Lyman Continuum Escape at Cosmic Noon

— From Typical Galaxies* to Extreme Starbursts —

UNIVERSITÉ DE GENÈVE

OBSERVATOIRE DE GENÈVE FONDÉ EN 1772

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*** LyC22 JWST survey**

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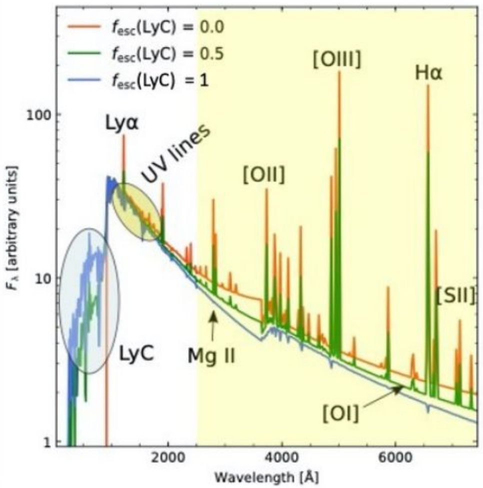
Low-z Lyman Continuum emitters (LzLCS) – main lessons (I)

Indirect LyC indicators established at low-z



- ✓ Lyman-alpha emission
  Verhamme+ 2015, Djikstra & Gronke 2016, Izotov+ 2018, 2021
- ✓ UV absorption lines
  Heckman+ 2011, Steidel+2018, Mauerhofer+ 2021
  Gazagnes+ 2018, Chisholm+ 2018, Saldana-Lopez+ 2022
- ✓ High CIV/CIII] ratio
  Schaerer+2022
- ✓ Blue UV slope: Chisholm+2022
- ✓ Mg II
  Henry+2018, Chisholm+2020, Xu+2022
- ✓ [SII] deficit
  Wang+ 2019, 2021; Ramambason +2020
- ✓ HeI lines
  Izotov+ 2017, Guseva+ 2020
- ✓ High [OIII]/[OII] ratio
  Jaskot & Oey 2013, Nakajima+ 2014, Izotov+ 2018, Flury+ 2022
- ✓ [OI] ?
  Plat+ 2019, Ramambason +2020, Flury+ 2022

- Multivariate prediction for fesc (Jaskot+2024ab, Mascia+2023,2024)
- Outflows (Amorin+2024)

LyC22 JWST survey: LCE 2.2 Gyr after the Big Bang (PI: D. Schaerer *)

- The last frontier to test indirect LyC indicators

- Deep NIRSpec medium-res program: 73.5h total
  18 hours on source (~ 9h with G140M and ~9h with G235M)

- Extensive ancillary data:
  Ground-based + HST, Spitzer, JWST photometry
  HST LyC imaging
  Deep Keck LRIS spectroscopy (rest-UV)

- Medium-res spectroscopy of known **z~3 LyC emitters + non-emitters**

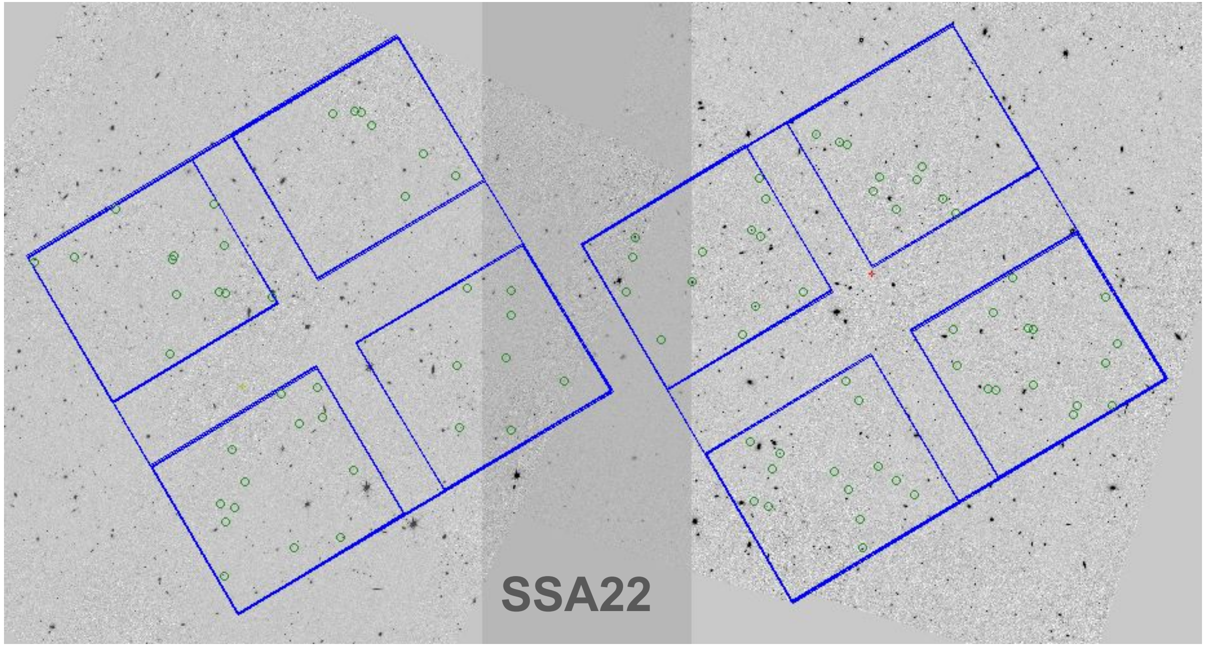
- Full spectral coverage from **MgII 2800 to [SII] (~6700 Ang) + rest-UV coverage from Keck spectroscopy**

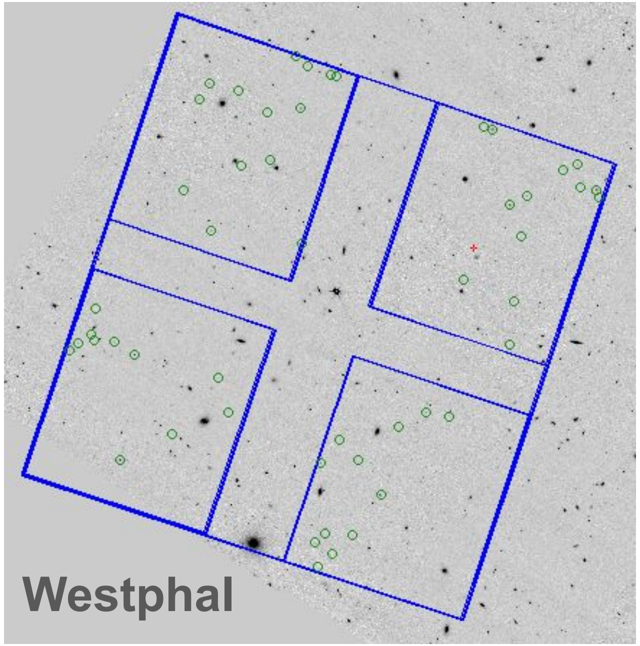
- Primary targets from :
  Keck Lyman Continuum Survey – KLCS (Steidel+2018, Pahl+)
  HST z~3 leakers – LACES (Robertson+, Fletcher+2019) - 12 LCE
  New deep Keck spectroscopy
  -> careful reanalysis of LyC candidates + searches for new sources

*** many other Co-Is (some here: Mascia, Reddy, Pentericci, Verhamme, Vanzella, Kerutt, Flury, Oestlin, RMC, etc.)**

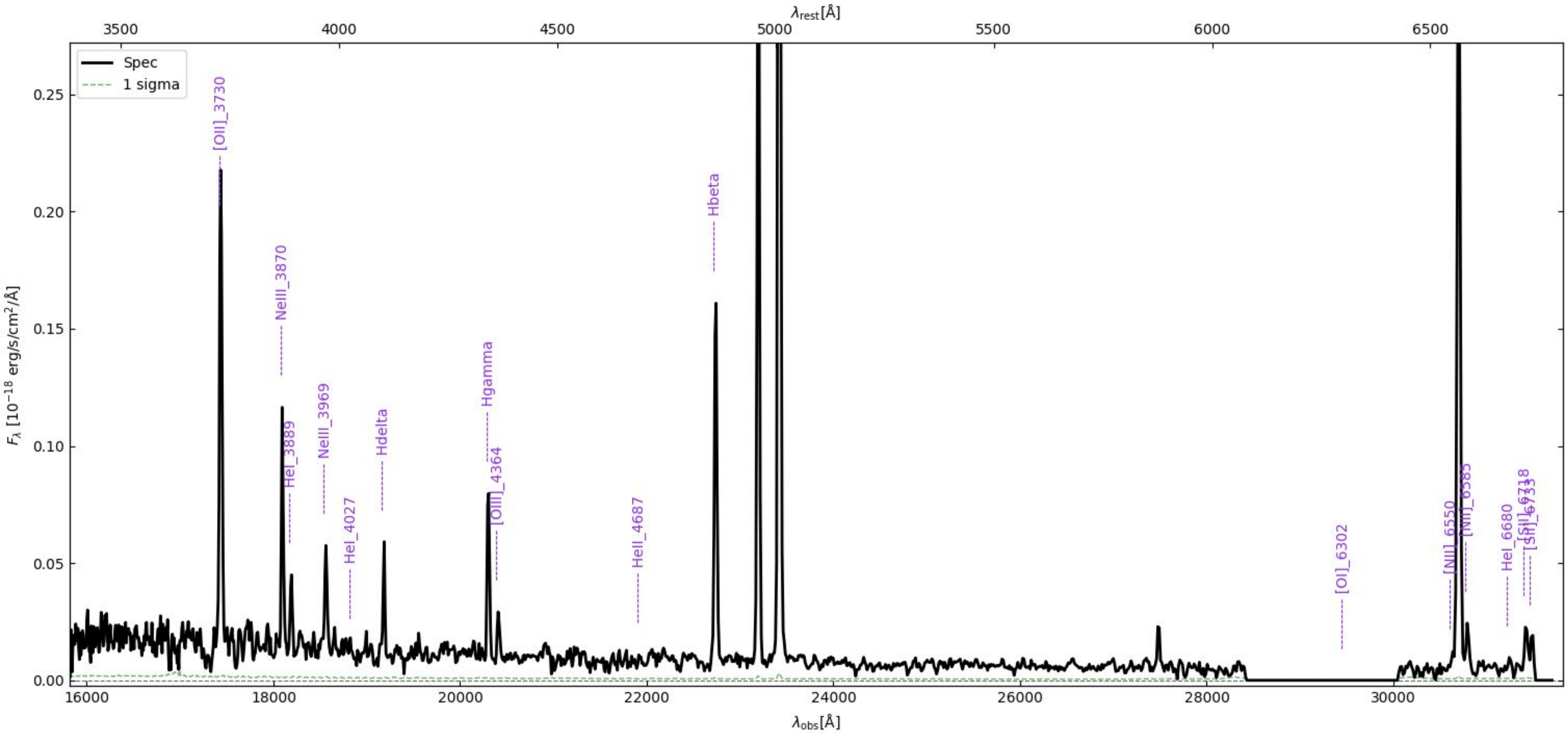
Overview:

- 3 MSA pointings: 2 in SSA22 and 1 in Westphal (see below)
- 18 hours on source (~ 9h with G140M and ~9h with G235M)
- 3-Shutter-Nod dither pattern





LyC22 spectra - some examples:



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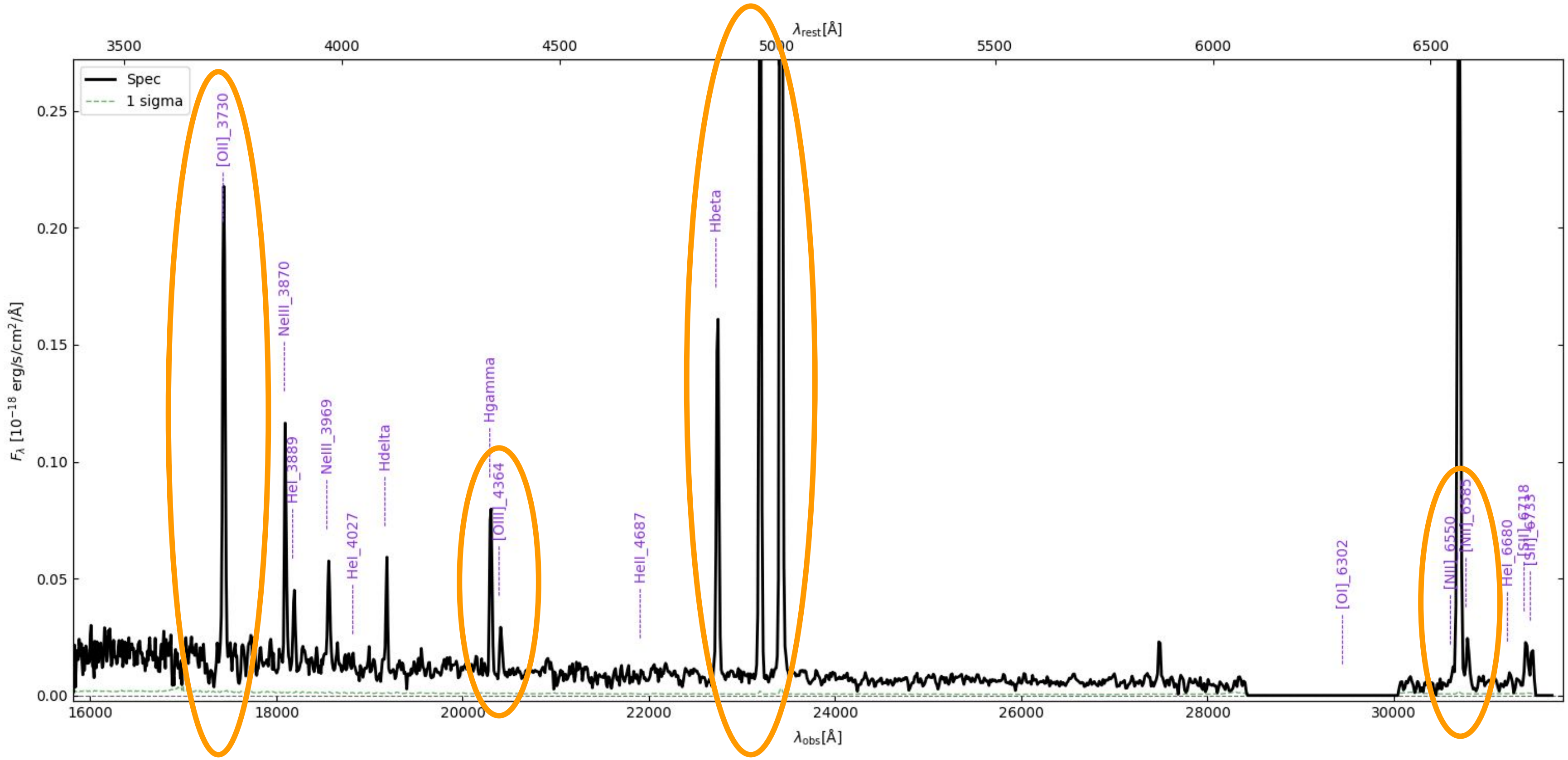

