Deciphering the True Properties of Galaxies Across Cosmic Time with UV spectroscopy

Bethan James

Danielle Berg, Valentina Abril-Melgarejo, Matilde Mingozzi , Alessandra Aloisi, Kaelee Parker & CLASSY collaboration

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Galaxy Assembly and Growth

What properties characterized the first galaxies?
How do those properties drive galaxy evolution?

Galaxy Assembly and Growth

What properties characterized the first galaxies?
How do those properties drive galaxy evolution?

Analogues in the nearby Universe are **rest-frame UV laboratories** for understanding the **primeval systems**

If you want an accurate understanding of the ISM, you need a detailed view.

Credits: NAOJ

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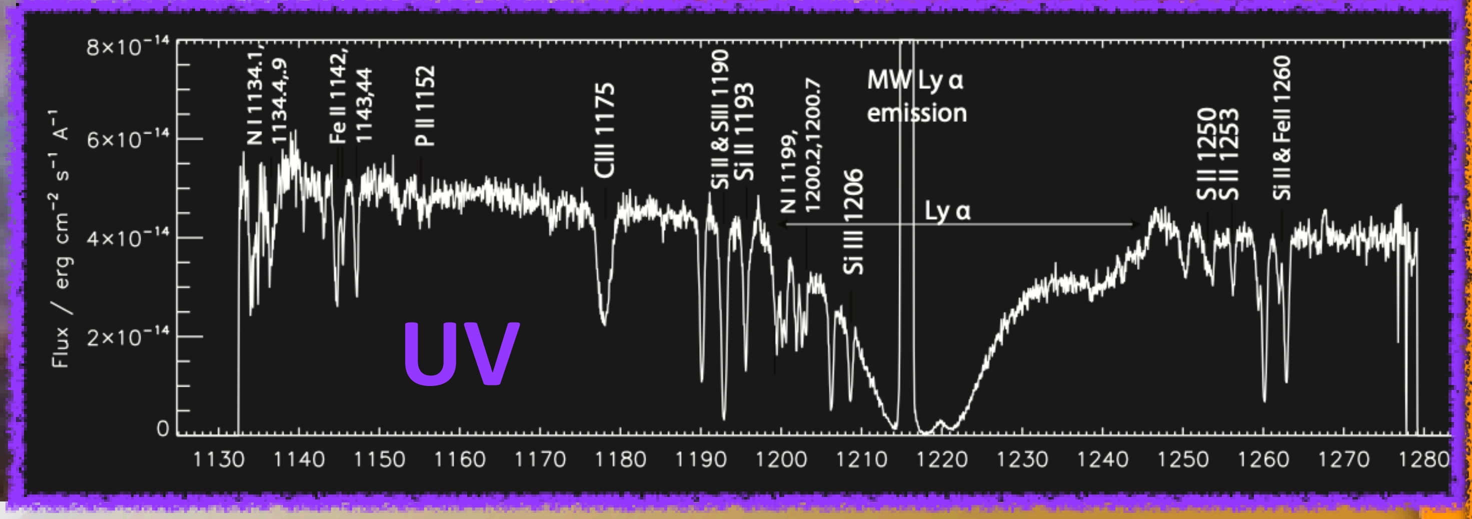
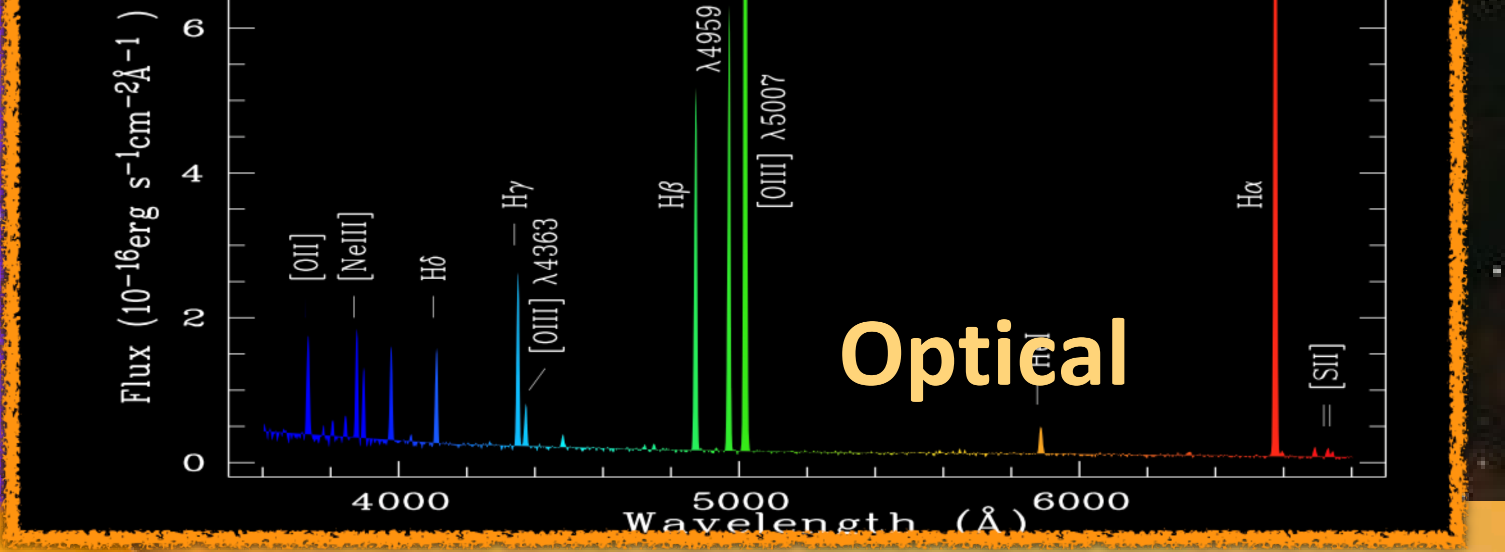
Understanding Galaxies at EoR

What can the UV do for you?



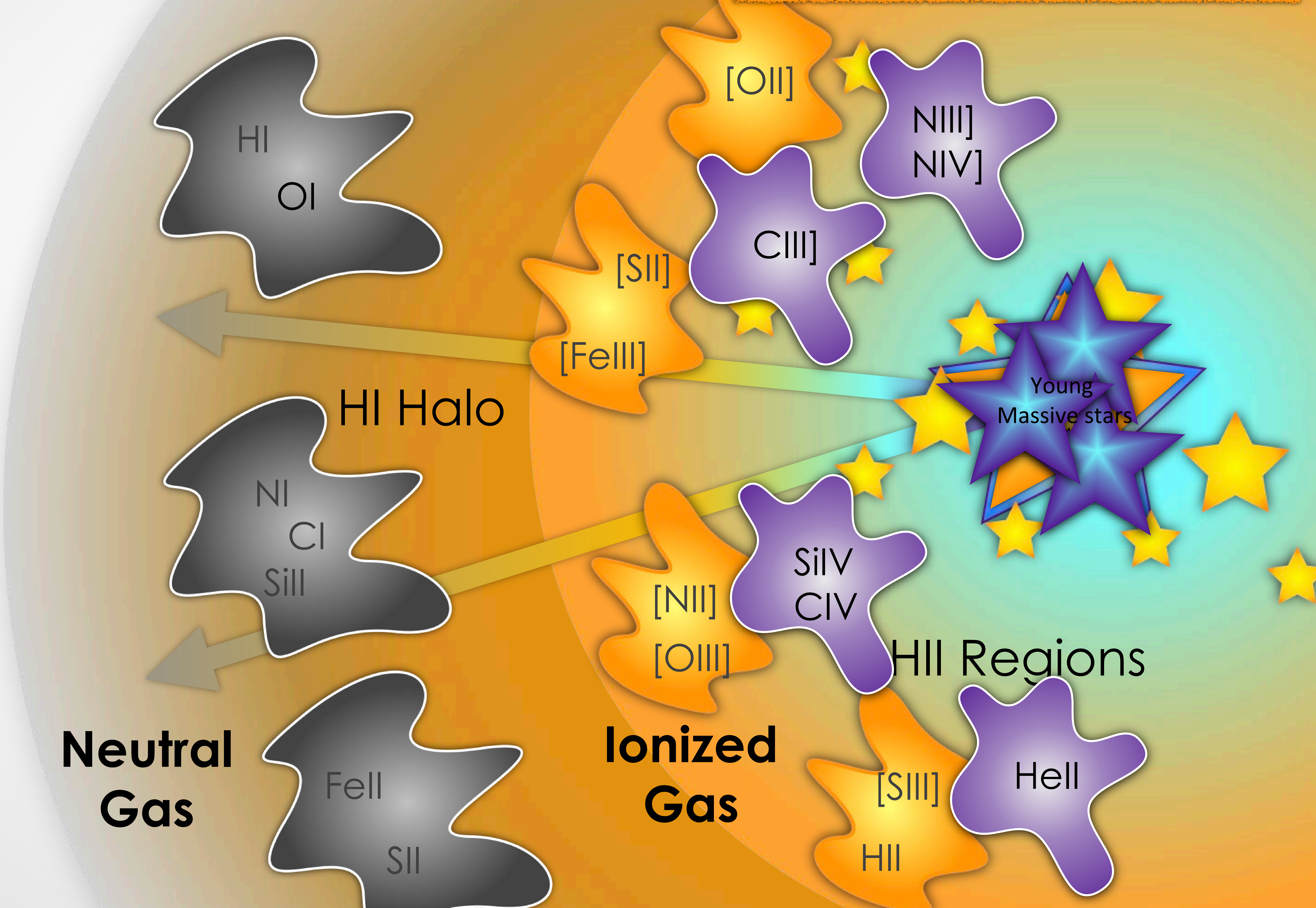


How are metals *truly* distributed throughout a galaxy?

What are the timescales of chemical enrichment?

How dense is the ISM?

How intense are the high energy photons and where are they being produced?



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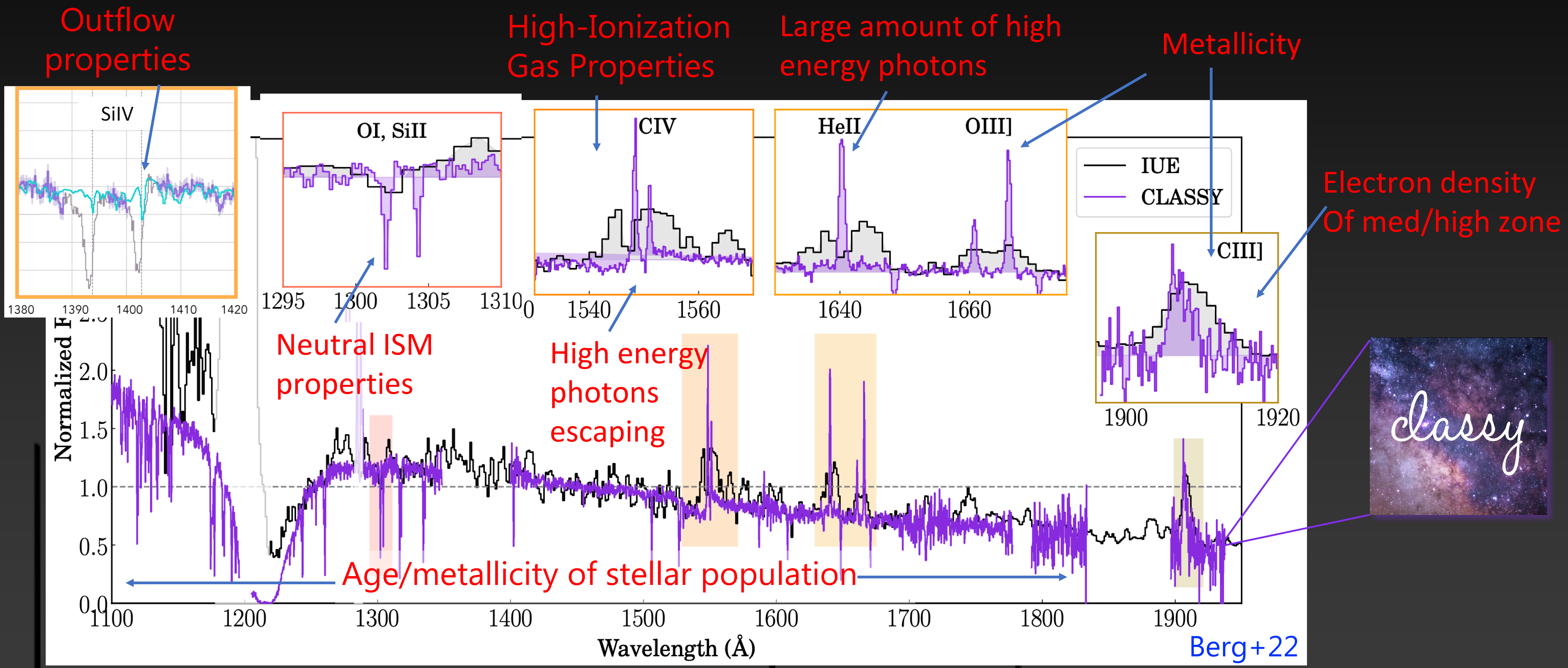
Galaxy Properties Revealed by the UV



