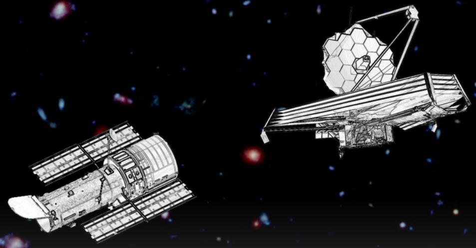
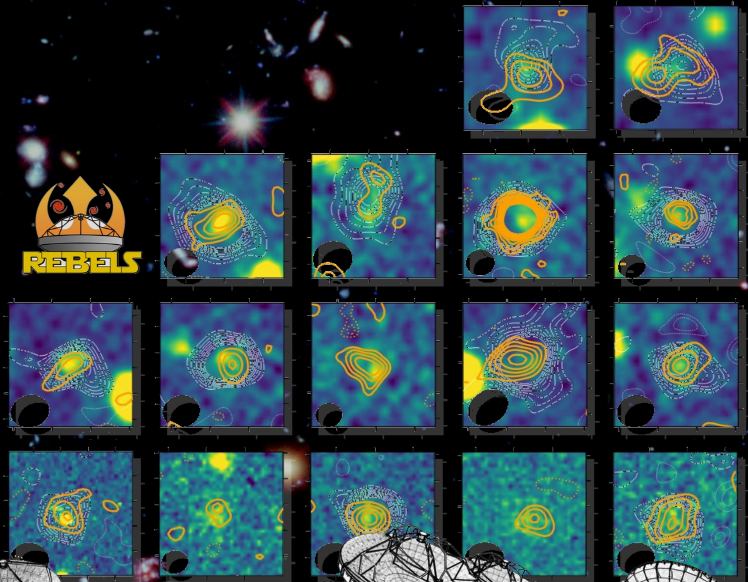


Newborn but dusty: The obscured(d) puzzle of EoR galaxies

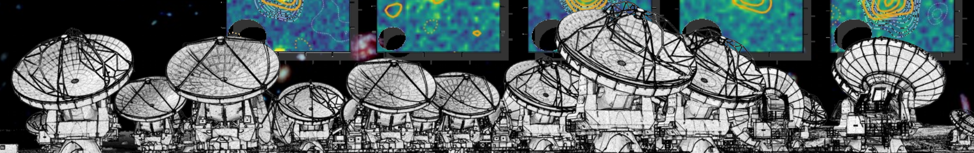
Laura Sommovigo



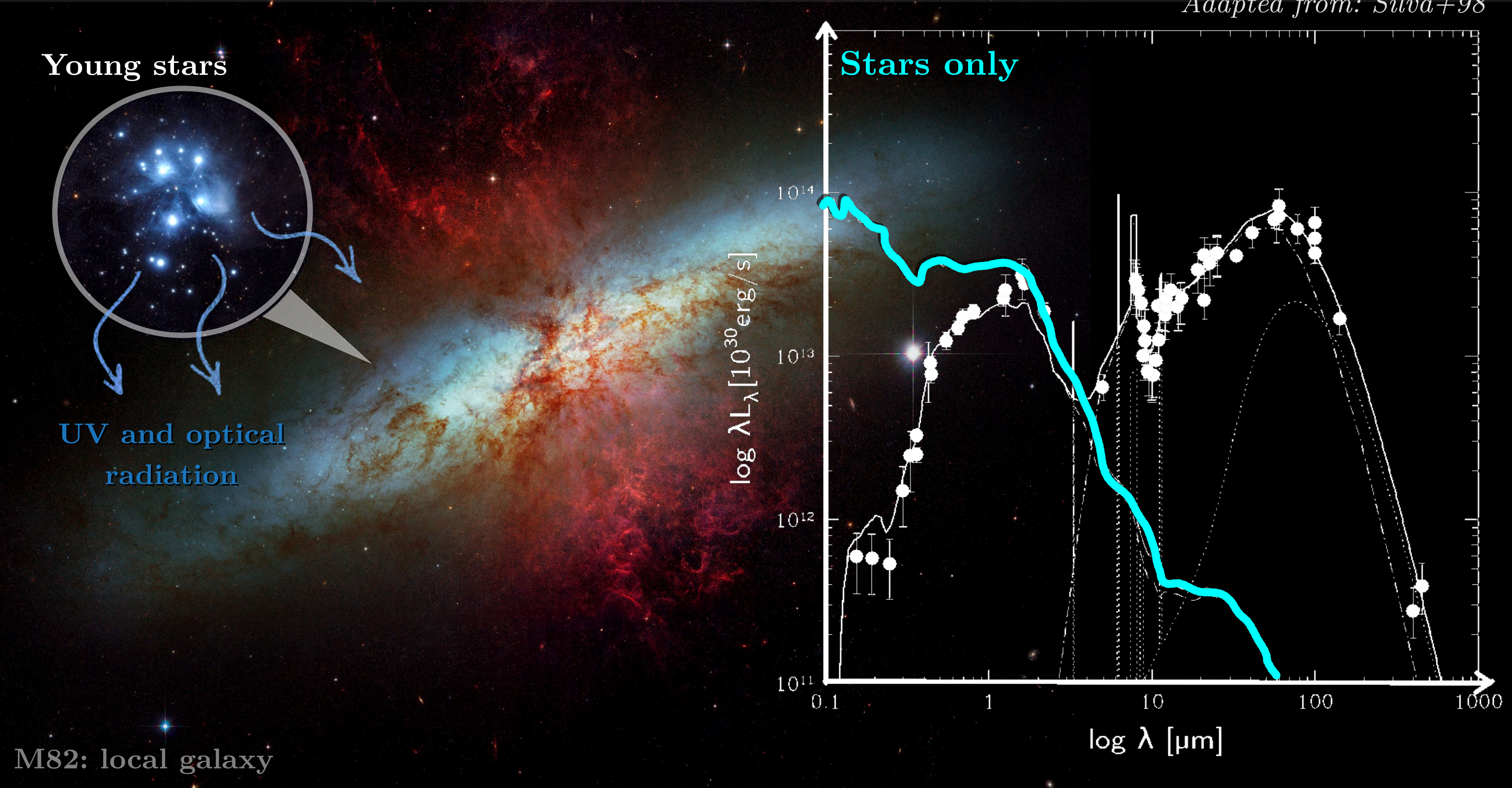
SCUOLA
NORMALE
SUPERIORE

In collaboration with:

A. Ferrara, S. Carniani, A. Pallottini,
T. Bakx, P. Dayal, S. Gallerani, L. Vallini,
A. Zanella & **REBELS** team



Why do we care about dust?



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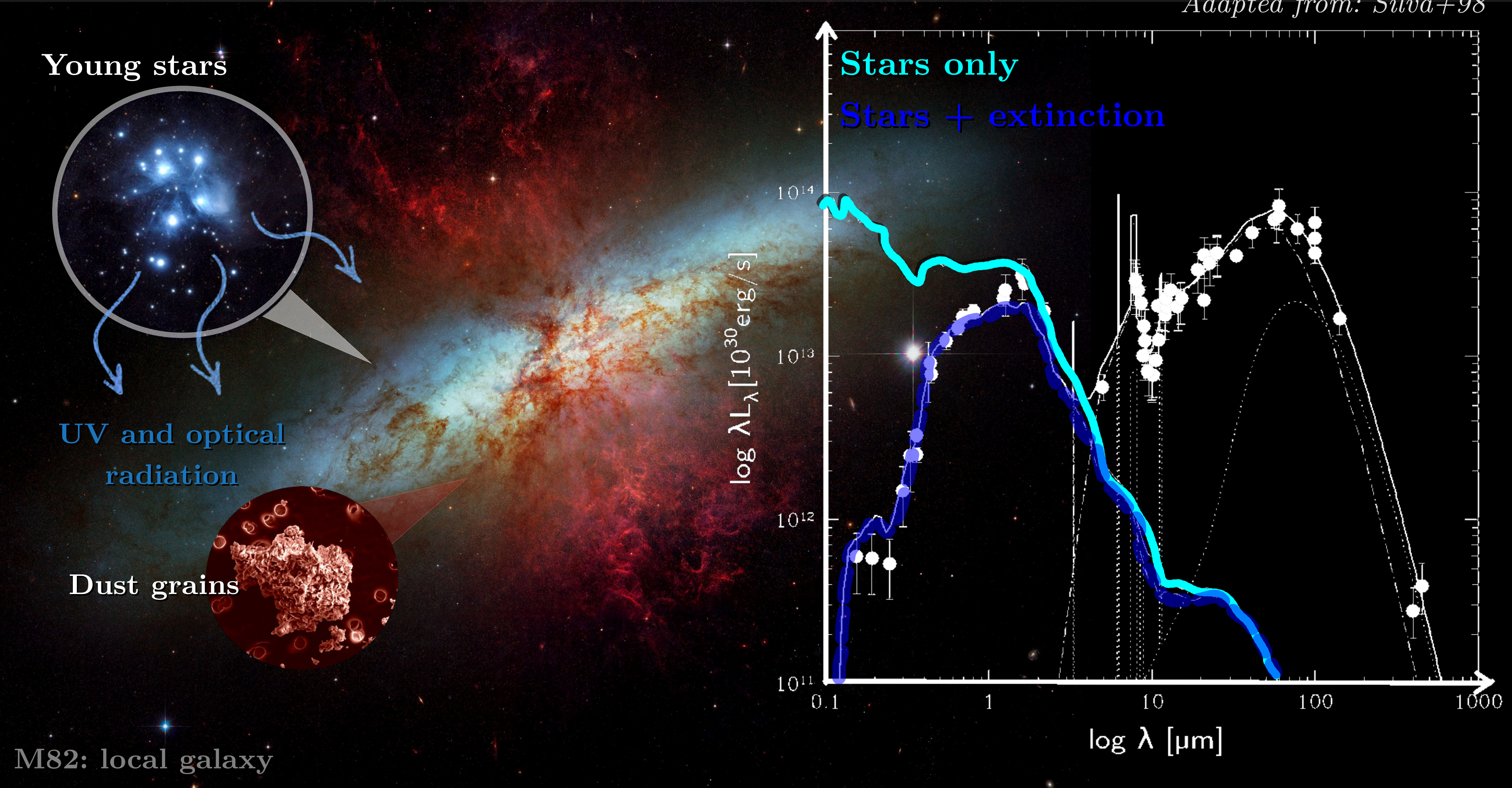

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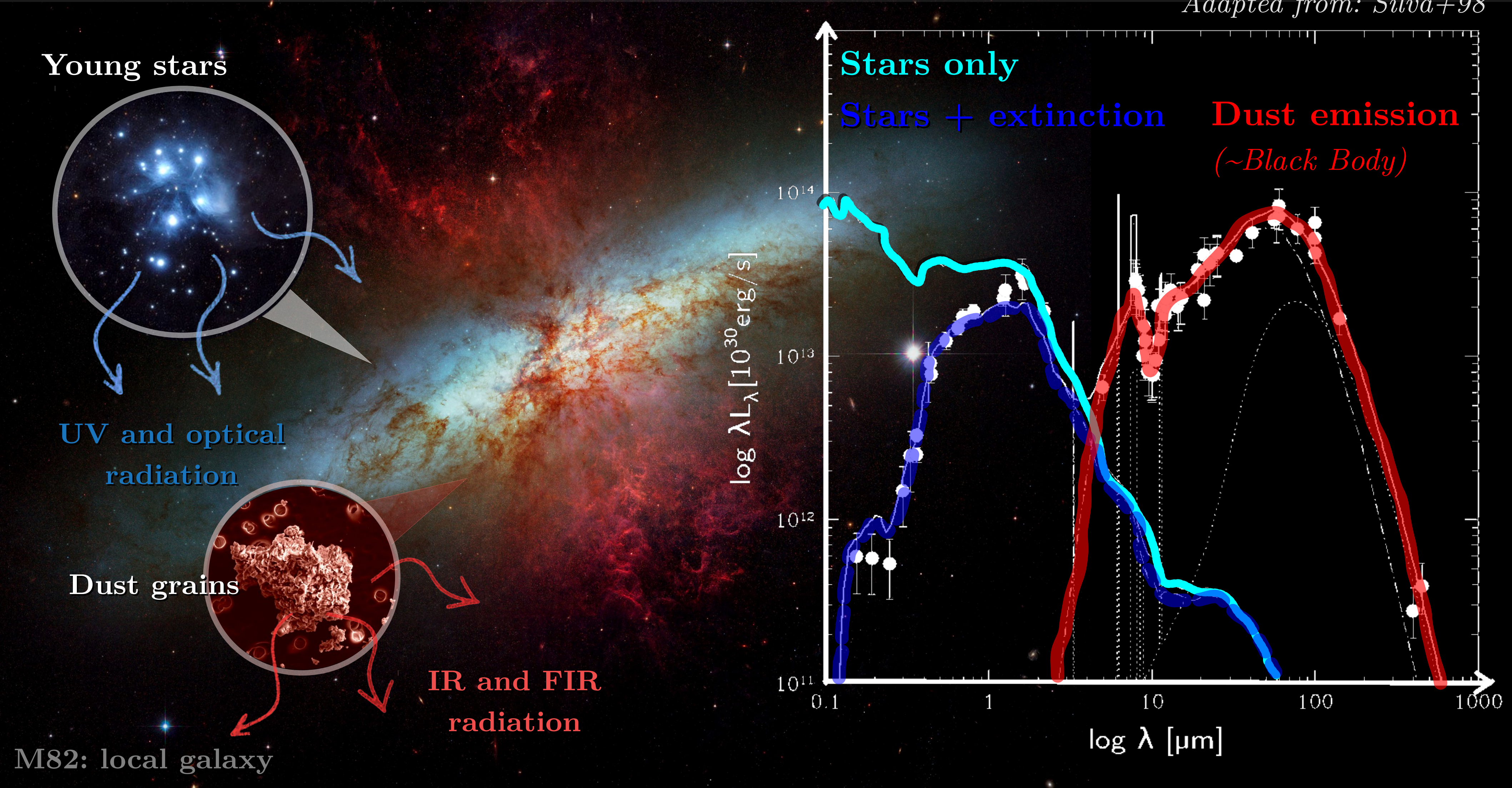
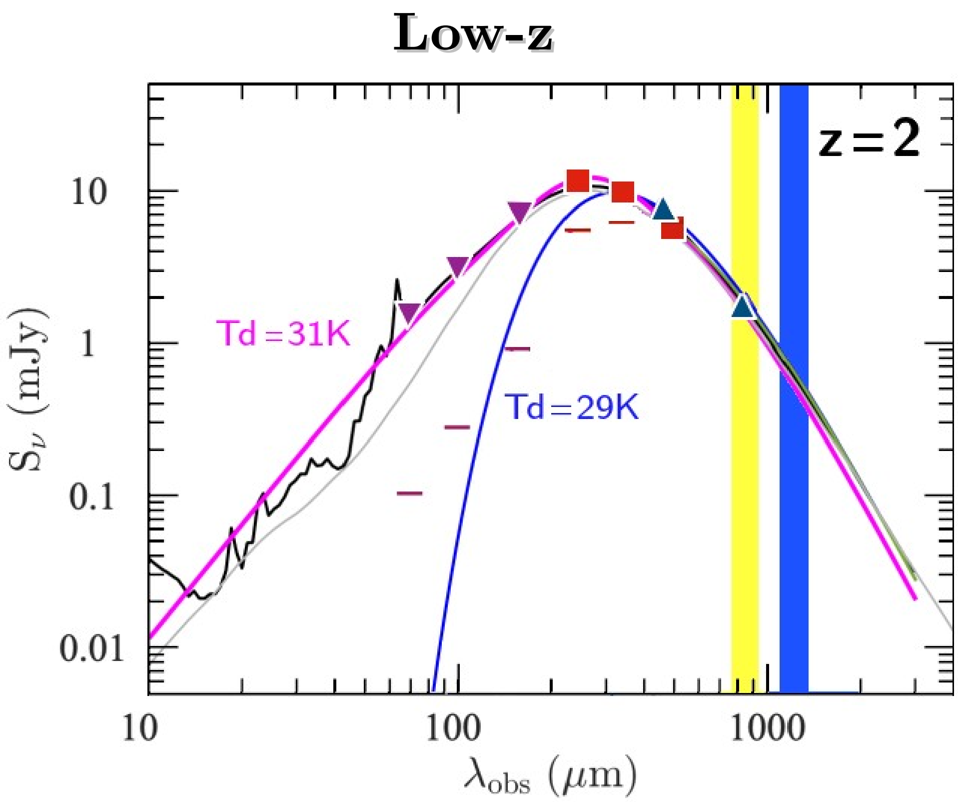
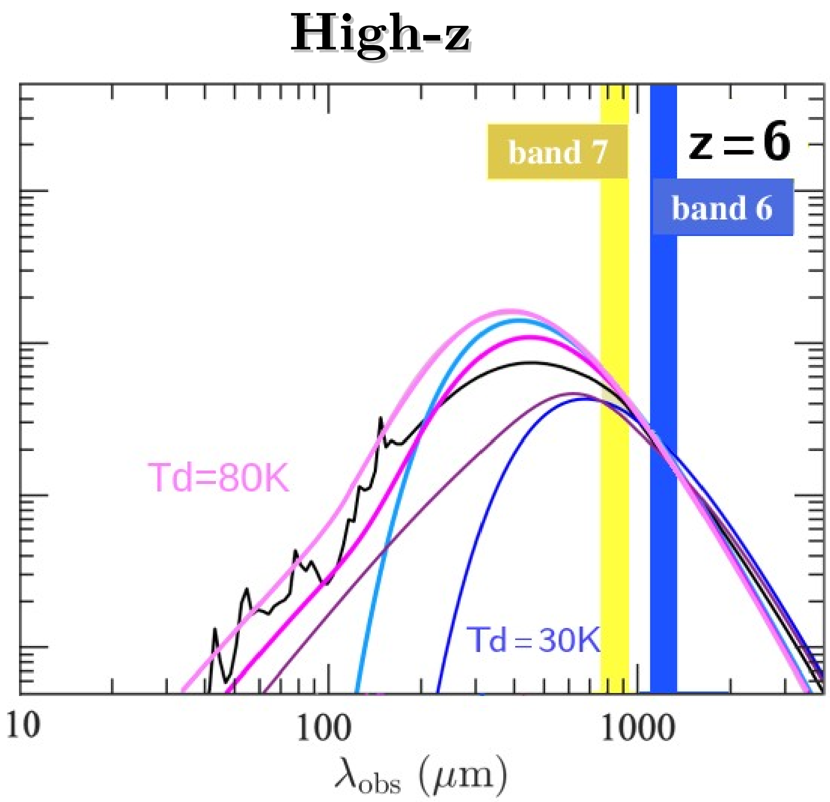


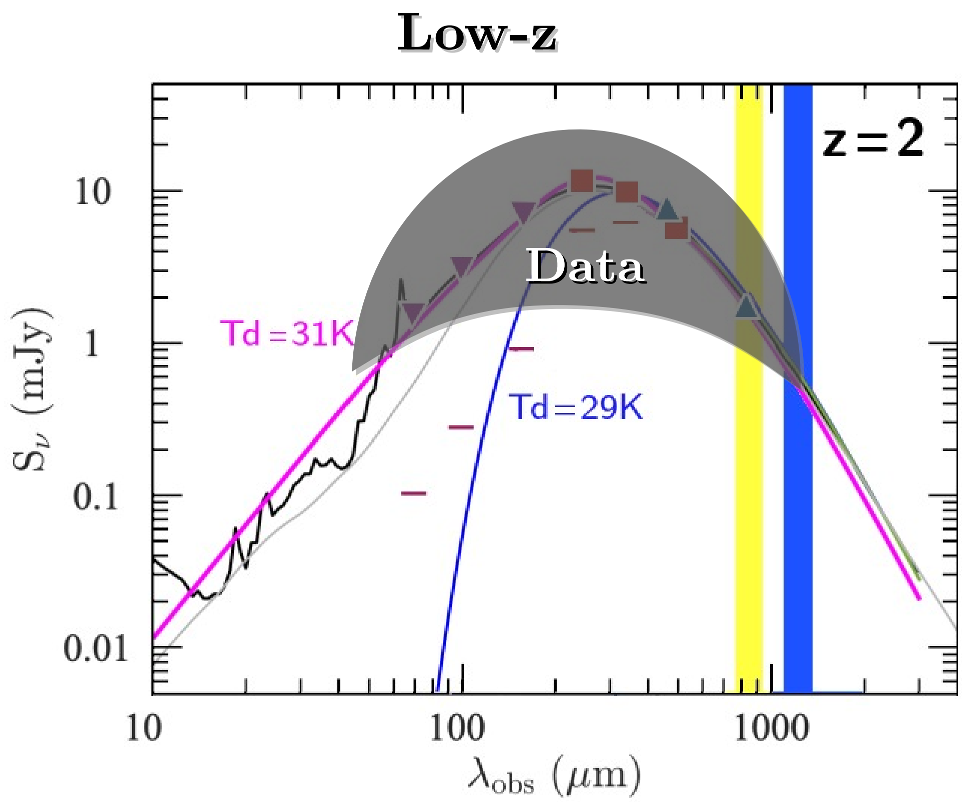
Observational challenges at high-redshift

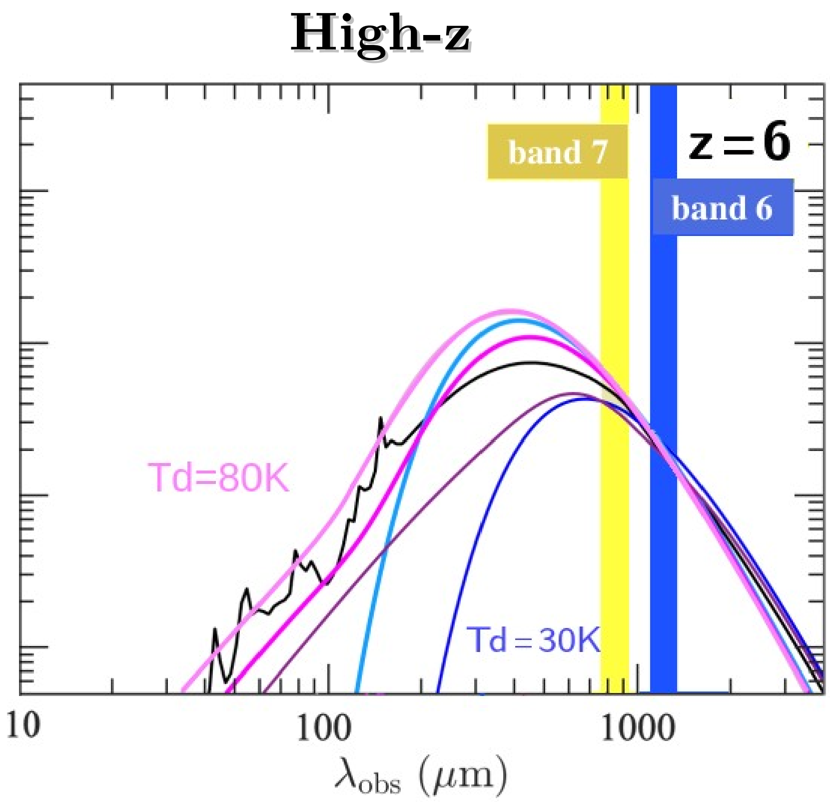




Liang+19

Observational challenges at high-redshift





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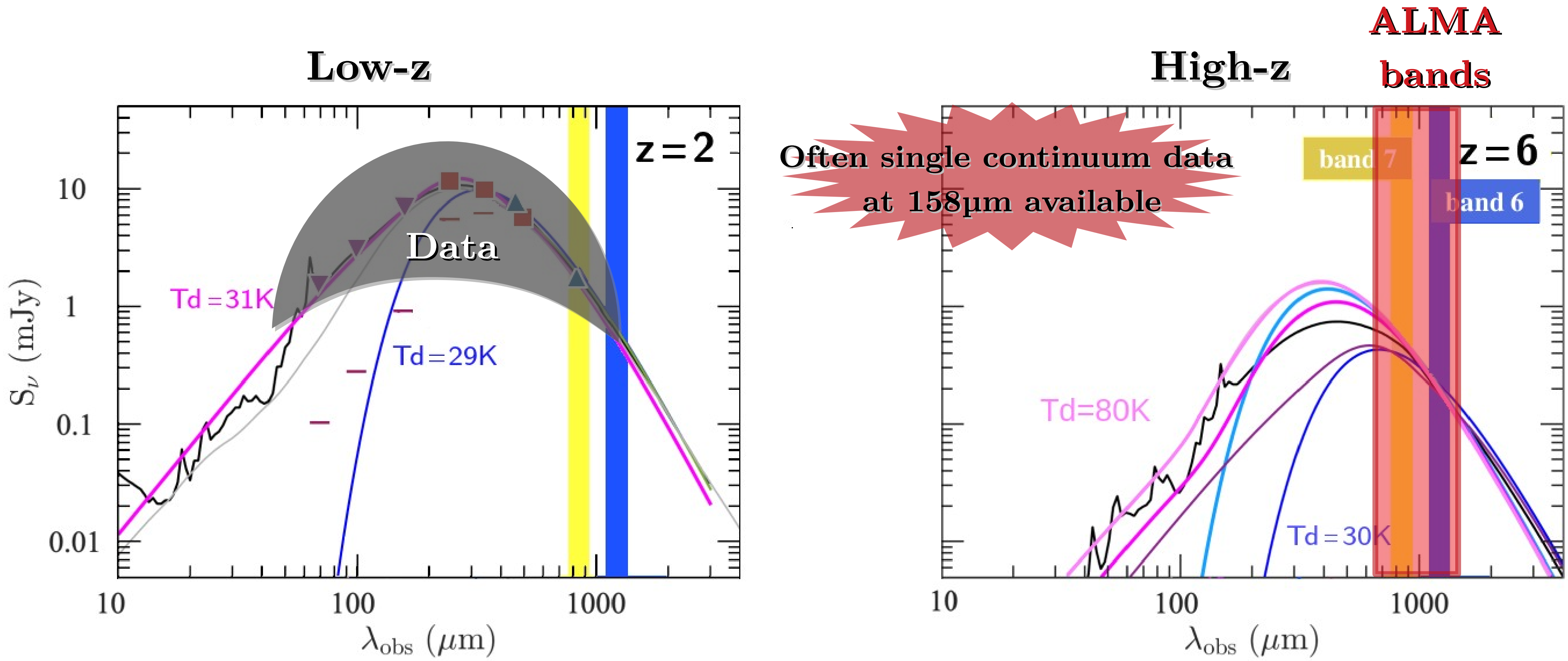

Liang+19

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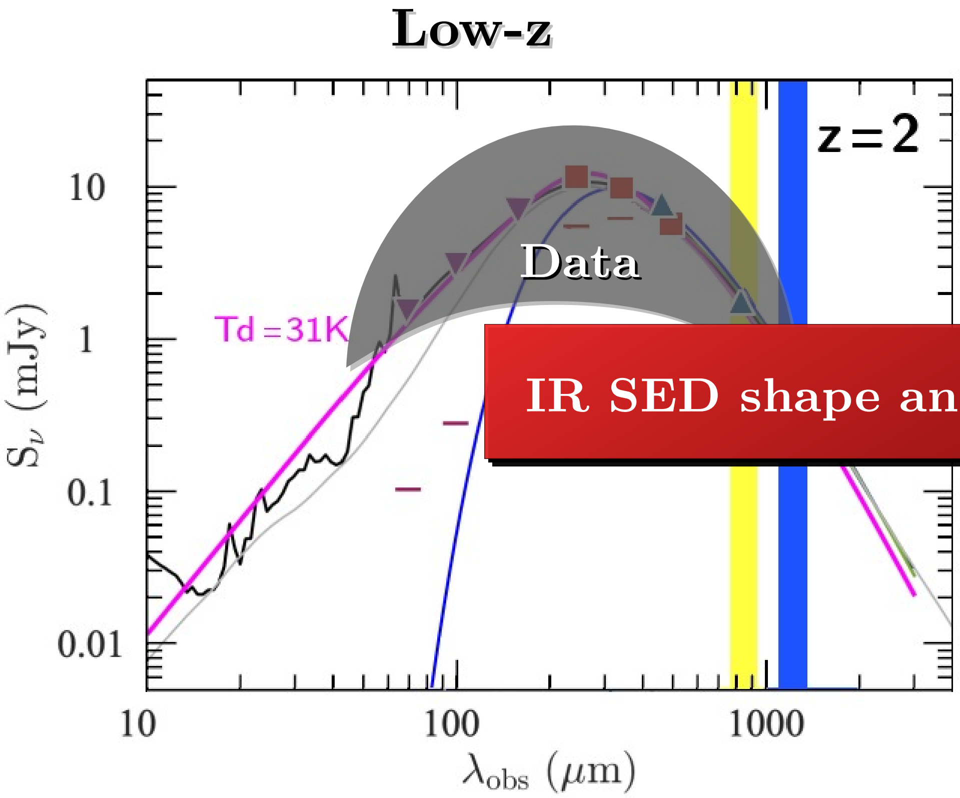
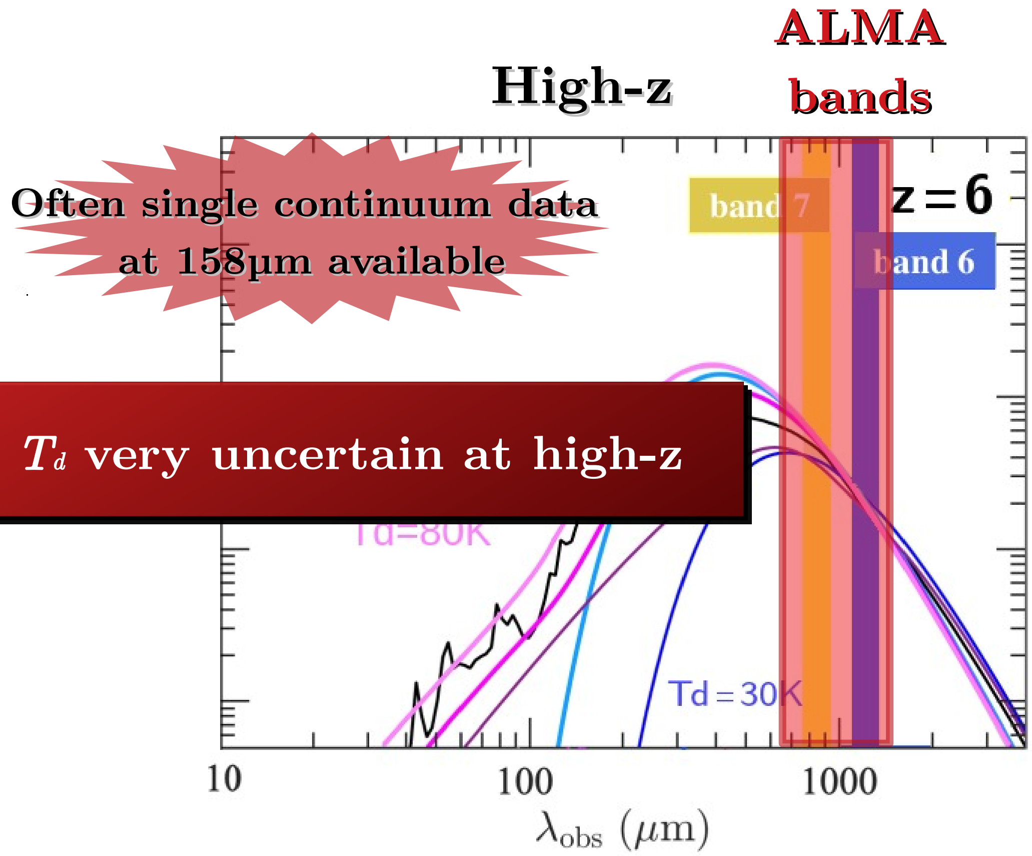




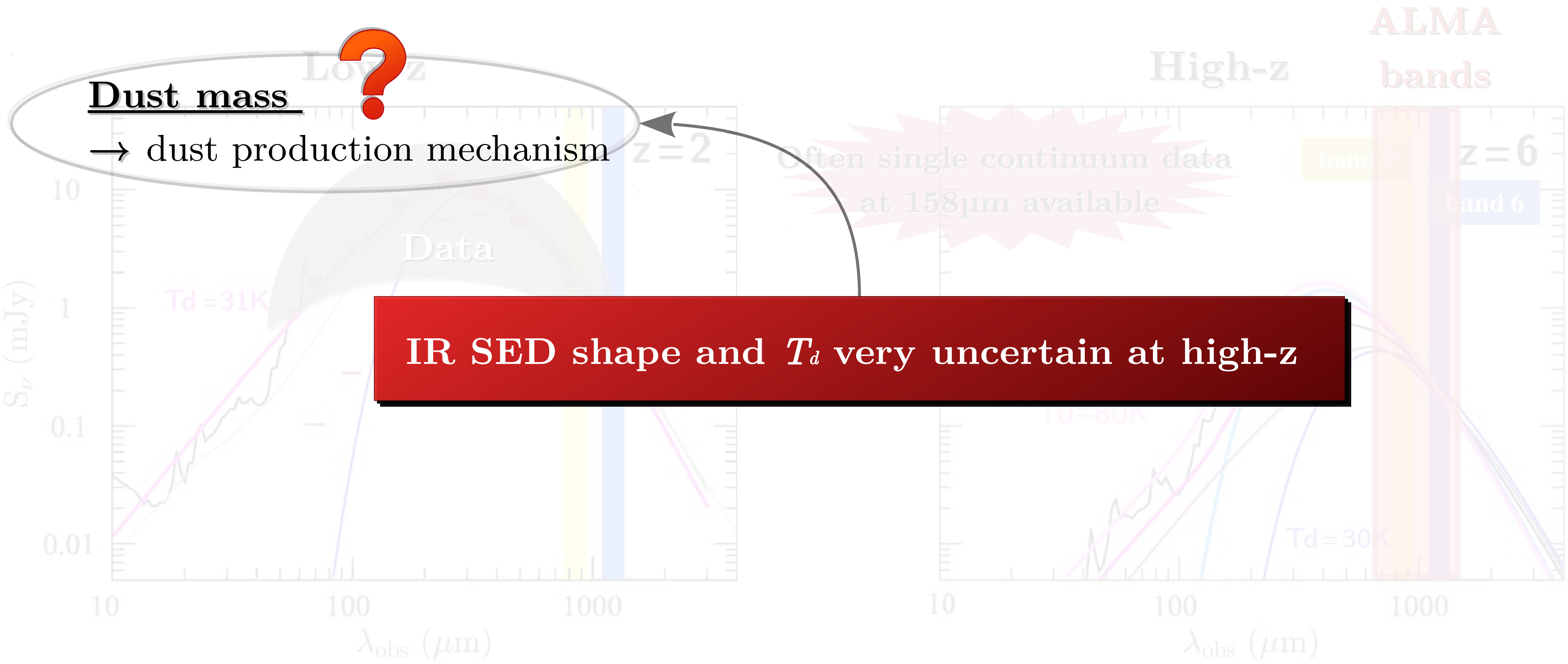
IR SED shape and T_d very uncertain at high-z

Liang+19

Observational challenges at high-redshift

Dust mass

→ dust production mechanism



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Liang+19

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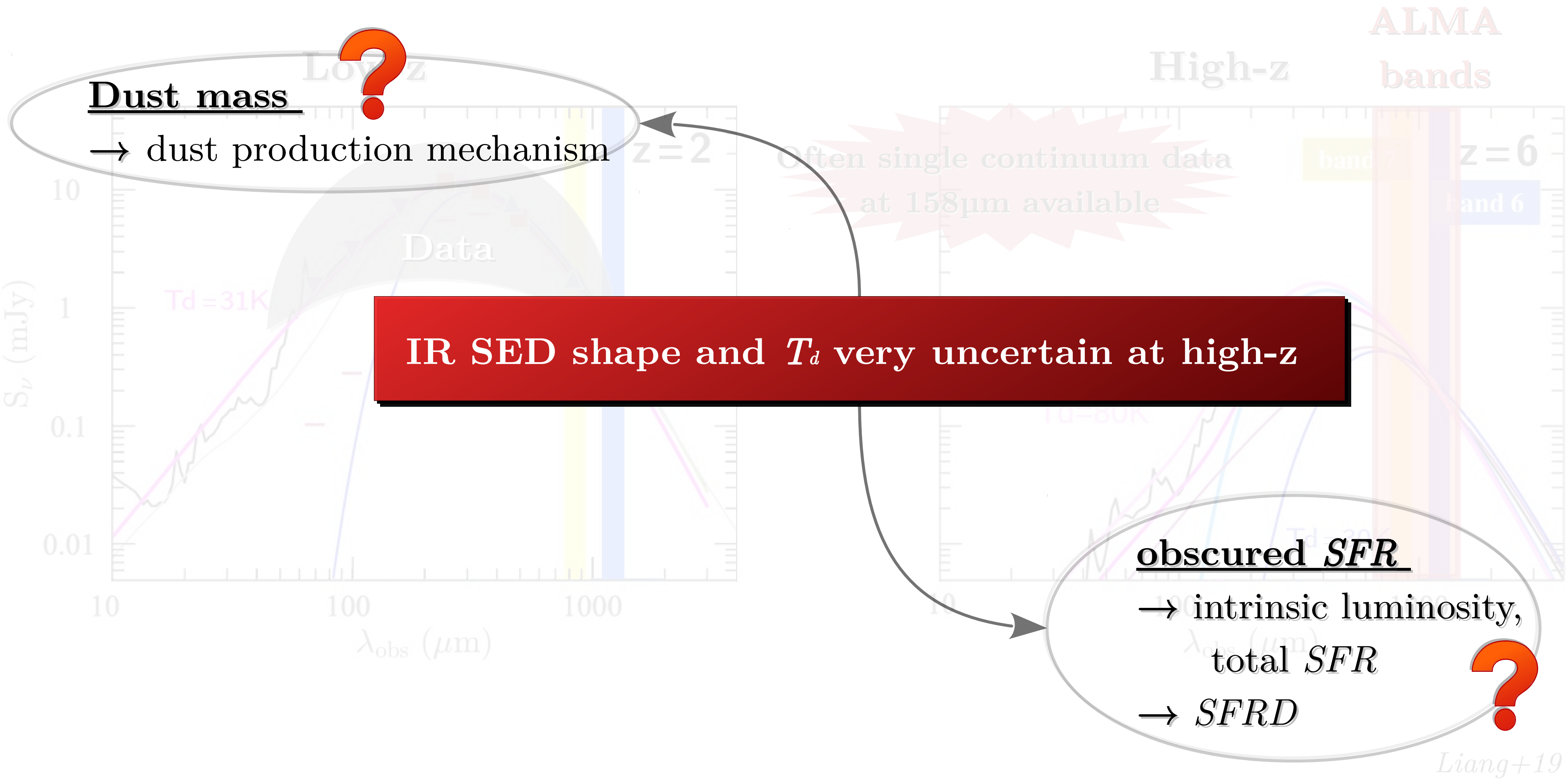


Dust mass

→ dust production mechanism

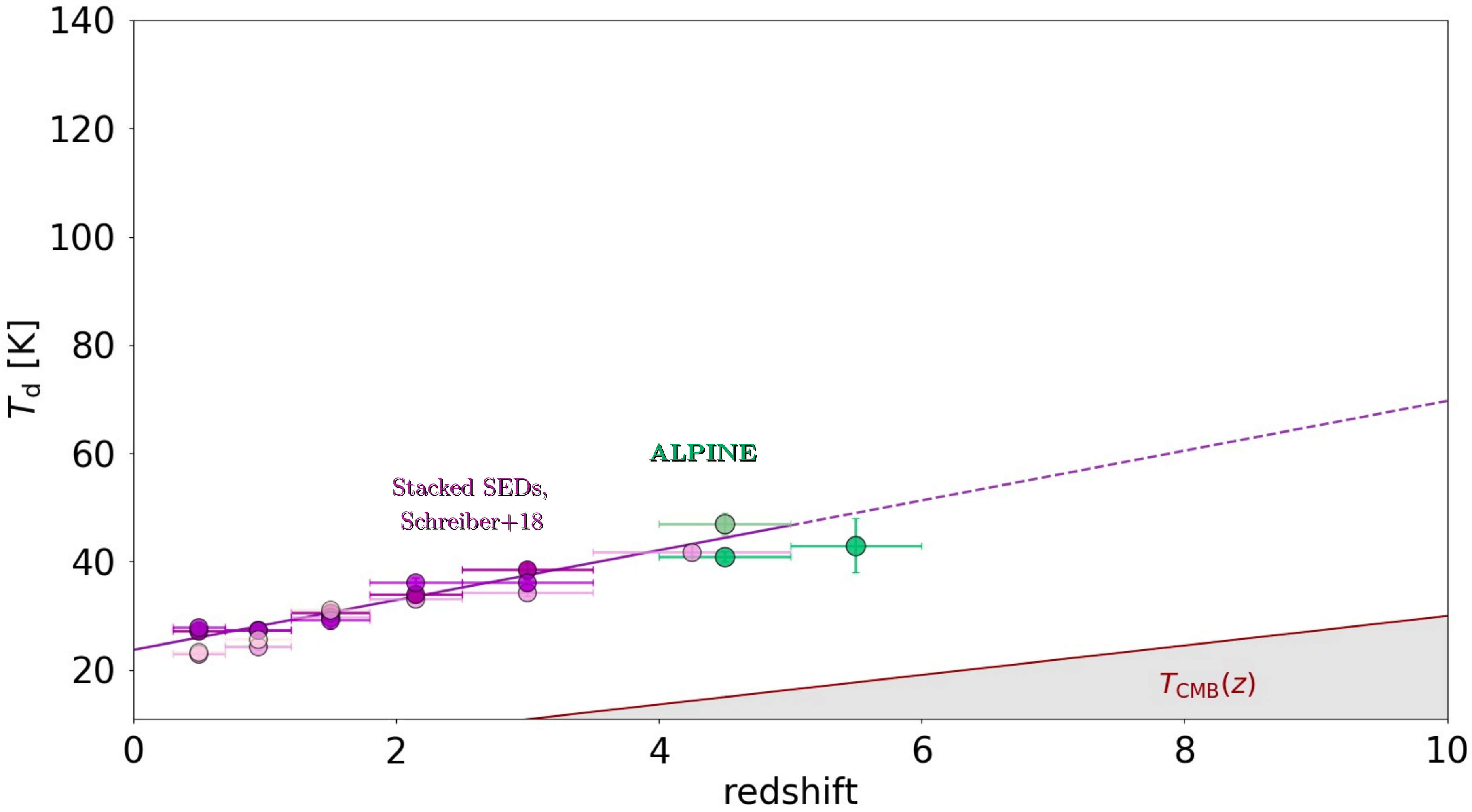
IR SED shape and T_d very uncertain at high-z

obscured *SFR*

→ intrinsic luminosity, total *SFR*

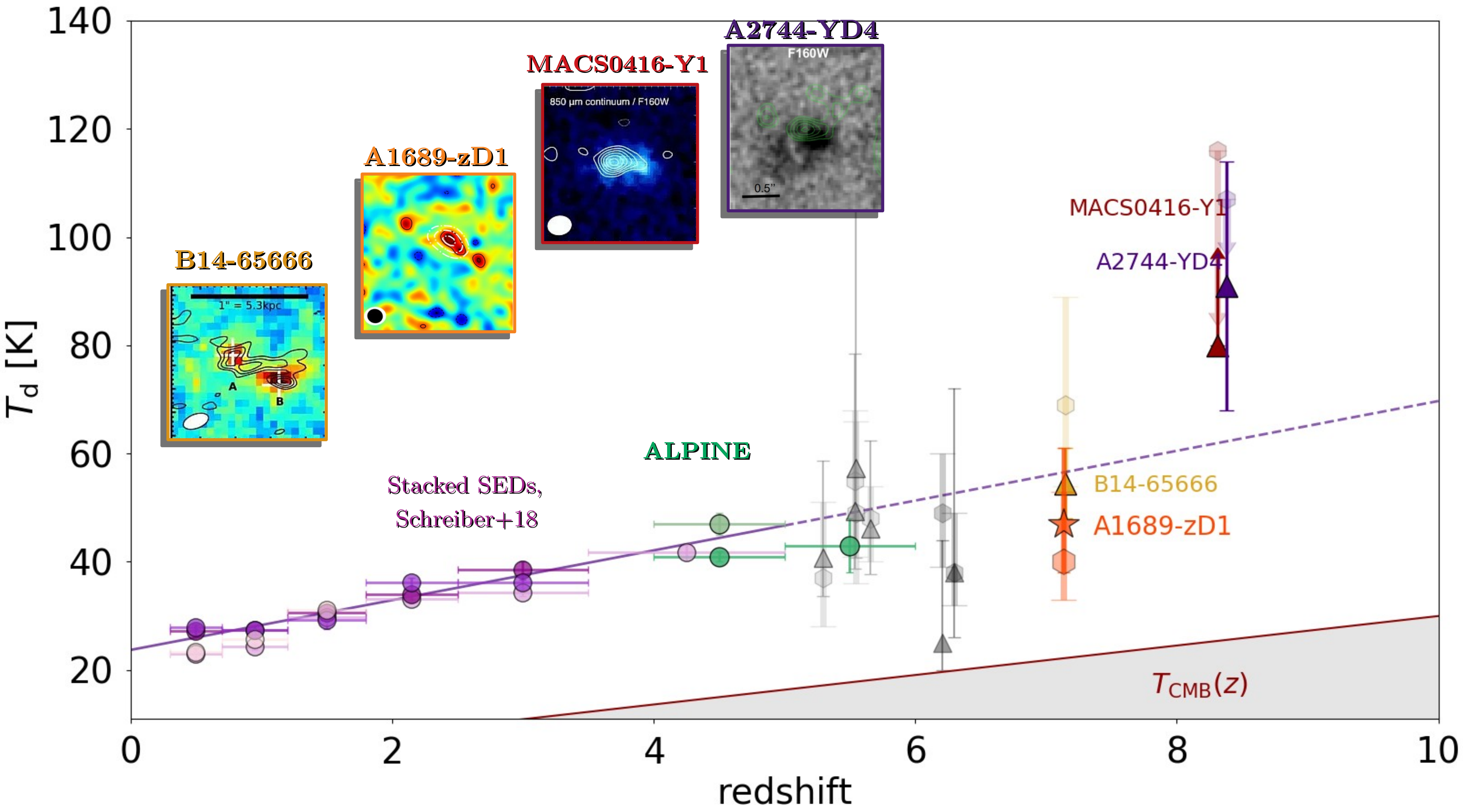
→ *SFRD*

Cosmic dust temperature evolution?



See also: Magdis+12a; Magnelli+13; Bethermin+15,+20, Liang+19, Faisst+20; Bouwens+20; Reuter+20

Cosmic dust temperature evolution?



