Deepest views of the early galaxy

Primordial Rotating Disk Composed of ≥15 Dense Star-Forming Clumps at Cosmic Dawn

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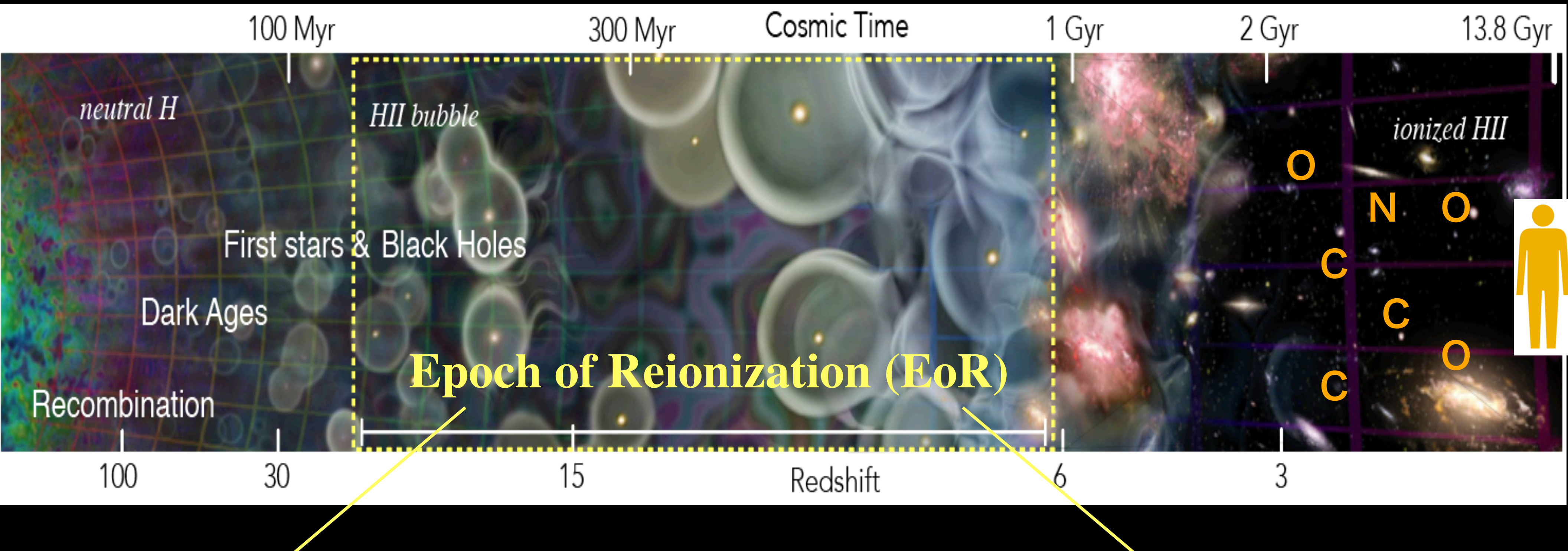
(UT Austin)
↓
U. Toronto
from July 2025

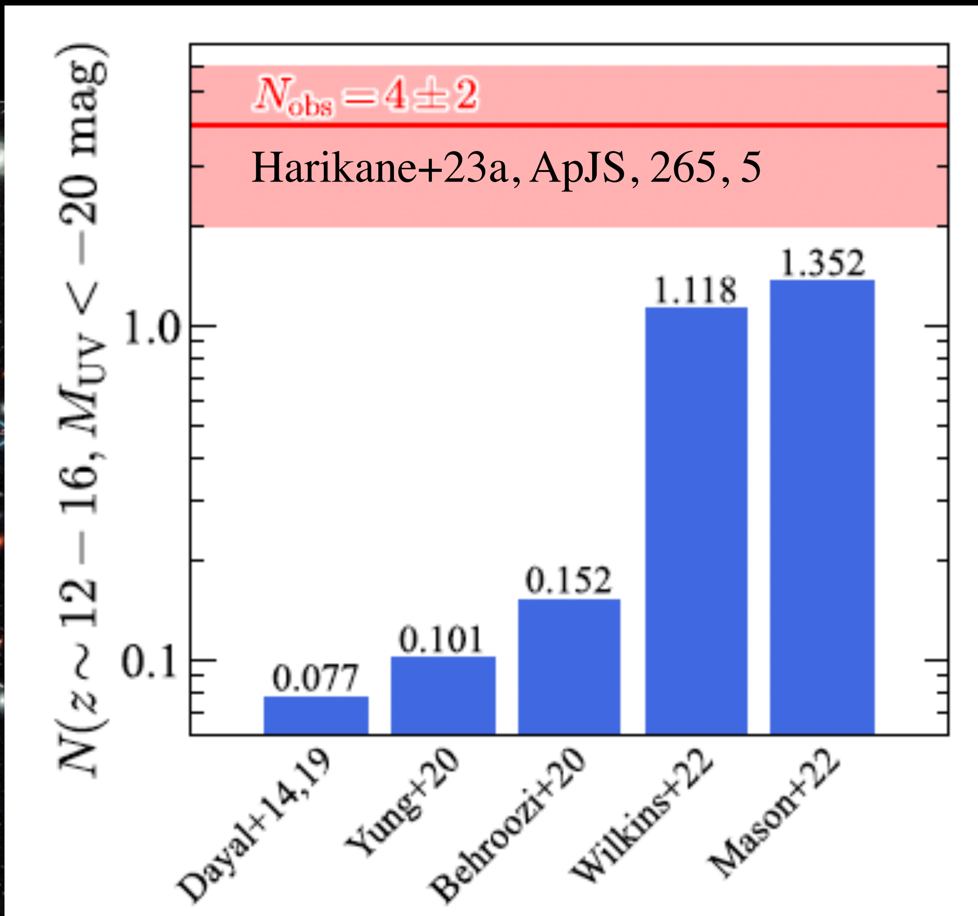
Why High Redshift?



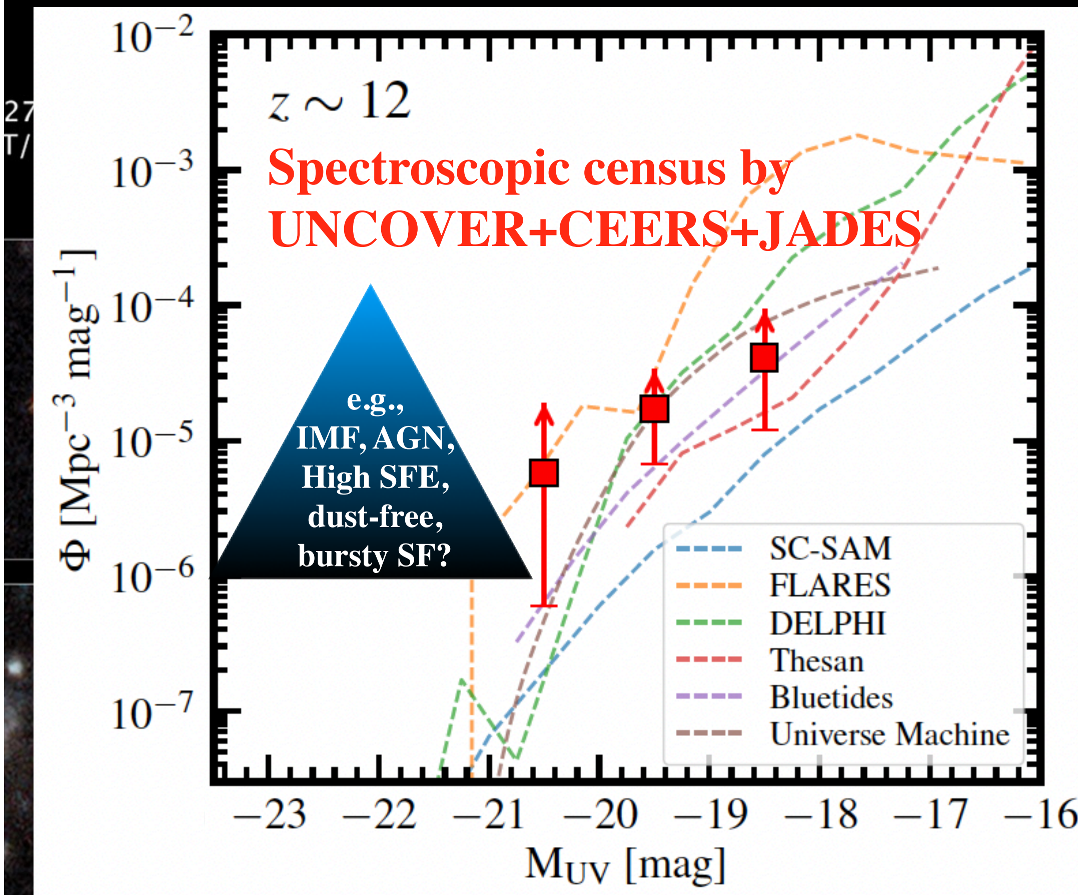
- Development of large scale structure
- Process of cosmic reionization (bright vs. sum of faint objects?)
- Emergence of first galaxies and blackholes

Early galaxies at EoR are tightly involved with fundamental cosmological questions

JWST Exploration of Highest-z Universe



Fujimoto, UNCOVER+23 (see also e.g., Harikane+23, 24)

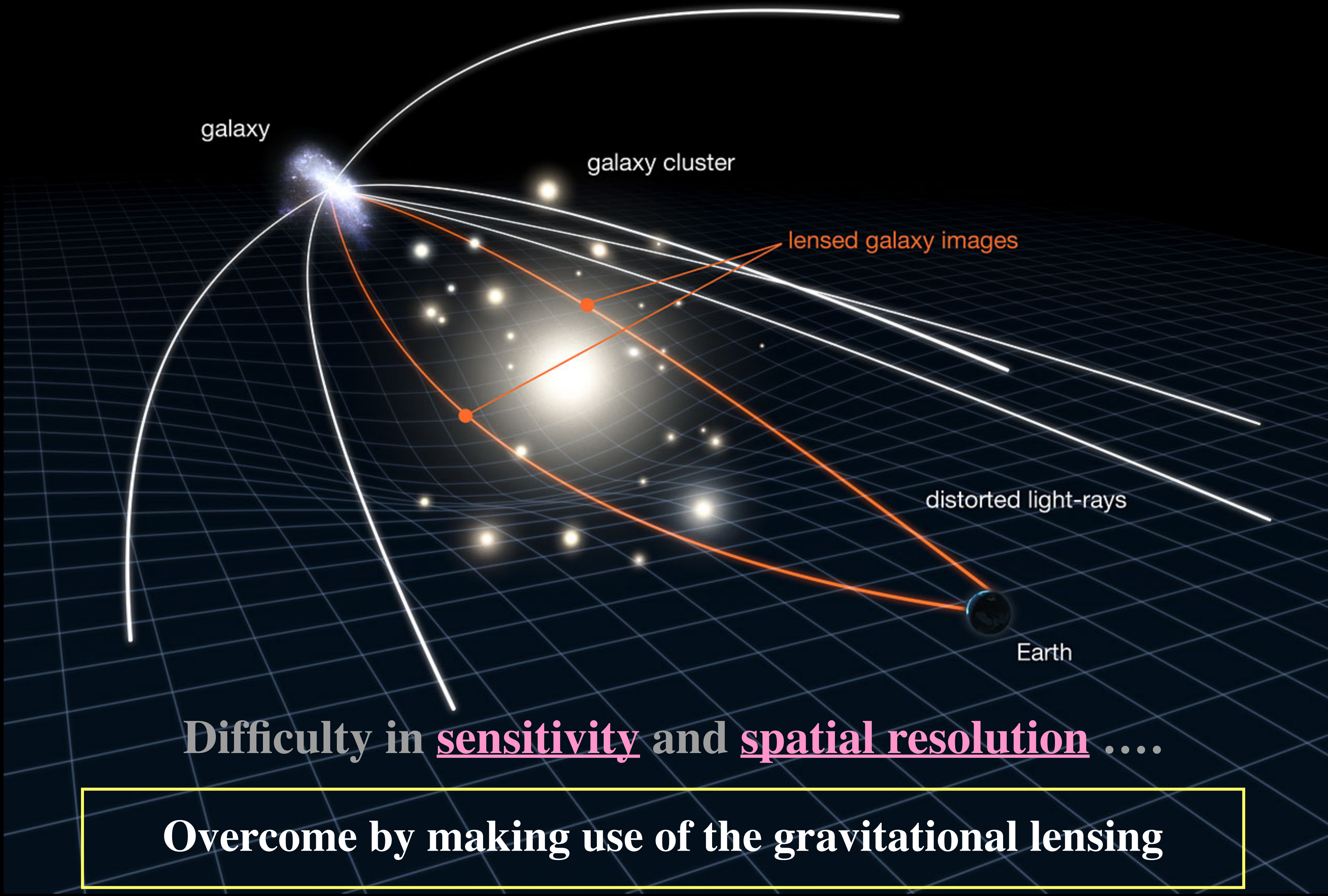


Discovery of uniquely bright galaxies at z=10-12; NASA press release Nov, 2022 (e.g., Naidu+22; Castellano+22)

Remarkably overabundance of Bright/Massive Galaxies

Q. What is the physical origin?

How to dive into detailed physics in early galaxies?



Difficulty in <u>sensitivity</u> and <u>spatial resolution</u> ….

Overcome by making use of the gravitational lensing

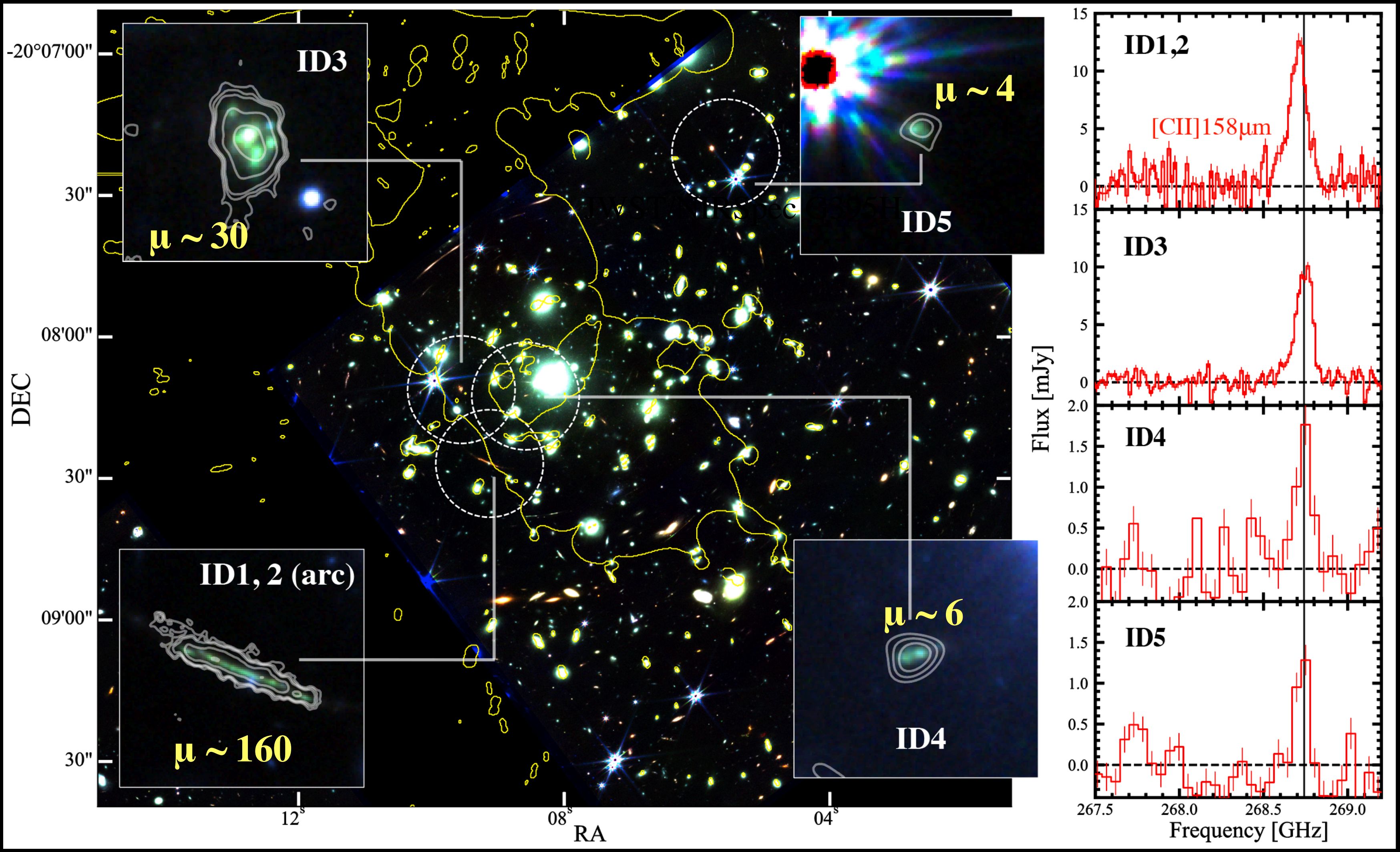
Approved programs scheduled in 2022–2024 for a single lensed galaxy at z = 6

Telescope	Instrument/band	PI	Time (hrs)	Scope	Observation
JWST cy1	NIRSpec IFU, NIRCam	S. Fujimoto	13.2	Key optical emission lines & UV-optical continuum	late 2022 ~ early 2023
JWST cy2	NIRCam	S. Fujimoto	5.0	Mapping Hα	early 2024
ALMA cy8	Band6, 5	S. Fujimoto	16.3	Deep [CII]158um & [OI]146um follow-up	late 2022
ALMA cy8	Band7, 8	S. Fujimoto	19.2	Detecting [OIII] & [NII]122um, 205um	late 2022
ALMA cy8	Band 3	F. Valentino	19.4	Detecting CO(7-6), [CI](2-1), 3-mm continuum	late 2021
ALMA cy9	Band 6	S. Fujimoto	26.5	High-resolution (~0.”05) deep [CII] follow-up	July~Sep 2023
ALMA cy9	Band7, 8	S. Fujimoto	24.5	Detecting [OIII] & [NII]122um, 205um (resub)	partially taken in early 2023
ALMA cy10	Band 6	S. Fujimoto	16.4	Low resolution (~1.”5) deep [CII] follow-up	early 2024
VLT S22A	MUSE	S. Fujimoto	8.9	Detecting Lya	complete in early 2023
Keck S22B	MOSFIRE	Y. Ono	1 night	Detecting rest-UV lines	bad weather
JVLA S20A, S21A	Band Ku	S. Fujimoto	23.2	Detecting CO(1-0)	complete in early 2022

