Dust at High Redshifts

Irene Shivaei
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JWST MIRI/NIRCam US GTO

Why should we care about dust?

- Shapes our view of galaxies by absorption in UV and optical and re-emission in IR

- Important roles in physics and chemistry of ISM

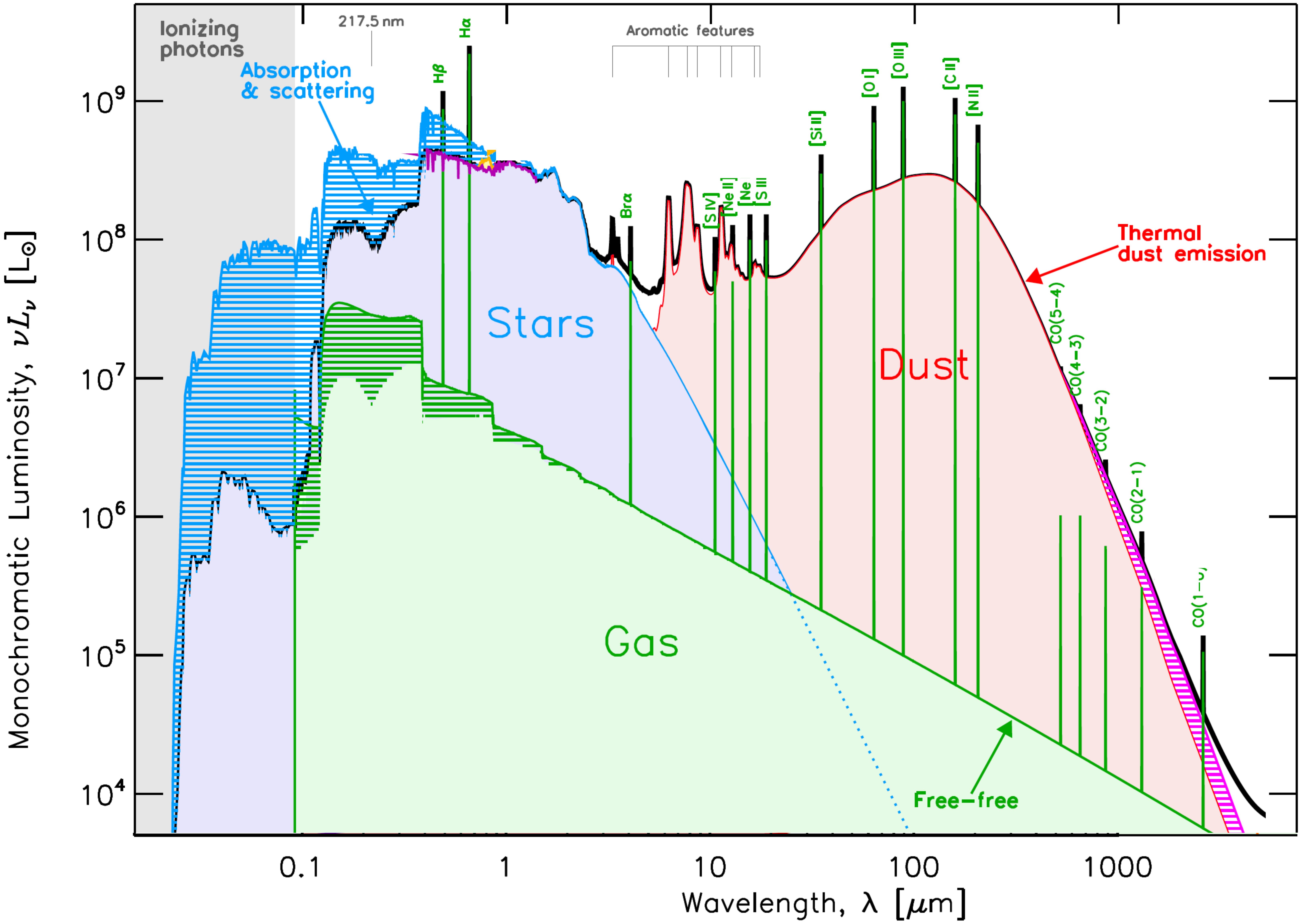
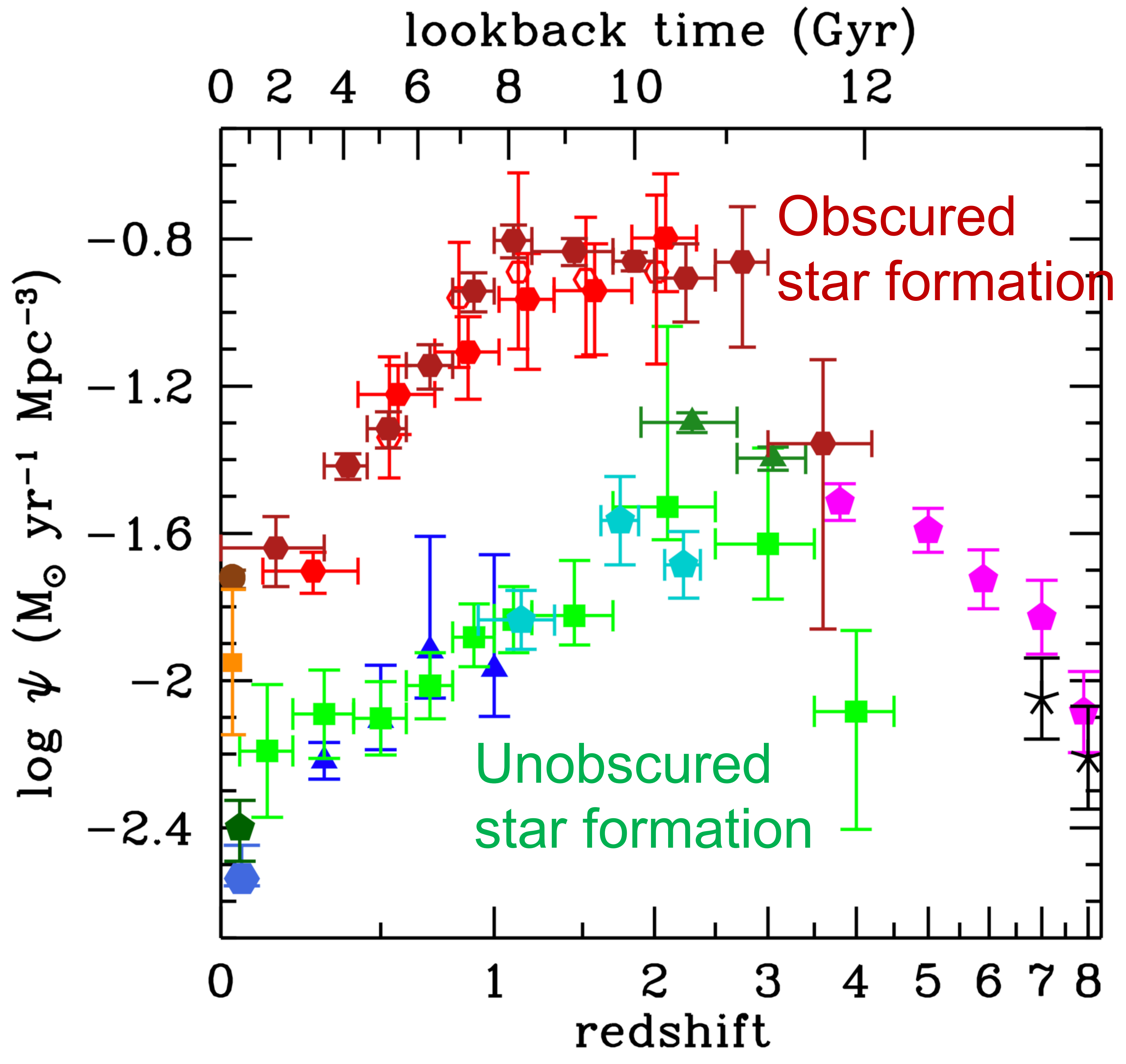
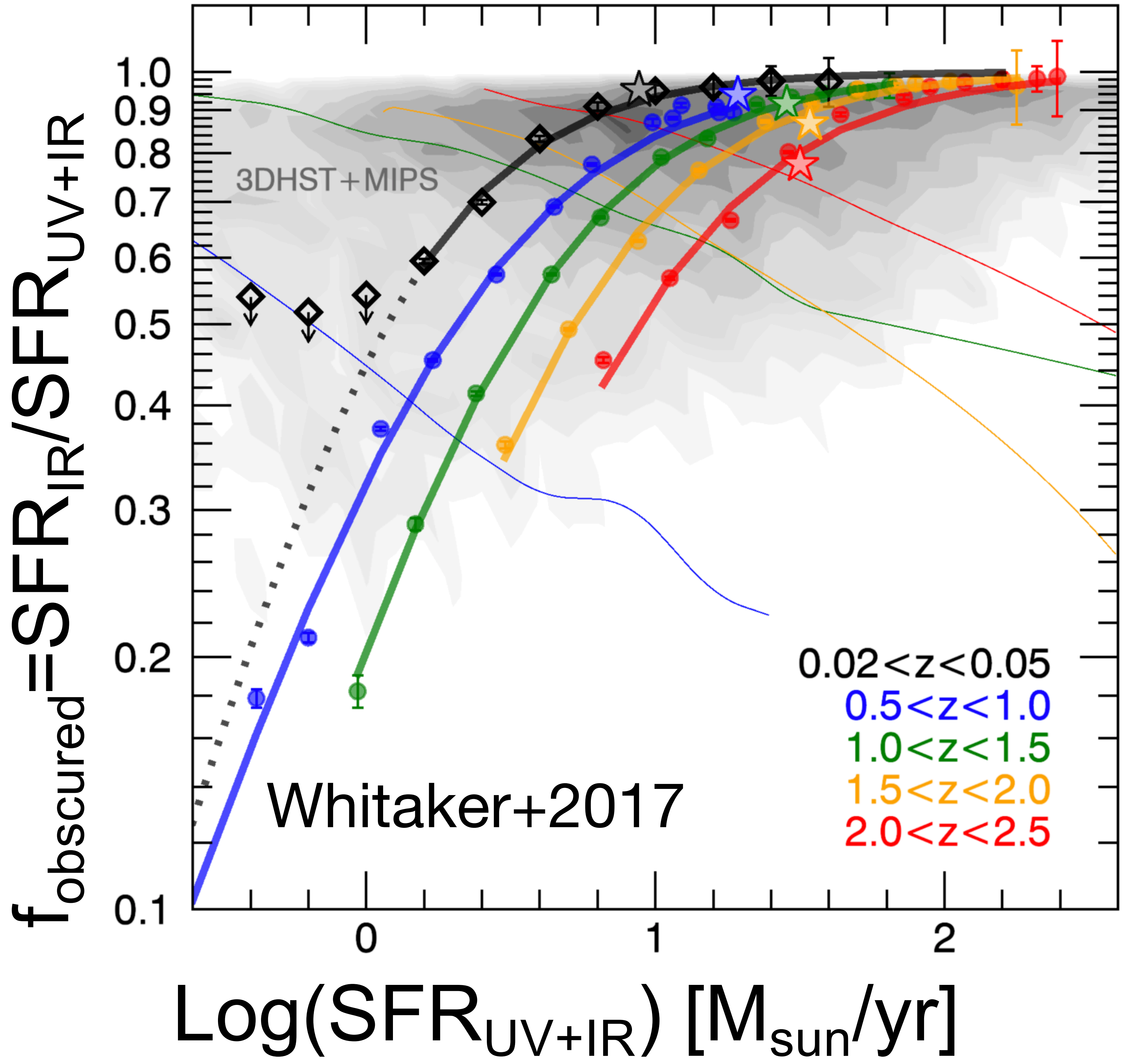


Figure from Galliano et al. (2017)

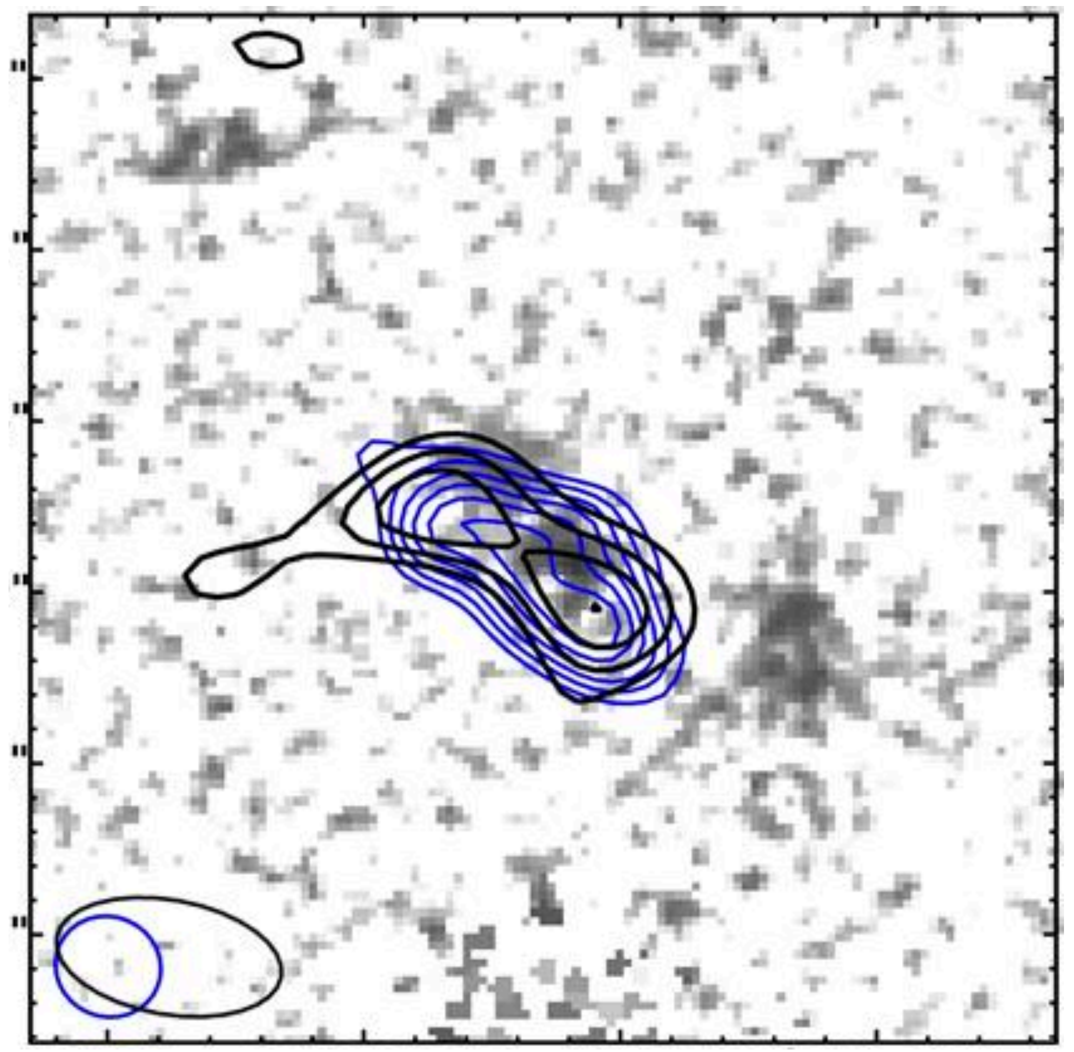
Why should we care about dust at *high redshifts*?



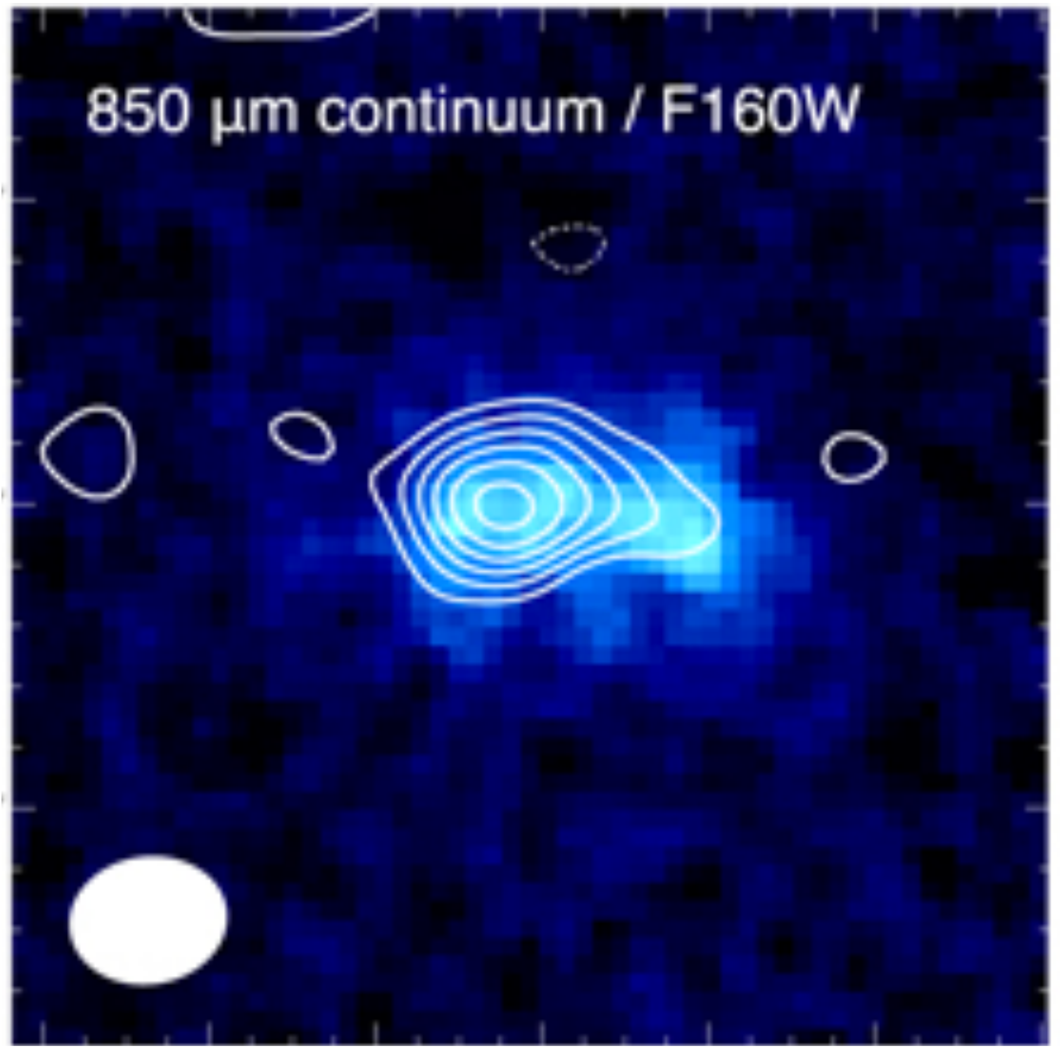
Madau & Dickinson (2014)



Why should we care about dust in *early universe*?

