Bridging Theory and Observations: Insights into

SFE and Dust attenuation in high-z galaxies

(DT et al. 2025, MNRAS, 541, 5606)

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in collaboration with

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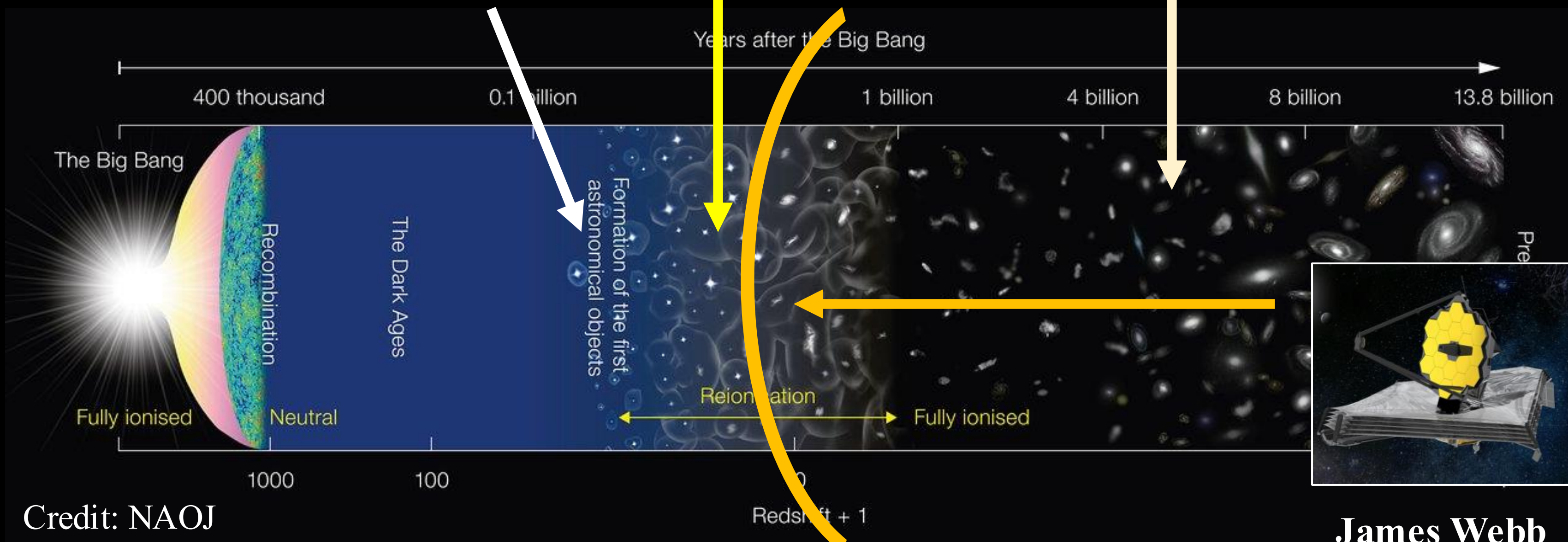
z ~ 20-30
First stars

z ~ 15
First galaxies

- Luminosity function
- M*-SFR-Z relation
- Size evolution

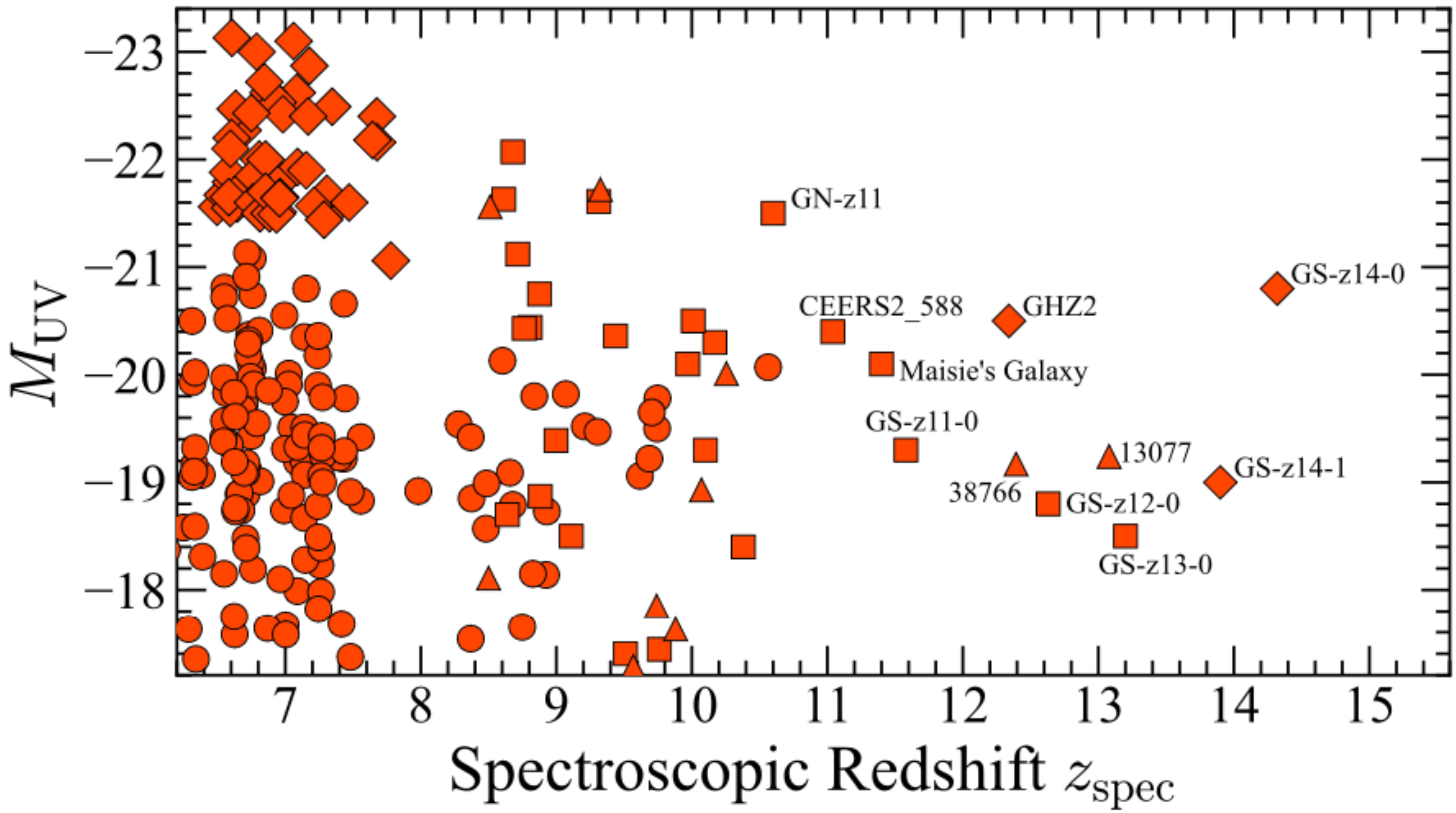


Credit: NAOJ

JWST is reaching z > 10 galaxies!!

James Webb Space Telescope (JWST)

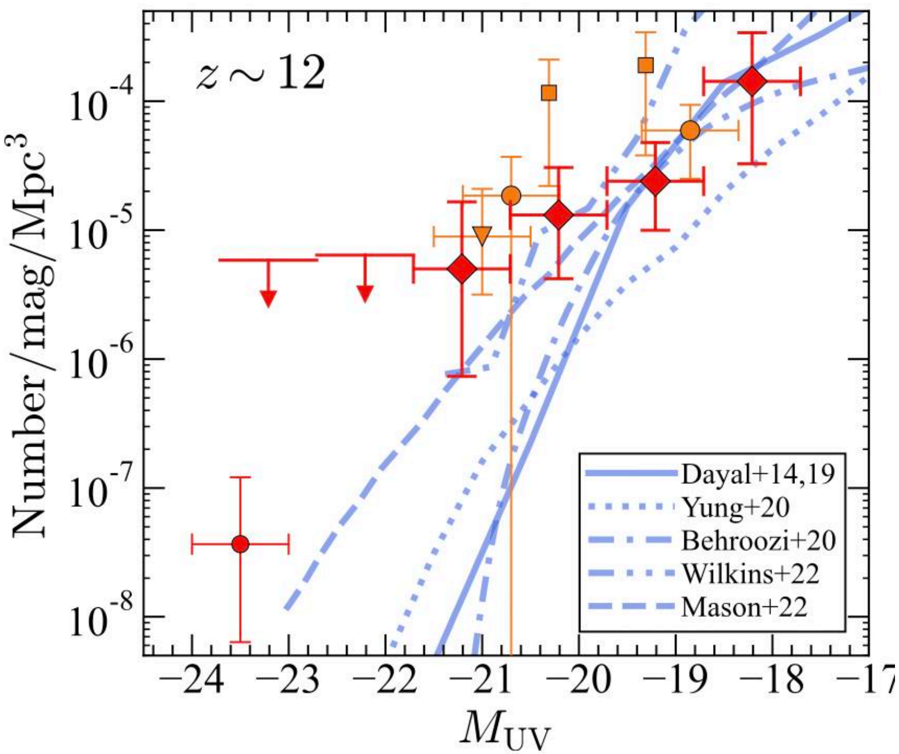
z > 6 galaxies identified by JWST



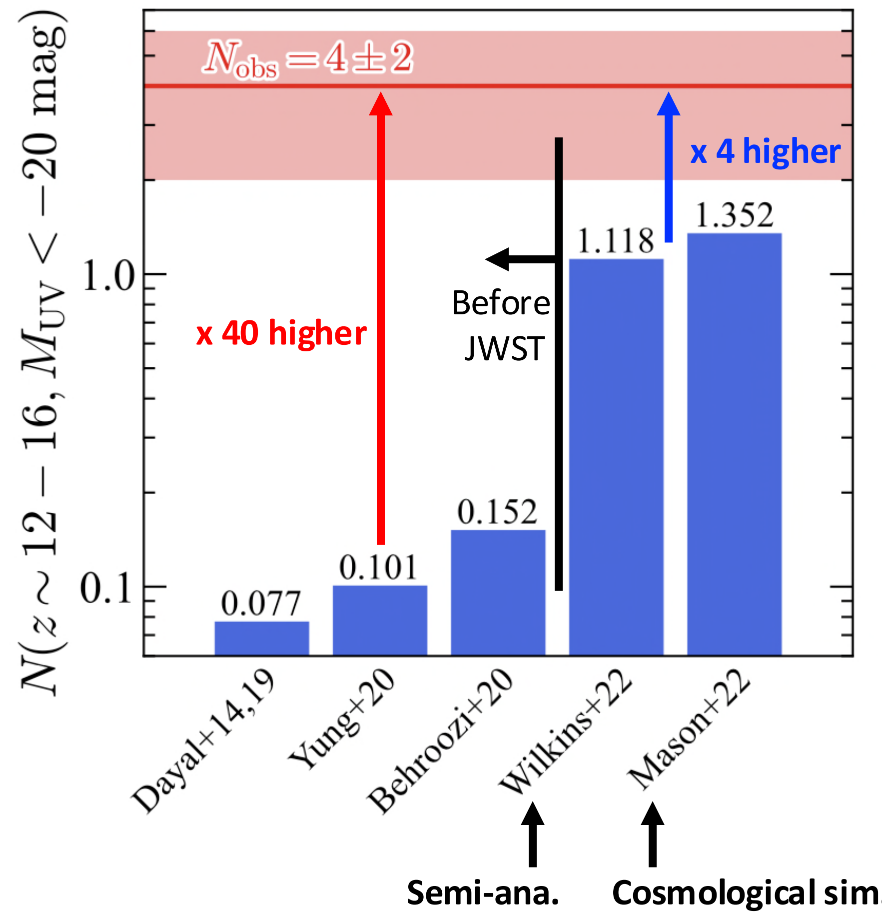
Harikane+(2024)

Too many UV-bright galaxies at z > 10?