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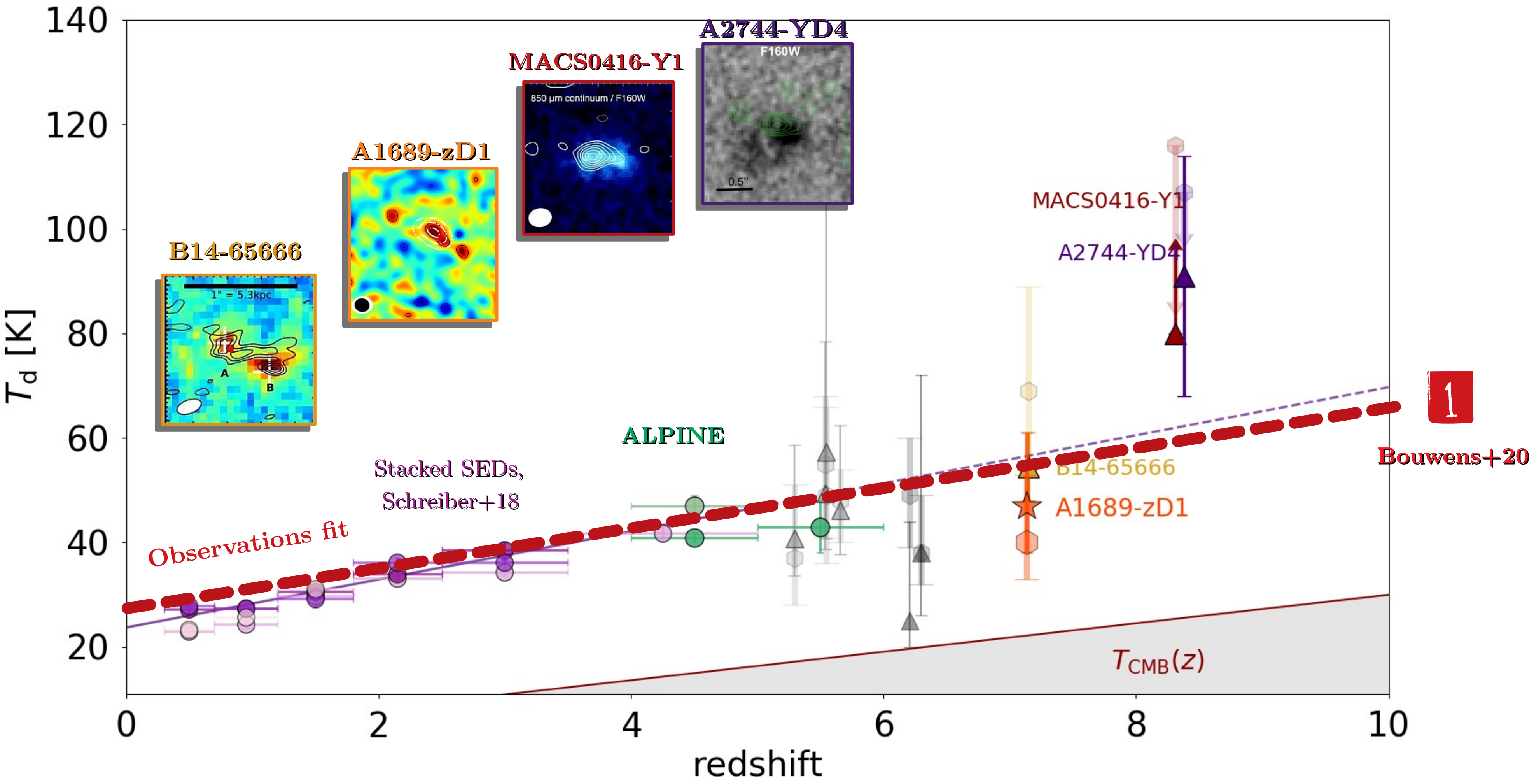

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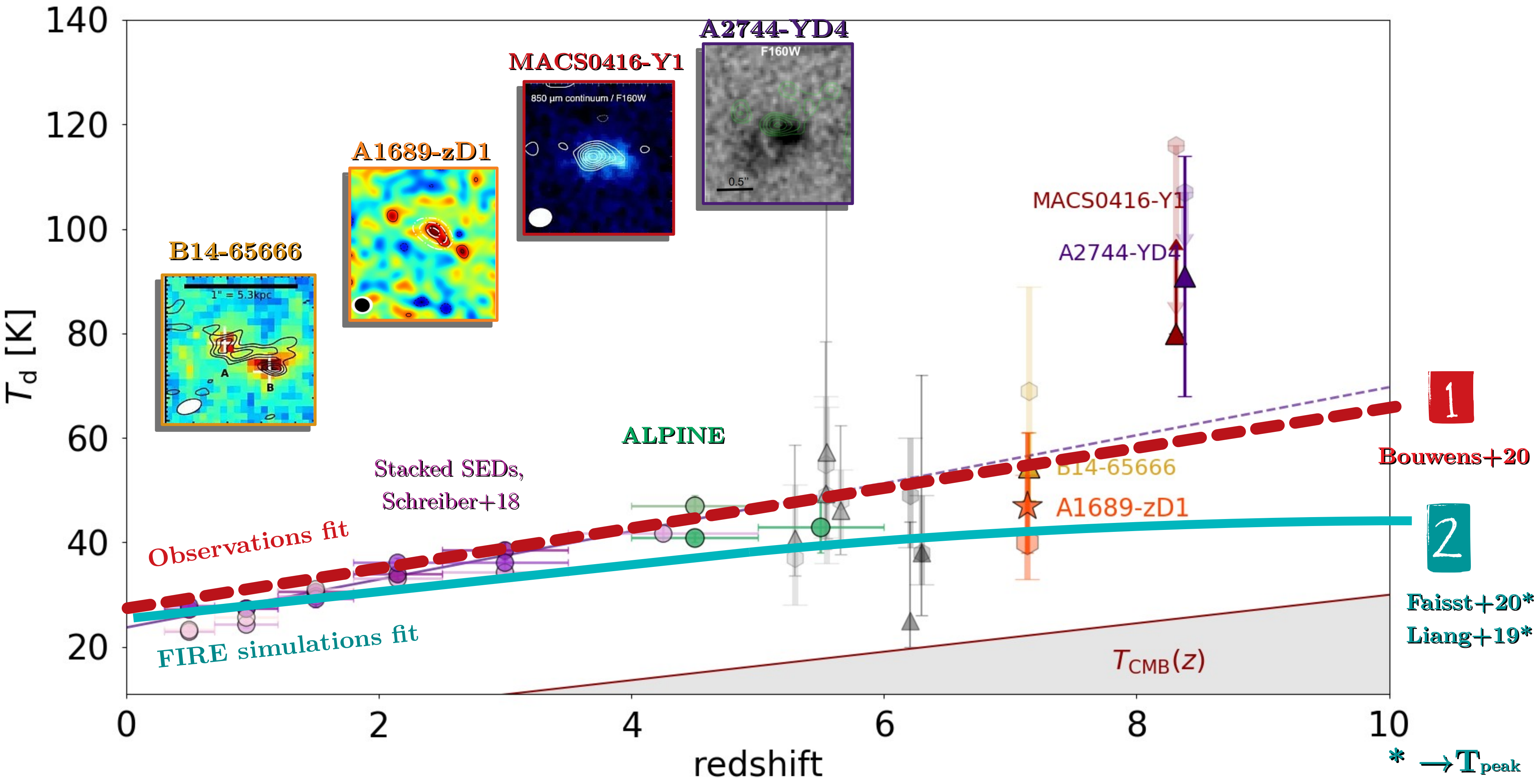
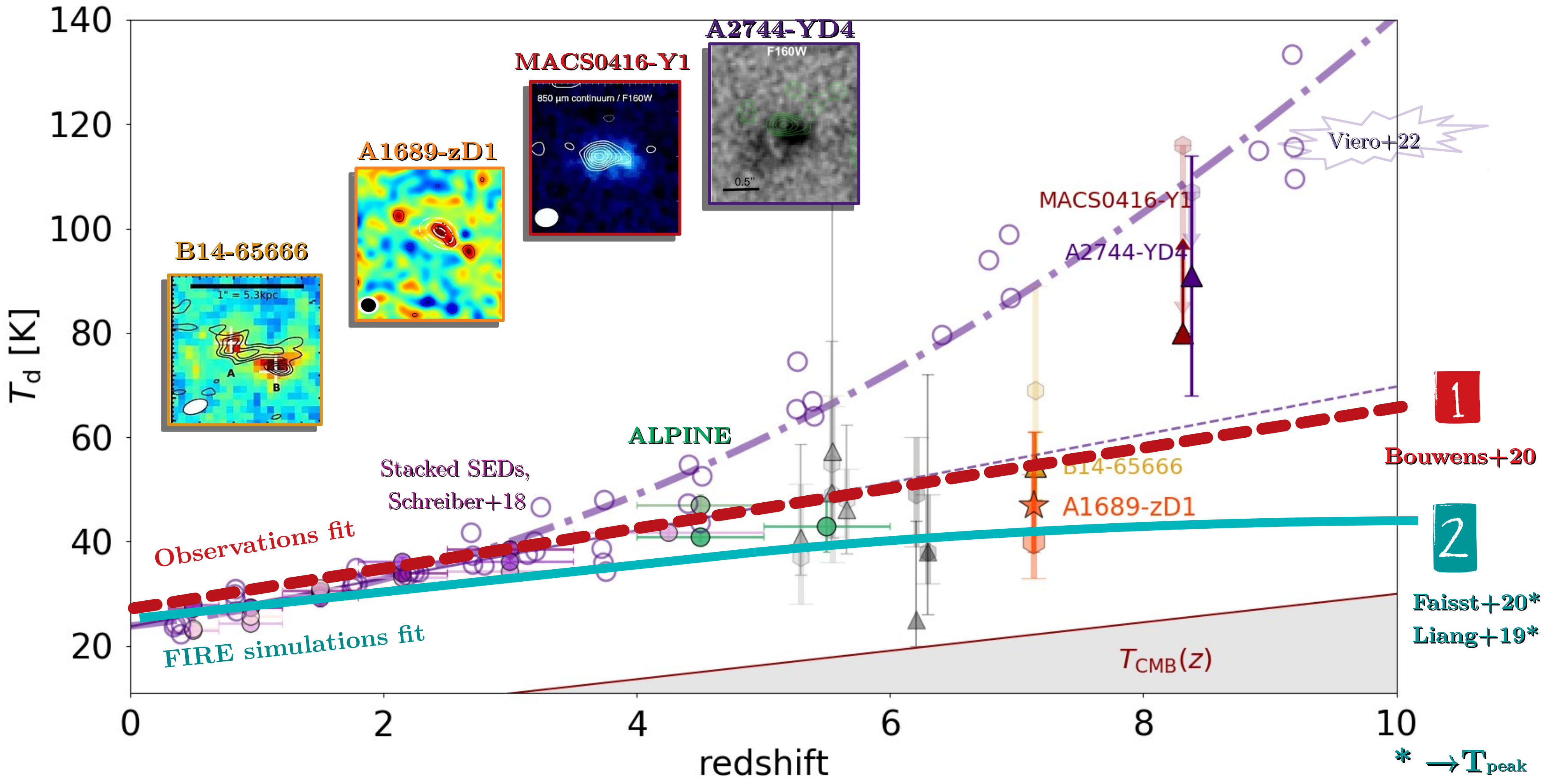


* → T_{peak}

See also: Magdis+12a; Magnelli+13; Bethermin+15,+20, Liang+19, Faisst+20; Bouwens+20; Reuter+20

Cosmic dust temperature evolution?



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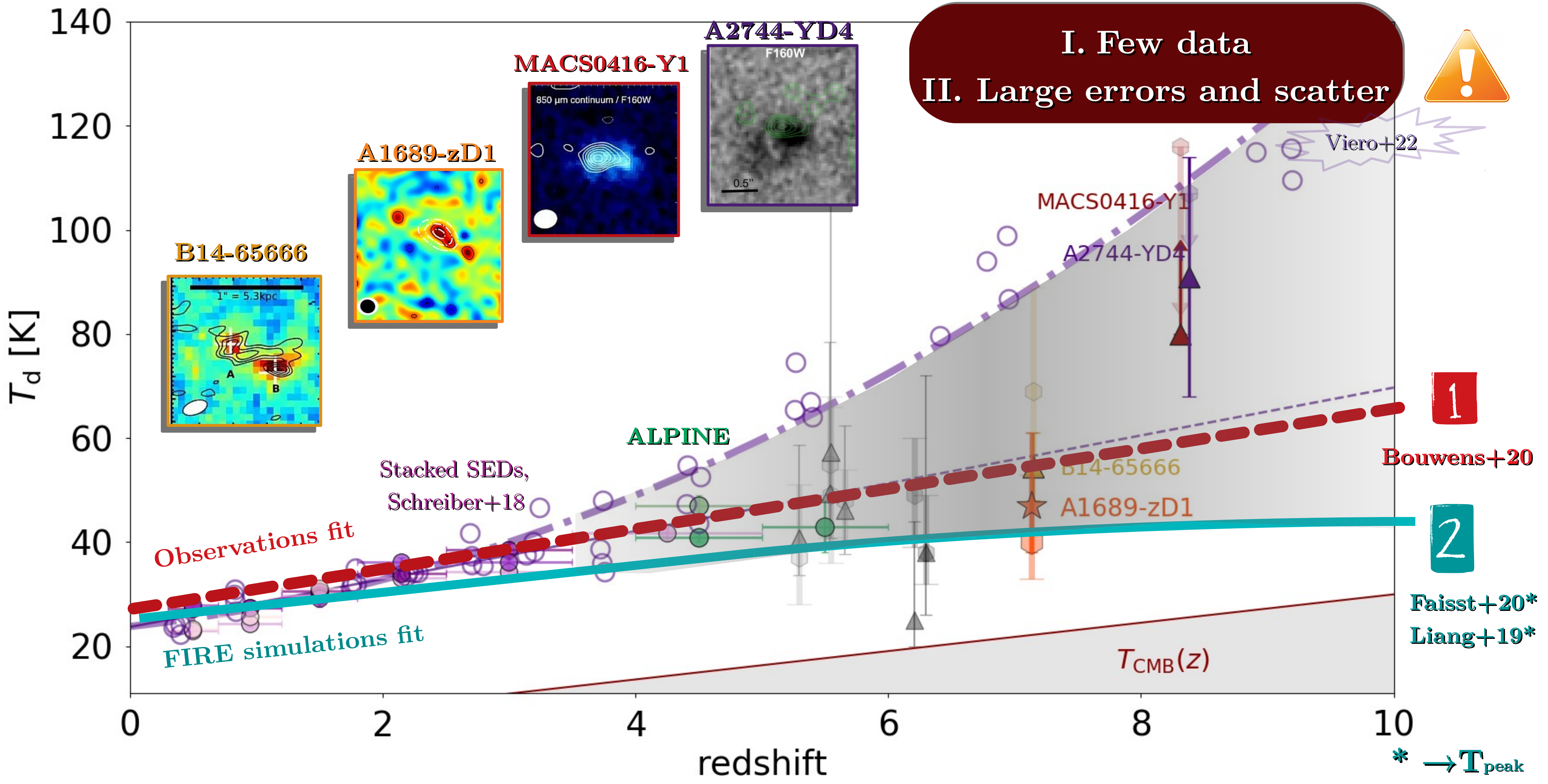

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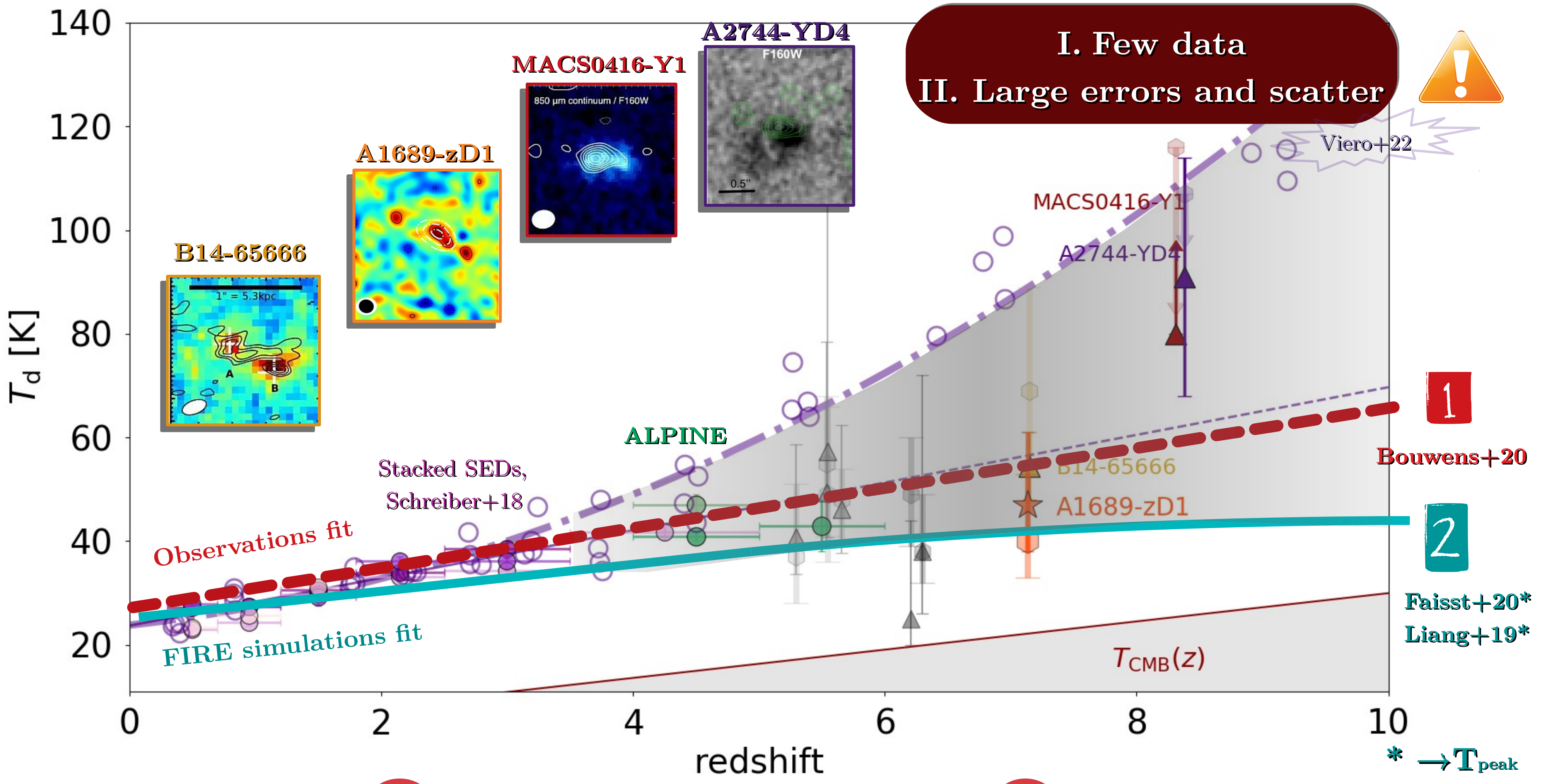
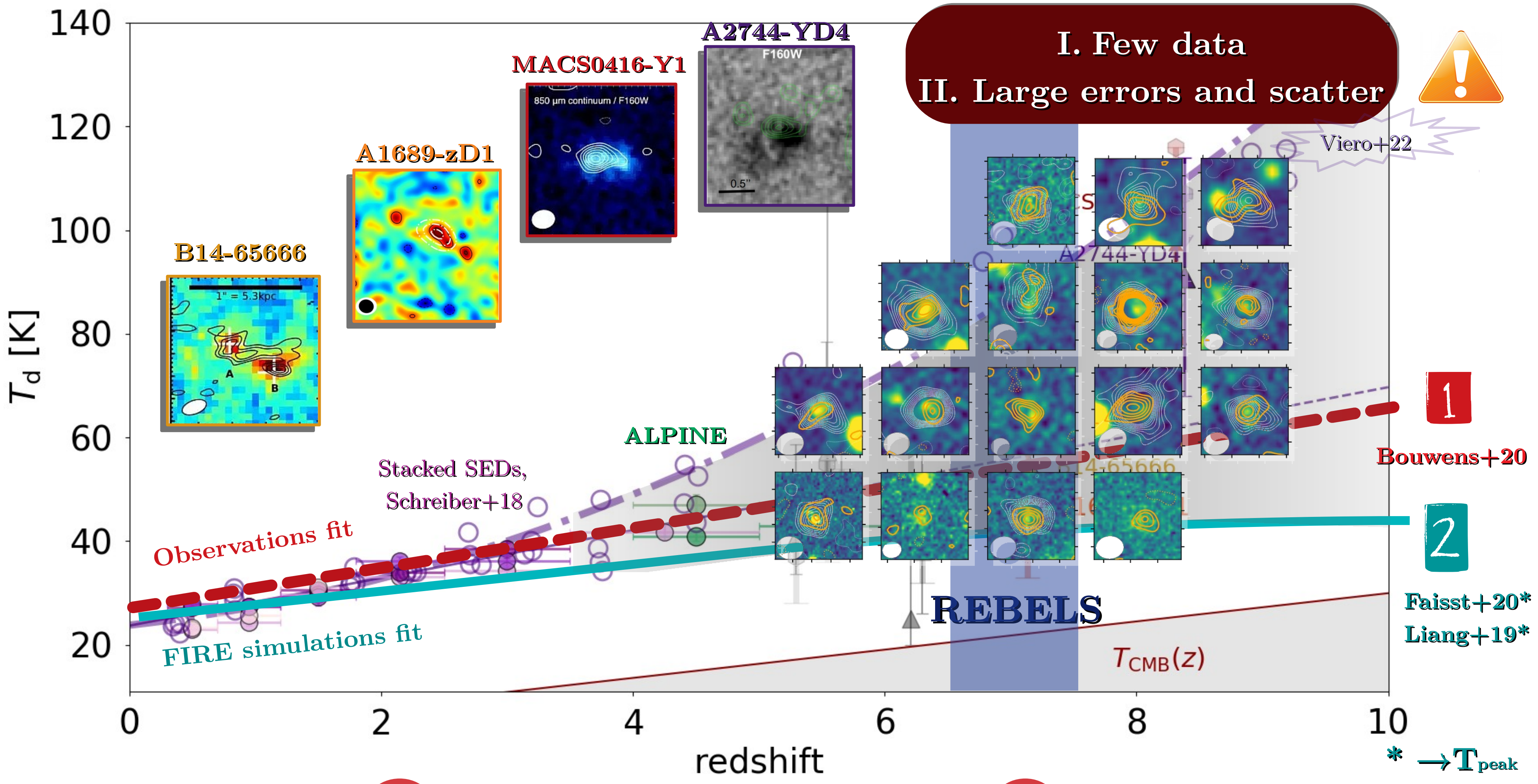


No physical motivation

Cosmic dust temperature evolution?



No physical motivation

REBELS ALMA Large Program

Reionization Era Bright Emission Line Survey

(PI: Bouwens, co-PIs: Gonzalez, Inami, Stark)

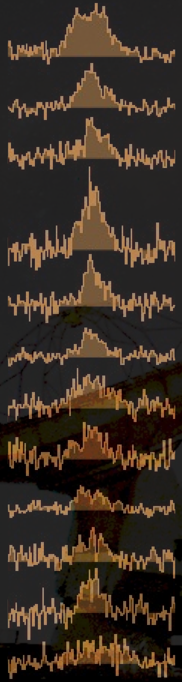
70-hours of Observations

For further details see: Bouwens+21

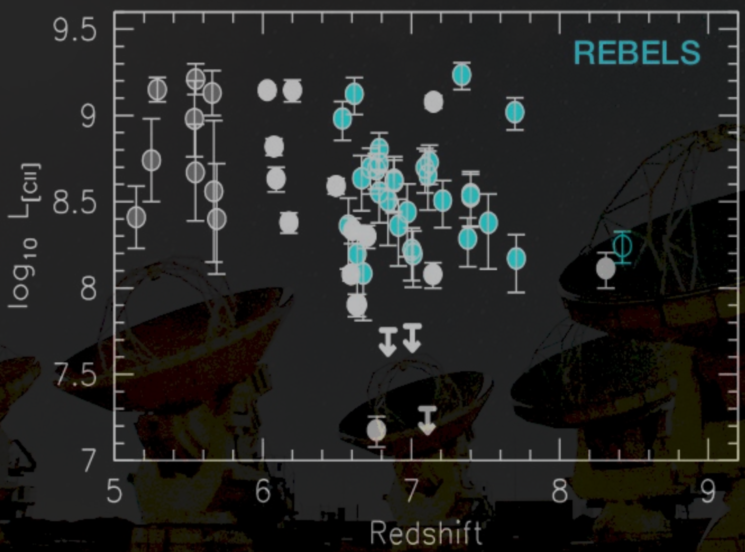
co-Is: Renske Smit, Pascal Oesch, Sander Schouws, Mauro Stefanon, Rebecca Bowler, Ryan Endsley, Manuel Aravena, Luca Graziani, Elisabete da Cunha, Cameron White, Jacqueline Hodge, Cindy Yuexing Li, Dominik Riechers, Yoshi Fudamoto, Ivo Labbe, Ilse de Looze, Rafaella Schneider, Themiya Nanayakkara, Paul van der Werf, Andrea Ferrara, Pratika Dayal, Andrea Pallottini, Alex Hygate, Laia Barrufet De Soto, Laura Sommovigo

Targeting 40 Very Bright z=6.5-9.5 Galaxies from 7 deg² Search and Scanning for [CII] + [OIII] / Looking for Dust

[CII] Flux



Many Bright [CII] Detections



Many Bright Dust Continuum Detections at 158 microns

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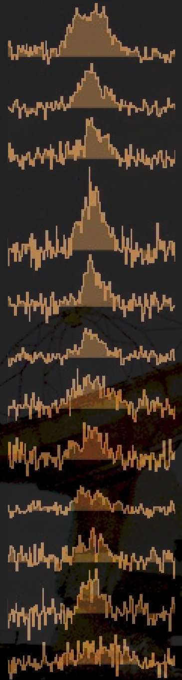

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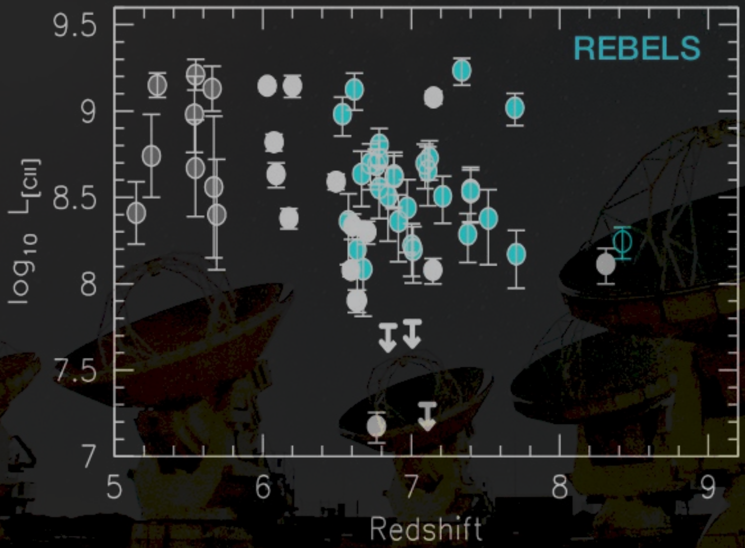

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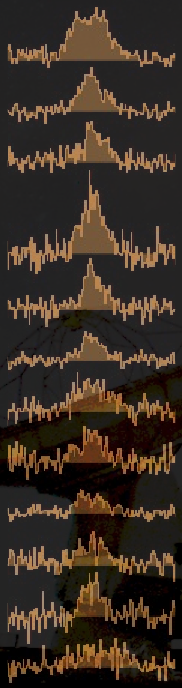

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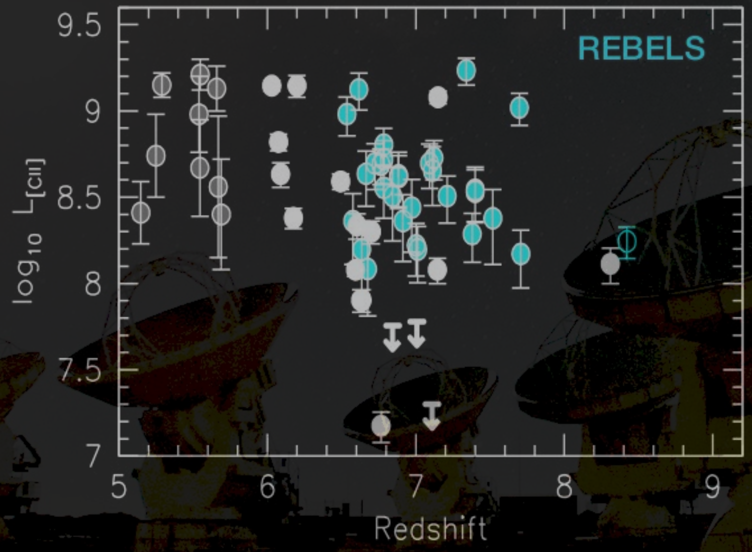

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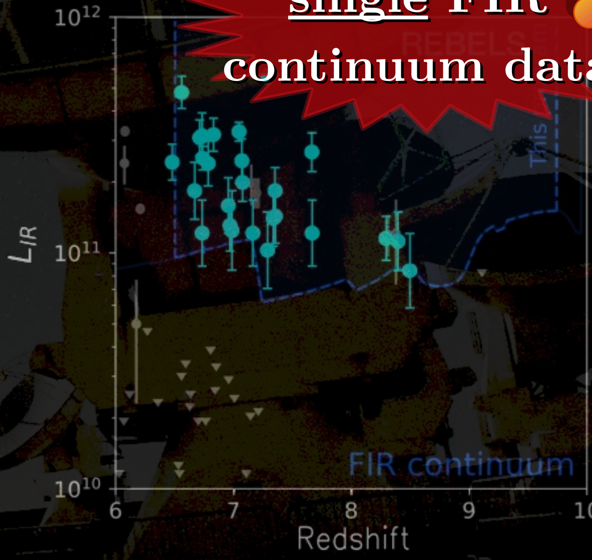

BUT: **single FIR continuum data**

New method to derive T_d using [CII] information

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

Sommovigo+21

New method to derive T_d using [CII] information

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

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$D \propto Z$ → Dust to gas ratio

Sommovigo+21

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

Sommovigo+21

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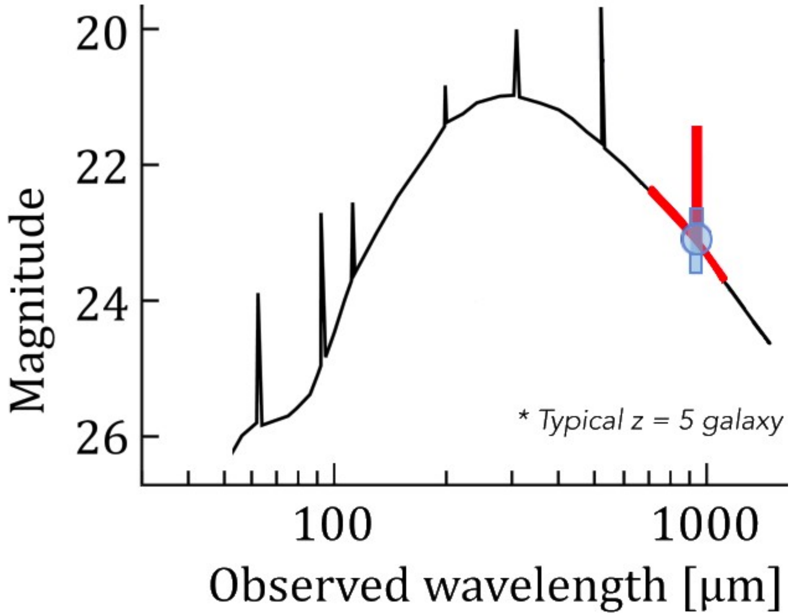

Inputs: **Outputs:**

[CII] → M_d

Continuum → T_d

Sommovigo+21

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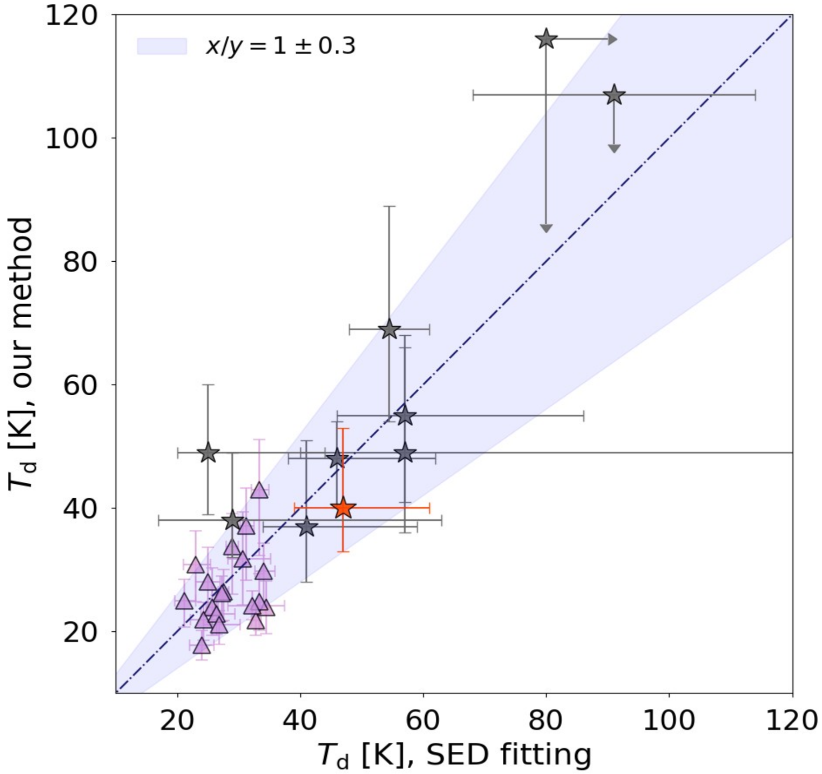

Inputs: **Outputs:**

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Continuum → ***T_d***

Method tested on several local and high-z galaxies:

We recover T_d from "traditional" SED fitting within 1σ

Sommovigo+21

New method to derive T_d using [CII] information

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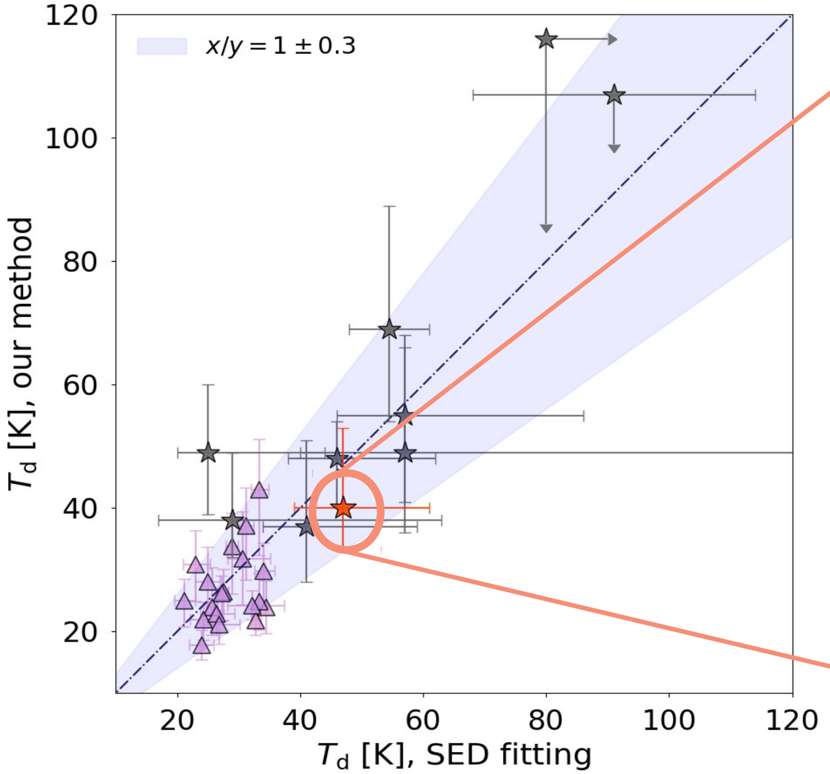
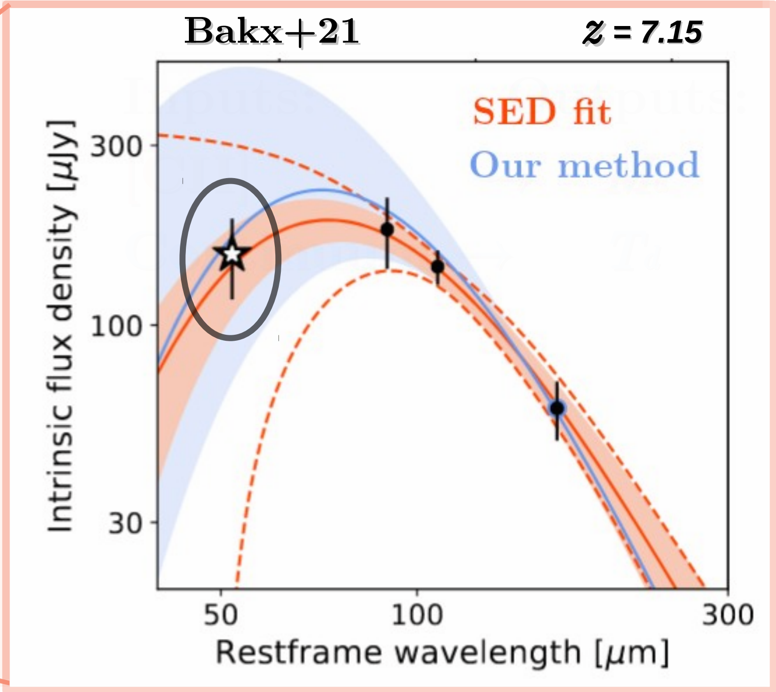
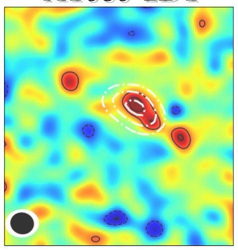




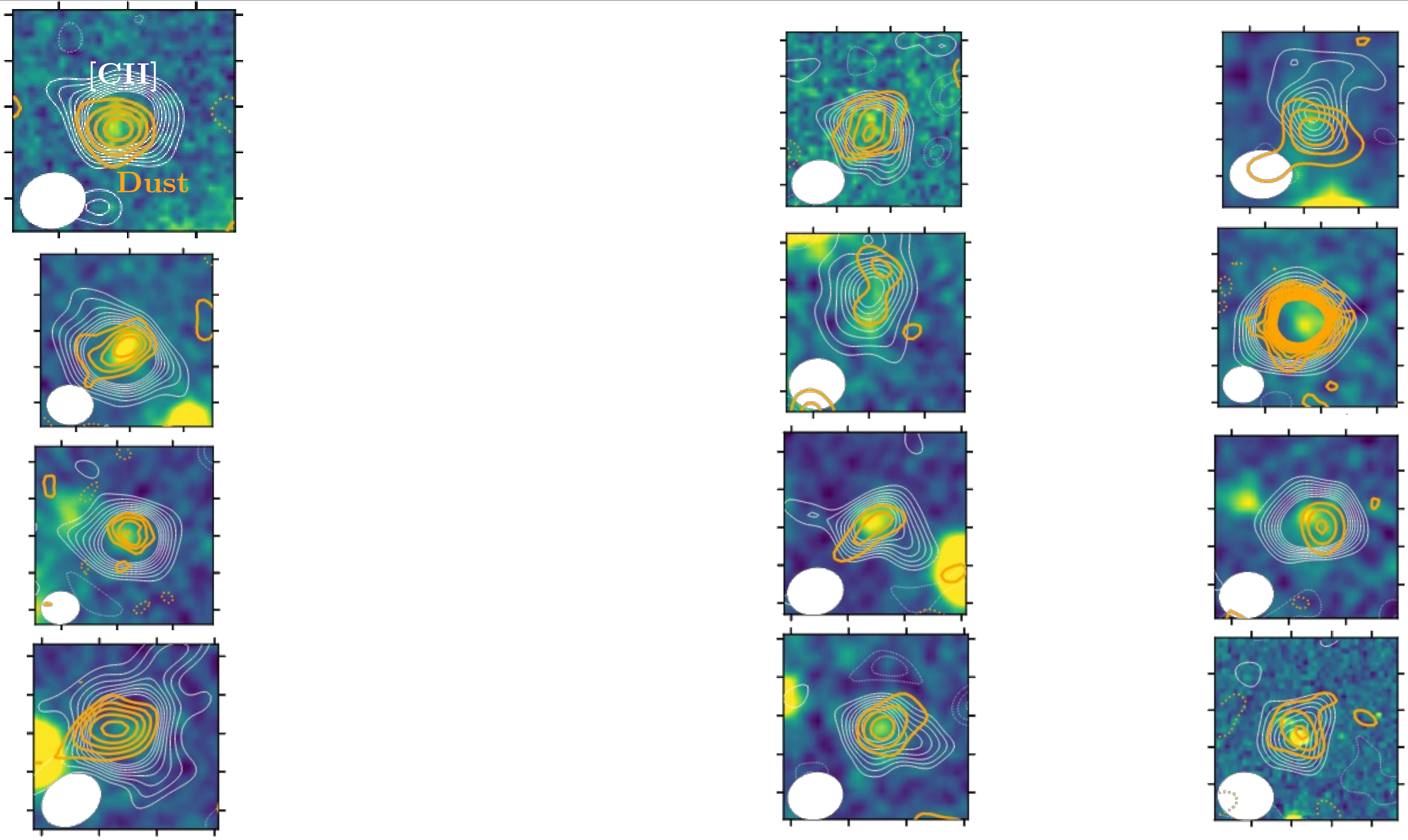
See: Watson+15, Knudsen +17



ALMA **Band 9**

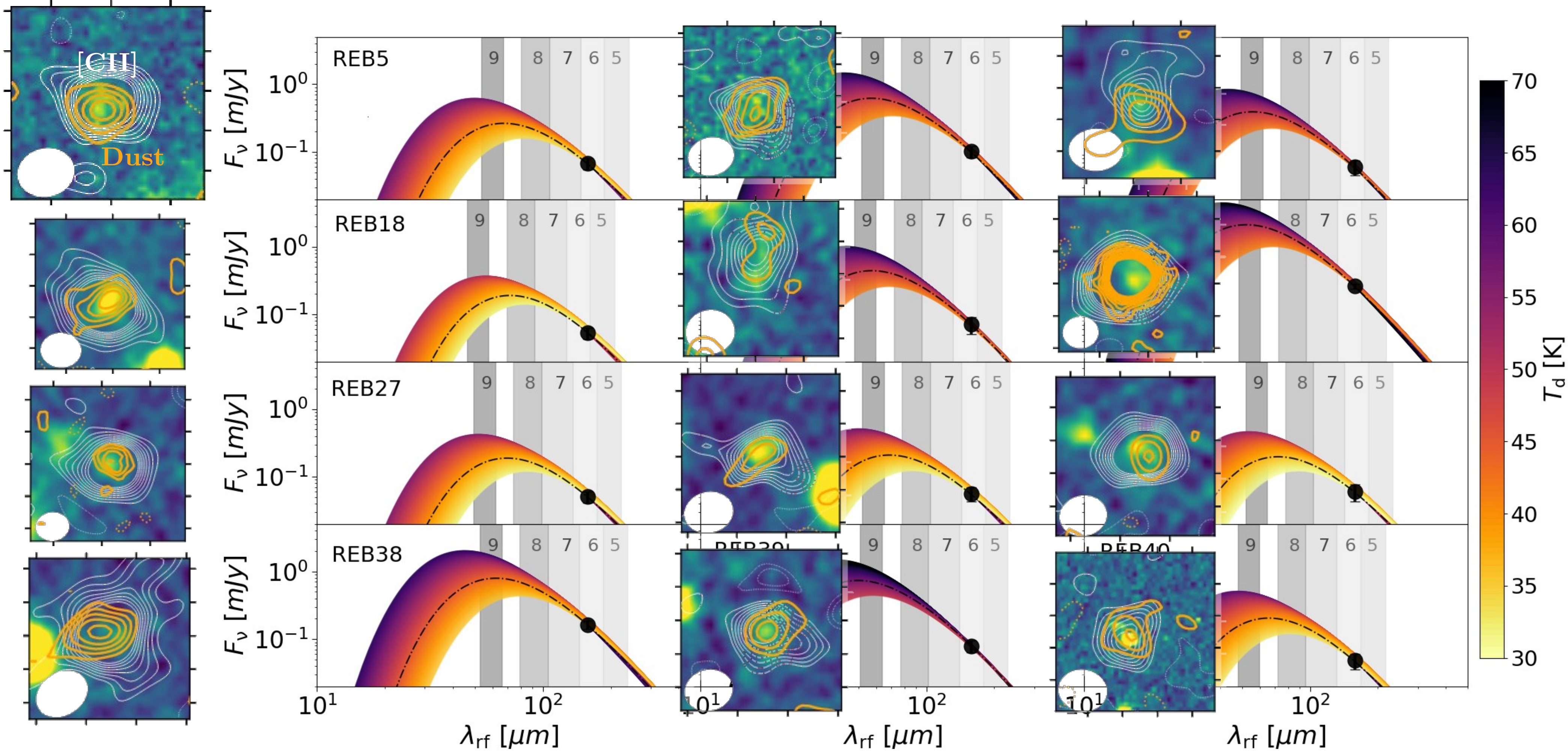
Sommovigo+21

REBELS galaxies dust properties



Continuum emission maps from: Inami+22

REBELS galaxies dust properties



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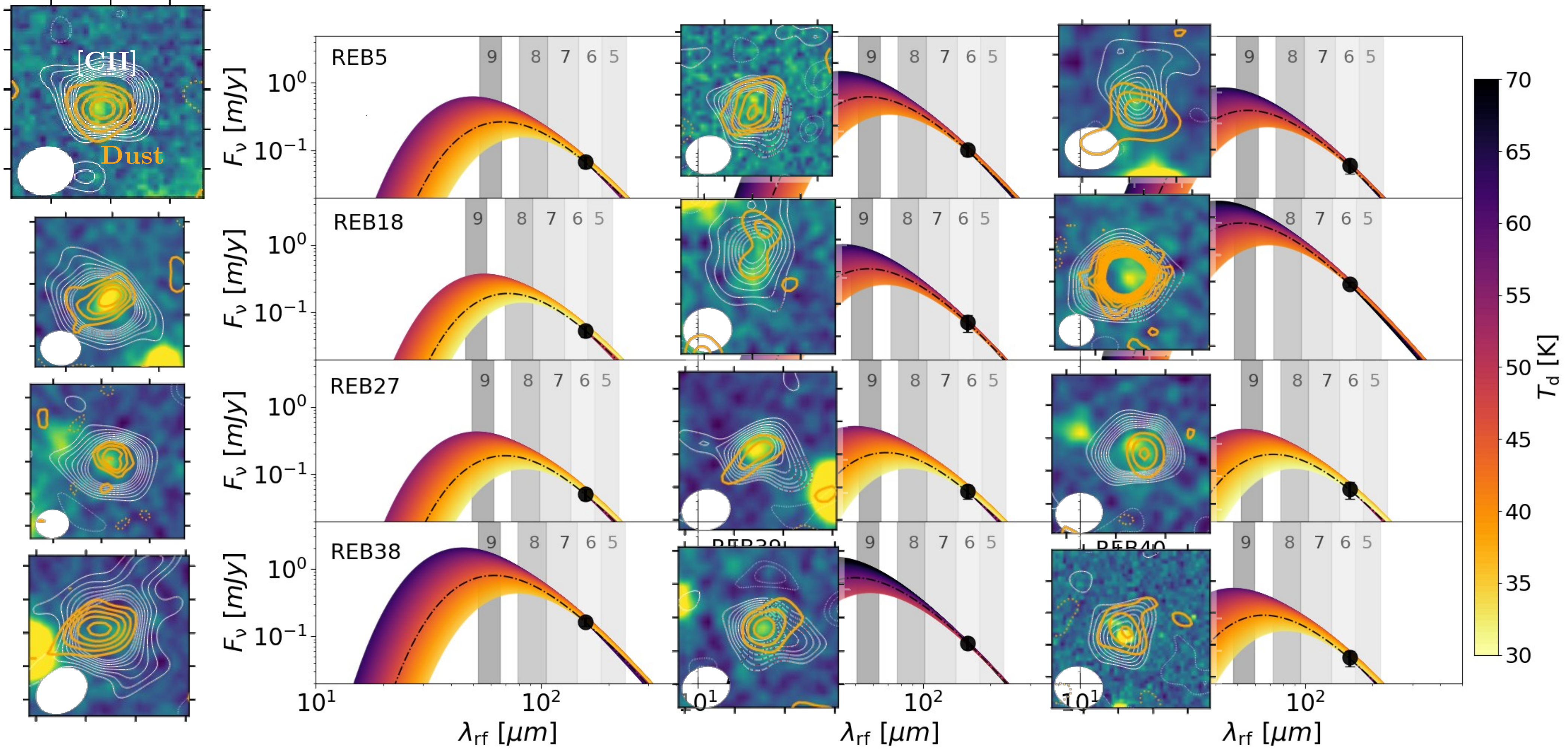

