Vetenskapsrådet

Rymdstyrelsen
Swedish National Space Agency

Stockholm University

Stellar clumps in the JWST era

The little sparks that trace galaxy evolution through cosmic time

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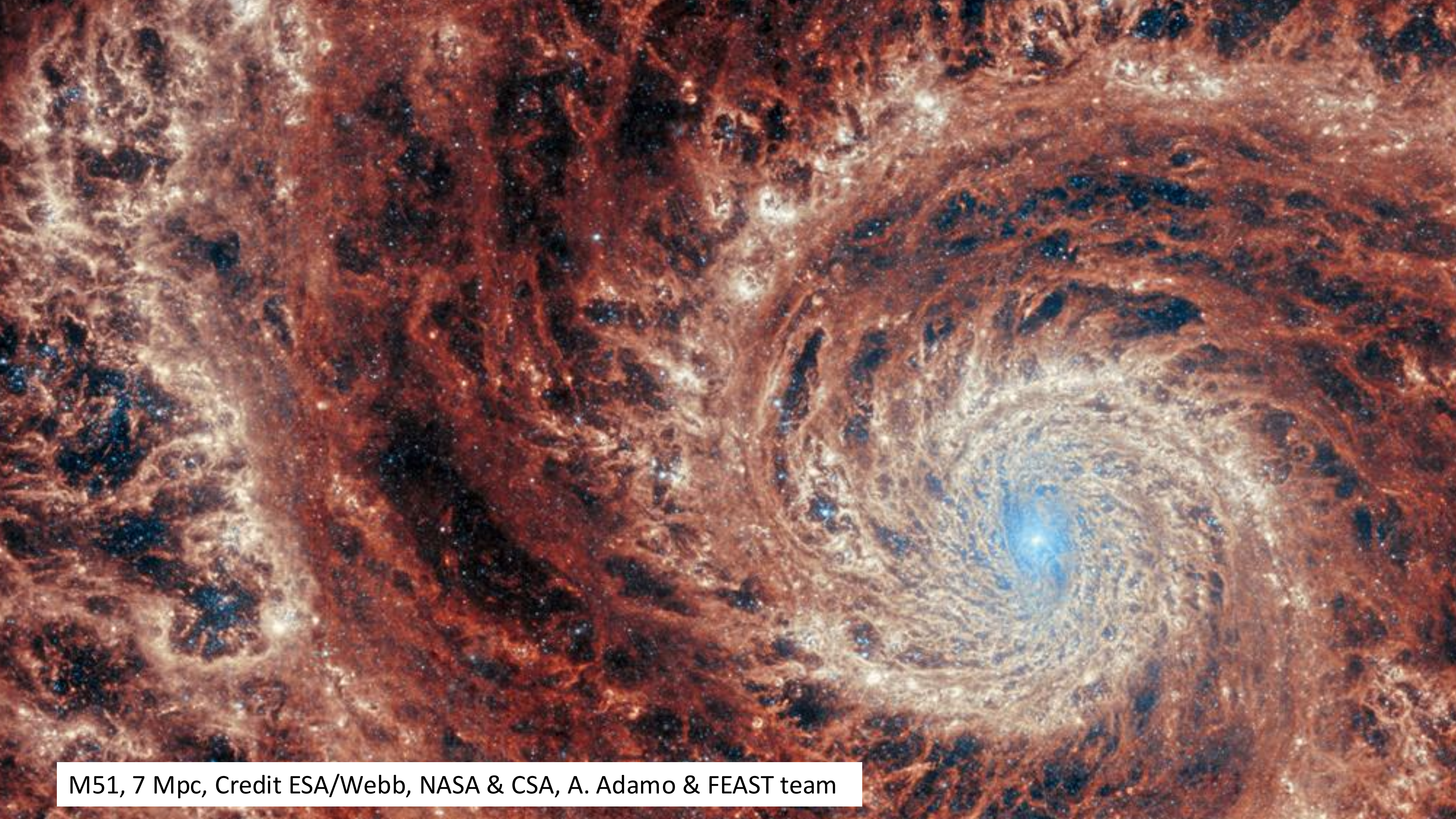
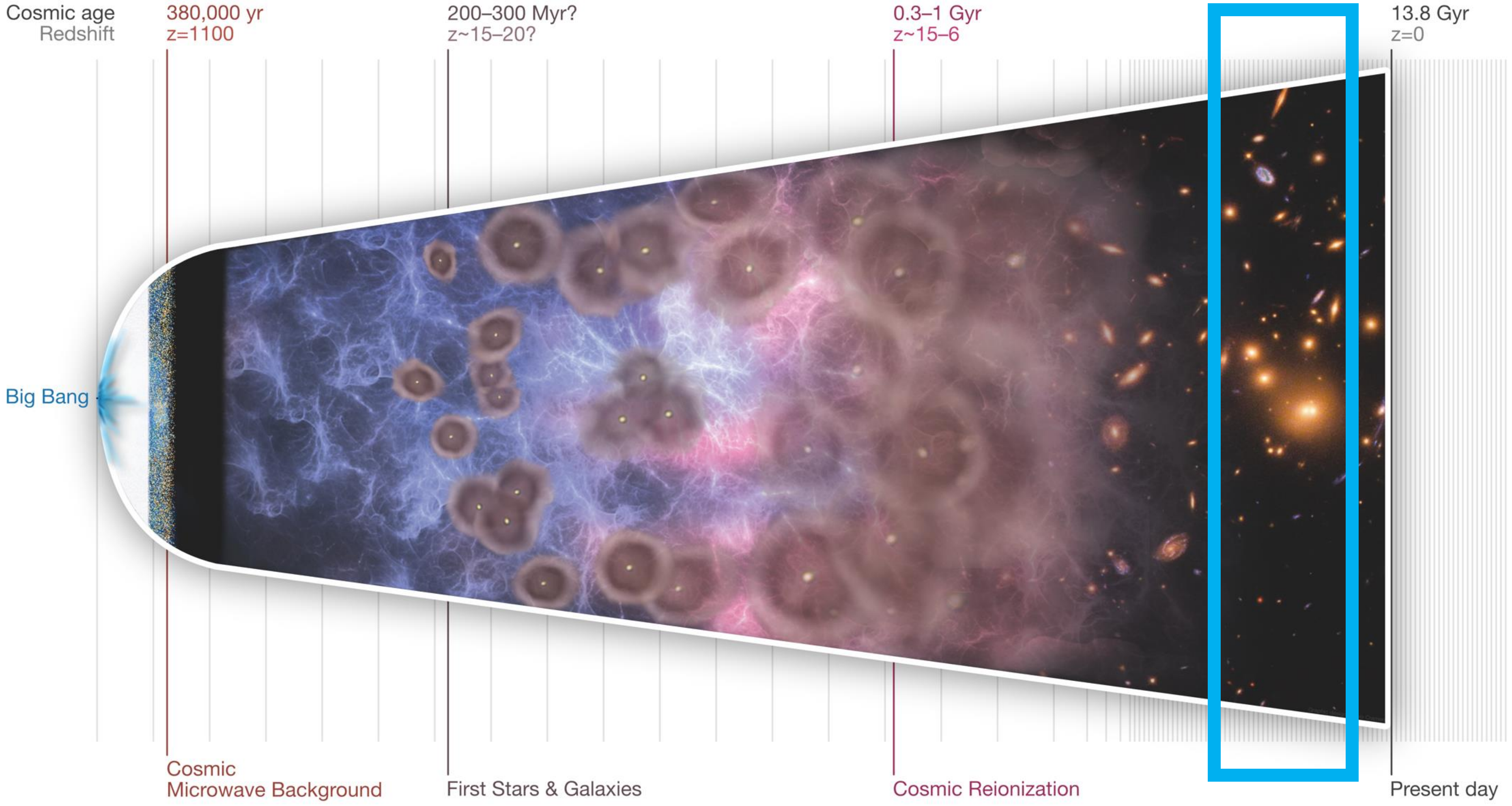
In collaboration with Adelaide Claeyssens (CRAL), Mirka Dessauges-Zavadsky (UGen), Matteo Messa (INAF-Bo), Johan Richard (CRAL), Eros Vanzella (INAF-Bo) & the Cosmic Spring collaboration



M51, 7 Mpc, Credit ESA/Webb, NASA & CSA, A. Adamo & FEAST team

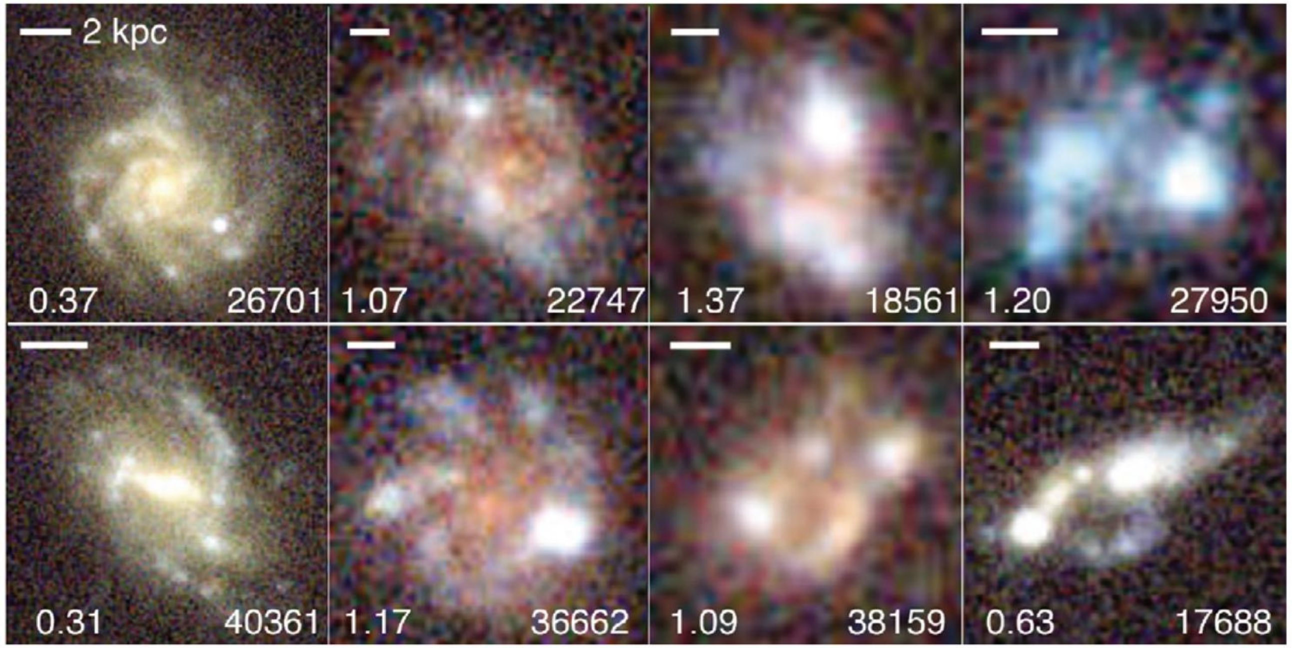
Finding our way home



Hubble Space Telescope

Studying star formation within high-z galaxies is not trivial

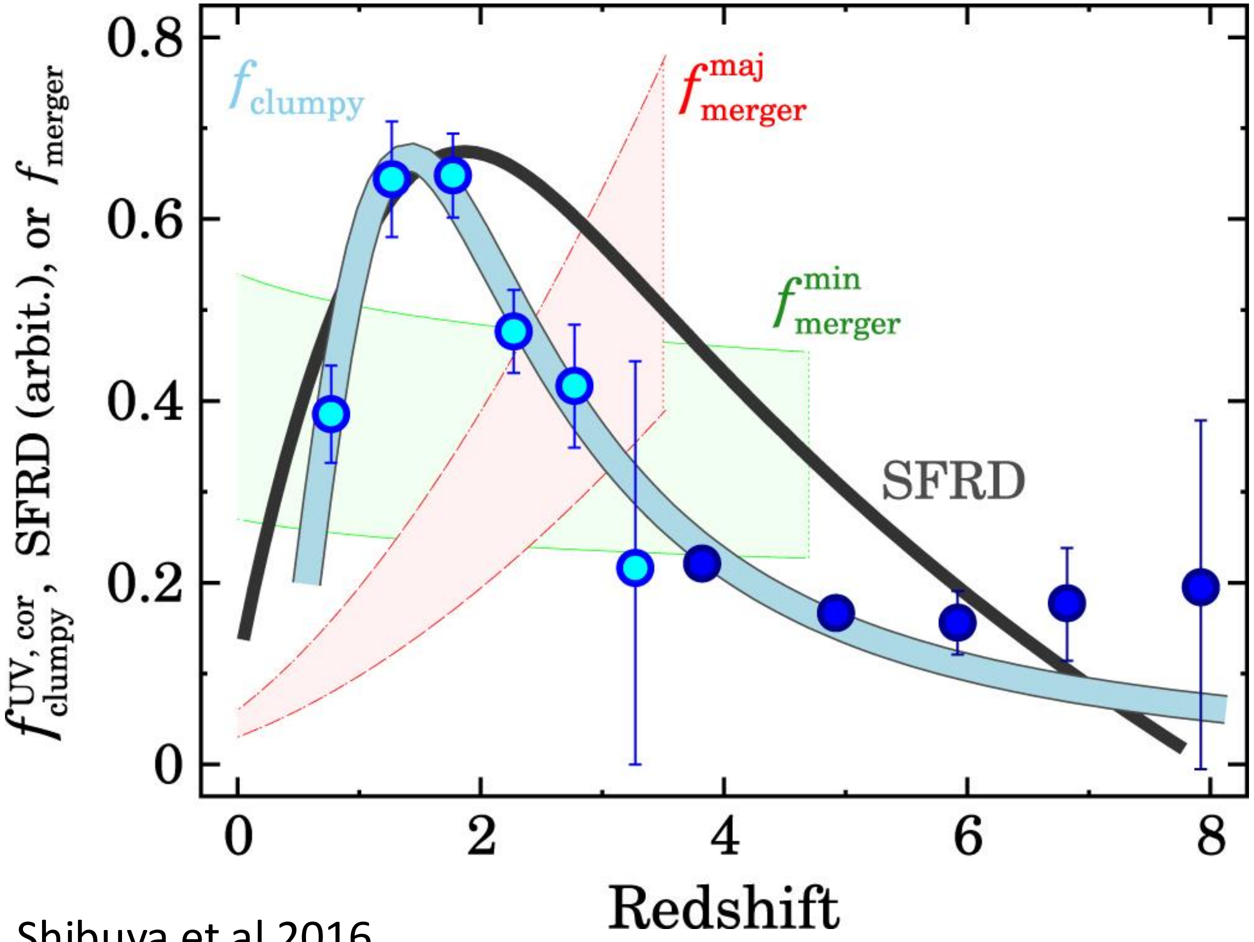
Field stellar clumps at z<2 and size >500 pc scales



Plot from Elmegreen et al 2009, Guo et al 2012, 2015, Shibuya et al 2016, Zanella et al 2019, Agertz+2009, Bourneau+2010, 2024, Ceverino+2012, Tamburello+2015 among many others..

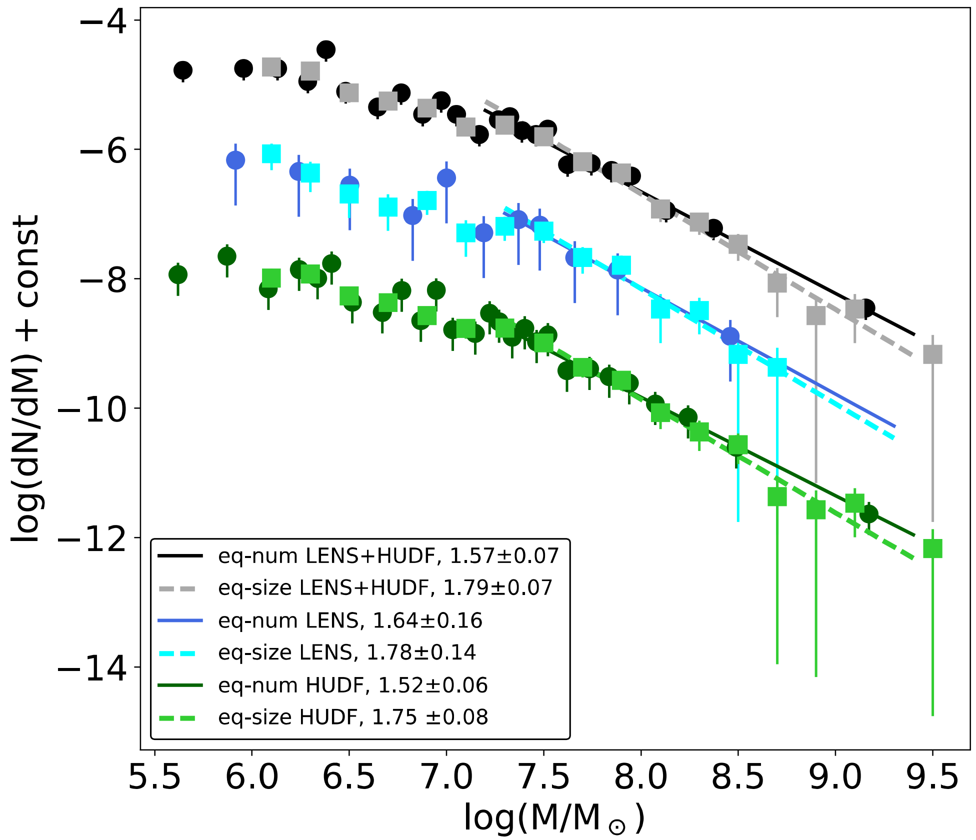
+ Galaxy morphologies are changing
+ Clumps (compact kpc-scale structures) dominate the UV appearance
+ Disks in place at z<2
+ Instable disks, gas rich disks go through violent fragmentation

Clump formation: in-situ vs. ex-situ



Shibuya et al 2016

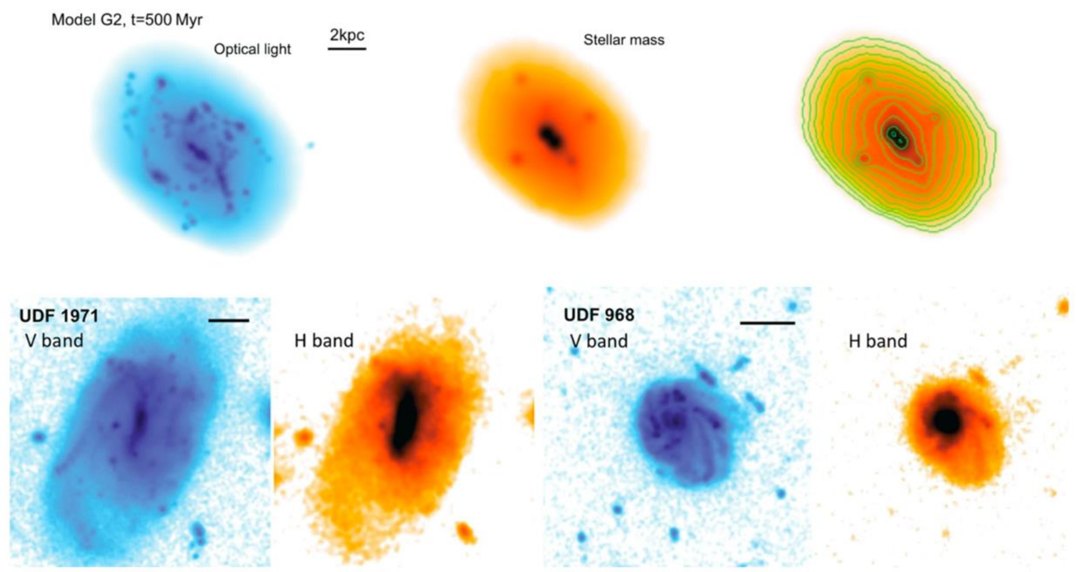
Clump mass function 1<z<3



Dessauges-Zavadsky& Adamo 2018

Open questions

- Clump formation mechanism?
- Clump survival time scales and migration?

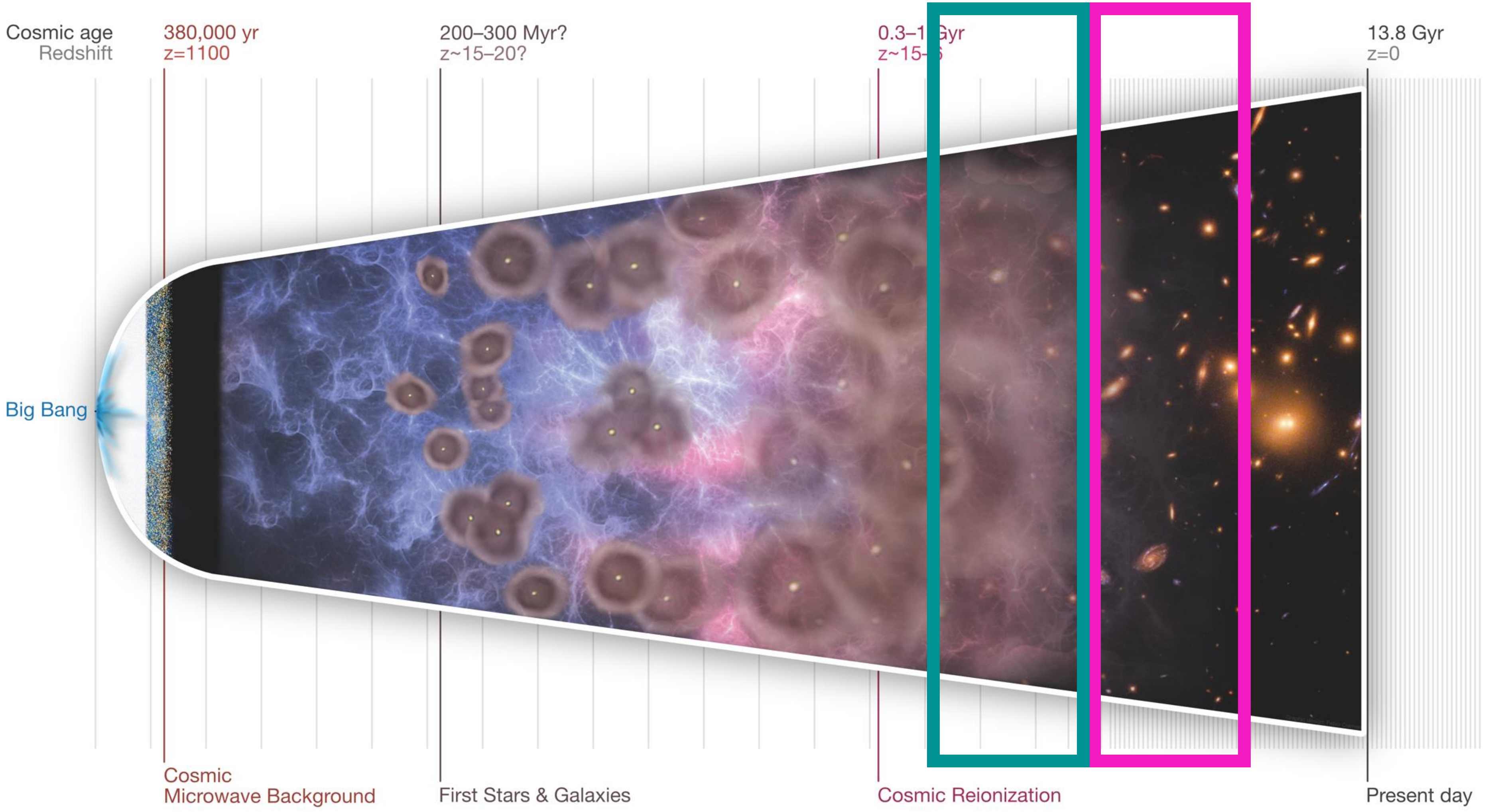


Even simulations had hard time to explain them
→ High gas fraction and massive disks leads to clump formation HOWEVER:

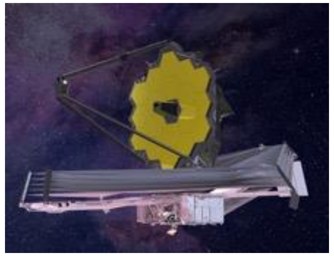
1. Clump formation is very sensitive to feedback prescriptions
2. Very massive clumps formed by merger of clumps?
3. Not clear if they truly play a role in bulge formation

Plot from Bournaud et al 2014, however see also Tamburello et al 2015, and many others