→ Accurate UV diagnostics for measuring properties of local + high-z galaxies

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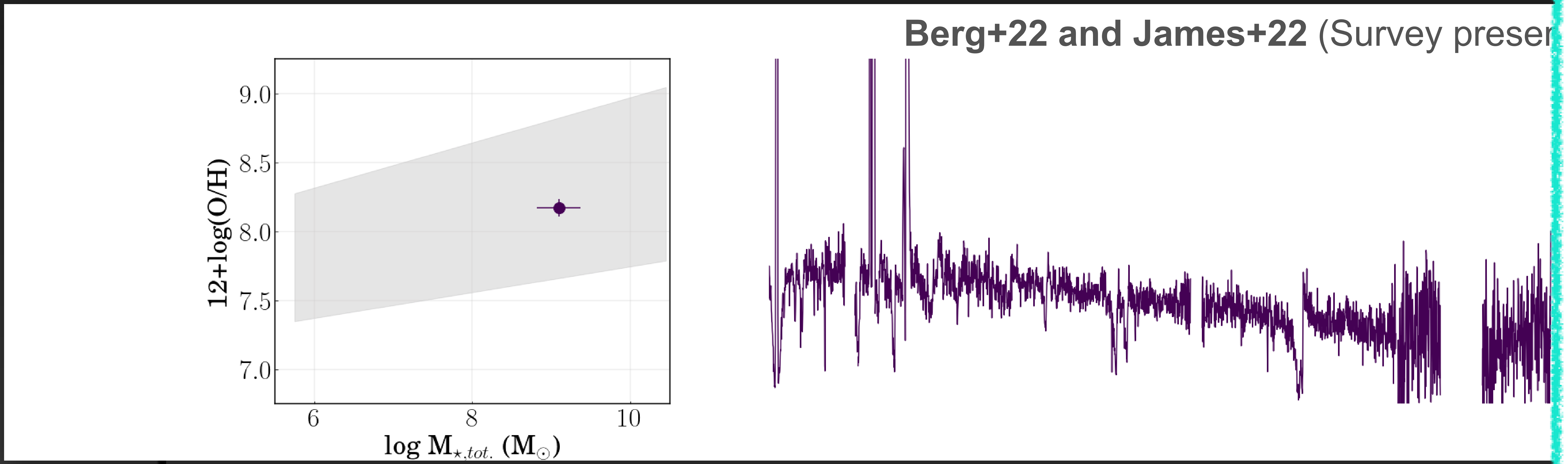
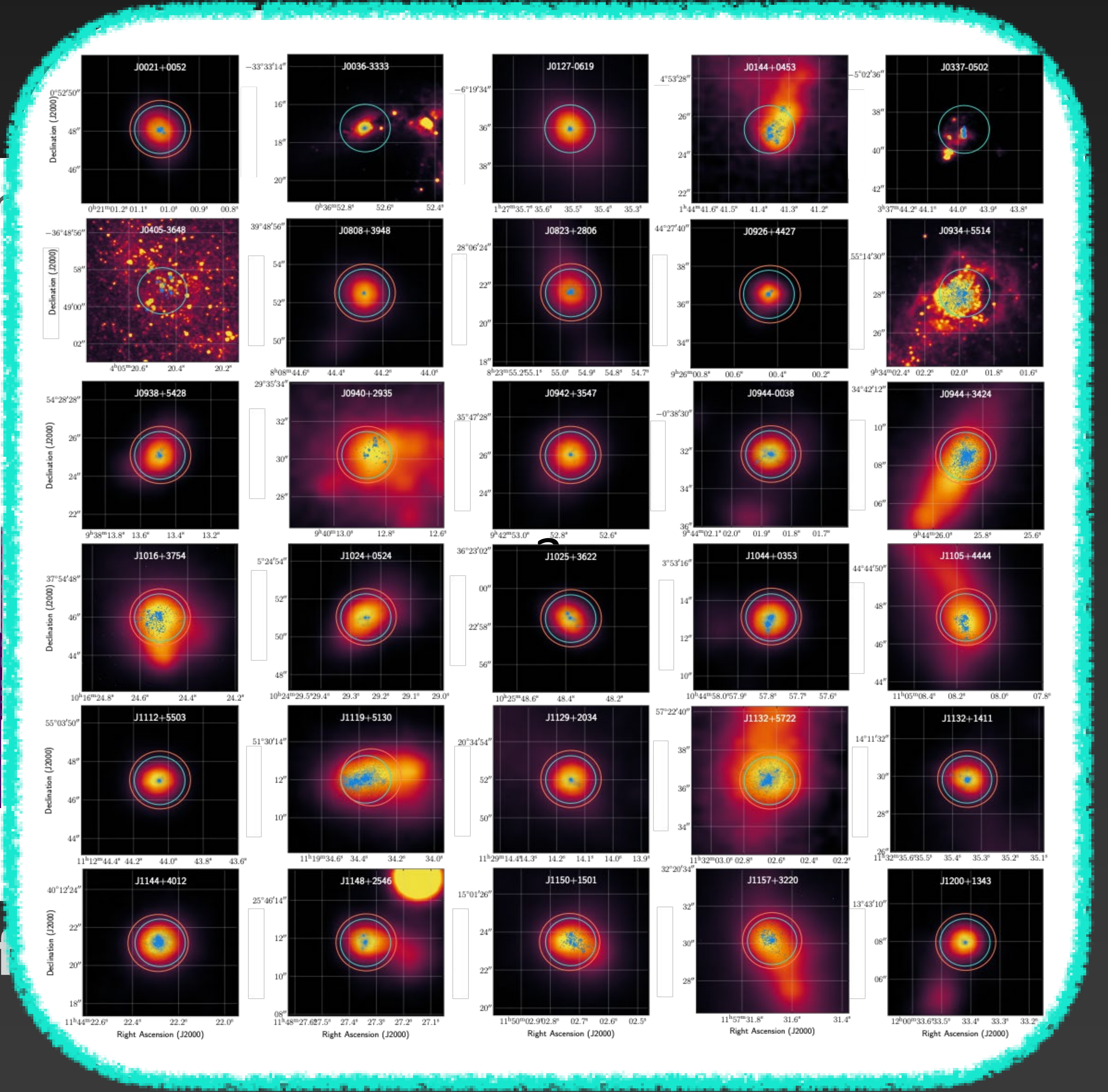
What are we already learning from the UV?

The COS Legacy Spectroscopic Survey

First **high-quality, high-resolution FUV** spectral database of 45 nearby star-forming galaxies collecting together the HST/COS gratings G130M (1200-1450 Å), G160M (1450-1775 Å) and G185M (1775-2000 Å)
https://stdatu.stsci.edu/hlsp/classy

Berg+22 and James+22 (Survey preser





0.1-10kpc scales
James et al, 2022

M*, SFR, sSFR, metallicity, ionization parameter and density **highly representative of** **Universe**

- Optical spectral data for entire CLASSY sample
- (SDSS, LBT, MMT, VIMOS, KCWI, MUSE)
- 12+ CLASSY papers so far

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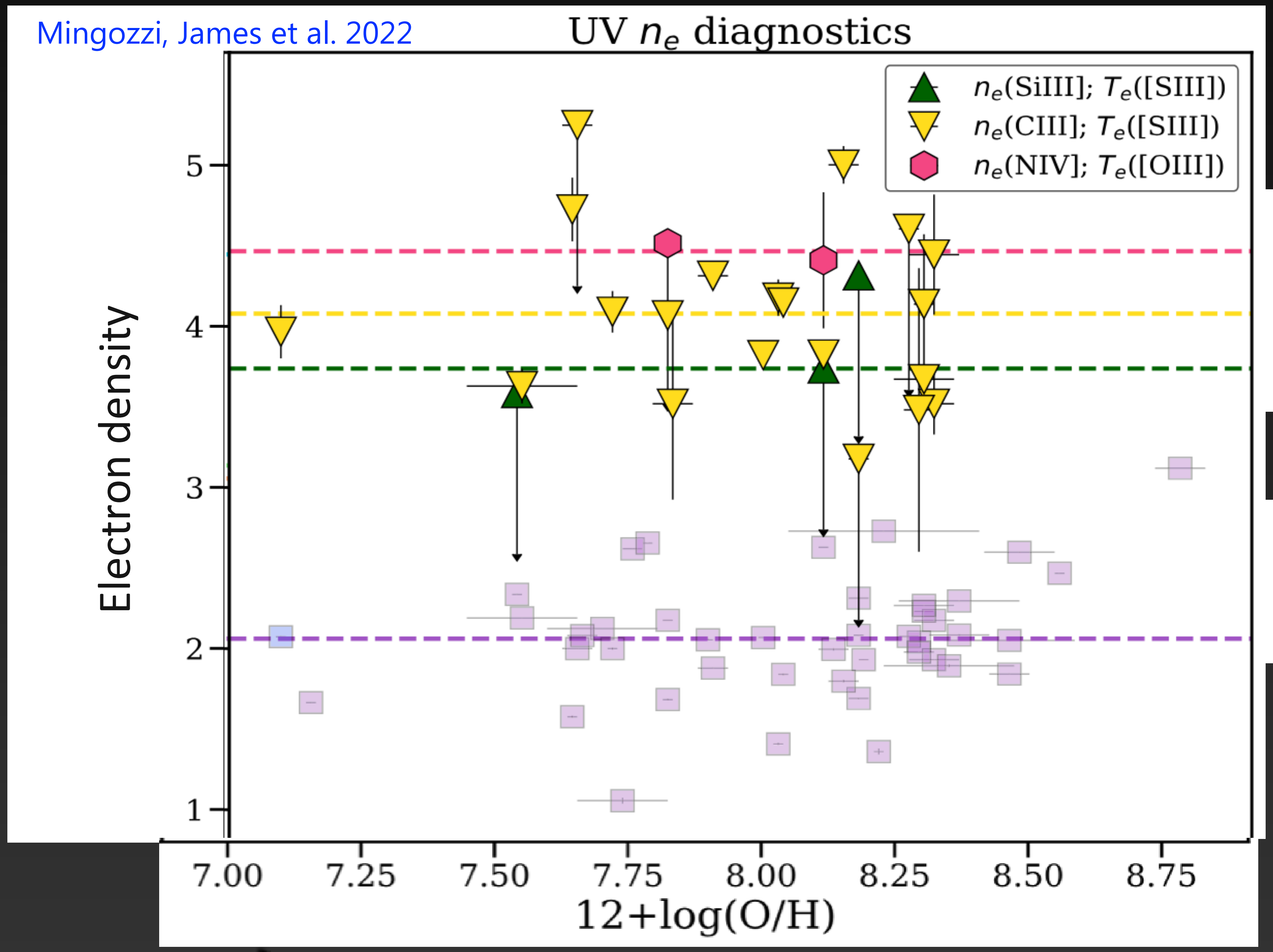
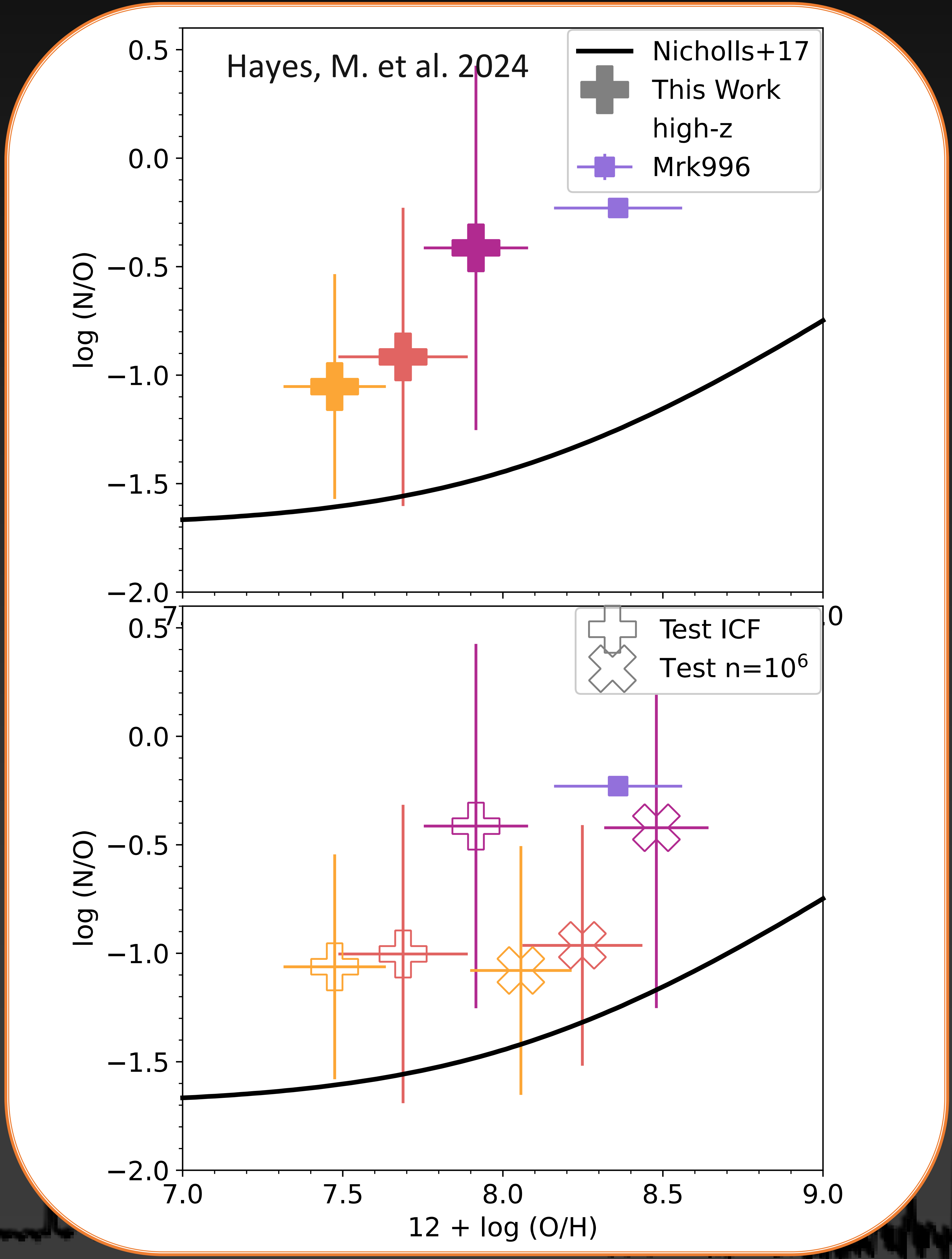
Secrets from the UV:
Density stratification & effects on metallicity



UV density tracers:
[CIII]λ1907/CIII]λ1909
[SiIII]λ1883/SiIII]λ1892
NIV]λ1483/NIV]λ1486

Most common **optical** density tracers:
[SII]λ6717/[SII]λ6731
[OII]3729/3727



UV densities are 1-2 dex higher than optical diagnostics

The UV is tracing higher ionization zones

Collisional de-excitation of O^{2+} @N_e=$10^{5\text{-}6}$ cm^{-3}
→ Lower temperatures = higher metallicity

Using the correct density dramatically changes abundance calculations!

