What regulates LyC escape fraction?

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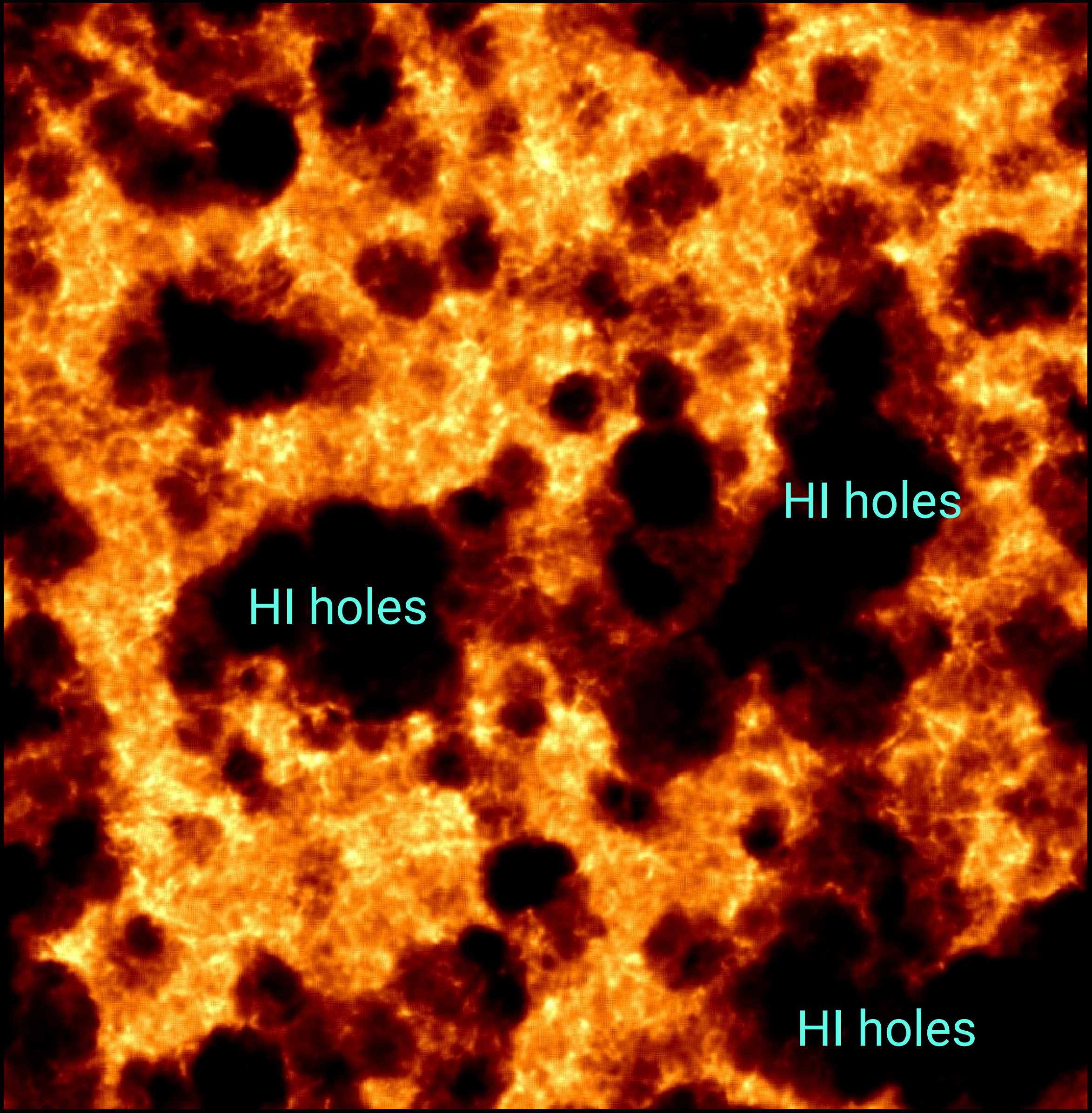
HI density map in a 400 cMpc box @ z=8



Baek & AF 2012

A PERSISTING PUZZLE

$$f_{esc}$$

OPEN QUESTIONS

- Redshift evolution ? If yes, why?
- At fixed redshift, is there a mass (luminosity) dependence?
- Key modulating physical processes (rad. transfer, SF, feedback)?
- Escape through cleared paths in a patchy ISM?
- Is it an intermittent process?

WHAT DO WE KNOW?

- Most observations in $2 < z < 4$

  Inoue et al. 2006; Vanzella et al. 2010; Nestor et al. 2011; Boutsia et al. 2011; Siana et al. 2015; Vasei et al. 2016; Grazian et al. 2016; Matthee et al. 2017; Alavi et al. 2020; Pahl et al. 2021, 2022; Begley et al. 2022; Flury et al. 2022

- Overall increasing f_{esc} trend with redshift and decreasing mass

- Typical values are $f_{esc} < 5\%$, but large scatter

- Further corroborated by JWST results using Hα in $4 < z < 7$

  Prieto-Lyon et al. 2023

- However, examples of higher ($f_{esc} > 15\%$) values reported

  Mostardi et al. 2015; de Barros et al. 2016; Shapley et al. 2016; Leethochawalit et al. 2016; Vanzella et al. 2016; Naidu et al. 2017; Vanzella et al. 2018, 2019; Rivera-Thorsen et al. 2019; Saxena et al. 2021; Metri et al. 2021; Prichard et al. 2021; Yuan et al. 2021; Rivera-Thorsen et al. 2022; Griffiths et al. 2022

OBSERVATIONAL TECHNIQUES

Direct detection of LyC photons is difficult due to low IGM transmission

Alternative methods

1. High [OIII]5007Å/[OII]3727Å ratio (density bounded HII regions)

   Jaskot & Ravindranath 2016; Nakajima & Ouchi 2014; Faisst 2016; Nakajima et al. 2019; Barrow et al. 2020; Tang et al. 2020; Mascia et al. 2023)

