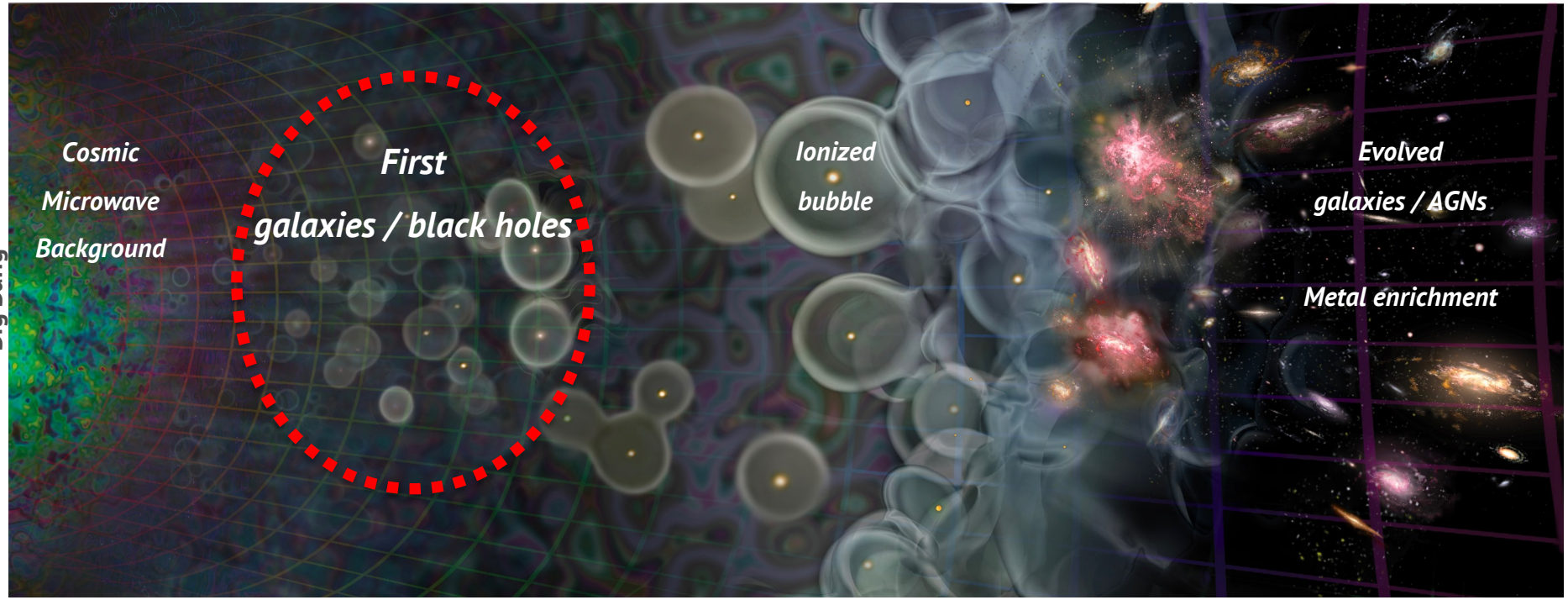
初代星・初代銀河研究会 @ Fukui on December 3, 2025

JWST時代の初代星・初代銀河研究：観測の最前線

中島 王彦　Kimihiko Nakajima

金沢大学　Kanazawa Univ.

Key Science: First Sources of light in Early Universe



© Loeb 2006

Key Science: First Sources of light in Early Universe

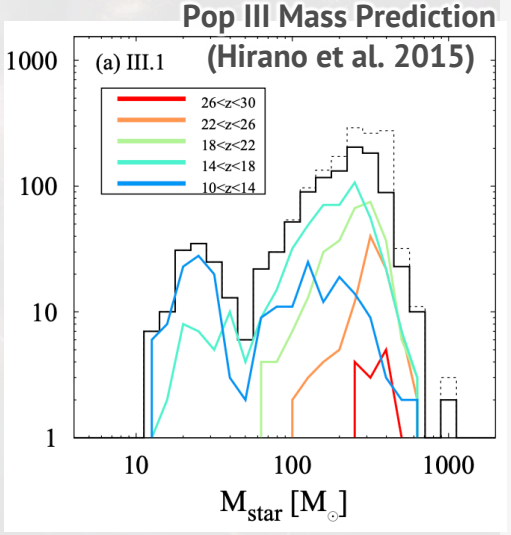
Cosmic Dark Ages | Cosmic Dawn | Epoch of Reionization | Peak of Cosmic Star-Formation

Big Bang

Cosmic Microwave Background

First galaxies / black holes

- Pop III Masses ?
- Chemical enrichment by Pop III stars ?
- Pop III star vs. Black hole (DCBH) ?
- … (as reviewed through workshop)

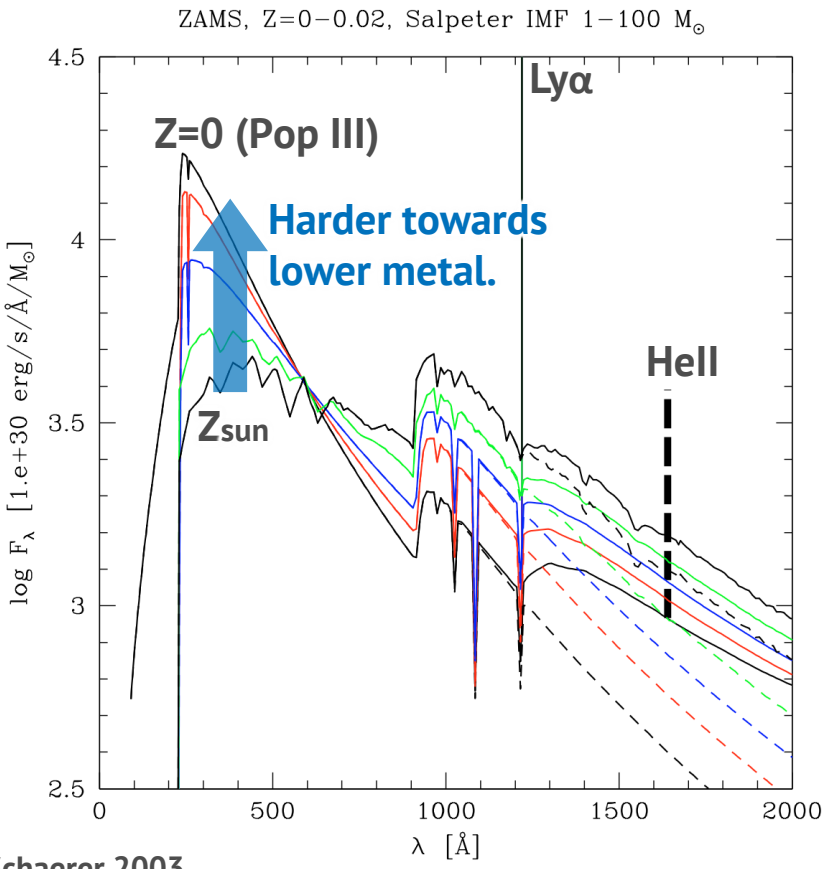


380,000 yr | ~100-300 Myr | -- Age of Universe -- | 1 Gyr | 3 Gyr

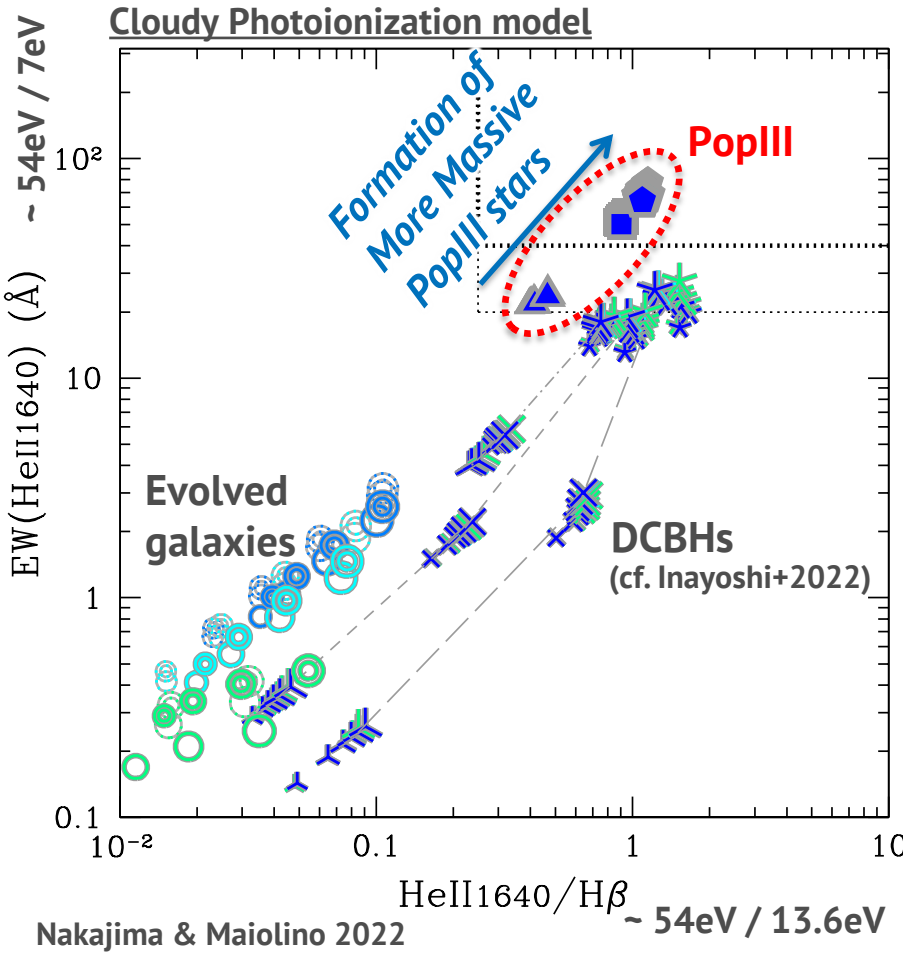
z=1,100 | z~15-25 | -- Redshift -- | z=6 | z=2

© Loeb 2006

Predicting Observational Signatures of Population III Galaxies: Hard spectrum & Ext. low metallicity



Schaerer 2003

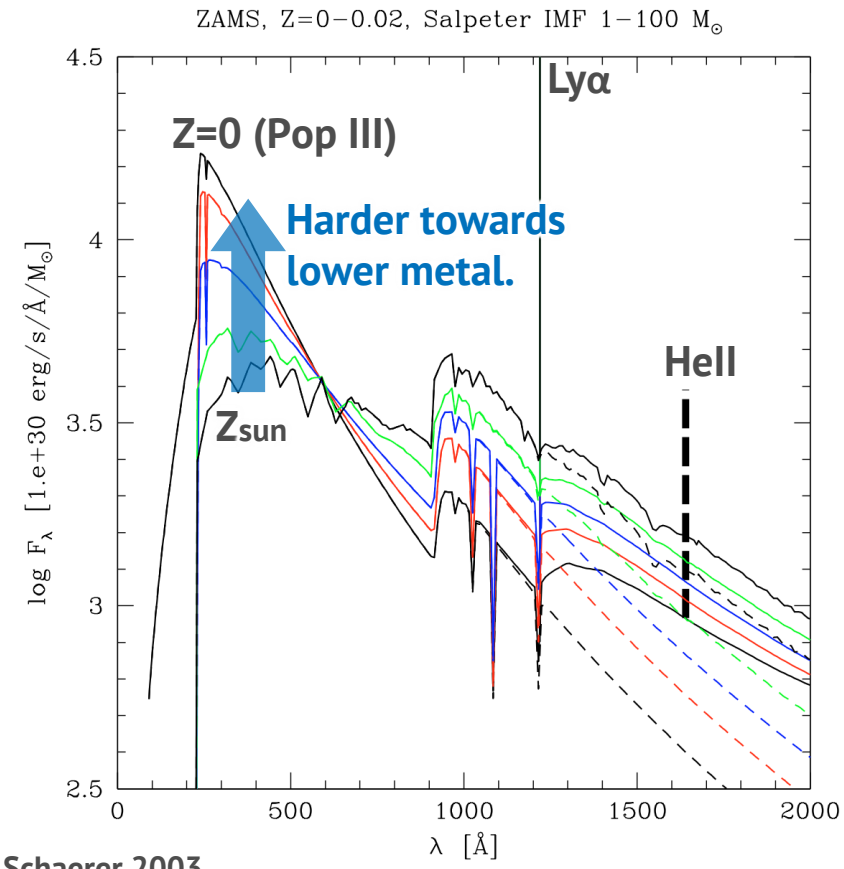


Nakajima & Maiolino 2022

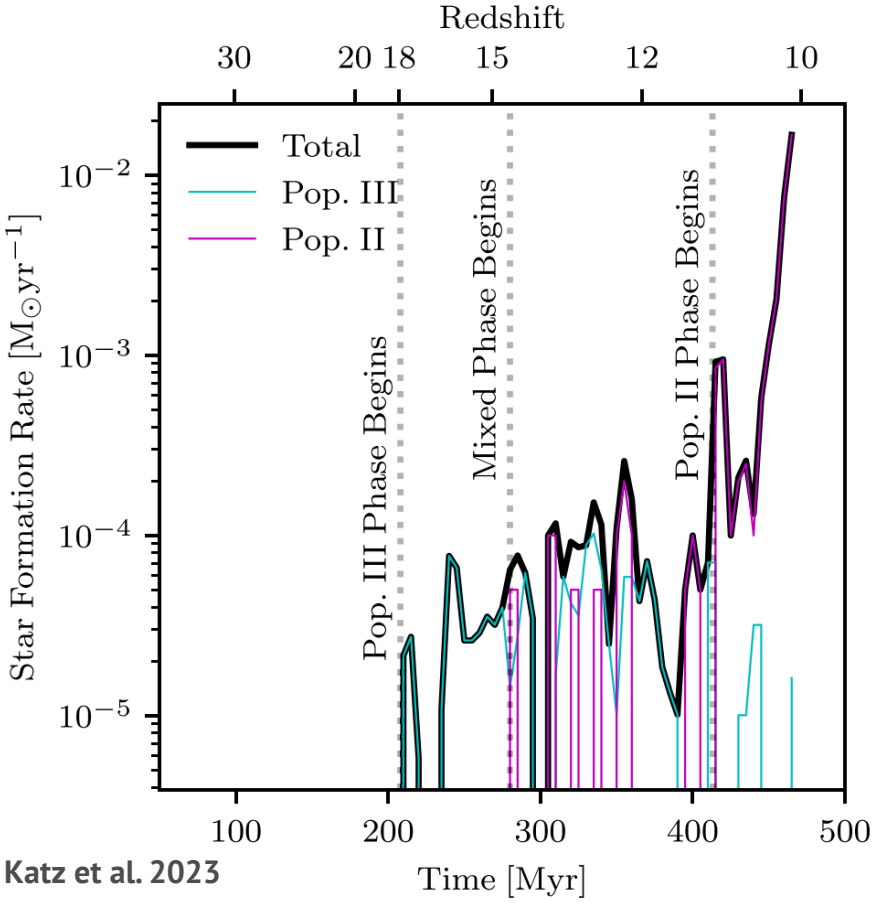
Strong HeII emission / Efficient production of ionizing photons as Probe of Pop III

