

The Earliest Dusty Galaxies. Lessons from ALMA and JWST

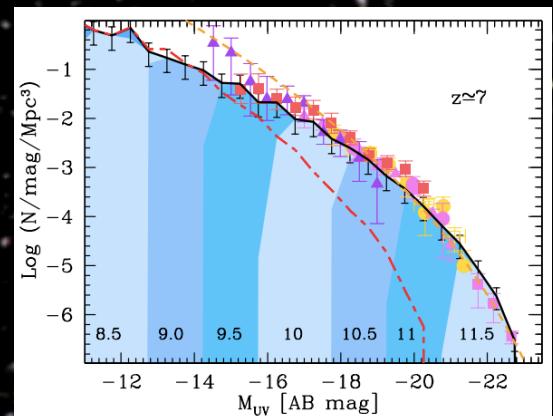
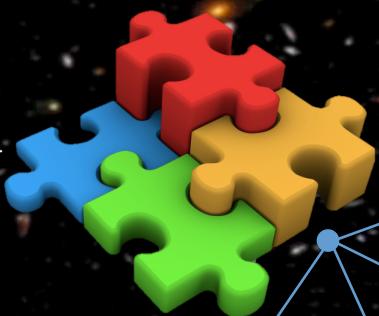
Andrea Ferrara

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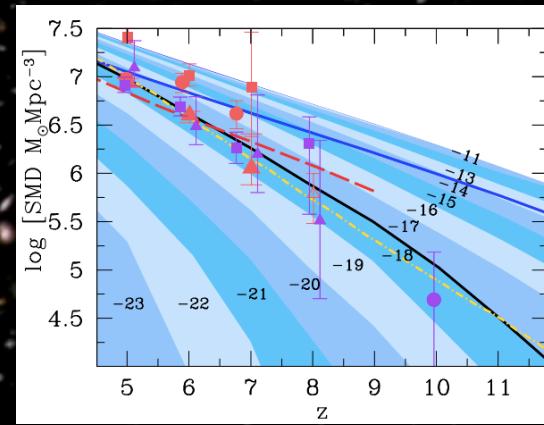


