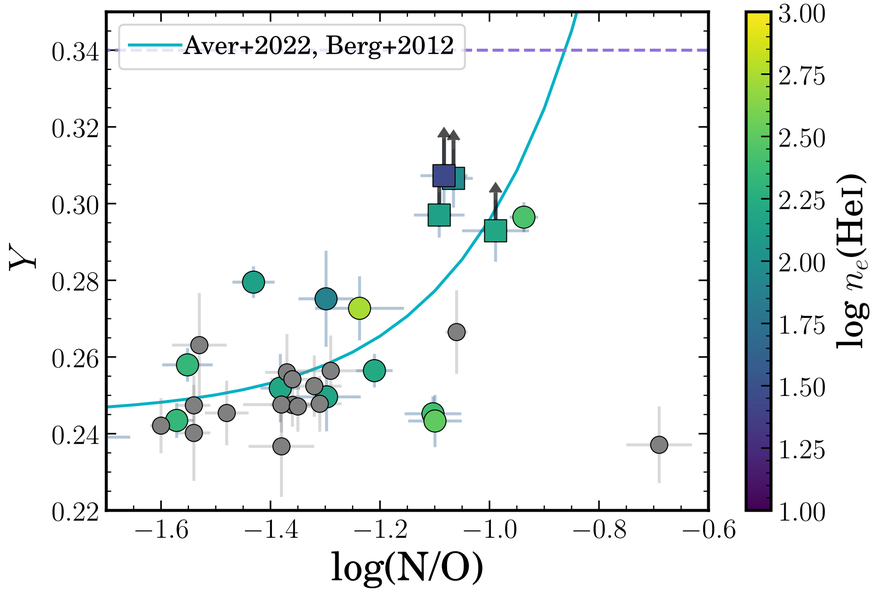


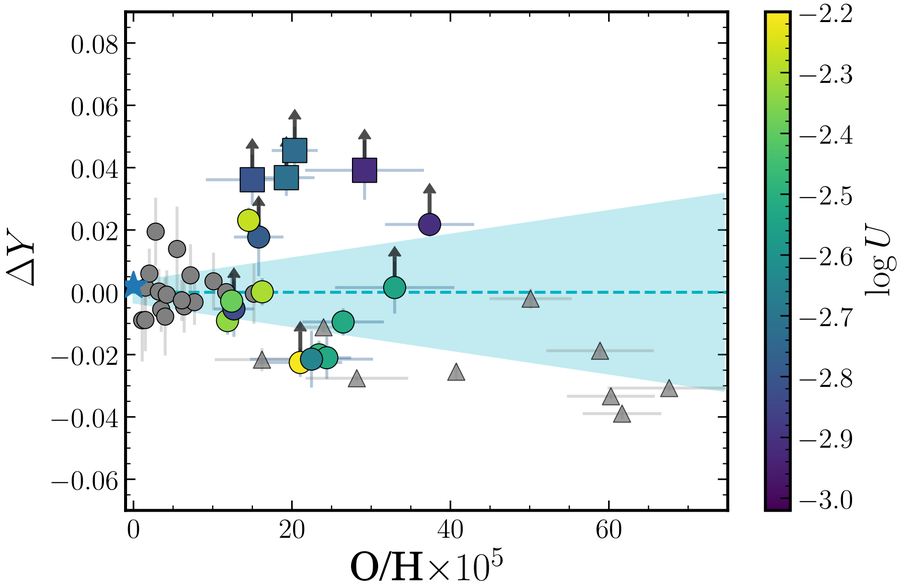
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Berg, et al., 2025, on arxiv.









HE/H EVOLUTION

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N/O EVOLUTION

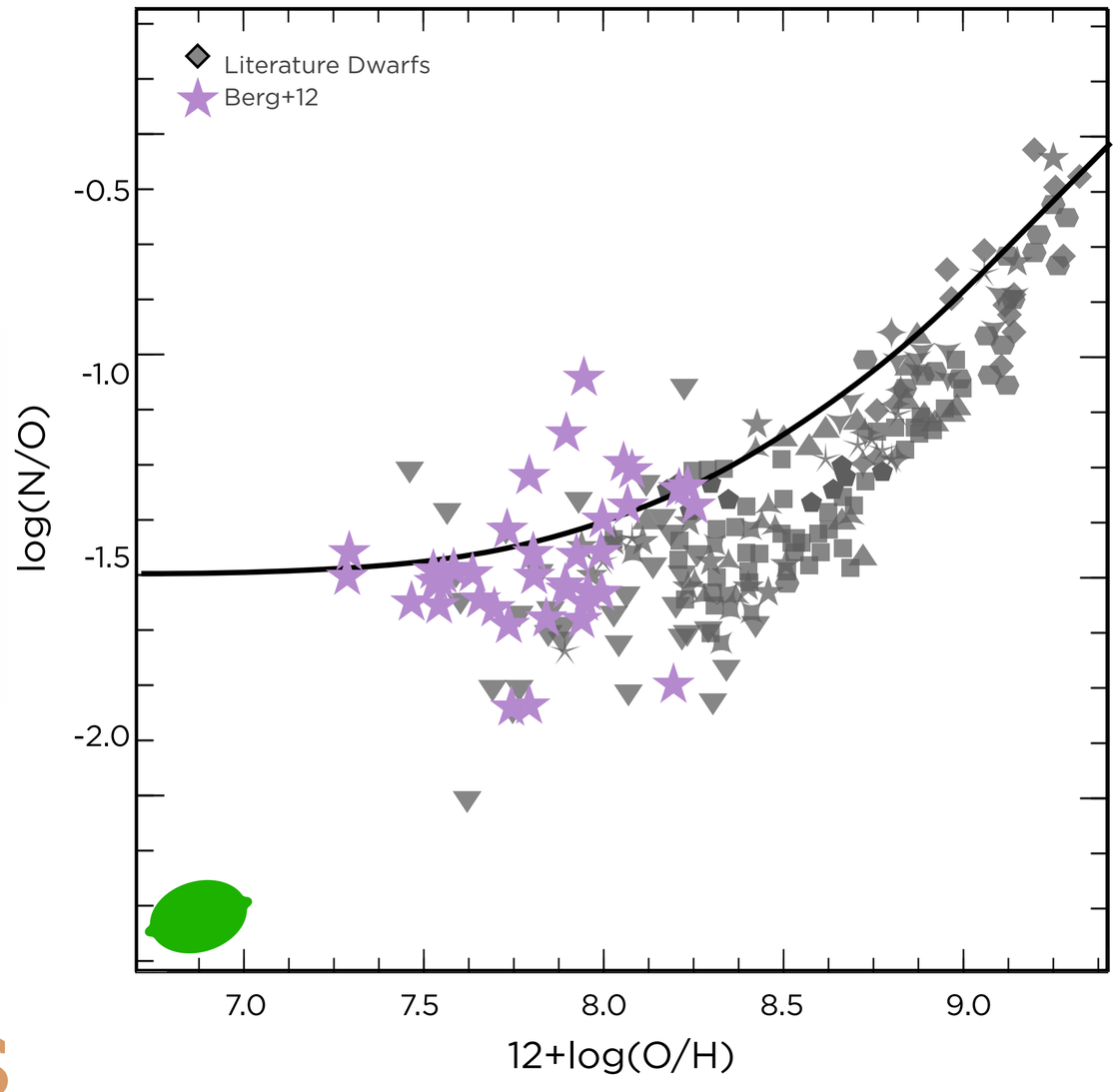
Relative abundances trace SFH and stellar feedback

N production via the CNO cycle is bimodal

Primary:
'Seed' created from initial H & He of star

Secondary:
'Seed' present at birth of the star

$$
\begin{aligned}
&{}^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} + \gamma \\
&{}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
&{}^{13}\mathrm{C} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + \gamma \\
&{}^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{O} + \gamma \\
&{}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
&{}^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
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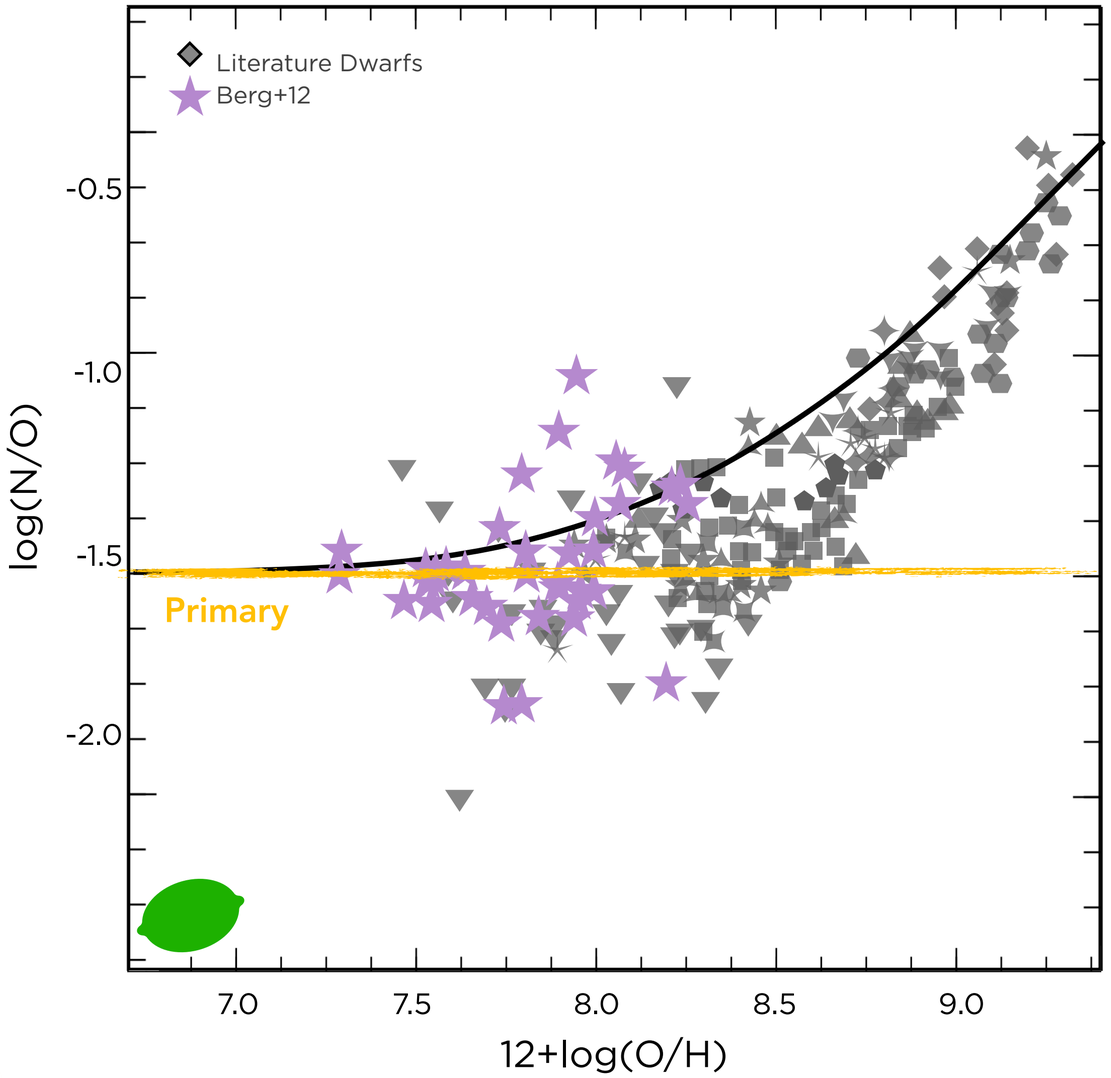
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Seed

Bottleneck

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$
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$$^{13}C + p \rightarrow {}^{14}N + \gamma$$
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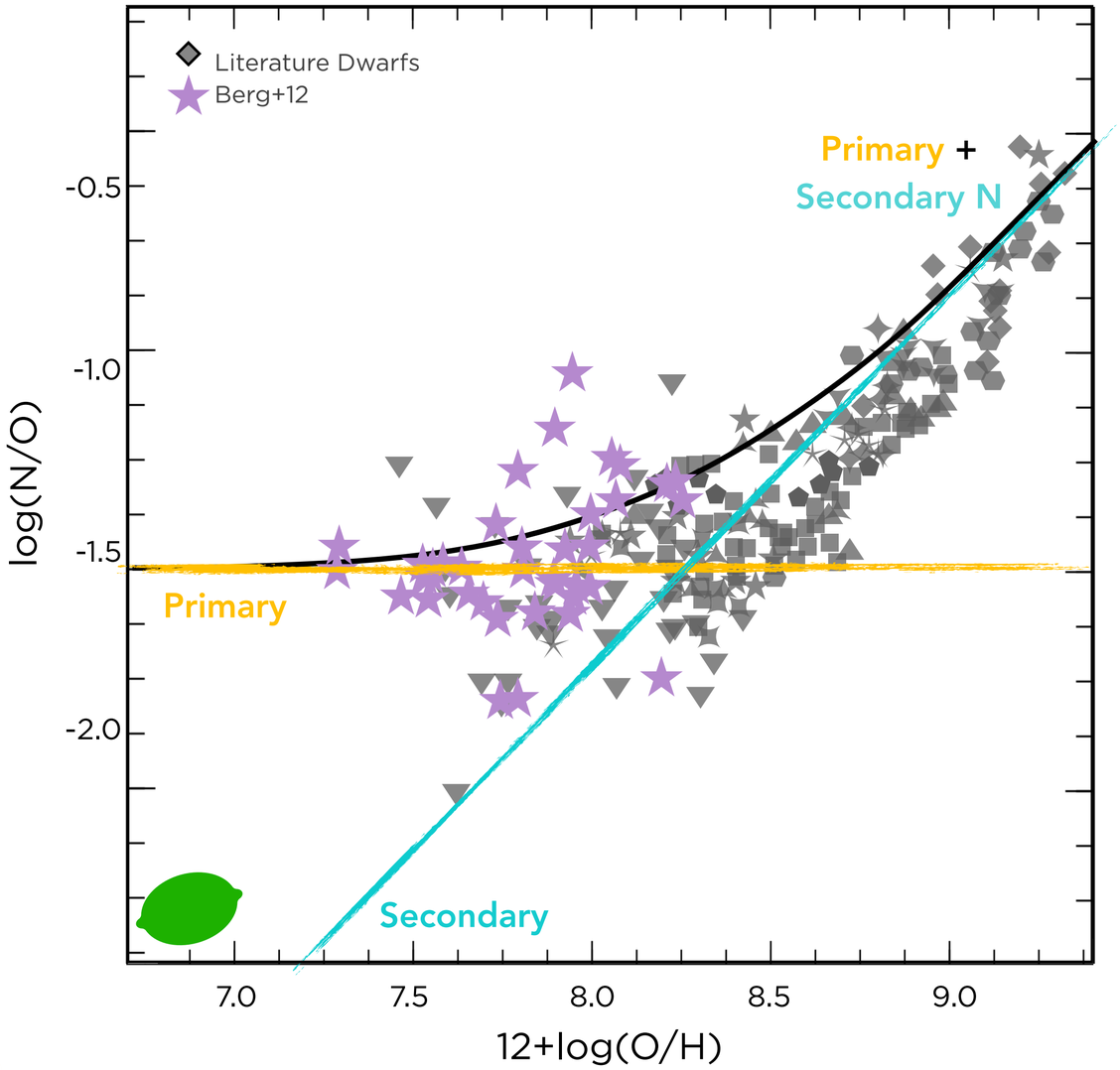
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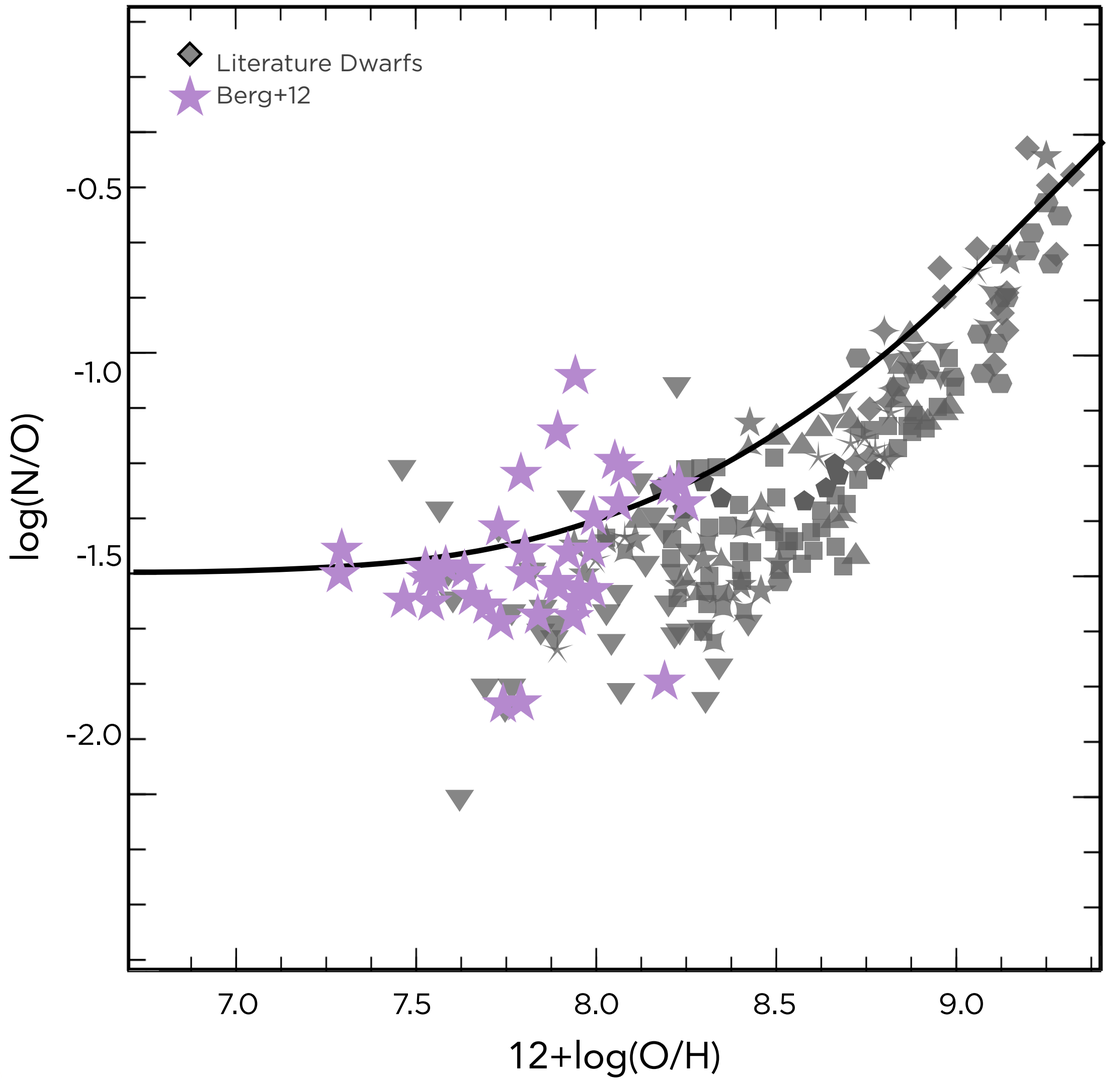
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07.22.2025

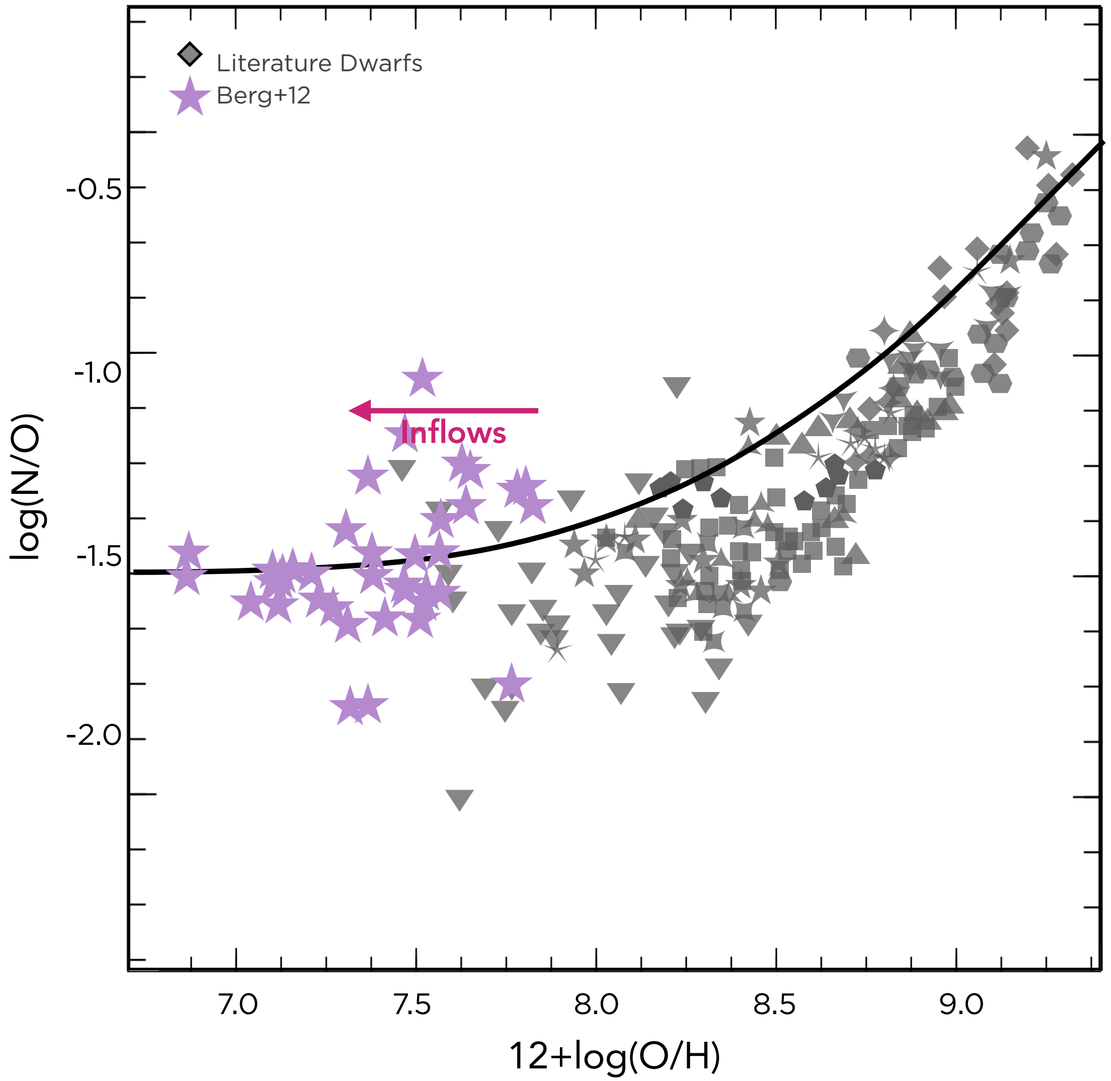
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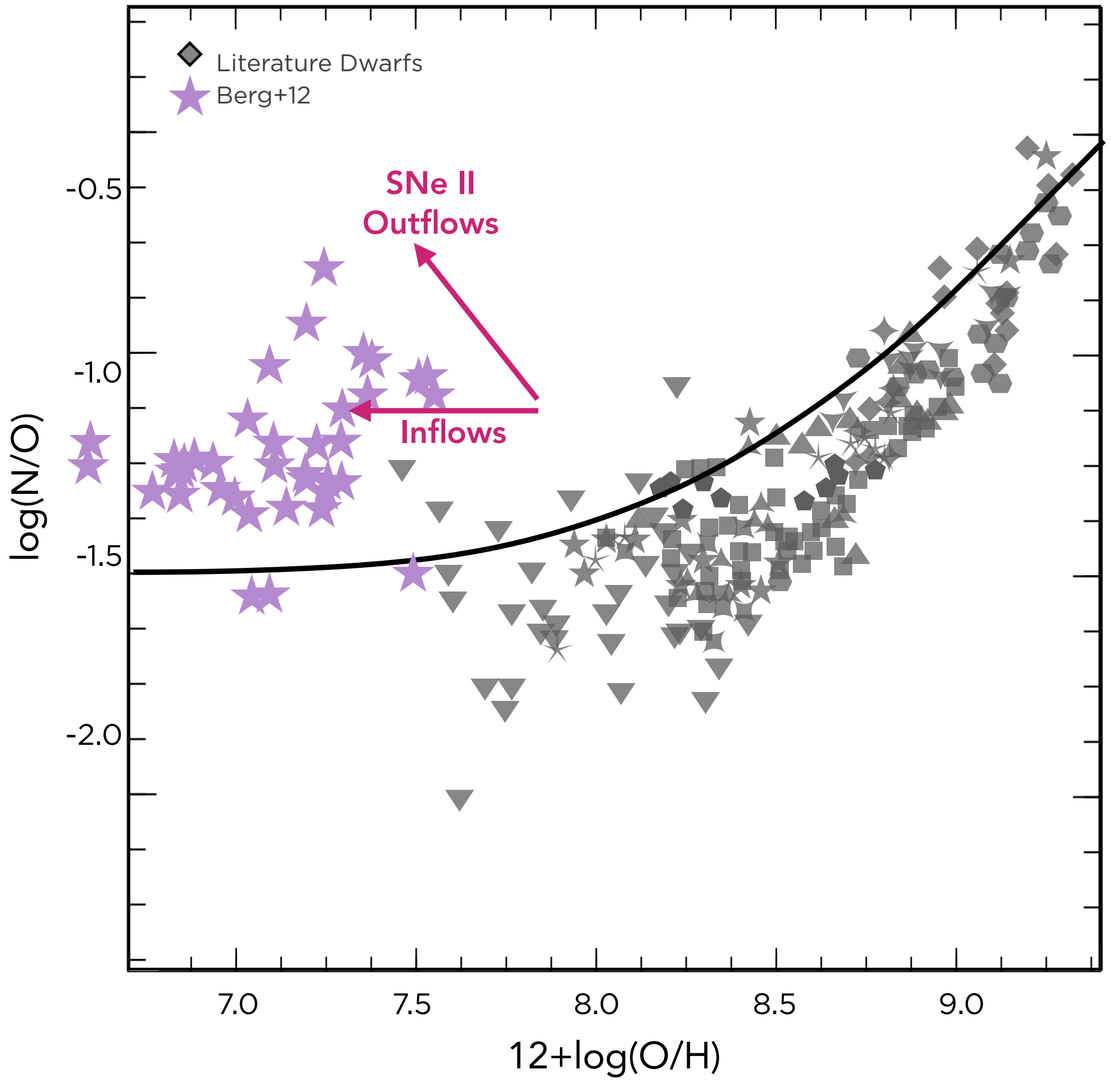
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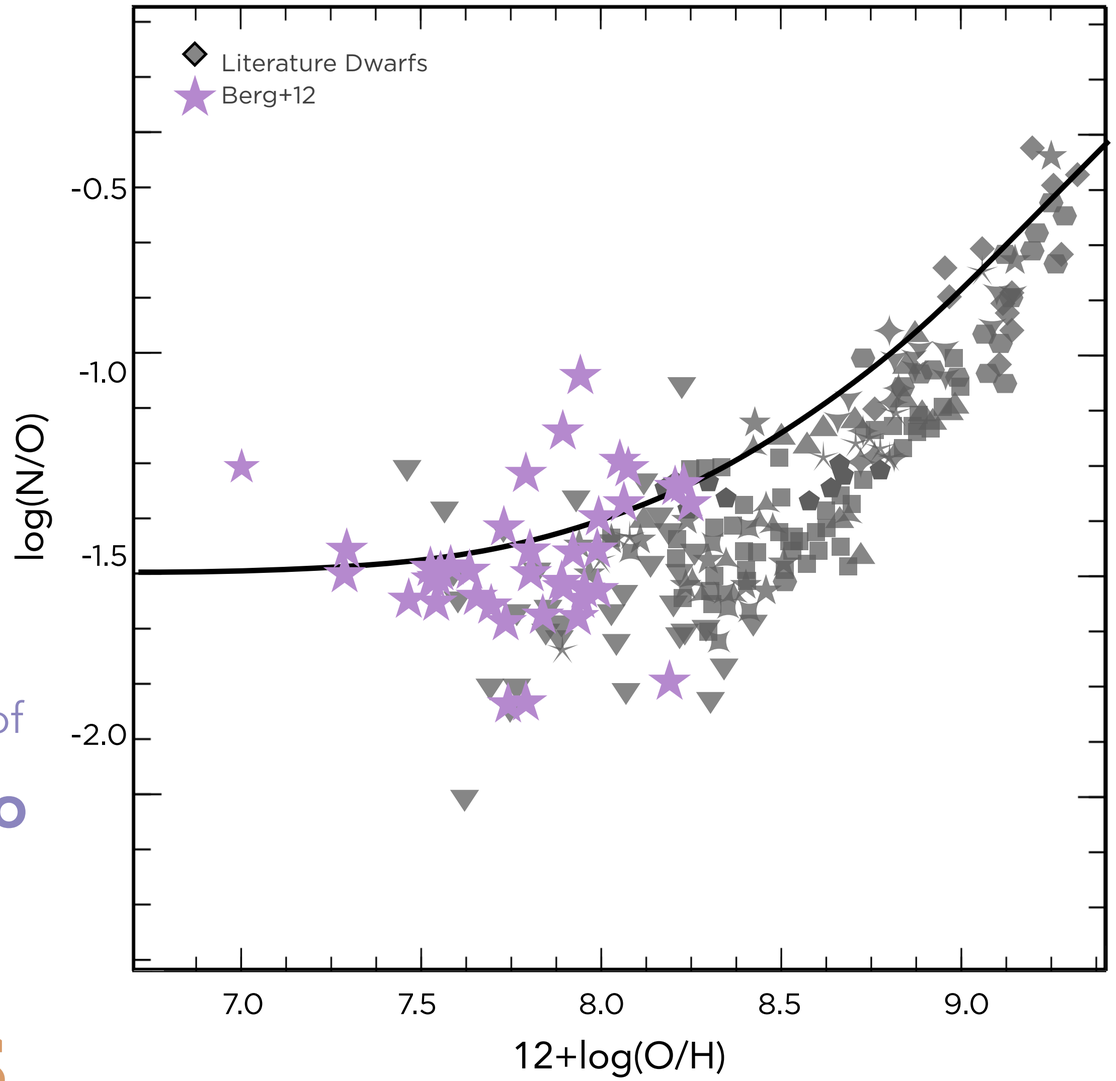
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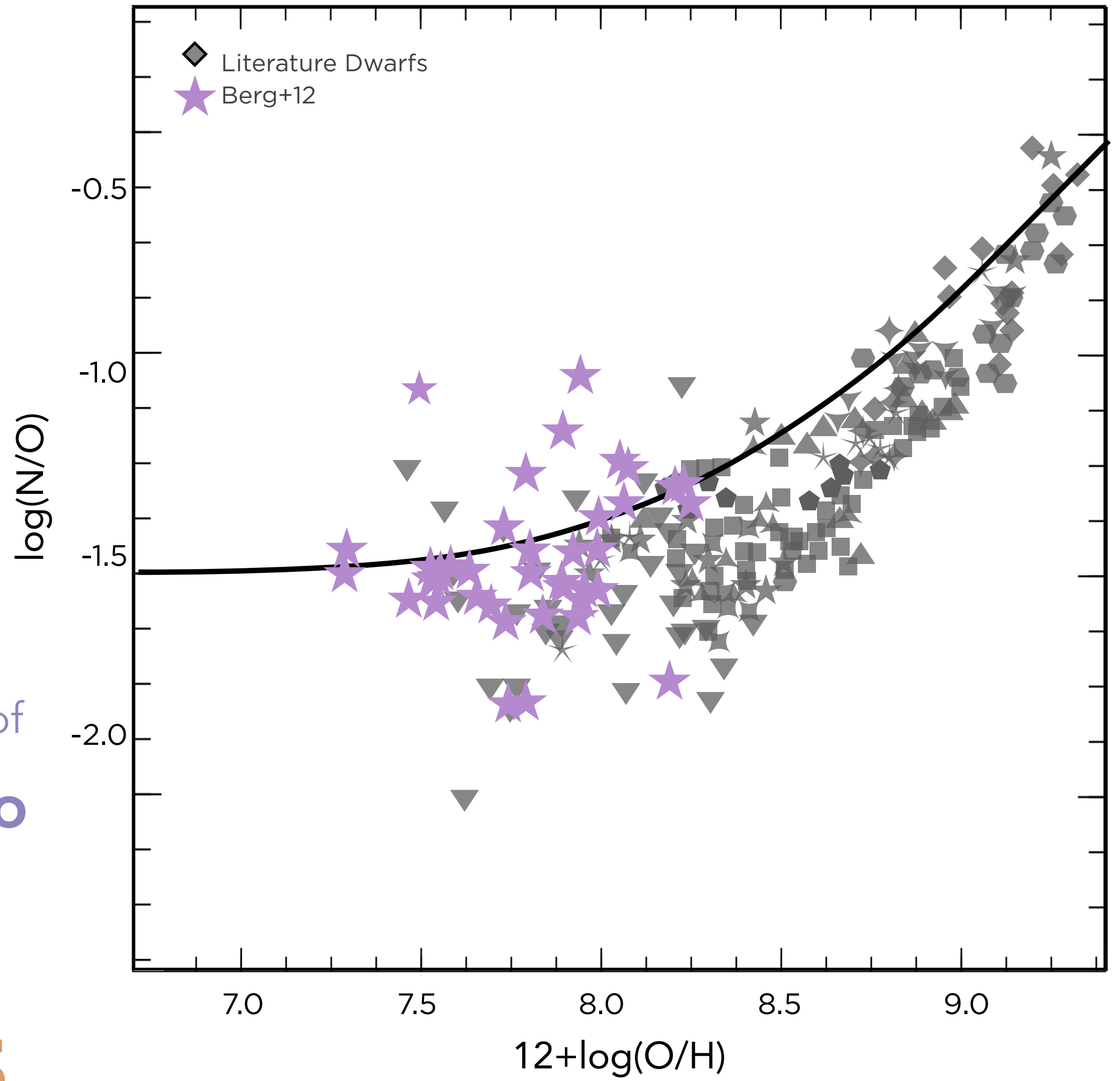
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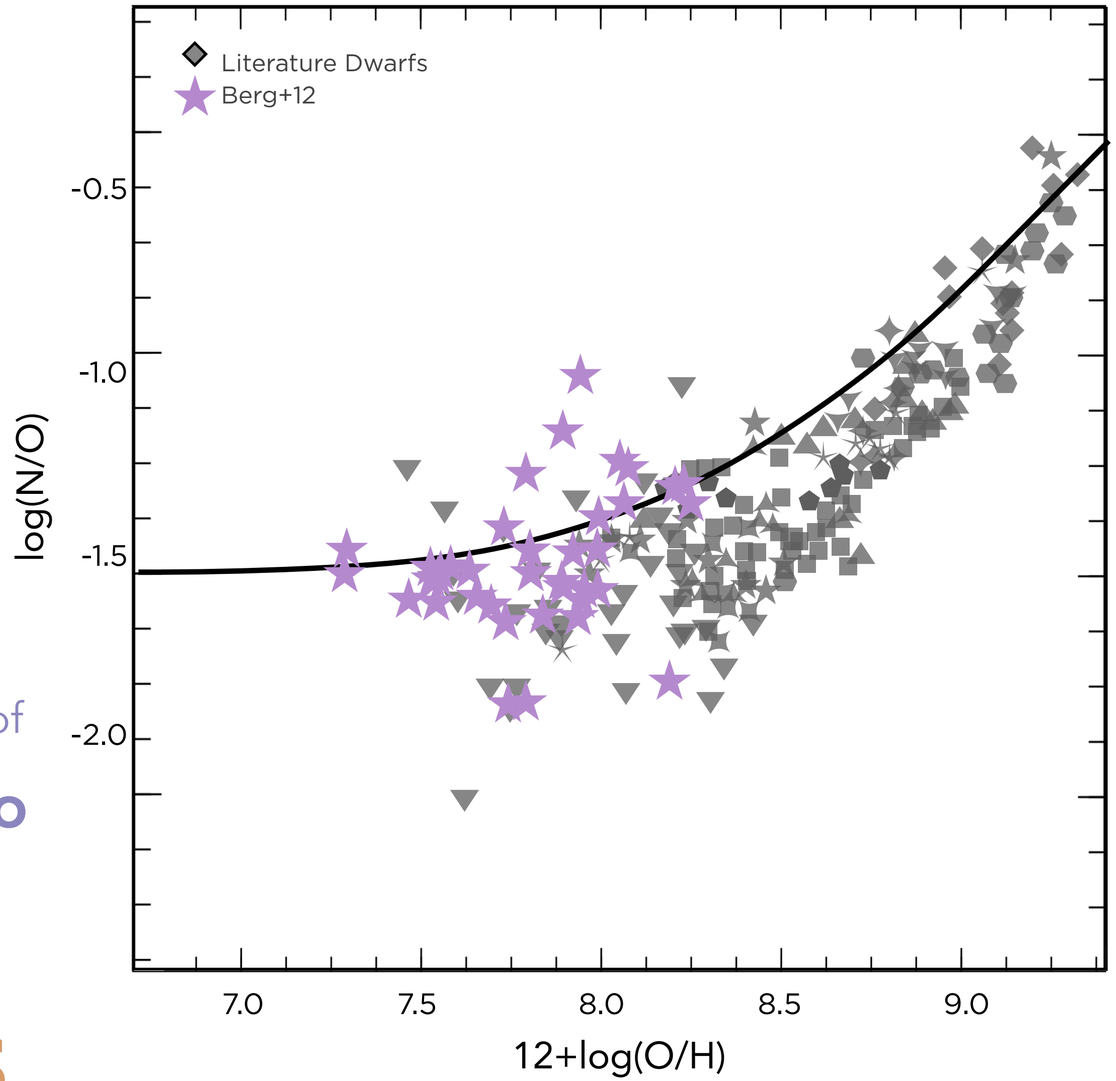
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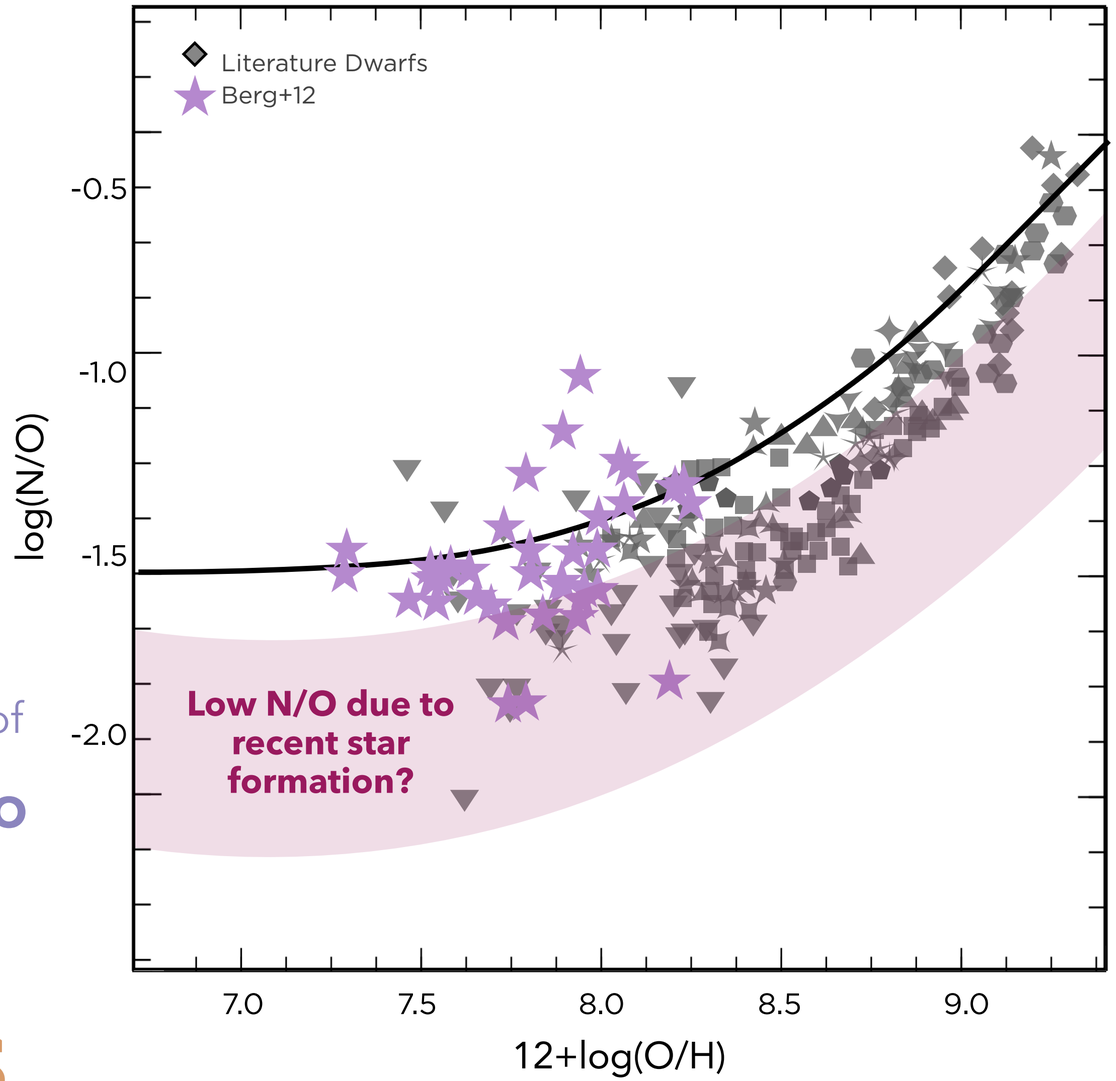
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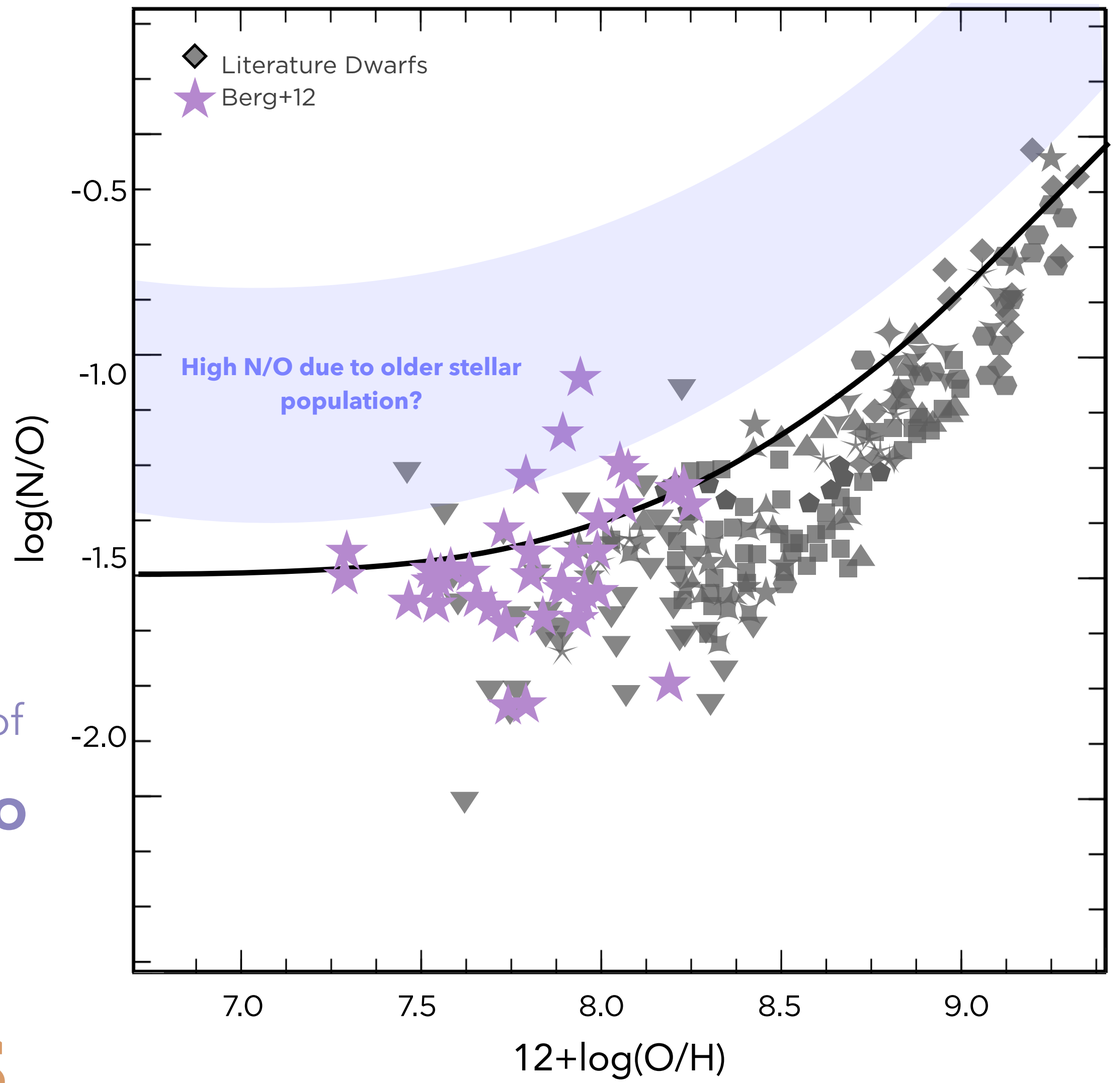
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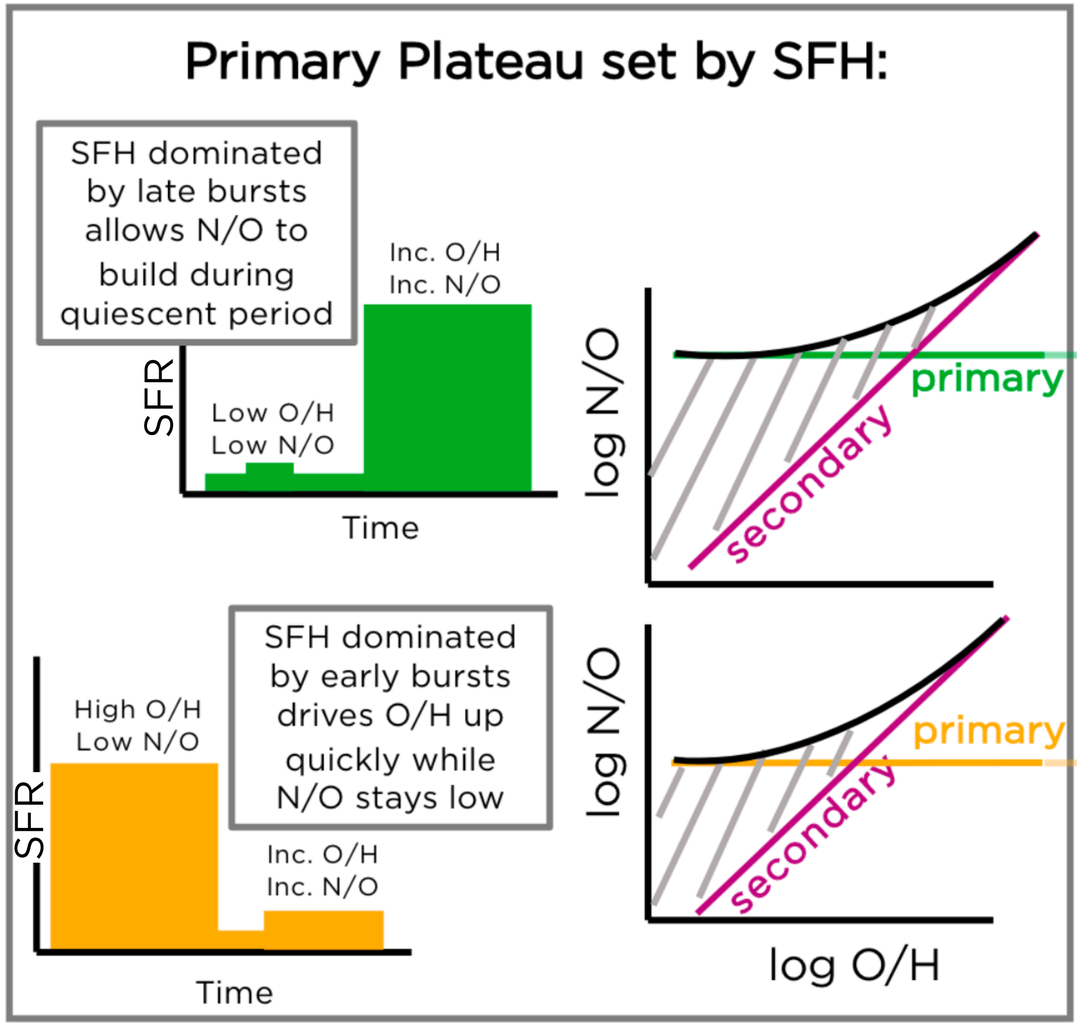
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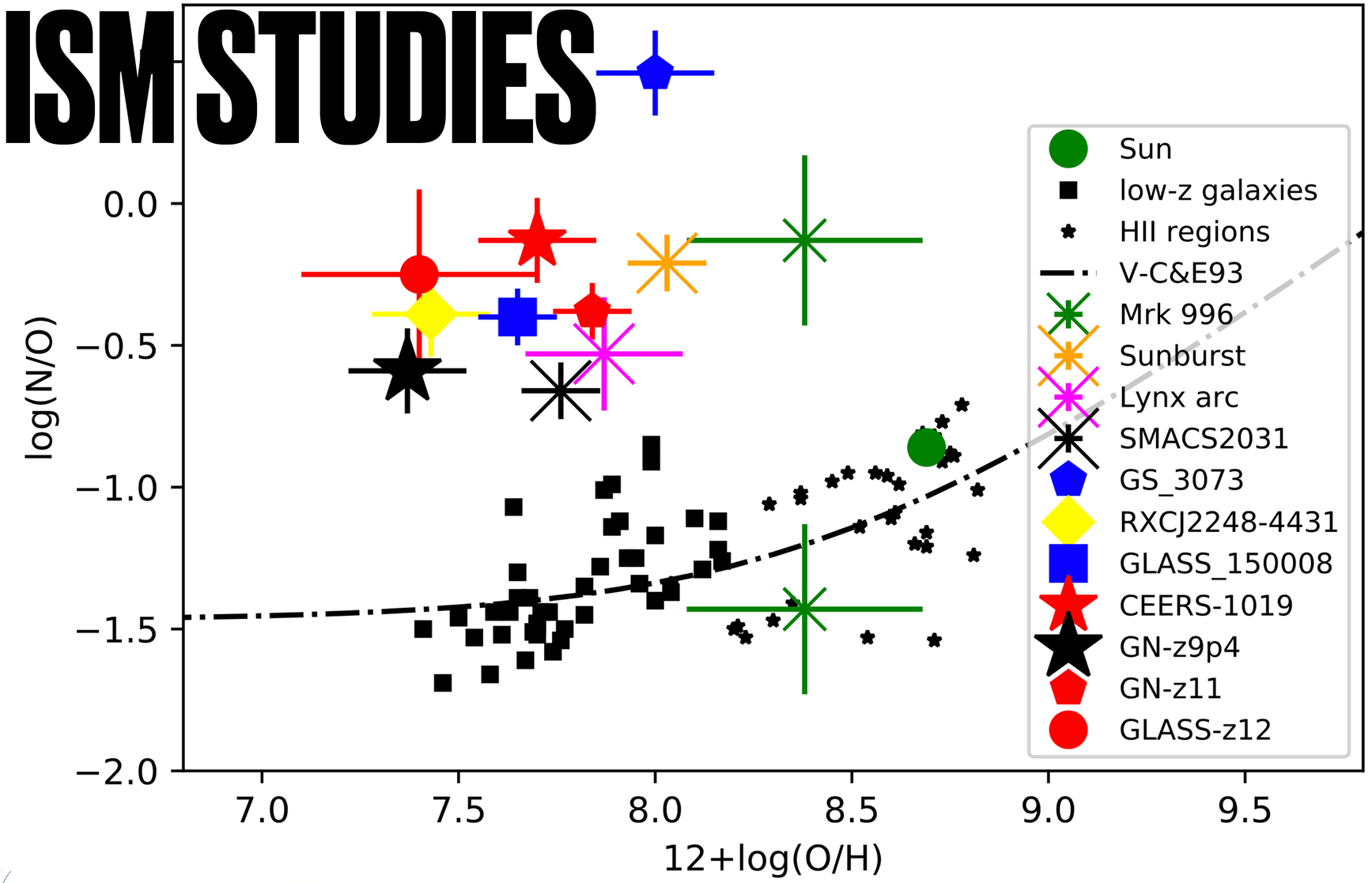
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Berg, D.A.+2020

