

# Quinto workshop sull'astronomia millimetrica in Italia

Bologna, June 12-14, 2023



## Fast and Furious: the dust enrichment of the early Universe

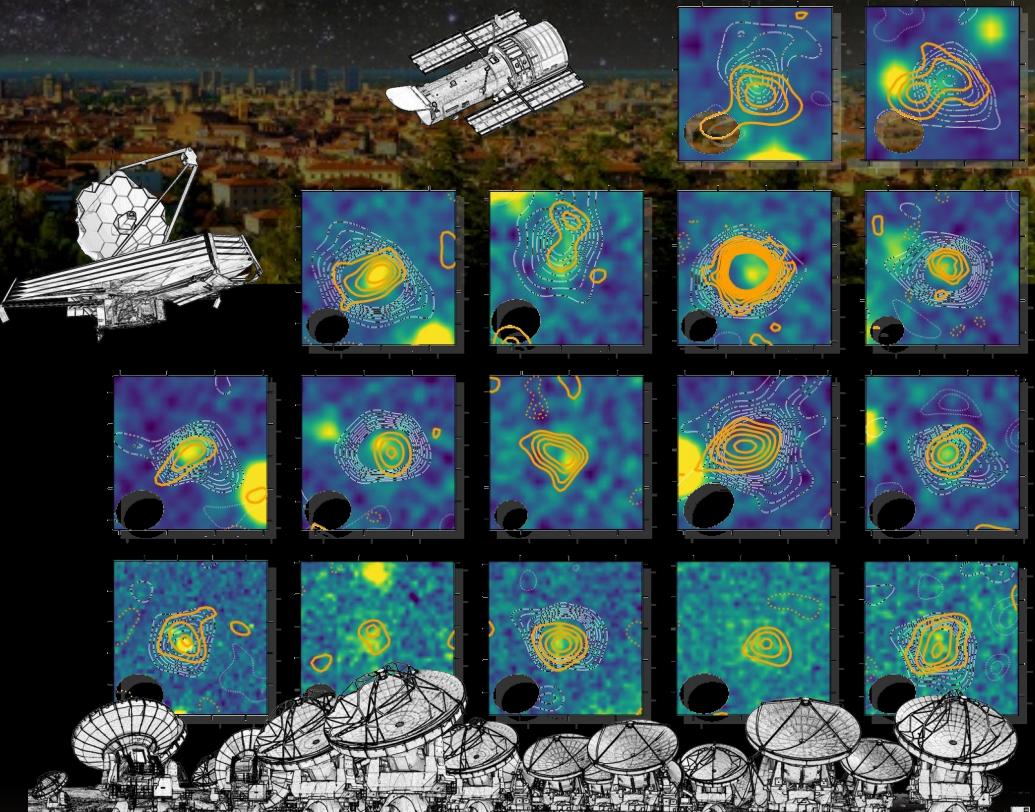
Laura Sommovigo



SCUOLA  
NORMALE  
SUPERIORE

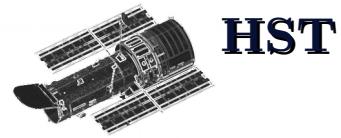
In collaboration with:

A. Ferrara, S. Carniani, A. Pallottini, P. Dayal, E. Pizzati, M. Ginolfi, V. Markov, A. Faisst & REBELS team



# Dust at high-z: where are we at?

---

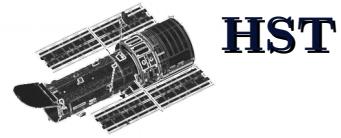


**HST**

- ... Universe <1 Gyr old
- ... Blue UV slopes
- No dust

# Dust at high-z: where are we at?

---

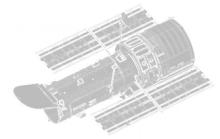


**HST**

- ... Universe <1 Gyr old
- ... Blue UV slopes
- No dust

# Dust at high-z: where are we at?

---



HST

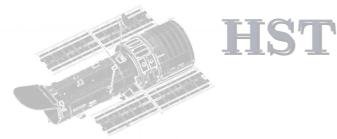
ALMA



... Universe <1 Gyr old  
... Blue UV slopes  
→ No dust

# Dust at high-z: where are we at?

---



HST

ALMA

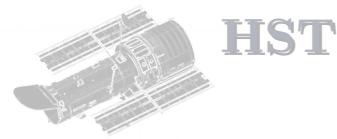


... Universe <1 Gyr old  
... Blue UV slopes  
→ No dust

Dust continuum emitting  
galaxies at  $z=5-7$



# Dust at high-z: where are we at?



HST

... Universe <1 Gyr old  
... Blue UV slopes  
→ No dust

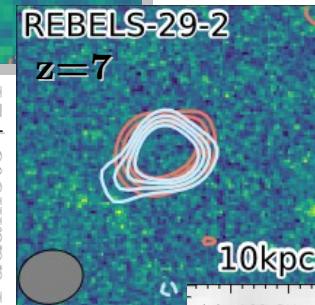
ALMA



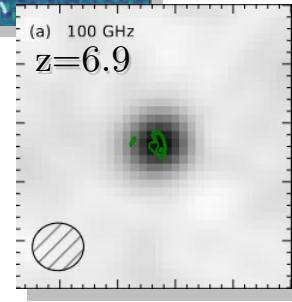
Dust continuum emitting galaxies at  $z=5-7$



Fudamoto+21

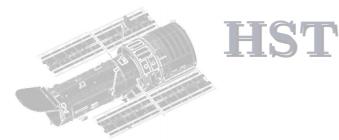


Marrone+18



fully dust-obscured galaxies

# Dust at high-z: where are we at?



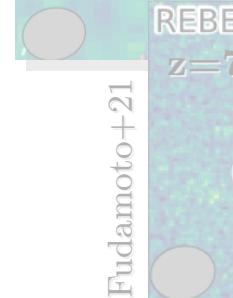
HST

- ... Universe <1 Gyr old
- ... Blue UV slopes
- No dust



ALMA

Dust continuum emitting galaxies at  $z=5\text{--}7$



Fudlamoto+21

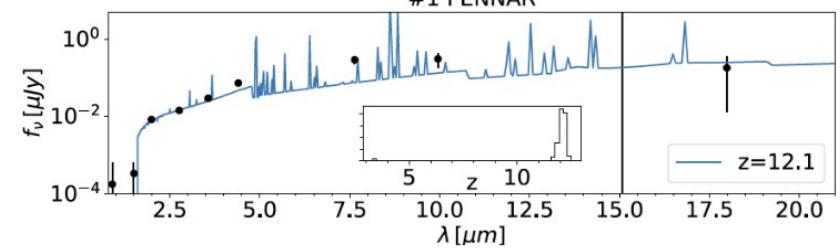
REBELS-12-2  
 $z=7$   
REBELS-29-2  
 $z=7$   
10kpc

fully dust-obscured galaxies



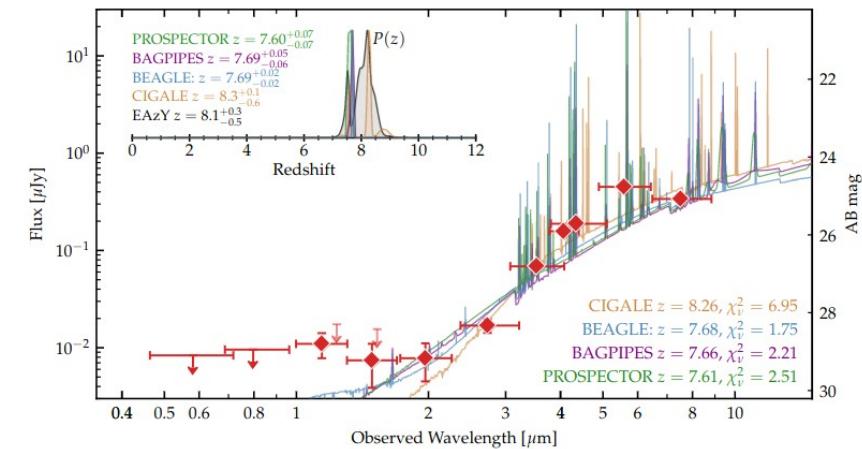
JWST

Rodighiero+22



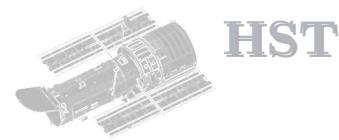
$\mathbf{A_V \sim 4.4}$

Akins+22



$\mathbf{A_V \sim 3.2}$

# Dust at high-z: where are we at?

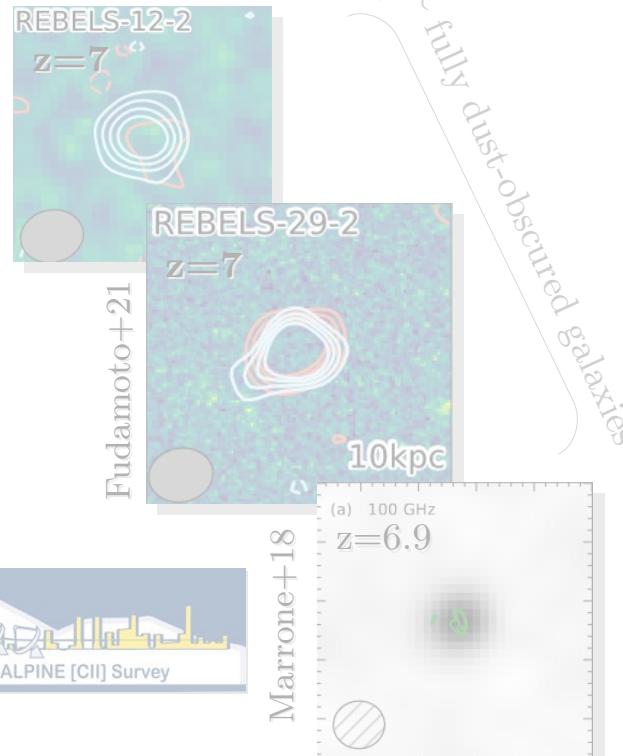


HST

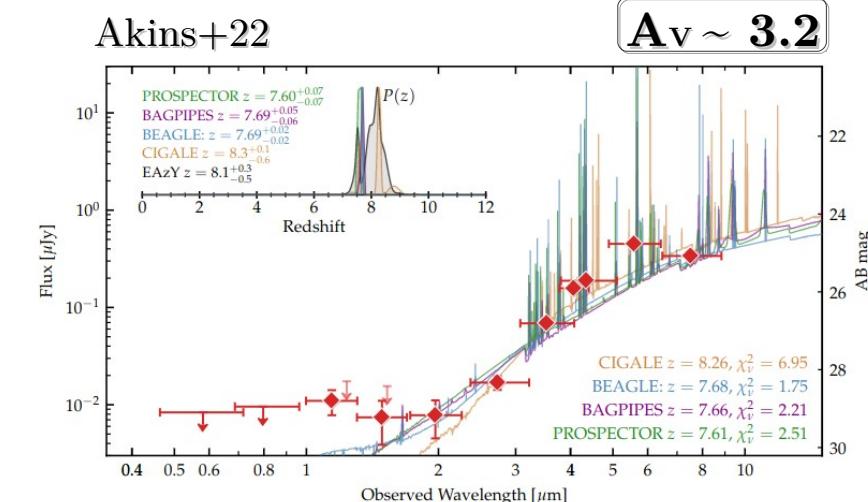
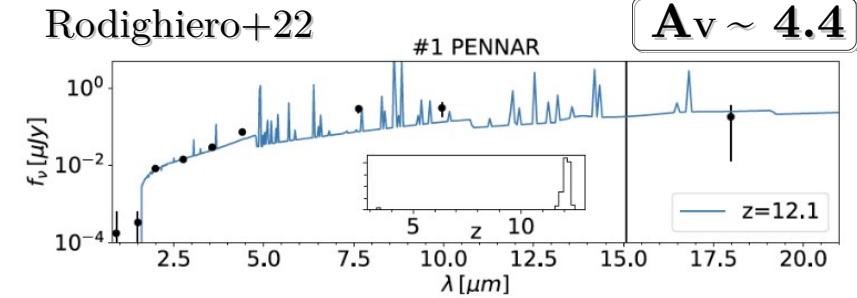
- ... Universe <1 Gyr old
- ... Blue UV slopes
- No dust



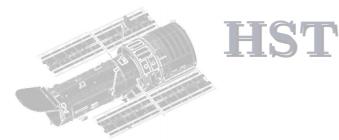
ALMA



JWST



# Dust at high- $z$ : where are we at?



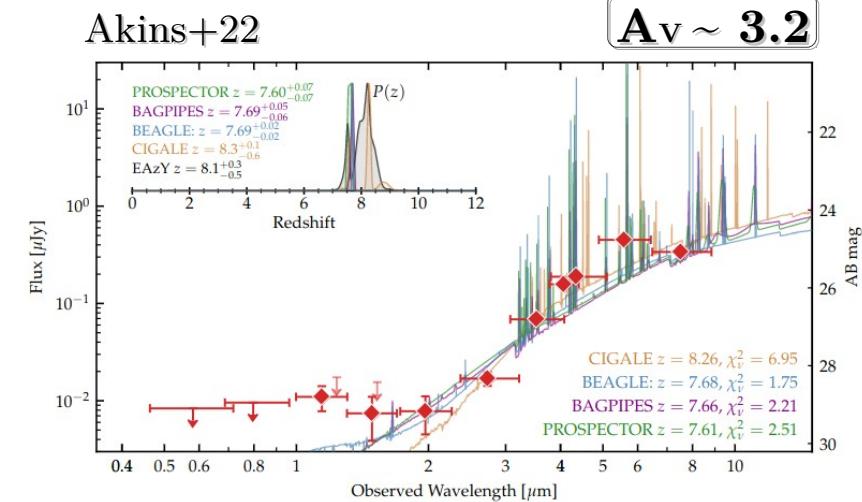
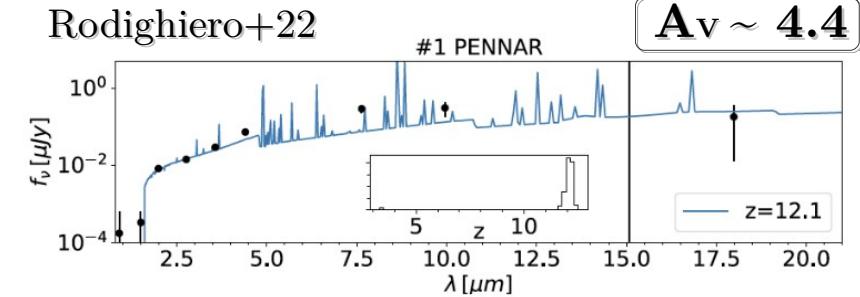
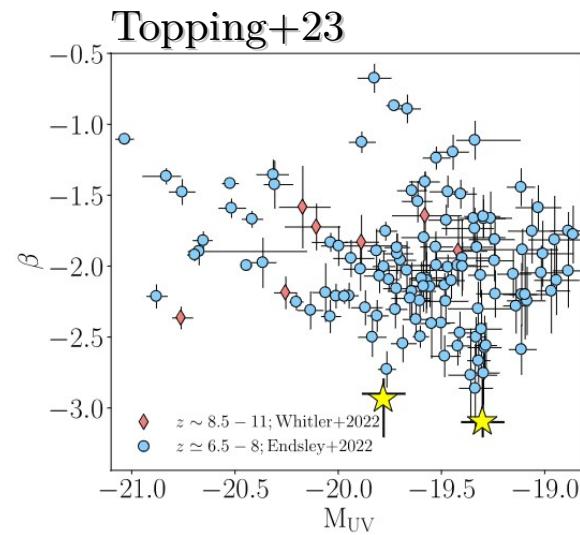
HST



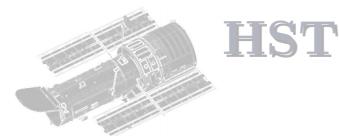
ALMA



JWST



# Dust at high-z: where are we at?



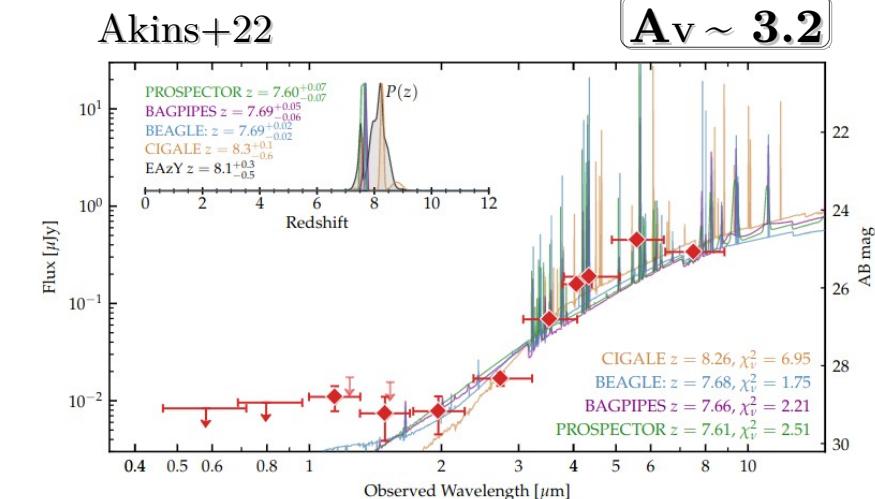
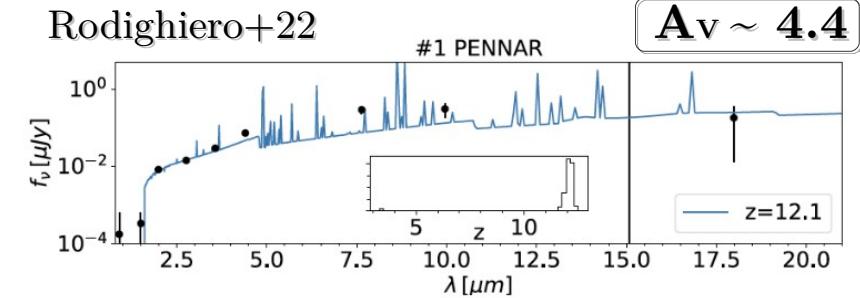
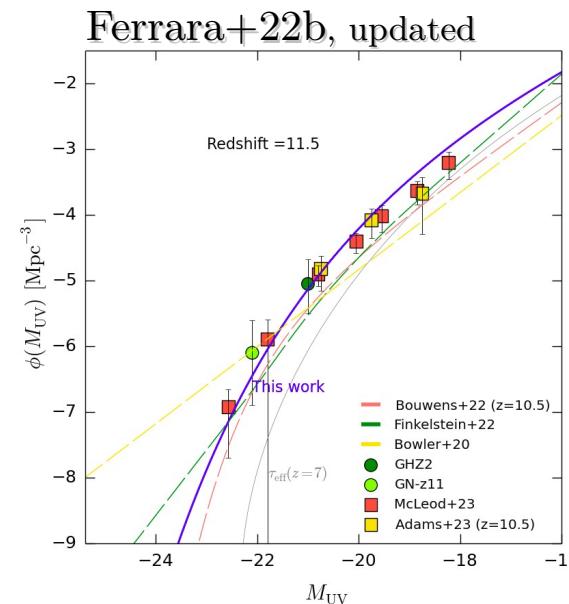
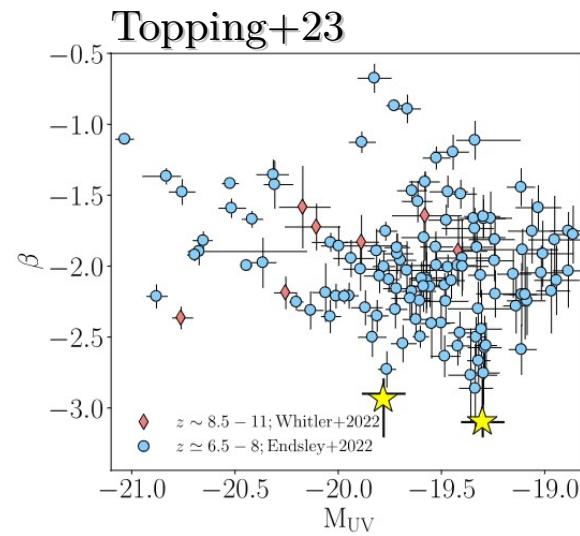
HST



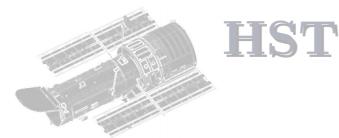
ALMA



JWST



# Dust at high-z: where are we at?



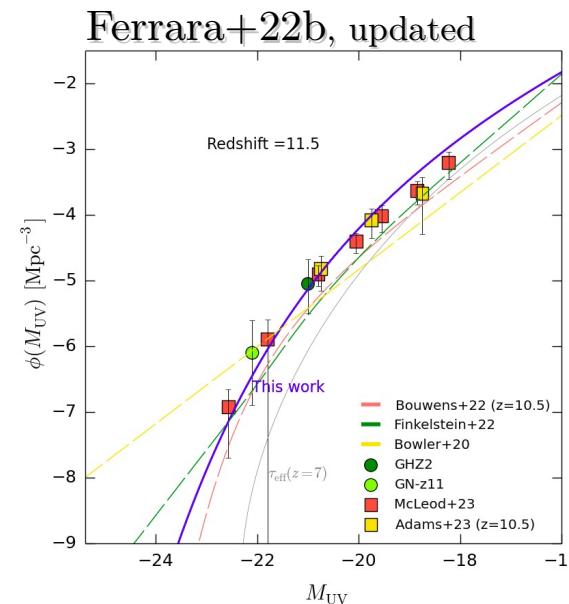
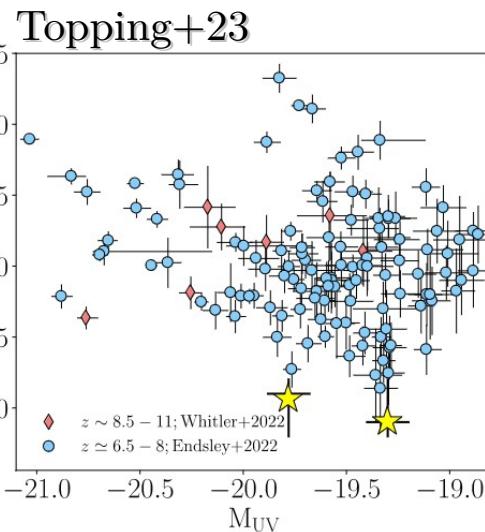
HST



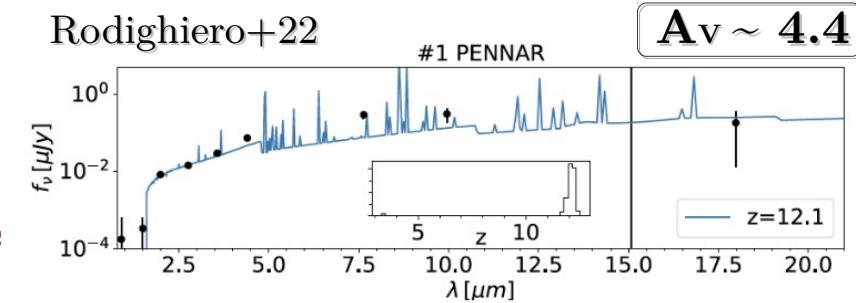
ALMA



JWST

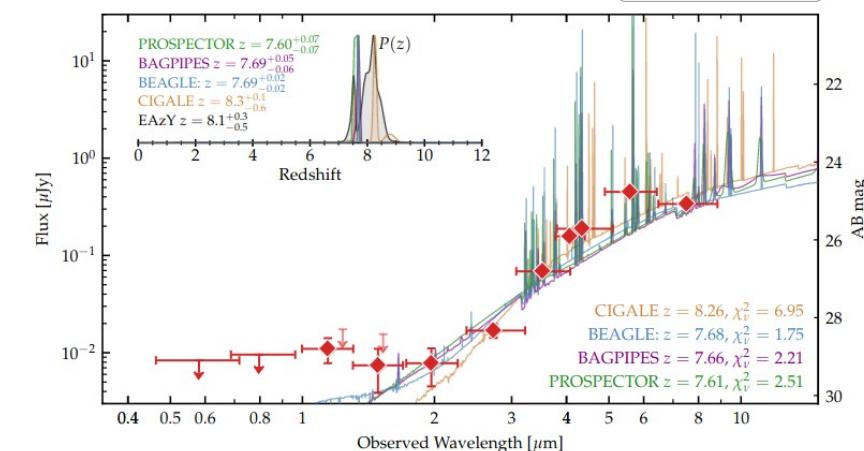


Rodighiero+22



$A_V \sim 4.4$

Akins+22



$A_V \sim 3.2$

## (Some) Open questions:

---

-  Which are the mechanisms responsible for the dust/metal enrichment in the early universe?
-  How much SFR are we missing at high-z due to dust obscuration?
-  Do dust properties evolve with redshift?

# ALMA observations of UV-bright z>4 galaxies

## ALPINE

120 targets

70 hours of obs.

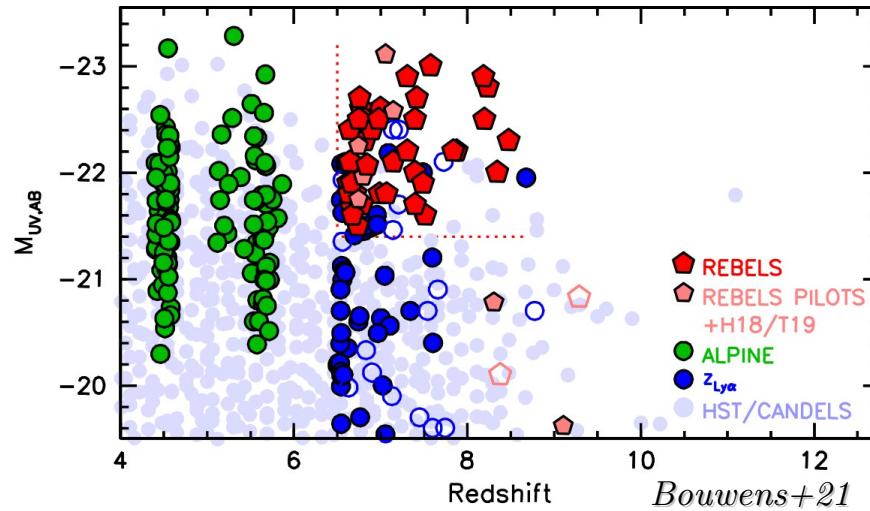
[CII]158 $\mu$ m & Dust

## REBELS

60 targets

70 hours of obs.

[CII], [OIII]88 $\mu$ m &  
Dust



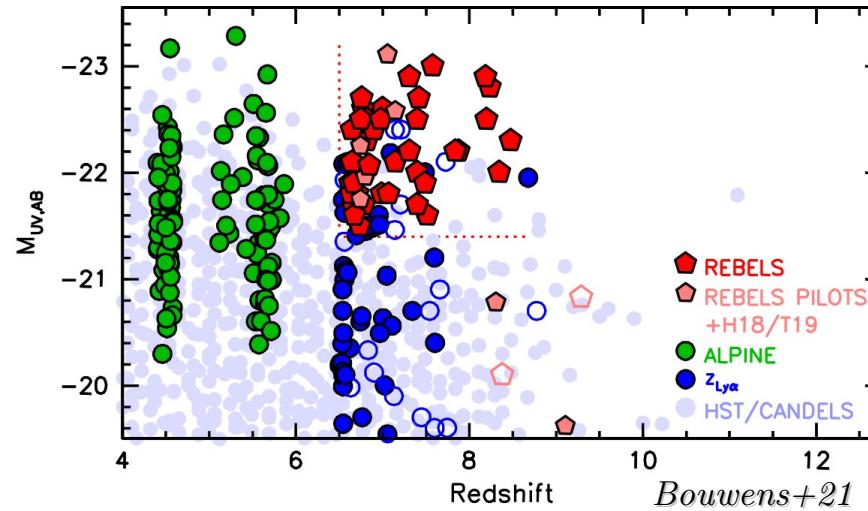
# ALMA observations of UV-bright $z > 4$ galaxies

## ALPINE

120 targets

70 hours of obs.

[CII]158 $\mu\text{m}$  & Dust

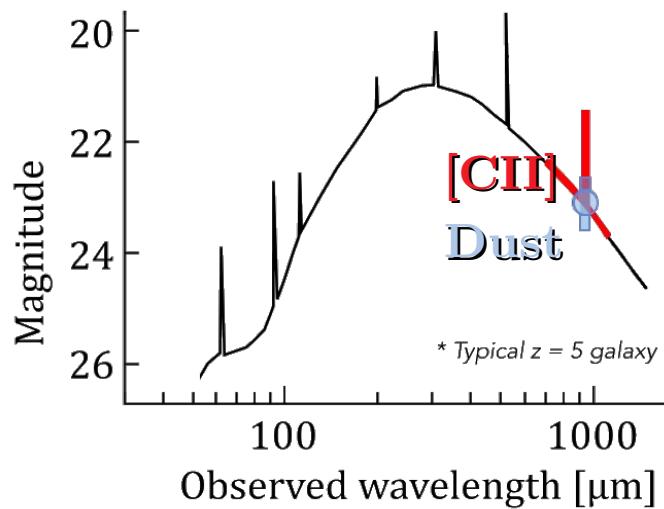


## REBELS

60 targets

70 hours of obs.

[CII], [OIII]88 $\mu\text{m}$  & Dust



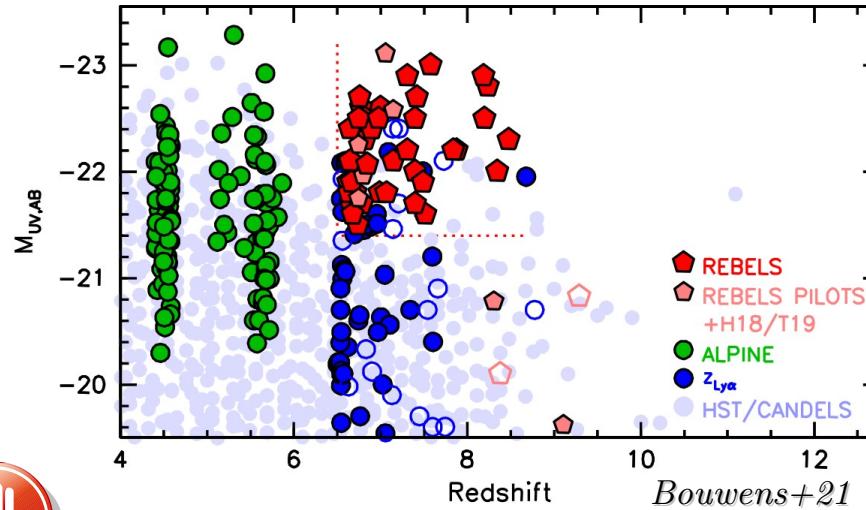
# ALMA observations of UV-bright z>4 galaxies

## ALPINE

120 targets

70 hours of obs.

[CII]158 $\mu$ m & Dust

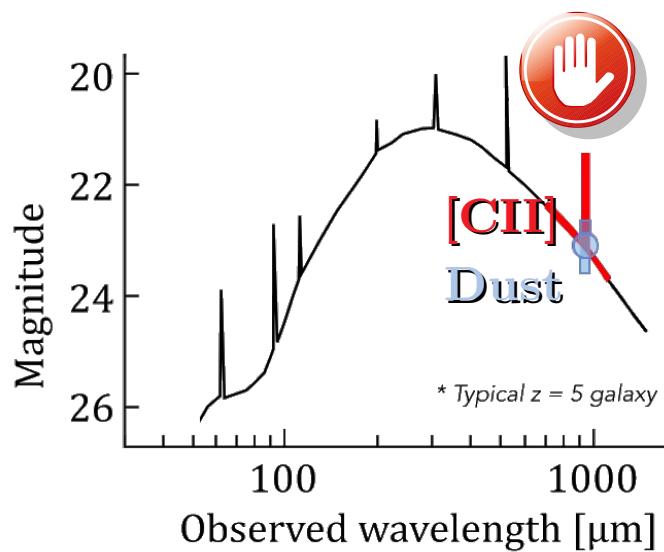


## REBELS

60 targets

70 hours of obs.

[CII], [OIII]88 $\mu$ m & Dust



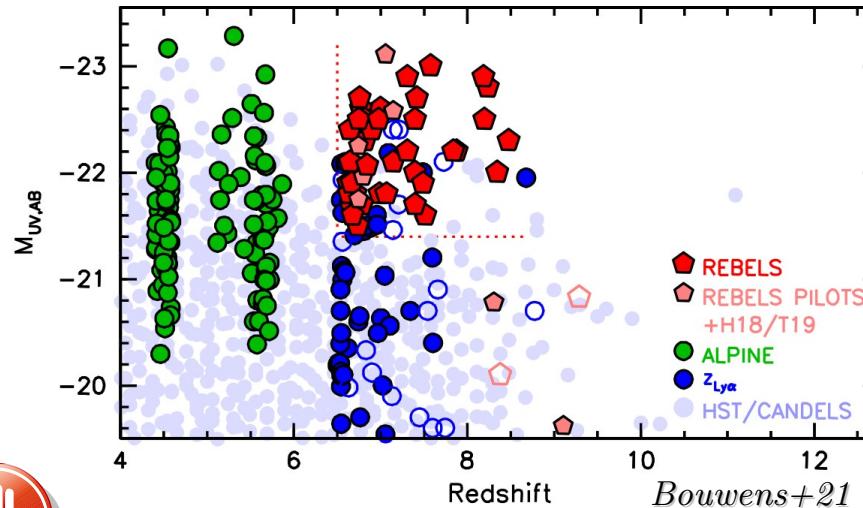
# ALMA observations of UV-bright z>4 galaxies

## ALPINE

120 targets

70 hours of obs.

[CII]158μm & Dust

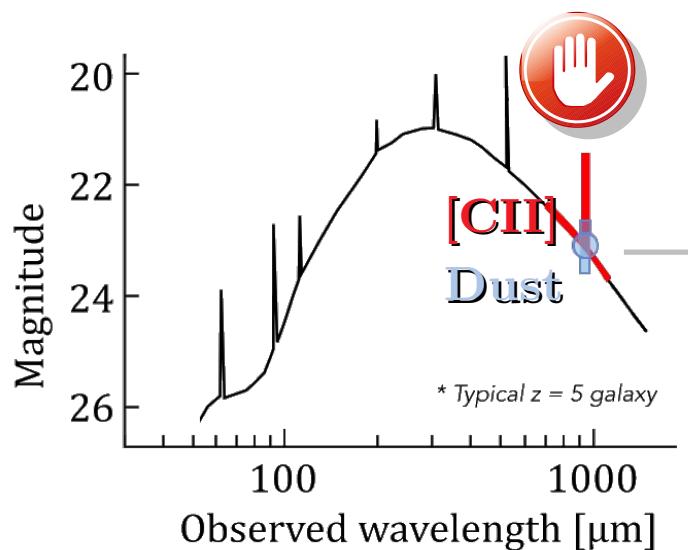


## REBELS

60 targets

70 hours of obs.

[CII], [OIII]88μm & Dust



## New method to derive $T_d$ :

Inputs:

$L_{[CII]}$

$F_{158\mu m}$

Outputs:

$M_d$

$T_d$

*Sommovigo+21*

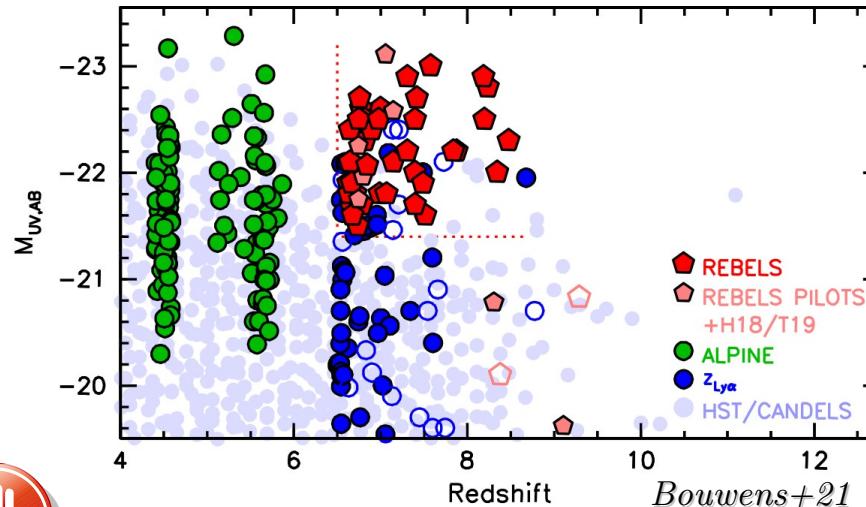
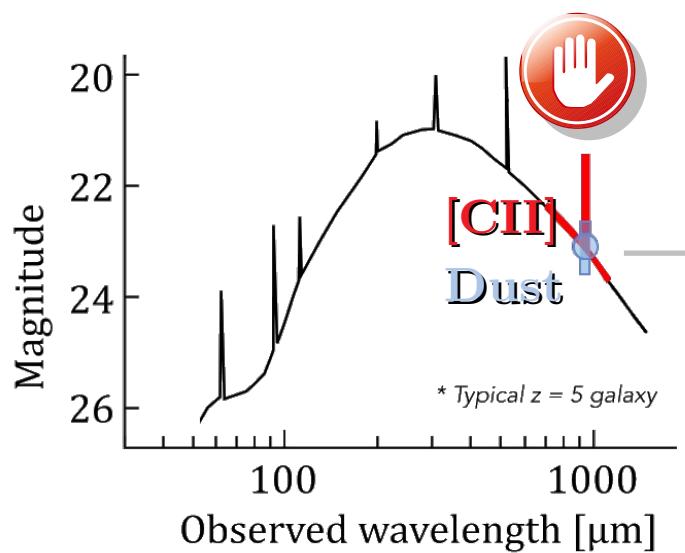
# ALMA observations of UV-bright $z > 4$ galaxies

## ALPINE

120 targets

70 hours of obs.

[CII]158 $\mu\text{m}$  & Dust



## New method to derive $T_d$ :

Inputs:

$L_{\text{[CII]}}$

$F_{158\mu\text{m}}$

Outputs:

$M_d$

$T_d$

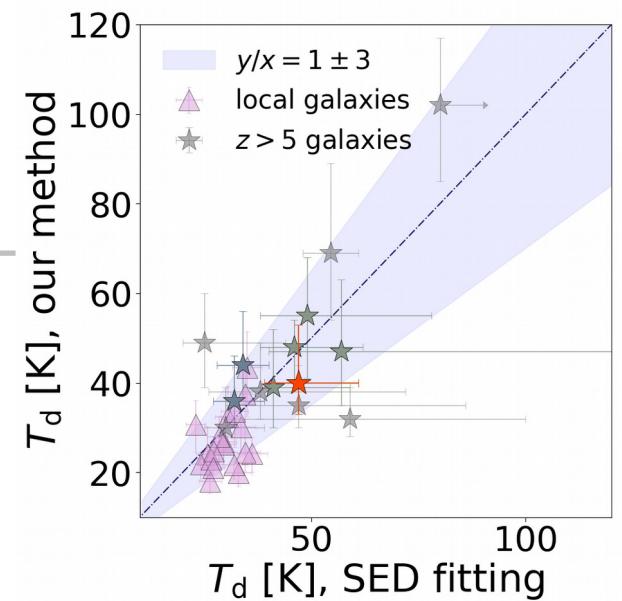
Sommovigo+21

## REBELS

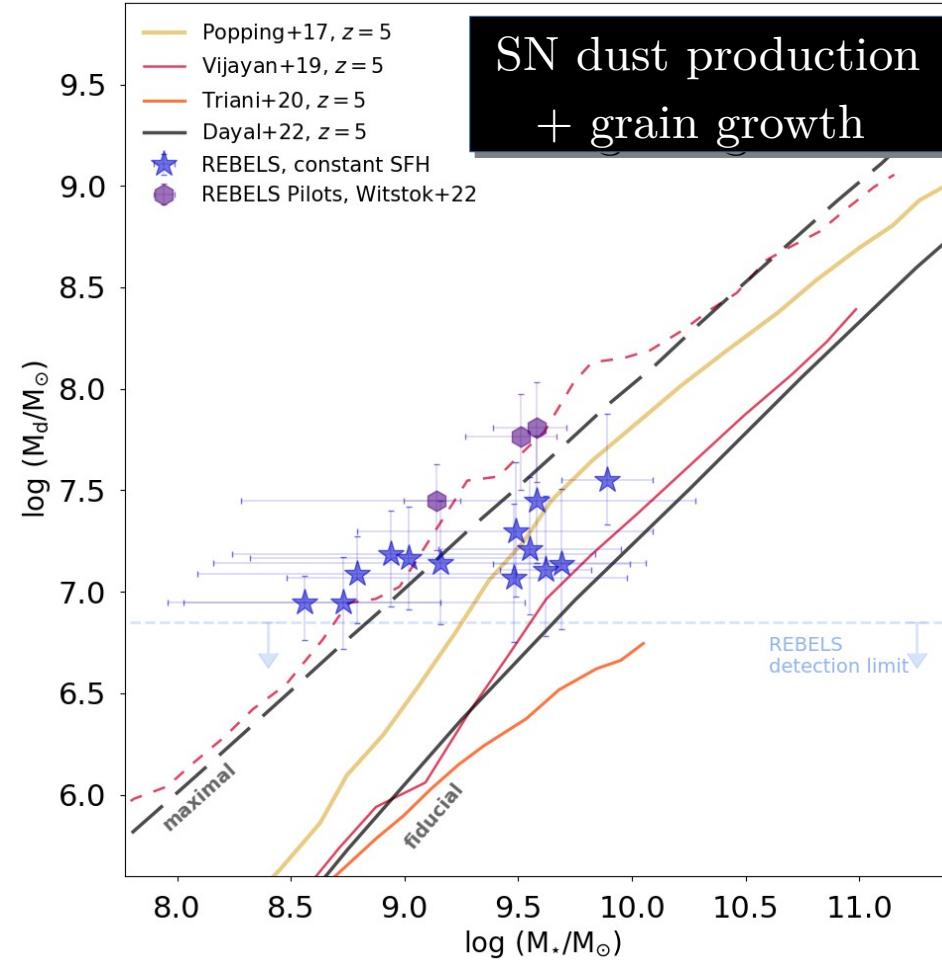
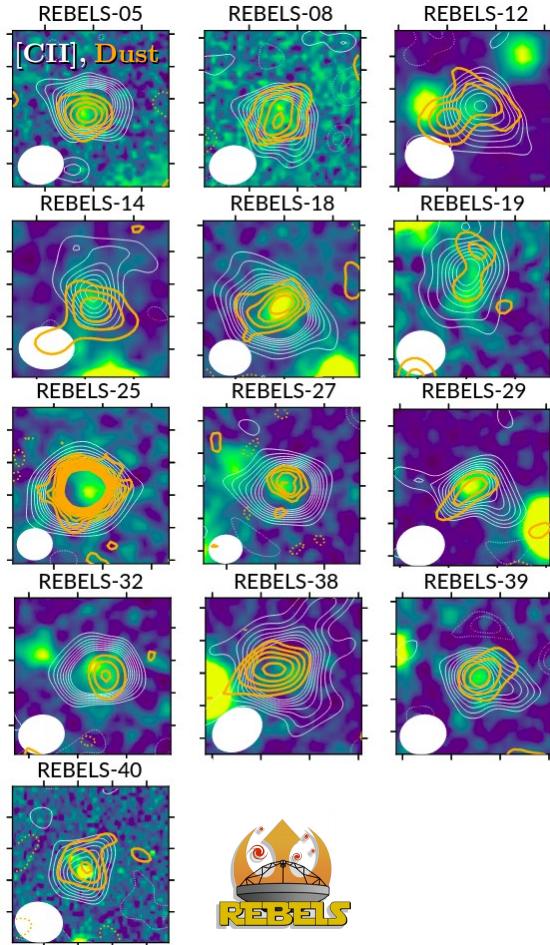
60 targets

70 hours of obs.

[CII], [OIII]88 $\mu\text{m}$  & Dust



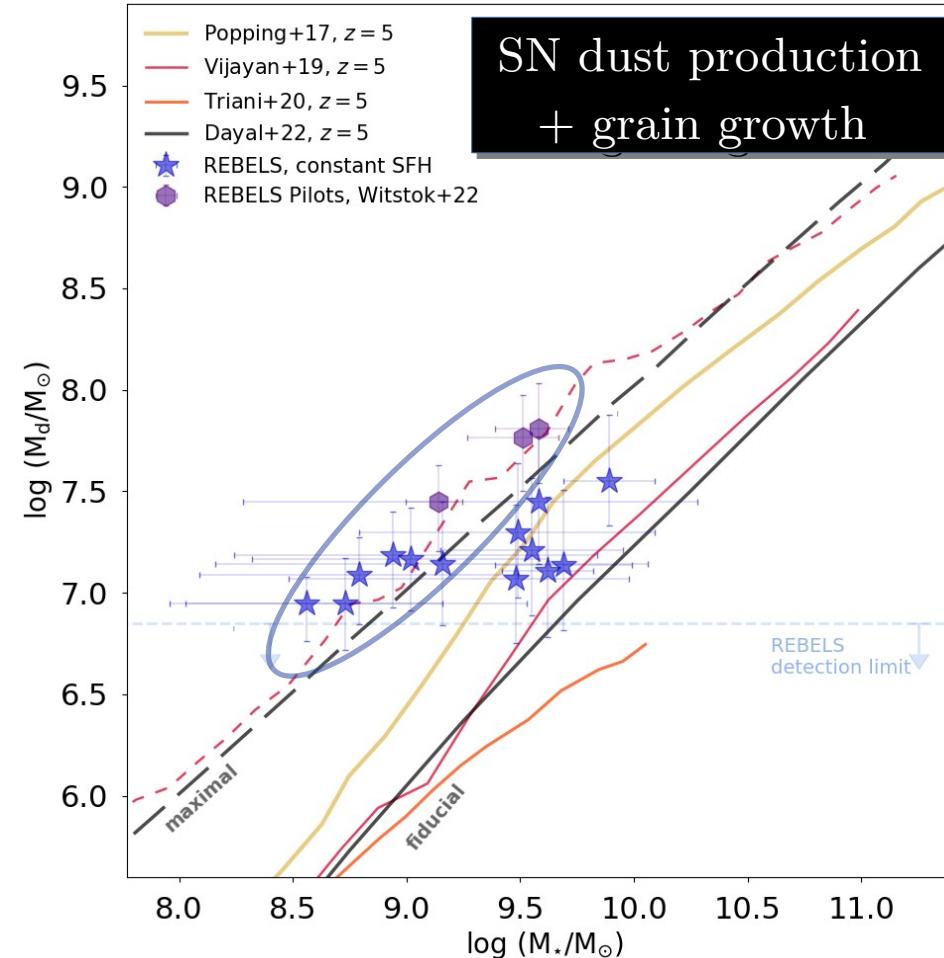
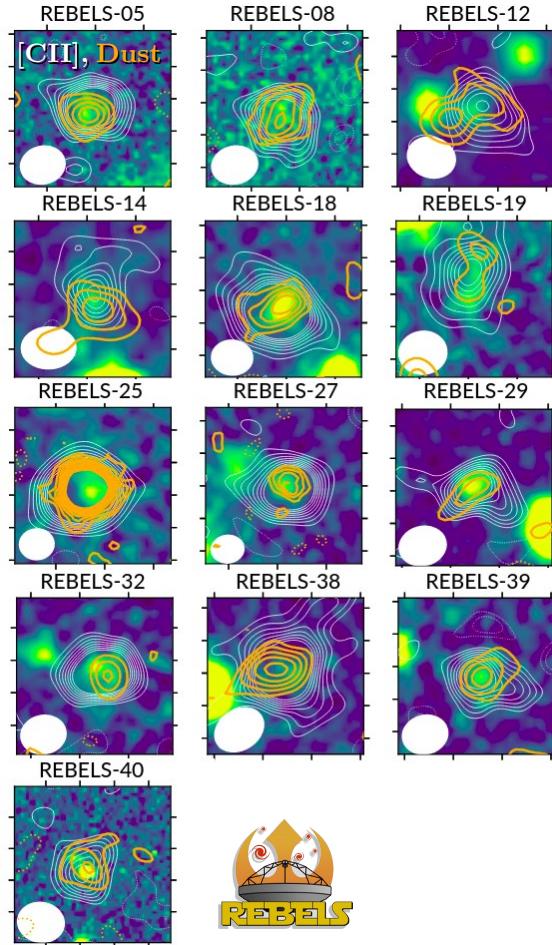
# Understanding the dust build-up at $z>4$



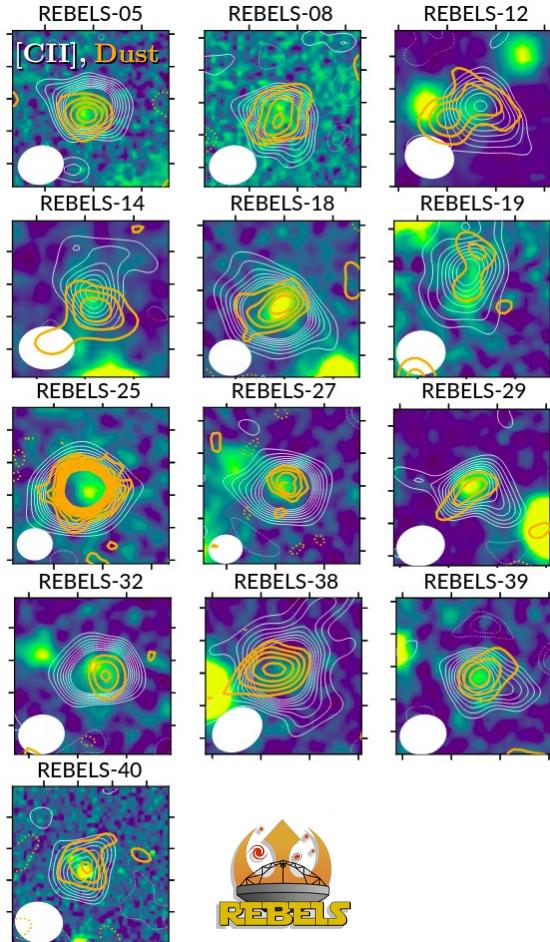
Sommovigo+22b

See also: Dayal+22, Ferrara+22, Topping+22, Di Cesare+22

# Understanding the dust build-up at $z>4$

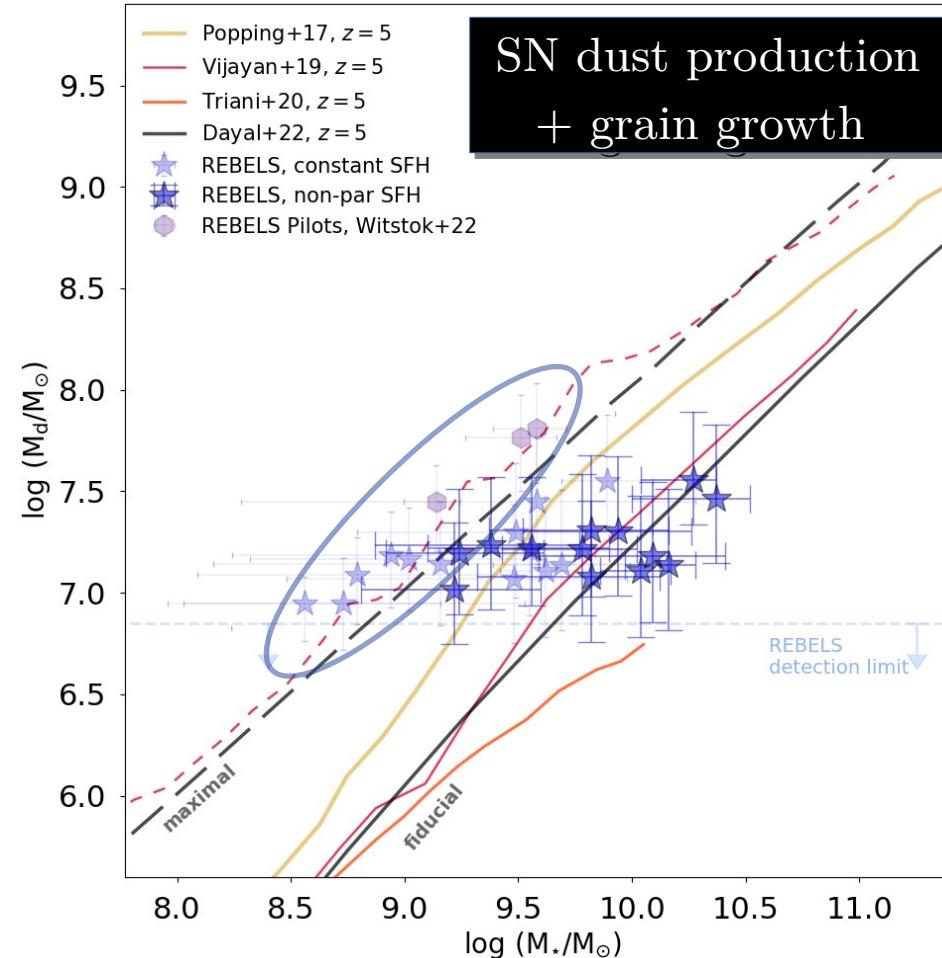


# Understanding the dust build-up at $z>4$

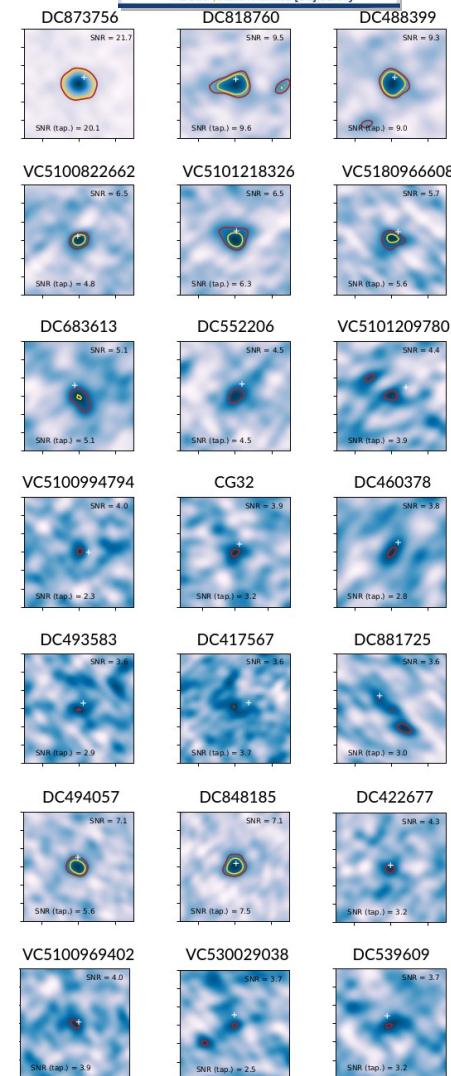
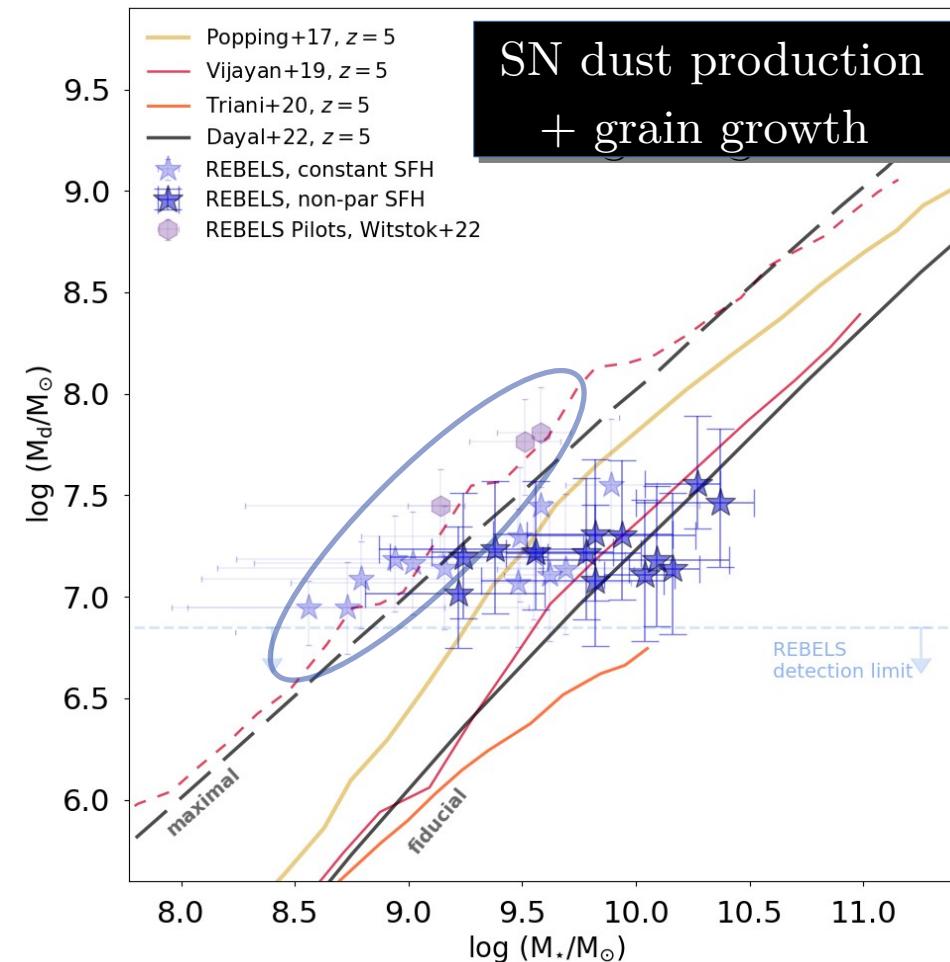
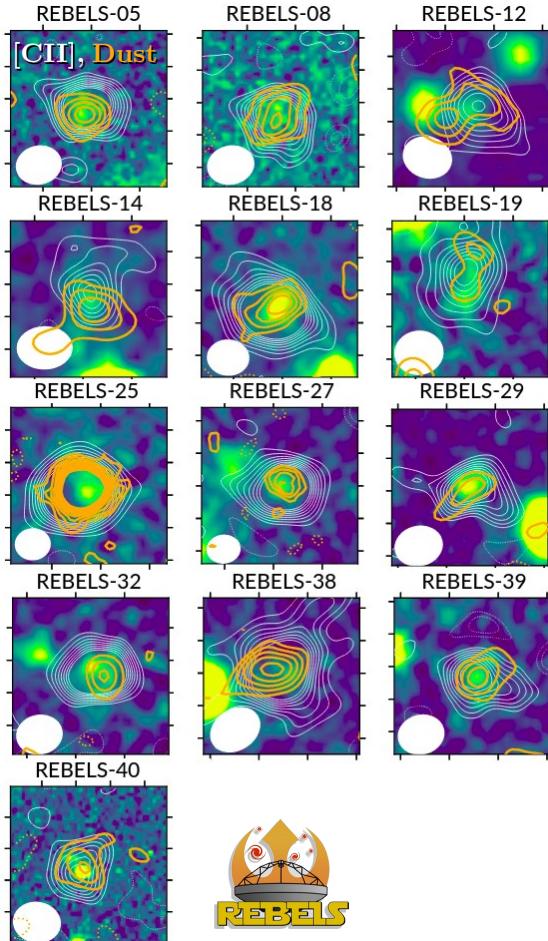