2. High Lyα EW (also Hβ) (low neutral column density)

   Verhamme et al. 2015; Dijkstra et al. 2016; Verhamme et al. 2017; Ostlin et al. 2021; Begley et al. 2022; Izotov et al. 2022, Yamanaka et al. 2020; Marques-Chavez et al. 2022

3. Weak low-ionization absorption lines, such as SiII1260Å (HI tracers)

   Heckman et al. 2011; Jones et al. 2013; Chisholm et al. 2017; Mainali et al. 2022; Wang et al. 2019, 2021;

4. Anticorrelation with UV β-slope (low dust content)

   Chisholm et al. 2022; Ramambason et al. 2022

THEORY

Escape fraction from low-mass ($10^{6\text{-}9}$ $M_\odot$) galaxies predicted in the range

$$f_{esc} = 10^{-5} - 0.6 \text{ (!)}$$

with weak consensus on decreasing f_{esc} with halo mass and Hubble time

Dove et al. 2000; Wise & Cen 2009; Ferrara & Loeb 2013; Paardekooper et al. 2011, 2013; Wise et al. 2014; Roy et al. 2015; Ma et al. 2015; Ma et al. 2020; Yeh et al. 2022; Rosdahl et al. 2022;Kostyuk et al. 2022; Trebitsch et al. 2022; Gnedin et al. 2008; Razoumov & Sommer-Larsen 2010; Ocwirk et al. 2021; Mitra & Chatterjee 2023.

Is it hopeless?

The terrestial atmosphere, similar to the ISM of galaxies, is a very complex system whose properties are shaped by nonlinear physical processes that are extremely hard to predict.

Yet, we produce reliable weather forecasts!

Rather than predicting f_{esc} values, pose the question:

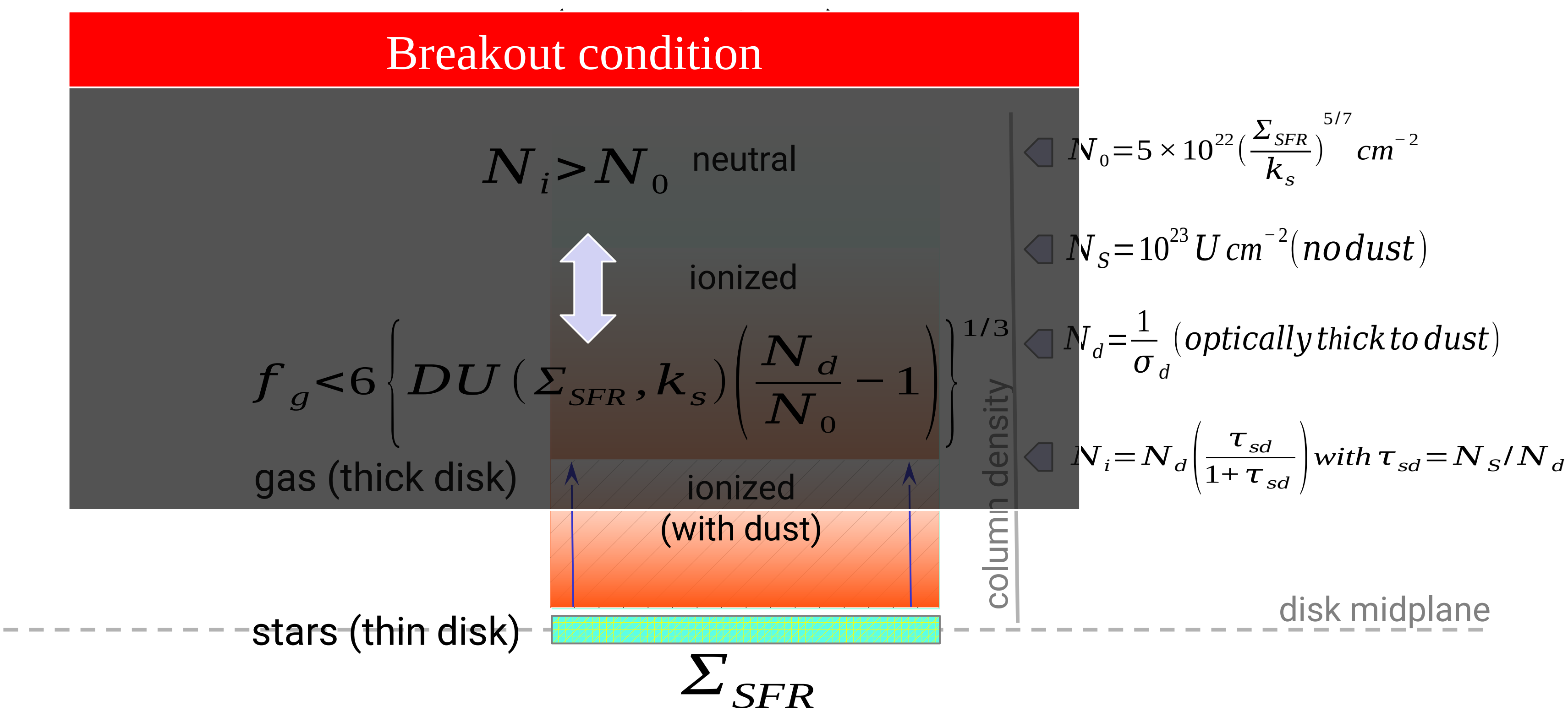
Given a galaxy with known global properties, such as SFR, stellar mass, gas fraction/density, size, stellar populations, metallicity, dust content, can we predict whether that galaxy is a LyC leaker?