Finding our way home

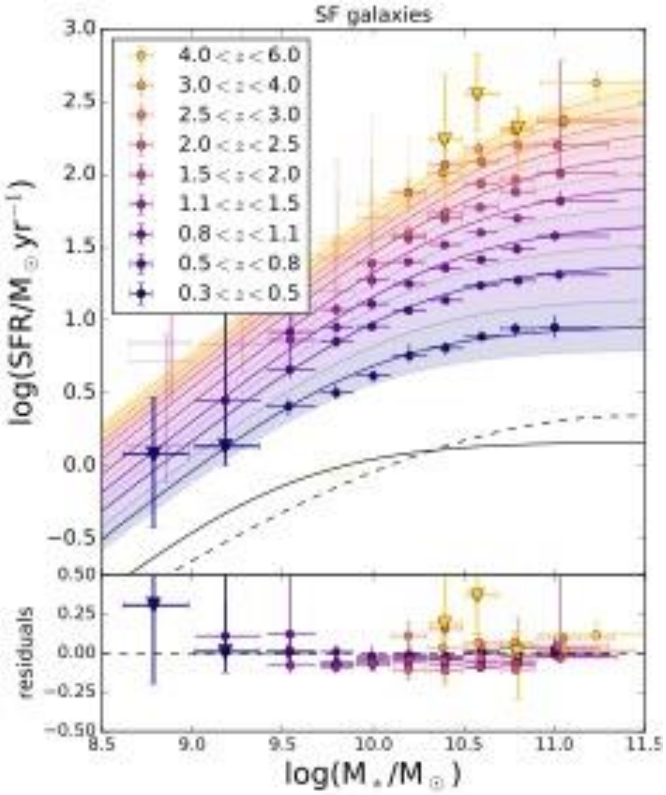


Hubble Space Telescope

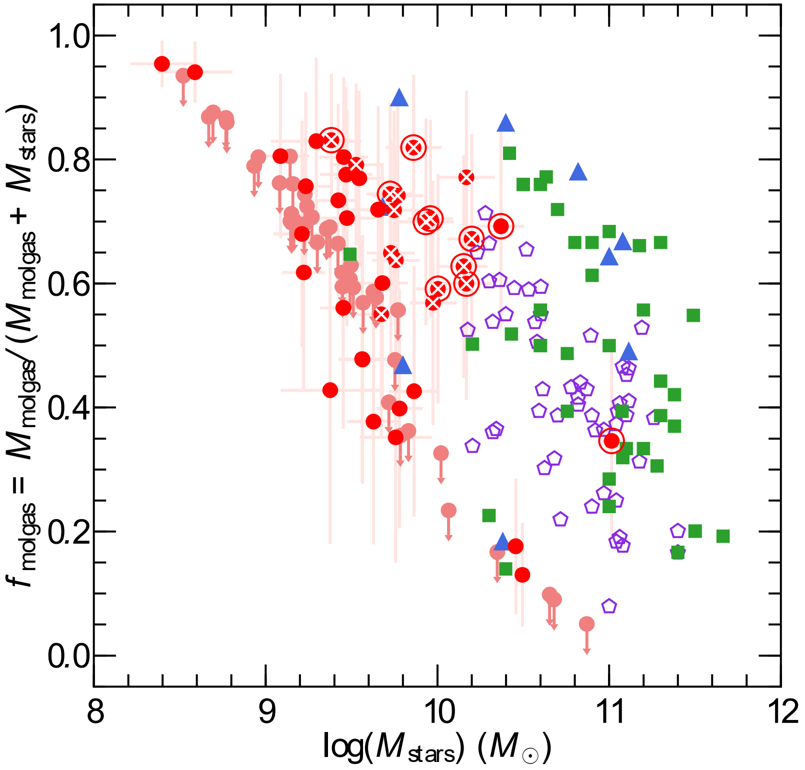


James Webb Space Telescope

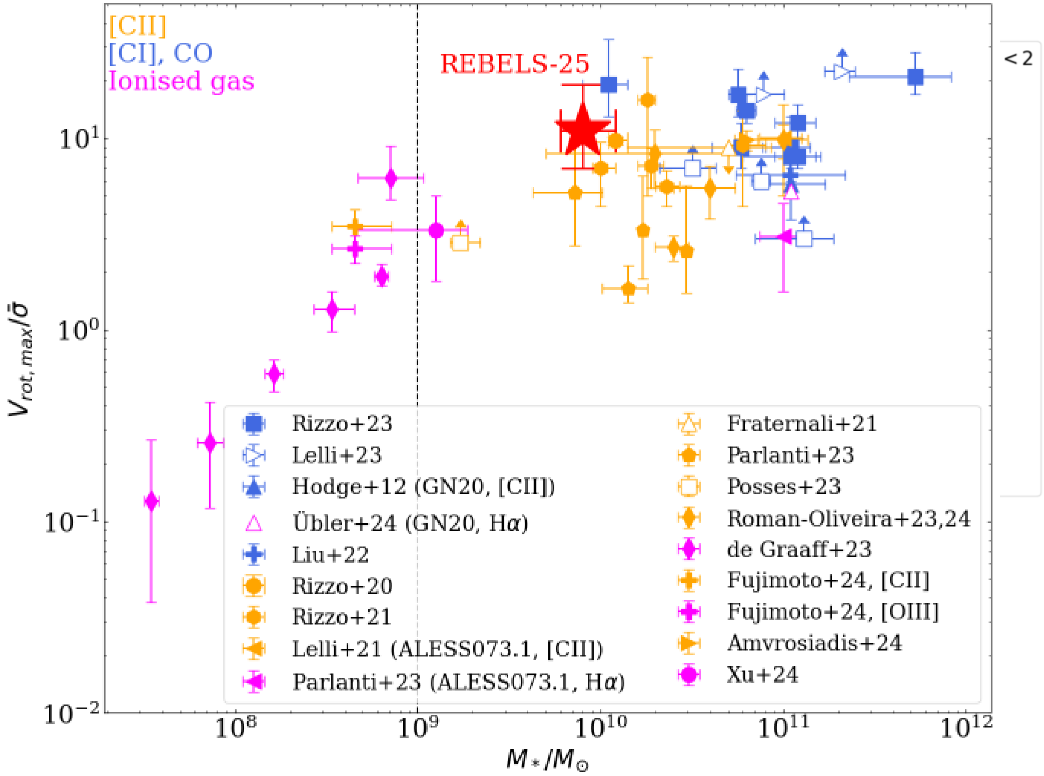
Galaxies evolving across cosmic time



Leslie et al 2020

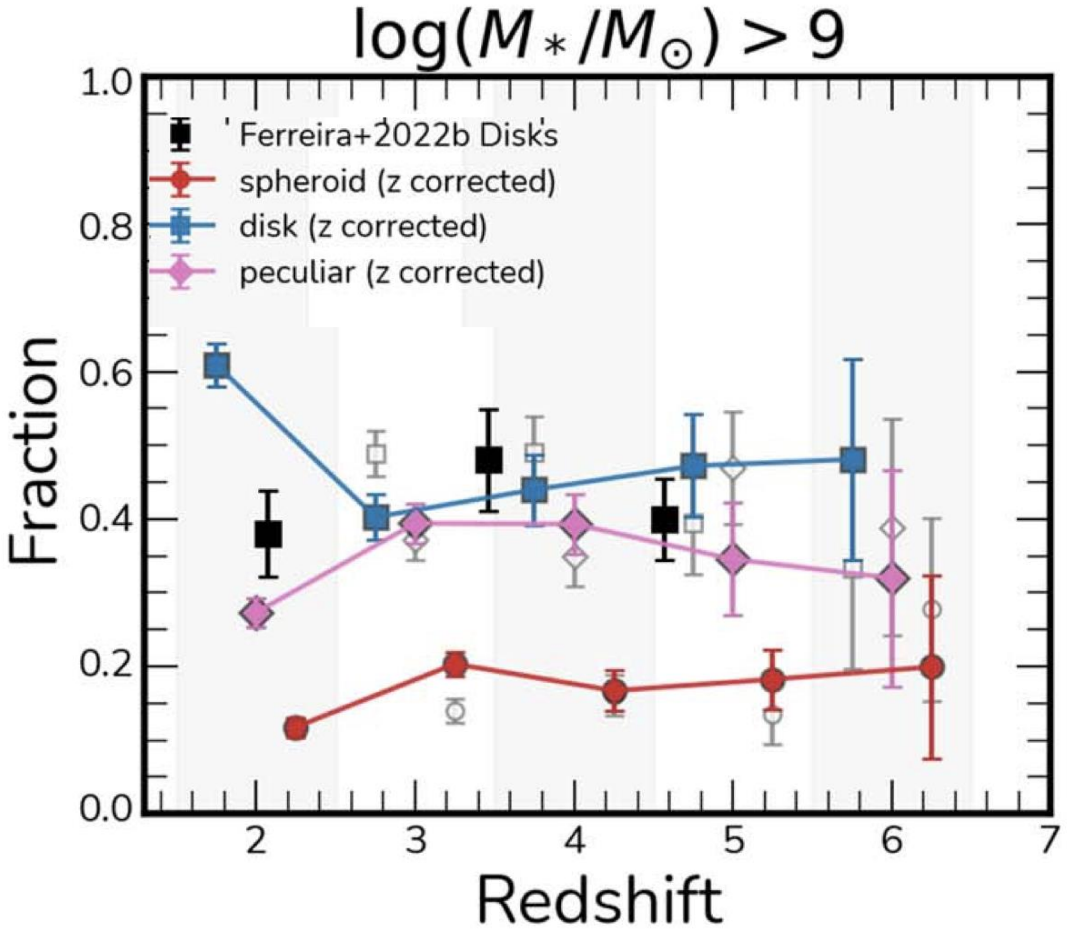


Dessauges-Zavadsky et al 2020



Rowland et al 2024

Galaxies evolving across cosmic time

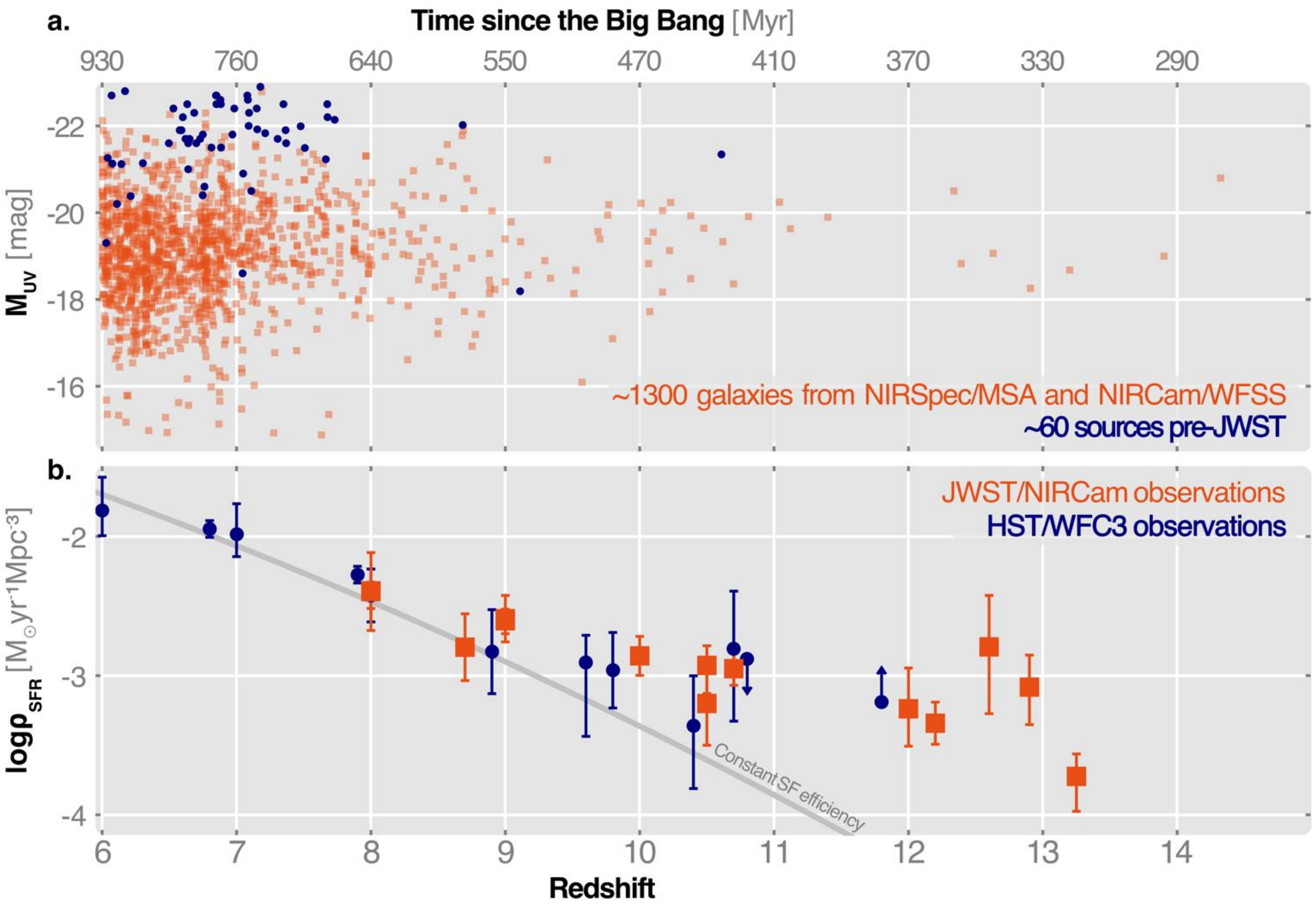


Disks already in place at redshift 6-7

Bulges and bars detected already at z~3

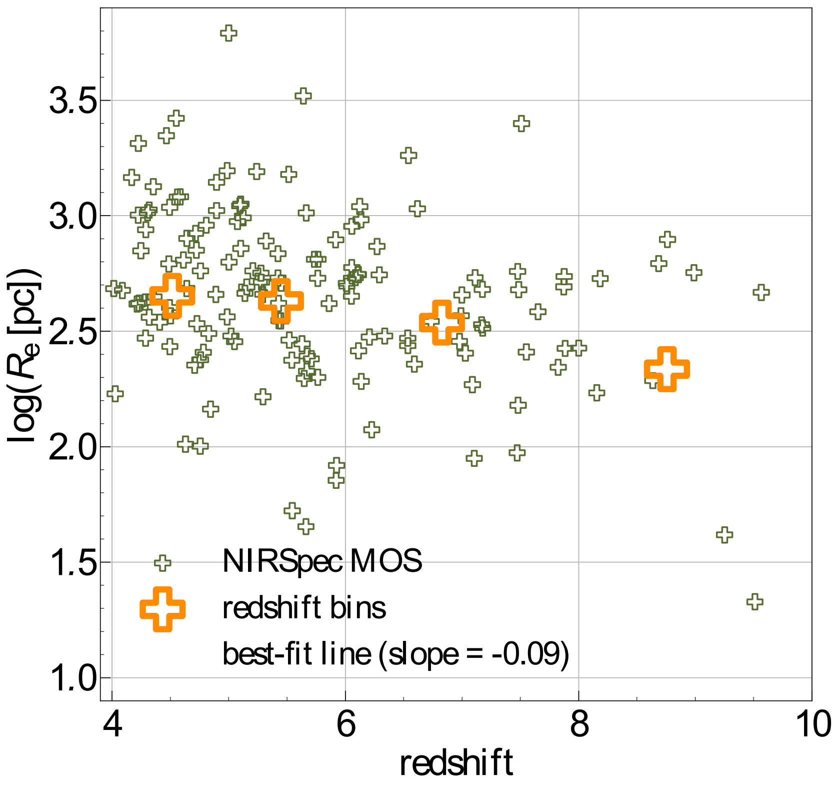
Ferreira et al 2022, 2023, Kartaltepe et al 2023, Rowland et al 2024, Fujimoto et al 2024, among many others

Galaxies evolving across cosmic time



Plot from ISSI breakthrough workshop review

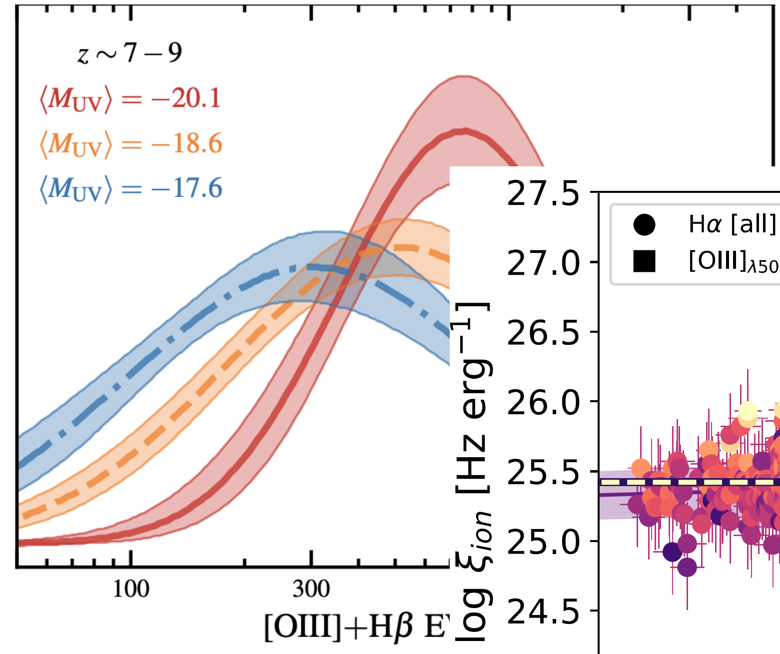
Increasingly compact morphologies



Langeroodi & Hjort 2023

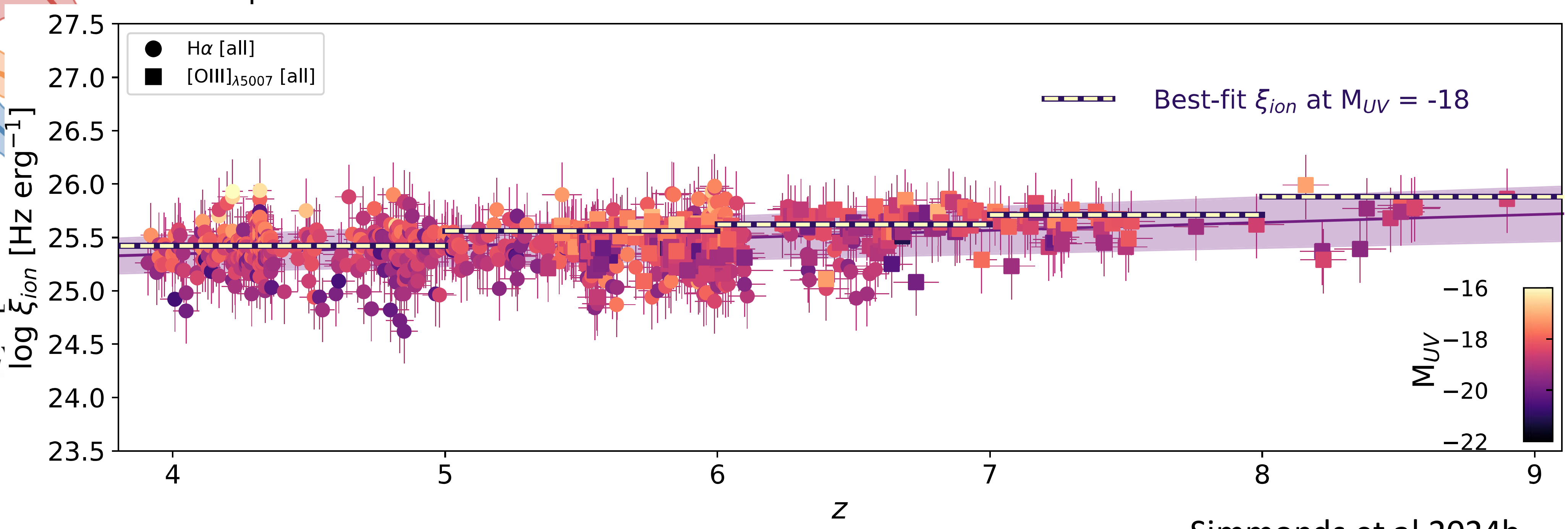
Galaxies evolving across cosmic time

Bursty star formation cycles



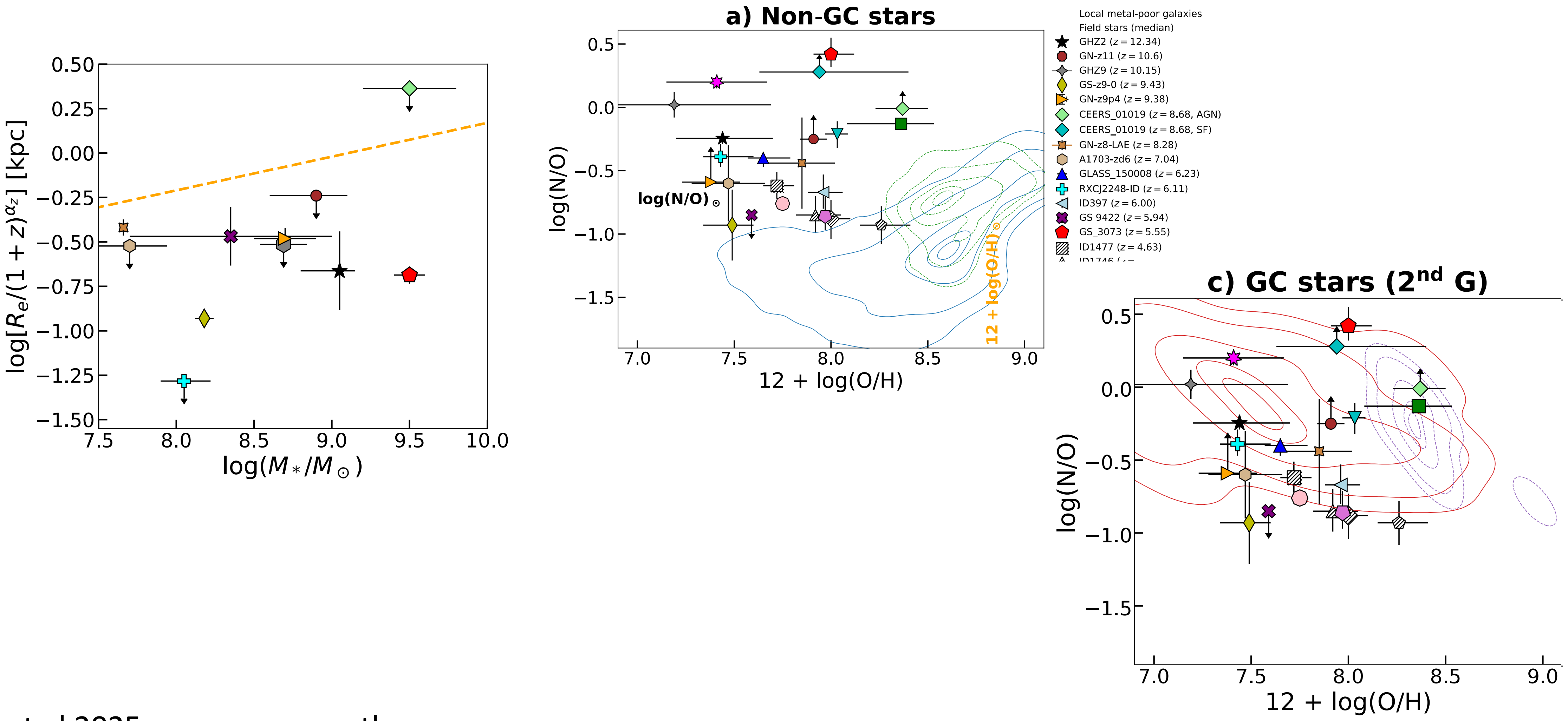
Endsley et al 2024

Efficient to produce ionizing radiation!