EoR GALAXIES: PROPERTIES

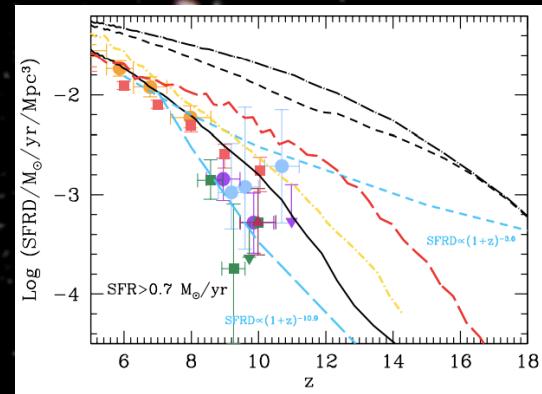
UV Luminosity Functions



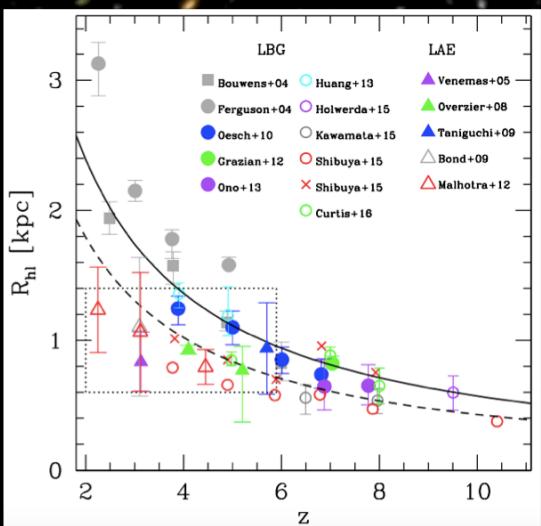
Stellar Mass Density Evolution



Star Formation Rate Evolution



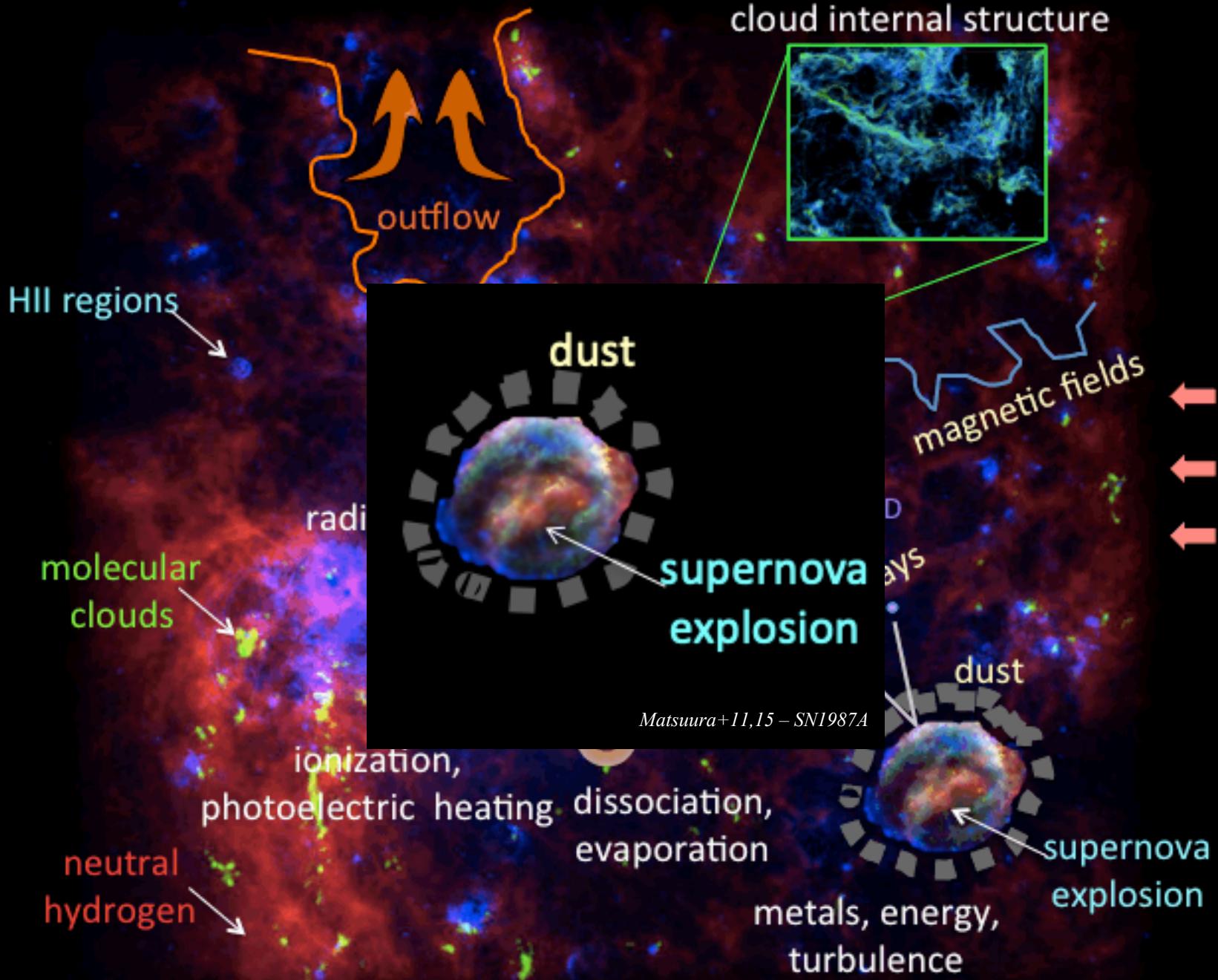
Size Evolution



For a review see:
Dayal & Ferrara 2018, Physics Reports, 780, 1

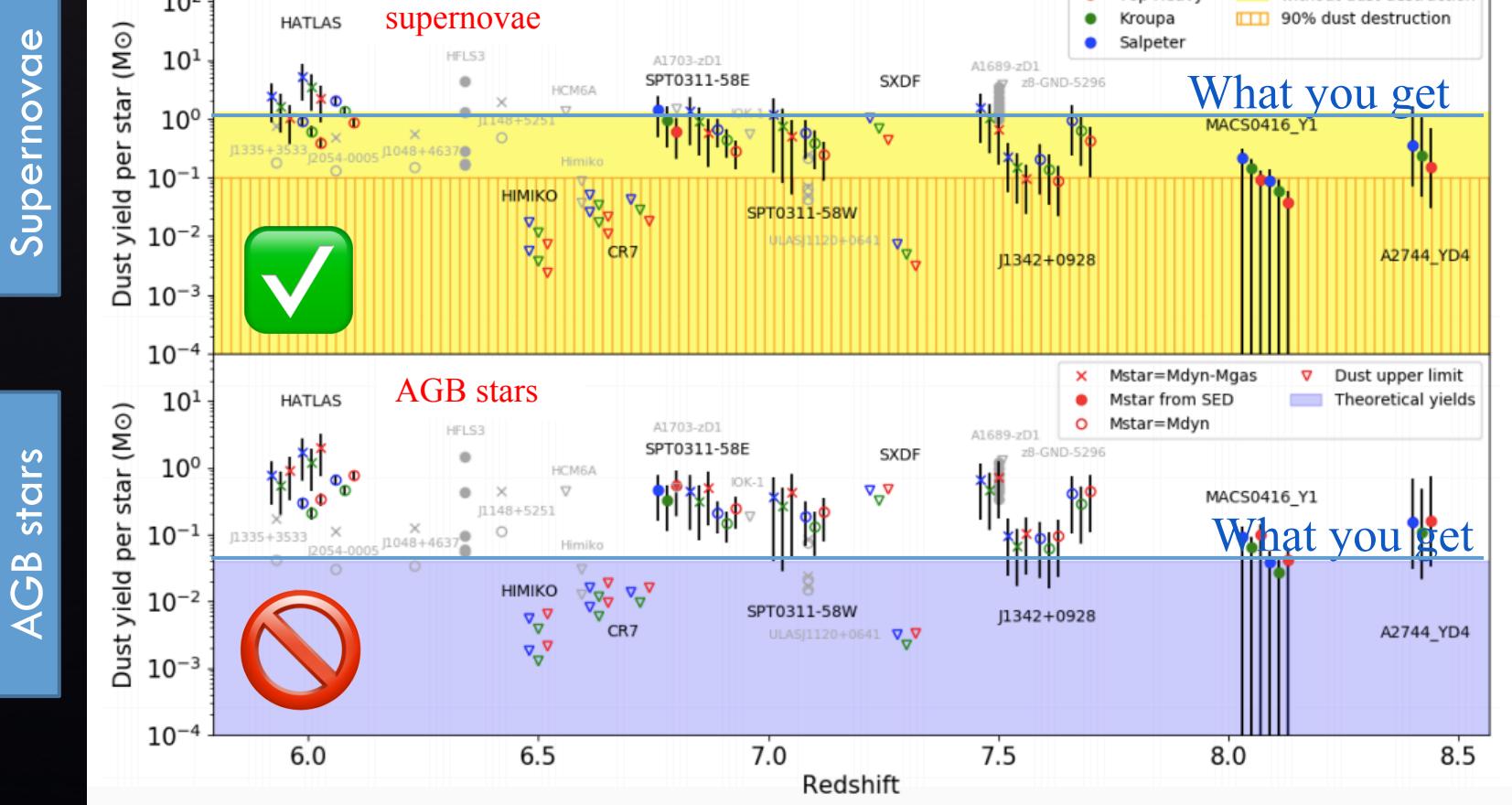
WHAT ABOUT THE INTERSTELLAR MEDIUM?

Cosmic Microwave Background



EARLY DUST COMES FROM SUPERNOVAE

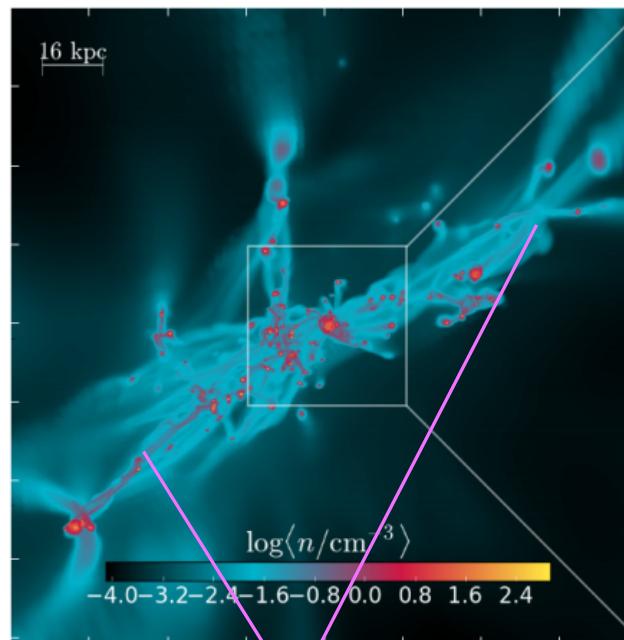
Dust yield per SN or AGB required to explain dust masses in $6 < z < 8.3$ galaxies