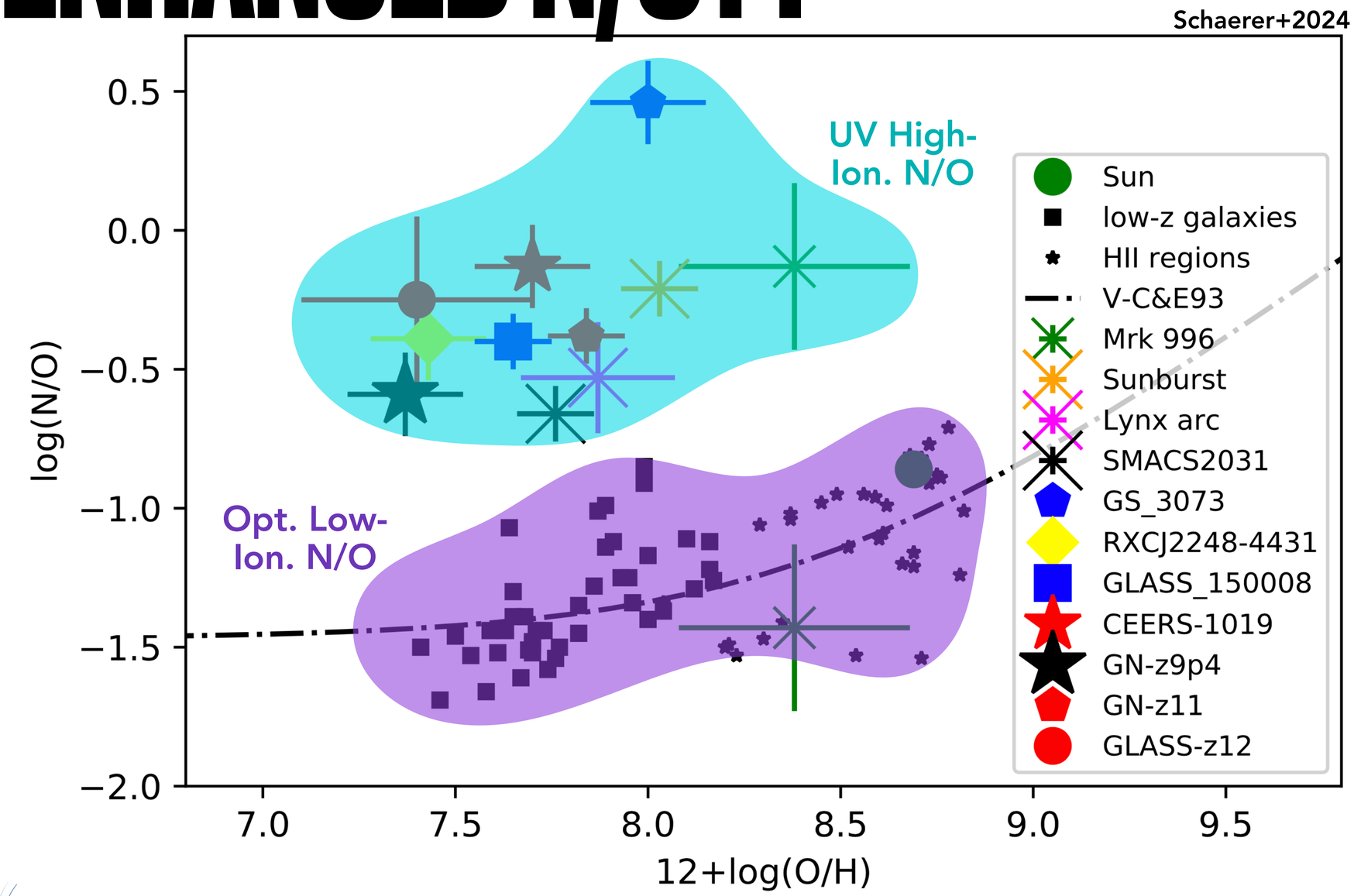
RENEWED INTEREST IN ISM STUDIES

Schaerer+2024



see also
Bunker+2023,
Cameron+2023,
Charbonnel+2023,
D'Antona+2023,
Kobayashi & Ferrara 2023
Maiolino+2023,
Marques-Chaves+2023,
Castellano+2024,
Curti+2024,
Ji+2024,
Navarro-Carrera+2024,
Pascale+2024,
Senchyna+2024
Topping+2024a,b,
Stiavelli+2025,
Isobe+2025
more

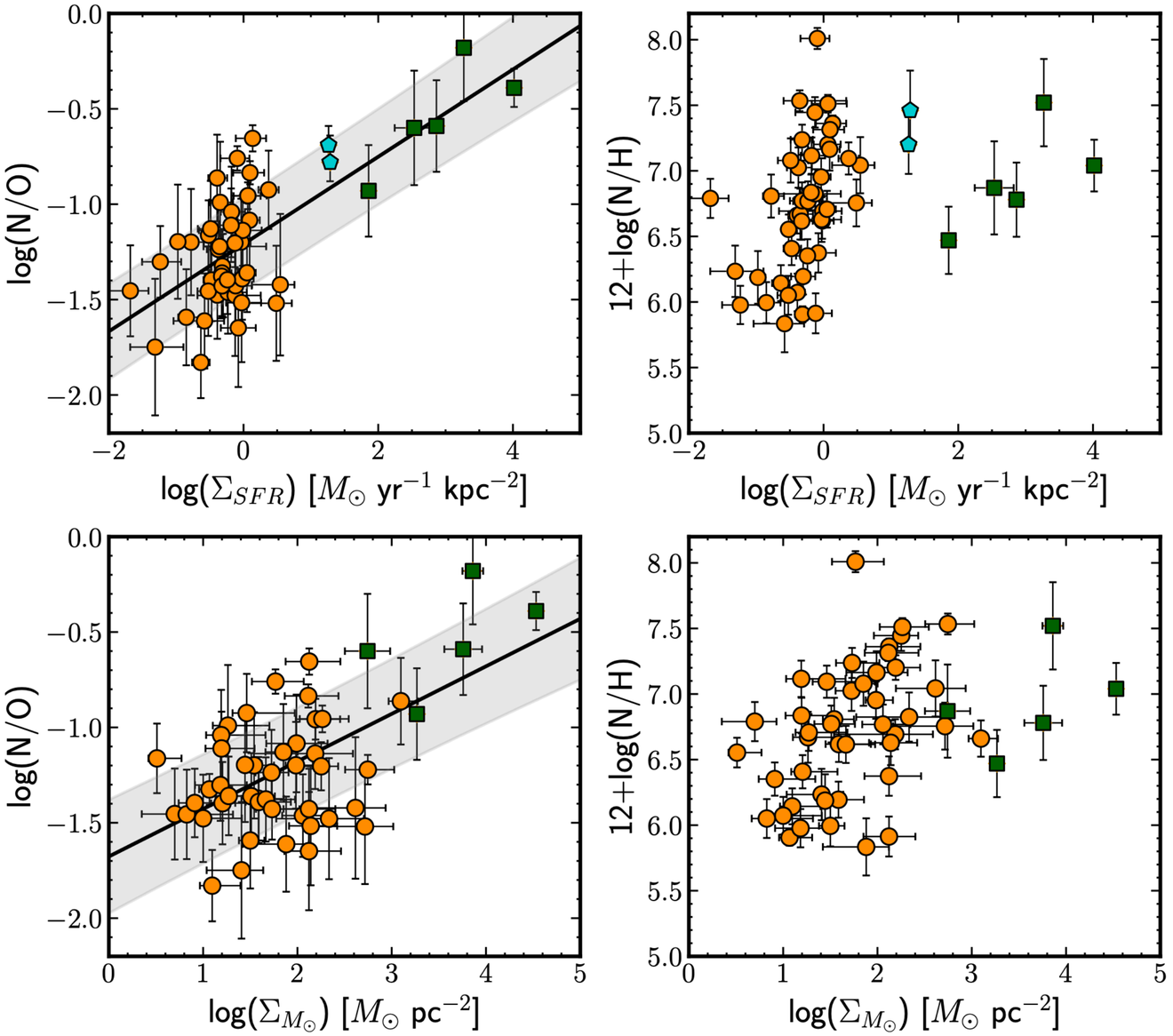
ENHANCED N/O??



We do **not** yet **understand UV N emission**, but it might require extreme conditions, such as very high densities and temperatures

primary vs secondary
low vs. high-ionization
super massive stars
WR stars
burstiness
duty cycle
TDEs
shocks
role of environment density
effective yields
population fraction

N/O EVOLUTION



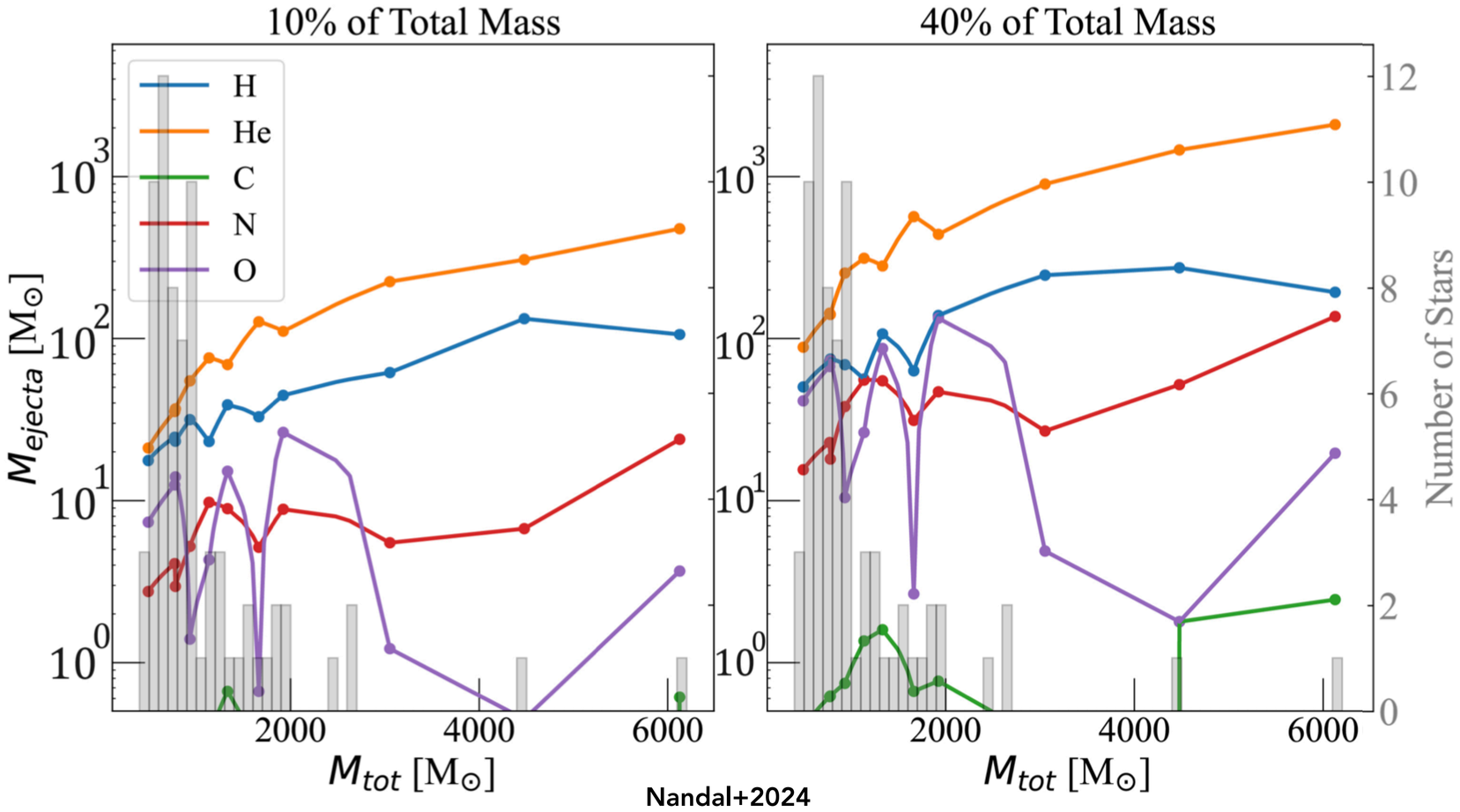
See, also, e.g.,
Schaerer+2024,
Martinez+2025

Arellano-Cordova+25 submitted to ApJ



Karla Arellano-Córdova
Postdoc
University of Edinburgh

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The University of Texas at Austin



Nandal+2024

see, also, Charbonnel+2023, Vink 2023, Schaerer+2024, etc.
see Kobayashi & Ferrara 2023 for SFH argument

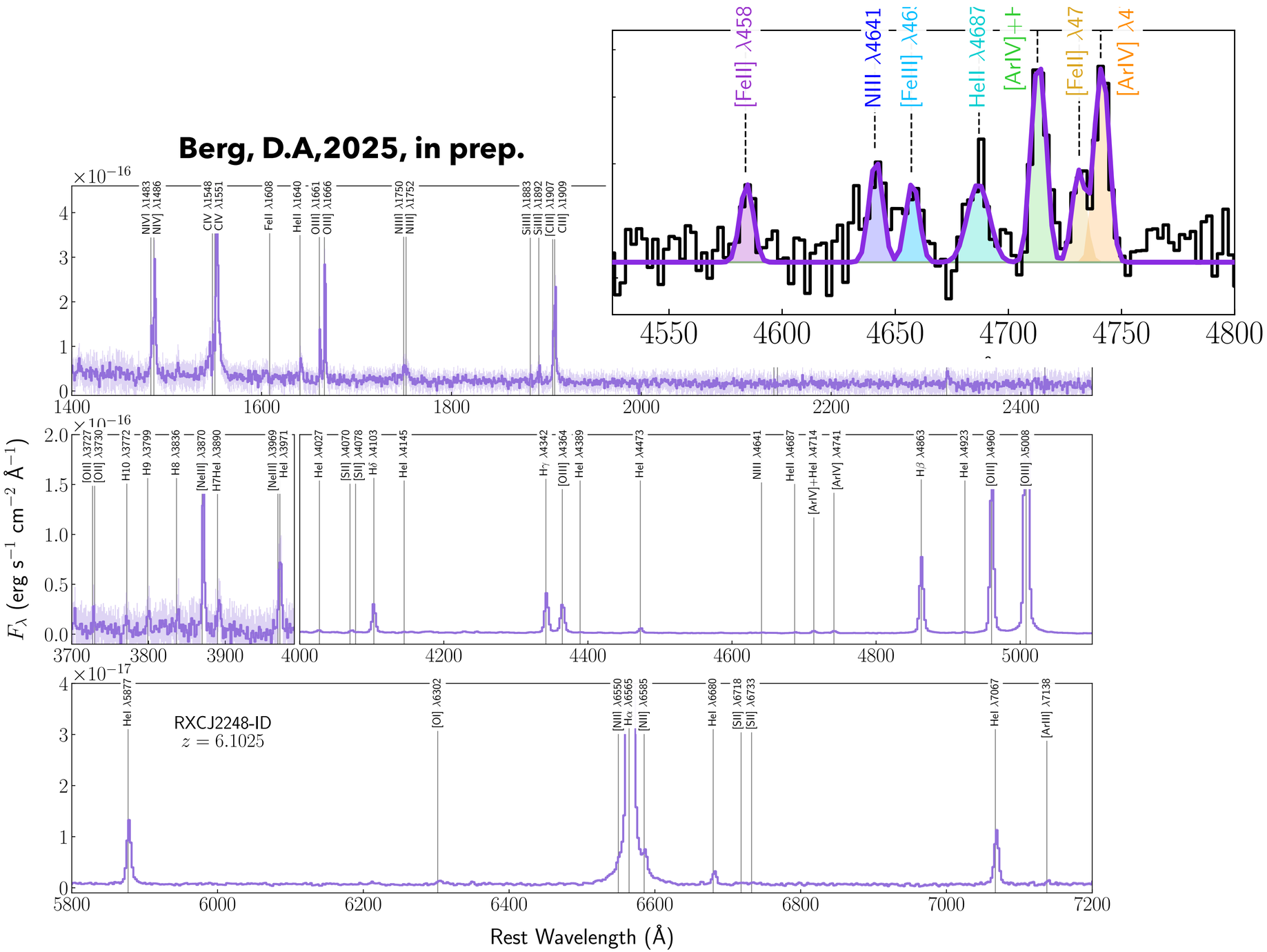
N/O EVOLUTION

Very massive stars could be responsible for **extreme enrichment patters** in early universe

Many studies argue for the **importance** of **timing /** recent **SFH**
e.g., intermittent SFH w/WRs; Kobayashi & Ferrara 2024

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N/O EVOLUTION



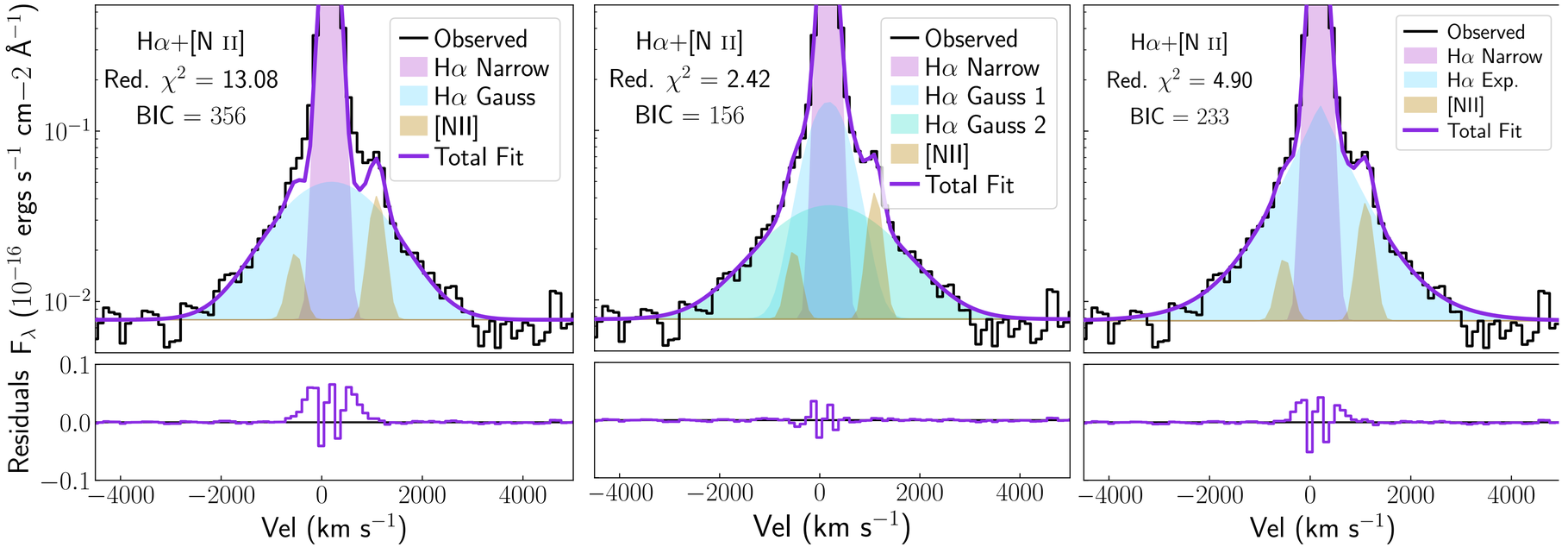
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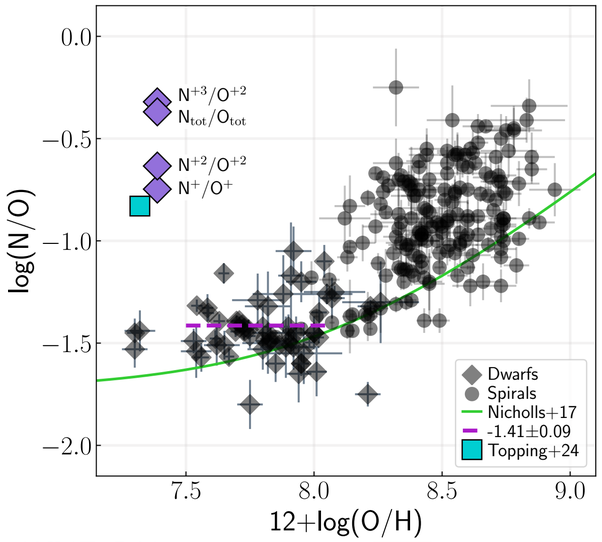
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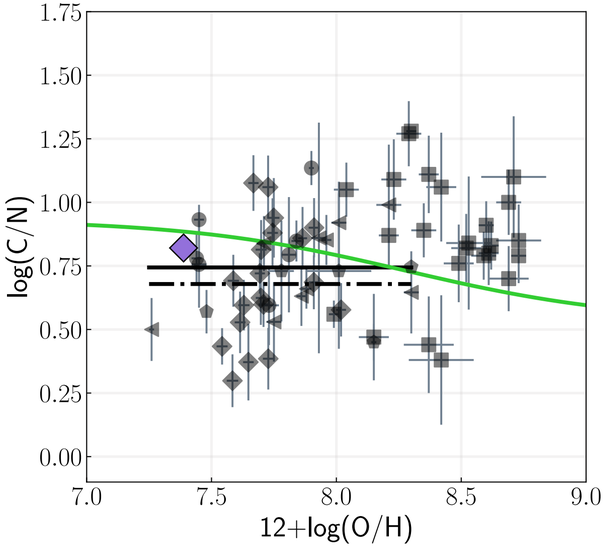
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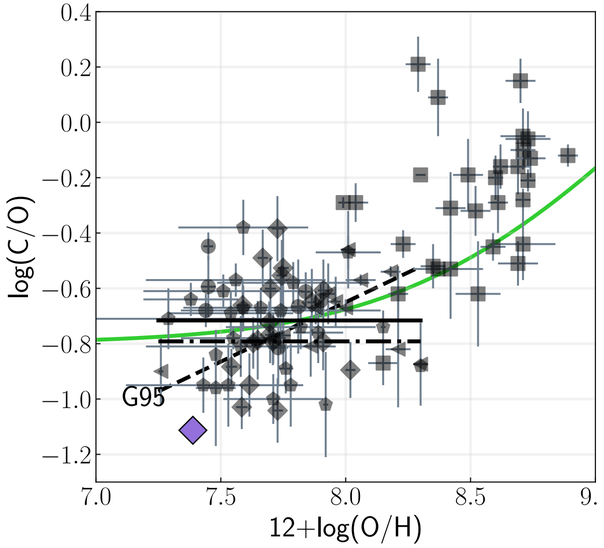
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Berg, D.A,2025, in prep.









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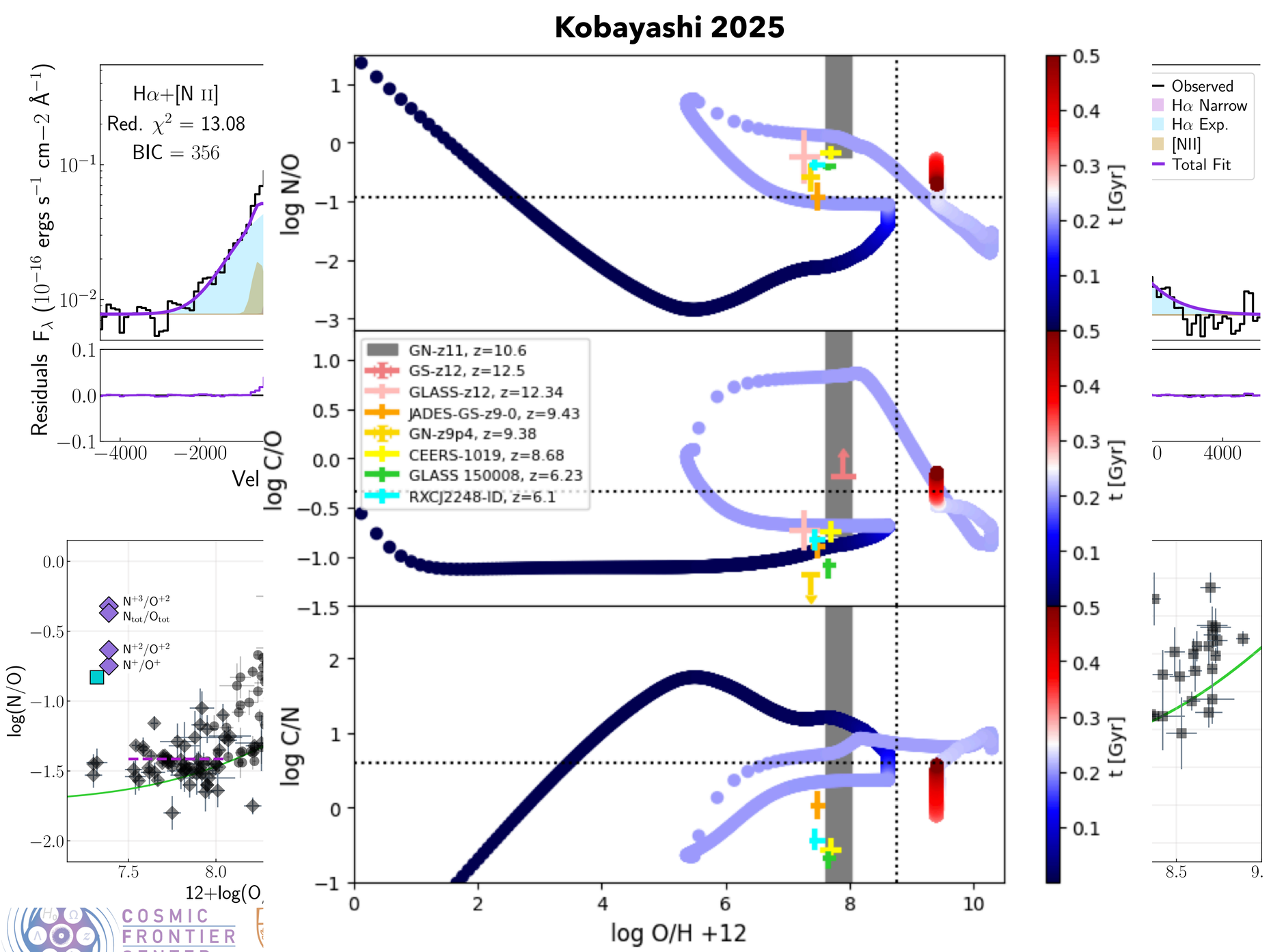
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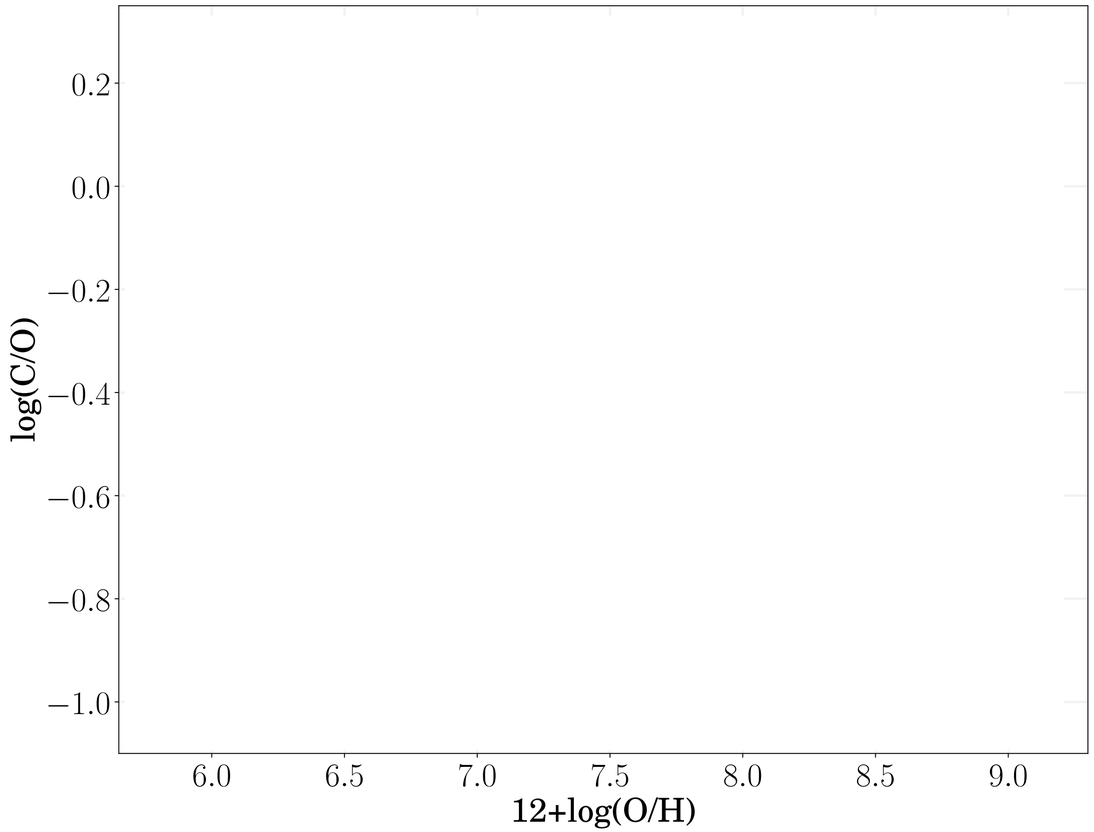
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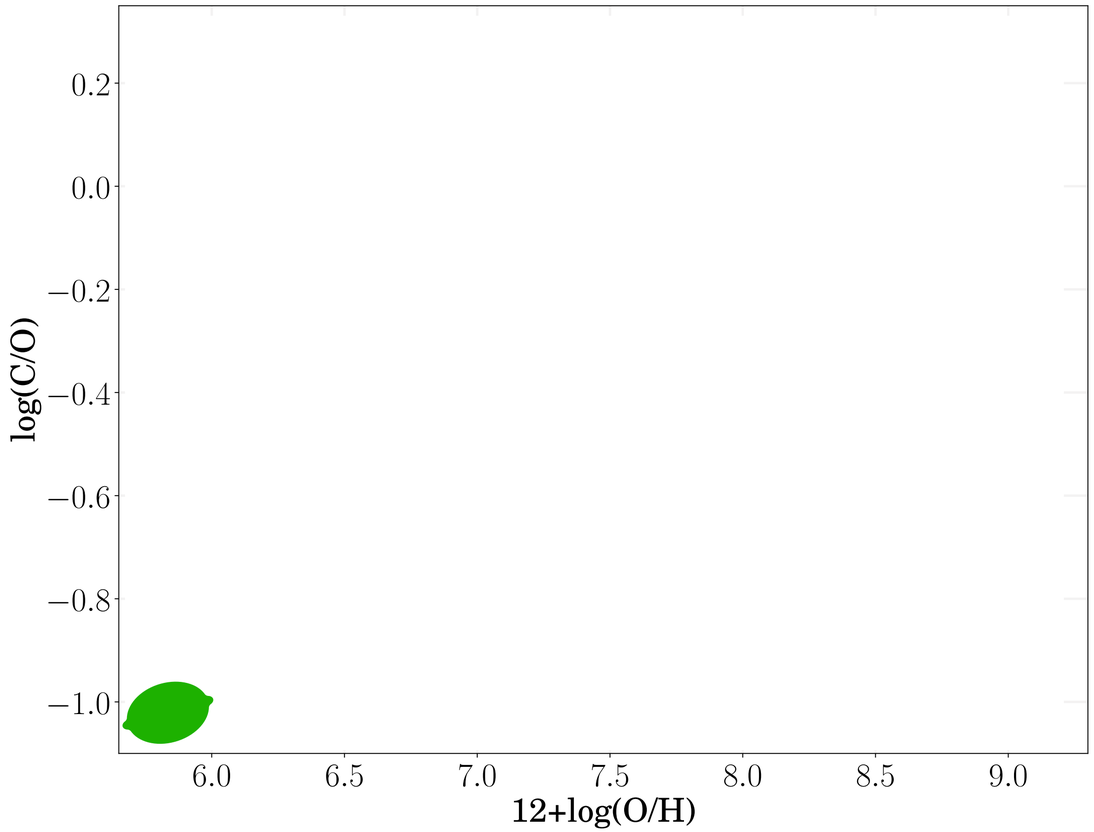
C/O EVOLUTION

