ALMA unveils the dust properties of galaxies at cosmic noon

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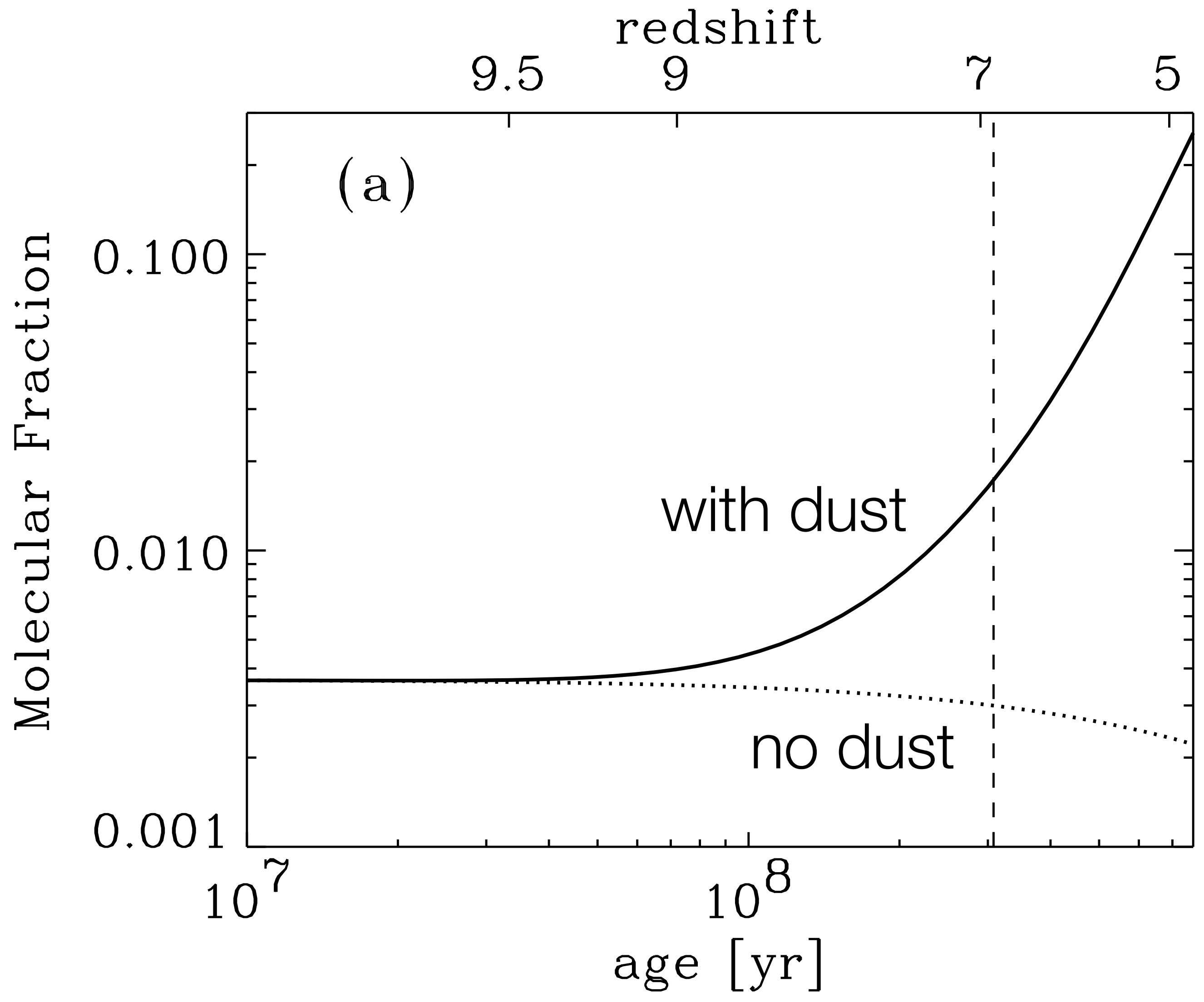
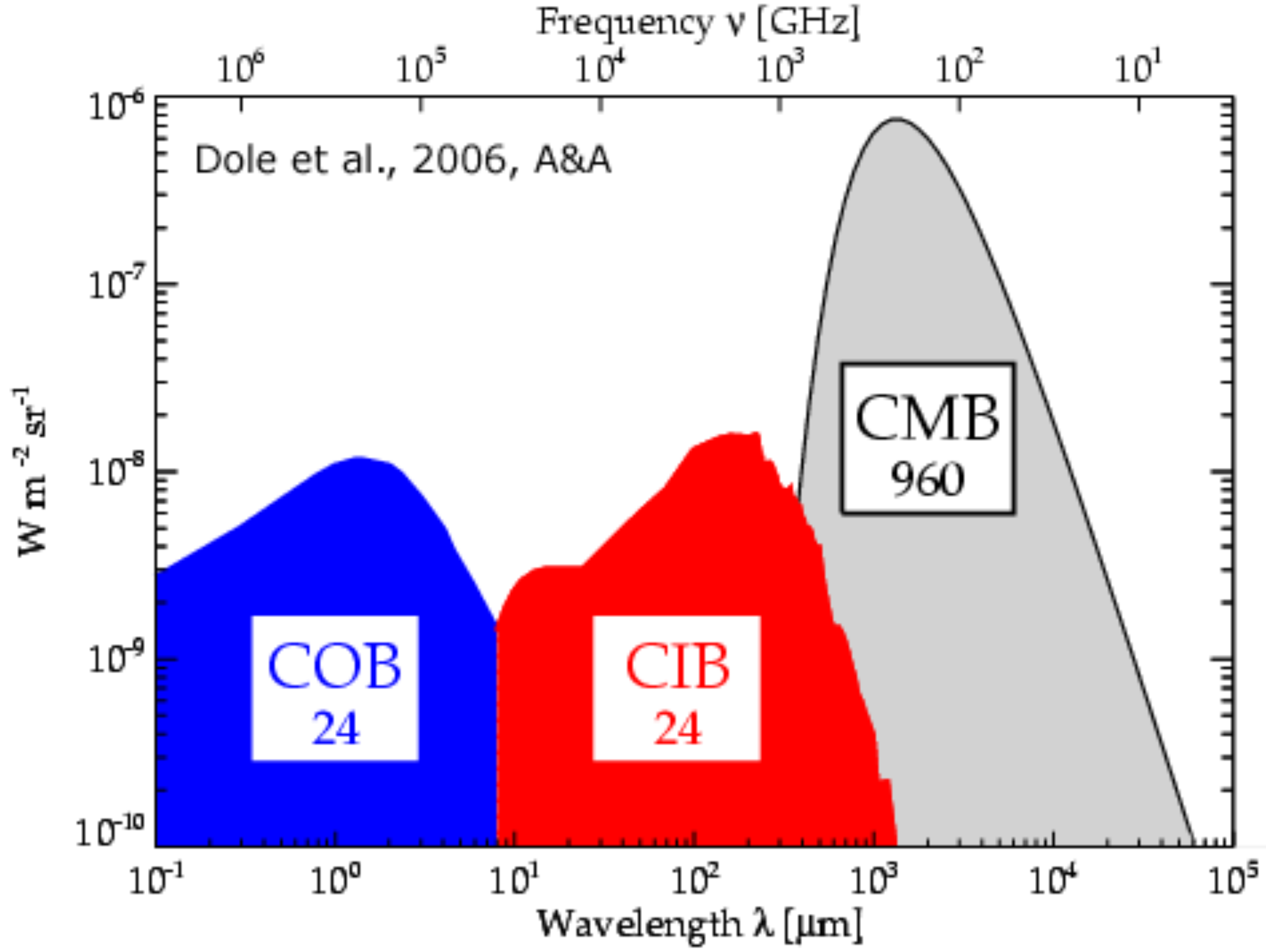
Dust plays a crucial role in galaxy assembly

Dust grains are a site of efficient H_2 formation which leads to star formation which leads to galaxy assembly.

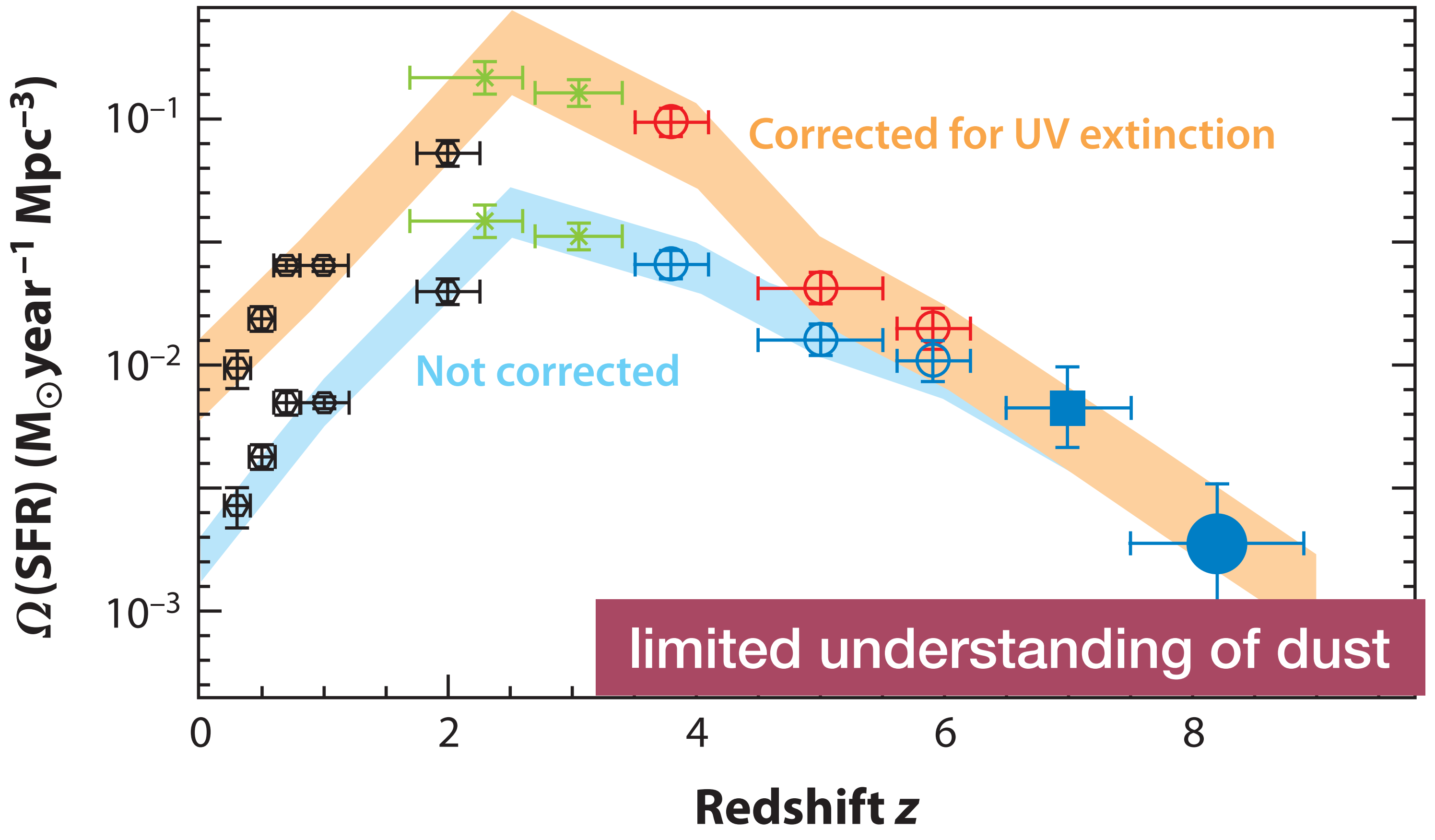


Hirashita & Ferrara (2002)

Dust grains reprocess half of all the UV/optical light in the Universe which affects how we observe galaxy assembly.



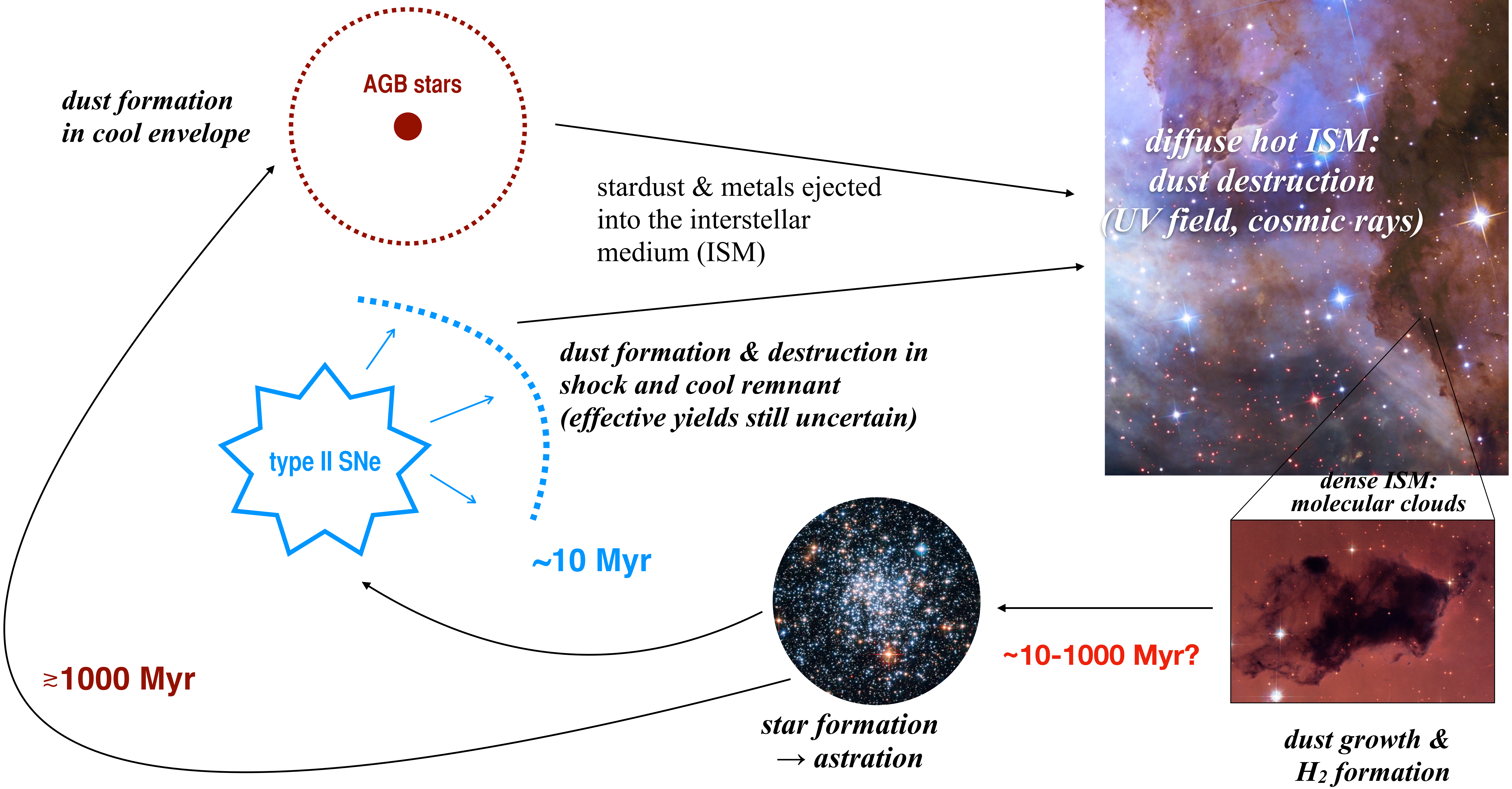
The exact contribution of dust-obscured star formation to the cosmic SFR density at z>3 remains unknown.