LBGs @ $z=6$

AMR zoom simulations

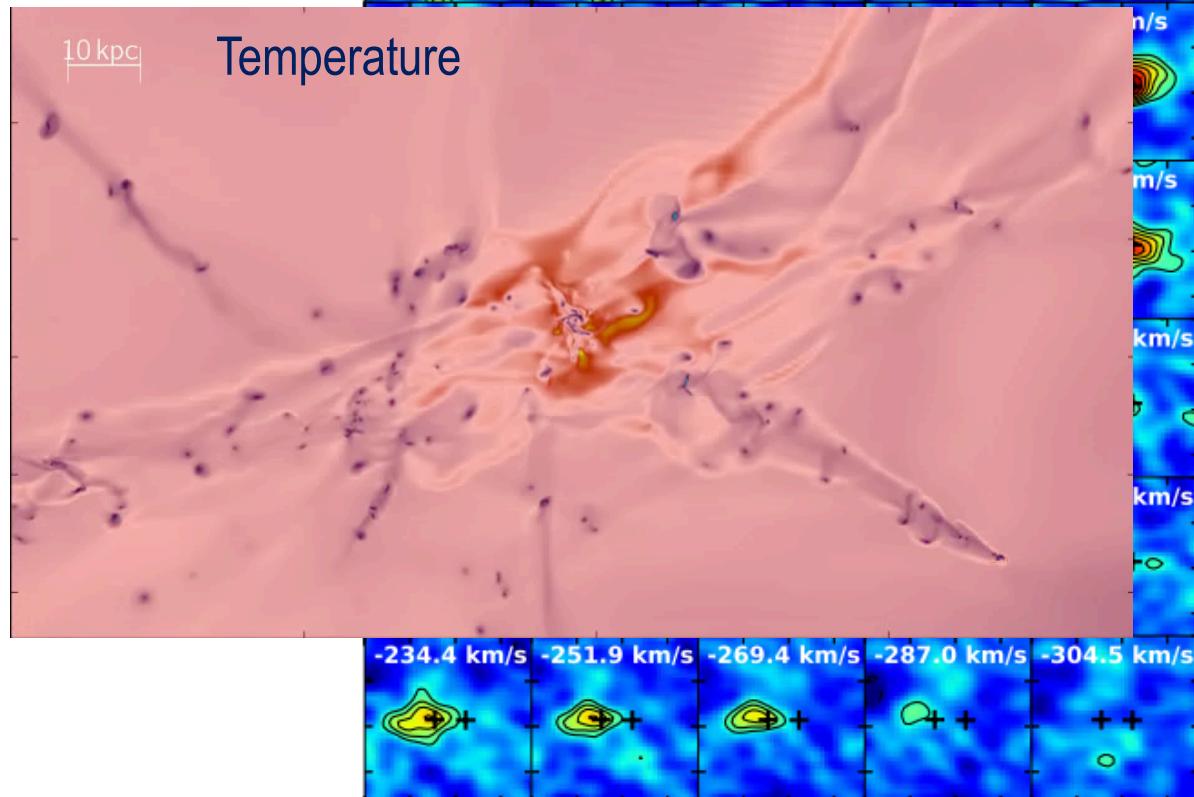
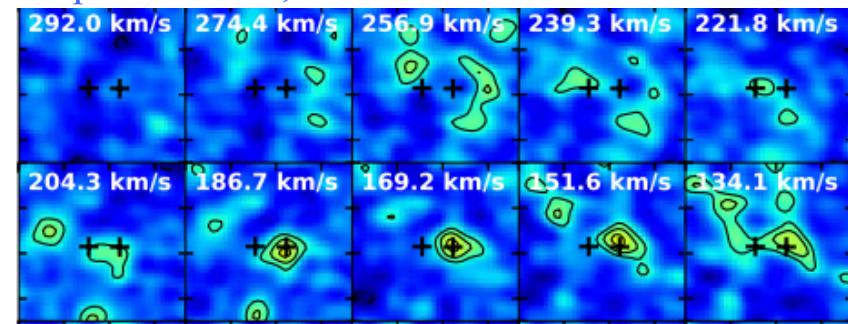
Spatial res = 8 pc
 H_2 -based SFR prescription
 Non-equilibrium chemistry
 Updated SN feedback model
 Radiation pressure on dust
 On-the-fly RT in 11 bands



A survey of high- z galaxies: SERRA simulations

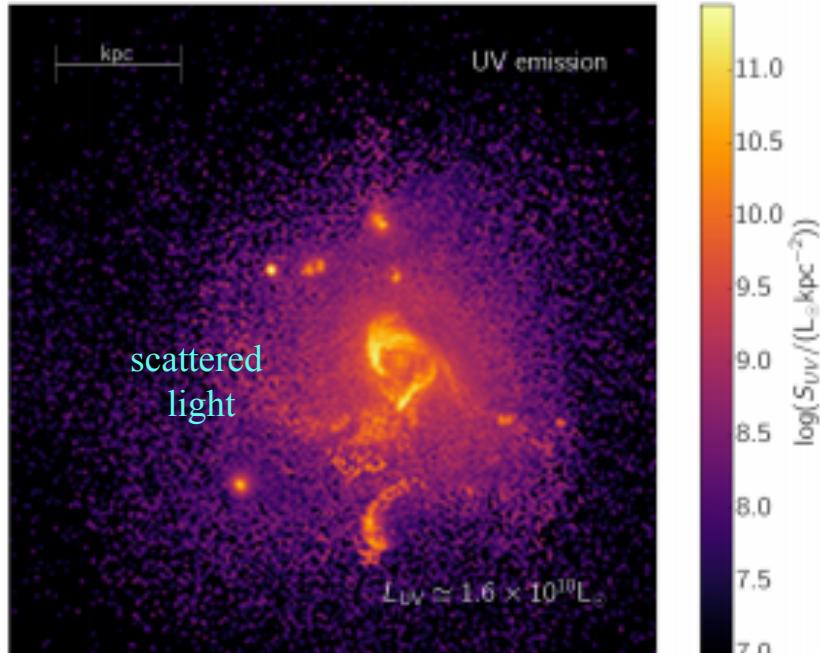
A. Pallottini ^{1,*}, A. Ferrara ¹, S. Gallerani, ¹ C. Behrens, ² M. Kohandel ¹, S. Carniani ¹, L. Vallini ¹, S. Salvadori ^{3,4}, V. Gelli ^{3,4}, L. Sommovigo, ¹ V. D'Ororico ^{1,5,6}, F. Di Mascia ¹ and E. Pizzati ¹