- Bright-end galaxies at z > 10 are more abundant than theoretical expectation.



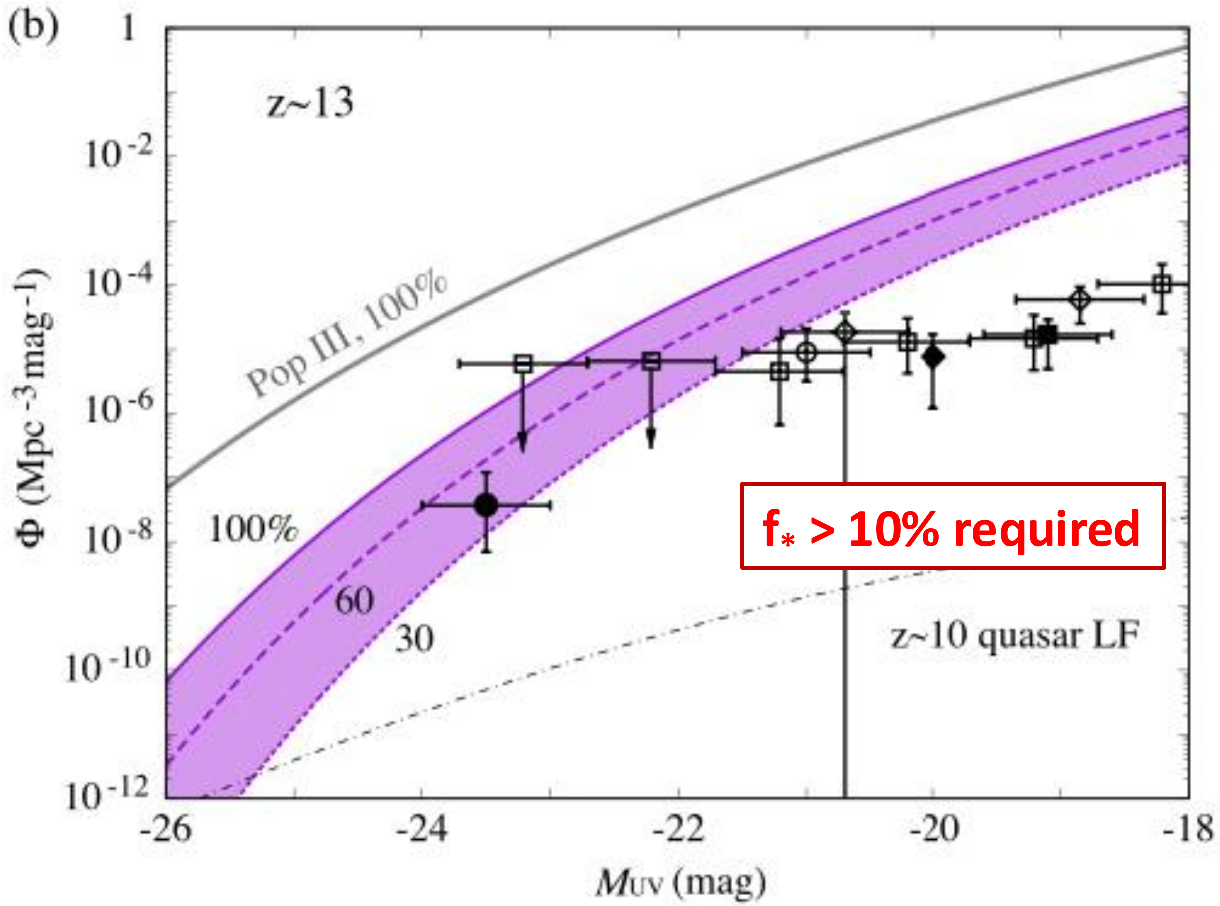
Harikane+2023



High star formation efficiency?

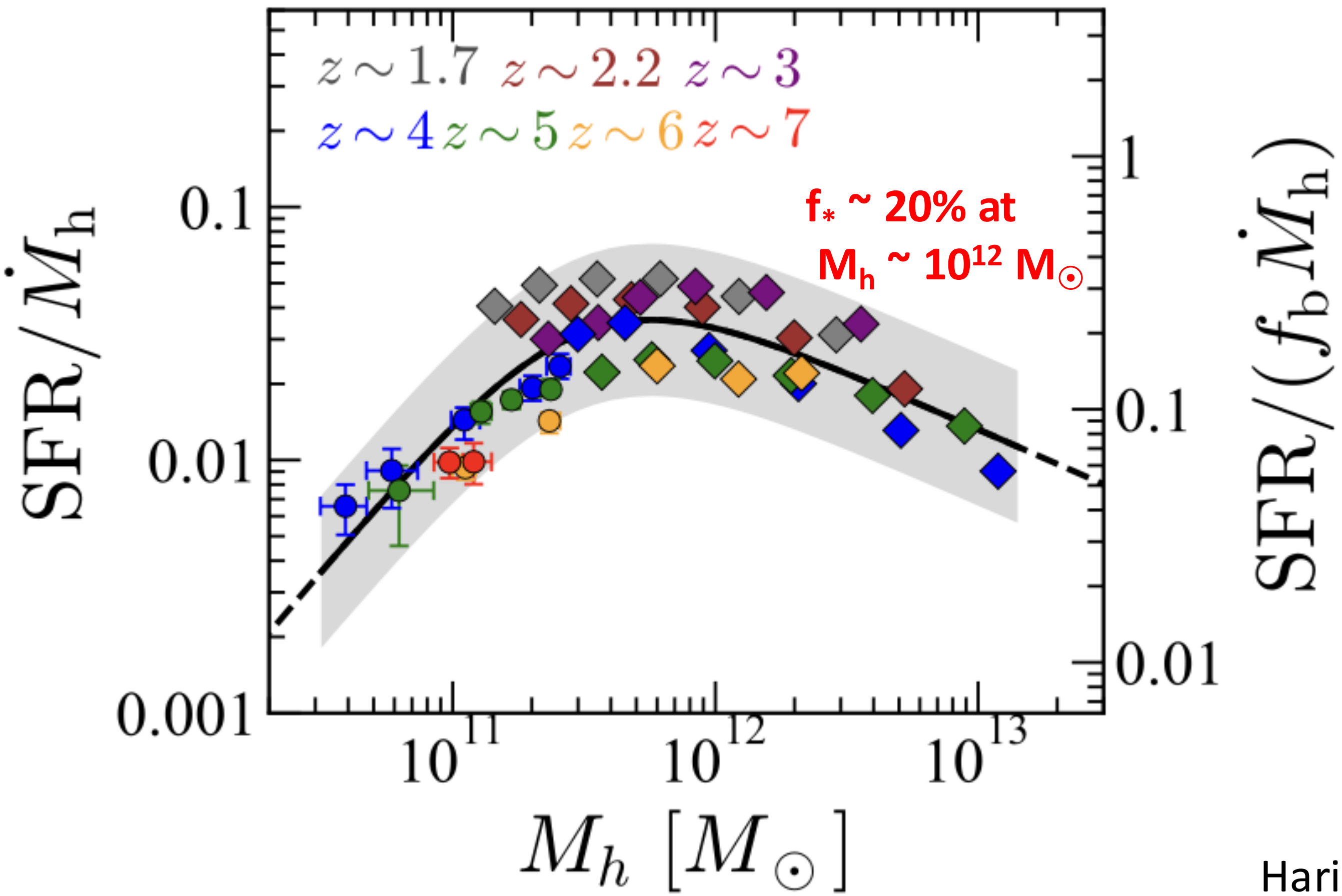
- The observed number densities can constrain the SFEs of z > 10 galaxies.

