*Dust in galaxies: from the local interstellar medium to distant galaxies,*
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# Dusty star formation in the early Universe: lessons from ALMA

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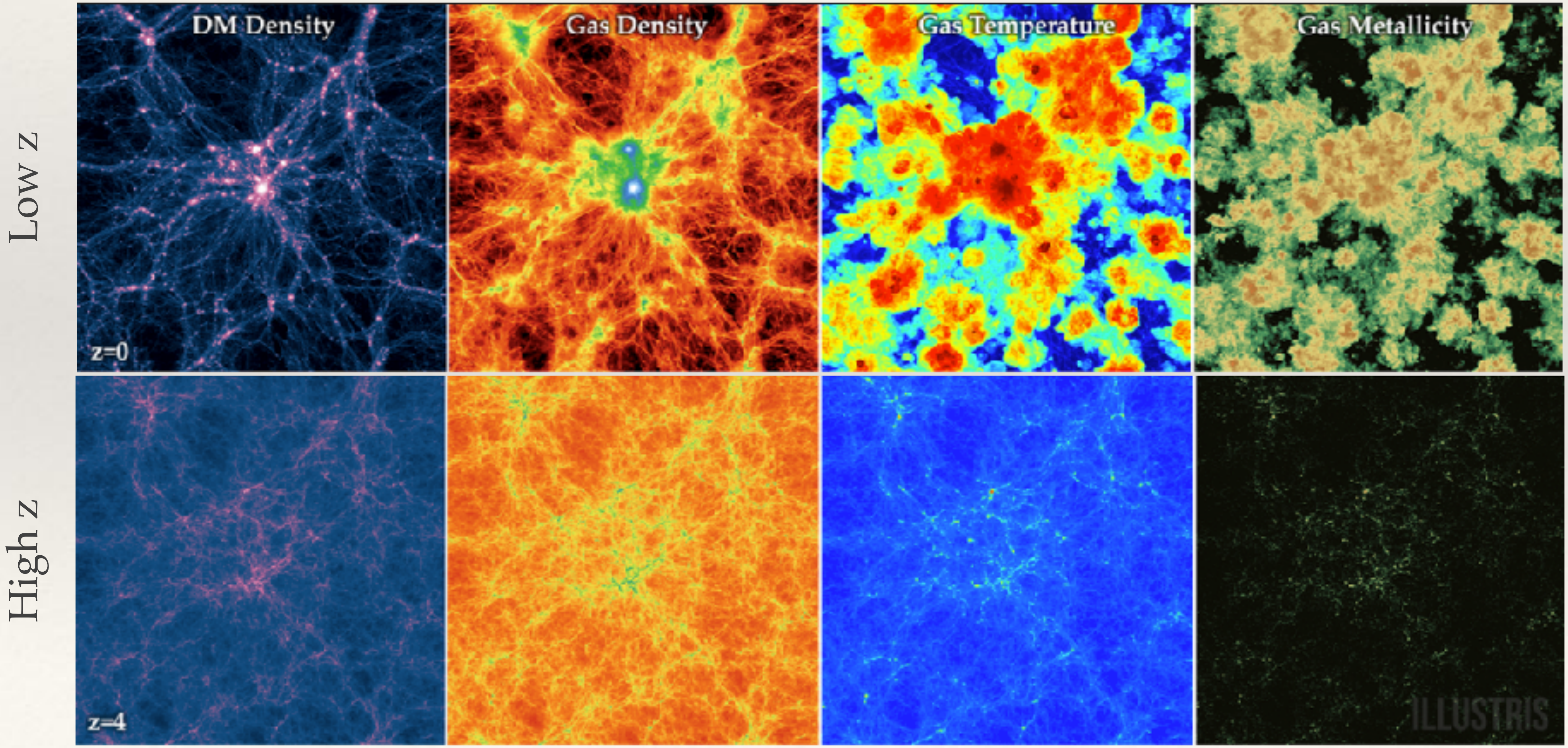
# Why are high-z massive galaxy interesting?

- High-z massive galaxies form in the first assembled ~$10^{12}$ Msun dark-matter halos
- Gas is not hot yet and metallicity remains low except in the densest area

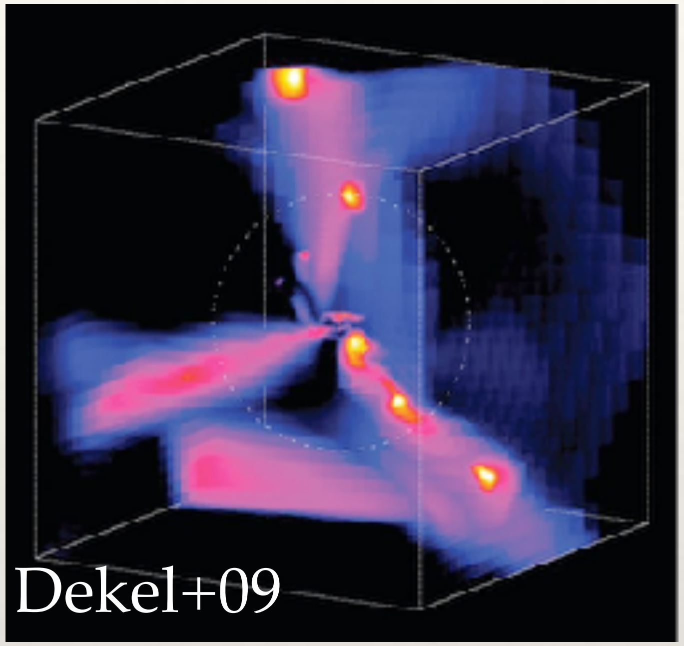


# Why are early massive galaxy interesting?

- Gas accretion on the first massive halos (~$10^{12}$ Msun) is very intense (>100 Msun/yr of baryons)
  => more material available for star formation, dilution of the metals

- Major mergers are more frequent than at low z
  => potentially more merger-induced starbursts, dust destruction in extreme events?

Gas accretion

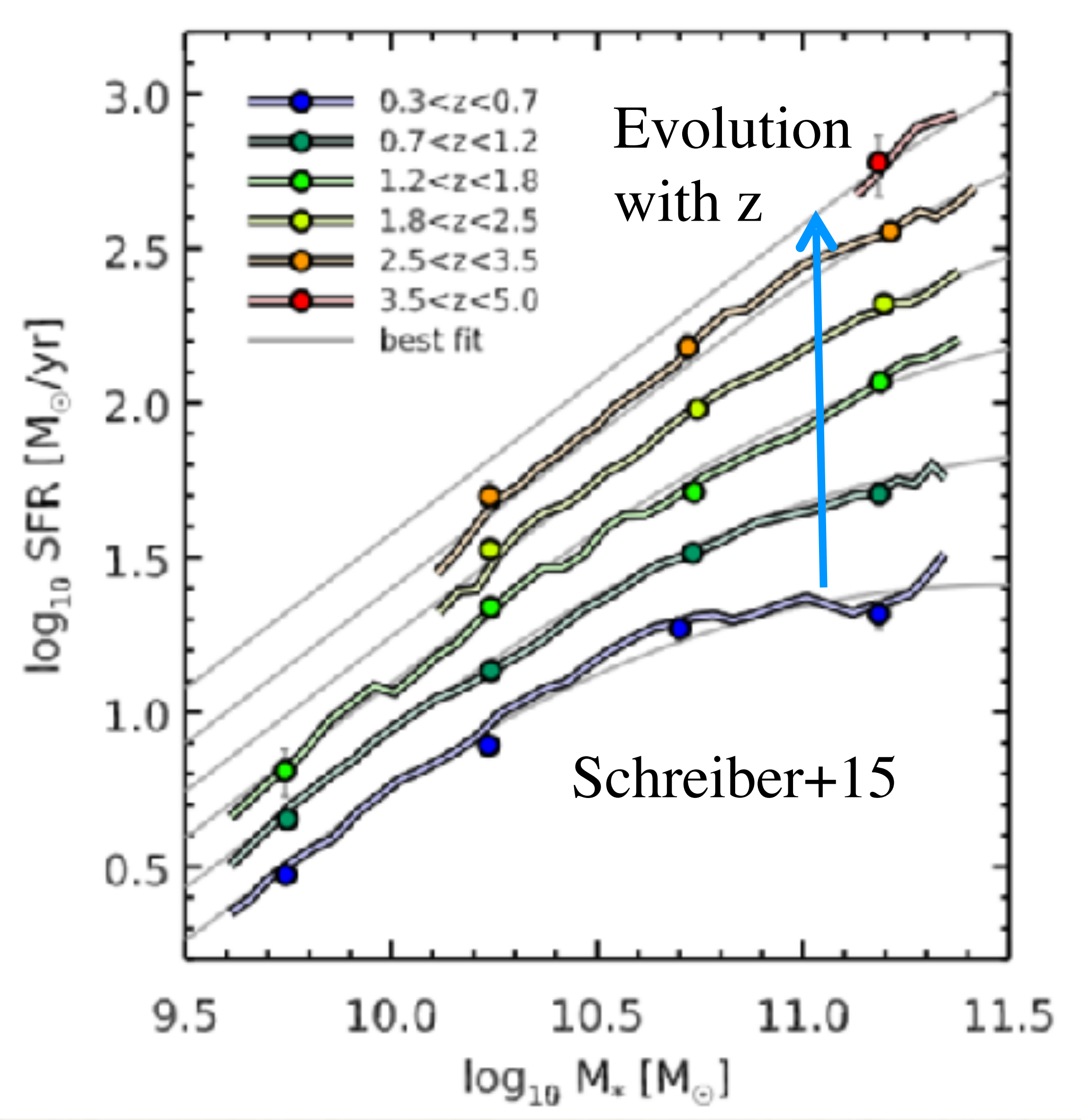



Major merger

# High-z massive and star-forming galaxies

- Most of the star-forming galaxies on a correlation between stellar mass and SFR ("main sequence »)
- Evolve with redshift
- Massive galaxies at high-z are more star forming

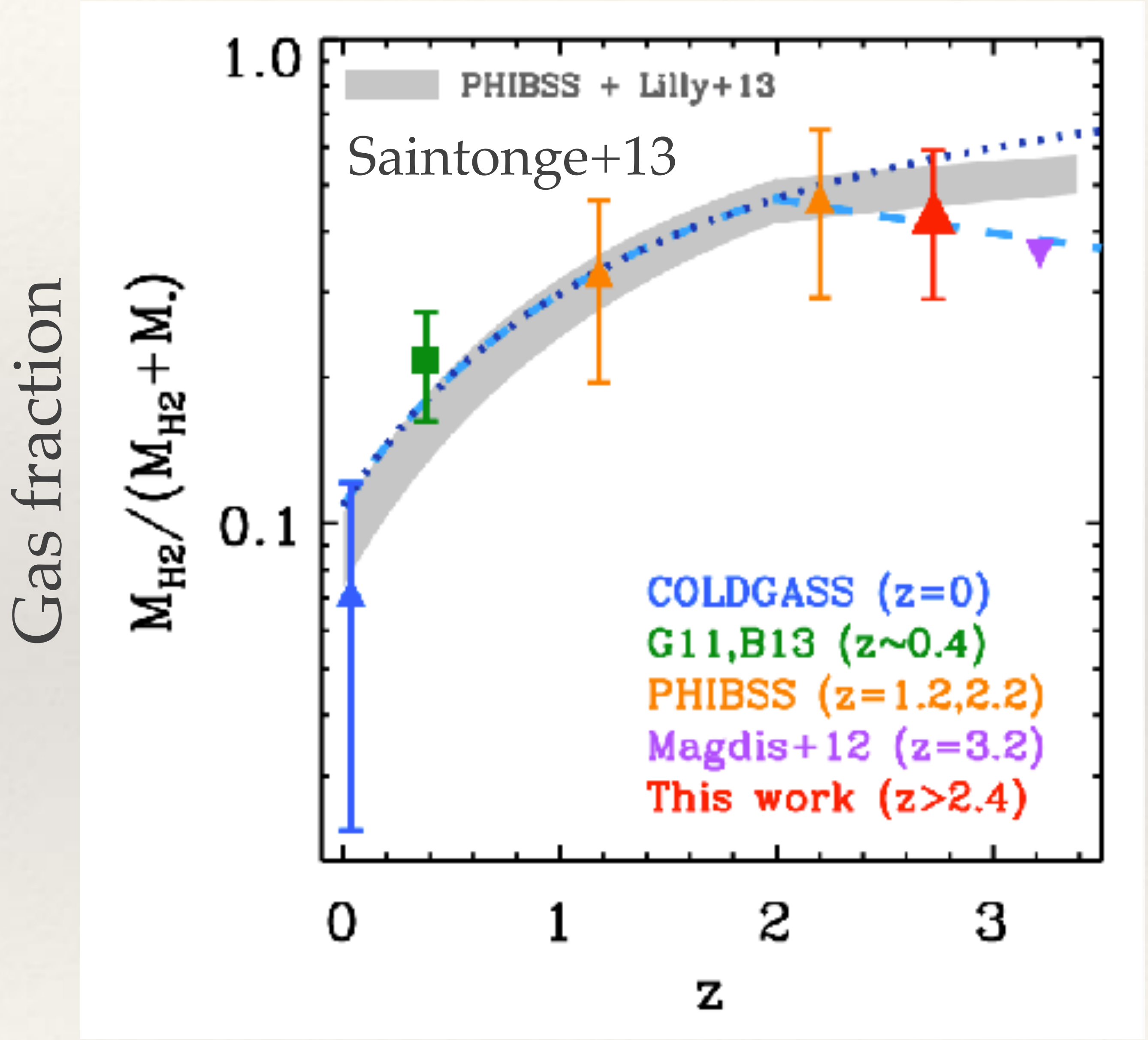
Star formation rate




Stellar mass

# High-z Universe: high gas fractions

- The intense accretion on high-z systems leads to large gas reservoirs
- At z>2, gas fractions are usually around 50%



# Dust at high z: a laboratory, a nuisance, and an opportunity

- **A laboratory**: they allow us to study dust in very different conditions than in the local Universe (gas-rich, lower metallicity, extreme starbursts, young and massive systems)
- **A nuisance:** dust absorbs the UV light from young stars and makes difficult to study star formation
- **An opportunity:** dust probes the early presence of metals and the quick evolution of the ISM in high-z massive systems

# Some open questions about dust at high-redshift

- How quickly is dust formed at high redshift?
- Which processes leads to its creation/destruction?
- Why some high-redshift systems are more dust-rich/obscured than others?
- Up to which redshift dust obscured star formation is significant?
- Do we still miss interesting high-z objects because of dust?

