

Metallicities of $z > 6$ galaxies with JWST

Andreea Șuta
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based on: Curti et al., 2023 & Vanzella et al., 2023

Metallicity as tracer of assembly history

- Metal productions: through **star formation** and **supernovae**

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Metallicity as tracer of assembly history

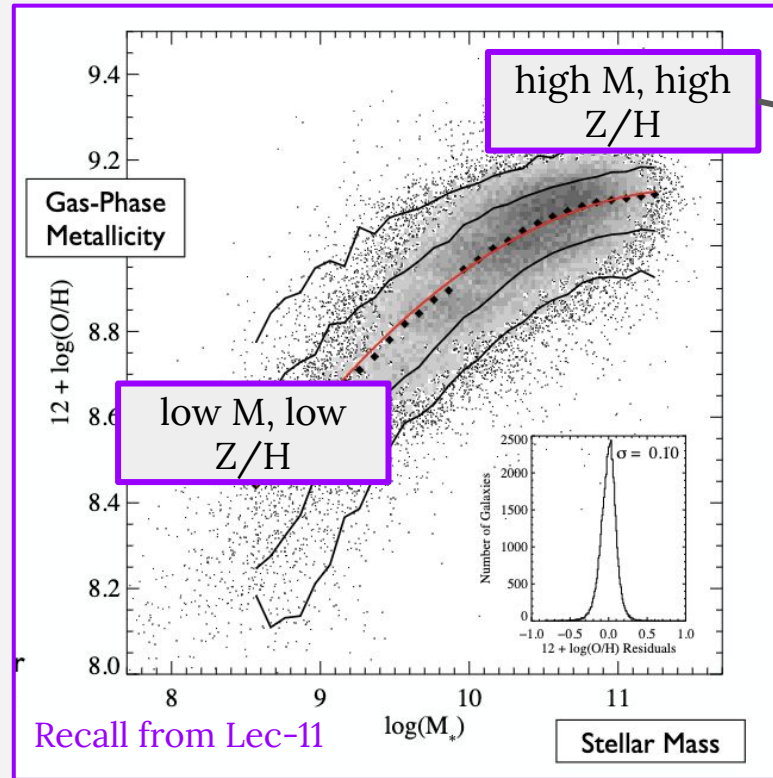
- Metal productions: through **star formation** and **supernovae**
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- Metal loss: **galactic winds** and **outflows** (*Sharda et al., 2021*)

Metallicity as tracer of assembly history

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Metallicity encodes the integrated history of star formation, gas accretion, and outflows.

Mass-metallicity relationship (MZR)

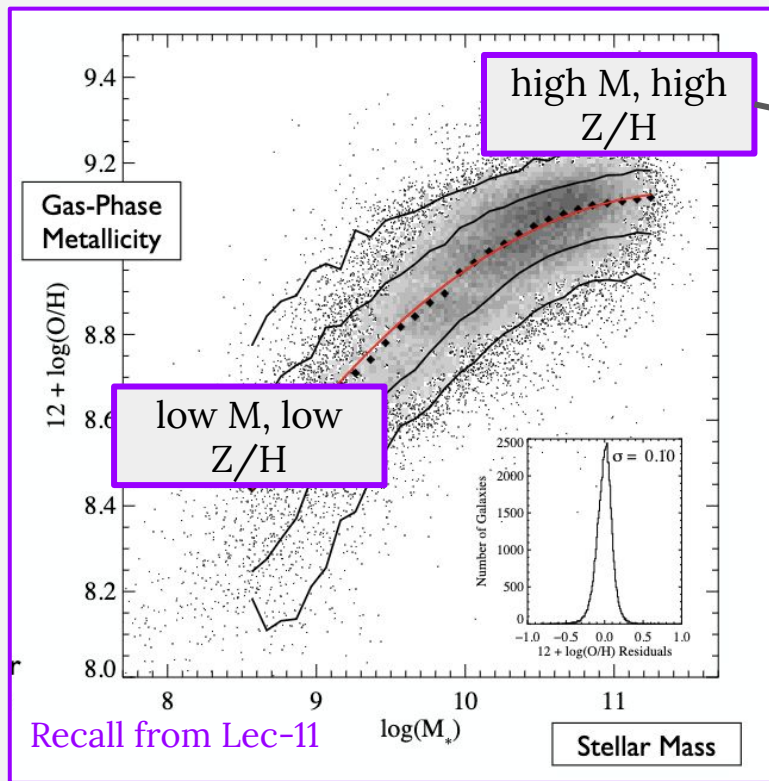


Mass \leftrightarrow integrated star formation

- more stars \rightarrow more metals
- deeper potential \rightarrow less loss

Mass-metallicity relationship (MZR)

+ SFR dependence



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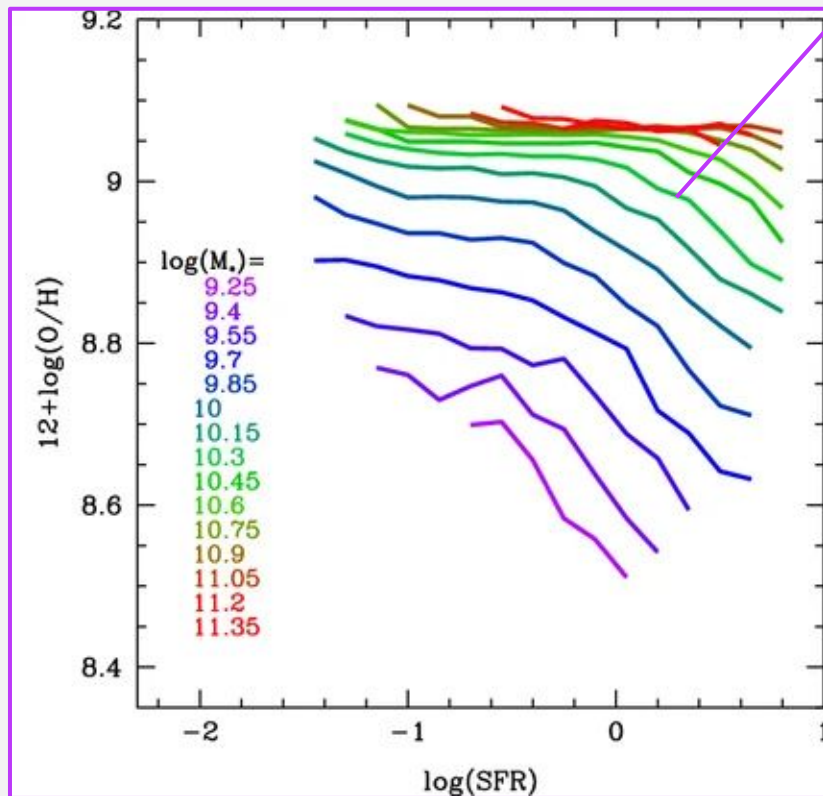
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Fundamental metallicity relation (FMR)

= equilibrium between
gas-flow and **secular
evolution**

+ SFR dependence

$$Z = f(M_*, \text{SFR})$$



At fixed mass:

- higher SFR → lower metallicity

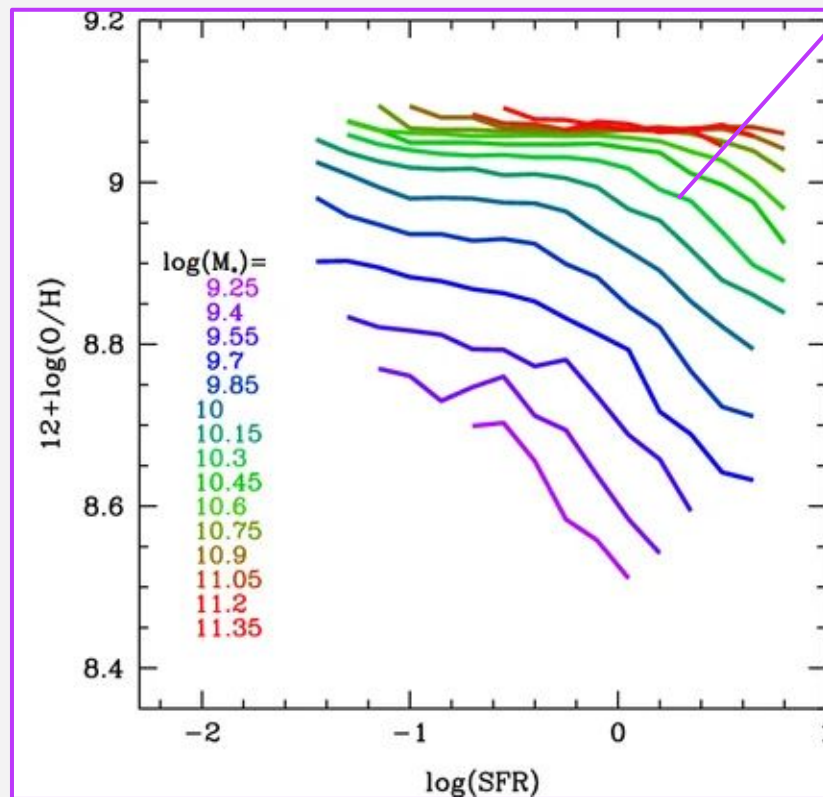
Fixed up to $z \sim 3.3$
(e.g., Mannucci et al. 2010)

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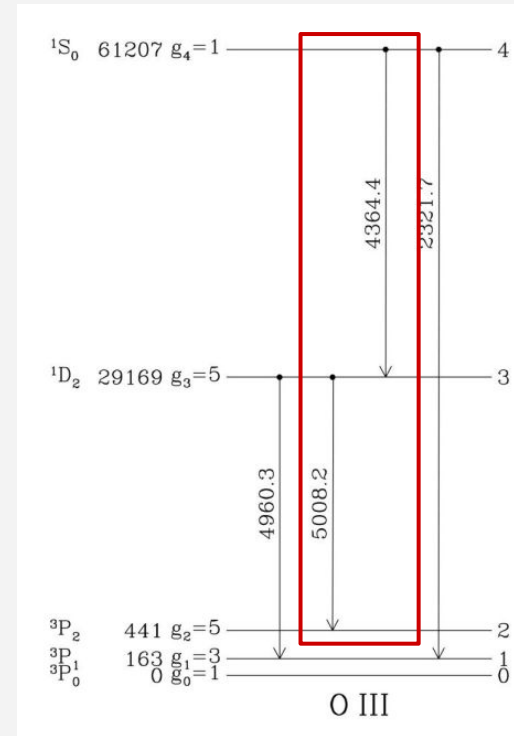
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higher redshifts?