[CII] channel map of WMH5, $z = 6.1$ *Jones+17*

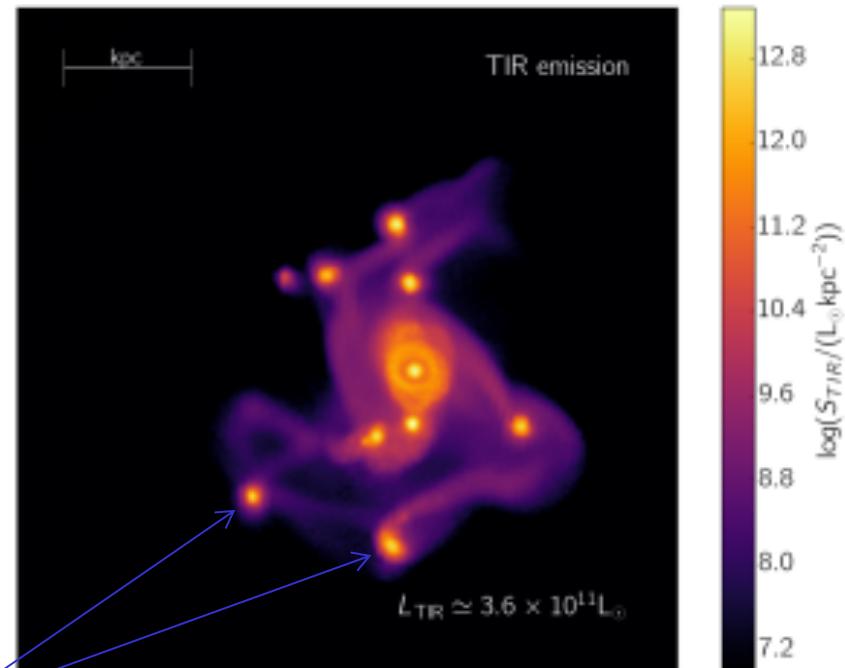


RADIATIVE TRANSFER SIMULATIONS

Simulated UV Map
1000-3000 Å

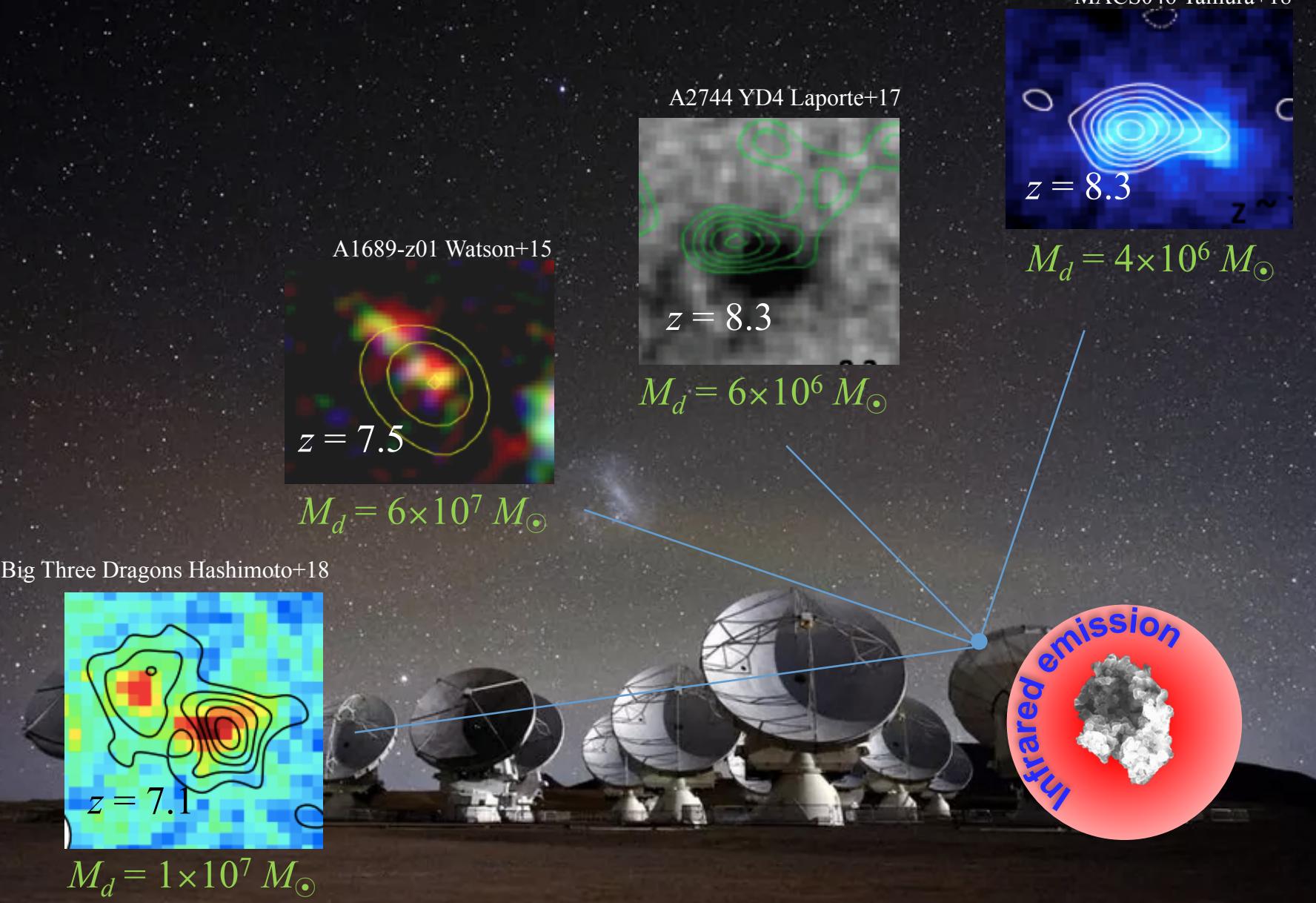


Simulated IR Map
8-1000 μm



IR bright, UV optically thick ($\tau_V > 8$)
star-forming molecular complexes

DUST IN THE EoR REVEALED BY ALMA





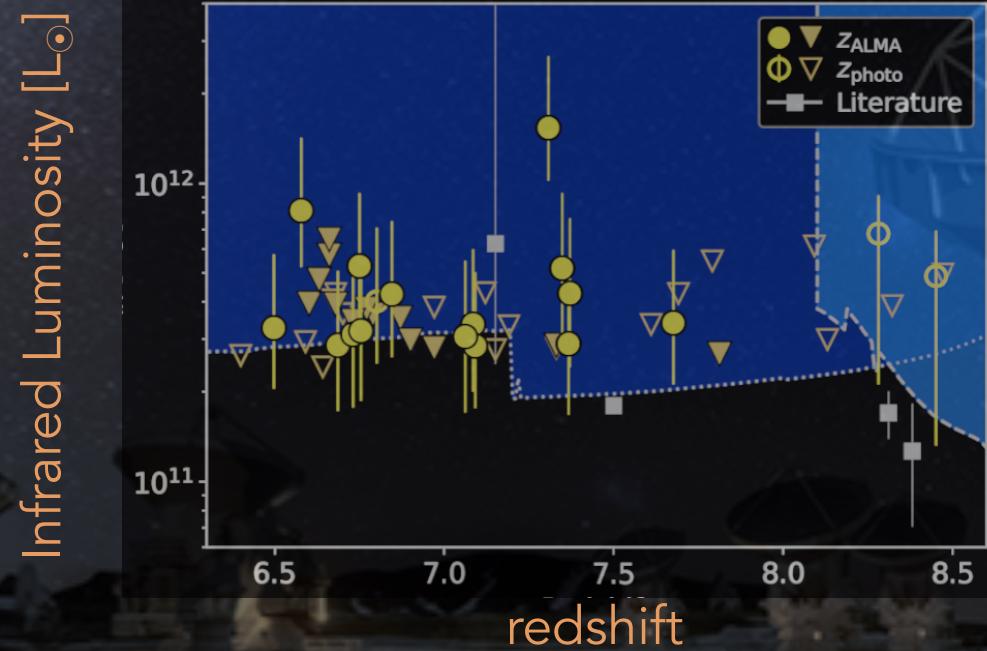
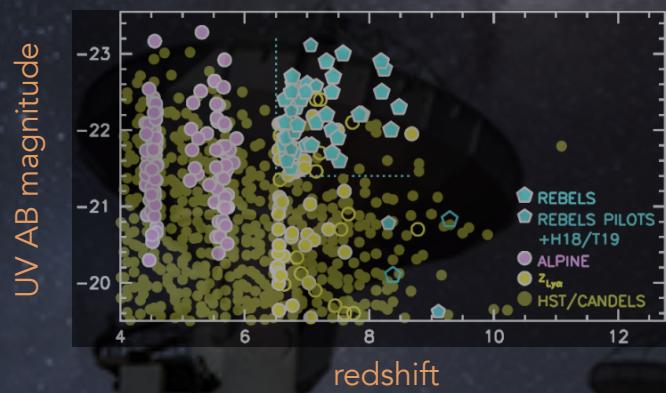
REBELS ALMA LARGE PROGRAM