# Summary

- Evolution of the dust temperature with redshift
- Dust-attenuation and obscured star formation
- Dust and gas content of high-z galaxies

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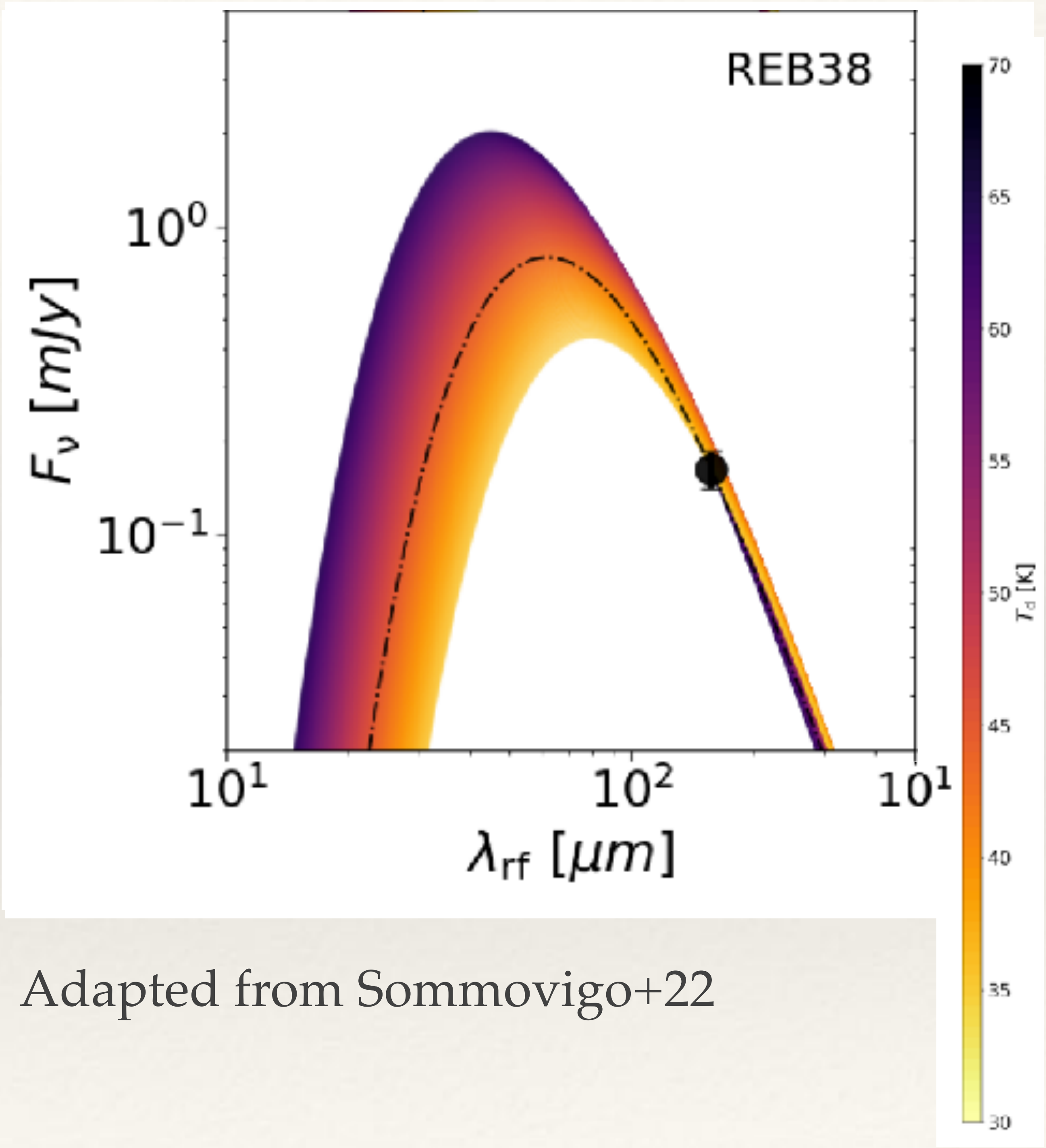
# Why dust temperature is important?

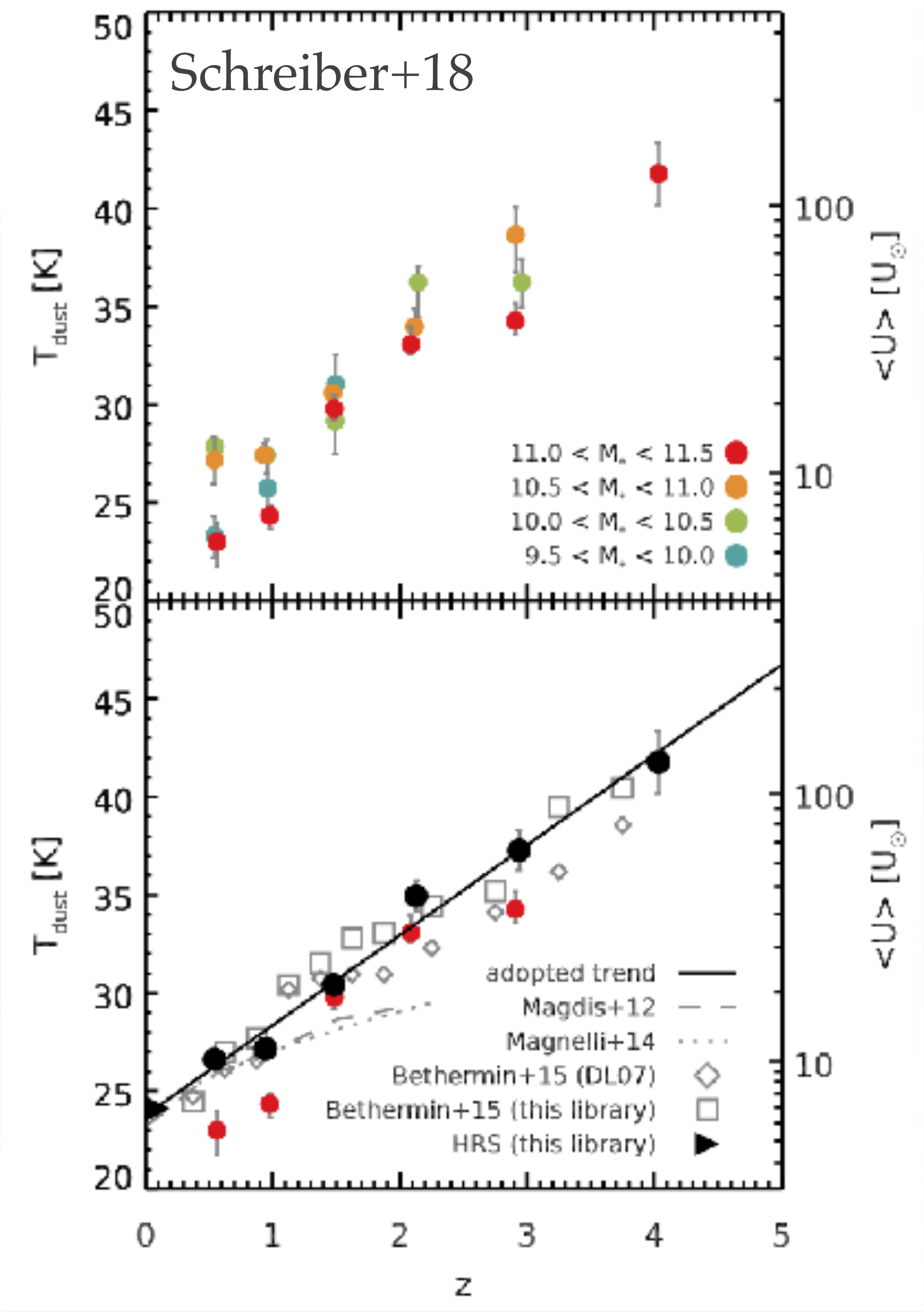
- The dust temperature provides information about the ISM properties (e.g., radiation field)
- ALMA observations usually probe only the Rayleigh-Jeans and we need an assumption on the temperature to obtain the infrared luminosity




Adapted from Sommovigo+22

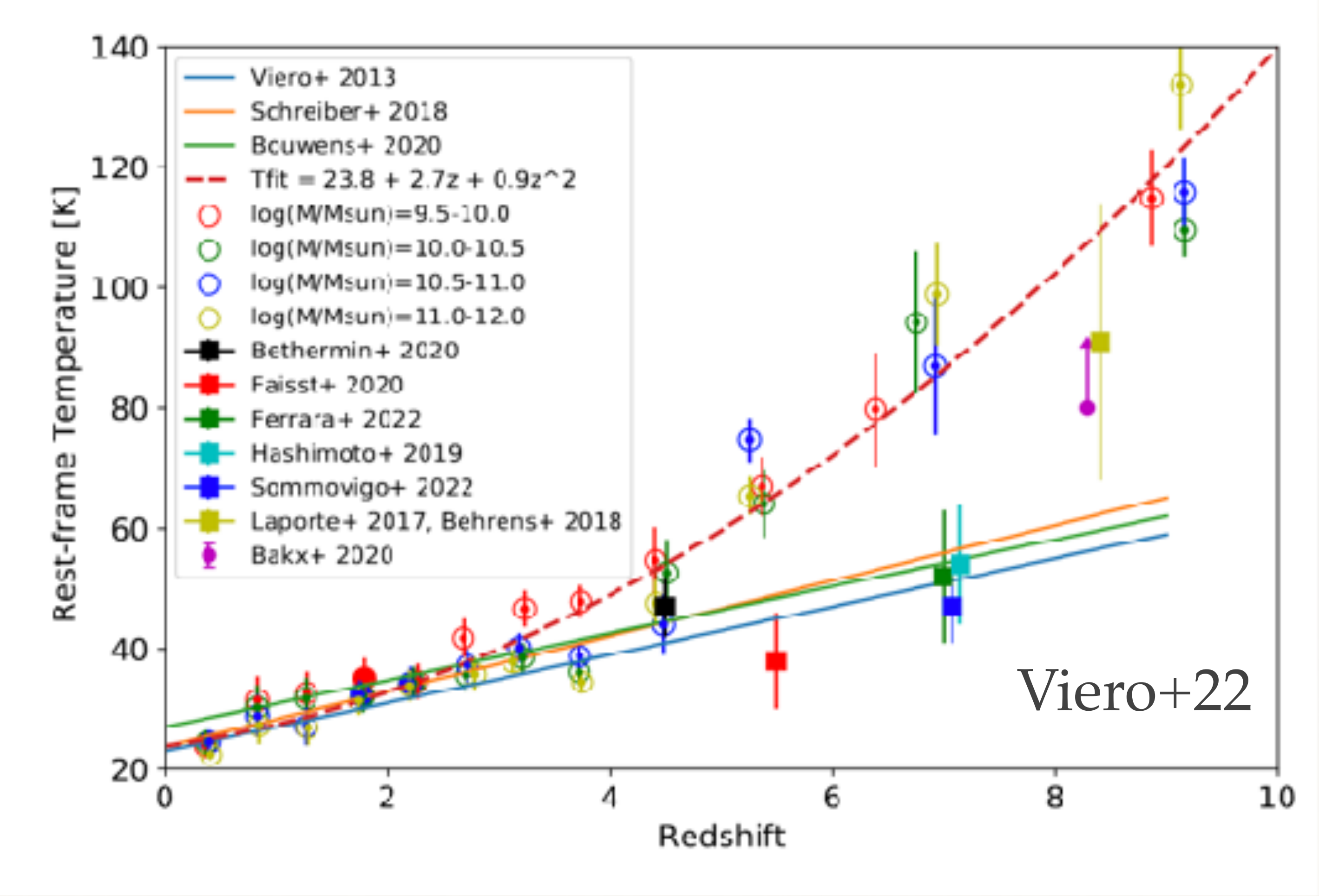
# Constraints from Herschel stacking

- Because of the confusion, Herschel cannot measure the SED of "normal" high-z galaxies
- Average SED of the full population can be measure by stacking
- Revealed a strong evolution in temperature with warmer dust at higher z



# Very hot dust at z=10?

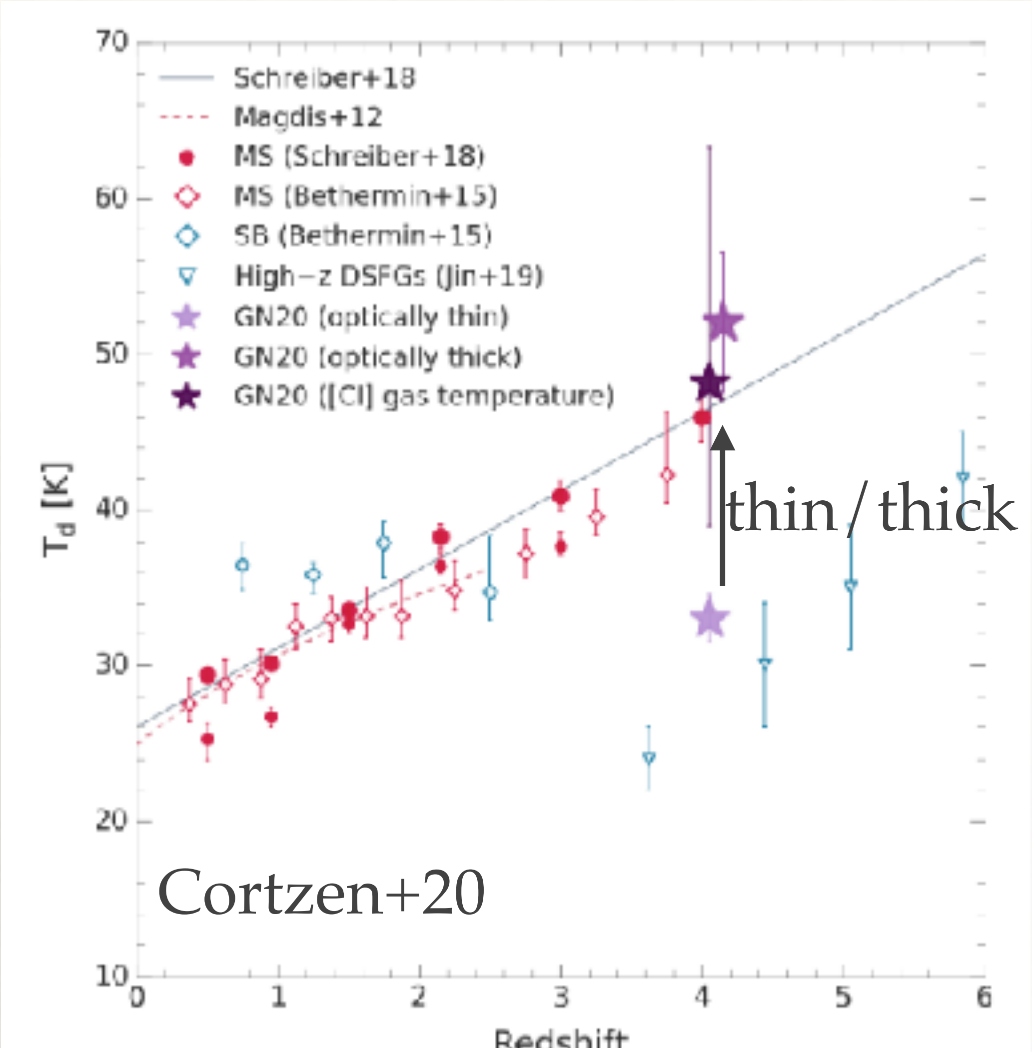
- Recent attempt to push the method at high redshift using the new COSMOS catalog as input (Viero+22)
- Very high temperatures at z~10 (~100 K)
- Prediction of very high temperature from numerical simulations (Behrens+18) too
- BUT, reliability of the input catalogs? possible stacking artifacts?