Metallicity determination: **direct Te method**

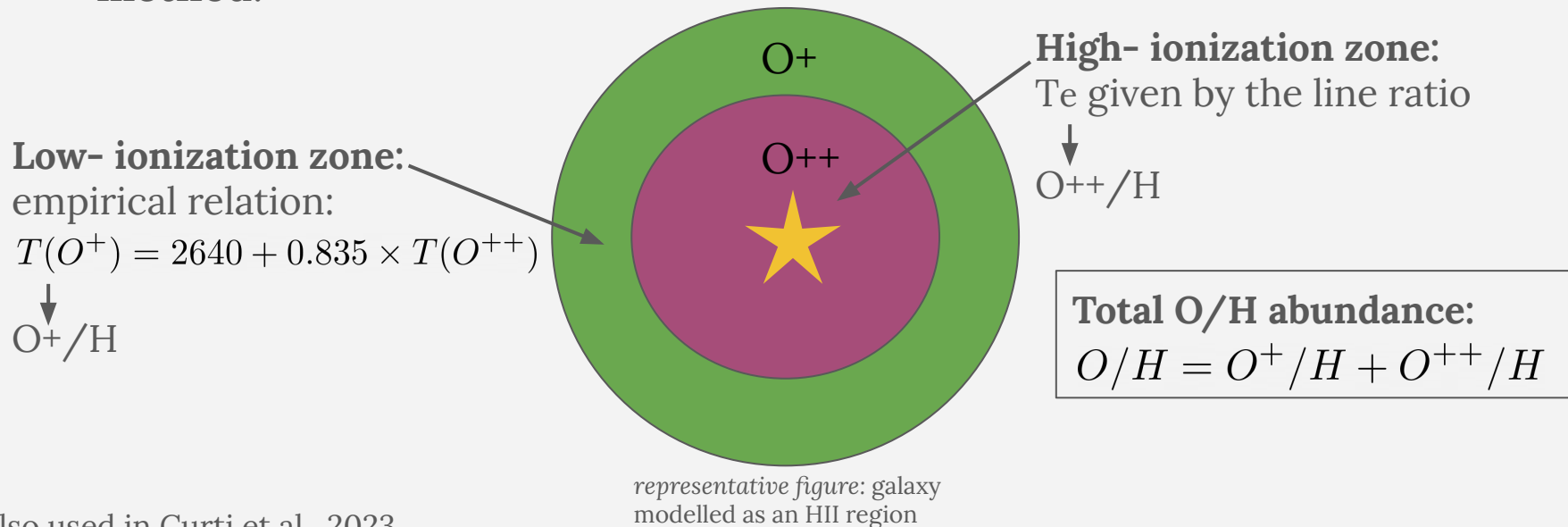
- ratio of lines from different levels of an ion $\propto T_e$
- e.g., $[\text{O III}]\lambda 4363/[\text{O III}]\lambda 5007$ (auroral-to-nebular)



Draine, 2011- Figure 18.1

Metallicity determination: **direct Te method**

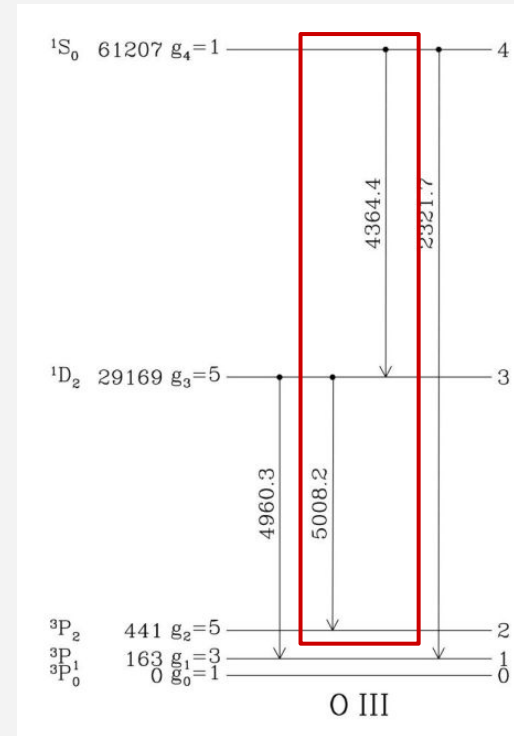
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- e.g., $[\text{O III}]\lambda 4363 / [\text{O III}]\lambda 5007$ (auroral-to-nebular)
- **method:***



*also used in Curti et al., 2023

Metallicity determination: **direct Te method**

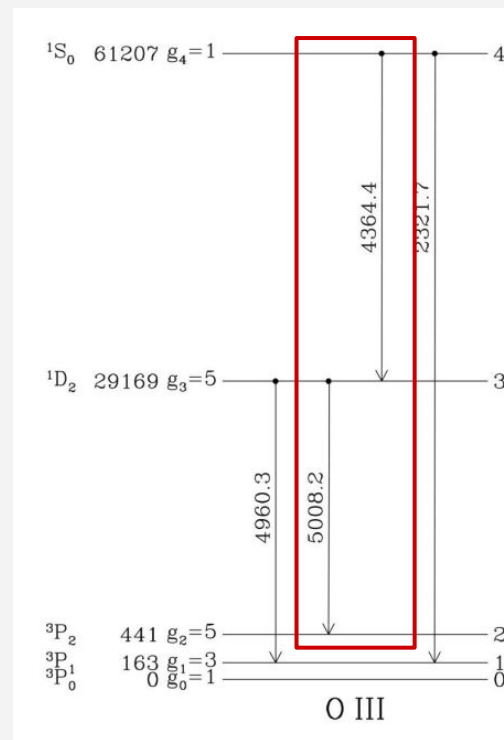
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- pros: calibration independent
- cons: aurora lines usually **too faint to be detected**



Draine, 2011- Figure 18.1

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 - revolutionalized by JWST



Draine, 2011- Figure 18.1

Metallicity determinations: **strong-line method**

- ratio between dust-corrected, **bright lines**:

Metallicity determinations: **strong-line method**

- ratio between dust-corrected, **bright lines**:

$$R3 = [OIII] \lambda 5007 / H\beta$$

$$R2 = [OII] \lambda 3727, 3729 / H\beta$$

$$R_{23} = ([OIII] \lambda 4959, 5007 + [OII] \lambda 3727, 3729) / H\beta$$

$$O_{32} = [OIII] \lambda 5007 / [OII] \lambda 3727, 3729$$

$$Ne3O2 = [NeIII] \lambda 3869 / [OII] \lambda 3727, 3729$$

Metallicity determinations: **strong-line method**

- ratio between dust-corrected, bright lines
- **calibration curves**

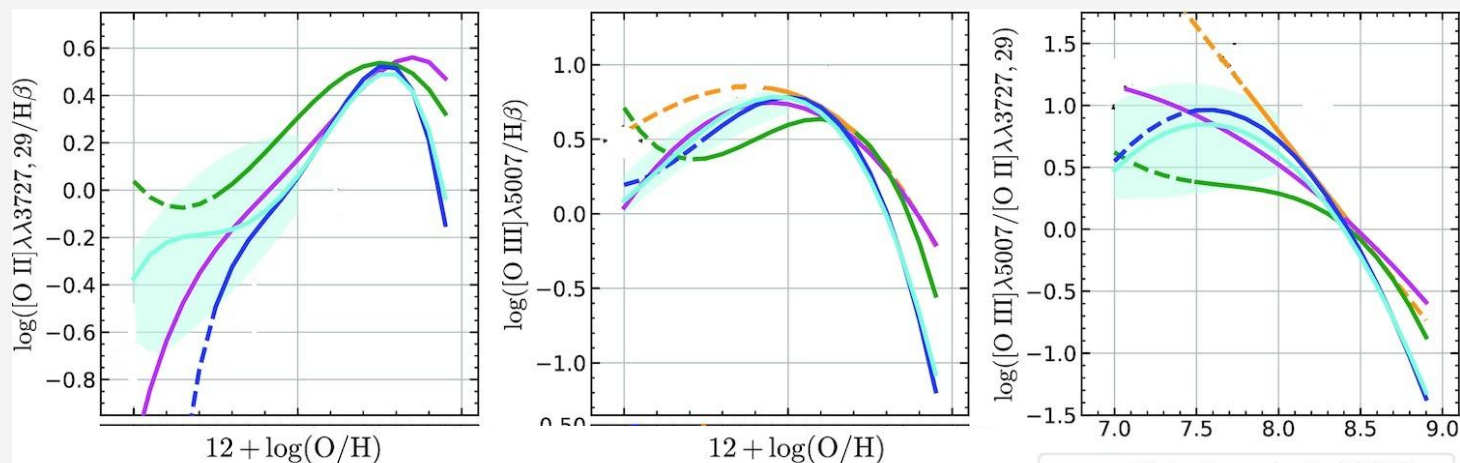
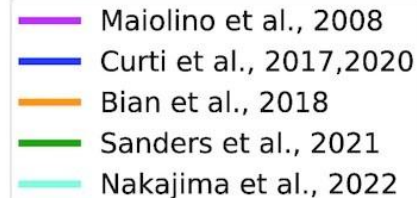


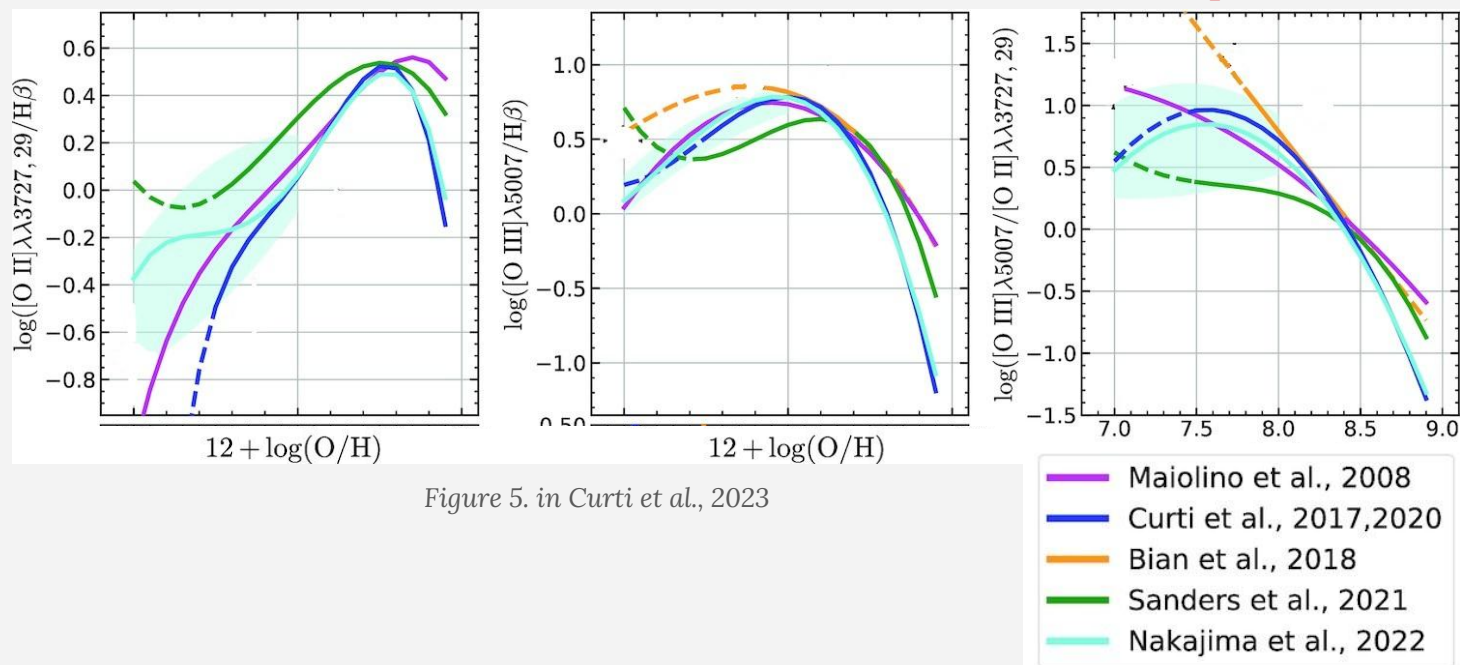
Figure 5. in Curti et al., 2023

auroral lines+photoionization
Te based measurements
empirical, high-z tuned
empirical, low-z tuned
SDSS stacks



Metallicity determinations: **strong-line method**

- ratio between dust-corrected, bright lines
- calibration curves- **derived in the local universe** → **potential bias?**



Curti et al., 2023: metallicity measurements at $z \sim 8$

- 3 gravitationally lensed targets: **ID 4590** ($z = 8.496$), **ID 6355** ($z = 7.665$), **ID 10612** ($z = 7.658$)
- count rate data from MAST archive
- custom flux calibration using in-flight commissioning star
- dust attenuation correction
- auroral line detected: **[OIII] λ 4363**

