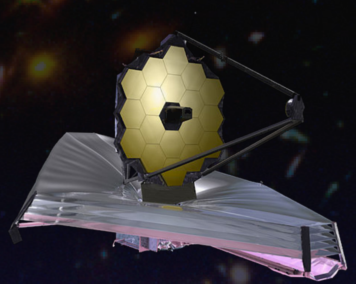
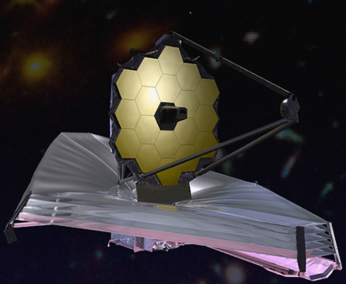
Enigmatic first stars and where to find them



Eros Vanzella (INAF - OAS/Bologna)

Collaborators: F. Loiacono, M. Meneghetti, F. Calura, R. Mignoli, M. Bradac, R. Gilli, A. Comastri
F. Annibali, C. Gruppioni, U. Mestric, et al.
+ Univ. Ferrara + OAR + OATS + Univ. Milano + Univ. Salerno + (rest of the planet)

Enigmatic first stars and where to find them
& when?



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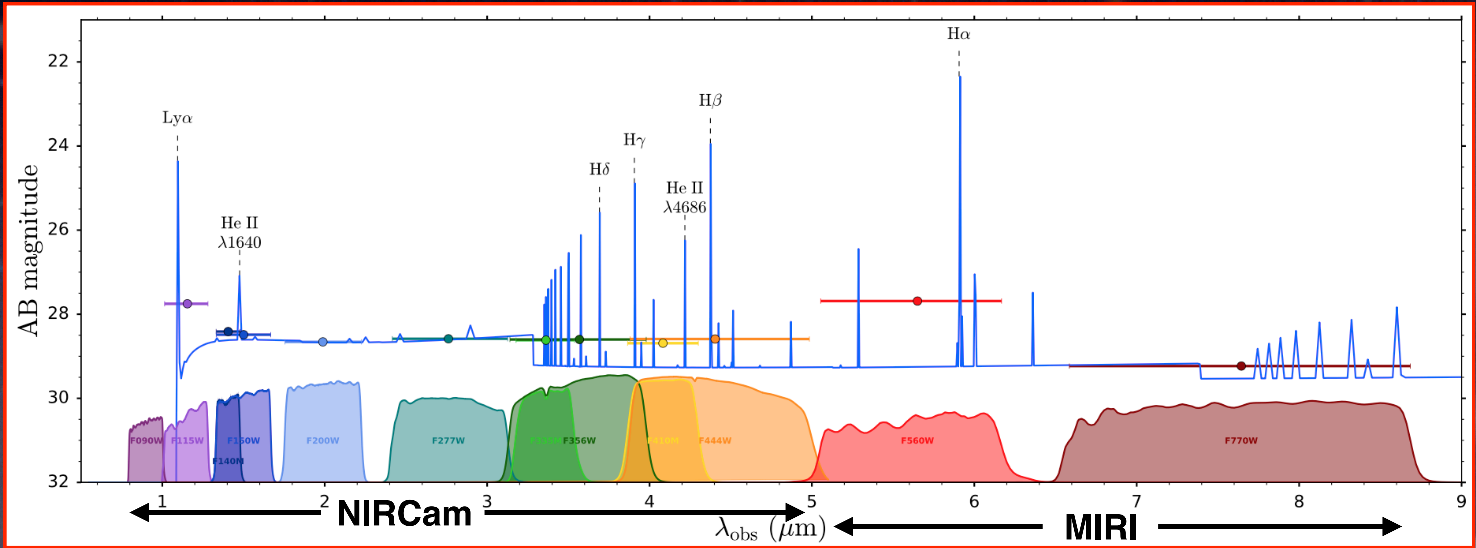
Enigmatic first stars

JWST (new!) => can probe deficit of metal lines & prominent hydrogen lines + helium in the first Gyr (z>5)

Imaging & Spectroscopy: UV+Optical rest-frame up to z~10-15

Trussler+22, model of PopIII at z=8 (from Zackrisson+11)



M=1e6 $M_\odot$, t=0.01Myr, PopIII.1

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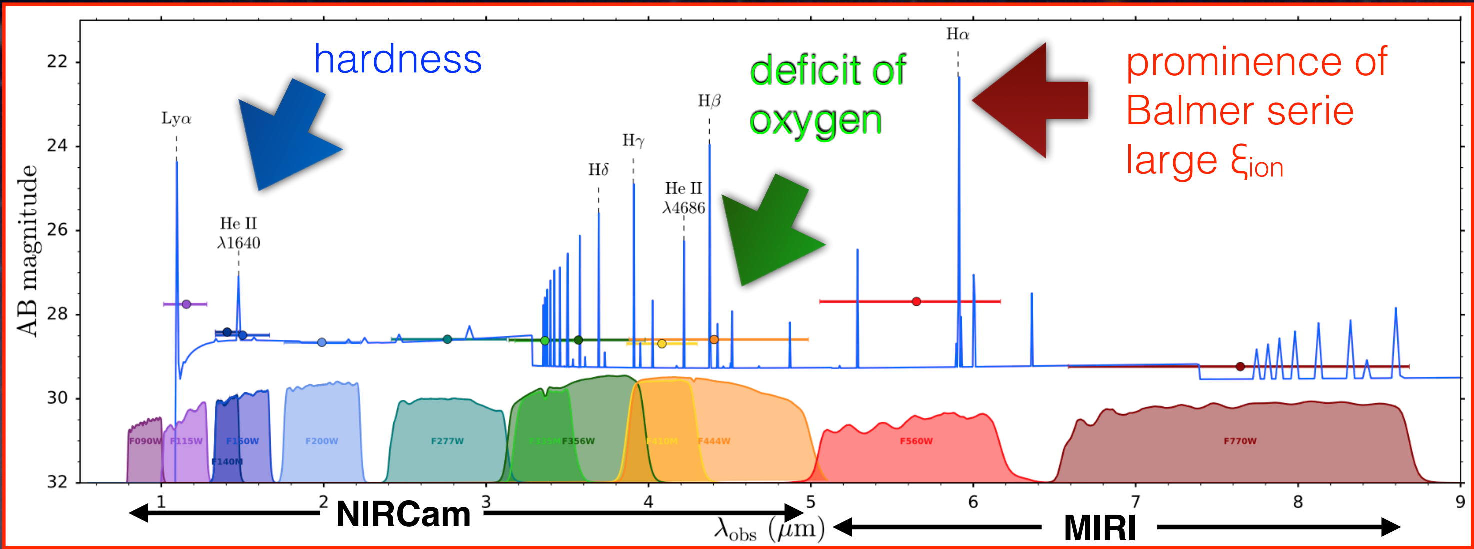

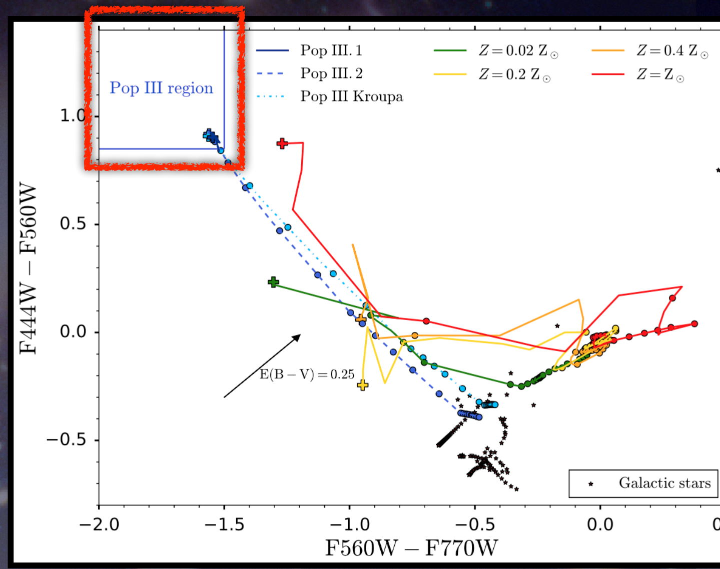

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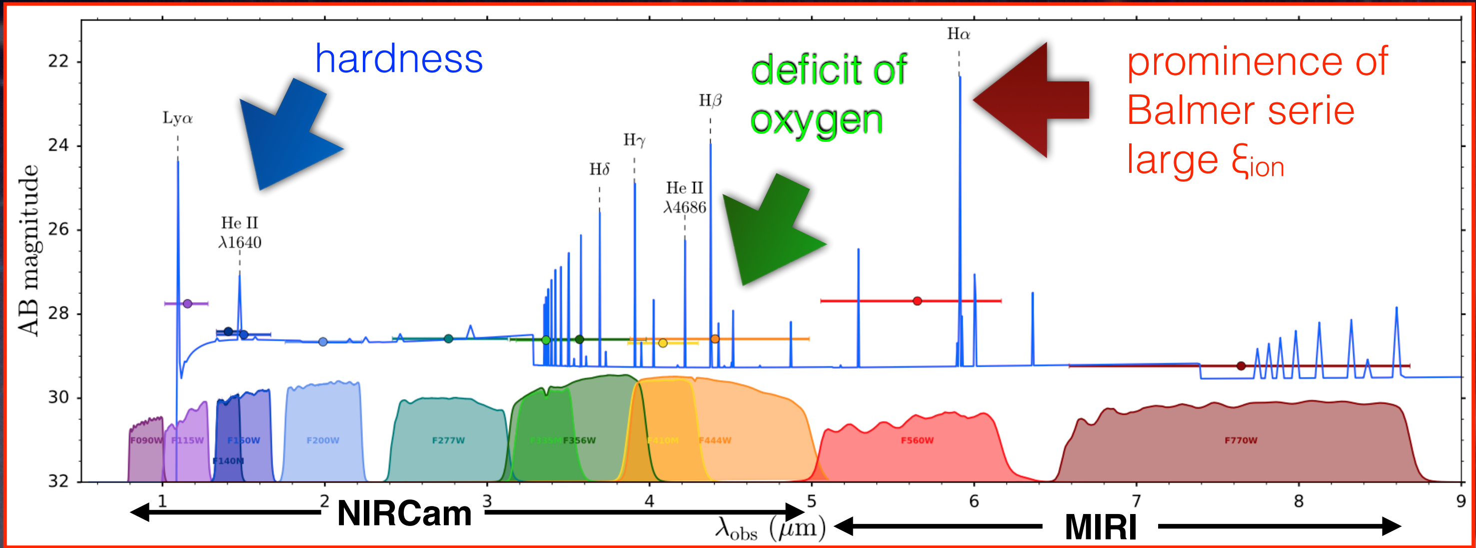

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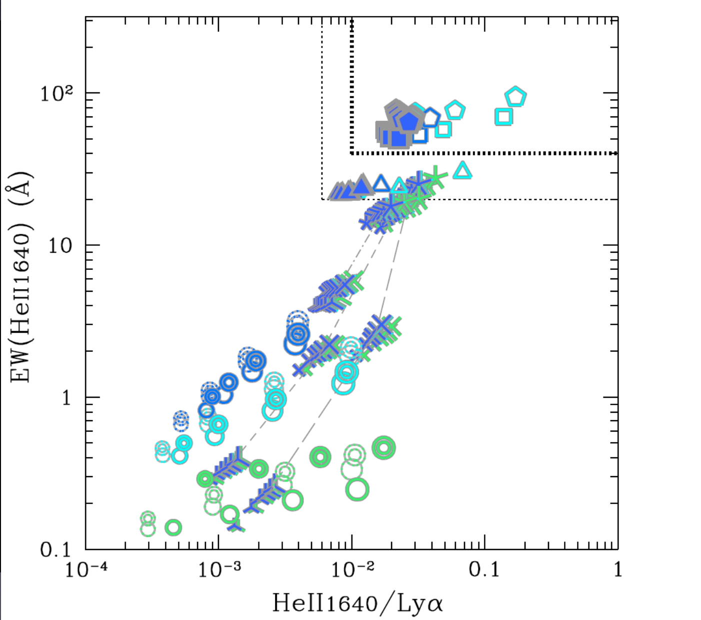
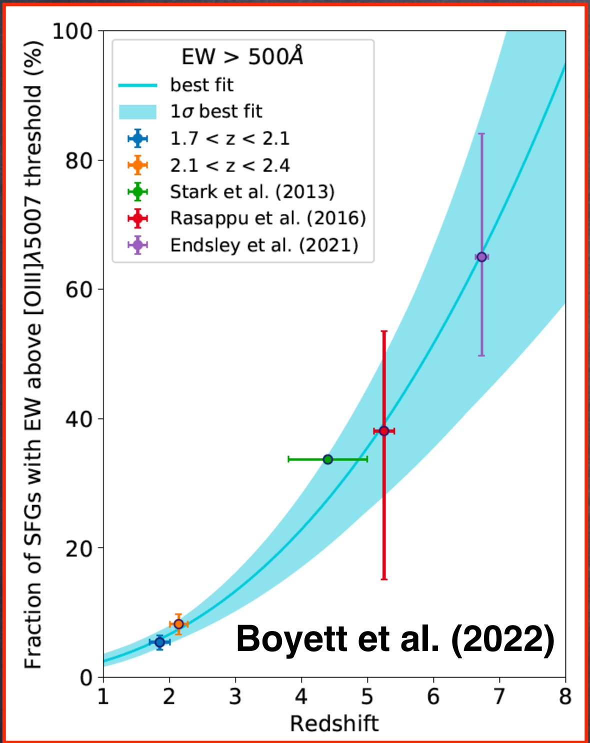


Nakajima, K. & Maiolino, R. (2022)

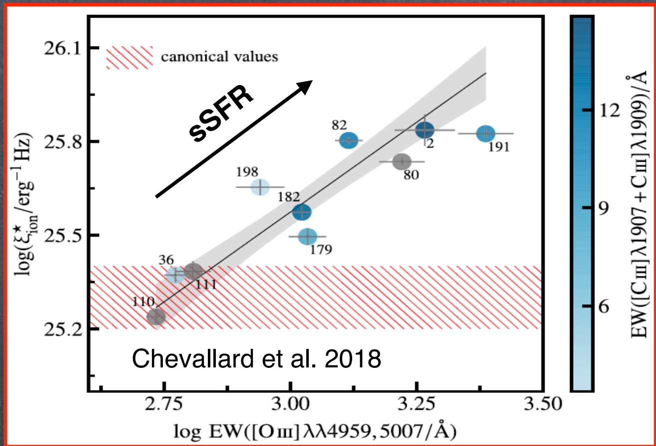
(also Mas-Ribas+16; Raiter+10; Schaerer+03)

Strong nebular emission ([OIII]5007) at z ≳ 6 seems (currently) ubiquitous (?!)

HIGH-Z: Bursty star formation



At z=7
Typical EW 760A
23% EW>1200A
sSFR>10-30 Gyr^{-1}
Endsley+21,22



Why such a behaviour?
What's the origin of these bursty events?

Need to look at small spatial scales

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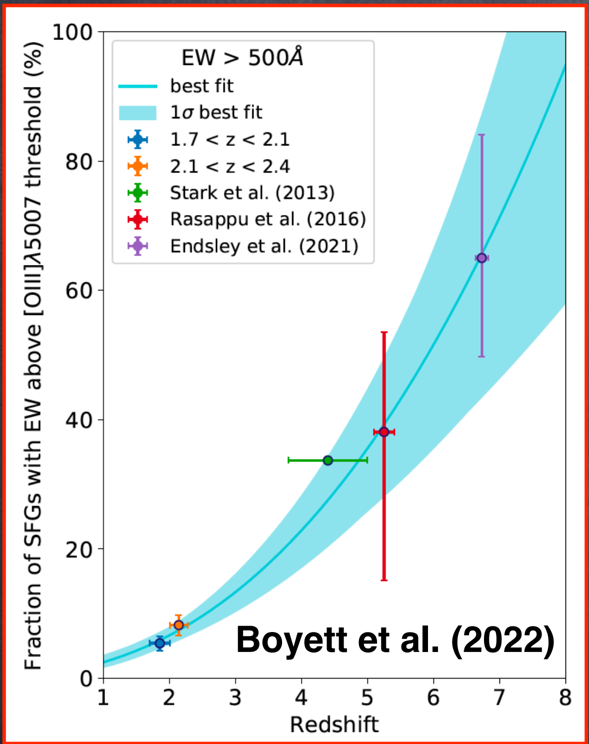

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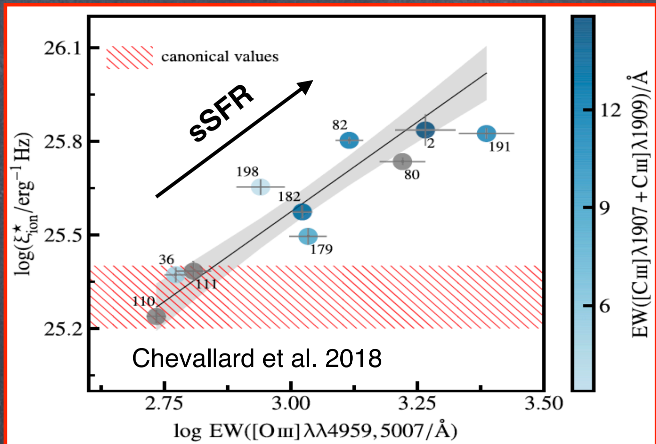

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What's the origin of these bursty events?

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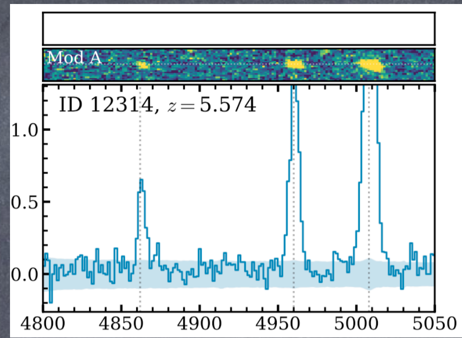
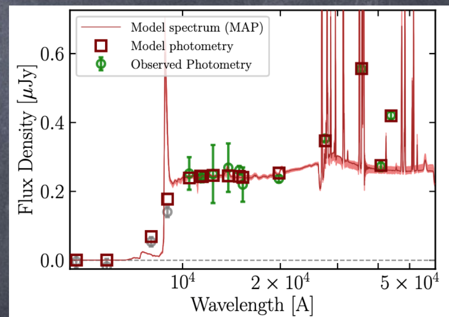
JWST spectroscopy



Large EWs are ubiquitous at z>~6
Matthee et al. 2022 (JWST)

JWST photometry



Large EWs: photometric signature

(See also Castellano+17, De Barros et al. 2019, Smit+14,15,16;, Roberts-Borsani+16; Laporte+14; Finkelstein+13, and many others)

Elusive PopIII, observational prospective (UV+optical): when, where? What's spatial scale? Luminosity?