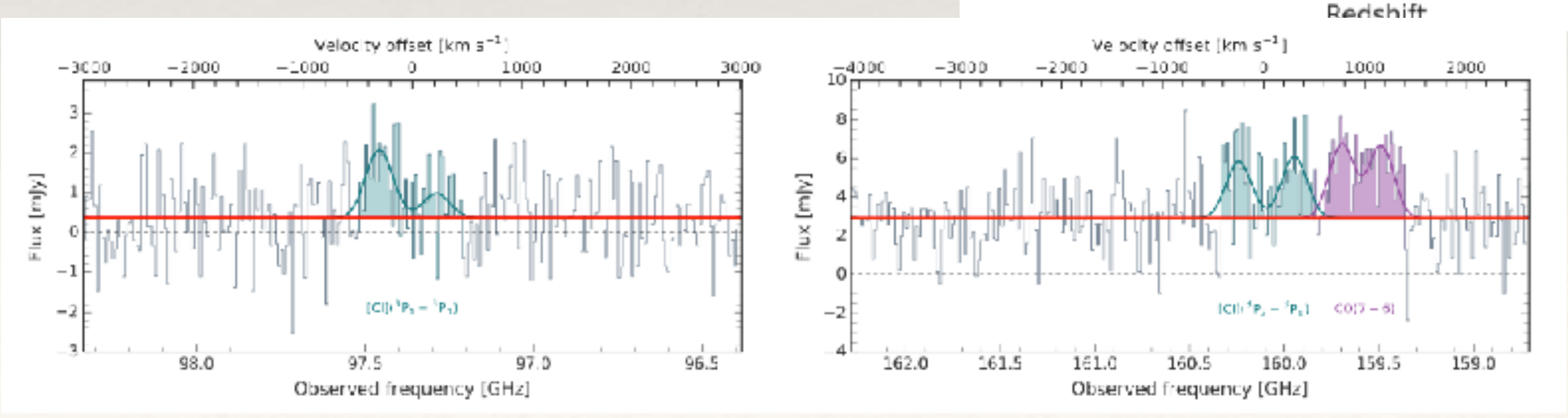



Viero+22

# Deceptively cold dust in extreme objects?

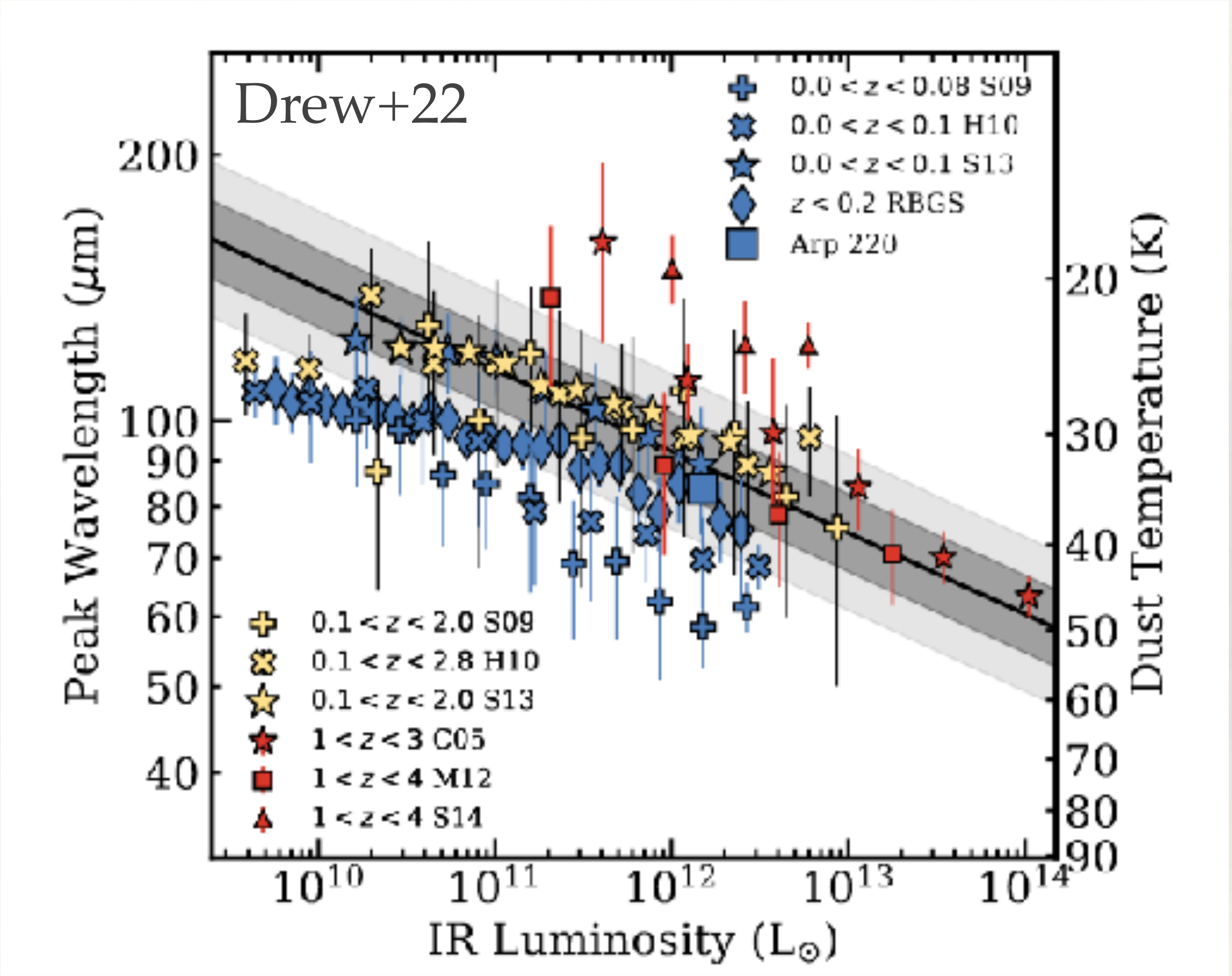
- Some starbursts as GN20 have surprisingly cold dust temperature
- These temperature are not compatible with high excitation of the [CI] lines (Cortzen+20)
- Optically thick dust in some starbursts?
- Hints from 2mm surveys (stay tuned!), but not in the majority of sources (see Gayathri's talk)



# Debates about the interpretation

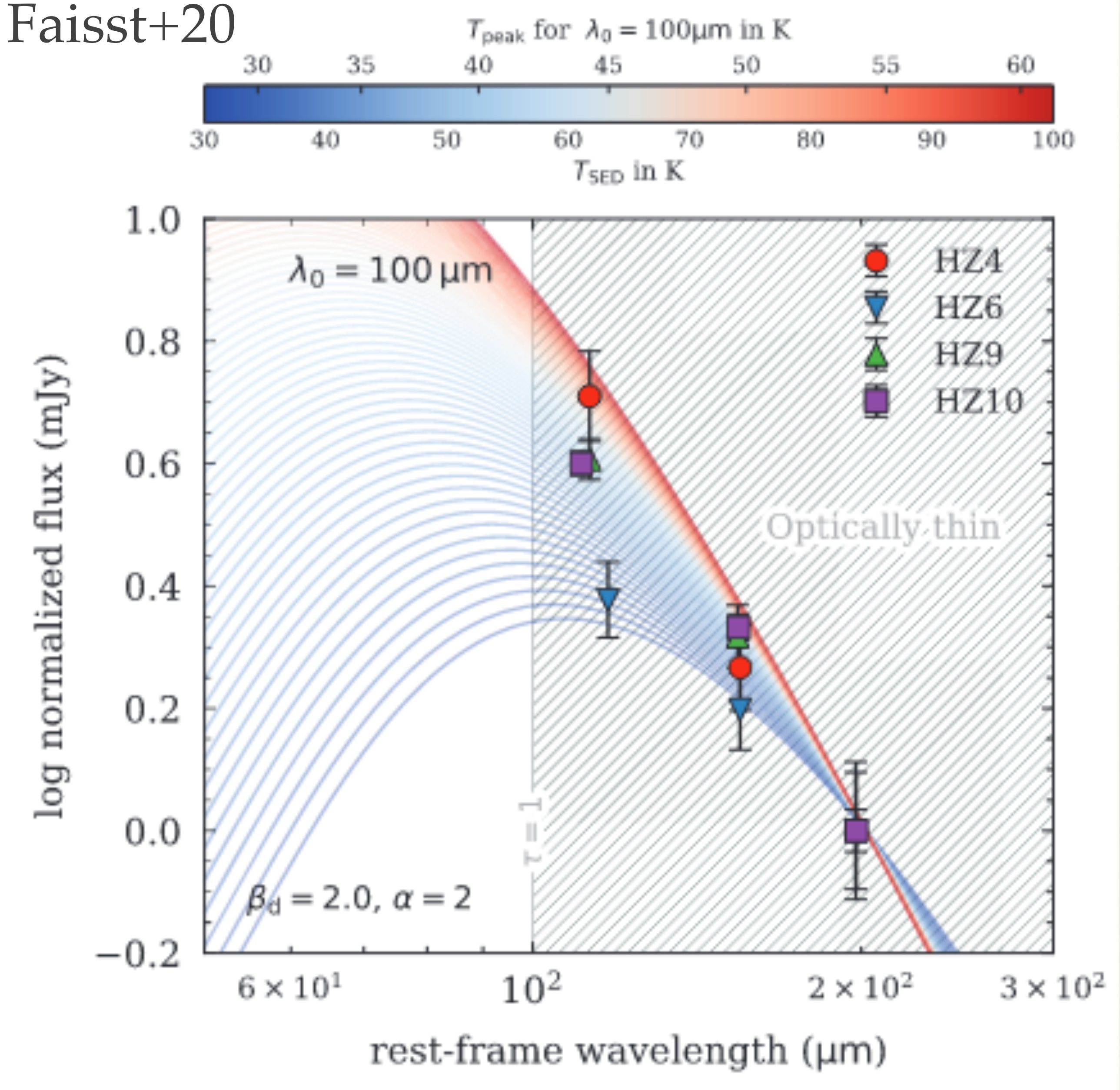
- Lower metallicity and higher radiation field of the ISM in higher redshift galaxies
  (e.g., Magdis+12, Bethermin+15,Behrens+18)
- Consequence of the $L_{IR}$-$T_{dust}$ relation and the evolution of the main sequence
  (e.g., Drew+22)
- Cannot be fully explained by the CMB being warmer at higher z
- Other mechanism? (compactness, evolution of the star formation efficiency, different geometries)



# The difficult challenge of high-frequency observations

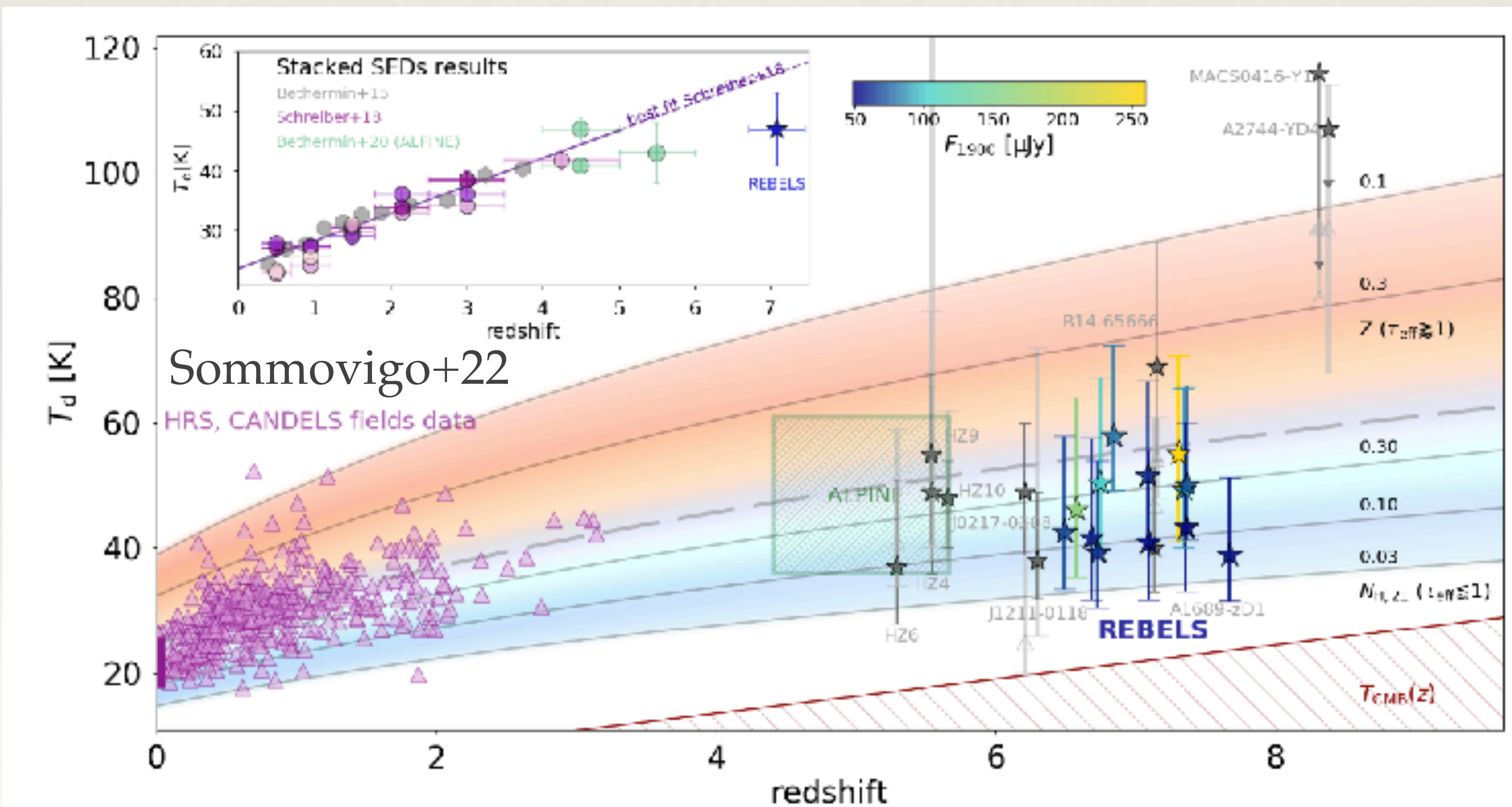
- Dust peaks around 100 micron rest-frame
- ALMA cannot observe efficiently below 450 micron
- High-frequency observations of z>5 sources can provide us constraints
- BUT, expensive in time, only in compact configuration with excellent weather

Faisst+20



# A new method based on [CII]

- Sommovigo+22 proposed an approach using the [CII] luminosity (proxy of SFR) to break the degeneracies and estimate Tdust
- Most of the z>6 objects in the 40-50K range, flattening of the Tdust evolution? In tension with Viero+22.