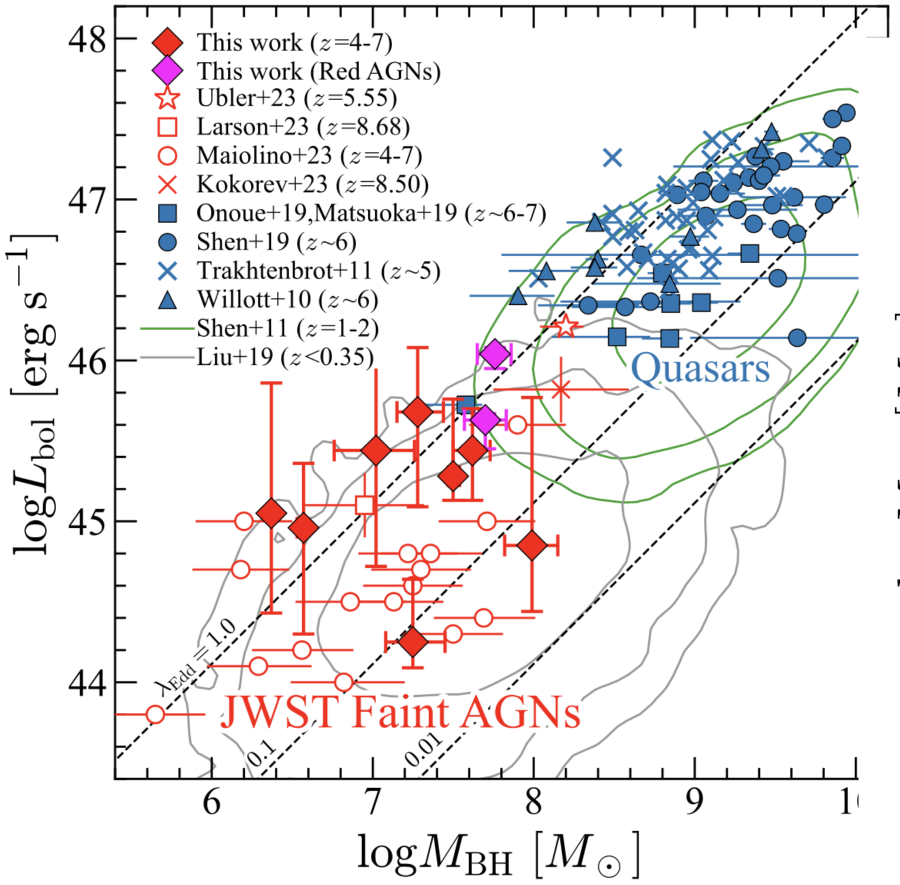
Simmonds et al 2024b

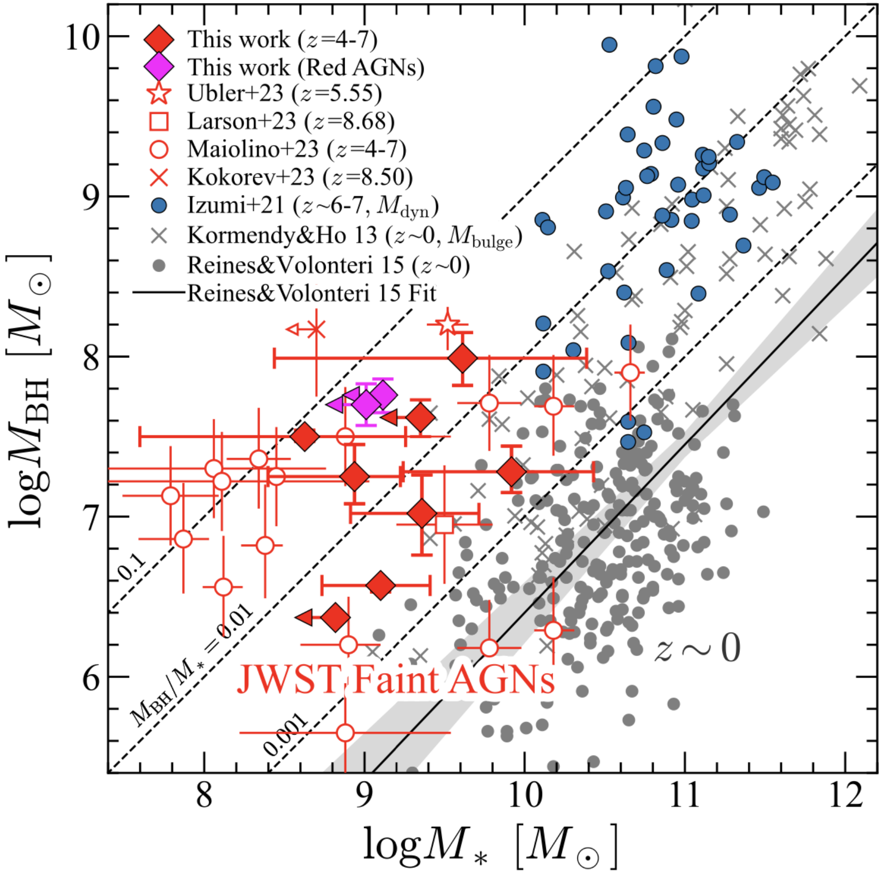
Galaxies evolving across cosmic time



Ji et al 2025, among many others

BHs across cosmic time



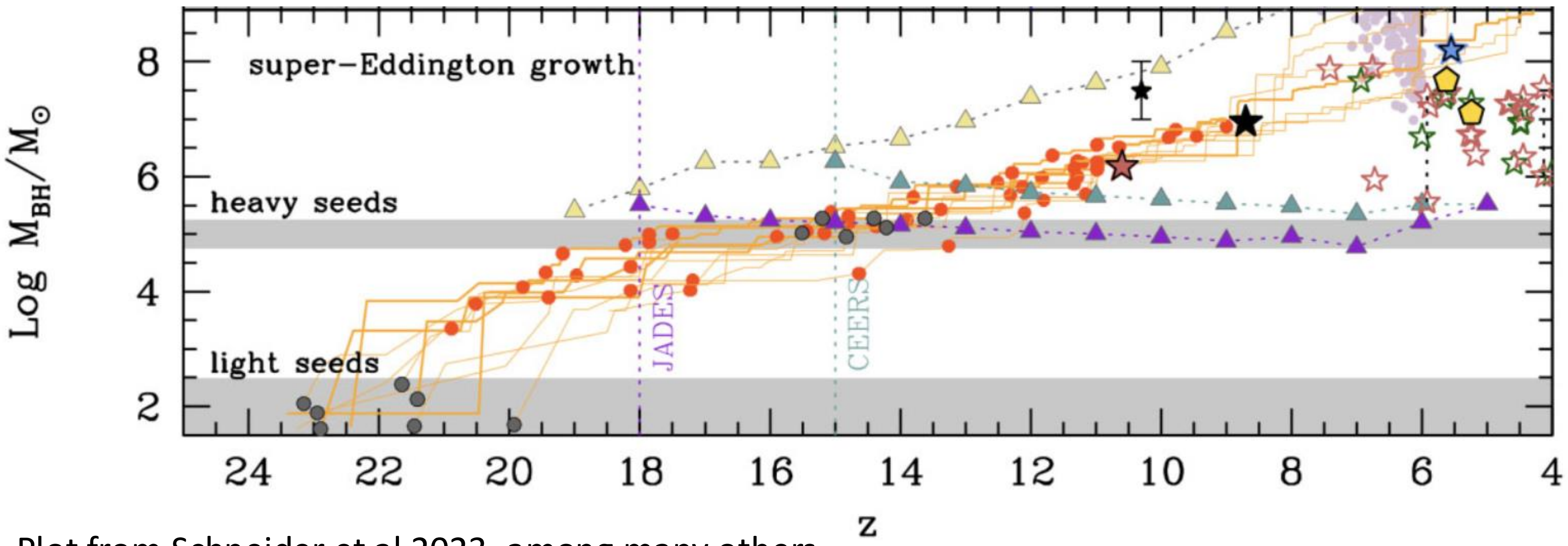


- (Super) Eddington BH accretion?
- Will galaxies catch up later?
- What's going on really?

Faint AGN population revealed by JWST

Plots from Harikane et al 2023, but huge number of publications on the topic

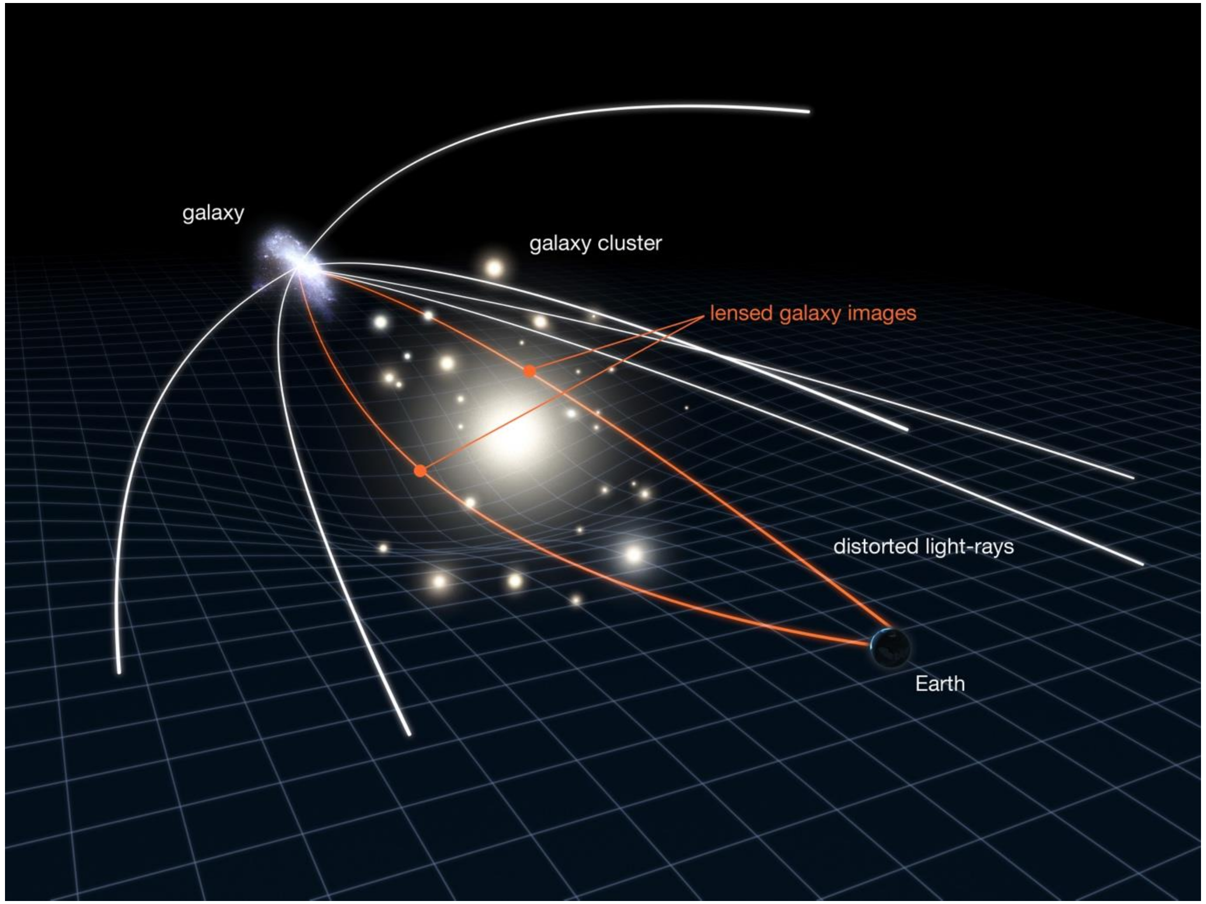
BHs across cosmic time

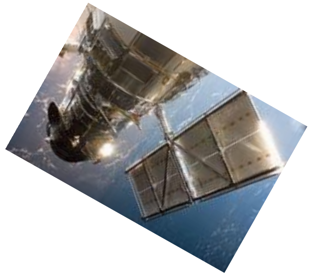


Plot from Schneider et al 2023, among many others

- (Super) Eddington BH accretion?
- Will galaxies catch up later?
- What's going on really?

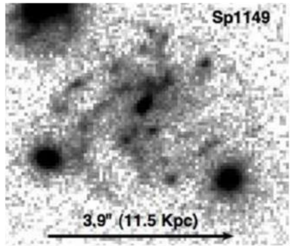
Combination gravitational telescopes is a unique opportunity to break the kpc resolution



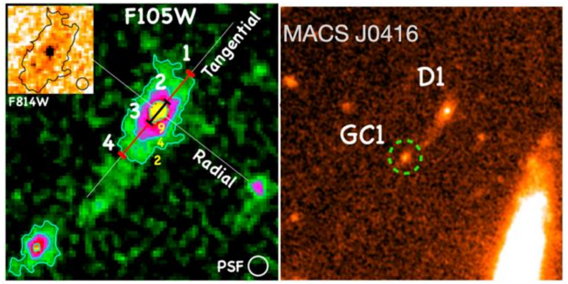


Combination with lensing is a unique opportunity to break the kpc resolution

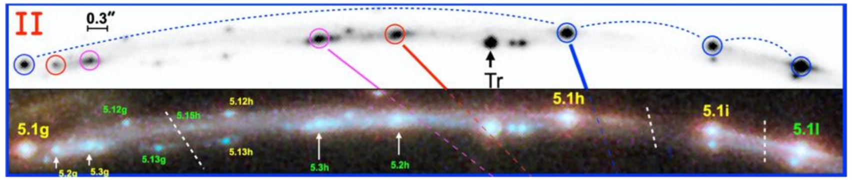
Single-case studies at 1<z<6



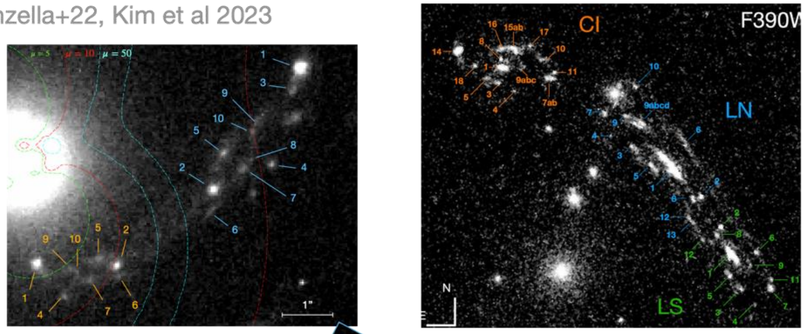
Adamo+13



Vanzella+17

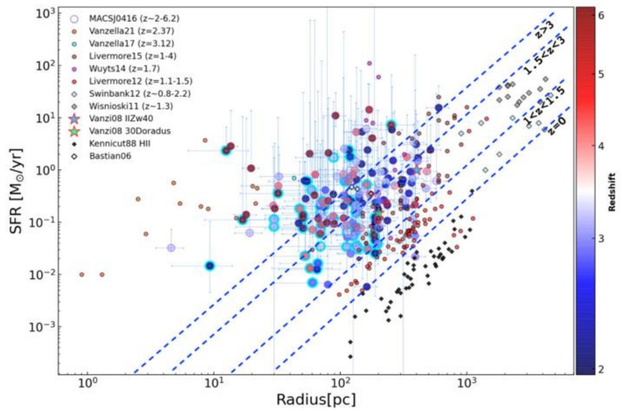


Vanzella+22, Kim et al 2023

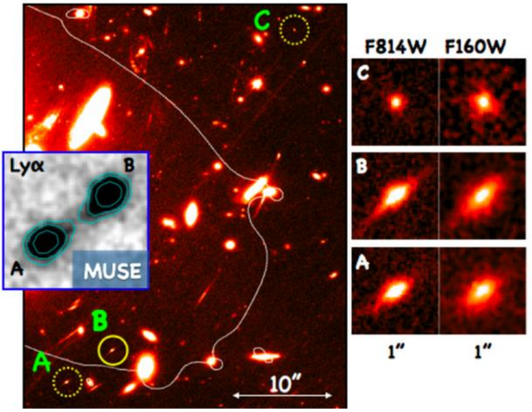


Messa+22

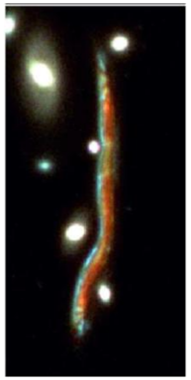
Studies of samples z:1-6



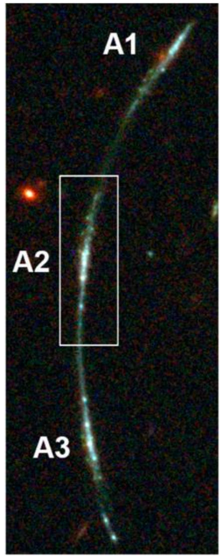
Plot from Meštrić et al 2022, see also Livermore et al 2012, 2015



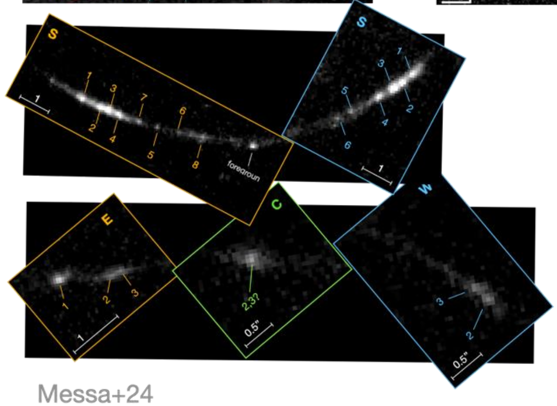
Vanzella+17



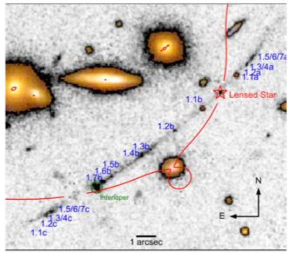
Cava+18



Johnson+18



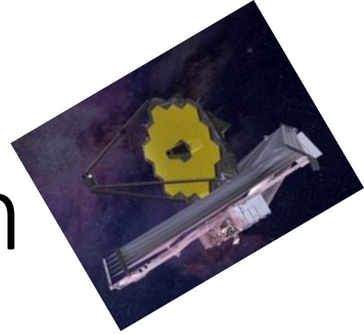
Messa+24



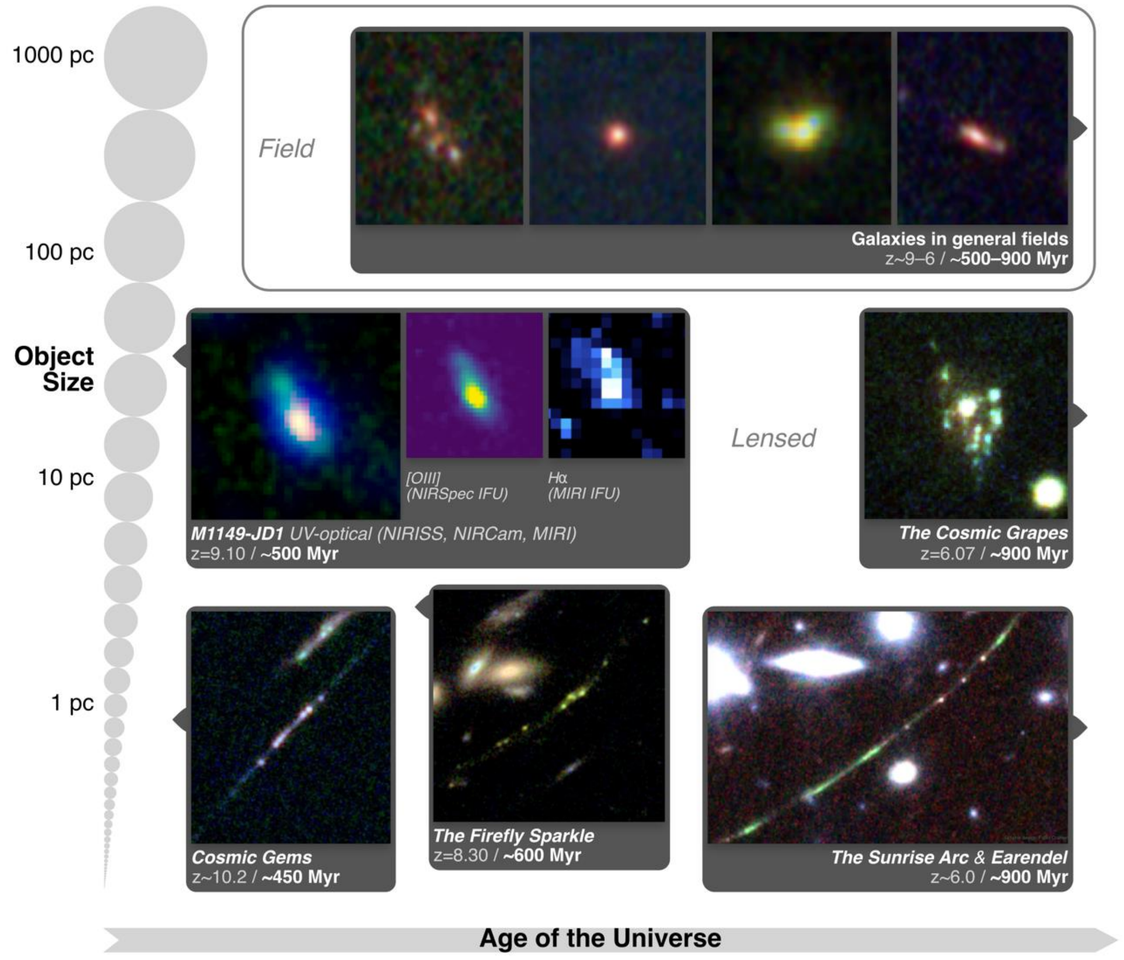
Welch et al 2022, 2023

*Slide courtesy of Matteo Messa

JWST is providing fundamental information



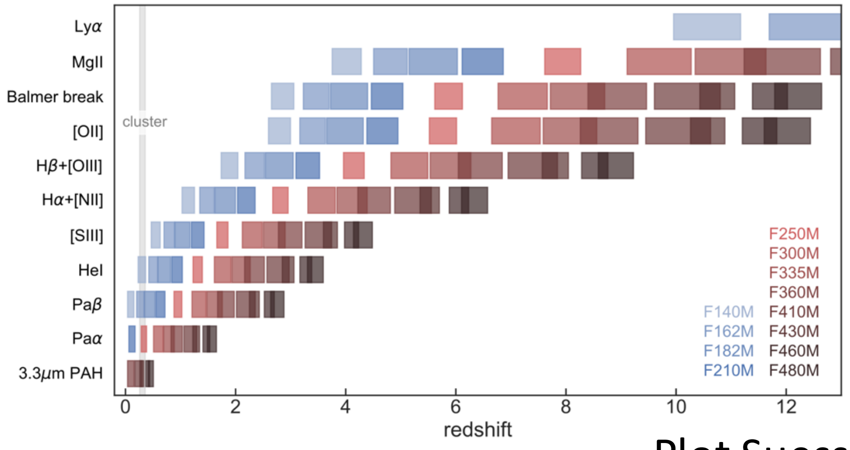
We can study star formation at all redshift and extend at z>6



Plot from ISSI breakthrough workshop review

*For clump studies, considering only NIRCam

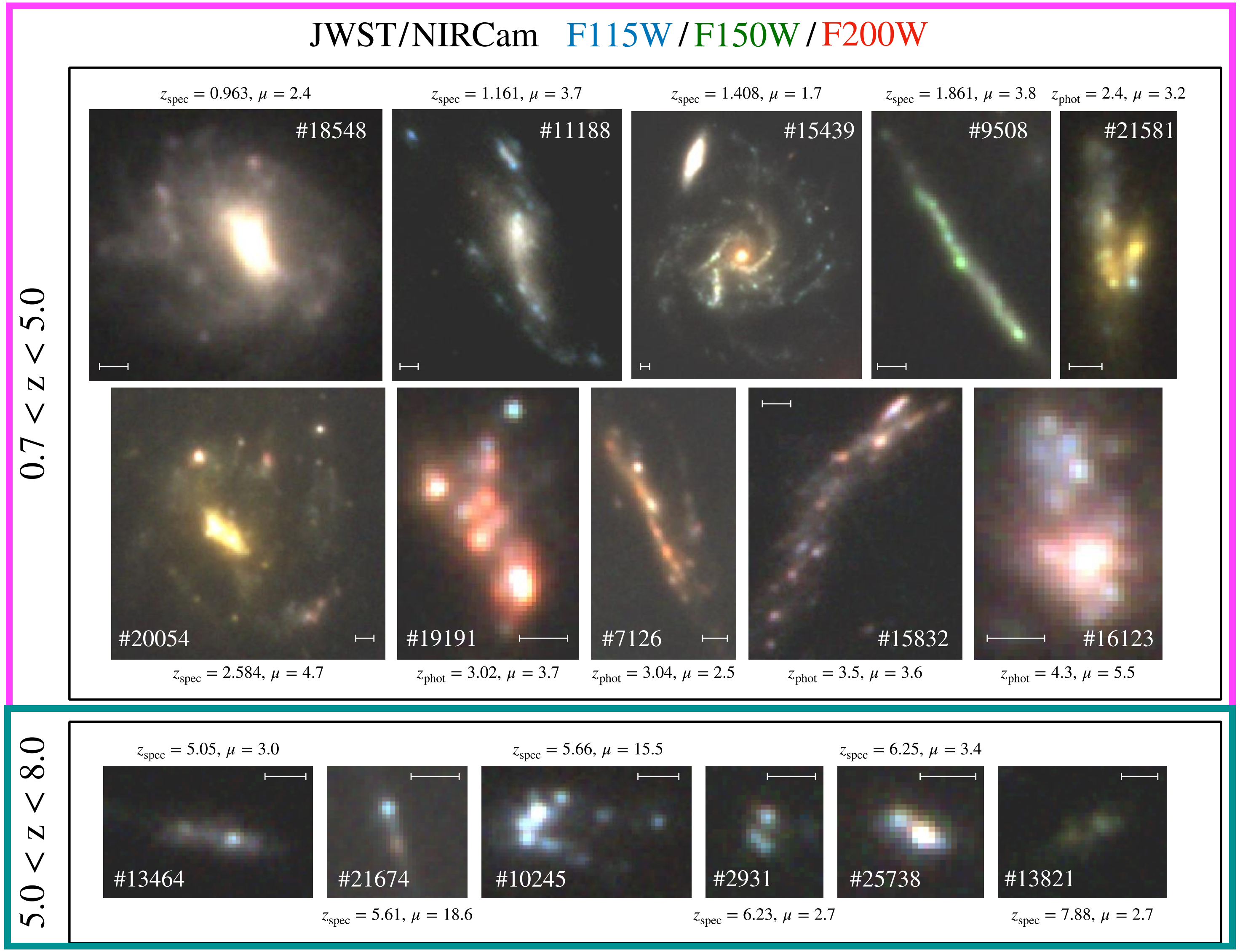
1<z<4 Optical+NIR → Robust age, mass, extinction
4<z<6.5 FUV+optical → Secure age, mass, extinction
6.5<z<9.5 FUV+5000Å → Good age, mass , fair extinction estimate
z>9 FUV+4000 Å→ UV based ages, mass, extinction



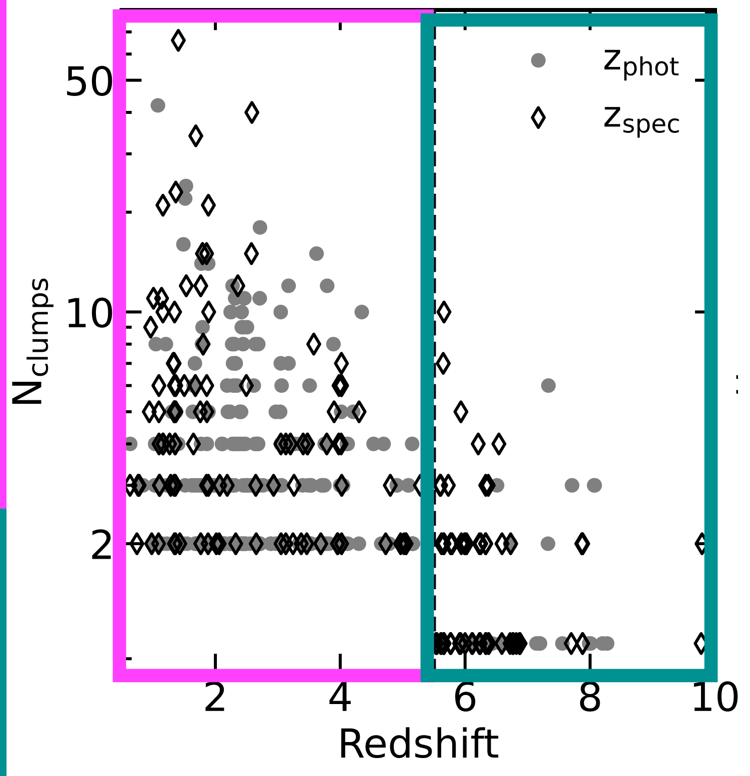
Plot Suess et al 2024

NASA, ESA, CSA, Ivo Labbe (Swinburne), Rachel Bezanson (University of Pittsburgh)

