The Beautiful Confusion.

Super-early galaxies seen by *JWST*

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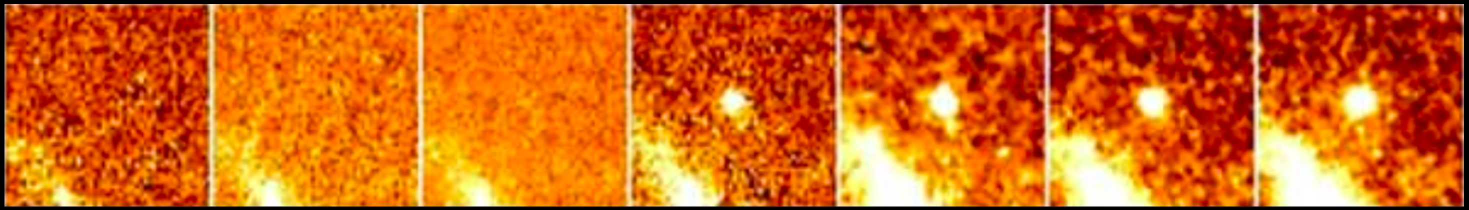
JWST DISCOVERY

- Unexpected overly large number of luminous galaxies at $z \gtrsim 10$
- These galaxies tend to be massive ($M_* \approx 10^9 M_\odot$)
- They have blue colors
- Little dust attenuation ($A_V \lesssim 0.1$)
- Are super-compact (effective radius ~ 100 pc)

Blue Monsters

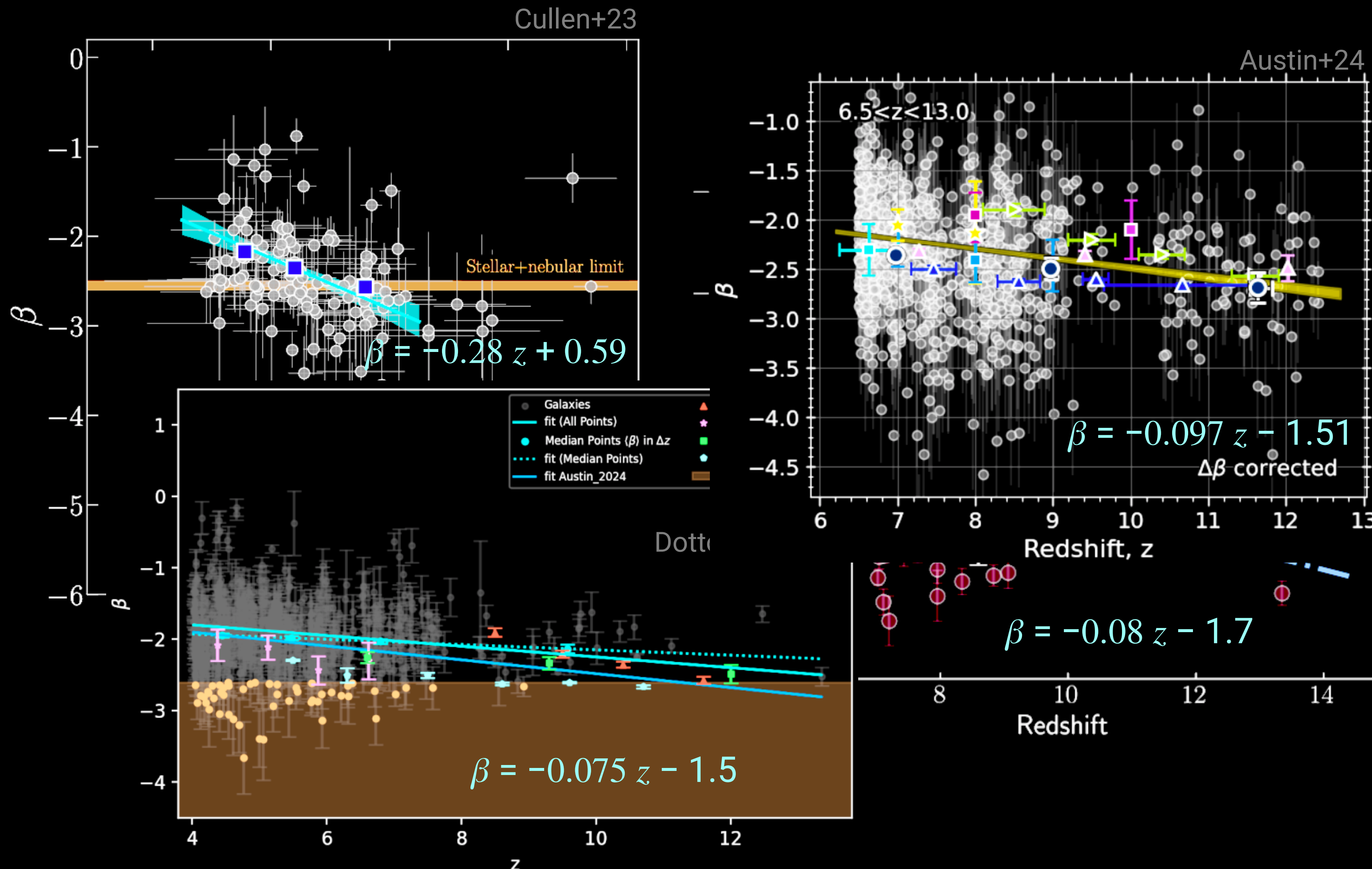
GHZ2, z=12.34

Castellano+23



Castellano et al. 2022; Santini et al. 2022; Adams et al. 2023; Furtak et al. 2022; Donnan et al. 2022; Atek et al. 2022; Yan et al. 2022; Topping et al. 2022; Finkelstein et al. 2022; Rodighiero et al. 2022; Naidu et al. 2022; Bradley et al. 2022; Whitler et al. 2022; Barrufet et al. 2022; Trussler et al. 2022; Leethochawalit et al. 2022; Harikane et al. 2022; Curti et al. 2022; Robertson et al. 2022, Curtis-Lake et al. 2023; Tacchella et al 2023; Bunker et al. 2023; Hsiao et al. 2023; Dressler et al. 23; Austin et al. 2023; Adams et al. 2023; McLeod et al. 2023, Conselice et al. 2024, Casey et al. 2024.

