HIGH-REDSHIFT GALAXY FORMATION AND OUTFLOWS AT COSMIC NOON

🔥 TOPICS ASSOCIATED WITH GALACTIC FEEDBACK

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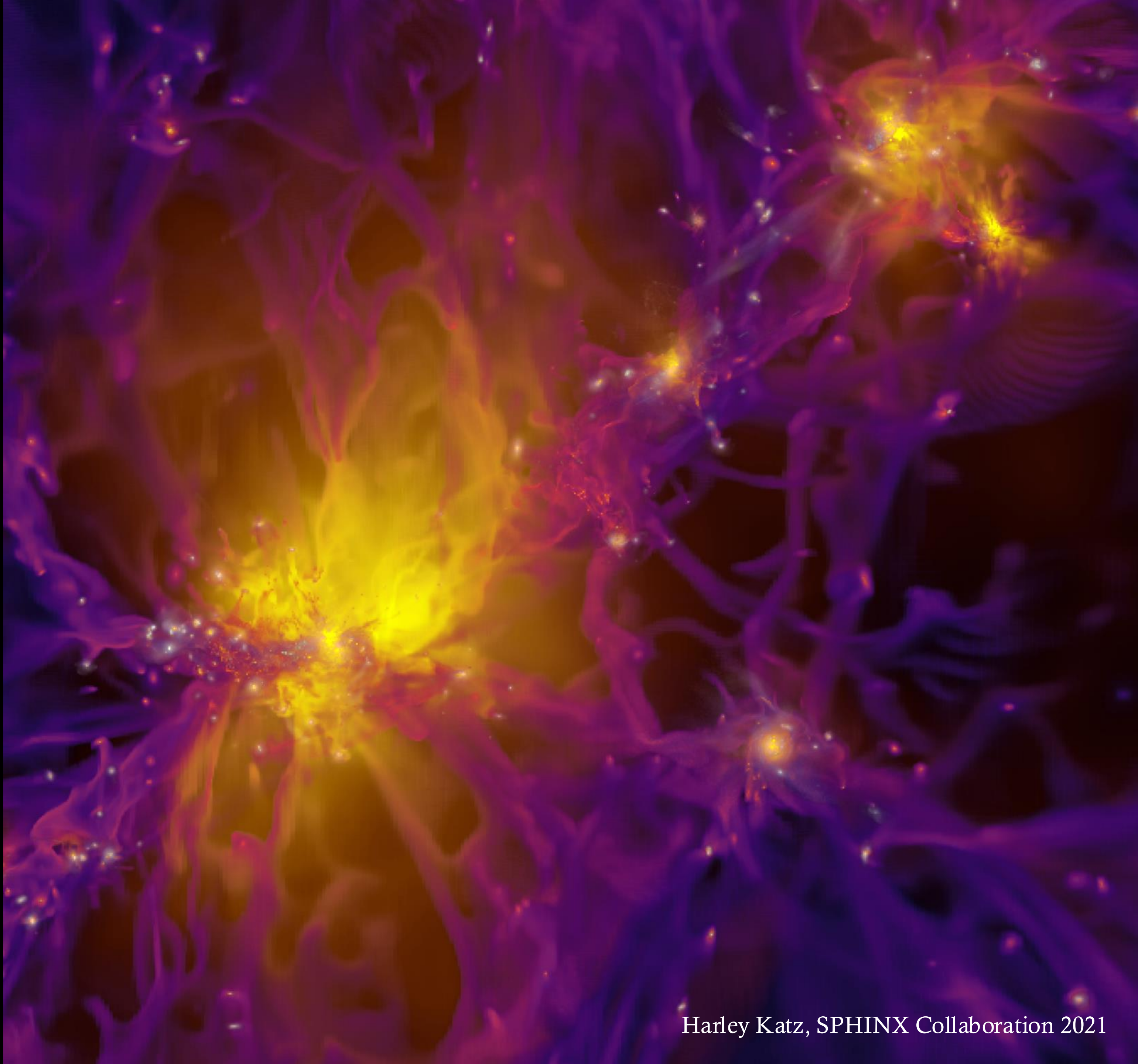
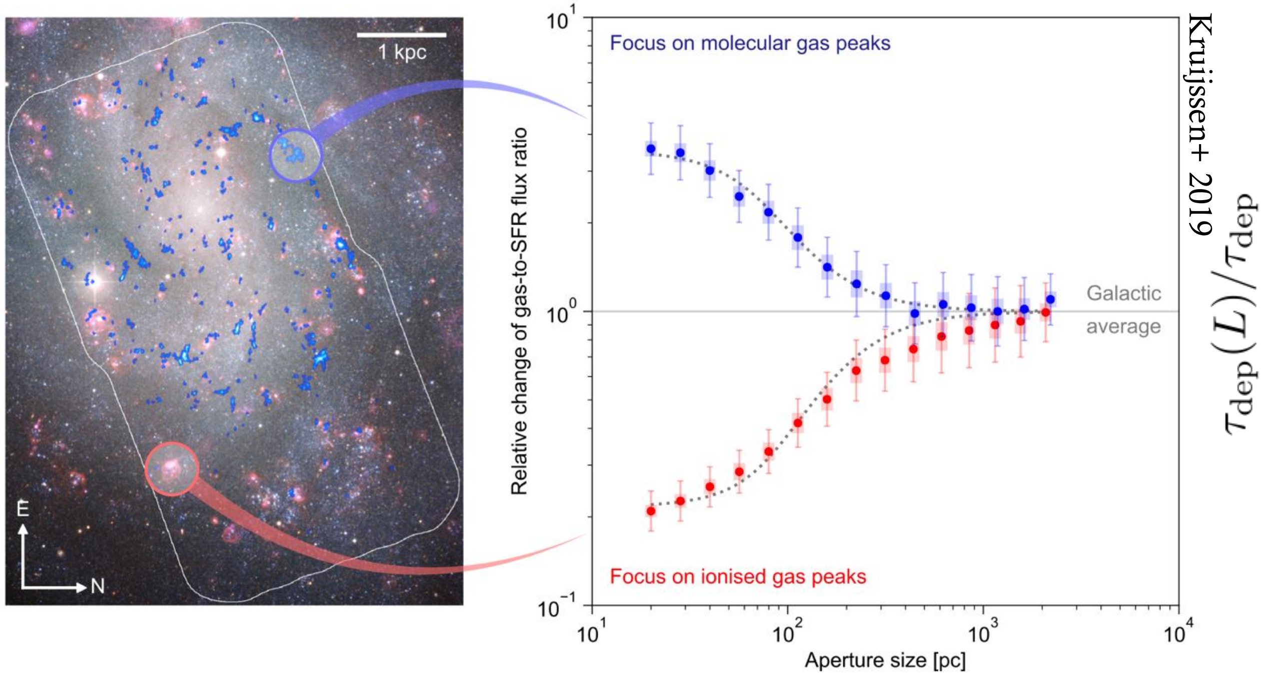
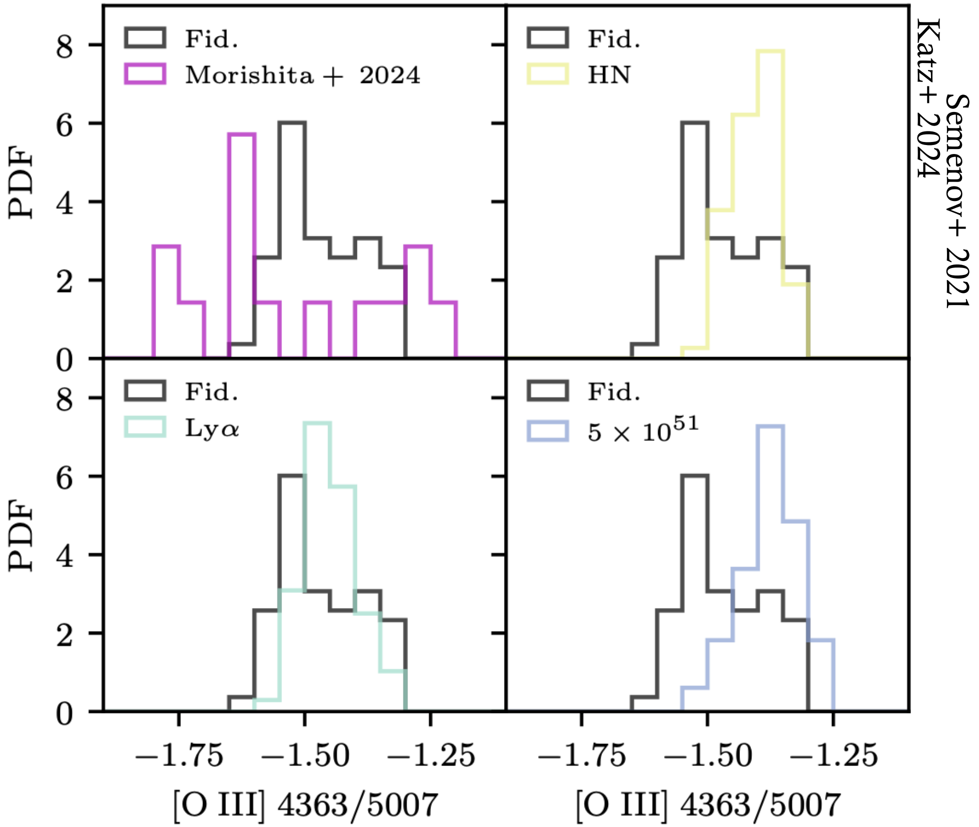
July 18, 2025



