Blue monsters. Why are JWST super-early, massive galaxies so blue?

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Quick Background

- Galaxies are gravitationally bound supermassive structures composed of stars, planets, gas, dust, dark matter and black holes.
- Can be classified as spiral, barred spiral, elliptical, irregulars based on the observed morphologies/structures.
- Depending on its star formation rate, it can be classified as star forming or quiescent.
- Depending on its star populations, it can be classified as a “blue” or “red” galaxy.
- Dust are free floating solid molecules. Typically formed of silicates.

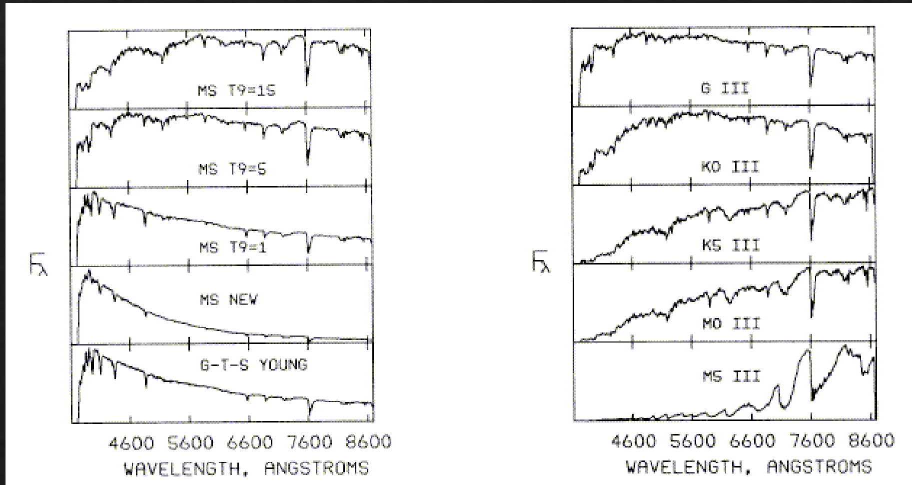
UV Spectral Slope β

- To determine age, metallicity and dust content of galaxies, the UV spectral slope β is used.
- This is found by applying a least square power fit to the spectrum (UV to NIR) of a galaxy.

$$F \propto \lambda^{\beta} \quad \text{or} \quad \log(F) \propto \beta \log(\lambda)$$

- Young stars mostly emit in the ultraviolet and blue optical part of the spectrum, resulting in a negative beta or a "blue" galaxy. (Example: 3 bottom left plots)
- Old stars mostly emit in the red optical and near-infrared part of the spectrum, resulting in a positive beta or a "red galaxy". (Example: 3 bottom right plots)
- Age usually correlates with dust content and metallicity.
- However, dust can absorb UV radiation and remit it in the infrared. Making a galaxy appear "red".

Theoretical Star Spectrums
Keel et al 1983



Findings and Issues

Found with JWST:

- Several authors report ~20 potential sources at $z > 11$ with brightness of $M_{UV} \leq -23$ and $-2 \leq \beta \leq -2.6$.
- Furtak et al. 2022 reports sources with evolved metallicities ($Z = 0.1\ Z_{\odot}$) and **low dust** attenuation (absorption coefficient) ($A < 0.02$).
- Naidu et al. (2022a); Donnan et al. (2022) Found minimal evolution of the bright-end of the UV Luminosity function.
- High Stellar Mass $\left(10^{8-9}\ M_{\odot}\right)$.

Expected:

- High redshift galaxies should be "red", **dusty** and have low or primal metallicities.
- Bouwens et al. (2016) extrapolated luminosities functions and predicted sharp drop on number density of sources $M_{UV} \leq -21$.

The expected dust is missing from these sources!!!

Proposed Solutions

To explain the lack of dust other authors have proposed:

- Higher star formation efficiency (with respect to lower redshift systems). Implying JWST probing relatively small and abundant halos. Mason and Inayoshi et al. (2022).
- Galaxies at $z > 10$ are simply unattenuated by dust (drastic drop in dust optical depth results in brighter galaxies, compensating lower abundance). Ferrara et al. (2022a)