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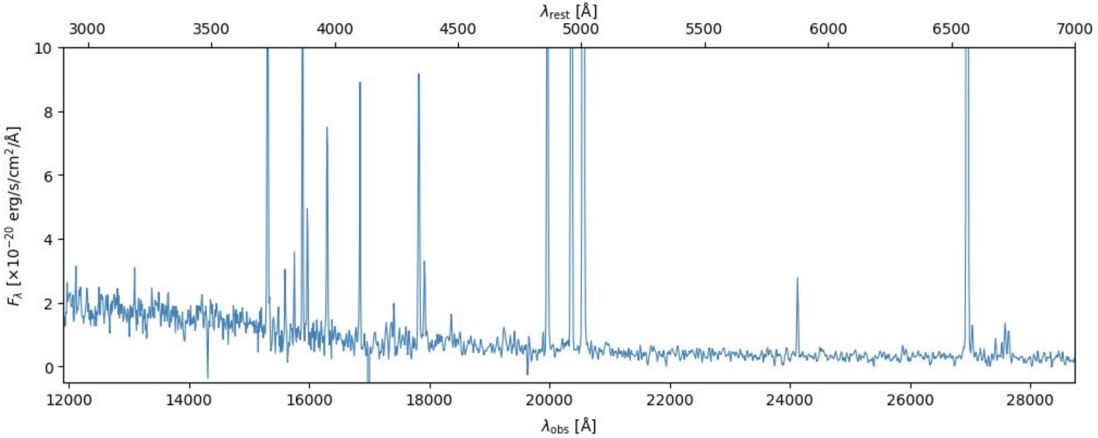
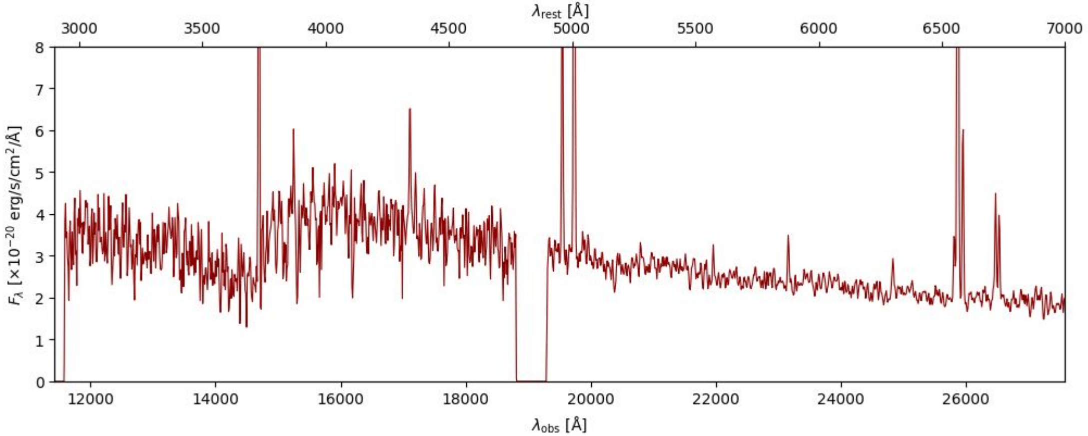


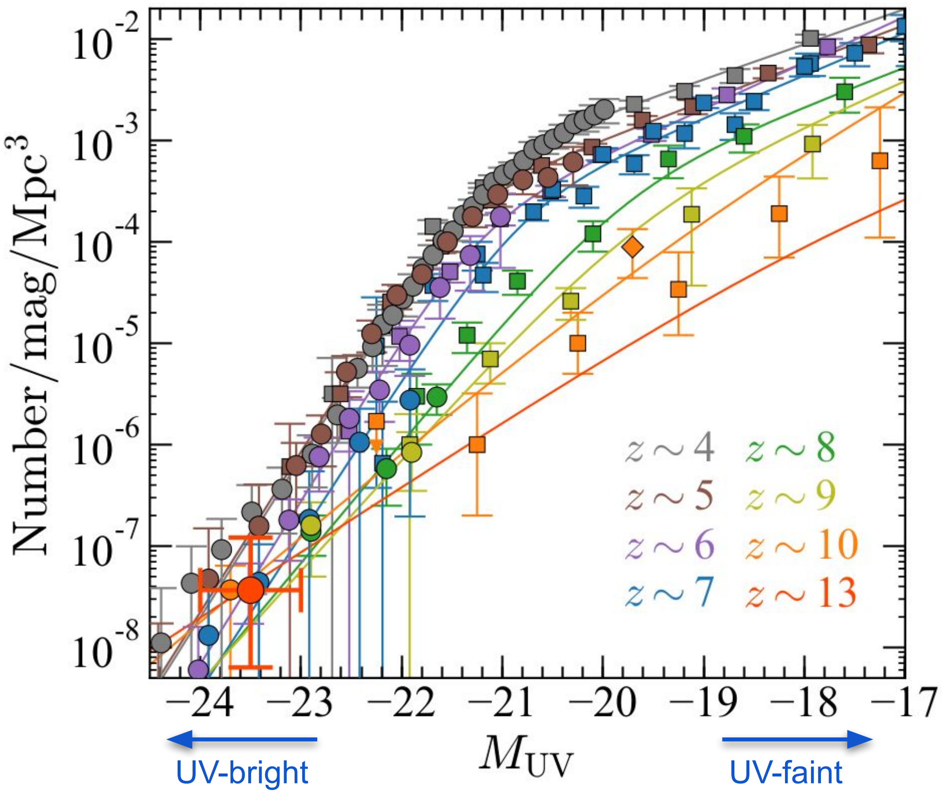
Rest-optical dominated by nebular lines and continuum



Evolved stellar population (Balmer break)

Part II - Extremely UV-bright starbursts

UV-Luminous sources are unexpectedly numerous in the EoR



Harikane +2022

$$\frac{\text{Number UV-bright SFGs}}{\text{Number UV-faint SFGs}}$$

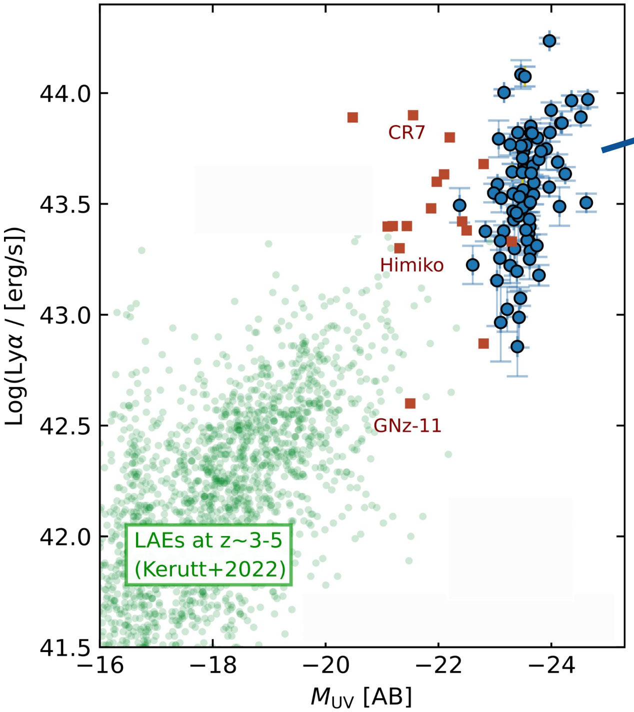
Increases with redshift

But what do we know about UV-bright galaxies ?

The most UV and Lyα luminous star-forming galaxies known so far

Selected from BOSS/SDSS (9000 deg2)

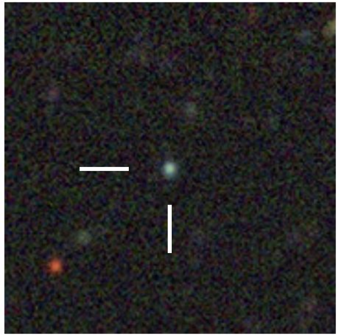
***Fillers:** there should be many more …*



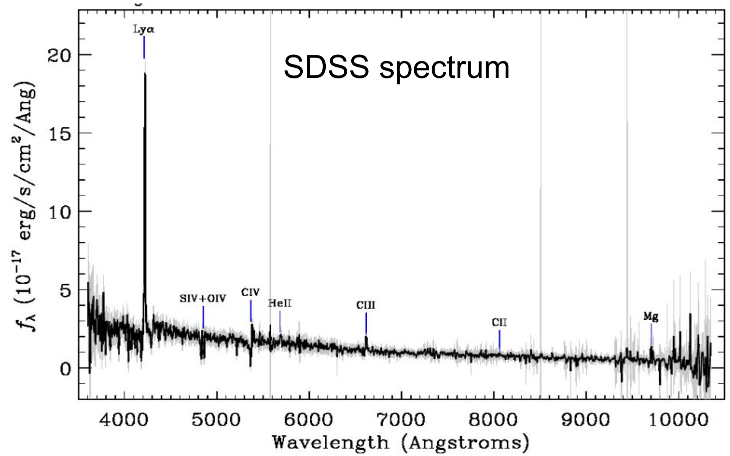
Marques-Chaves + (in prep.)

New sample of ~80 UV-luminous SFGs at *z* = 2-4

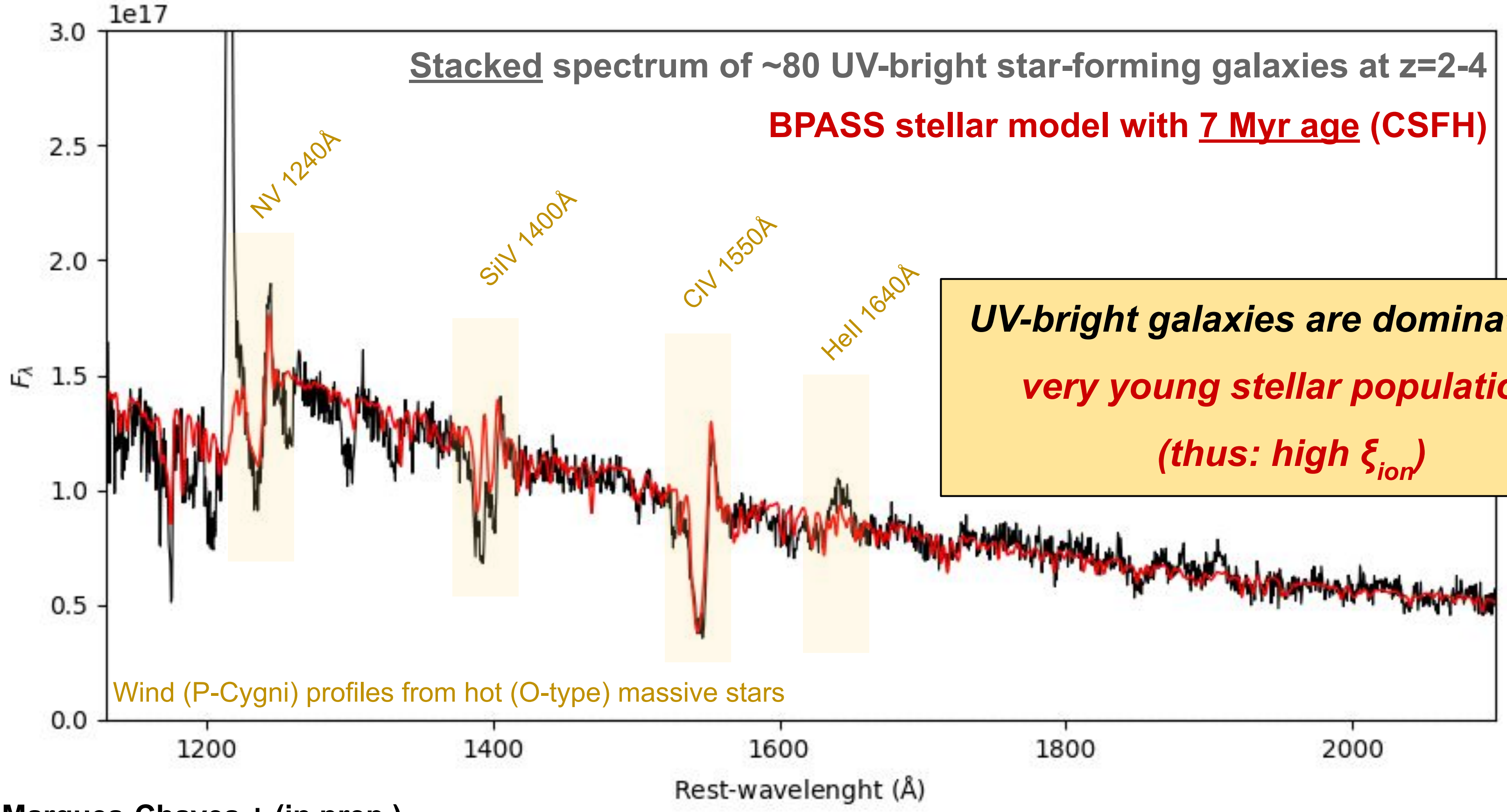
- Selected within the BOSS/SDSS survey as QSOs
- Bright apparent magnitudes R ~ 21 AB (ie, rest-frame UV)
- But no evidence of AGN activity or lensing*



Compact morphologies



Stellar populations: average properties



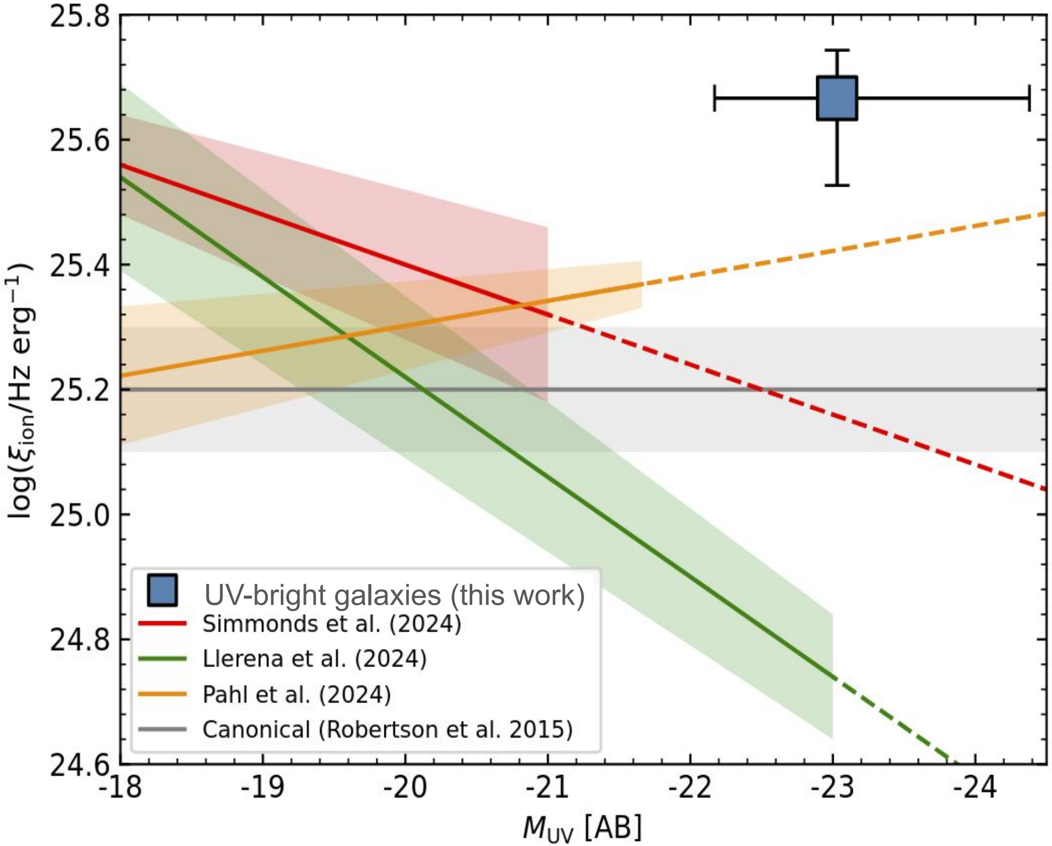
UV-bright galaxies are dominated by very young stellar populations (thus: high ξ_{ion})

Marques-Chaves + (in prep.)