Requirements | From current facilities

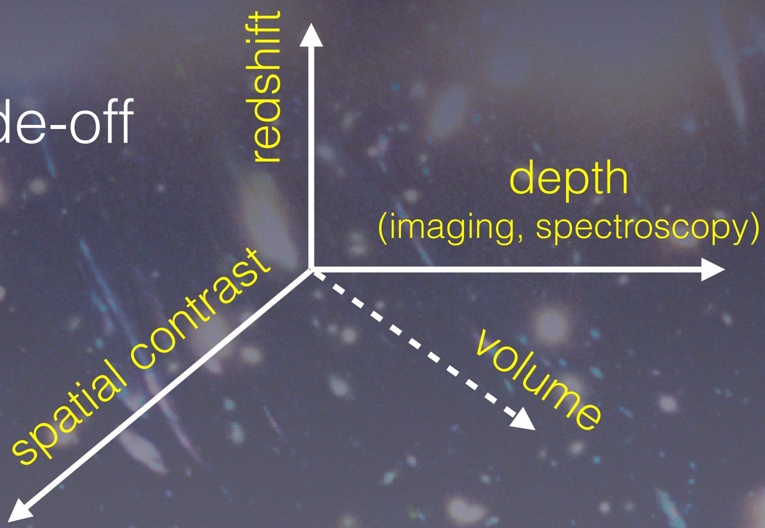
When: early Universe, the higher the z the better [first Gyr] => z ~< 15 … ?

Where: isolated pristine star clusters/complexes/star [few pc] => >~ 150(80) pc z~3(12)

Luminosity: 1e3 $M_\odot$ PopIII source @z=7 [m~37.6; $f_{HeII} < 10^{-20}$ cgs] => mag < 32, $f_{HeII} > 10^{-19}$ cgs

Imaging (UV slope) and spectroscopy (hydrogen+helium lines + **deficit** of metal lines)

Trade-off

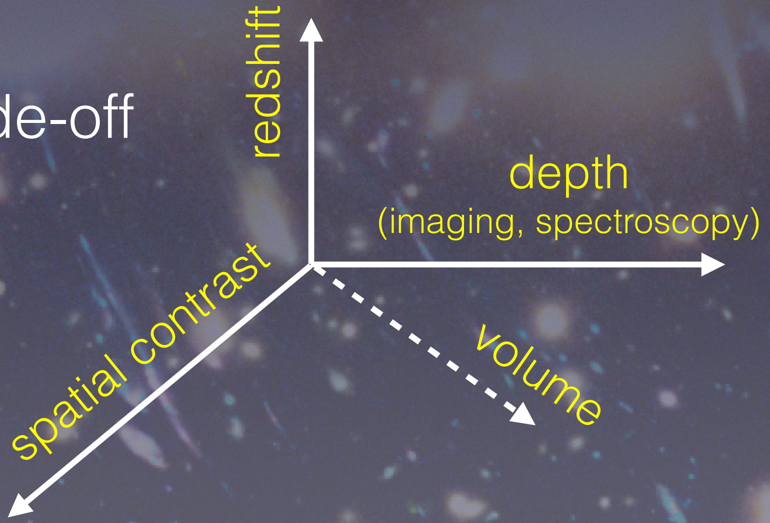


Elusive PopIII, observational prospective (UV+optical): when, where? What's spatial scale? Luminosity?

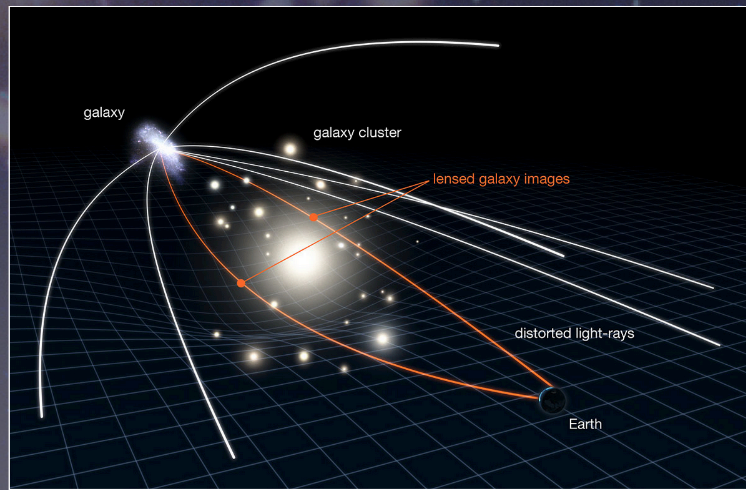
Requirements	From current facilities	adding Strong Lensing
When: early Universe, the higher the z the better [first Gyr] =>	z ~< 15 … ? →	boost the redshift (but small volume)
Where: isolated pristine star clusters/complexes/star [few pc] =>	>~ 150(80) pc z~3(12) →	< 30 pc scale
Luminosity: 1e3 $M_{\odot}$ PopIII source @z=7 [m~37.6; $f_{HeII} < 10^{-20}$ cgs] =>	mag < 32, $f_{HeII} > 10^{-19}$ cgs →	m~38, f~1e-20 cgs fainter than Muv -11 extreme SL

Imaging (UV slope) and spectroscopy (hydrogen+helium lines + **deficit** of metal lines)

Trade-off



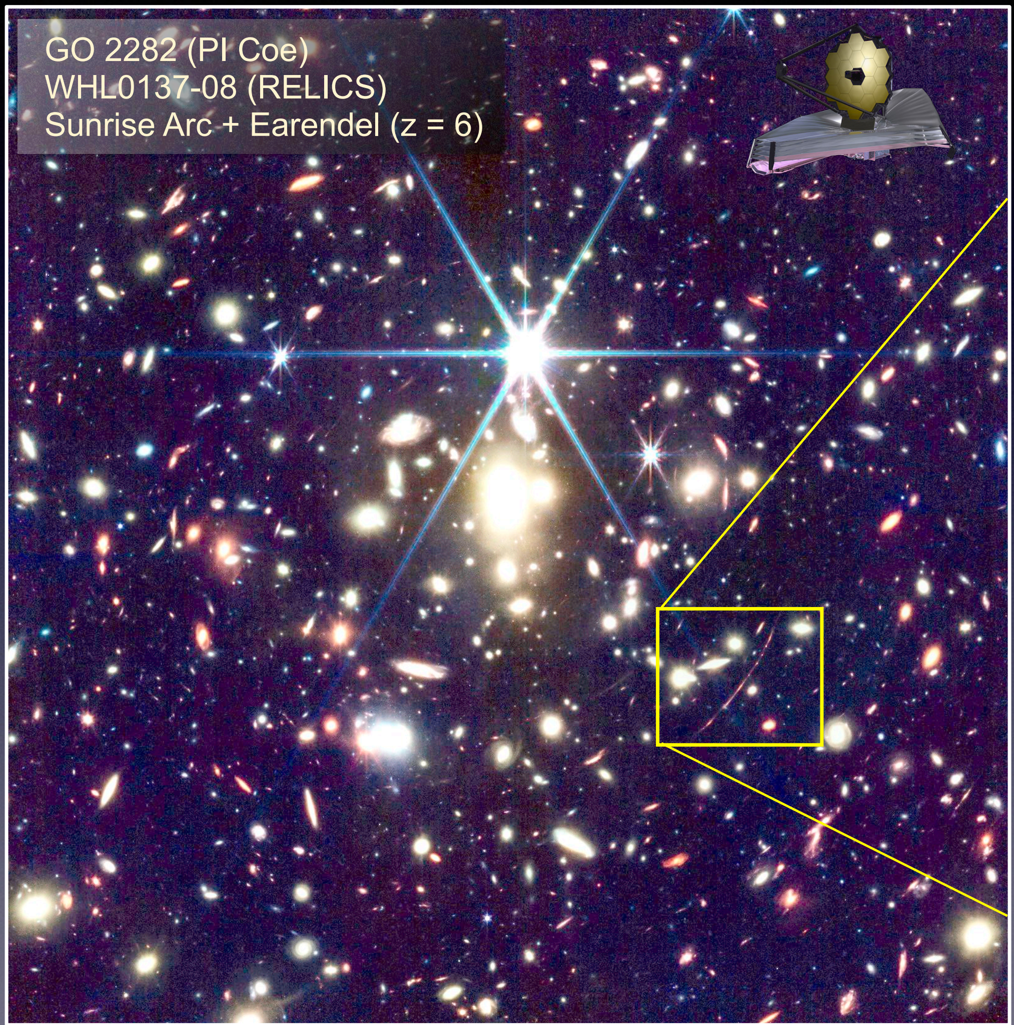
+

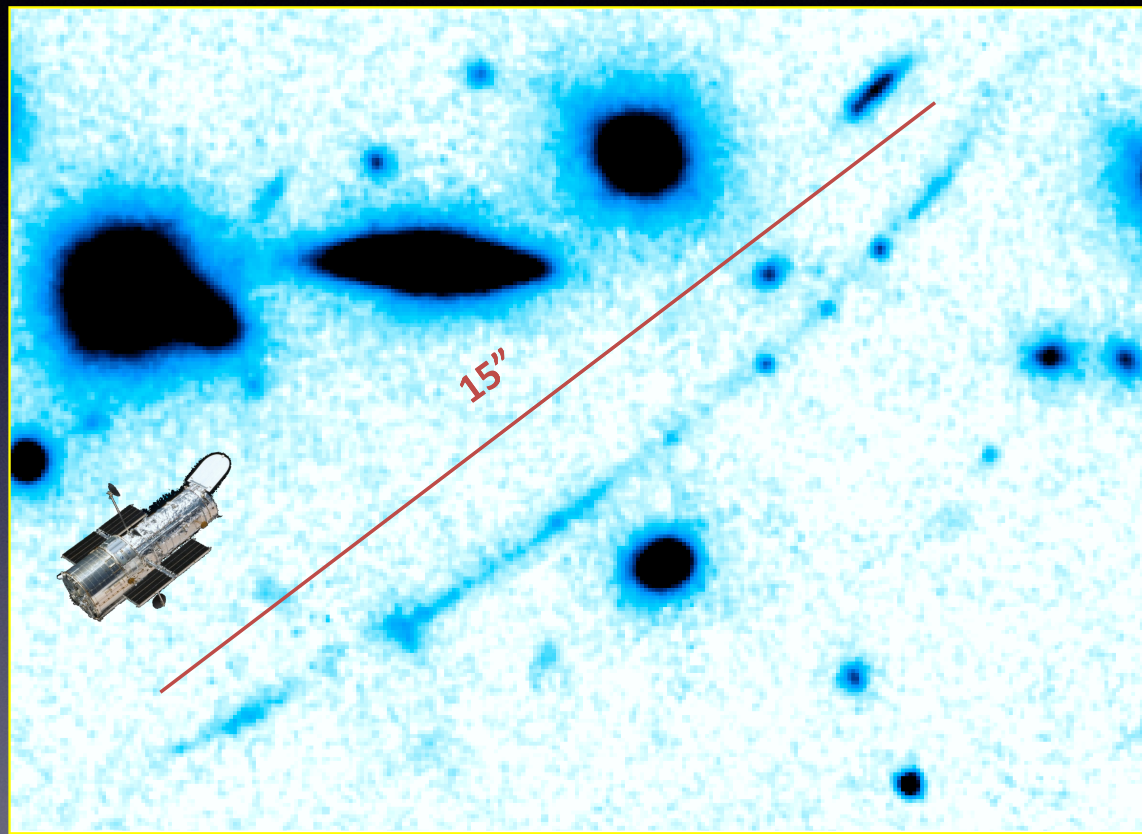


Strong gravitational lensing

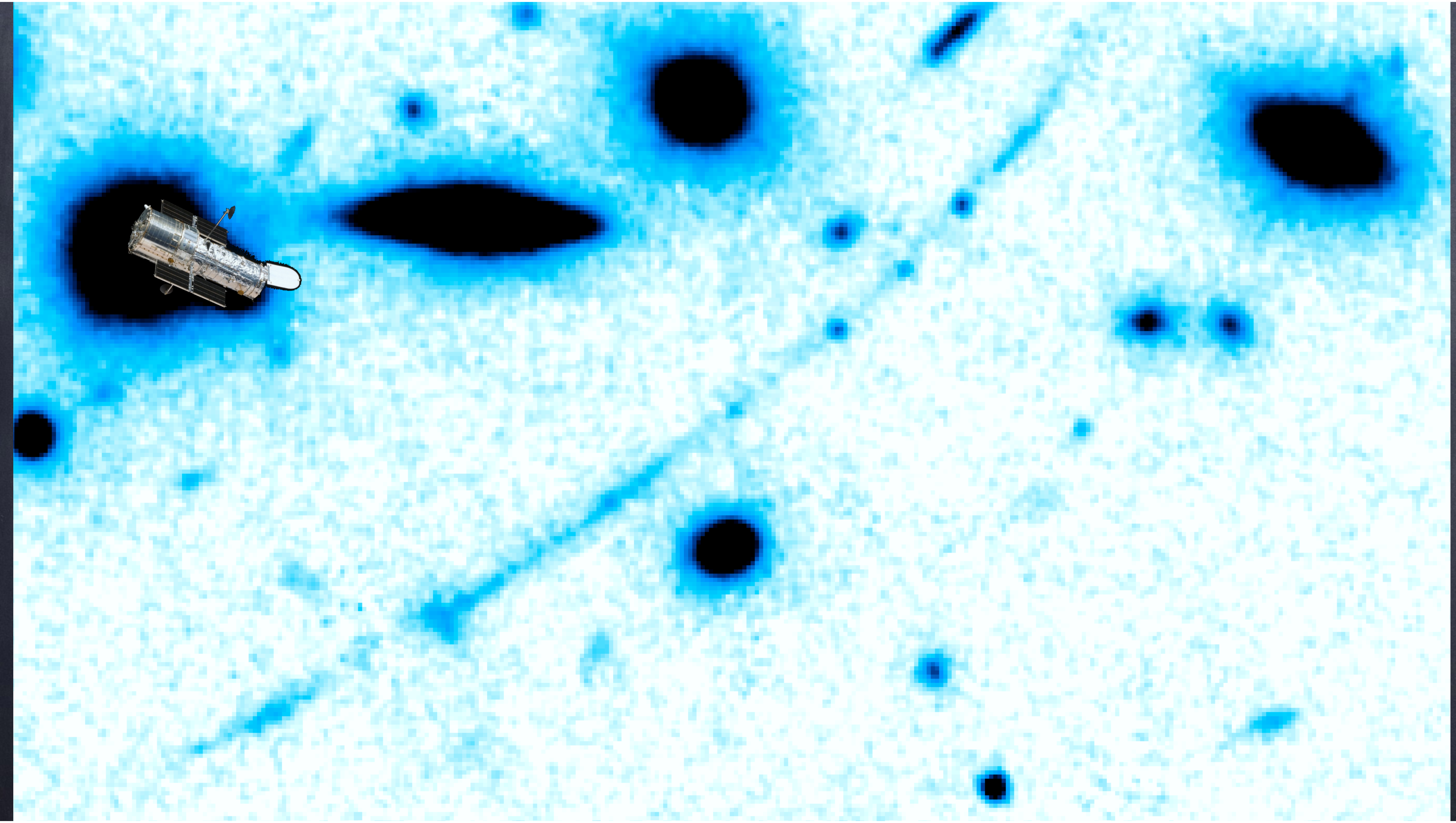
Example (I): the **Sunrise** arc, proto-globulars at redshift 6

High spatial contrast (pc scale)

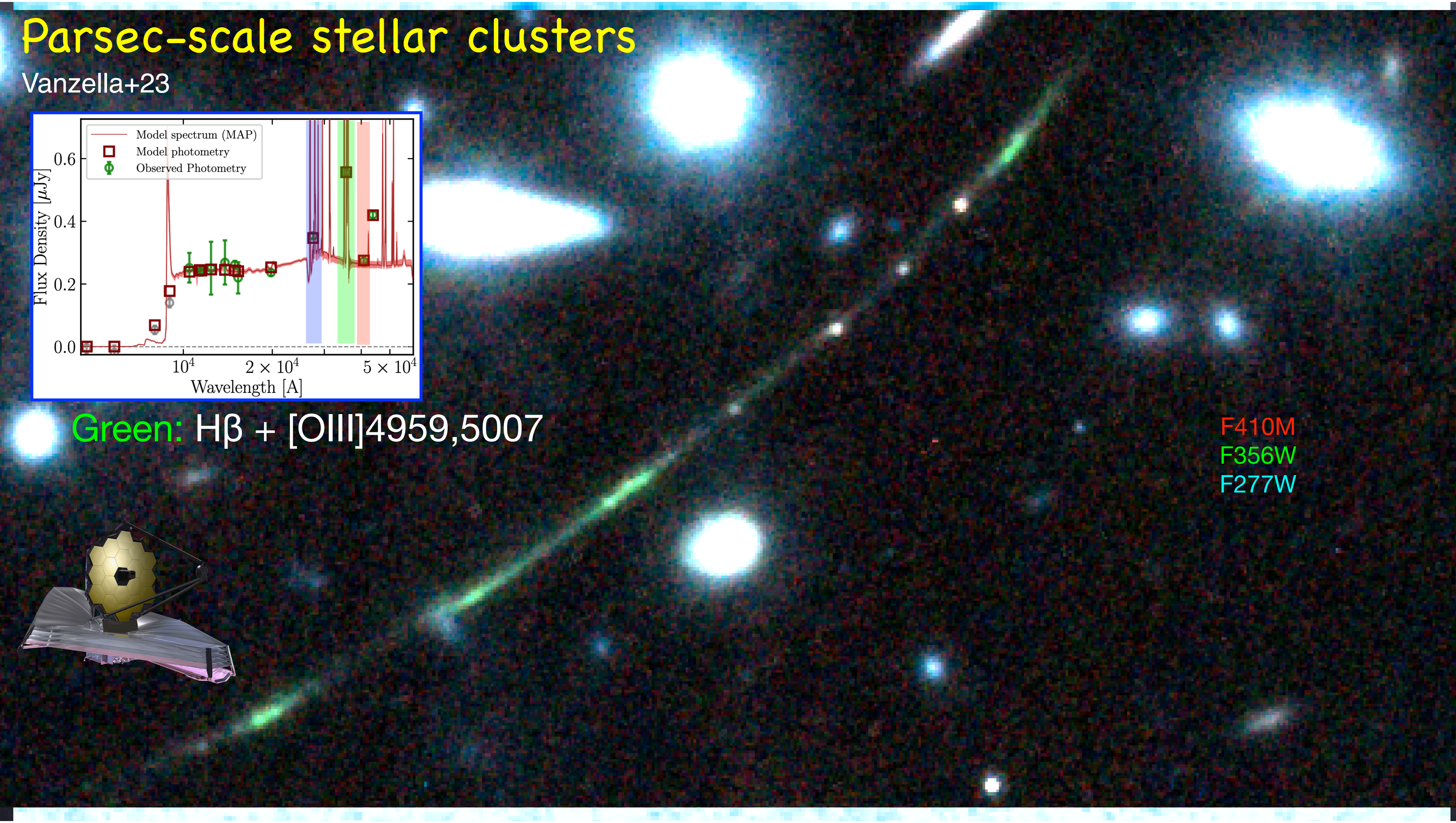




Welch et al. 2022a,b




Parsec-scale stellar clusters
Vanzella+23
Model spectrum (MAP)
Model photometry
Observed Photometry
Flux Density [μJy]
0.0
0.2
0.4
0.6
10^4
2 × 10^4
5 × 10^4
Wavelength [A]
UV: 1600-2800Å
F200W
F150W
F115W