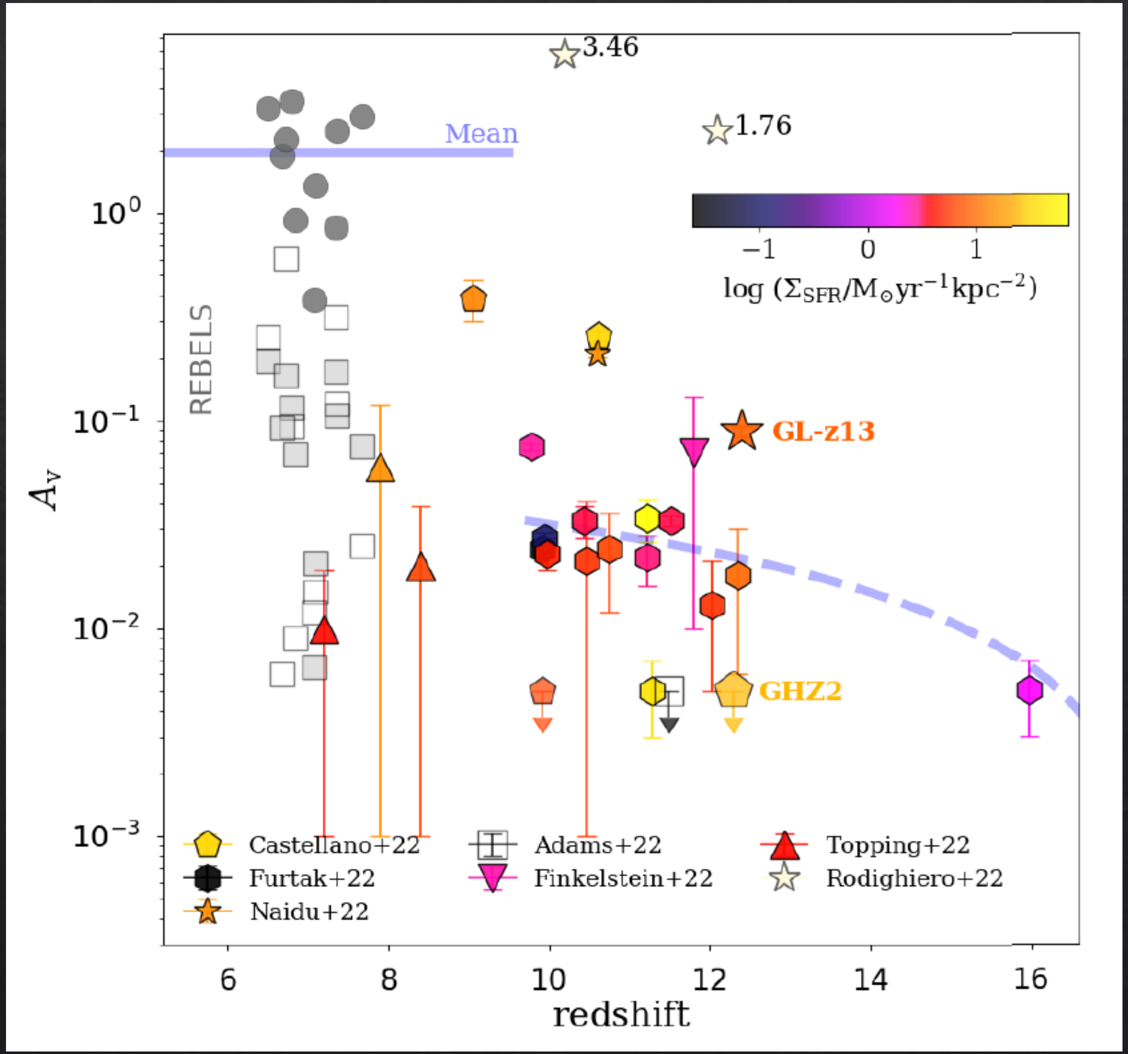
Evidence contradicts solutions:

- High stellar mass/moderate metallicity implies high dust content.
- Low dust optical depth implies low dust content/attenuation.

Preliminary Considerations

Through assumptions and "simple calculations", the authors found that the proposed sources have:

- Trend of decreasing dust attenuation and increasing redshift. (Presented in plot)
- $\sim 3 * 10^6\ M_\odot$ of dust on the sources.
- Dust to stellar mass ratio of 0.00189 (2 times larger than in our galaxy).
- Dust to gas ratio 0.001 (6 times lower than in our galaxy).
- Optical depth at 0.15 μm of $\tau_{1500} = 25$. Heavily obscured sources!