~160hrs

Target: A sub-L* main-sequence galaxy at z=6.07

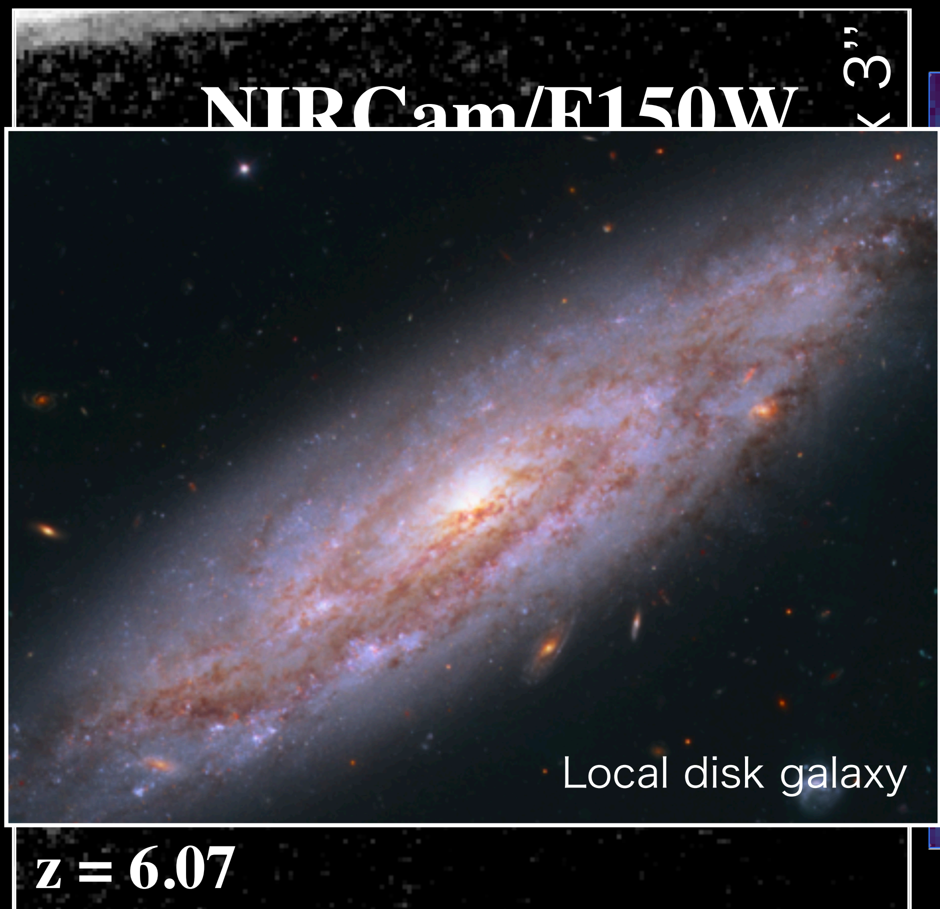
Laporte et al. 2021, MNRAS, 505; Fujimoto et al. 2021, ApJ, 911, 99; Fujimoto et al. 2024a submitted (arXiv: 2402.18543)

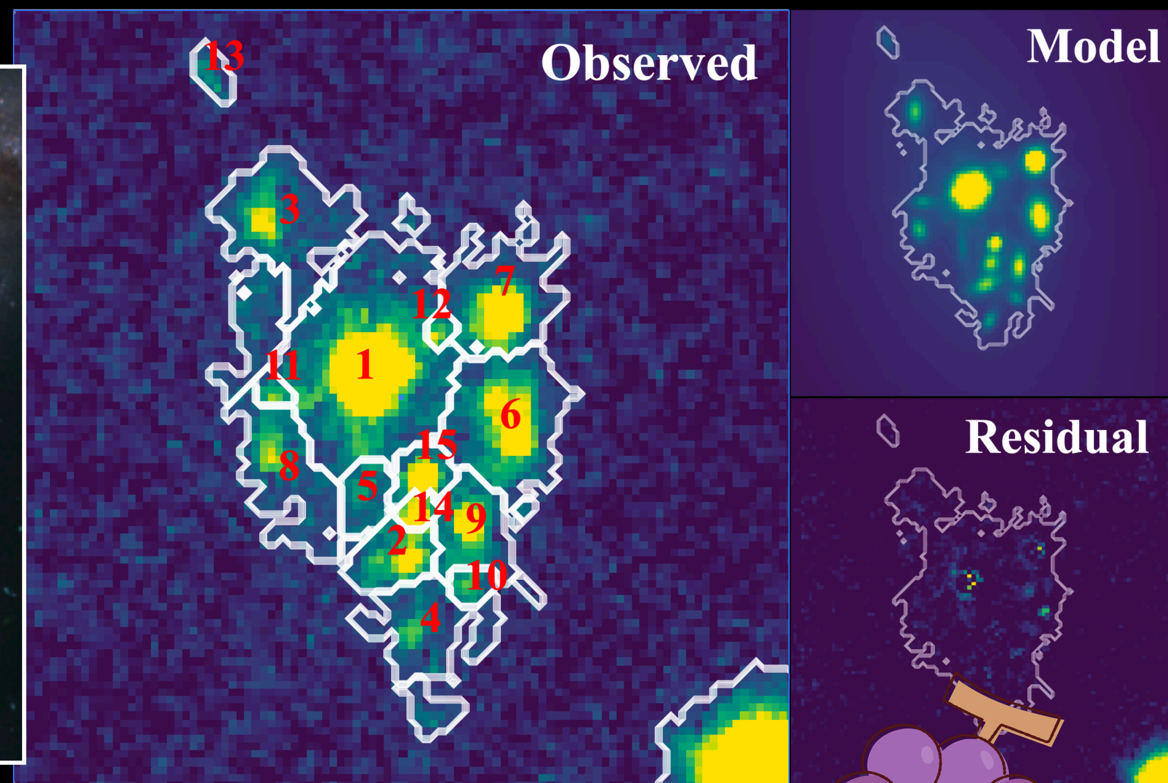


- **Multiple images** spectroscopically confirmed at = 6.07 with [CII]158um
- **Brightest** ([CII]~20mJy, F160W~23.5mag) so far known at zspec > 6 in the observed-frame, but still intrinsically **a low-mass main-sequence galaxy (M_{star} ~ 10^9 M_{sun}, ~local dwarf)**

Deepest Dive into the true picture of Early Galaxy

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)





"The Cosmic Grapes"

A single rotating disk galaxy resolved into
~ 15 individual small (Re ~ 10-60pc, after lens corr.) **clumps,**
accounting for *~70%* of total flux in F150W

Deepest Dive into the true picture of Early Galaxy

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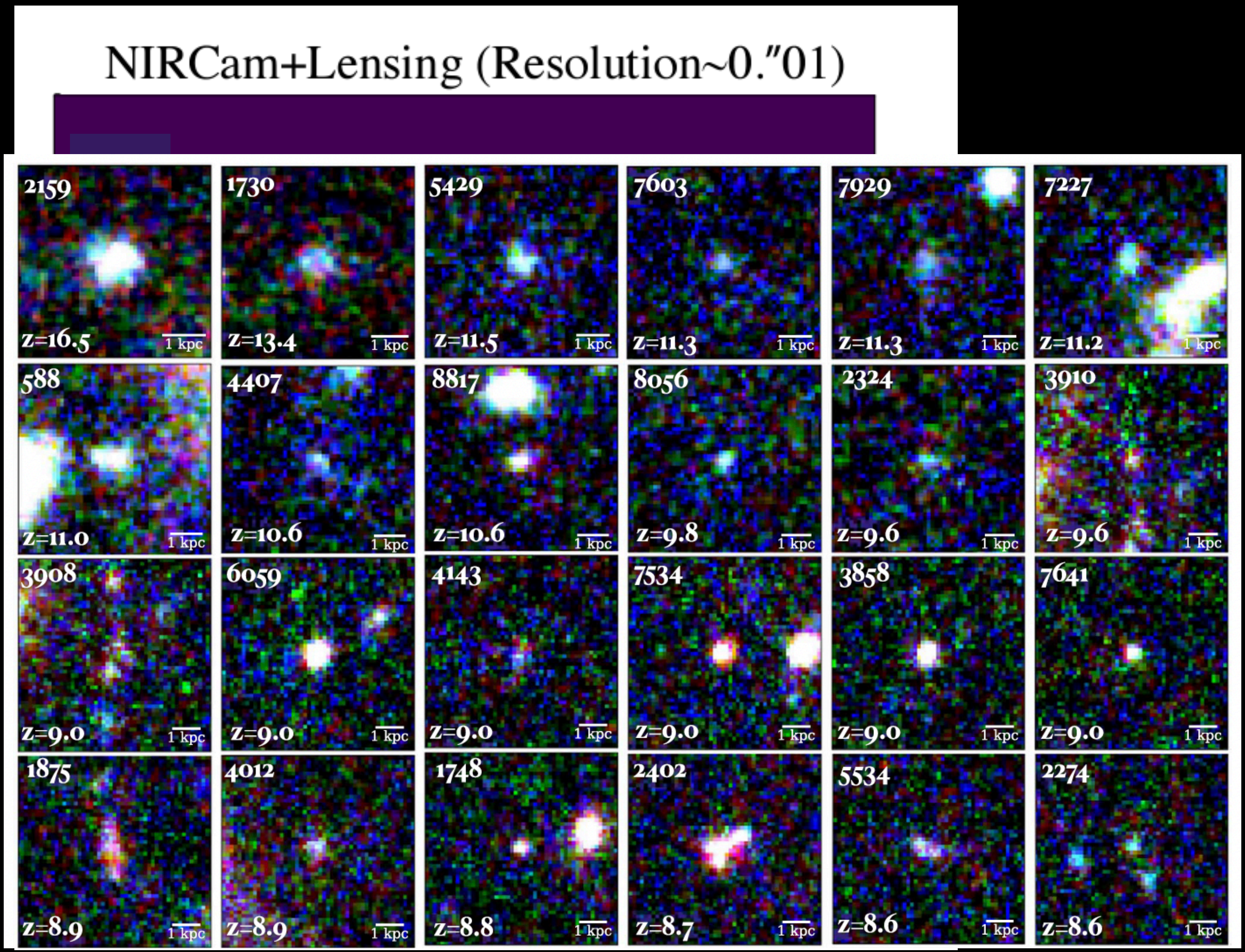
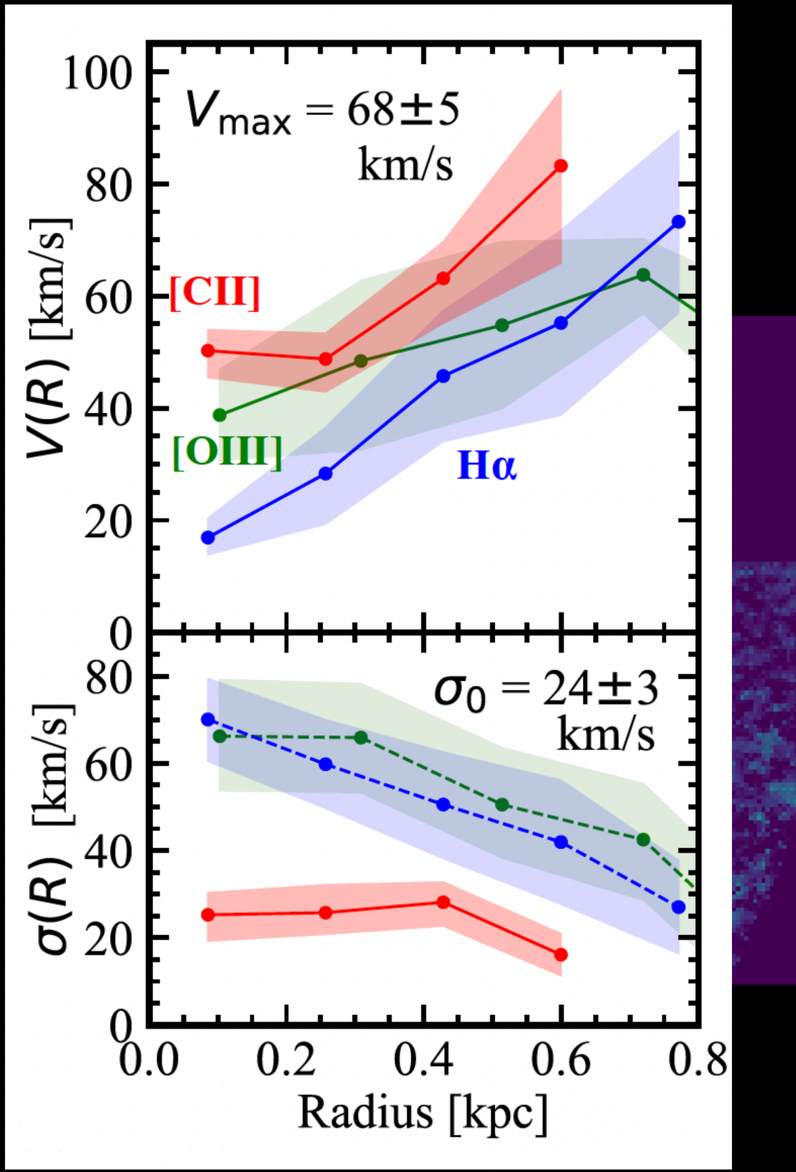


CEERS z >~9 candidates (Finkelstein+23)

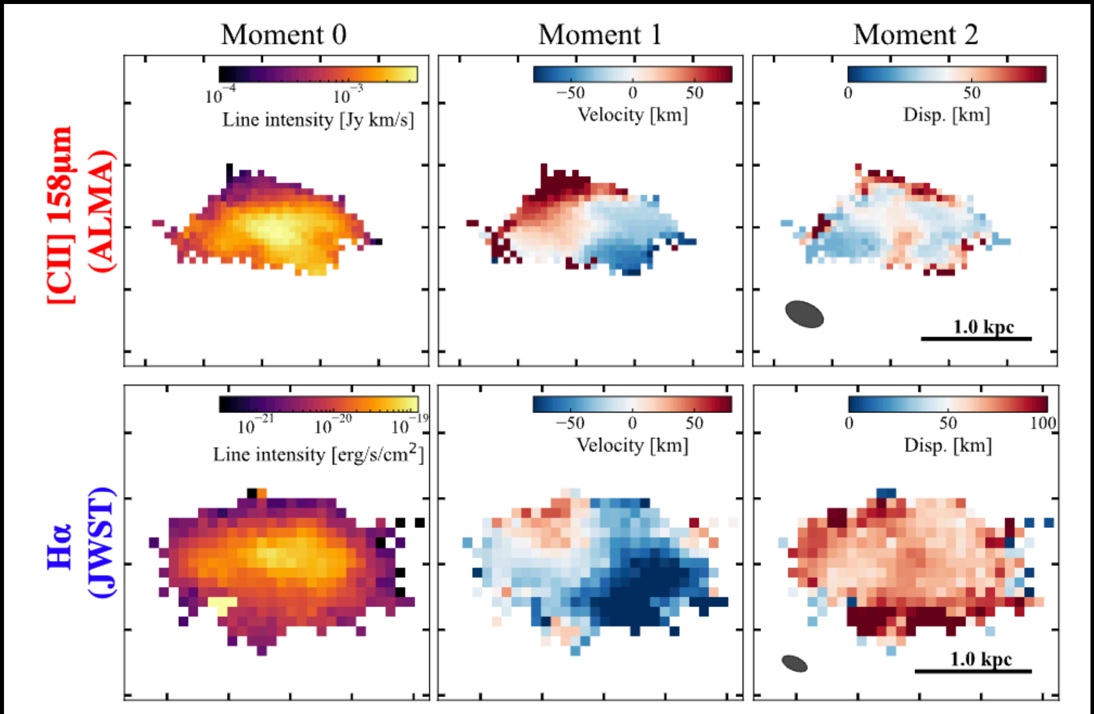
Many single-disk like JWST early galaxies may also be highly clumpy

How about Dynamics ?

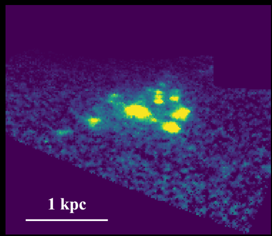
Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



ALMA + NIRSpec IFU (in the source plane)



- Numerous clumps + Smooth rotating disk (σ ~ 20km/s, V/σ ~ 3)



How about Dynamics ?

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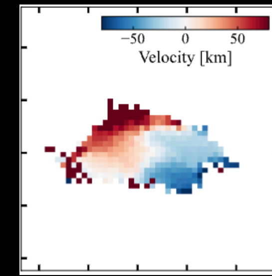
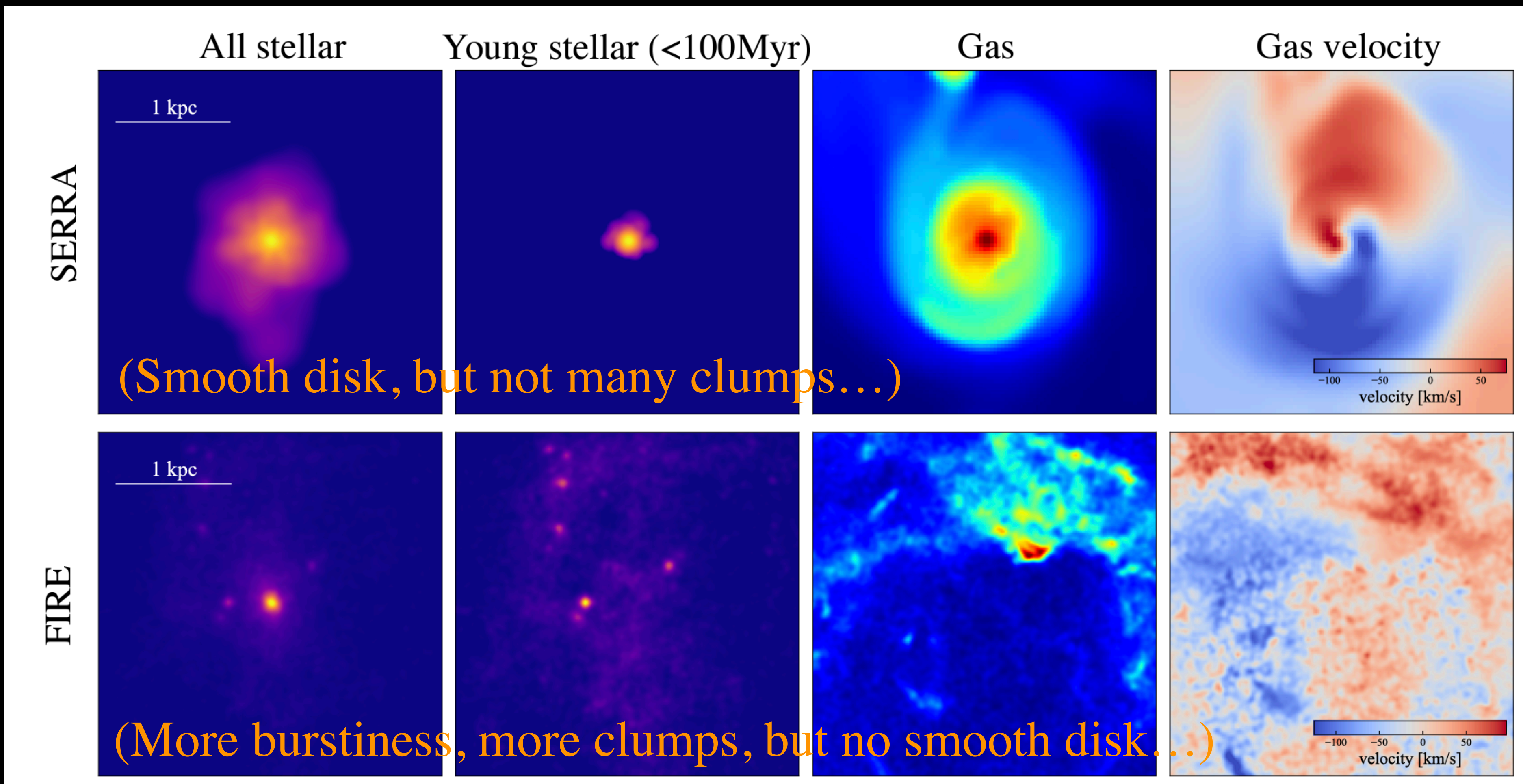
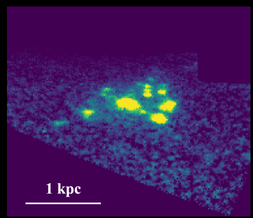




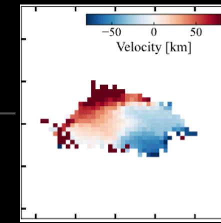
- **Challenging to early galaxy formation models**

Frequent bursty star-formation ⇔ Smooth rotating disk = Weak feedback?