Super-early galaxies are very blue



SUPER-EARLY GALAXIES ARE ATTENUATION-FREE

Ferrara+25
arXiv:2410.19042

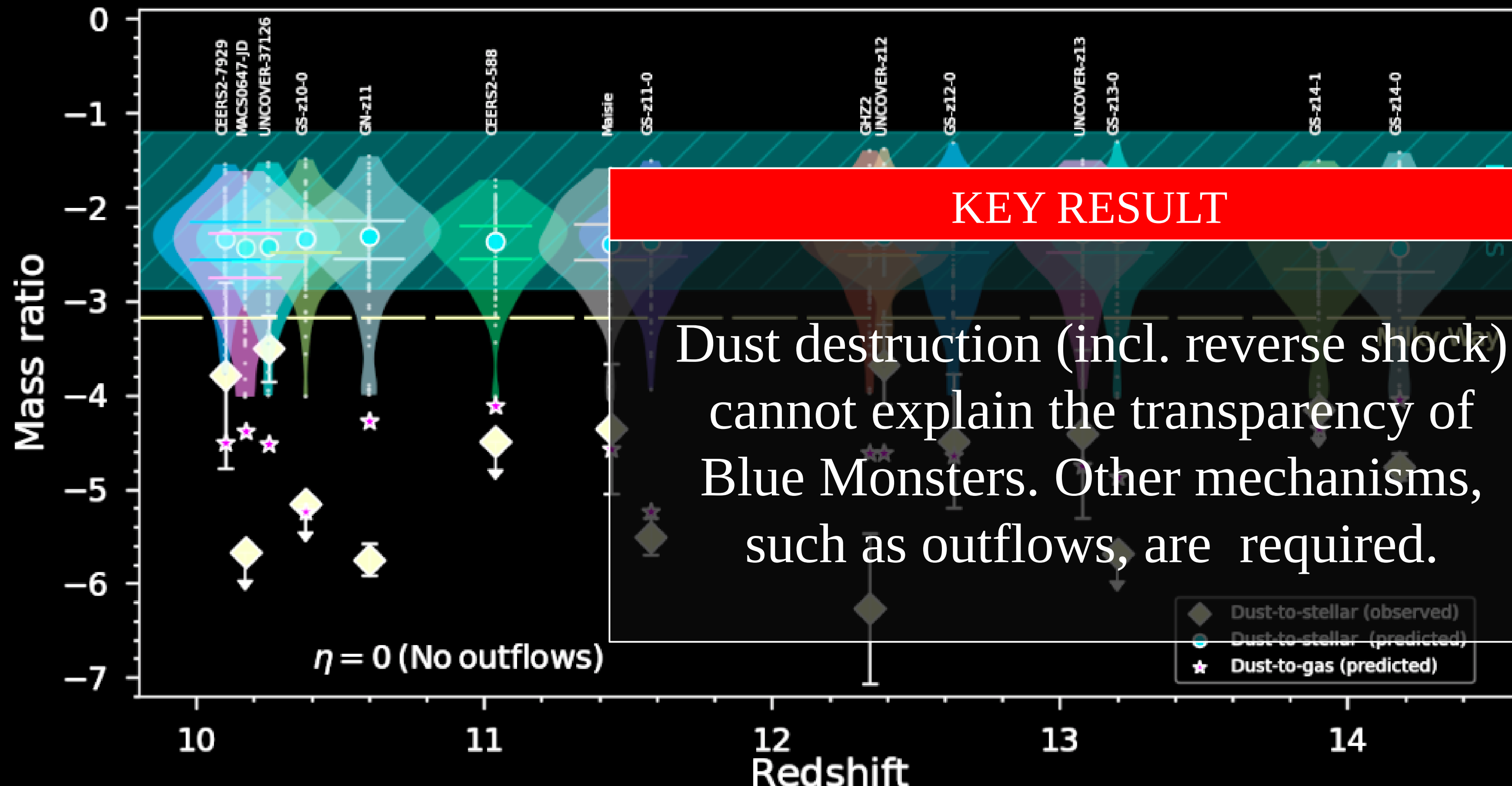
Relevant properties of spectroscopically confirmed galaxies at z>10

ID (1)	redshift (2)	A_V [mag] (3)	$\log(Z/Z_\odot)$ (4)	r_e [pc] (5)	$\log(M_d/M_\odot)$ (6)	$\log(M_\star/M_\odot)$ (7)	$\log \xi_d$ (8)
CEERS2-7929[a]	10.10	$0.14^{+0.29}_{-0.14}$	—	520^{+127}_{-127}	$5.2^{+10.9}_{-5.2} \times 10^4$	$8.50^{+0.30}_{-0.40}$	$-3.78^{+0.99}_{-0.99}$
MACS0647-JD[b]	10.17	< 0.01	$-0.90^{+0.09}_{-0.09}$	70^{+24}_{-24}	$< 6.7 \times 10^1$	$7.50^{+0.10}_{-0.10}$	< -5.67
UNCOVER-37126[c]	10.25	$^*0.18^{+0.14}_{-0.14}$	—	426^{+40}_{-42}	$4.5^{+3.5}_{-3.5} \times 10^4$	$8.16^{+0.08}_{-0.07}$	$-3.51^{+0.35}_{-0.35}$
GS-z10-0[d]	10.38	$0.05^{+0.03}_{-0.02}$	$-1.91^{+0.25}_{-0.20}$	< 62	$< 2.6 \times 10^2$	$7.58^{+0.19}_{-0.20}$	< -5.16
GN-z11[e]	10.60	$0.17^{+0.03}_{-0.03}$	$-0.92^{+0.06}_{-0.05}$	64^{+20}_{-20}	$9.6^{+3.4}_{-3.4} \times 10^3$	$8.73^{+0.06}_{-0.06}$	$-5.75^{+0.17}_{-0.17}$
CEERS2-588[a]	11.04	$0.10^{+0.11}_{-0.07}$	$-0.84^{+0.16}_{-0.12}$	< 477	$< 3.1 \times 10^4$	$8.99^{+0.54}_{-0.22}$	< 4.49
Maisie[f]	11.44	$0.07^{+0.09}_{-0.05}$	—	340^{+14}_{-14}	$1.1^{+1.4}_{-1.1} \times 10^4$	$8.40^{+0.30}_{-0.40}$	$-4.35^{+0.69}_{-0.69}$
GS-z11-0[d]	11.58	$0.18^{+0.06}_{-0.06}$	$-1.87^{+0.28}_{-0.18}$	$^\dagger 77^{+8}_{-8}$	$1.5^{+0.5}_{-0.5} \times 10^3$	$8.67^{+0.08}_{-0.13}$	$-5.50^{+0.20}_{-0.20}$
GHZ2[g]	12.34	$0.04^{+0.07}_{-0.03}$	$-1.40^{+0.27}_{-0.24}$	105^{+9}_{-9}	$6.1^{+10.6}_{-6.1} \times 10^2$	$9.05^{+0.10}_{-0.25}$	$-6.27^{+0.80}_{-0.80}$
UNCOVER-z12[c]	12.39	$0.19^{+0.17}_{-0.10}$	$-1.34^{+0.60}_{-0.42}$	426^{+40}_{-42}	$4.7^{+4.2}_{-4.2} \times 10^4$	$8.35^{+0.14}_{-0.18}$	$-3.67^{+0.43}_{-0.43}$
GS-z12-0[d]	12.63	$0.05^{+0.03}_{-0.02}$	$-1.44^{+0.23}_{-0.22}$	$^\dagger 144^{+15}_{-15}$	$1.4^{+0.9}_{-0.9} \times 10^3$	$7.64^{+0.66}_{-0.39}$	$-4.49^{+0.71}_{-0.71}$
UNCOVER-z13[c]	13.08	$0.04^{+0.08}_{-0.03}$	$-1.57^{+0.35}_{-0.28}$	309^{+110}_{-74}	$5.2^{+10.7}_{-5.2} \times 10^3$	$8.13^{+0.11}_{-0.15}$	$-4.41^{+0.89}_{-0.89}$
GS-z13-0[d]	13.20	$0.05^{+0.03}_{-0.02}$	$-1.69^{+0.28}_{-0.31}$	< 52	$< 1.9 \times 10^2$	$7.95^{+0.19}_{-0.29}$	< -5.68
GS-z14-1[h]	13.90	$0.20^{+0.11}_{-0.07}$	$-1.10^{+0.60}_{-0.50}$	< 160	$< 7.0 \times 10^3$	$8.00^{+0.40}_{-0.30}$	< -4.15
GS-z14-0[h]	14.18	$0.31^{+0.14}_{-0.17}$	$-0.75^{+0.03}_{-0.03}$	260^{+2}_{-2}	$1.2^{+0.3}_{-0.3} \times 10^4$	$8.84^{+0.09}_{-0.10}$	$-4.76^{+0.14}_{-0.14}$

Dust-to-stellar ratios are very low

Ferrara+25
arXiv:2410.19042

Spectroscopically confirmed z > 10 galaxies



KEY RESULT

Dust destruction (incl. reverse shock) cannot explain the transparency of Blue Monsters. Other mechanisms, such as outflows, are required.

