Early dusty galaxies in the Obelisk simulation

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Kapteyn Astronomical Institute → LERMA/Observatoire de Paris (Sept 2024)

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Dusty galaxies at high-z: puzzling results from JWST

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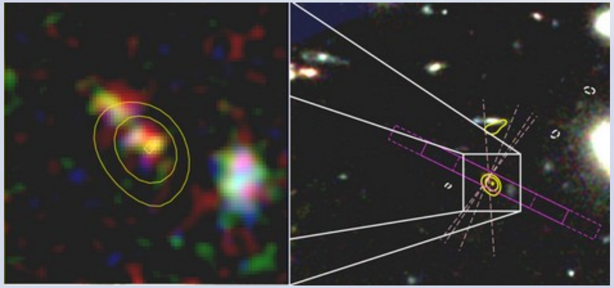

Watson+2015

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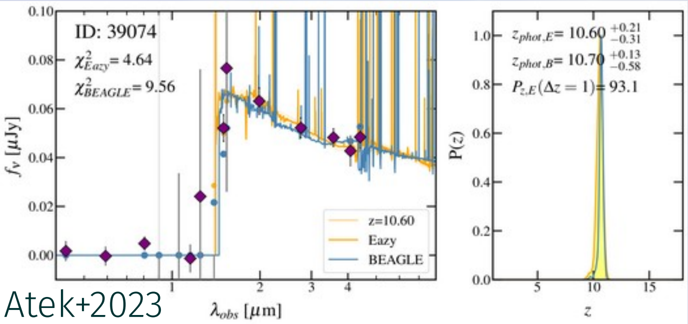

Atek+2023

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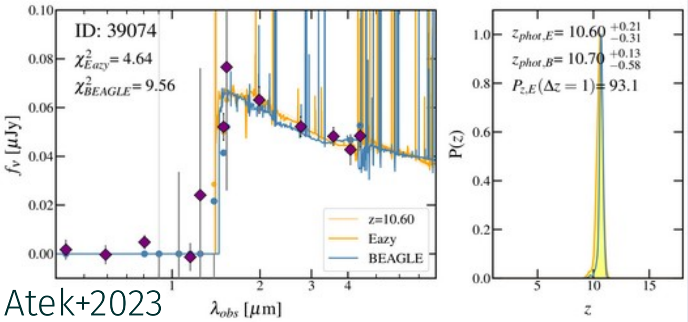

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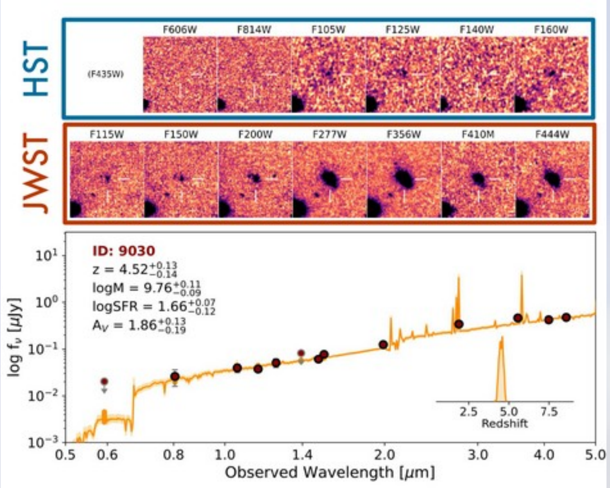

Gottumukkala+2023

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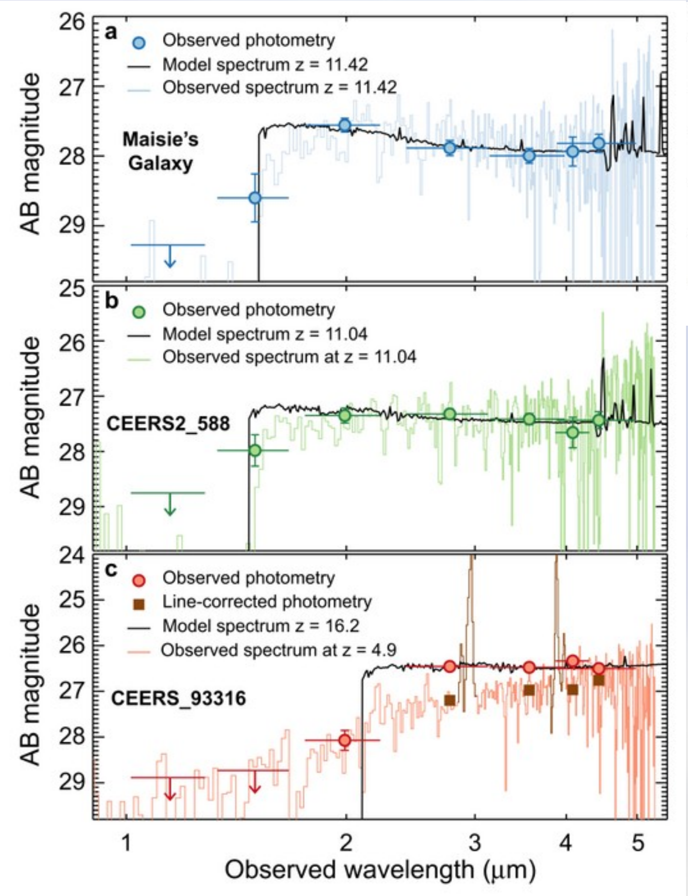

Arrabal-Haro+2023

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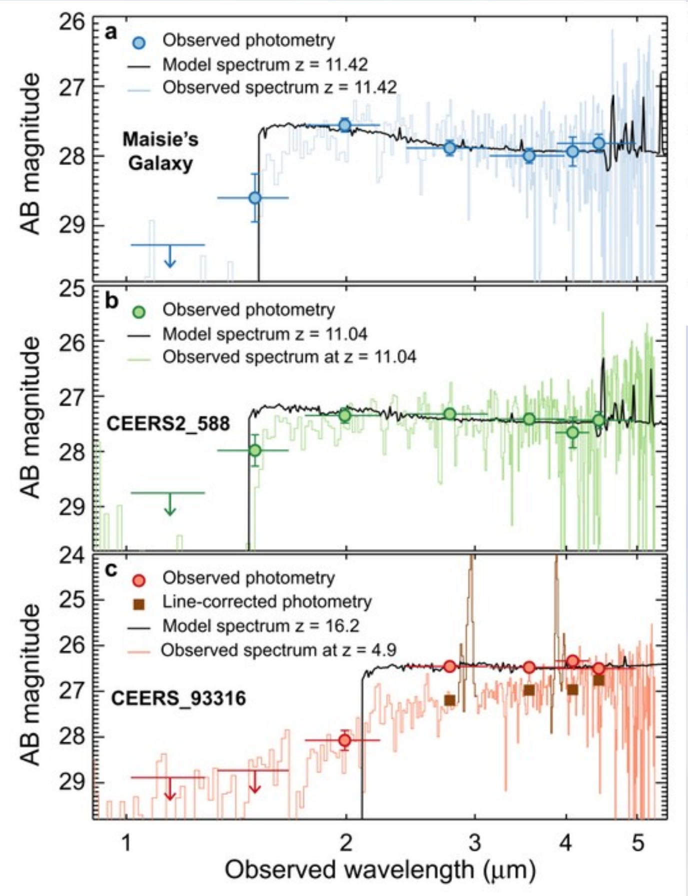
- High-z dusty galaxies can be mistaken for very high-z sources!

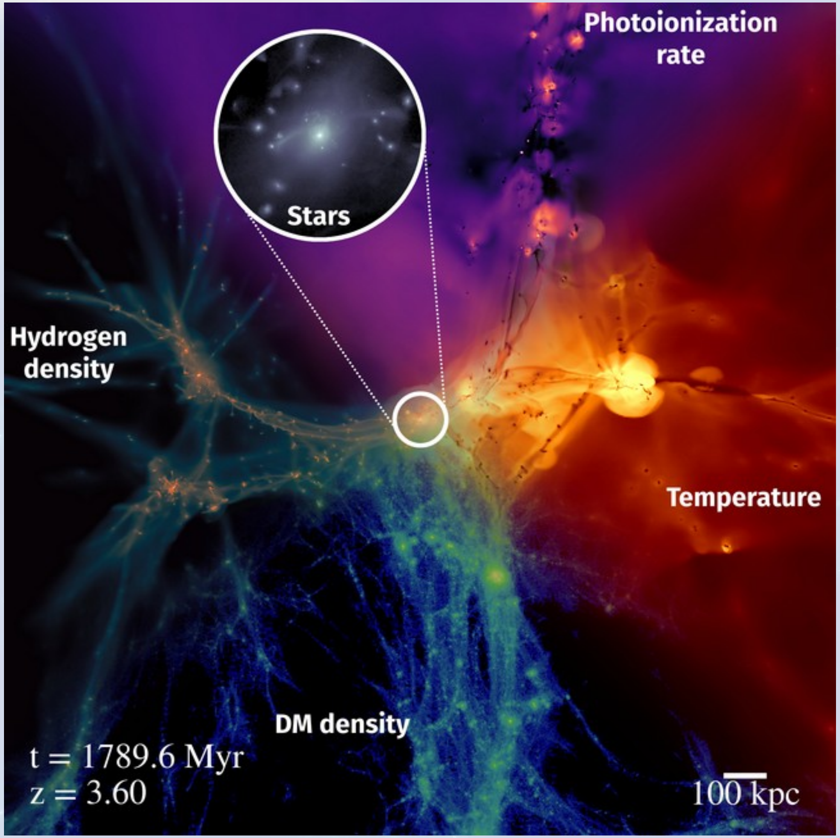
- This makes our life much harder, but much more interesting.
- To understand this, we need:
  - Detailed galaxy simulation with a "good" **ISM and dust model**
  - A way to **properly compare with observed galaxies**