Galaxy ID	4590	6355	10612
Redshift	8.496	7.665	7.658
μ^a	3.74 ± 0.07	1.231 ± 0.002	1.339 ± 0.003
$\log(M_\star/M_\odot)^b$	7.75 ± 0.07	8.72 ± 0.04	8.08 ± 0.04
$\log(\text{SFR } (M_\odot \text{yr}^{-1}))^b$	0.35 ± 0.07	1.47 ± 0.04	0.90 ± 0.04
A_V (nebular) ^c	$0.68^{+0.34}_{-0.25}$	$0.0^{+0.1}_{0.0}$	$0.40^{+0.46}_{-0.27}$
A_V (stellar) ^d	0.37 ± 0.04	0.50 ± 0.03	0.21 ± 0.03
T_e ([O III])(10^4 K)	2.77 ± 0.42	1.20 ± 0.07	1.75 ± 0.16
$12 + \log(\text{O}/\text{H})$	6.99 ± 0.11	8.24 ± 0.07	7.73 ± 0.12

Notes. ^a derived from the lens models presented in Mahler et al. (2022)
^b values are corrected for magnification (errors on μ are propagated)
^c inferred from ratios of Balmer lines
^d inferred from SED fitting

Table 2. in Curti et al., 2023

Curti et al., 2023: comparison with strong-line calibrations

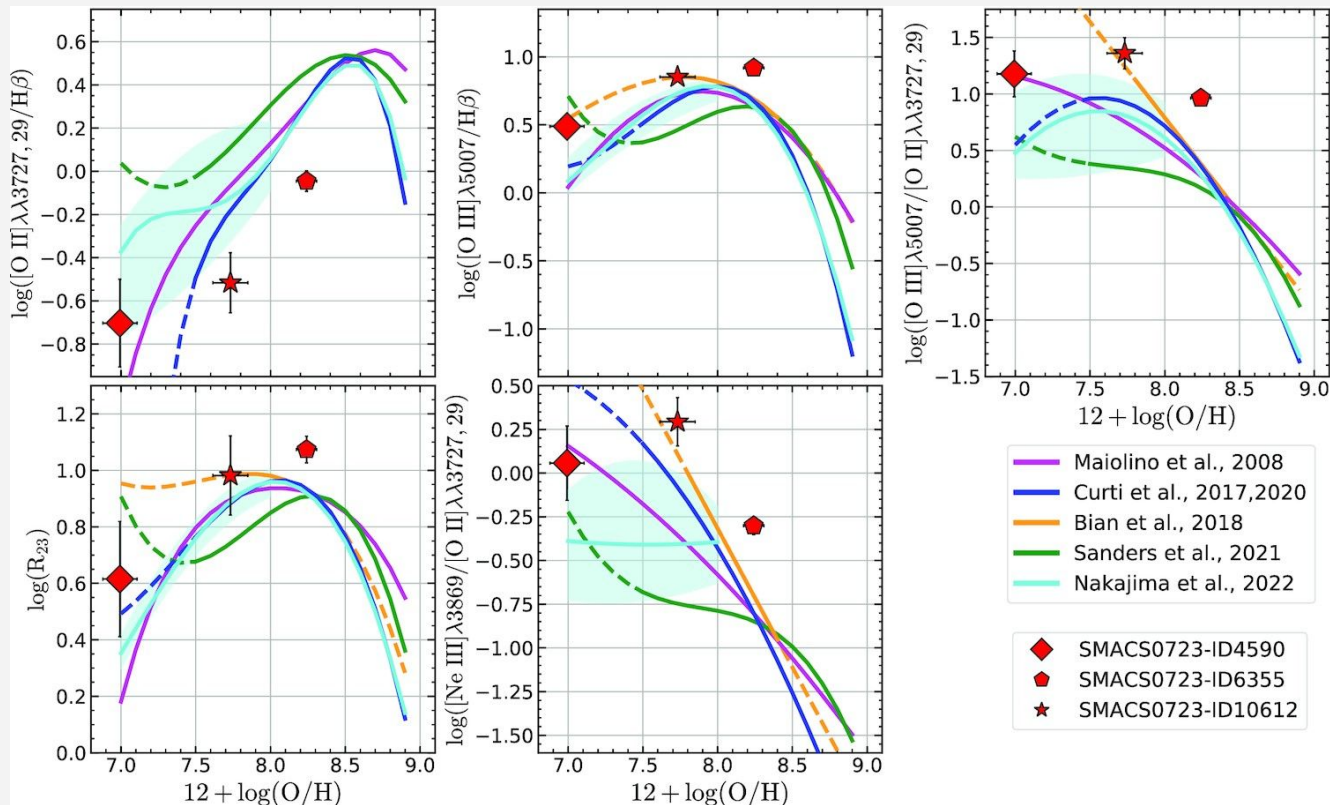
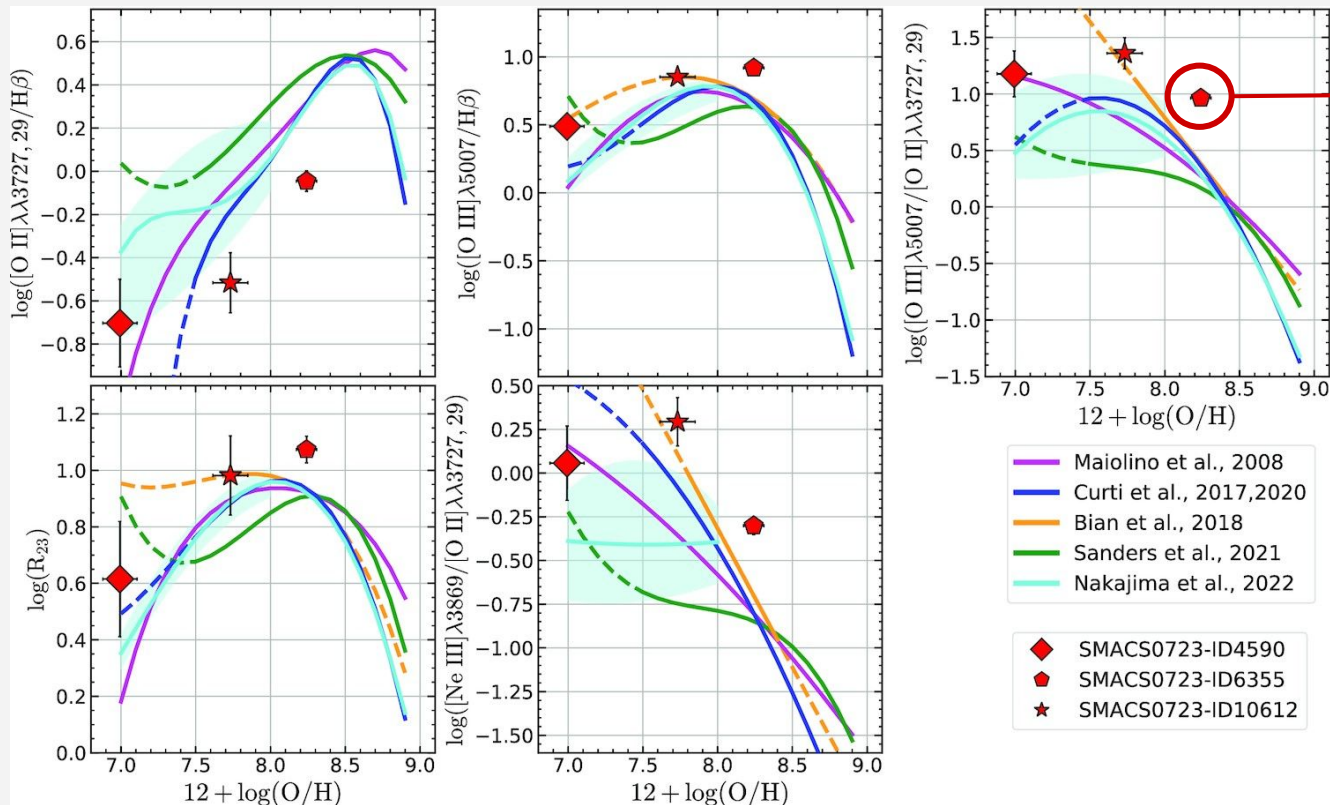


Figure 5. in Curti et al., 2023

Curti et al., 2023: comparison with strong-line calibrations



outside most calibrations!

line ratio resembling those of **extremely metal-poor galaxies** in the local Universe

Figure 5. in Curti et al., 2023

Curti et al., 2023: comparison with strong-line calibrations

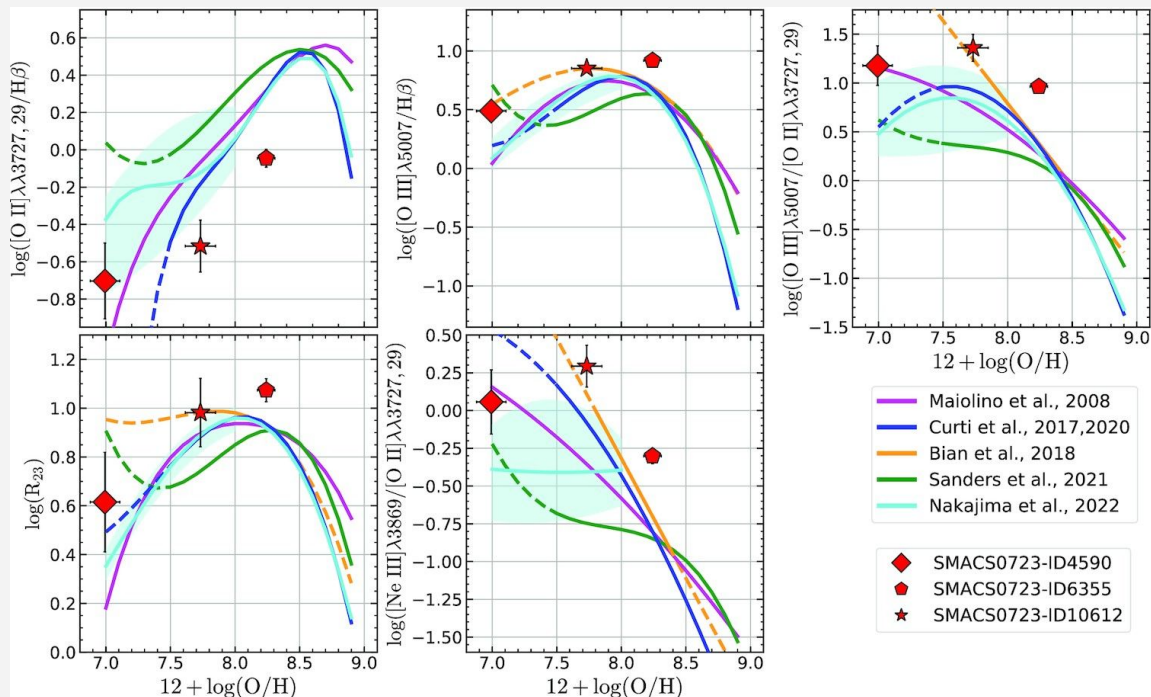


Figure 5. in Curti et al., 2023

None of the local strong-line metallicity calibrations **provide good predictions** of the observed metallicities simultaneously!