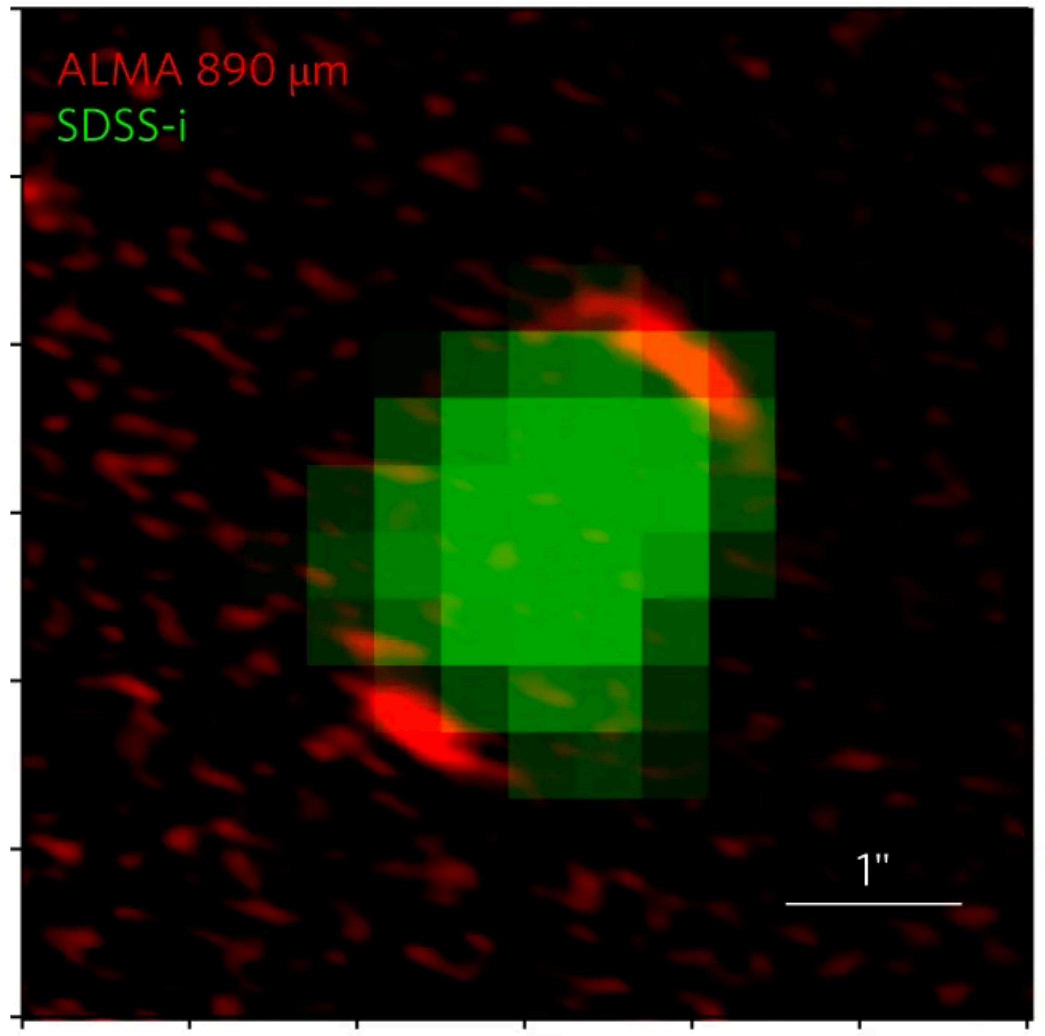


Knudsen+2017
z=7.5



Tamura+2019
z=8.31

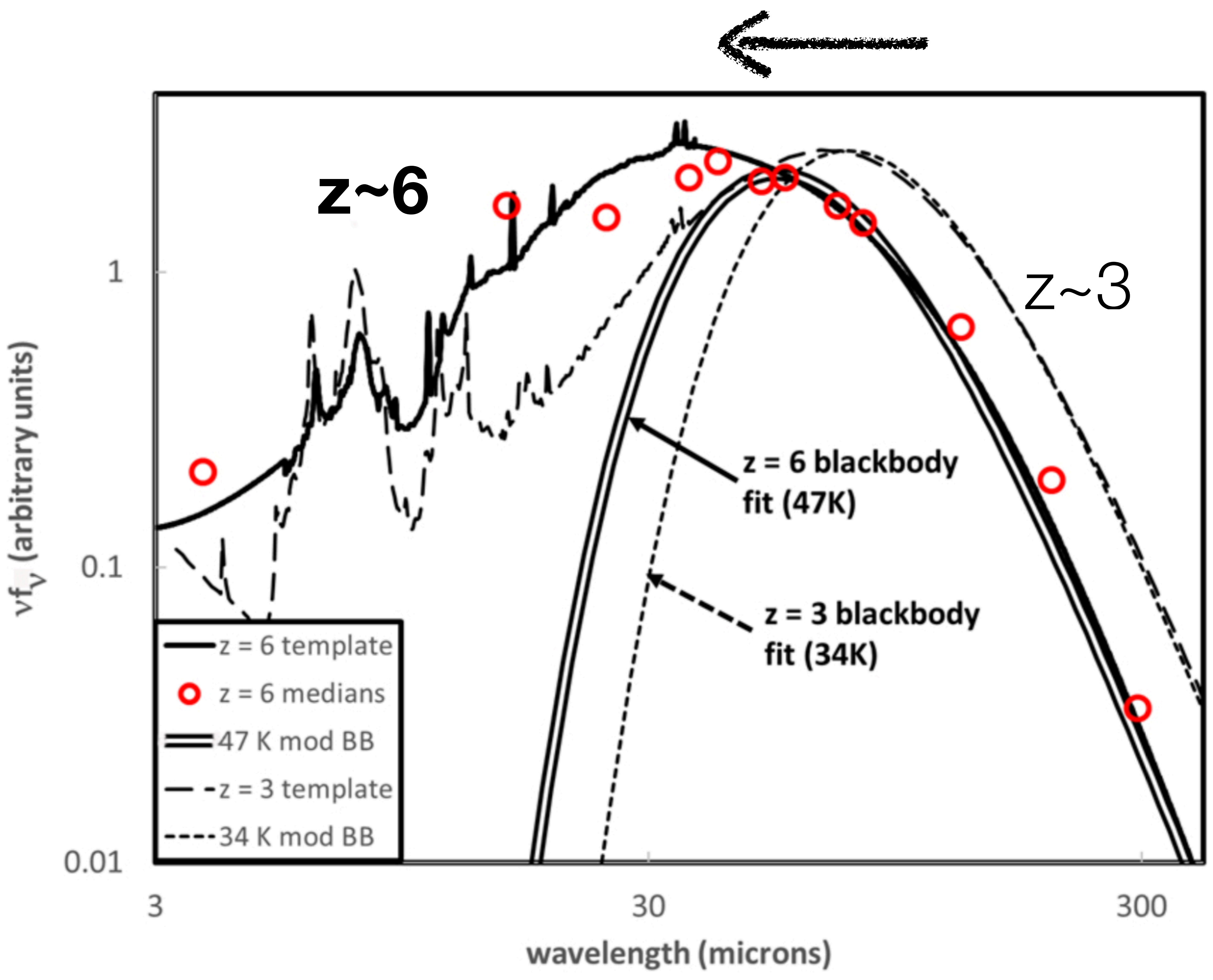
Bowler+2018
z=7.17



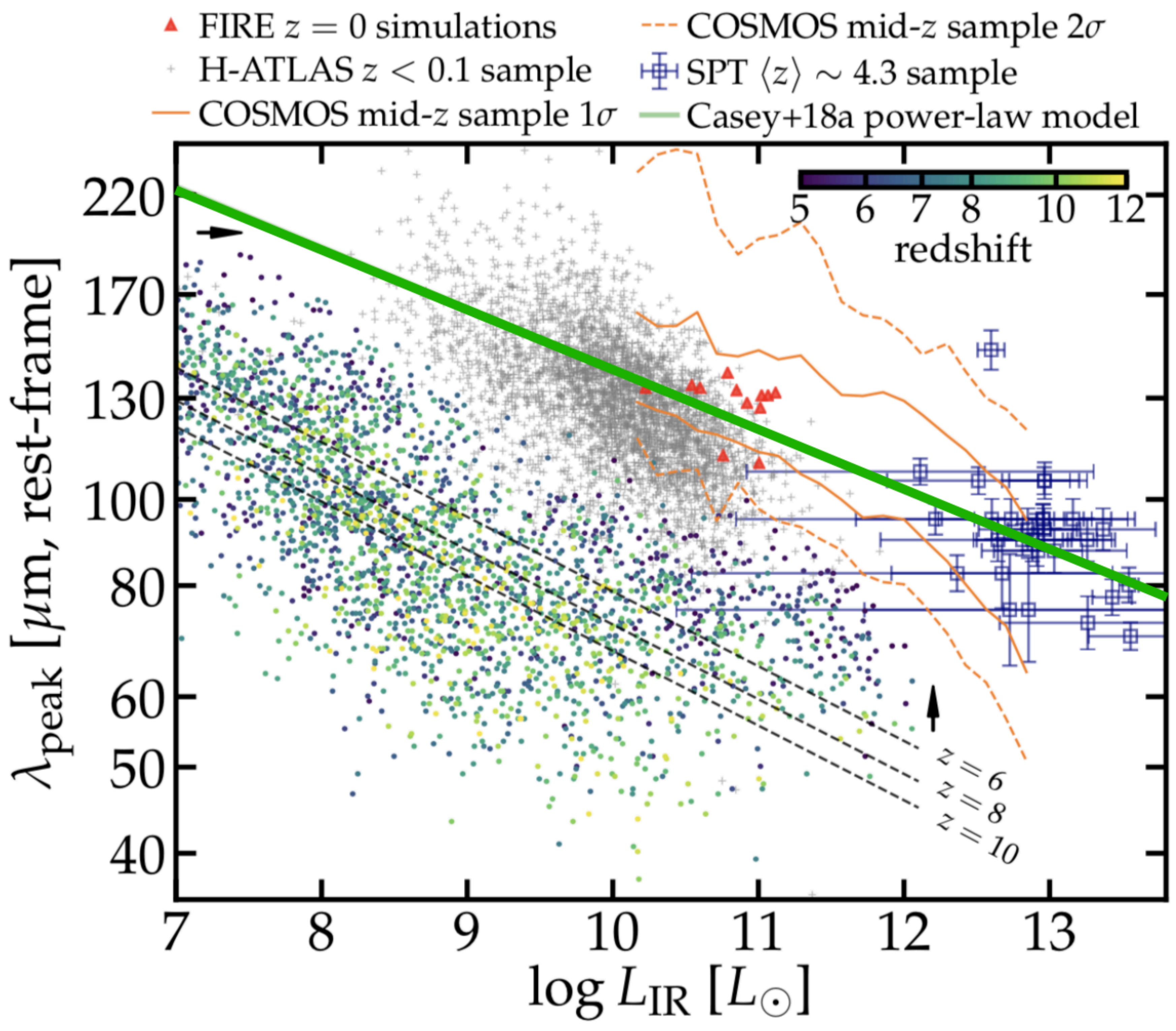
Zavala+2018
z=6.02

How much do we know about dust at high redshifts?

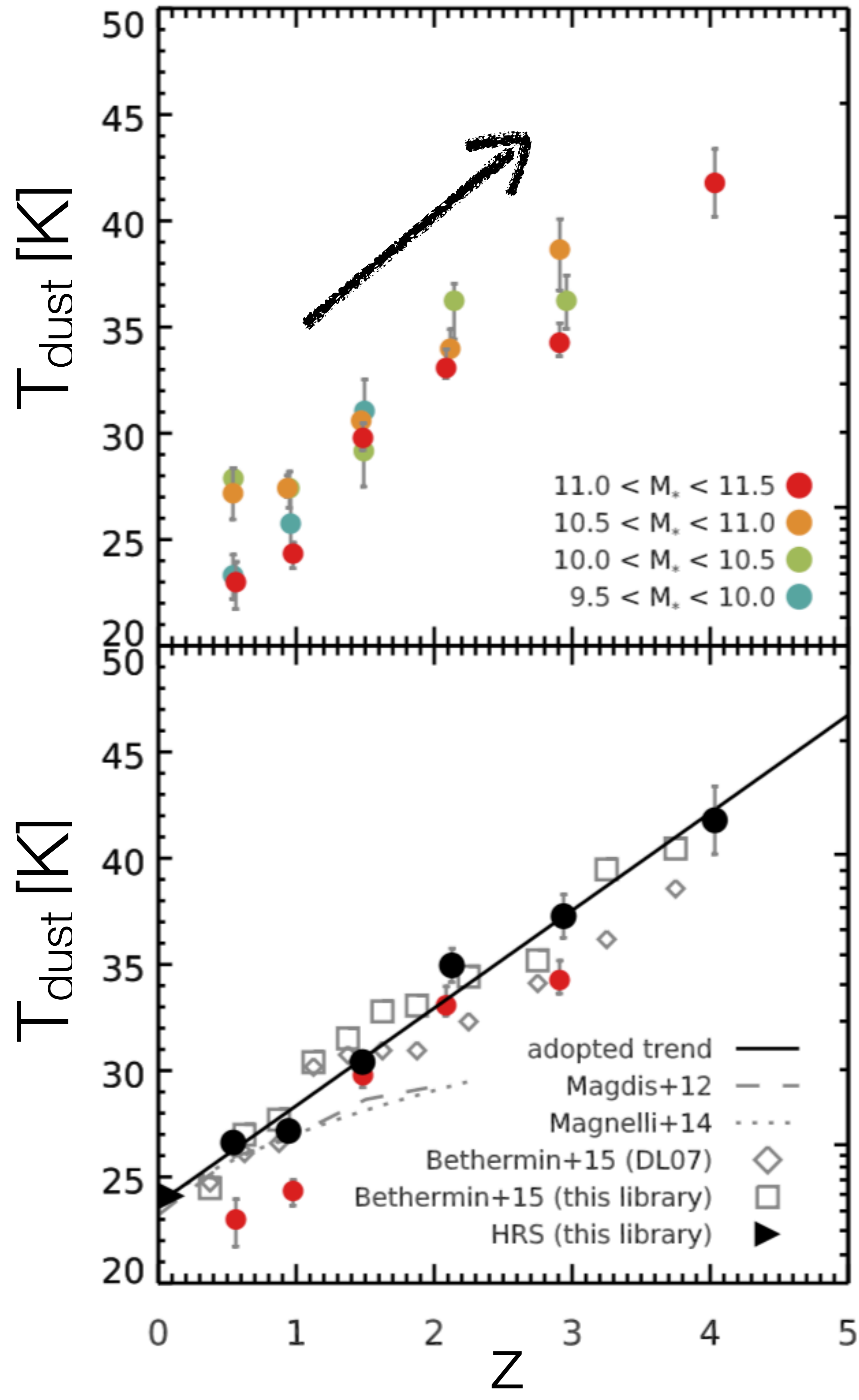
- Does the IR emission evolve with redshift?



De Rossi, Rieke, Shivaei+2018



Ma+2019

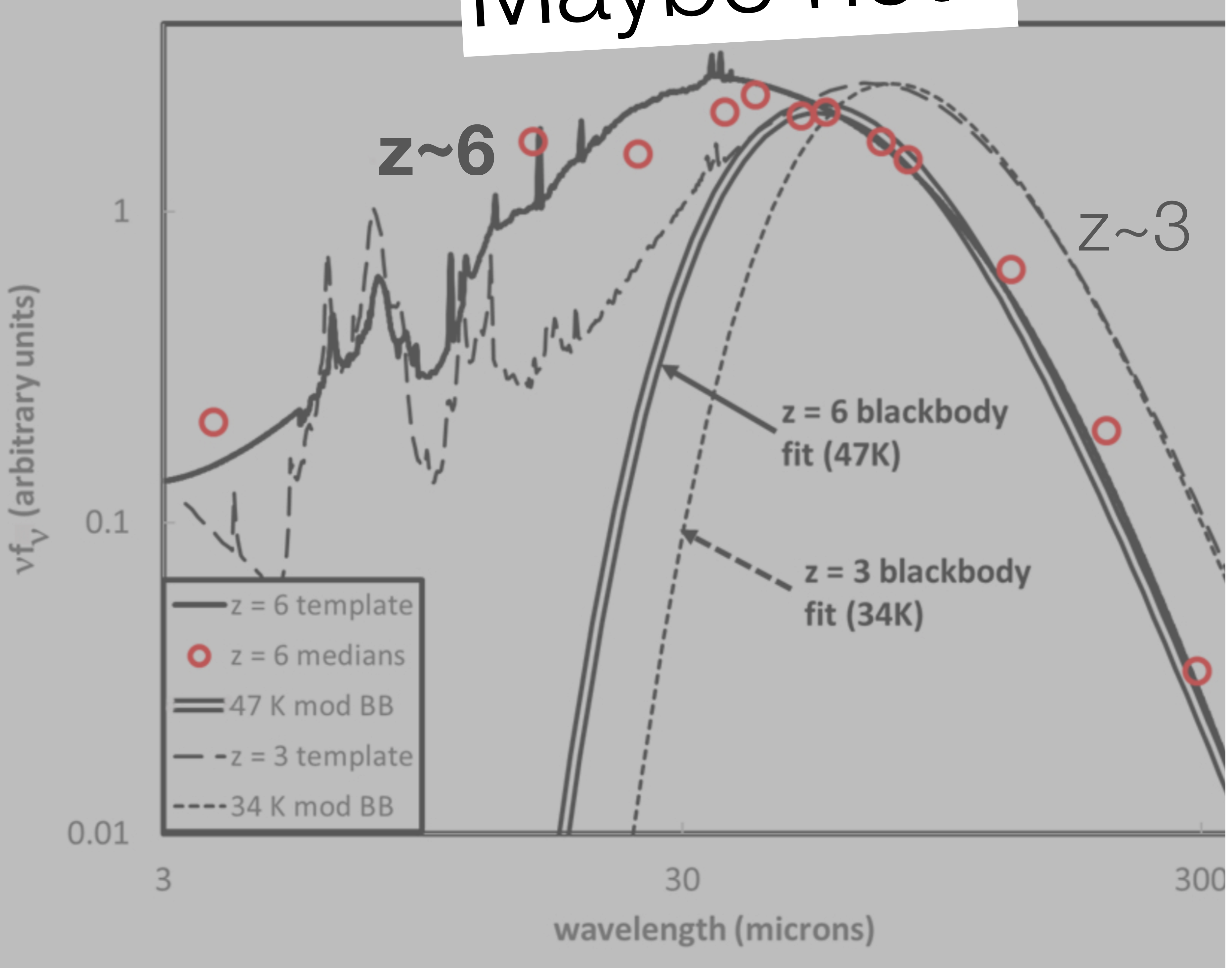


Schreiber+2018

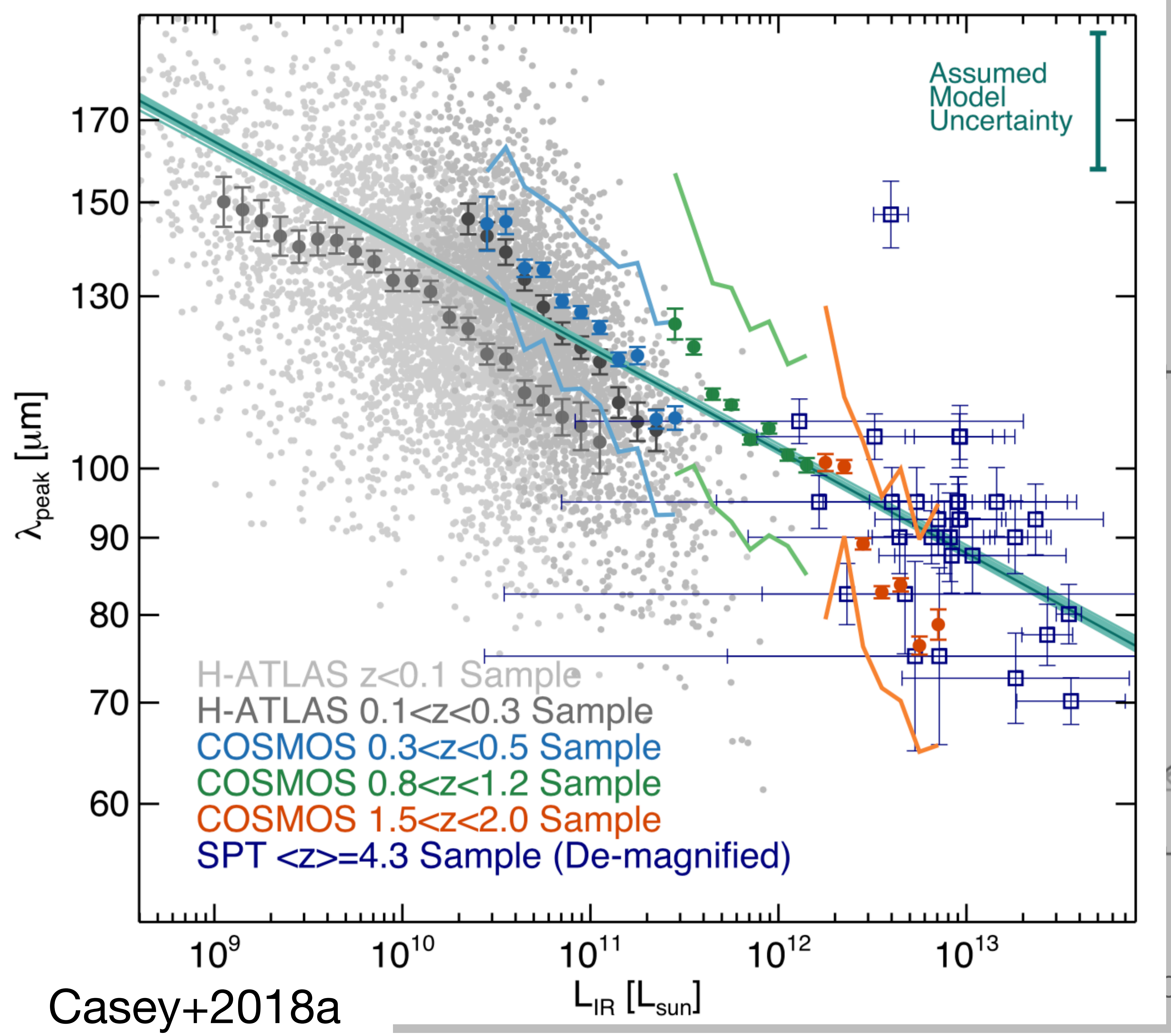
How much do we know about dust at high redshifts?

- Does the IR emission evolve with redshift?

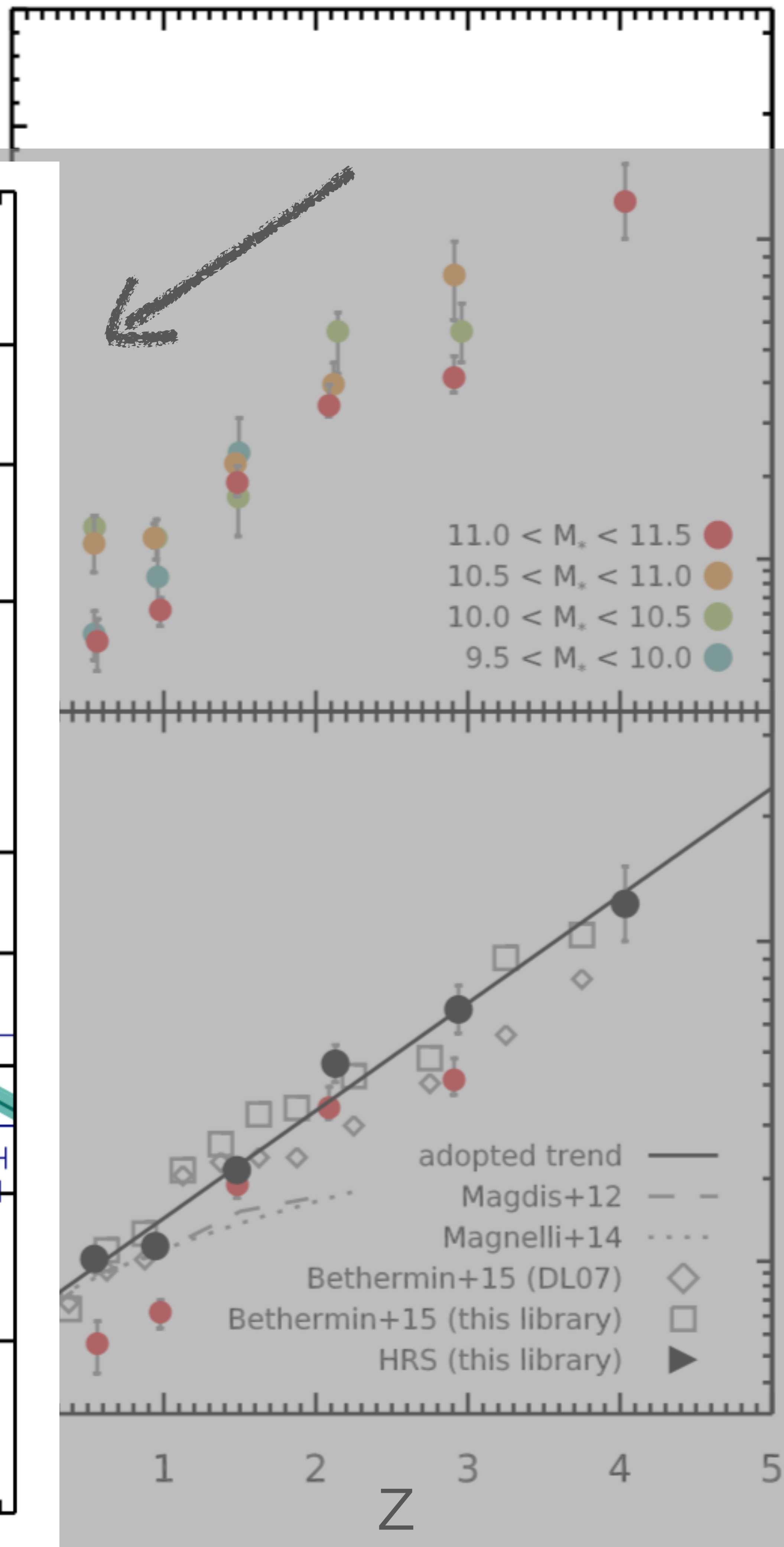
Maybe not?



De Rossi, Rieke, Shivaei+2018



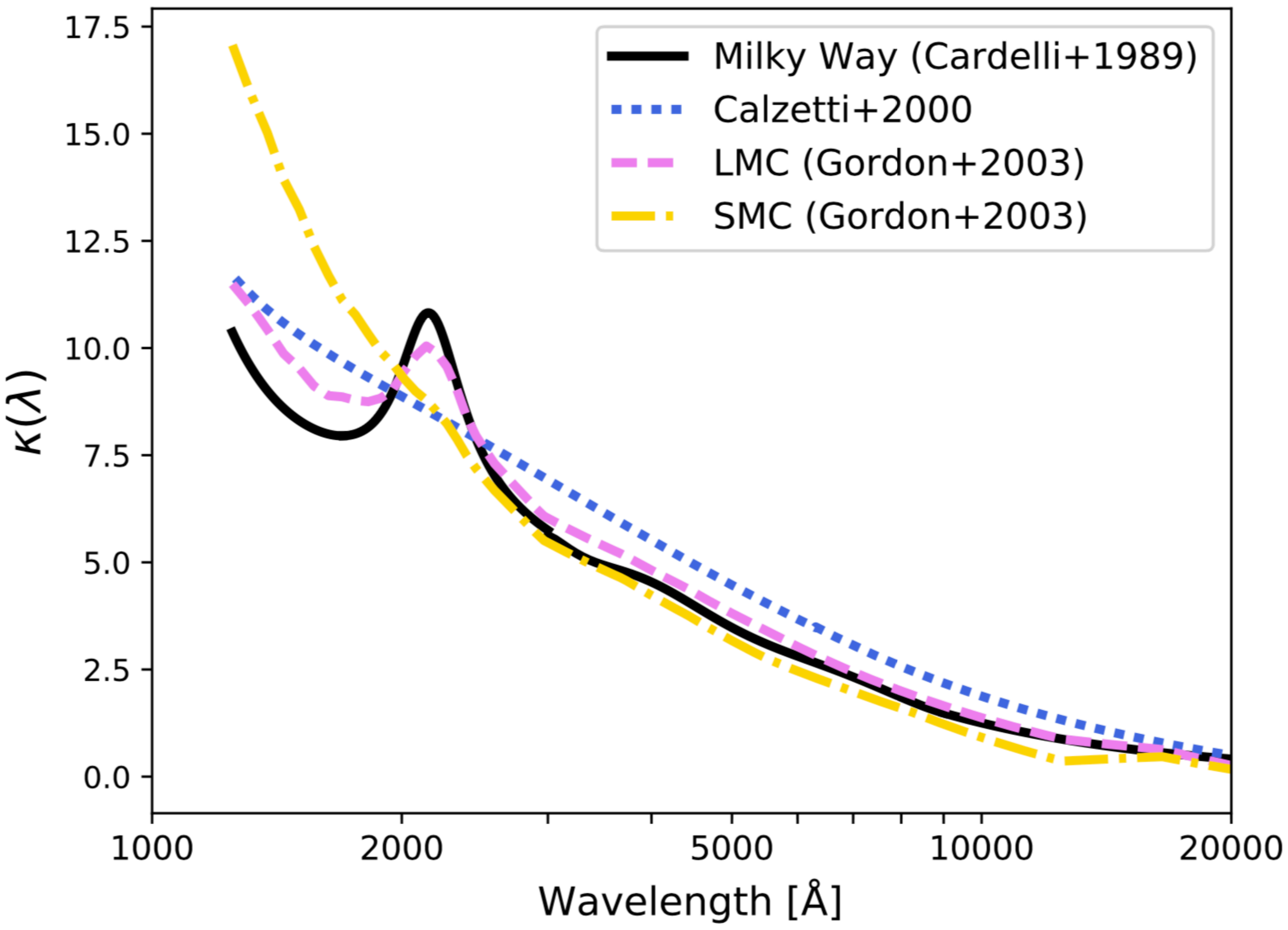
Casey+2018a



chreiber+2018

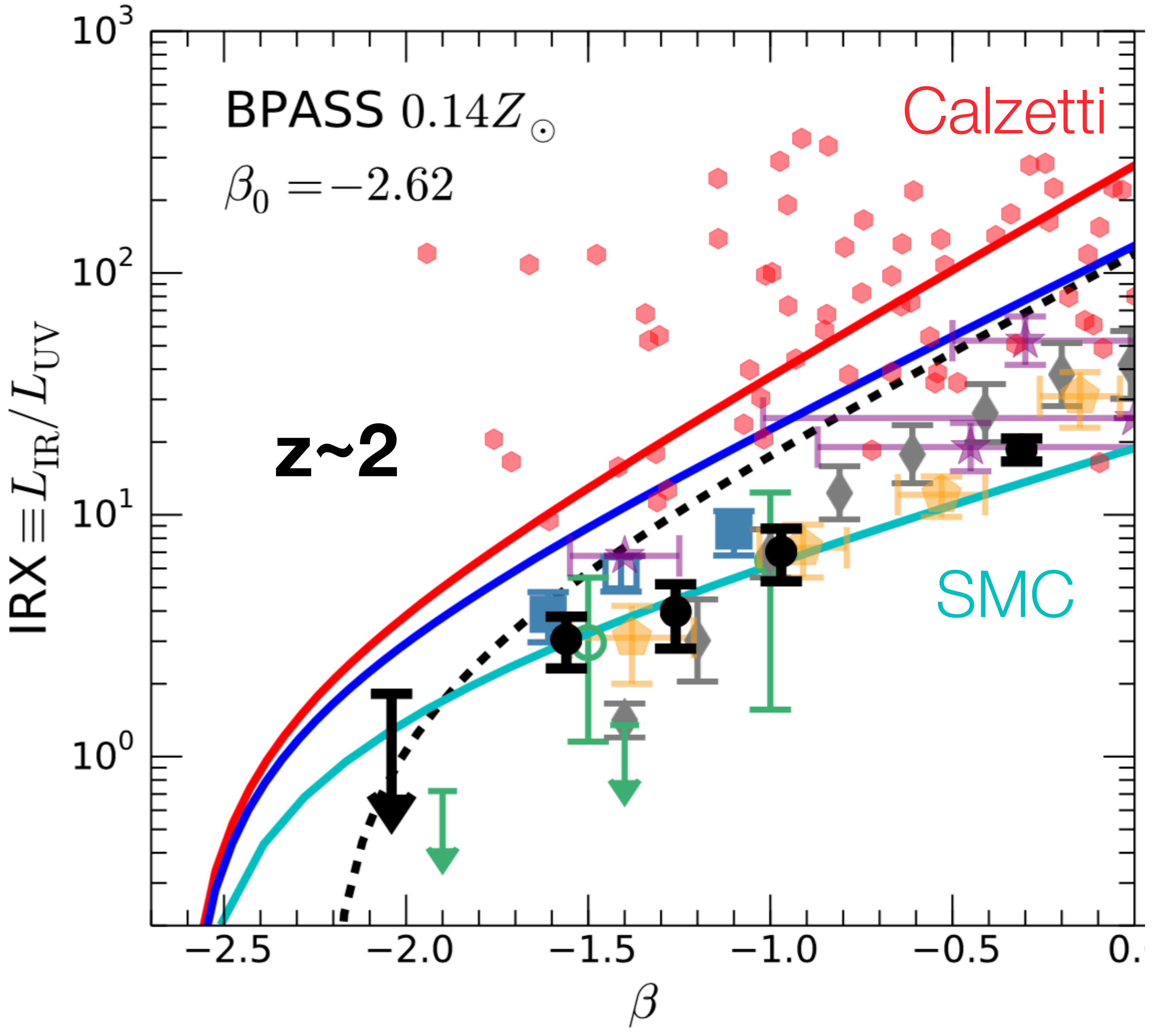
How much do we know about dust at high redshifts?