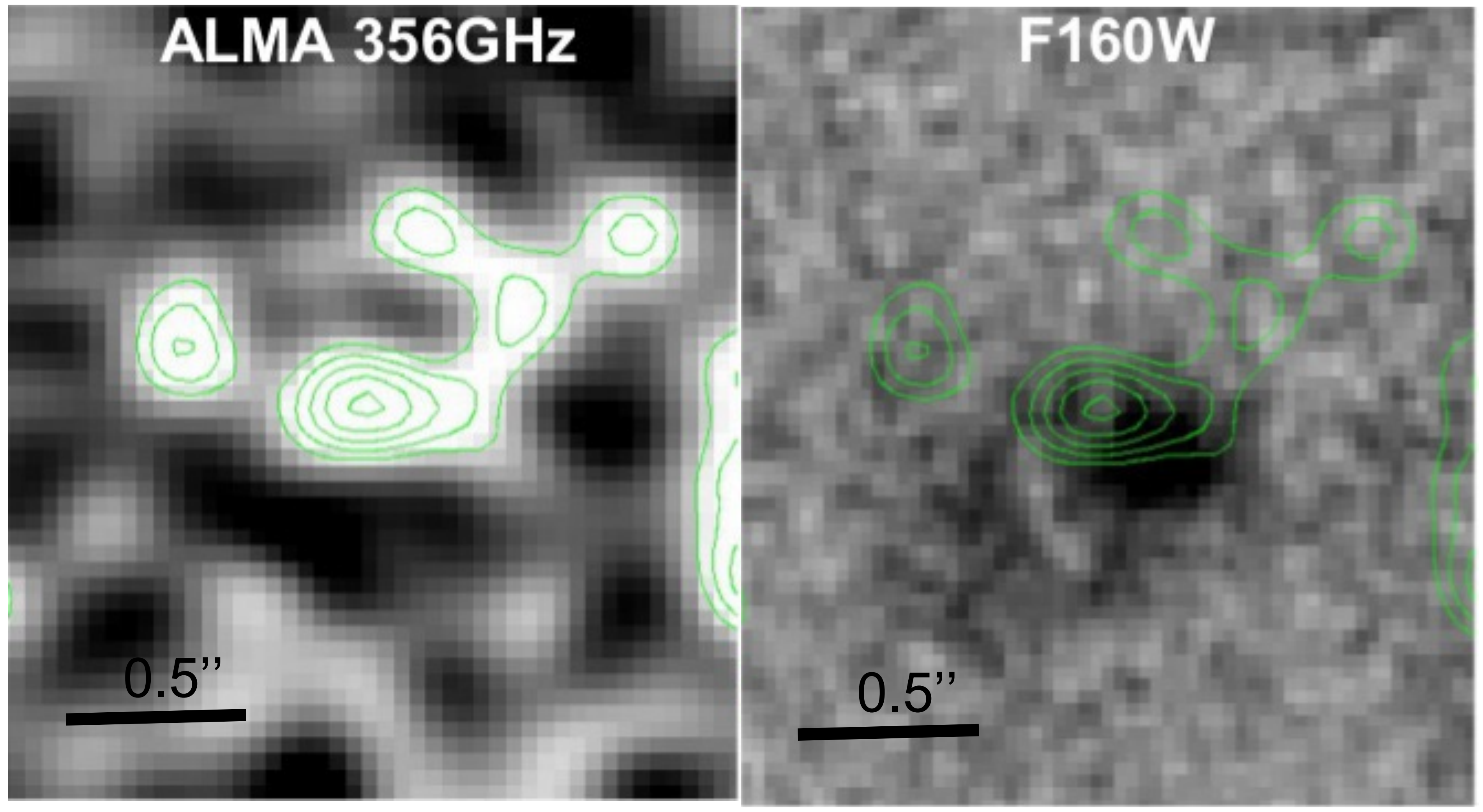
(adapted from Bouwens+2010)

The lifecycle of dust

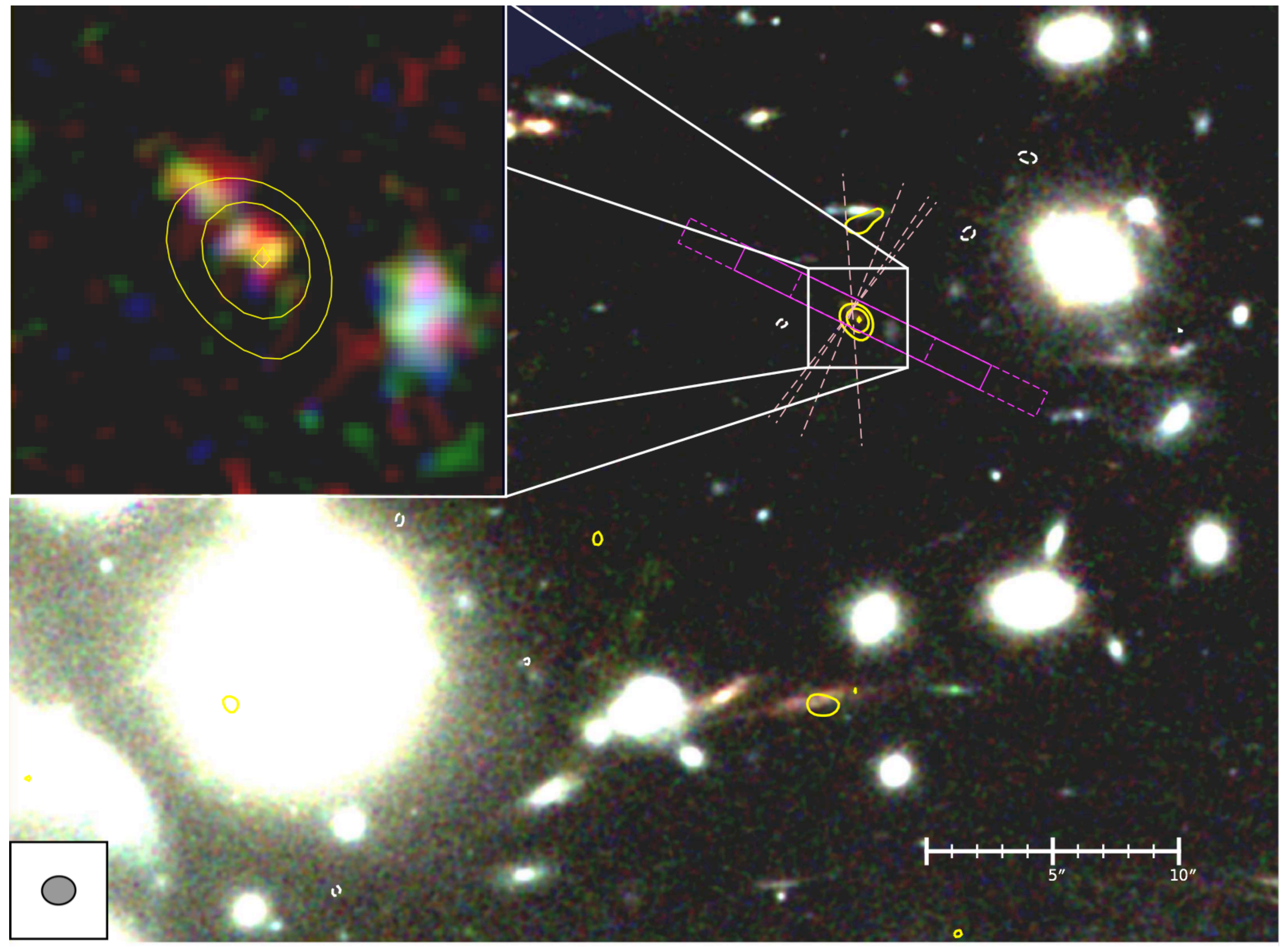
e.g., Dwek 1998; Dwek & Cherchneff 2011; Zhukovska et al. 2008; Zhukovska 2014



A dust budget crisis?

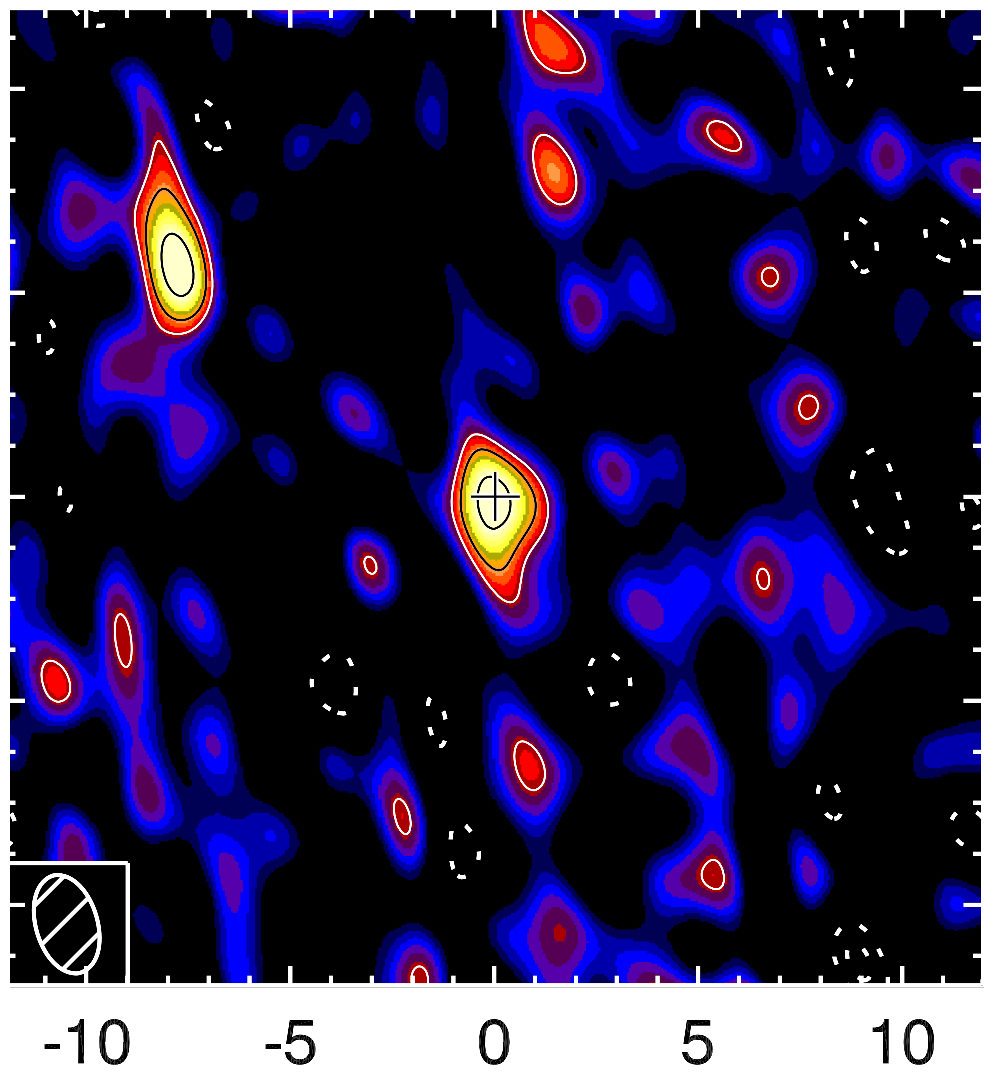


Laporte+2017



Watson+2015

223.5 GHz continuum



Venemans+2017

z=8.38
stellar mass ~ 2 x 10^9 Msol
SFR ~ 20 Msol/yr
dust mass ~ 6 x 10^6 Msol

z=7.5
stellar mass ~ 2 x 10^9 Msol
SFR ~ 9 Msol/yr
dust mass ~ 4 x 10^7 Msol

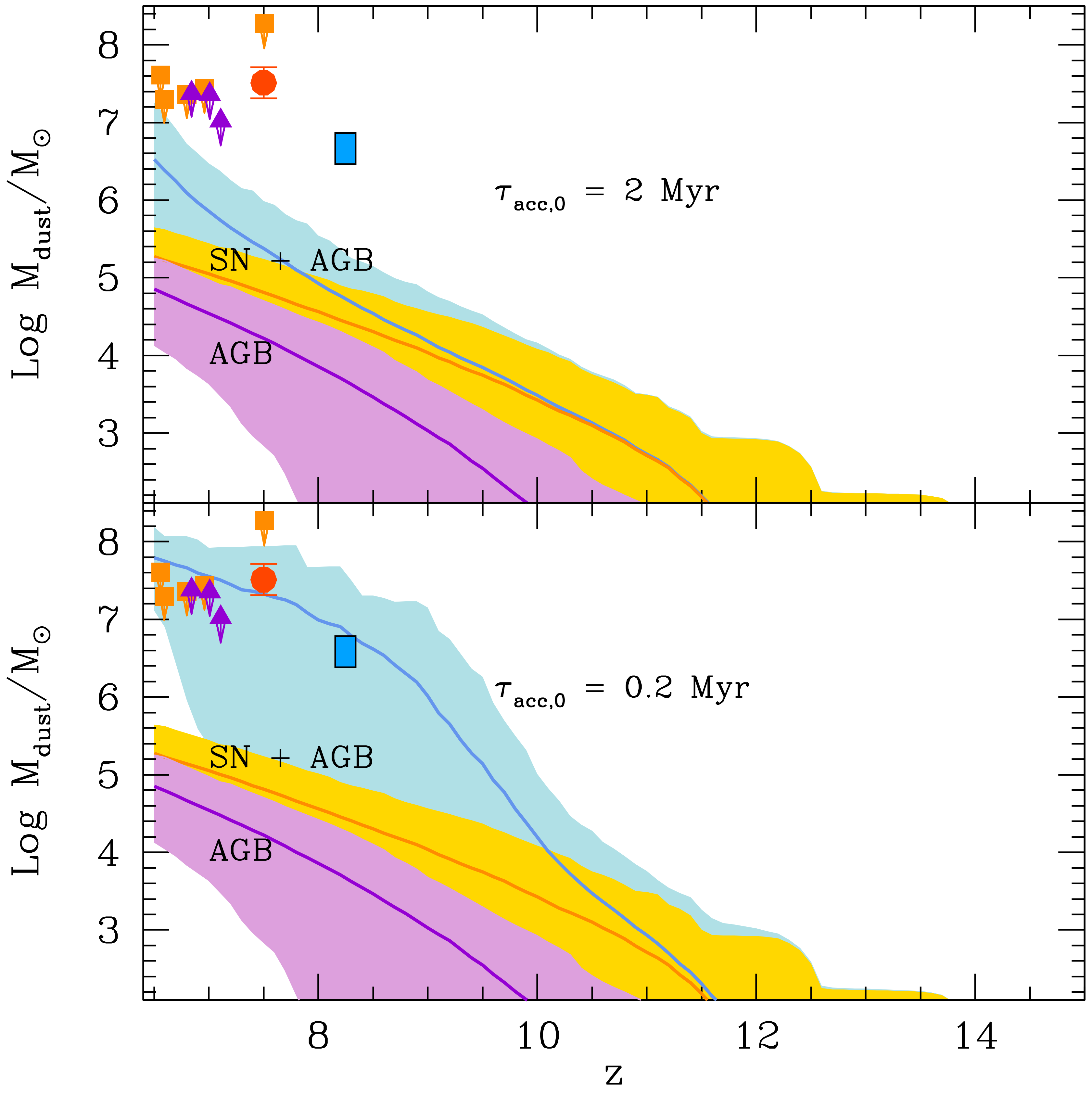
z=7.54
stellar mass ~ unknown (QSO)
SFR ~ 20-300 Msol/yr
dust mass ~ 3 x 10^8 Msol

Often in excess of local Mdust/Mstar relations (e.g., da Cunha+2010)!

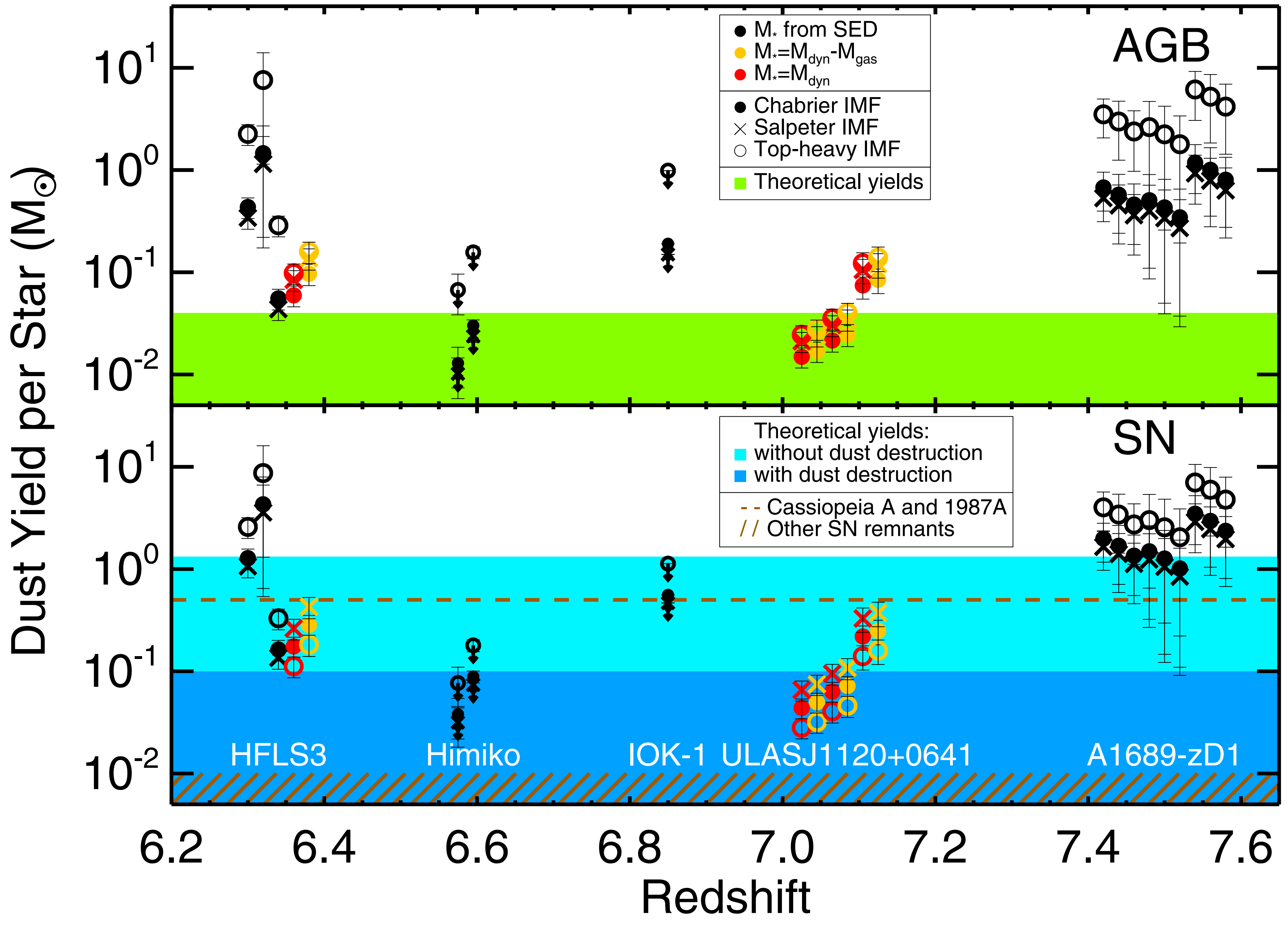
How are these huge dust masses being produced so early?