Parsec-scale stellar clusters
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0.0
0.2
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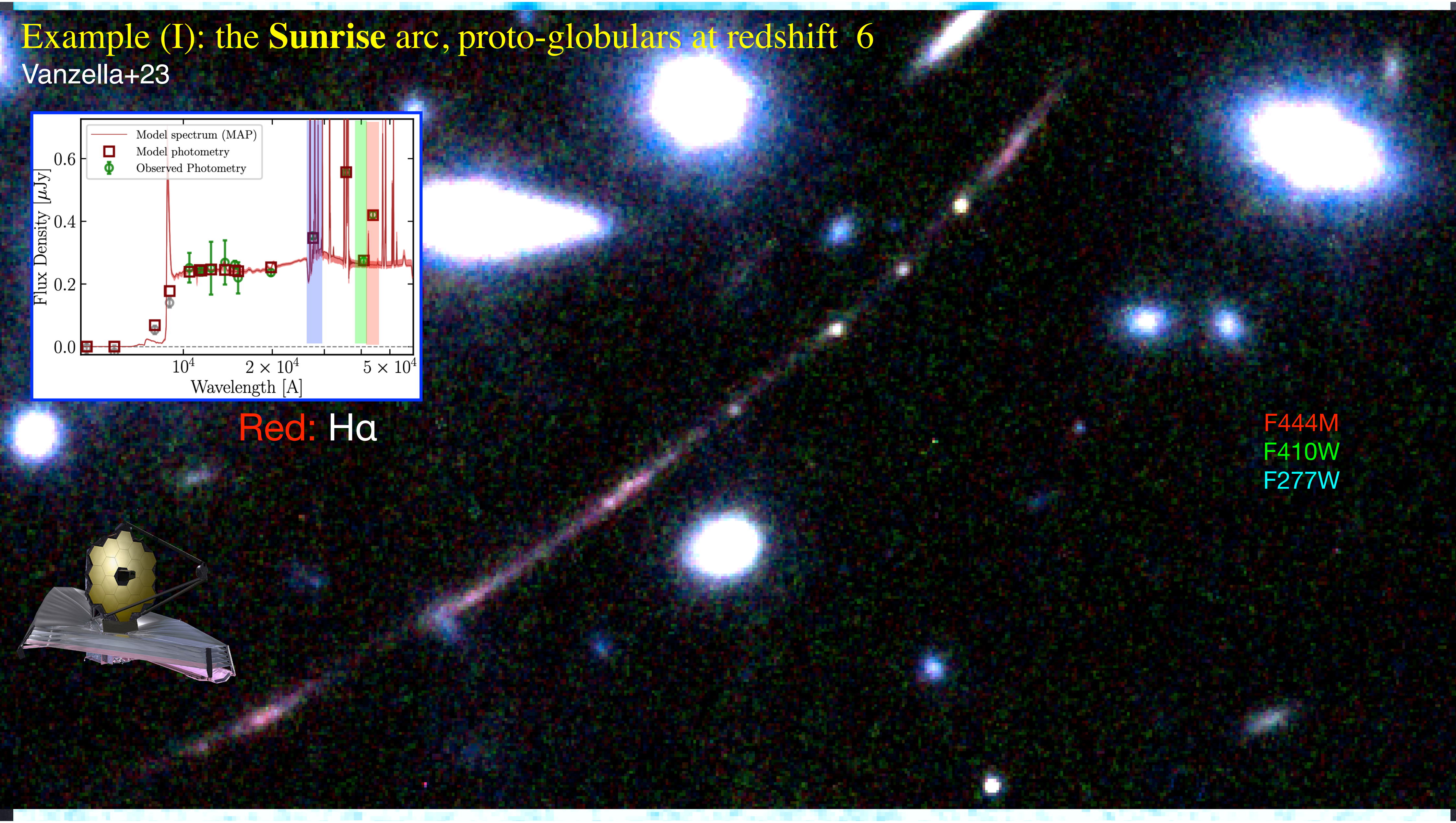
0.6
10^4
2 × 10^4
5 × 10^4
Wavelength [A]
Green: Hβ + [OIII]4959,5007
F410M
F356W
F277W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Observed Photometry
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0.0
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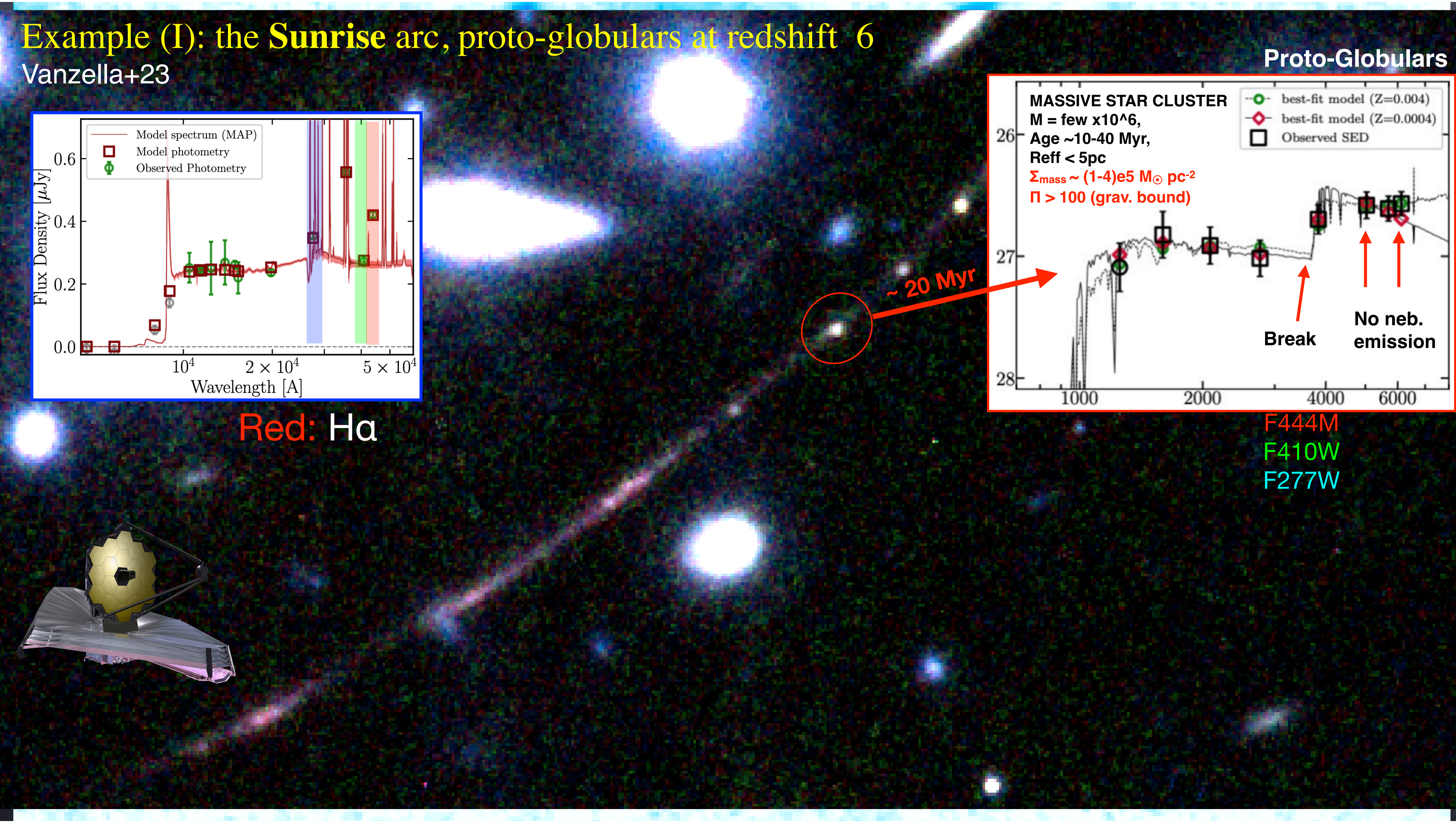
0.6
10^4
2 × 10^4
5 × 10^4
Wavelength [A]
Red: Hα
F444M
F410W
F277W



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Flux Density [μJy]
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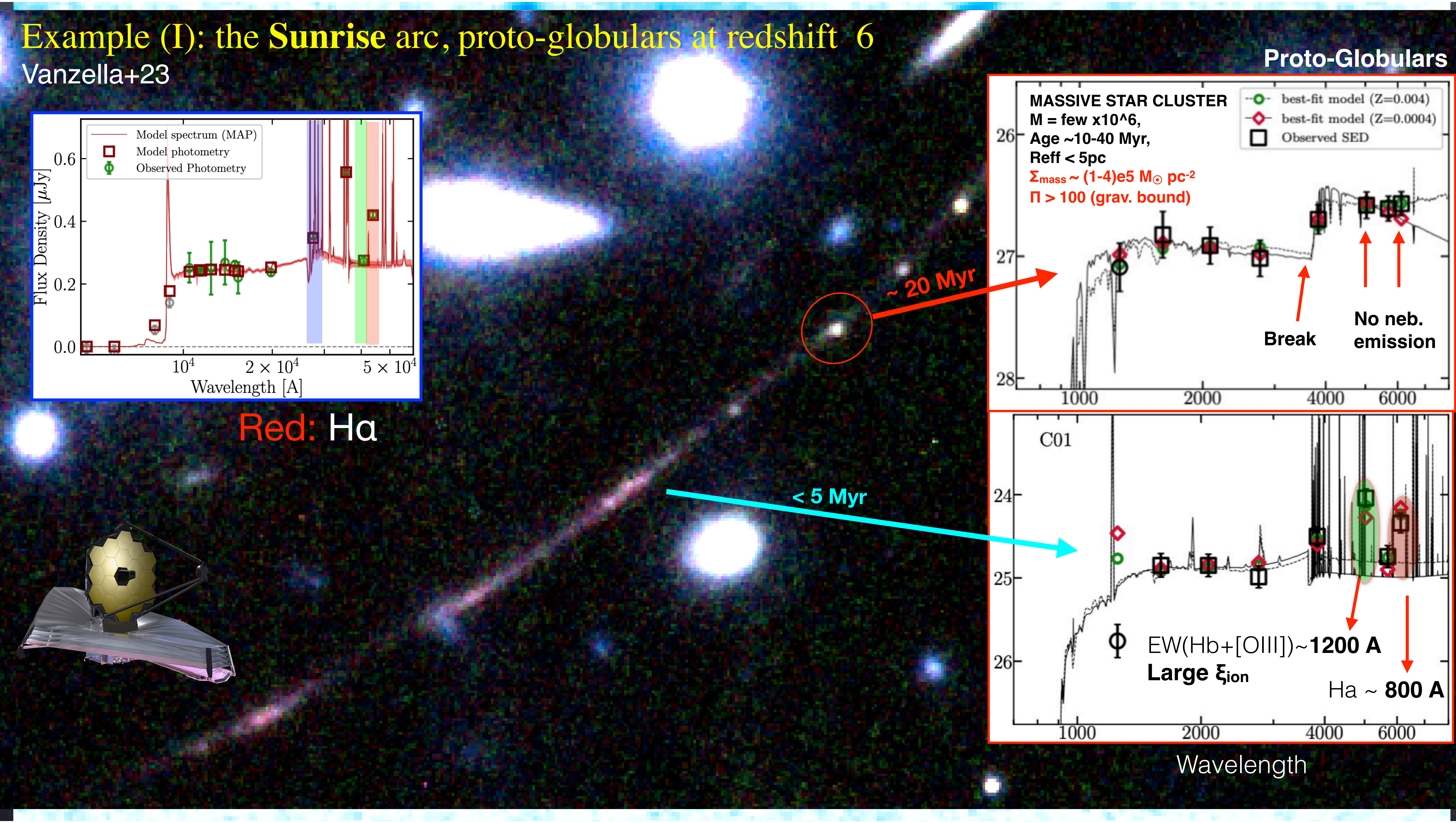
0.2
0.4
0.6
10^4
2 × 10^4
5 × 10^4
Wavelength [A]
Red: Hα
~ 20 Myr
Proto-Globulars
MASSIVE STAR CLUSTER
M = few x10^6,
Age ~10-40 Myr,
Reff < 5pc
Σmass ~ (1-4)e5 M⊙ pc-2
Π > 100 (grav. bound)
best-fit model (Z=0.004)
best-fit model (Z=0.0004)
Observed SED
26
27
28
1000
2000
4000
6000
Break
No neb. emission
F444M
F410W
F277W



Example (I): the Sunrise arc, proto-globulars at redshift 6
Vanzella+23
Model spectrum (MAP)
Model photometry
Observed Photometry
Flux Density [μJy]
Wavelength [A]
Red: Hα
~ 20 Myr
< 5 Myr
Proto-Globulars
MASSIVE STAR CLUSTER
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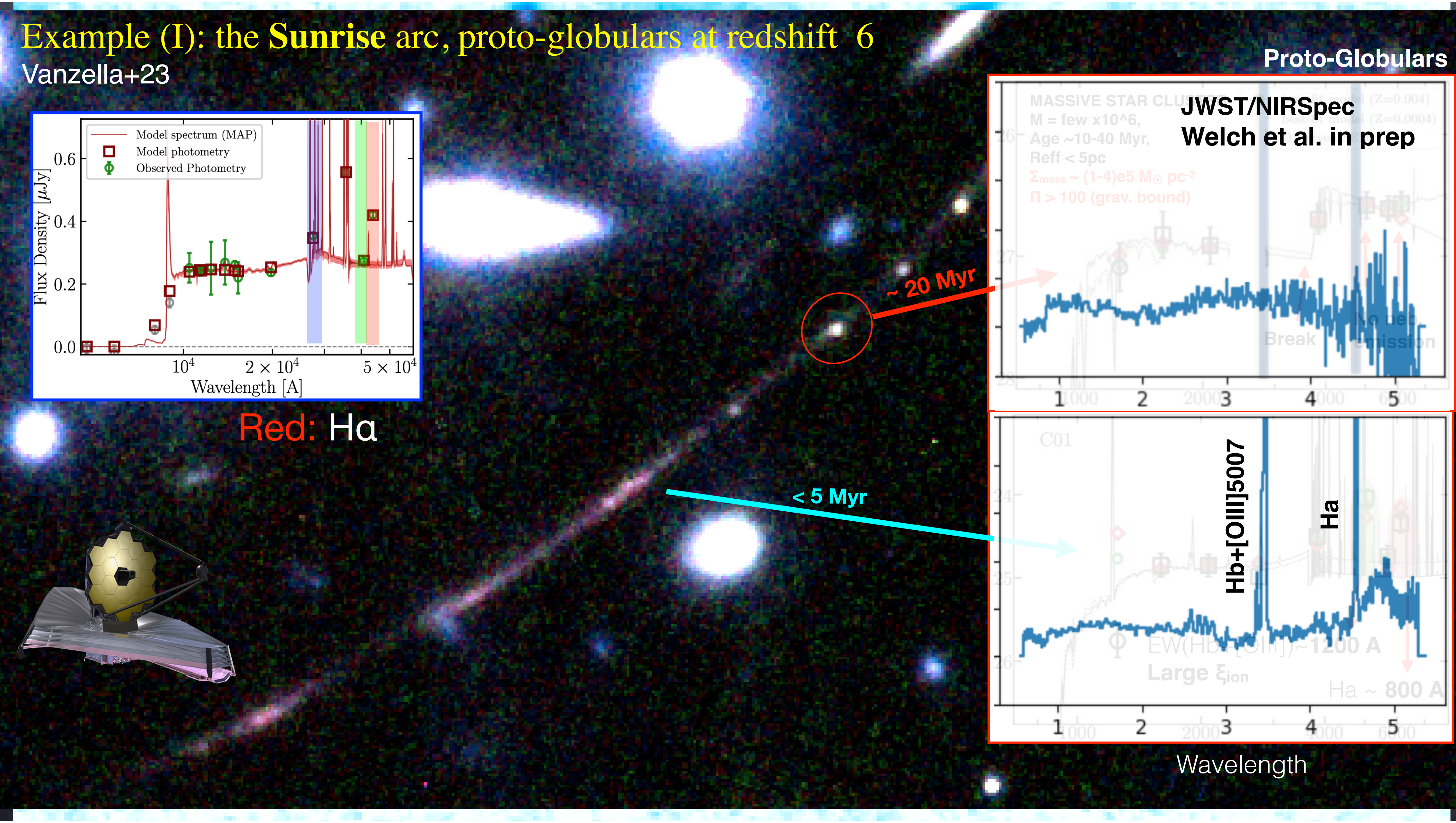
Observed SED
Break
No neb. emission
C01
EW(Hb+[OIII])~1200 A
Large ξion
Ha ~ 800 A
Wavelength



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Vanzella+23
Proto-Globulars
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Model photometry
Observed Photometry
Flux Density [μJy]
Wavelength [A]
Red: Hα
JWST/NIRSpec
Welch et al. in prep
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EW(Hb+[OIII])~1200 A
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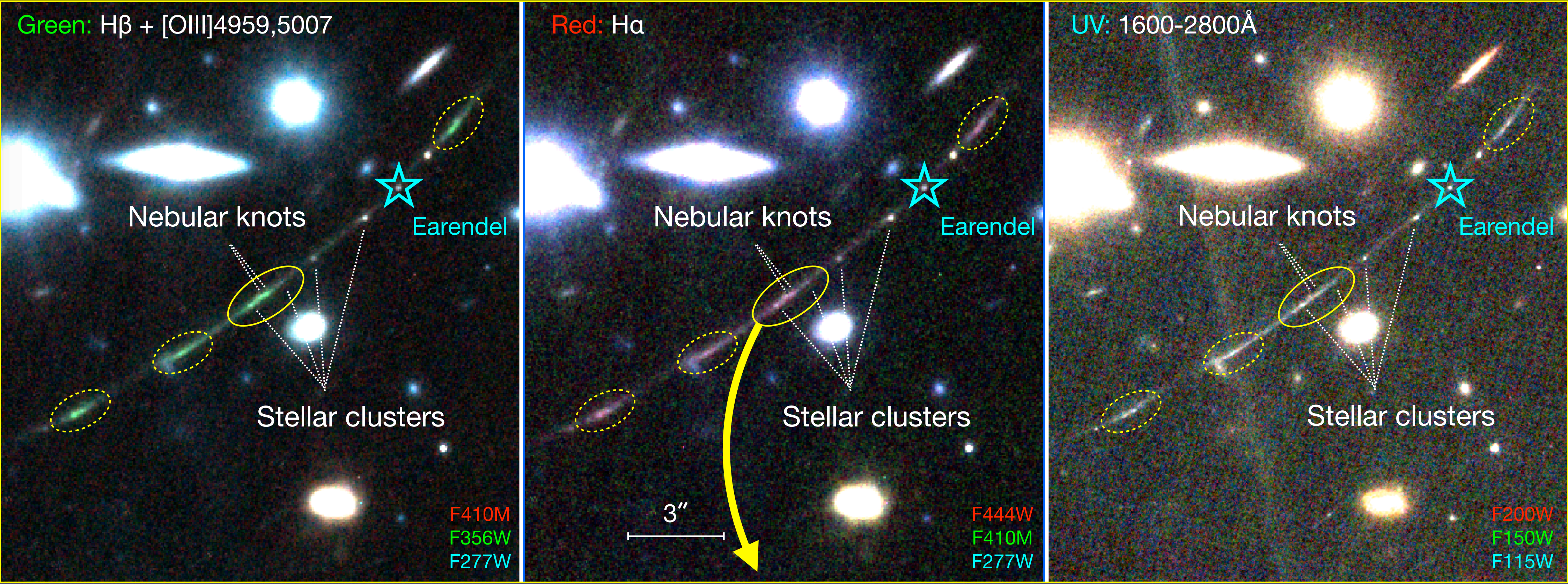
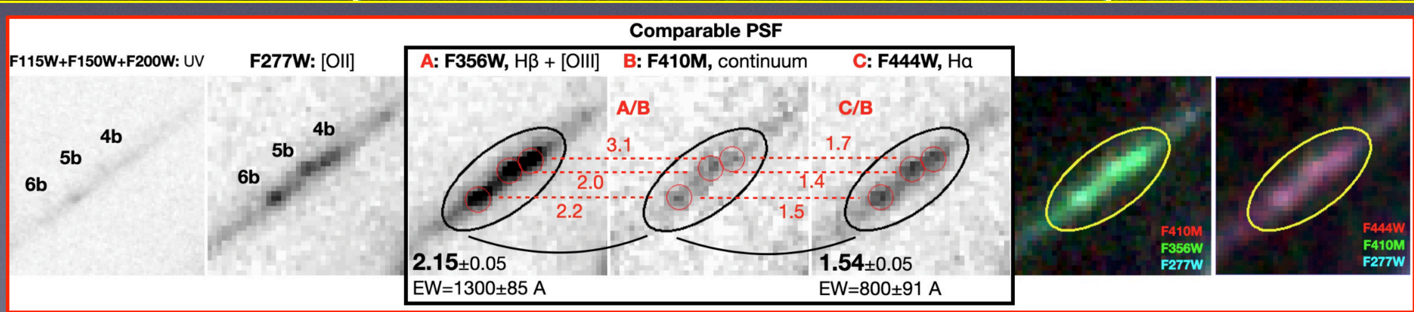
Ha ~ 800 A
Wavelength

Detection of nebular knots (hidden stellar clusters in the UV?)