image created using Open AI DALL.E2

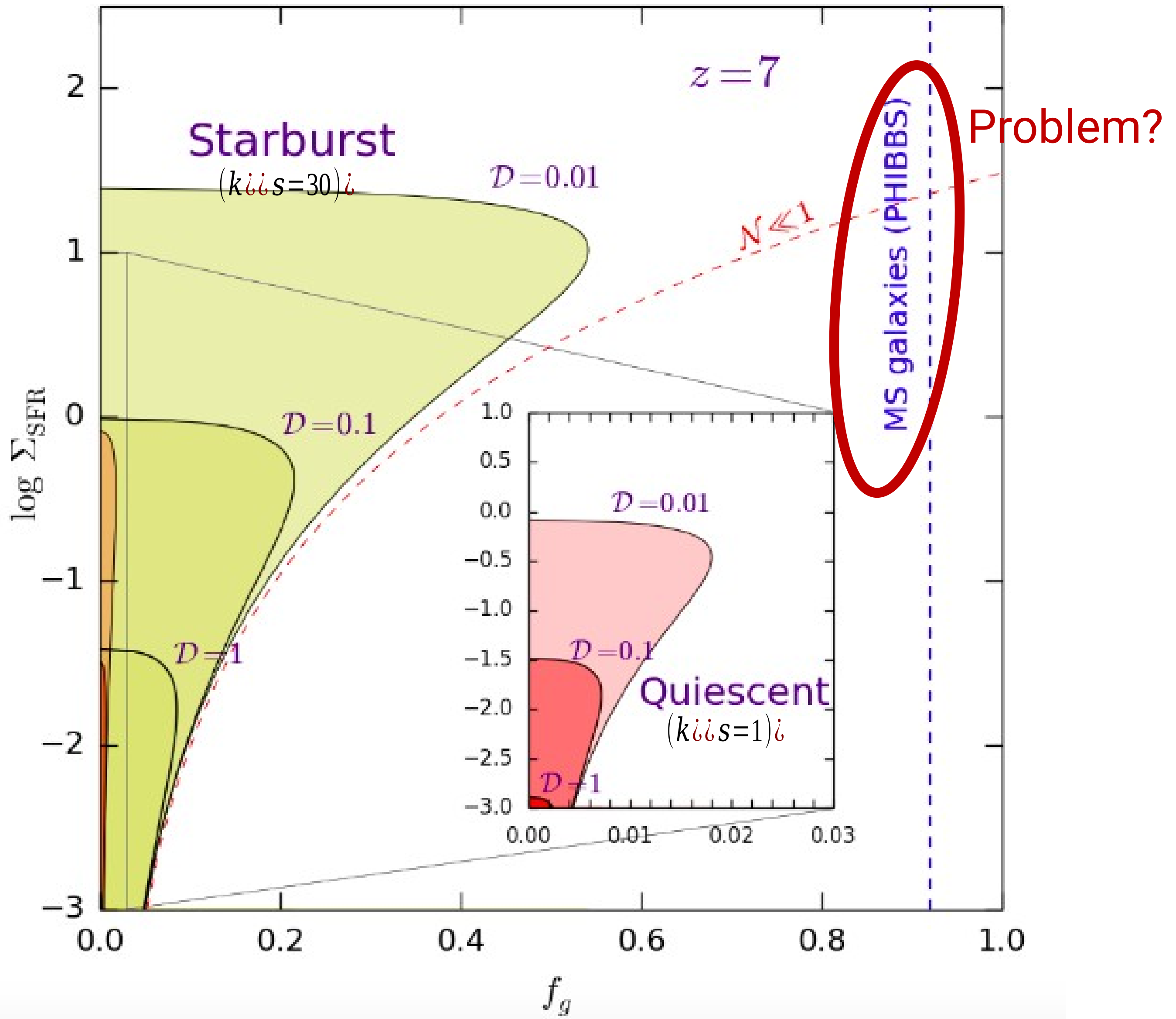
MODEL
AF 2023, in prep.

