

Dust in galaxies at $5 < z < 10$

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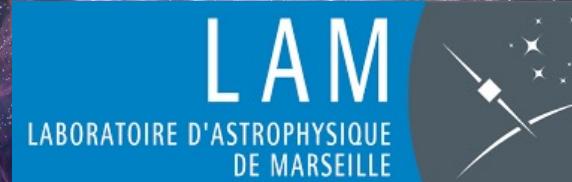
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3 published papers at the origin of this talk +1 in preparation

Observational and theoretical constraints on the formation and early evolution of the first dust grains in galaxies at $5 < z < 10$

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Received November , 2019; accepted February 4, 2020

[2020A&A...637A..32B](#)

UV dust attenuation as a function of stellar mass and its evolution with redshift

[2020MNRAS.496.5341B](#)

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The gas, metal and dust evolution in low-metallicity local and high-redshift galaxies

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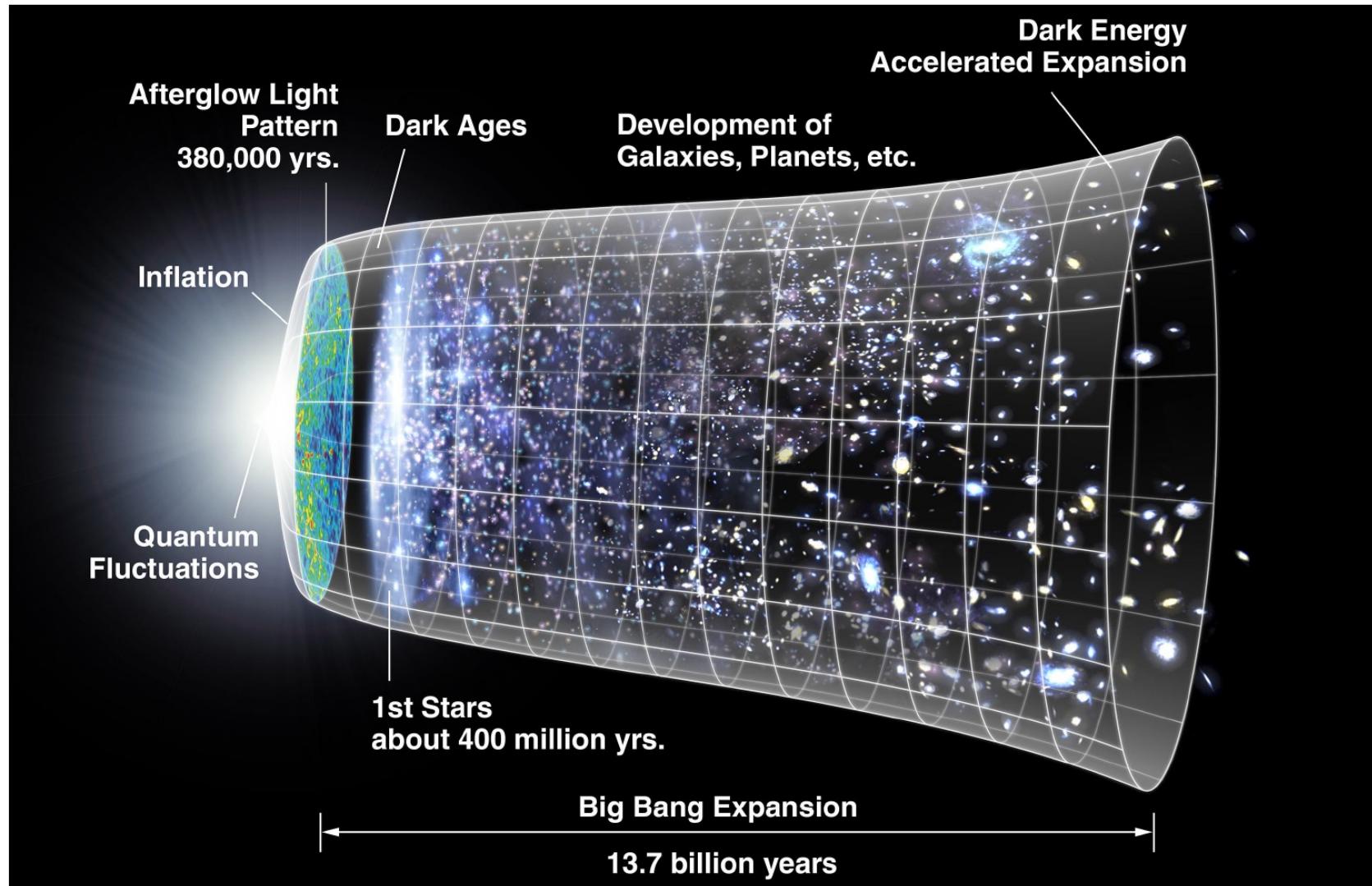
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[2020A&A...641A.168N](#)

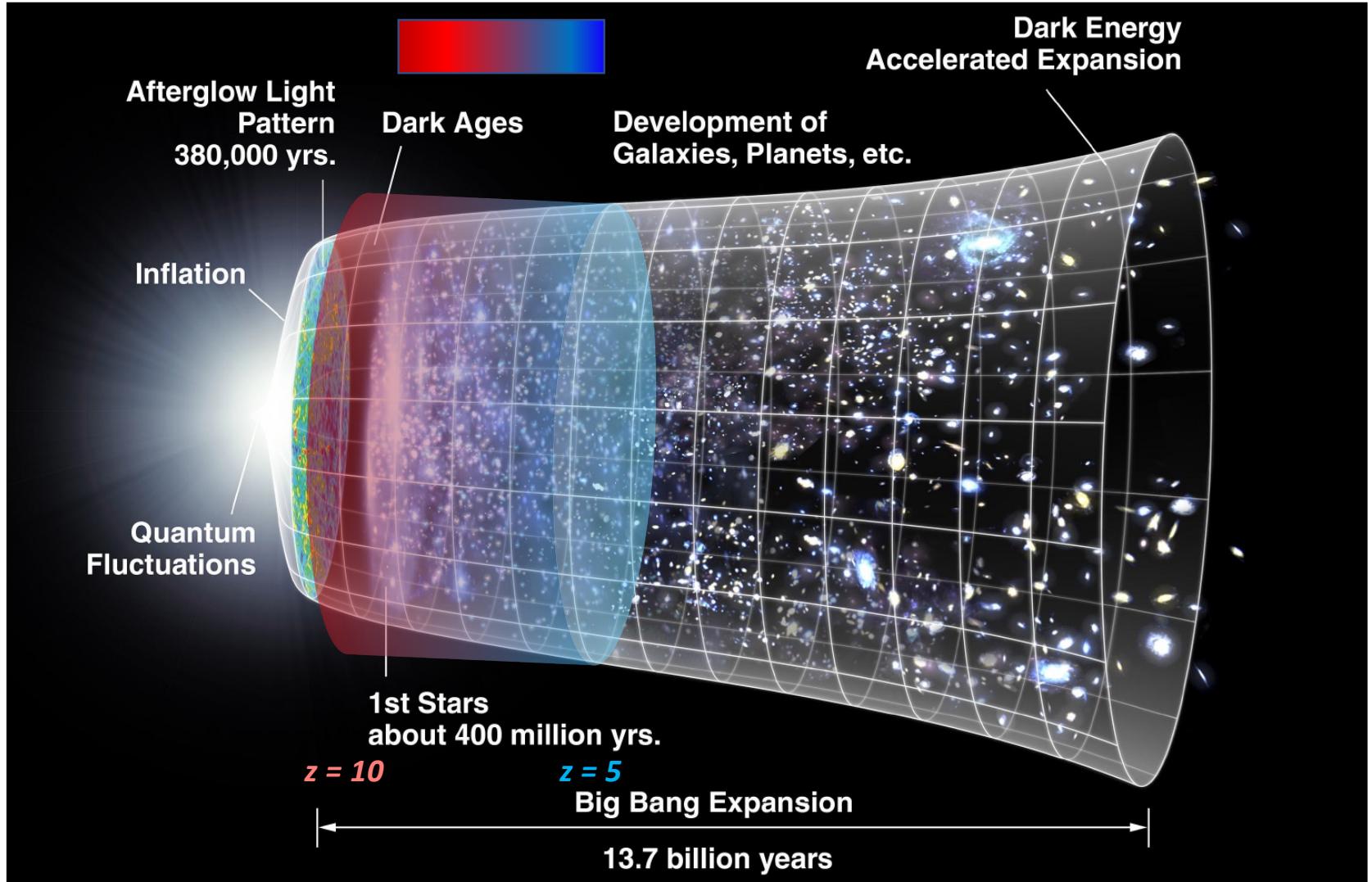
The Early Universe



Credit: NASA / WMAP Science Team,
denis.burgarella@lam.tr, IPhU Seminars, 8 April 2021

The Early Universe

... in between
the Dark Ages
and
the End of Reionization



Credit: NASA / WMAP Science Team,
denis.burgarella@lam.fr, IPhU Seminars, 8 April 2021

Outline of the Talk

- **Introduction**
 - Dust in the early Universe 🤔 ... Why?
- **The FIR + sub-mm Emission of High-z LBGs @ $5 < z < 10$**
 - *Introduction*
 - *Selection*
 - *Method*
 - *Results*
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- **The evolution of the relation stellar mass vs. dust attenuation with the redshift**
- **Conclusions**
- **NECO & IPhU**

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Dust in the early Universe 🤔... Why?

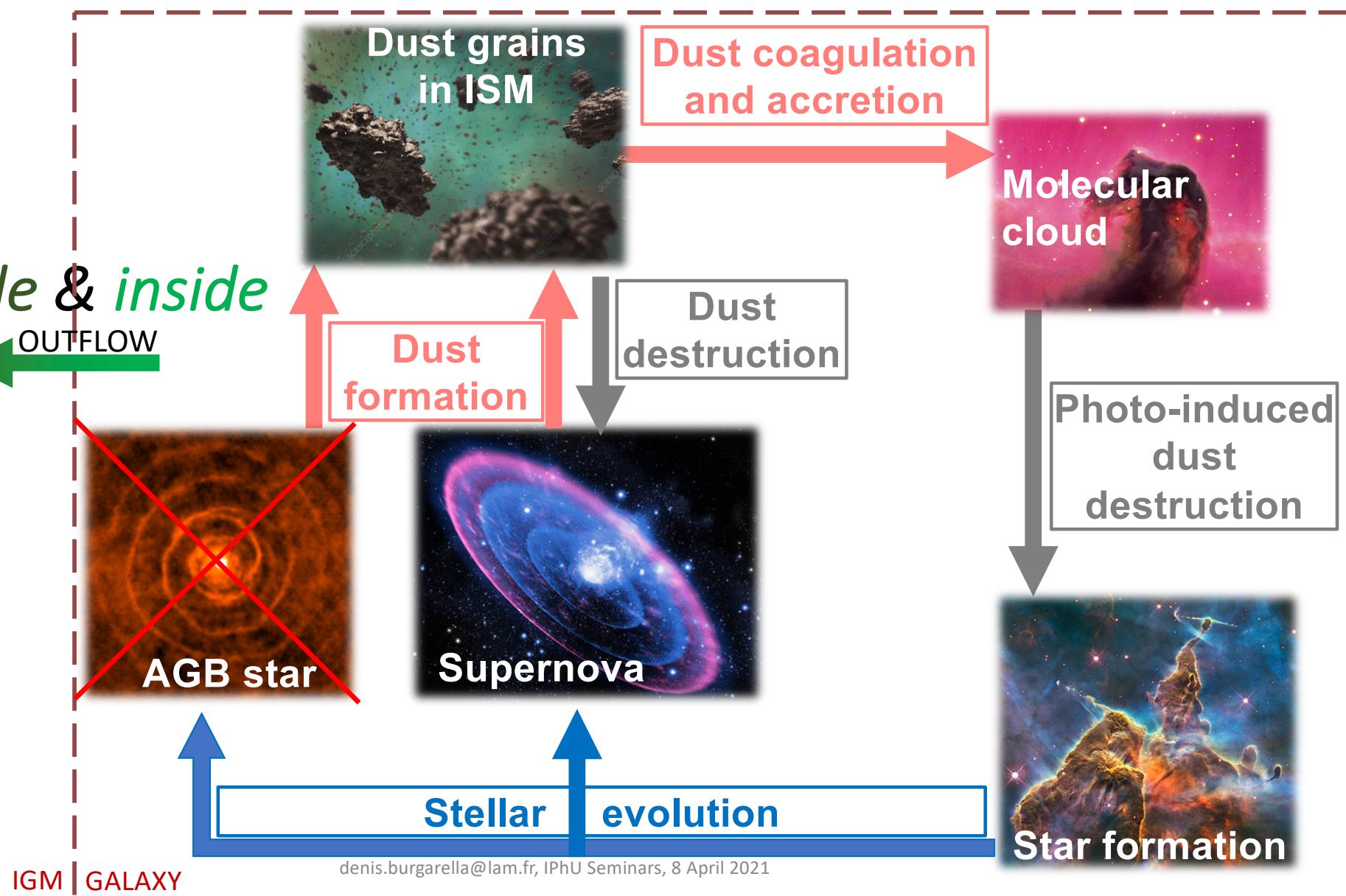
1. Understand the dust cycle in galaxies in the Epoch of Reionization and in the first galaxies.
 2. Understand the formation of the first low-mass stars.
 3. Follow the universe's star formation history to the first galaxie(s).
-
- **Keywords:** First Stars, First Dust Grains, First Galaxies

Dust in the early Universe 🤔... Why?