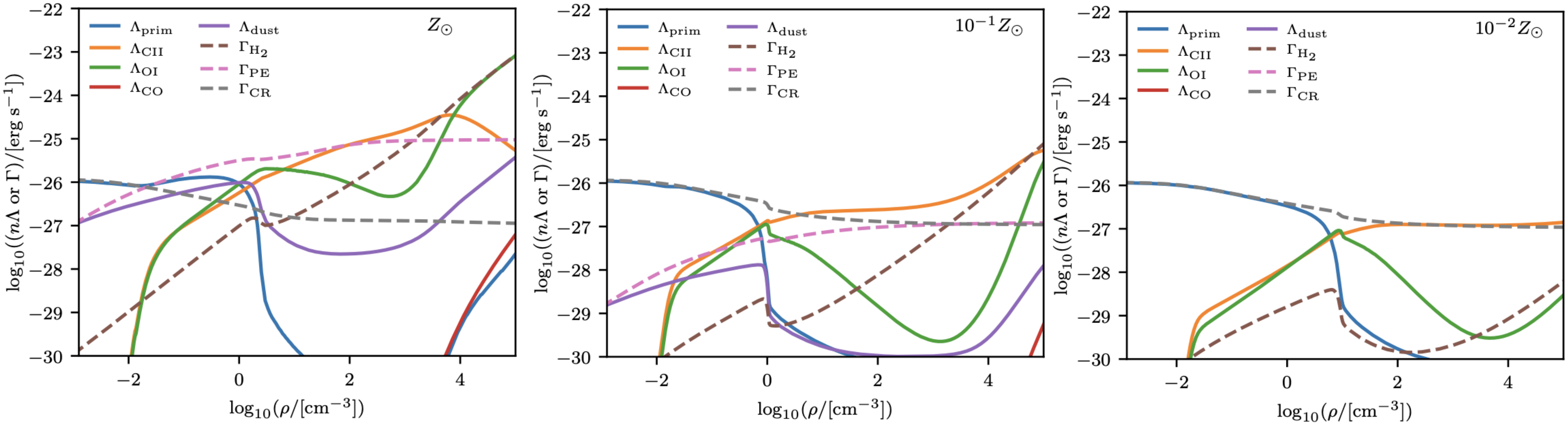
Harley Katz, SPHINX Collaboration 2021

THE ISM IS A VERY SENSITIVE TRACER OF FEEDBACK

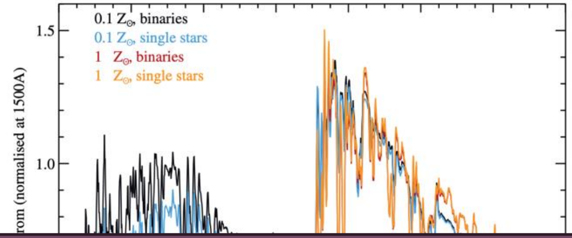




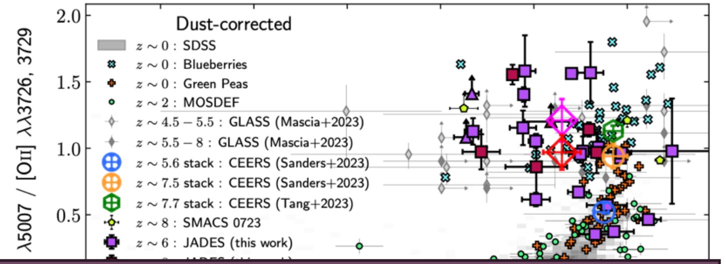
GAS HEATING AND COOLING IS DRIVEN BY DIFFERENT PROCESSES AT LOW METALLICITY



OBSERVATIONS TELL US THAT THERE ARE CLEAR PHYSICAL DIFFERENCES BETWEEN THE HIGH AND LOW-REDSHIFT ISM



Eldridge+ 2017

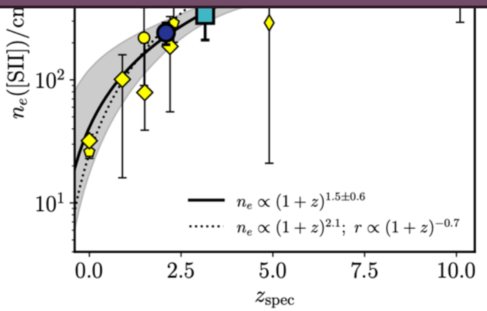


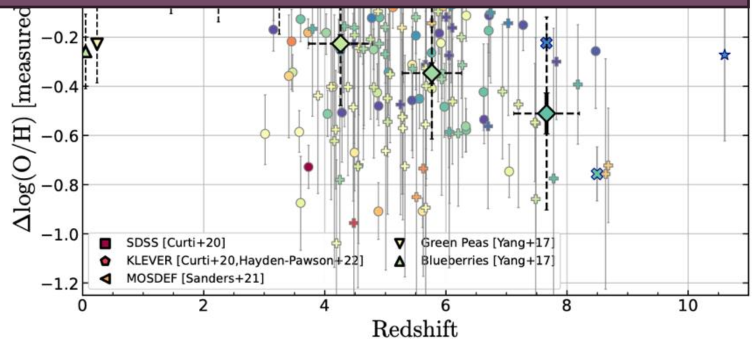
Cameron+ 2023

1. Harder radiation fields

How do the different stellar and ISM properties impact feedback?