Curti et al., 2023: Mass- metallicity relation

- ID 6355, ID 10612
consistent with $z \sim 3.3$ MZR → little evolution between $z \sim 3.3$ and $z \sim 7.6$

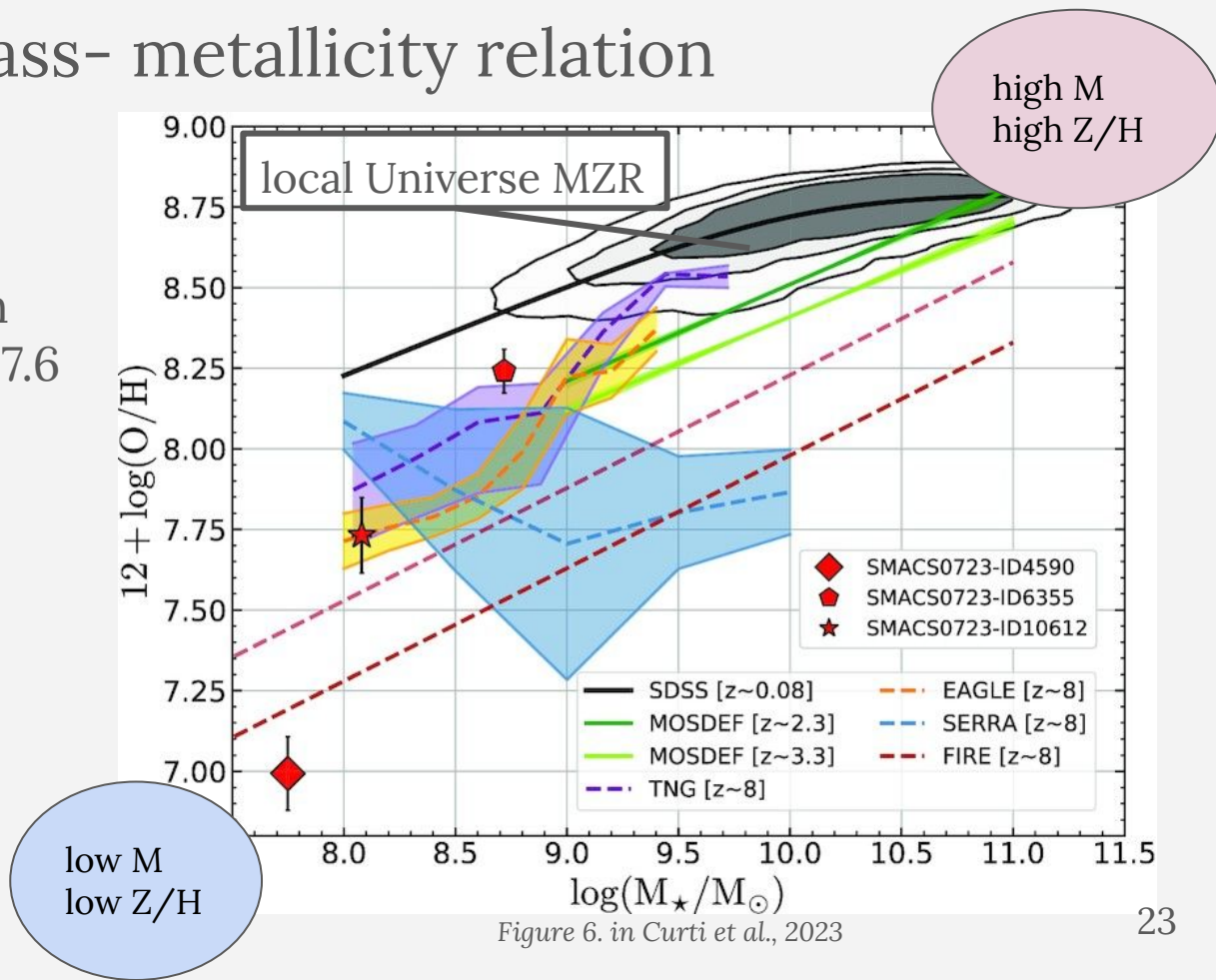


Figure 6. in Curti et al., 2023

Curti et al., 2023: Mass- metallicity relation

- ID 6355, ID 10612
consistent with $z \sim 3.3$ MZR → little evolution between $z \sim 3.3$ and $z \sim 7.6$
- ID4560 outlier:
 - **early evolutionary stage**, building up its metals
 - MZR has a **much steeper slope** at such low masses.

low M
low Z/H

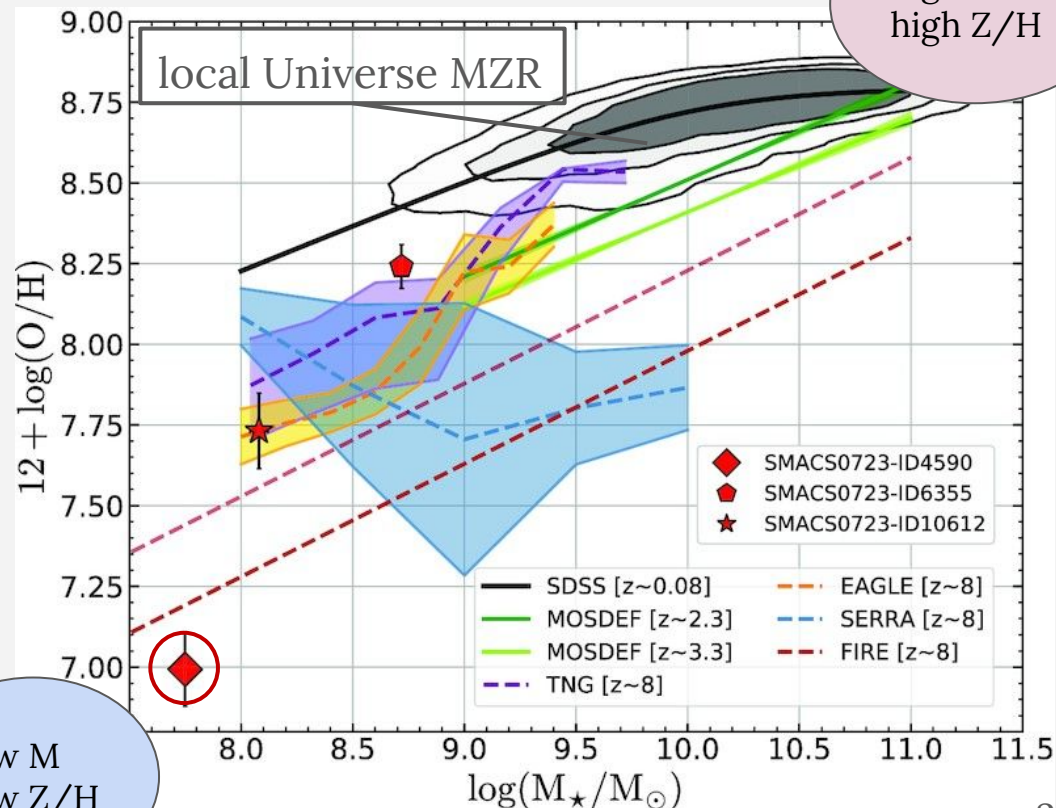


Figure 6. in Curti et al., 2023

Curti et al., 2023: Fundamental metallicity relation

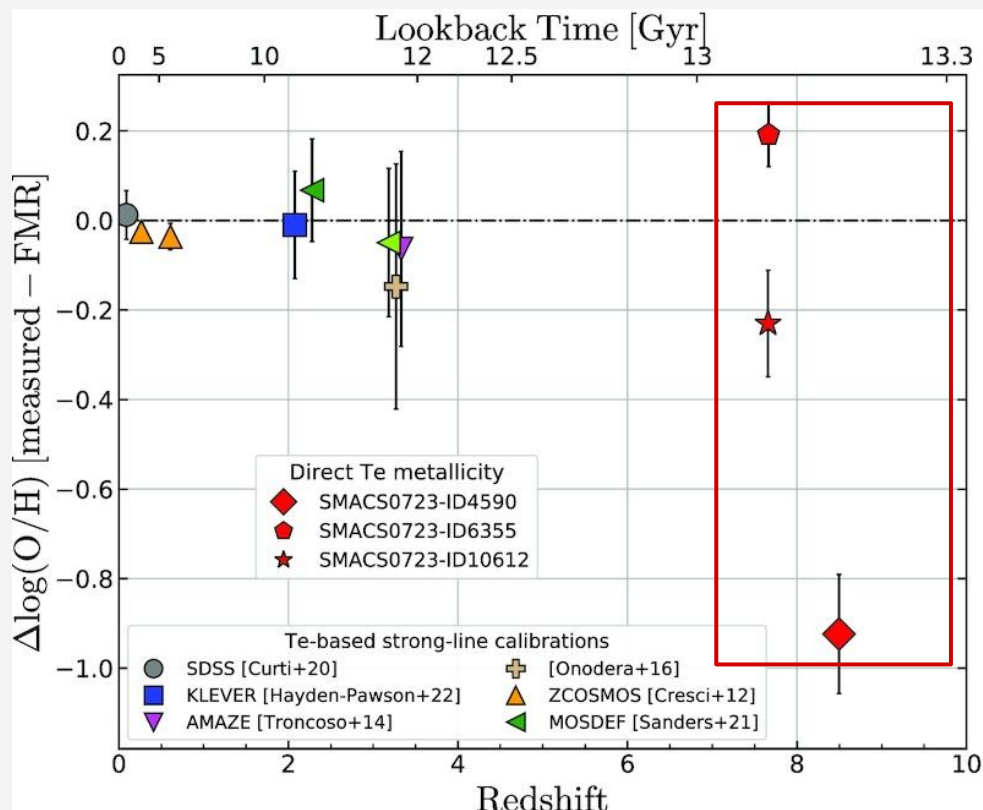


Figure 7. in Curti et al., 2023

- **Significant scatter** around FMR, mainly for ID 4590 → **far from equilibrium** between chemical enrichment and gas flows

FMR not in place at these redshifts?

* corroborated by: Heintz et al. 2023; Langeroodi & Hjorth 2023; Nakajima et al. 2023, Curti et al., 2024