UV-bright galaxies are dominated by very young stellar populations

→

UV-bright galaxies are Powerful ionizing sources!



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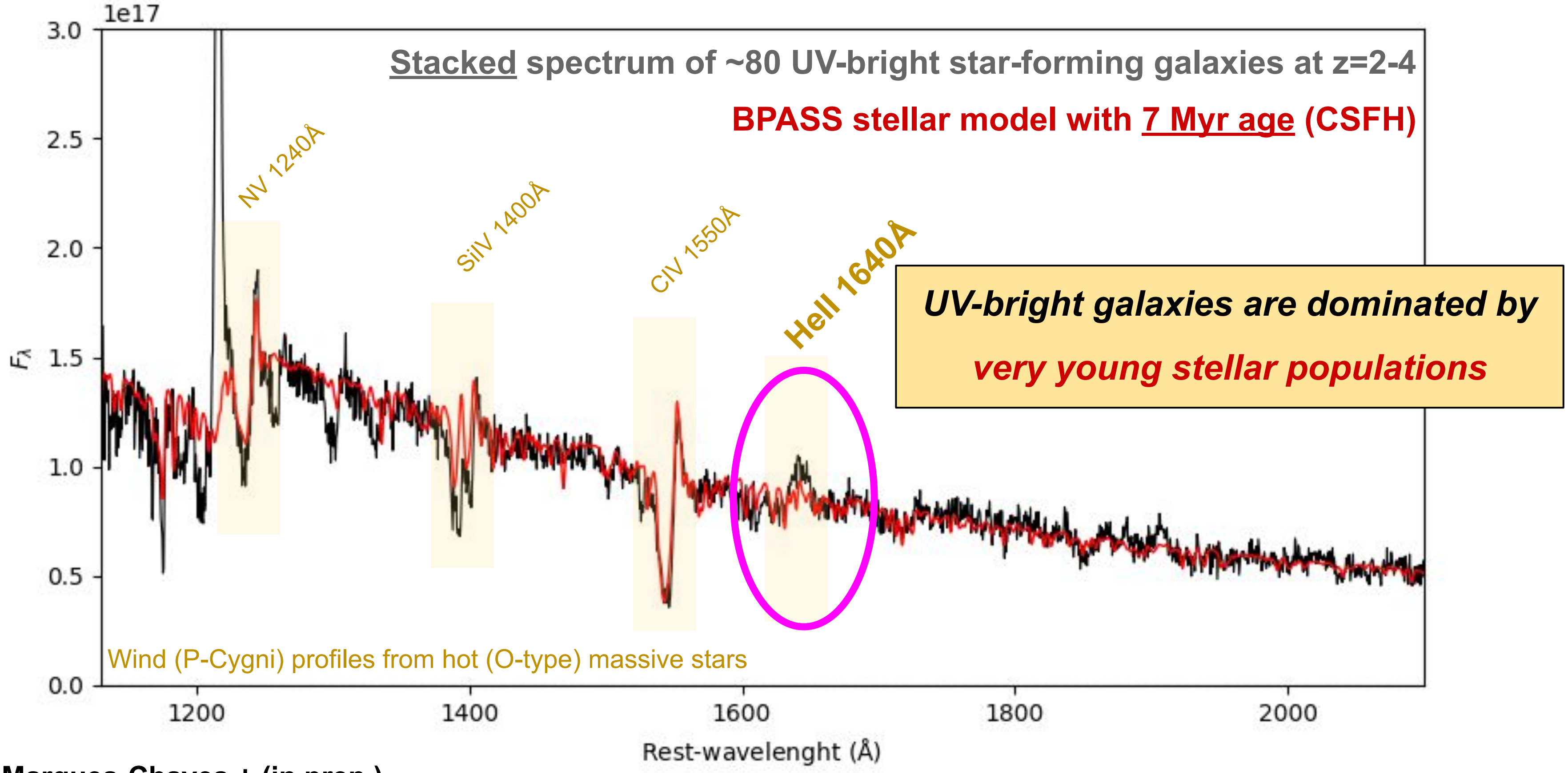
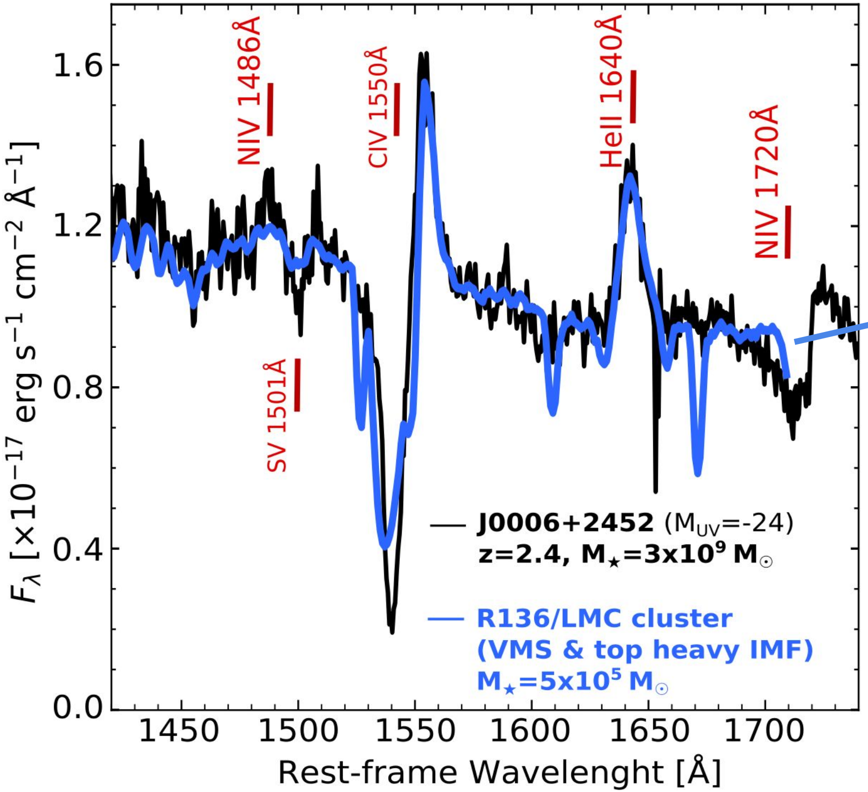
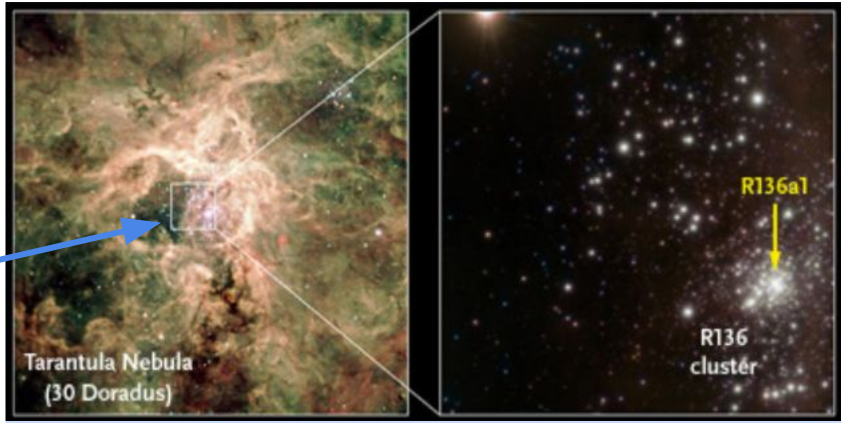


Marques-Chaves + (in prep.)

UV-bright starbursts resembling young and massive star-clusters with VMS





R136 Cluster (30 Dor @LMC):

Stellar Mass = ~ 0.5 x 10^5 $M_\odot$, Age ~ 1 - 2 Myr

- Known to harbor **Very Massive Stars** (Crowther+16)
- Top-heavy IMF (slope~ -1.9, Schneider+18)
- **Strong and broad HeII 1640Å as a key feature of VMS**

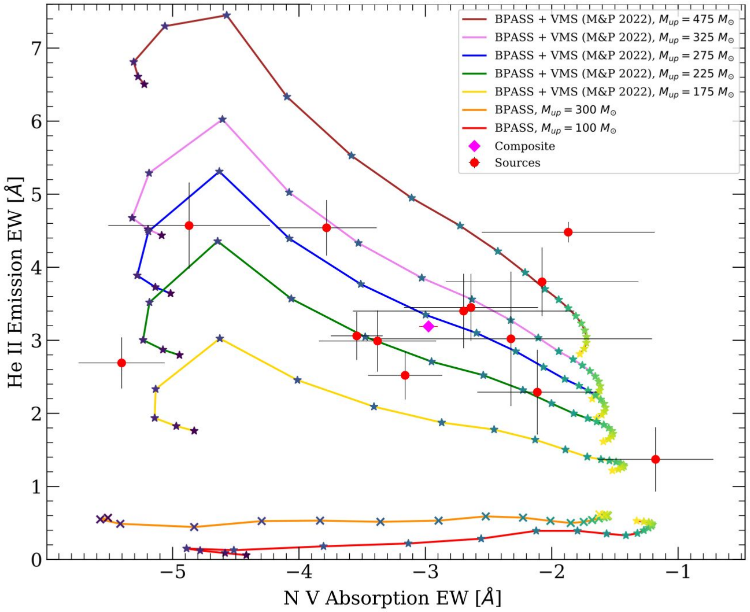
Important: N=5 VMS in R136 contribute 30% of L_{UV} and ~50% of LyC of the cluster!!!

Upadhyaya, RMC +2024

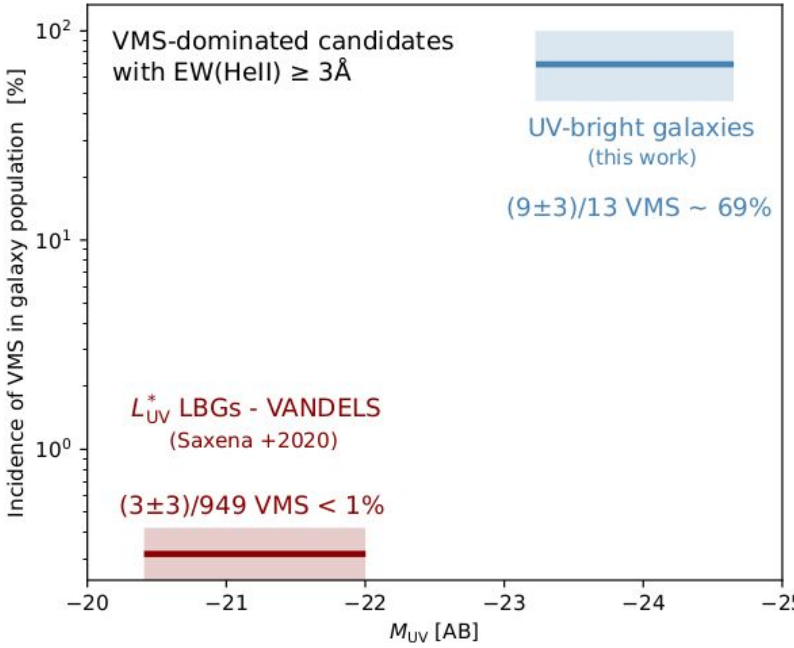
Strong indications of Very Massive Stars (VMS) in UV-bright sources

Rest-UV spectra show intense HeII 1640 emission:

- EW(HeII) ≥ 3.0 Å (not reproduced by standard models/IMFs)
- VMS are required
- I.e., like R136 cluster and otherVMS-dominated clusters



Upadhyaya, RMC +2024

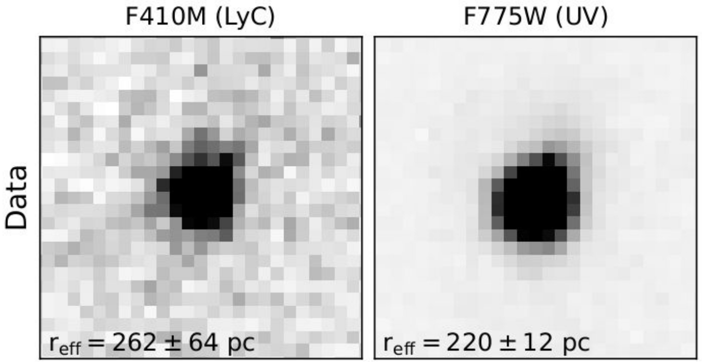


*Signatures of **Very Massive Stars** are ubiquitous in the spectra of UV-bright galaxies:*

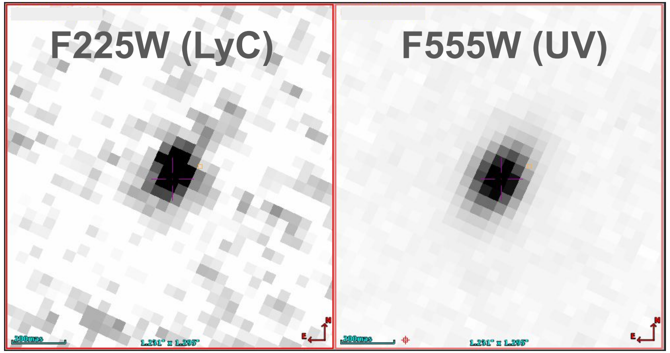
*Ie, **the IMF is different** (Mup extended up to >300M$_\odot$)*

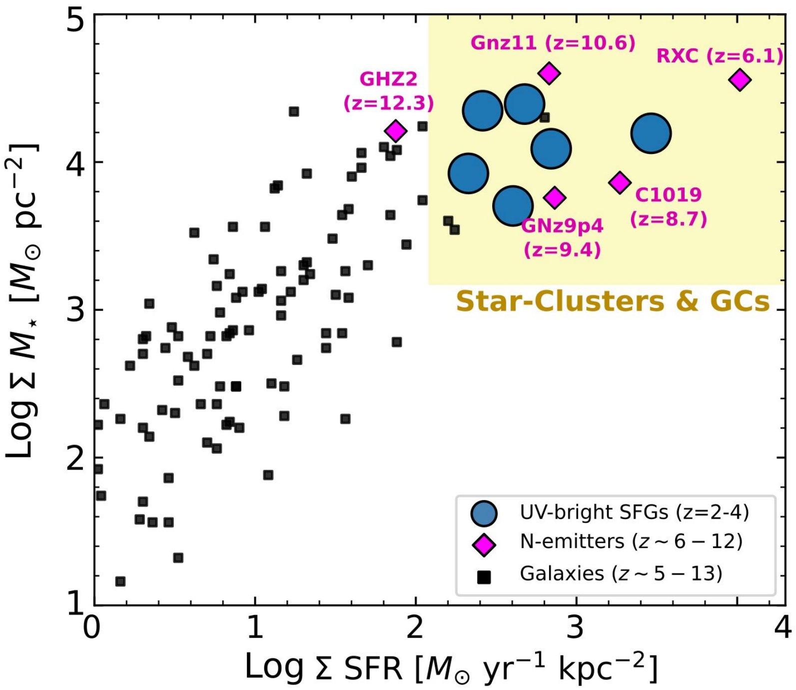
UV-bright starbursts resembling young and massive star-clusters (II)