$f_* \equiv \mathrm{SFR}/(f_\mathrm{b}\dot{M}_\mathrm{h}) \gtrsim 10~\%$ (Inayoshi et al. 2022)



SFEs for z < 7 galaxies

- Tight relation between SFE and halo mass, almost independent of redshifts across 2 < z < 7.
- Can this relation be applicable for even beyond z ~ 10?
- **What is the underlying mechanism?**

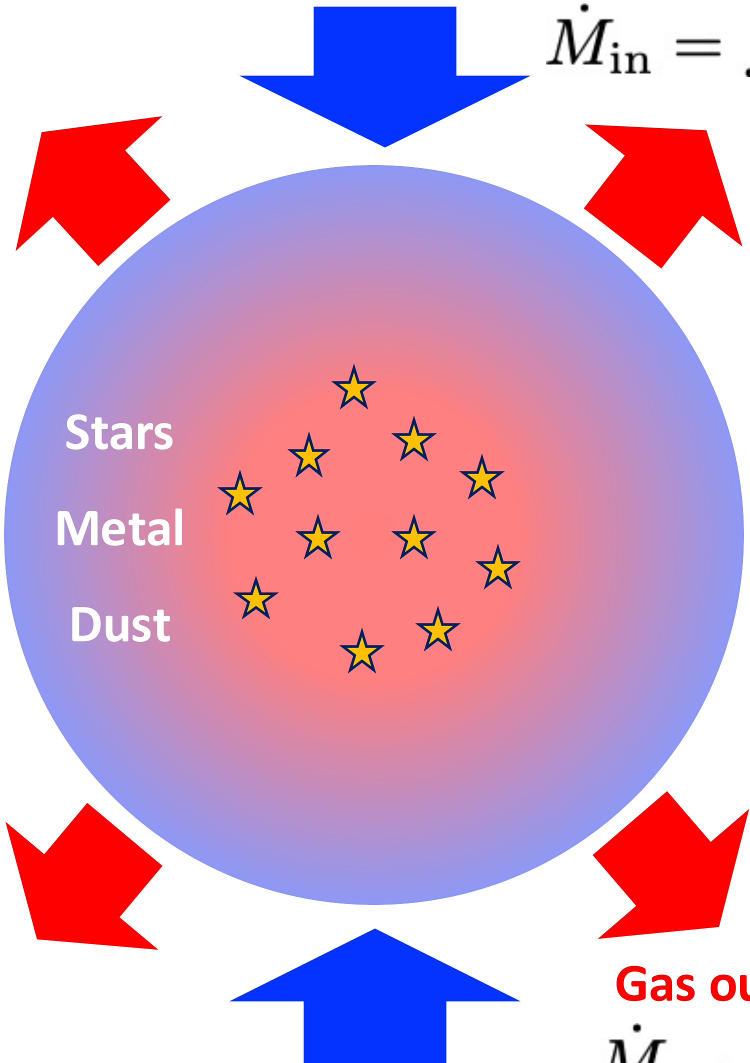


Harikane+2022

Toy galaxy evolution model

Gas inflows

$$\dot{M}_{\rm in} = f_{\rm b}\epsilon_{\rm in}\dot{M}_{\rm h}$$



Gas outflows

$$\dot{M}_{\rm out} = \eta {\rm SFR}$$

Reduction factor via AGN or virial shock (cf. Birnboim & Dekel 2003)

$$\epsilon_{\rm in} = (1 + M_{\rm h}/M_{\rm h,ch})^{-1}$$

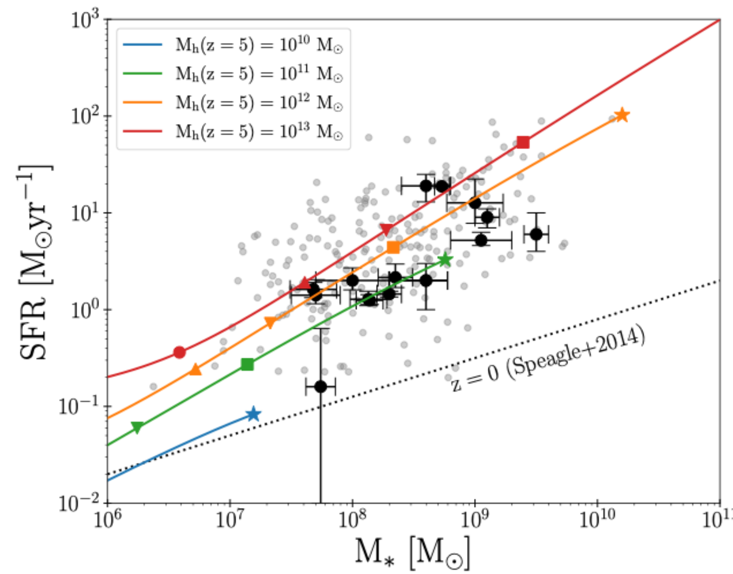
&

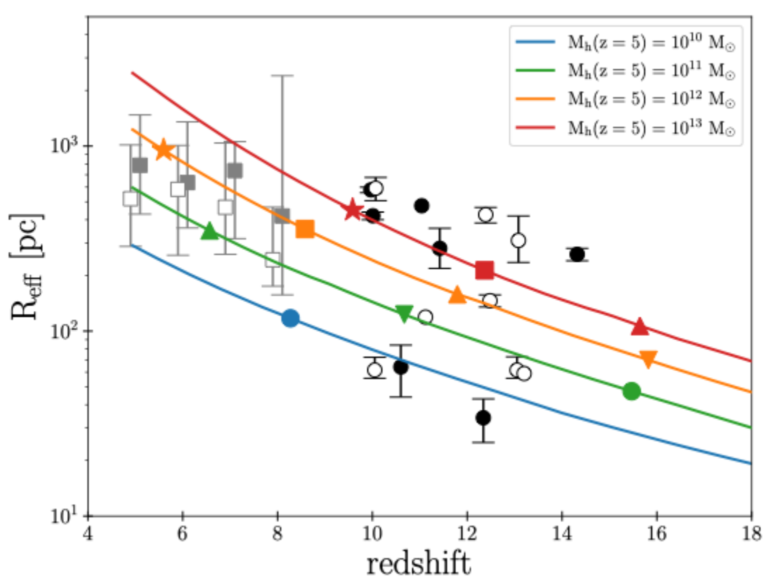
Mass loading factor (cf. Muratov+15)

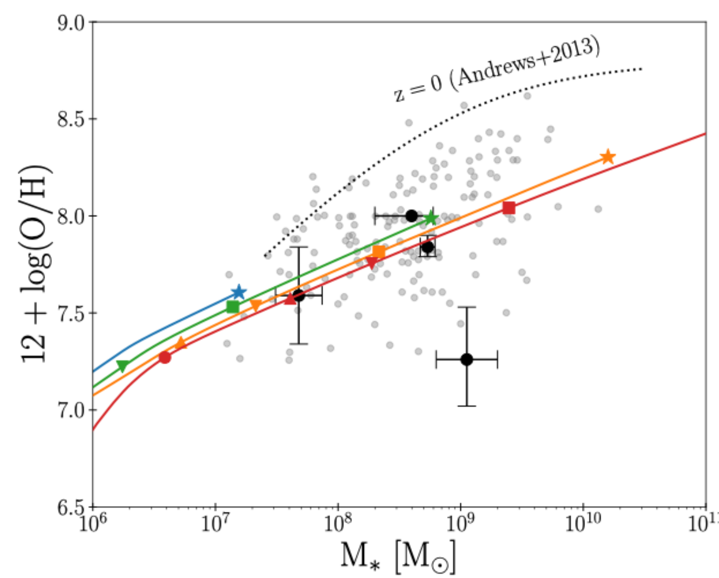
$$\eta = \eta_0 \left\{ \frac{1}{2}\left(\frac{M_{\rm h}}{M_{\rm h,0}}\right)^{-1.1} + \frac{1}{2}\left(\frac{M_{\rm h}}{M_{\rm h,0}}\right)^{-0.33} \right\}$$

Results: Basic properties of z > 5 galaxies

- Our model successfully explains
  - ✓ **Size evolution**
  - ✓ **M_*-SFR-Z relation**
  - ✓ **Dust-to-stellar mass ratio**
  - ✓ **FIR flux (dust thermal emission) etc.**