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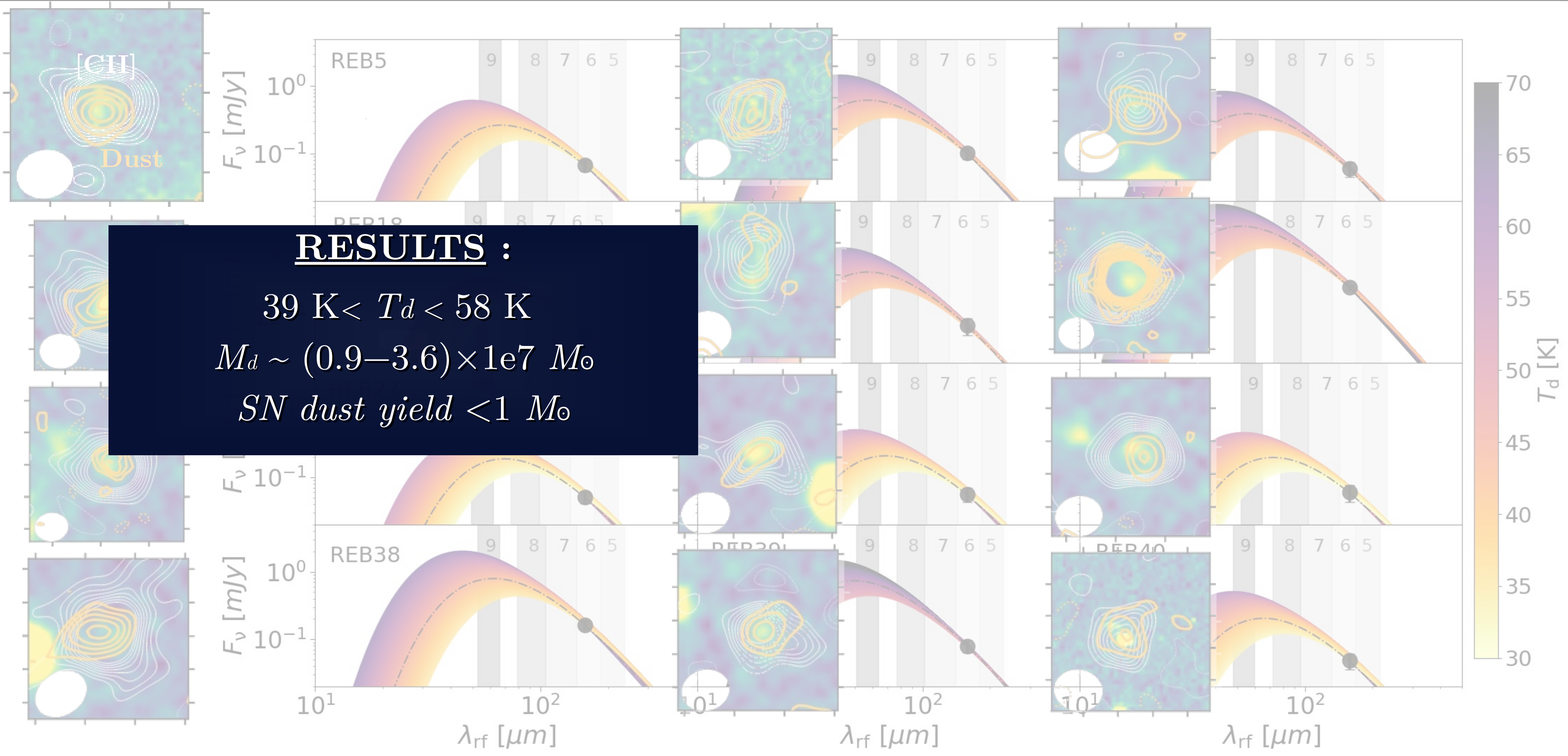

RESULTS :

39 K< T_d < 58 K

M_d ~ (0.9–3.6)×1e7 $M_\odot$

SN dust yield <1 $M_\odot$

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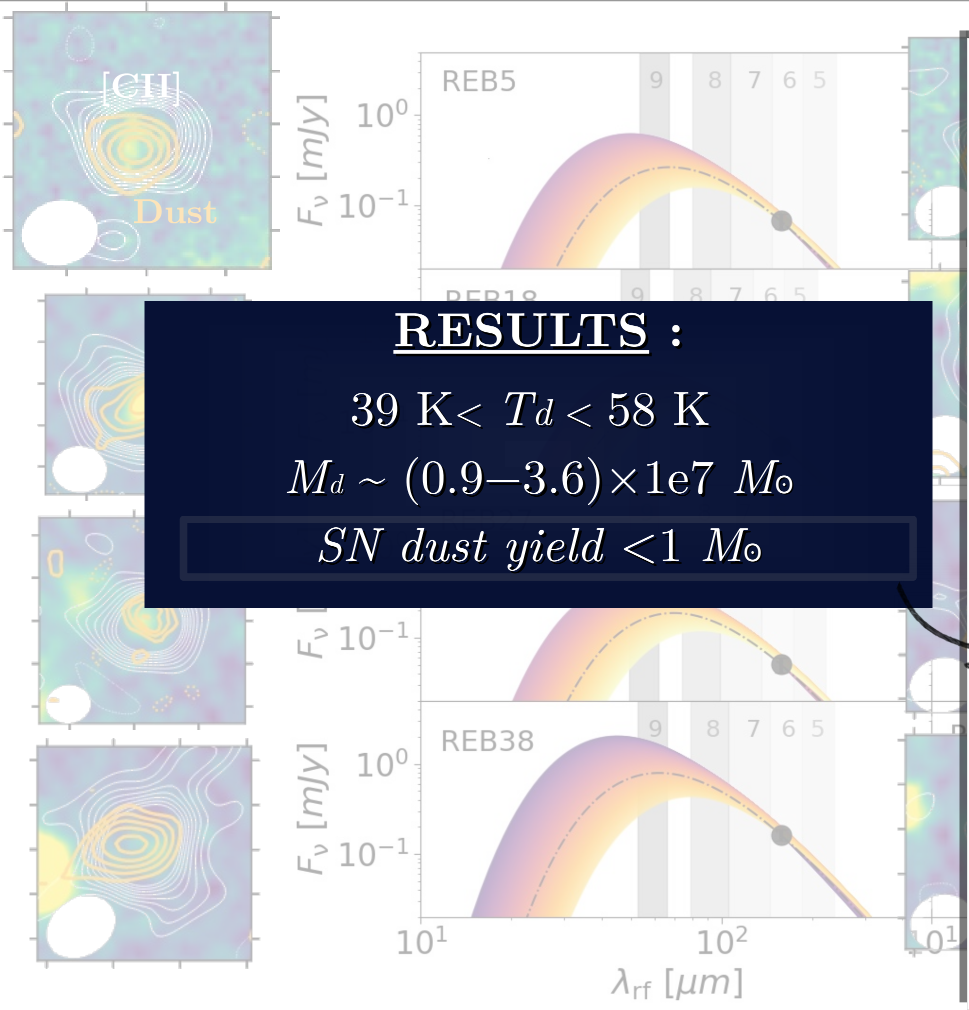

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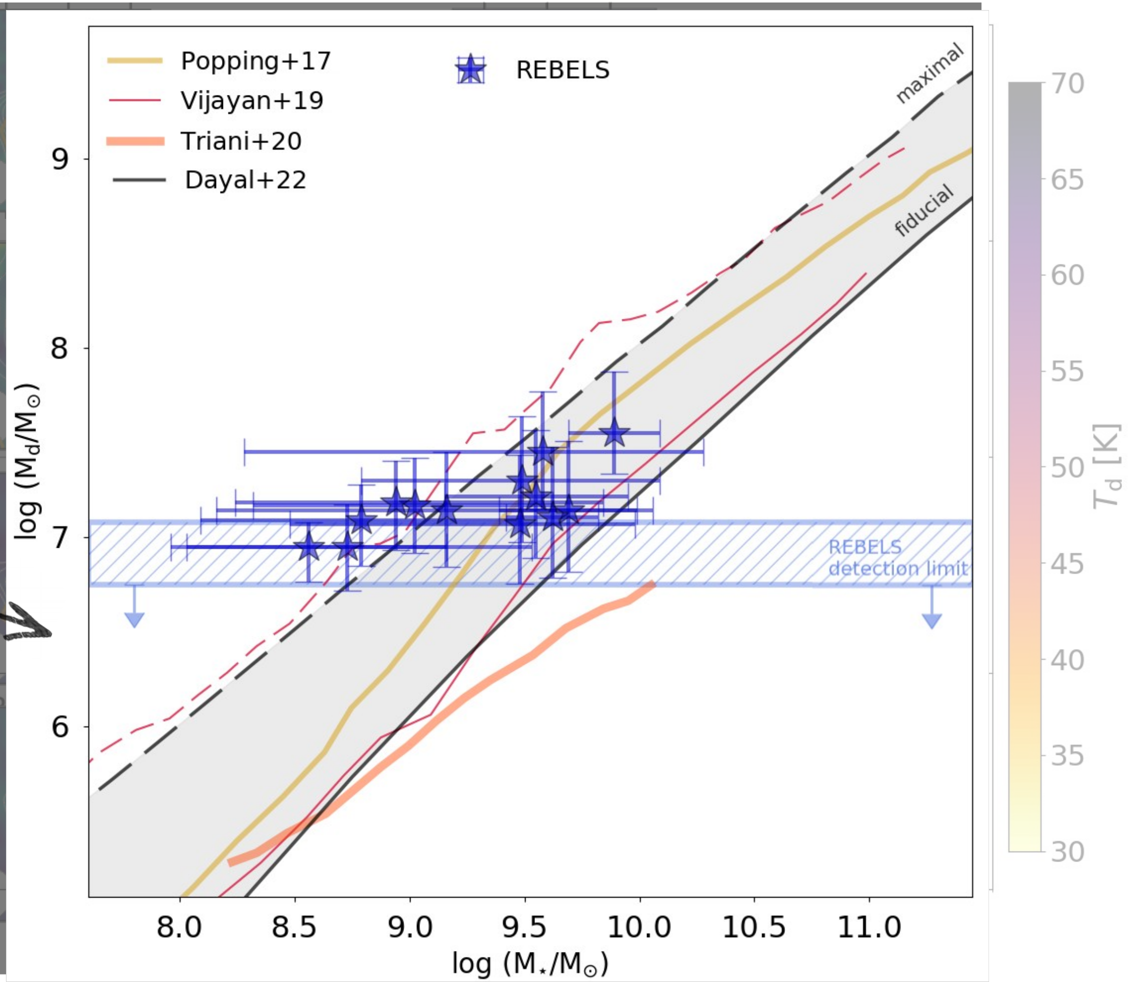

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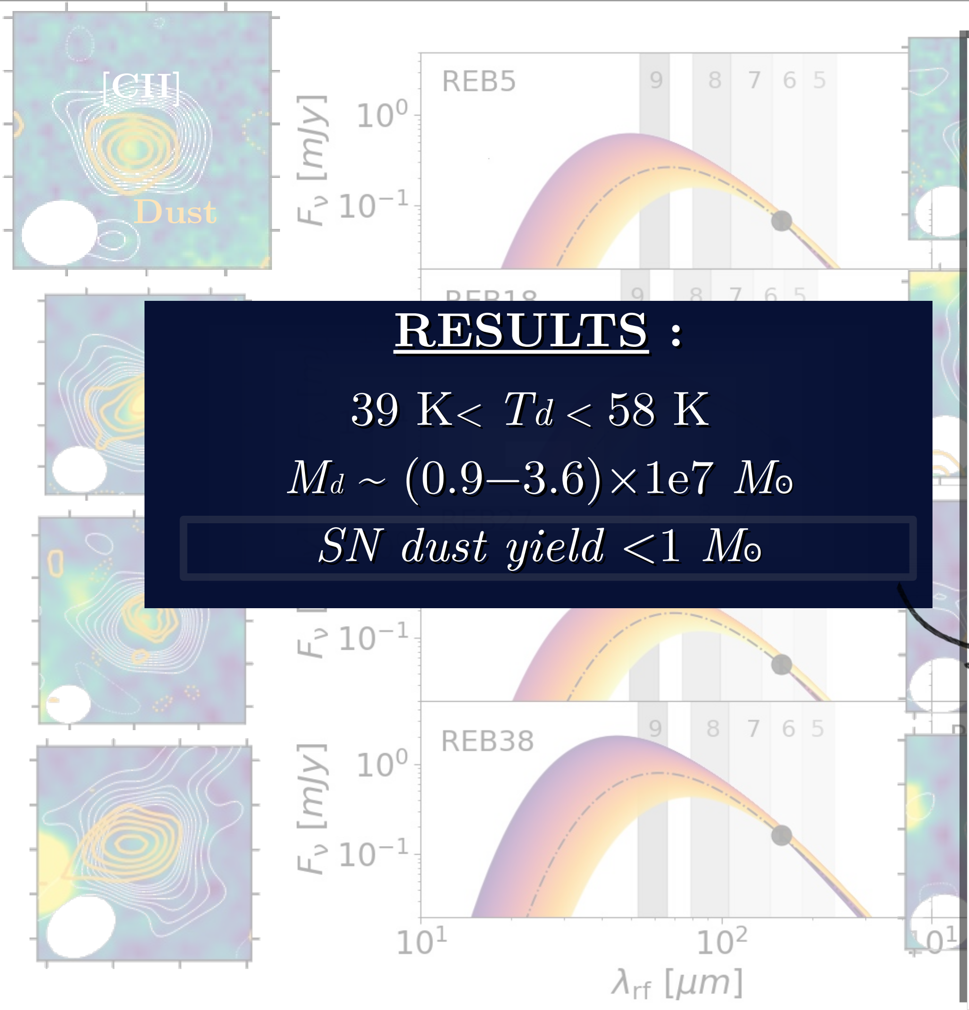

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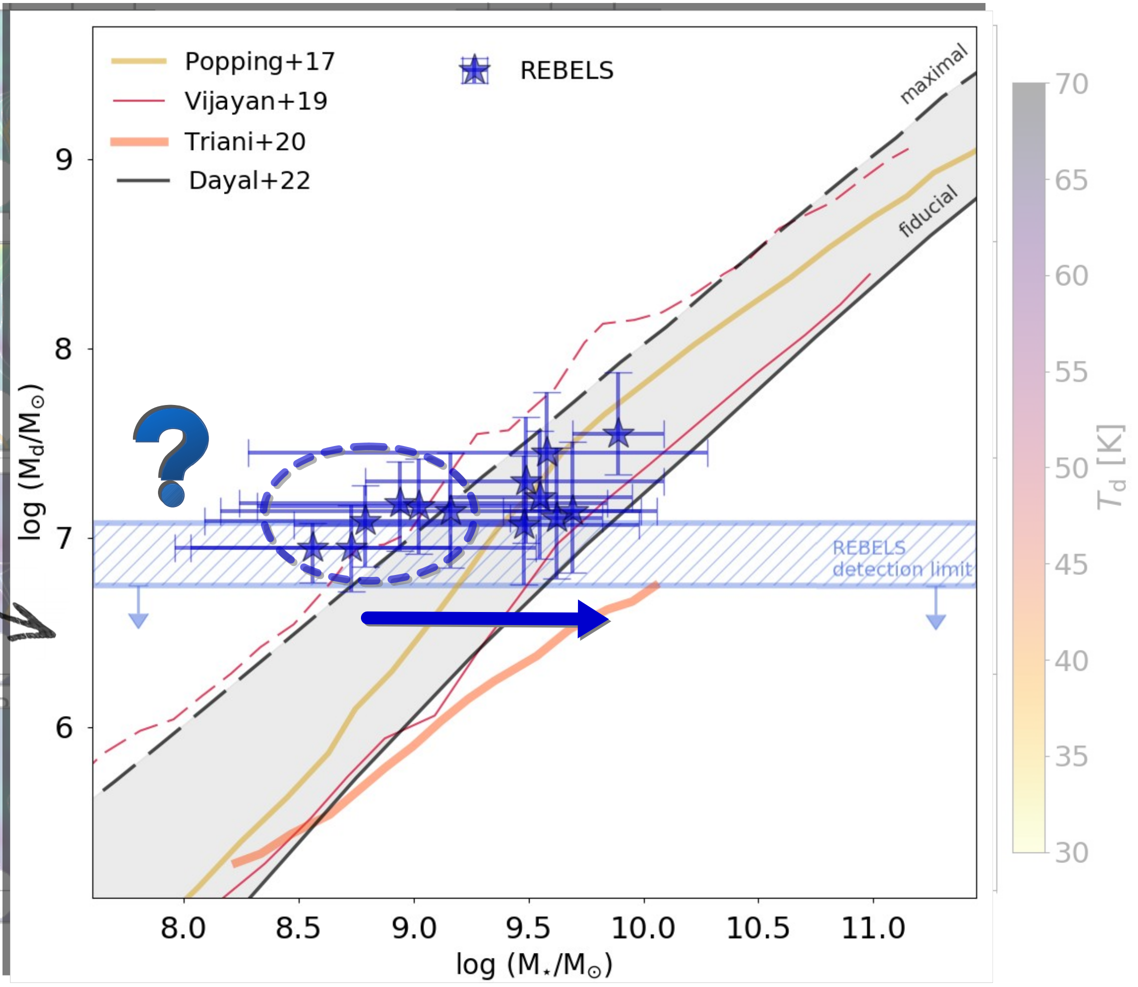

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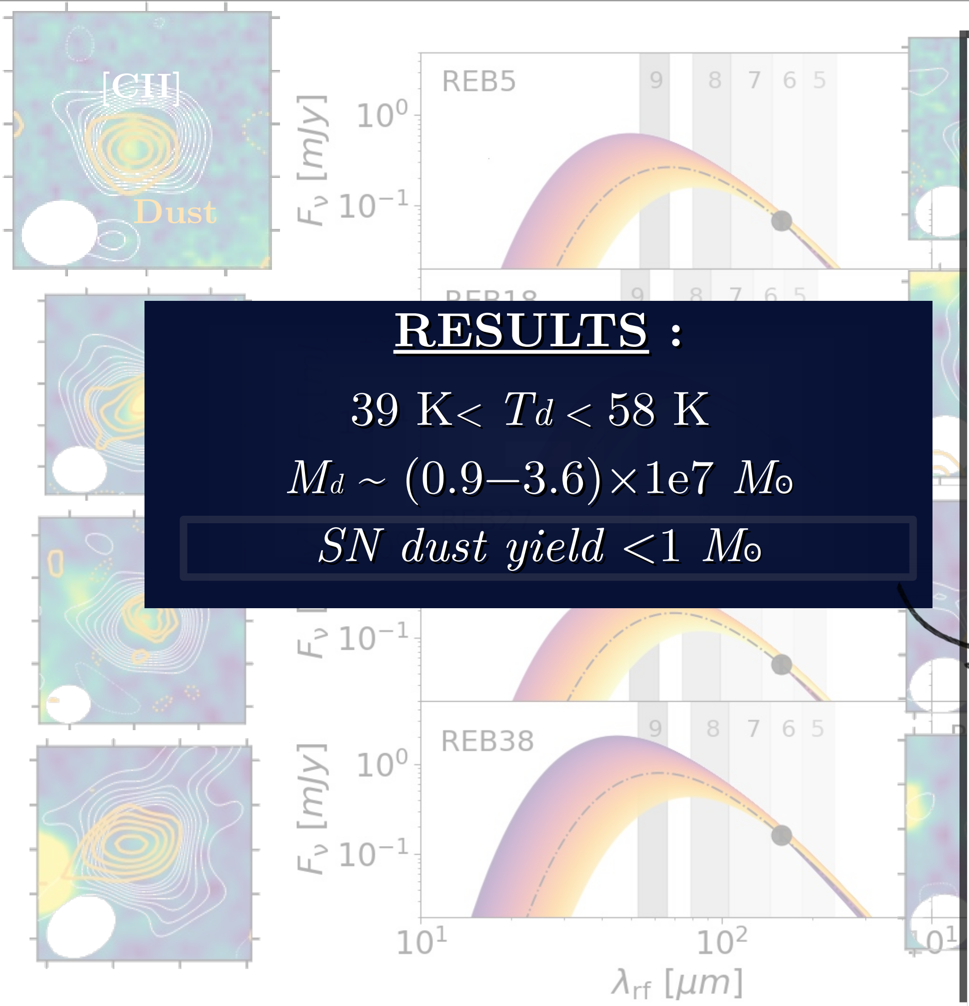

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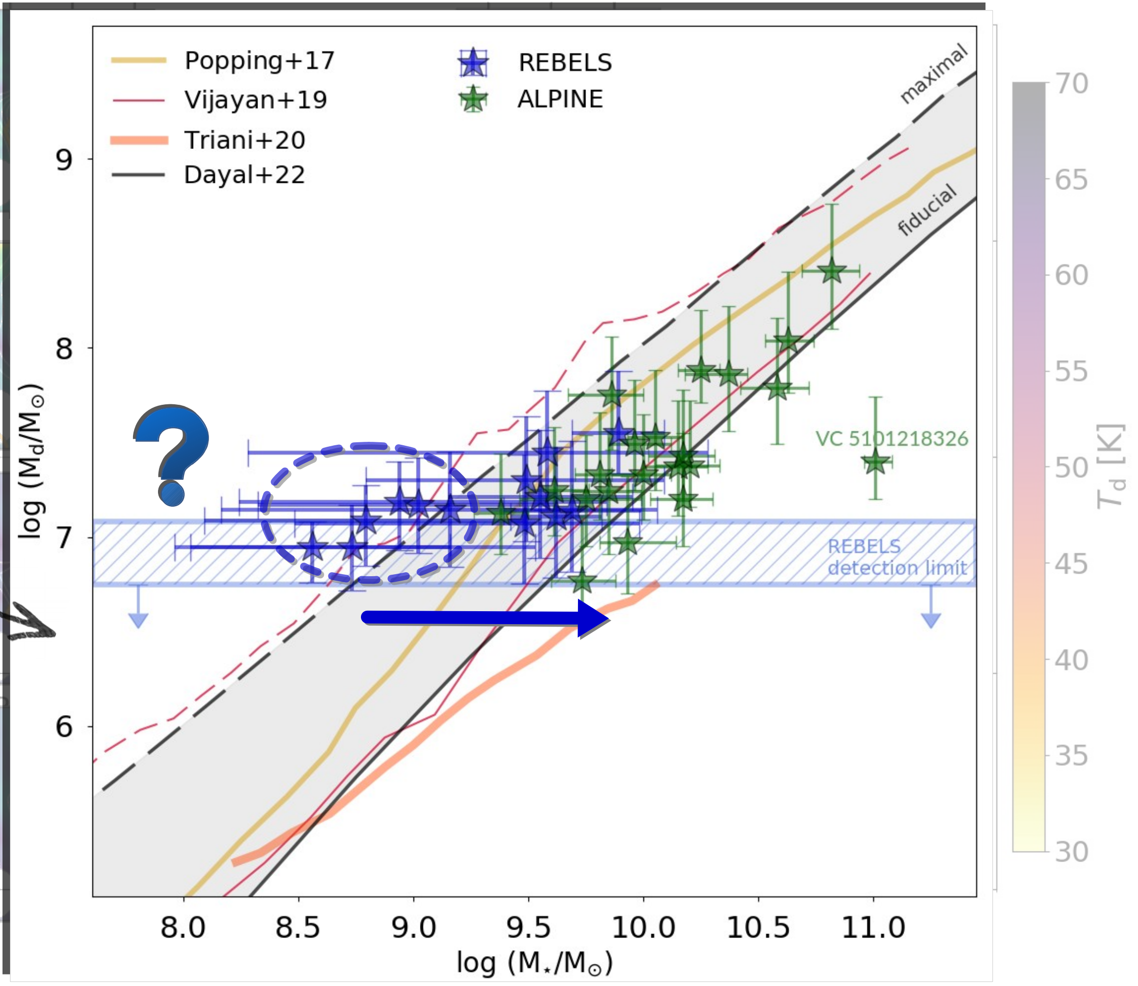

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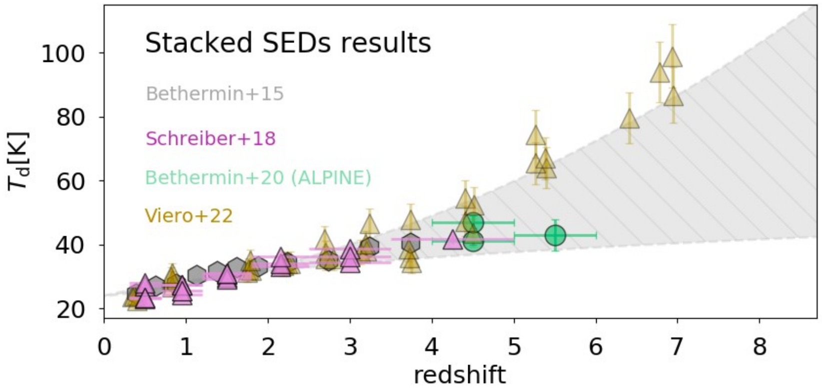
Cosmic dust temperature evolution



Sommovigo+22

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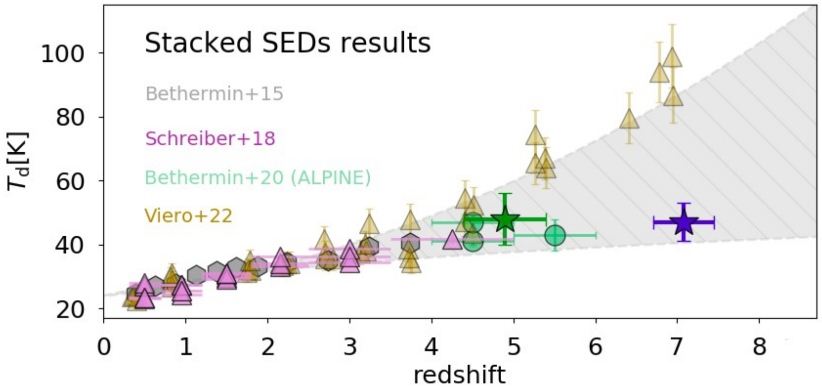

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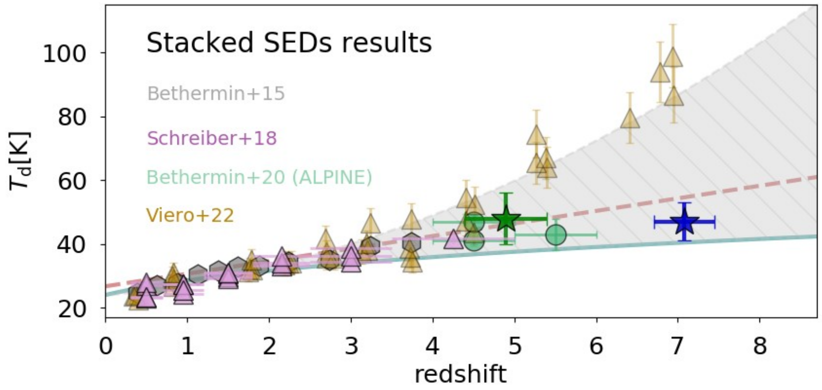

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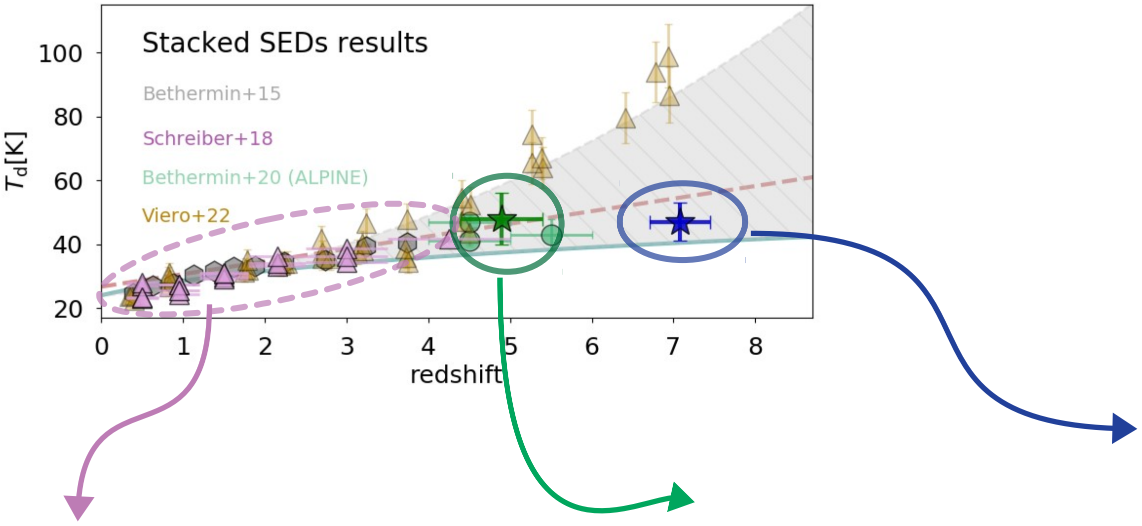

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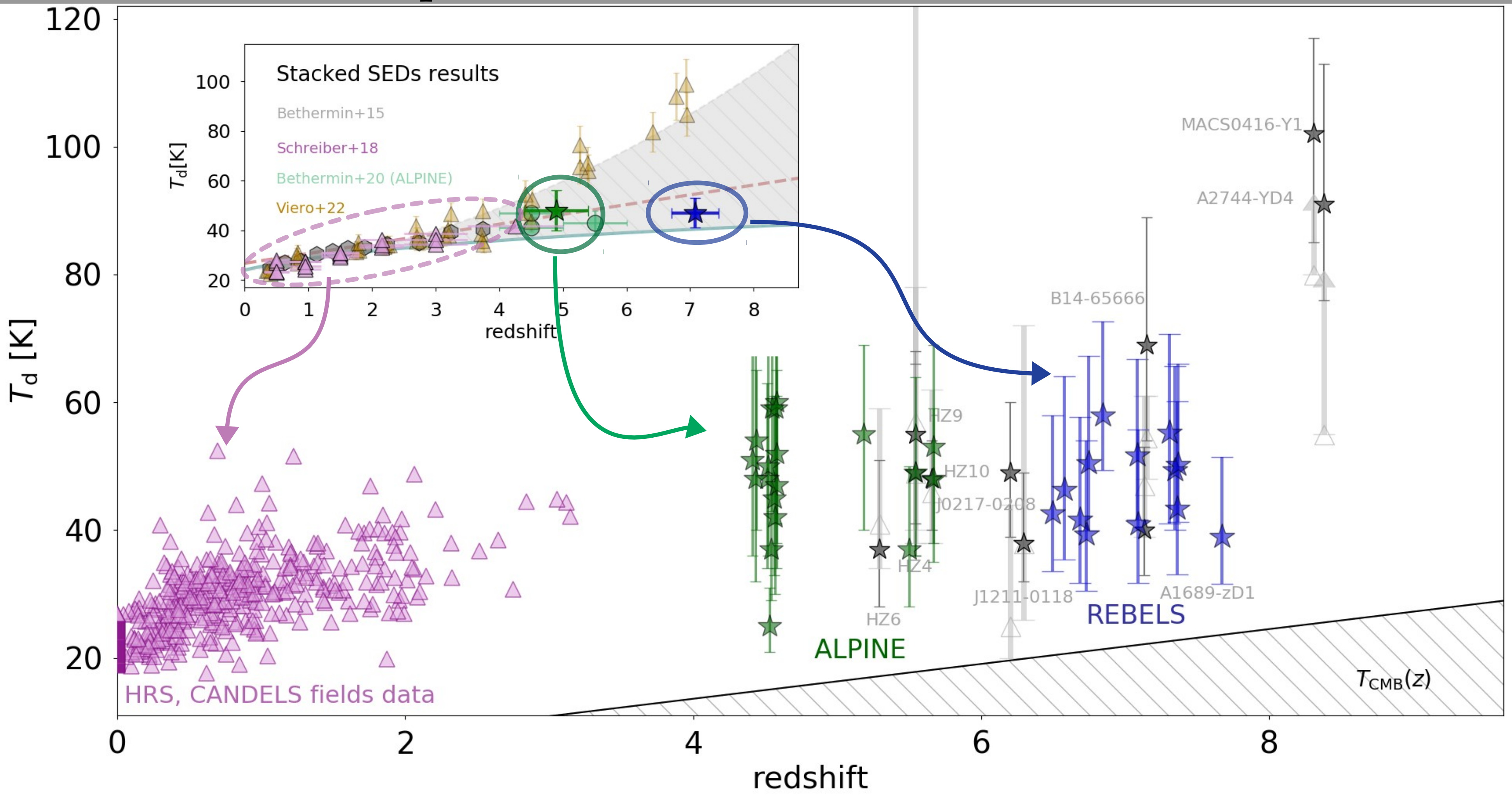
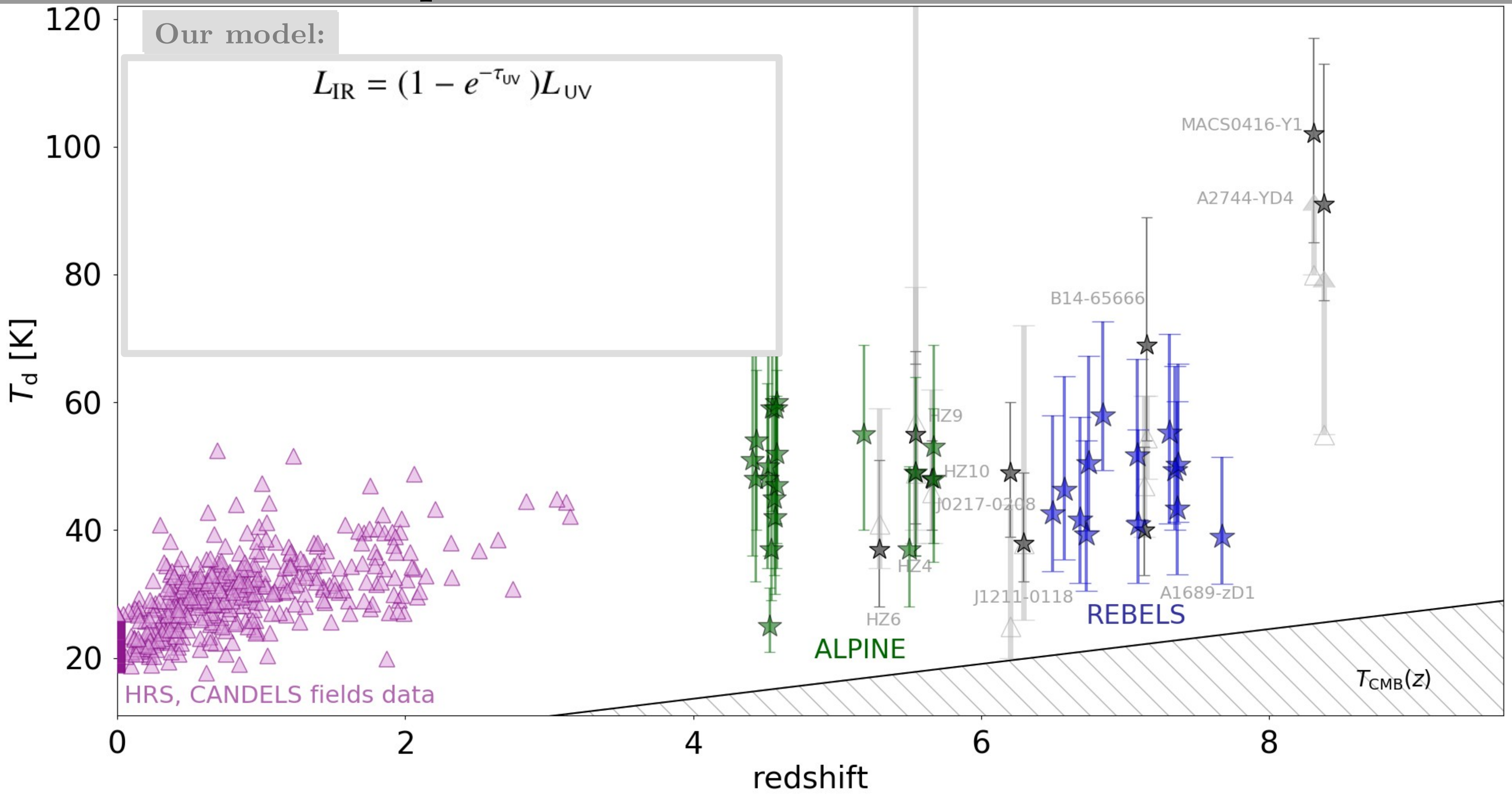


Sommovigo+22

Cosmic dust temperature evolution



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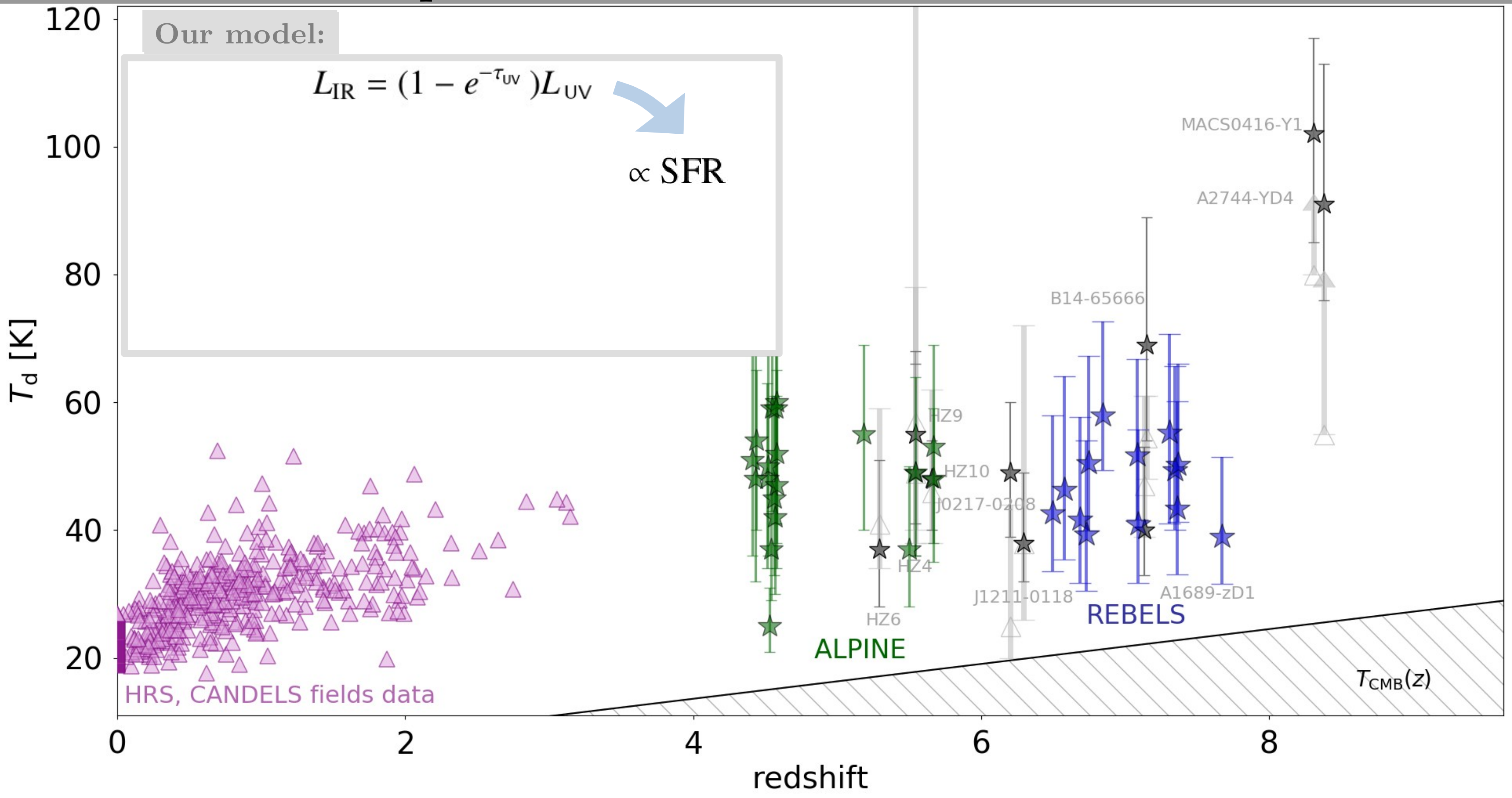

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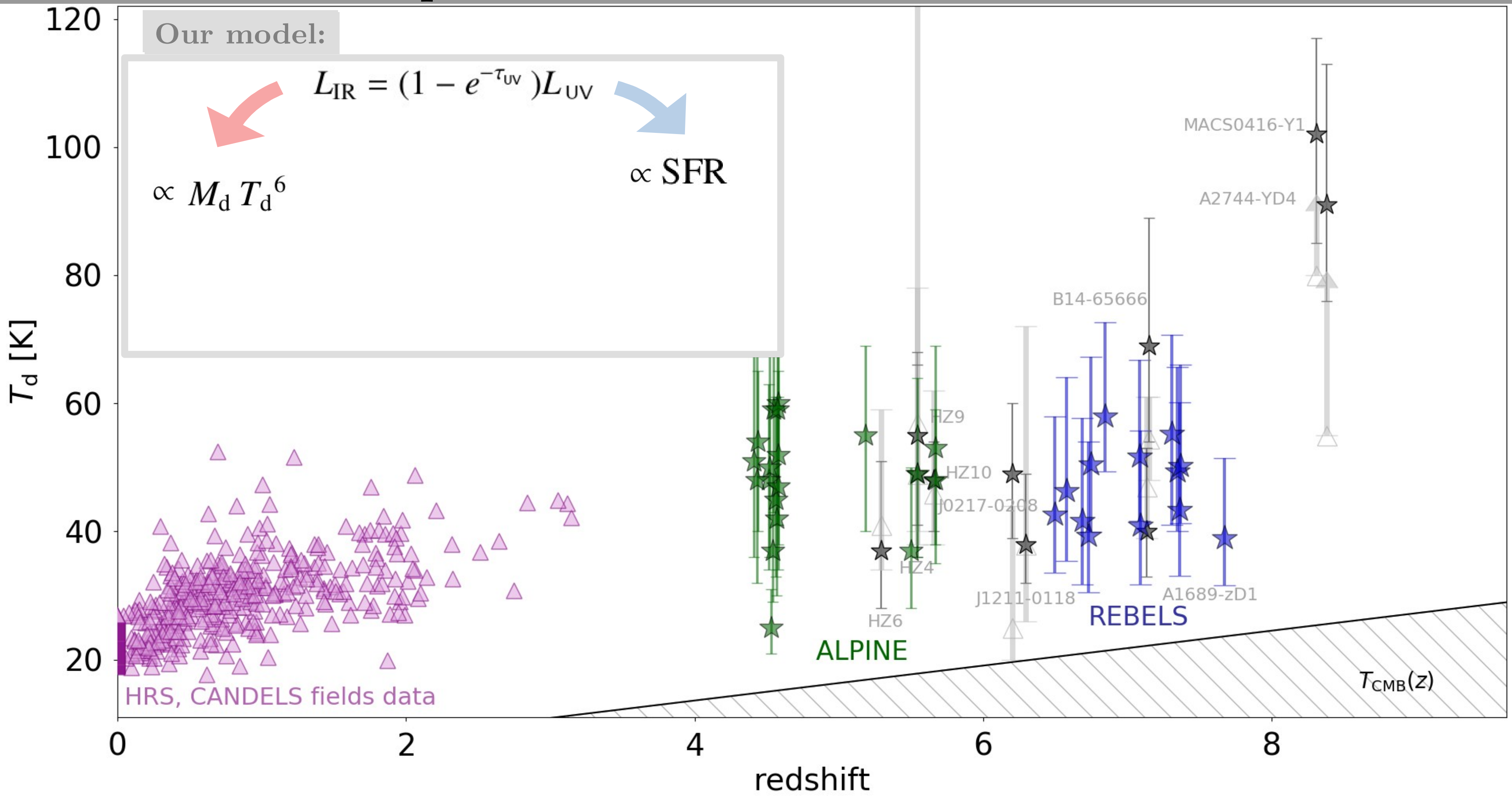