Arrabal-Haro+2023

The Obelisk simulation

Overview of the simulation



- Zoom on a **proto-cluster** region (V ~ 10^4 cMpc^3), down to z~3.5
- **RHD simulation** with Variable Speed of Light Approximation
- **High resolution**
  - Δx = 35 pc
  - $M_{DM} = 10^6 M_\odot$
  - Snapshots every 15 Myr
- **Stellar physics**
  - Turbulent star formation
  - Mechanical SN feedback
  - BPASS model for radiation
- **Black-hole physics**
  - Eddington-limited Bondi accretion
  - Thermal + jet AGN feedback
  - Spin evolution of the BH
  - Radiation following the BH properties
- Traces source of radiation (stars or AGN)
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- **Subgrid model for dust** (purely passive)

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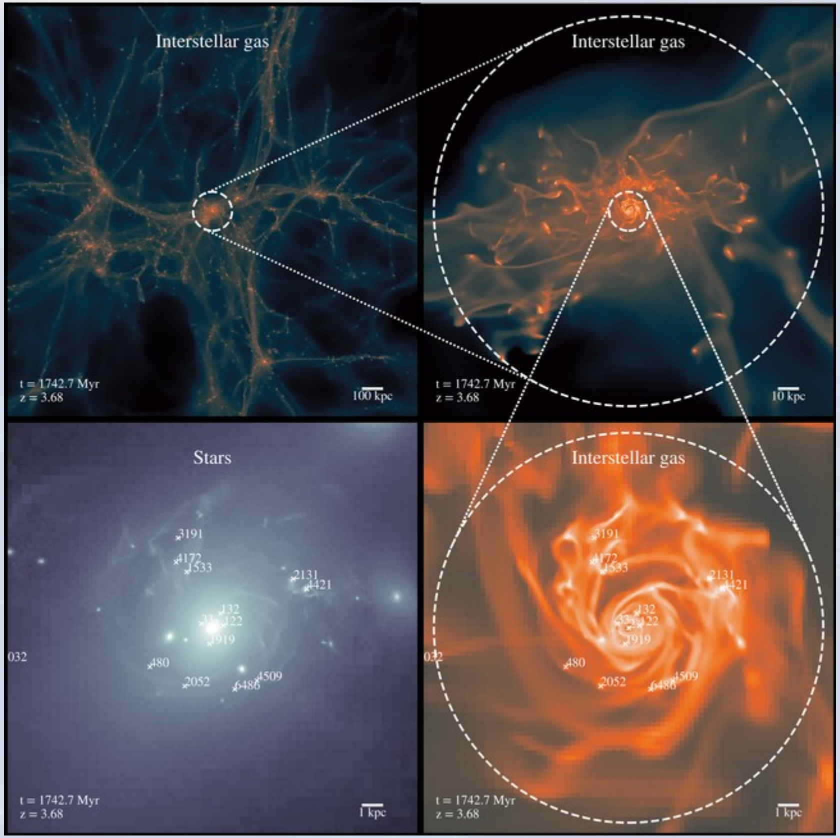

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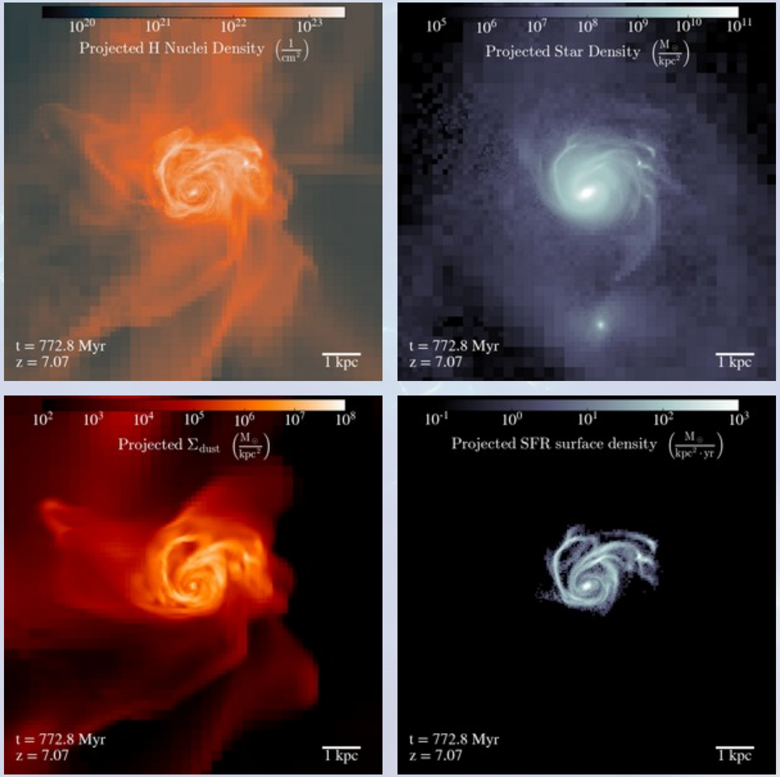
Dust model: physical processes included

- **Dust growth:**
  - Injection by stellar processes (SN release about ~ **0.75 $M_\odot$** of dust per event)
  - Accretion of metals from the gas phase:
    - $dM_{growth}/dt \propto (1\text{-}DTM) \cdot M_d \;/\; t_{growth}$
    - $t_{growth} \propto 1/(\rho \sqrt{T})$ at $T \lesssim 50$ K

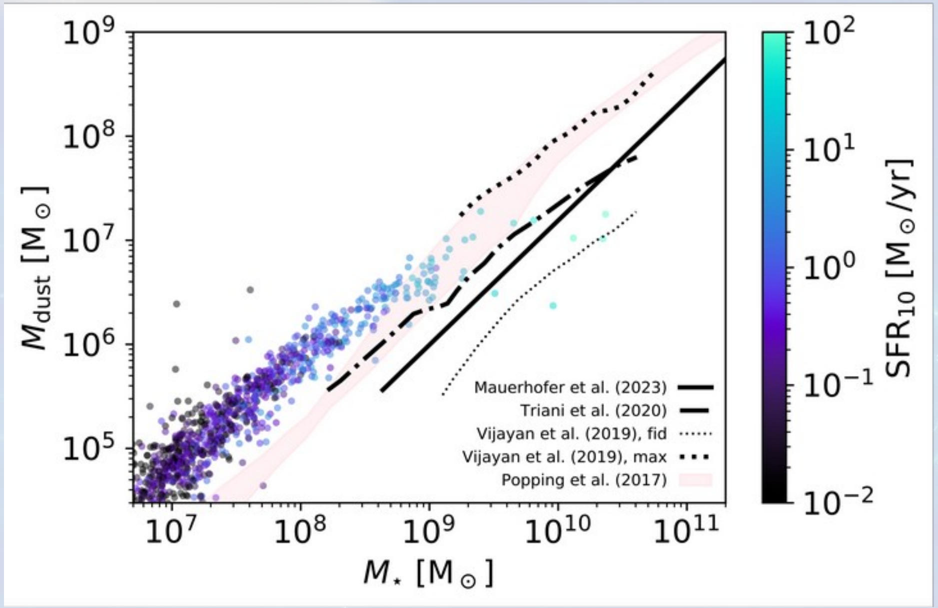
      → Efficient at **high-density, low temperature**
- **Dust destruction**
  - SN shocks destroy 30% of the dust in shocked gas → **ΔM_{dust} ~ (2000 $\mathcal{D}$) $M_\odot$** per event
  - Thermal sputtering of dust grains in hot gas → mostly efficient at $T \gtrsim 10^6$ K