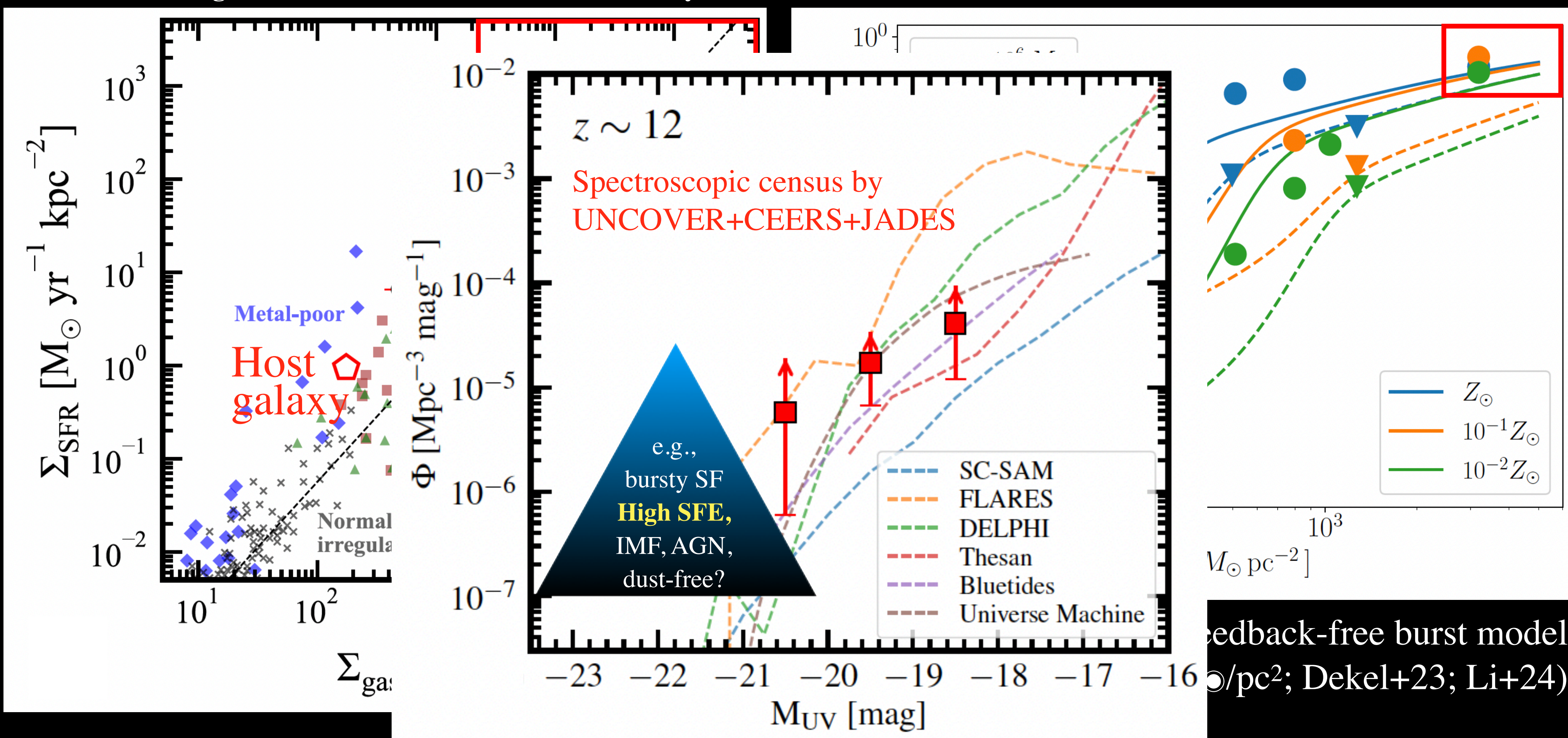


Weak feedback in Early Galaxies?

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



($L_{[CII]} \rightarrow M_{gas}$; Cross-checked with M_{dyn}, $\delta_{GDR}(Z)$)



eedback-free burst model

⊙/pc²; Dekel+23; Li+24)

$\epsilon_* \equiv M_{star} / (f_{baryon} M_{halo})$: Integrated over the lifetime of the system

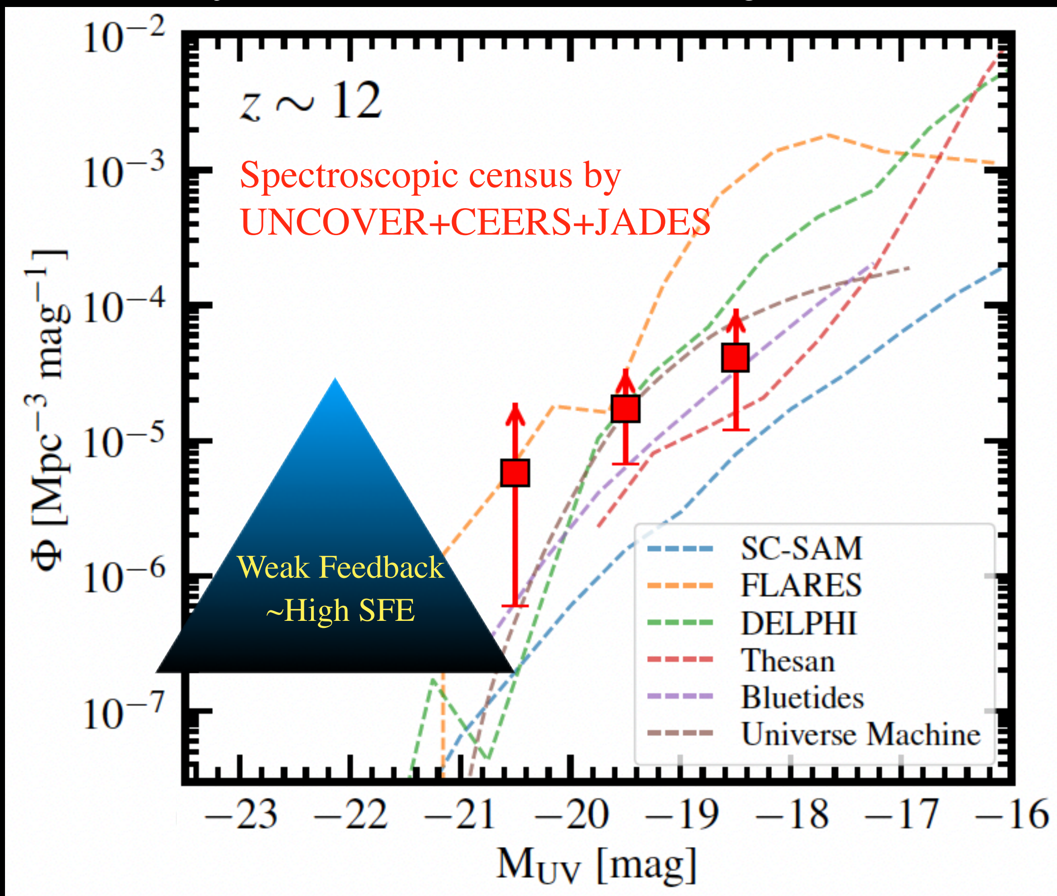
Very high gas density (~comparable to local ULIRGs) observed, well aligned with high star-formation efficiency of ε > 0.6 - 0.8

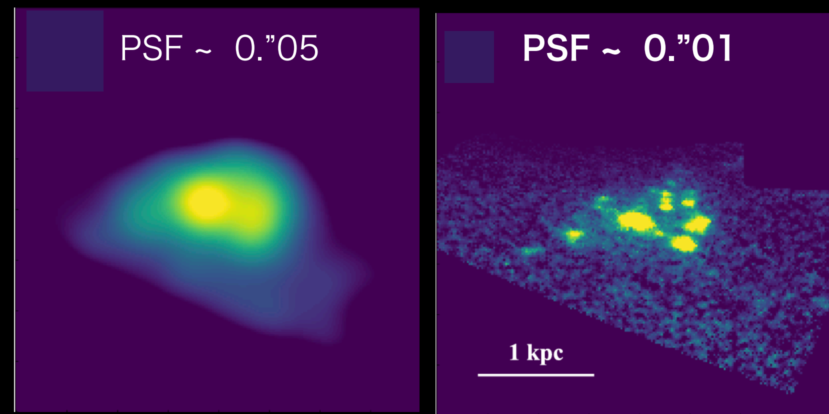
* ε < 0.1 in local galaxies

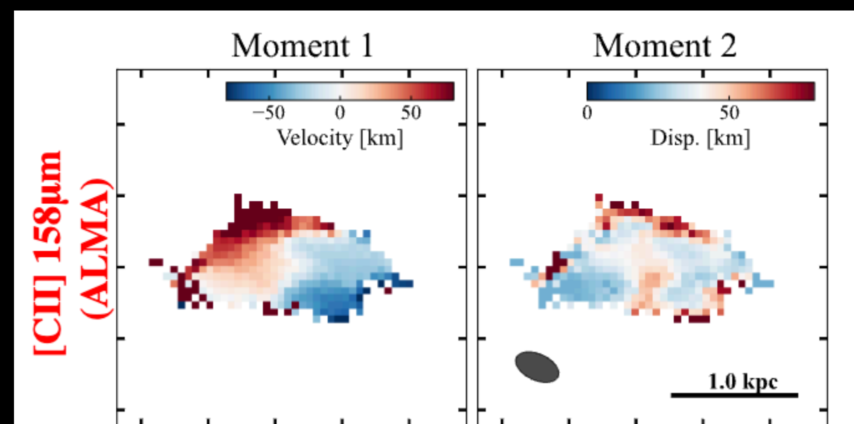
Summary

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)

Fujimoto, UNCOVER+23 (see also e.g., Harikane+23, 24)



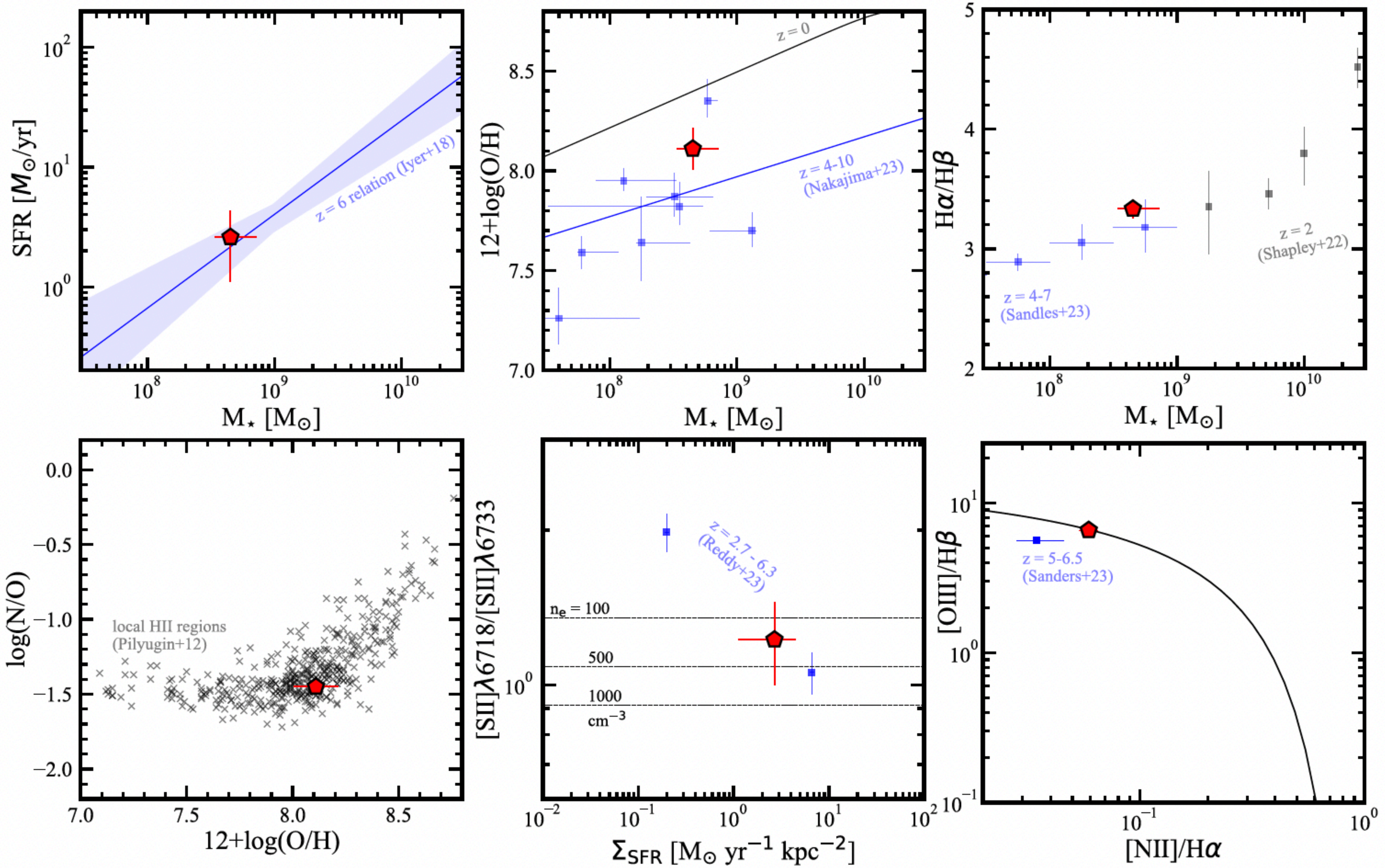




Q. Why high abundance of bright galaxies z >~9 ?

A. Early galaxy = Numerous clump + smooth disk = Weak feedback

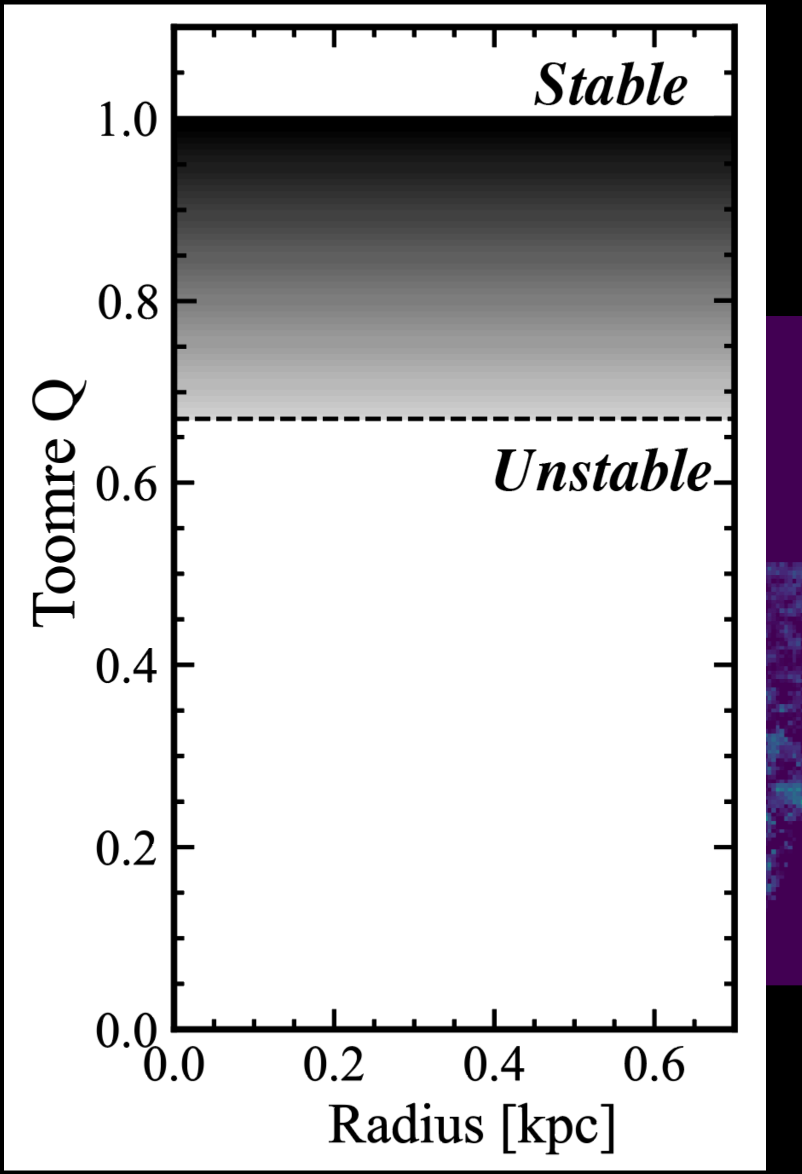
Backup



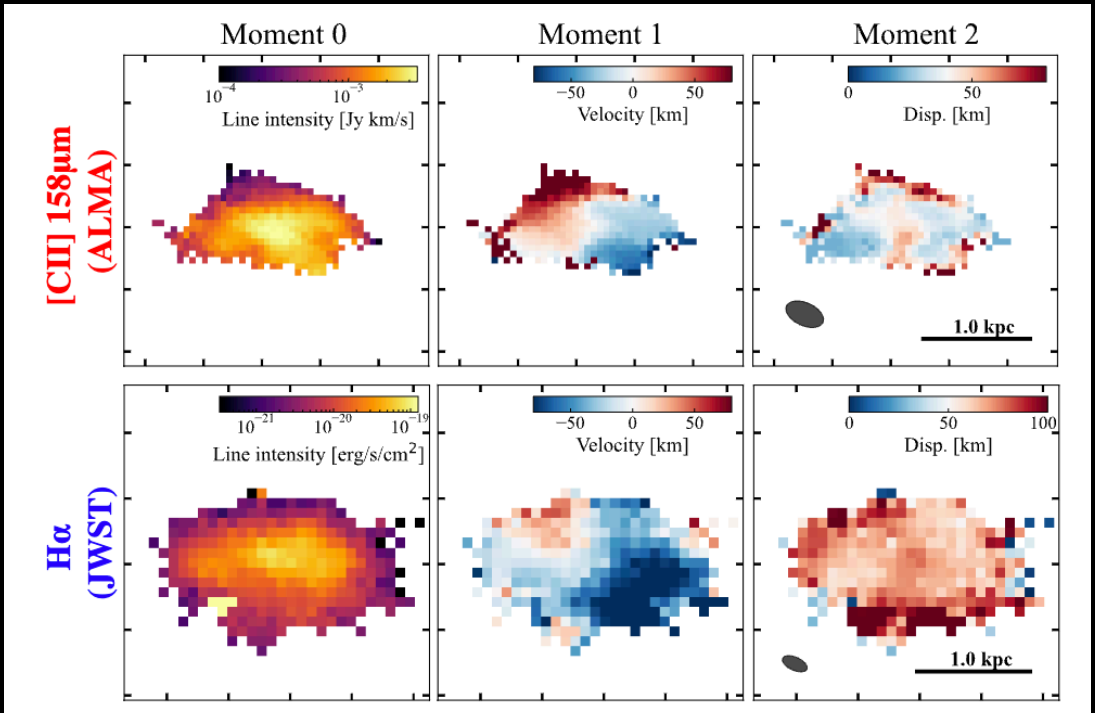
SFR [$M_\odot$/yr]
z = 6 relation (Iyer+18)
$M_\star$ [$M_\odot$]
12+log(O/H)
z = 0
z = 4-10 (Nakajima+23)
Hα/Hβ
z = 4-7 (Sandles+23)
z = 2 (Shapley+22)
log(N/O)
local HII regions (Pilyugin+12)
[SII]λ6718/[SII]λ6733
z = 2.7 - 6.3 (Reddy+23)
n_e = 100
500
1000
cm^{-3}
Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]
[OIII]/Hβ
z = 5-6.5 (Sanders+23)
[NII]/Hα

How about Dynamics ?

