High-z Galaxy Formation & Feedback: Observations ⇔ Theory

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Department of Physics


JADES
JWST ADVANCED DEEP
EXTRAGALACTIC
SURVEY
1 µm
2 µm
4 µm


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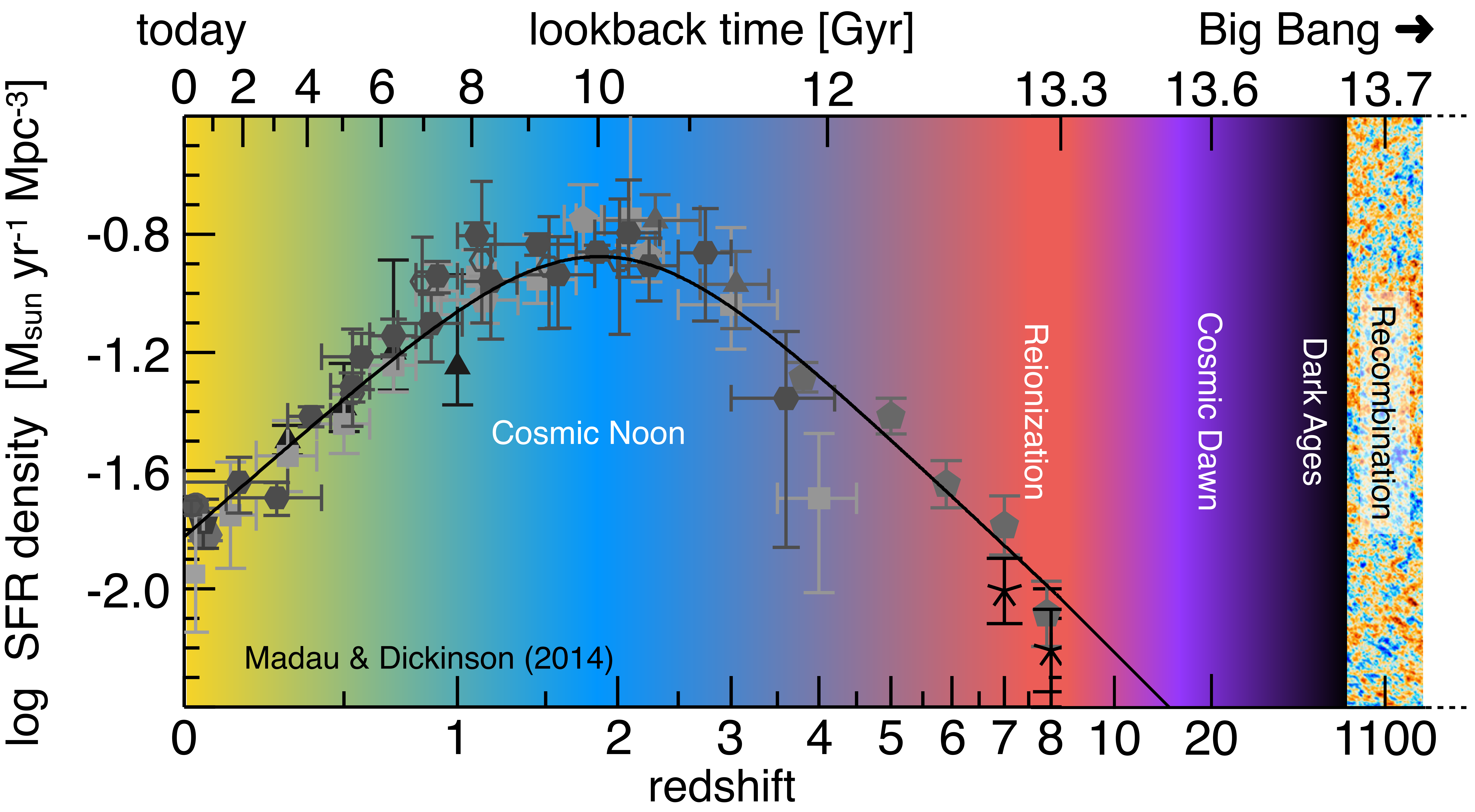
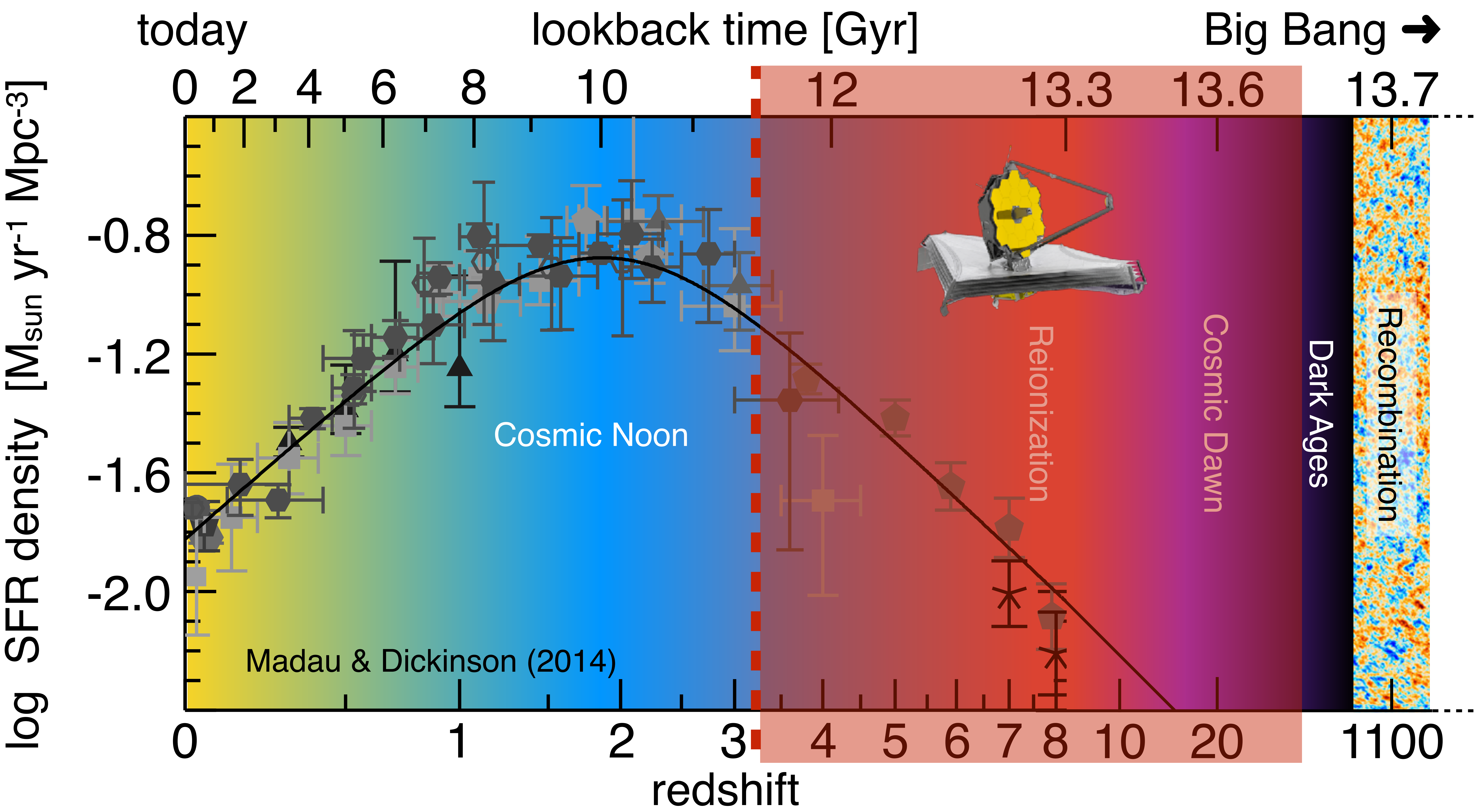
JADES • JWST ADVANCED DEEP EXTRAGALACTIC SURVEY
JADES NIRCam
3"
F090W F200W F444W
JADES (Eisenstein+ 2023)

JADES · JWST ADVANCED DEEP EXTRAGALACTIC SURVEY
JADES NIRCam
GS9422
$z_{spec} = 5.943$
Lyα
CIV
HeI
C I]
[O II]
He I
Hε
Hδ
[FeV]
Hγ
Hβ
[OIII]
Hα+[N II]
HeI
F090W
F115W
F150W
F182M
F210M
F200W
F277W
F335M
F356W
F410M
F430M
F444W
F460M
F480M
f_ν [nJy]
observed wavelength [micron]
9422
z = 5.943
N
E
1.0 kpc
B - F090W
G - F200W
R - F444W
3"
JADES (Eisenstein+ 2023)
F090W F200W F444W



today
lookback time [Gyr]
Big Bang ➜
0
2
4
6
8
10
12
13.3
13.6
13.7
log SFR density [M_{sun} yr^{-1} Mpc^{-3}]
-0.8
-1.2
-1.6
-2.0
Cosmic Noon
Reionization
Cosmic Dawn
Dark Ages
Recombination
Madau & Dickinson (2014)
0
1
2
3
4
5
6
7
8
10
20
1100
redshift



JWST revolutionised observations of early galaxies, thanks to is wavelength coverage and spectral resolution!


9 kpc
z = 9.9
Halo assembly time
at z~10: 50-100 Myr
➜ rapid growth!
log M★ = 7.71
SFR = 0.2 M☉ yr⁻¹
30 kpc
stars
gas
1 kpc
TNG50 Simulation
z = 10 ➜ 2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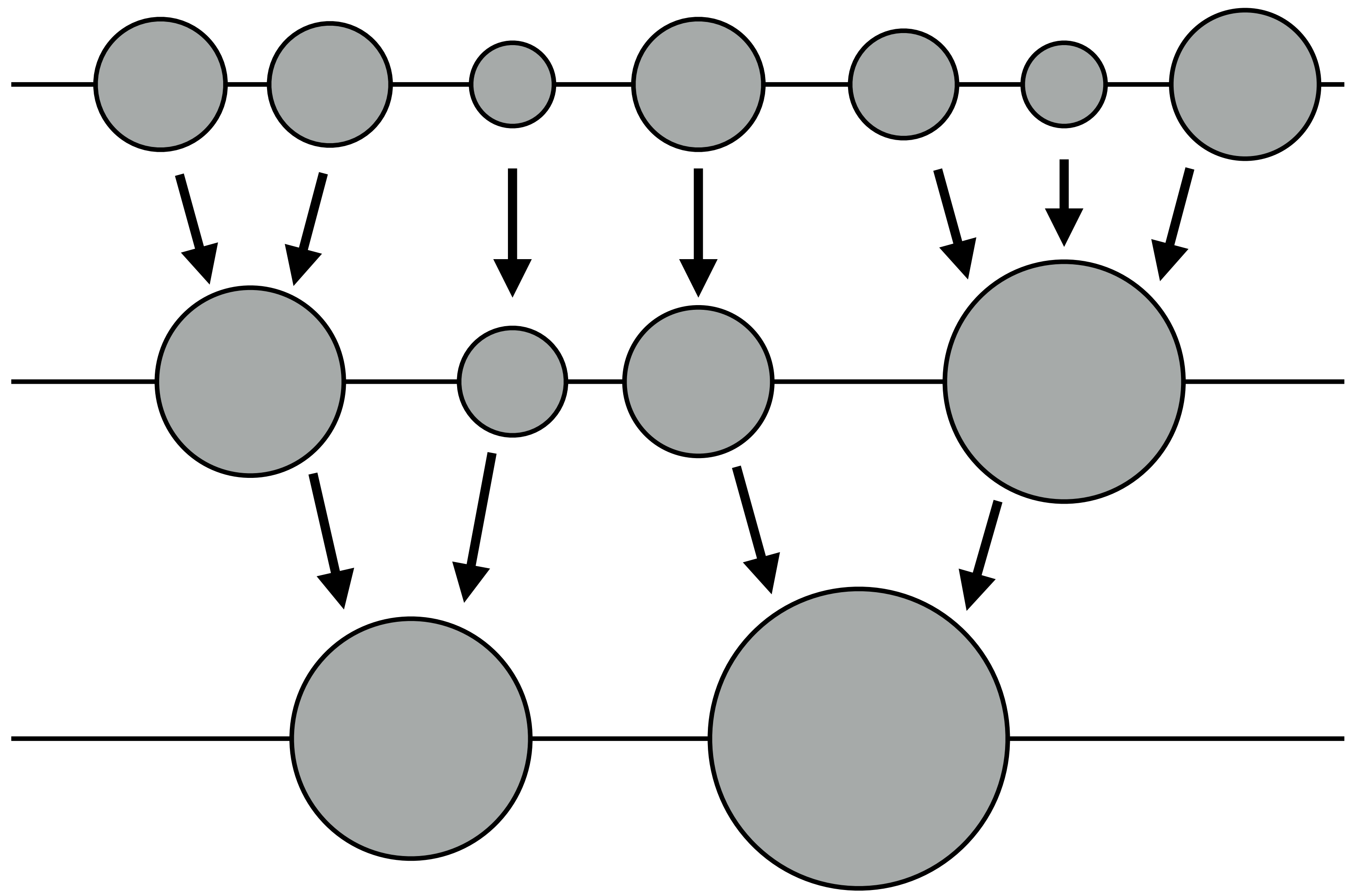
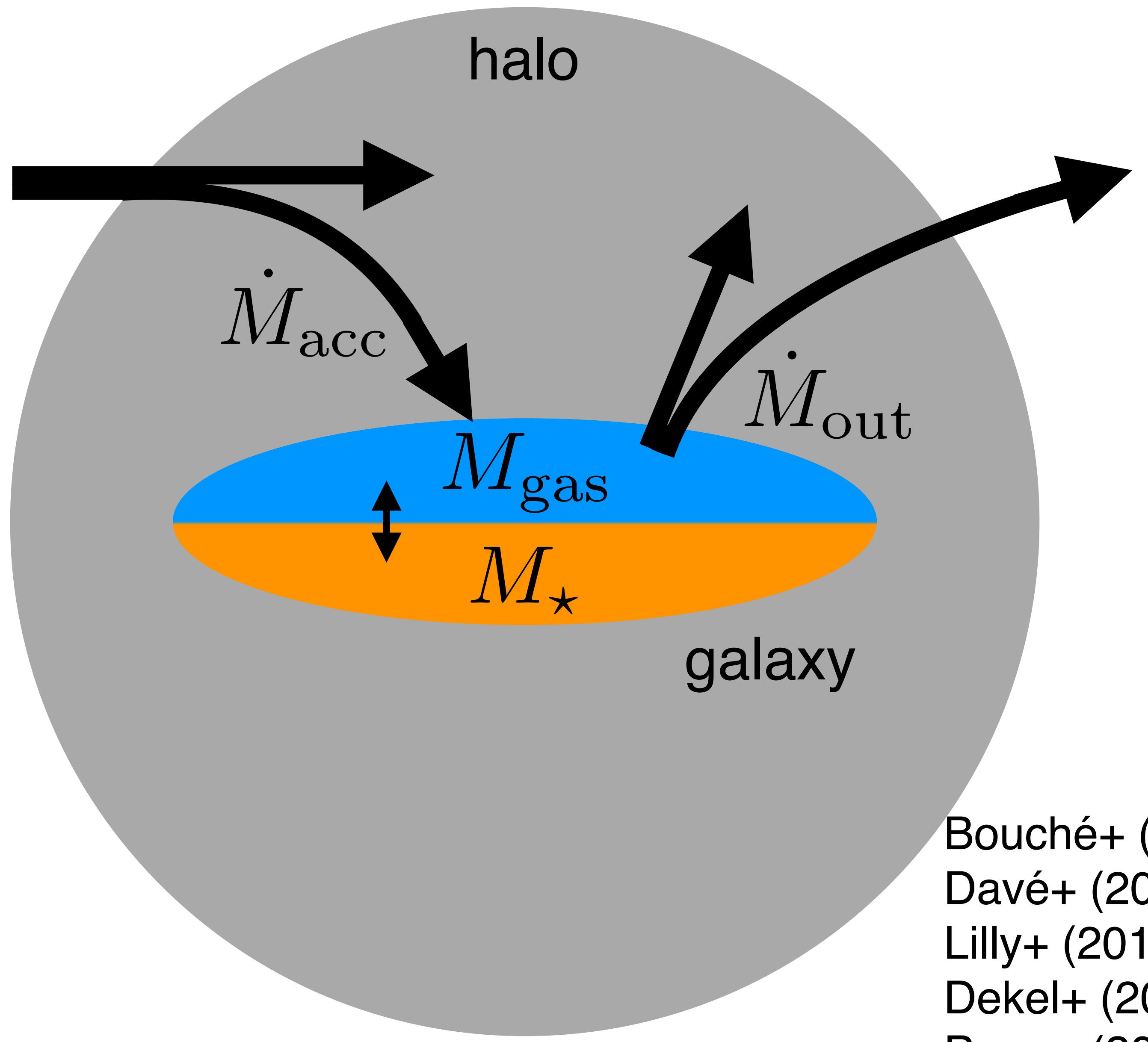
based on Tacchella+ (2013; 2018)
see also Mason+ (2015), Mashian+ (2016)

Simple model for star formation in haloes

$$\mathrm{SFR}(M_h, z) = \varepsilon(M_h) \cdot f_b \cdot \dot{M}_h$$

Star-formation efficiency (SFE):
- conversion of gas accretion rate to SFR
- gas mass to SFR ($1/t_{dep}$; e.g. KS law: $\mathrm{SFR} = \varepsilon \cdot M_{gas}$)
- integrated SFE = $M_\star/(f_b\, M_h)$





Bouché+ (2010)
Davé+ (2012)
Lilly+ (2013)
Dekel+ (2014)
Peng+ (2014)
Tacchella+ (2020)

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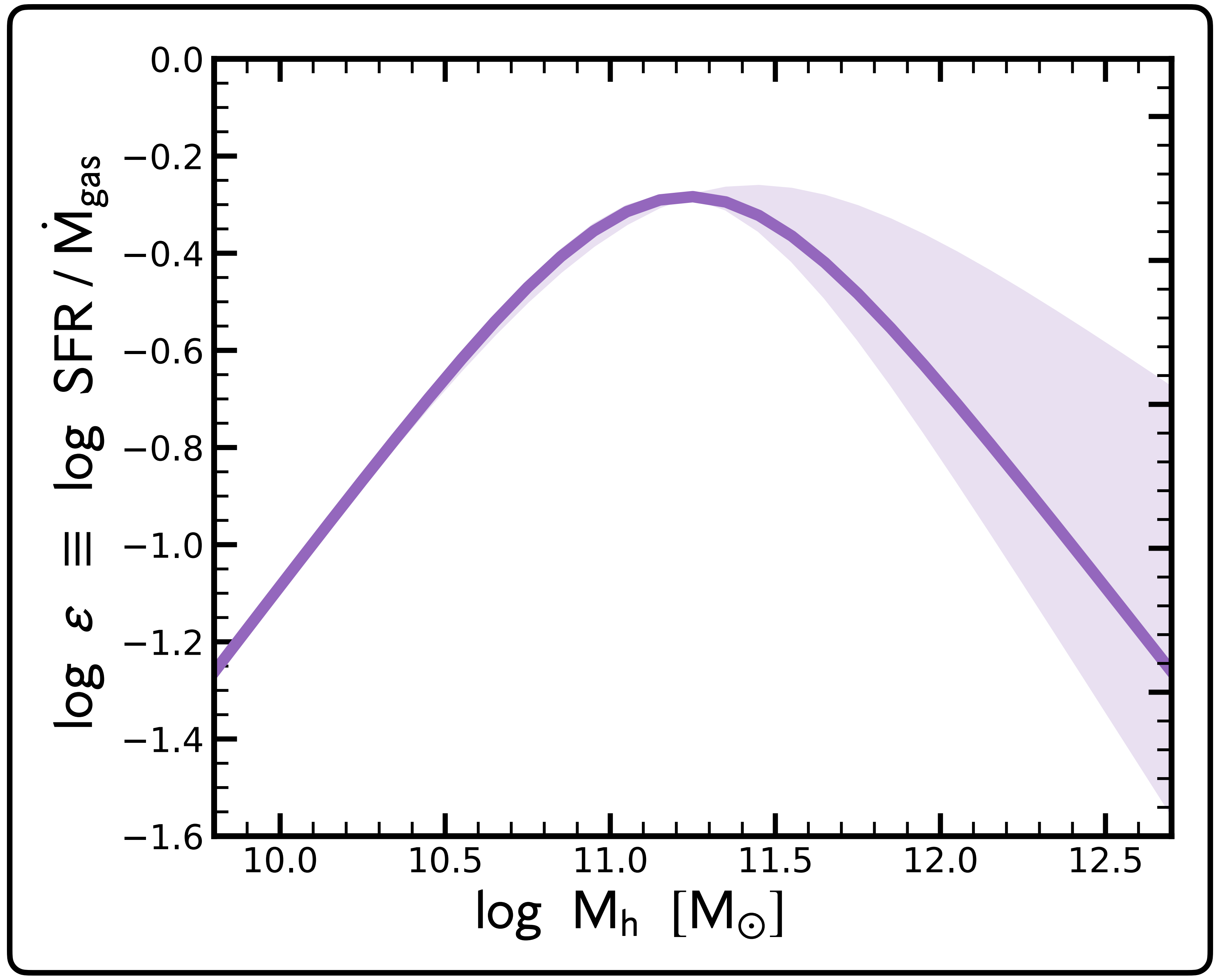

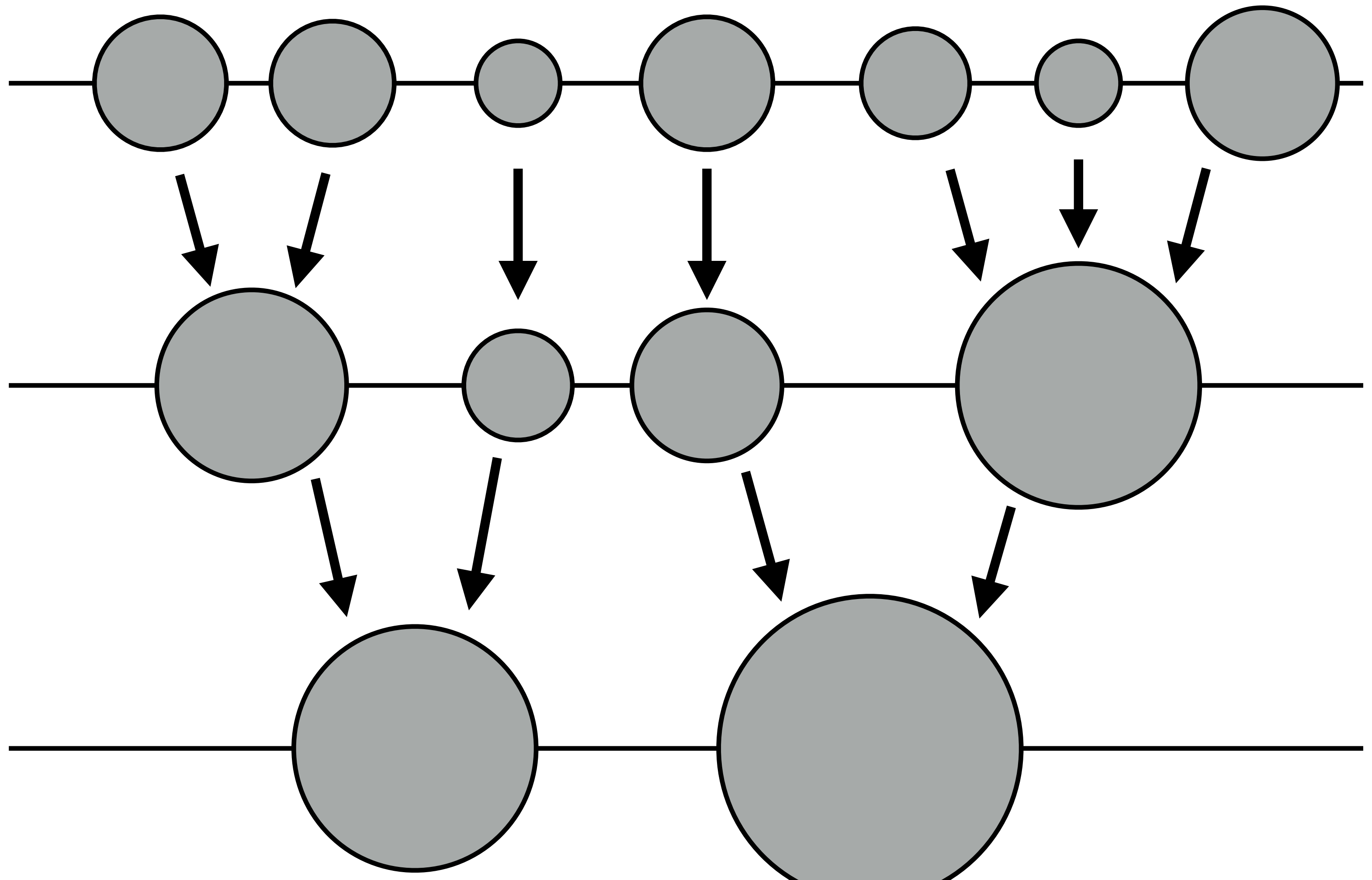

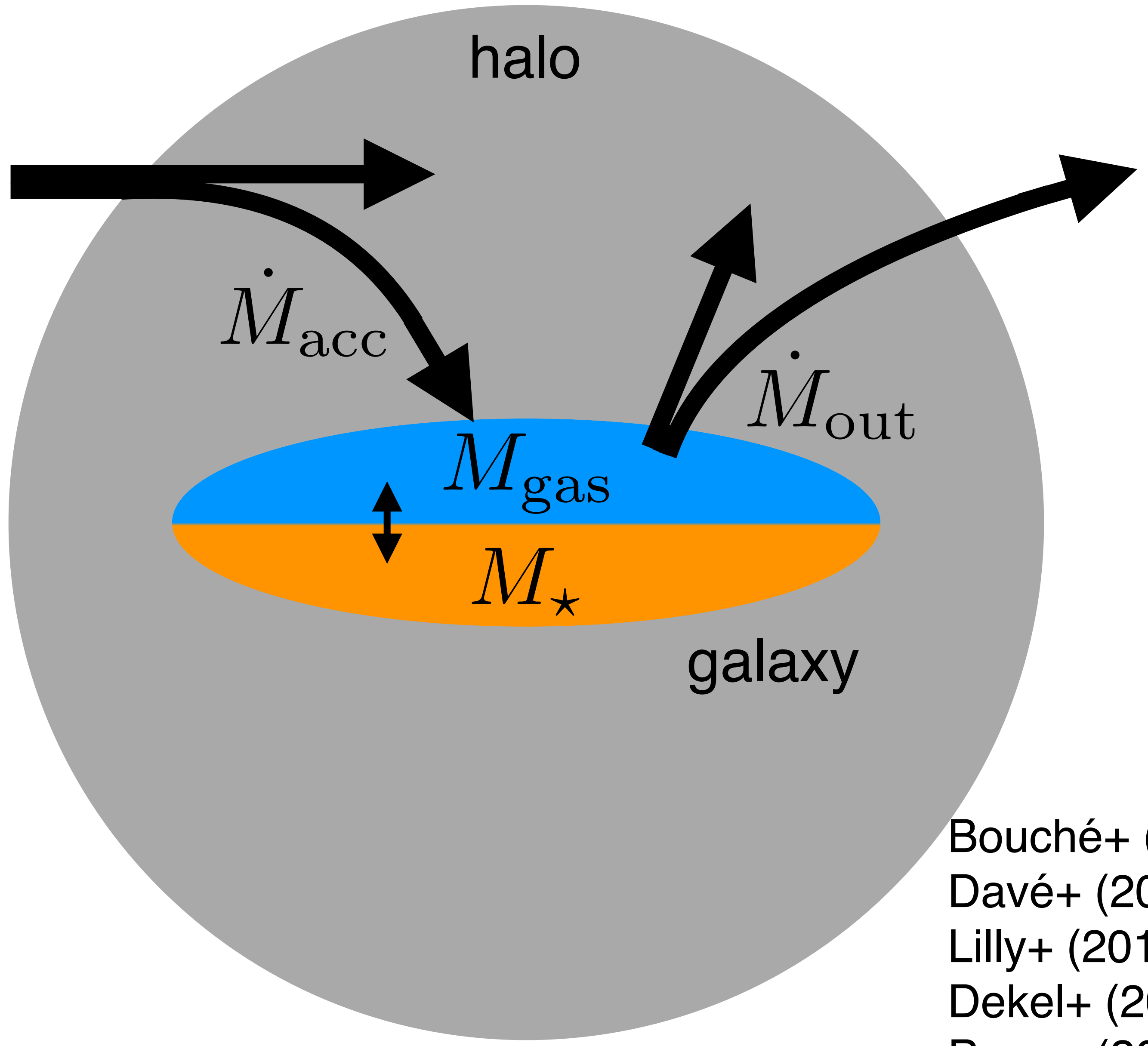

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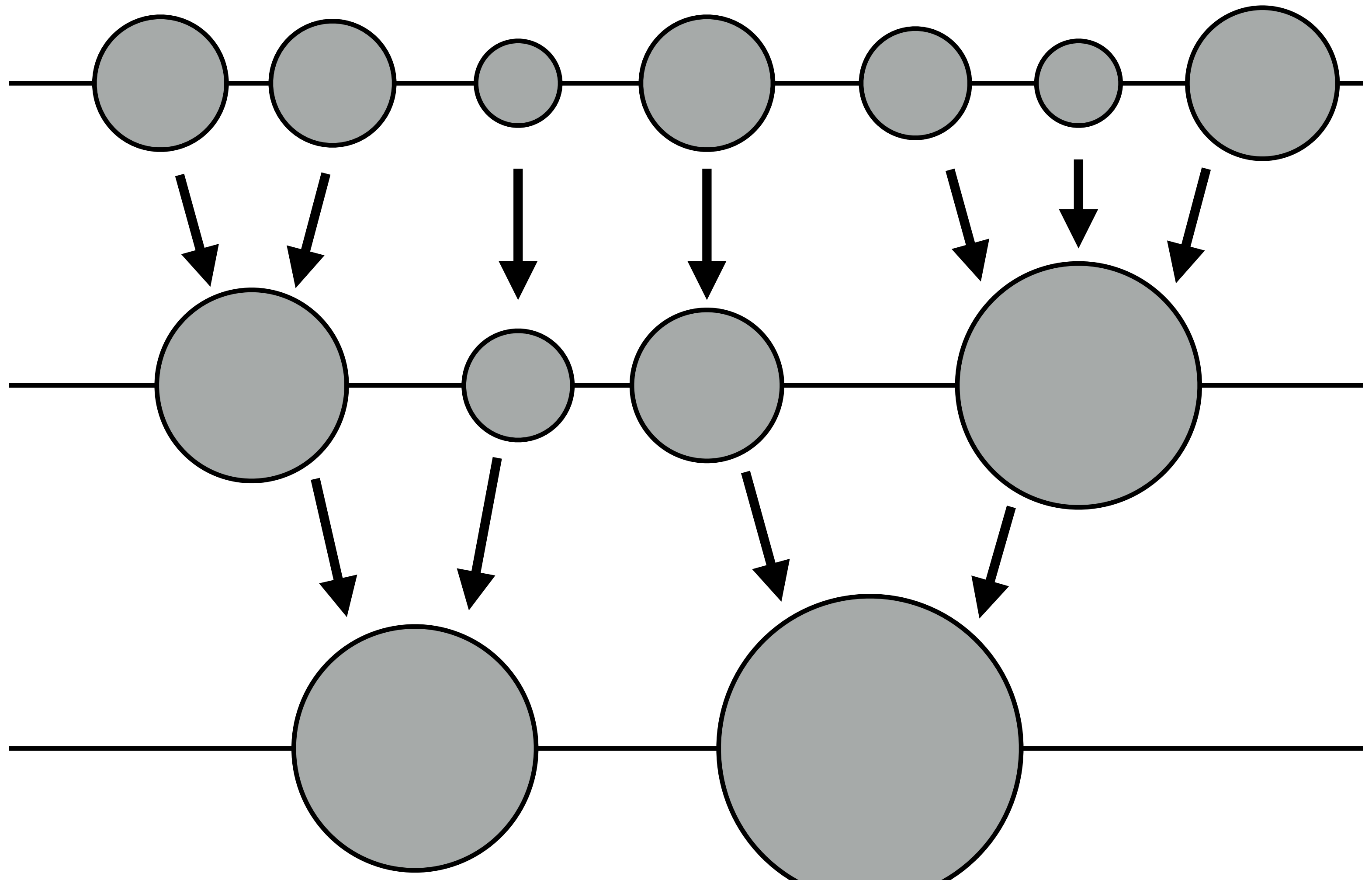