# Perspetives on dust temperature

- Consolidation of the stacking results: better input catalogs with JWST, extensive end-to-end simulations
- Larger ALMA high-frequency samples: gold nugget at very high redshifts? Lensed sources at z>8 found by JWST?
- Long-term: deeper ~100 micron photometry than Herschel (PRIMA? See Laure's talk)

# Summary

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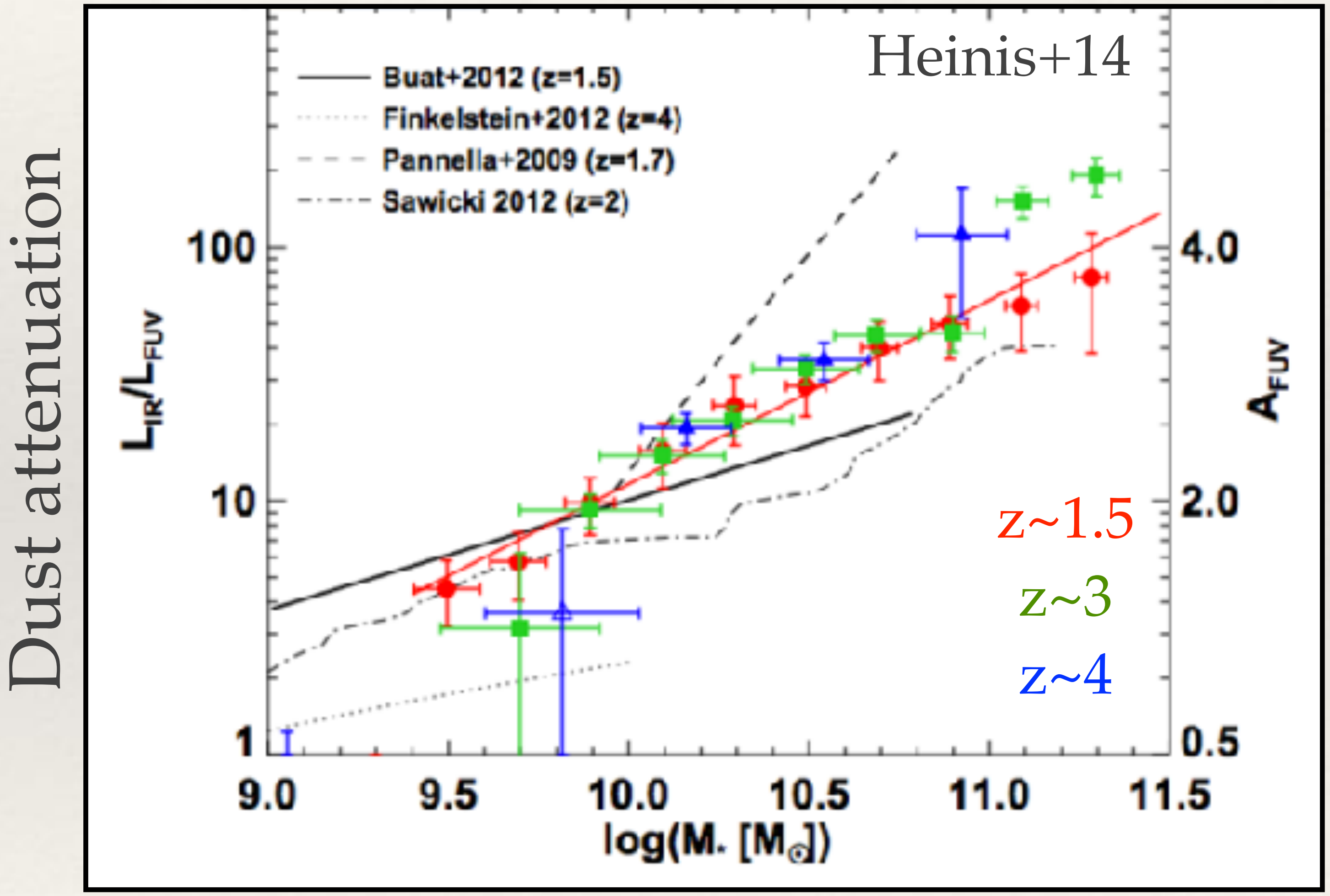
- **Dust-attenuation and obscured star formation**
- Dust and gas content of high-z galaxies

# Herschel: massive galaxies tend to be dustier

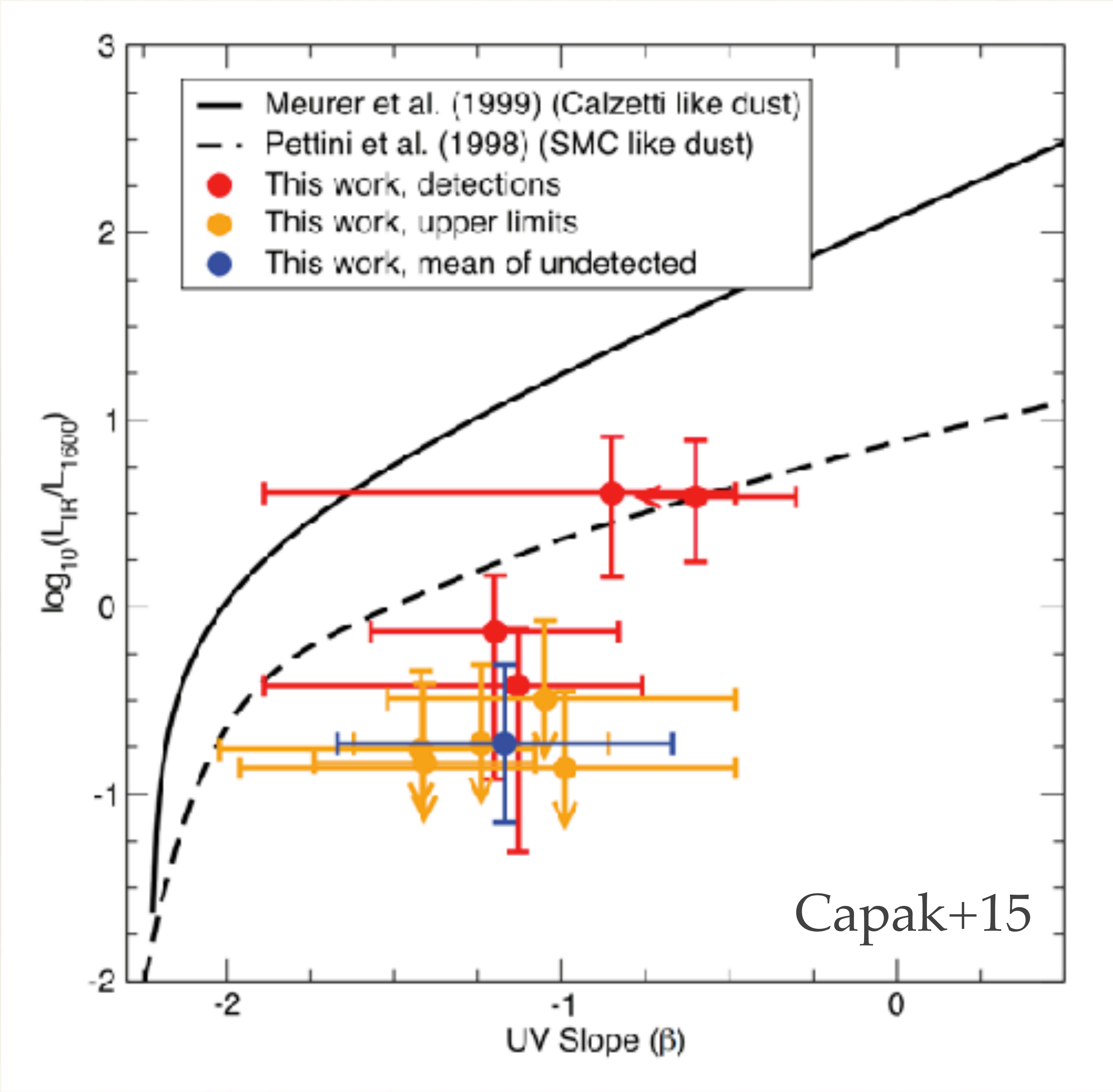
- Average attenuation versus stellar mass measured using Herschel stacking
- Very massive galaxies: ~99% of the UV is absorbed
- Low mass: mostly transparent
- What about higher z?




Stellar mass

# Weak dust continuum in early ALMA observations

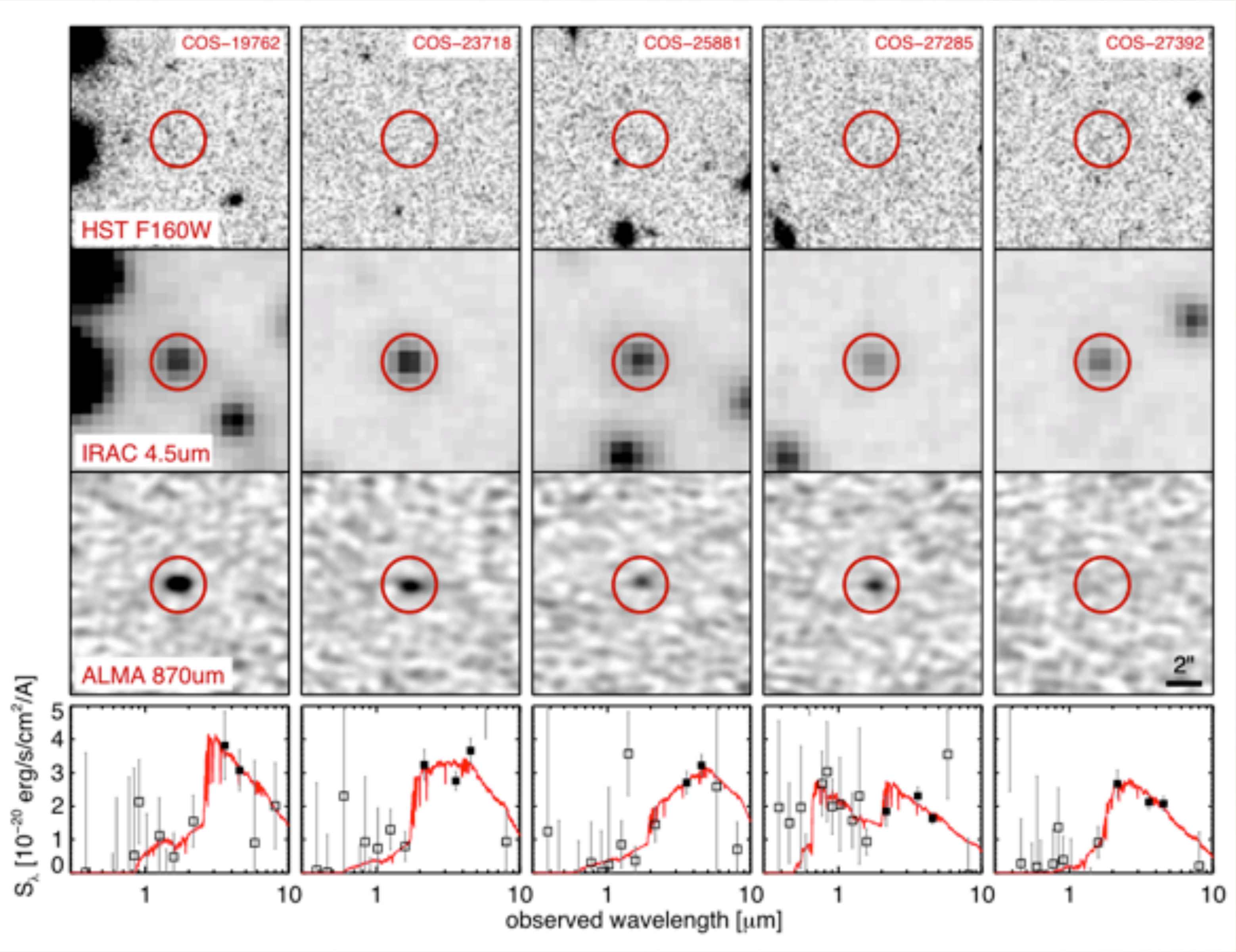
- Early ALMA targets (Lyman break, Lyman alpha emitters): very few continuum detections and even in [CII]
- BUT, analysis problems (marginally resolved sources, e.g. Carniani+21)
- Pilot ALMA z~5 sample: low attenuations (Capak+15)



# Optically-faint IR-bright galaxies

- Discovery of z>3 galaxies detected in the near-IR and by ALMA, but not HST
- Massive objects with strong dust attenuation
- Important galaxy populations missed by optical surveys?