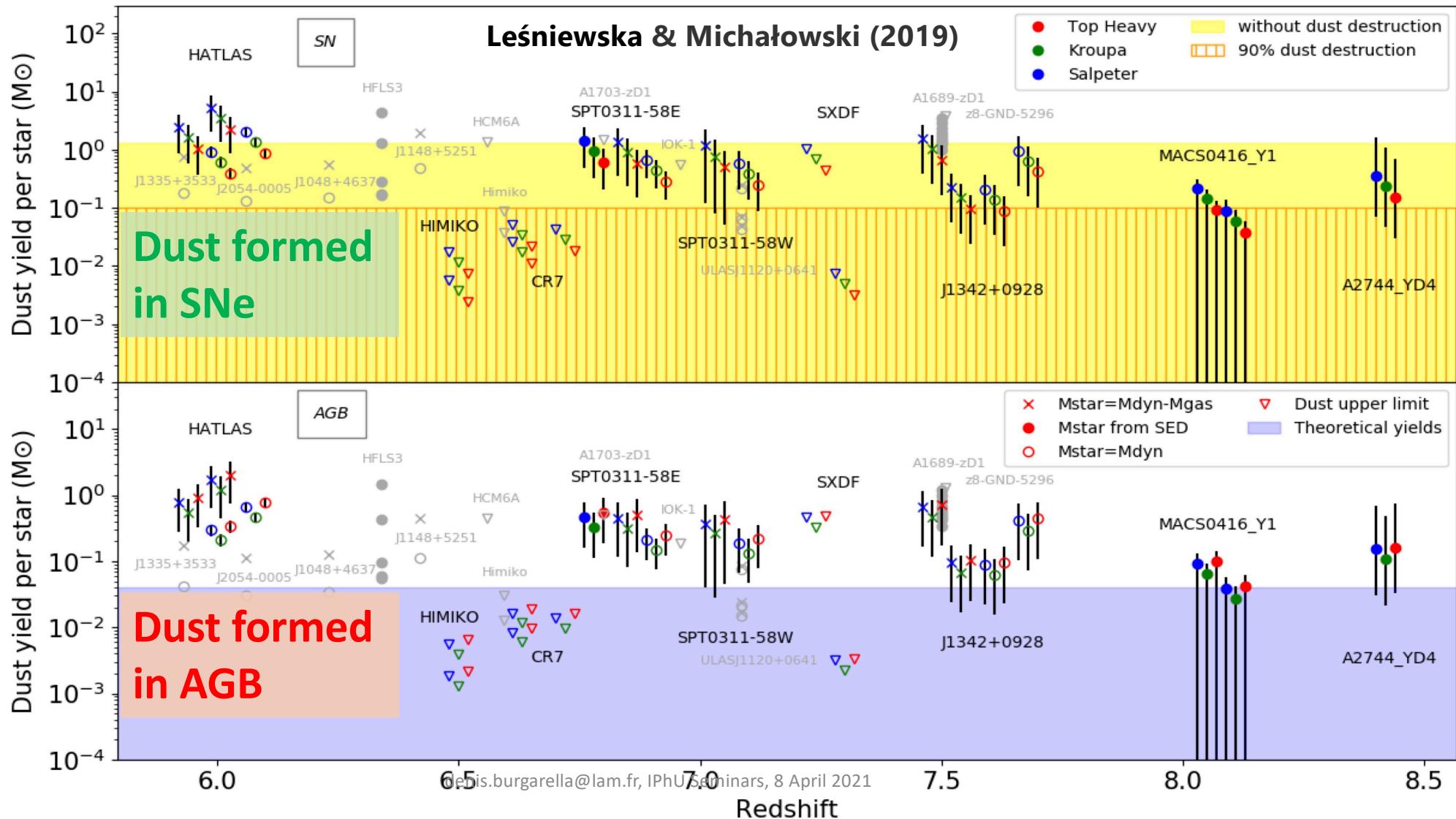
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The Life Cycle of Dust Grains

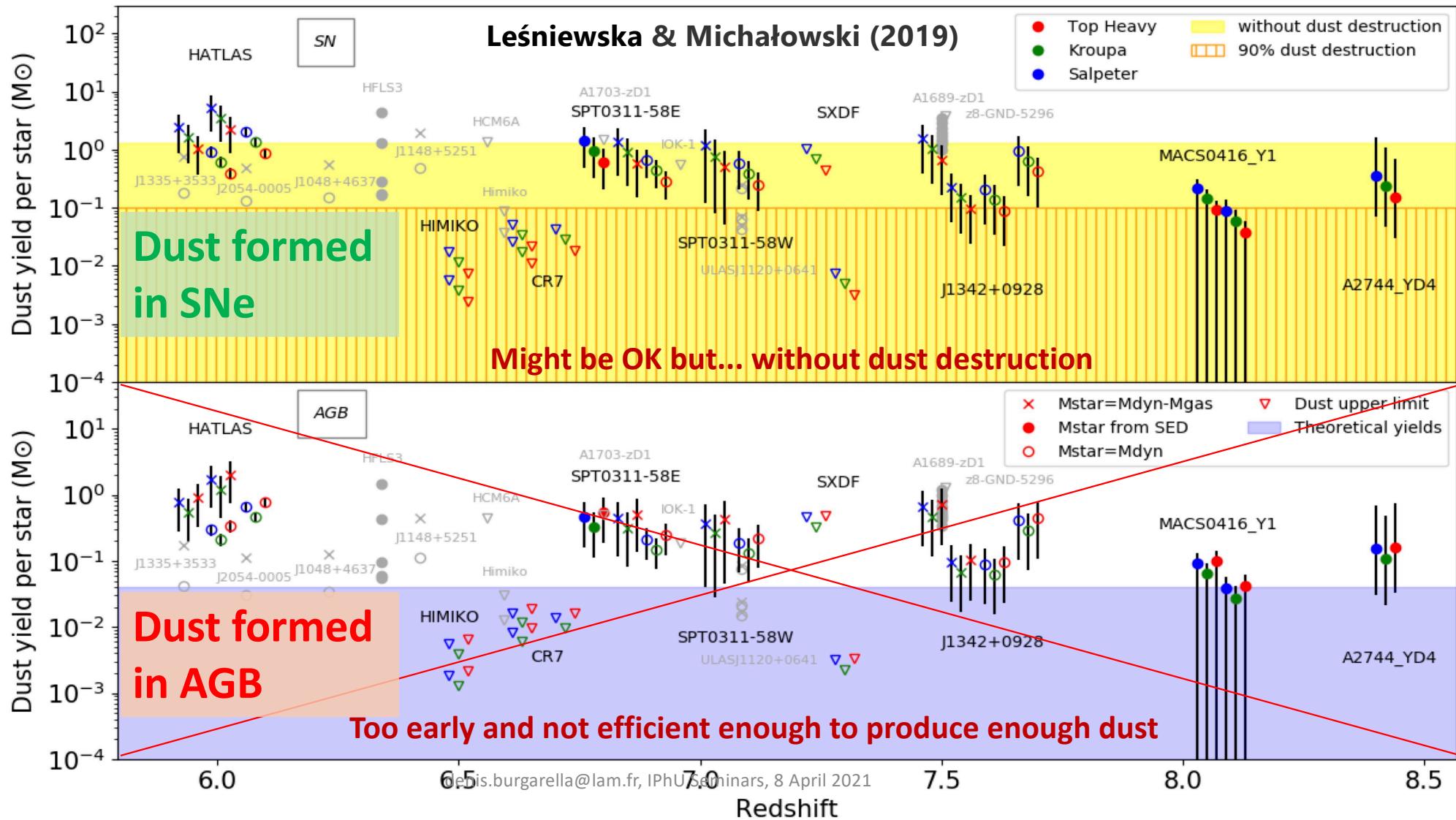
outside & inside
Galaxies



How to form so much dust in the early universe?



How to form so much dust in the early universe?

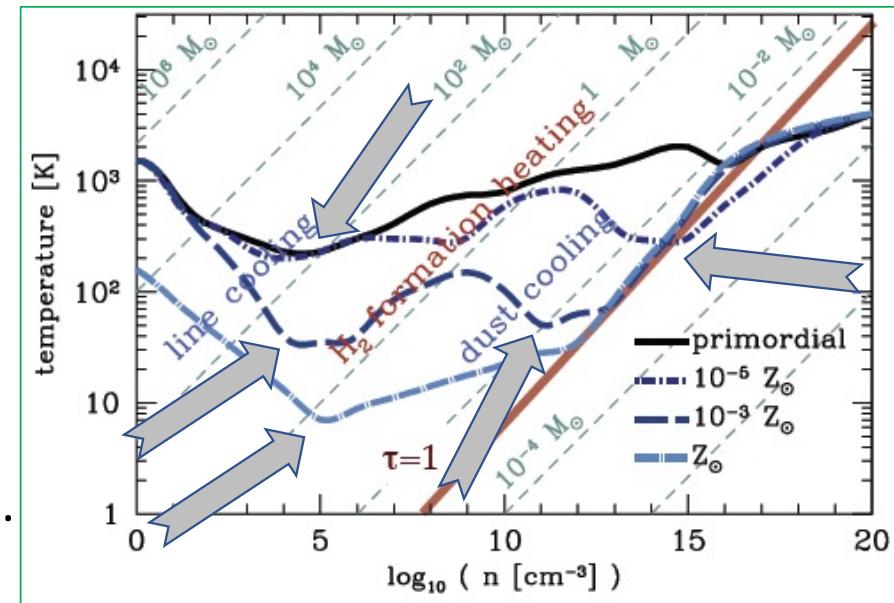


Dust in the early Universe 🤔... Why?

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Dust and star formation at very low metallicity

- When gas collapses to form stars, gravitational energy is transformed to thermal energy that can halt the collapse. Thermal energy needs to be dissipated by :
 - atomic fine structure line emission,
 - molecular rotational or vibrational line emission,
 - heating of dust grains.
- After pop. III stars become supernovae, they seed the cosmic gas with the first metals (time-scales < 50 Myr).
- A significant fraction (25 – 50%) of these heavy elements could be in the form of **dust grains** (Kozasa, Hasegawa & Nomoto 1989; Schneider, Ferrara & Salvaterra 2004).
- This has important implications for the formation of the first low-mass and long-lived stars.