J1316+2614 (z=3.6, M_{UV}= -24.7; Marques-Chaves +2024b)



Another example (M_{UV}= -23.2; Marques-Chaves + in prep)

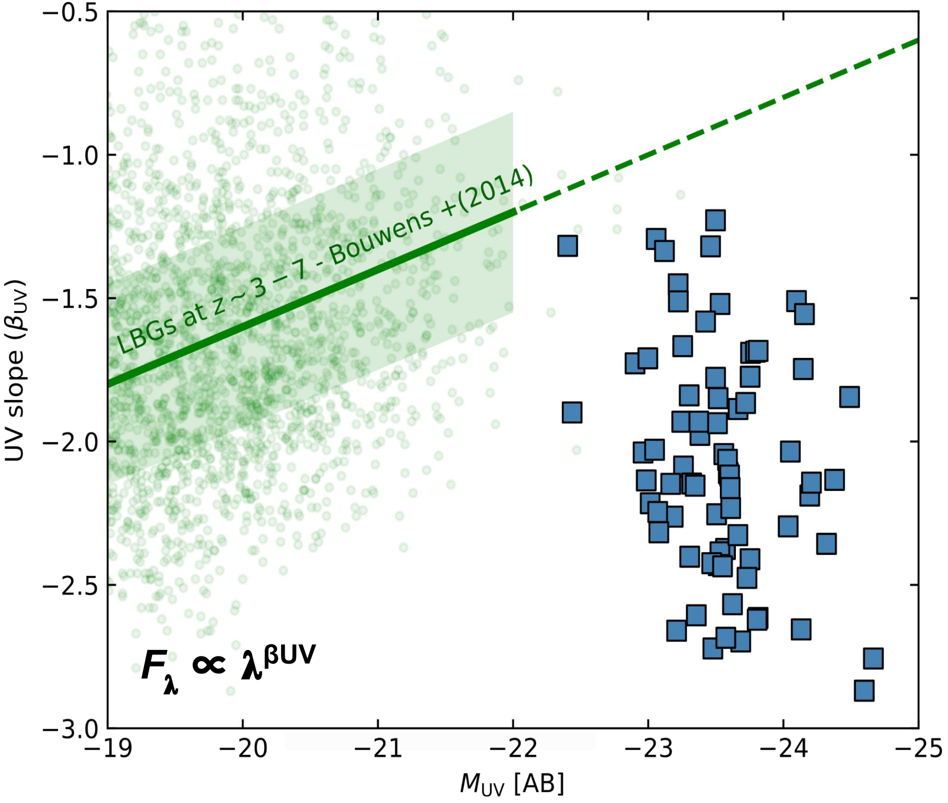




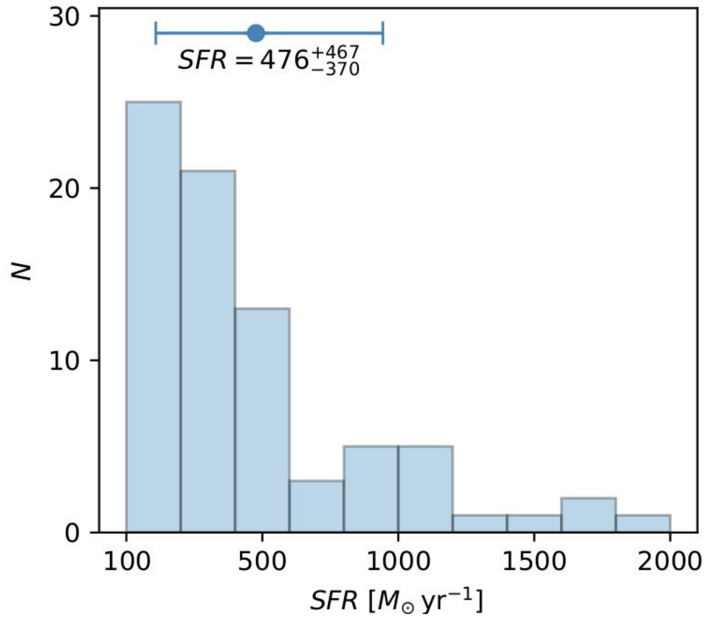
- *SFRs ~ 200-1000 $M_\odot$/yr*
- *M_* ~ 10^9 - 10^{10} $M_\odot$*
- *r_{eff} ~ 220 - 600 pc*

Among the highest ΣM_* and ΣSFR -> comparable star clusters

Large SFRs but residual dust attenuation



Marques-Chaves + (in prep.)

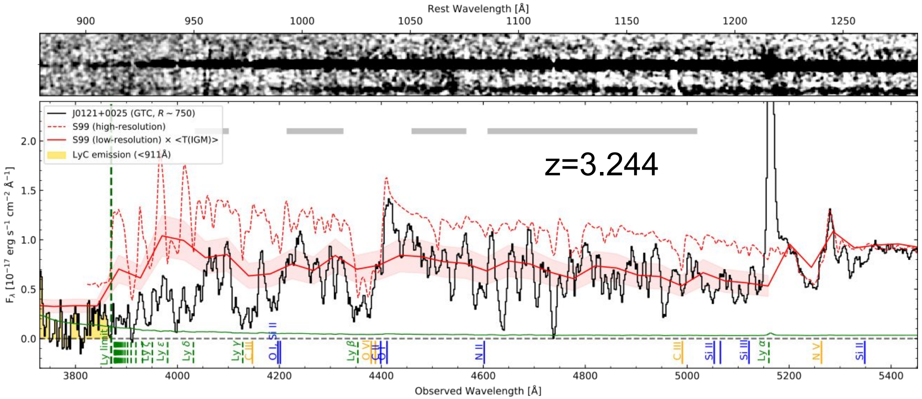


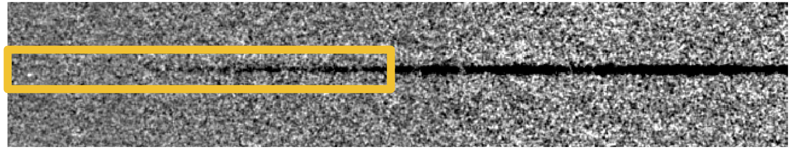
UV-bright galaxies show intense star formation, But residual dust attenuation…

…. Very different than eg, sub-mm galaxies (HyLIRGs)

UV-bright galaxies are strong LyC emitters

Marques-Chaves +(2021)

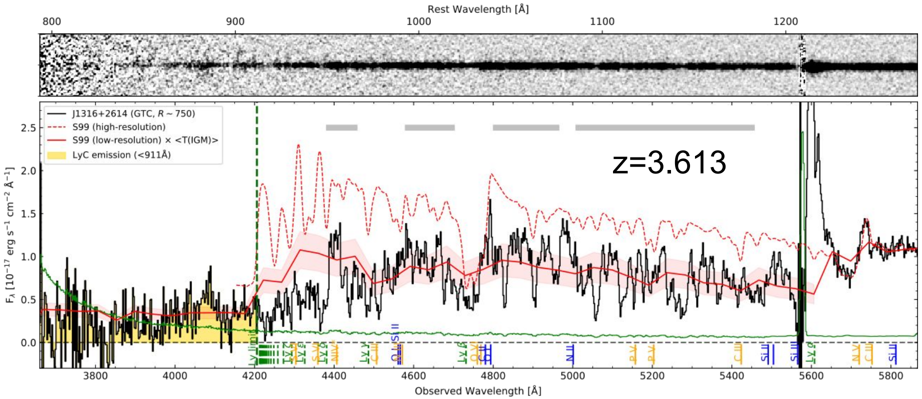




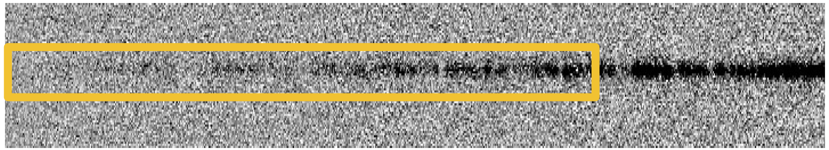
Detection of Lyman continuum (LyC) emission
with high significance

LyC: λ_0 < 912 Å or > 13.6 eV

Marques-Chaves +(2022b)

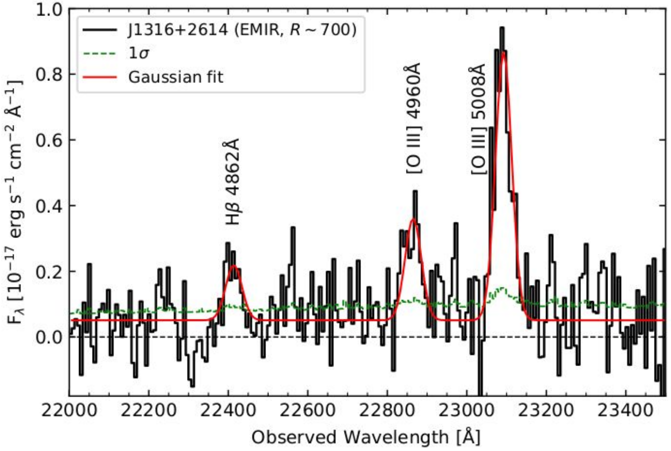


LyC escape fractions of ~ 40% to 90% !

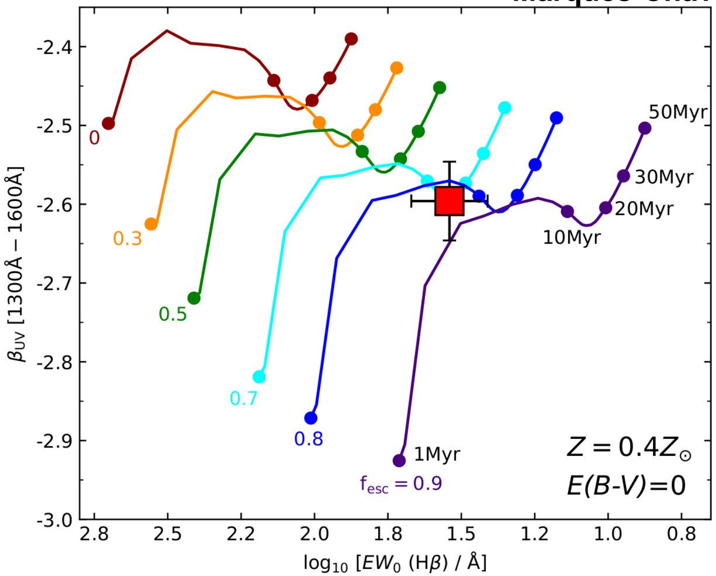


The impact of high fesc(LyC) on the nebular emission

J1316+2614 is a very young starburst (~6Myr with CSFH) but shows very weak nebular emission
— still the only confirmed LyC leaker where the effect of fesc(LyC) on nebular emission is detected —



Marques-Chaves +22b

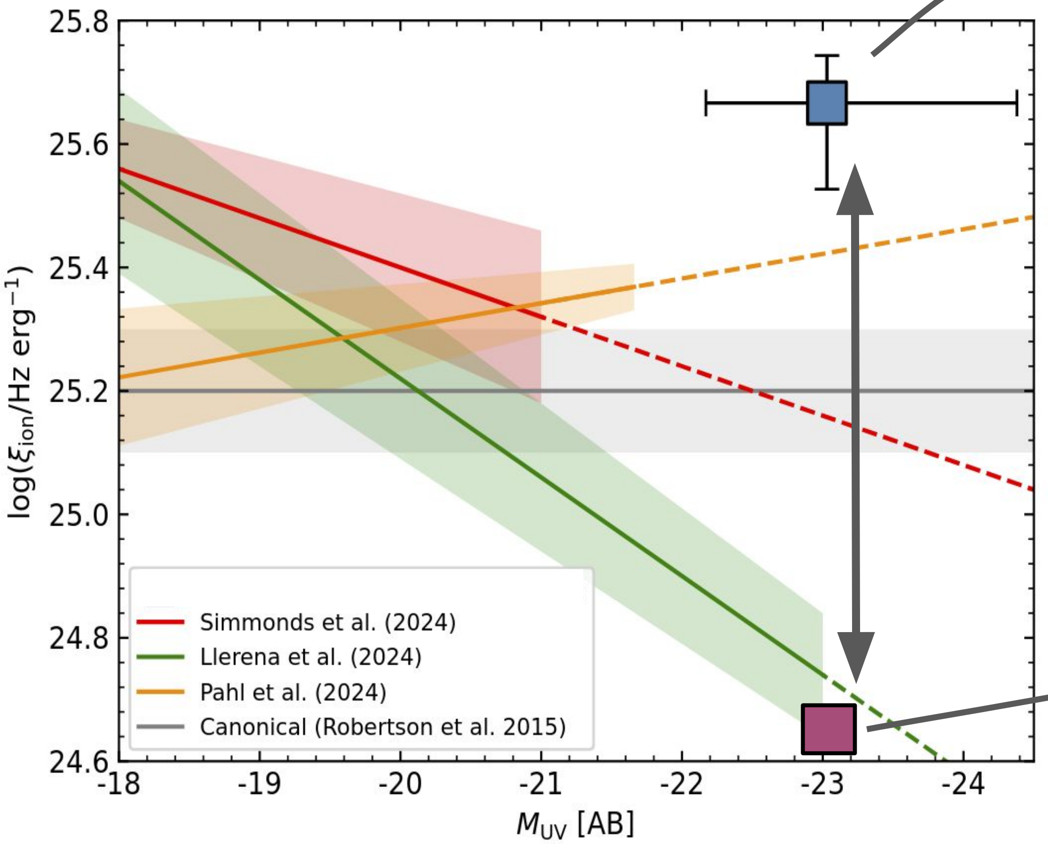


"weak" rest-frame optical lines:

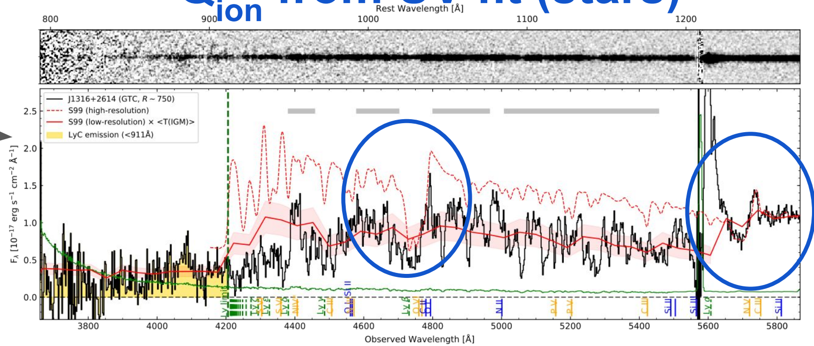
- EW_0 (Hβ 4826Å) = 28 ± 8 Å
- EW_0 ([OIII 5008Å]) = 144 ± 21 Å

…i.e., weaker by a factor ≈ 1/[1-fesc(LyC)]
Consistent with our estimates > fesc(LyC) ~ 80% !