From “**normal**” galaxies to **extreme** regimes

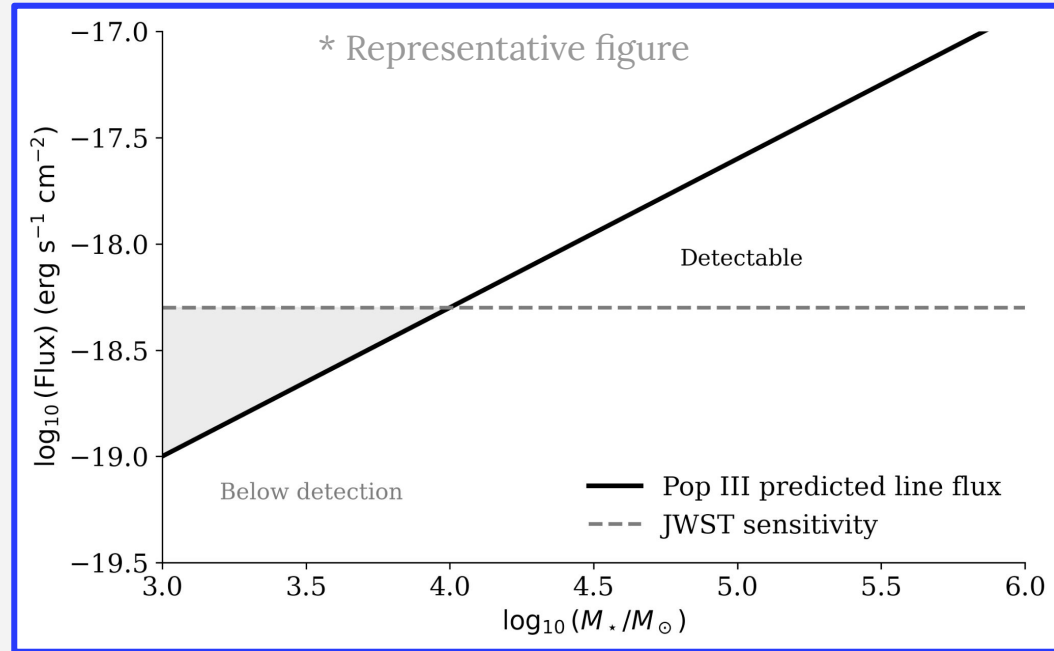
Curti+23 showed galaxies at

- Redshifts : $z \sim 7-8$
- Metallicities $\sim 10^{-2} - 10^{-1} Z_{\odot}$

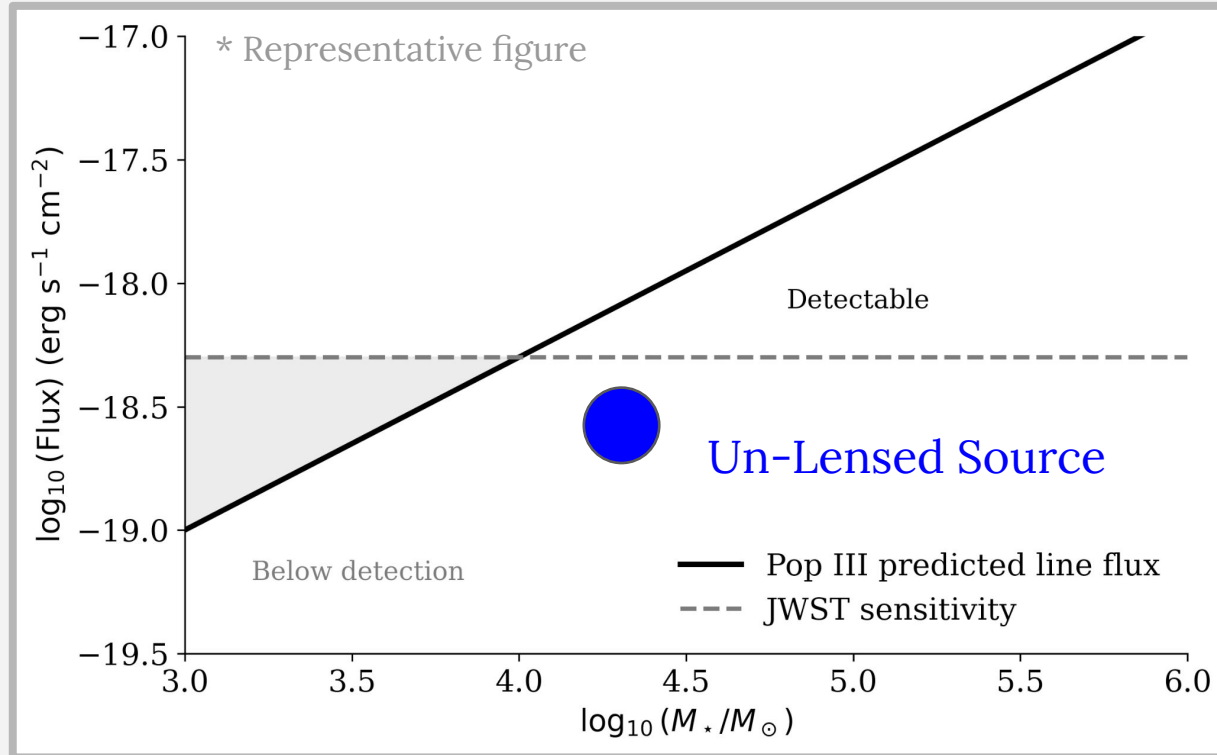
Can we probe even lower metallicities?

Why is pristine star formation hard to detect?

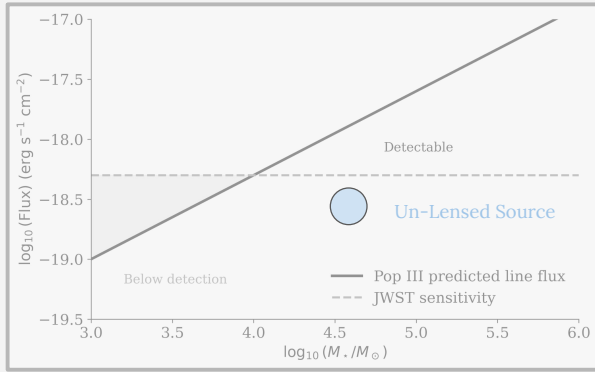
- Pop III = metal-free stars
- Expected signatures:
 - Strong HeII
 - Strong Balmer lines
 - No metal lines
- Observational Challenges:
 - Faint signals
 - IMF dependence
 - Long exposure times



Why use Gravitational Lensing?

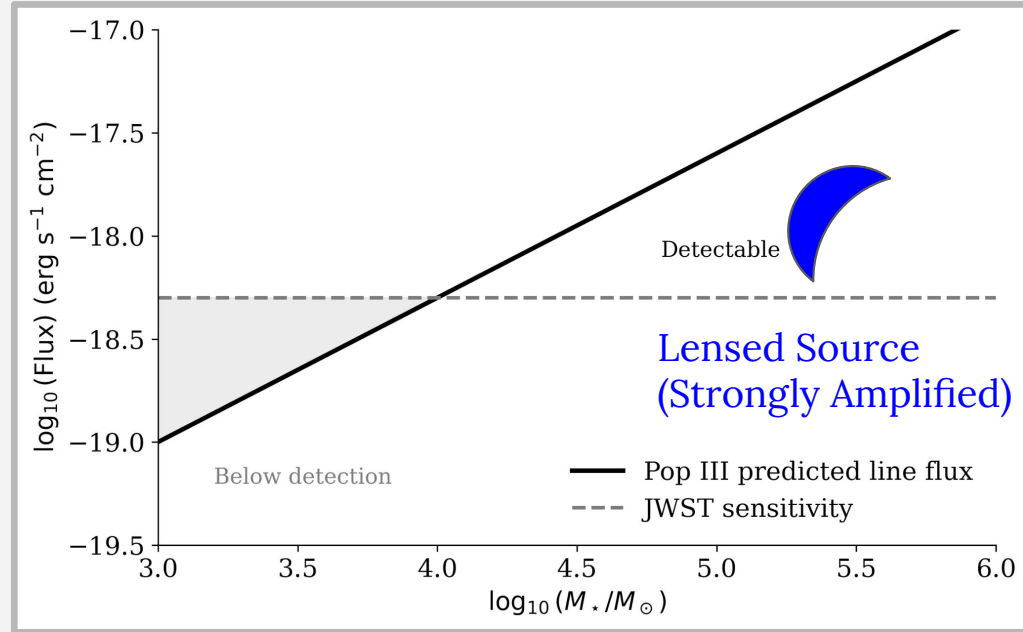


Why use Gravitational Lensing?



$\mu \gg 1$

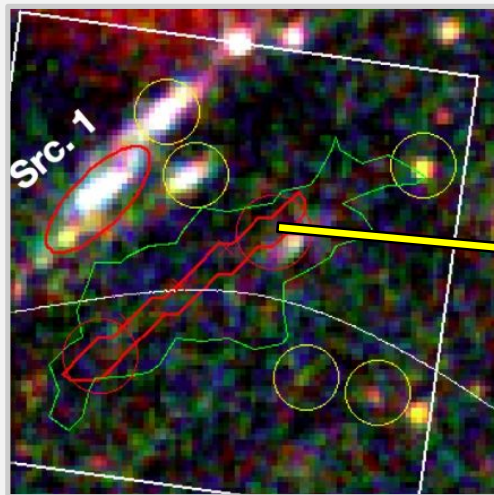
$F_{\text{obs}} = \mu F_{\text{int}}$



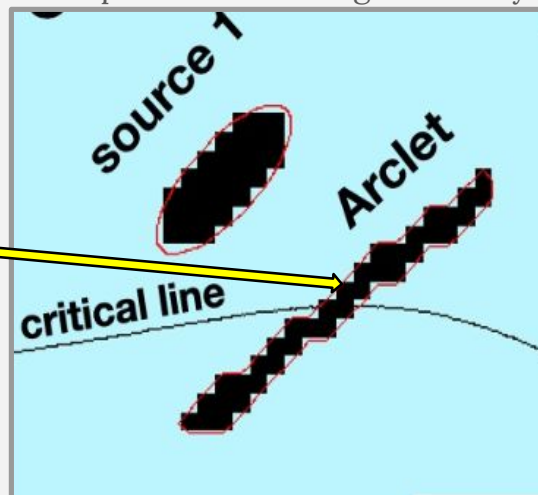
* Representative figures

PoP III Candidate: LAP1 (Lensed And Pristine)