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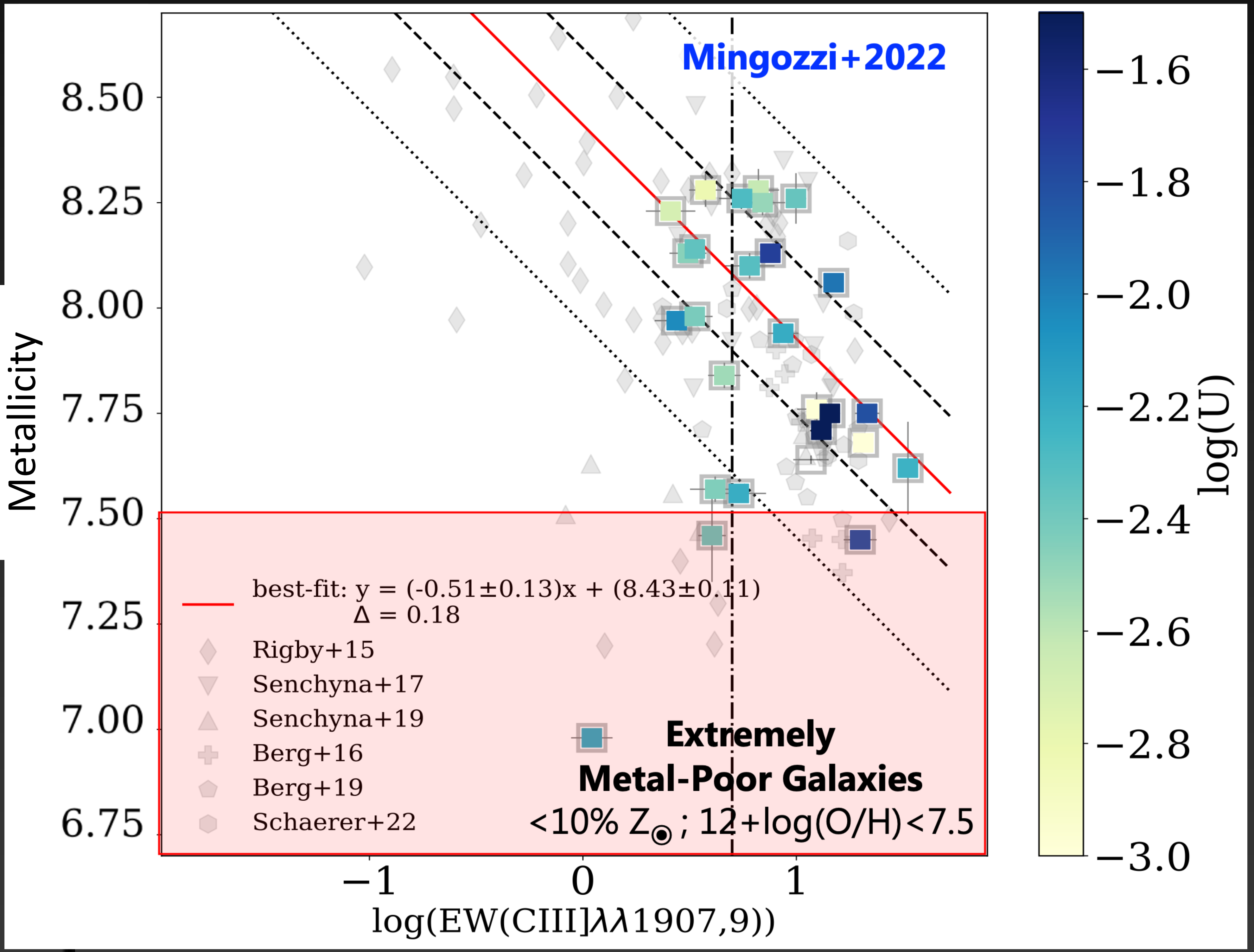
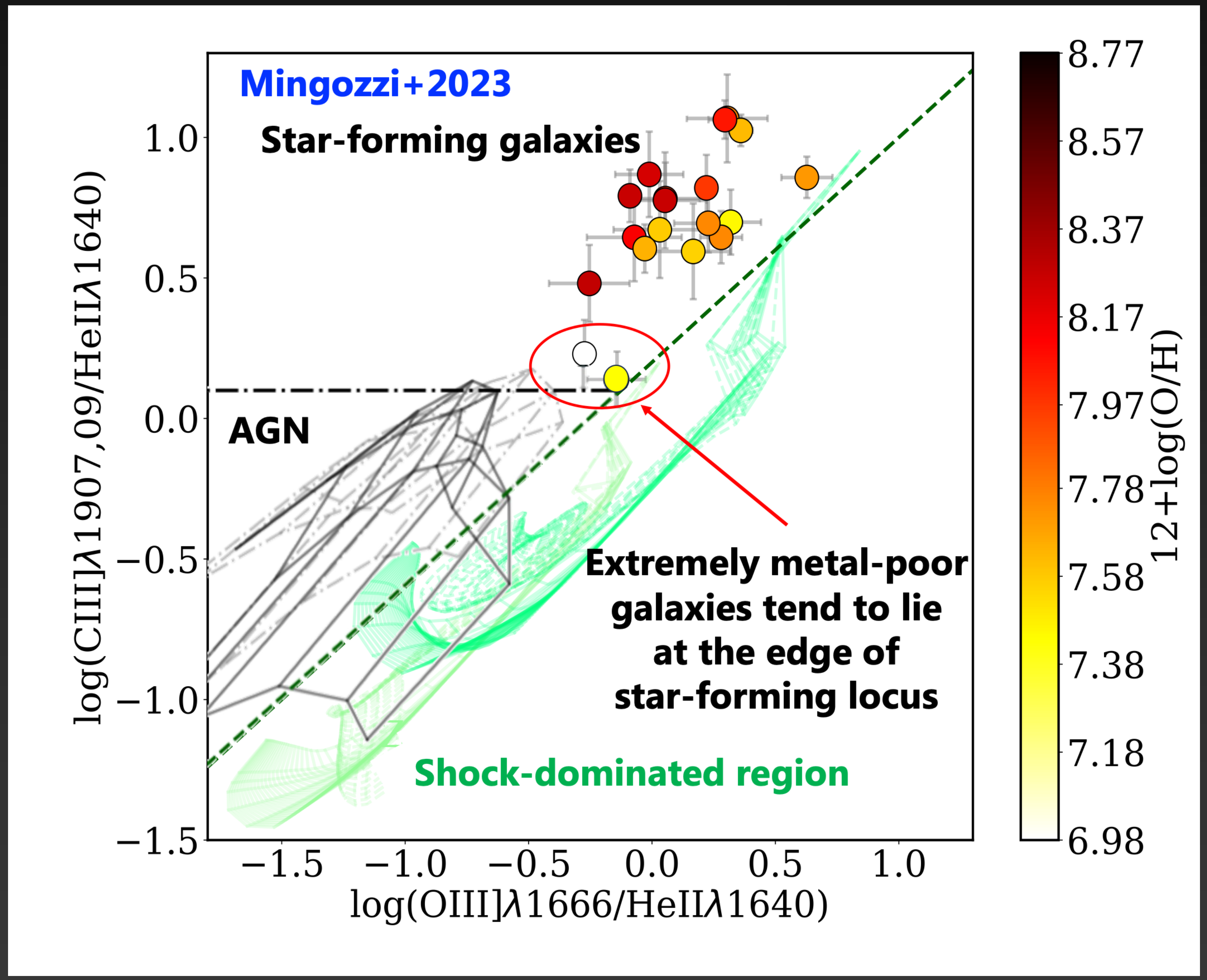
Secrets from the UV: Diagnosing Metallicity & Ionization Source

Matilde Mingozzi





- UV diagnostic emission lines trace the ISM properties
- **Gas-phase metallicity** and source of **ionization** of the CLASSY galaxies using *only* UV lines

→UV toolkit to interpret the high-z Universe.

- However, still need accurate calibration on spatially resolved data!!

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Secrets from the UV:
How are metals distributed between the phases?

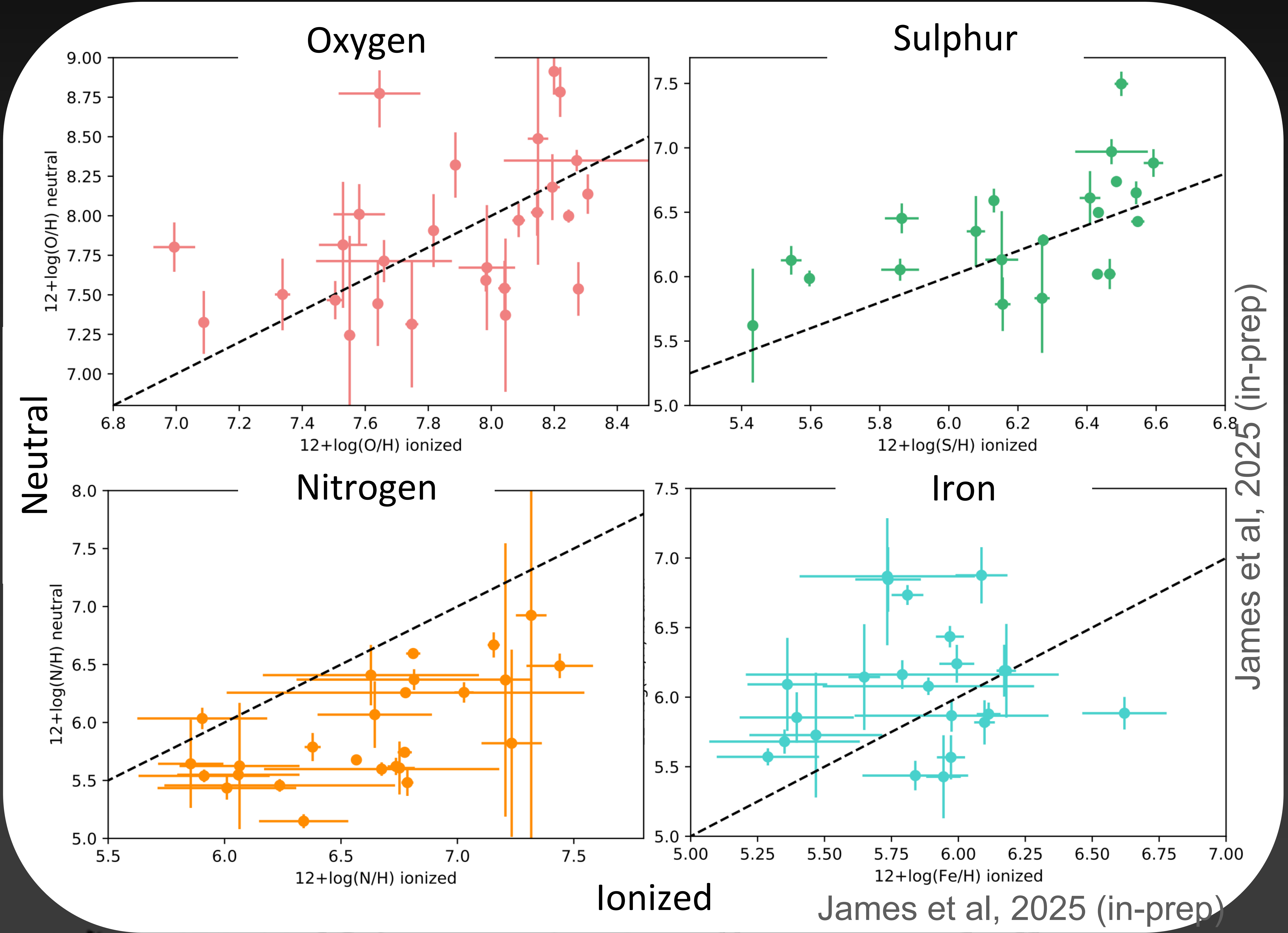
classy

Alpha elements behave similarly

T~5-100 Myr
Via Type II SNe

More nitrogen in the ionized phase

T~>100 Myr
via AGB stars



James et al, 2025 (in-prep)

S (&O) well mixed between phases

T~5-100 Myr
Type II SNe

Iron-peak
Depletion effects?
ICF issues?