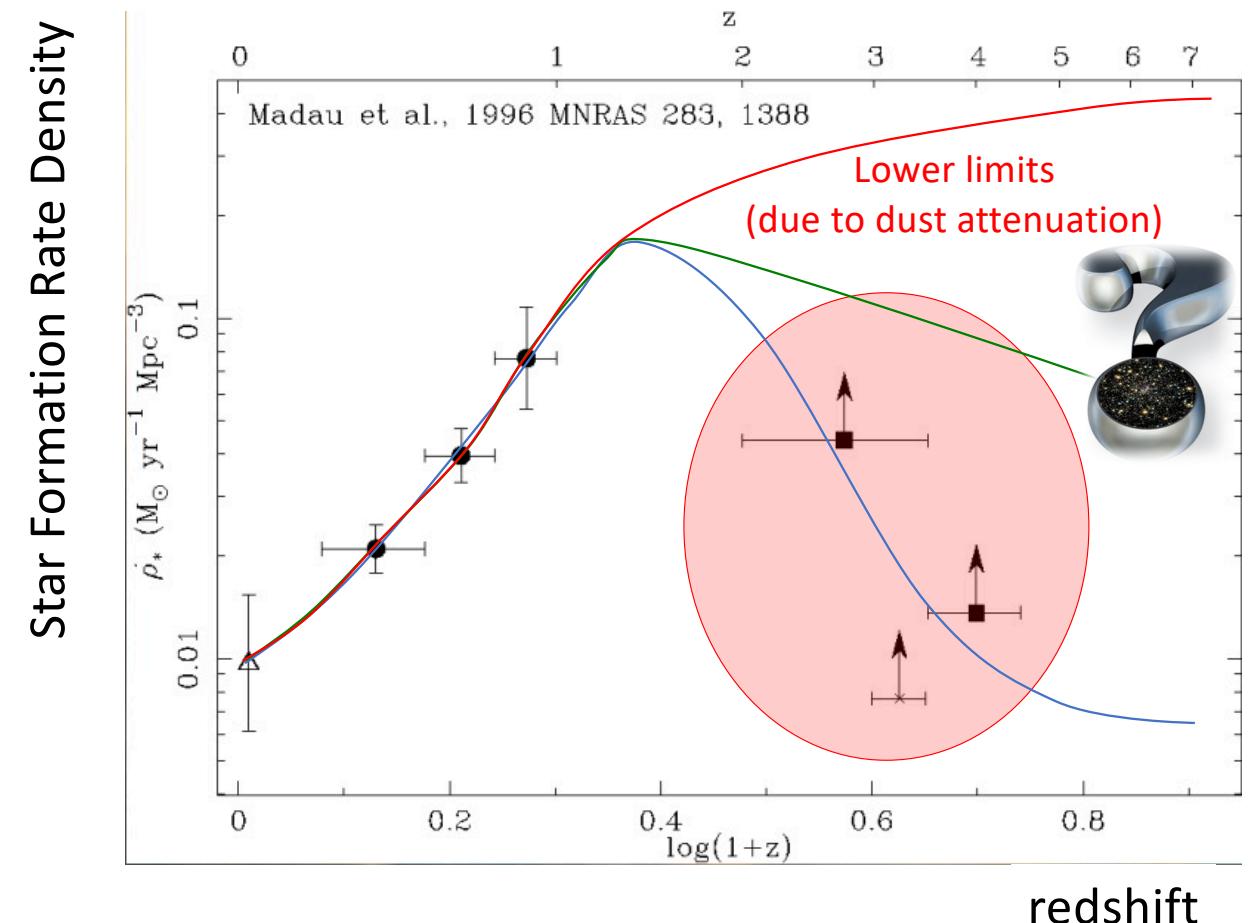


Dust in the early Universe 🤔... Why?

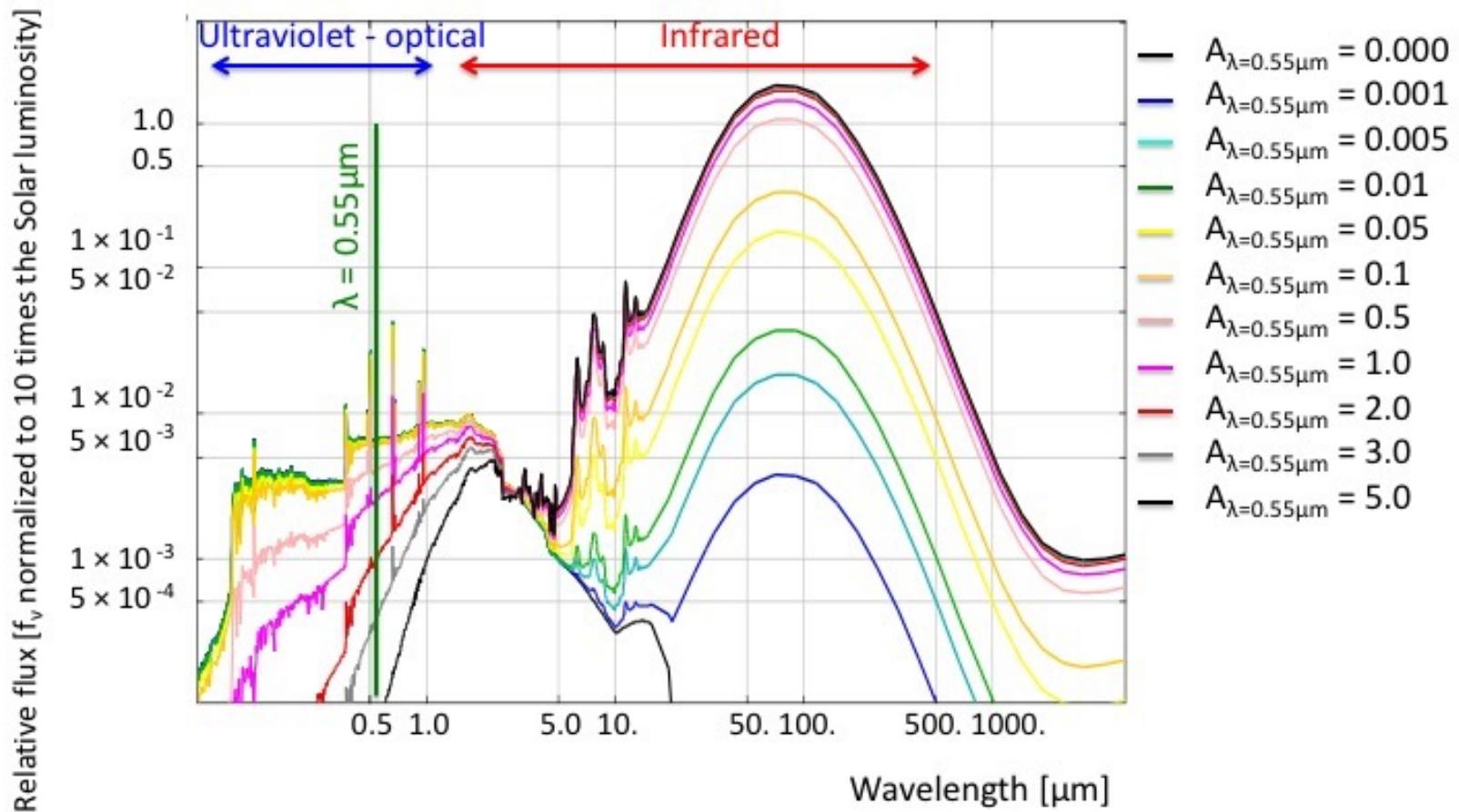
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Madau Plot (1996)

- Using results of the Canada-France Redshift Survey (CFRS: Lilly et al. 1995) over the redshift range $0 < z < 1$
- HST results from the Hubble Deep Field

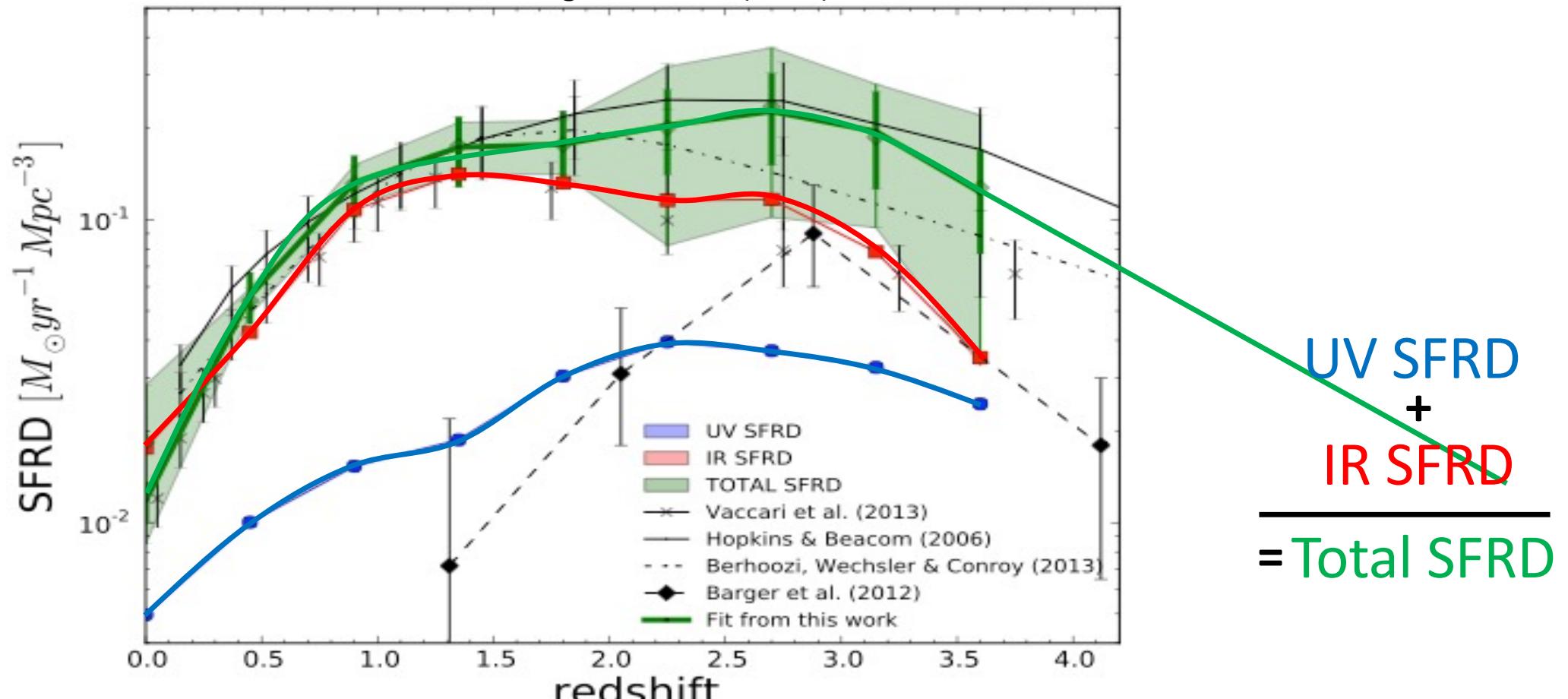


UV & IR



Estimating the Total Star Formation Rate Density (SFRD)