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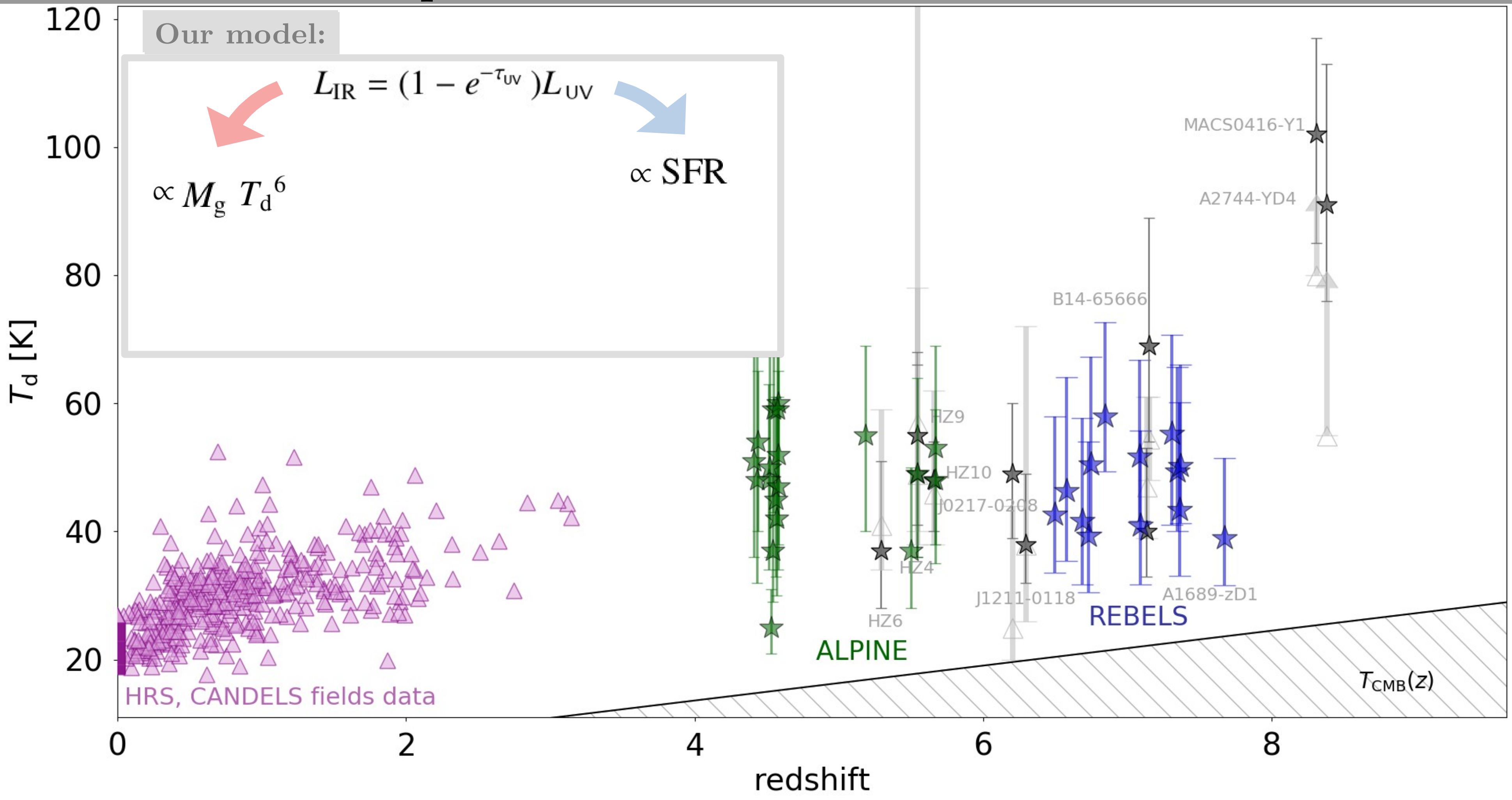

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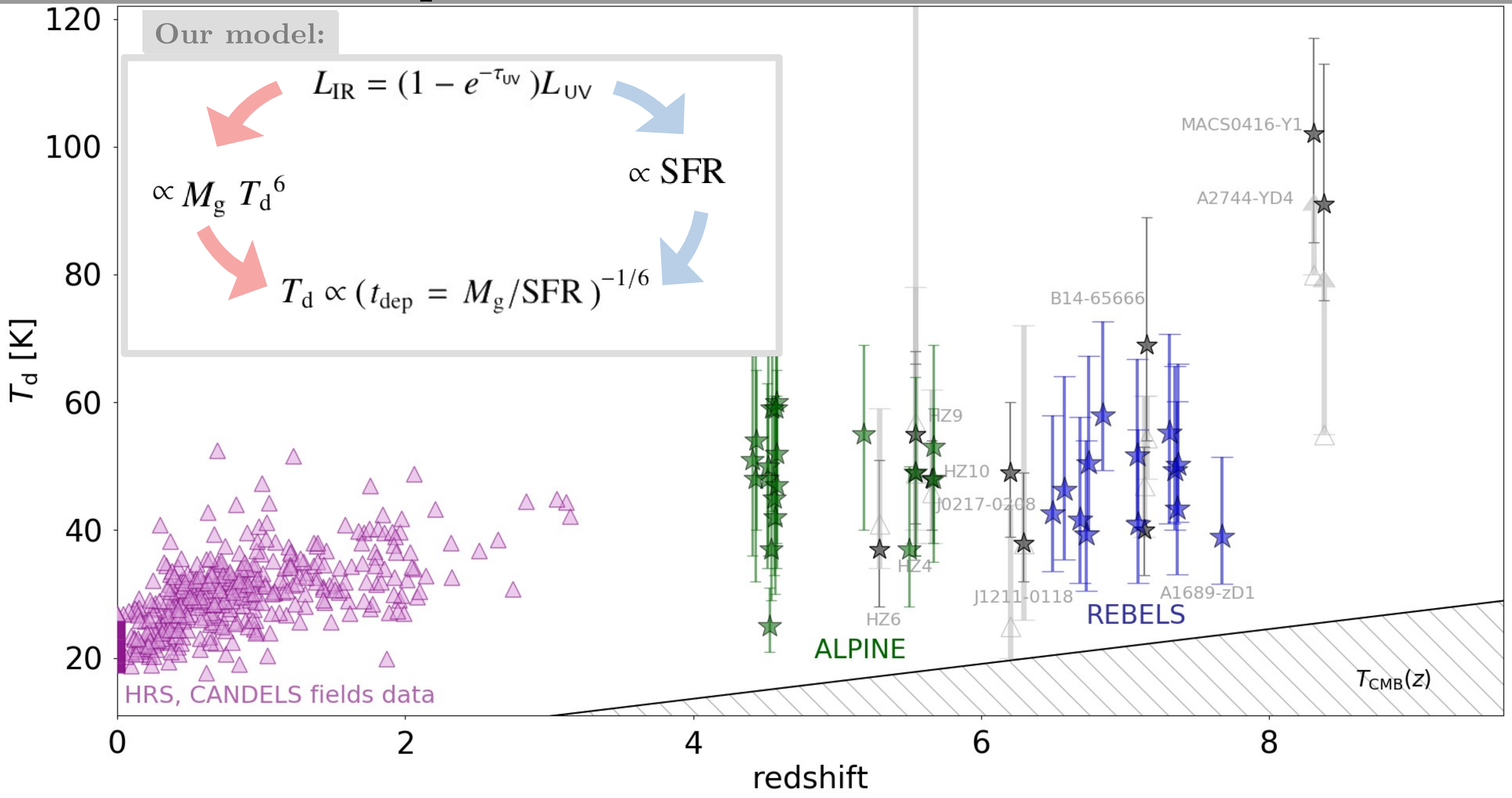

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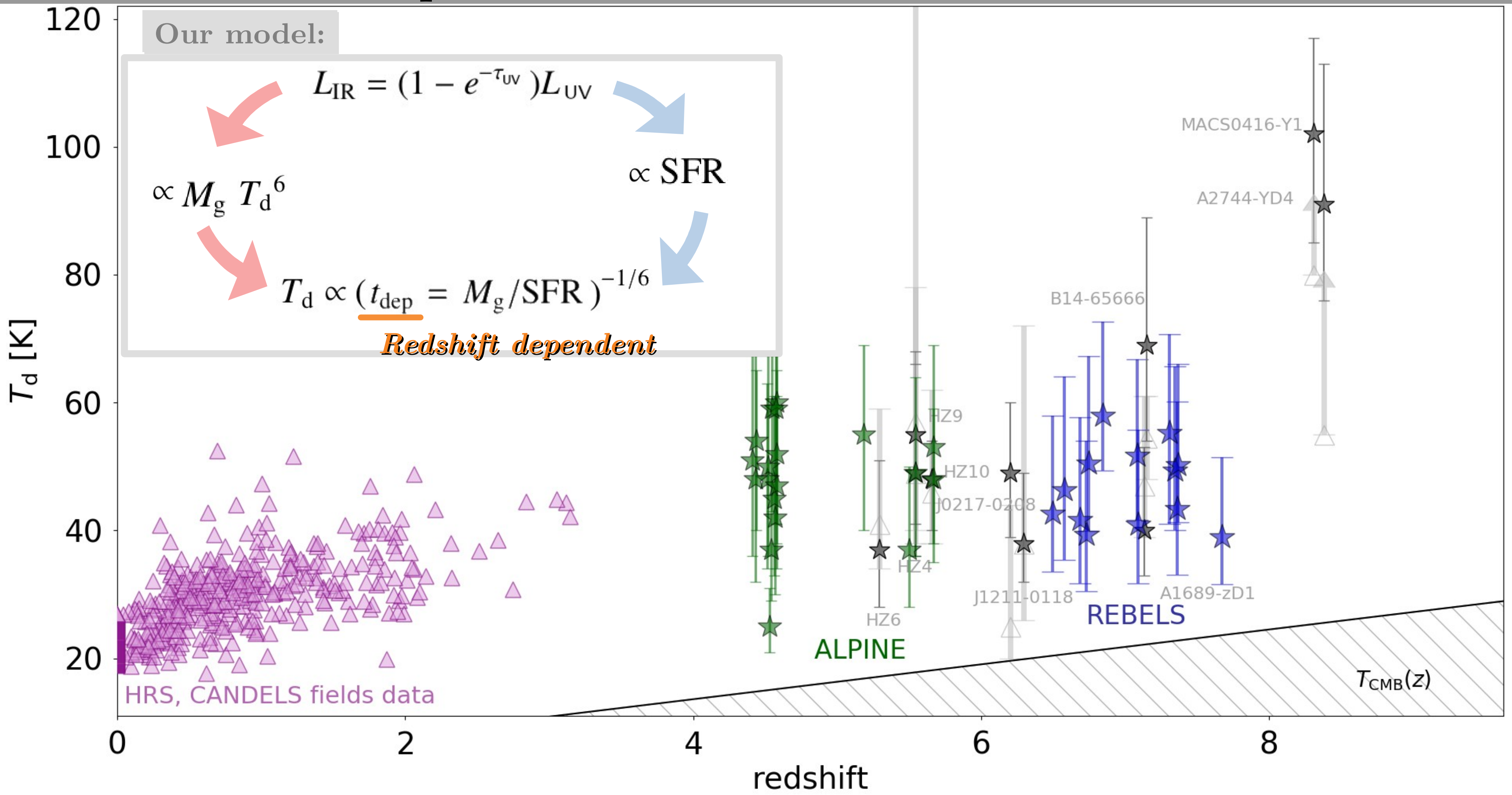

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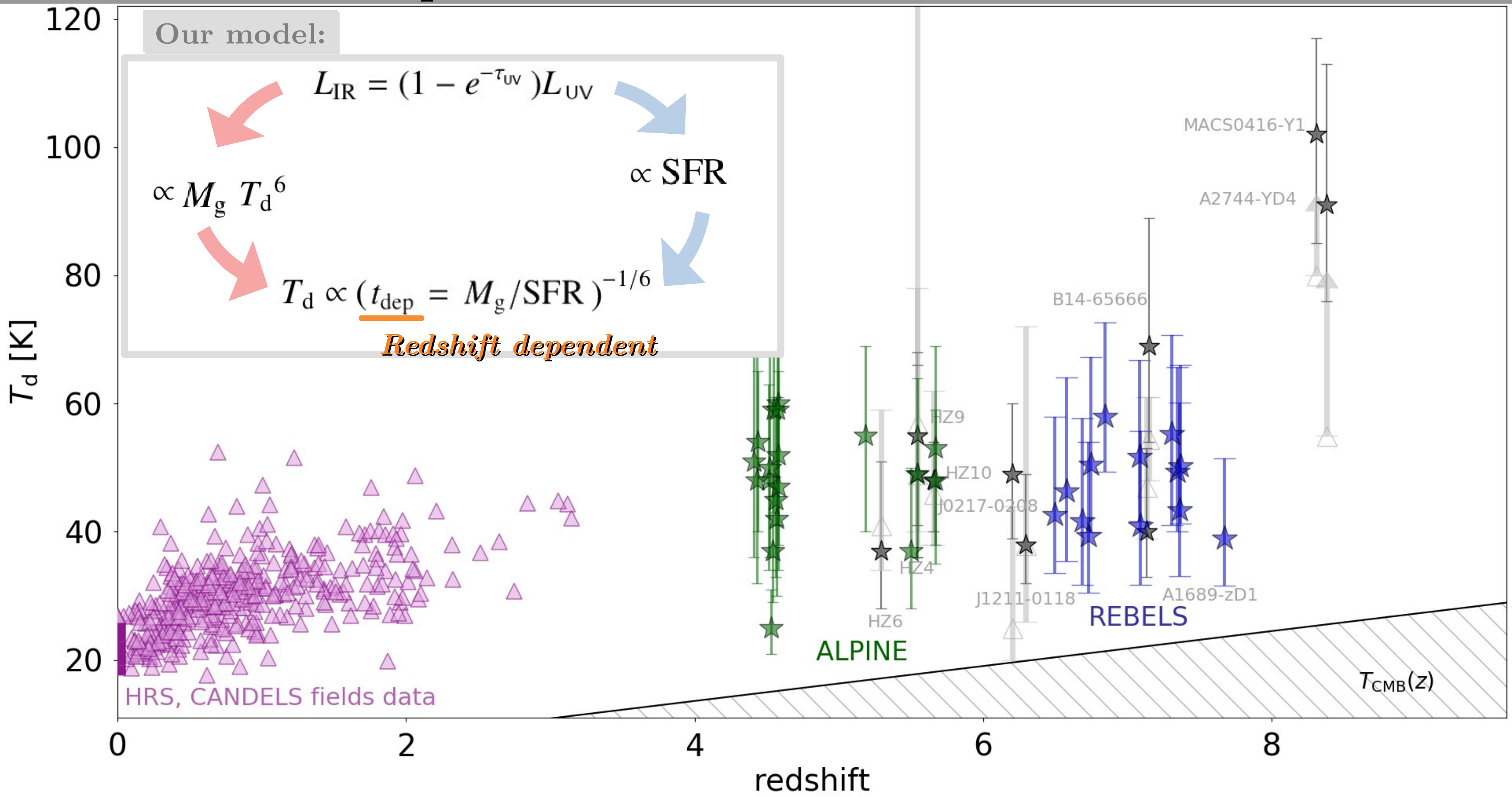
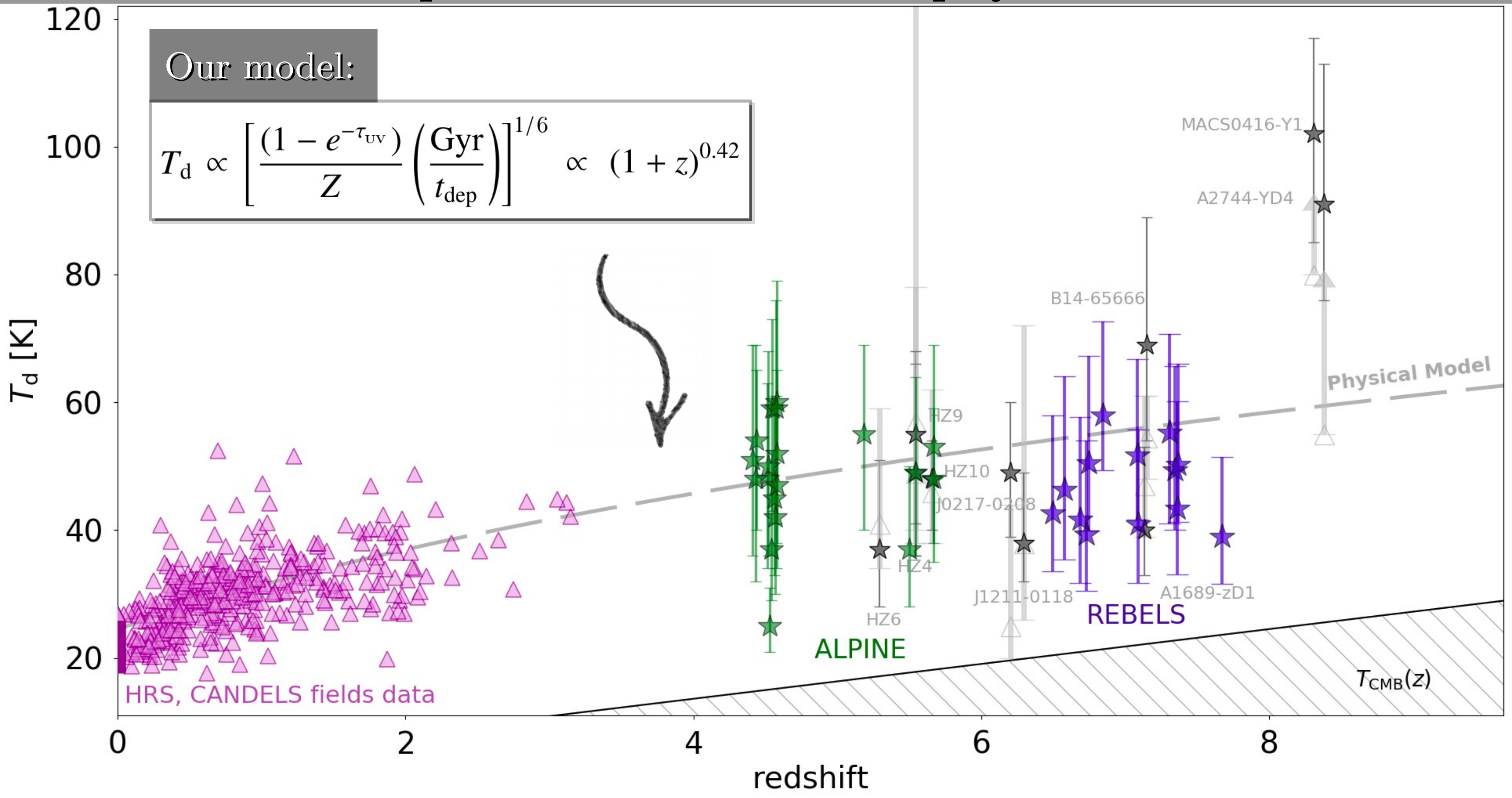


***T_d* raises with redshift** due to decreasing gas depletion time at high-z

Sommovigo+22

Cosmic dust temperature evolution: a physical model

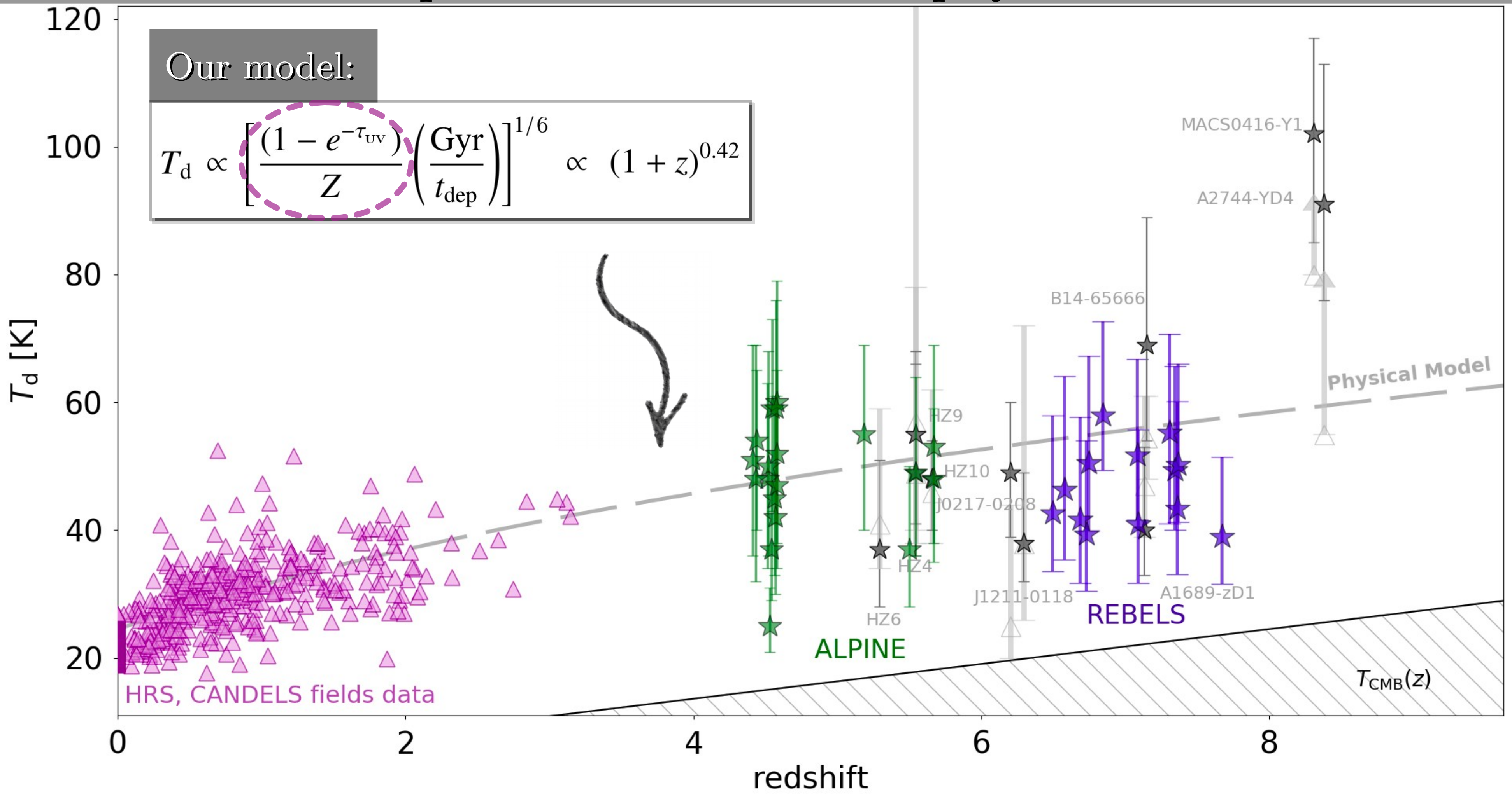


Sommovigo+22

Cosmic dust temperature evolution: a physical model

Our model:

$$T_d \propto \left[\frac{(1 - e^{-\tau_{UV}})}{Z} \left(\frac{\text{Gyr}}{t_{dep}} \right) \right]^{1/6} \propto (1+z)^{0.42}$$



Sommovigo+22

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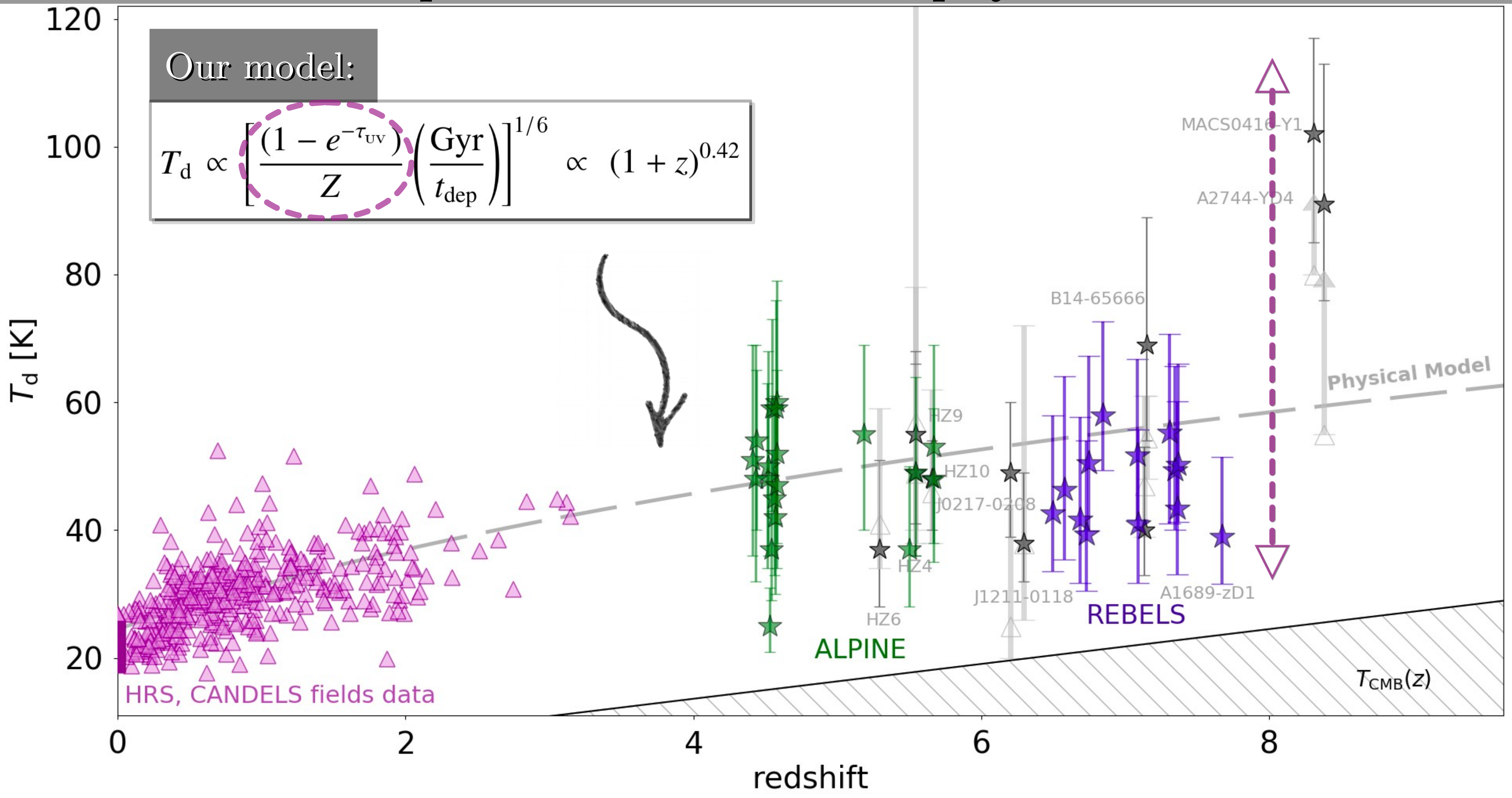

Sommovigo+22

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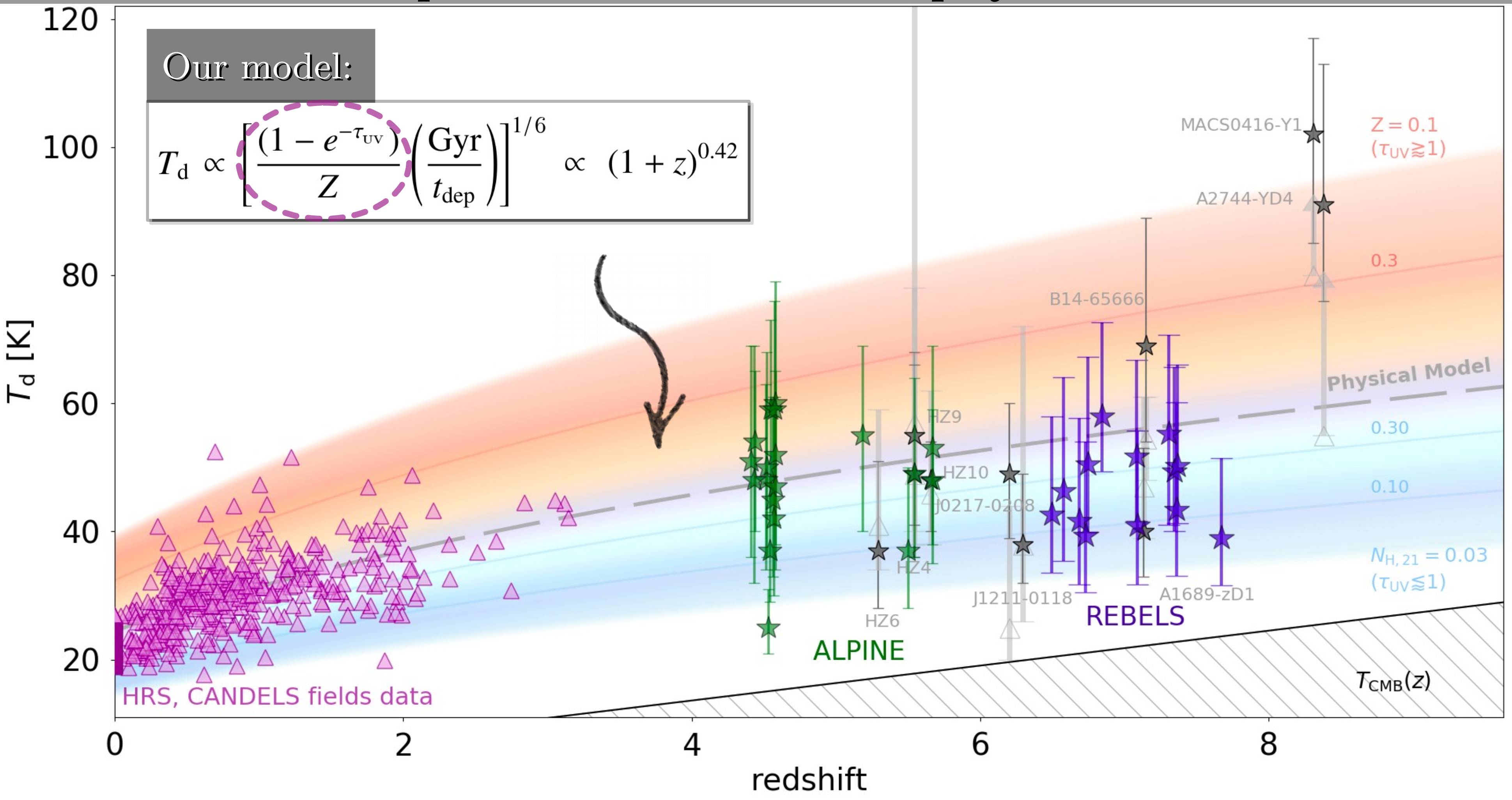

Sommovigo+22

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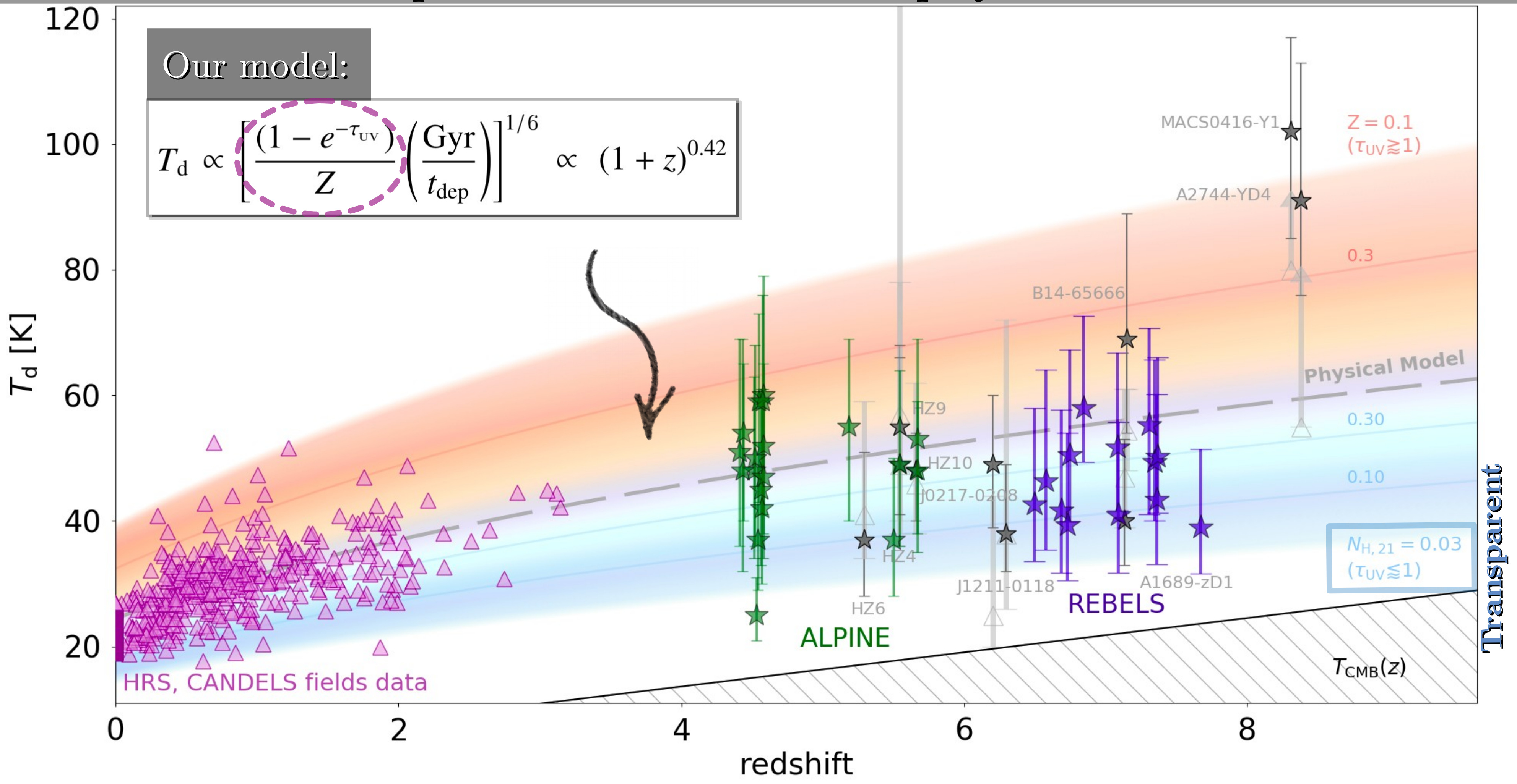

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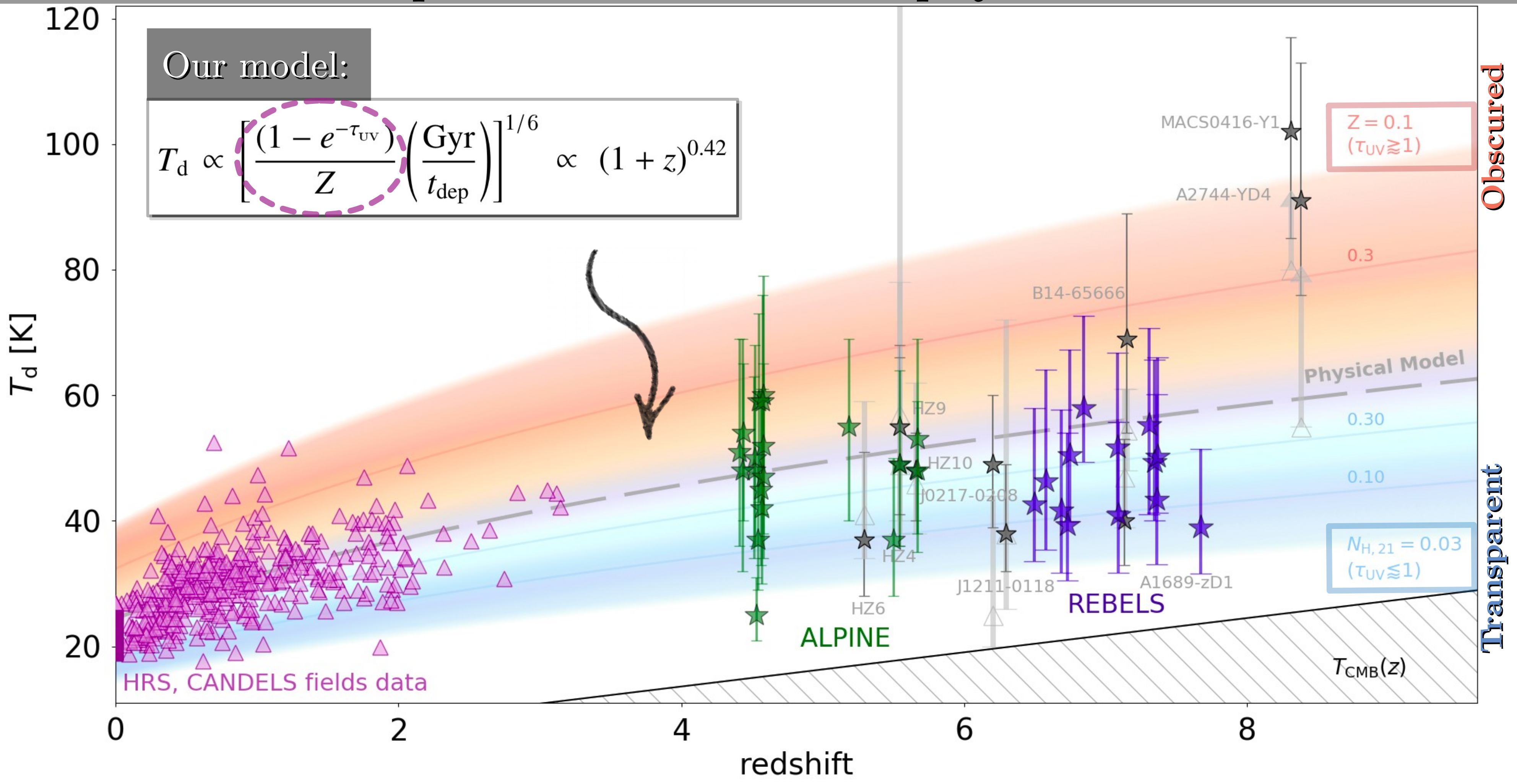

Sommovigo+22

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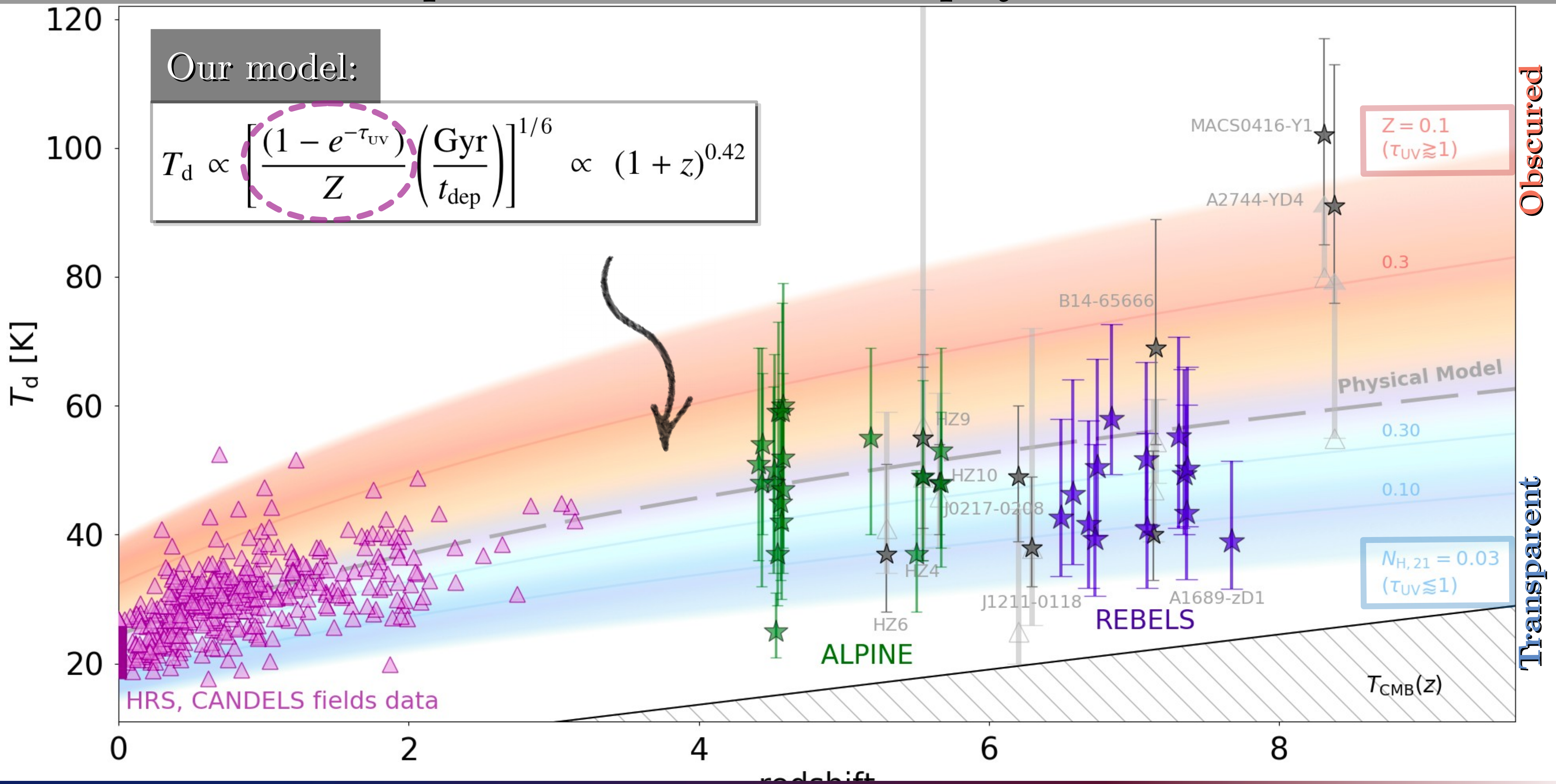
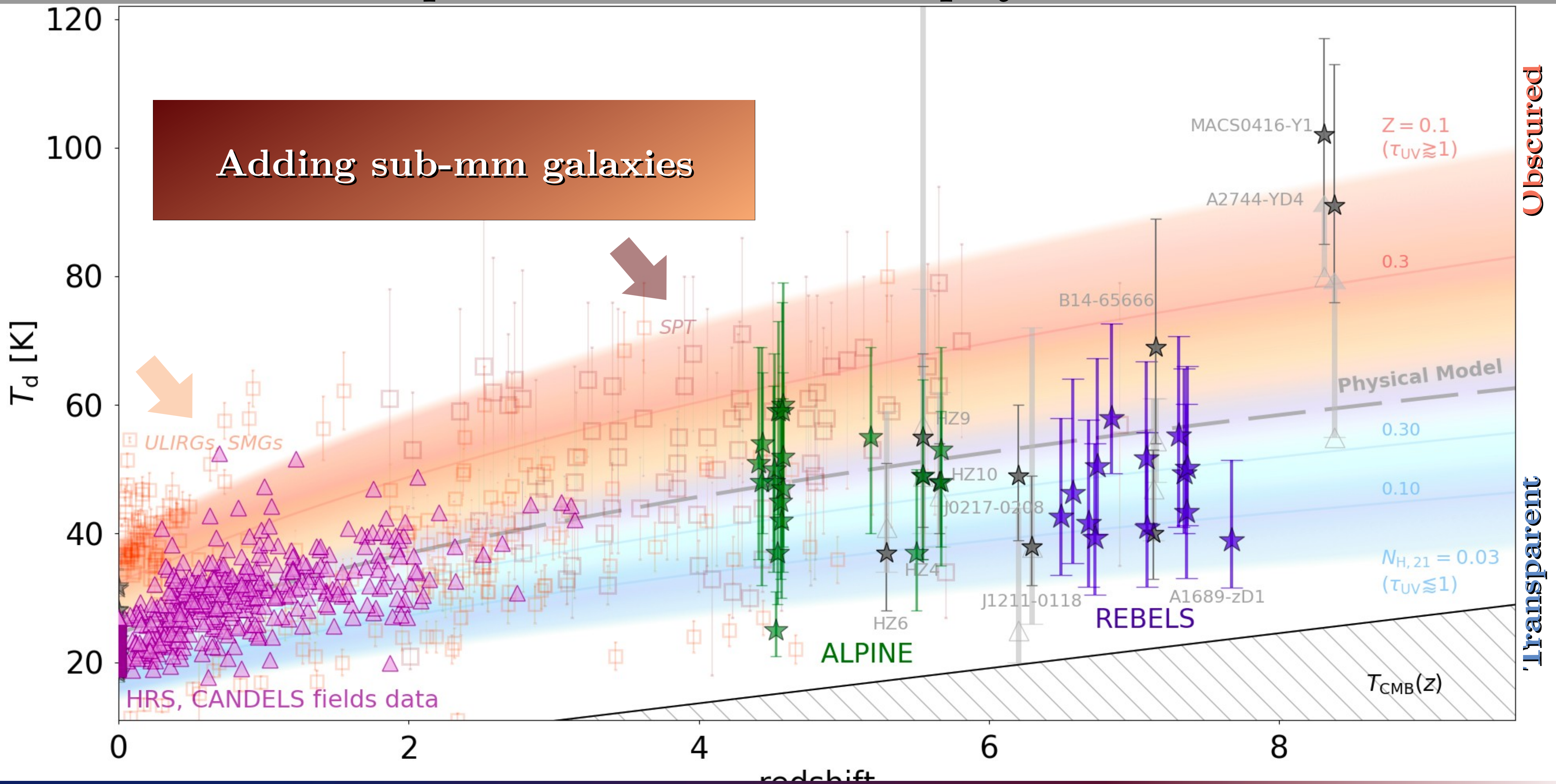


At given redshift: for UV-transparent (*obscured*) galaxies,
T_d only depends on gas column density (*metallicity*)

Sommovigo+22

Cosmic dust temperature evolution: a physical model



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

Sommovigo+22

Summary

Thanks to REBELS, we can address these questions:

- *What is the dust content of massive EoR galaxies?*

  Dust masses vary in the range $M_d \sim (0.9\text{—}3.6)1e7\ M_\odot$;

- *How do they build their dust masses?*

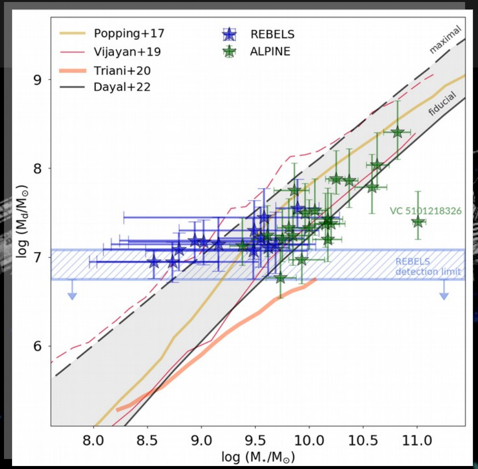
  Dust masses compatible with dust production from Supernovae except few outliers;

- *Which is the dust temperature of massive EoR galaxies?*

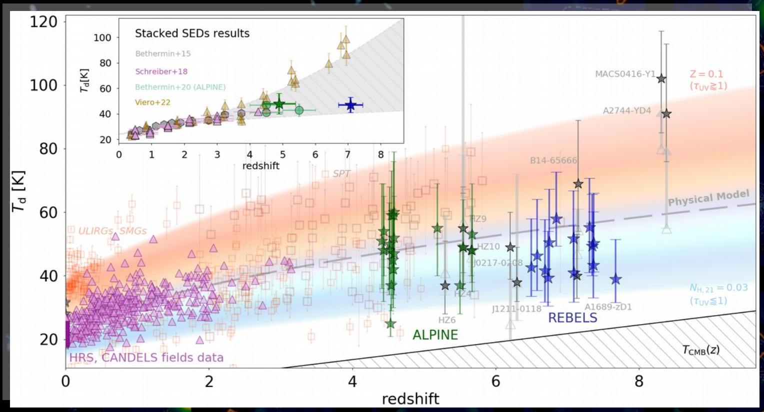
  Dust temperatures vary in the range 39 K$< T_d < 58$ K; warmer dust possibly missed by current observations.

- *Does the dust temperature evolve with redshift?*

  Yes, $T_{\rm d} \propto (1+z)^{0.42}$ due to the decrease of the depletion times in early galaxies. At any z: scatter induced by optical depth and metallicity variations.