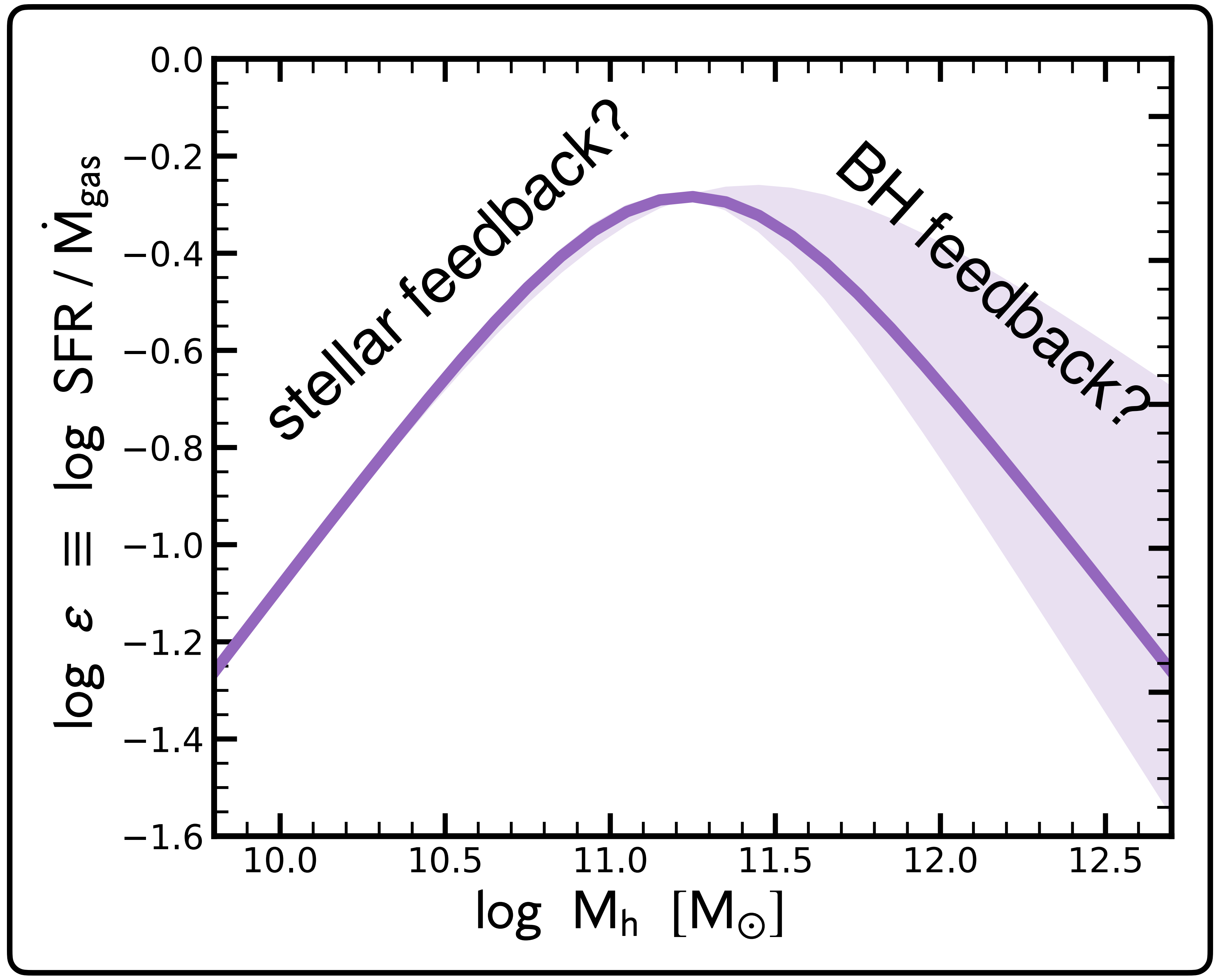

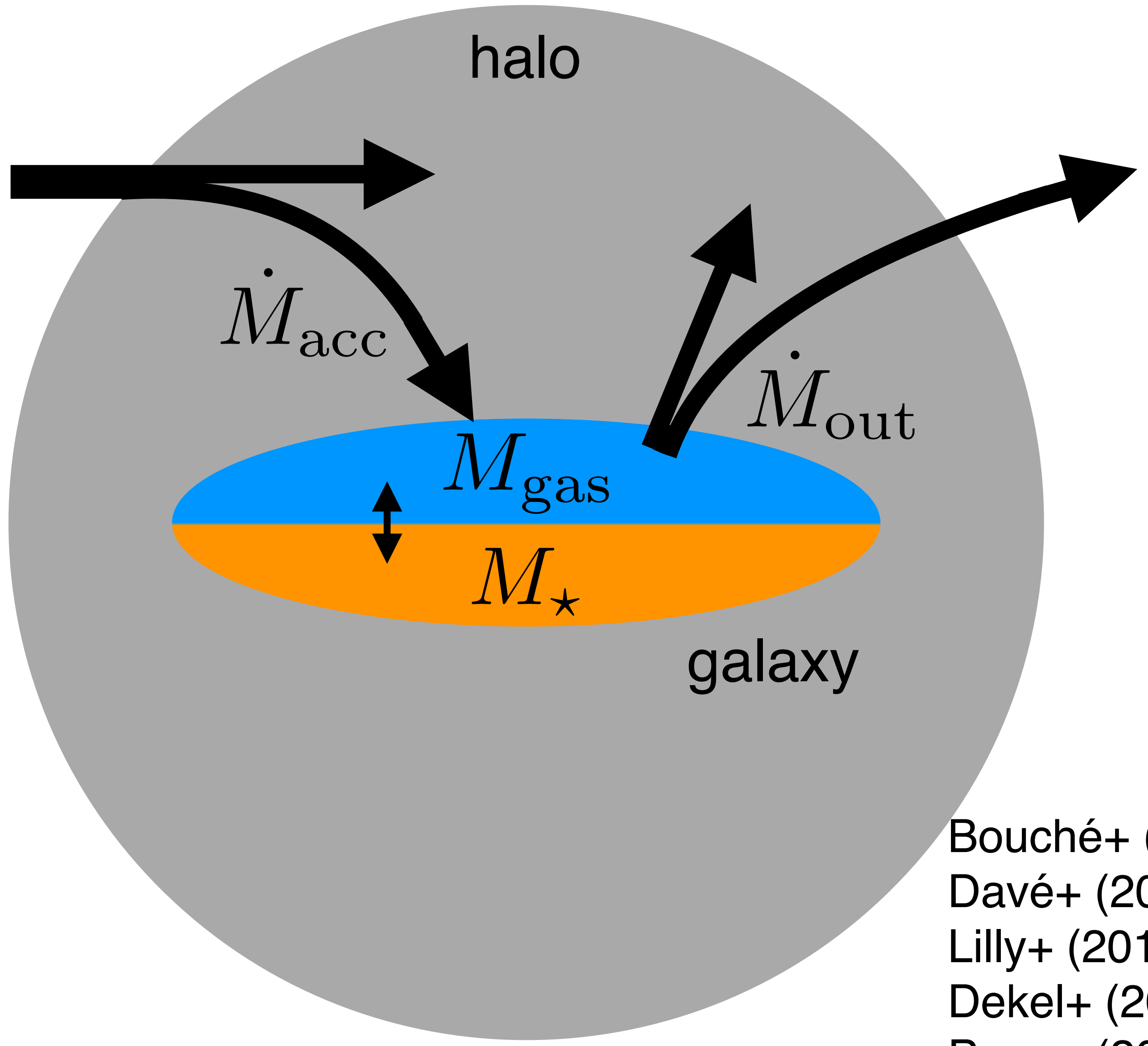

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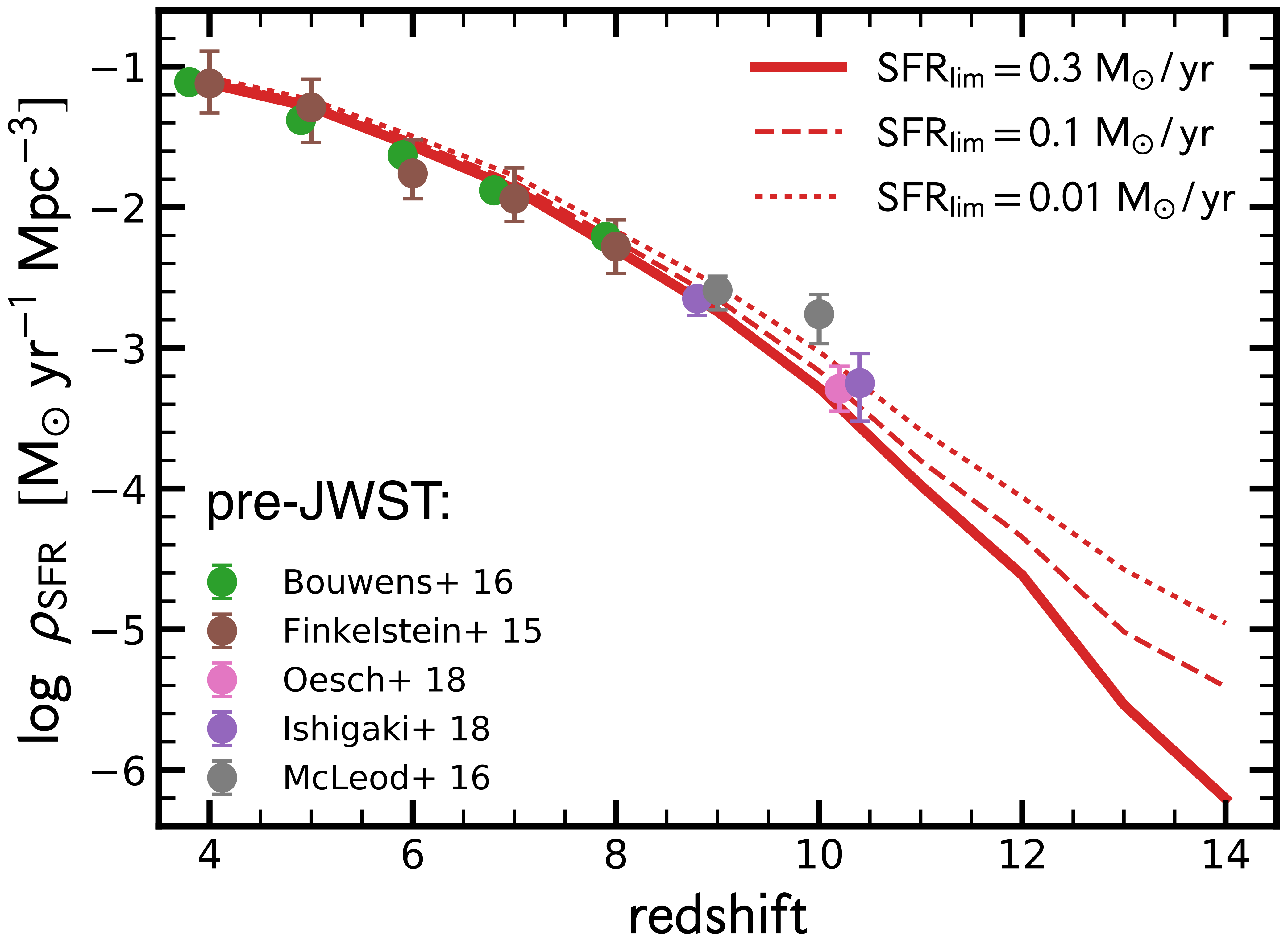

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- primary driver of galaxy evolution is the buildup of DM halos

Simple model for star formation in haloes

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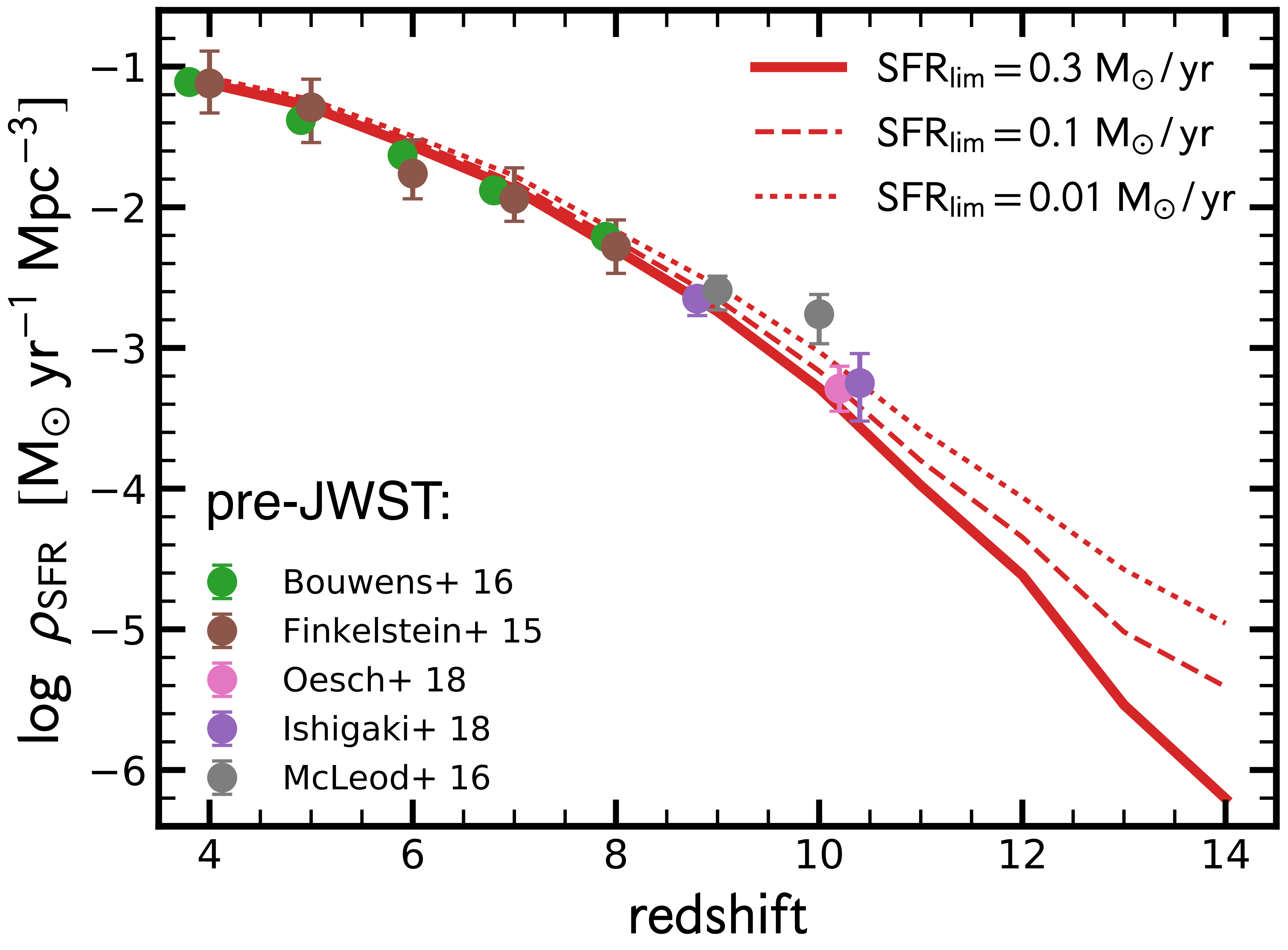

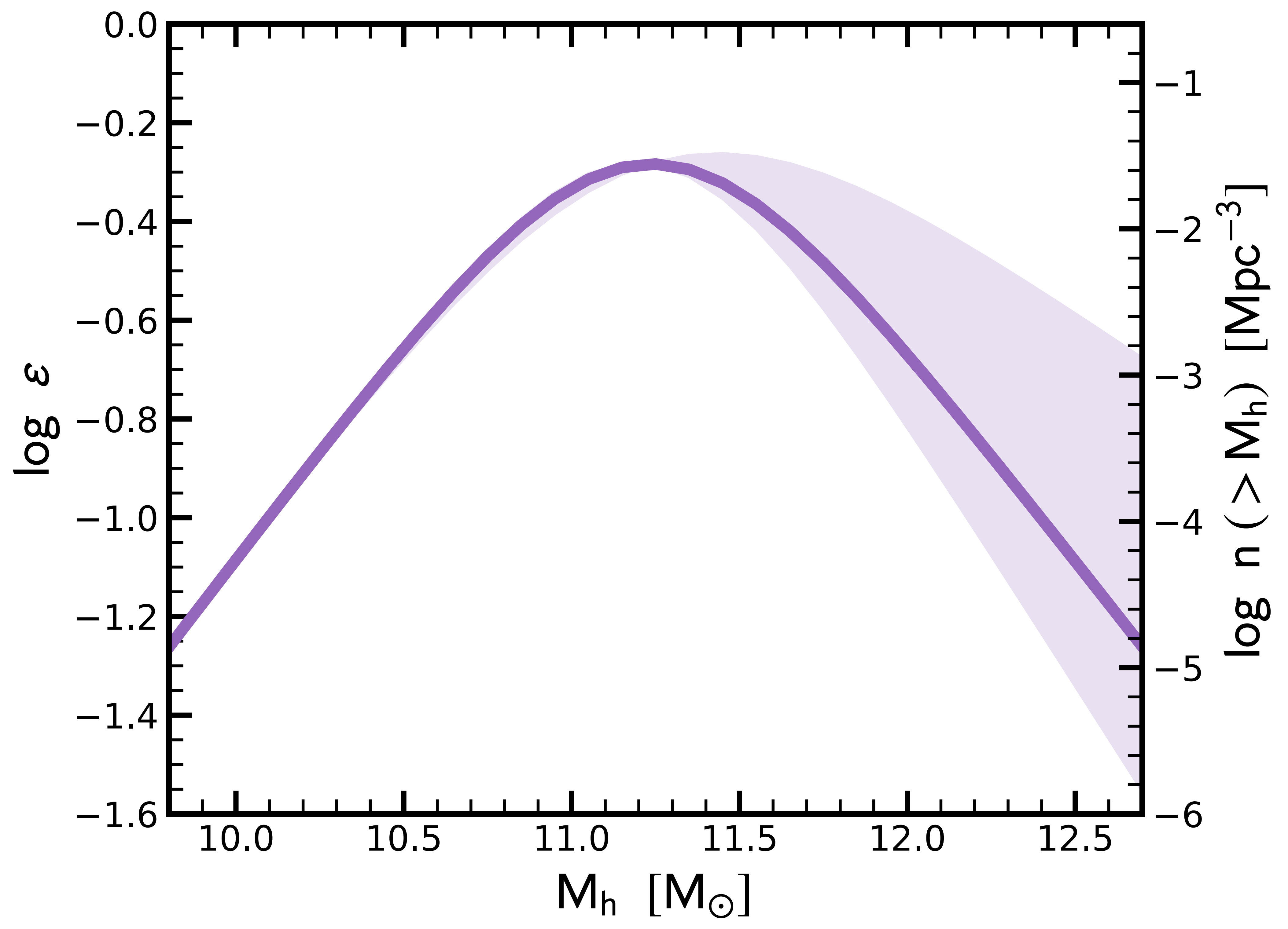

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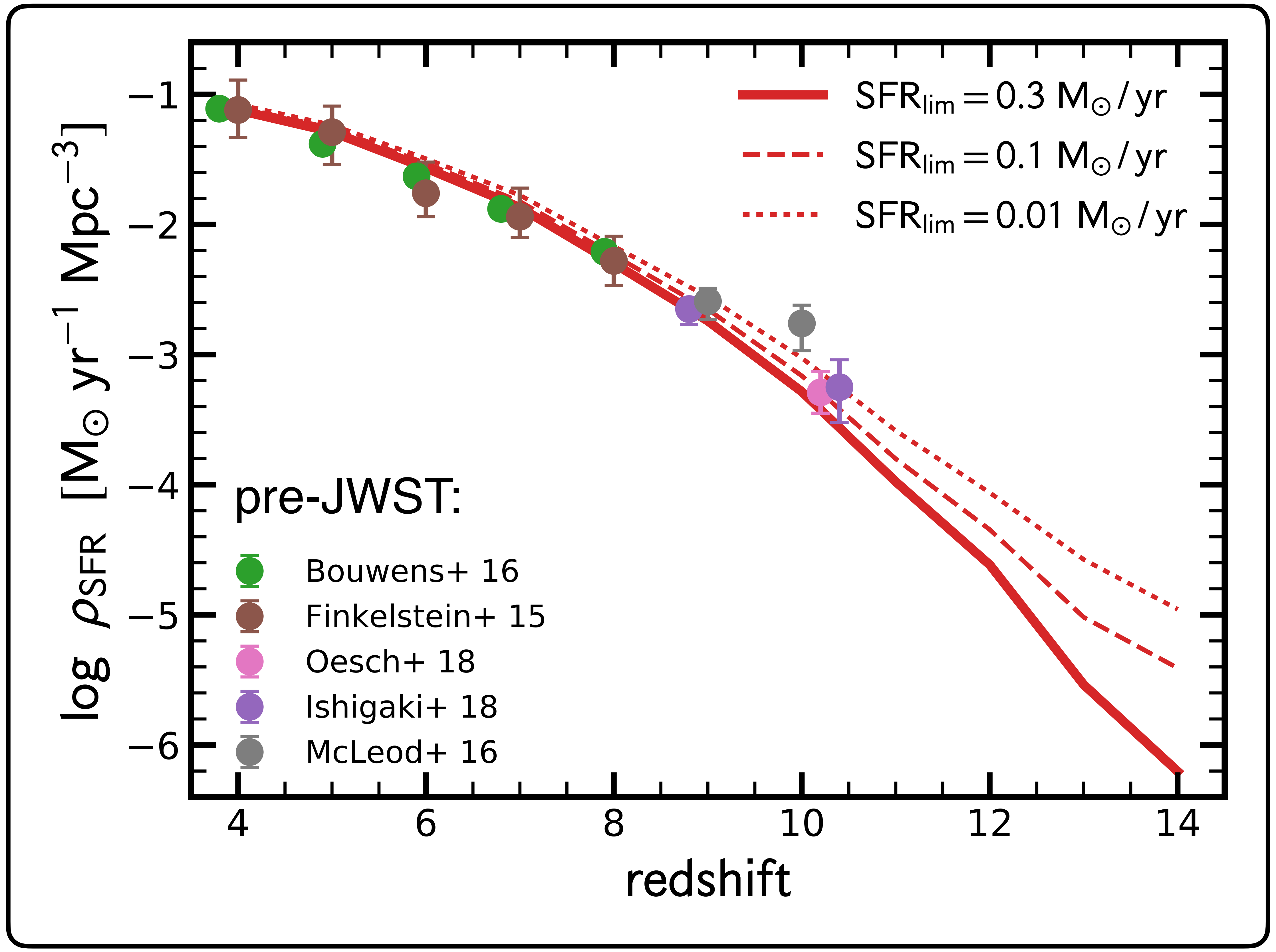

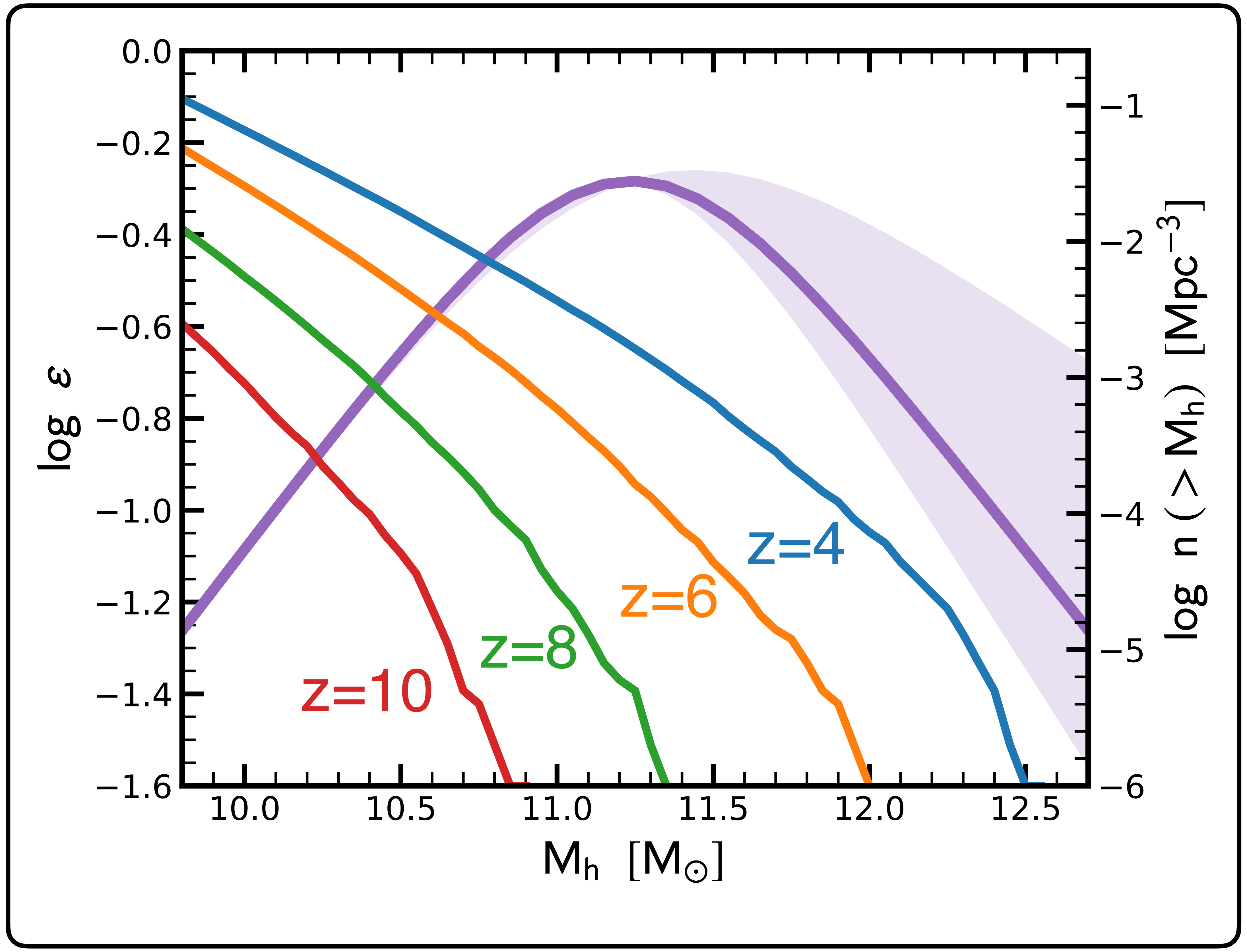

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Overview

Probing early galactic feedback

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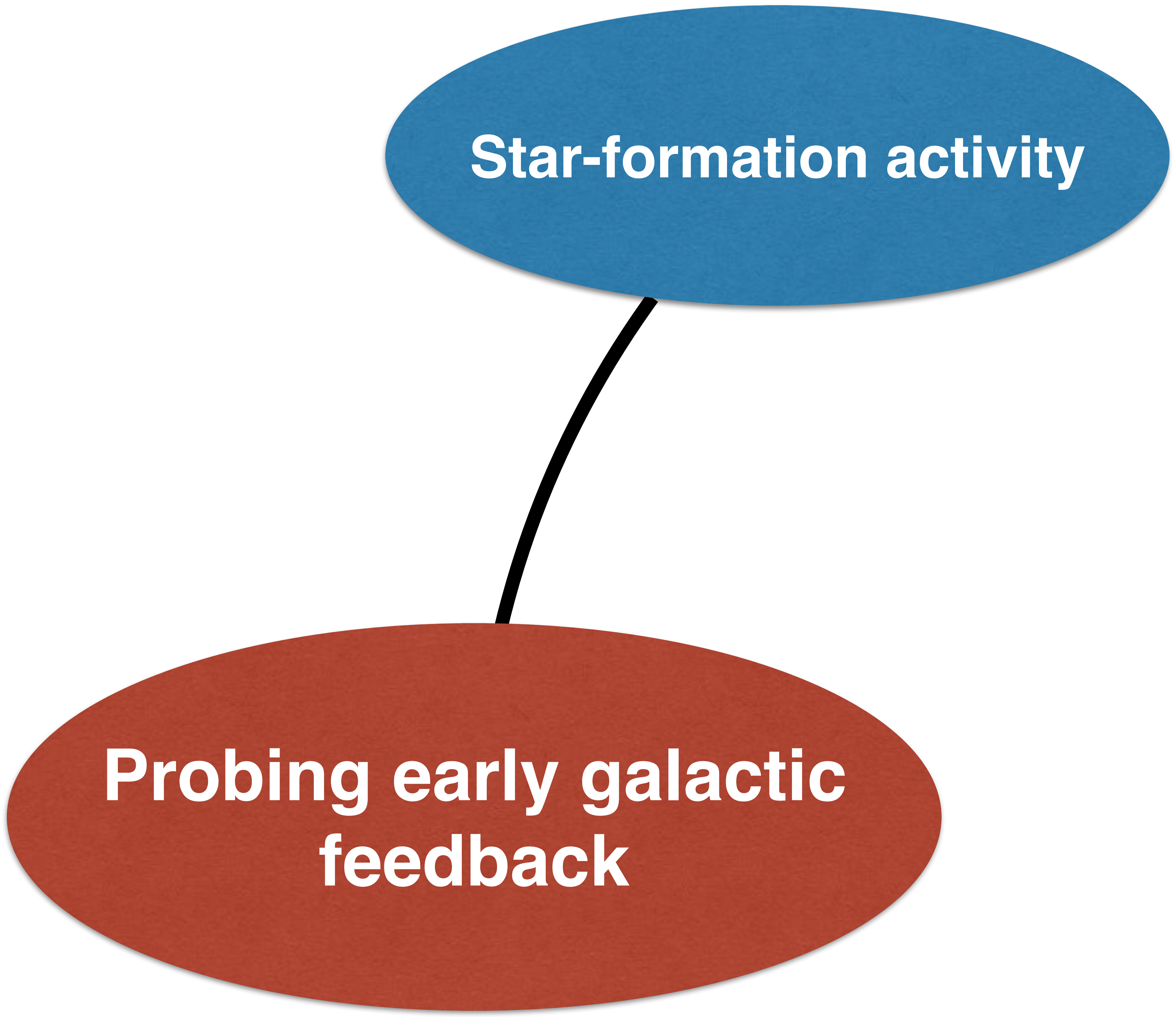
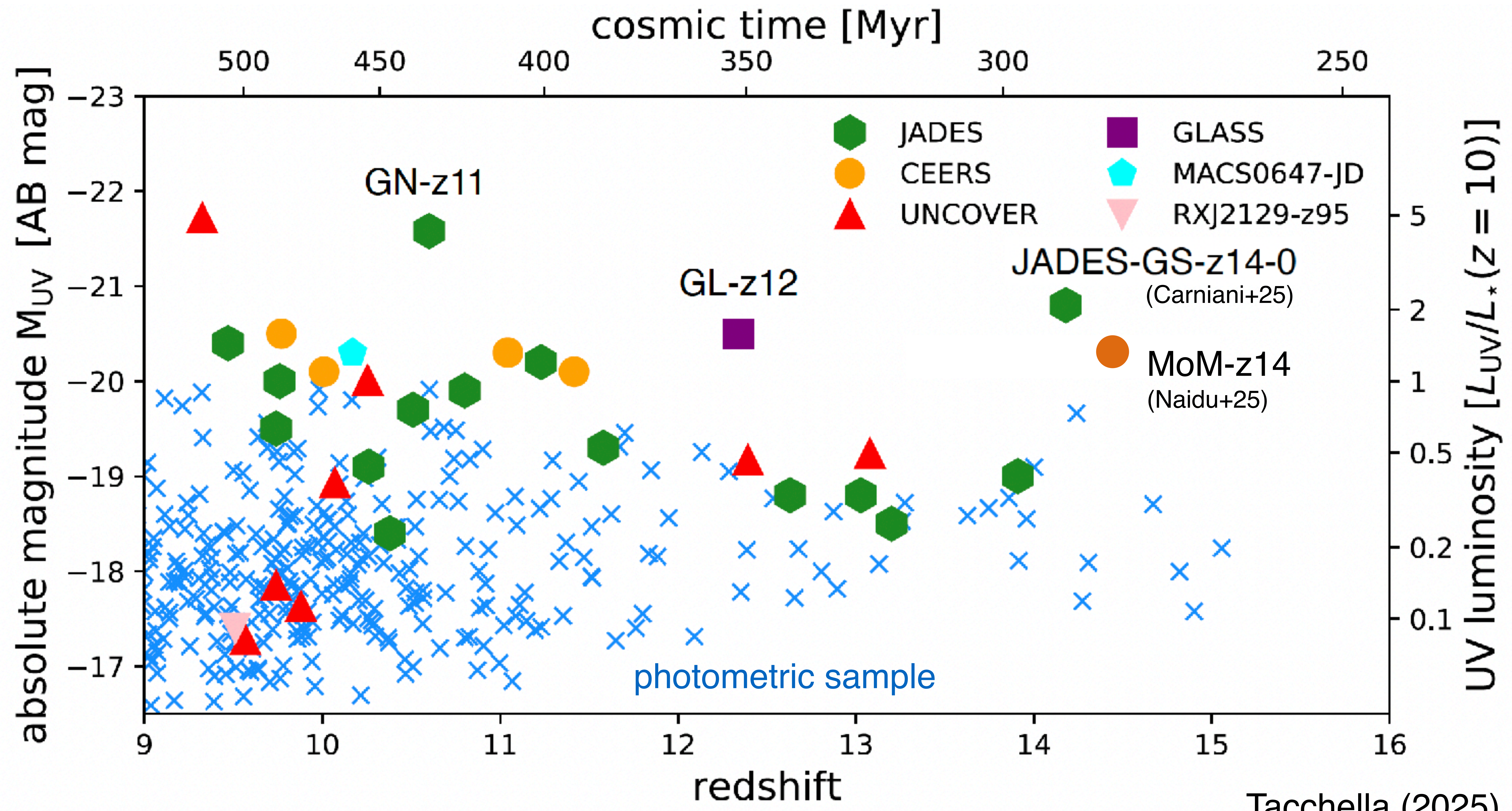


SF scaling relations (SFMS, KS)
SFR function (~ UVLF)
SF variability (“burstiness”)

Pushing the frontier: discovering first light



Tacchella (2025)

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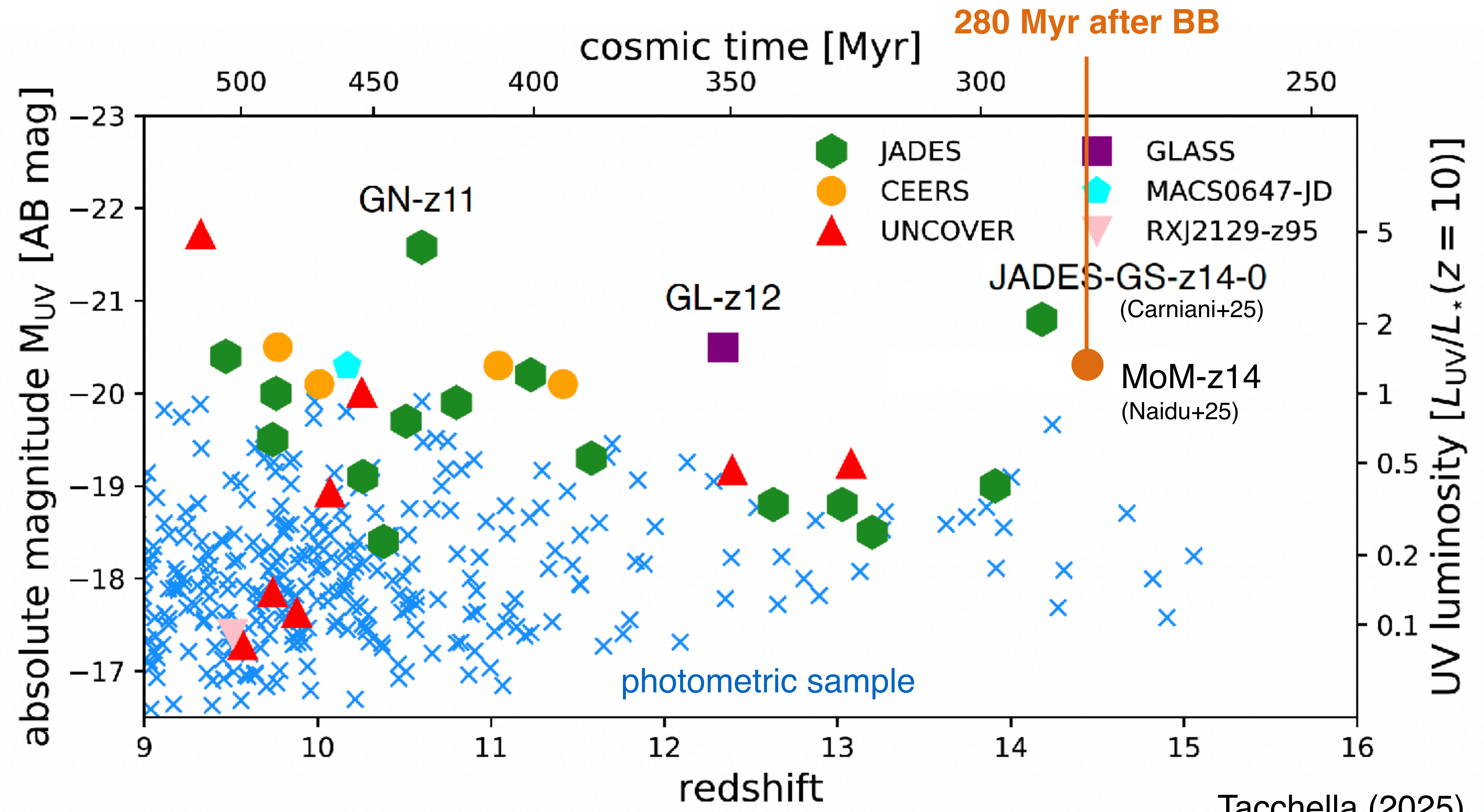
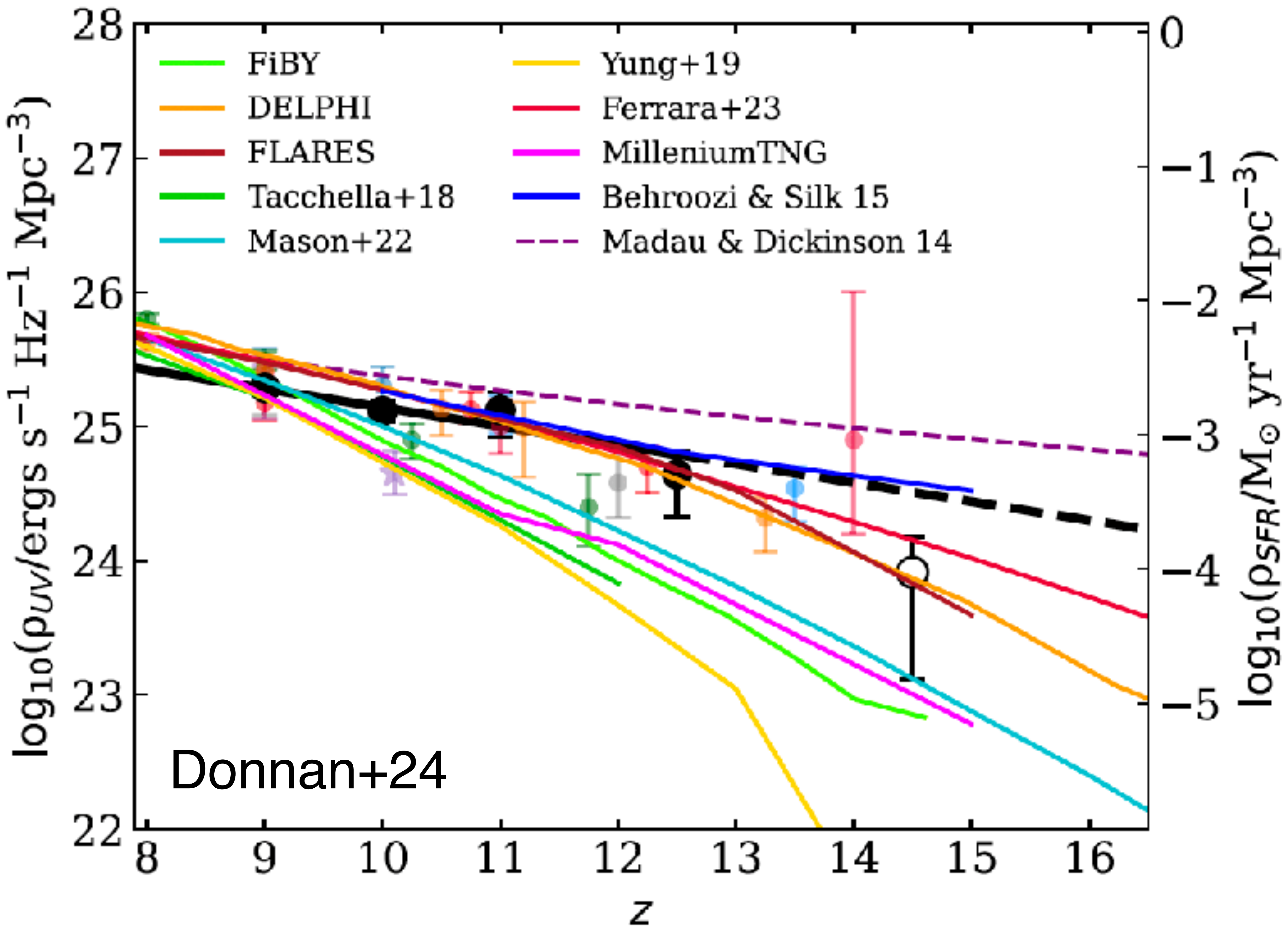
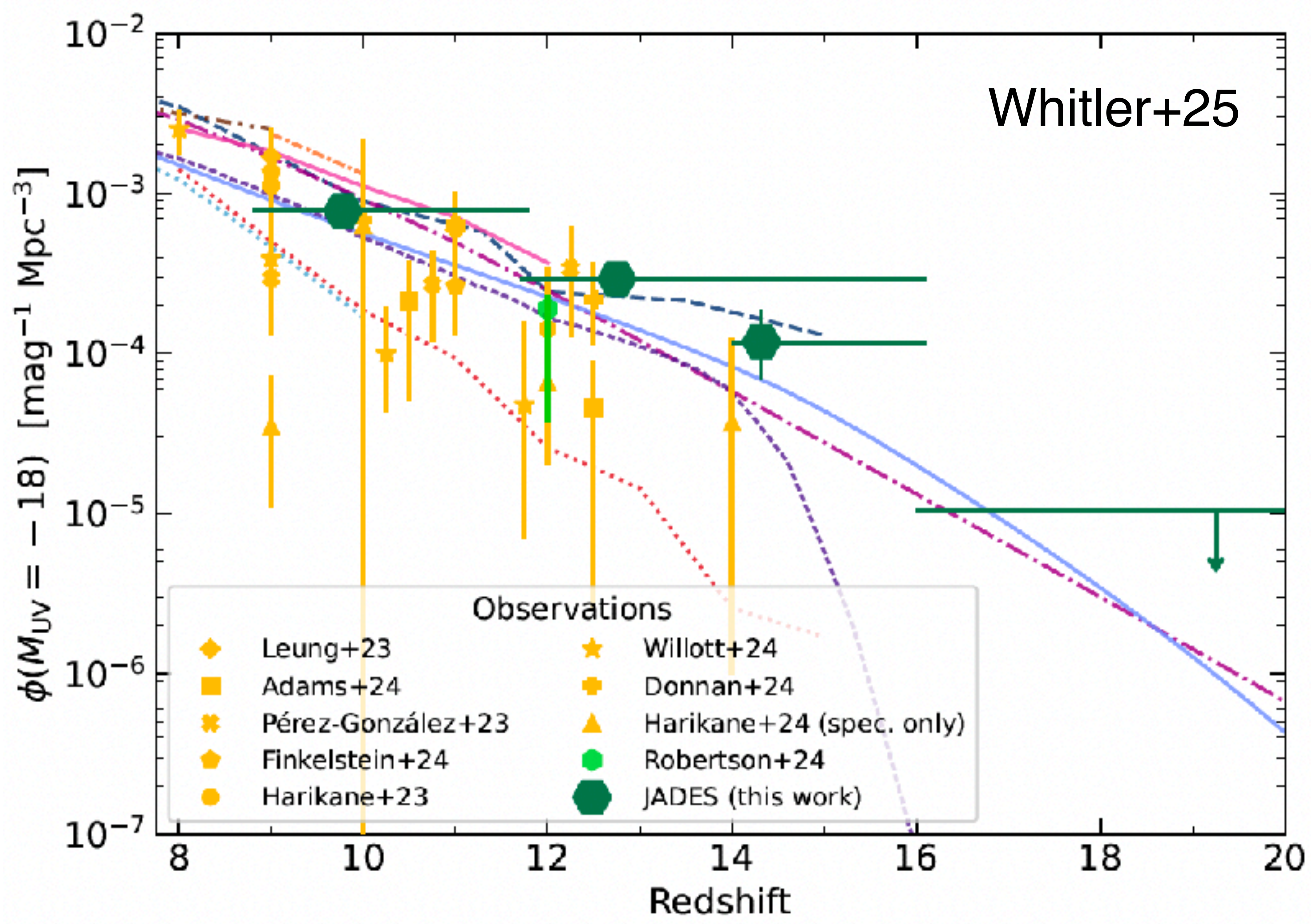