Burgarella et al. (2013) from VLT + Herschel



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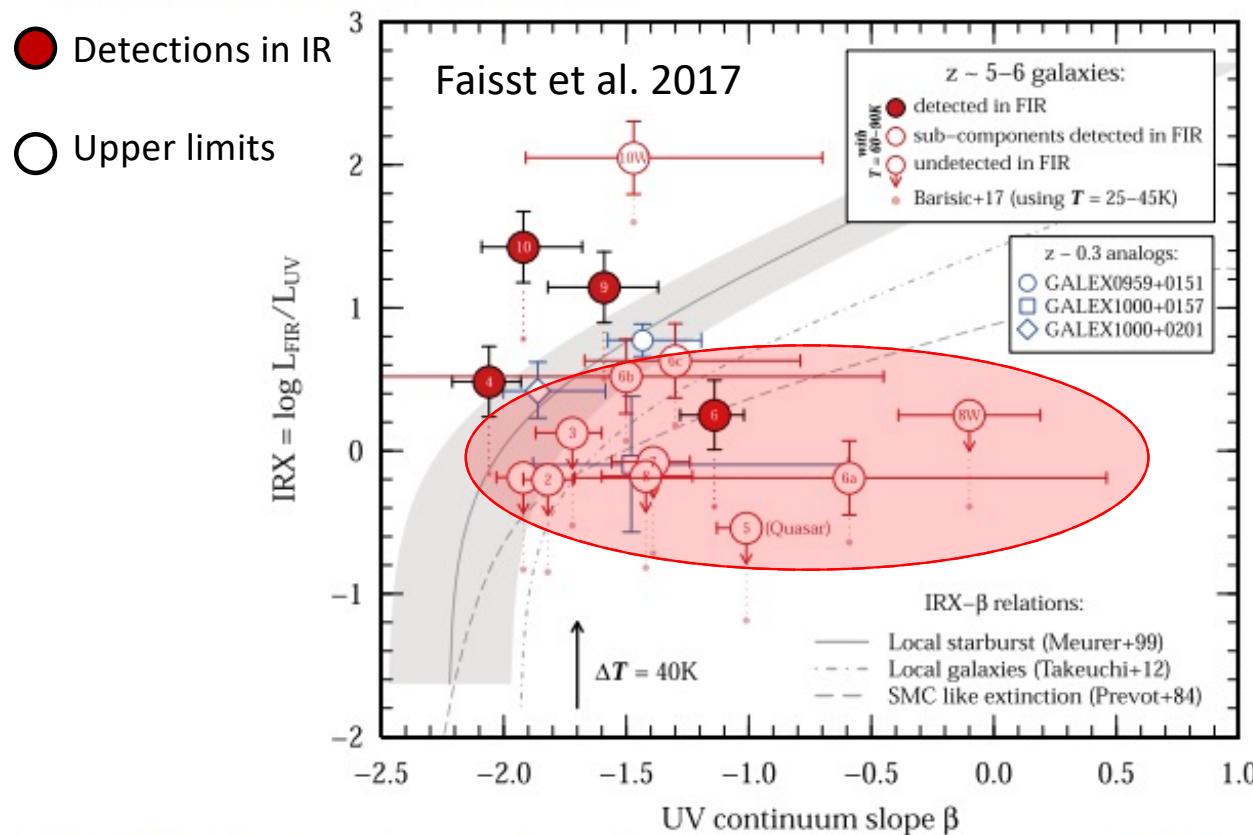


Figure 11. IRX- β diagram at $z \sim 5.5$ for a maximally warm IR SED prior with luminosity-weighted temperature $T = 60\text{--}90\text{ K}$ ($T_{\text{peak}} \sim 35\text{--}50\text{ K}$). We show the $z = 5\text{--}6$ galaxies from Barisic et al. (2017) with FIR detection (red filled circles) and without FIR detection (empty circles, upper limits), as well as the FIR-detected subcomponents as described in their paper (empty circles). The position of the galaxies with a cooler IR SED prior ($T = 25\text{--}45\text{ K}$, i.e., $T_{\text{peak}} \sim 18\text{--}28\text{ K}$) as assumed previously (e.g., Capak et al. 2015) is indicated by faint red dots. The arrow indicates the change in IRX for $\Delta T = 40\text{ K}$. Our three $z \sim 0.3$ analogues are shown in blue and are consistent with the location of the high-redshift galaxies. Common IRX- β relations for local starbursts (Meurer et al. 1999, with scatter; Takeuchi et al. 2012; and galaxies with SMC-like dust, Prevot et al. 1984; Pettini et al. 1998) are indicated by solid, dotted-dashed, and long-dashed gray lines, respectively. Note that the upper limits of the FIR-undetected $z = 5\text{--}6$ galaxies are mostly consistent with the IRX- β relation expected for SMC-like dust using the maximally warm IR SED prior. However, some galaxies still show a deficit in IRX compared to the SMC relation and cannot be explained by common analytical models of dust attenuations in galaxies (see Section 4.5).

- We do not understand the dust emission of high-redshift Lyman break galaxies (LBGs) at $z = 5\text{--}6$ (~ 1 billion year after Big Bang)

- Their dust attenuation is too low compared to what is expected from their UV slope β .

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Hi-z LBGs in EoR

- 18 Lyman Break galaxies (LBGs) with z_{spec}
- All have been observed in submm with ALMA
- Low- M_{star} and probably low- Z
- Simple galaxies (simple SFH)

Burgarella, Nanni et al.: First Dust Grains in Galaxies

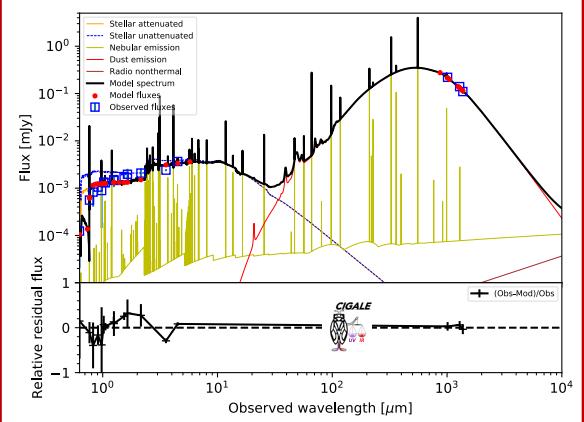
Source	Number of objects	Selection	redshift	Note
Bouwens et al. (2016)	3	UV	$5 \lesssim z \lesssim 10$	* ALMA 6 upper limits * $S/N_{HST} > 1.5$. * LBGs with > 5 data points in UV-optical only
Capak et al. (2015) & Faisst et al. (2017)	9 (HZ1 - HZ4 & HZ6 - HZ10)	UV	$z \sim 5.6$	* [CII]158 μ m for all Hi-z LBGs * ALMA 7 detections: HZ4, HZ6 (3) HZ9 & HZ10 (5) * ALMA 7 upper limits for the others * HZ5 detected in Chandra and not included in the sample * Additional data from Pavesi et al. (2016)
Scoville et al. (2016)	1 (566428)	UV	$z = 5.89$	* ALMA 6 detection * [CII]158 μ m measurement
Willott et al. (2015)	2 (CLM1 & WMH5)	UV	$z \sim 6.1$	* ALMA 6 detections * [CII]158 μ m measurement
Aravena et al. (2016)	2 (ID27, ID31)	UV	$z \sim 7.5$	* ALMA 6 detections * [CII]158 μ m measurement
Hashimoto et al. (2018)	1 (MACSJ01149)	UV	$z = 9.1$	* ALMA 7 upper limit * [OIII]88 μ m measurement

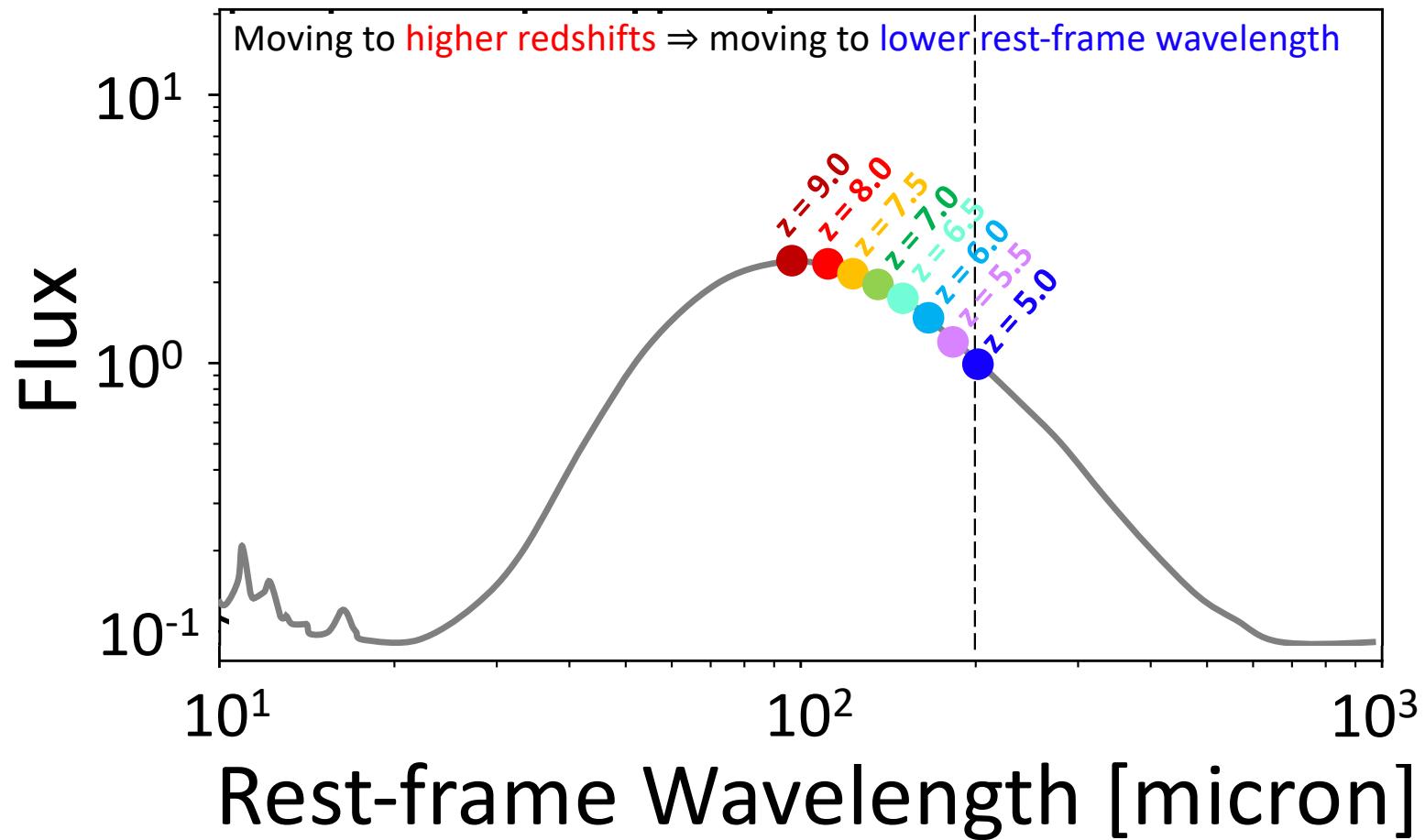
Table 1. Origins of data used in this paper. The Hi-z LBG sample contains 18 objects, while the Low-zZ sample contains 31 objects for which the final fits are adequate, i.e. $\chi^2_{\text{reduced}} \leq 5$. 9 Hi-z LBGs are detected in ALMA in Band 6 or Band 7, they provide 15 detected measurements, but only 11 measurements with $S/N_{\text{submm}} > 3$ are used to build the IR template.