SUPER-EDDINGTON CONDITION

Ferrara 23
arXiv:2310.12197

Compact structure + Large UV luminosity

=

The galaxy becomes super-Eddington and powerful

radiation-driven outflows are launched

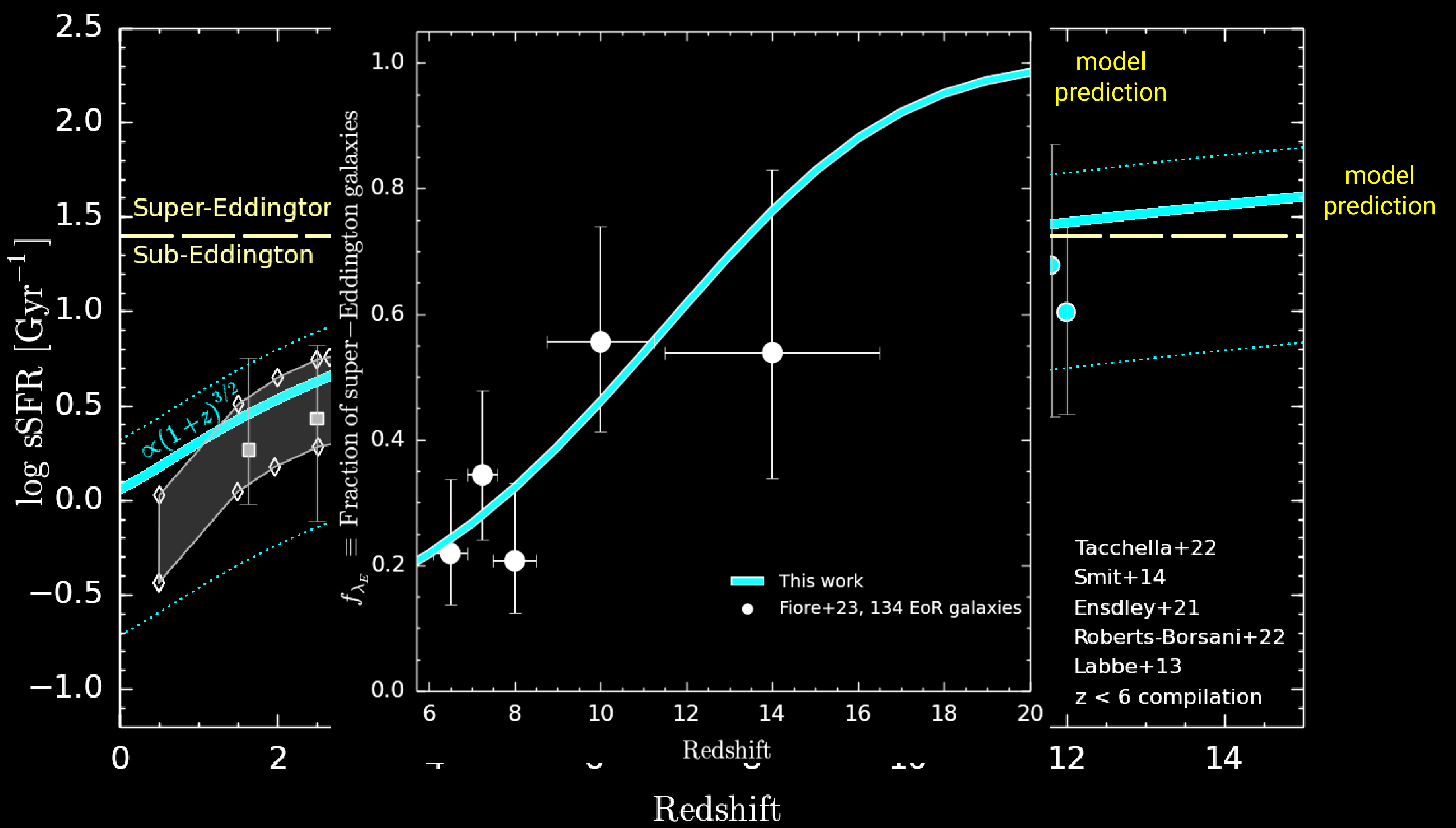
$$\lambda_E > 1 \quad \Longleftrightarrow \quad \mathrm{sSFR} \gtrsim 25\ \mathrm{Gyr}^{-1}$$

For a more refined calculation see Nakazato & Ferrara (2025), arXiv:2412.07598

SUPER-EDDINGTON FRACTION

Ferrara 24
arXiv:2310.12197

Deviations from mean sSFR ≃ 2x in 8<z<10.
Consistent with stochastic SFR predictions



Key refs

Ferrara+ 2023, MNRAS, 522, 3986
Ferrara 2024a, A&A, 684, 207
Ferrara 2024b, A&A, 689, 31
Ferrara+ 2025, arXiv2410.19042

AF
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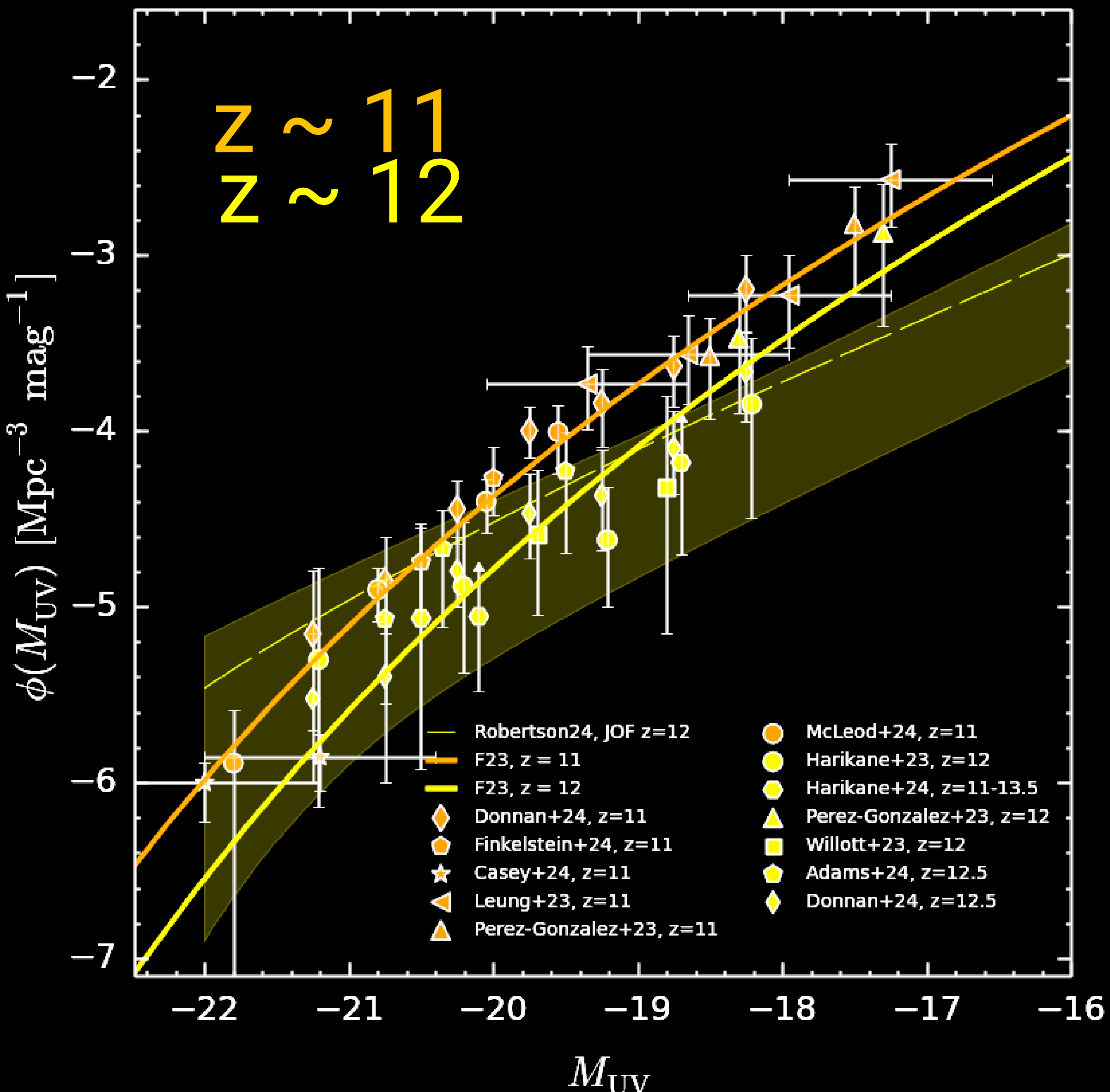
Attenuation-free model*