C/O relative abundances
probe yields, feedback,
and **timescales**



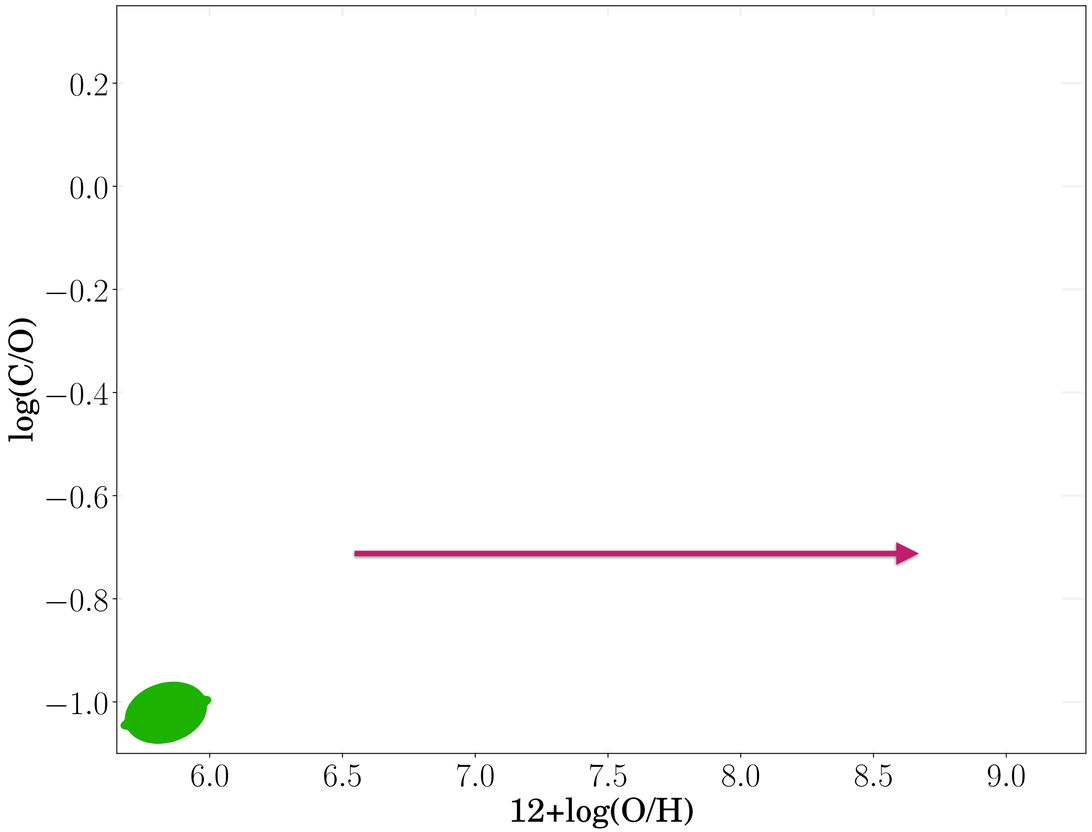
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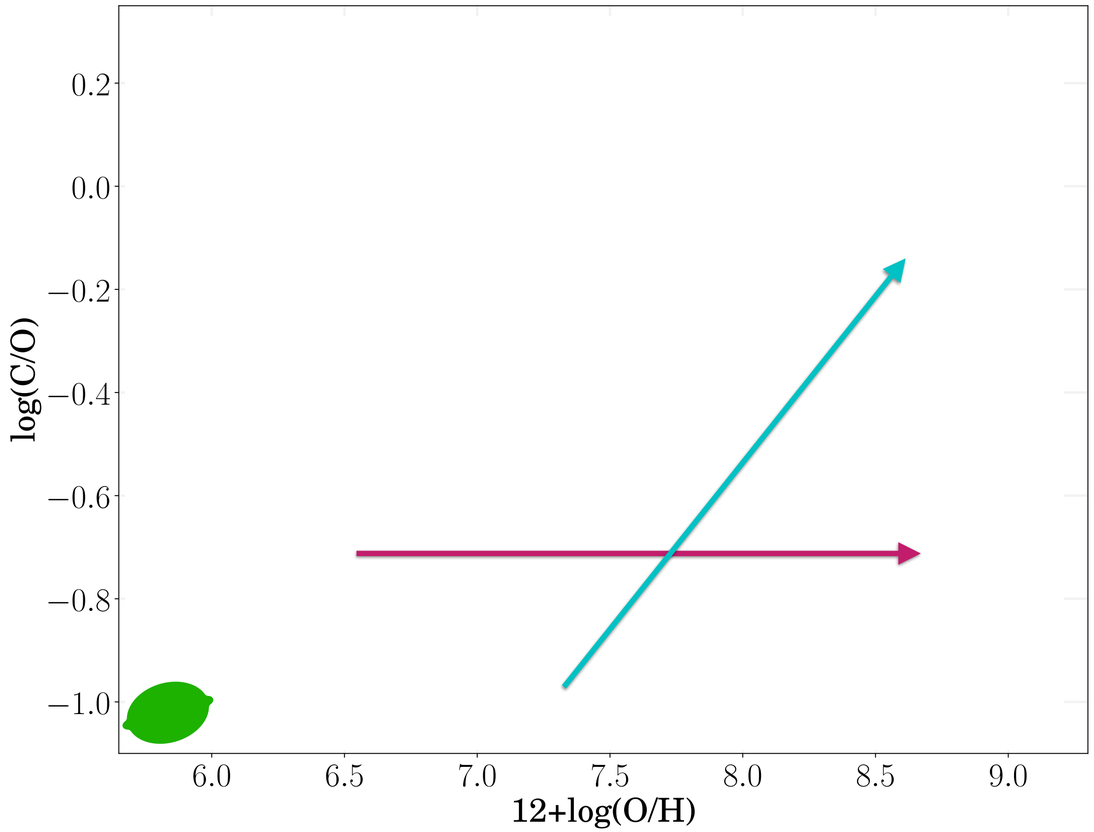
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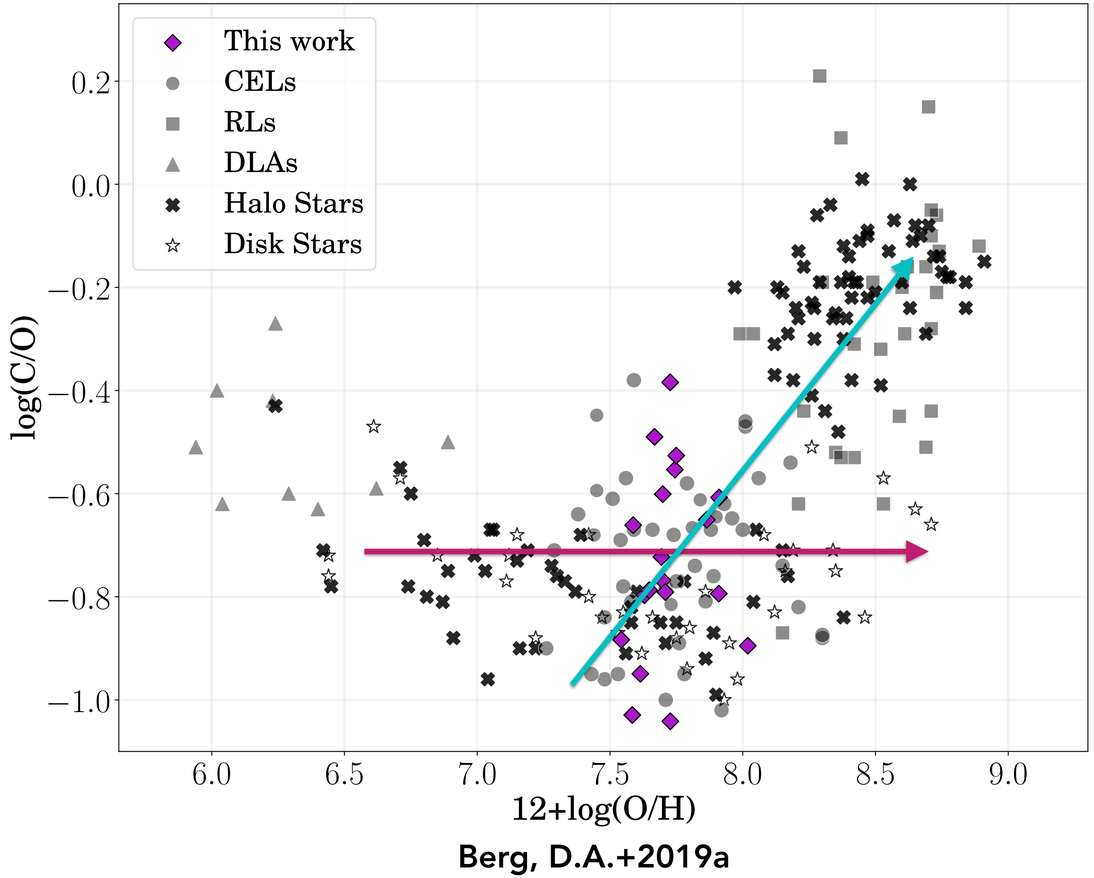
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DLAs:
Cooke+ 2017

Disk Stars:
Gustafsson+ 99
Halo Stars:
Akerman+04
Fabbian+ 09
Nissen+14

RLs:
Esteban+02
Peimbert+05
García-Rojas+07
López-Sánchez+07
Esteban+09
Esteban+14

High z:
Pettini+02
Fosbury+03
Erb+10
Christensen+12
Bayliss+14
James+14
Llerena+23
Stark+14
Steidel+16
Vanzella+16
Amorín+17
Rigby+17
Berg+18



Berg, D.A.+2019a

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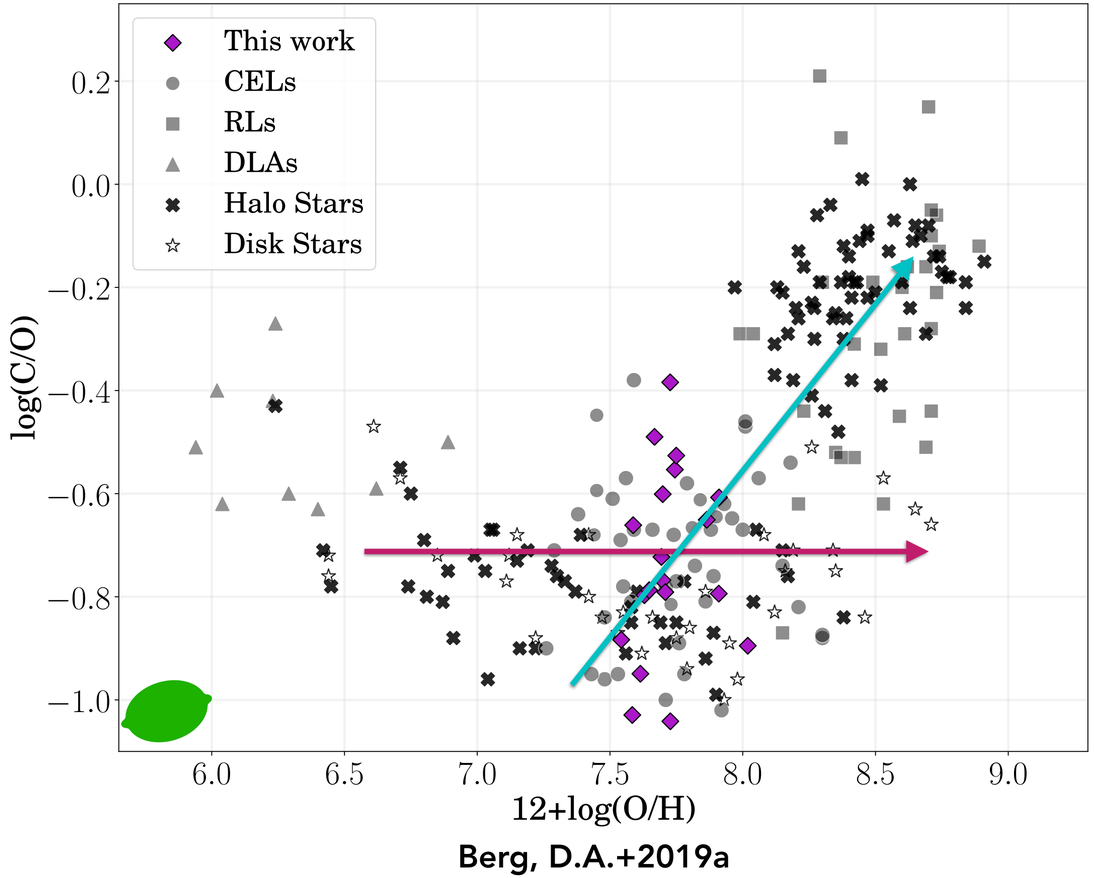
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Berg, D.A.+2019a

C/O EVOLUTION

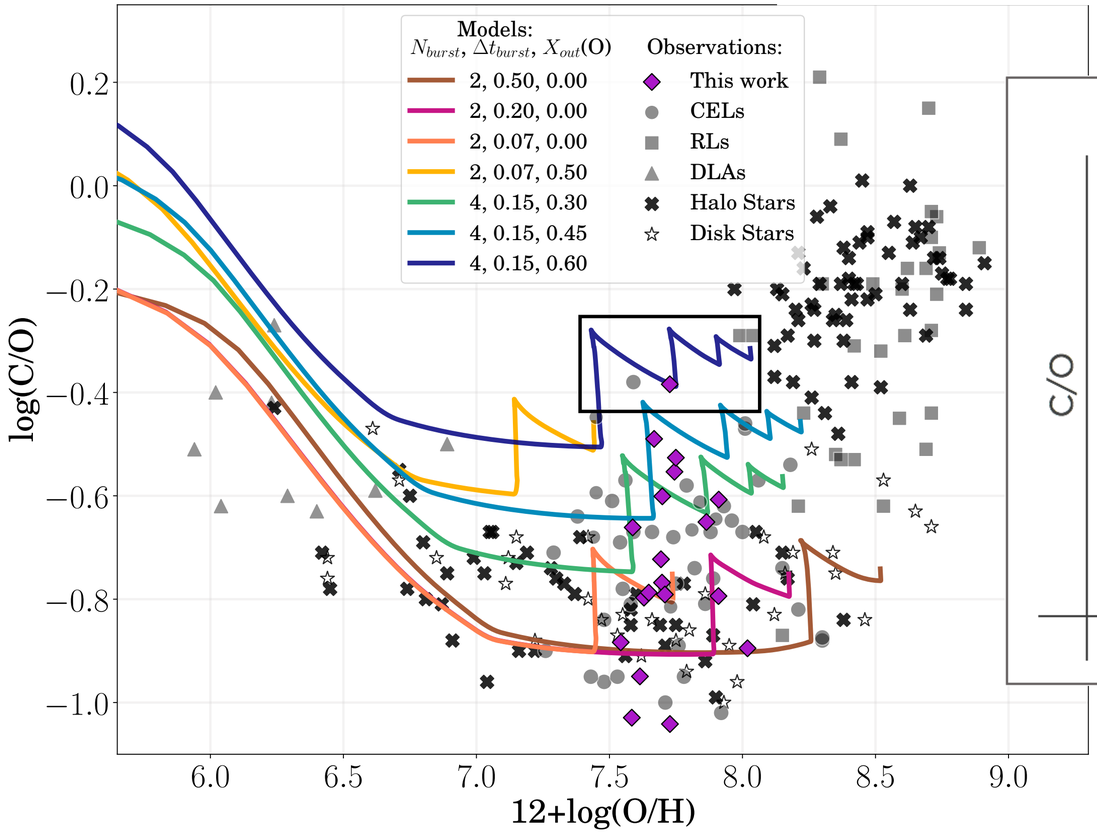
C/O relative abundances **probe yields, feedback**, and **timescales**

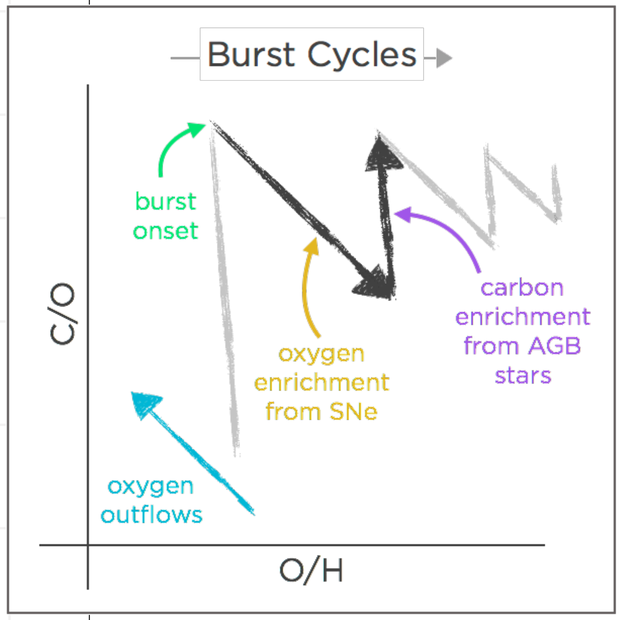
Disk Stars:
Gustafsson+ 99
Halo Stars:
Akerman+04
Fabbian+ 09
Nissen+14

RLs:
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Peimbert+05
García-Rojas+07
López-Sánchez+07
Esteban+09
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DLAs:
Cooke+ 2017

High z:
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Fosbury+03
Erb+10
Christensen+12
Bayliss+14
James+14
Llerena+23
Stark+14
Steidel+16
Vanzella+16
Amorín+17
Rigby+17
Berg+18





Berg, D.A.+2019a

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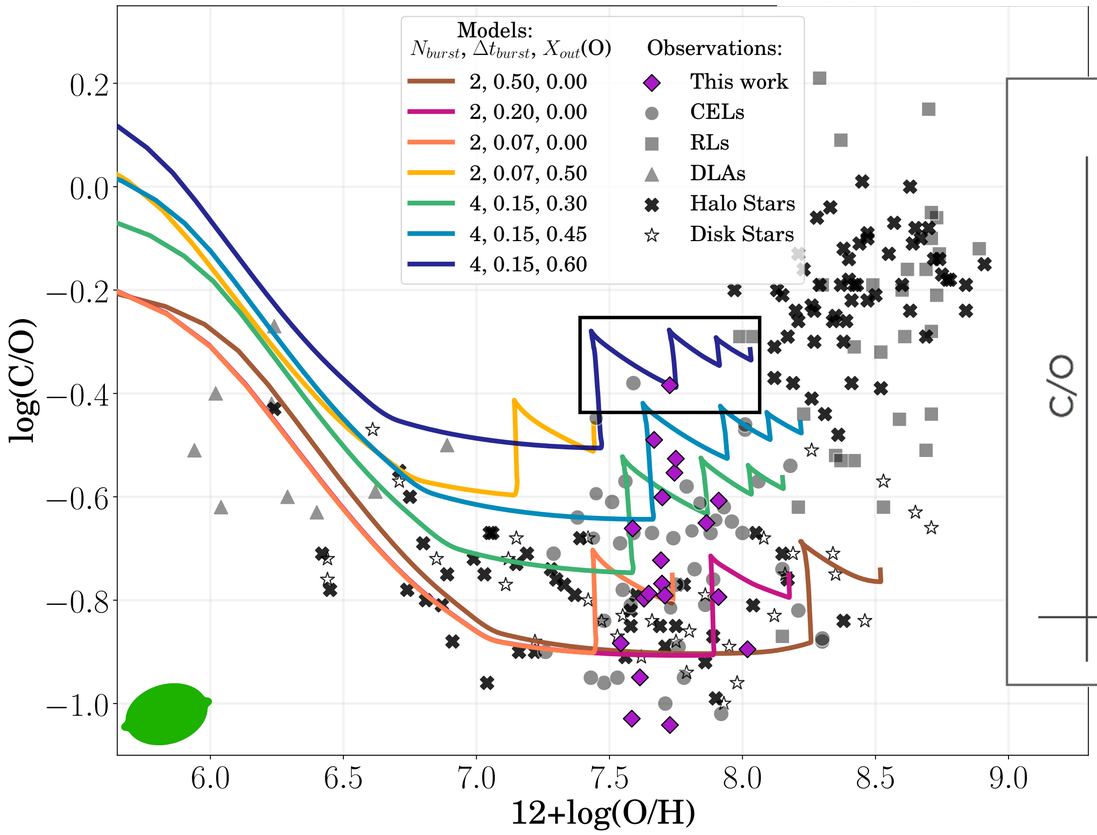
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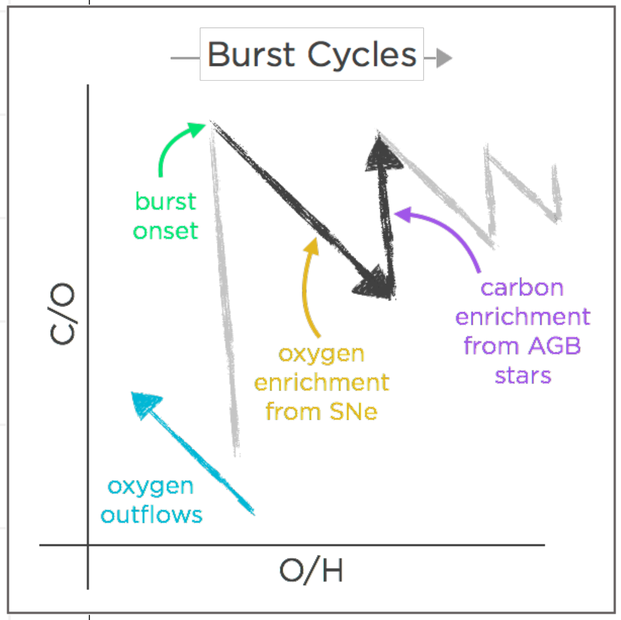
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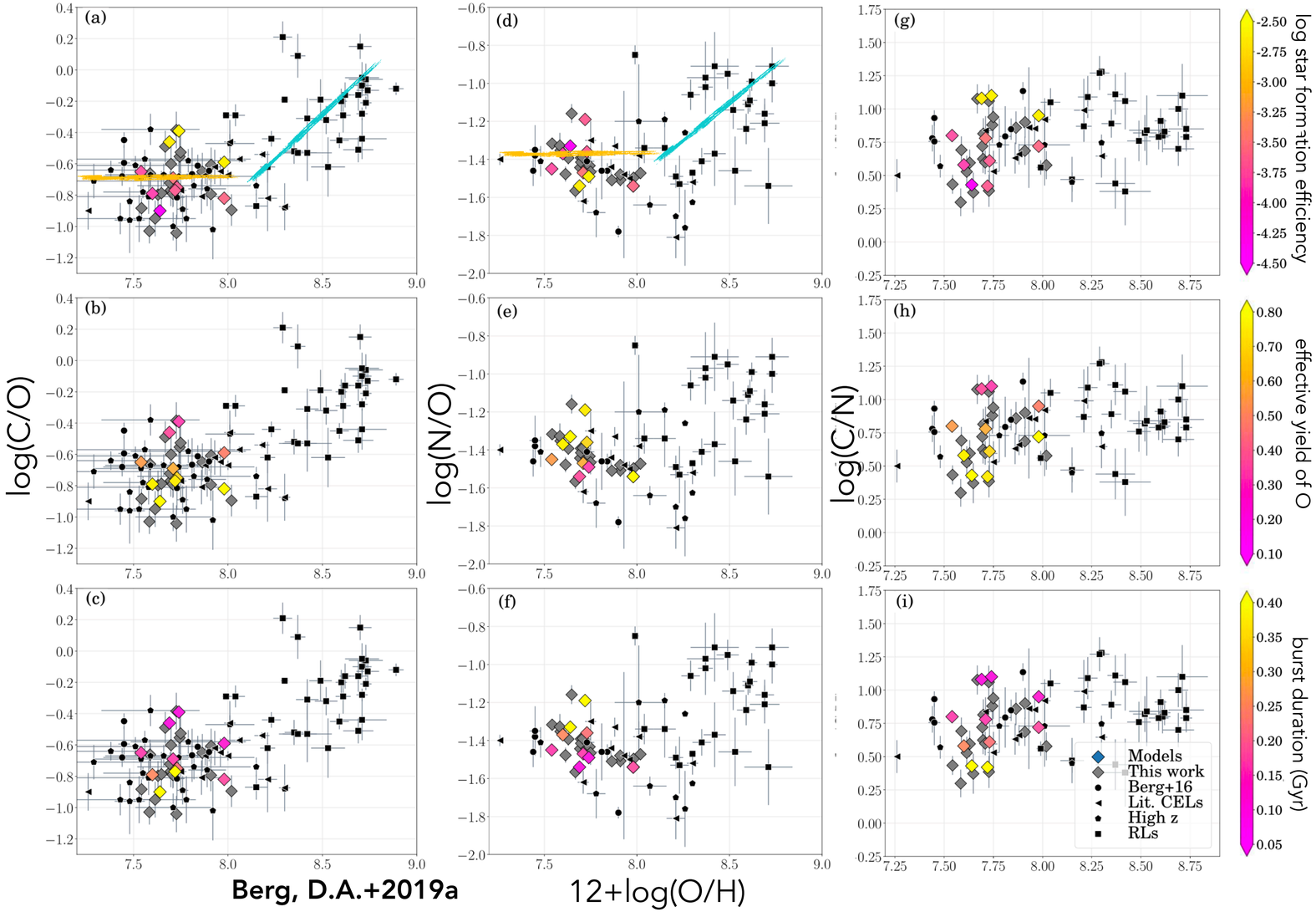


Berg, D.A.+2019a

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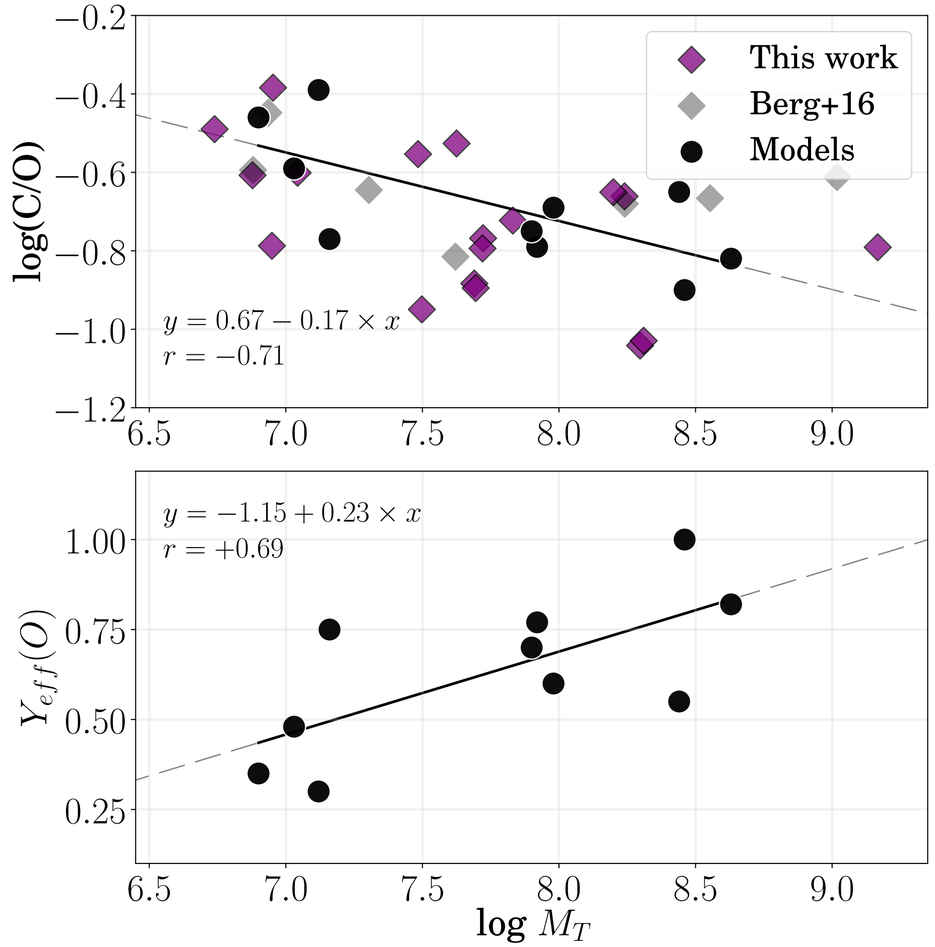
See, also, McQuinn+2019, Hamel Bravo+2024, and others

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High total galaxy **baryonic mass** produces stronger gravitational potential that **reduces outflows** / mass ejected

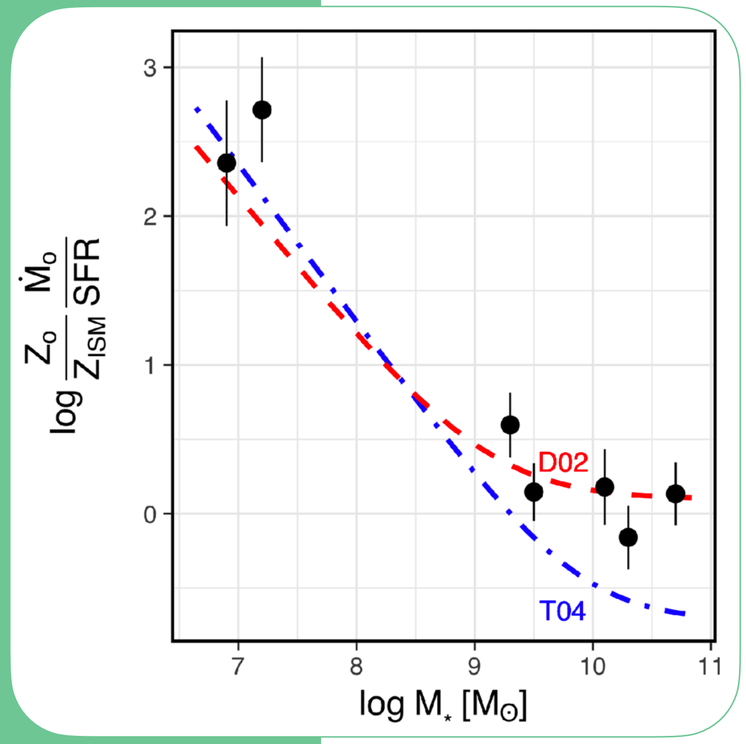


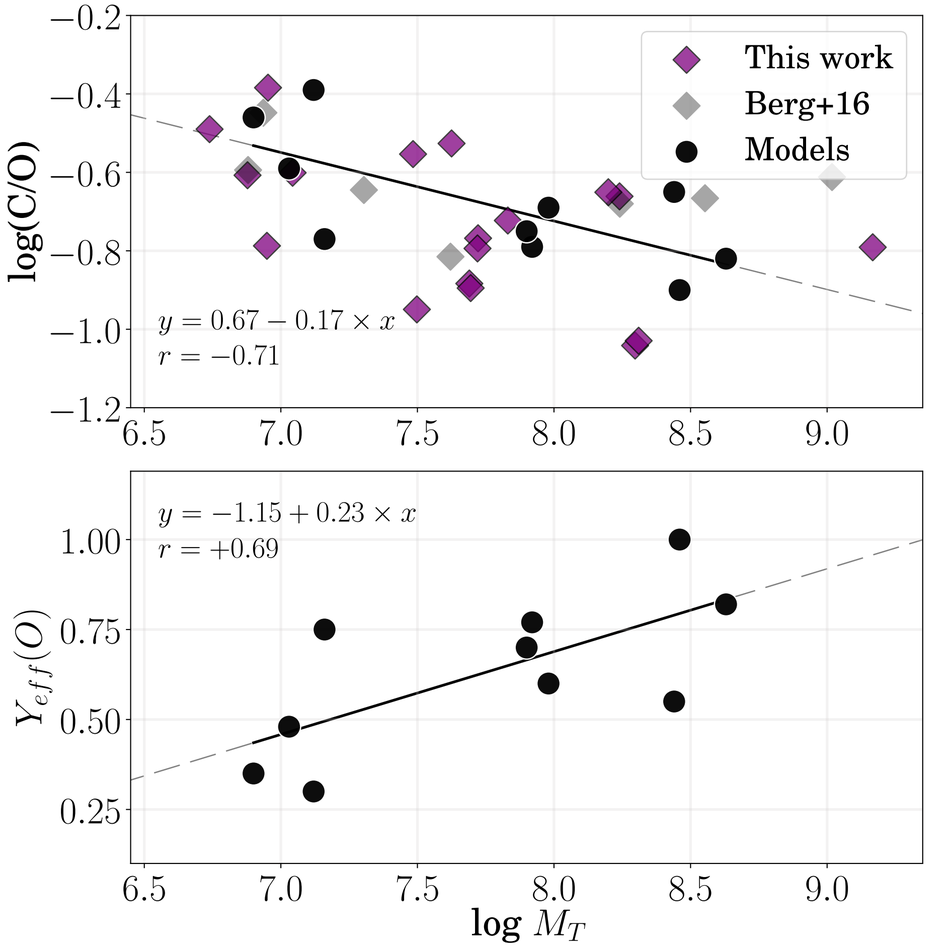
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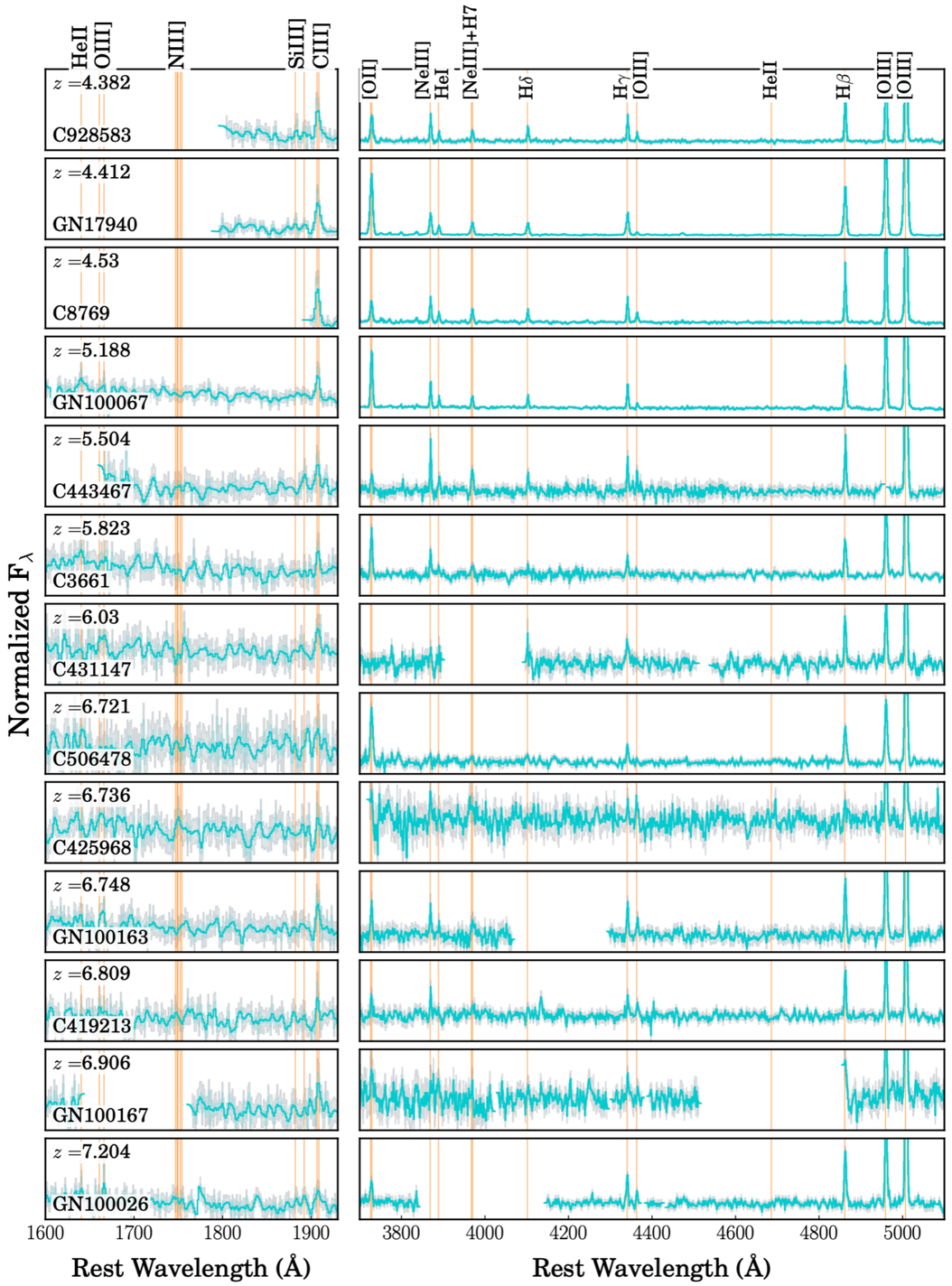




Consistent with **Chisholm+18** who found that: outflows from **lower-mass galaxies remove a larger fraction of** their gas-phase **metals** than more massive galaxies

C/O EVOLUTION

High-z sample from **Aurora** can trace significant C/O evolution for the first time





Aurora sample of 11 galaxies at 4.3 < z < 7.2

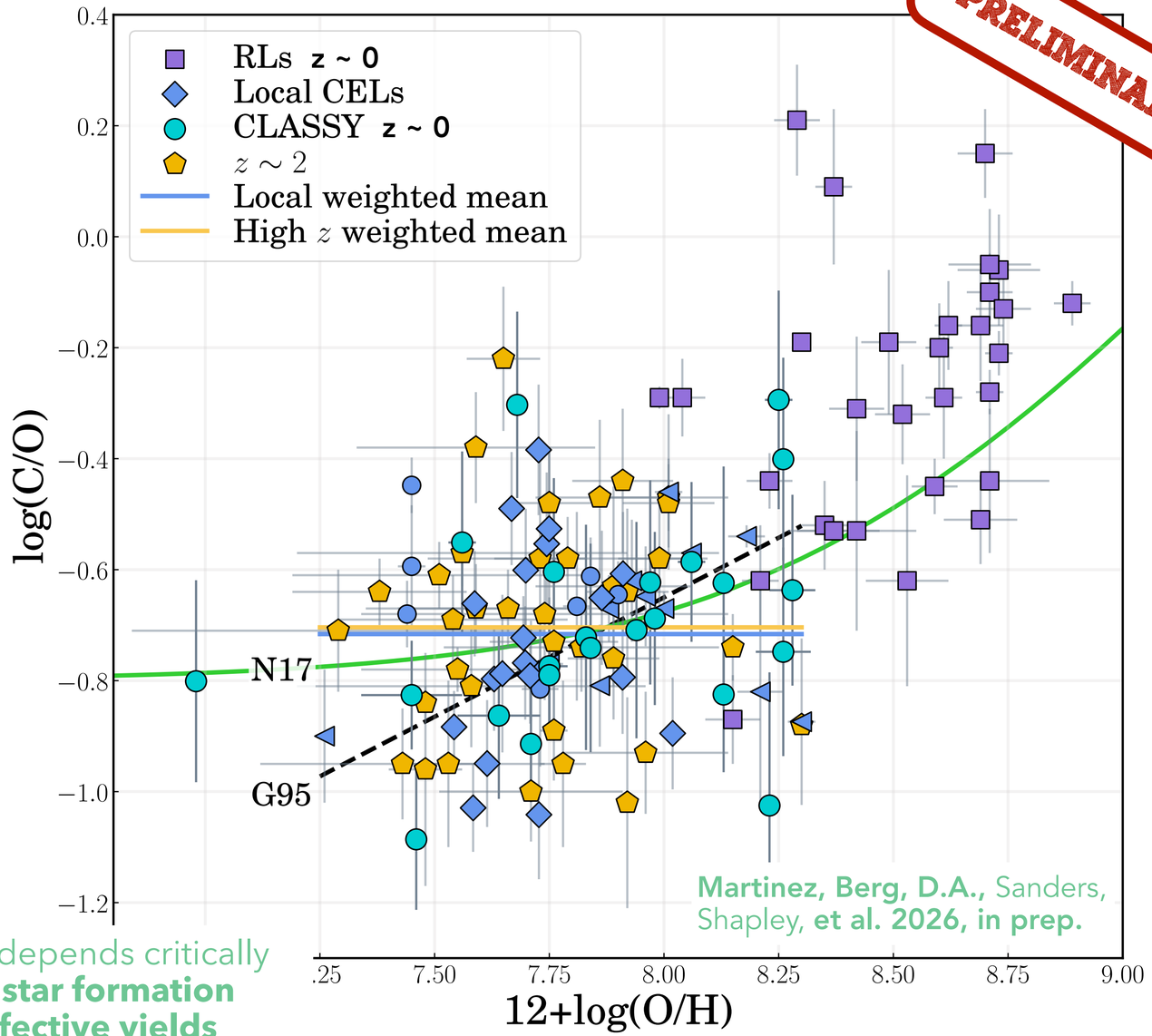
Martinez, Berg, D.A., Sanders, Shapley, et al. 2026, in prep.

C/O EVOLUTION

Our current measurements show **no evolution of C/O.**

PRELIMINARY





Martinez, Berg, D.A., Sanders, Shapley, **et al. 2026, in prep.**

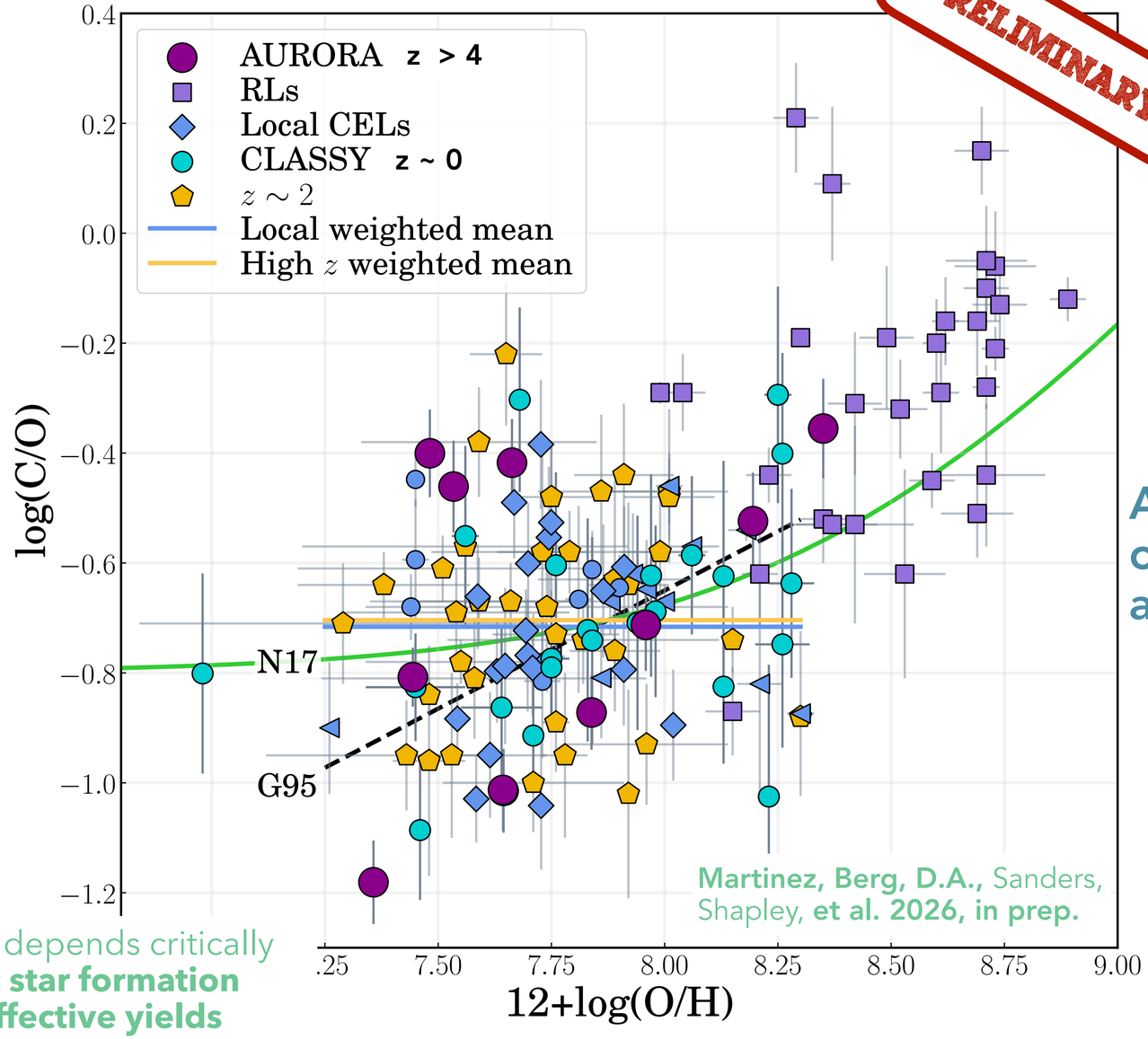
C production is complicated, unknown dependence on metallicity(?), SFH, burst age, preferential outflows, etc.