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



ALMA + NIRSpec IFU (in the source plane)



$$Q = \kappa\sigma_{0,\mathrm{gas}}/(\pi G\Sigma_{\mathrm{gas}})$$

κ : Stability term related to perturbation
σ : Velocity dispersion
Σ : Gas mass surface density

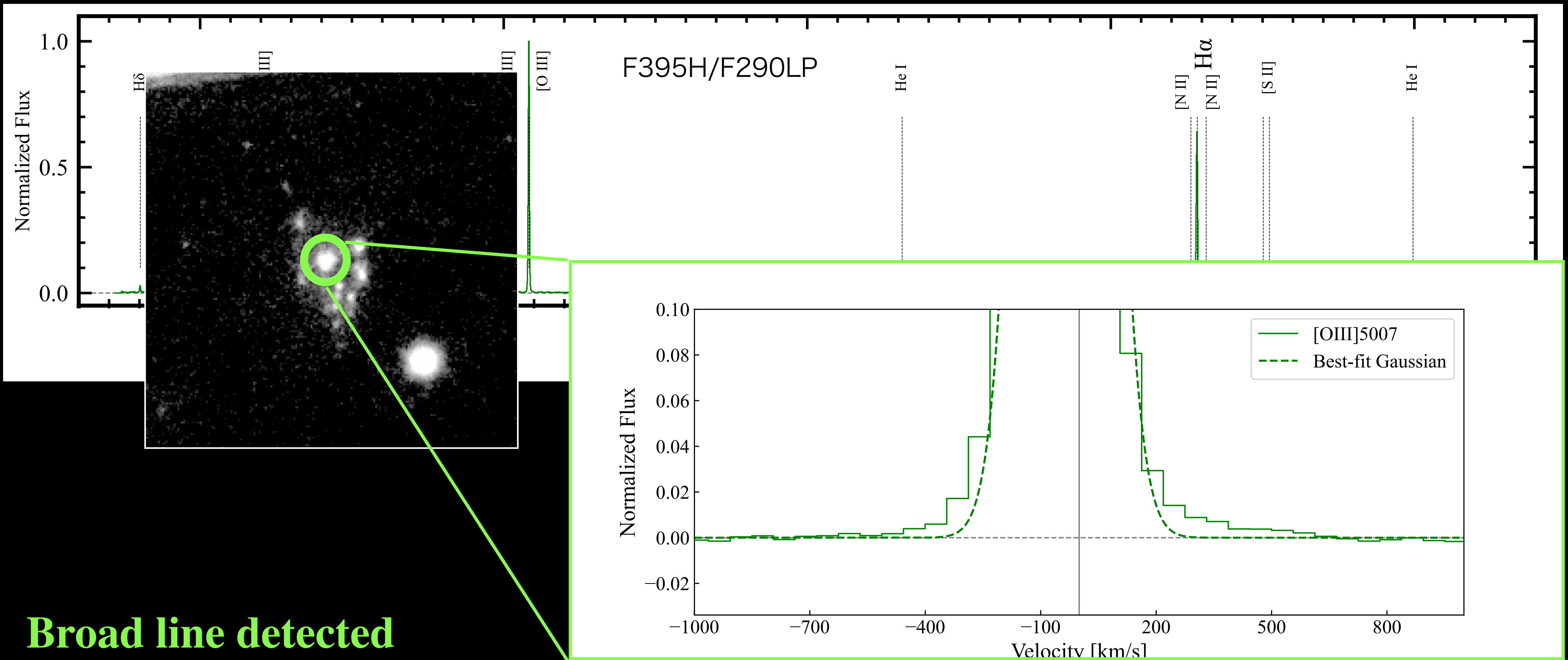
Balance between self-gravity of molecular gas and turbulent pressure by stellar radiation

- **Numerous clumps + Smooth rotating disk ($\sigma \sim$ 20km/s, $V/\sigma \sim 3$)**

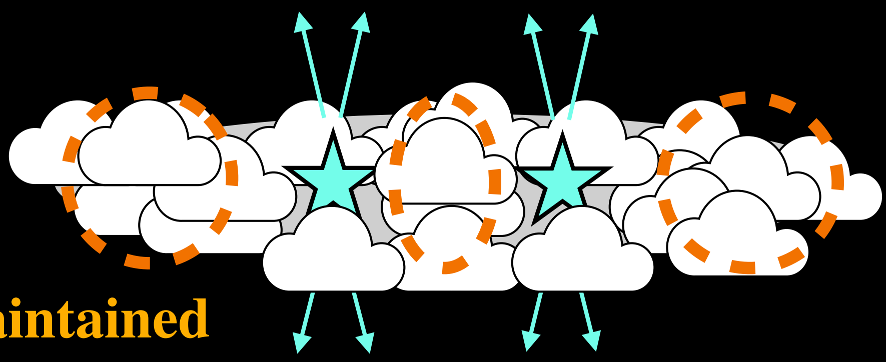
Numerous clumps are formed by disk instability

Presence of outflow does not contradict weak feedback

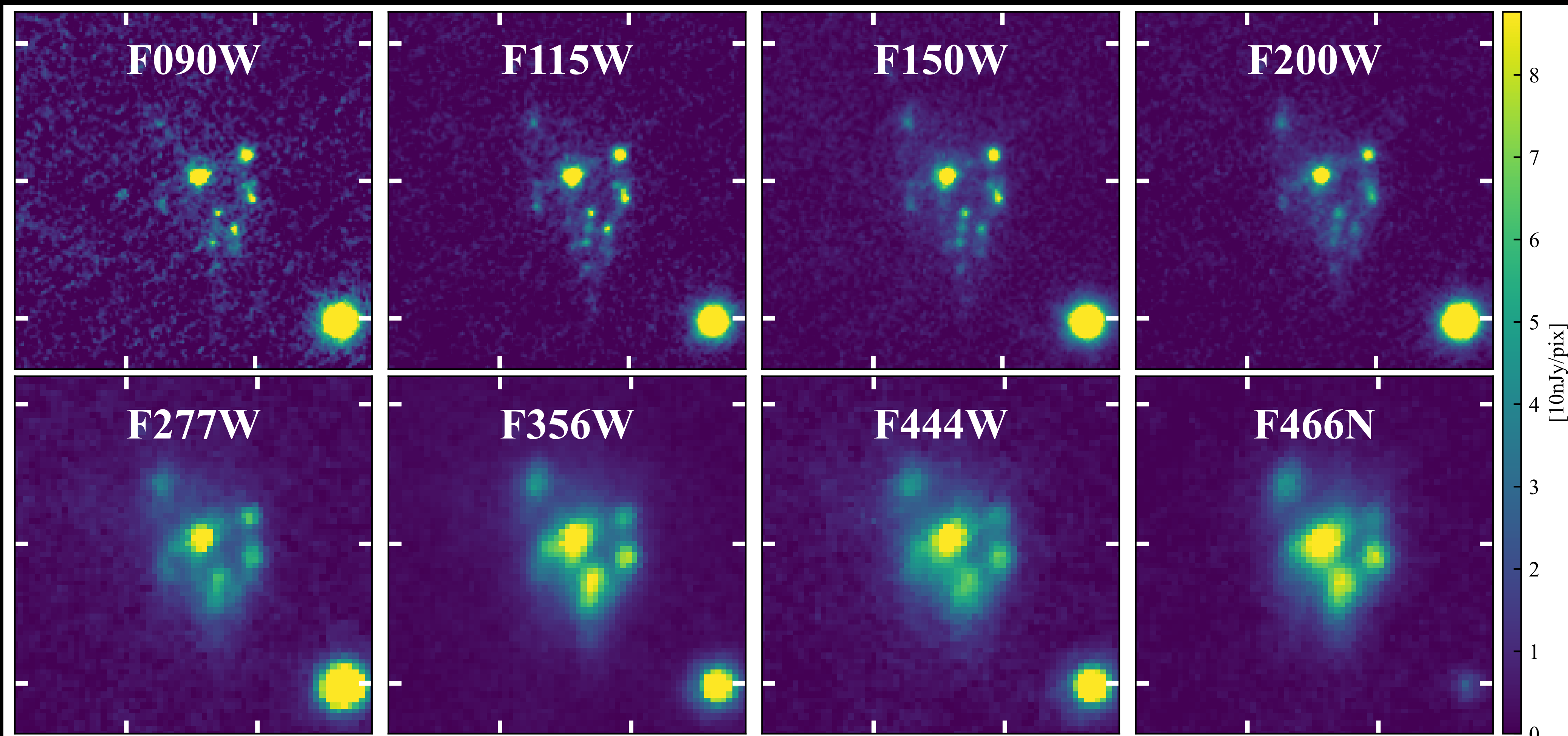
Fujimoto + in prep.; see also talks by e.g., Andrea, Avishai



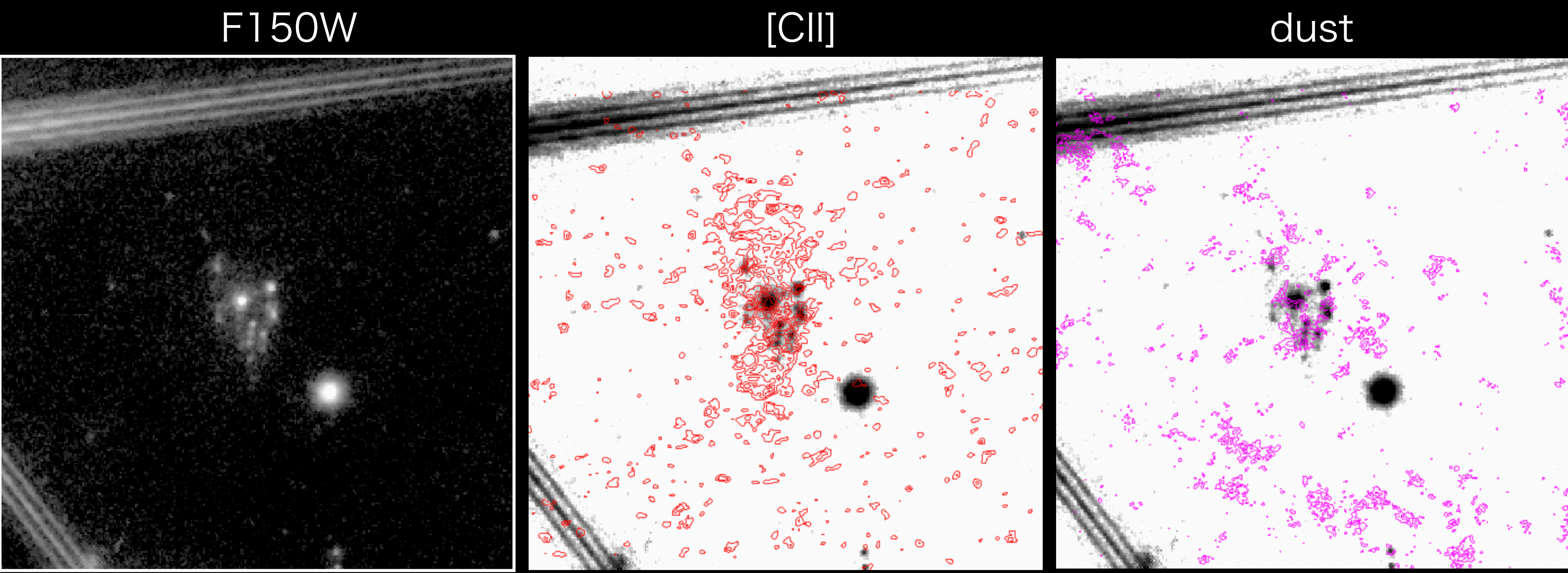
Broad line detected in both [OIII] & Hα

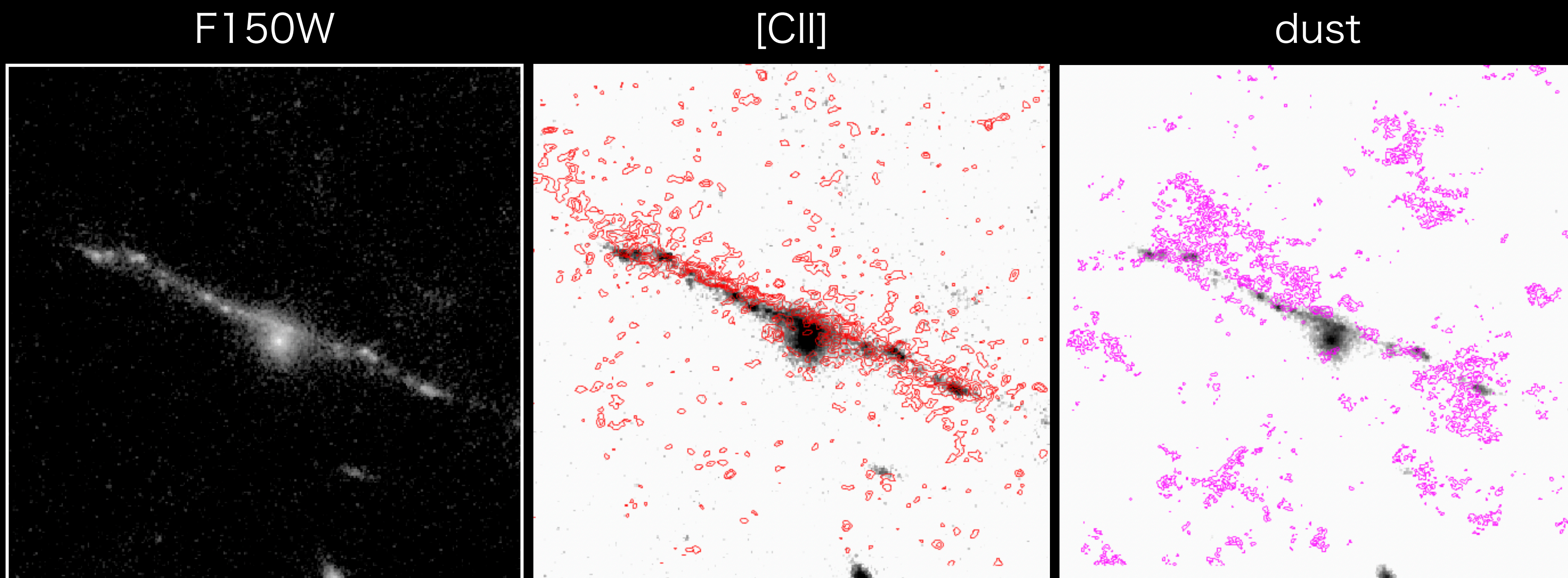


High SFE maintained



F090W
F115W
F150W
F200W
F277W
F356W
F444W
F466N
0
1
2
3
4
5
6
7
8
[10nJy/pix]

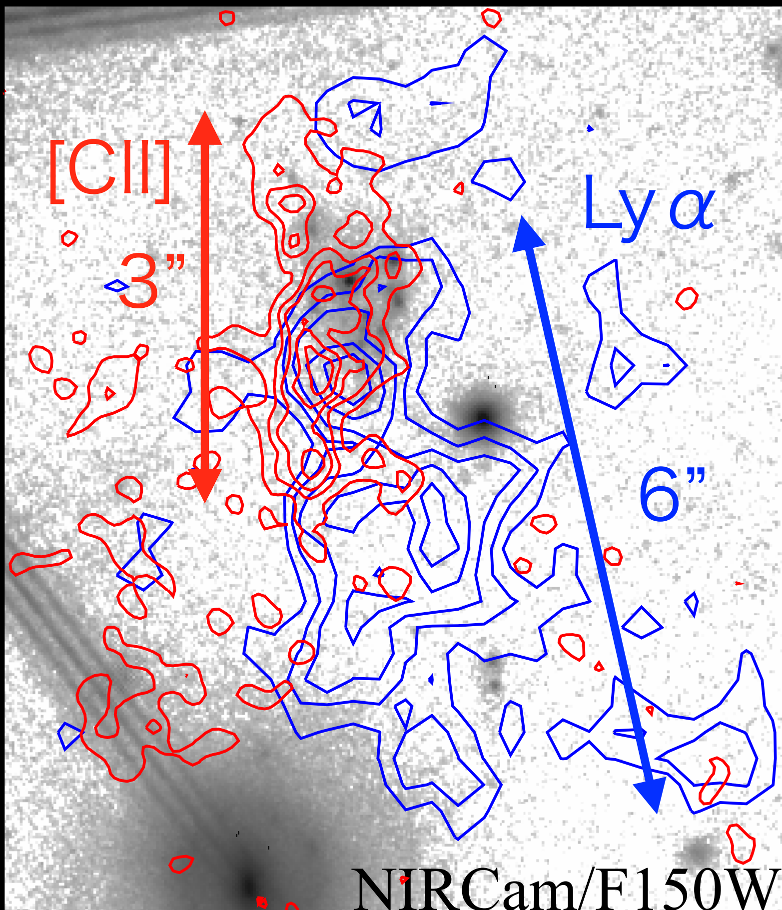

F150W
[CII]
dust

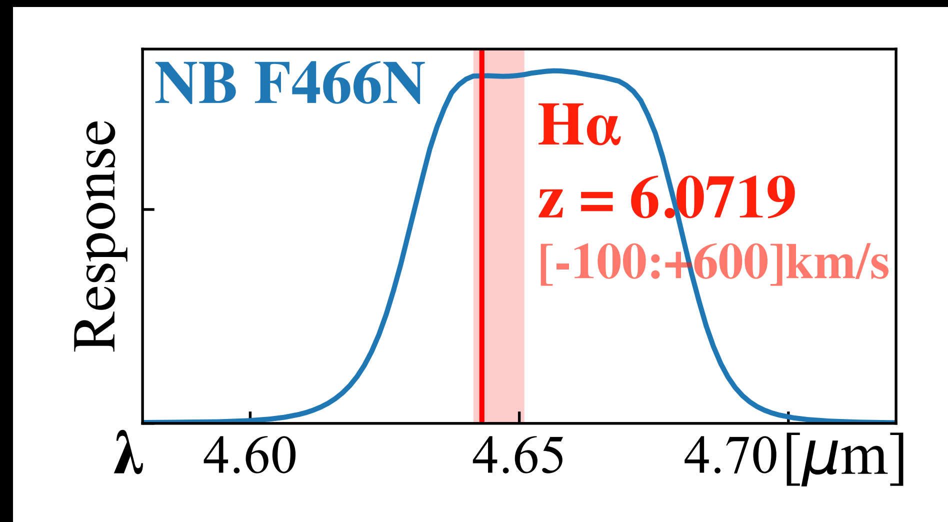


F150W
[CII]
dust

Approved JWST × ALMA joint program

2023.1.000149.S & #4573 (PI: S. Fujimoto)