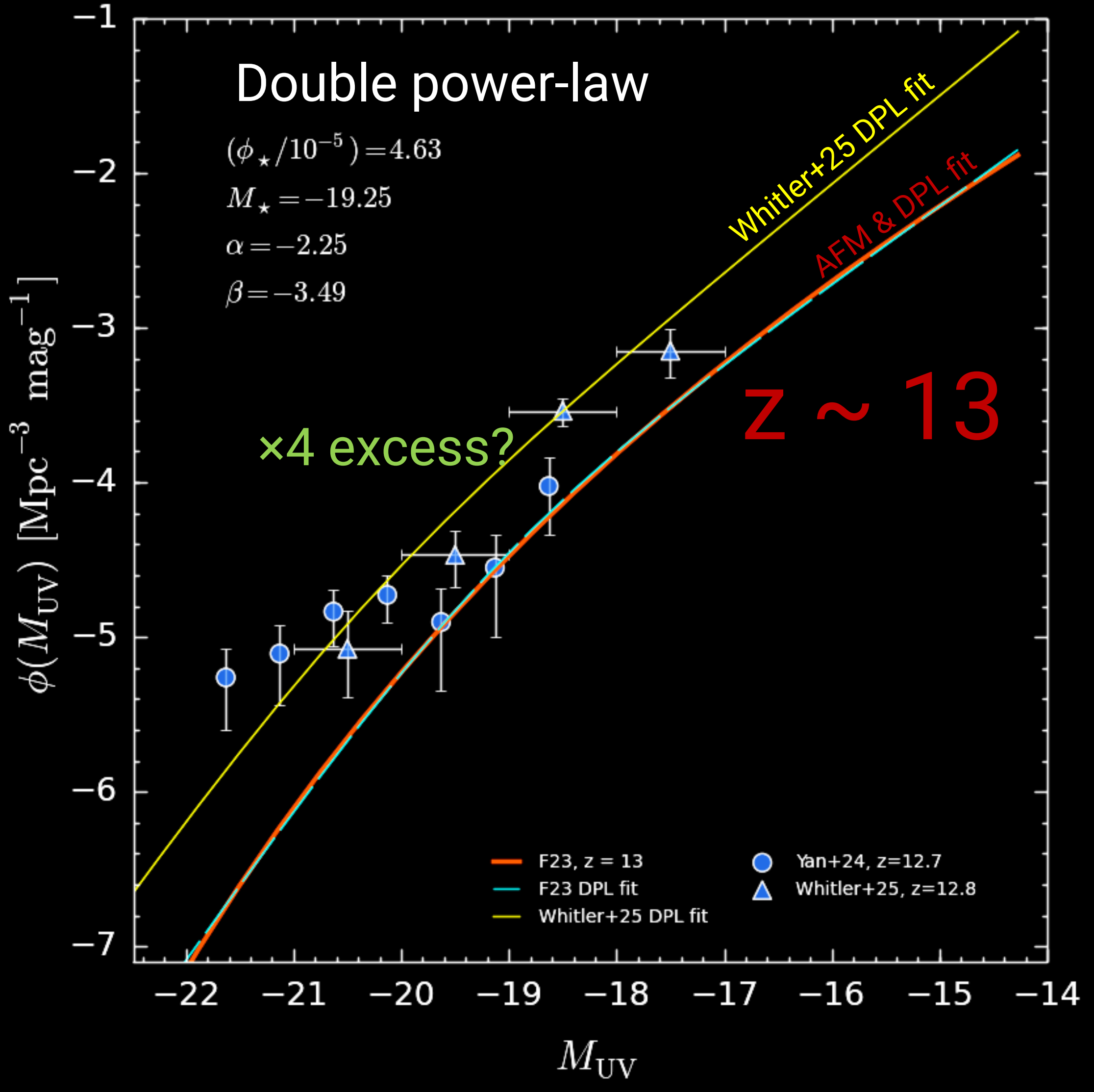
* Possibly the simplest successful model: no need for high SF efficiency, stochasticity, top-heavy IMF, ...