Galaxy with $M_\star$ ~ 2×10^{10} $M_\odot$ at z~7

High-z, dusty galaxies

Galaxies can be rich in dust as early as z>7



- Very expected: more massive and star-forming galaxies are more dusty

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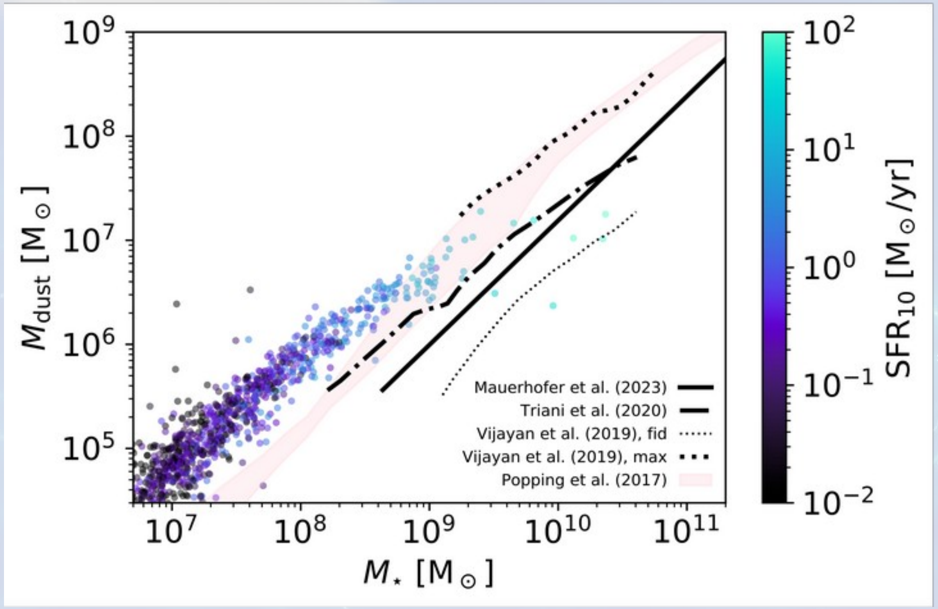

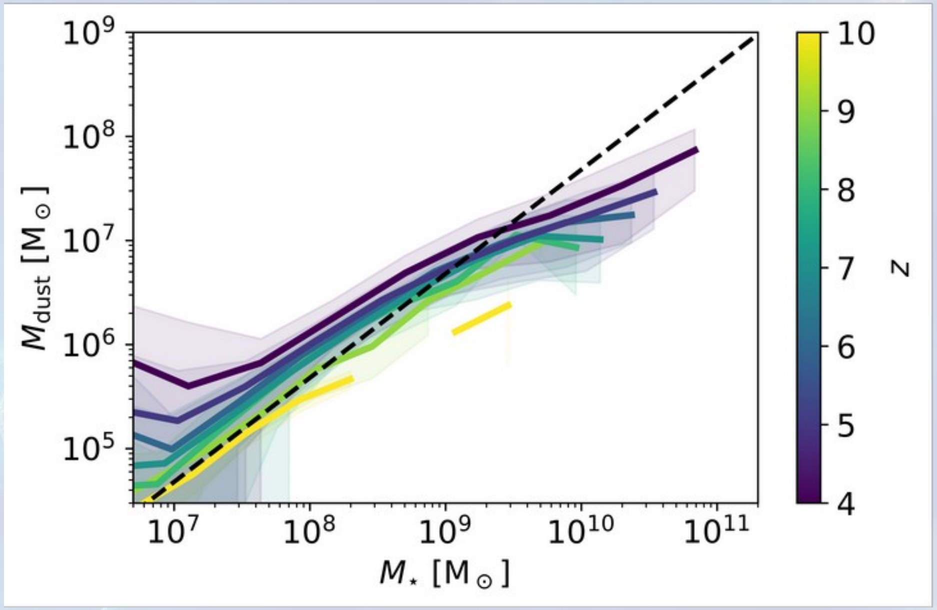

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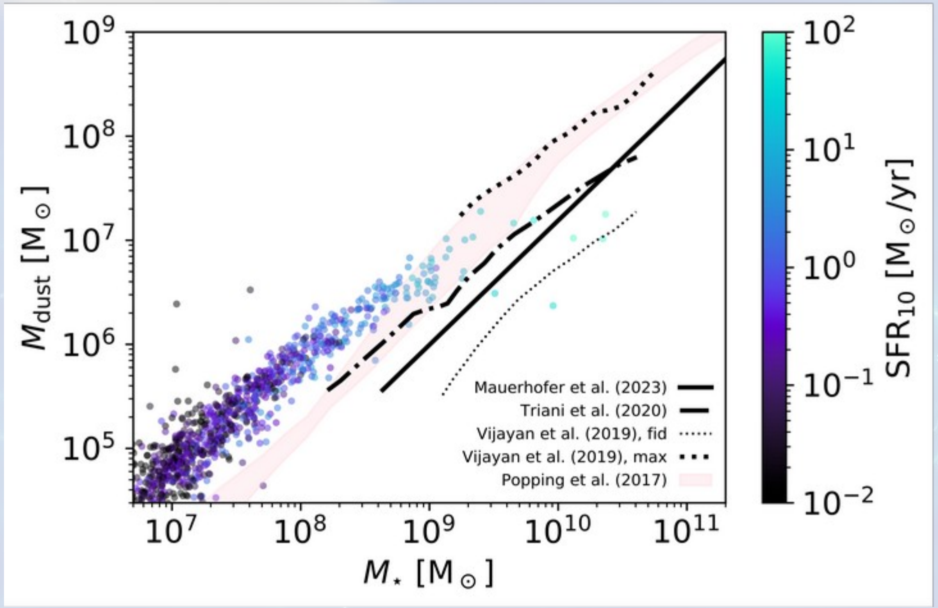
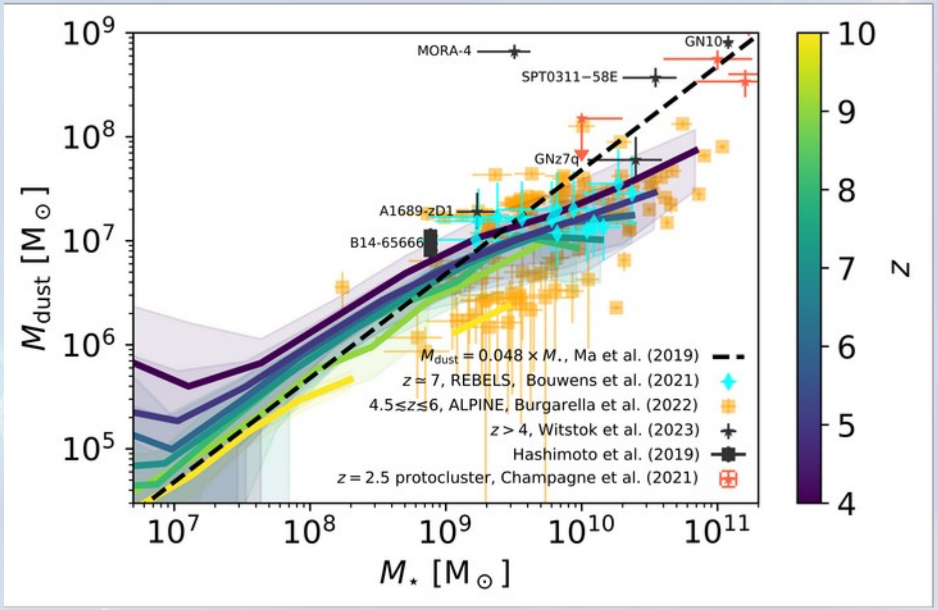
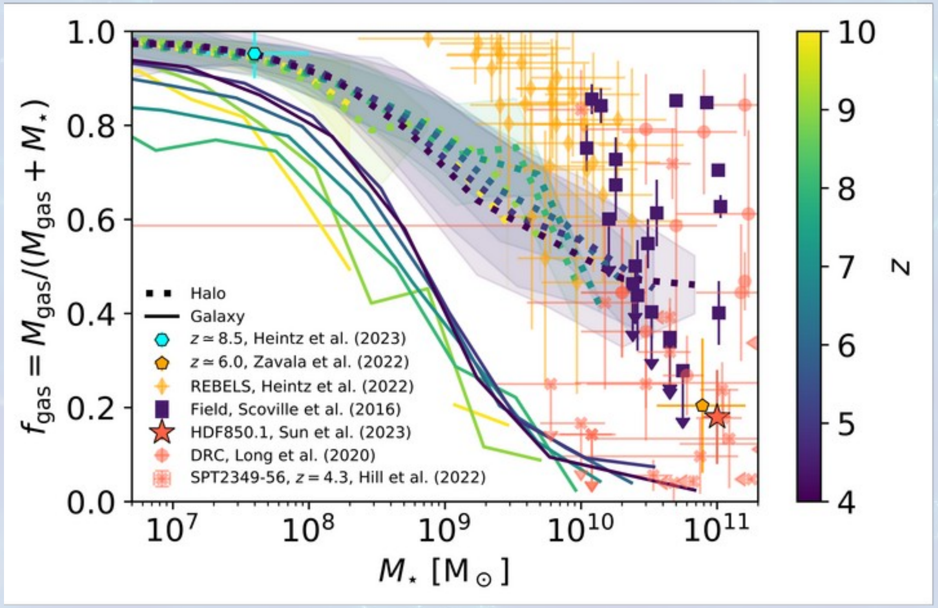