A dust budget crisis?

Mancini+2015



Michalowski+2015 (see also Rowlands+2014)



To explain measured dust masses, we need **either high SN yields, or fast ISM growth**.

…but, e.g., Ferrara+2016 say this is 'problematic' because dust growth at high-z can only occur in cooler dense MCs but icy mantles do not survive in the diffuse ISM.

Are we measuring dust masses accurately?

$$M_{\rm dust} \propto L_{\rm dust} T_{\rm dust}^{-(4+\beta)}$$

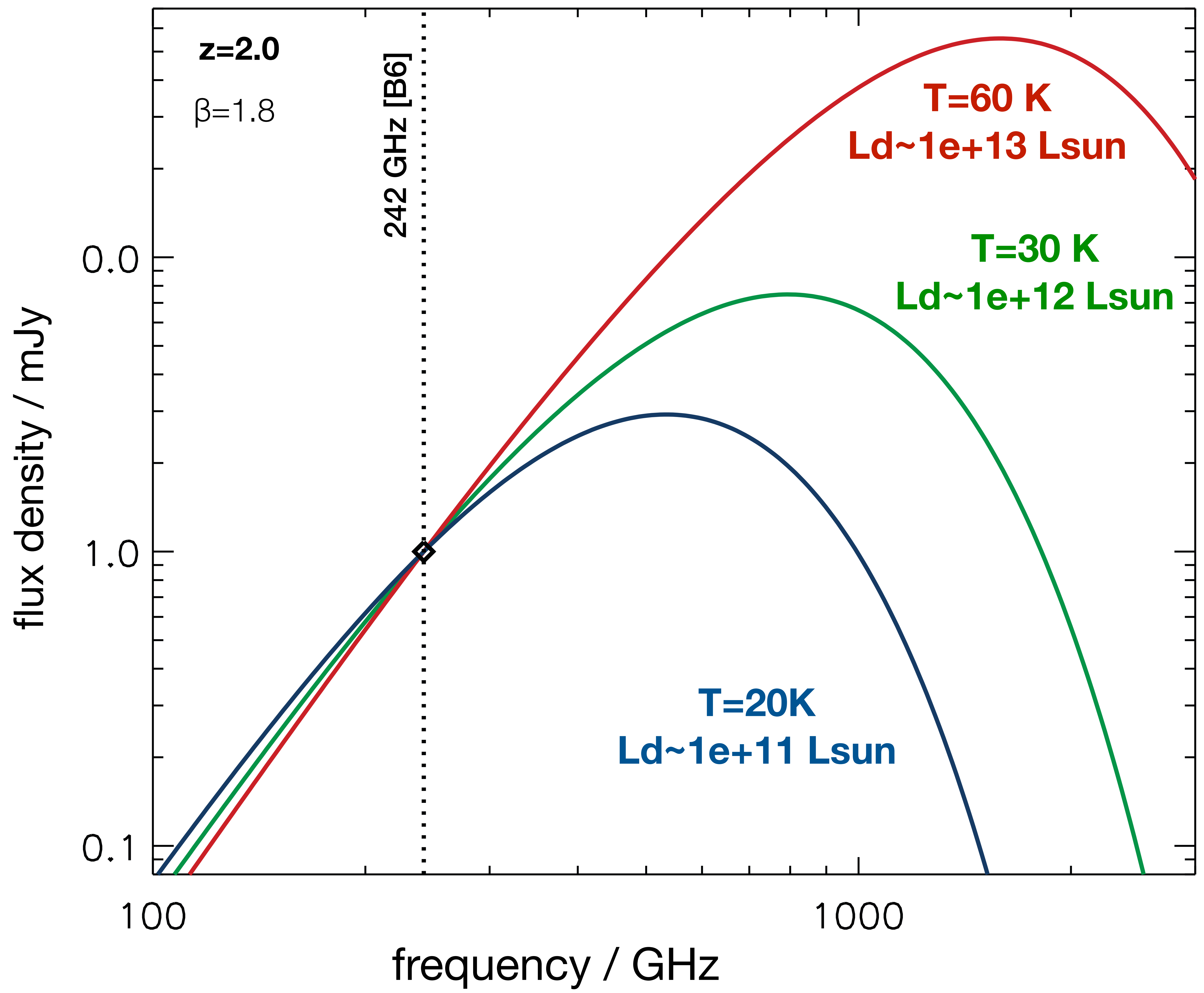
e.g., Hildebrand 1983 (isothermal, optically thin dust in thermal equilibrium)

Errors in assumed T and β can lead to order of magnitude systematics in total luminosity and mass!

L, T -> sample peak of the emission

β -> sample RJ regime

Need both to break degeneracies!



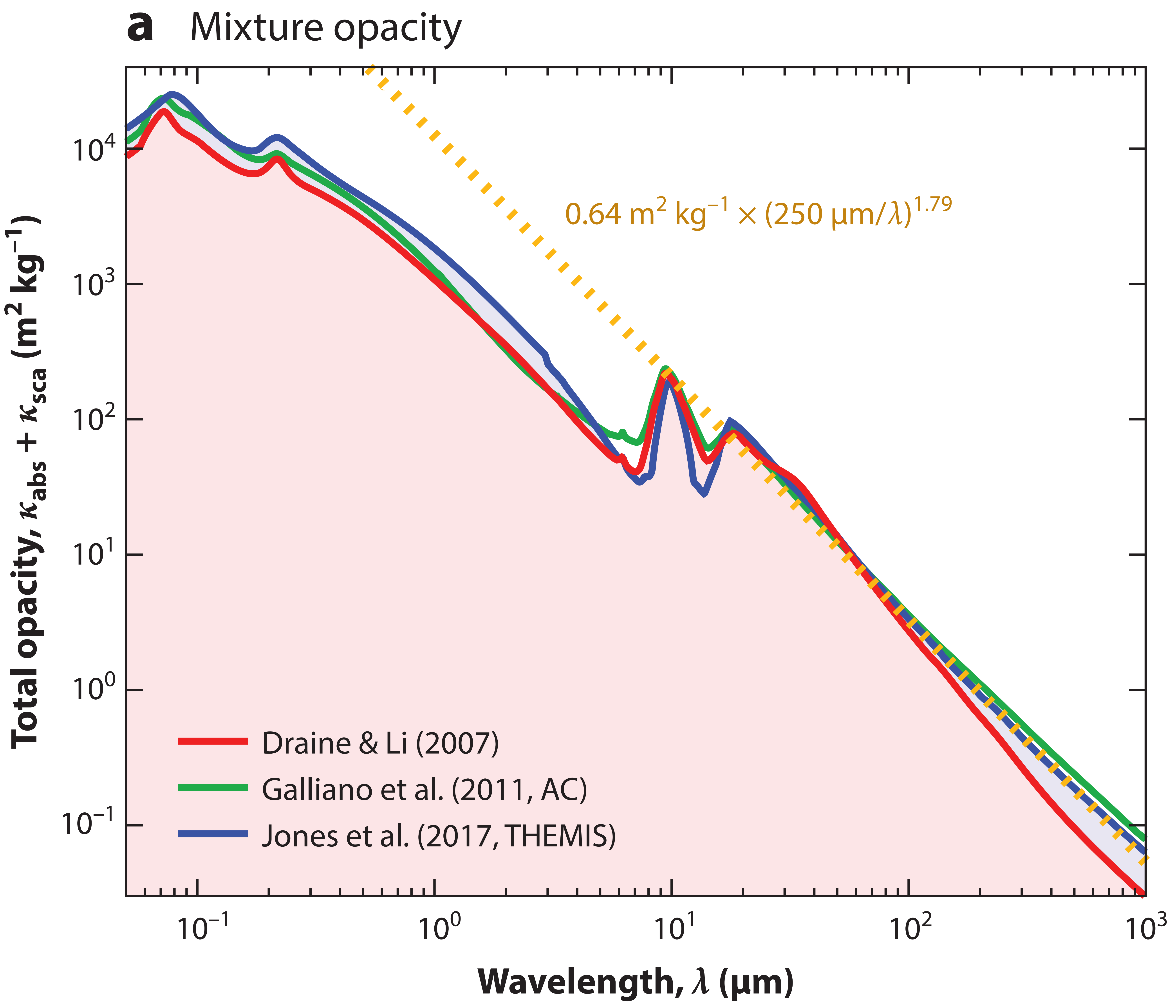
Dust emissivity

$$\kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta$$

Different dust mixtures -> different emissivities

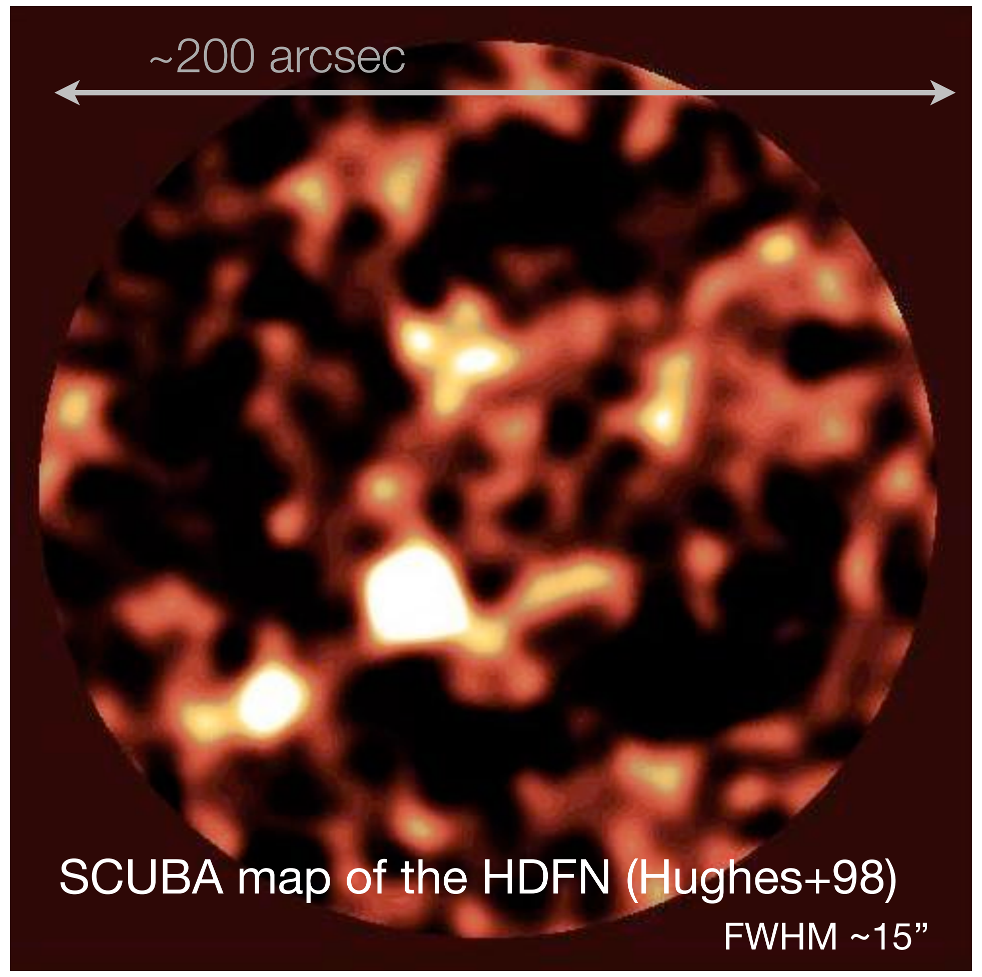
Local studies: β~2 (with variations)

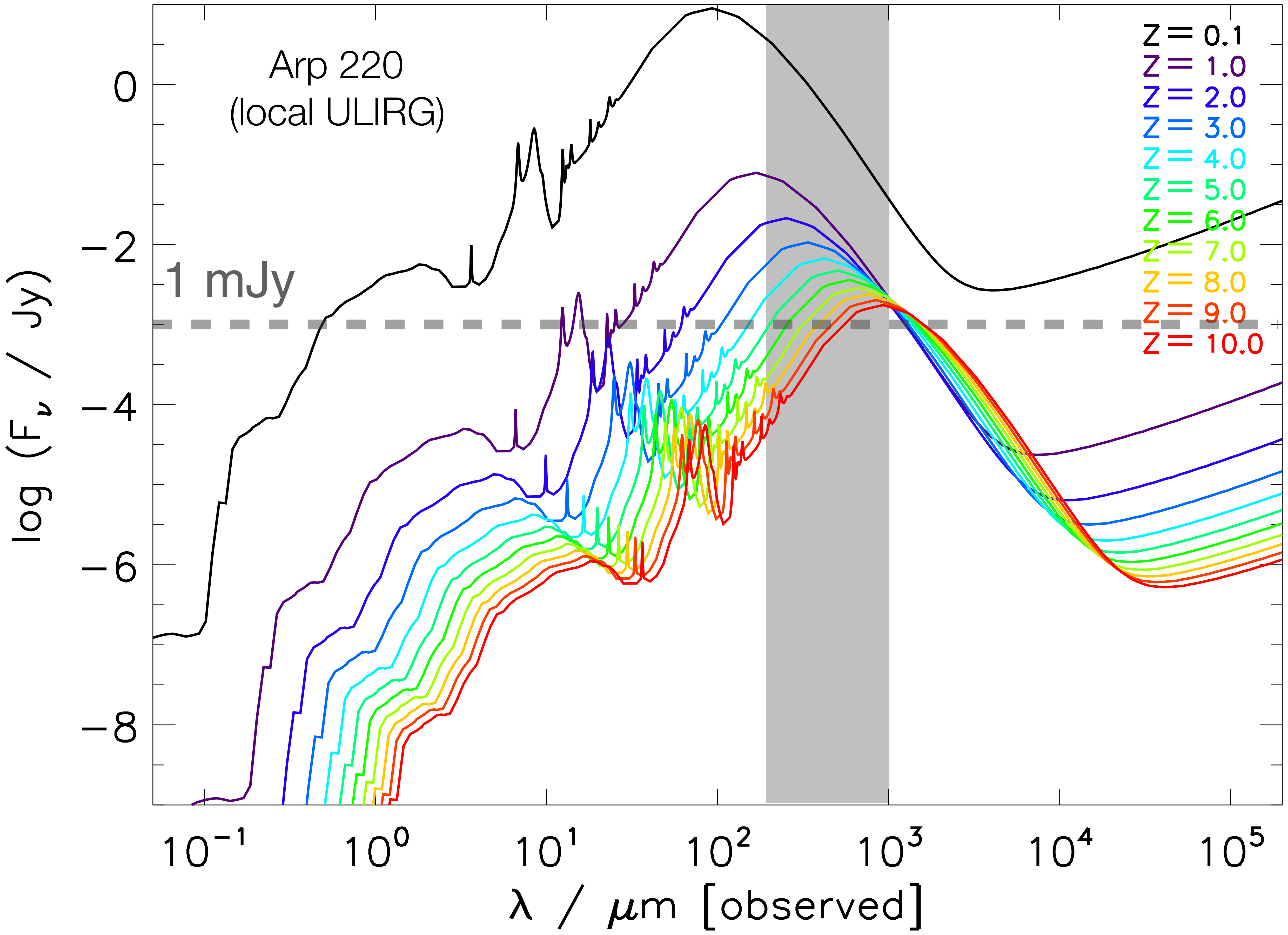
But β has not been measured at high-redshift so we assume it doesn't evolve!