Sommovigo et al. in prep., See also: Dayal+22

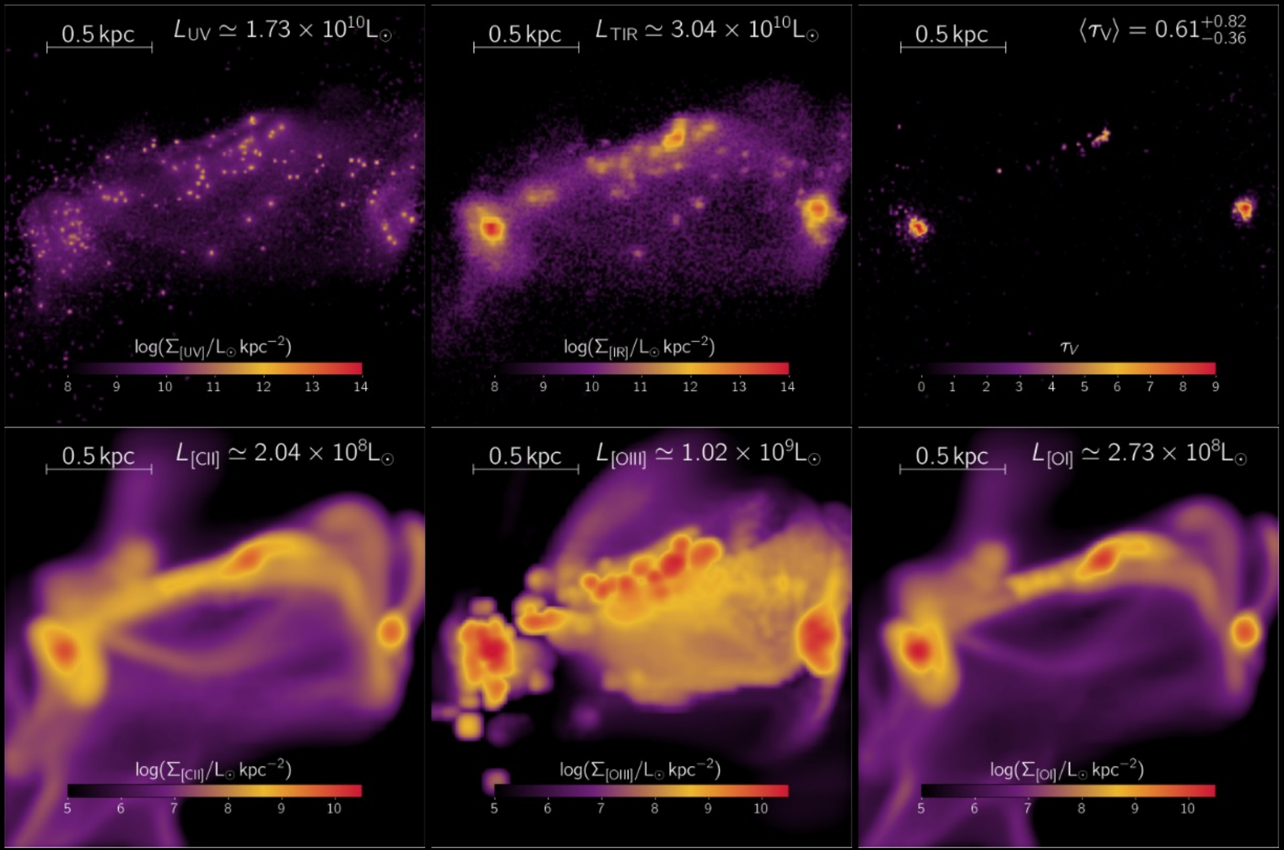


Sommovigo+22

Contact: *laura.sommovigo@sns.it*

Hints from zoom-in simulations at high-z

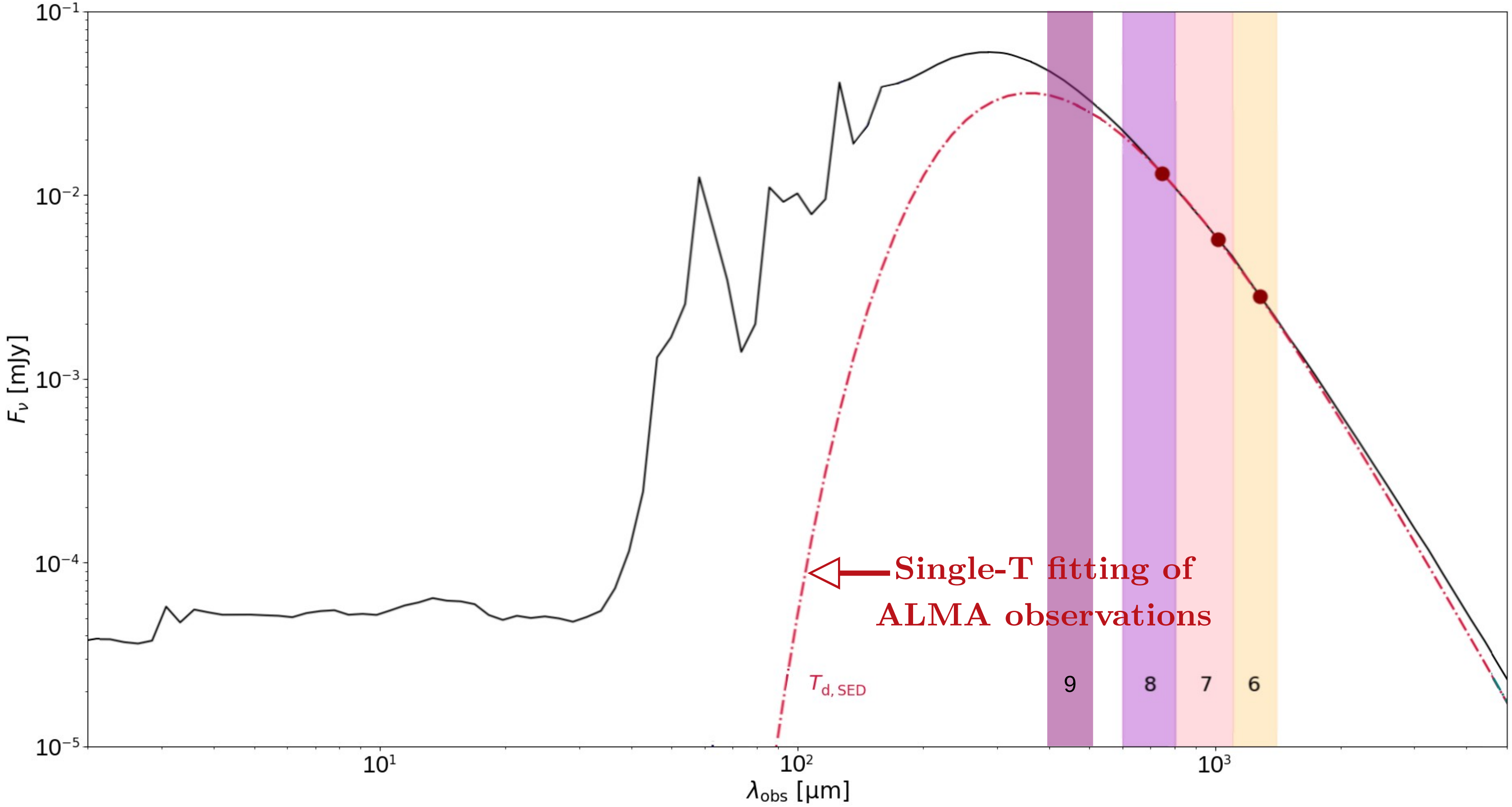
For SERRA *simulations details, see:* ***Pallottini+22***



Galaxy	z	$F_{\nu0}$ (μJy)	Z ($Z_\odot$)	$\log \Sigma_{SFR}$ ($M_\odot\,yr^{-1}\,kpc^{-2}$)	$L_{C\,II}$ ($10^8\,L_\odot$)	κ_s	$y = r_{C\,II}/r_\star$	$M_\star$ ($10^9\,M_\odot$)
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:



Sommovigo+21

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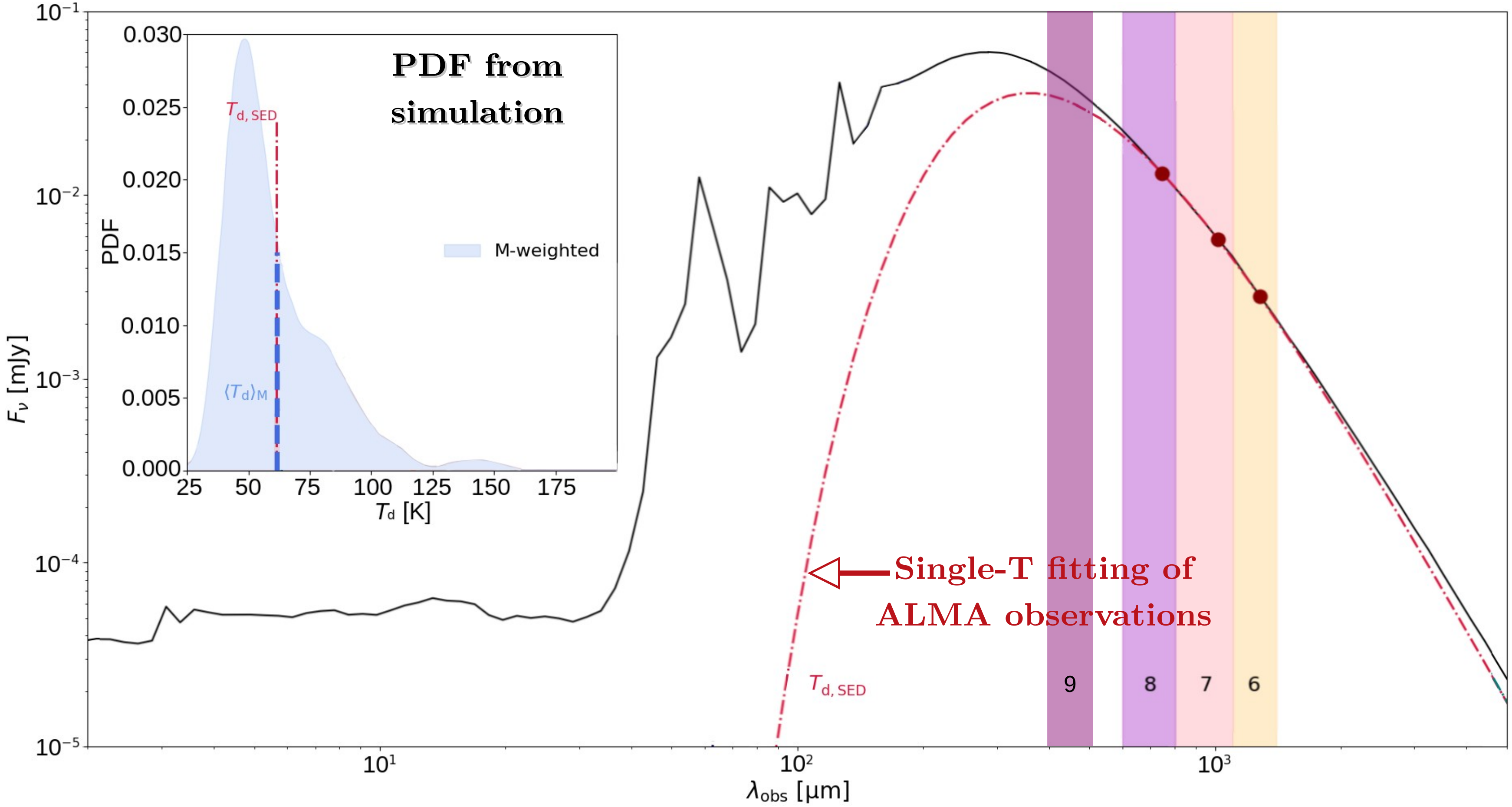

Sommovigo+21

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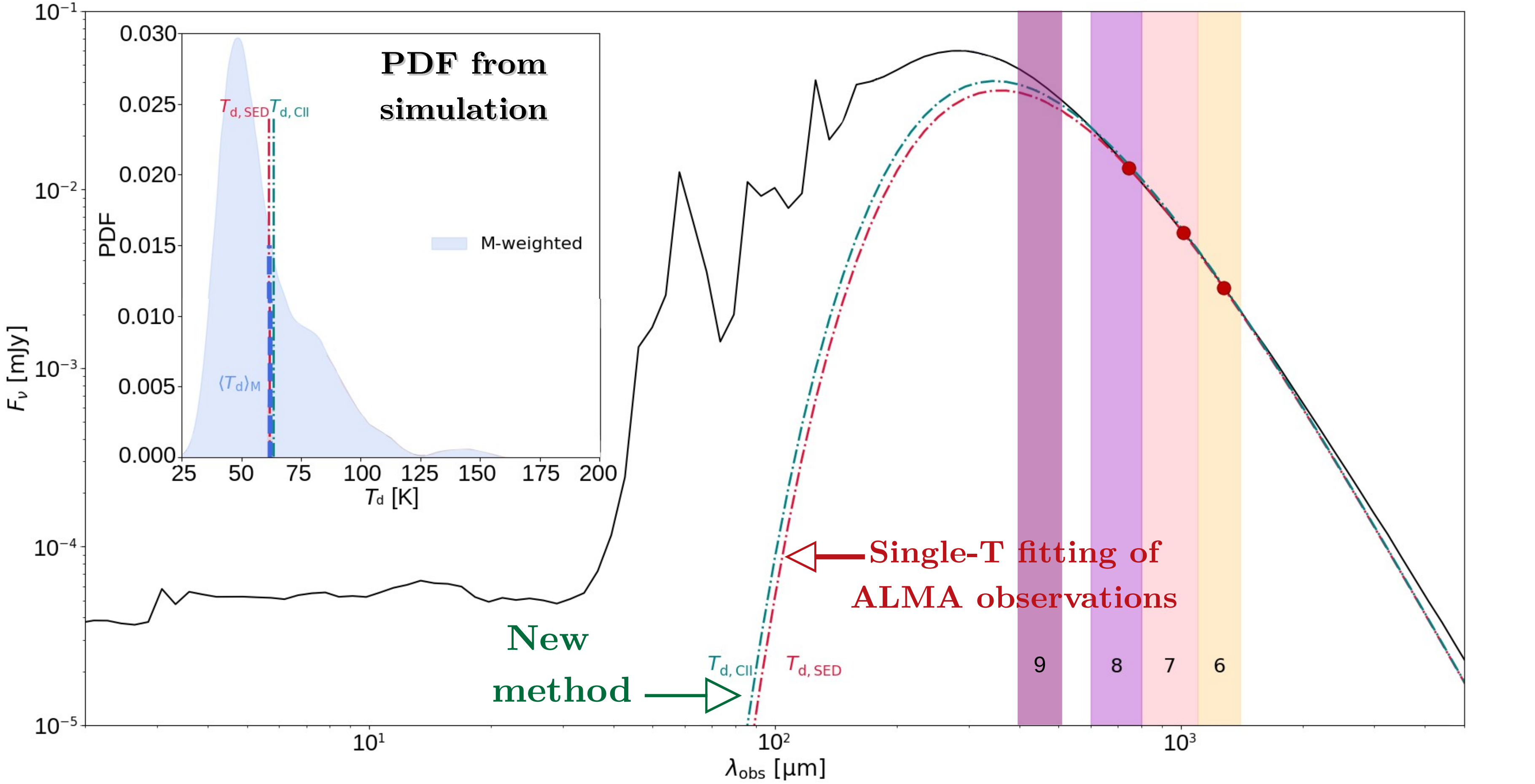

Sommovigo+21

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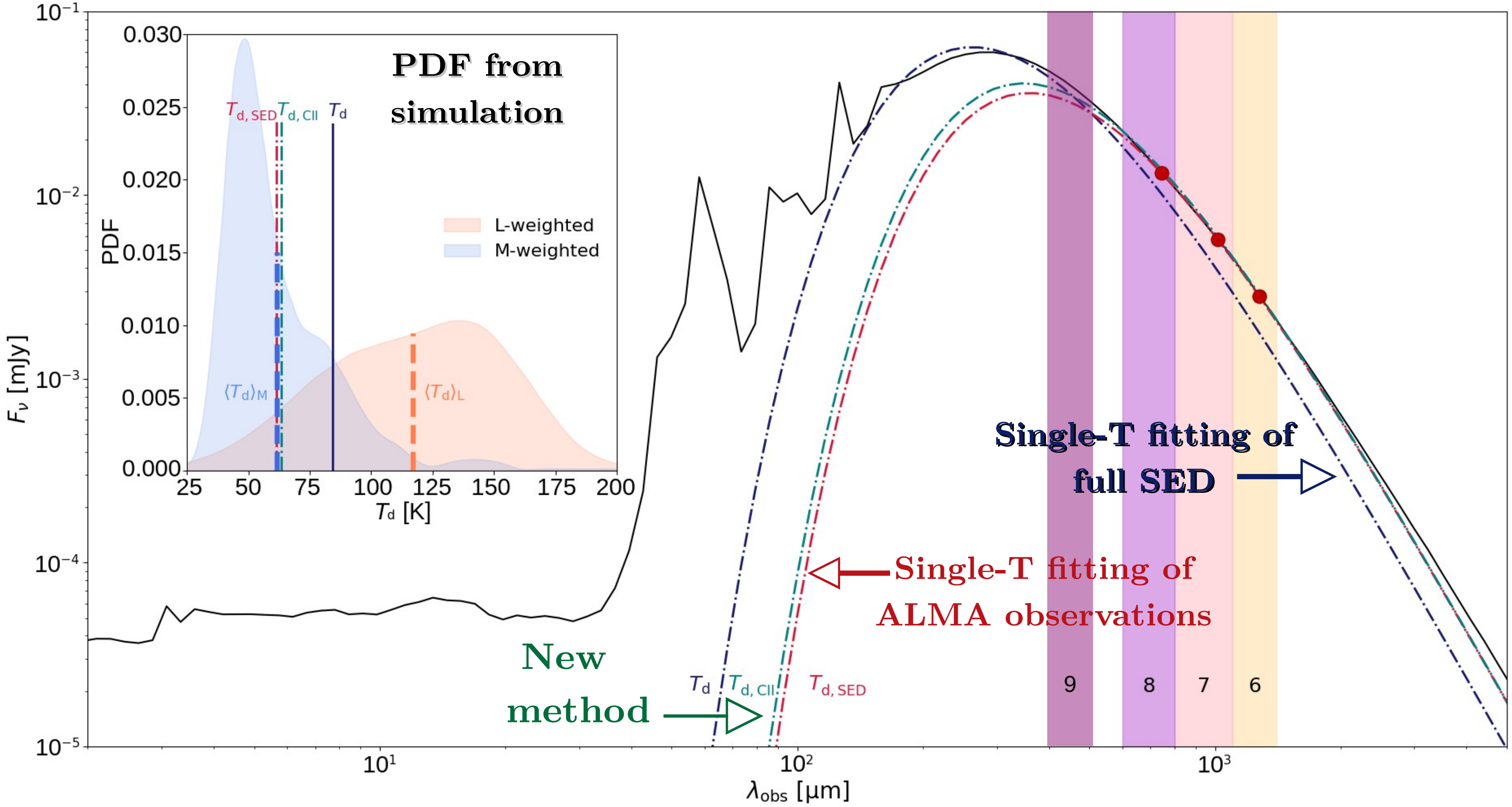

Sommovigo+21

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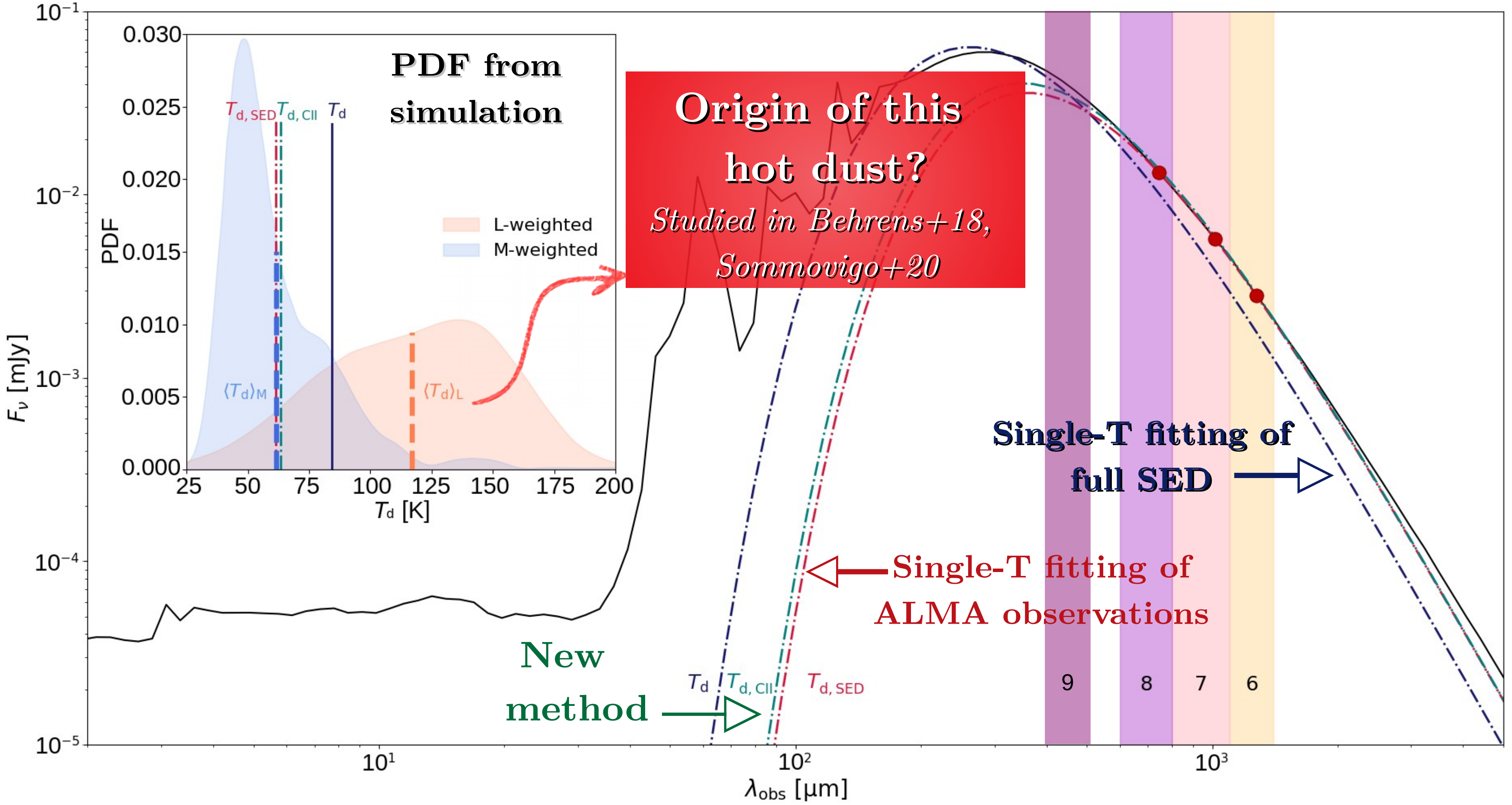

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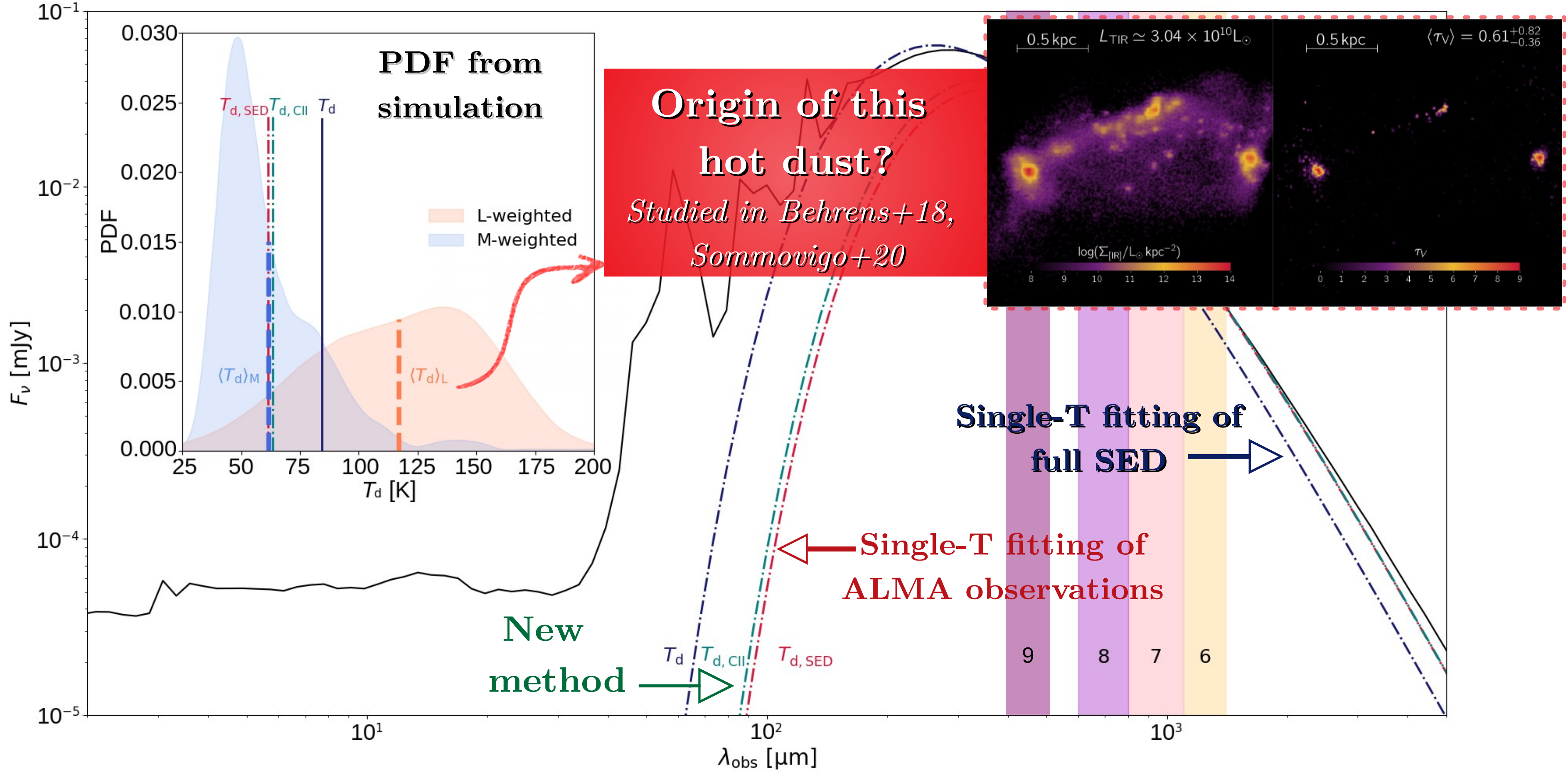

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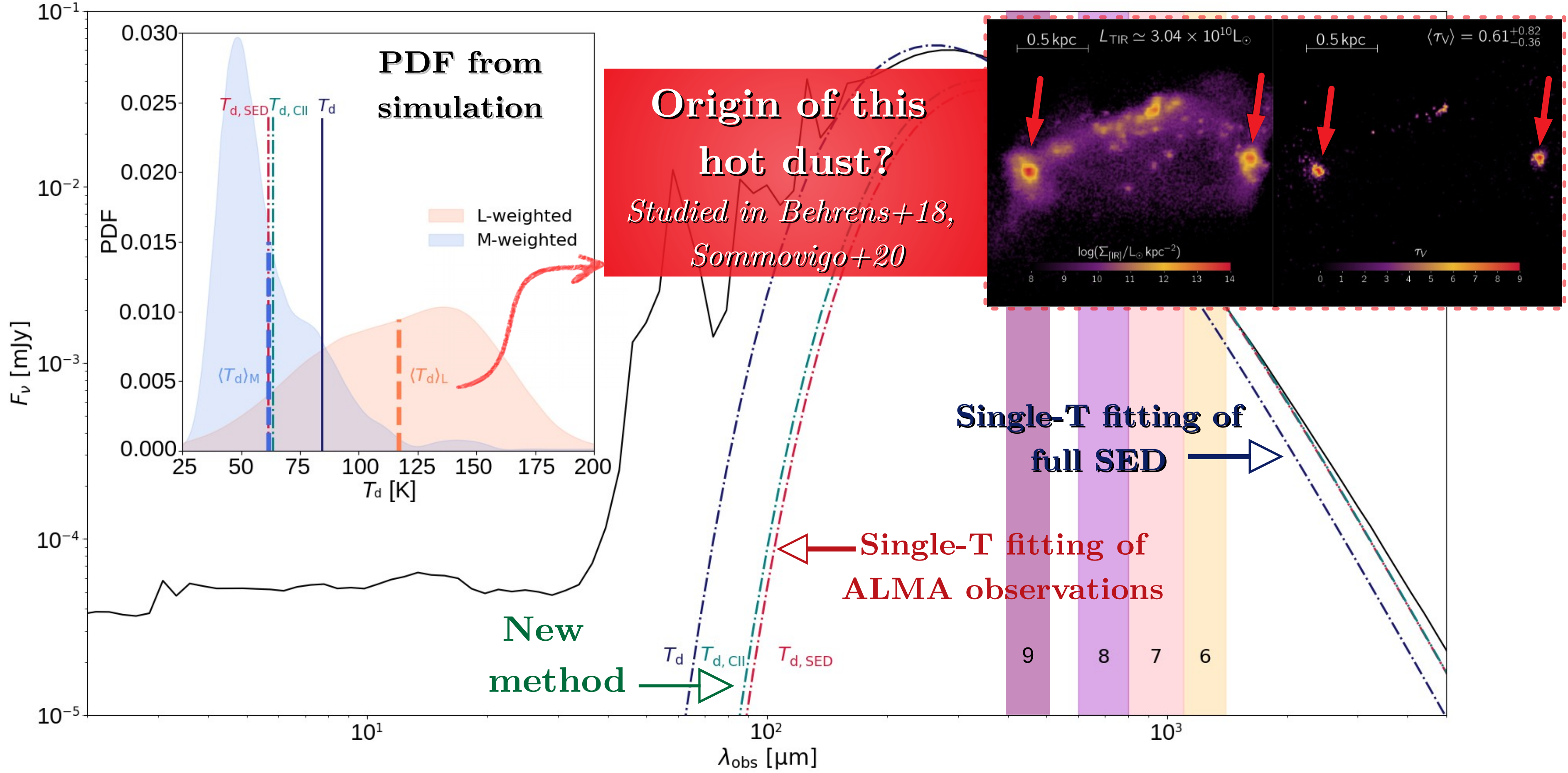

Sommovigo+21

$\alpha_{\rm CII}$: [CII]-to-total gas conversion factor

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

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

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

[CII]-*SFR* relation + Kenicutt-Schmidt relation $\rightarrow \alpha_{\rm CII} \propto \Sigma_{\rm SFR}^{-0.29}\ \kappa_s^{-5/7}\ y^2$

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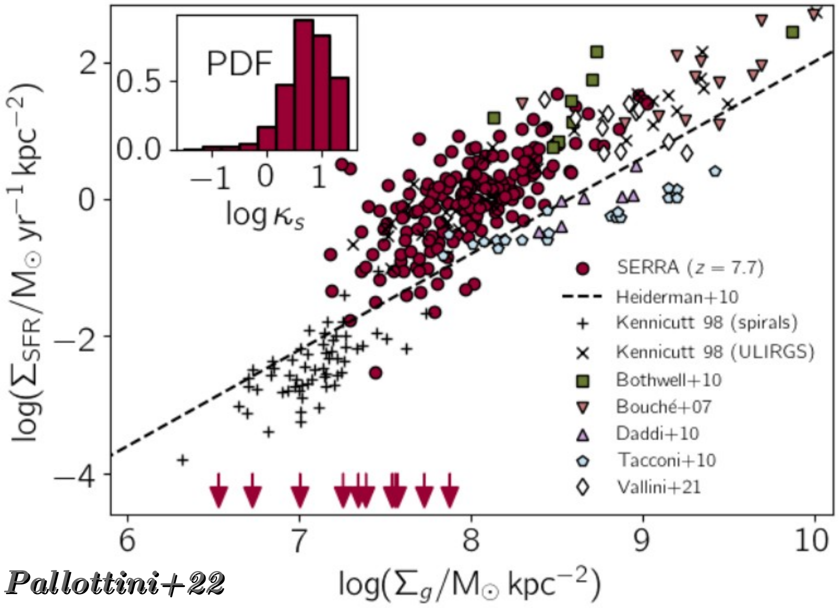

Pallottini+22

Burstiness parameter, k_s

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

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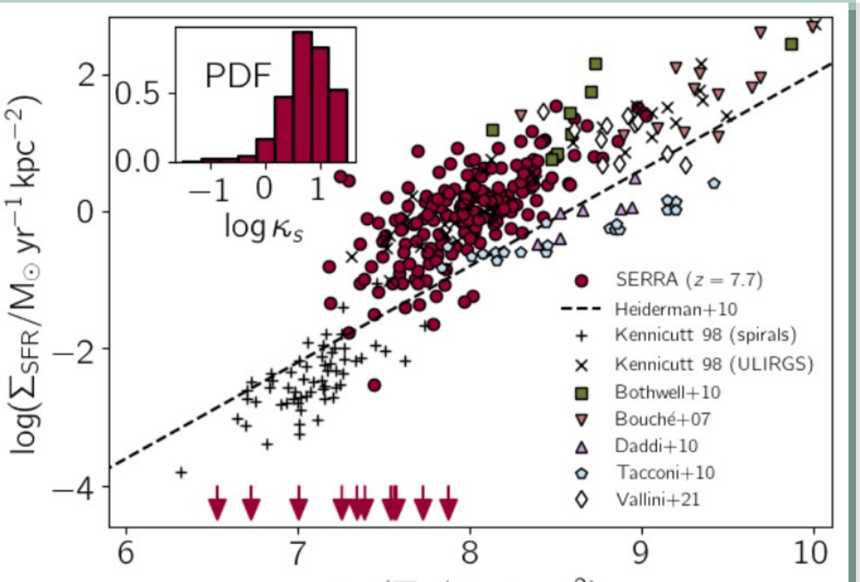

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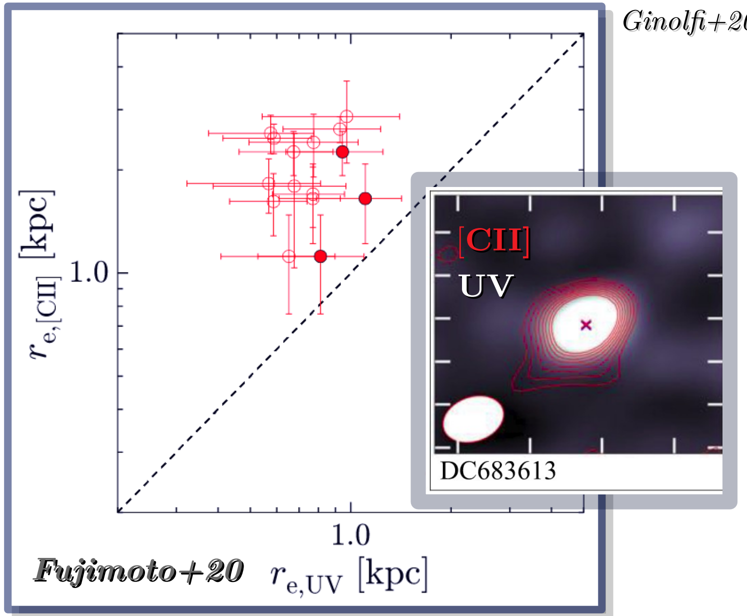
UV-to-[CII] extension ratio

See also: Carniani+17,18,20, Matthee+17,19, Fujimoto+19, Ginolfi+20



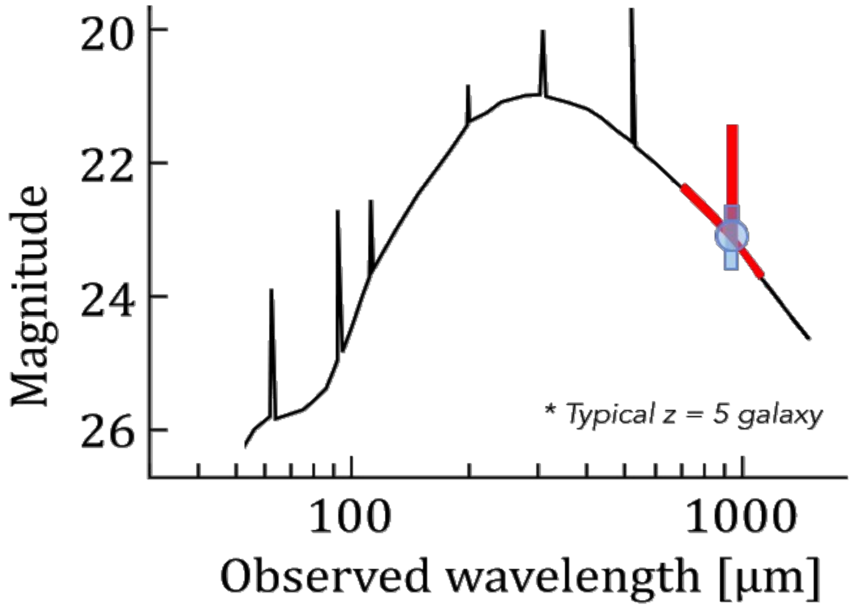
Fujimoto+20

New method to derive T_d using [CII] information

Inputs: **Outputs:**

[CII] → **M_d**

Continuum → **T_d**



Sommovigo+21

New method to derive T_d using [CII] information

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

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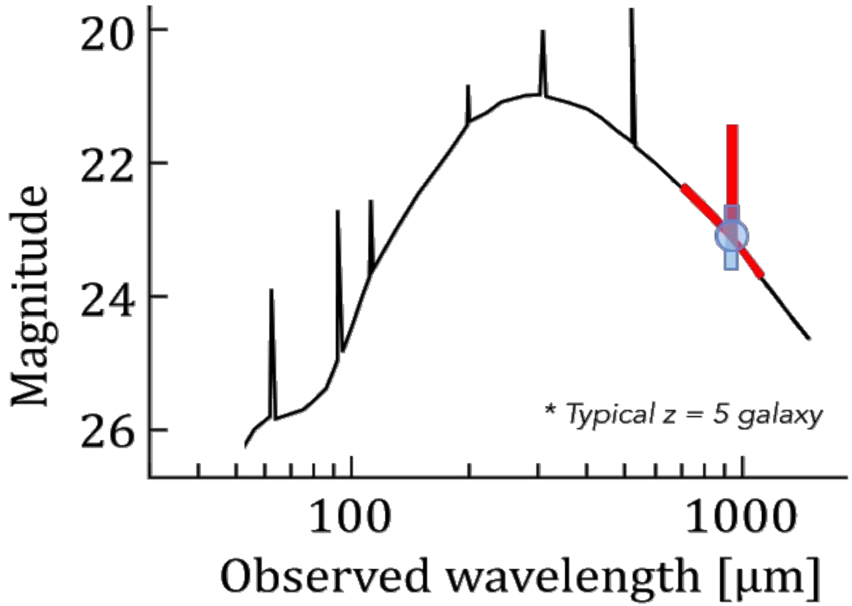

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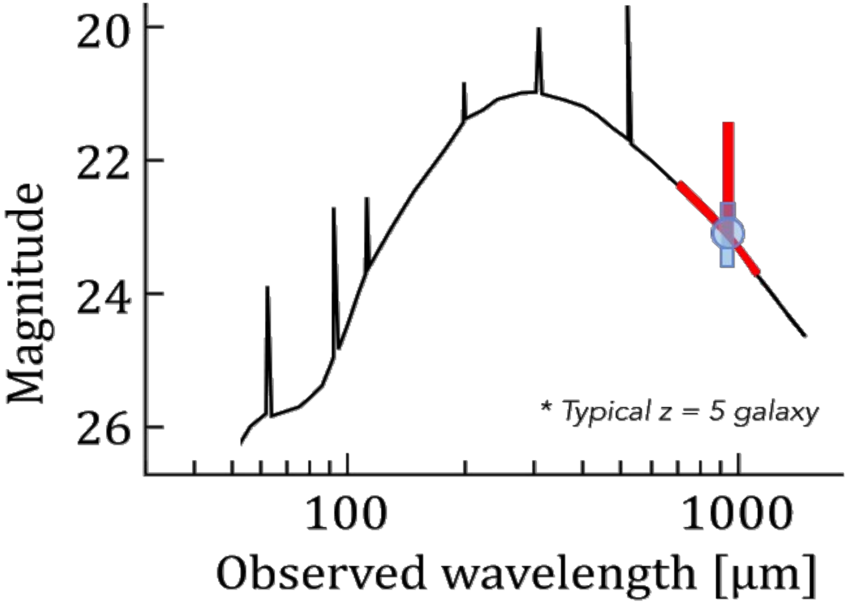
Md



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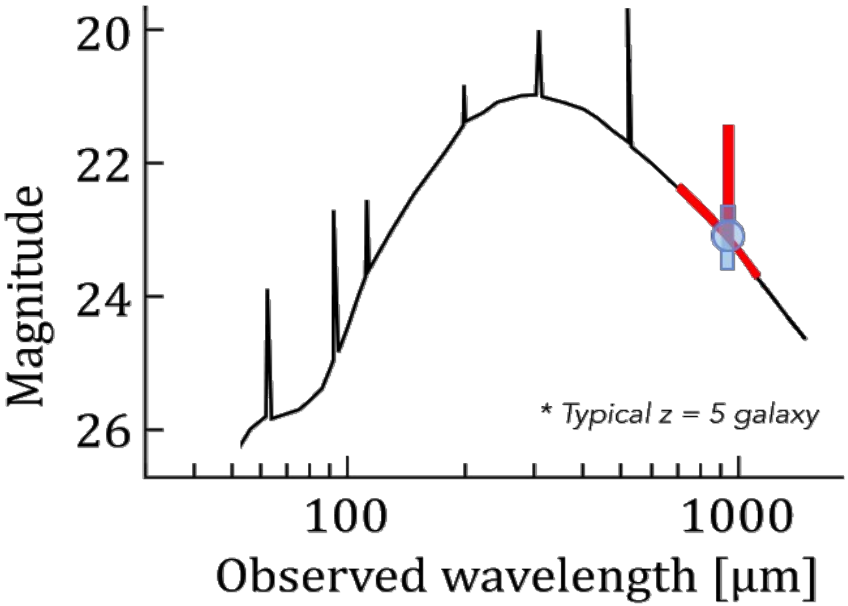

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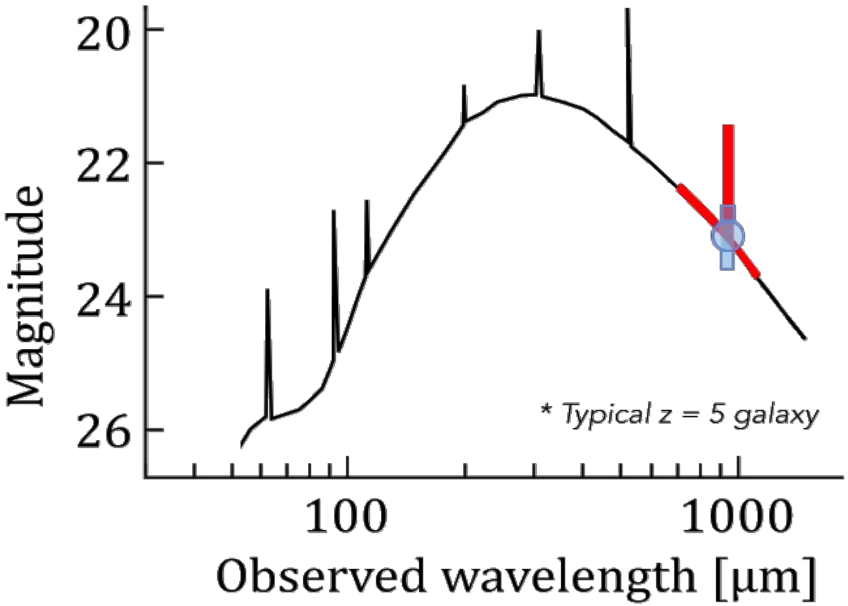

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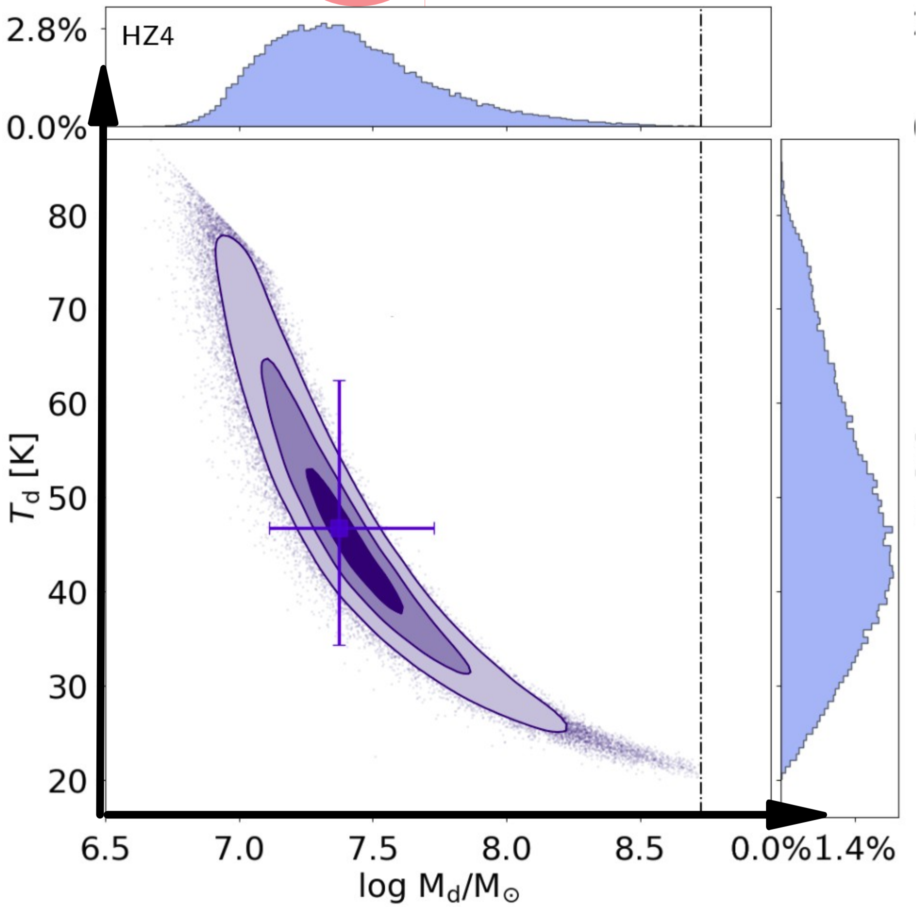

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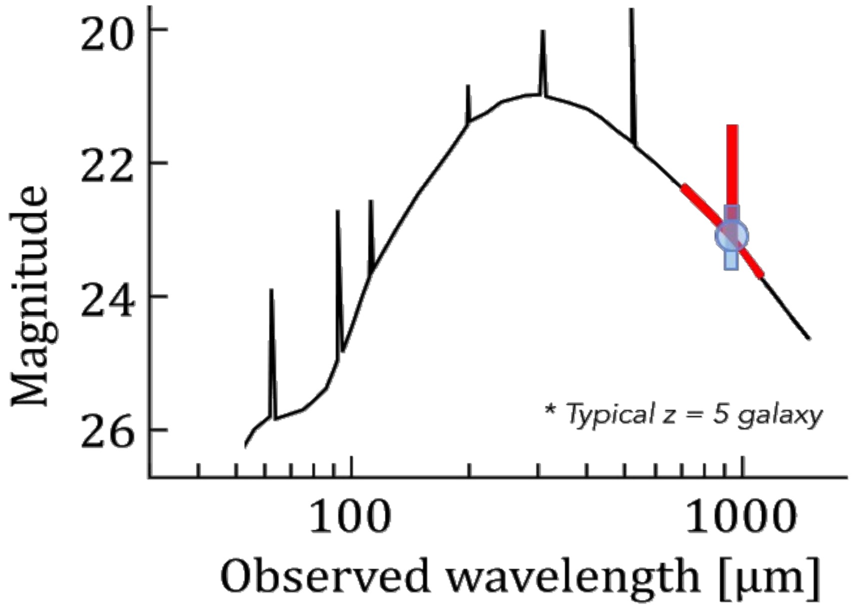