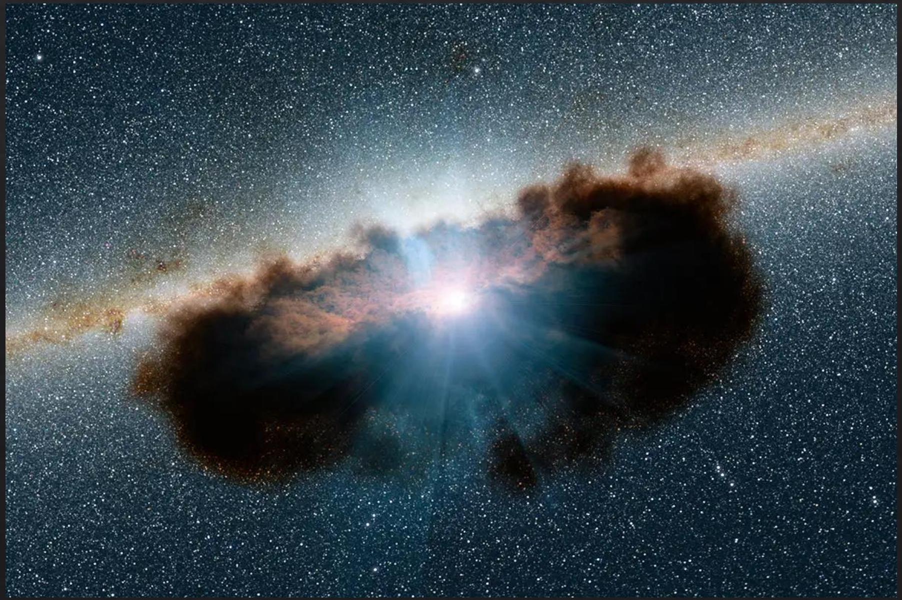
Dust attenuation as a function of redshift for JWST-detected galaxies
Ziparo et al. 2022

Proposed Scenarios

The authors of this paper proposed alternative explanations:

- Dust ejection from radiation pressure from UV emitting stars.
- Dust spatial segregation with respect to UV emitting regions.

Courtesy of: Caltech



Courtesy of: NASA/JPL-Caltech

Dust Ejection Scenario

- The dust produced by the supernovae on very short time scales is ejected into the intergalactic medium at a rate exceeding its production rate. Evacuation can take place, via the strong radiation pressure exerted by the observed UV-emitting stars.
- The authors derived an expression for the dust ejection rate:

$$\dot{\Sigma}_w = \frac{1}{2} v_\infty \frac{\Sigma_g}{H} D$$

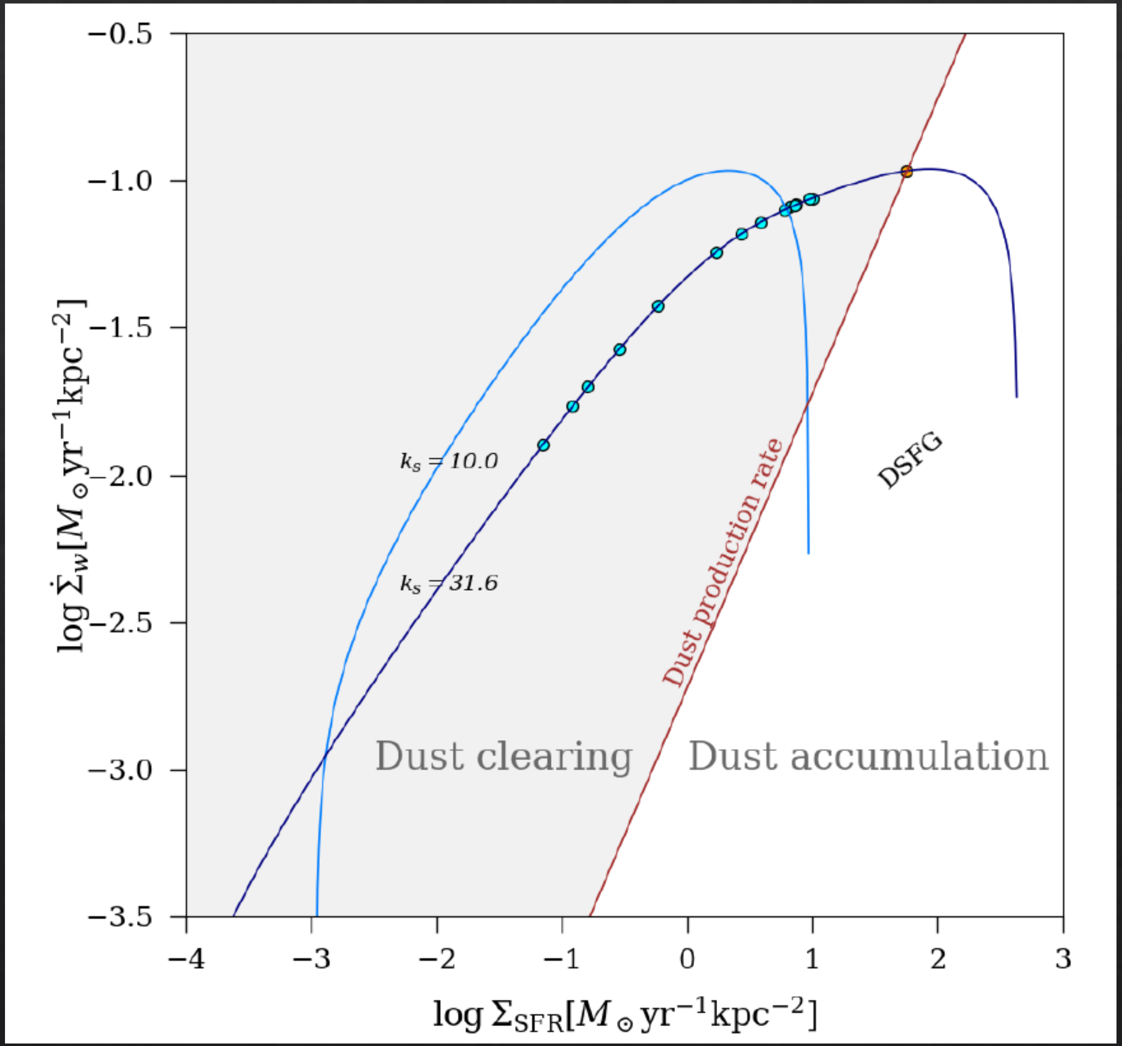
where H is scale height, v_∞ is the gas velocity at H, D is the dust-to-gas ratio, and Σ_g is the gas surface density. H depends on Σ_{SFR} is the disk star formation rate per unit area.