T~1Gyr
Via Type Ia SNe

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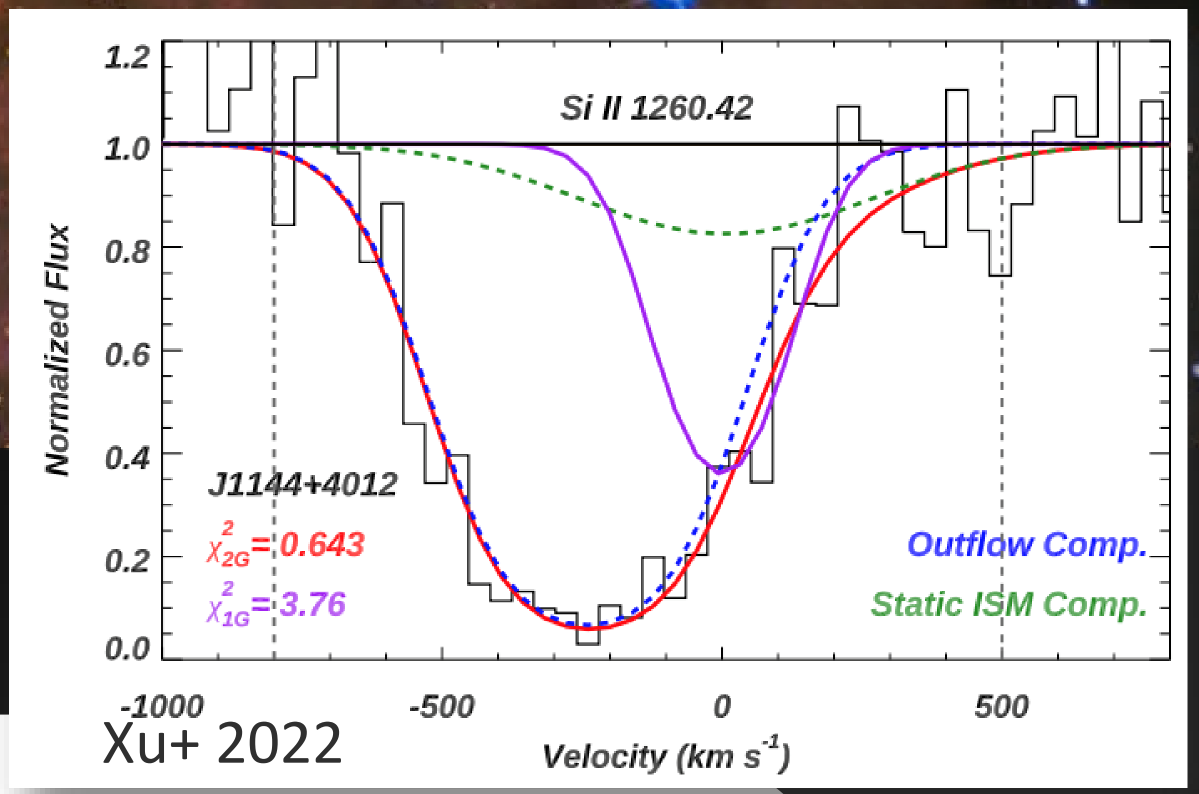
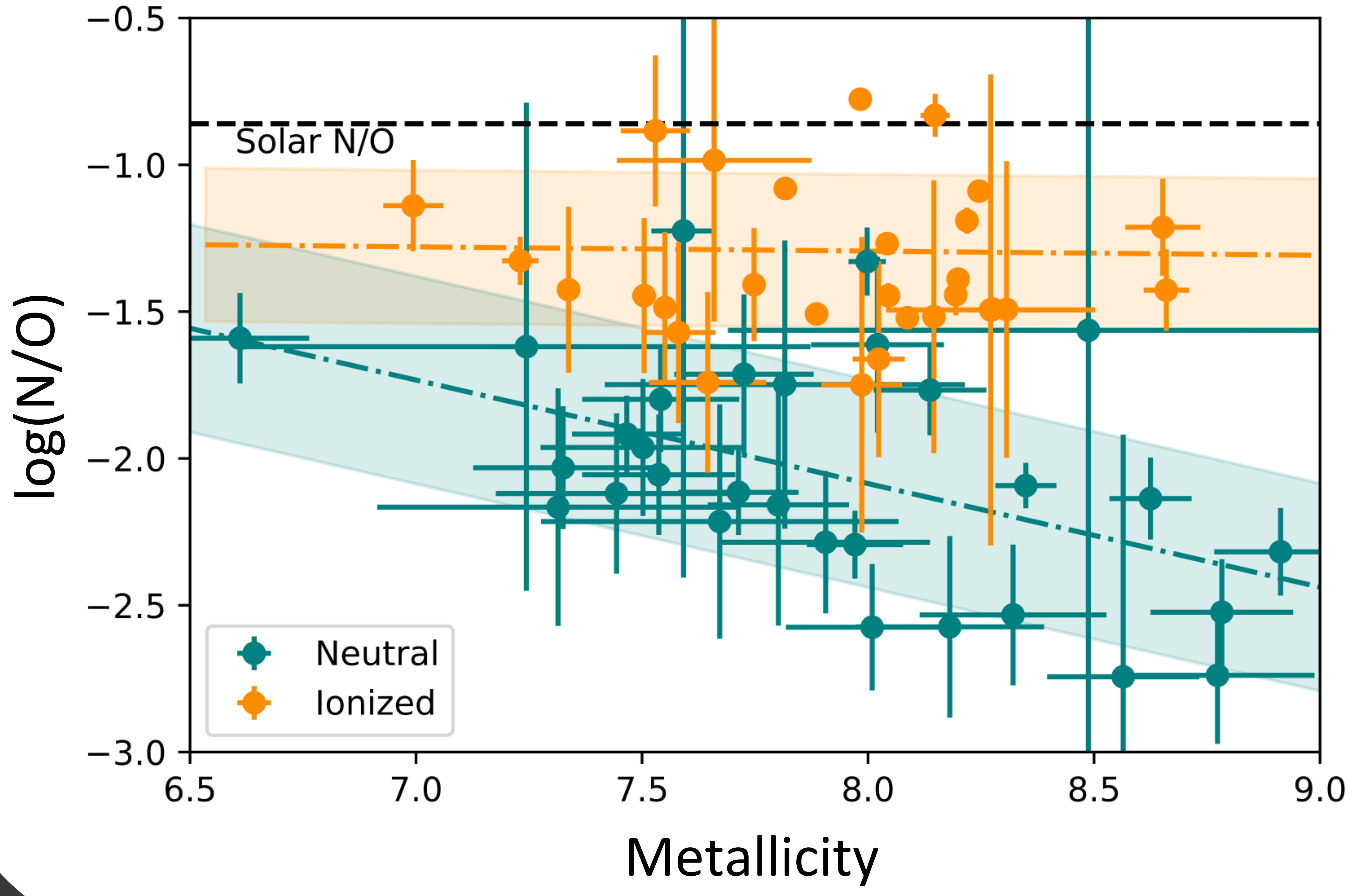
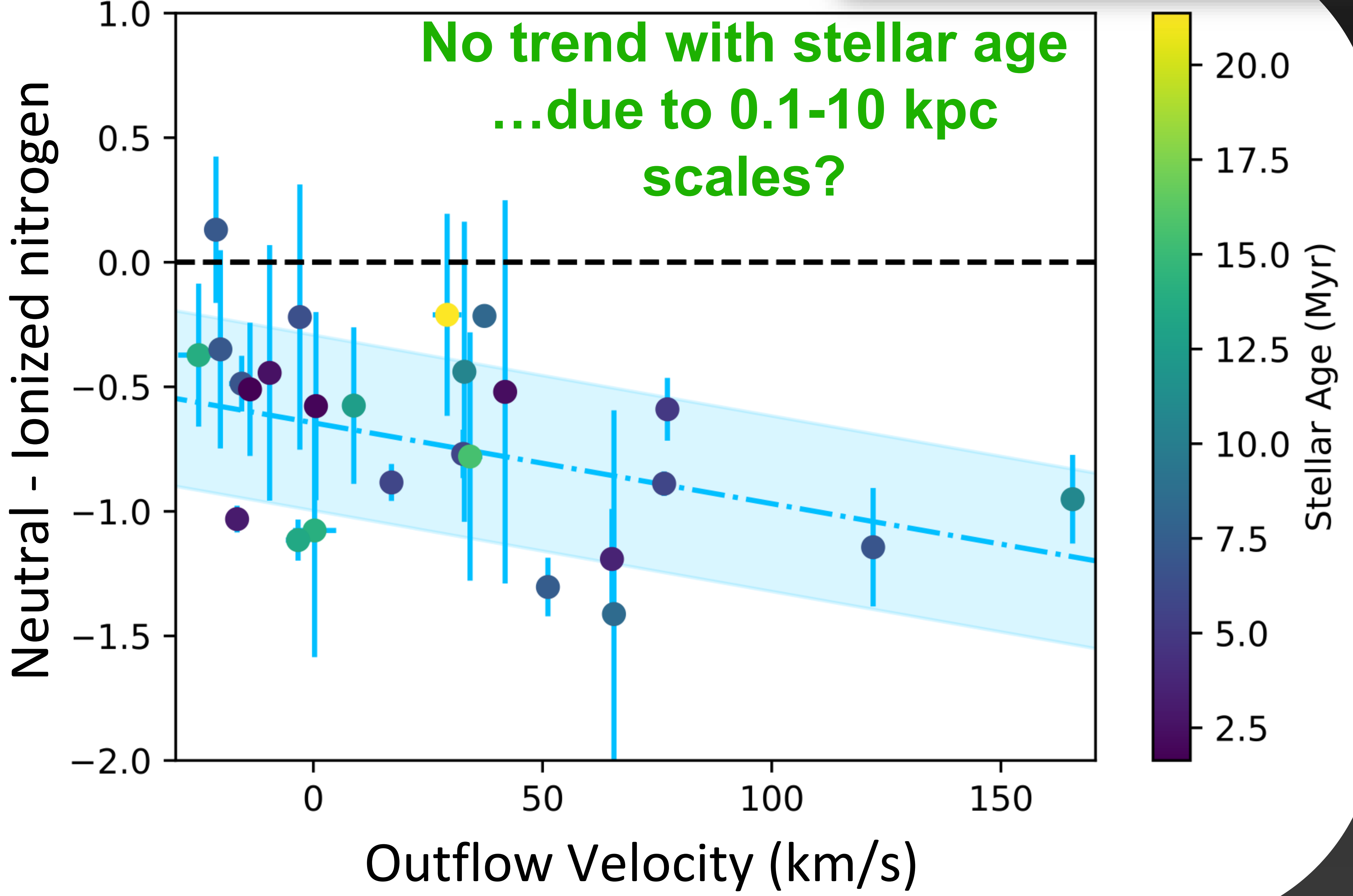
Secrets from the UV:
Outflows affect nitrogen enrichment



Xu+ 2022

James et al. 2025 (in-prep)





Higher metallicity + strong outflows
→ more nitrogen in ionized gas than neutral gas
→ gas less mixed on long timescales

