Using Galaxies at z>10 to Probe Burstiness and the IMF

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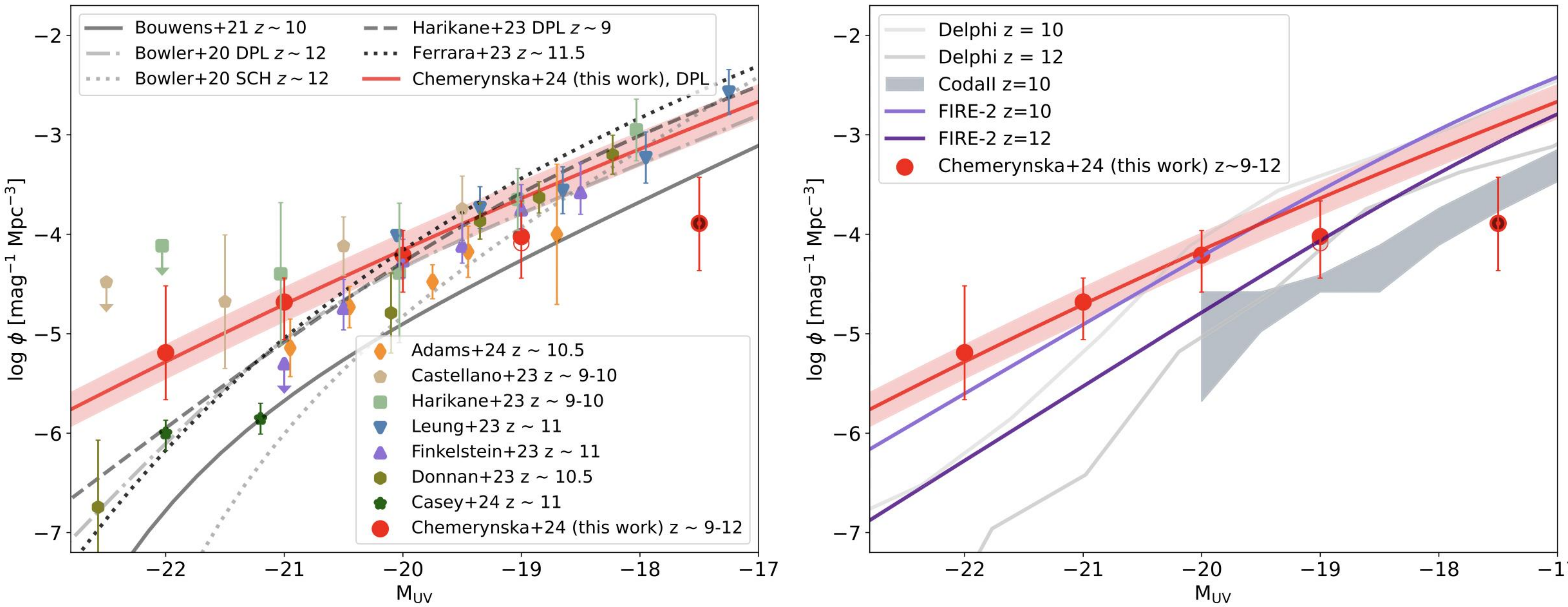
What have we learned about Cosmic Dawn from three years of JWST?

1. There are too many UV-luminous galaxies compared to pre-launch predictions.



Figures from UNCOVER (Chemerynska+24), see also JADES (Robertson+24) and other listed refs

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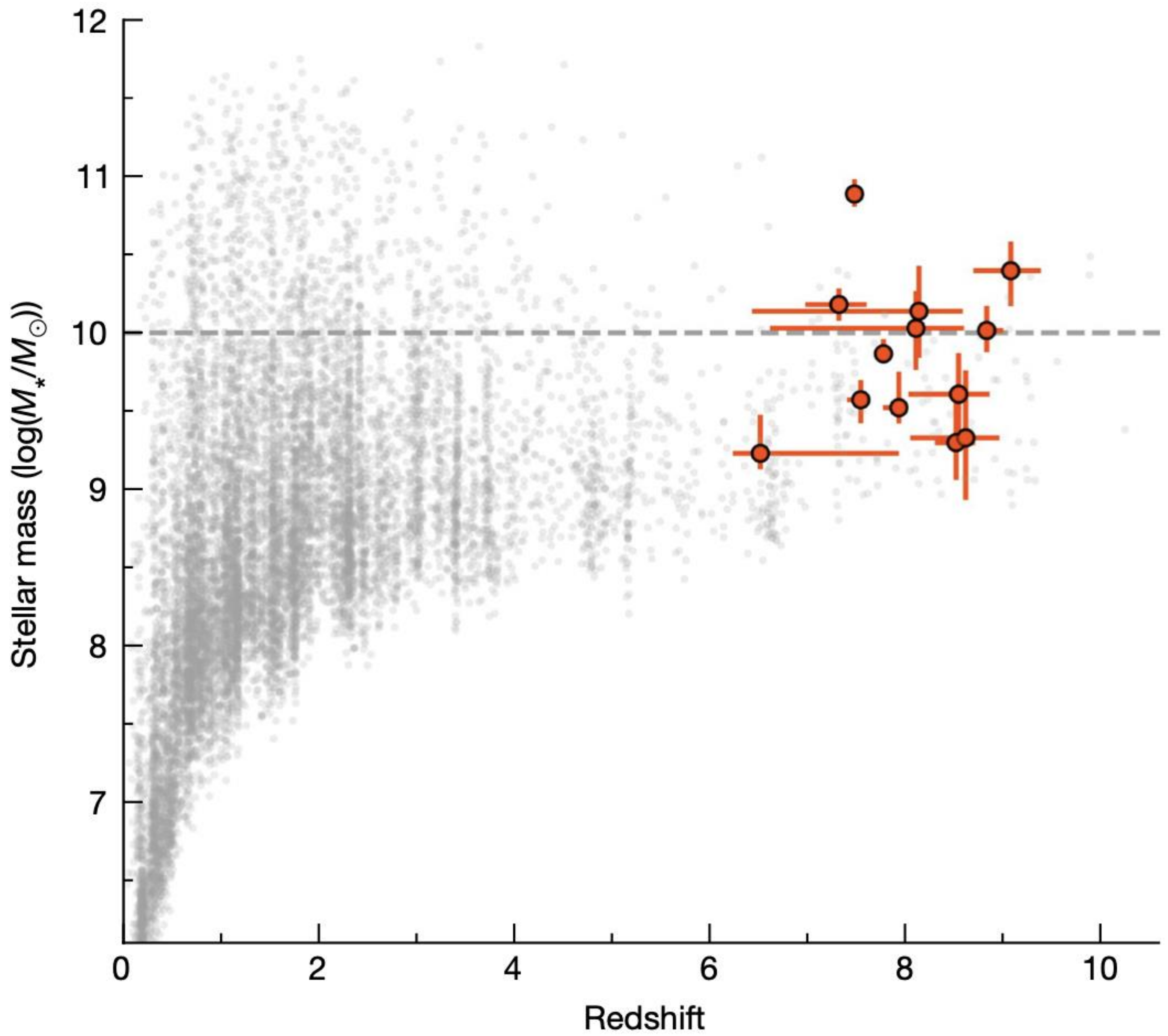

Figure from Labbe+23 showing six massive ($>10^{10}$ M_{sun}) galaxy candidates at 7.5<z<9

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3. Lyman Alpha Emission can somehow escape IGM absorption at z~8… and z~13!