- Does the IR emission evolve with redshift?
- Does the attenuation curve evolve with redshift?

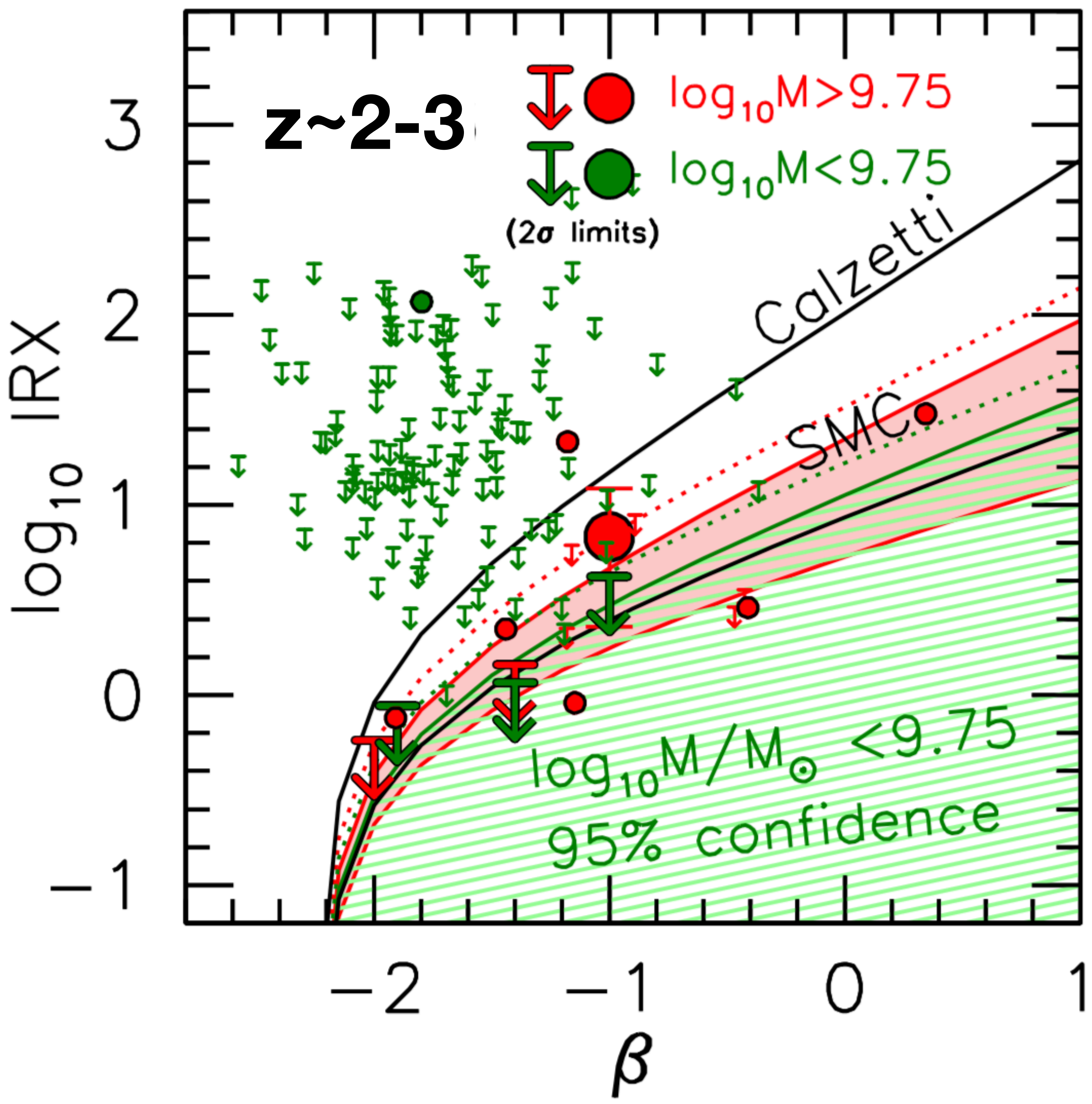


How much do we know about dust at high redshifts?

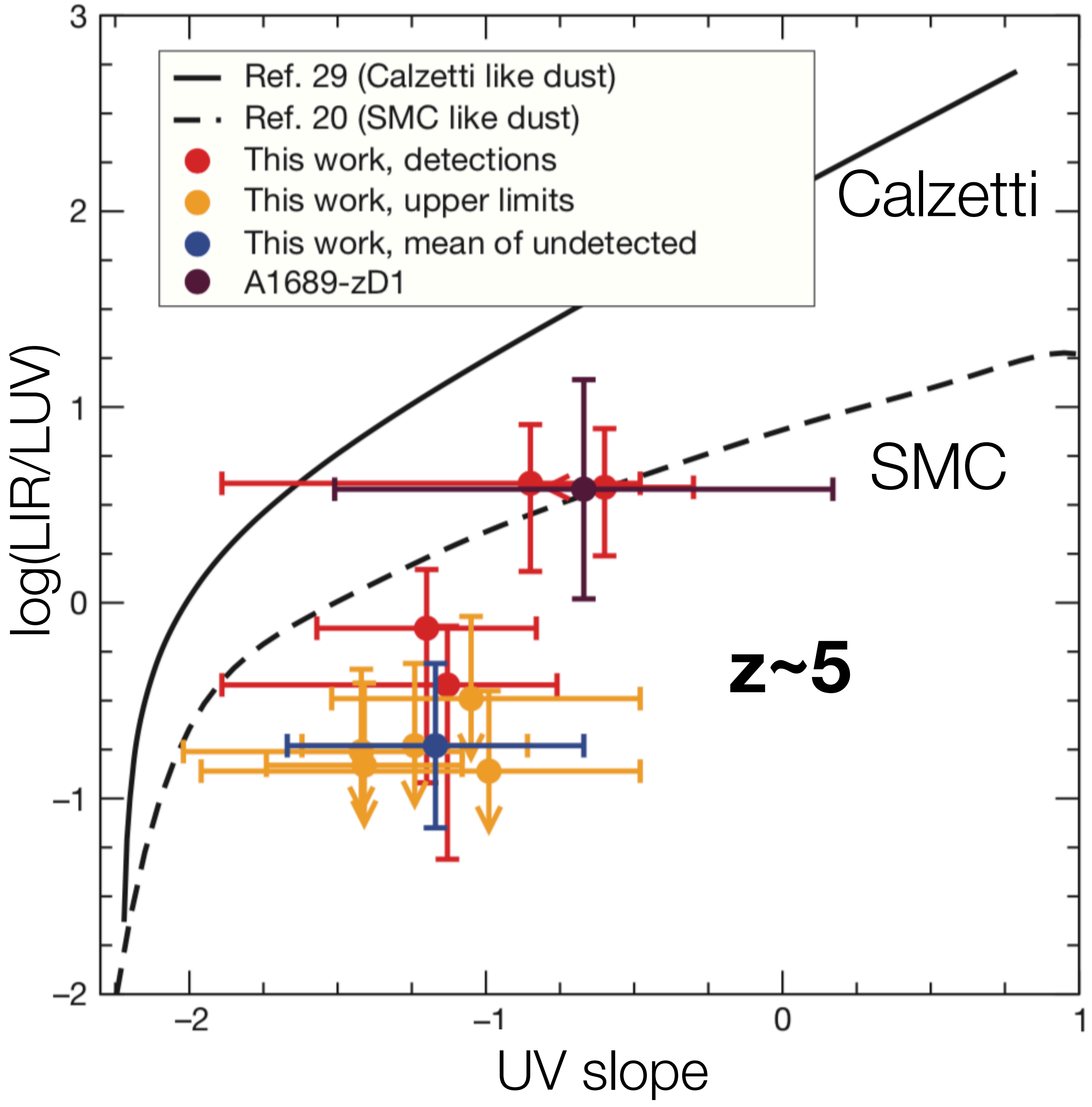
- Does the IR emission evolve with redshift?
- Does the attenuation curve evolve with redshift? IRX-beta relation/attenuation curve slope



Reddy+2017



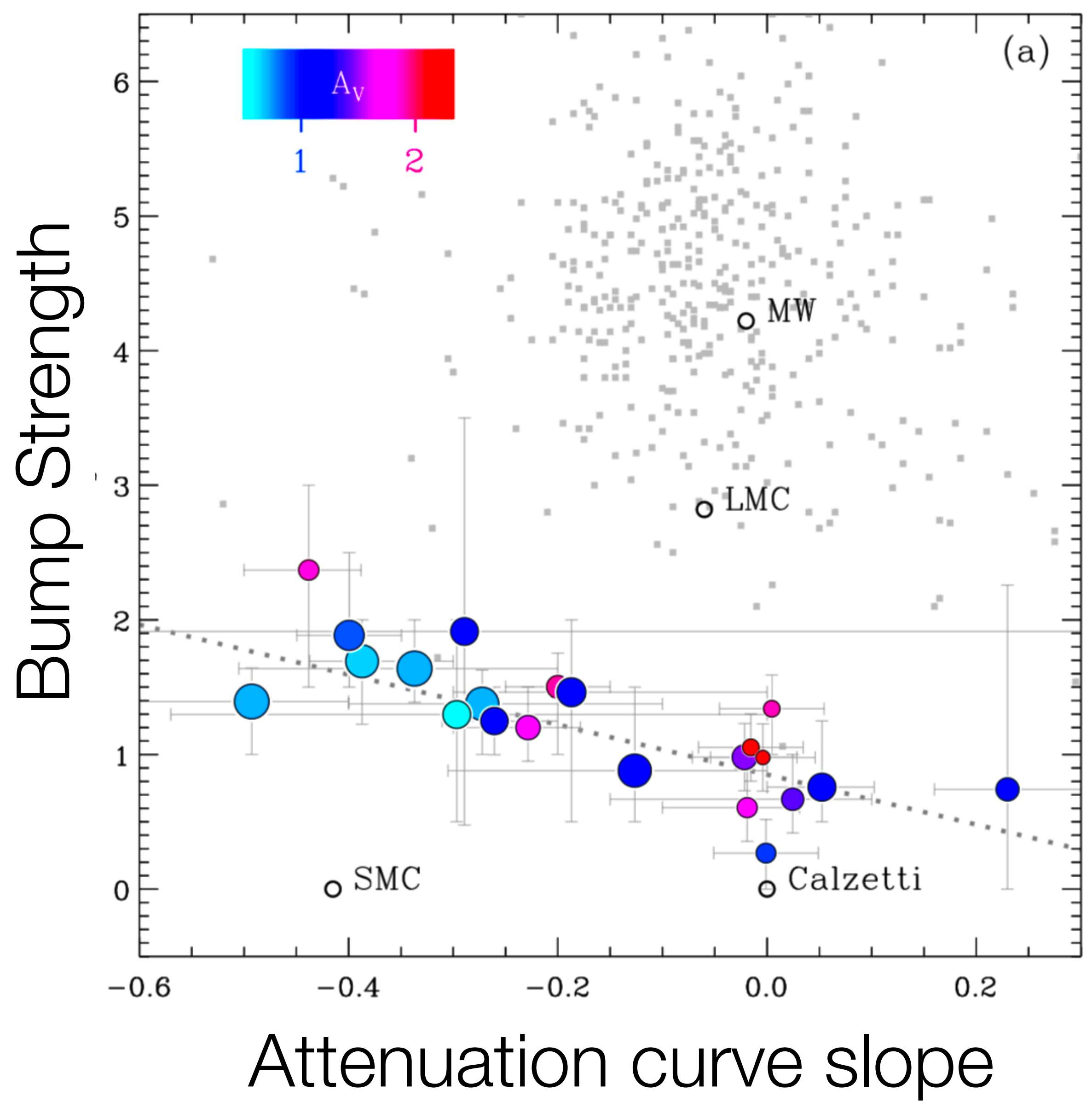
Bouwens+2016



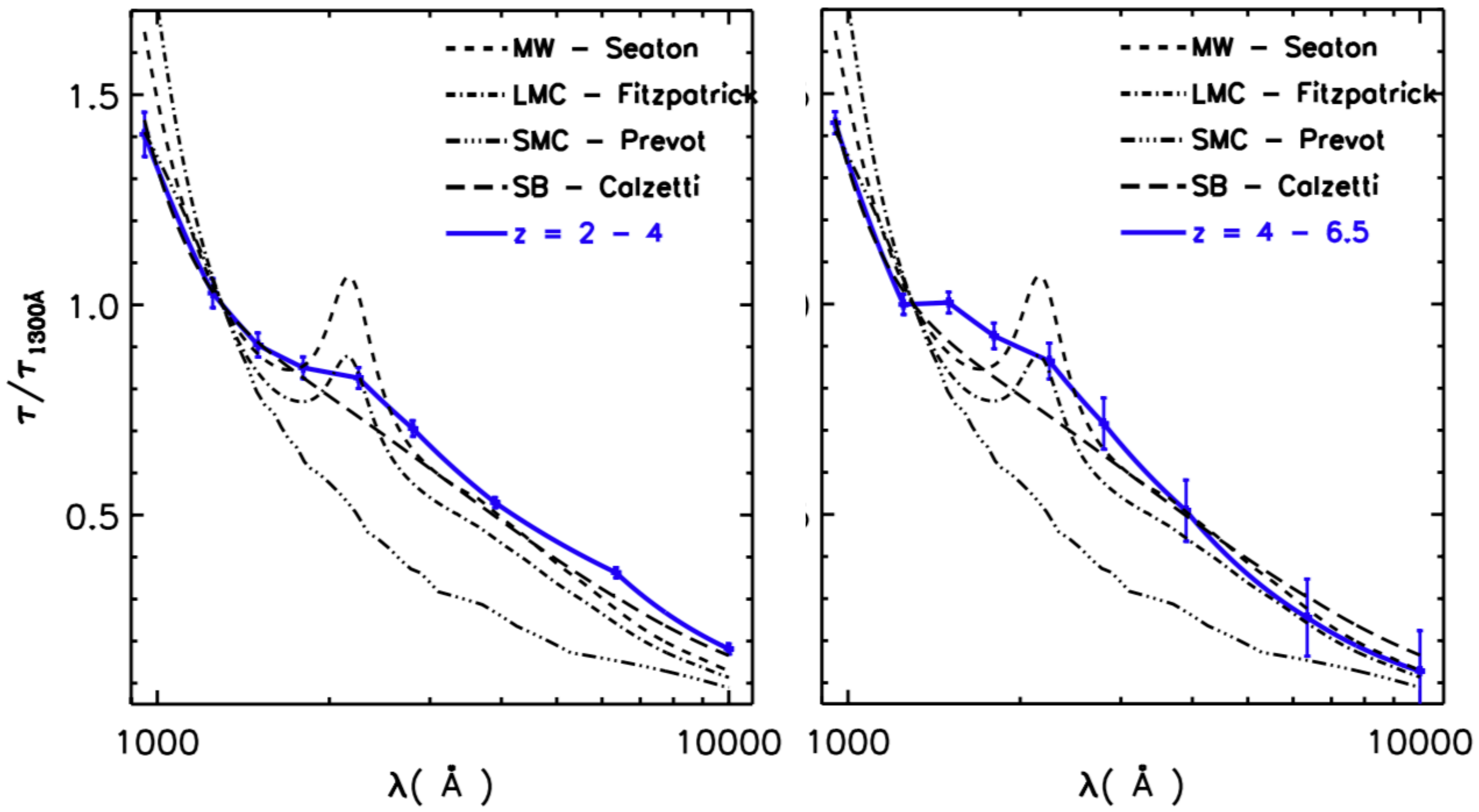
Capak+2015

How much do we know about dust at high redshifts?

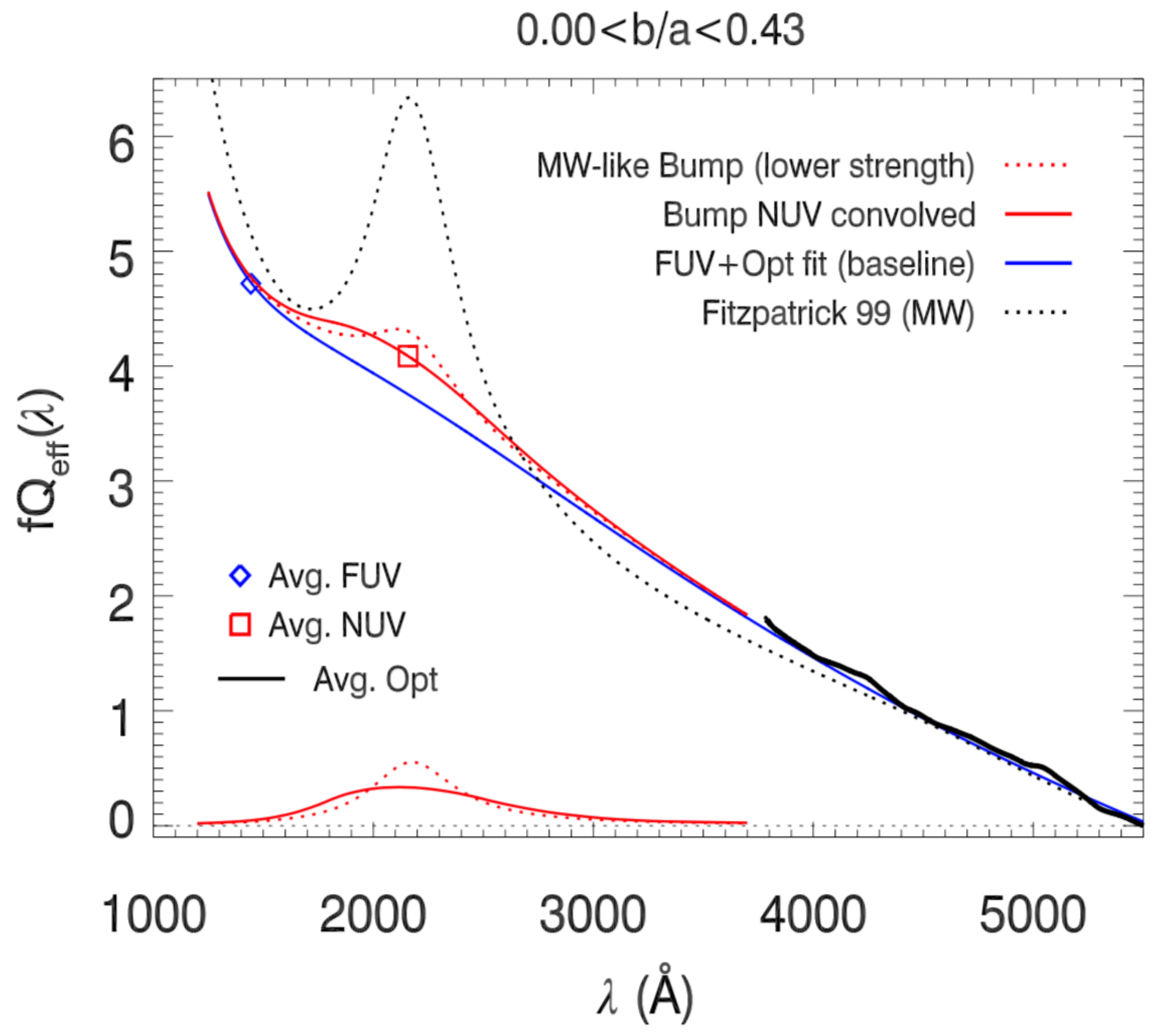
- Does the IR emission evolve with redshift?
- Does the attenuation curve evolve with redshift? UV extinction bump



Kriek & Conroy (2013)