See also: Tumlinson+2000, 2001, Schaerer 2002, Raiter+2010, Inoue 2011, Zackrisson+2011, Nakajima & Maiolino 2022, Rusta+2025

Predicting Observational Signatures of Population III Galaxies: Hard spectrum & Ext. low metallicity



Schaerer 2003



Katz et al. 2023

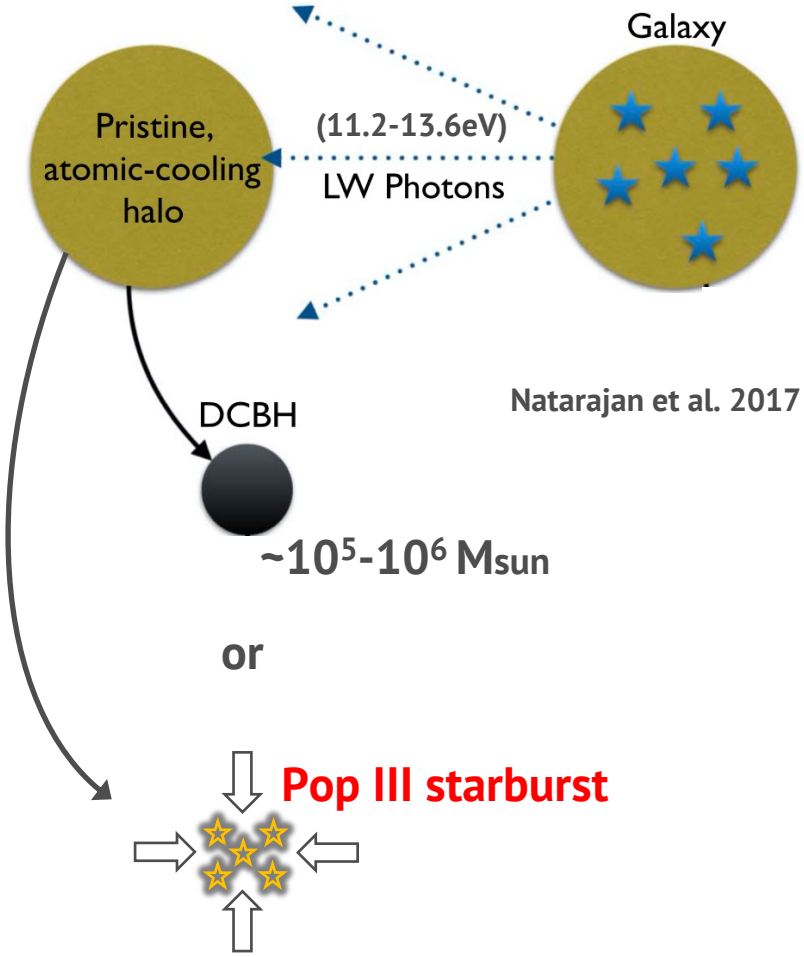
Strong HeII emission / Efficient production of ionizing photons as Probe of Pop III

Quick metal enrichment (see: Wise et al. 2012)
+ One PISN to enrich Z~10^{-3} Zsun (10^6 Msun halo)

Pop III stars and ISM metals coexist

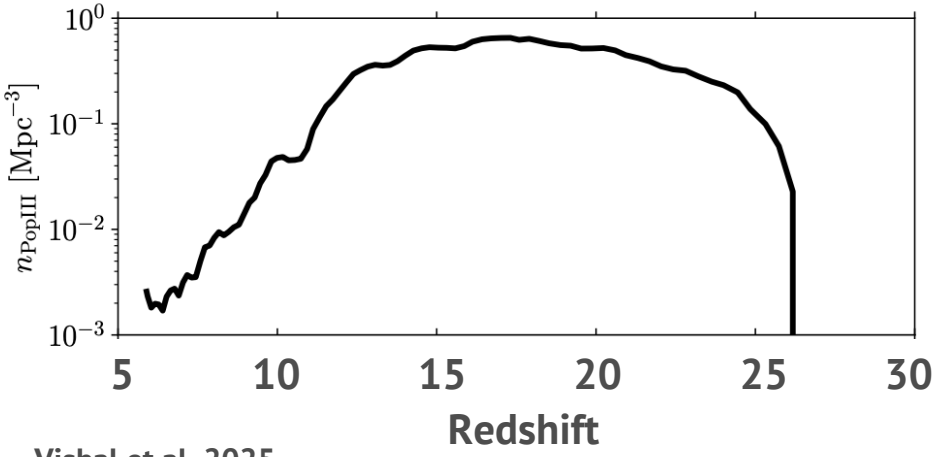
See also: Tumlinson+2000, 2001, Schaerer 2002, Raiter+2010, Inoue 2011, Zackrisson+2011, Nakajima & Maiolino 2022, Rusta+2025

Predicting Observational Signatures of Population III Galaxies: Possibly in Vicinity of Luminous Obj at Moderate-Redshift



Theoretical predictions for Abundance of Pop III sources

+ LW feedbacks
+ External metal-enrichment
+ Reionization feedbacks



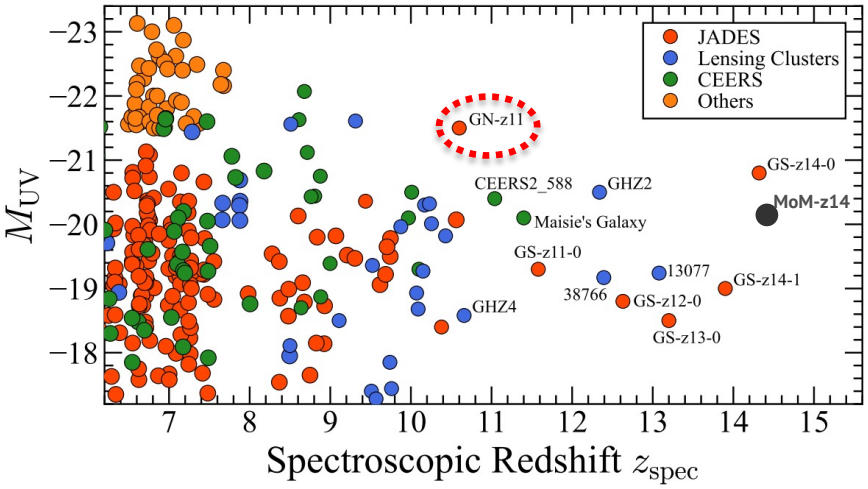
Visbal et al. 2025

We have chances to catch
Pop III star formation in later epochs
(in ~1st Gyr, down to z~6)

See also: e.g. Haiman et al. 1997, Omukai 2001, Bromm & Loeb 2003
O'Shea & Norman 2008, Stiavelli & Trenti 2010,
Chon et al. 2016, Wise et al. 2019, Johnson & Aykutalp 2019

See also: e.g. Skinner & Wise 2020, Liu & Bromm 2020,
Jaacks et al. 2019, Visbal et al. 2020,
Venditti et al. 2023

Recent Progress w/ JWST
Highest-redshift Galaxies so far



Adapted from Harikane et al. 2025

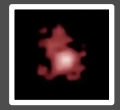
See also: Naidu+25, Carniani+24, Castellano+24, Harikane+24, Curtis-Lake+23, Bunker+23

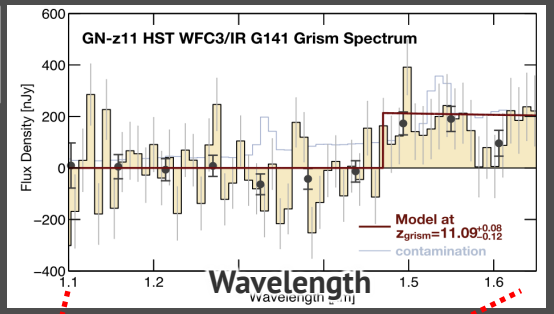
Great improvement of spec. capability over 1-5um w/ JWST

→ High-redshift galaxy confirmations up to z=14.4

GN-z11 @ z=10.6

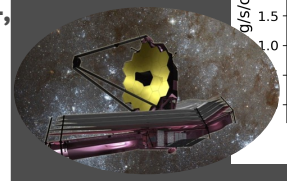
Hubble (1990 -)





Oesch et al. 2016

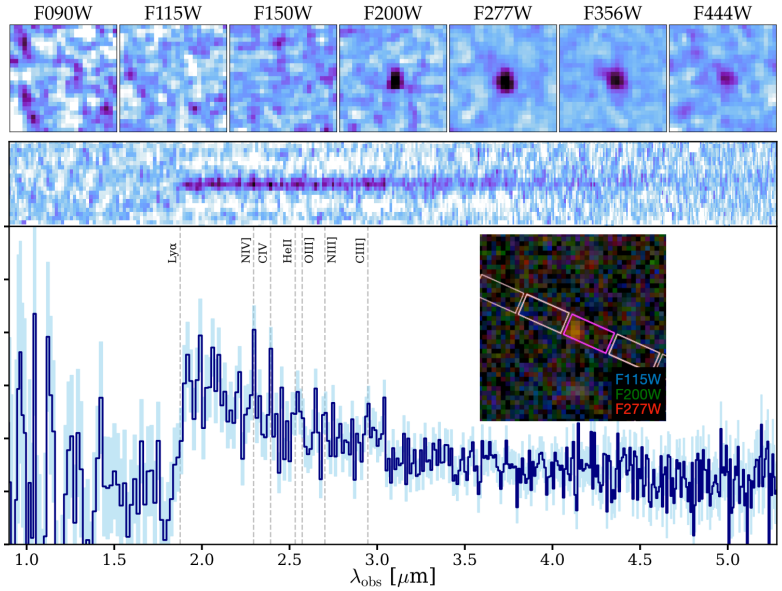
JWST (2022 -)



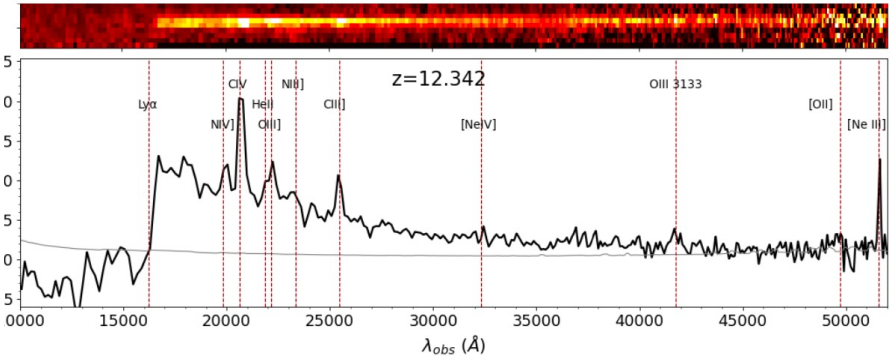
Bunker et al. 2023

Recent Progress w/ JWST
Highest-redshift Galaxies so far: Already Chemically-Enriched