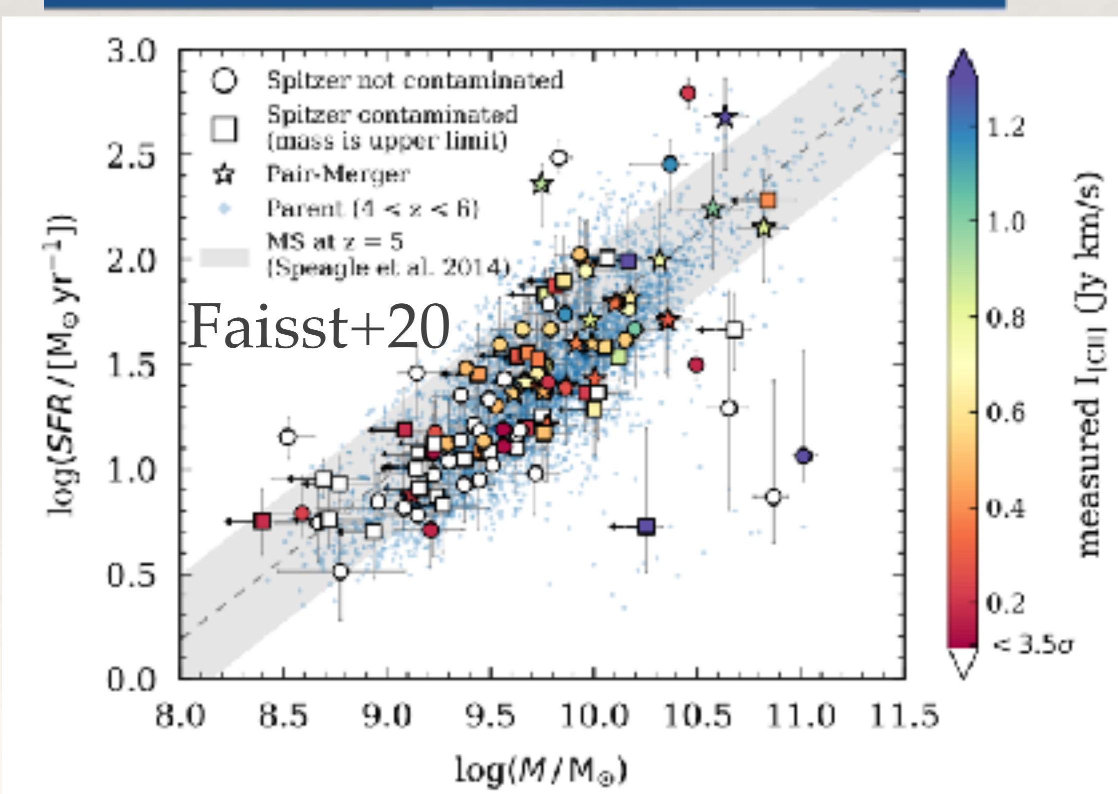
Wang+19

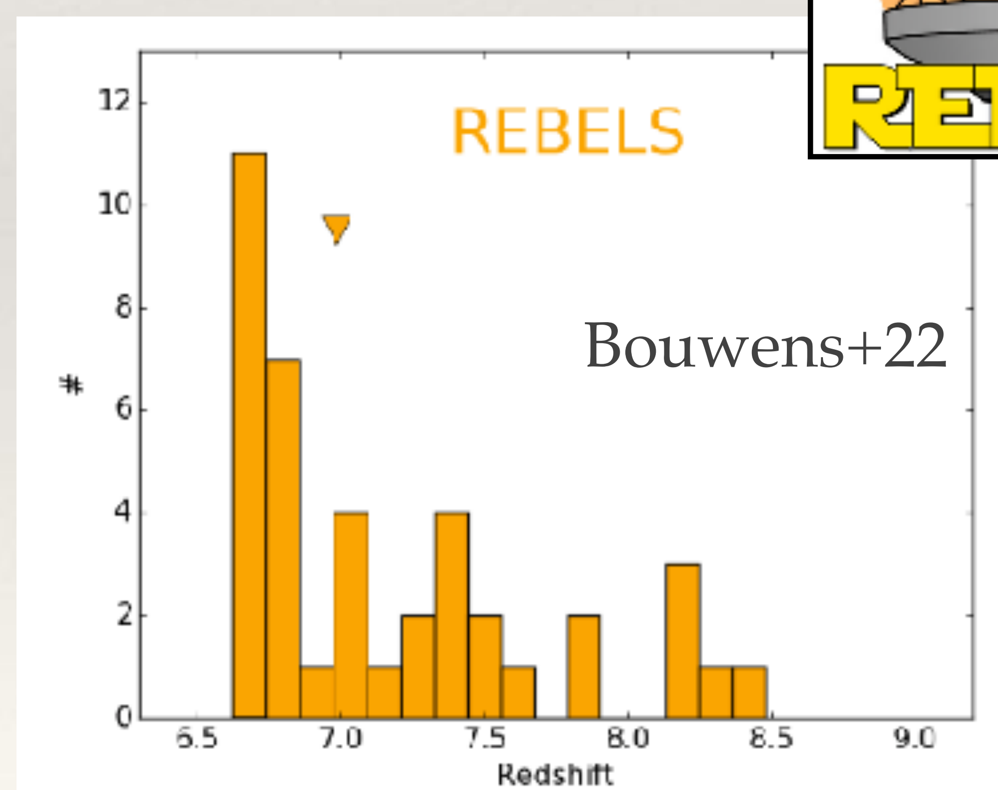


# The ALPINE and REBELS large programs

- ALMA is not very efficient to perform deep blind surveys
- Even the most ambitious deep field, only a handful of z>4 galaxies can be detected
- Other approach for the high-z Universe: target known sources from shorter wavelength (but risk of bias)

A2C2S | ALMA ALPINE [CII] Survey



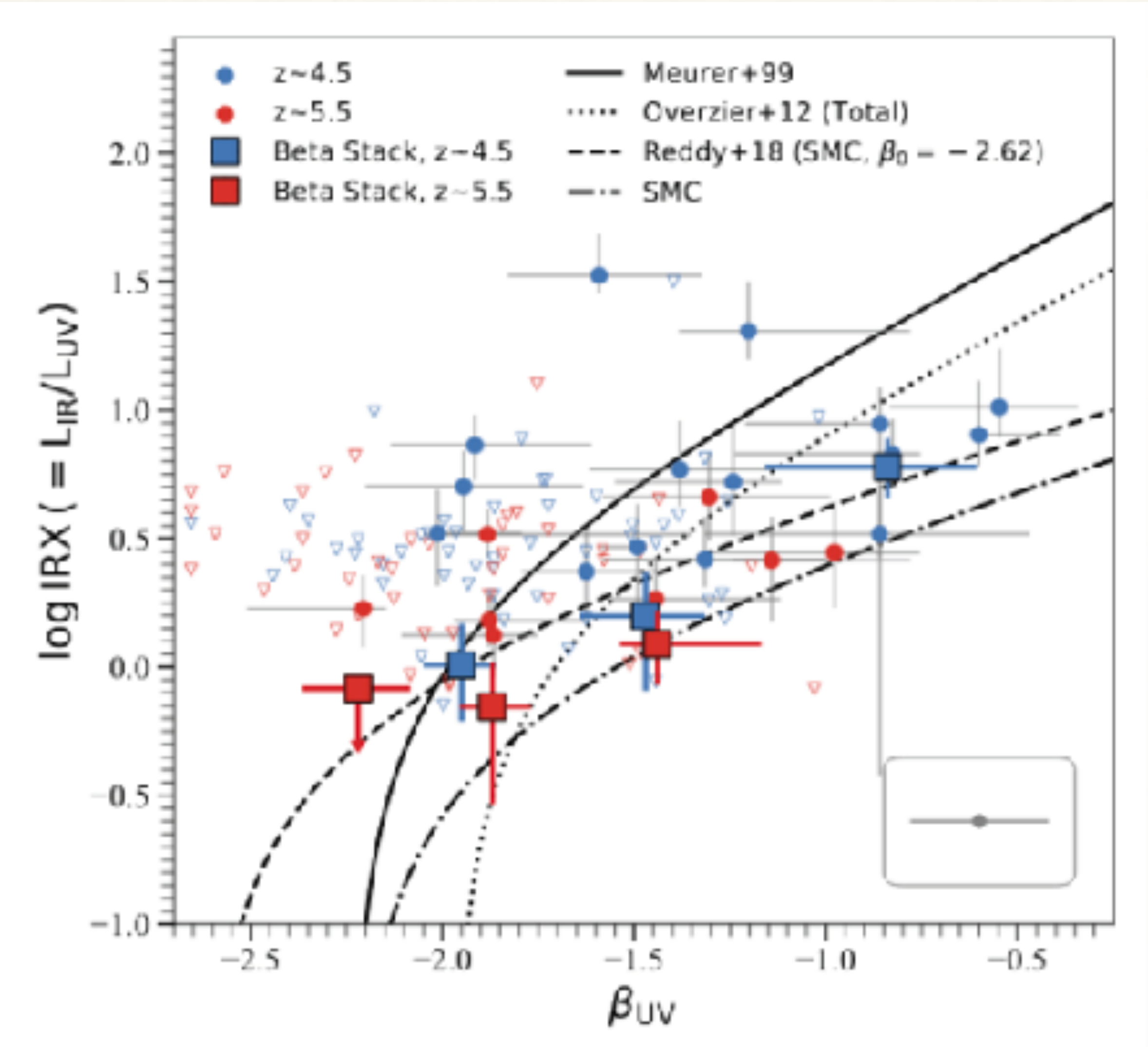

REBELS

References: Le Fèvre+20, Béthermin+20, Faisst+20

Reference: Bouwens+22

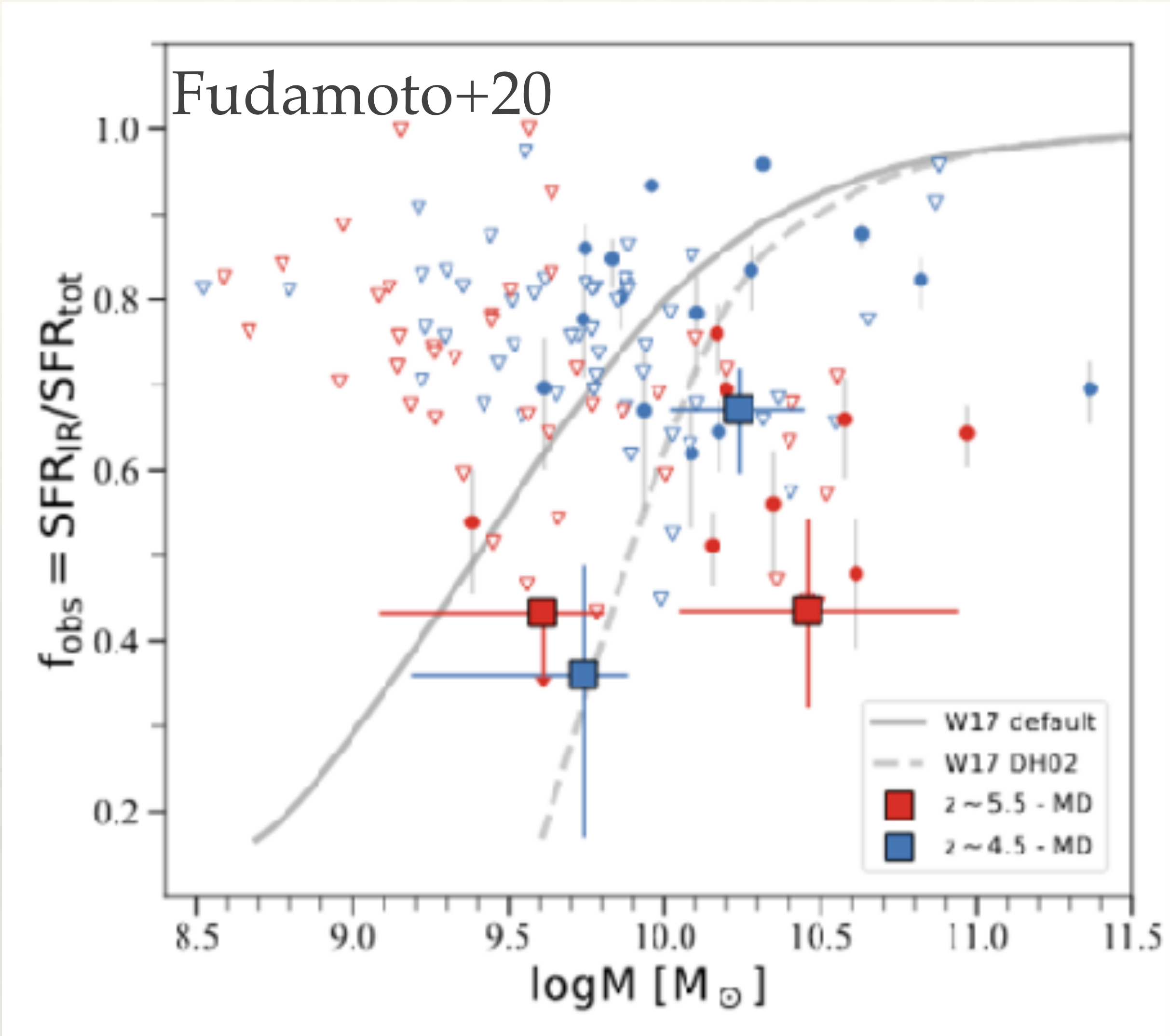
# Dust attenuation vs physical parameters

Ratio between IR and UV luminosity




UV slope

Obscured star formation fraction

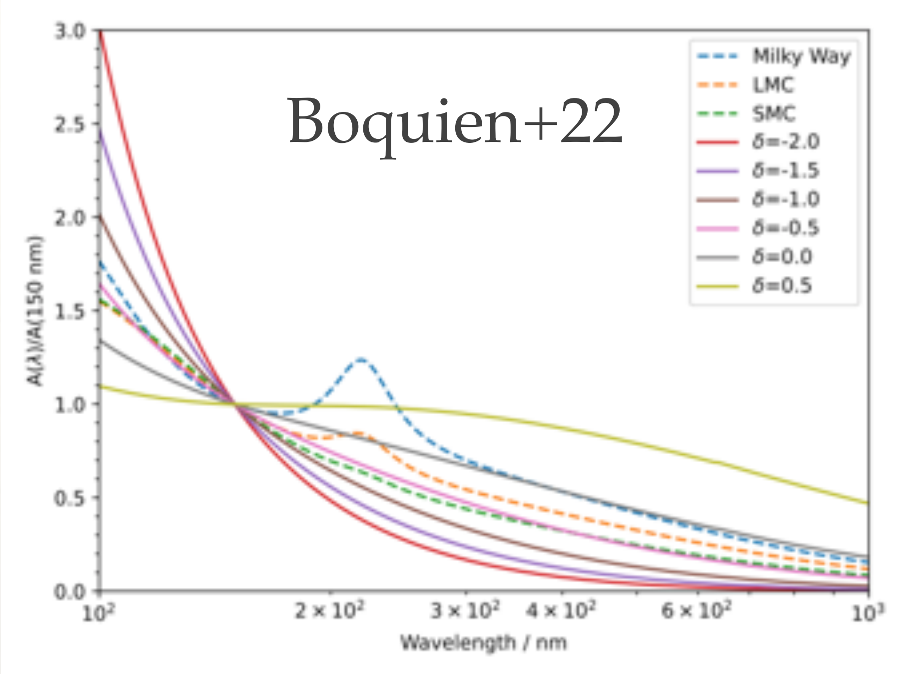


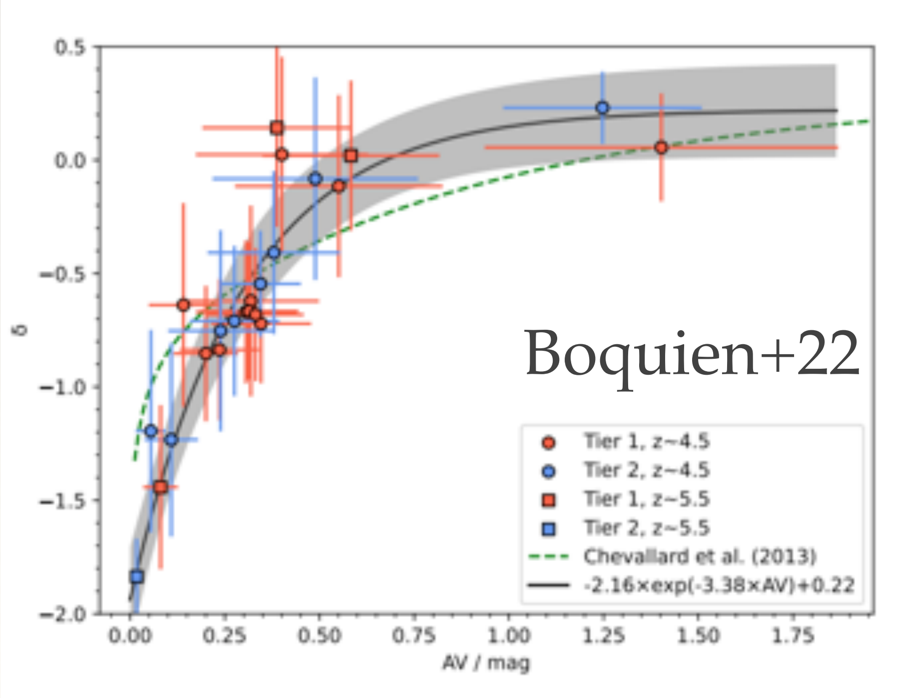

Stellar mass

- Attenuation versus UV slope close from SMC, but a lot of scatter!
- Even at z~5, massive galaxies have ~50% of obscured star formation