Bouwens & REBELS Collaboration, 2022

R. J. Bouwens (PI), R. Smit , S. Schouws , M. Stefanon, R. Bowler, R. Endsley, V. Gonzalez, H. Inami, D. Stark, P. Oesch, J. Hodge, M. Aravena, E. da Cunha, P. Dayal, I. de Looze, A. Ferrara, Y. Fudamoto, L. Graziani, C. Li, T. Nanayakkara, A. Pallottini, R. Schneider, L. Sommovigo, M. Topping, P. van der Werf, H. Algera, L. Barrufet, A. Hygate, I. Labbé, D. Riechers , J. Witstok

70 hours of observations

Targeting 40 very bright $z=6.5\text{-}9.5$ galaxies
from a 7 deg^2 search for [CII], [OIII] lines and dust continuum.



REBELS_GALAXIES.ZIP

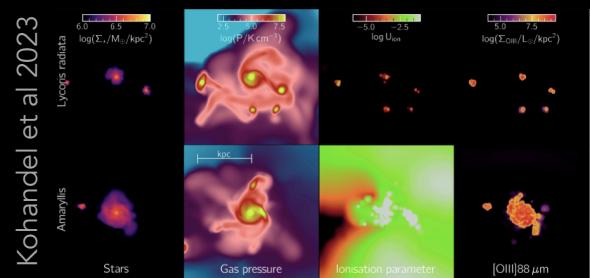


- Star formation significantly **obscured** (28-90.5%)
- Total (UV+IR) star formation rates $31.5 < \text{SFR}/(\text{M}_\odot \text{ yr}^{-1}) < 129.5$
- Average **dust mass** $(1.3 \pm 1.1) \times 10^7 \text{ M}_\odot$
- Average **dust temperature** $52 \pm 11 \text{ K}$
- The **dust distribution** is compact (<0.3 kpc for 70% of the galaxies)
- The **dust yield/SN** is $0.1 \leq y_d/\text{M}_\odot \leq 3.3$ (70% with $y_d < 0.25 \text{ M}_\odot$)

JWST DISCOVERY

- Unexpectedly large number of luminous galaxies at $z \gtrsim 10$
- These galaxies tend to be massive ($M_* \gtrsim 10^9 M_\odot$)
- They also tend to have blue colors
- Four of them undetected in [OIII] by ALMA

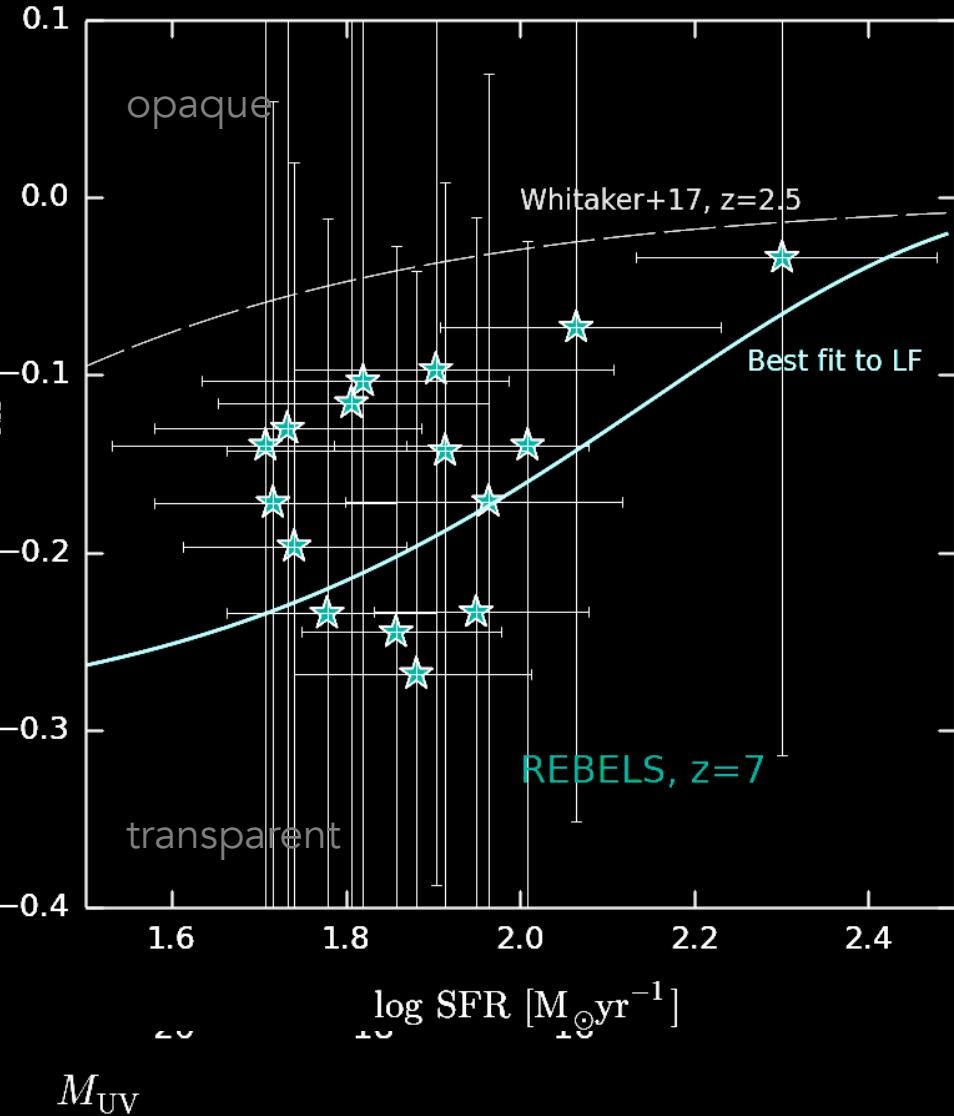
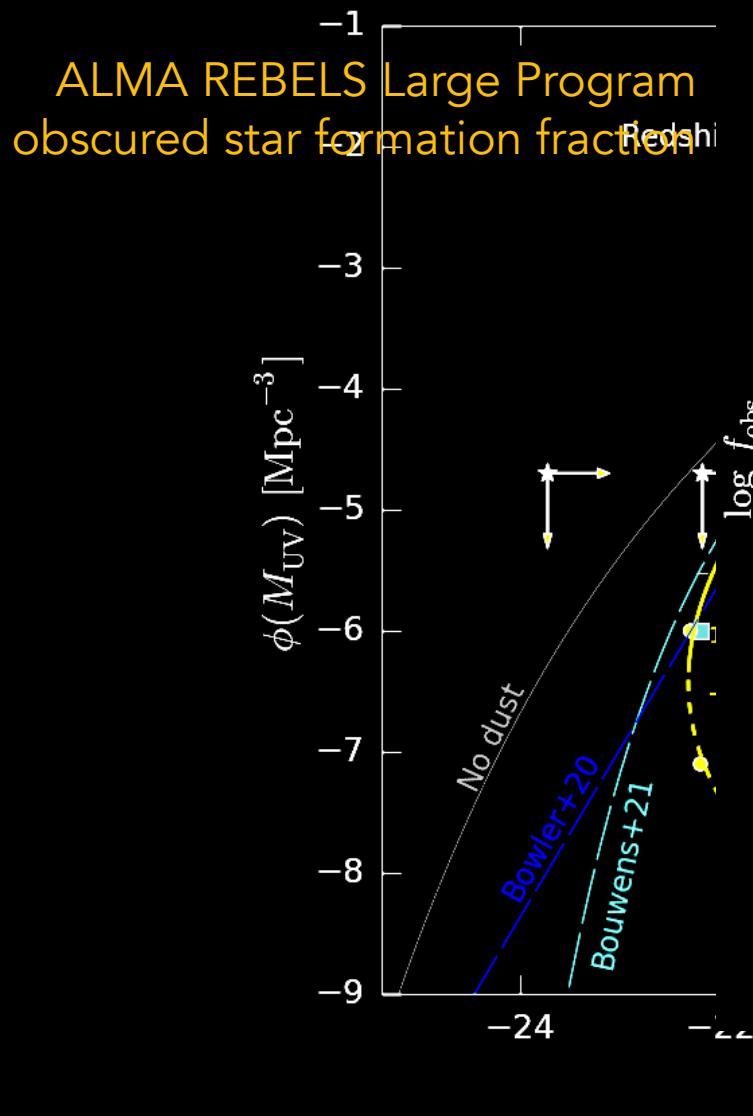
Bakx et al. 2022; Popping 2022; Yoon et al. 2022; Kaasinen et al. 2022; Fujimoto et al. 2022
For an interpretation: Kohandel et al 2023