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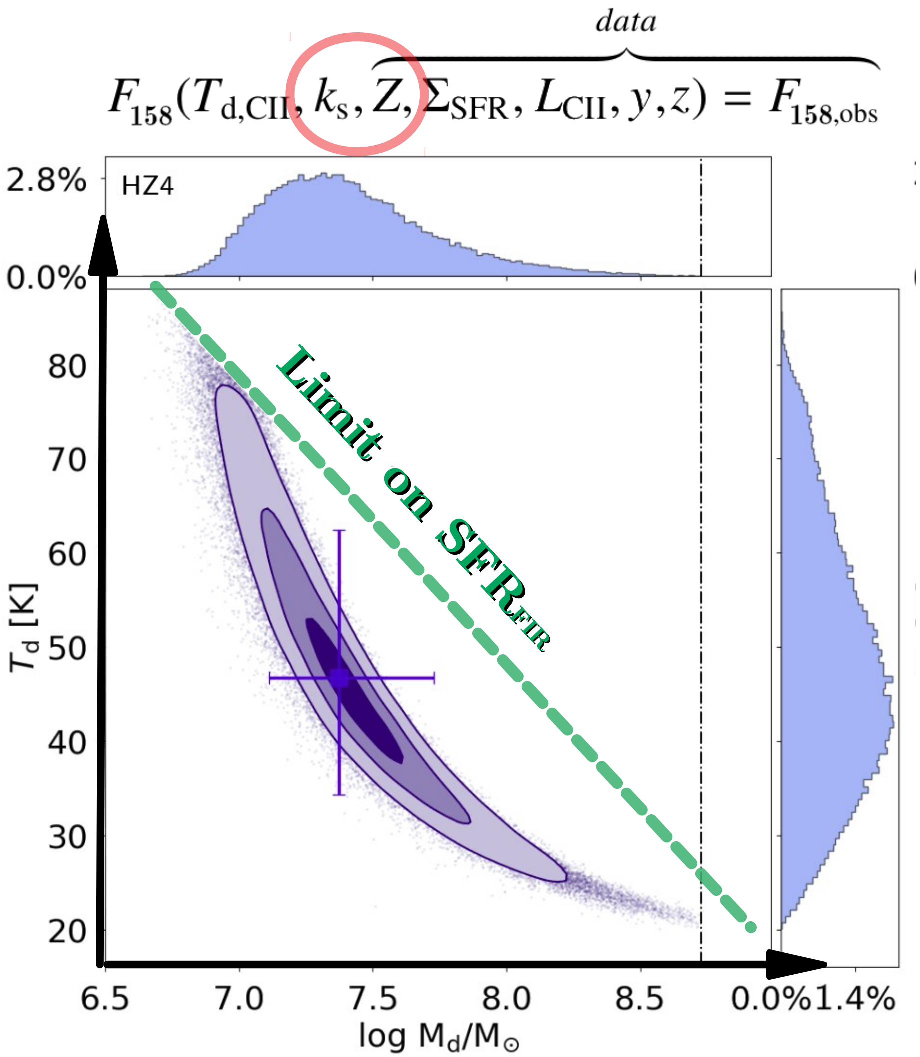

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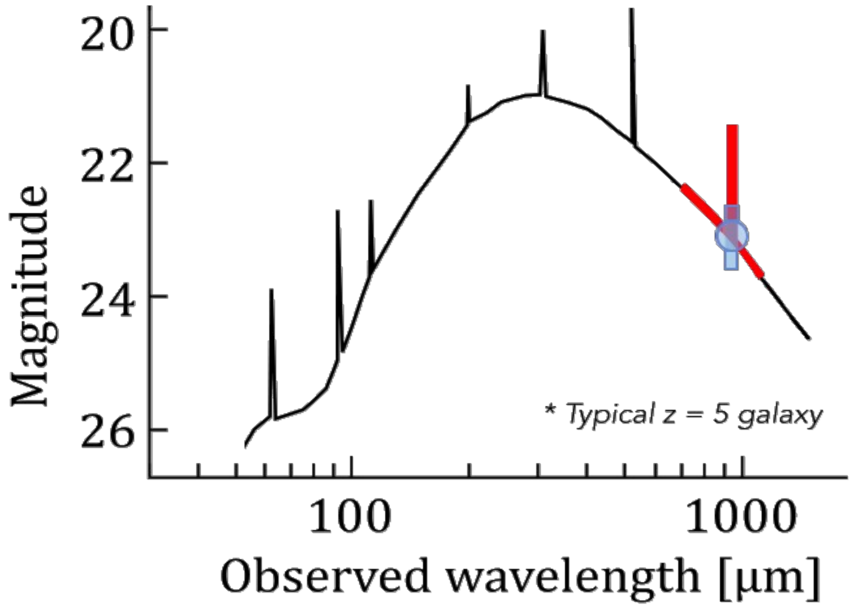

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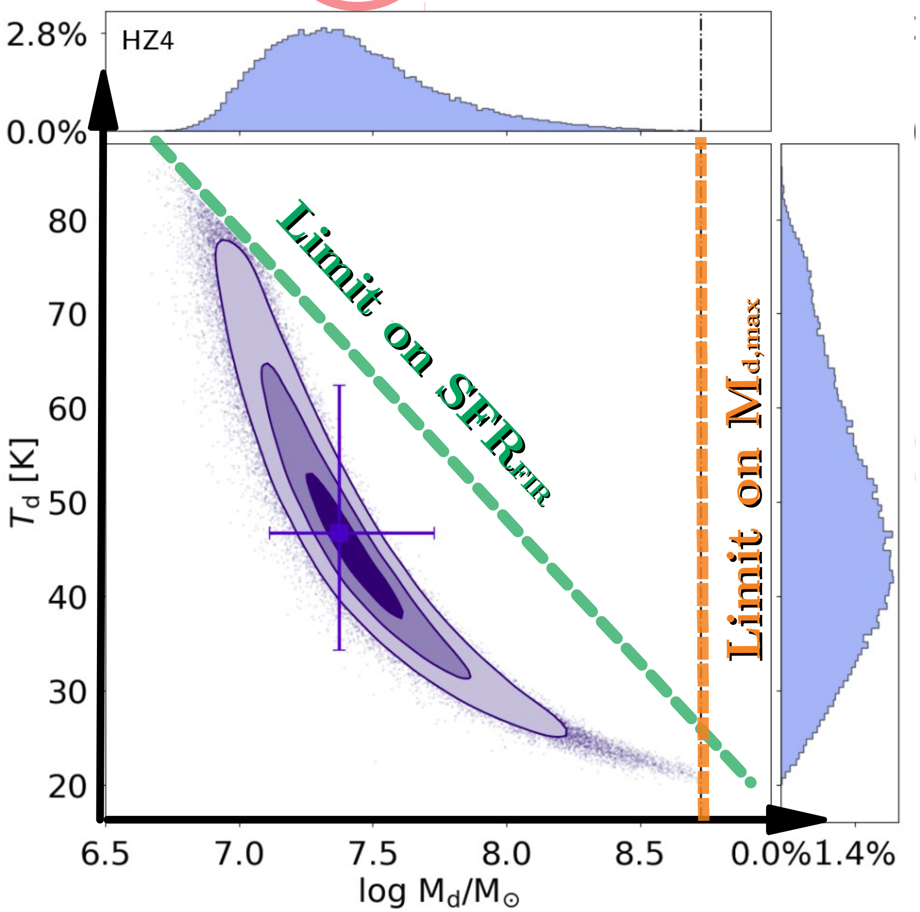

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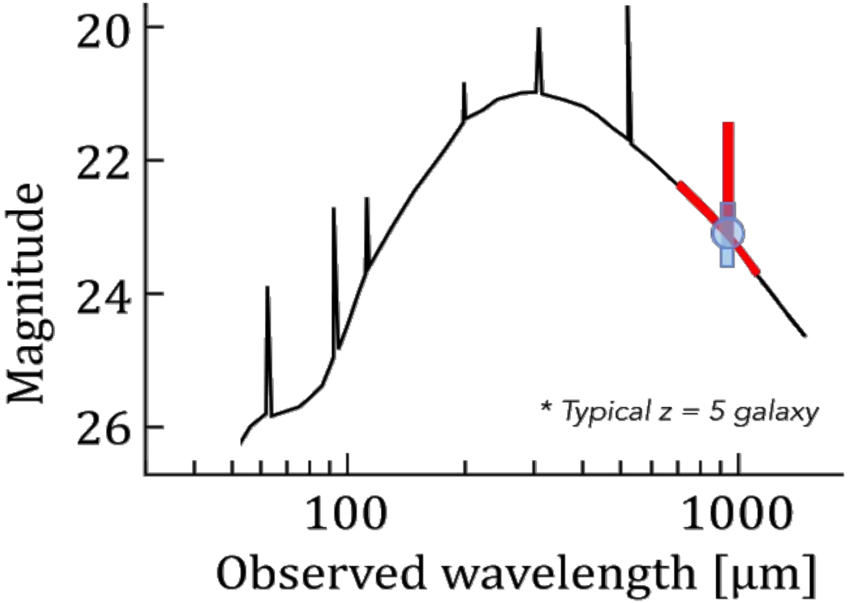

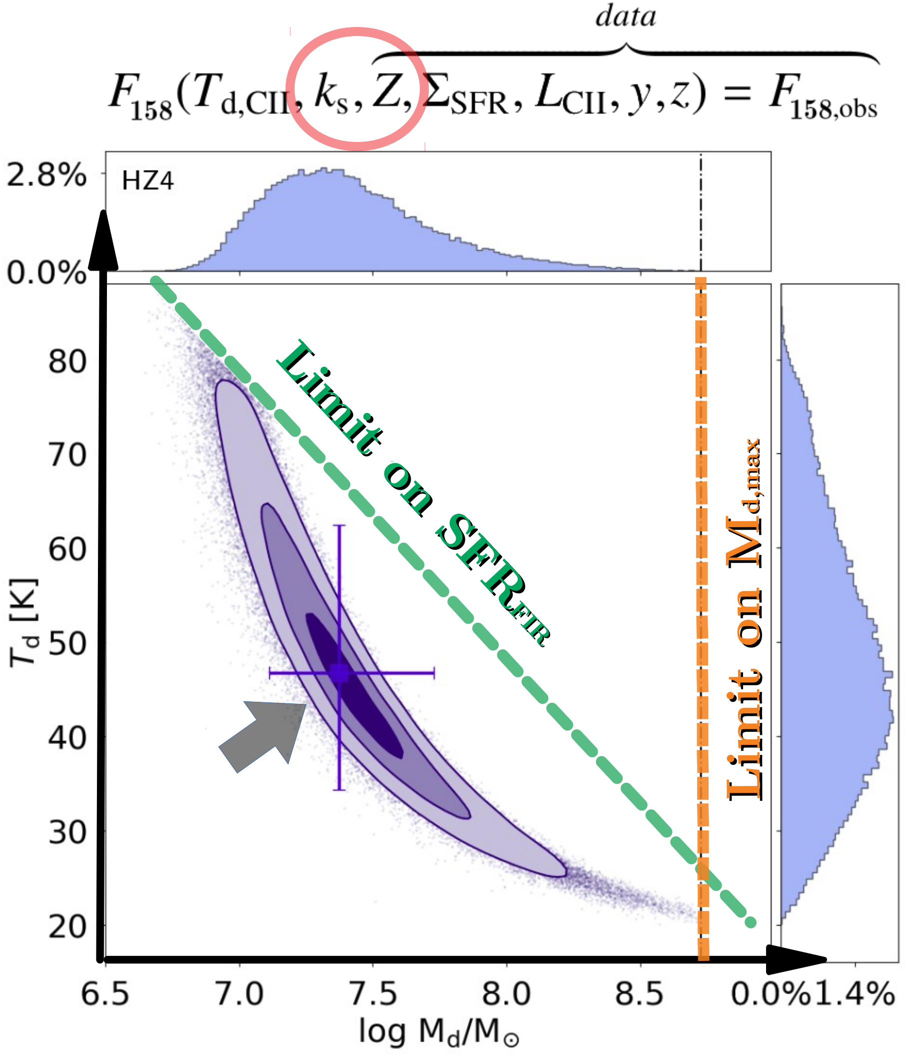

Sommovigo+21

Local testing

Sommovigo+21

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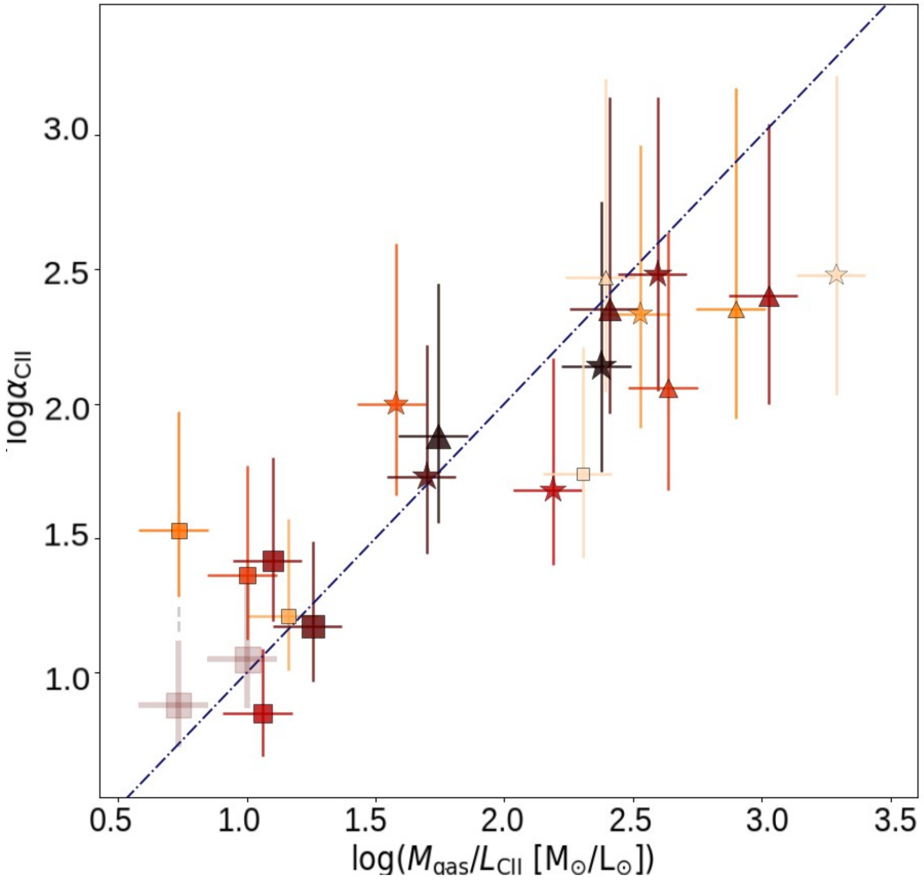

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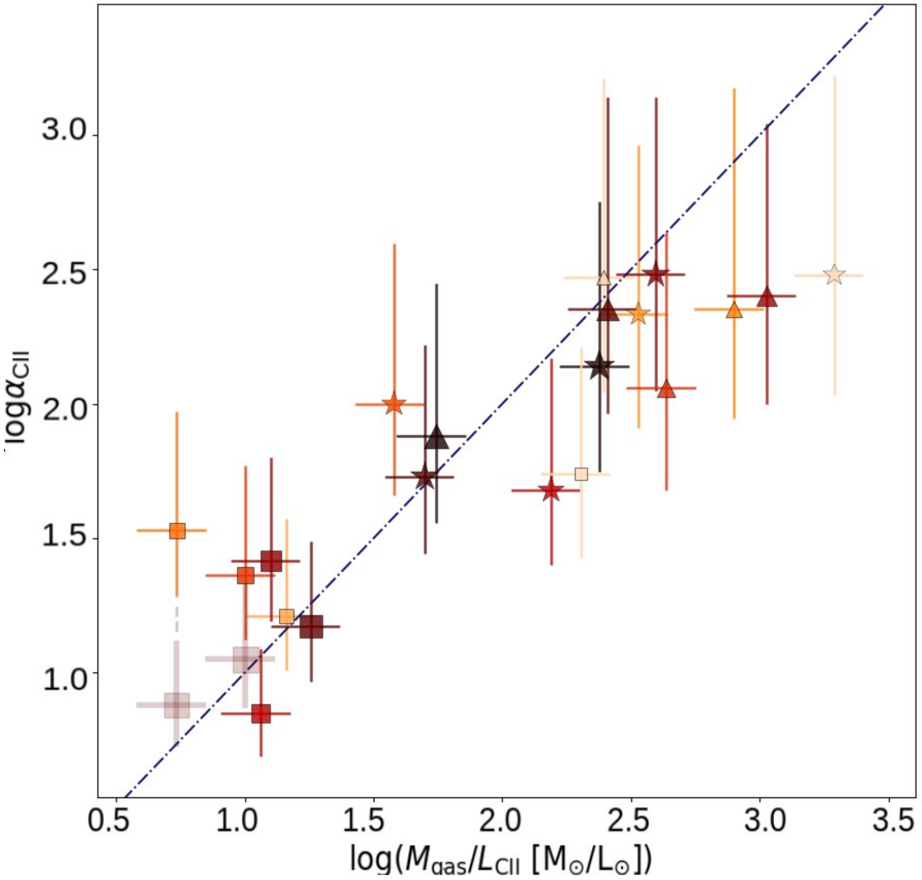
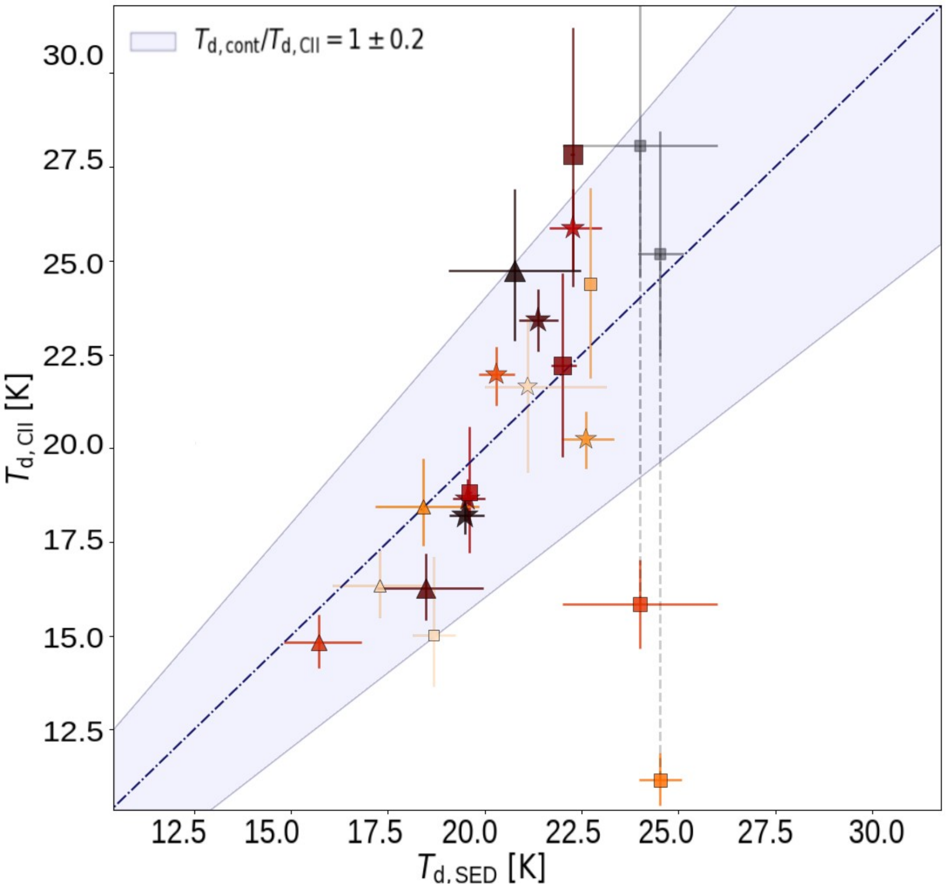
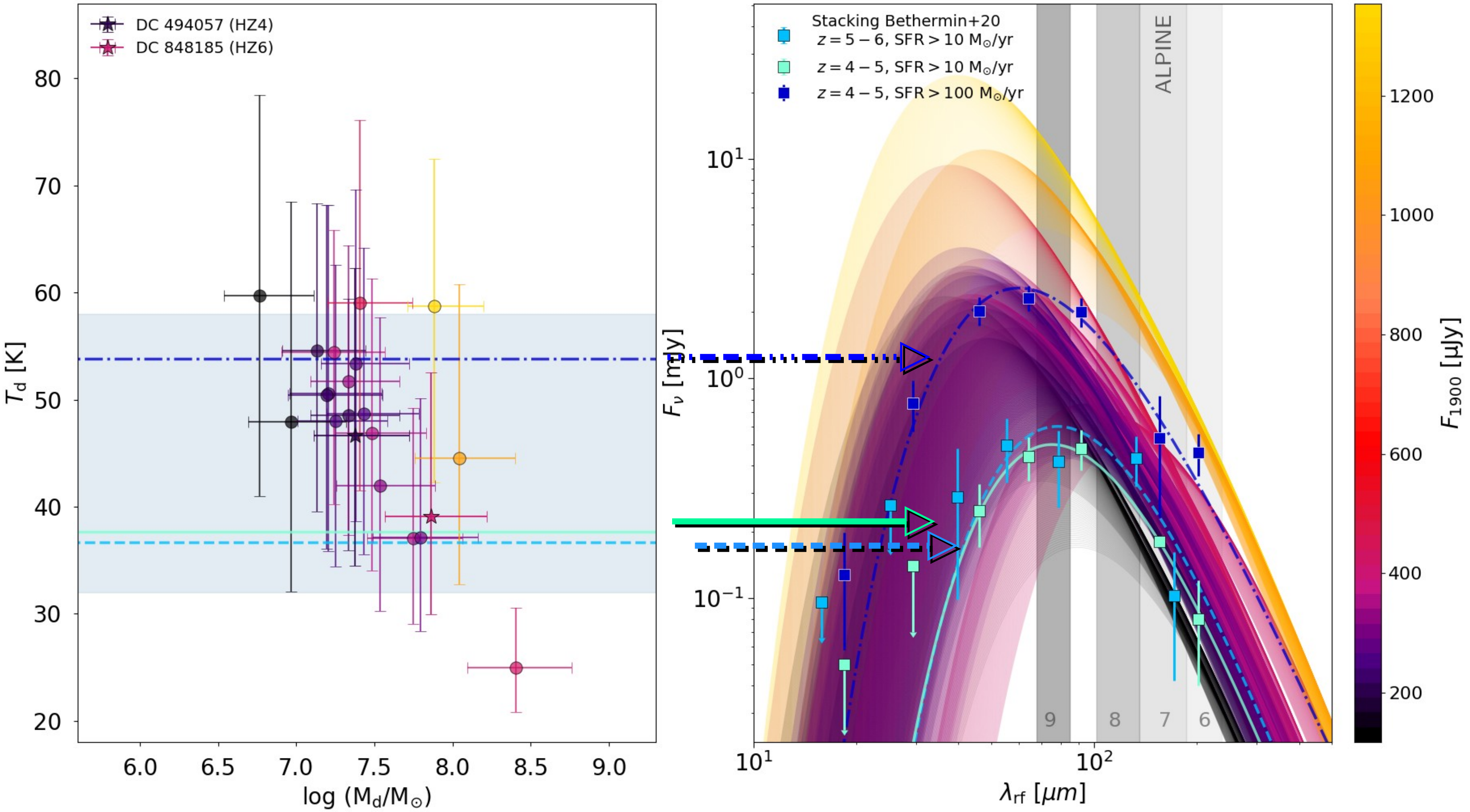




Sommovigo+21

Application of new method to ALPINE galaxies



Sommovigo et al. in prep.

Cosmic dust temperature evolution: a physical model

$$L_{\rm IR} = (1 - e^{-\tau_{\rm UV}})L_{\rm UV}$$

Sommovigo+22

Cosmic dust temperature evolution: a physical model

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$$\propto \text{SFR}$$

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{IR} = (1 - e^{-\tau_{UV}})L_{UV}$$

$\propto$ SFR

$\propto M_d T_d^6$

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{\rm IR} = (1 - e^{-\tau_{\rm UV}})L_{\rm UV}$$

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Sommovigo+22

Cosmic dust temperature evolution: <u>a physical model</u>

$$L_{\rm IR} = (1 - e^{-\tau_{\rm UV}})L_{\rm UV} \propto \rm SFR$$

$$\propto M_{\rm g}\, T_{\rm d}^{6}$$

$$T_{\rm d} \propto (t_{\rm dep} = M_{\rm g}/{\rm SFR})^{-1/6}$$

Sommovigo+22

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Sommovigo+22

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Redshift dependent

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{\rm IR} = (1 - e^{-\tau_{\rm UV}})L_{\rm UV}$$

$$\propto \ {\rm SFR}$$

$$\propto \ M_g \, T_d{}^6$$

$$T_d \propto (t_{\rm dep} = M_g/{\rm SFR})^{-1/6}$$

$$T_d \propto \left[\frac{(1 - e^{-\tau_{\rm UV}})}{Z}\left(\frac{\rm Gyr}{t_{\rm dep}}\right)\right]^{1/6}$$

Redshift dependent

$$\begin{cases} M_g = f_b M(1 - \epsilon_\star) \\ {\rm SFR} = \epsilon_\star f_b \left\langle \dfrac{dM}{dt} \right\rangle \end{cases}$$

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{IR} = (1 - e^{-\tau_{UV}})L_{UV} \propto \mathrm{SFR}$$

$$\propto M_g T_d^{\,6}$$

$$T_d \propto (t_{dep} = M_g/\mathrm{SFR})^{-1/6}$$

$$T_d \propto \left[\frac{(1 - e^{-\tau_{UV}})}{Z}\left(\frac{\mathrm{Gyr}}{t_{dep}}\right)\right]^{1/6}$$

Redshift dependent

$$\begin{cases} M_g = f_b M(1 - \epsilon_\star) \\ \mathrm{SFR} = \epsilon_\star f_b \left\langle \frac{dM}{dt} \right\rangle \end{cases}$$

Cosmic evolution from numerical simulations

See: Fakhouri et al. 2010; Dekel & Krumholz 2013; Correa et al. 2015

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{IR} = (1 - e^{-\tau_{UV}})L_{UV} \propto \mathrm{SFR}$$

$$\propto M_g T_d^{\,6}$$

$$T_d \propto (t_{dep} = M_g/\mathrm{SFR})^{-1/6}$$

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$$T_d \propto (1 + z)^{0.42}$$

Cosmic evolution of T_d

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Sommovigo+22

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Cosmic evolution of T_d

Cosmic evolution from numerical simulations

See: Fakhouri et al. 2010; Dekel & Krumholz 2013; Correa et al. 2015

At given z:

$$\begin{cases} T_d \propto [N_{H,21}\ t_{dep}^{-1}]^{1/6.03}\ \mathrm{K} & \tau_{UV} \lesssim 1 \\ T_d \propto [\,Z\, t_{dep}\,]^{-1/6.03}\ \mathrm{K} & \tau_{UV} \gtrsim 1 \end{cases}$$

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{IR} = (1 - e^{-\tau_{UV}})L_{UV} \propto \text{SFR}$$

$$\propto M_g \, T_d^{\,6}$$

$$T_d \propto (t_{dep} = M_g/\text{SFR})^{-1/6}$$

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Redshift dependent

$$\begin{cases} M_g = f_b M (1 - \epsilon_\star) \\ \text{SFR} = \epsilon_\star f_b \left\langle \frac{dM}{dt} \right\rangle \end{cases}$$

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Cosmic evolution of T_d

Cosmic evolution from numerical simulations

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UV-transparent

Sommovigo+22

Cosmic dust temperature evolution: a physical model

$$L_{\rm IR} = (1 - e^{-\tau_{\rm UV}})L_{\rm UV} \propto \text{SFR}$$

$$\propto M_{\rm g}\, T_{\rm d}^{\,6}$$

$$T_{\rm d} \propto (t_{\rm dep} = M_{\rm g}/\text{SFR})^{-1/6}$$

$$T_{\rm d} \propto \left[\frac{(1 - e^{-\tau_{\rm UV}})}{Z}\left(\frac{\text{Gyr}}{t_{\rm dep}}\right)\right]^{1/6}$$

Redshift dependent

$$\begin{cases} M_{\rm g} = f_{\rm b} M (1 - \epsilon_\star) \\ \text{SFR} = \epsilon_\star f_{\rm b} \left\langle \dfrac{dM}{dt} \right\rangle \end{cases}$$

$$t_{\rm dep}(z) \propto (1+z)^{-5/2}$$

$$T_{\rm d} \propto (1+z)^{0.42}$$

Cosmic evolution of T_d

Cosmic evolution from numerical simulations

See: Fakhouri et al. 2010; Dekel & Krumholz 2013; Correa et al. 2015

At given z:

$$T_{\rm d} \propto [N_{\rm H,21}\; t_{\rm dep}^{\,-1}]^{1/6.03}\ \text{K} \qquad \tau_{\rm UV} \lessapprox 1 \quad \text{UV-transparent}$$

$$T_{\rm d} \propto [\, Z\, t_{\rm dep}\,]^{-1/6.03}\ \text{K} \qquad \tau_{\rm UV} \gtrapprox 1 \quad \text{UV-obscured}$$

Sommovigo+22

Zoom into Giant Molecular Clouds at high-z

GMC model:

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

Sommovigo+2020

Zoom into Giant Molecular Clouds at high-z

GMC model:

- Uniform density
- Star forming
- Turbulent, σ
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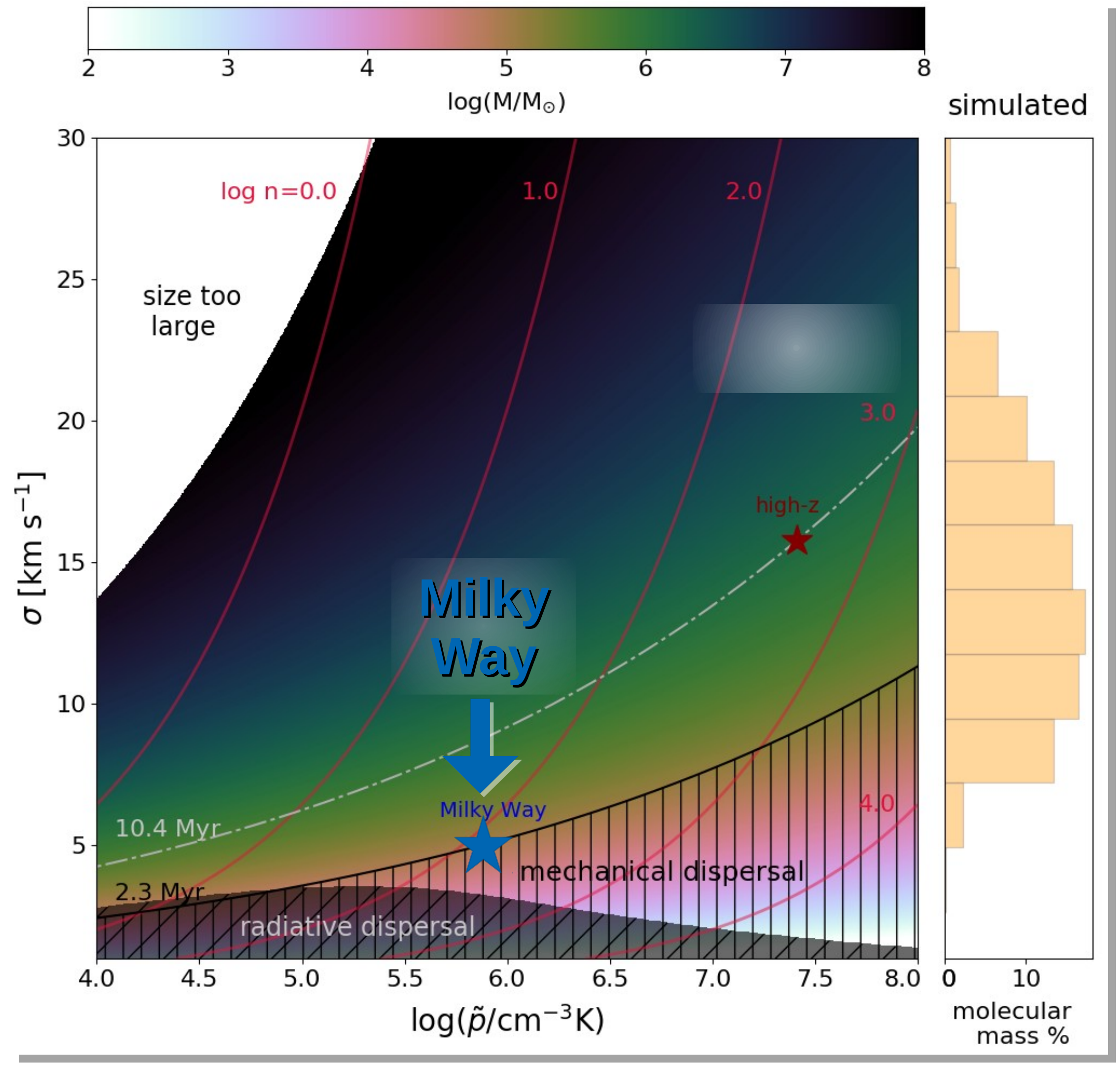
Sommovigo+2020

Zoom into Giant Molecular Clouds at high-z



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Sommovigo+2020

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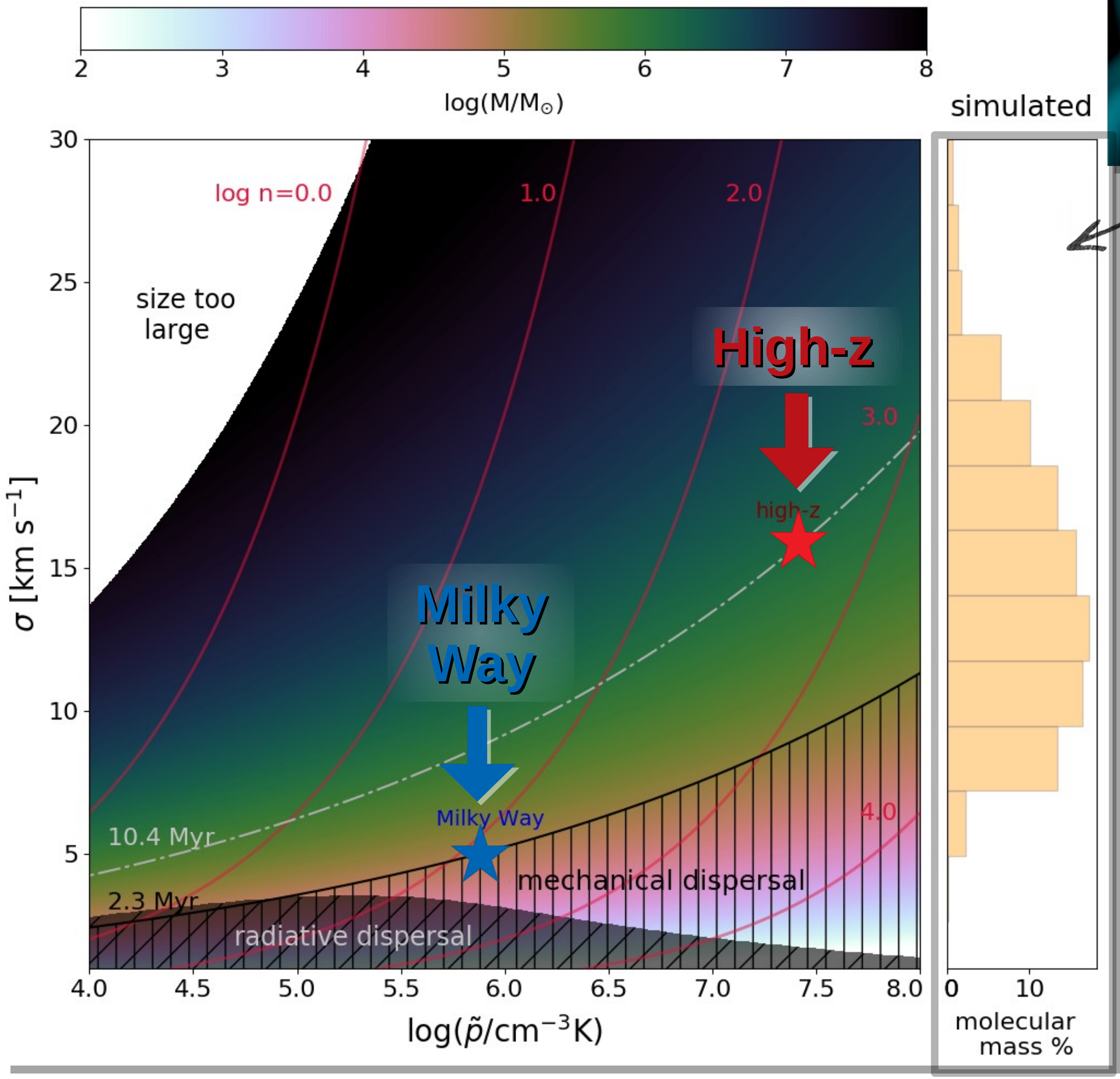

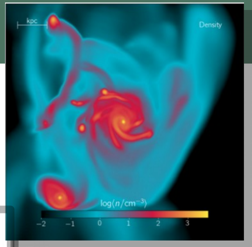

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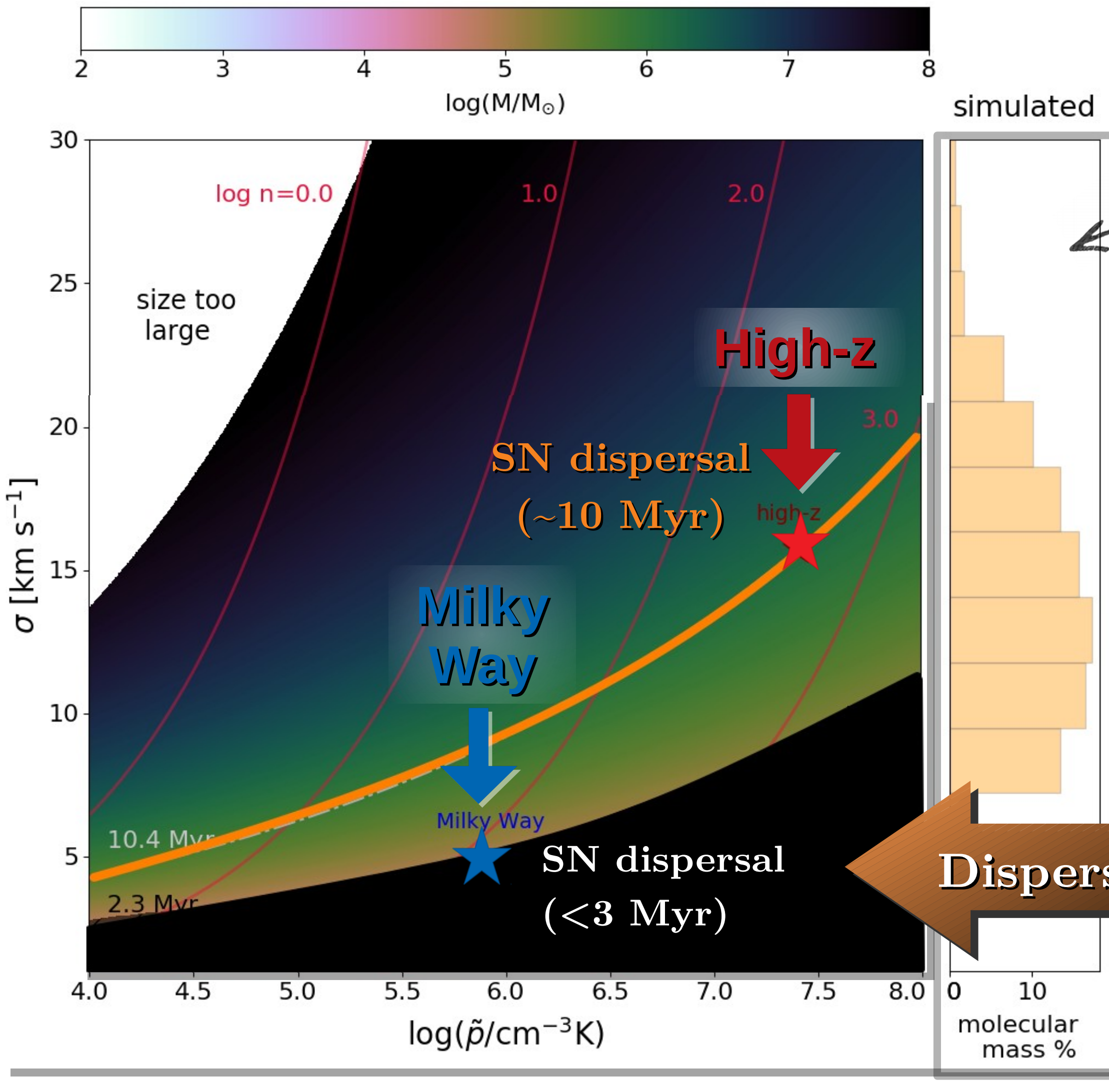

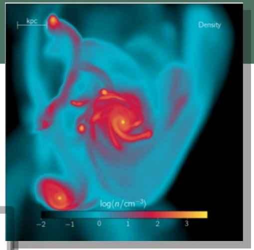

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Sommovigo+2020

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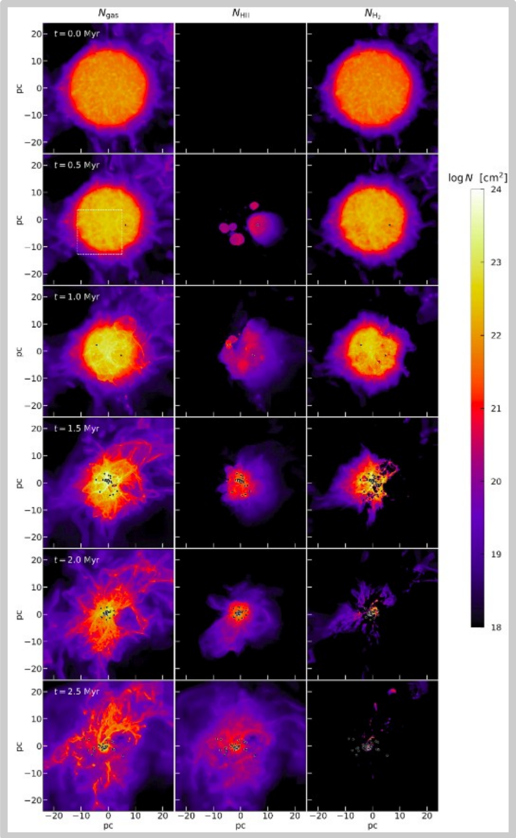
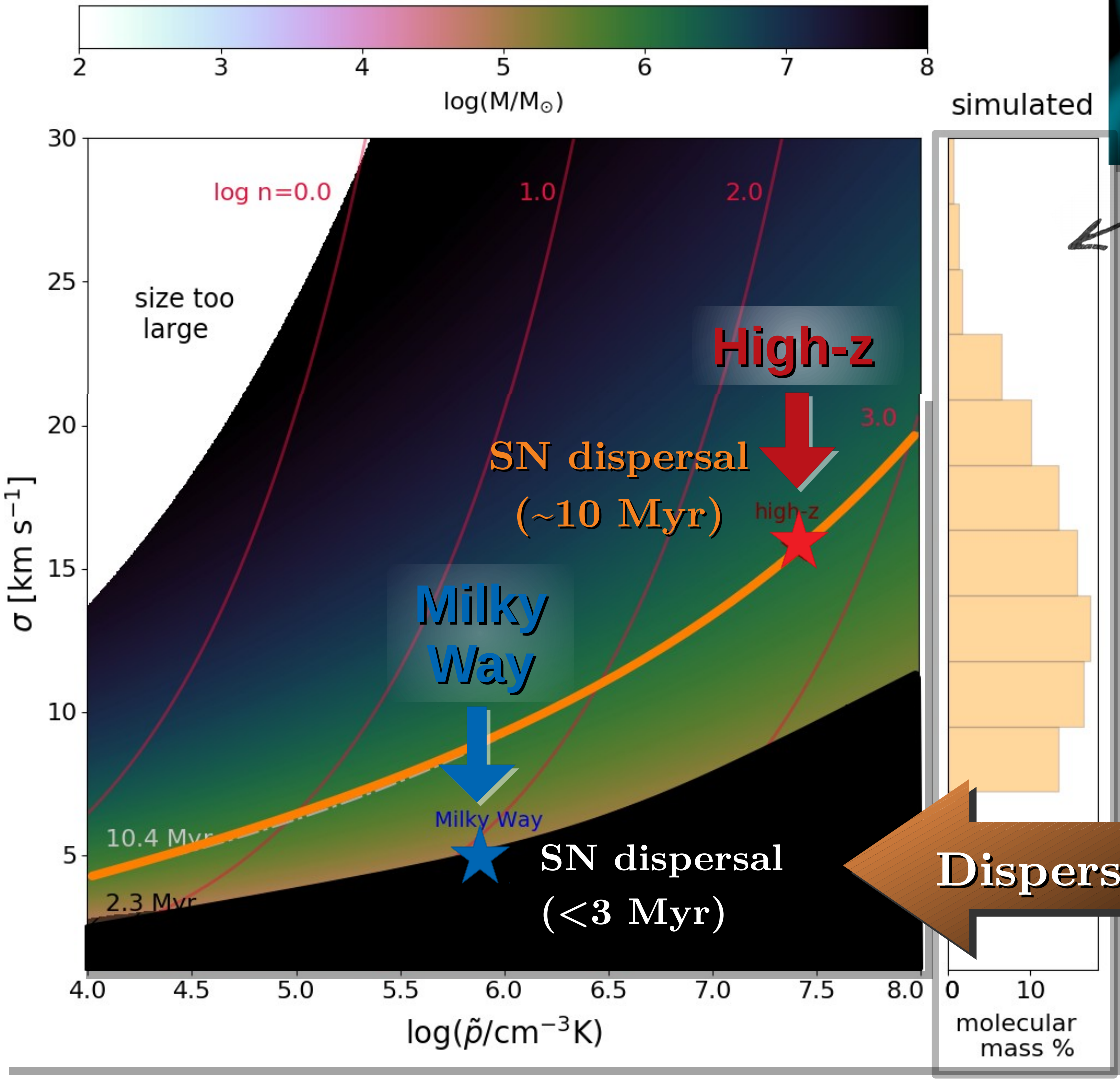
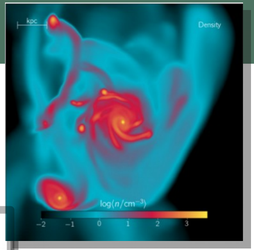