<u>JWST</u>

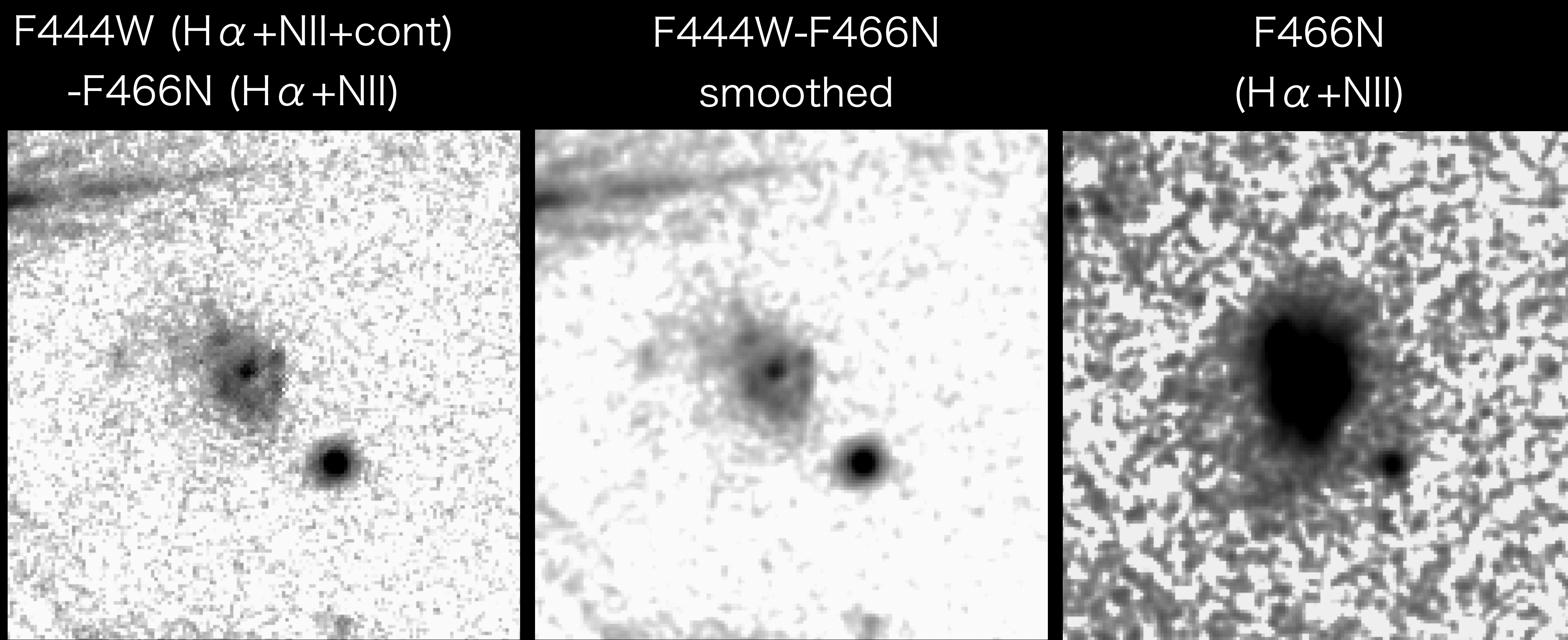
NIRCam NB F466N → Mapping out Hα (~5hrs)

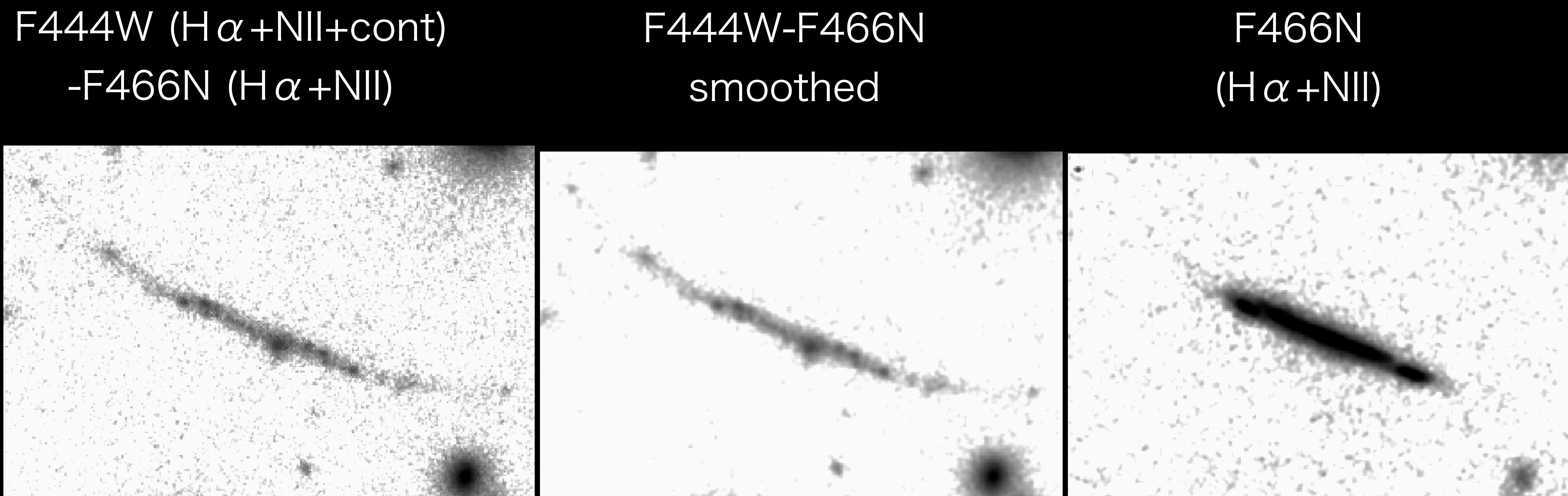
<u>ALMA</u>

Low deep resolution [CII]158um (~16hrs)

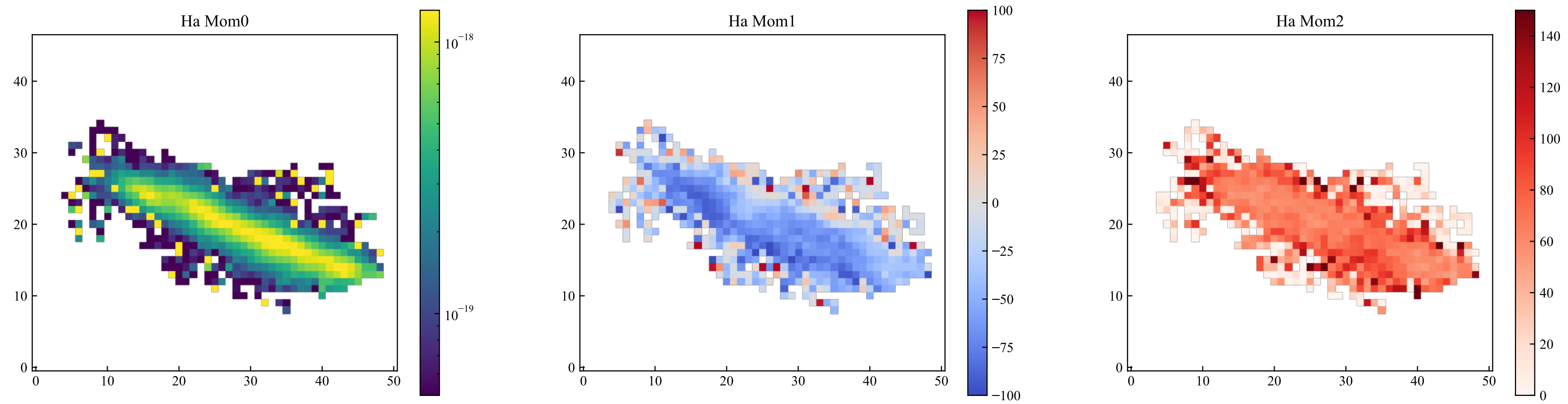
<u>Cold Gas Inflow</u> vs. <u>Ionized Gas Outflow</u>

will be investigated by the Hα structure

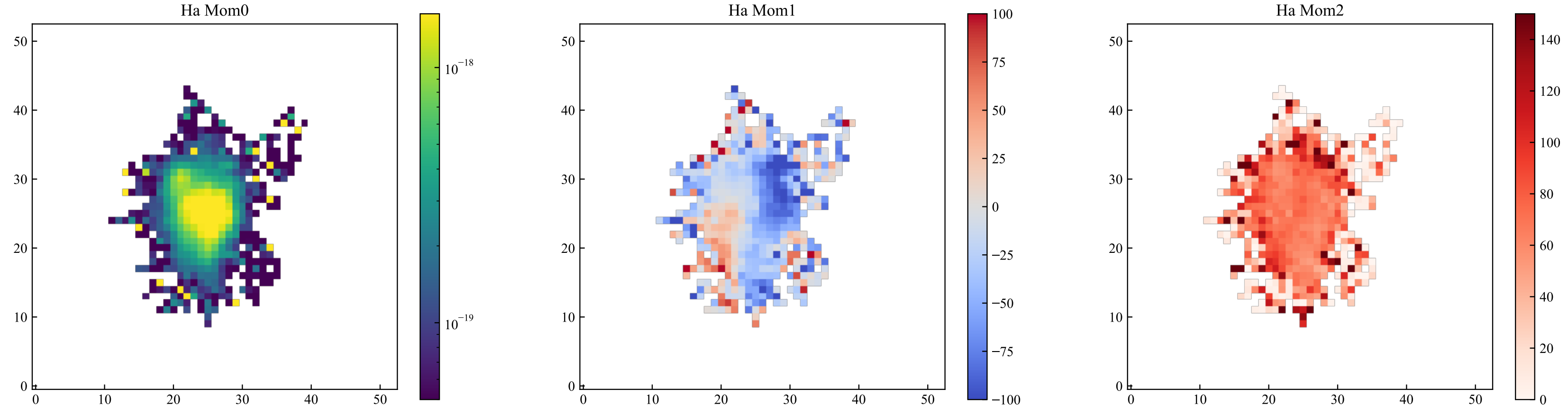

F444W (Hα+NII+cont)
-F466N (Hα+NII)
F444W-F466N
smoothed
F466N
(Hα+NII)


F444W (Hα+NII+cont)
-F466N (Hα+NII)
F444W-F466N
smoothed
F466N
(Hα+NII)

[redacted]

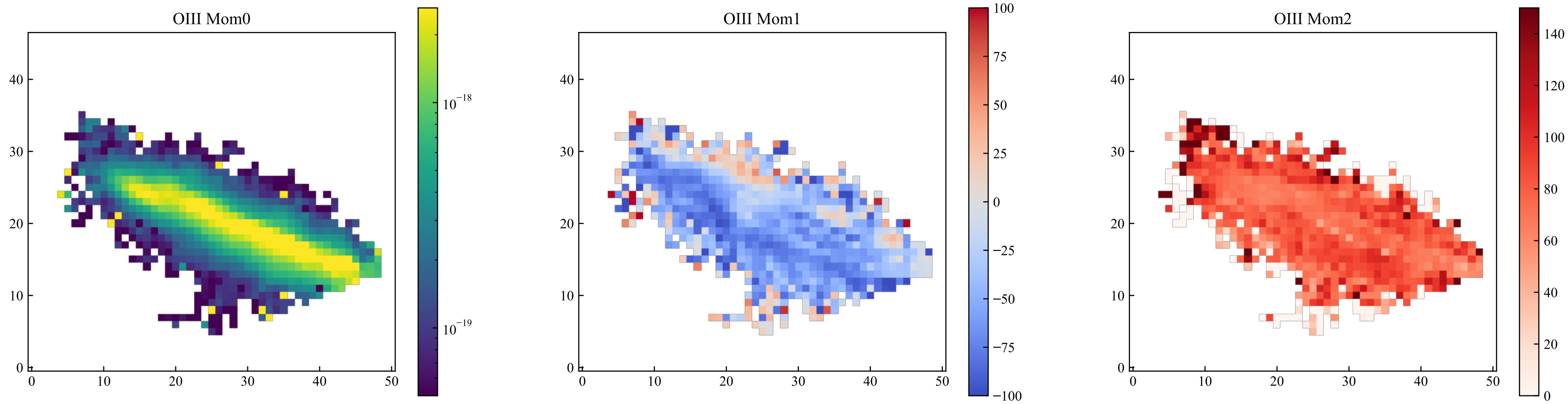


[redacted]

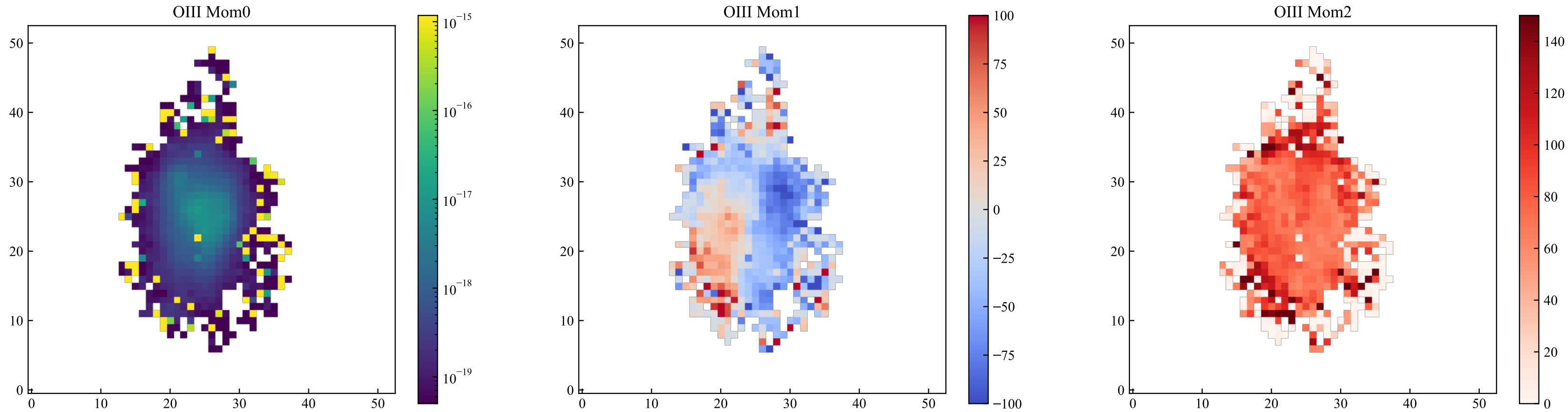


[redacted]

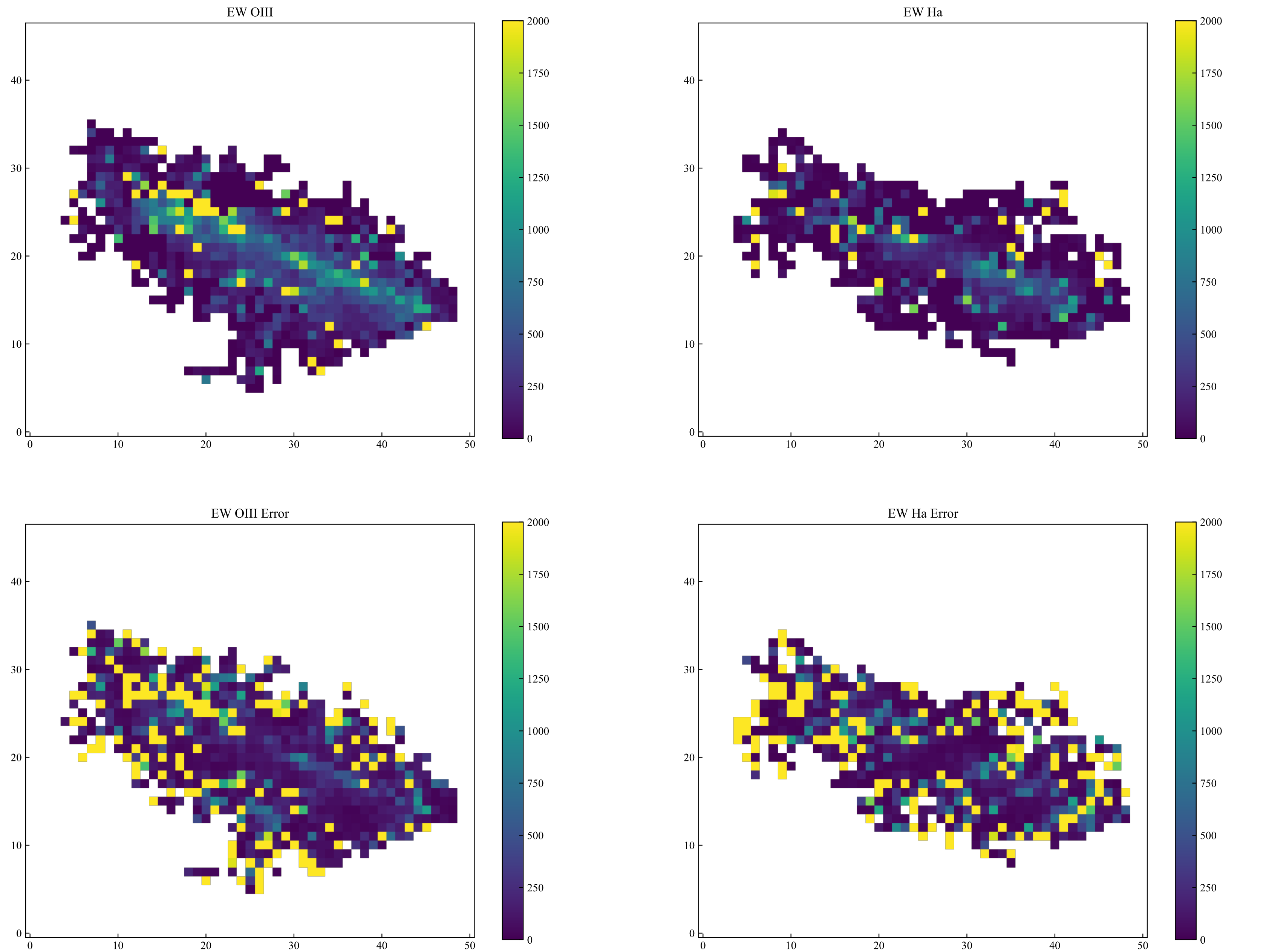
[redacted]