Clump population in A2744



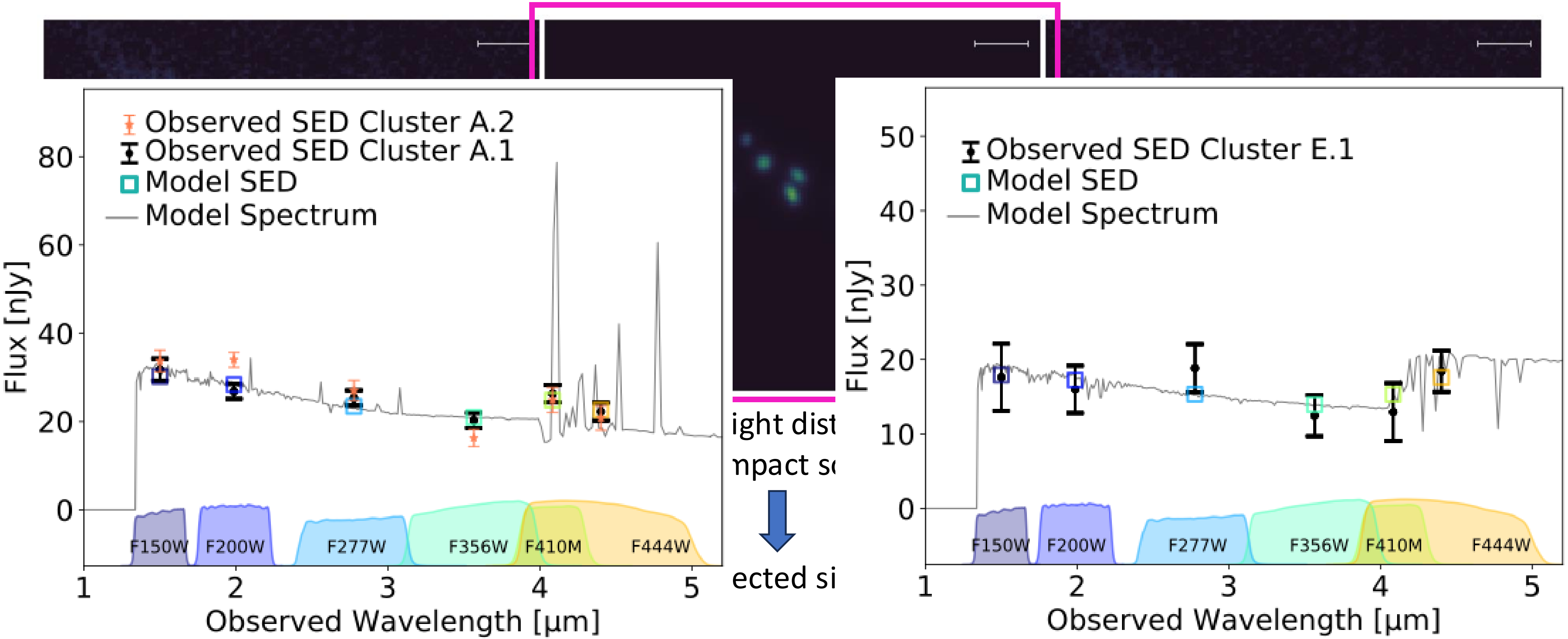
484 galaxies between redshift 1 and 10 (~40% spectroscopic redhsift) resulting in 2000 clumps (magnification μ < 2)



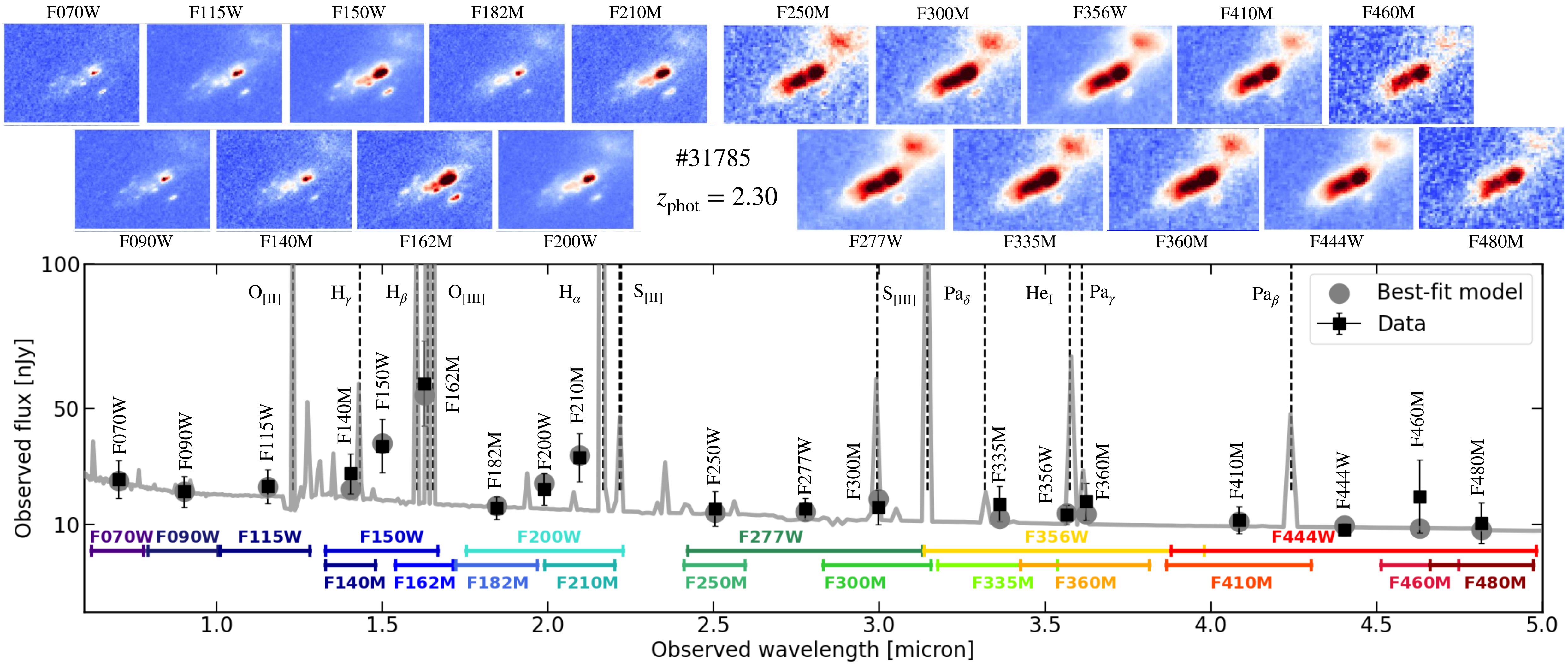
Claeyssens, AA et al 2024, and in prep.

Adelaide Claeyssens
Researcher at CRAL

Stellar clump physical properties



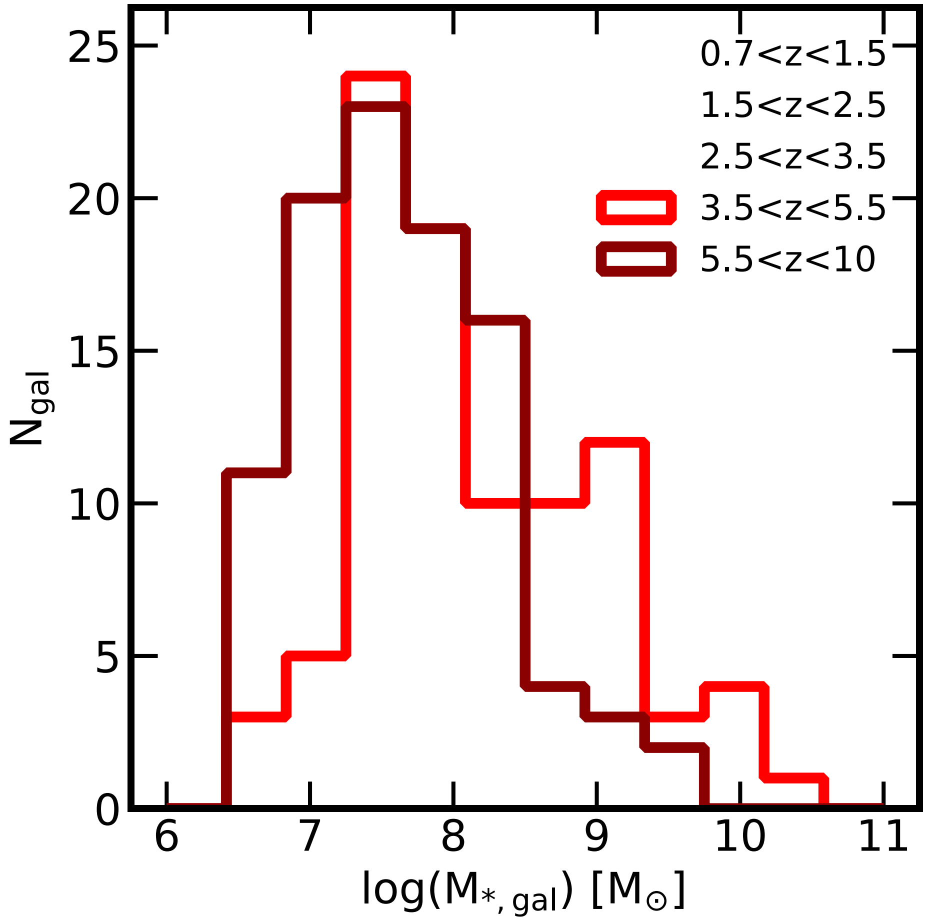
The power of spectro-photometry for clump studies



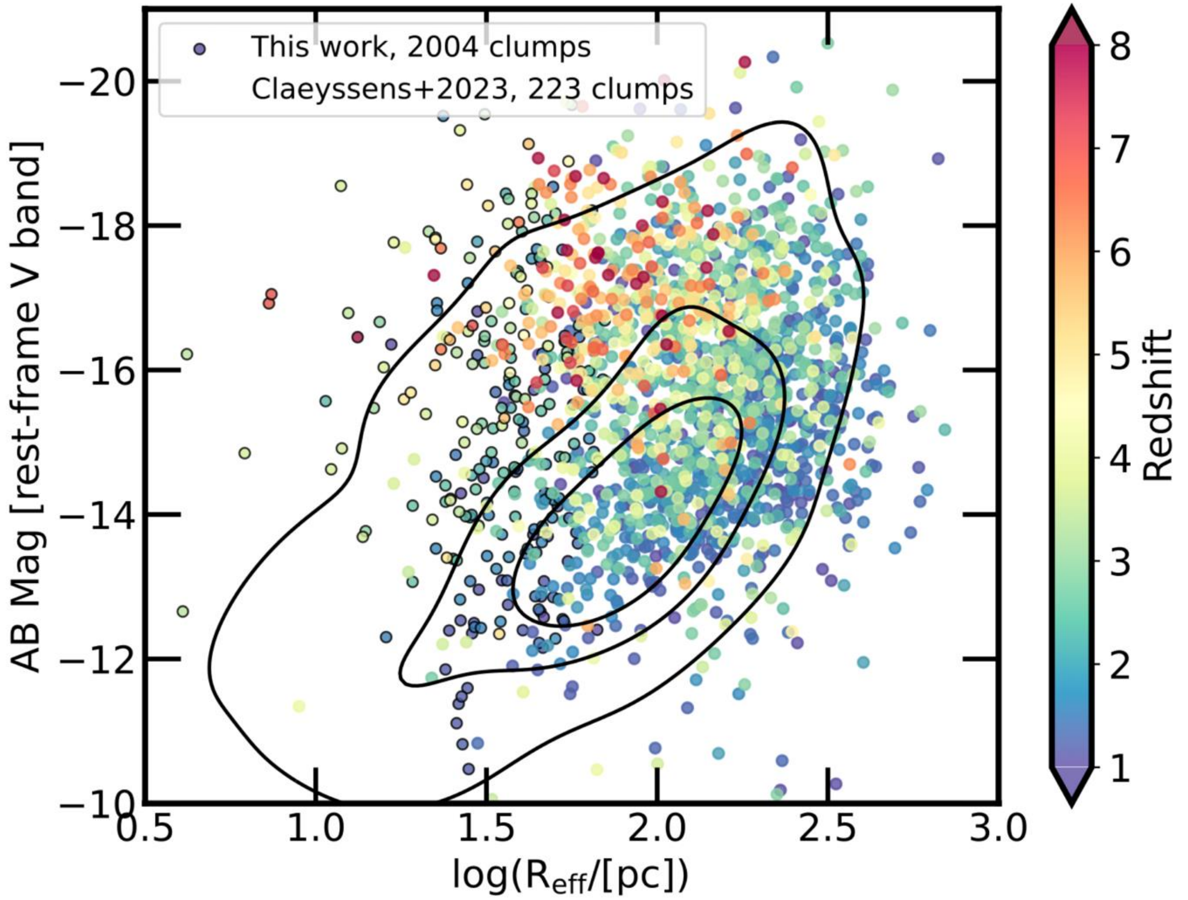
Claeyssens, AA et al 2024

Clump population in A2744

Galaxy's stellar masses

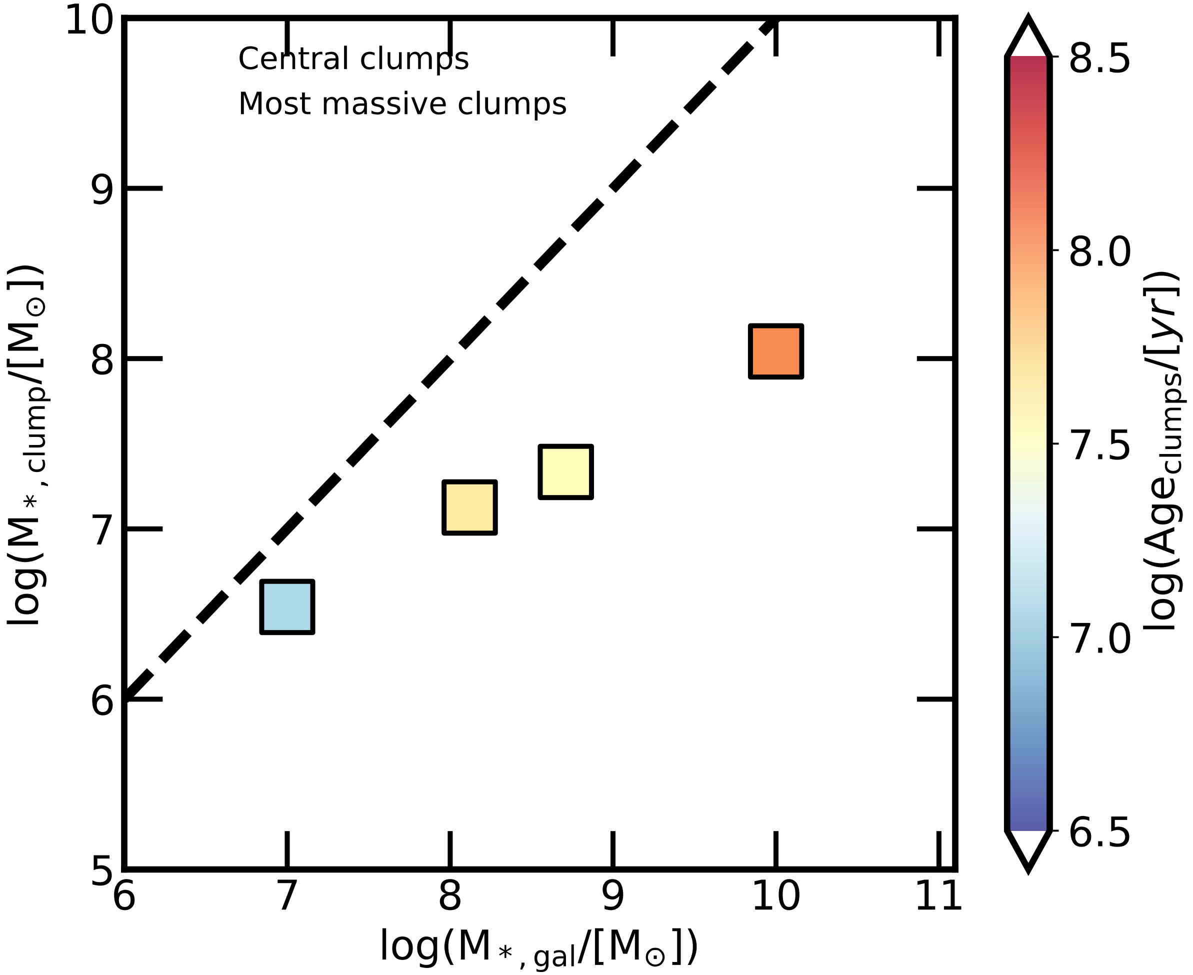


Observed clumps physical properties



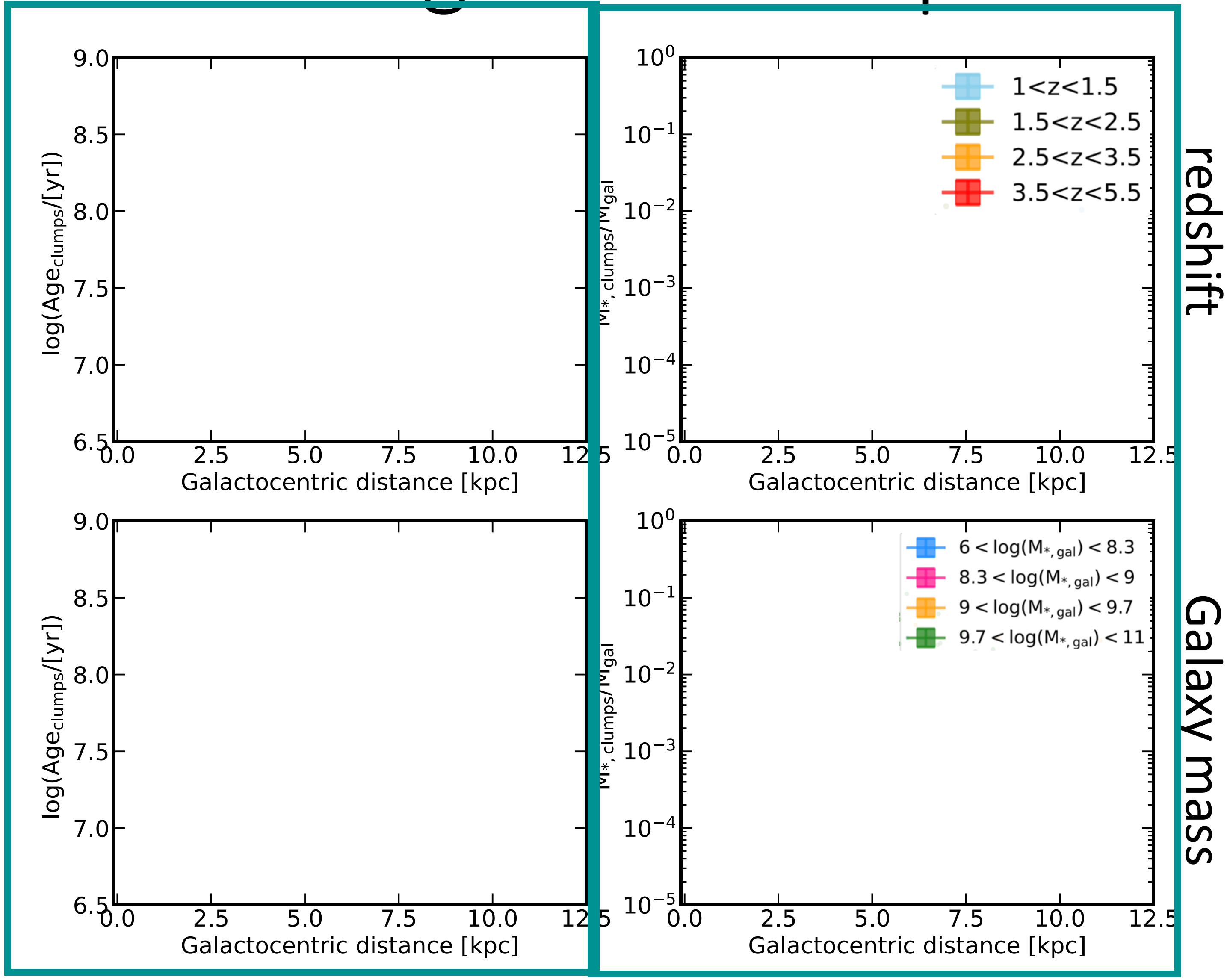
Claeyssens, AA et al 2024

Clump population in A2744



Claeyssens, AA et al 2024

Looking at the 10s pc scales across cosmic time

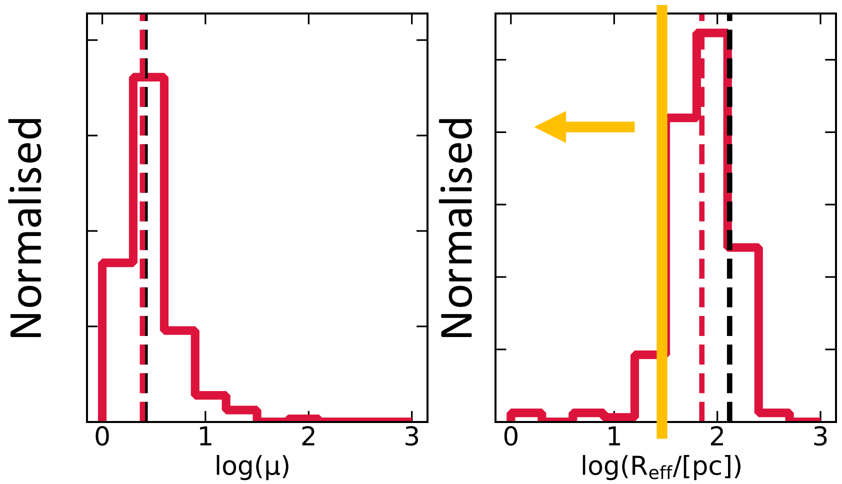


- Galaxies become more compact as a function of redshift and decreasing mass
  - Clumps grow older as a function of galaxy mass and lower redshift
  - No clear trend with age indicating migration

  - More massive clumps are closer to the centre of galaxies
  - At increasing redshifts and decreasing mass clump dominate galaxy mass

Claeyssens, AA et al 2024

Clump population in A2744



- No changes in mass distributions

- z>5 clumps on average younger

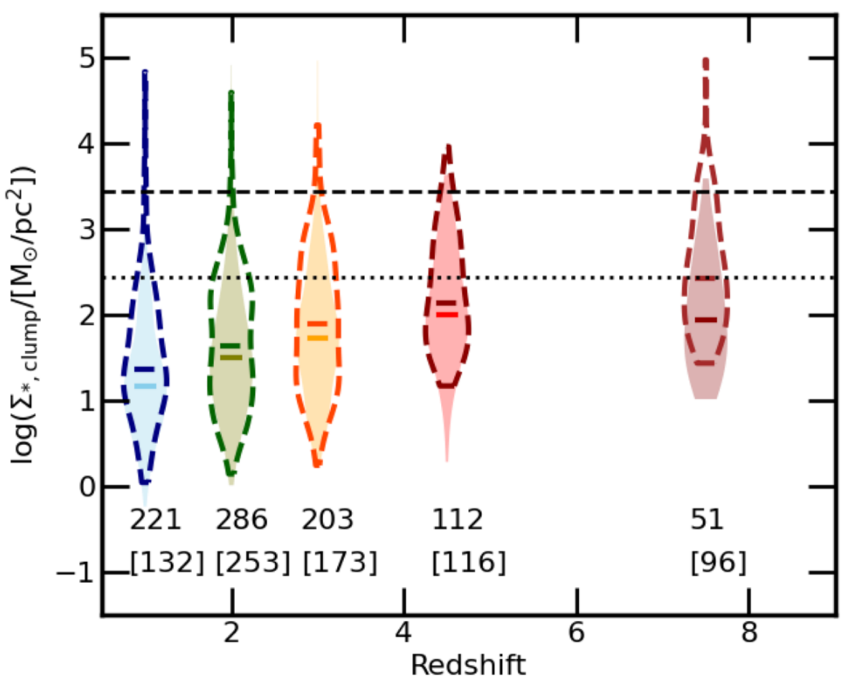
- z>5 clumps higher stellar densities

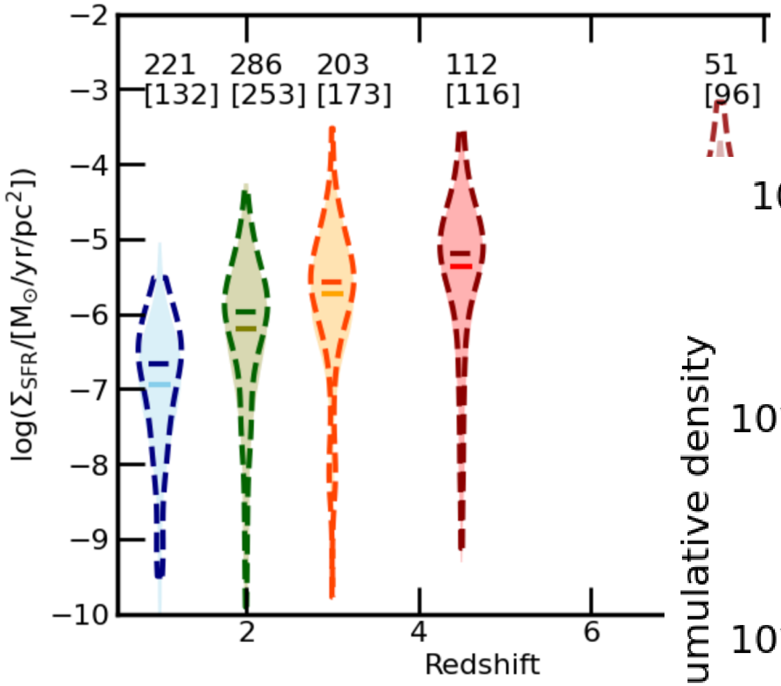
- z>5 clumps higher SFR densities

- z>5 clumps higher sSFR (over 10 Myr)

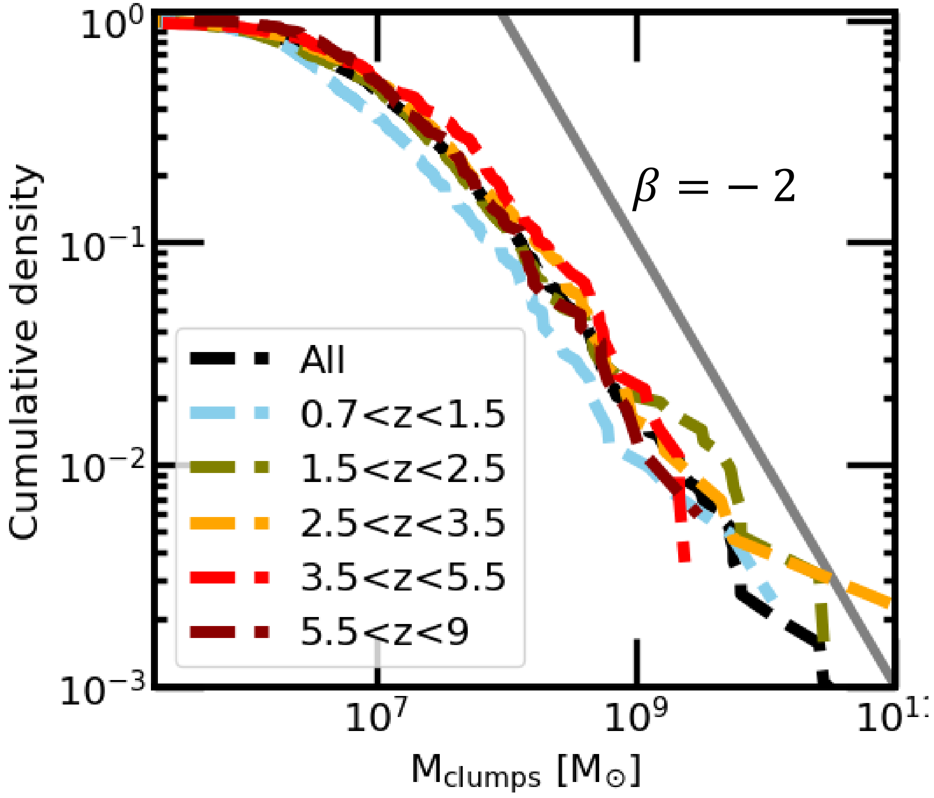
Claeyssens, AA et al 2025, and the z>5 sample Claeyssens, AA in prep.