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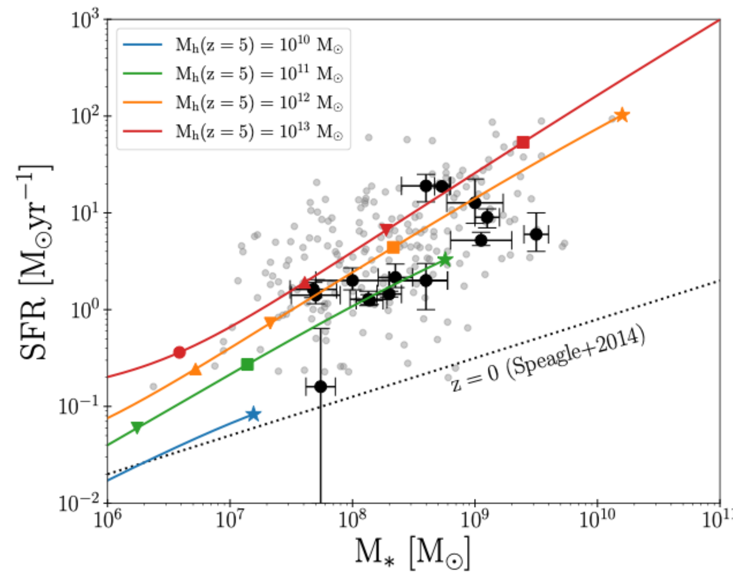
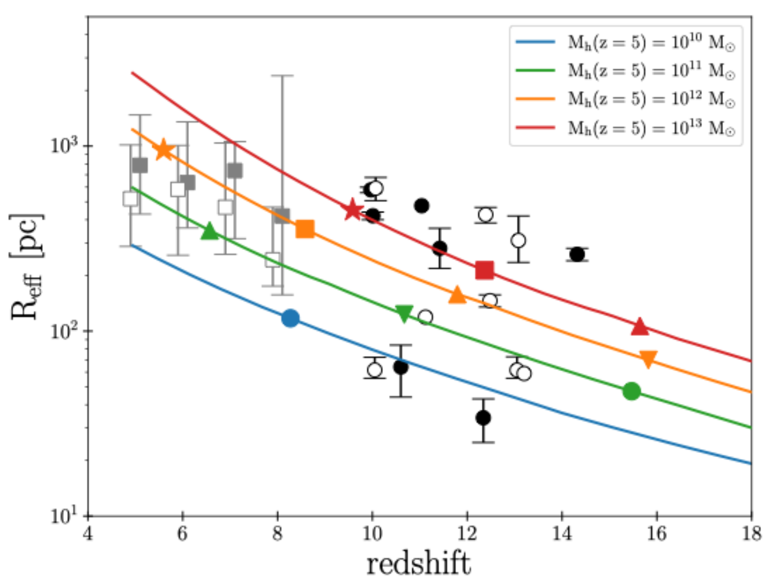
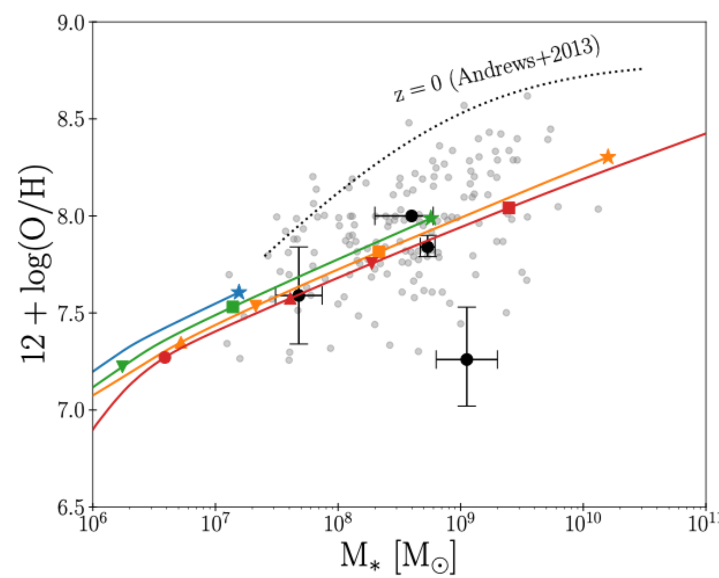
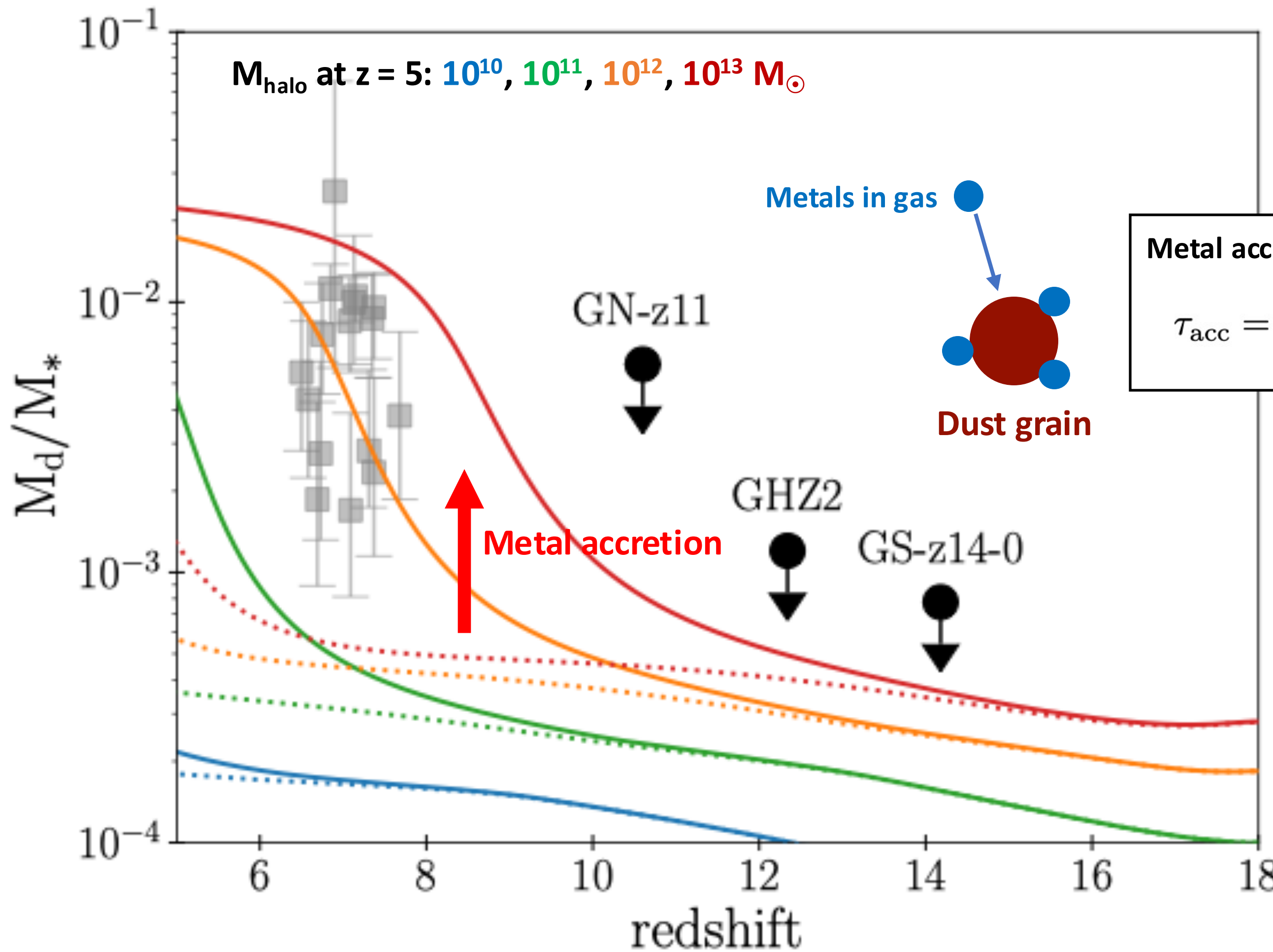






Dust-to-stellar mass ratio

- Dust mass rapidly increases at $z < 10$ due to metal accretion on dust grains.
- Explain both **dust-rich galaxies at z ~ 7** and **the upper limits for z > 10 galaxies**.