Sommovigo+22b

See also: Dayal+22, Ferrara+22, Topping+22, Di Cesare+22



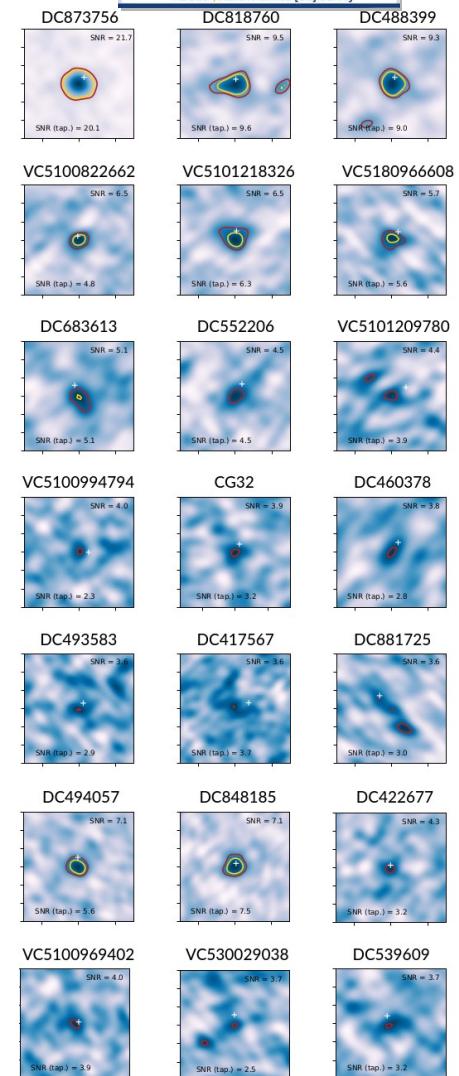
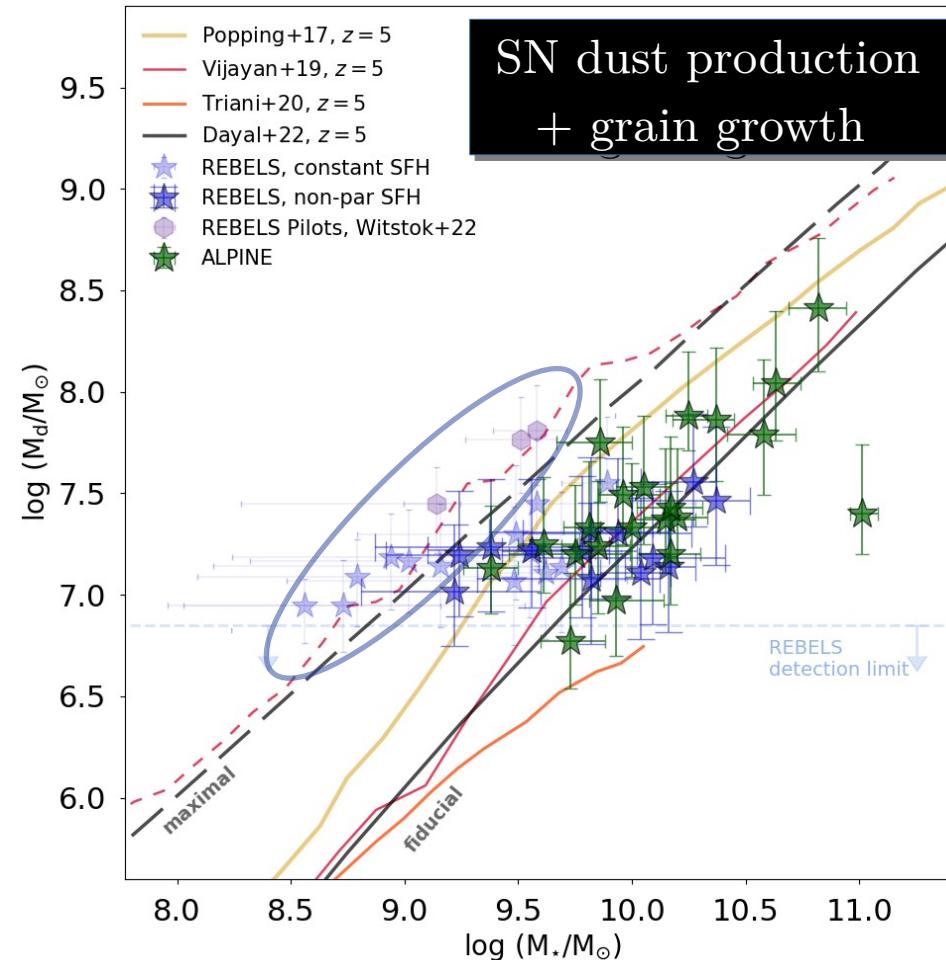
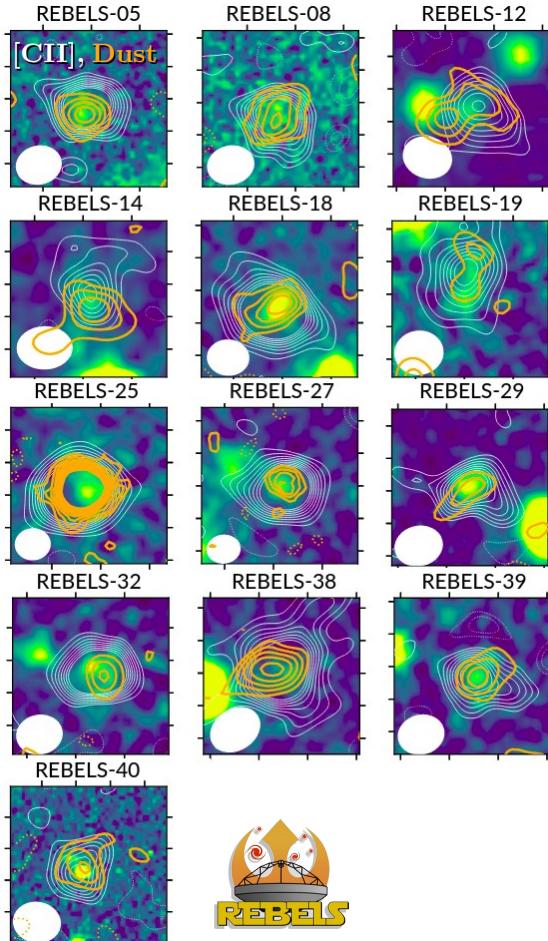
# Understanding the dust build-up at $z > 4$



Sommovigo+22b

See also: Dayal+22, Ferrara+22, Topping+22, Di Cesare+22

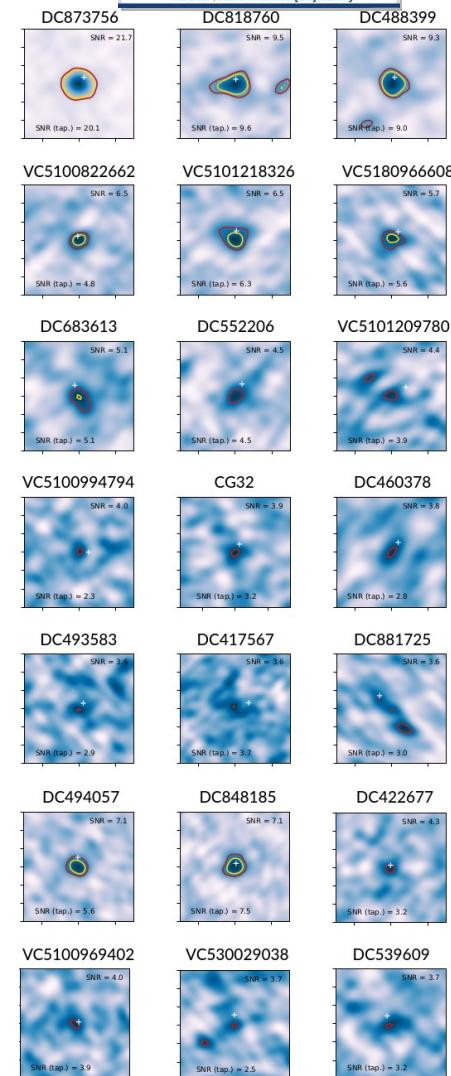
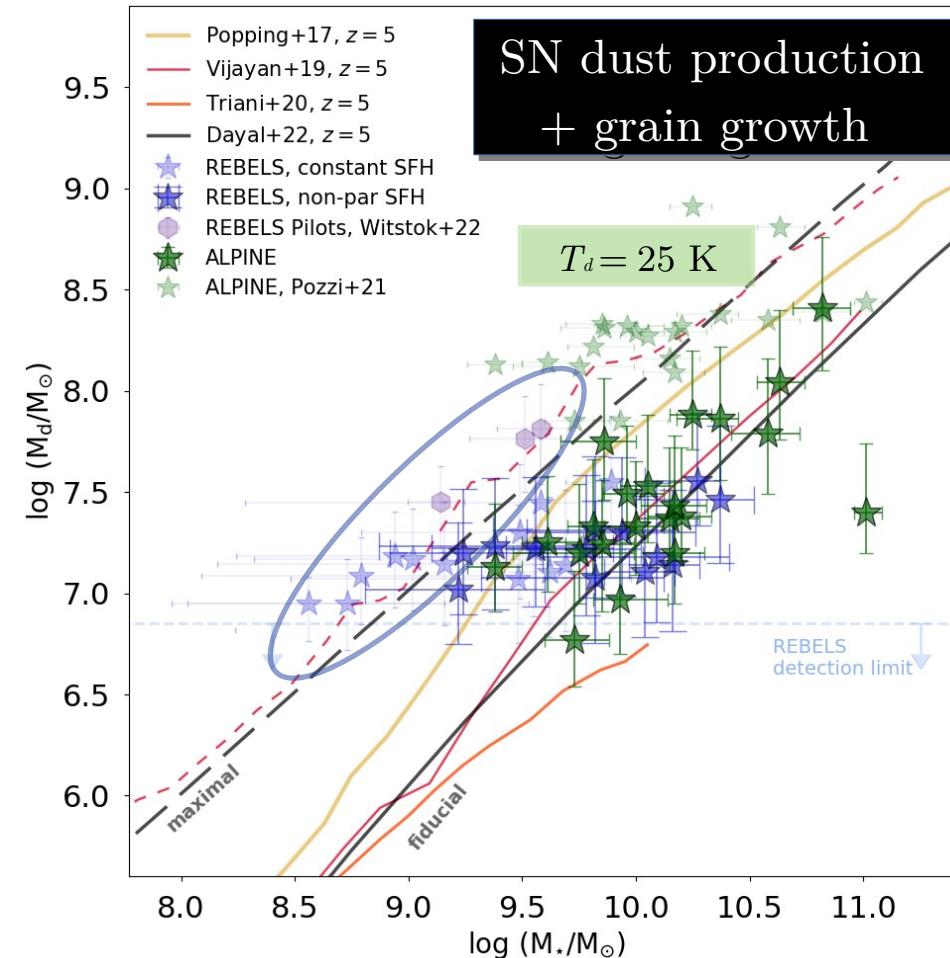
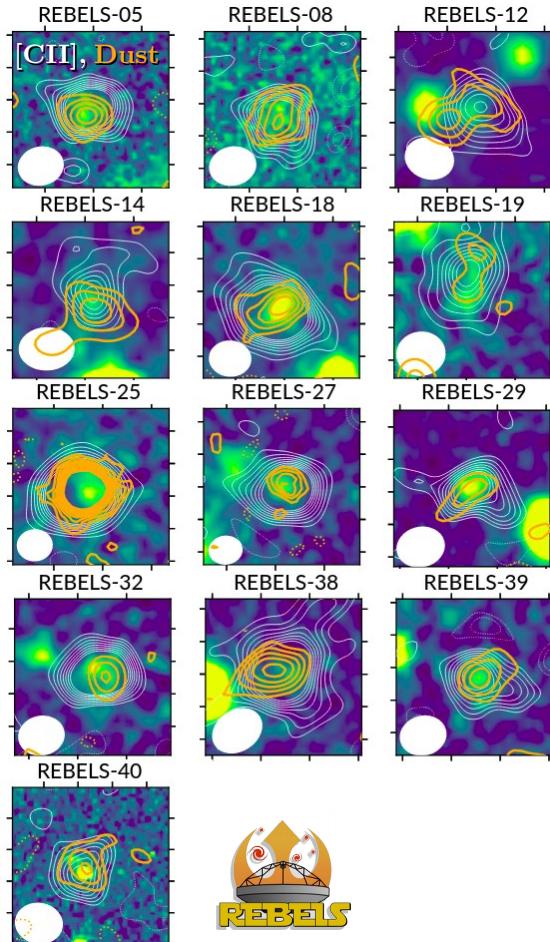
# Understanding the dust build-up at $z > 4$



Sommovigo+22b

See also: Dayal+22, Ferrara+22, Topping+22, Di Cesare+22

# Understanding the dust build-up at $z > 4$

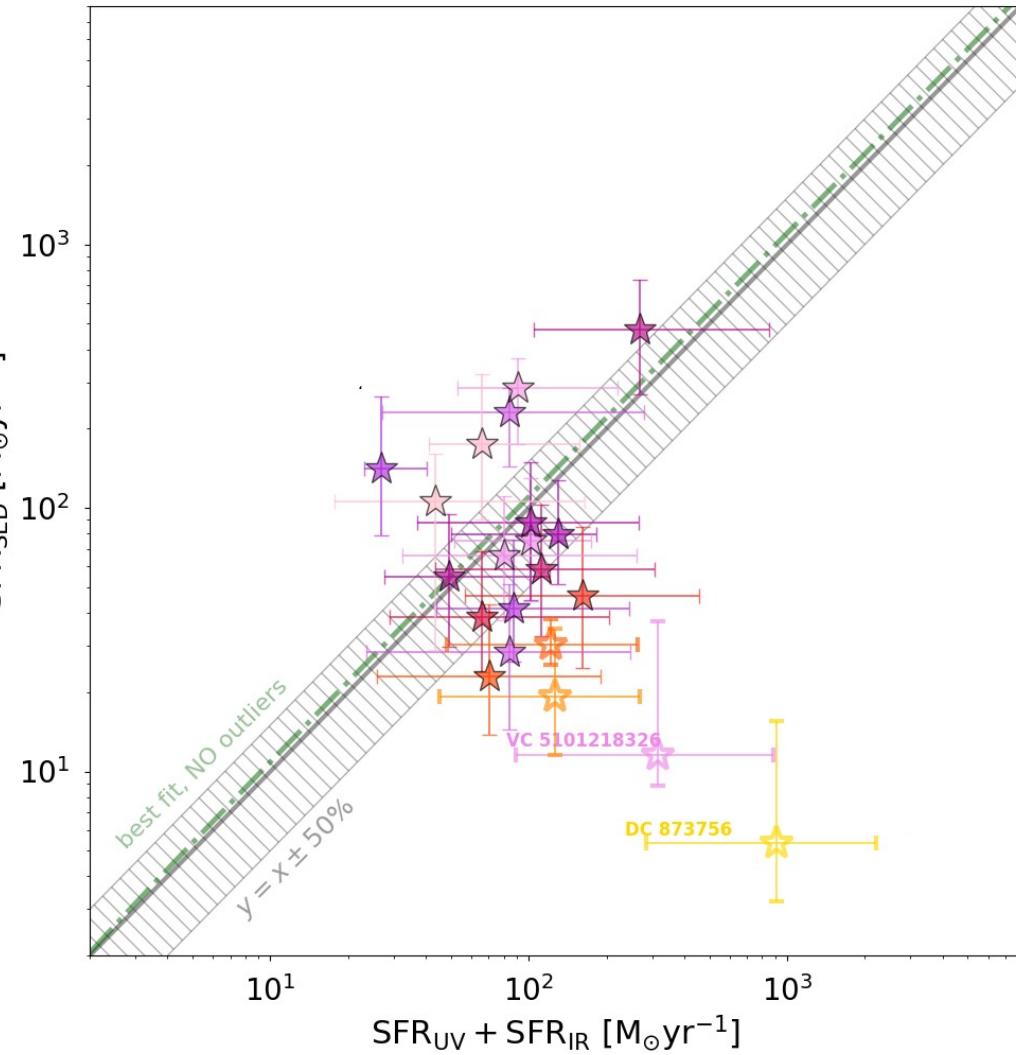


Sommovigo+22b

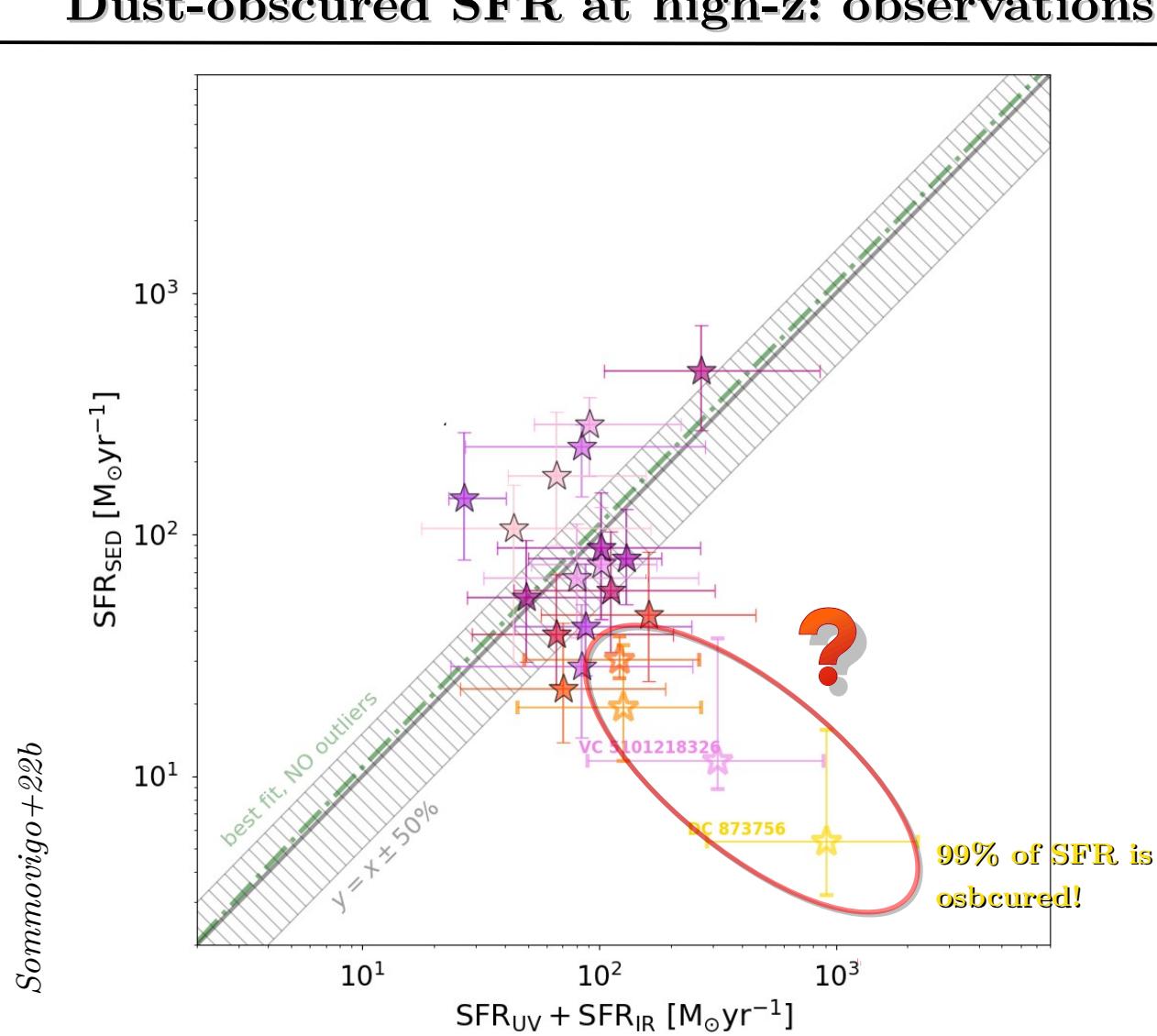
See also: Dayal+22, Ferrara+22, Topping+22, Di Cesare+22

# Dust-obscured SFR at high-z: observations

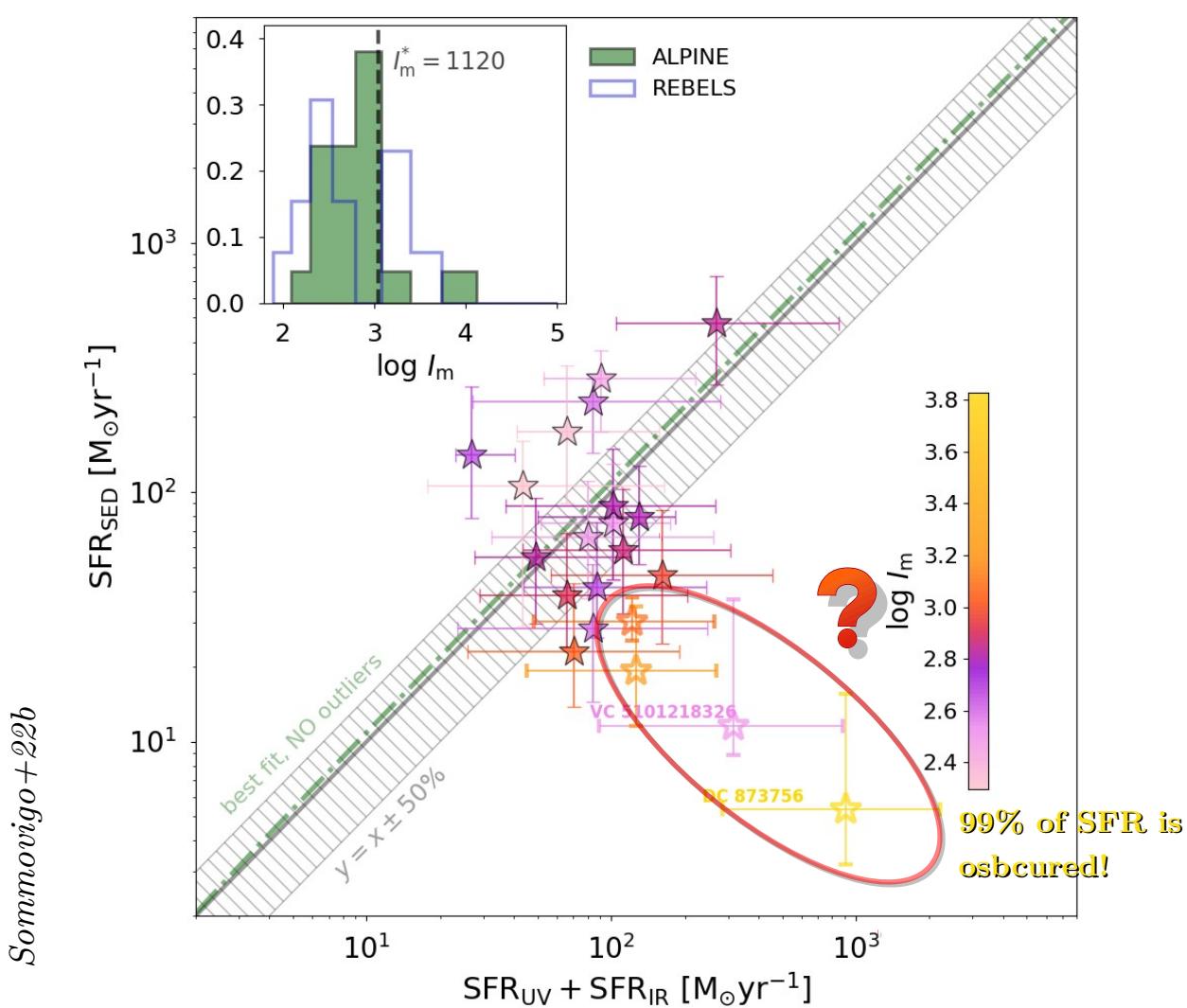
Sommario + 22b



# Dust-obscured SFR at high-z: observations



# Dust-obscured SFR at high-z: observations



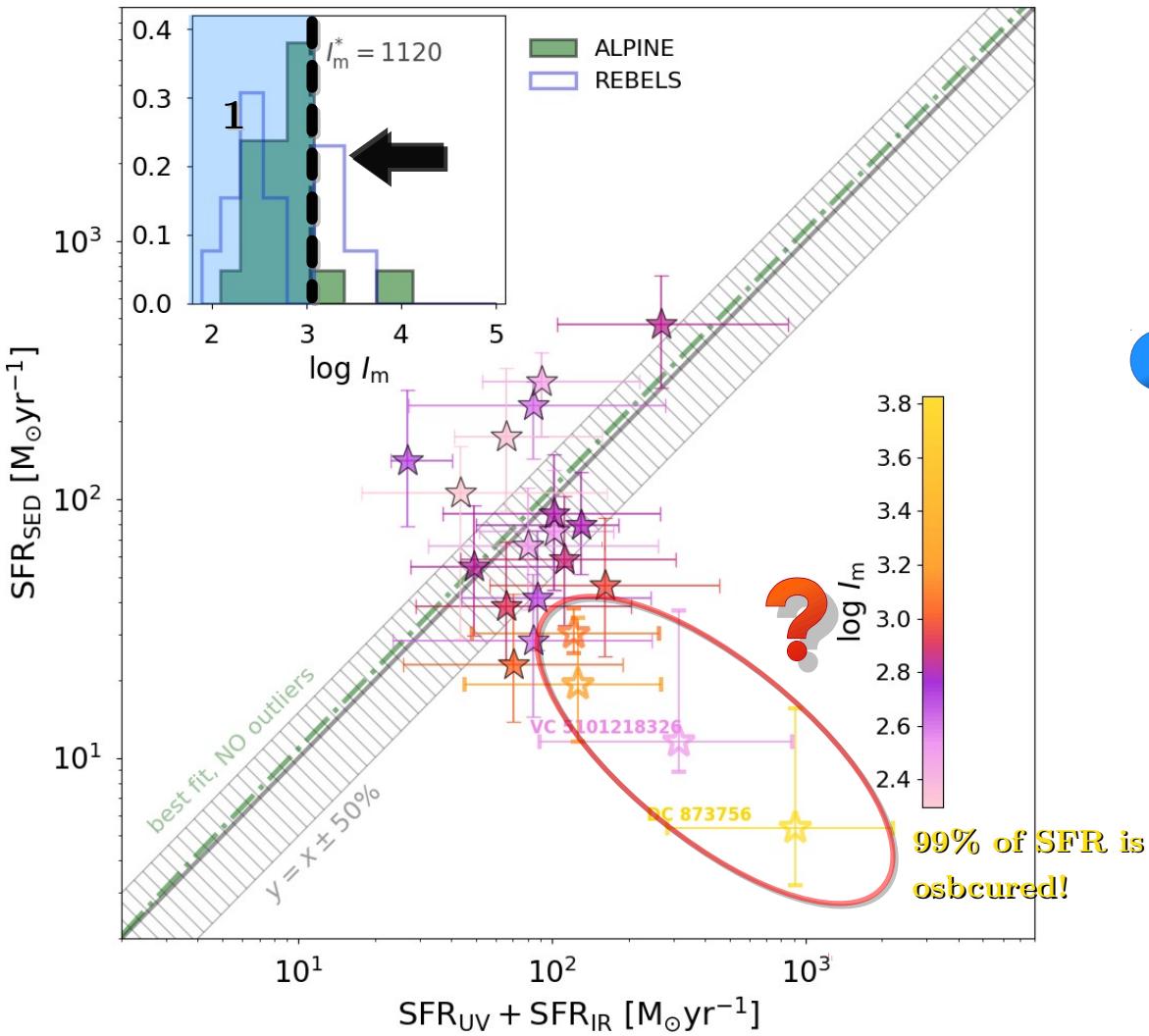
## MOLECULAR INDEX:

(Ferrara+22)

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{int})}$$

# Dust-obscured SFR at high-z: observations

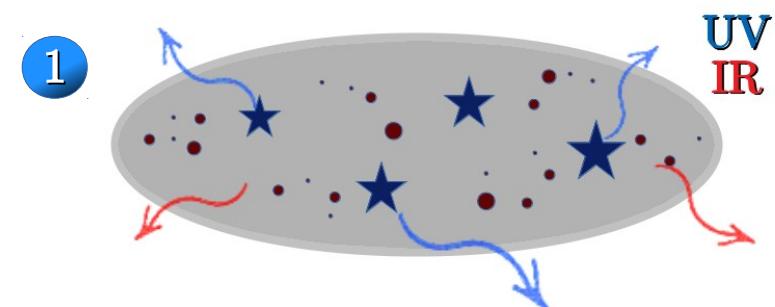
Sommario [go + 222b](#)



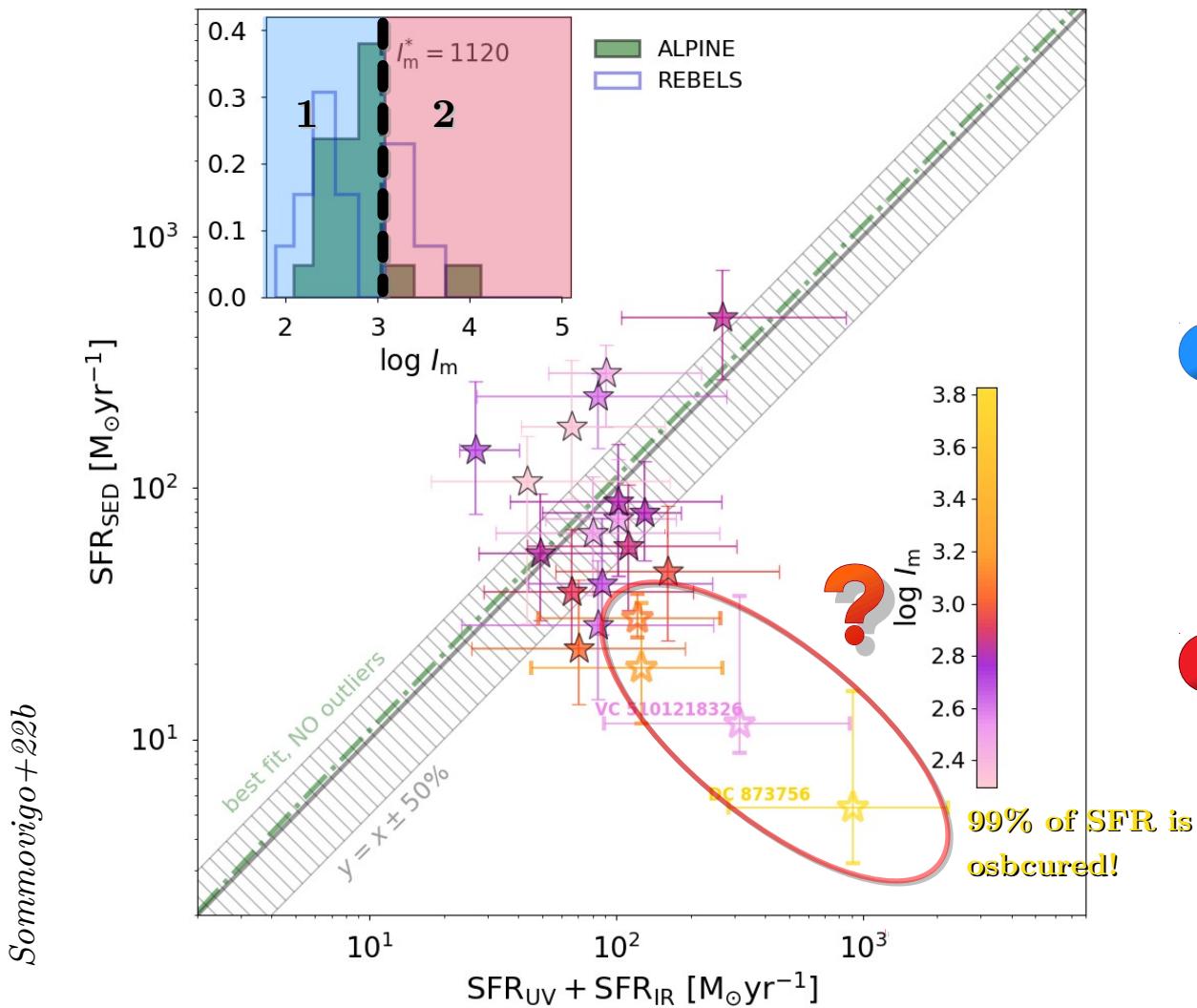
## MOLECULAR INDEX:

(Ferrara+22)

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})} < I_m^* \simeq 1120$$



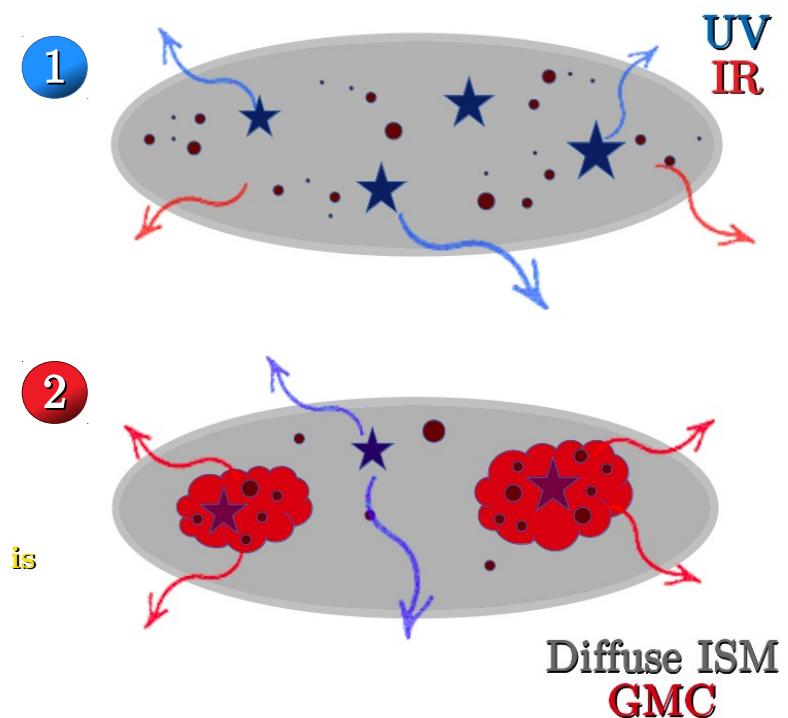
# Dust-obscured SFR at high-z: observations



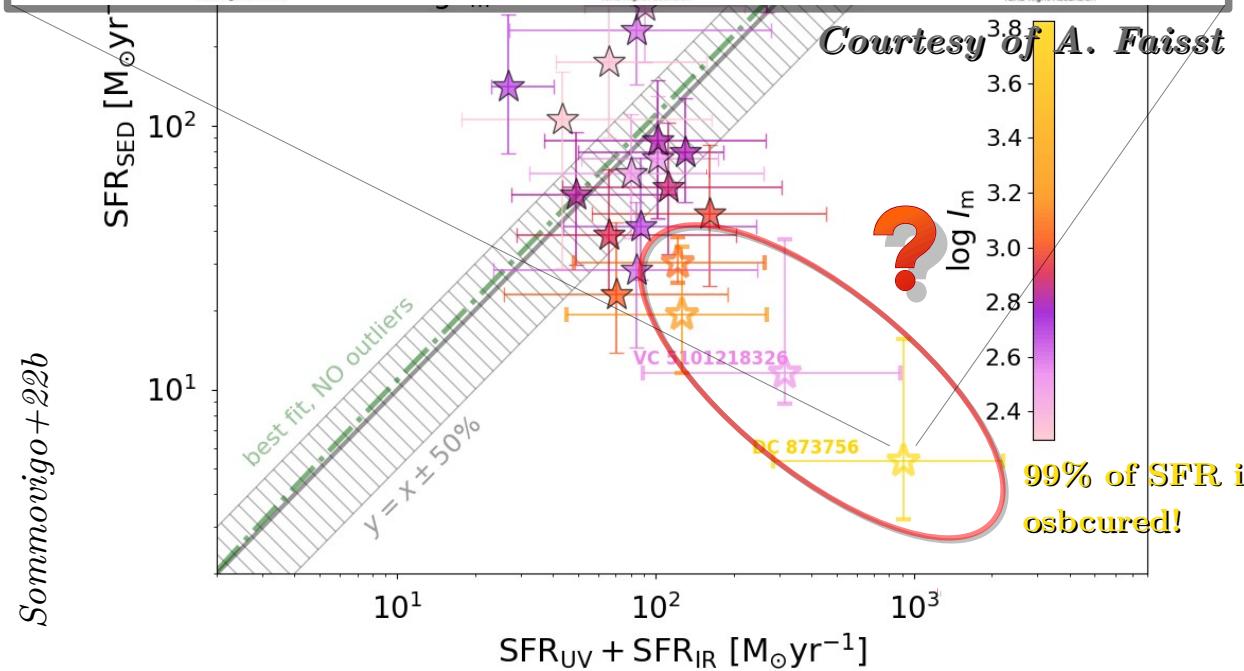
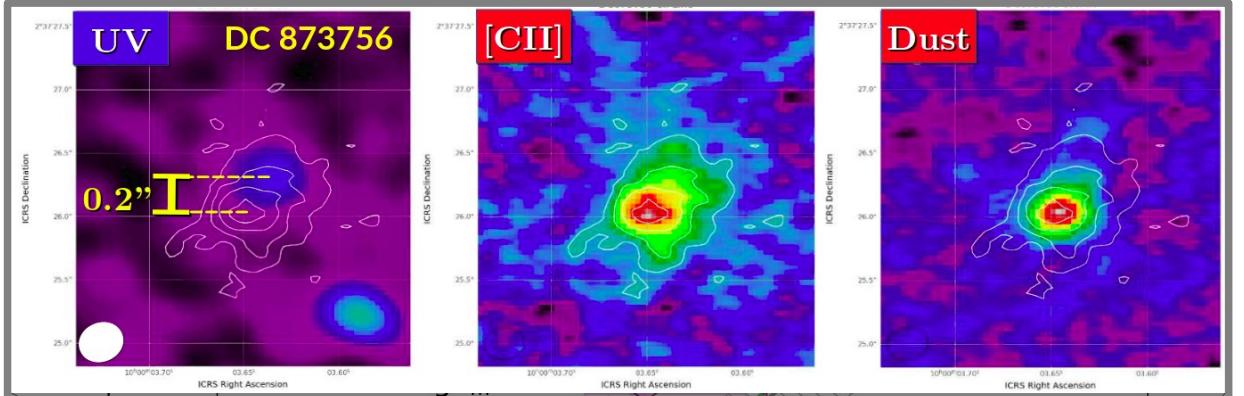
## MOLECULAR INDEX:

(Ferrara+22)

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})} < I_m^* \simeq 1120$$



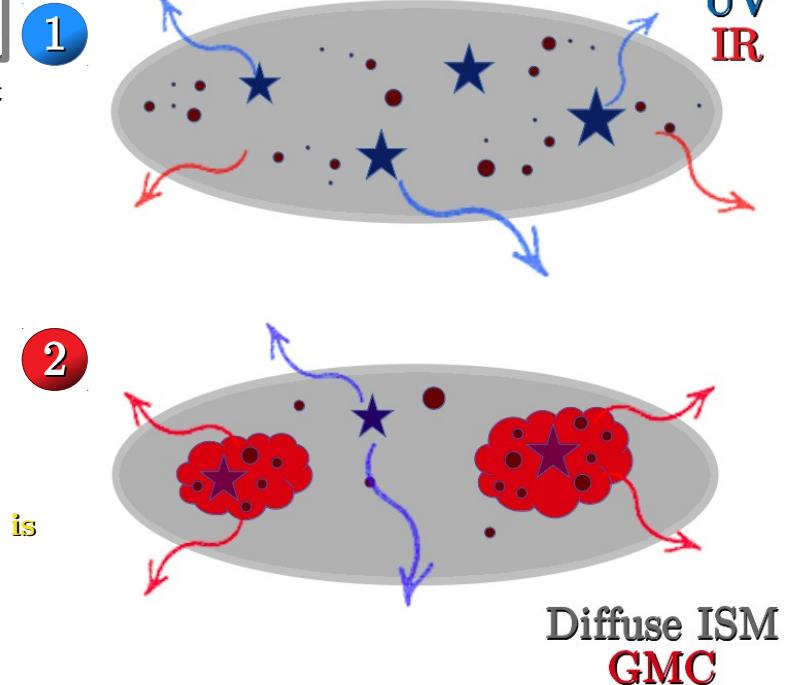
# Dust-obscured SFR at high-z: observations



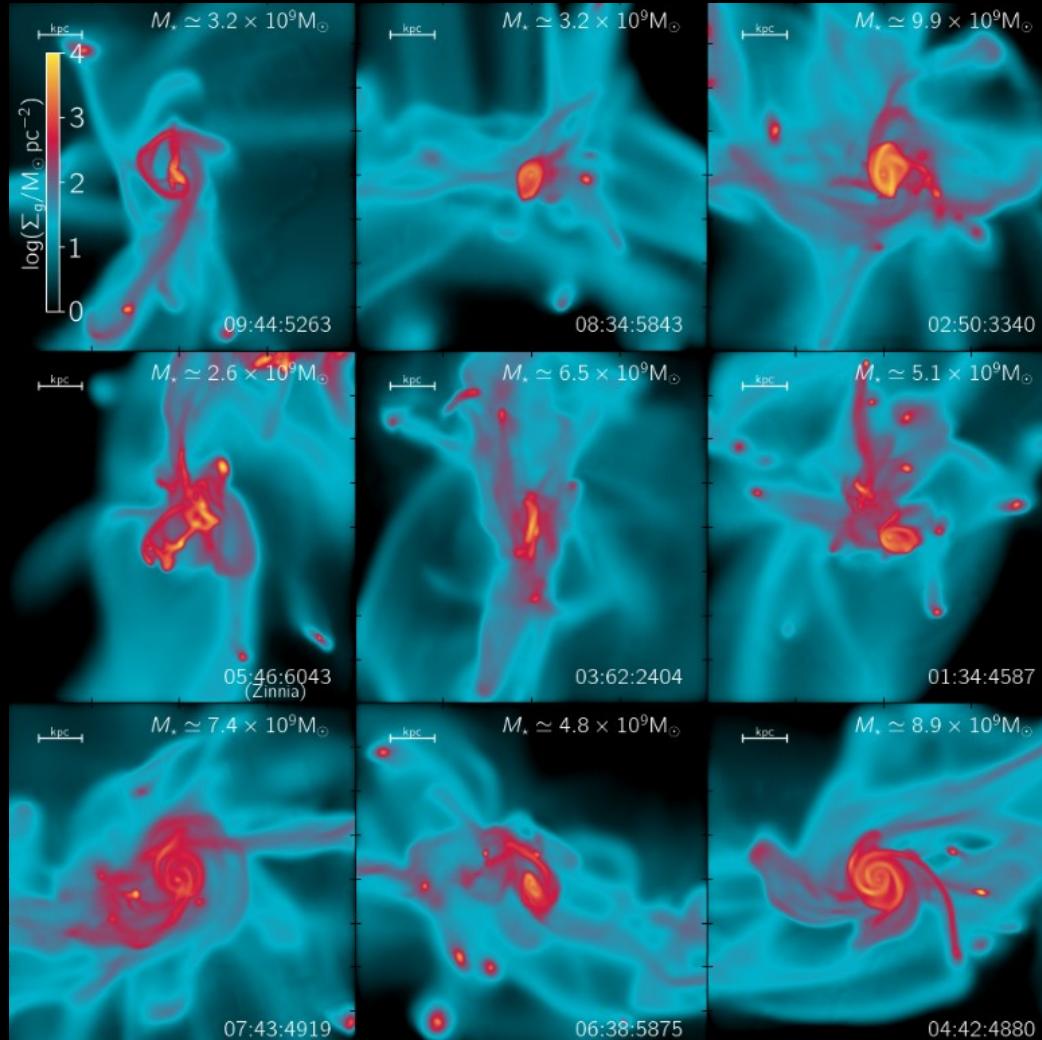
## MOLECULAR INDEX:

(Ferrara+22)

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})} < I_m^* \simeq 1120$$



# Dust-obscuration at high-z: zoom-in SERRA simulations



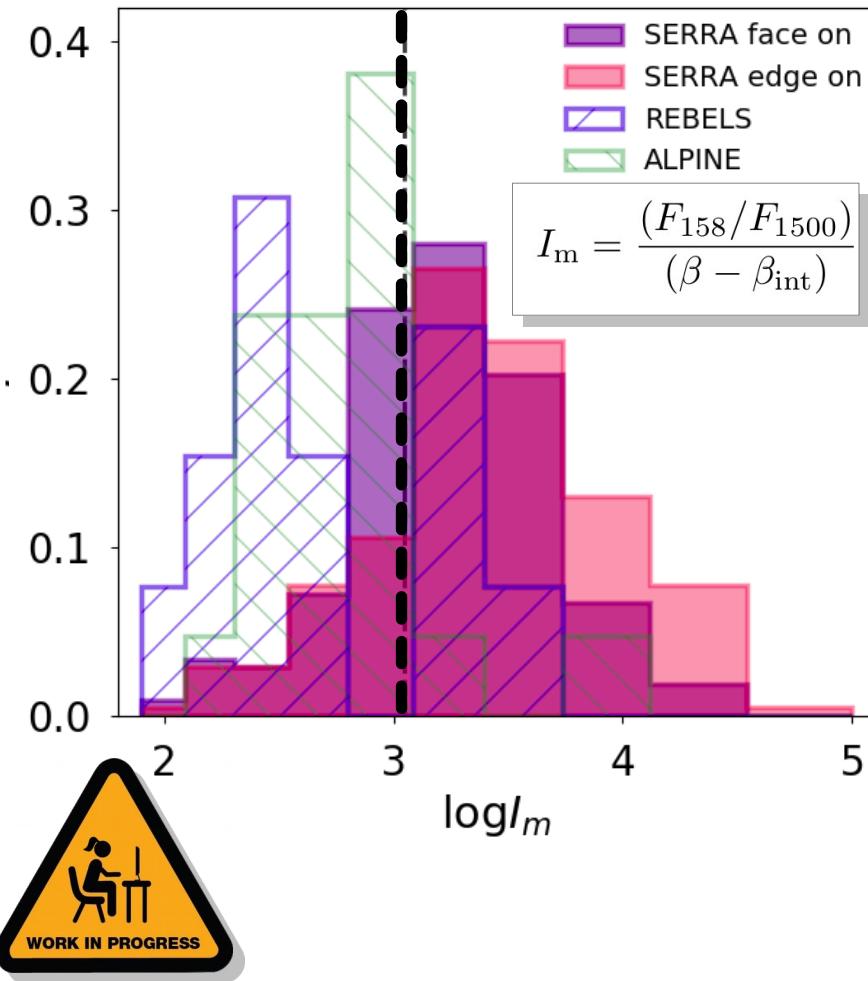
some info:

- zoom-in high-resolution (~25 pc at  $z = 7.7$ ) cosmological simulation
- including non-equilibrium chemistry and on-the-fly radiative transfer
- 202 galaxies at  $z=7.7$
- $10^7 M_{\odot} \lesssim M_{\star} \lesssim 5 \times 10^{10} M_{\odot}$
- sSFR  $\sim 10 \text{ Gyr}^{-1} - 100 \text{ Gyr}^{-1}$

Set up:

*RAMSES + KROME  
SKIRT  
CLOUDY*

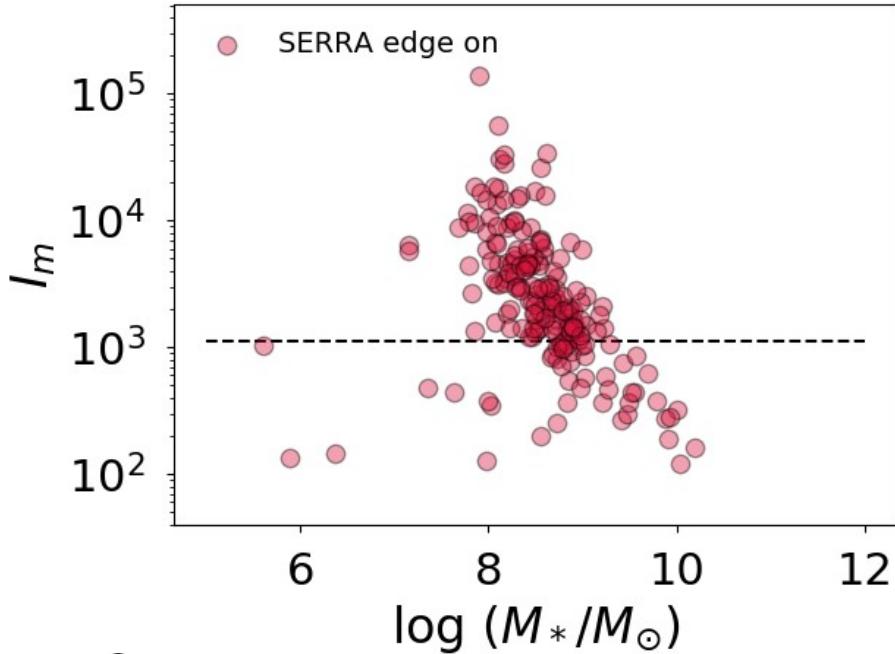
# Dust-obscuration at high-z: zoom-in SERRA simulations



# Dust-obscuration at high-z: zoom-in SERRA simulations

---

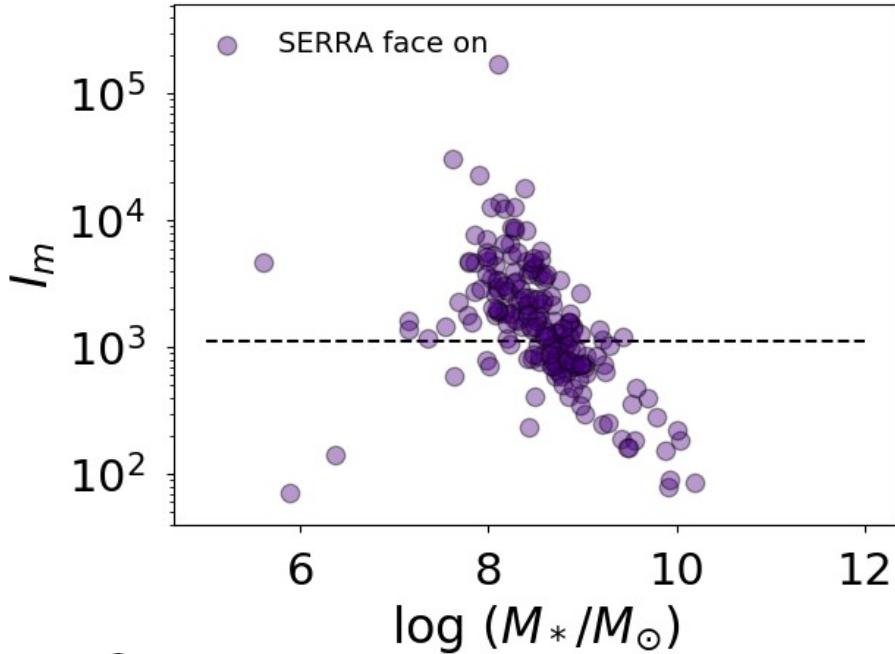
$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})}$$



# Dust-obscuration at high-z: zoom-in SERRA simulations

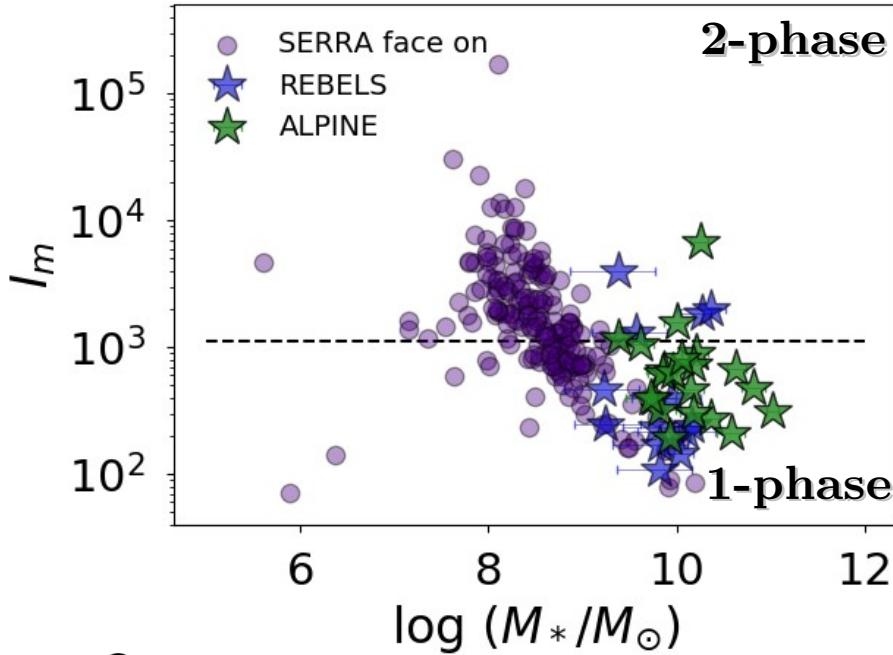
---

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})}$$



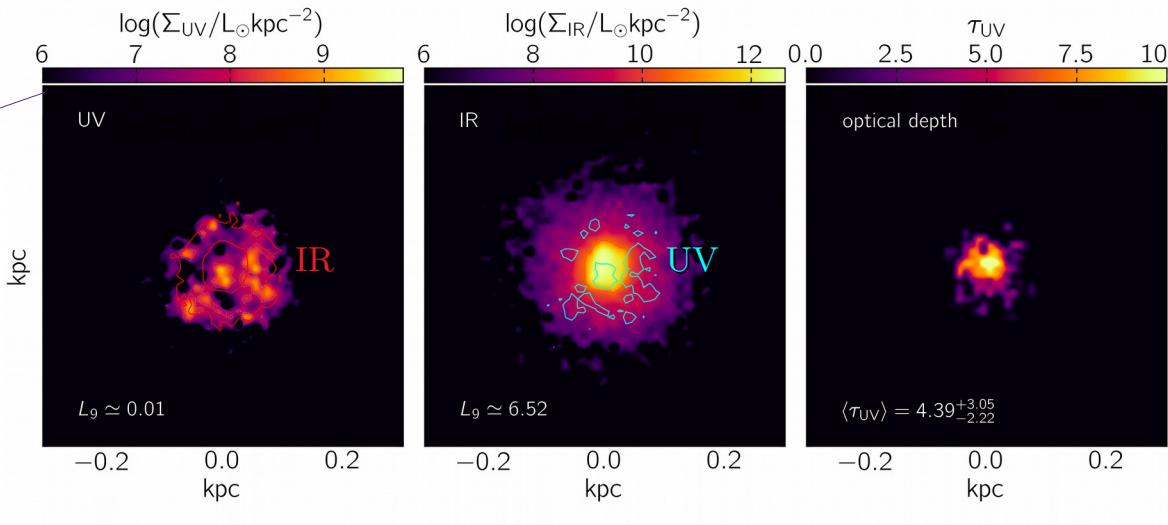
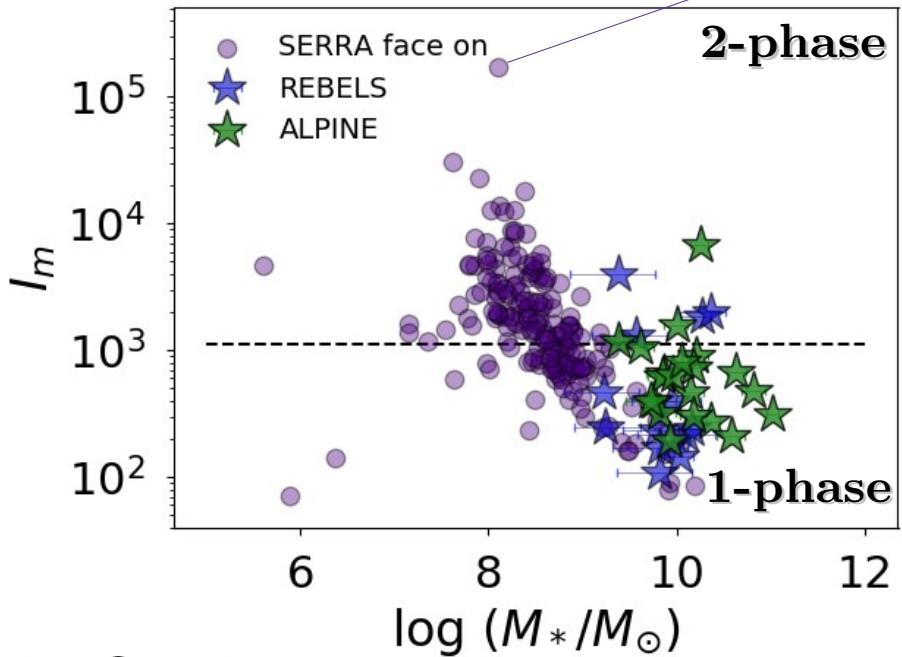
# Dust-obscuration at high-z: zoom-in SERRA simulations