burstiness parameter

Assume Kennicutt-Schmidt law: $\Sigma_{SFR} = 10^{-12} k_s \Sigma_g^{7/5}$



Leakage of LyC photons occurs in colored areas



LACES SURVEY (Z ≃ 3.1) DATA

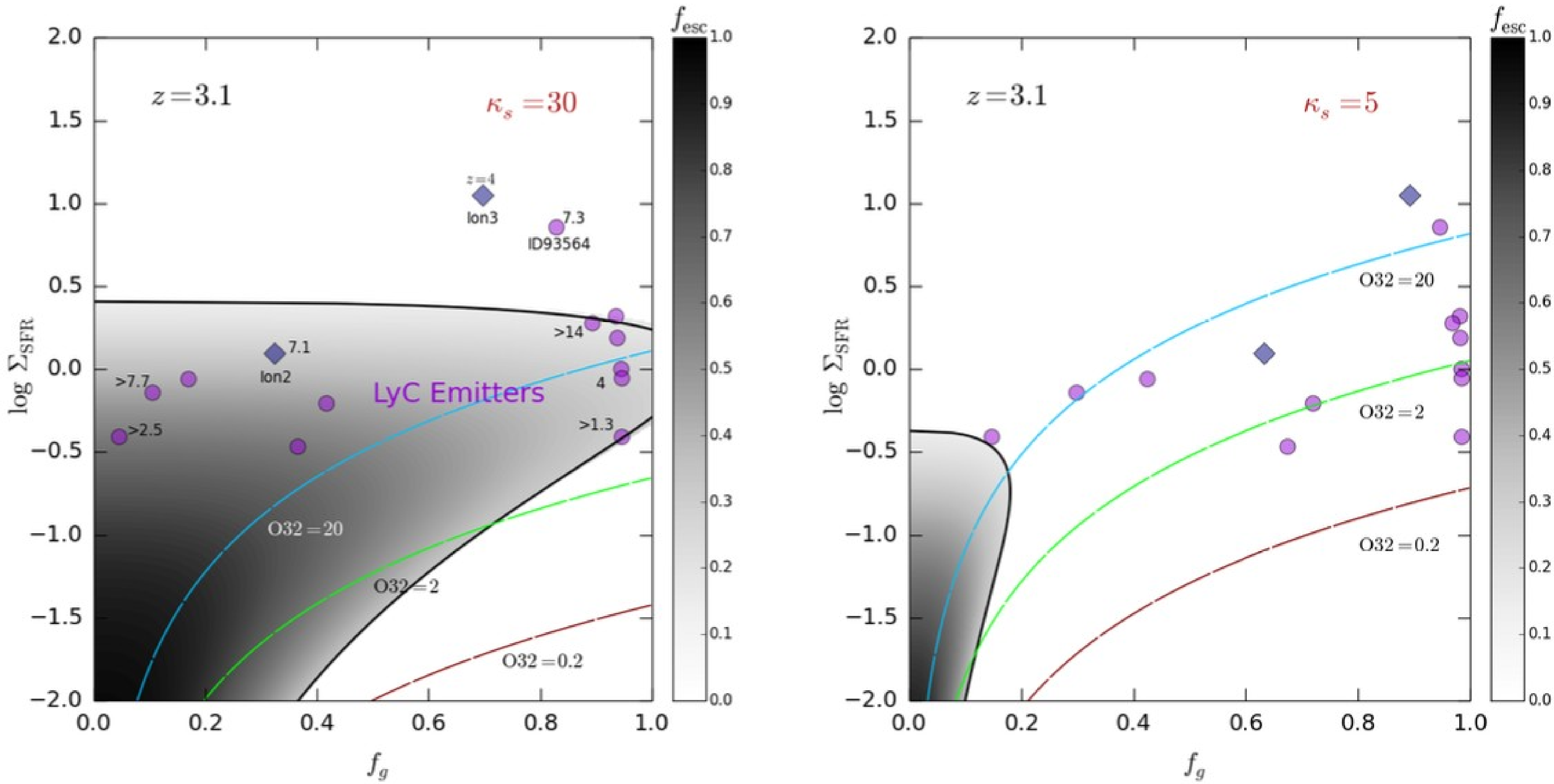
Table 1. Key LyC emitter galaxy properties used for the model comparison at $z = 3.1$

ID	SFR $M_\odot \mathrm{yr}^{-1}$	$\log M_*$ $M_\odot$	$E(B-V)$	O32	f_{esc}	$\log \Sigma_*^a$	Σ_{SFR}^a	$\log \Sigma_g^a$	f_g^a	$\mathcal{D}^a$
86861	9.06	9.44	0.003	> 10.0	0.46	8.34	0.72	7.41	0.1058	0.005
93564	89.96	8.54	0.050	10.1	0.31	7.44	7.16	8.13	0.8289	0.016
90675	12.53	7.38	0.030	···	0.39	6.28	1.00	7.51	0.9448	0.040
90340	4.29	8.52	0.030	···	0.30	7.42	0.34	7.18	0.3659	0.087
84986	19.39	7.57	0.030	···	0.26	6.47	1.54	7.65	0.9379	0.030
92863	7.75	8.61	0.070	···	0.15	7.51	0.62	7.37	0.4171	0.133
92616	26.13	7.68	0.020	···	0.60	6.58	2.08	7.74	0.9355	0.016
94460	23.81	7.89	0.036	> 17.3	0.33	6.79	1.89	7.71	0.8933	0.031
105937	4.91	9.64	0.040	> 3.4	0.32	8.54	0.39	7.22	0.0460	0.105
104037	10.94	9.26	0.011	5.9	0.13	8.16	0.87	7.47	0.1701	0.016
101846	4.92	7.08	0.030	> 1.9	0.42	5.98	0.39	7.22	0.9460	0.079
100871	11.0	7.33	0.020	···	0.47	6.23	0.88	7.47	0.9460	0.030
Ion3	140.0	9.00	0.050	···	0.20	7.90	11.14	8.26	0.6973	0.012
Ion2	15.6	9.00	0.050	9.2	0.50	7.90	1.24	7.58	0.3246	0.058