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

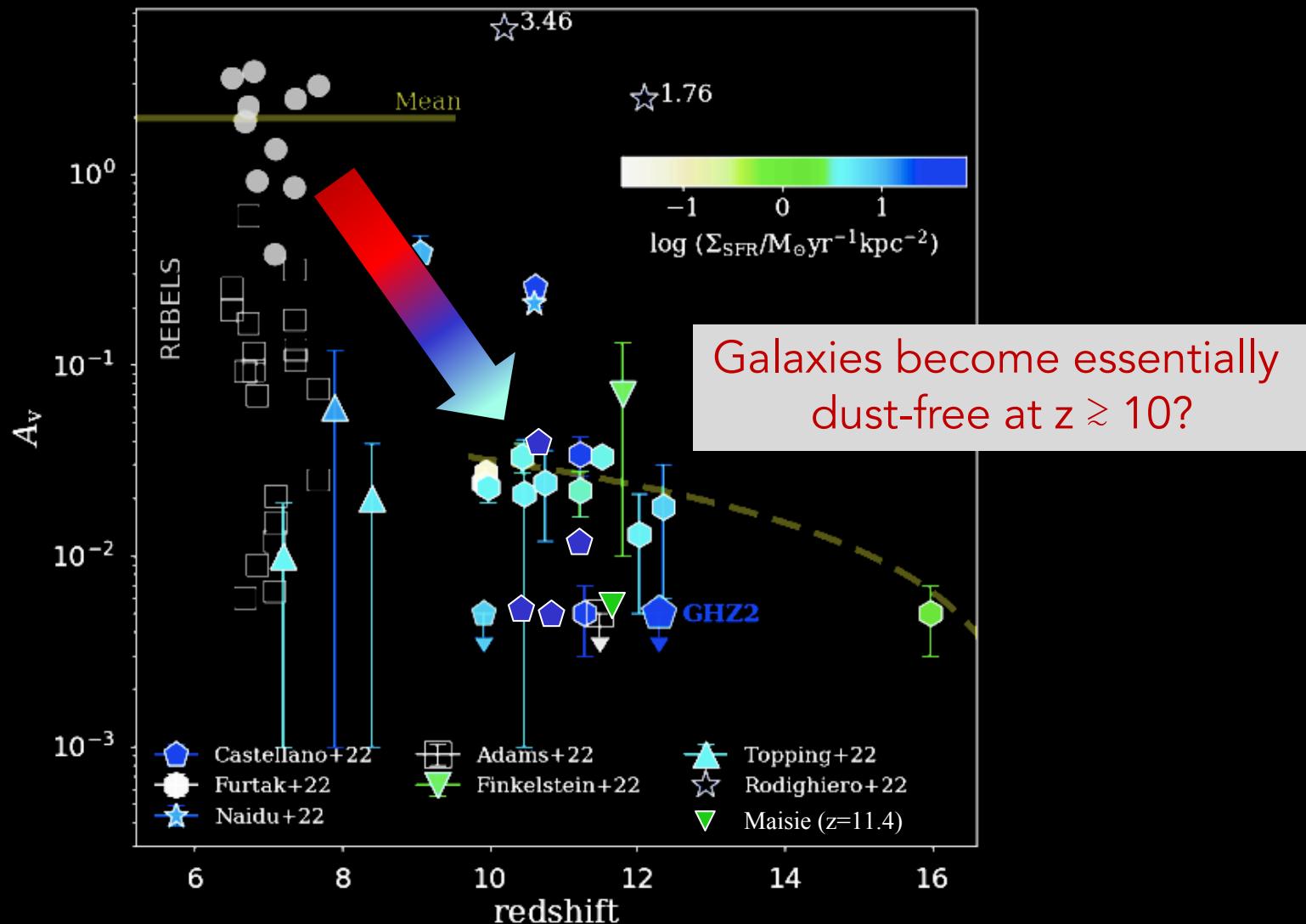
ANCHORING THE UV LF @Z=7

Ferrara+22b
arXiv:2208.00720



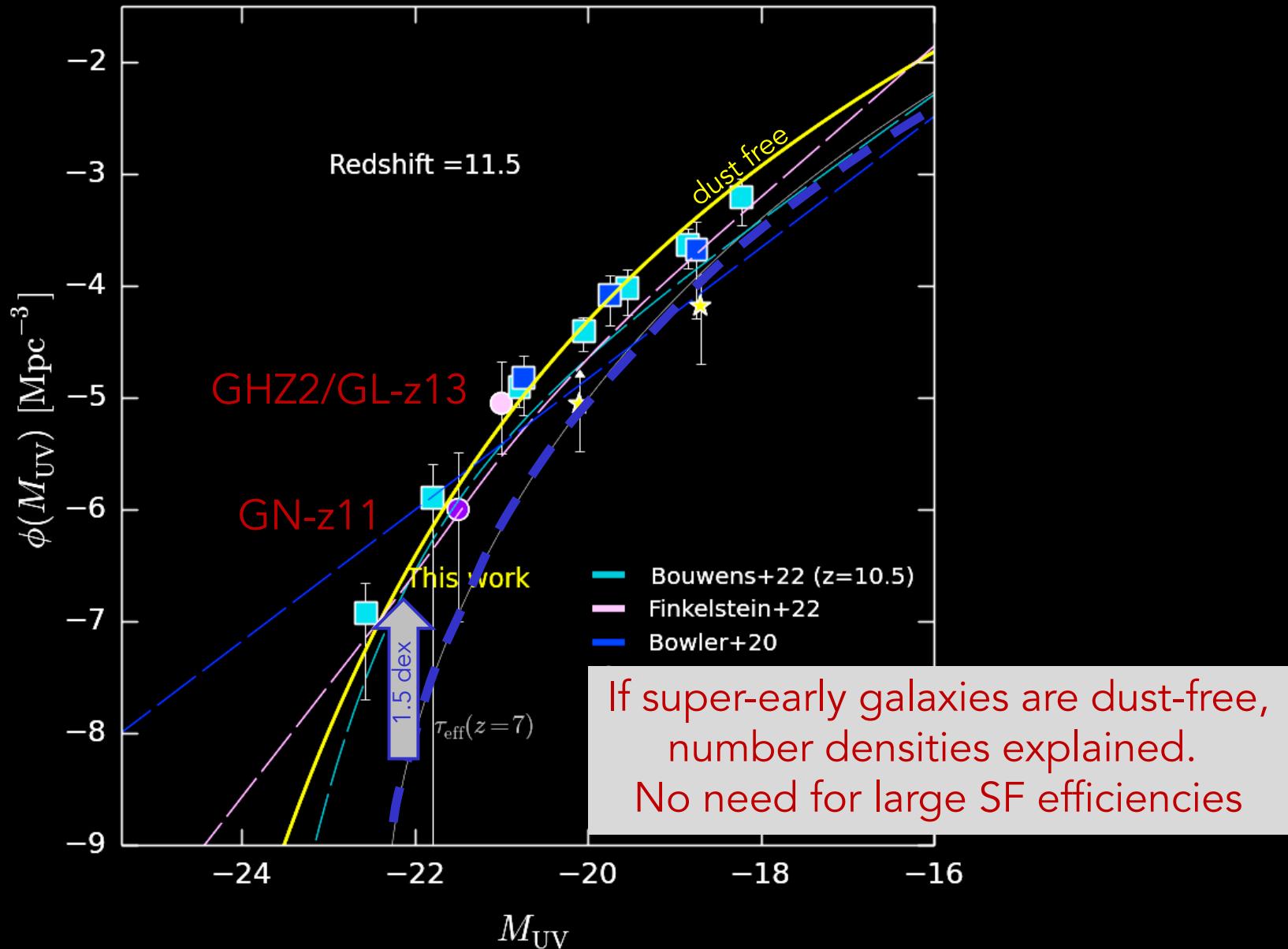
JWST 'BLUE MONSTERS'

Ziparo, AF+22



SUPER-EARLY GALAXY ABUNDANCES

Ferrara+22b
arXiv:2208.00720



WHY AREN'T THEY OBSCURED?

Ziparo, AF+22

GHZ2/GL-z13 key properties