Tacchella (2025)

Abundance of UV-bright galaxies

- large number of groups constrained the UV LF and luminosity density at z>8:
  Finkelstein+22; Castellano+22; Adams+23; Atek+23; Austin+23; Harrikane+23; McLeod+23; Naidu+23; Hainline+23; Donnan+24; Robertson+24; Whitler+25
- bright-end of UV LF remarkably constant, with luminosity density >2× larger than using constant star formation efficiency models





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  - change abundance of DM halos (e.g. cosmology)
    - negative cosmological constant + evolving DE (Menci+ 24)
    - introduce early dark energy, incl. fix H-tension (Shen+ [incl. ST] 24)

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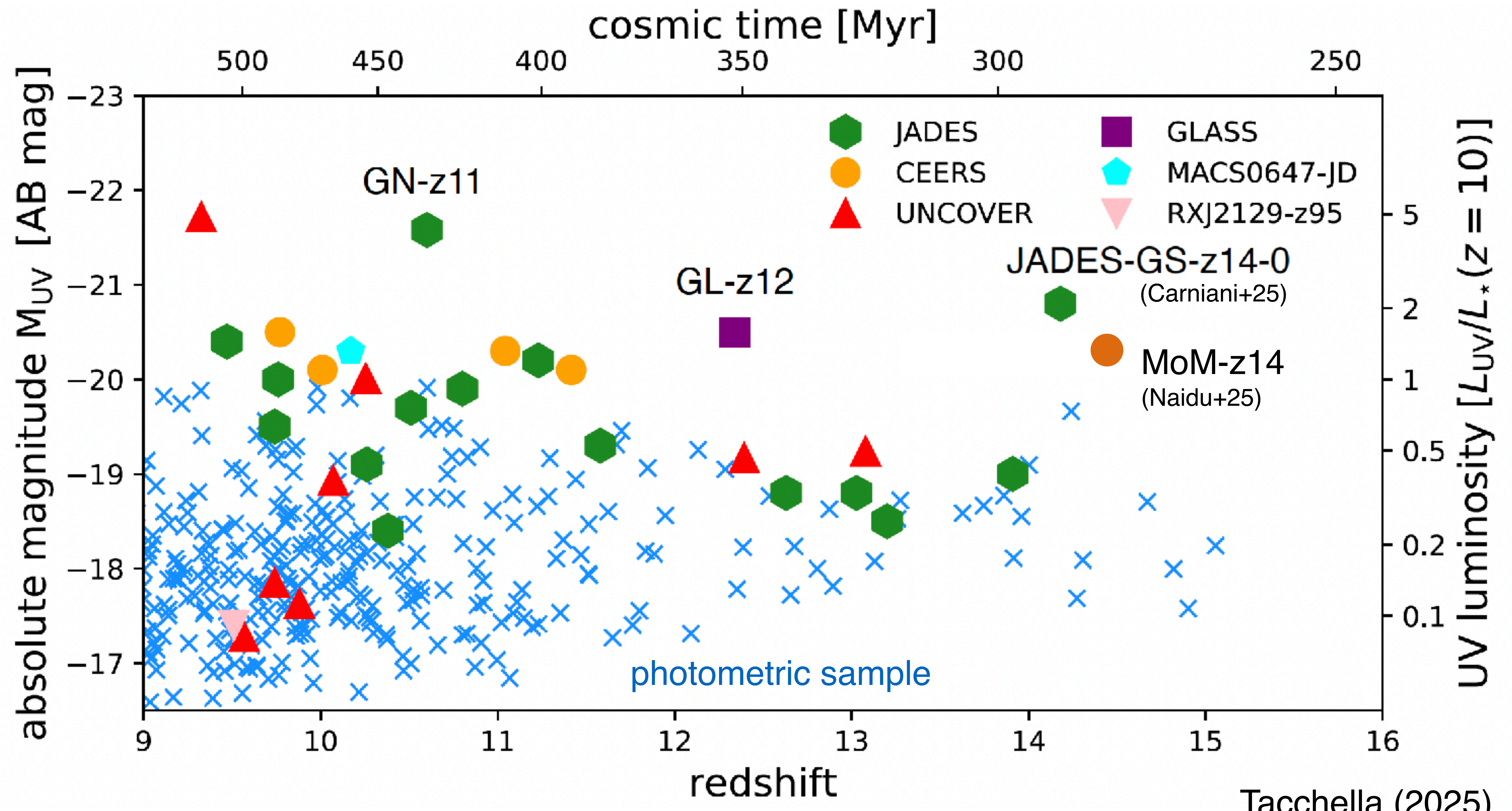
➜ z>10 galaxies are diverse: sizes, attenuation, SFR, AGN, intense star formation

Pushing the frontier: discovering first light



Tacchella (2025)

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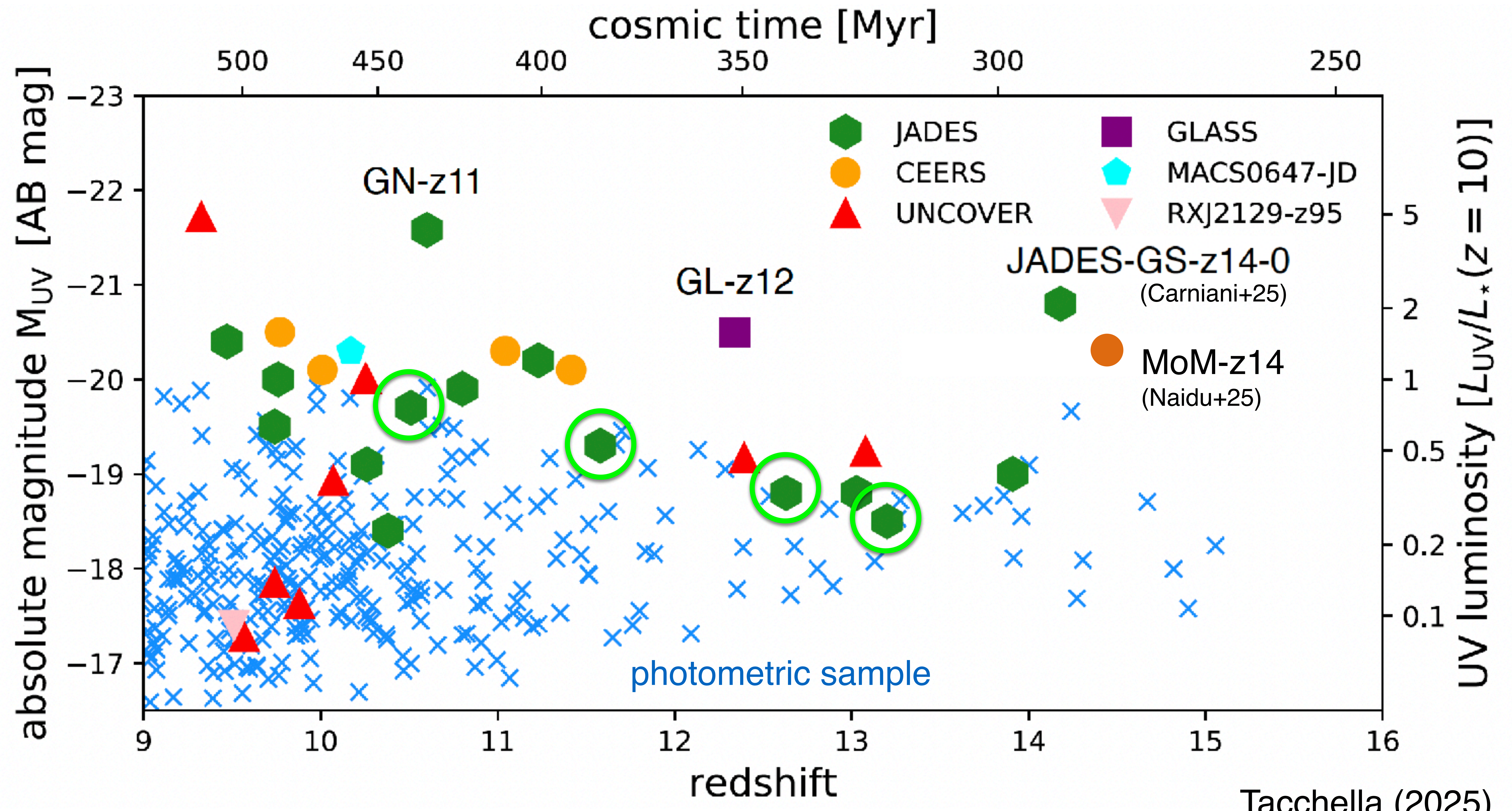
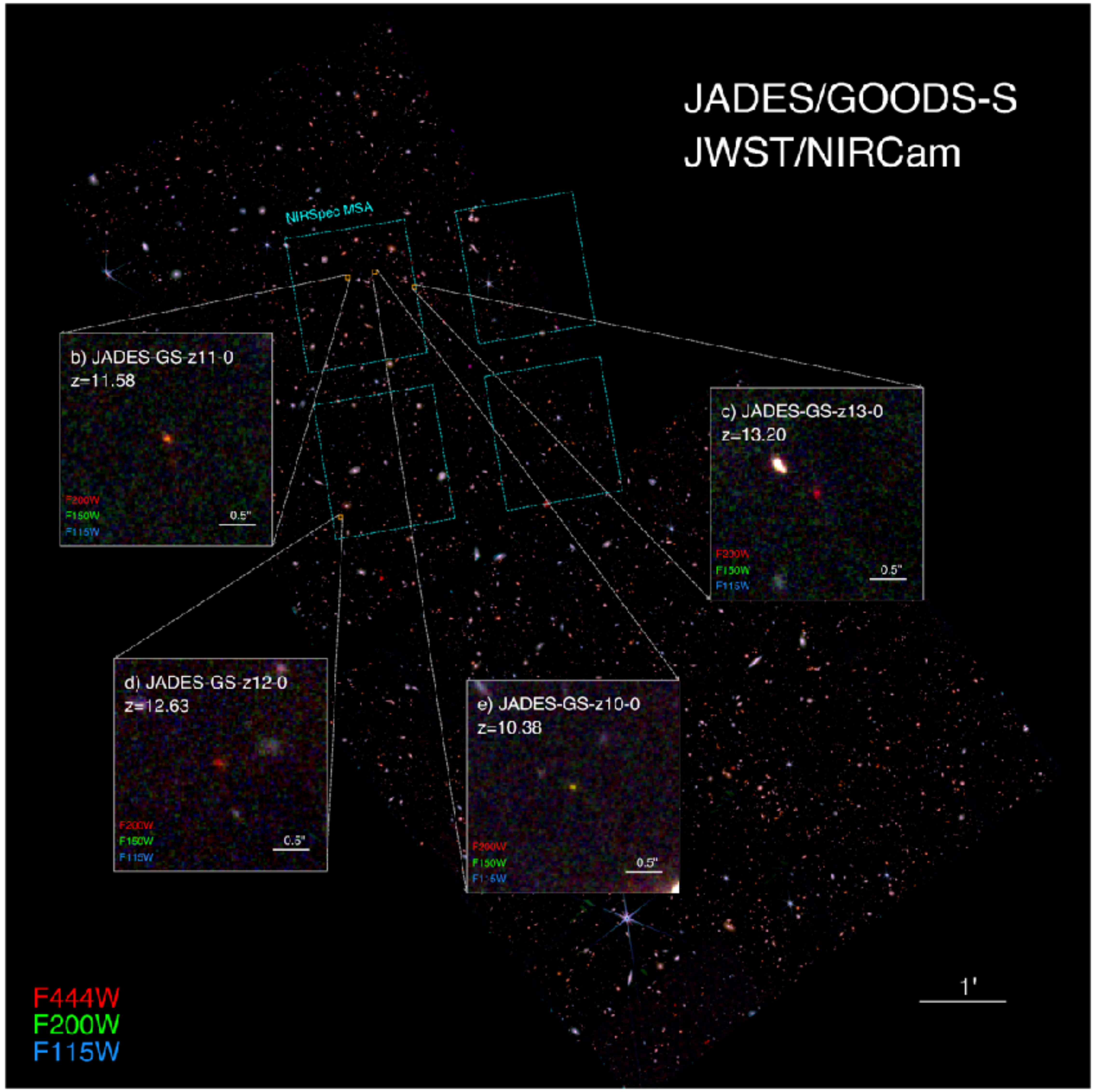


Tacchella (2025)

Earliest galaxies with confirmed distances

Robertson, Tacchella+ (2023)
Curtis-Lake, Carniani+ (2023)

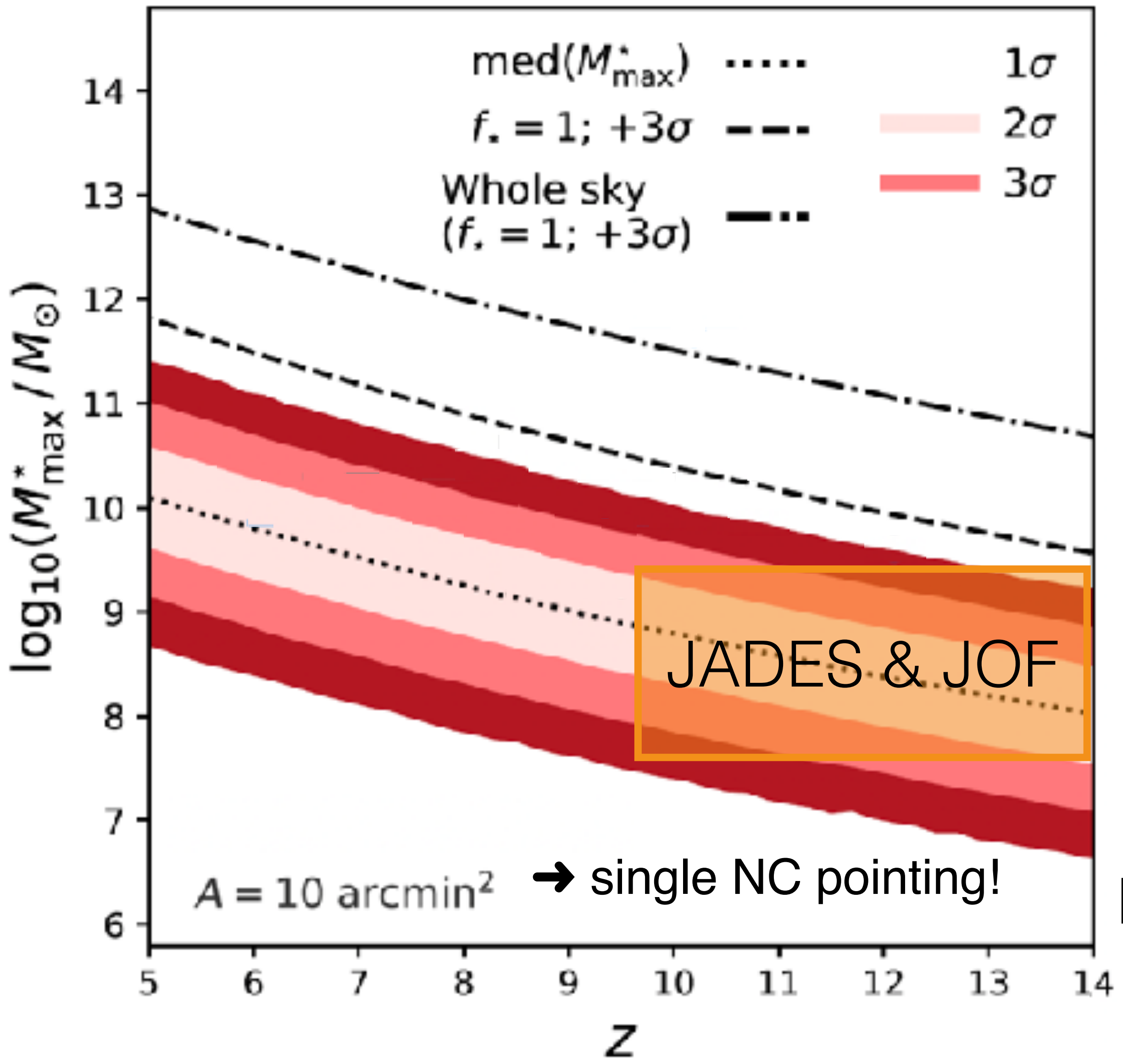


4 spectroscopically confirmed galaxies:

- z_{spec} = 10.4–13.2
- M_{UV} = -19.3 to -18.4
- $\log(M_\star/M_\odot)$ = 7.8—8.9
- SFR = 1—2 $M_\odot$ / yr ➜ mass doubling timescale of few tens of Myr
- compact sizes with 50-165 pc

➜ high SFR densities: $\Sigma_{SFR} \approx$ 15—180 $M_\odot$/yr/kpc^2

➜ consistent with galaxy formation in ΛCDM at these redshifts (Tacchella+18; Wilkins+22; Lovell+23)



Lovell+ (incl. ST) 23

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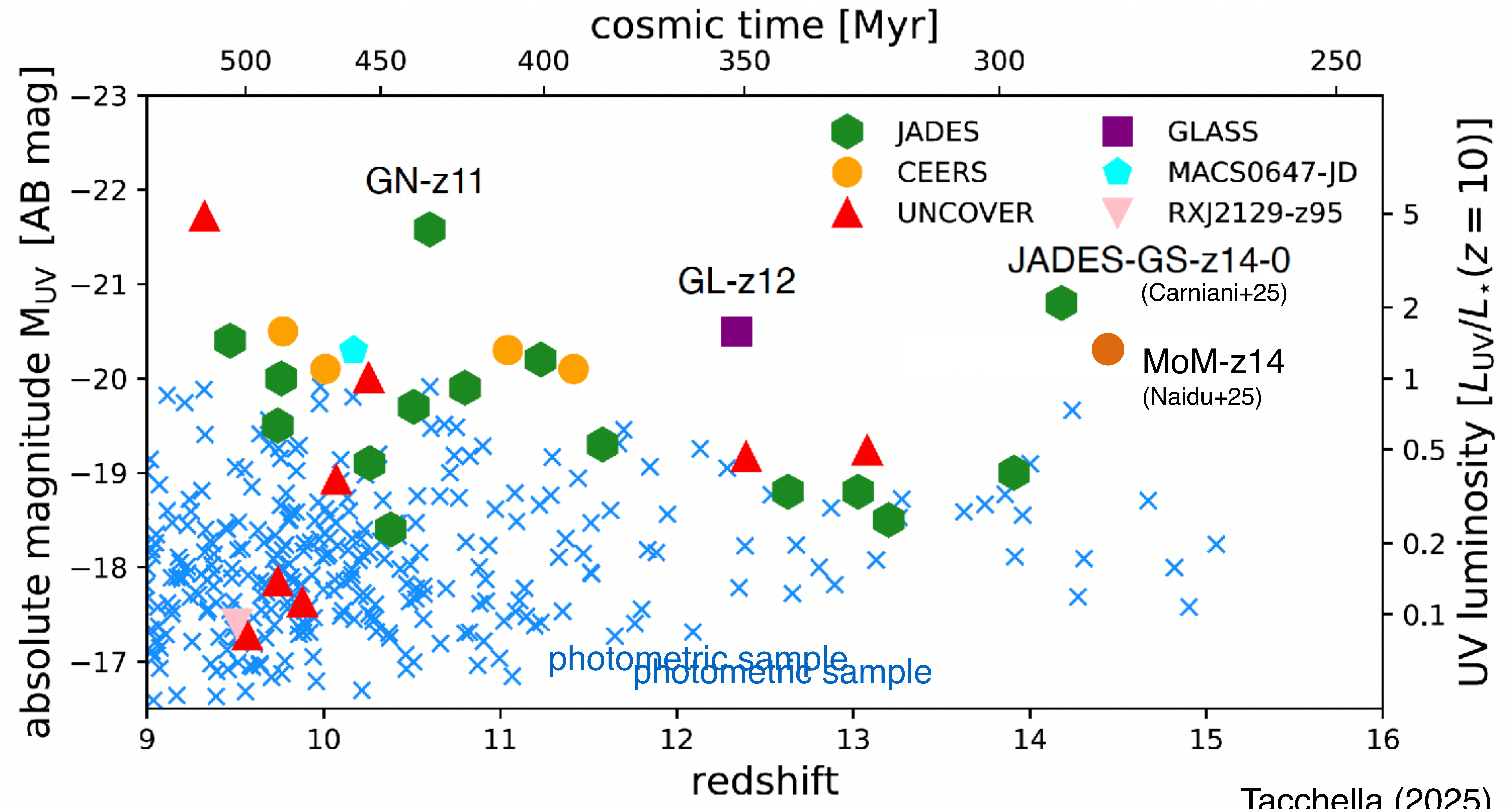

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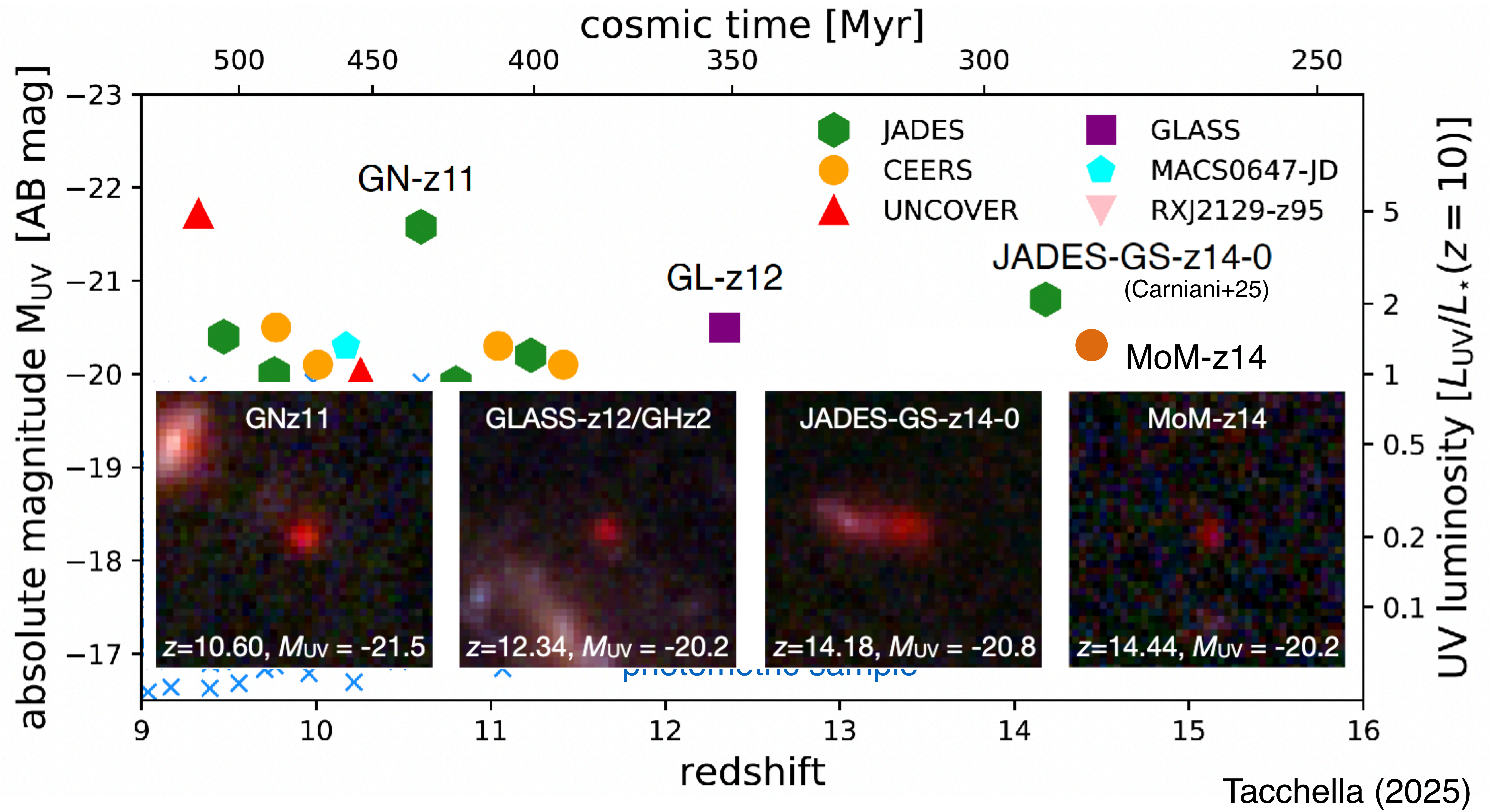
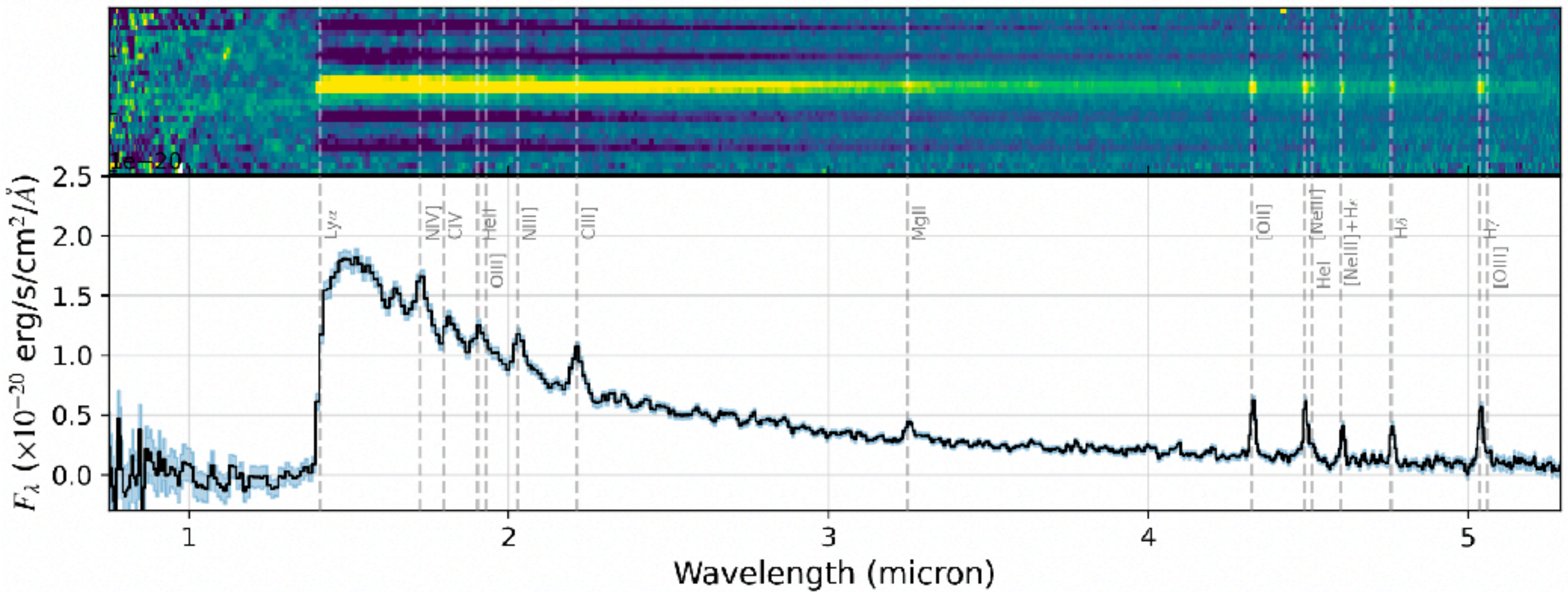


Tacchella (2025)

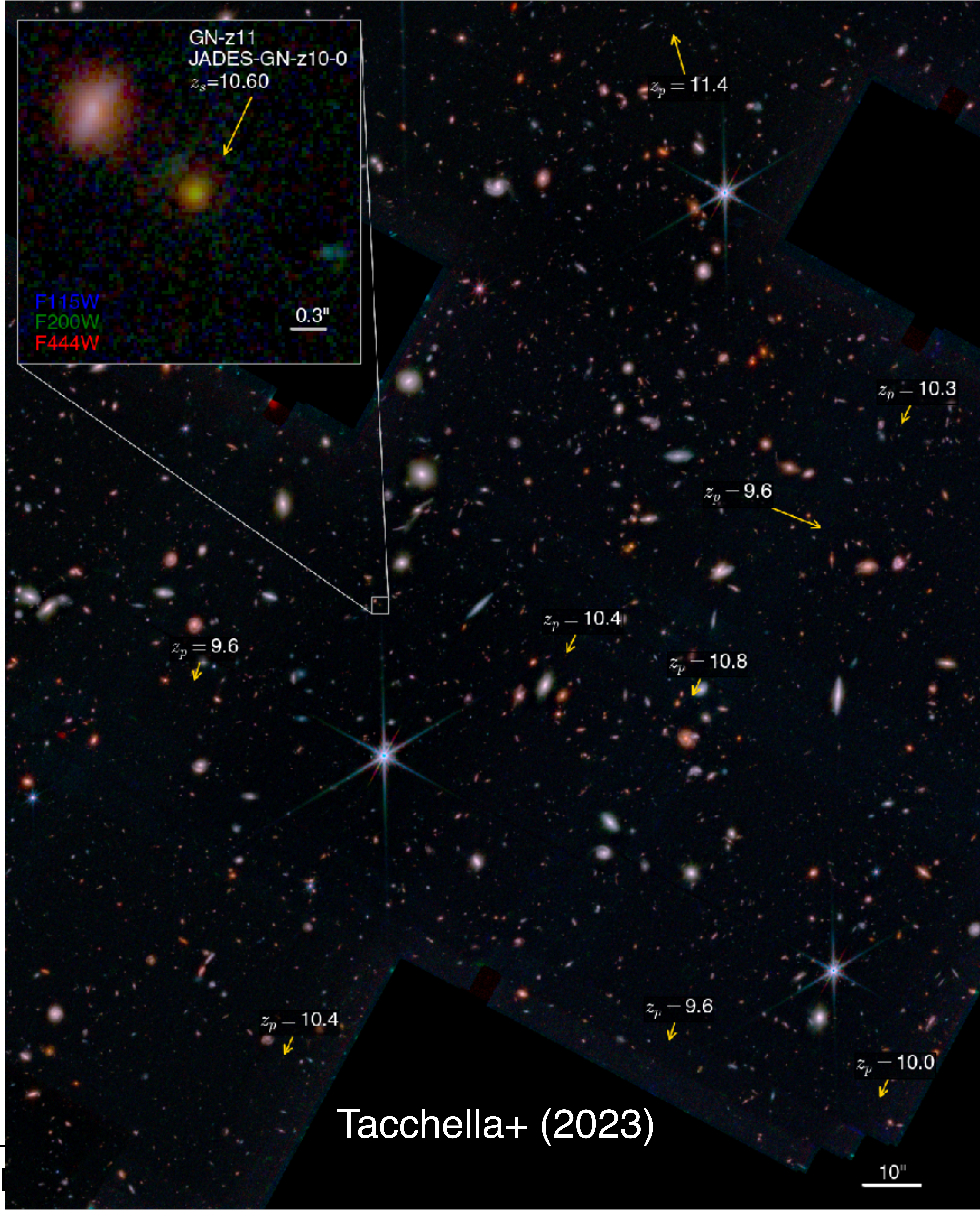
Nature of GN-z11

Bunker+ (2023)



GN-z11 is at z=10.60,
with Ly-α and high N/O abundance (if SF)

… and possibly not alone:
9 galaxies out to ~5 cMpc transverse
➜ massive dark-matter halo (~8x10^{10} M$_\odot$)



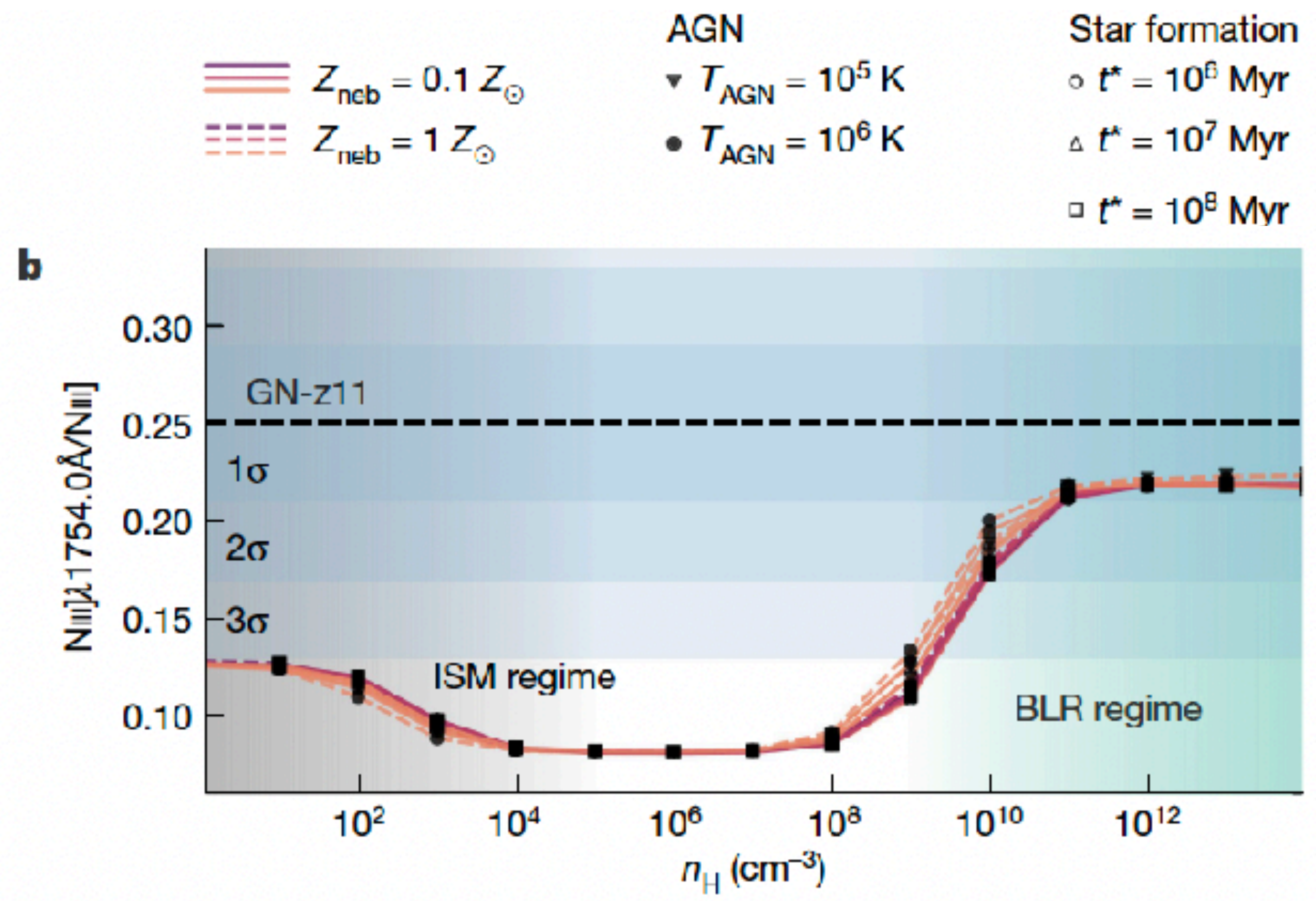
Tacchella+ (2023)