Observation: HST + JWST



Interpretation: Lensing Geometry



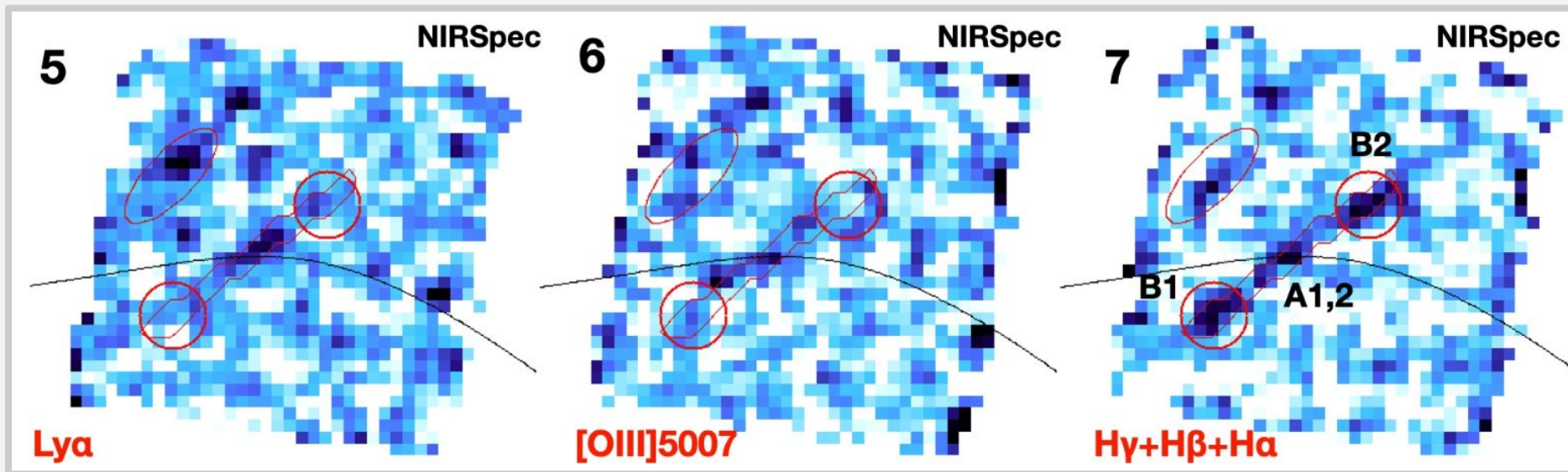
MACS J0146 Galaxy Cluster

Redshift: $z = 6.639$

Lensing-corrected mass
 $\rightarrow M \leq 10^4 M_{\odot}$

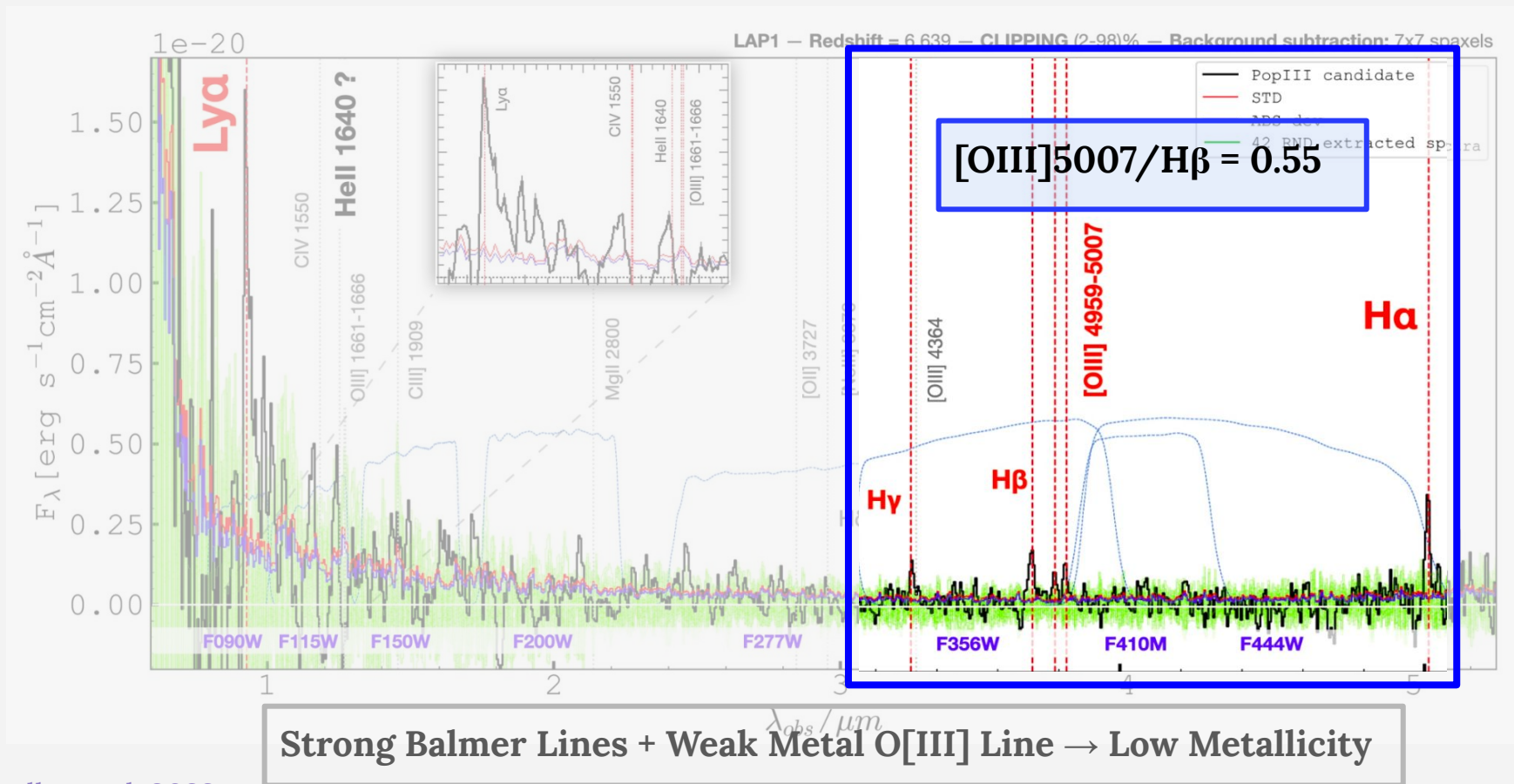
Absolute Luminosity
 $\rightarrow M_{uv} > -11.2$

LAP 1 at $z = 6.639$

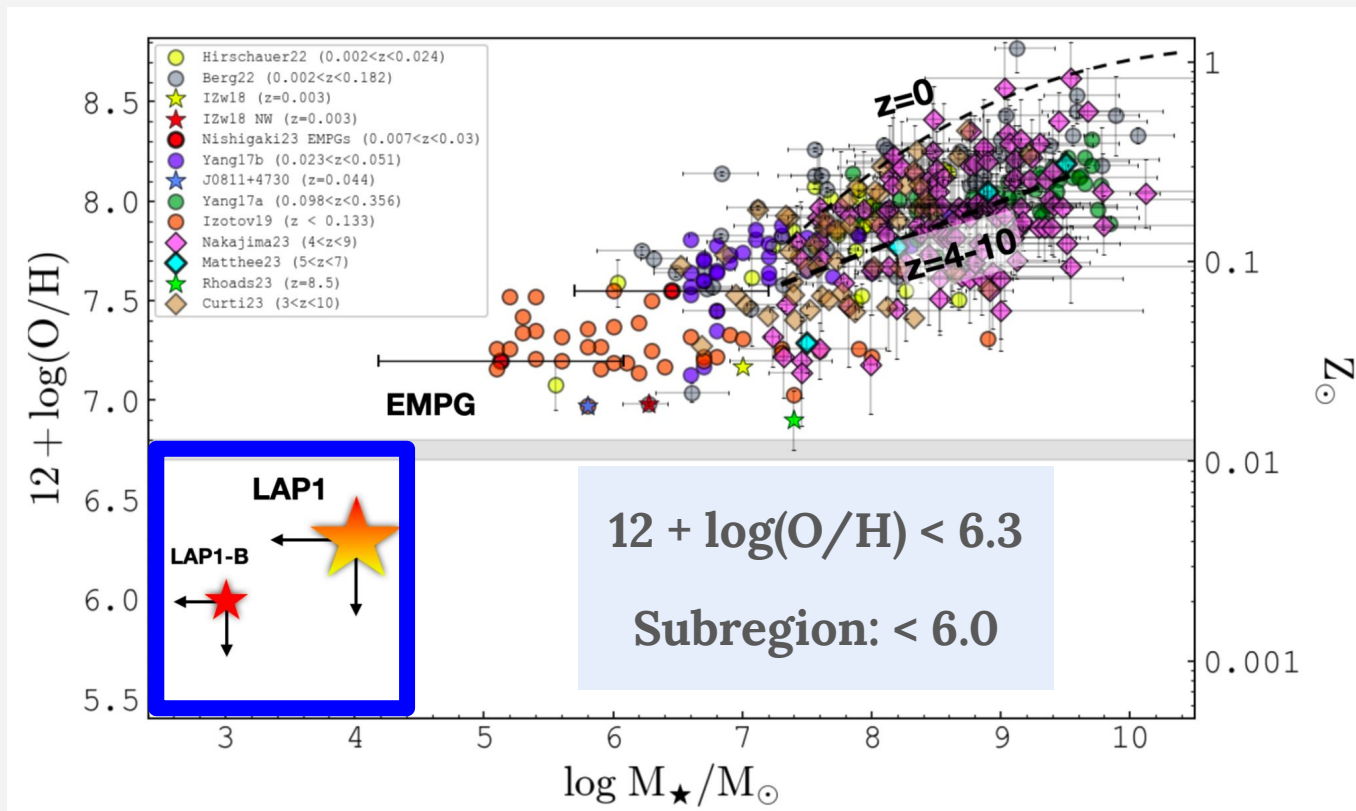


No significant stellar-counterpart detected!

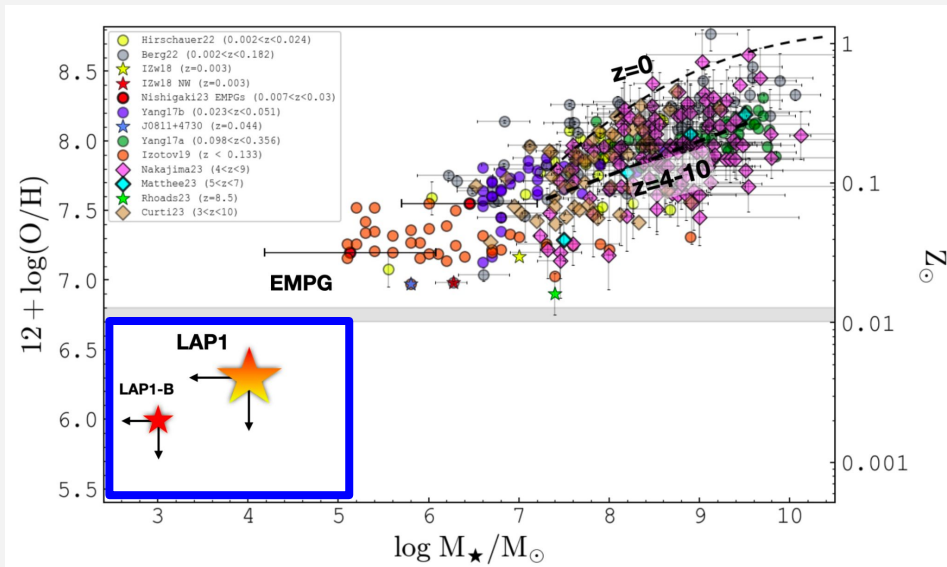
Evidence for extremely low metallicity



Metallicity Constraint for LAP 1

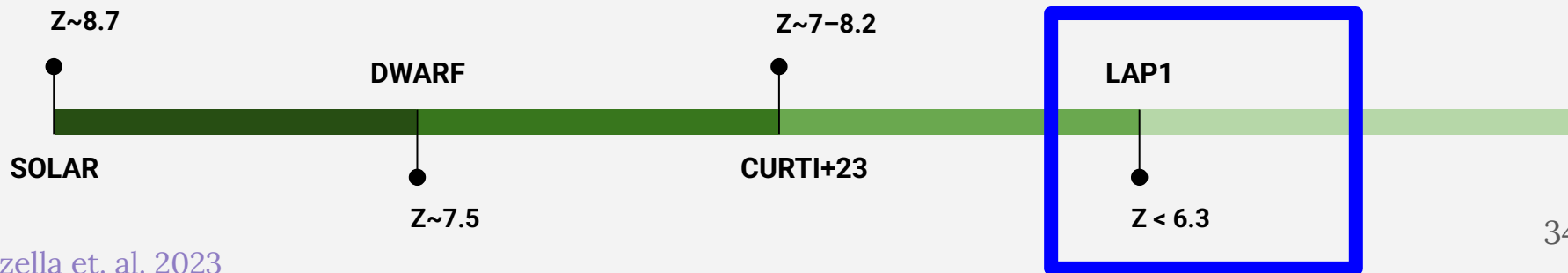


Metallicity Constraint for LAP 1



$$12 + \log(\text{O}/\text{H}) < 6.3$$

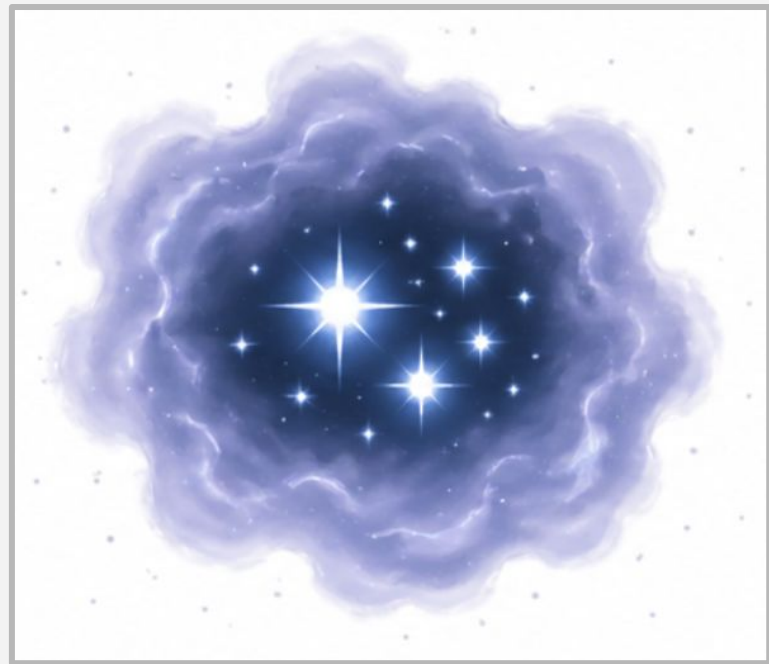
$$\text{Subregion: } < 6.0$$



What are we actually observing?