Scoville+2015



Battisti+2017

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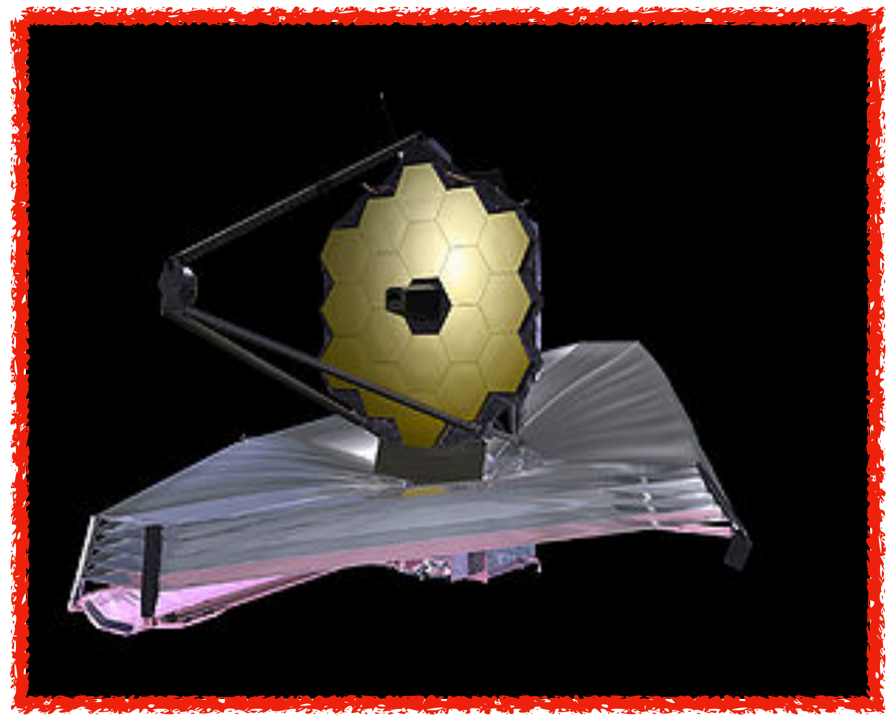
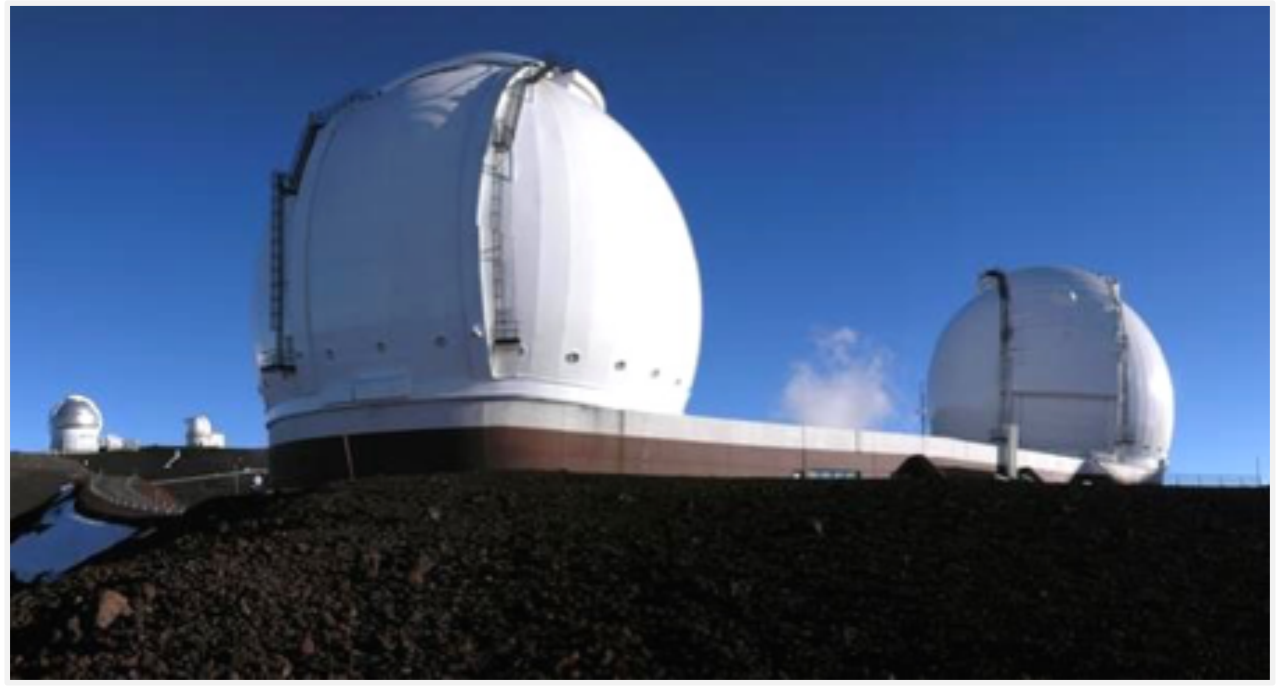
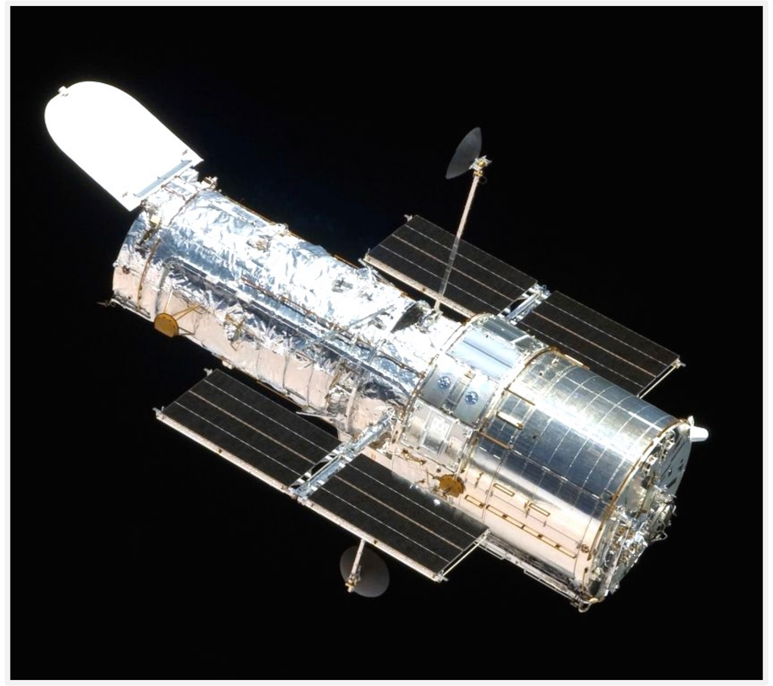
Kriek & Conroy (2013)

Reddy+2015 Scoville+2015

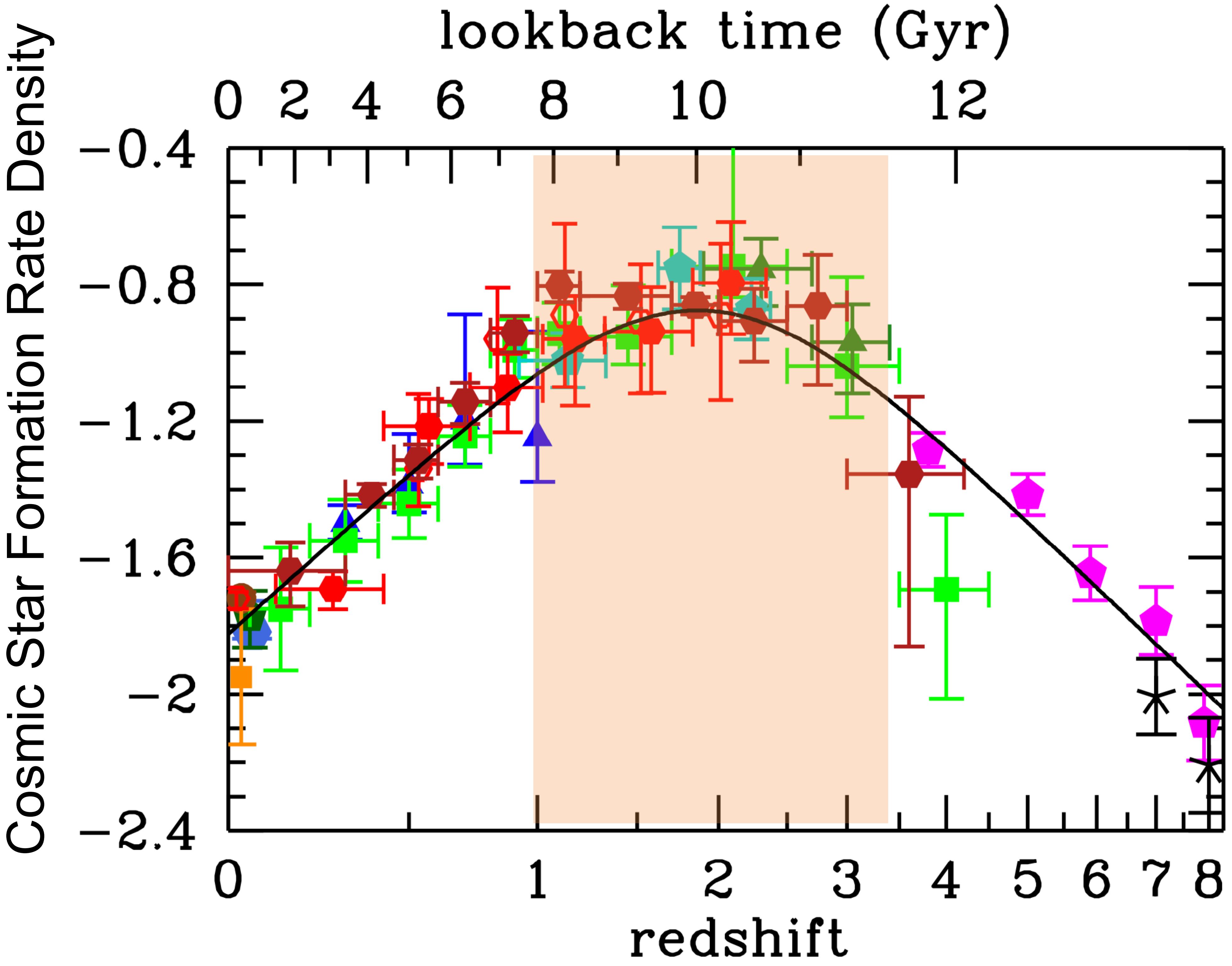
Battisti+2017



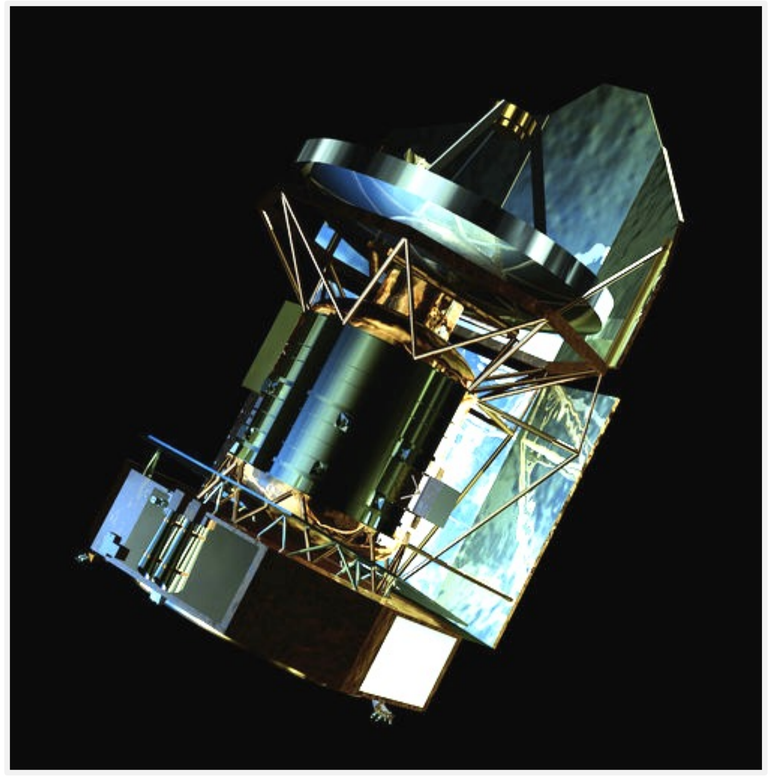




z~1-3: peak epoch of cosmic star formation activity

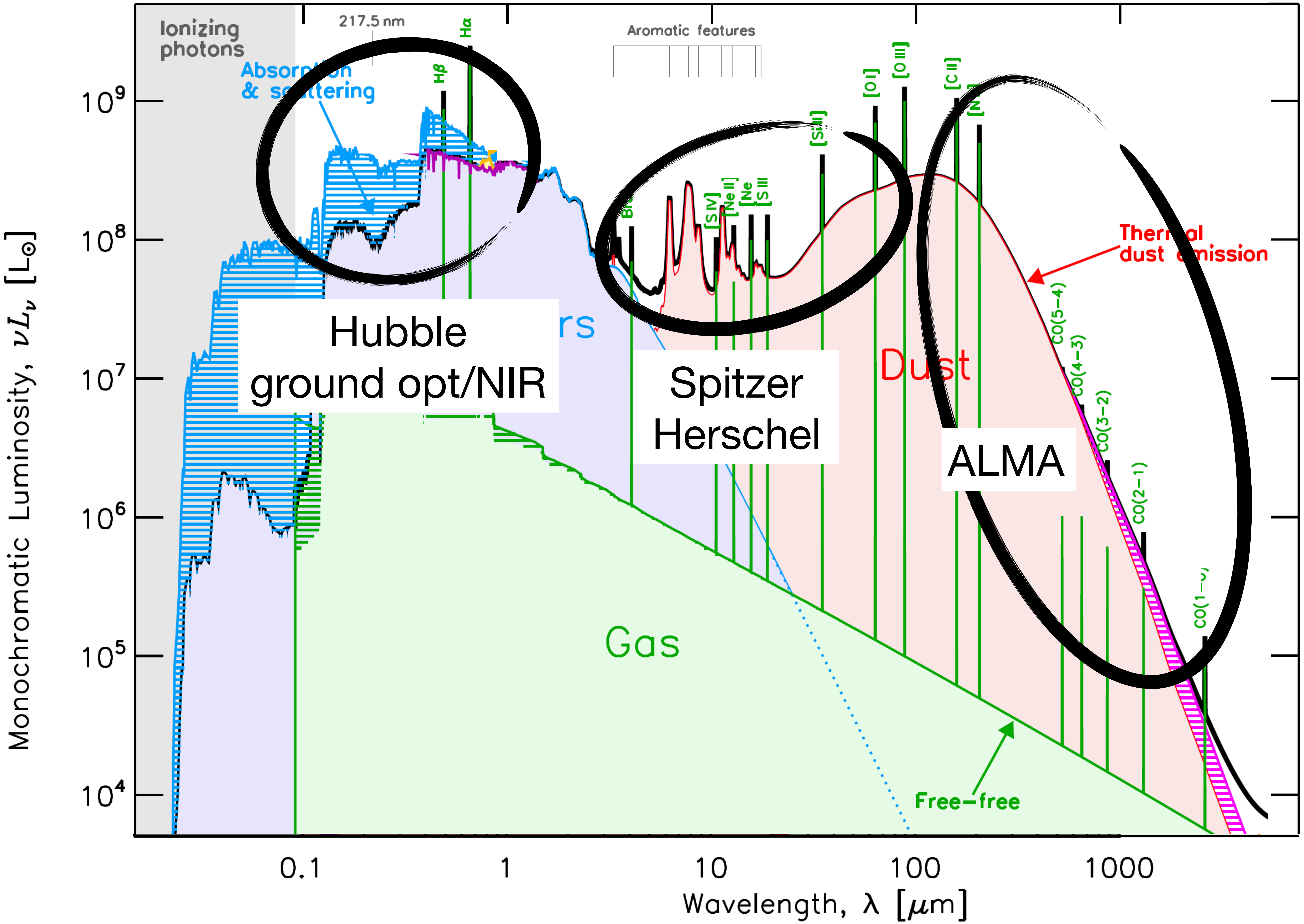


Madau & Dickinson (2014)



At z~1-3:

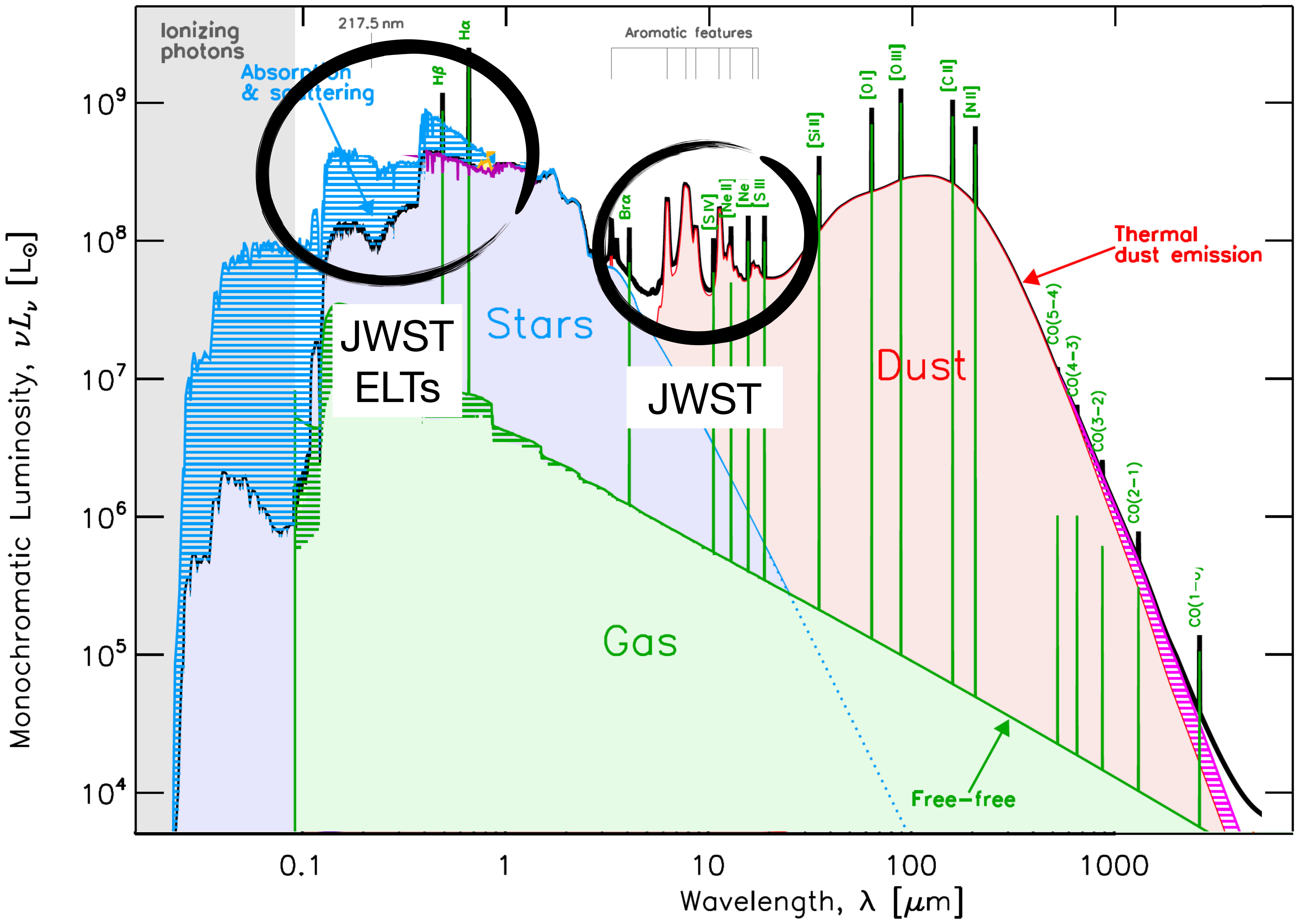
Current data/ facilities



SED from Galliano et al. (2017)

At z~1-3:

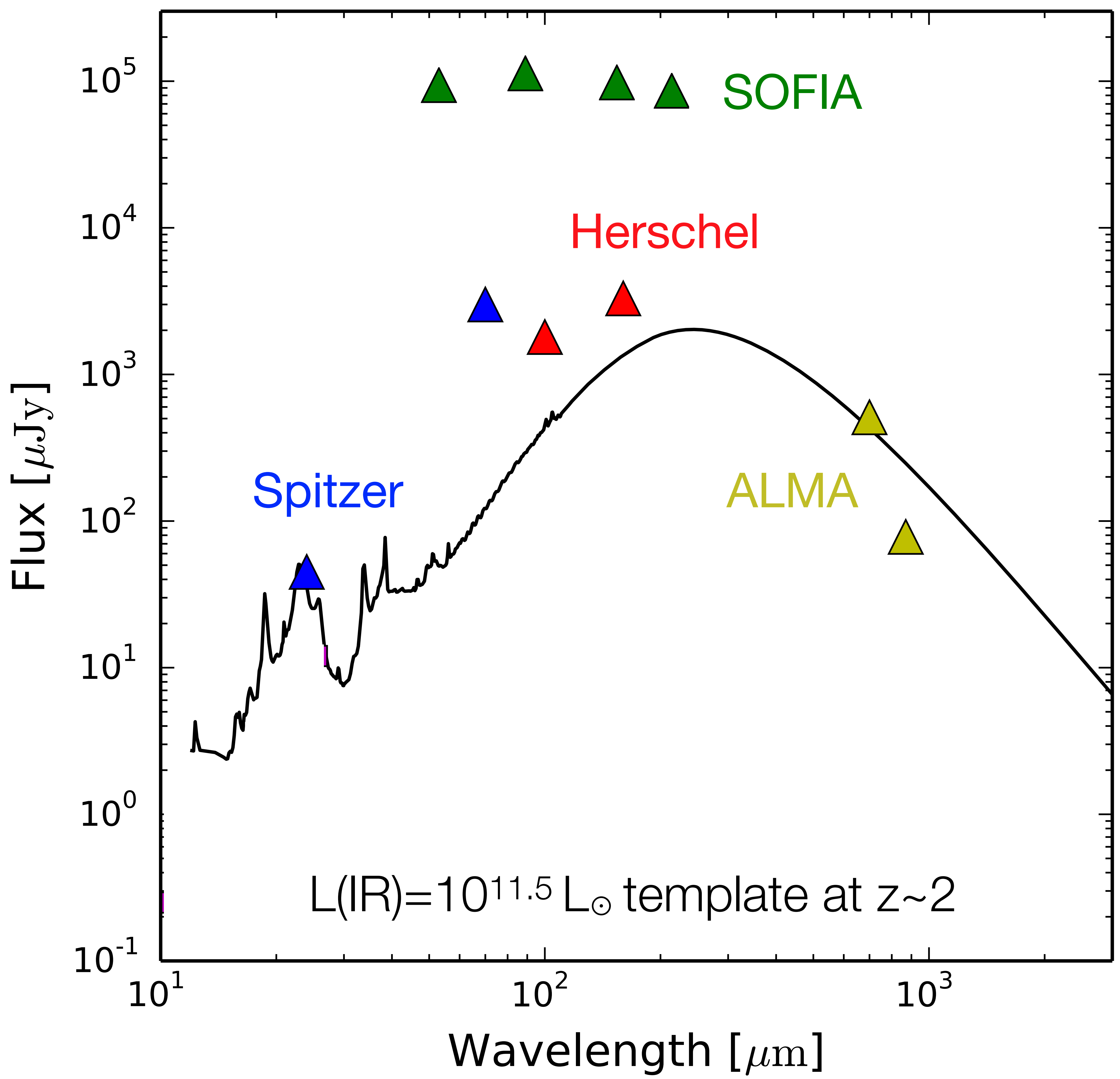
Future facilities



SED from Galliano et al. (2017)

Current data/facilities

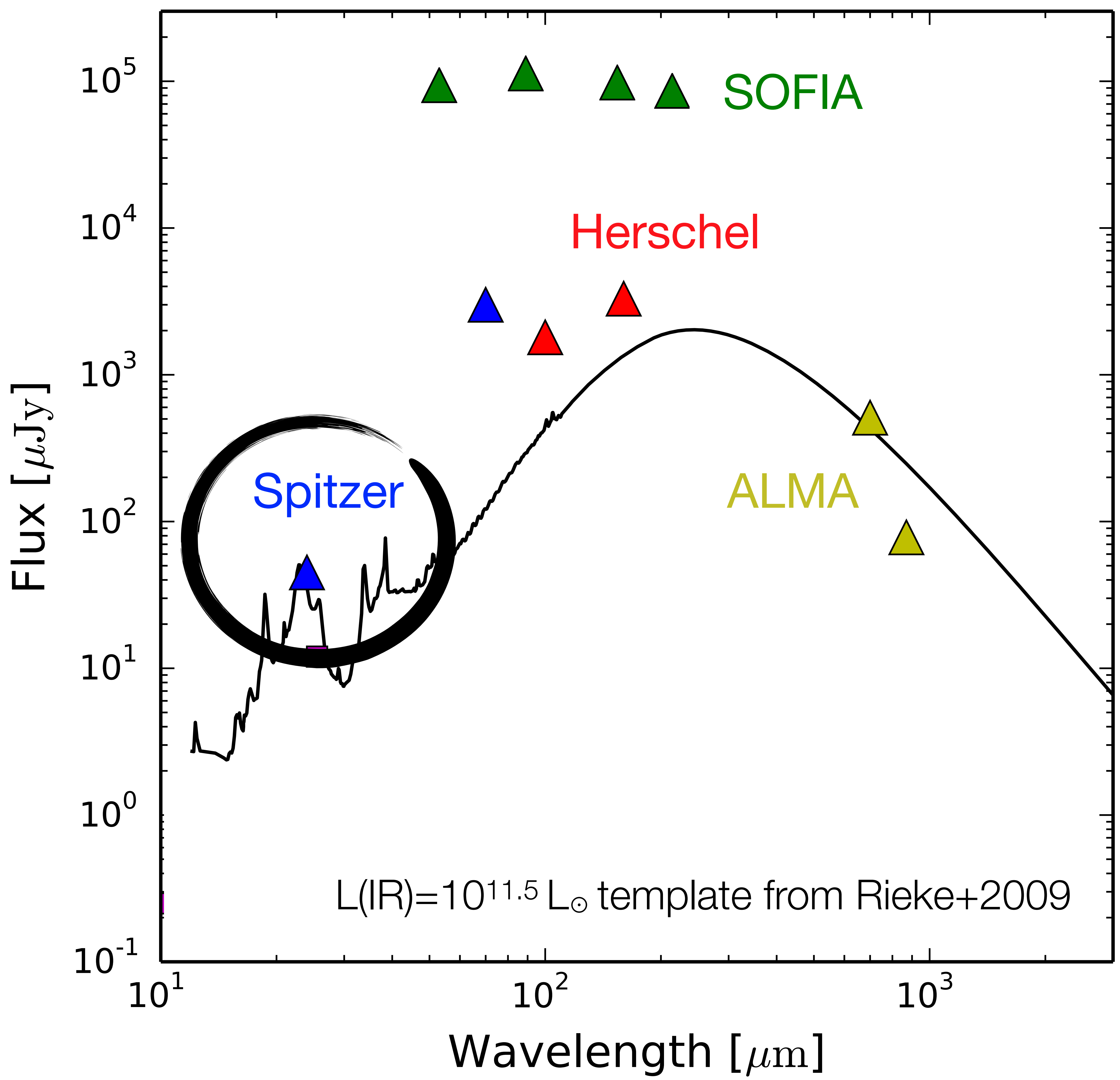
IR emission of a typical z~2 galaxy, with 3-sigma detection limits of different instruments in 1 hour integrations



- Mid-IR traces the PAH emission at z~2
- Good tracer of IR emission, given the higher sensitivity and spatial resolution of Spitzer

- Any redshift evolution in L(PAH)/L(IR)?