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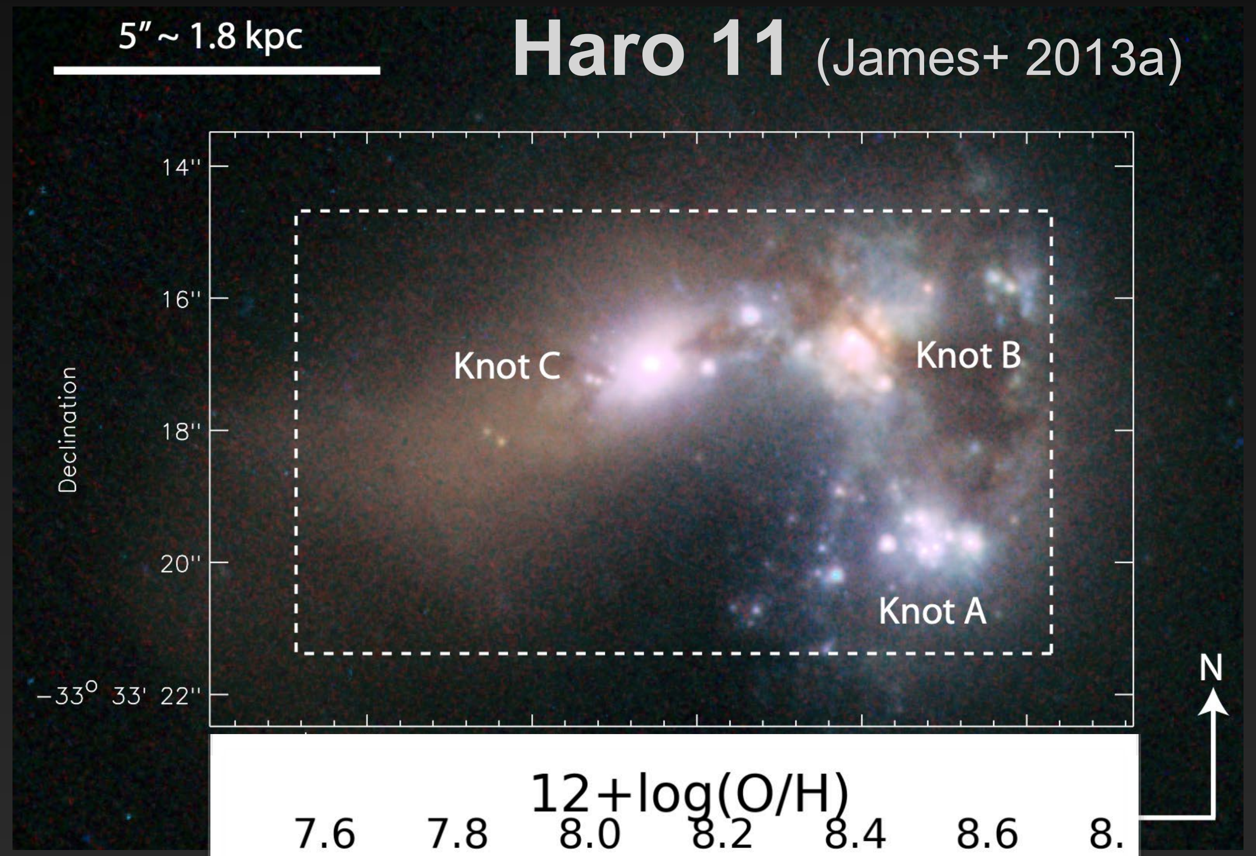
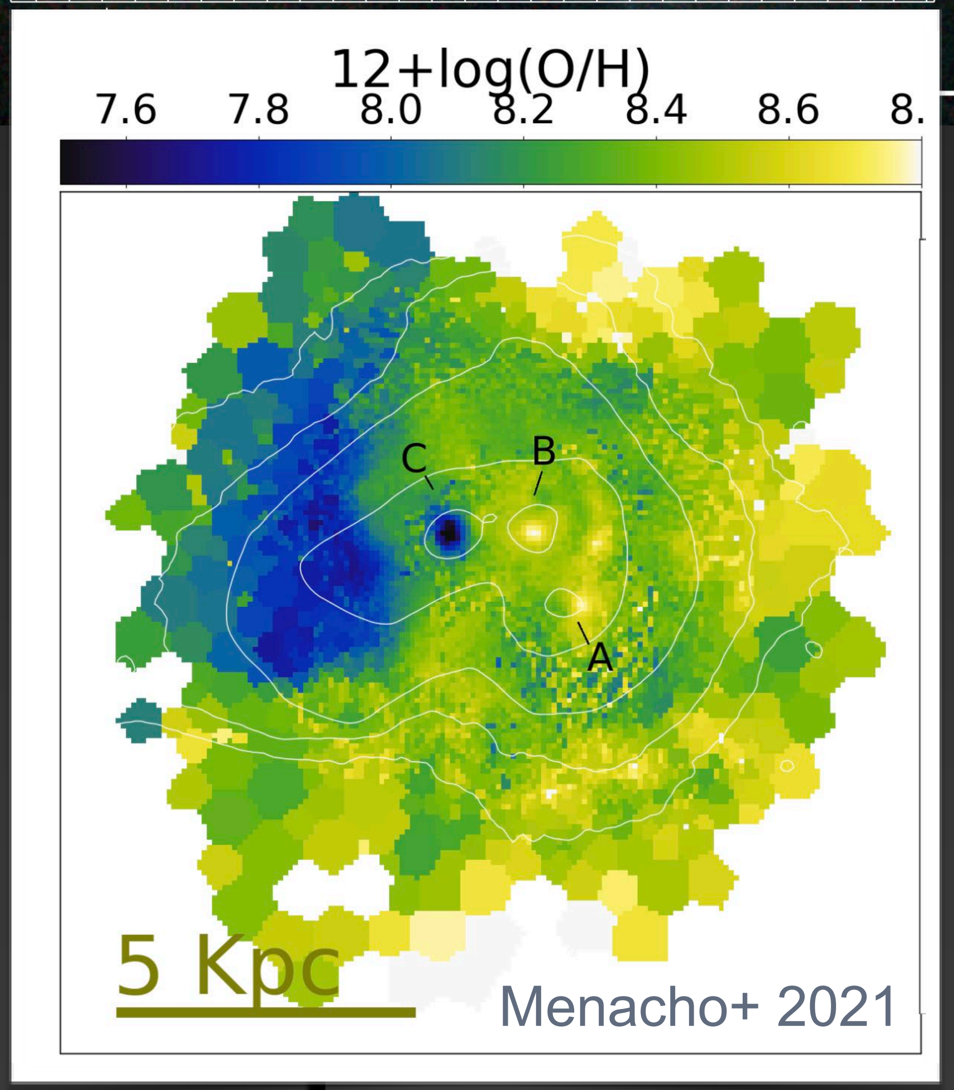
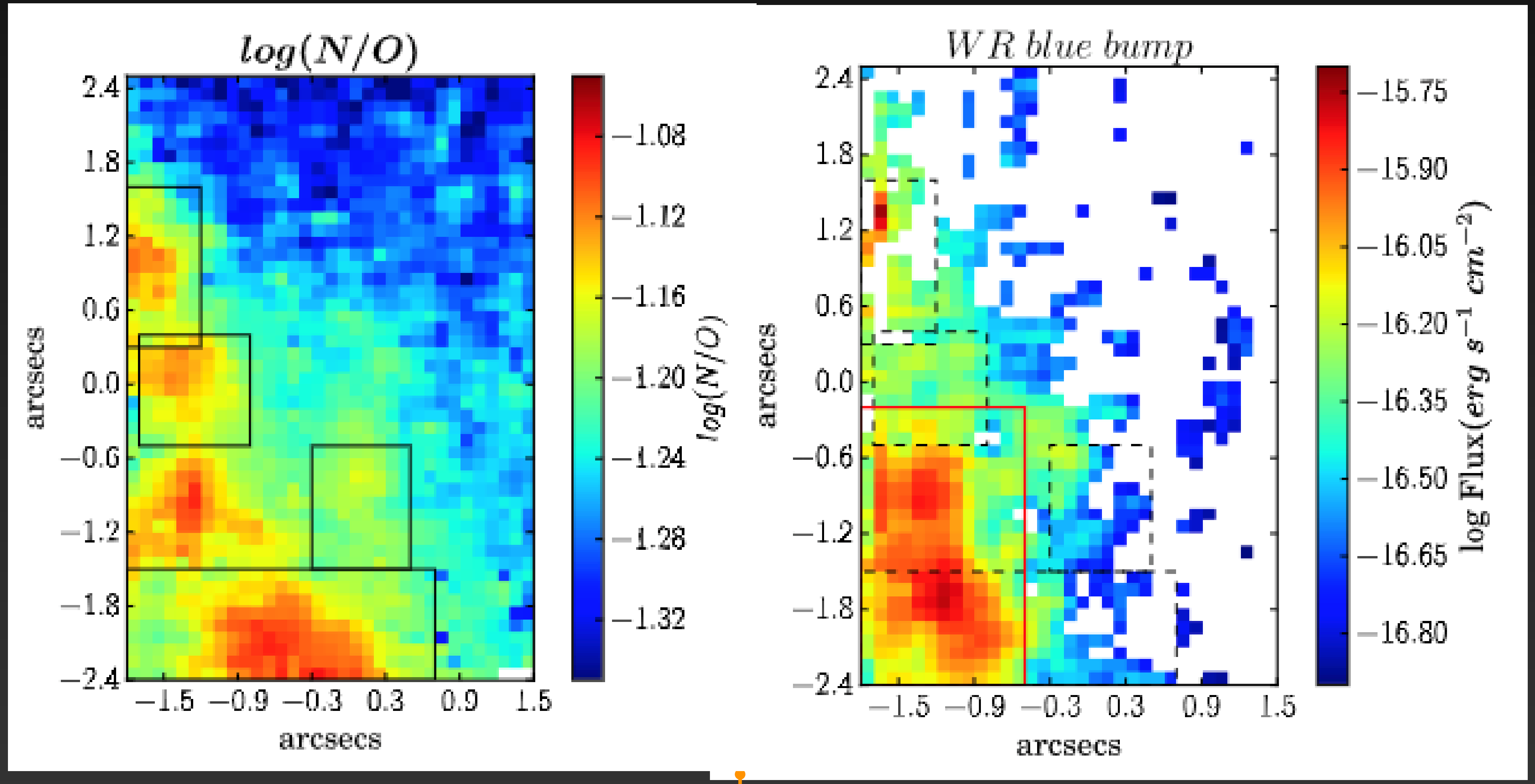
Optical IFUs show that galaxies are not homogeneous





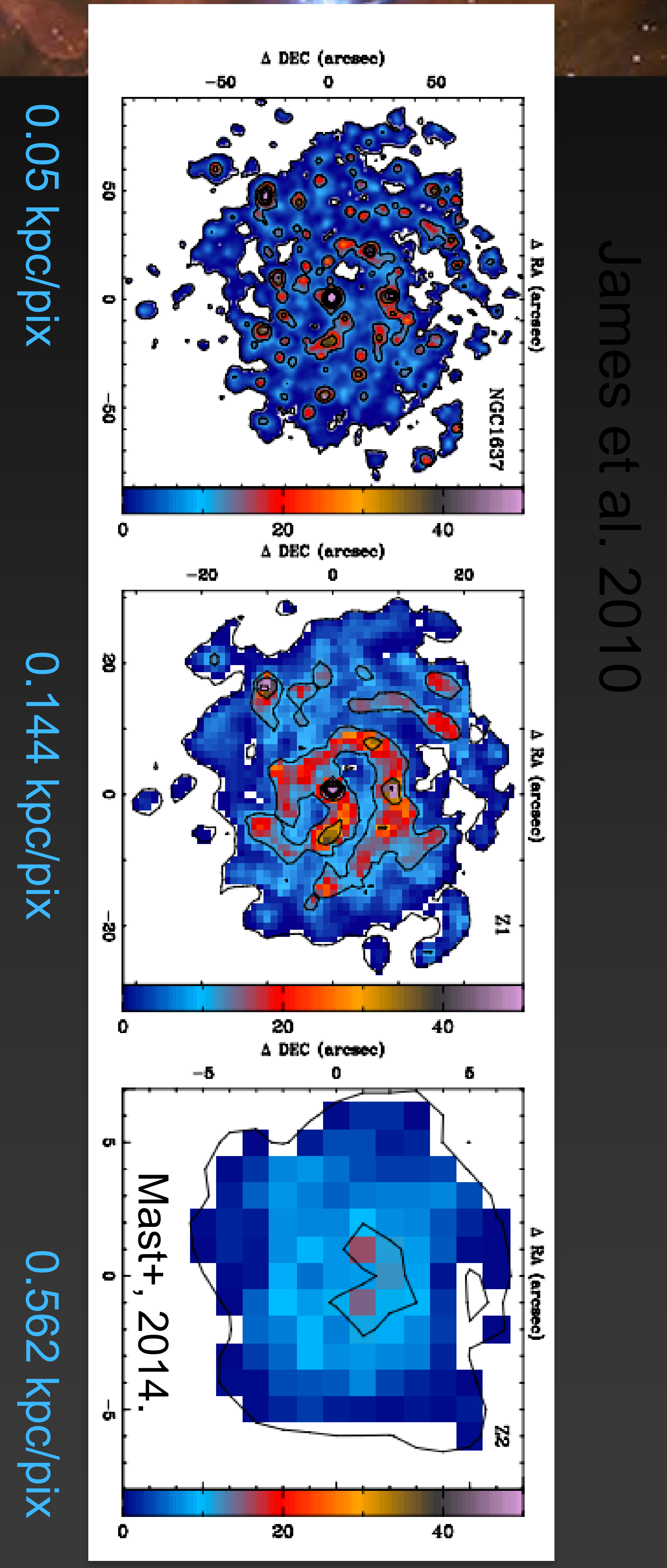
Accretion of pristine gas → star-formation

NGC4670: Kumari, James et al. 2018



Self-pollution of Nitrogen + young (WR) cluster
→ rapid mixing timescales

Spatially resolved observations
→Localized outflow effects
→Accurate gas abundances
→How/why do stars affect their surroundings?



Information lost using integrated light

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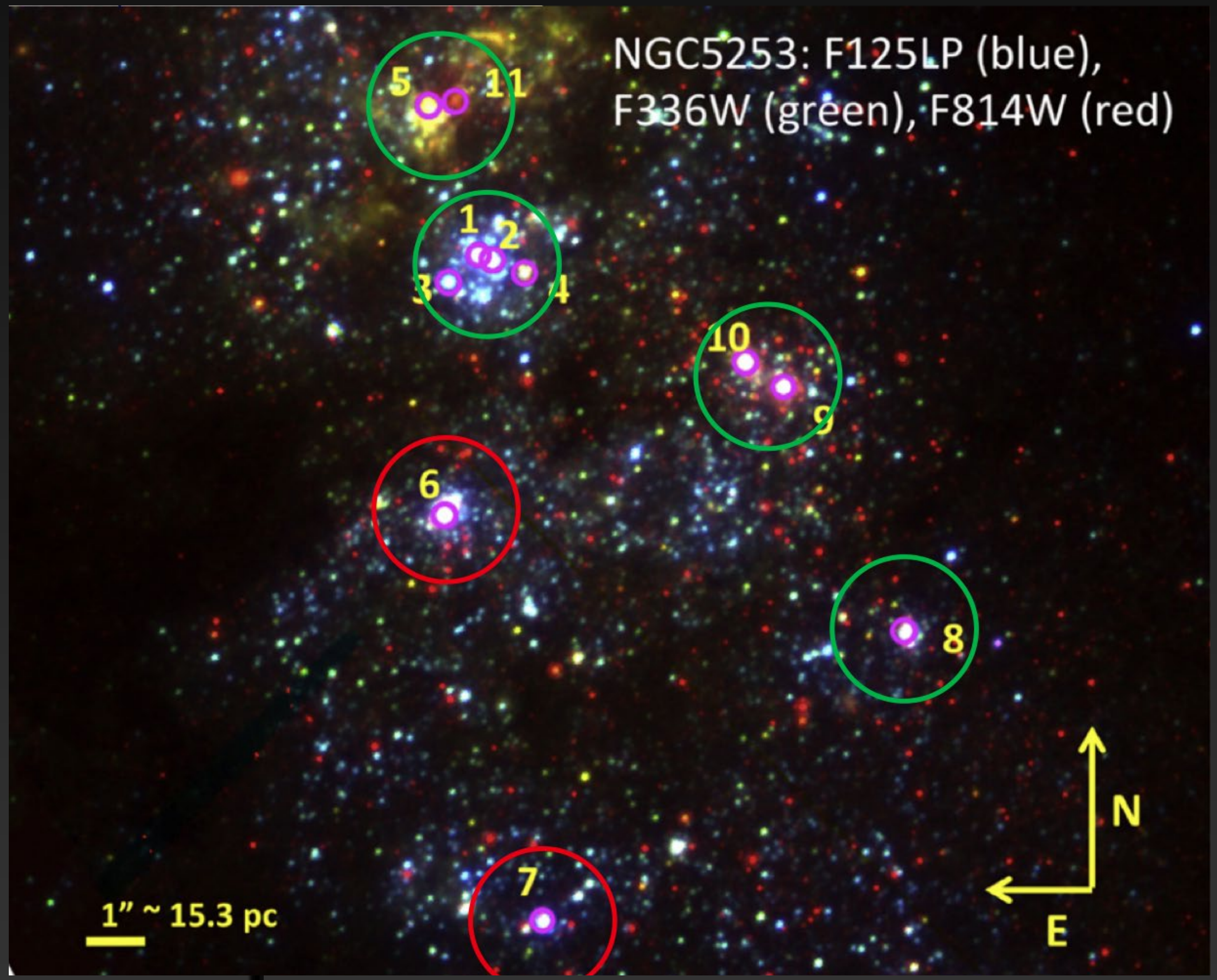
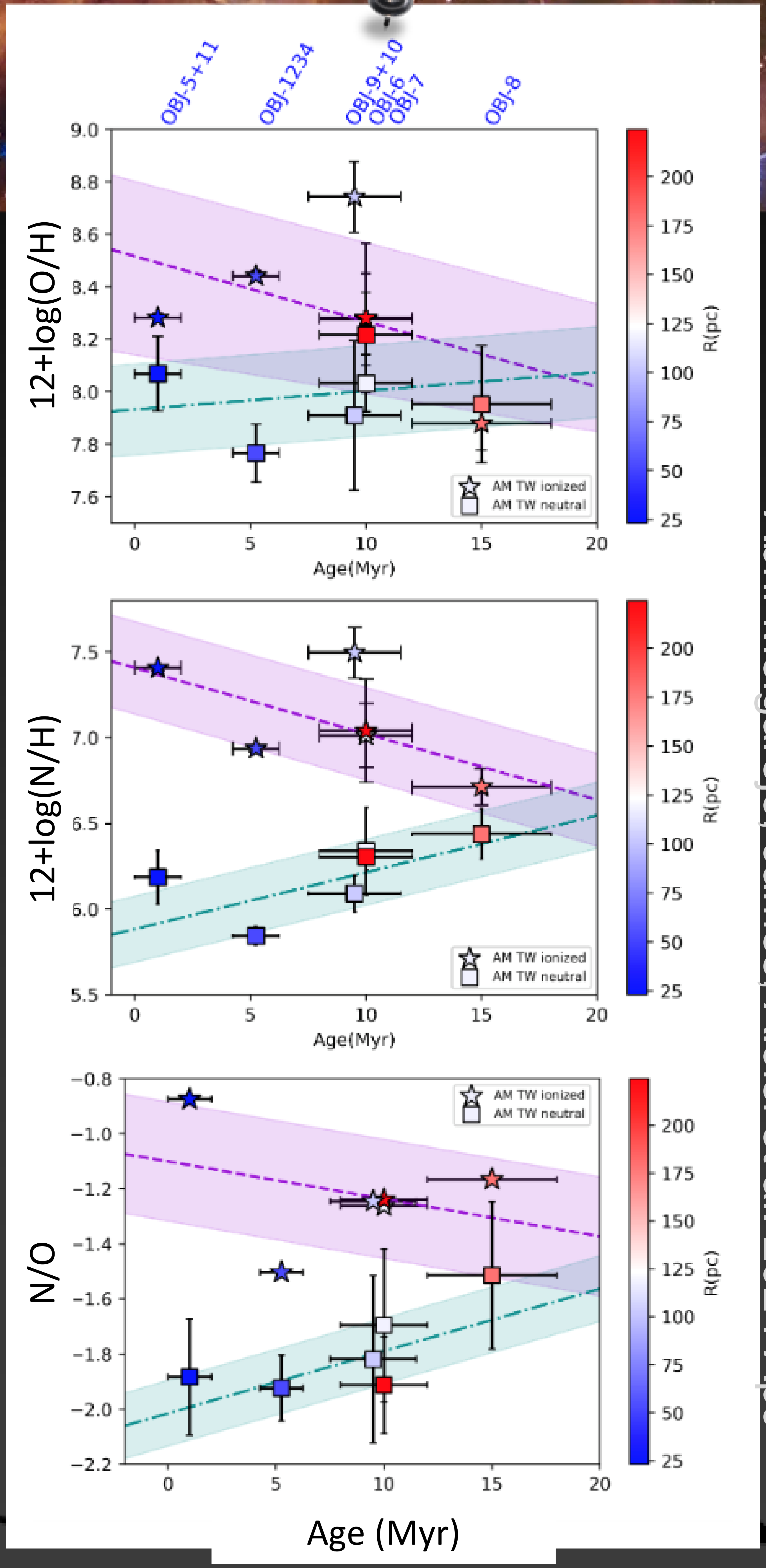
Spatially Resolved UV:
Multi-phase metals in NGC5253