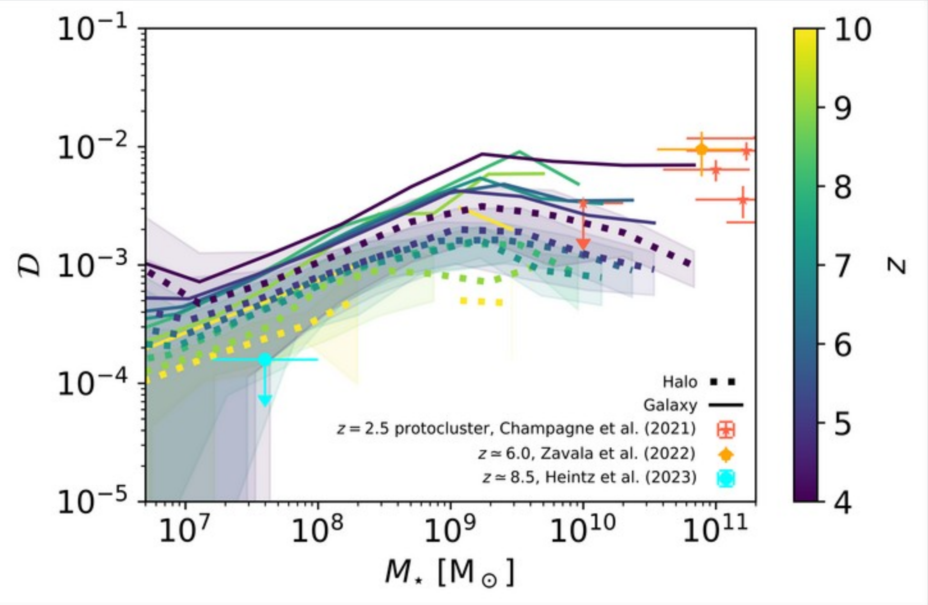


- Very expected: more massive and star-forming galaxies are more dusty
- Also very expected: at fixed mass, galaxies become more dusty at late times
- Much less expected: the dust masses from ALPINE or REBELS are very well matched!

Massive galaxies are less gas-rich but more dusty

- The gas content of Obelisk galaxies evolves with mass, but very little with z
- Details depend on "where" we measure the gas: within the halo vs within the galaxy
- The dust-to-gas ratio $\mathcal{D}$ increases with time: galaxies really get "dustier" at later times





What can we actually see?
-
Effect on (synthetic) observations

How do we do this? Synthetic observations with RASCAS

- Radiative transfer with RASCAS [Michel-Dansac+2020]
- Modified to account for the Obelisk dust model
- “Observational” setup
  - Cast 10^5 photons from star particles
  - Follow scattering+absorption by dust
  - Synthetic observations along 12 lines of sight
- **Big uncertainty: dust extinction/attenuation**
  - Assume MRN grain size distribution
  - We test and compare two compositions

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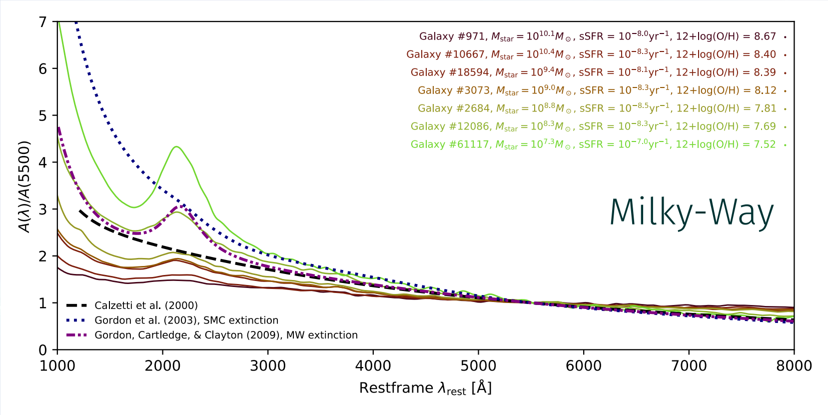

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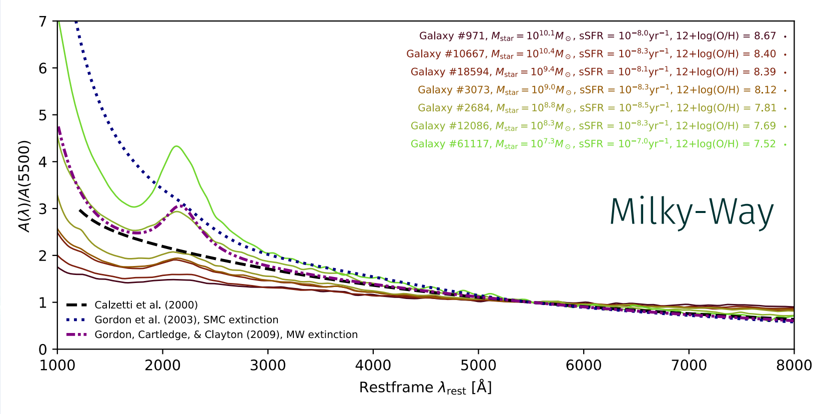
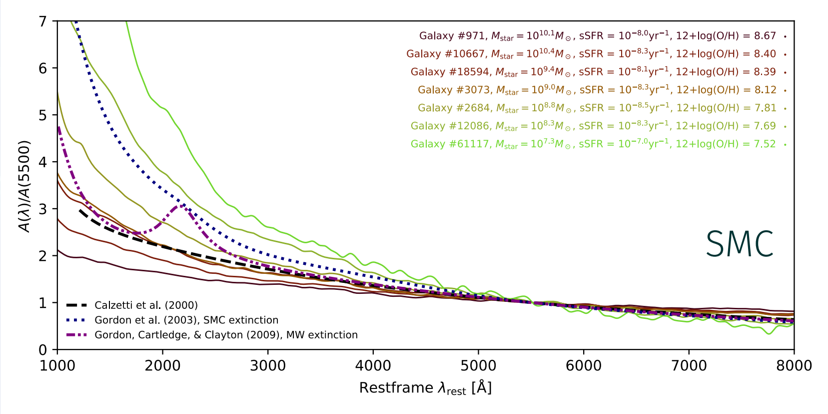
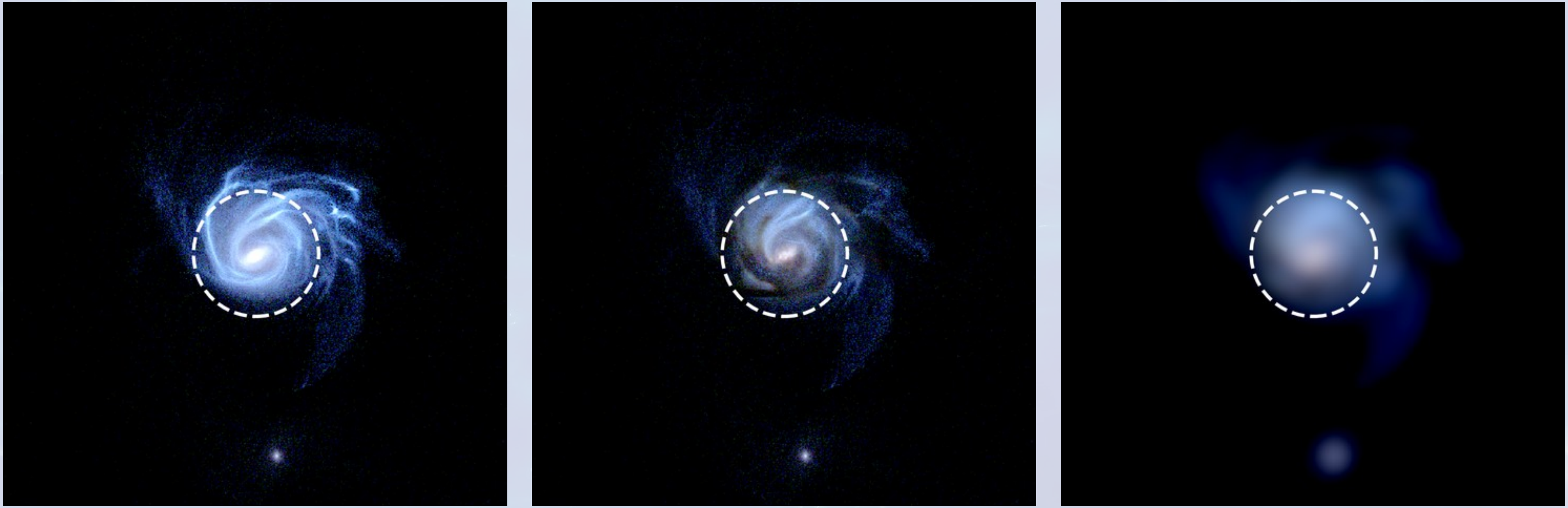
    - Extreme (SMC-like): 100% silicates