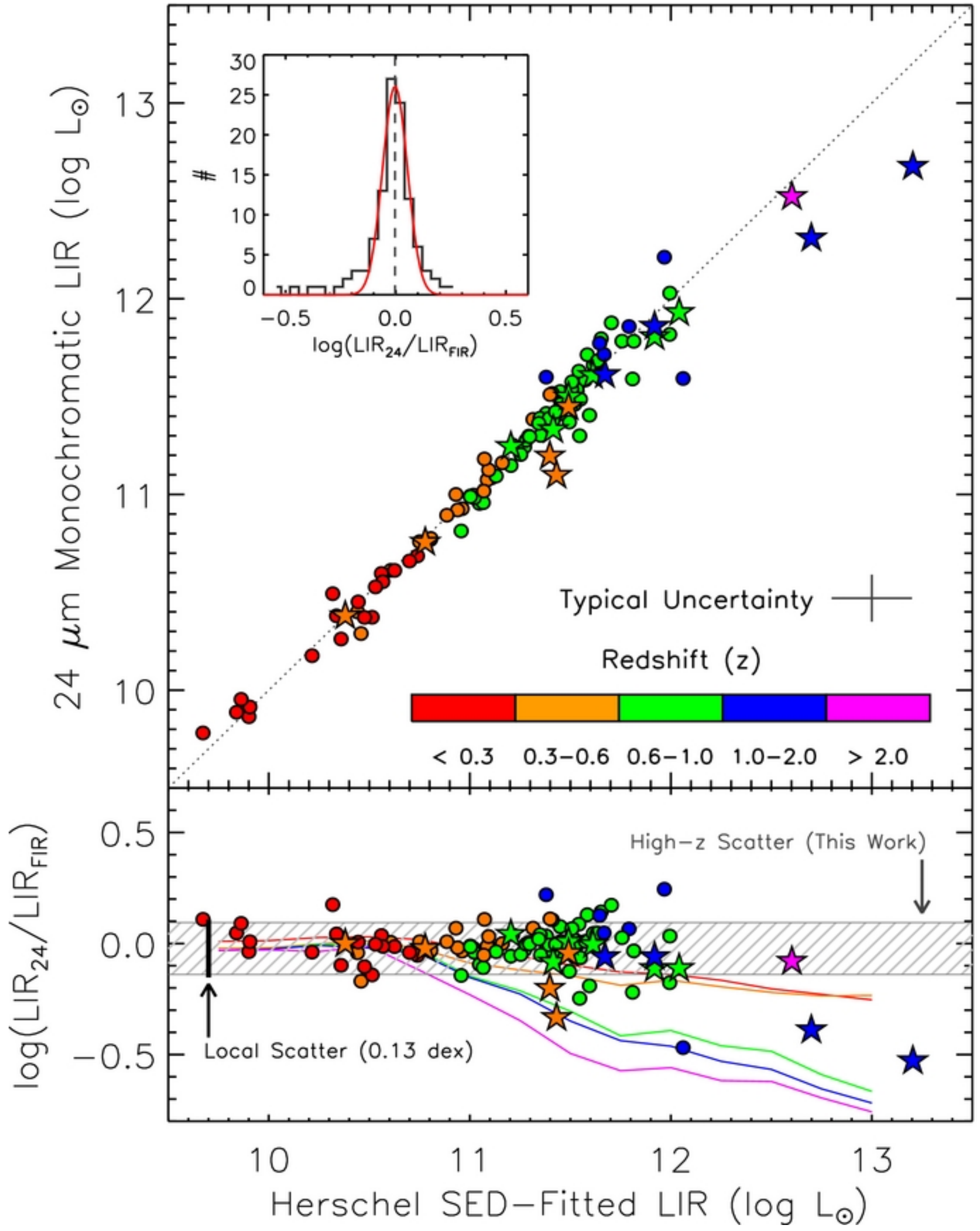
IR emission of a typical z~2 galaxy



Limited to dusty and highly star-forming galaxies at z>1

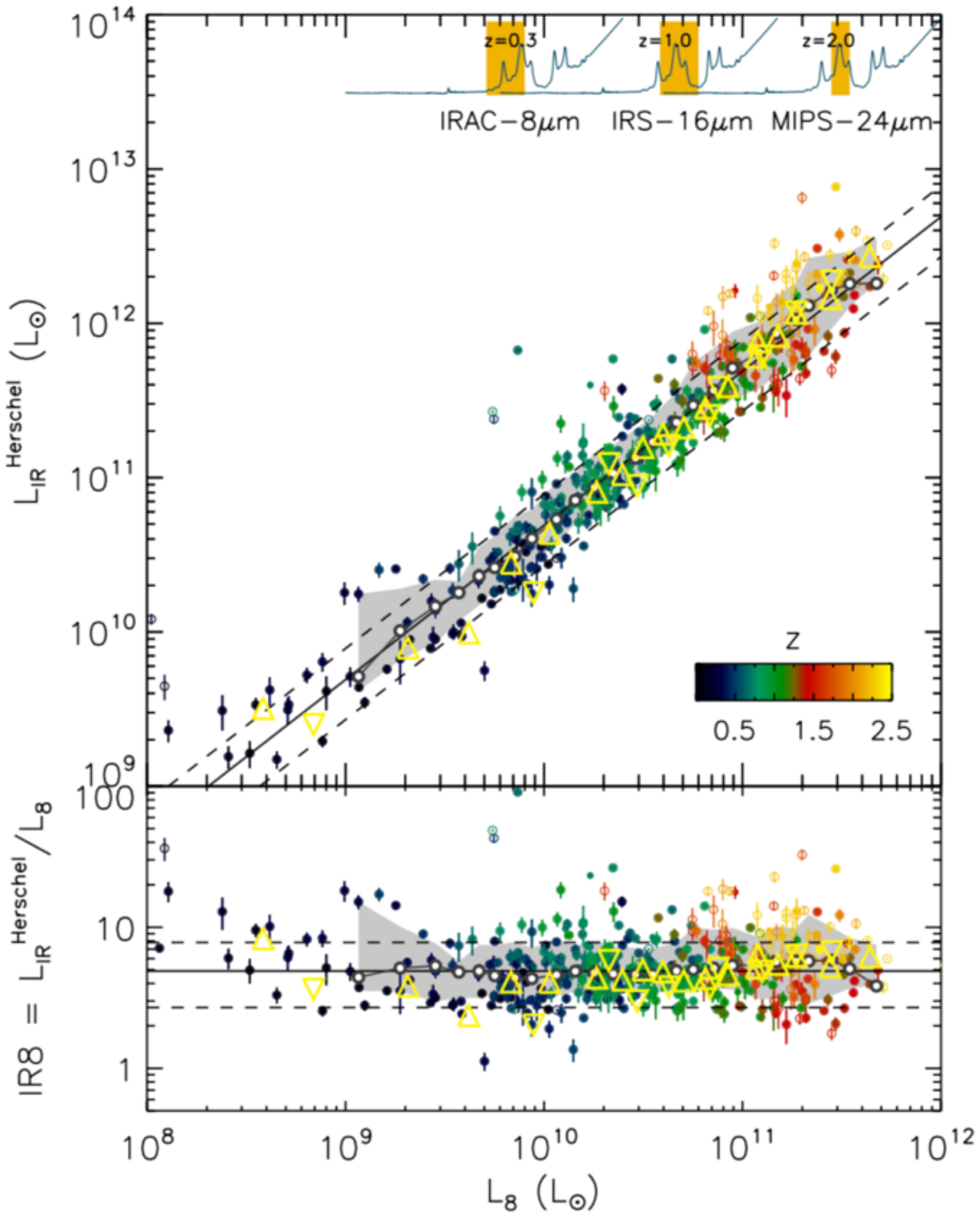
Rujopakran+2014

LIR_{24} /LIR_{FIR}



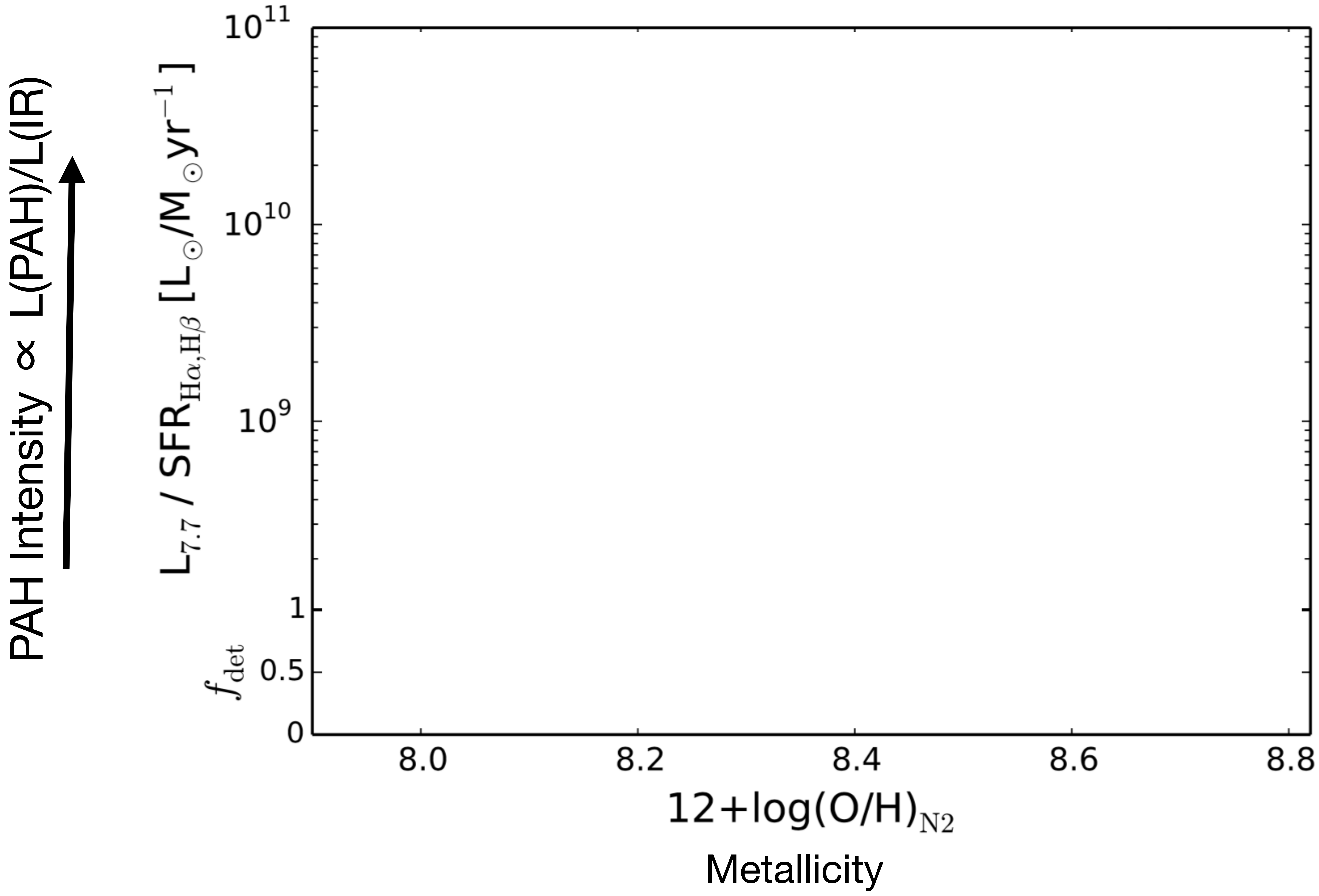
Elbaz+2011

L(IR)/L(PAH)



See also: Kennicutt & Evans (2012), Reddy et al. (2012), Wuyts et al. (2008), Bavouzet et al. (2008), Rigby et al. (2008), Caputi et al. (2007)

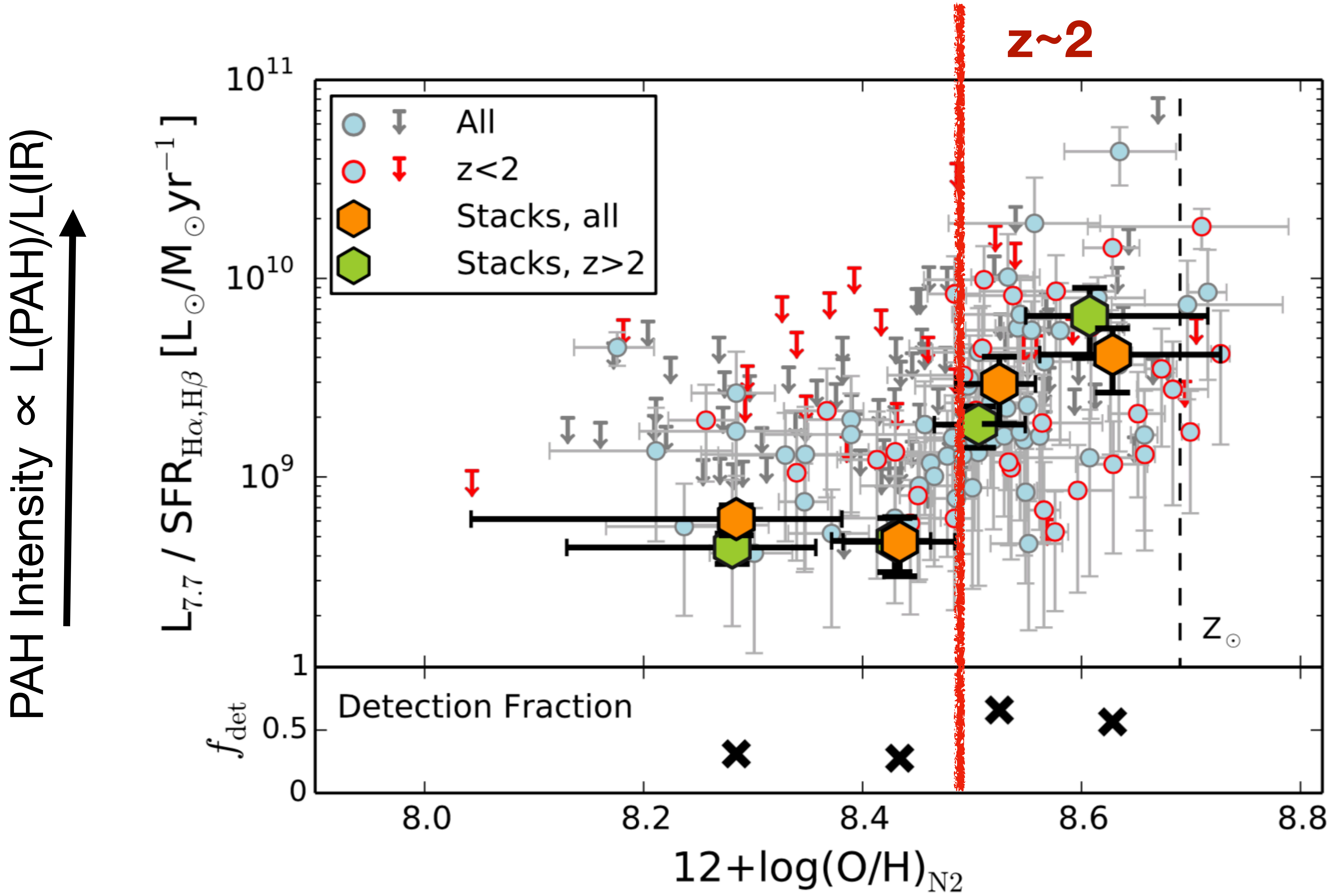
How does the PAH intensity changes in lower-mass, lower-metallicity galaxies at z~2 compared to z~0?



Shivaei+2017:

MOSDEF survey
Sample of ~450 galaxies with Spitzer/MIPS24um data and rest-optical metallicity measurements

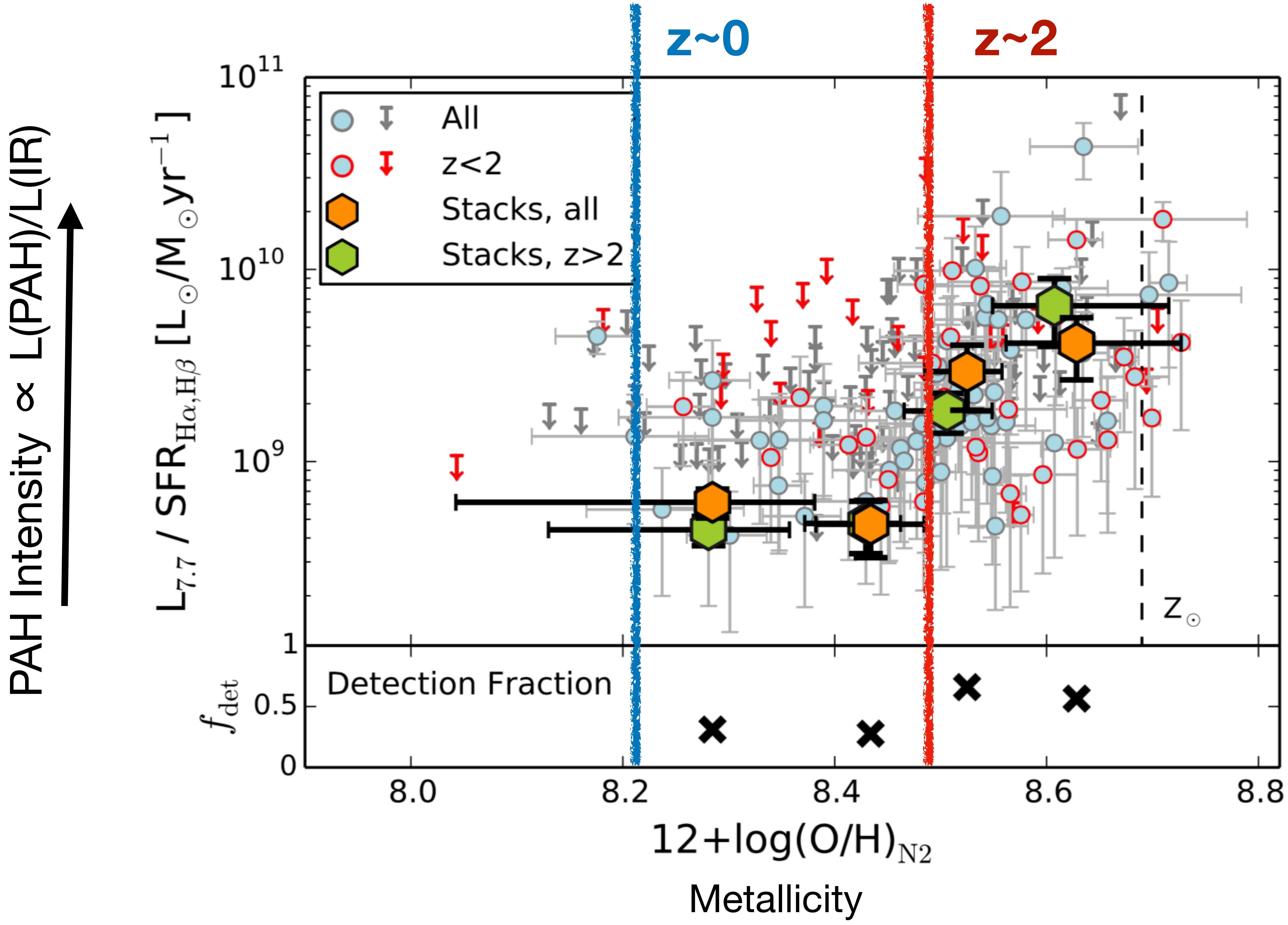
The PAH intensity decreases with decreasing metallicity in agreement with low-redshift studies



Metallicity

Shivaei+2017

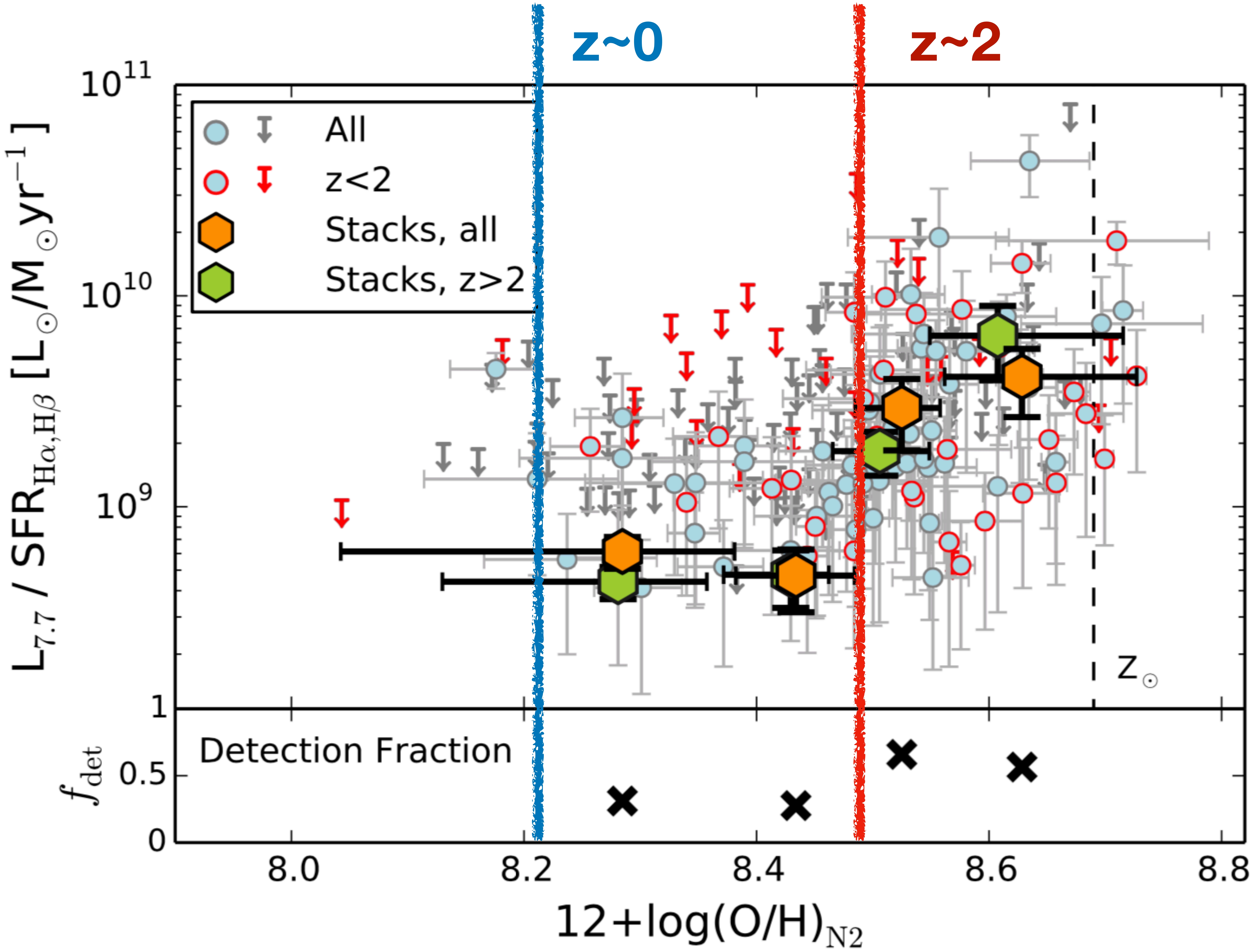
The PAH intensity decreases with decreasing metallicity in agreement with low-redshift studies, but at a different oxygen abundance



Shivaei+2017

Local calibrations to convert PAH emission to L(IR) should be used with caution at high redshifts

ISM conditions are different (e.g., harder ionizing radiation, alpha enhancement)