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})}$$



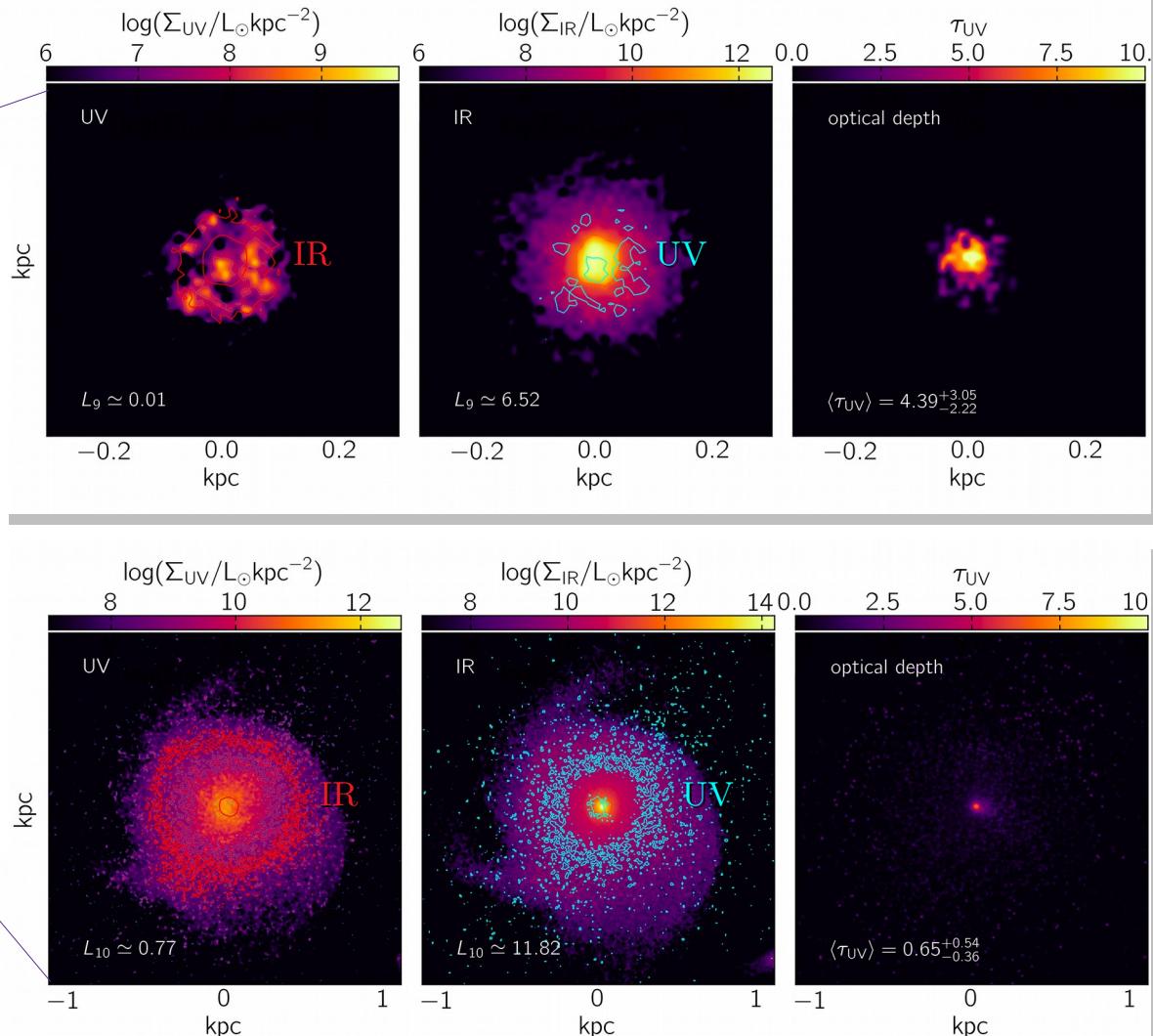
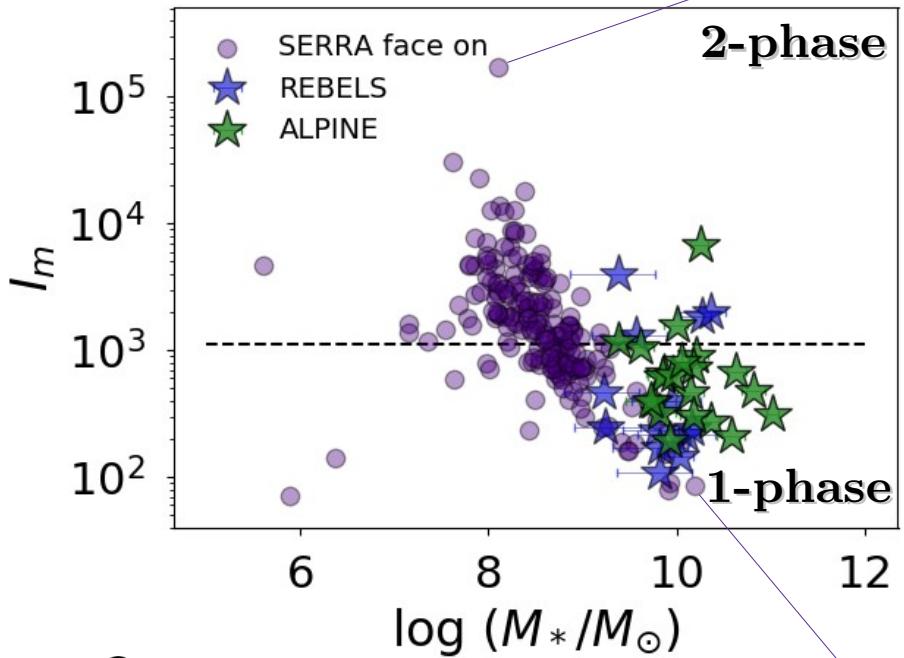
# Dust-obscuration at high-z: zoom-in SERRA simulations

$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})}$$

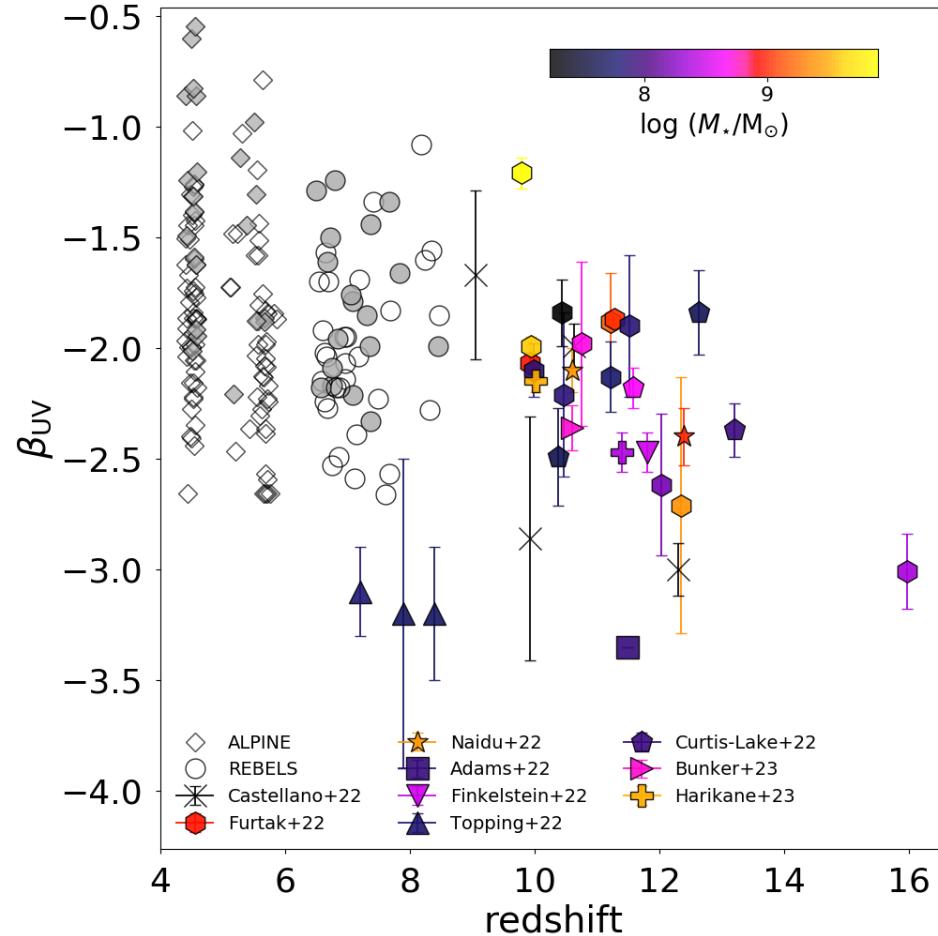


# Dust-obscuration at high-z: zoom-in SERRA simulations

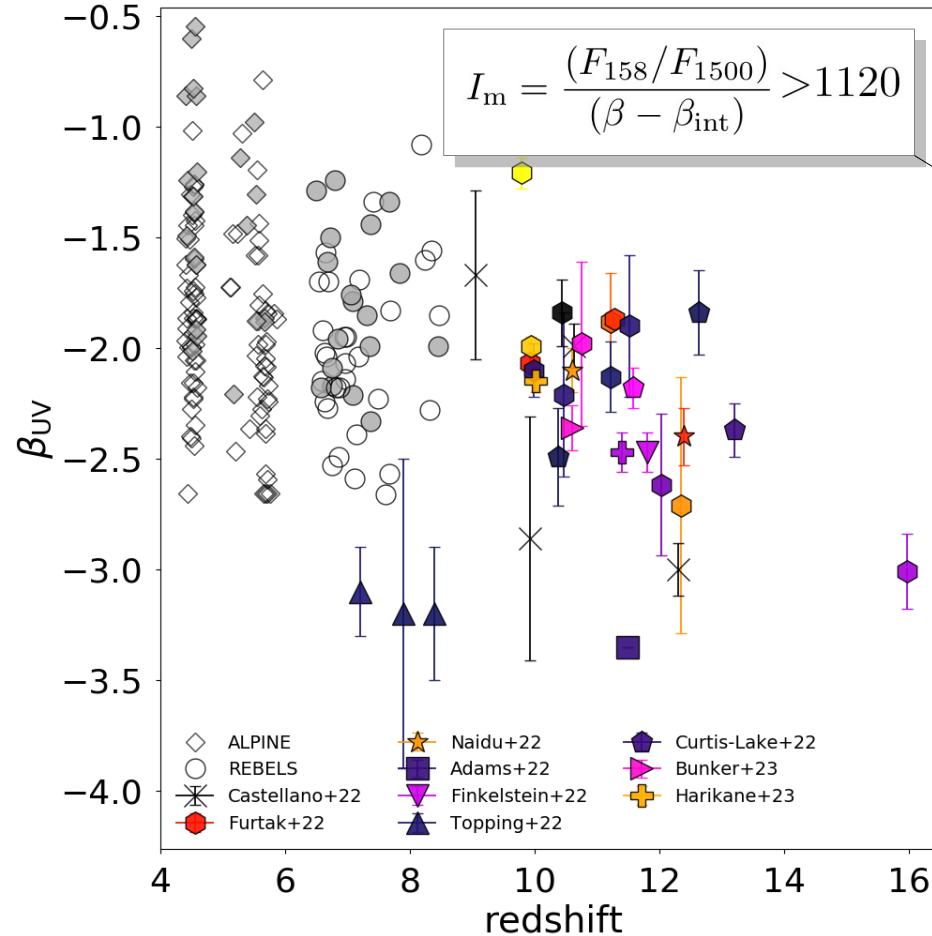
$$I_m = \frac{(F_{158}/F_{1500})}{(\beta - \beta_{\text{int}})}$$



# JWST $z > 10$ galaxy candidates: opening a Pandora's box?

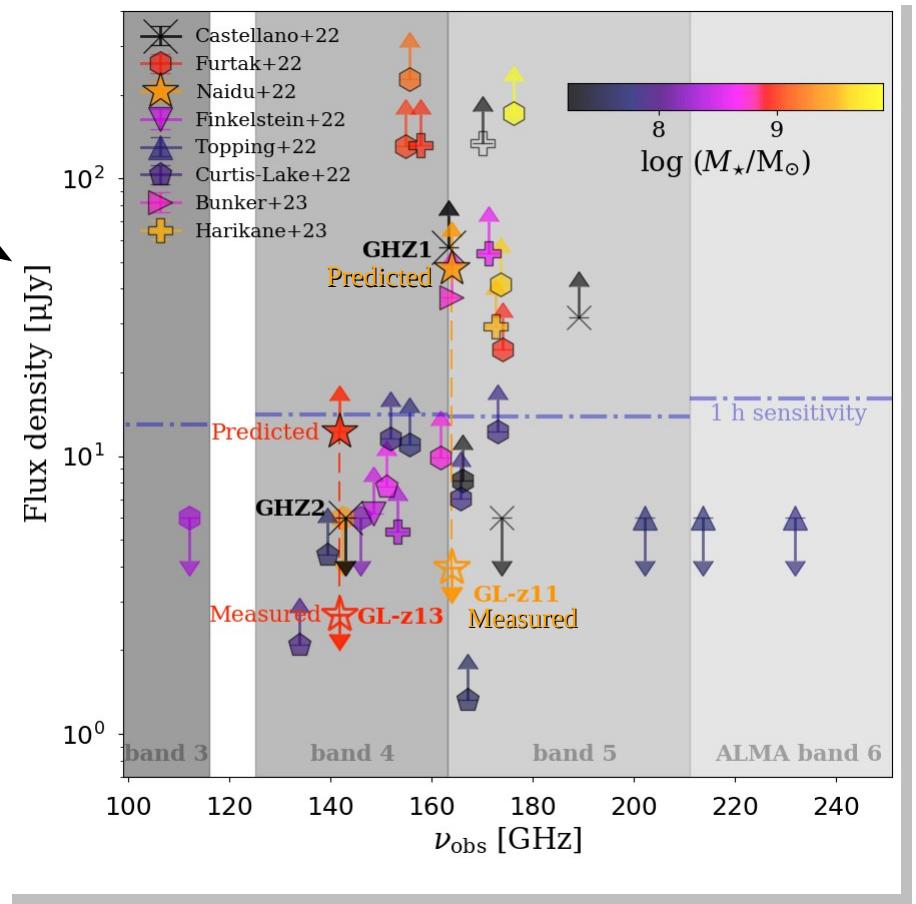
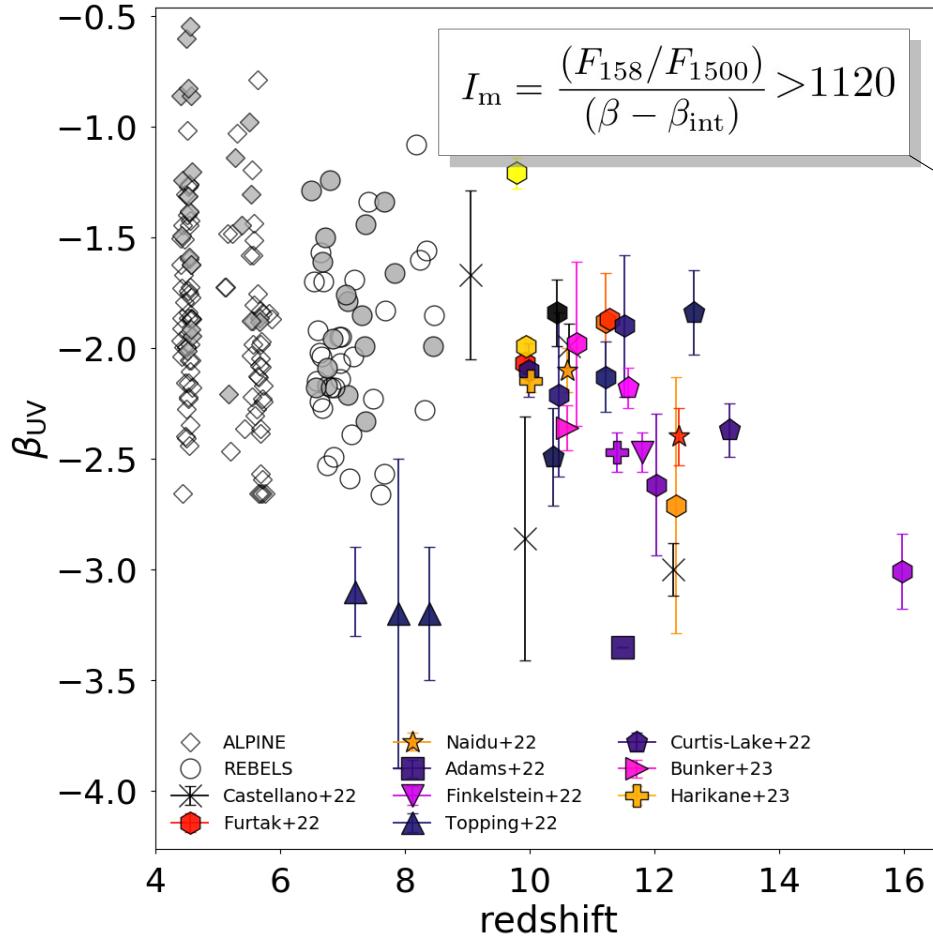


# JWST z>10 galaxy candidates: opening a Pandora's box?



Updated from: Ziparo, Ferrara & LS+22

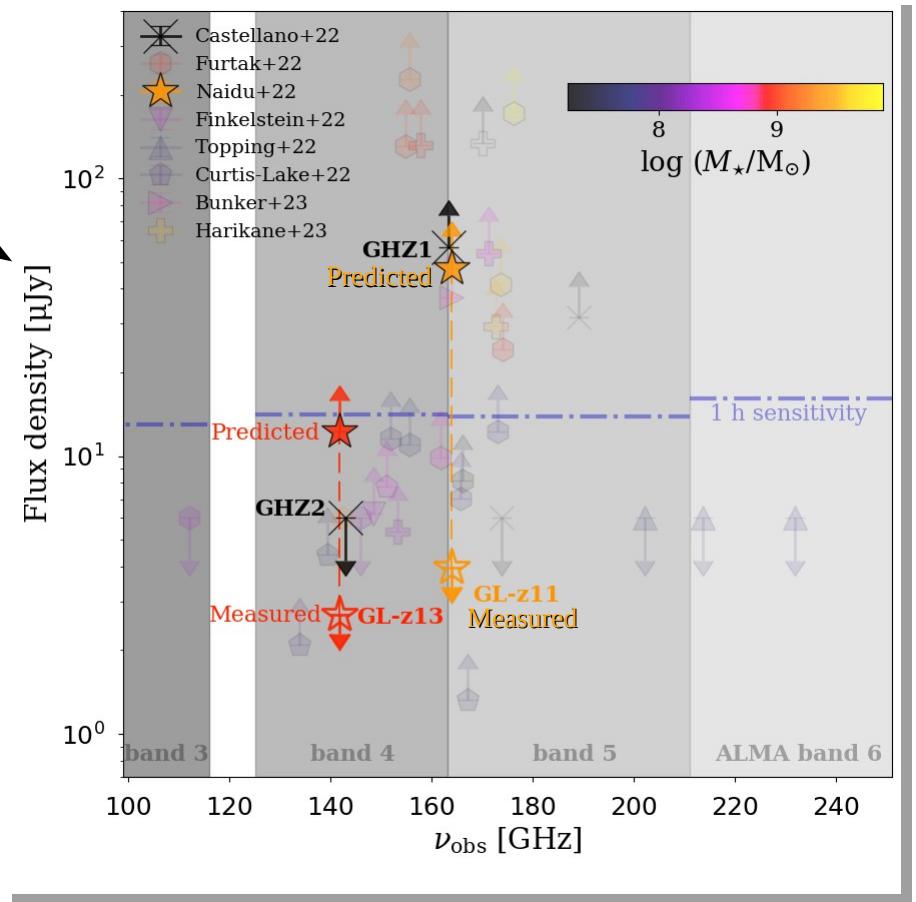
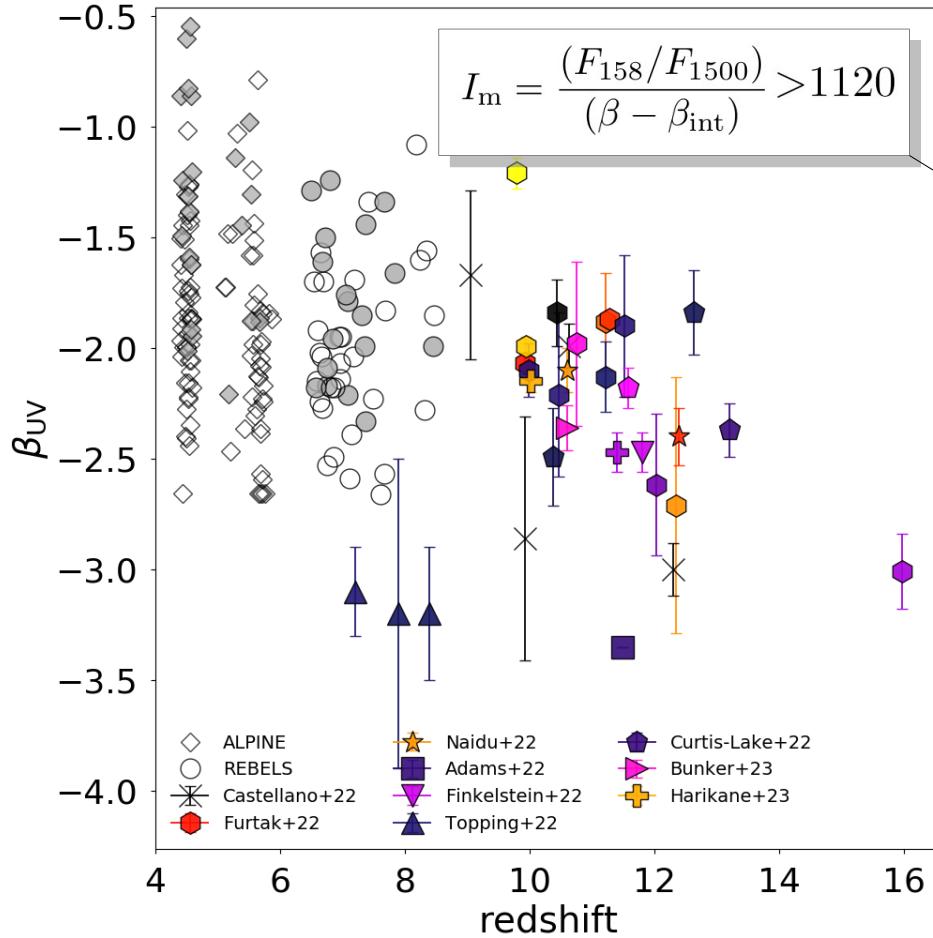
# JWST $z > 10$ galaxy candidates: opening a Pandora's box?



ALMA follow-ups of JWST sources at  $z > 10$ :

GHZ2 (Bakx+22, Popping+22), GHZ1 (Yoon+22), HD1 (Kaasinen+22), and S5-z17-1 (Fujimoto+22)

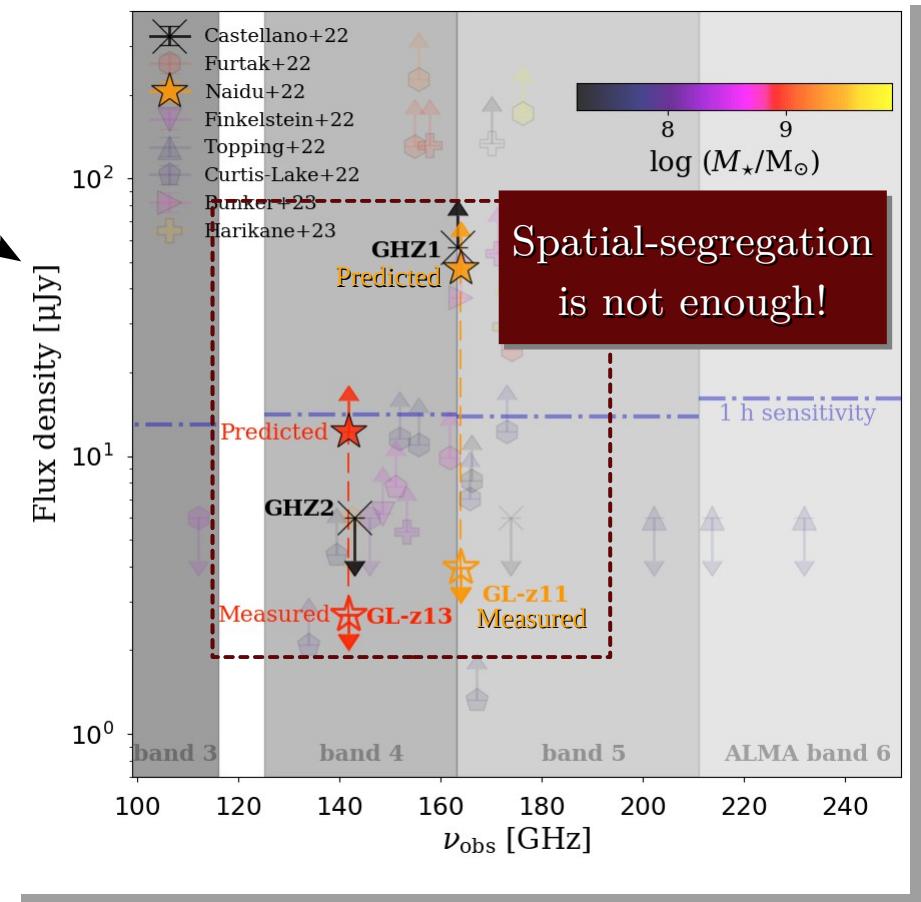
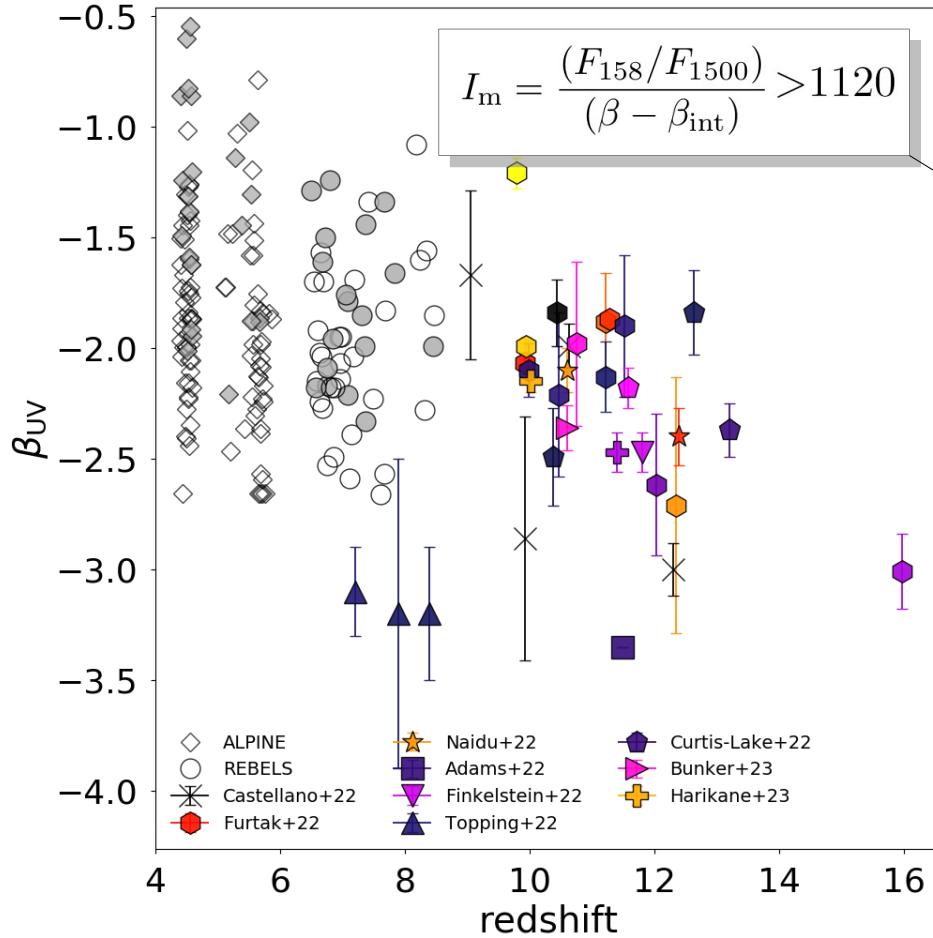
# JWST $z > 10$ galaxy candidates: opening a Pandora's box?



ALMA follow-ups of JWST sources at  $z > 10$ :

GHZ2 (Bakx+22, Popping+22), GHZ1 (Yoon+22), HD1 (Kaasinen+22), and S5-z17-1 (Fujimoto+22)

# JWST $z>10$ galaxy candidates: opening a Pandora's box?



Updated from: Ziparo, Ferrara & LS+22

ALMA follow-ups of JWST sources at  $z>10$ :

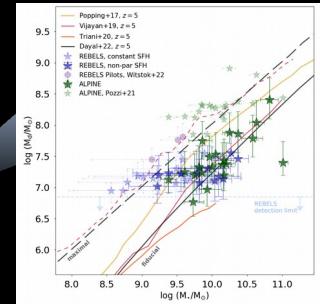
GHZ2 (Bakx+22, Popping+22), GHZ1 (Yoon+22), HD1 (Kaasinen+22), and S5-z17-1 (Fujimoto+22)

# Summary



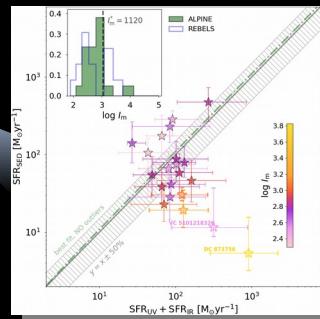
Which are the mechanisms responsible for the dust/metal enrichment in the early universe?

No conclusive answer, but dust masses compatible with dust production from Supernovae for massive ( $\log(M_*/M_\odot) > 9$ )  $z > 5$  galaxies, except few outliers.



How much SFR are we missing at high-z due to dust obscuration?

More than 50% of the SFR is obscured even in UV-selected EoR, massive galaxies. Some peculiar sources show “spatially-segregated” UV and FIR emitting regions. There, the total SFR can be underestimated up to 2 dex when relying only on UV/optical data.



Do dust properties evolve with redshift?

$T_d$  raises with redshift due to decreasing gas depletion time at high-z. Dust morphology is increasingly irregular at high-z. At  $z > 10$ , dust ejection is needed to motivate low dust attenuation in massive galaxies ( $\log(M_*/M_\odot) > 8$ ).

Contact:

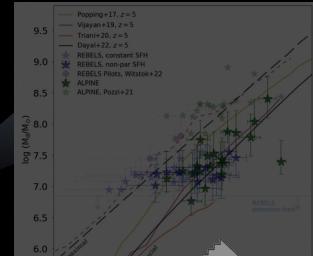
[laura.sommovigo@sns.it](mailto:laura.sommovigo@sns.it)

# Summary



Which are the mechanisms responsible for the dust/metal enrichment in the early universe?

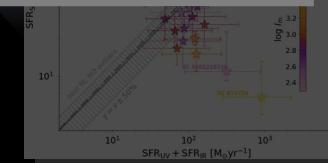
No conclusive answer, but dust masses compatible with dust production from



## NEEDED:

- **ALMA band 9-10 observations to constrain obscured SFR in high-z galaxies;**
- **High-resolution observations for ISM morphology (JWST & ALMA);**
- **Attenuation curve studies with JWST and multiple ALMA bands observations to improve upon local dust templates.**

emitting regions. There, the total SFR can be underestimated up to 2 dex when relying only on UV/optical data.



Do dust properties evolve with redshift?

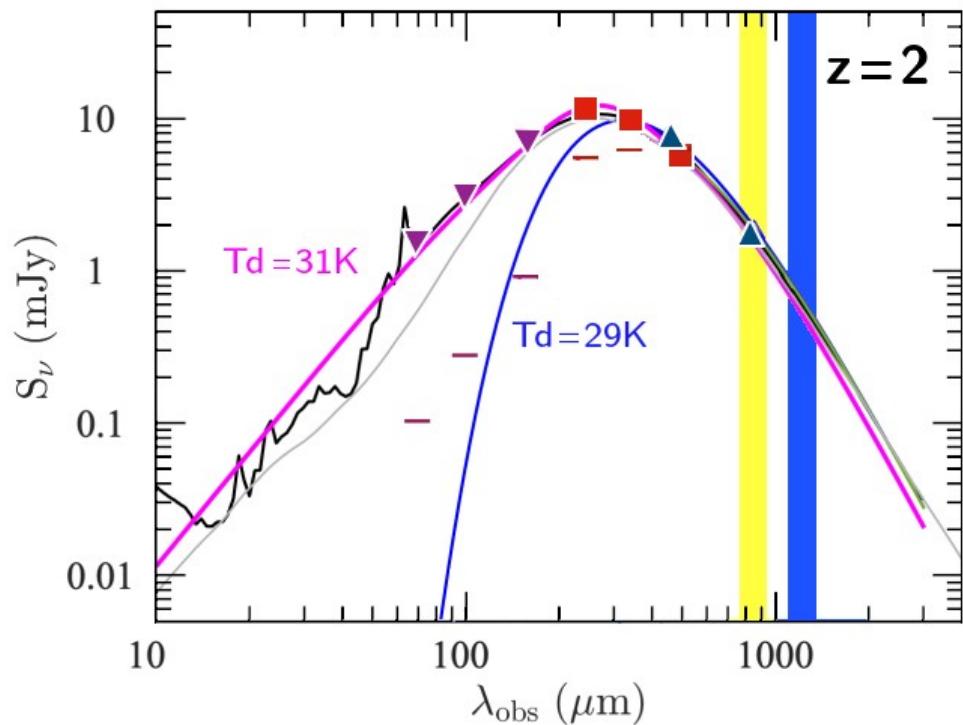
$T_d$  raises with redshift due to decreasing gas depletion time at high-z. Dust morphology is increasingly irregular at high-z. At  $z>10$ , dust ejection is needed to motivate low dust attenuation in massive galaxies ( $\log(M_*/M_\odot)>8$ ).

Contact:

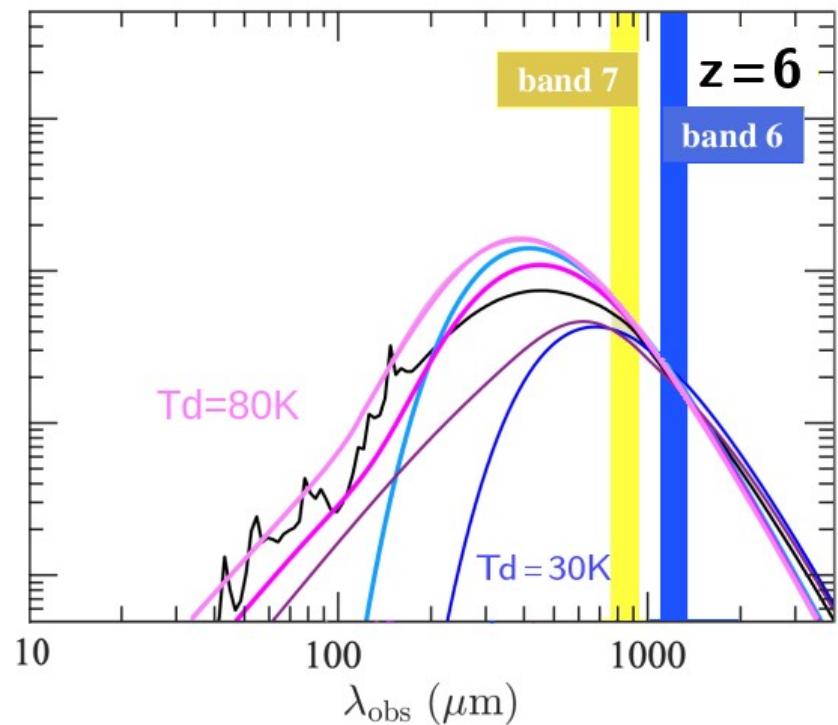
[laura.sommovigo@sns.it](mailto:laura.sommovigo@sns.it)

# Some of the many Observational challenges at $z \geq 5$

**Low-z**

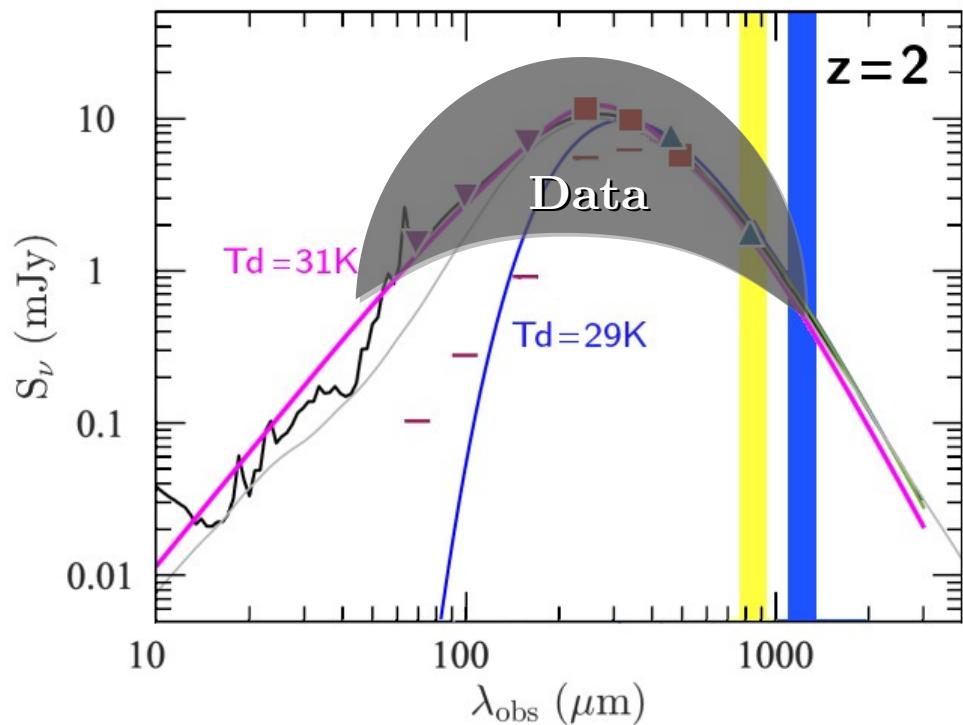


**High-z**

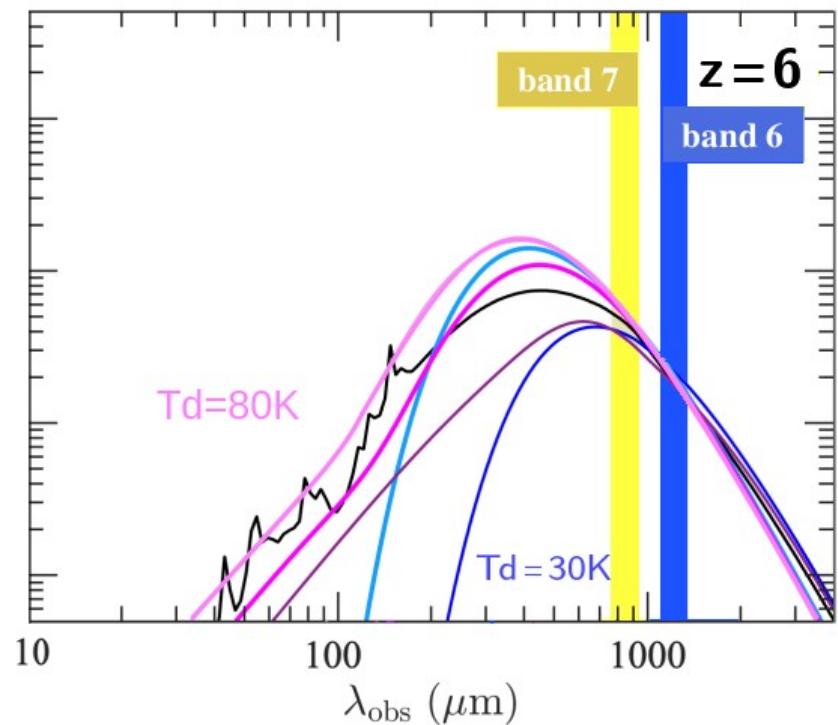


# Some of the many Observational challenges at $z \geq 5$

**Low-z**

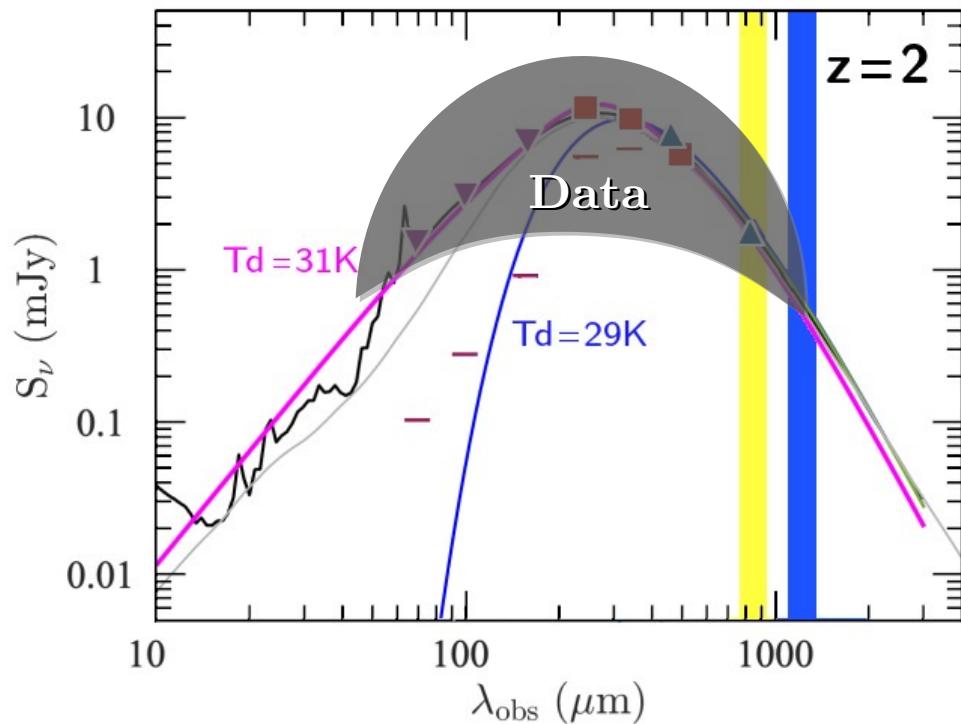


**High-z**

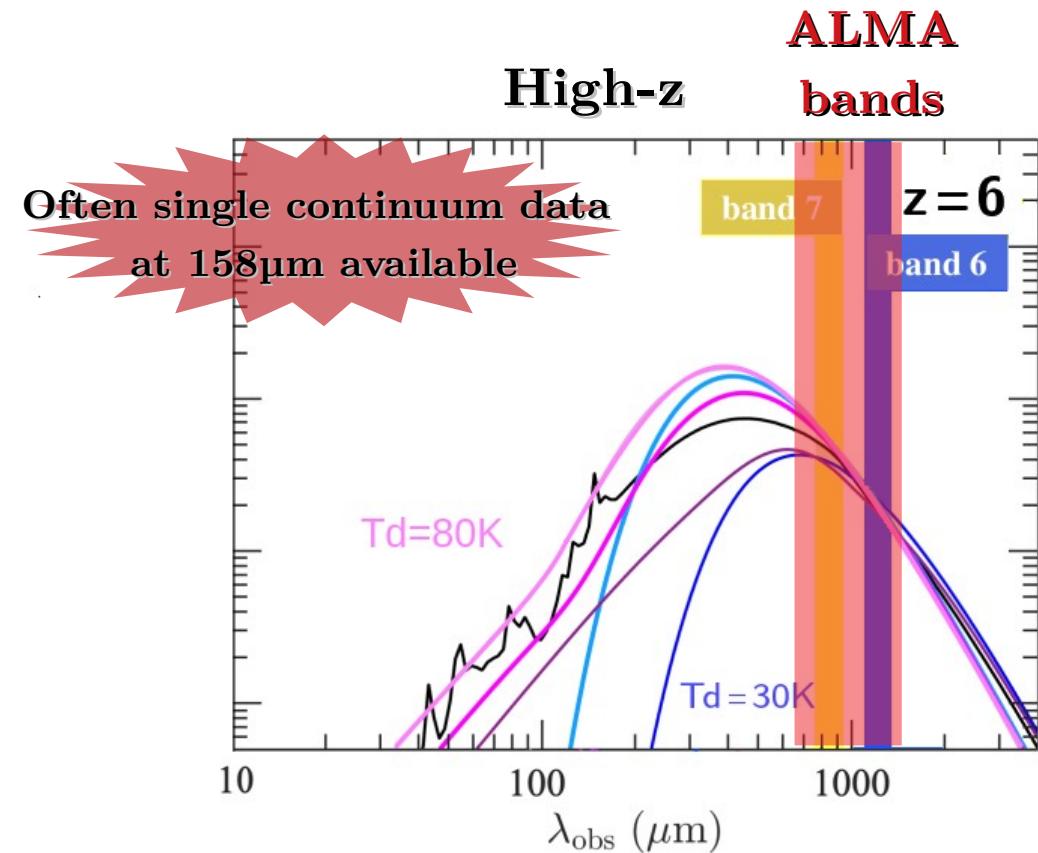


# Some of the many Observational challenges at $z \geq 5$

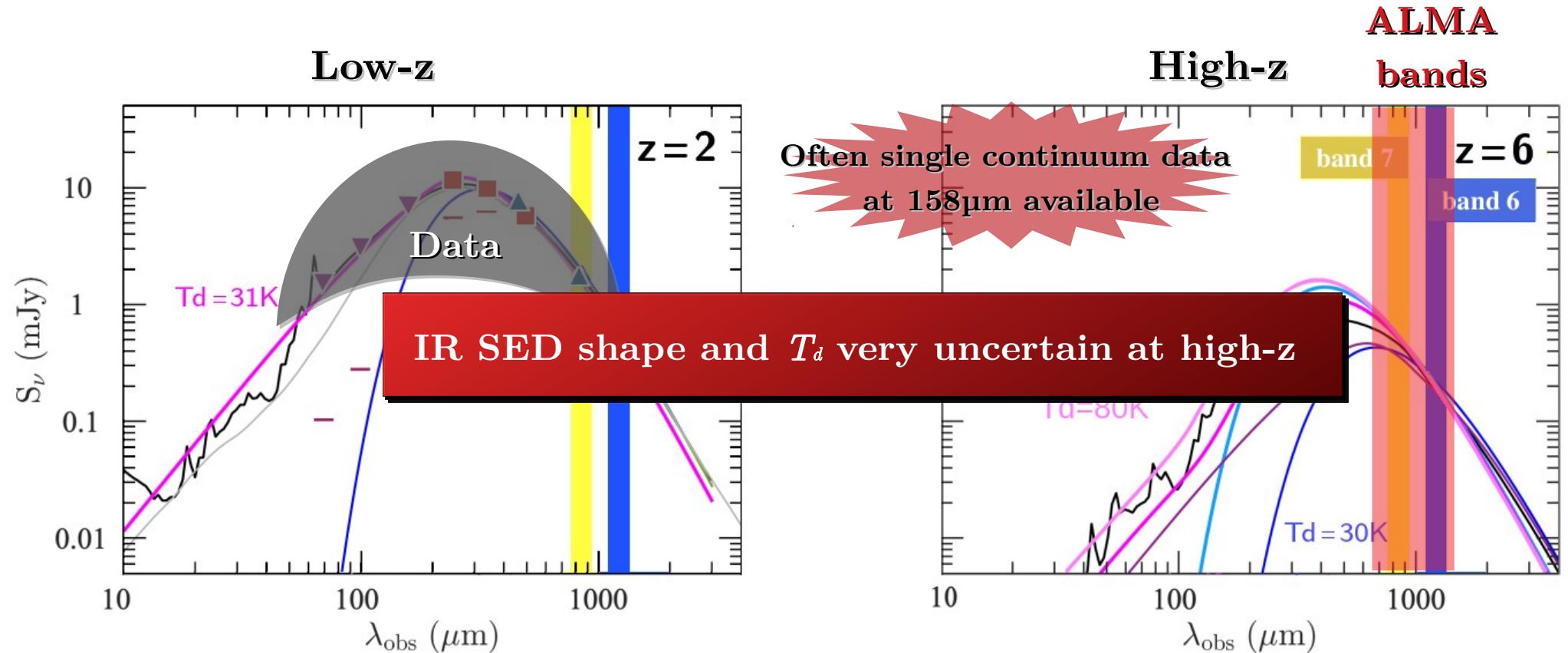
Low-z



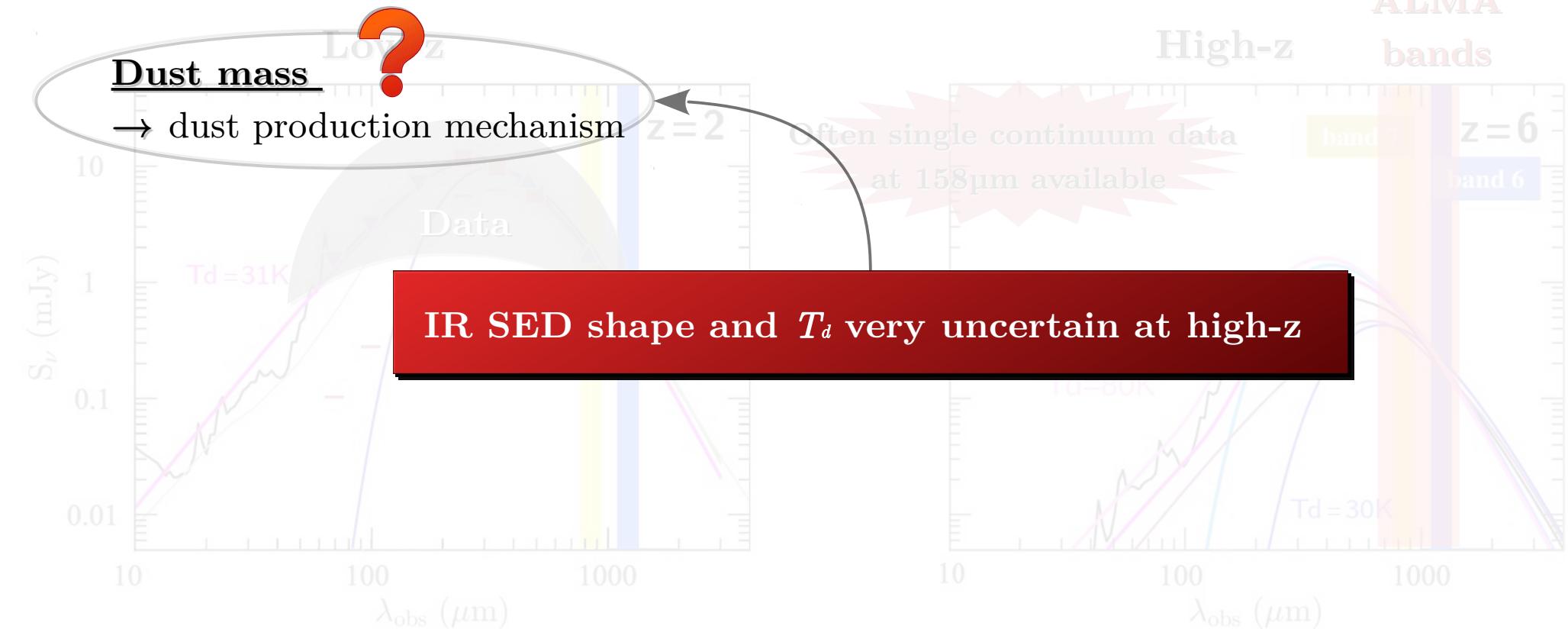
High-z



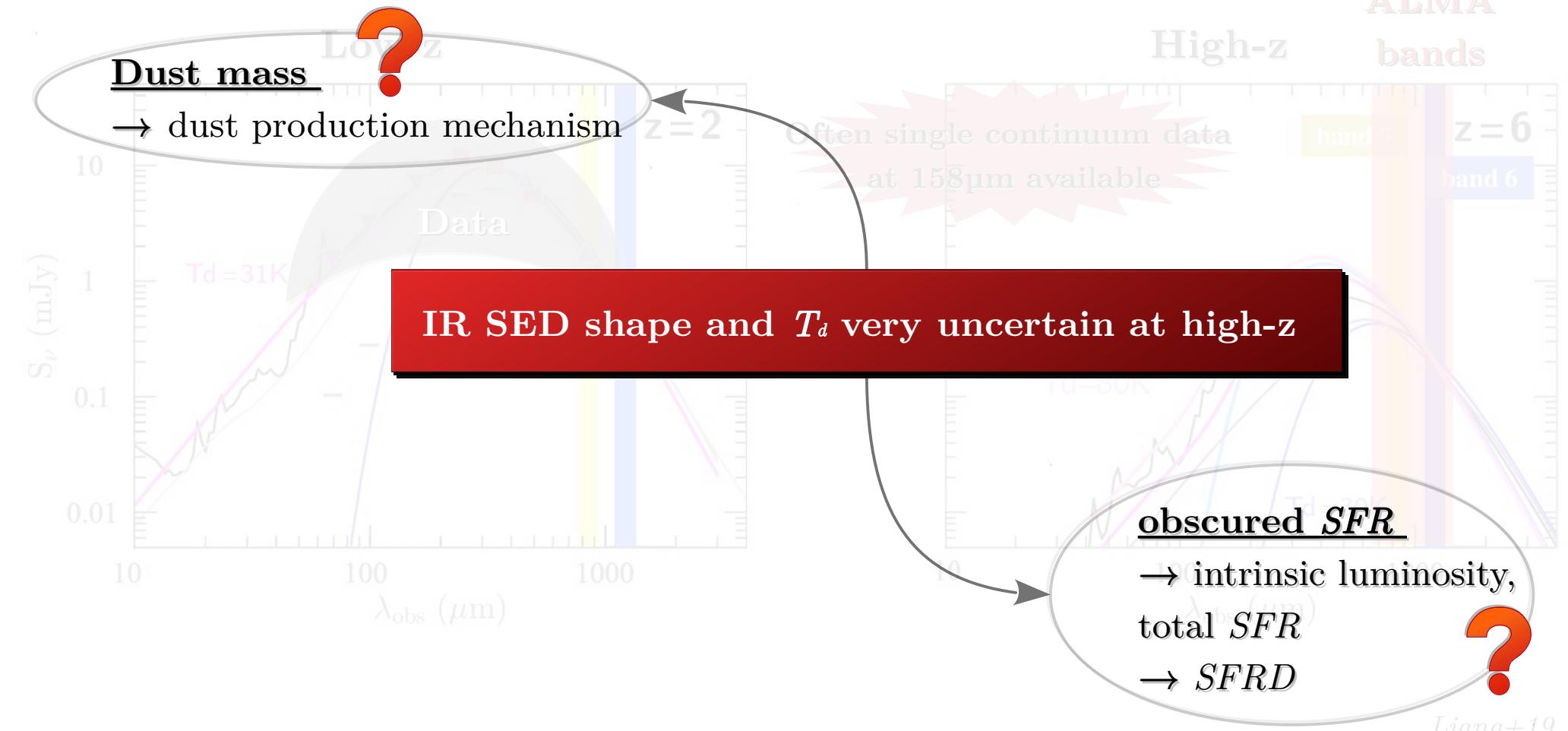
# Some of the many Observational challenges at $z \geq 5$



# Some of the many Observational challenges at $z \geq 5$

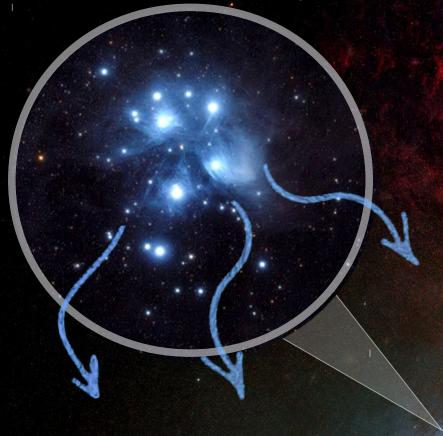


# Some of the many Observational challenges at $z \geq 5$



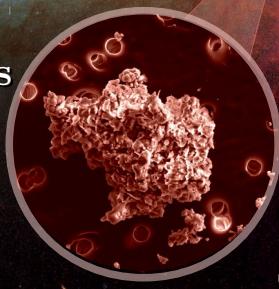
# Why should you care about dust?

Young stars

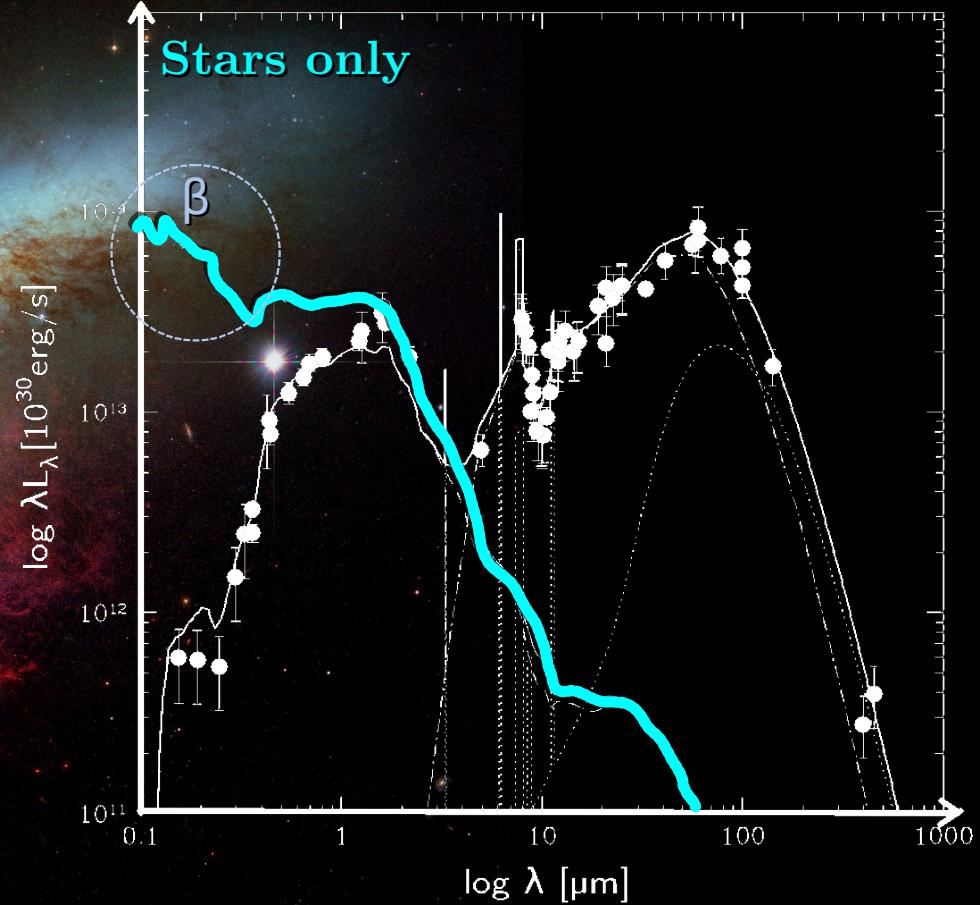


UV and optical  
radiation

Dust grains



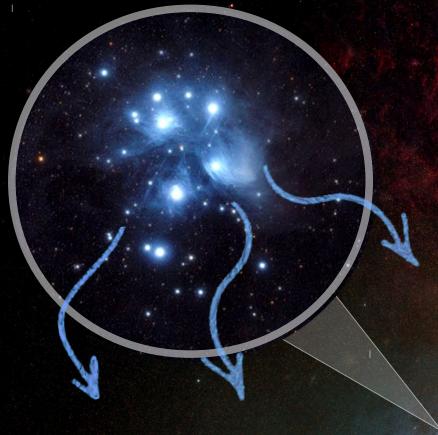
M82: local galaxy



Silva+98

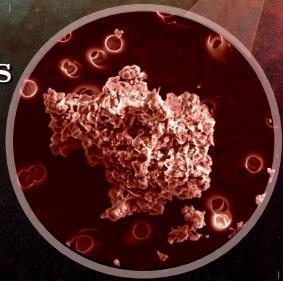
# Why should you care about dust?