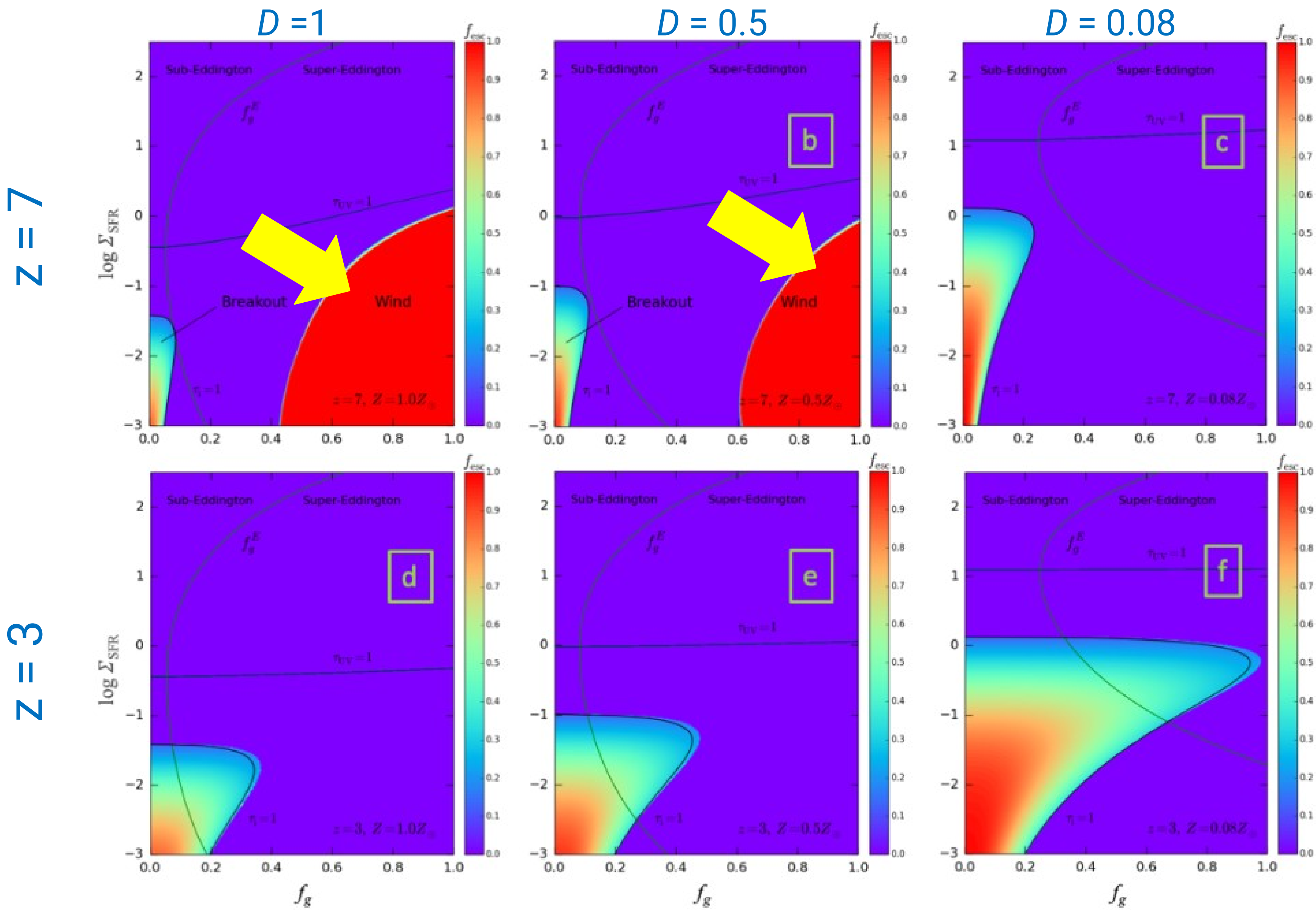
NOTE—Data in columns marked with the apex ^{a} are derived from those in the previous columns assuming a fixed stellar effective radius $r_e = 2$ kpc, and burstiness parameter $\kappa_s = 30$ (see text for explanation). Data in the first 12 rows are from the LACES survey (Fletcher et al. 2019; Nakajima et al. 2019); those for Ion2 and Ion3 (at $z = 4$) are taken from (Vanzella et al. 2016) and (Vanzella et al. 2018, 2019), respectively. Note that in Fig. 4 for consistency we correct O32 values by removing the contribution of the $\lambda 4959$ line using Nakajima et al. (2019) data.

TRUST O32 RATIOS?

Model fits correctly z = 3 data (LACES Survey)

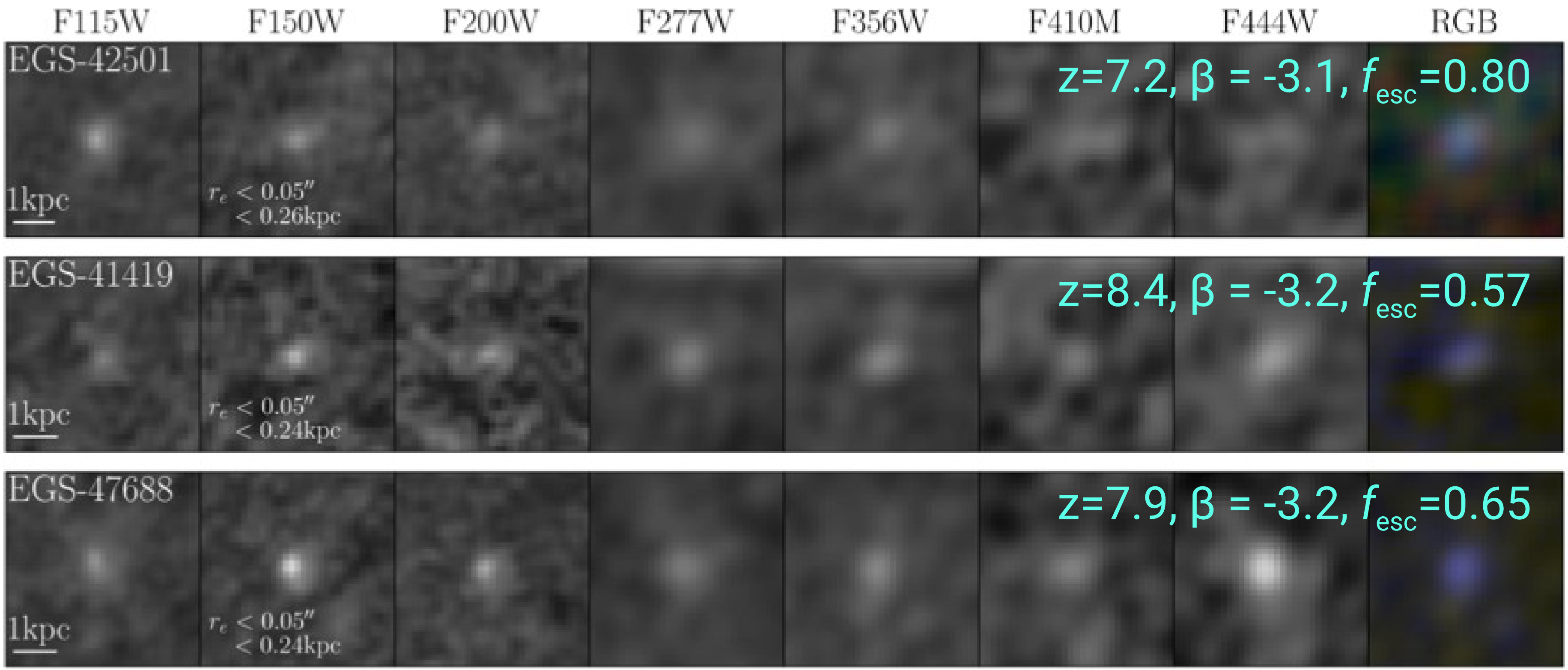


Radiation pressure opens a new LyC escape mode at high-z



JWST LEAKERS AT Z>7

Topping+22 (CEERS)



$$f_{esc} \approx 1.3 \times 10^{-4} \times 10^{-1.22\beta}$$

Chisholm+20

WHY AREN'T THEY OBSCURED?