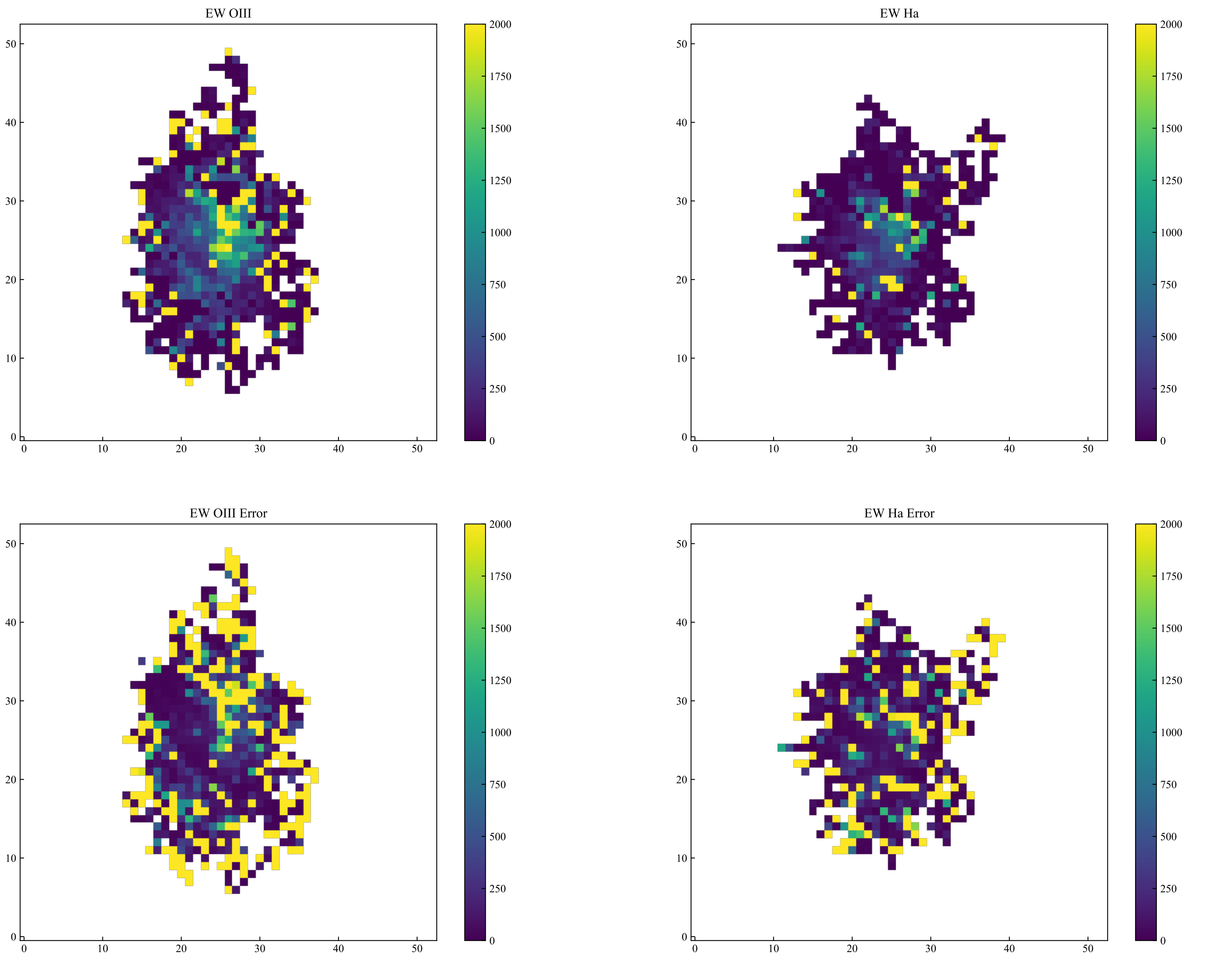
[redacted]

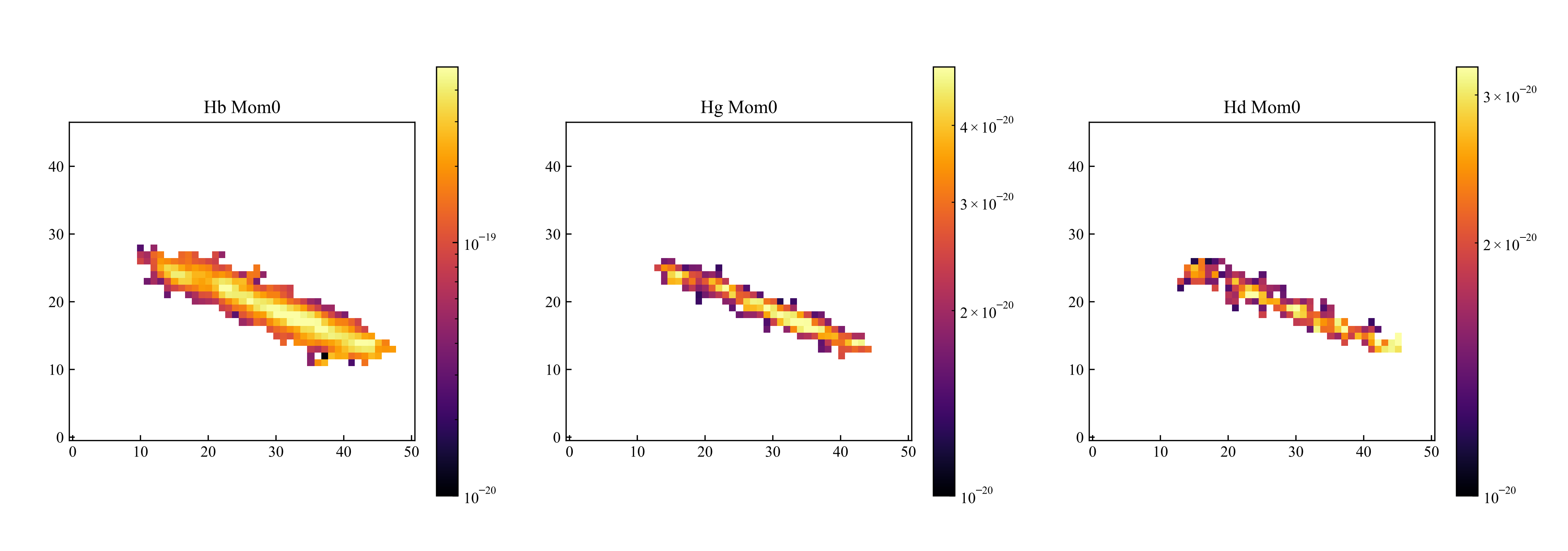


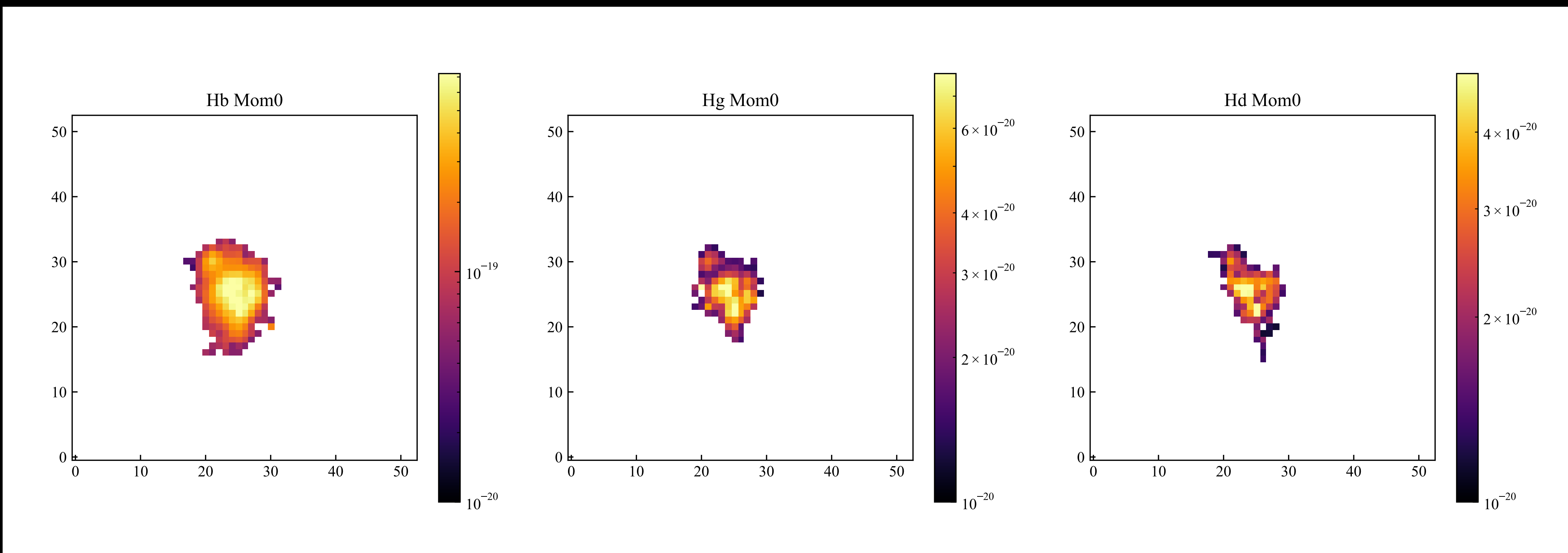
[redacted]

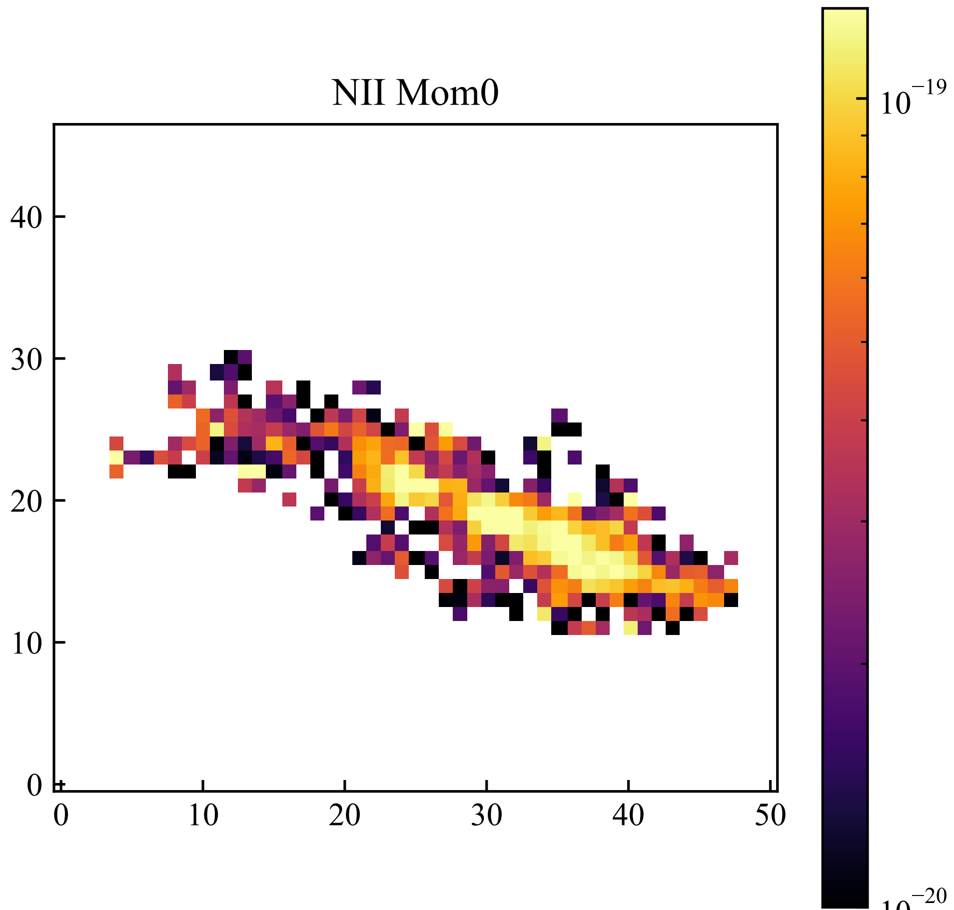


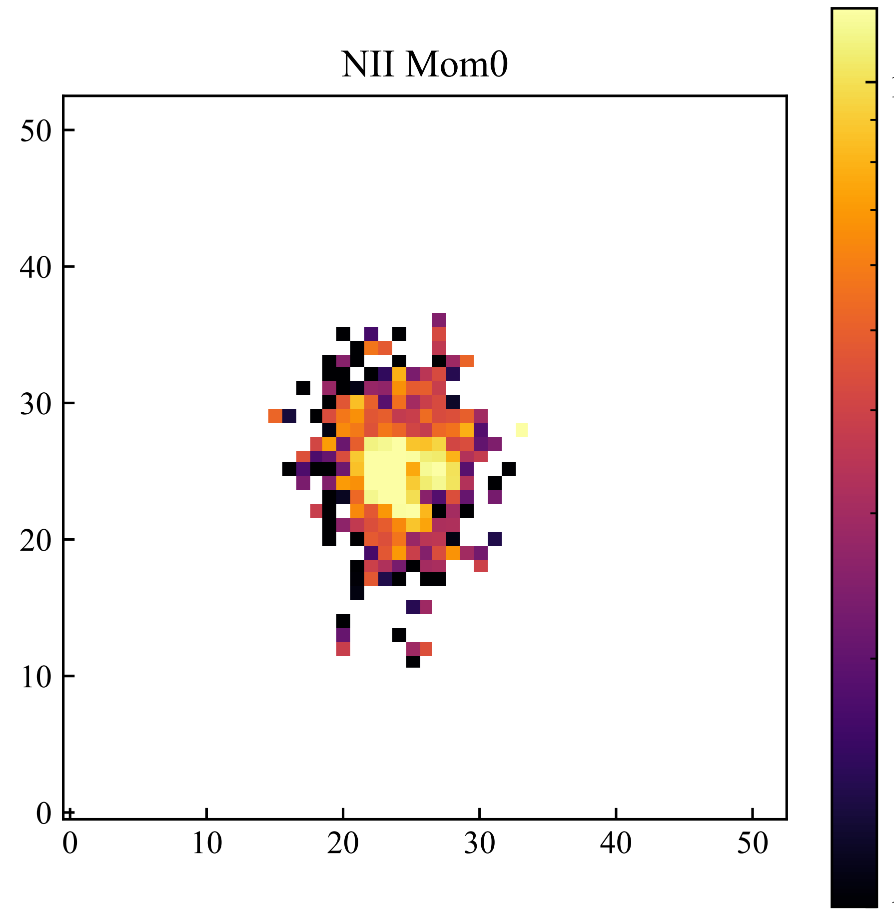
EW OIII
EW Ha
EW OIII Error
EW Ha Error
0
10
20
30
40
50
250
500
750
1000
1250
1500
1750
2000

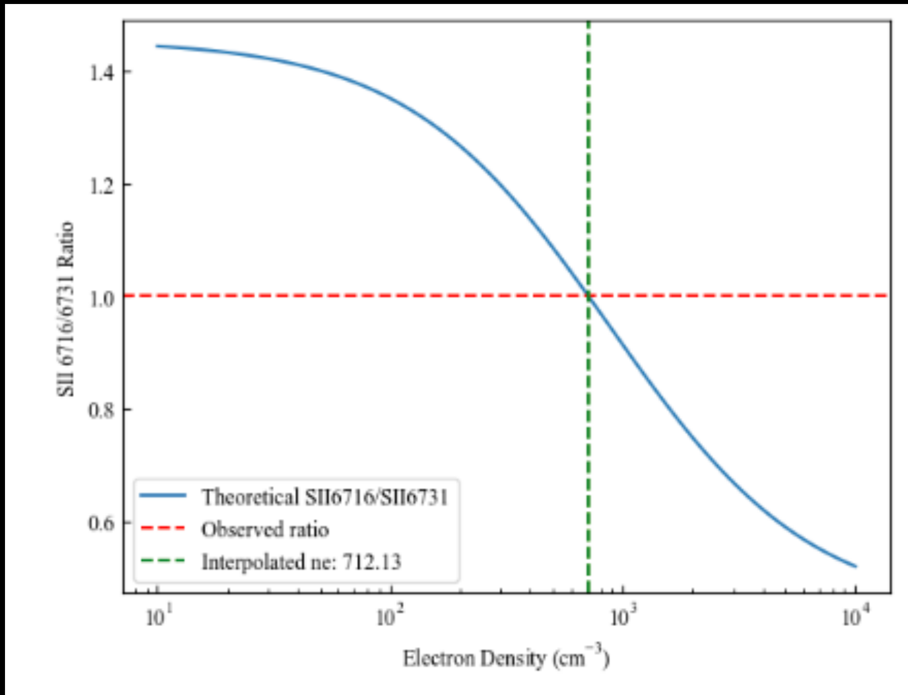

EW OIII
EW Ha
EW OIII Error
EW Ha Error
0 10 20 30 40 50
0 250 500 750 1000 1250 1500 1750 2000


Hb Mom0
Hg Mom0
Hd Mom0
10^{-19}
10^{-20}
4×10^{-20}
3×10^{-20}
2×10^{-20}
10^{-20}
3×10^{-20}
2×10^{-20}
10^{-20}