UV LF OF BLUE MONSTERS

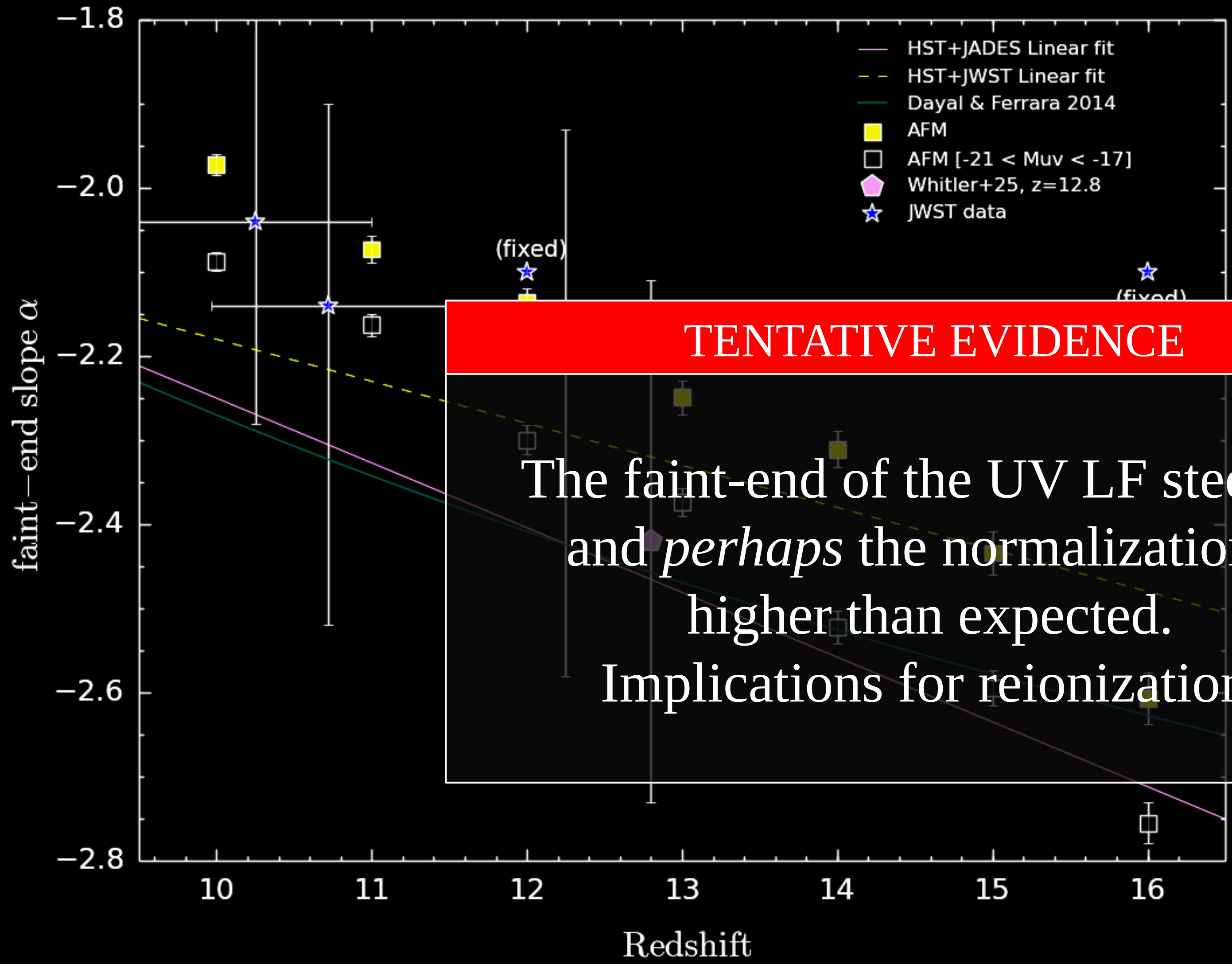
Ferrara+23
Ferrara24



ULTRA-HIGH REDSHIFT LF



LF FAINT-END SLOPE EVOLUTION

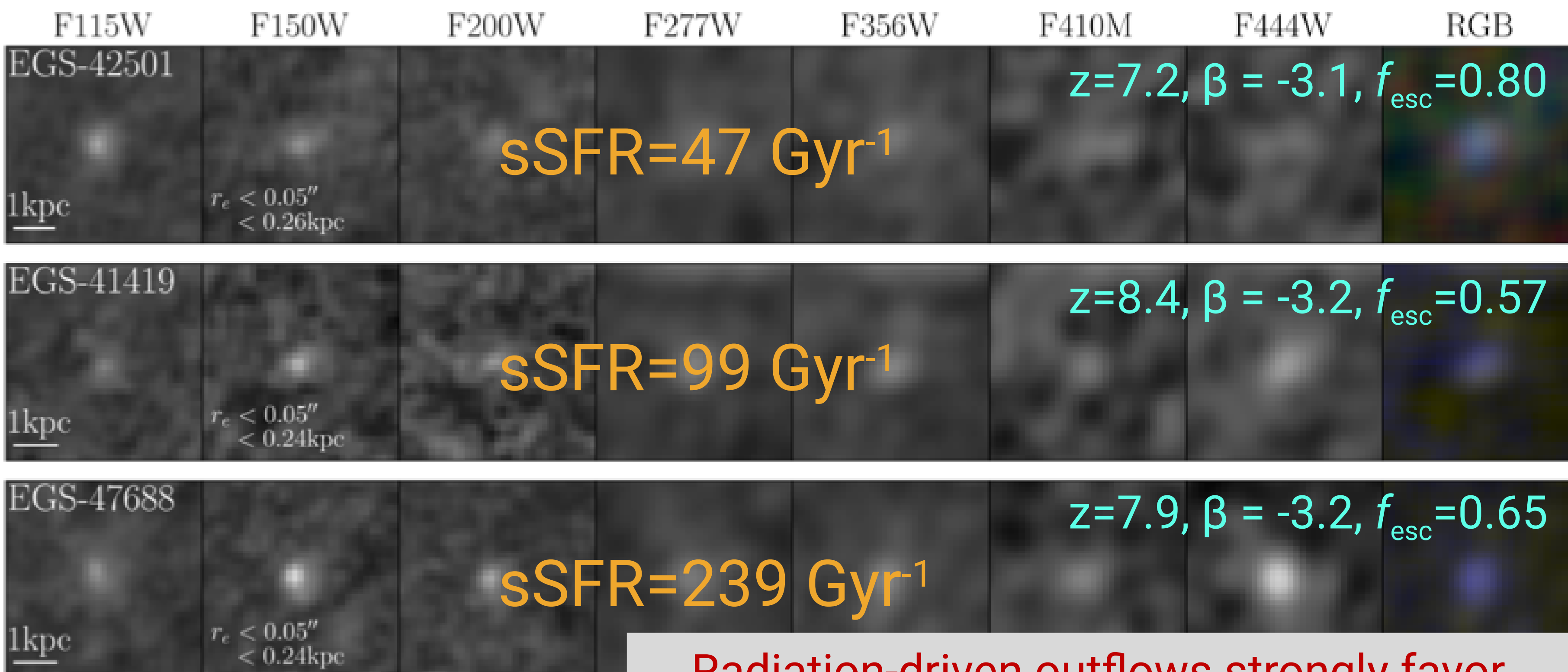


TENTATIVE EVIDENCE

The faint-end of the UV LF steepens and *perhaps* the normalization is higher than expected.
Implications for reionization?

BLUE MONSTERS ARE LYC LEAKERS?

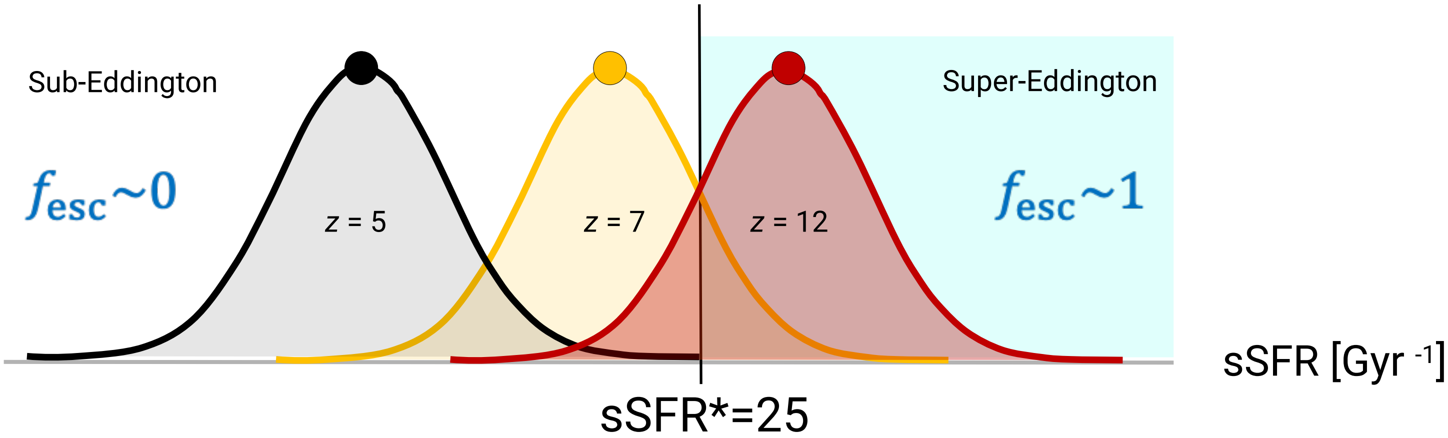
Topping+22 (CEERS)