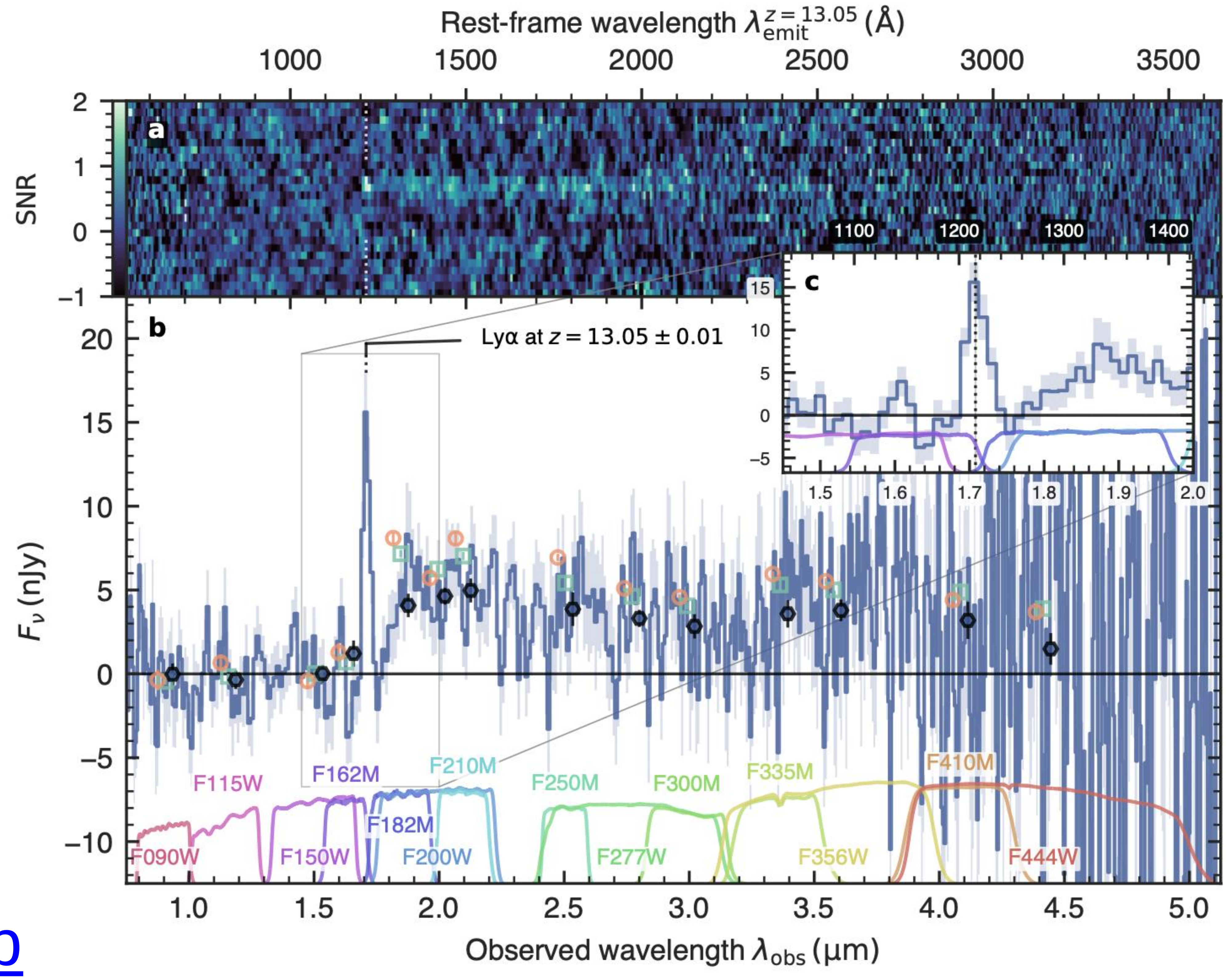

Figure from [Witstok+24b]