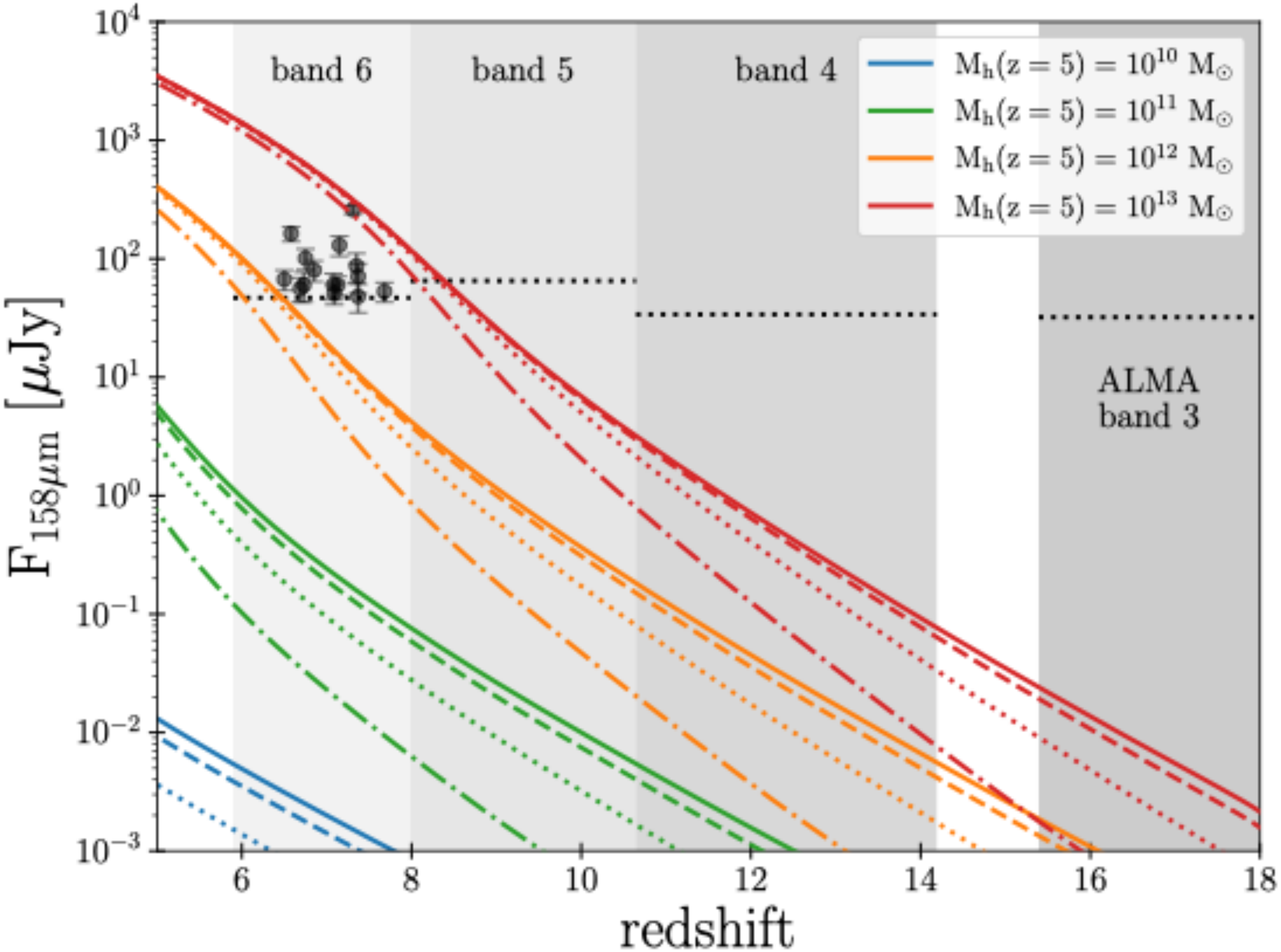


Metal accretion timescale

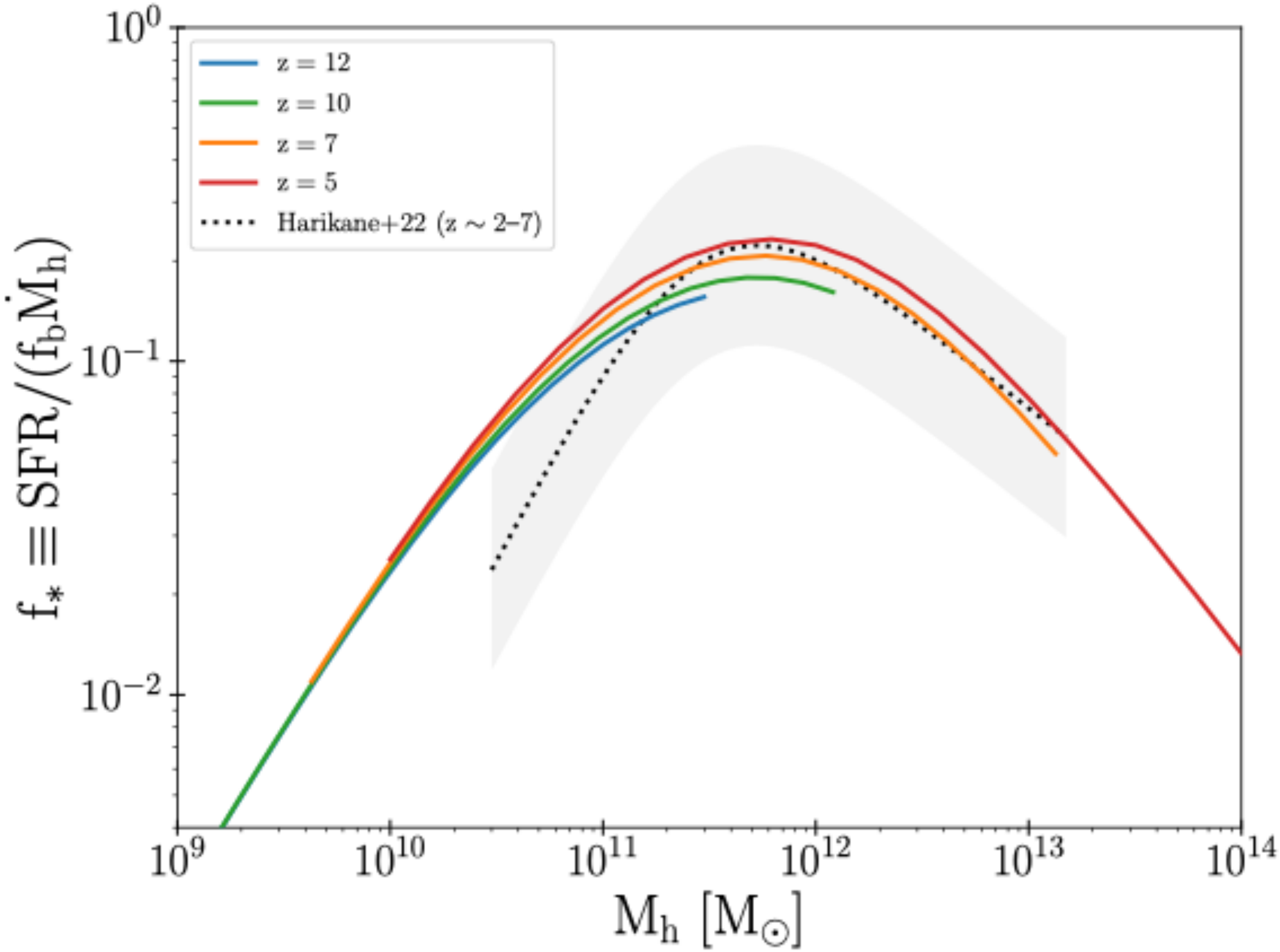
$$\tau_{acc} = 5\ \mathrm{Myr} \left(\frac{Z}{Z_\odot}\right)^{-1}$$

FIR flux of dust continuum

- Consistent with the presence of FIR-bright galaxies at z ~ 7 and non-detection of dust continuum in z > 10 galaxies (Fudamoto+24, Zavala+24, Carniani+24).



Star formation efficiency



Physical origin of the SFE-M_h relation

Mass conservation equation

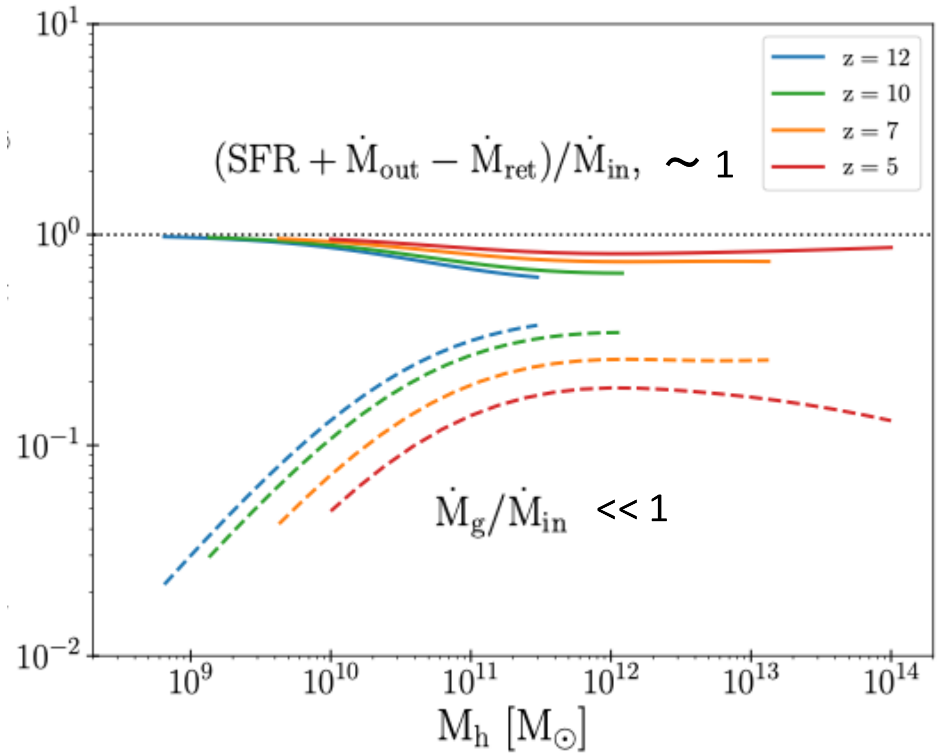
$$\dot{M}_{\rm g} = -({\rm SFR} + \dot{M}_{\rm out}) + \dot{M}_{\rm in} + \dot{M}_{\rm ret}$$

$$= \underbrace{-(1-\mathcal{R}+\eta){\rm SFR}}_{\text{Consumption}} + \underbrace{f_{\rm b}\epsilon_{\rm in}\dot{M}_{\rm h}}_{\text{Supply}} ,$$

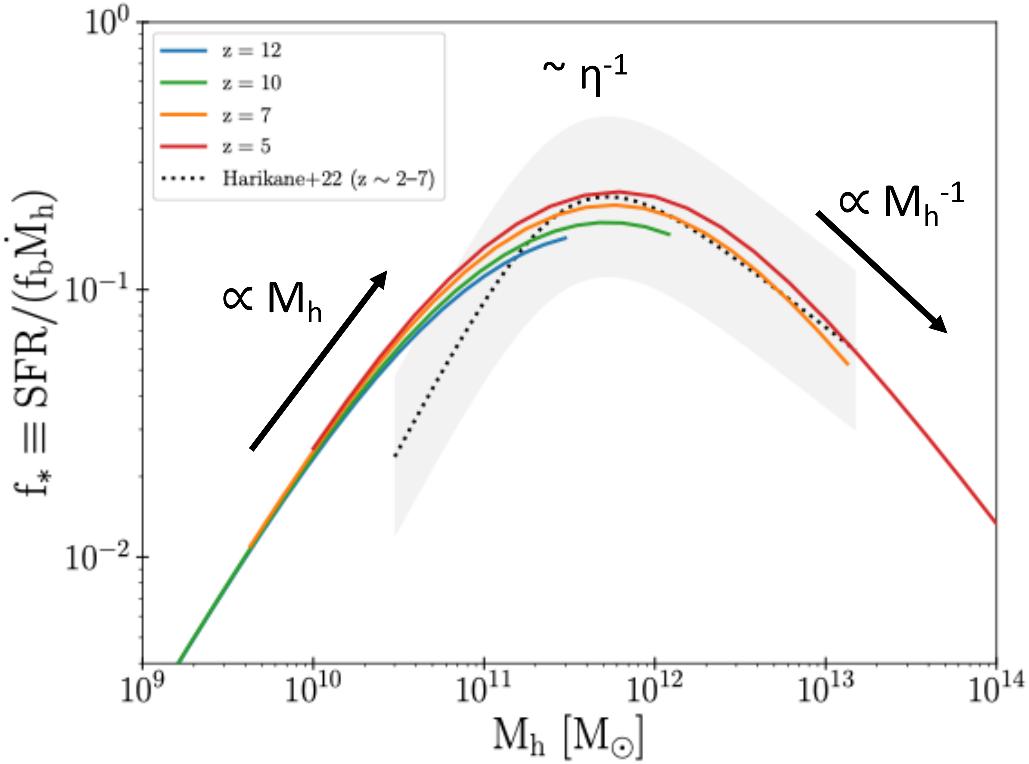
- Galaxies evolve in **a quasi-steady state**, where (SFR+OFR) generally balances with IFR.

$$(1-\mathcal{R}+\eta){\rm SFR} \sim f_{\rm b}\epsilon_{\rm in}\dot{M}_{\rm h}$$

$$f_* \equiv \frac{\rm SFR}{f_{\rm b}\dot{M}_{\rm h}} \sim \frac{\epsilon_{\rm in}}{1-\mathcal{R}+\eta}$$



Physical origin of the SFE-M_h relation



Reduction factor via AGN or virial shock (cf. Birnboim & Dekel 2003)

$$\epsilon_{\rm in} = (1 + M_{\rm h}/M_{\rm h,ch})^{-1}$$

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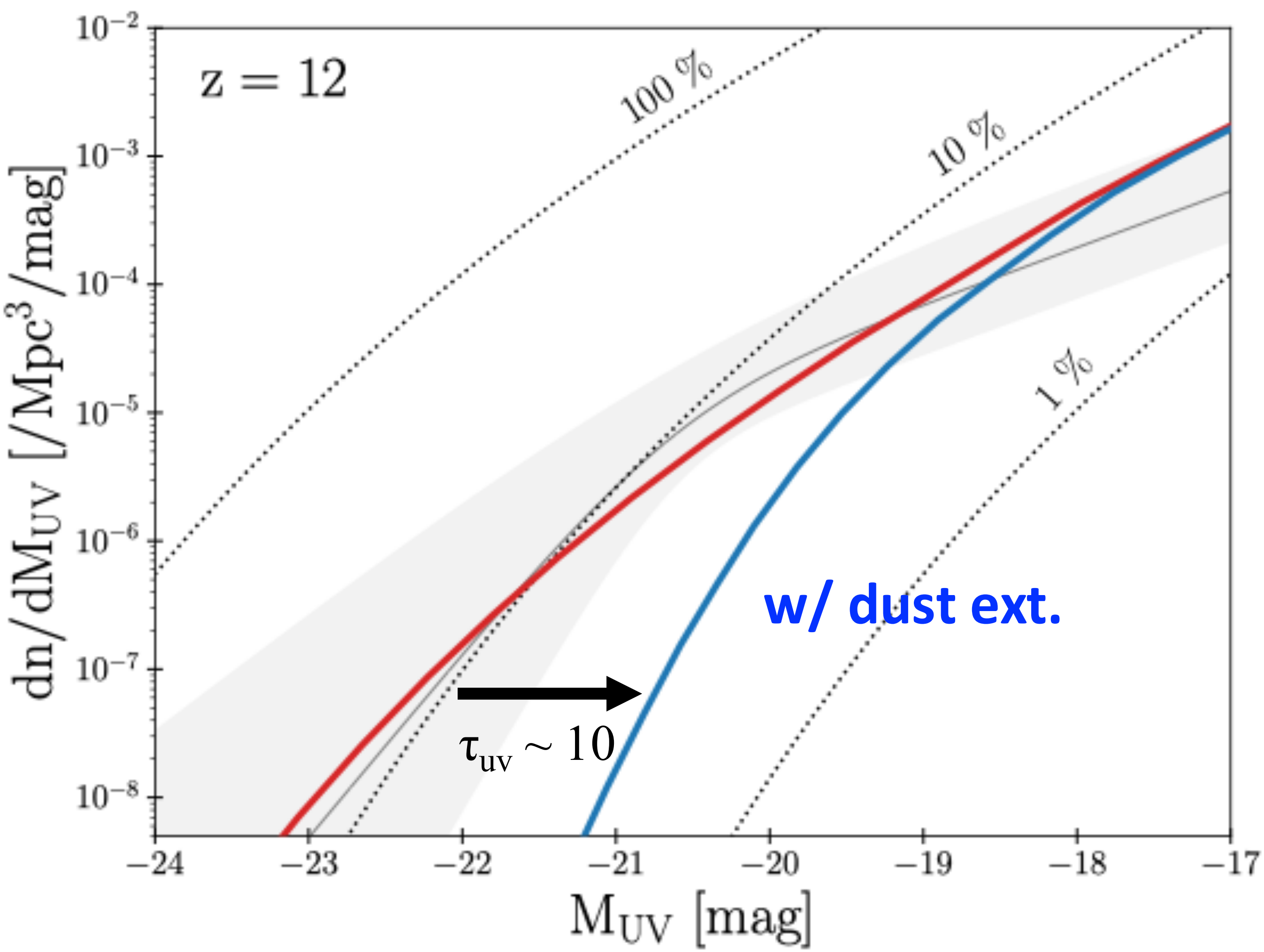
$$f_* \equiv \frac{\rm SFR}{f_{\rm b}\dot{M}_{\rm h}} \sim \frac{\epsilon_{\rm in}}{1 - \mathcal{R} + \eta}$$