Young stars

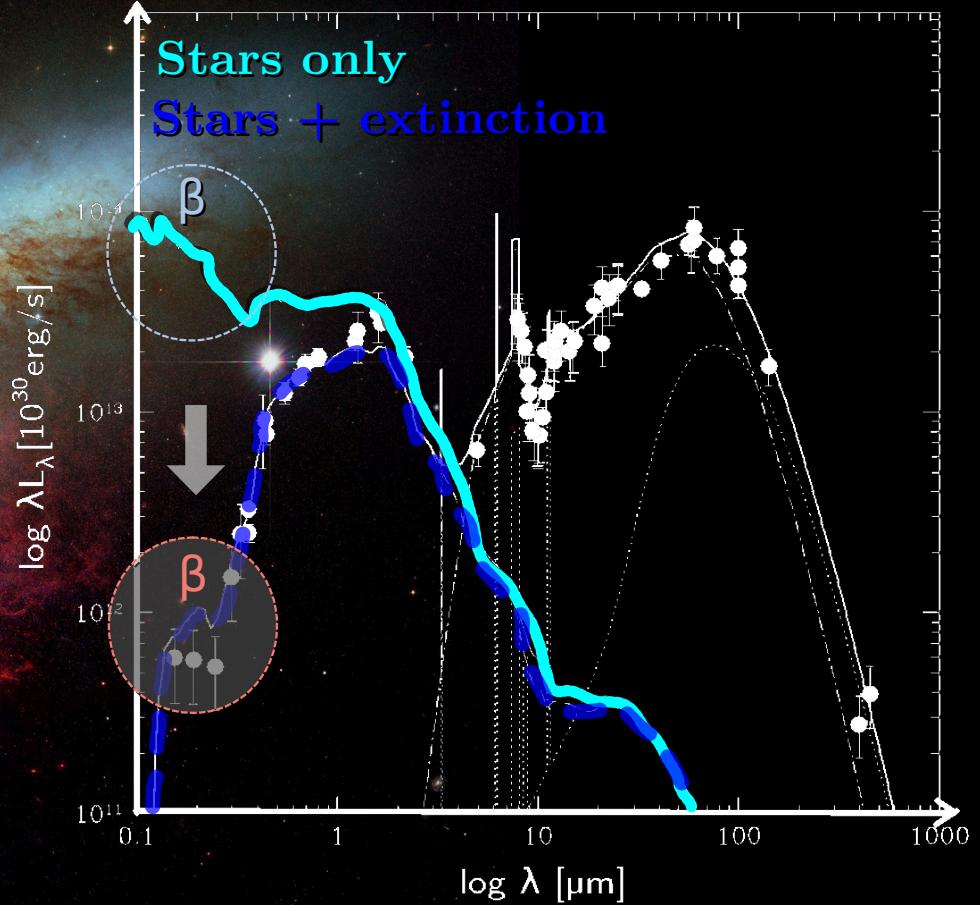


UV and optical  
radiation

Dust grains



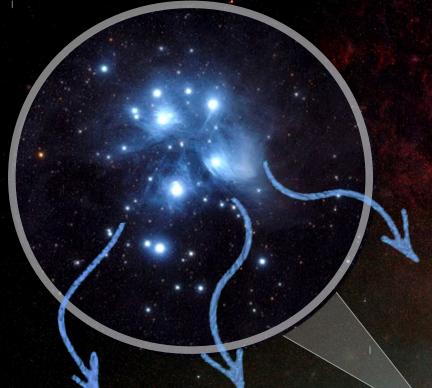
M82: local galaxy



Silva+98

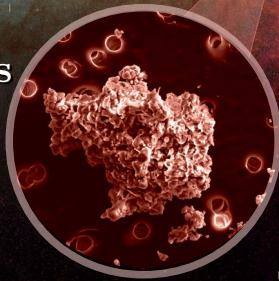
# Why should you care about dust?

Young stars

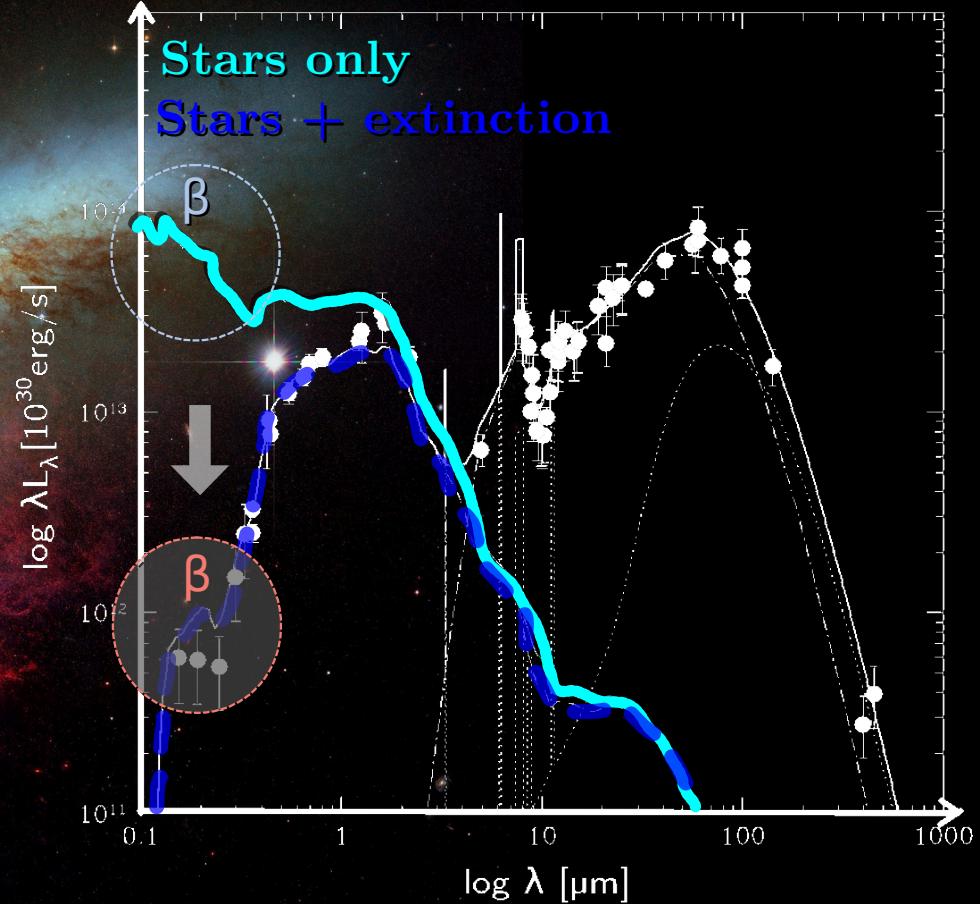


UV and optical  
radiation

Dust grains

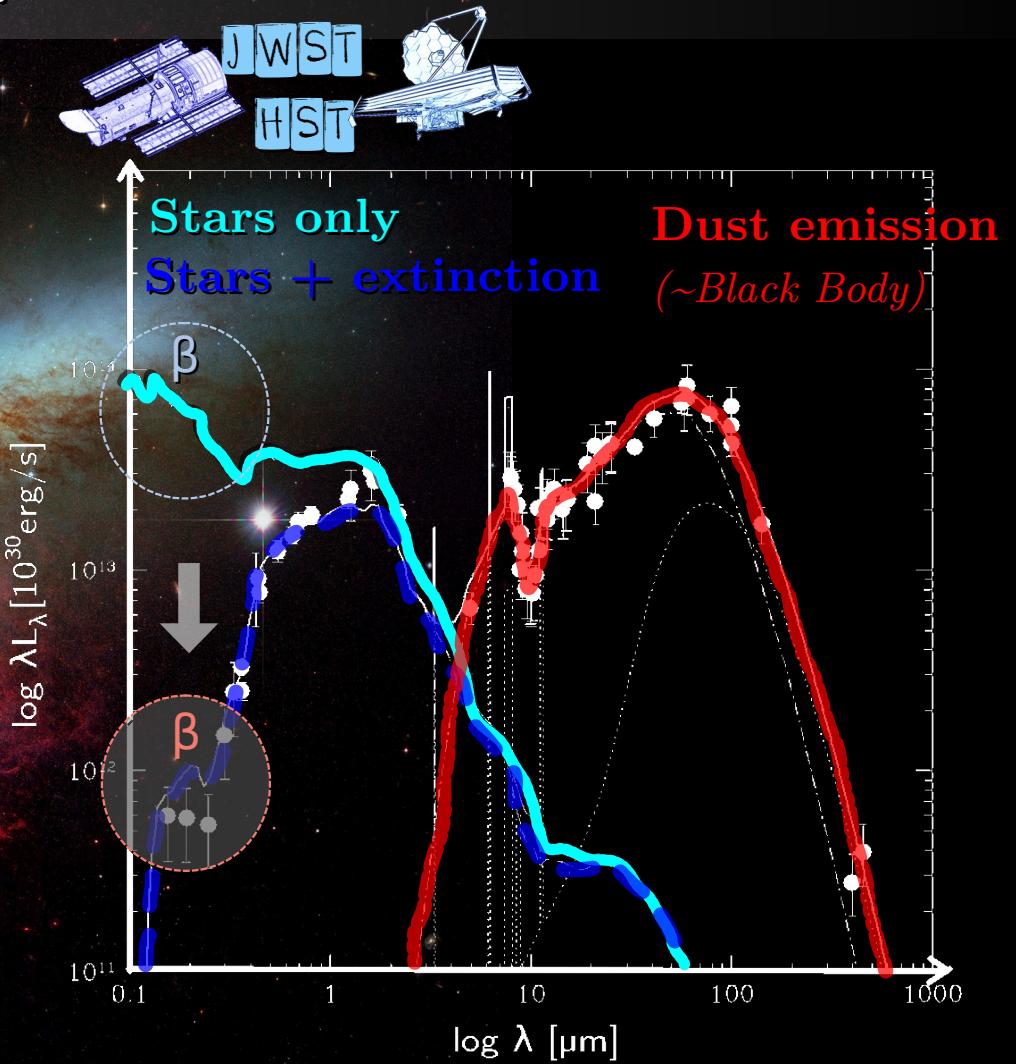
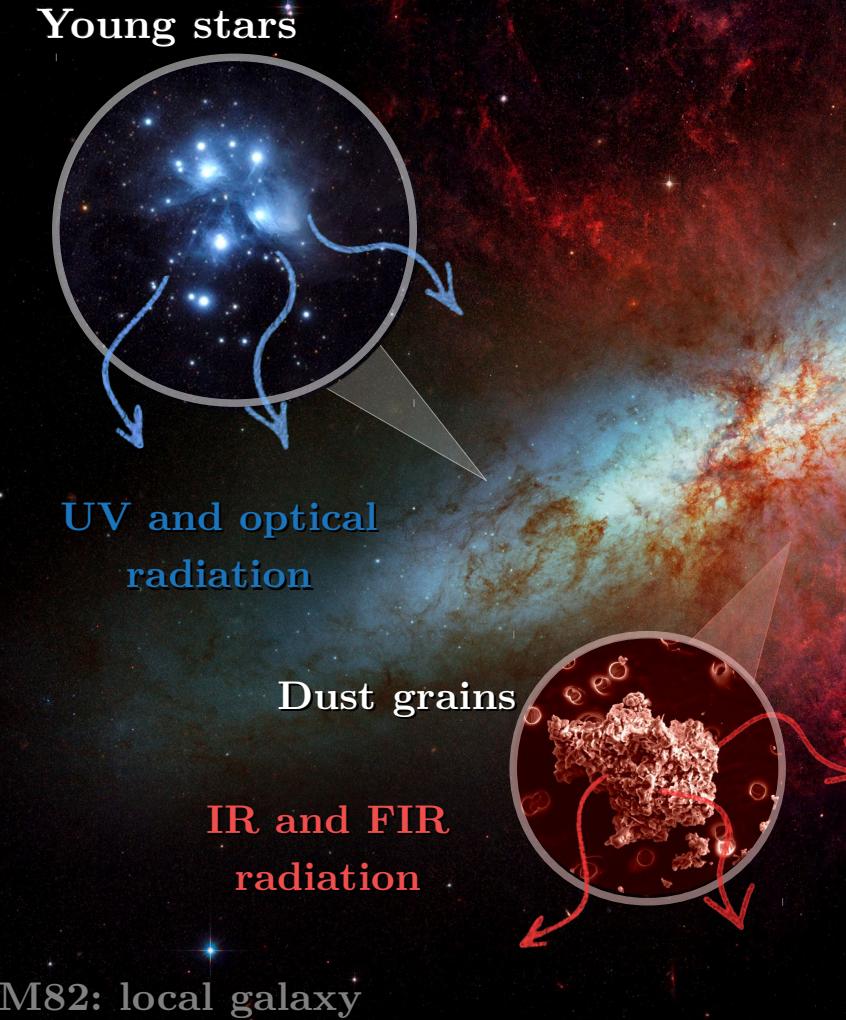


M82: local galaxy

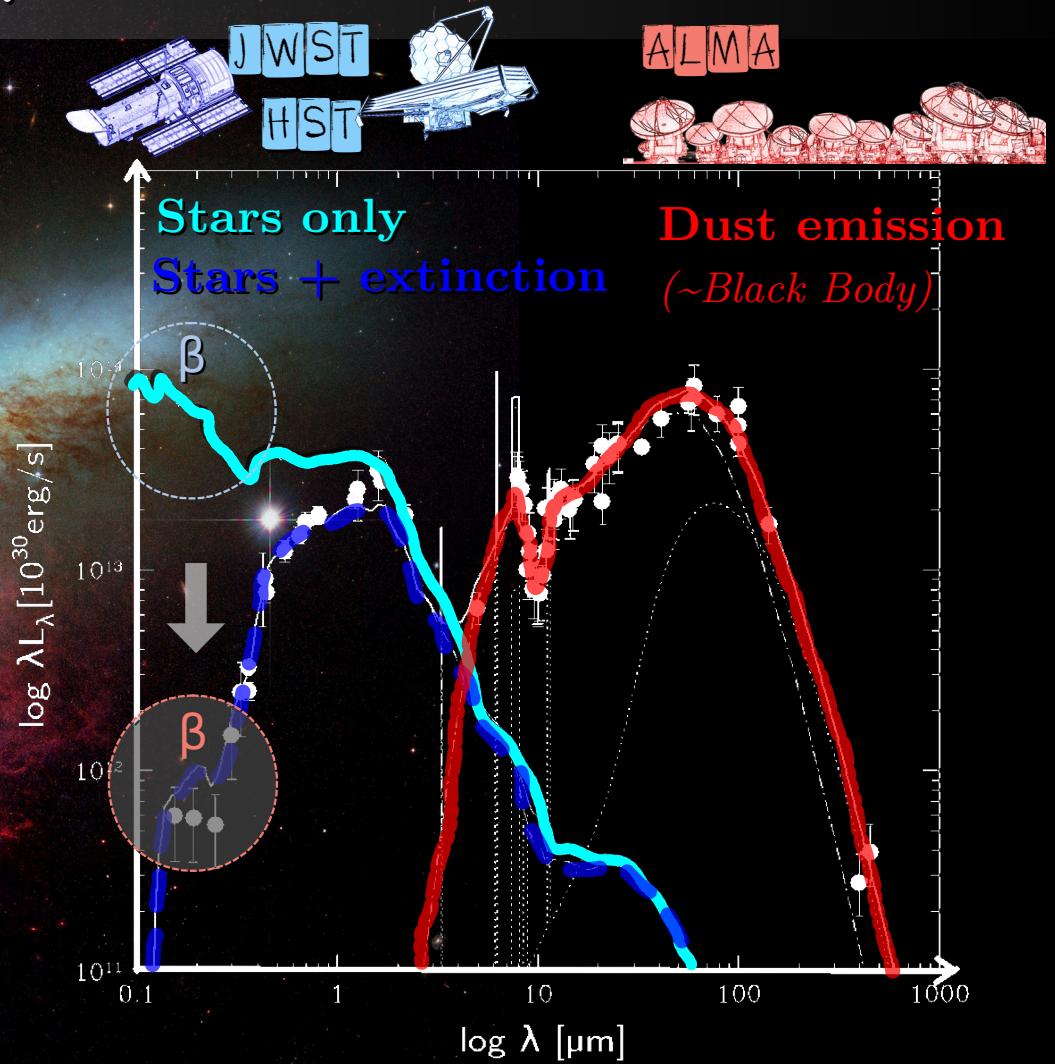
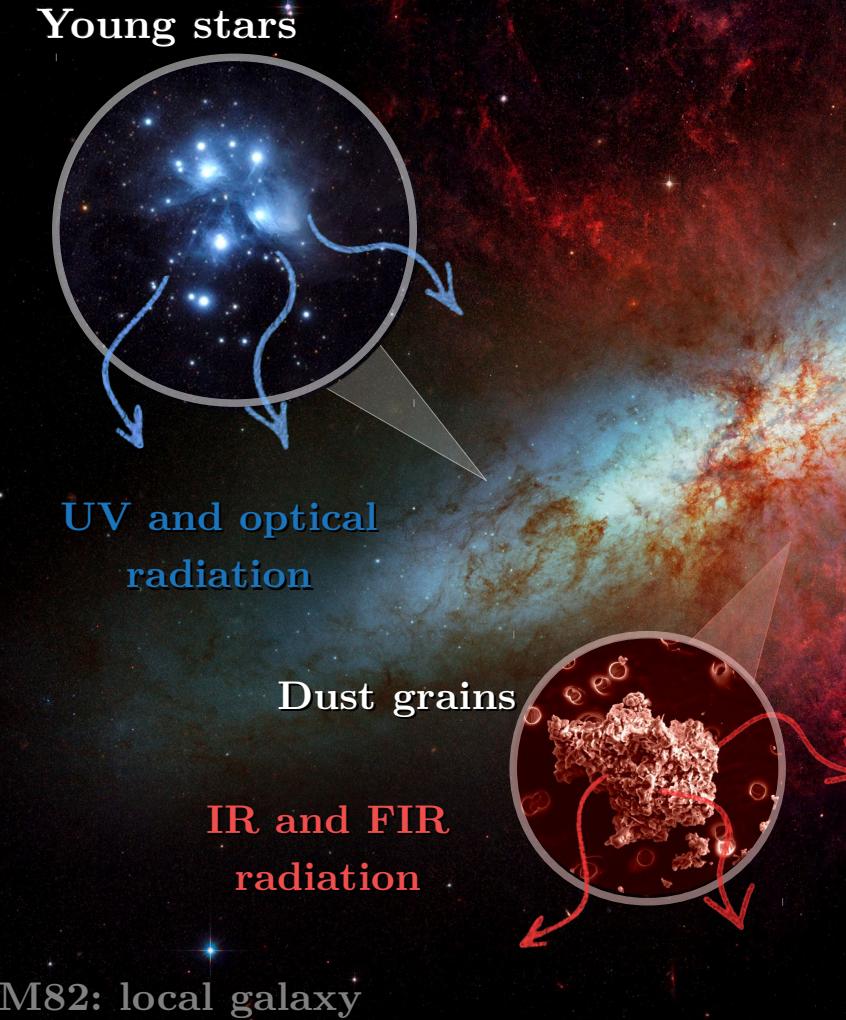


Silva+98

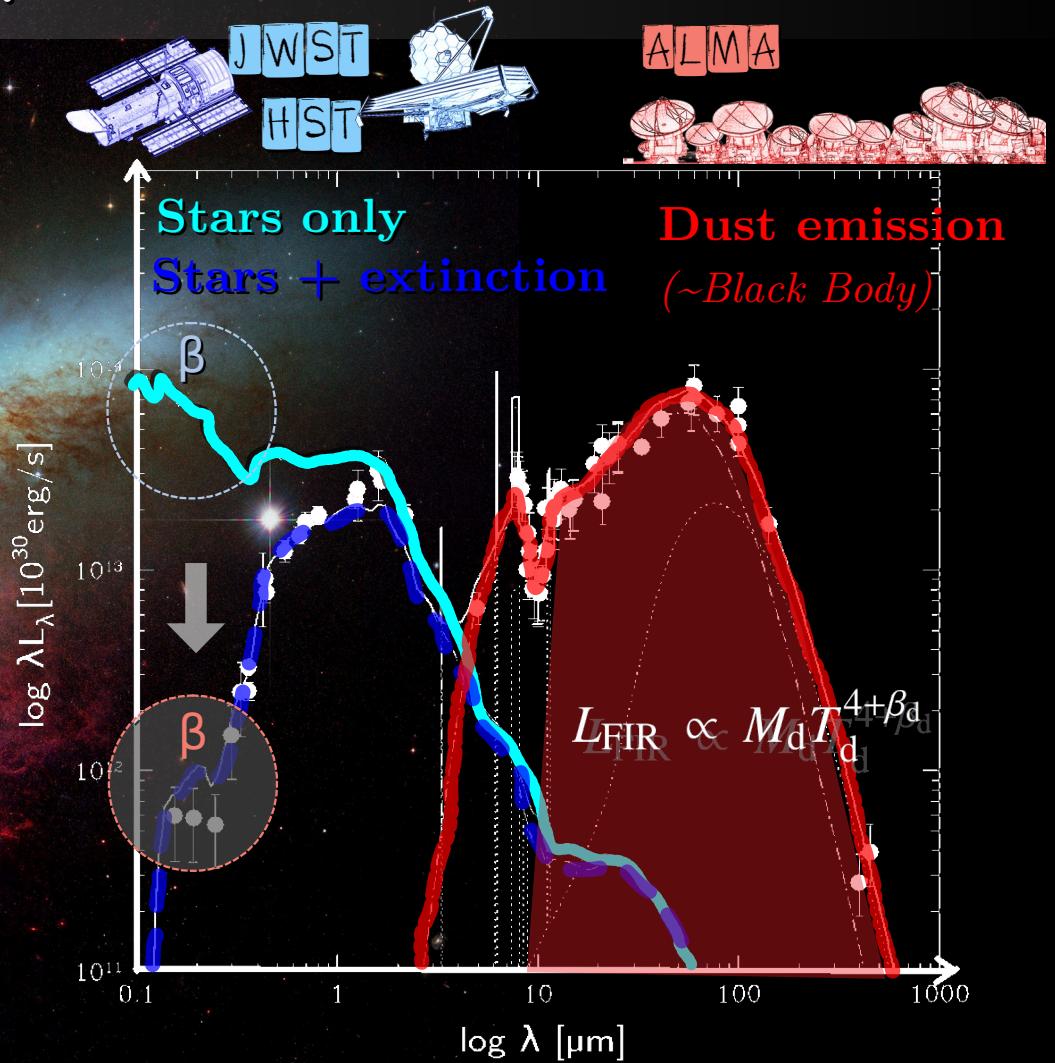
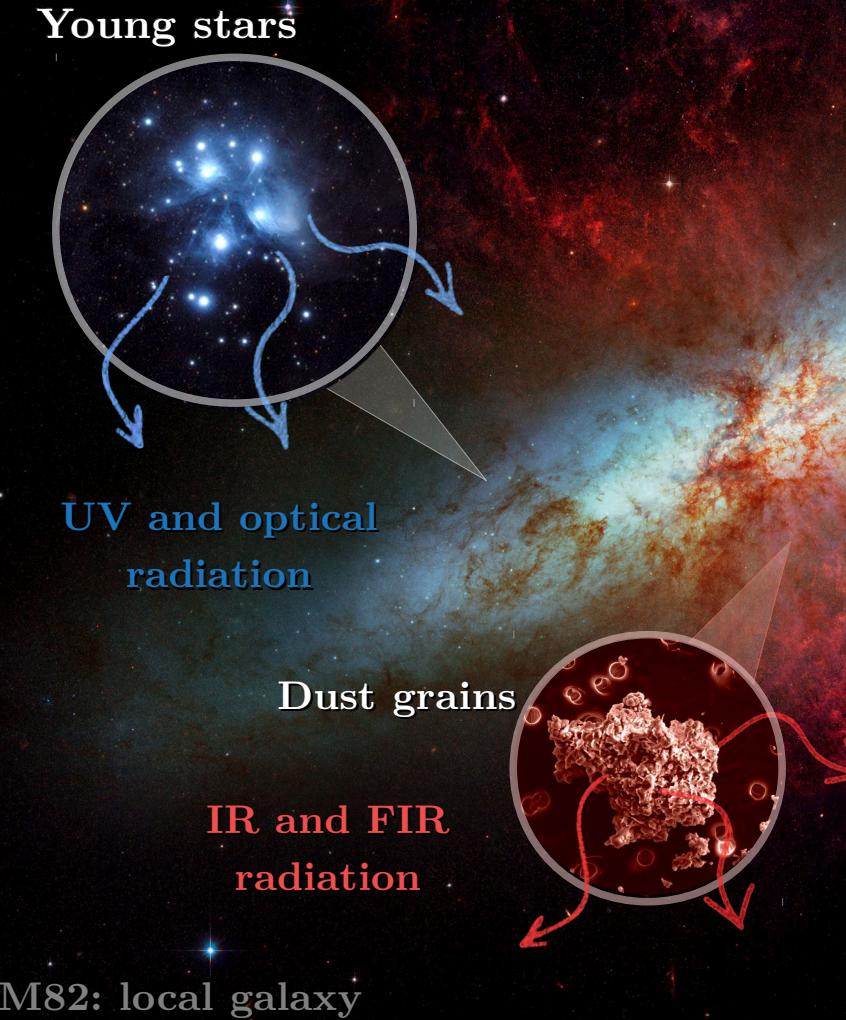
# Why should you care about dust?



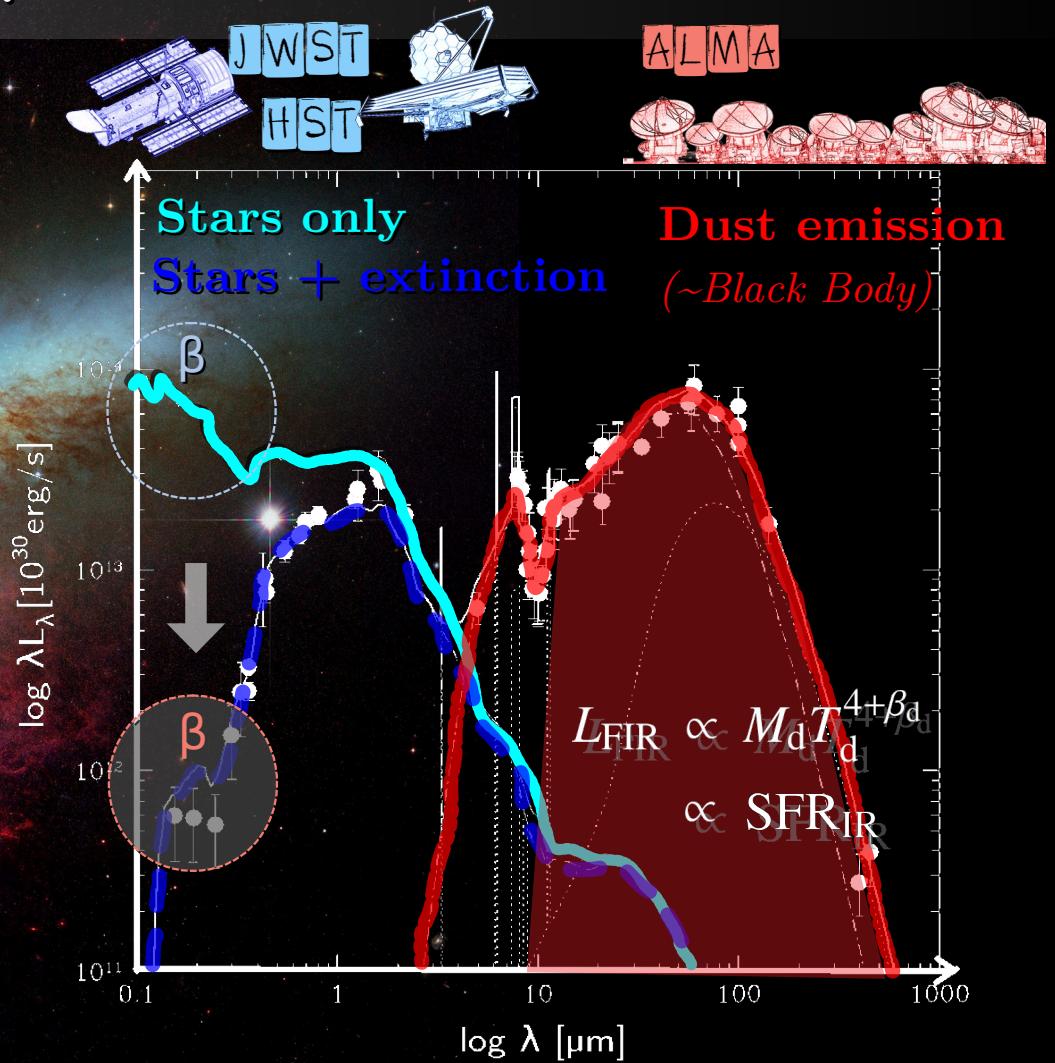
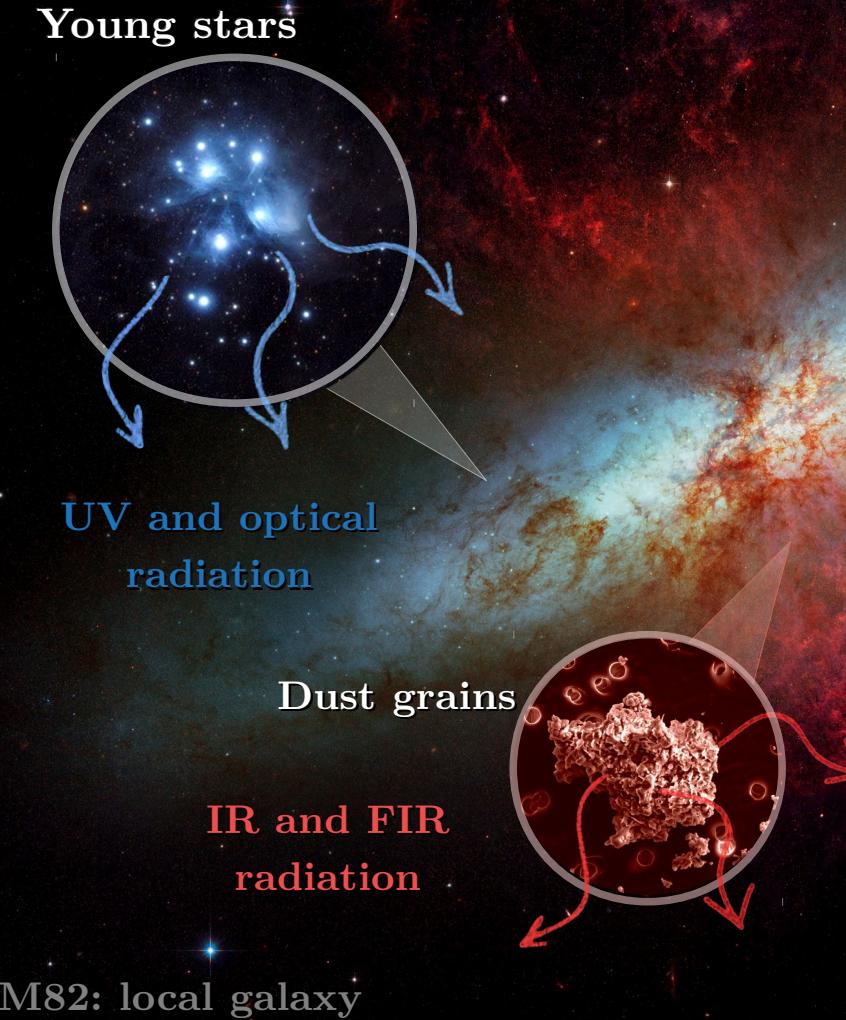
# Why should you care about dust?



# Why should you care about dust?



# Why should you care about dust?



## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d$$

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

DeLooze relation + Kennicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}}$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

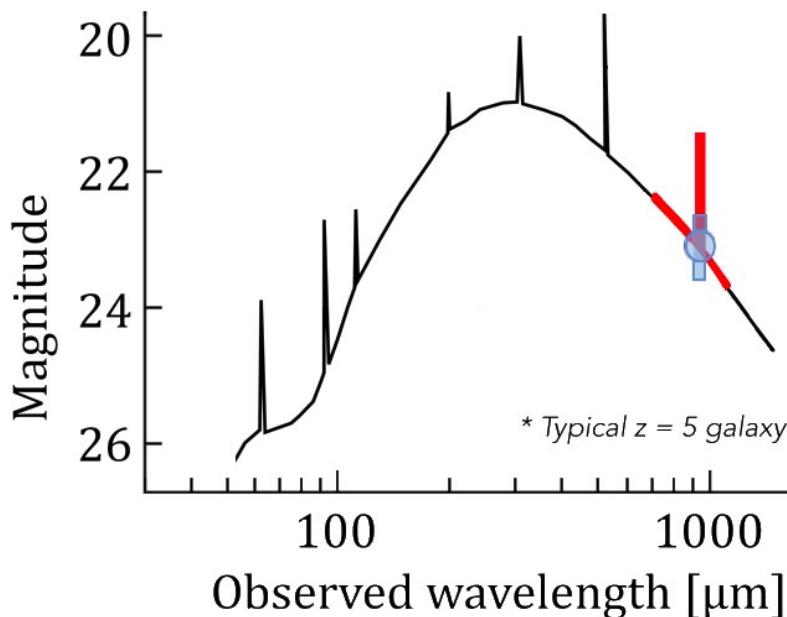
## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

DeLooze relation + Kennicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}}$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}}/\Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor



**Inputs:**

[CII]

Continuum  $\rightarrow$

**Outputs:**

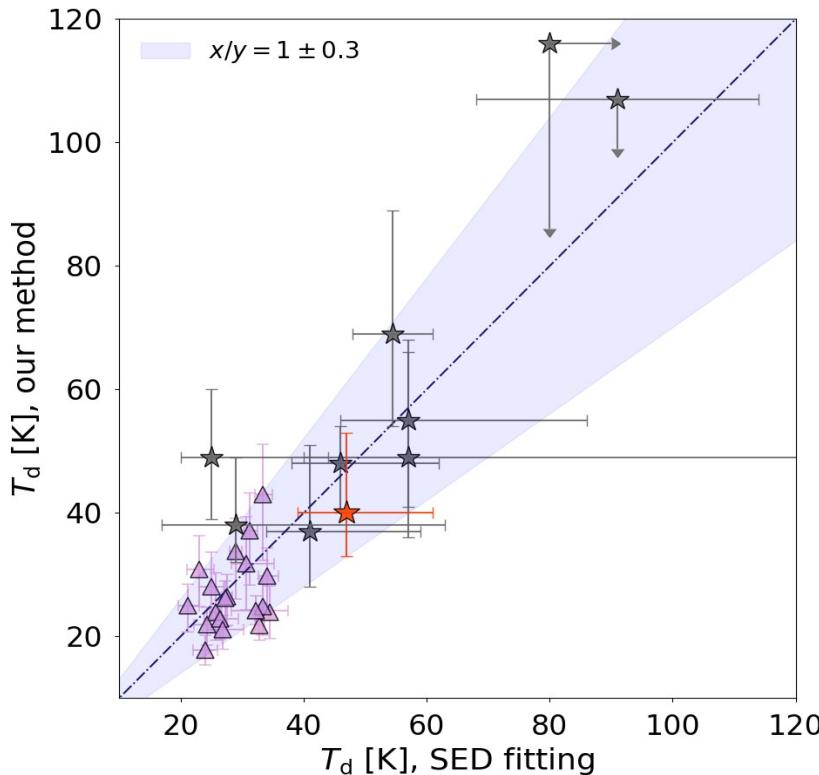
$M_d$

$T_d$

# New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

DeLoze relation + Kennicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}}$



$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

**Inputs:**

[CII]

Continuum  $\rightarrow$

**Outputs:**

$M_d$

$T_d$

Method tested on several local and high-z galaxies:  
We recover  $T_d$  from “traditional” SED fitting within  $1\sigma$

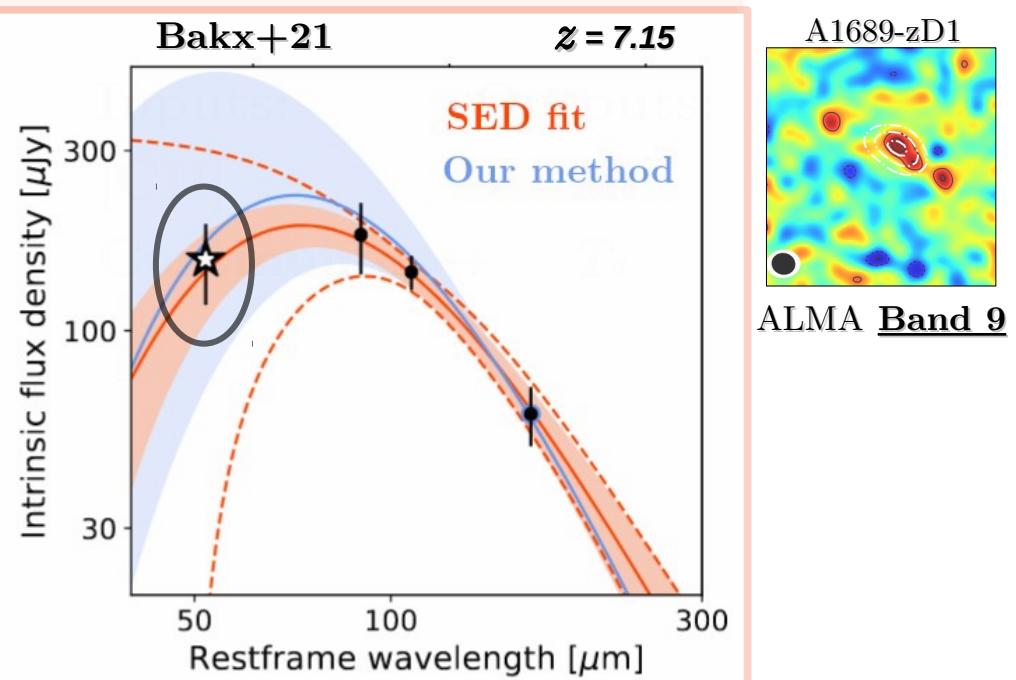
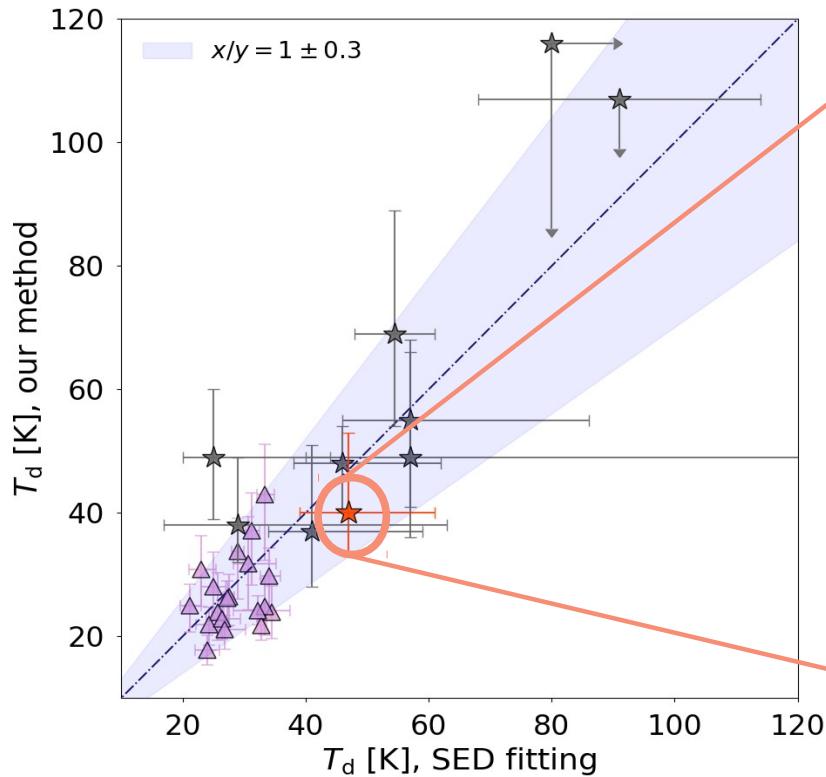
# New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}}/\Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

DeLooze relation + Kennicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}}$



See: Watson+15, Knudsen +17

Sommovigo+21

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d$$

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d$$

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

## New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

[CII]-SFR relation + Kenicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}} \propto \Sigma_{\text{SFR}}^{-0.29} \kappa_s^{-5/7}$

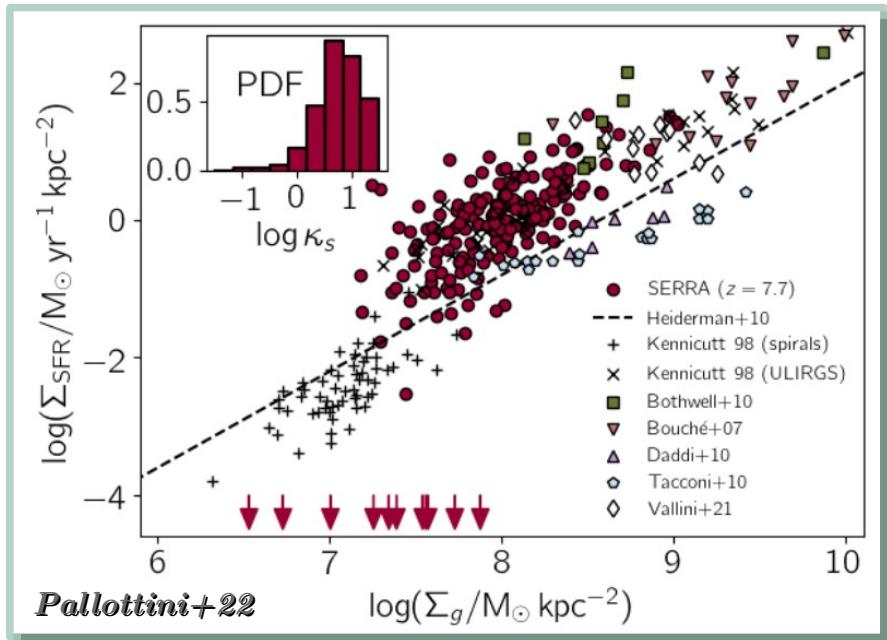
# New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

[CII]-SFR relation + Kenicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}} \propto \Sigma_{\text{SFR}}^{-0.29} \kappa_s^{-5/7}$



## Burstiness parameter, $\kappa_s$

See also: Heiderman+10,  
Ferrara+19, Vallini+21,22

# New method to derive $T_d$ using [CII] information

$$F_\nu = \frac{1+z}{d_L^2} k_\nu [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] M_d = D \alpha_{\text{CII}} L_{\text{CII}}$$

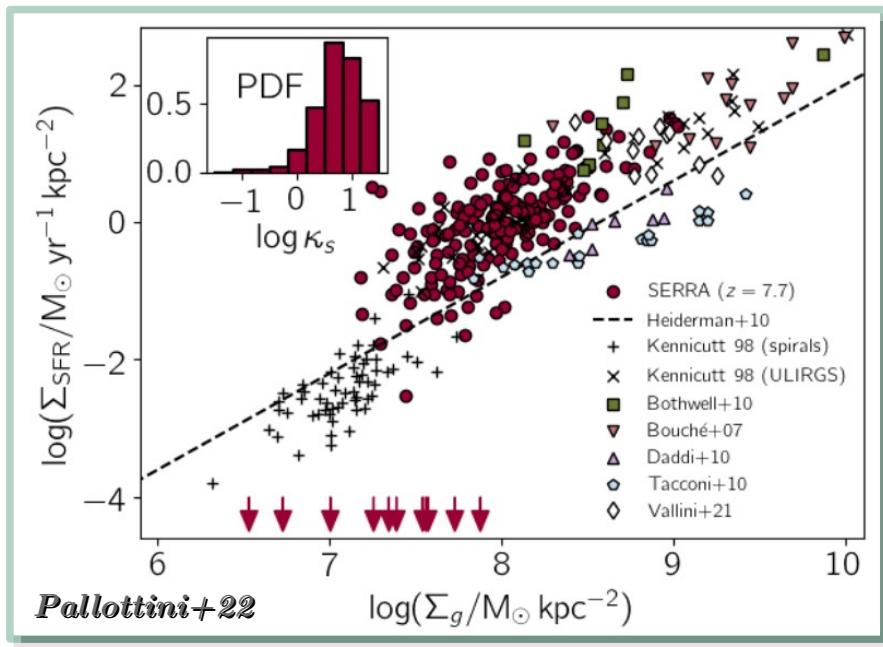
$D \propto Z \rightarrow$  Dust to gas ratio

$\alpha_{\text{CII}} = \Sigma_{\text{gas}} / \Sigma_{\text{CII}} \rightarrow$  [CII]-to-total gas conversion factor

[CII]-SFR relation + Kenicutt-Schmidt relation  $\rightarrow \alpha_{\text{CII}} \propto \Sigma_{\text{SFR}}^{-0.29}$

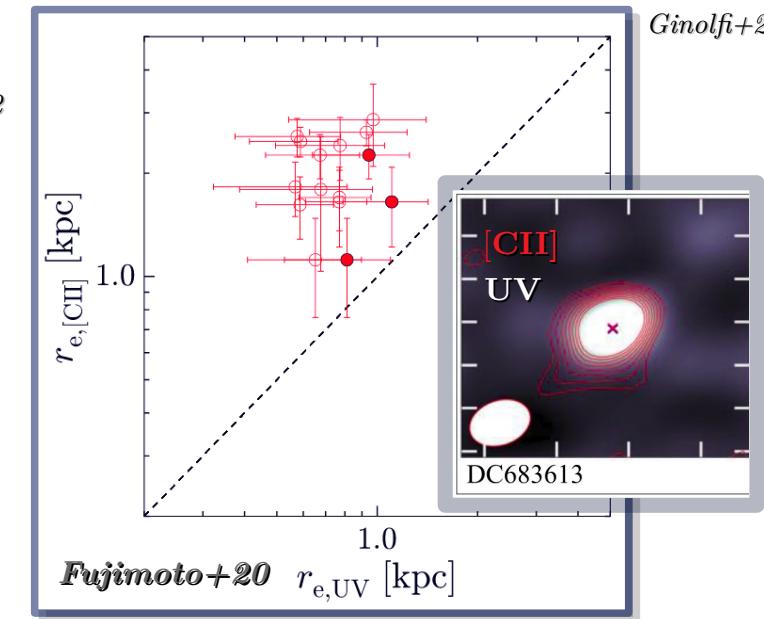
$$\kappa_s^{-5/7} y^2$$

**UV-to-[CII] extension ratio**



**Burstiness parameter,  $k_s$**

See also: Heiderman+10,  
Ferrara+19, Vallini+21,22

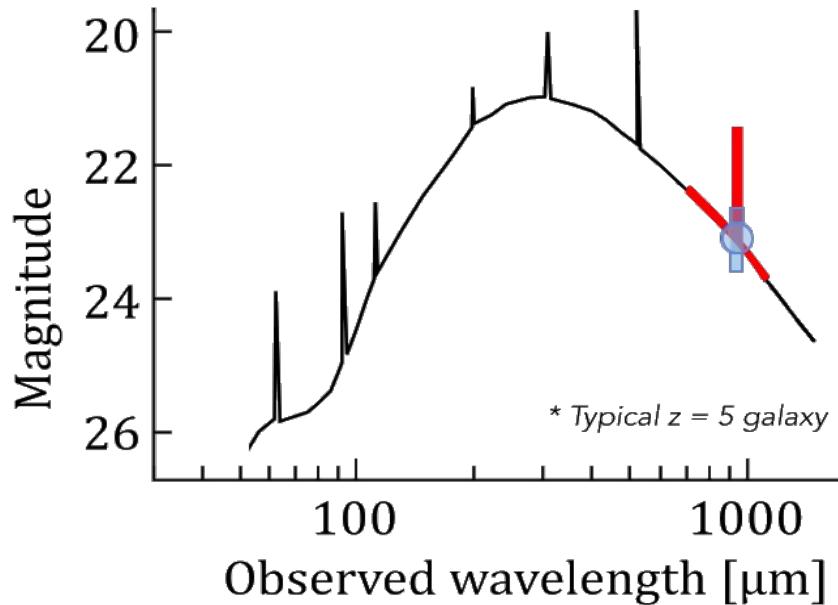


## New method to derive $T_d$ using [CII] information

Inputs:      Outputs:

[CII]               $\rightarrow M_d$

Continuum  $\rightarrow T_d$



## New method to derive $T_d$ using [CII] information

Inputs:

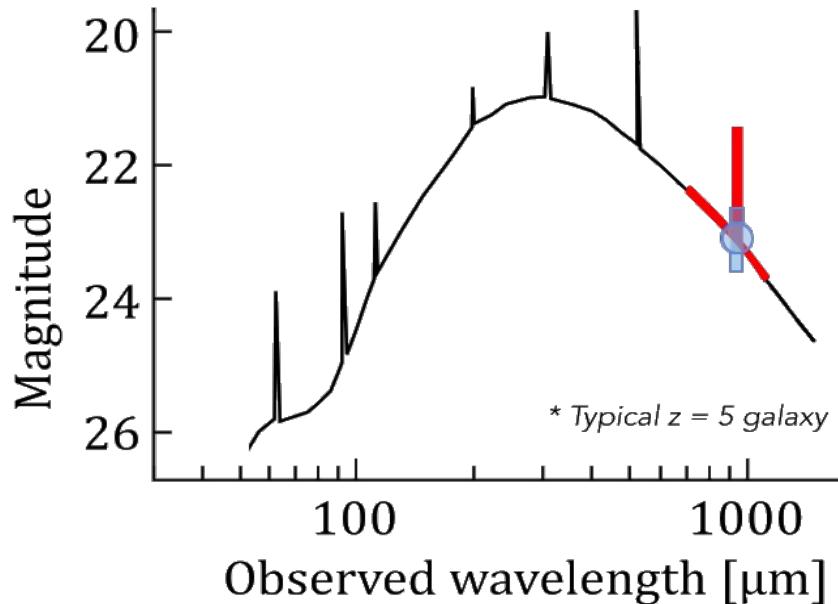
[CII]

Outputs:

→ Md

Continuum → Td

$$F_{158}(T_{d,CII}, k_s, \overbrace{Z, \Sigma_{SFR}, L_{CII}, y, z}^{data}) = F_{158,obs}$$



## New method to derive $T_d$ using [CII] information

Inputs:

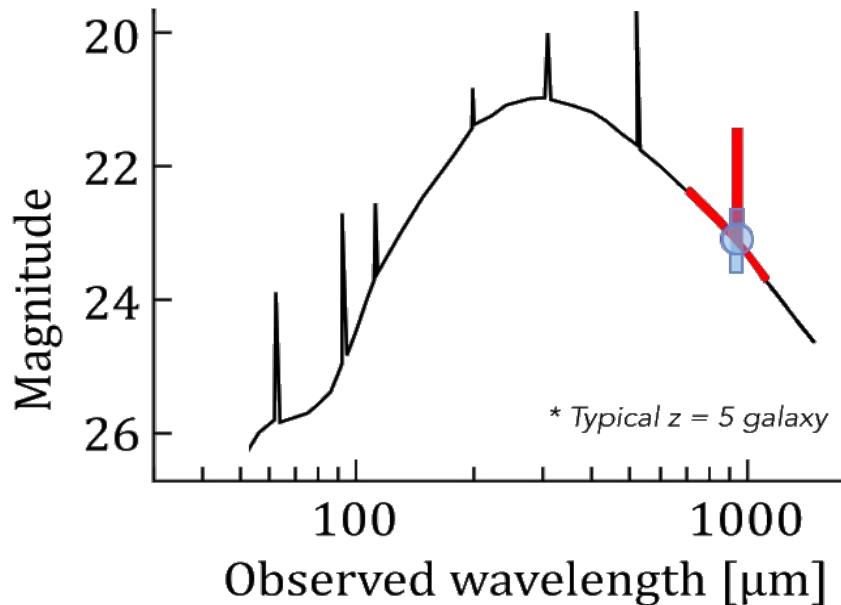
[CII]

Outputs:

$\rightarrow M_d$

Continuum  $\rightarrow T_d$

$$F_{158}(T_{d,CII}, k_s, \overbrace{Z, \Sigma_{SFR}, L_{CII}, y, z}^{\text{data}}) = F_{158,\text{obs}}$$



# New method to derive $T_d$ using [CII] information

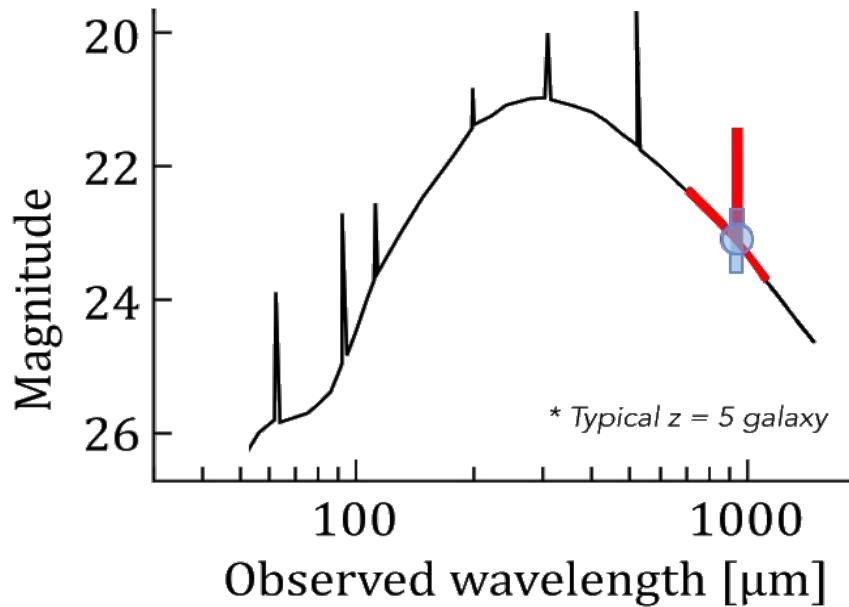
Inputs:

[CII]

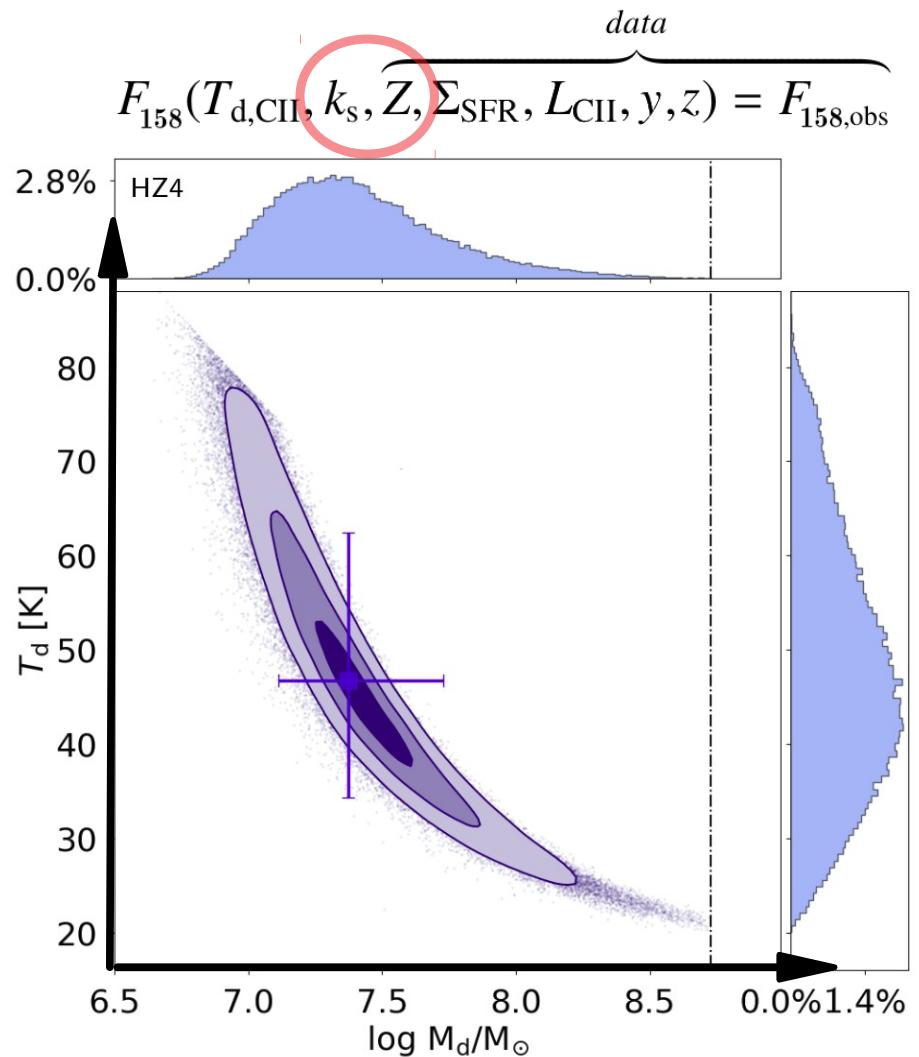
Continuum →  $M_d$

Outputs:

→  $M_d$



Sommovigo+21

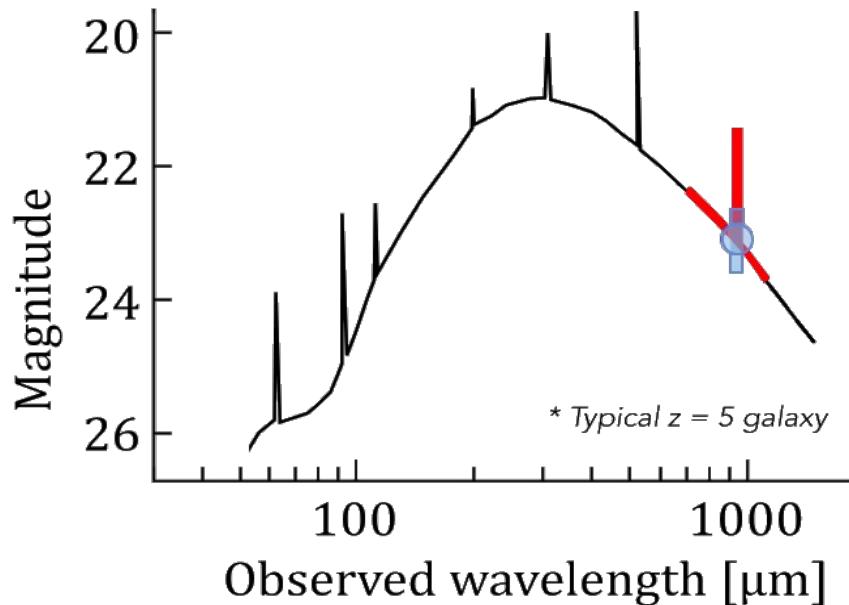


# New method to derive $T_d$ using [CII] information

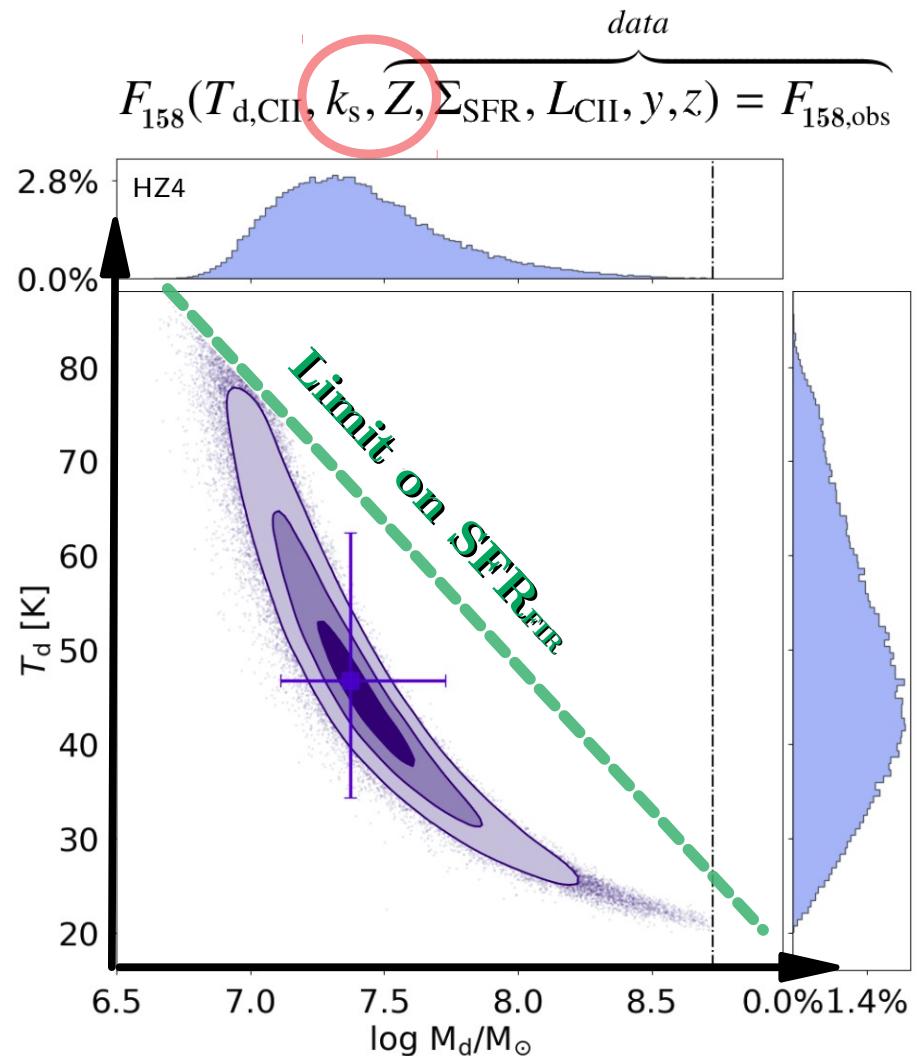
Inputs:      Outputs:

[CII]                   $\rightarrow M_d$

Continuum  $\rightarrow T_d$



Sommovigo+21

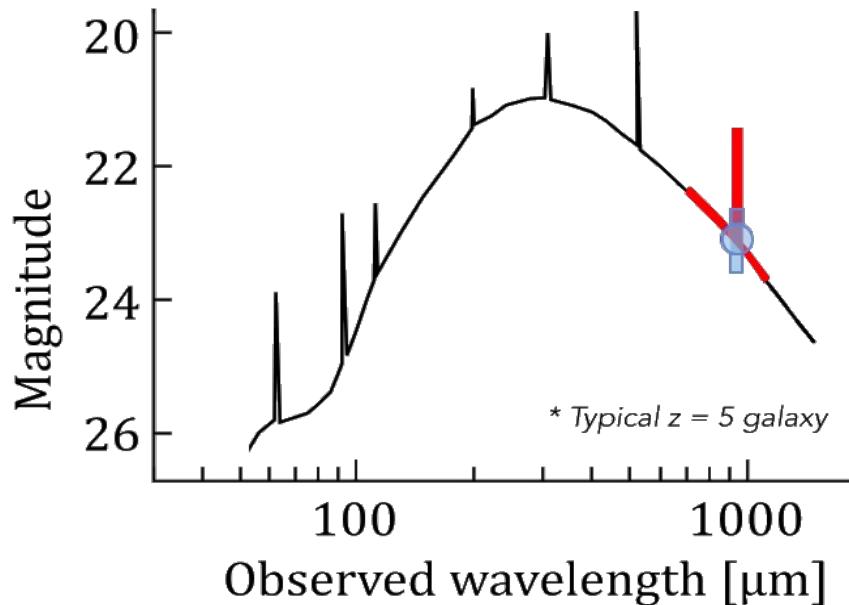


# New method to derive $T_d$ using [CII] information

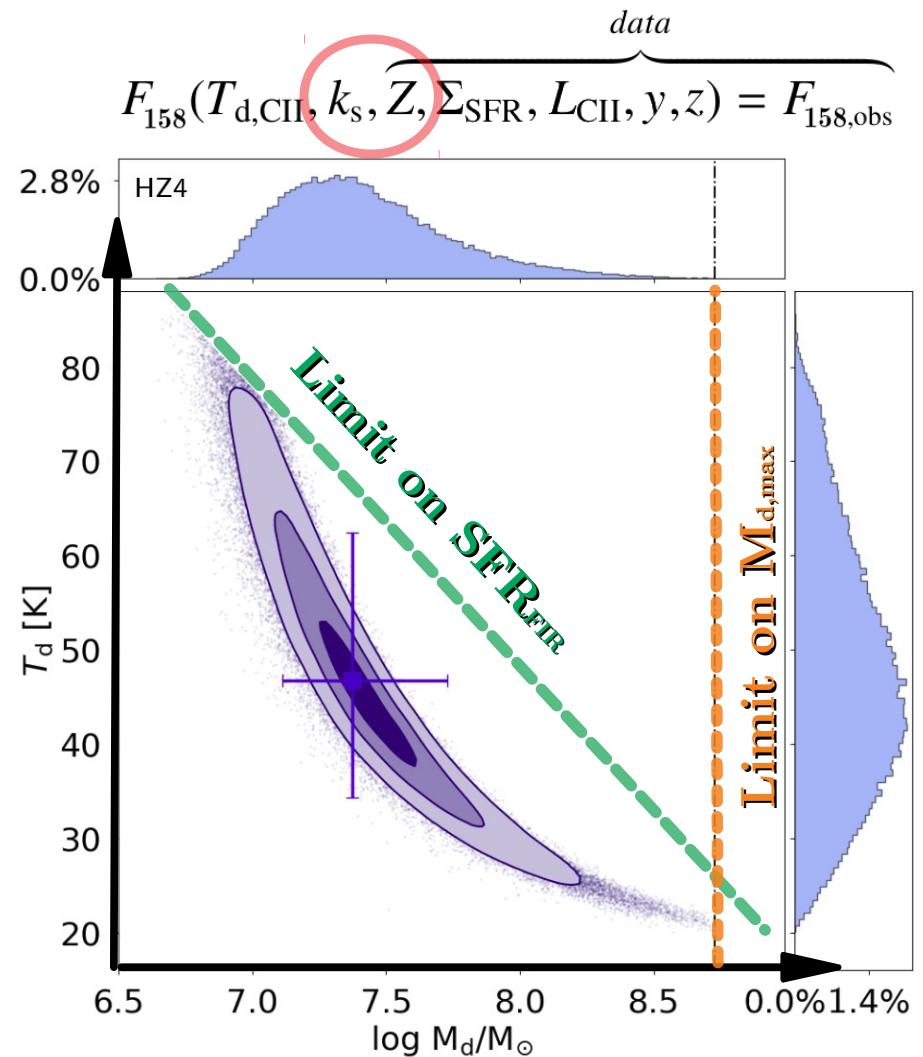
Inputs:      Outputs:

[CII]                   $\rightarrow M_d$

Continuum  $\rightarrow T_d$



Sommovigo+21



# New method to derive $T_d$ using [CII] information

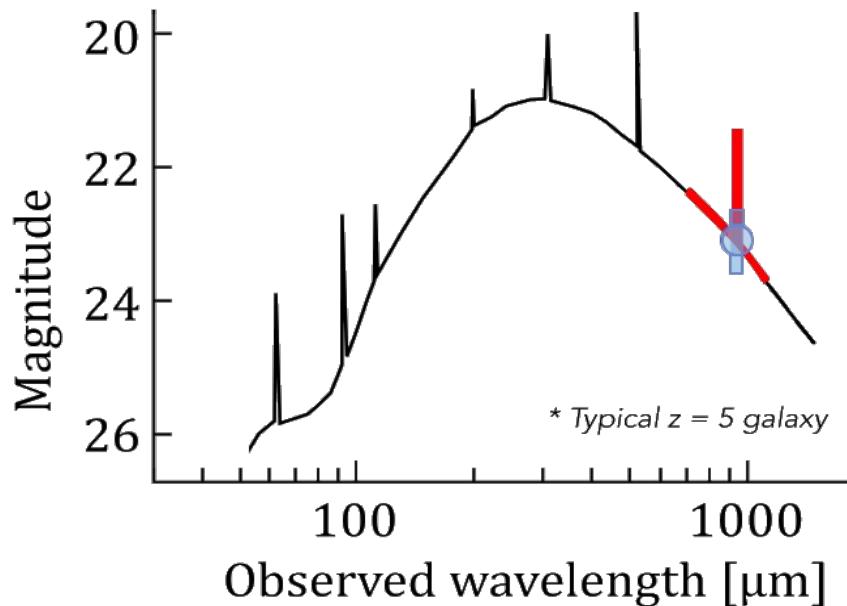
Inputs:

[CII]

Continuum →  $M_d$

Outputs:

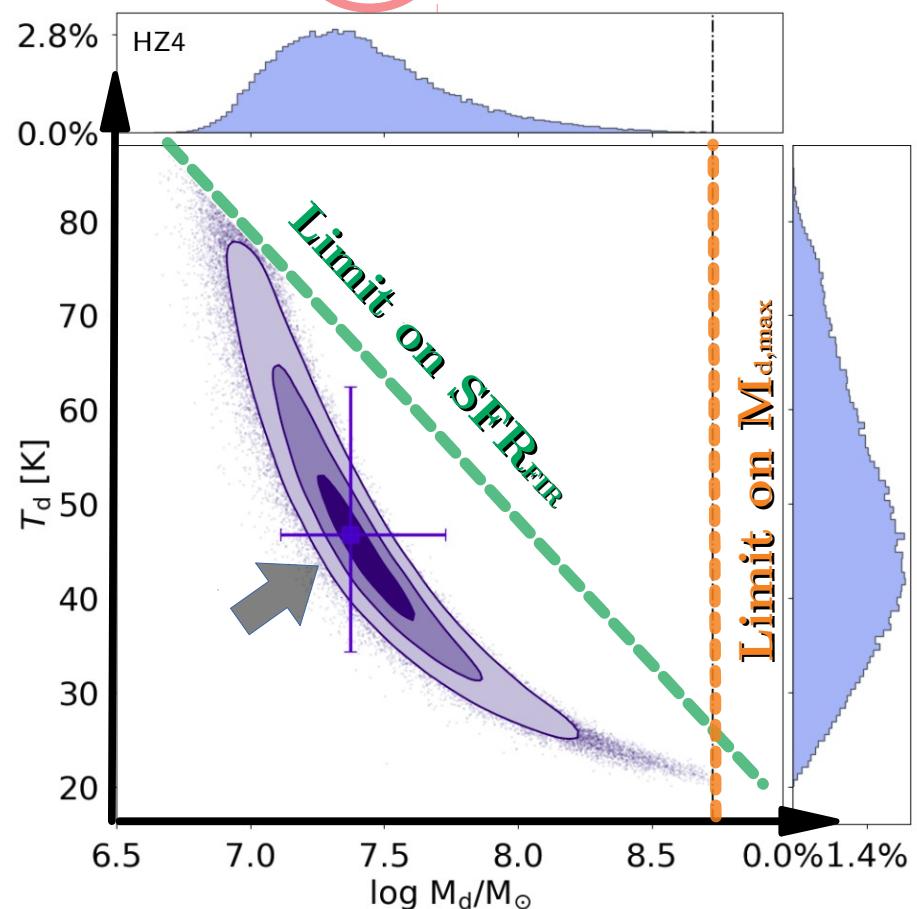
→  $T_d$



Sommovigo+21

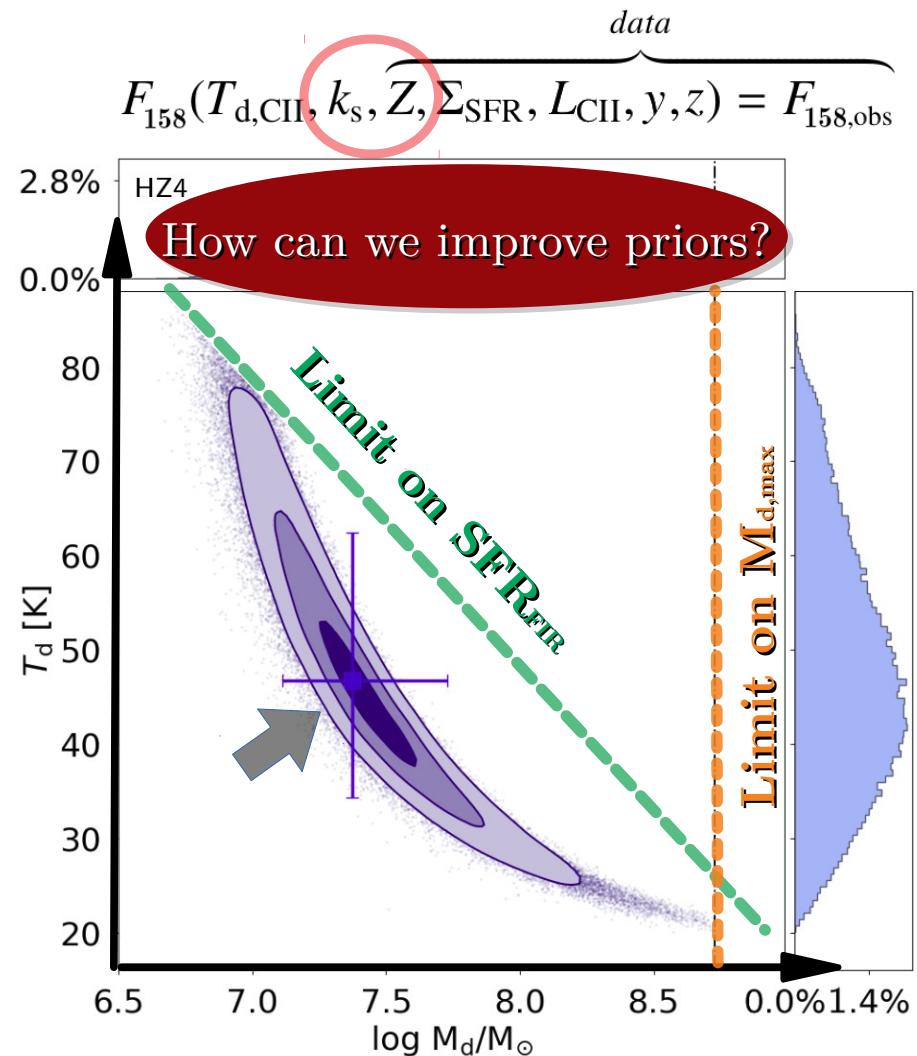
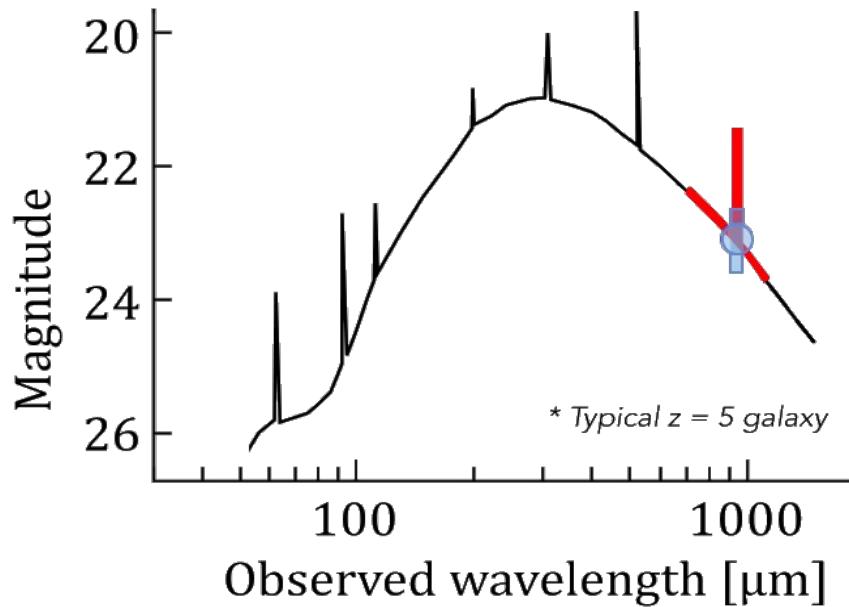
data

$$F_{158}(T_{d,\text{CII}}, k_s, \overbrace{Z, \Sigma_{\text{SFR}}, L_{\text{CII}}, y, z}^{\text{data}}) = F_{158,\text{obs}}$$

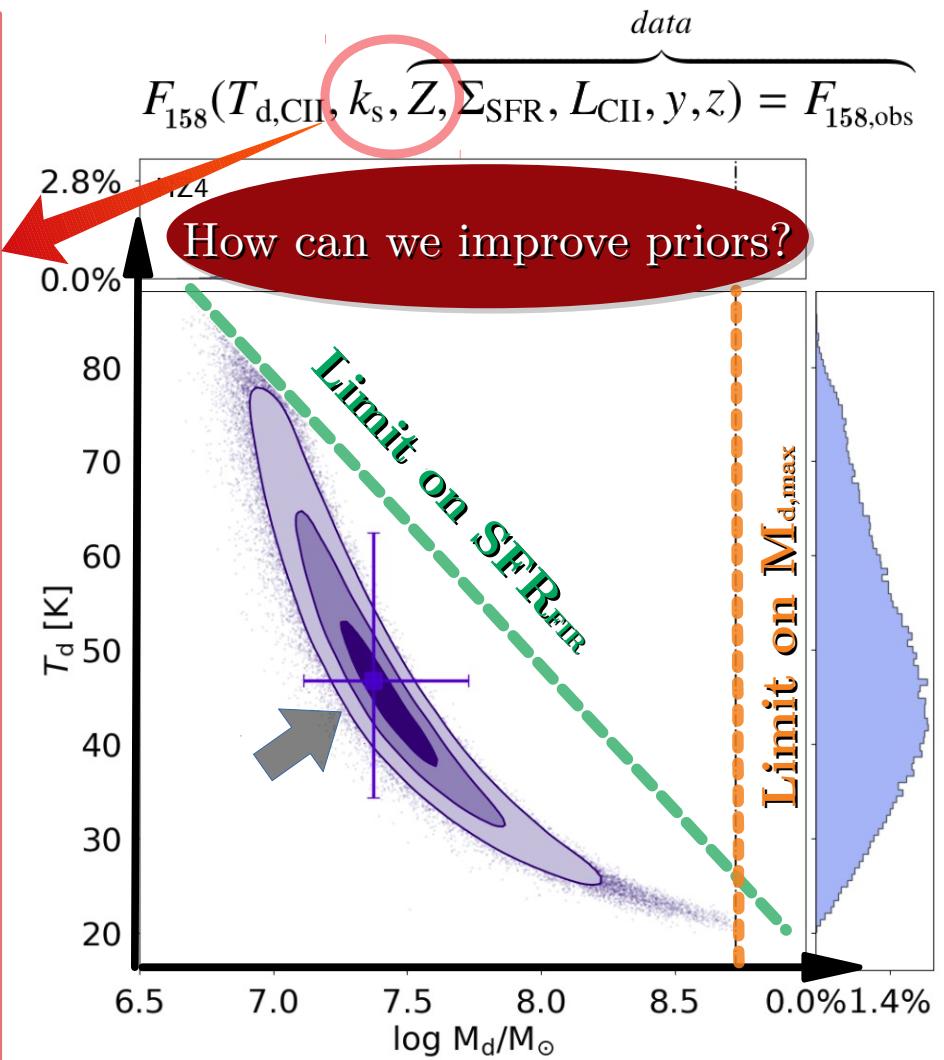
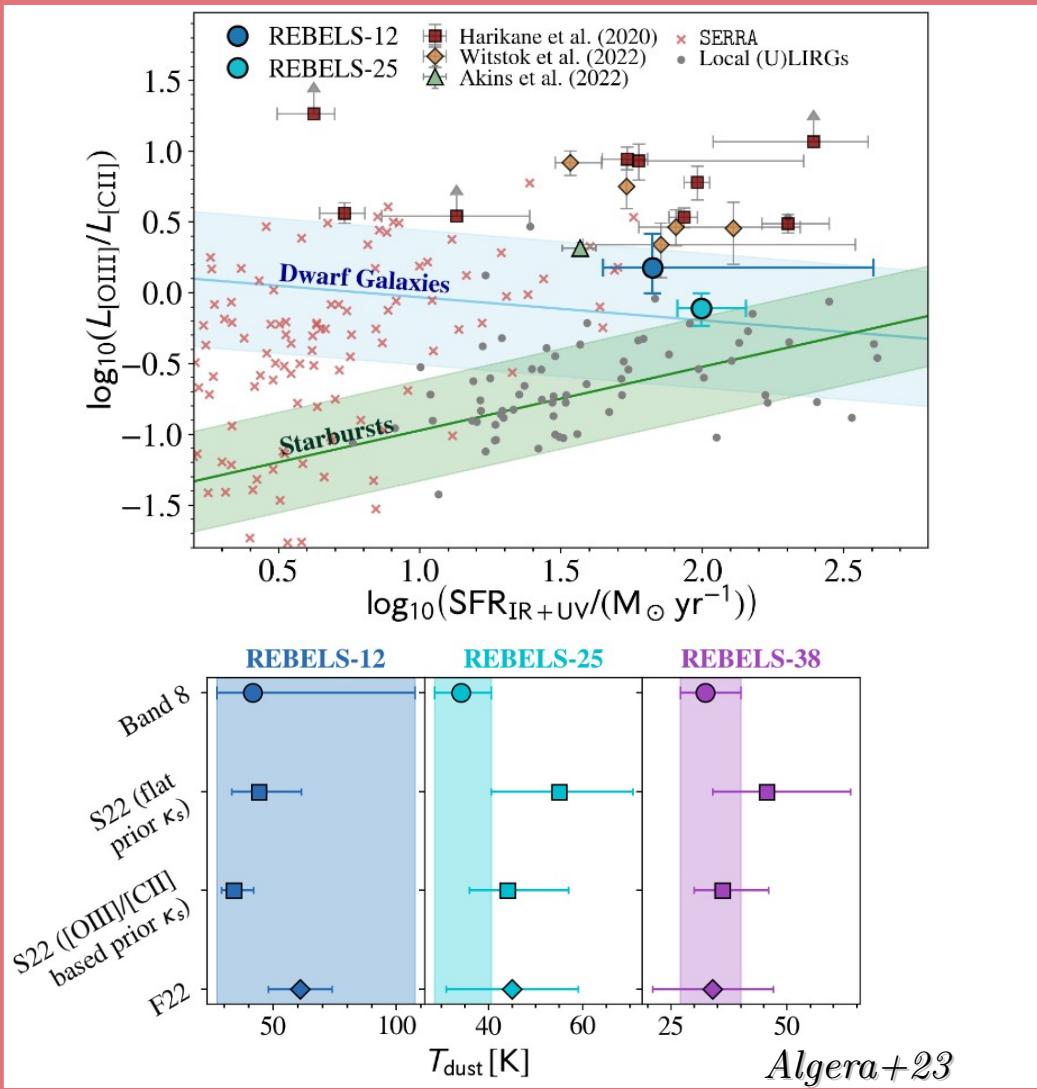


## New method to derive $T_d$ using [CII] information

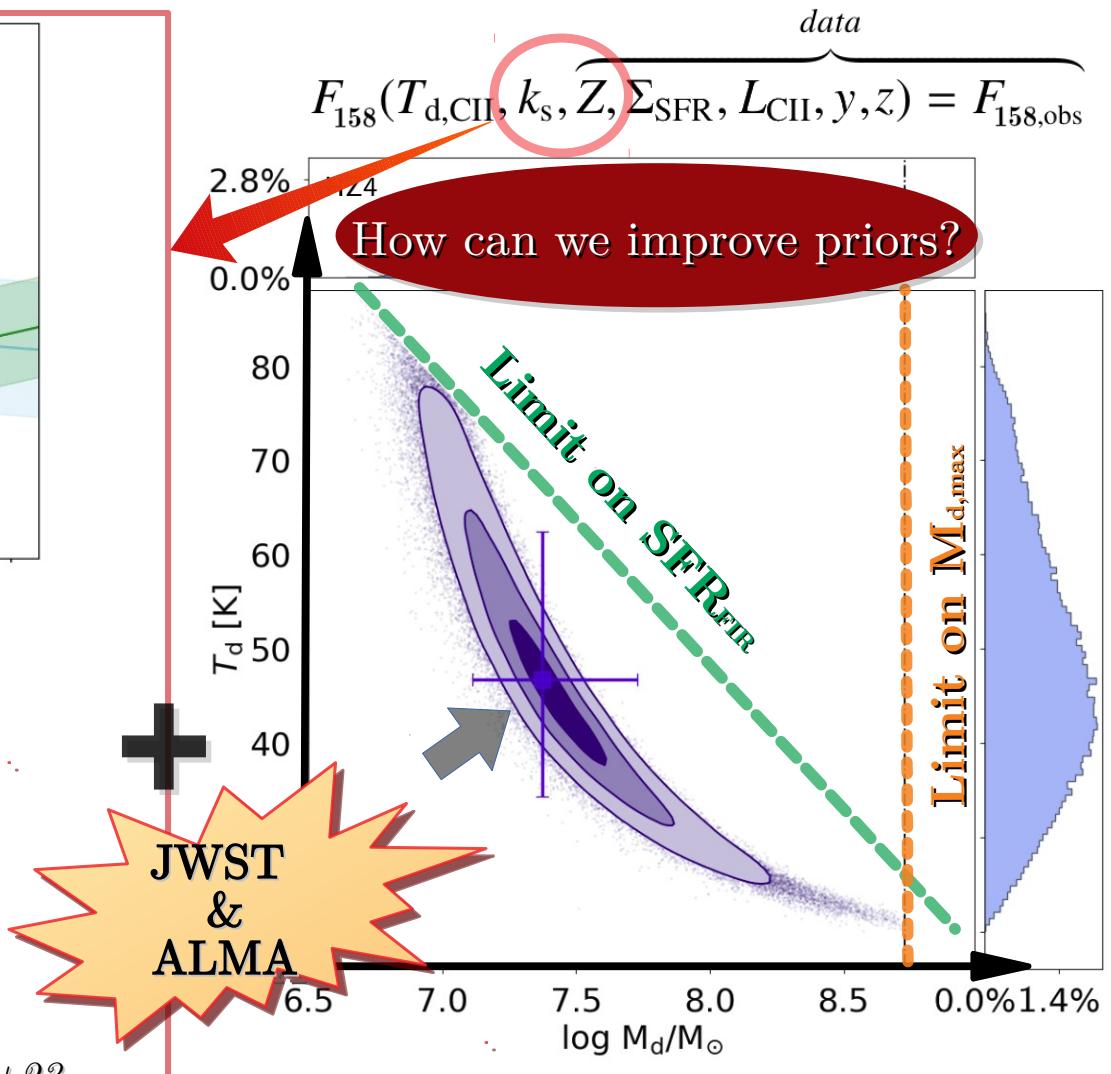
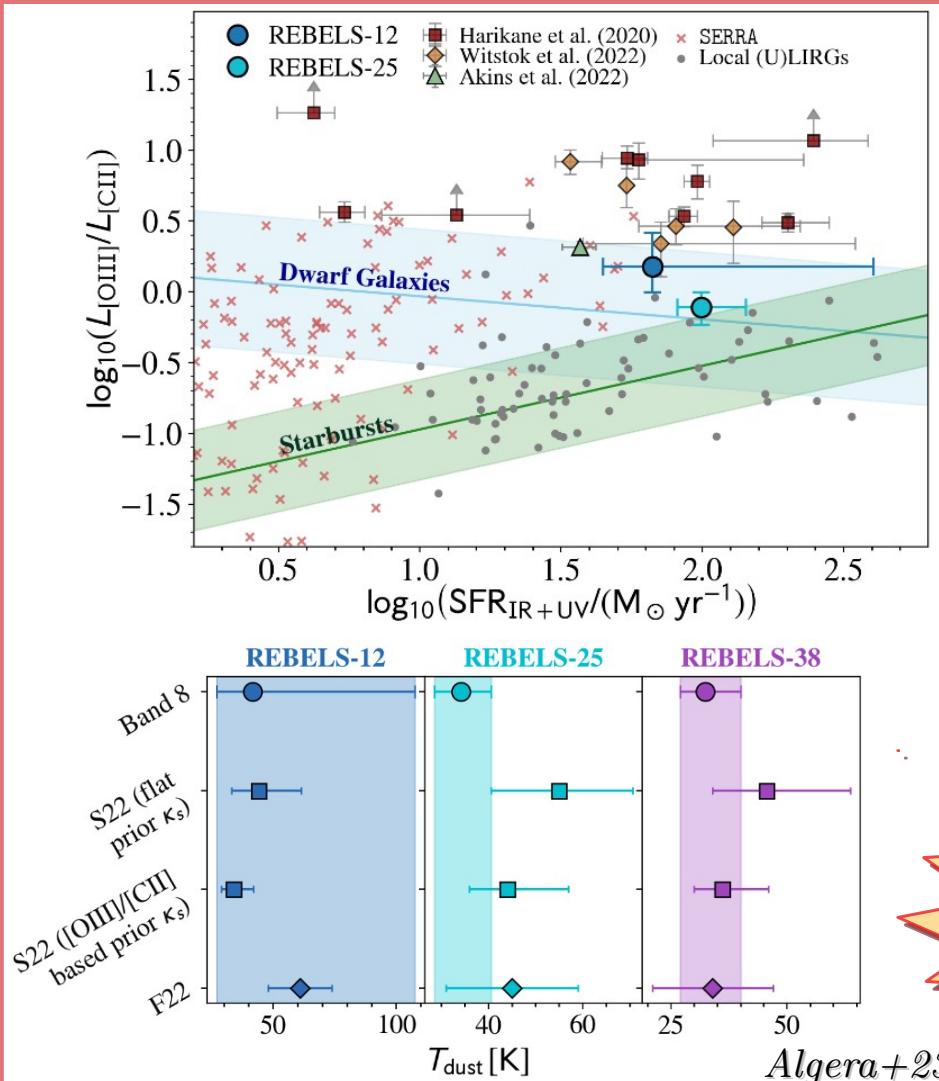
**Inputs:** [CII] Continuum → **Outputs:** Md Td



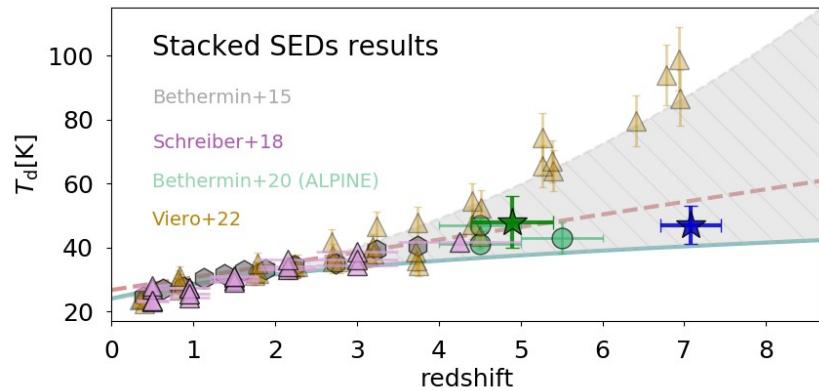
# New method to derive $T_d$ using [CII] information



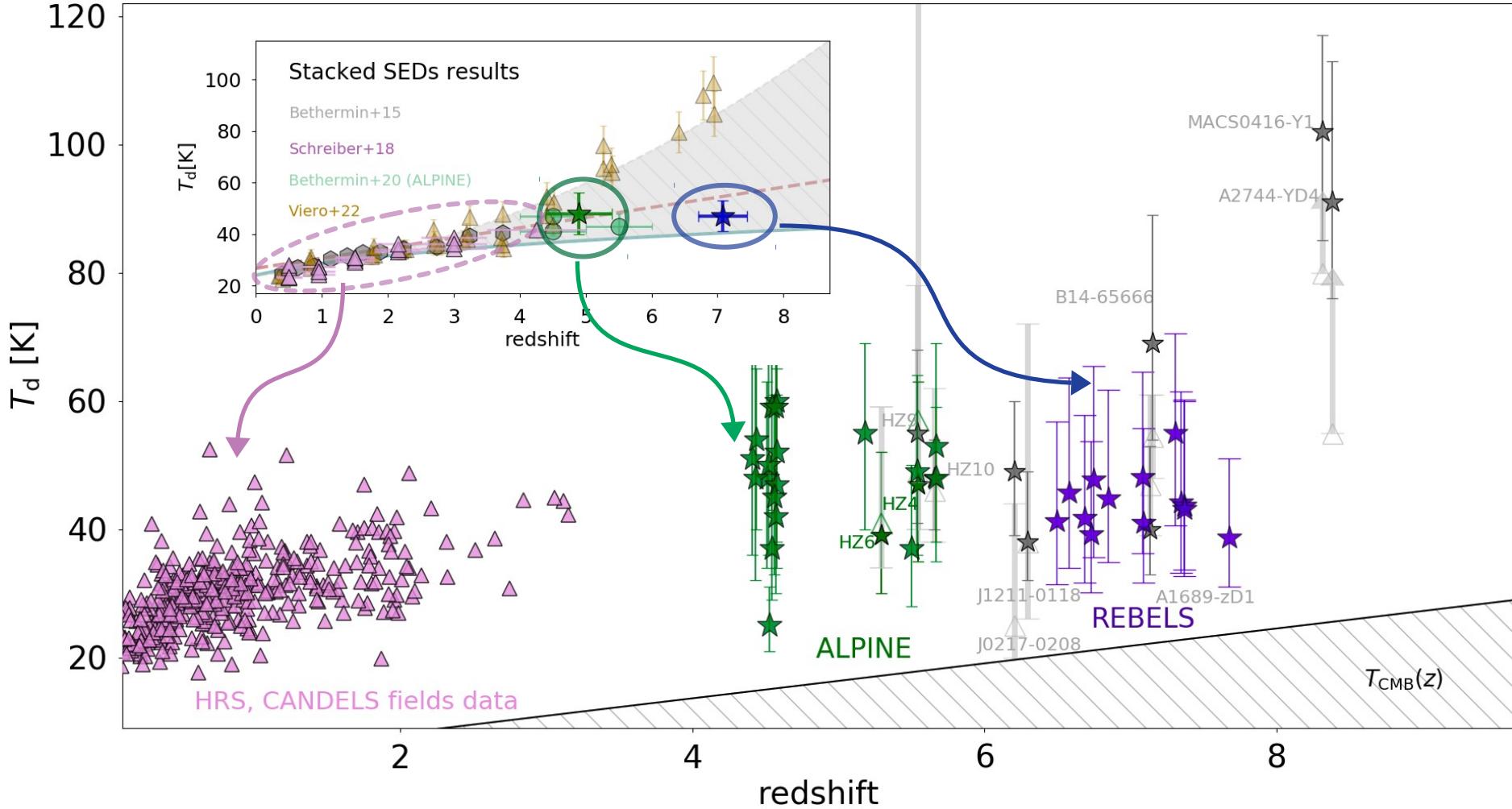
# New method to derive $T_d$ using [CII] information



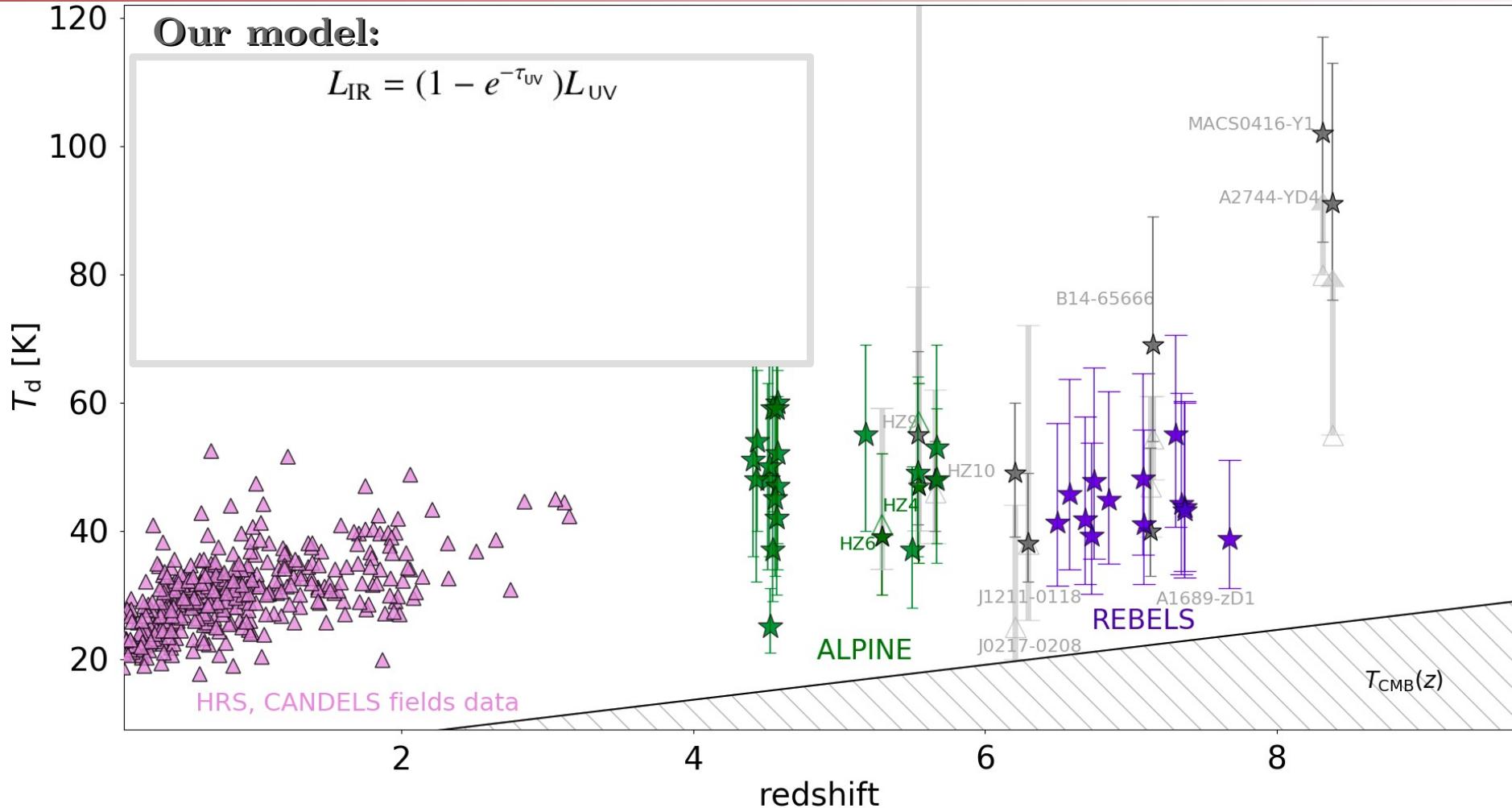
# Cosmic dust temperature evolution out to z~7



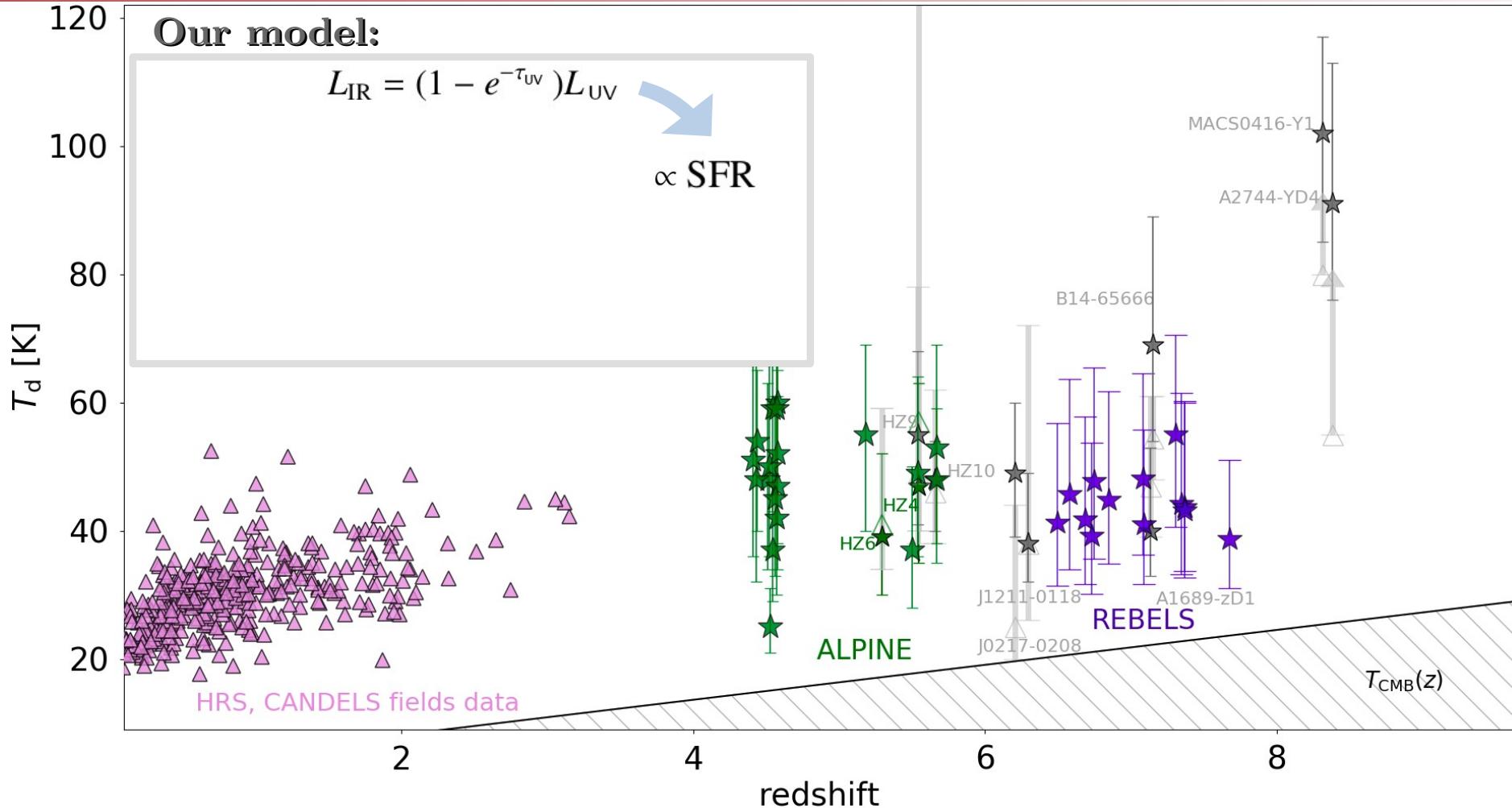
# Cosmic dust temperature evolution out to $z \sim 7$



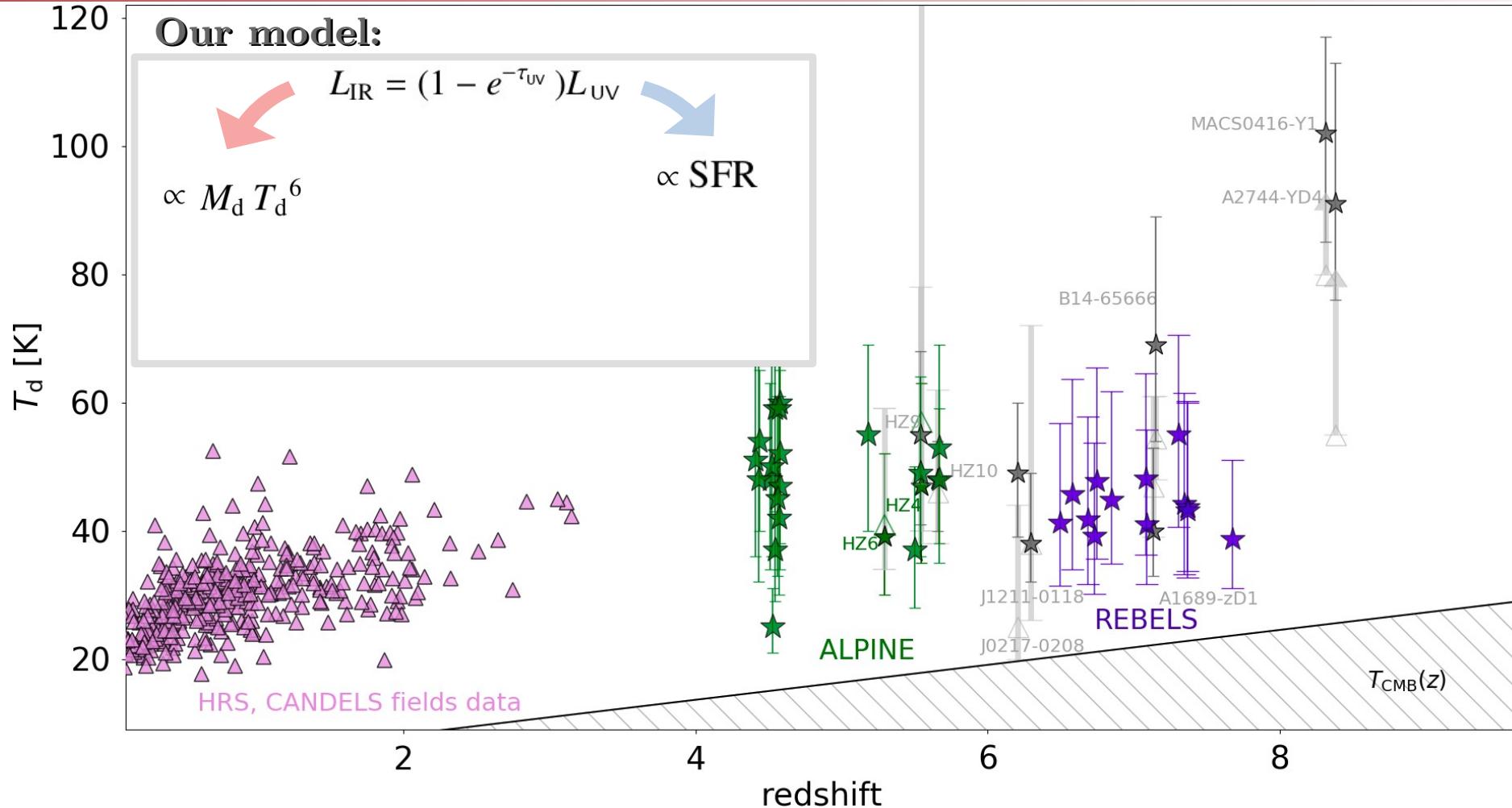
# Cosmic dust temperature evolution out to z~7



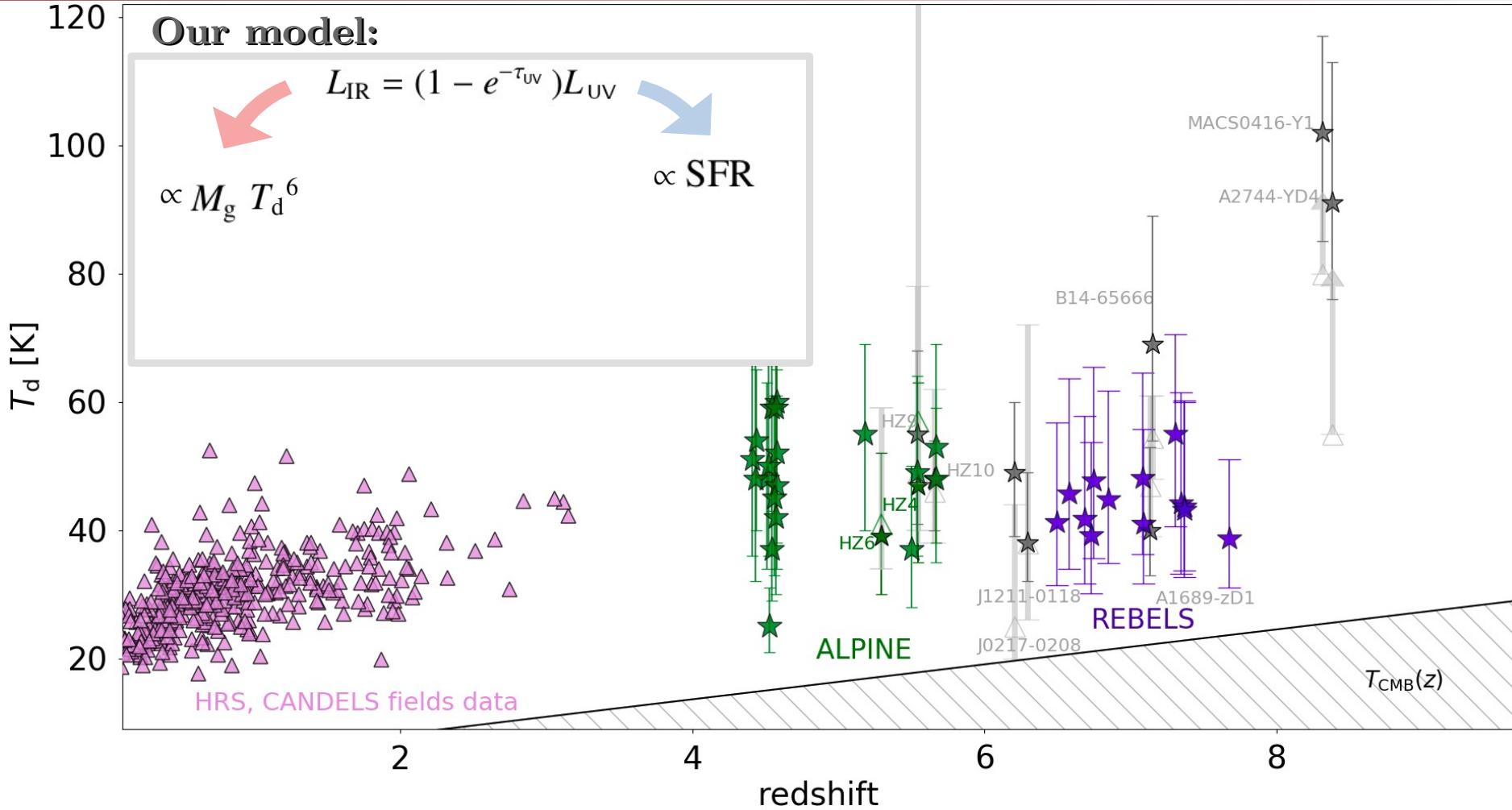
# Cosmic dust temperature evolution out to z~7



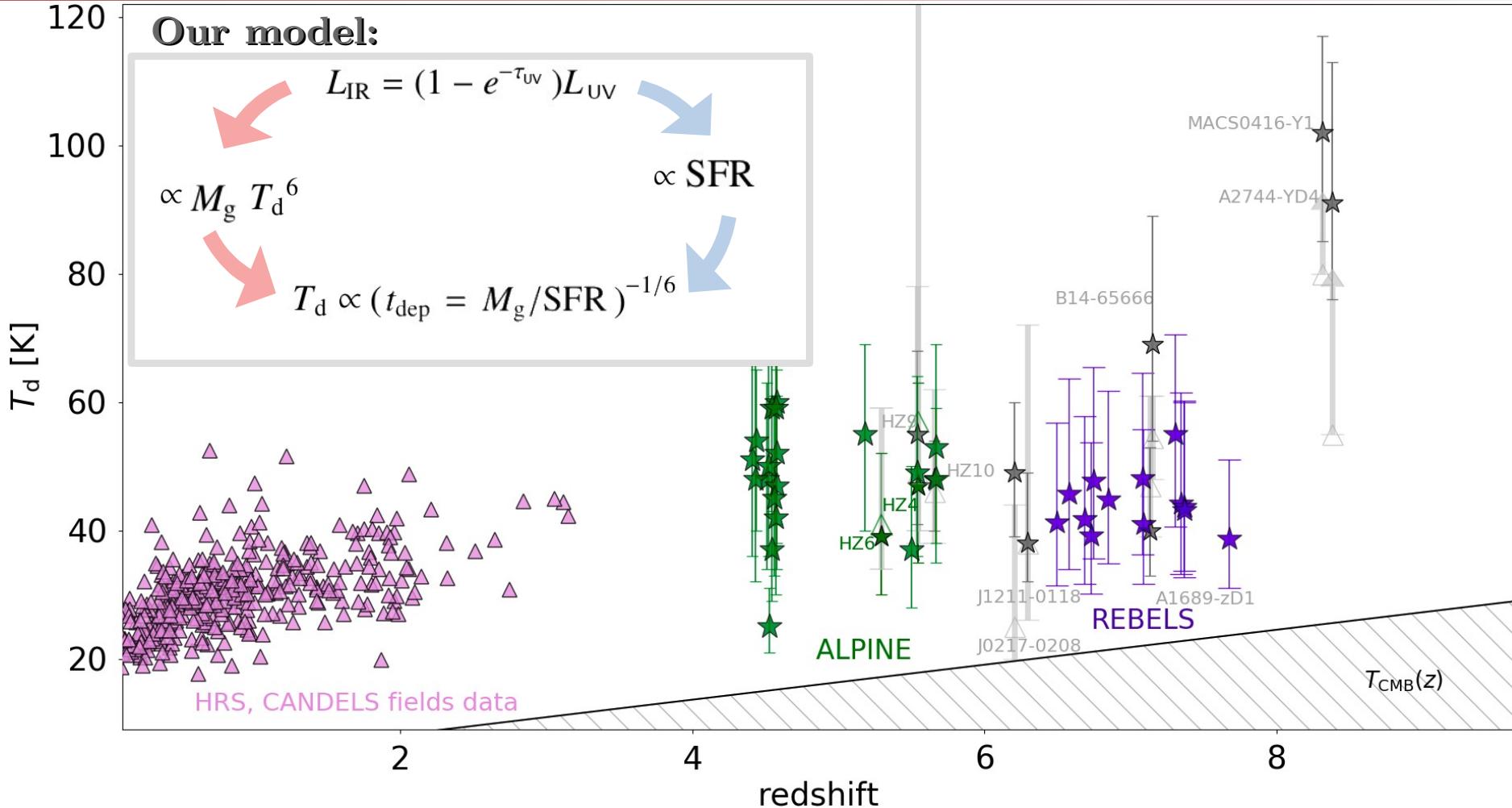
# Cosmic dust temperature evolution out to z~7



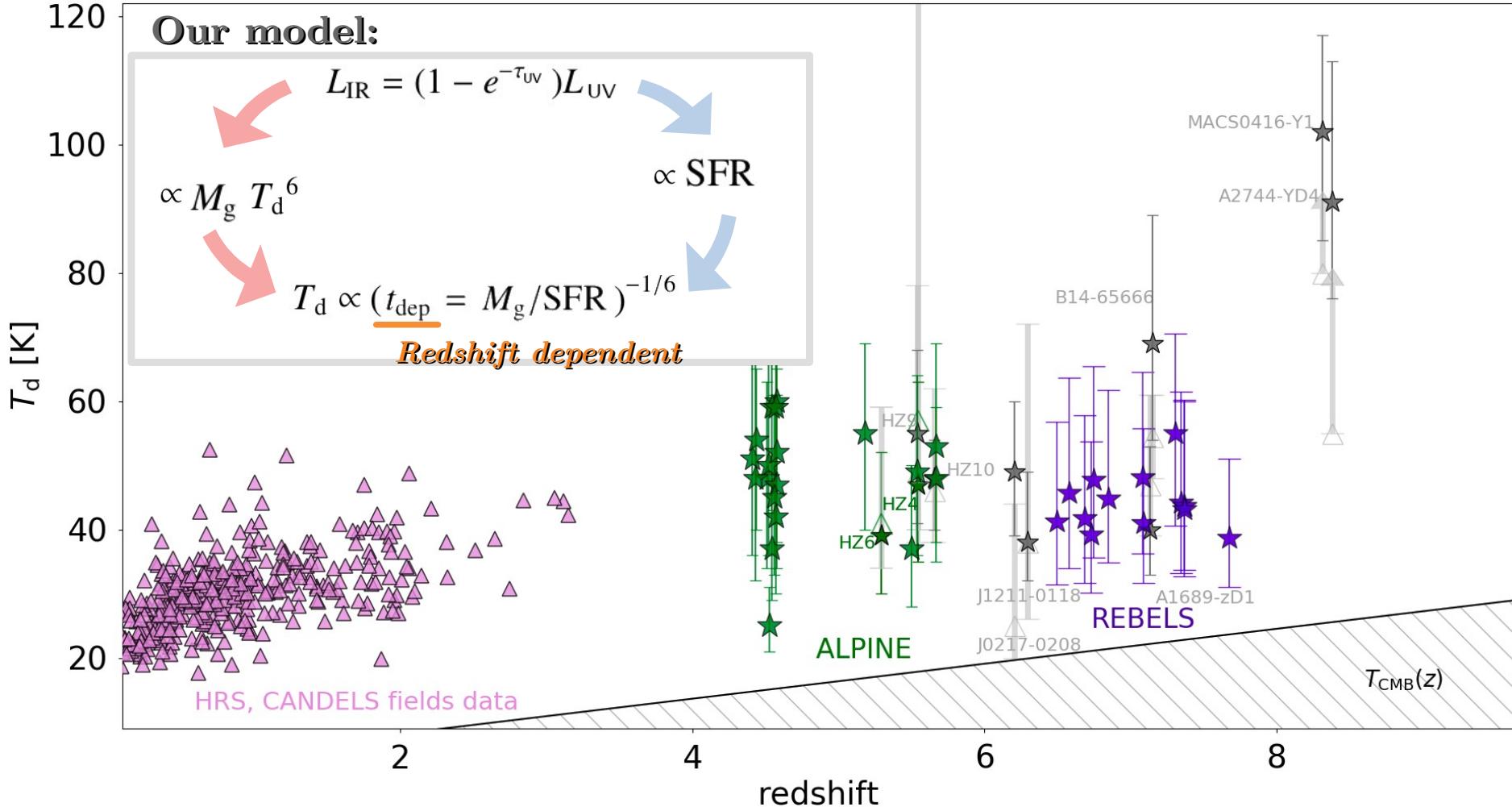
# Cosmic dust temperature evolution out to z~7