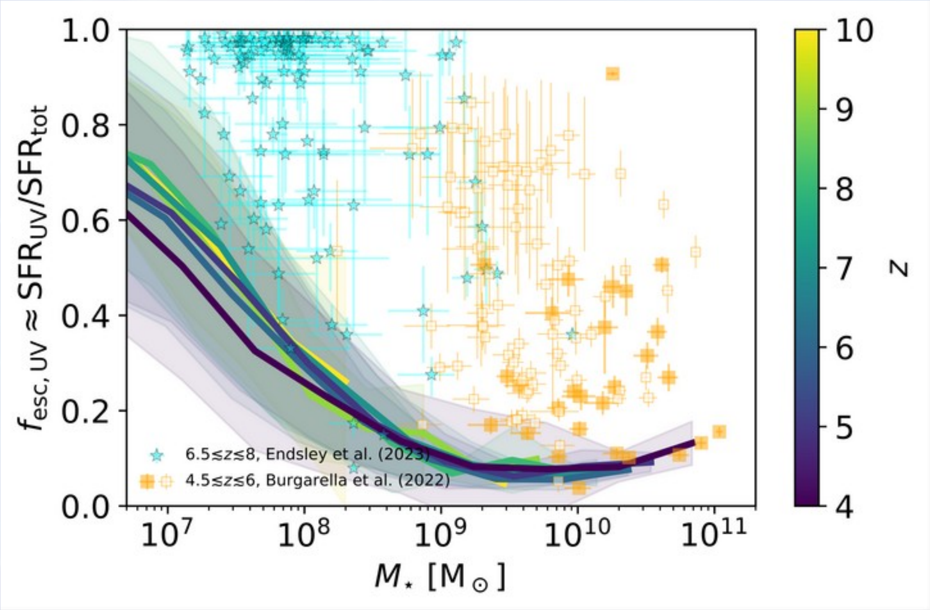


Synthetic observation: F150W + F277W + F444W image of a galaxy at z=7



Intrinsic | After dust transfer | After dust + PSF

Far-UV attenuation: obscured star-formation



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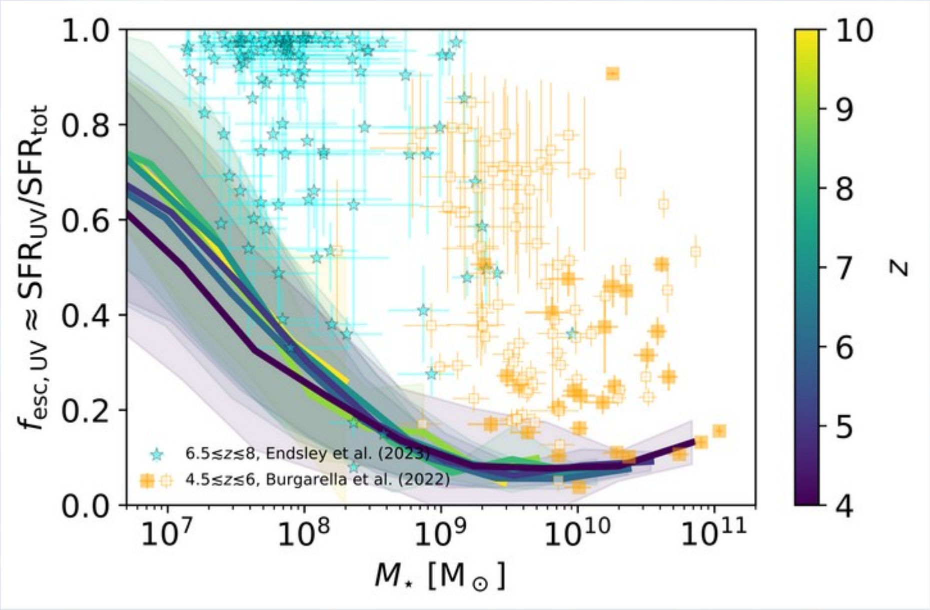

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- But **not a fair comparison**!
  - most observations are UV-selected
  - for the ALPINE sample, A_{UV} is derived from the IR luminosity
    → using their IRX-A_{UV} relation changes A_{UV} by ΔA_{UV} = 0.2-0.6

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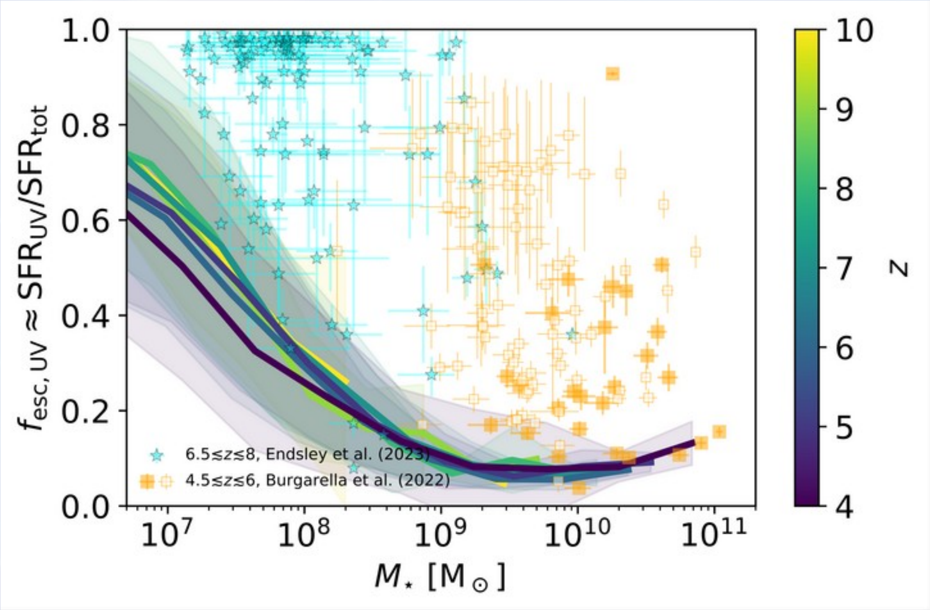

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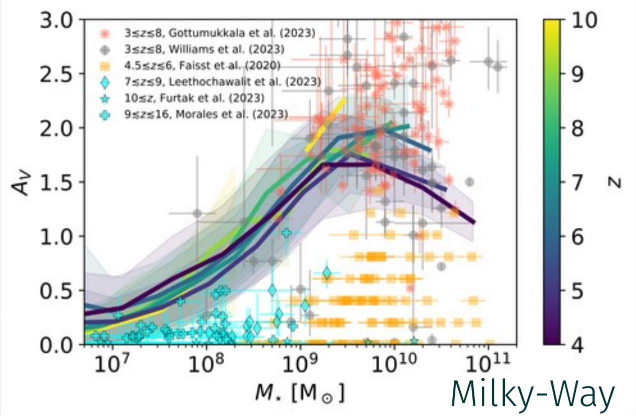
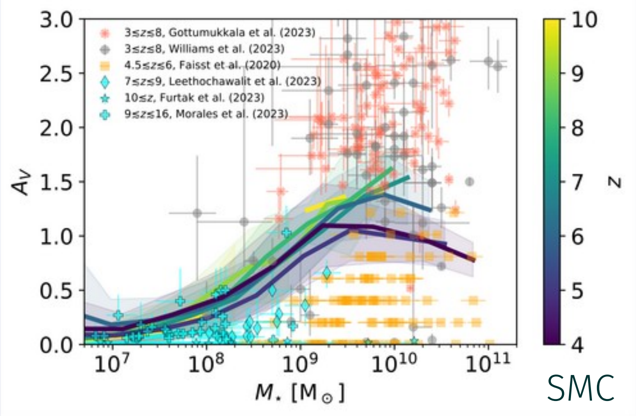
- However, this at least is **robust to changes in the extinction curve**

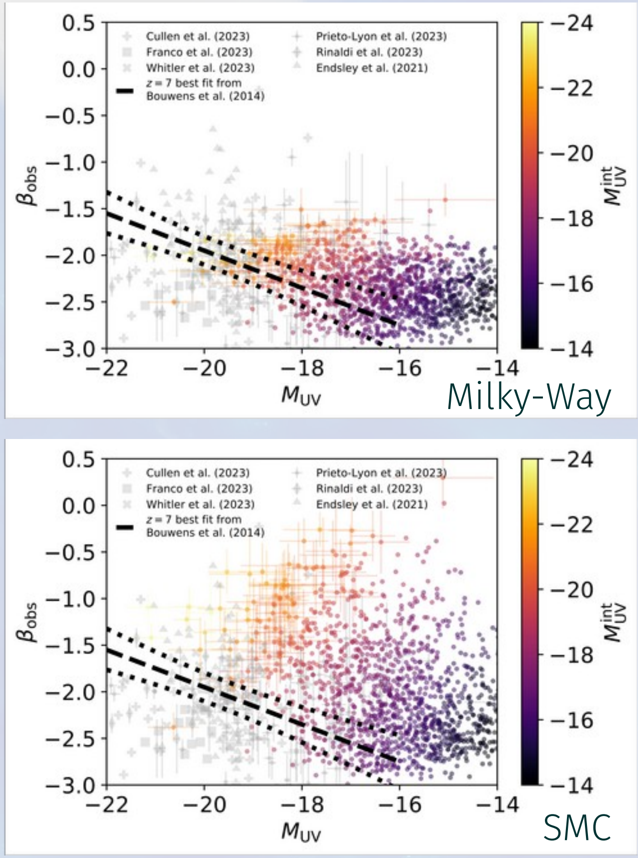
How about optical wavelengths?