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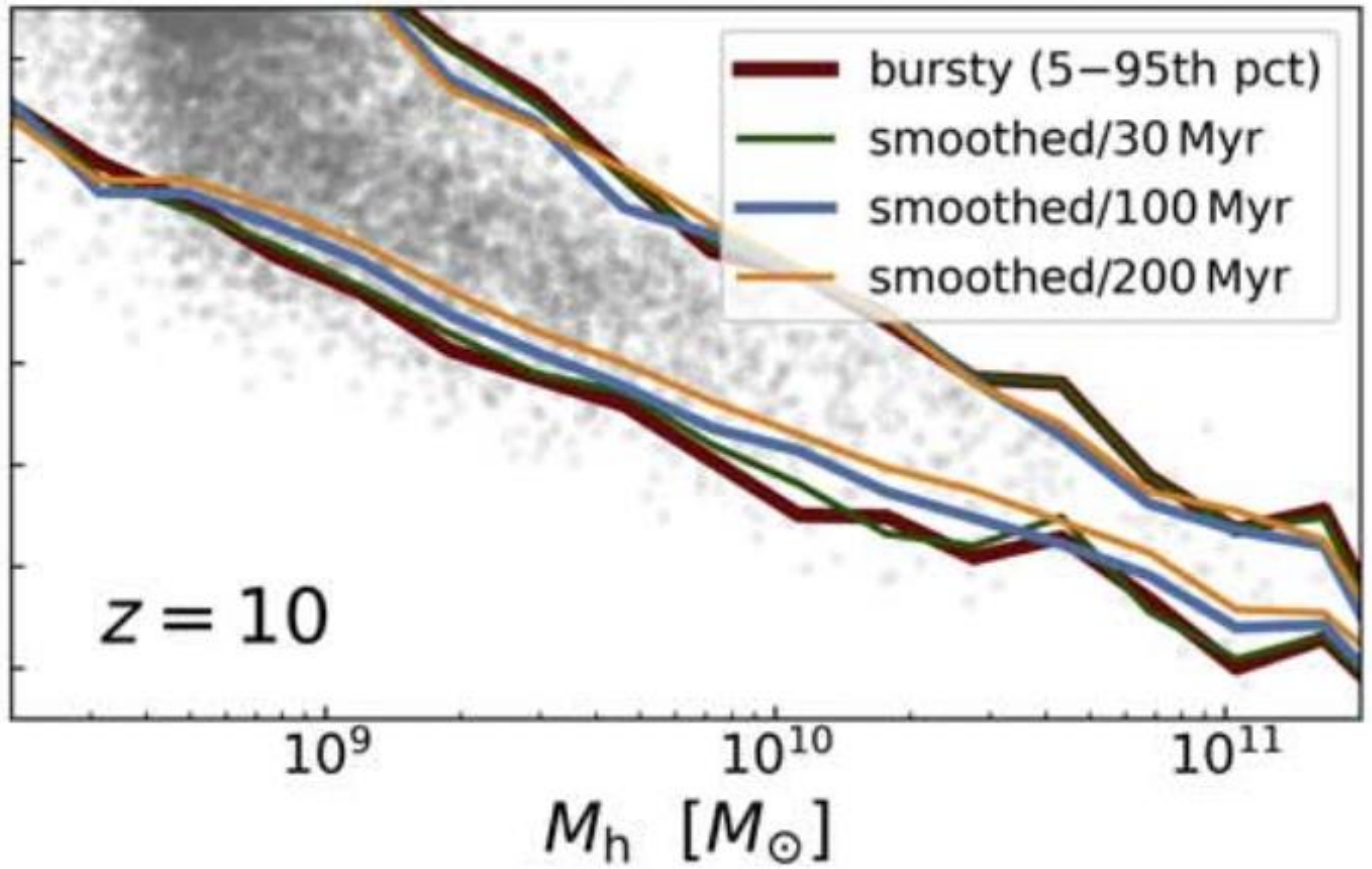
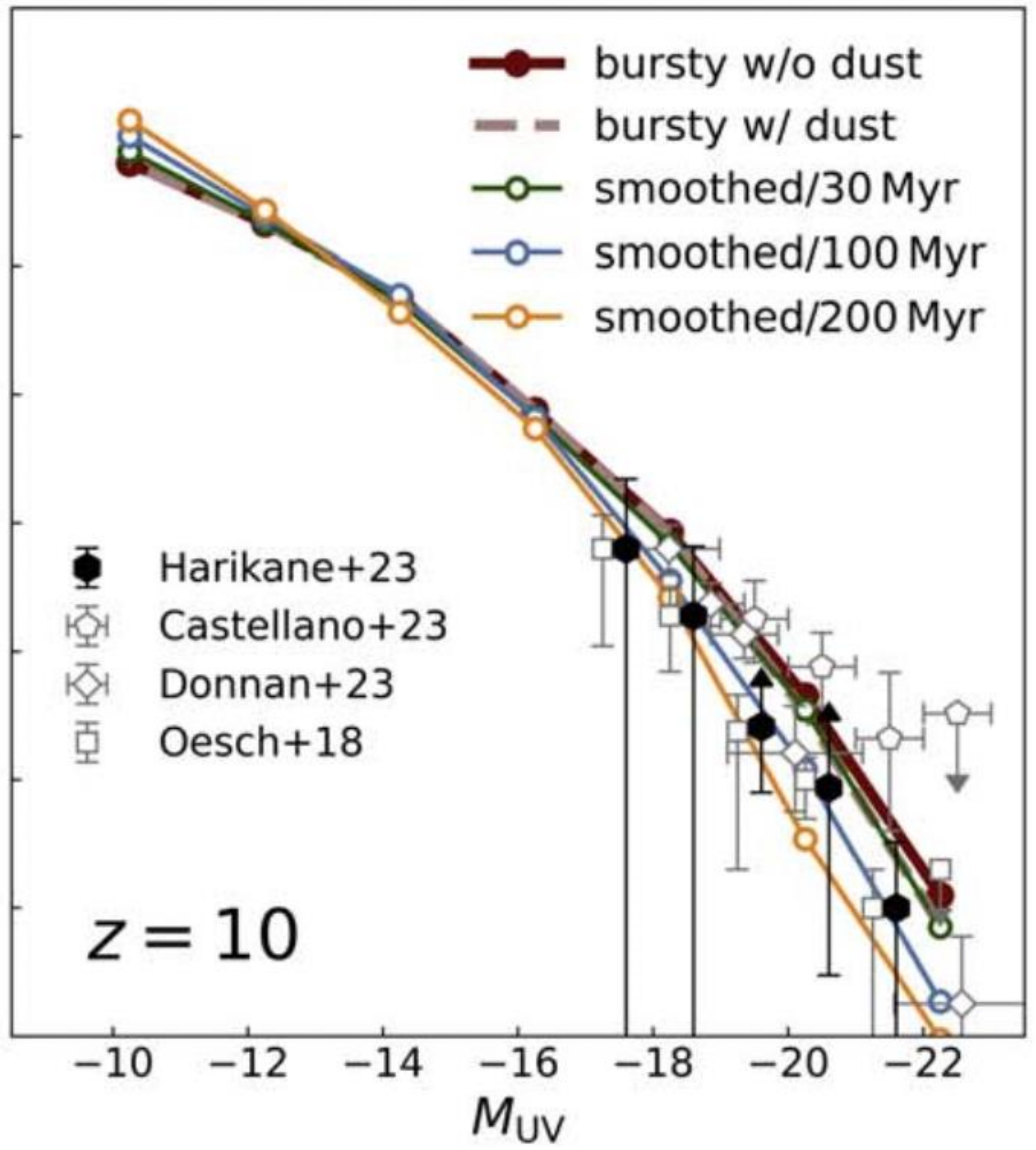
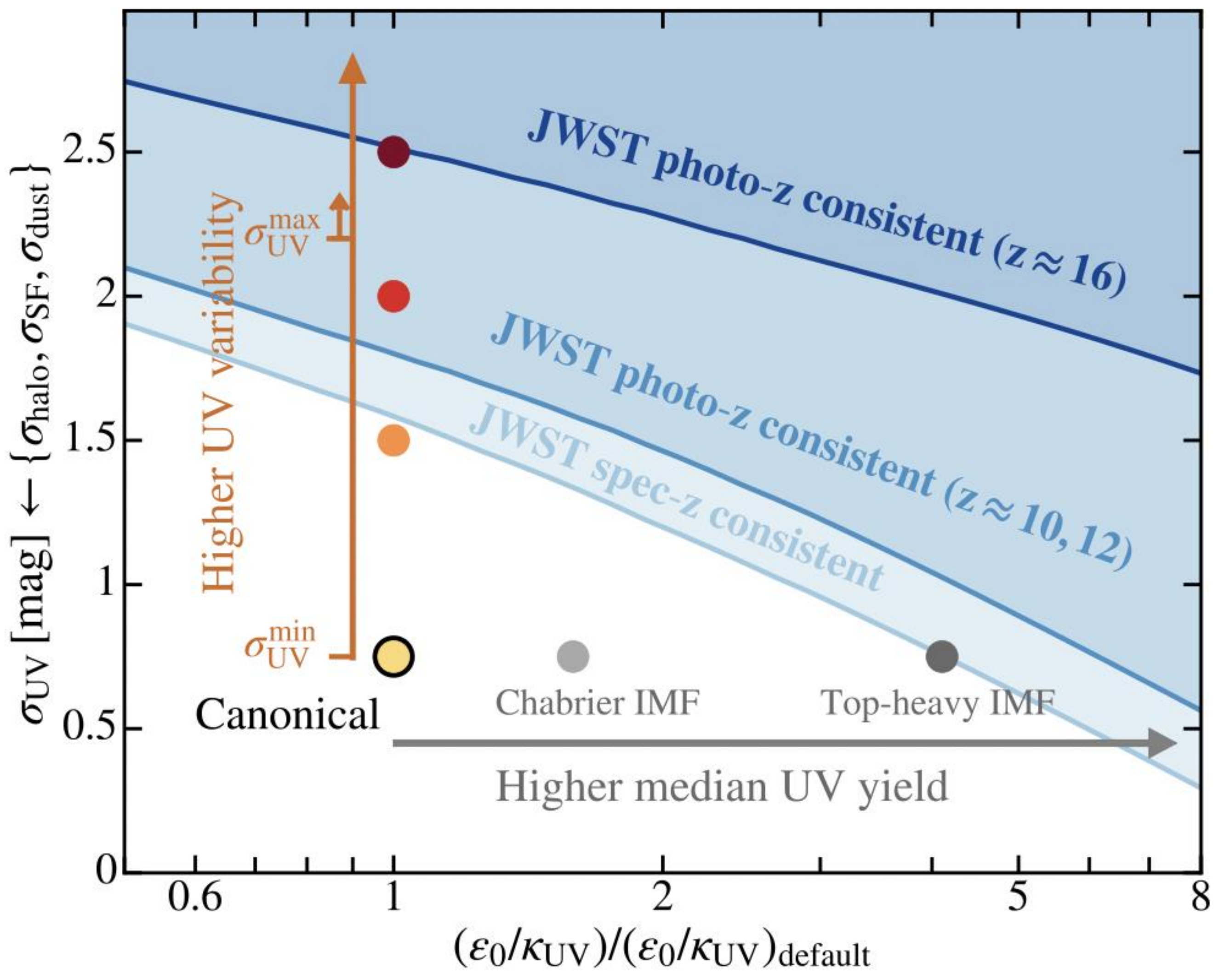
Possible explanations:

1. SF was bursty, with observational limits meaning that the galaxies we see are in temporary excursions to higher luminosity.







Above: Shen+23 combined bursty SF and dust creation/destruction into UV variability and needed huge-but-plausible UV variability at z>10.

Left: Sun+23 found that though bursty SF is more common in FIRE-2 at low-mass, Eddington bias makes it more impactful at higher masses vs. smoothing the SF history over ~100 Myr.

Middle: Sun+23 found good agreement between the (bursty) FIRE-2 sims and UVLF data.

1. There are too many UV-luminous galaxies compared to pre-launch predictions.

Possible explanations:

1. SF was bursty, with observational limits meaning that the galaxies we see are in temporary excursions to higher luminosity.
2. SF was more efficient i.e., feedback enhanced rather than slowed SF. Observed galaxies not atypical, but SF uses up gas reservoir quickly. (e.g., Nikopoulos & Dayal 24)
3. The IMF was top-heavy, giving us a high light-to-mass ratio and an intense ionizing environment. (e.g., Hutter+24)
4. ΛCDM is wrong; we should immediately notify the public that our observations have ruled it out and start writing a Nobel Prize acceptance speech!

Burstiness is an ensemble property

As pointed out by Broussard+(2019, 2022), the burst indicator SFR_{Ha}/SFR_{NUV} only tells us if an individual galaxy's SFR is rising or falling. The burstiness of a galaxy population is best probed not by the average of this ratio but by its **scatter**.

Ha-to-FUV flux ratio analyzed by Asada+24 on CANUCS galaxies at $4.7<z<6.5$.

See also Cole+23 for analysis of scatter in the SFR-M_* diagram out to z=9 interpreted as burstiness.

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At z>7, we can instead use SFR_{Hb}/SFR_{FUV} which is also insensitive to dust reddening (Guo+16) assuming a Calzetti dust law with $E(B\text{-}V)_{stars}=0.44\ E(B\text{-}V)_{gas}$.
Need to correct for variations in ionizing photon production (related to high-mass slope of IMF) as well as dust law.