Ziparo, AF+22

Key properties

Stellar mass	$M_* = 10^8 M_\odot$
Dust mass	$M_d = 10^5 M_\odot$
UV sizes	$r_e < 260$ pc

expected

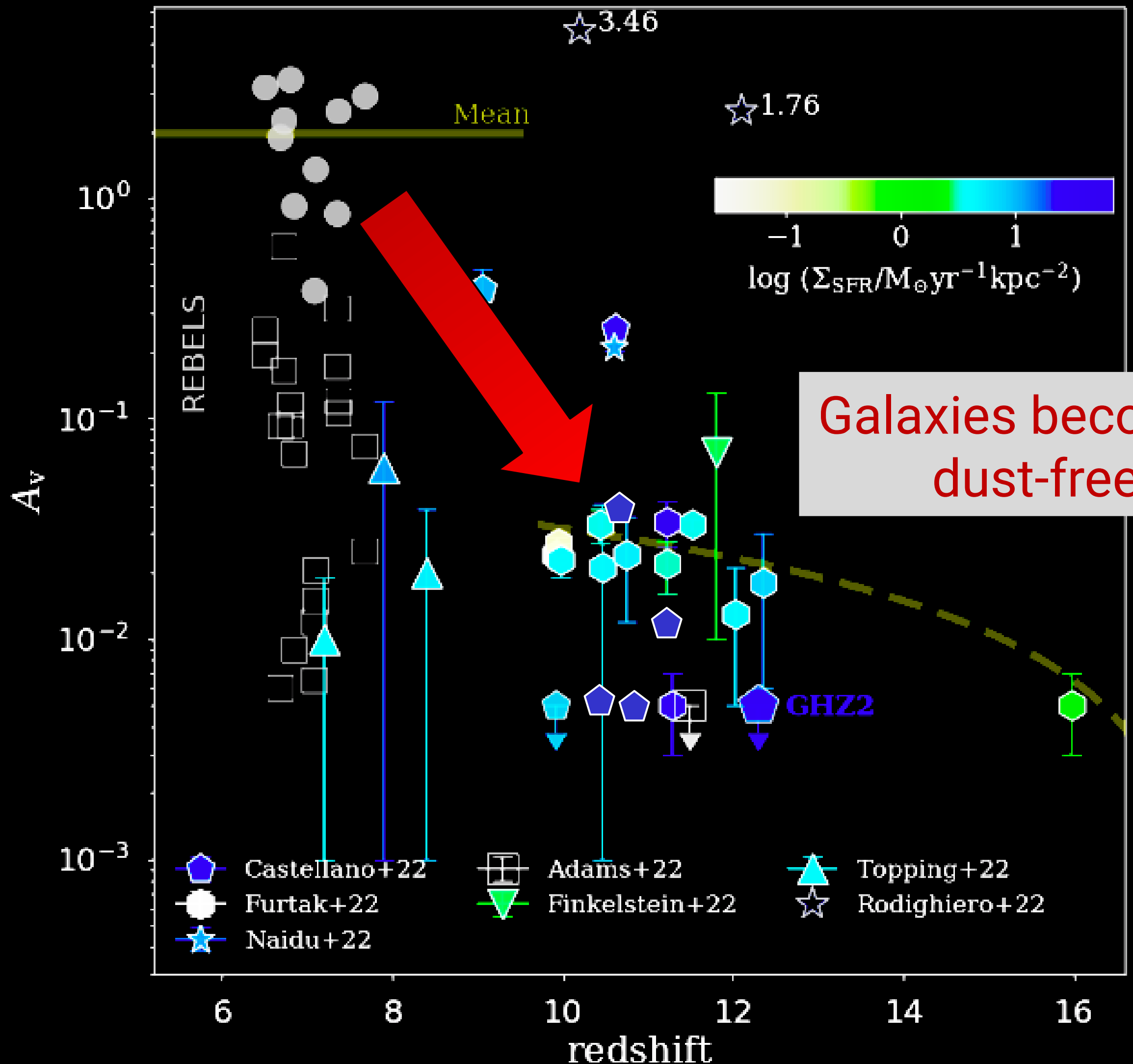
observed

50-300x less opaque

Dust ejected by radiatively driven outflows!

JWST 'BLUE MONSTERS'