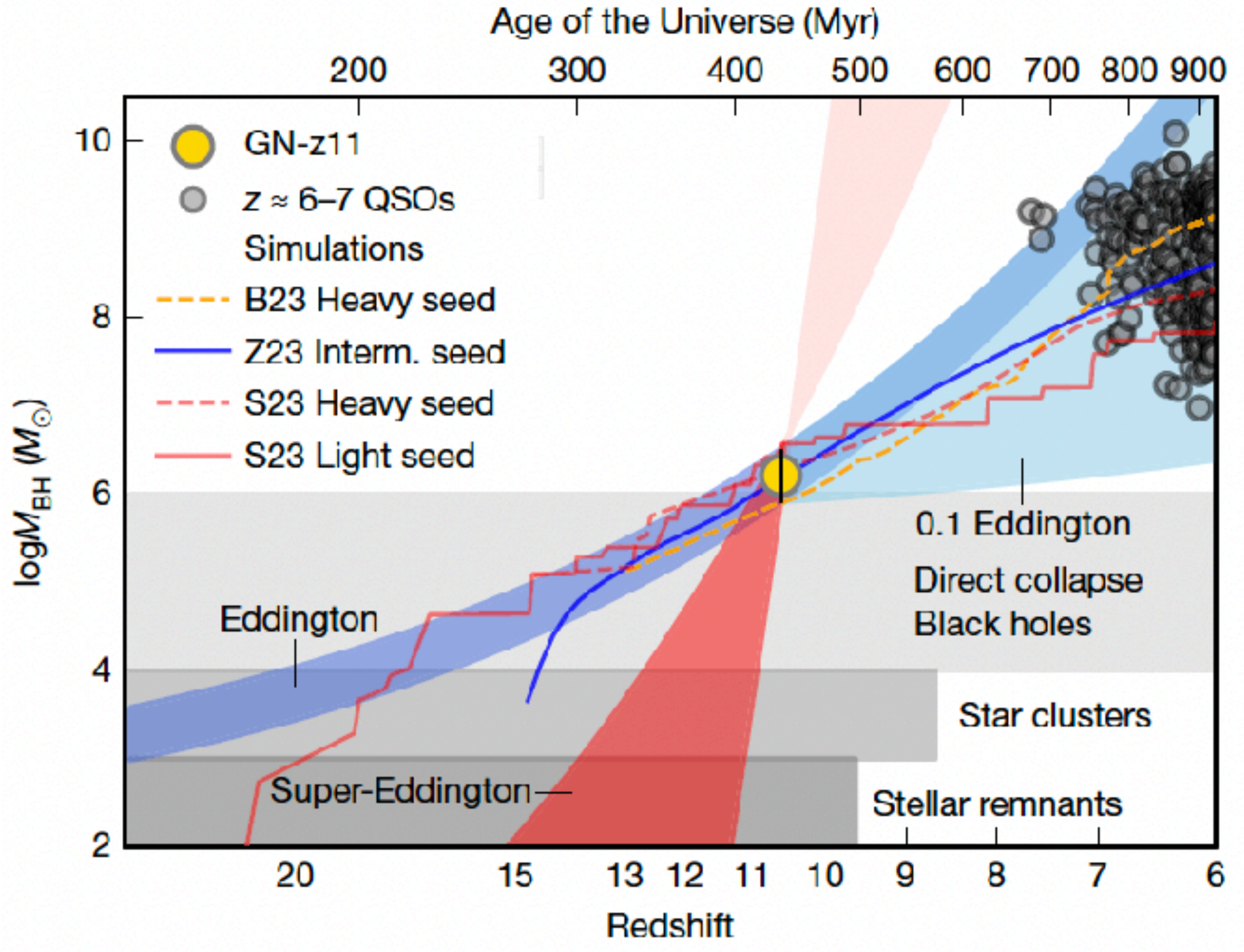
Nature of GN-z11

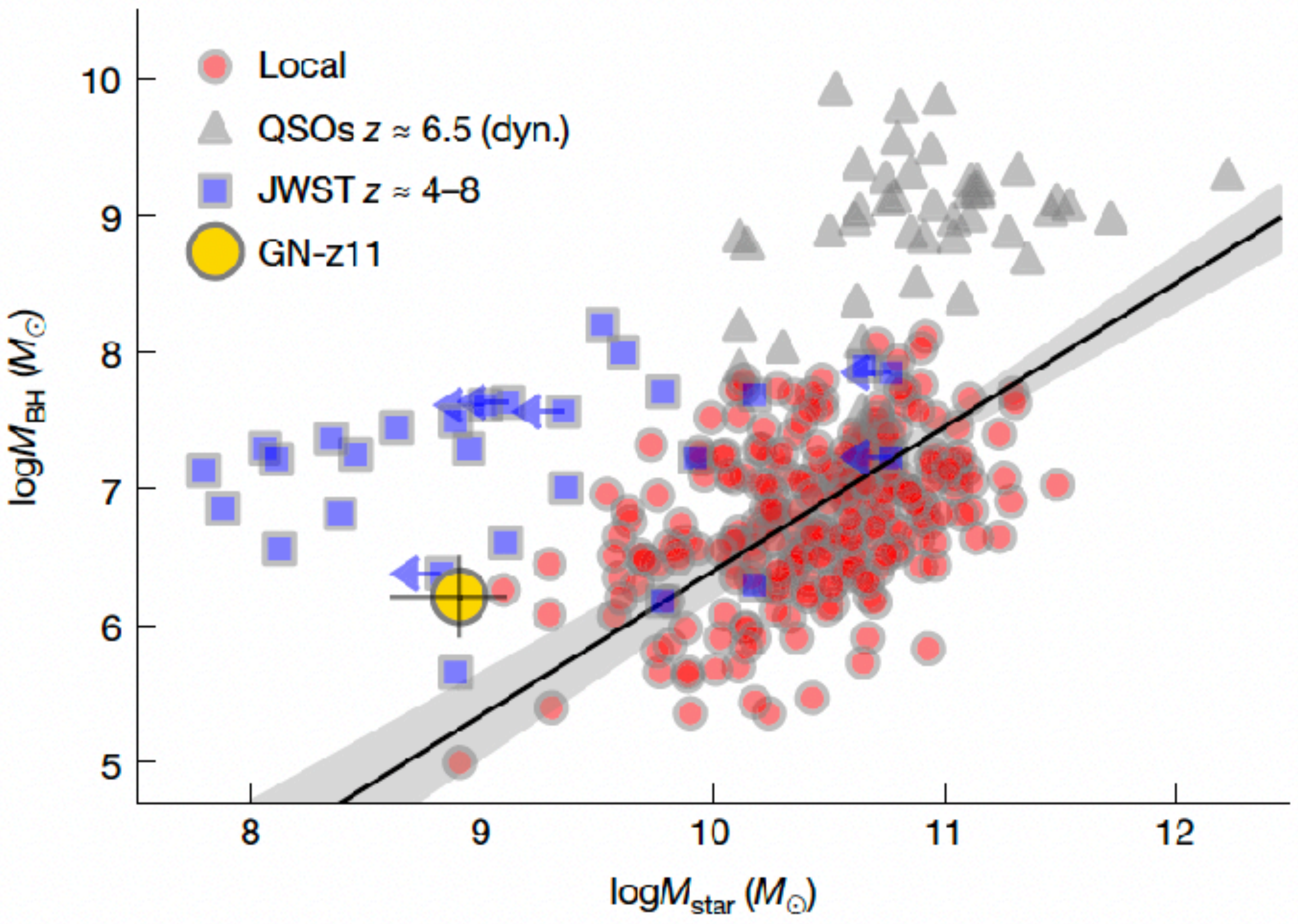
- But GN-z11 might also host an accreting black hole Maiolino+ (2024)

➜ central point source is an AGN

➜ several spectral features (CIV1549; continuum spectral slope; density implied from permitted lines) point to Broad Line Region of AGN





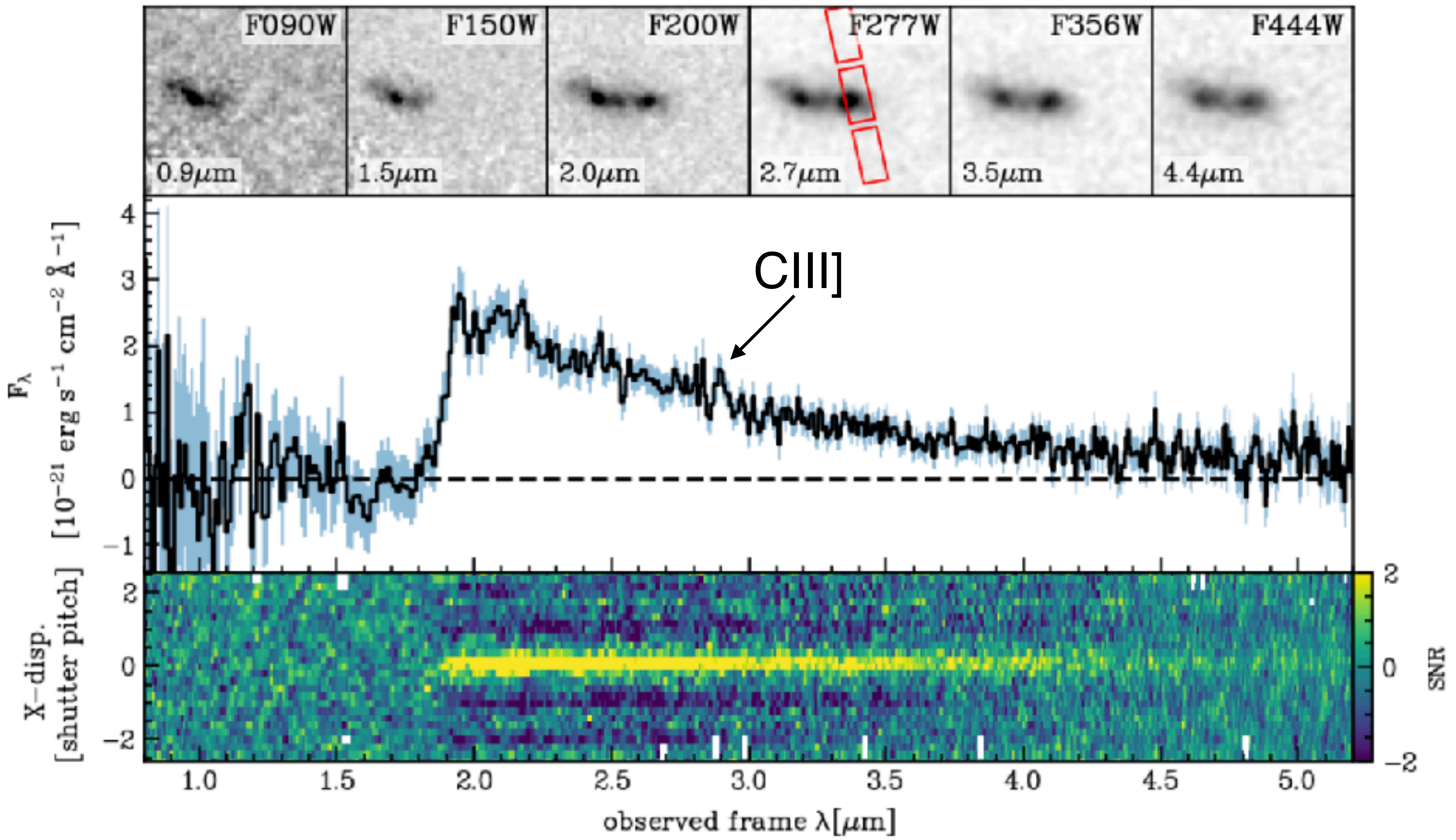


consistent with efficient BH formation in the early universe: heavy seeds? super-Eddington accretion?

Matthee+23, Scholtz+23, Harikane+23, Taylor+24, Maiolino+24, …

JADES-GS-z14-0: extended galaxy

Carniani+ 2024, Nature



redshift z=14.18 via Lyman break (damping wing!)

➜ extended (~200 pc), no indication for an AGN!
➜ enriched with 20% solar metallicity

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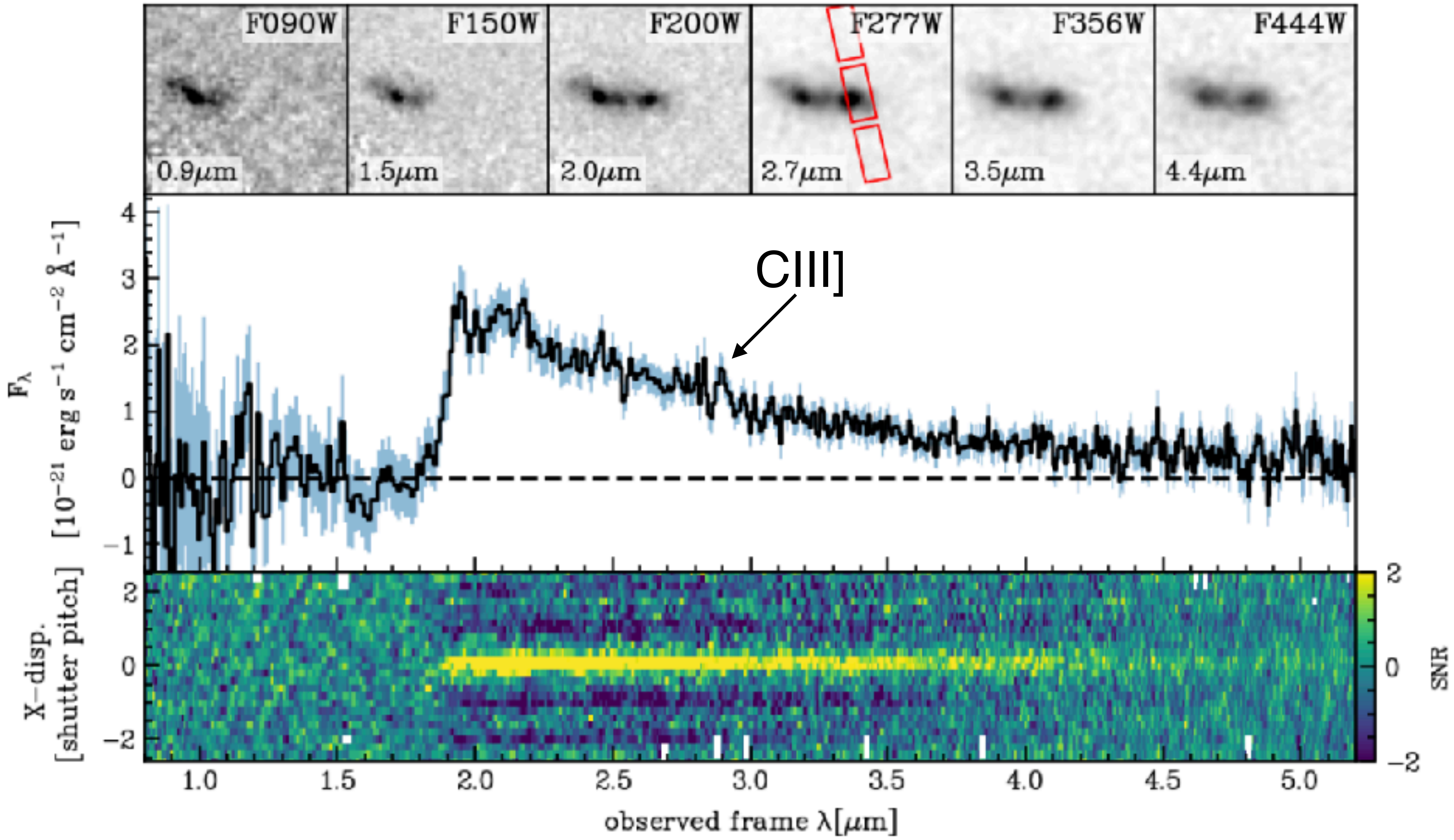
Carniani+ 2024, Nature



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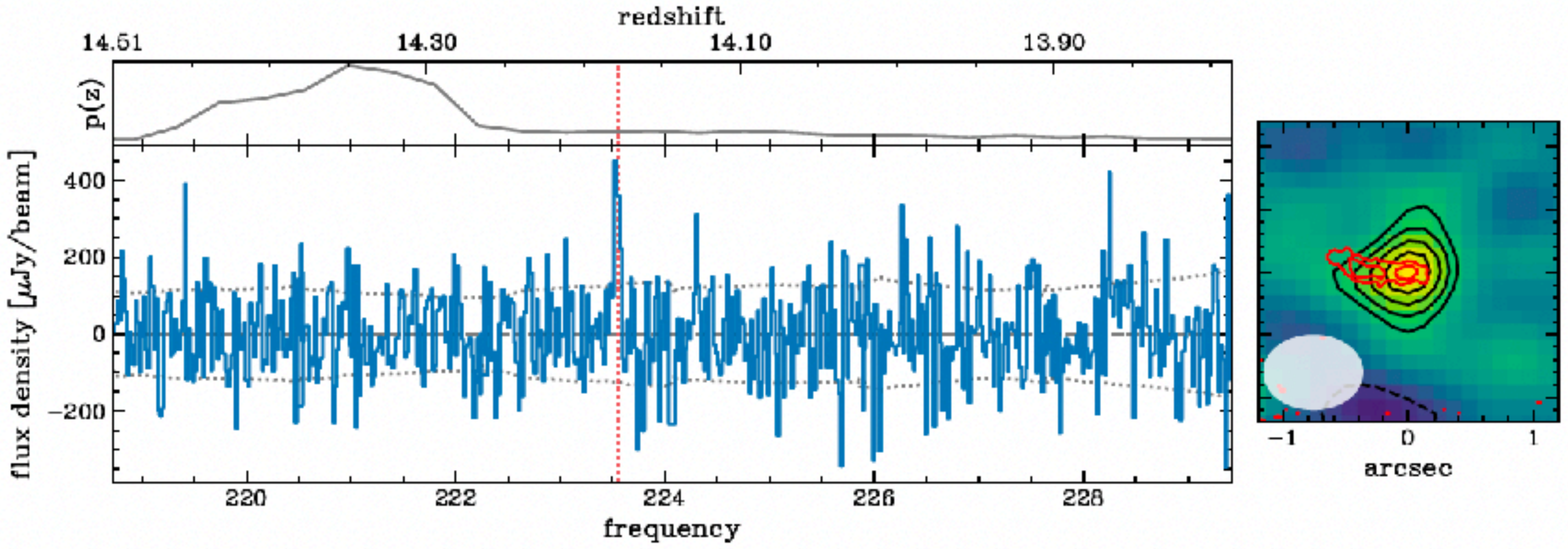
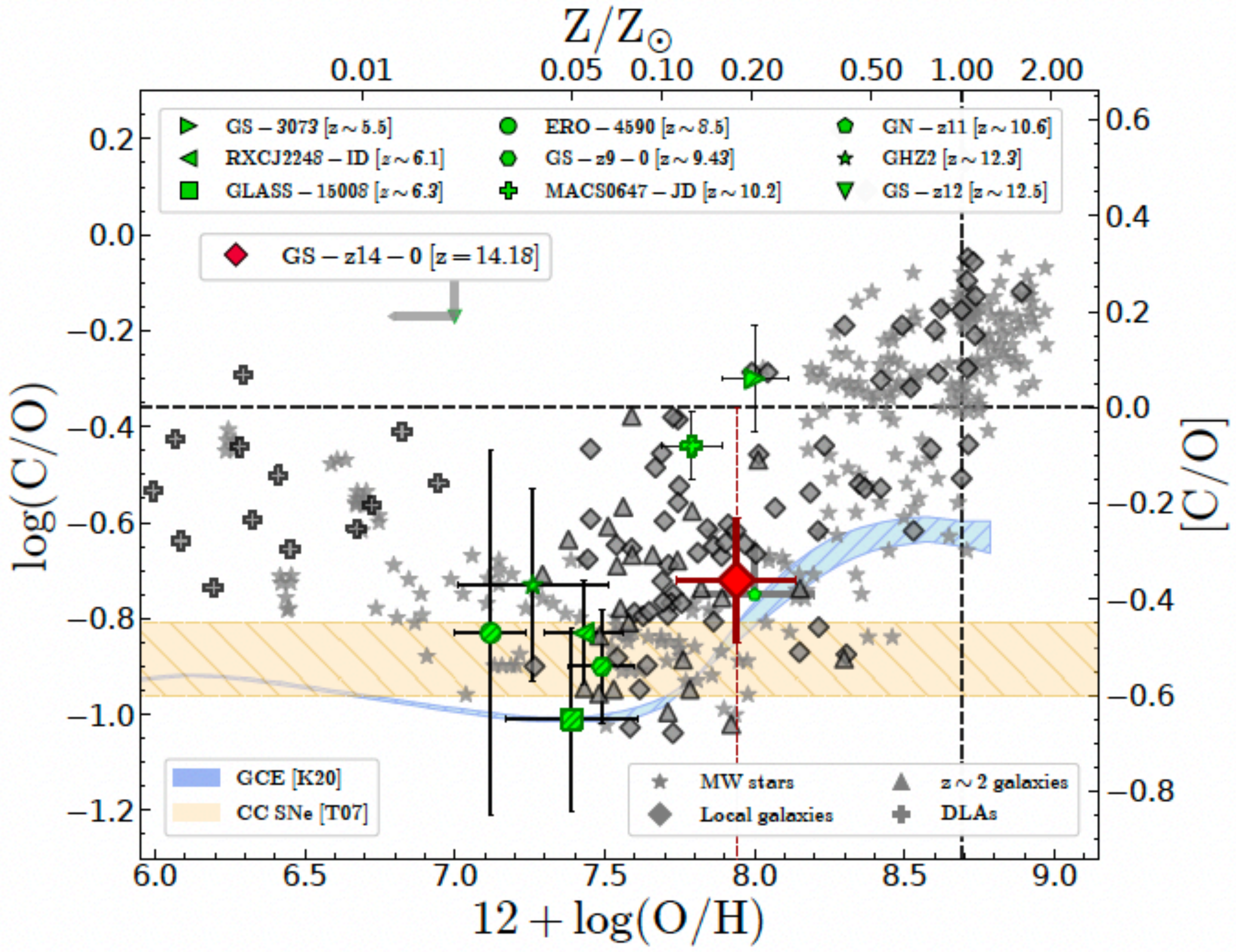


Detection of [OIII]88μm with ALMA

(Carniani+25, Schouws+25)



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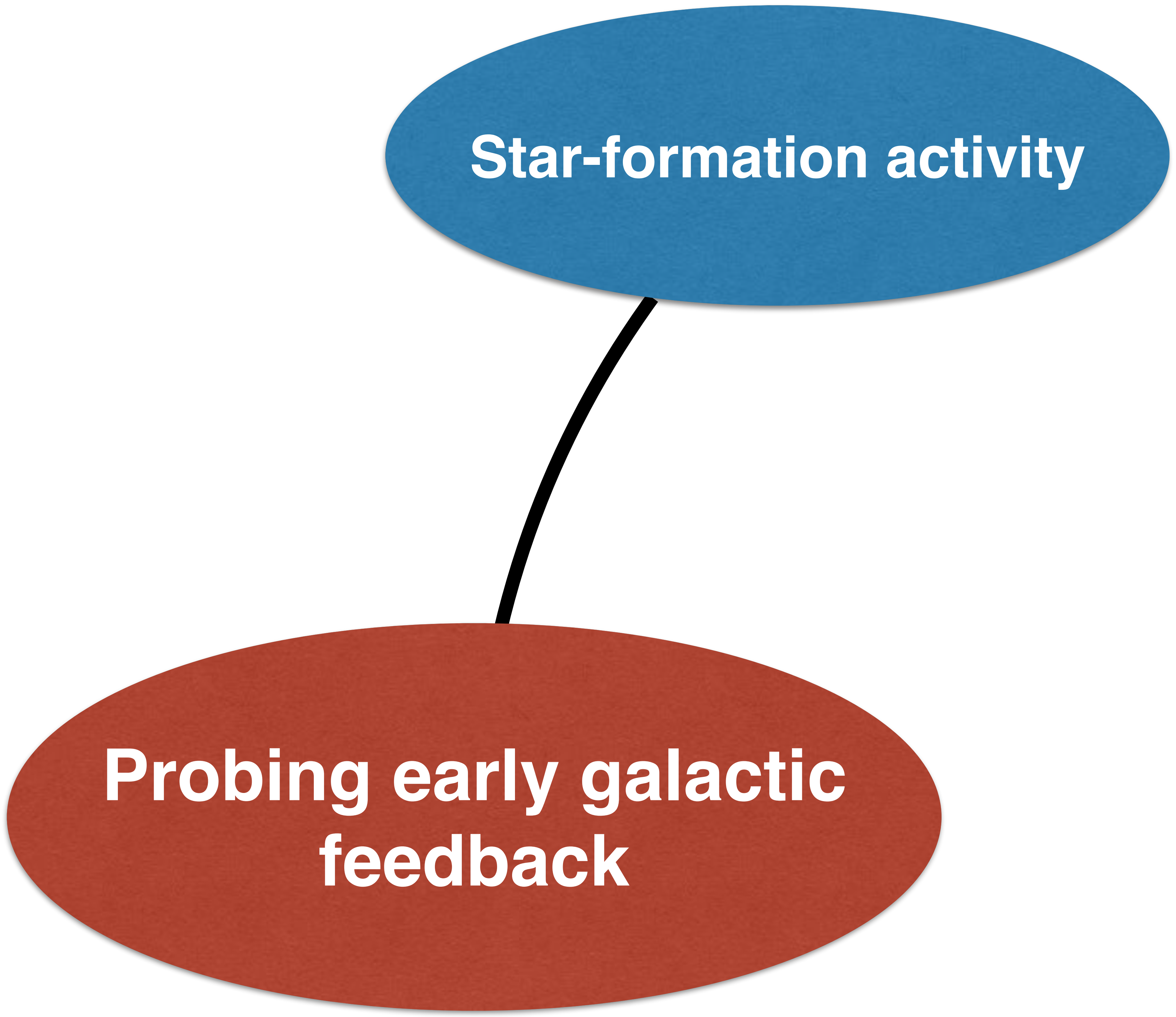

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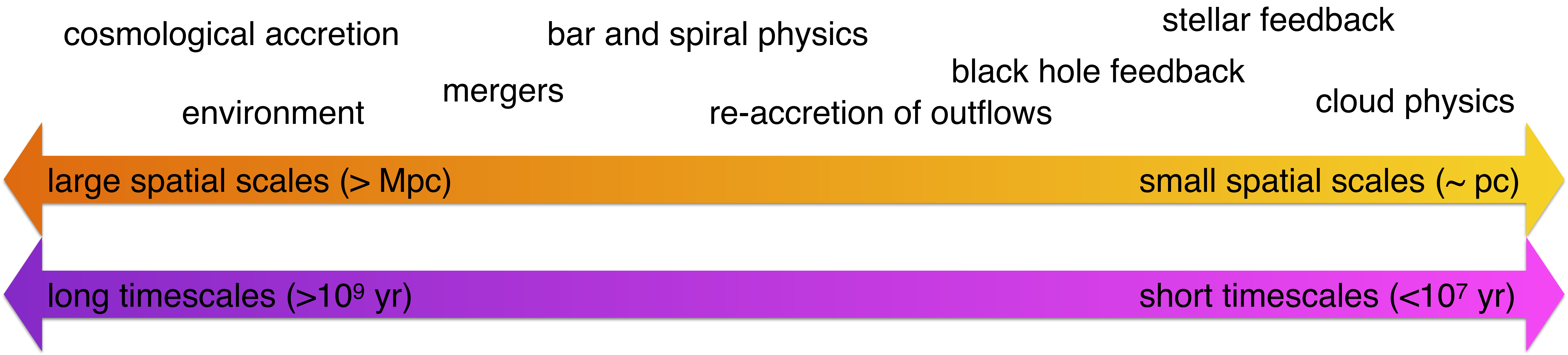
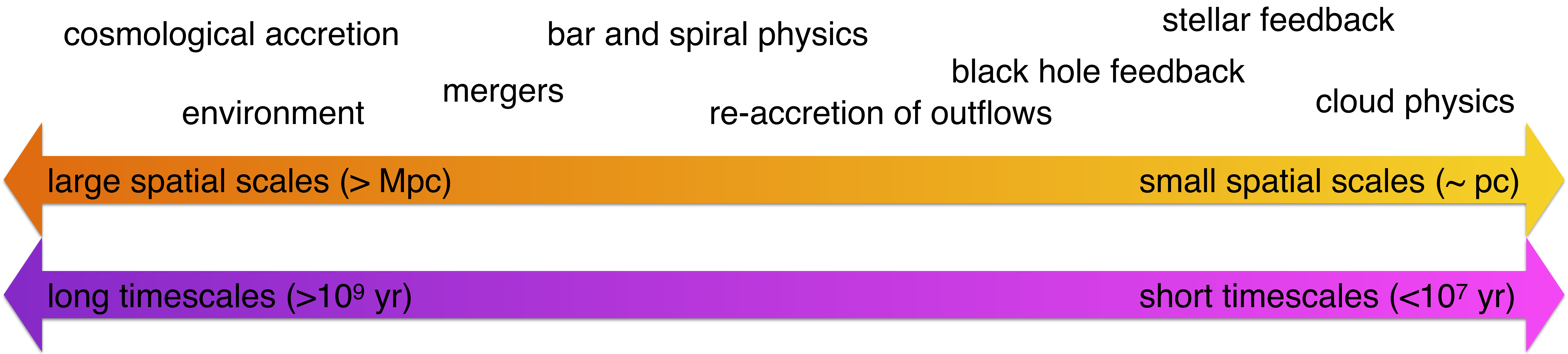
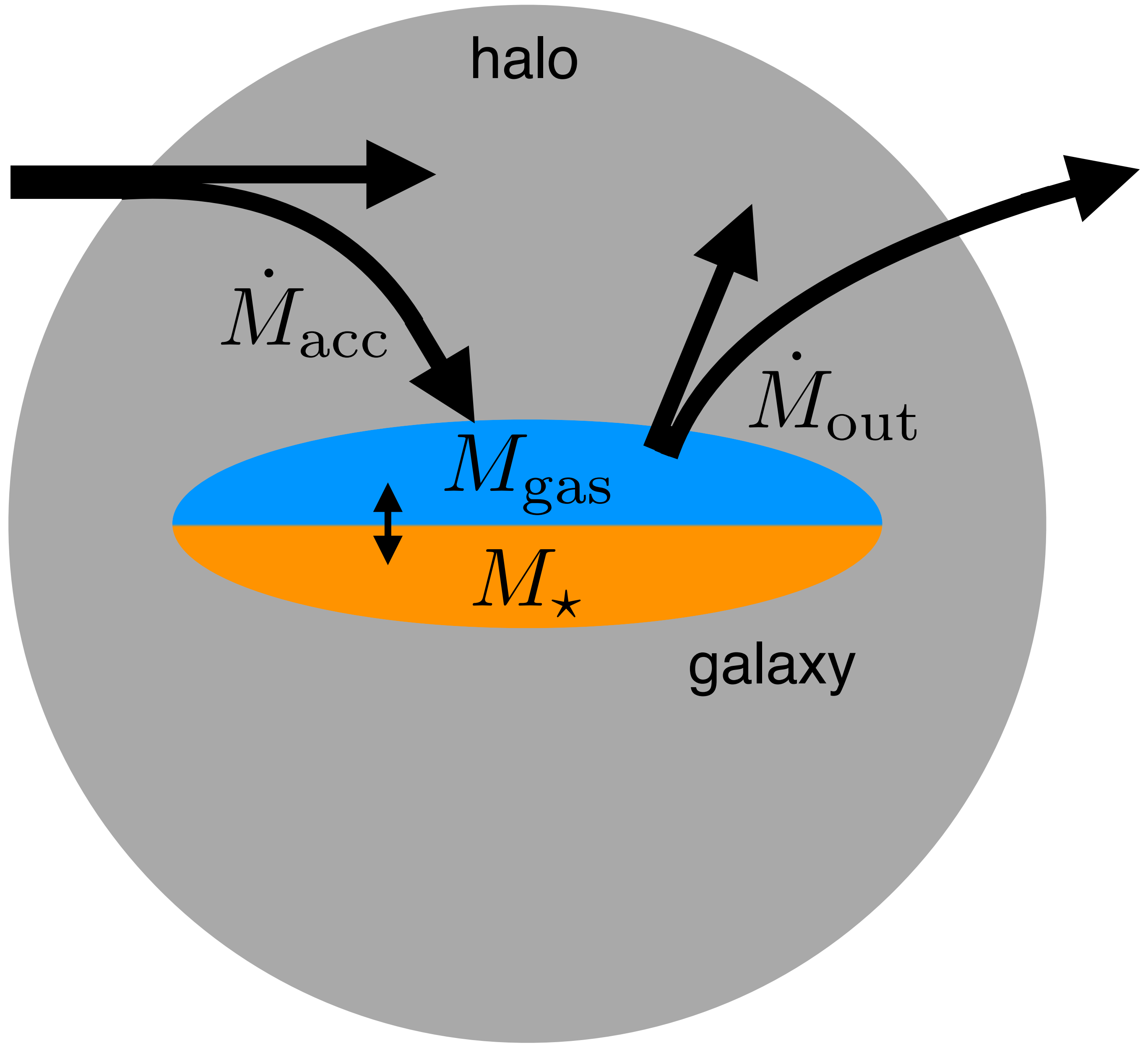
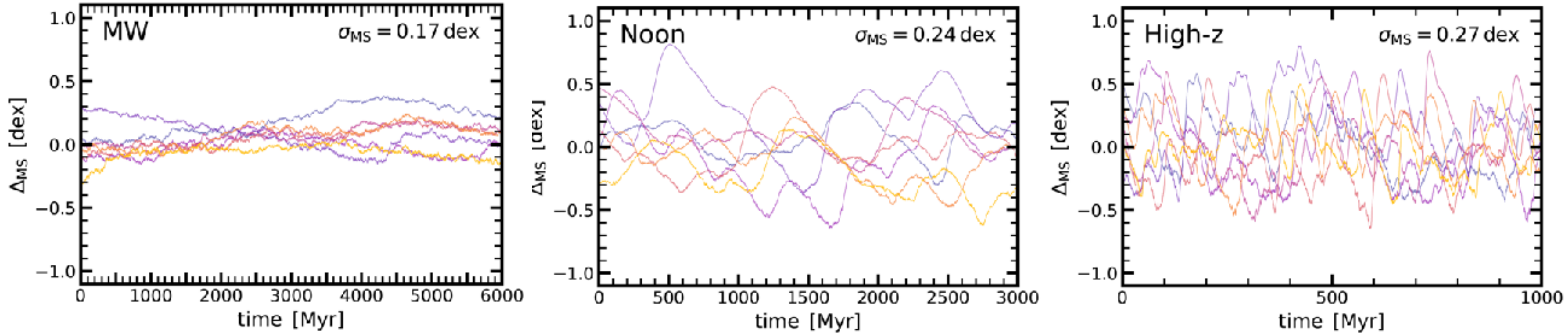
SFR function (~ UVLF)
SF variability (“burstiness”)


cosmological accretion
environment
mergers
bar and spiral physics
re-accretion of outflows
black hole feedback
stellar feedback
cloud physics
large spatial scales (> Mpc)
small spatial scales (~ pc)
long timescales (>10⁹ yr)
short timescales (<10⁷ yr)



- High-z galaxies cannot be resolved as local galaxies
  ➜ instead of spatially resolving galaxies, let's resolve them temporarily
- Temporal power spectral density (Caplar & Tacchella 19; Tacchella+20)
  ➜ bursty star formation at high redshifts:
  - external: stochastic inflow
  - internal: sampling and lifetime ("feedback") of individual SF regions
- same scatter σ can be caused by fluctuation on different timescale
  ➜ need to study σ as a function of timescale





Burstiness of star formation

➜ Wan, Tacchella+24
jaxified Prospector (Stoffers, in prep.)

Burstiness of star formation

- Burstiness (short-term fluctuations) of star formation: population property
  ➜ cannot asses this from an individual system

➜ Wan, Tacchella+24
jaxified Prospector (Stoffers, in prep.)

Burstiness of star formation

- Burstiness (short-term fluctuations) of star formation: population property
  ➜ cannot asses this from an individual system
- Two approaches:
  - Lick-like approach: measure SFRs from different indicators (emission lines, UV, etc.)
  ➜ challenges:
    - which timescale do these tracers probe?
    - source of emission lines (AGN vs stars; collisional vs recombination)
    - dust attenuation (law, absorption of LyC, stars vs nebular emission, …)
    - escape fractions
    - chemical abundance pattern (stars and gas)
    - stars: IMF, libraries, isochrones (binarity, rotation, etc.)