2.5” COS aperture
@3.7Mpc ~40 pc
Several clusters in each pointing

- 11 clusters: 15 orbits COS (PI: James) + 1 MUSE cube
- low-metallicity , starbursting + highly ionized gas
- WR stars → N-enriched gas (Westmoquette+ 2012)

How fast does enrichment happen? <6-8 Myr
How quickly do metals mix? 10-15Myrs



Valentina
Abril-Melgarejo

Abril-Melgarejo, James, Aloisi et al. 2024 ApJ

★ Ionized
■ Neutral

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What do we still need to understand?

How do massive stars affect their surroundings?

<100pc scales = stop averaging properties over clusters
→ accurate abundances
→ full sampling of stellar population ages/timescales
→ directly link outflows + photons to their source

How much C, N and Si within a galaxy? And where?

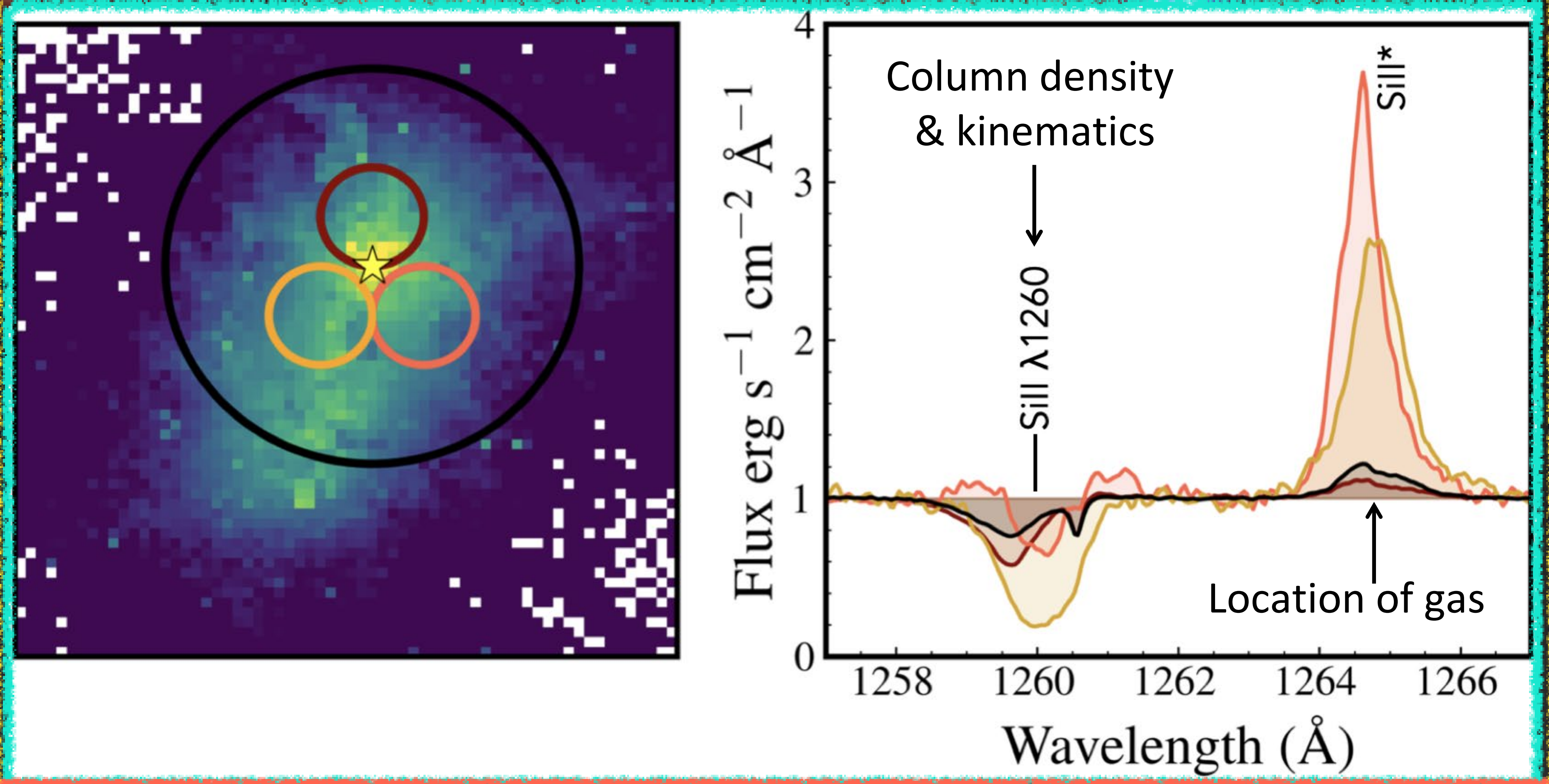
Sensitive mapping of UV emission lines:
→ actual C or Si emission lines (absent in optical λ)
→ high ionization NIII], NIV lines
→ map all ionic stages, stop relying on ICFs
→ Highly accurate C, N, Si

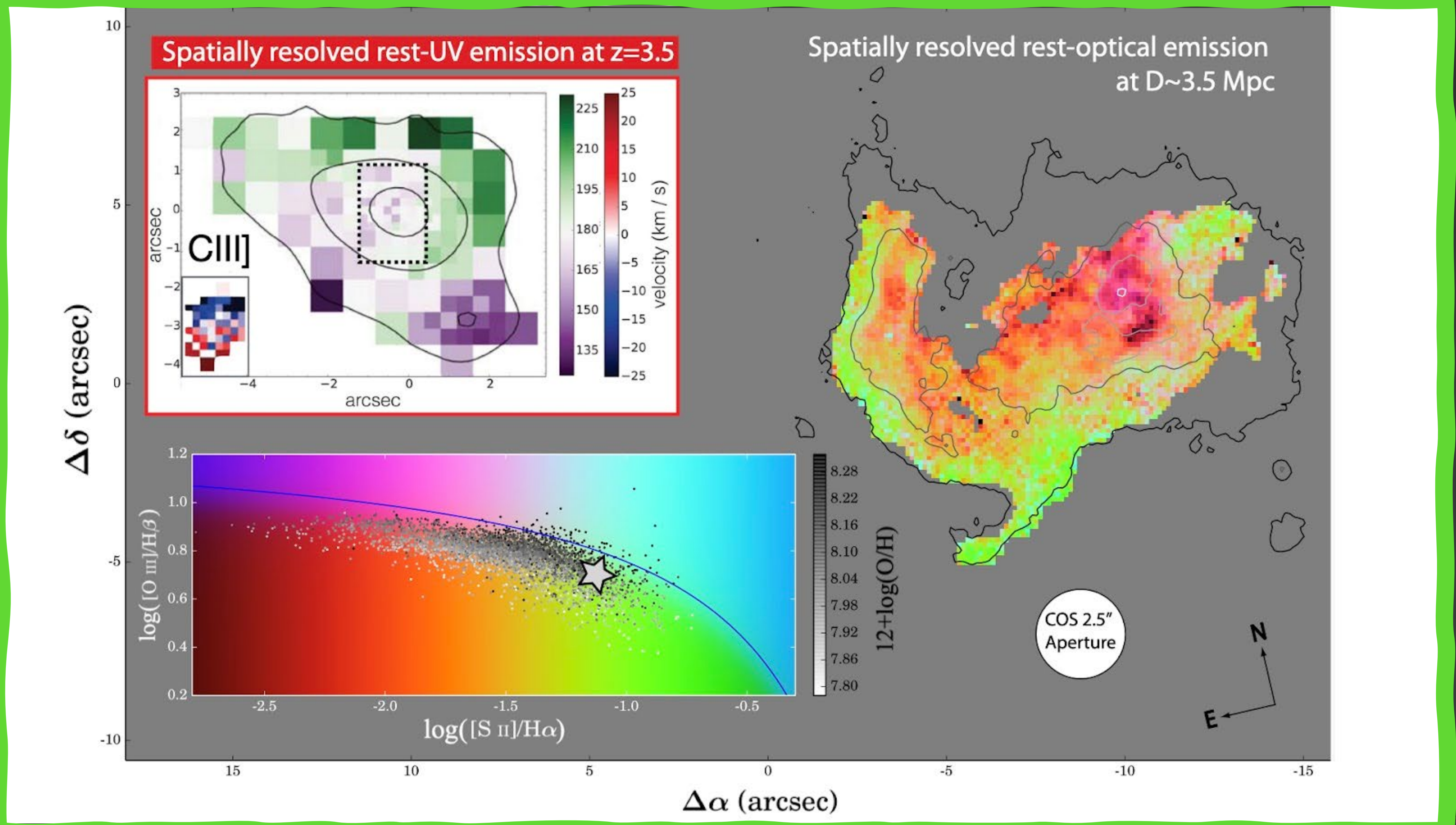
Are high-z systems *really* N-enriched?

Map full density structure & accurate N/H
→ determine role of electron density
Sample range of stellar populations
→ Is it a timing issue?

Where are the high energy photons coming from?

Map high ionization lines at <100pc resolution
→ disentangle shocks vs AGN vs SF





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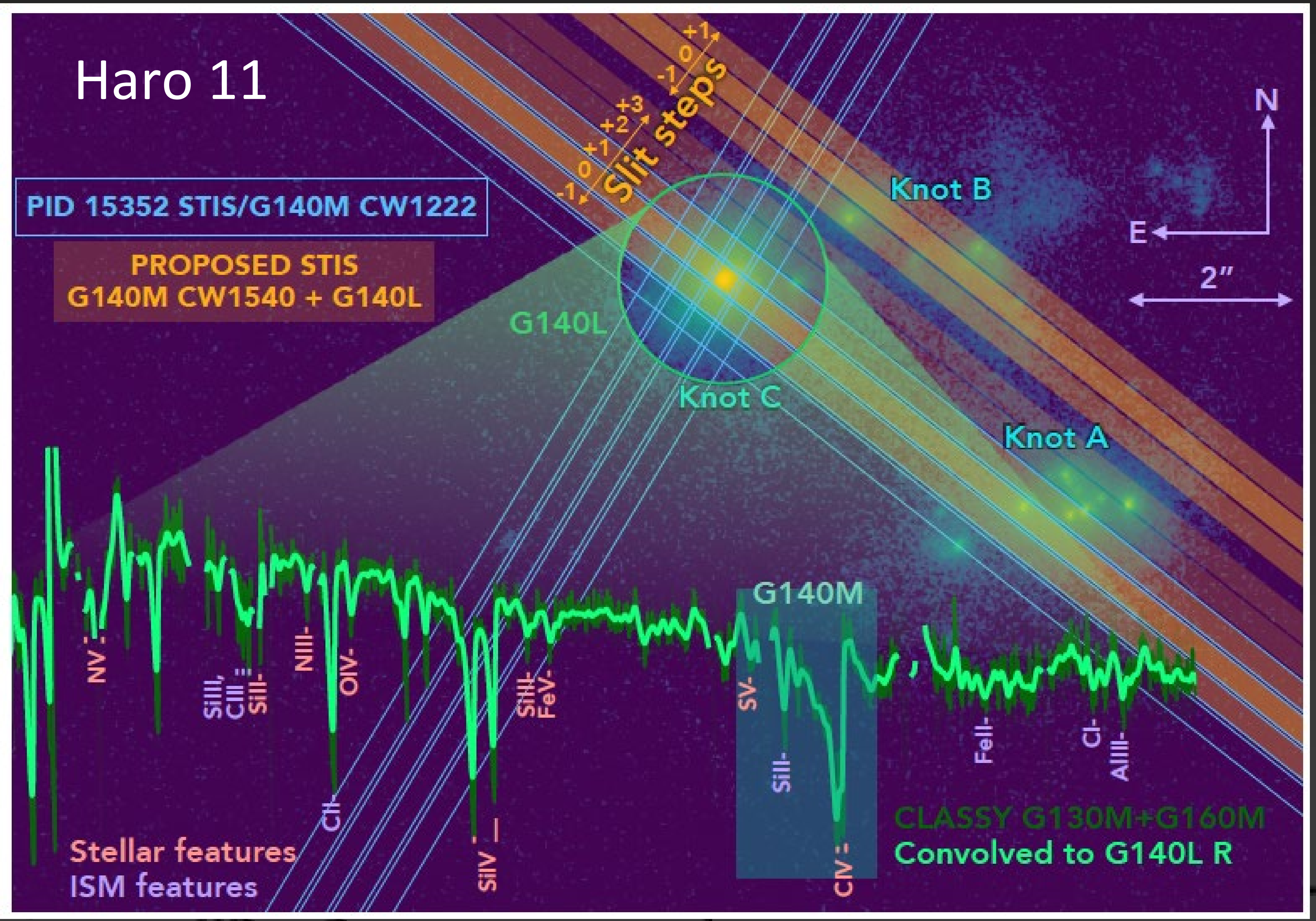
(Slit)-Stepping into the future:
Simulating a UV-IFU with HST/STIS