Shivaei+2017

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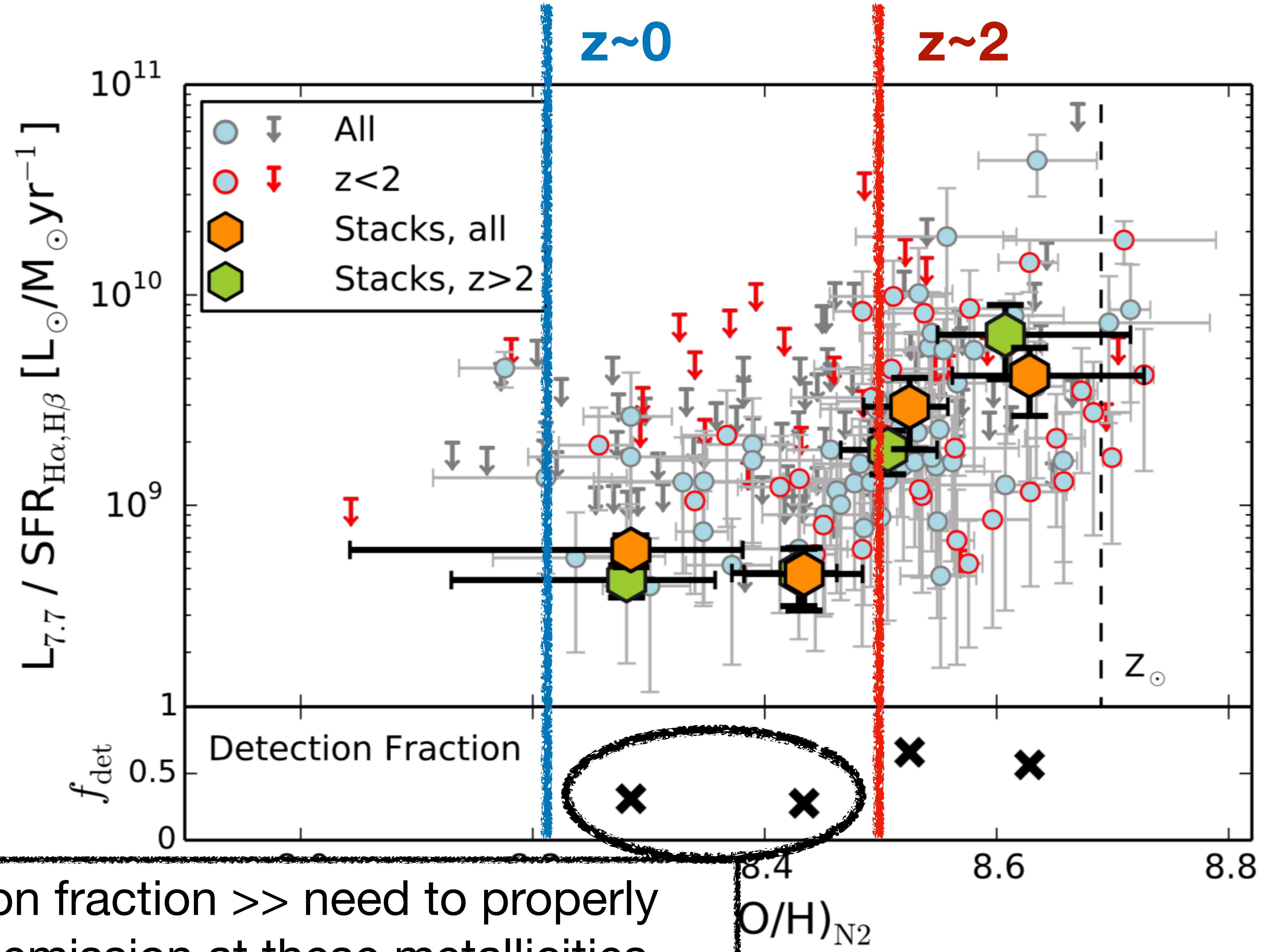
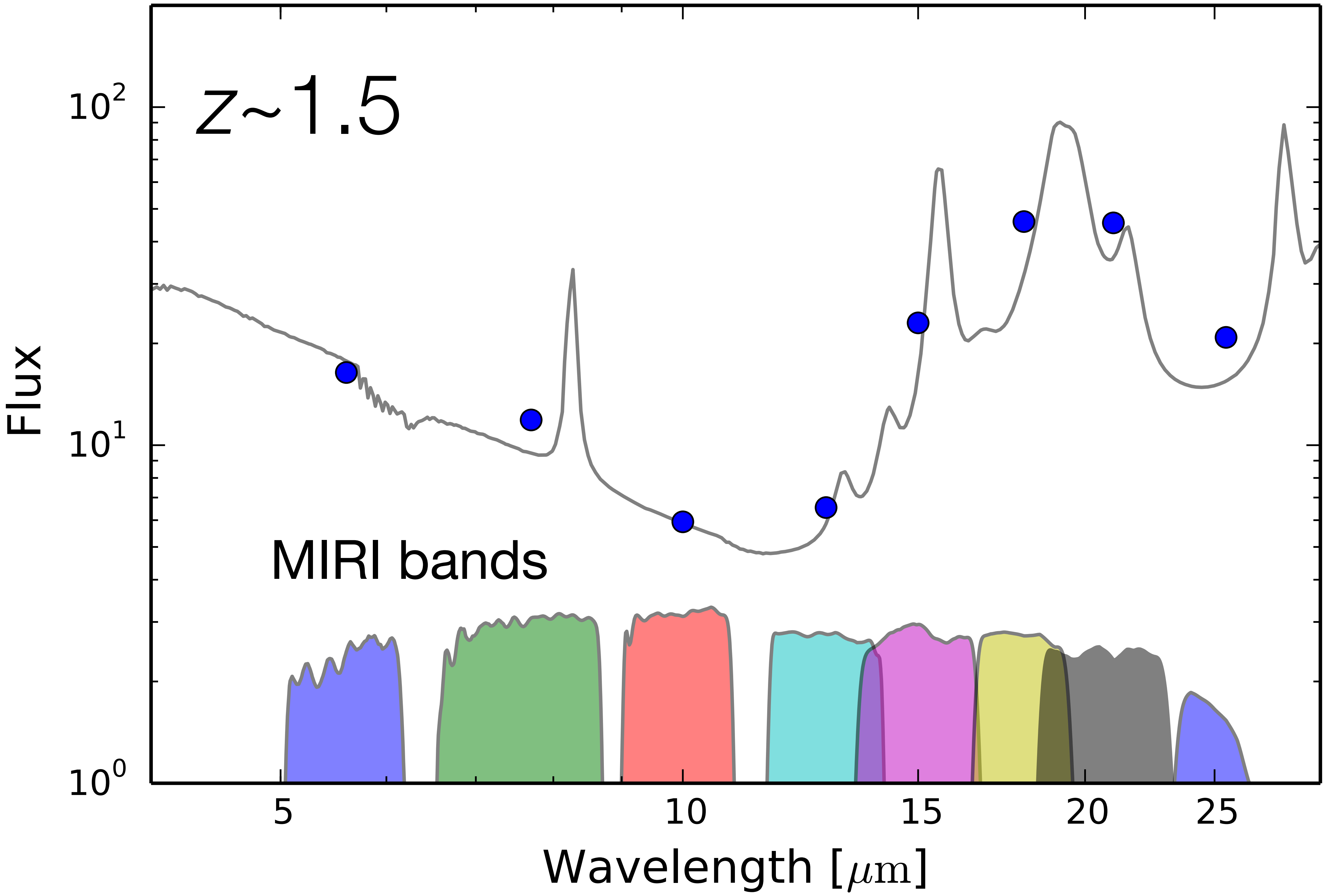


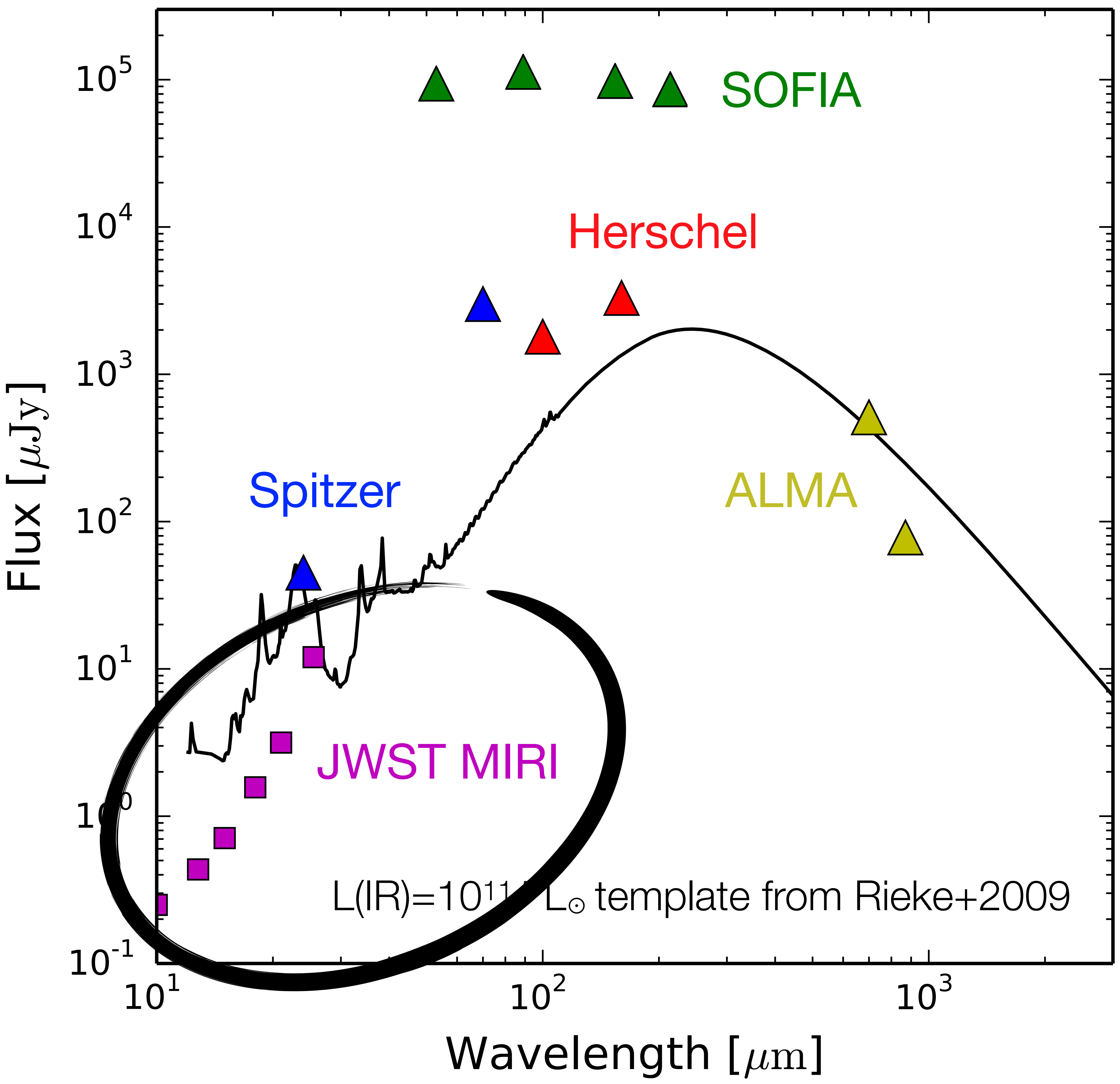
Shivaei+2017

Low detection fraction >> need to properly detect PAH emission at these metallicities

JWST to the rescue!



IR emission of a typical z~2 galaxy

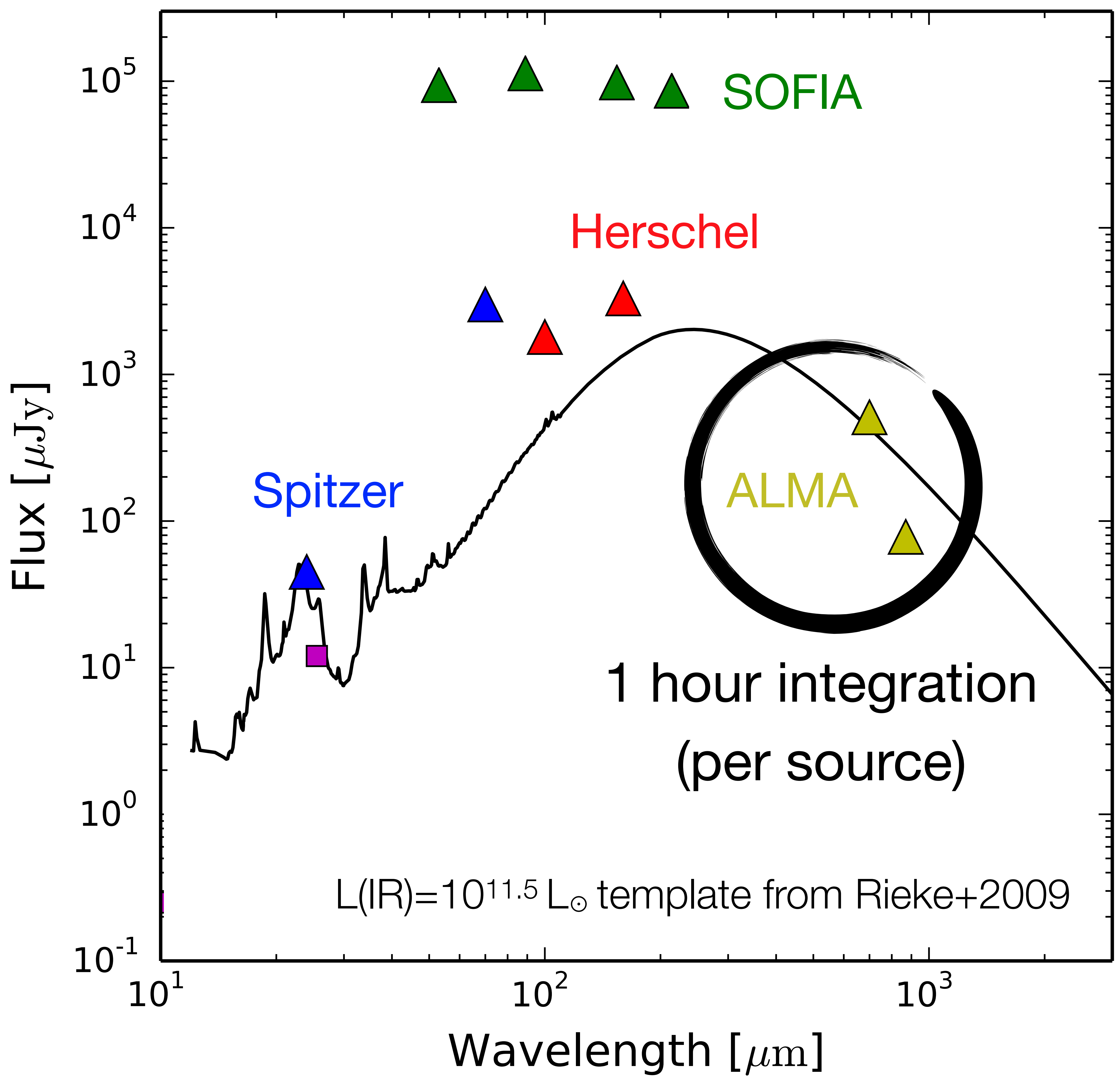


JWST/MIRI Survey in HUDF (US GTO):

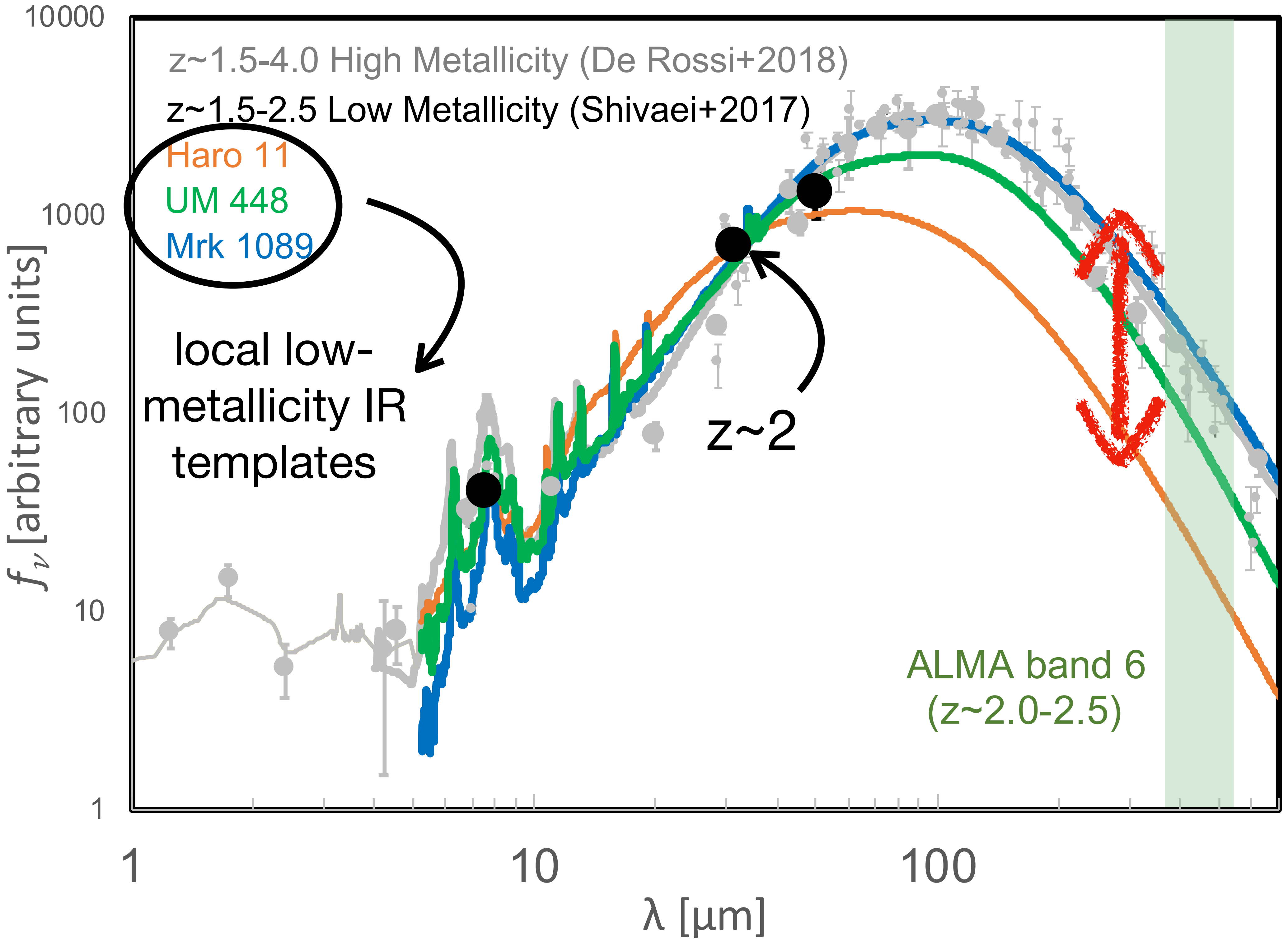
Deep MIRI imaging in multiple bands (5-28μm)

We have another tracer of IR emission for individual galaxies:

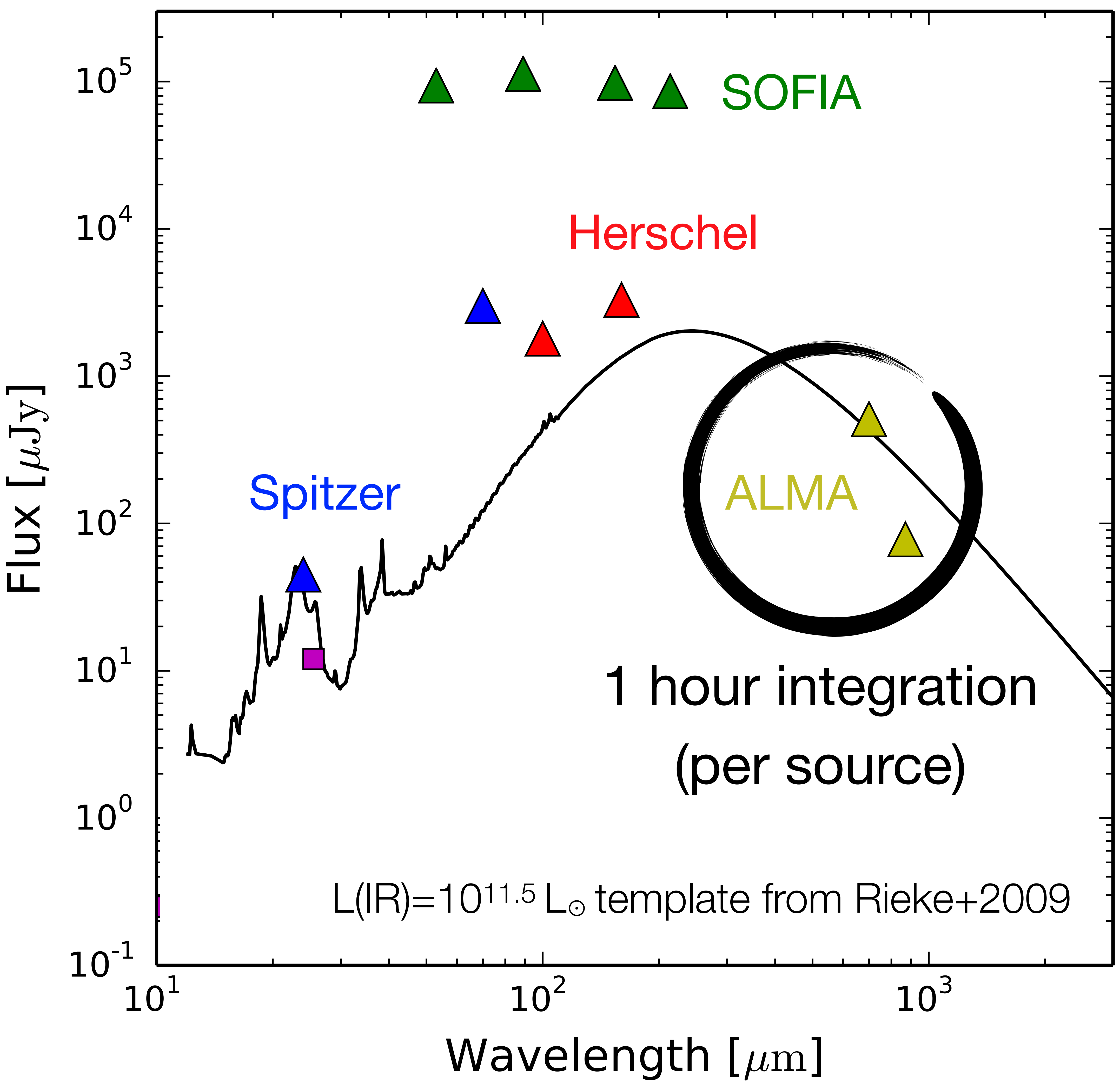
IR emission of a typical z~2 galaxy



- Does the Rayleigh-Jeans emission change with metallicity?