  ➜ bring the sims into the observational space (Katz+19,21,24; Tacchella+22; McClymont+25)

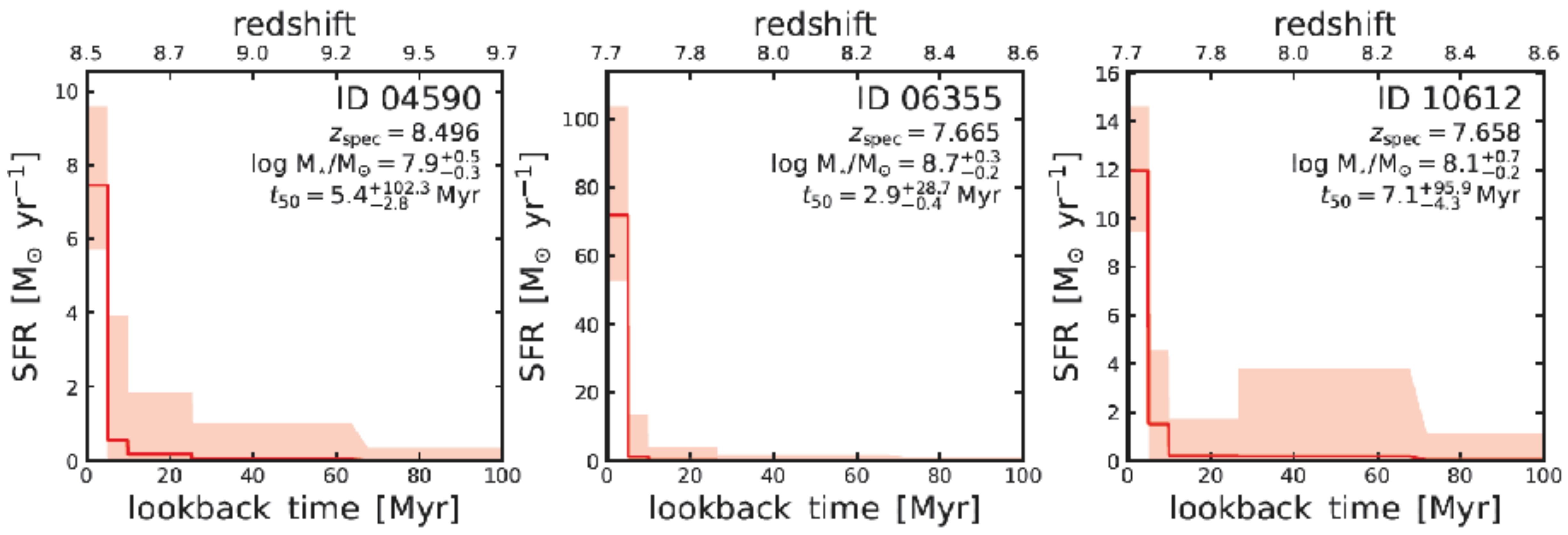
  - SED modelling: want to marginalise over above uncertainties, build Bayesian hierarchical model
  ➜ challenges:
    - spectral sensitivity falls off ~ log(lookback time)
    - emission lines with broad-band photometry needs to be modelled consistently
    - priors on the SFH matter a lot
    - insitu vs exsitu

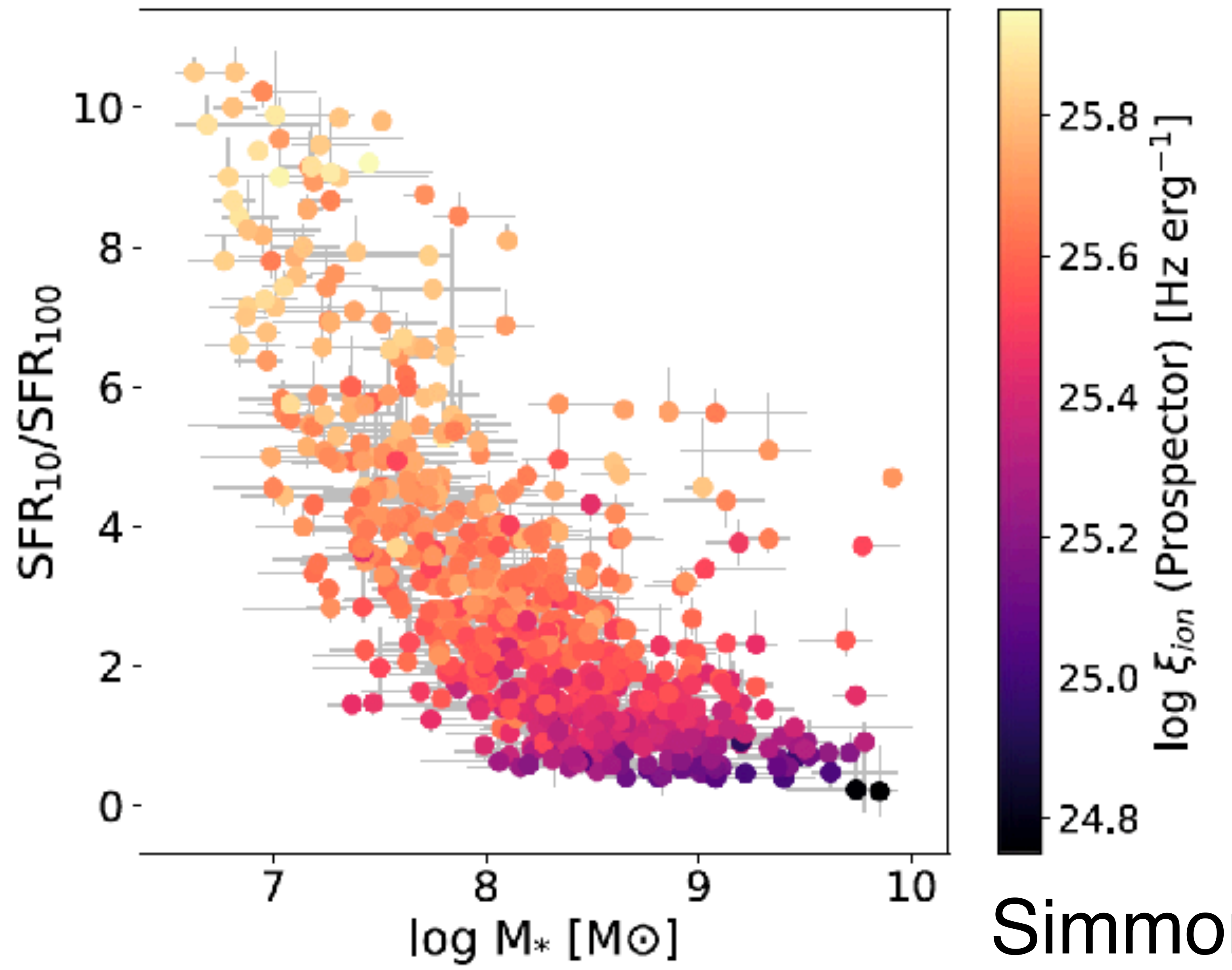
  ➜ Wan, Tacchella+24 jaxified Prospector (Stoffers, in prep.)

Observing bursty galaxies… in the ups

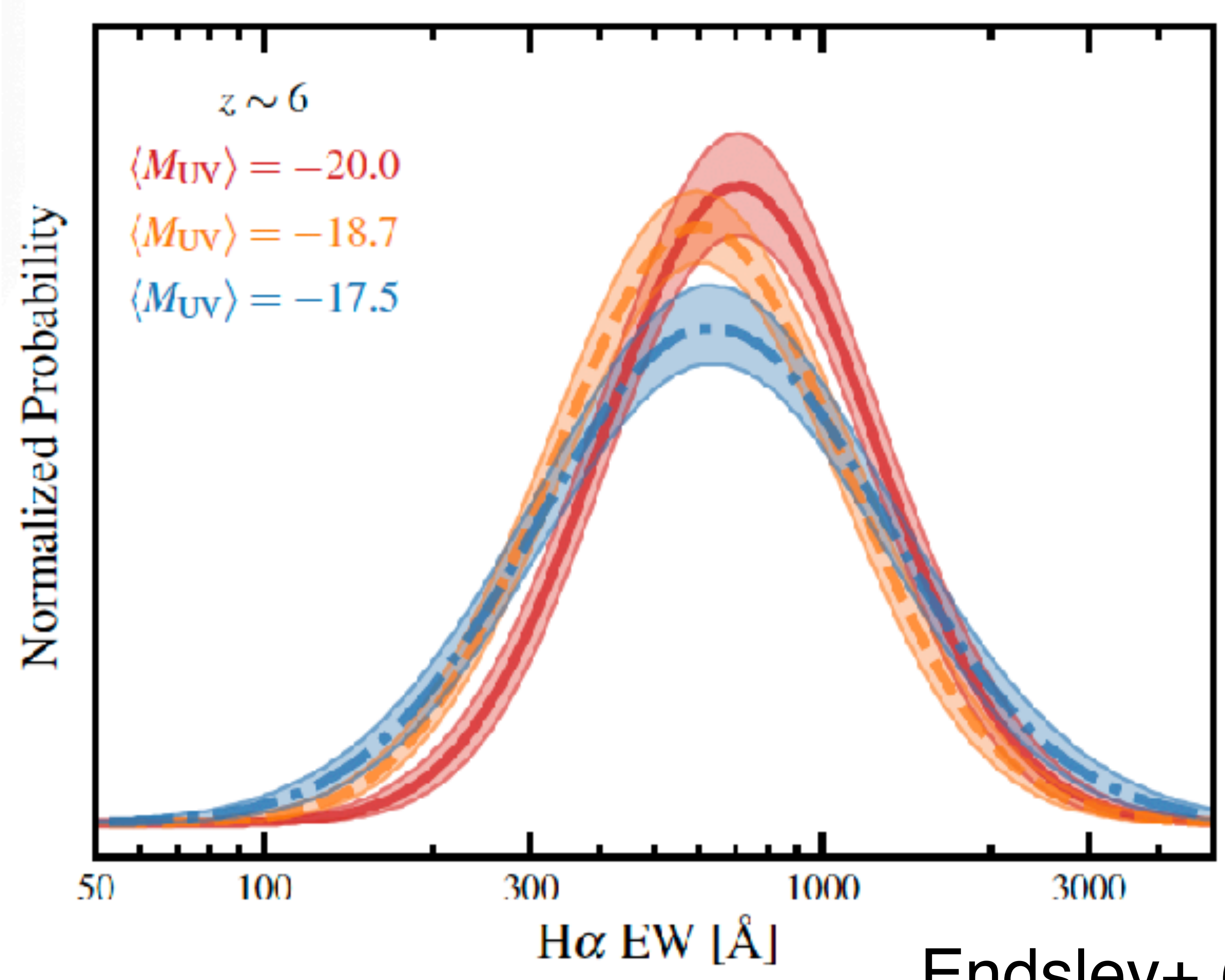
- Thanks to medium-band photometry and spectroscopy: clear indications for **upturns** of the recent star-formation histories of galaxies at z~6 (e.g., Endlsey+23, Simmonds+24, Tacchella+23)
- Strong emission line contribution can complicate interpretation of Balmer breaks (medium-bands!)
- Significant biases at low stellar masses

Tacchella+ (2023)



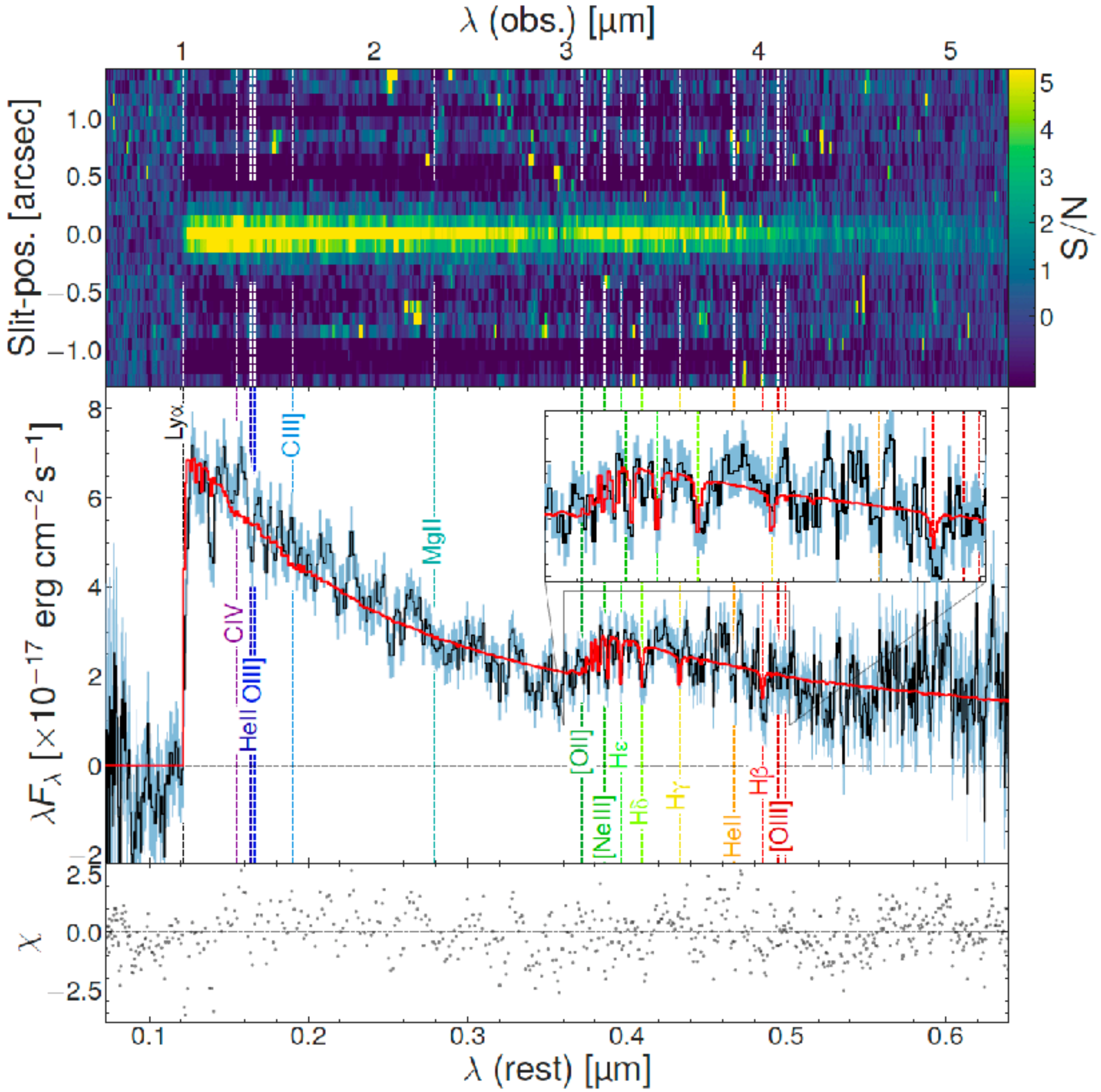


Simmonds+ (2024)



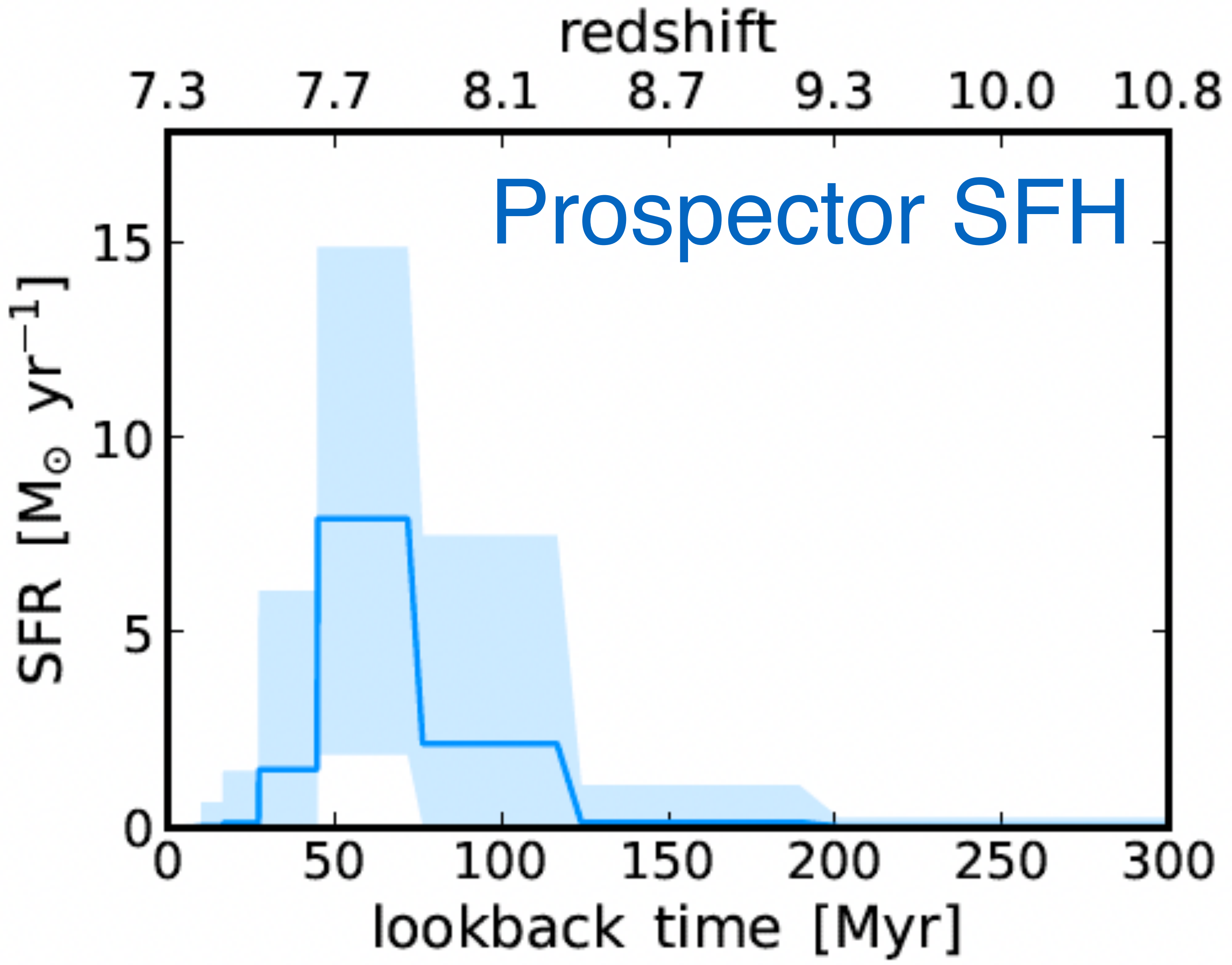
Endsley+ (2023)

Observing bursty galaxies… in the lows



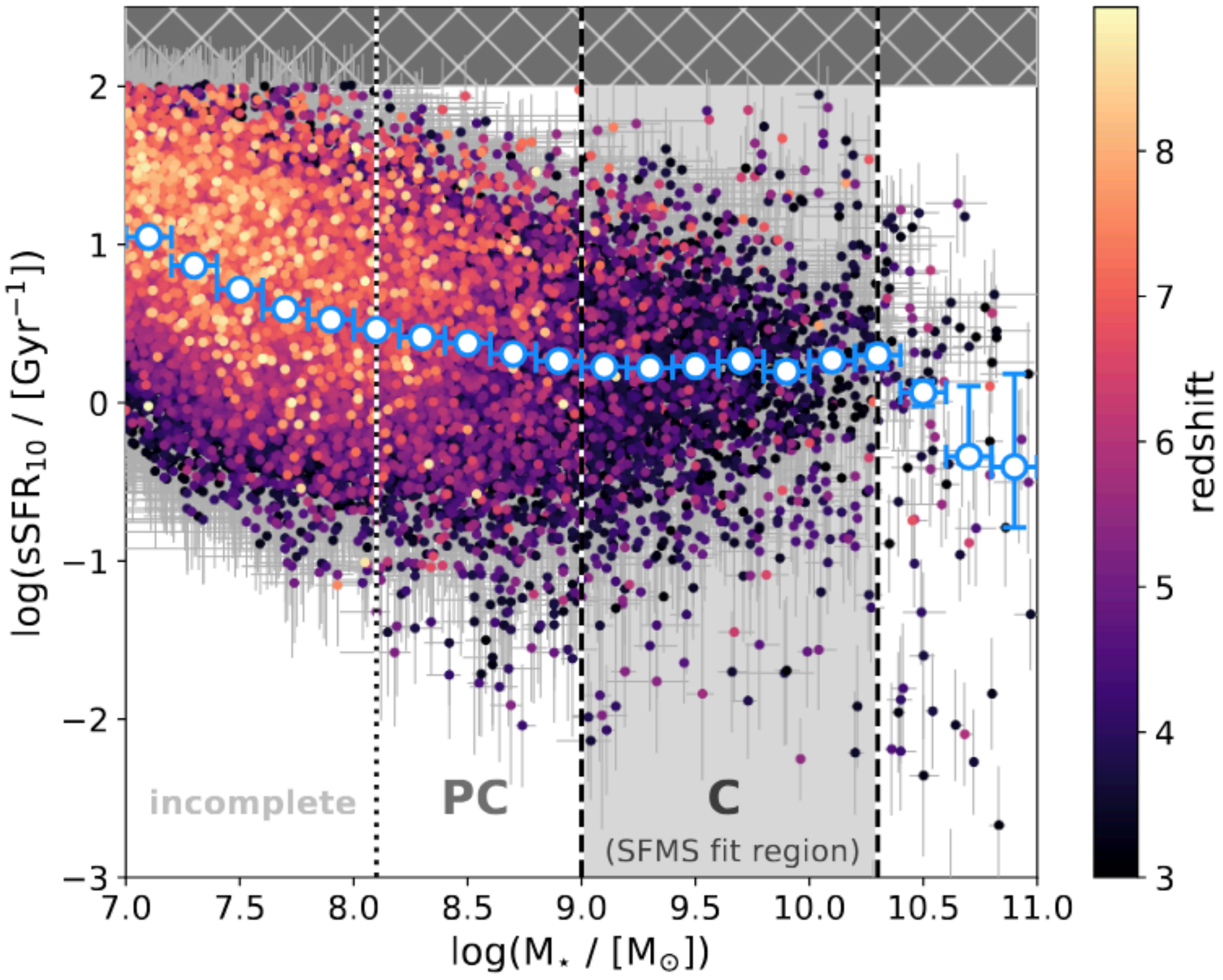
- We find several low-SFR systems in JADES
  ➜ consistent with **mini-quenching** as part of bursty SF
- Number density and duty cycle is sensitive probe of feedback (Dome+24;25; Gelli+25)

Looser+ (2024)



Scatter of the SFMS

~20k galaxies at z~3-9 from JADES photometry



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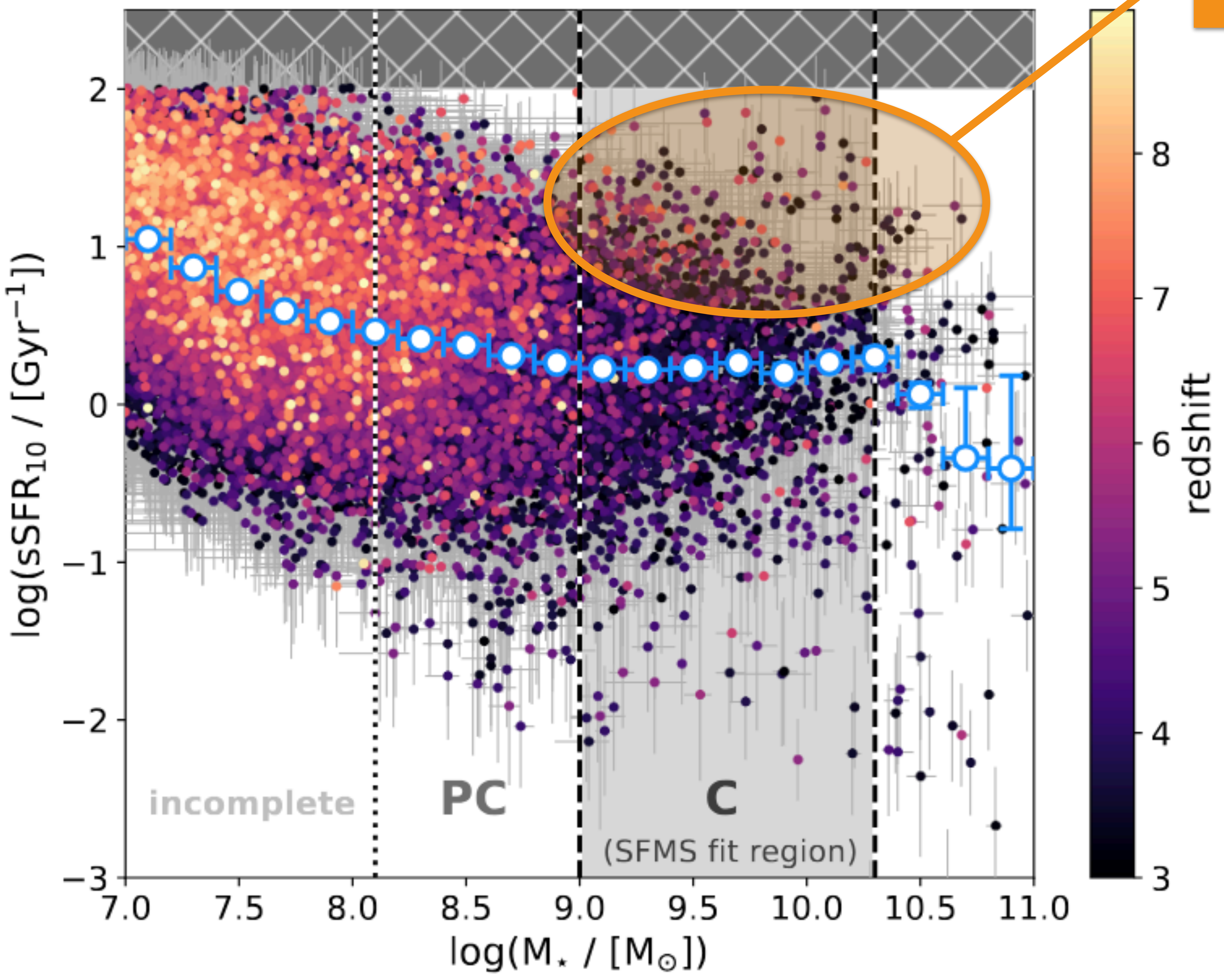

Spectroscopic samples are biased to highly SF objects!
➜ need to combine phot + spec sample

Scatter of the SFMS

Simmonds+ (in prep.)

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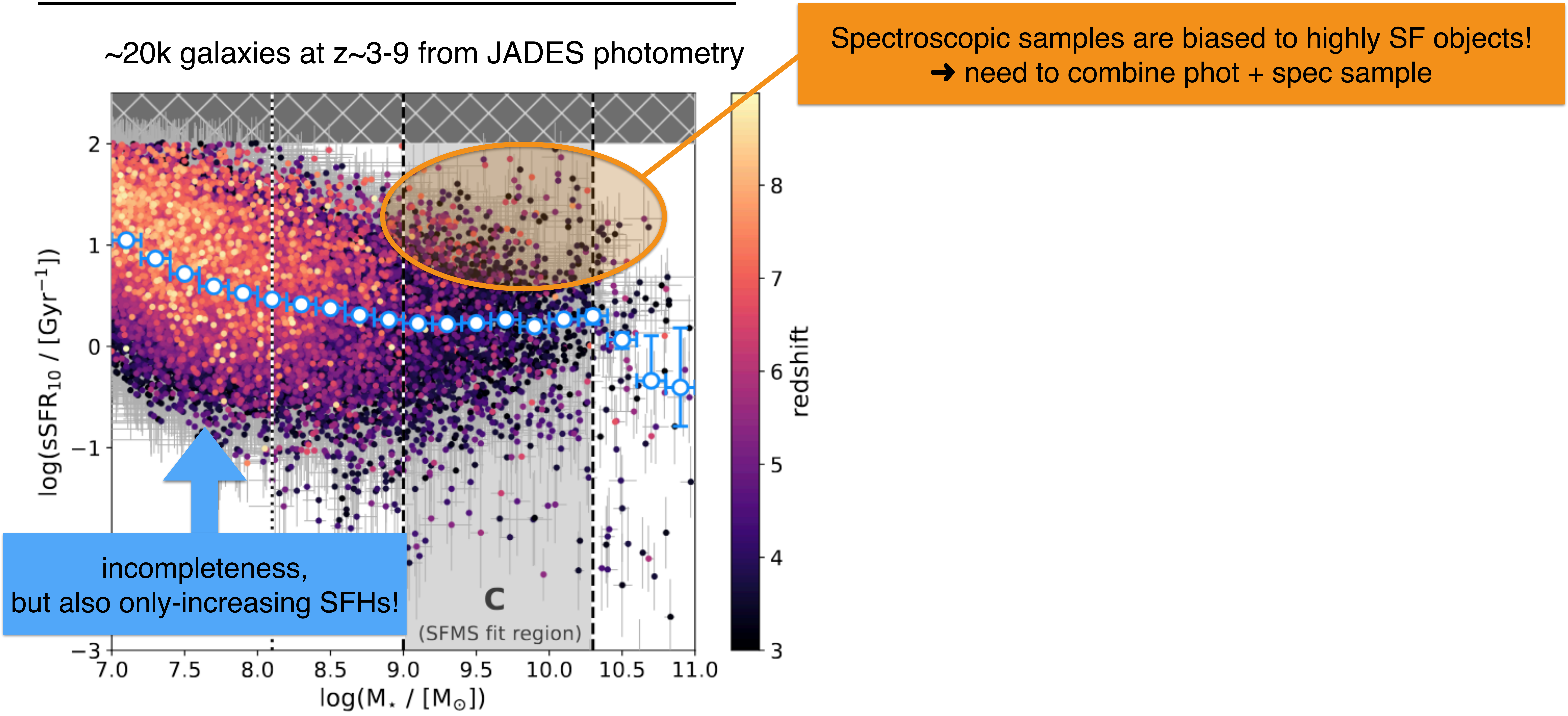

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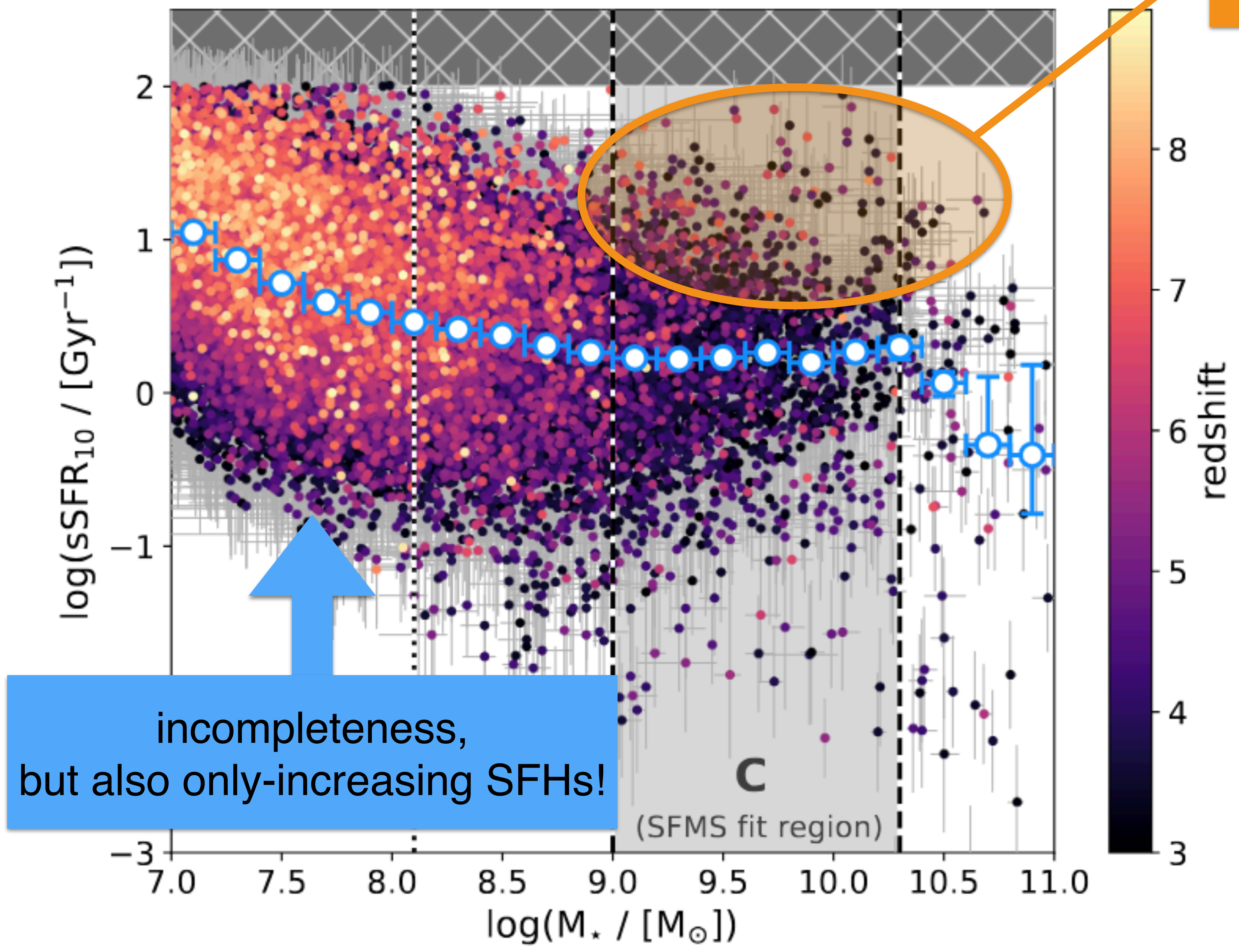

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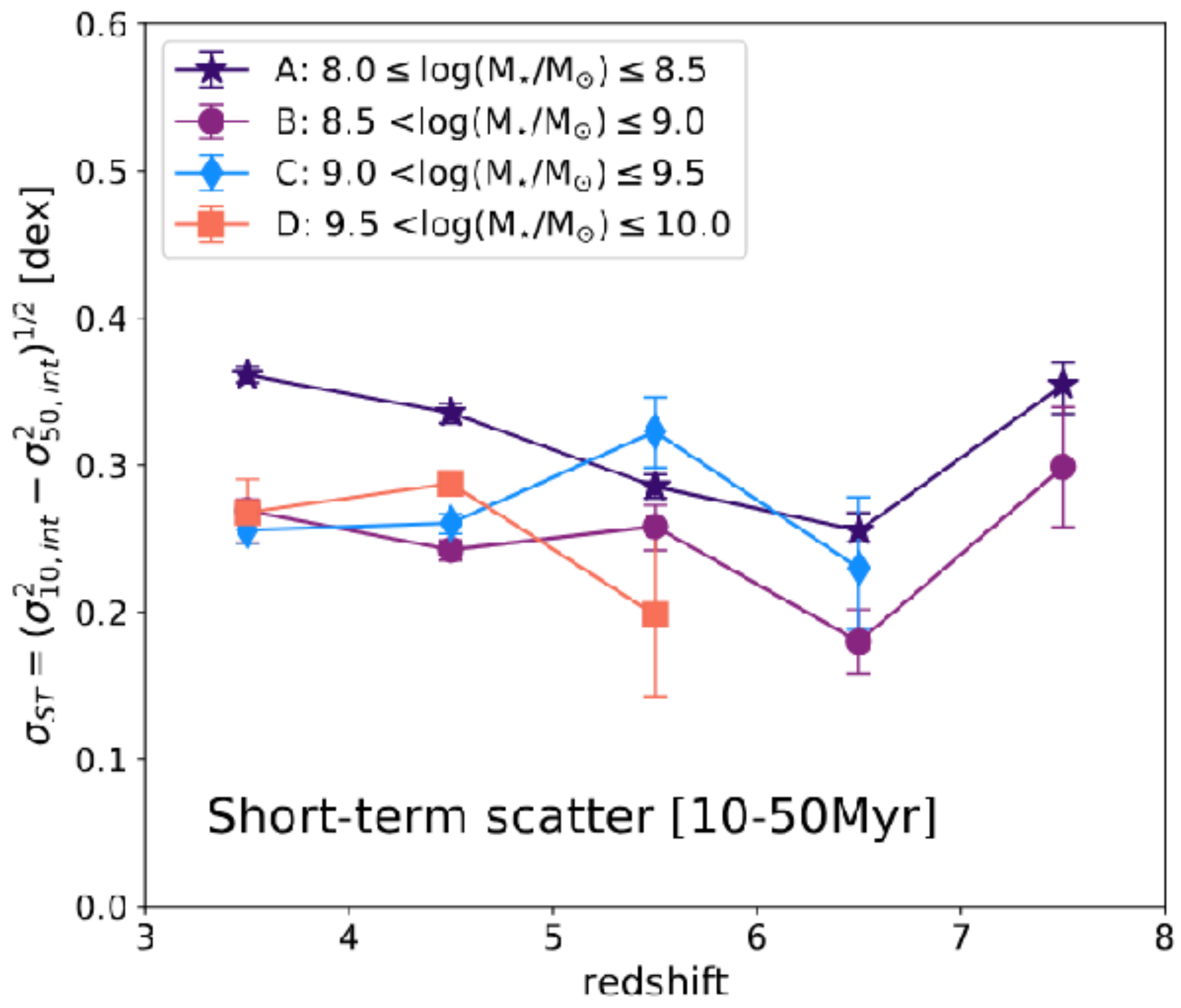
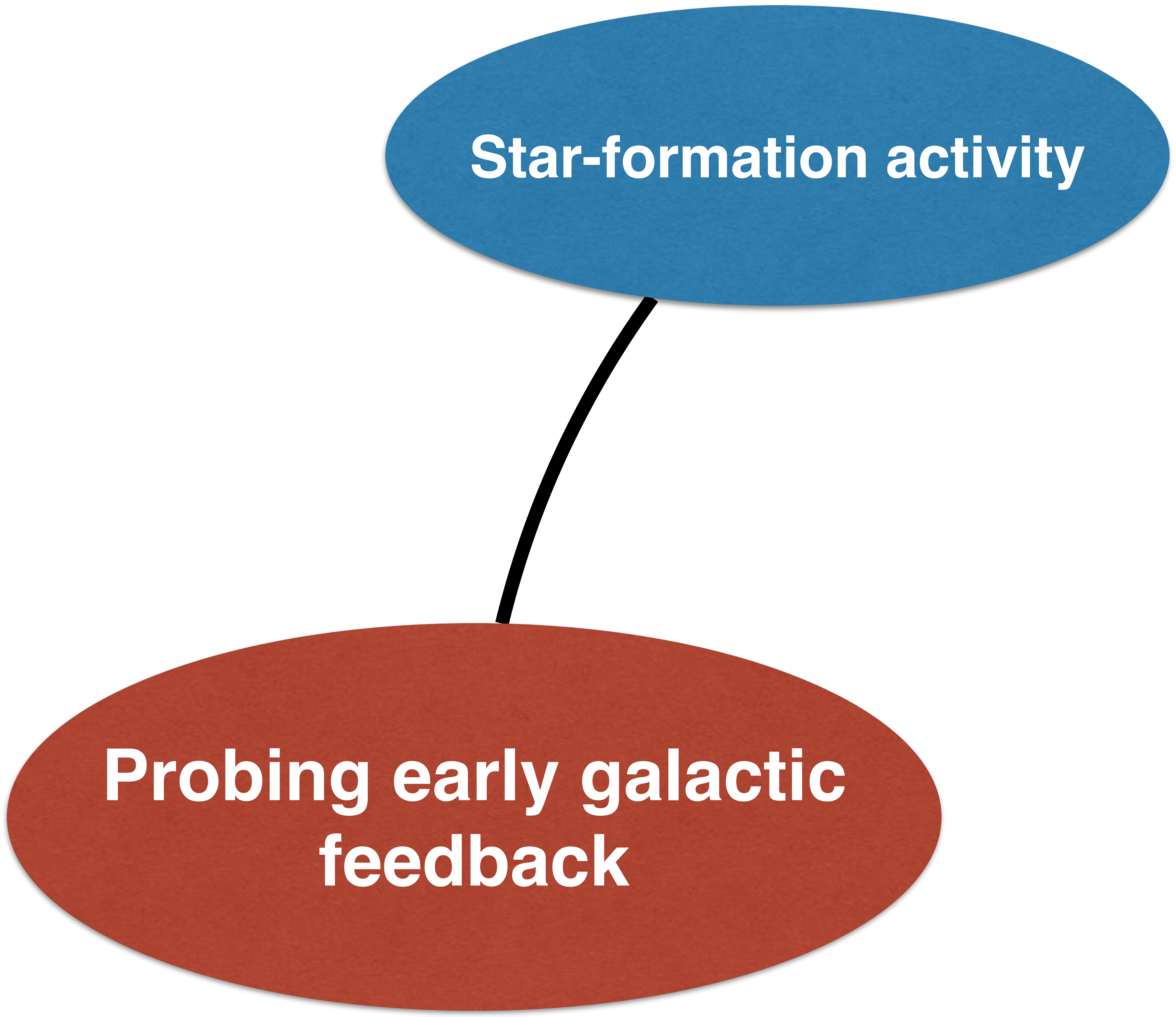