MoM-z14 @ z=14.4 **(Naidu et al. 2025)**

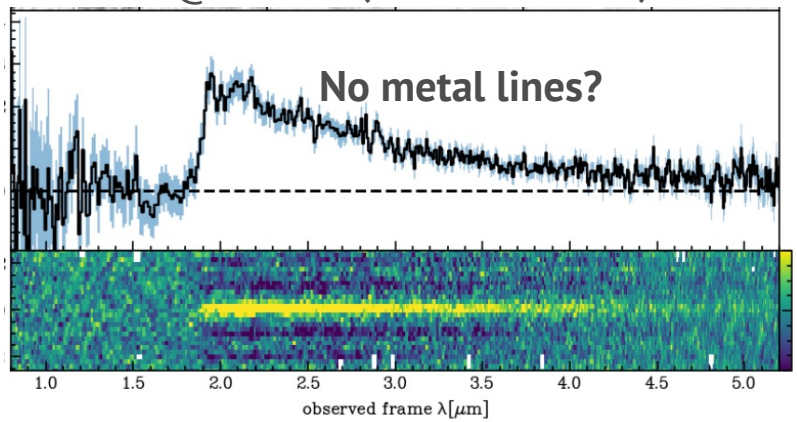


GHZ2 @ z=12.3 **(Castellano et al. 2024, Zavala et al. 2025)**

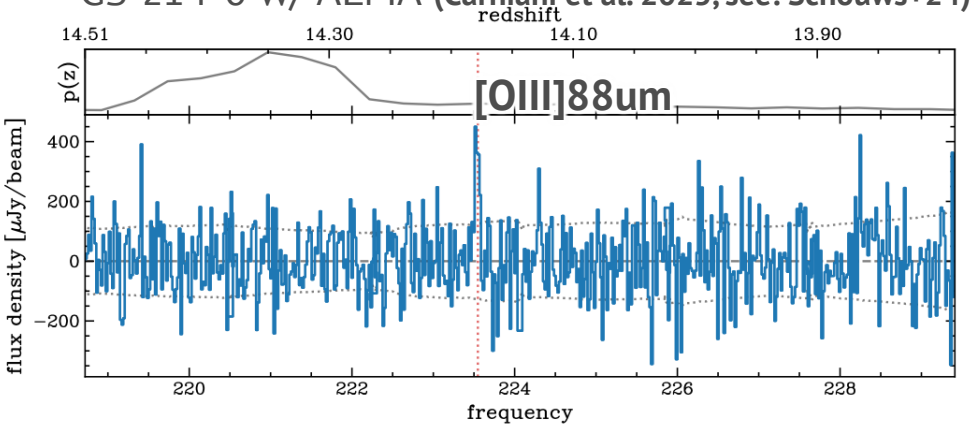


Prominent metal lines
→ Already Enriched ISM

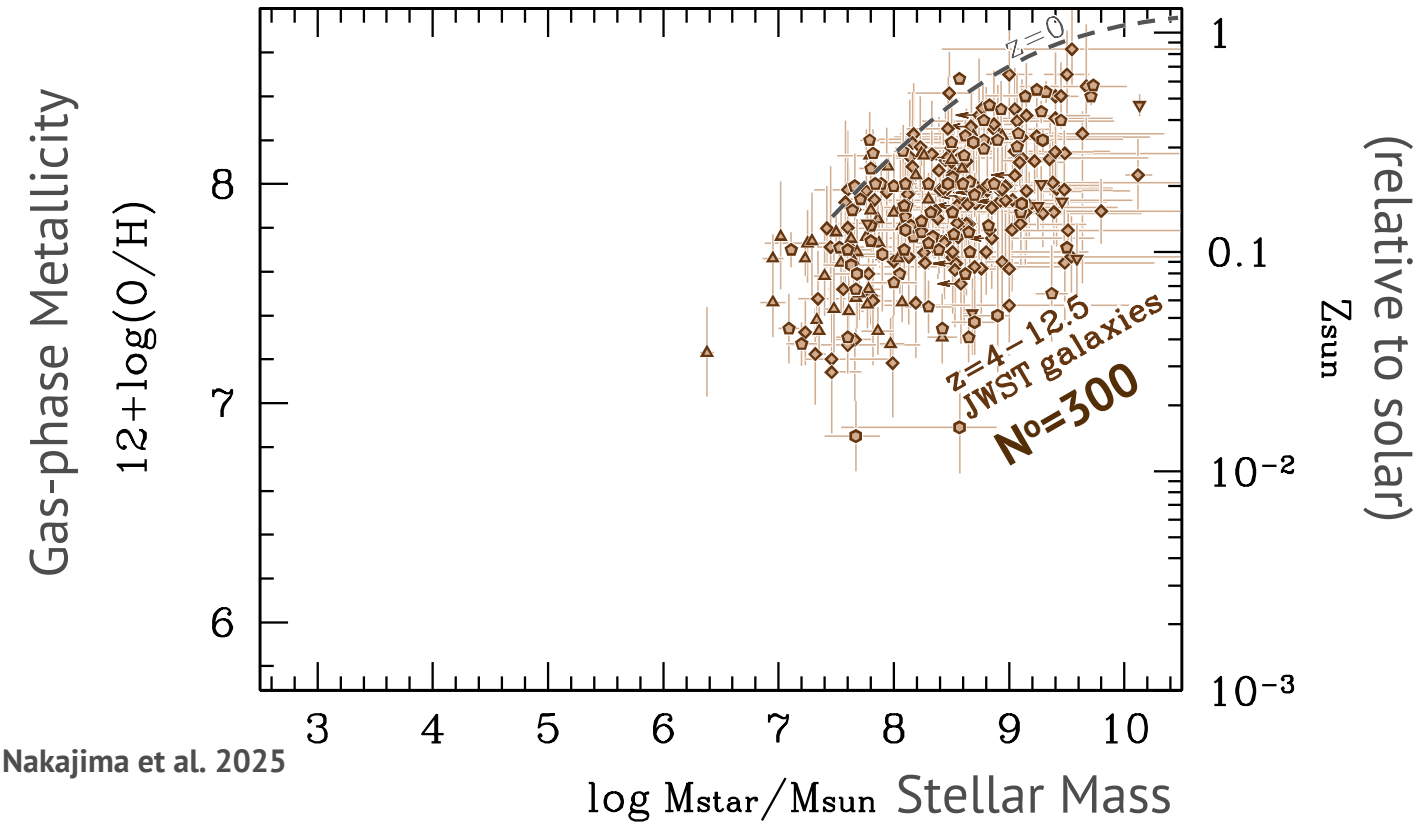
GS-z14-0 @ z=14.2 **(Carniani et al. 2024)**



GS-z14-0 w/ ALMA **(Carniani et al. 2025, see: Schouws+24)**



Recent Progress w/ JWST
Absence of likely Pop III cand in "typical" high-redshift sample



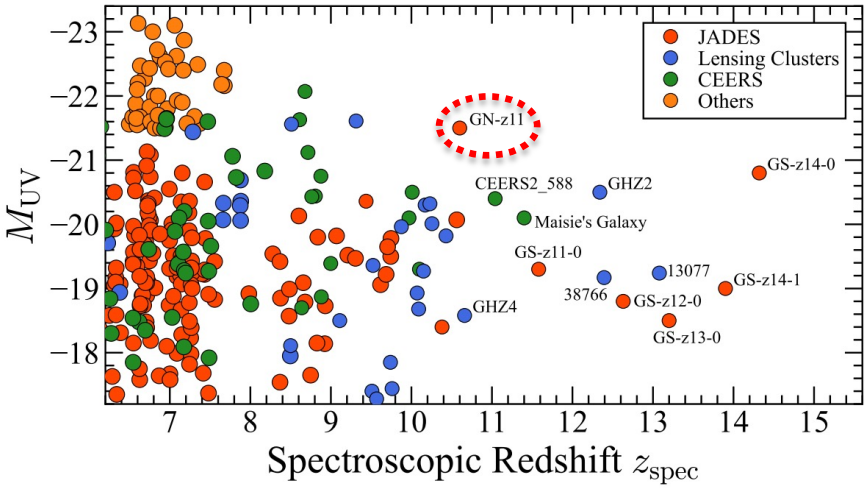
Adapted from Nakajima et al. 2025

No metal-deficient galaxies are found below ~1% Zsun among continuum-selected galaxies at z=4-12.5 down to 10^7 Msun

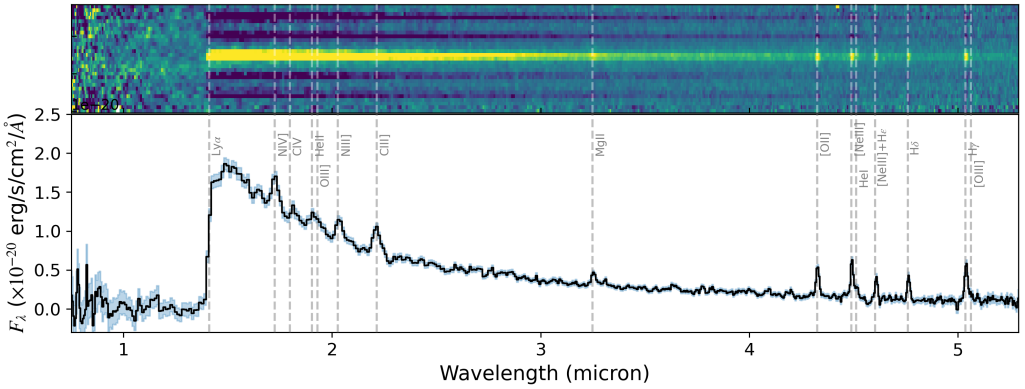
→ Dedicated searches are needed for Pop III

See also: Nakajima+2023, Curti+2024, Morishita+2024, Sarkar+2025

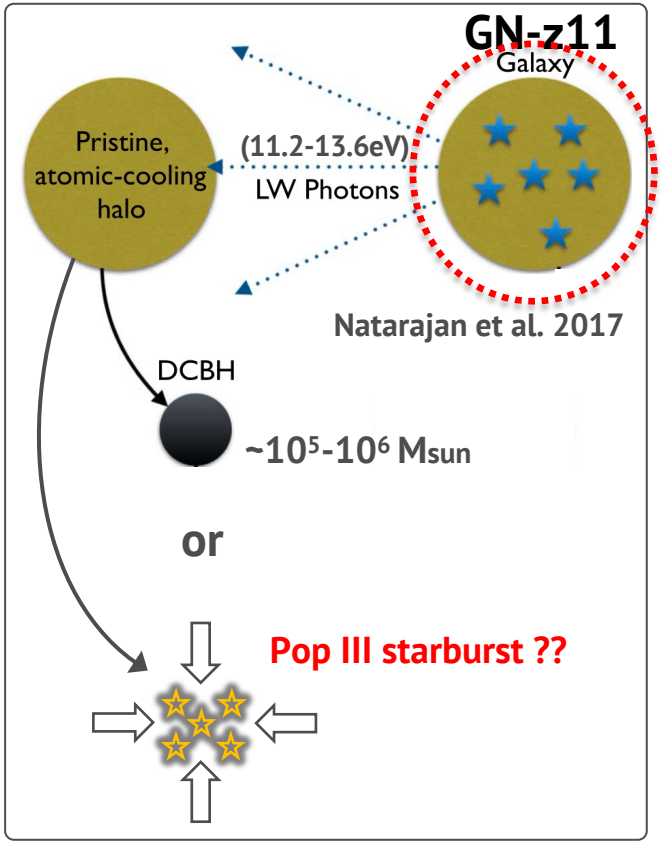
Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11



