Anatomy of an ionized bubble

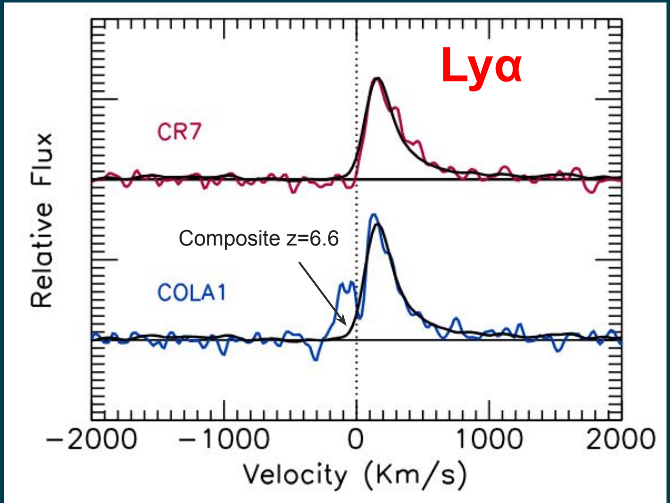
Alberto Torralba-Torregrosa, Jorryt Matthee, Rohan Naidu, Ruari Mackenzie, Gabriele Pezzulli, Anne Hutter, Pablo Arnalte-Mur, Siddhartha Gurung-López, Sandro Tacchella, Pascal Oesch, Daichi Kashino, Charlie Conroy, David Sobral

VNIVERSITAT DE VALÈNCIA

Observatori Astronòmic
VNIVERSITAT DE VALÈNCIA

COSMIC DAWN

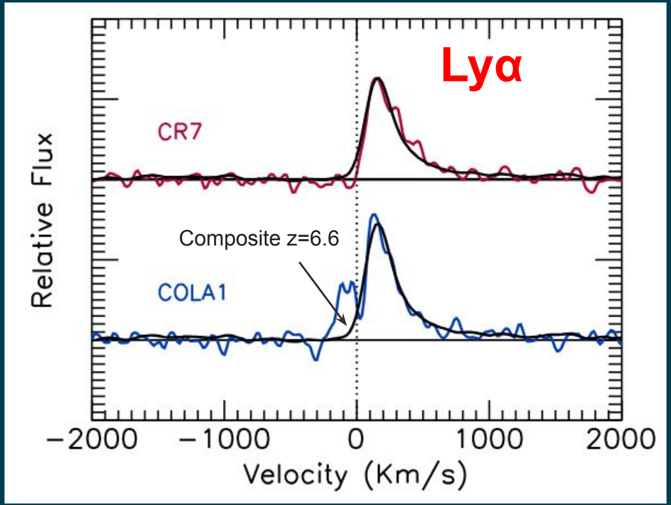
COLA1: An unusual Lyα emitter at z = 6.6



Hu+2016

- COLA1, a double-peaked Lyα emitter in the COSMOS field (Hu+16)

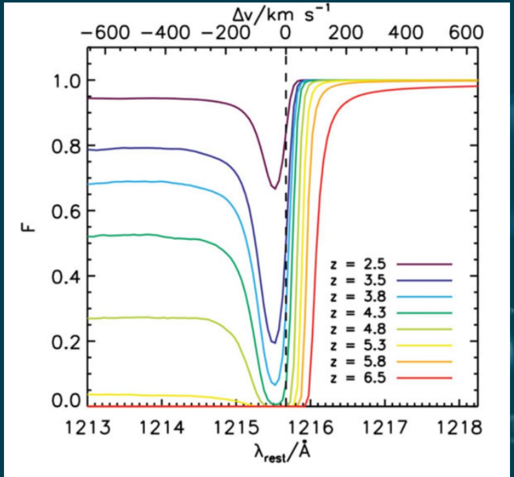
COLA1: An unusual Lyα emitter at z = 6.6



Hu+2016

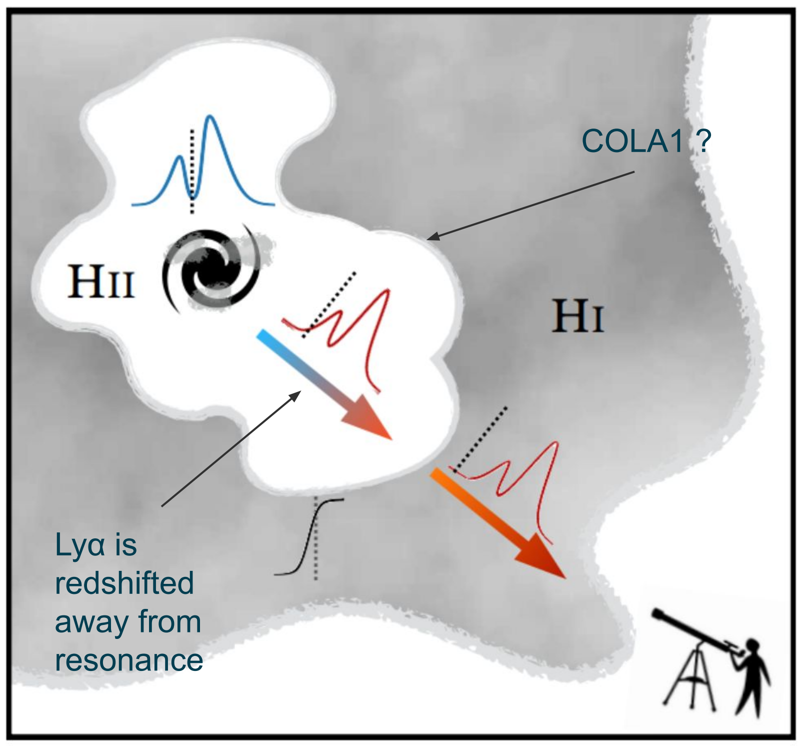
- At z = 6.6 reionization is incomplete:

  Significantly neutral IGM absorbs blue Lyα peak



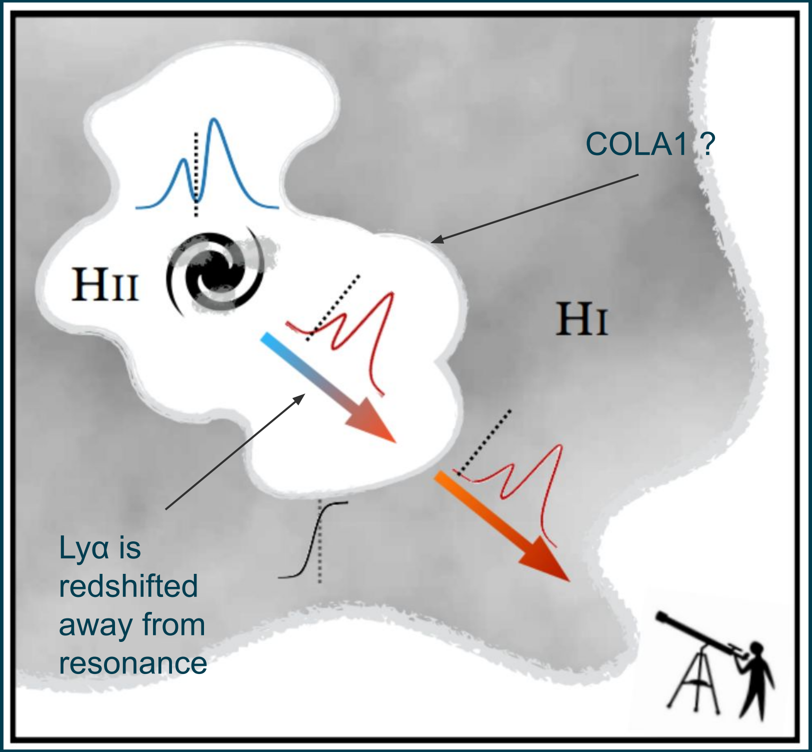
Dijkstra 2017

Does COLA1 live inside a bubble?



Matthee+2018

Does COLA1 live inside a bubble?