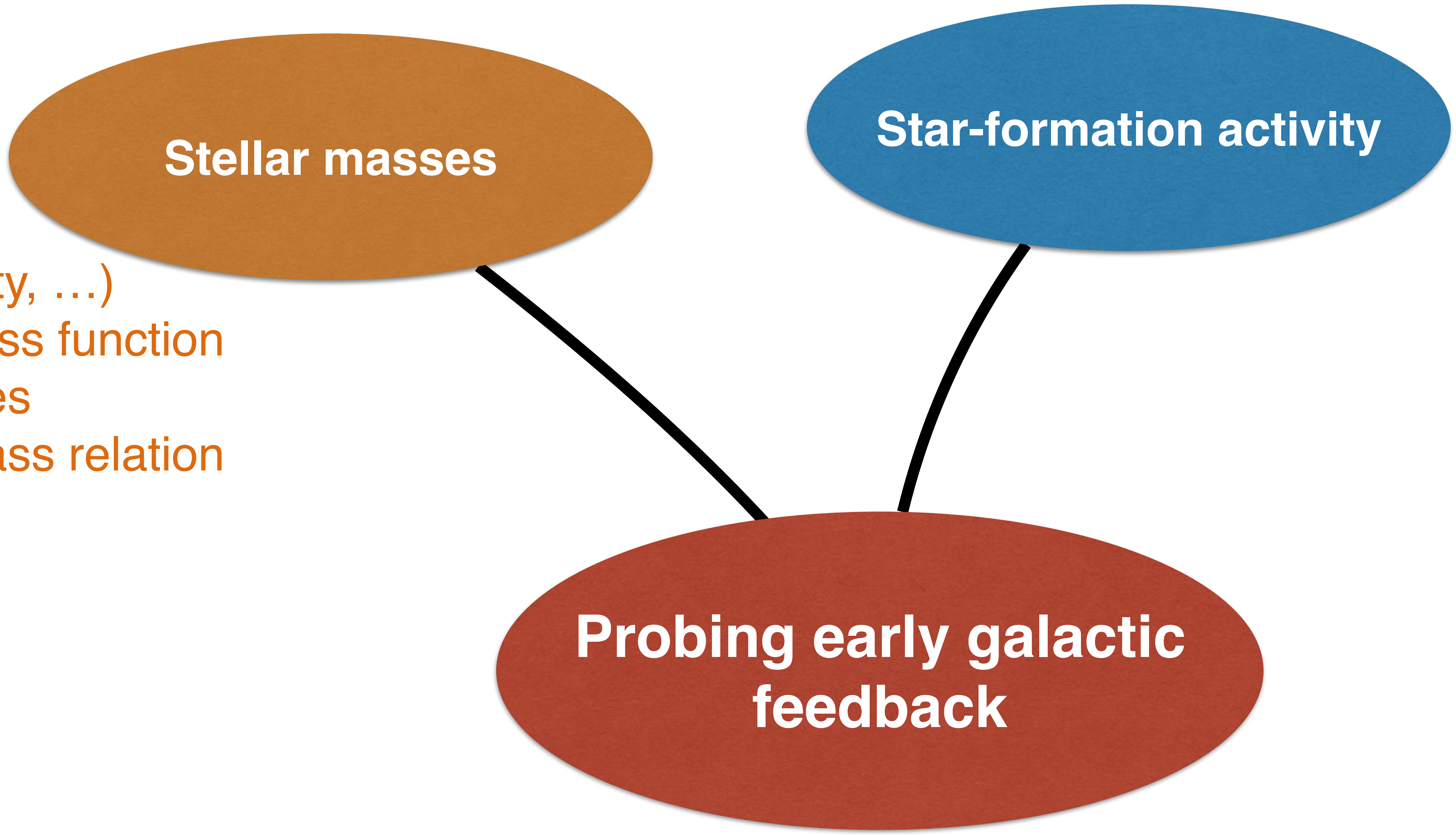
- Short-term variability (e.g. burstiness) is the highest for low-mass galaxies, with a weak redshift trend.

Overview



SF scaling relations (SFMS, KS)
SFR function (~ UVLF)
SF variability (“burstiness”)

Overview



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stars (IMF, binarity, …)
galaxy stellar mass function
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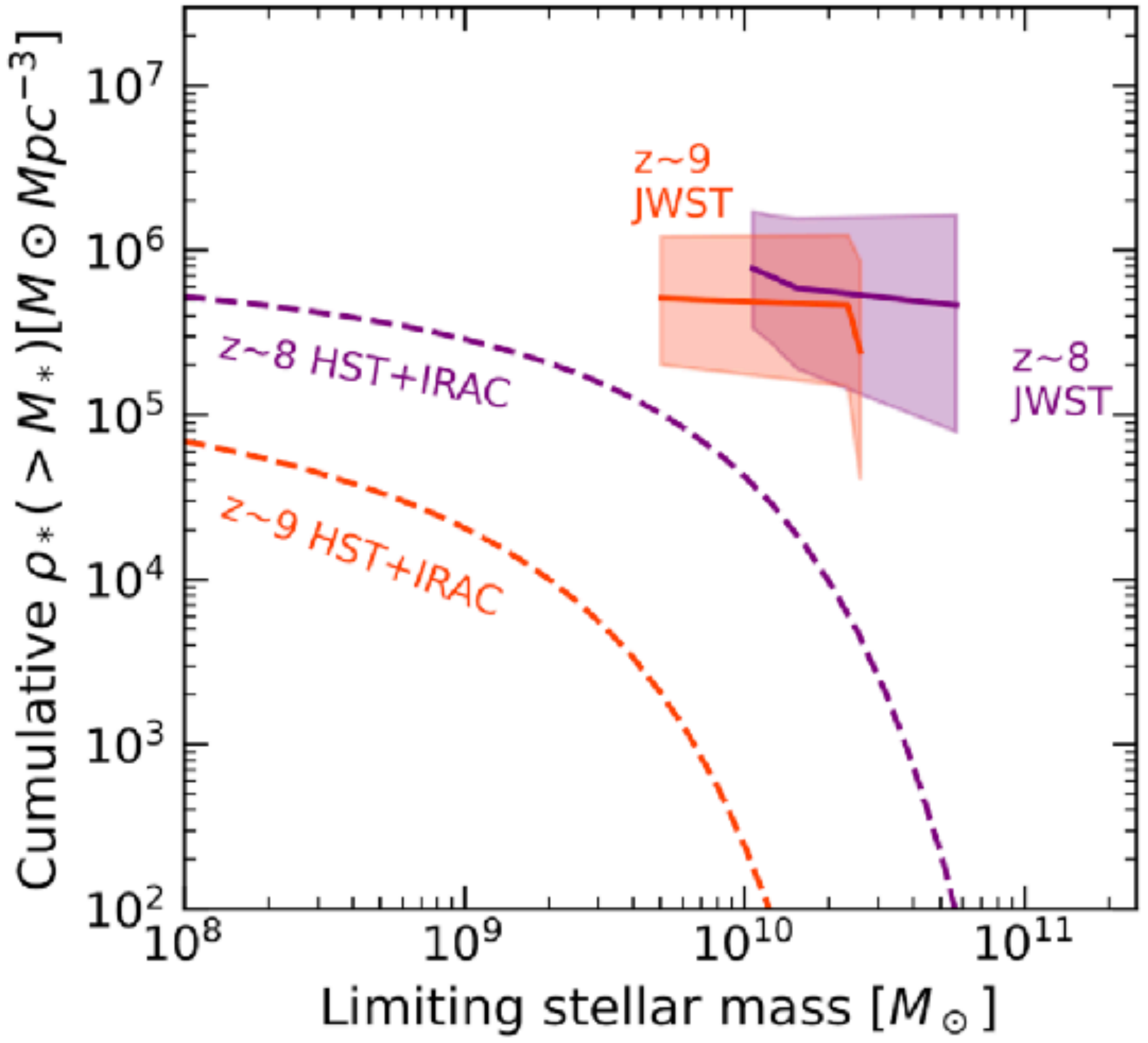
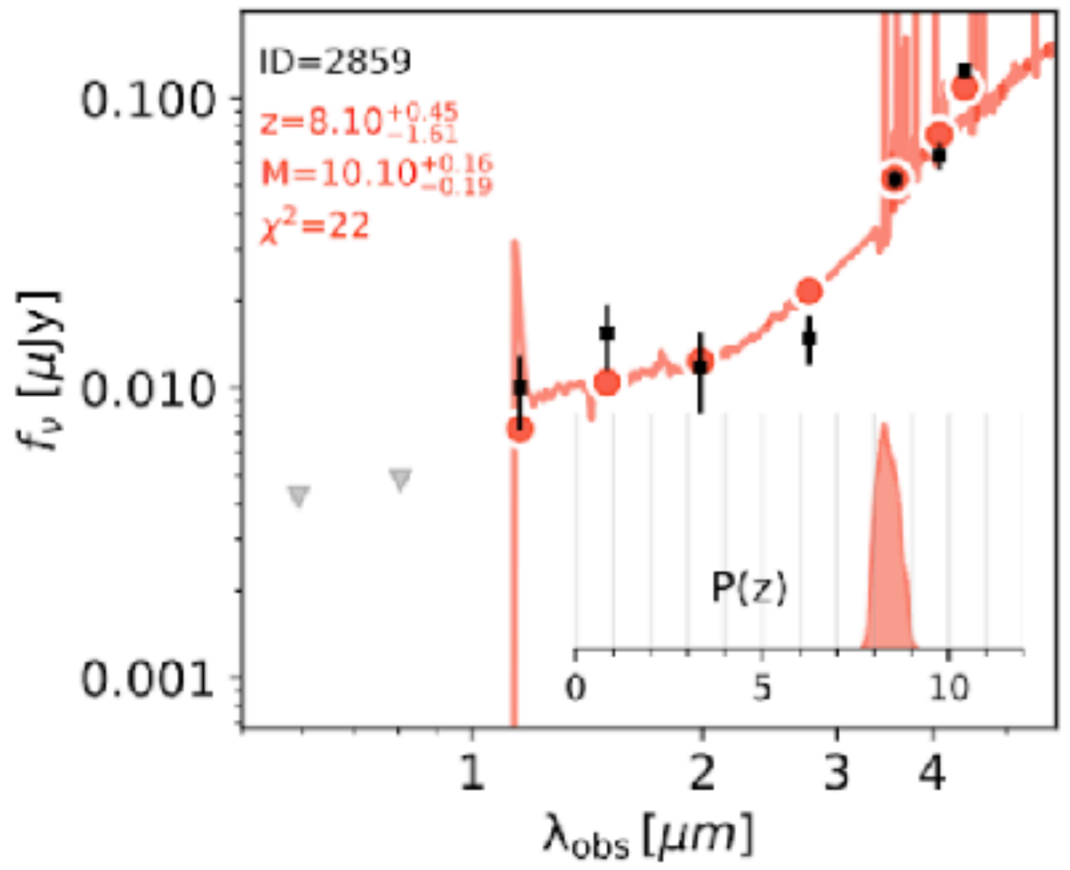
stellar-to-halo mass relation

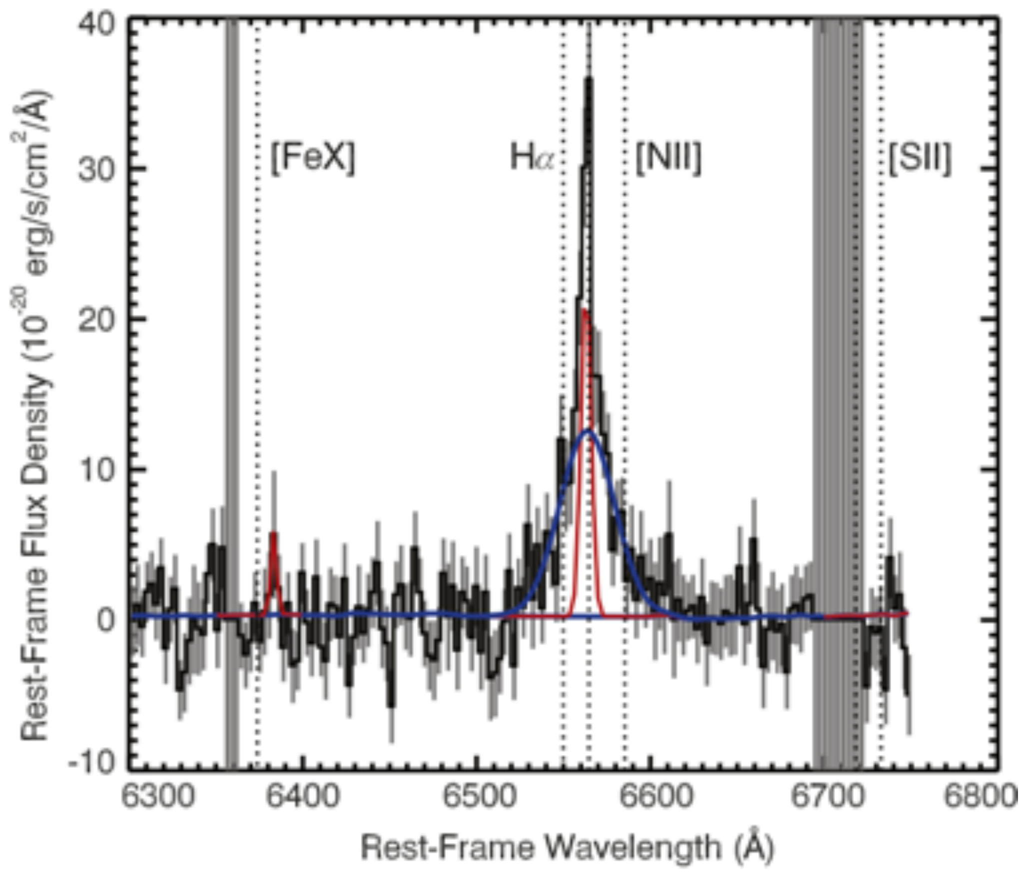
Stellar masses… overly massive galaxies?

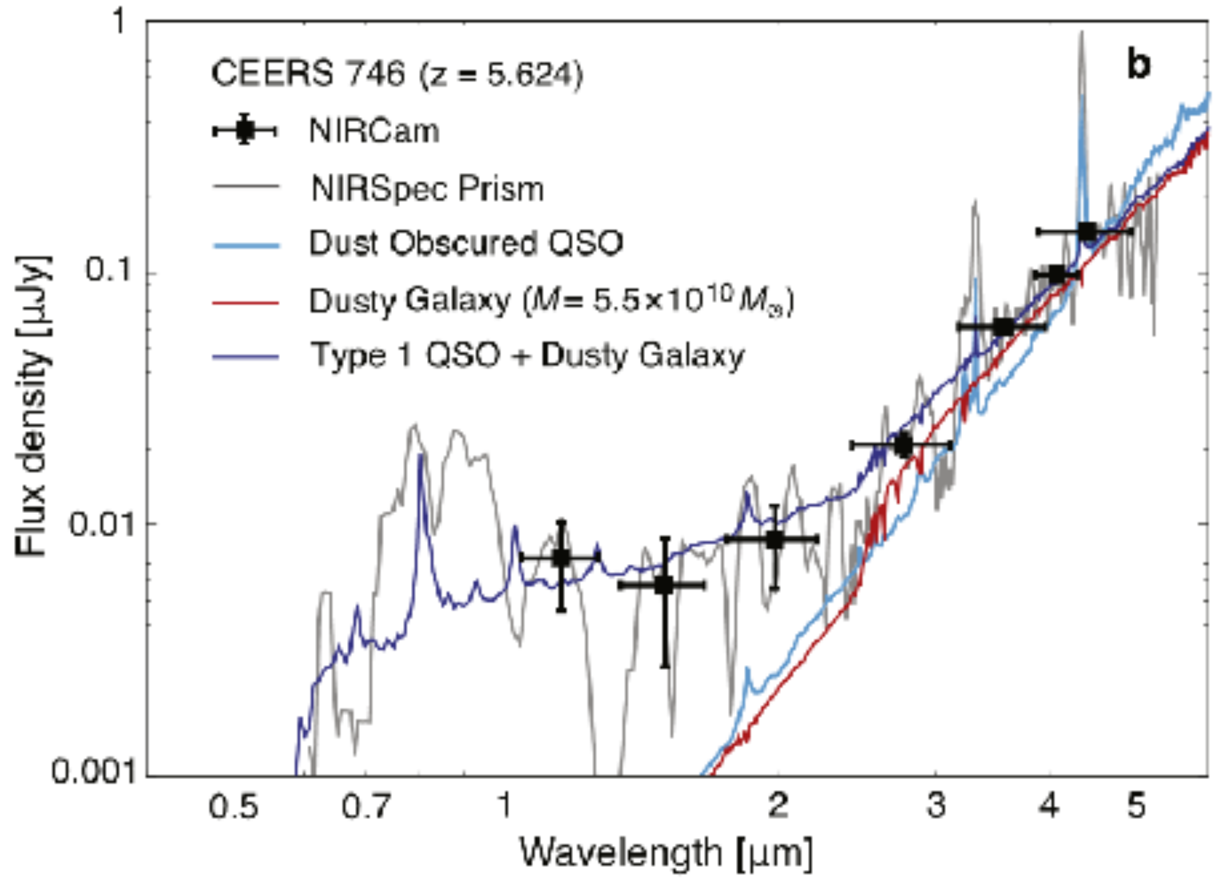
- Estimating stellar masses is challenging at high redshift:
  wrong distances (i.e. photo-z), uncertainties in estimating stellar masses (stellar population model [incl. IMF], emission lines vs Balmer break, outshining, SFH prior, dust attenuation, AGN)
- Most massive galaxies: constraints on SFE ($M_{\star}/(f_b x M_h)$) [and could challenge ΛCDM]
  - Labbé+ (2023): six massive galaxies (stellar mass > 10^{10} $M_{\odot}$) at $7.4 \leq z \leq 9.1$, based on photometry
    ➜ the stellar mass density in massive galaxies would be much higher than anticipated
    ➜ AGN (Xray detections), emission line contributions to photometry, wrong redshift (Kocevski+23, Endsley+23)





Labbé+23





Kocevski+23

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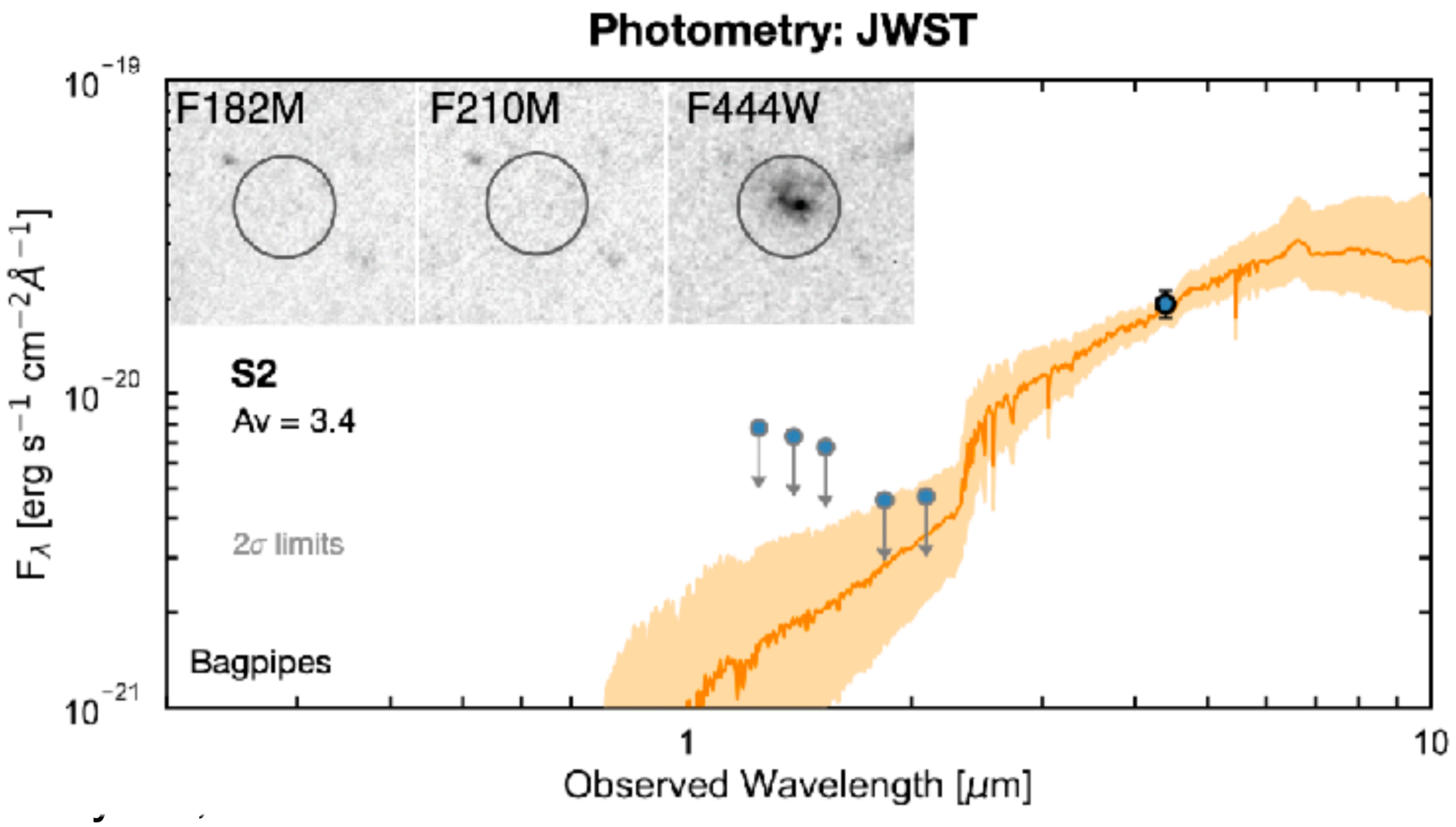
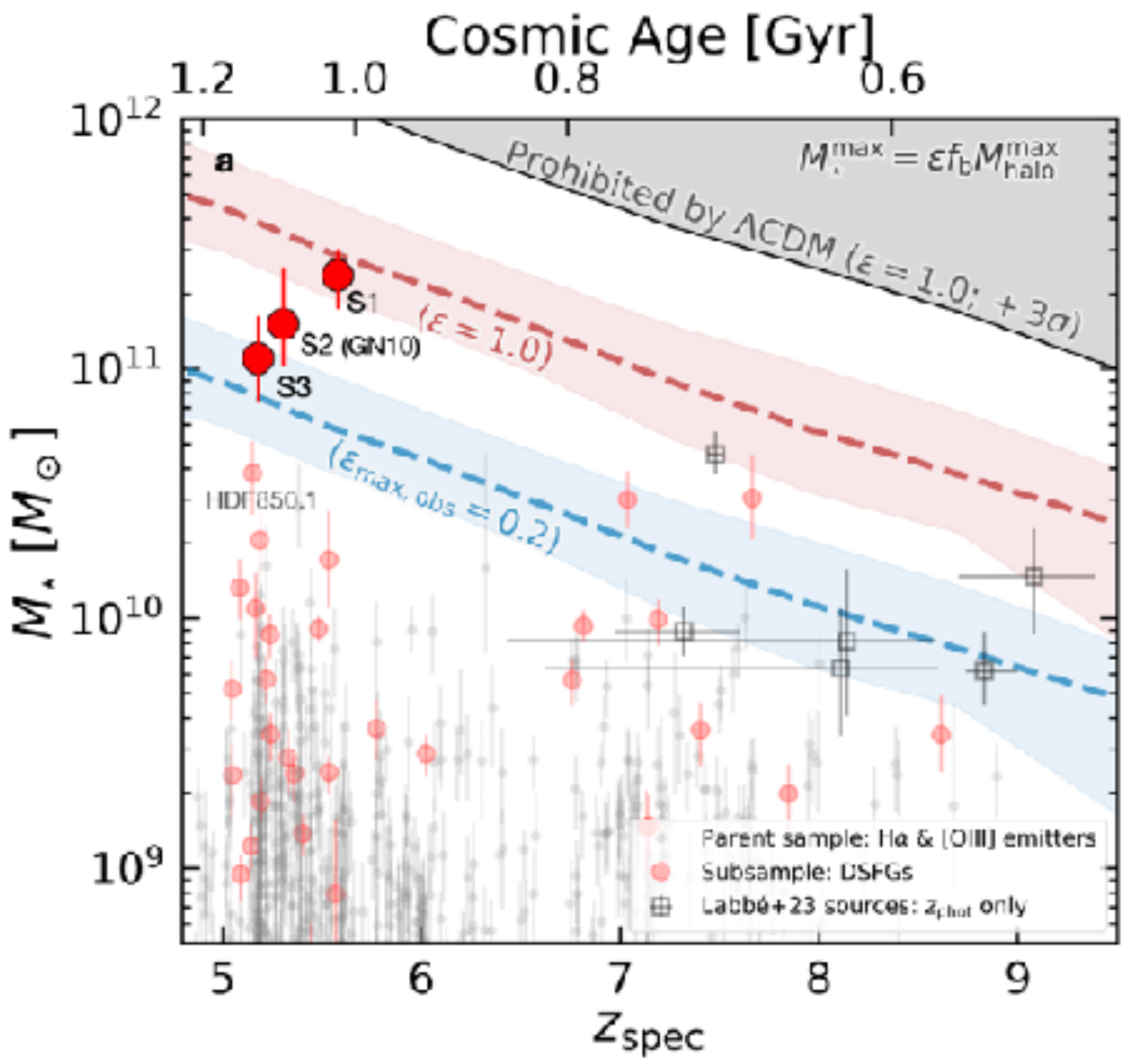
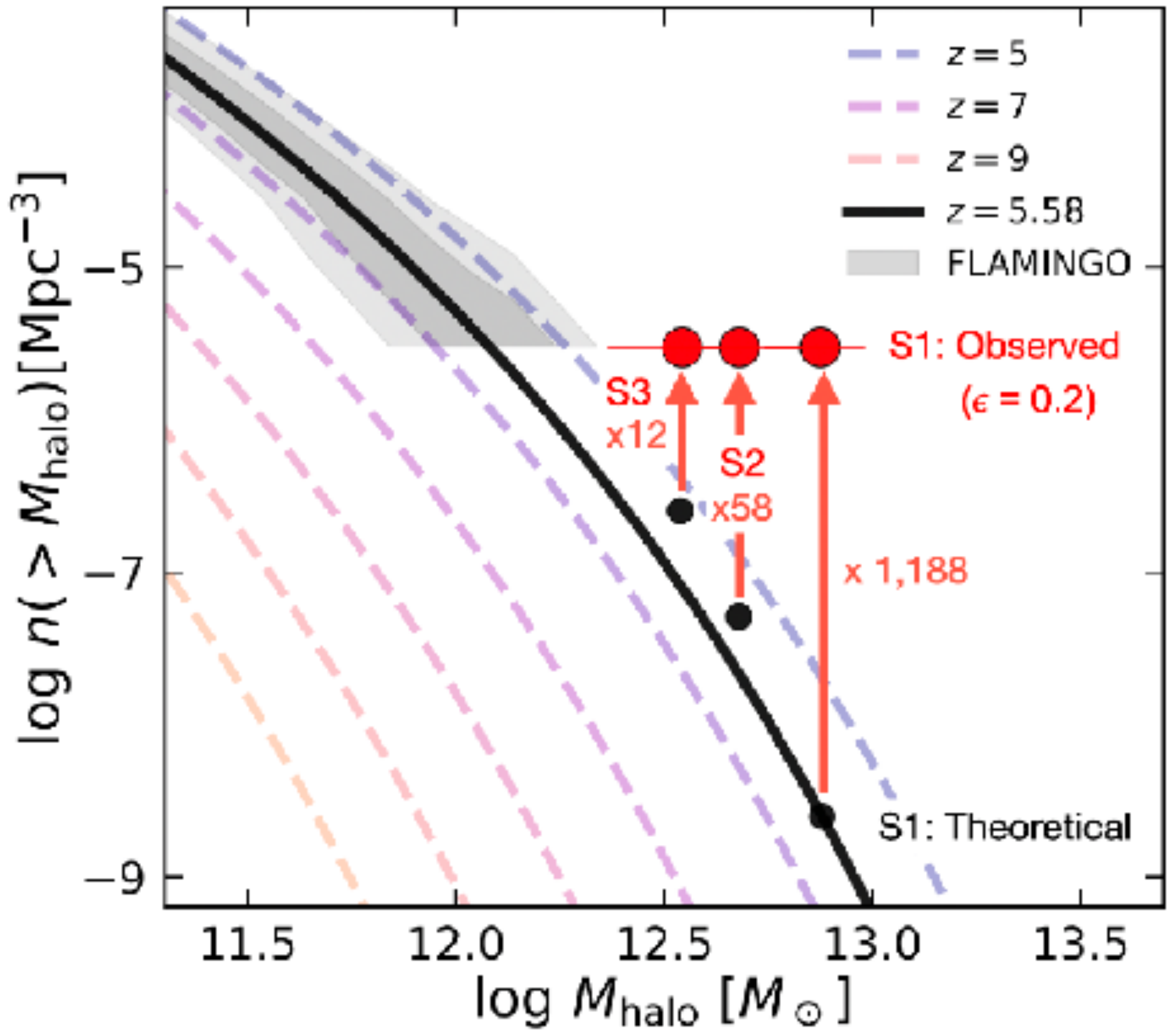
    ➜ HST-dark galaxies, based on photometry (3 bands) + spec-z from grism observations
    ➜ z-spec challenged for S1, degeneracy between dust law and stellar mass (Malek+18; Lapasia+ in prep.)







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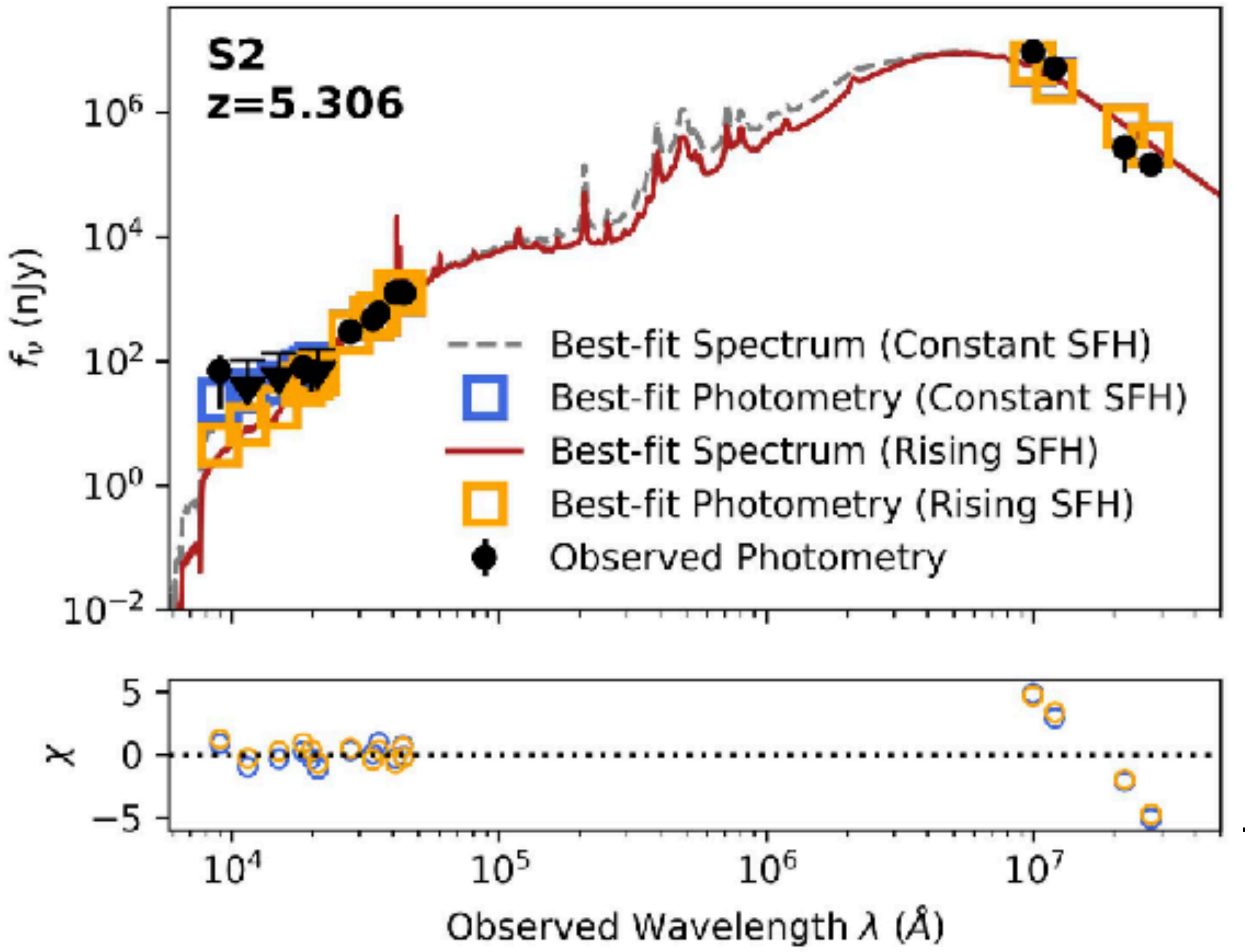
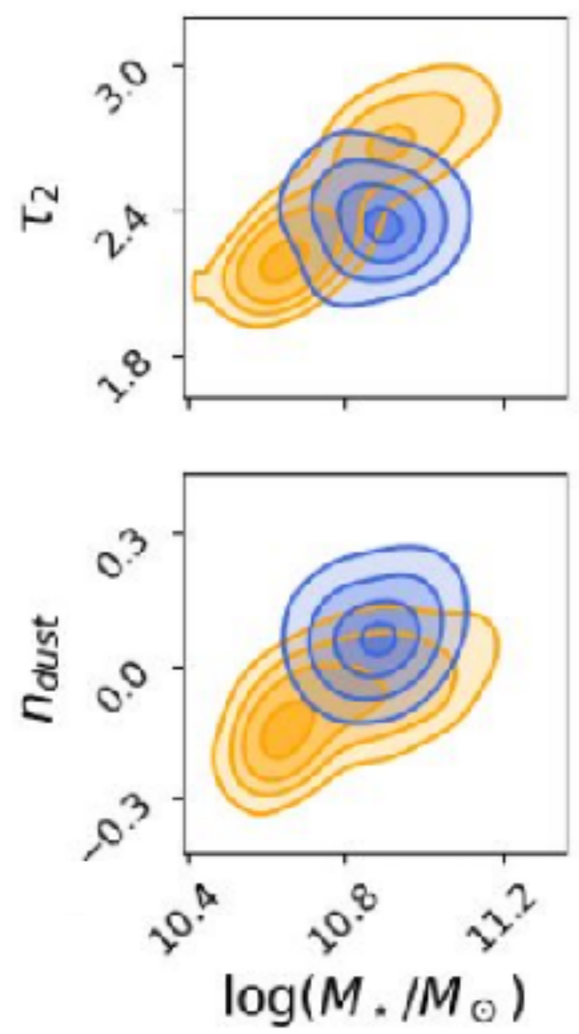
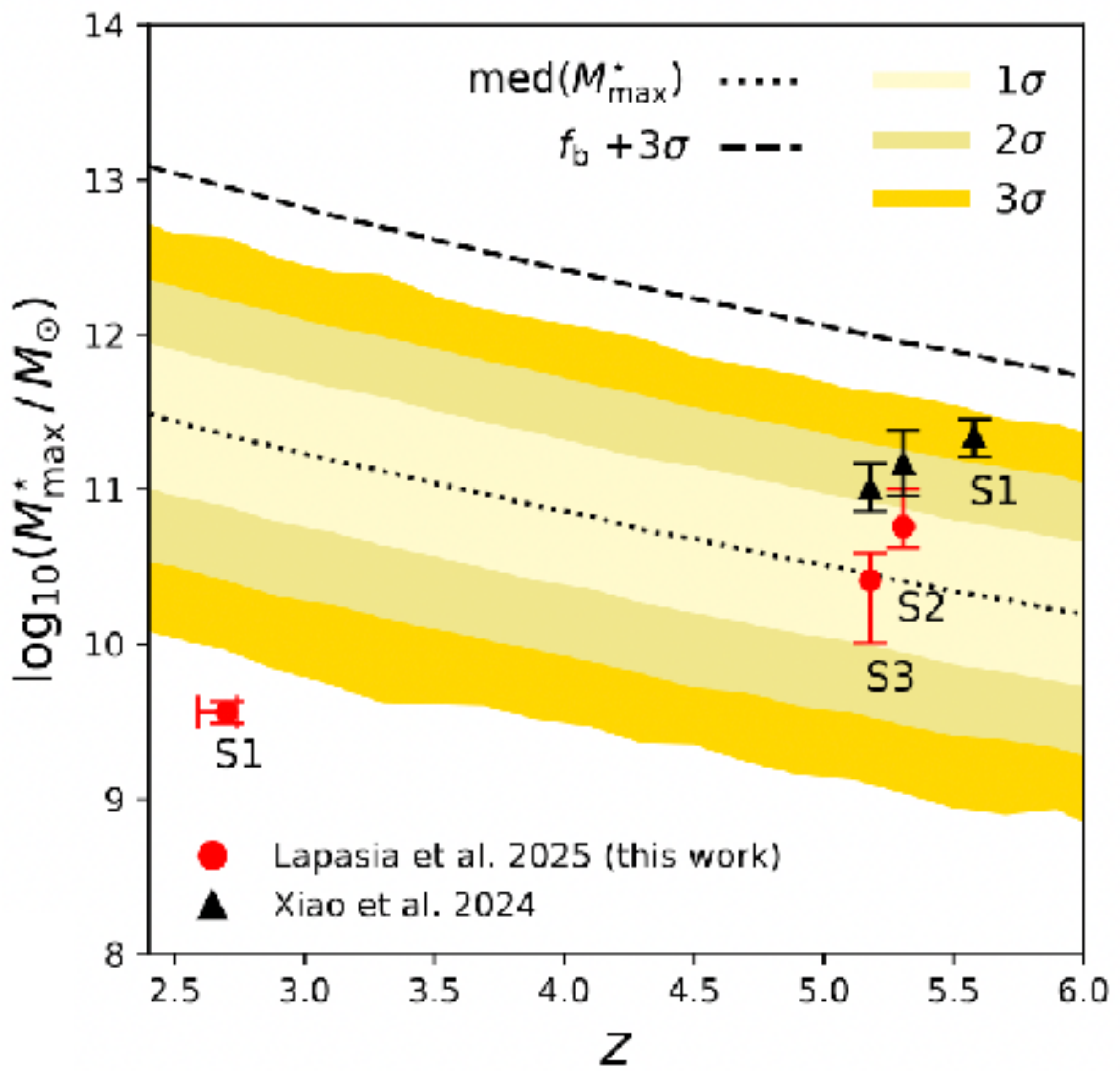