Decataldo+20





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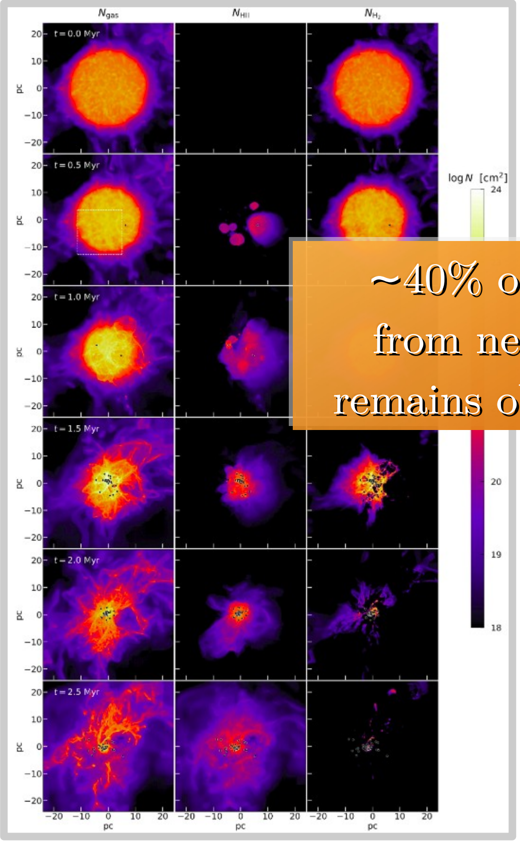
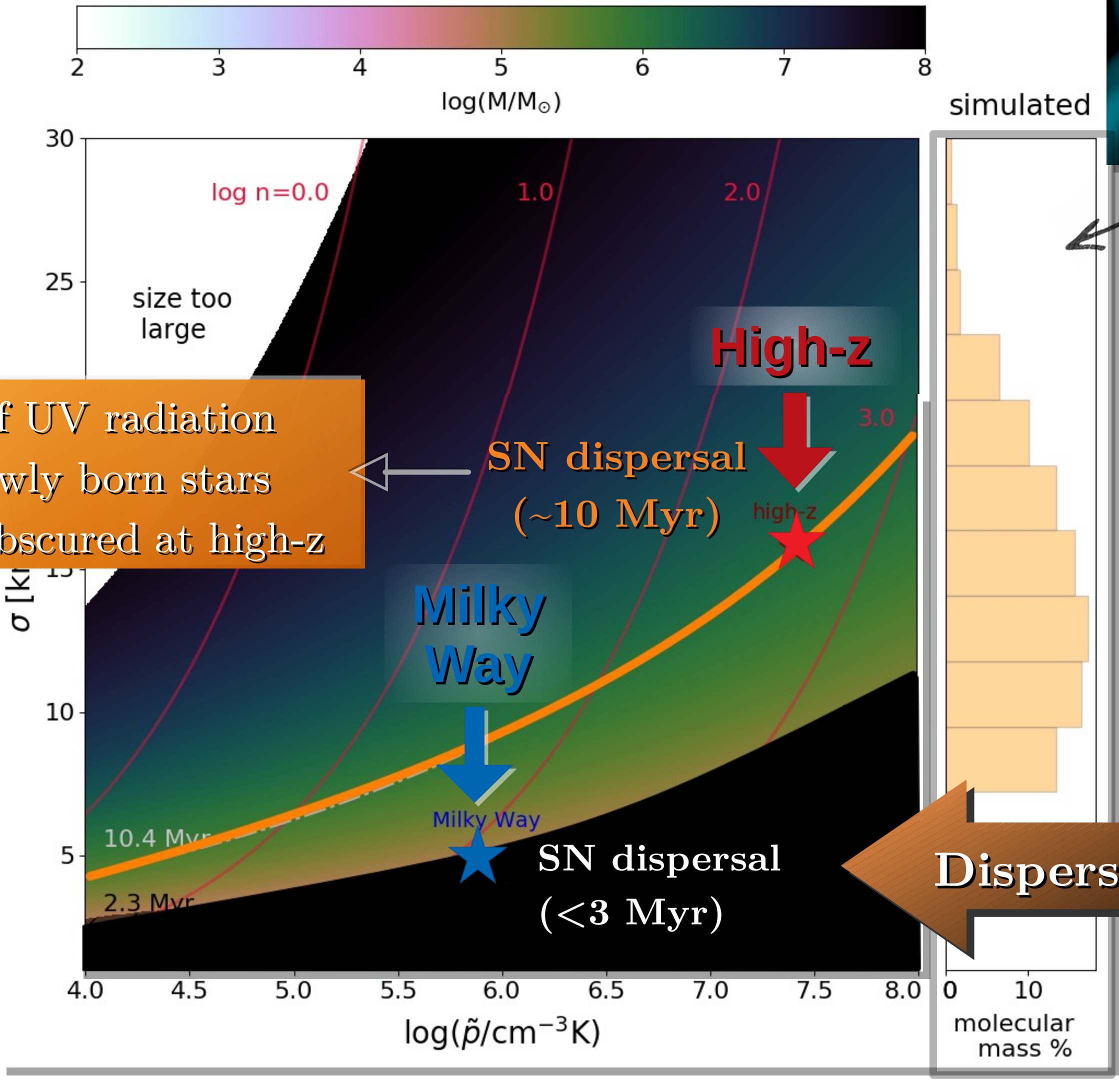
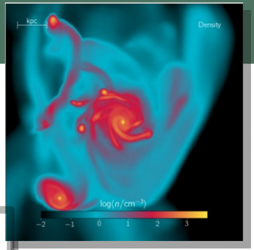


Decataldo+20

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





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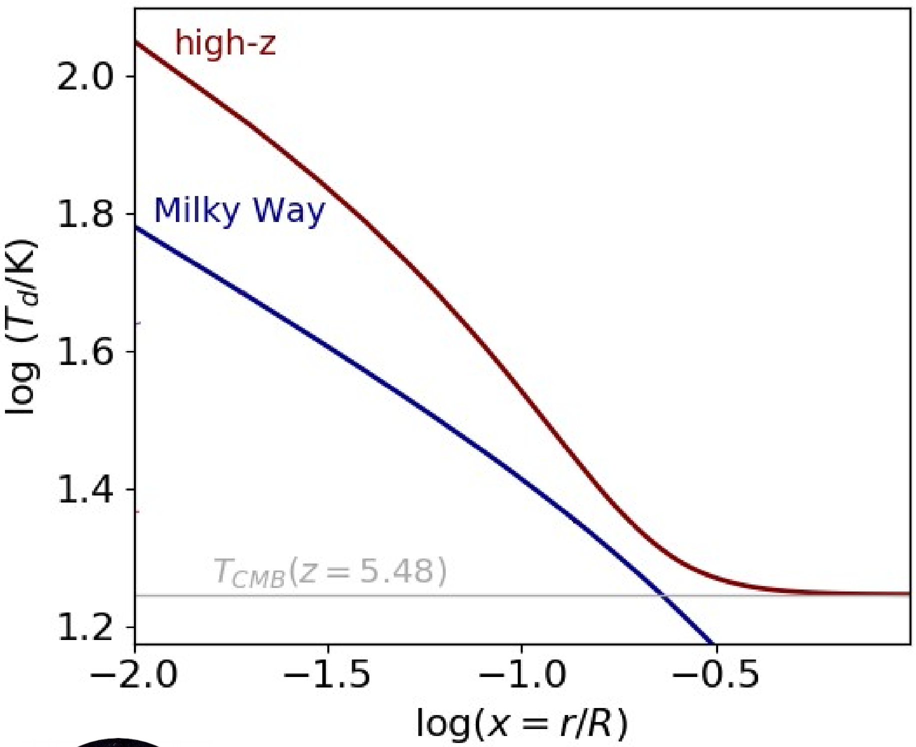
Sommovigo+2020

Dust temperature in GMCs

Uniform cloud



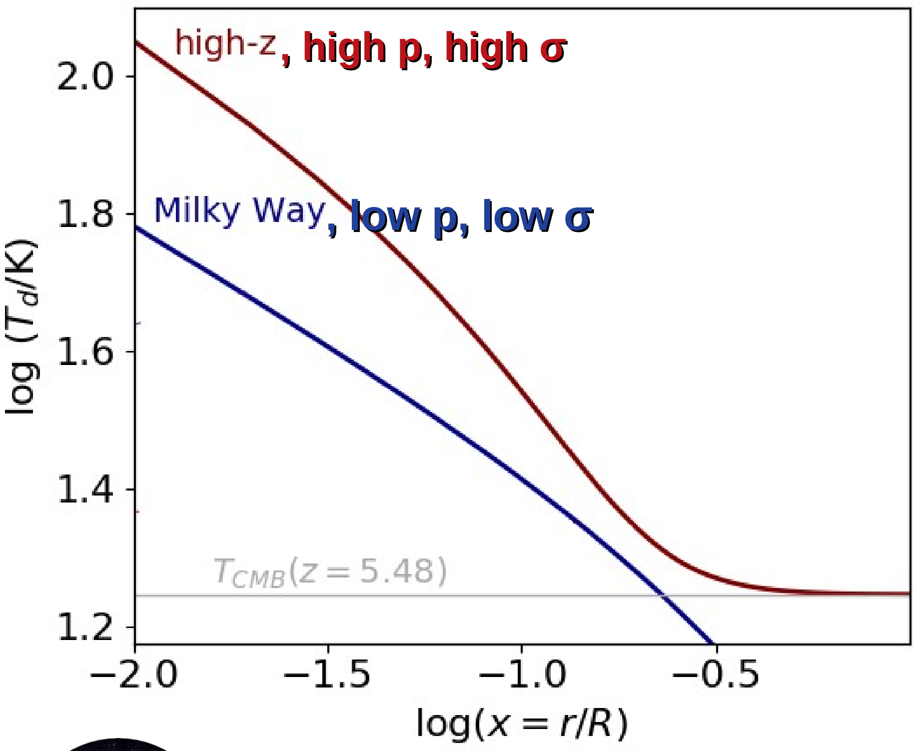
Towards the center of the cloud

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

Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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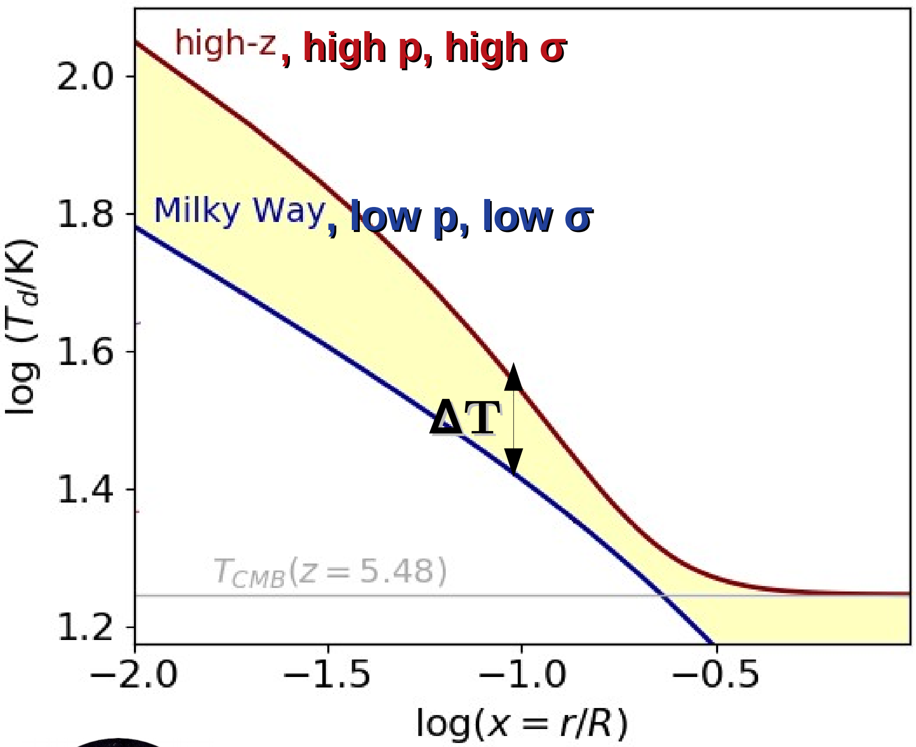


Towards the center of the cloud

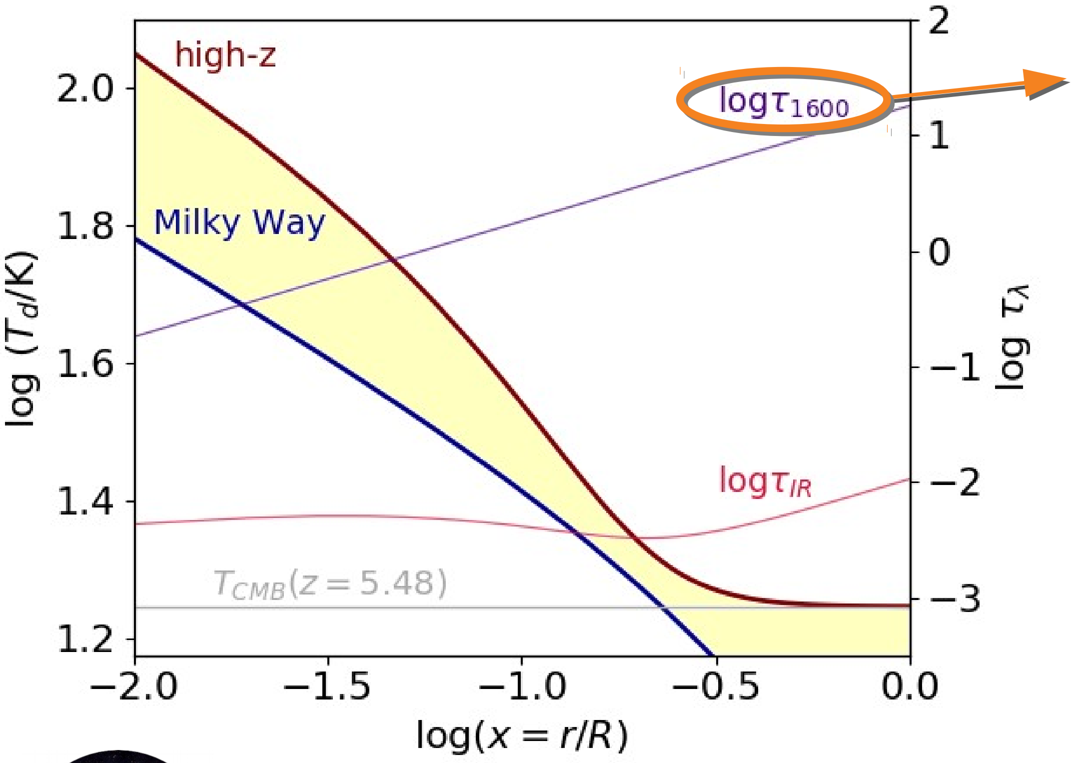
(MW grain size distribution: *Weingartner & Draine, 2001*)

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

Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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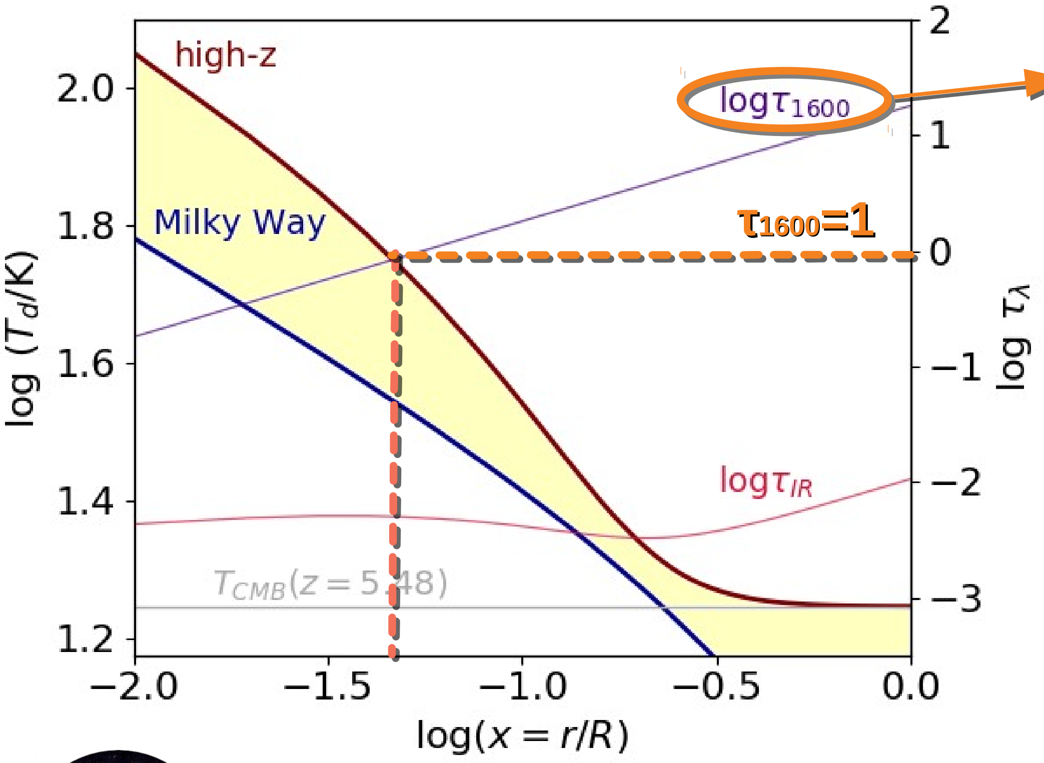
- **Hotter dust due to high pressure at high-*z***

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

Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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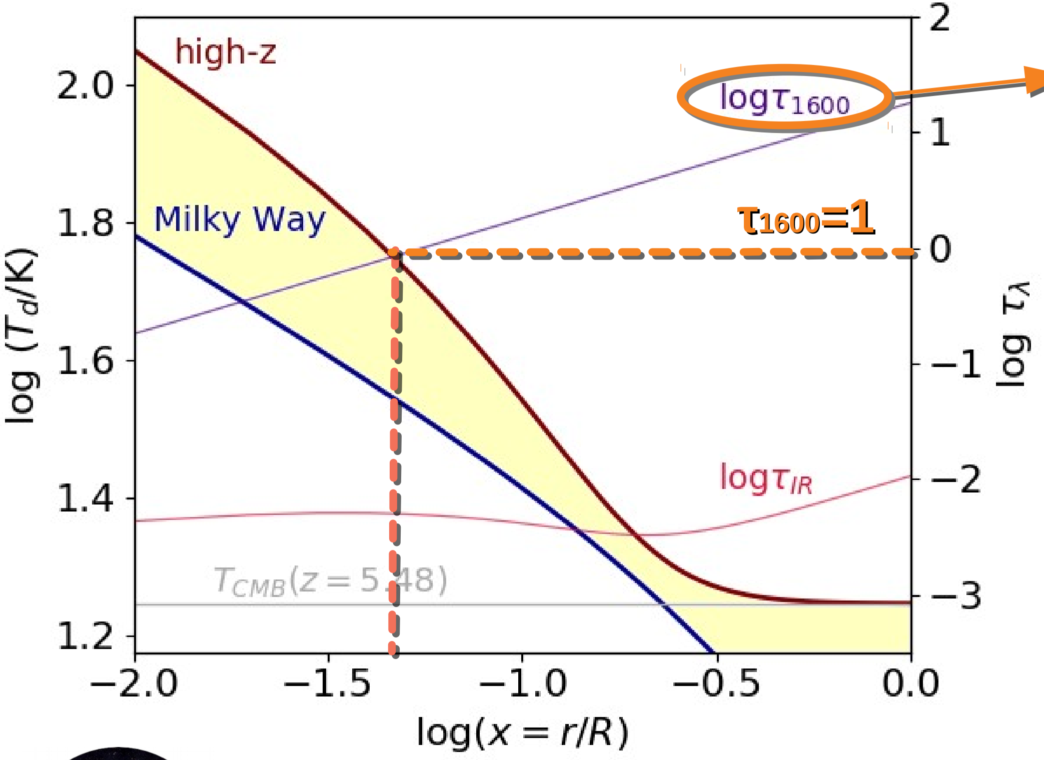


- **Hotter dust due to high pressure at high-*z***

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

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

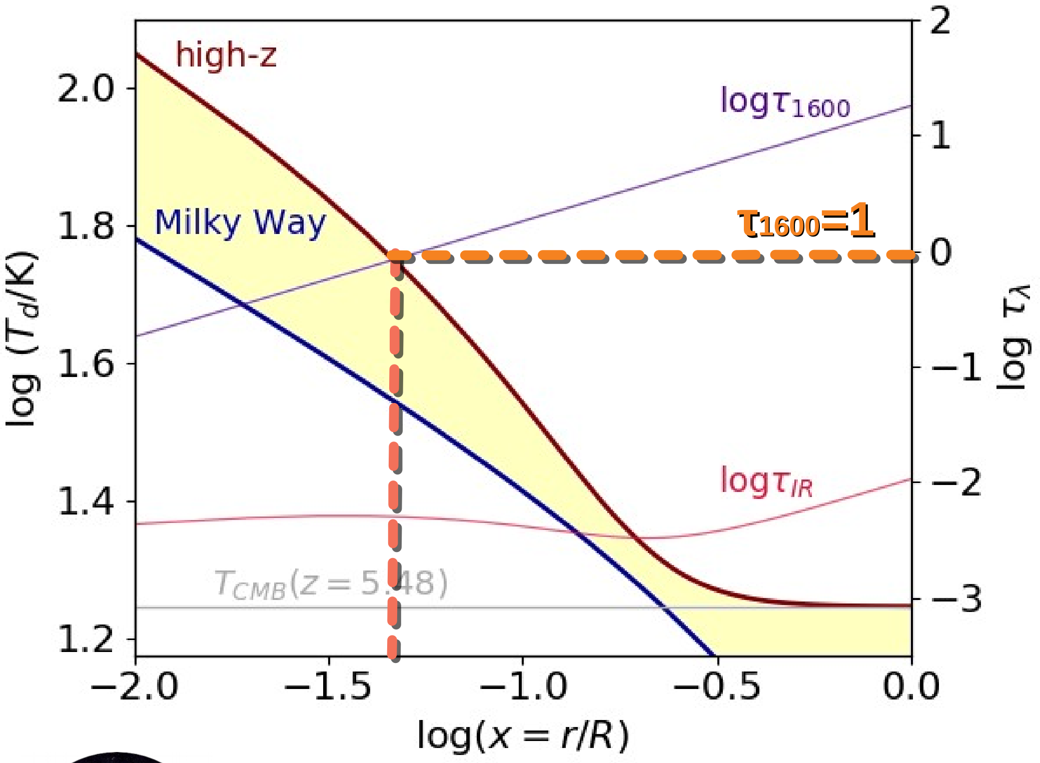
Towards the center of the cloud

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

Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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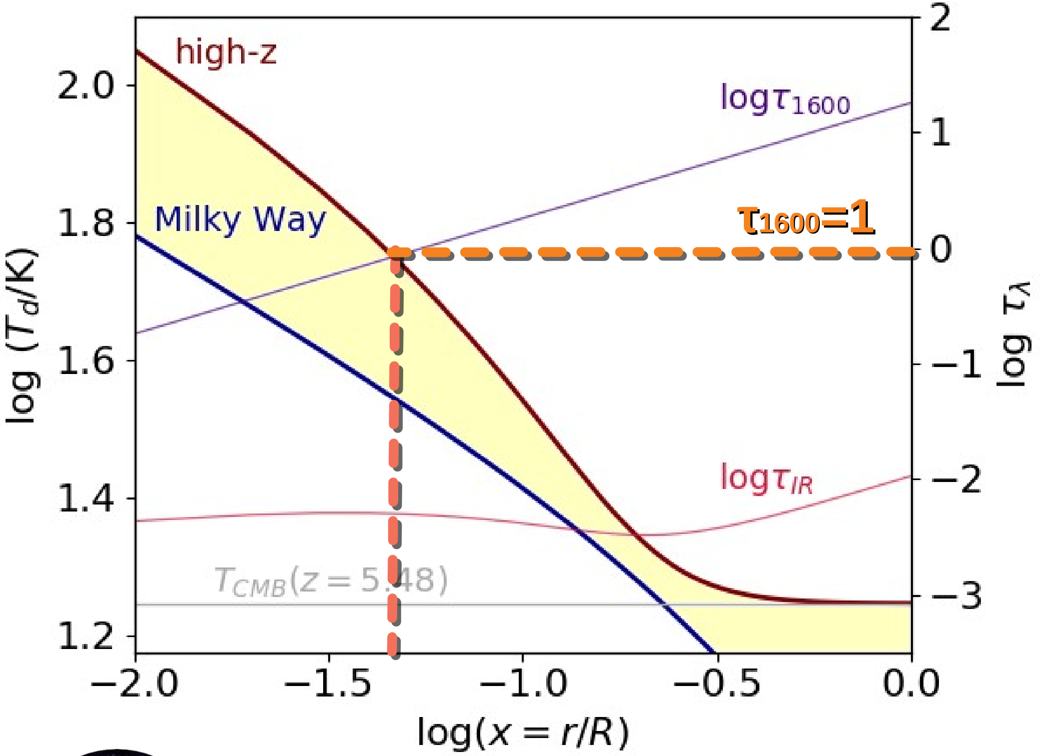
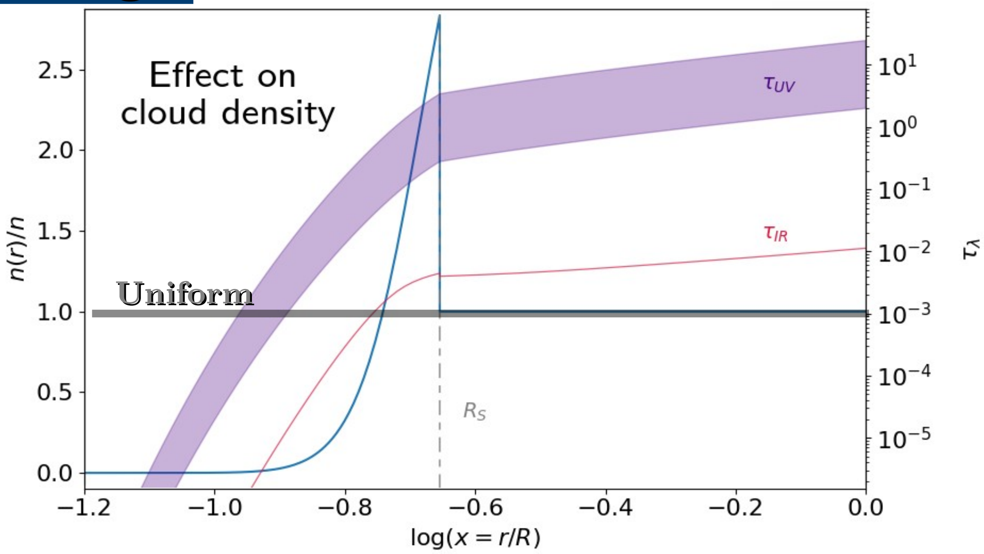
Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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



Towards the center of the cloud

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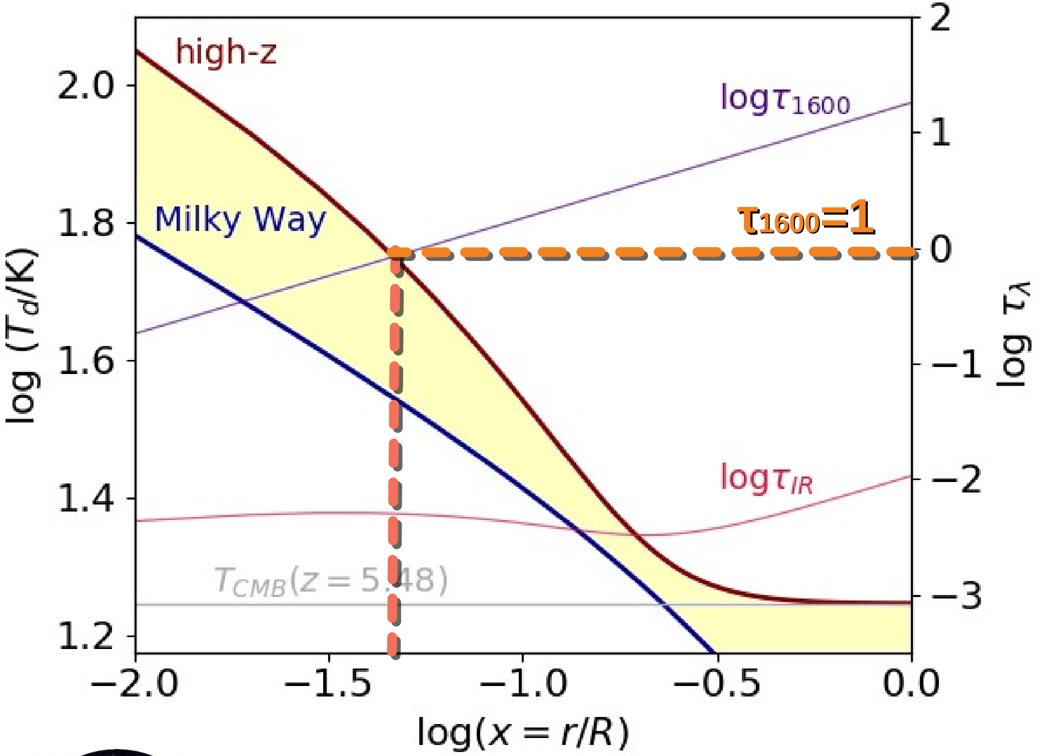
Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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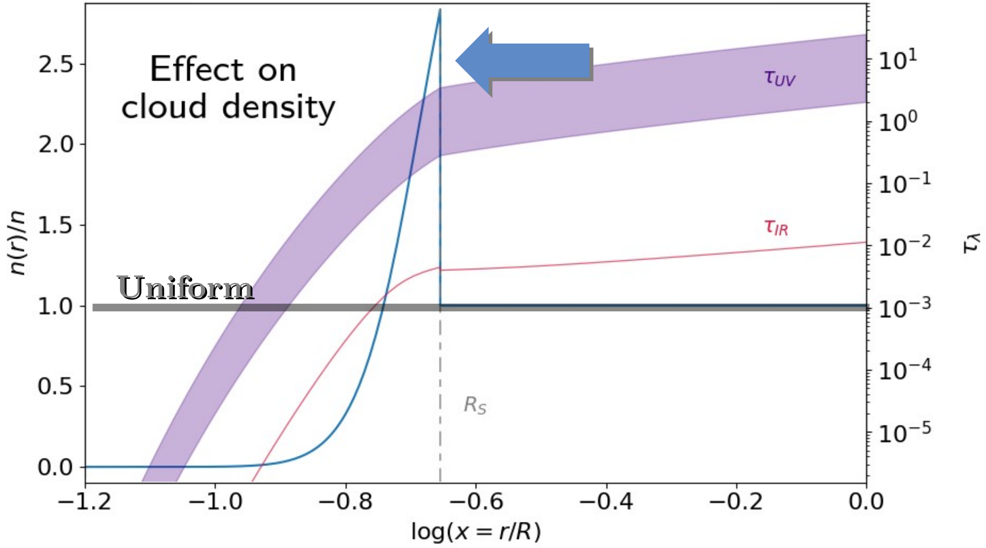

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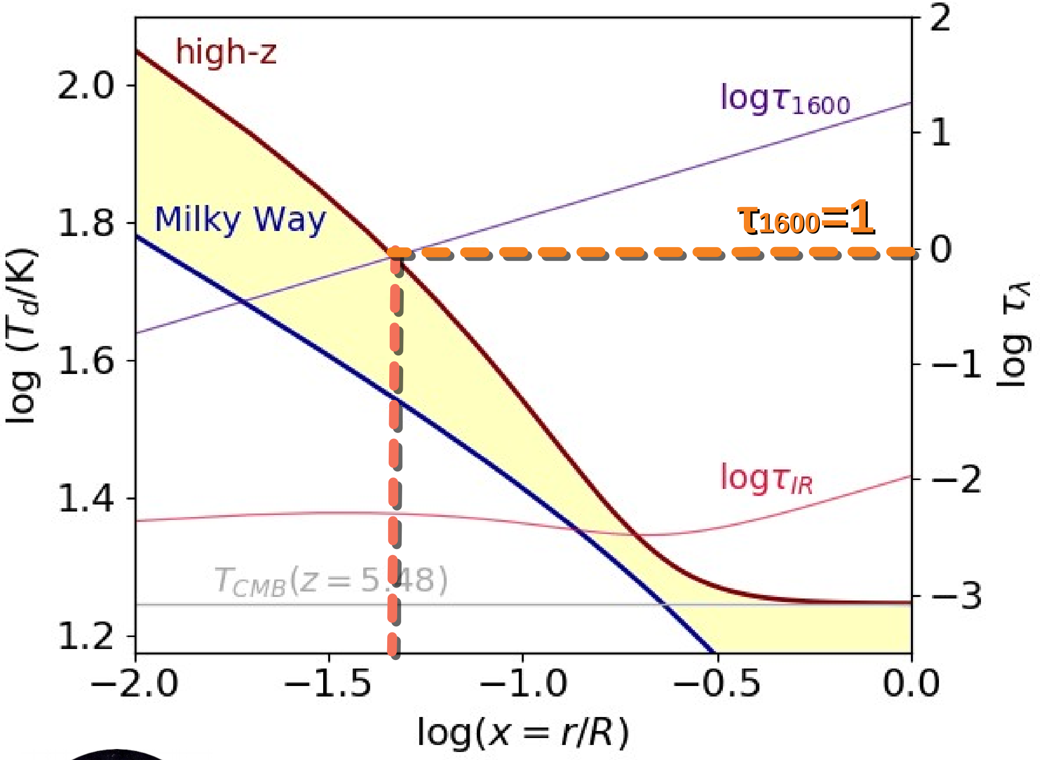
Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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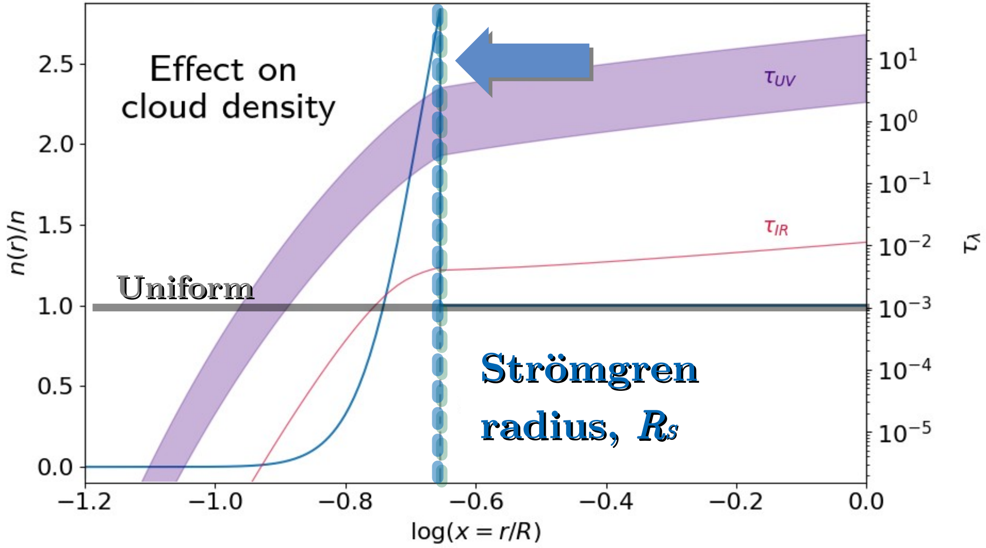

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Sommovigo+20

Dust temperature in GMCs

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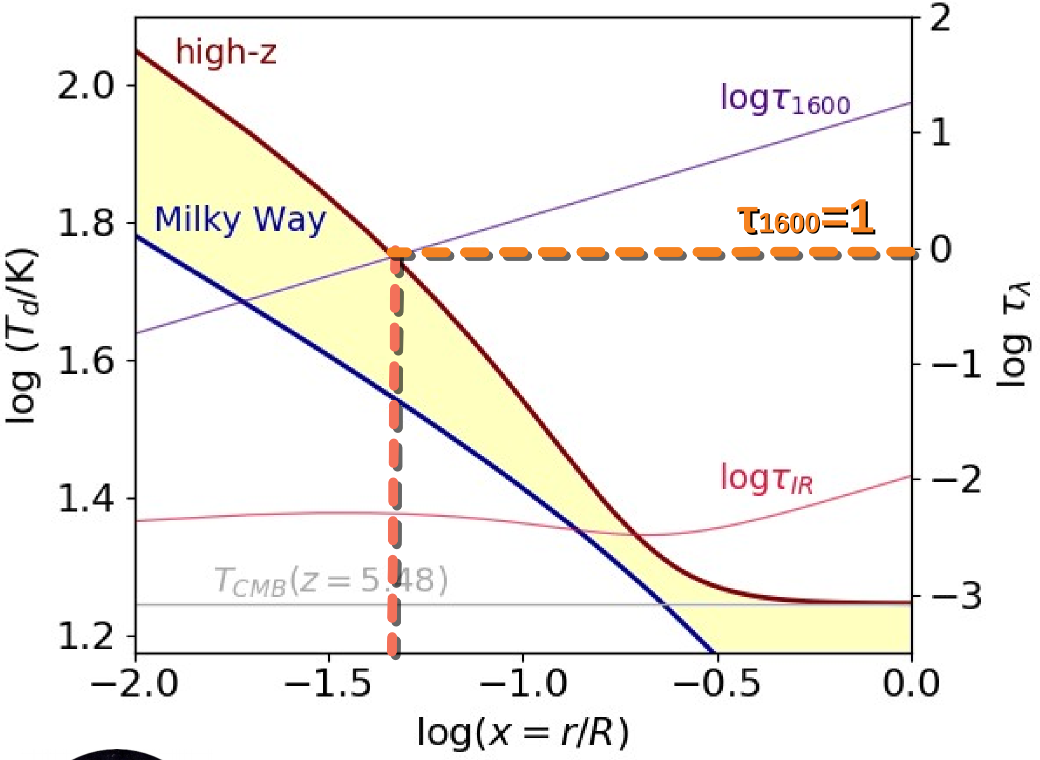

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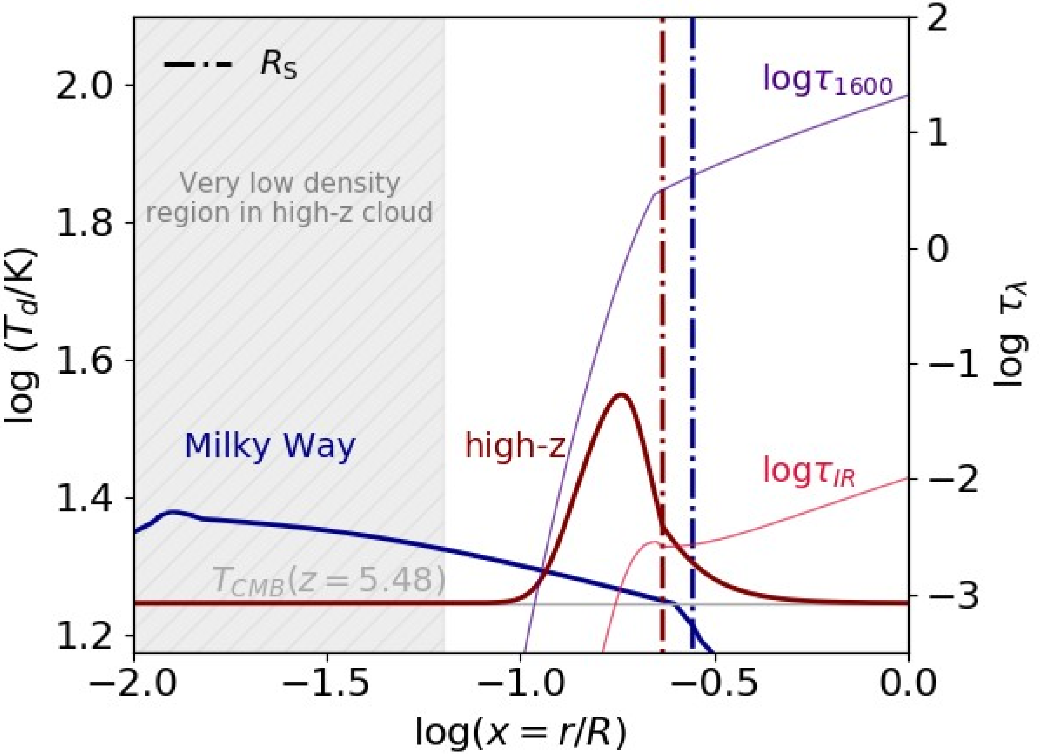

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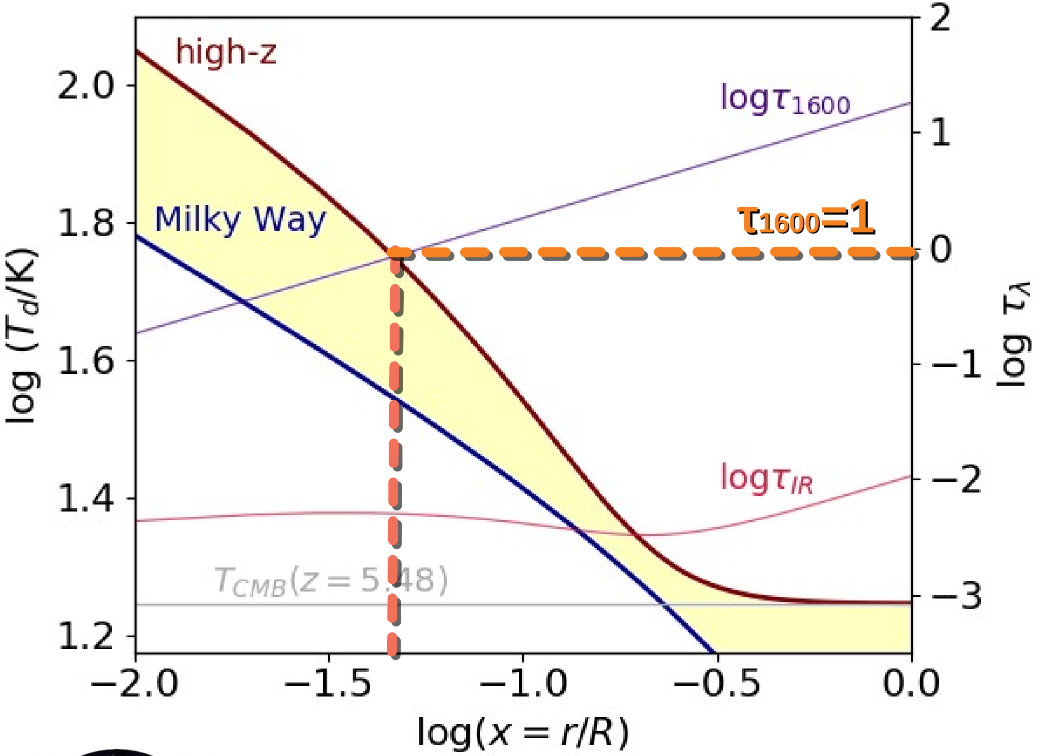

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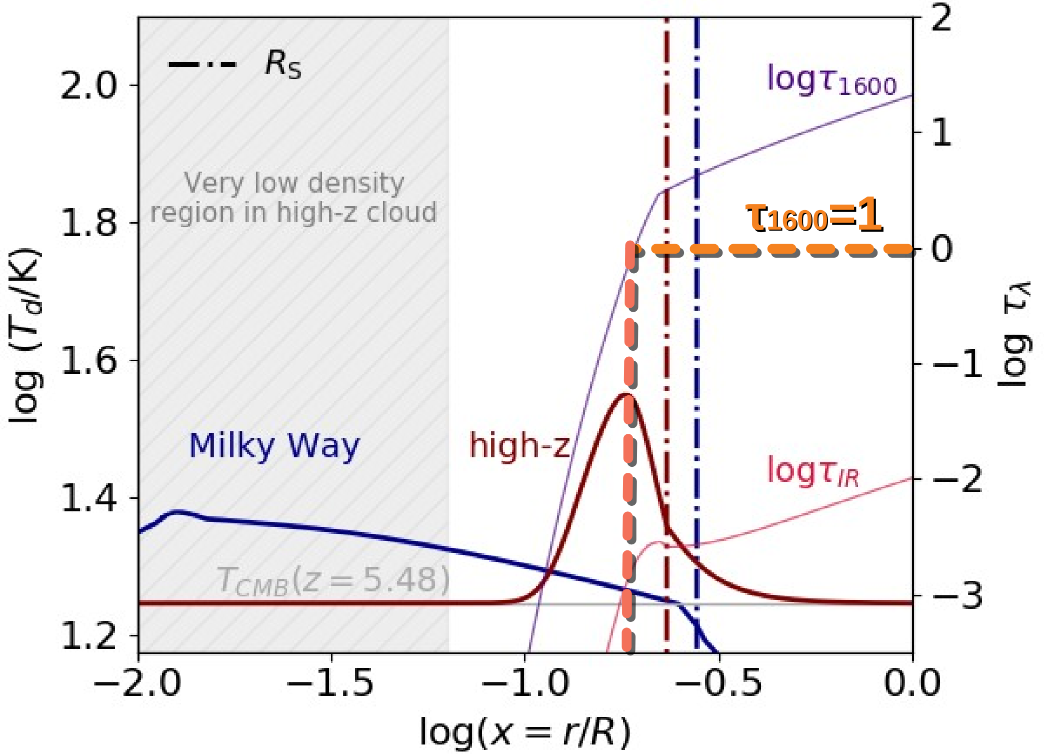

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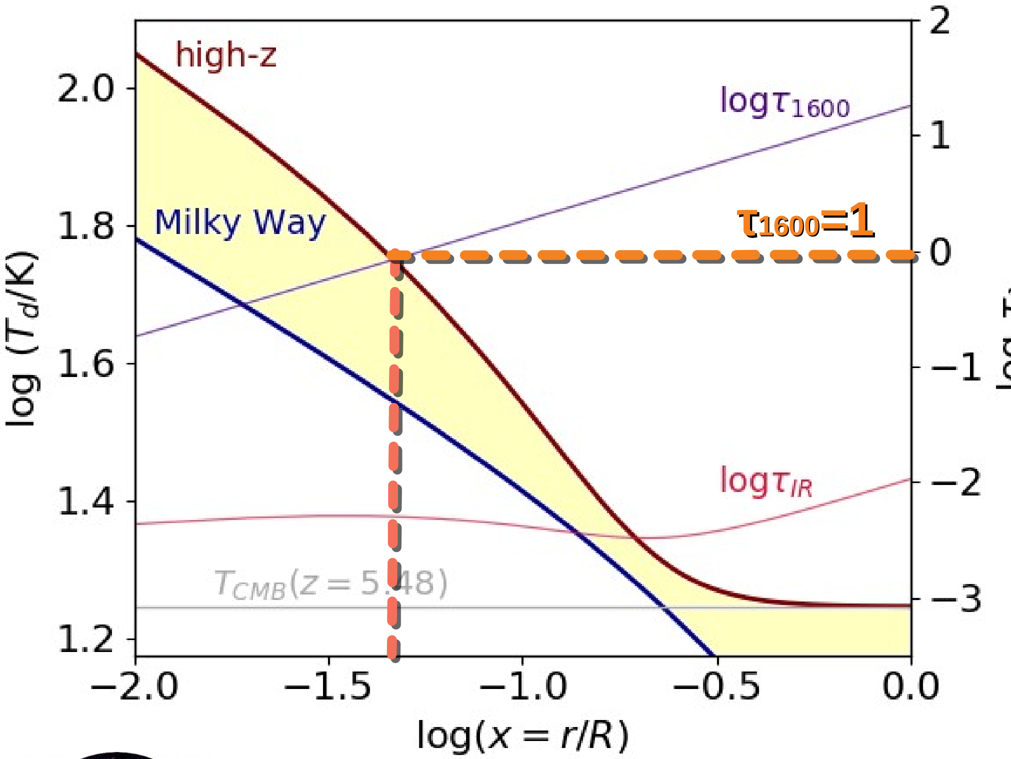
Sommovigo+20