4. Lower metallicities

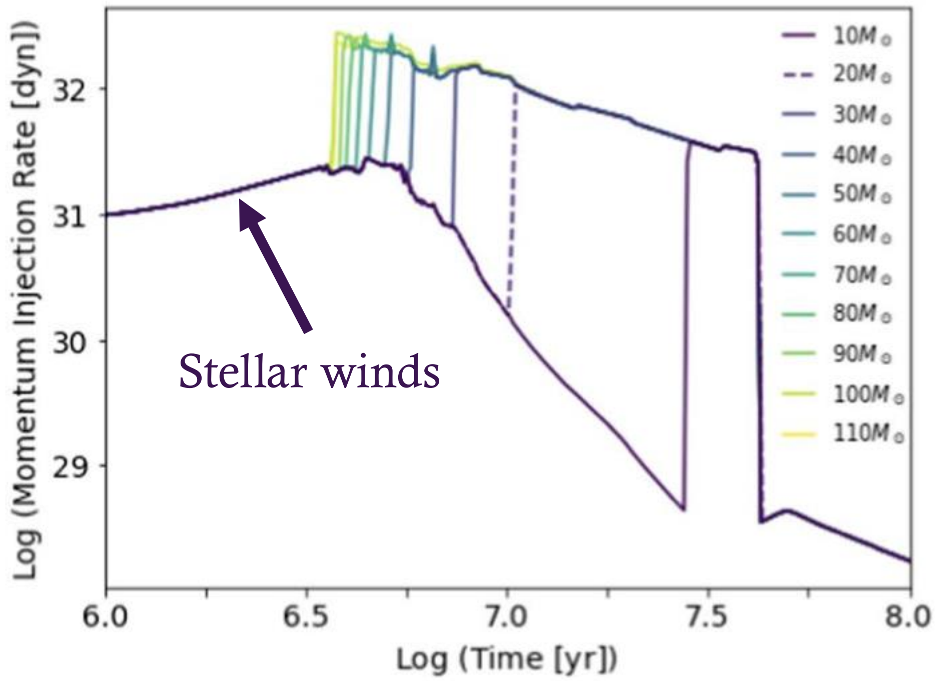




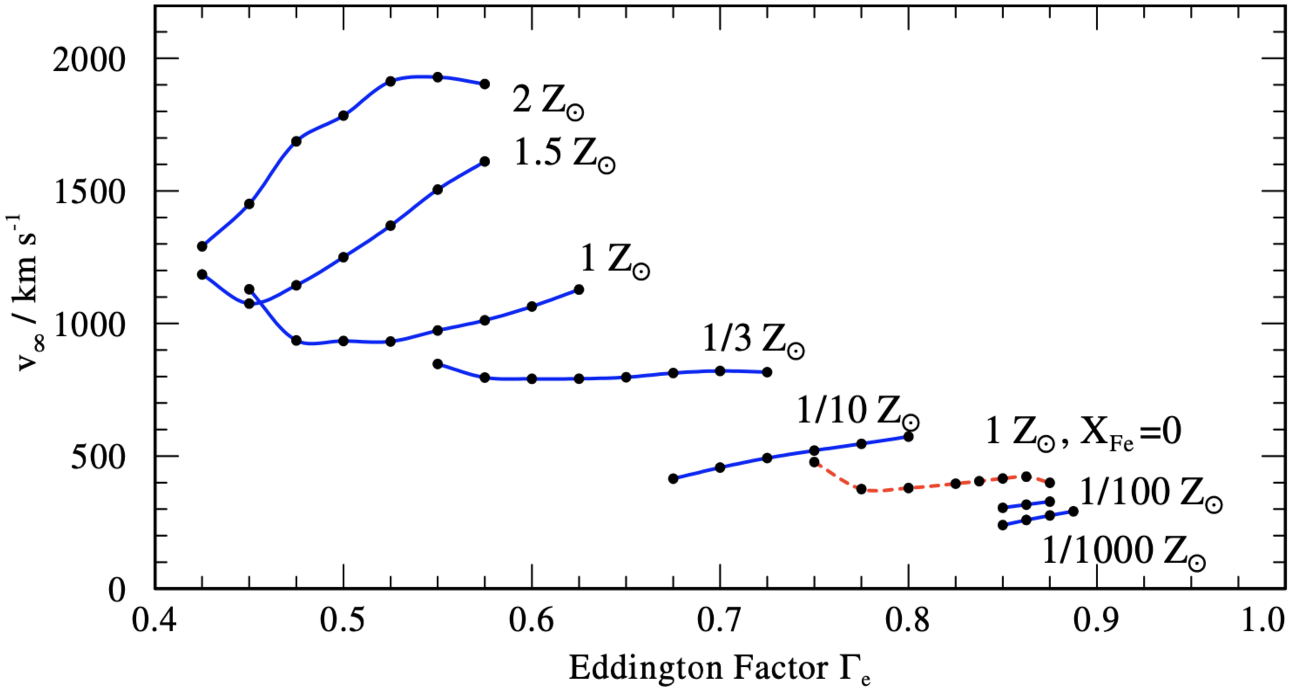
Curti+ 2023

1. STELLAR MODELS PREDICT DELAYED MOMENTUM INJECTION AND WEAKER WINDS AT LOW METALLICITY

If only stars < 20 M☉ explode as SN, Feedback timescale is delayed by 3x



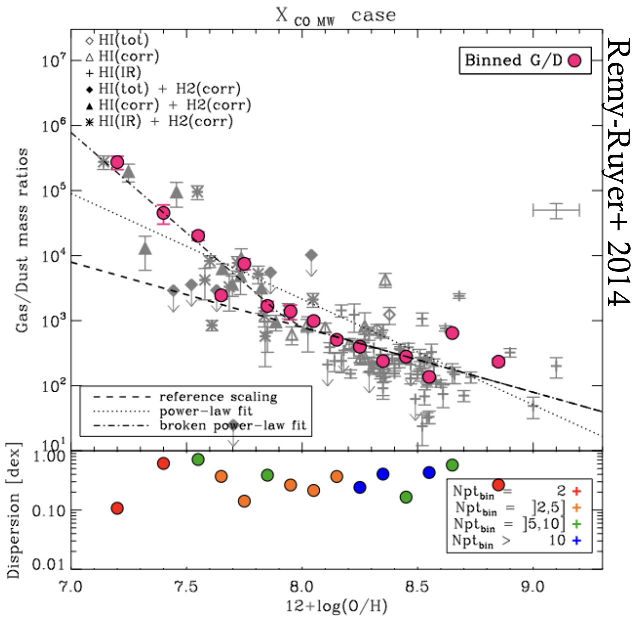
Momentum injection from stellar winds decreases significantly at low metallicity