Looking at the 10s pc scales across cosmic time



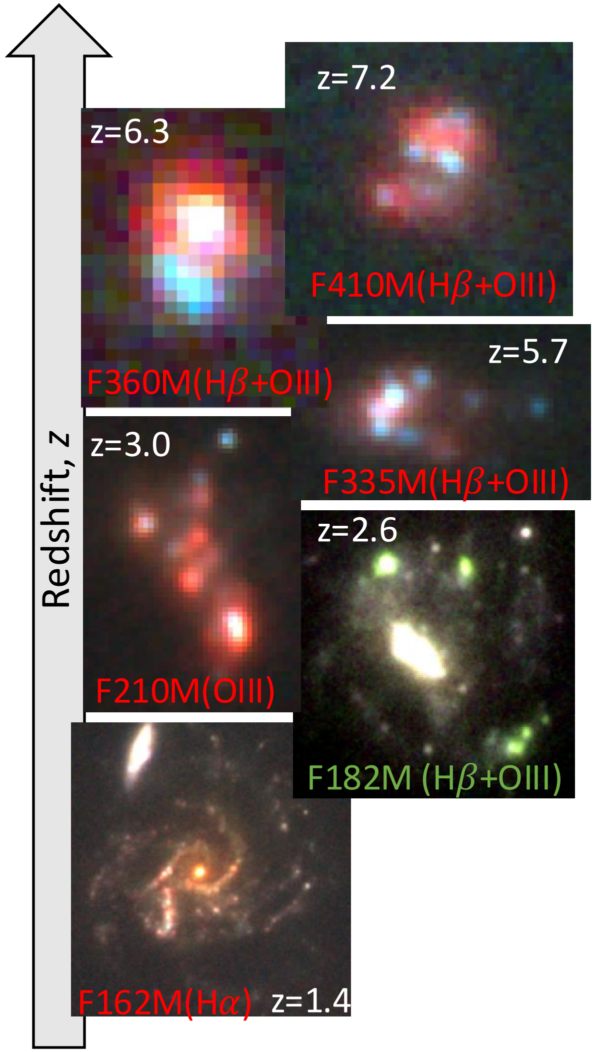


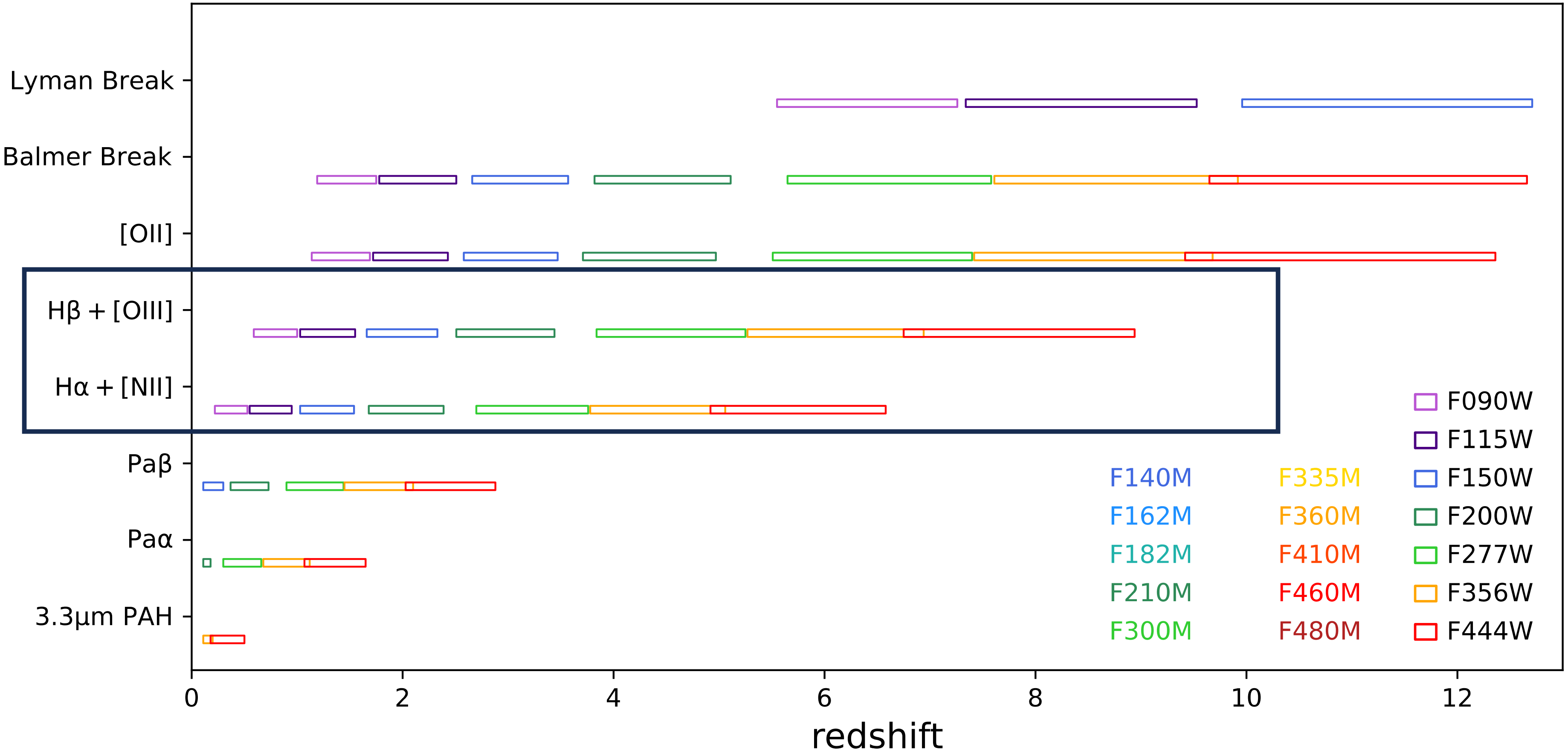
Clump mass function consistent with fragmentation
At all redshifts



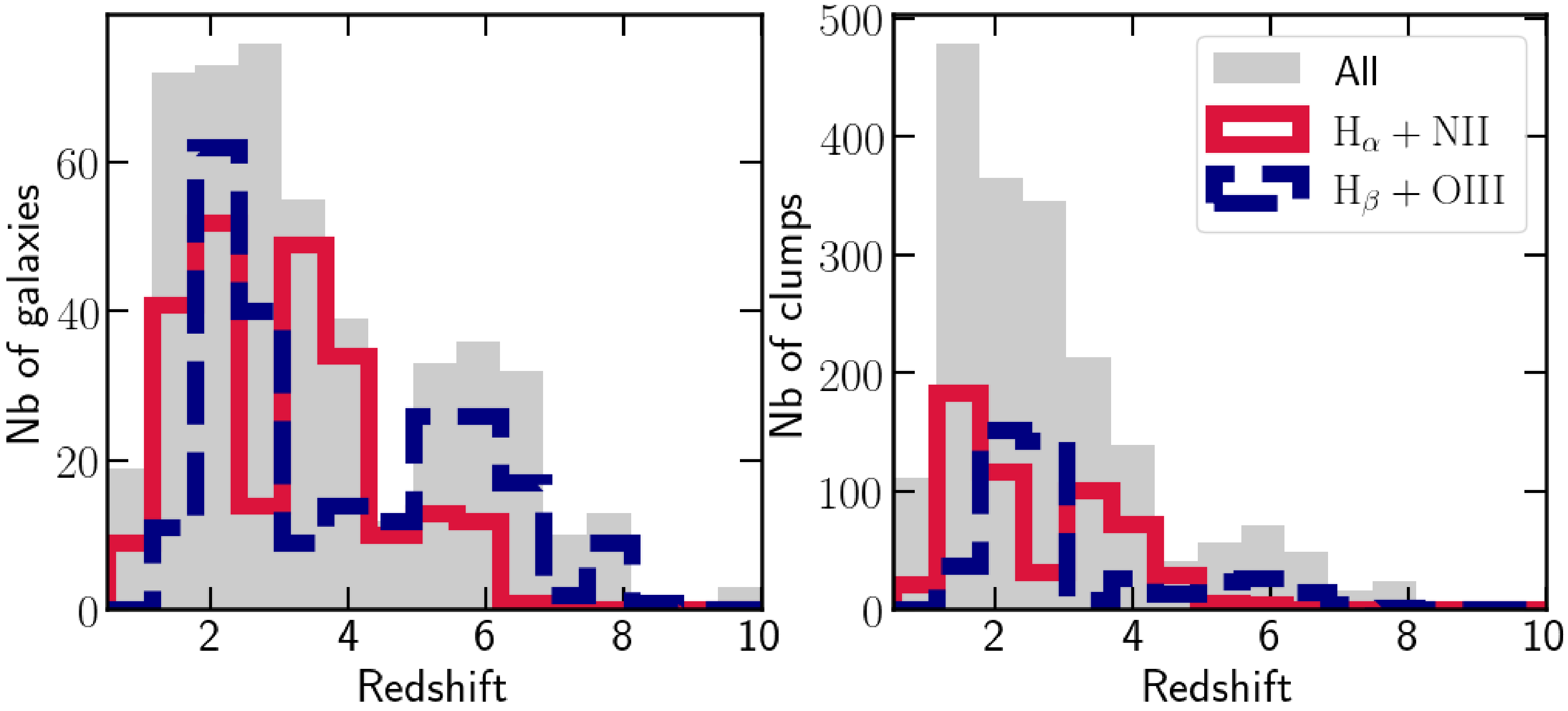
Claeyssens, AA et al in prep.

Looking at the sites of LyC photon production





Looking at the sites of LyC photon production

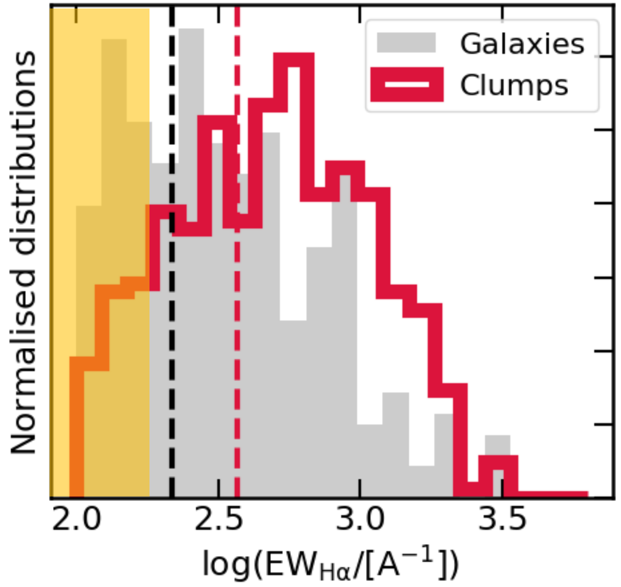


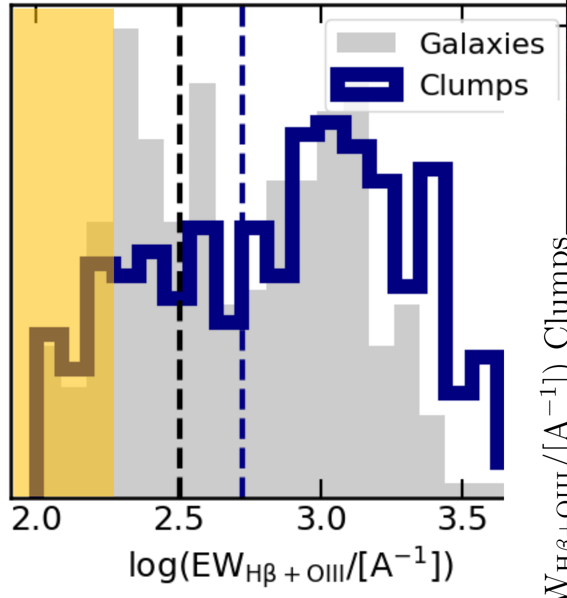
235 galaxies with Halpha+NII (49%)
567 clumps

229 galaxies with Hbeta+OIII (48%)
455 clumps

Claeyssens, AA et al in prep

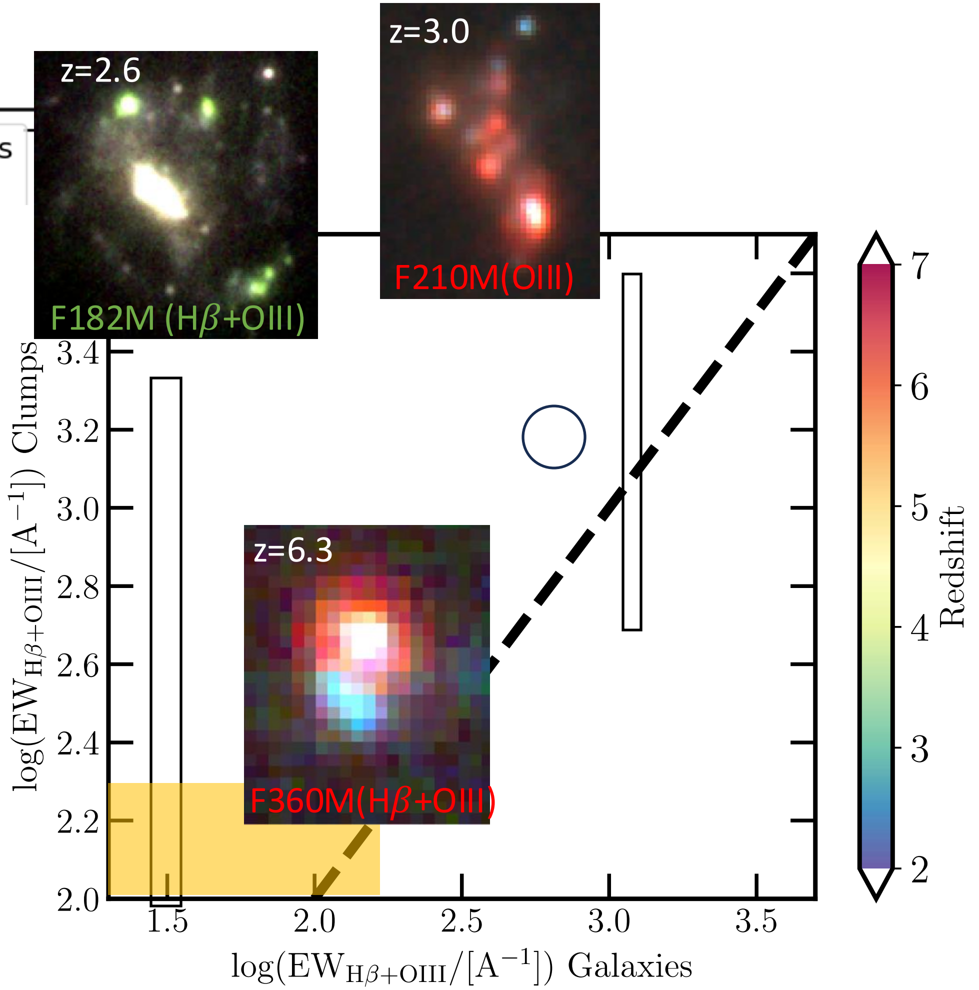
Looking at the sites of LyC photon production





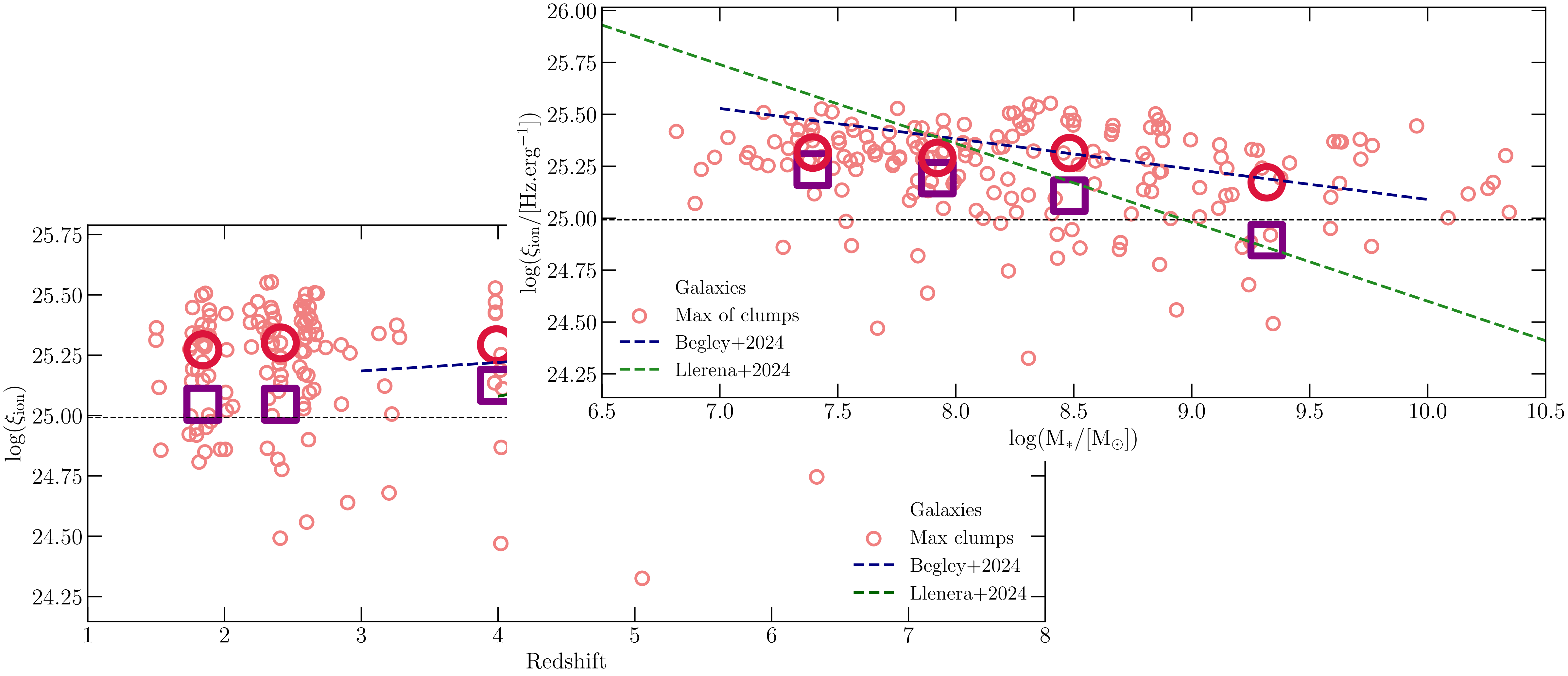
30 % clumps EW > 750 Å

50 % clumps EW >



Claeyssens, AA et al in prep

Looking at the sites of LyC photon production



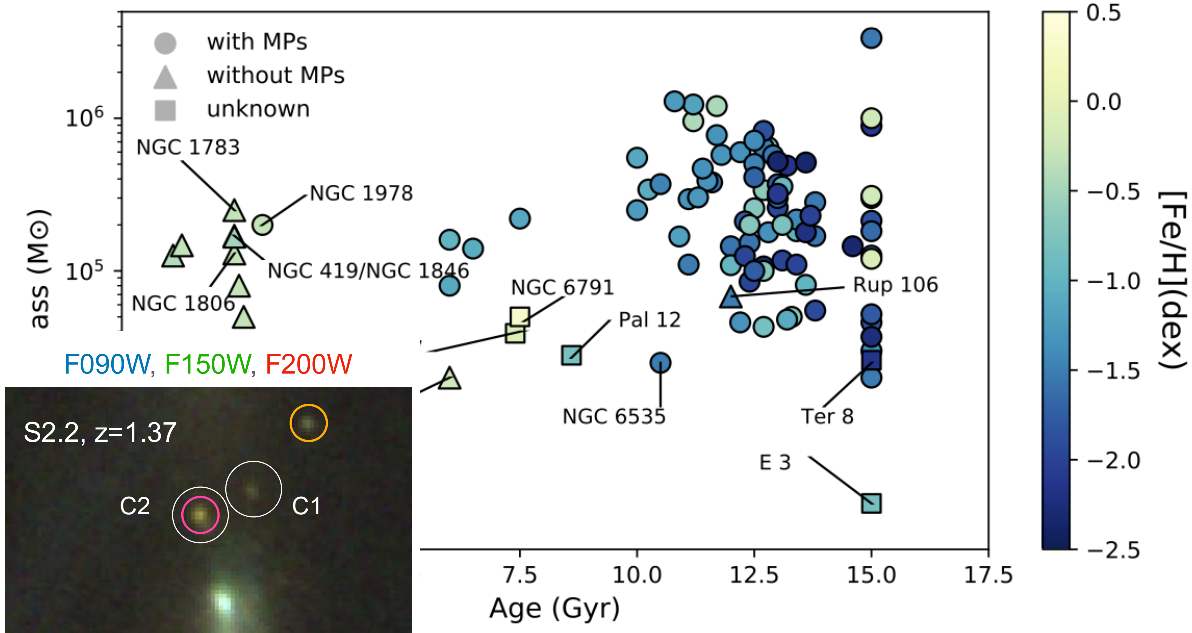
Claeyssens, AA et al in prep

When & where did the first star clusters form?