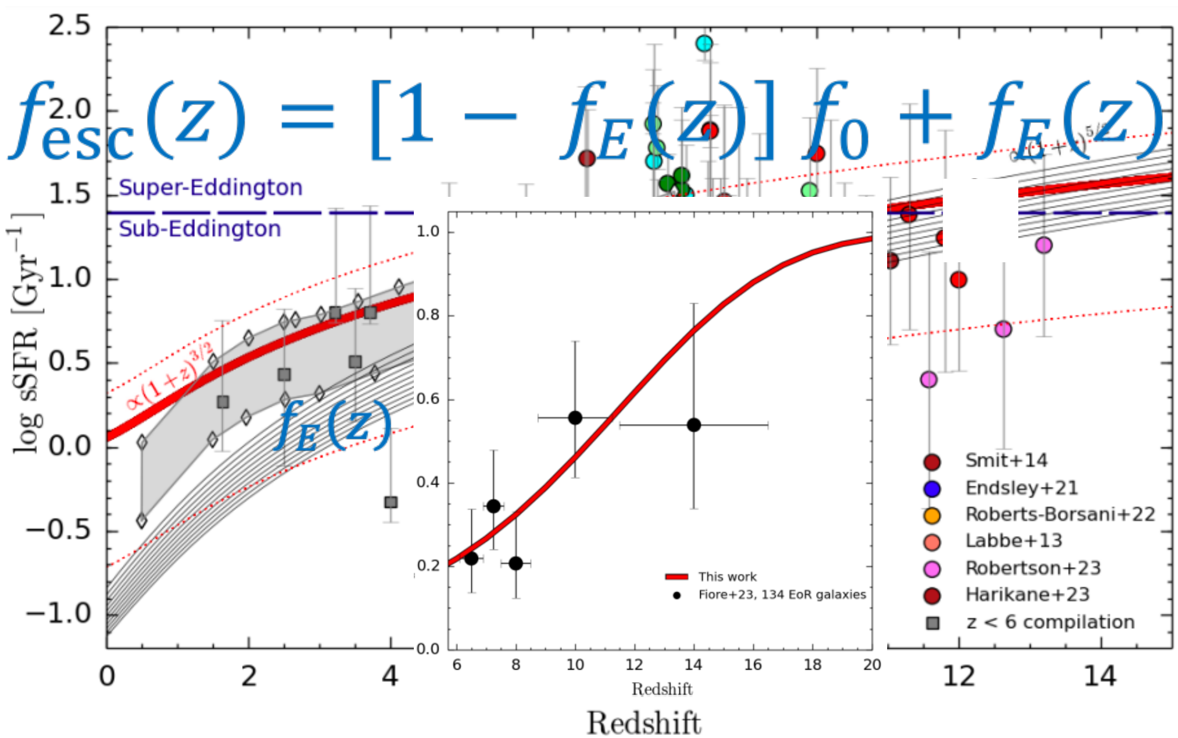
Radiation-driven outflows strongly favor the escape of both Lya and LyC photons.