Harikane et al. 2025

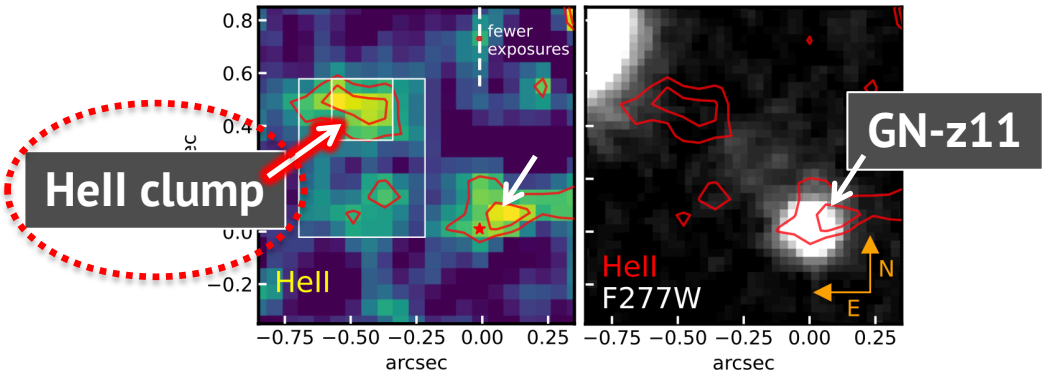


Bunker et al. 2023

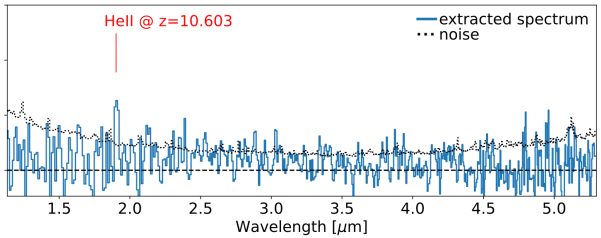


Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11

NIRSpec-IFU uncovers Halo of GN-z11 at z=10.6

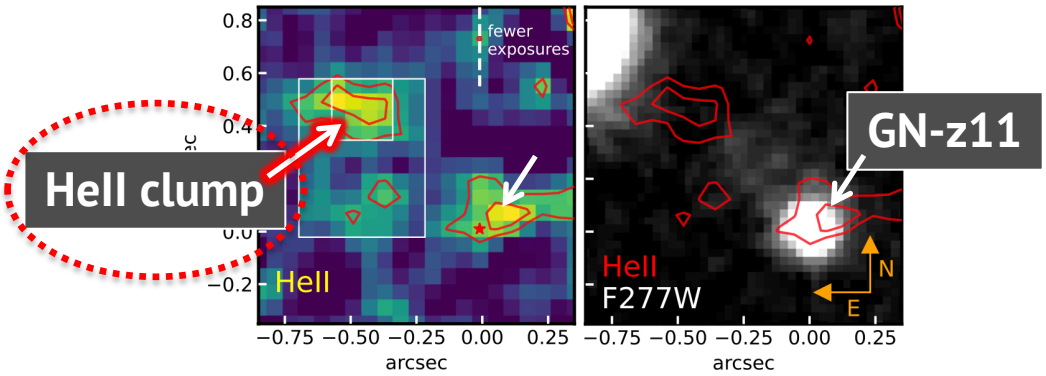


Maiolino, .., Nakajima et al. 2024

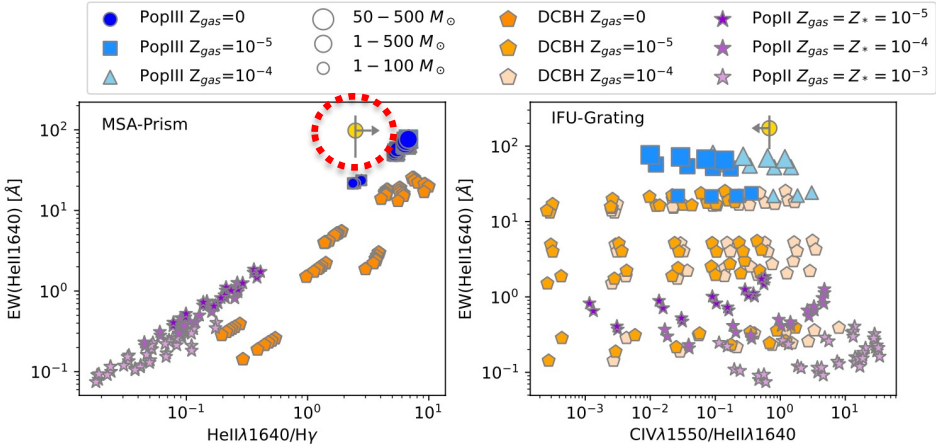


Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11

NIRSpec-IFU uncovers Halo of GN-z11 at z=10.6



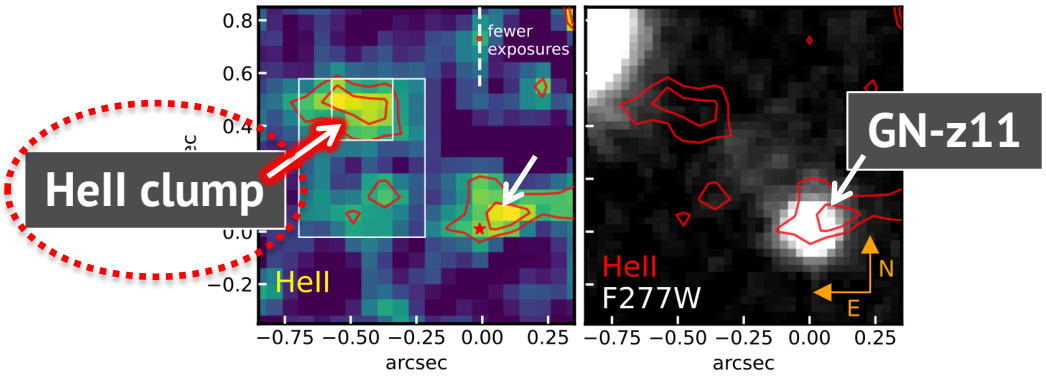
Maiolino, .., Nakajima et al. 2024



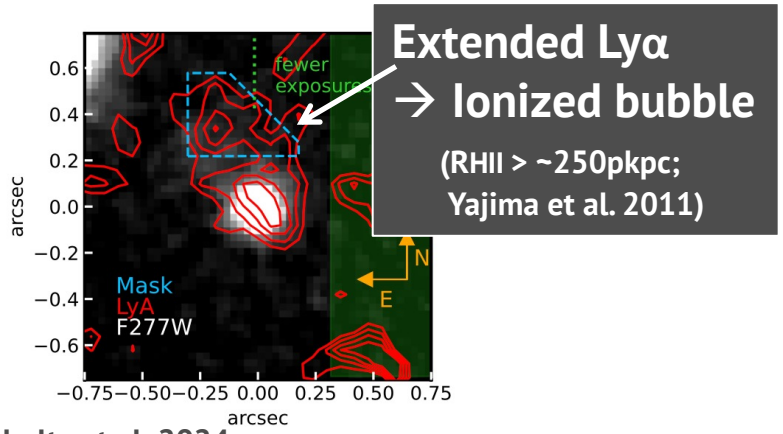
Intense HeII: Reproduced only w/ hosting very massive PopIII stars (>100Msun)
(Nakajima&Maiolino 2022)

Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11

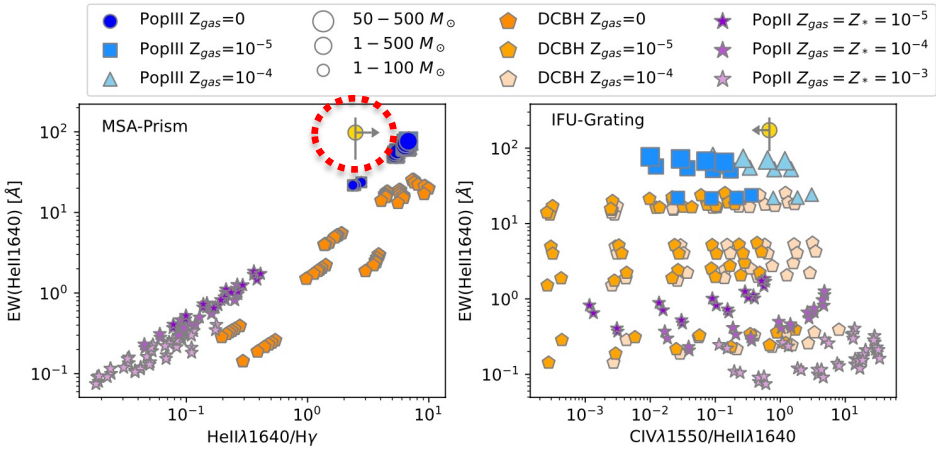
NIRSpec-IFU uncovers Halo of GN-z11 at z=10.6



Maiolino, .., Nakajima et al. 2024



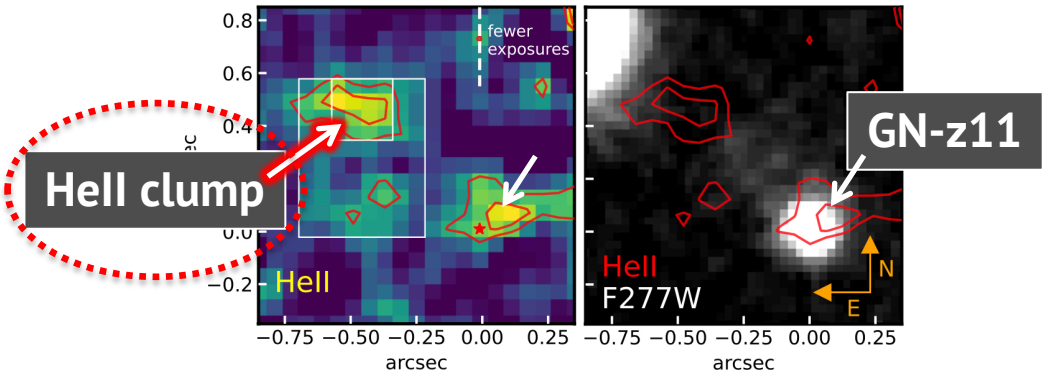
Scholtz et al. 2024



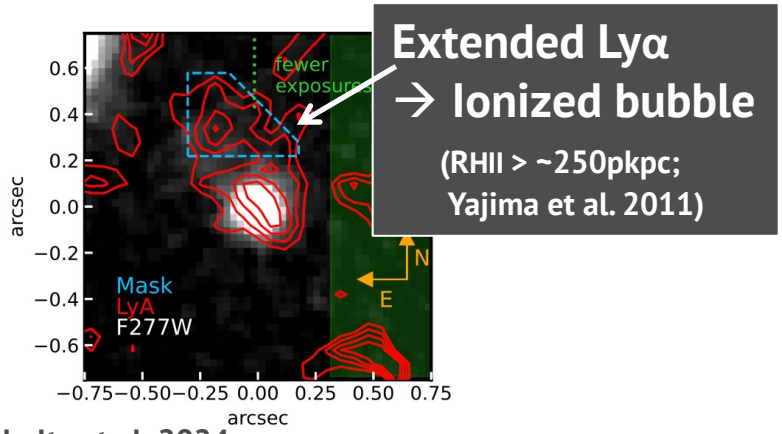
Intense HeII: Reproduced only w/ hosting very massive PopIII stars (>100Msun)
(Nakajima&Maiolino 2022)

Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11

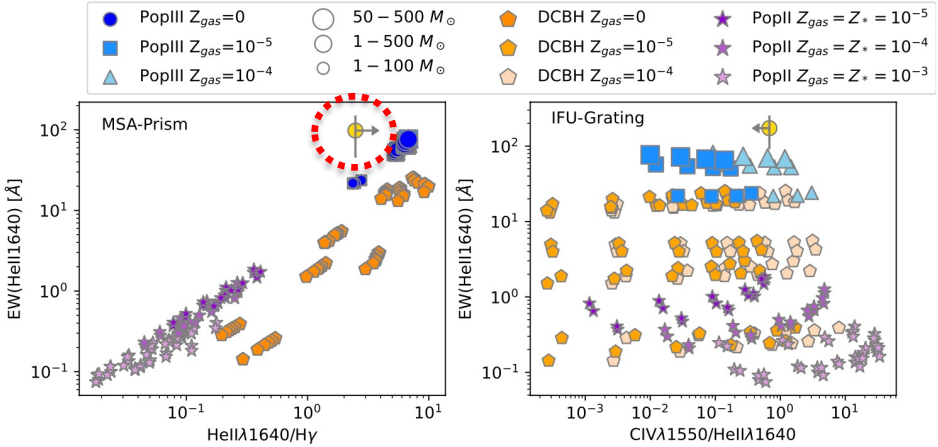
NIRSpec-IFU uncovers Halo of GN-z11 at z=10.6



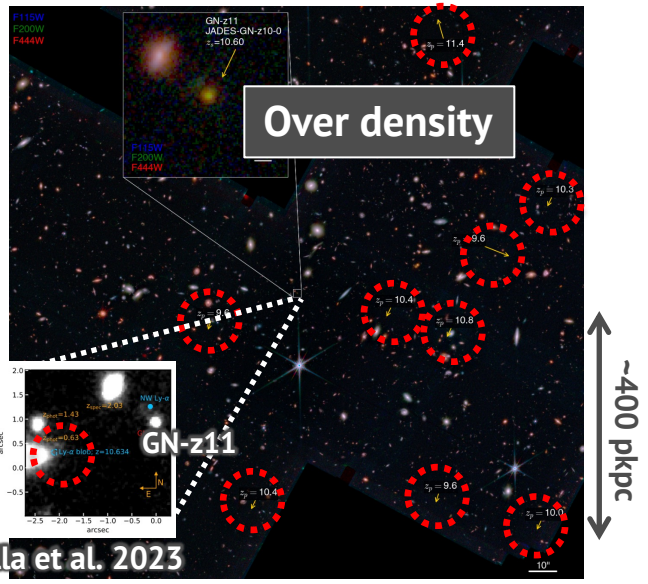
Maiolino, .., Nakajima et al. 2024



Scholtz et al. 2024



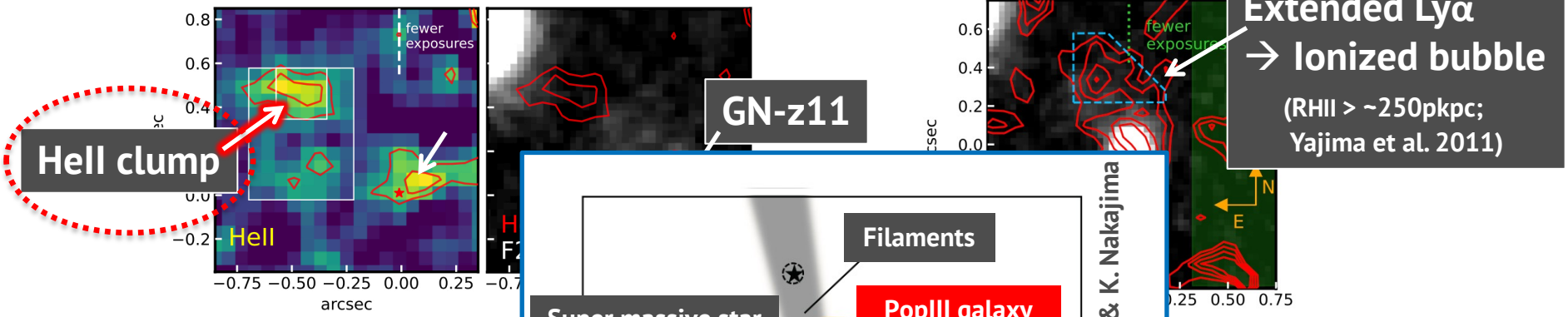
Intense HeII: Reproduced only w/ hosting very massive PopIII stars (>100Msun)
(Nakajima&Maiolino 2022)