Scenario-A: Near-Pristine Star Formation

- Extremely low metallicity
- young (~few Myr)
 - Lack of stellar continuum + strong Balmer lines
- high ionising efficiency
 - Large widths of Balmer lines
→ high production rate of ionizing photons

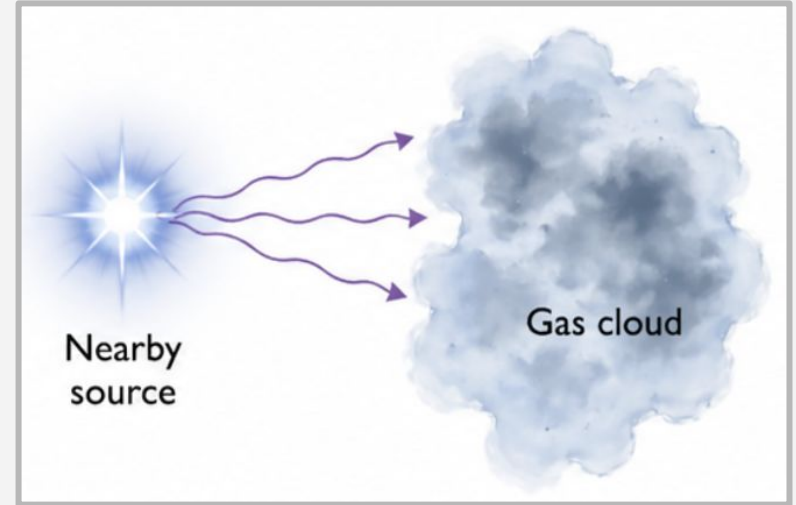


* Representative figure

What are we actually observing?

Scenario-B: Externally Ionized Gas

- Emission not locally produced
- Fluorescence possible
 - Strong Balmer emission
 - very faint or absent continuum

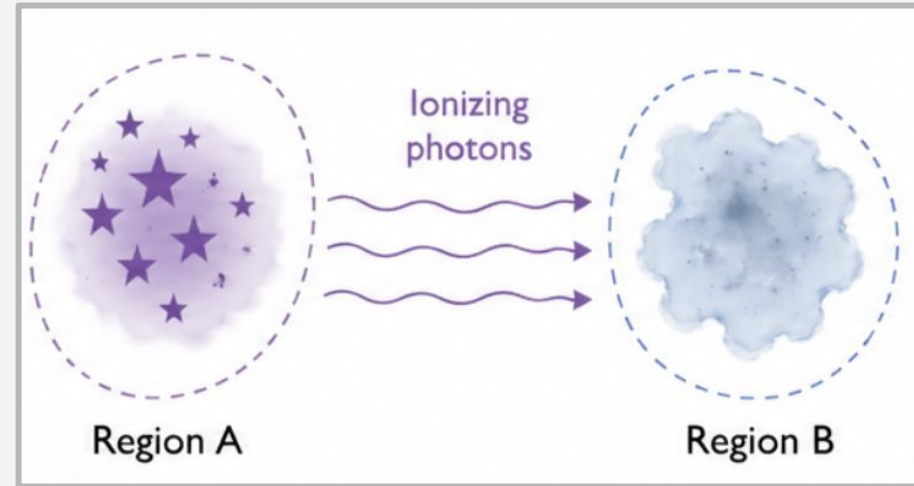


* Representative figure

What are we actually observing?

Scenario-C: Ionizing Leakage

- Radiation escapes from nearby region
- Induces Balmer emission

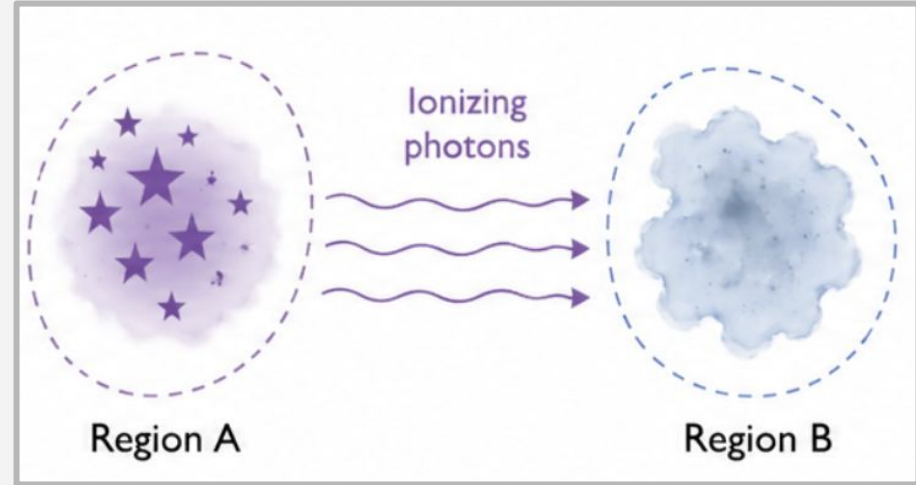


* Representative figure

What are we actually observing?

Scenario-C: Ionizing Leakage

- Radiation escapes from nearby region
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* Representative figure

All scenarios produce similar signatures, the exact origin remains unknown

Chemical Enrichment at Cosmic Dawn

Curti+2023

- 3 sources at $z \sim 7.6, 8$
- $12 + \log(\text{O}/\text{H}) \sim 7-8.2$
- Strong-line calibrations fail to match observed metallicity
- Sources deviate from the FMR
 - no equilibrium between chemical enrichment & gas flow

Vanzella+2023

- $12 + \log(\text{O}/\text{H}) < 6.3$
 - Subregion < 6.0
- Extreme Outlier to MZR
 - Nature of LAP 1 is unknown
- Consistent with near-pristine gas
 - But not a definitive Pop III detection
- No stellar counterpart detected

Early galaxies are **chemically inhomogenous**

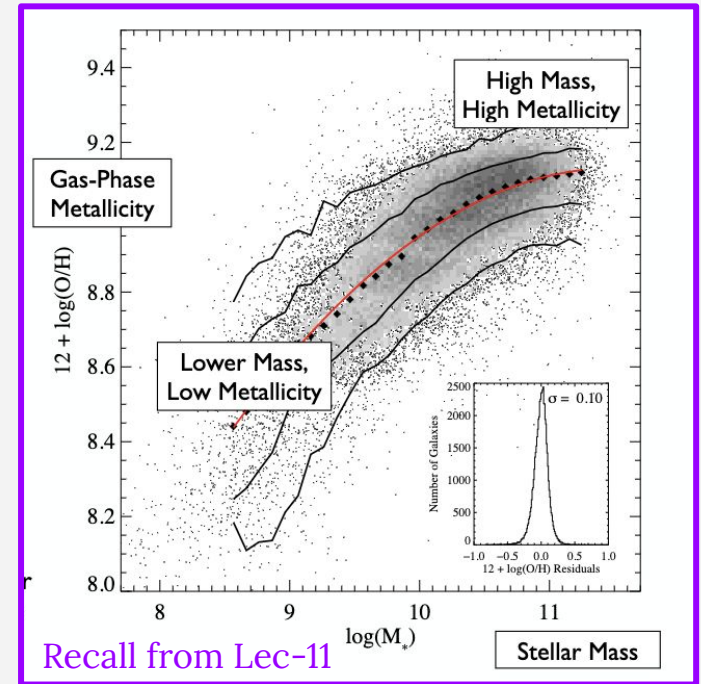
Mass-Metallicity Relation (MZR)

Fundamental Metallicity Relation (FMR)

$$Z = f(M_*, \text{SFR})$$

- At fixed mass:
 - Higher SFR \rightarrow Lower metallicity

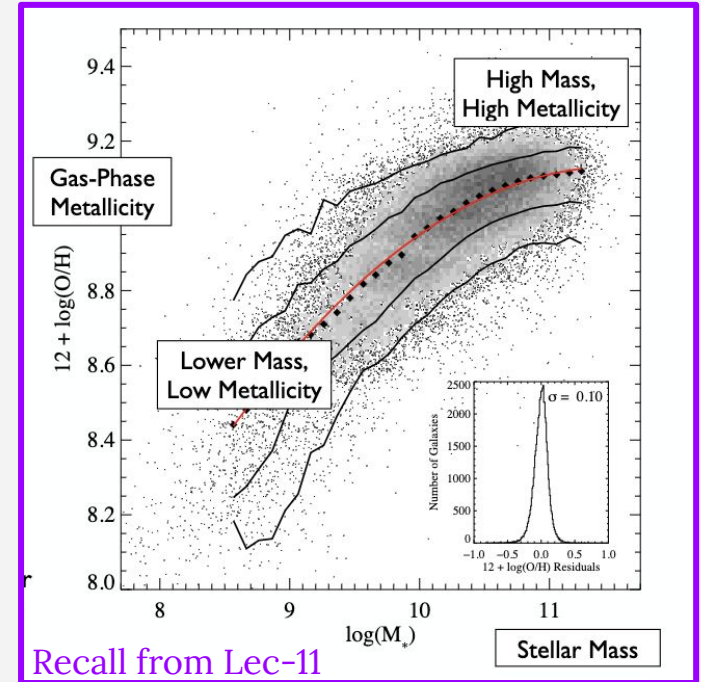
Gas inflow \rightarrow boosts SFR, dilutes metals



Low-z galaxies follow regulated equilibrium between inflow, SF & feedback

Mass-Metallicity Relation (MZR)

- Z increases with M_*
 - More massive galaxies retain metals
 - Deeper potential \rightarrow less metal loss
- Physical Drivers
 - Star Formation efficiency
 - Gas inflows & Metal outflows