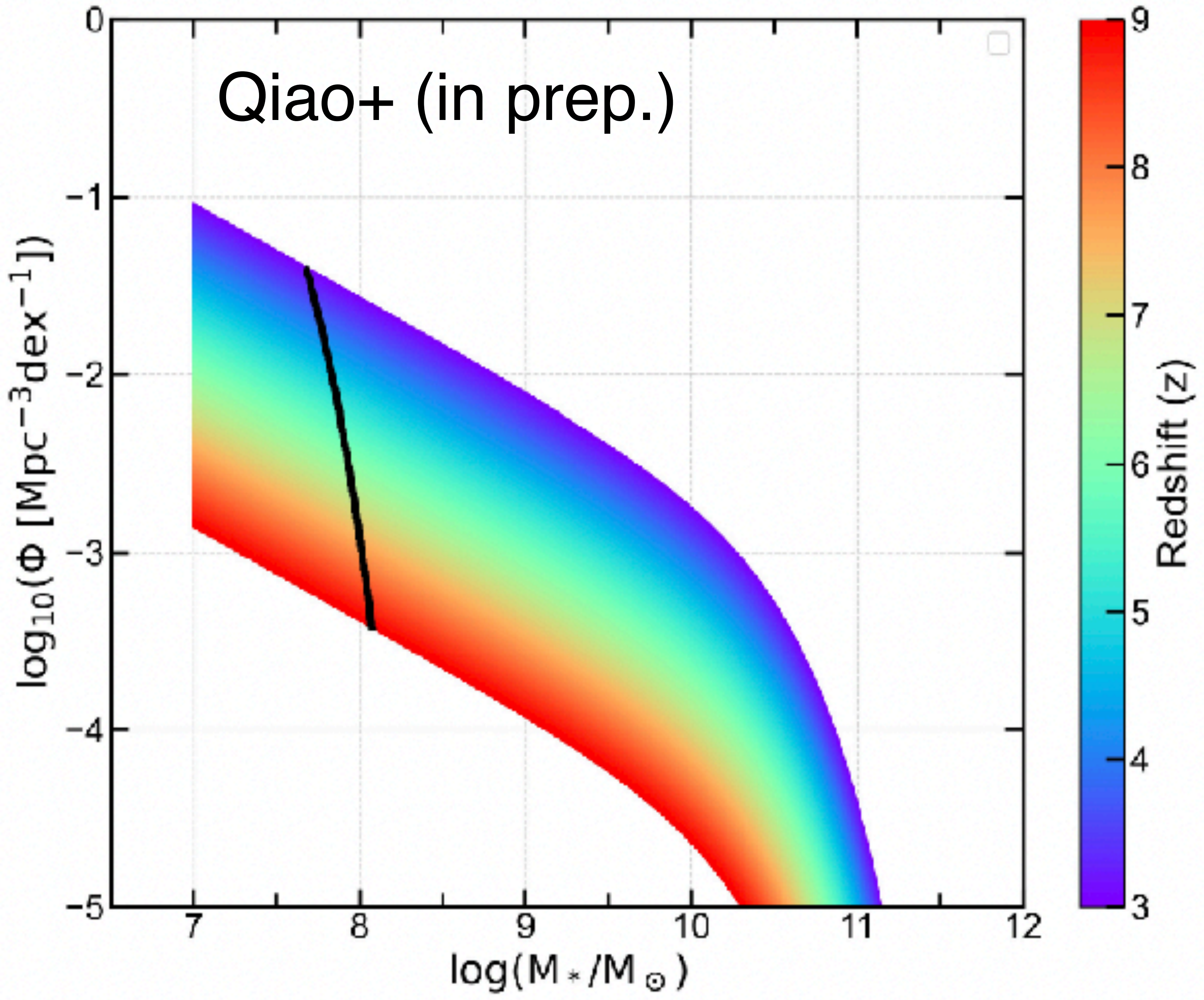


Degeneracy between dust attenuation parameters and stellar mass

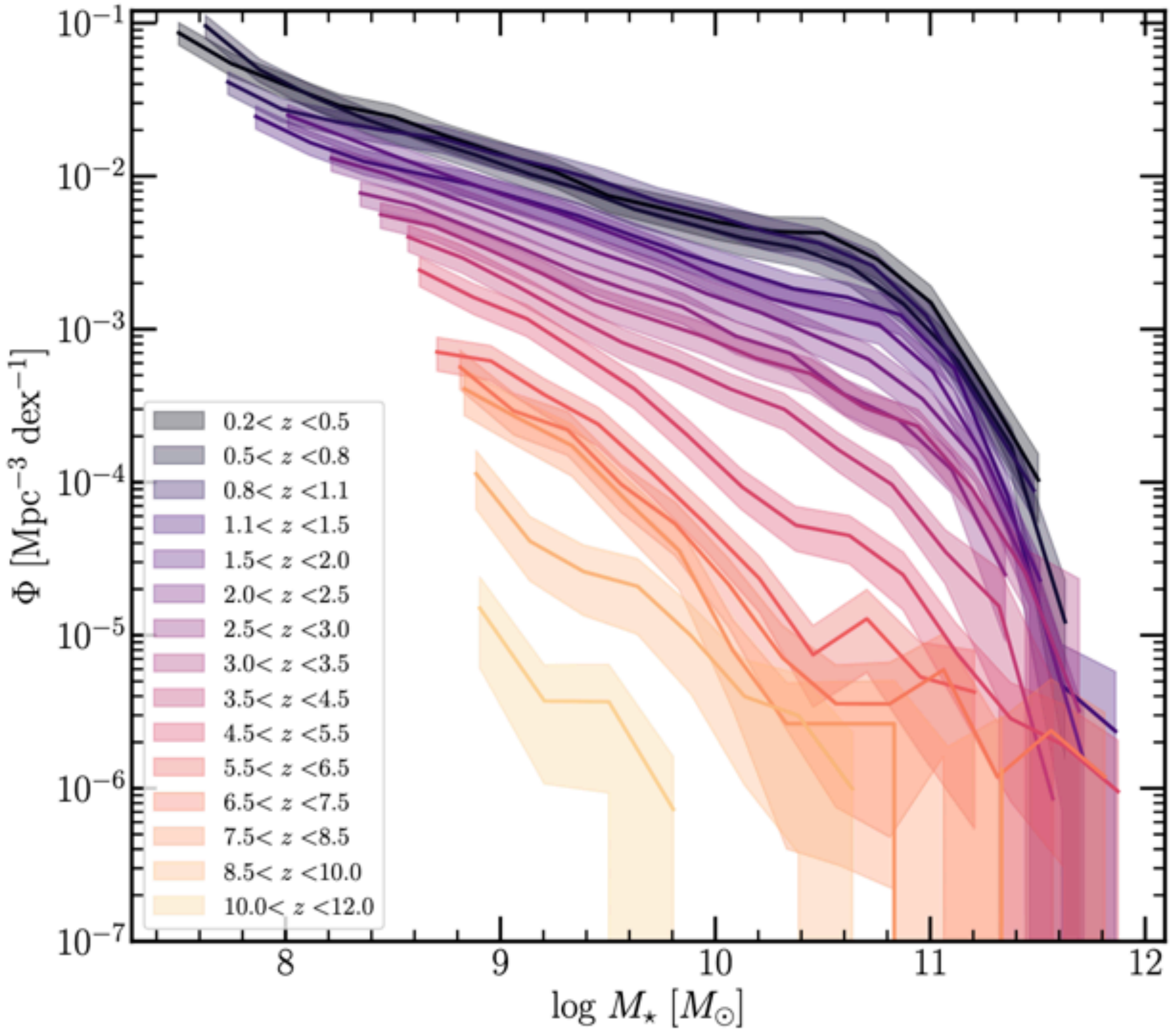


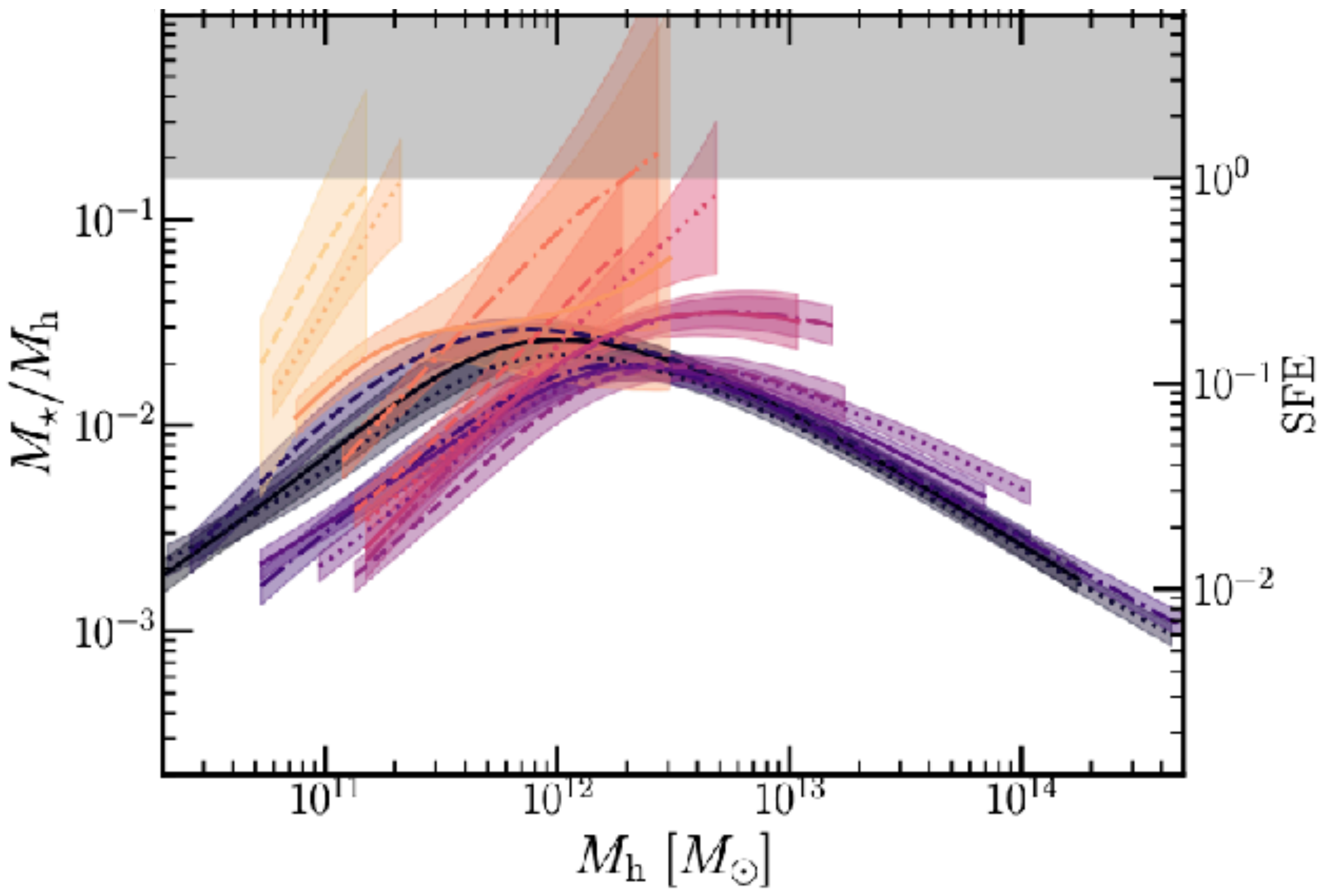
High star-formation efficiency

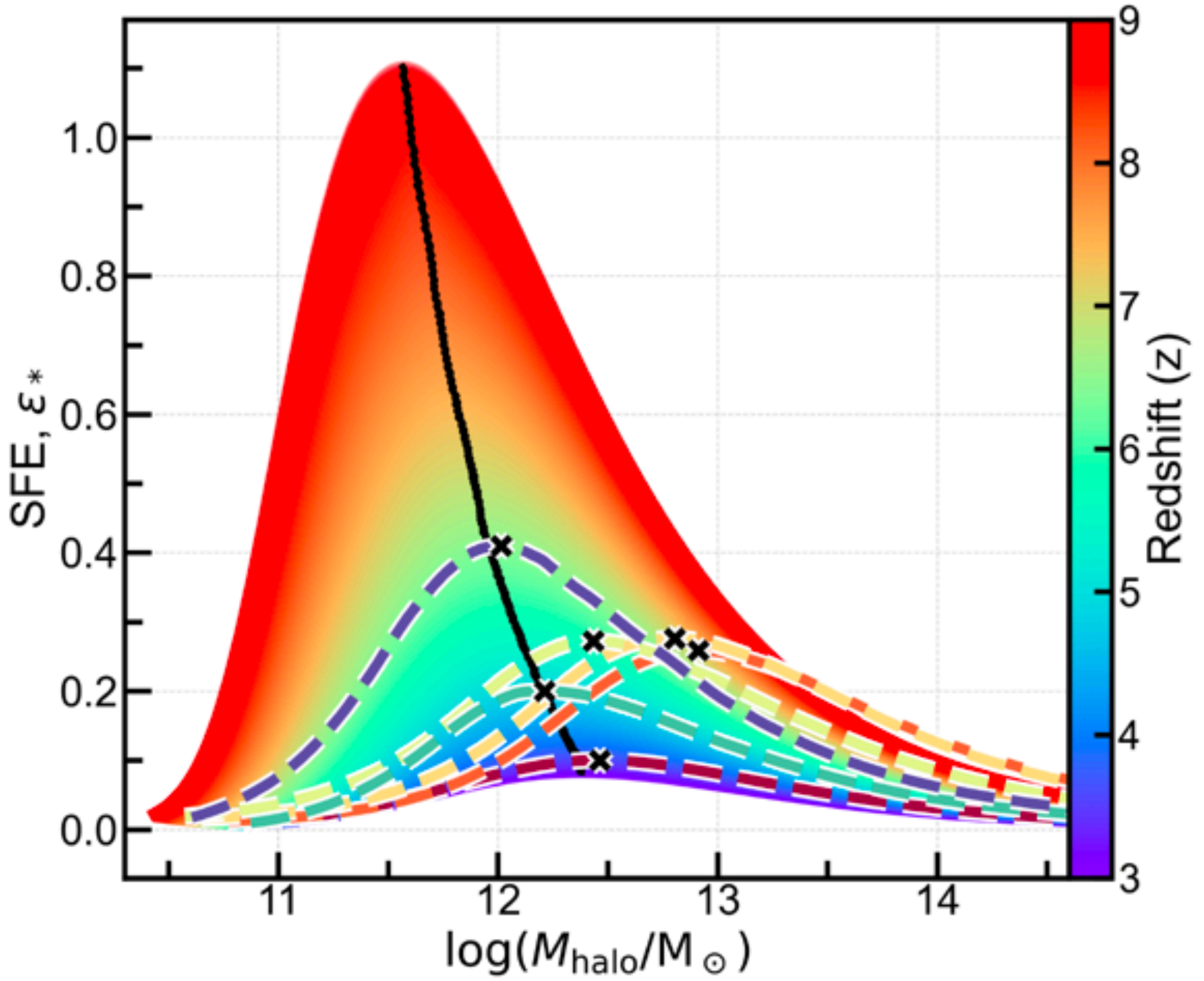
- On the population level: stellar mass function
  ➜ abundance matching to infer (integrated) SFE
  ➜ work in progress: propagate uncertainties
- High integrated SFE towards higher redshifts!



Shuntov+25

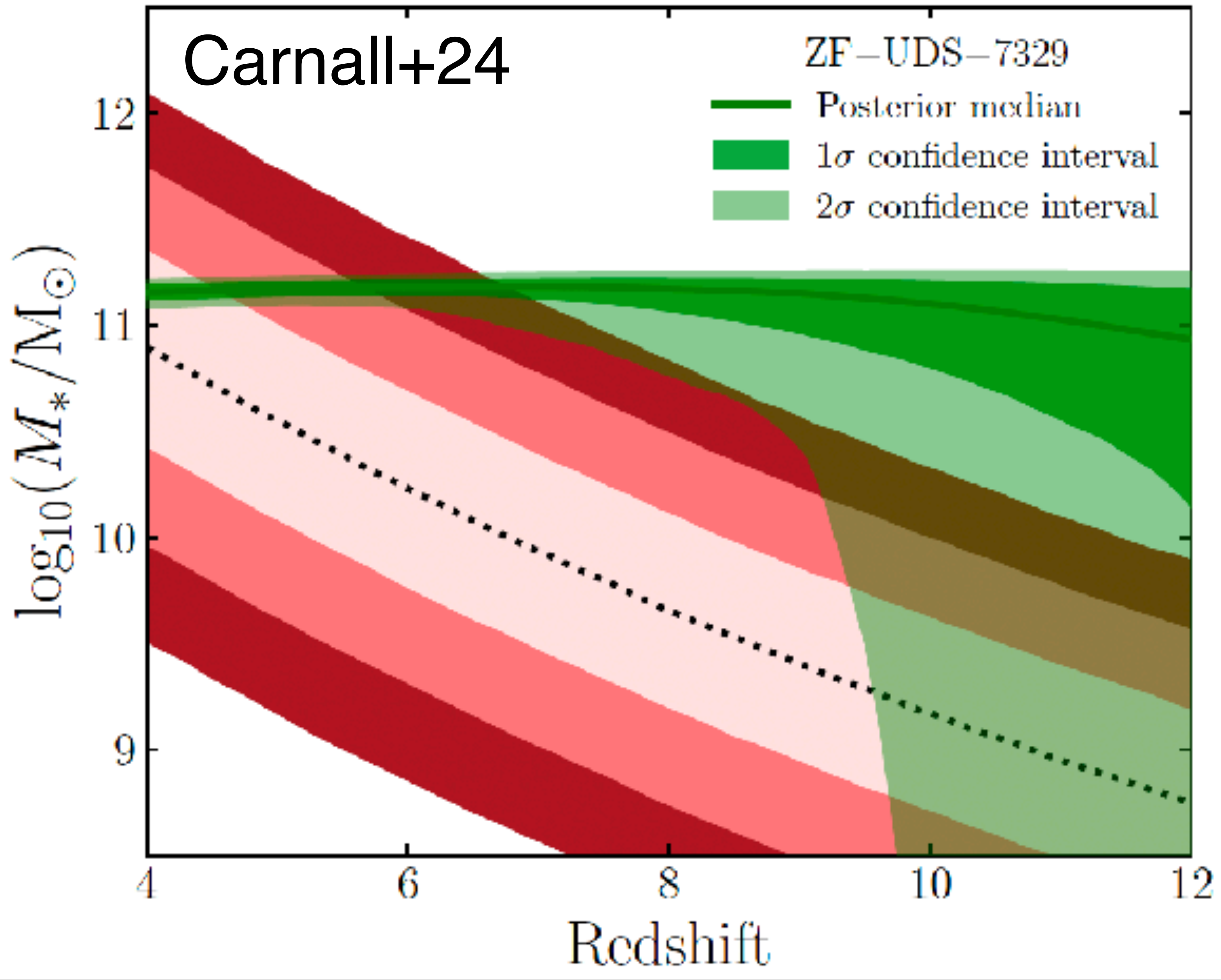


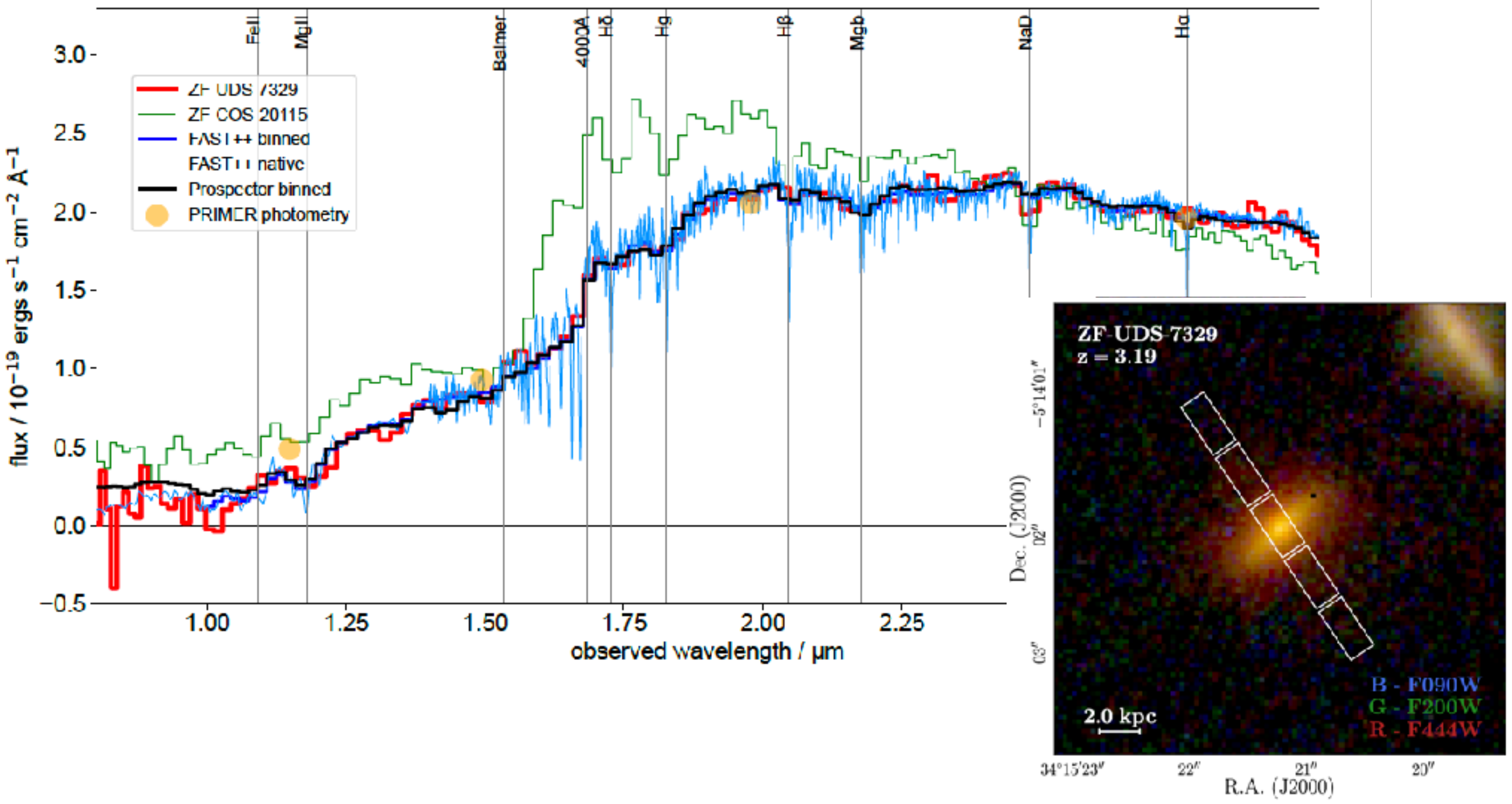


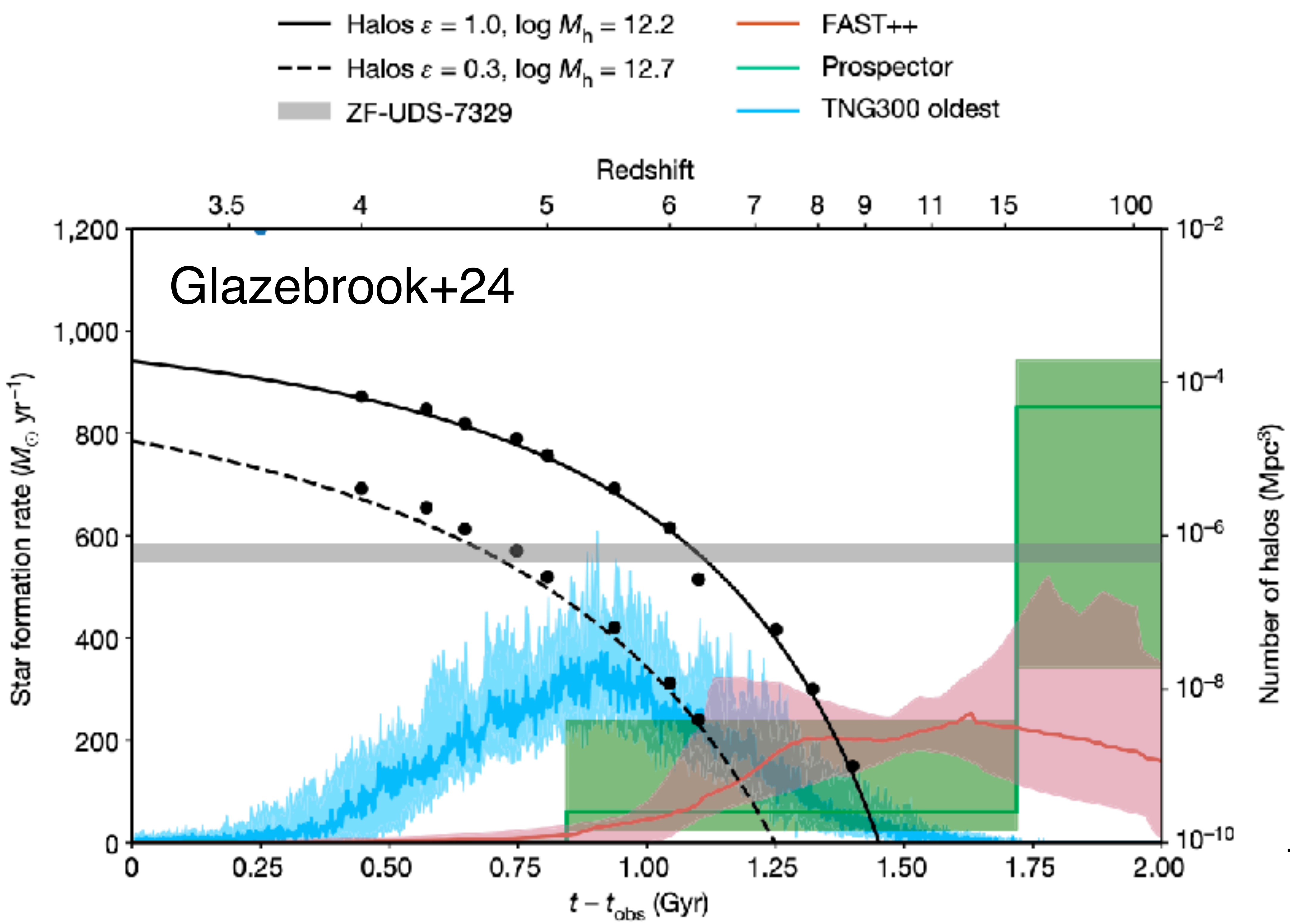


High star-formation efficiency

- Massive ($M_\star \approx 10^{11}\ M_\odot$) quiescent galaxies at z=3-4 ➜ very old! (Glazebrook+24; Carnall+24)
  ➜ turn all (100%) baryons into stars? ➜ halo mass function?
  ➜ very high-SFR (~800 $M_\odot$/yr) at z>15 ➜ hidden population?

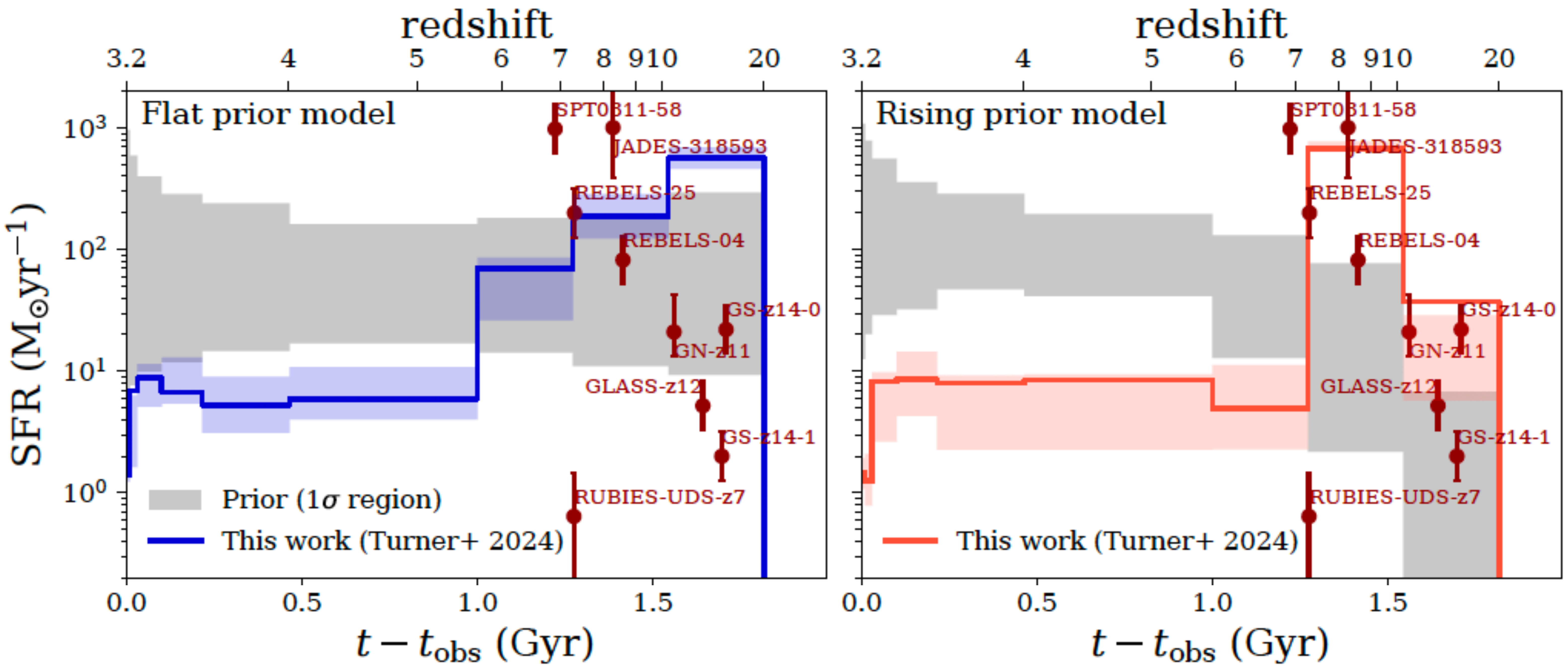


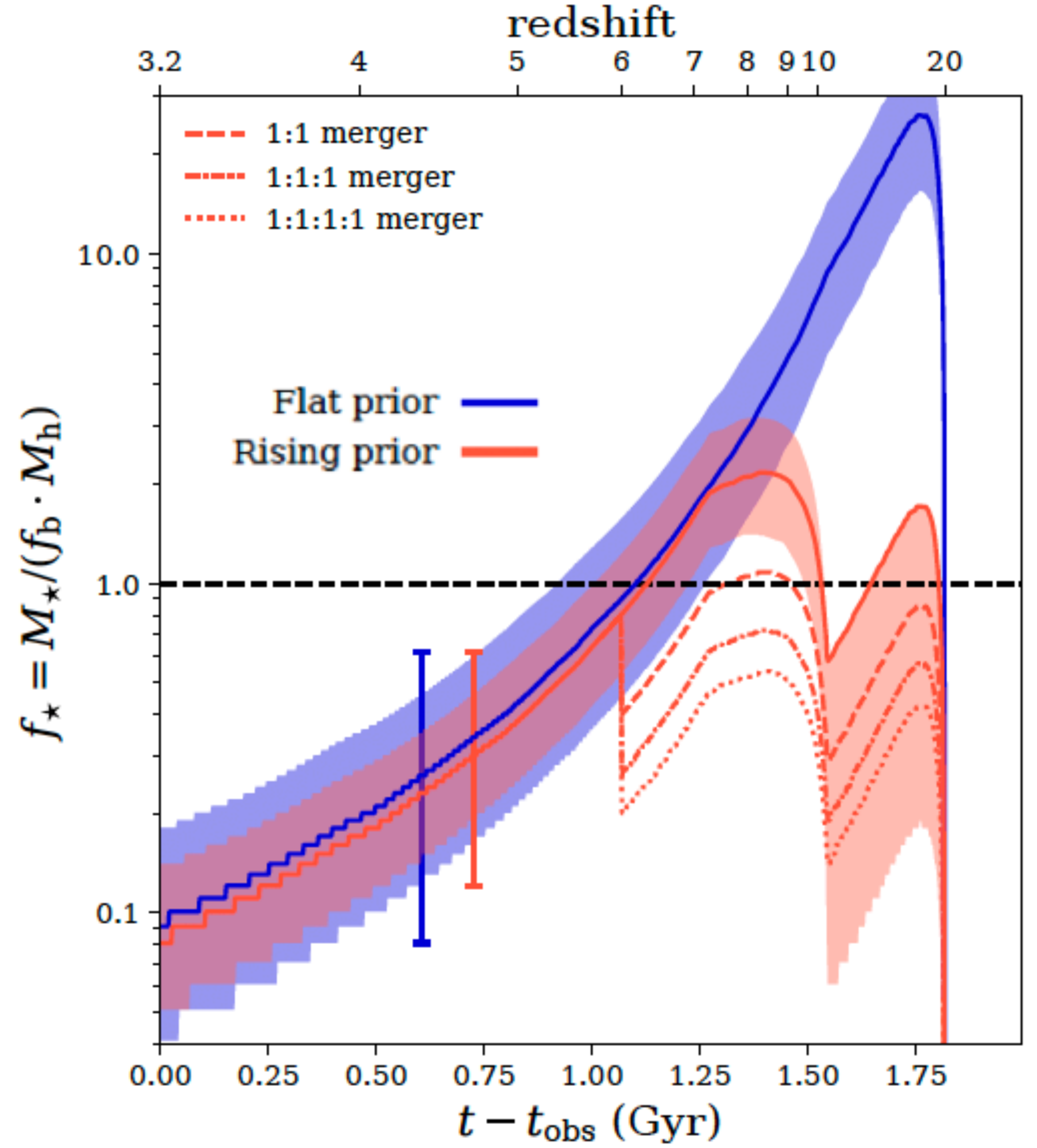




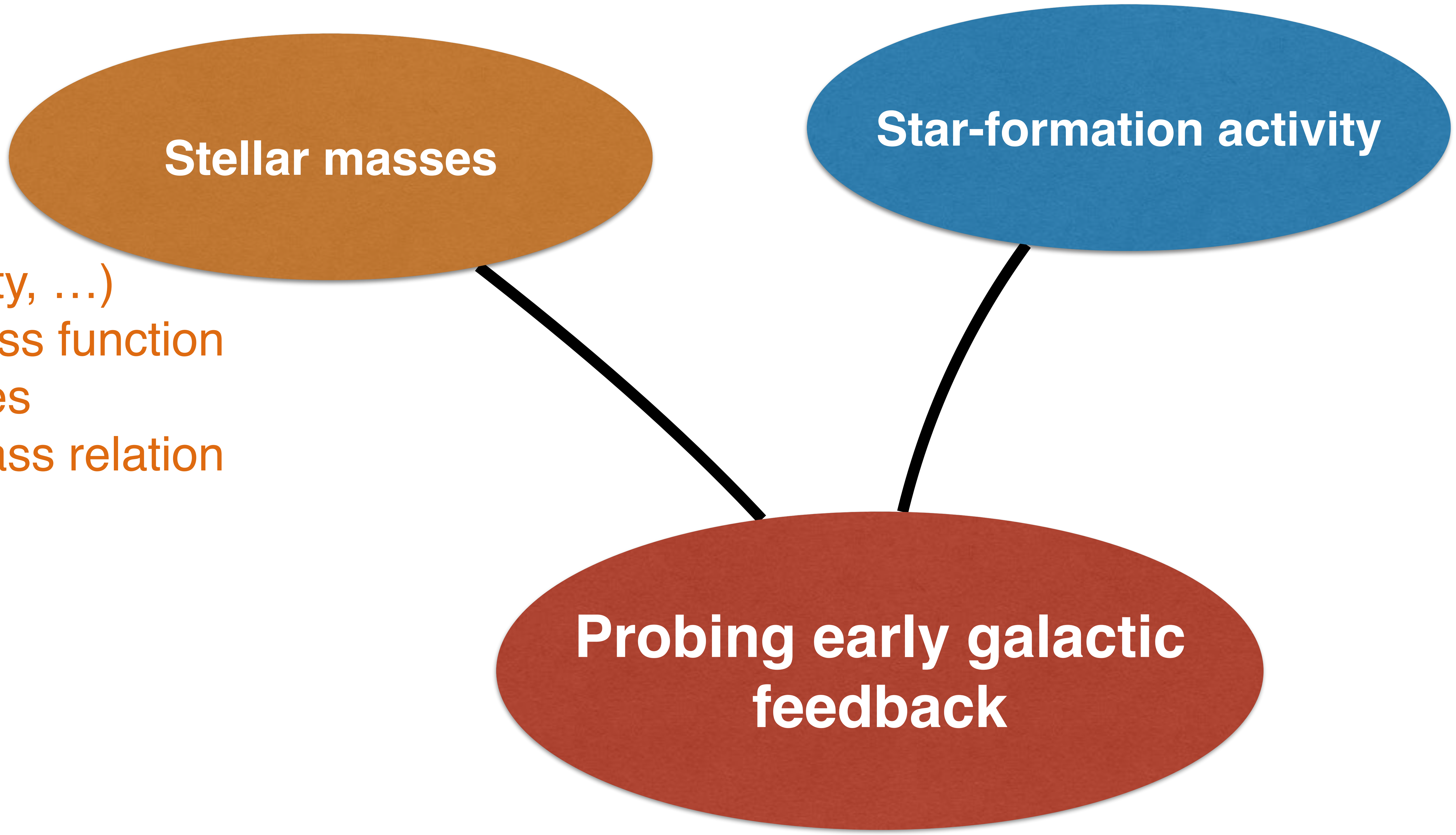
High star-formation efficiency

- Massive quiescent galaxies
  ➜ challenge to differentiate between 1.3 and 1.6 Gyr old population
  ➜ with a new, rising SFH prior, we are able to fit a SFH consistent with direct observations
  ➜ still very high stellar fraction
    ➜ mergers? merger rate ~5 major merger / Gyr (Puskas+25)
    ➜ α-enhancement (Park+24)