Tracing star cluster formation across cosmic time

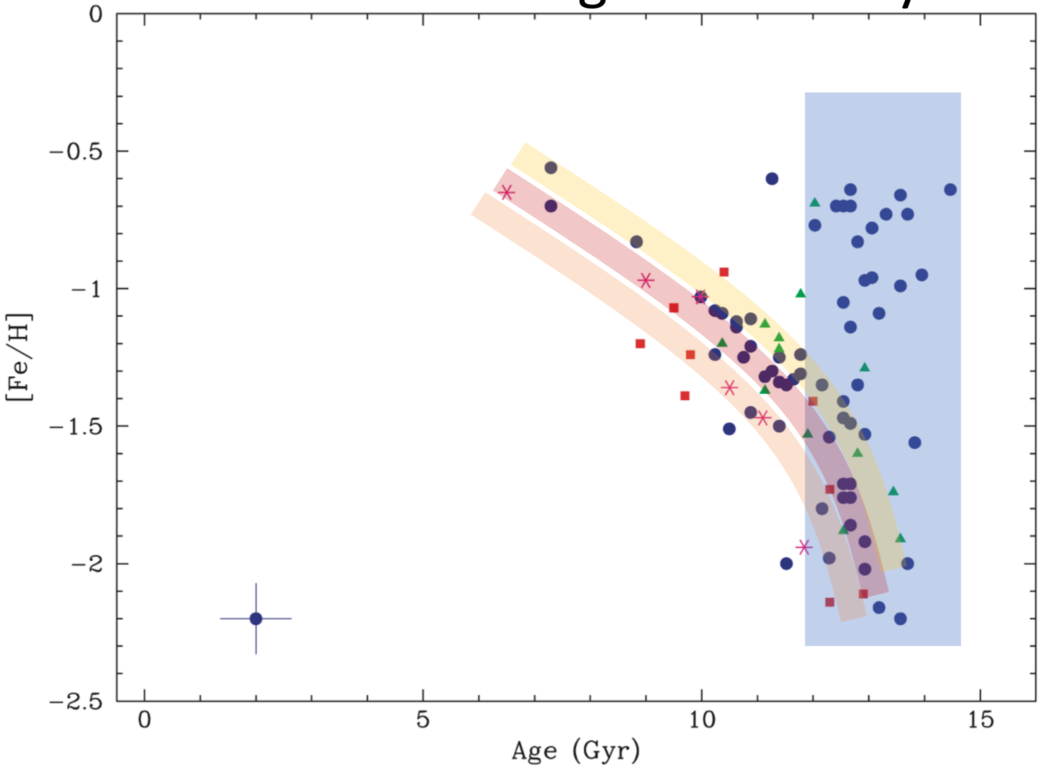
GC demographics

With fraction of second population mass going from 99 to a few %



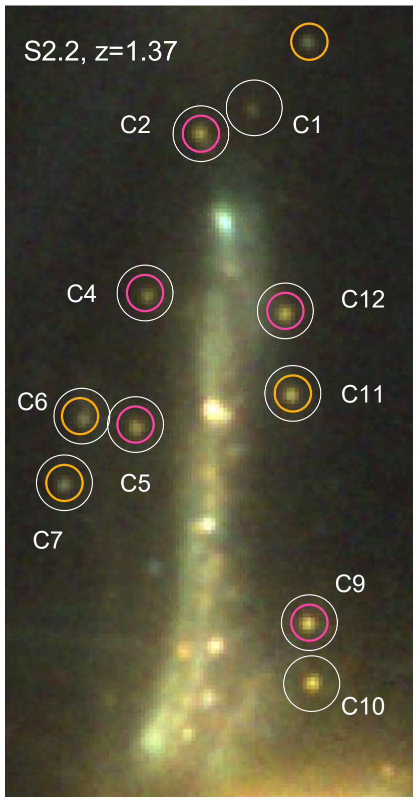
From Bastian & Lardo 2018

Globular cluster age metallicity relation



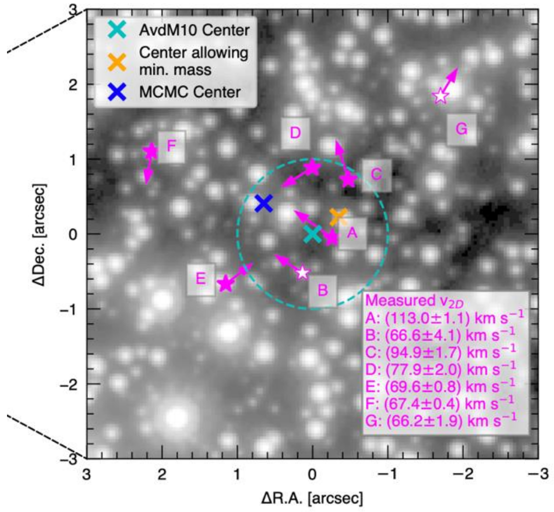
Forbes & Bridges 2010, Brodie & Strader 2006

F090W, F150W, F200W



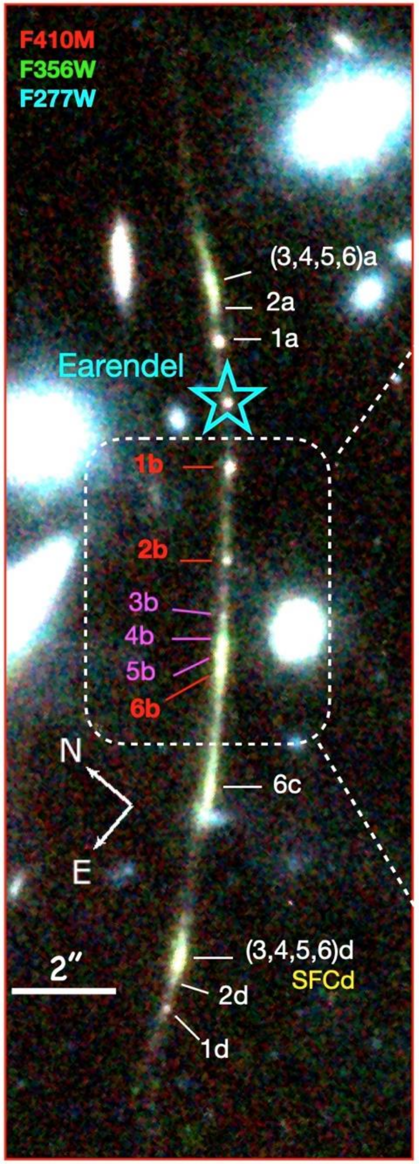
Mowla et al 2022, Adamo et al 2023

Evidence for IMBHs



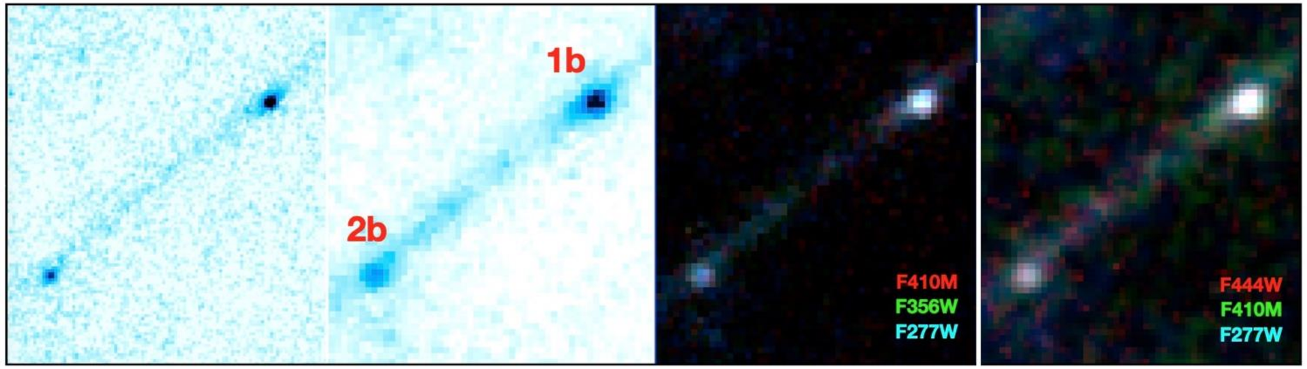
Häberle et al 2024

Resolving galaxies to pc scales in the first Gyr



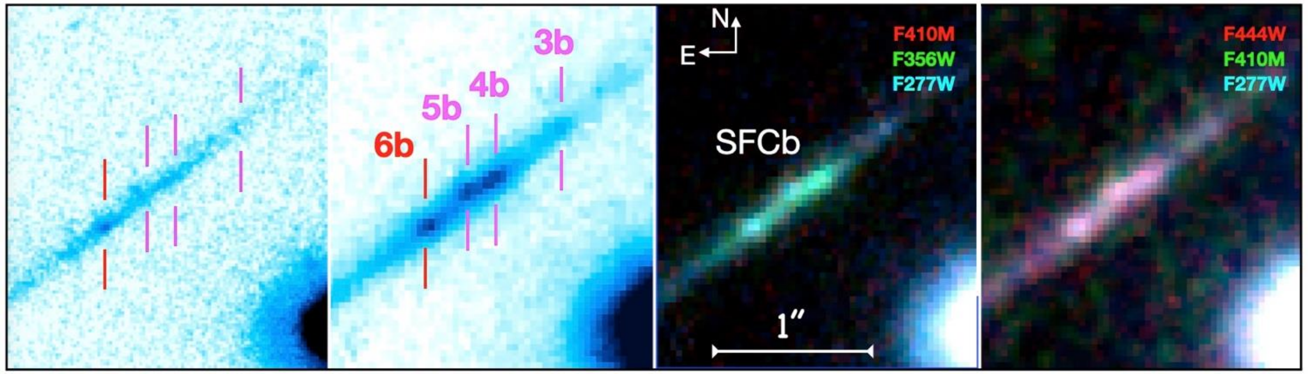
The sunrise arc at z~6

F115W+F150W+F200W F277W+F356W+F444W



UV restframe 4000-7000 Å rest-frame

R_{eff}~1 -5 pc,
age~10-30 Myr,
M ~few 10^6 M_{sun}
Gravitationally bound
$\Sigma_* \sim 10^{4-5}\ M_\odot/pc^2$



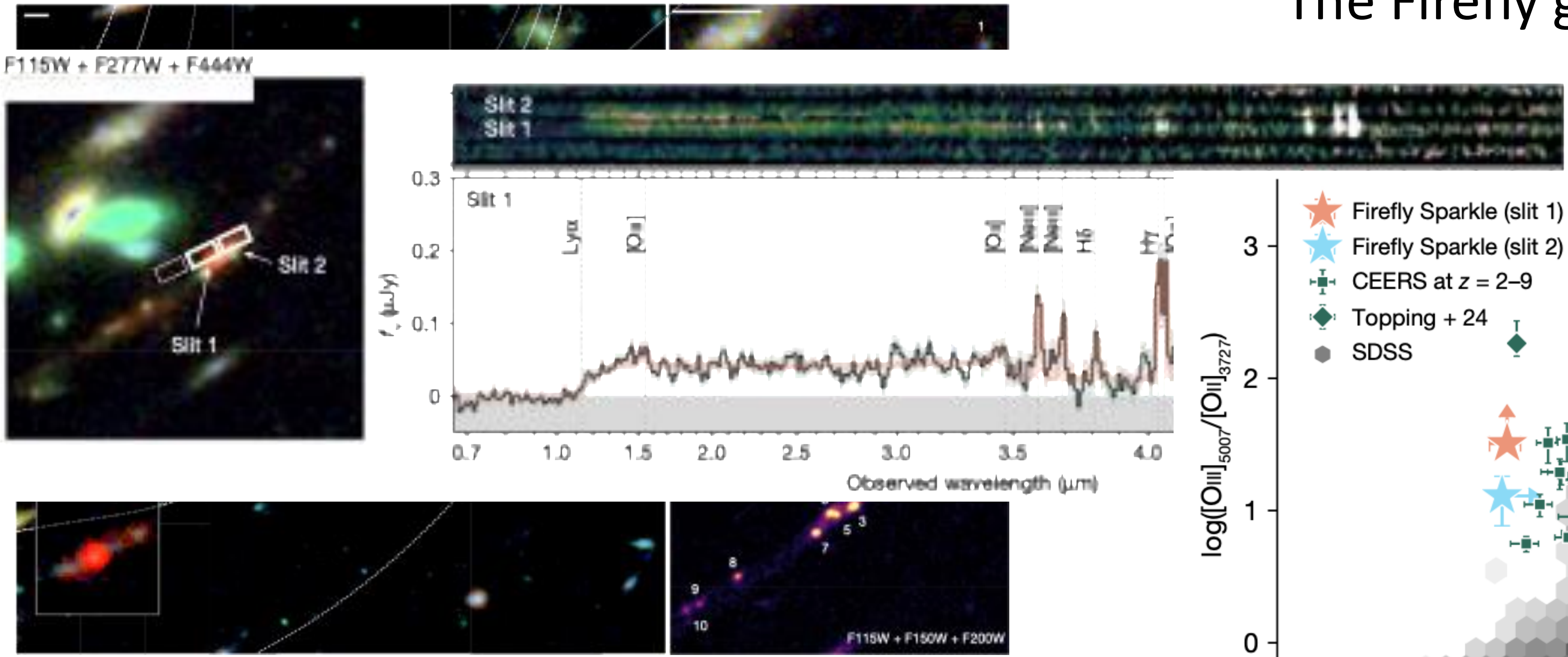
EW(Hb+[OIII])~1300 Å, EW(Ha) ~ 800 Å

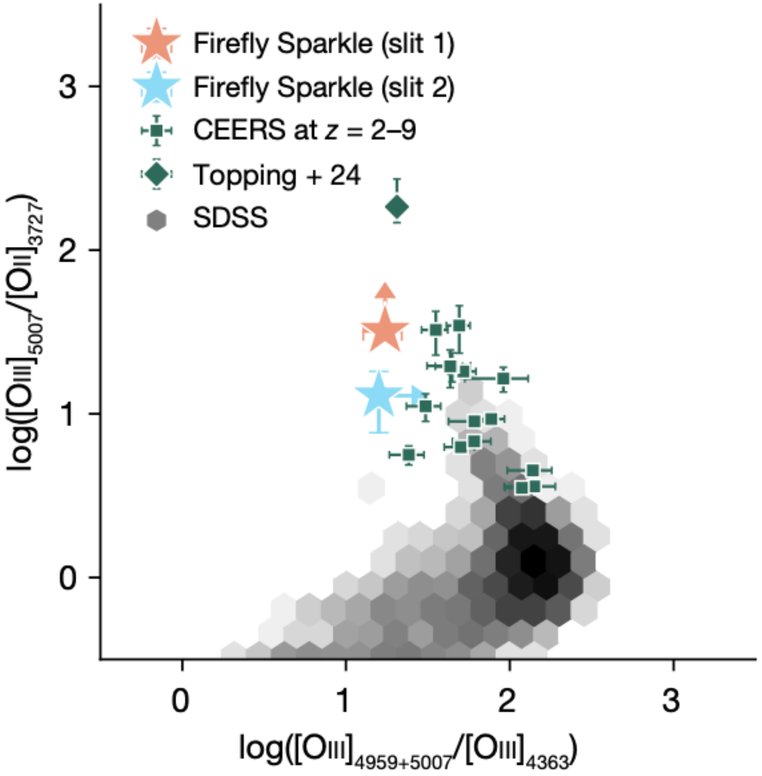
R_{eff}~5-20 pc,
age~3 - 6 Myr,
M ~ $10^{6\text{-}7}$ M_{sun}
$\Sigma_* \sim 10^{3-4}\ M_\odot/pc^2$
E(B-V)~0.2-0.4 mag

Vanzella, et al 2023

Resolving galaxies to pc scales in the first Gyr

The Firefly galaxy z~8.29

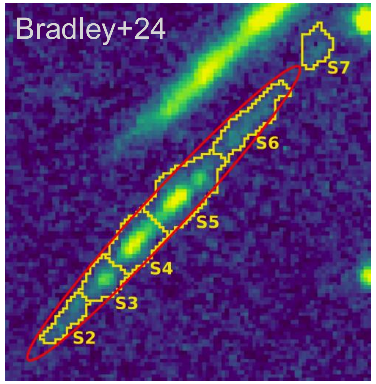


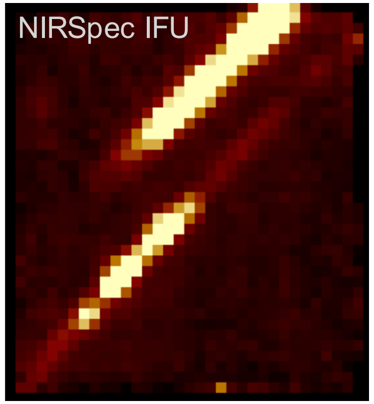


10 YSCs of ~10^5 M_{sun} associated to very hot ionising sources and extreme ionising field radiation

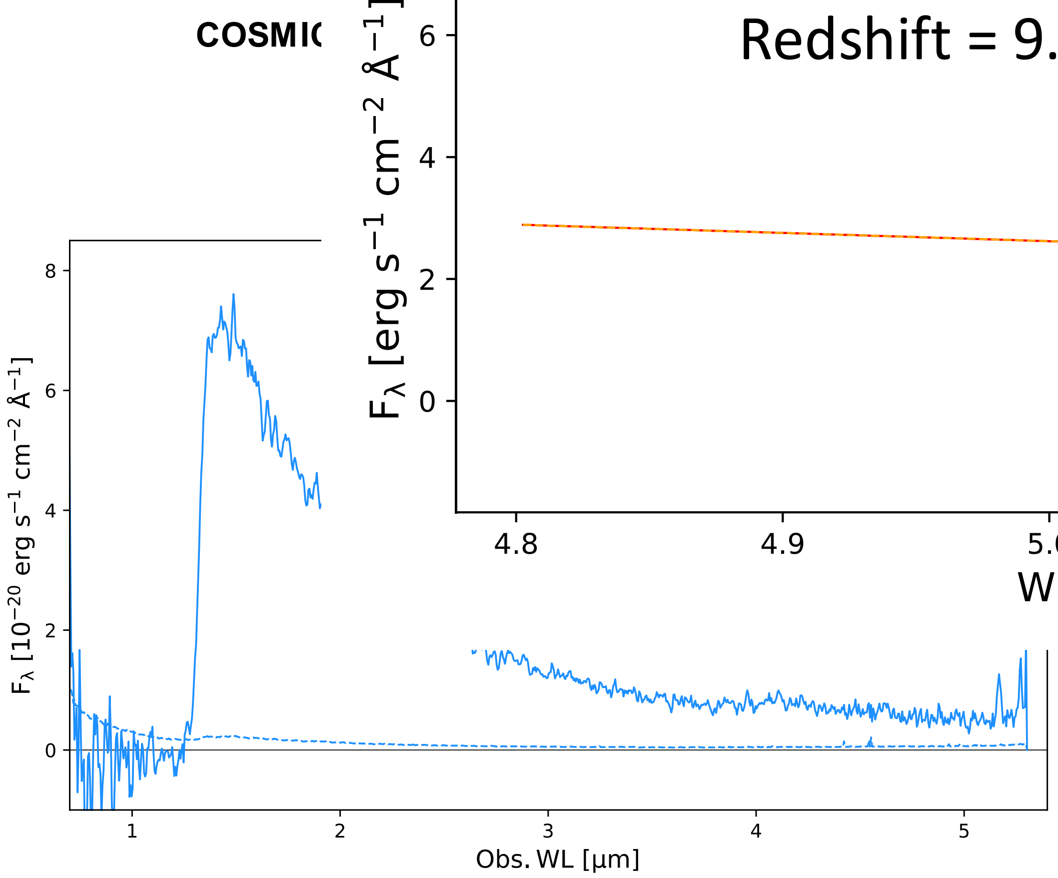
Mowla et al 2024

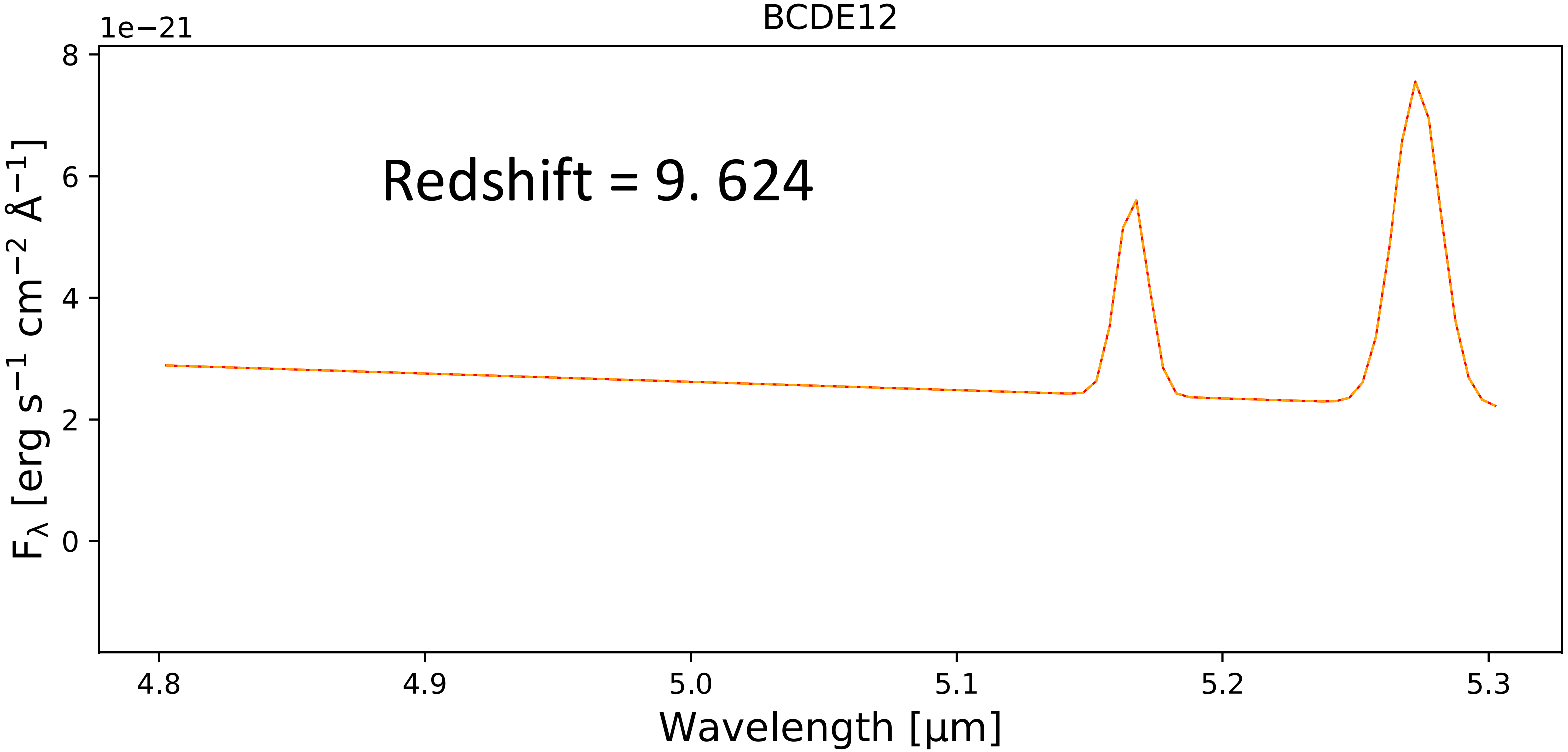
Resolving galaxies to pc scales in the first 500 Myr

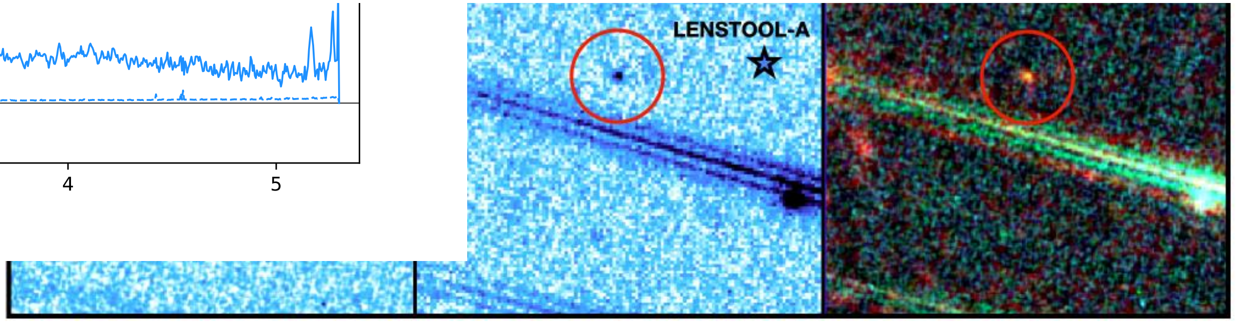




Messa et al in prep.



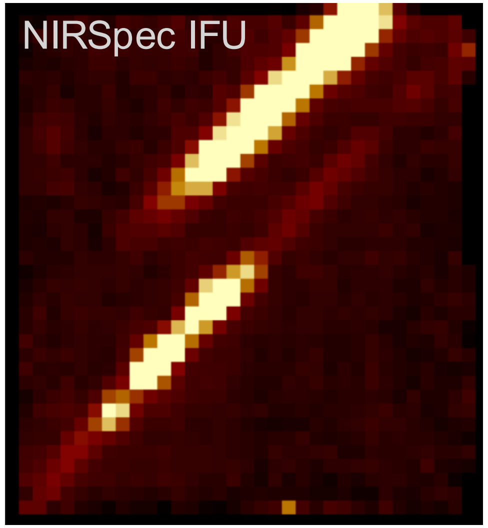




SPT 0615-57 galaxy cluster with JWST observations

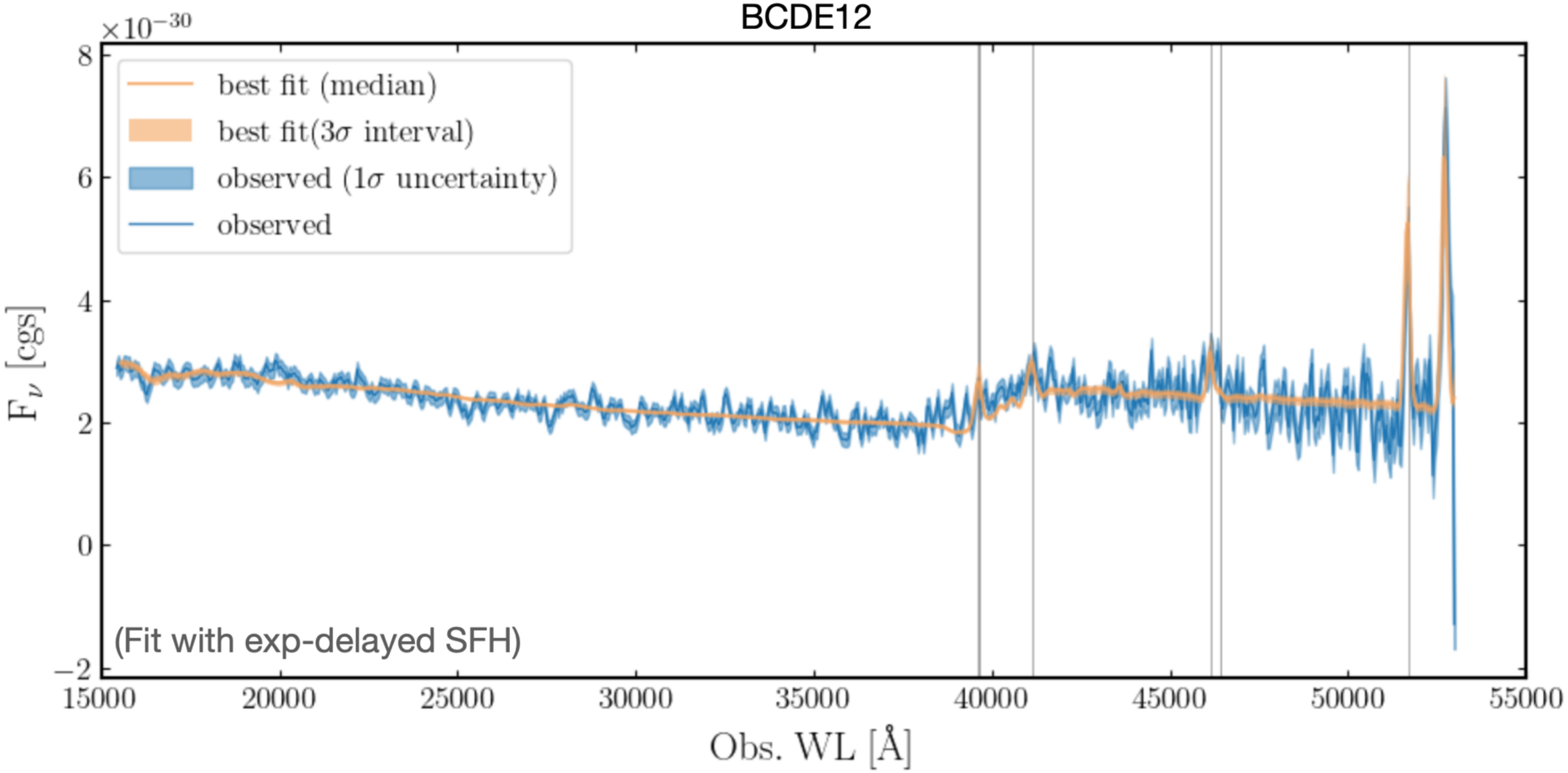
Bradley, AA et al

Resolving galaxies to pc scales in the first 500 Myr



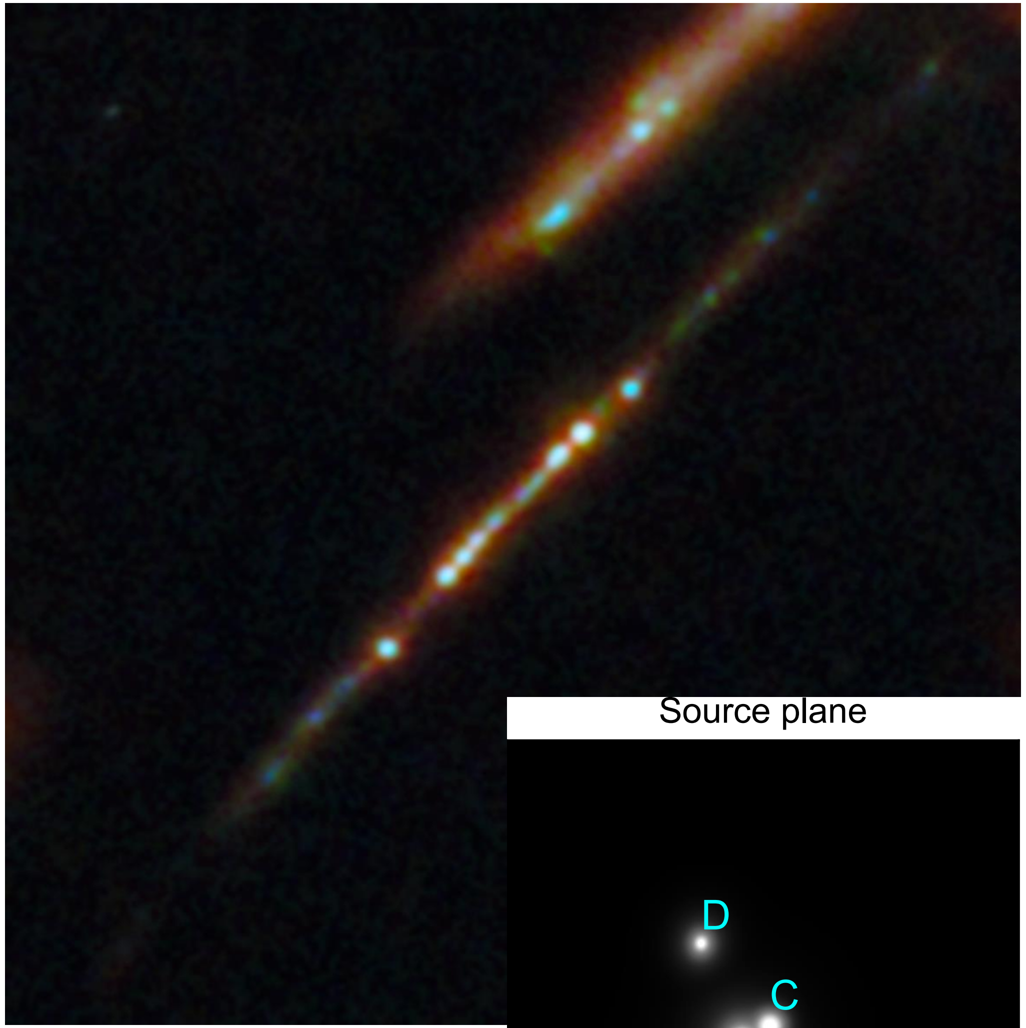
post-burst phase galaxy at Muv~-18 AB

(mass-weighted) age	Short-burst	Metallicity	Av
13^{+3}_{-2} Myr	$\tau = 3 \pm 1$ Myr	$0.15^{+0.01}_{-0.03}\ Z_\odot$	$0.22^{+0.03}_{-0.02}$ mag