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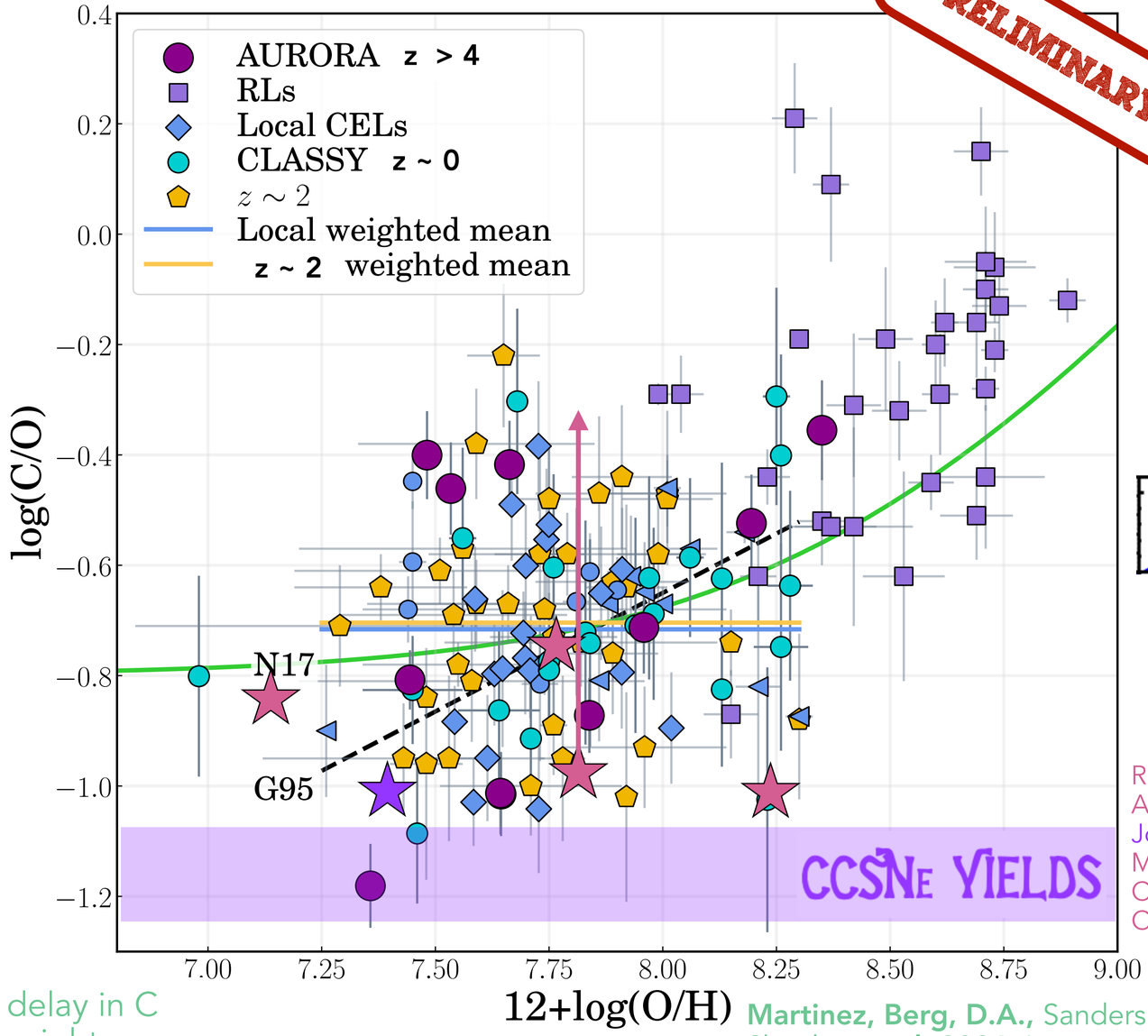
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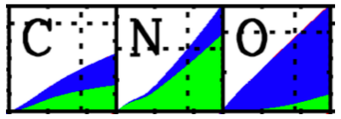
PRELIMINARY







CCSNe AGB



Kobayashi+2020

References (left to right):
Arellano-Cordova+22 (z=8.5)
Jones+23 (z=6.2)
Marques-Chaves+23 (z=8.7)
Cameron+23 (z=10.6)
Citro, Berg, D.A.+23 (z~4)

Martinez, Berg, D.A., Sanders, Shapley, **et al. 2026, in prep.**

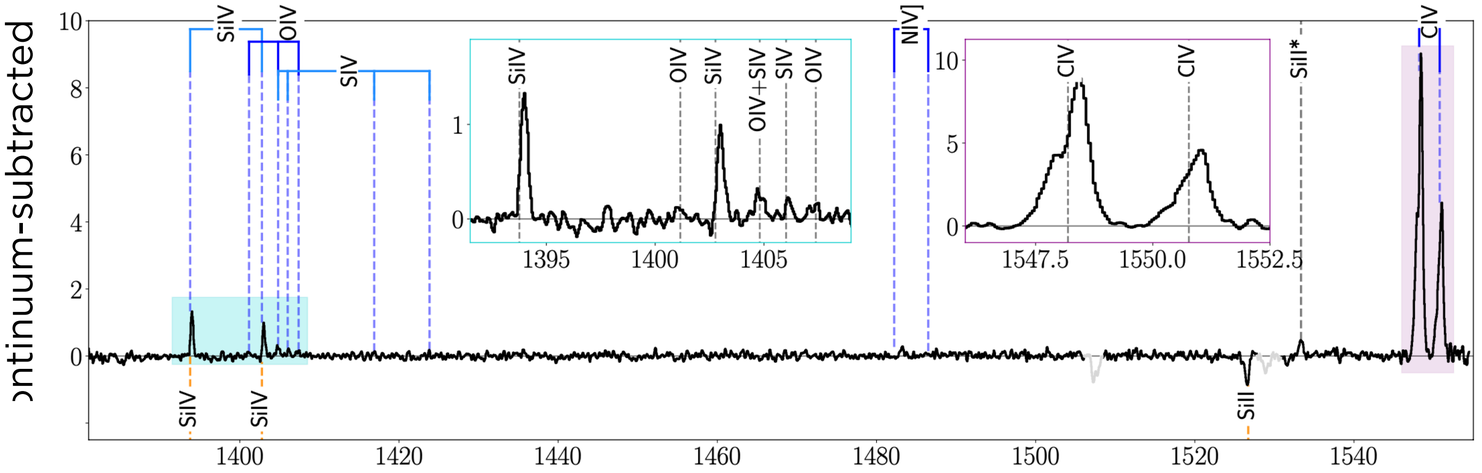
Could C/O be used as a diagnostic of very young galaxies?

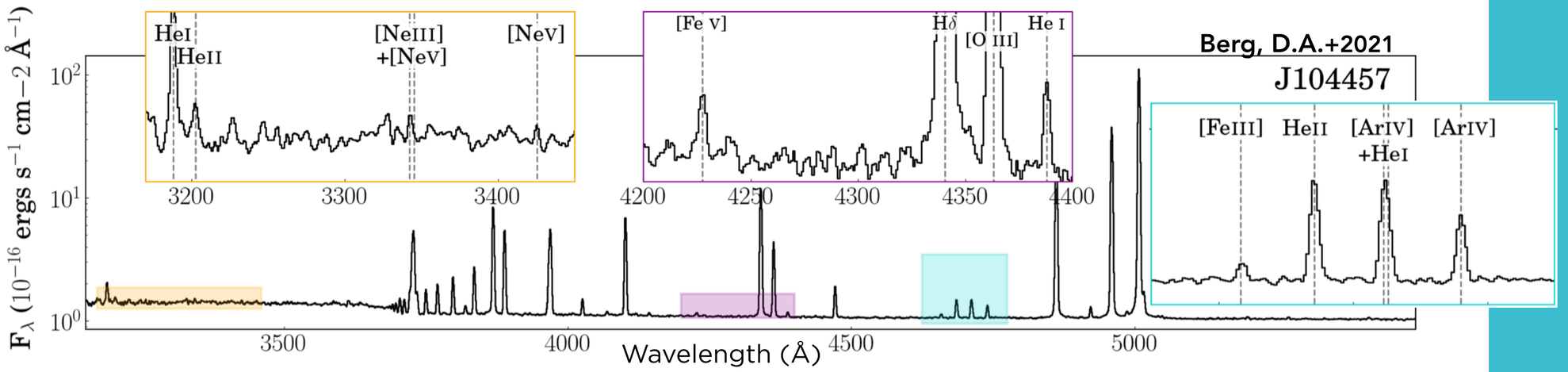
Given the time delay in C production, we might expect to see a delay in C enrichment at high-z …

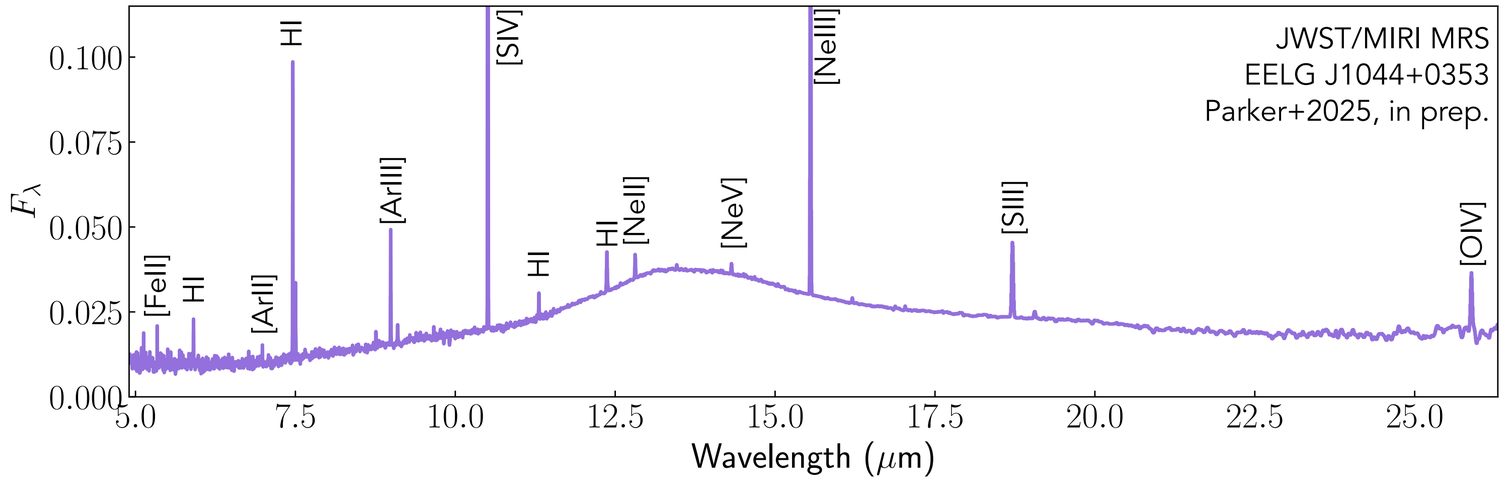
PART III:
EELGS OFFER PROBES OF EARLY UNIVERSE CONDITIONS

EELGS

J1044+0353







We can ***map*** the **ionizing continuum** with **emission lines**

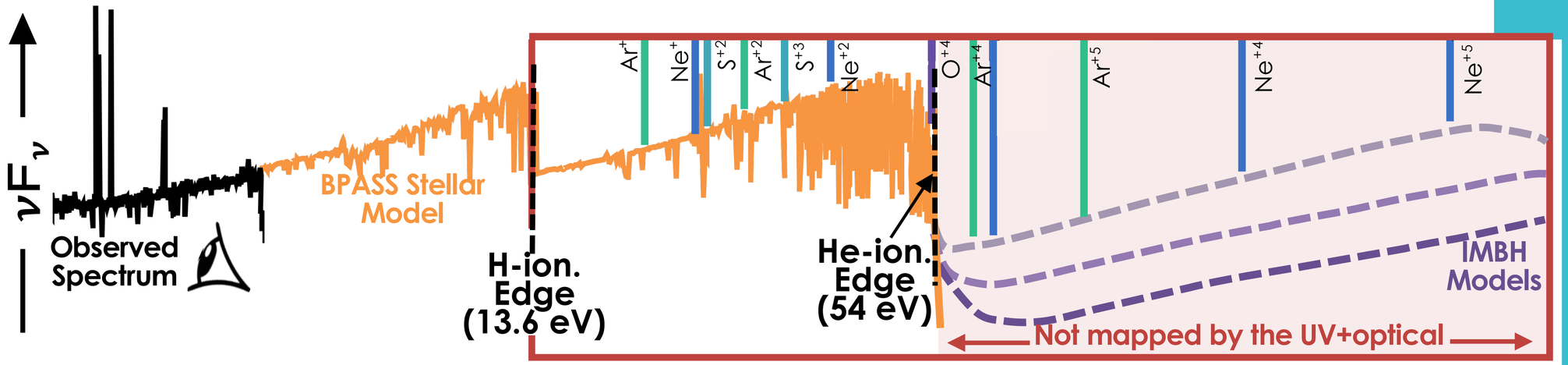
We do **not** have direct empirical constraints on the **shape of ionizing continua**

So use **emission lines** at **many** ionization **energies** as markers

Danielle A Berg
COSMIC FRONTIER CENTER

EELGS

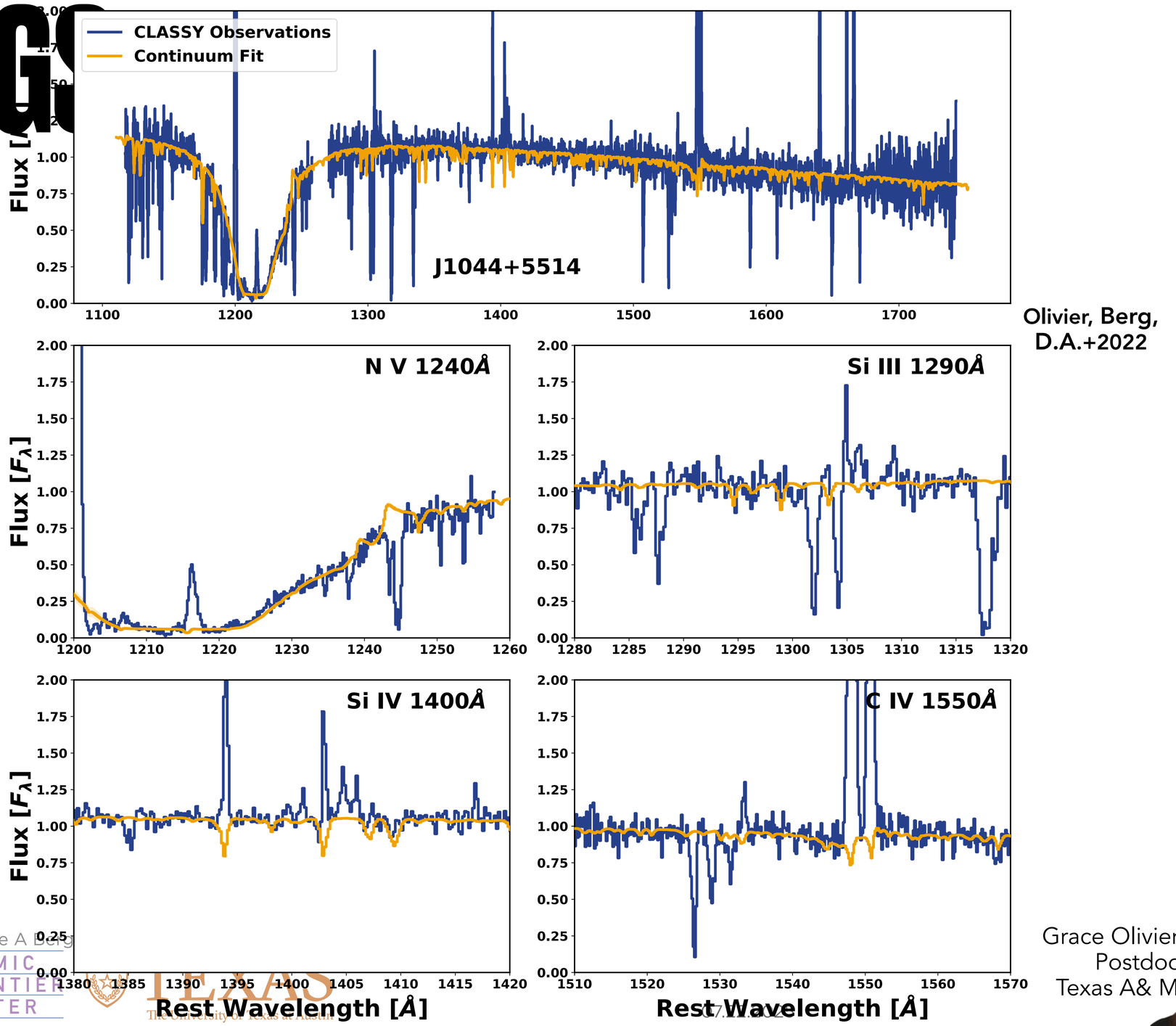
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Olivier, Berg, D.A.+2022

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First consistent stellar + nebular photoionization modeling

Grace Olivier
Postdoc
Texas A& M

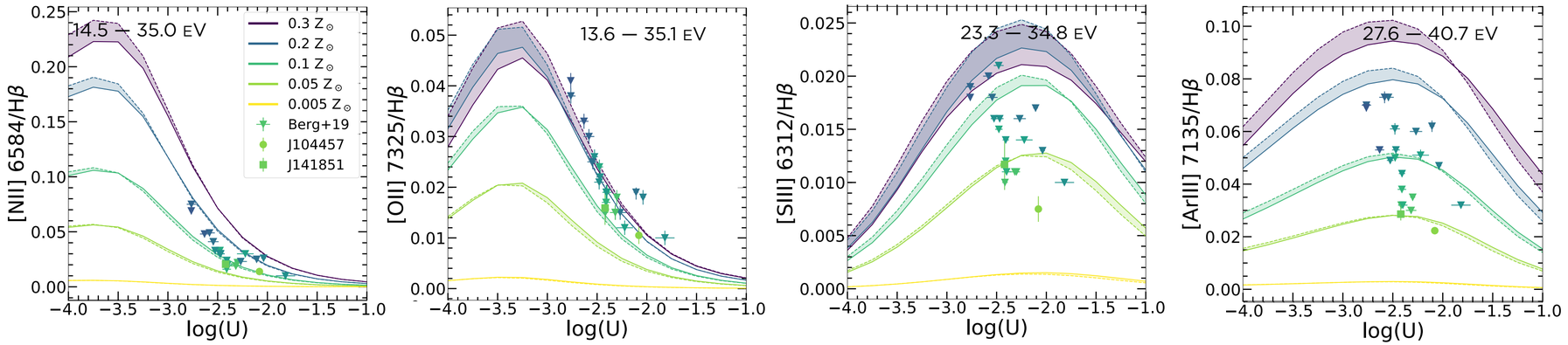


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COSMIC FRONTIER CENTER
TEXAS
The University of Texas at Austin

EELGS

The High-Energy Photon Production Problem (HEIP^3):
Stellar population synthesis models are unable to reproduce emission lines with ionization energies ≳ 35 eV

Low Ionization



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07.22.2025

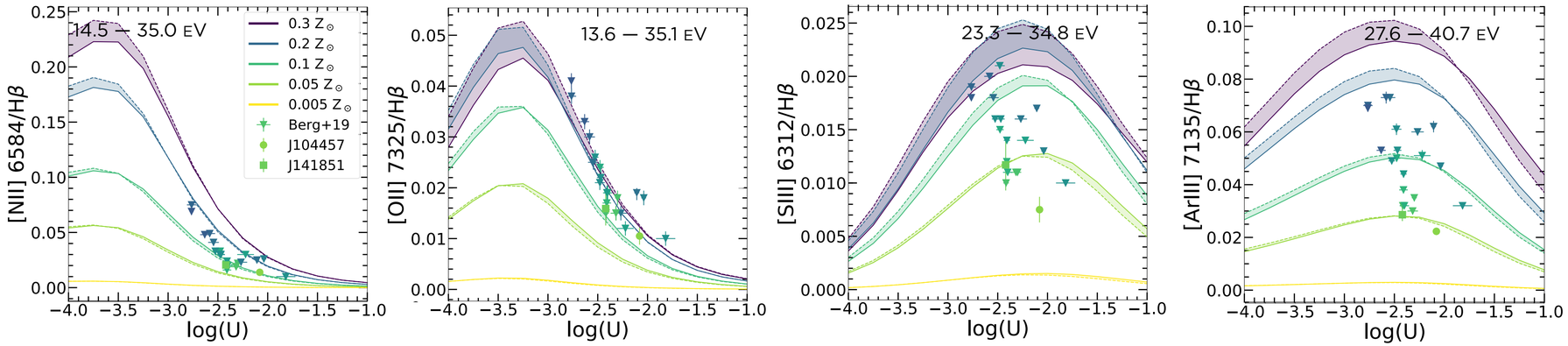
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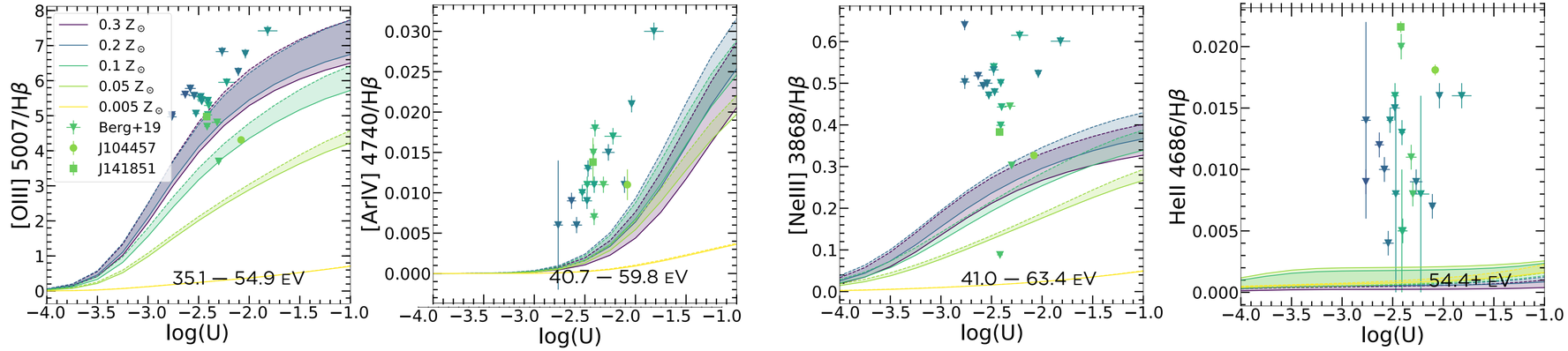
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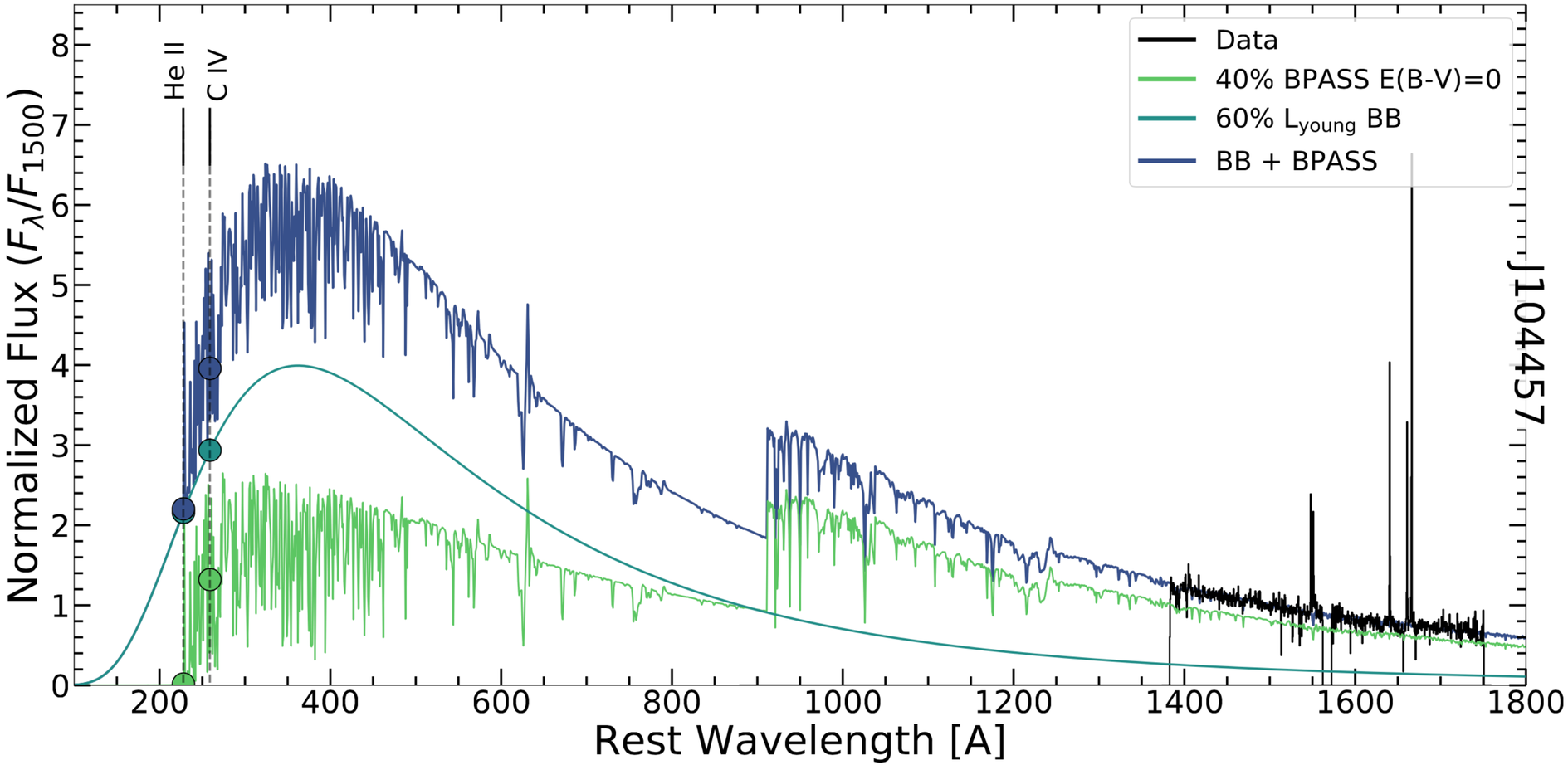
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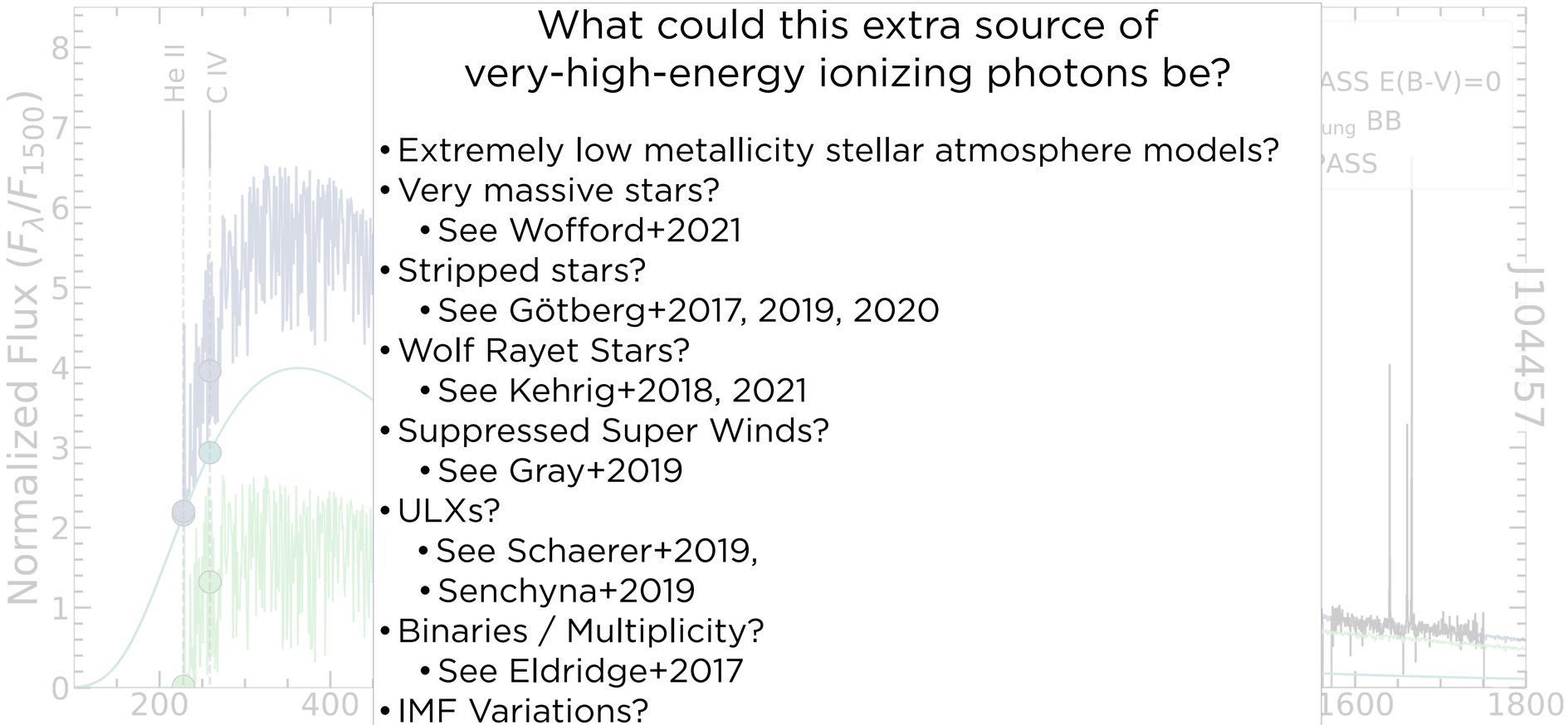
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What could this extra source of very-high-energy ionizing photons be?

- Extremely low metallicity stellar atmosphere models?
- Very massive stars?
  - See Wofford+2021
- Stripped stars?
  - See Götberg+2017, 2019, 2020
- Wolf Rayet Stars?
  - See Kehrig+2018, 2021
- Suppressed Super Winds?
  - See Gray+2019
- ULXs?
  - See Schaerer+2019,
  - Senchyna+2019
- Binaries / Multiplicity?
  - See Eldridge+2017
- IMF Variations?
  - See Stanway & Eldridge 2019

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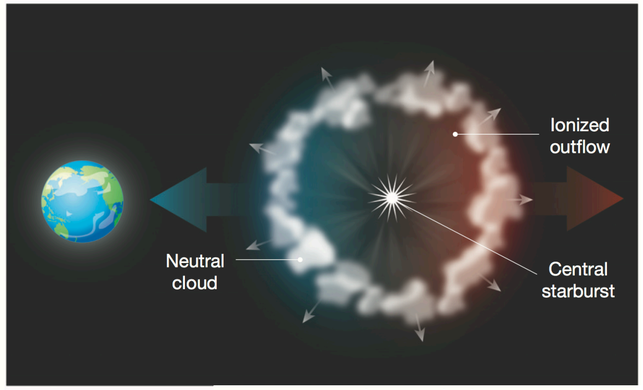


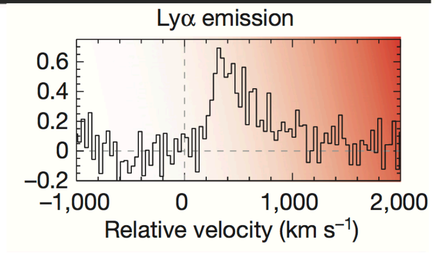
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EELGS

FUV resonant extreme emission lines tells us about the **porosity of the CGM** and the **escape of ionizing radiation**

Lyα profiles tells us about the geometry/ porosity of the neutral H
CGM gas is complex.
LyA profile observed depends on both aperture and viewing angle.



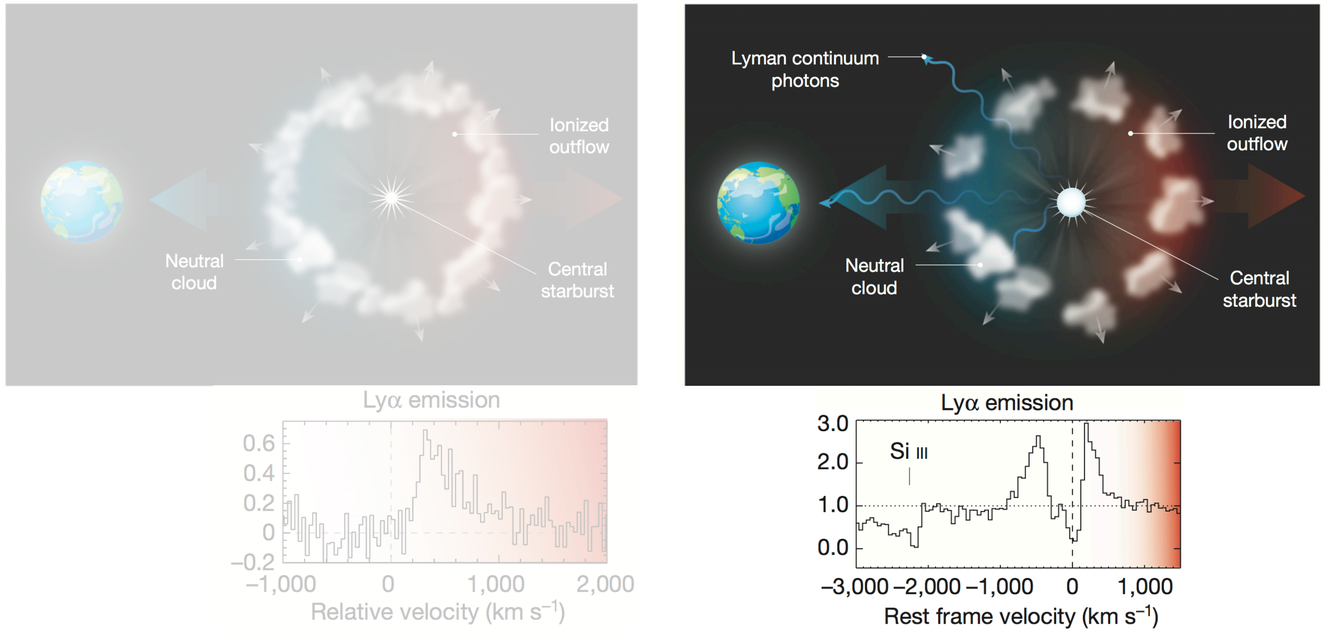


Erb 2015

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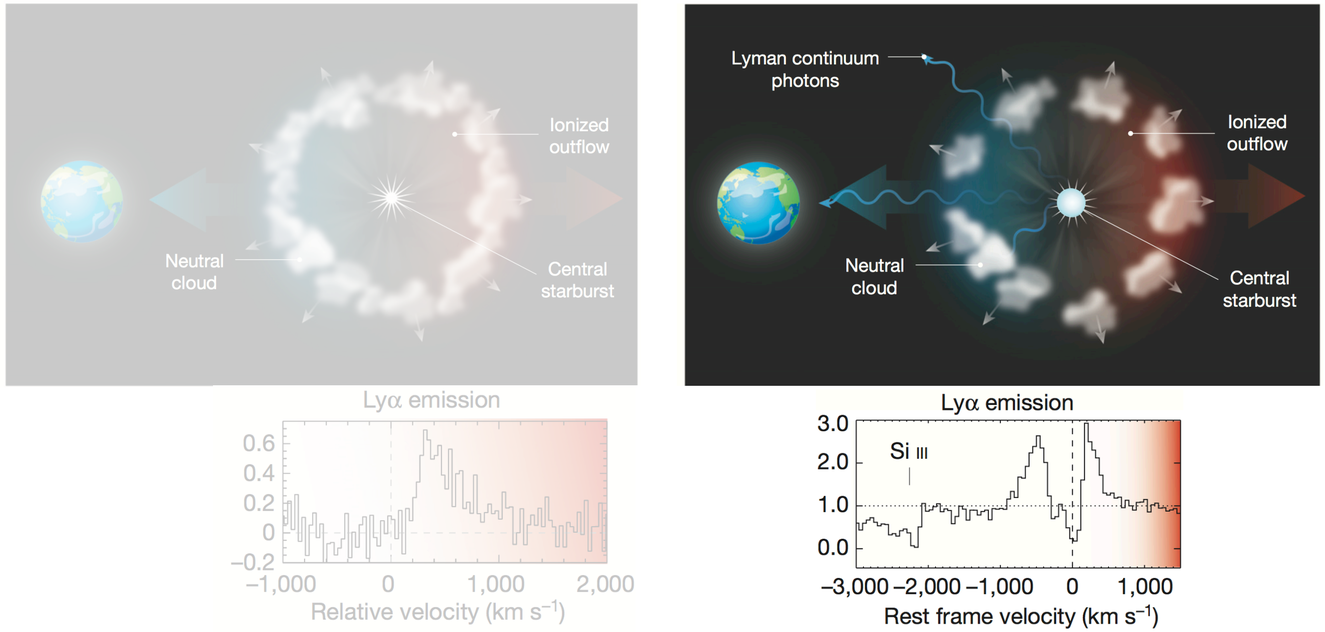


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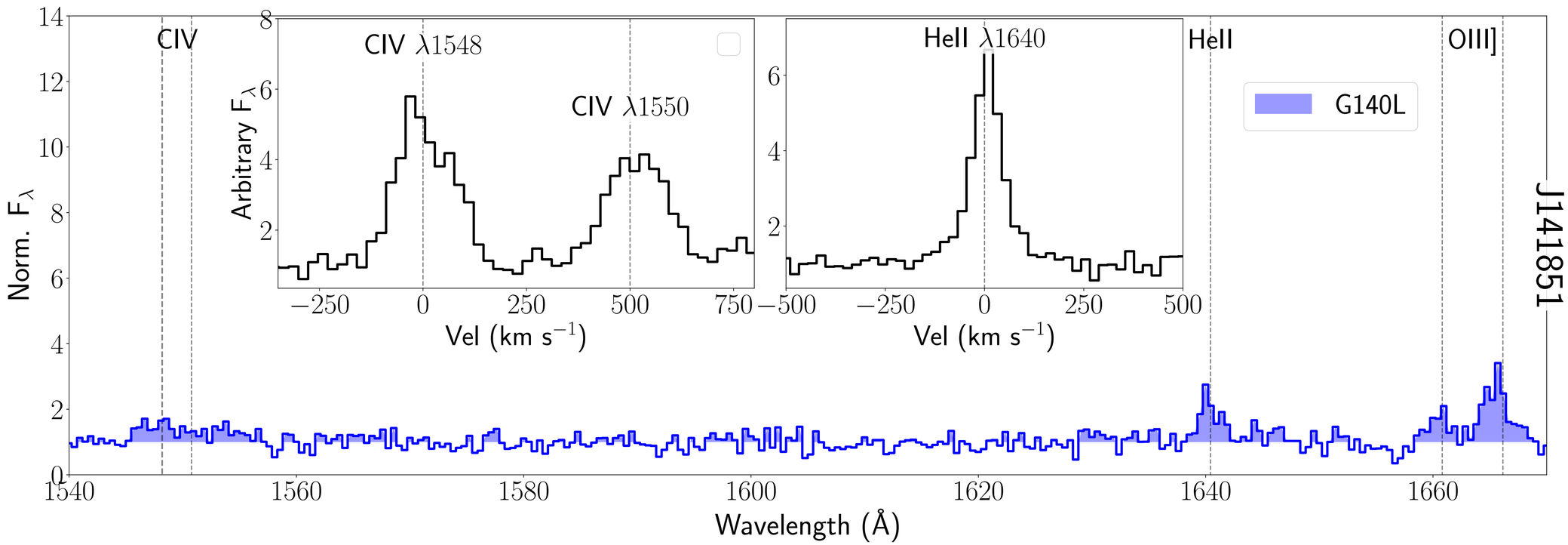
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EELGS

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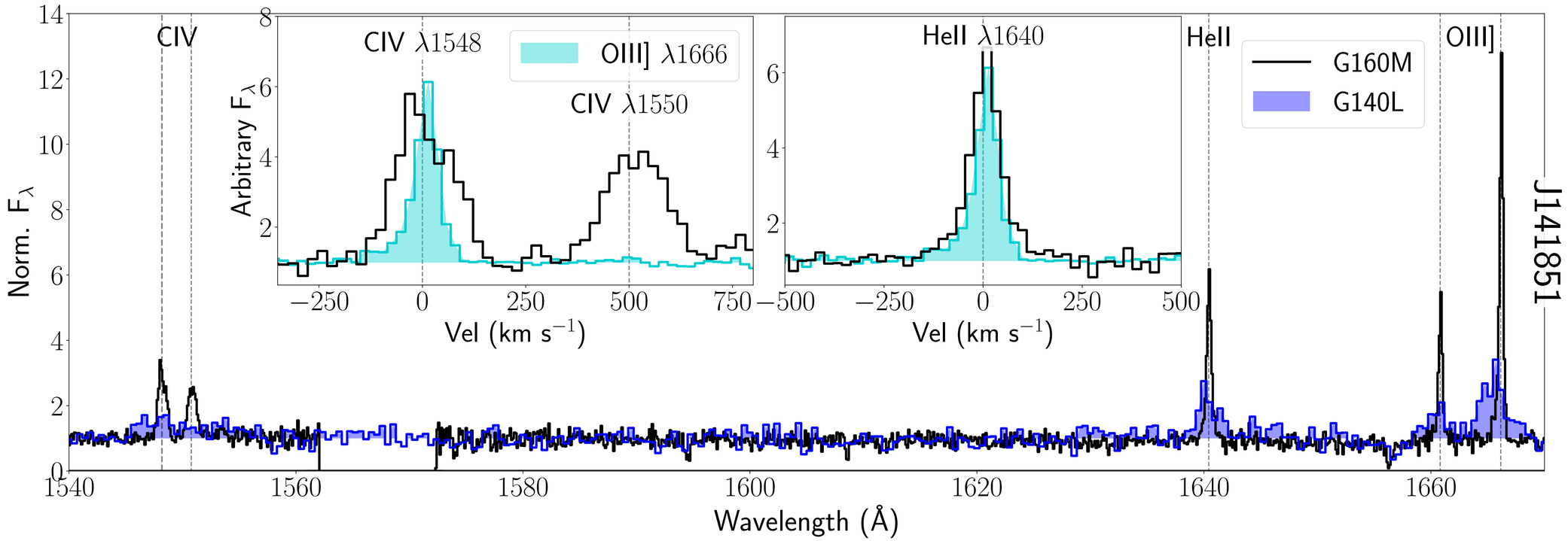
Berg, D.A.+2019b