# Which attenuation curve in high-z galaxies?

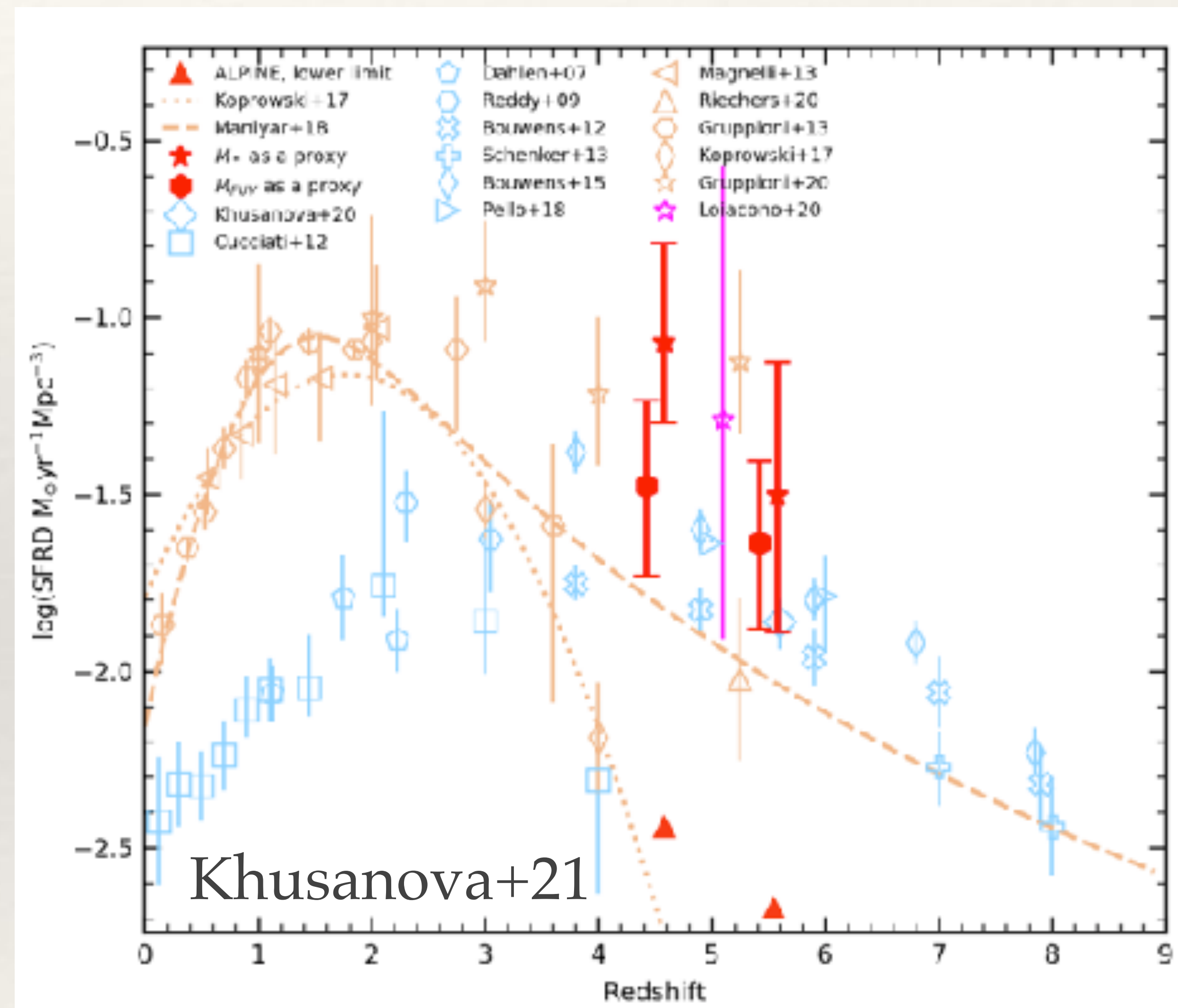
- Hard to explain the panchromatic SED of high-z dusty galaxies without assuming shallow attenuation curves (Buat+19)
- ALPINE: large diversity of attenuation slope, more attenuated objects have flatter curves (Boquien+22)



# Obscured versus unobscured star formation

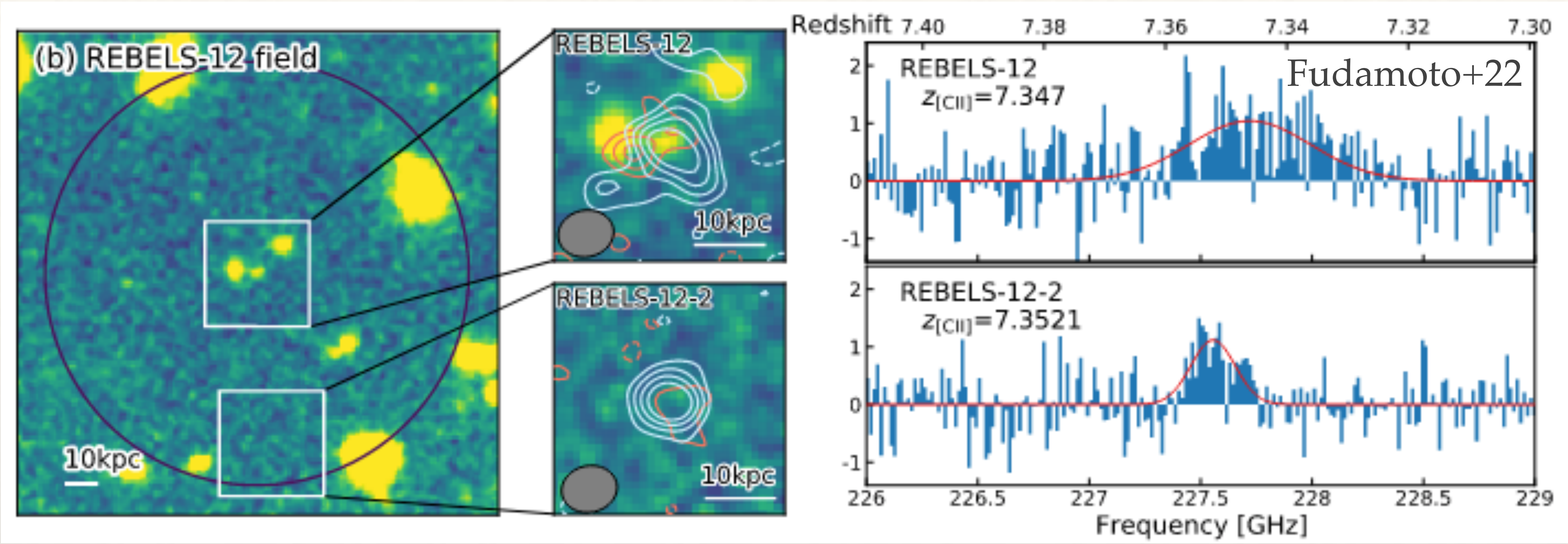
- At cosmic noon, 10x more obscured than unobscured SFR density
- At z~5, close from 50-50%
- Still not clear when the Universe stops to be dust free



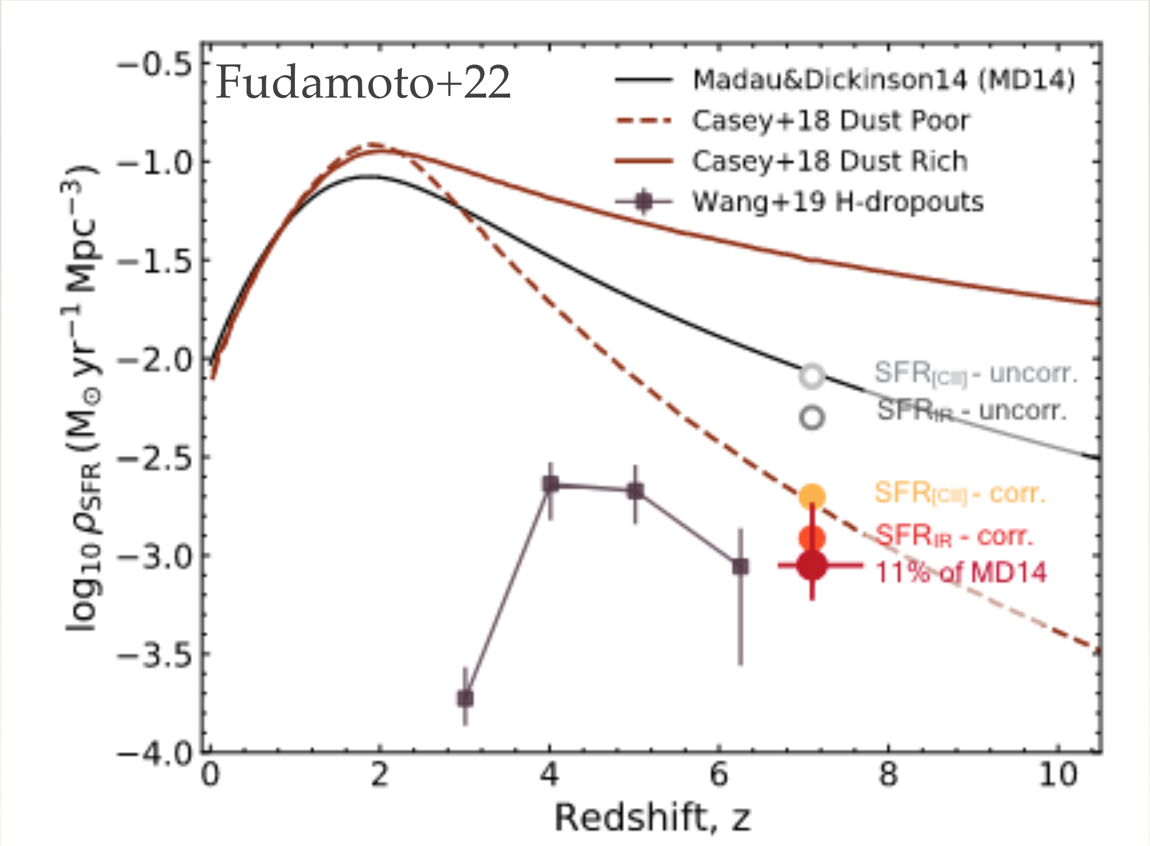

Star formation rate density

Redshift

# Dust at even higher z?




- Discovery of 2 dusty galaxies without HST counterparts at z~7
- Implies a non-negligible contribution of obscured galaxies still contributing to star formation at z~7



# Perspectives on dust attenuation

- Resolved dust attenuation maps combining ALMA in extended configuration with HST+JWST
- Wide sub-mm surveys to find rare massive and dusty systems (30m/NIKA2, LMT/TolTEC)
- Better coverage from the mid-IR to the millimeter to better measure LIR and break degeneracies between attenuation laws (PRIMA?)

# Summary

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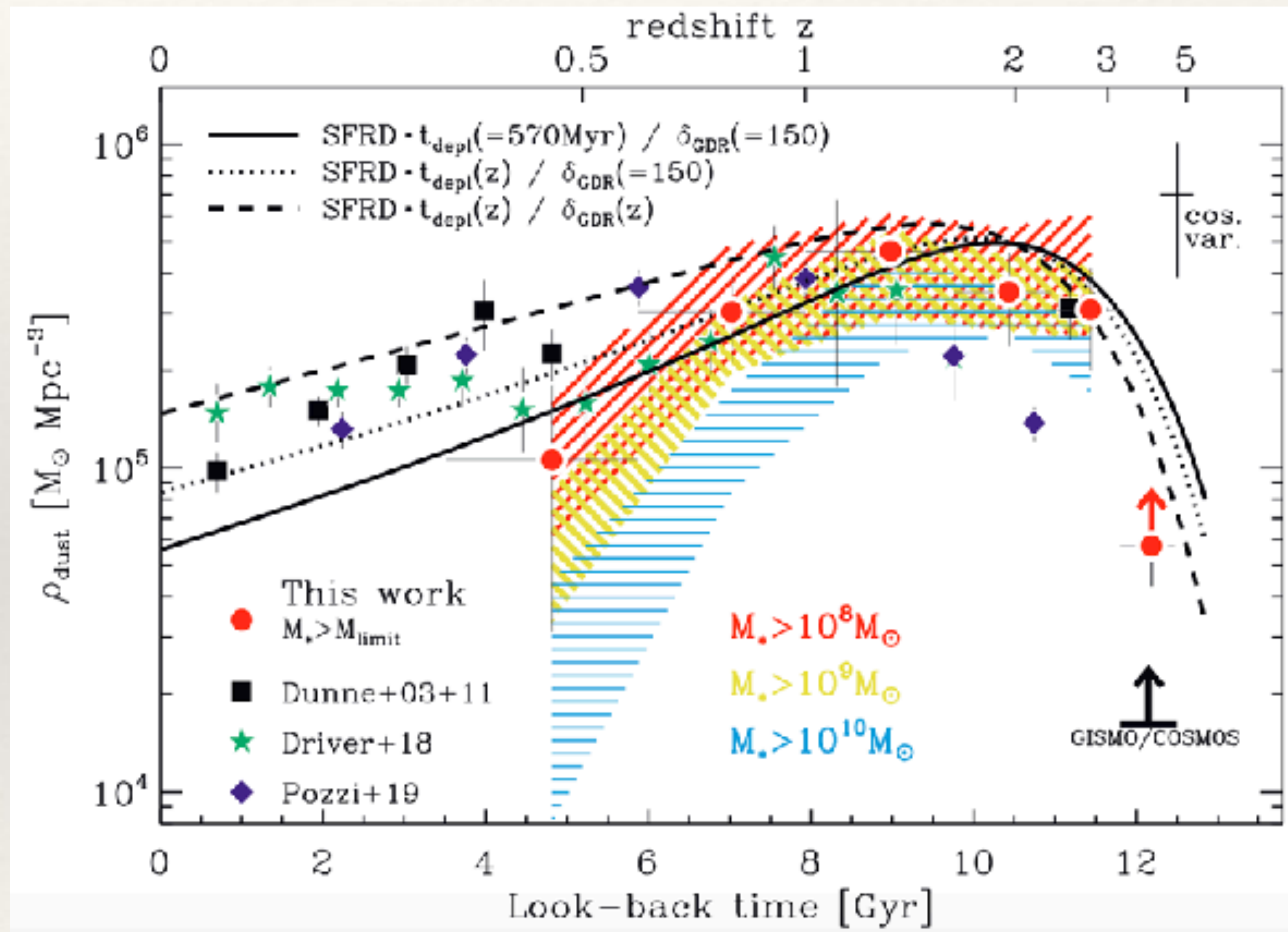
# Cosmic dust density