ξ_{ion} ~ 25.7
sSFR > 50-100 Gyr^{-1}

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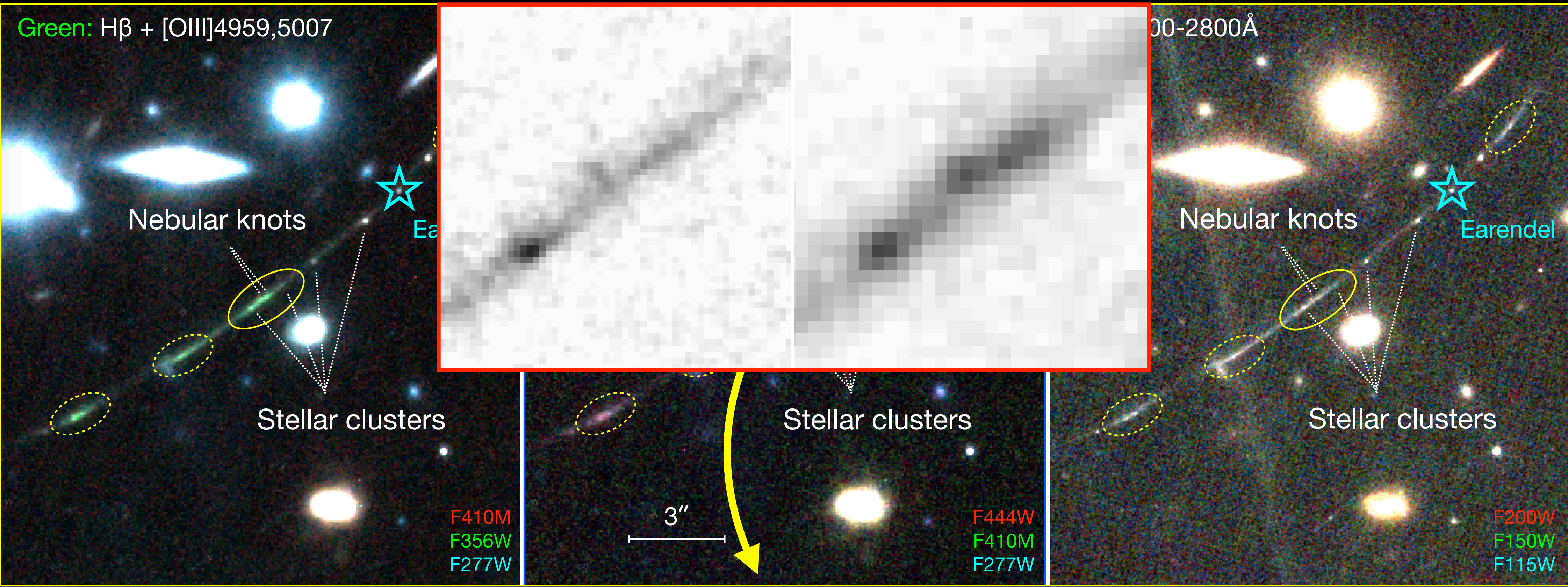
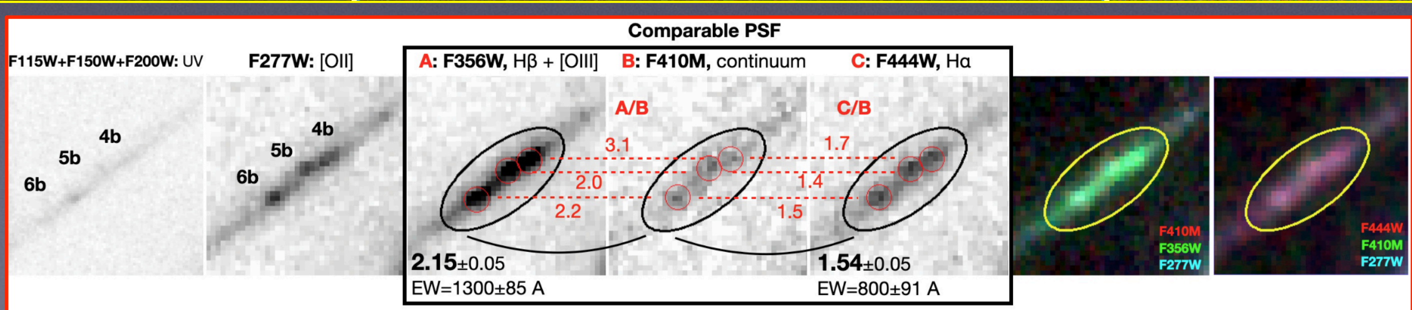
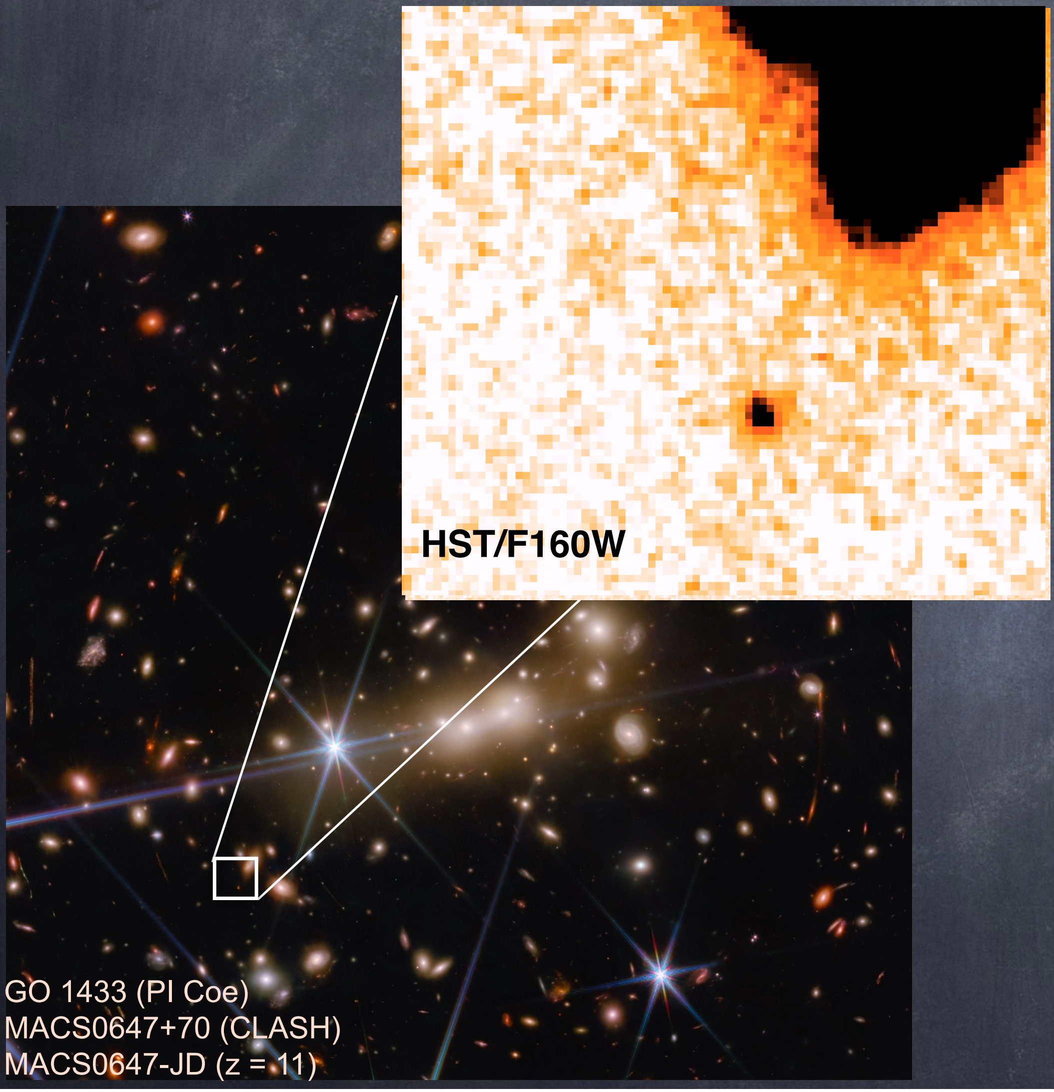




$\xi_{ion} \sim 25.7$
sSFR > 50-100 Gyr^{-1}

Example (II): sub-Structures at z=10.17

Hsiao+23a,b



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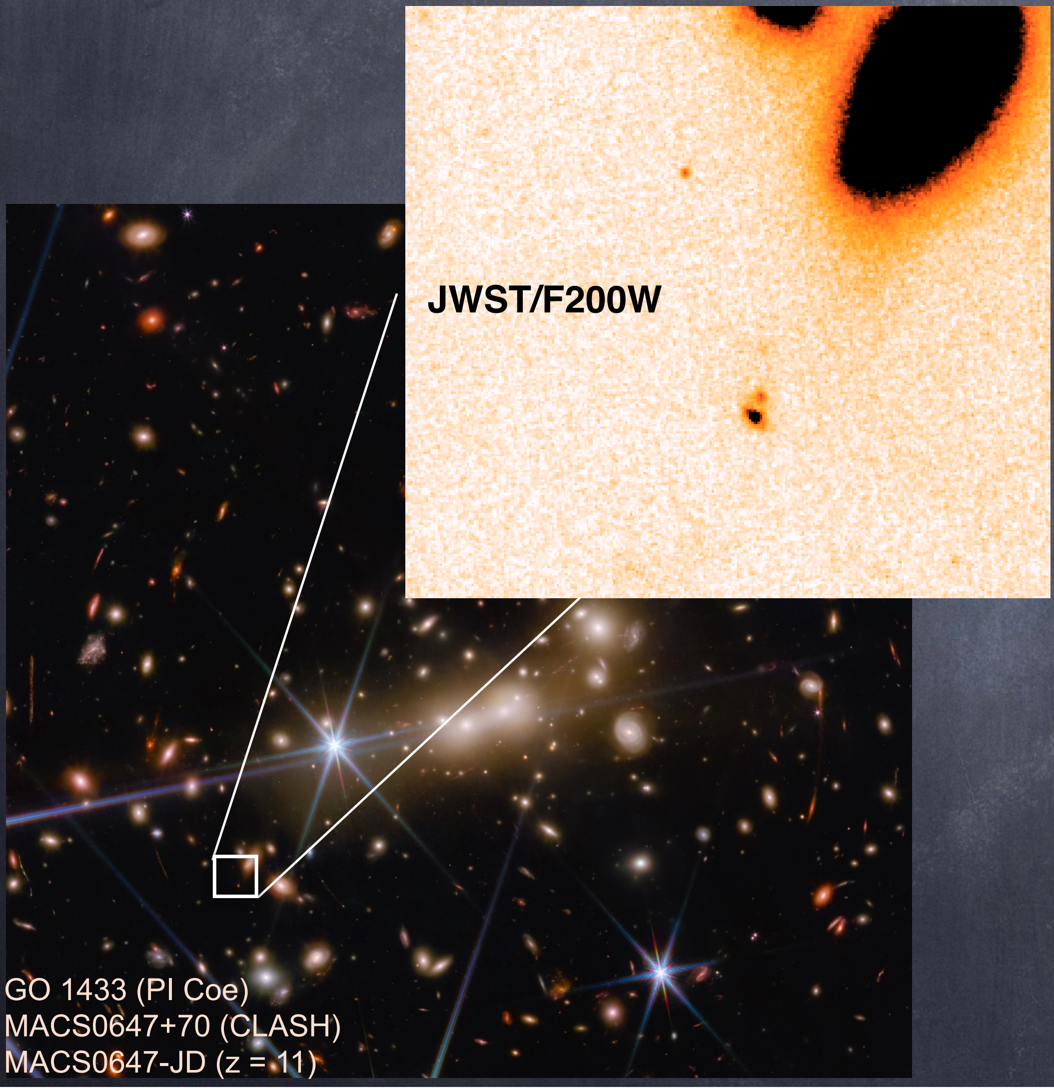

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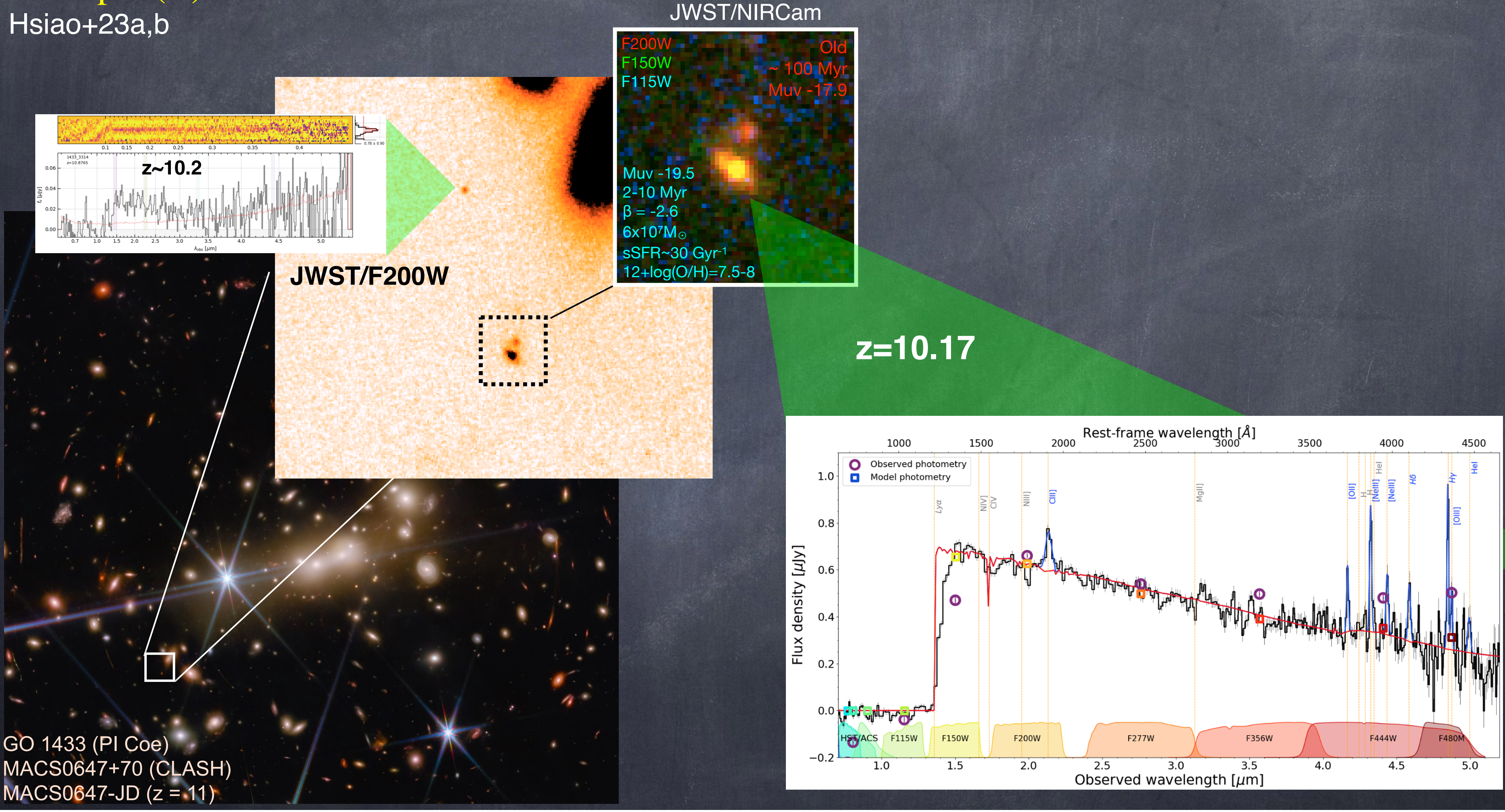