EELGS

Resonant CIV emission suggests **high-energy photons can escape**

High-ionization emission indicates **production of very high-energy photons**

FUV resonant ext
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Berg, D.A.+2019b

EELGS



If gas within a galaxy **is generally uniform and low-column density**, then all resonant lines should have **narrow, symmetric emission** profiles

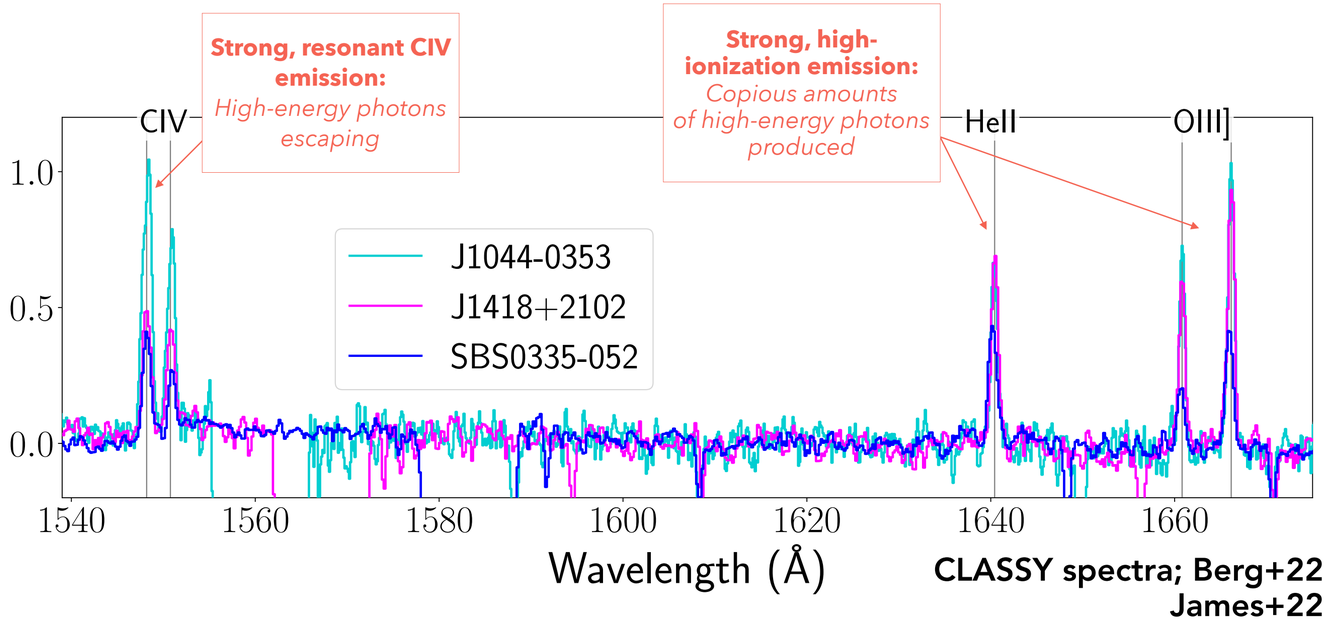
Resonant transitions of different ions will allow us to trace the escape of **both low- and high-energy ionizing photons** through **neutral/low- and high-ionization gas**

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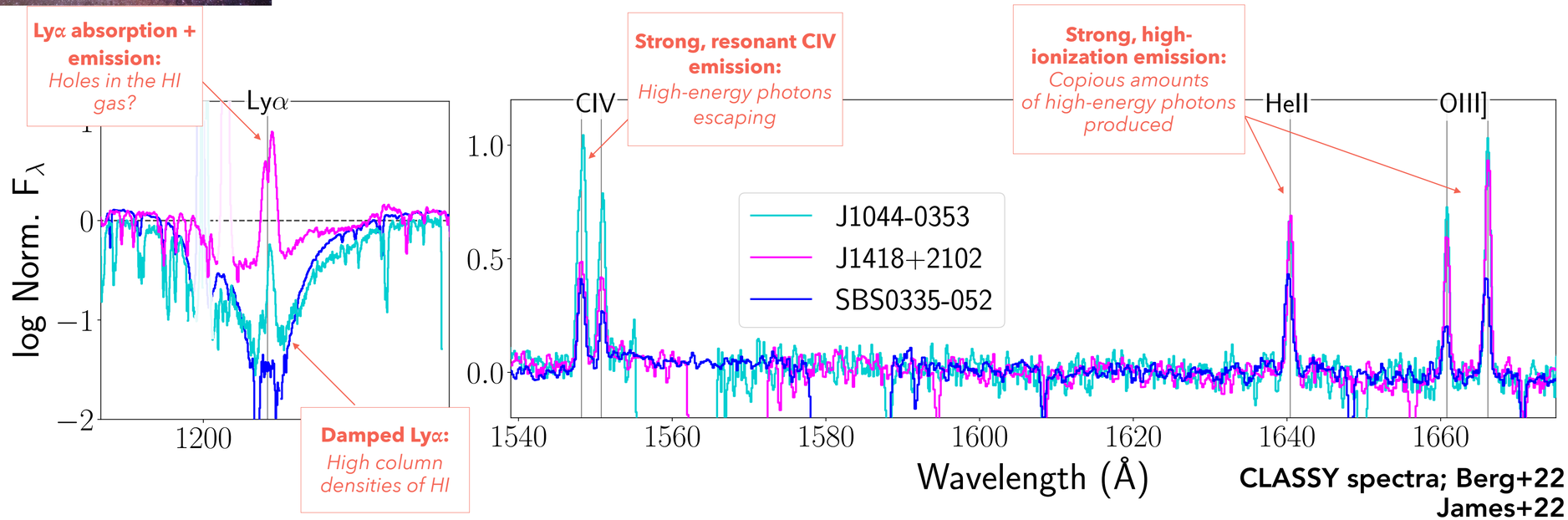
CLASSY spectra; Berg+22 James+22

EELGS



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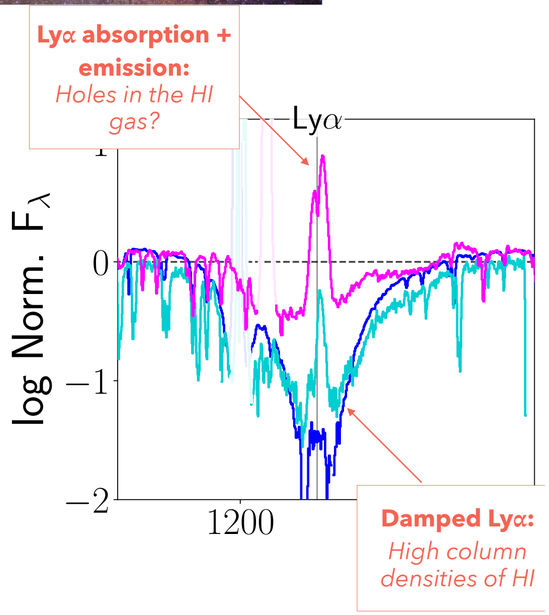
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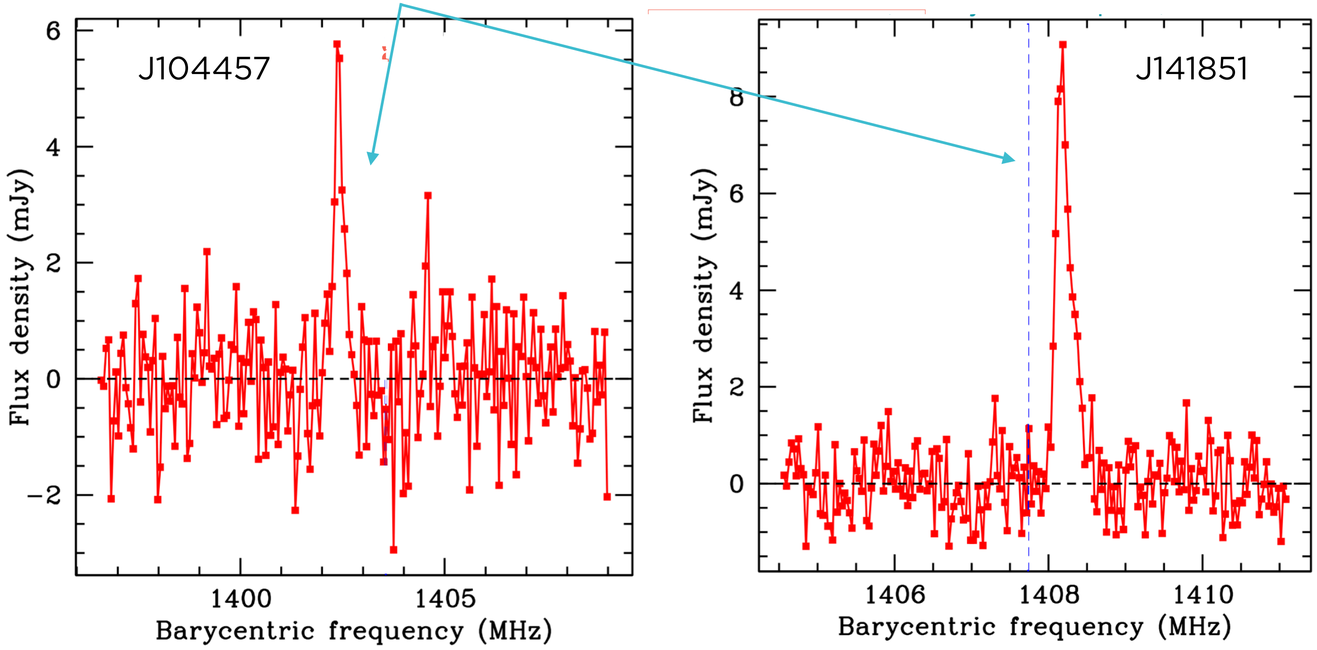


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HICLASS: CLASSY GBT observations reveal large reservoirs of cold neutral gas
Parker, Berg, D.A., & the CLASSY team, 2025, submitted



$M_{HI} = 2.04\times10^8\ M_\odot$
$M_\star = 6.31\times10^7\ M_\odot$
$\mu_{gas} = M_{HI} / (M_{HI} + M_\star) = 0.76$

$M_{HI} = 1.69\times10^8\ M_\odot$
$M_\star = 4.27\times10^7\ M_\odot$
$\mu_{gas} = M_{HI} / (M_{HI} + M_\star) = 0.80$

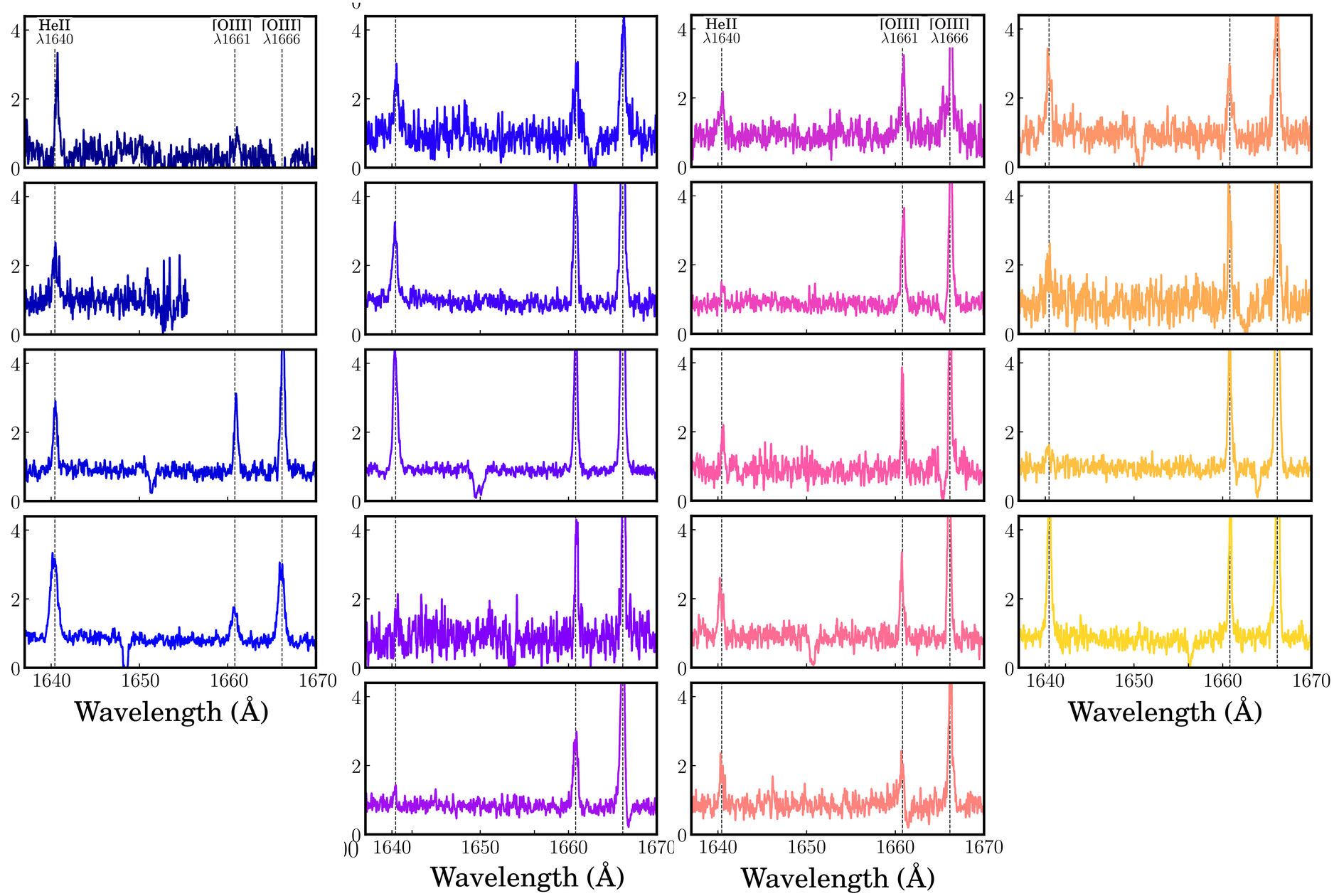
Evidence of holes?

EELGS

Resonant transitions of high-ionization ions will allow us to trace the escape of **high-energy ionizing photons** through **high-ionization gas**

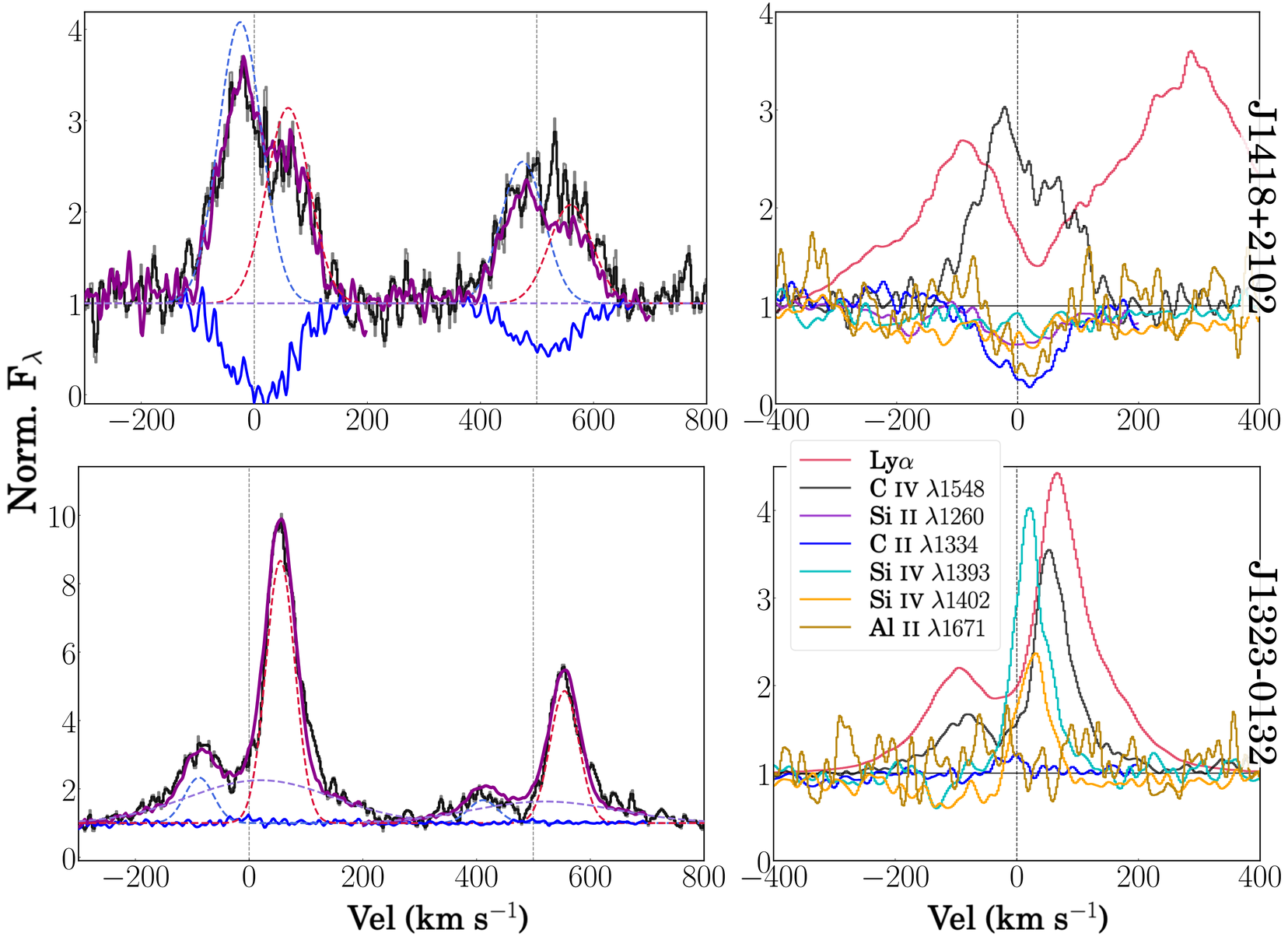
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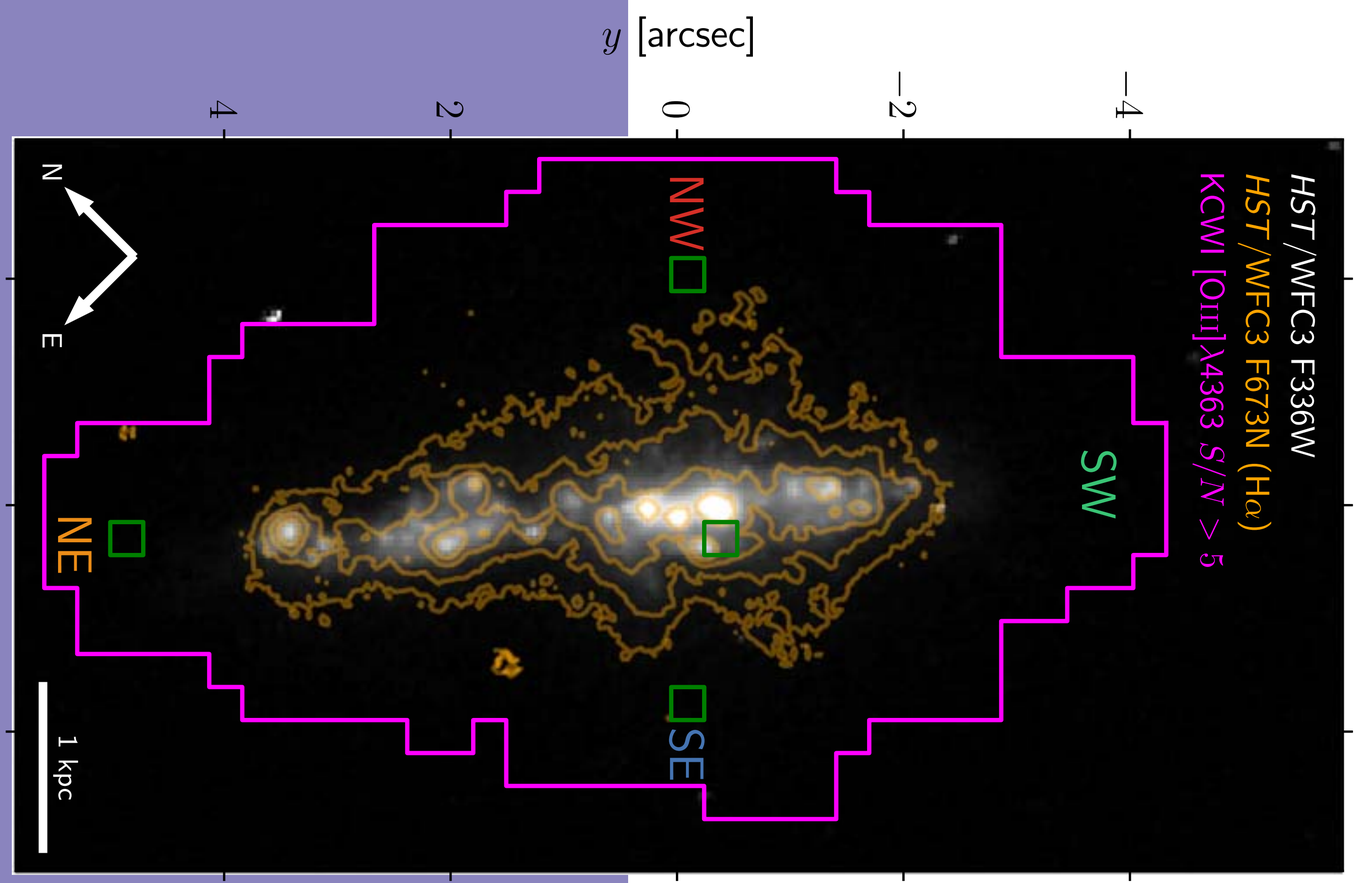
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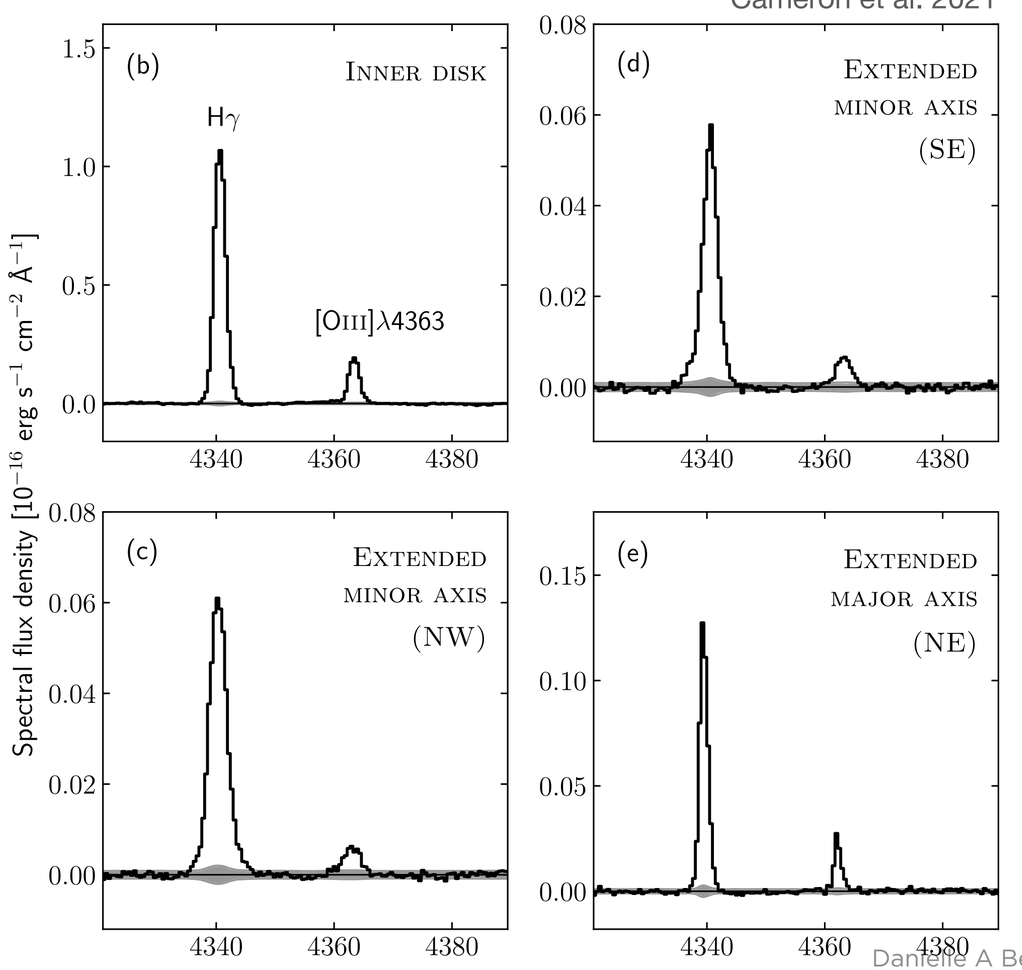


PART IV:
IFU STUDIES OF THE NEARBY UNIVERSE

MAPPING THE BARYON-CYCLE

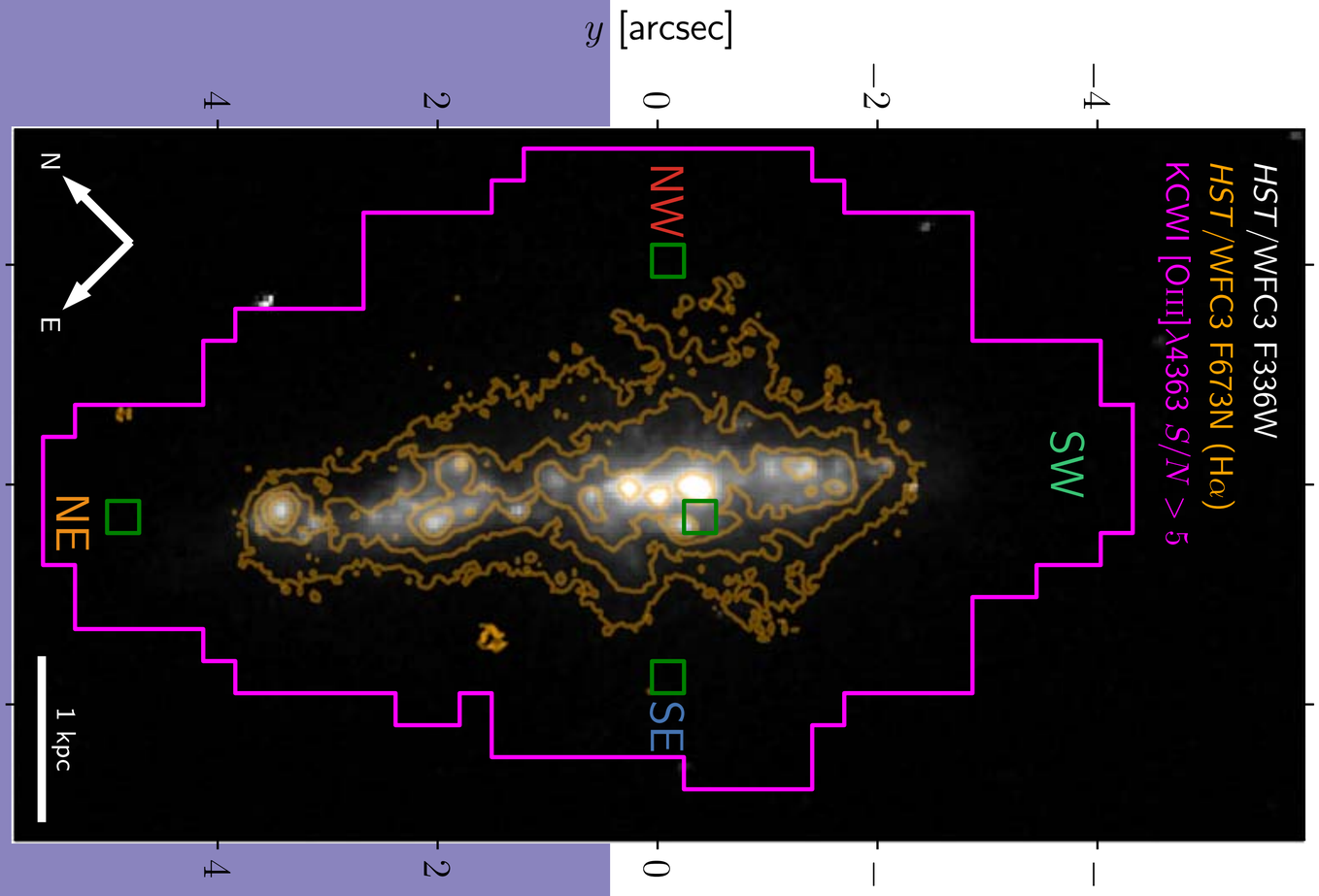
Cameron et al. 2021



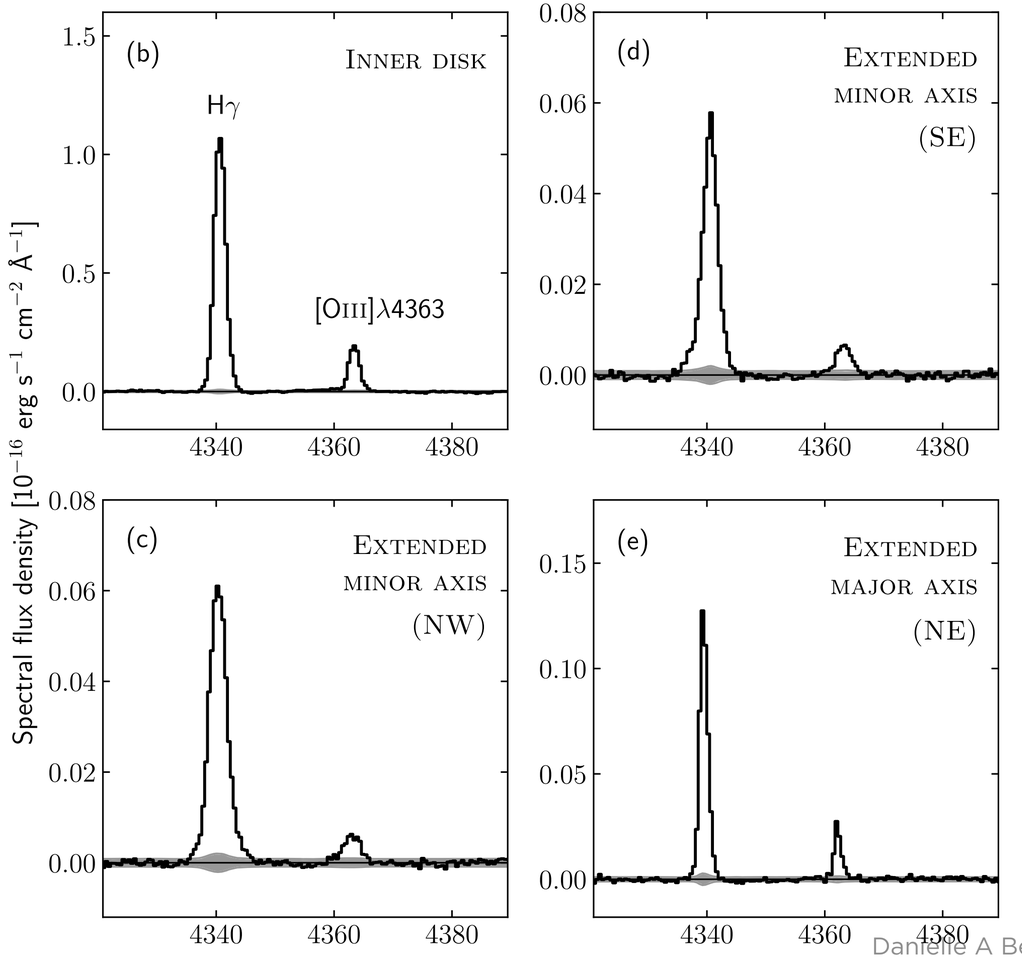


MAPPING THE BARYON-CYCLE

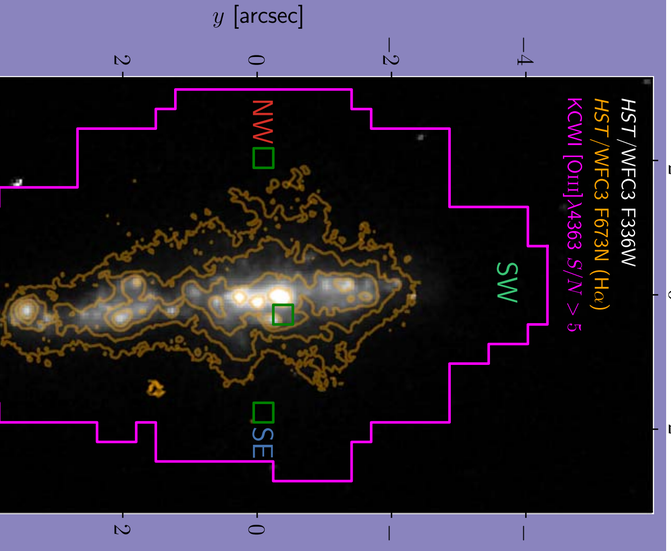
Can measure **direct method** metallicities across **disk** and into **CGM**!

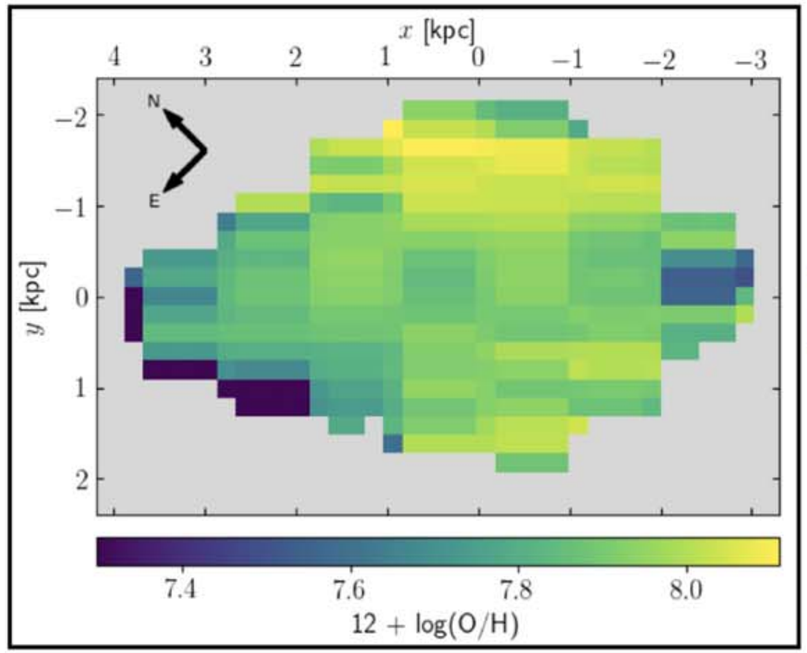


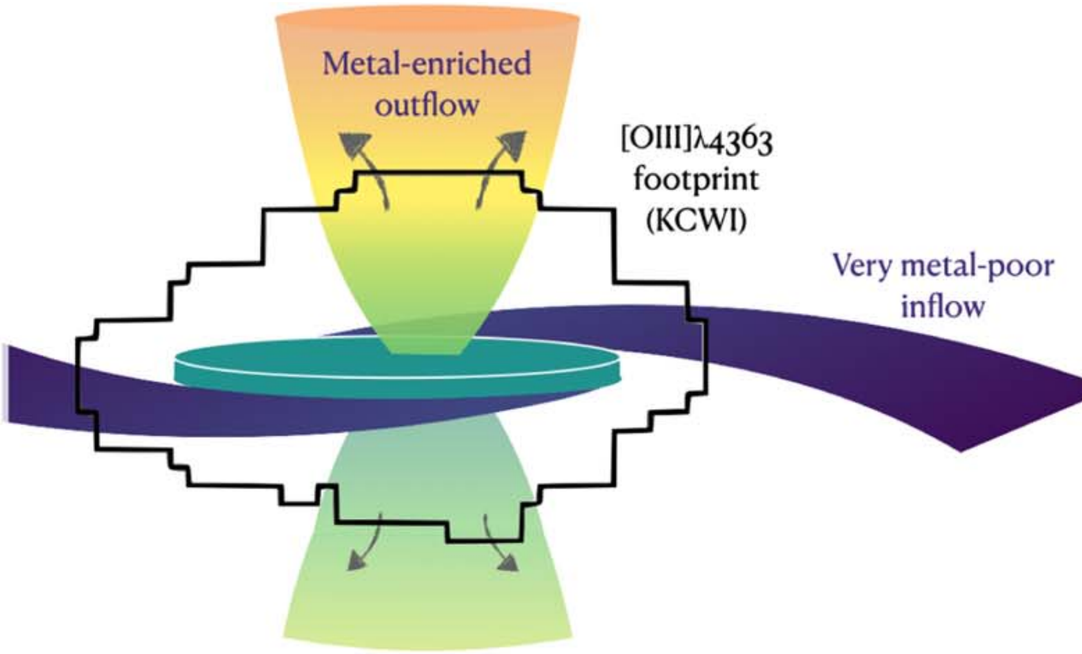
Cameron et al. 2021



MAPPING THE BARYON-CYCLE







Cameron et al. 2021

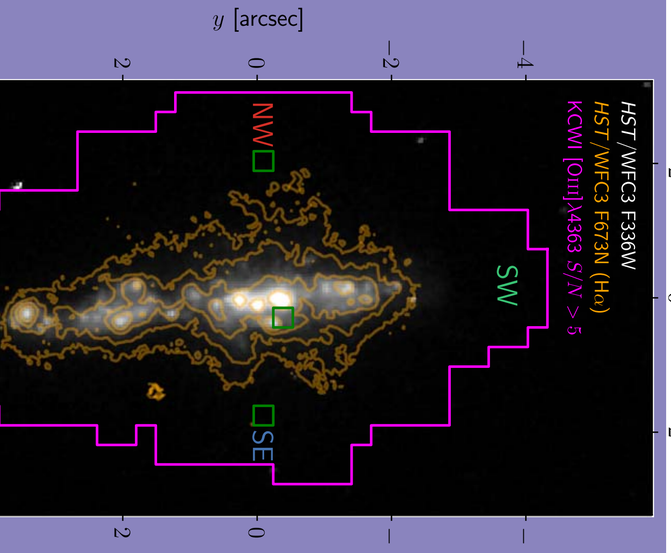
MAPPING THE BARYON-CYCLE

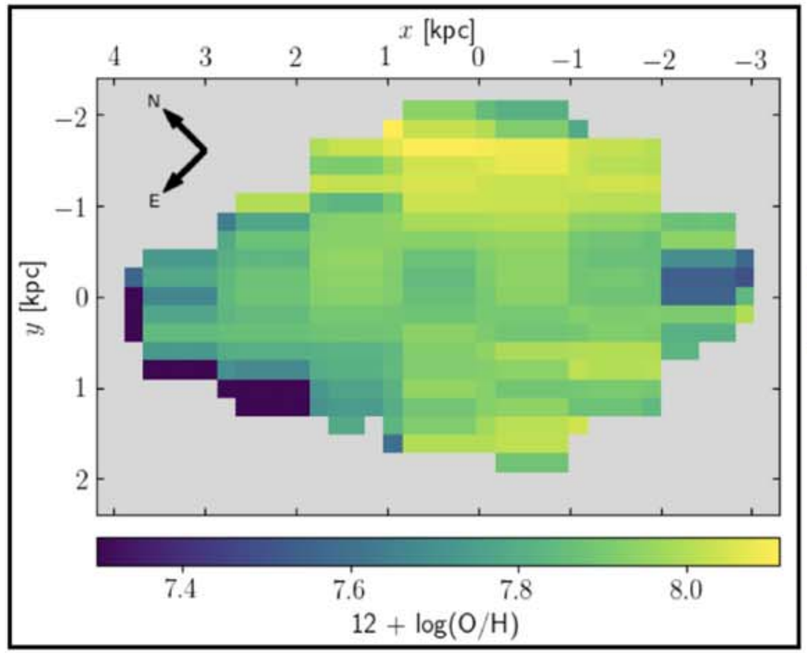
Increasing metallicity gradient across **minor axis**

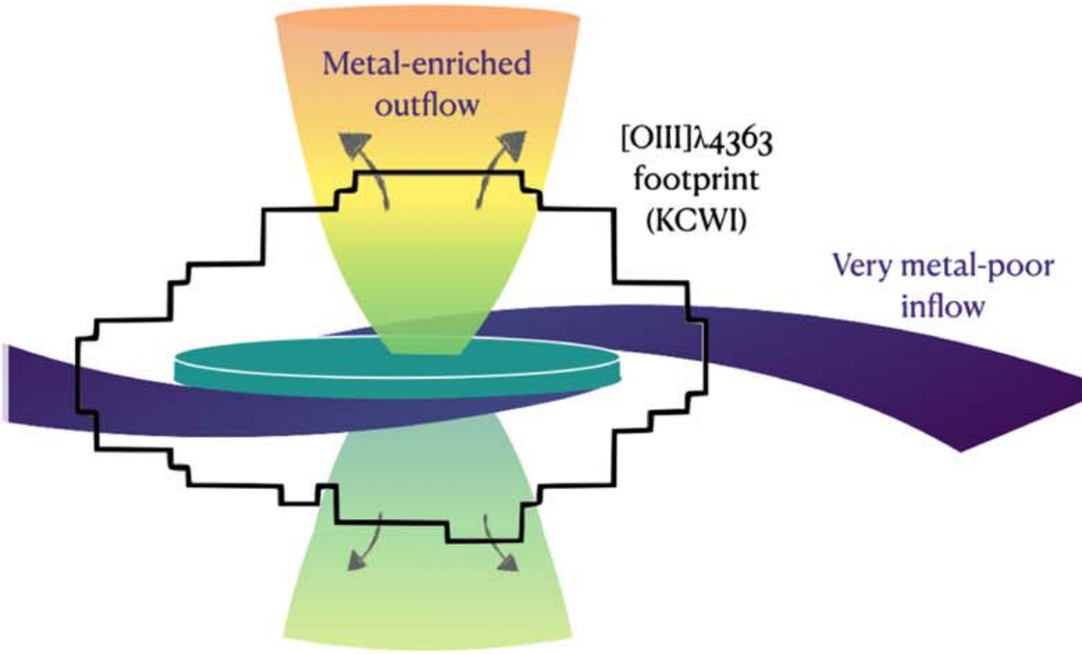
Decreasing metallicity gradient across **major axis**