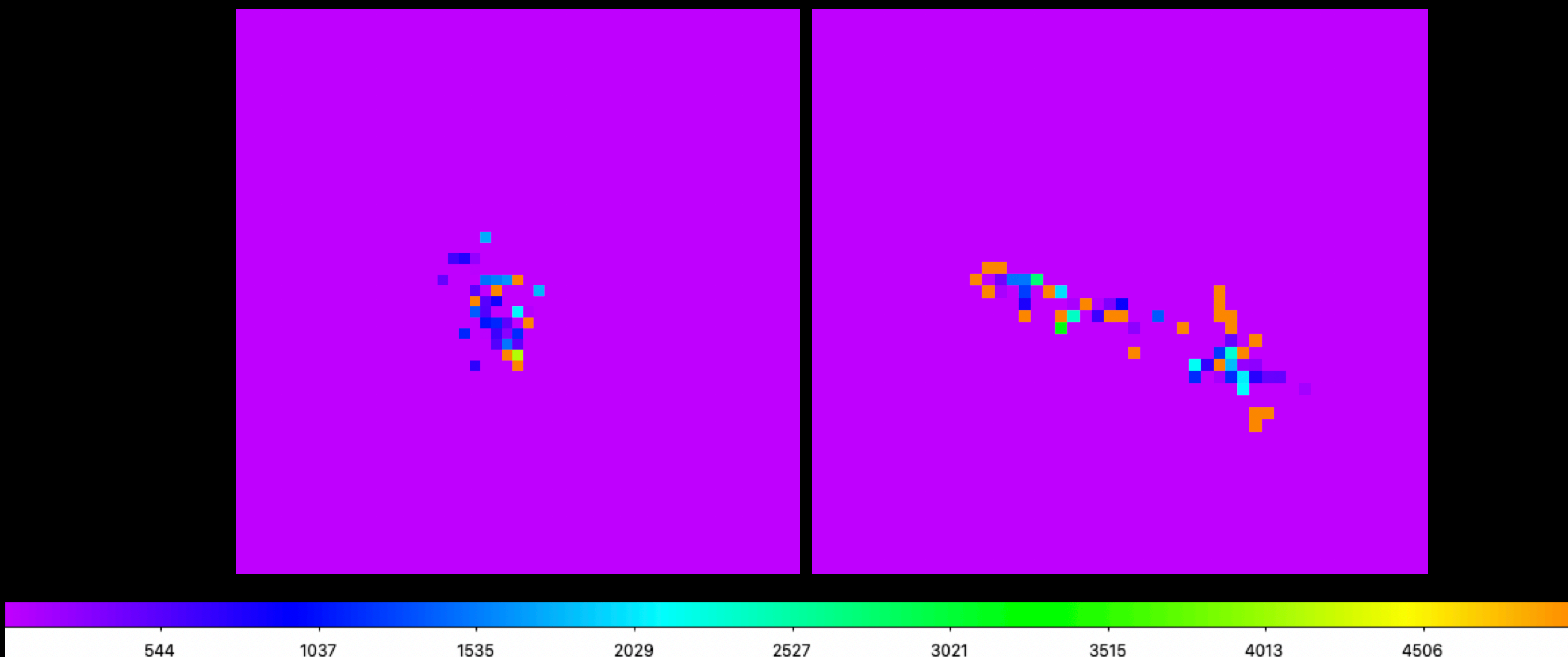

Hb Mom0
Hg Mom0
Hd Mom0
10^{-19}
10^{-20}
6×10^{-20}
4×10^{-20}
3×10^{-20}
2×10^{-20}
10^{-20}
4×10^{-20}
3×10^{-20}
2×10^{-20}
10^{-20}


NII Mom0
40
30
20
10
0
0
10
20
30
40
50
10^{-19}
10^{-20}

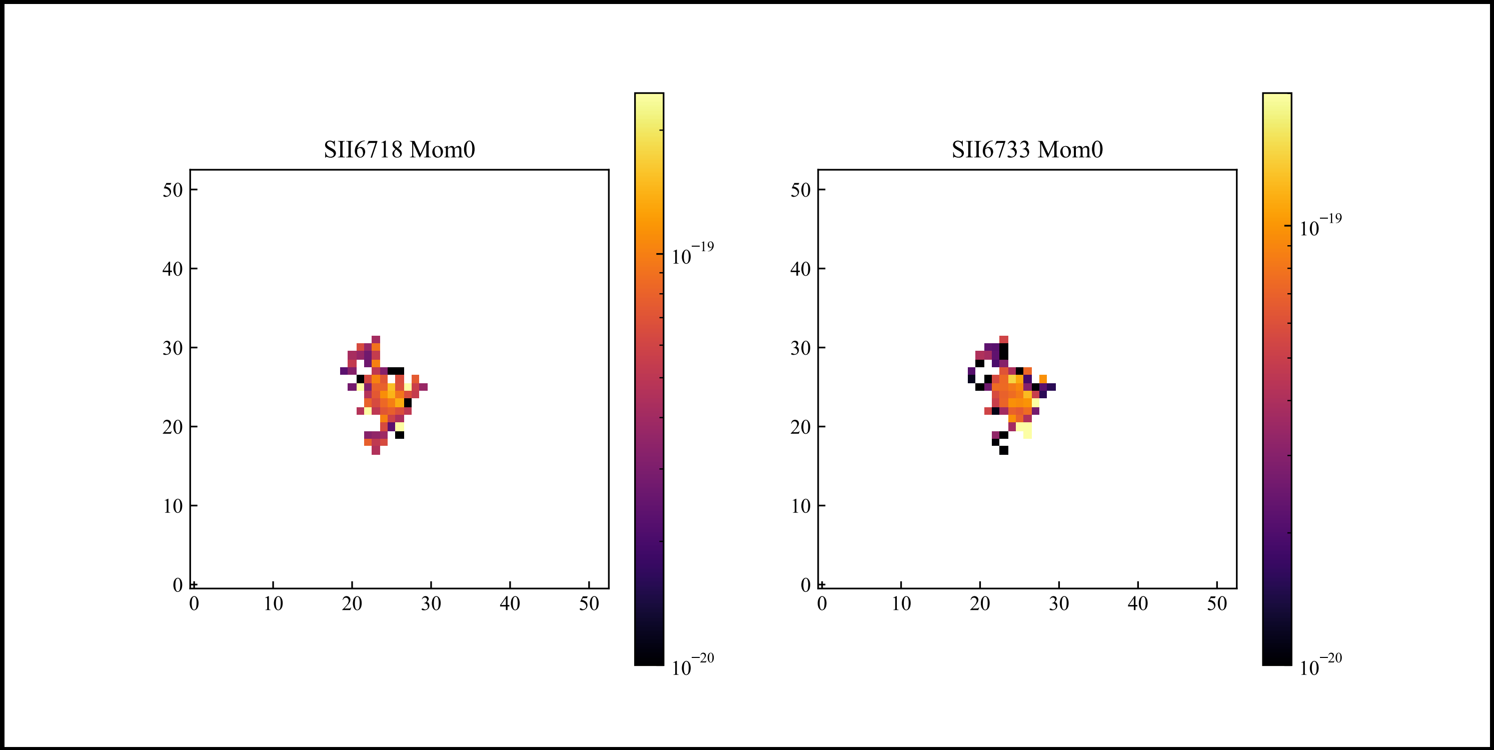

NII Mom0
50
40
30
20
10
0
0
10
20
30
40
50



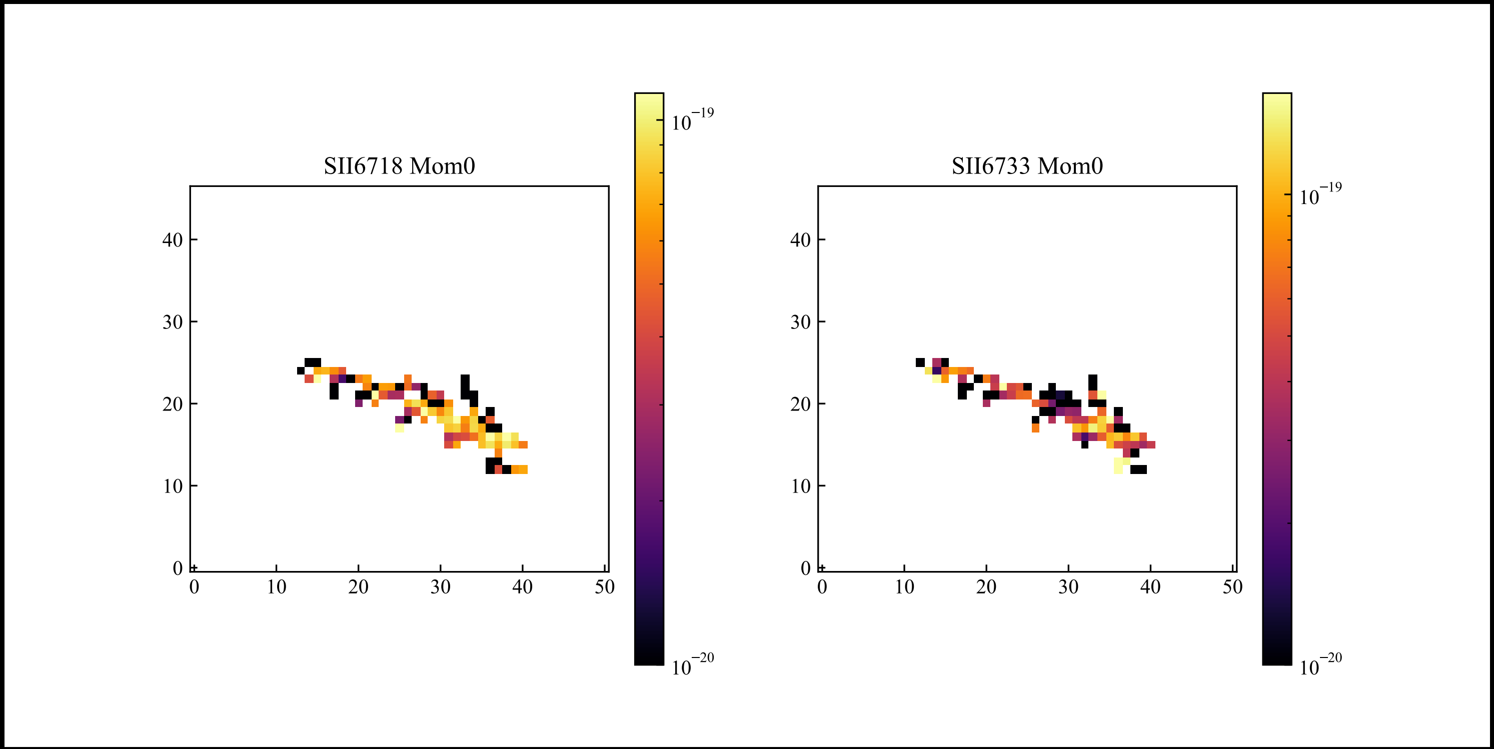
SII 6716/6731 Ratio
Electron Density (cm^{-3})
Theoretical SII6716/SII6731
Observed ratio
Interpolated ne: 712.13



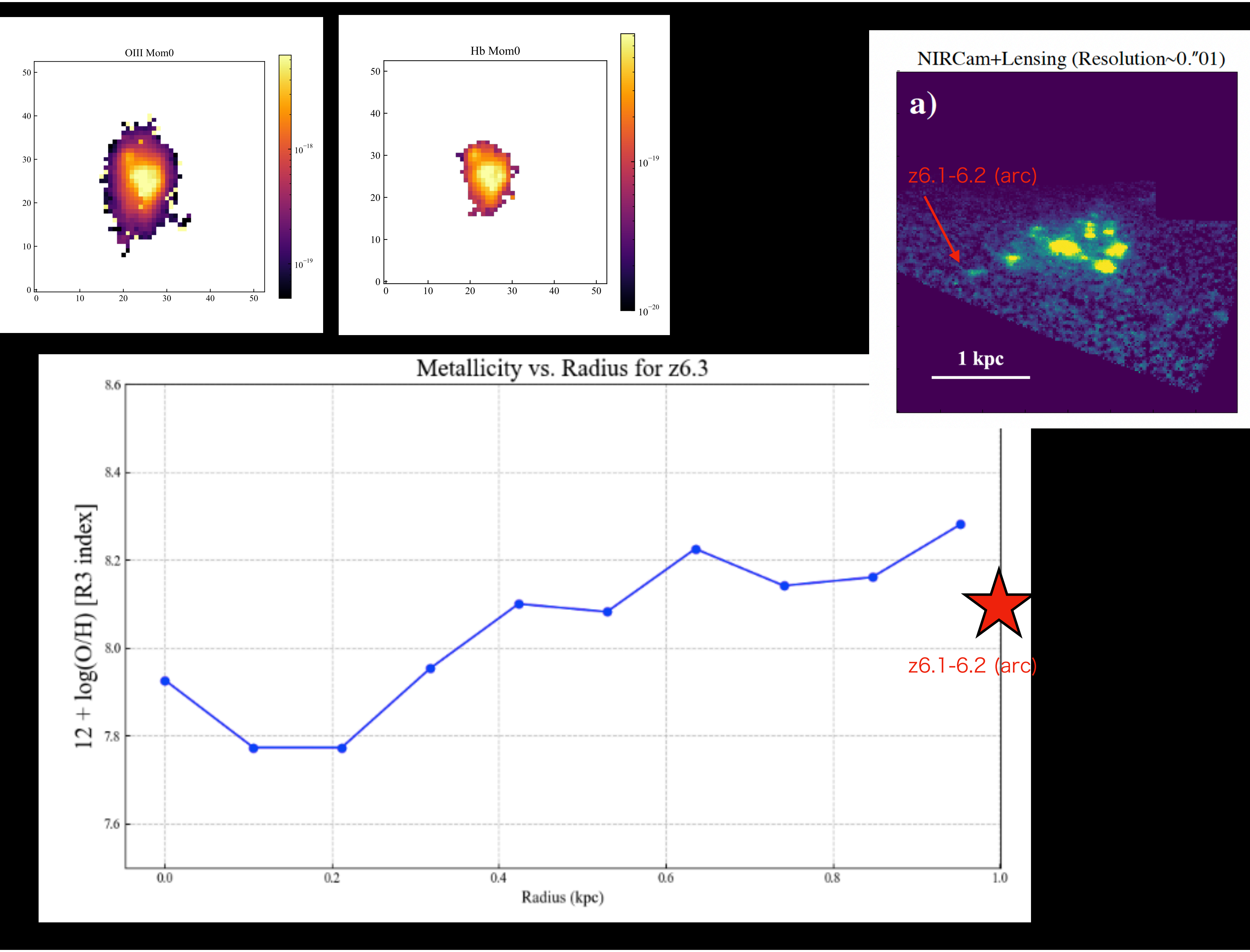
544
1037
1535
2029
2527
3021
3515
4013
4506



SII6718 Mom0
SII6733 Mom0
0
10
20
30
40
50
10^{-19}
10^{-20}



SII6718 Mom0
SII6733 Mom0
0
10
20
30
40
50
10^{-19}
10^{-20}


OIII Mom0
Hb Mom0
NIRCam+Lensing (Resolution~0.″01)
a)
z6.1-6.2 (arc)
1 kpc
Metallicity vs. Radius for z6.3
12 + log(O/H) [R3 index]
Radius (kpc)
z6.1-6.2 (arc)

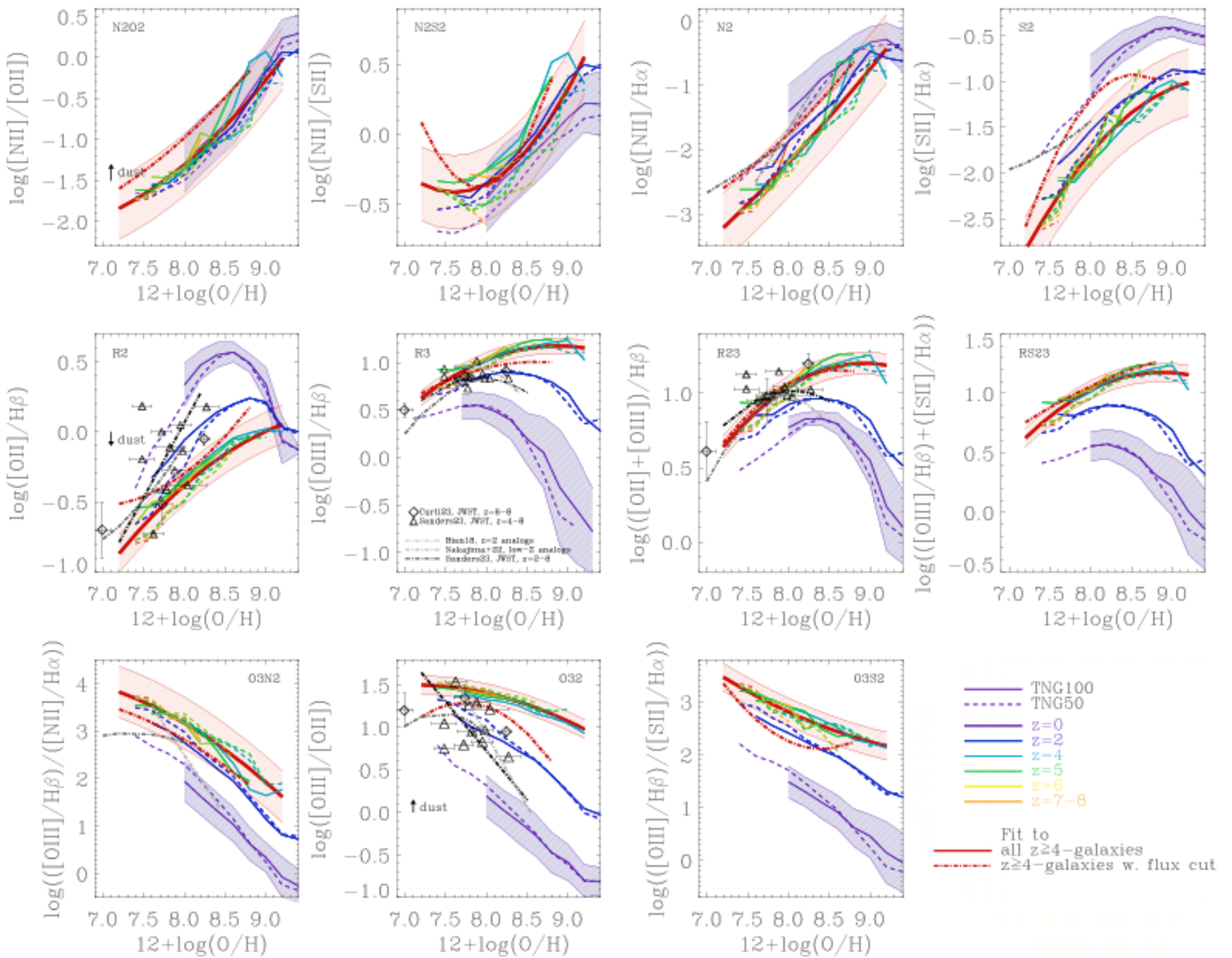
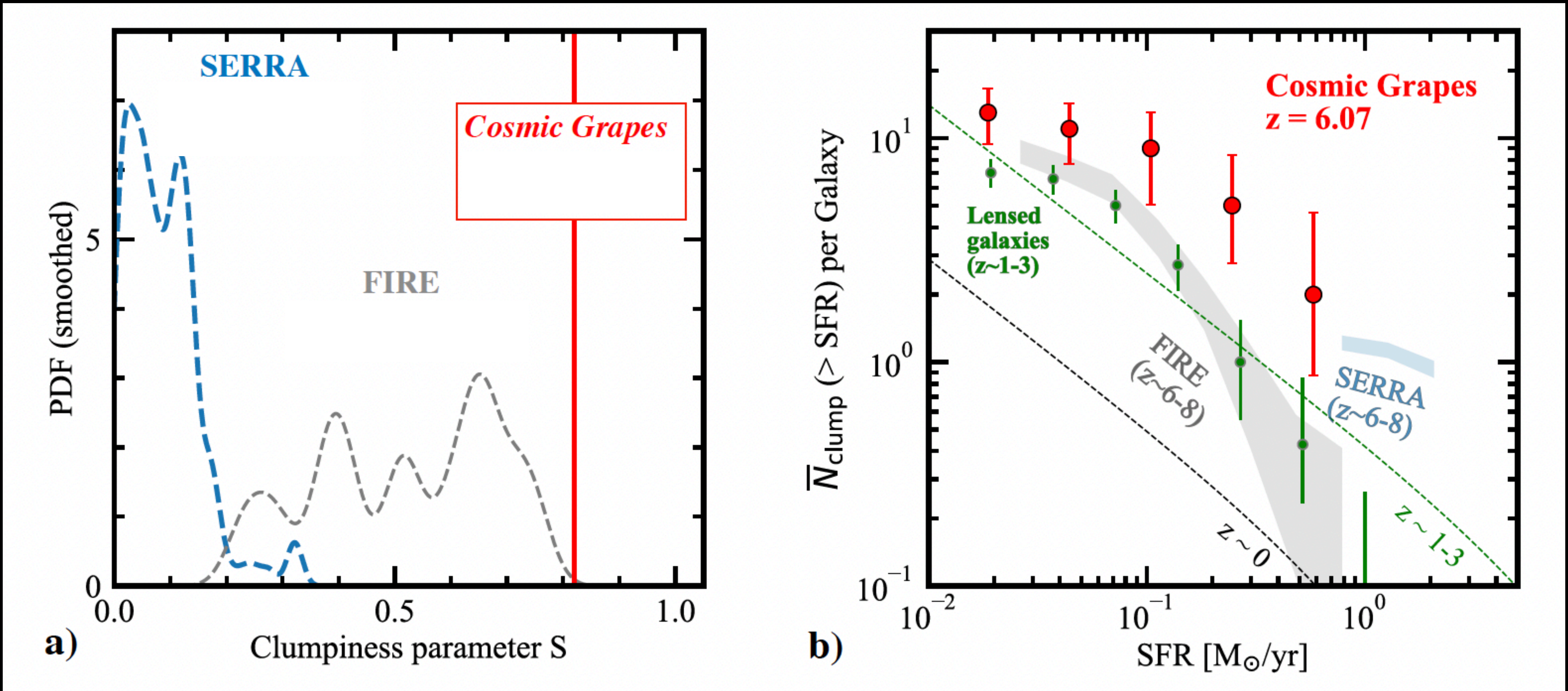