$$f_* \sim \begin{cases} \eta^{-1} \propto M_{\rm h}^{1.1}, & (M_{\rm h} \ll 10^{11}\ {\rm M_\odot}) \\ \epsilon_{\rm in}/(1-\mathcal{R}) \propto M_{\rm h}^{-1} & (M_{\rm h} \gg 10^{12}\ {\rm M_\odot}) \end{cases}$$

Our model

Sheth-Tormen MF $\Phi(M_{\rm h}, z)$ → $L_{\rm UV}(M_{\rm h}, z)$ → **UV LF** $\Phi(L_{\rm UV}, z)$



Possible mechanisms to reduce dust attenuation

$$\tau_{1500} \sim \kappa_{1500} \frac{D M_{\rm g}}{2\pi R_{\rm eff}^2}$$
$$\sim 34.6 \left(\frac{\kappa_{1500}}{1.26 \times 10^5\ {\rm cm^2 g^{-1}}}\right) \left(\frac{M_{\rm g}}{10^{10}\ {\rm M_\odot}}\right) \left(\frac{R_{\rm eff}}{500\ {\rm pc}}\right)^{-2} \left(\frac{D/D_{\rm MW}}{0.01}\right)$$

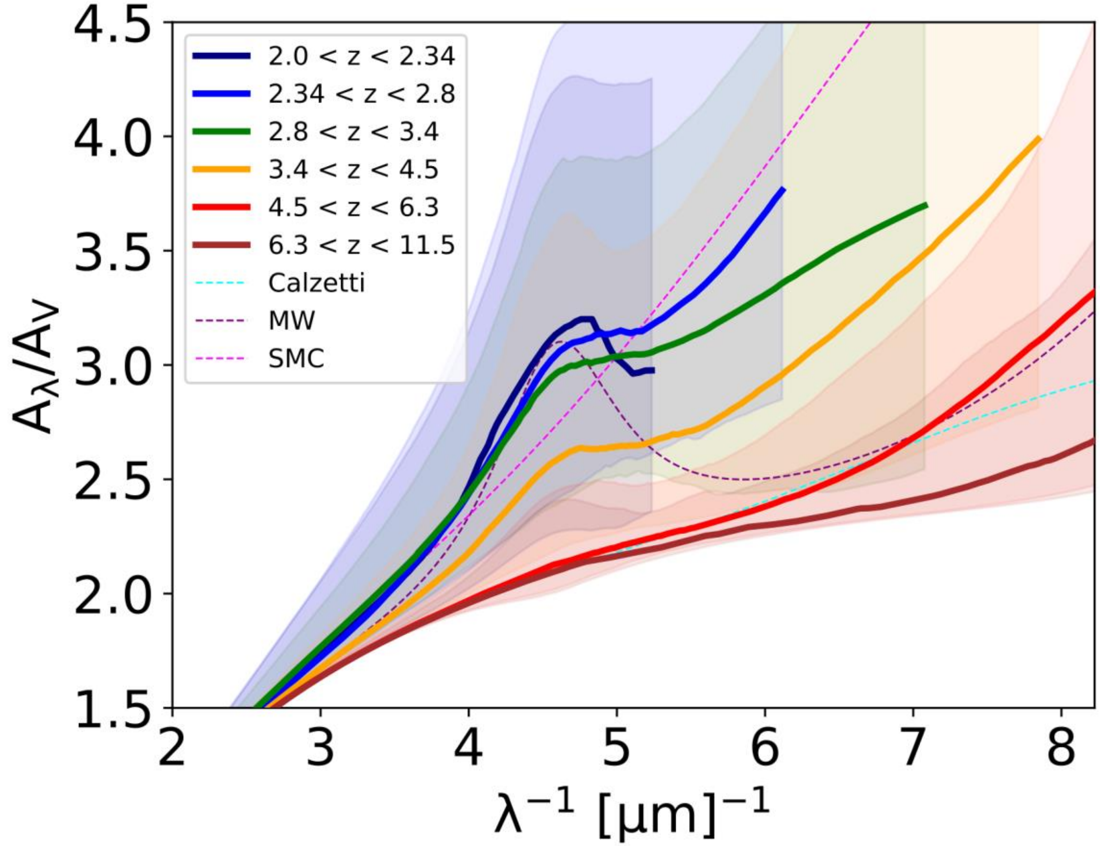
1. **Decrease M_g and D?**
   - ✓ Stronger outflows can do, but they might prevent us from explaining high SFEs.
2. **Increase R_{eff} for dust?**
   - ✓ Stellar feedback temporally displaces dust to a few kpc scale far from galactic disk (Fiore+23, Ziparo+23, Ferarra+24).
3. **Decrease κ_{1500}?**
   - ✓ High-z galaxies might have more top-heavy dust size distributions than the MW.

Large grain size in high-z galaxies?

- ✓ If large grains with a = 0.5 μm are dominant, the UV opacity can be ~ 20 times lower than the MW.

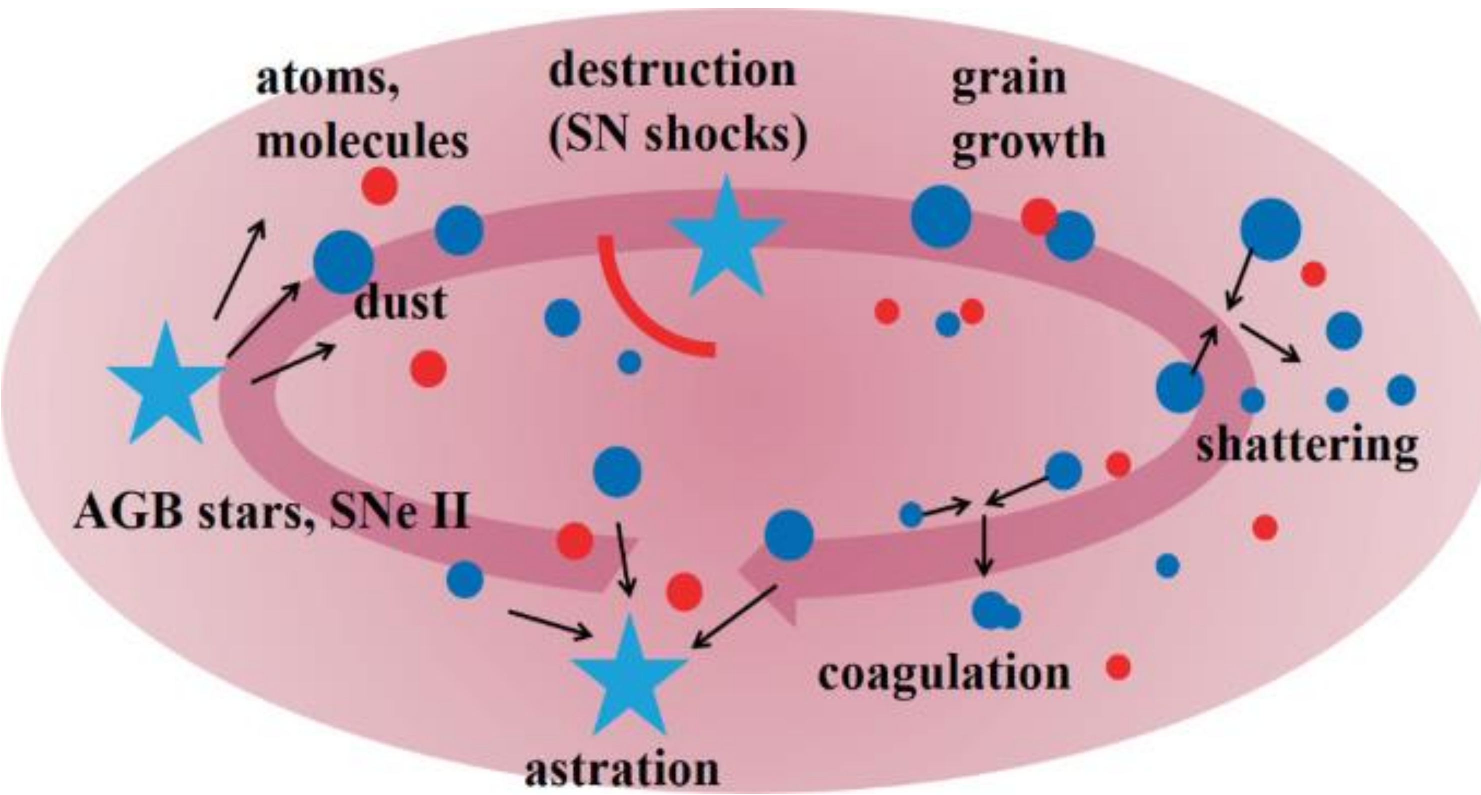
$$\kappa_{1500}^{\rm large} \sim \frac{\pi a_{\rm g}^2}{\frac{4\pi}{3}\delta_{\rm g} a_{\rm g}^3} \sim 5085\ {\rm cm^2 g^{-1}} \left(\frac{a_{\rm g}}{0.5\ \mu{\rm m}}\right)^{-1} \sim 0.04\ \kappa_{1500}^{\rm MW}$$

- ✓ A flatter dust attenuation curve has been observed at z < 6 (Markov+24, 25)



Calculation of dust size distribution

- DT+25 just adopted the dust size distribution of the MW.
- Implementation based on Hirashita+2019.
- Dust size distribution: 32 bins, a = 3×10^{-4} - 10 μm for two species of Graphite (C) and Silicate (Si).
- All the key mechanisms are considered.