$\Longrightarrow$ Low metallicity **inflows dilute** gas at edges of **major axis** of disk

$\Longrightarrow$ **Star formation** drives metal-enriched **outflows** along **minor axis**

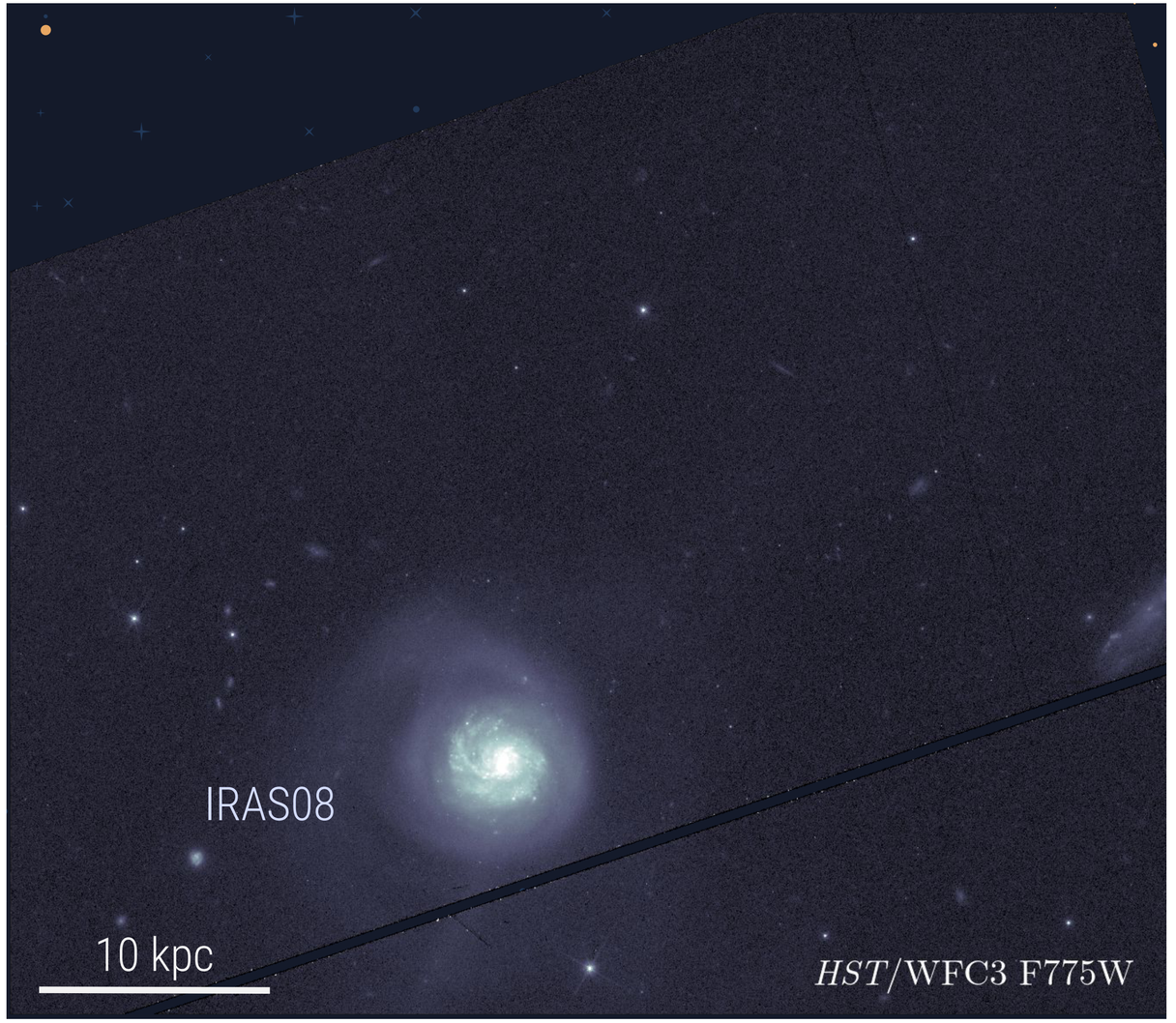






Cameron et al. 2021

MAPPING THE BARYON-CYCLE



Nielsen et al. 2024

IRAS08: A nearby starbursting galaxy

$Z_{\rm gas} = 0.10\ Z_\odot$

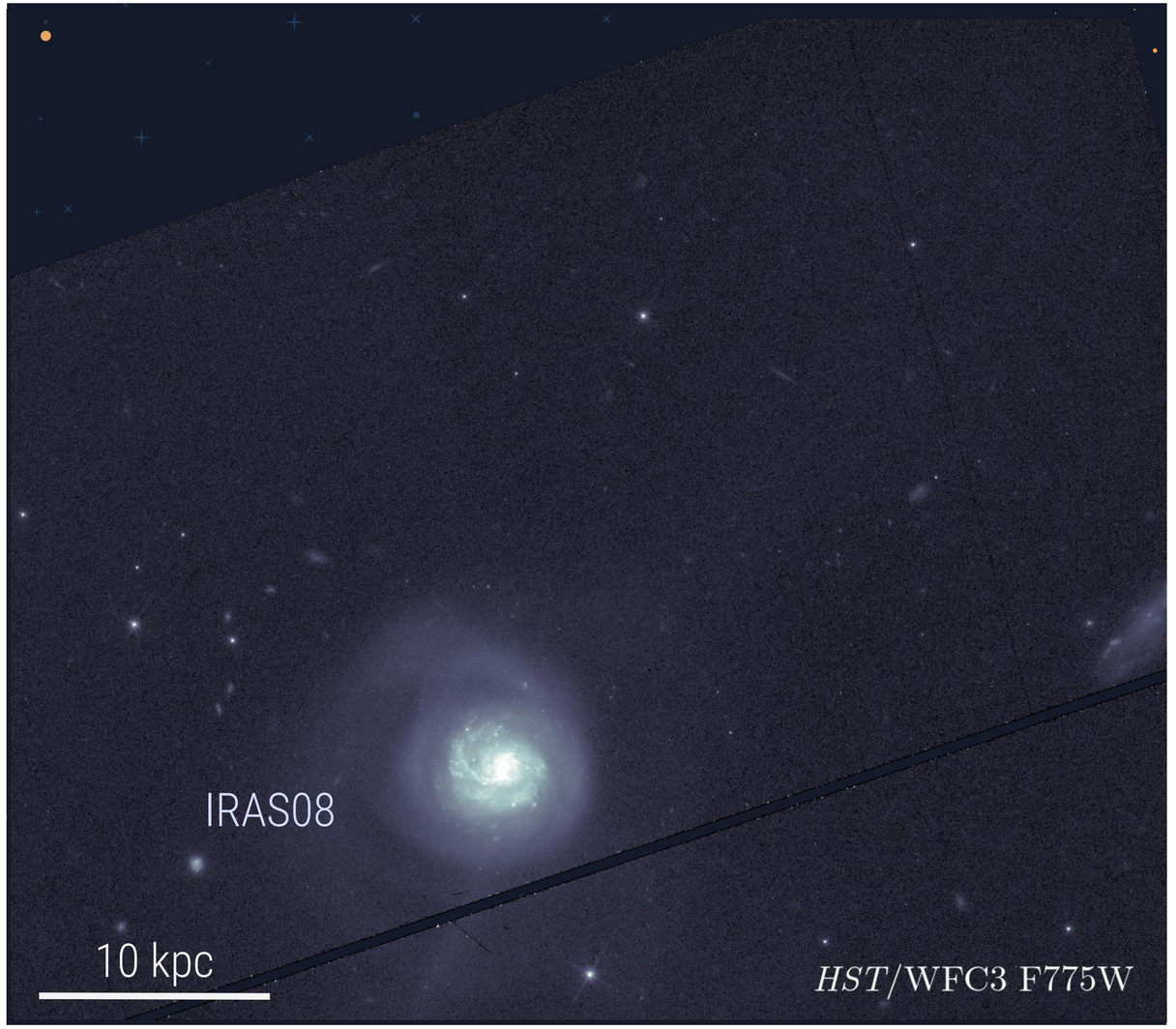
$M_\star = 10^{10}\ M_\odot$

$i \sim 15^\circ$

compact: $r_{90} = 2.4$ kpc

(r_{90} = 90% of optical light profile)

MAPPING THE BARYON-CYCLE



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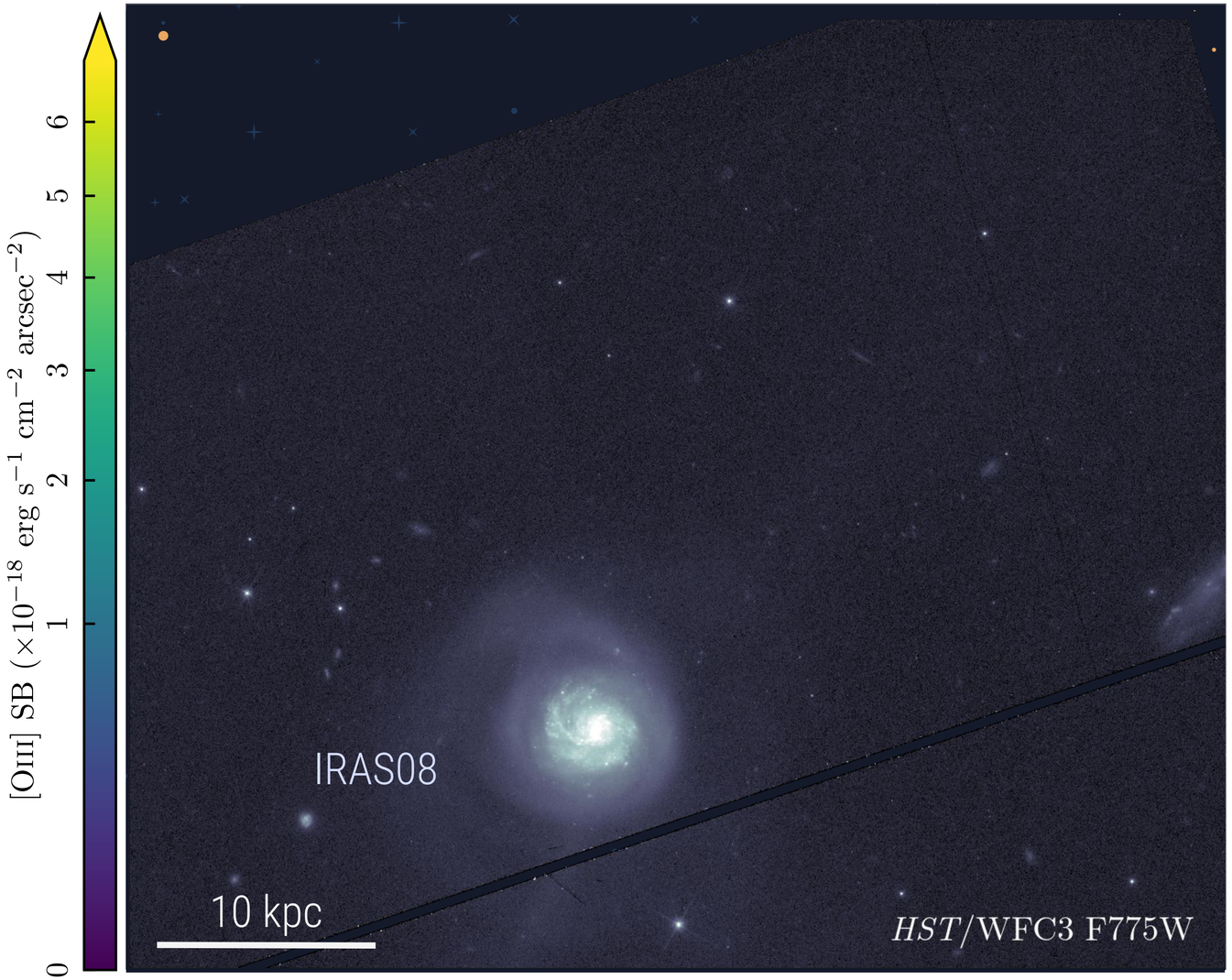
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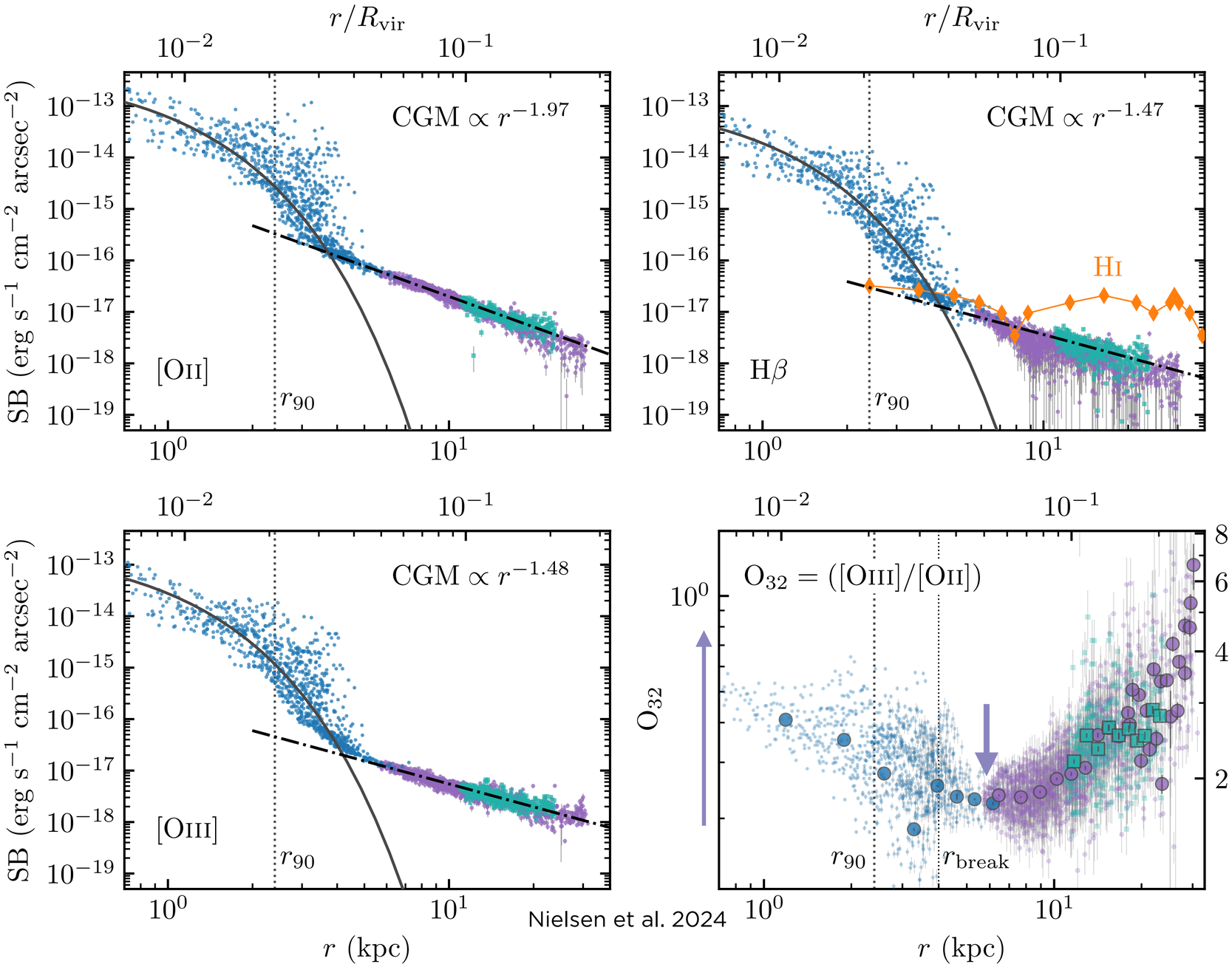
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Nielsen et al. 2024

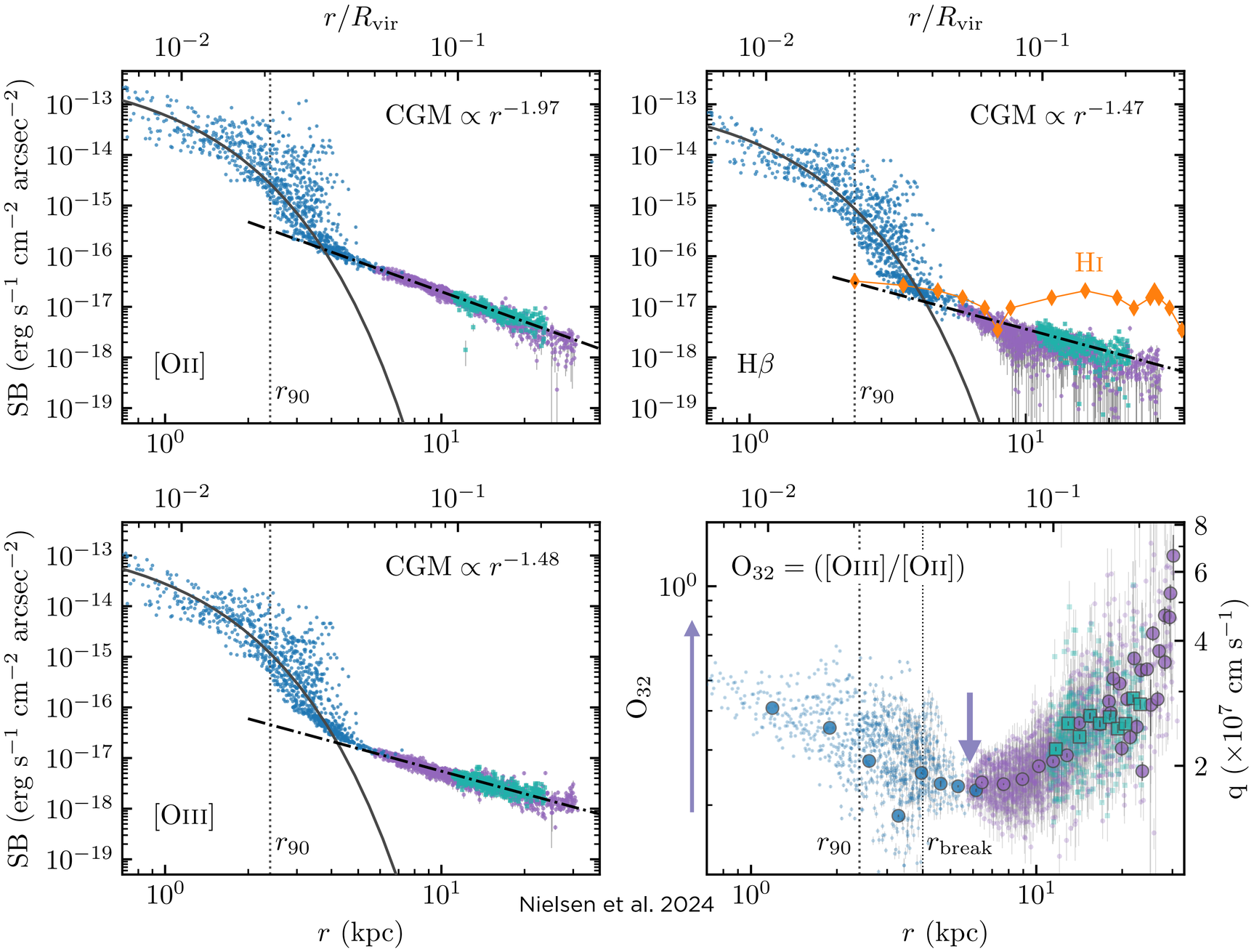
PRING THE BARYON CYCLE



Nielsen et al. 2024

Transition between ISM and CGM at ~4 kpc ($2 \times r_{90}$)

ISM: *Decreasing* ionization with radius
CGM: *Increasing* ionization with radius
The ionization mechanism changes in the CGM

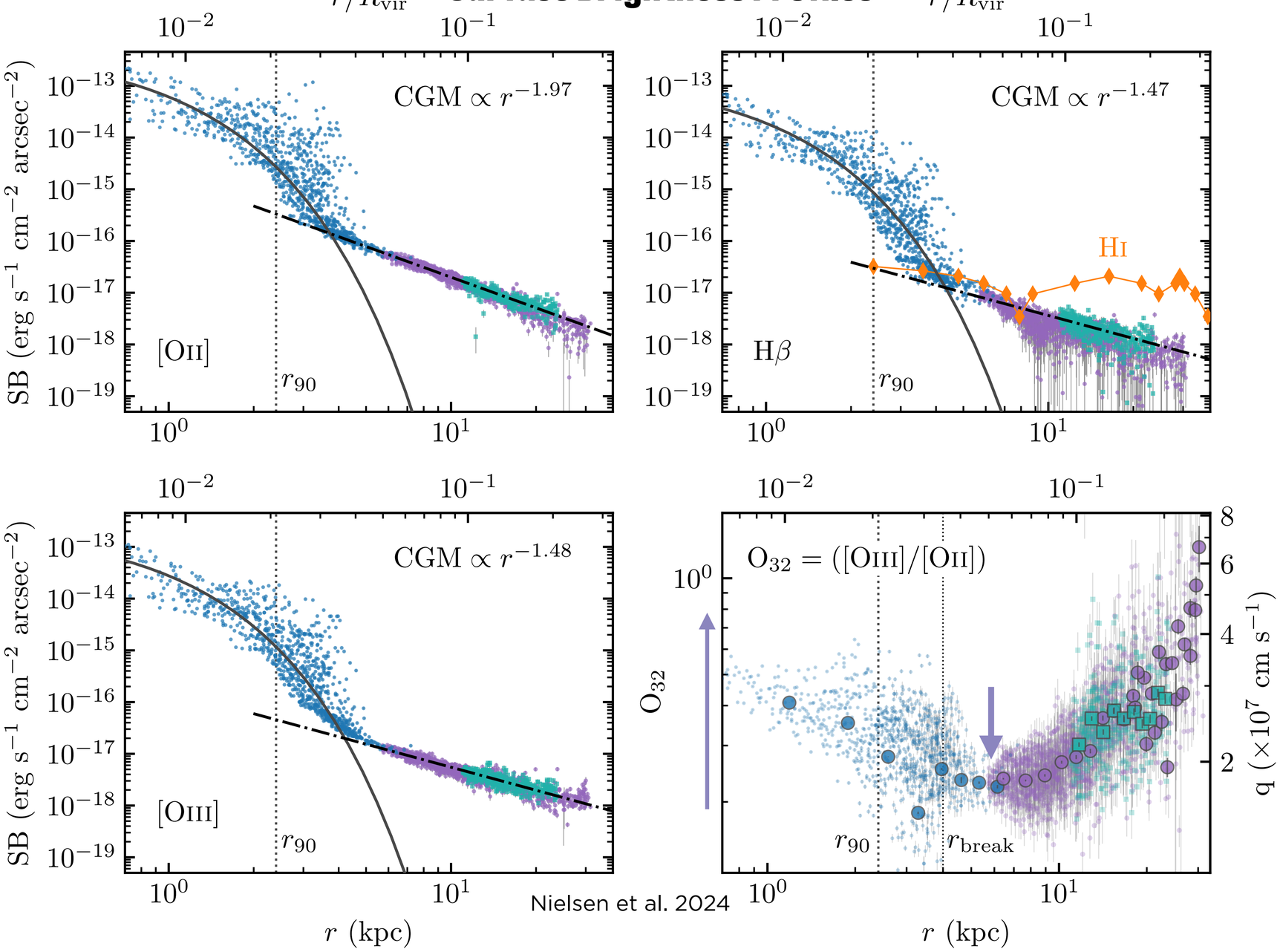


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Surface Brightness Profiles

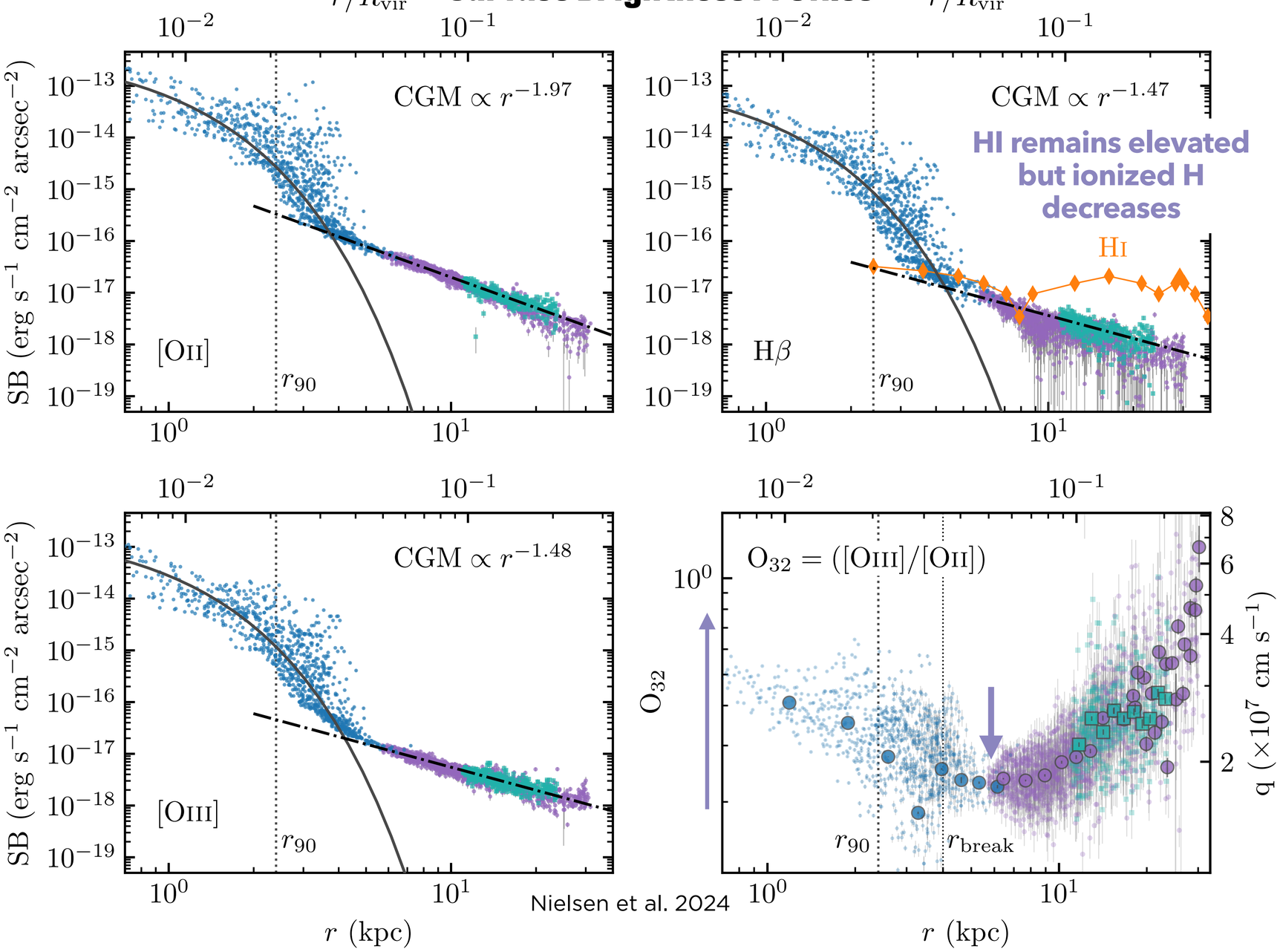


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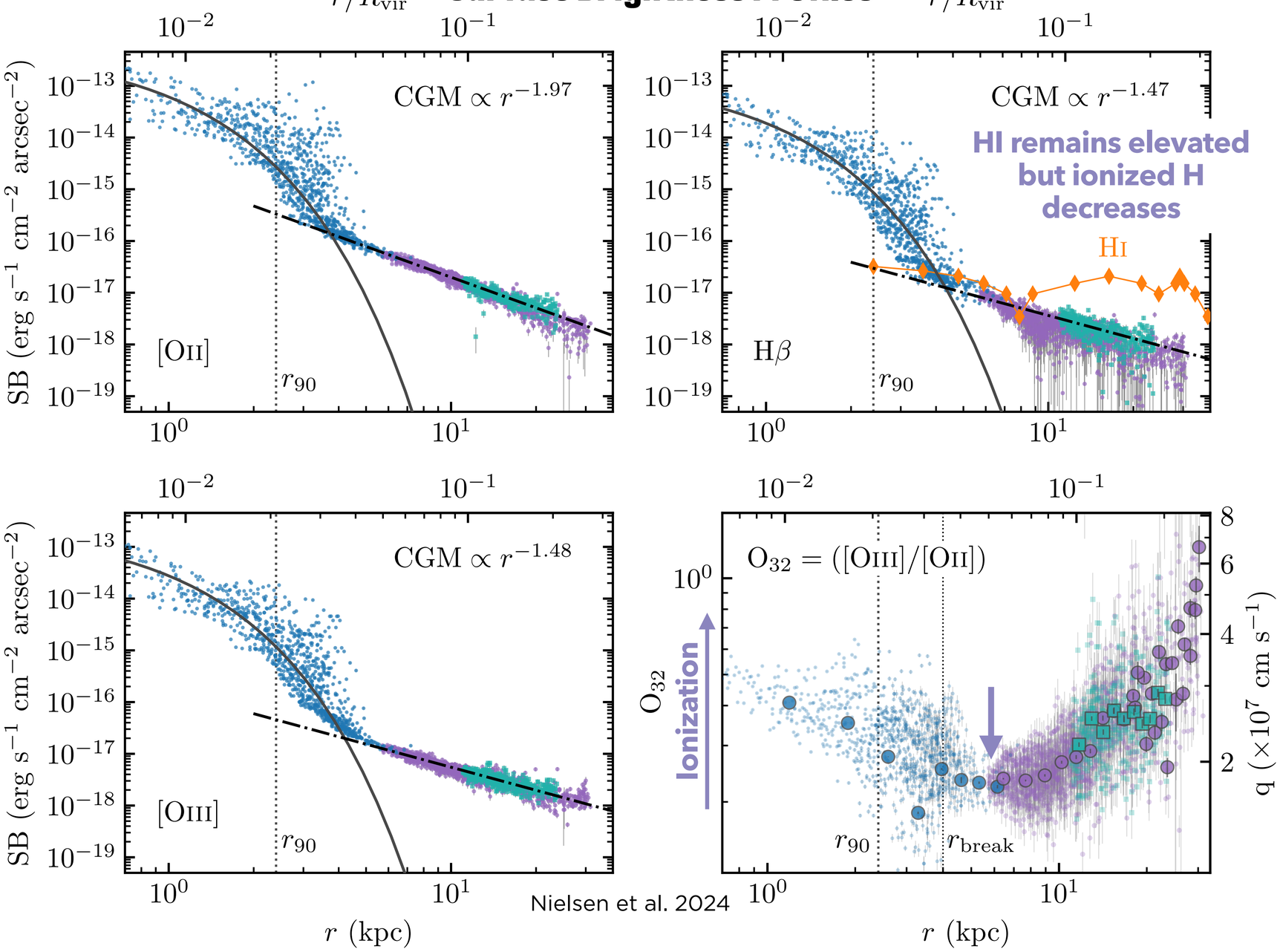


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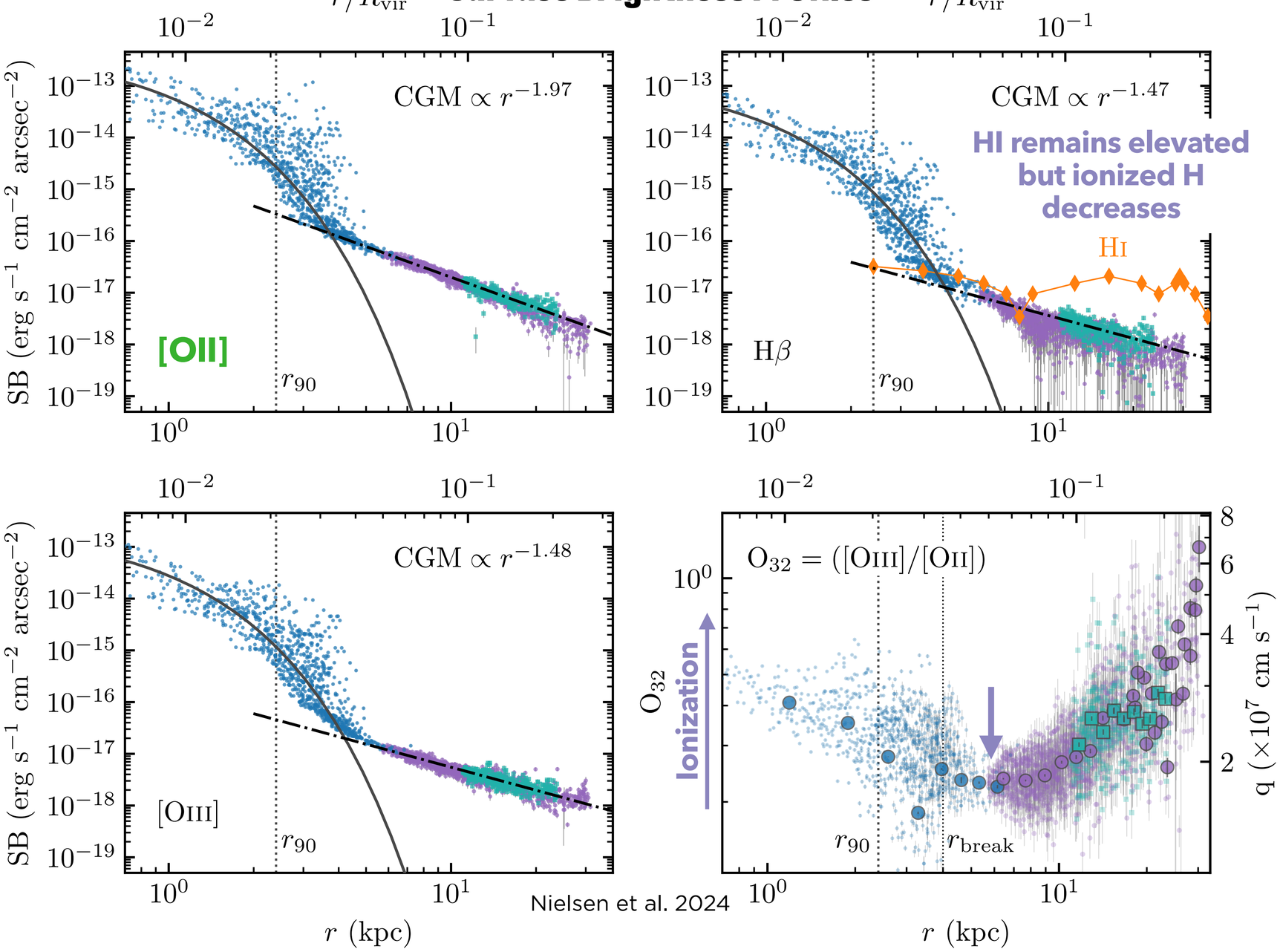


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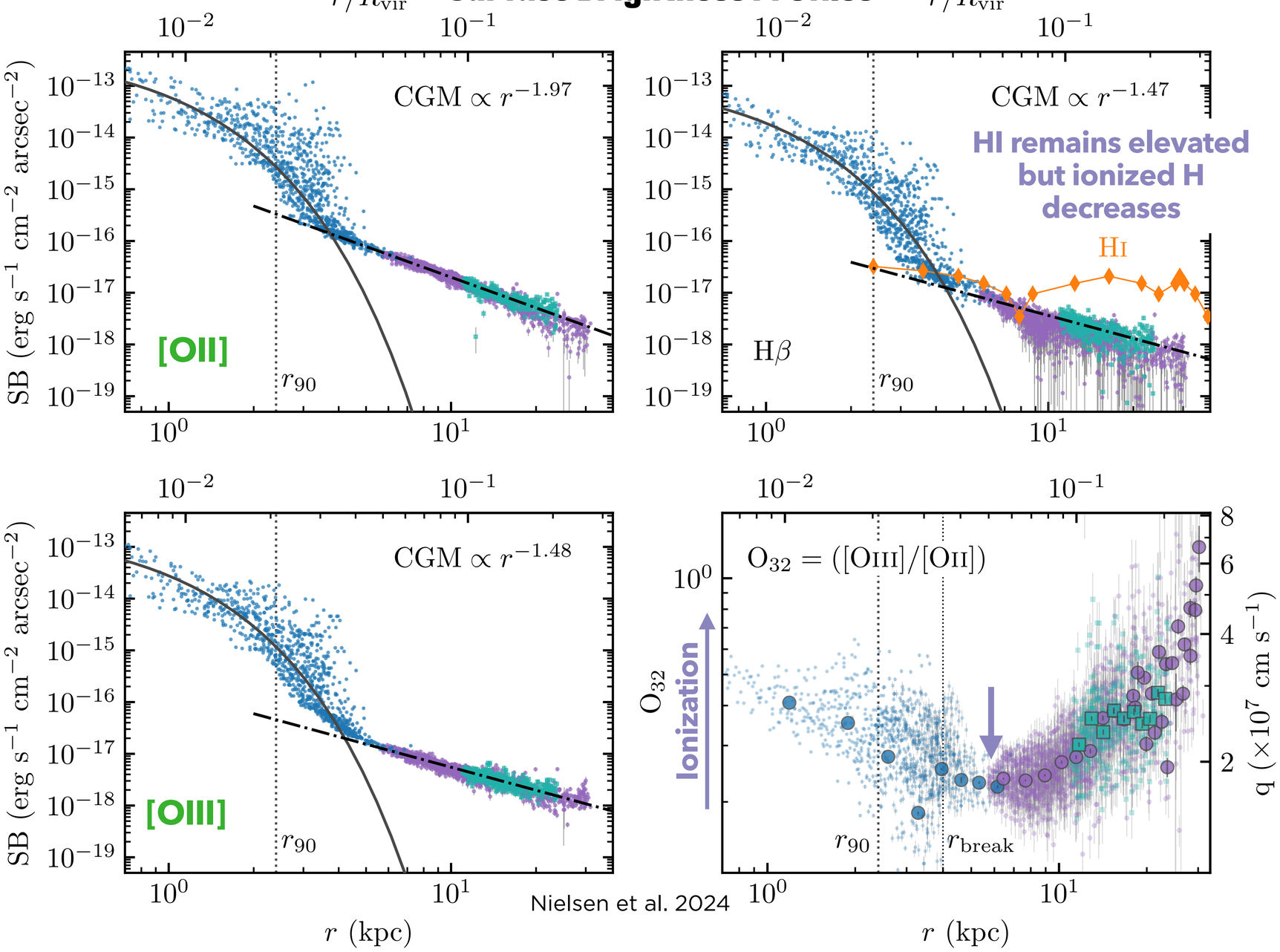


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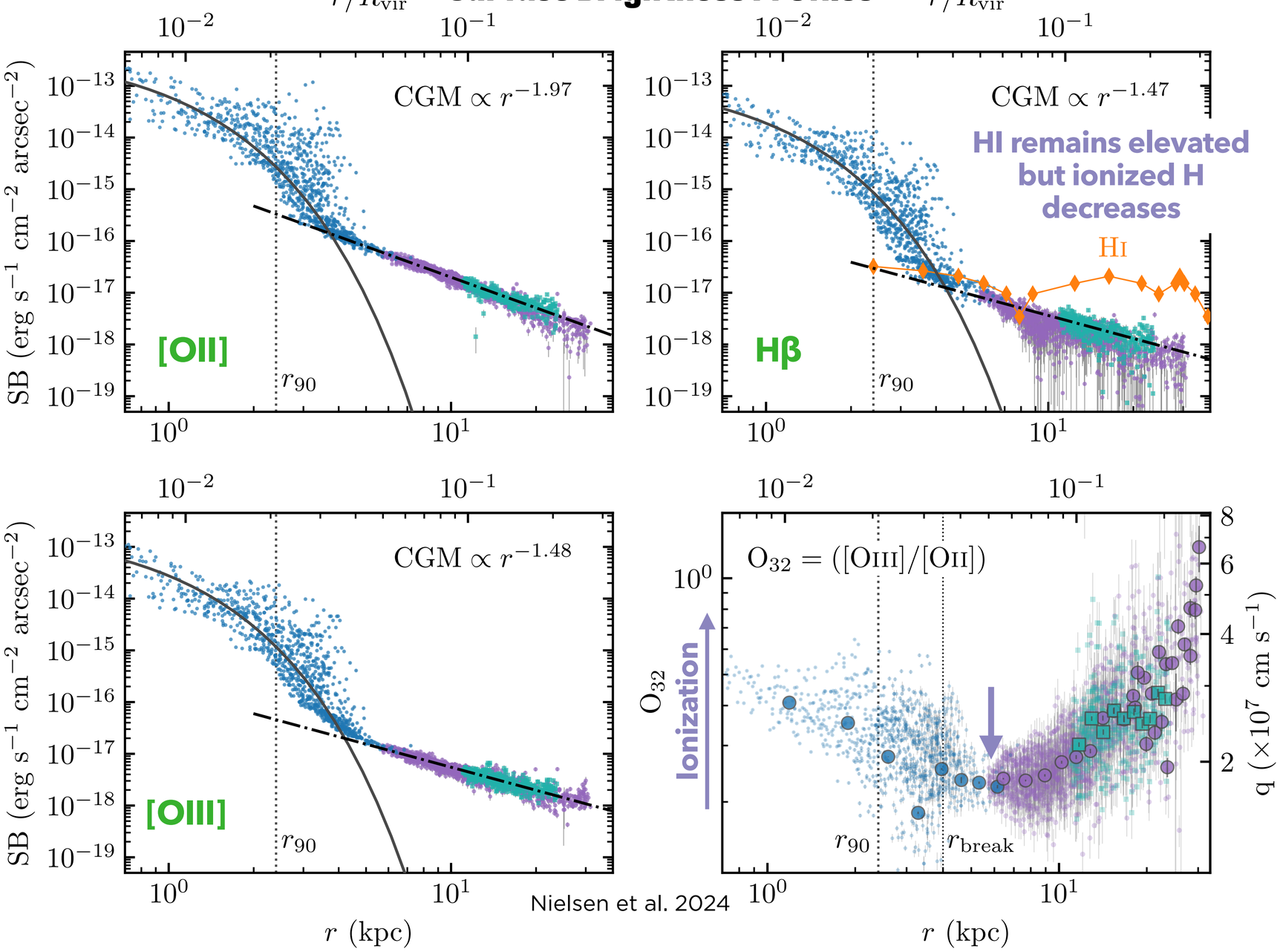