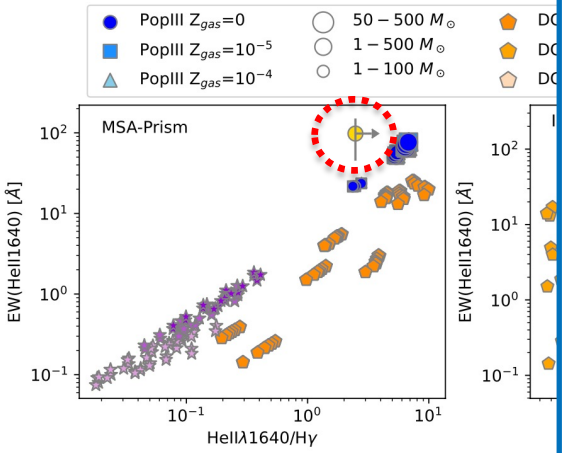
Tacchella et al. 2023

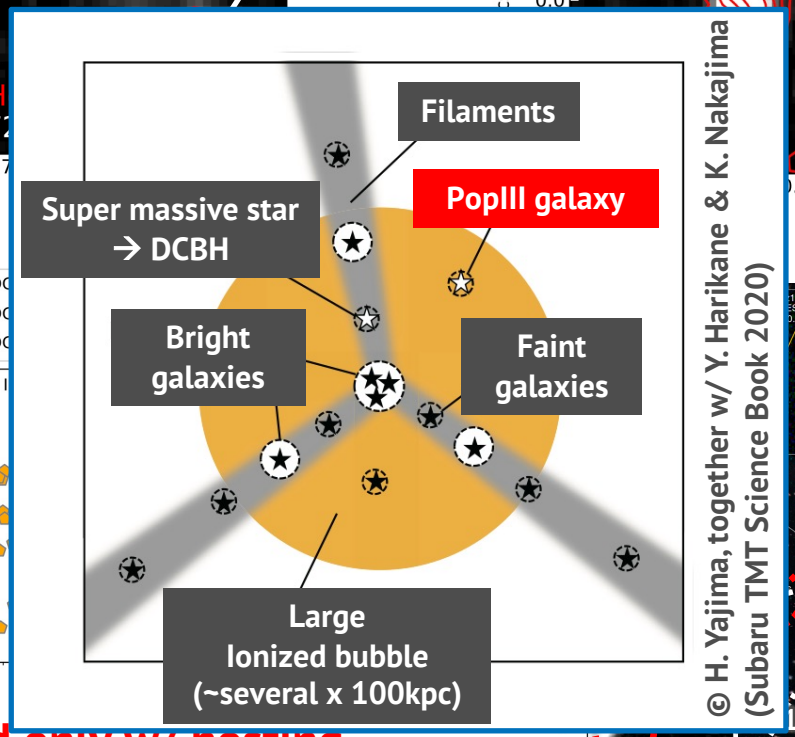
Recent Progress w/ JWST
HeII clump in Vicinity of Luminous GN-z11

NIRSpec-IFU uncovers Halo of GN-z11 at z=10.6



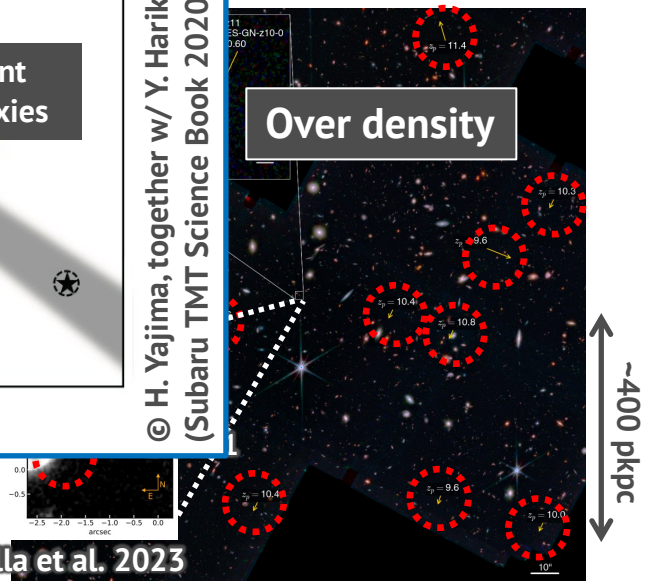
Maiolino, .., Nakajima et al. 2024





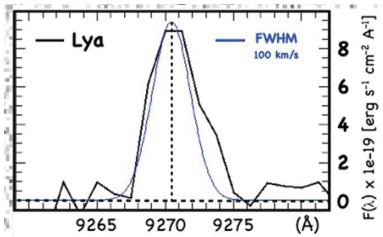
© H. Yajima, together w/ Y. Harikane & K. Nakajima
(Subaru TMT Science Book 2020)

Intense HeII: Reproduced only w/ hosting very massive PopIII stars (>100Msun)
(Nakajima&Maiolino 2022)



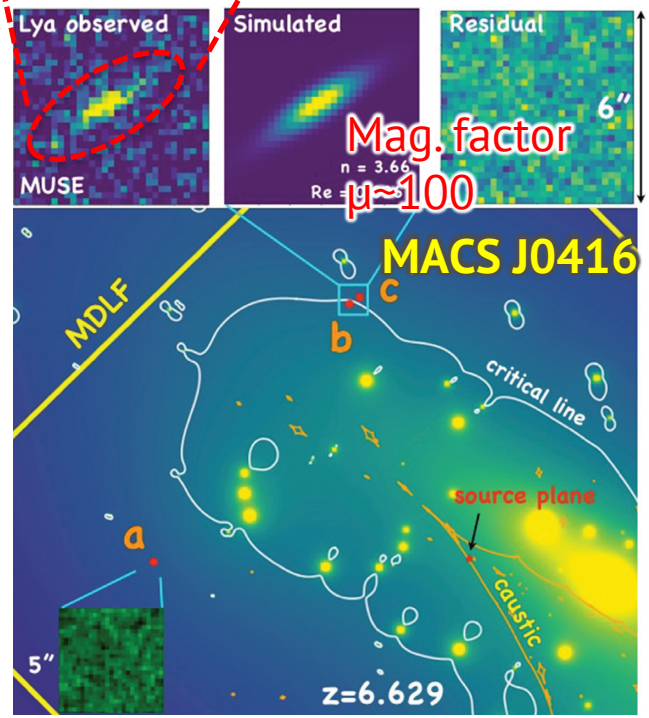
Tacchella et al. 2023

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy



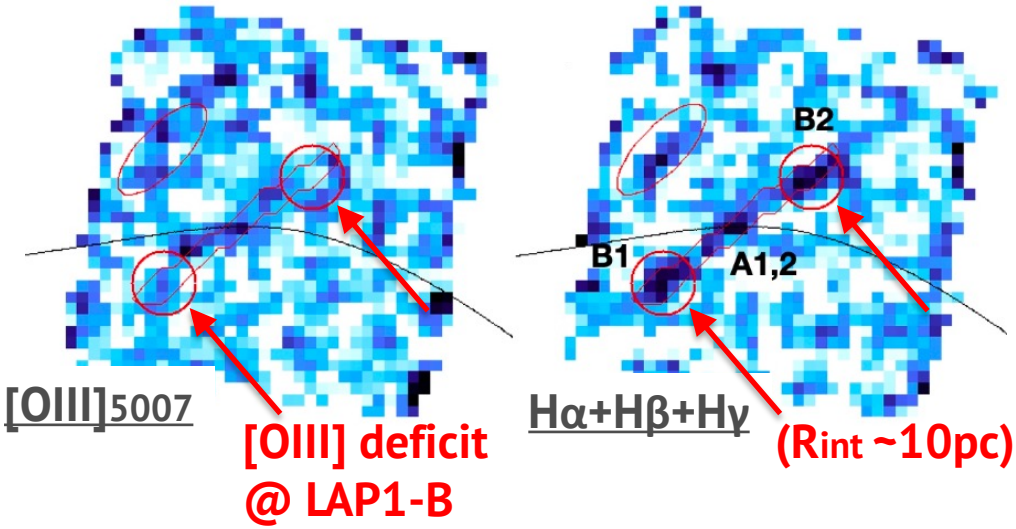
@z=6.6

Discovery of Intense Lyα (EW>1120A) w/ MUSE



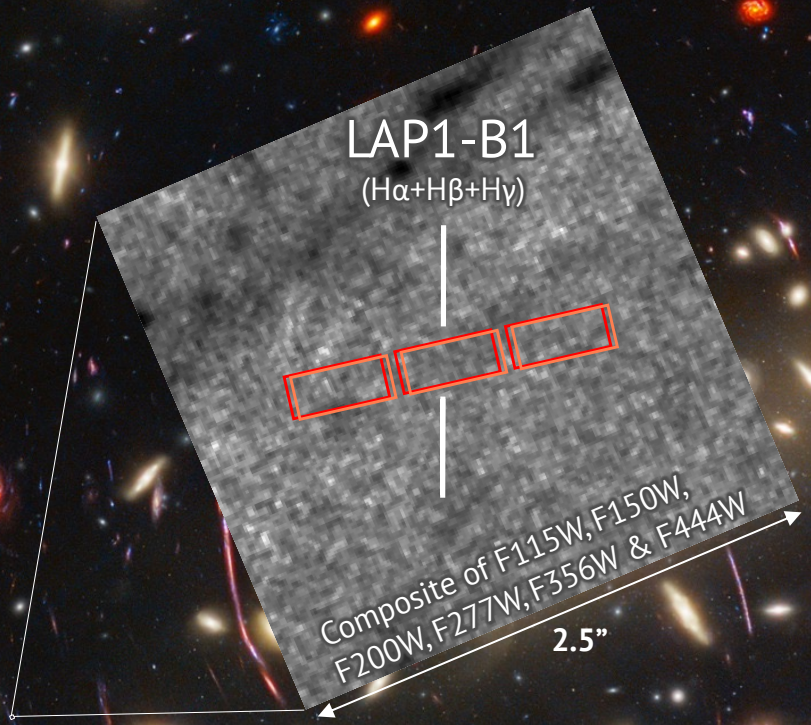
Vanzella et al. 2020

Weak [OIII] suggested by JWST/NIRSpec IFU



Vanzella et al. 2023

Deep JWST/NIRSpec MSA Medium-grating Observations targeting LAP1-B



JWST PID: 4750 (Cycle 3 GO) a.k.a.
DREAMS
- Deep Reconnaissance of Early Assemblies with Metal-poor Star formation

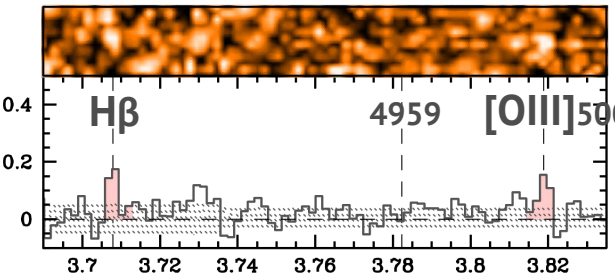
PI: K. Nakajima

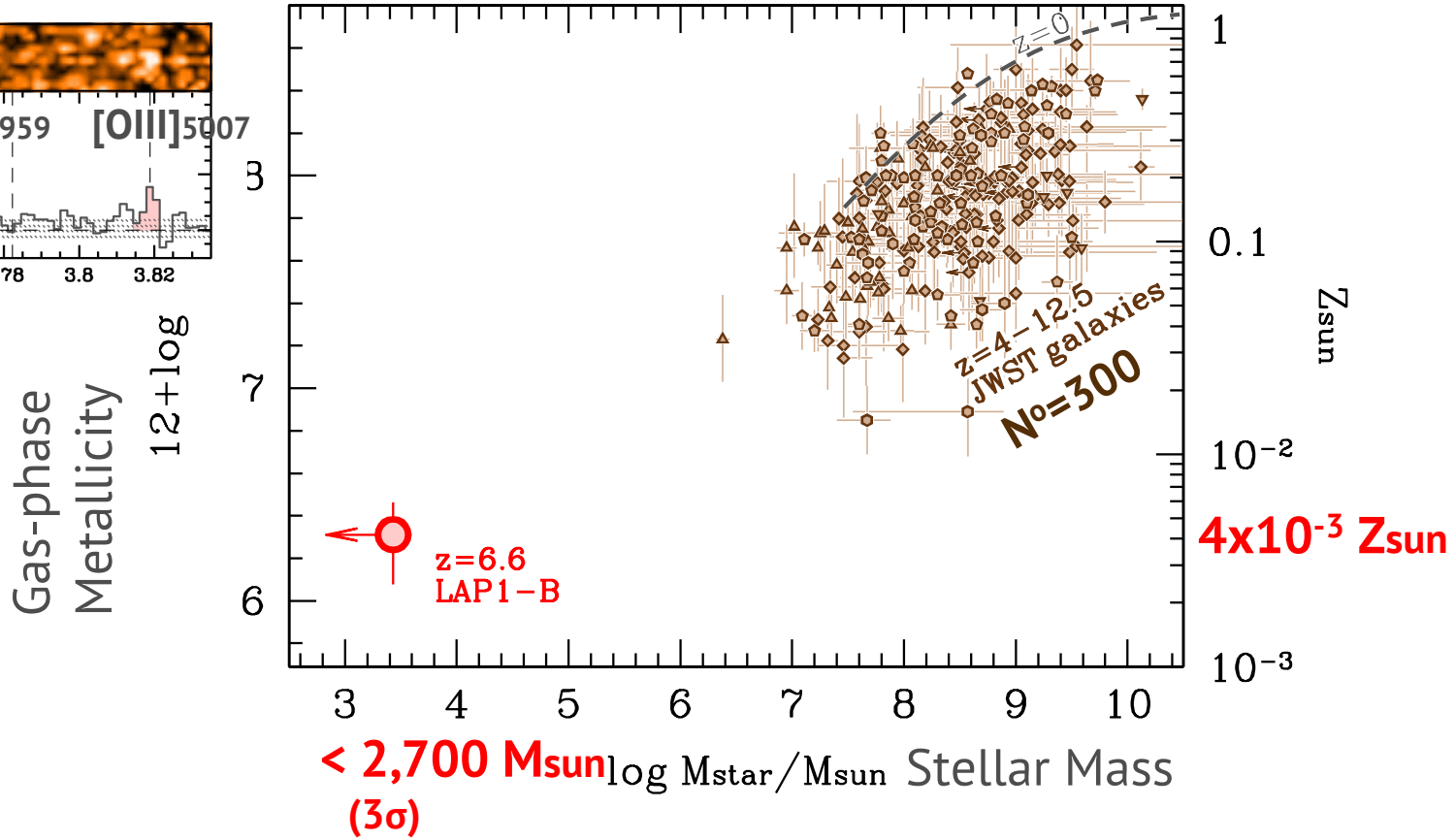
Allocated Time: 63 hours

ExpTime for LAP1-B:
- 16.4 hr (G140M; 0.8-1.8um)
- 16.4 hr (G395M; 2.9-5.2um)