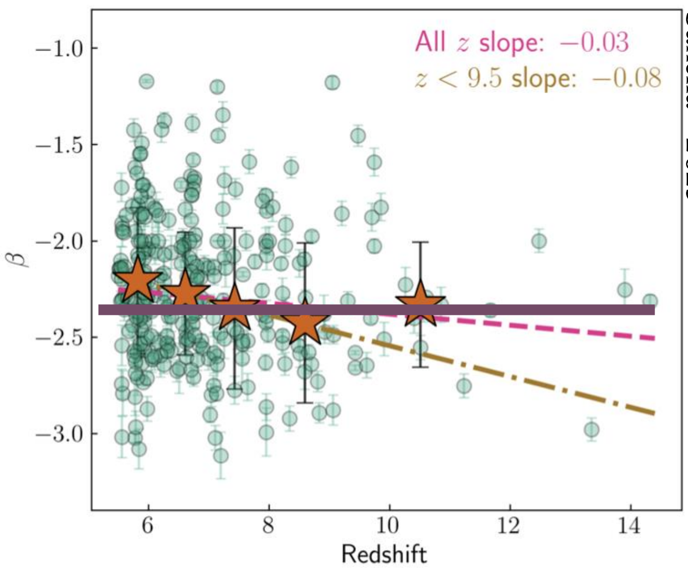
Grafener+2005

2. IR RADIATION PRESSURE DECREASES BUT UV AND LYA RADIATION PRESSURE LIKELY INCREASE

Probably not much dust to push on

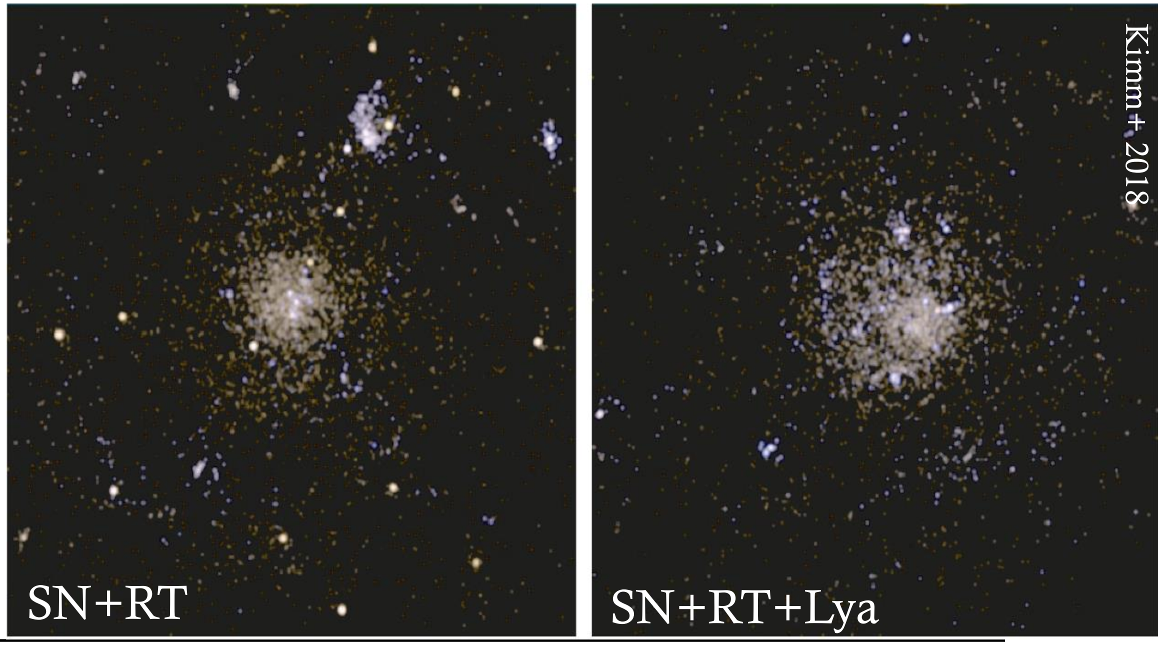


Remy-Ruyer+ 2014

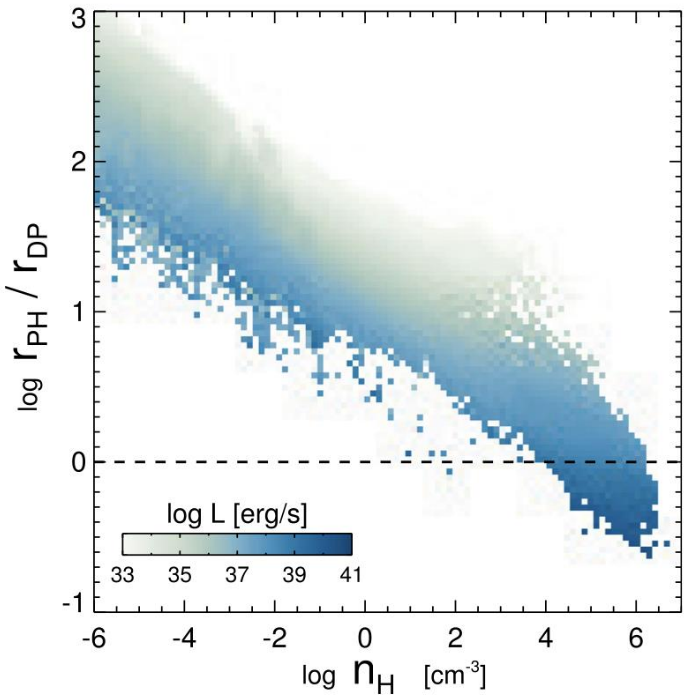


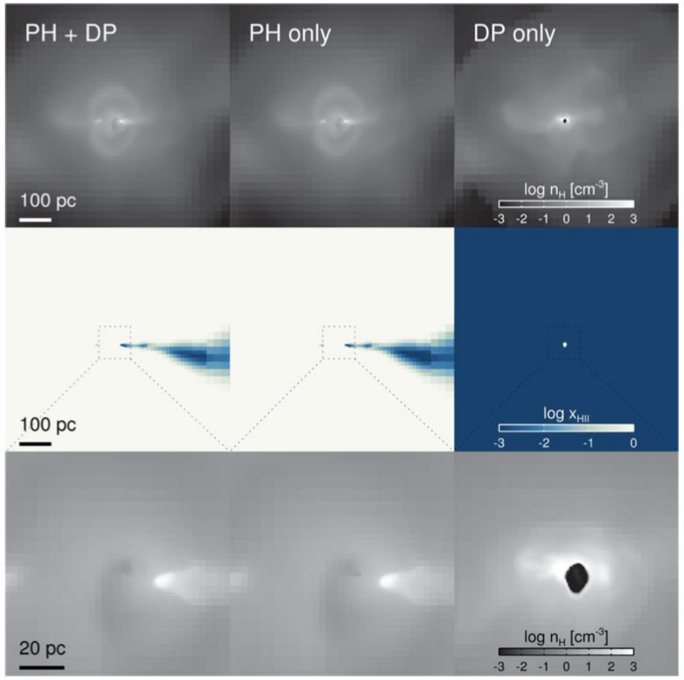
Saxena+ 2025

Lya is much less destroyed at low metallicity

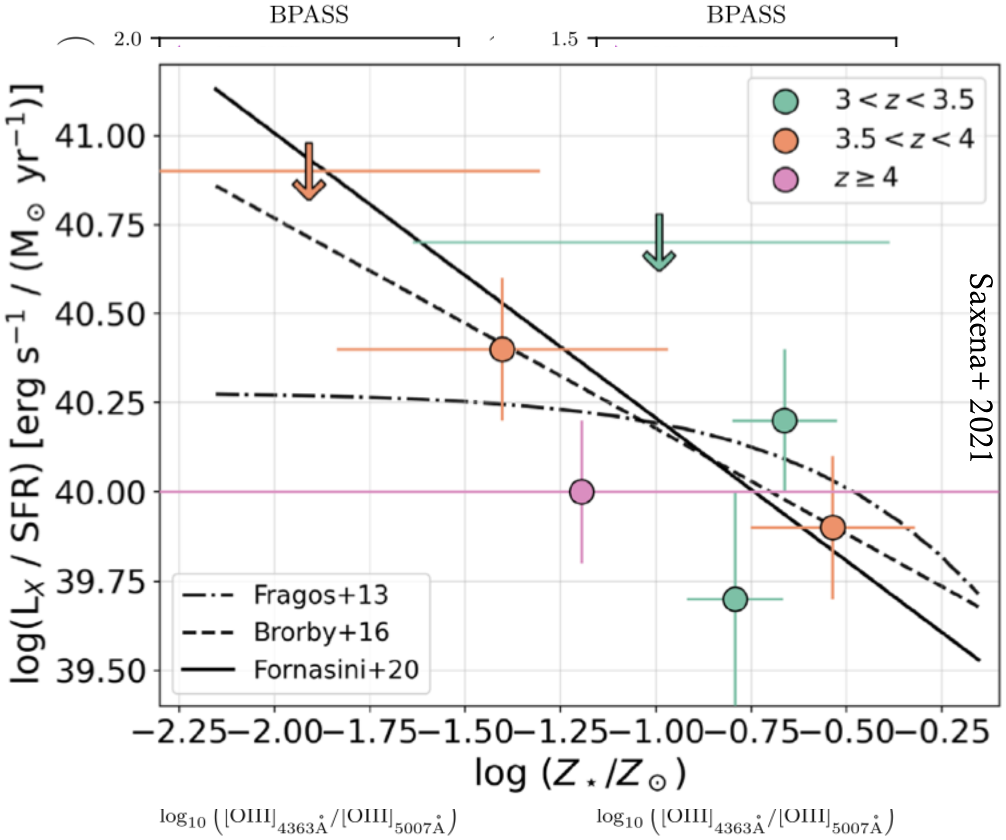


3. FOR THE MOST METAL-POOR GALAXIES, PHOTO-HEATING MAY DOMINATE OVER UV RADIATION PRESSURE → EXCESS HEATING MAY BE REQUIRED