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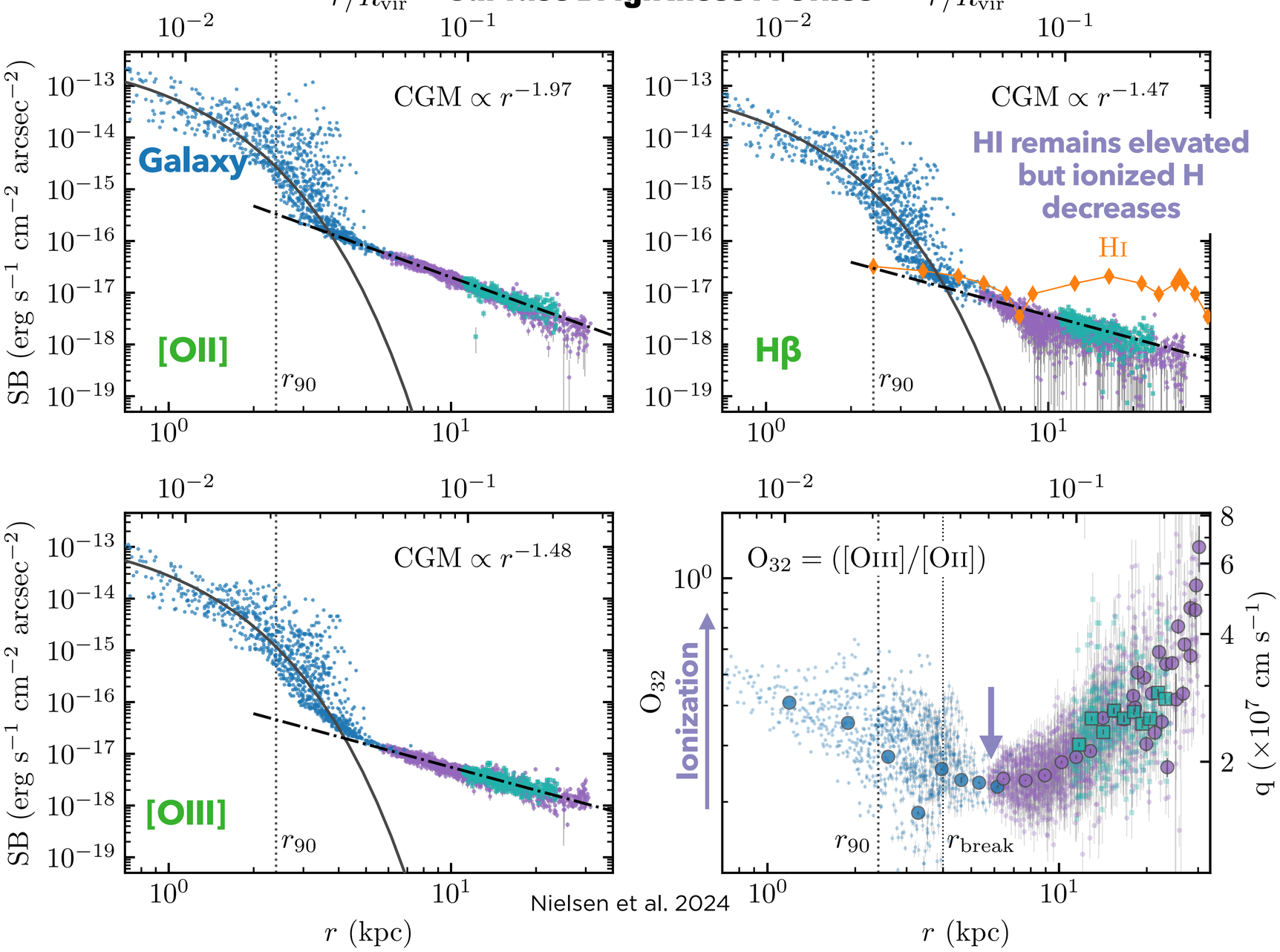


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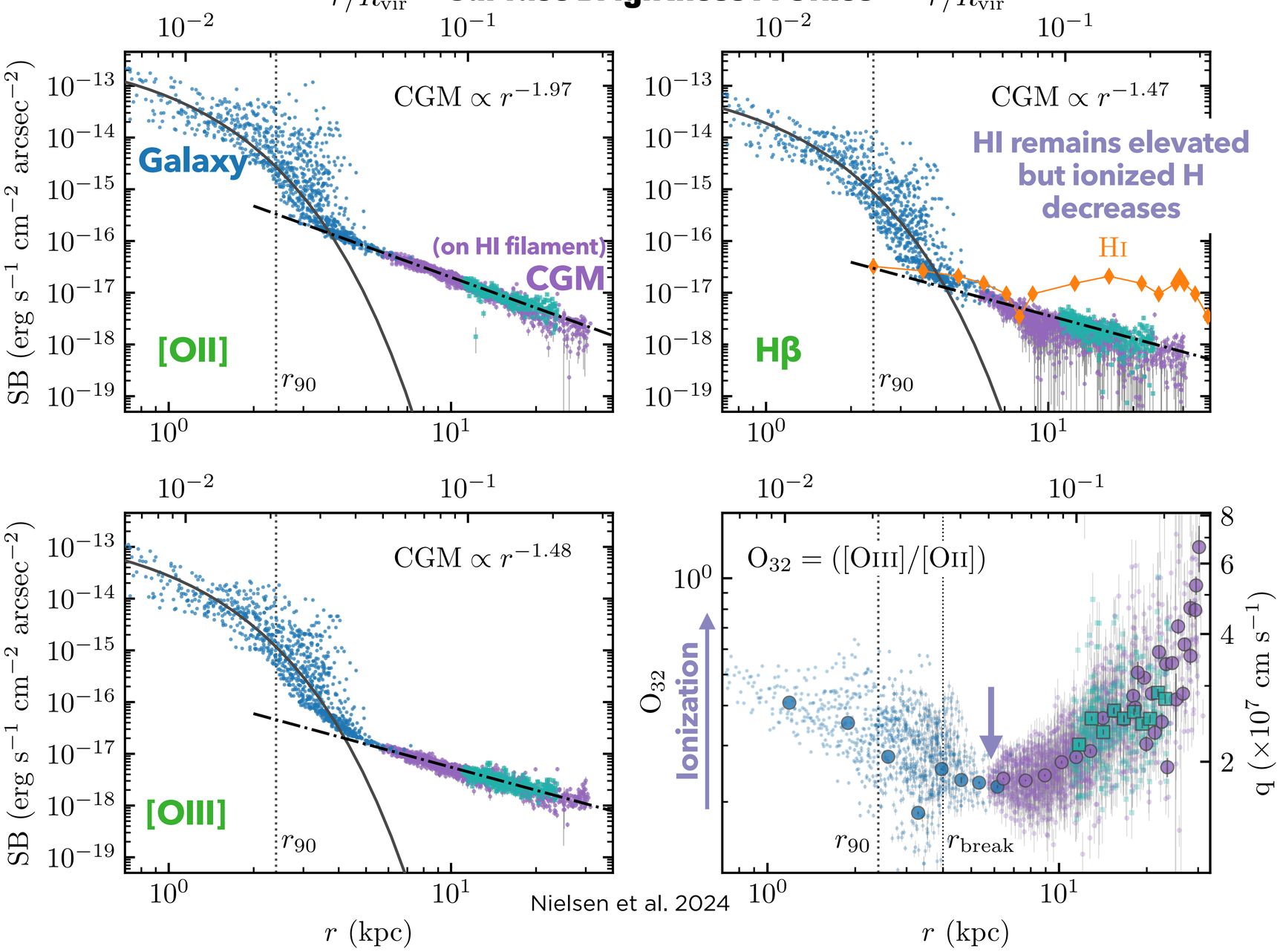


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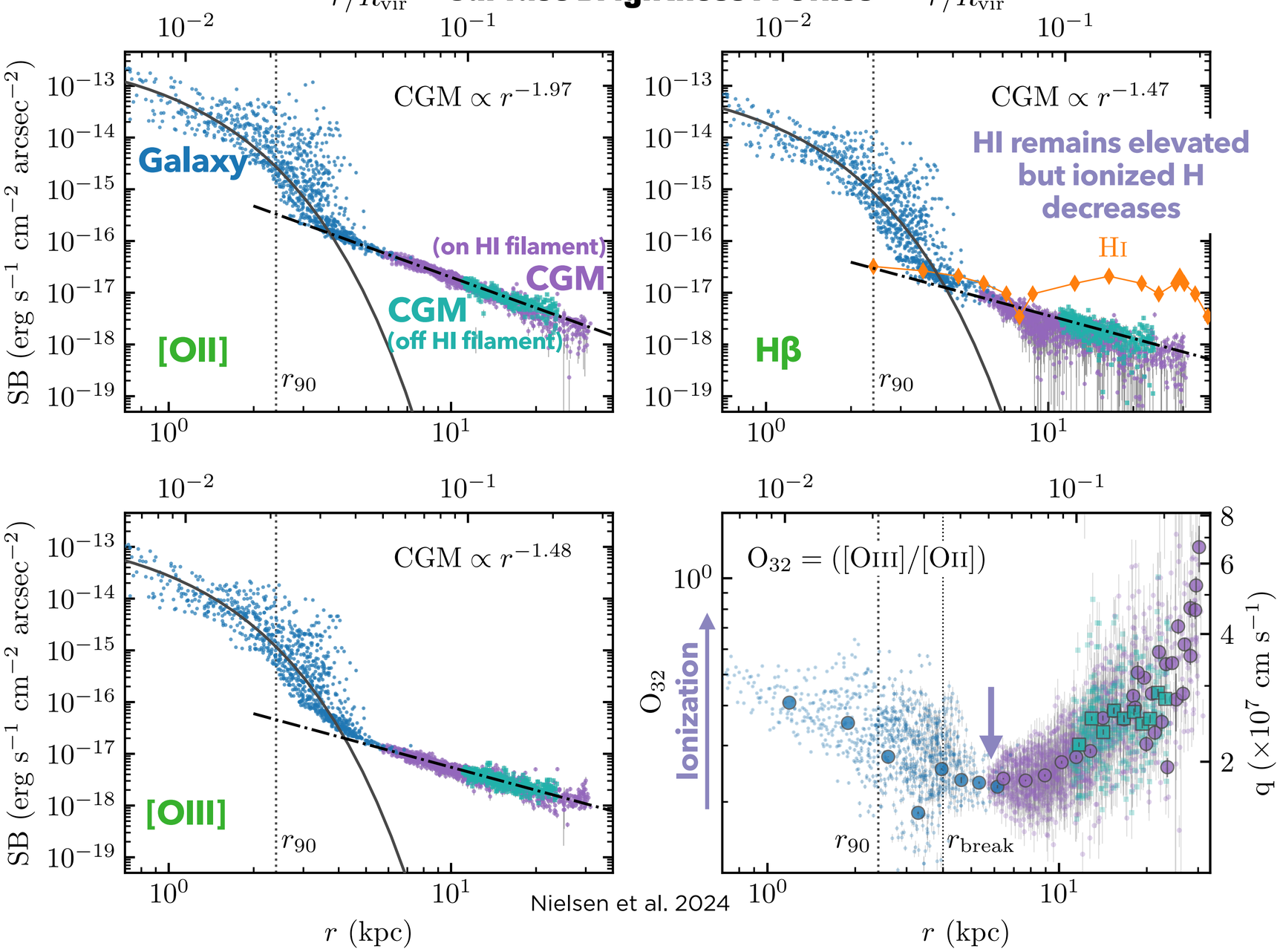


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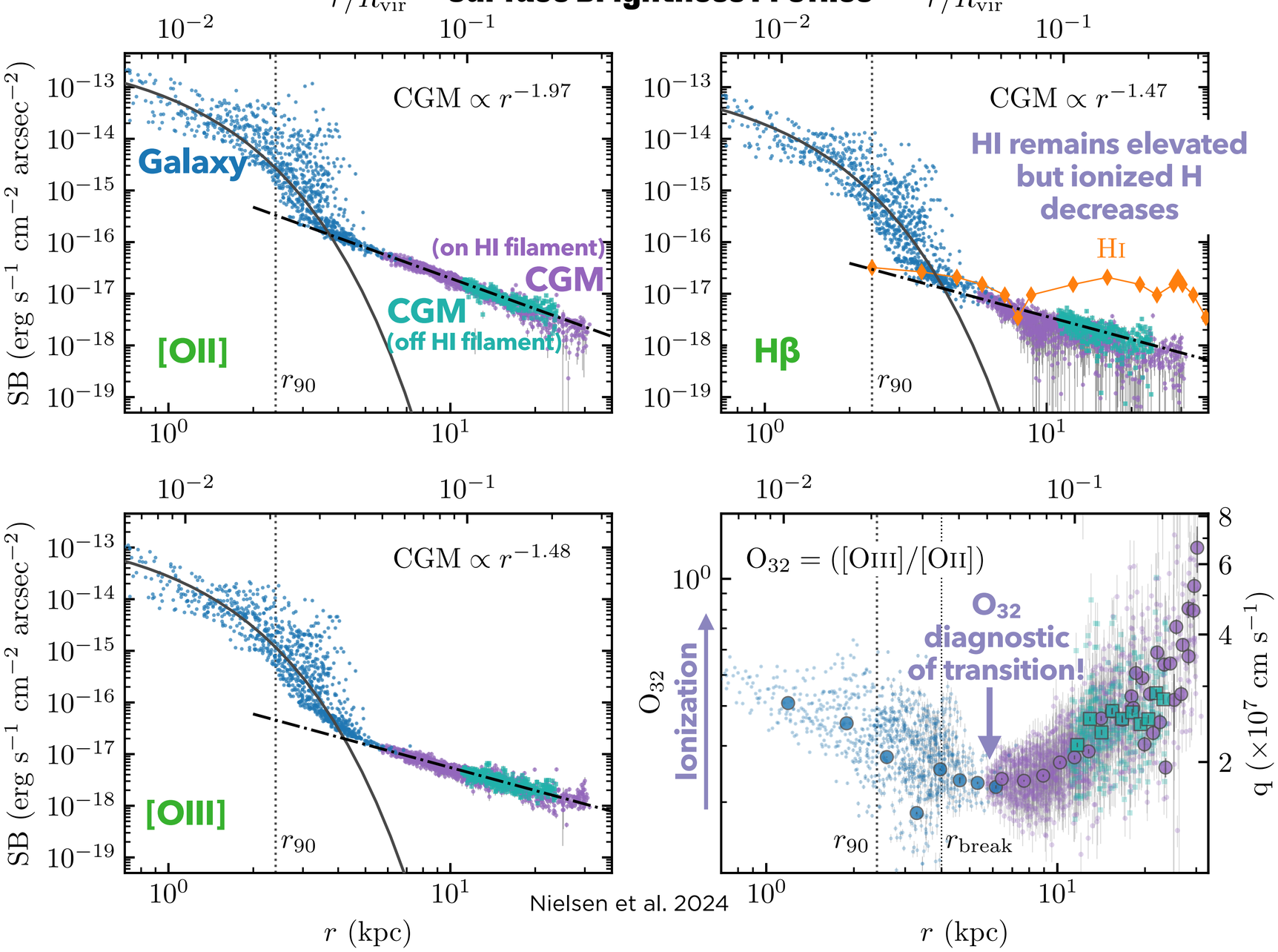


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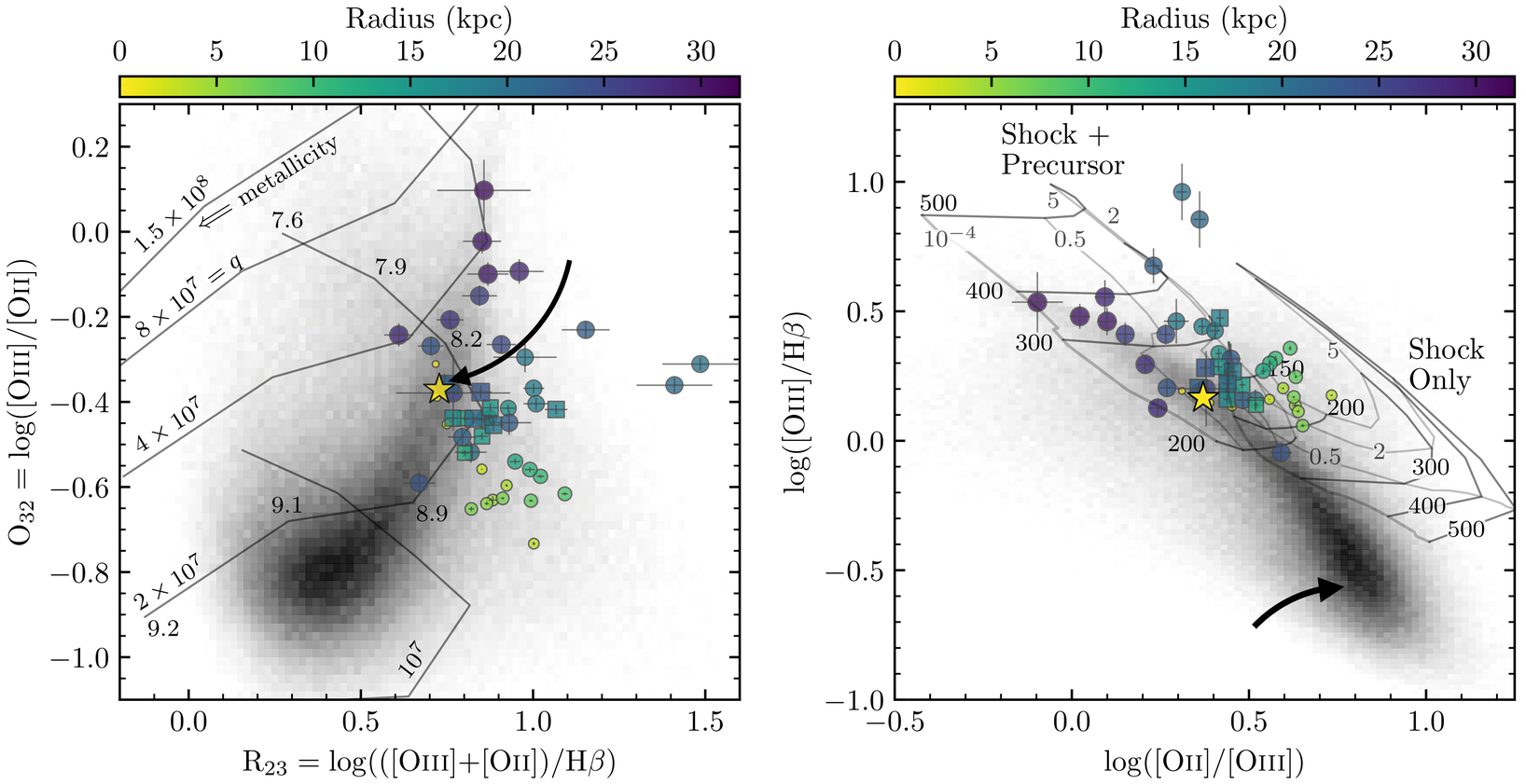
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Surface Brightness Profiles



Nielsen et al. 2024

MAPPING THE BARYON-CYCLE



Nielsen et al. 2024

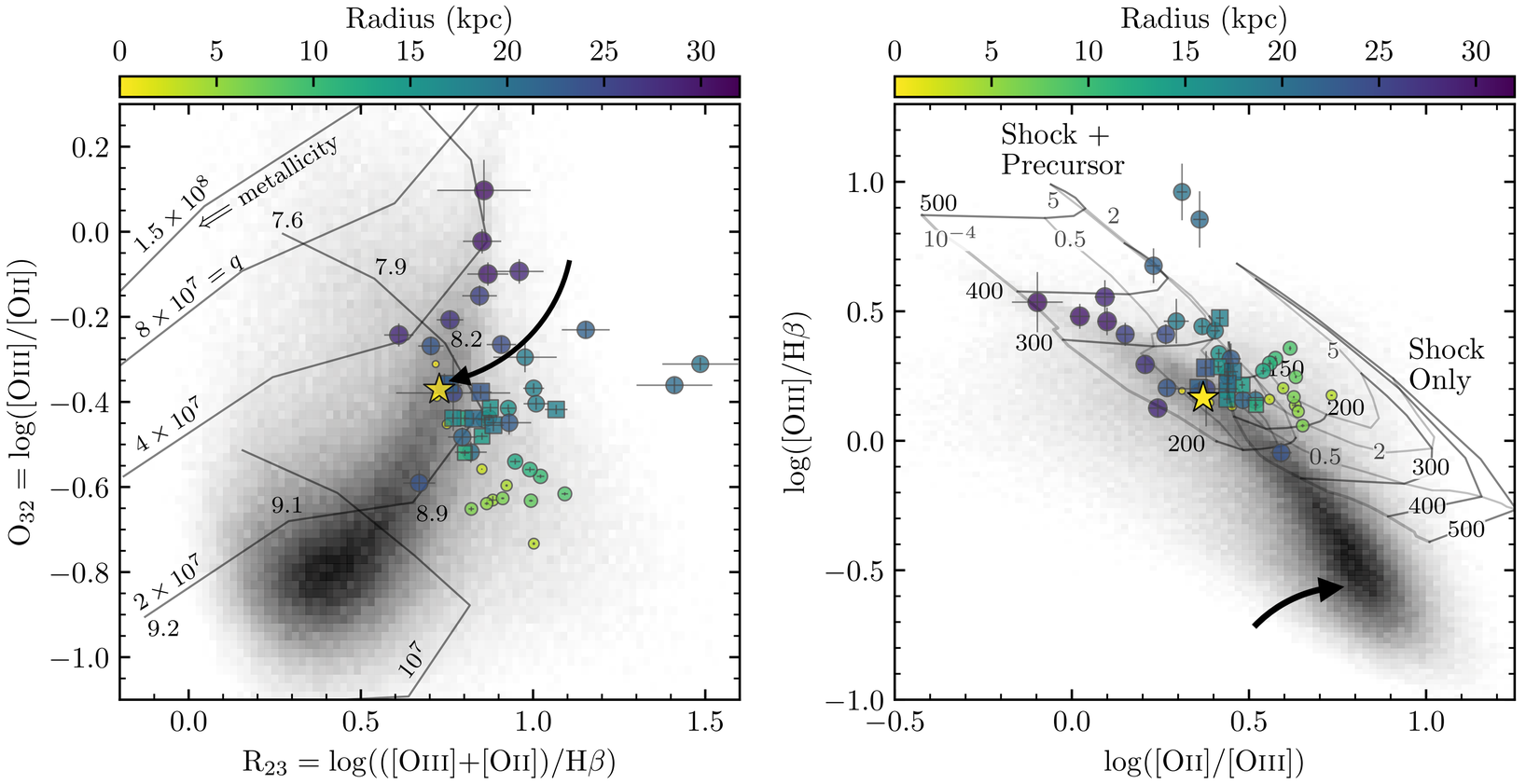
MAPPING THE BARYON-CYCLE

IRAS08 disk consistent with photoionization of typical galaxies

CGM emission behaves differently than ISM → Ionization mechanism changes

→Consistent with shock models

→ Extragalactic UV background taking over



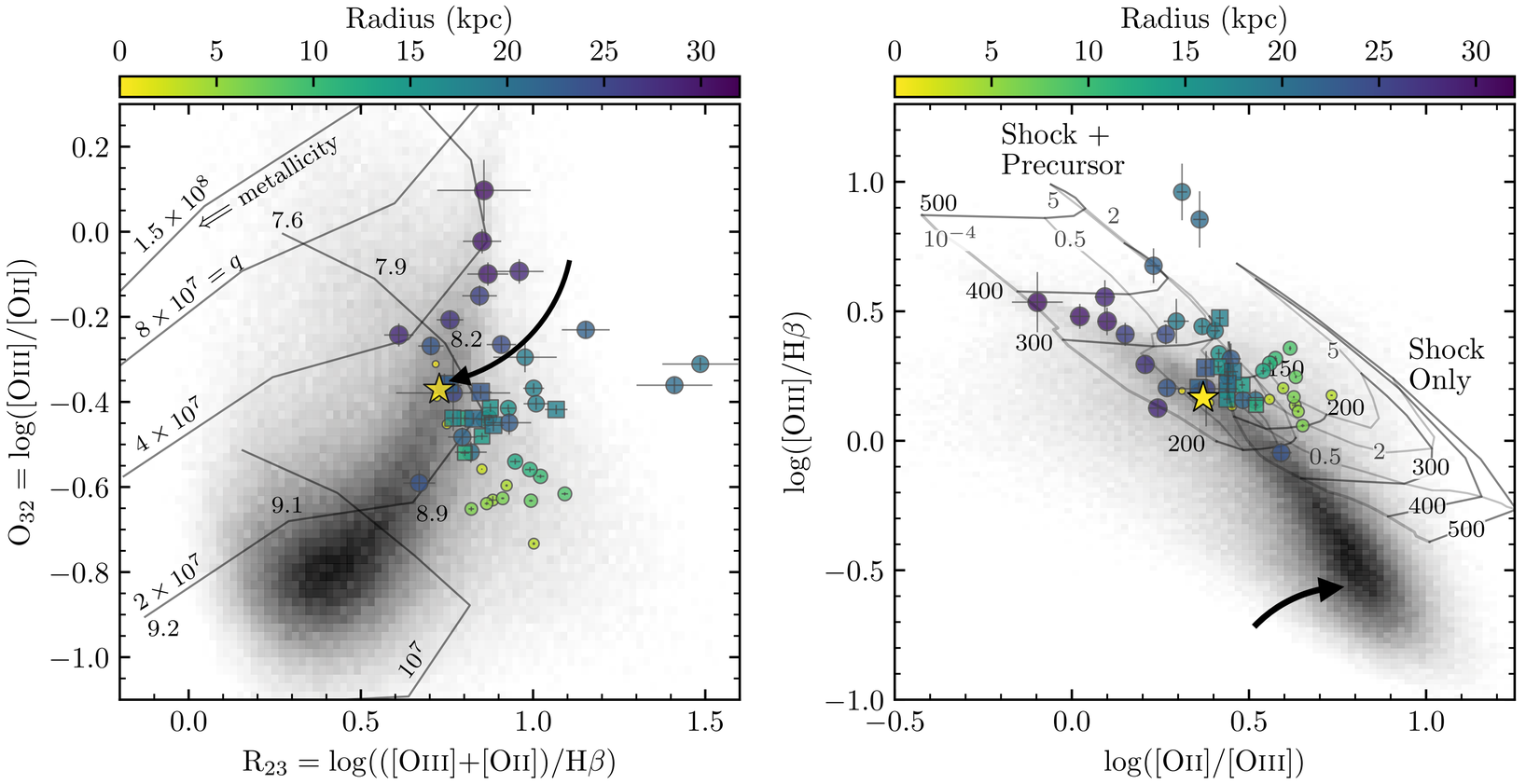
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Shocks: mechanical energy from turbulence or energy deposition from outflows (Allen+2008)



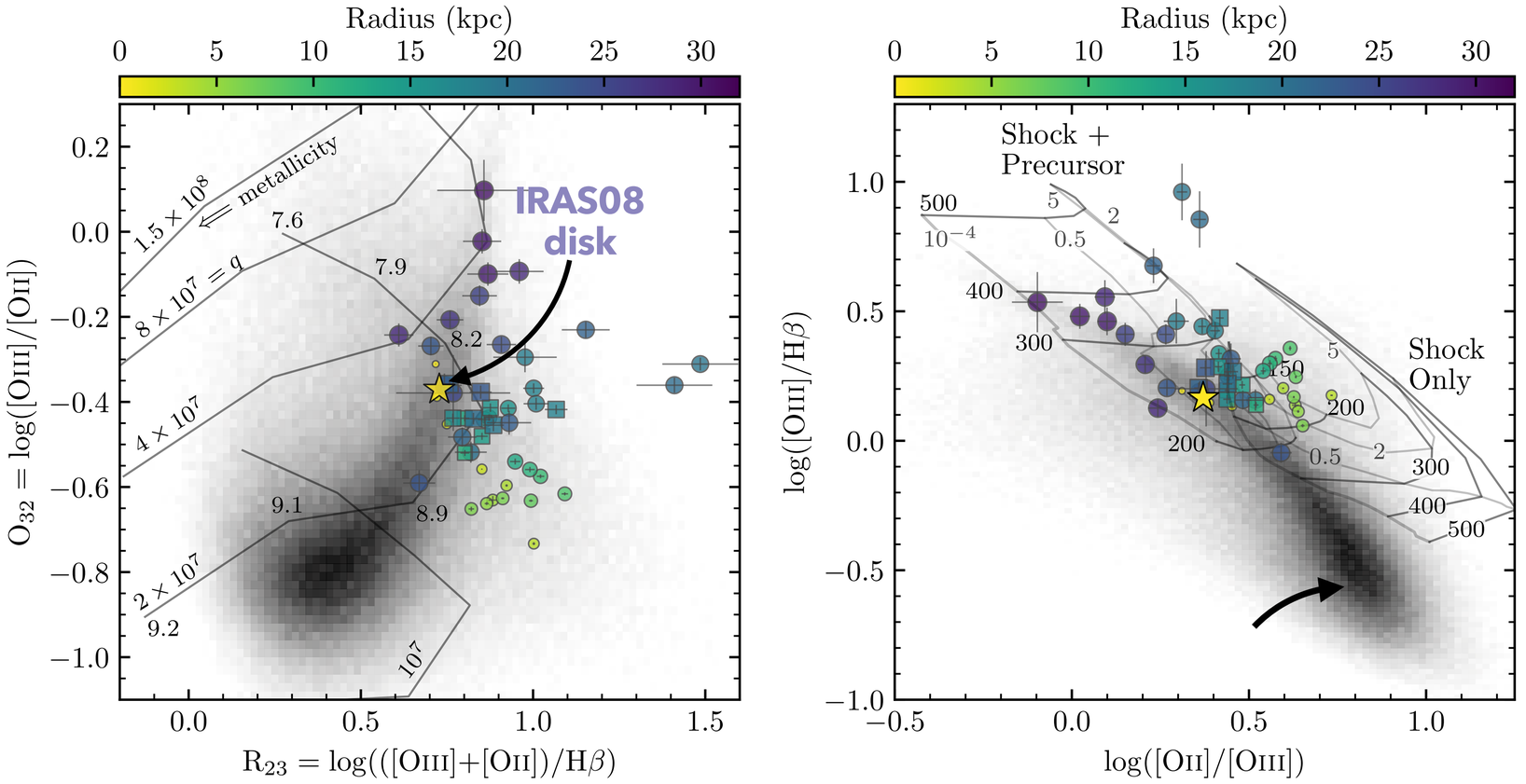
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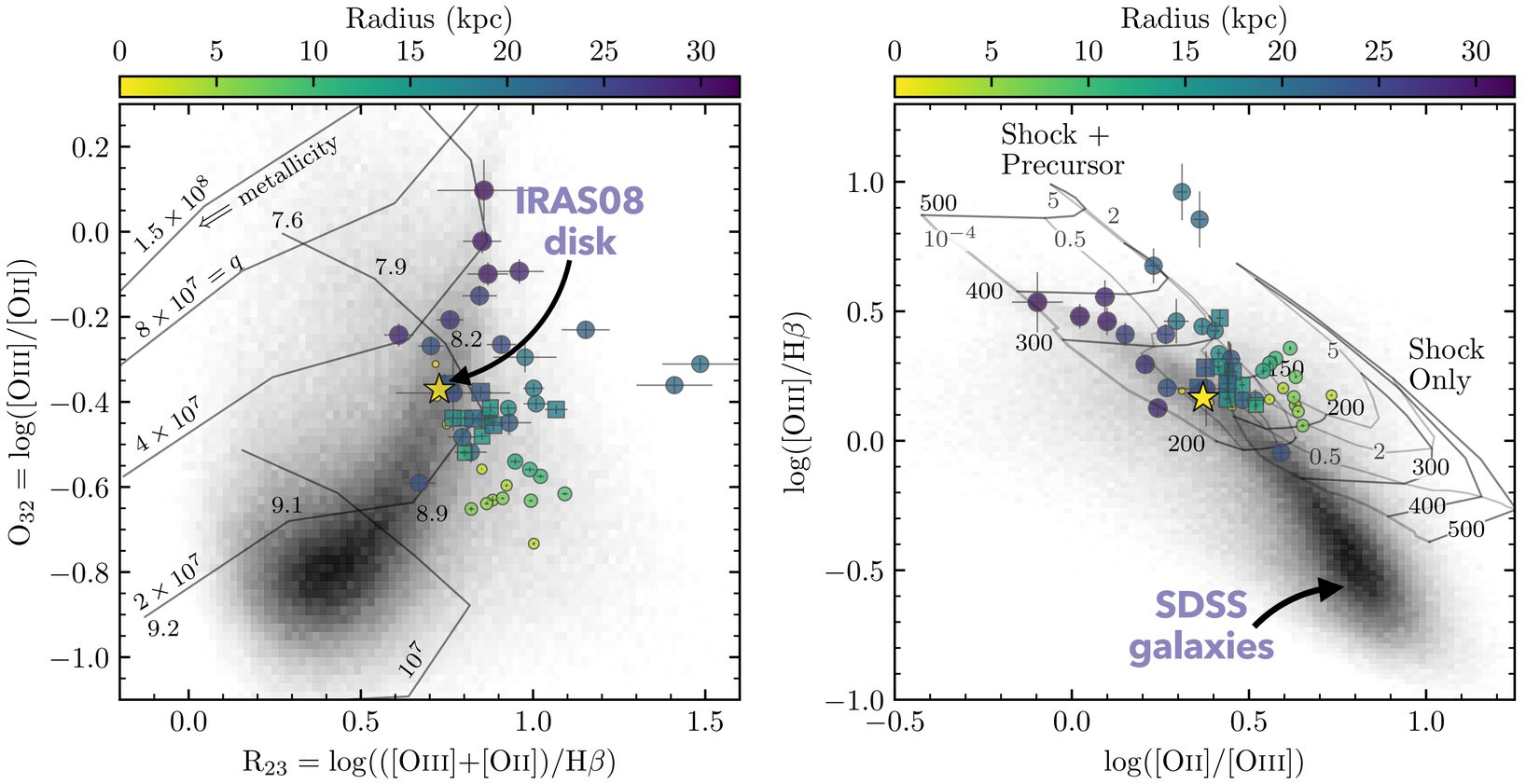
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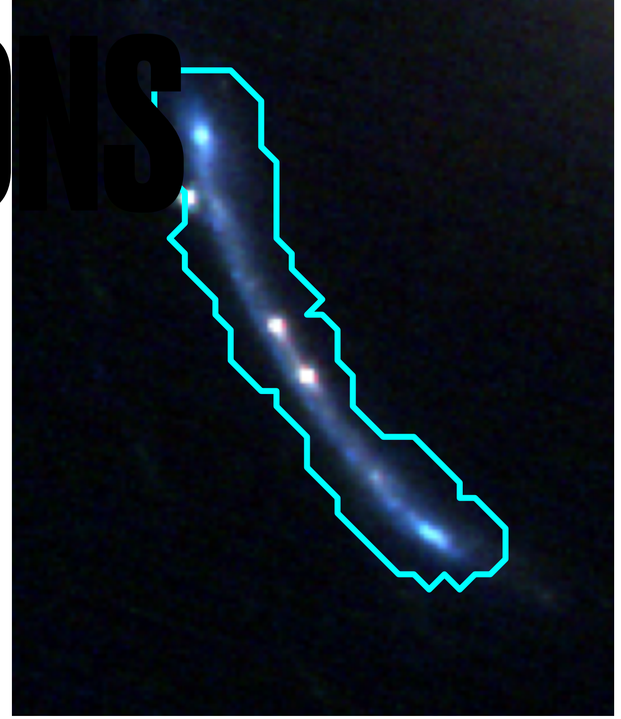


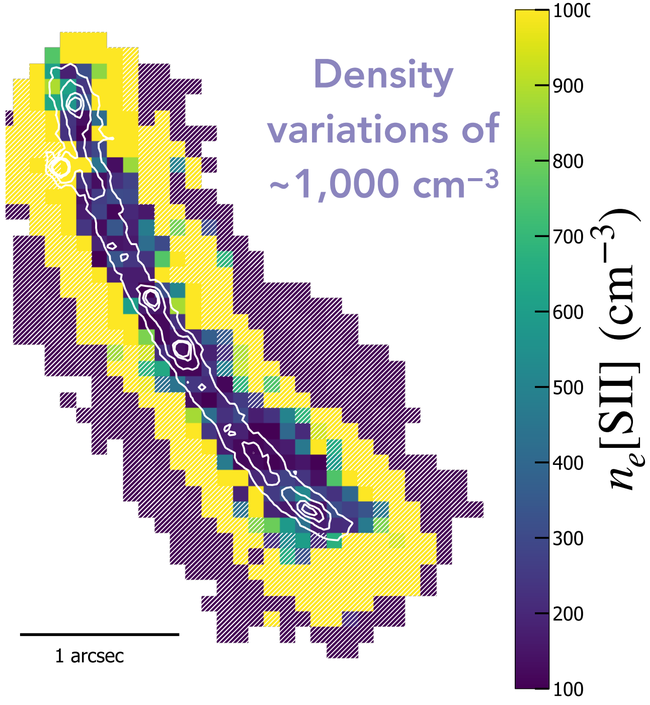
Nielsen et al. 2024

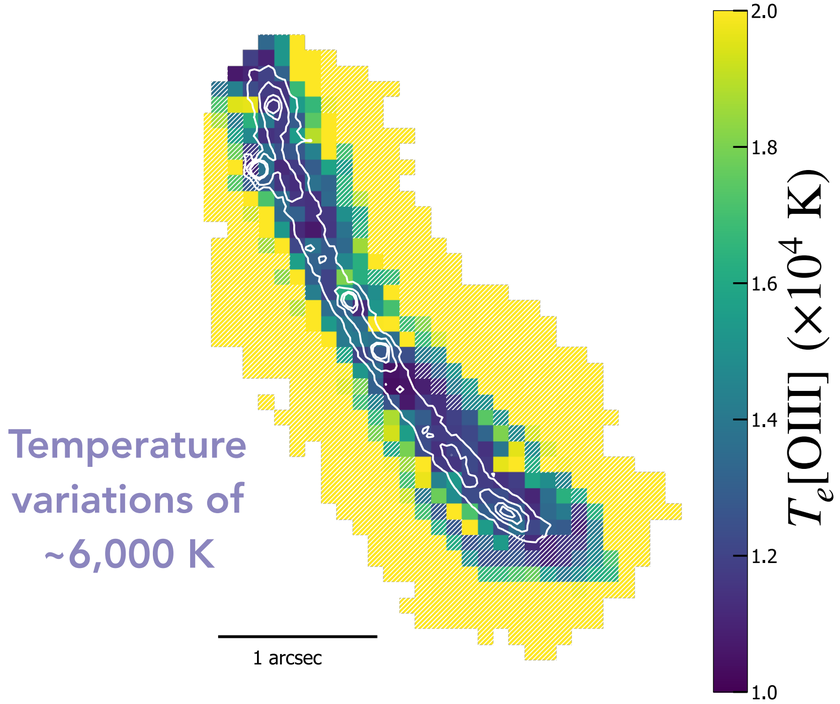
ISM FLUCTUATIONS

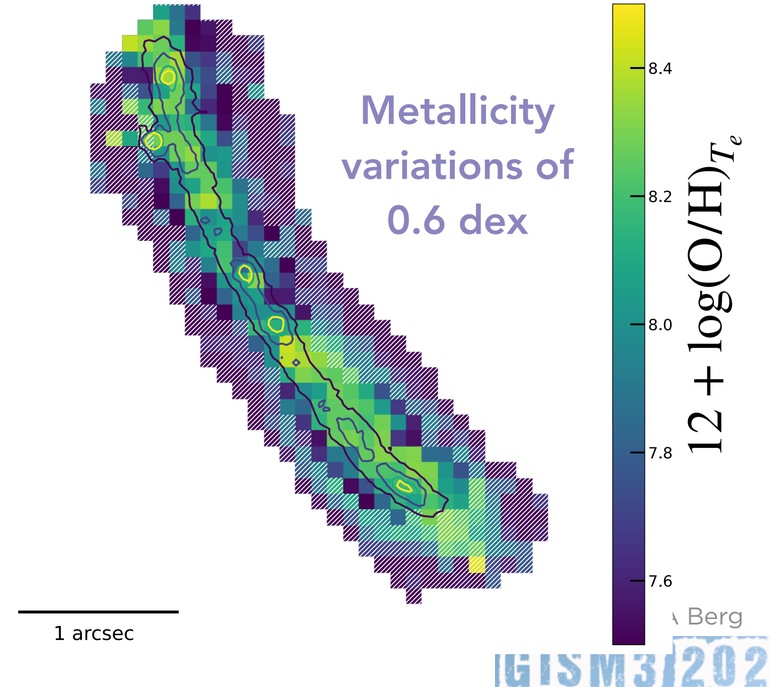
TEMPLATES DD-ERS
(PID 1355, PIs: Rigby, Viera)