Figure 2. Analogue of Fig. 1, but now only for the global TNG50 (dashed lines) and TNG100 galaxy populations (solid lines) and at different redshifts (lilac: $z = 0$, dark blue: $z = 2$, light blue: $z = 4$, turquoise: $z = 5$, green: $z = 6$, orange: $z = 7$–8). Overplotted are fits to the predicted $z \geq 4$ relations of all galaxies (thick red line in each panel, with the fitted error shown by the red shaded area) and of galaxies above a flux limit of 3×10^{-17} erg s^{-1} cm^{-2} (thick, red dashed line). Model predictions are compared to T_e-based measurements of 12 + log(O/H) for local SDSS analogues of $z \sim 2$ galaxies from Bian et al. (2018, light grey, dash–dotted lines in the O3N2, O32, R3, and R23 panels), and for local extremely metal-poor galaxies in the Subaru EMPRESS survey from Nakajima et al. (2022, dark grey, dash–dotted lines in the R2, R3, R23, O3N2, and O32 panels). Also shown are the results inferred from *JWST*/NIRSpec spectroscopy for three galaxies at $z \sim 6$–8 from Curti et al. (2023, black diamonds with error bars in the R2, O32, R3, and R23 panels), 11 galaxies at $z \sim 4$–9 from Sanders et al. (2023, black triangles with error bars in the R2, O32, R3, and R23 panels), and their associated proposed new calibrations of the R2, R3, R23, and O32 metallicity estimators at redshifts $z \sim 2$–9 (black dash–dotted lines).

Is it expected?

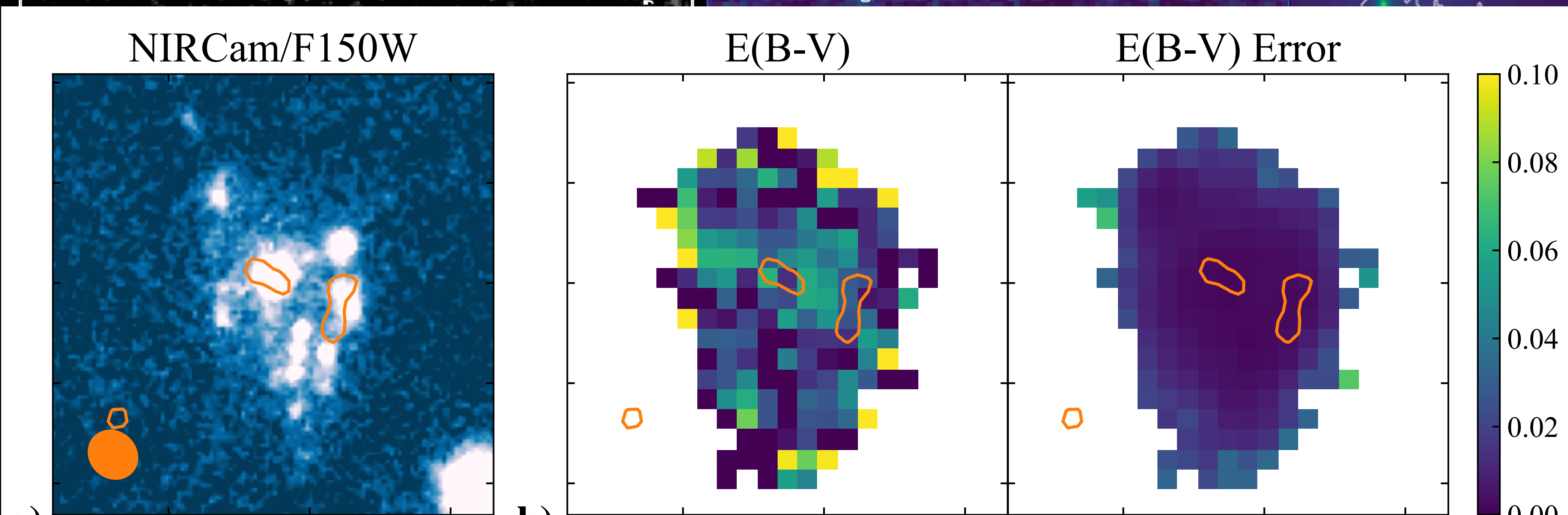
Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



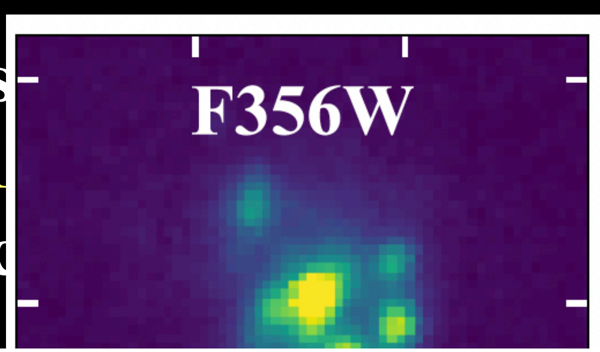
Much clumpier than expected

Deepest Dive into the true picture of Early Galaxy

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



✅ Not caused by dust obscuration



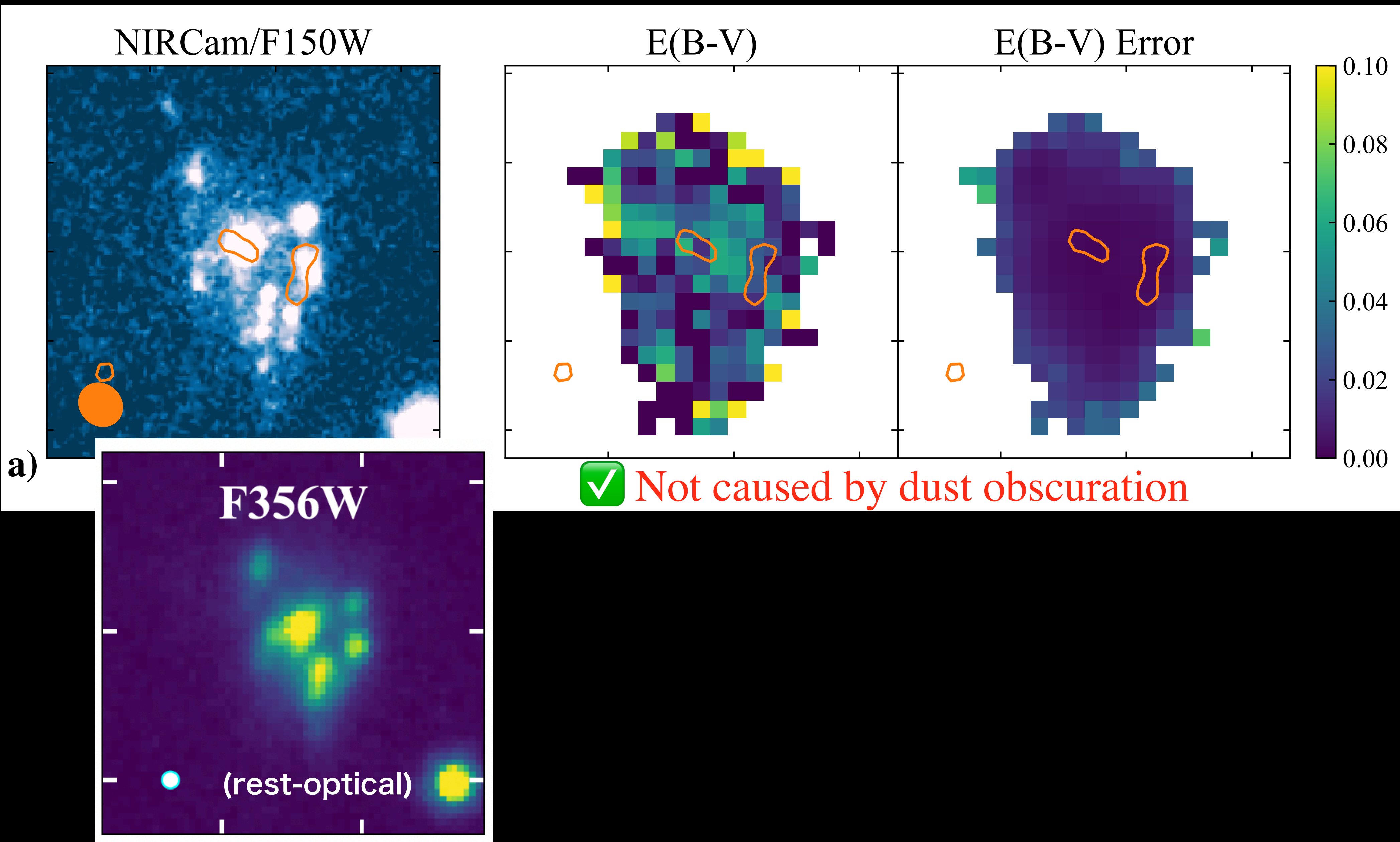
A s galaxy resolved into

~ 1 Re ~ 10-60pc, after lens corr.) **clumps,**

acc f total flux in F150W

Deepest Dive into the true picture of Early Galaxy

Fujimoto et al. 2024a, submitted (arXiv: 2402.18543)



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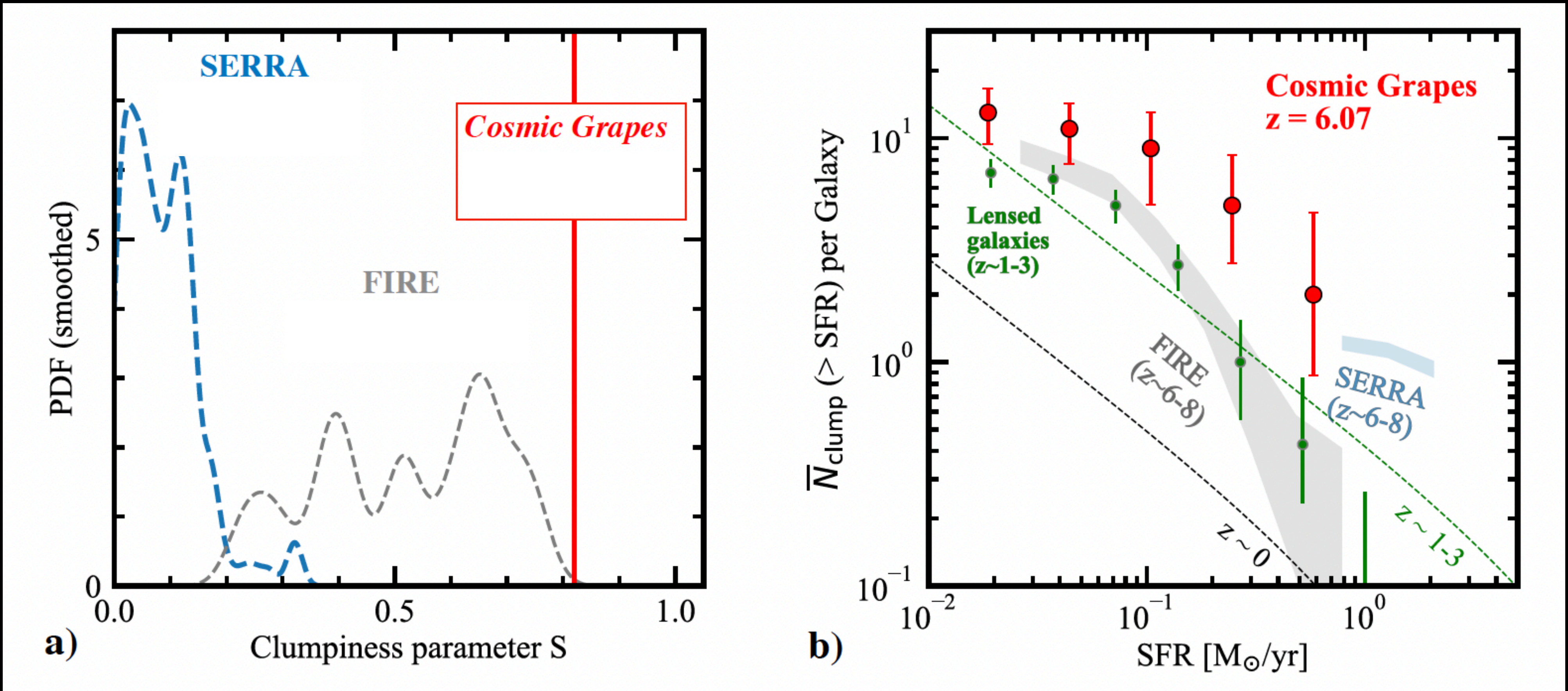
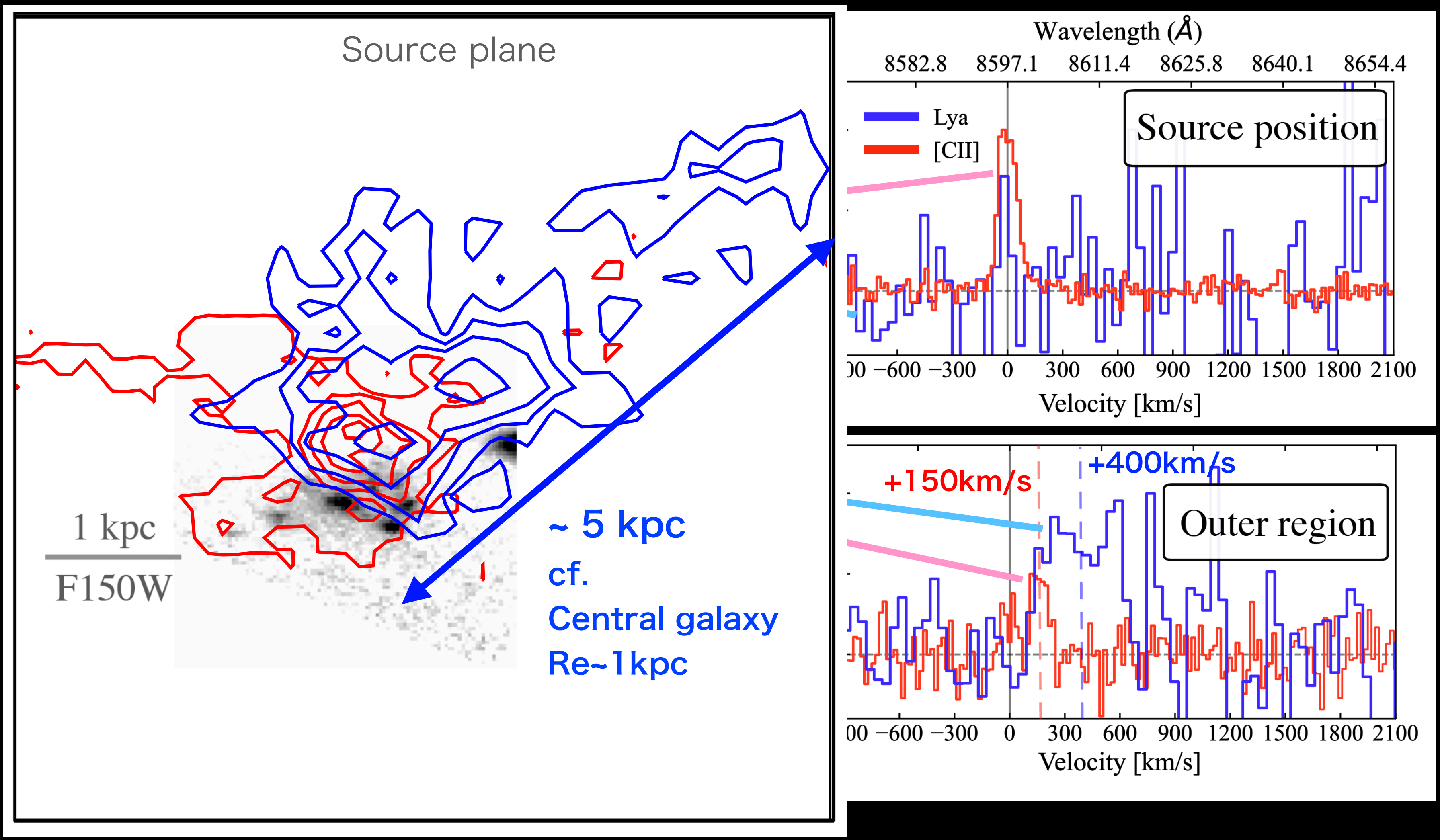


Much clumpier than expected

IFU Trio: Extended [CII] & Lya with MUSE + ALMA

Fujimoto + ALCS team (in prep.)



- Extended Lya (~6”) & [CII] (~3”) line structures appear
- Extended Lya & [CII] lines are both red-shifted w.r.t z_sys

Dynamical Interplay of Ionized gas outflow / Cold gas inflow / Scattering

Deepest views of the early galaxy

Early Galaxy Assembly Probed by JWST × ALMA × Lensing: From Small Clumps to Dynamical Interplay at z=6

Seiji Fujimoto
NASA Hubble Fellow
(UT Austin → U. Toronto)

Deepest views of the early galaxy

Early Galaxy Assembly Probed by JWST × ALMA × Lensing: From Small Clumps to Dynamical Interplay at z=6

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