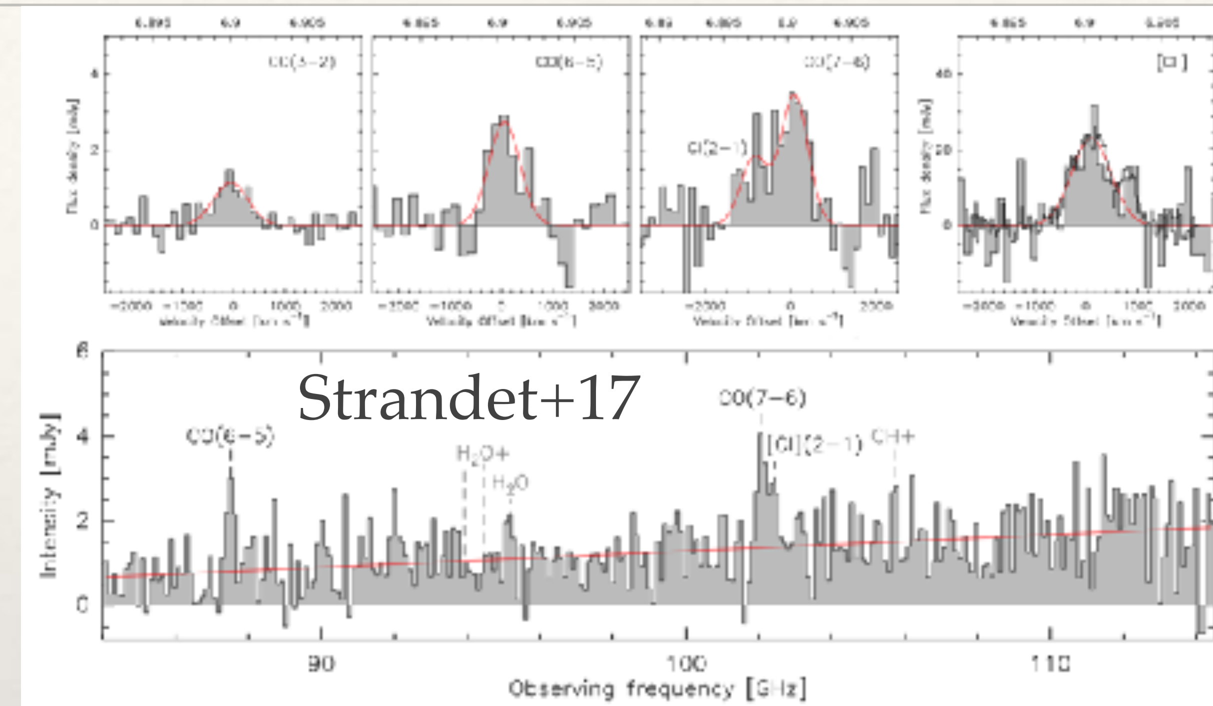
- Millimeter surveys allow to derive the cosmic dust density history
- Maximal dust content around cosmic noon

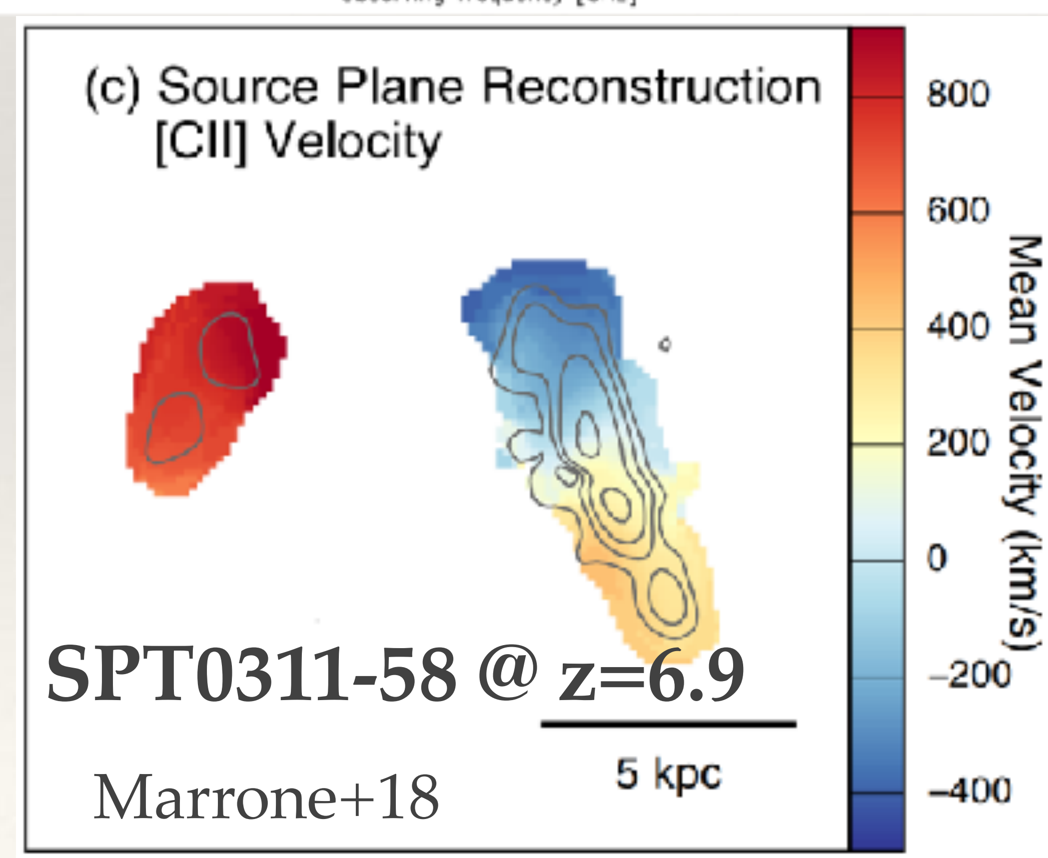
Magnelli+20



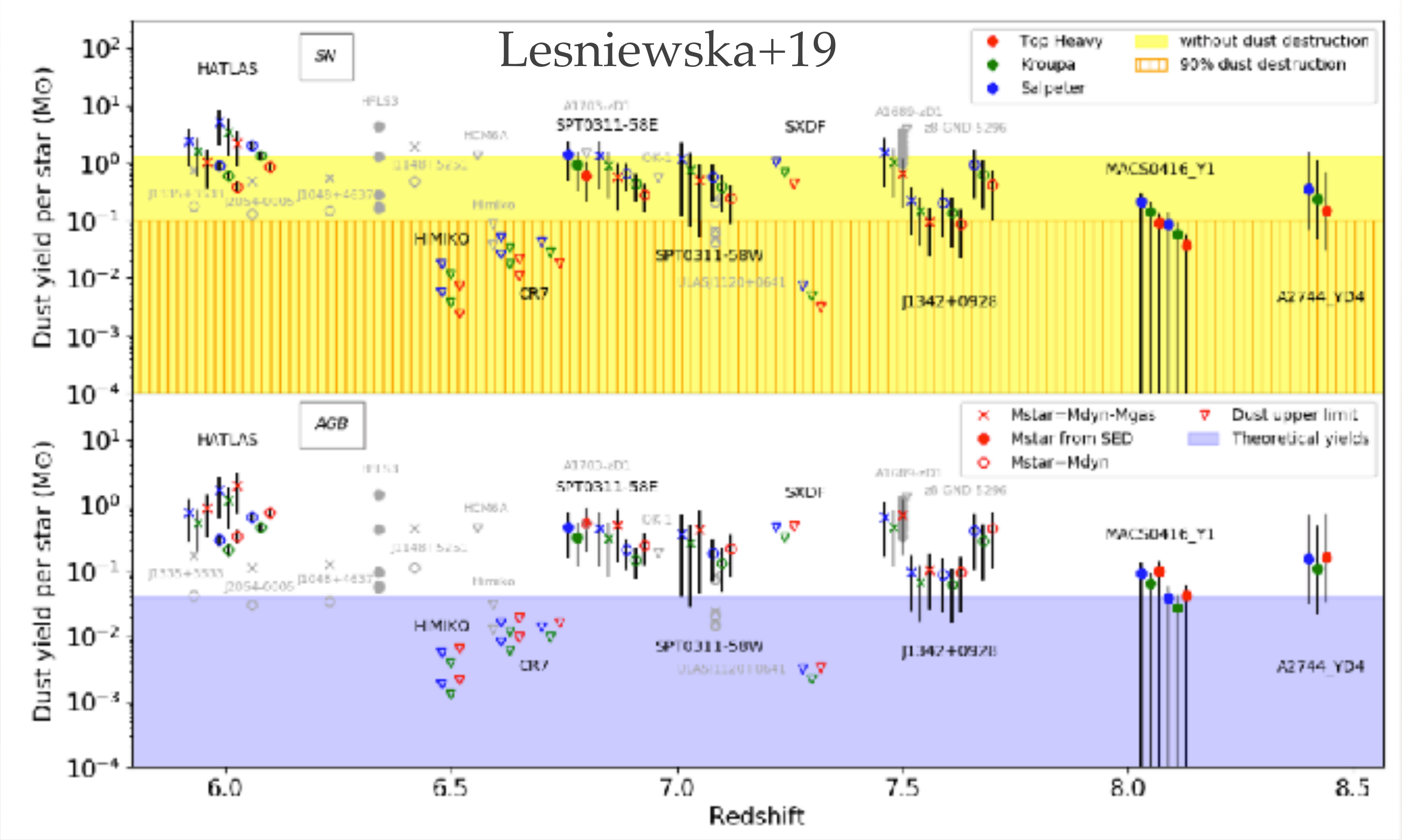
# Extremely dusty starbursts

- Current record for a mm-selected galaxy: SPT0311-58 at z = 6.9
- SFR~2900 Msun/yr
  Mgas ~ 2 x $10^{11}$ Msun
  Mdust ~ 2 x $10^{9}$ Msun
- Huge amount of dust very early in the Universe



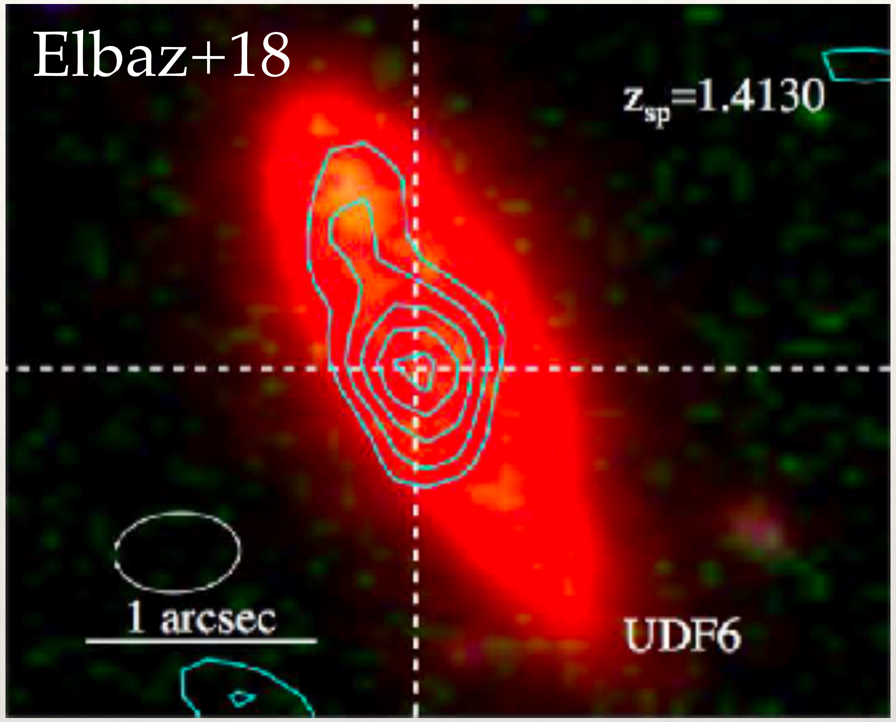
# Where does this dust come from?

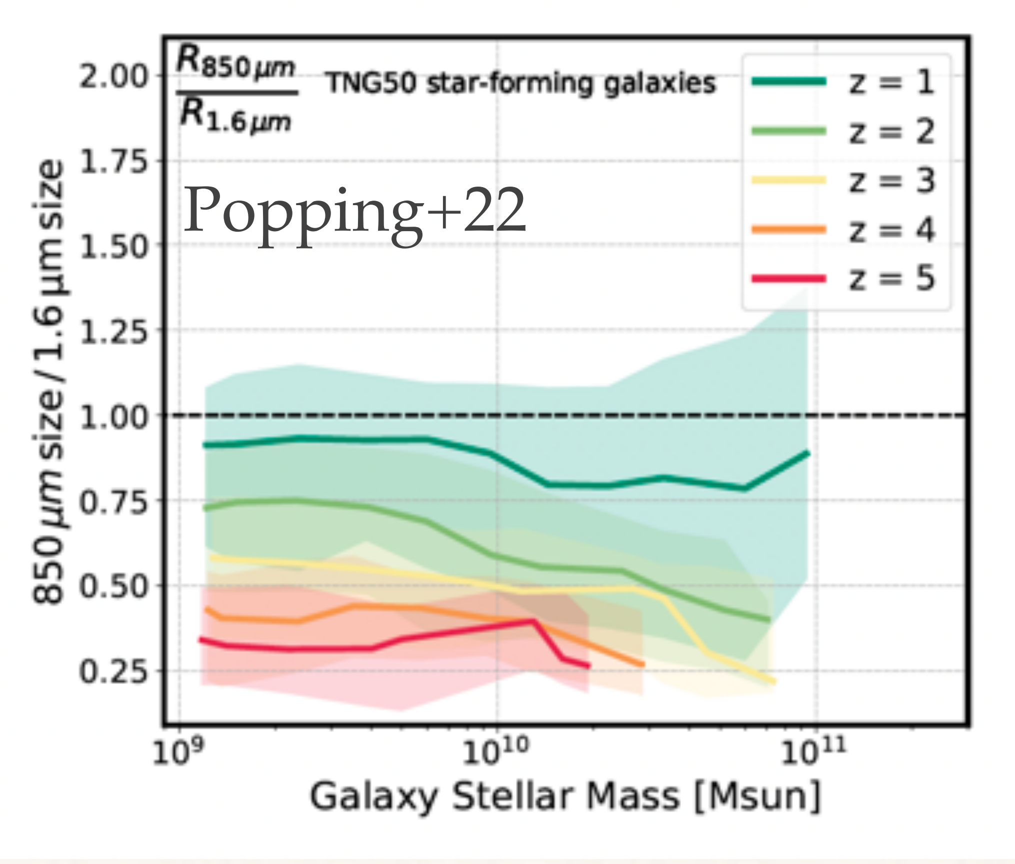



- The measured dust masses at high redshift are at the limit of what we can explain. It needs a very low dust destruction by supernovae.
- However, there are many caveats on the modeling and the measurement of the dust masses (e.g., Ferrara+16)
- More discussion in Denis' talk!