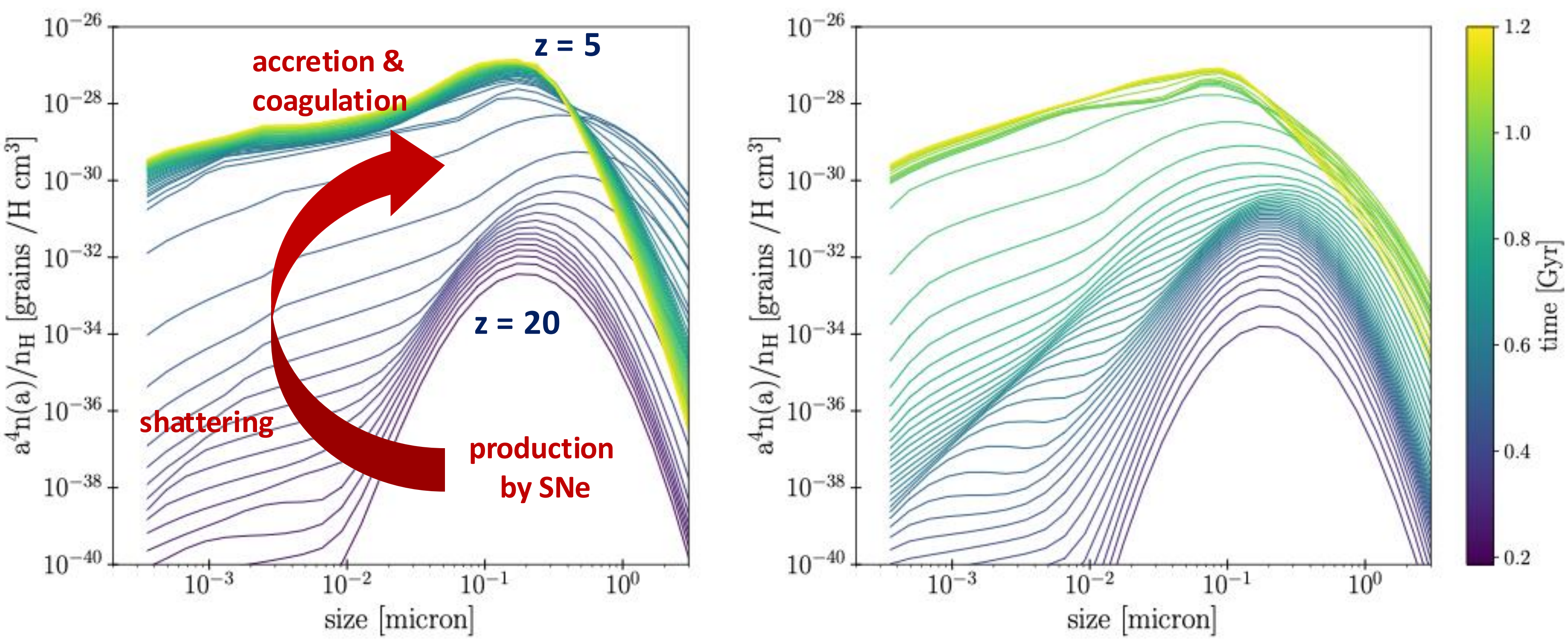


Credit: Physics of the Formation and Evolution of Galaxies

Evolving dust size distributions

✓ For a galaxy evolving $M_{halo} = 10^{12}\ M_{sun}$ at $z = 5$

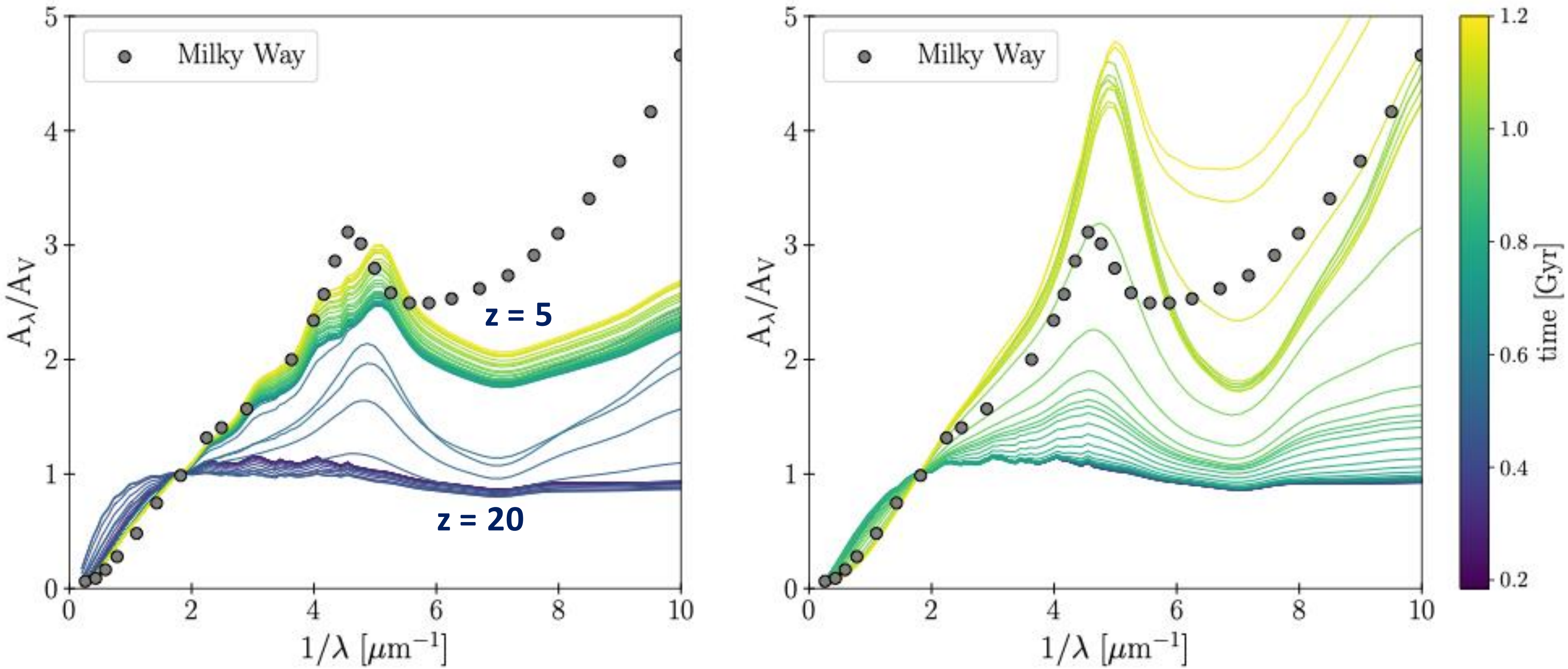
R = 100 pc ($R < R_{eff}$) R = 1000 pc ($R > R_{eff}$)



Evolving dust extinction curve

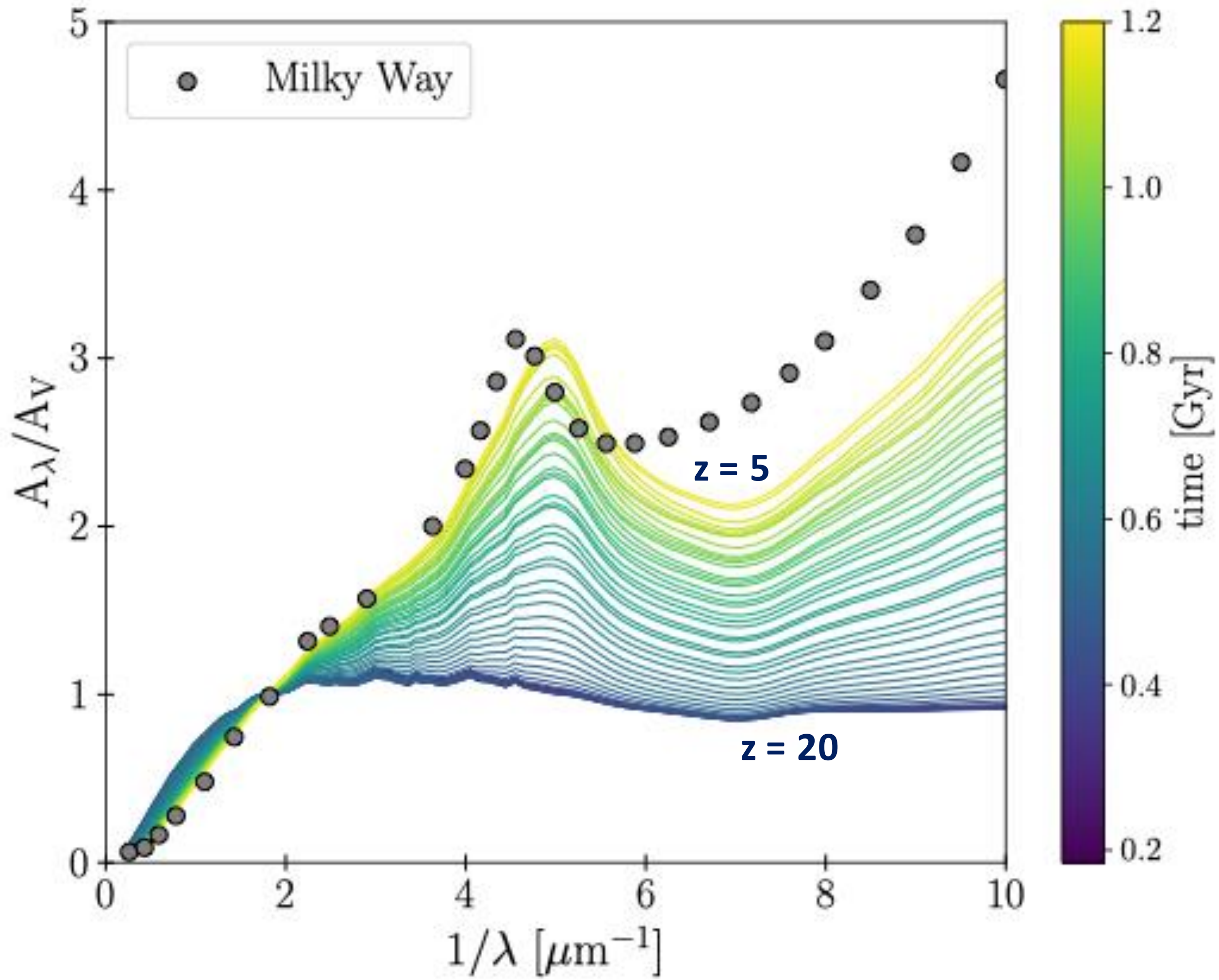
✓ For a galaxy evolving $M_{halo} = 10^{12}\ M_{sun}$ at $z = 5$