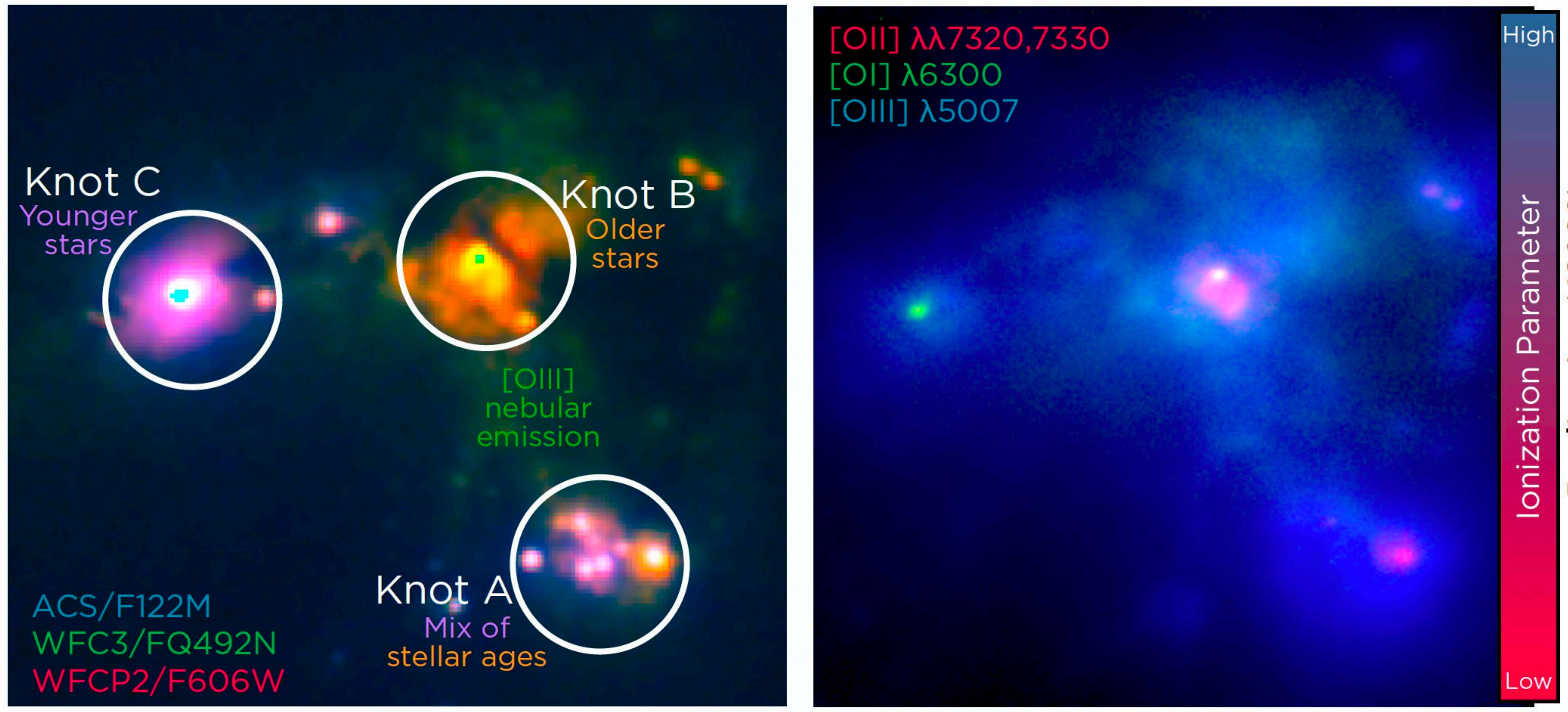
65 Orbits with HST/STIS (PI: James)
G140M: R~10,000, 1540-1594A → CIV, SiII, SiII*
G140L: R~1000, 1150-1736A → full stellar continuum

High-R UV cube + low-R UV cube
0.2" x 0.2" spaxels (0.2"=86pc)



Haro 11

archival optical MUSE-AO (0.13"/spaxel) data



(a) Three-colored image highlighting range of stellar ages.
(b) Three-colored MUSE spectral cube showing range of gas ionization.

Science Objectives:

1. map the structure and content of the cold neutral ISM
2. characterize multi-phase outflows
3. directly map the effects of young massive stars
4. decipher the conditions for nebular CIV emission

Data due July 2025

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(Slit)-Stepping into the future:
Simulating a UV-IFU with HST/STIS

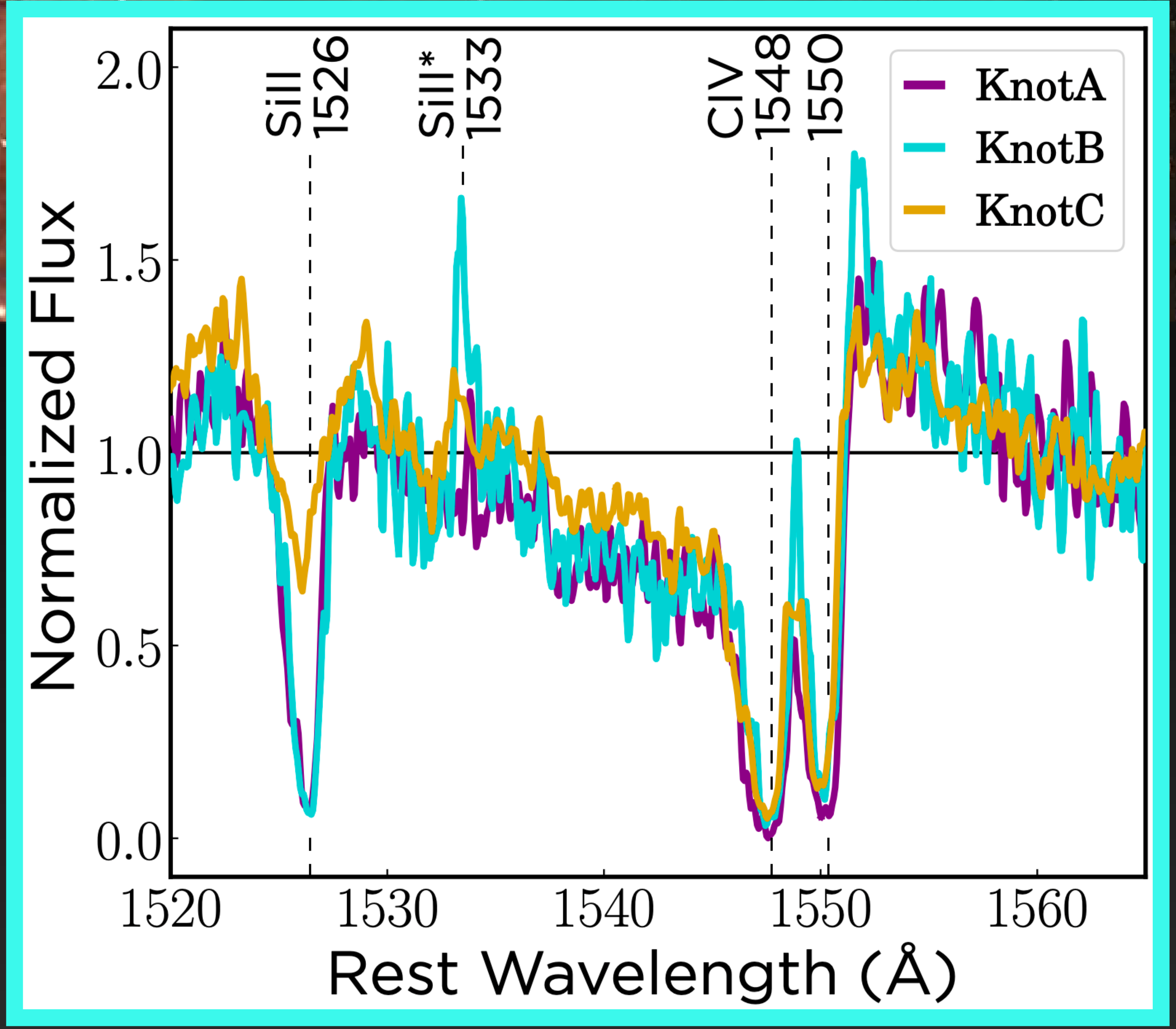
G140M: R~10,000, 1540-1594A → CIV, SiII, SiII*
G140L: R~1000, 1150-1736A → full stellar continuum

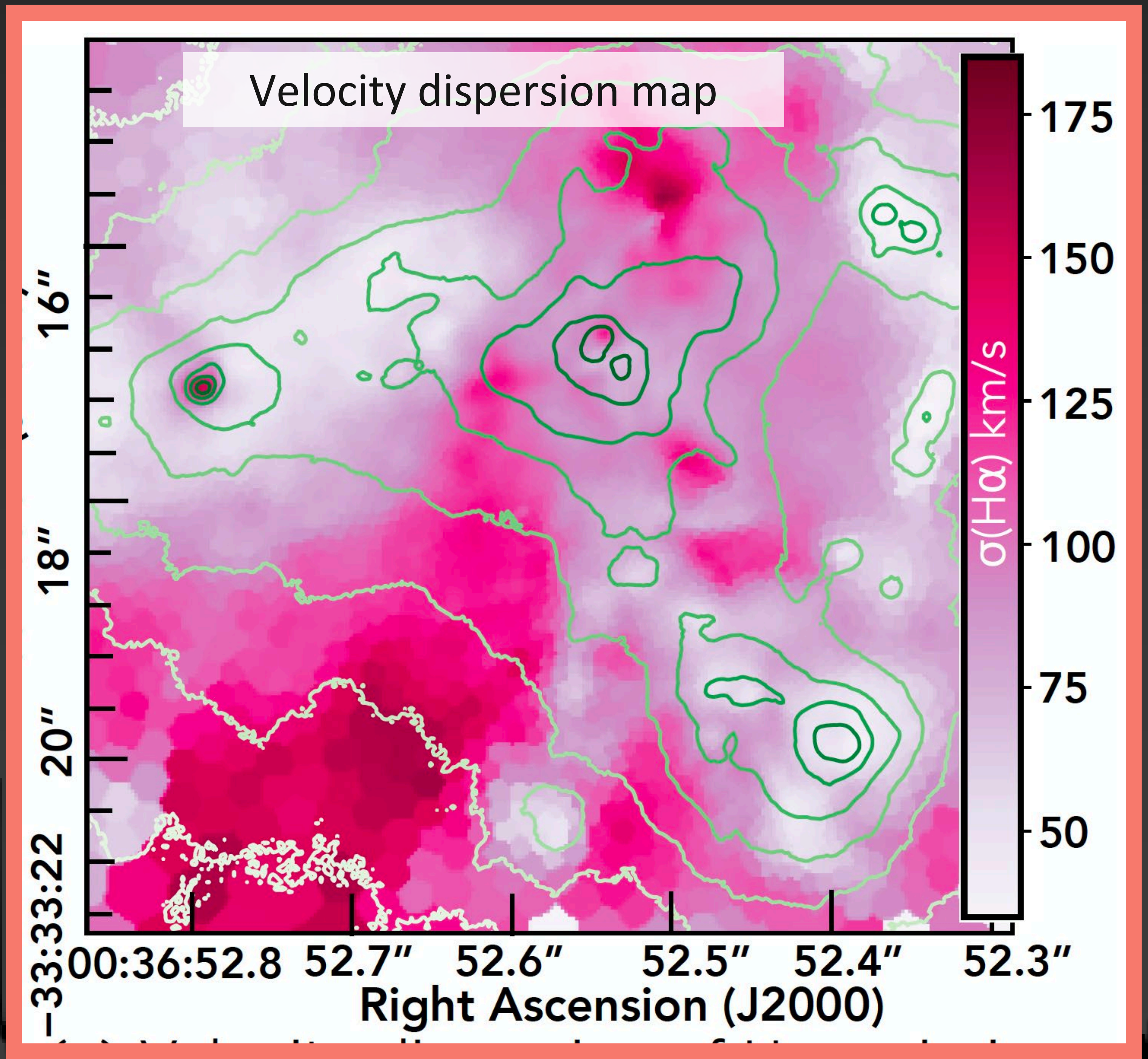
Grid of UV cubes sampling:
0.2” → 0.8” spatial resolution (86pc - 350 pc)
R = 1000 → 10,000

Maps of optical properties:
(temperature, density, kinematics, ionization)

Address four fundamental questions for a HWO UV-IFU:

a. Over what physical extent can UV spectra be sampled?
b. At what spatial scales do UV properties vary?
c. What is the minimum spectral resolution required to map outflows?
d. How do UV properties change with respect to stellar+ISM conditions?