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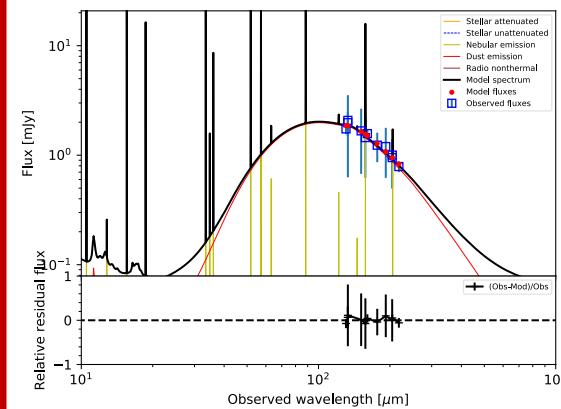
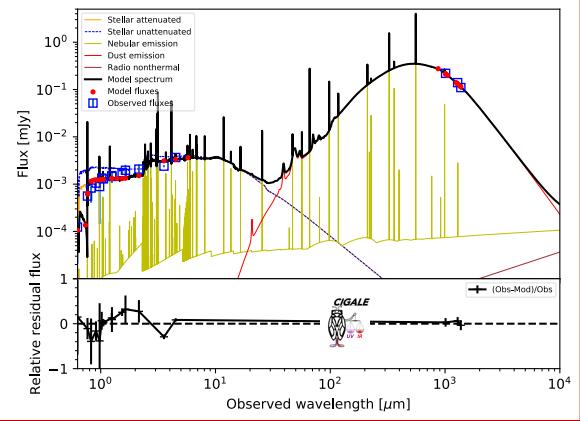
ALMA FIR-detected LBGs



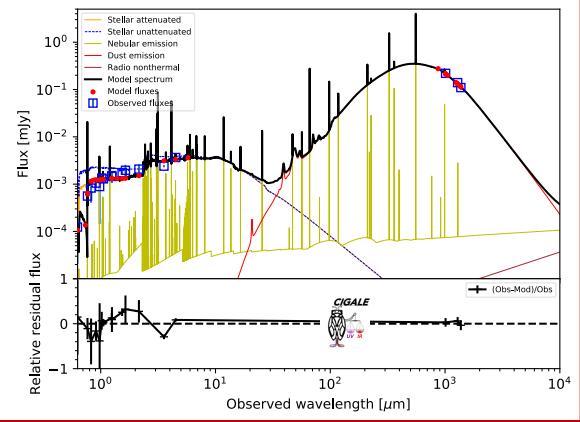


ALMA FIR-detected LBGs

IR template from
FIR-detected LBGs

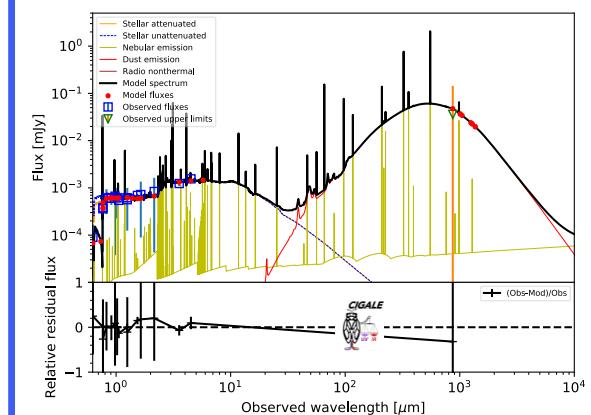
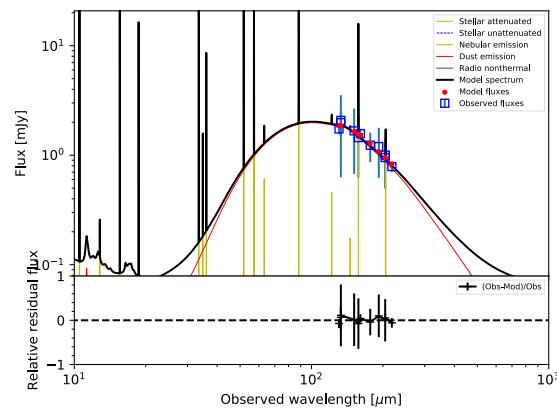


ALMA FIR-detected LBGs

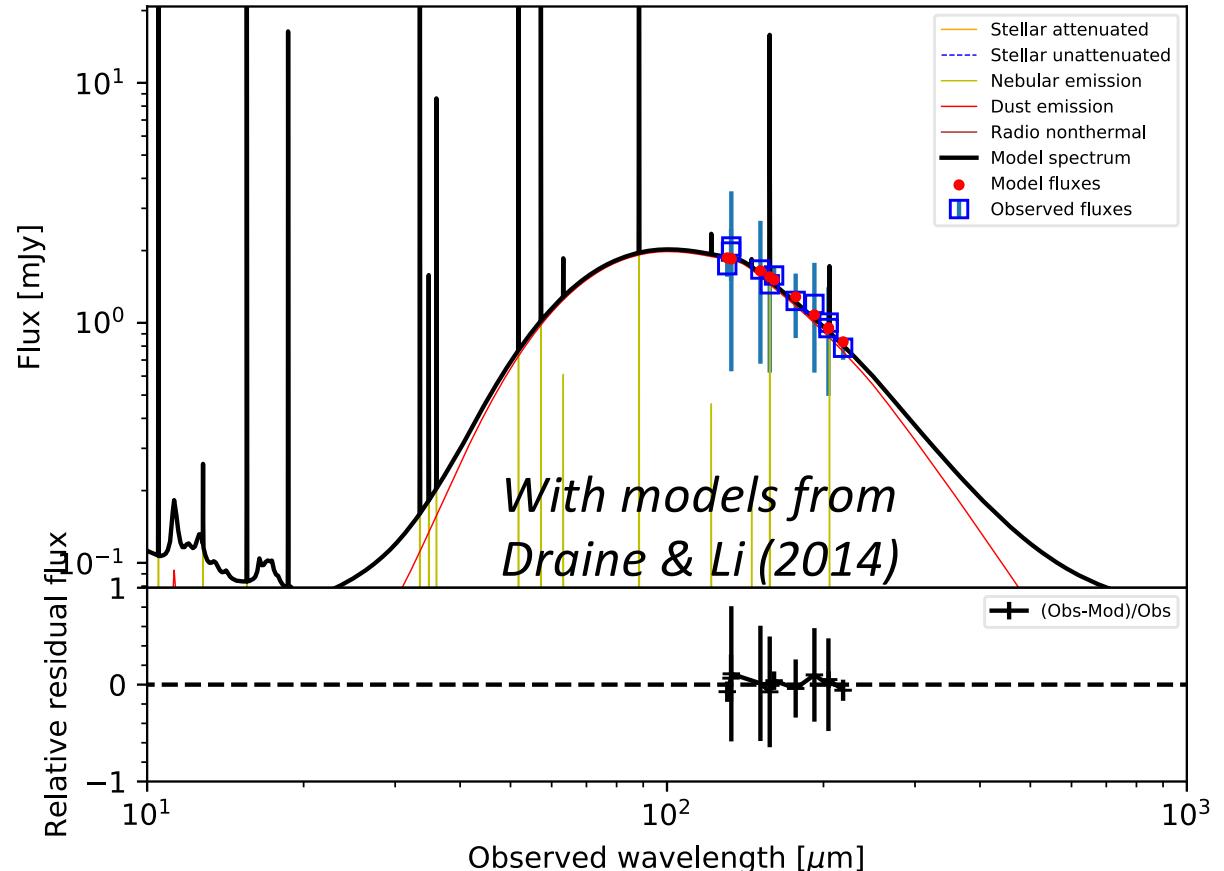


IR template from
FIR-detected LBGs

ALMA FIR-undetected LBGs



- We densify the IR SED
- We fit all LBG SEDs using this template
- We tried both with modified blackbodies and Draine & Li models in CIGALE. We used Draine & Li.
- $SFR(t) = t/\tau^2 e^{-t/\tau}$ with short $\tau \sim 100$ Myrs



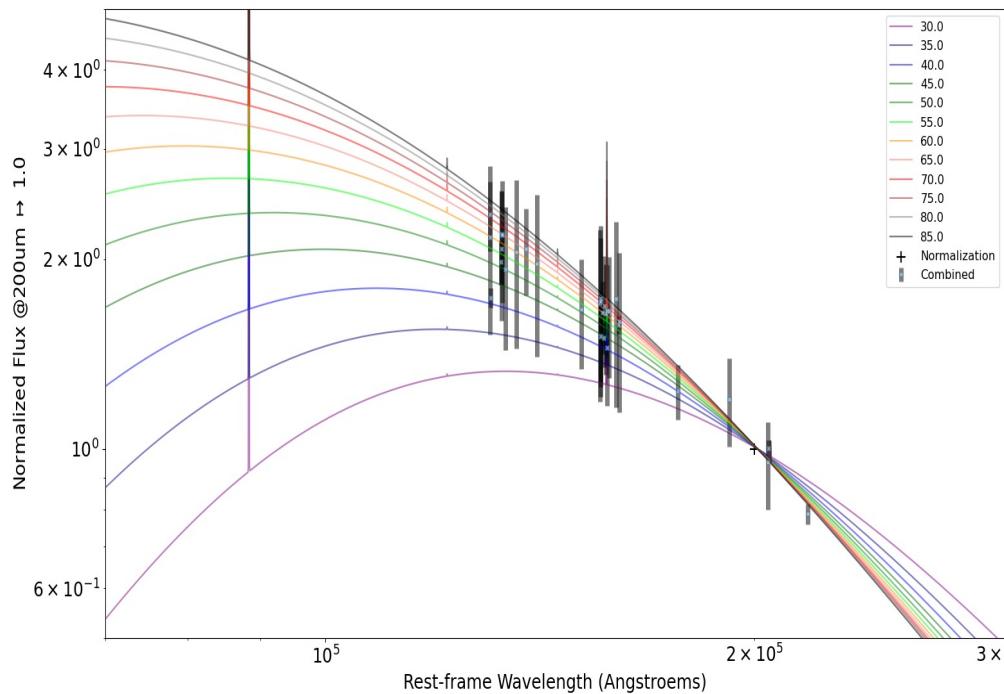
Hi-z LBGs

id	M_{\odot}	M_{\odot}	L_{\odot}	L_{IR}	$\log L_{\text{IR}} \text{ err}$	$M_{\odot} \text{ yr}^{-1}$	$SFR \text{ err}$	A_{FUV}	$A_{\text{FUV}} \text{ err}$	Myr	Age	Age err
	$\log M_{\text{star}}$	r				SFR						
HZ1	10,32	0,04	6,77	0,26	10,20	0,26	6,06	0,84	0,1	0,1	231,5	11,2
HZ2	10,10	0,08	6,85	0,22	10,28	0,22	9,03	3,91	0,1	0,1	212,7	55,8
HZ3	10,15	0,04	6,99	0,24	10,42	0,24	5,51	1,13	0,2	0,1	216,9	14,1
HZ4	9,98	0,08	7,92	0,10	11,35	0,10	29,94	7,25	0,6	0,1	138,6	61,6
HZ6	10,50	0,04	8,10	0,02	11,54	0,02	29,13	2,15	0,7	0,0	172,6	8,4
HZ7	10,13	0,04	6,82	0,25	10,25	0,25	6,67	0,89	0,1	0,1	204,2	10,3
HZ8	10,13	0,04	6,72	0,26	10,15	0,26	7,94	0,86	0,1	0,1	195,2	9,3
566428	10,15	0,06	7,75	0,24	11,18	0,24	14,70	8,25	0,6	0,4	177,0	36,1
HZ9	10,04	0,11	8,36	0,05	11,79	0,05	56,65	10,21	1,8	0,1	191,7	93,8
HZ10	10,25	0,13	8,80	0,04	12,24	0,04	142,74	26,33	2,5	0,1	99,4	49,6
CLM1	10,41	0,05	6,62	0,22	10,06	0,22	9,82	1,44	0,0	0,0	217,8	14,2
WMH5	10,38	0,08	8,27	0,06	11,70	0,05	35,96	9,75	1,2	0,1	169,7	57,5
A1689z1	10,08	0,16	8,68	0,05	12,11	0,05	124,38	20,96	2,0	0,2	95,1	56,8
ID27	8,91	0,28	7,26	0,19	10,69	0,19	10,18	3,23	0,6	0,3	109,3	107,5
ID31	8,73	0,34	7,33	0,17	10,76	0,17	16,26	4,40	0,5	0,2	49,8	76,6
MACSJ1149	10,03	0,09	6,25	0,28	11,72	0,14	16,85	10,25	0,0	0,0	178,3	39,5