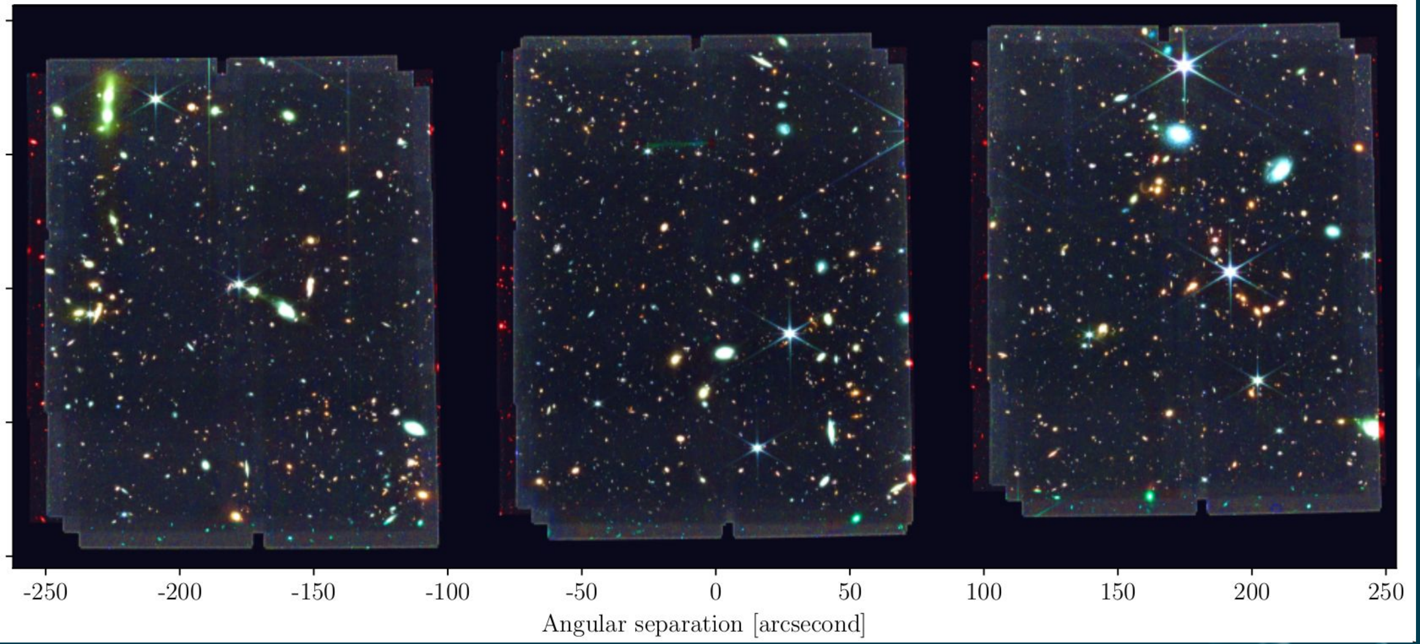


Matthee+2018

If it does, can COLA1 power the bubble?

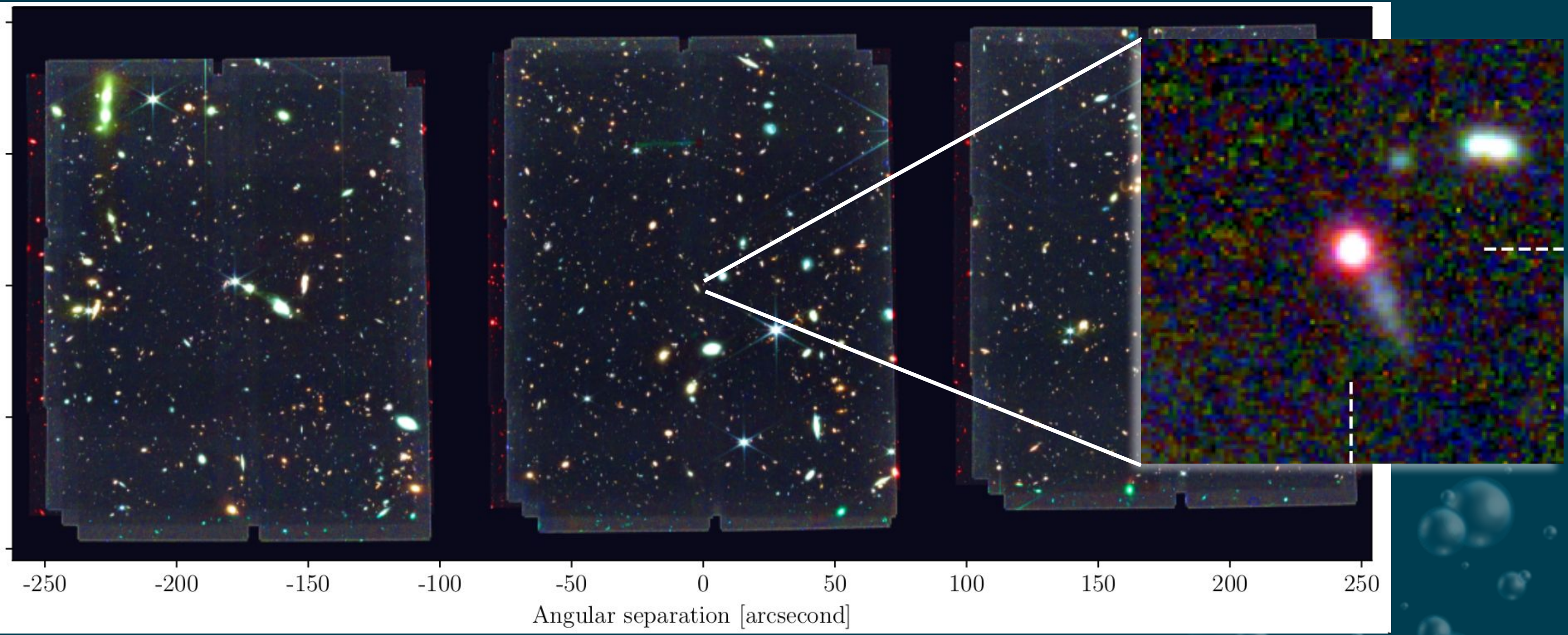
JWST COLA1 field

- Program JWST GO-1933 (PIs: Matthee & Naidu)
- NIRCam imaging: F115W, F150W, F200W, F356W
- NIRCam grism spectroscopy in F356W

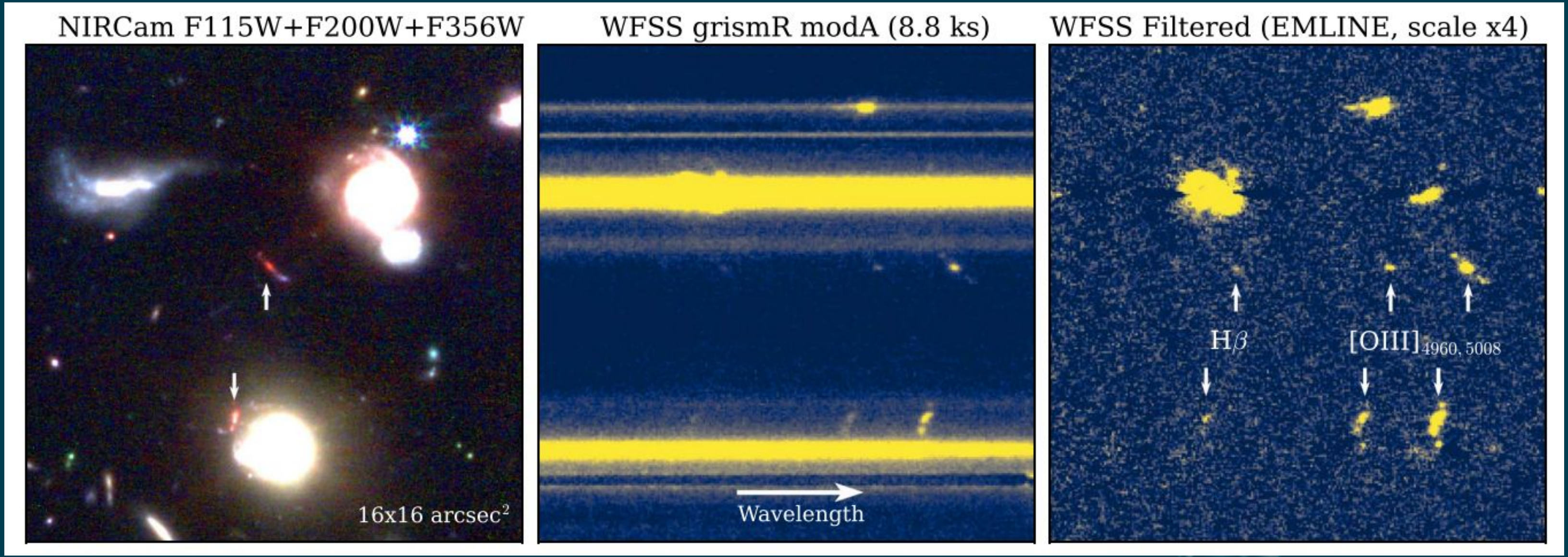


JWST COLA1 field

- Program JWST GO-1933 (PIs: Matthee & Naidu)
- NIRCam imaging: F115W, F150W, F200W, F356W
- NIRCam grism spectroscopy in F356W