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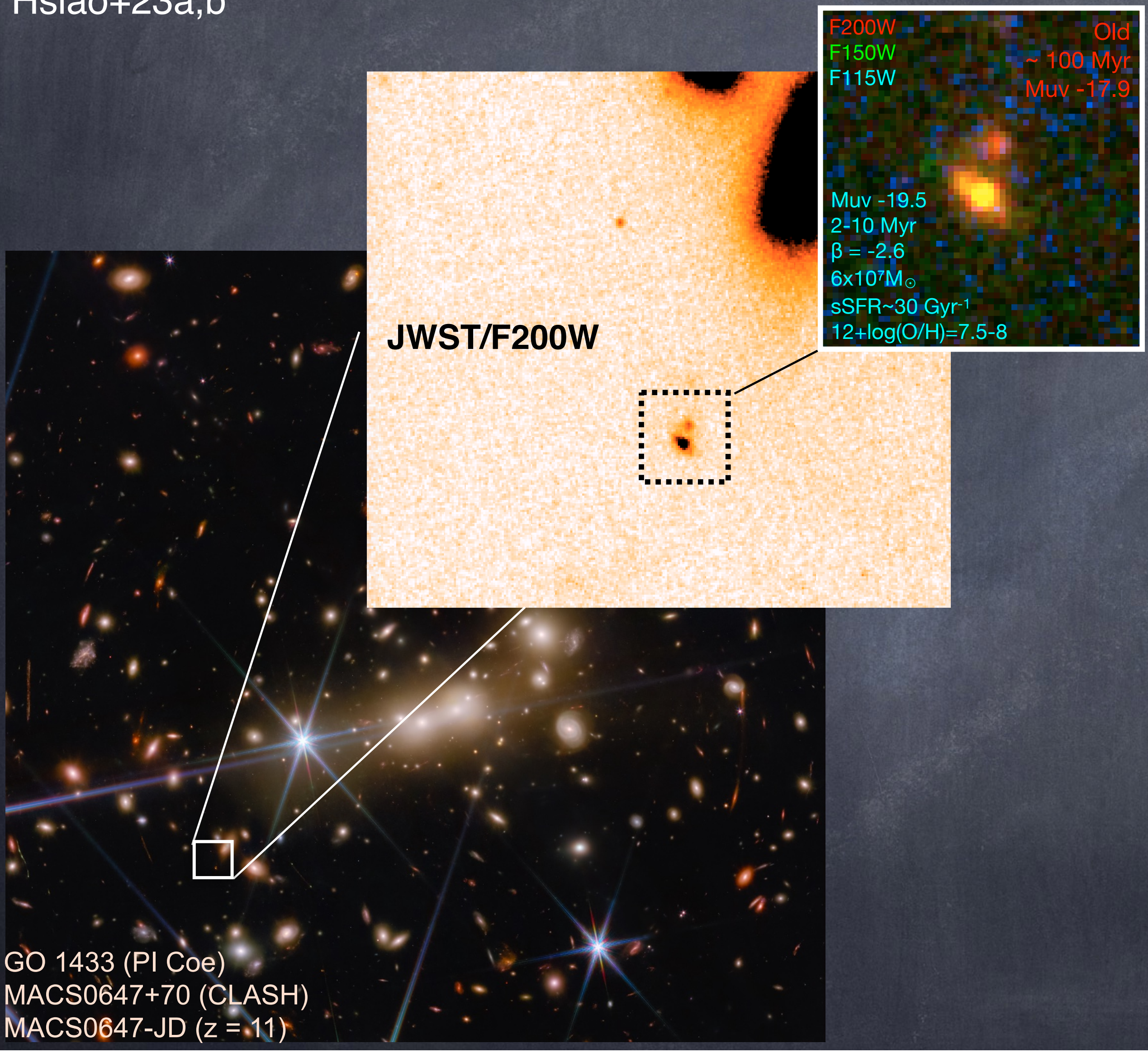
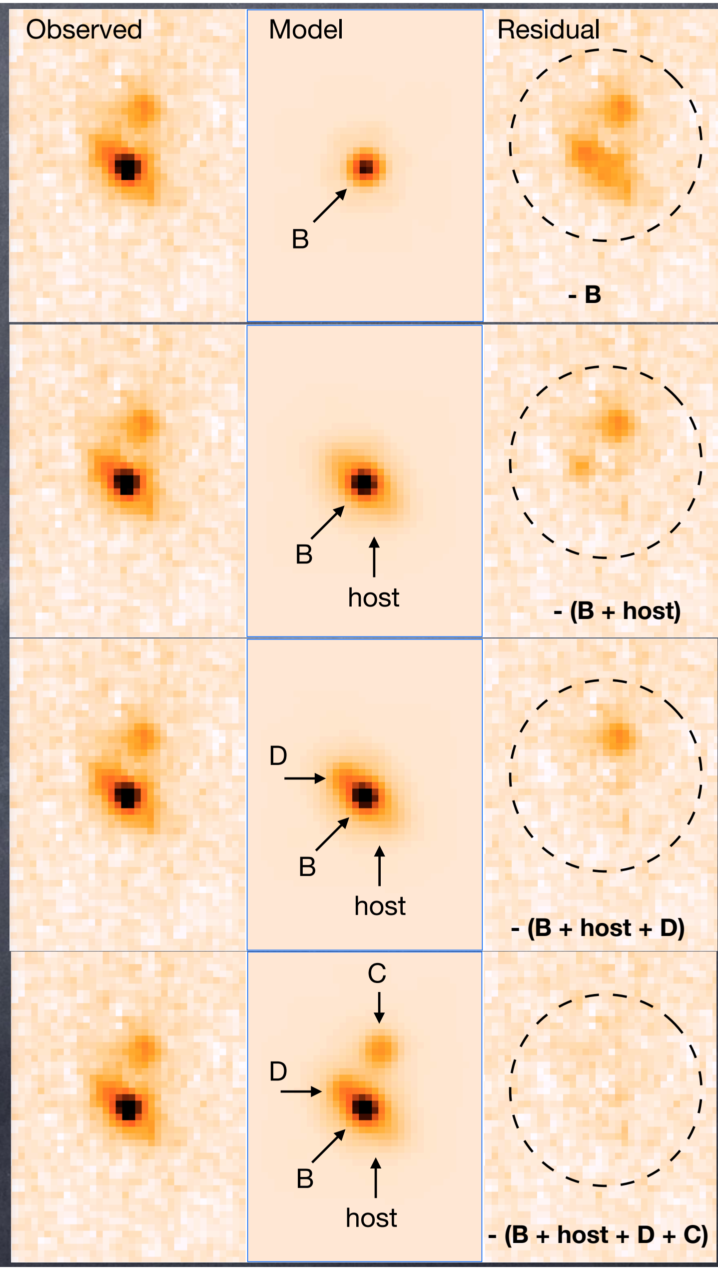




Galfit Modeling

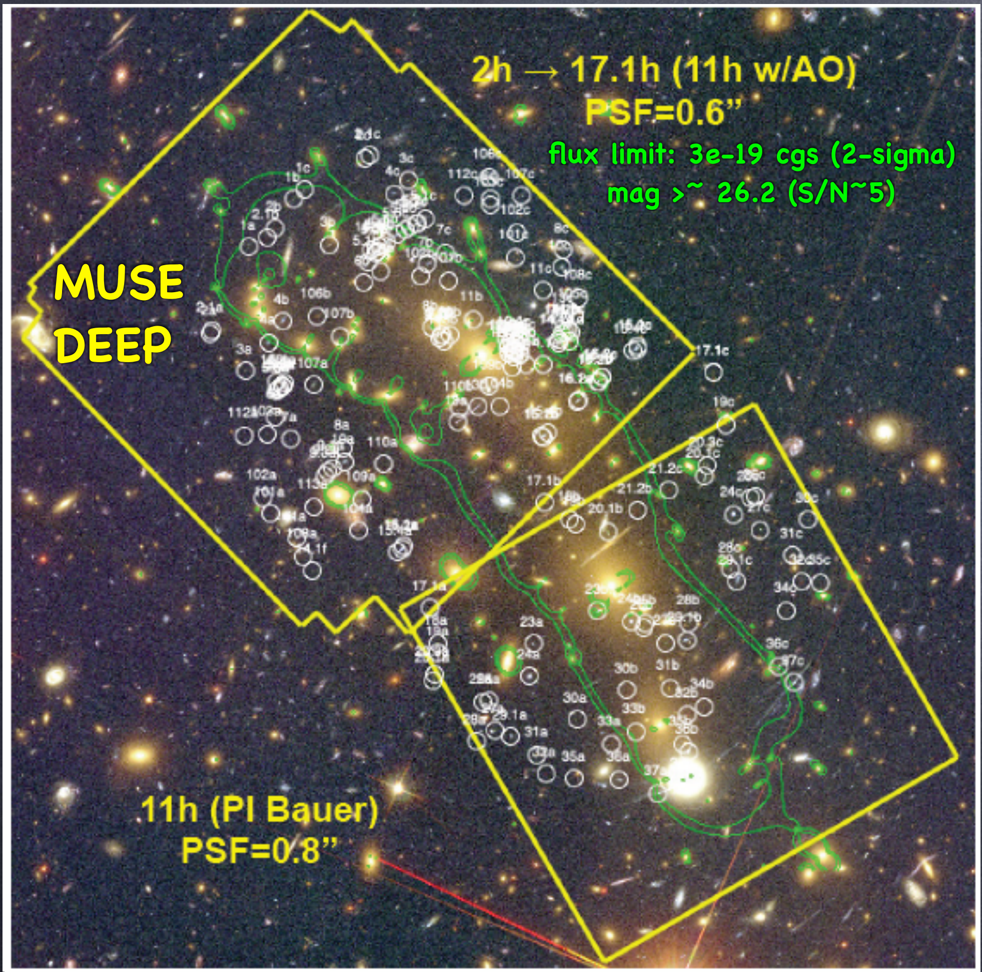
structured morph. at z~10

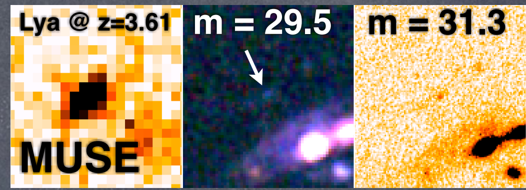
Reff
B < 30 pc
Host ~ 70 pc
C < 30 pc
D < 30 pc

The need of gravitational lensing & the role of the IFU spectroscopy

Wide Field Mode with Ground Layer Adaptive Optics, GLAO , offered by the GALACSI module

Vanzella et al. (2021), A&A, MDLF
Bergamini et al. (2021,2022), A&A, lens model



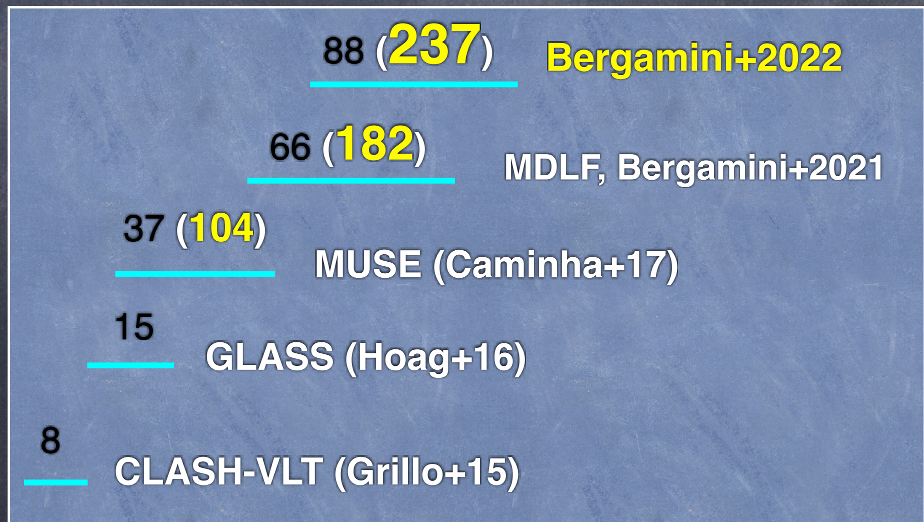


1) **No target pre-selection**
(boost the discovery space, m>28)

2) **Uniform coverage on caustics**
(extreme magnified regions)

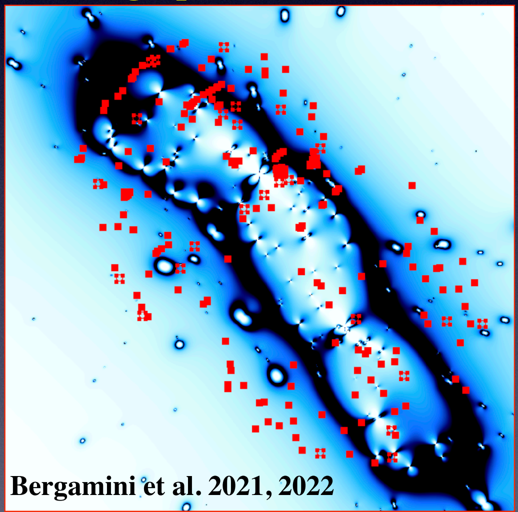
3) **Efficient multiple-image finder**

237 spectroscopic multiple images ! RMS = 0.42”



Constraining the nature of the first stellar complexes:
globular cluster precursors and Population III stellar clusters at z~6-7
PI Vanzella (INAF/OAS) — 24.5h

HFF MACS J0416
Need high-precision lens models



Lens model based on ~ 237 multiple images with zspecs

Five pointings: total integration time 88200 sec
p1,2,3=17690s each (G395H/F290LP, ,R=2700), p4=22034s (PRISM), p5=13305s (G395H/F290LP, R=2700)

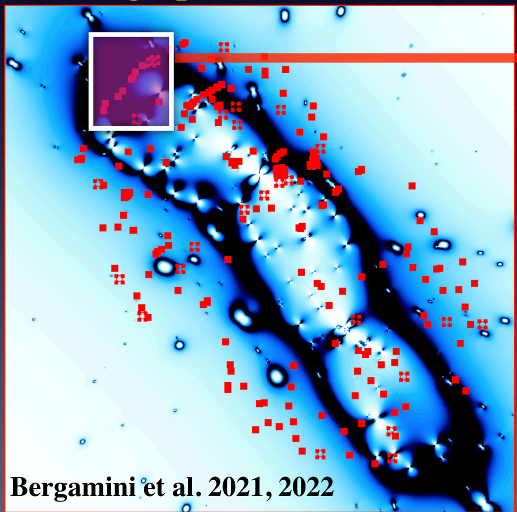
Constraining the nature of the first stellar complexes: globular cluster precursors and Population III stellar clusters at z~6-7

PI Vanzella (INAF/OAS) — 24.5h

Scientific GOALs
- ➜ Proto-GC (z=6.149)
- ➜ **PopIII cand(s) (z=6.63)**
- ➜ Proto-galaxy; ionizing radiation
- ➜ Ha nebula? (Fluorescence, local fesc?)
- ➜ ”HST-dark” MUSE sources

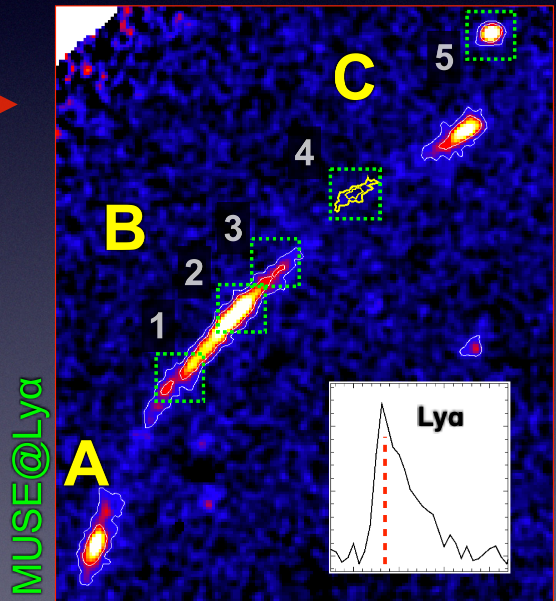
HFF MACS J0416

Need high-precision lens models



Lens model based on ~ 237 multiple images with zspecs

JWST/NIRSpec IFU n.1908



5 Pointings = **24.5h in total** (PI EV)

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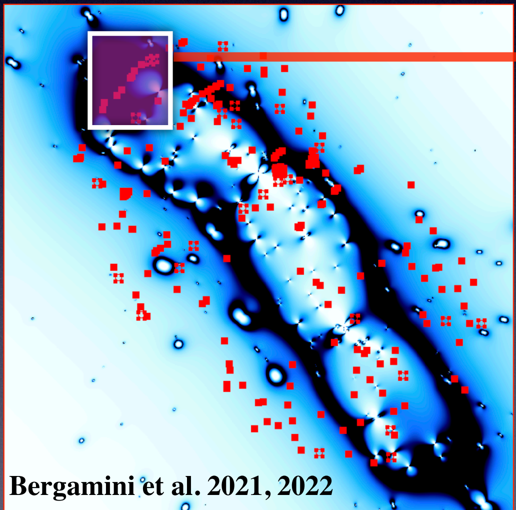
HFF MACS J0416

Need high-precision lens models



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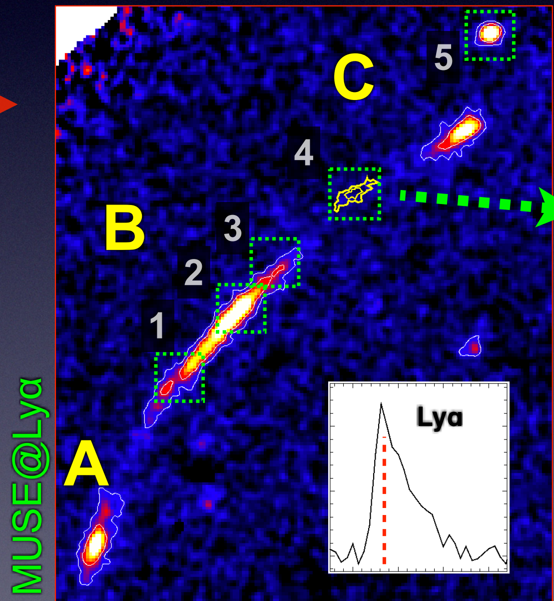

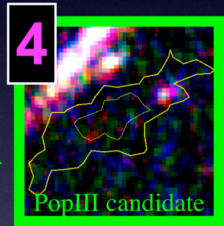

z=6.63

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Constraining the nature of the first stellar complexes:
globular cluster precursors and Population III stellar clusters at z~6-7
PI Vanzella (INAF/OAS) — 24.5h

Situation pre-JWST (EV20)

Scientific GOALs

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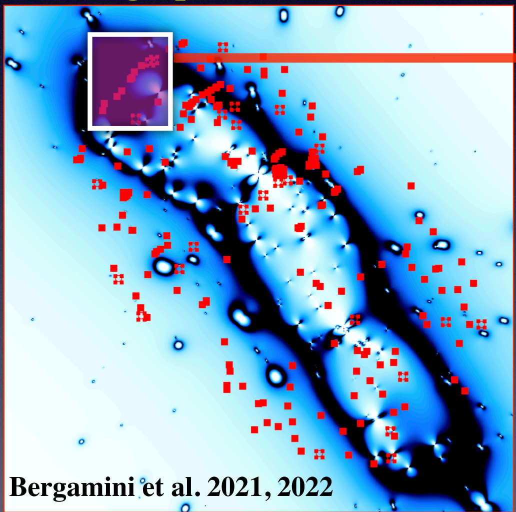
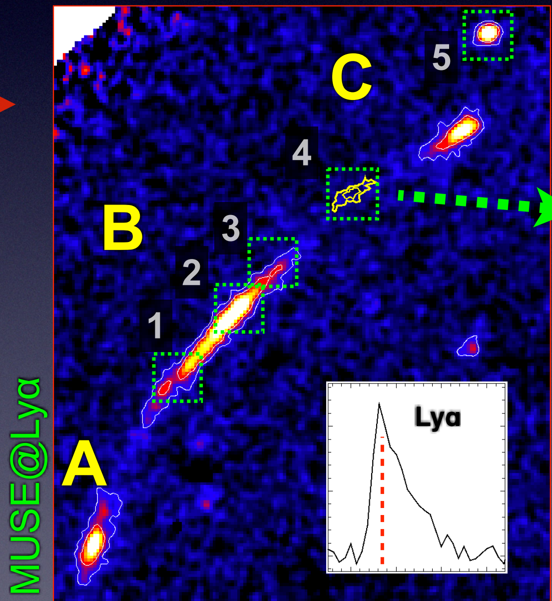
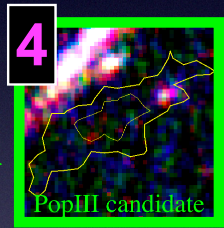
HFF MACS J0416
Need high-precision lens models