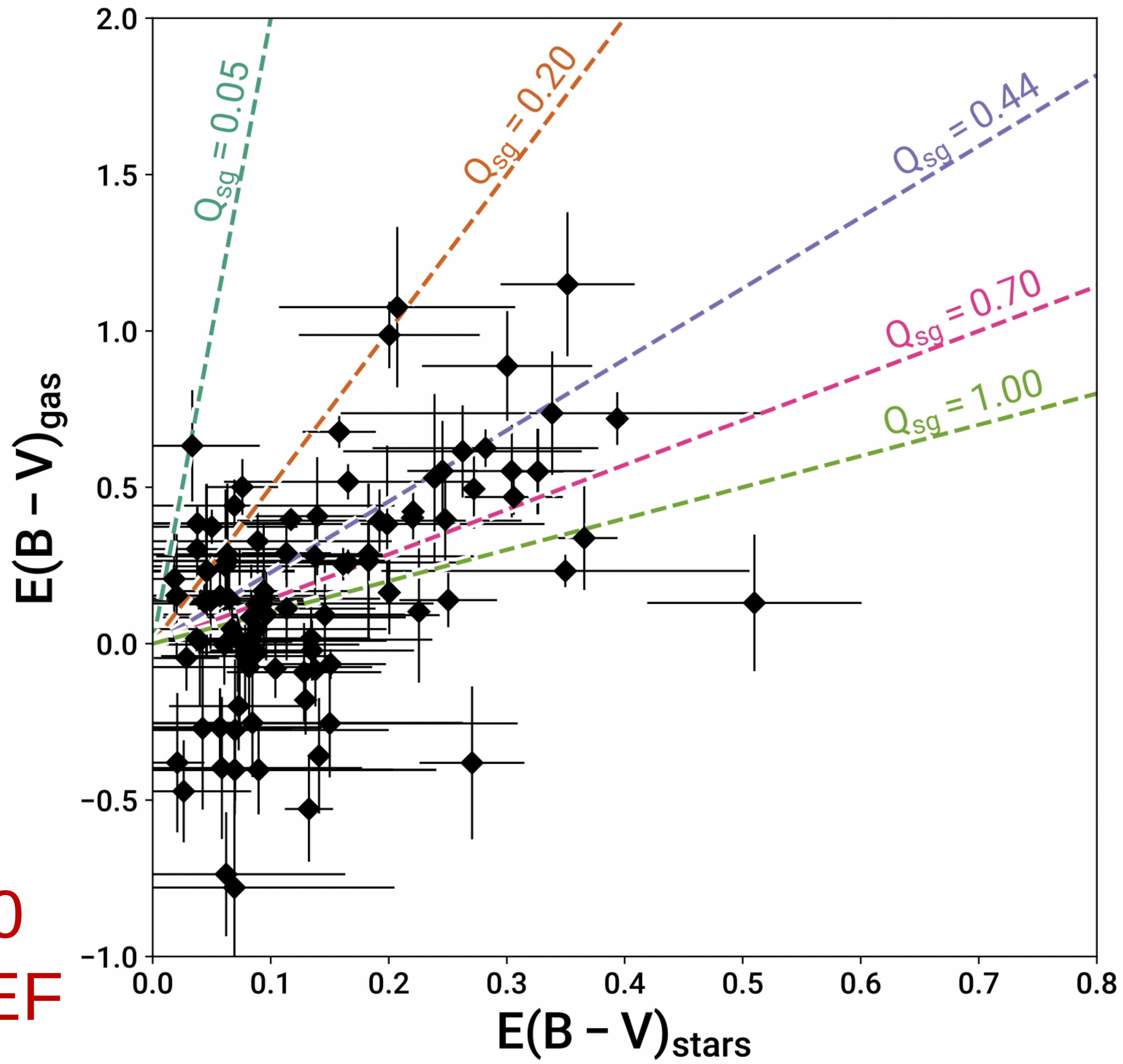


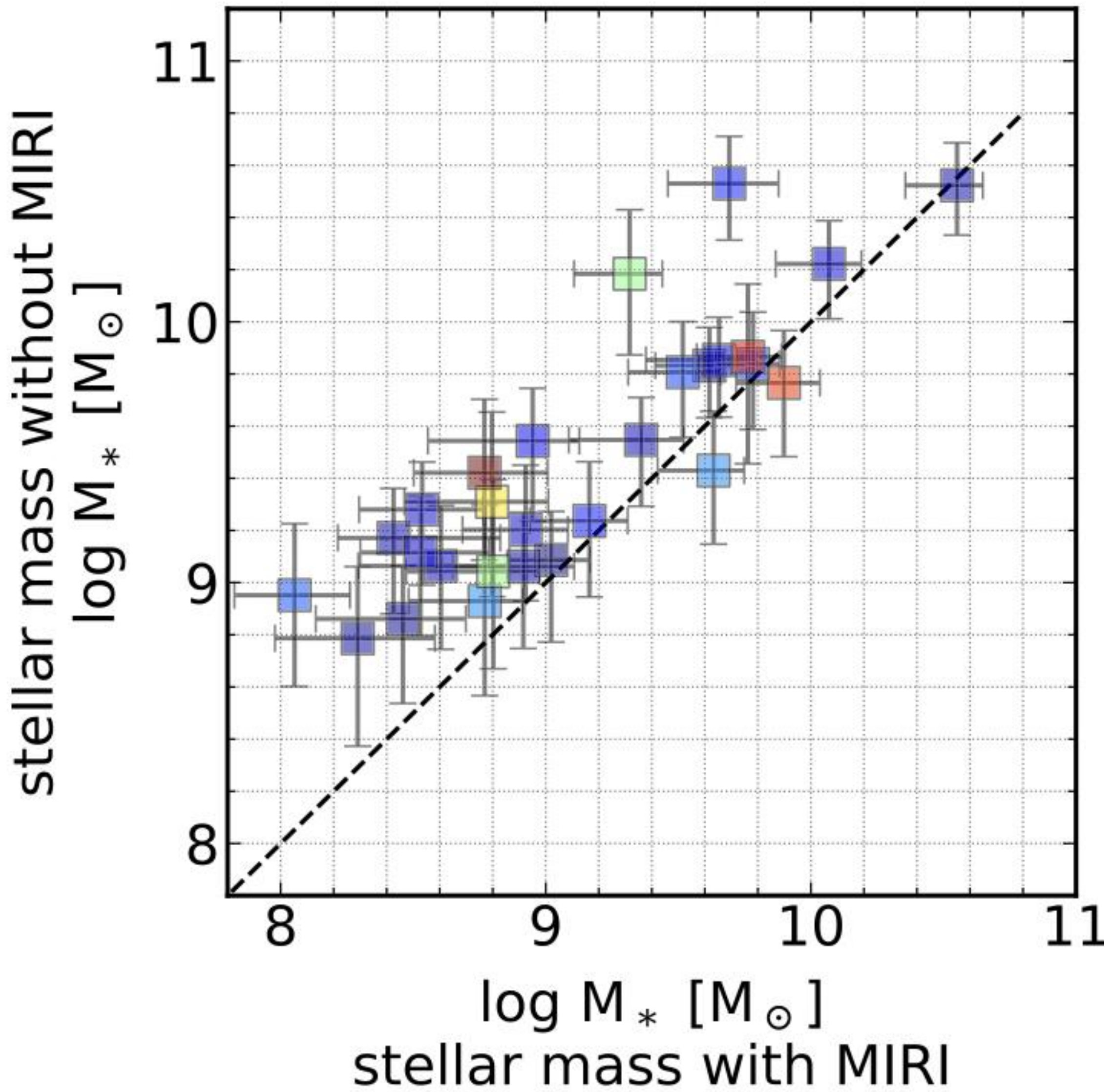
Figure from Broussard, EG & Iyer 2022; E(B-V)_gas<0 is caused by unphysical Balmer decrements in MOSDEF

2. Are z>10 galaxies too massive compared to pre-launch predictions?

Even at such high z, JWST observes rest-frame optical light, which traces stellar mass.