- They also derived an expression for the dust production rate:

$$\dot{\Sigma}_\pi = y_d v_{SN} \Sigma_{SFR}$$

where y_d is the amount dust produced per supernovae, v_{SN} is the number of supernovae produced per stellar mass, and Σ_{SFR} is the disk star formation rate per unit area. Σ_{SFR} itself depends on the star formation burstiness parameters κ_s.

- Therefore, to drive outflow the dust ejection rate must overcome dust production rate. $\dot{\Sigma}_w > \dot{\Sigma}_\pi$
- The graph shows the outflow rate model as a function of SFR per unit area for $\kappa_s = 10$ (blue curve) and 31.6 (purple curve).
- The dust production rate (red curve) separates the two regimes of dust clearing and dust accumulation.
- In the clearing region (grey area) dust is efficiently evacuated. Outside that region, dust ejection becomes inefficient, and dust accumulates.
- Assuming $\kappa_s = 31.6$ for sources reported by Furtak et al. (2022) (cyan points), the model predicts these should be almost dust free. An obscured galaxy (red point) by Rodighiero et al. (2022) lies just in the border of the dust accumulation zone.



Dust outflow rate as a function of start formation
Ziparo et al. 2022

Dust Spatial Segregation Scenario

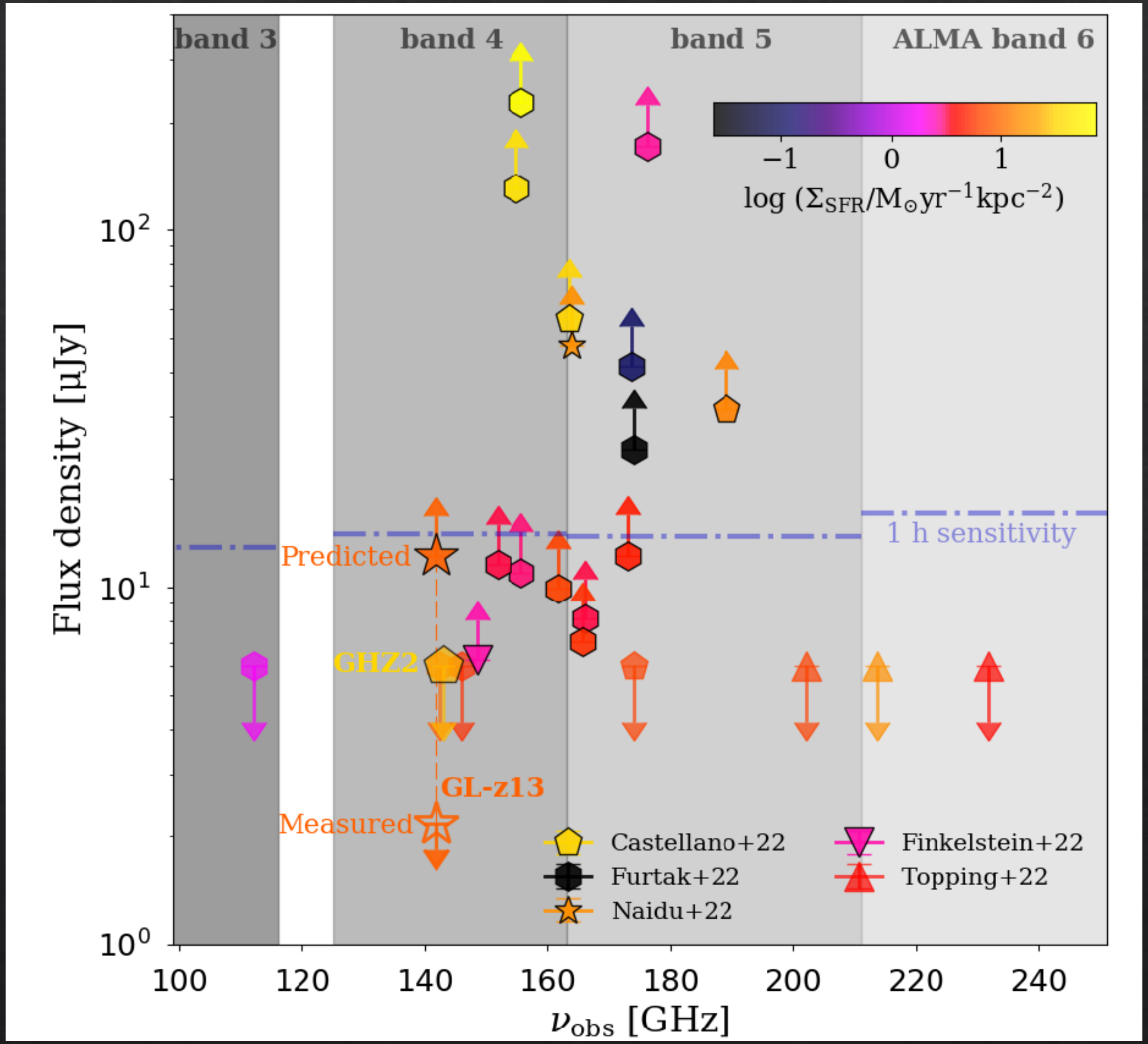
- The stellar (optical-to-UV) and dust (IR) emitting regions are physically located on different parts of the galaxy.
- UV comes from transparent diffuse interstellar medium (ISM), hosting either little or cold dust. The dust-obscured SFR is instead located in giant molecular clouds (GMCs), strongly emitting at IR wavelengths.
- The authors used a model proposed by Ferrara et al. (2022b), that quantifies the morphology of the interstellar medium of galaxies, to predict the expected IR fluxes for these sources.

$$I_m = \frac{(F_{IR}/F_{UV})}{(\beta - \beta_{int})}$$