- Galaxies in Obelisk have a **wide range of A_V**
  - Low mass galaxies have low (but not tiny) average A_V
  - More massive galaxies can reach A_V ~ 2
- Strong sightline dependence, but probably not extreme enough to account for the full range of A_V
- Much more dependent on the extinction curve
- No clear redshift evolution *at fixed stellar mass*





Colour-magnitude in the far UV: β-M_{UV}



- UV β slopes measured on continuum spectra in the range 1400 Å ≤ λ ≤ 3000 Å
- VERY sensitive to the underlying extinction curve
  - MW-like curve leads to **good agreement with β slopes**
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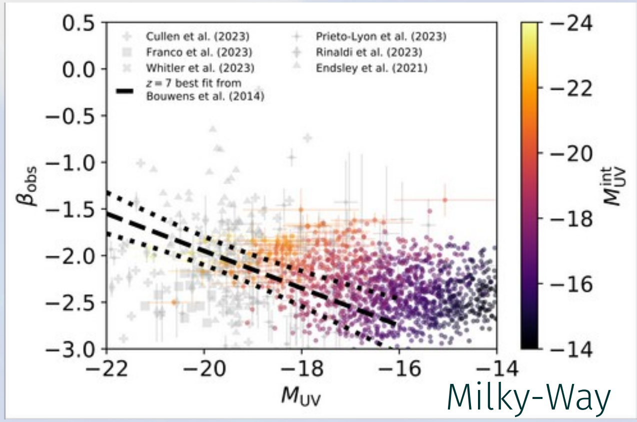

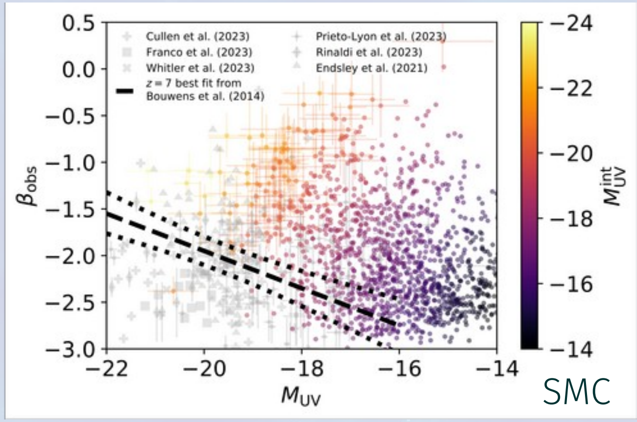

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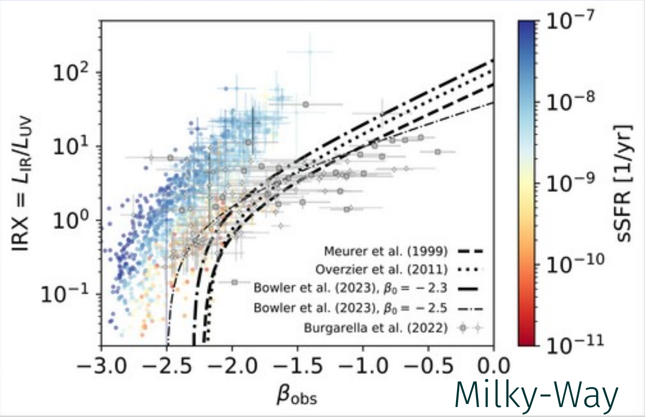
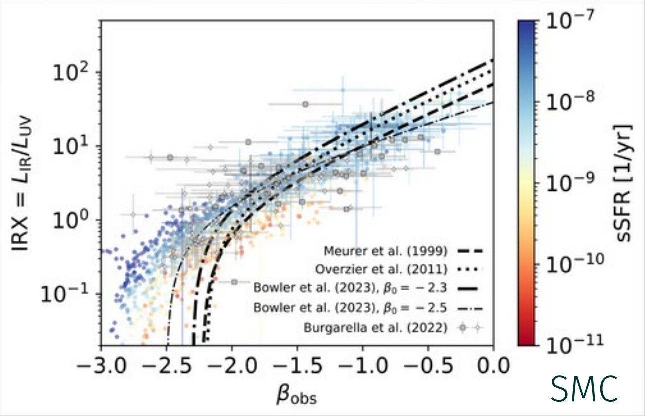
- In both cases, we do not find the "extremely blue", dust-free-like galaxies with β ~ -3 from e.g. Cullen+2023
  - Including line of sight effects would only help a little
  - Maybe due to emission lines contamination?

IRX-β: conflicting results?

- Assuming all absorbed UV-optical photons are re-emitted in the IR, we can estimate IRX = L_{IR}/L_{UV}
- General trend: high sSFR → bluer β at fixed IRX





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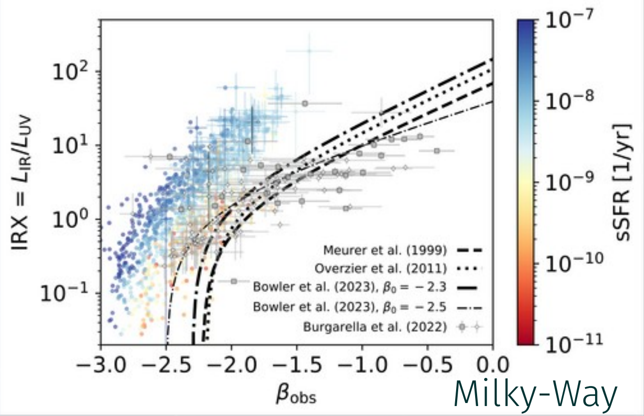