JWST NIRSpec IFU
SGAS J1723+3411
z = 1.3293









Olivier et al. 2025, submitted to ApJ

Berg

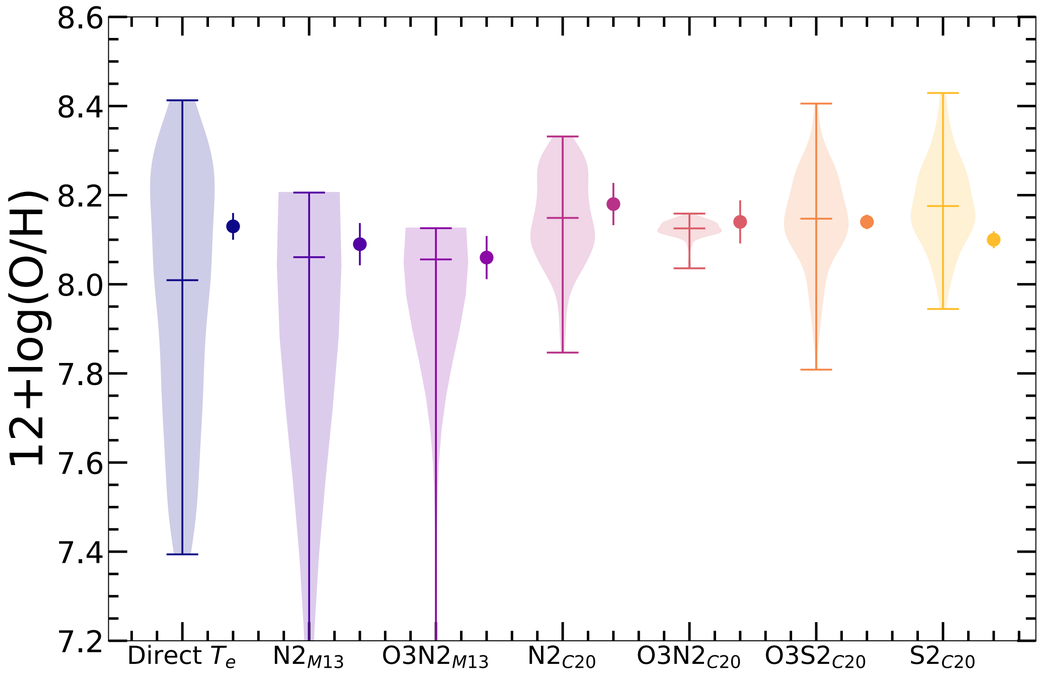
GISM3 2025

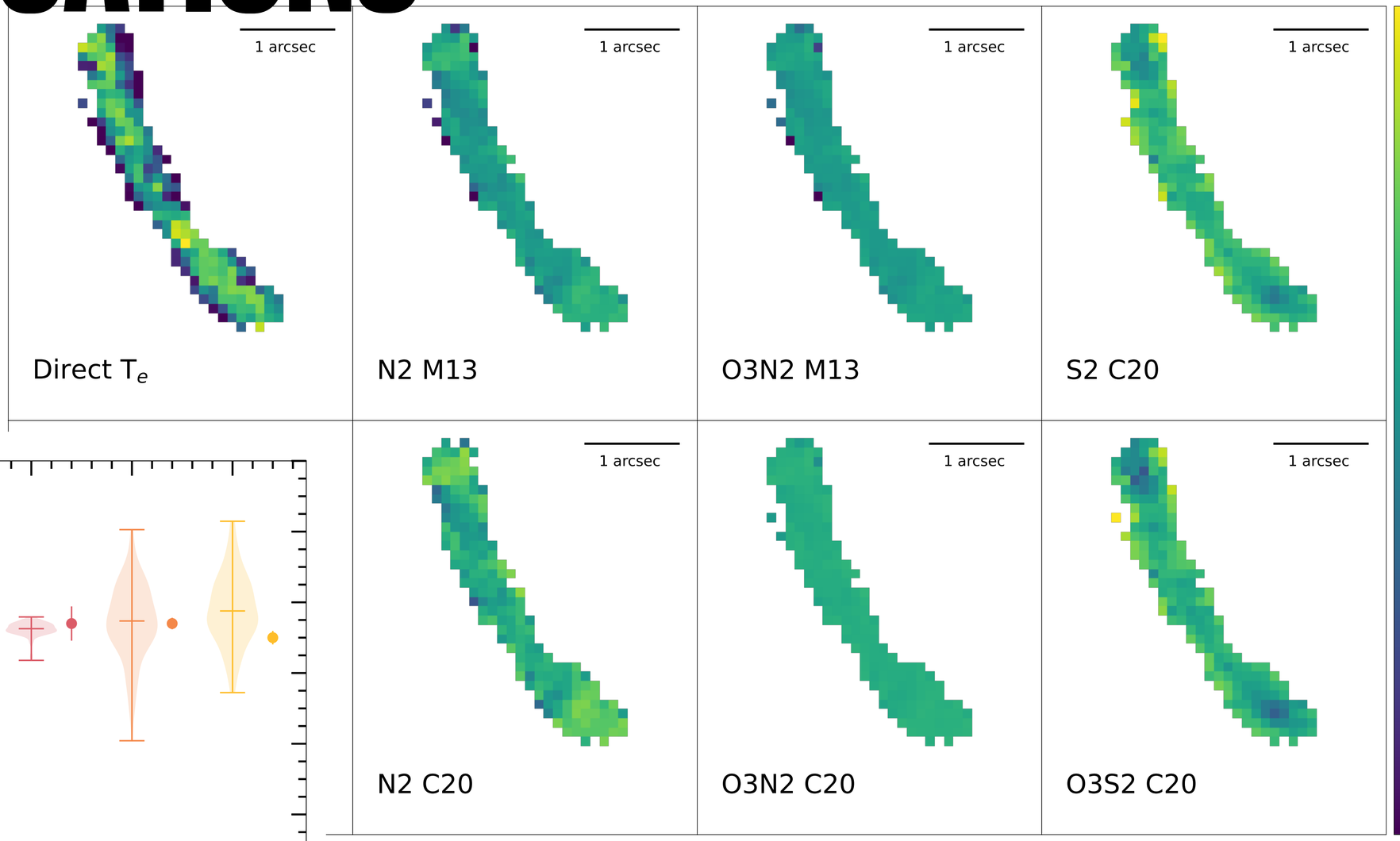
ISM FLUCTUATIONS

Real variations in metallicity largely washed out by strong-line methods

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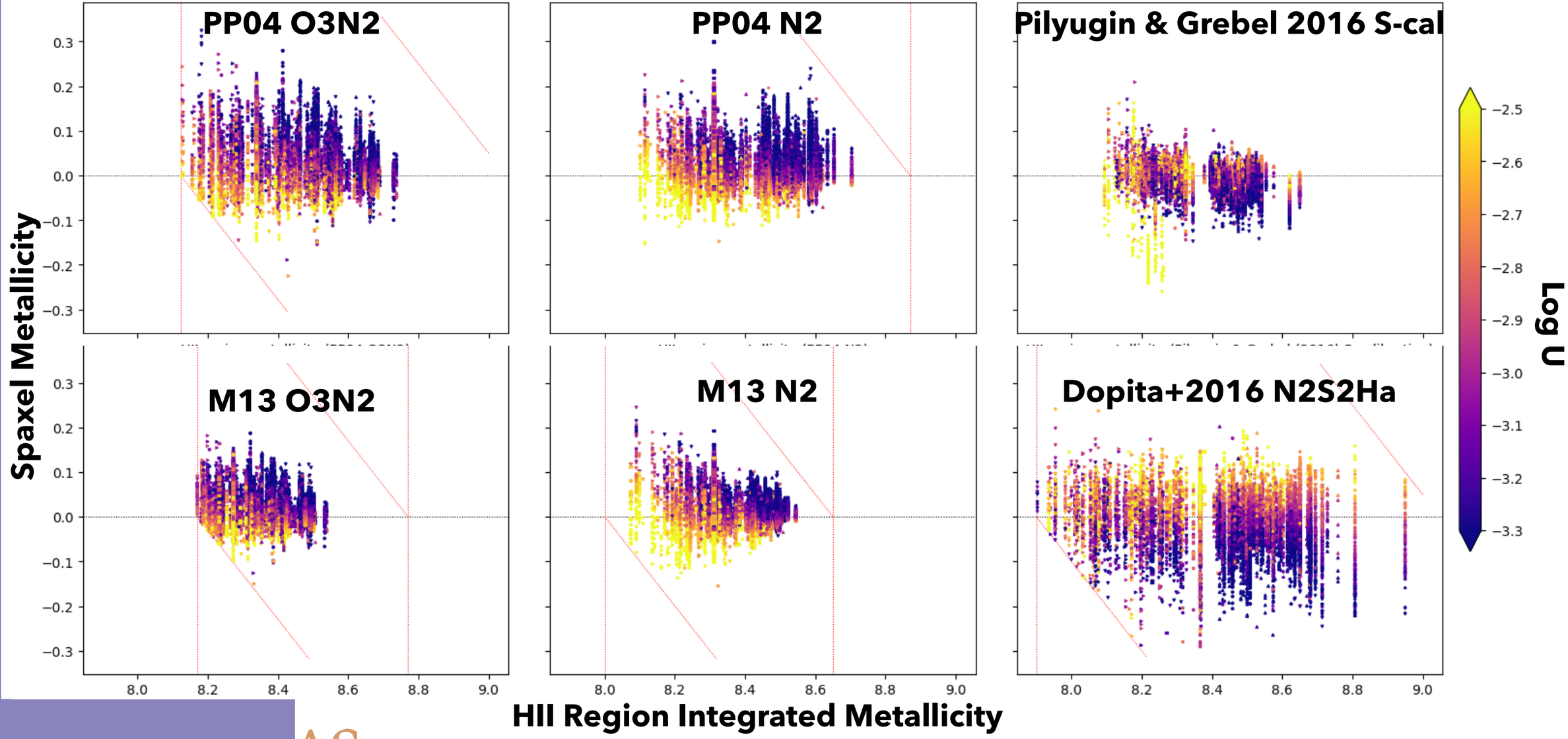


Olivier et al. 2025, submitted to ApJ

ISM FLUCTUATIONS

Real variations in metallicity largely washed out by integrated spectra

Easeman et al. 2024



IFU ISM STUDIES

IFU revolution: MUSE and other IFUs have revolutionized the study of the resolved ISM using galaxy-wide studies of the ISM on sub-kpc scales, including maps of metallicity, ionization, kinematics, feedback.

- **PHANGS-MUSE**: detailed metallicity maps & BPT diagnostics (e.g., Emsellem+2022; Groves+2023)
- **AMUSING surveys**: SN environments (e.g., Galbany+2016) and HII region properites
- **MUSE UDF**: resolved ISM in intermediate-z galaxies e..g, (Bacon et al. 2017)
- **EDGE-CALIFA synergy**: ISM conditions in molecular gas-dominated disks

PART V:
LOOKING FORWARD TO NEXT GEN. CAPABILITIES

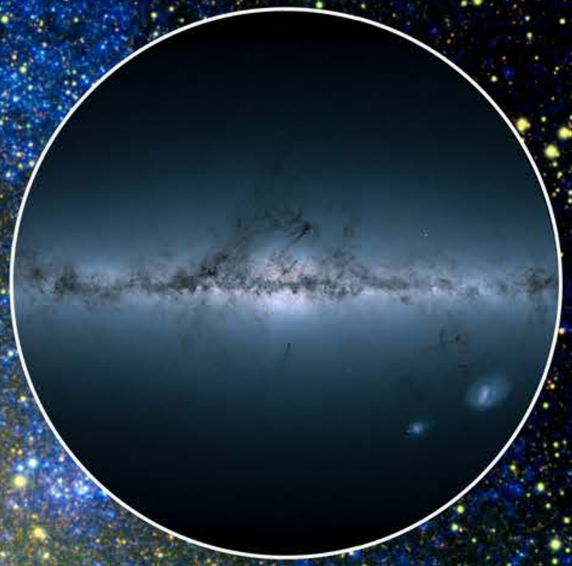
UVEX
Ultraviolet Explorer

All-Sky Imaging

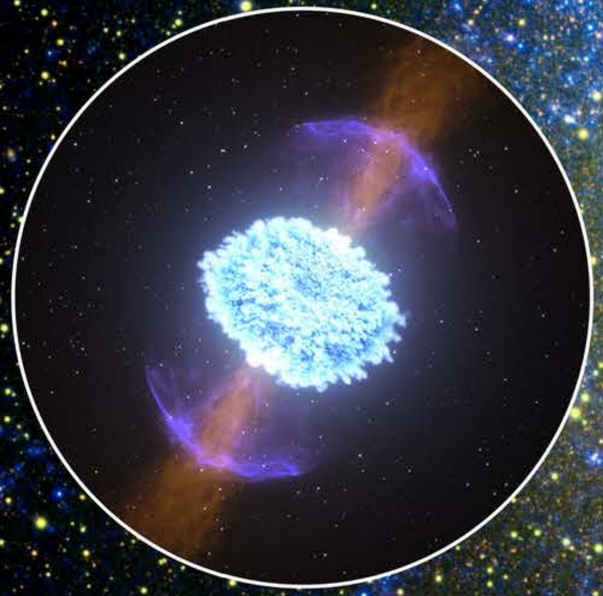
Time Domain

Spectroscopy

Exploring the Low Mass Galaxy Frontier



Legacy of Deep Synoptic Surveys



New Views of the Dynamic Universe

PRINCIPAL INVESTIGATOR

Fiona A. Harrison
California Institute of Technology

AUTHORIZING OFFICIAL

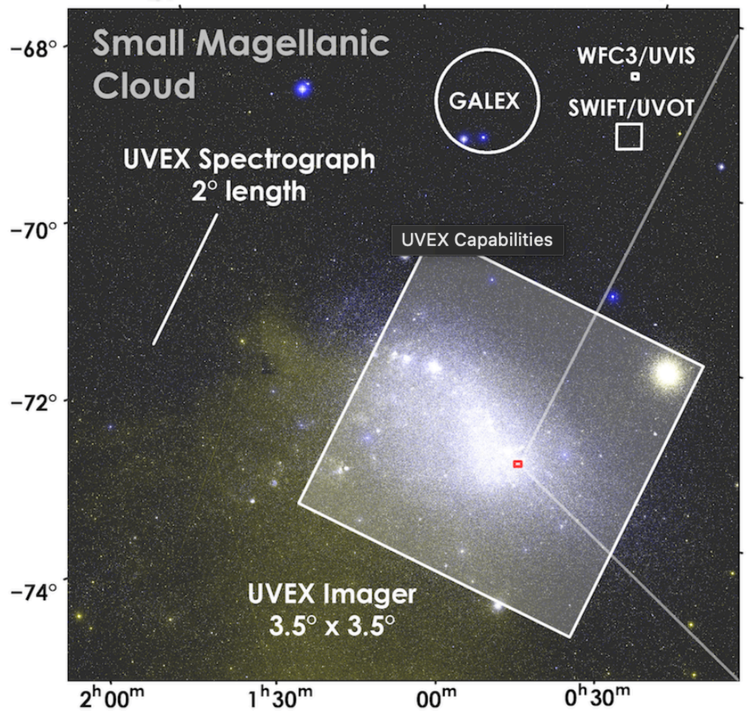
David J. Mayo
Director, Office of Sponsored Research
California Institute of Technology

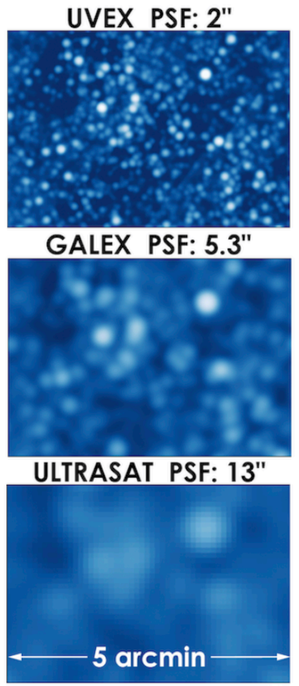
LOOKING FORWARD

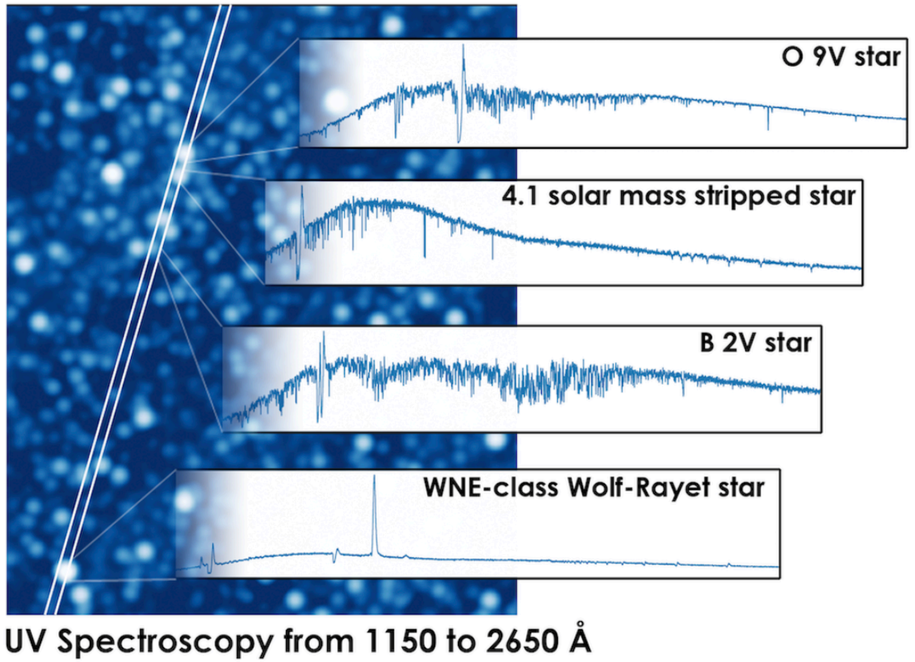
UVEX will perform a modern synoptic all-sky survey, reaching depths of > 25 AB mag over 2 years
- Simultaneous FUV and NUV imaging over a 12 deg^2 field of view and a PSF of ~2”

UVEX will efficiently probe dense stellar regions and resolved galaxies, and obtaining a wealth of serendipitous spectra.
- 2-degree-long spectroscopic slit with multiple widths will obtain sensitive, R > 1000 spectra across a broad UV bandpass that includes many important diagnostic lines.

UVEX will be able to rapidly respond to targets of opportunity
- Photometric or spectroscopic follow-up within ~3 hours of a trigger, probing the bright, fast UV emission of neutron star mergers and cosmic explosions.







UV Spectroscopy from 1150 to 2650 Å

UVEX
Ultraviolet Explorer

All-Sky Imaging
Time Domain
Spectroscopy

LOOKING FORWARD

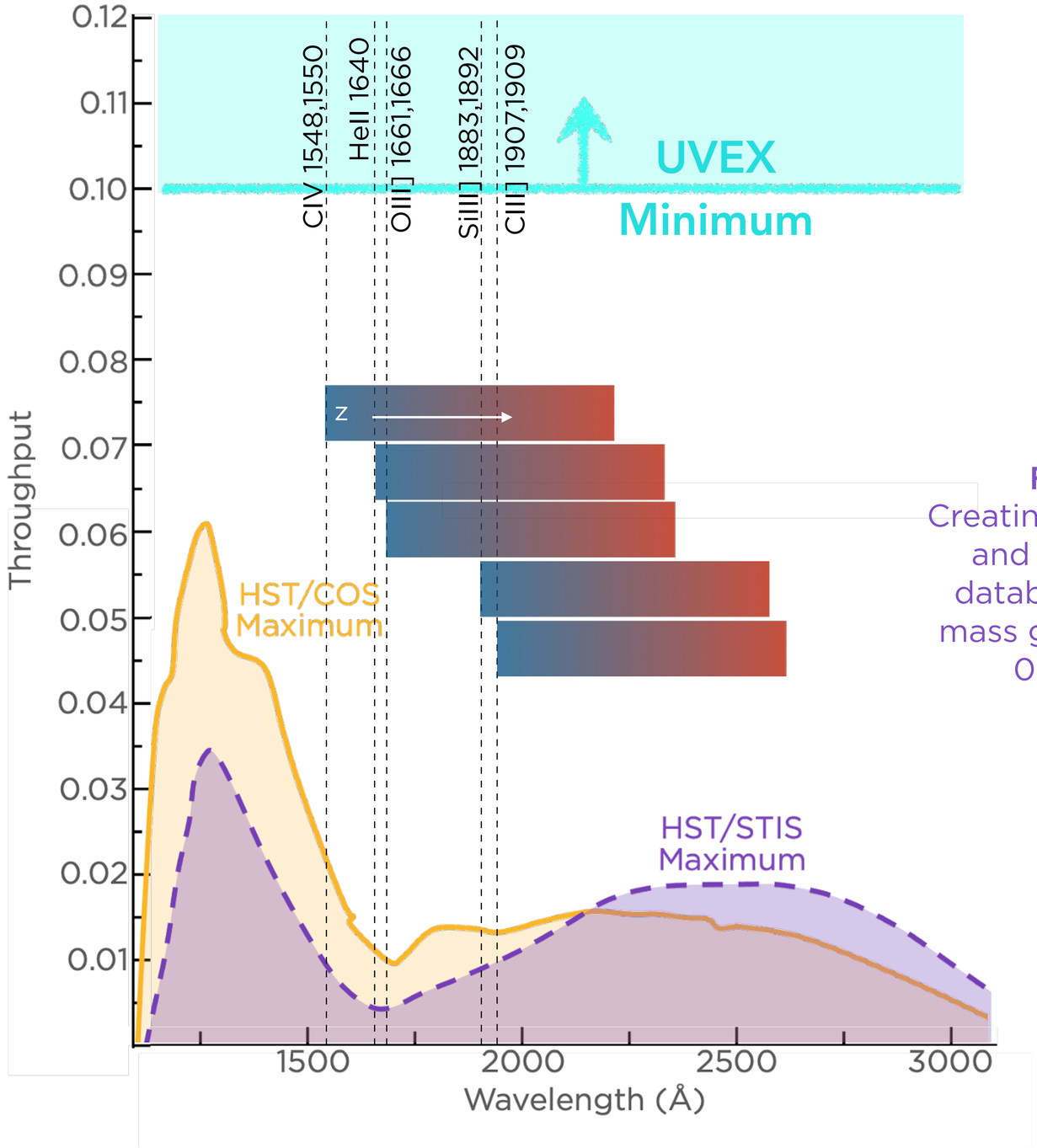
UVEX will leverage the diagnostic power of the FUV to trace the baryon cycle for the smallest galaxies

UVEX
Ultraviolet Explorer

All-Sky Imaging

Time Domain

Spectroscopy



FUV spectra:
Creating a homogeneous and comprehensive database of FUV low-mass galaxy spectra for $0.03 < z < 0.3$.

LOOKING FORWARD

UVEX will leverage the diagnostic power of the FUV to trace the baryon cycle for the smallest galaxies

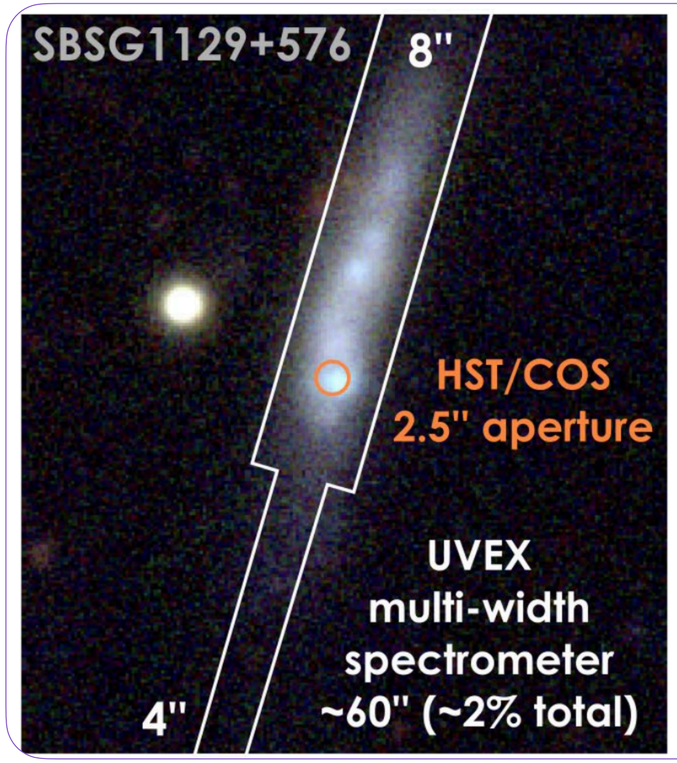
UVEX
Ultraviolet Explorer

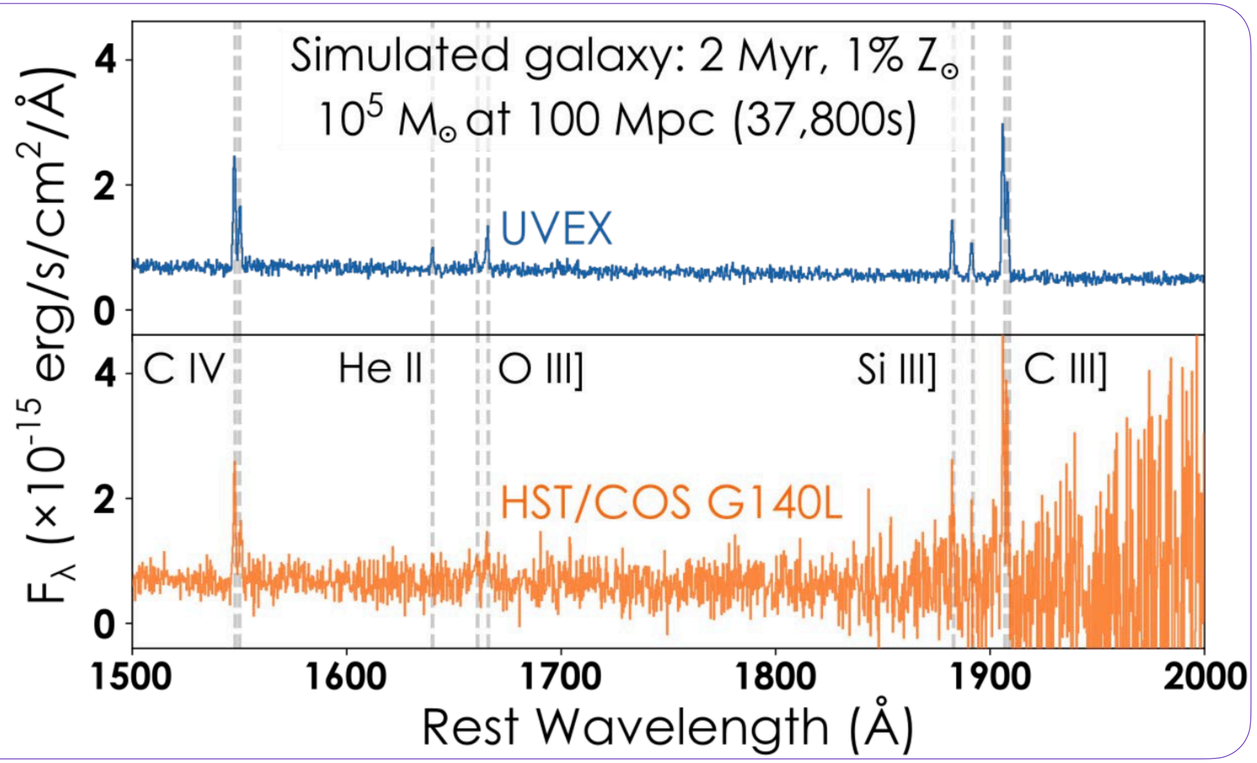
All-Sky Imaging

Time Domain

Spectroscopy

The optimized throughput and sensitivity of UVEX will enable **unprecedented studies of UV emission & absorption lines in metal-poor galaxies.**



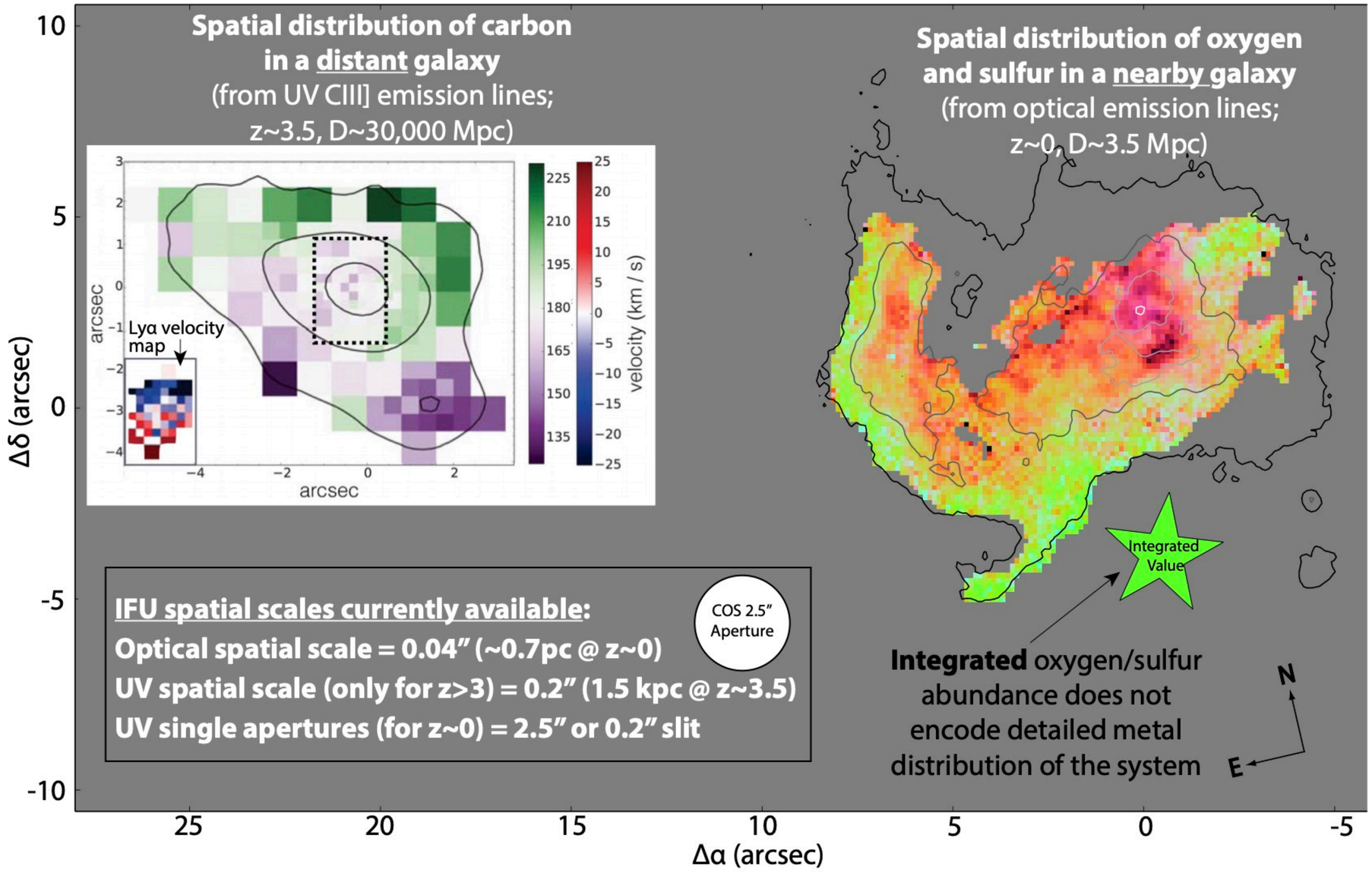


Kulkarni, UVEX Team, 2021

UVEX spectroscopy will detect emission line fluxes down to 3×10^{-16} erg s^{-1} cm^{-2} with a S/N = 10 in 20,000 ks.

LOOKING FORWARD

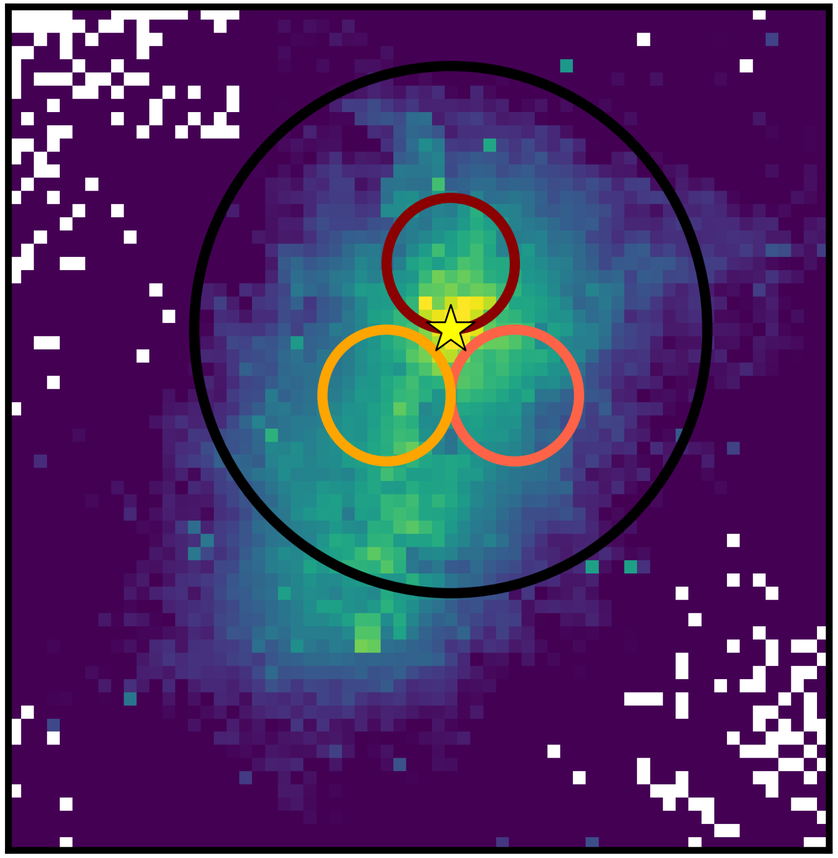
UV+optical IFU will revolutionize ISM studies

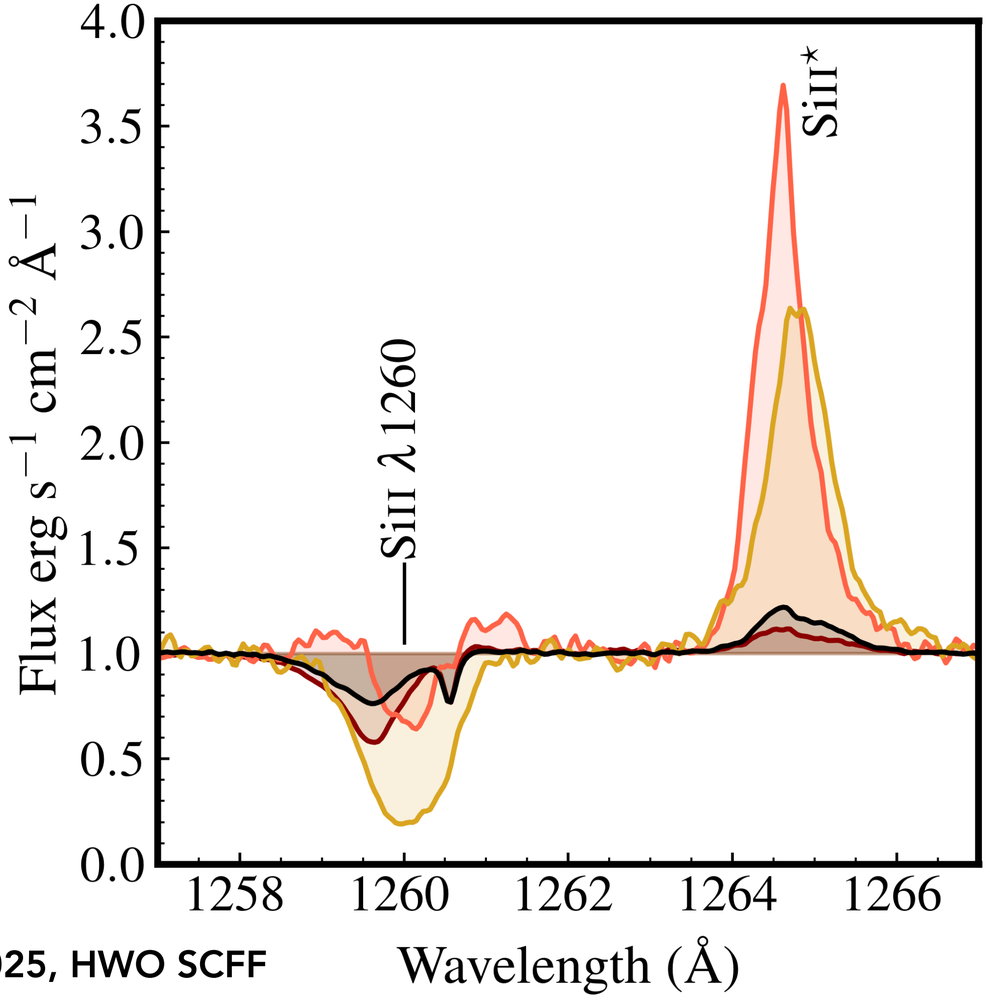


Berg & James 2025, HWO SCFF

LOOKING FORWARD

UV+optical IFU will revolutionize ISM studies

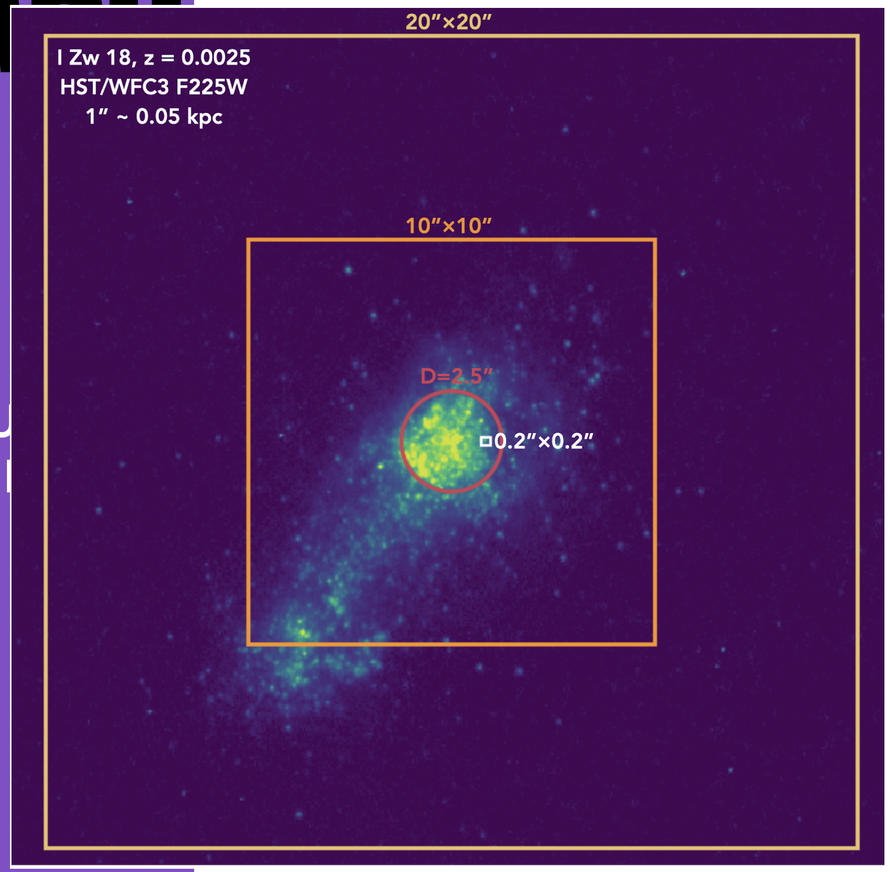


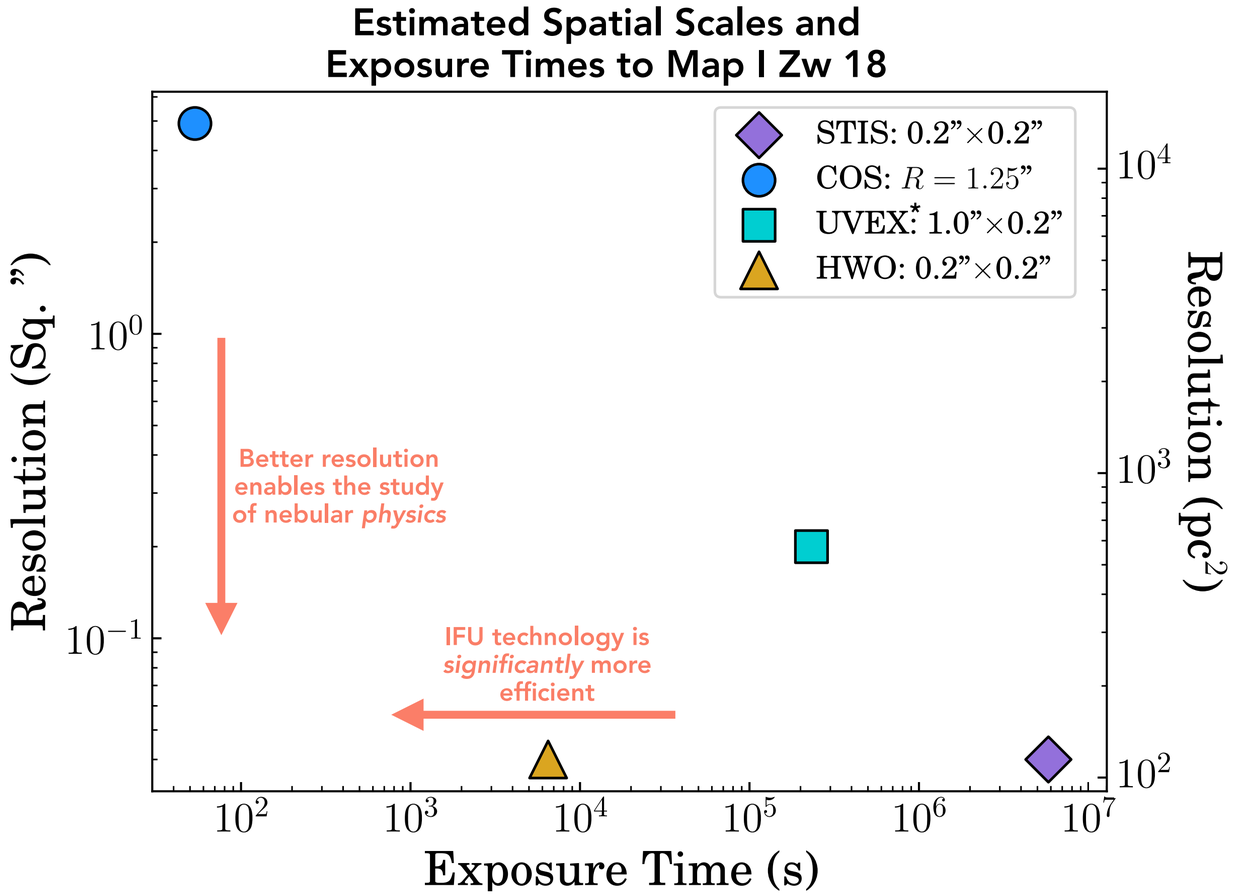


Berg & James 2025, HWO SCFF

LOOKING FORWARD

UV+optical IFU
revolutionize
studies





Berg & James 2025, HWO SCFF

TAKE AWAYS

- **UV + optical + MIR diagnostics** remain core tools for understanding galaxy evolution throughout the ISM.
- **UV + optical + MIR spectroscopy** uncovers the full ISM cycle: gas, metals, dust and allows us to trace chemical evolution, feedback, and ionizing radiation.

- **Nearby metal-poor galaxies** act as crucial analogs to early Universe systems.
- **EELGs** are still producing many questions, but are critical to understand the formation and enrichment of the earliest galaxies.
- **High-redshift studies** are the frontier of global chemical evolution, but need further calibration.
- Progress will be in robustly determining the physical conditions of galaxies across cosmic time (local to first galaxies).

- **Depletions and dust** influence both ISM physics and our measurements—understanding them is essential.
- **Dust** may be substantially different in extreme environments, like at high-z.

- **Integral field spectroscopy** (e.g., MUSE) enables a spatially resolved understanding of the ISM, CGM, and stellar feedback.

- The **future of UV astronomy** (e.g., HWO) will be pivotal for studying faint, low-metallicity, and early galaxies.
- **UVEX** will enabling detection and spectroscopy of faint, nearby galaxies—crucial for refining models and calibrations of ISM diagnostics.
- **HWO+MUSE+MIRI** will revolutionize our spatially-resolved understanding of the star-gas cycle and gas conditions.