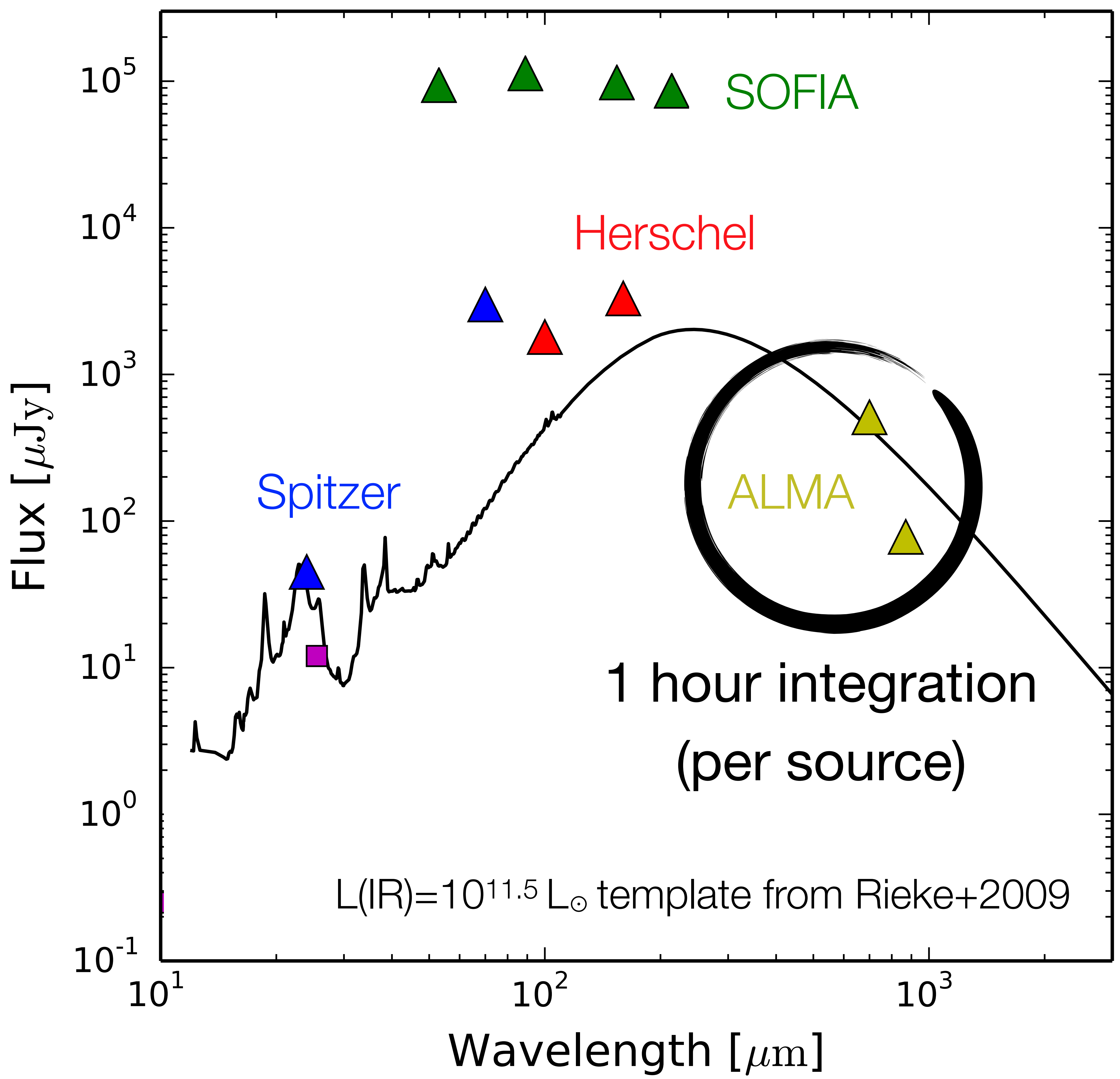
IR emission of a typical z~2 galaxy



- Does the Rayleigh-Jeans emission change with metallicity?

- We need a sample with:
  1. Metallicity measurements
  2. ALMA observations of typical z~2 galaxies (not detected in any of the current ALMA deep field surveys)

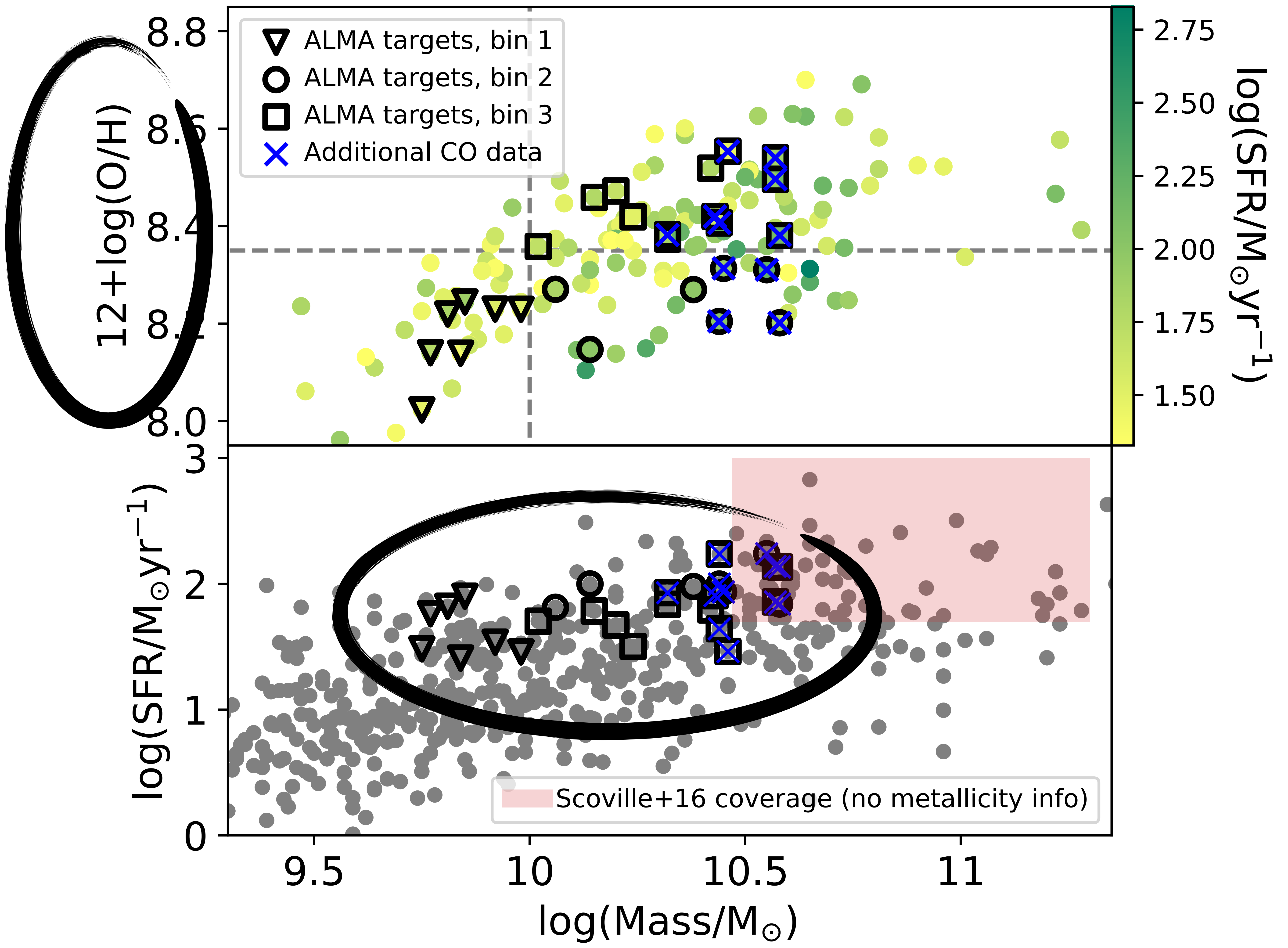
IR emission of a typical z~2 galaxy



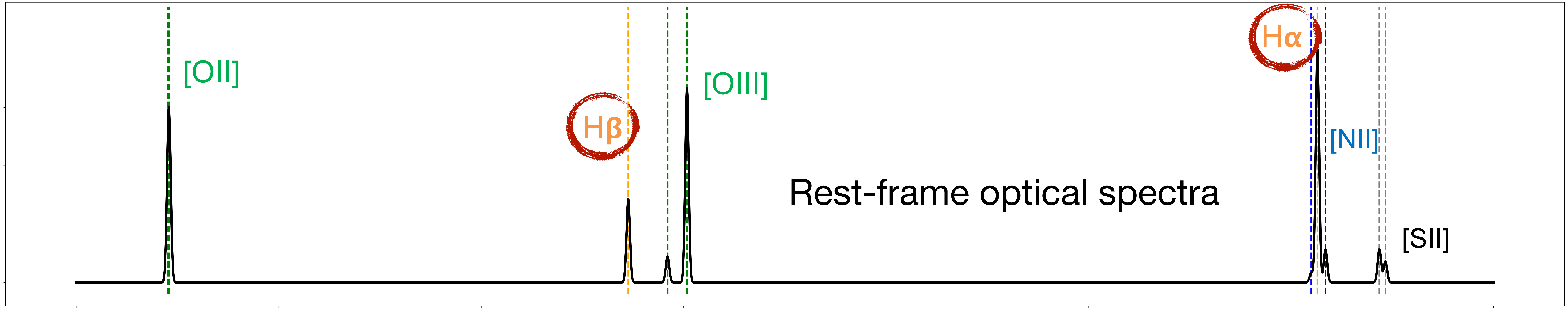
40-hour ALMA cycle-7 program to trace dust continuum emission in *typical* z~2 galaxies (PI: I. Shivaei)

Metallicity measurements (MOSDEF survey)

Tracing a new unexplored parameter space



What can optical/near-IR telescopes add to this picture?



Balmer decrement: $\frac{\mathrm{H}\alpha}{\mathrm{H}\beta}$

Balmer optical depth: $\tau_b \equiv \ln(\frac{\mathrm{H}\alpha/\mathrm{H}\beta}{2.86})$

Reddening along the line of sight towards the ionized gas: $\mathrm{E(B-V)} = \frac{2.5}{k(\mathrm{H}\alpha) - k(\mathrm{H}\beta)} \log(\frac{\mathrm{H}\alpha/\mathrm{H}\beta}{2.86})$

Getting accurately dust-corrected instantaneous SFRs

- Hα is associated to the most massive stars with short life times >> instantaneous SFR indicator

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  … but needs **dust correction**

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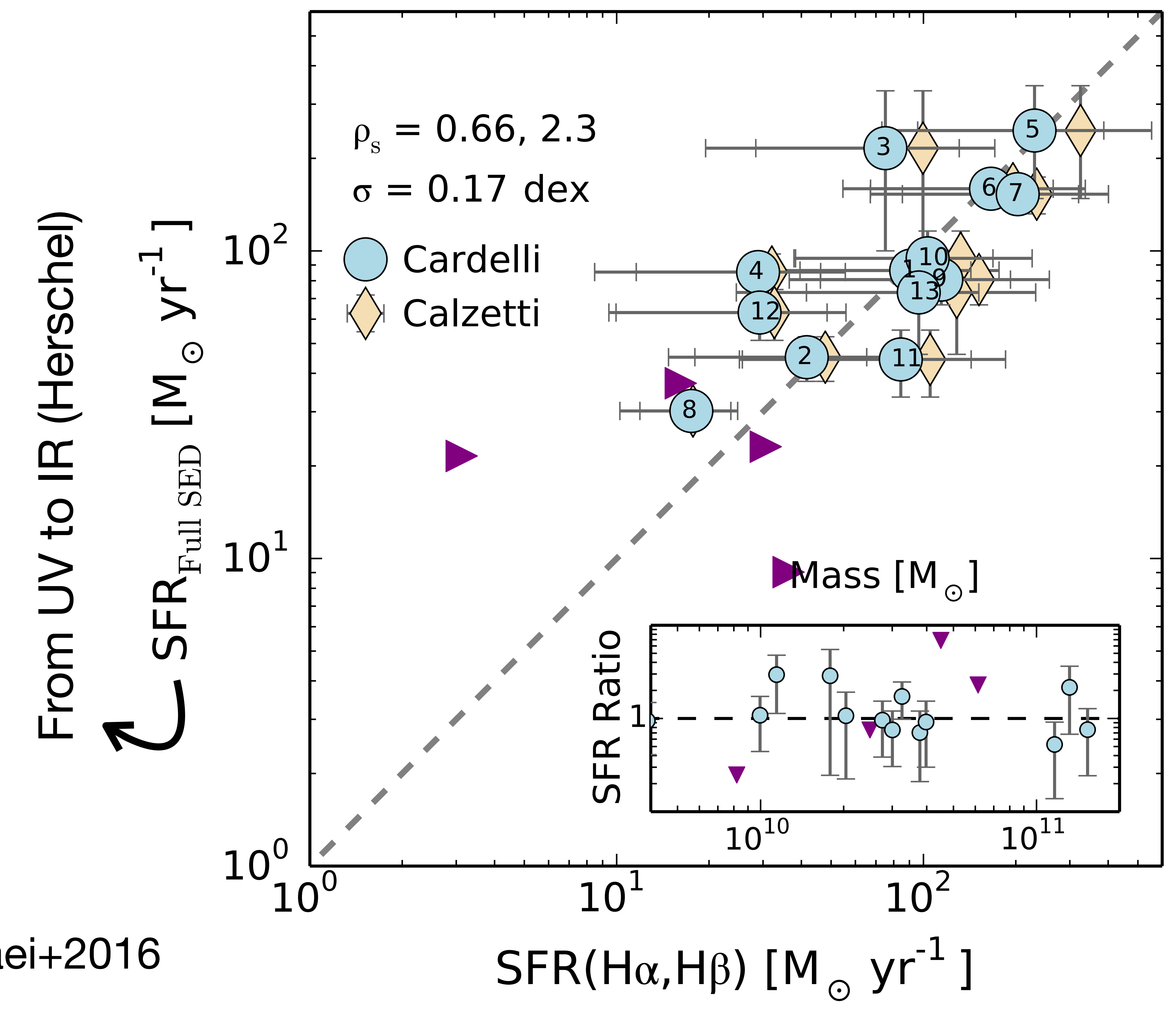
Getting accurately dust-corrected instantaneous SFRs

- Hα is associated to the most massive stars with short life times >> instantaneous SFR indicator
  … but needs **dust correction**

$$E(B-V) = \frac{2.5}{k(H\alpha) - k(H\beta)} \log\left(\frac{H\alpha/H\beta}{2.86}\right)$$

> Dust-corrected Hα luminosity (using Balmer decrement) accurately traces SFR in dust star-forming galaxies at z~2

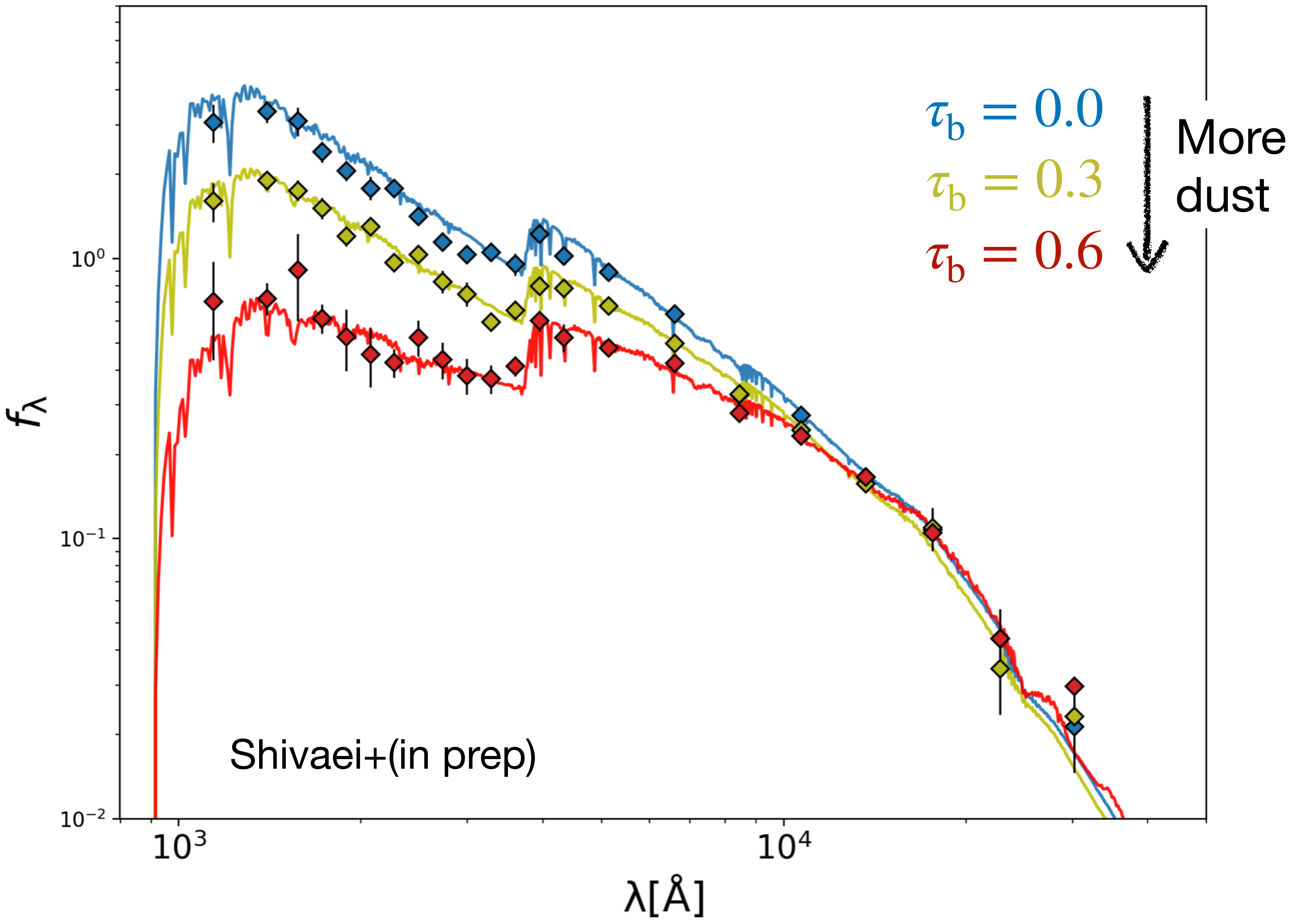


Shivaei+2016

Constraining dust attenuation curve at high redshifts

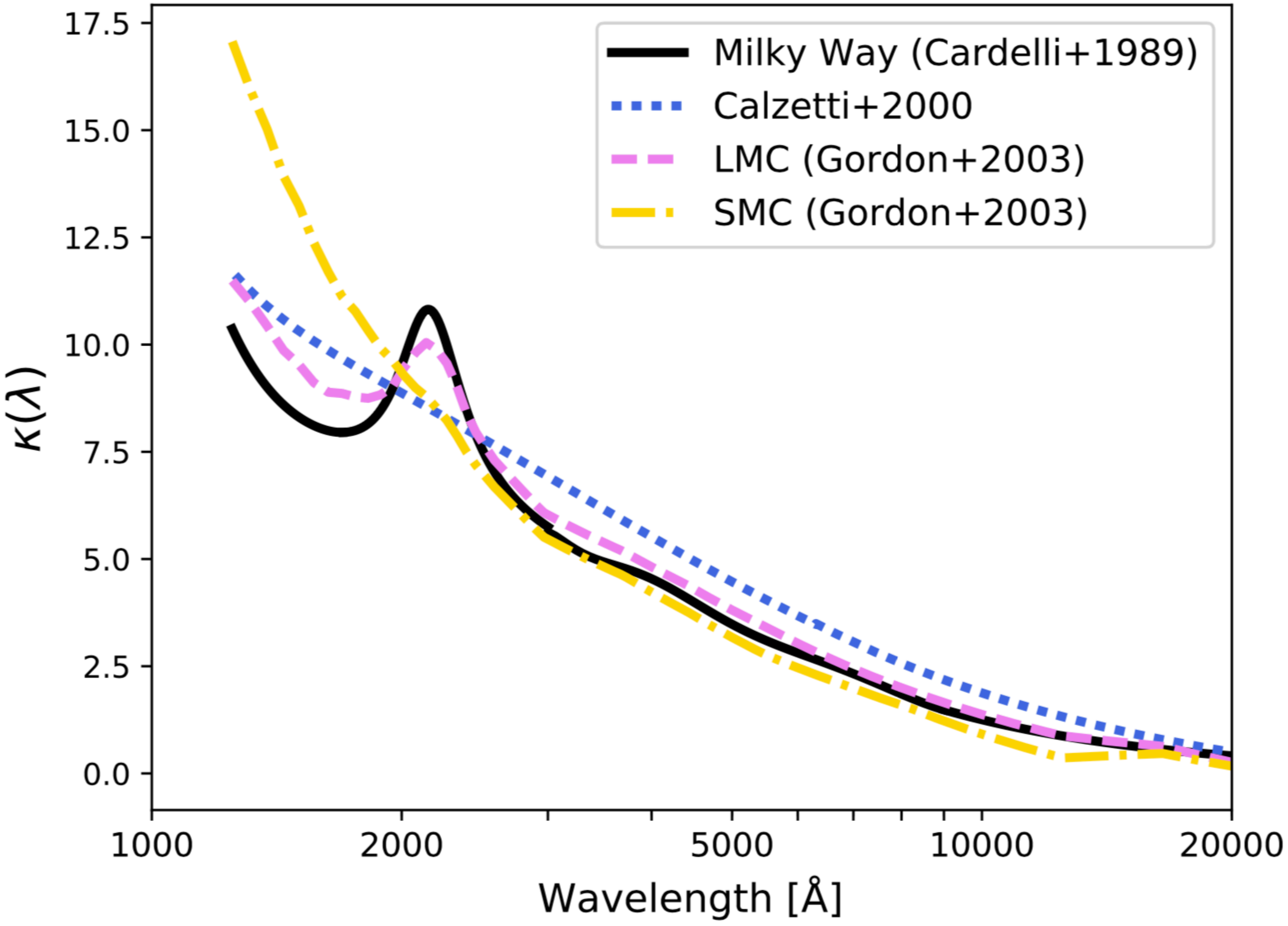
Average SEDs with the same intrinsic shape but different dust reddening, defined independently by Balmer optical depth:

$$\tau_b \equiv \ln\left(\frac{H\alpha/H\beta}{2.86}\right)$$



Constraining dust attenuation curve at high redshifts

- Does the attenuation curve evolve with redshift?
- Does the attenuation curve vary from galaxy to galaxy?
- What are the main physical properties that determine the shape of the attenuation curve?

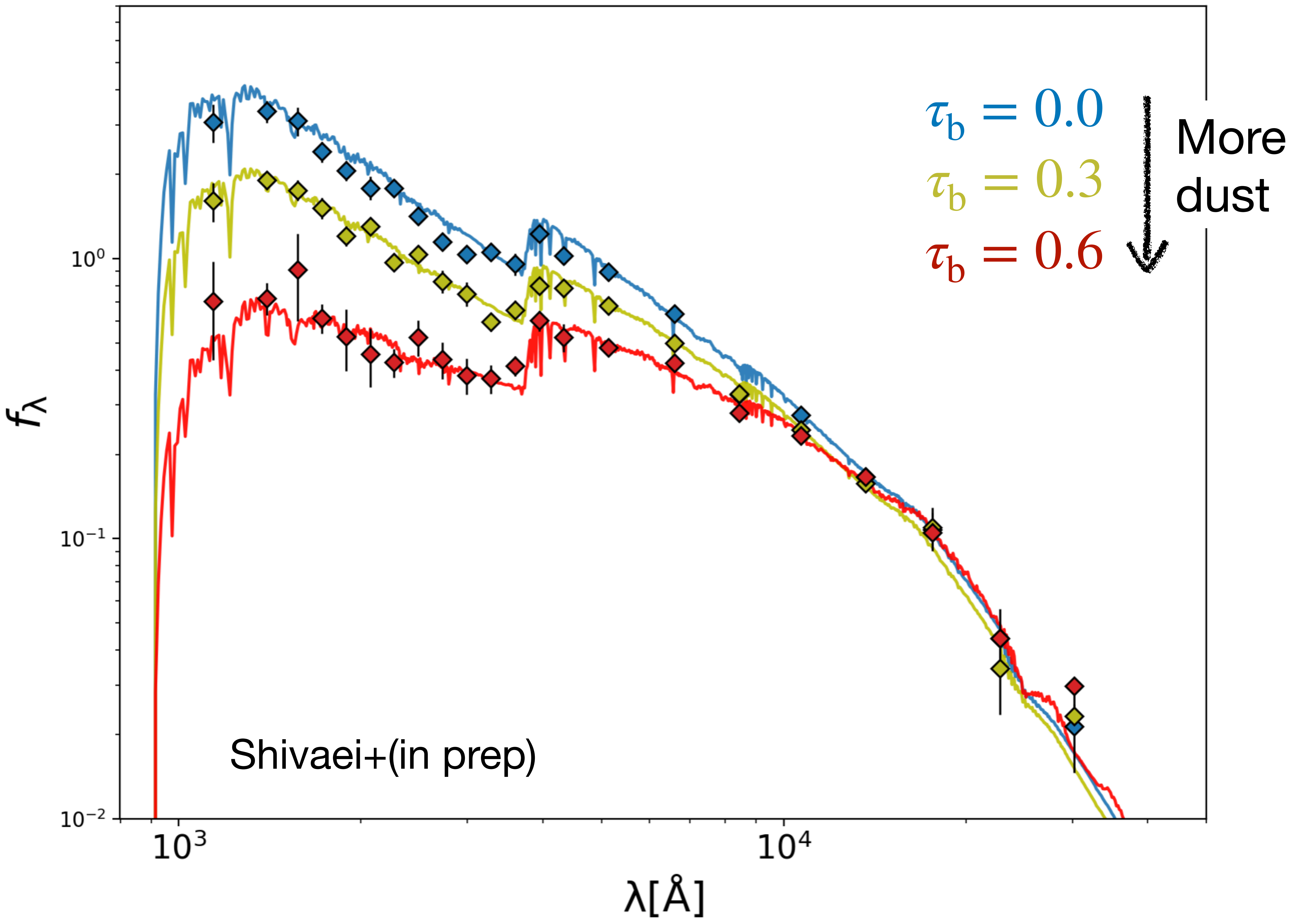


Constraining dust attenuation curve at z~2

Sample of ~330 galaxies with robust (>3σ) Hα and Hβ from the MOSDEF survey (Keck/MOSFIRE NIR spectra)