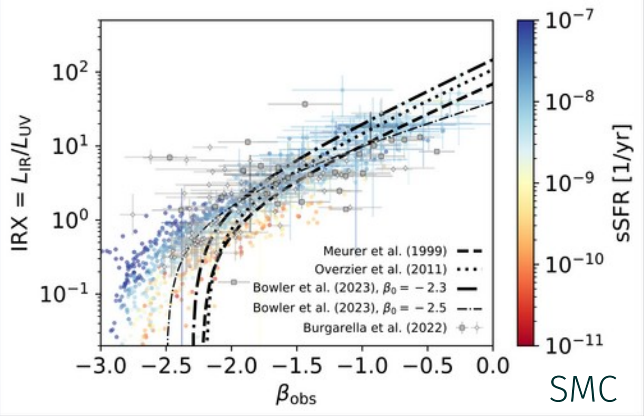

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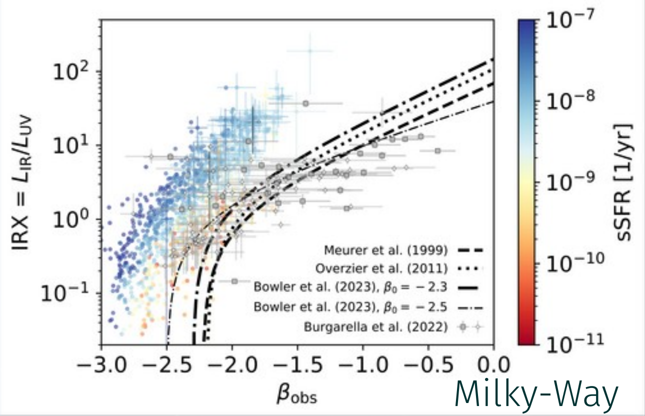
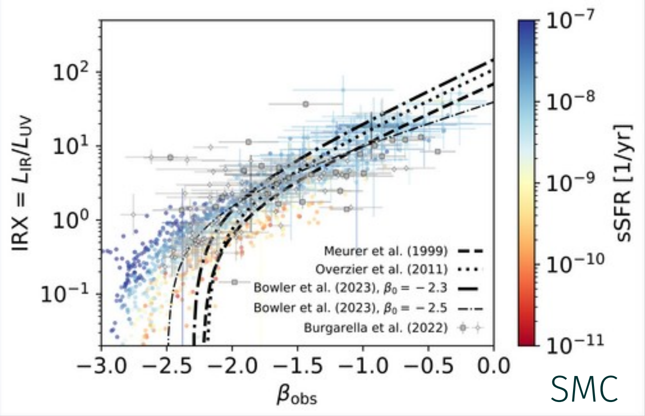
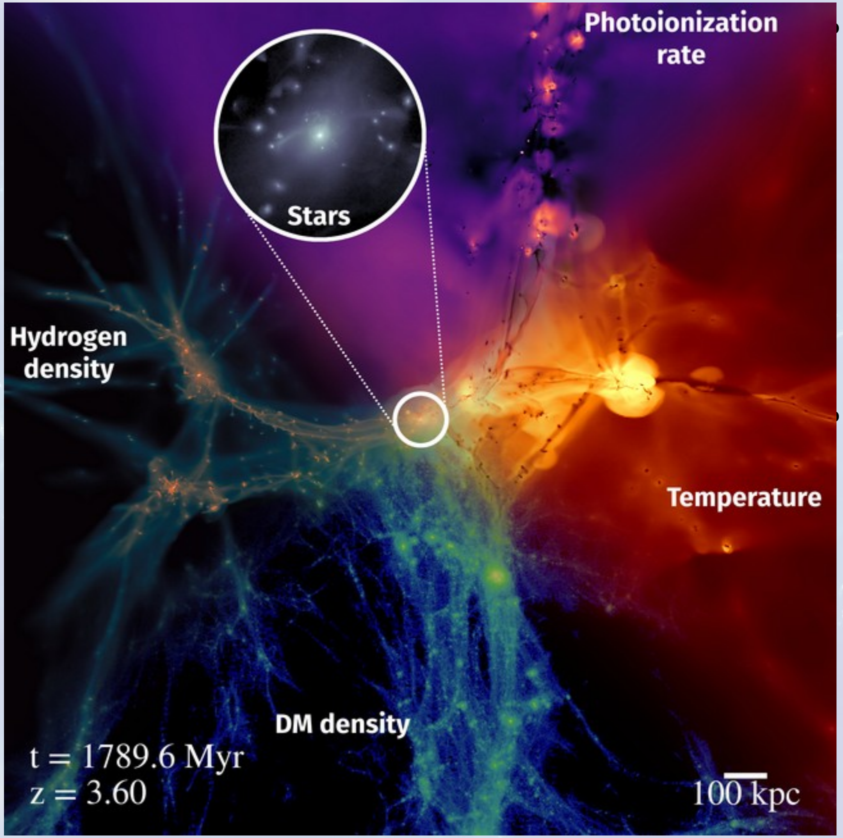
    … but at the cost of a "less good" β-M_{UV} relation
- No consensus from simulations on this, but:
  - the flattening of the IRX-β relation with steeper extinction curve is expected [Liang+2021, Hsu+2023]
  - elevated IRX values usually go with high sSFR [Safarzadeh+2017, Liang+2021, …]





Summary

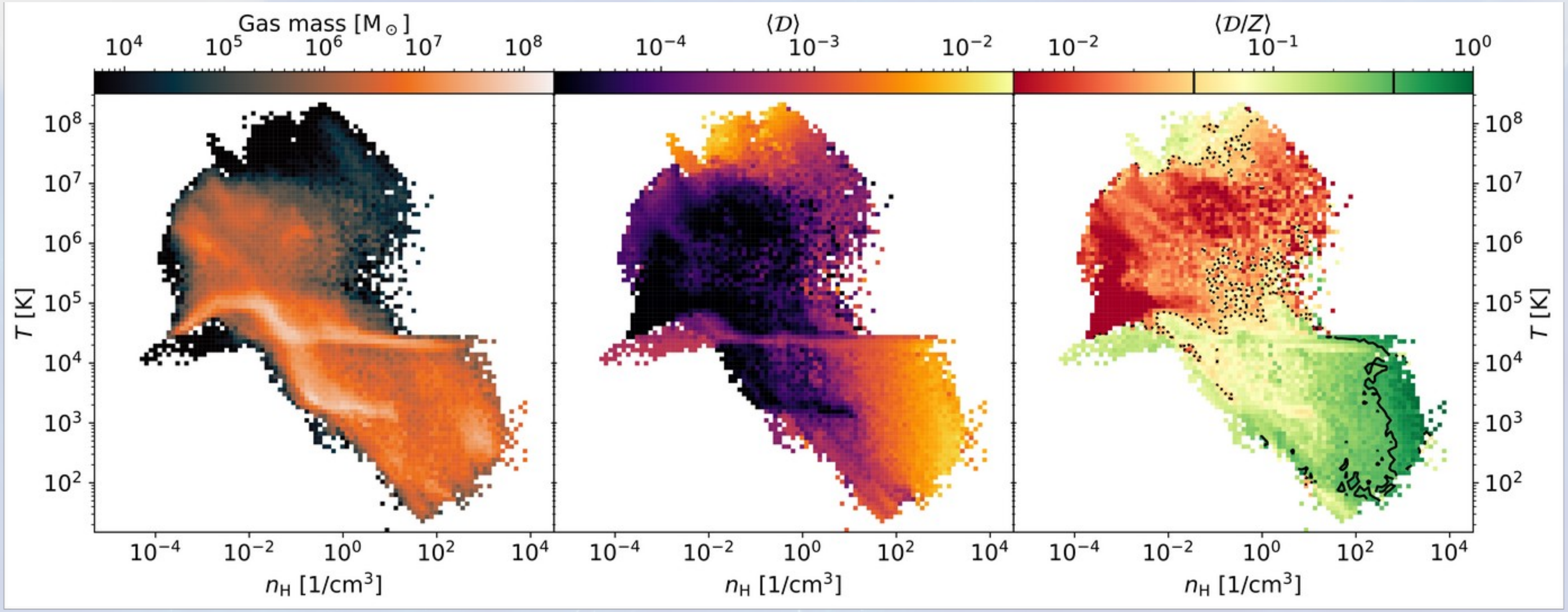


- The Obelisk simulation models **dust formation and evolution** in a large sample of z>3.5 galaxies
  - The gas and dust content in the simulation is in good agreement with high-z observations
  - Dust evolution at z>4 is driven by **grain growth**

- Full "**forward-modelling**" to compare with observations:
  - High levels of **obscured star formation** especially in massive galaxies ($M_\star \gtrsim 10^{9.5}\ M_\odot$)
  - UV β slopes agree with observations, but depend a lot on the assumed extinction curve → grain properties
  - High-z galaxies are **above the canonical IRX-β relation** → Seems due to the inhomogeneous ISM