Recall from Lec-11

Curti et al., 2023: excitation diagnostics

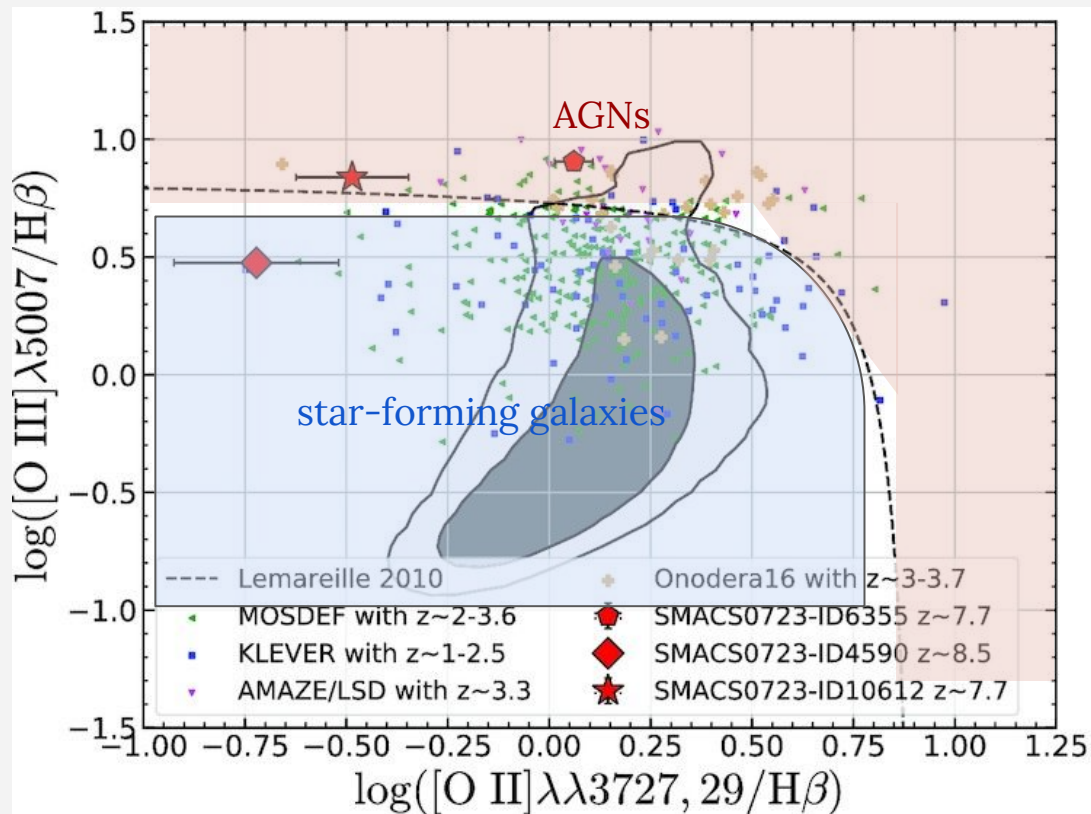


Figure 3. in Curti et al., 2023

Curti et al., 2023: excitation diagnostics

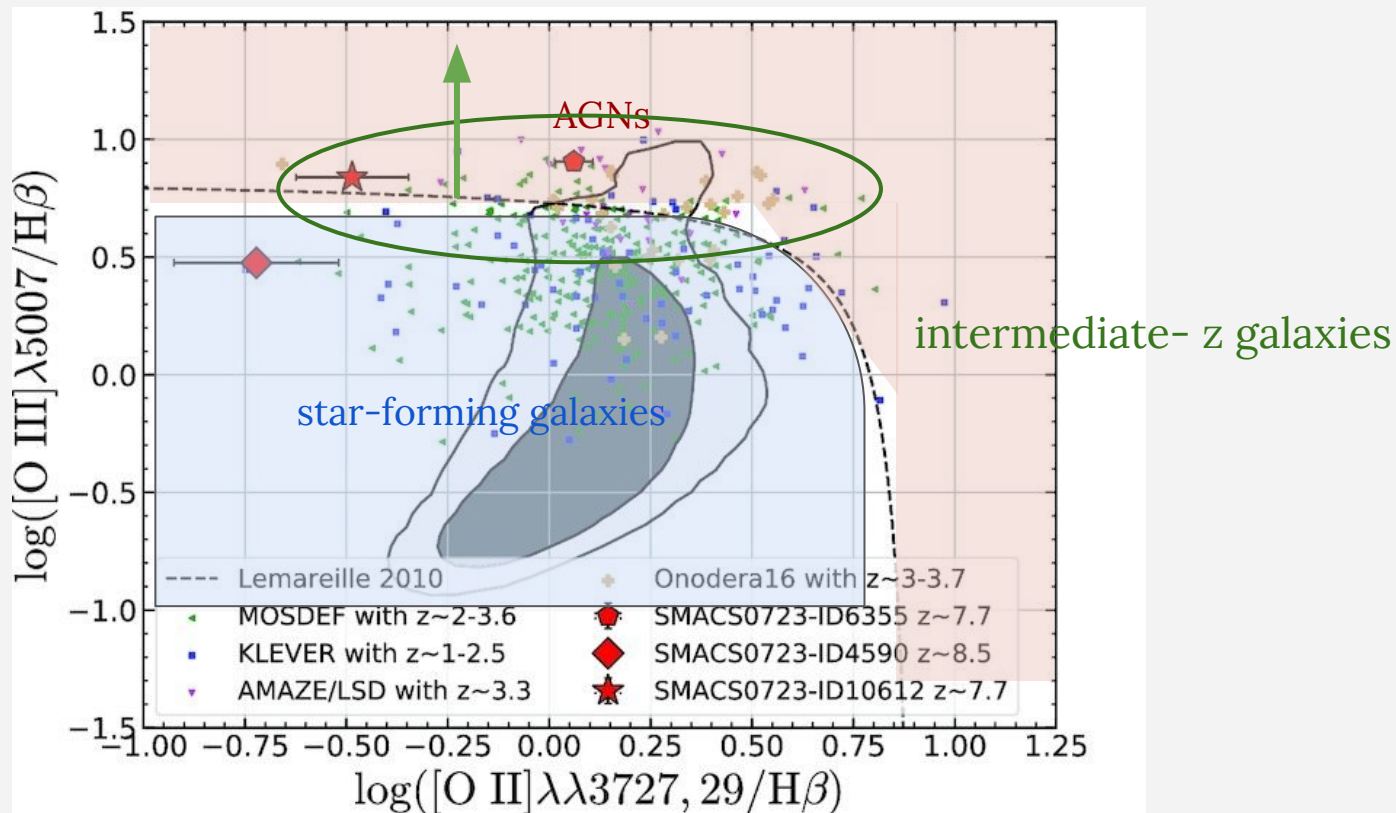
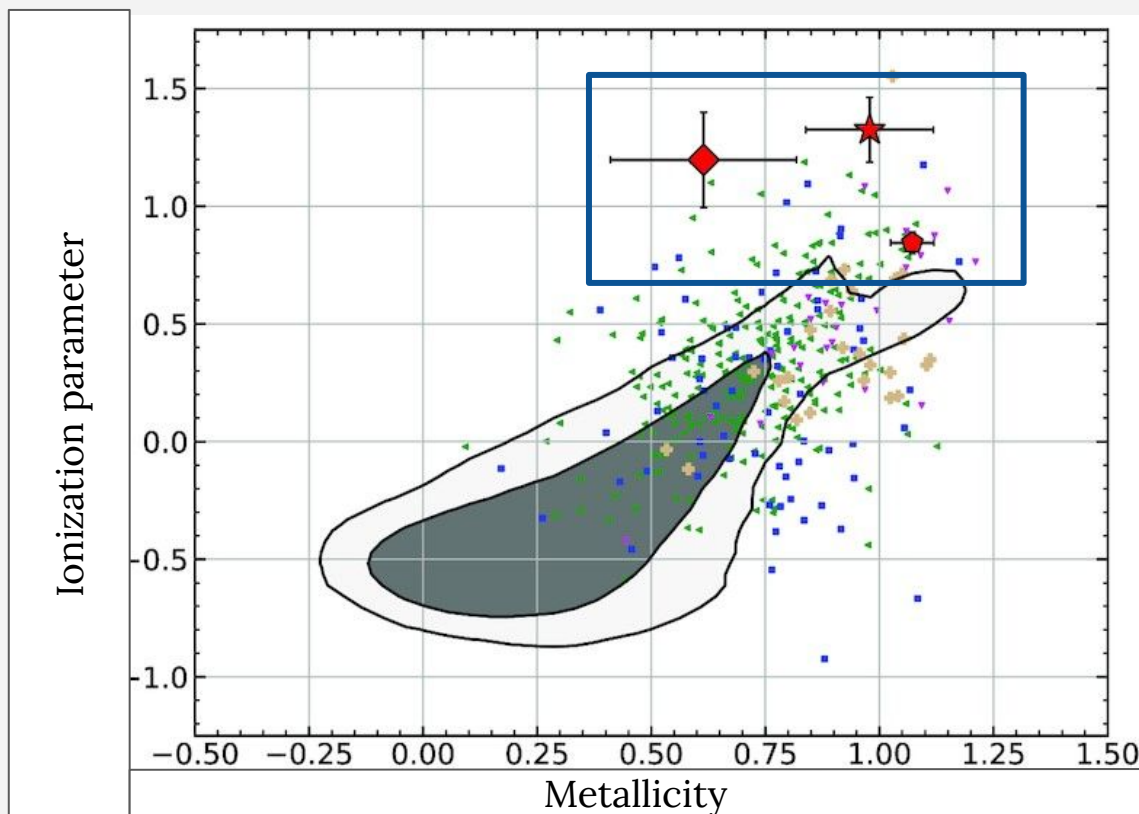


Figure 3. in Curti et al., 2023

Curti et al., 2023: ionization parameter



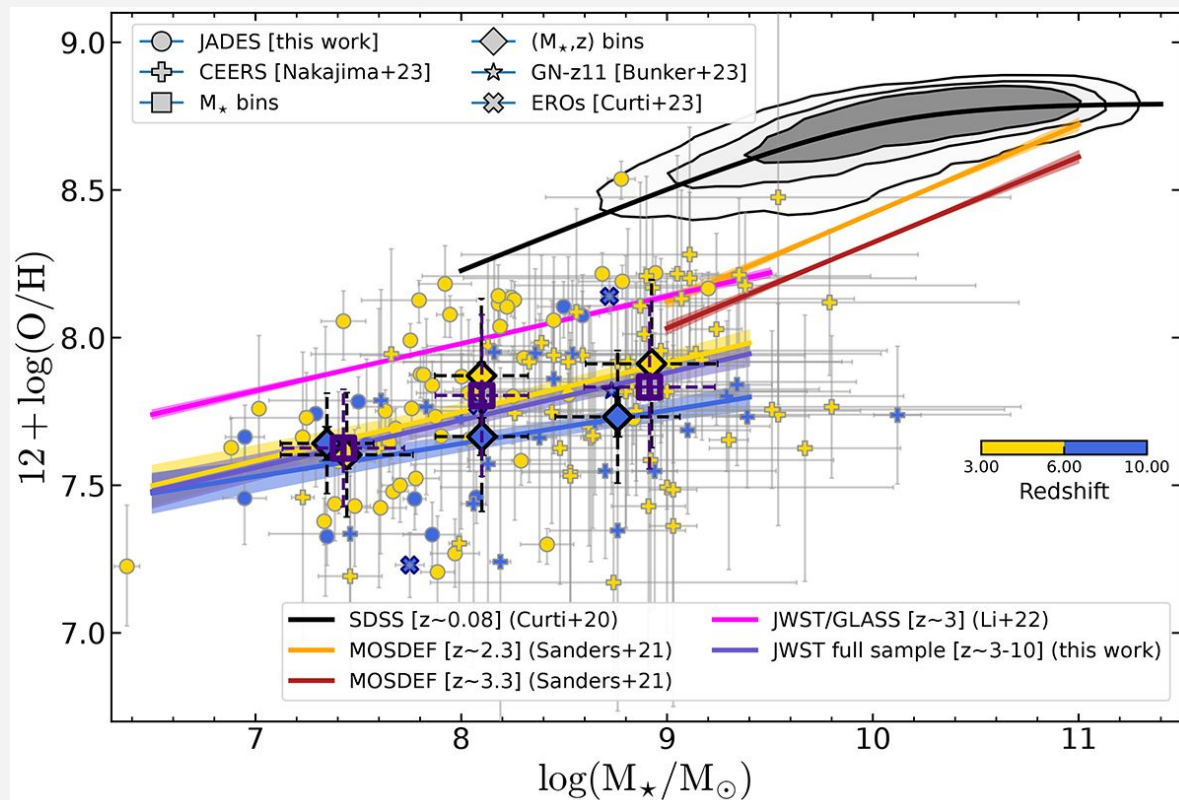
extremely high values compared to intermediate- z galaxies

↓
high ionization params. &/

large LyC escape fraction ($f \sim 0.1$)

Figure 3. in Curti et al., 2023

Curti et al., 2024:



- **More metal poor** than local galaxies of same mass and SFR
- **Offset grows with redshift**
- **No smooth equilibrium** between gas accretion, star formation and enrichment at this redshifts!