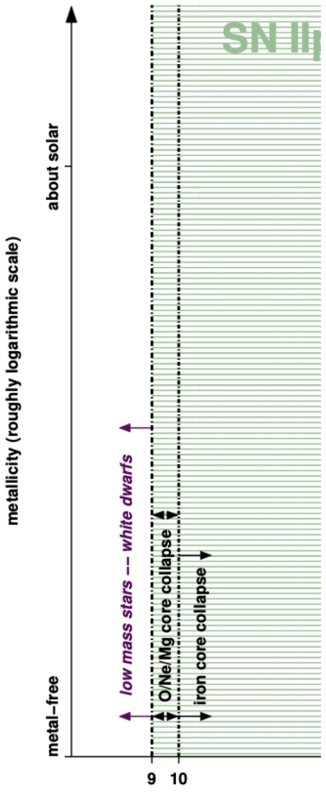


Kimm+ 2017

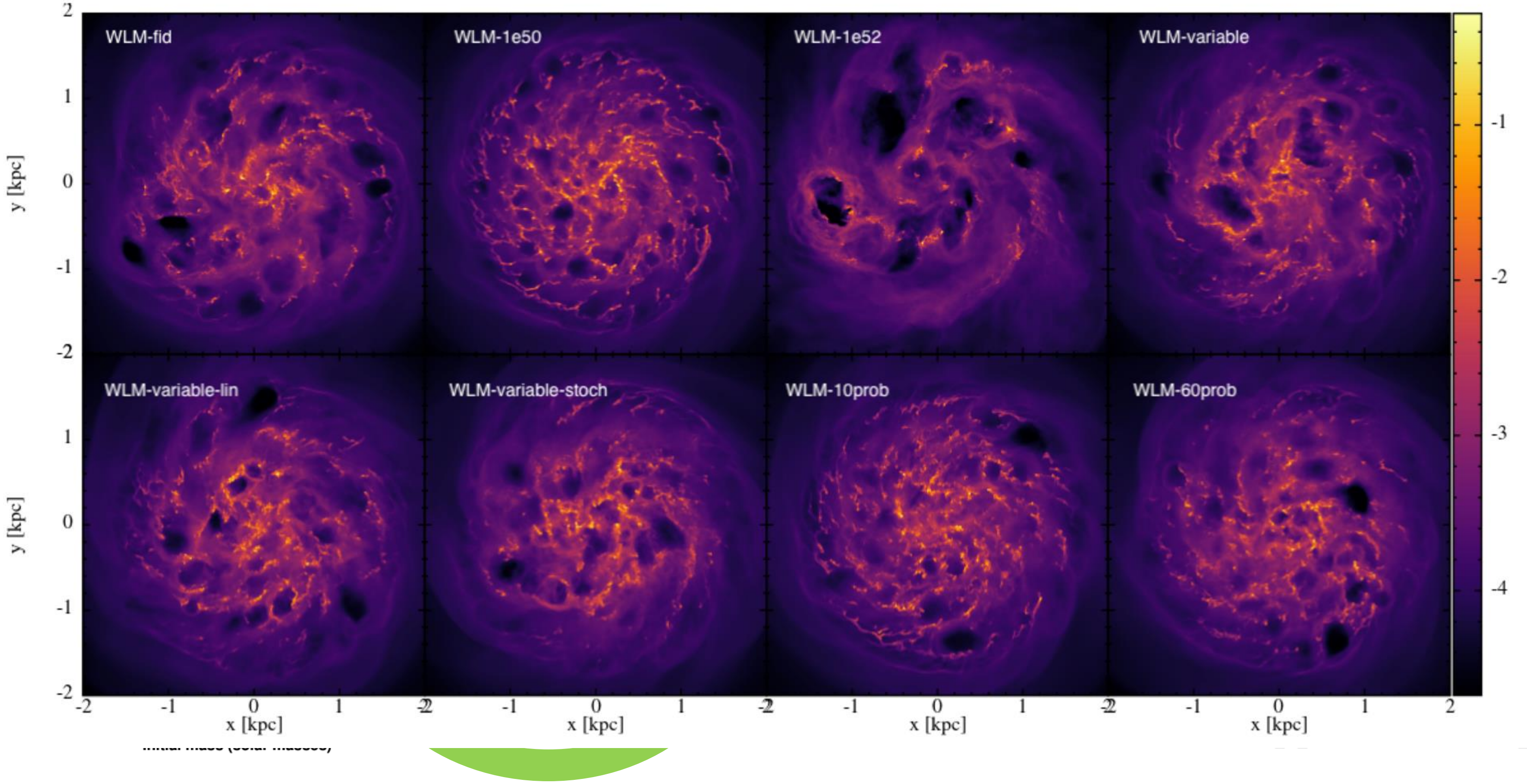


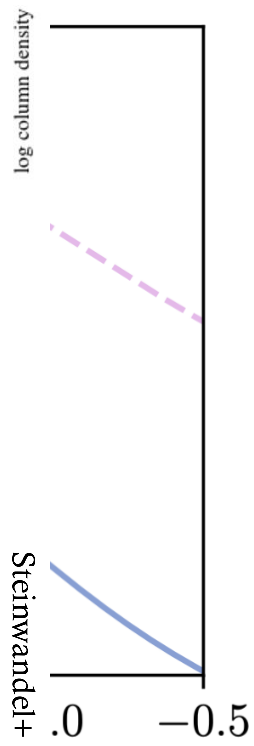
Saxena+ 2021

4. EXOTIC SN CHANNELS MAY BECOME AVAILABLE AND SN MAY OR MAY NOT BE ENHANCED BY A TOP-HEAVY IMF



Heger+ 2003





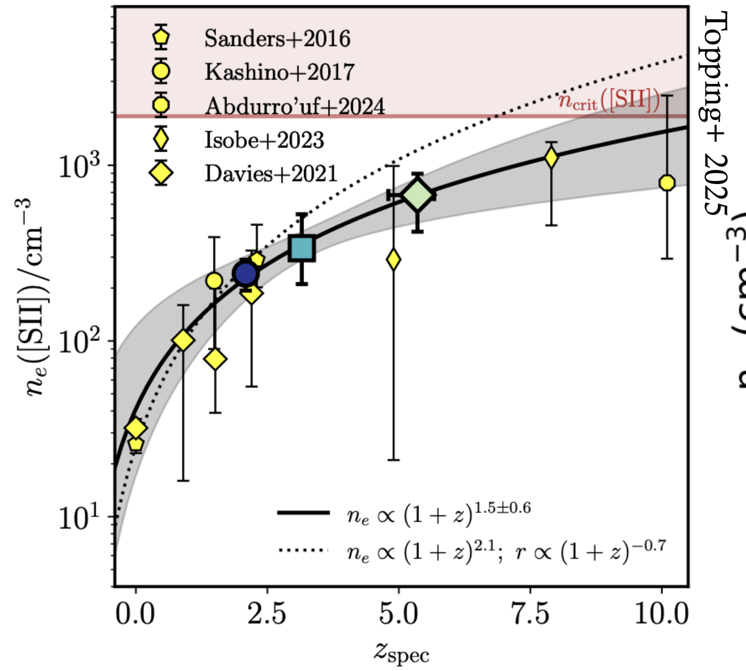
Steinwandel+ 2025

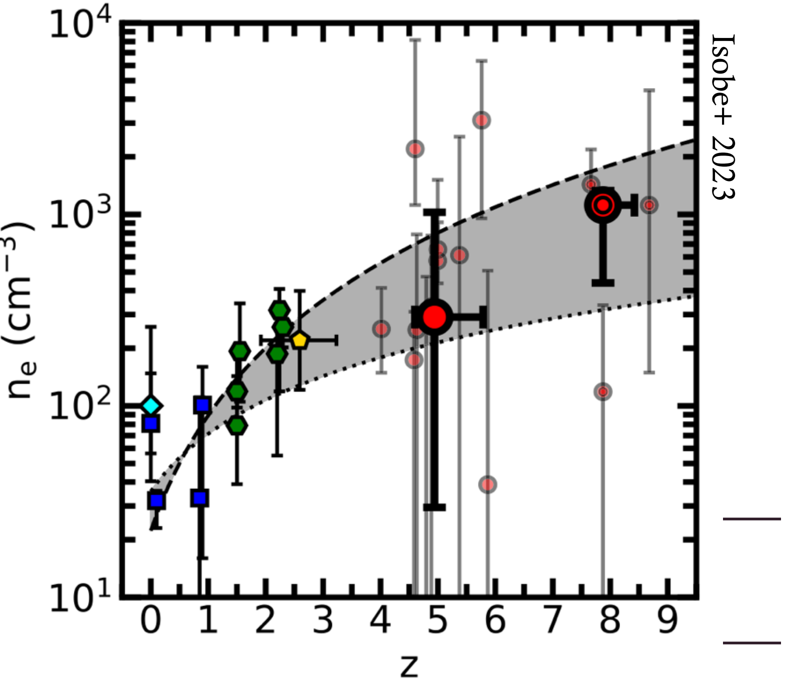
4(CONT.). THE EFFECTS OF DENSITY AND METALLICITY MAY CANCEL EACH OTHER

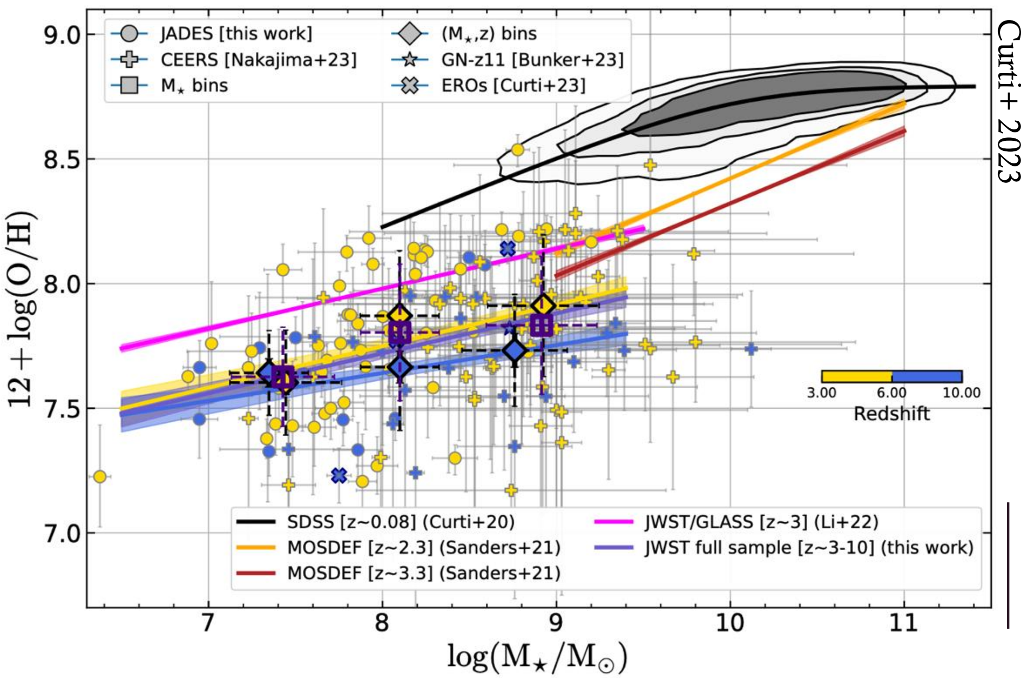
$$p_{\rm SN,snow} \approx 3 \times 10^5 \,{\rm km\,s^{-1}\,M_\odot}\, E_{51}^{16/17} n_{\rm H}^{-2/17} Z'^{-0.14}$$