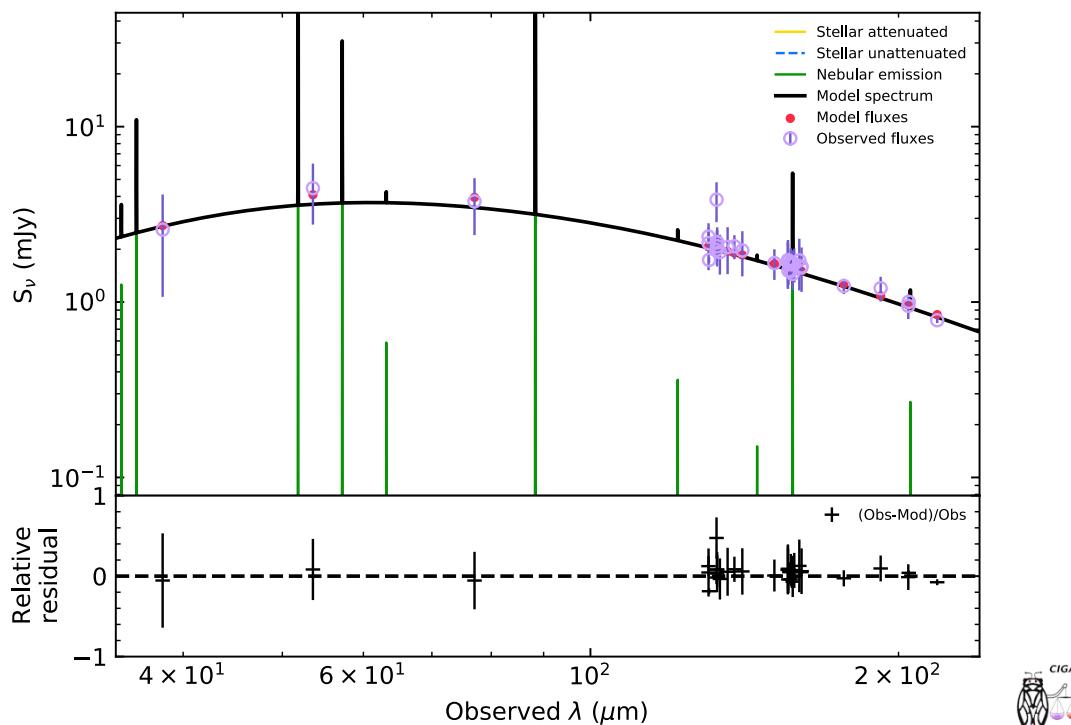
We estimate: $\text{sSFR} = \text{SFR} / M_{\text{STAR}}$, $\text{sM}_{\text{DUST}} = M_{\text{DUST}} / M_{\text{STAR}}$ and Age

Update with respect to Burgarella et al. (2020): we add the ALPINE sample (Béthermin et al. 2020)

- Burgarella et al. 2020
- **ALPINE detected sample**



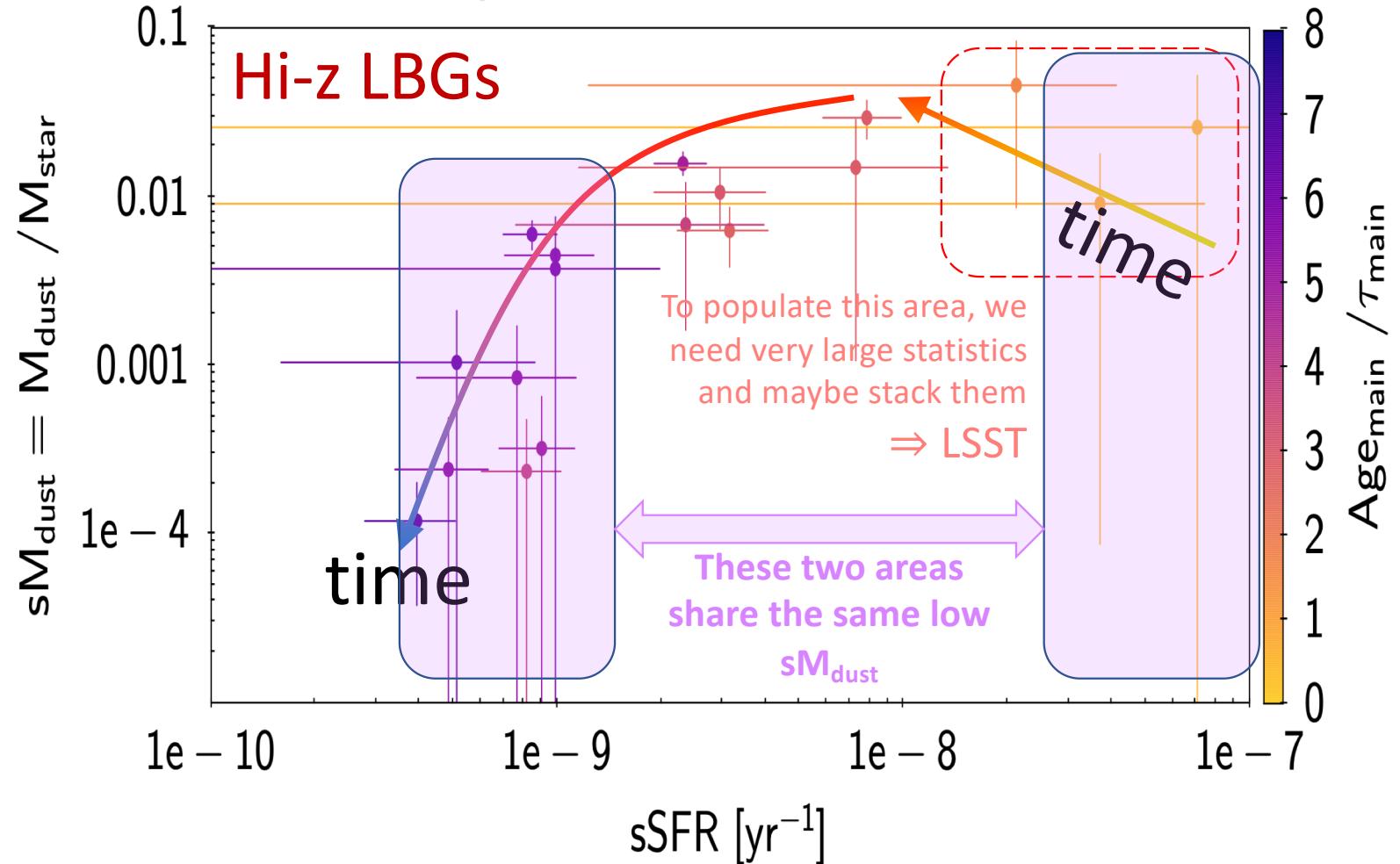
- Burgarella et al. 2020
- Stacking galaxies at $5.5 < z < 5.9$
- **ALPINE detected sample**



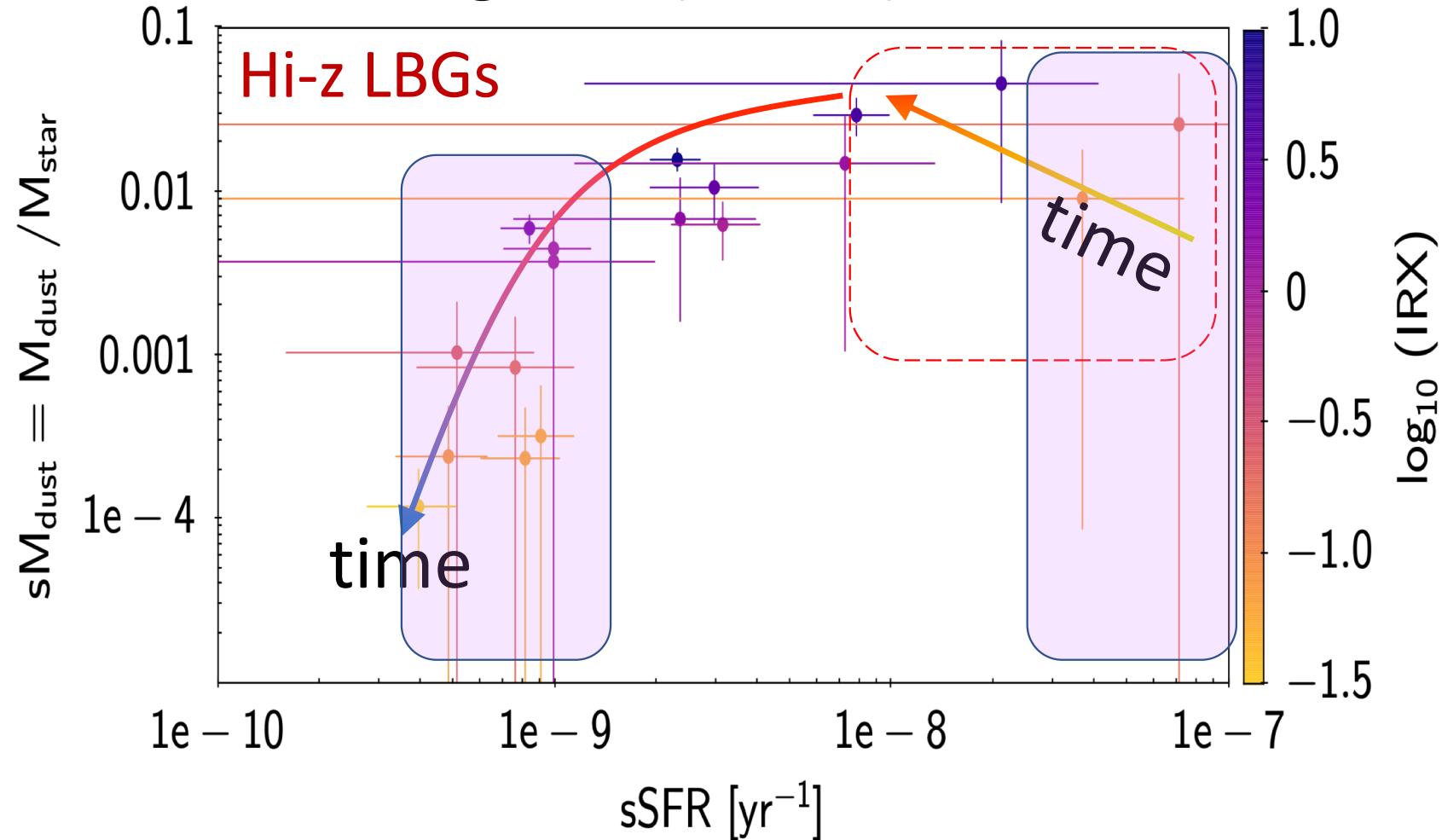
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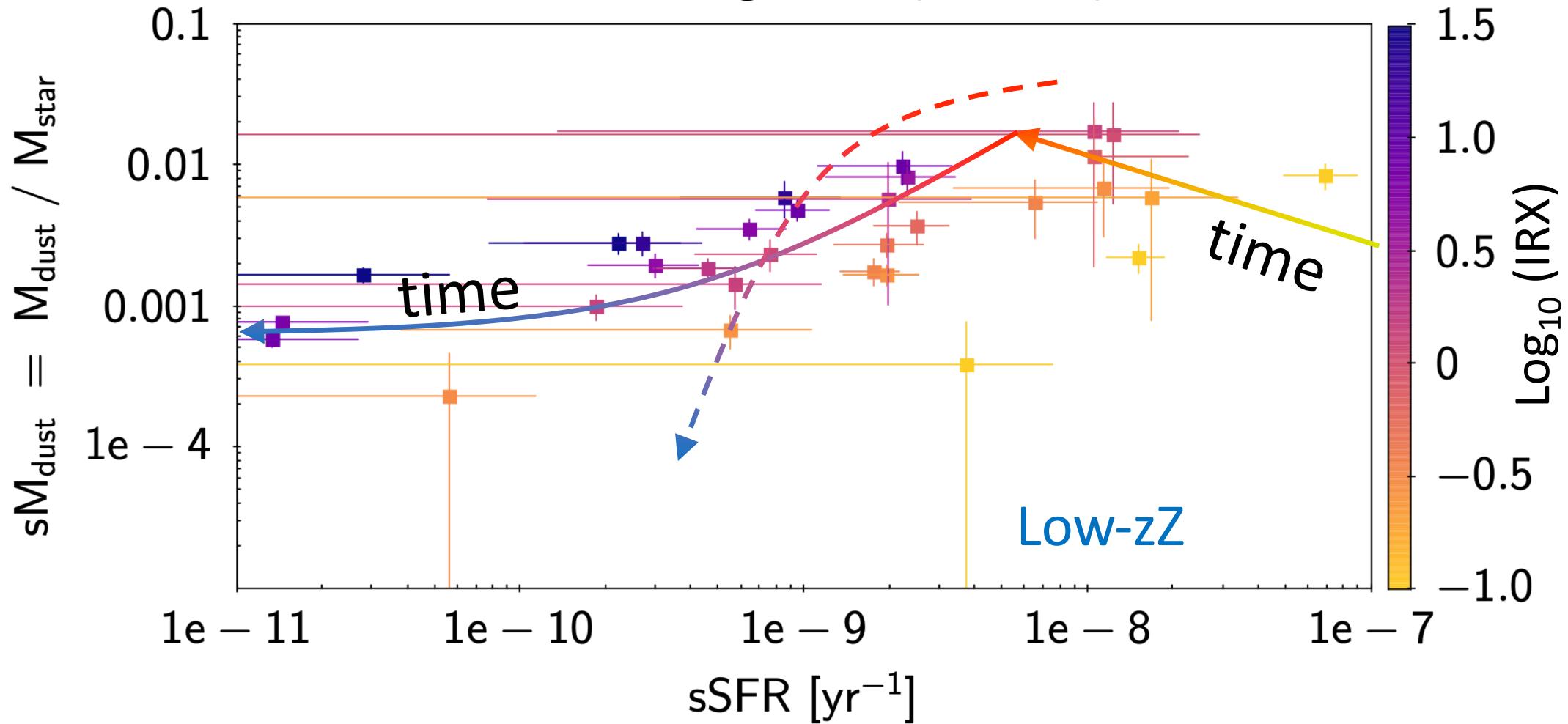
Dust Formation Rate Diagram (DFRD)