Galliano+2018

Submillimetre galaxies:
our favourite dust laboratories





First discovered with SCUBA at 850μm (Smail+97, Hughes+98, Barger+98)

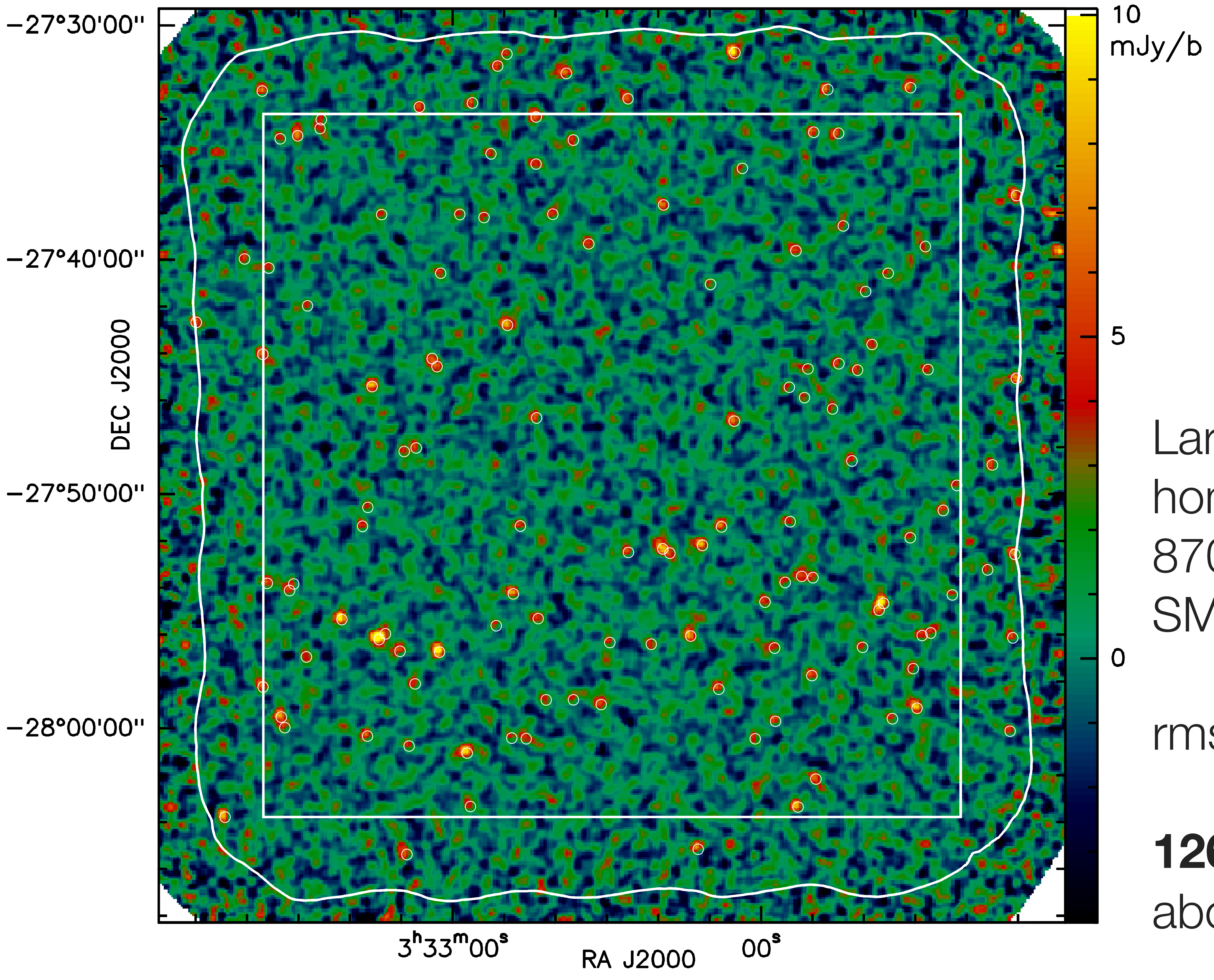
$F_\nu(850\mu m) > 1$ mJy

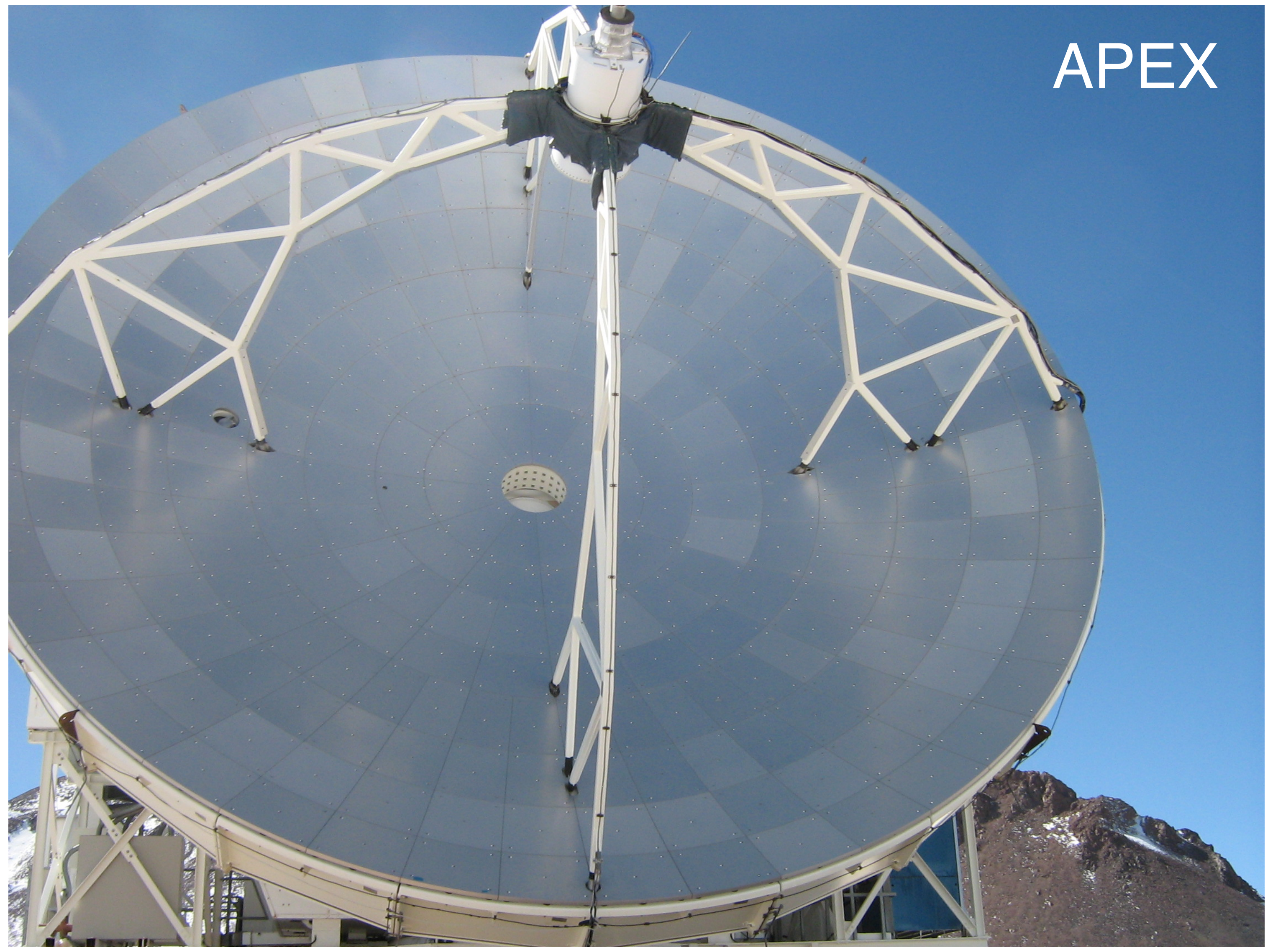
High-z galaxies (z>1) with large infrared luminosities powered by intense star formation (>100 Msun/yr)

>90% of the emission from stars is reprocessed by dust

The ALESS survey

LESS: LABOCA 870µm map of the ECDF-S (Weiss+2009)





Large, deep and homogenous blind 870µm survey - optimal SMG sample

rms~1.2 mJy/beam

126 SMGs detected above 3.7sigma

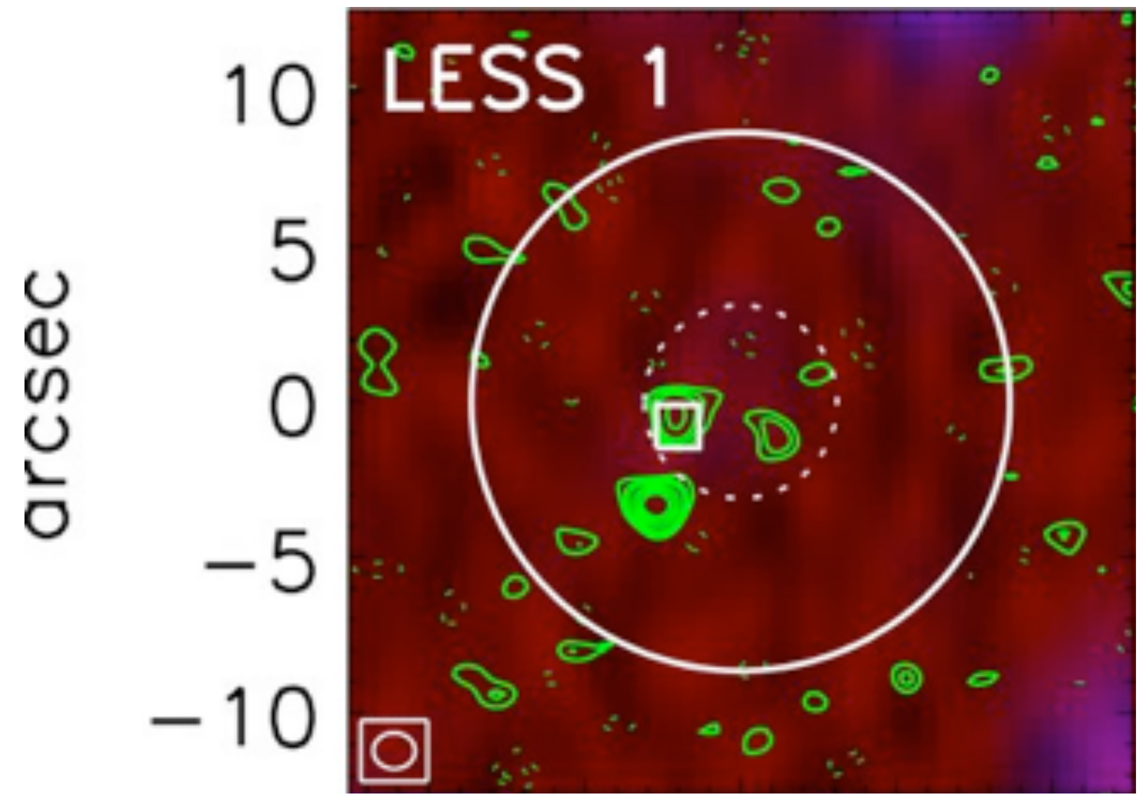
The ALMA revolution:

1. Spatial resolution

- **counterpart identification** of SMGs: enabled analysis of the physical properties of a statistically reliable, unbiased sample (ALESS)

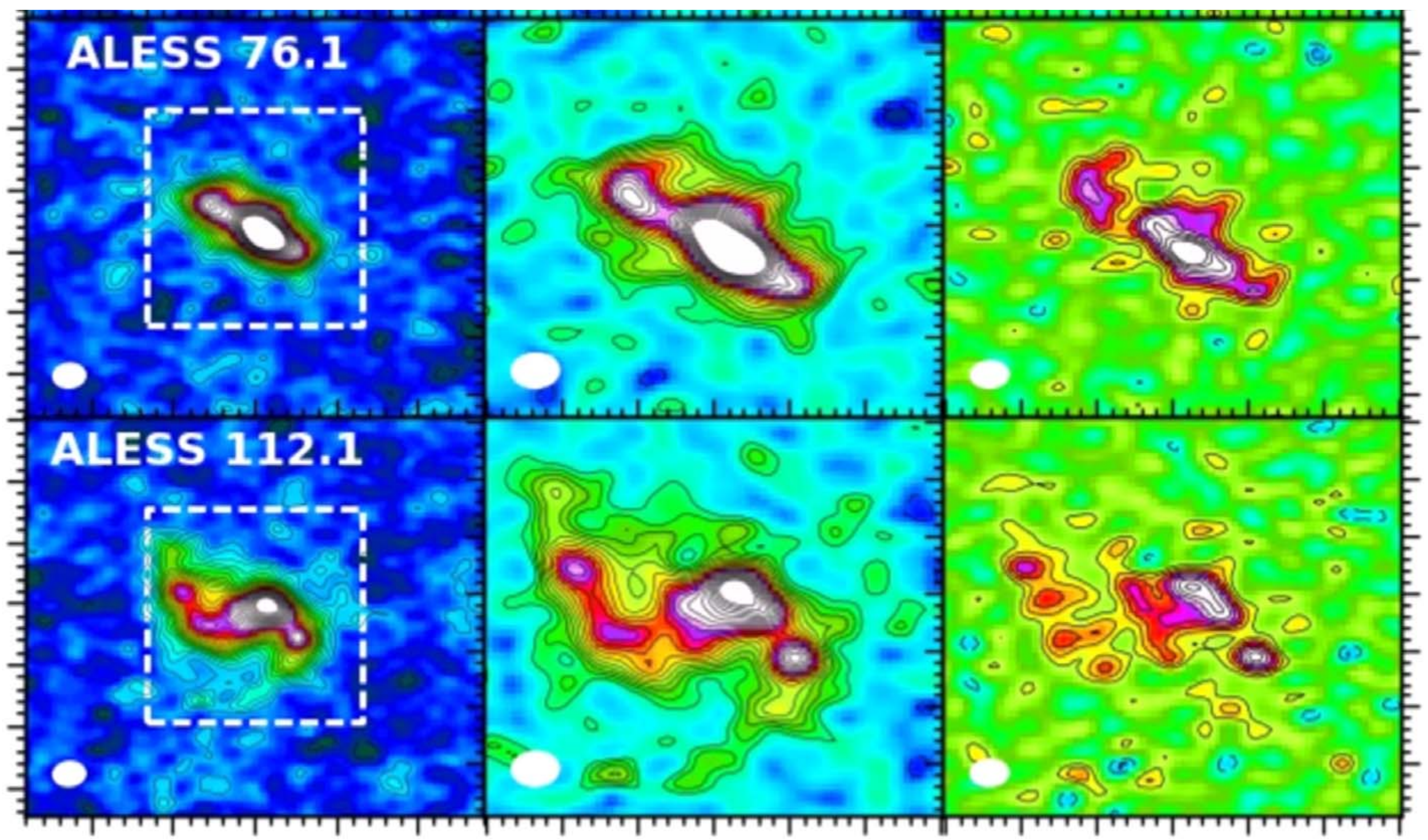
- **spatially-resolved studies**: sizes, dust and gas distribution, dynamics, and even morphology!

~1.5 arcsec resolution



Hodge+2013

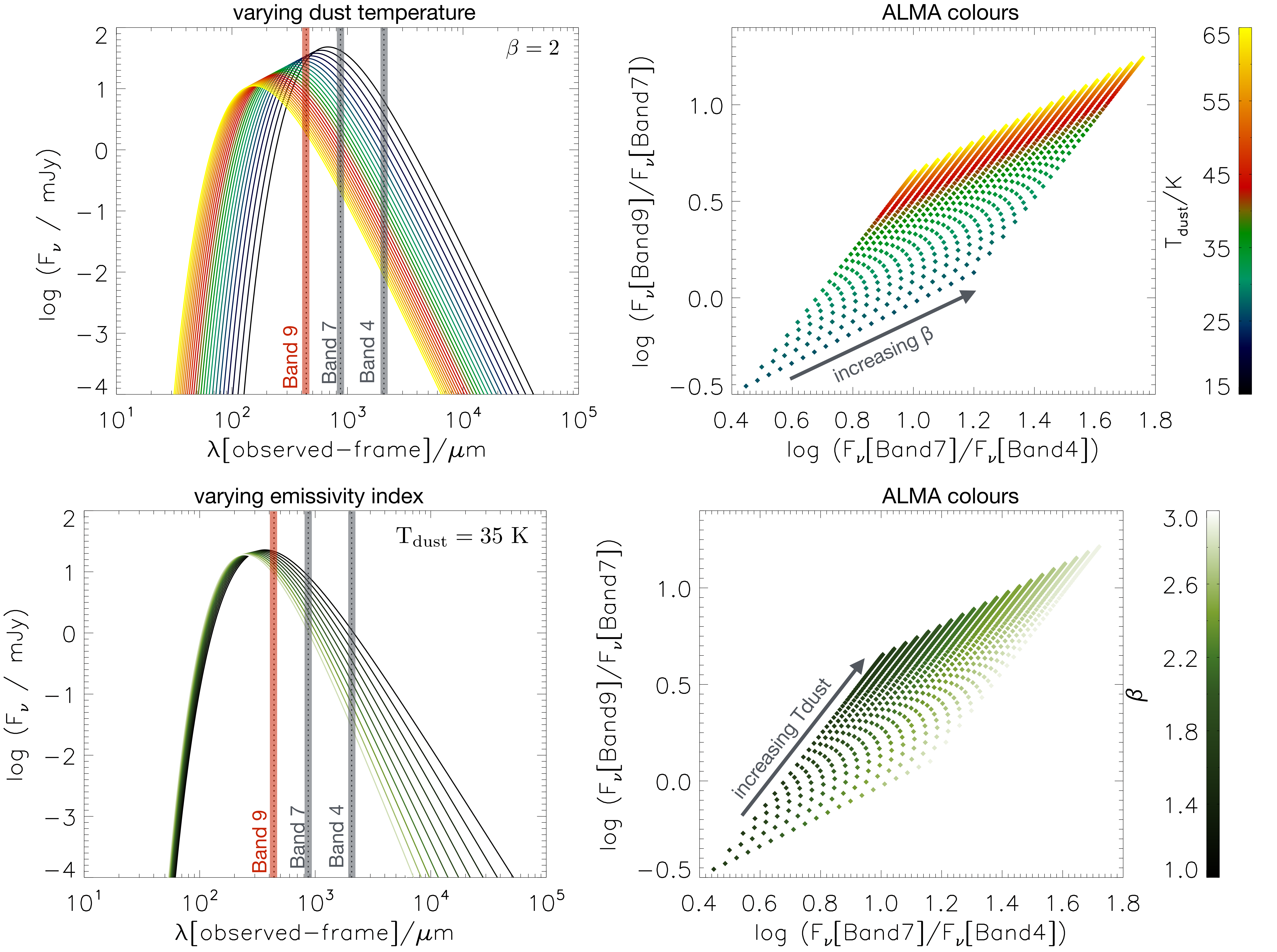
~0.1 arcsec ***~0.07 arcsec*** ***~0.05 arcsec***



Hodge+2019

The ALMA revolution:

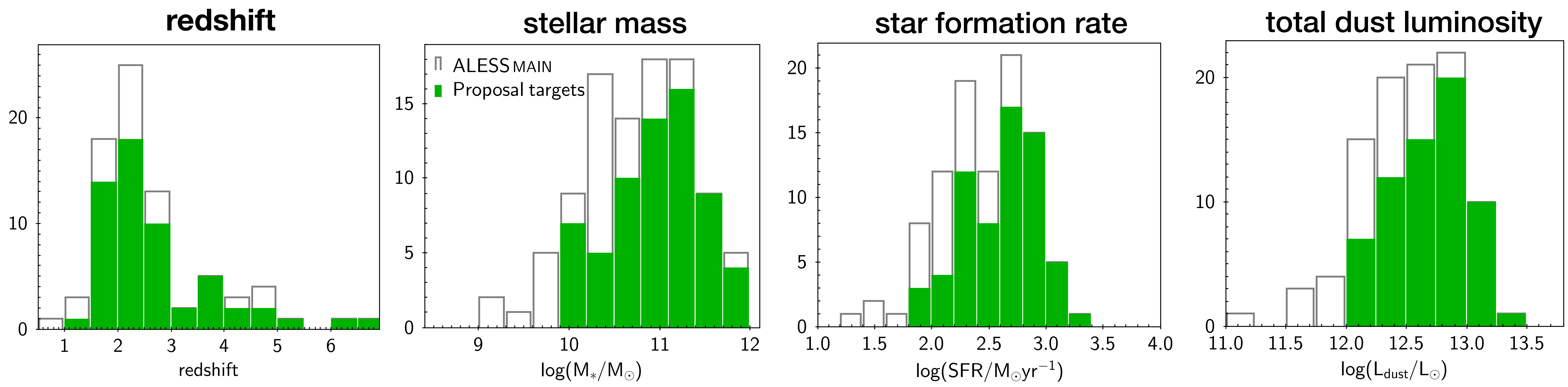
2. Frequency coverage



3 Bands: orthogonal parameter space to break degeneracies!

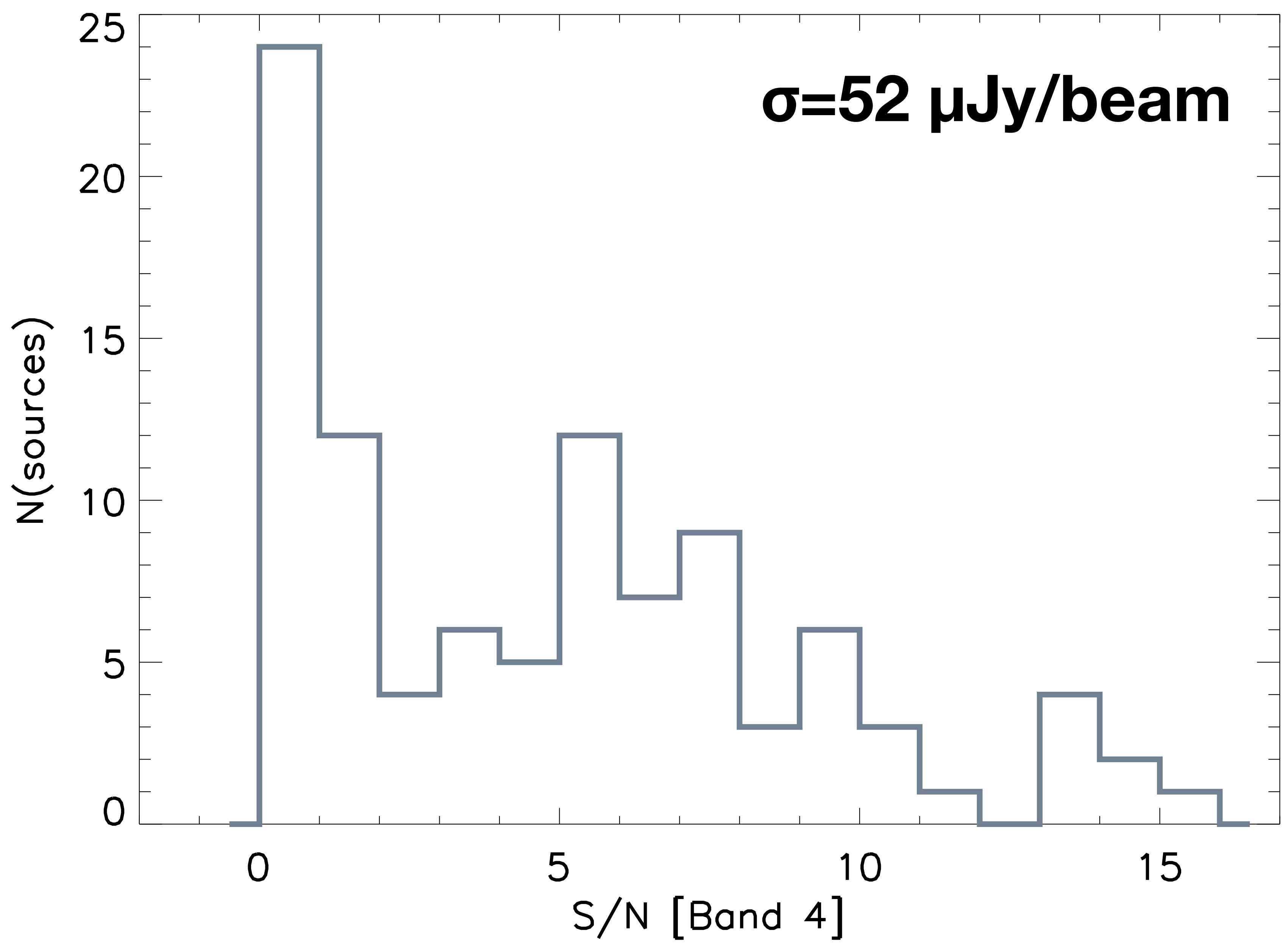
Properties of our SMG targets

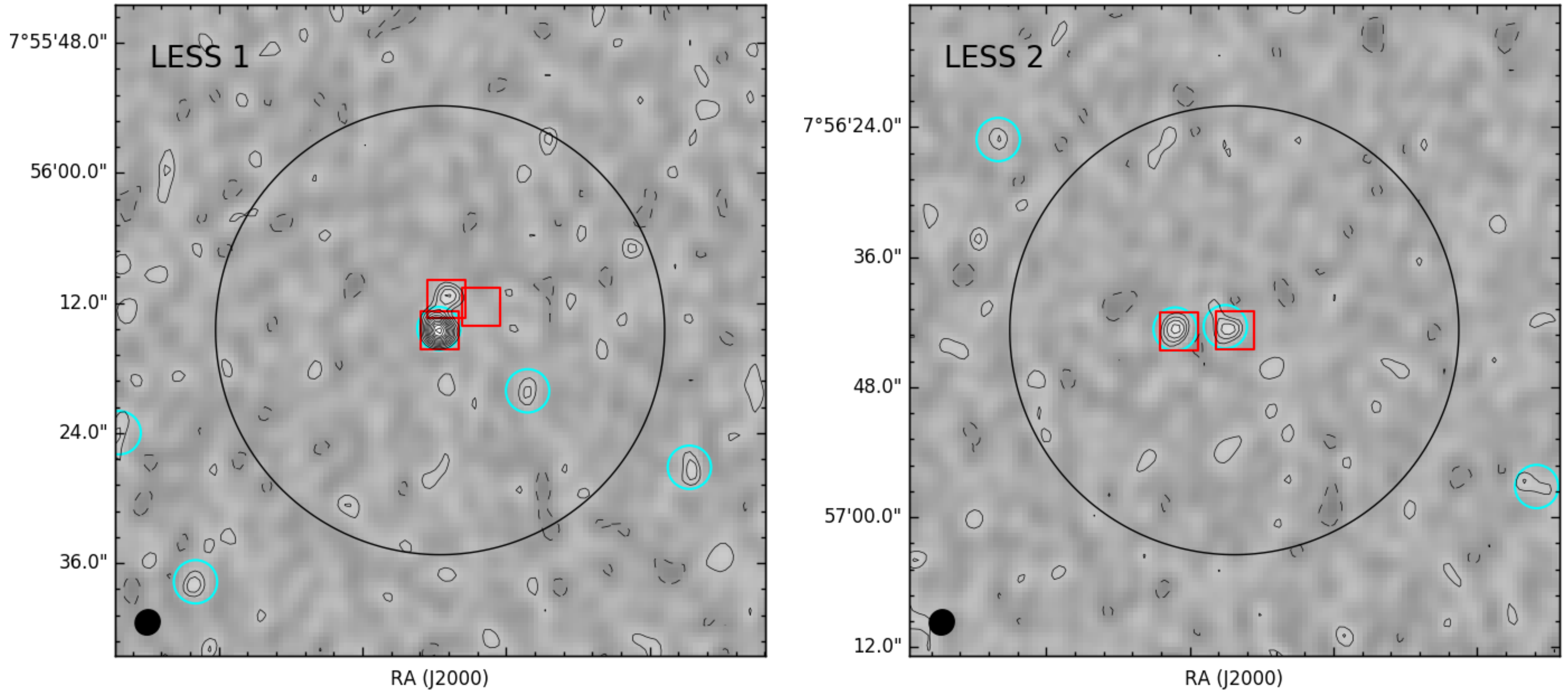
69 ALMA pointings centered on the brightest SMGs (total 99 SMGs)



(Hodge+2013, Simpson+2014, Swinbank+2014, da Cunha+2015)

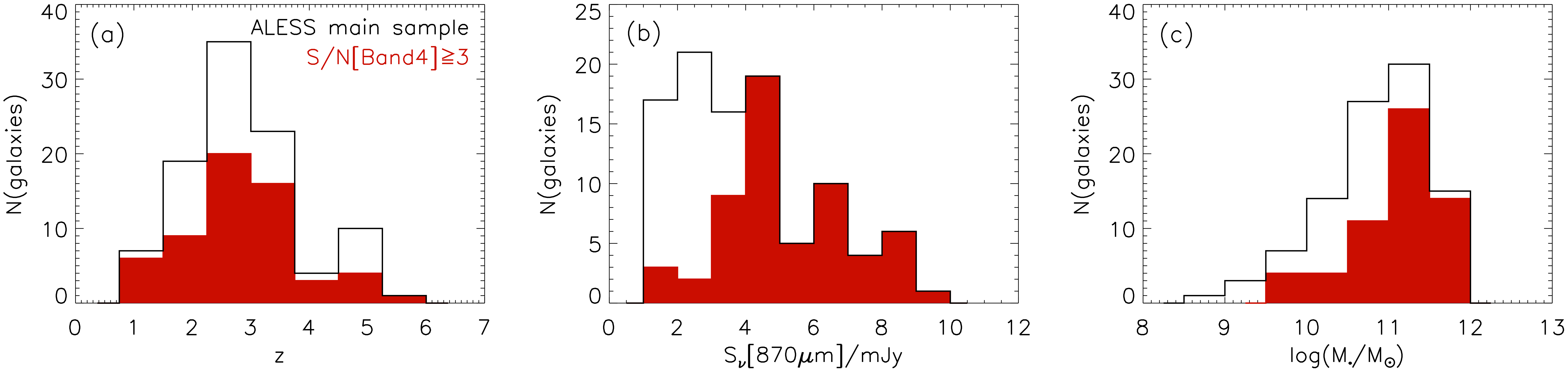
Band 4 observations (2mm or 150GHz)





We are able measure a 2mm flux for 70 sources (29 are undetected).

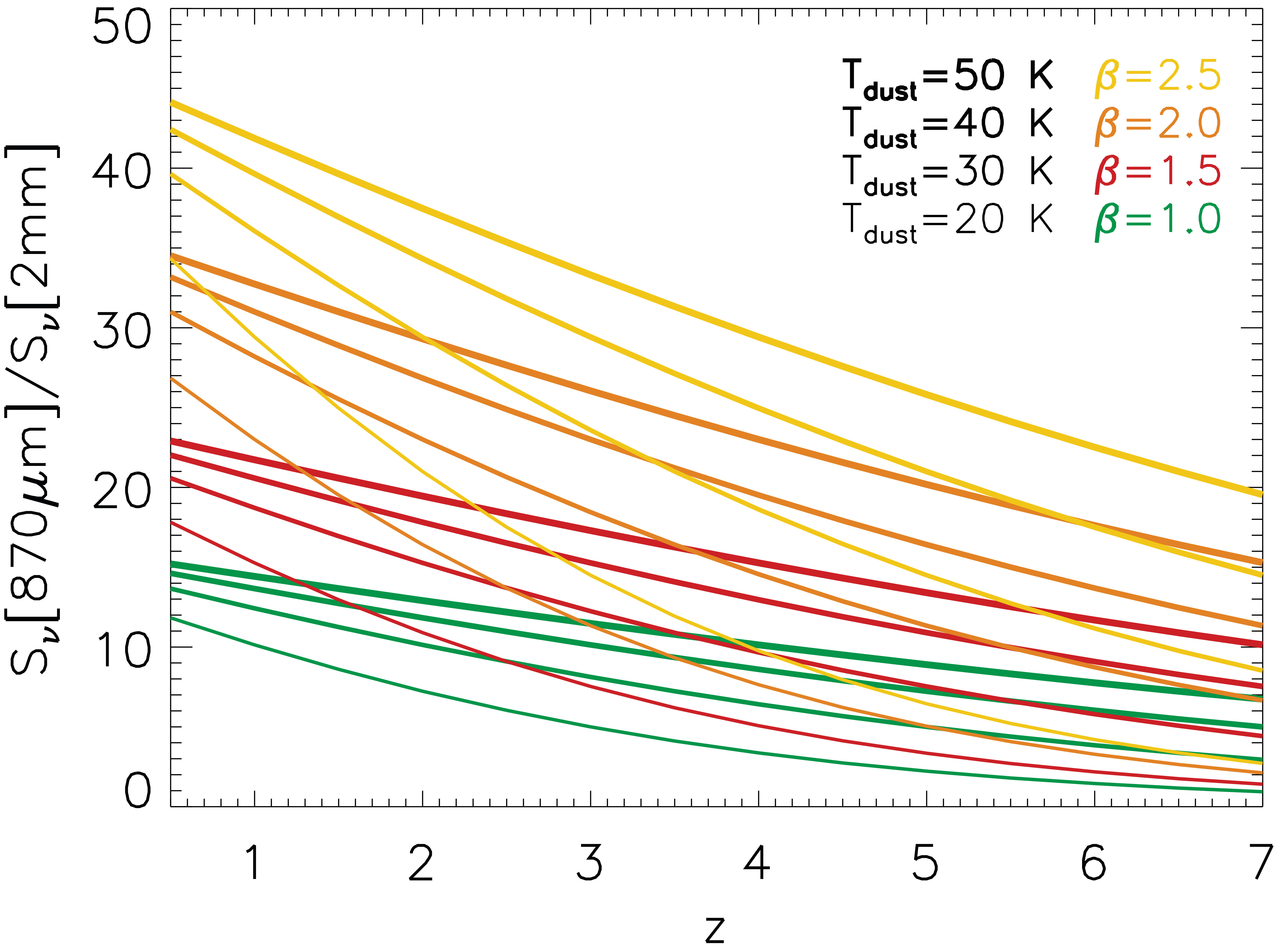
Which sources are detected?



- Brightest and most massive 870-um sources are preferentially detected
- No bias of detection rate with redshift
- 2mm bright means high stellar masses (as also noted for Band 6 observations, e.g. Dunlop+16, Bouwens+16)

The 870µm/2mm colours - redshift evolution?

- No strong evolution of the colours with redshift
- Implies evolution of dust properties with redshift
- More statistics needed!