$$\frac{p_{z>6}}{p_{z=0}} \sim 100^{-2/17} 0.2^{-0.14} = 0.73$$

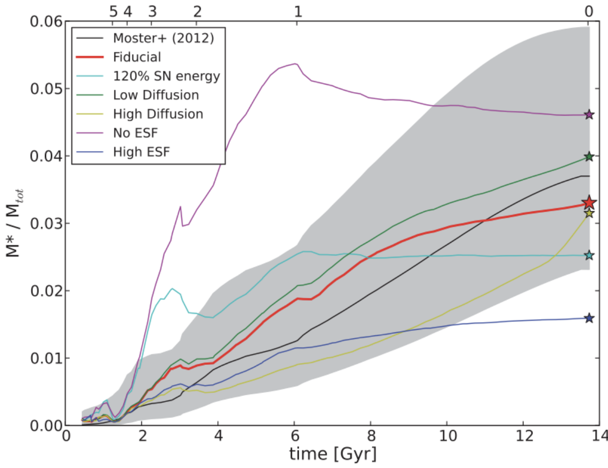
See e.g. Blondin+1998, Thornton+1998



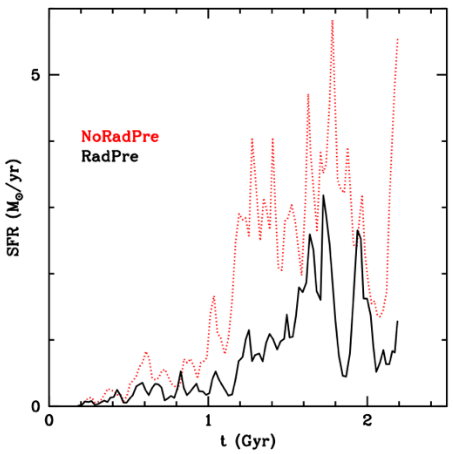




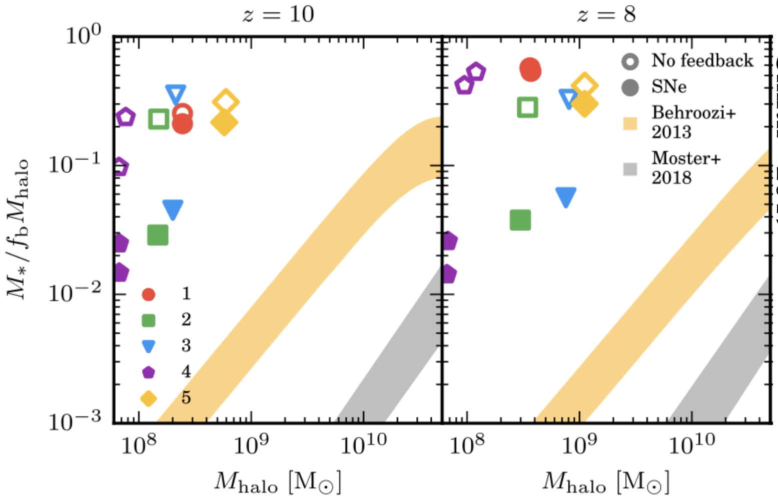
MANY GROUPS ARGUE THAT EARLY (PRE-SN) FEEBACK IS NECESSARY TO REGULATE (HIGH-Z) STAR FORMATION



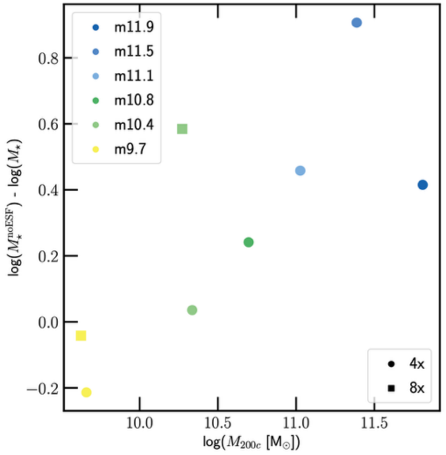
Stinson+ 2013



Ceverino+ 2014



Smith+ 2019



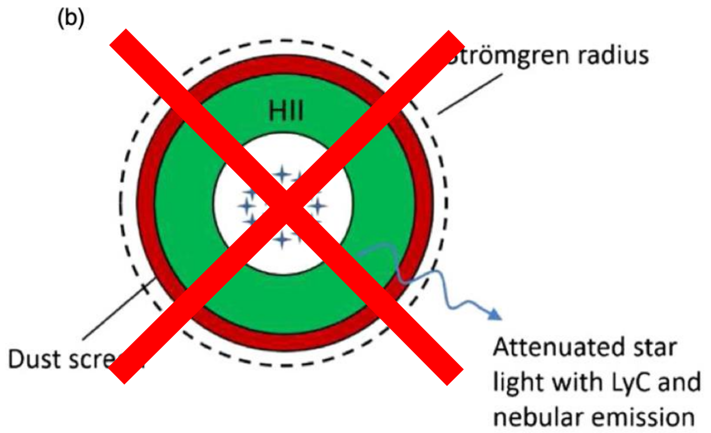
Kannan+ 2025

We don’t yet know:

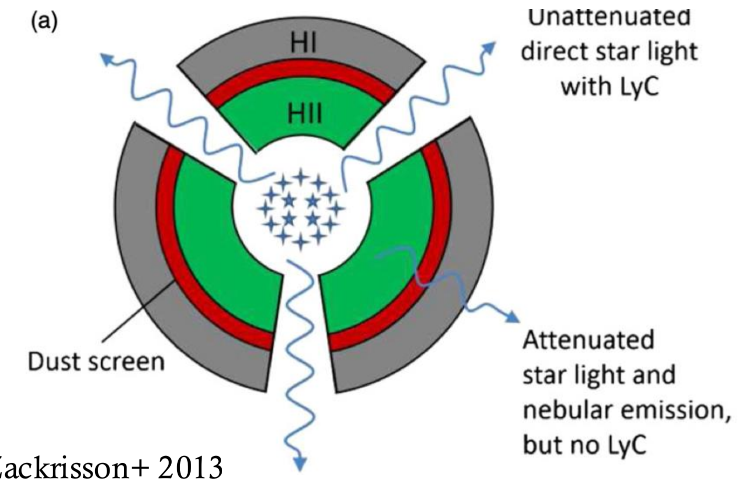
1. Whether this pre-SN feedback simply corrects for limited spatial and mass resolution → these simulations do not fully resolve cloud scales and sims like FIRE don’t require extra energy
2. If the energy genuinely is required, what mode of feedback, e.g. radiation pressure, winds, photoheating, etc. (or all of the above) matters