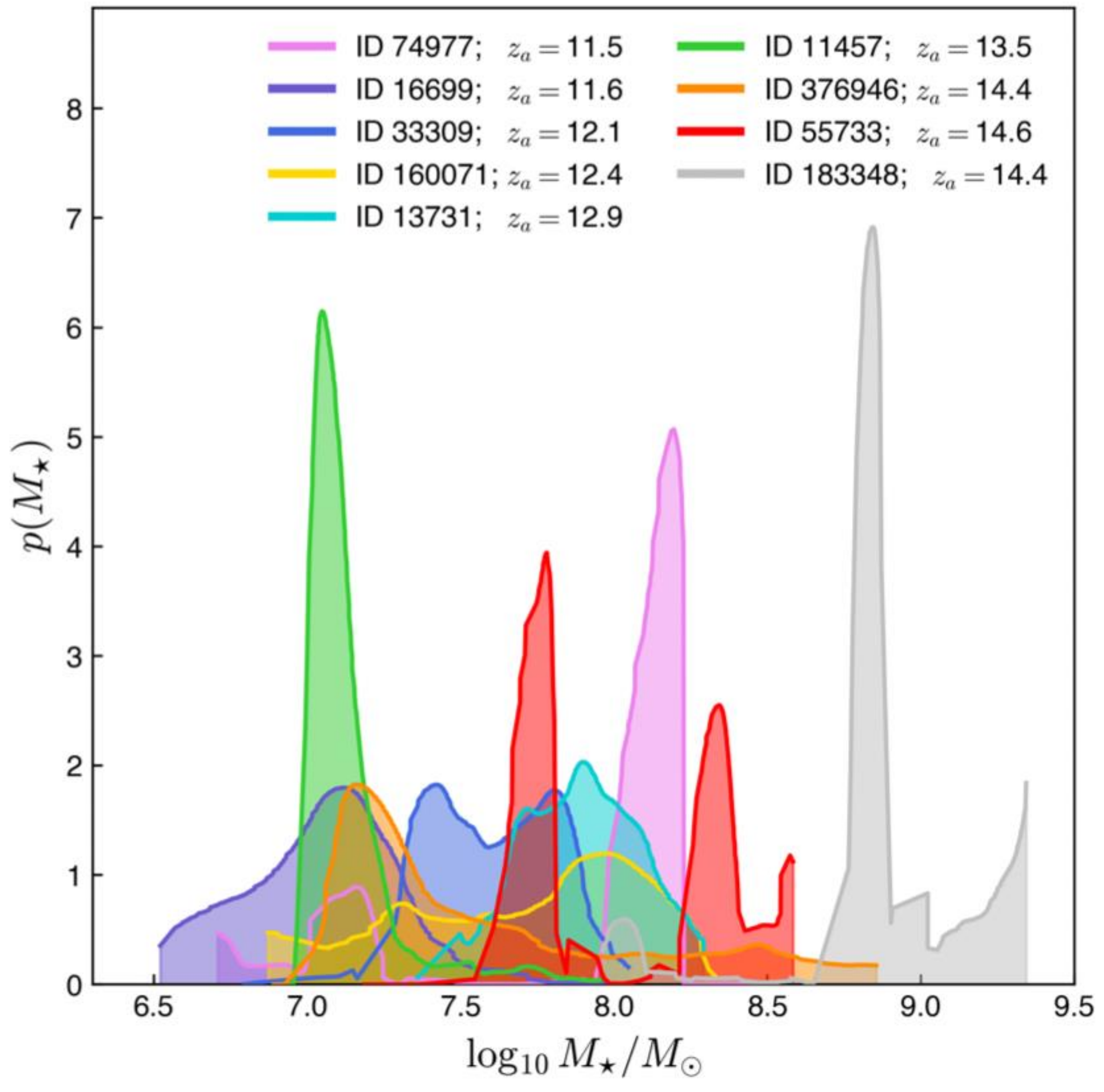
But you cannot count stars to get the total stellar mass unless you know the IMF. And even the rest-frame optical mass-to-light ratio varies rapidly as you change the IMF.

Instead of assuming a standard IMF, SF efficiency, and smooth SF histories, and finding that galaxies are too massive compared to ΛCDM predictions, assume ΛCDM and figure out what's going on at Cosmic Dawn.



Left: [Papovich+23](#) found a 1 dex decrease in stellar mass density at 4<z<9 when rest-frame 1 micron light included via MIRI photometry

Right: [Robertson+24b](#) found all but one z>11 galaxy has $M_* < 10^9\ M_{sun}$ when more flexible SF histories are used

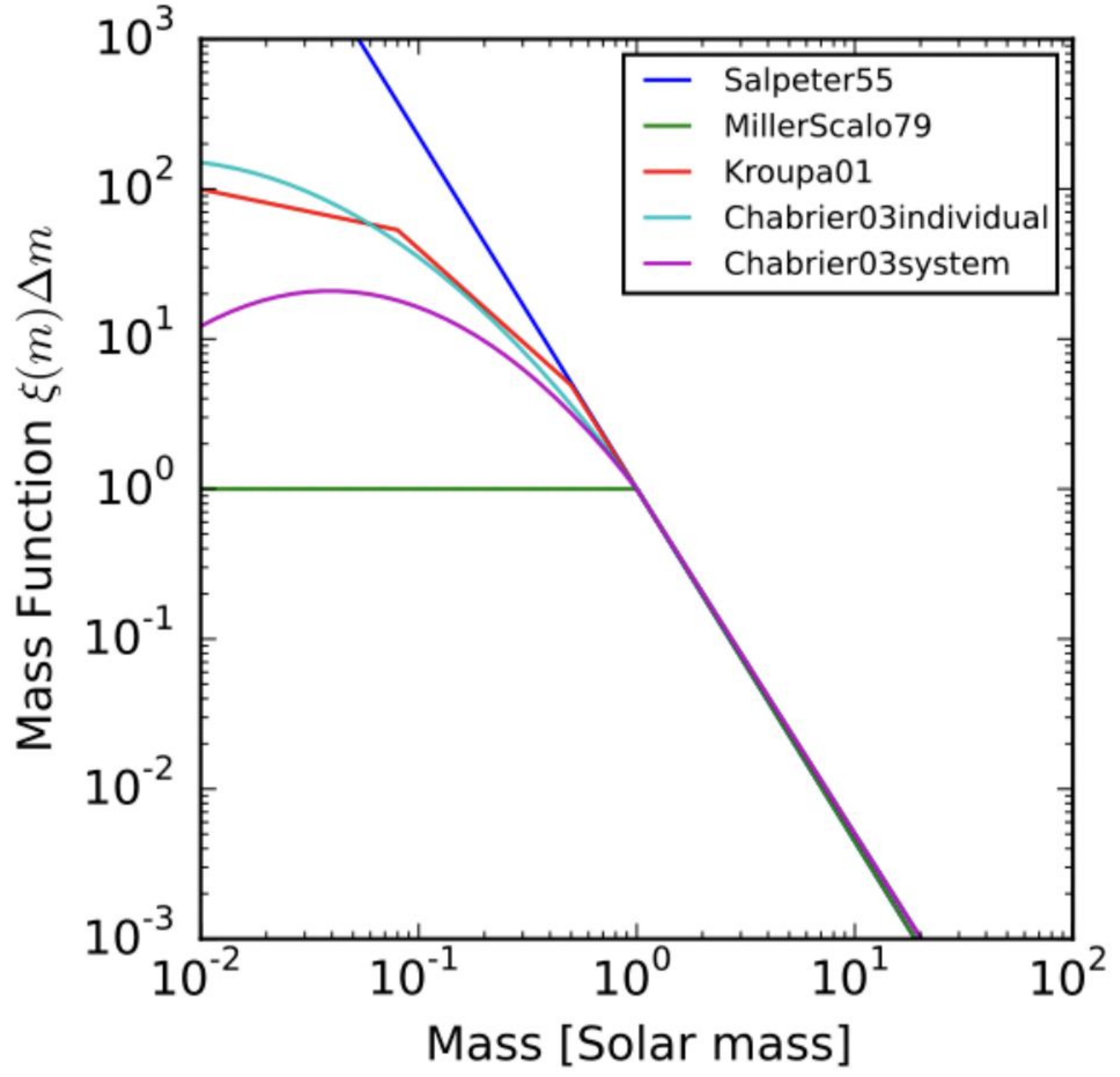


Is the z>10 IMF top-heavy or bottom-light?