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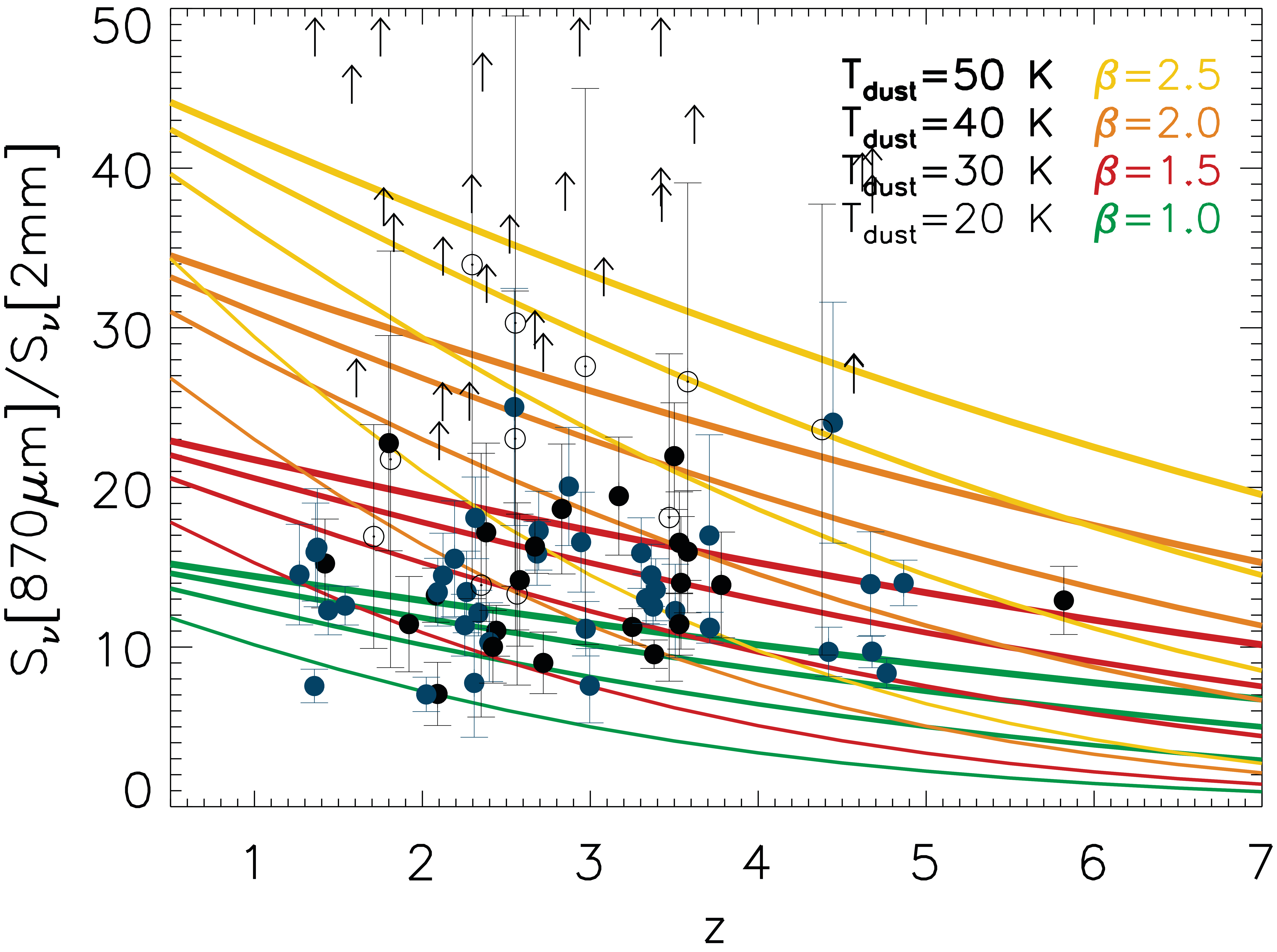
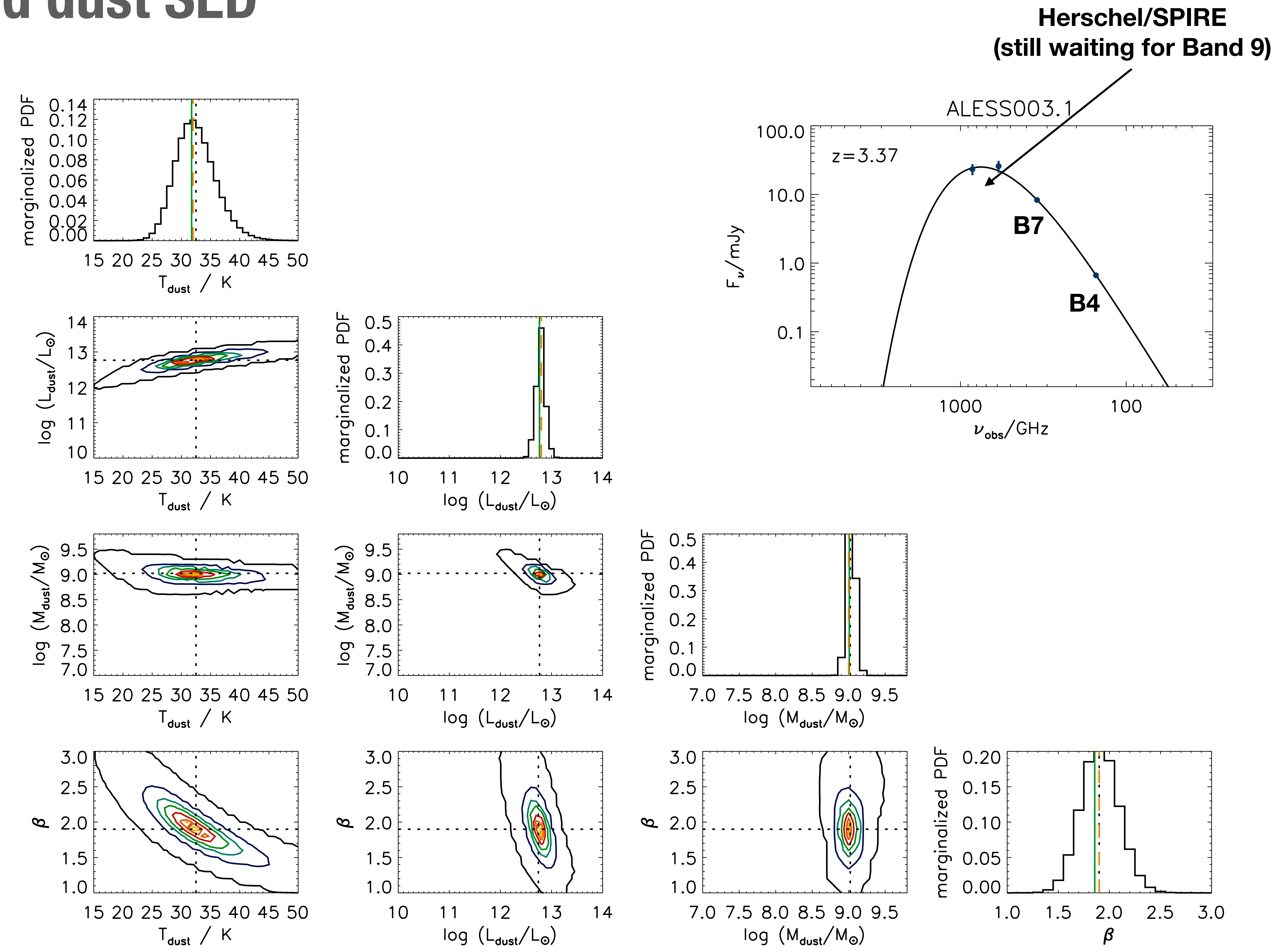
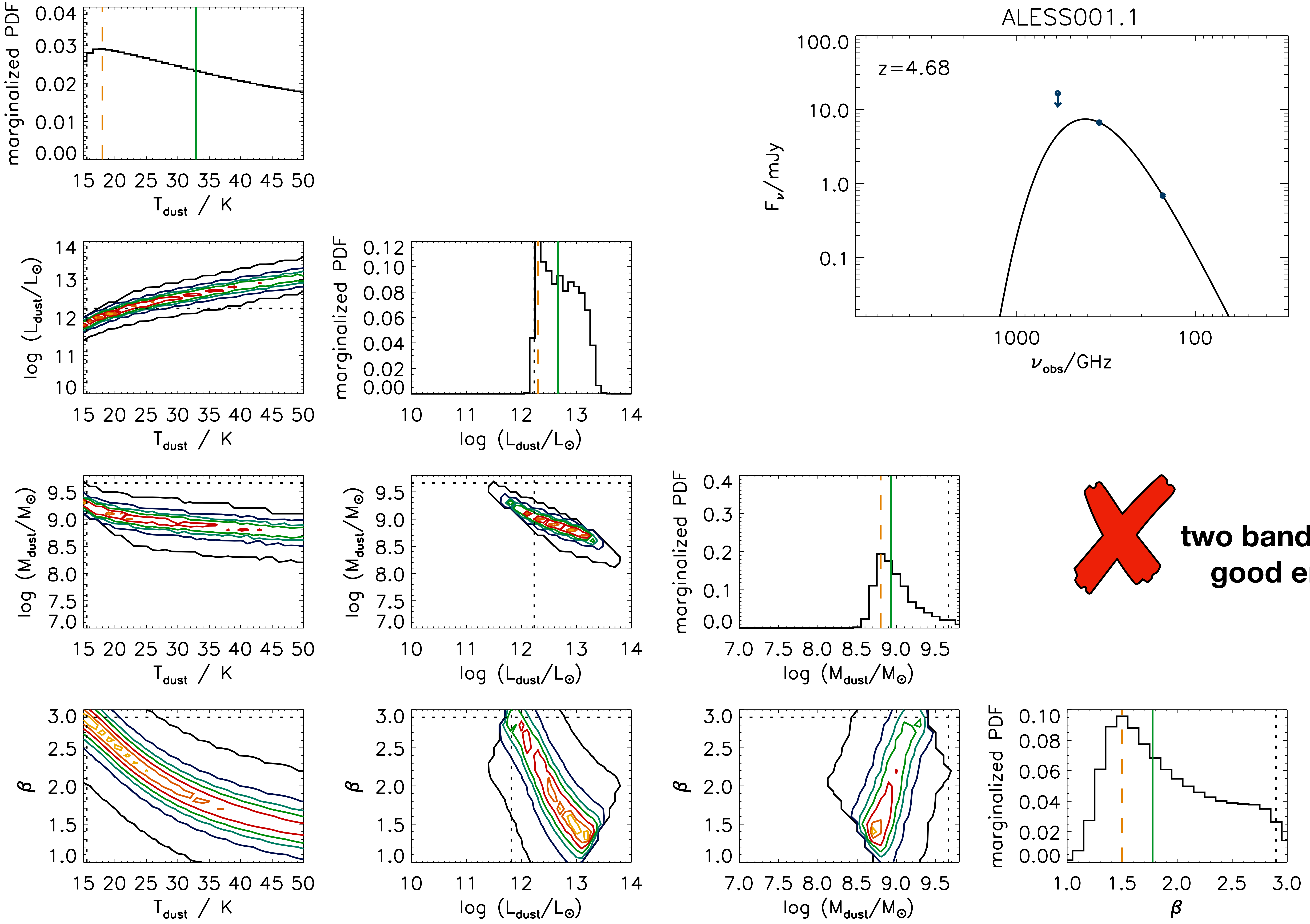


Individual fits of the cold dust SED

Bayesian method: important to avoid degeneracy between β and T_{dust} (can cause to fall in local χ^2 minima) [as shown by, e.g., Shetty+2009, Kelly+2012 work on local compact dust cores]

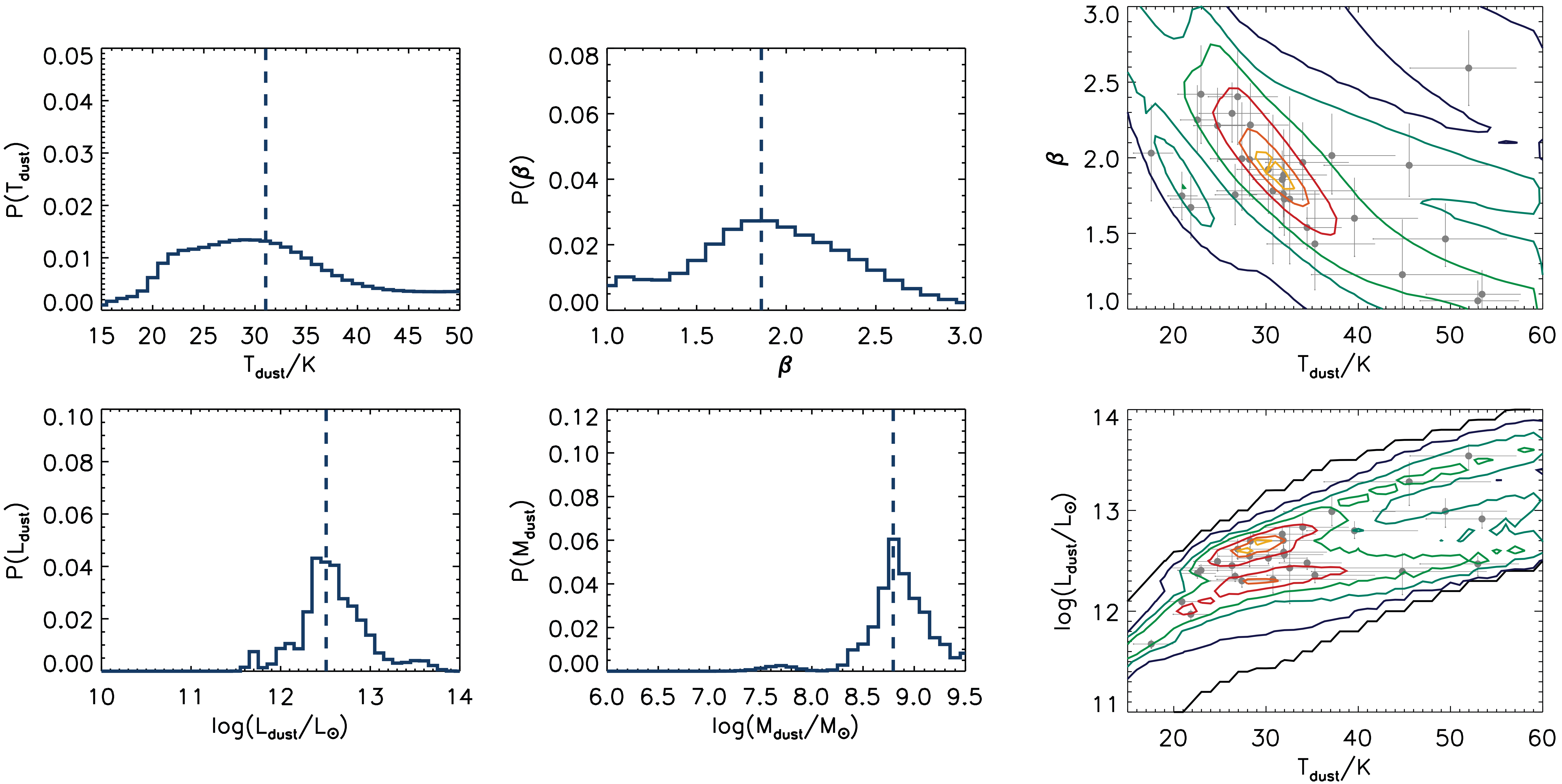




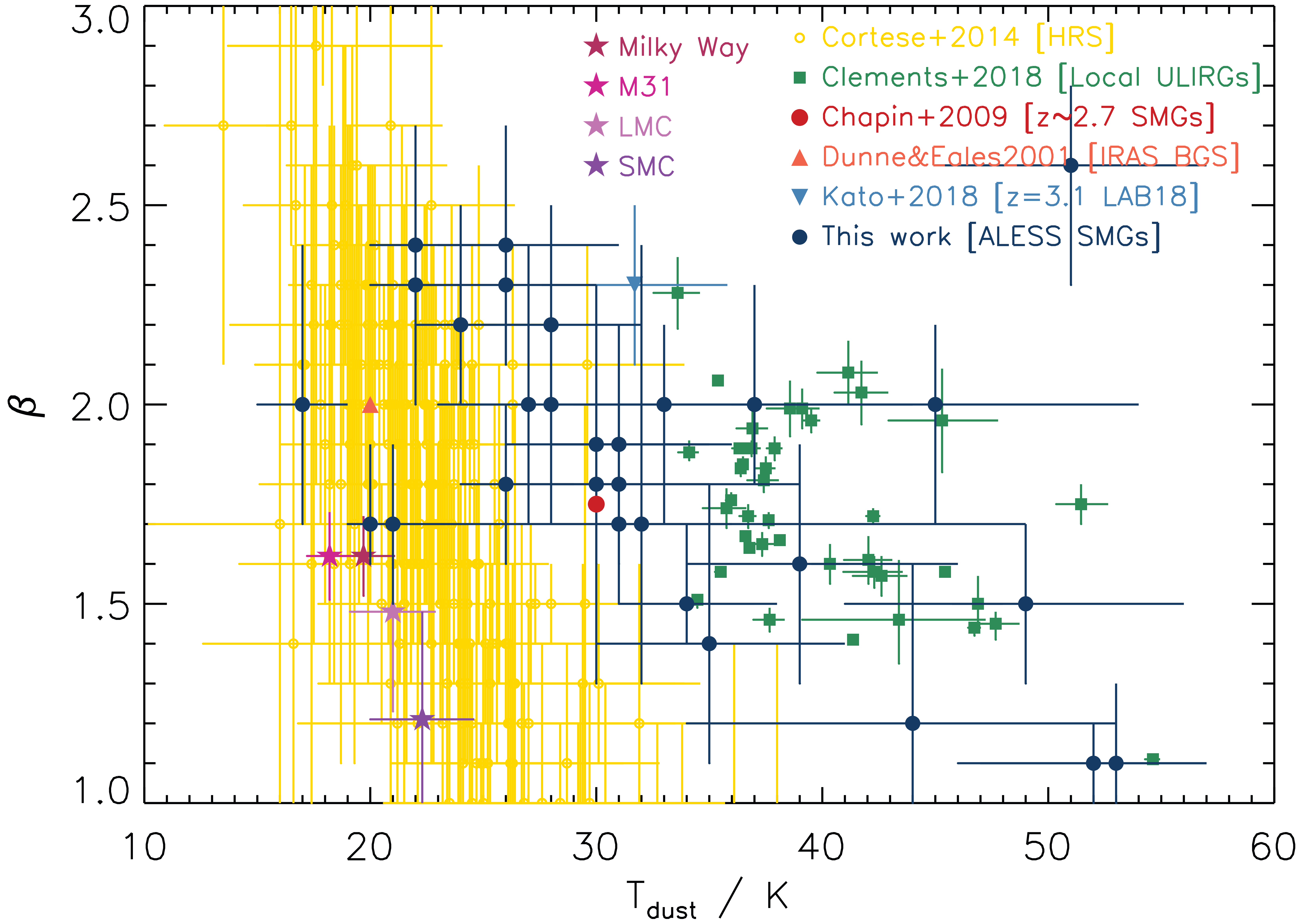
two bands are not good enough!