Castellano+22

Stellar mass $M_* = 10^{9.2} M_\odot$

Dust mass $M_d = 3 \times 10^6 M_\odot$

UV sizes $r_e < 500 \text{ pc}$

expected

$$\tau_{1500} > 25 \left(\frac{M_d}{3 \times 10^6 M_\odot} \right) \left(\frac{500 \text{ pc}}{r_e} \right)^2$$

observed

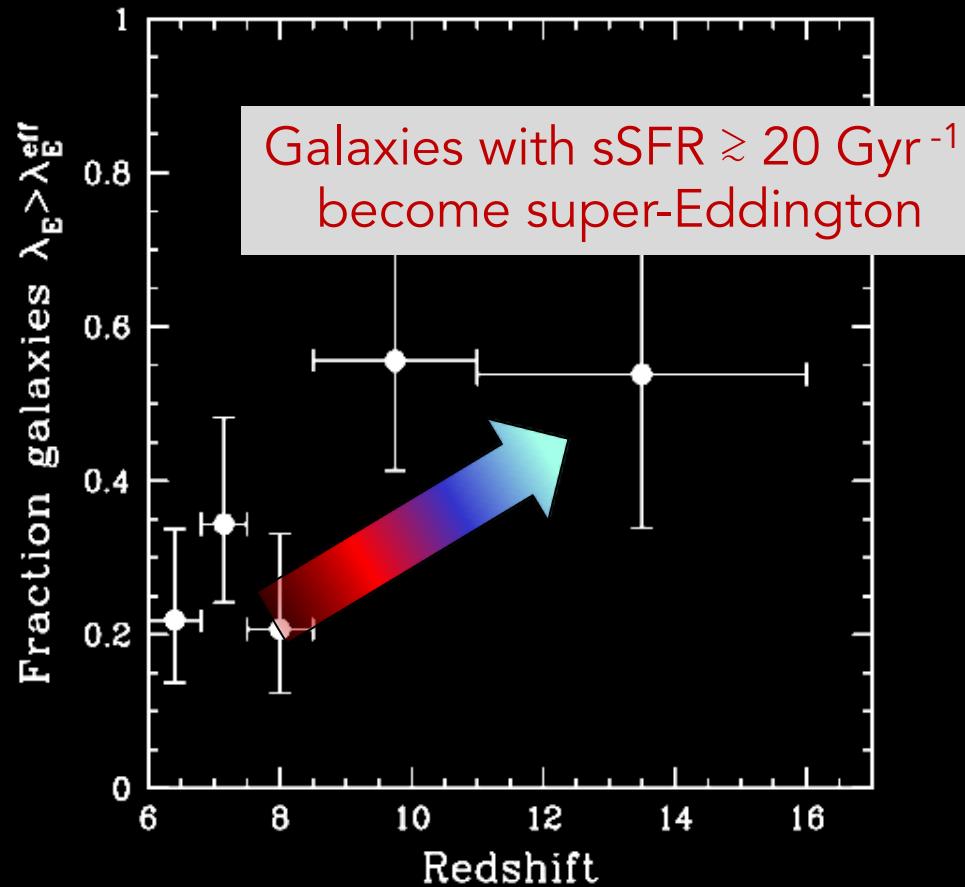
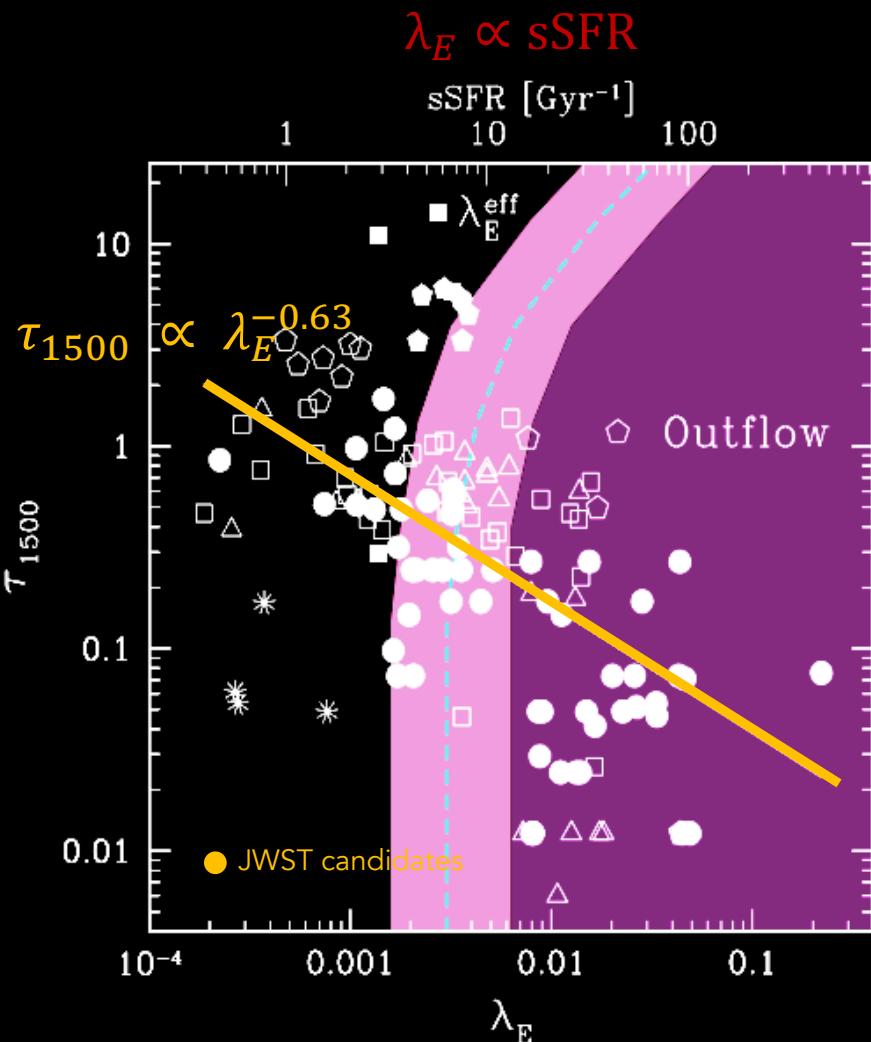
$$\tau_{1500} \lesssim 0.01$$