Nakajima et al. 2025

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy





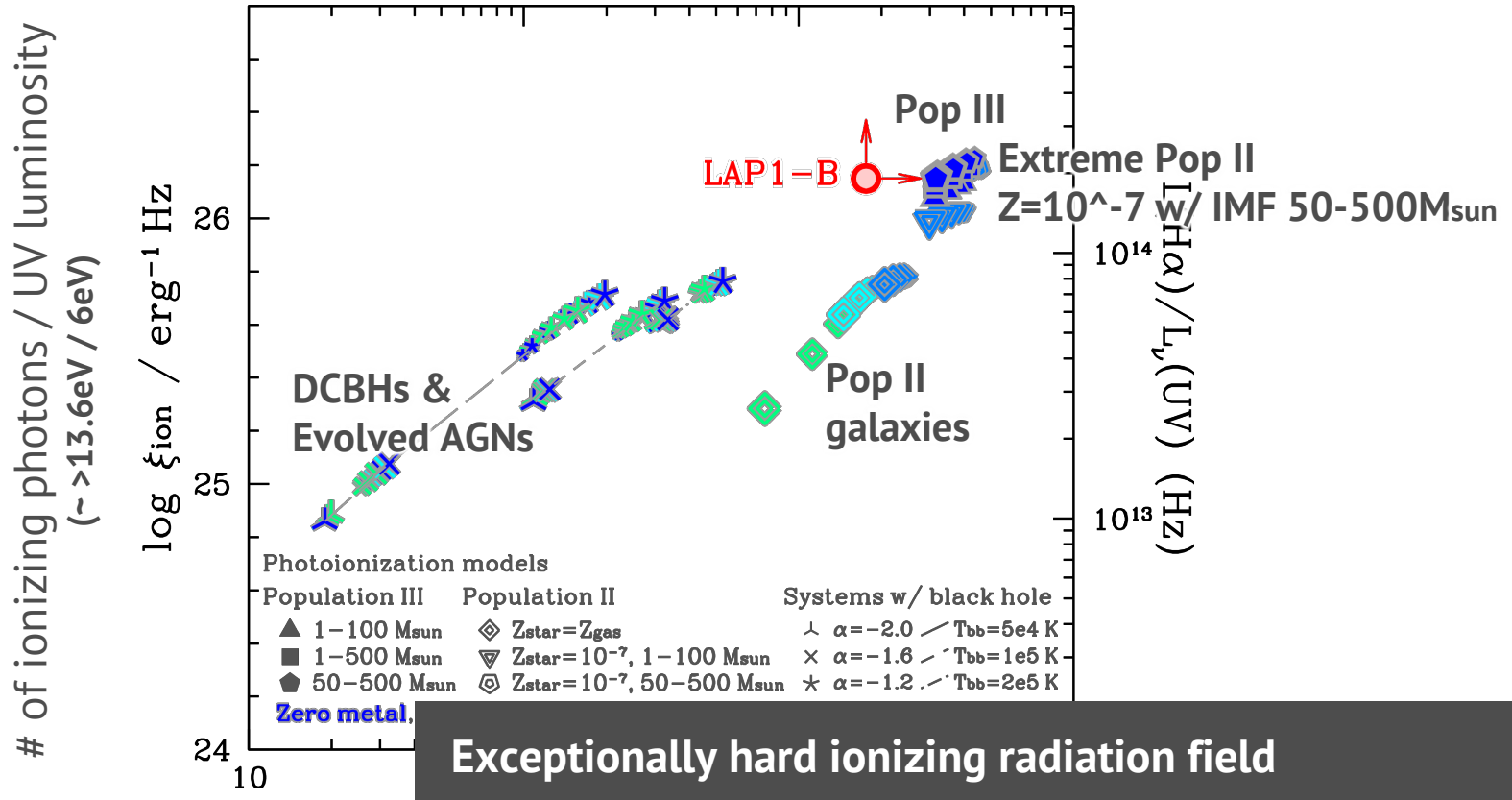
Nakajima et al. 2025

Extremely low metallicity is revealed by deep NIRSpec-MSA observations
→ Nascent, chemically-primitive galaxy
What kind of stars are currently shining?

See also: Vanzella+2023

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy

Ionizing Photon Production Efficiency



Exceptionally hard ionizing radiation field

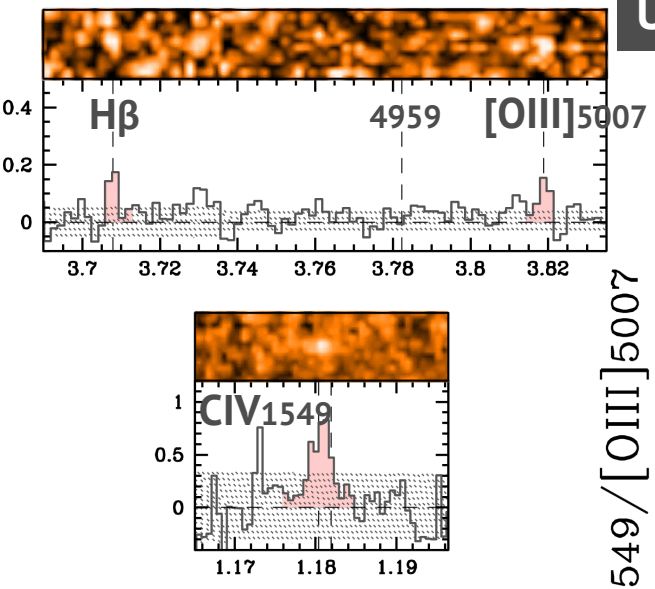
✓ Inconsistent w/ standard Pop II or accreting blackholes