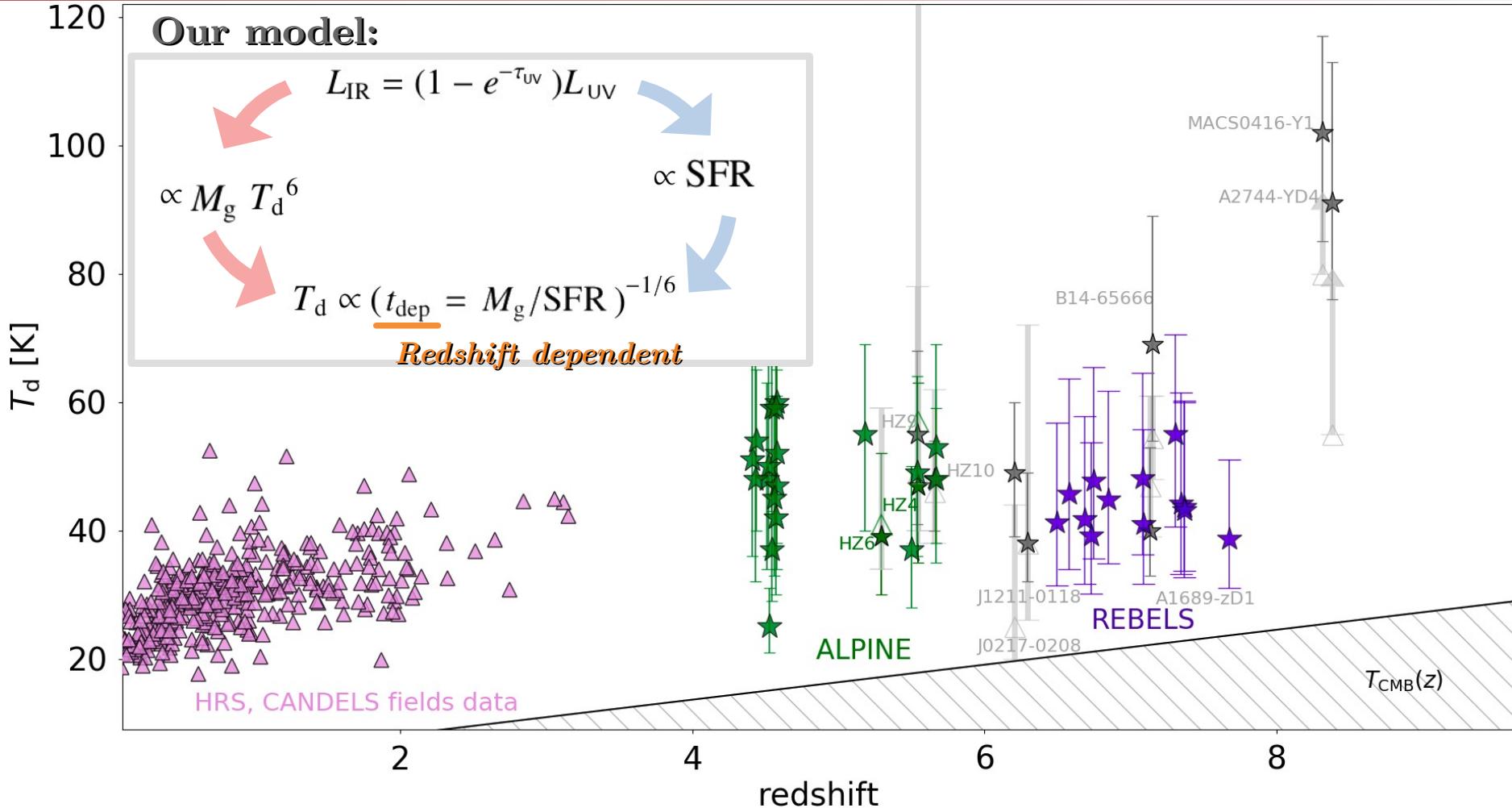
# Cosmic dust temperature evolution out to $z \sim 7$



# Cosmic dust temperature evolution out to $z \sim 7$



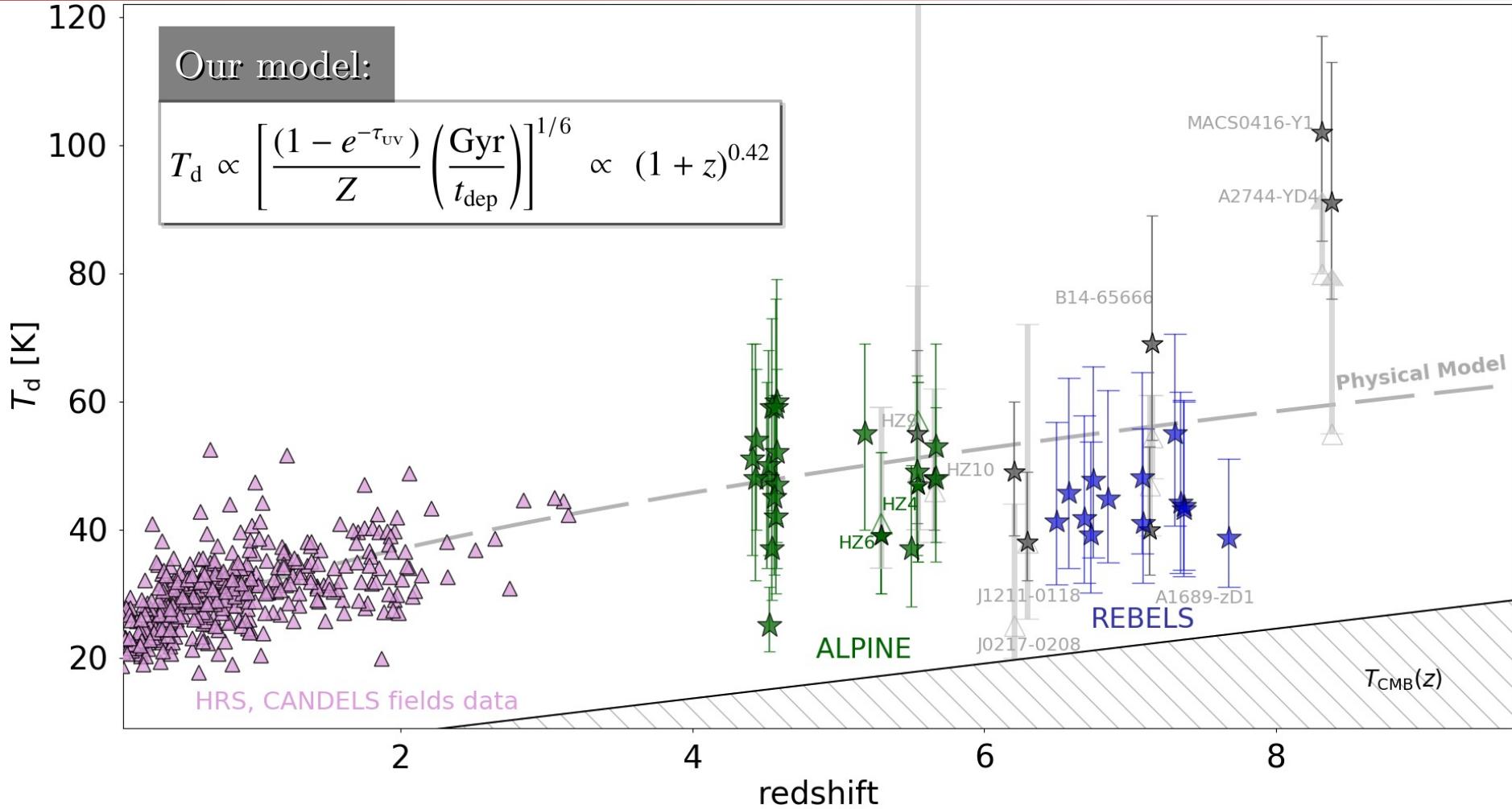
# Cosmic dust temperature evolution out to z~7



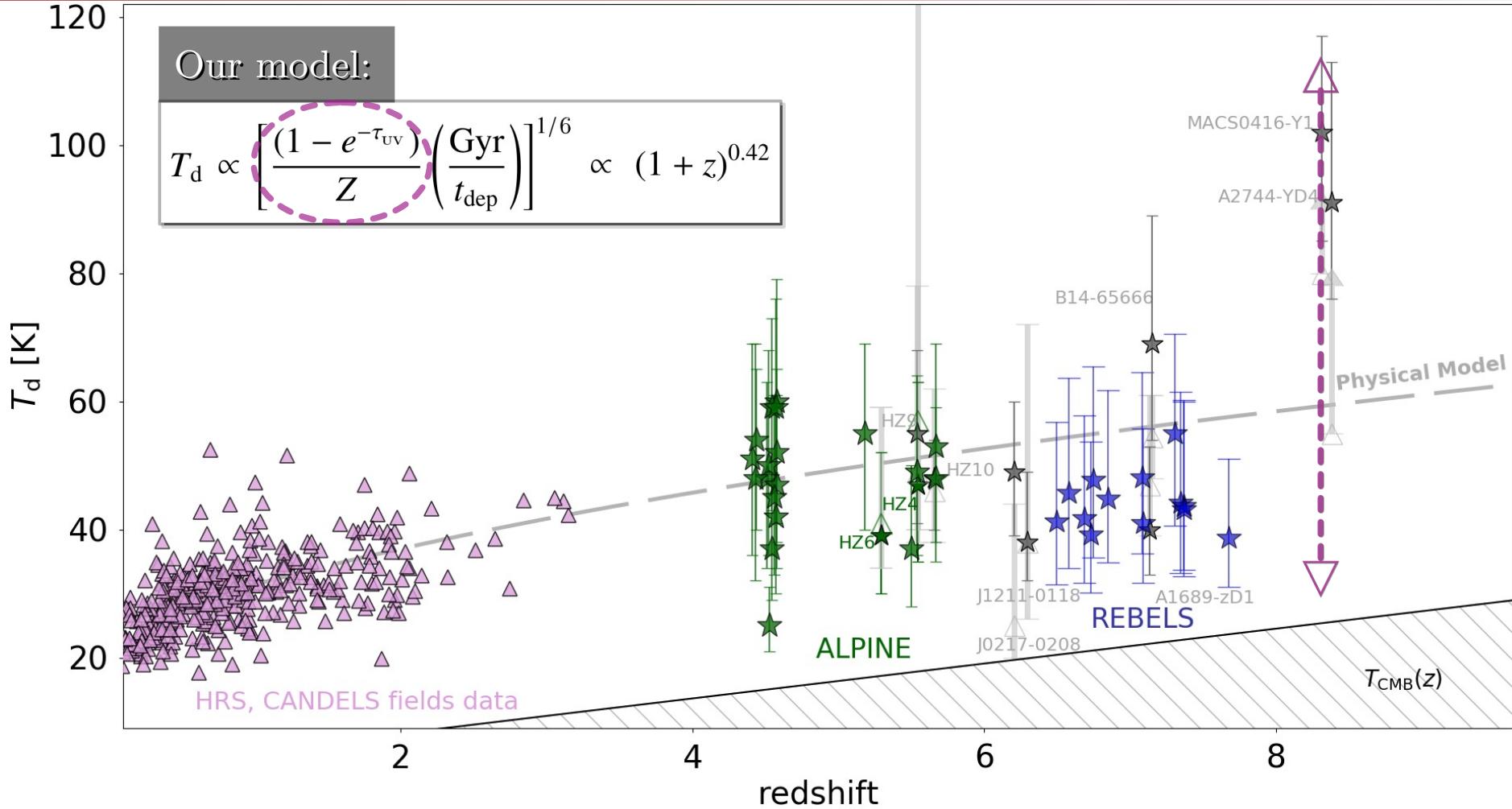
$T_d$  raises with redshift due to decreasing gas depletion time at high-z

Sommovigo+22

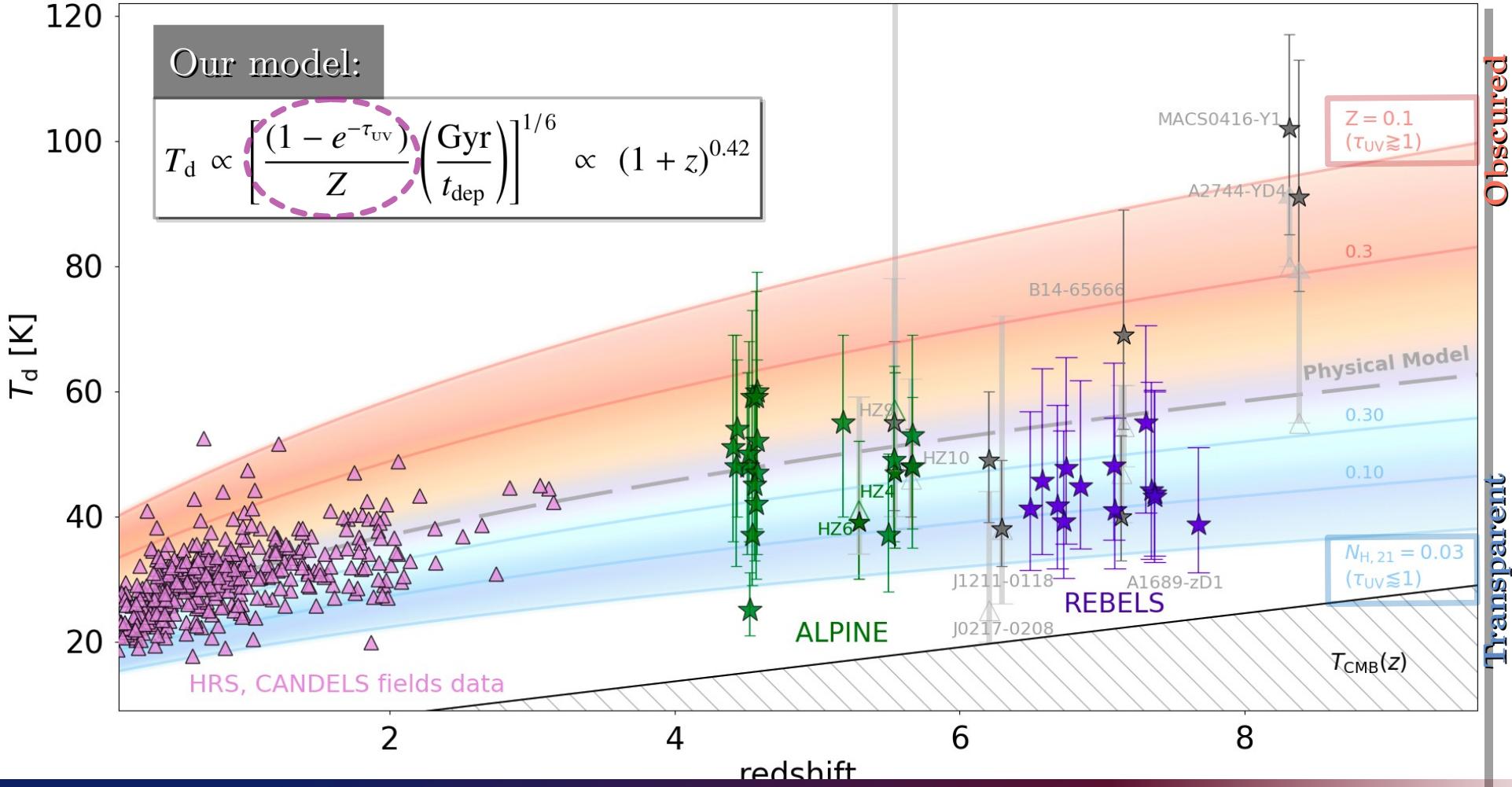
# Cosmic dust temperature evolution out to $z \sim 7$



# Cosmic dust temperature evolution out to $z \sim 7$

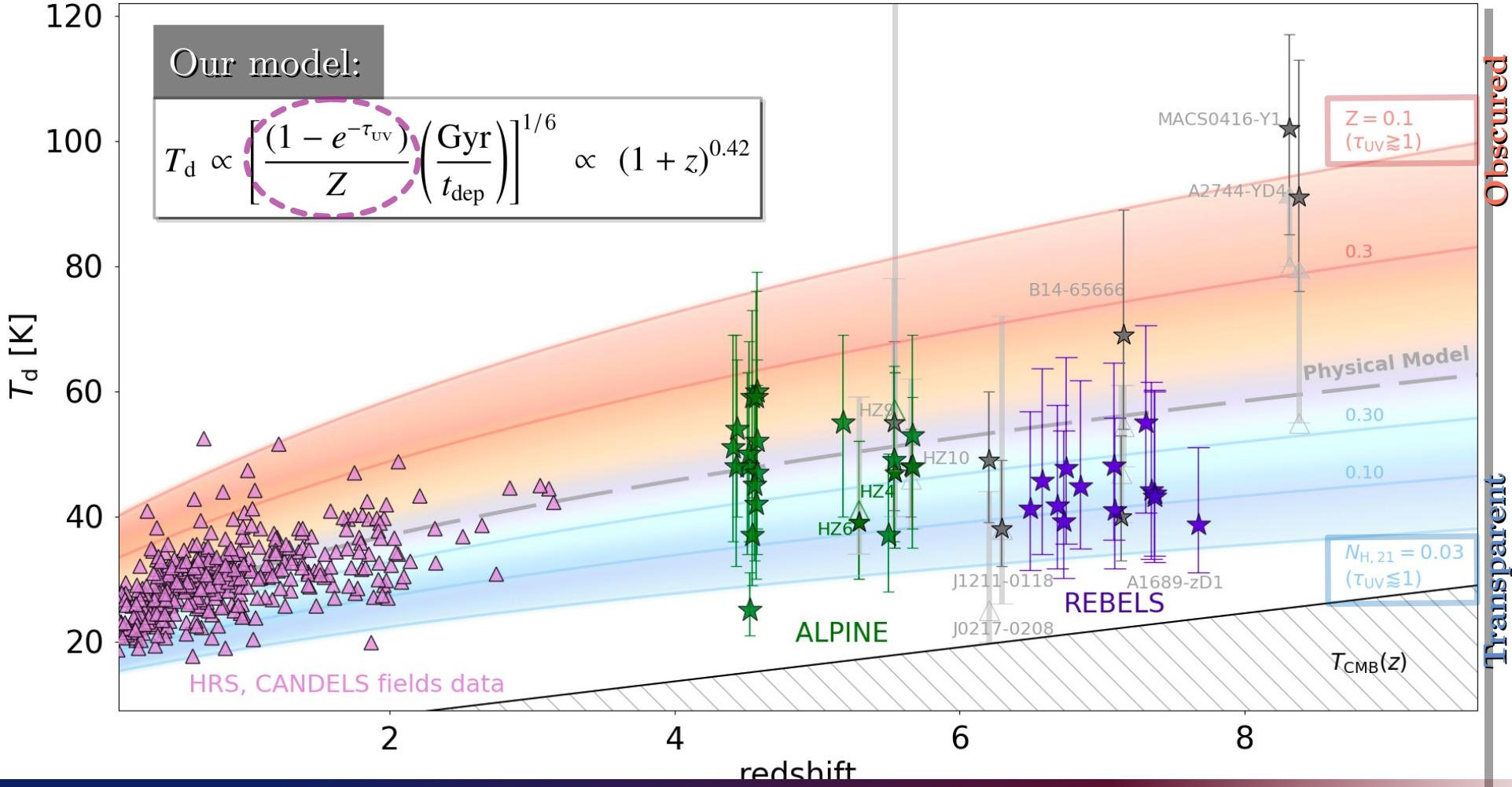


# Cosmic dust temperature evolution out to $z \sim 7$



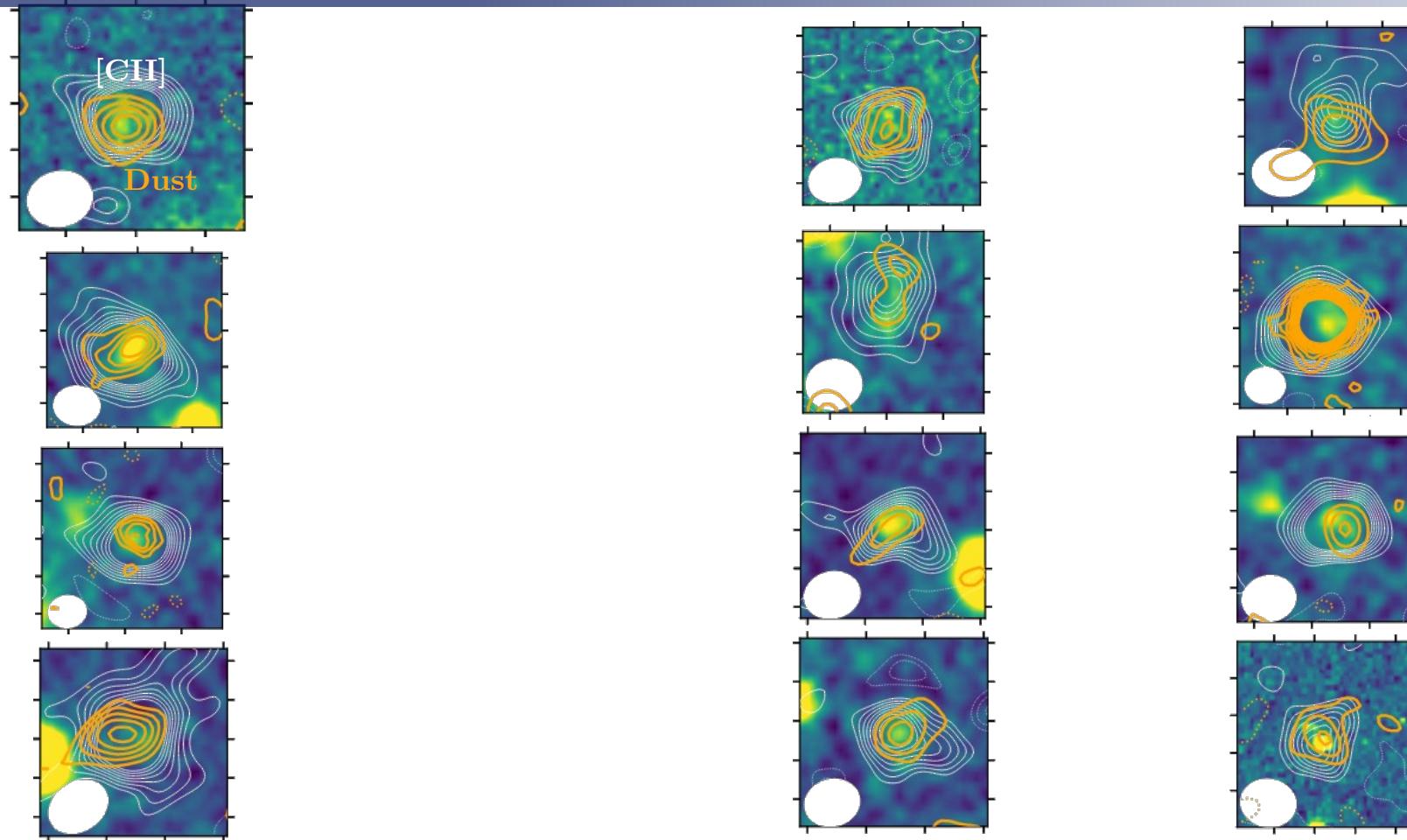
At given redshift: for UV-transparent (*obscured*) galaxies,  
 $T_d$  only depends on gas column density (*metallicity*)

# Cosmic dust temperature evolution out to $z \sim 7$

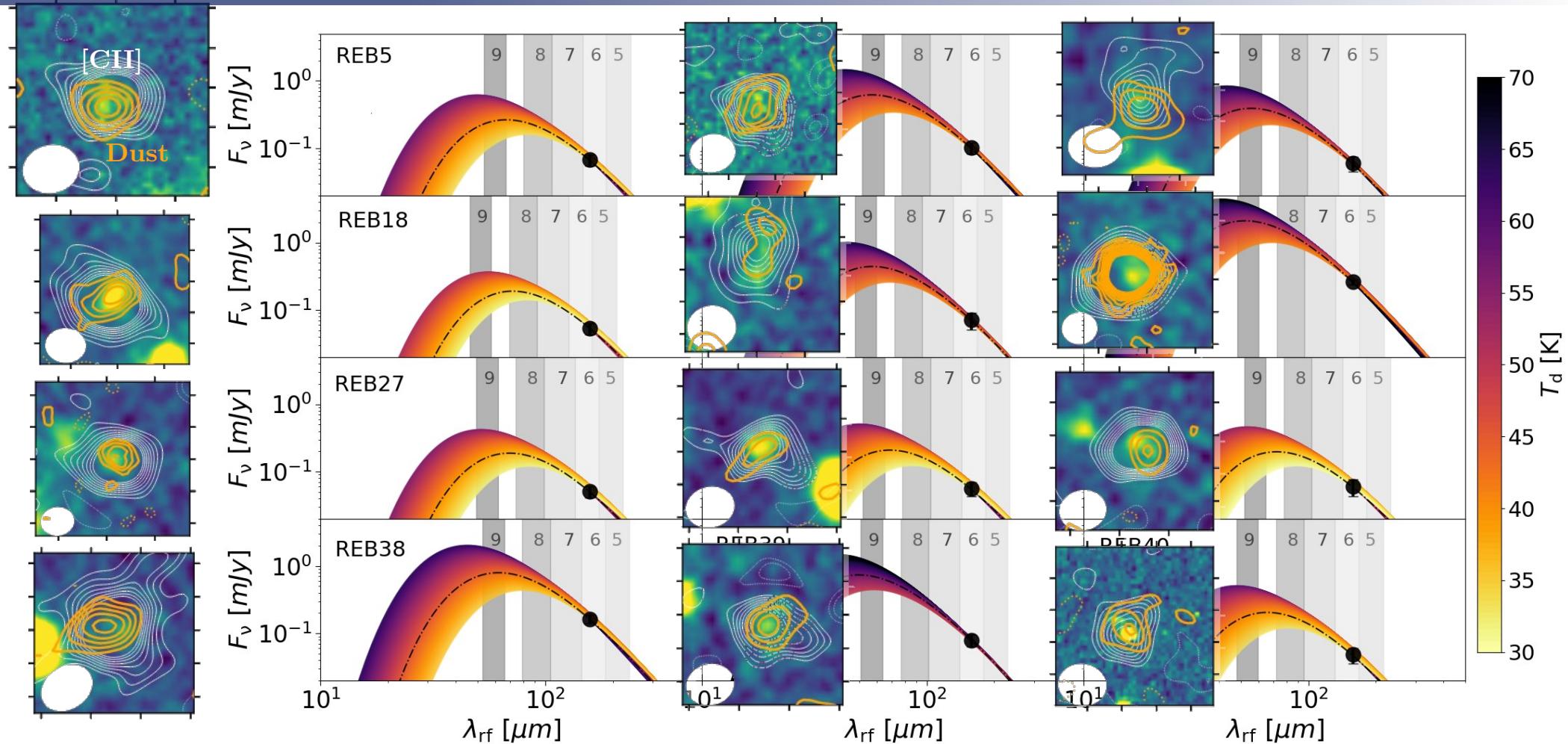


At given redshift: for UV-transparent (*obscured*) galaxies,  
 $T_d$  only depends on gas column density (*metallicity*)

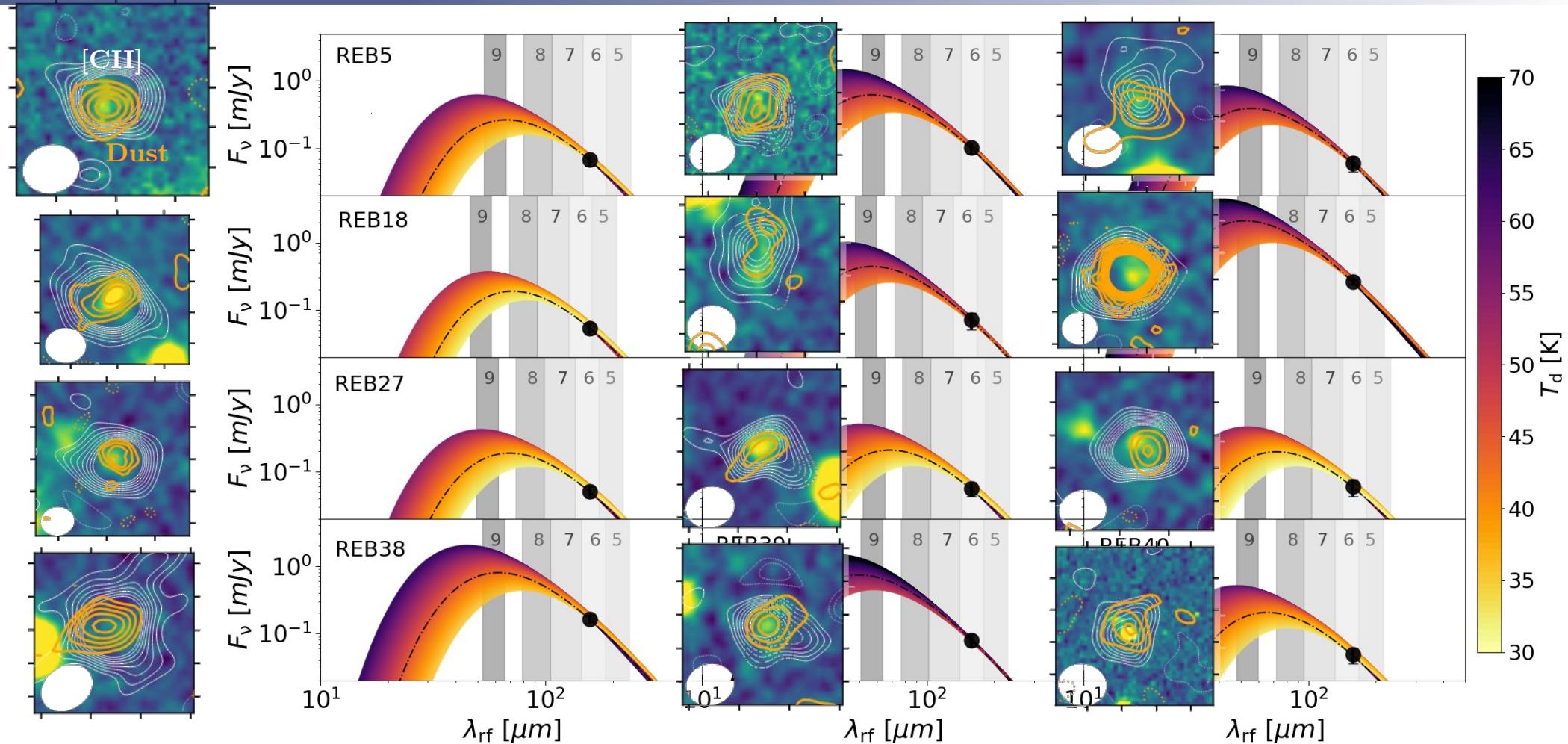
# REBELS galaxies dust properties



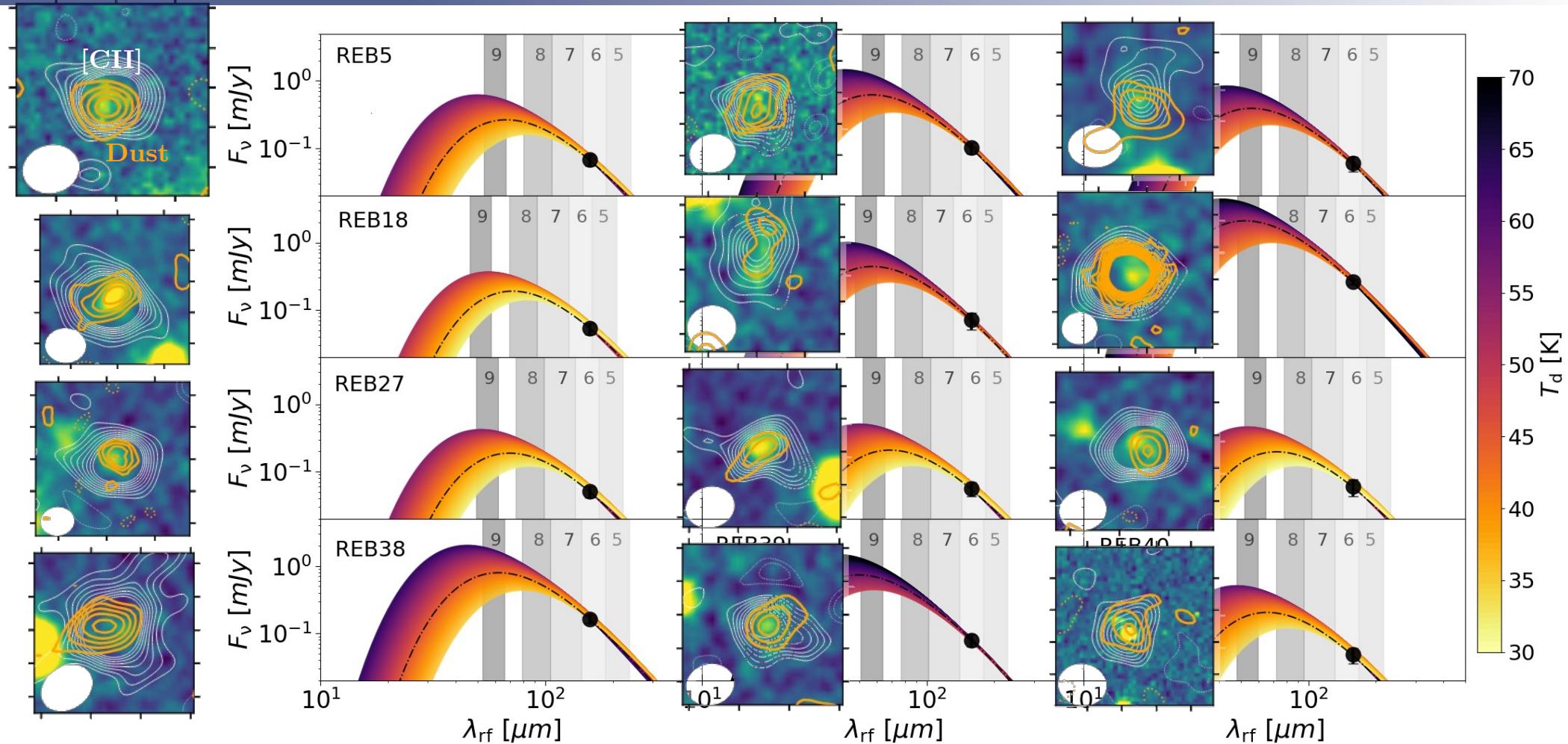
# REBELS galaxies dust properties



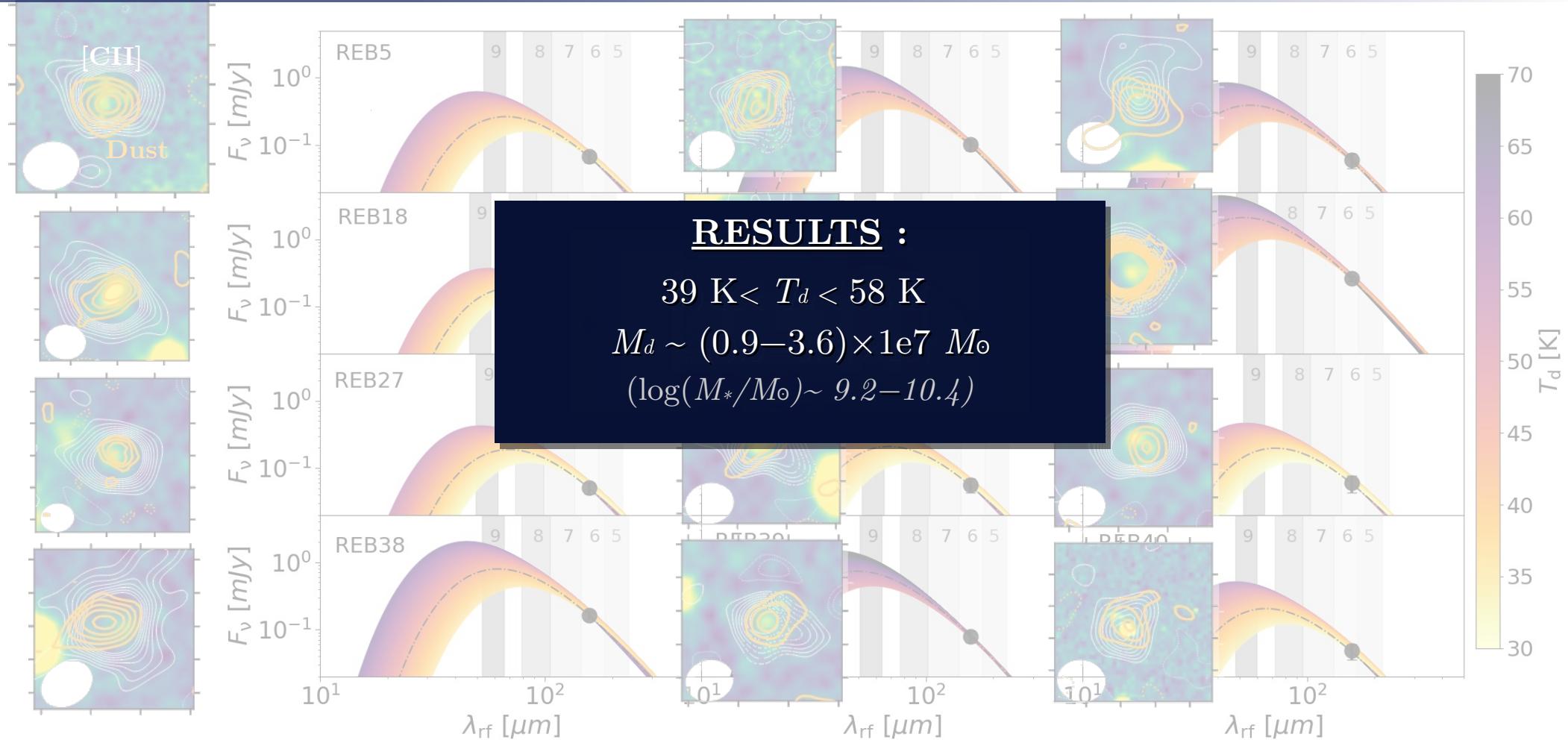
# REBELS galaxies dust properties



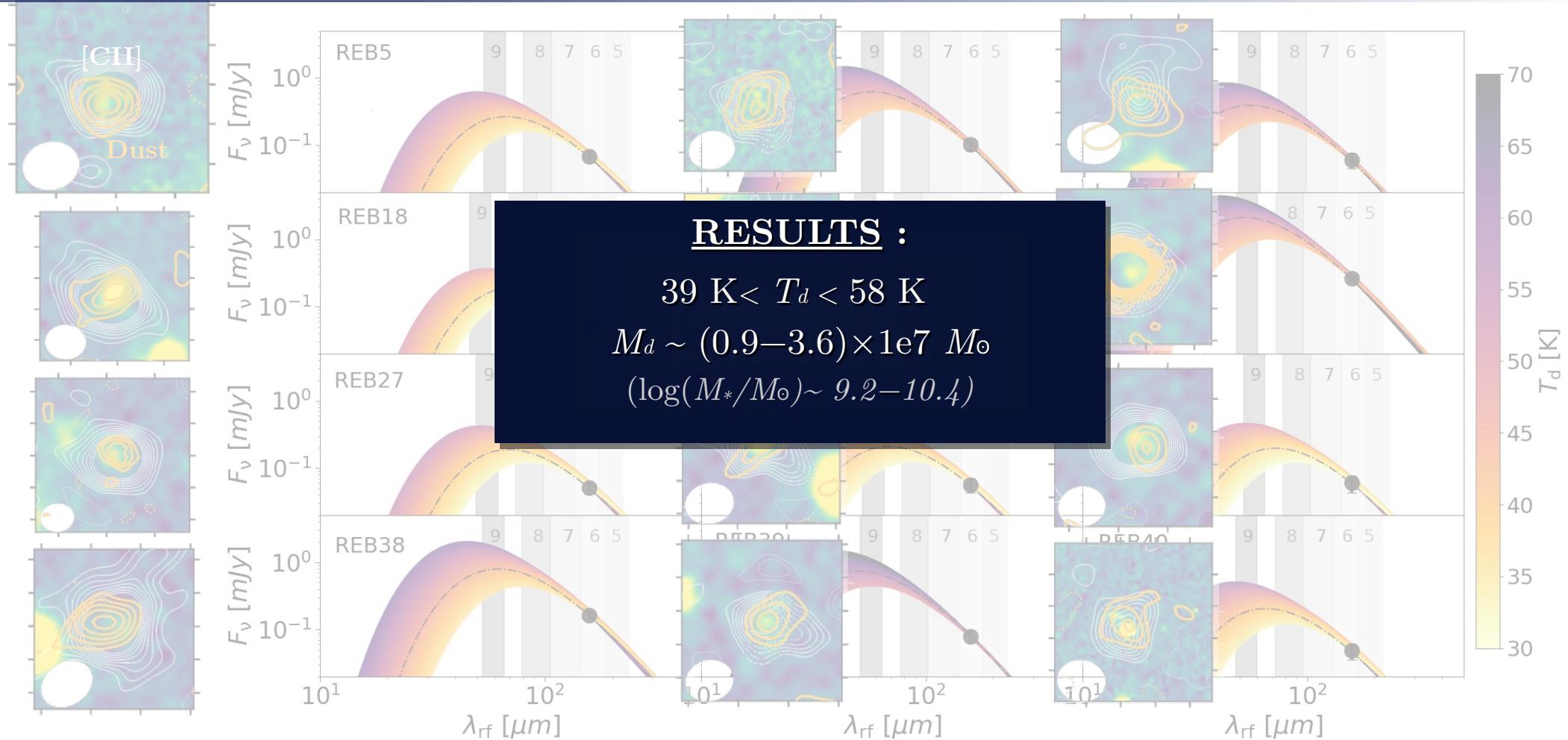
# REBELS galaxies dust properties



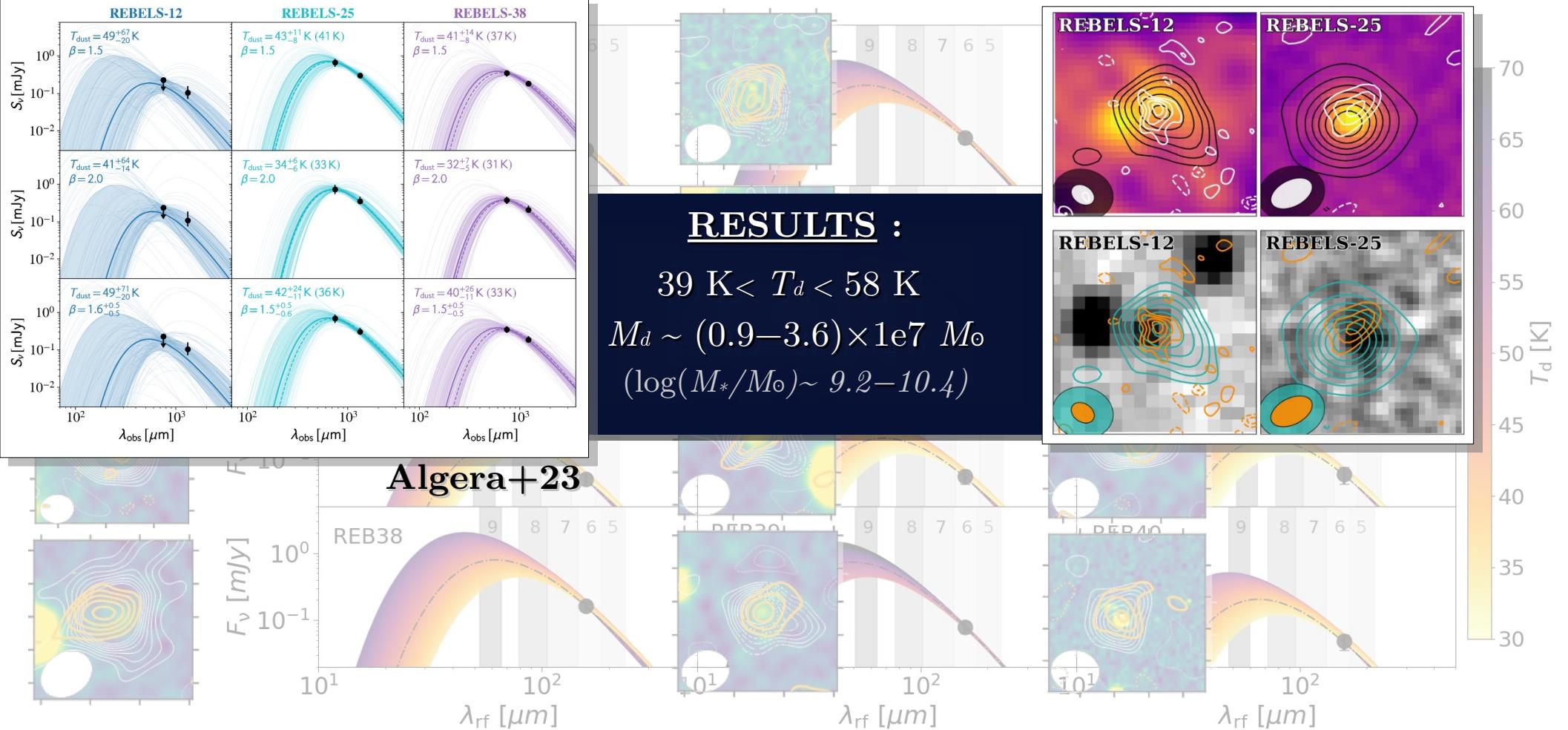
# REBELS galaxies dust properties



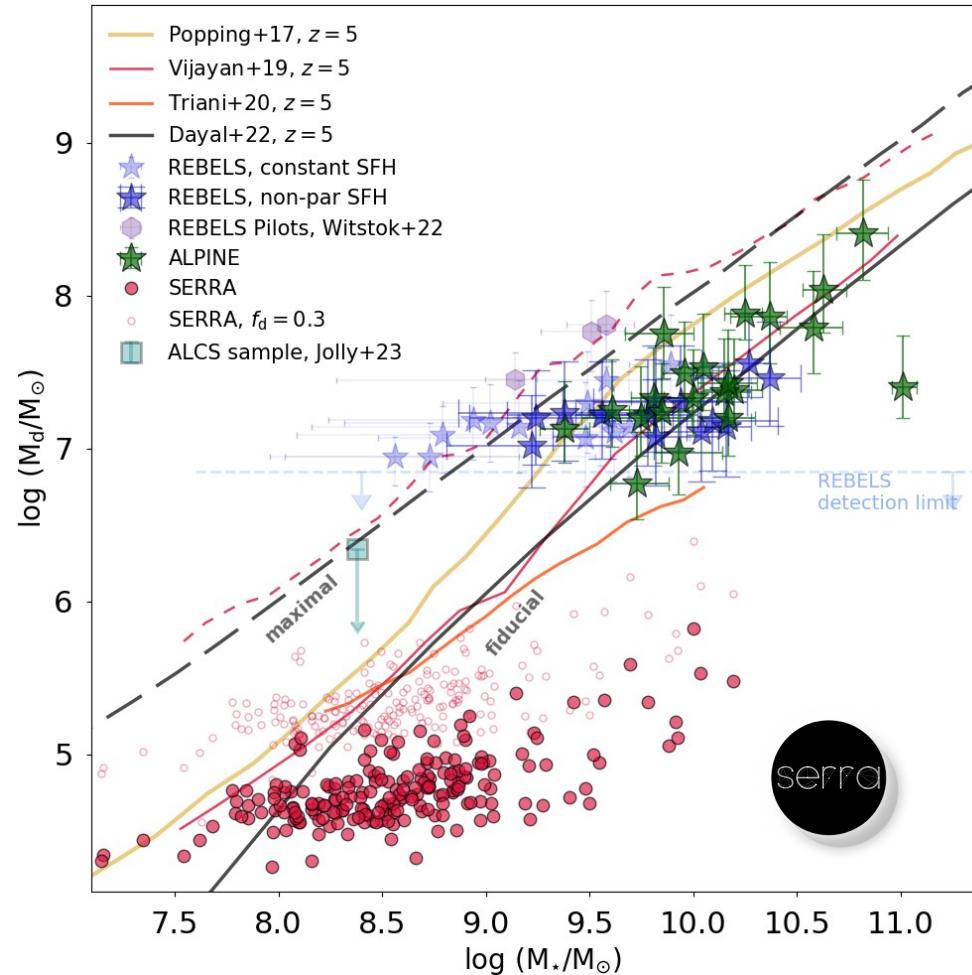
# REBELS galaxies dust properties



# REBELS galaxies dust properties



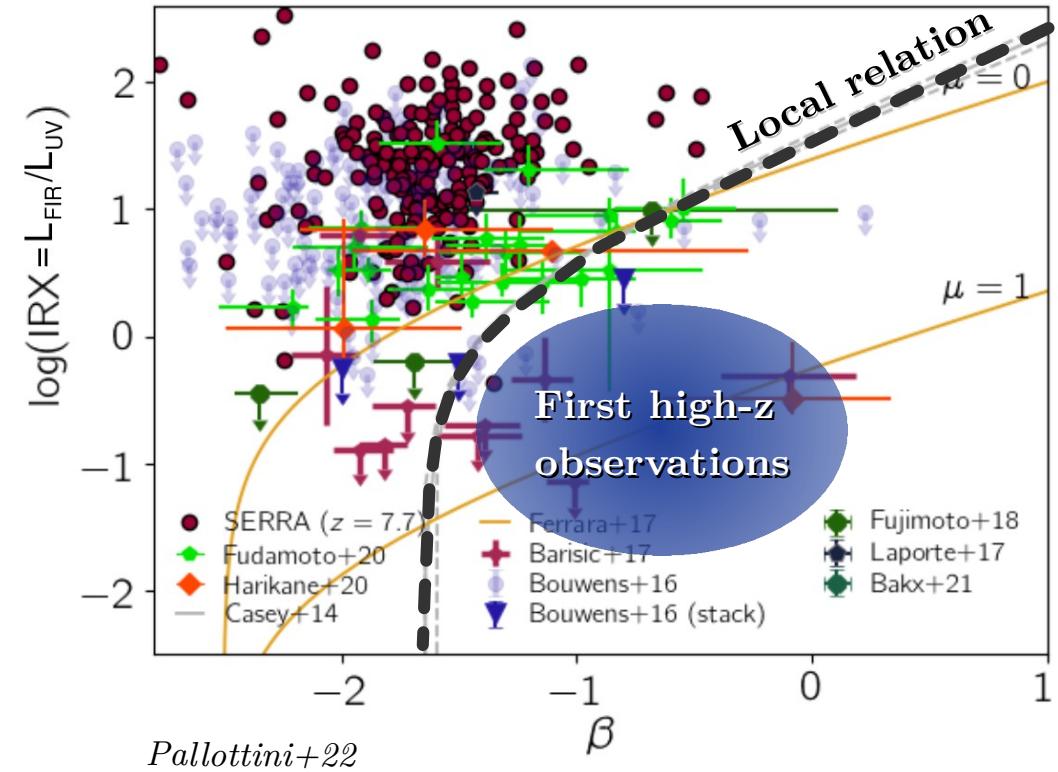
# Understanding the dust build-up at $z>5$



Sommovigo+22b

See also: Dayal+22, Ferrara+22, Topping+22

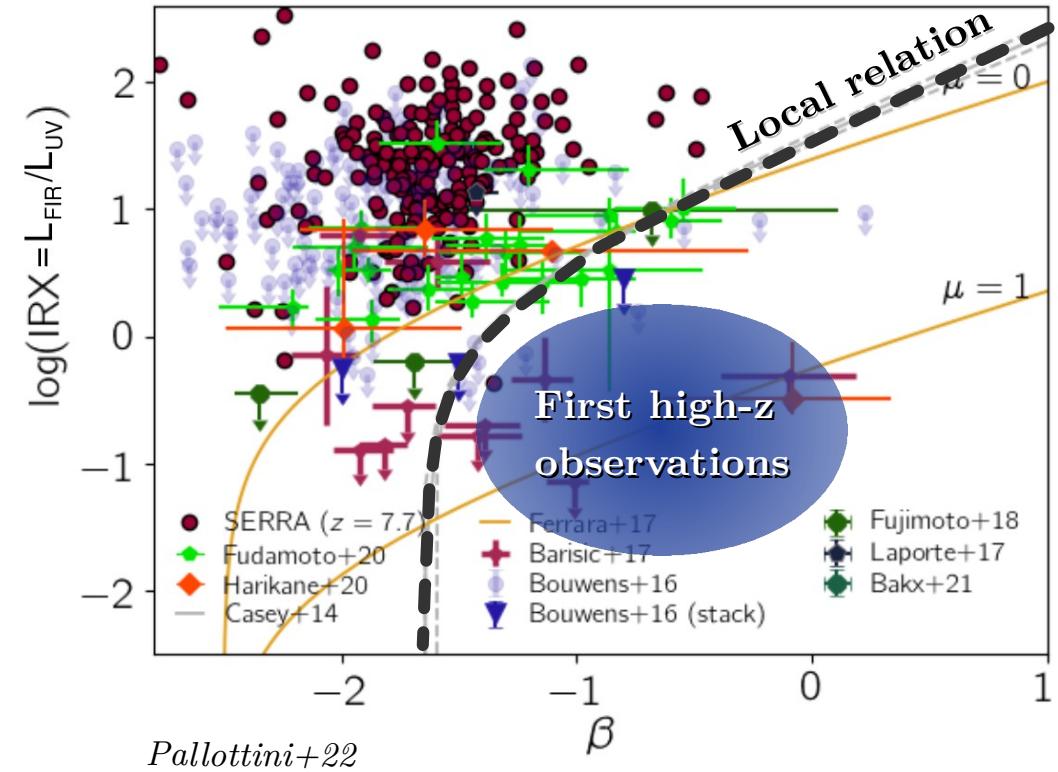
# Can we trust the $\text{IRX}-\beta$ relation to correct for dust at high- $z$ ?



See also: Behrens+18, Liang+19...

Pallottini+22

# Can we trust the $\text{IRX}-\beta$ relation to correct for dust at high- $z$ ?

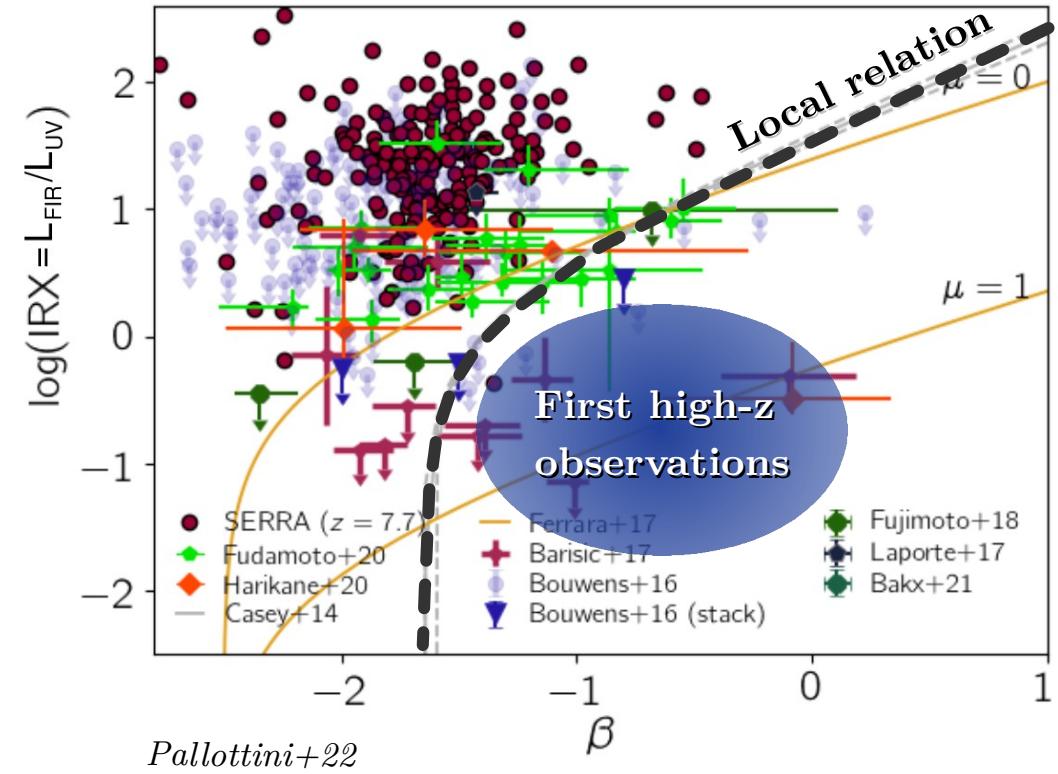


See also: Behrens+18, Liang+19...

Pallottini+22

# Can we trust the $\text{IRX}$ - $\beta$ relation to correct for dust at high- $z$ ?

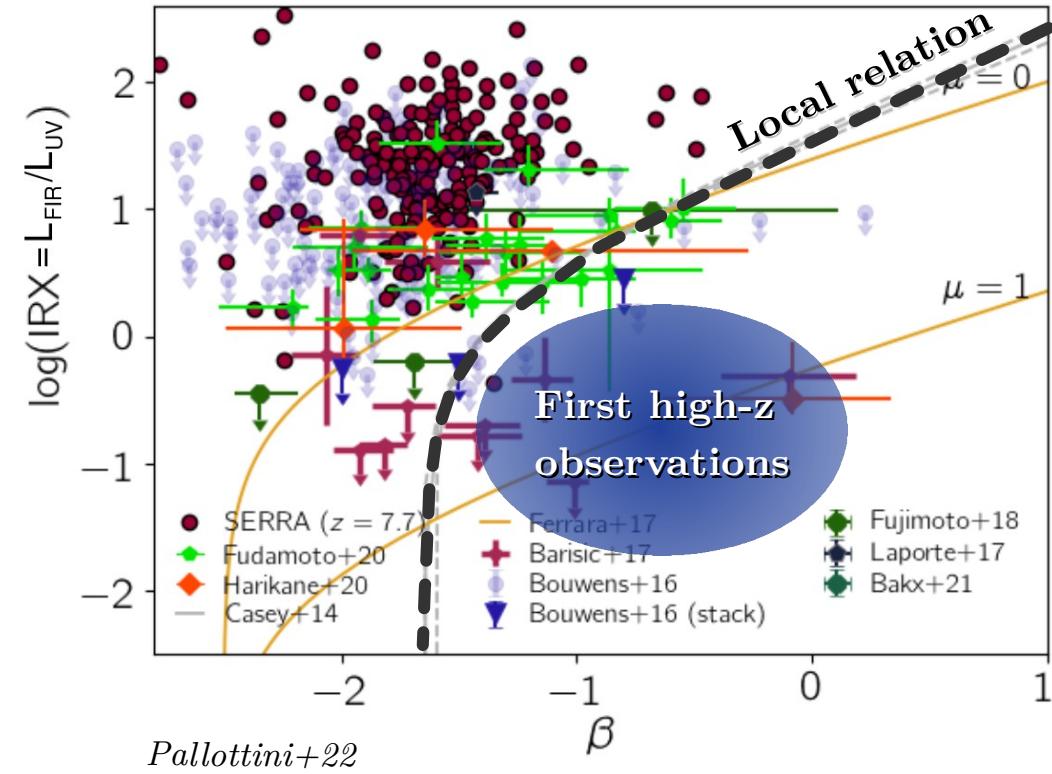
Spatial separation between UV and IR?