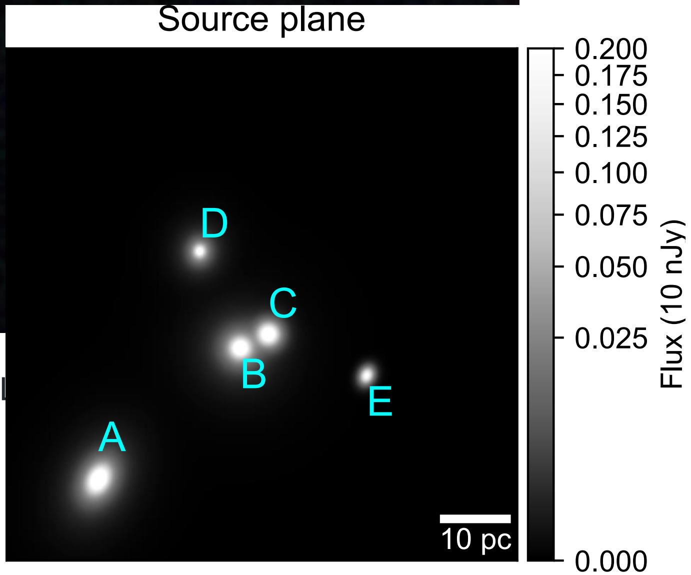


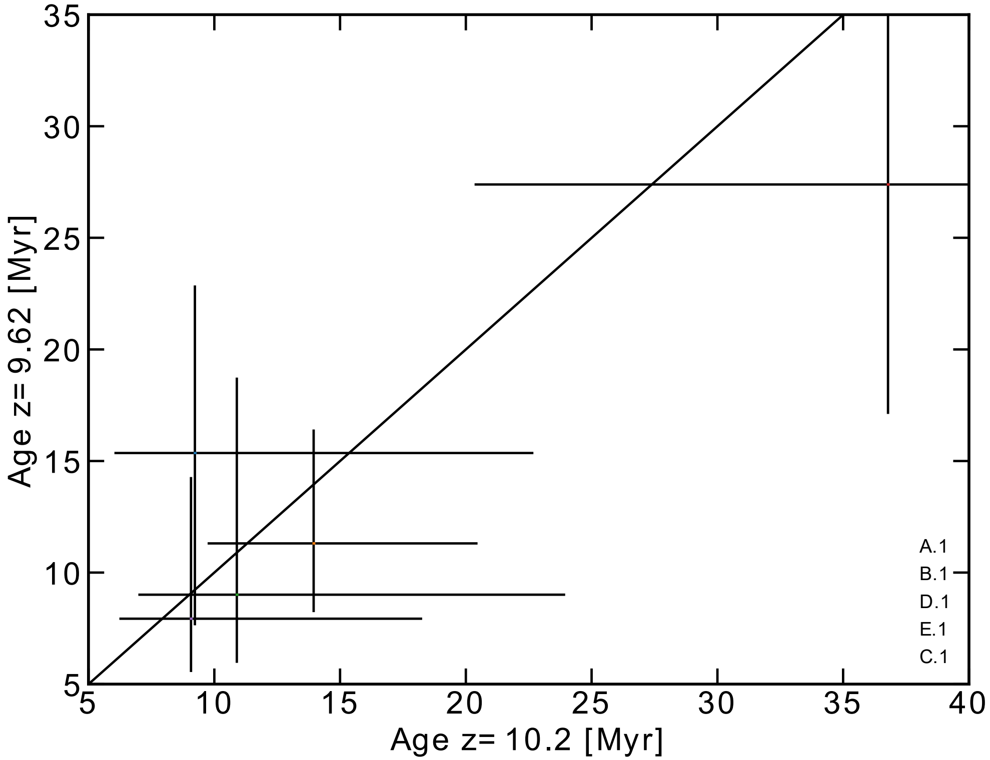
Messa et al in prep.

The Cosmic Gems Arc



Credit: ESA/Webb, NASA & CSA, L



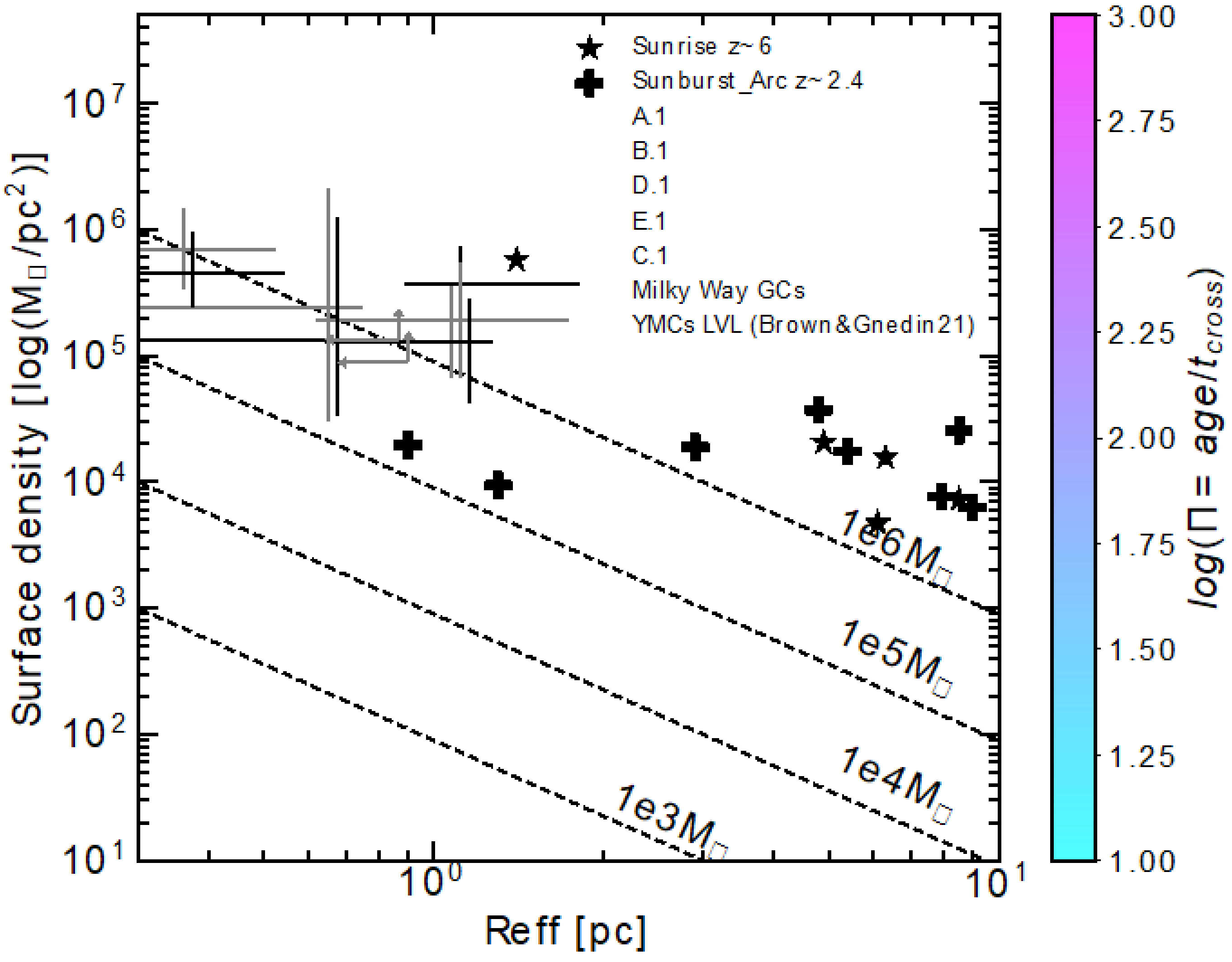


Star cluster properties

- 5 star clusters with ~10^6 M_{sun} and ages < 50 Myr within a region of 50 pc
- Star clusters produce 60% of UV light, 30% of the galaxy mass

Messa et al in prep   Adamo et al. 2024

Star clusters in early reionisation era



1. Very small sizes
2. High densities

Main effects that can make them expand:

1. Stellar evolution → under assumption of adiabatic expansion:

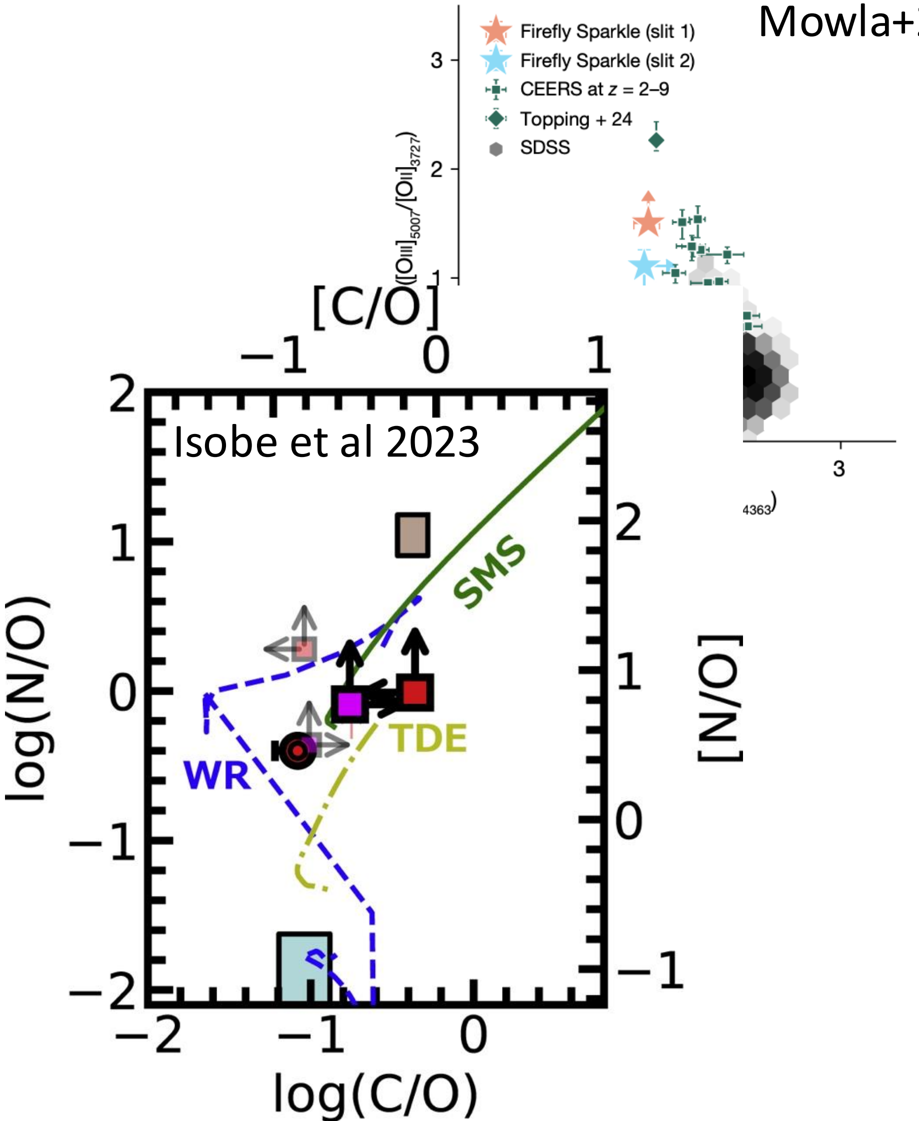
$$R_{eff,t} = M_{in}/M_t * R_{eff,in}$$

2. Relaxation
3. BH?

Messa et al in prep Adamo et al. 2024

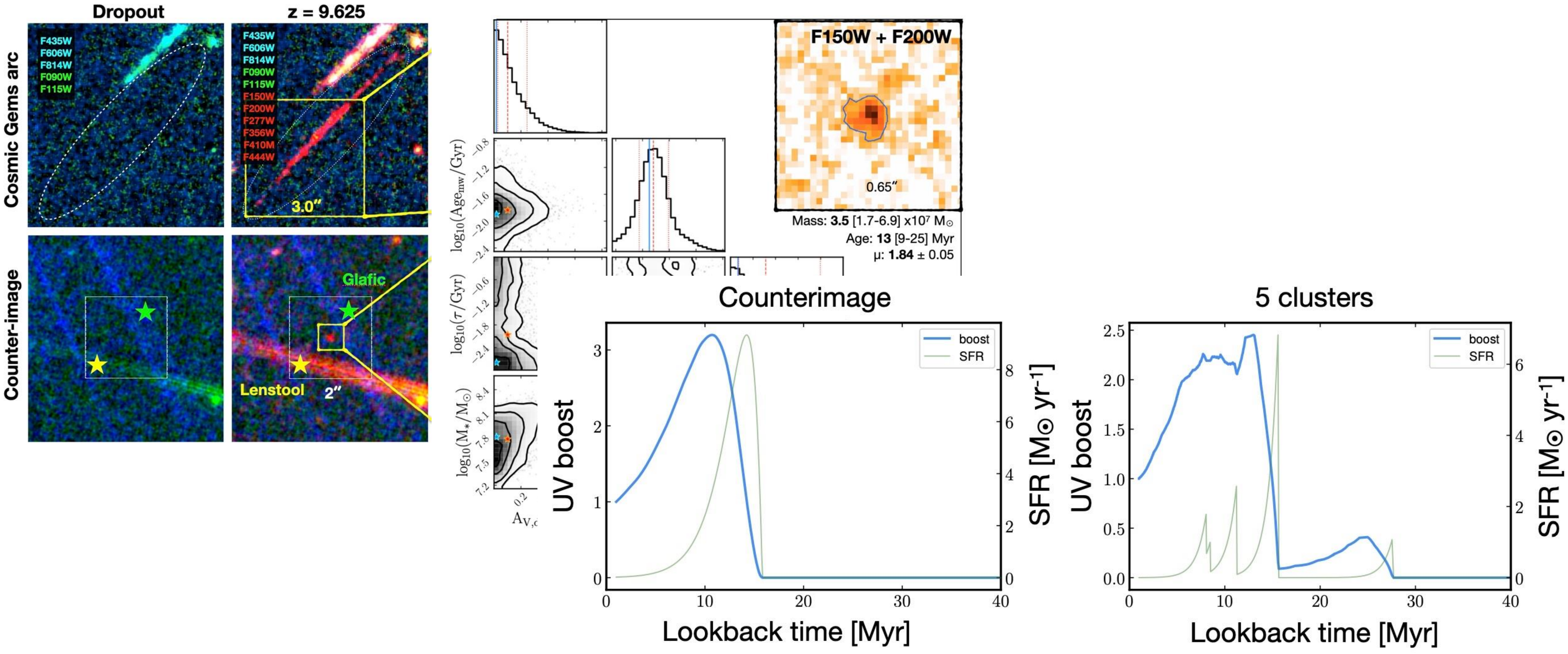
Laboratories for stellar physics & feedback

Mowla+2024



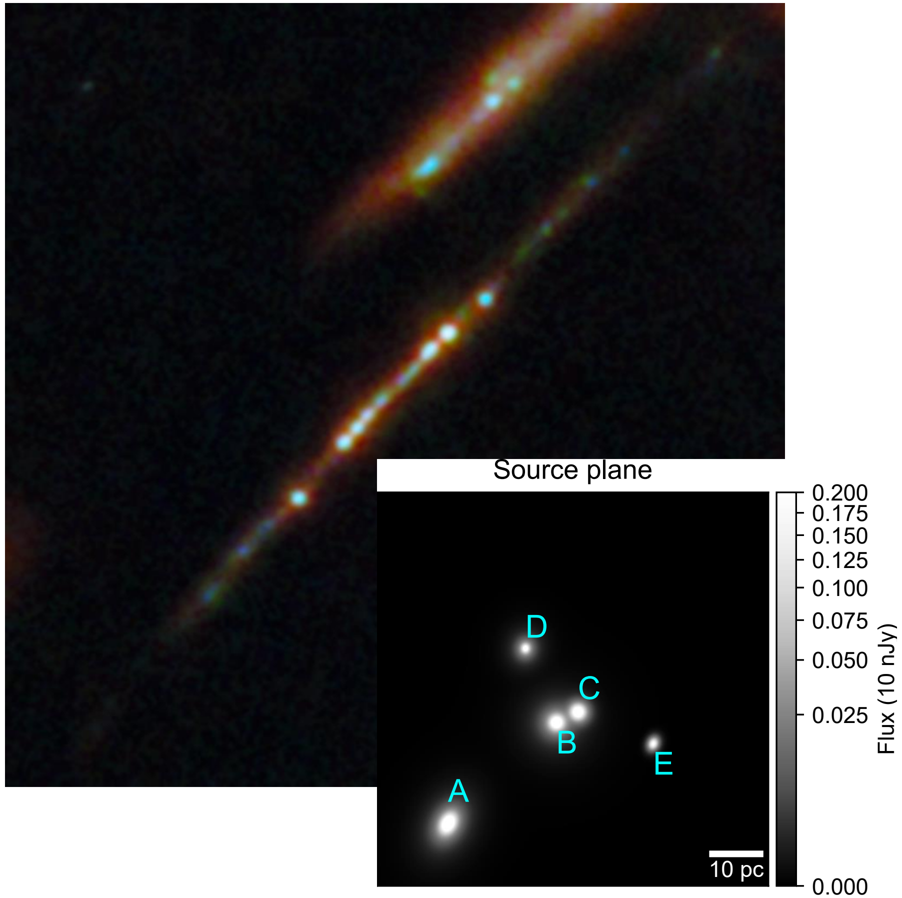
- Naturally harbour very massive stars (VMS, M>> 100 M_{sun}) and WRs
- The stellar densities ($\Sigma_* > 10^5\ M_{sun}/pc^2$ $\rho_h \sim 10^5\ M_{sun}/pc^3$) in their core become furnaces to produce:
  1. *Massive star mergers* (Portegies-Zwart +1999, Gieles+2018) → *SMSs* (Charbonelle+2023, Ruiz-Marques+2023, Schaerer+2024)
  2. *Stellar BH mergers* → *formation of intermediate mass BHs* (Portegies-Zwart+2004, Antonini+2019, Rantala+2024, Arca-Sedda+2024)

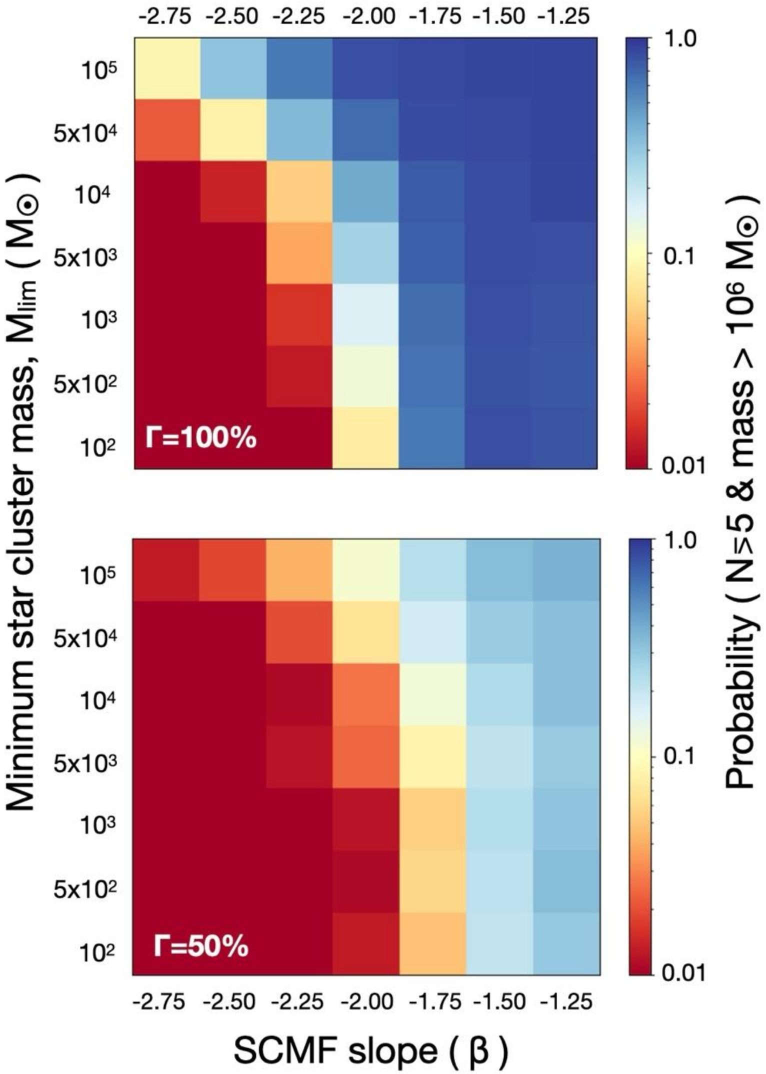
Cosmic Gems *was* a UV ~-20 ABmag

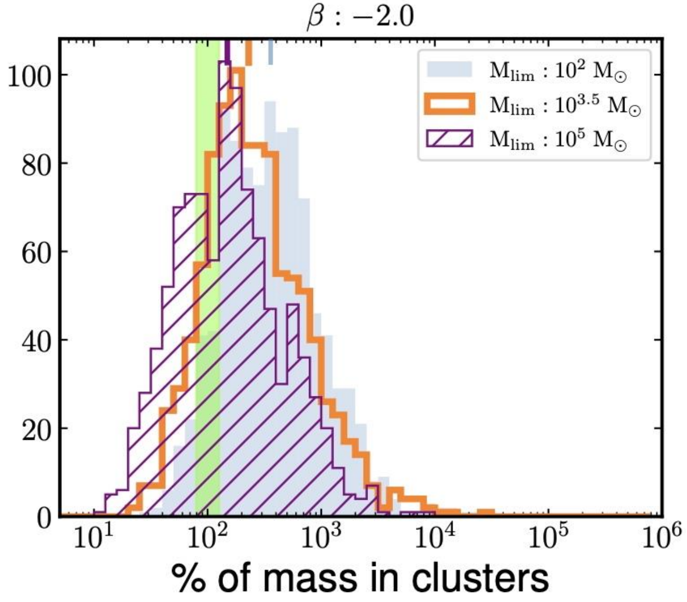


Vanzella et al TBS

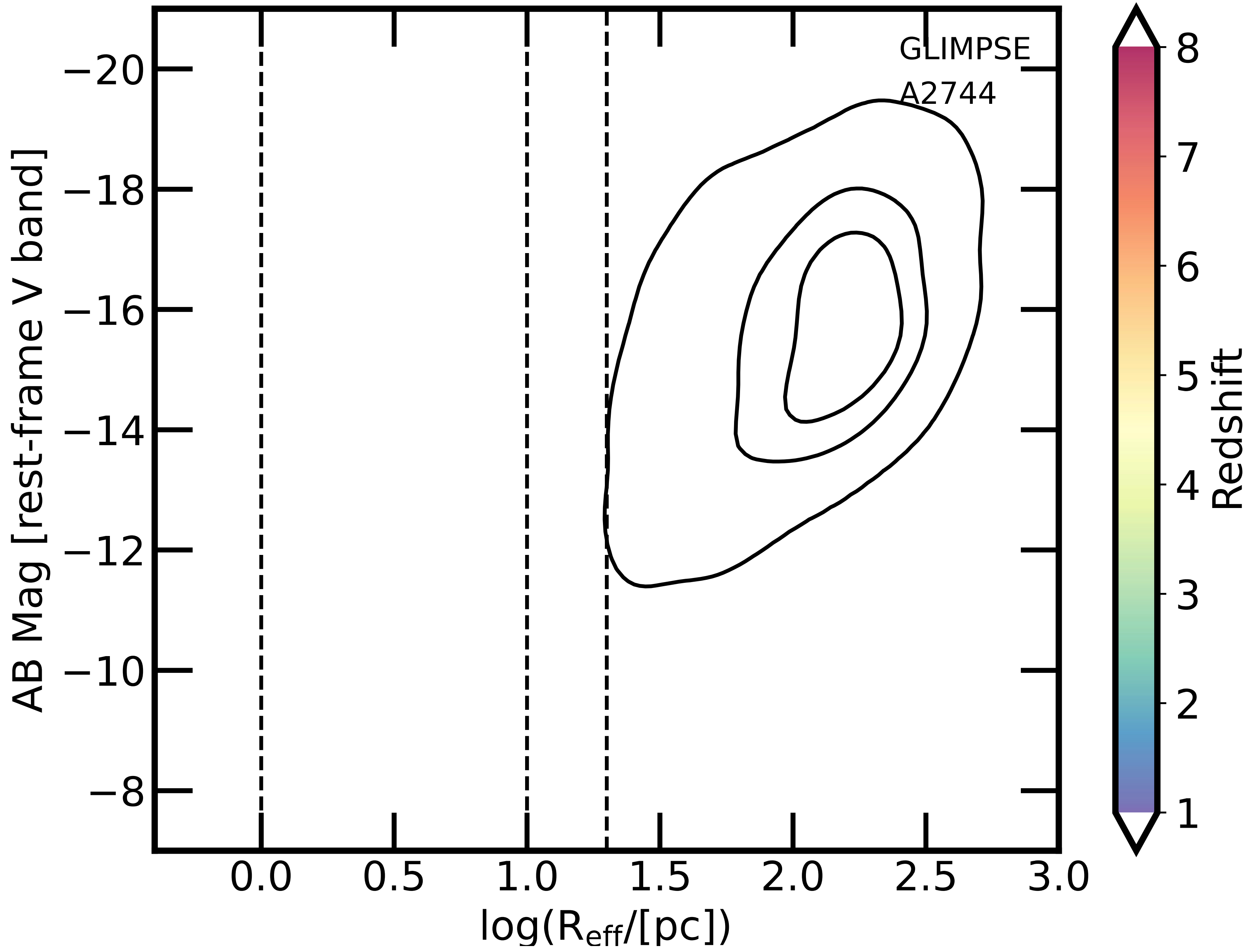
Star cluster mass function?