Lens model based on ~ 237 multiple images with zspecs

JWST/NIRSpec IFU n.1908





z=6.63

5 Pointings = **24.5h in total** (PI EV)

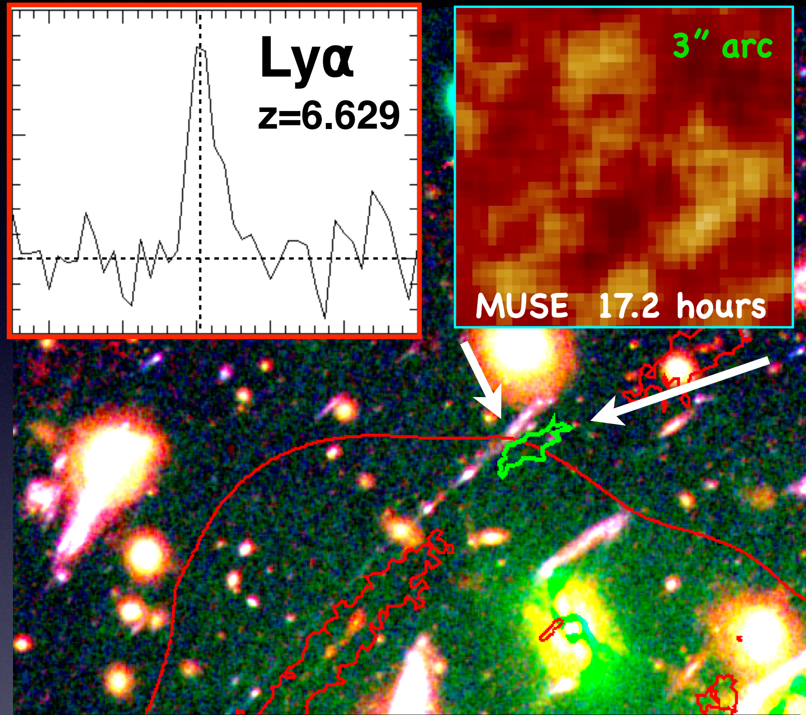
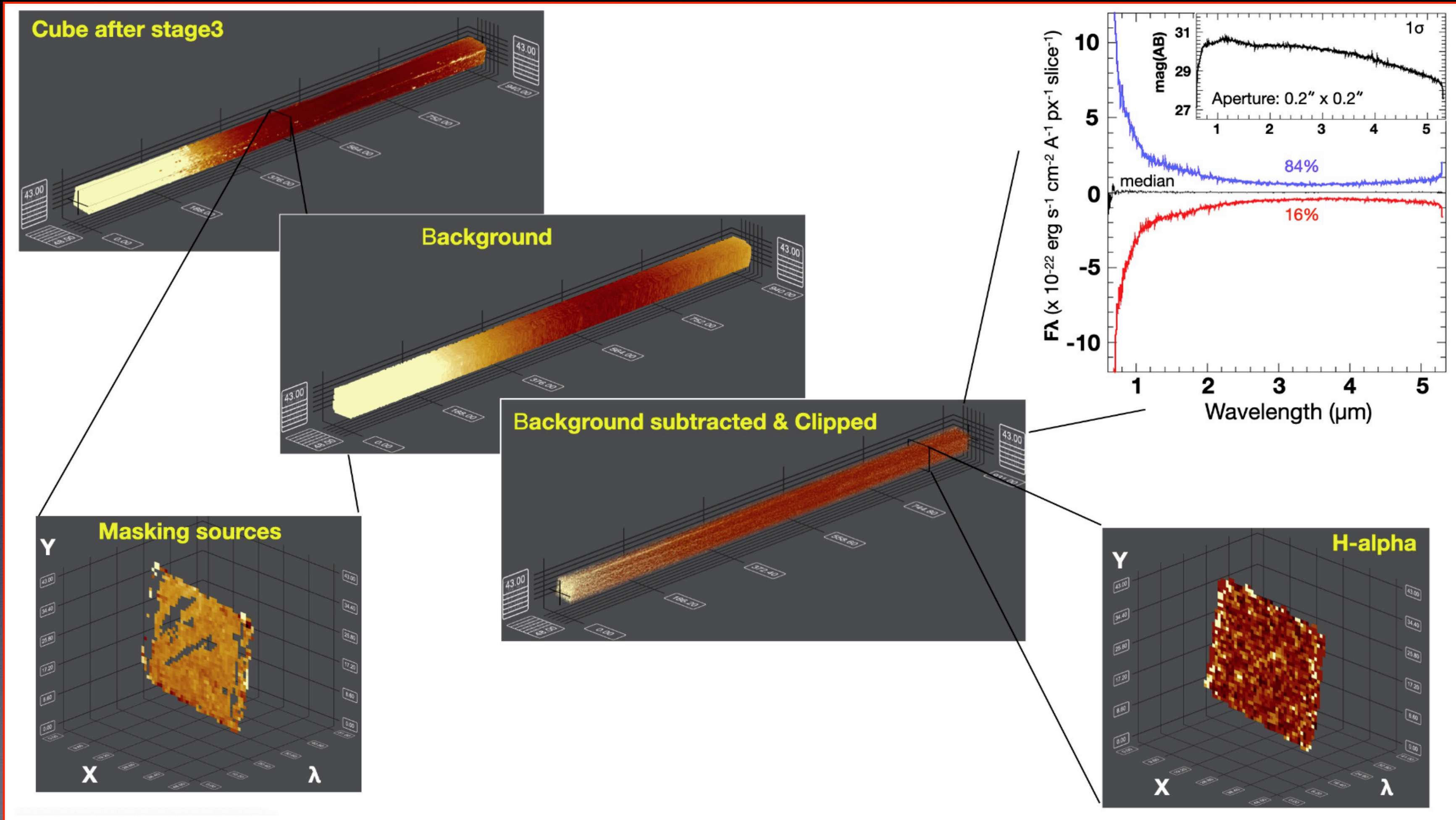


Table 1. Properties of the Lyα emitter in the source plane.

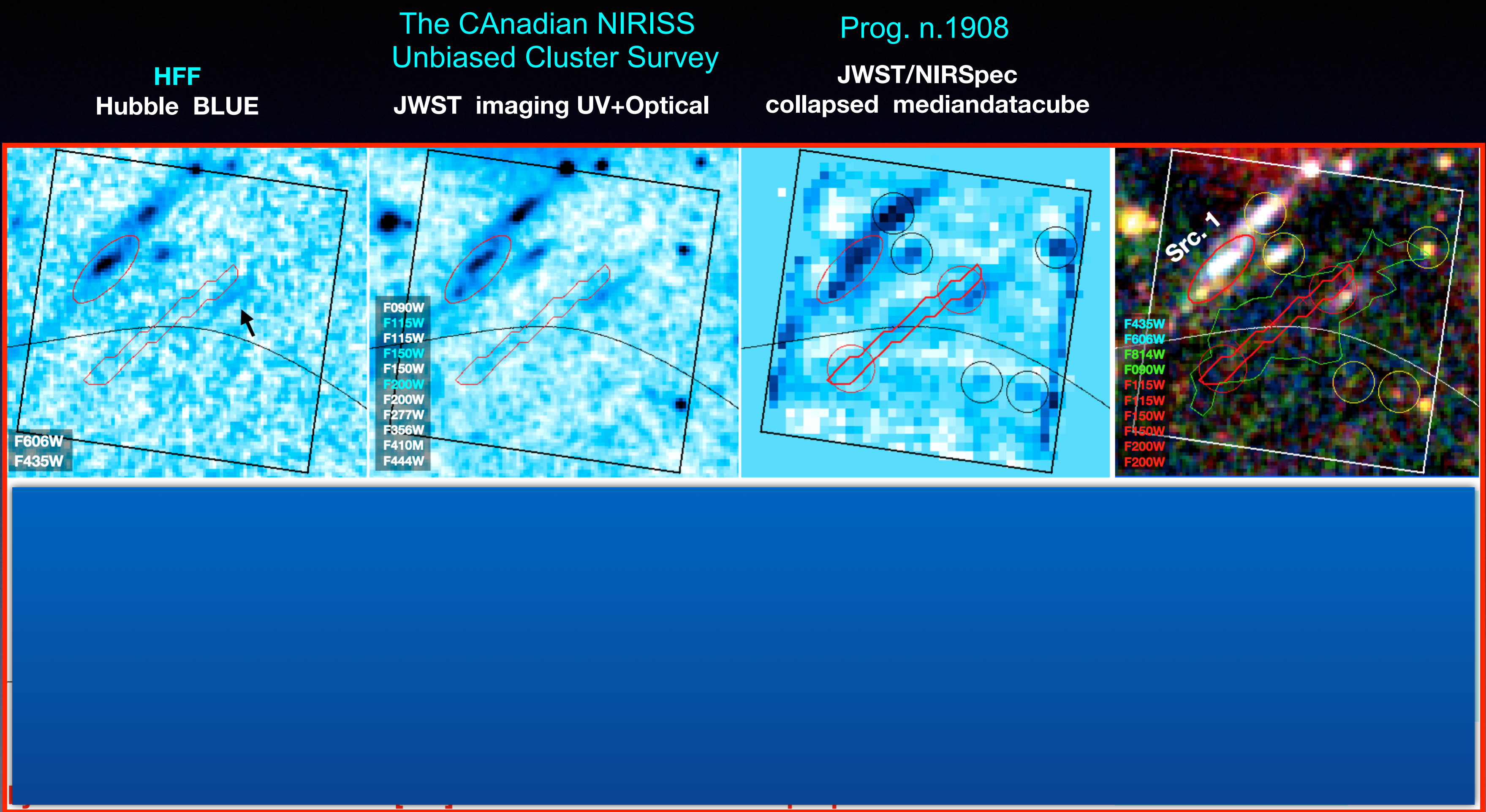
Stellar mass	~3E+04 Msun
Lyα [erg s^{-1} cm^{-2}]	5.5×10^{-20}
Lyα [erg s^{-1}]	2.8×10^{40}
EW_0(Lyα) [Å] ($T_{IGM} < 0.5$)	> 1120
$M_{1500}(m_{1500})$ (2σ)	$\gtrsim -11.9$ ($\gtrsim 35$)
R_e Lyα region [pc]	< 150
Magnification [$\mu(b) = \mu(c)$]	$\mu(b) + \mu(c) \gtrsim 80$; $\mu(a) \simeq 4.5$

Five pointings: total integration time 88200 sec
p1,2,3=17690s each (G395H/F290LP, ,R=2700), p4=22034s (PRISM), p5=13305s (G395H/F290LP, R=2700)

JWST/NIRSpec integral field spectroscopy (pointing 4)



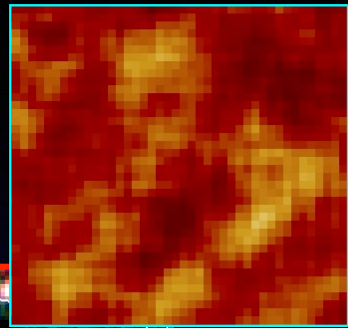
Lensed And Pristine 1 (LAP1): "pure" emission lines emerge with arclet-like shape



no stellar continuum is detected !

prominent Balmer emission

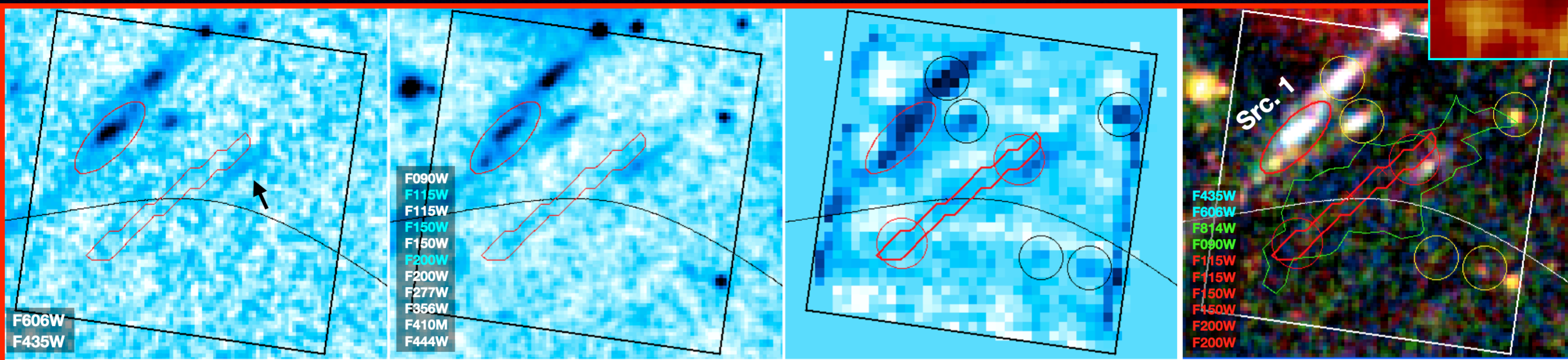
Lensed And Pristine 1 (LAP1): “pure” emission lines emerge with arclet-like shape



HFF
Hubble BLUE

The CAnadian NIRISS Unbiased Cluster Survey
JWST imaging UV+Optical

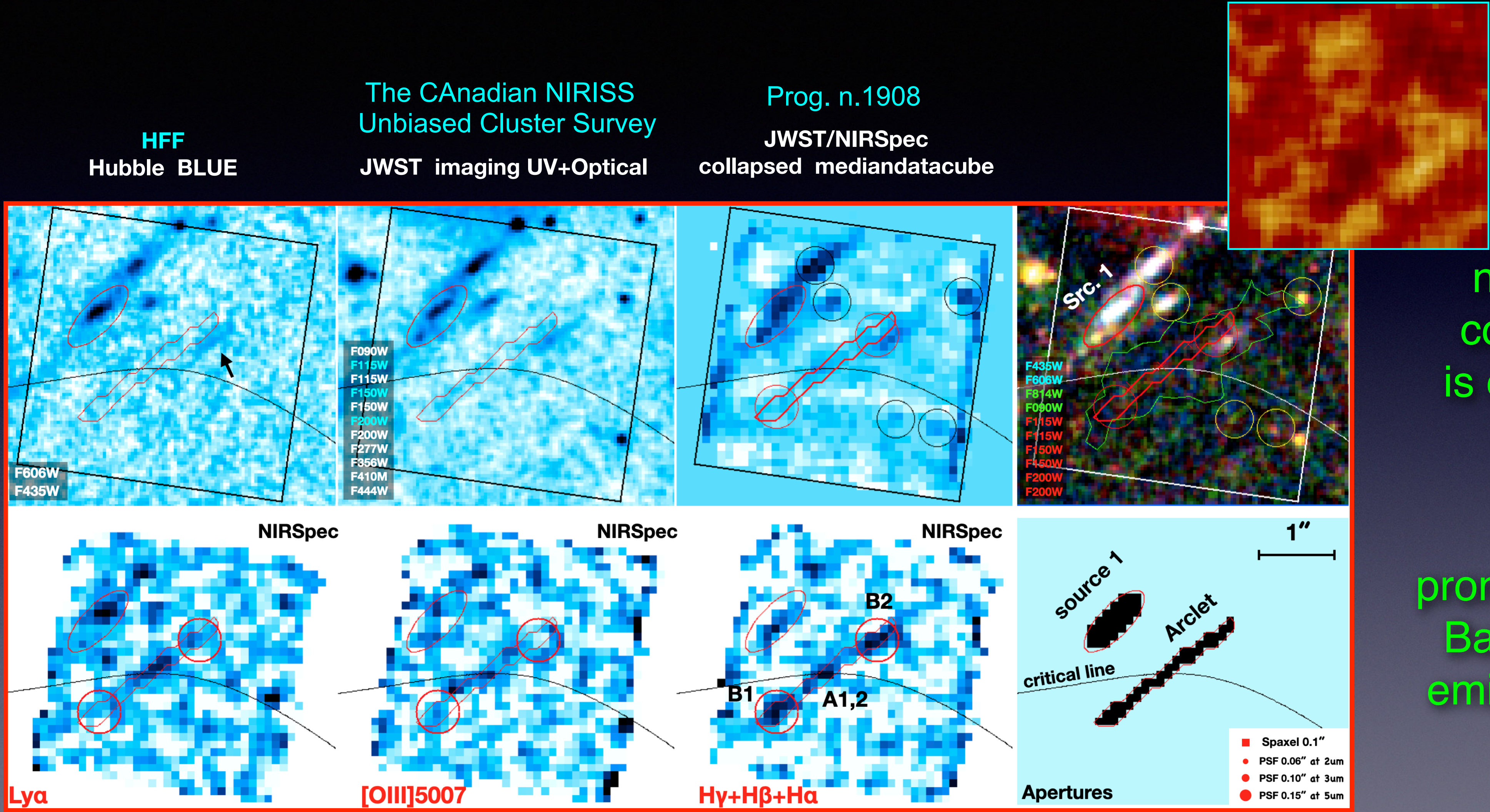
Prog. n.1908
JWST/NIRSpec collapsed mediandatacube



no stellar continuum is detected !

prominent Balmer emission

Lensed And Pristine 1 (LAP1): "pure" emission lines emerge with arclet-like shape

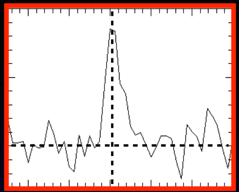


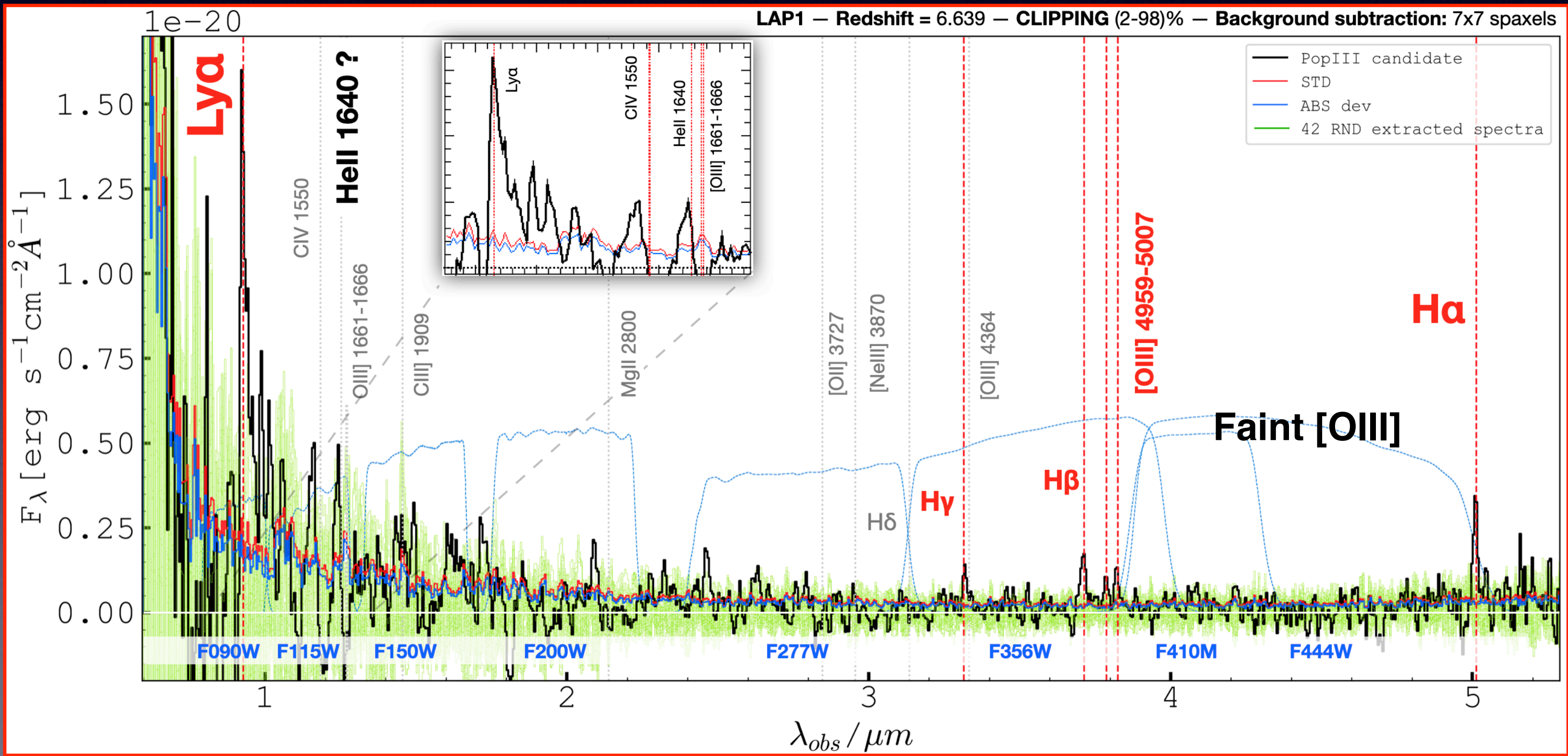
no stellar continuum is detected !