where I_m is the molecular index, β is the expected obscured spectral slope, and β_{int} is the intrinsic (unattenuated) spectral slope.

- Predict $F_{IR} > 6\ \mu Jy$ for sources $\beta > -2.616$. Few hours of observation ALMA can test the prediction.

- The authors verified the predicted value for GHZ2/GL-z13 galaxy via extrapolation.
- By rescaling the upper flux limit for the 88 μm continuum reported by Bakx and Popping et al.(2022) up to 158 μm, they found an upper limit of $F_{IR} > 2\ \mu Jy$ at 50 K.
- This rescaled value is 6 times lower than the predicted value for that specific source ($F_{IR} > 12\ \mu Jy$).
- The plot shows the predicted IR continuum flux at the 158 μm rest-frame as a function of frequencies for observation for all considered sources.
- The plot also shows the ALMA bands (shaded in tones of grey) in which F_{IR} would be measured are shown, alongside the sensitivity reached with 1 hour of observation.



Predicted Flux as a function of Frequencies
Ziparo et al. 2022

Summary and Discussion

- Although both the dust ejection and segregation scenarios provide a physical explanation for the blue colors of the observed galaxies, they make distinct prediction concerning the IR dust continuum flux.
- If dust is ejected, its density and temperature drop, making it impossible to detect. On the other hand, the segregation scenario should result in 158 μm rest frame $F_{IR} > 6\ \mu Jy$.
- The "non-detection" from the extrapolation favors the ejection scenario.
- Under dust ejection, the outflow might also carry a significant fraction of the gas causing galaxies to retain a limited fraction of gas.
- Important to note: these galaxies were detected by using the standard Lyman-break. This can be misinterpreted as dusty star-forming lower redshift (z < 7) interlopers.
- The extremely blue values might be spuriously produced by an observational bias, due to faint sources near the detection threshold.