Stacked likelihood distributions

30 sources with existing Herschel/SPIRE measurements; whole sample later with Band 9 data



Dust in z~3 SMGs: not so different from local galaxies

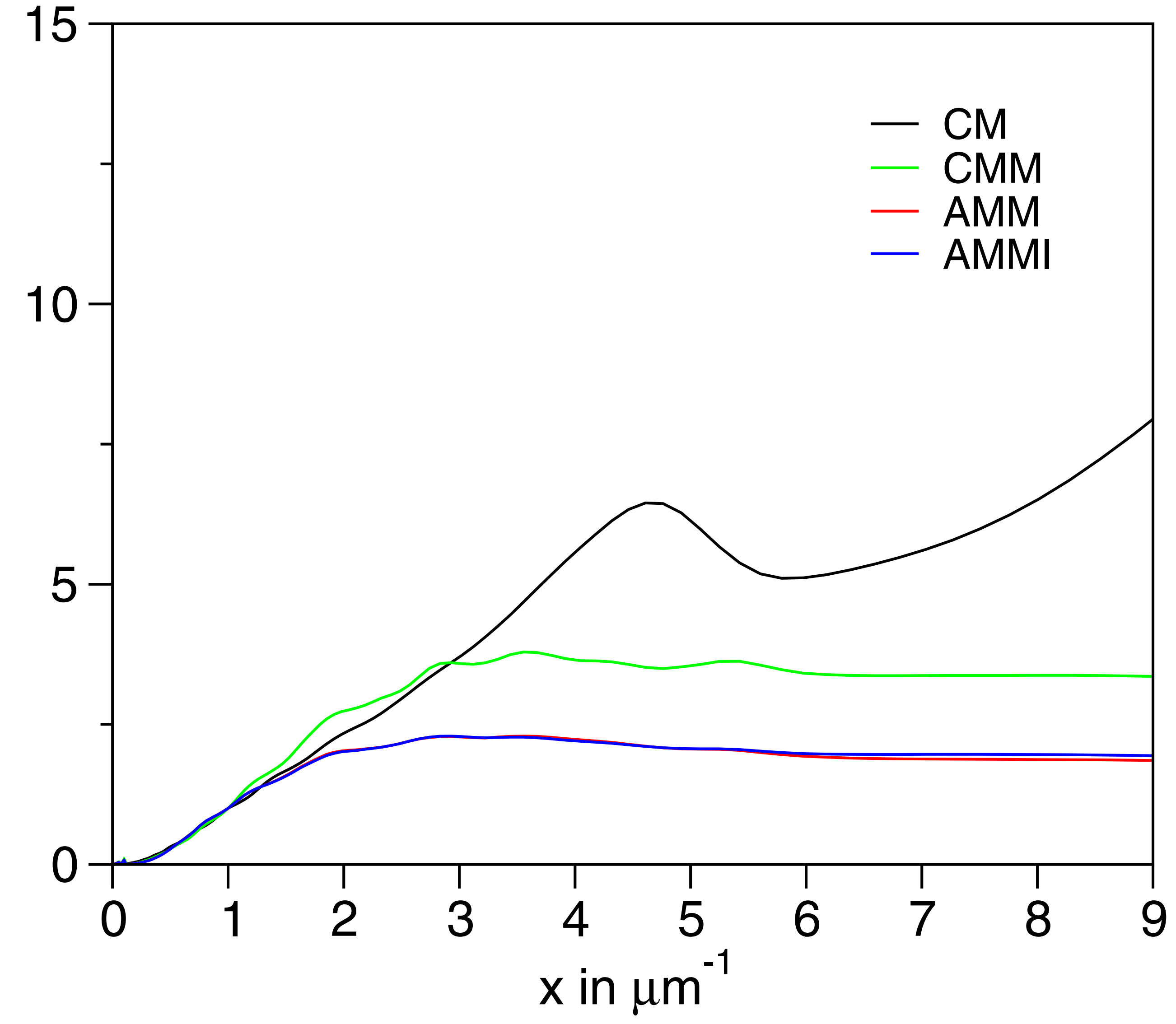


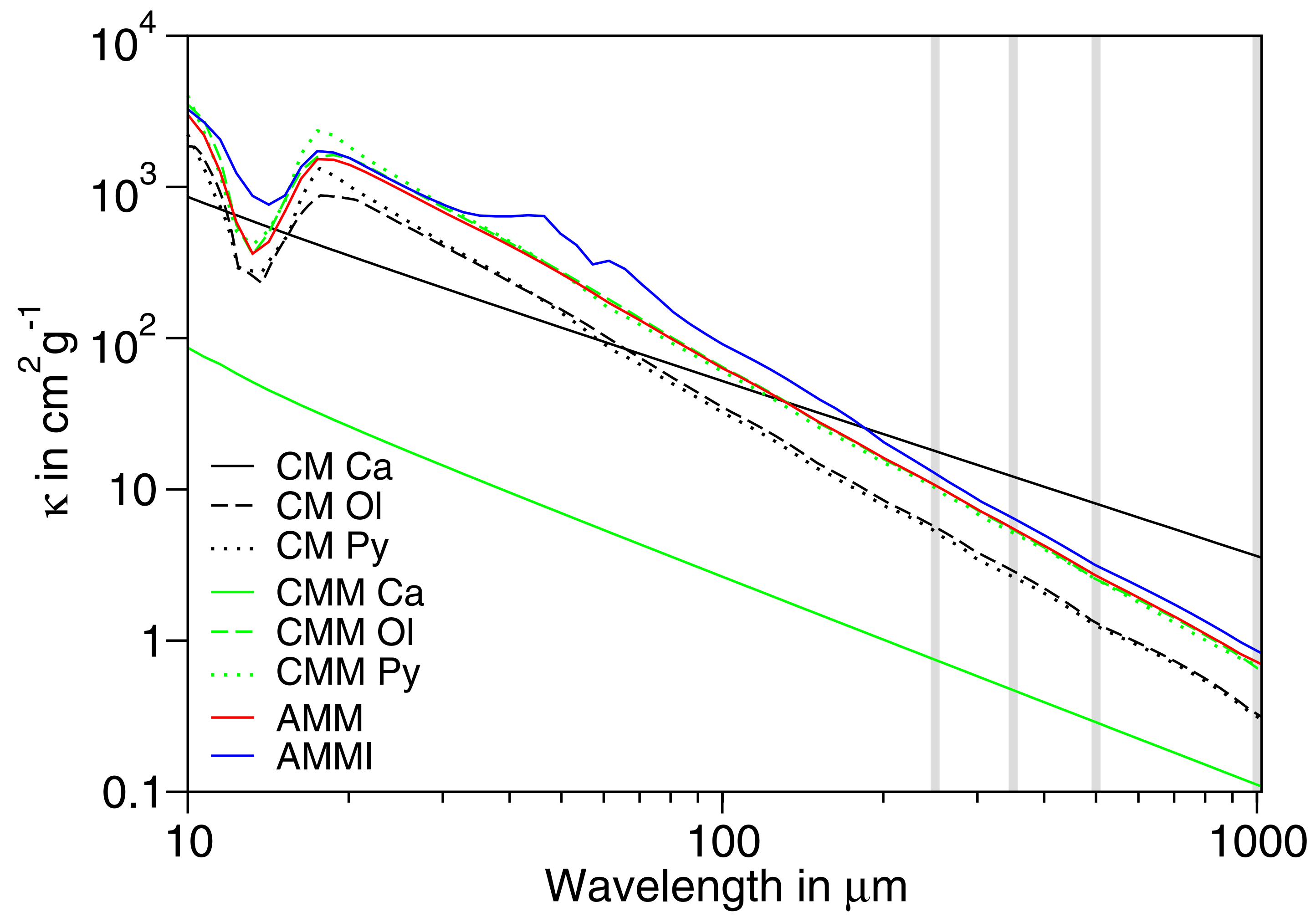
β~2 is an ok assumption for SMGs at cosmic noon! (needed to be checked)

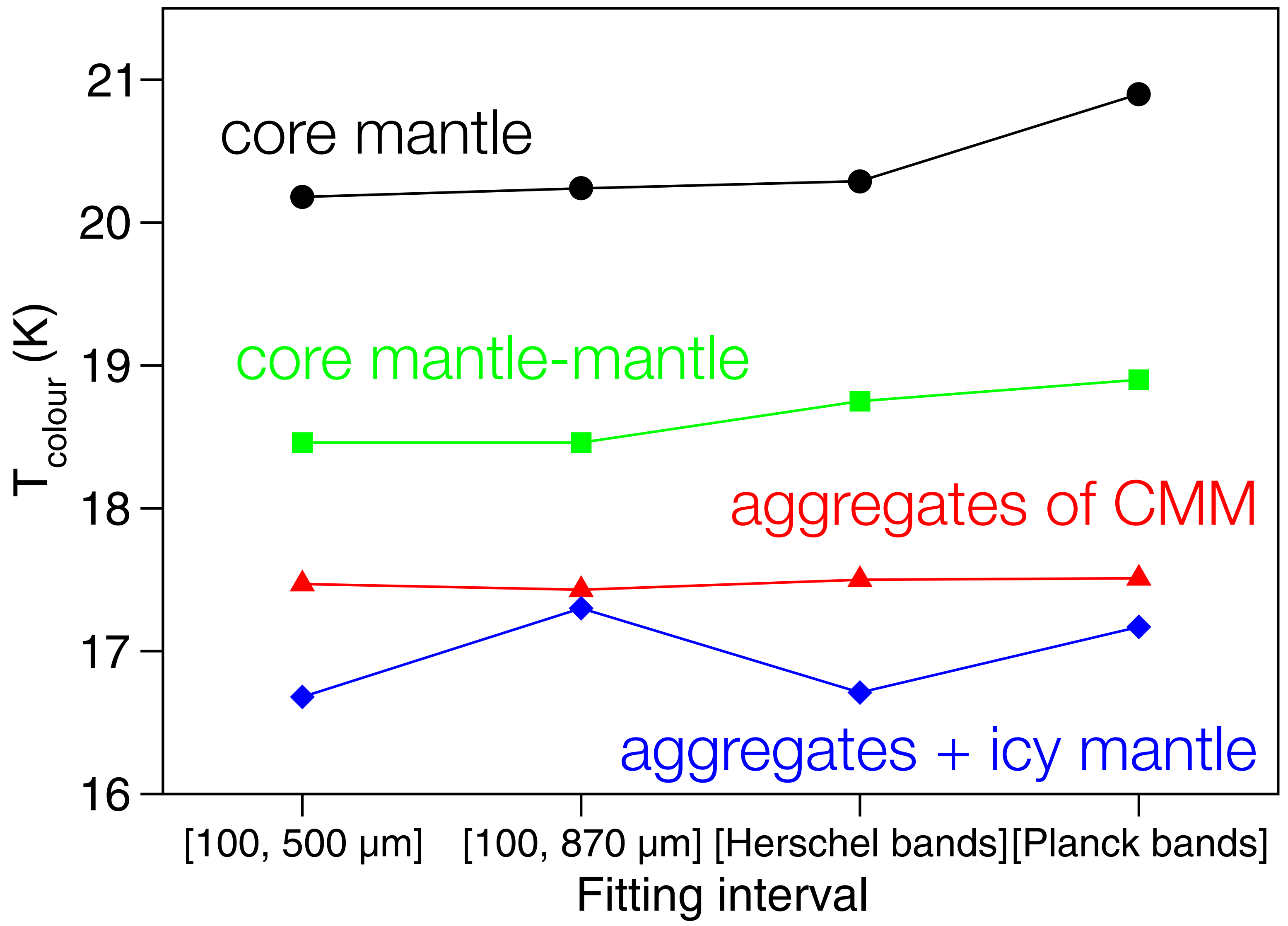
What does it mean?

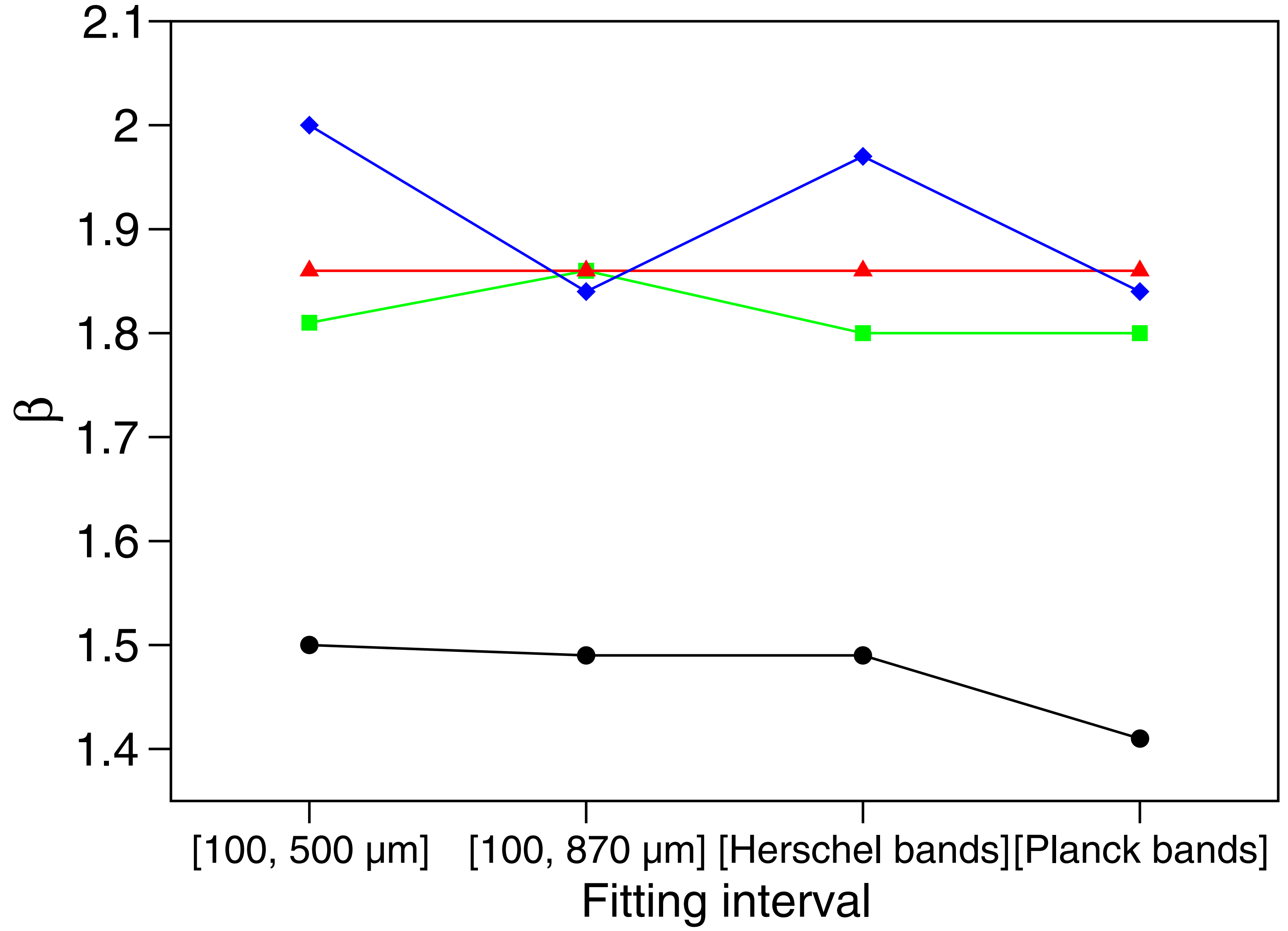
Koehler+2015 investigate how dust grain evolutionary processes (such as accretion and coagulation) change the optical properties of dust grains from the diffuse ISM to denser regions ($n_H > 1500$ cm^{-3}).

Dust is already pretty evolved in z~3 SMGs?





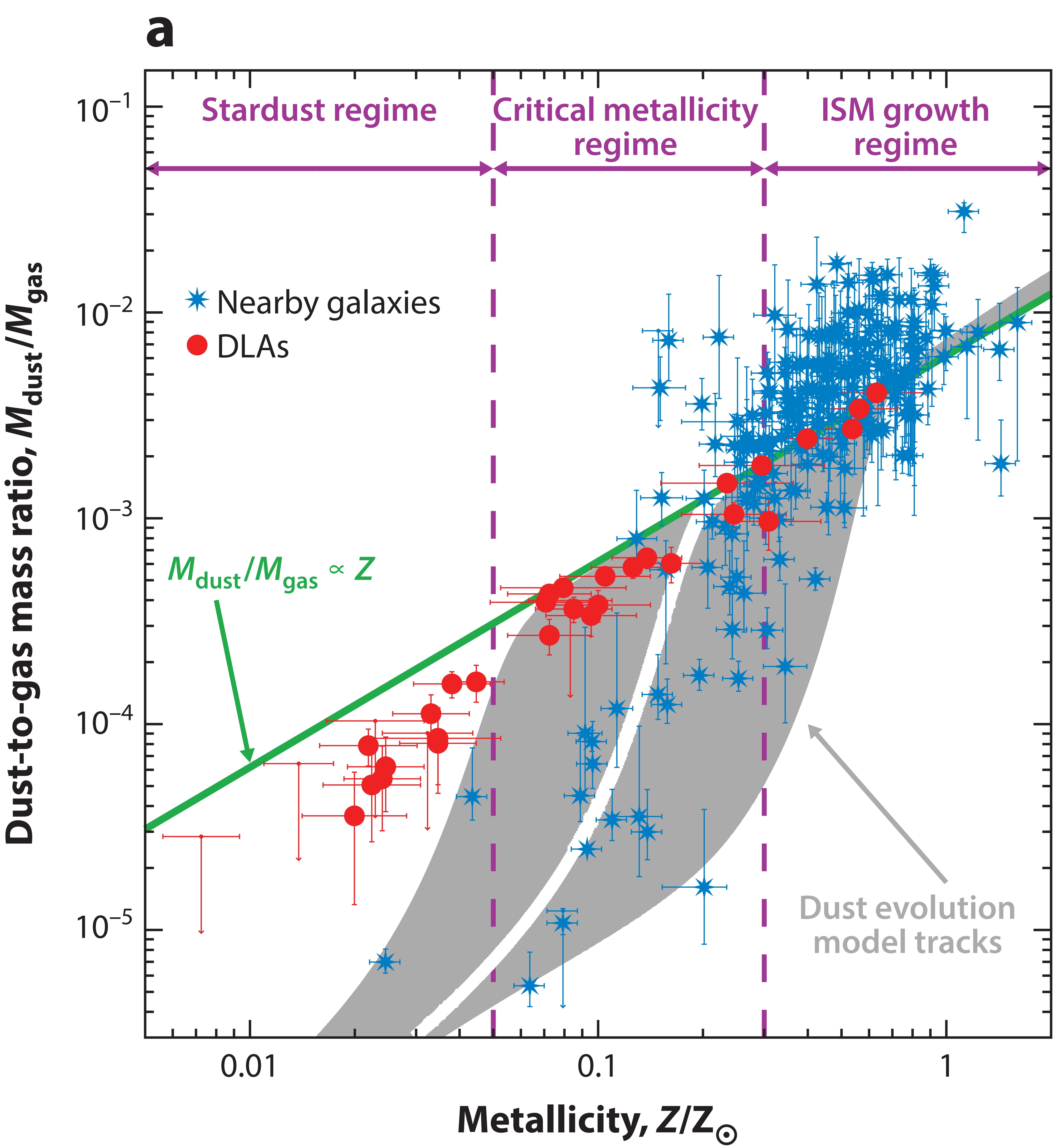




Dust evolution with metallicity

SMGs are massive and chemically evolved (~solar metallicities), so perhaps not surprising that they have lots of dust and that dust is perhaps similar to that in Milky-Way type galaxies.