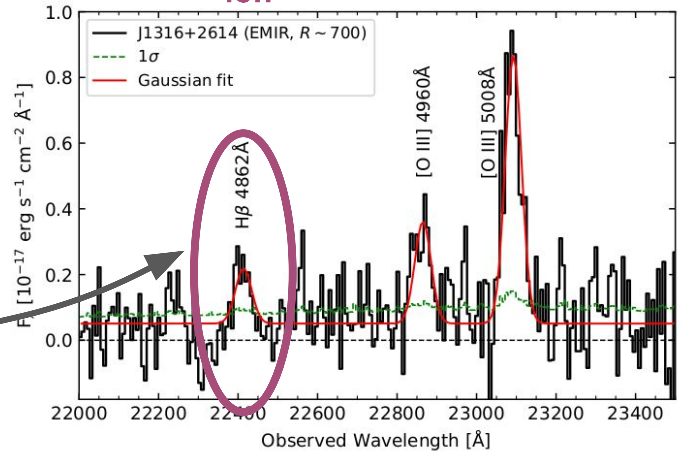
$$\xi_{ion} = Q_{ion} / L_{UV} \approx L(H\alpha) / L_{UV}$$



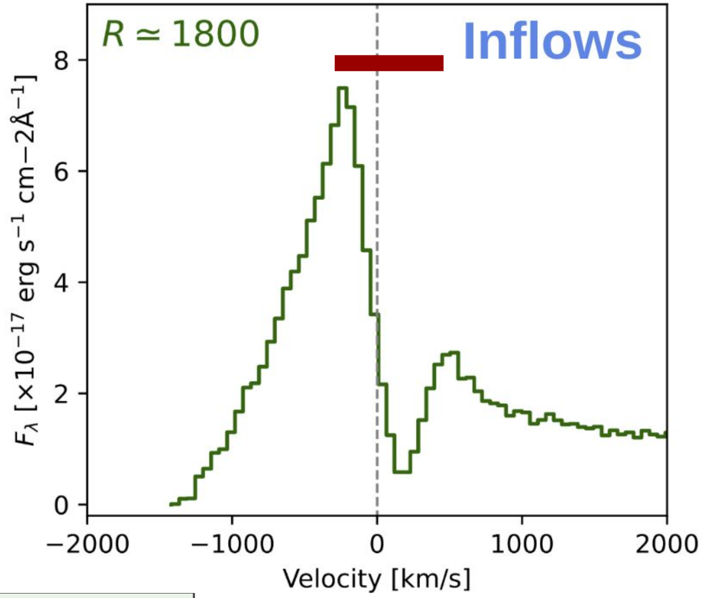
Q_ion from UV fit (stars)

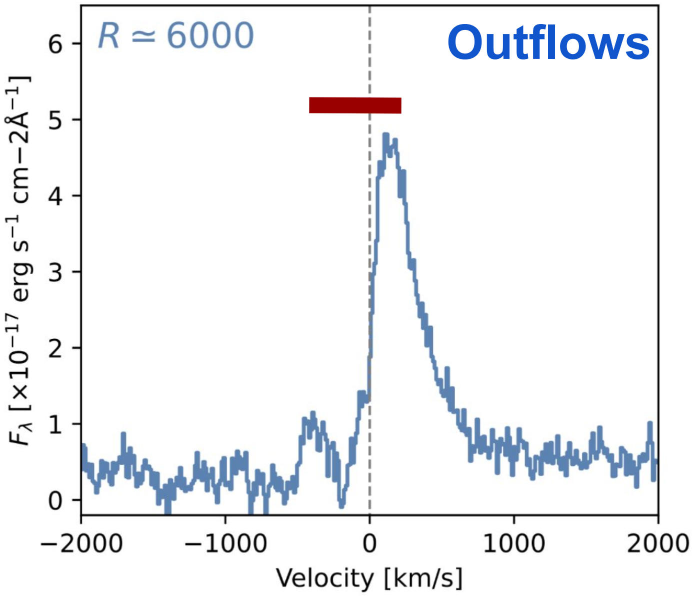


Q_ion from Hβ flux



Lyman-alpha profiles of UV-bright strong LyC emitters





J1316+2614:
z = 3.613
M_{UV} = -24.70
log(Lyα) = 44.1 [erg/s]
f_{esc}(Lyα) = 43 %
$f_{esc,abs}$(LyC) = 89 %

Marques-Chaves+22,24b

Δv (Lyα) ~ 500-700 km/s

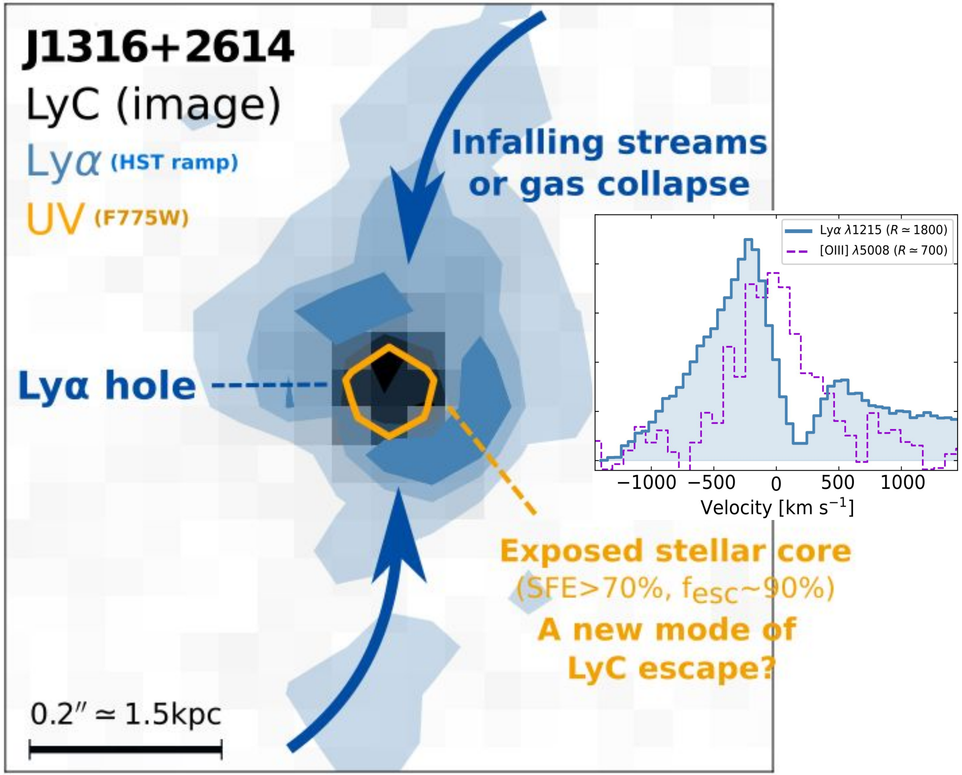
EW_0(Lyα) = 21 & 14 Å

[OIII]5008 / [OII]3727 ~ 4 - 5

J0121+0025:
z = 3.244
M_{UV} = -24.11
log(Lyα) = 43.8 [erg/s]
f_{esc}(Lyα) = 14 %
$f_{esc,abs}$(LyC) = 40 %

Marques-Chaves +2021

J1316+2416: the UV-brightest and strongest LyC emitter - HST view



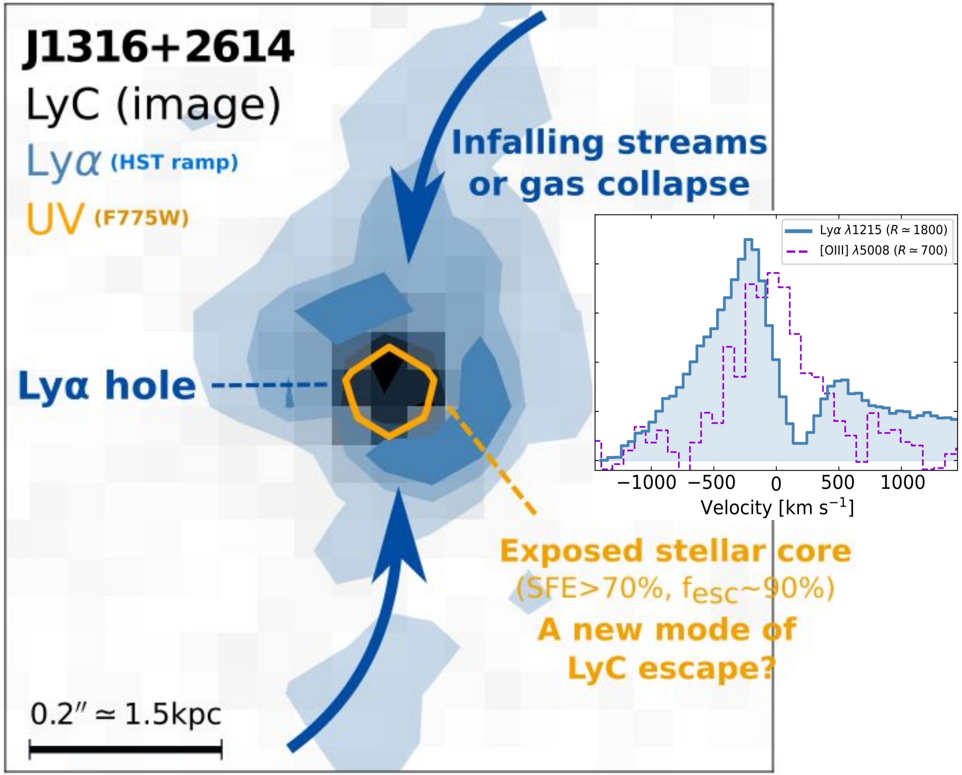
J1316+2614 at z = 3.613:

- ***M_{UV} = -24.65, SFR = 900 $M_\odot$/yr , E(B-V) ~ 0***
- *M_* = 5x10^9 $M_\odot$; 6 Myr age (CSFH)*
- *f_{esc}(LyC) ~ 90%*
- ***Resolved LyC emission** and with similar size as the non-ionizing emission (**r_{eff} = 220 pc**)*
- ***Lyα emission is blueshifted** and shows an elongated morphology **> massive inflows***
- *However, **Lyα is weak/absent within the stellar emission > exposed stellar core***

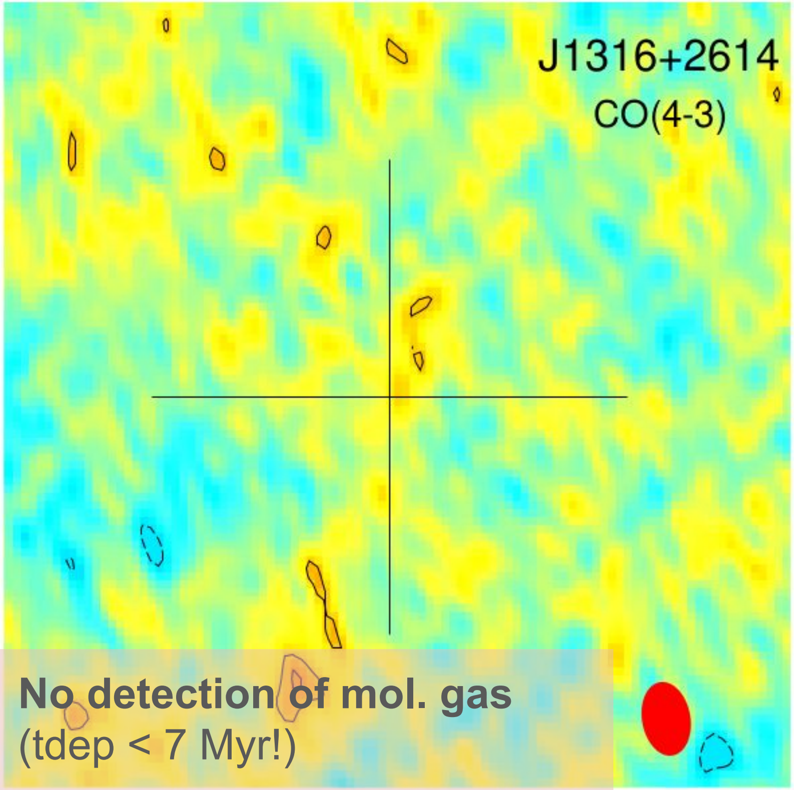
How is that possible?