# Morphological mismatches

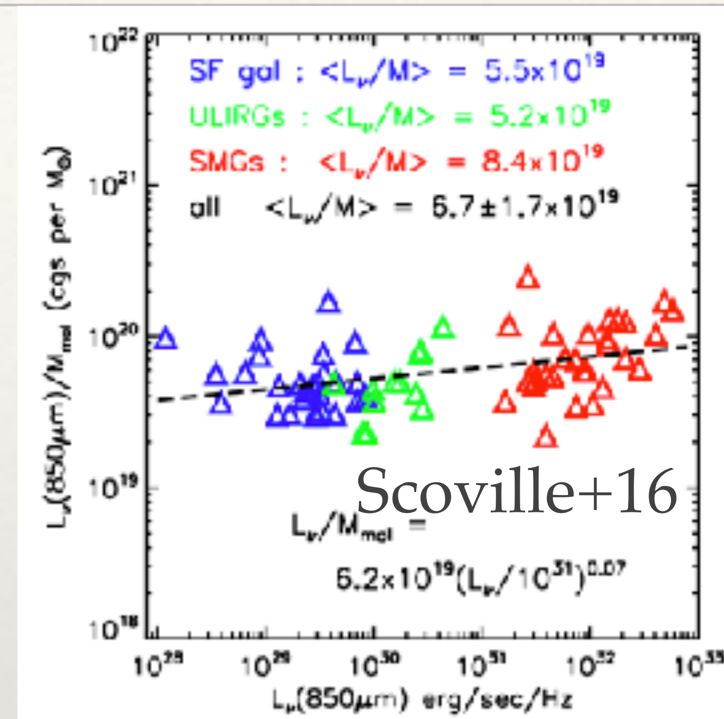
- Optical/near-IR and ALMA morphologies can be very different
- Simulations: dust not really more compact than stellar component, mostly an effect of dust attenuation (e.g., Popping+22)

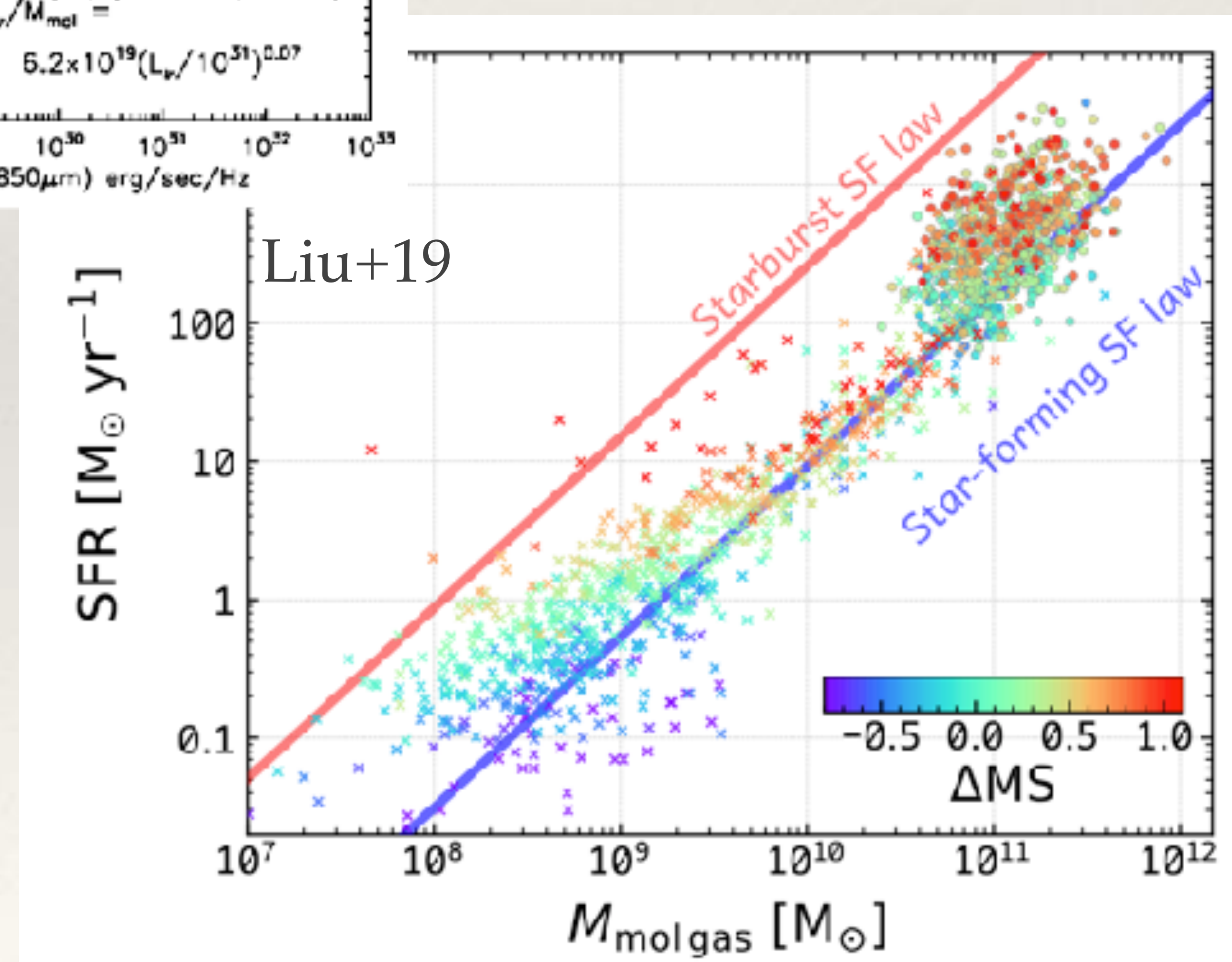


# Dust continuum as a gas tracer

- Rayleigh-Jeans continuum of galaxies advocated as a quick gas tracer of galaxies (e.g., Scoville+16)
- Most of high-z galaxies on the star-forming sequence



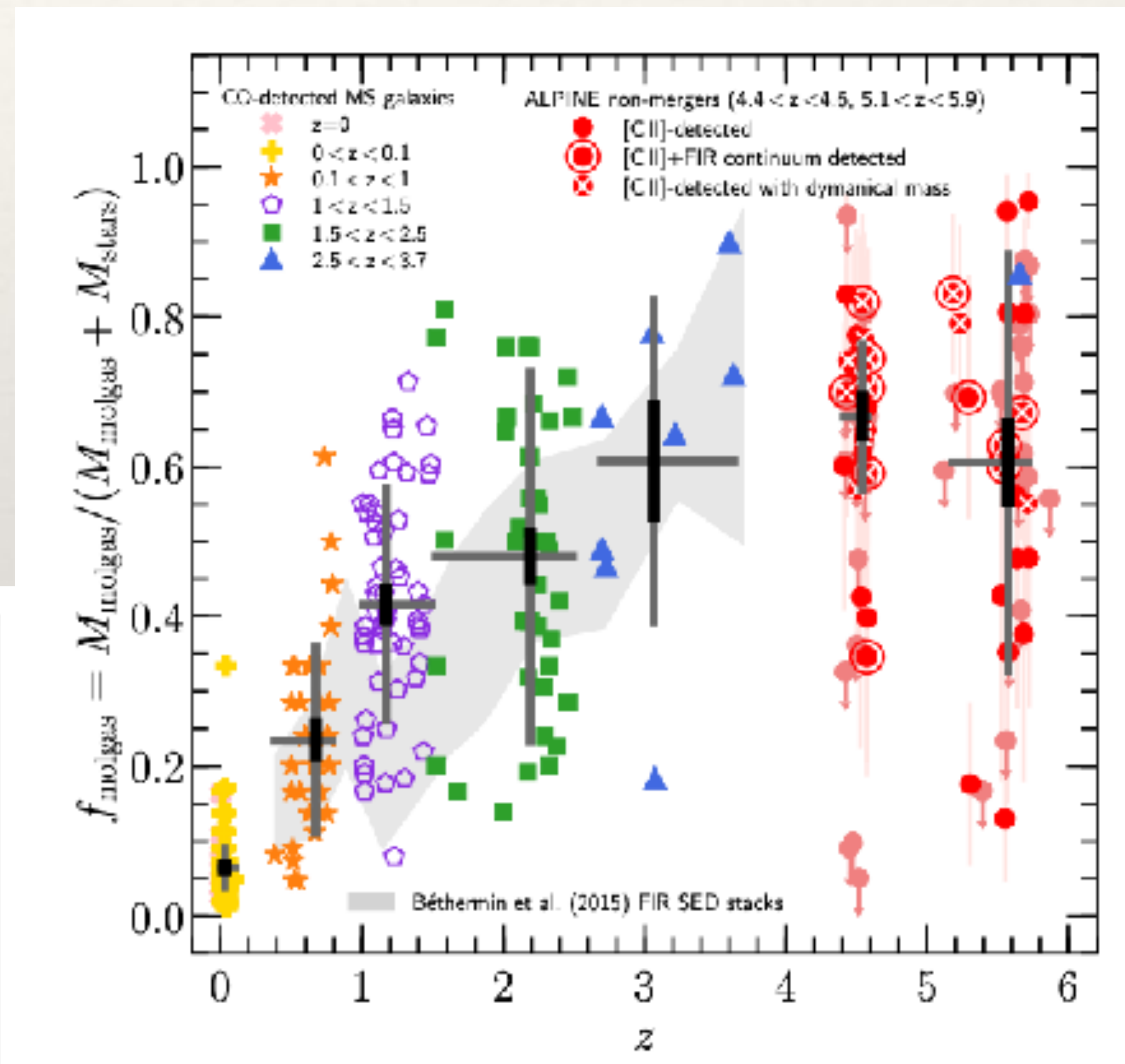



# [CII] and dust as gas tracers at high redshift?

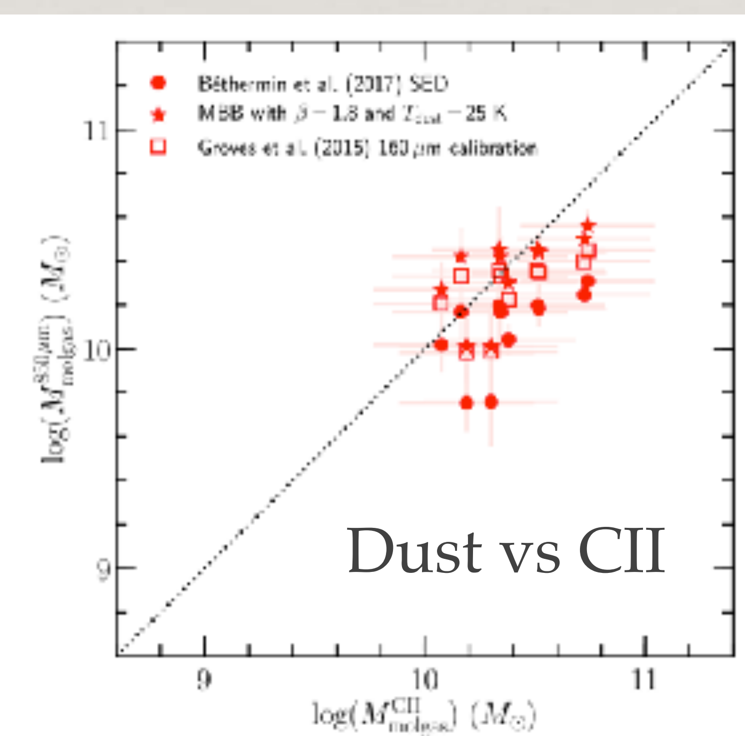
- Overall agreement between the various gas tracers
- Flattening at z>3

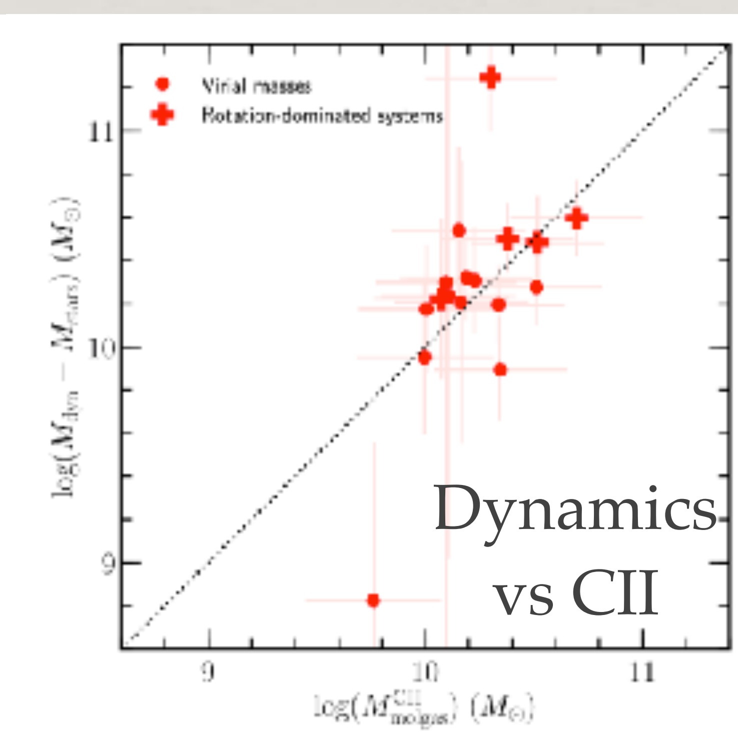
Dessauges-Zavadsky+20

Gas fraction




Redshift



# Perspectives

- Dust content versus metallicity based on JWST
- Better calibration of dust-based gas tracers (using dynamics from high-resolution ALMA data?)
- Improve the models of high-z dust enrichment (see Denis' talk)

# Conclusion

- Dust is already present in the early Universe especially in massive galaxies
- Dust temperature increases with increasing redshift (explanation debated)
- Obscured star formation still important at z~5, some massive galaxies missed by optical surveys
- Quick dust formation in massive systems. Large gas fractions at z>4.