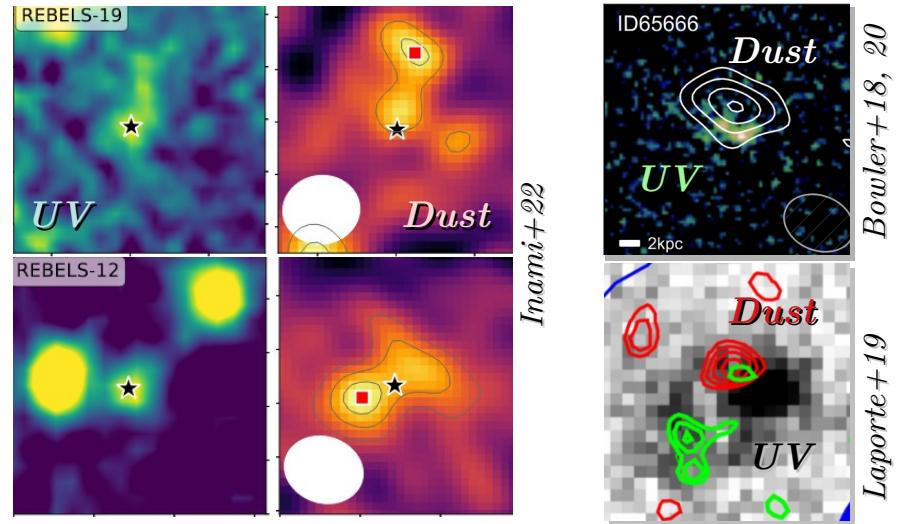
See also: Behrens+18, Liang+19...

Pallottini+22

# Can we trust the $\text{IRX}-\beta$ relation to correct for dust at high-z?



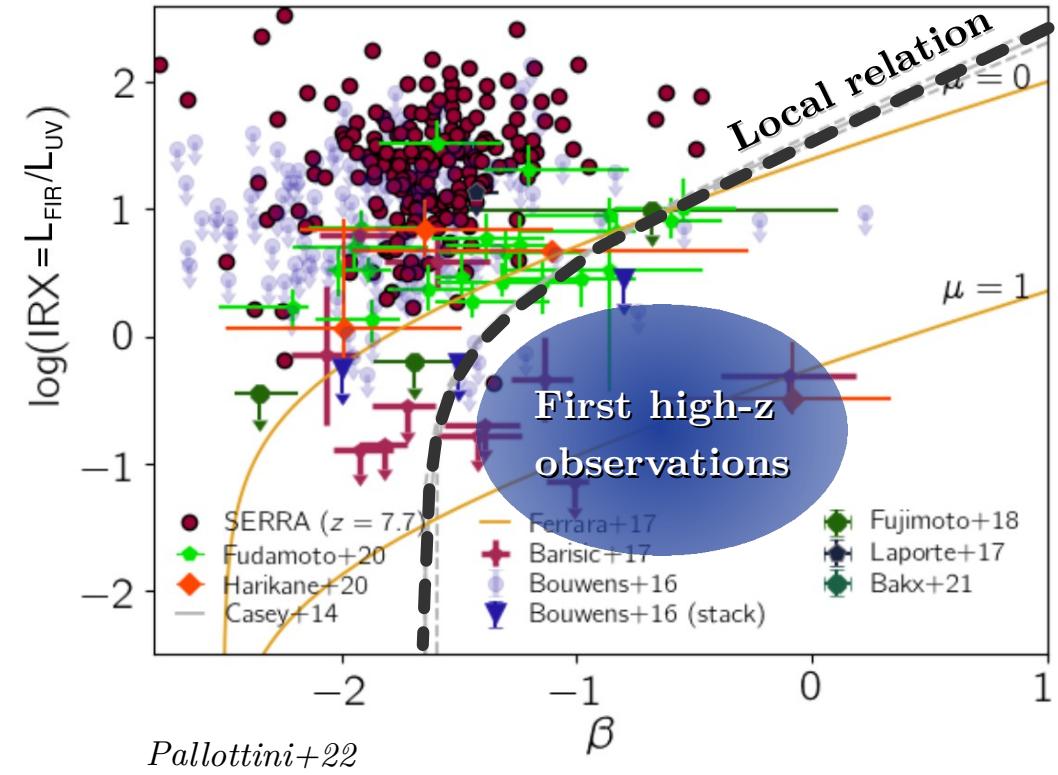
Spatial separation between UV and IR?



See also: Behrens+18, Liang+19...

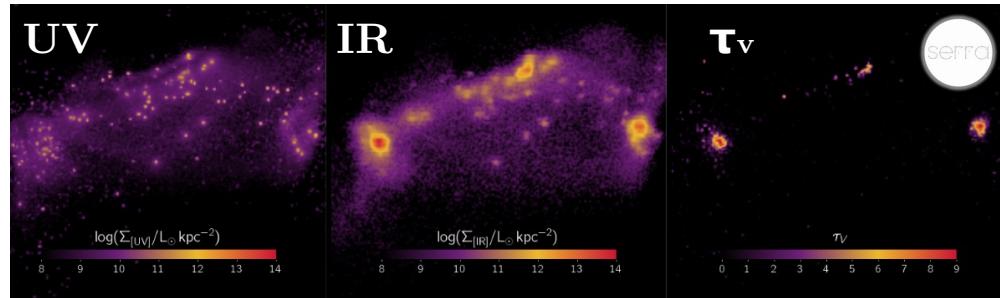
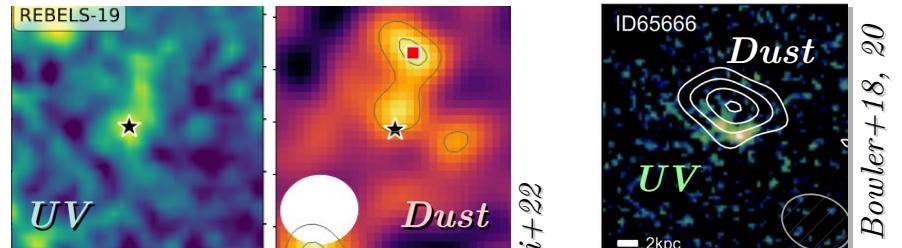
Pallottini+22

# Can we trust the $\text{IRX}-\beta$ relation to correct for dust at high-z?



See also: Behrens+18, Liang+19...

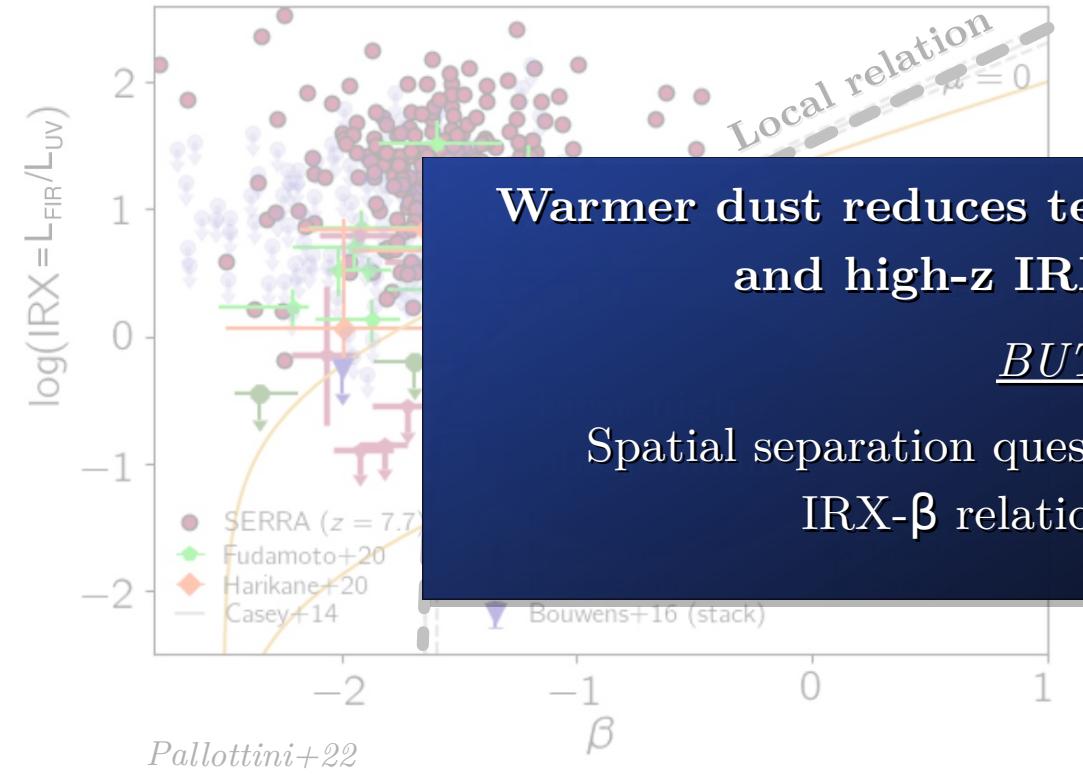
## Spatial separation between UV and IR?



Pallottini+22

# Can we trust the IRX- $\beta$ relation to correct for dust at high-z?

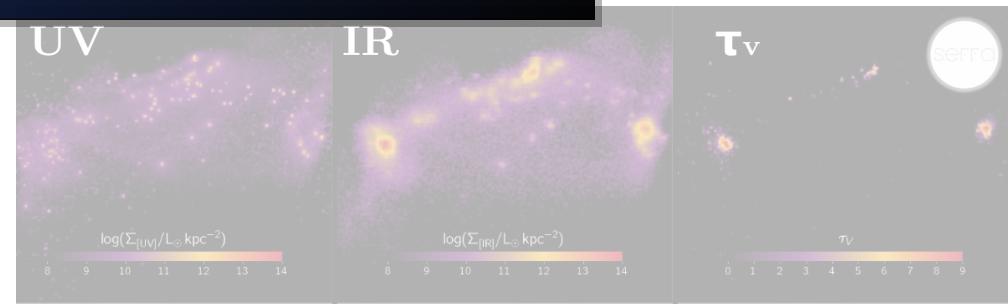
Spatial separation between UV and IR?



Warmer dust reduces tension between local  
and high-z IRX- $\beta$  relation

BUT:

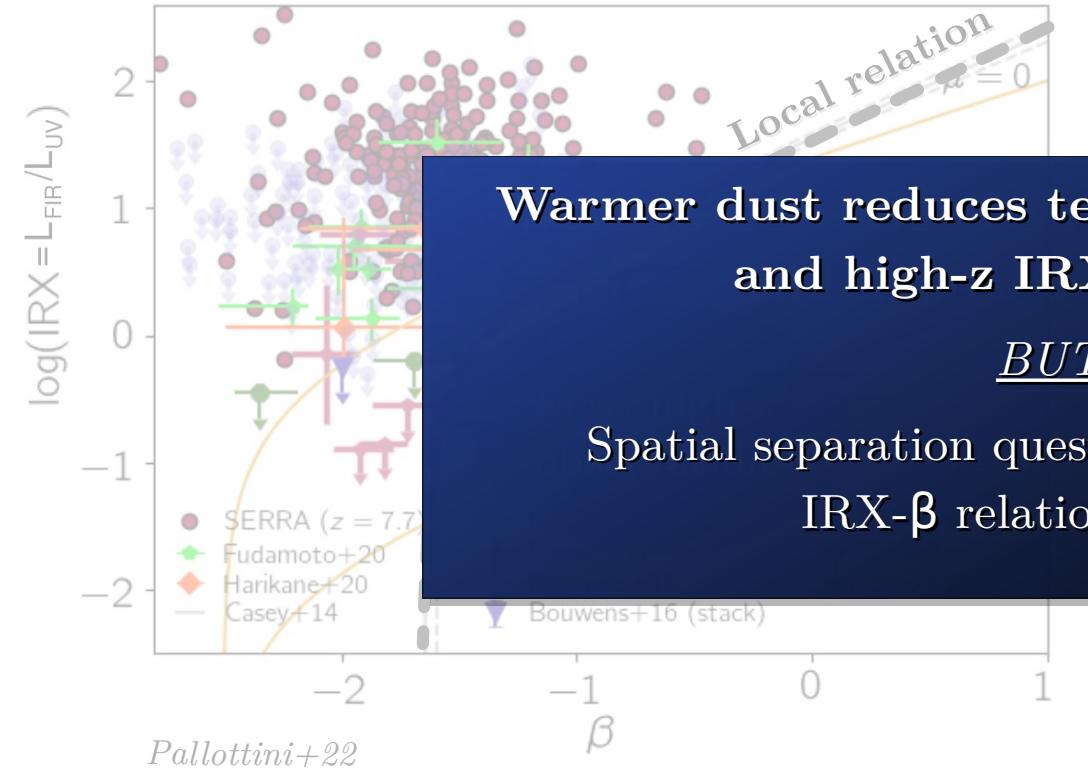
Spatial separation questions the validity of  
IRX- $\beta$  relation at high-z



See also: Behrens+18, Liang+19...

# Can we trust the $\text{IRX}-\beta$ relation to correct for dust at high-z?

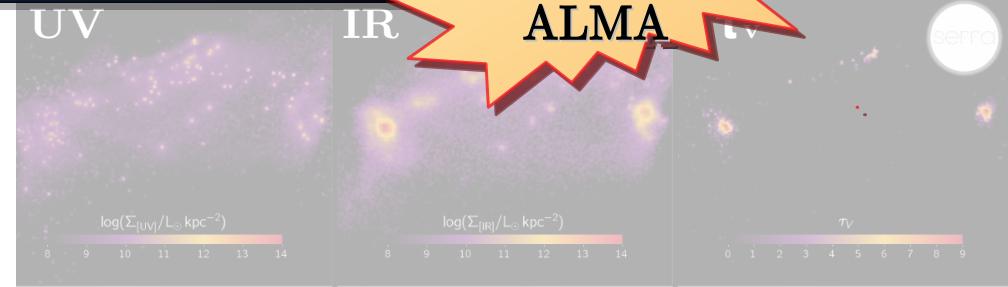
Spatial separation between UV and IR?



Warmer dust reduces tension between local  
and high-z  $\text{IRX}-\beta$  relation

BUT:

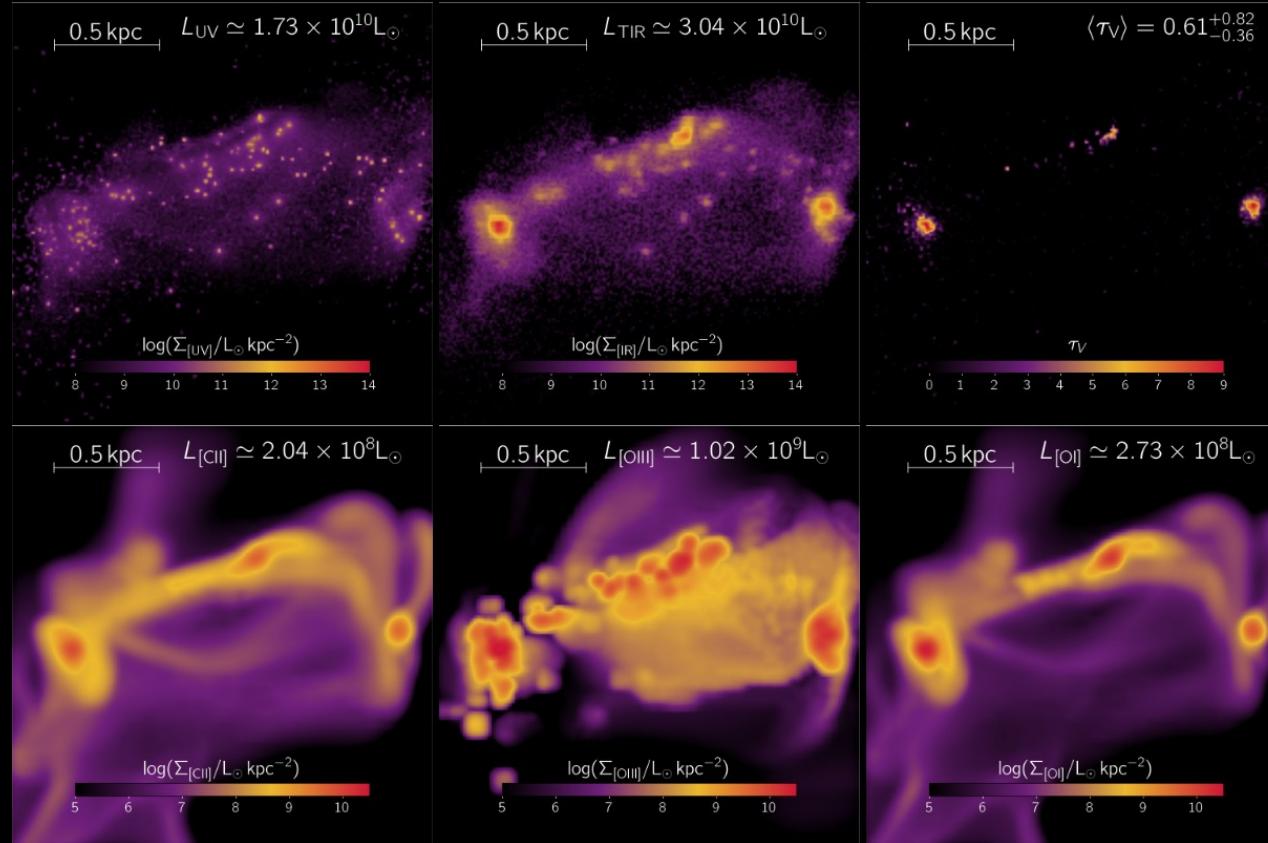
Spatial separation questions the validity of  
 $\text{IRX}-\beta$  relation at high-z



See also: Behrens+18, Liang+19...

# Hints from zoom-in simulations at high-z

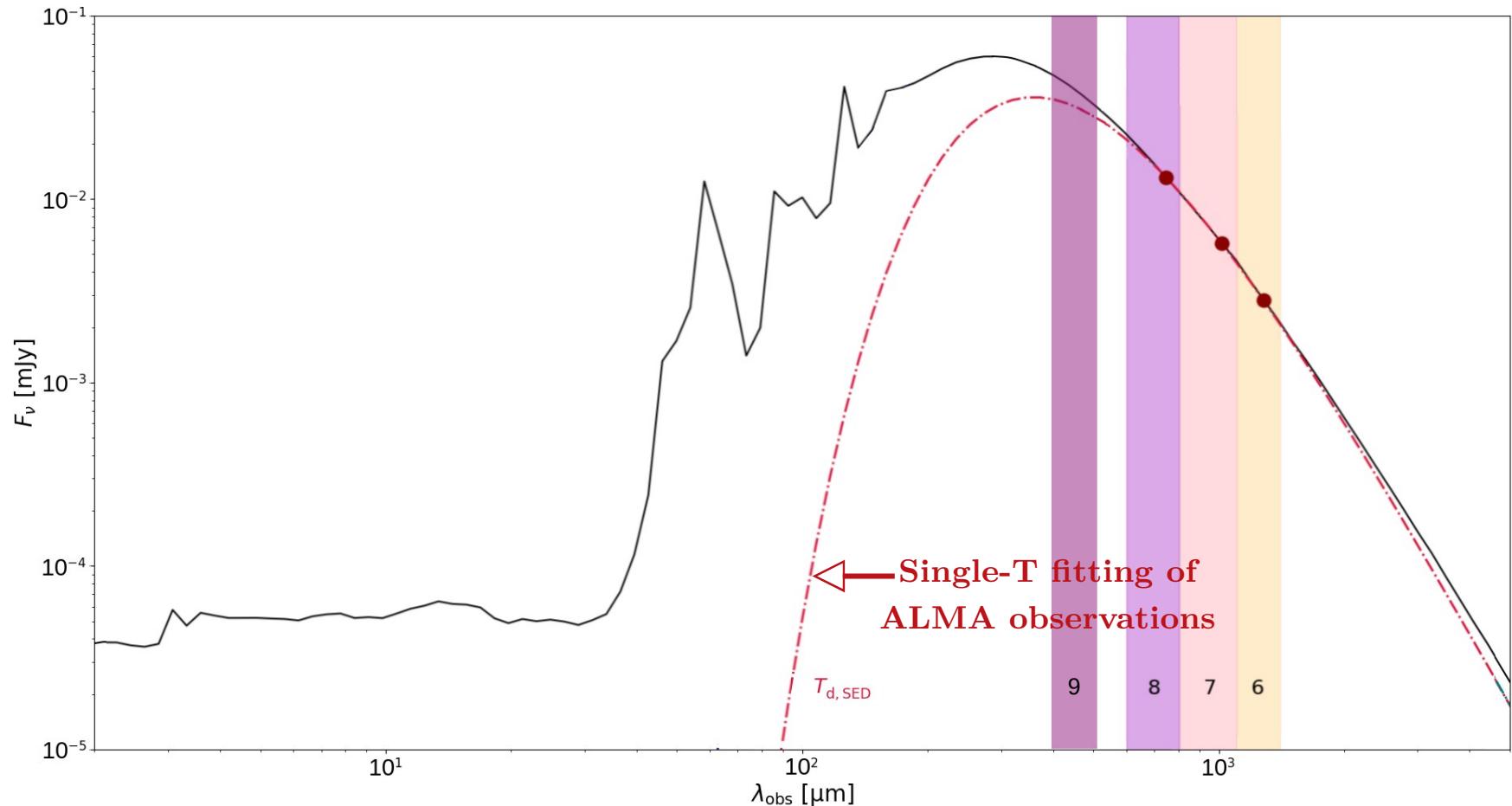
For SERRA simulations details, see: [Pallottini+22](#)



Galaxy	$z$	$F_{\nu_0}$ ( $\mu\text{Jy}$ )	$Z$ ( $Z_\odot$ )	$\log \Sigma_{\text{SFR}}$ ( $M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ )	$L_{\text{CII}}$ ( $10^8 L_\odot$ )	$\kappa_s$	$y = r_{\text{CII}}/r_\star$	$M_\star$ ( $10^9 M_\odot$ )
Zinnia	6.6847	2.81	0.07	2.56	2.05	4.29	1.00*	2.19

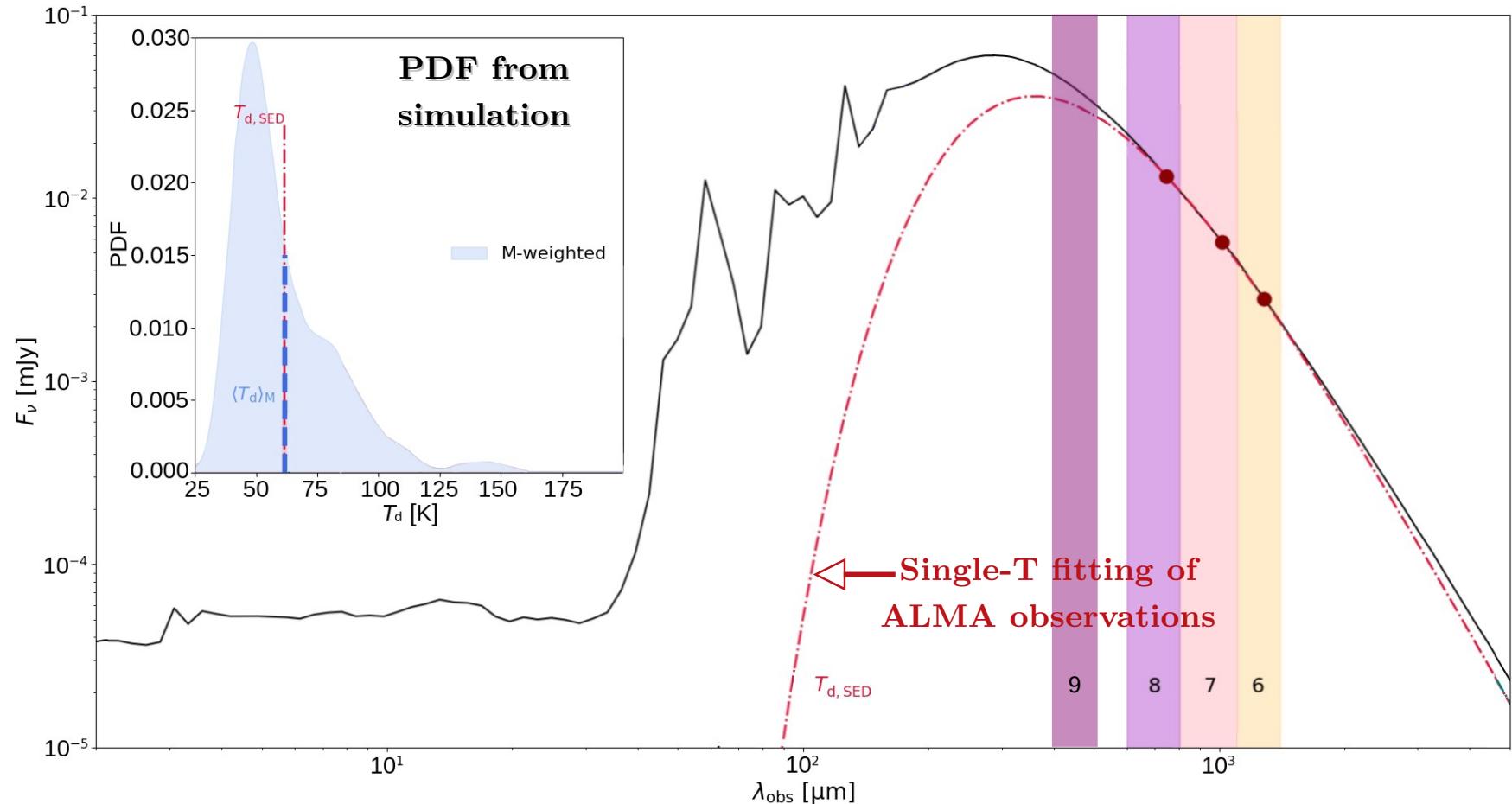
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



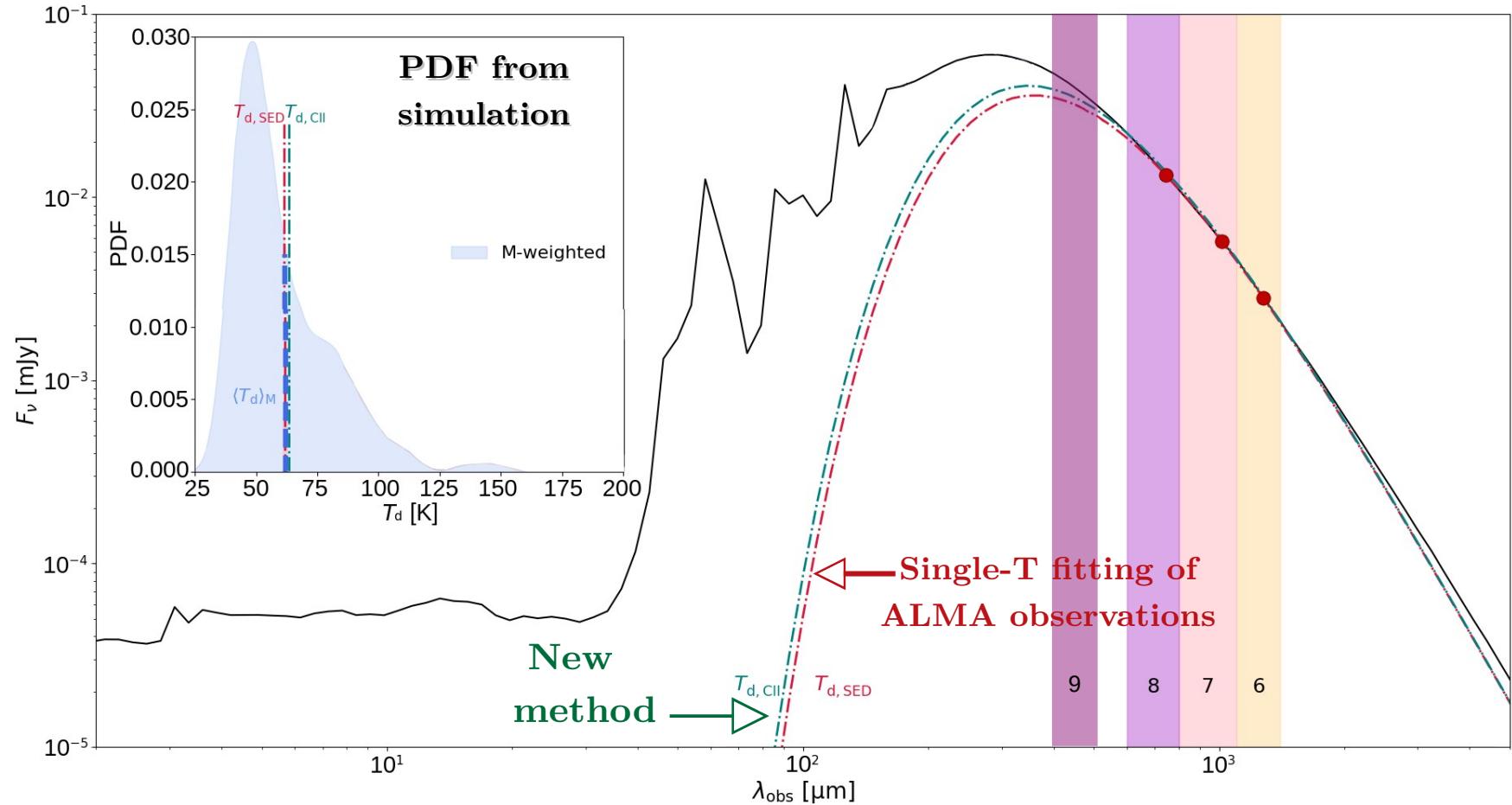
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



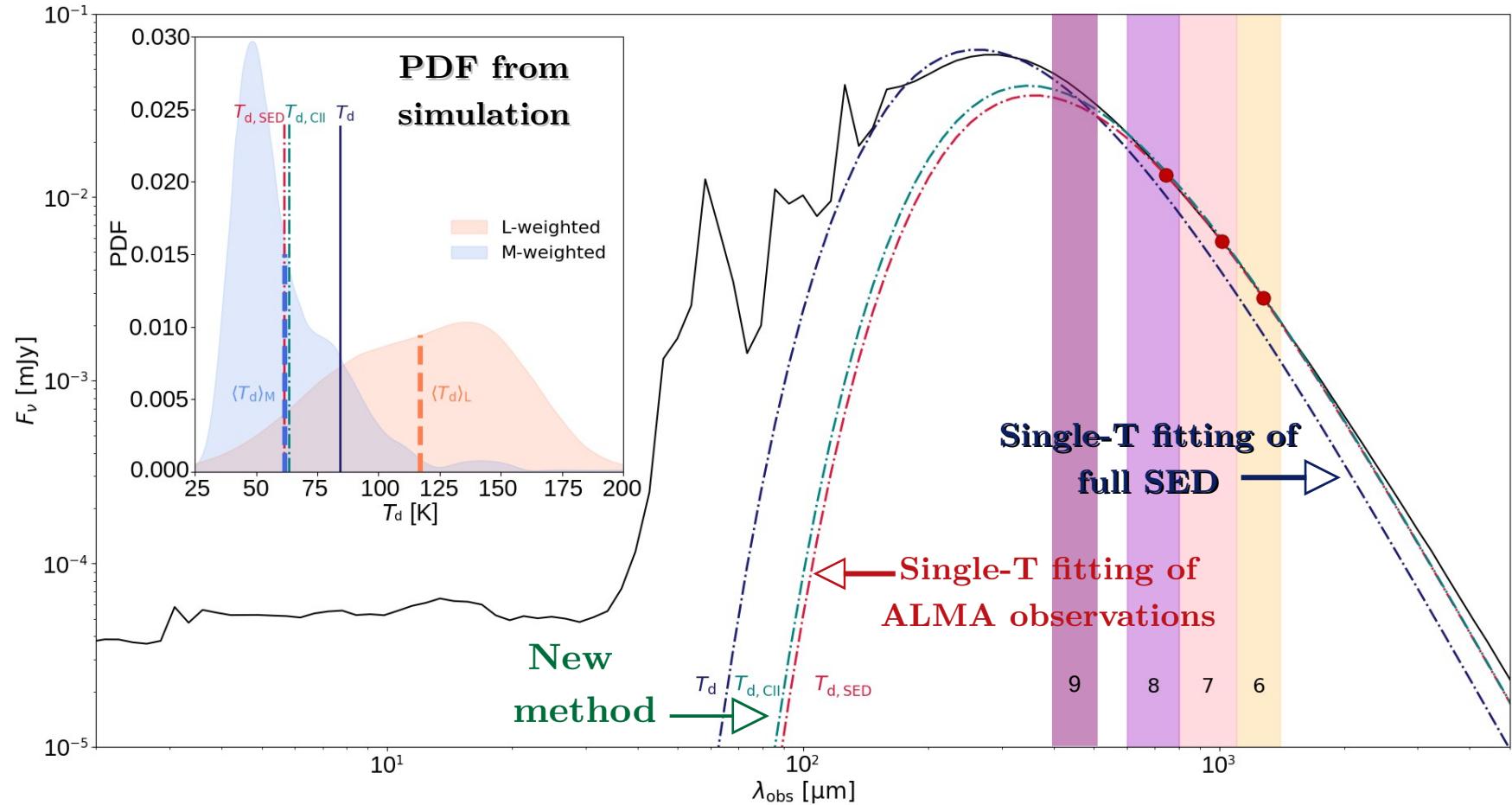
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



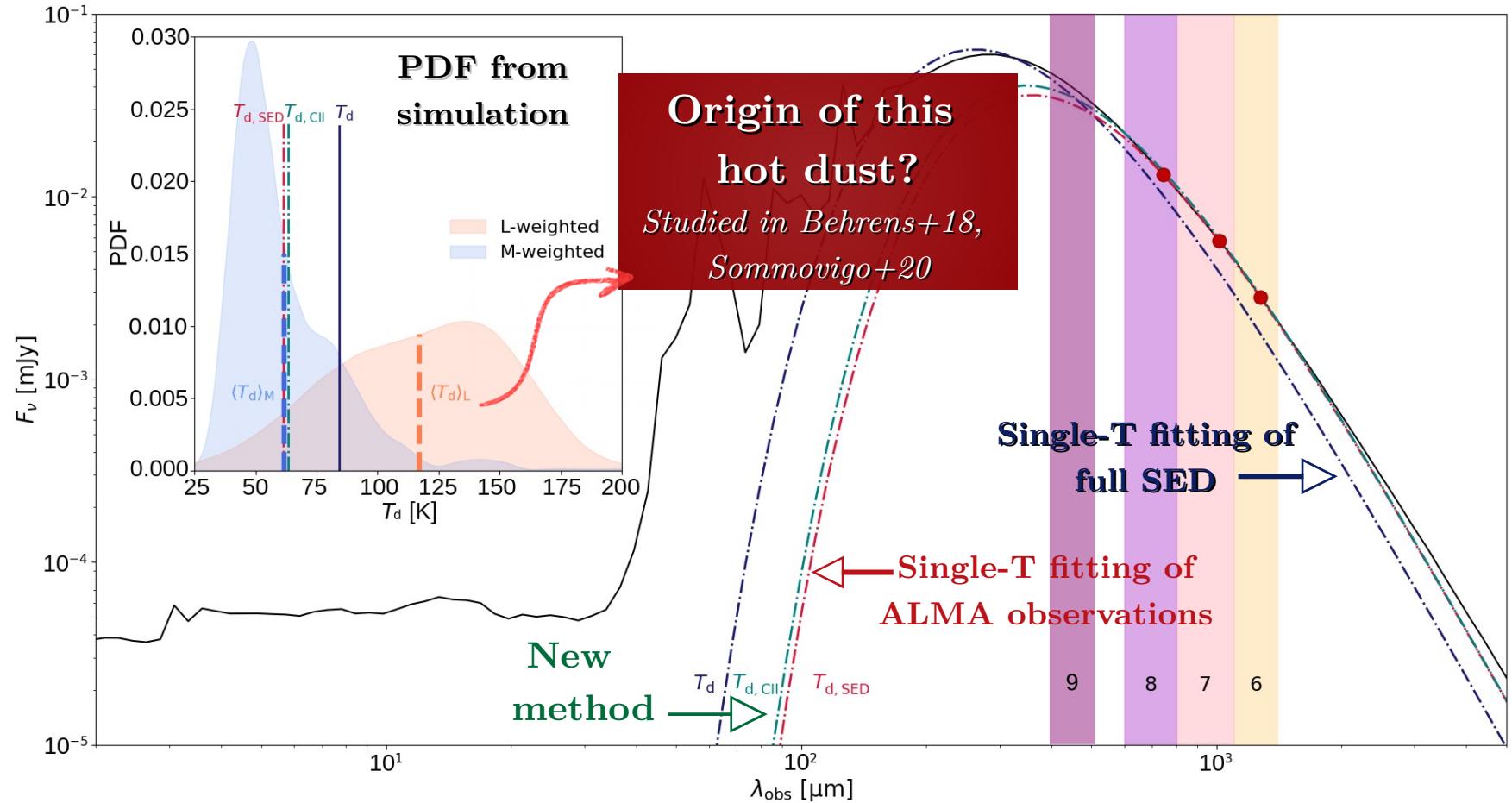
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



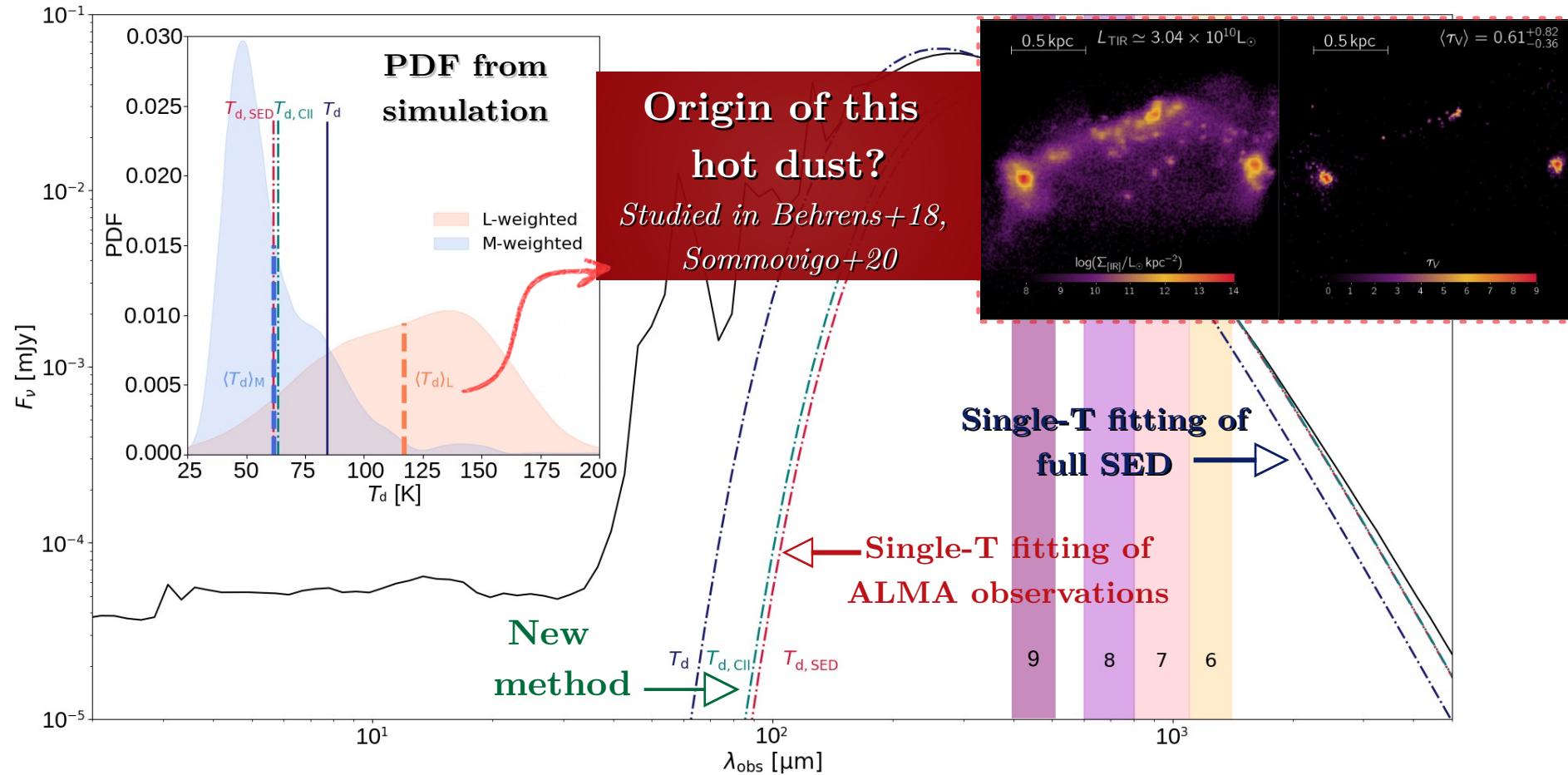
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



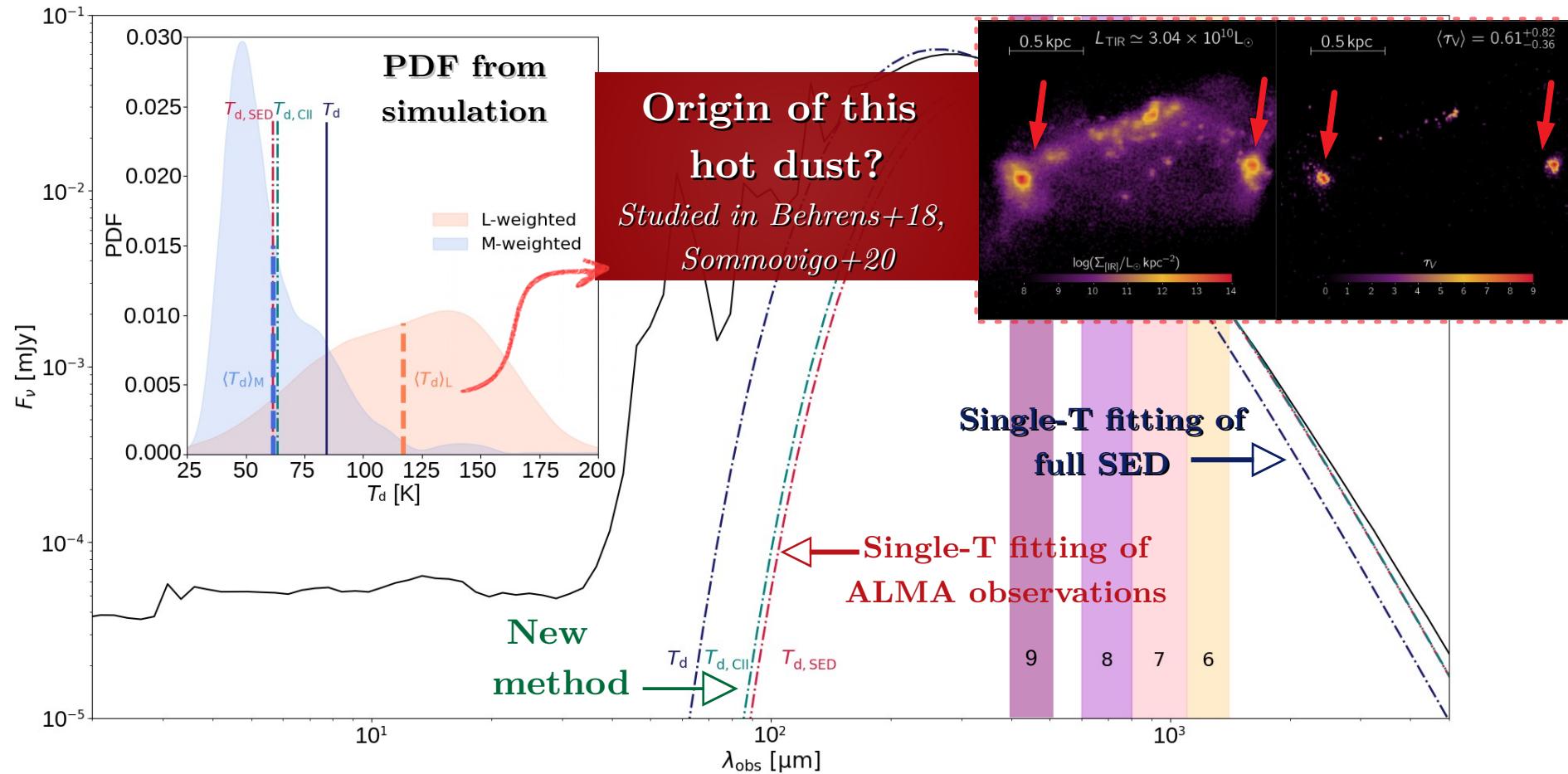
# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



# Hints from zoom-in simulations at high-z

Studying the spectrum of the simulated galaxy Zinnia at redshift  $z=6.7$ :



# Zoom-in on Giant Molecular Clouds

## GMC model:

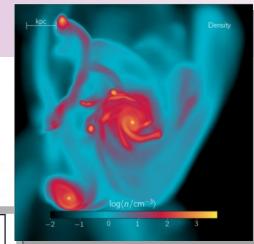
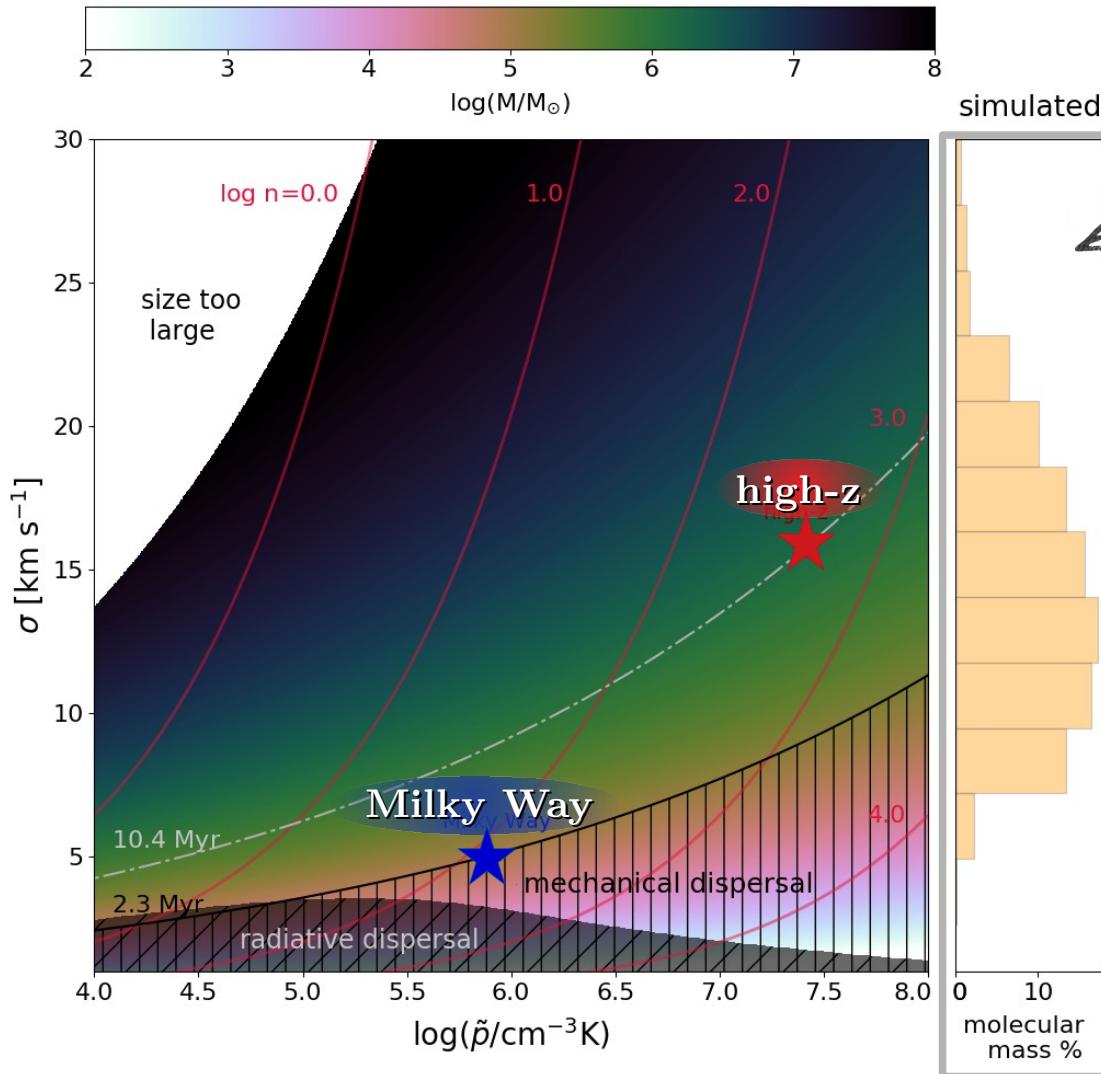
- Uniform density
- Star forming
- Turbulent,  $\sigma$
- Pressure supported, p
- $\alpha_{\text{vir}} = 5/3$

# Zoom-in on Giant Molecular Clouds

## GMC model:

- Uniform density
- Star forming
- Turbulent,  $\sigma$
- Pressure supported,  $p$
- $\alpha_{\text{vir}} = 5/3$

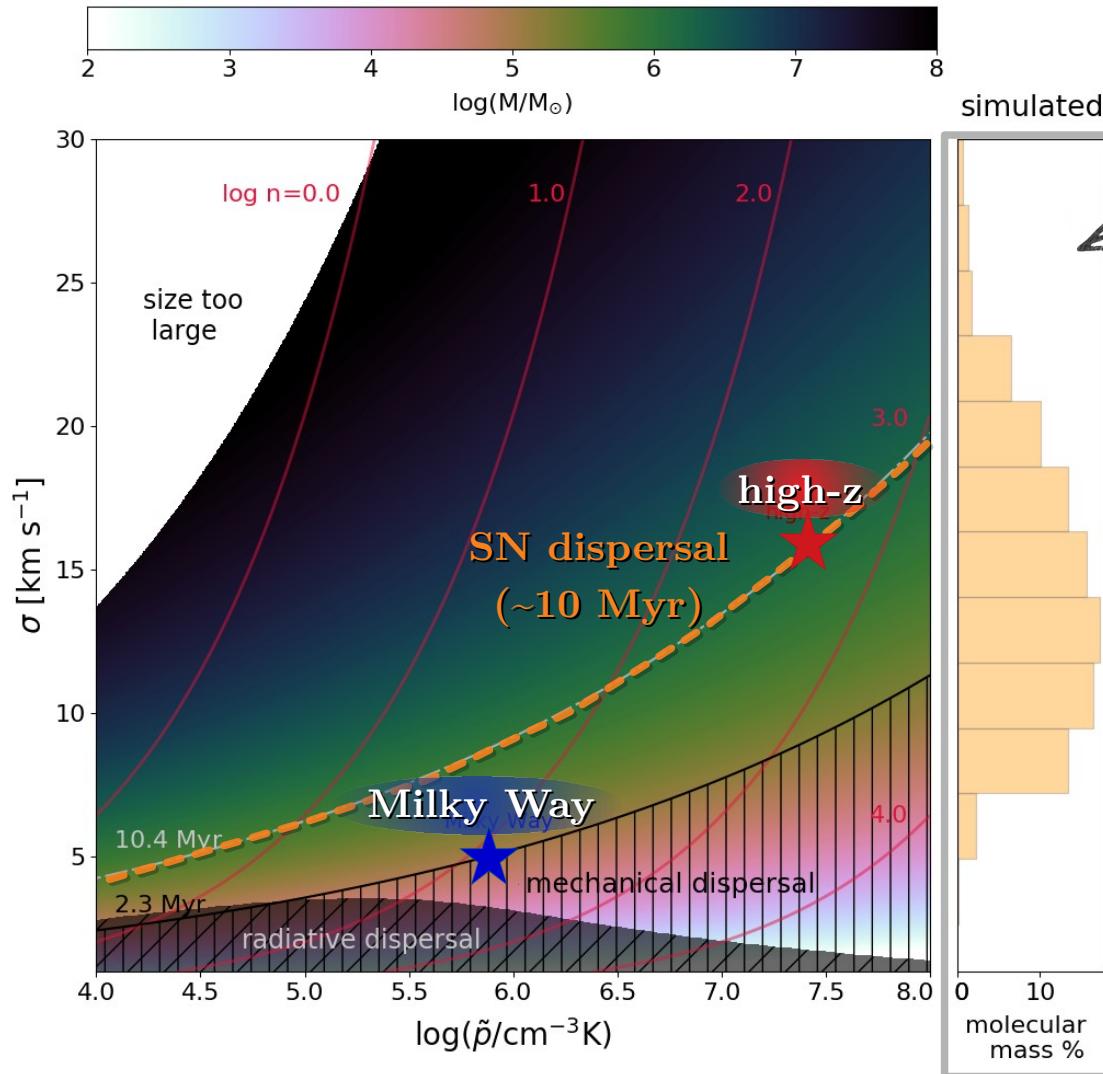
# Zoom-in on Giant Molecular Clouds



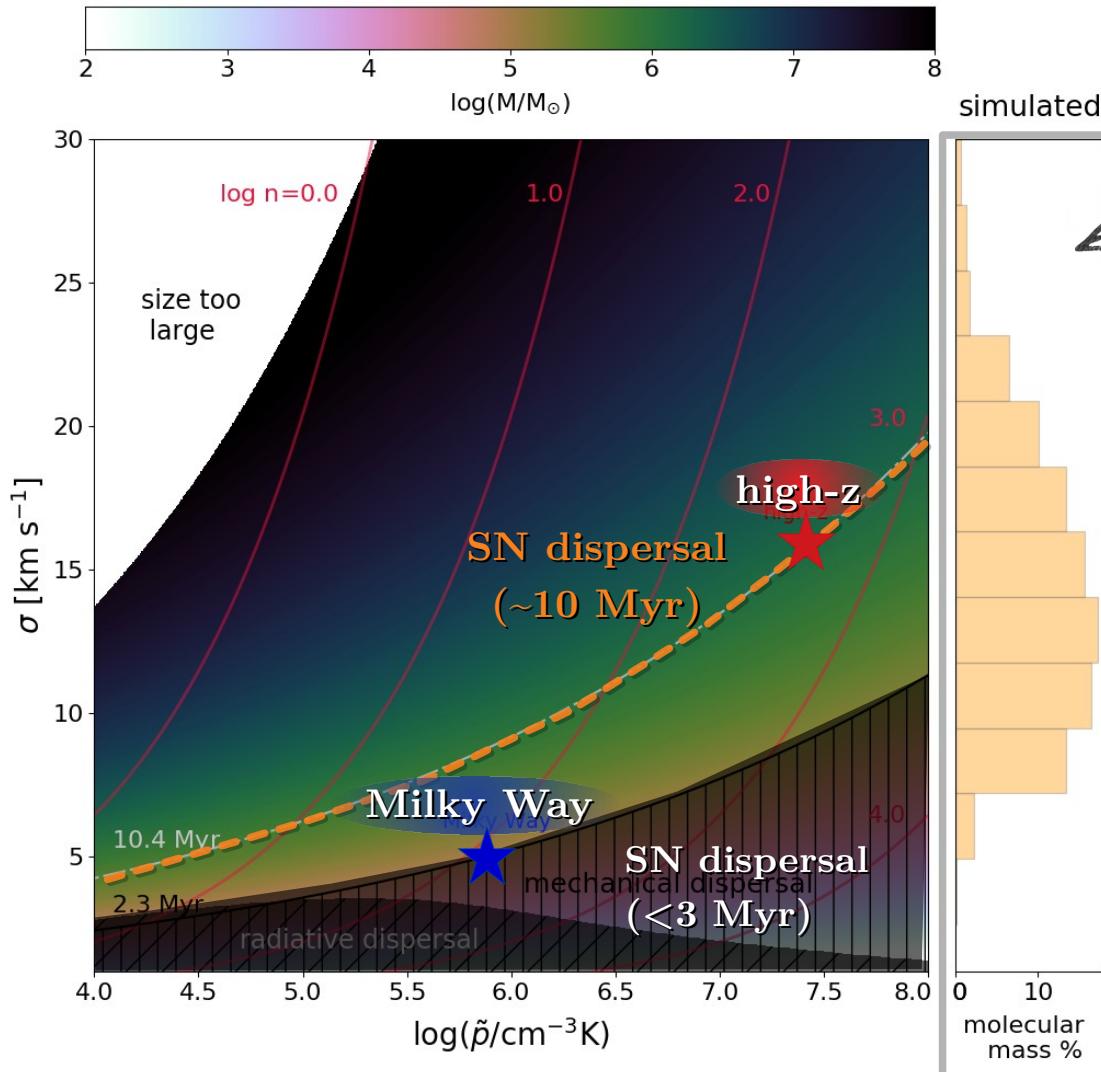
## GMC model:

- Uniform density
- Star forming
- Turbulent,  $\boxed{\sigma}$
- Pressure supported,  $\boxed{p}$
- $\alpha_{\text{vir}} = 5/3$