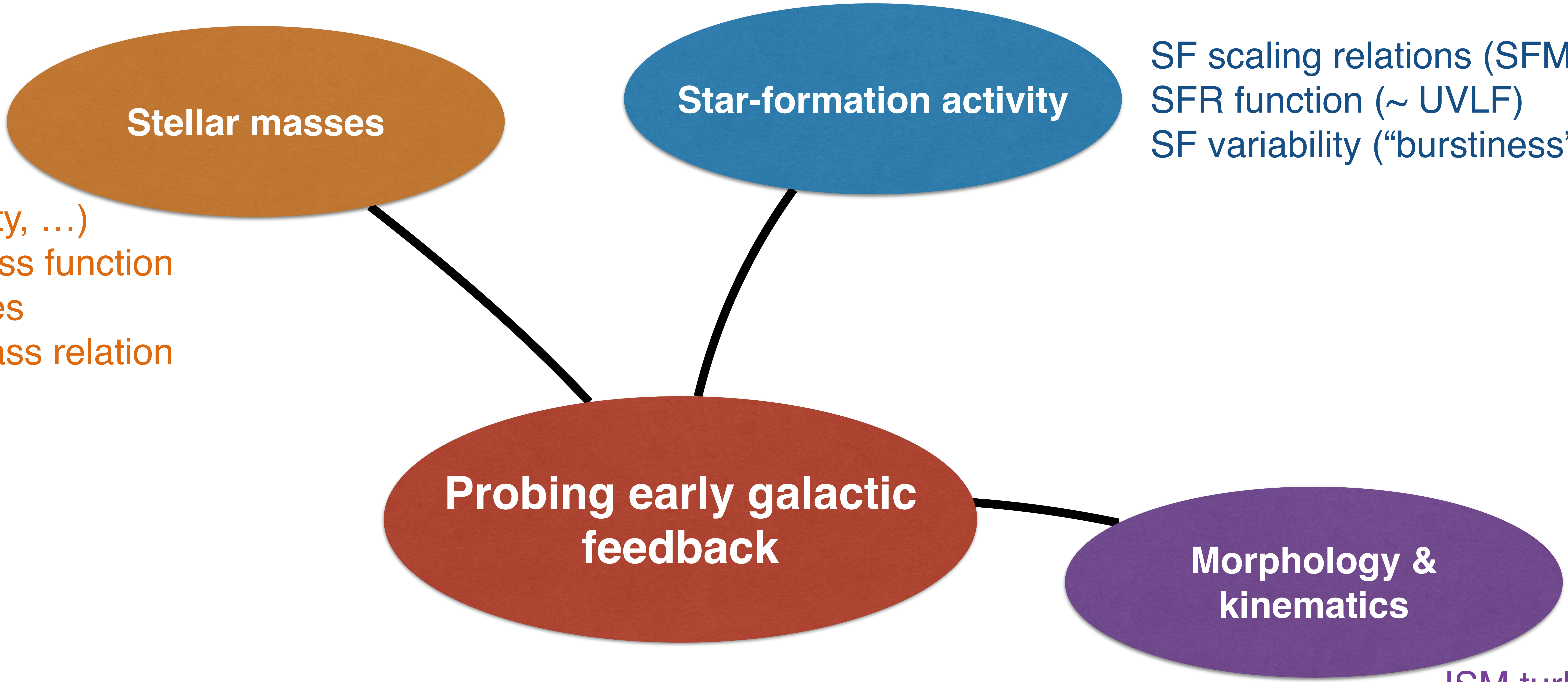
Overview



SF scaling relations (SFMS, KS)
SFR function (~ UVLF)
SF variability (“burstiness”)

stars (IMF, binarity, …)
galaxy stellar mass function
dynamical masses
stellar-to-halo mass relation

Overview



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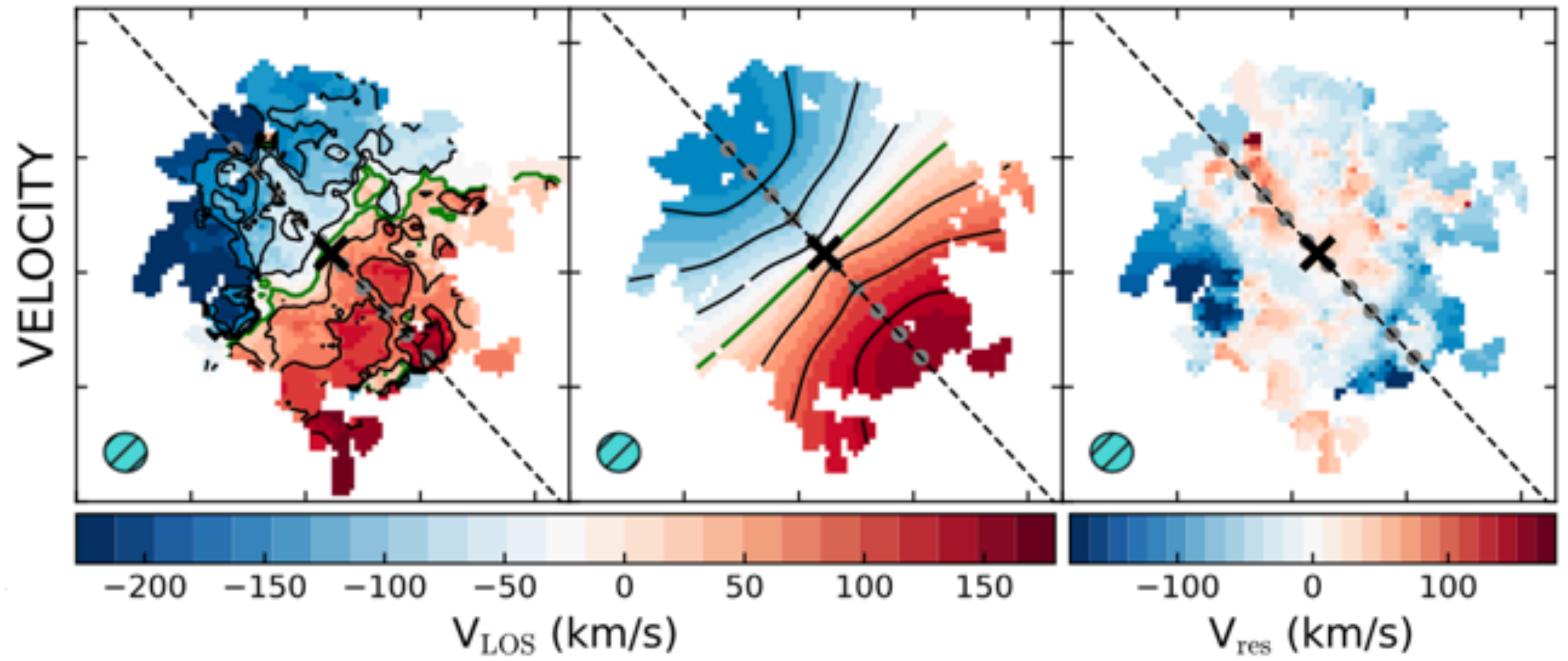
ISM turbulence
rotational support
sizes and shapes
brightness profiles
clumpy galaxies

Tracing the kinematics at z>3

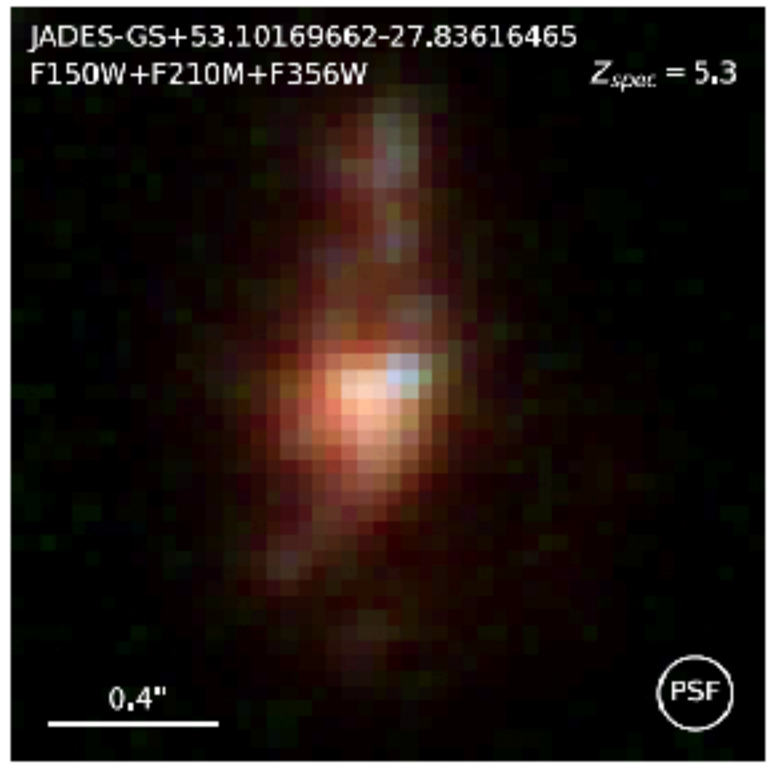
- ALMA: probes cold gas via f.e. [CII]
  ➜ few galaxies
- JWST NIRSpec IFU: high resolution, tracing warm ionised gas (e.g. Hα)
  ➜ few galaxies
- JWST NIRSpec MOS: high resolution, tracing warm ionised gas (e.g. Hα)
  ➜ covers only part of the galaxies (De Graaff+24)
- JWST NIRCam slitless spectroscopy (grism), tracing warm ionised gas (e.g. Hα)
  ➜ large samples of galaxies, but need to break morphology-kinematics degeneracy

[CII] ALMA



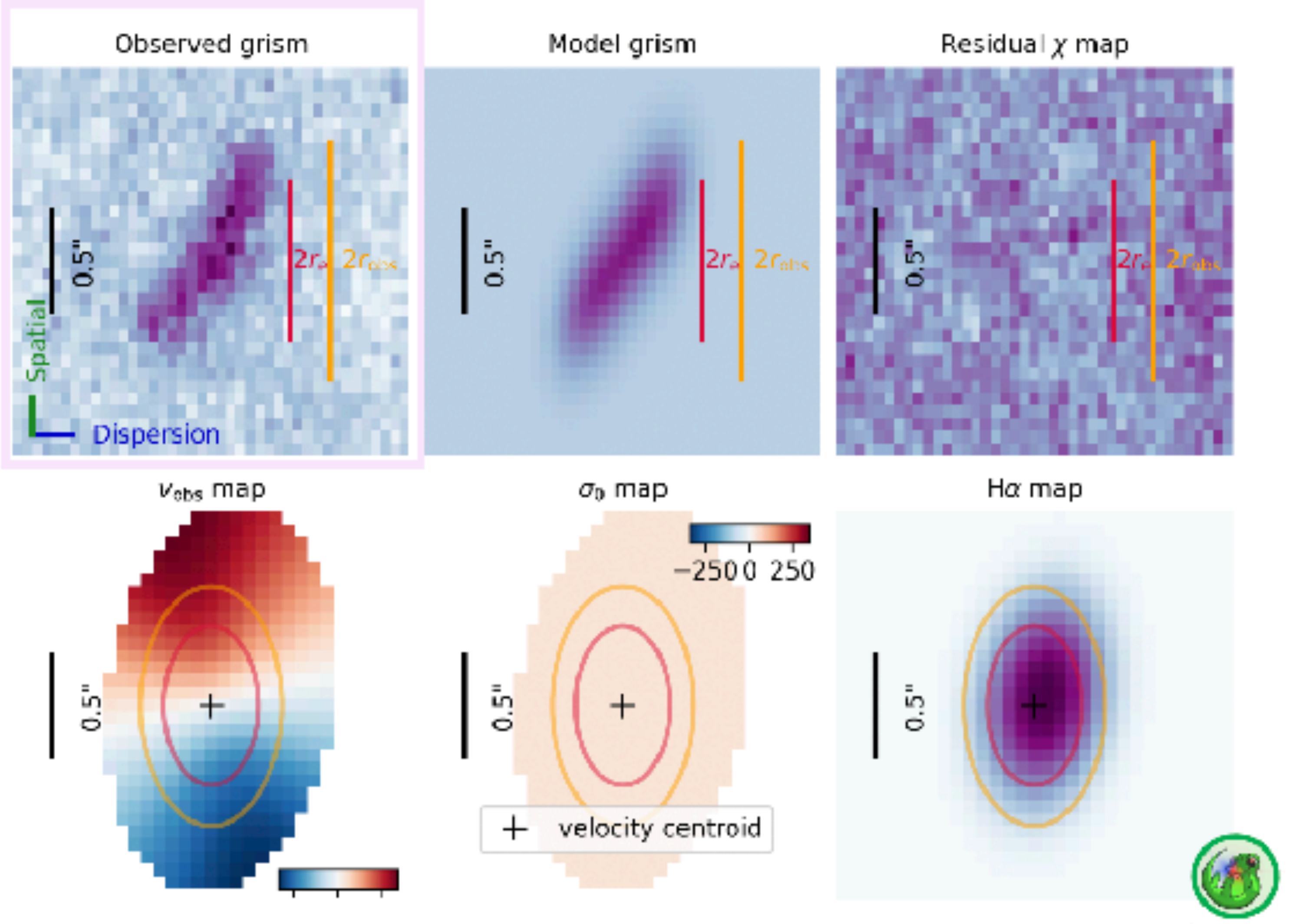
Rowland+24
(see also Rizzo+20,Lelli+21 Neeleman+20, Pope+23)

- Deep imaging in 8-10 NIRCam wide and medium bands



The JWST Advanced Deep Extragalactic Survey (JADES)

- Grism data from CONGRESS ($z \sim 4-5$) and FRESCO ($z \sim 5-6$)

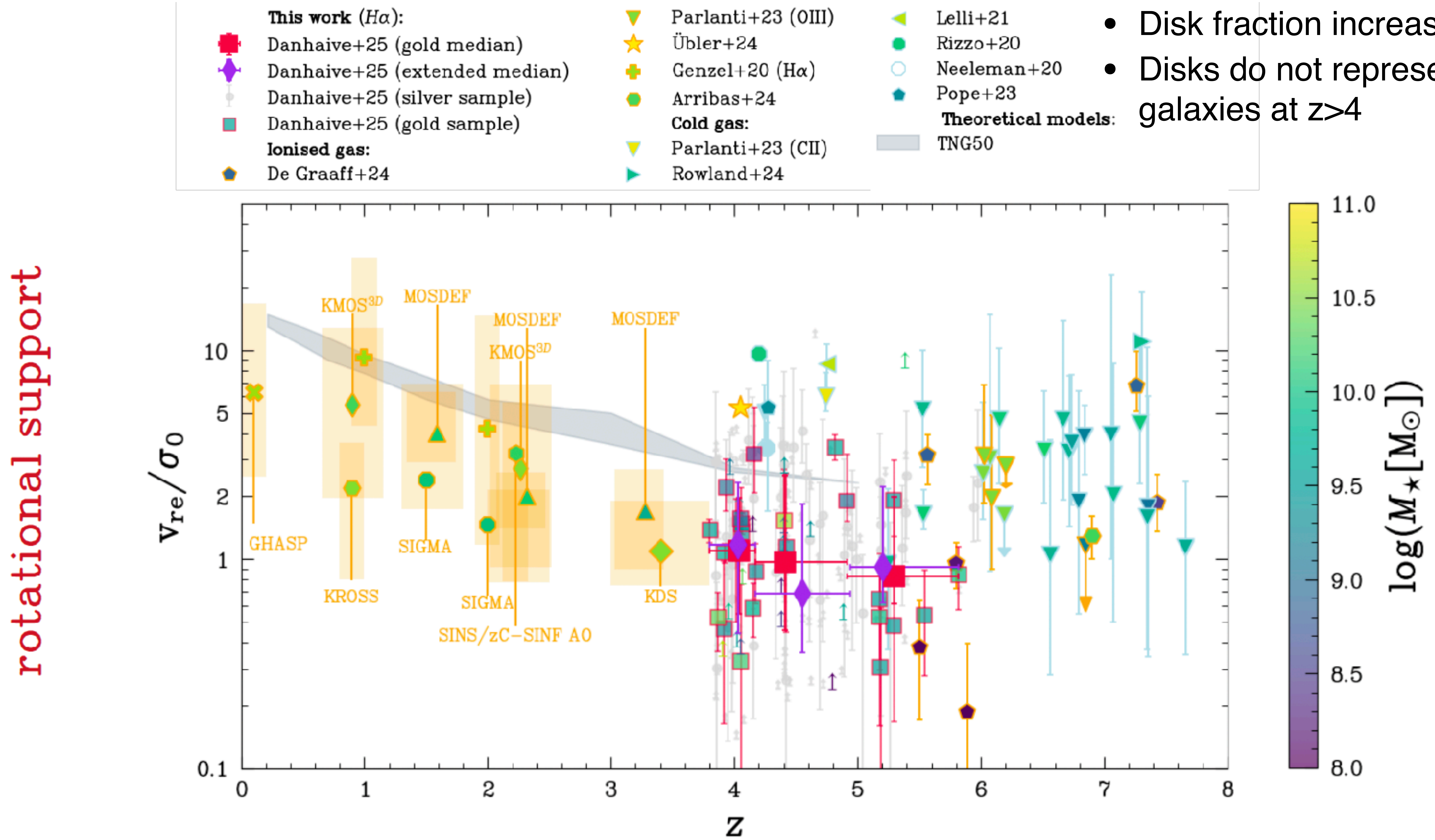


GEKO
the Grism Emission-line Kinematics tOol

Danhaive & Tacchella (in prep.)

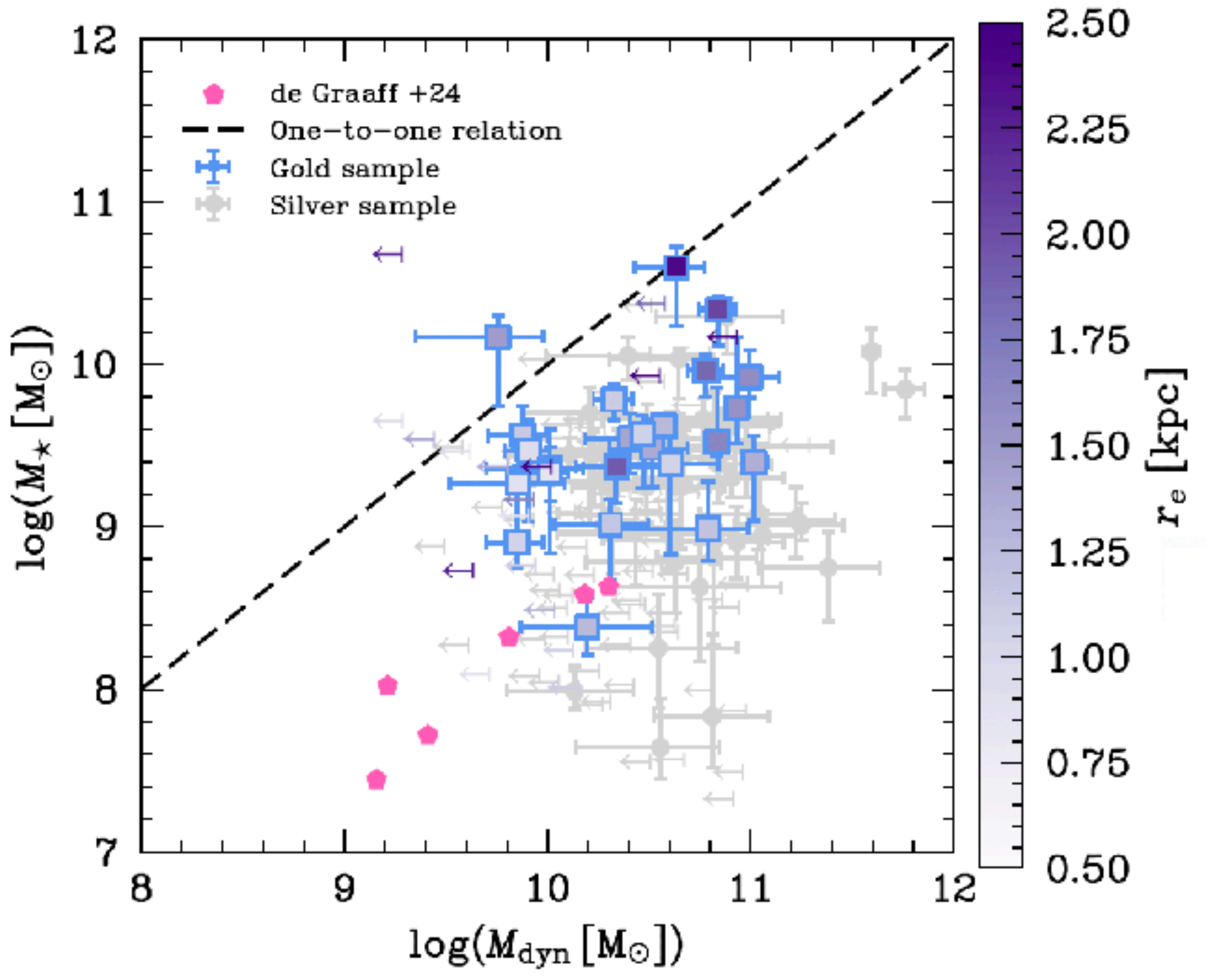
Danhaive+ (2025)

Ionised-gas kinematics of Hα emitters at z~4-6



- Disk fraction increases with cosmic time
- Disks do not represent the majority of galaxies at z>4

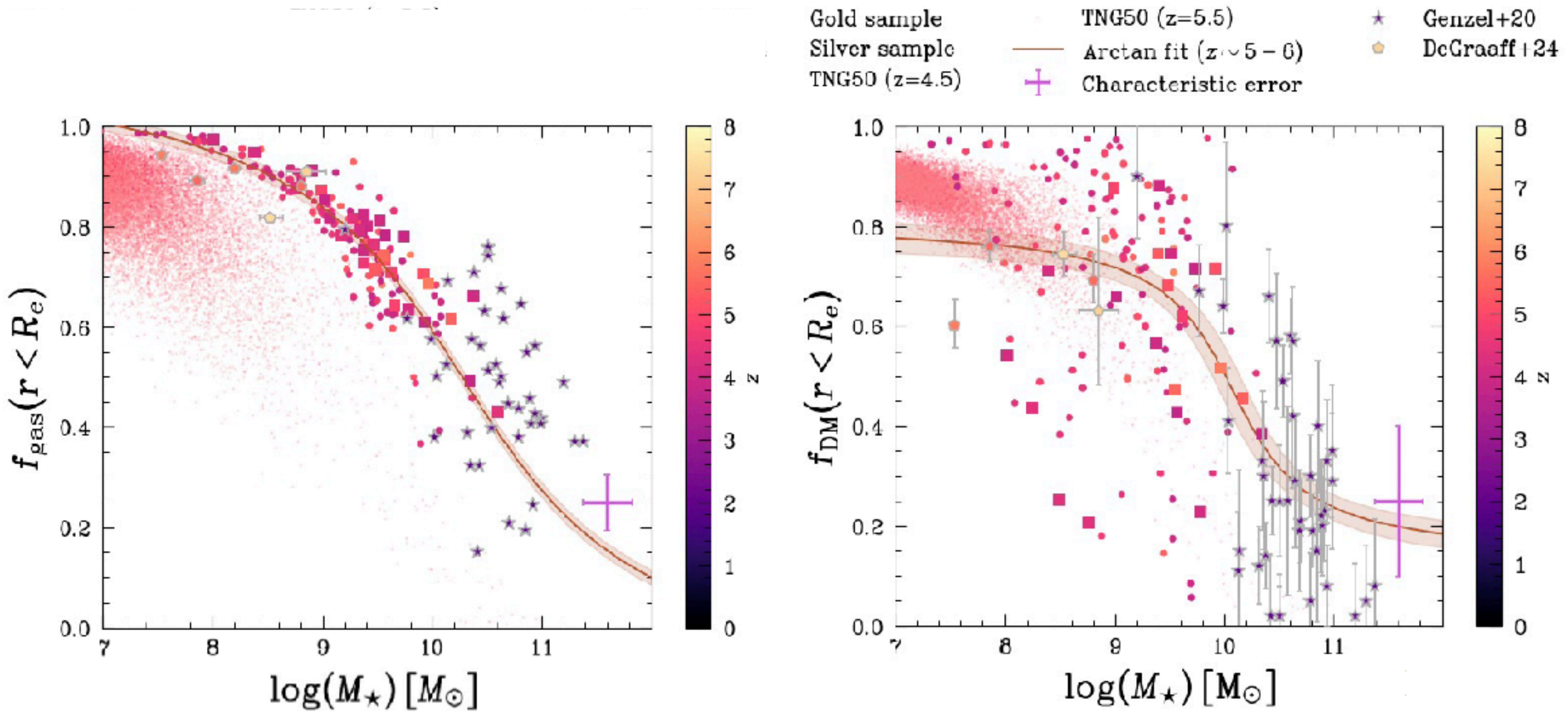
Dynamical masses: gas and dark matter rich



$$v_{\rm circ}(r) = \sqrt{v_{\rm rot}^2(r) + 2(r/r_s)\sigma_0^2}$$

$$M_{\rm dyn} = k_{\rm tot}\frac{r_e v_{\rm circ(r_e)}^2}{G}$$

- find a strong dependence on f_{gas} and f_{DM} on stellar mass (de Graaff+24, Danhaive in prep.)
- High dark matter fraction expected from stellar-to-halo mass relation, see de Graaff, Pillepich & Six (2025)



Danhaive+ (in prep.)

Overview

Stellar masses

stars (IMF, binarity, …)
galaxy stellar mass function
dynamical masses
stellar-to-halo mass relation

Star-formation activity

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SF variability (“burstiness”)

Probing early galactic feedback

Morphology & kinematics

ISM turbulence
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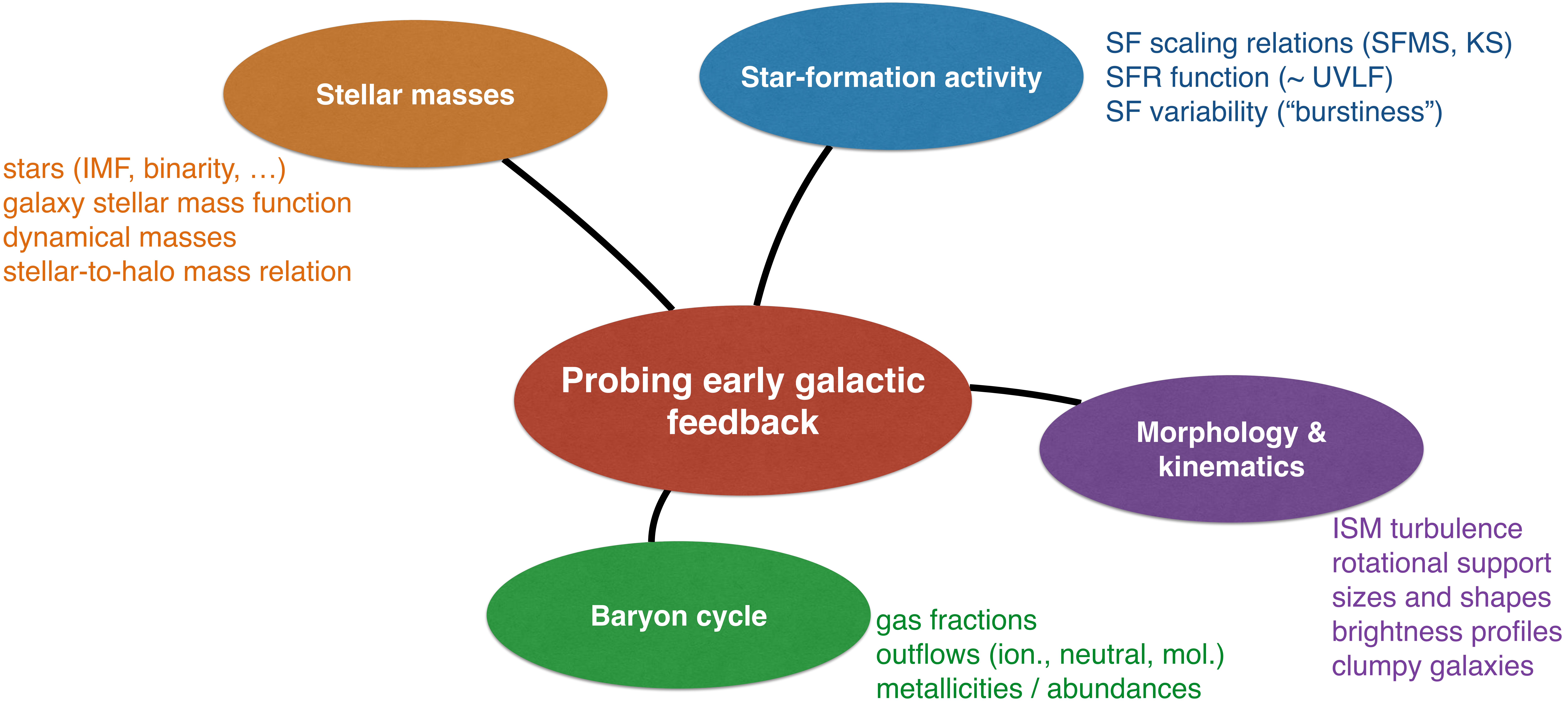
Overview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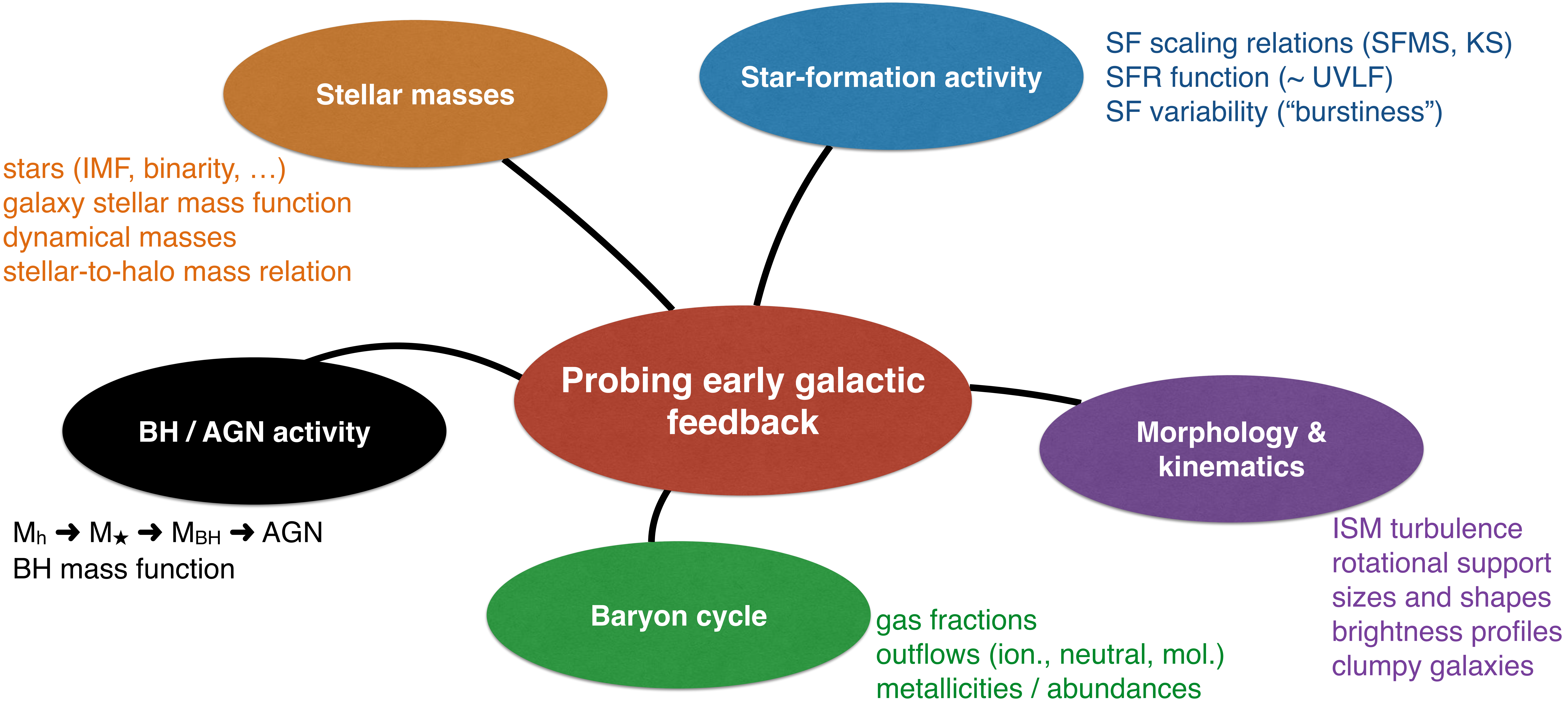
gas fractions
outflows (ion., neutral, mol.)
metallicities / abundances

Overview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Probing early galactic feedback
BH / AGN activity
Morphology & kinematics
$M_h \rightarrow M_\star \rightarrow M_{BH} \rightarrow$ AGN
BH mass function
Baryon cycle
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Overview

Probing early galactic feedback

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Reionisation

Ionising flux
IGM neutral fraction
IGM temperature

BH / AGN activity

$M_h \rightarrow M_\star \rightarrow M_{BH} \rightarrow$ AGN
BH mass function

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Baryon cycle

gas fractions
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Conclusions

- Galaxies form rapidly: 20% $Z_\odot$ system with ~10^9 $M_\odot$ at z=14 in place (+ high UV abundance)
  ➜ efficient and bursty SF, different stellar pops? AGN? IMF?
- indirect via archeological approach: probe rest-optical at z~3-9
  ➜ overly massive, star-forming galaxies at redshifts z~6-9…
  <u>Challenges:</u> AGN, wrong distances (i.e. photo-z), uncertainties in estimating stellar masses (stellar population model [incl. IMF], emission lines vs Balmer break, outshining, dust, SFH prior)
  ➜ look-back studies of massive quiescent galaxies at z~3-4 imply high SFE
  <u>Challenges:</u> SFH prior? α-enhancement? IMF?
- EoR galaxies in phases of SF bursts and mini-quenching, consistent with bursty SF
- Kinematics: large diversity, with only a small fraction of rotationally supported systems, high DM fractions
- current high-z (z>3) spectroscopic samples are biased
  ➜ understanding selection function and sample completeness is crucial

integrated approach between theory and observations is needed!