Dust temperature in GMCs

Uniform cloud



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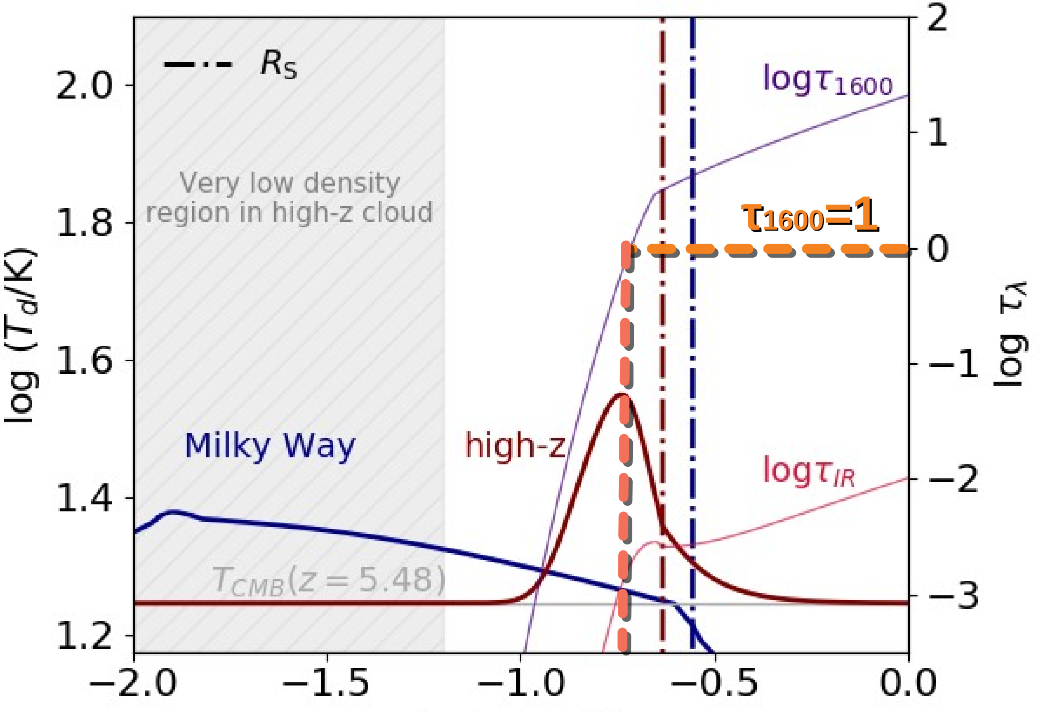


Towards the center of the cloud

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

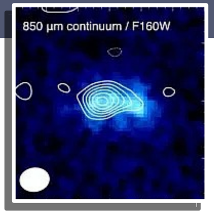
In high-z GMC:

- Dust temperature ~60 K in few Myr
- Luminosity-to-gas mass ratio ~10 L⊙/M⊙ (while locally ~1 L⊙/M⊙)

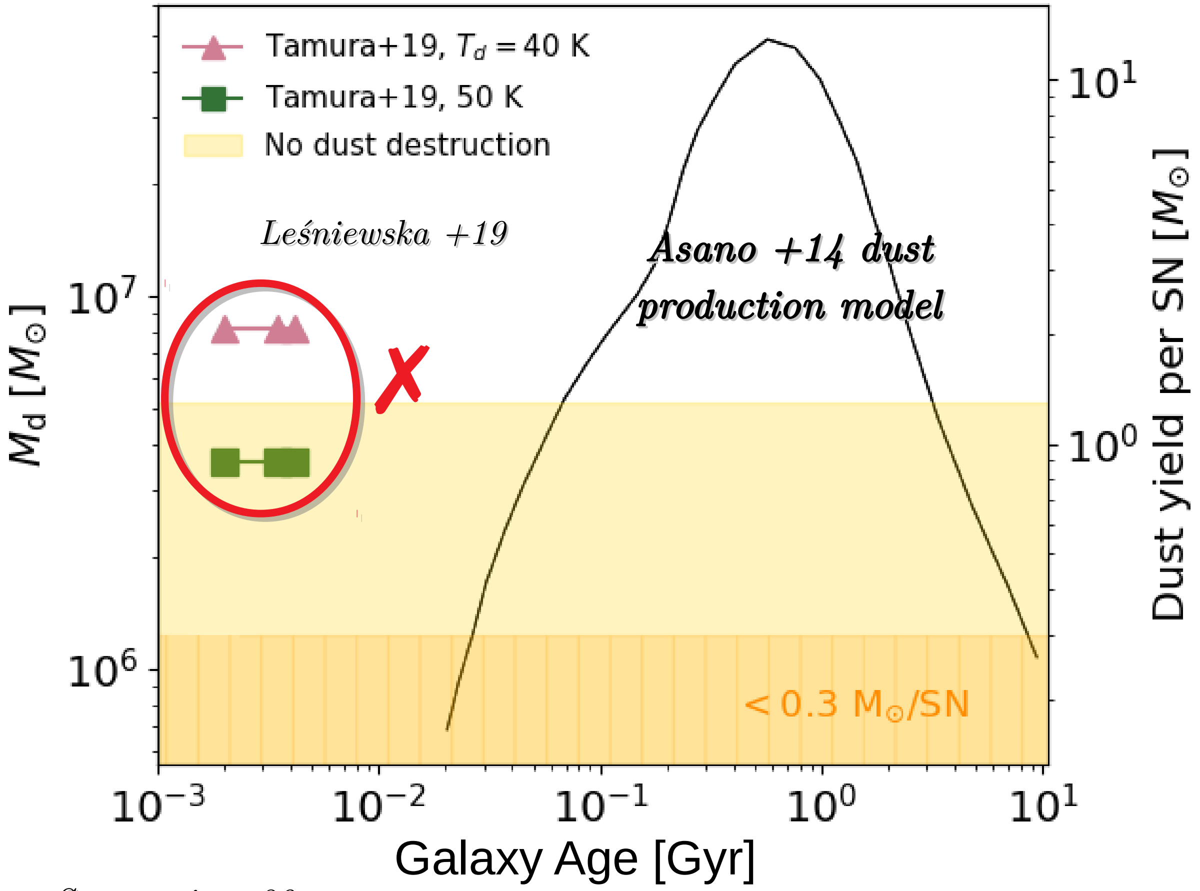
Sommovigo+20

Warm T_d: Implications for the dust mass

MACS0416-Y1



From our model $\mathbf{T_d \gtrsim 60\ K}$: higher than usually assumed (T_d=25-35 K)



Sommovigo+20

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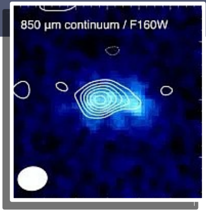

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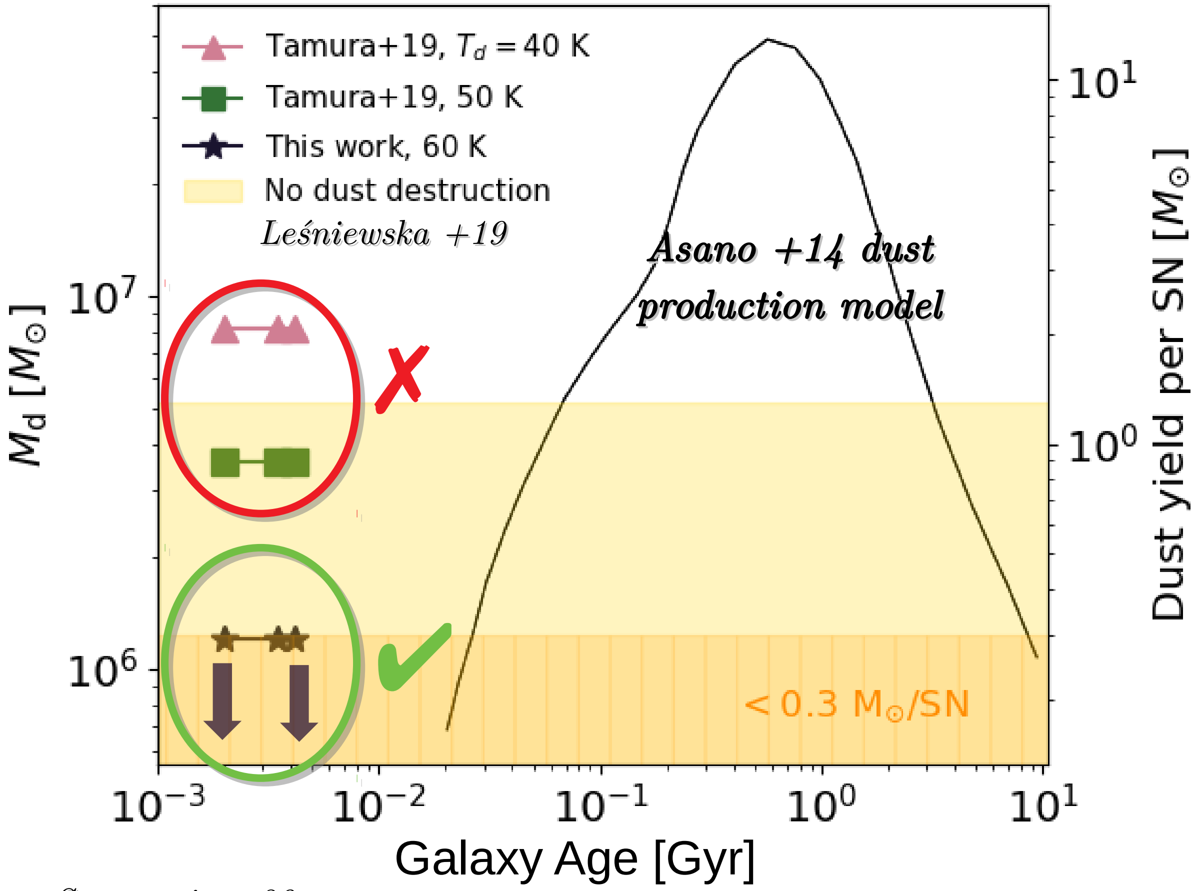

Sommovigo+20

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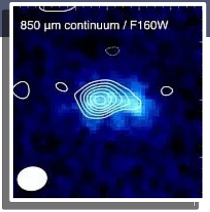

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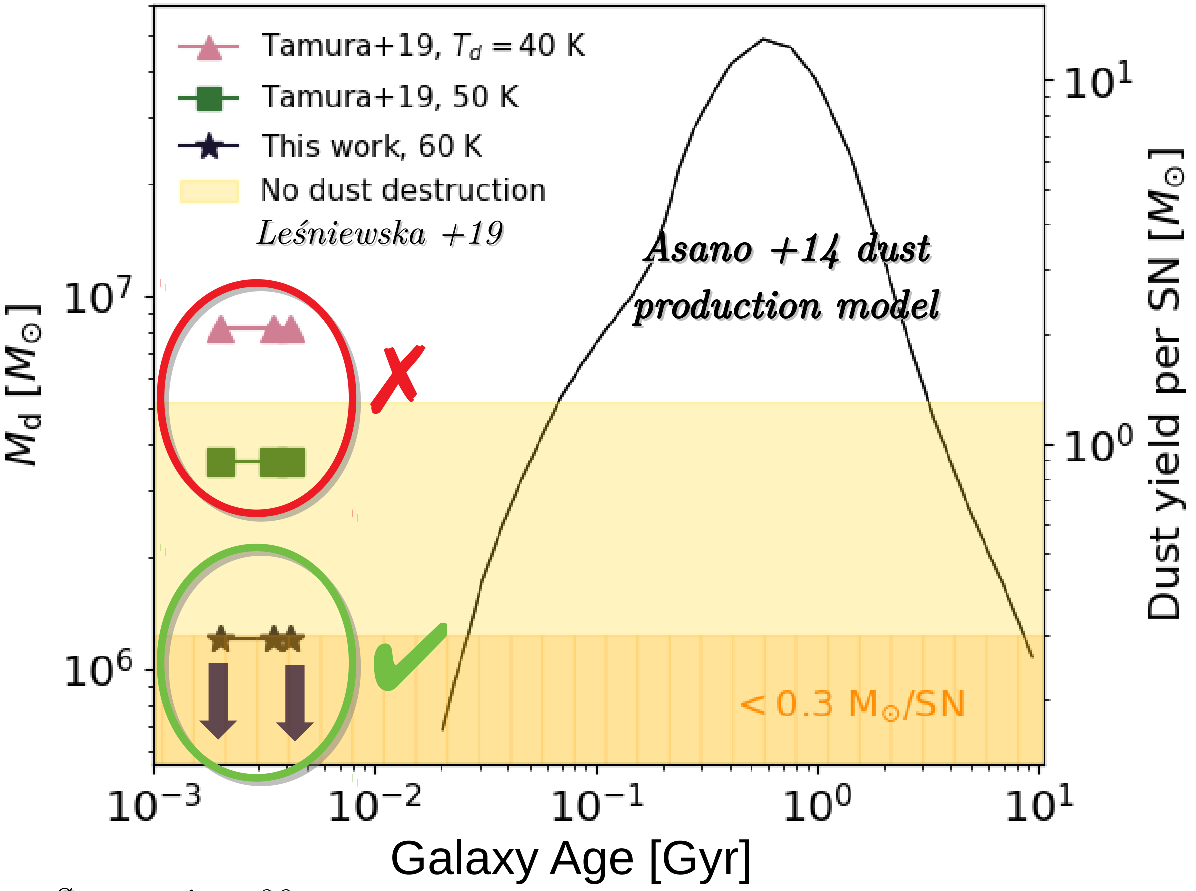
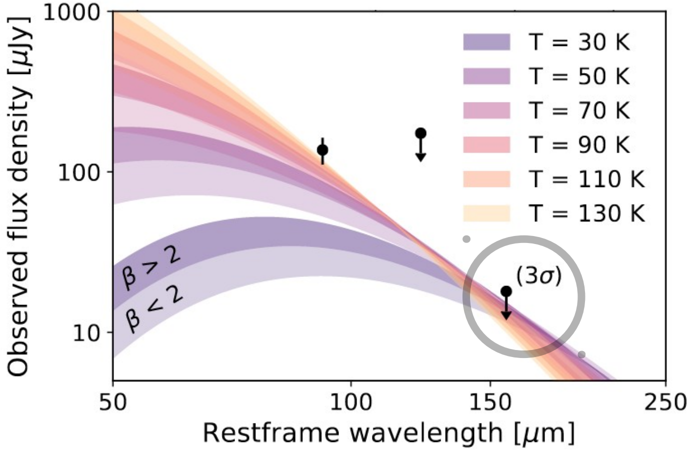


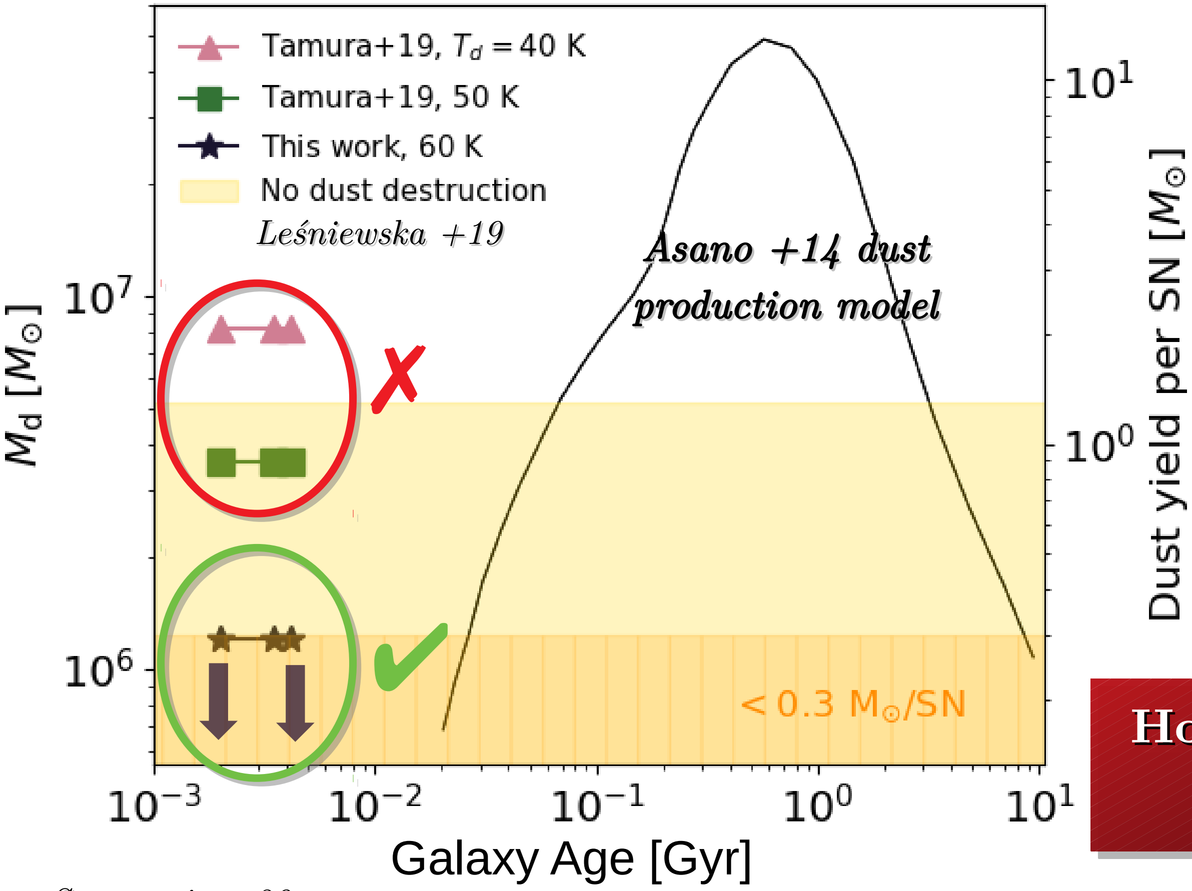
Sommovigo+20

Consistent with latest observations by *Bakx+20*:



Warm T_d: Implications for the dust mass

From our model **$T_d \gtrsim$ 60 K**: higher than usually assumed (T_d=25-35 K)



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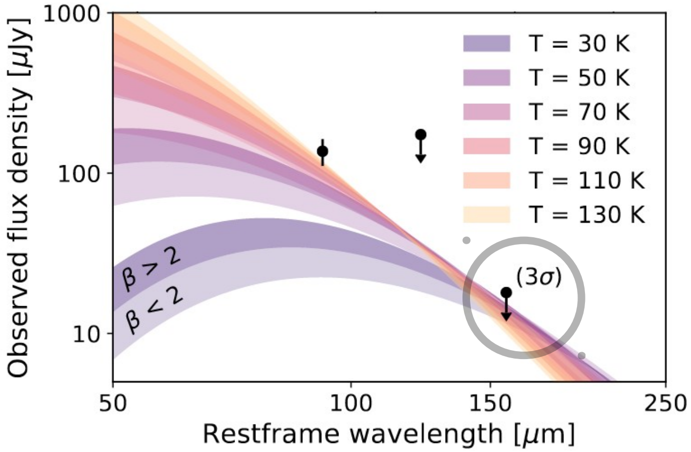
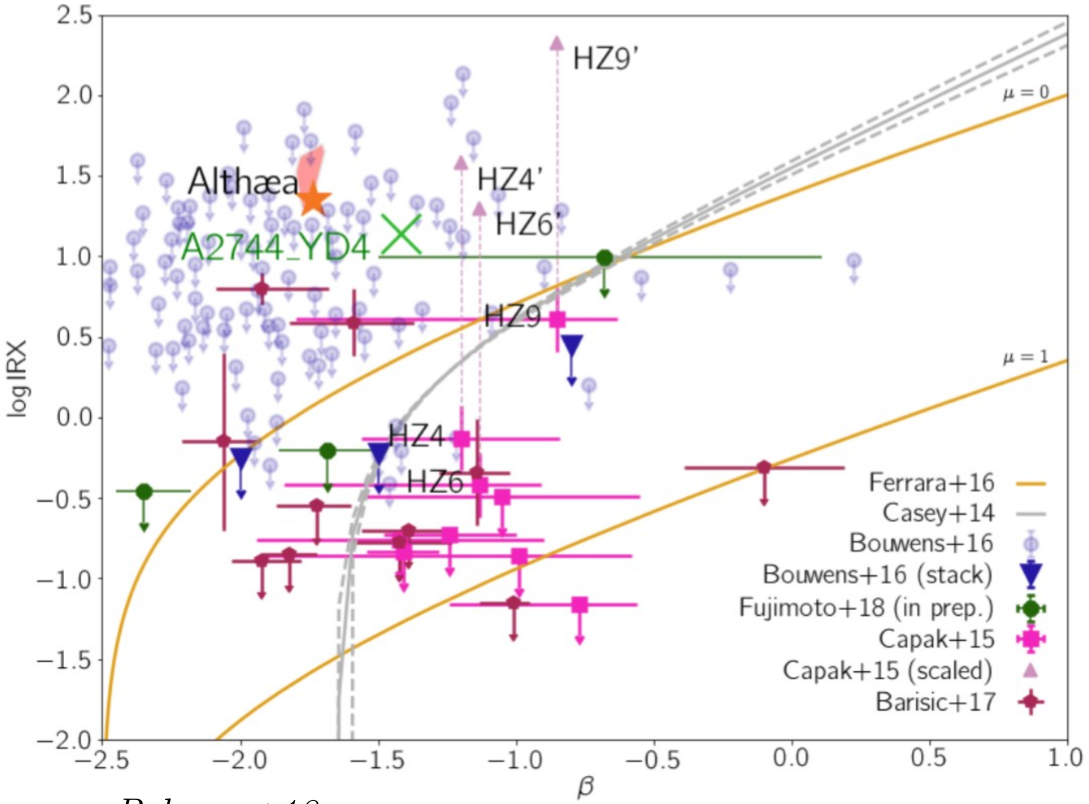


Hotter dust reduces requirements on M_d to produce the observed L_{FIR}

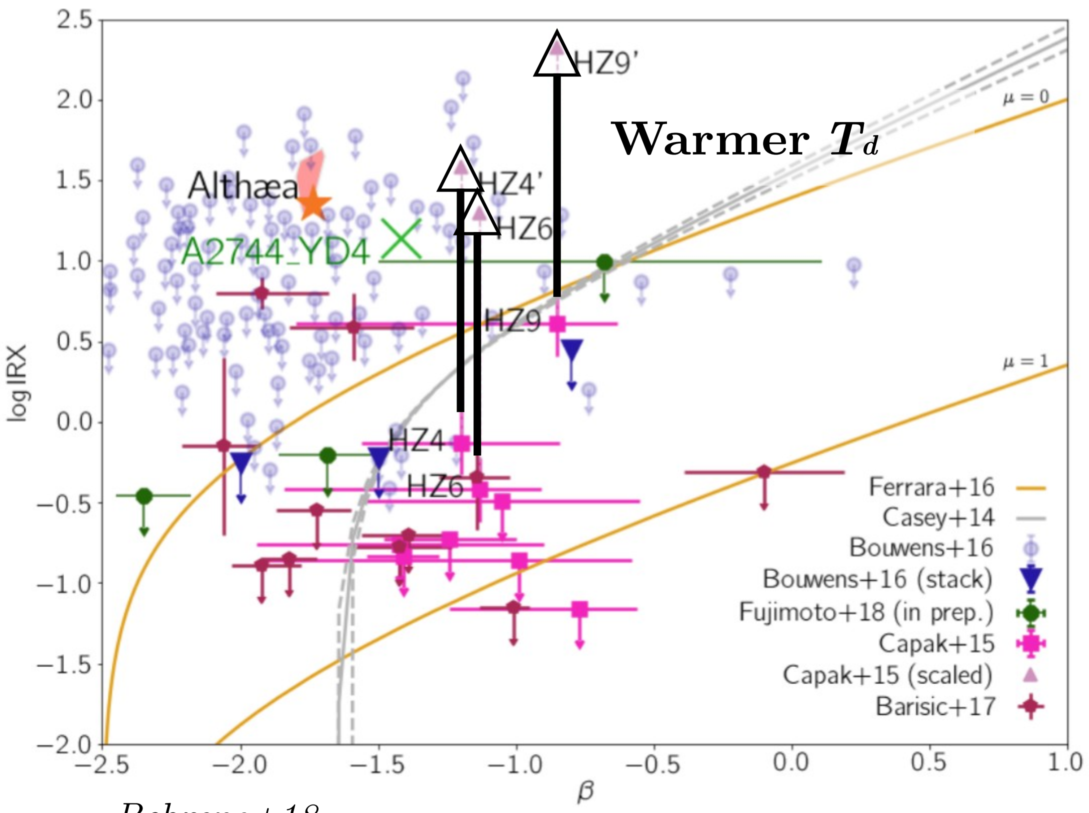
Warm T_d: Implications for the IRX-β relation



Behrens+18

Pallottini+22

Warm T_d: Implications for the **IRX-β** relation



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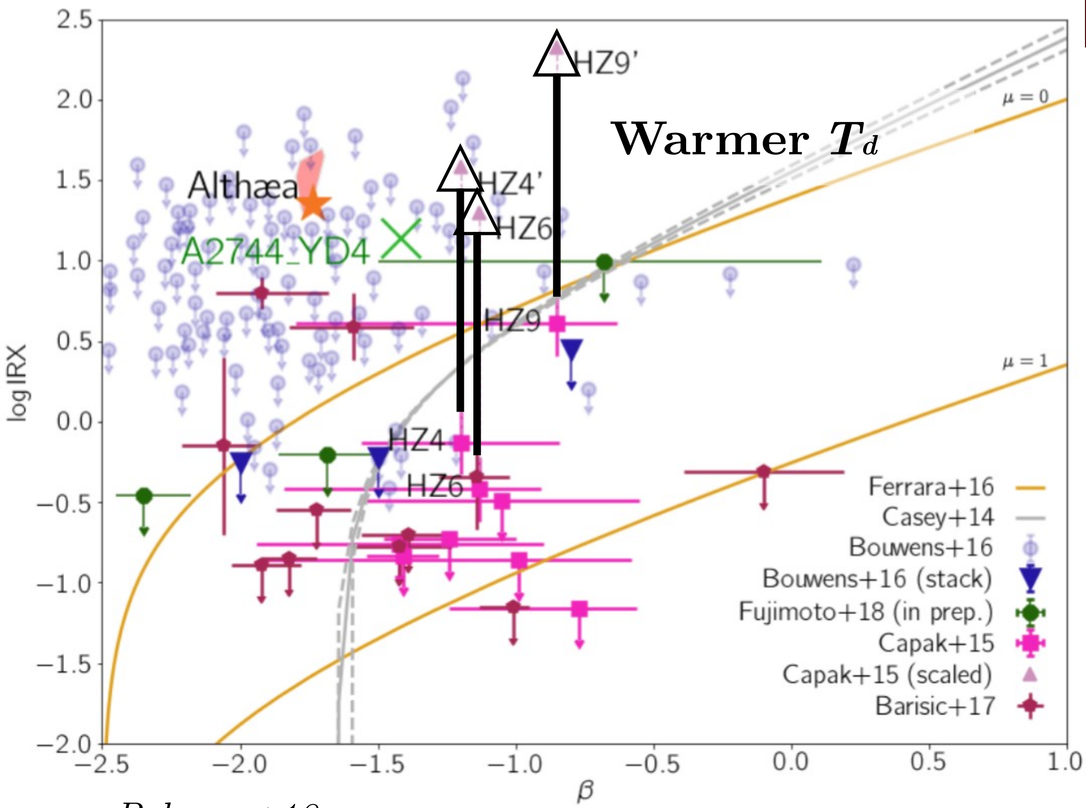
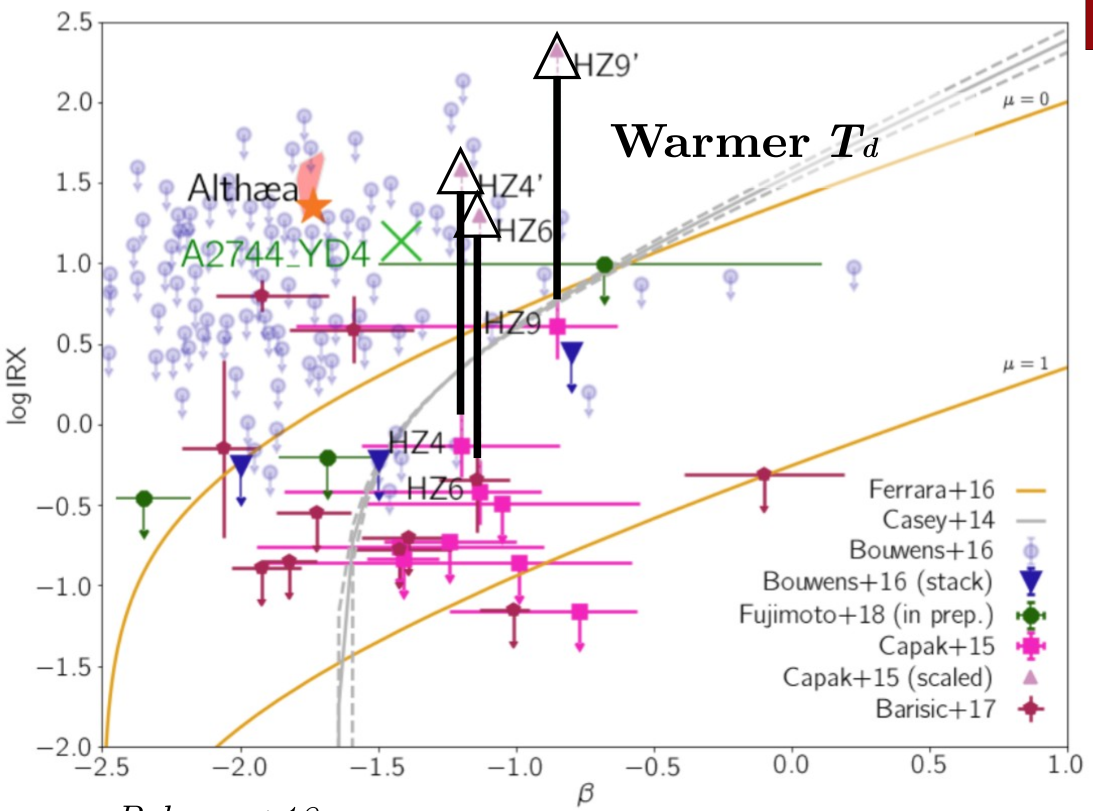


Behrens+18

Spatial separation between UV and IR?

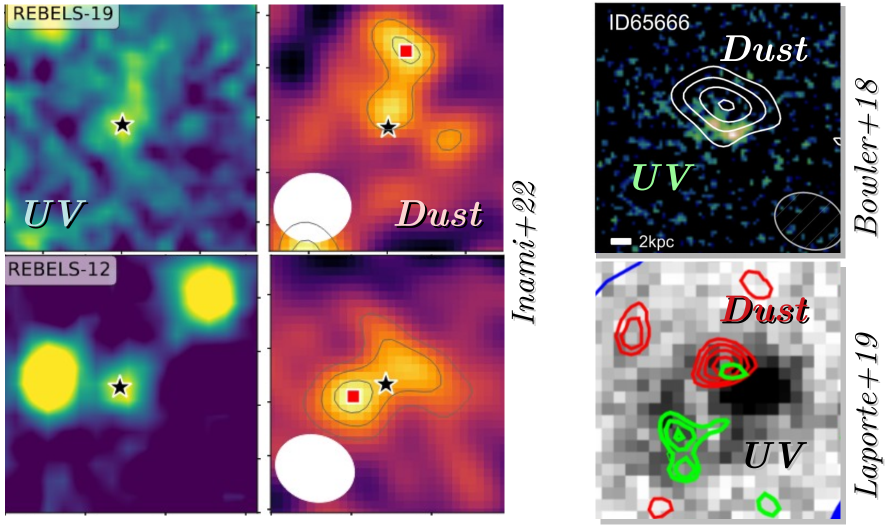
Pallottini+22

Warm T_d: Implications for the IRX-β relation



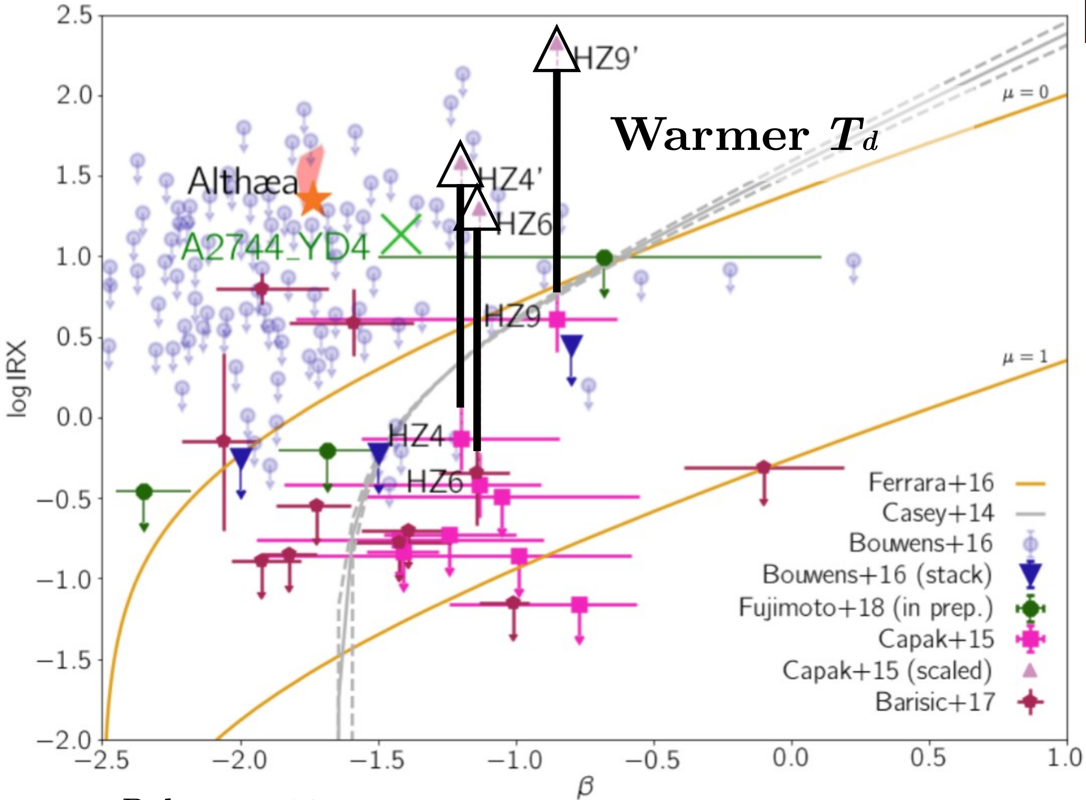
Behrens+18

Spatial separation between UV and IR?



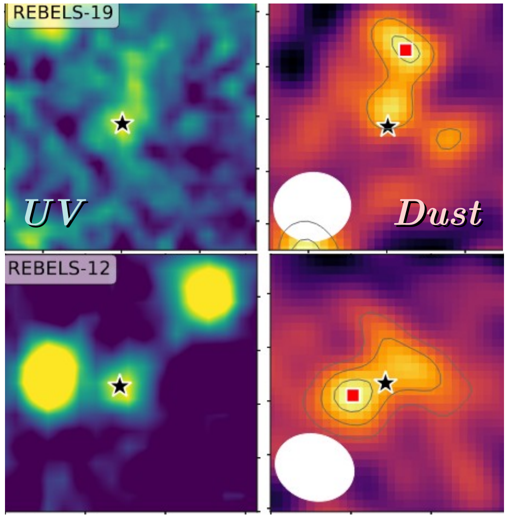
Pallottini+22

Warm T_d: Implications for the IRX-β relation

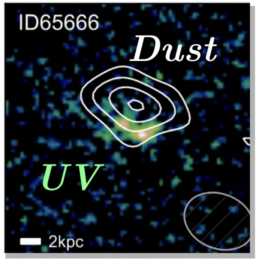


Behrens+18

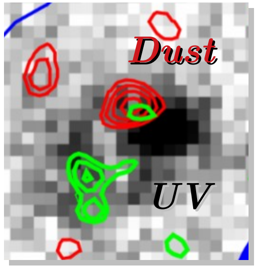
Spatial separation between UV and IR?



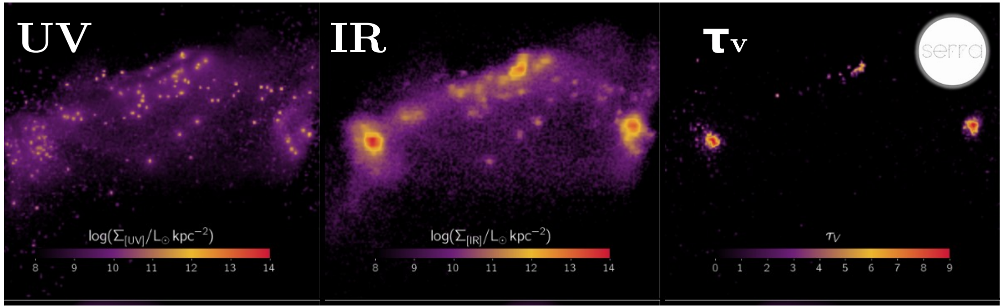
Inami+22



Bowler+18

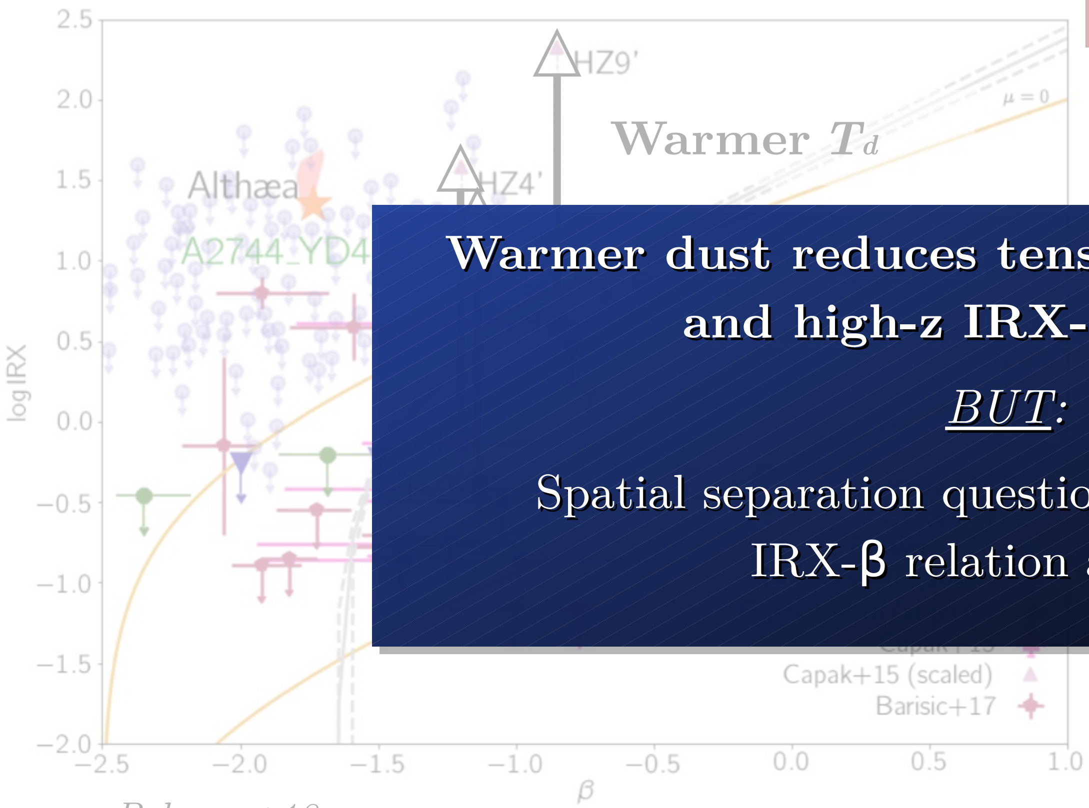


Laporte+19



Pallottini+22

Warm T_d : Implications for the IRX-β relation



Behrens+18

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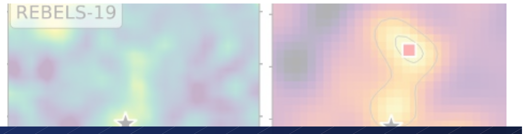
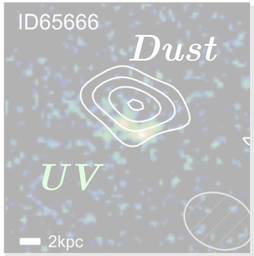
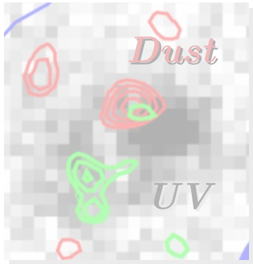


Inami+22



Bowler+18

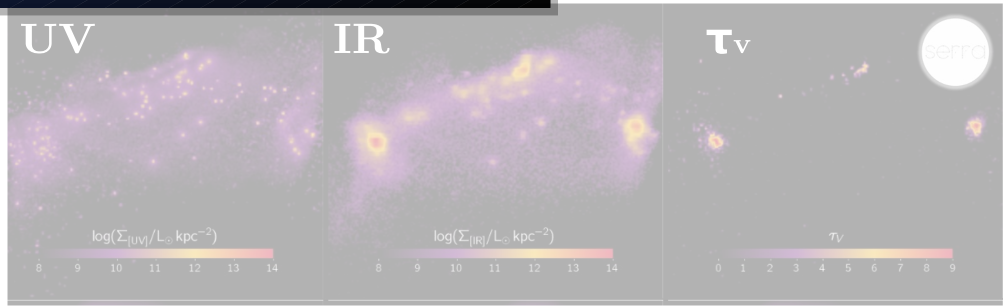


Laporte+19

Warmer dust reduces tension between local and high-z IRX-β relation

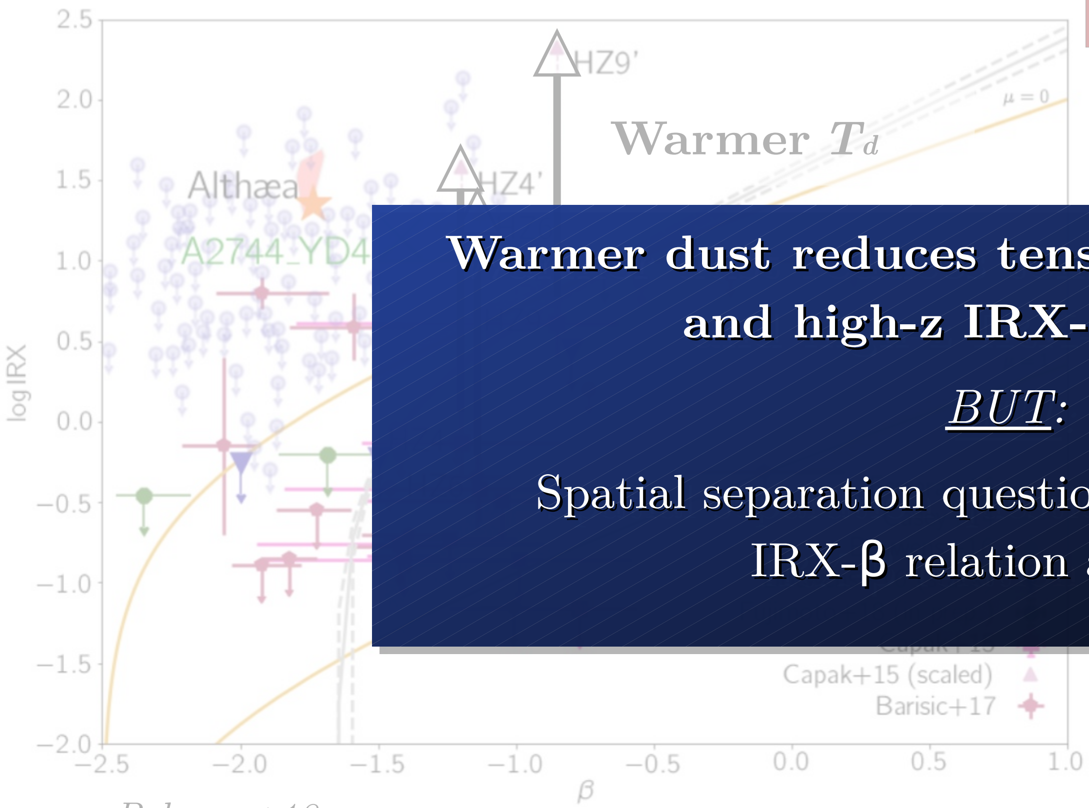
BUT:

Spatial separation questions the validity of IRX-β relation at high-z



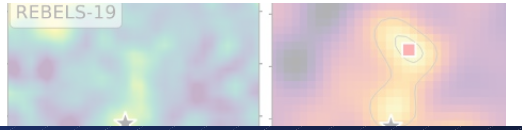
Pallottini+22

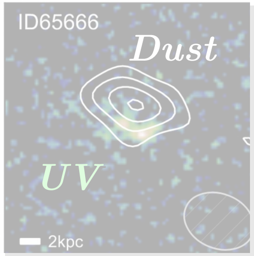
Warm T_d: Implications for the IRX-β relation



Behrens+18

Spatial separation between UV and IR?





Bowler+18

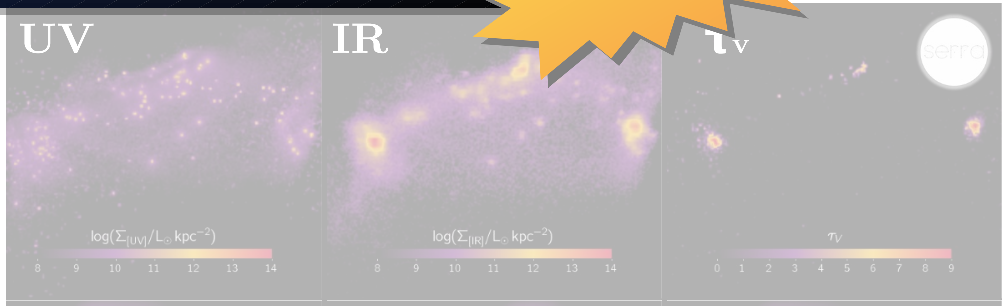
Laporte+19

Warmer dust reduces tension between local and high-z IRX-β relation

BUT:

Spatial separation questions the validity of IRX-β relation at high-z

JWST



Pallottini+22