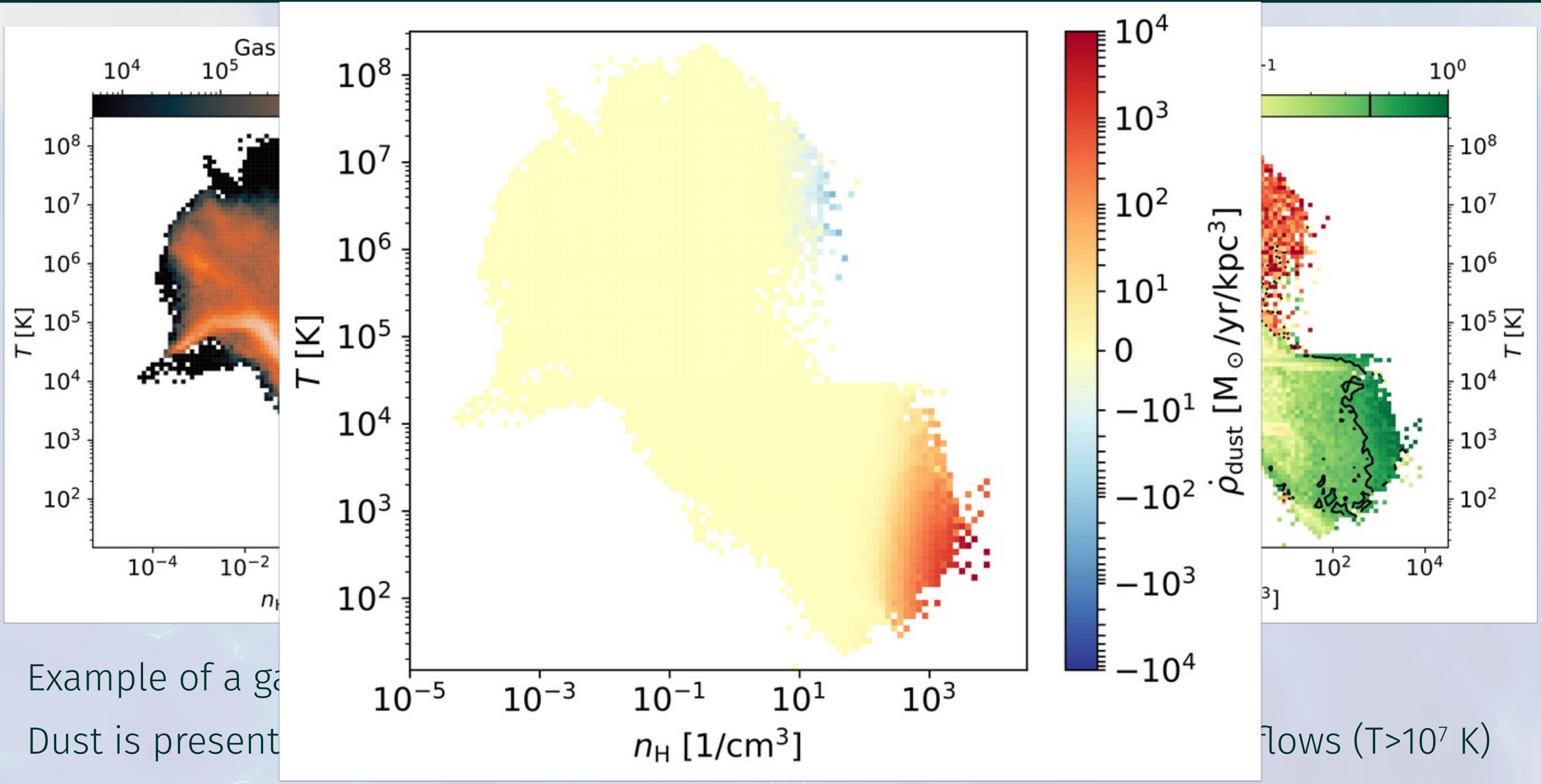
Backup slides

Dust processes: inside the galaxy



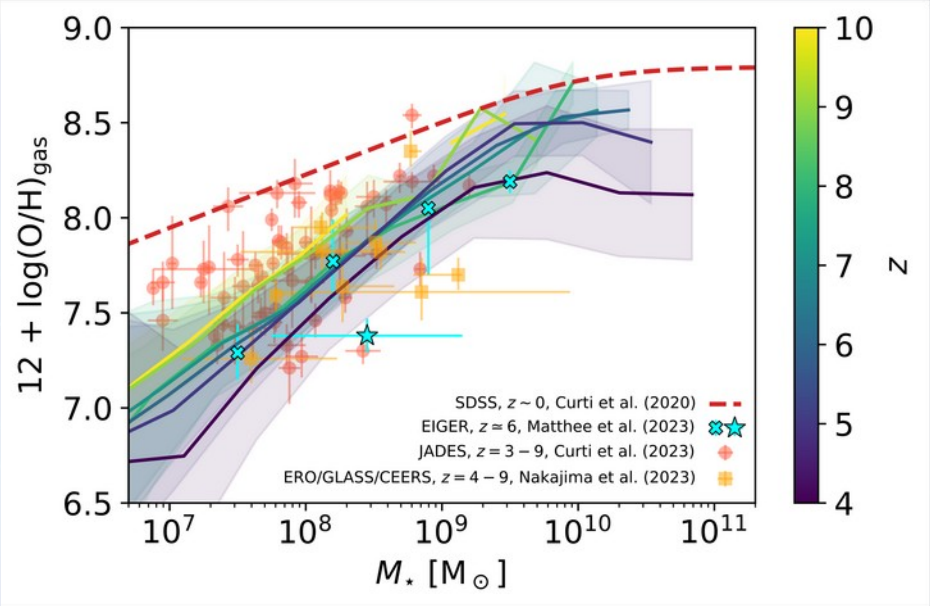
- Example of a galaxy with $M_\star \sim 2\times10^{10}\ M_\odot$ at z~7
- Dust is present in the cold ISM ($T<1000$ K, $n>1000$ cm^{-3}) and in the hot outflows ($T>10^7$ K)

Dust processes: inside the galaxy

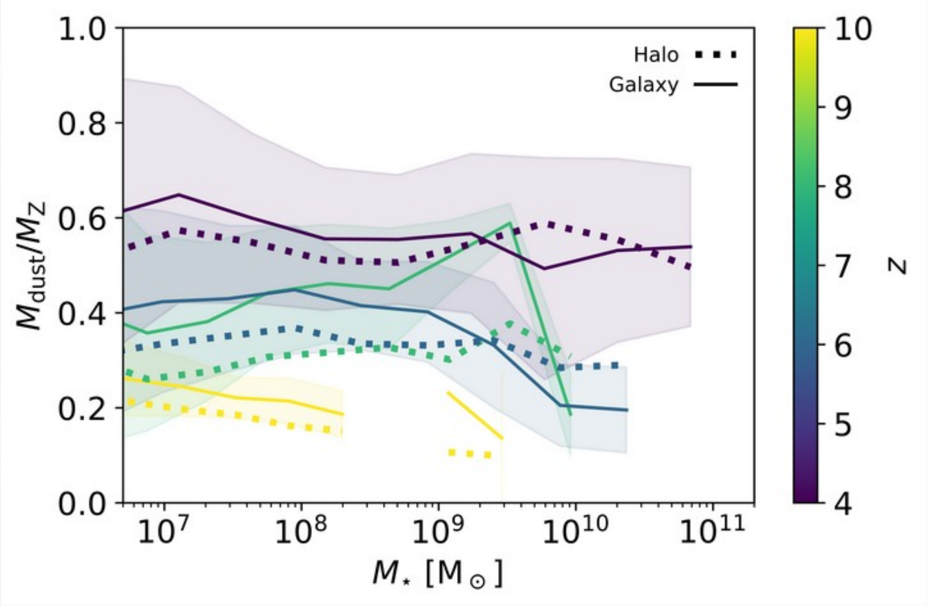


- Example of a ga
- Dust is present ... flows (T>10[7] K)
- This comes from the balance between dust growth (ISM) and sputtering (in outflows)

Dust or metal evolution ?



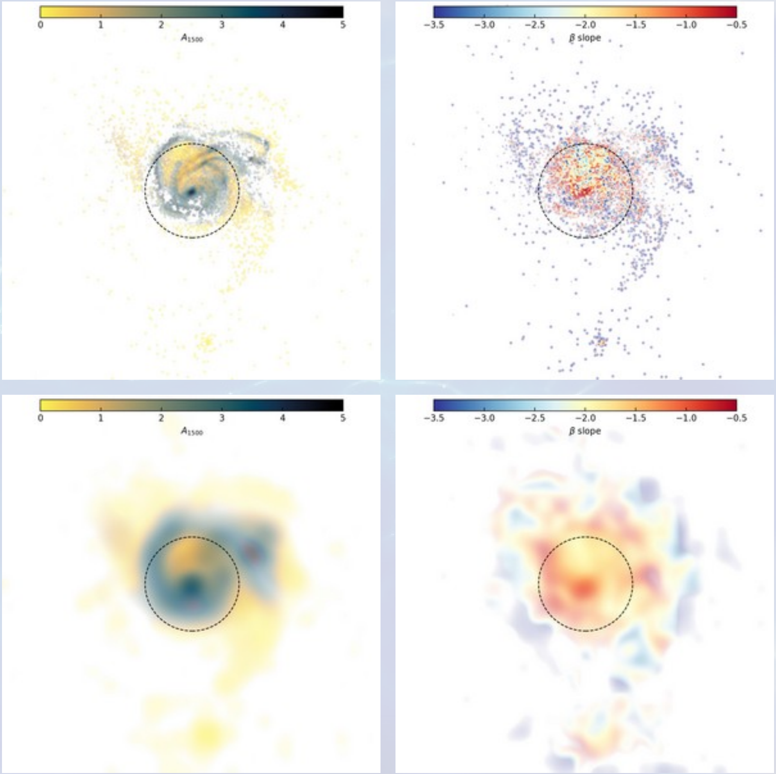
- The (gas-phase) MZR in Obelisk is in broad agreement with observations
- Surprisingly, 12+log(O/H) **seems to decrease** towards low z at fixed mass



- This is mostly driven by the evolution of the dust-to-metal ratio
- The evolution of the DTM predominantly comes from **grain growth in the ISM**

Spatially-resolved attenuation and β slopes

- Mismatch between UV and IR properties could be partly due to inhomogeneous dust distribution
  - “Reddest” regions are more attenuated, so the inferred β will be biased towards the brighter regions
  - IR luminosity include these high-A_{UV} regions
  - When averaging, this leads to high IRX even if the observed β is fairly blue
- This suggests that high-resolution + detailed synthetic observations are needed to capture the **diversity of lines of sight**



Assembly of a (proto-)cluster

Trebitsch+2021