Ziparo, AF+22

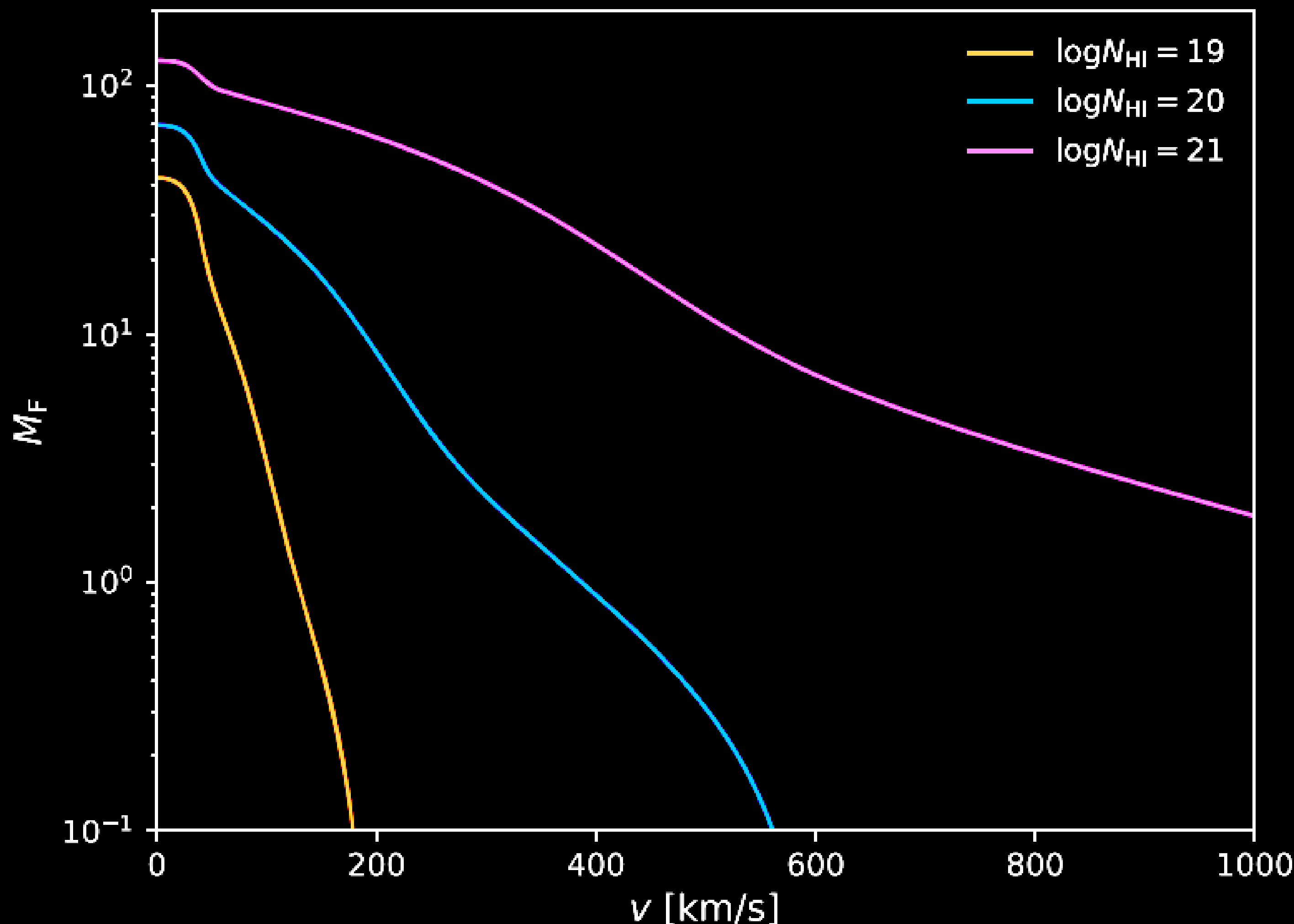


Galaxies become essentially dust-free at z ≳ 10?

LYA RADIATION PRESSURE?

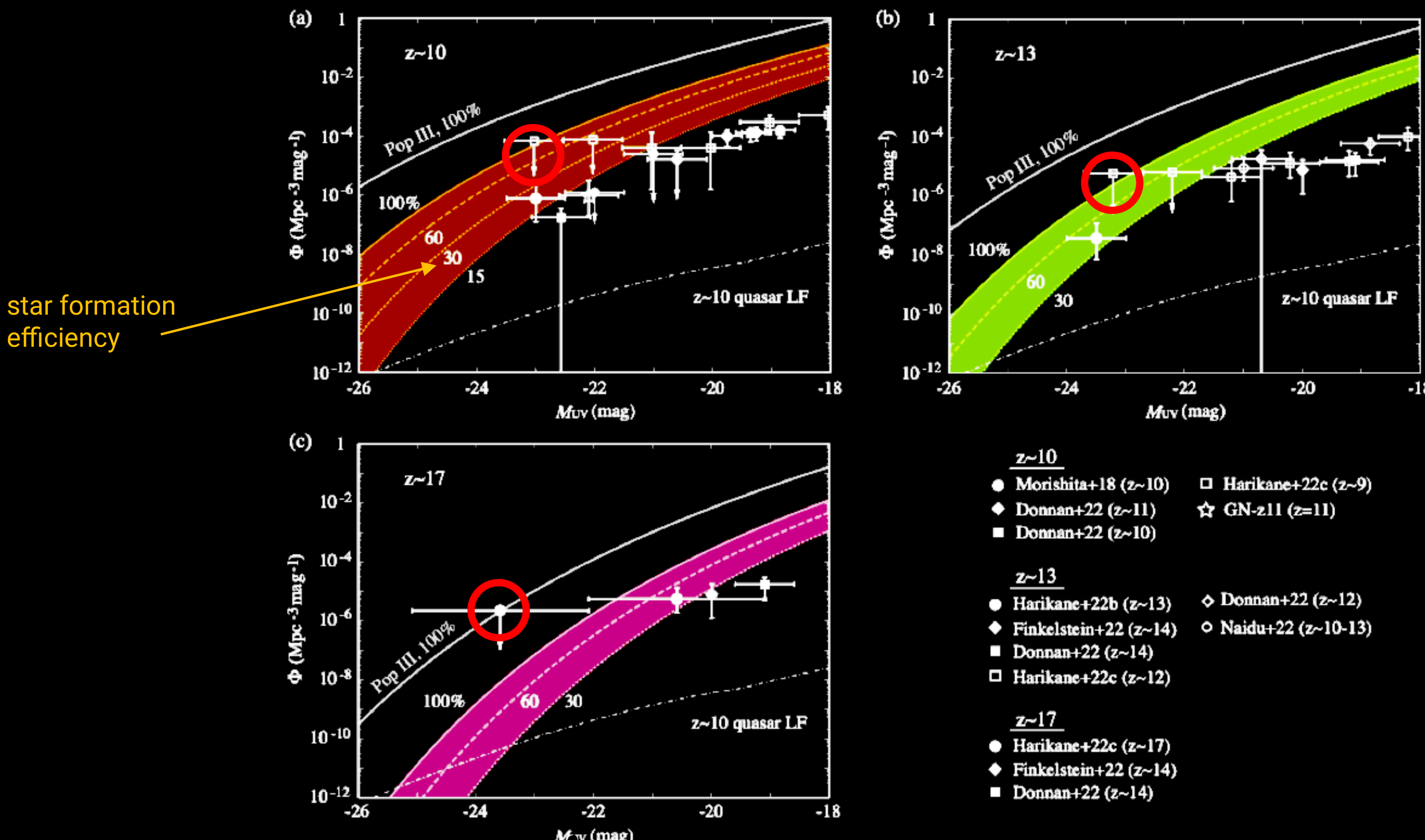
Tomaselli & AF 2021
Kim+2018

Force multiplier vs. outflow velocity



HYPER-EFFICIENT STAR FORMATION?