Marques-Chaves+2024b

J1316+2416: the UV-brightest and strongest LyC emitter

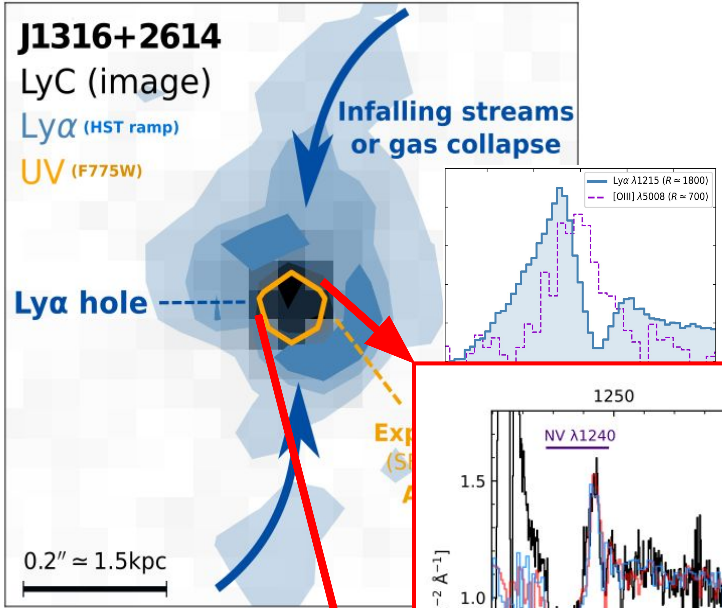


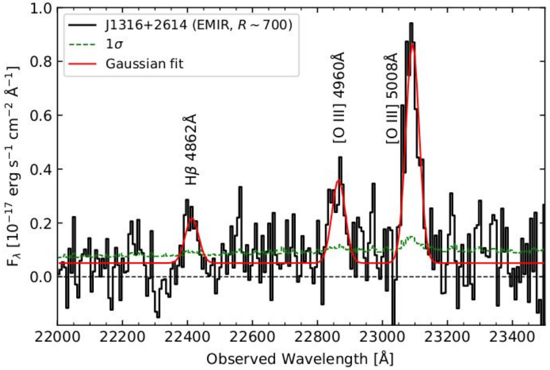
Marques-Chaves+2024b



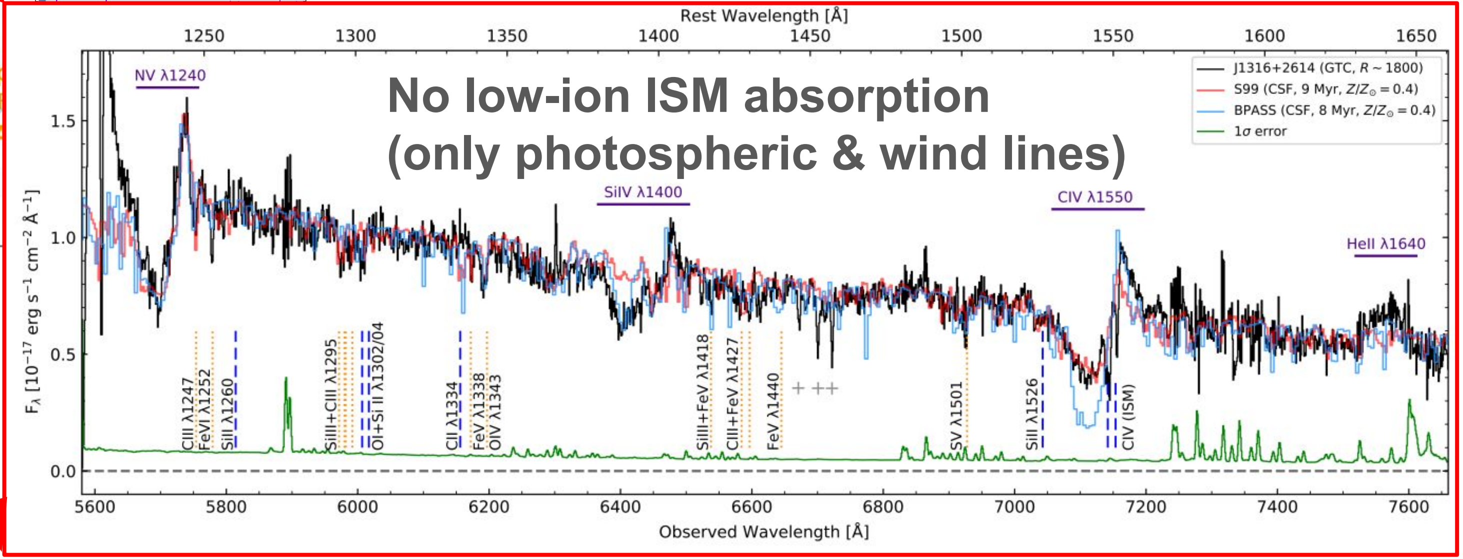
Dessauges-Zavadsky, RMC +2025

J1316+2416: the UV-brightest and strongest LyC emitter





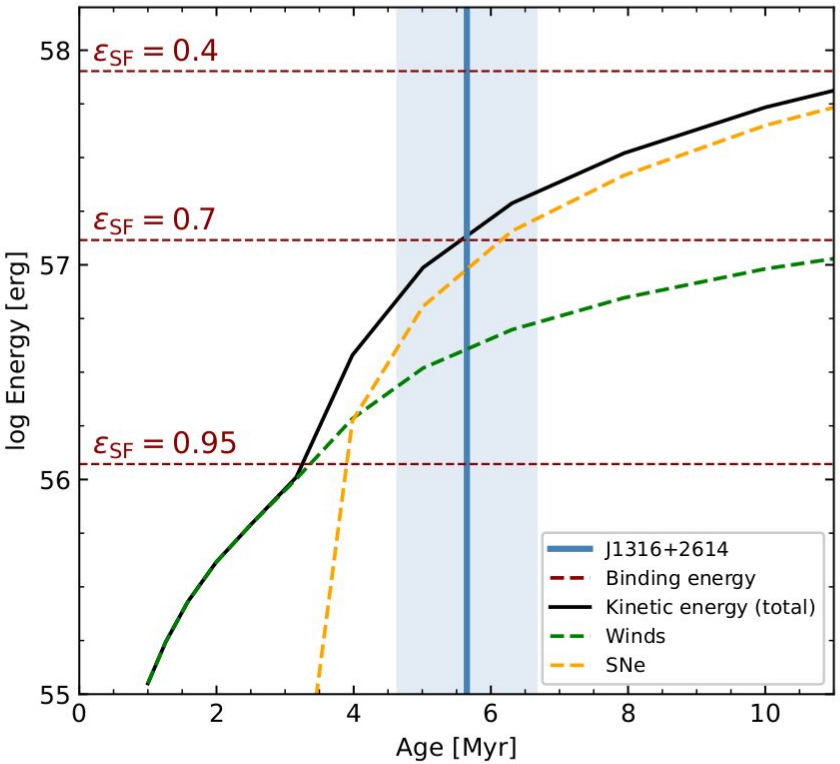
Weak nebular emission (cont. & lines)



No low-ion ISM absorption (only photospheric & wind lines)

Marques-Chaves+22,24b

J1316+2416: Energetics and SF efficiency (ε_{SF})



Binding energy: $E_b \propto (1-\varepsilon_{SF})\, M_{total}^2 / r_{eff}$

Kinetic energy: $E_k \propto$ SFR

Gas clearance (i.e., $E_k > E_b$) only occurs when ε_{SF} > 70%

(similar for radiative driven outflows)

Higher ε_{SF}:

*-increases SFR -> thus **Qion***

*-increases **feedback** (rad. & mech.)*

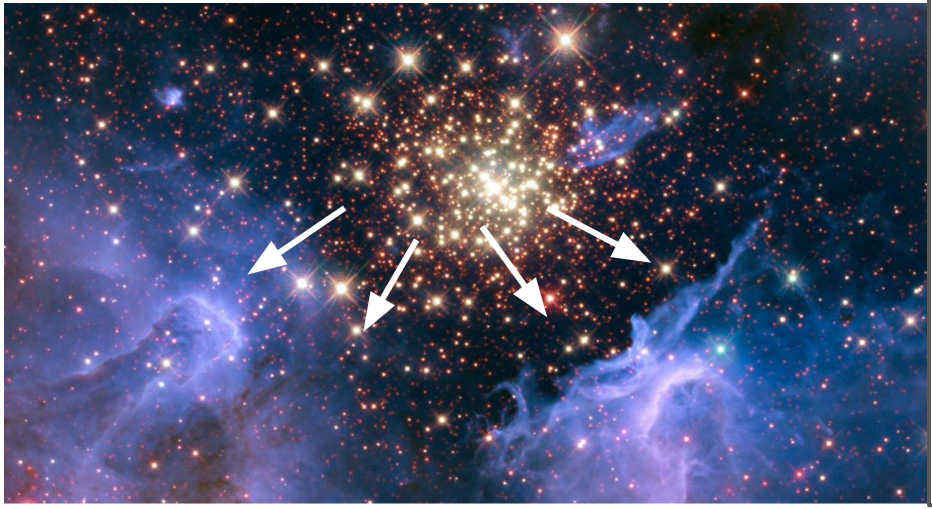
*-consumes more gas -> **less amount of gas available to absorb LyC** radiation*

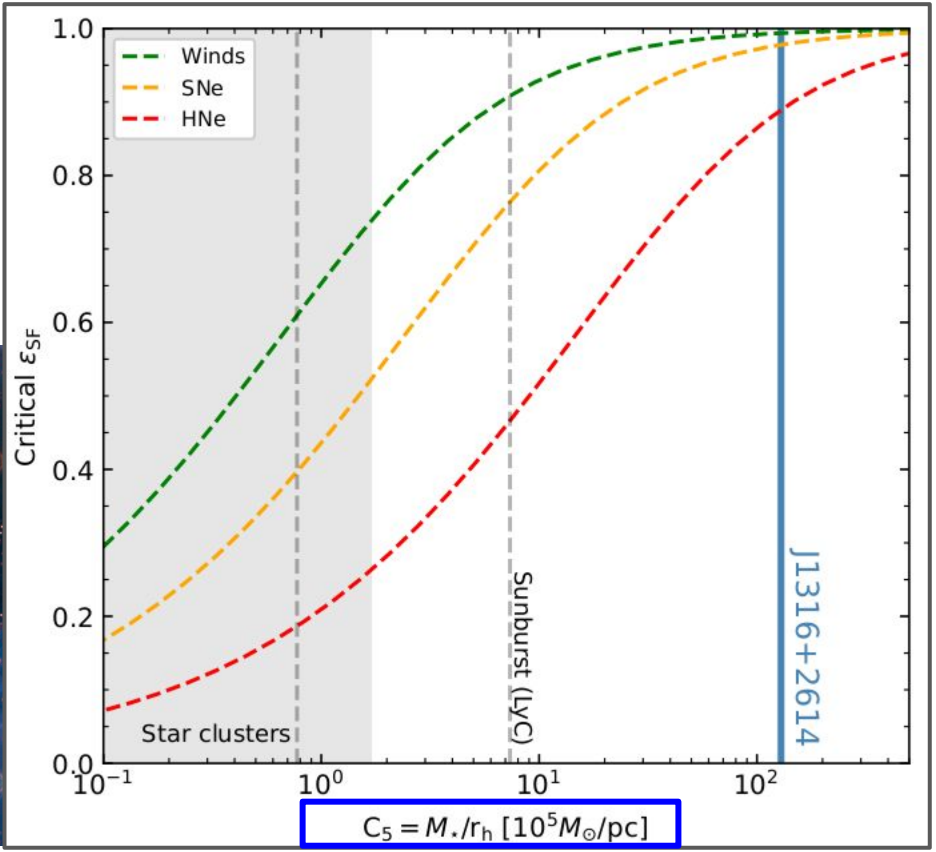
High LyC leakage driven by high SF efficiency ?

Marques-Chaves+2024b

J1316+2416: Energetics and SF efficiency (ε_{SF})

High LyC leakage driven by high SF efficiency ?

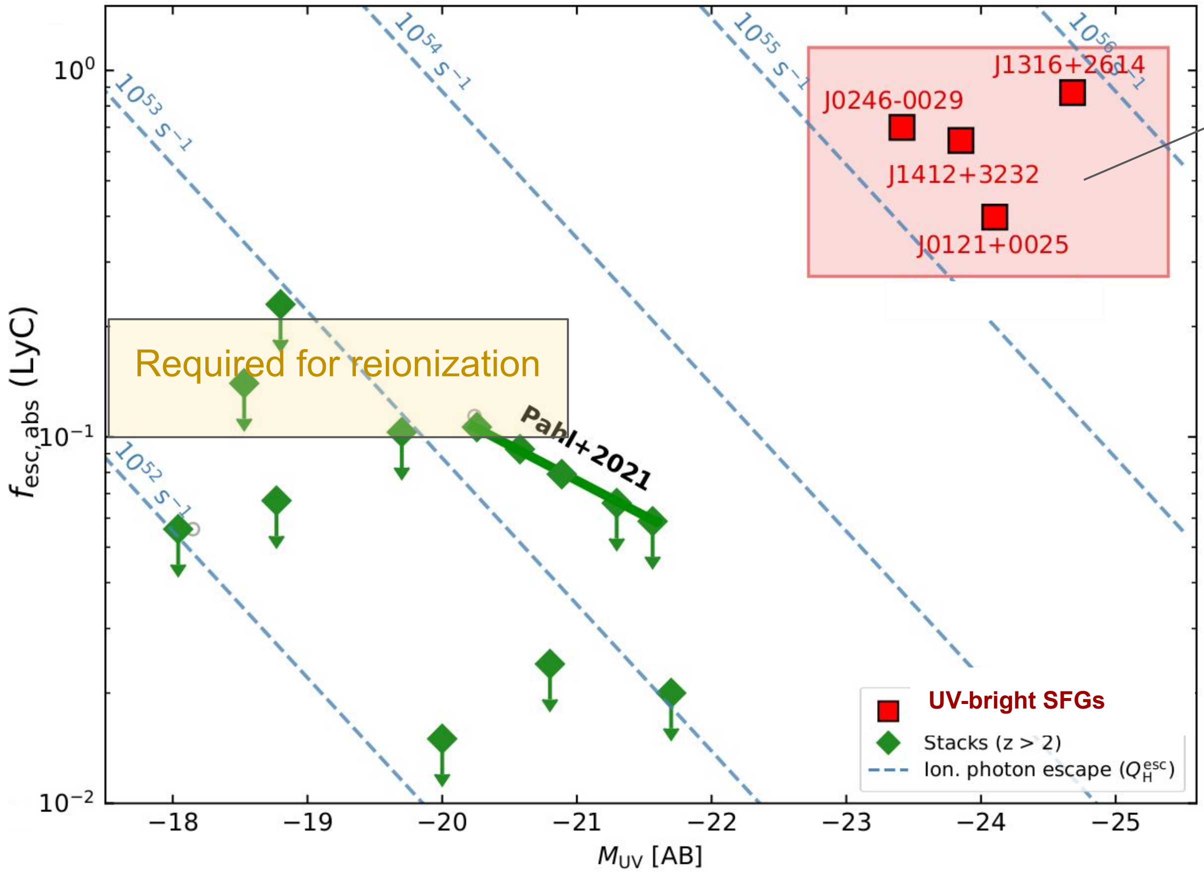




C5 -> compactness index: KEY PARAMETER

Marques-Chaves+2024b

UV-bright galaxies are strong LyC emitters



From Marques-Chaves+2021, 2022, in prep.

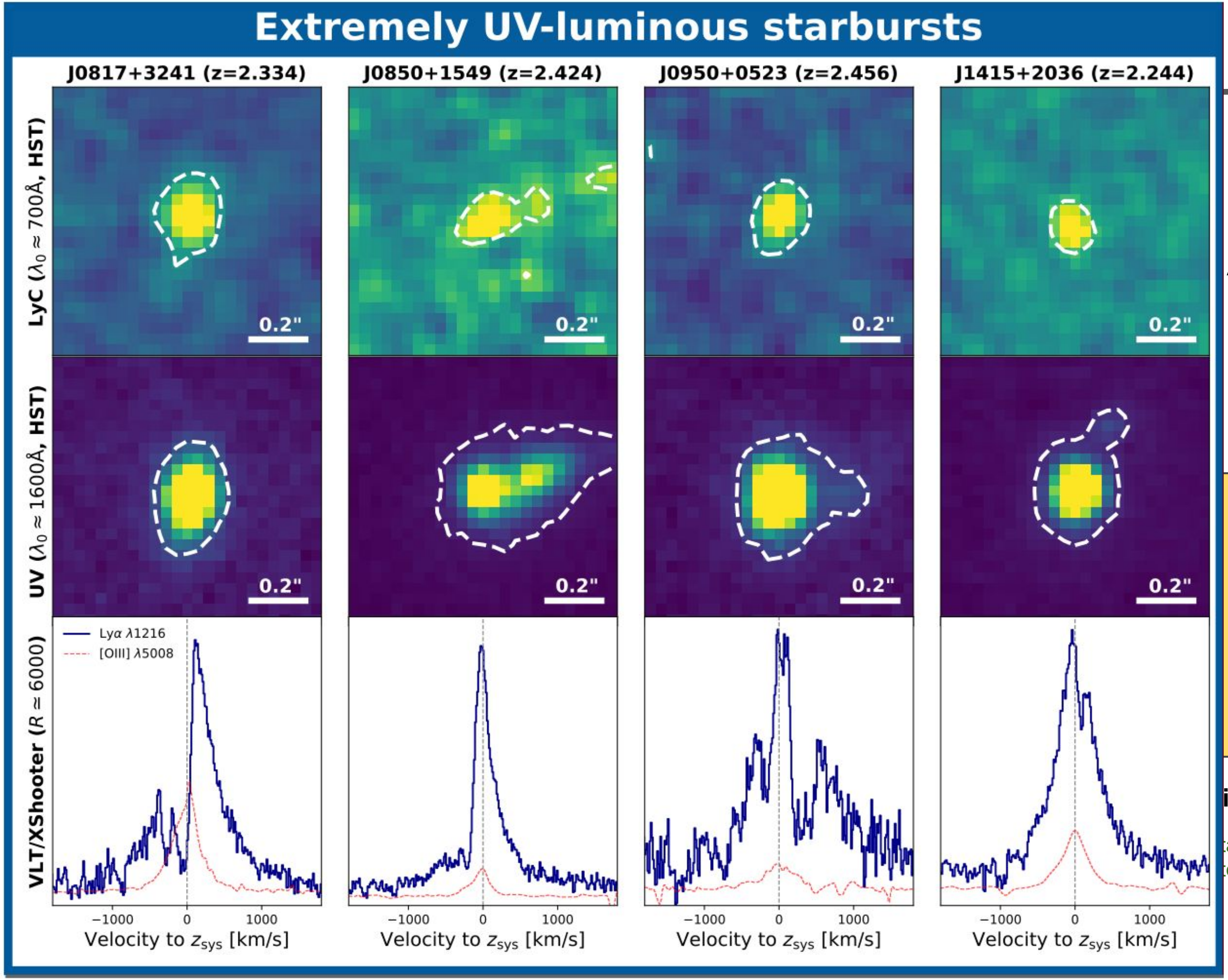
And more to come soon…

UV-bright galaxies are strong ionizing sources

Do they contribute significantly to cosmic reionization??