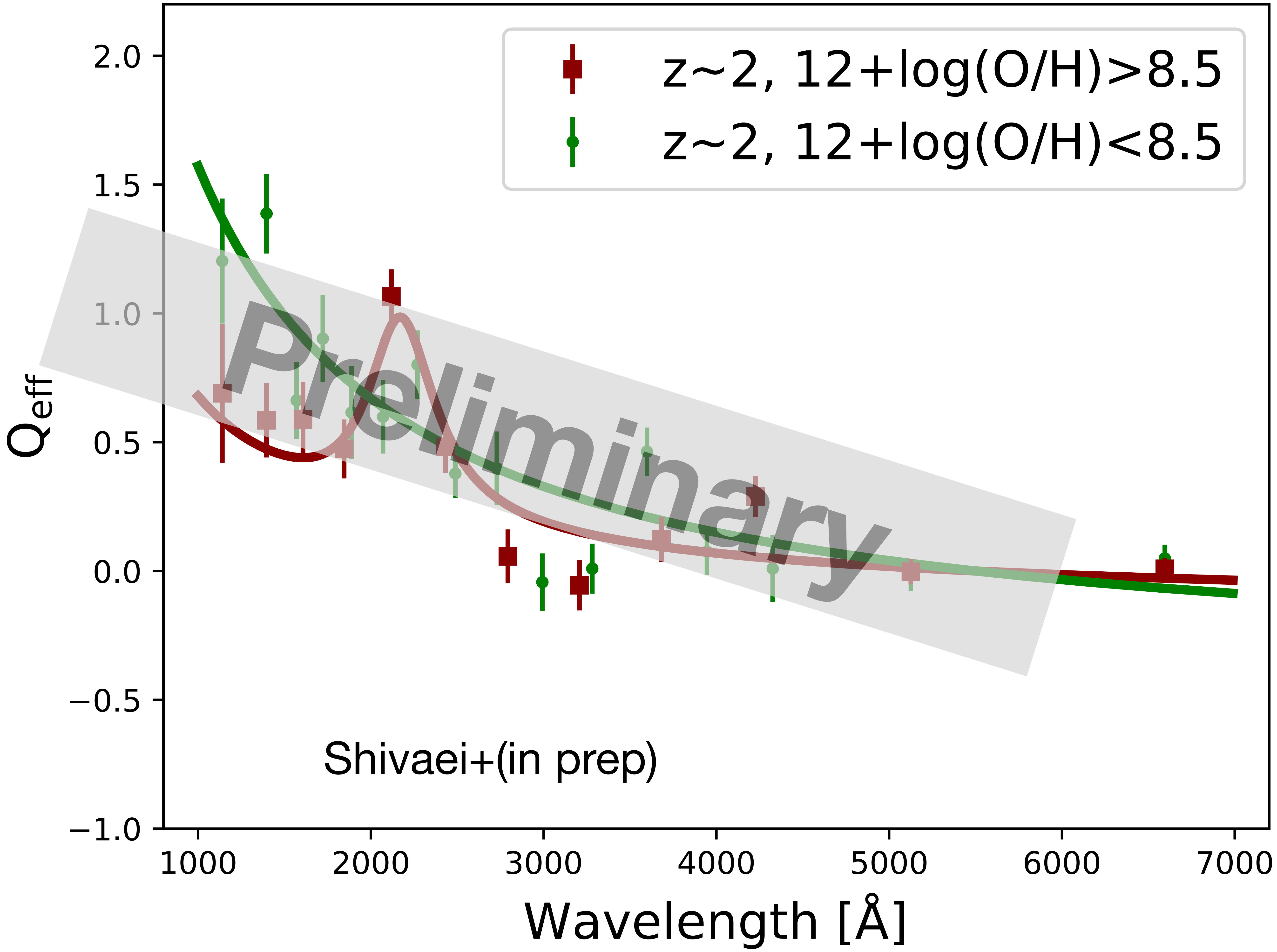
We removed:
- AGN
- Quiescent
- ULIRG
- Very young (< 100Myr)

➡ ~ 210 with robust O3N2 metallicity
- Separated at 12+log(O/H) = 8.5
- Each in 4 τ_b bins

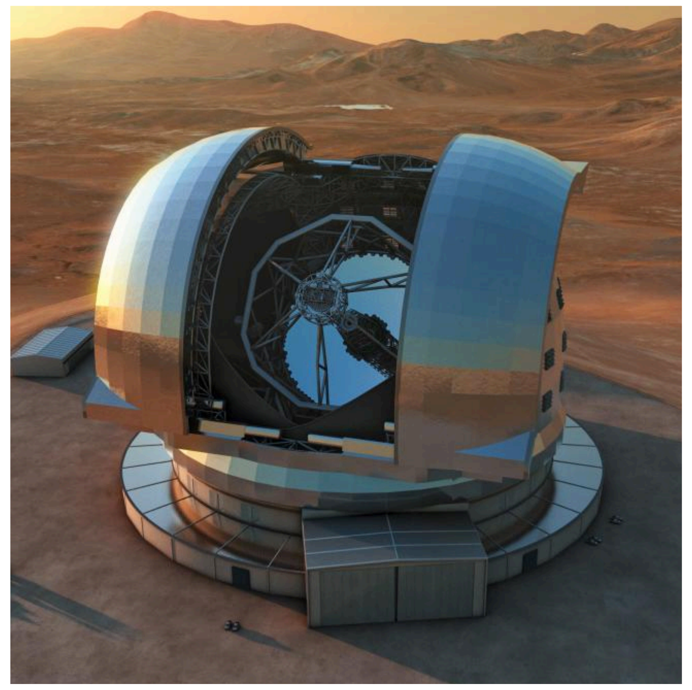


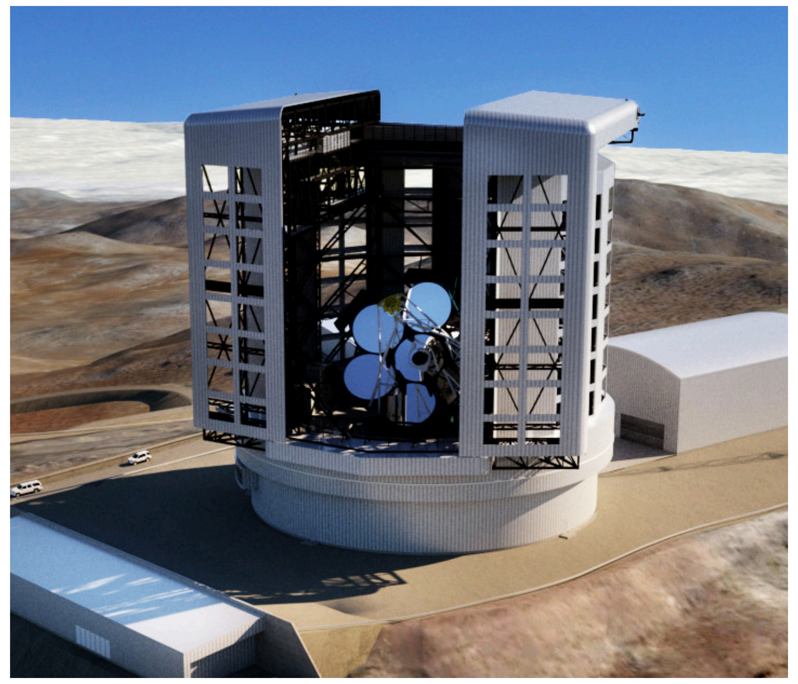
Constraining dust attenuation curve at z~2

- Preliminary results show that the shape of the attenuation curve changes with metallicity
- Important implications for rest-frame UV dust attenuation correction of high-z galaxies



Big Eyes





ELT HARMONI
TMT IRIS
GMT GMTIFS

Spatial Resolution

resolved maps of emission lines: dust/star geometry in high-redshift galaxies >> NIR IFU

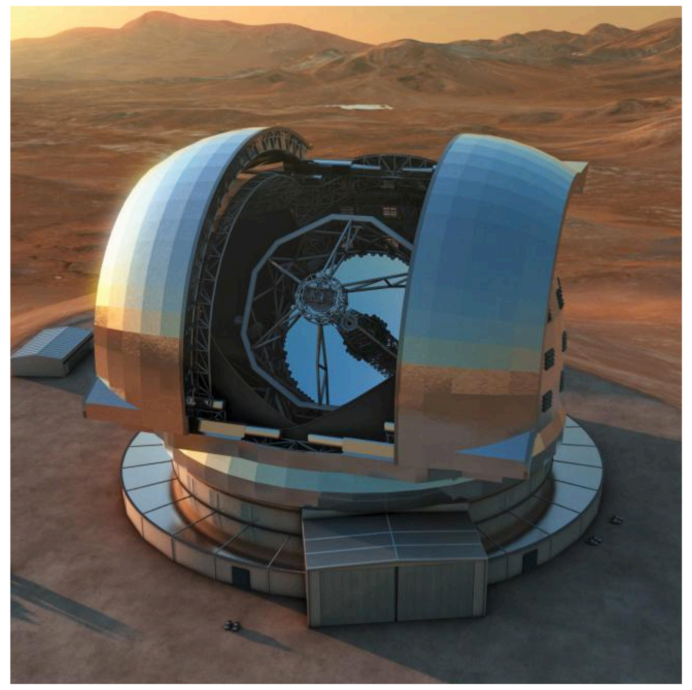
Sensitivity

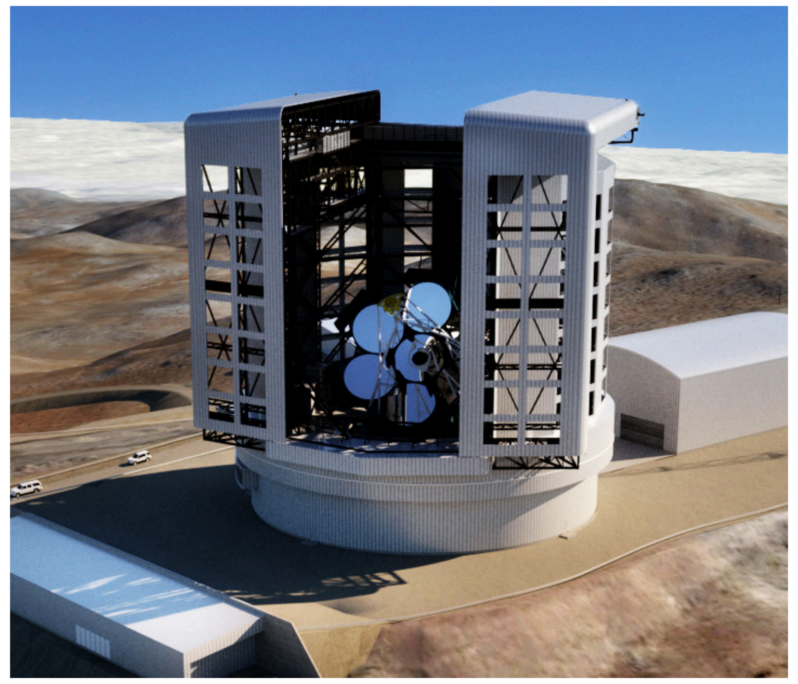
pushing the limits to fainter targets >> multi-obj NIR spectrograph

Shorter (optical) wavelength access

dust features in the rest-frame UV >> multi-obj optical spectrograph

Big Eyes





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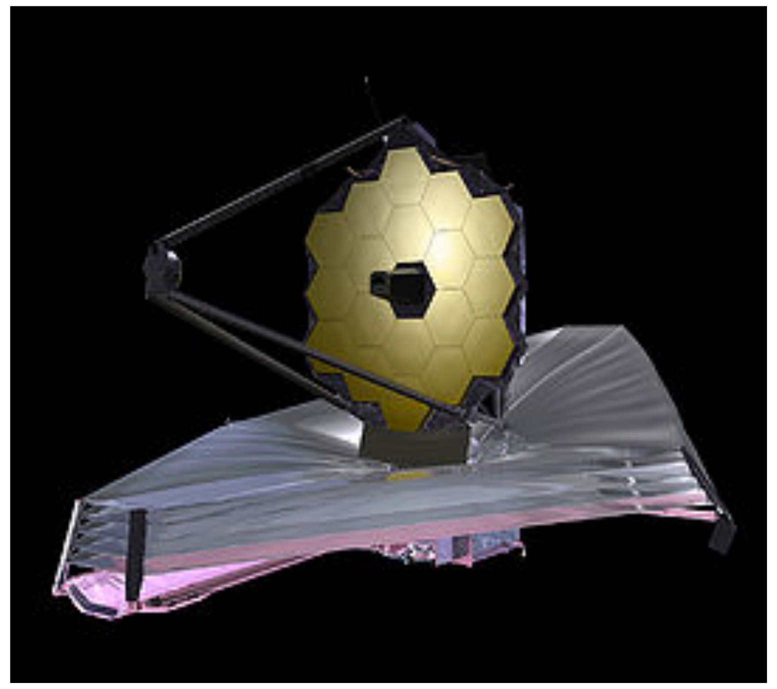
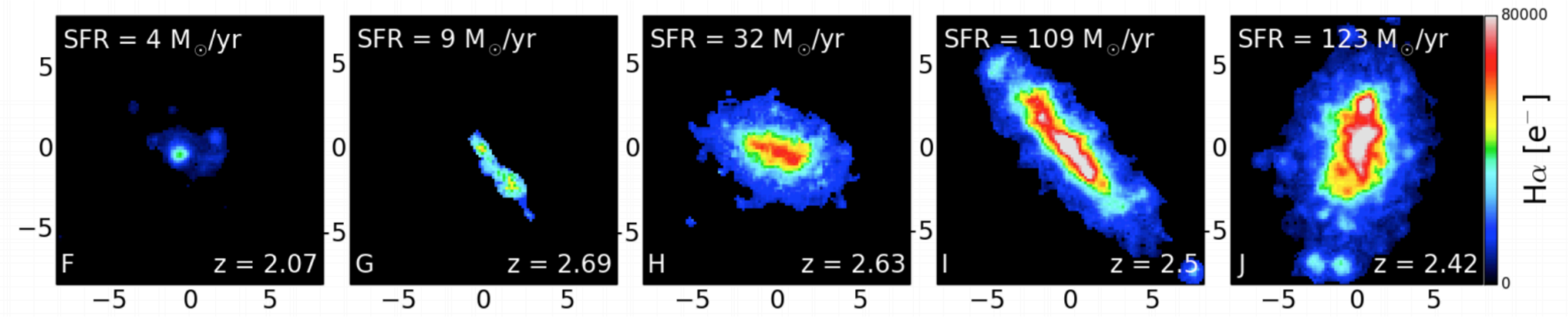


Spatial Resolution (synergy with JWST/NIRCam and ALMA)

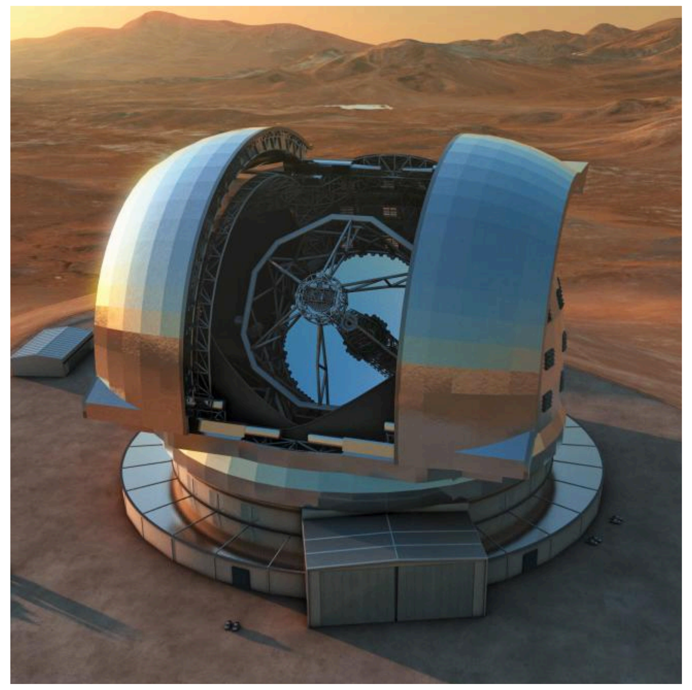
Resolved optical stellar continuum images >> JWST/NIRCam (also ELT MICADO)

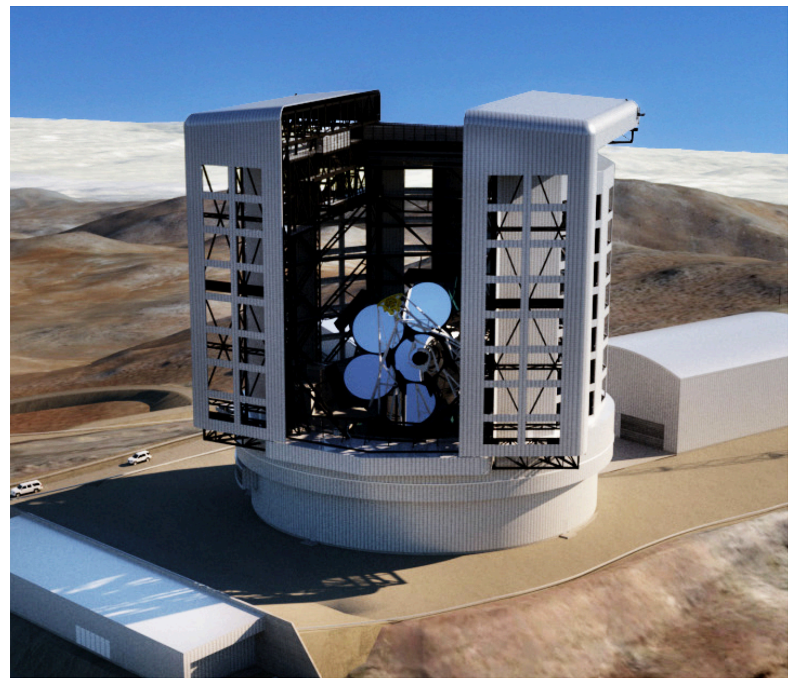
Resolved maps of emission lines: dust/star geometry in high-redshift galaxies



Hα map simulations of HARMONI on ELT for z~2 clumpy galaxies in 10 hours integration
Zieleniewski+2015

Big Eyes





ELT HARMONI
TMT IRIS
GMT GMTIFS

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Sensitivity

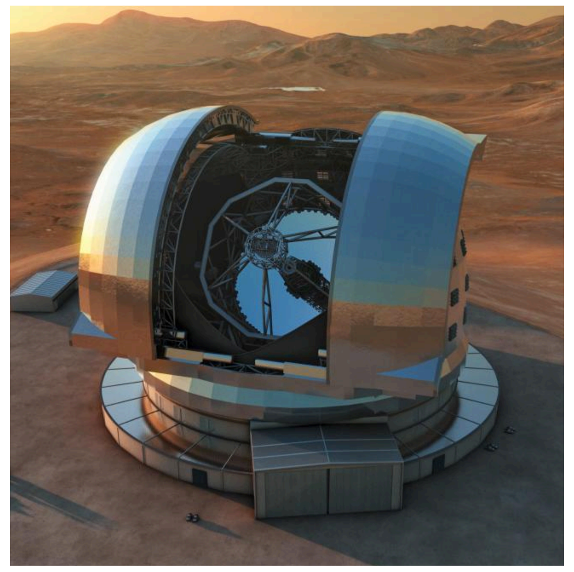
pushing the limits to fainter targets >> multi-obj NIR spectrograph

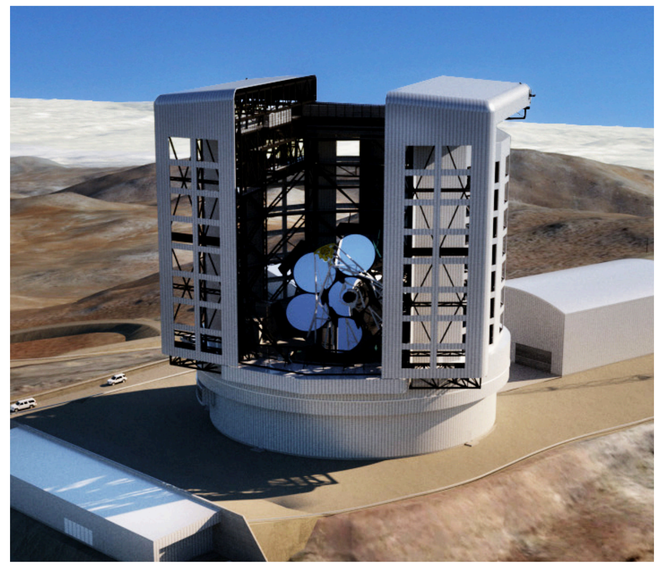
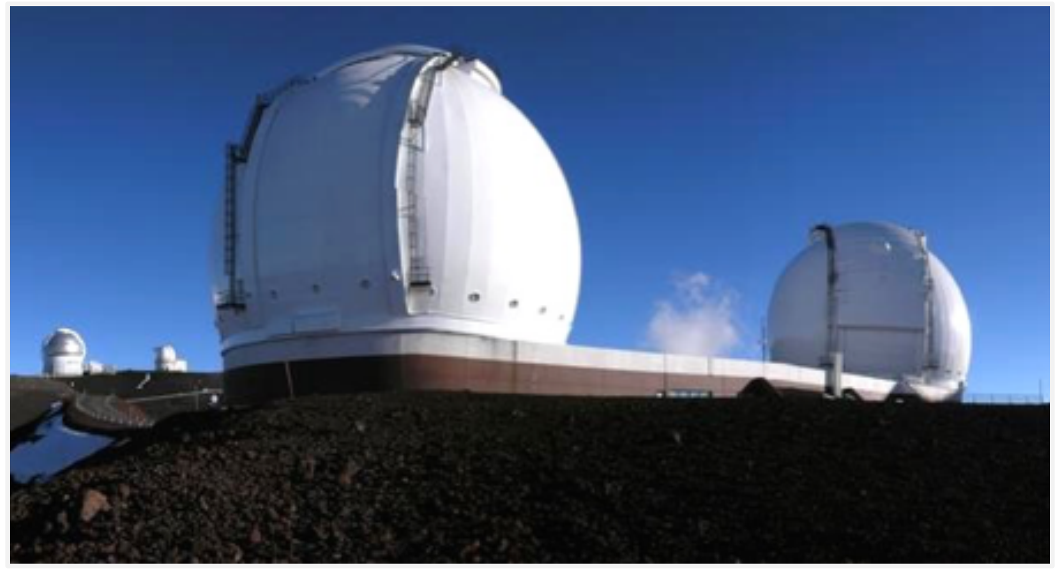
?
TMT MODHIS (2nd gen)

Shorter (optical) wavelength access

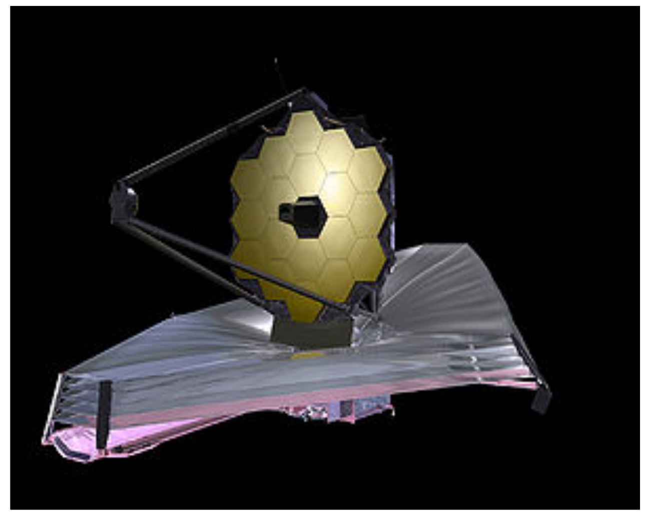
dust features in the rest-frame UV >> multi-obj optical spectrograph

TMT WFOS
GMT GMACS




Summary



- Our understanding of the dust properties in high-z universe is very incomplete
  - Knowing that the ISM conditions are different at high redshifts compared to the local universe, we cannot apply the same local relations to the high-redshift galaxies
- Spitzer and ALMA provide us with individual detections of obscured SF at z ~ 2
  - JWST/MIRI will improve upon these results, given its higher sensitivity and spatial resolution compared to Spitzer/MIPS
- Rest-optical Balmer lines (Hα and Hβ) tells us about dust attenuation towards nebular regions
  - With data from 10-m class telescopes, for the first time, we are able to constrain the attenuation curve at high redshifts
  - Next generation of 30-m class telescopes will improve our understanding of nebular and stellar dust attenuation given their higher spatial resolution and sensitivity