✓ Consistent w/ exceptionally metal-deficient stellar pop

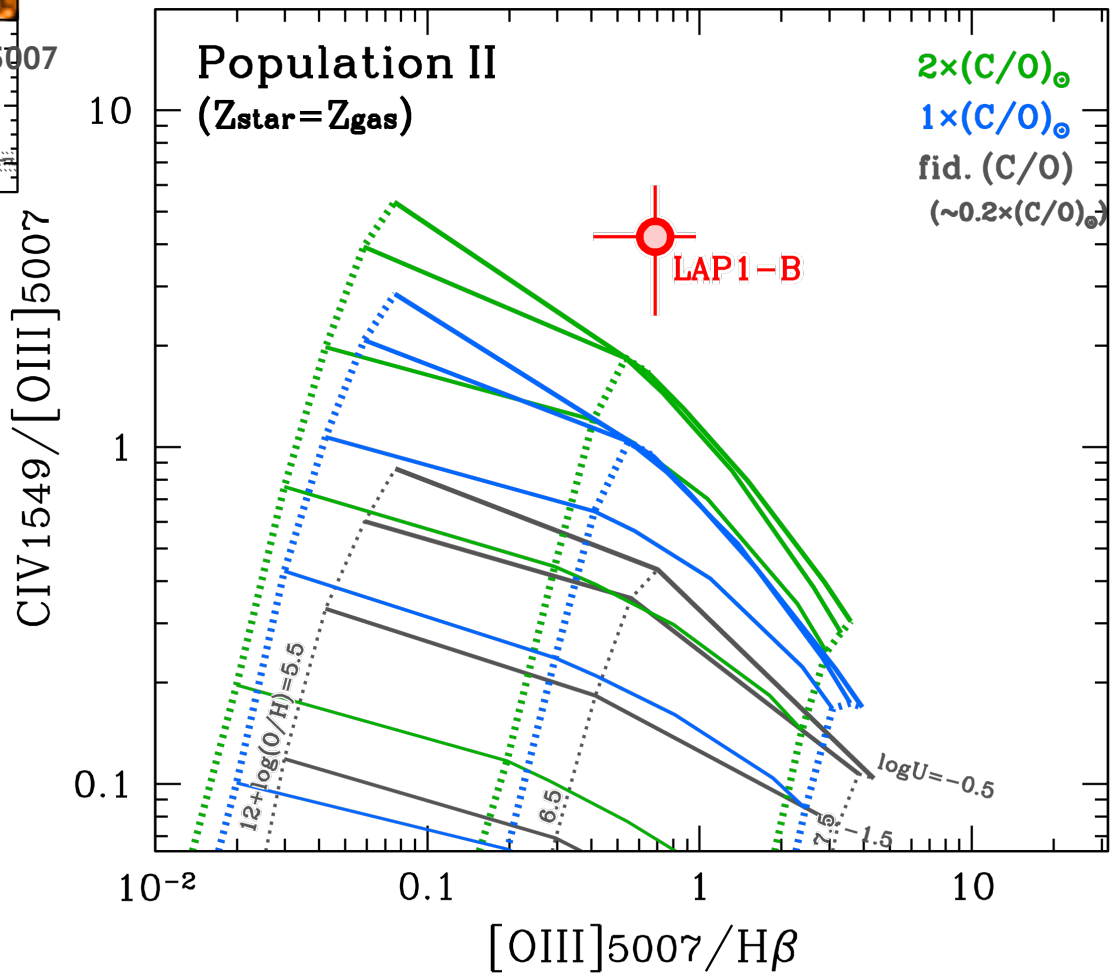
Nakajima et al. 2025

Photoionization models from Nakajima & Maiolino 2022

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy



UV emission line Diagnostics

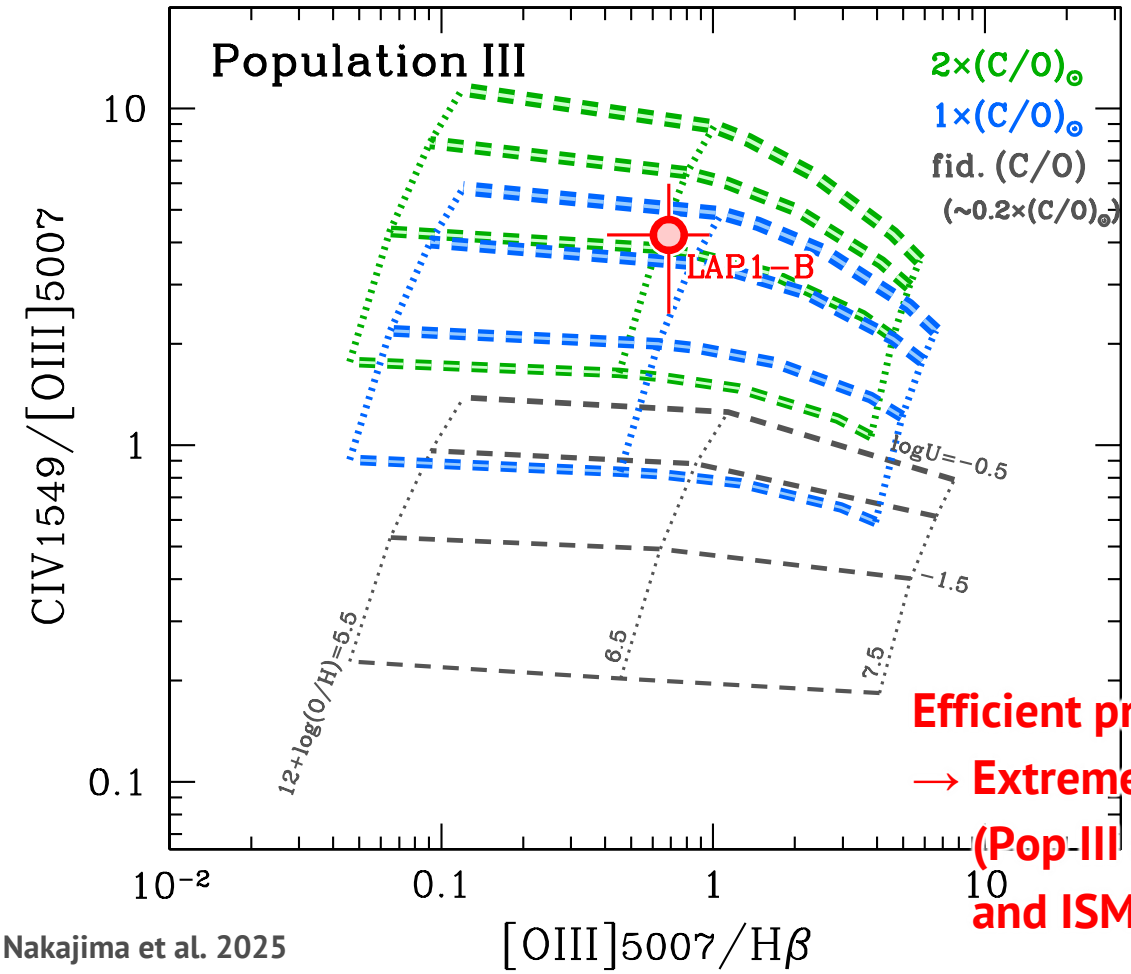


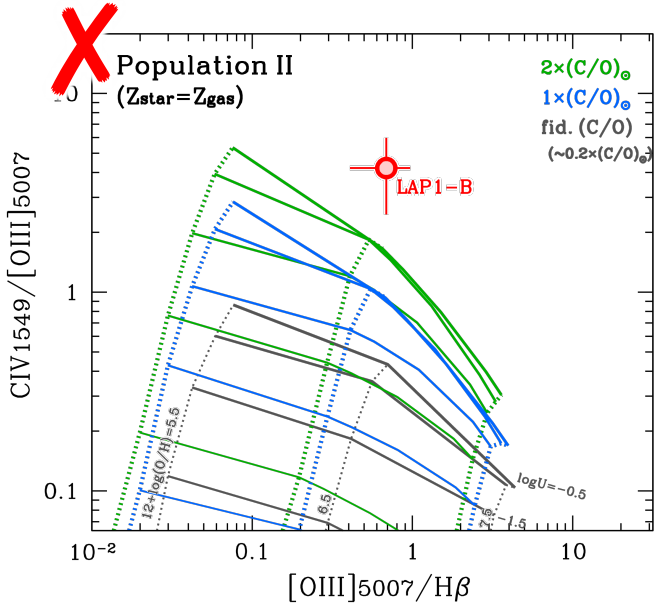
Nakajima et al. 2025

Photoionization models from Nakajima & Maiolino 2022

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy

UV emission line Diagnostics



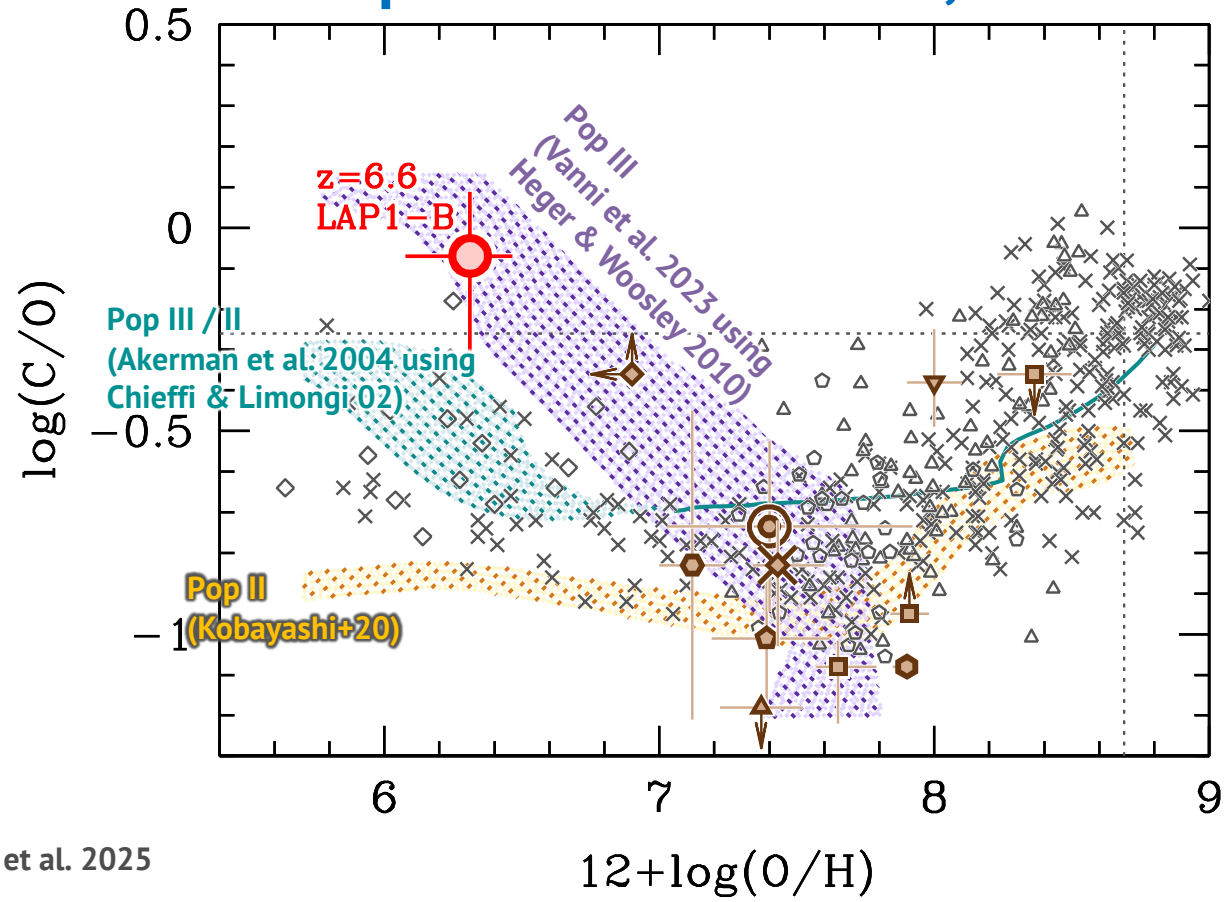


Efficient production of photons (>~50eV)
→ Extremely metal-deficient ionizing sources
(Pop-III or massive Pop II w/ no depletion)
and ISM metals coexist ?

Nakajima et al. 2025

Photoionization models from Nakajima & Maiolino 2022

Recent Progress w/ JWST
LAP1-B: Hard Spec. & Ext. Low- M⋆, Low-Metallicity Galaxy



z=5.6-12.5 JWST galaxies
z=1.5-3.5 galaxies
z=0 galaxies / HII regions
Galactic stars
DLAs

See also: D'Eugenio et al 2024

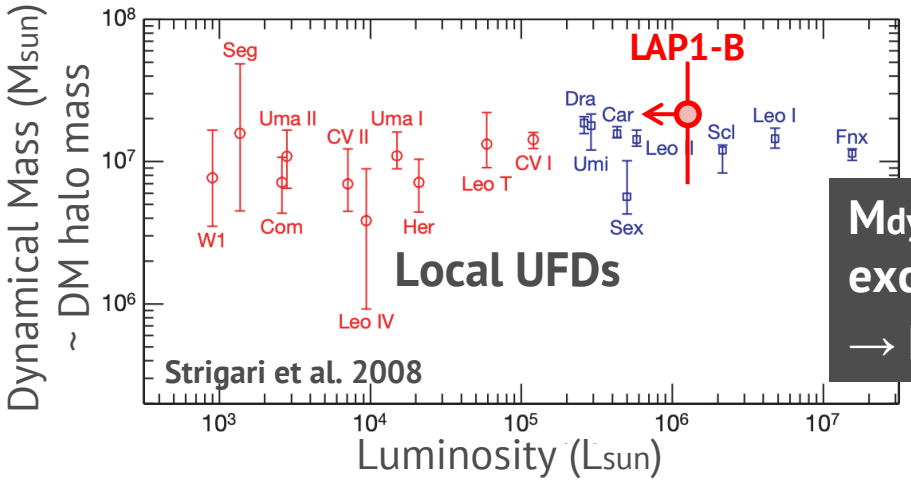
Nakajima et al. 2025

Elevated C/O at low metallicity

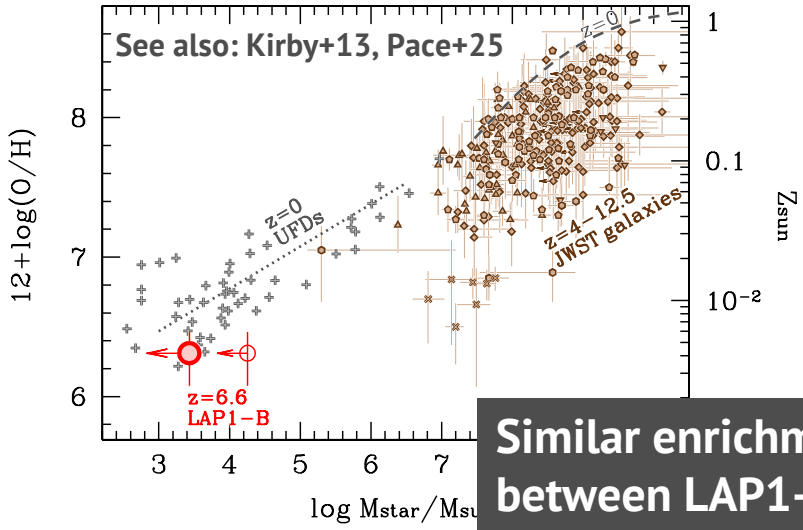
Consistent w/ nucleosynthetic yields expected from Pop III stars (failed SNe?)

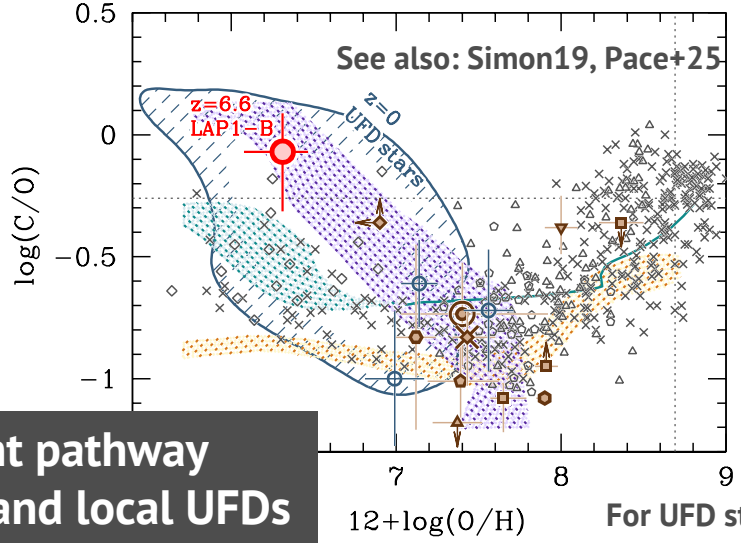
→ Immediate aftermath of 1st enrichment from Pop III stars, with ionizing flux dominated by co-eval (subsequent) gen. of metal-deficient stars

Recent Progress w/ JWST
LAP1-B: Formative Phase of Ultra-Faint Dwarf at EoR?



M_{dyn} derived from emission line kinematics exceeds $M_\star$ (<2,700 Msun) and M_{gas} (~10^5 Msun)
→ Embedded within Dominant Dark Matter Halo





Similar enrichment pathway between LAP1-B and local UFDs

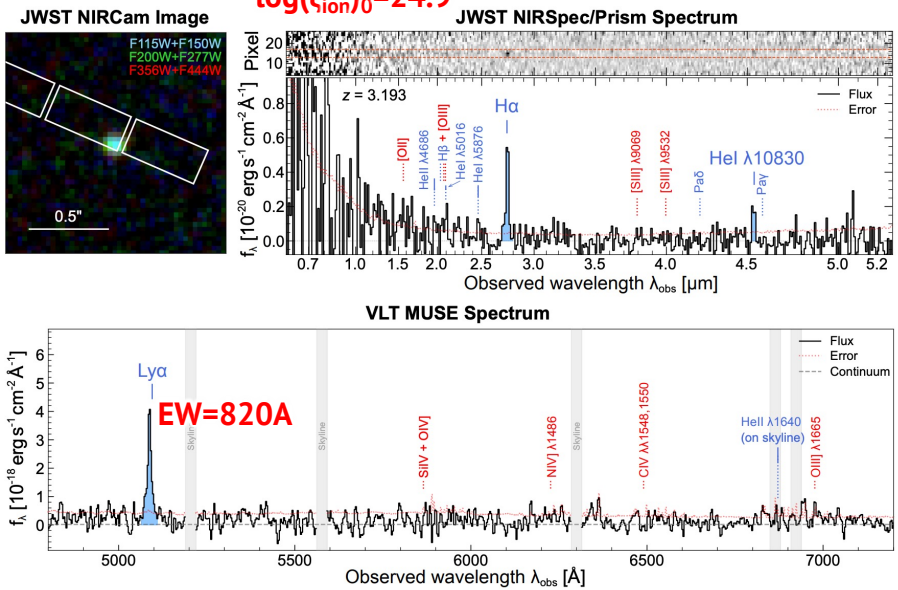
Nakajima et al. 2025

For UFD stars, [O/Fe]=+0.5 assumed

Recent Progress w/ JWST
Metal-deficient galaxies at lower-redshifts: Late Pop III SF?