UV Luminosity Function evolution

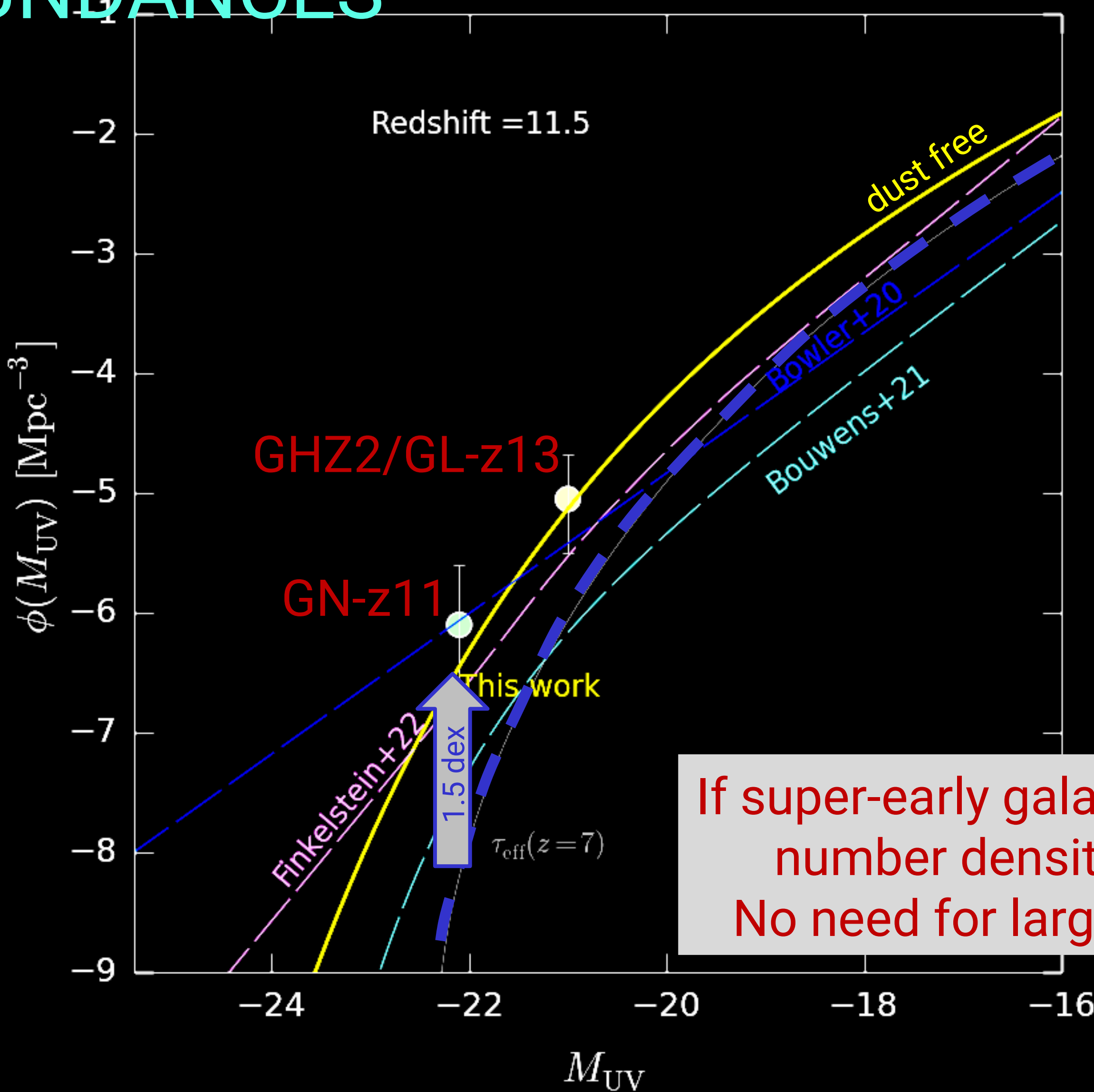


Inayoshi+22

Donnan+22, Finkelstein+22, Harikane+22, Yan+22, Atek+22

SUPER-EARLY GALAXY ABUNDANCES

Ferrara+22b
arXiv:2208.00720



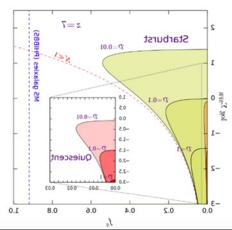
See Harikane, McLeod, Bouwens works for updated UV LF at z=11

If super-early galaxies are dust-free, number densities explained.
No need for large SF efficiencies

Summary

General results

- LyC leakers must necessarily be starburst galaxies ()
- Among these, only those with can have large escape fractions
- These findings are in agreement with LACES data on LyC leakers at z=3.1
- A large [OIII]/O[II] ratio guarantees only if simultaneously



Results for EoR galaxies (z>6)

- Early galaxies have large gas fractions, hence they should have
- However, due to their small sizes, they develop radiatively-driven winds if
- Such winds clear the dust (and likely the gas) boosting their LyC luminosity
- These galaxies should have blue UV slopes () and low
- “Blue monsters” are observed by JWST at z >8 up to about z=15
- If blue monsters are dust-free, their abundance is explained by LCDM