REIONIZATION GIVES US INSIGHT INTO FEEDBACK COUPLING IN THE ISM

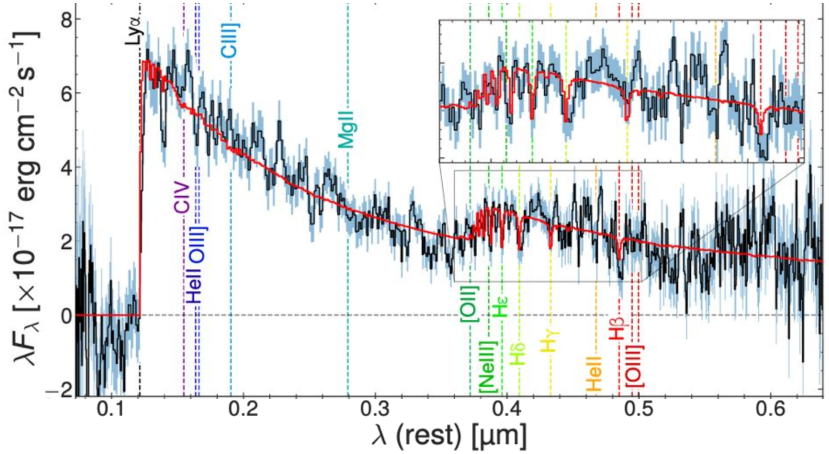
Density Bounded



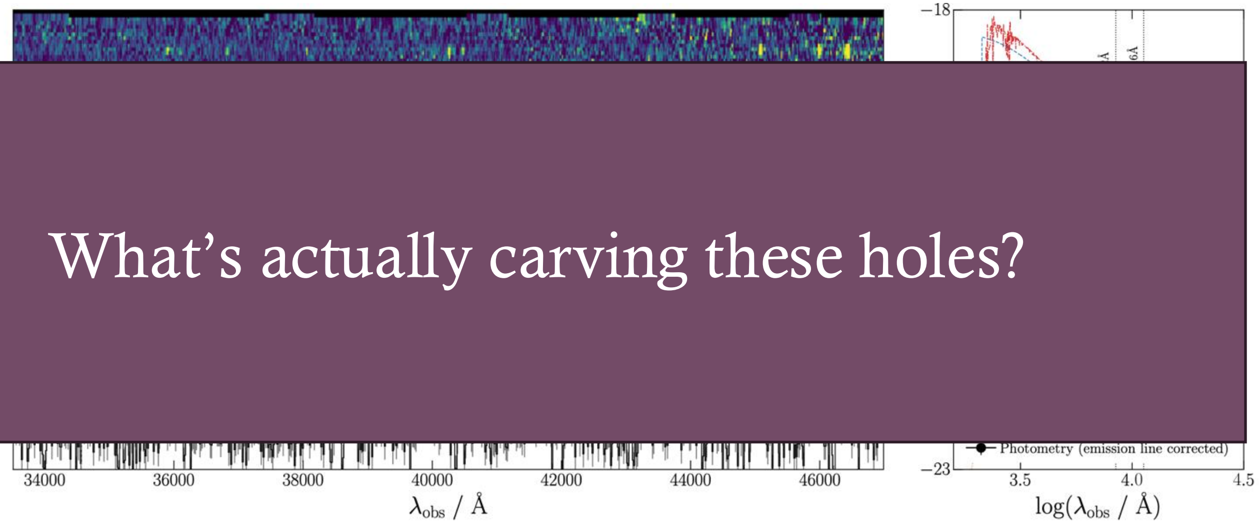
Ionization Bounded w/Holes



Zackrisson+ 2013



Looser+ 2023

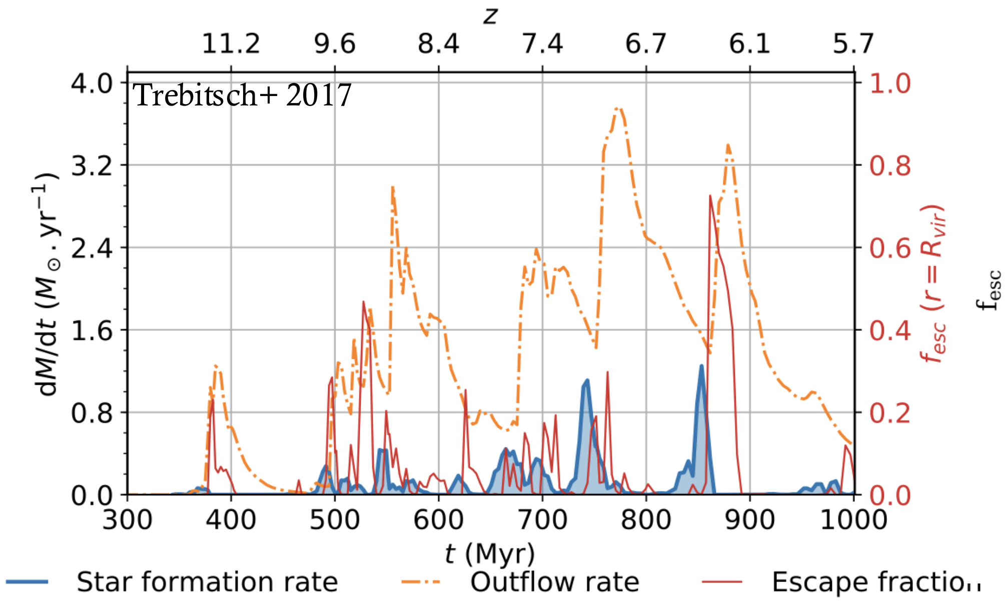


What's actually carving these holes?

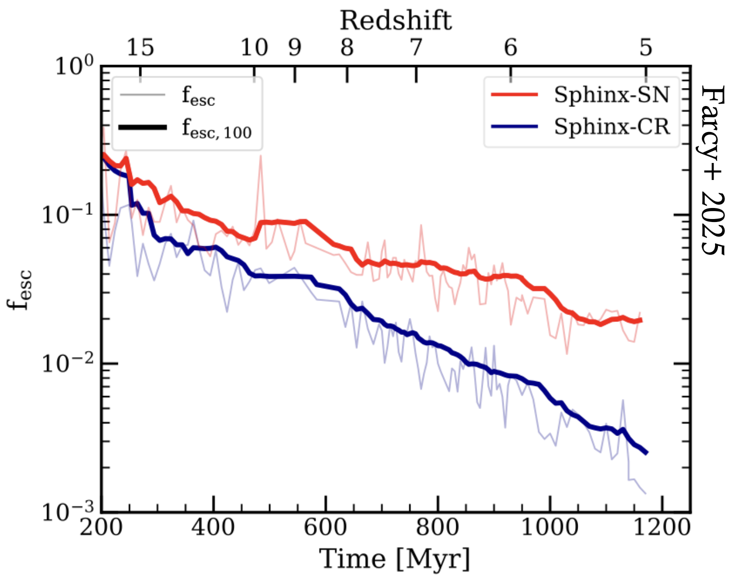
Cullen+ 2025

SN VS EARLY FEEDBACK IN DRIVING LYC LEAKAGE

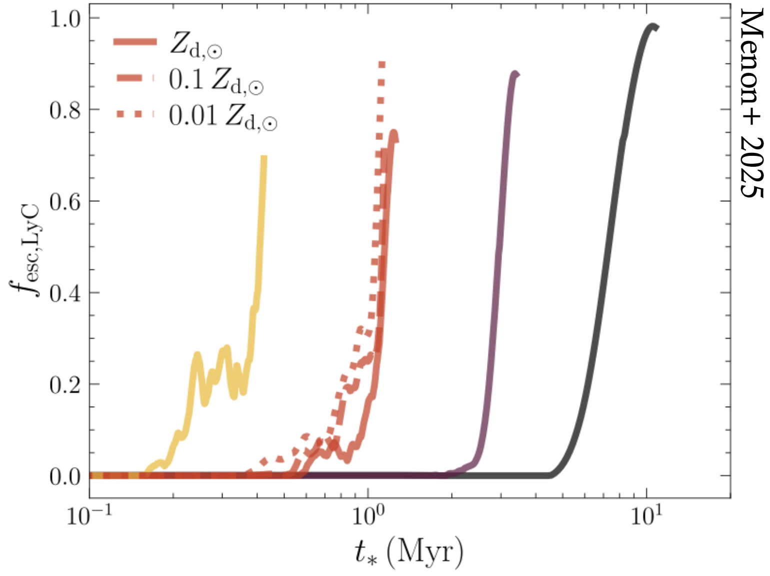
f_{esc} is controlled by SN



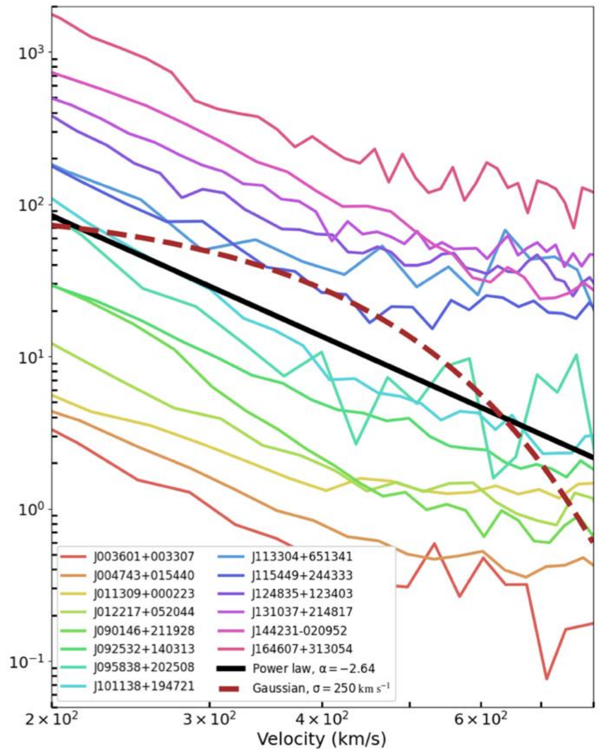
Cosmic rays may plug the holes

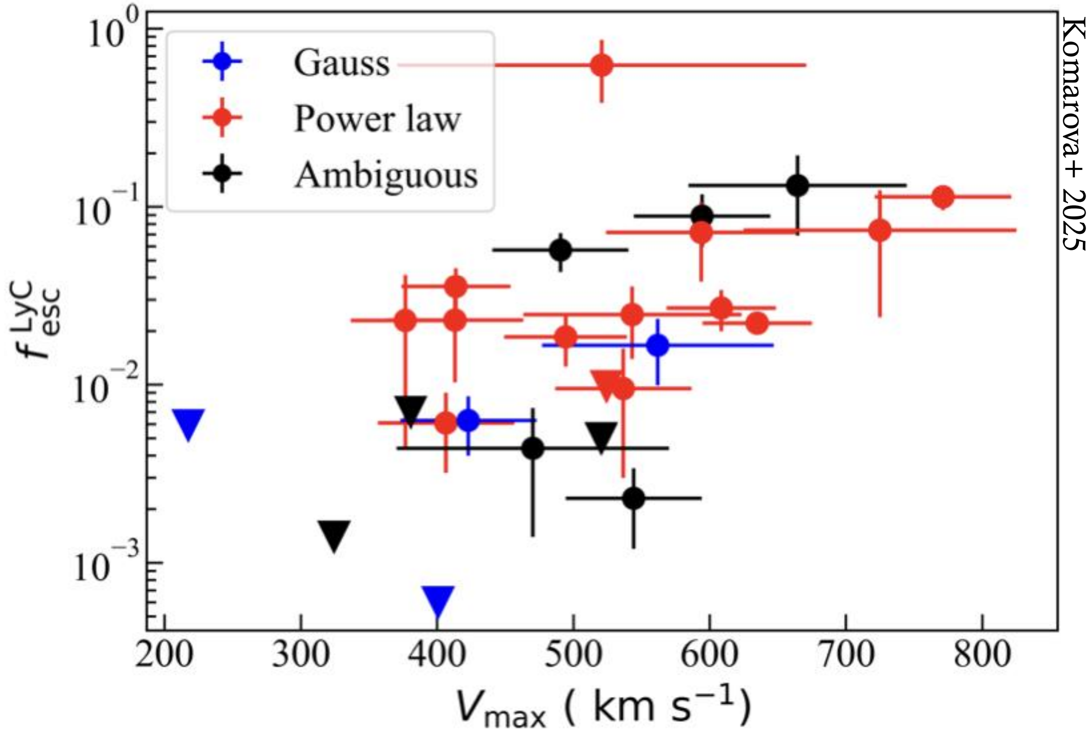


Pre-SN feedback most important



OBSERVATIONAL EVIDENCE OF EARLY FEEDBACK DISRUPTING CLOUDS (BUT SN CAN PLAY A ROLE)