Vanzella et al TBS



160 star clusters, $\mu > 5$, R_{eff}<20 pc

GLIMPSE

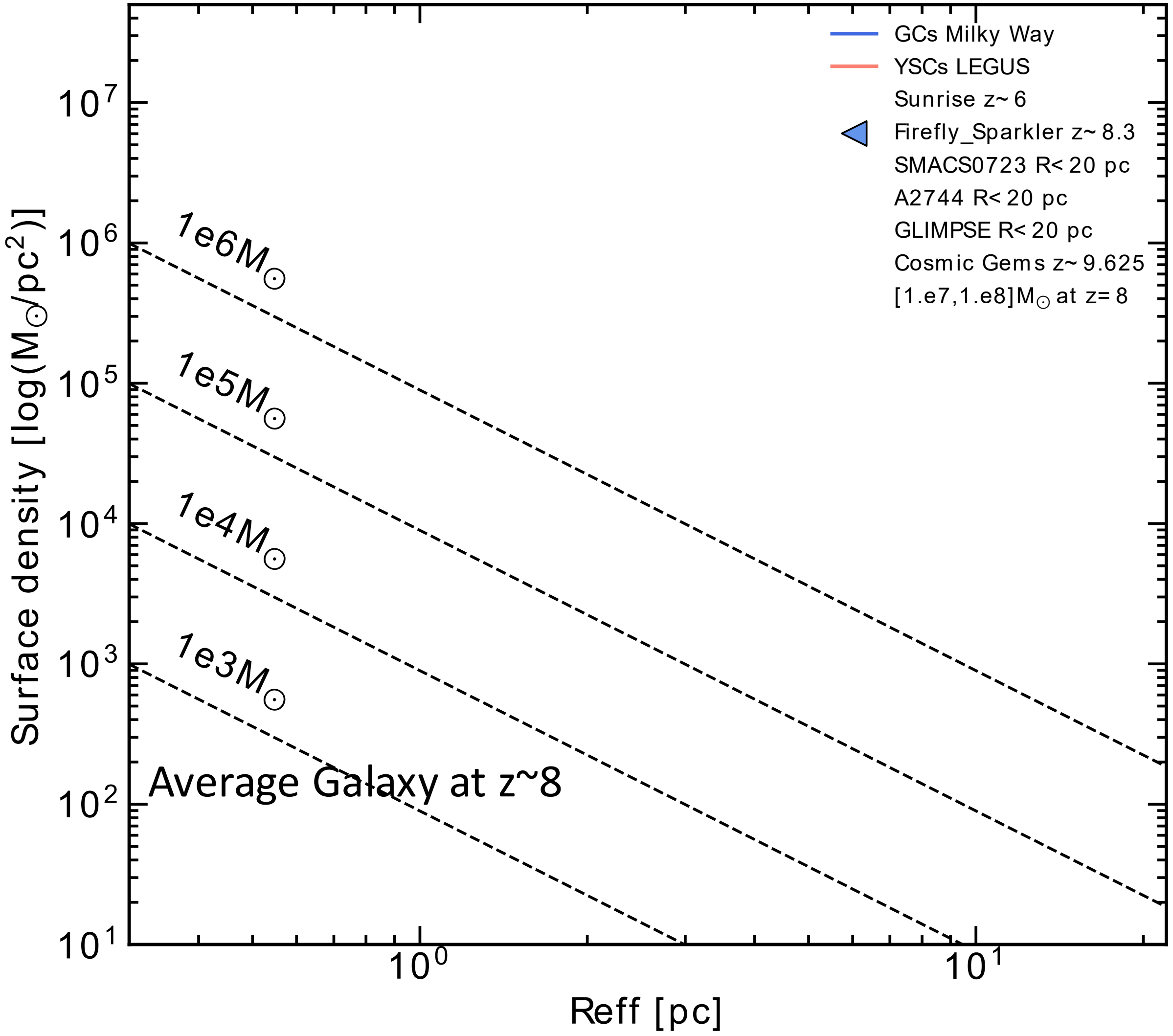
Cycle 2 JWST large program;

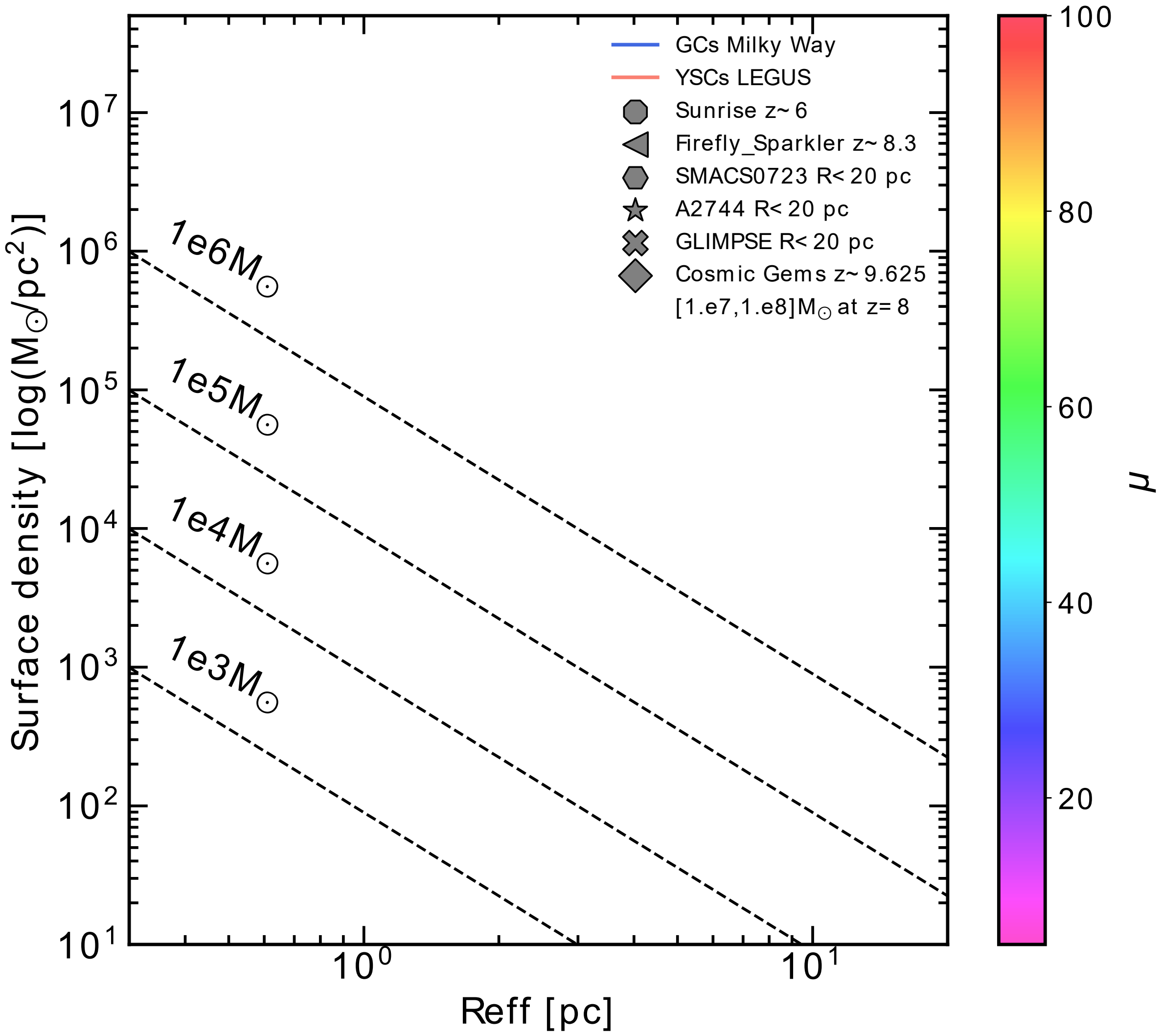
PI: Atek & Chisholm

155 h in AS1063
in 7 broadband + 2 medium band

Detection limits
~30.5 ABmag

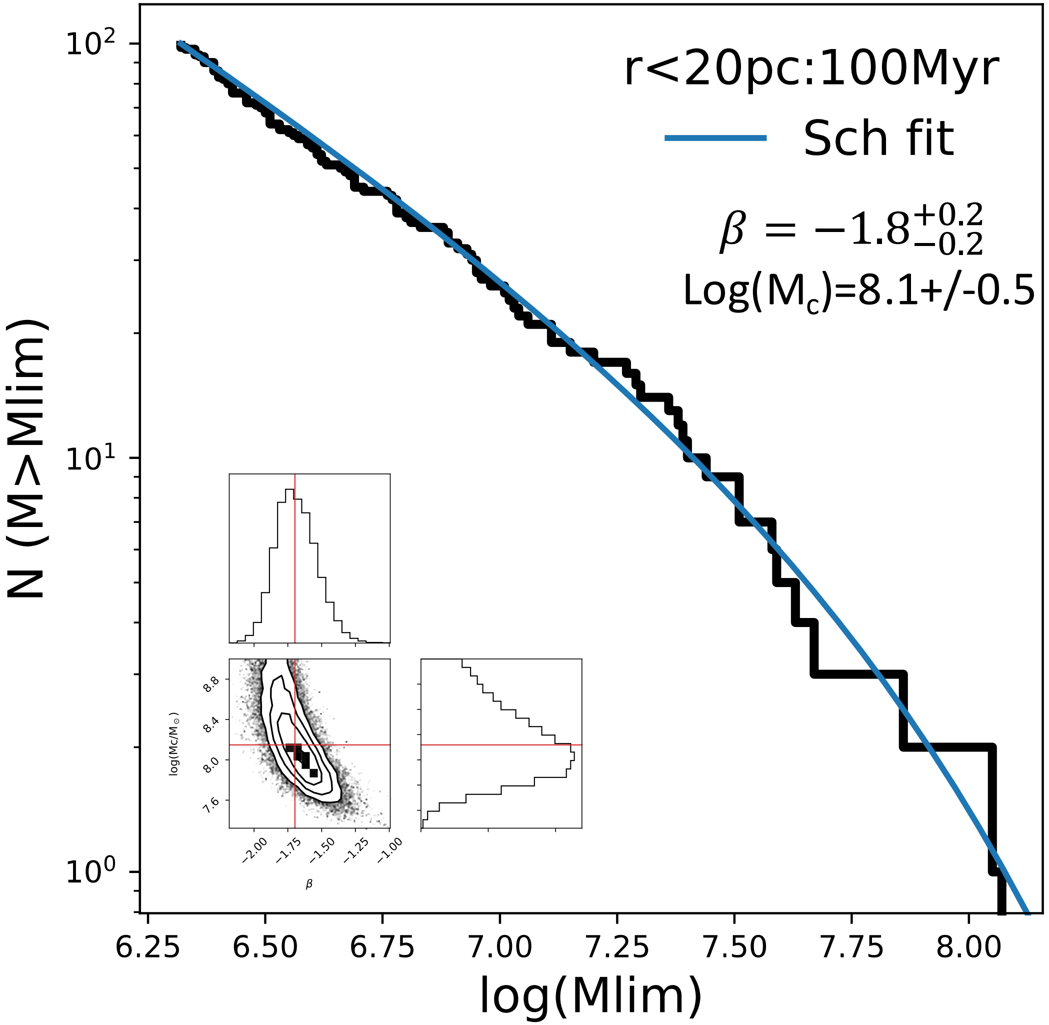
GLIMPSE & Literature

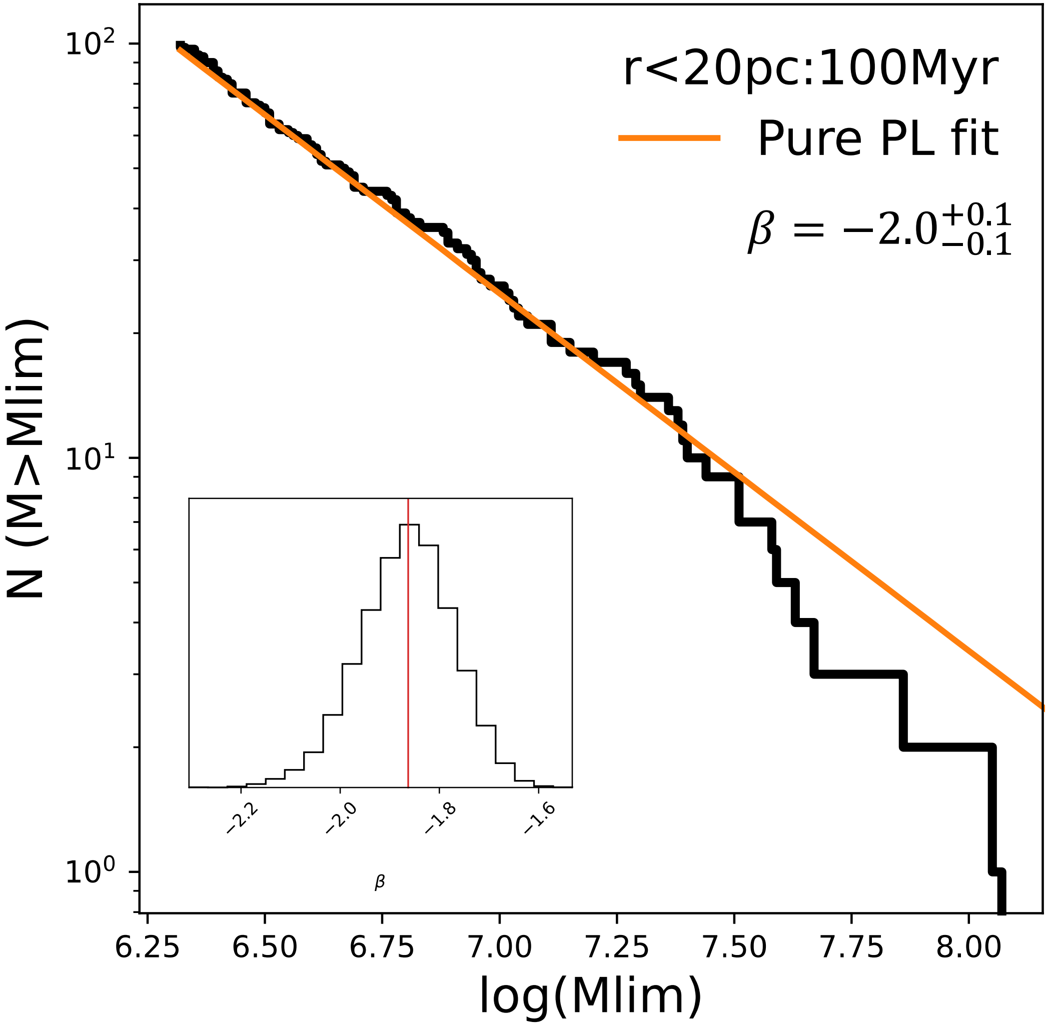




Claeyssens & Adamo 2025, in prep.

GLIMPSE & Literature

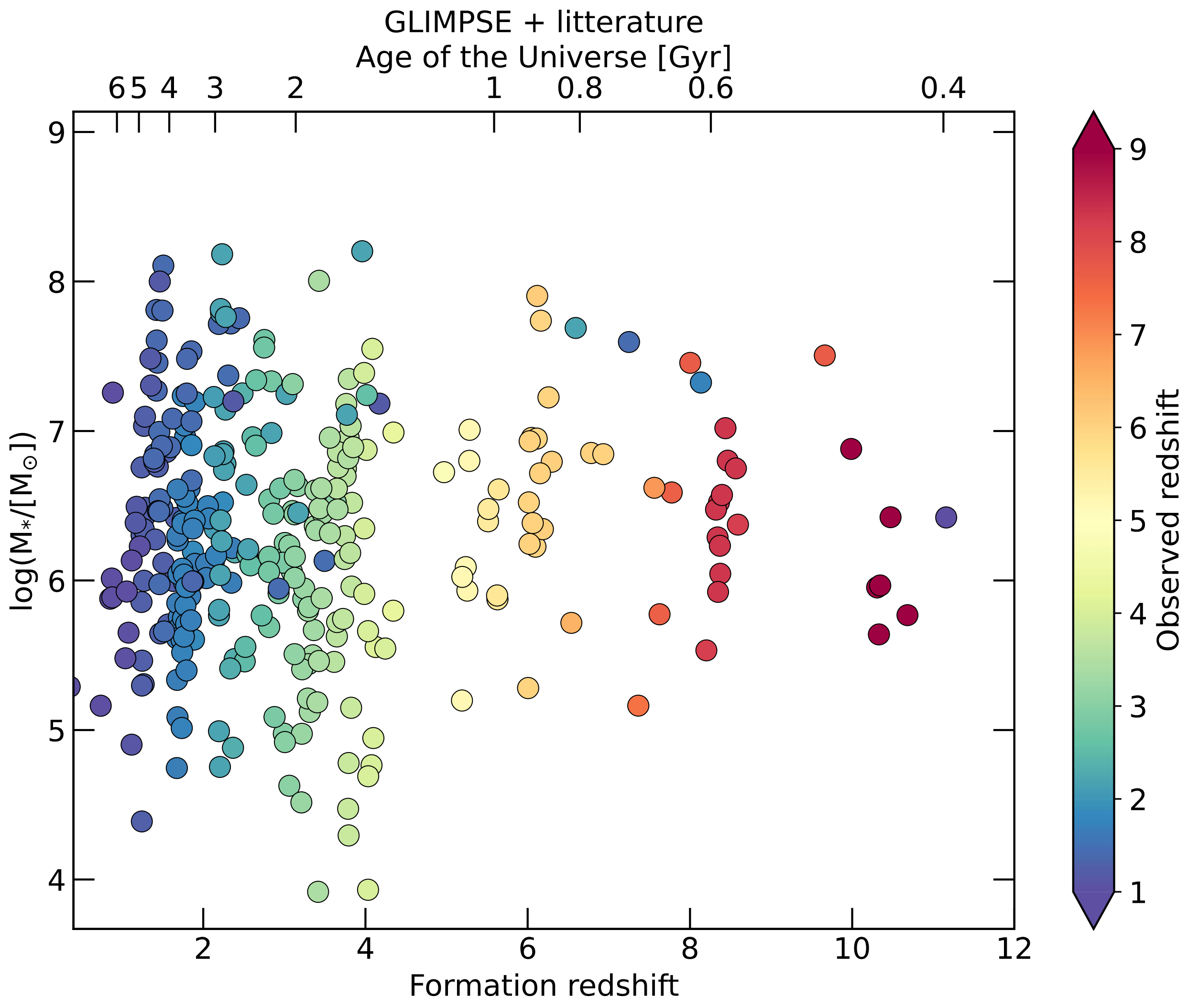




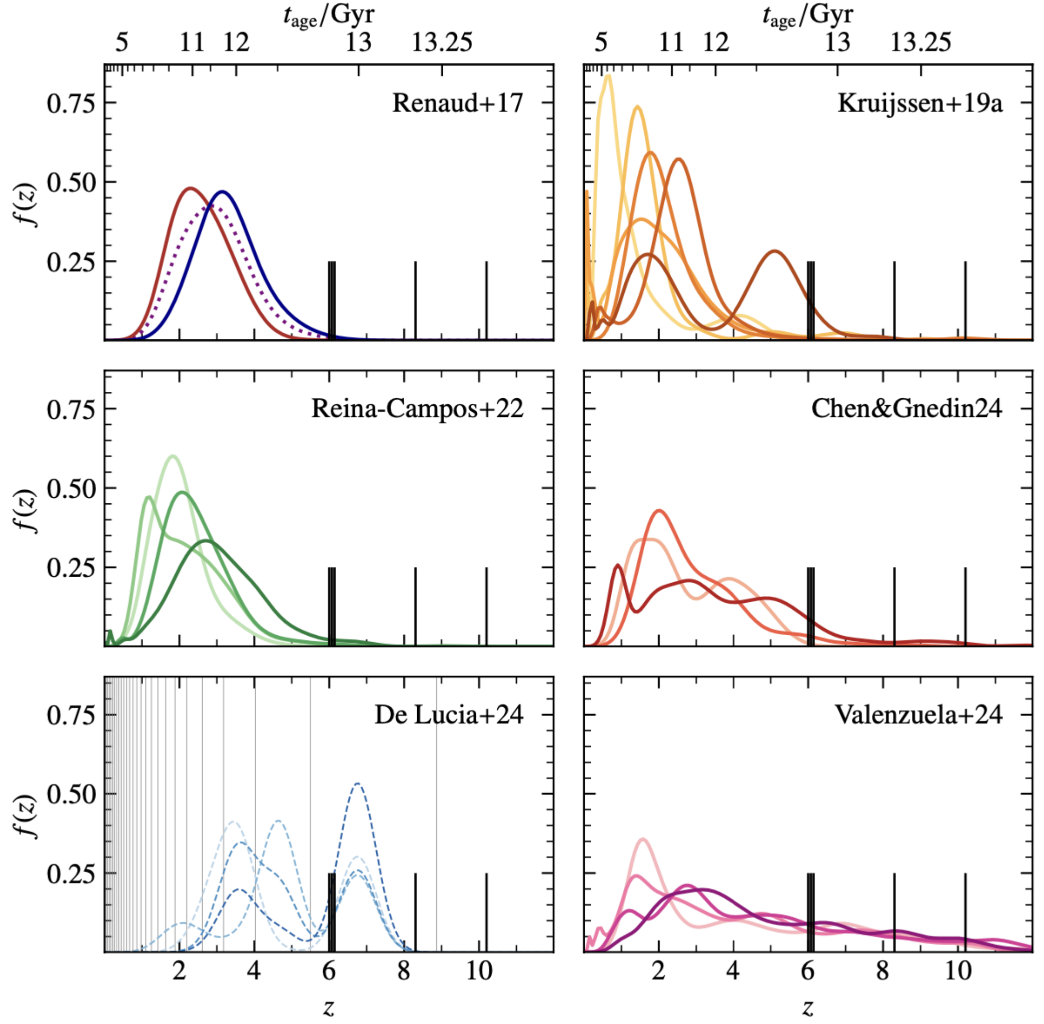
Age< 100 Myr, M>2e6Msun resulting in 68 star clusters

Claeyssens & Adamo 2025, in prep.

Will these clusters survive to be GCs?



Claeyssens & Adamo 2025, in prep.



Valenzuela et al 2025

Summary

- As we move to increasingly higher redshift, we see galaxy stellarclumps becoming progressively younger, denser, elevated Σ_{SFR}, and EWs

- We do not find clear signal of migration → mass of galaxy matter

- Cluster and clump mass function close to power law -2, but…

- Stellar densities in proto-GCs are significantly higher than seen in YSCs and GCs on average, thus we need to be careful when we set initial conditions:
    - Implications for massive star formation, BHs, and chemical enrichment patterns
    - Implications for stellar feedback in reionisation era galaxies

Thank you for your time!