Literature sample:

Stacks (z~2-4): Grazian +2017; Marchi +2017; Rutkowski +2017; Steidel +2018: Fletcher +2019; Bian & Fan 2020; Pahl +2021



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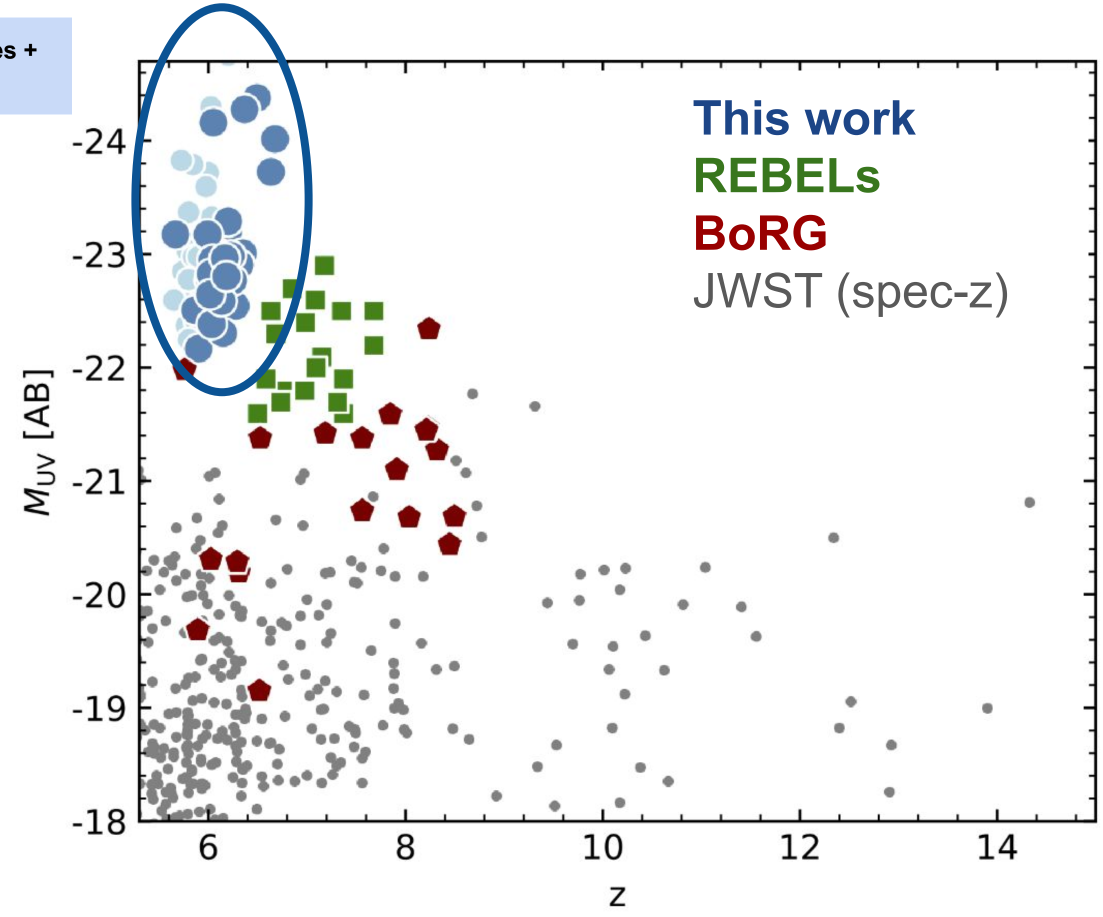
Do extremely UV-bright galaxies also exist at higher redshifts?

Marques-Chaves + In prep.

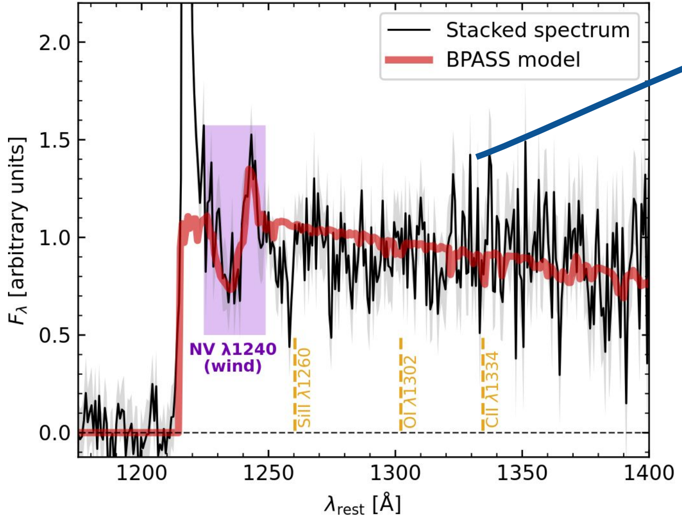


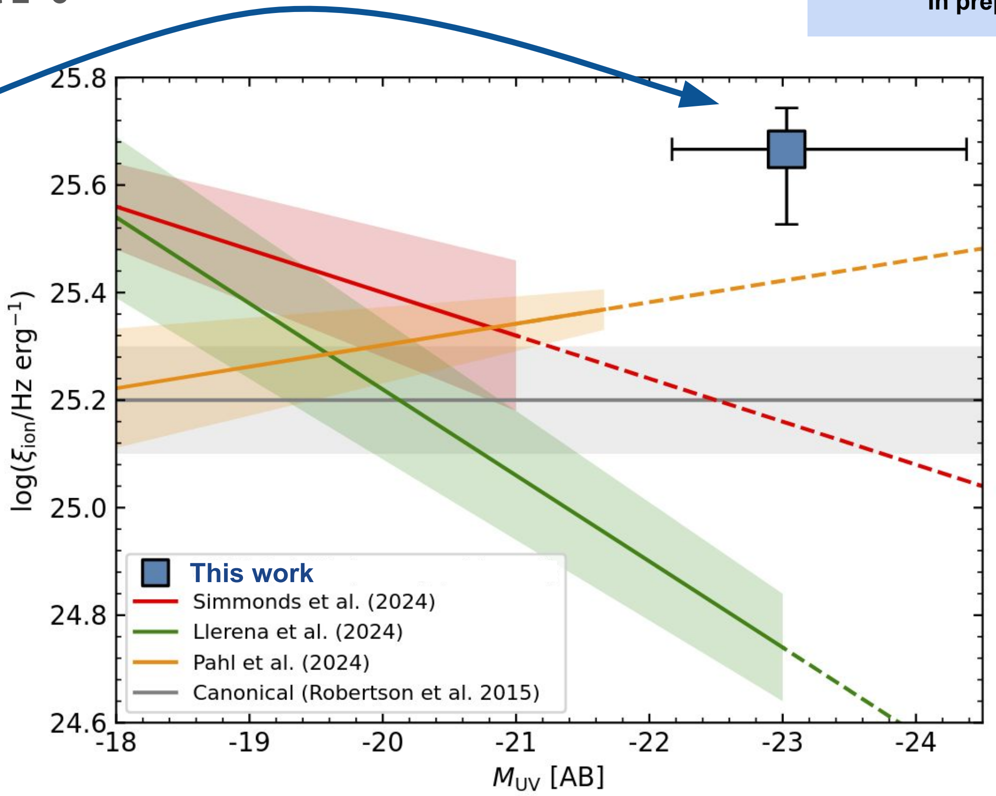
Yes, extremely UV-bright galaxies also exist at higher redshifts

Do extremely UV-bright galaxies also exist at higher redshifts? -> yes
How do they like?

Marques-Chaves +
In prep.

Stacked spectrum of UV-bright galaxies at z~6





… and they are also very efficient producers
of ionizing photons

Summary / Main Properties

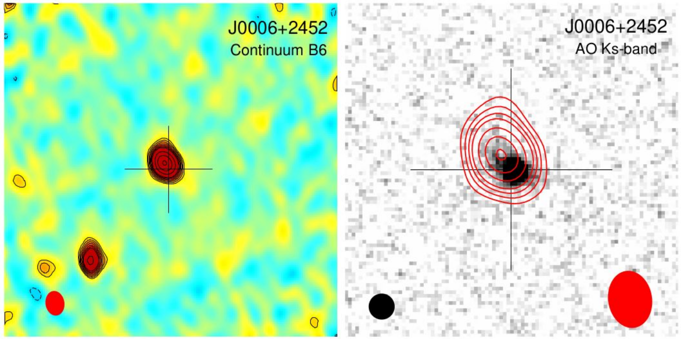
- UV-bright galaxies (M_{UV} ~ -23 to -25) are blue / almost unobscured
- Emission dominated by very young stellar populations (~ 5-10 Myr)
- Spectra and M_* and SFR surface densities similar to young massive star clusters

  -> but how is that possible ?
- UV spectra dominated by Very Massive Stars > **different IMF, towards top-heavy** ?
- Among the strongest Lyman continuum emitting galaxies known -> **but why / how** ?
- Indications of high SF efficiencies > **key for high LyC escape** ?
- Short gas depletion timescales > very short-lived phases / **how many are we missing** ?

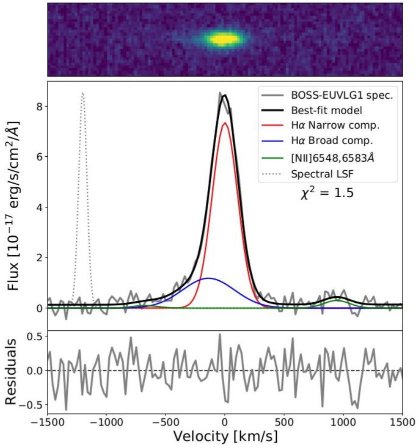
Can models of galaxy formation & evolution predict these properties?

*** To be investigated in JWST GO4**

UV-bright galaxies: ALMA observations of dust and molecular gas



Due to radiative (cf, Ferrara)
or mechanical feedback?



Outflows are also detected

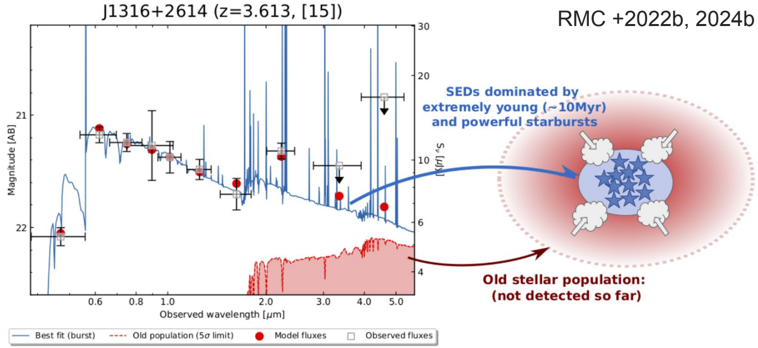
Hα with GTC/EMIR

(Alvarez-Marquez, RMC +2021)

When detected, dust is usually more extended than the UV/optical emission

Or produced by previous SF
eg, underlying disk
(but not detected so far) ?

RMC +2022b, 2024b



See discussion in Dessauges-Zavadsky, RMC +2025

Introduction

- **JWST is now discovering a stunning population of UV-bright sources (even up to z~14)** (Bunker+23, Castellano+24, Carniani+24, etc.)

- **Far more numerous than previously thought** (based on models and pre-JWST extrapolations)

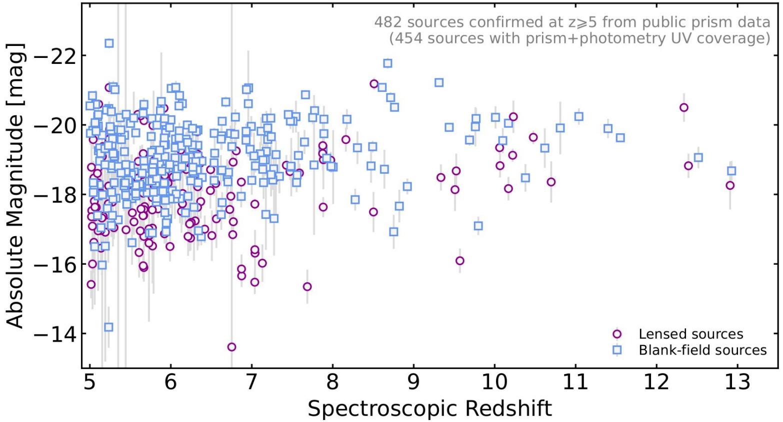
- **Why? Possible explanations:**

  Higher SF efficiency? *(Dekel+23, Li+24, Ceverino+24, Renzini 24, etc.)*

  Dust removal? (*Ferrara+23, 24, Fiore+23, Ziparo+24)*

  Top-heavy IMF? (*eg, Chon+21, 24, Trinca+23, Rasmussen Cueto+24)*

  Stochastic SFHs? *(eg, Mason+24, Gelli+2024, Mirocha & Furlanetto 2023, Shen+23)*

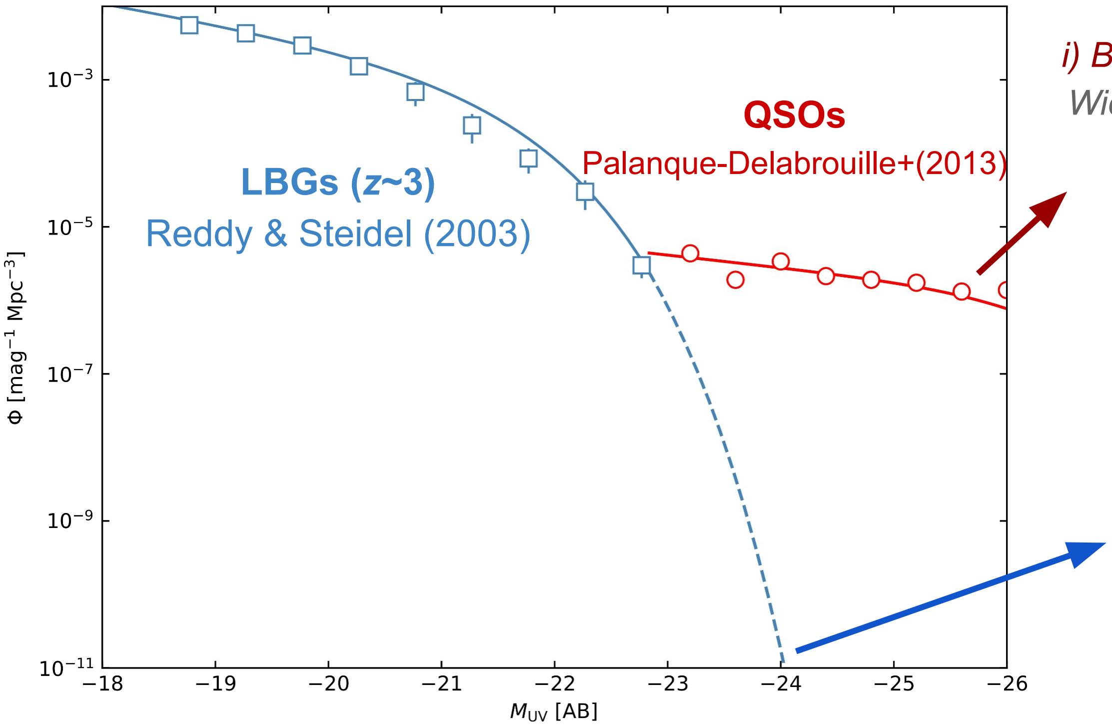


(Roberts-Borsani+2024)

Do they represent a specific phase in galaxy formation/evolution ?
Why are these sources so bright? Formation/properties/nature ?