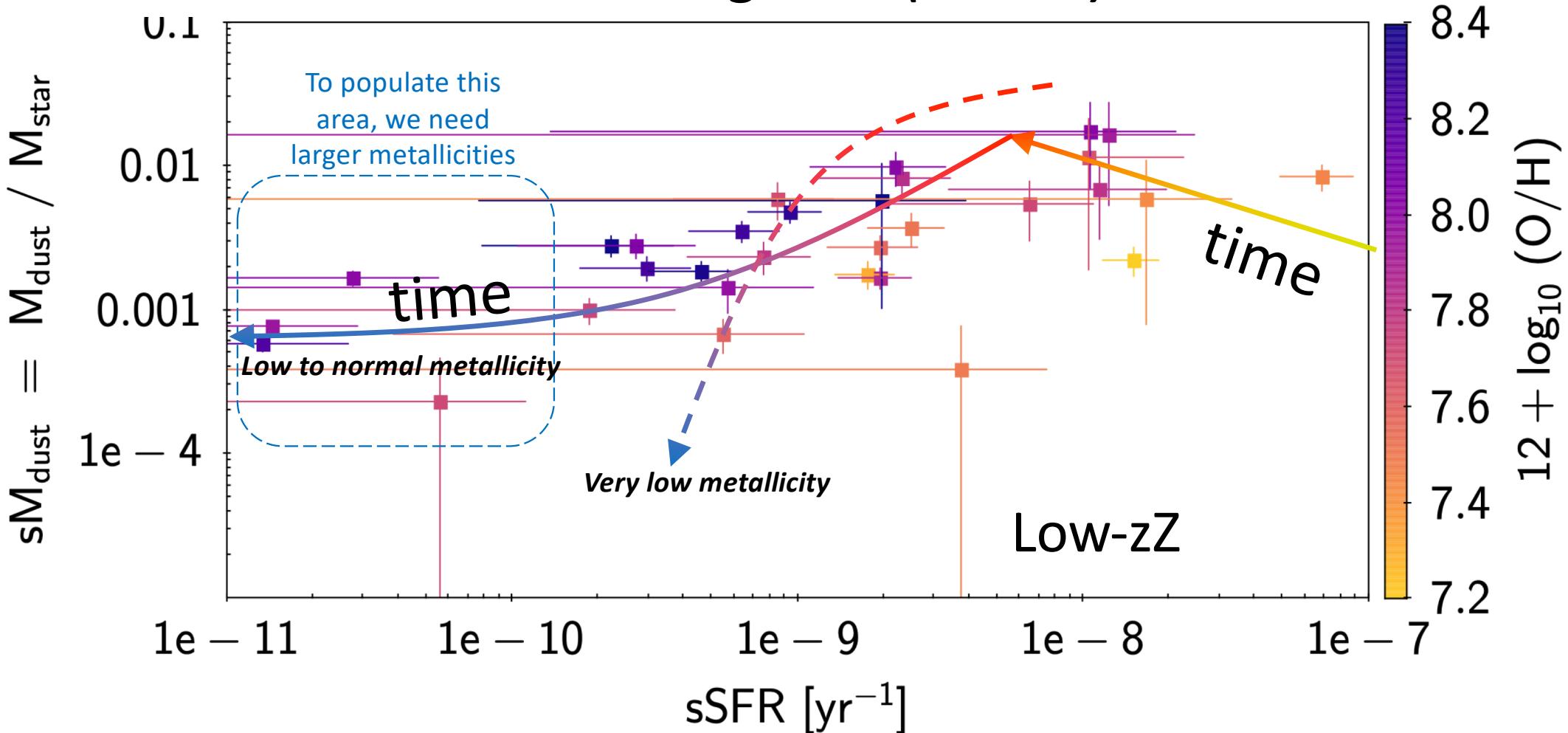
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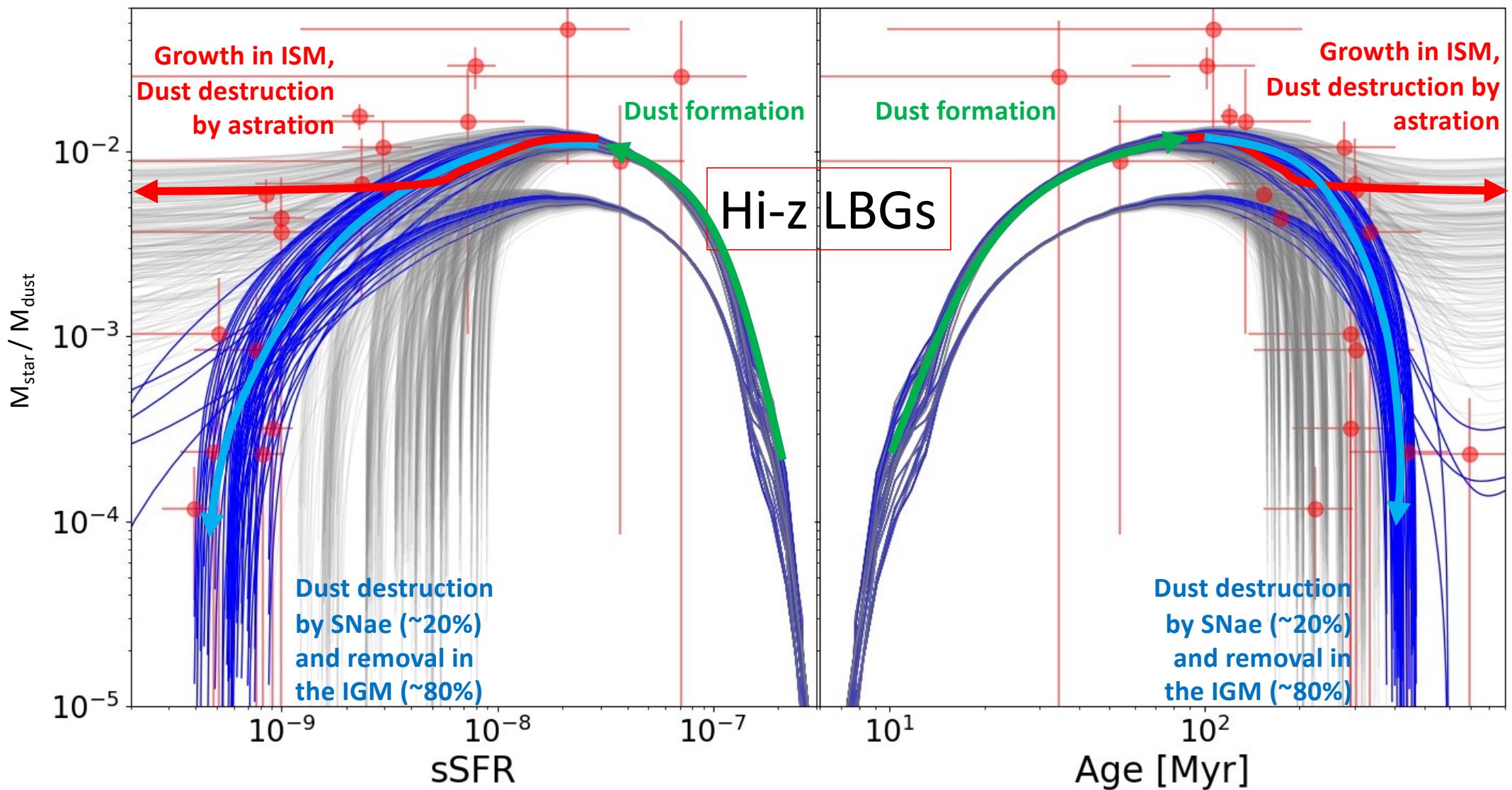


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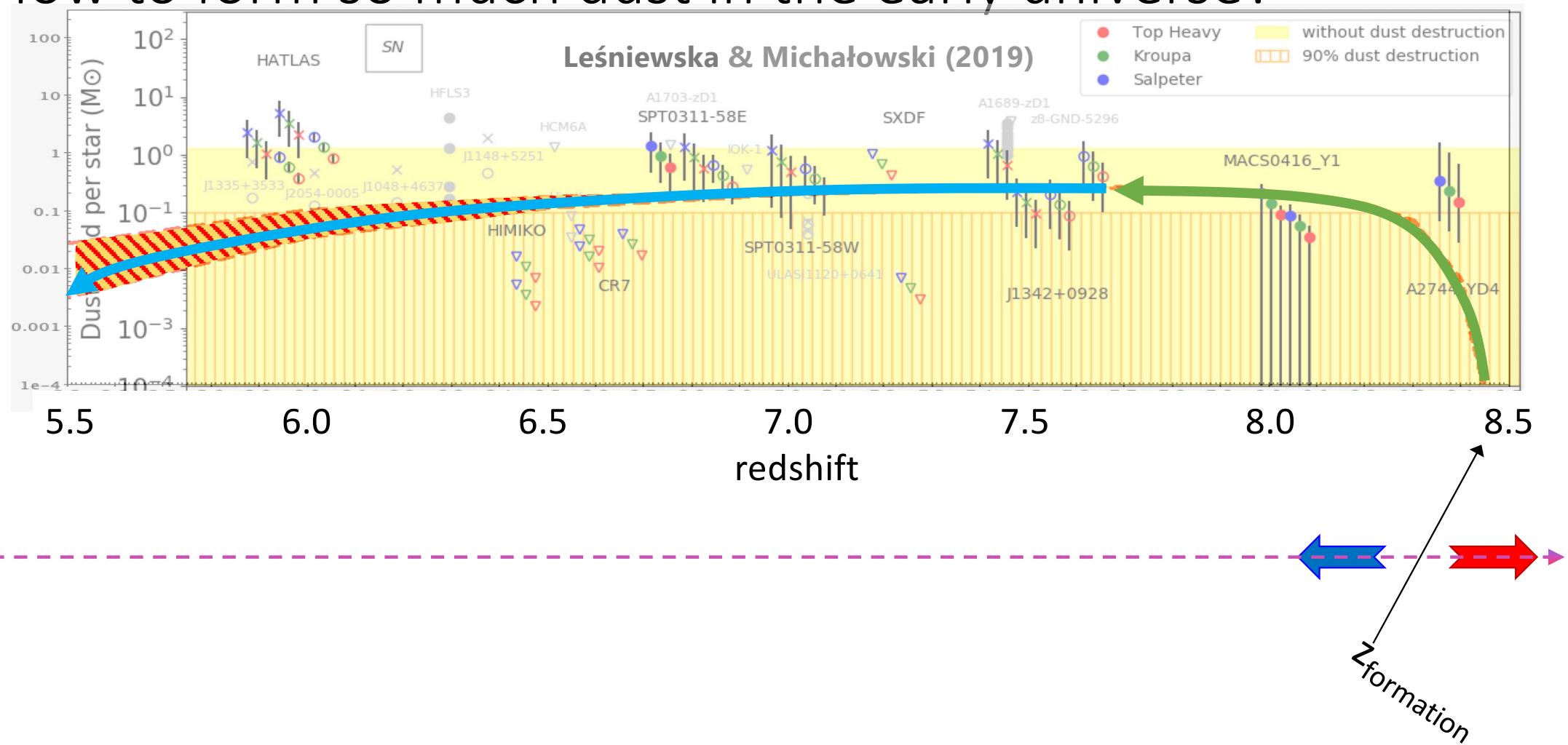