# Zoom-in on Giant Molecular Clouds



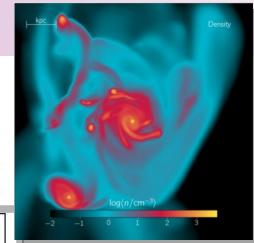
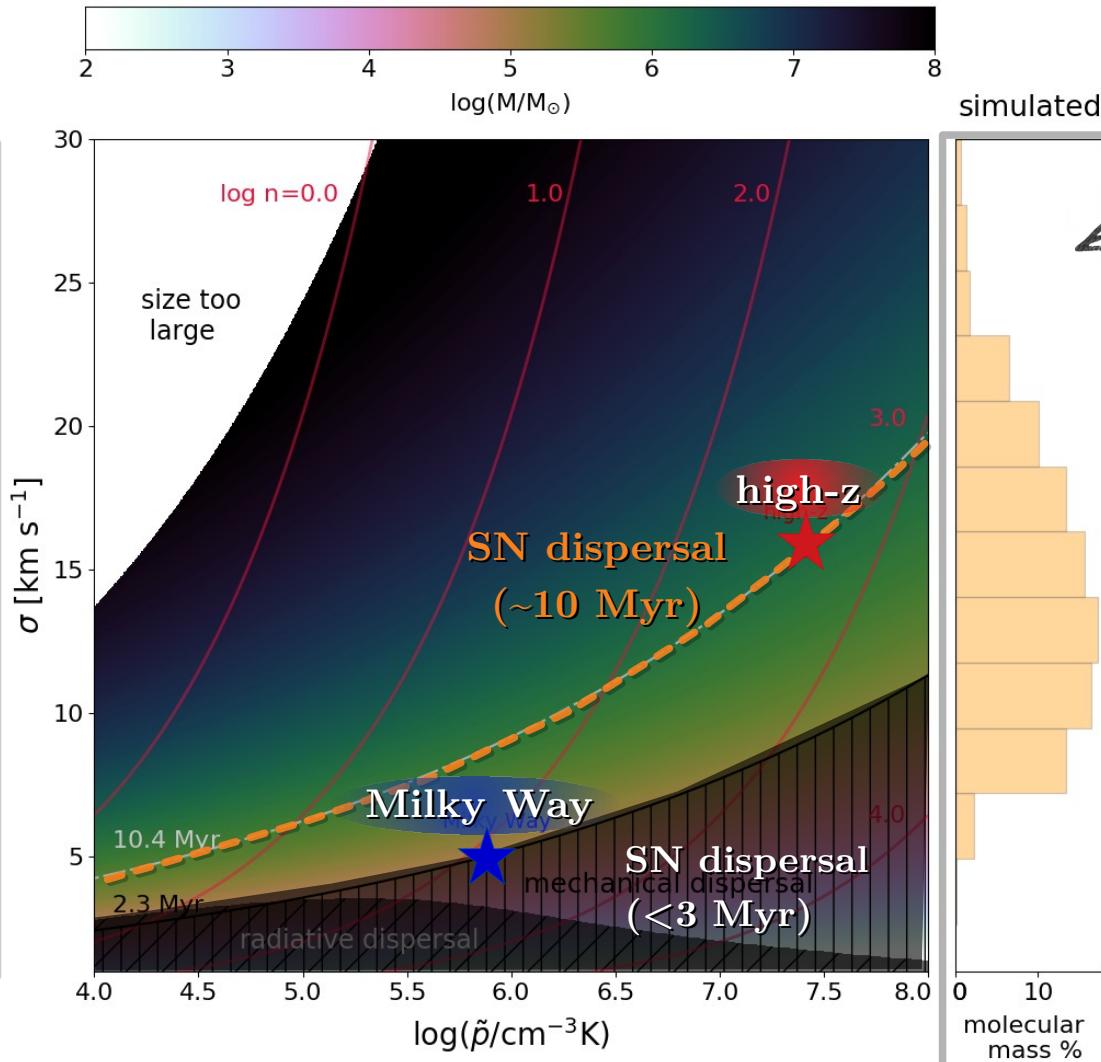
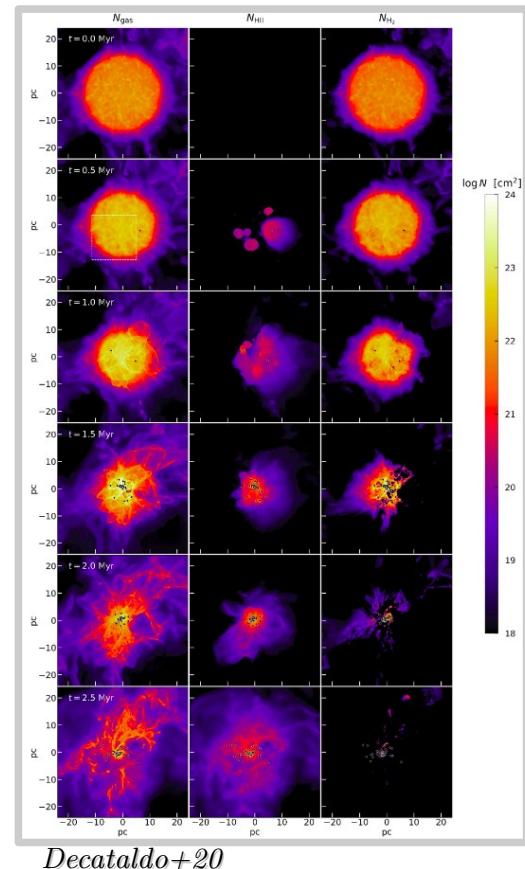
# Zoom-in on Giant Molecular Clouds



## GMC model:

- Uniform density
  - Star forming
  - Turbulent,  $\sigma$
  - Pressure supported, p
  - $\alpha_{\text{vir}} = 5/3$

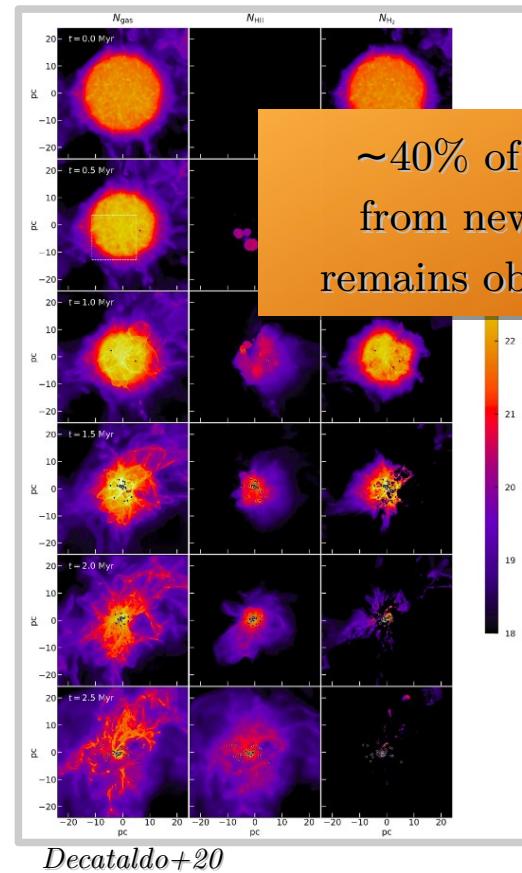
# Zoom-in on Giant Molecular Clouds



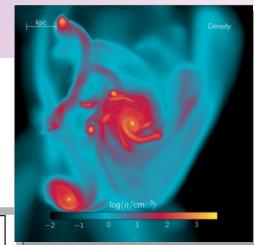
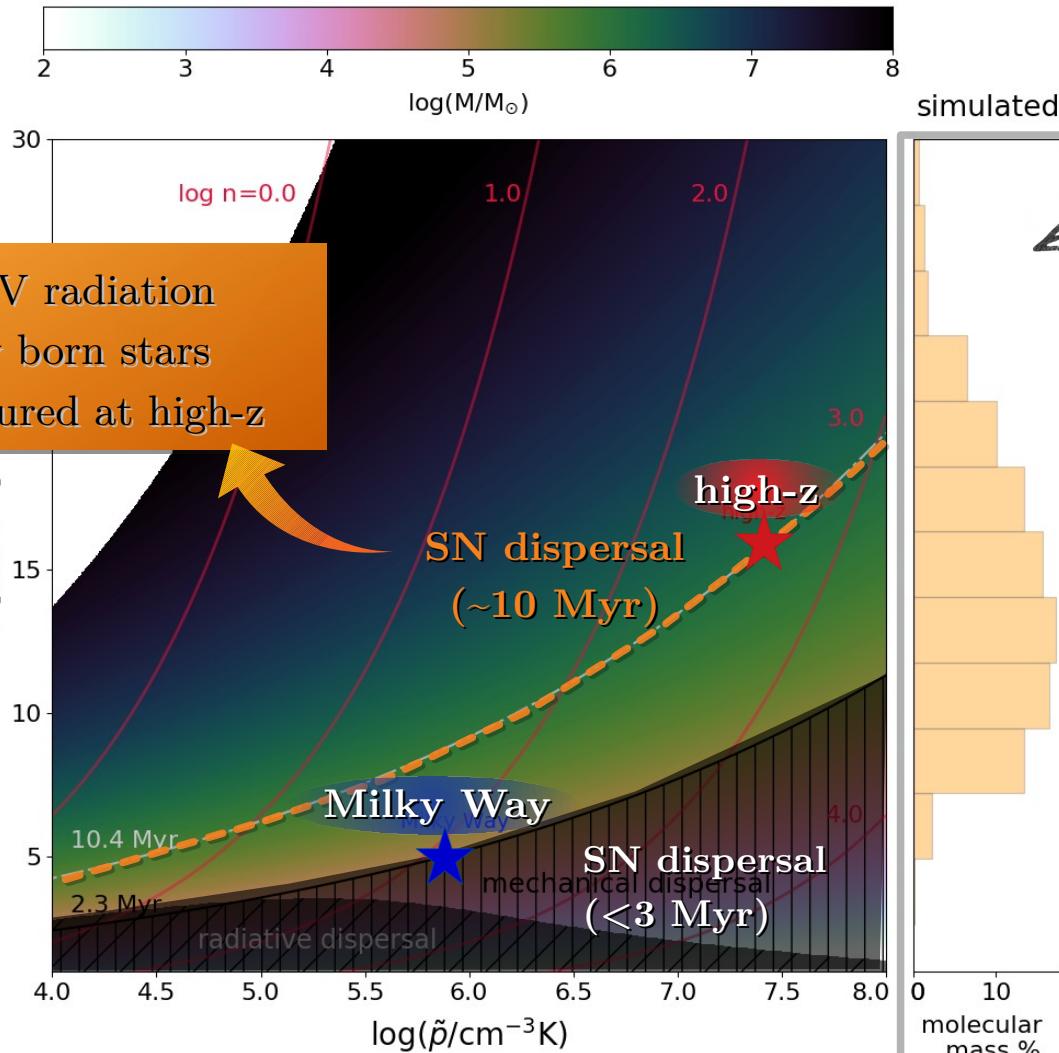
## GMC model:

- Uniform density
- Star forming
- Turbulent,  $\sigma$
- Pressure supported,  $p$
- $\alpha_{\text{vir}} = 5/3$

# Zoom-in on Giant Molecular Clouds



~40% of UV radiation  
from newly born stars  
remains obscured at high-z

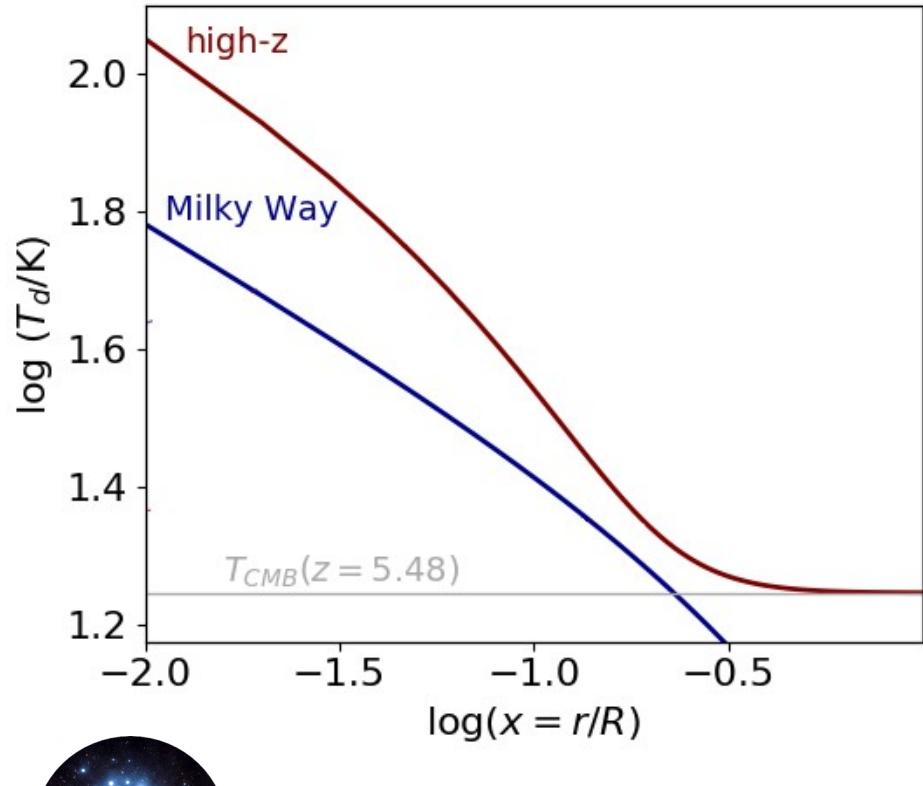


## GMC model:

- Uniform density
- Star forming
- Turbulent,  $\sigma$
- Pressure supported,  $p$
- $\alpha_{\text{vir}} = 5/3$

# Zoom-in on Giant Molecular Clouds

## Uniform cloud



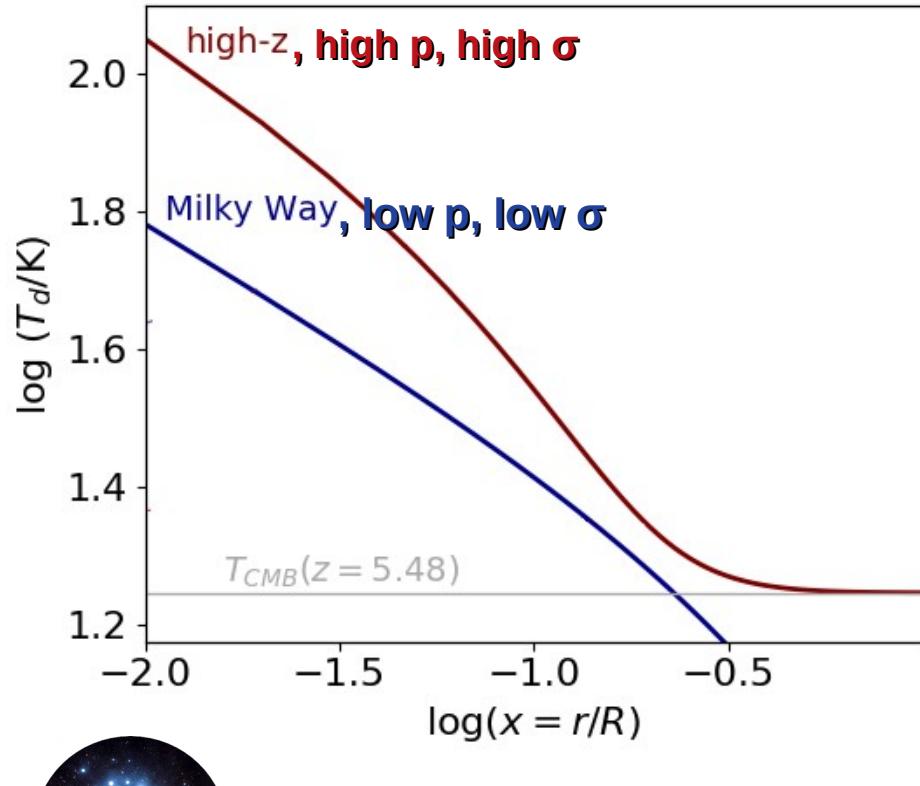
Towards the center of the cloud

(MW grain size distribution: *Weingartner & Draine, 2001*)

*Sommovigo+20*

# Zoom-in on Giant Molecular Clouds

## Uniform cloud



Towards the center of the cloud

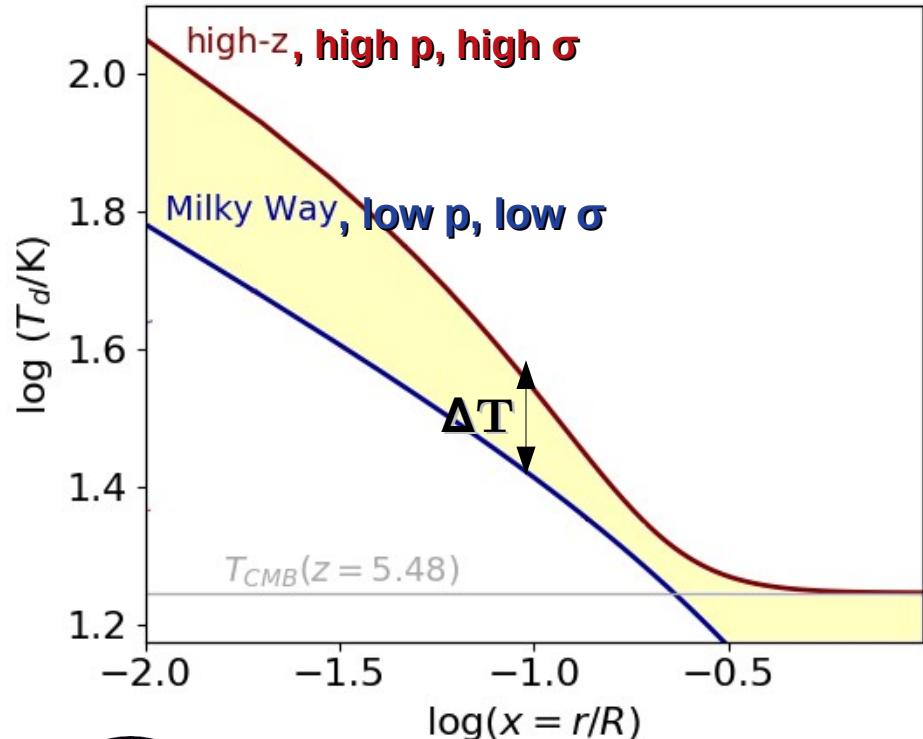
(MW grain size distribution: *Weingartner & Draine, 2001*)

Sommovigo+20

# Zoom-in on Giant Molecular Clouds

Uniform cloud

- Hotter dust due to high pressure at high- $z$



Towards the center of the cloud

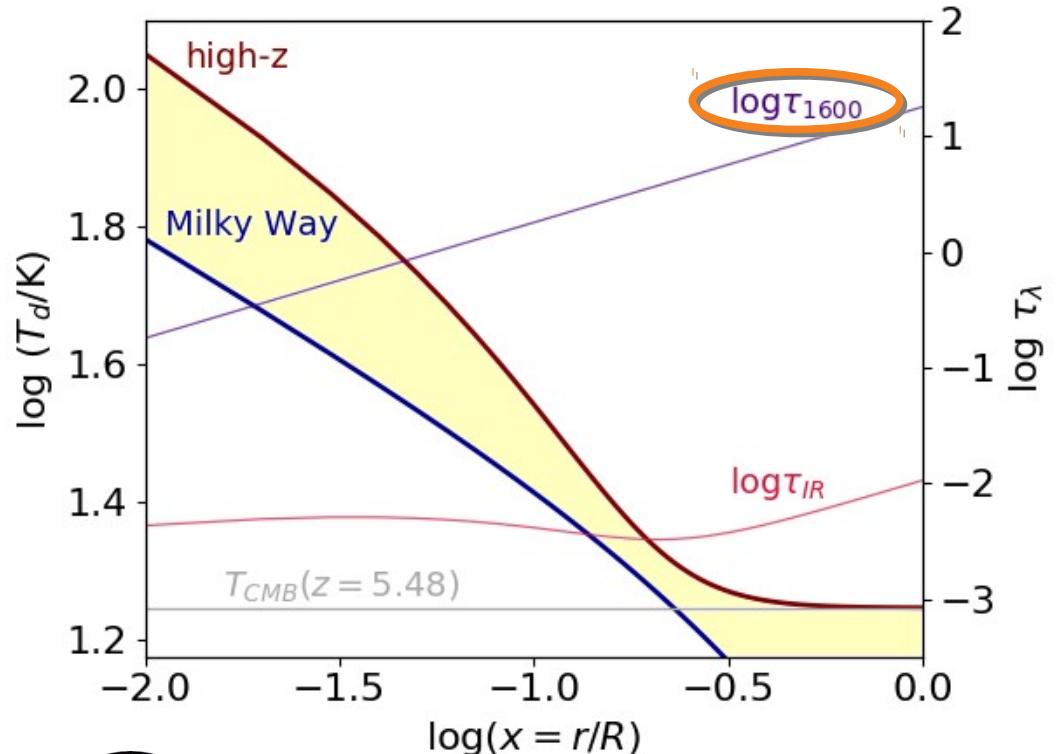
(MW grain size distribution: Weingartner & Draine, 2001)

Sommovigo+20

# Zoom-in on Giant Molecular Clouds

Uniform cloud

- Hotter dust due to high pressure at high- $z$



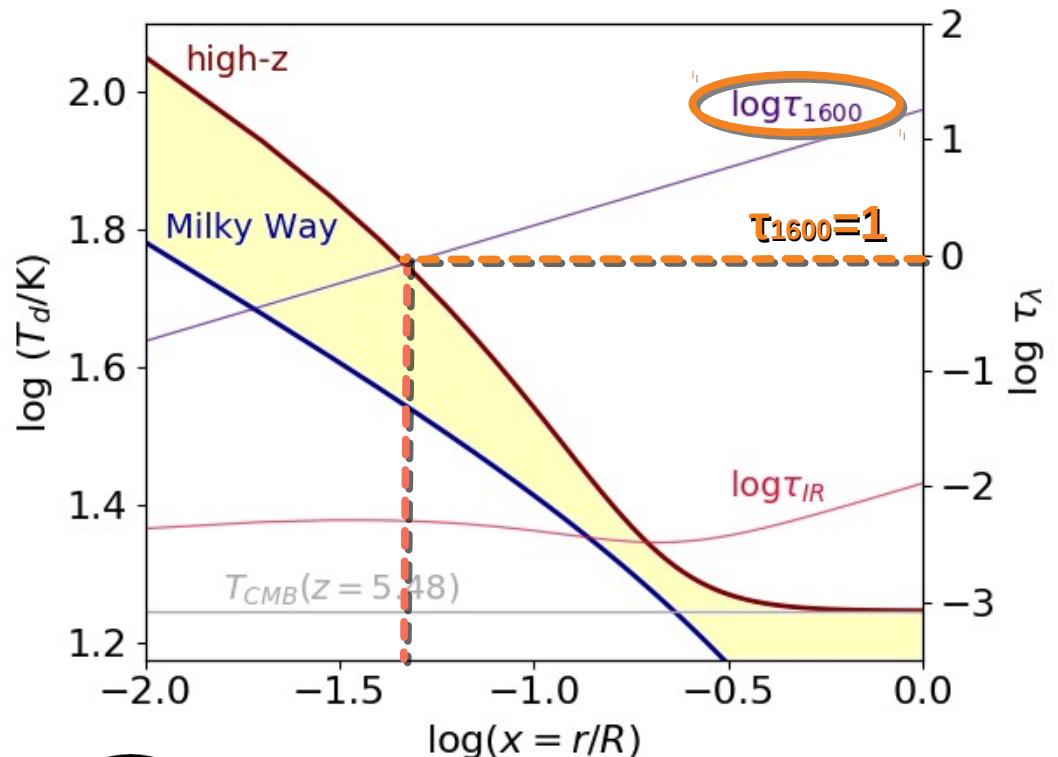
Towards the center of the cloud

$$\tau_\lambda \propto N_H \propto p^{1/2}$$

# Zoom-in on Giant Molecular Clouds

Uniform cloud

- Hotter dust due to high pressure at high- $z$

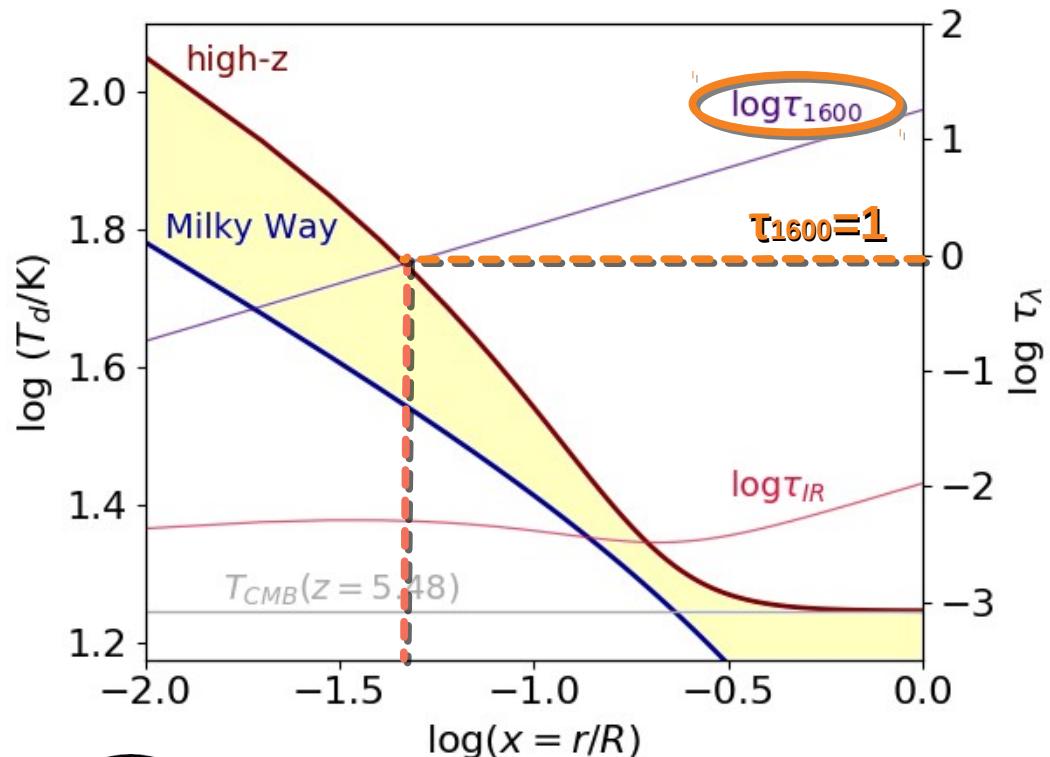


Towards the center of the cloud

$$\tau_\lambda \propto N_H \propto p^{1/2}$$

# Zoom-in on Giant Molecular Clouds

Uniform cloud



Towards the center of the cloud

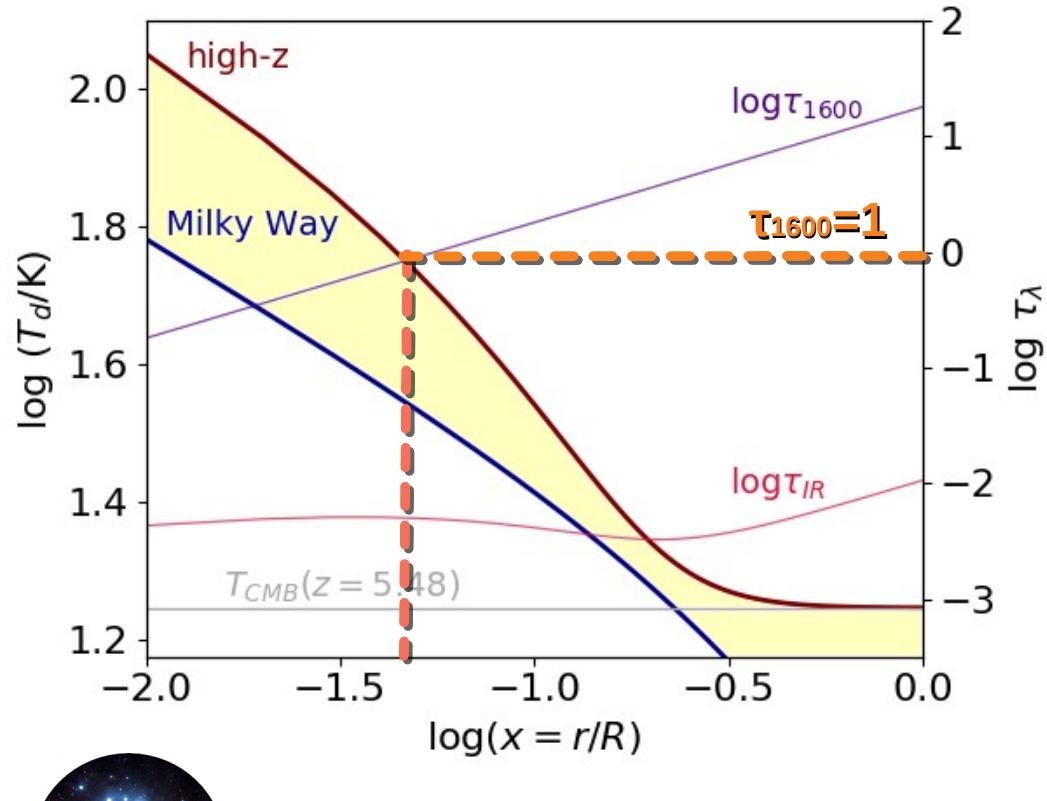
- Hotter dust due to high pressure at high- $z$

$$\tau_\lambda \propto N_H \propto p^{1/2}$$

Dust is hotter due to compact  
dust configuration in high- $z$   
GMCs

# Dust temperature in GMCs

## Uniform cloud



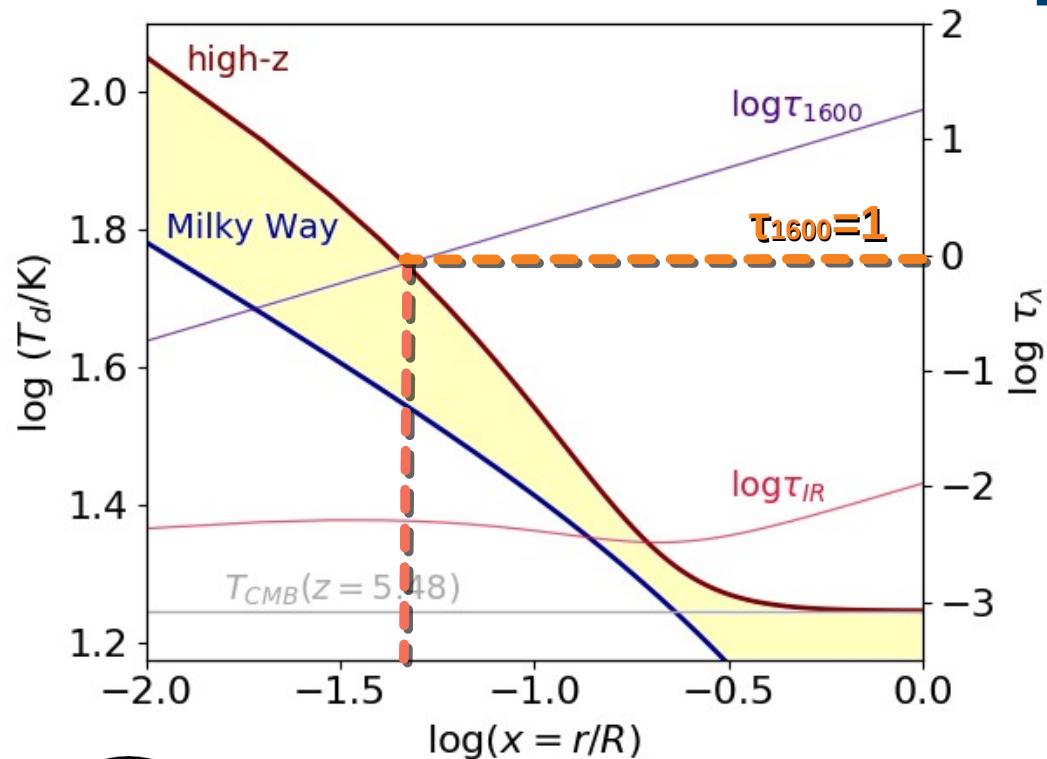
← Towards the center of the cloud

(MW grain size distribution: Weingartner & Draine+01)

Sommovigo+20

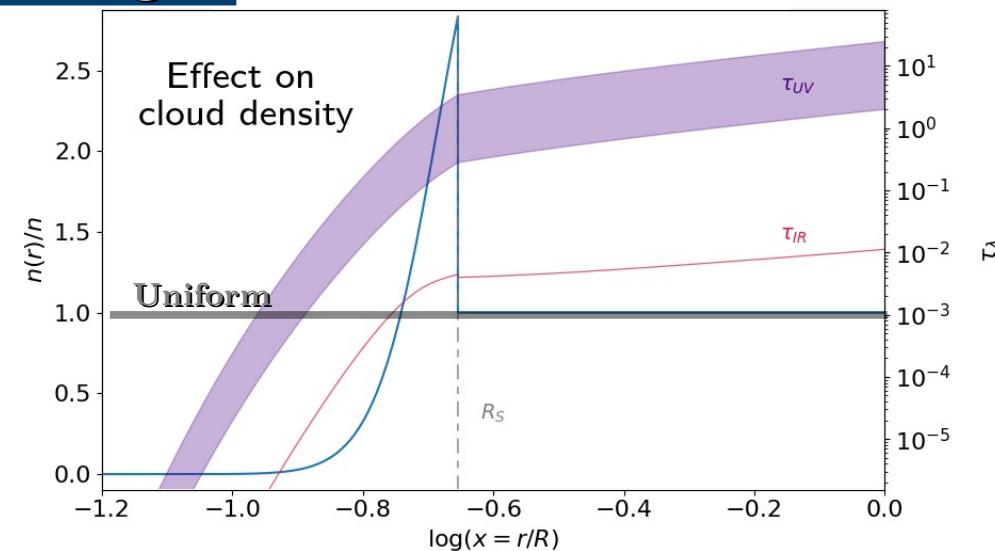
# Dust temperature in GMCs

## Uniform cloud



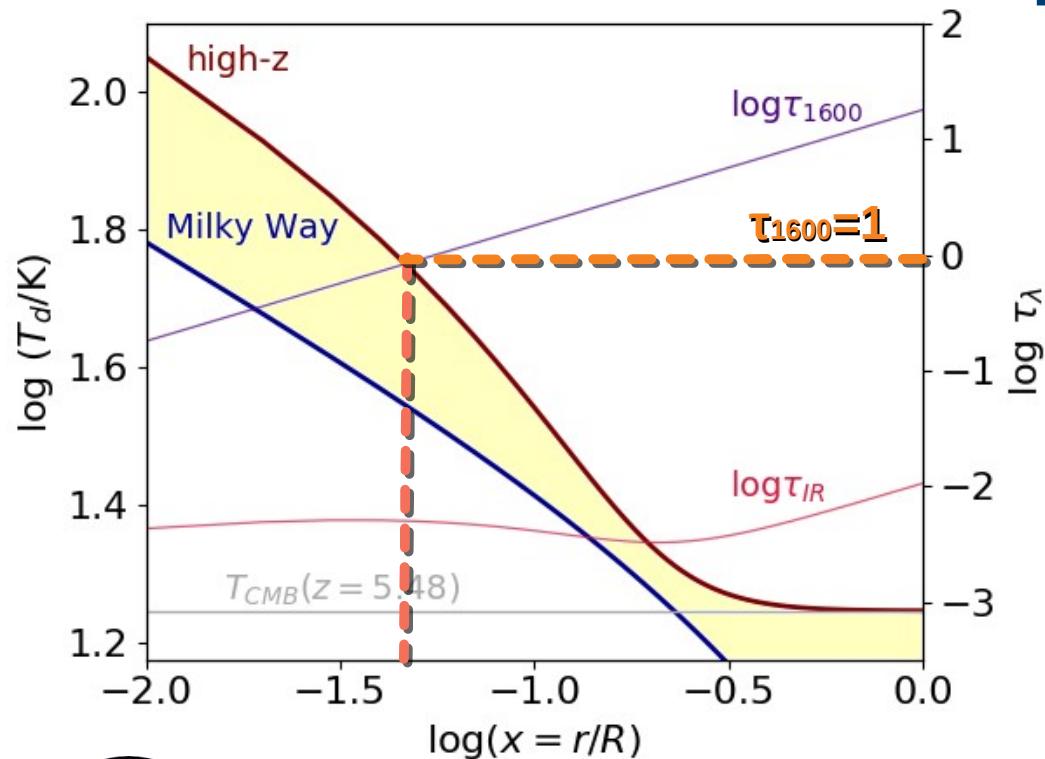
Towards the center of the cloud

Adding : **Radiation pressure** *Draine+11*



# Dust temperature in GMCs

## Uniform cloud

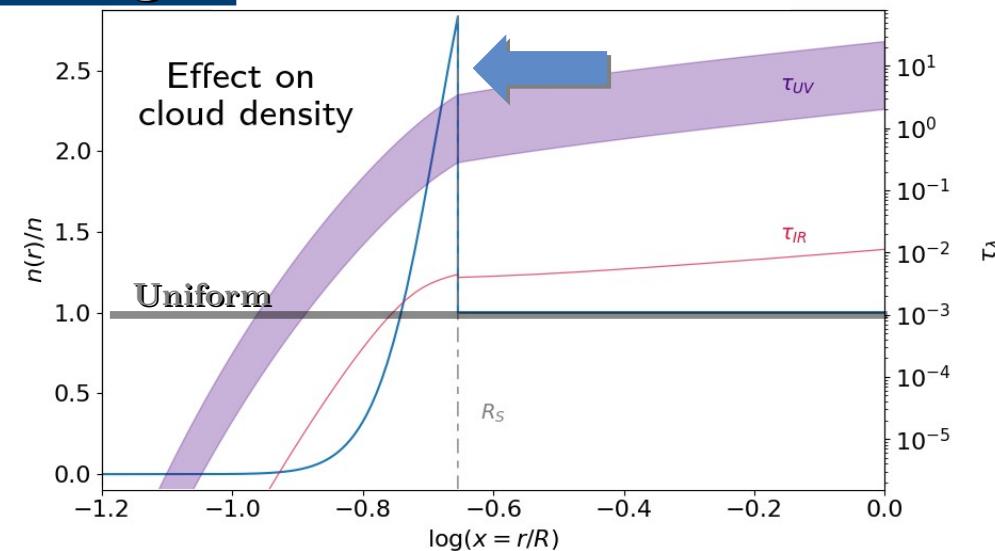


Towards the center of the cloud

Adding :

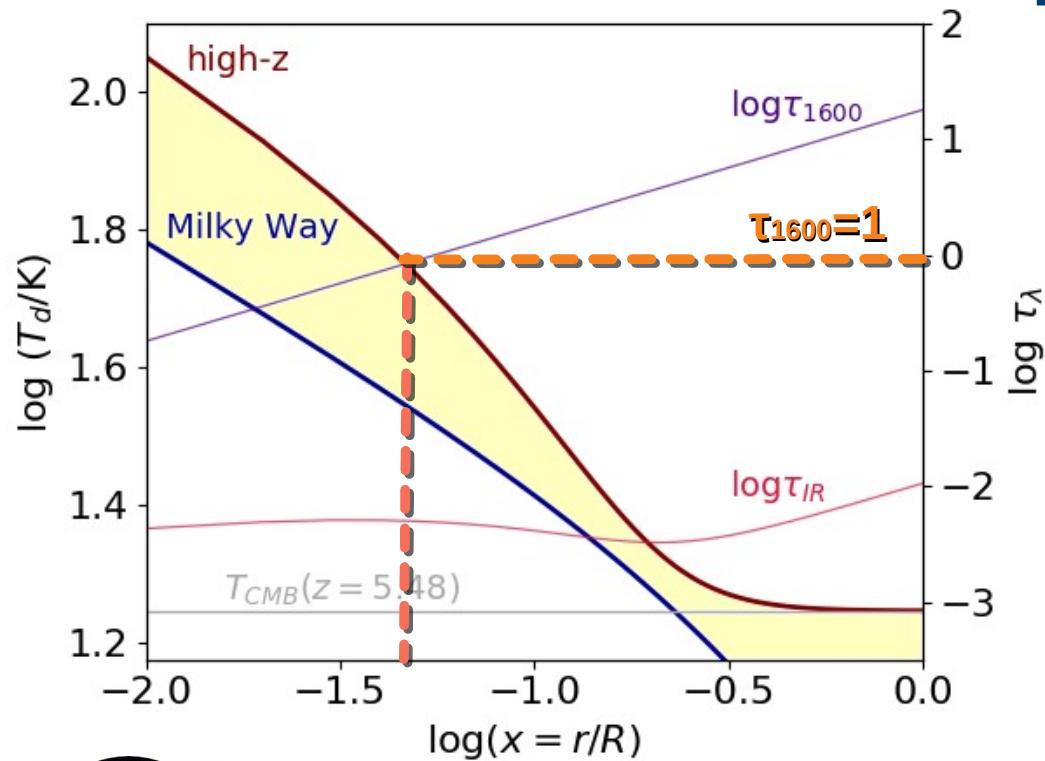
**Radiation pressure**

Draine+11



# Dust temperature in GMCs

## Uniform cloud

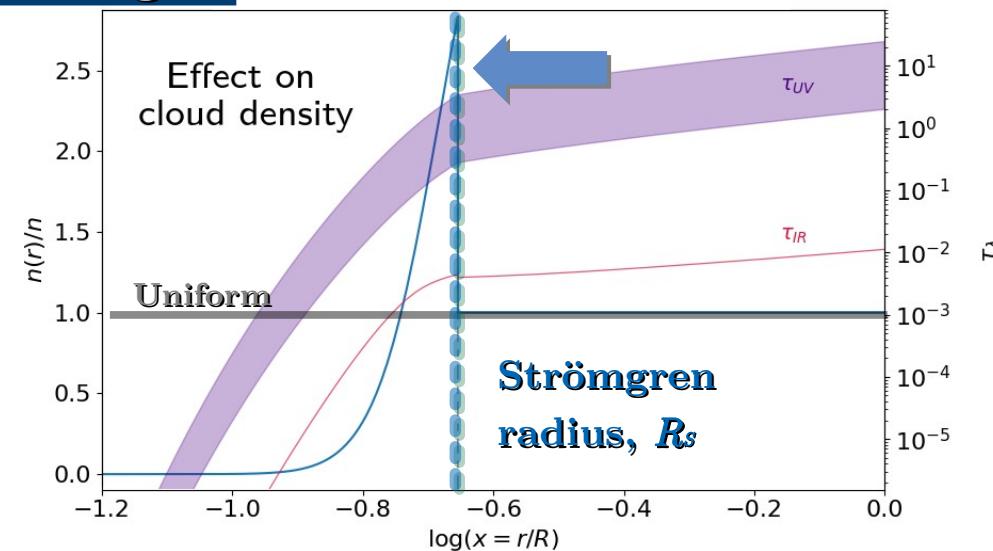


Towards the center of the cloud

Adding :

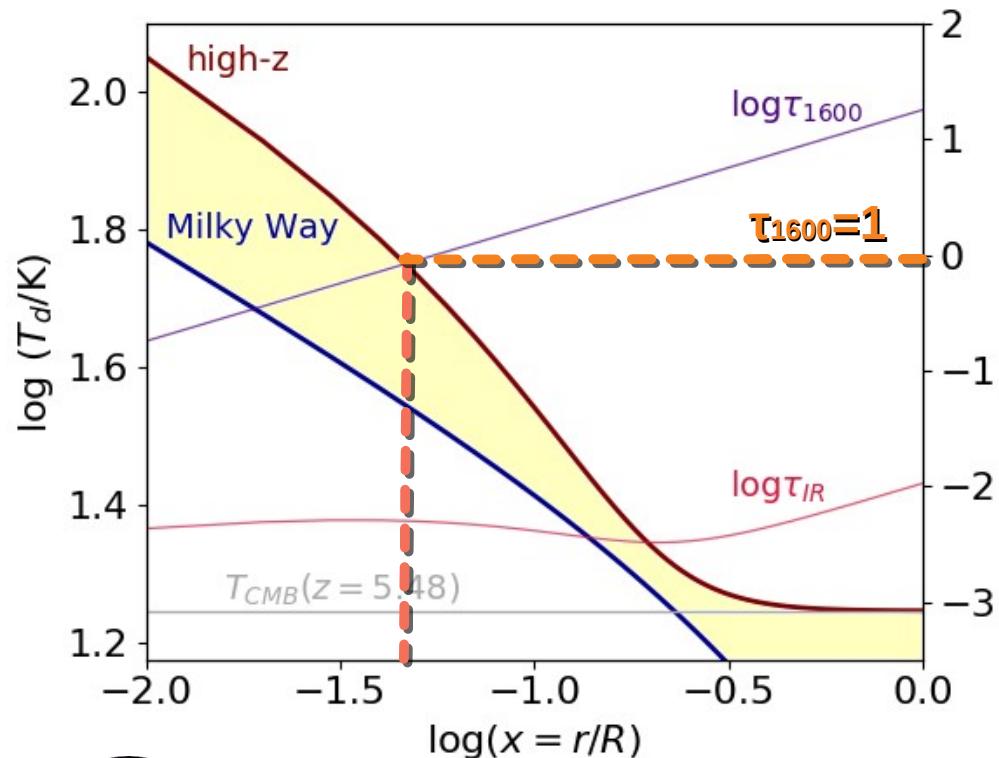
Radiation pressure

Draine+11



# Dust temperature in GMCs

Uniform cloud

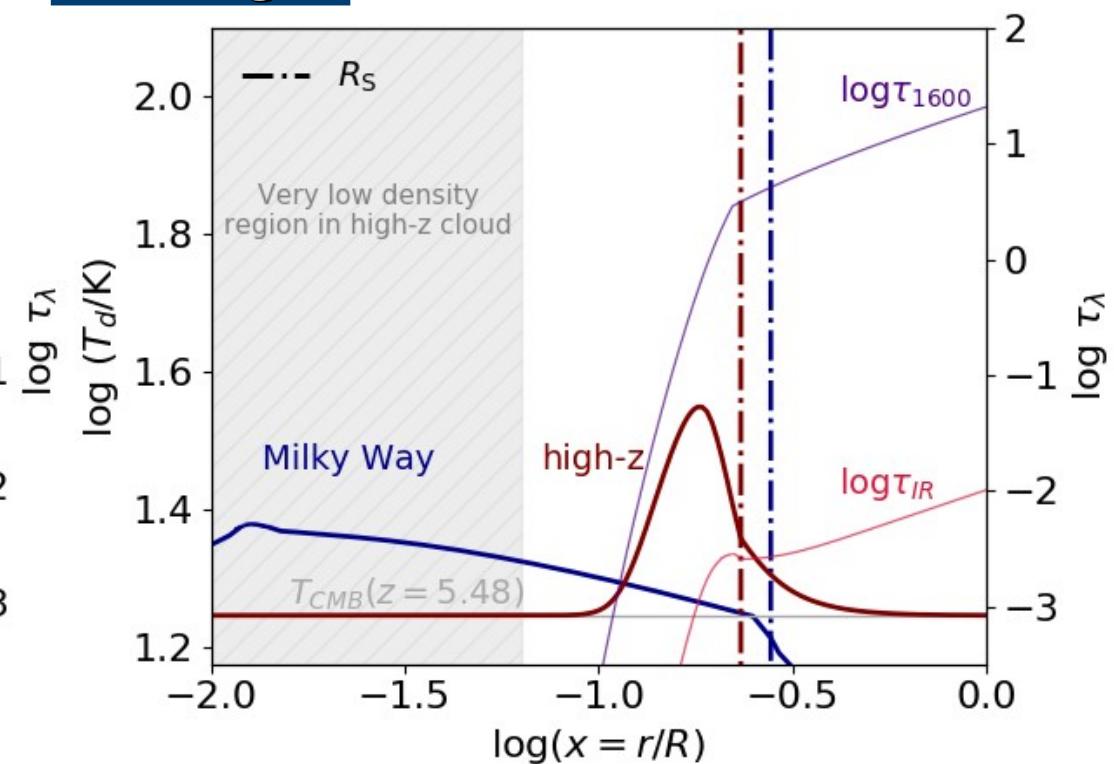


Towards the center of the cloud

Adding :

Radiation pressure

Draine+11

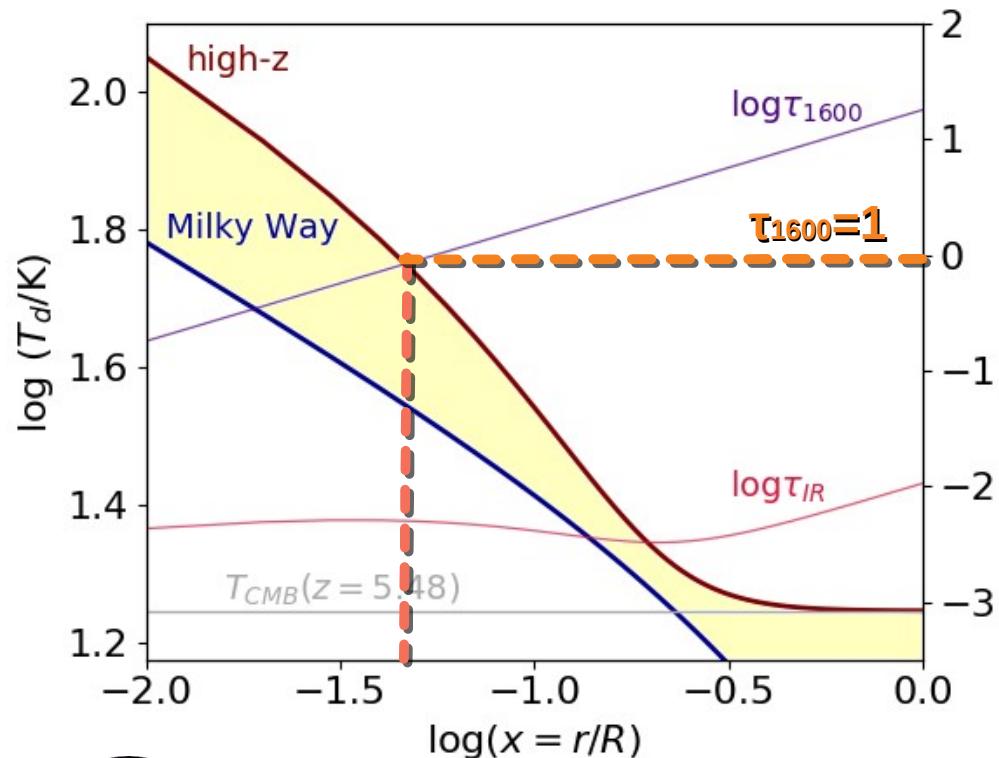


(MW grain size distribution: Weingartner & Draine+01)

Sommovigo+20

# Dust temperature in GMCs

Uniform cloud

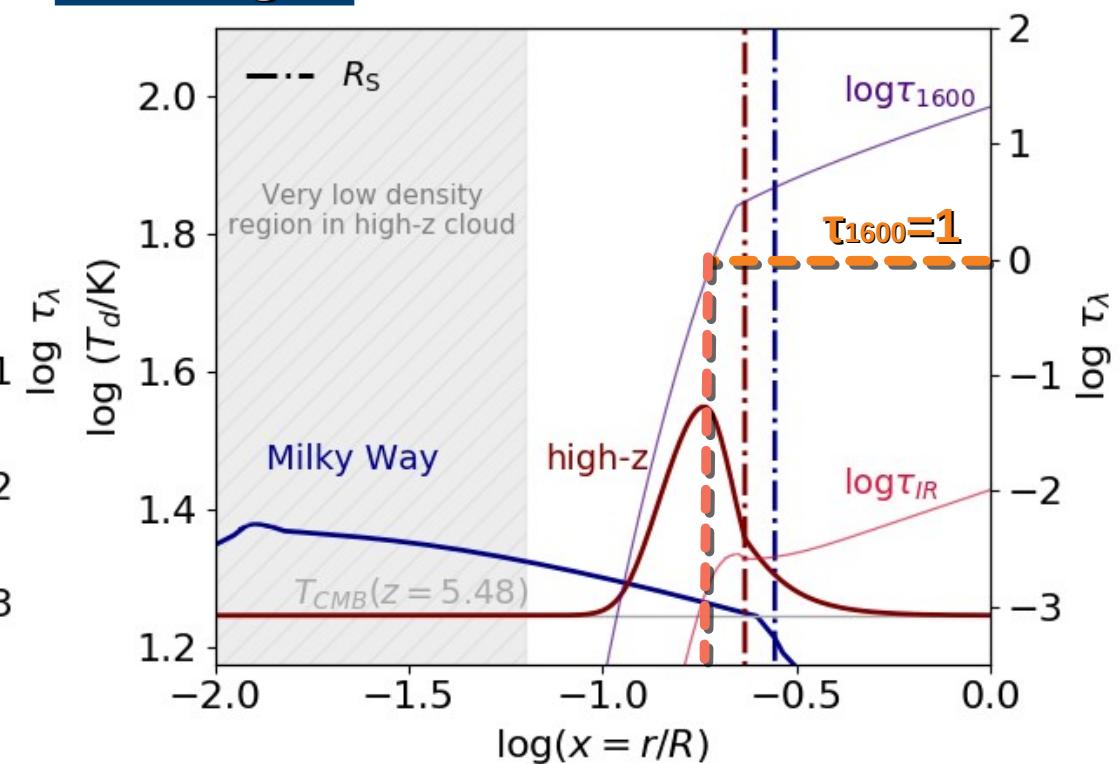


Towards the center of the cloud

Adding :

Radiation pressure

*Draine+11*

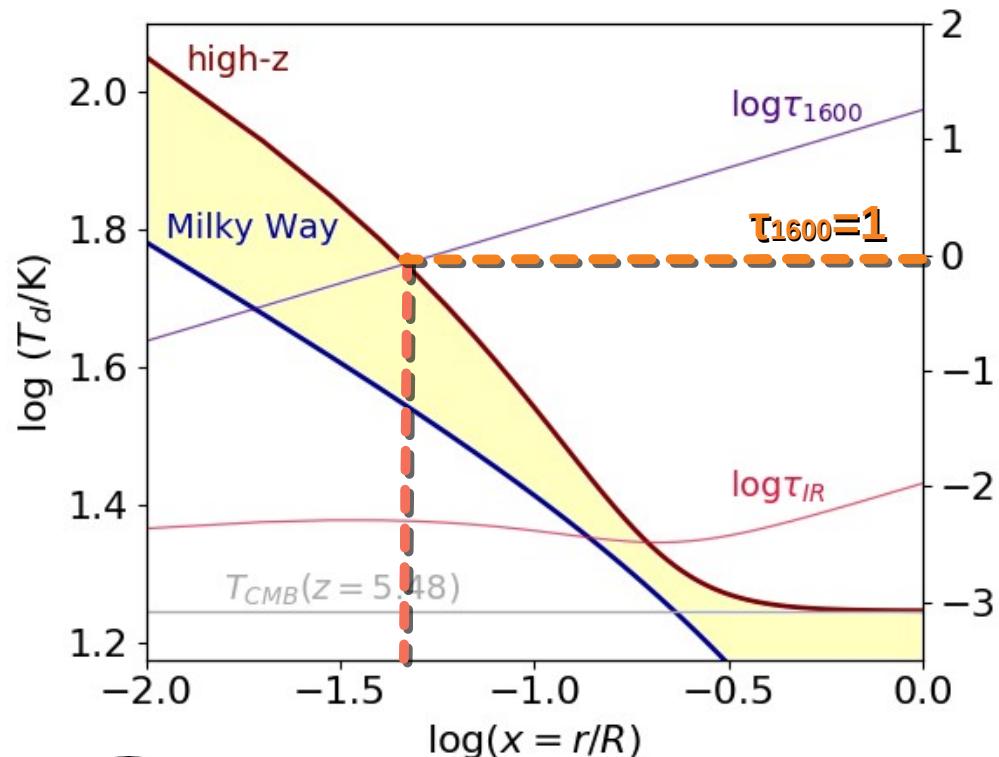


(MW grain size distribution: *Weingartner & Draine+01*)

*Sommovigo+20*

# Dust temperature in GMCs

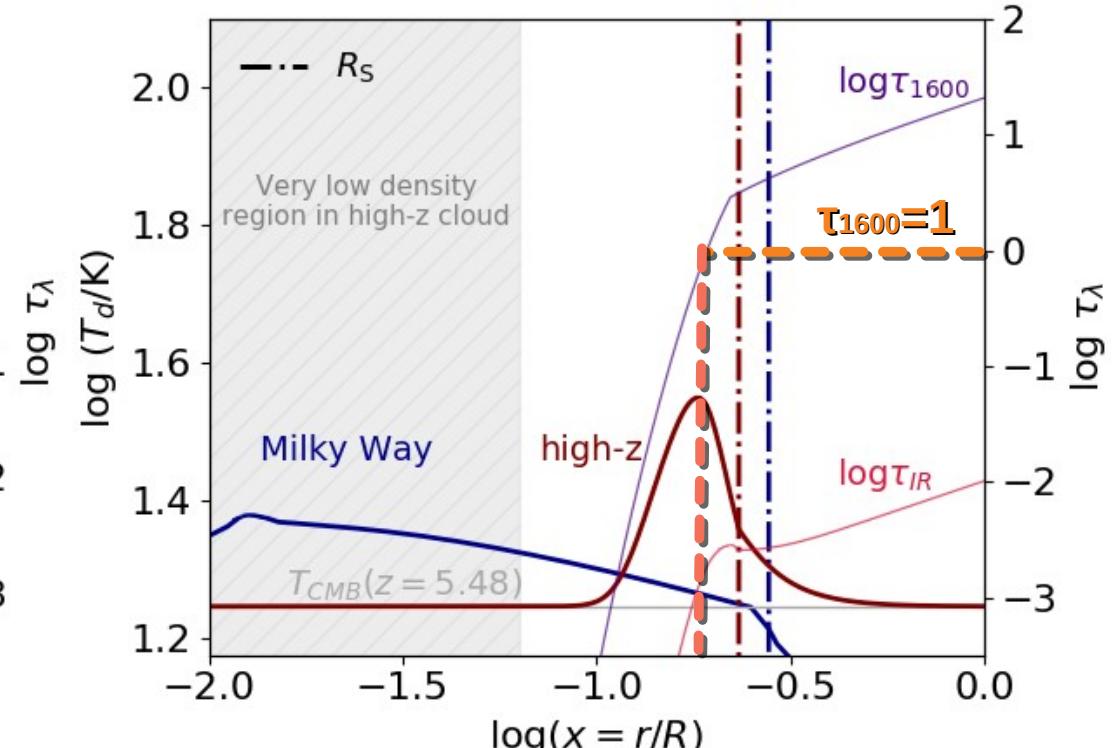
Uniform cloud



Towards the center of the cloud

(MW grain size distribution: Weingartner & Draine+01)

Adding : **Radiation pressure** *Draine+11*



In high-z GMC:

- Dust temperature  $\sim 60$  K in few Myr
- Luminosity-to-gas mass ratio  $\sim 10$   $L_\odot/M_\odot$  (while locally  $\sim 1$   $L_\odot/M_\odot$ )

*Bonnerot et al. 2018*