2500x less opaque!

Dust ejected by radiatively-driven outflows?

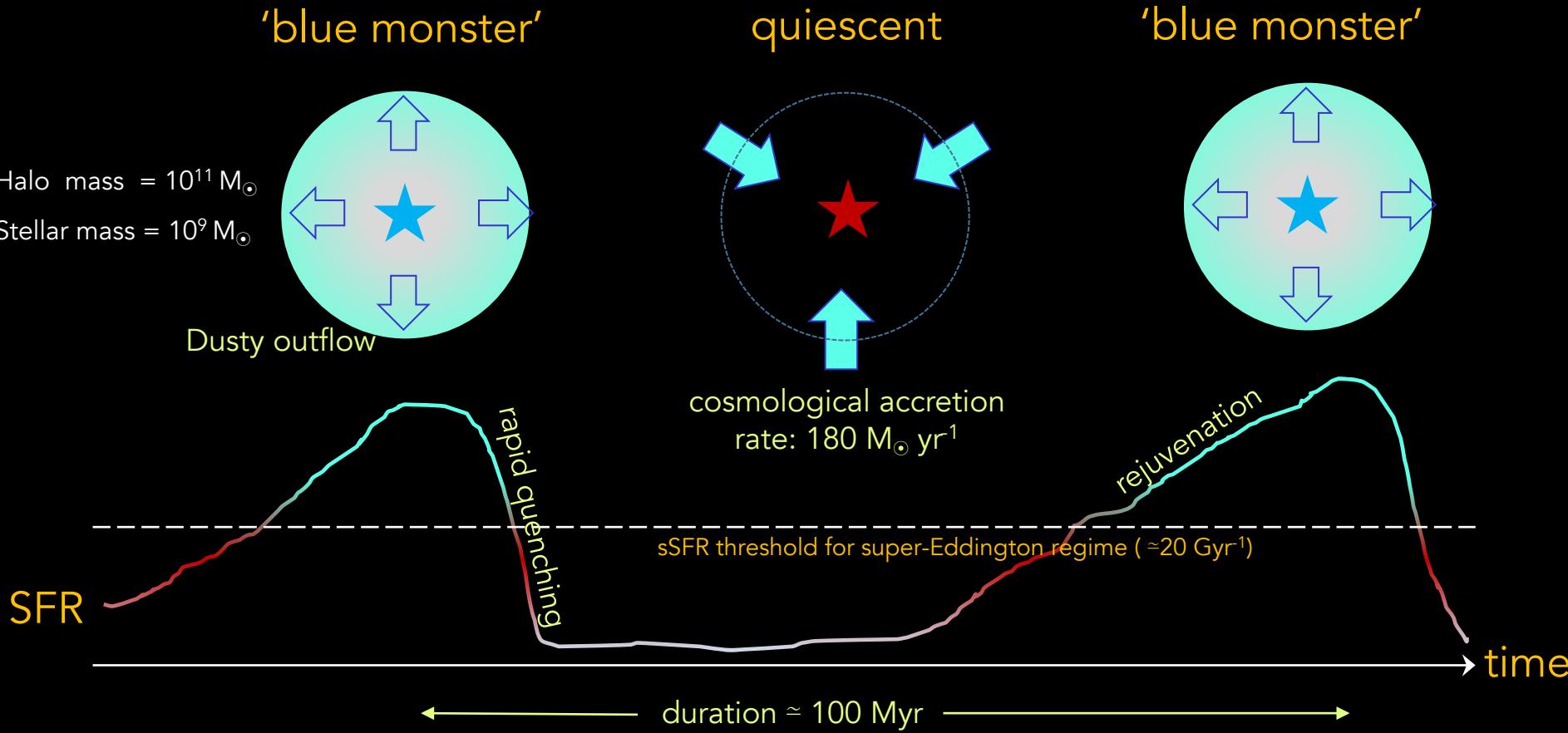
AN EMPIRICAL TEST

Fiore, AF+22



OUTFLOW SCENARIO

$z \gtrsim 10$



Summary

- Radiation-driven dust outflows are almost unavoidable at high redshift.
- They clear dust from early, massive galaxies making them blue and abundant.
- They (temporarily, abruptly) quench star formation making the galaxy quiescent.