Introduction

But how well established is the *very* bright-end of the UV-LFs at lower-z?



i) Bright QSOs are more numerous at M_{UV} < -23

Wide field surveys with spectroscopic follow-up are essential … but expensive

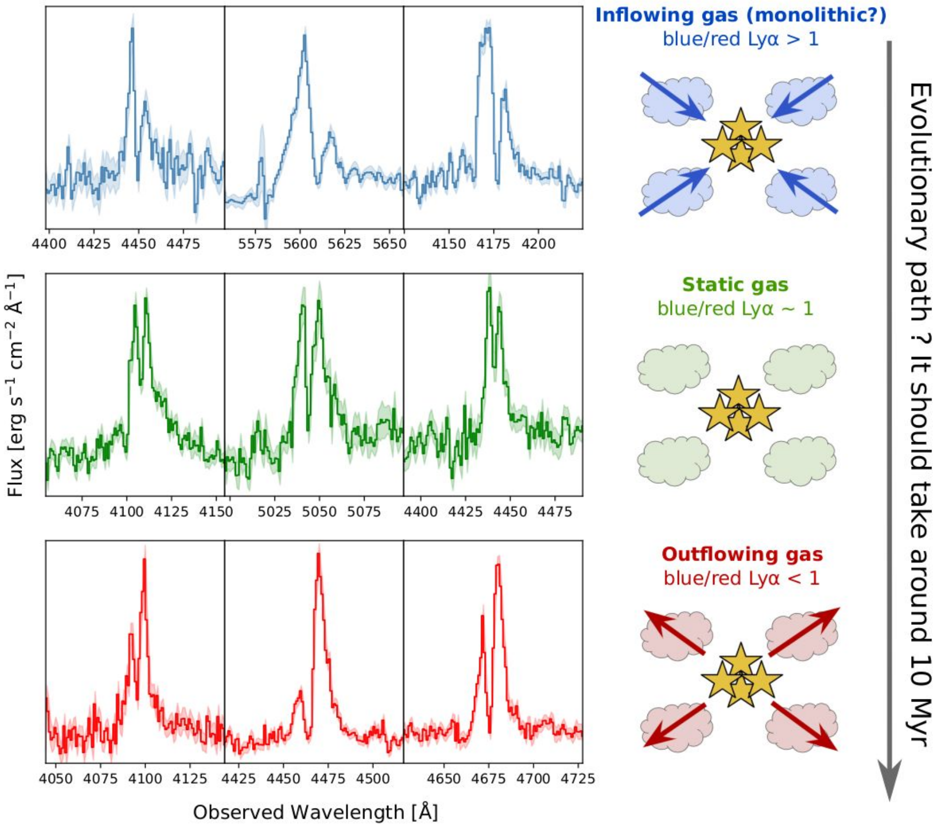
*ii) Even if we could observe the whole sky***

… we will not expect any galaxy brighter than M_{UV} = -24 !!

*** area ~40k deg^2 and Δz = 0.1*

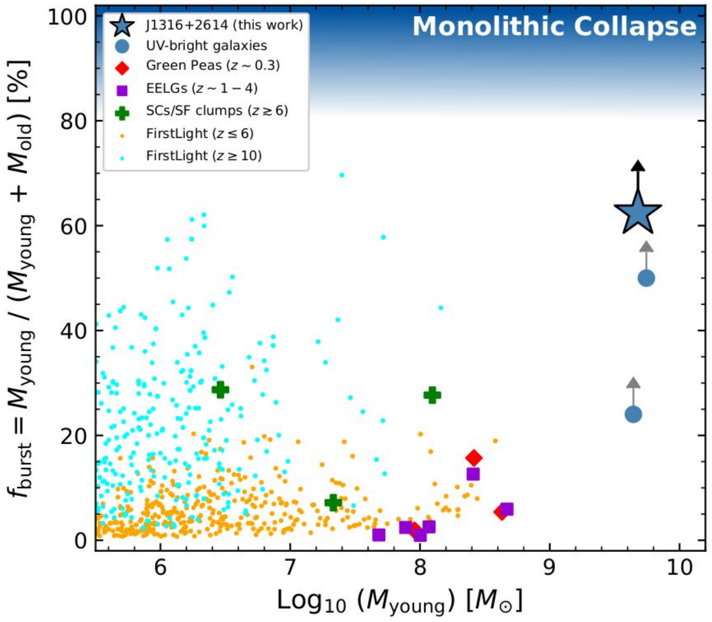
What triggers these powerful starbursts? Diversity of Lyman-alpha profiles

Gas kinematics probed by (**resonant**) Lyman-alpha emission



Some examples of Lyman-alpha spectral profiles

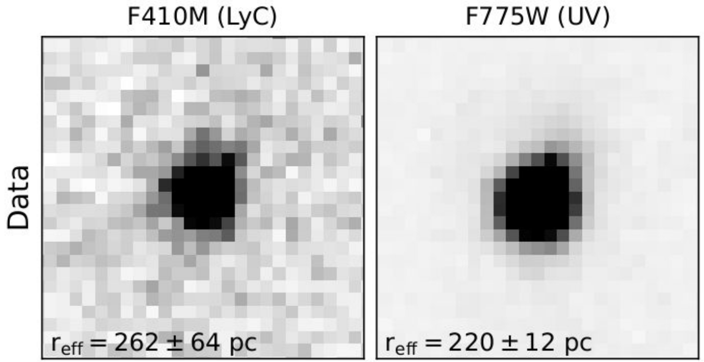
Are UV-bright galaxies triggered by massive gas inflows, gas collapse ? (monolithically?)



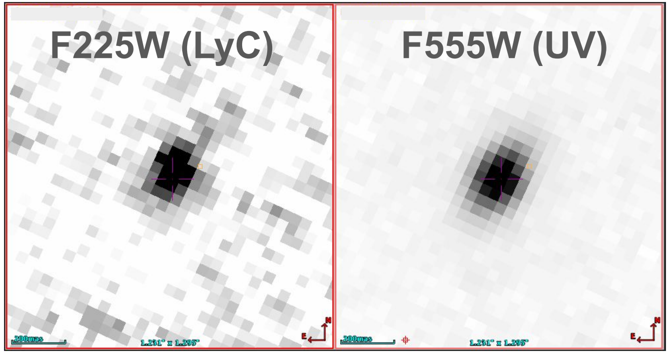
Marques-Chaves +2022, 2024b

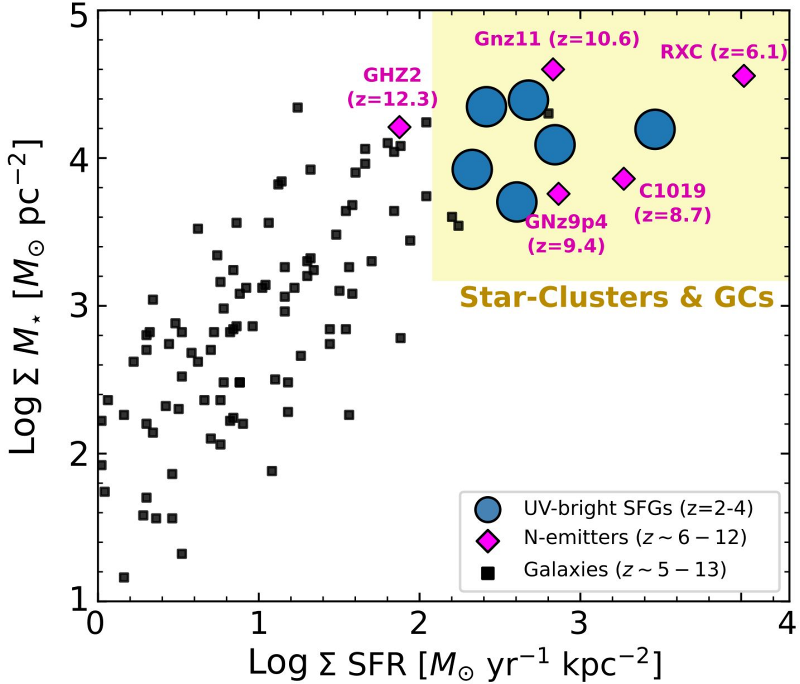
UV-bright starbursts resembling young and massive star-clusters (II)

J1316+2614 (z=3.6, M_{UV}= -24.7; Marques-Chaves +2024b)



Another example (M_{UV}= -23.2; Marques-Chaves + in prep)

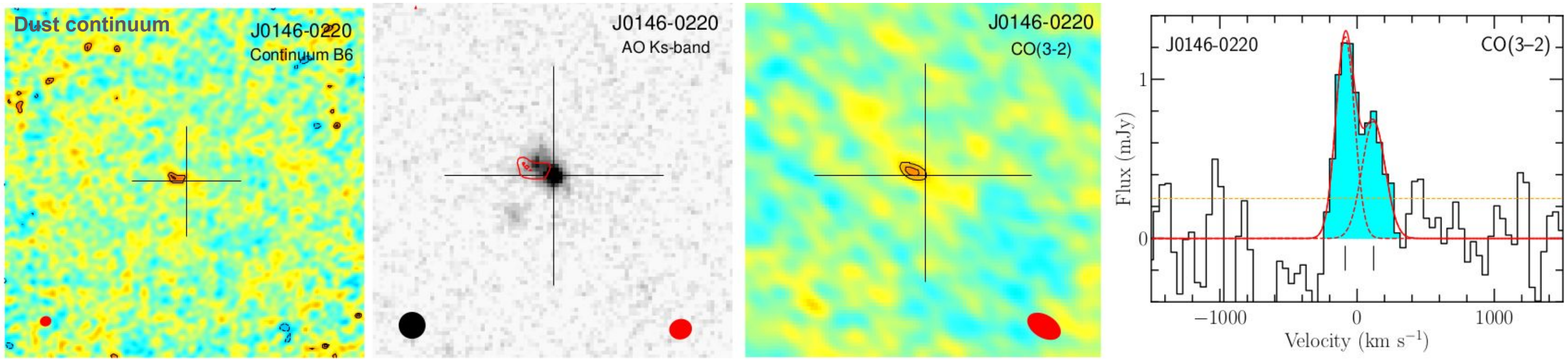




- *SFRs ~ 200-1000 $M_\odot$/yr*
- *M_* ~ 10^9 - 10^{10} $M_\odot$*
- *r_{eff} ~ 220 - 600 pc*

Among the highest ΣM_* and ΣSFR
-> comparable star clusters

UV-bright galaxies: ALMA observations of dust and molecular gas

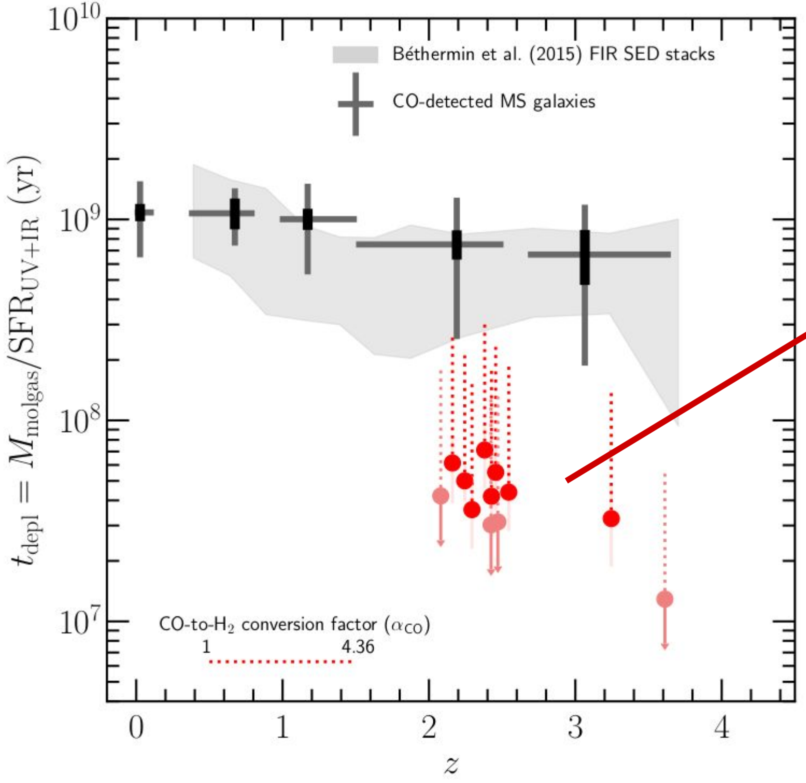


Target	$z_{nebular}$[a]	M_{UV}	β_{UV}	ϵ_{SF}[h] (%)
J1322+0423	2.0800	−23.49	−2.06 ± 0.12	> 31
J0146–0220	2.1595	−23.68	−1.98 ± 0.12	21 ± 3
J1415+2036	2.2435	−23.53	−3.49 ± 0.11[†]	> 14 ± 3
J1249+1550	2.2928	−23.41	−1.84 ± 0.12	37 ± 5
J0006+2452	2.3796	−24.17	−2.30 ± 0.10	8 ± 0.9
J0850+1549	2.4235	−23.76	−2.62 ± 0.14	> 20
J1220–0051	2.4269	−23.50	−2.43 ± 0.11	13 ± 2
J0950+0523	2.4548	−23.69	−2.41 ± 0.15	9 ± 1
J1220+0842	2.4698	−24.36	−2.36 ± 0.09	> 24
J1157+0113	2.5450	−23.40	−2.15 ± 0.34	15 ± 6
J0121+0025	3.2445	−24.11	−2.19 ± 0.20	> 29 ± 10
J1316+2614	3.6122	−24.65	−2.59 ± 0.05	> 40

On average, UV-bright galaxies show high SF efficiencies (8% to > 40%)

Dessauges-Zavadsky, RMC +2025

UV-bright galaxies: ALMA observations of dust and molecular gas



Dessauges-Zavadsky, RMC +2025

They also show very short gas depletion timescales (<10 Myr to 70 Myr)

… which suggests that, while observationally rare, these UV-ultraluminous phases may be common at high-z

Game changers in our understanding of early galaxy formation and cosmic reionization ???