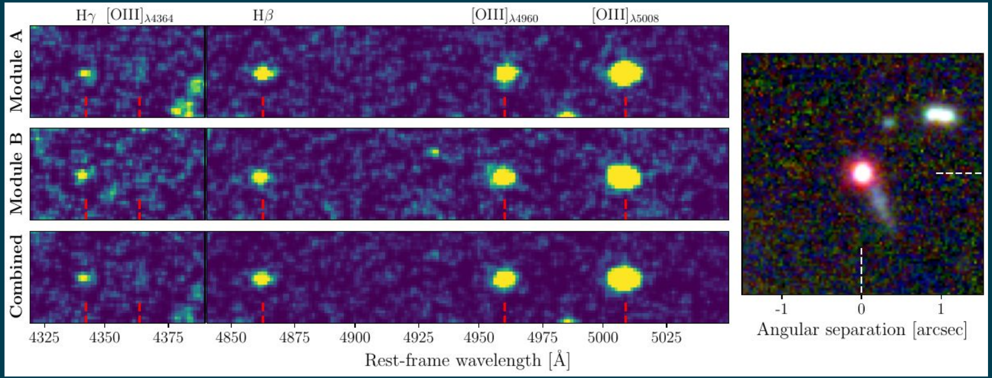
NIRCam Wide Field Slitless Spectroscopy



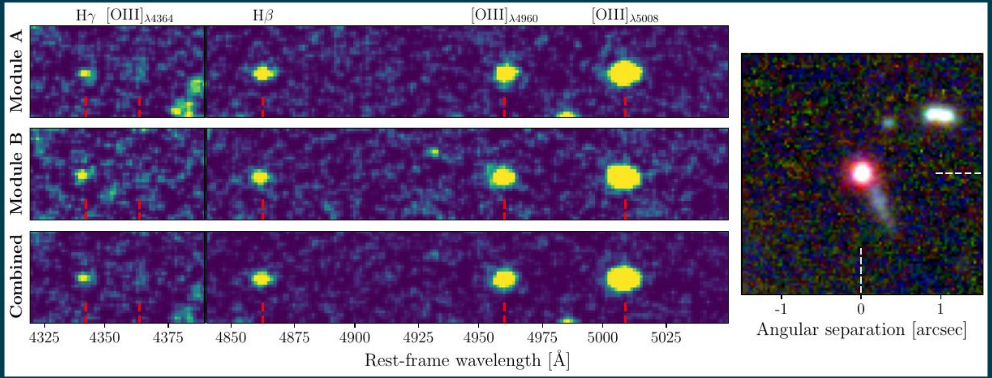
Matthee+2023

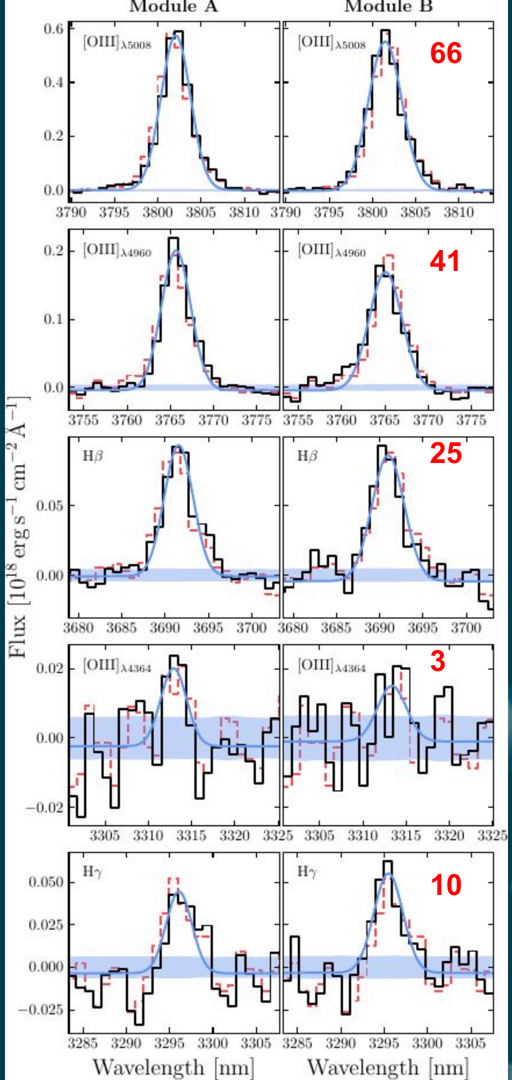
140 [OIII] emitters found in the COLA1 field

COLA1's optical lines



COLA1's optical lines

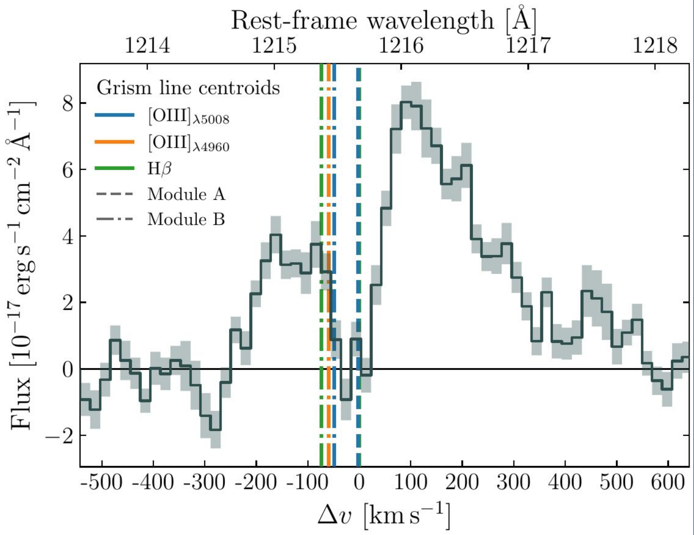




S/N

Systemic redshift

VLT/X-shooter Lyα spectrum

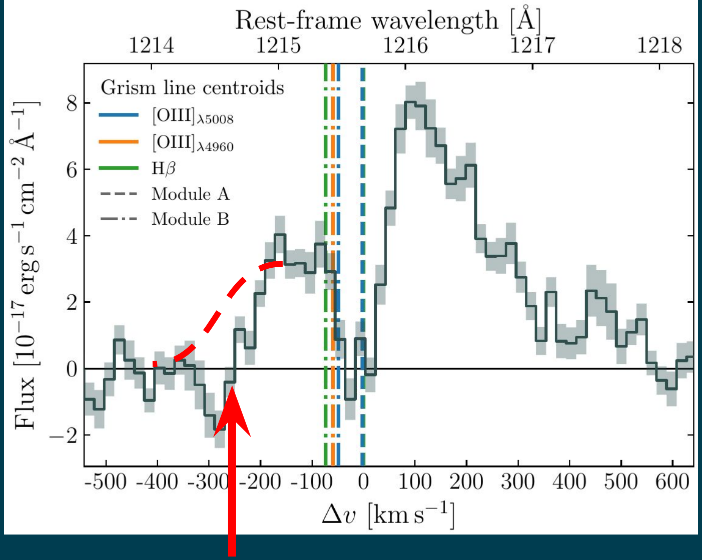


- $z_{[OIII]} = 6.5917$

- Confirmed systemic Lyα redshift!

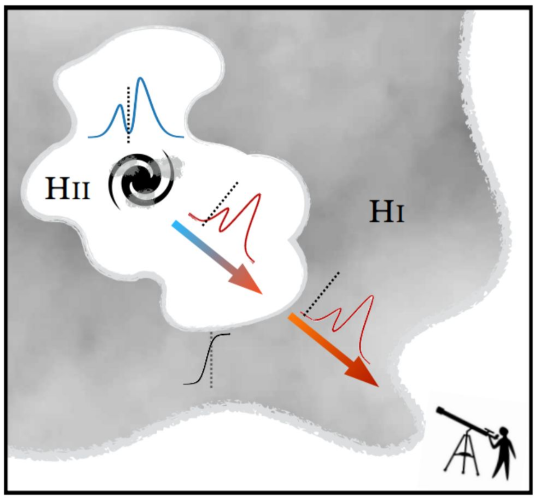
Systemic redshift

VLT/X-shooter Lyα spectrum



~0.3 pMpc

- $z_{[OIII]}$ = 6.5917 (module A)



Matthee+2018

Extent of the ionized bubble

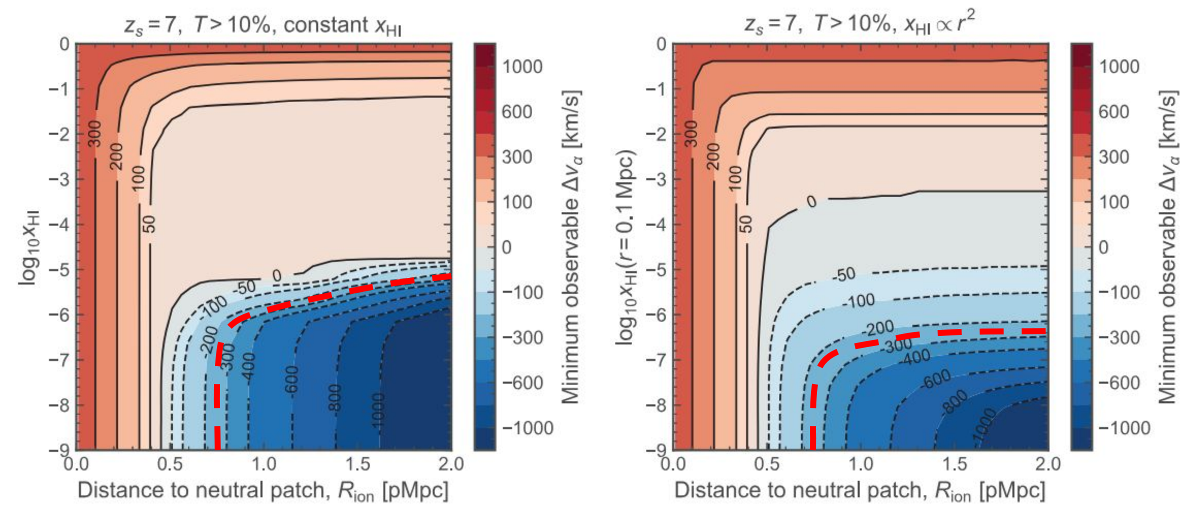
- $\Delta v_{min} \approx -250$ km/s

Accounting for the contribution of a Lyα damping wing, the size of the bubble must be **at least**

~0.7 pMpc

Uniform bubble

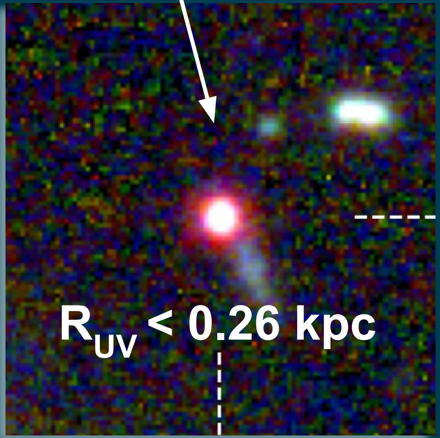
Neutral fraction ∝ r²



Mason & Gronke 2020

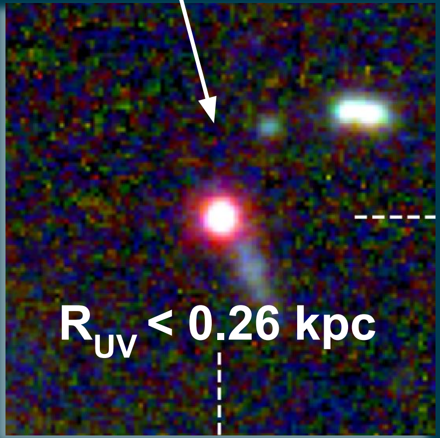
Some extreme UV properties

Unresolved in the NIRCam imaging!