CR3 @ z=3.2 Gas Metallicity <0.7% Z_{sun}

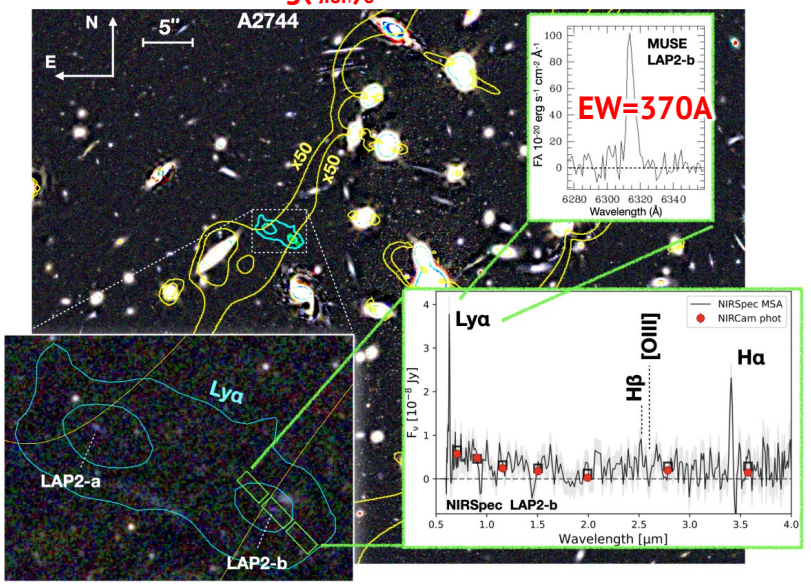
$\log(\xi_{ion})_0$=24.9



Cai et al. 2025

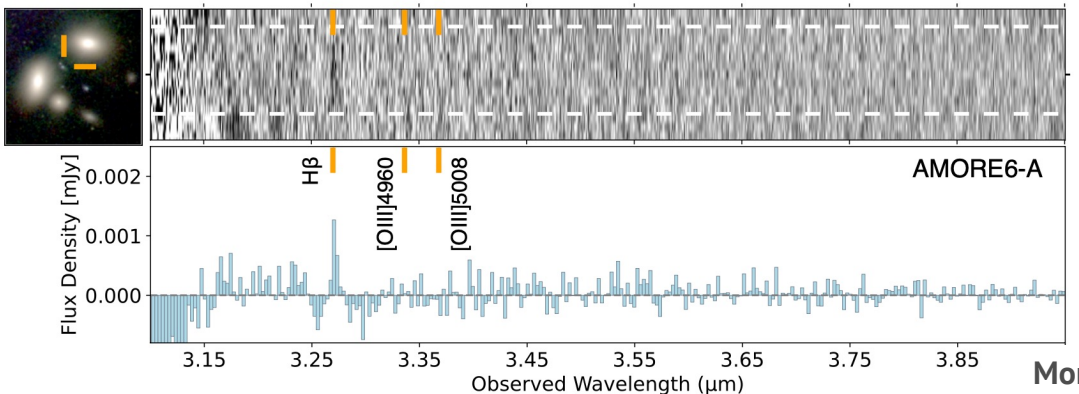
LAP2 @ z=4.2 Gas Metallicity < 0.6% Z_{sun}

$\log(\xi_{ion})_0$=25.1



Vanzella et al. 2025

AMORE6 @ z=5.7 Gas Metallicity < 0.12% Z_{sun} (2σ)

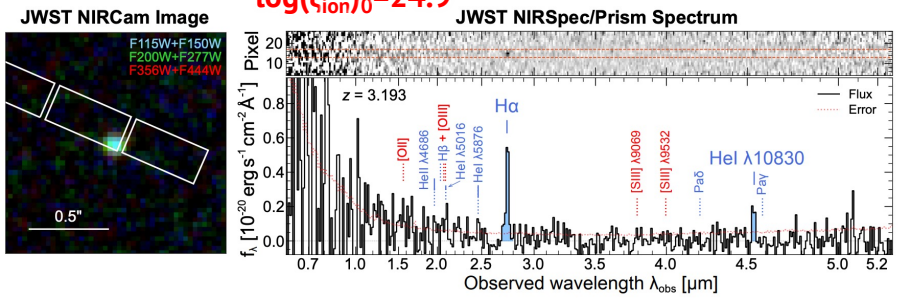


Morishita et al. 2025

Recent Progress w/ JWST
Metal-deficient galaxies at lower-redshifts: Late Pop III SF?

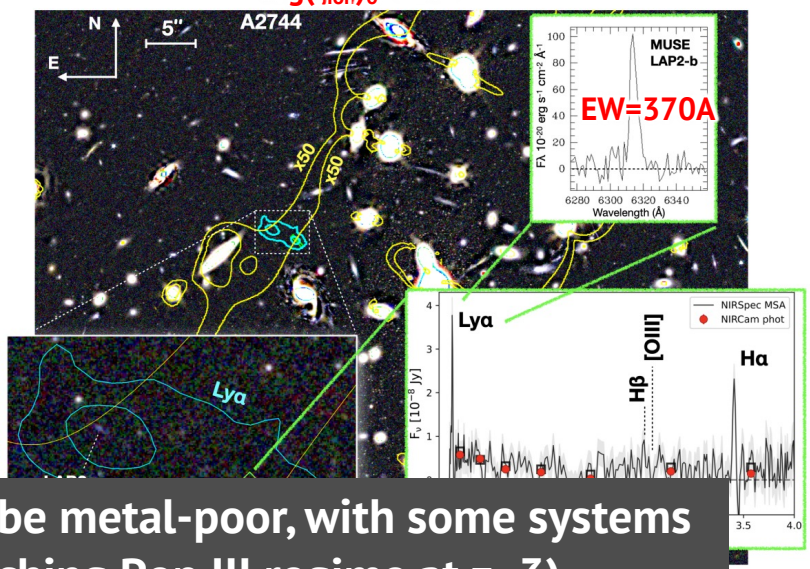
CR3 @ z=3.2 Gas Metallicity <0.7% Z_{sun}

$\log(\xi_{ion})_0$=24.9



LAP2 @ z=4.2 Gas Metallicity < 0.6% Z_{sun}

$\log(\xi_{ion})_0$=25.1

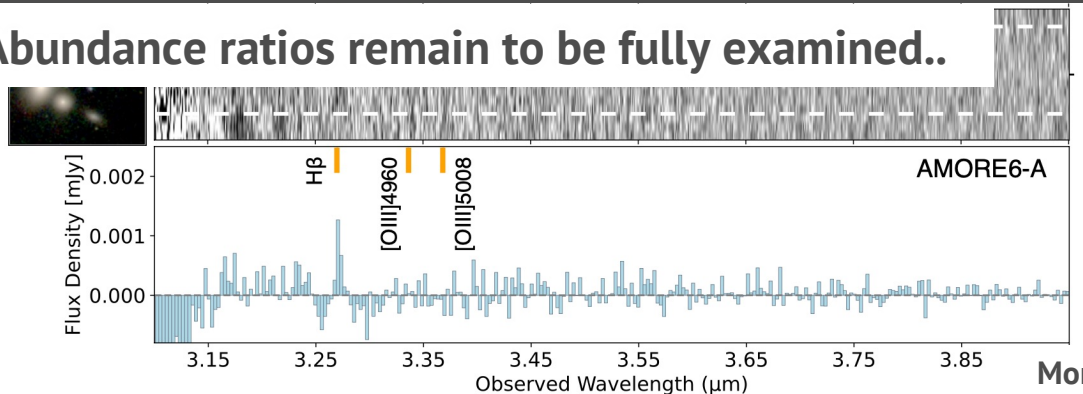


Cai et a 025

Intense Lyα emitting sources are confirmed to be metal-poor, with some systems exhibiting extremely low metallicities (approaching Pop III regime at z~3)

→ Theoretical challenge against current models of late-time Pop III SF?

* Hardness / Abundance ratios remain to be fully examined..

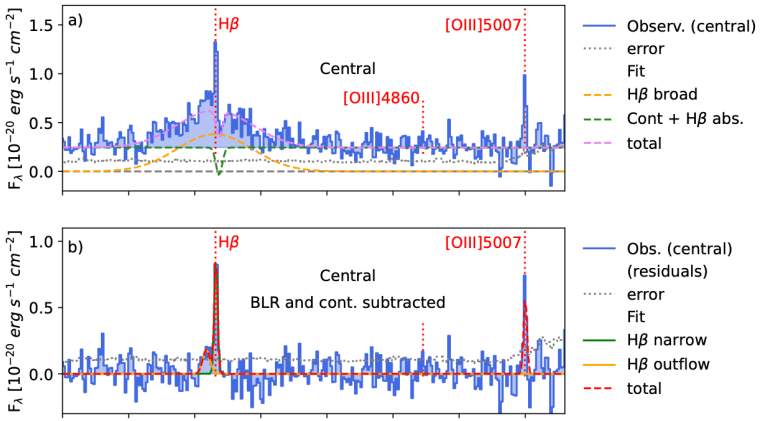


Morishita et al. 2025

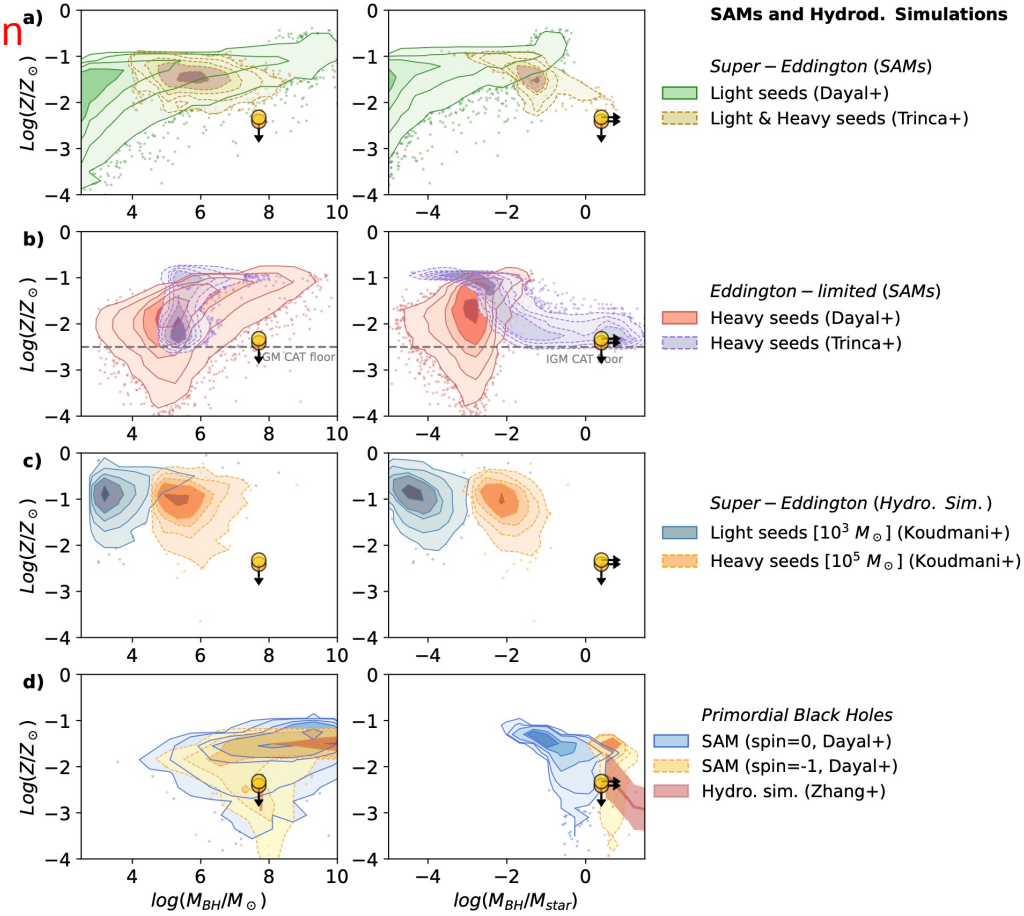
Recent Progress w/ JWST
Metal-deficient Black hole (Little Red Dot): Too massive?

Abell2744-QSO1 @ z=7.0 Gas Metallicity = 0.47% Z_{sun}

Selected as Little Red Dot BH Mass = 5×10^7 Msun



Maiolino et al. 2025



Challenging for most current models to reproduce Ext. Low Metallicity for such Massive Blackhole

See also: Furtak+23,24, Juodzbalis+25

Summary

Great spectroscopic capability at 1-5um w/ JWST

High-redshift galaxy confirmations **up to z=14.4**

→ **Absence of likely Pop III cand** in "typical" high-redshift sample

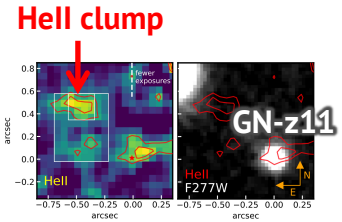
Recent JWST observations approaching Pop III galaxies

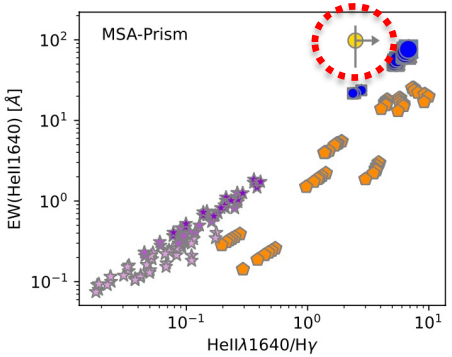
Proximity Searches: Near luminous, (moderate-) high-redshift obj

Vicinity of GN-z11

(Maiolino+2024

see also: Visbal+2020, 2025)



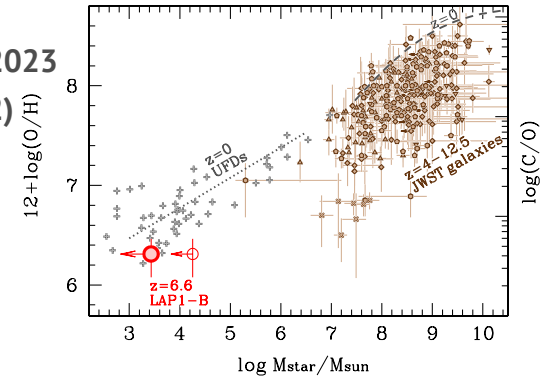


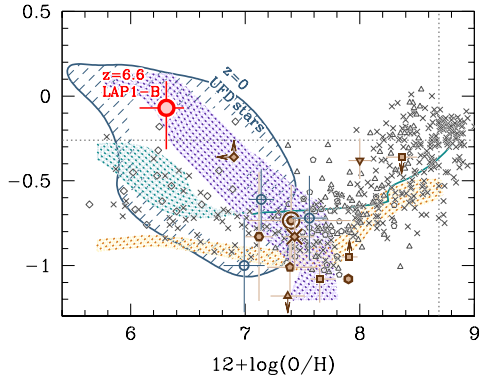
Spectral Signatures: Intense H-line emitters (w/ weak/no metal lines)

LAP1-B

(Nakajima+2025, Vanzella+2023

cf. Nakajma&Maiolino 2022)





→ **Pop III star (blackhole) formation**

Chemical enrichment by Pop III

Link to local relics