Chisholm+20

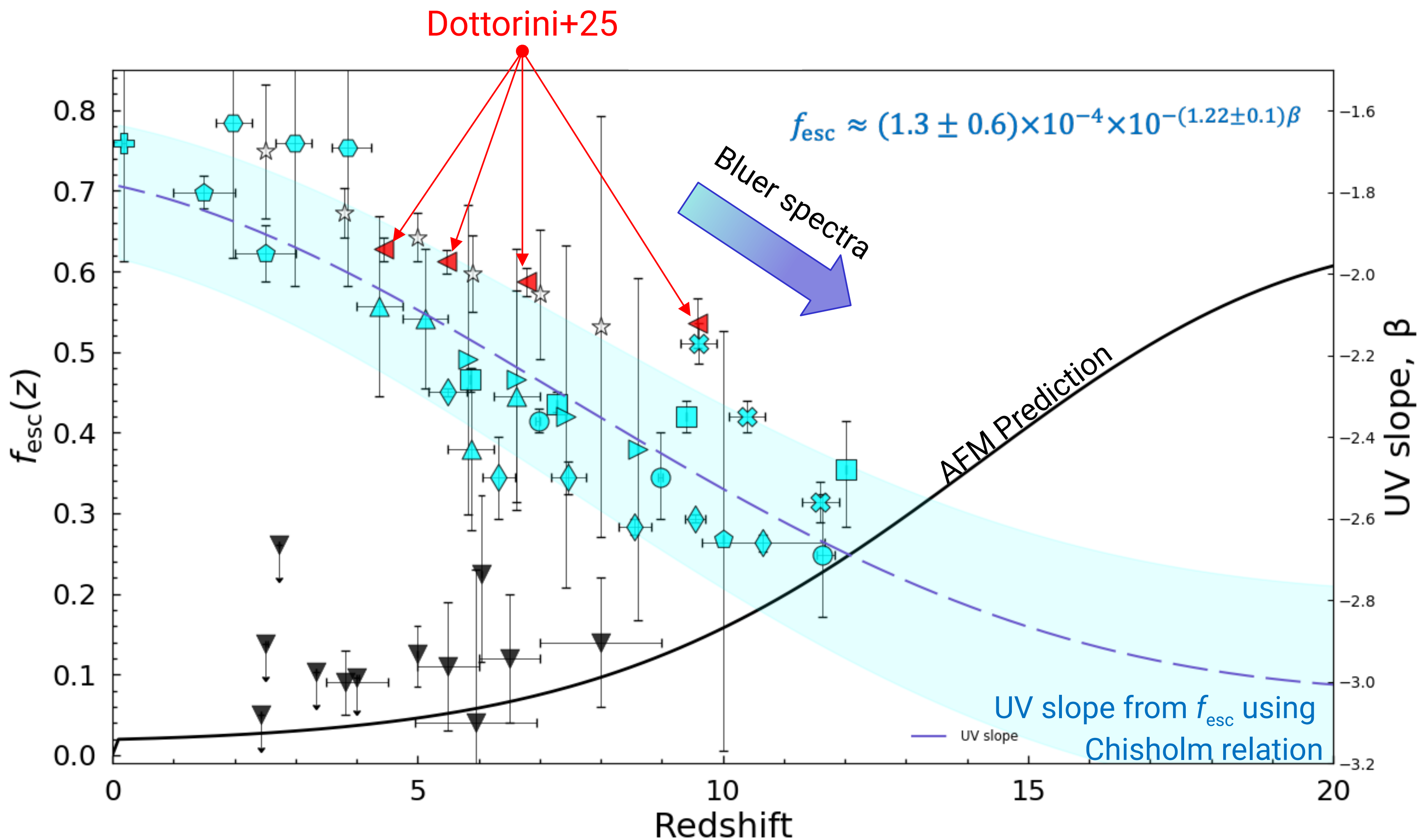
SUPER-EDDINGTON FAVORS LARGE f_{esc}



$$f_{esc}(z) = [1 - f_E(z)]\, f_0 + f_E(z)\, f_1$$

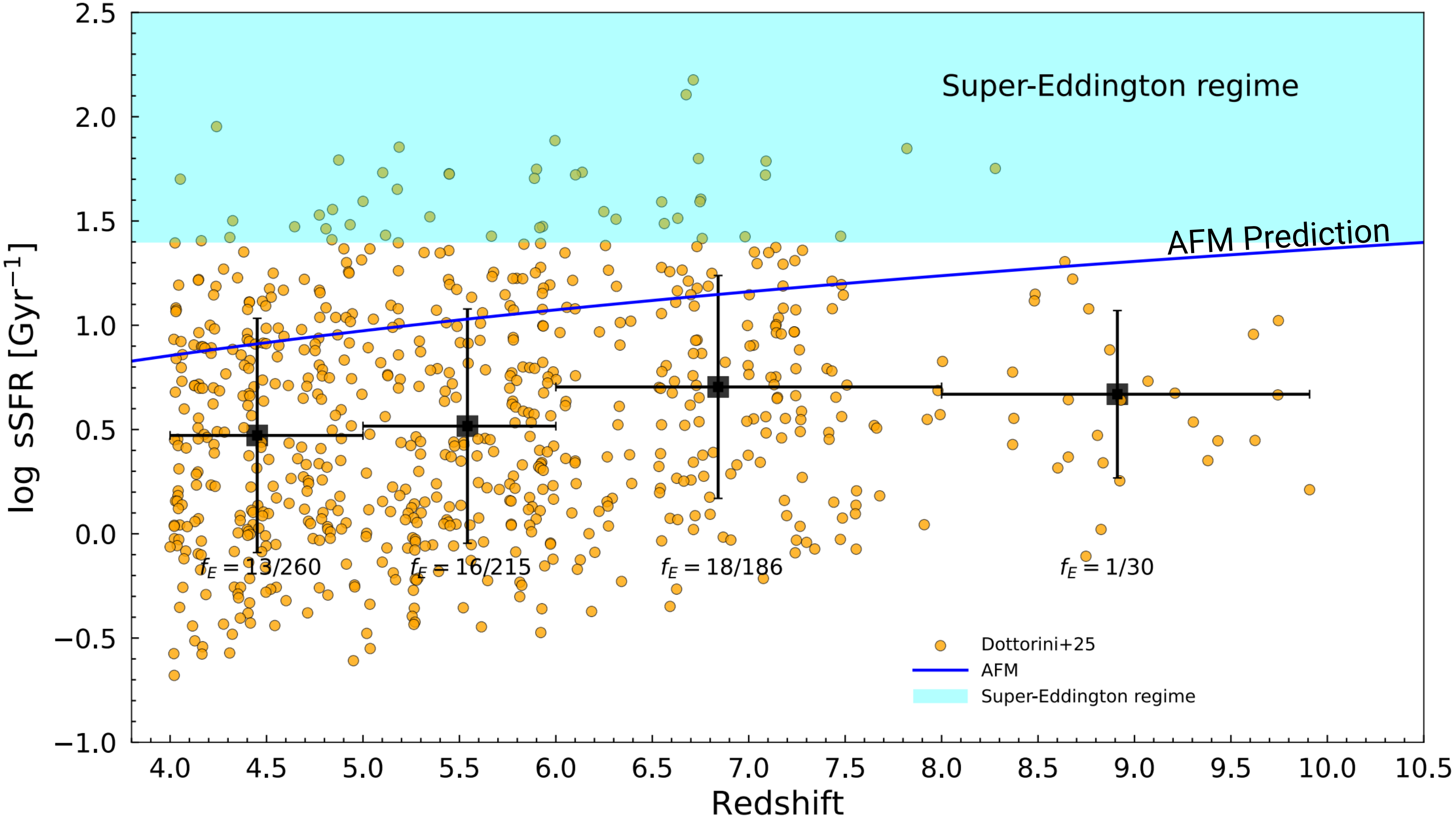


A RISING ESCAPE FRACTION

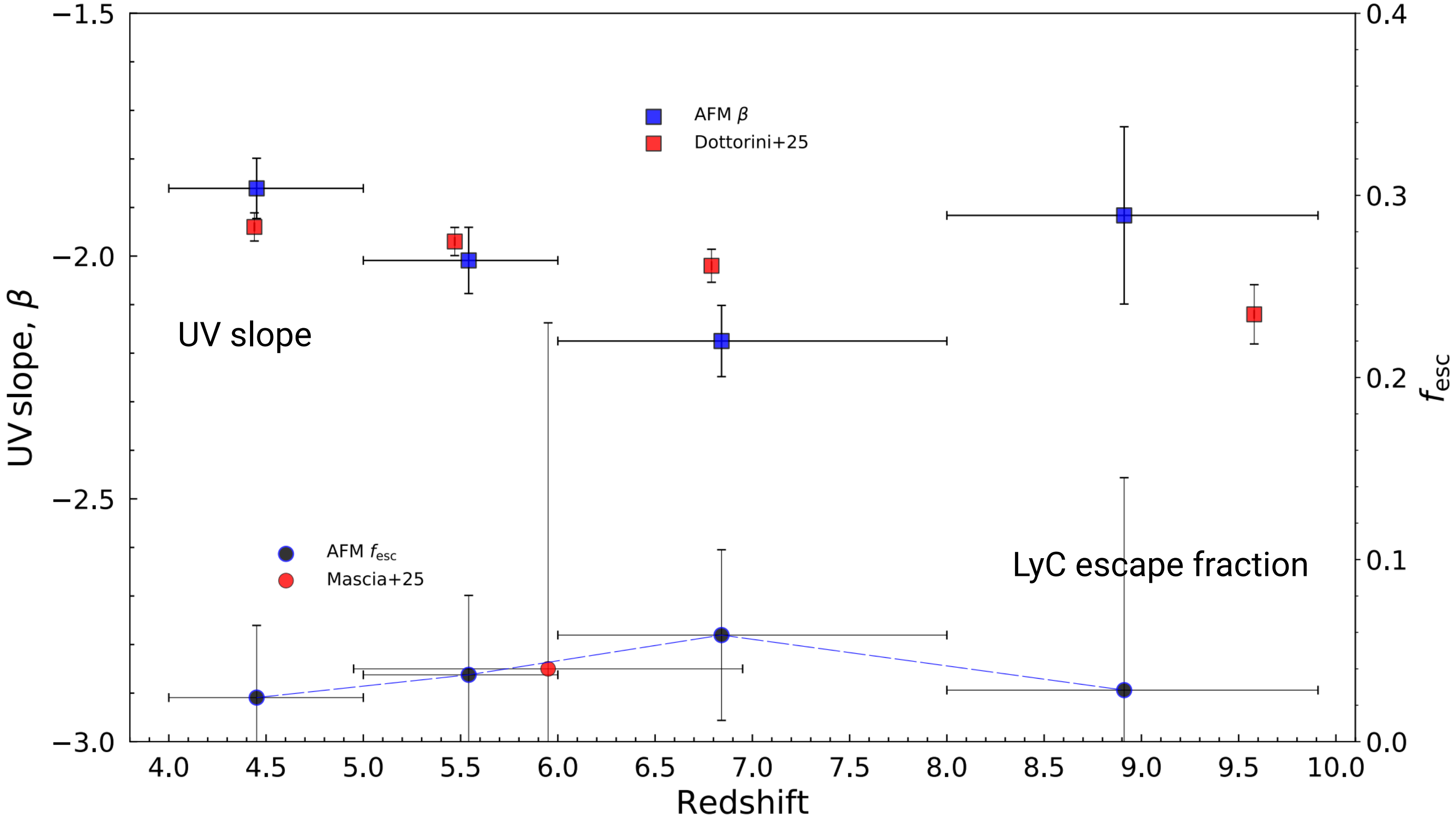


TESTING THE MODEL ON SPECIFIC SAMPLES

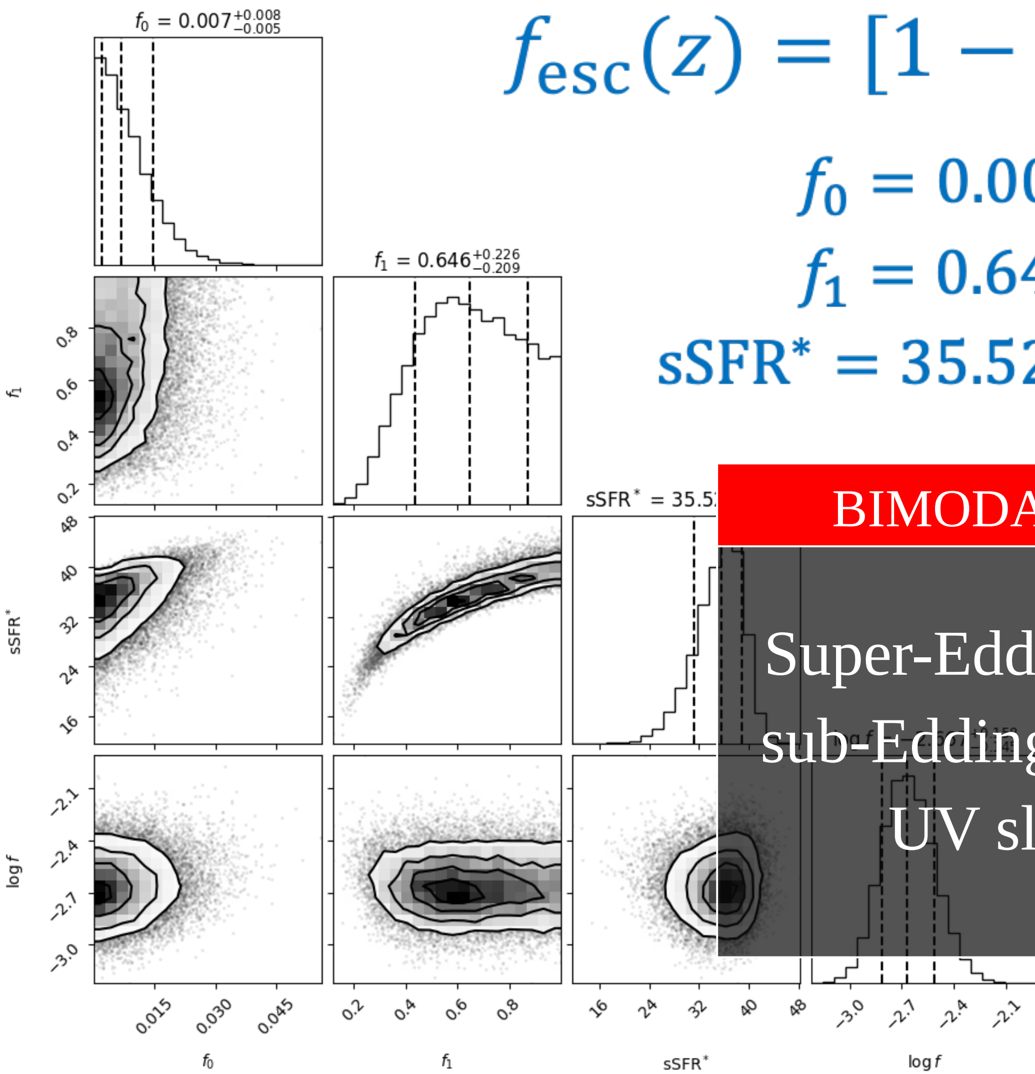
Dottorini+25 data



A CONSISTENT TREND



AFM MODEL FOR f_{esc}



$$f_{esc}(z) = [1 - f_E(z)]\, f_0 + f_E(z)\, f_1$$

$f_0 = 0.007^{+0.008}_{-0.005}$ LyC f_{esc} of sub-Eddington galaxies

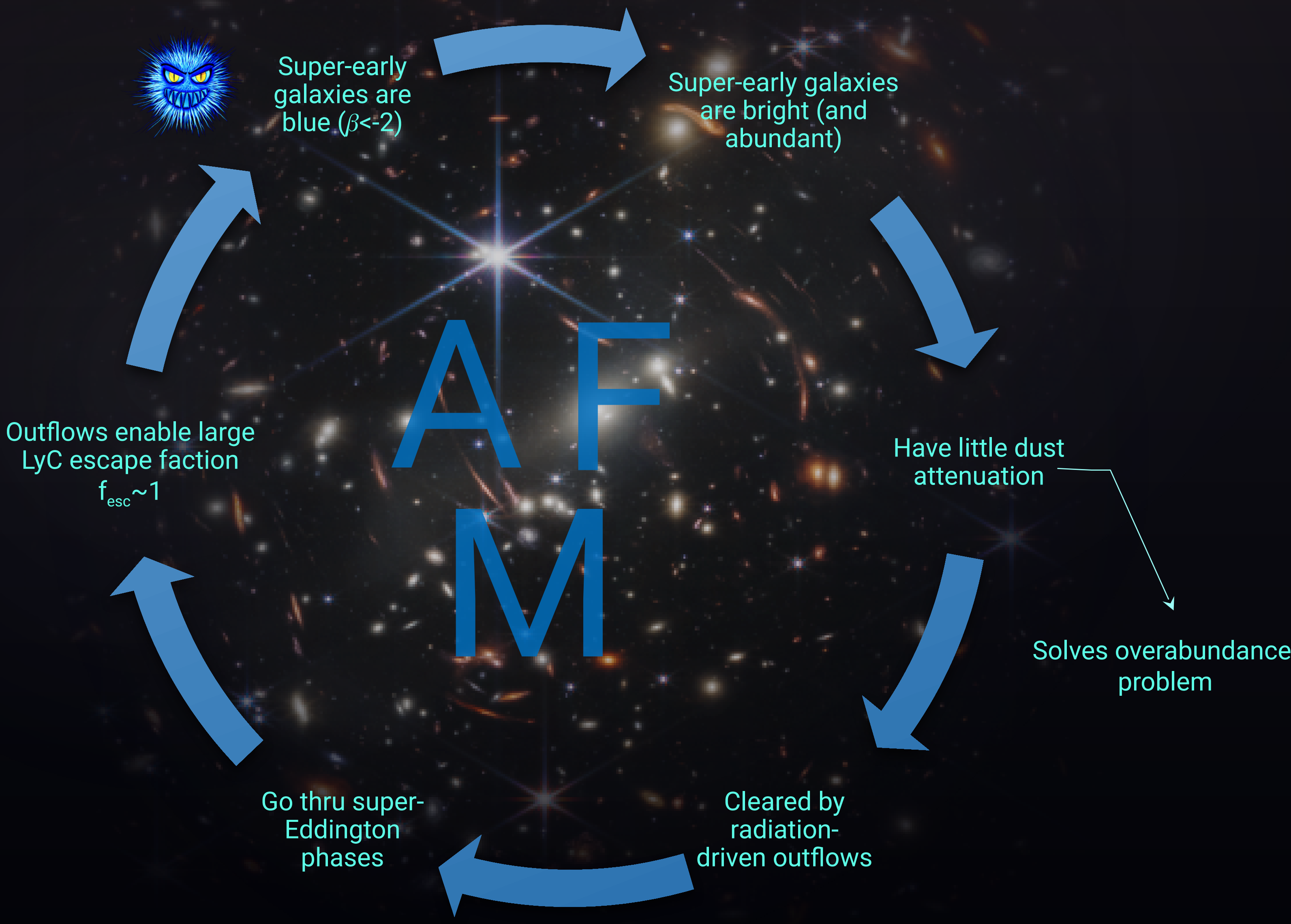
$f_1 = 0.646^{+0.226}_{-0.209}$ LyC f_{esc} of super-Eddington galaxies

$\mathrm{sSFR}^* = 35.521^{+3.264}_{-4.384}$ sSFR Eddington threshold

BIMODAL LyC ESCAPE FRACTION

Super-Eddington galaxies: $f_{esc} \sim 65\%$, sub-Eddington galaxies: $f_{esc} \sim 1\%$, fits UV slope redshift evolution

Summary



Super-early galaxies are blue (β<-2)
Super-early galaxies are bright (and abundant)
Have little dust attenuation
Solves overabundance problem
Cleared by radiation-driven outflows
Go thru super-Eddington phases
Outflows enable large LyC escape faction f_{esc}~1
AFM

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INAF, Bologna
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