R = 100 pc ($R < R_{eff}$) R = 1000 pc ($R > R_{eff}$)

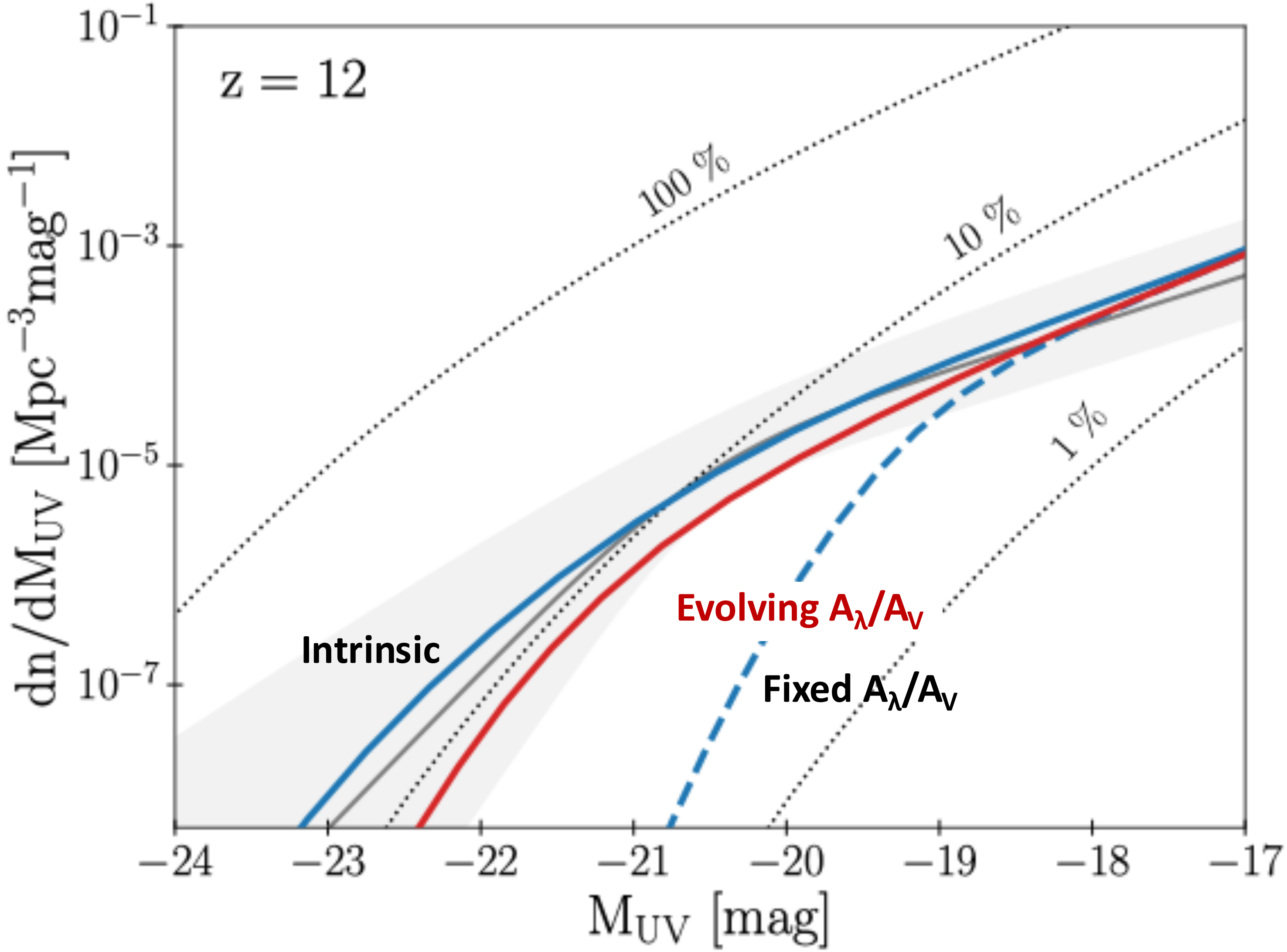


SFR-weighted average of A_λ/A_V

- ✓ For a galaxy evolving $M_{halo} = 10^{12}\ M_{sun}$ at $z = 5$

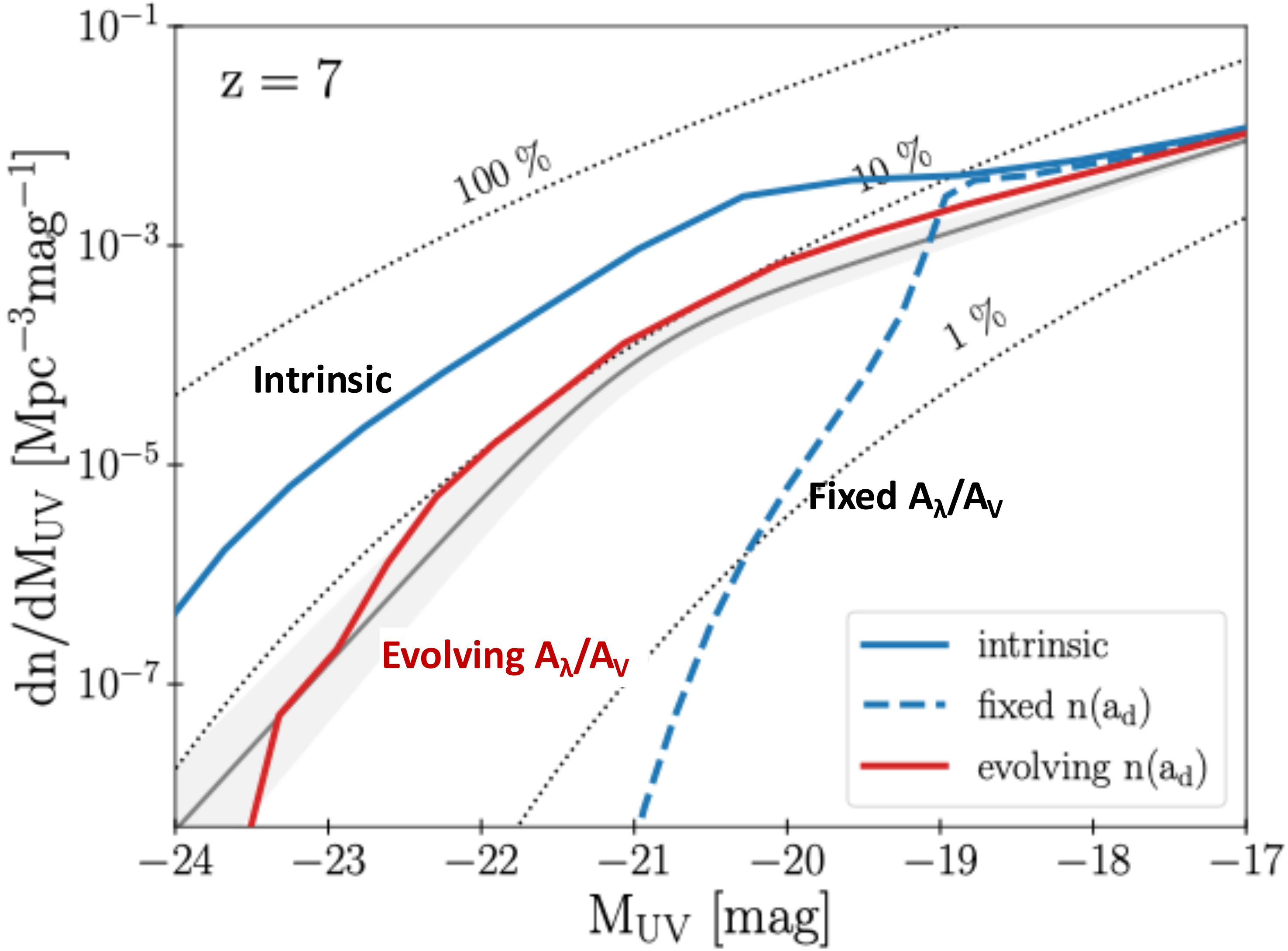


UV LF at z ~ 12



z = 12
100 %
10 %
1 %
Intrinsic
Evolving A_λ/A_V
Fixed A_λ/A_V
10^{-1}
10^{-3}
10^{-5}
10^{-7}
dn/dM_{UV} [$Mpc^{-3}mag^{-1}$]
−24
−23
−22
−21
−20
−19
−18
−17
M_{UV} [mag]

UV LF at z ~ 7


z = 7
100 %
10 %
1 %
Intrinsic
Fixed A_λ/A_V
Evolving A_λ/A_V
intrinsic
fixed $n(a_d)$
evolving $n(a_d)$
dn/dM_{UV} [$Mpc^{-3}mag^{-1}$]
M_{UV} [mag]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
−24
−23
−22
−21
−20
−19
−18
−17

Summary

- ✓ We developed **a toy model** to discuss various observational characteristics of JWST-identified galaxies at $z > 5$.
- ✓ Our model results successfully explain the size evolution, the M_*-SFR-Z relation, and the dust mass evolution with physically-motivated assumptions.
- ✓ Galaxies evolve in **a quasi-steady state**, where gas consumption and supply balances with each other. This equilibrium governs the SFE-Mh relation.
- ✓ Intrinsic UV LF aligns well with observations. However, when including dust attenuation, our model highly underestimate the number density of galaxies with $M_{UV} < -20$ mag.
- ✓ **A possible solution is the evolving, top-heavy dust size distribution.**