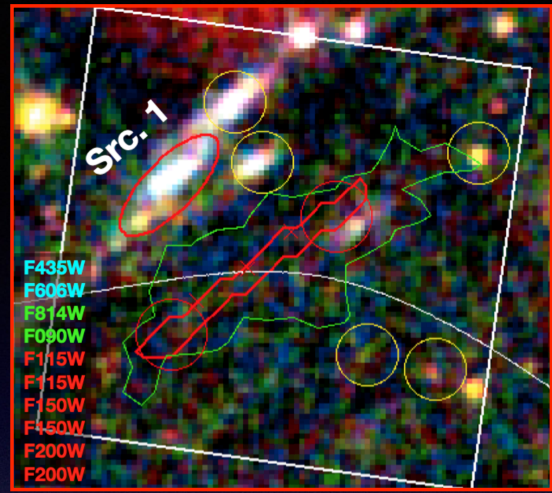
prominent Balmer emission

“pure” emission lines emerge with arclet-like shape

VLT/MUSE







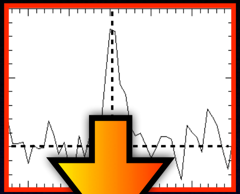
Arclet (LAP1)

Muv >~ 35.6 (2σ)   (> -11.2)

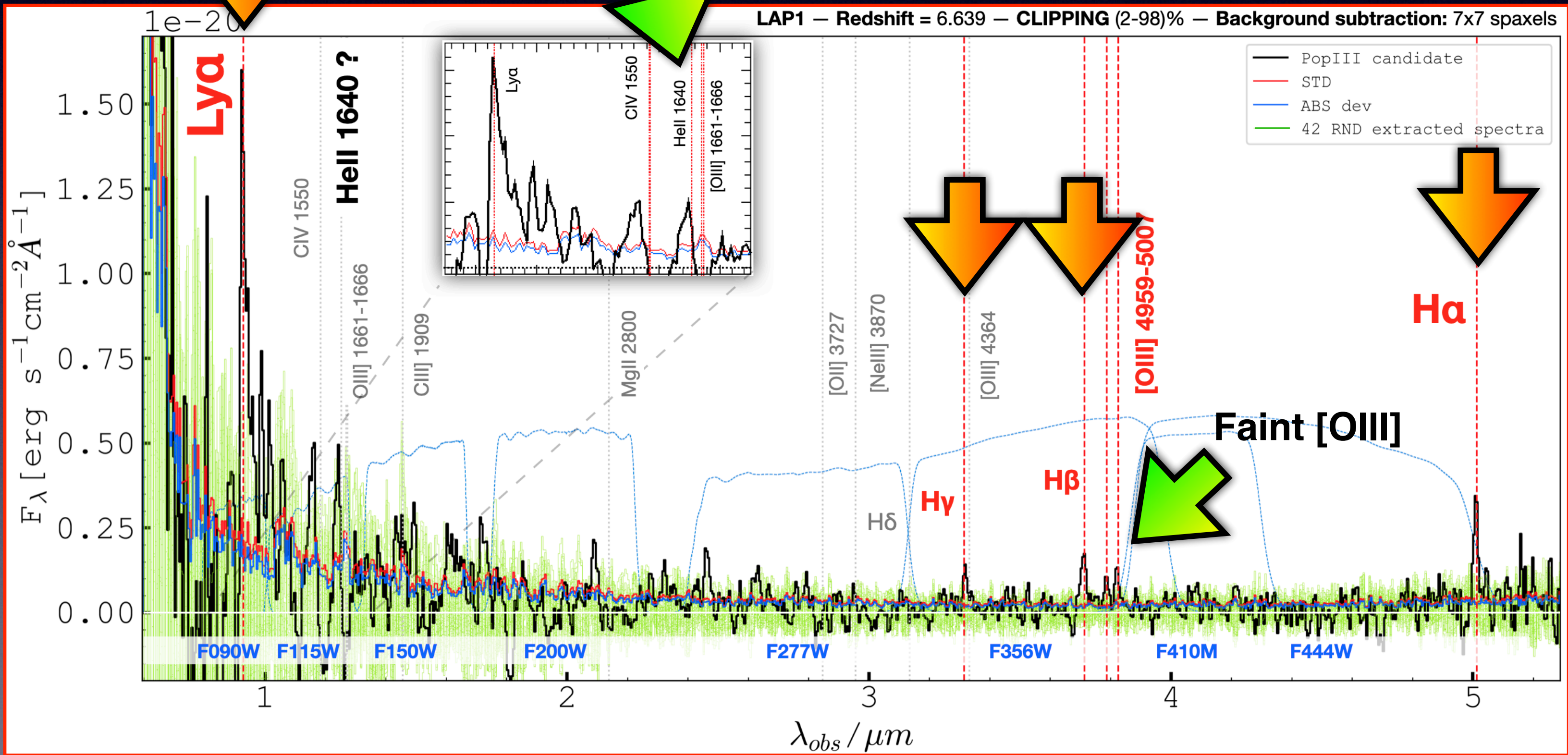
Stellar mass < 1e4 M⊙

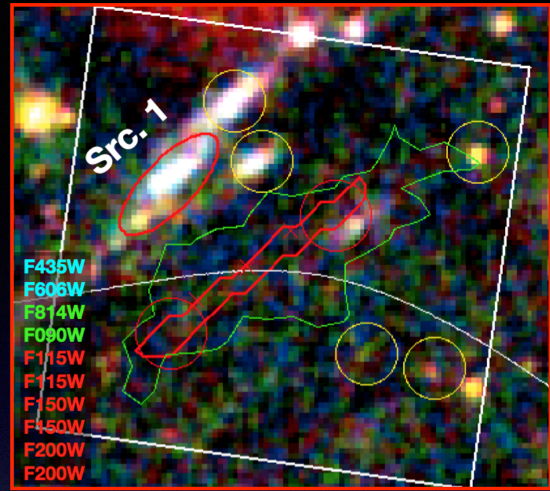
“pure” emission lines emerge with arclet-like shape

VLT/MUSE



No HeII?





Arclet (LAP1)

Muv >~ 35.6 (2σ) (> -11.2)

Stellar mass < 1e4 M$_\odot$

EW(Ha) > 2010 A

EW(Hb) > 420 A

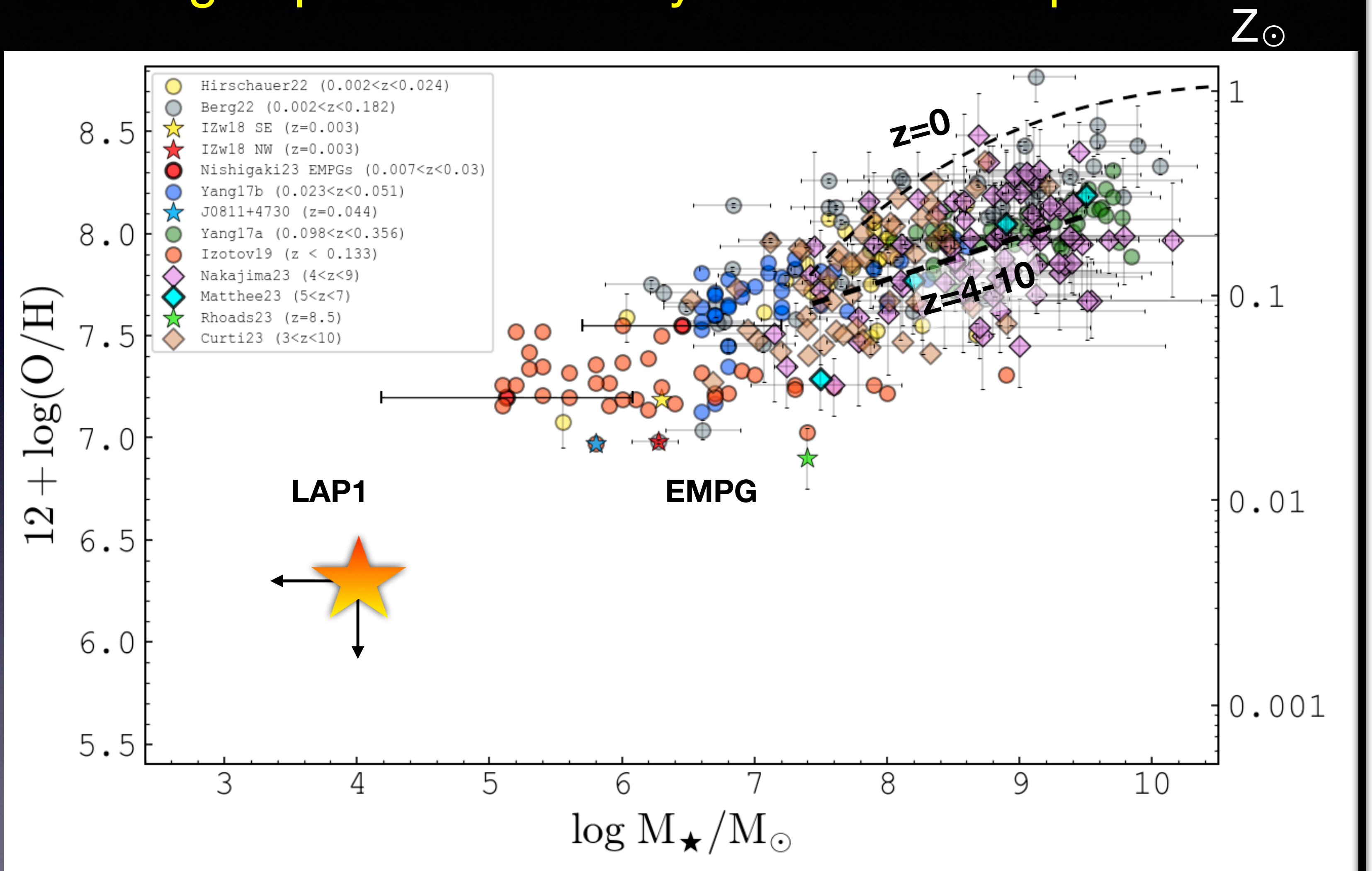
EW(Lya) > 370 A

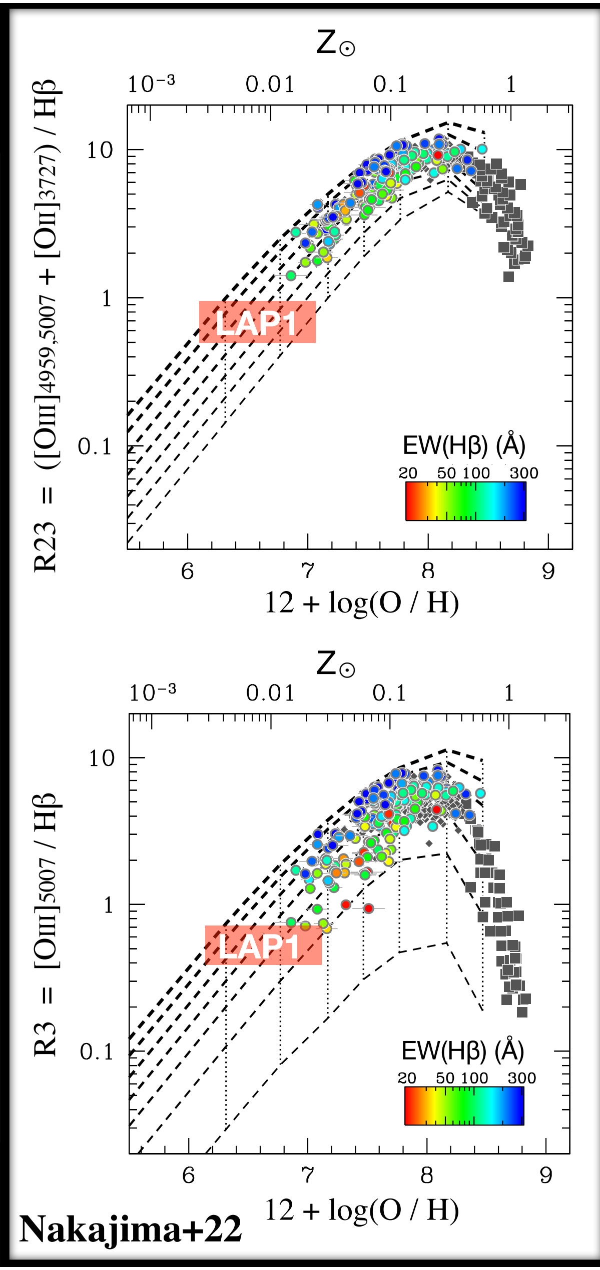
EW([OIII]) > 240 A

R23 = ([OII]+[OIII])/Hb < **0.74**

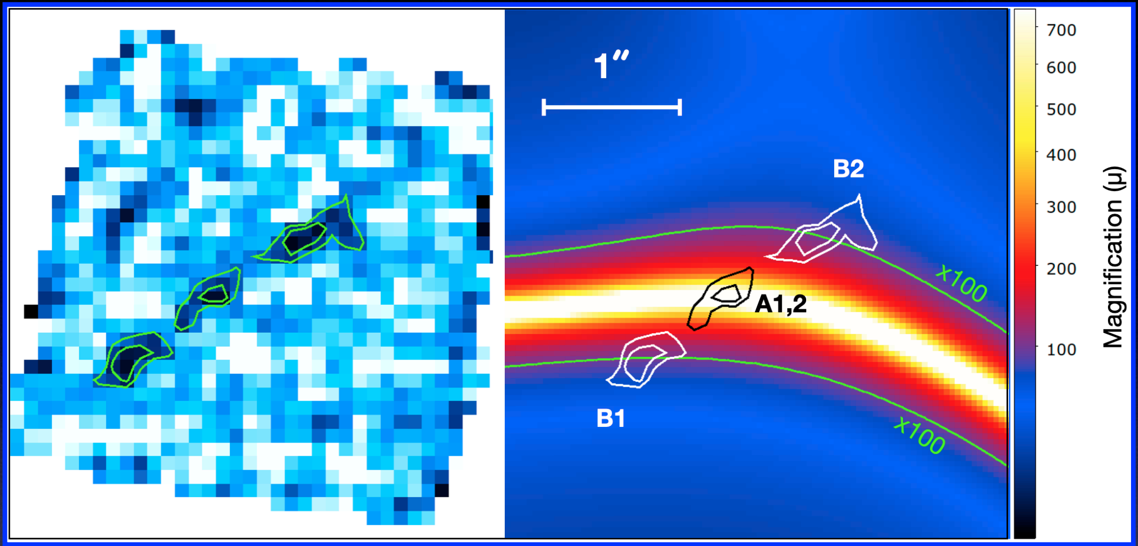
R3 = [OIII]/Hb ~ **0.55**

LAP1: gas-phase metallicity - stellar mass plane





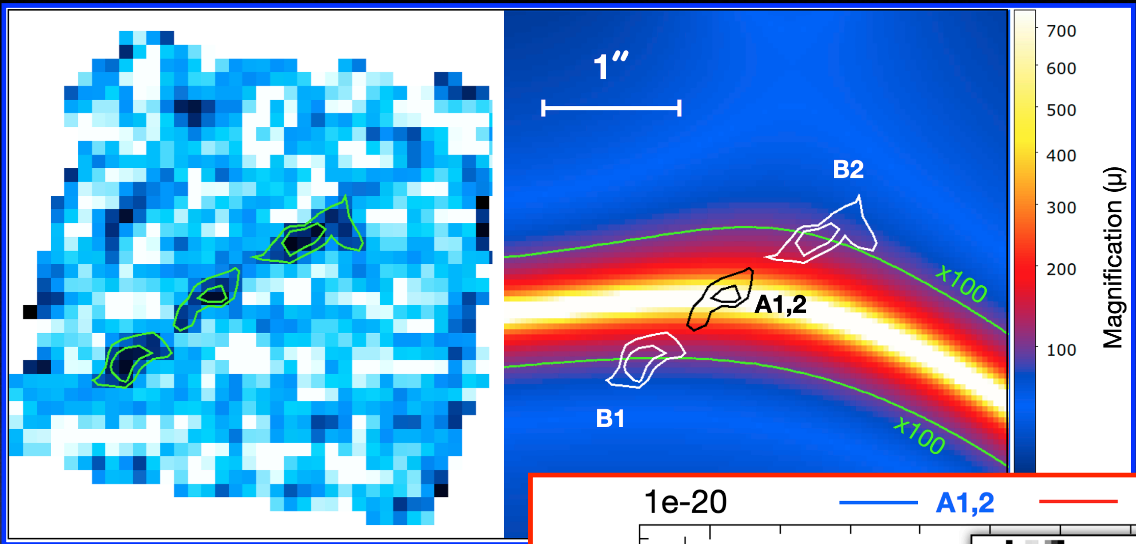
LAP1: the detailed emitting morphology gives even more intriguing scenarios



LAP1 is an arclet produced by two components in the source plane:

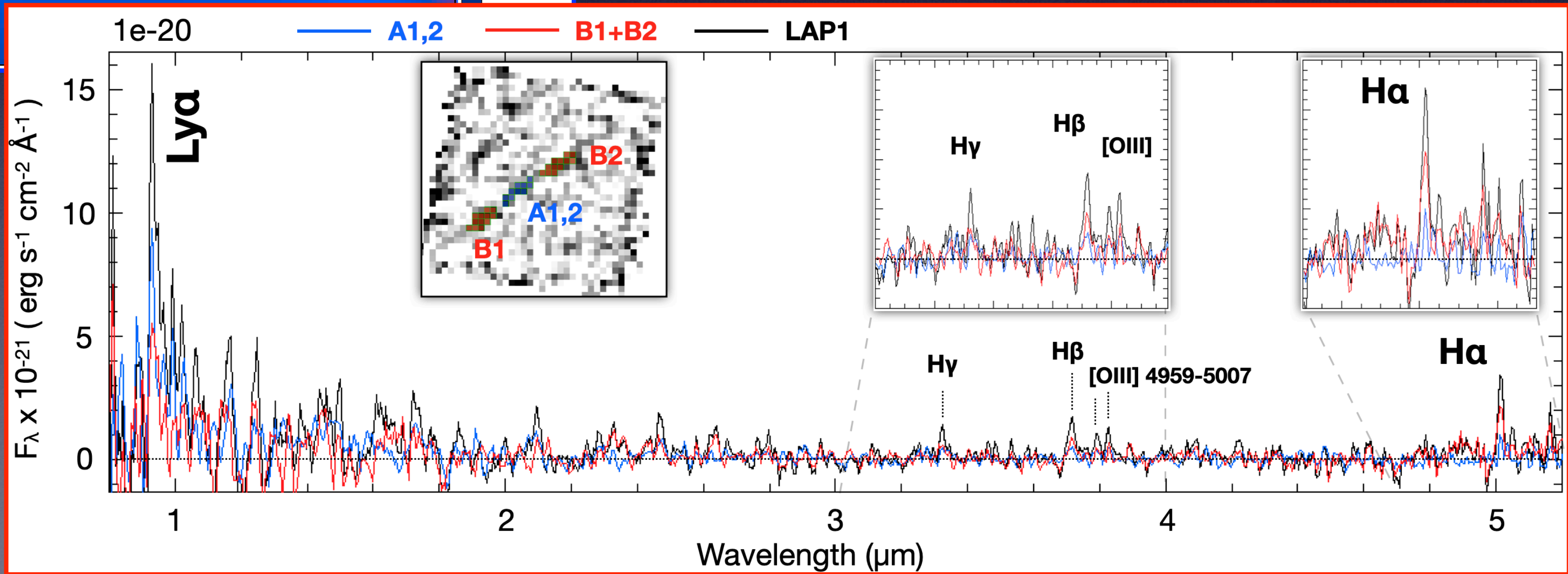
A) crossing the caustic! (A1,2 unresolved) (\mu > 500)
B) two mirrored images, B1,2 (\mu~100)