We truly have no idea! But at z>10, T_{CMB}>30K means the IMF was non-standard.

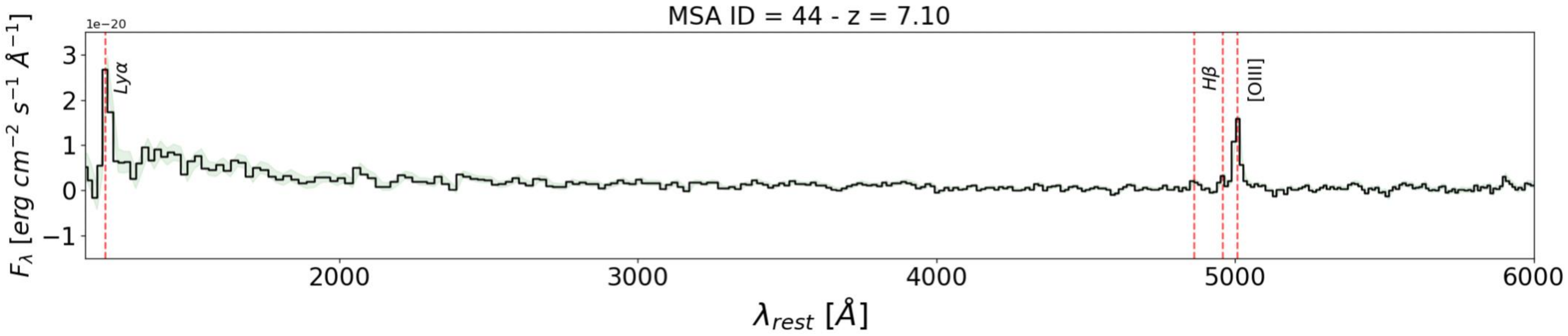
Parameterize it with “shift” (change in mode) and “stretch” (change in width) vs. a Chabrier IMF (shown in cyan and equation below from Wikipedia) to represent our simultaneous ignorance about the high-mass slope and mass-to-light ratio. Can be **both** top-heavy and bottom-heavy if width increases!

$$\xi(m) = \frac{0.158}{m\ln(10)} \exp\left[-\frac{(\log(m) - \log(0.08))^2}{2 \times 0.69^2}\right] \quad \text{for } m < 1$$

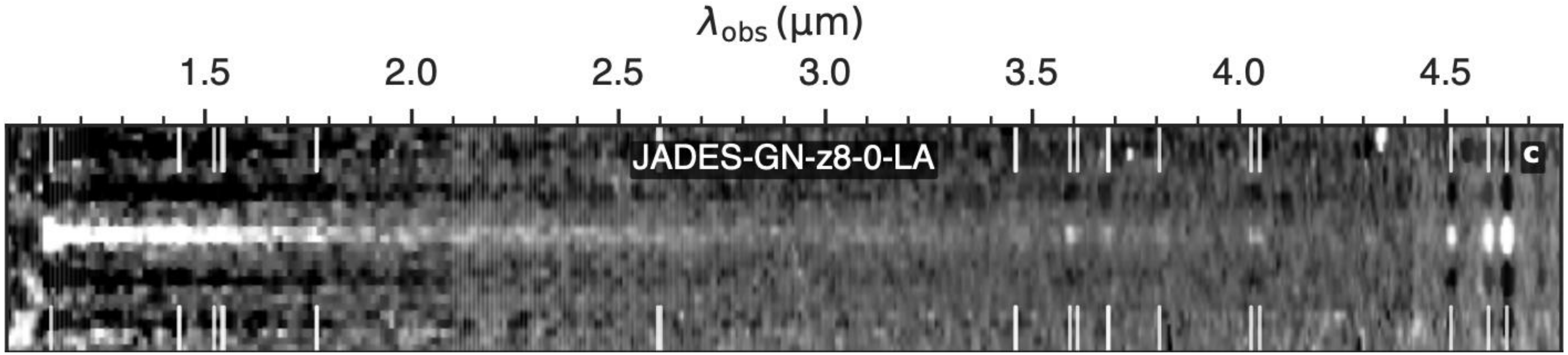


3. Lyman Alpha Emission can somehow escape IGM absorption at z~8… and z~13!

Napolitano+24 combined CEERS+JADES to find Lyman Alpha Emitters (LAEs) out to z=7.75.