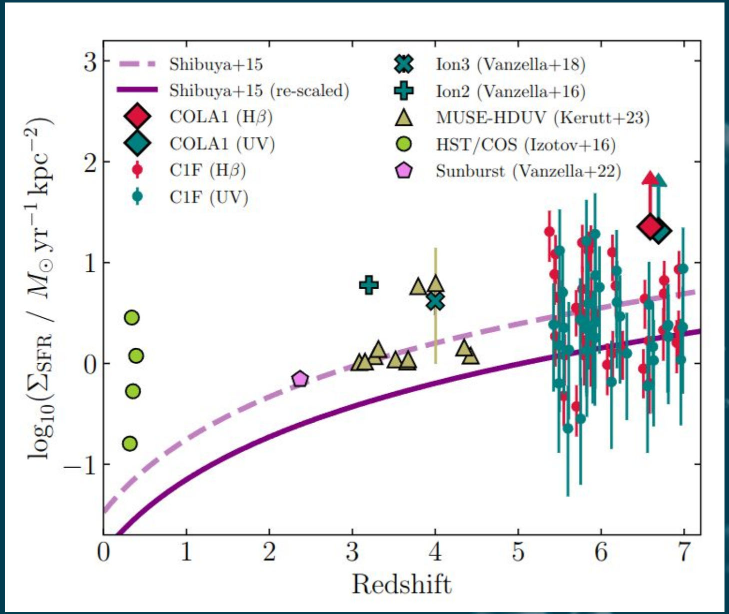


Some extreme UV properties

Unresolved in the NIRCam imaging!



Star formation surface density Σ_{SFR}



$$\Sigma_{SFR} = \frac{SFR/2}{\pi R_{UV}^2}$$

Some extreme UV properties

Table 2: The physical properties of COLA1.

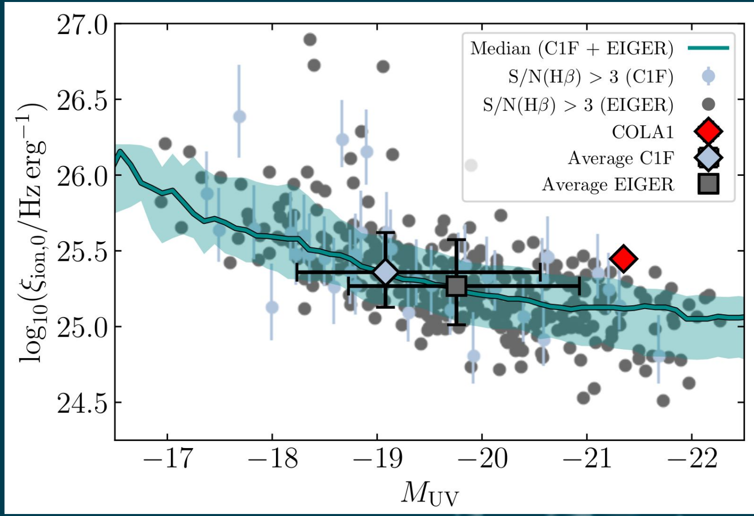
Property	Value
z^a	6.59165
$\log_{10}(\xi_{\mathrm{ion},0}/\mathrm{Hz\,erg}^{-1})^b$	$25.45^{+0.04}_{-0.05}$
$f_{\mathrm{esc}}(\mathrm{Ly}\alpha)^c$	$81 \pm 5\%$
$M_{\mathrm{UV}}{}^d$	$-21.35^{+0.07}_{-0.08}$
$\beta_{\mathrm{UV}}{}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
$T_{\mathrm{e}}{}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
$\mathrm{EW}_0([\mathrm{O\,III}]+\mathrm{H}\beta)^h$	870^{+90}_{-80}
$12 + \log_{10}(\mathrm{O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
$R_{\mathrm{UV}}{}^j$	<0.26 kpc
$\mathrm{SFR}_0(\mathrm{UV})^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,\mathrm{yr}^{-1}$
$\mathrm{SFR}_0(\mathrm{H}\beta)^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,\mathrm{yr}^{-1}$
$\log_{10}(\Sigma_{\mathrm{SFR}}/M_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2})(\mathrm{UV})^m$	>1.31
$\log_{10}(\Sigma_{\mathrm{SFR}}/M_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2})(\mathrm{H}\beta)^n$	>1.36

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^{a}	6.59165
$\log_{10}(\xi_{\rm ion,0}/{\rm Hz\,erg^{-1}})^{b}$	$25.45^{+0.04}_{-0.05}$
$f_{\rm esc}({\rm Ly}\alpha)^{c}$	81 ± 5%
$M_{\rm UV}{}^{d}$	$-21.35^{+0.07}_{-0.08}$
$\beta_{\rm UV}{}^{e}$	-3.2 ± 0.4
$E(B-V)^{f}$	$0.00^{+0.02}_{-0.00}$
$T_{\rm e}{}^{g}$	$1.7^{+0.4}_{-0.3} \times 10^{4}$ K
${\rm EW_0([O\,III]+H\beta)}^{h}$	870^{+90}_{-80}
$12 + \log_{10}({\rm O/H})_{T_e}{}^{i}$	$7.88^{+0.33}_{-0.30}$
$R_{\rm UV}{}^{j}$	<0.26 kpc
${\rm SFR_0(UV)}^{k}$	$9.6^{+1.7}_{-0.8}\ M_{\odot}\,{\rm yr^{-1}}$
${\rm SFR_0(H\beta)}^{l}$	$10.1^{+0.9}_{-0.5}\ M_{\odot}\,{\rm yr^{-1}}$
$\log_{10}(\Sigma_{\rm SFR}/M_{\odot}\,{\rm yr^{-1}\,kpc^{-2}})({\rm UV})^{m}$	>1.31
$\log_{10}(\Sigma_{\rm SFR}/M_{\odot}\,{\rm yr^{-1}\,kpc^{-2}})({\rm H\beta})^{n}$	>1.36

Moderately high ionizing photon production efficiency



Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^a	6.59165
$\log_{10}(\xi_{\rm ion,0}/{\rm Hz\,erg^{-1}})^b$	$25.45^{+0.04}_{-0.05}$
$f_{\rm esc}({\rm Ly}\alpha)^c$	$81 \pm 5\%$
${M_{\rm UV}}^d$	$-21.35^{+0.07}_{-0.08}$
${\beta_{\rm UV}}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
${T_{\rm e}}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
${\rm EW}_0([{\rm O\,III}]+{\rm H}\beta)^h$	870^{+90}_{-80}
$12 + \log_{10}({\rm O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
${R_{\rm UV}}^j$	<0.26 kpc
${\rm SFR}_0({\rm UV})^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,{\rm yr}^{-1}$
${\rm SFR}_0({\rm H}\beta)^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,{\rm yr}^{-1}$
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr^{-1}\,kpc^{-2}})({\rm UV})^m$	>1.31
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr^{-1}\,kpc^{-2}})({\rm H}\beta)^n$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}**(Lyα)**

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^a	6.59165
$\log_{10}(\xi_{ion,0}/\mathrm{Hz\,erg^{-1}})^b$	$25.45^{+0.04}_{-0.05}$
$f_{esc}(\mathrm{Ly}\alpha)^c$	$81 \pm 5\%$
$M_{UV}{}^d$	$-21.35^{+0.07}_{-0.08}$
$\beta_{UV}{}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
$T_e{}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
$\mathrm{EW_0([O\,III]+H\beta)}^h$	870^{+90}_{-80}
$12 + \log_{10}(\mathrm{O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
$R_{UV}{}^j$	<0.26 kpc
$\mathrm{SFR_0(UV)}^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,\mathrm{yr^{-1}}$
$\mathrm{SFR_0(H\beta)}^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,\mathrm{yr^{-1}}$
$\log_{10}(\Sigma_{SFR}/M_\odot\,\mathrm{yr^{-1}\,kpc^{-2}})(\mathrm{UV})^m$	>1.31
$\log_{10}(\Sigma_{SFR}/M_\odot\,\mathrm{yr^{-1}\,kpc^{-2}})(\mathrm{H}\beta)^n$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}**(Lyα)**