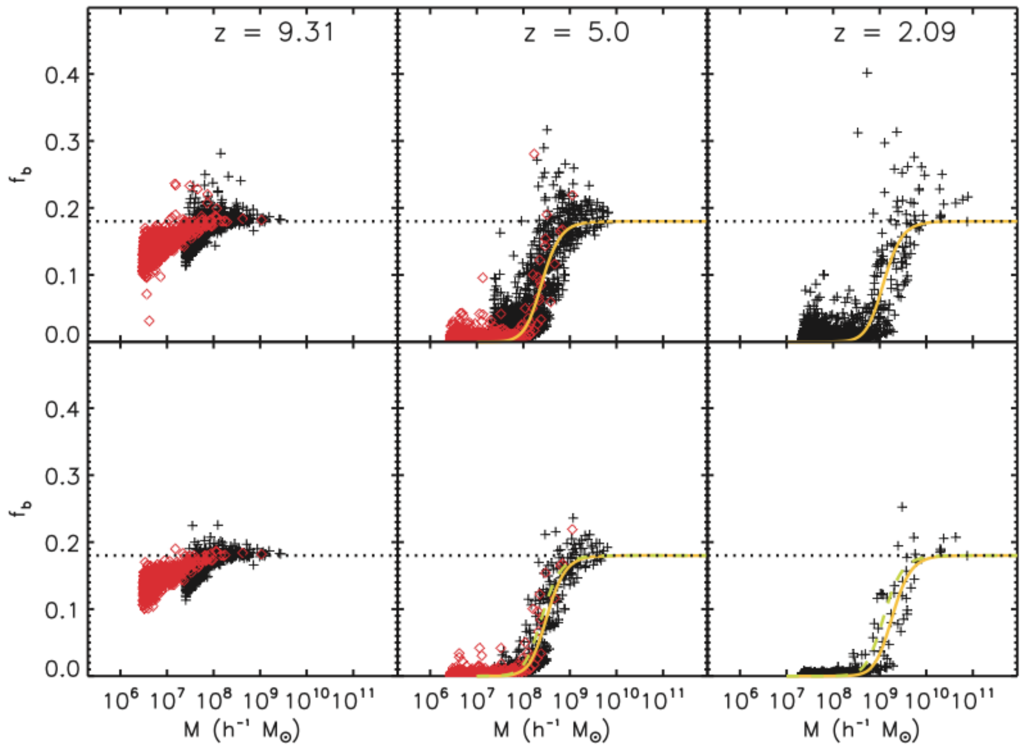




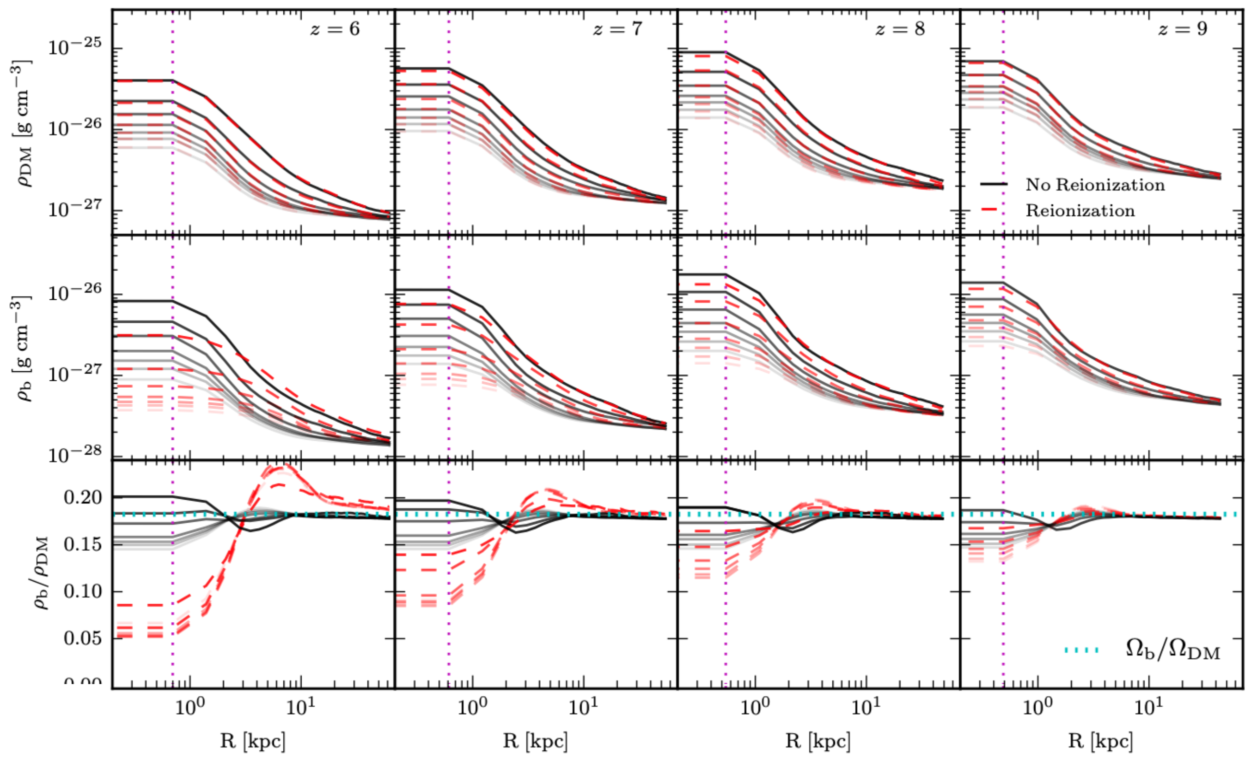
Komarova+ 2025

See also, Carr+ 2024, Bait+ 2024, Flury+ 2024

PREVENTATIVE FEEDBACK FROM RADIATION IS KEY FOR REGULATING EARLY DWARF GALAXIES



Okamoto+ 2008



Katz+ 2020

SUMMARY OF HIGH-REDSHIFT FEEDBACK (EXCLUDING AGN)

Process	Response	Notes
Stellar Winds (Massive Stars)	↓	Reduced opacity (particularly to do a lack of Fe) suppresses winds. Caveat: rotation may be higher
Multiscattered IR radiation pressure	↓	Signifiacntly reduced D2G ratio at low-metallicity. Caveat: much higher column densities and still may operate in massive galaxies
Direct UV radiation pressure	↑	Higher UV photon production per unit stellar mass, higher gas surface densities
Lya radiation pressure	↑↑	Reduced absorption by dust, higher column densities, higher ionizing photon production. Caveat: Turbulence
Photoheating	↑	Harder spectra, weaker cooling, enhanced X-ray contribution
SN	↑↓?	Possible exotic channels in PISN and HN but likely direct collapse over 40 $M_\odot$. Metallicity and density scaling likely cancel. IMF can go either way.
Cosmic Rays	?	Few benchmarks but some results show less porous ISM which is in tension with reionization

OTHER EFFECTS I HAVEN'T DISCUSSED

- There are massive uncertainties on the properties of massive star winds, particularly at low metallicity → winds may be orders of magnitude less strong than classic formulae
- Dense stellar clusters are probably more common at high-redshift → densest clusters can dynamically eject a large fraction of O stars (maybe 50% -- Oh & Kroupa (2016))
- Ionizing photon production of massive stars is highly uncertain, particularly at the He II edge
- Non-solar abundance patterns are very common, in particular C/O can be very low or very high → has strong impacts on how the gas cools
- There are anomalous ionizing sources at low-redshift w/ BB temperatures of ~80,000 K or more (see Olivier+ (2022)) → may be more common at high redshift
- Peculiar chemical abundance patterns imply the presence of hot massive stars where the metal yields do not escape the ISM → the physics that causes this is unknown

NO CONCLUSIONS, HERE'S A MEGATRON MOVIE