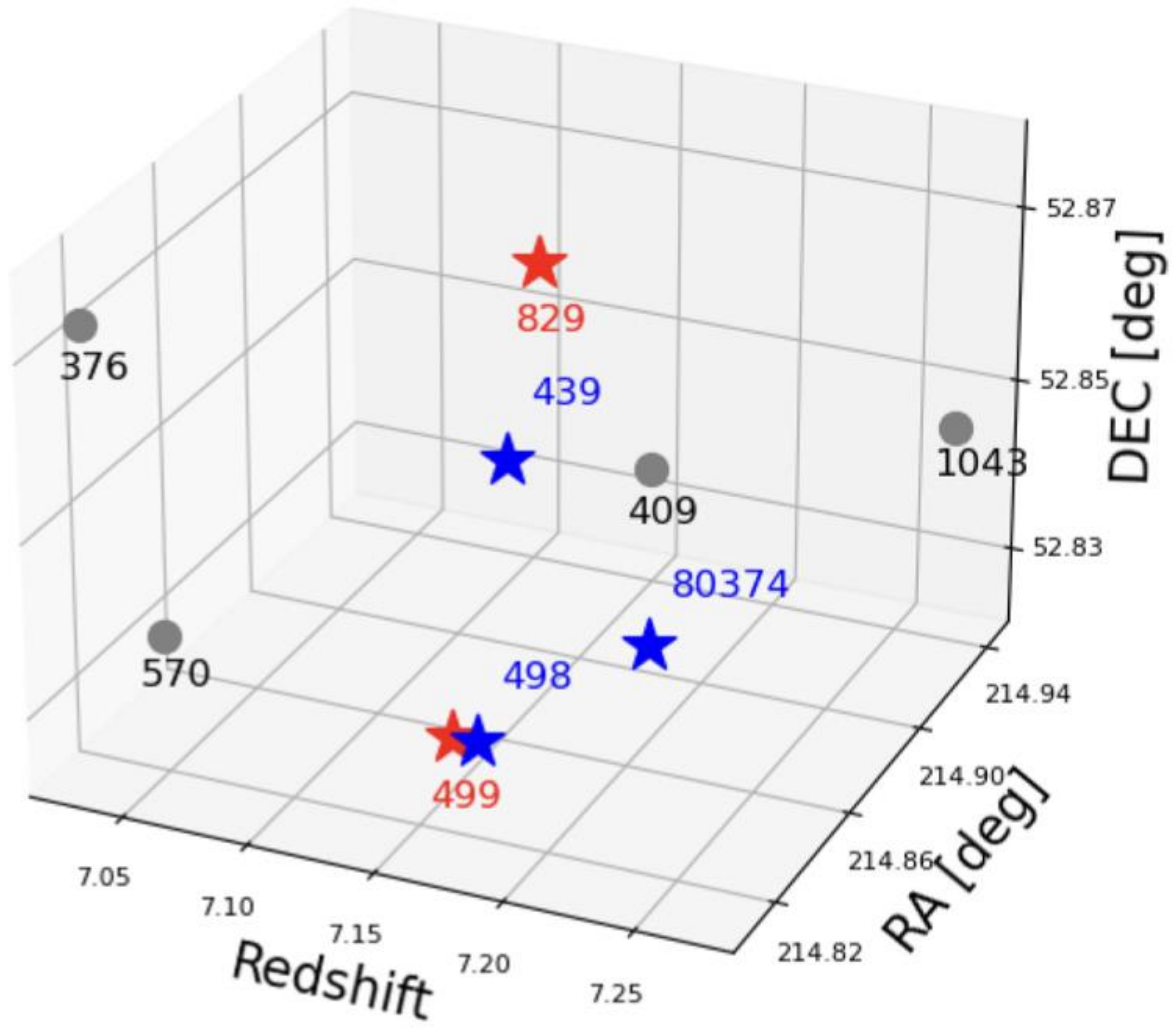


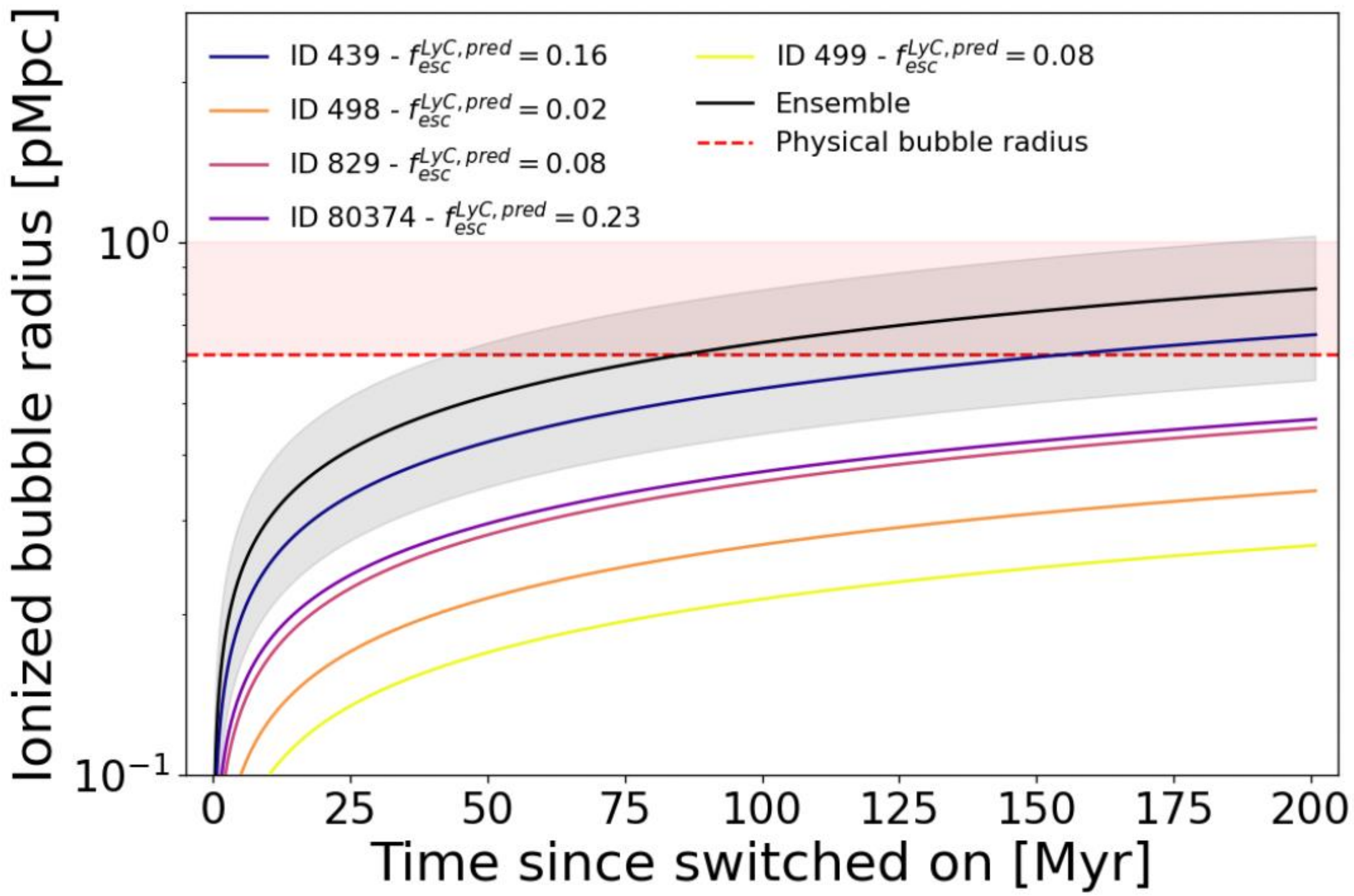
Then Witstok+24a found 3 LAEs in JADES at z>8, including this one:



And then Witstok+24b found a z=13 LAE in JADES.

There is evidence for larger-than-expected ionized bubbles at z>7





Figures from Napolitano+24 show z=7.18 ionized "bubble" in EGS field that could be formed after ~100 Myr of starburst, with a 3X larger z=7.49 region difficult to explain unless it's >1 bubble.

What does this tell us about reionization? Does it tell us anything about galaxy formation?

Other Projects You Can Ask Me About

- ODIN (100,000 Lyman Alpha Emitters at z=2.4, 3.1, 4.5 via DECam Narrowband Imaging, Co-PI)
- Hobby-Eberly Telescope Dark Energy eXperiment (HETDEX, Bayesian method for identifying Lyman Alpha Emitters at $1.9<z<3.5$)
- LSST Dark Energy Science Collaboration (cosmological parameter forecasts and ML post-processing to improve photo-z, Analysis Coordinator 2021-23)
- Simons Observatory (Cosmic Microwave Background; Engagement, Mentoring & Climate Committee = EMC^2)

Conclusions:
What have we learned about Cosmic Dawn from three years of JWST?

1. There are too many UV-luminous galaxies compared to **most** pre-launch predictions. **This likely results from a combination of bursty SF, high SF efficiency, and a non-standard IMF.**
2. **Assuming a standard IMF and smooth SF histories,** these galaxies ~~appear to~~ **might** be too massive compared to pre-launch predictions.
3. Lyman Alpha Emission can somehow escape IGM absorption at z~8… and z~13! **And there is evidence for larger-than-expected ionized bubbles at z>7. Could this patchy reionization also be caused by bursty SF, high SF efficiency, and/or a top-heavy IMF** (as in Hutter+24)?