Bright UV continuum

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^a	6.59165
$\log_{10}(\xi_{ion,0}/\mathrm{Hz\,erg^{-1}})^b$	$25.45^{+0.04}_{-0.05}$
$f_{esc}(\mathrm{Ly}\alpha)^c$	81 ± 5%
$M_{UV}{}^d$	$-21.35^{+0.07}_{-0.08}$
$\beta_{UV}{}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
$T_e{}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
$\mathrm{EW_0([O\,III]+H\beta)}^h$	870^{+90}_{-80}
$12 + \log_{10}(\mathrm{O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
$R_{UV}{}^j$	<0.26 kpc
$\mathrm{SFR_0(UV)}^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,\mathrm{yr}^{-1}$
$\mathrm{SFR_0(H\beta)}^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,\mathrm{yr}^{-1}$
$\log_{10}(\Sigma_{SFR}/M_\odot\,\mathrm{yr^{-1}\,kpc^{-2}})(\mathrm{UV})^m$	>1.31
$\log_{10}(\Sigma_{SFR}/M_\odot\,\mathrm{yr^{-1}\,kpc^{-2}})(\mathrm{H}\beta)^n$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}**(Lyα)**

Bright UV continuum

Very steep UV slope

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^{a}	6.59165
$\log_{10}(\xi_{\mathrm{ion},0}/\mathrm{Hz\,erg^{-1}})^{b}$	$25.45^{+0.04}_{-0.05}$
$f_{\mathrm{esc}}(\mathrm{Ly}\alpha)^{c}$	$81 \pm 5\%$
$M_{\mathrm{UV}}{}^{d}$	$-21.35^{+0.07}_{-0.08}$
$\beta_{\mathrm{UV}}{}^{e}$	-3.2 ± 0.4
$E(B-V)^{f}$	$0.00^{+0.02}_{-0.00}$
$T_{\mathrm{e}}{}^{g}$	$1.7^{+0.4}_{-0.3} \times 10^{4}$ K
$\mathrm{EW}_0([\mathrm{O\,III}]+\mathrm{H}\beta)^{h}$	870^{+90}_{-80}
$12 + \log_{10}(\mathrm{O/H})_{T_e}{}^{i}$	$7.88^{+0.33}_{-0.30}$
$R_{\mathrm{UV}}{}^{j}$	<0.26 kpc
$\mathrm{SFR}_0(\mathrm{UV})^{k}$	$9.6^{+1.7}_{-0.8}\ M_{\odot}\,\mathrm{yr}^{-1}$
$\mathrm{SFR}_0(\mathrm{H}\beta)^{l}$	$10.1^{+0.9}_{-0.5}\ M_{\odot}\,\mathrm{yr}^{-1}$
$\log_{10}(\Sigma_{\mathrm{SFR}}/M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2})(\mathrm{UV})^{m}$	>1.31
$\log_{10}(\Sigma_{\mathrm{SFR}}/M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2})(\mathrm{H}\beta)^{n}$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}**(Lyα)**

Bright UV continuum

Very steep UV slope

No dust attenuation

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^a	6.59165
$\log_{10}(\xi_{\rm ion,0}/{\rm Hz\,erg^{-1}})^b$	$25.45^{+0.04}_{-0.05}$
$f_{\rm esc}({\rm Ly}\alpha)^c$	$81 \pm 5\%$
$M_{\rm UV}{}^d$	$-21.35^{+0.07}_{-0.08}$
$\beta_{\rm UV}{}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
$T_{\rm e}{}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
${\rm EW_0([O\,III]+H\beta)}^h$	870^{+90}_{-80}
$12 + \log_{10}({\rm O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
$R_{\rm UV}{}^j$	<0.26 kpc
${\rm SFR_0(UV)}^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,{\rm yr^{-1}}$
${\rm SFR_0(H\beta)}^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,{\rm yr^{-1}}$
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr^{-1}\,kpc^{-2}})({\rm UV})^m$	>1.31
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr^{-1}\,kpc^{-2}})({\rm H\beta})^n$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}**(Lyα)**

Bright UV continuum

Very steep UV slope

No dust attenuation

Extremely compact

Some extreme UV properties

Table 2: The physical properties of COLA1.

Property	Value
z^a	6.59165
$\log_{10}(\xi_{\rm ion,0}/{\rm Hz\,erg^{-1}})^b$	$25.45^{+0.04}_{-0.05}$
$f_{\rm esc}({\rm Ly}\alpha)^c$	$81 \pm 5\%$
$M_{\rm UV}{}^d$	$-21.35^{+0.07}_{-0.08}$
$\beta_{\rm UV}{}^e$	-3.2 ± 0.4
$E(B-V)^f$	$0.00^{+0.02}_{-0.00}$
$T_{\rm e}{}^g$	$1.7^{+0.4}_{-0.3} \times 10^4$ K
${\rm EW}_0([{\rm O\,III}]+{\rm H}\beta)^h$	870^{+90}_{-80}
$12 + \log_{10}({\rm O/H})_{T_e}{}^i$	$7.88^{+0.33}_{-0.30}$
$R_{\rm UV}{}^j$	<0.26 kpc
${\rm SFR}_0({\rm UV})^k$	$9.6^{+1.7}_{-0.8}\ M_\odot\,{\rm yr}^{-1}$
${\rm SFR}_0({\rm H}\beta)^l$	$10.1^{+0.9}_{-0.5}\ M_\odot\,{\rm yr}^{-1}$
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2})({\rm UV})^m$	>1.31
$\log_{10}(\Sigma_{\rm SFR}/M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2})({\rm H}\beta)^n$	>1.36

Moderately high ionizing photon production efficiency

High f_{esc}(Lyα)

Bright UV continuum

Very steep UV slope

No dust attenuation

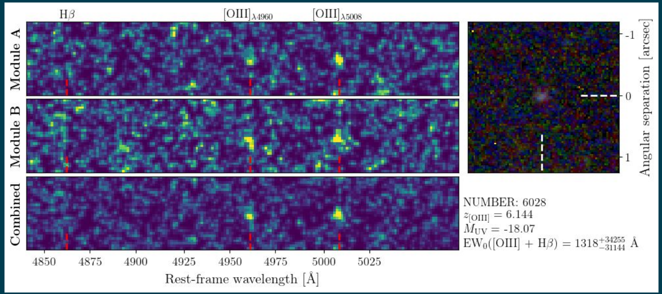
Extremely compact

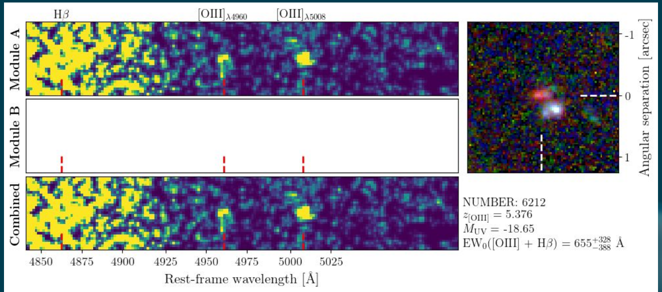
Moderately high SFR

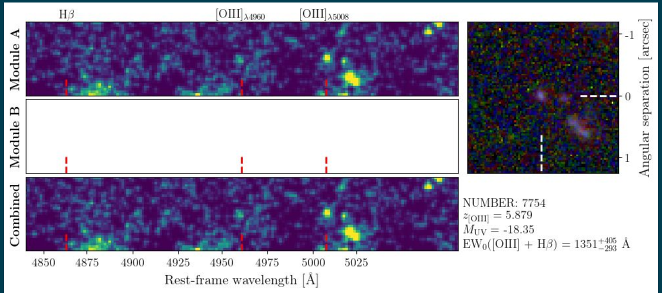
[OIII] emitters in the C1 Field

- 140 [OIII] emitters found in the COLA1 field (5.3 < z < 7)

Some examples:

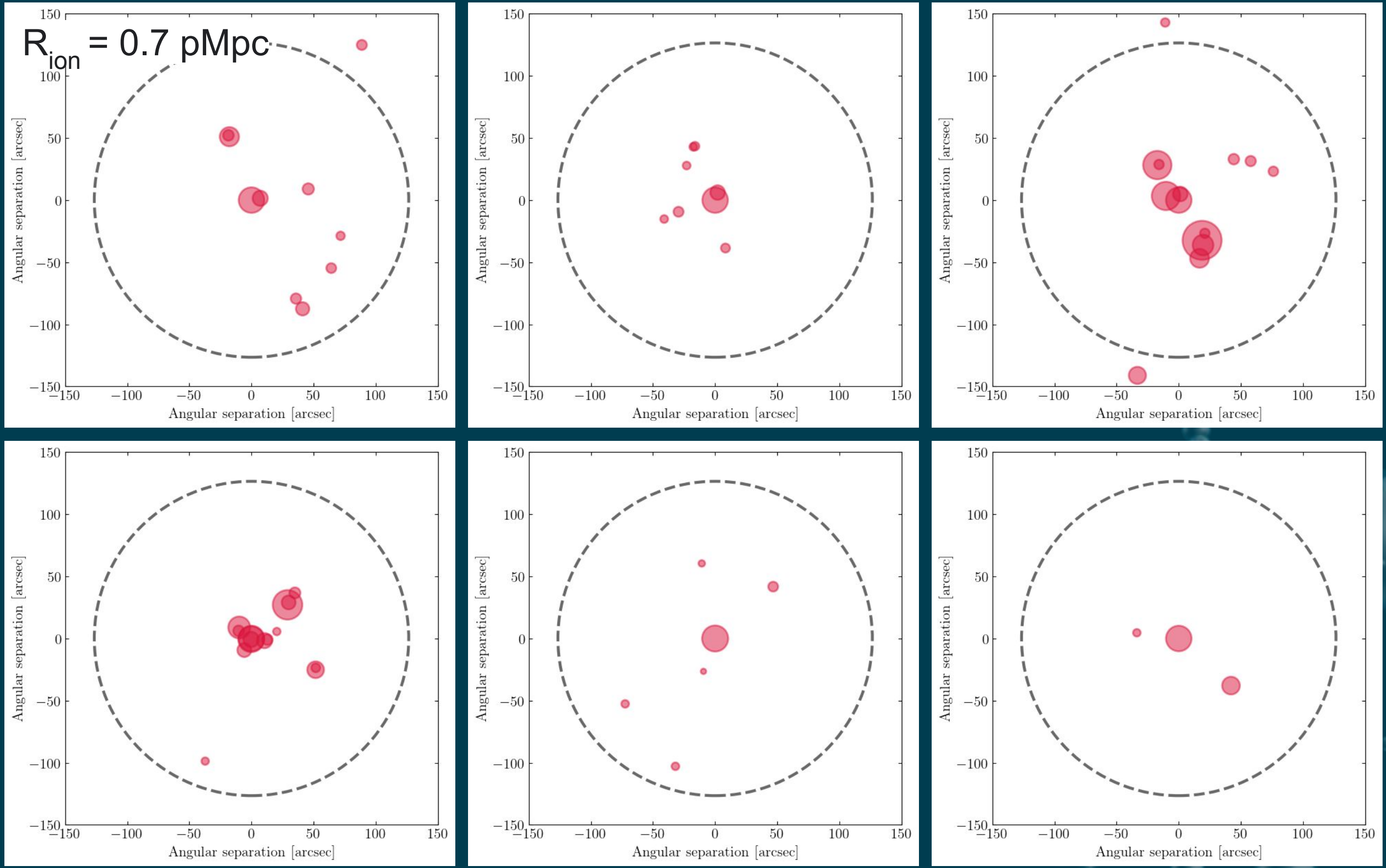




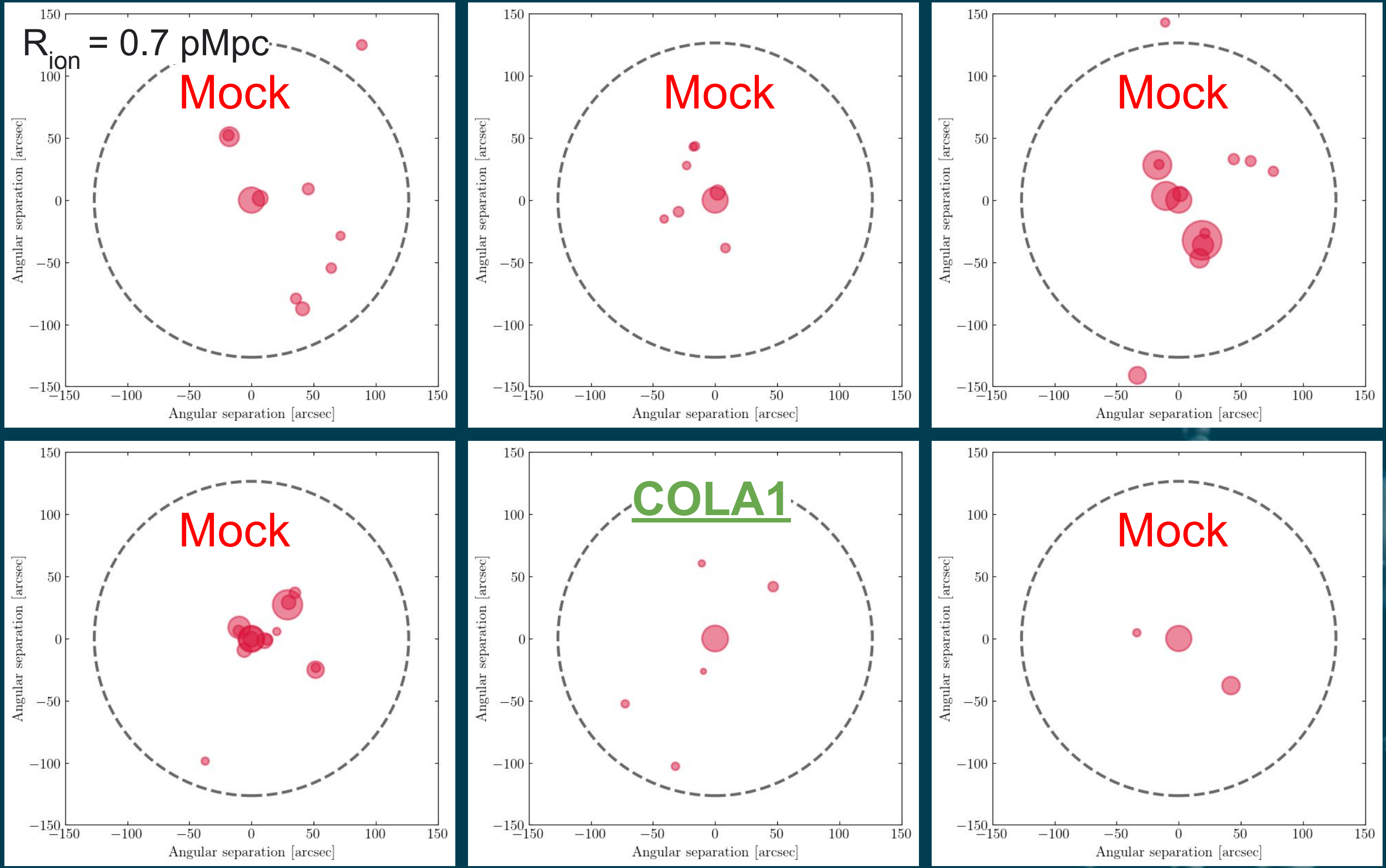


Torralba-Torregrosa+2024

Mock based on Uuchu DM simulation (Ishiyama+21) & Behroozi+19 UniverseMachine; $M_{UV} \lesssim -17.5$



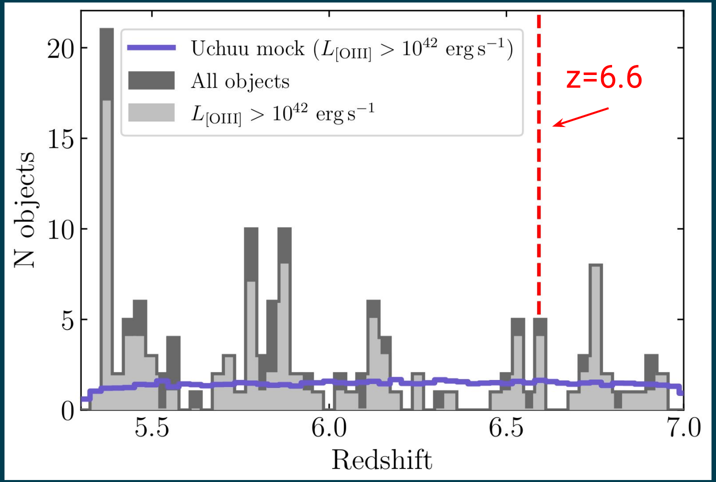
Mock based on Uuchu DM simulation (Ishiyama+21) & Behroozi+19 UniverseMachine; $M_{UV} \lesssim -17.5$

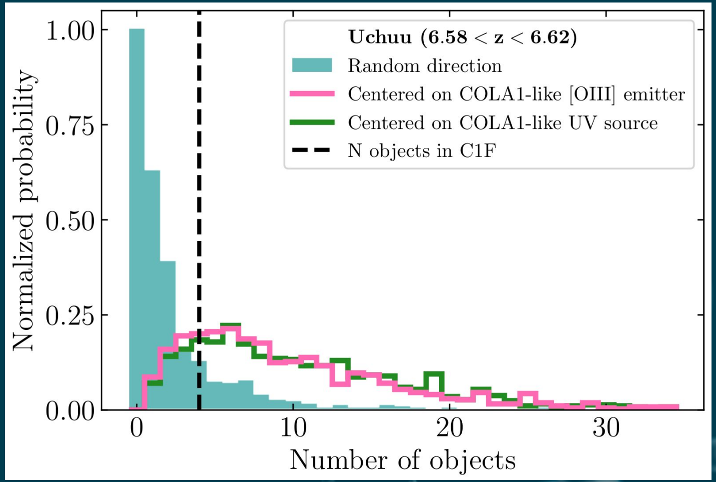


[OIII] emitters in the C1 Field

- 140 [OIII] emitters found in the COLA1 field

COLA1 lives in an overdensity, but not a particularly large one





Can COLA1 ionize its bubble?

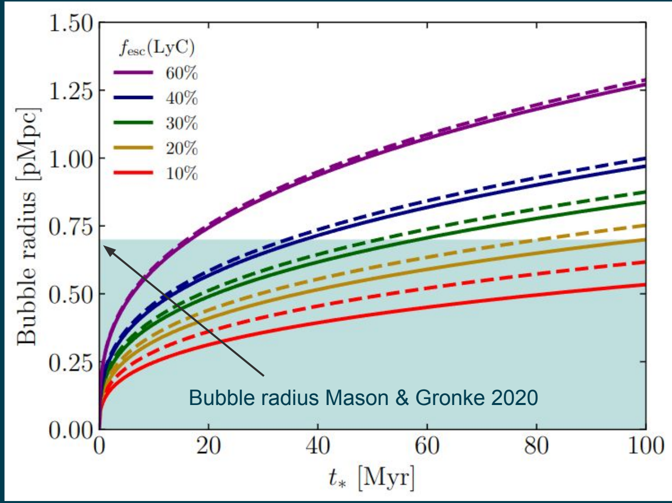
- LyC escape fraction?

f_{esc}(LyC)	Method	Reference
$28^{+10}_{-6}\%$	Lyα peak separation	Izotov et al. (2018)
$12 \pm 4\%^{\dagger}$	f_{esc}(Lyα)	Begley et al. (2024)
$56 \pm 7\%$	f_{esc}(Lyα)	Maji et al. (2022)
$45 \pm 10\%$	f_{esc}(Lyα)	Kimm et al. (2022)
$> 20\%$	f_{cen}(Lyα)	Naidu et al. (2022a)
$> 44\%$	Σ_{SFR}	Naidu et al. (2020)
$84^{+277}_{-65}\%^{\dagger}$	β_{UV}	Chisholm et al. (2022)

Every indicator suggests high f_{esc}!