Next step: probe lower mass/metallicity regime: lower luminosity and/or higher redshift.



Galliano+2018

Summary

- ALMA can constrain dust temperatures and emissivity indexes, bringing individual dust mass uncertainties down to <0.2 dex

- **β~2 for z~3 SMGs**: no obvious evolution of the dust properties at least for massive (likely solar metallicity) sources

WHAT's NEXT?

- 'normal' main sequence galaxies at z~1-3 (~10-100x fainter than SMGs): ongoing ALMA programme to follow-up of CO-bright sources from ASPECS Large Programme (PI: Walter)

- push to really high redshift: before there was time to make lots of metals, and for significant AGB star contribution: REBELS sources at z>7 (PI: Bouwens) [also needed to check dust luminosities]

- emissivity per unit dust mass: need independent method for dust mass (gas masses? A_V + radiative transfer?)

- JWST will be needed to measure stellar masses & chemical enrichment at high redshifts

Coming soon!

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Keywords:

xxxx, xxxx, xxxx

High-redshift star formation in the ALMA era

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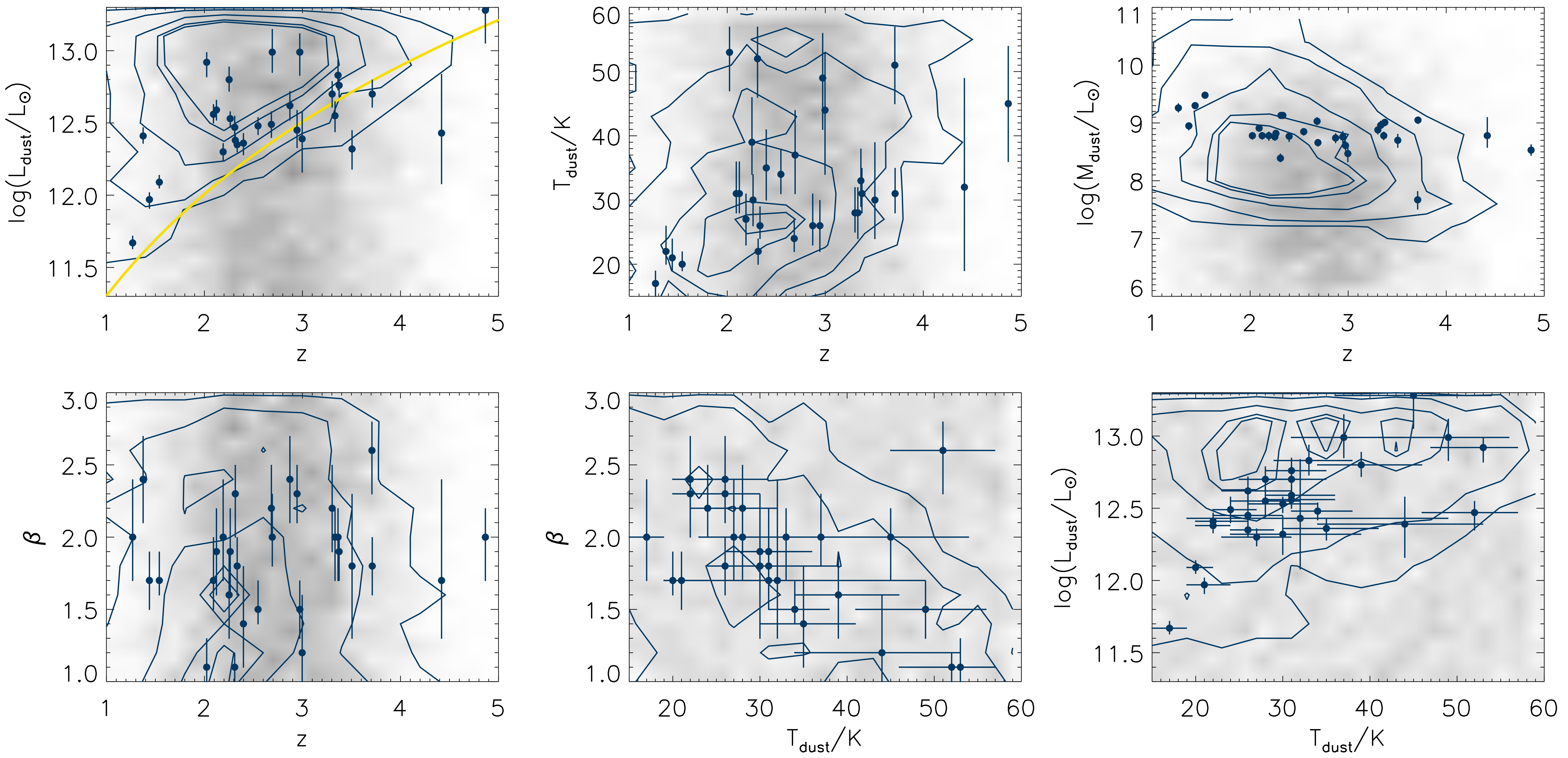
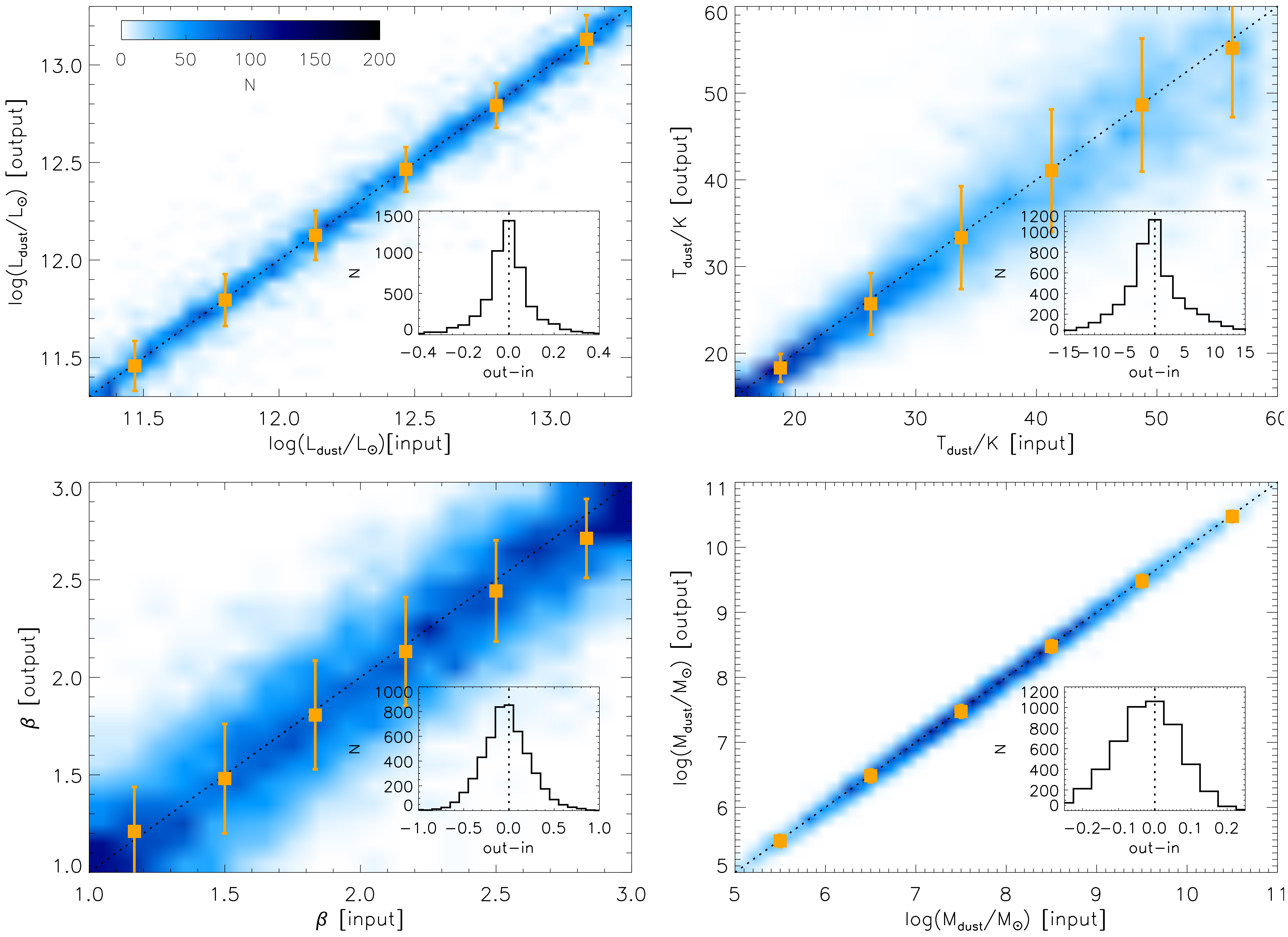
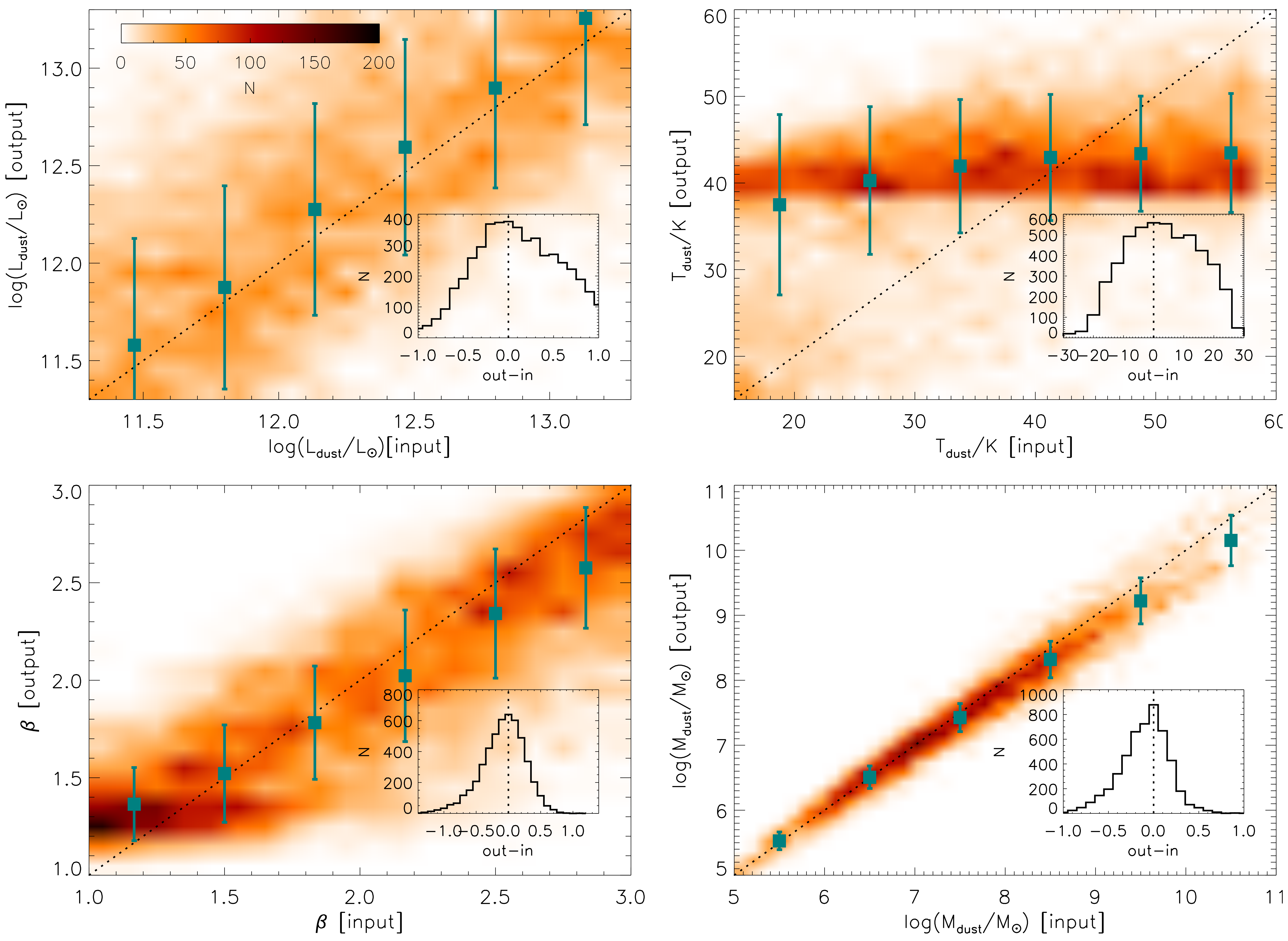
selection effects?



Accuracy of our fitting method: 3 bands



Accuracy of our fitting method: only Band 7 and Band 4



could we have just measured the RJ slope and called it a day? No. RJ approximation does not apply.

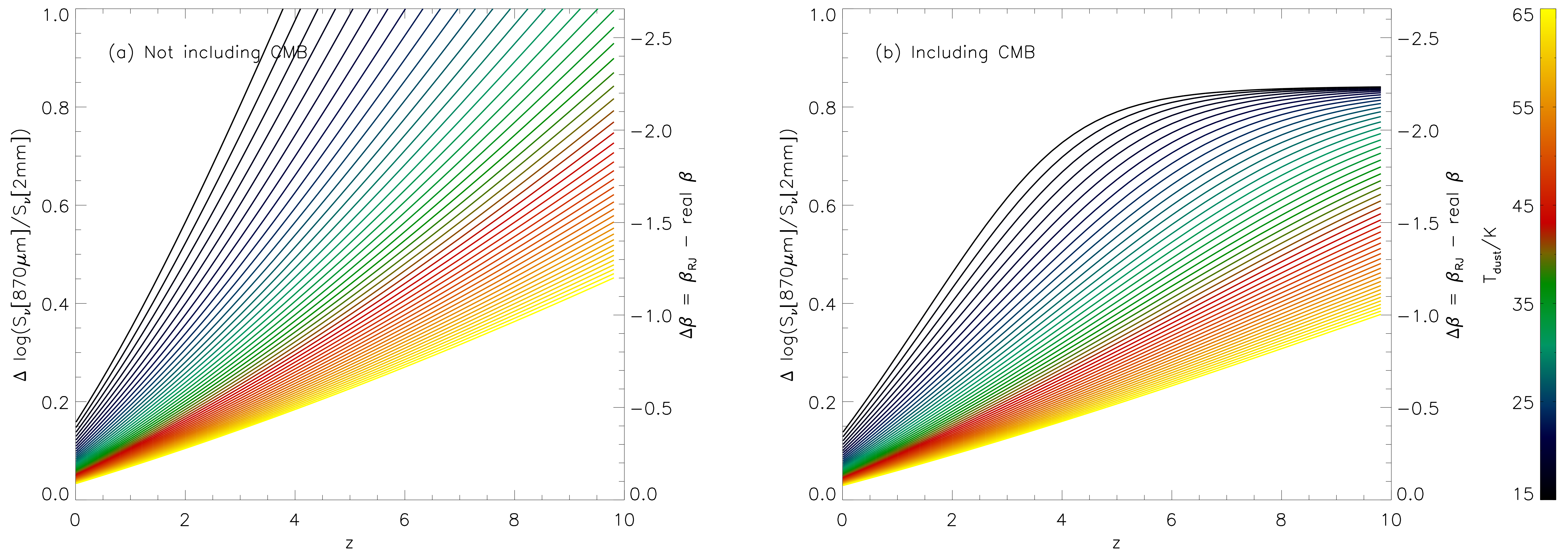


Figure 17. Deviation from the Rayleigh Jeans approximation as a function of redshift and temperature. The y-axis shows the difference between the ratio of Band 7 to Band 4 flux densities computed using the RJ approximation (eq. B2), and the true ratio computed using the modified black body fluxes (eq. 1), i.e., $\Delta \log(S_\nu[870\mu\text{m}]/S_\nu[2\text{mm}]) = \log(S_\nu[870\mu\text{m}]/S_\nu[2\text{mm}])_{\text{RJ}} - \log(S_\nu[870\mu\text{m}]/S_\nu[2\text{mm}])_{\text{MBB}}$. This translates linearly to a difference $\Delta\beta$ between the inferred RJ emissivity index β_{RJ} and the true emissivity index (right-hand y-axes).