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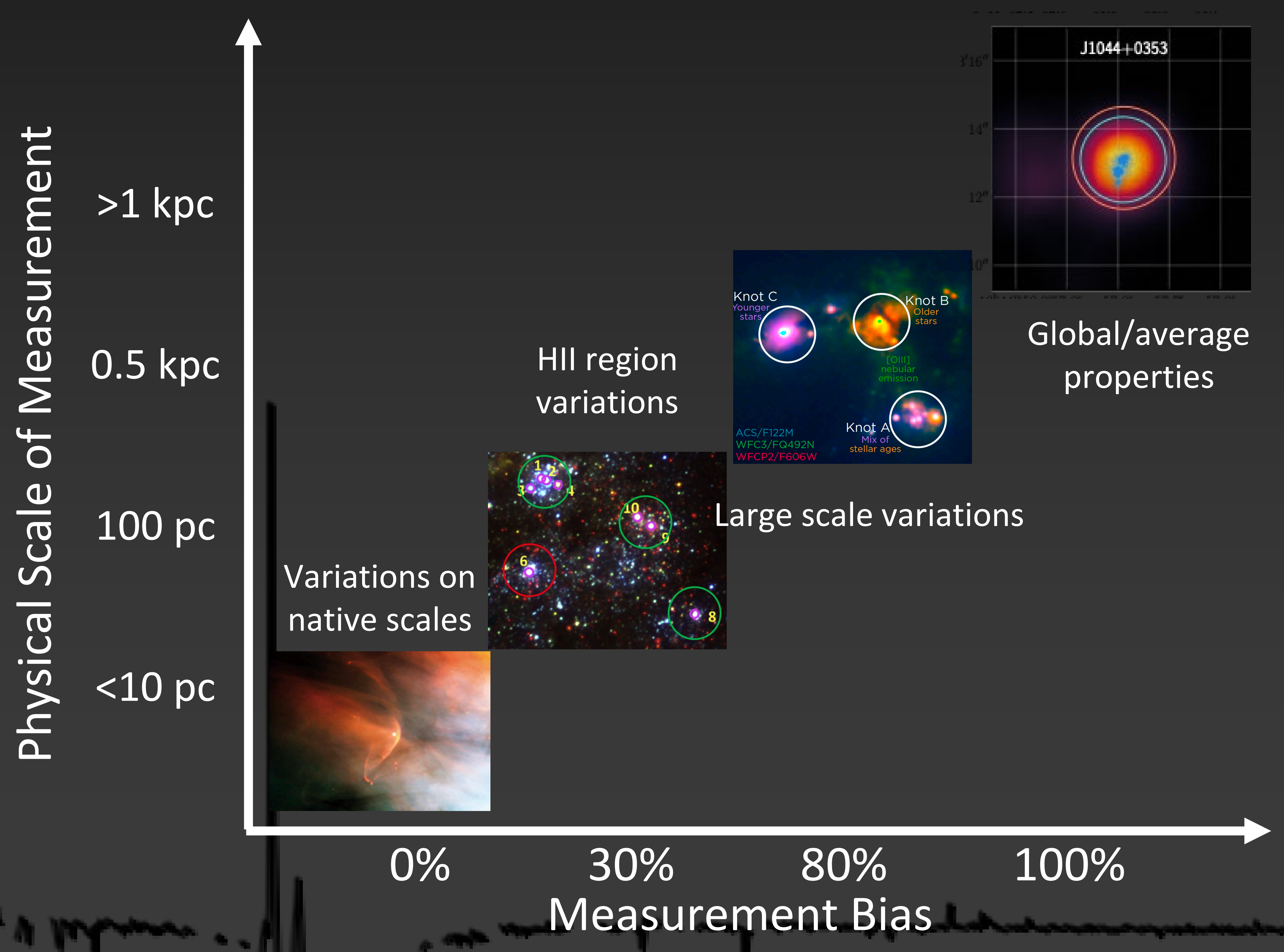
Stepping into the future:
Breakthrough Science with HWO UV-IFU

Read our SCDD!

SF&ISM HWO Science Case:

"How do evolutionary processes, traced by the spatial distribution of elements (e.g., O, N, C, Si), shape cosmic ecosystems from planets to galaxies across cosmic time?"

(Bethan James & Danielle Berg)



Measure: UV emission, absorption, nebular properties, kinematics, ionic abundances

Scale: <10pc

Why?: Resolve nebular structures & shock fronts in HII regions

→ Eliminate measurement bias by to study ISM physics.

→ Spatially map source to velocity components.

Designed to make major progress on:

1. Mixing of newly synthesized metals within the ISM on different time and spatial scales
2. Impact of star formation and feedback processes on elemental abundances
3. Production sites/mechanisms of the various elements
4. Effects of large-scale environment on elemental abundance patterns

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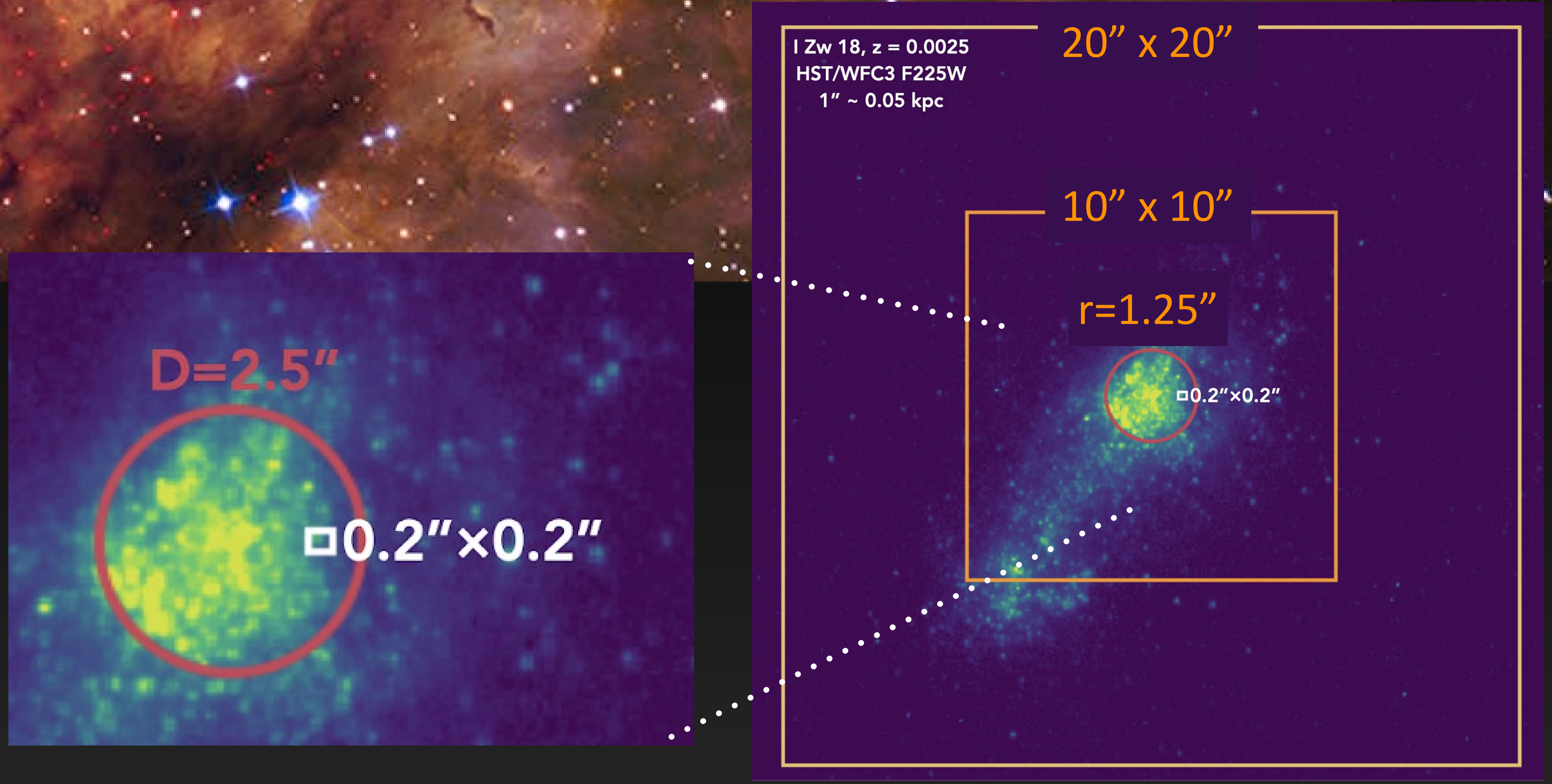
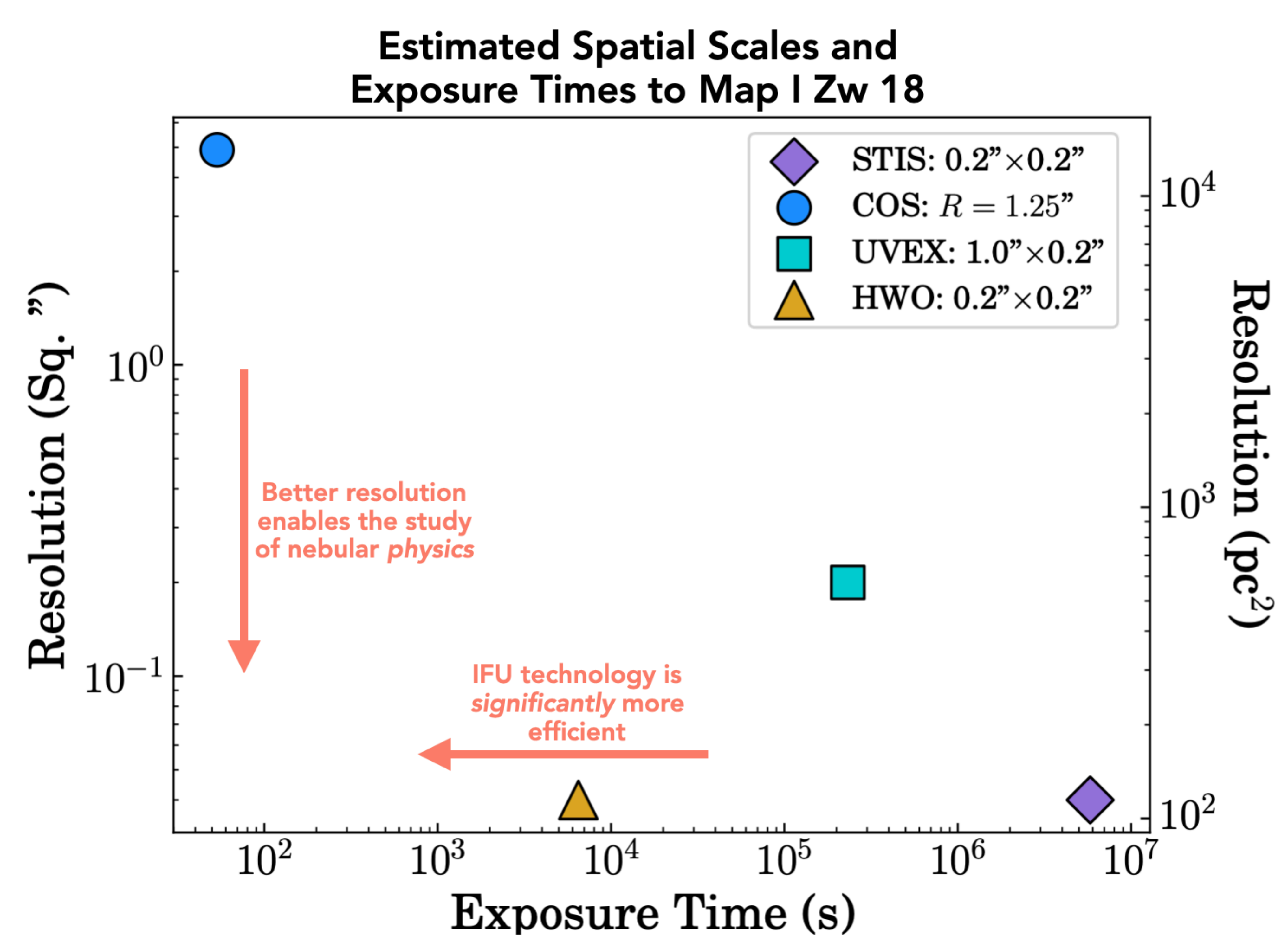
UV-IFU observational requirements

Observation Requirement	State of the Art	Incremental Progress (Enhancing)	Substantial Progress (Enabling)	Major Progress (Breakthrough)
Spectroscopy	HST/COS for FUV HST/STIS for NUV (single aperture spectroscopy)	MOS or multiple pointings in one system	Efficient slit stepping	IFU spectroscopy
Wavelength Range	1200-1950 (range with reasonable sensitivity with COS); haven't been able to successfully detect many NUV lines with STIS	900-1950A Complete FUV+NUV range available with COS when combining all gratings	1150-2850 Å (UVEX; 10x higher throughput)	950-2850 Å
FoV: Amount of sky covered	2.5″ aperture (COS) or 26″ long slit (STIS)	2° long slit (UVEX)	4″×4″	>10″x10″
Magnitude of target in chosen bandpass	19.5 (SNR > 5 in the continuum with COS)	Fainter galaxies - down to 20-21 magnitude	Faint galaxies with any spatial resolution	Mapping faint galaxies.
Spatial resolution	2.5″ aperture (COS) or 0.2″-1.0″ wide long slit (STIS)	0.2"x1" slit for slit stepping with STIS	0.2"x0.2" slit extractions (not available)	≤0.1″x0.1″ spaxels with contiguous spatial coverage
Spectral resolution	R=10,000 for extended objects at current lifetime position (COS; degraded from original 20,000)	R=10,000	R=10,000	R>10,000





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Conclusions

What do we currently know from UV observations?

→ Chemical evolution is a 4D problem: x, y, ionic structure, time

→ Galaxies are not homogeneous in density, temperature, metal content, ionization

<u>The UV provides key information on ALL these parts</u>

But we lack the spatial resolution and sensitivity to provide unbiased calculations

With a UV-IFU we could answer:

- How do massive stars affect their surroundings?
- How much C, N, Si is within a galaxy and where is it located?
- Are high-z systems really N-enriched? If so, why?
- Where are the high energy photons coming from?

What do we need from a UV-IFU? 0.1”x0.1” spatial resolution @ R~10,000

How can we progress in the meantime? Simulating UV-IFU using slit-stepping with STIS