LAP1: the detailed emitting morphology gives even more intriguing scenarios



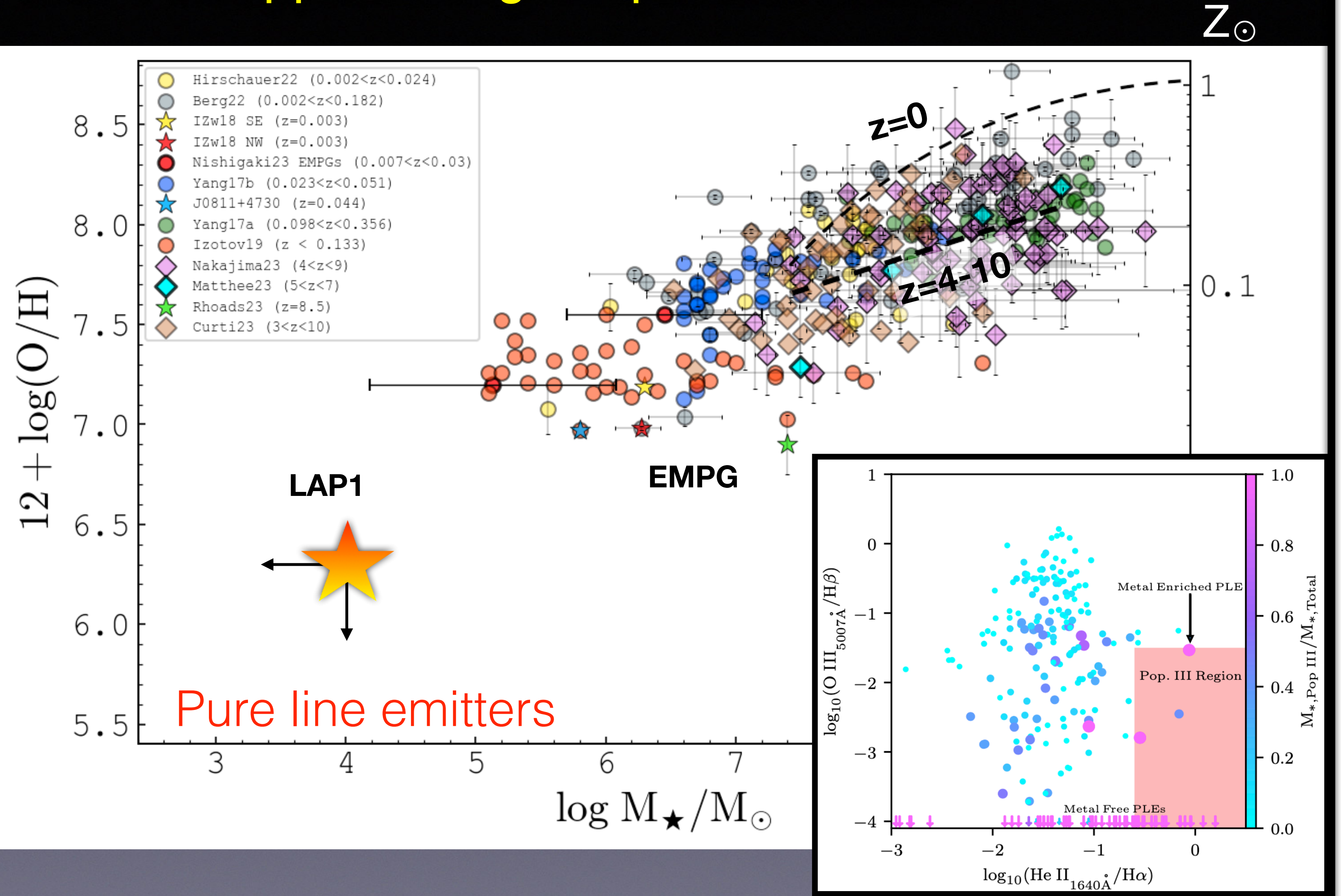
LAP1 is an arclet produced
by two components in the source plane:

A) crossing the caustic! (A1,2 unresolved) (\mu > 500)
B) two mirrored images, B1,2 (\mu~100)

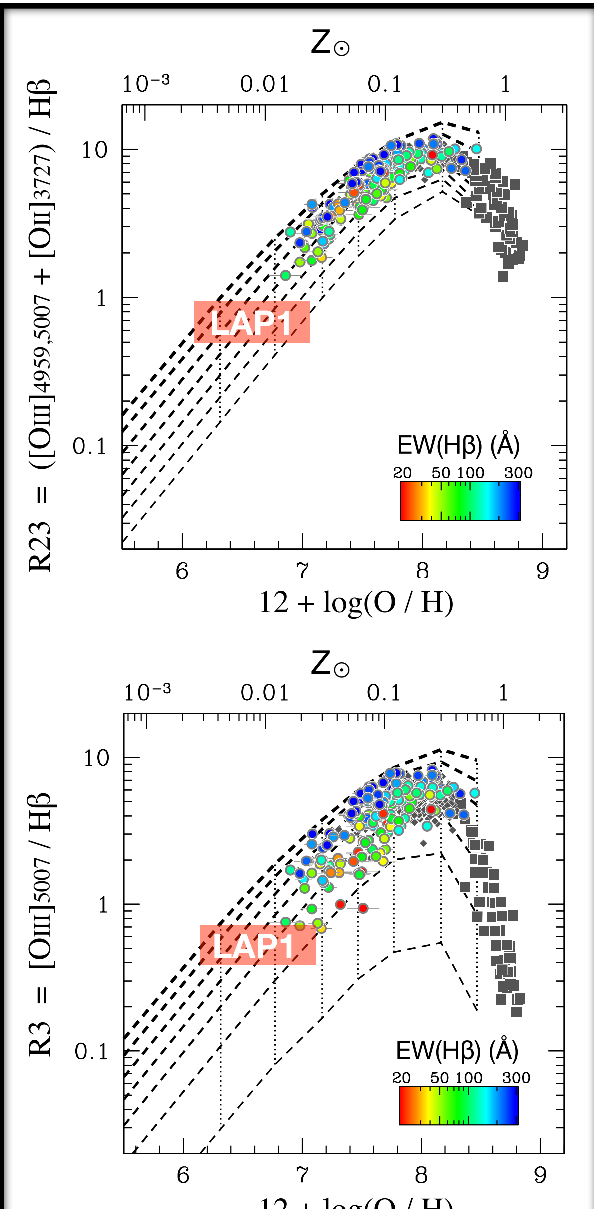


LAP1-B:
m_{UV} > 37.4 (>-10)
Stellar mass < 1e3 Msun
No oxygen [OIII]

LAP1-B: approaching the pristine stars?

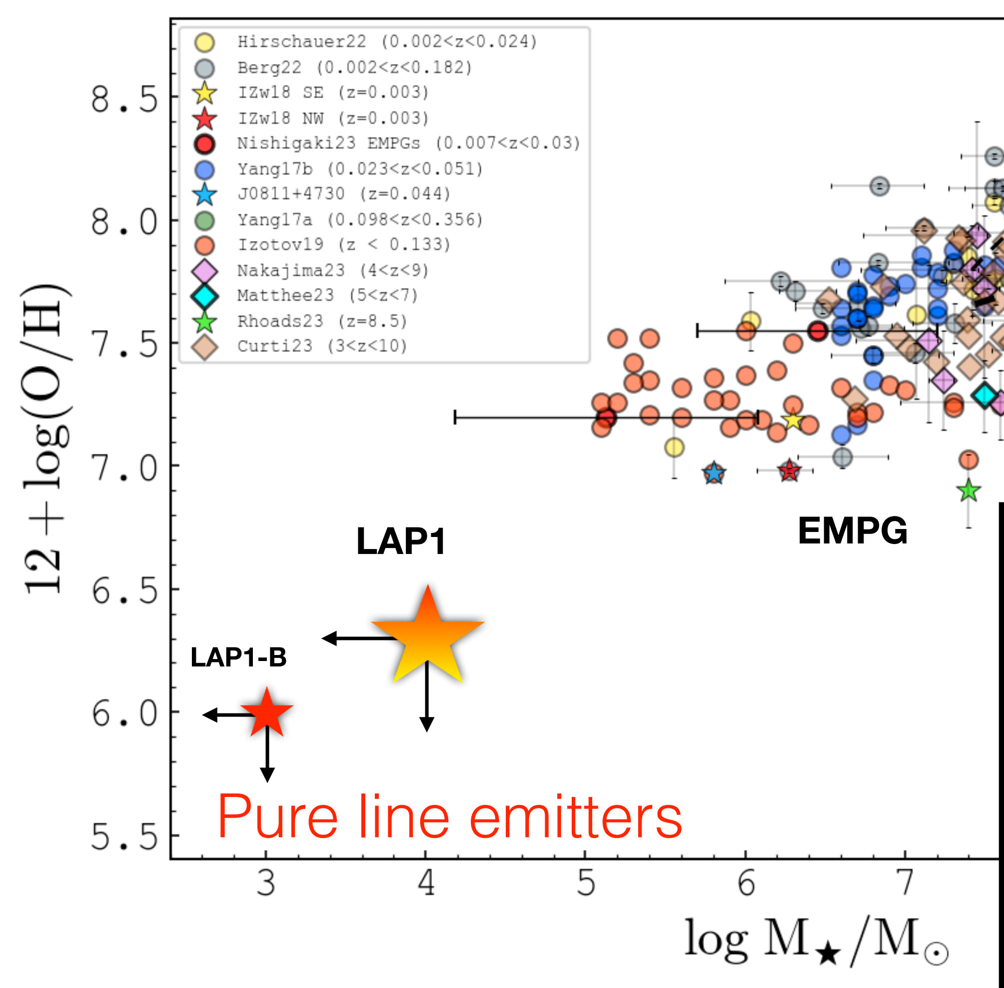


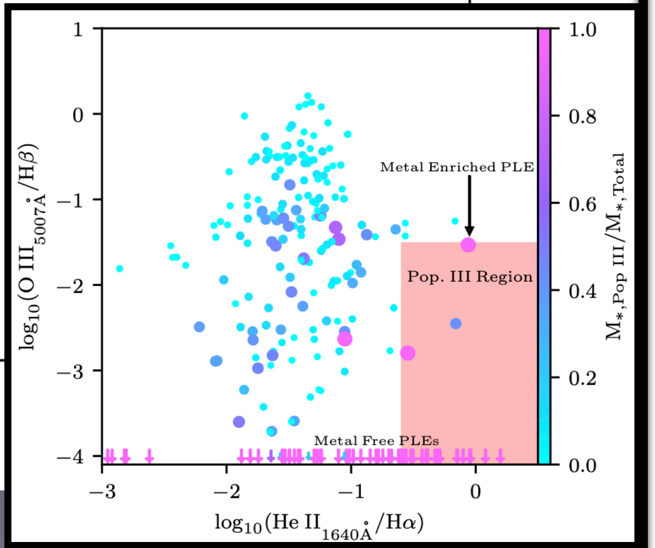
Katz+23



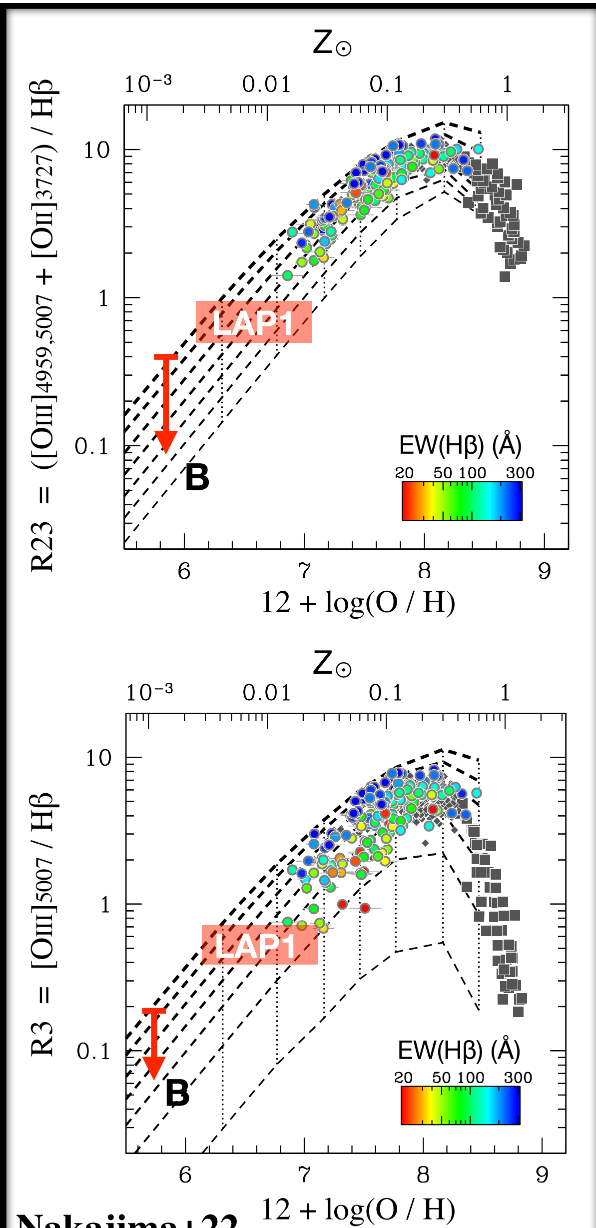
Nakajima+22

LAP1-B: approaching the pristine stars?





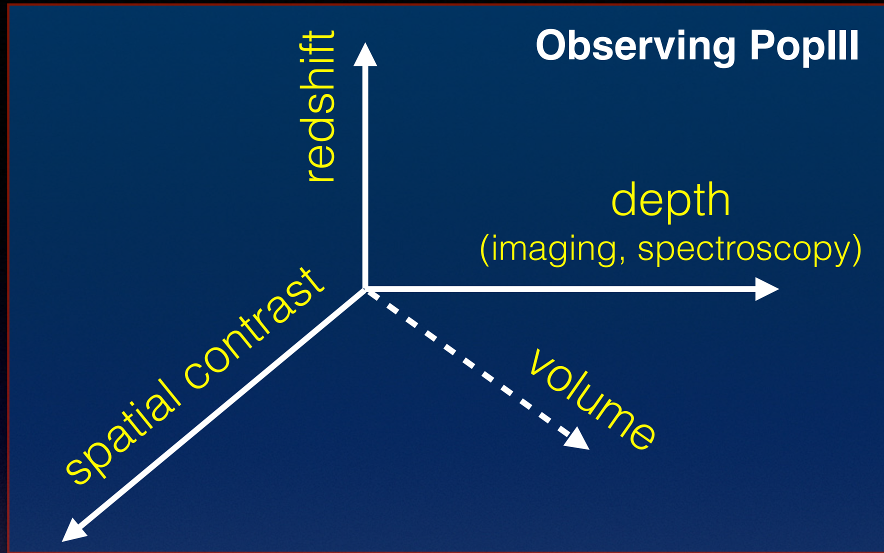
Katz+23



Nakajima+22

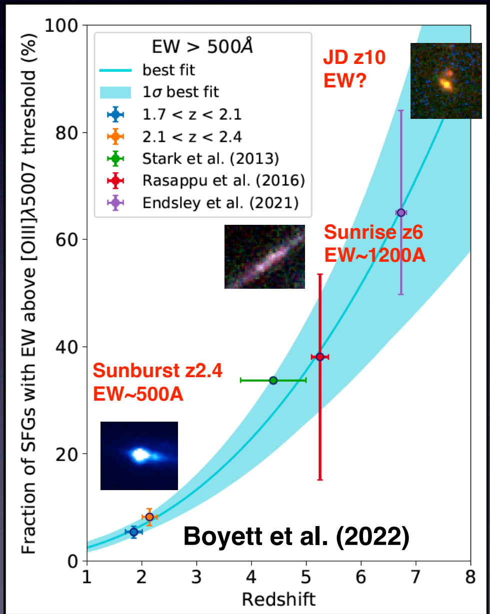
Summary

a) SL seems unavoidable to (try) probe PopIII;
b) Blind spectroscopy (IFU, slitless);
c) Imaging can identify deficient metal lines;



Occurrence of strong oxygen emitters

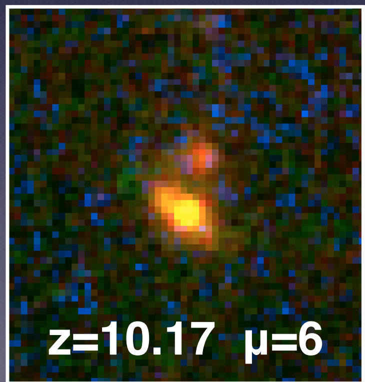
Bursty SF at high-z, large xi,ion & sSFR



Spatial contrast is key

Dense clumps at z>8-10?

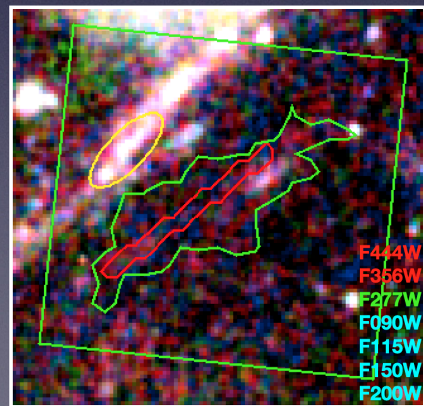
JWST, @70 mas at 2um
Probes **30**(**100**) pc **pix**(**PSF**)



ELT/MORFEO-MICADO @10 mas at 2um
Will probes **6**(**16**) pc **pix**(**PSF**)

Hyper metal poor source at z~7

Is LAP1-B approaching the PopIII condition?



Isolated, <1e4 Msun, Muv -11.8

Some questions, elusive PopIII stars…

- Do we expect star clusters of PopIII ? (If yes, what stellar mass? HK talk …)
    - What's the more suitable spatial scale we have to probe ? (stellar and nebular components)
        - What are the best spectral features we need to look at ?
            - Is the cosmic time eventually the game changer? [z>15-20]
                - Is some orthogonal axis missing here ?