Can COLA1 ionize its bubble?

- LyC escape fraction?



f_{esc}(LyC)	Method	Reference
$28^{+10}_{-6}\%$	Lyα peak separation	Izotov et al. (2018)
$12 \pm 4\%^{\dagger}$	f_{esc}(Lyα)	Begley et al. (2024)
$56 \pm 7\%$	f_{esc}(Lyα)	Maji et al. (2022)
$45 \pm 10\%$	f_{esc}(Lyα)	Kimm et al. (2022)
$> 20\%$	f_{cen}(Lyα)	Naidu et al. (2022a)
$> 44\%$	Σ_{SFR}	Naidu et al. (2020)
$84^{+277}_{-65}\%^{\dagger}$	β_{UV}	Chisholm et al. (2022)

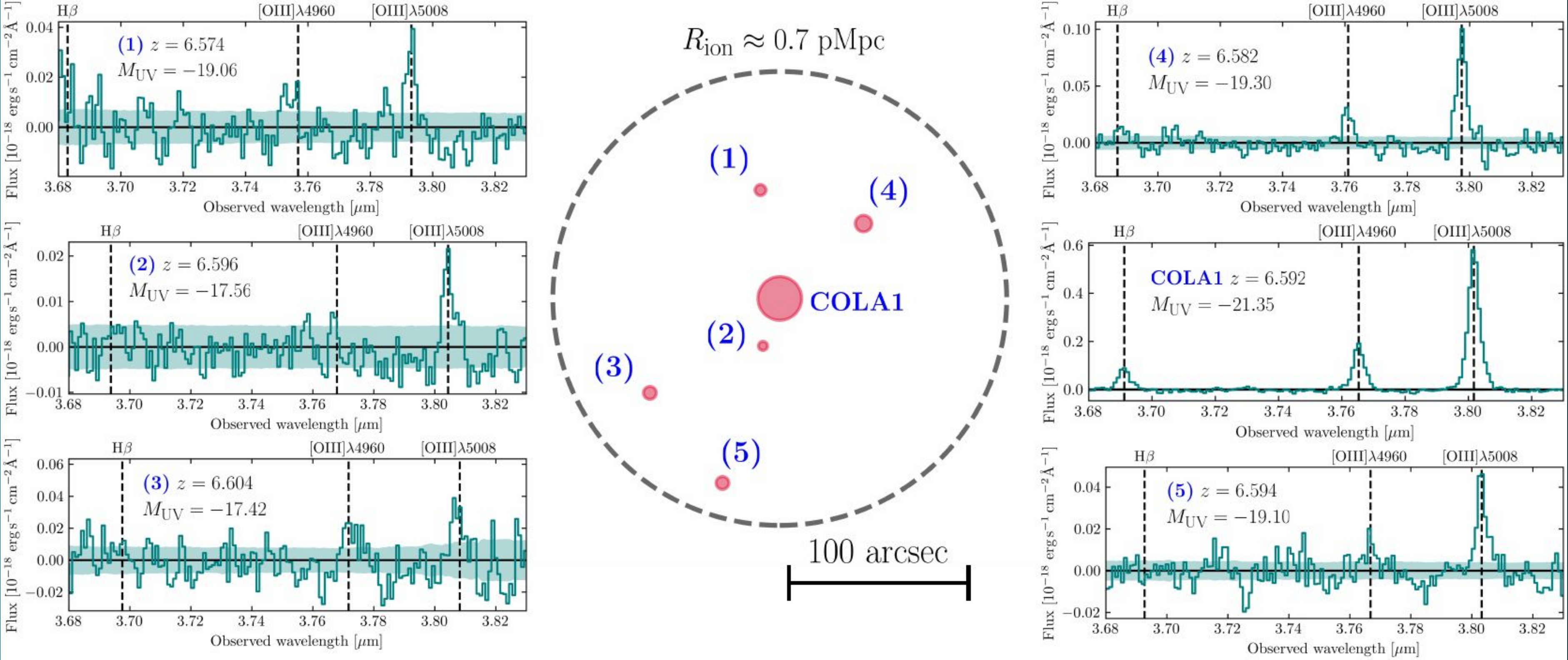
Every indicator suggests high f_{esc}!

Takeaways

- COLA1 has an unusual double-peaked Lyα at $z = 6.6$, which can be explained by the presence of an **ionized region**.
- It has all the signs of an **extremely luminous LyC leaker**.
- Extreme properties cannot be attributed to a particularly large overdensity.
- We could be witnessing **a luminous galaxy directly ionizing its surroundings**

Paper: arXiv:2404.10040

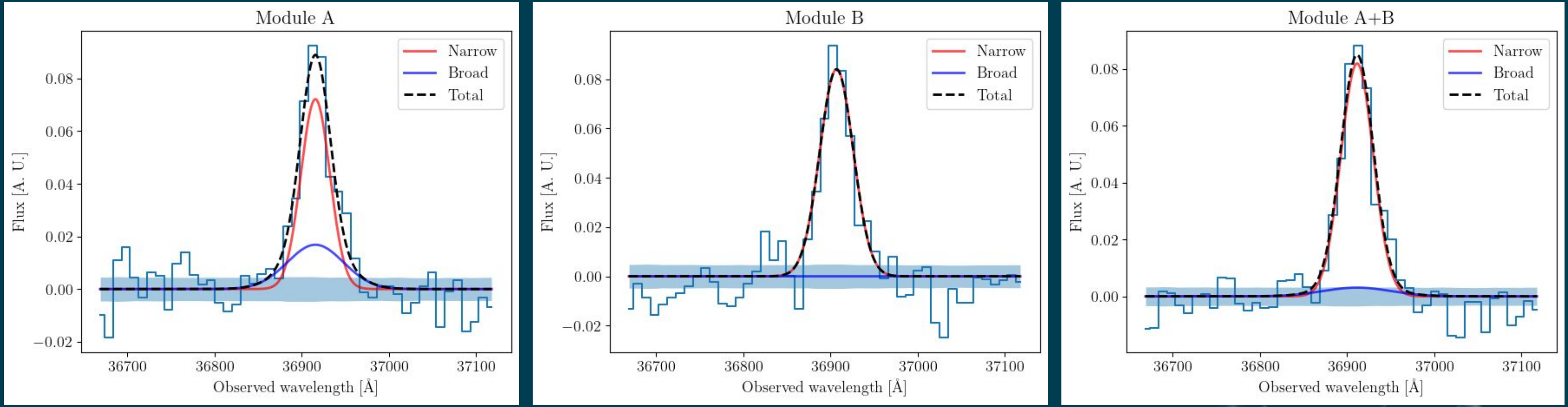
COLA1's neighbors



Is COLA1 powered by an AGN?

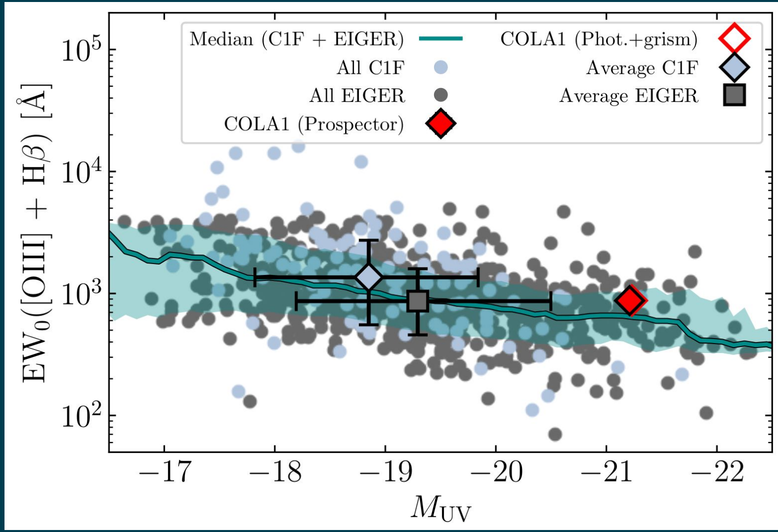
- Narrow Lyα, Hβ

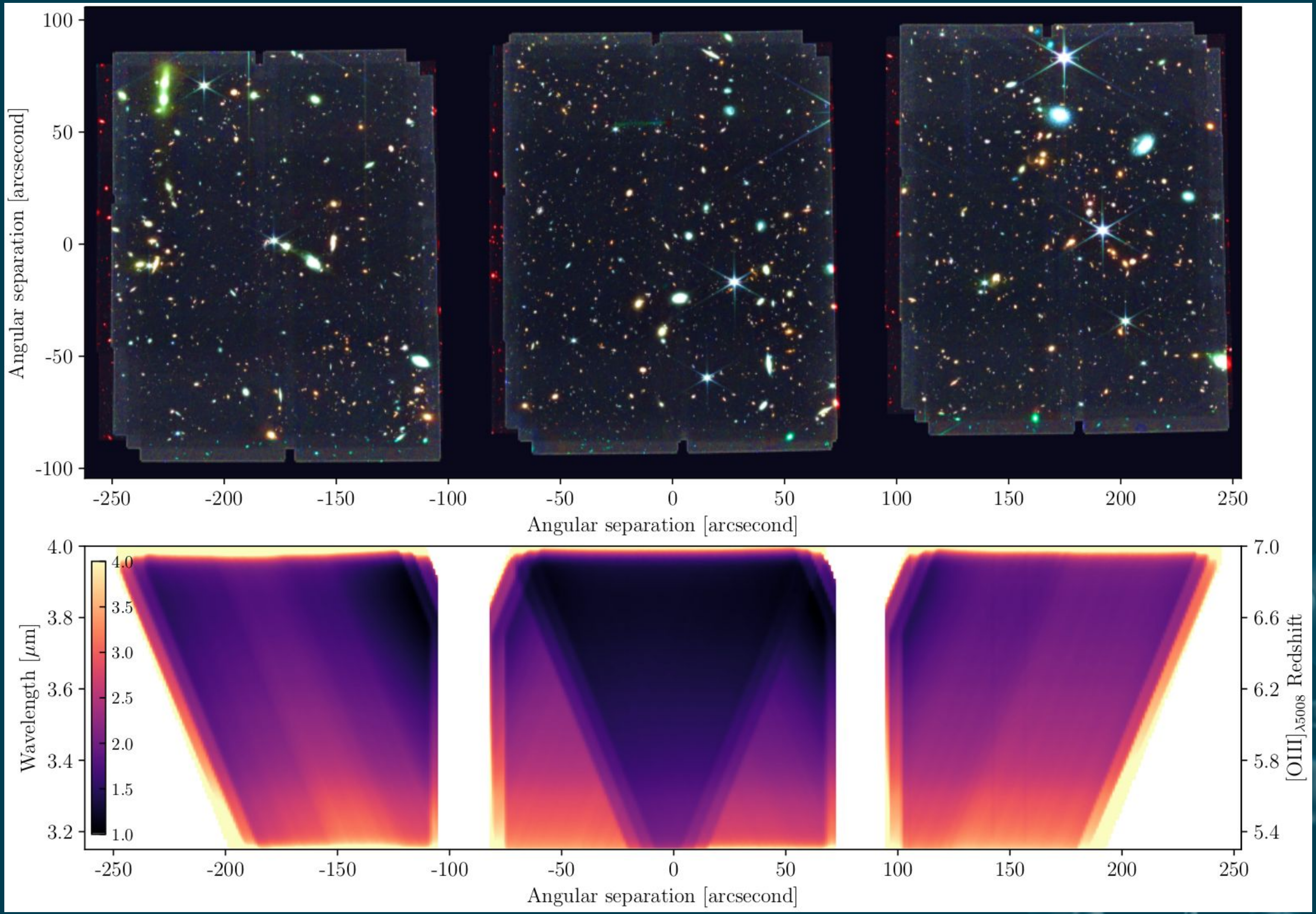
Hβ broad+narrow component fit



Broad Hβ component can only explain <30% of UV luminosity

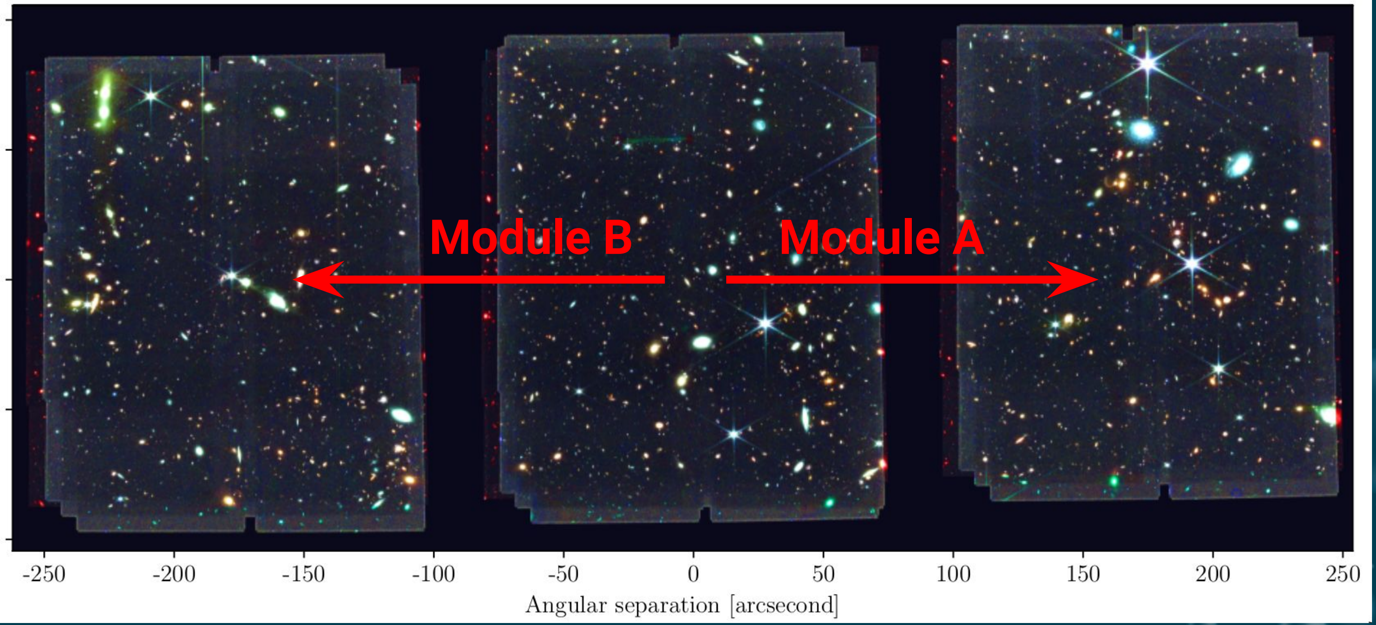
Backup slides





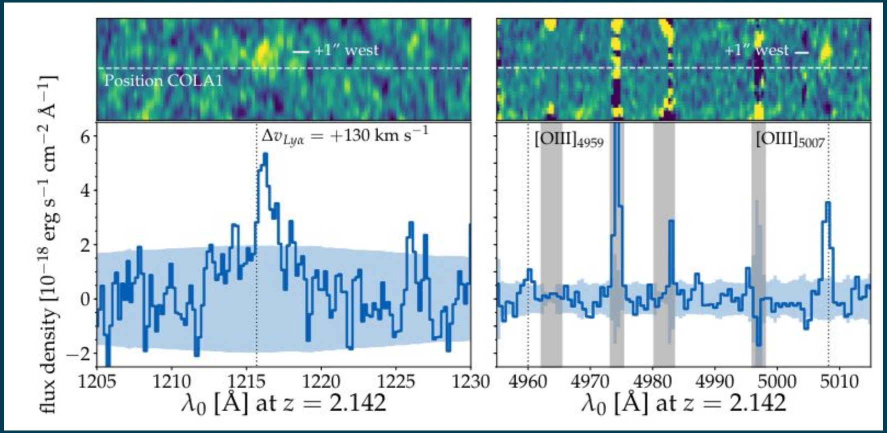
Angular separation [arcsecond]
Angular separation [arcsecond]
Wavelength [μm]
$[OIII]_{\lambda5008}$ Redshift
Angular separation [arcsecond]

NIRCam Wide Field Slitless Spectroscopy

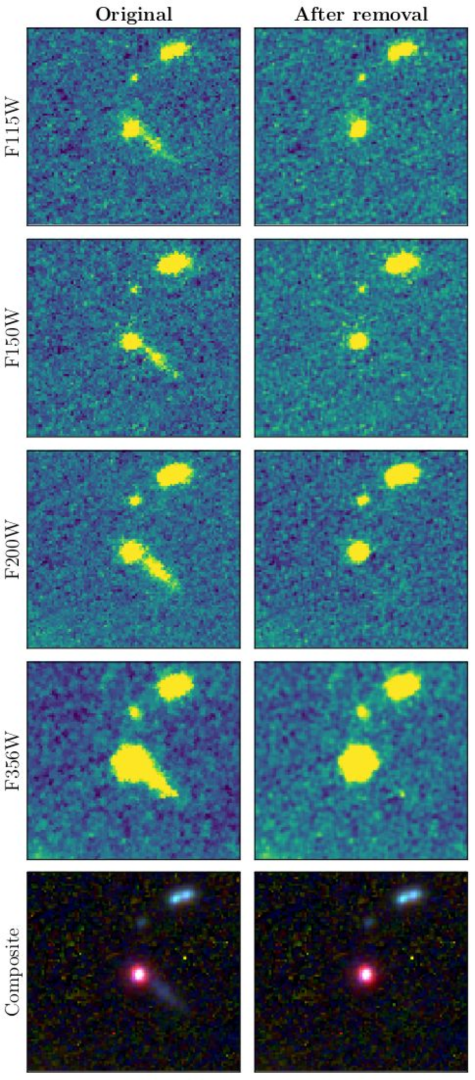


Torralba-Torregrosa et al. 2024

Backup slides



Matthee et al. 2018



Torralba-Torregrosa et al. 2024