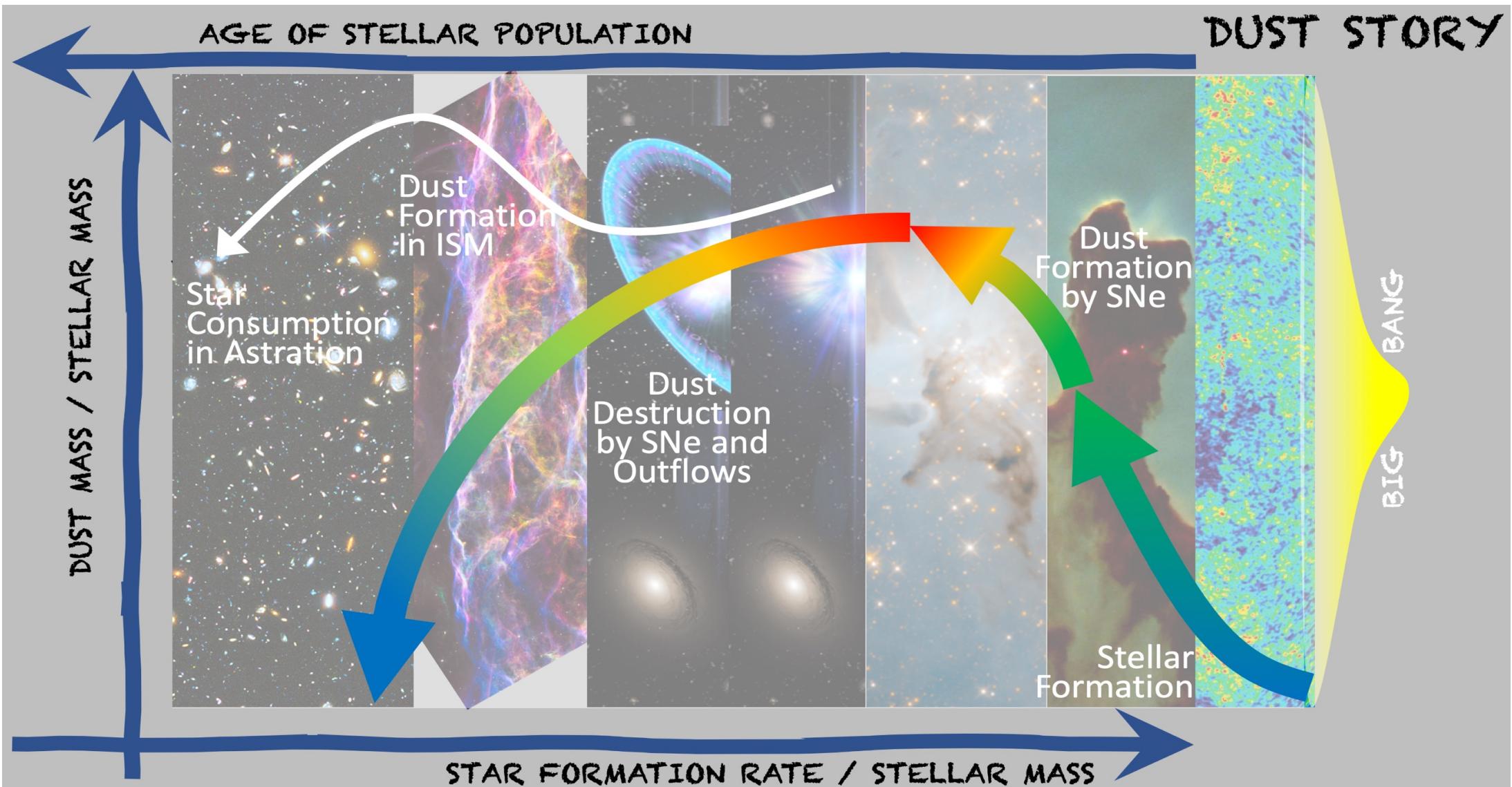
Dust Formation Rate Diagram (DFRD)





How to form so much dust in the early universe?

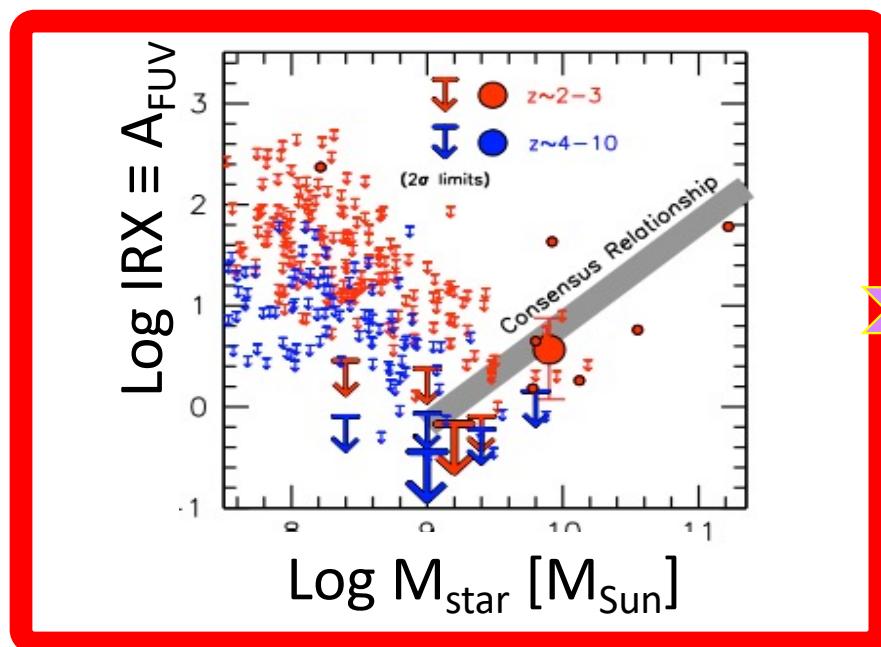




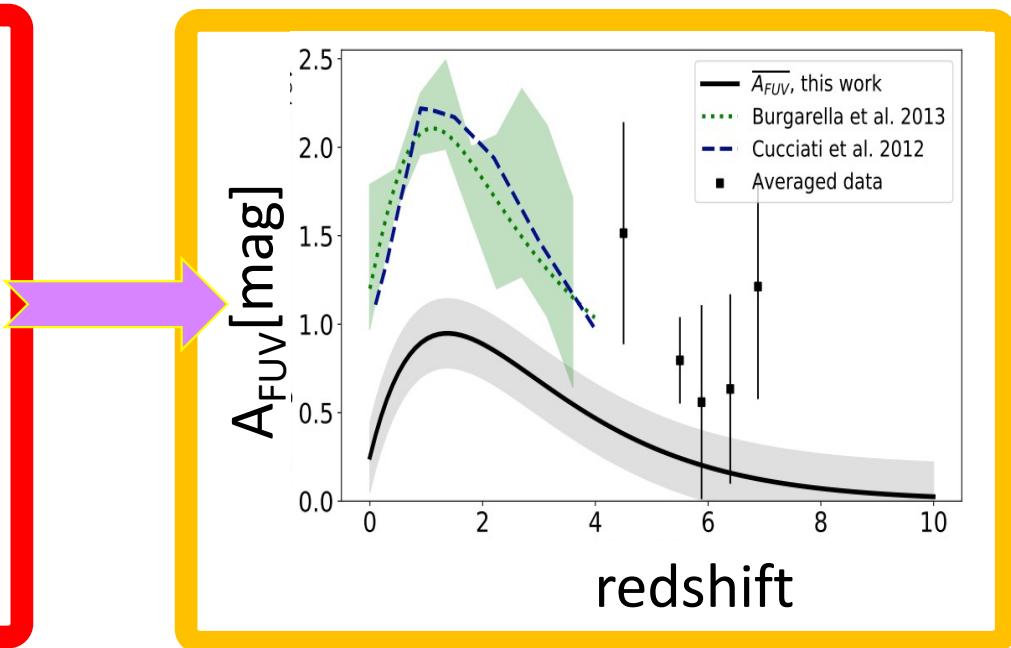
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The evolution of the relation stellar mass vs. dust attenuation with the redshift

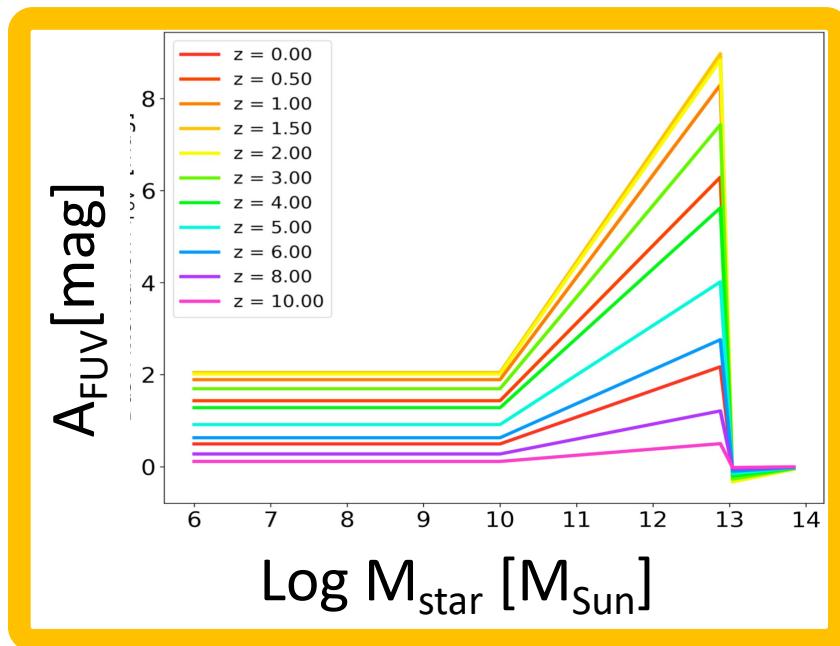


Bouwens et al. (2016)

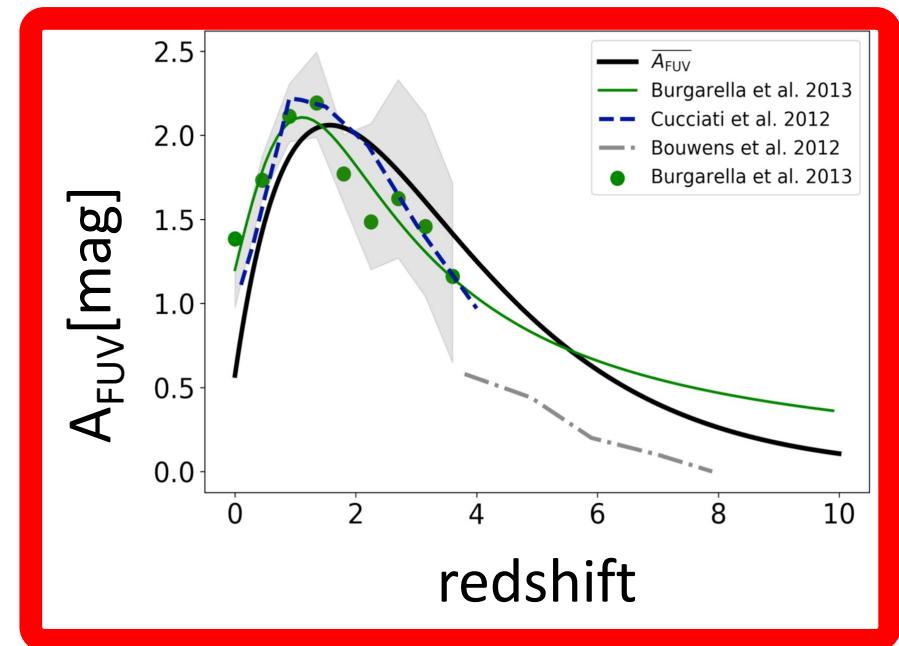


Burgarella & Bogdanoska (2020)

The evolution of the relation stellar mass vs. dust attenuation with the redshift

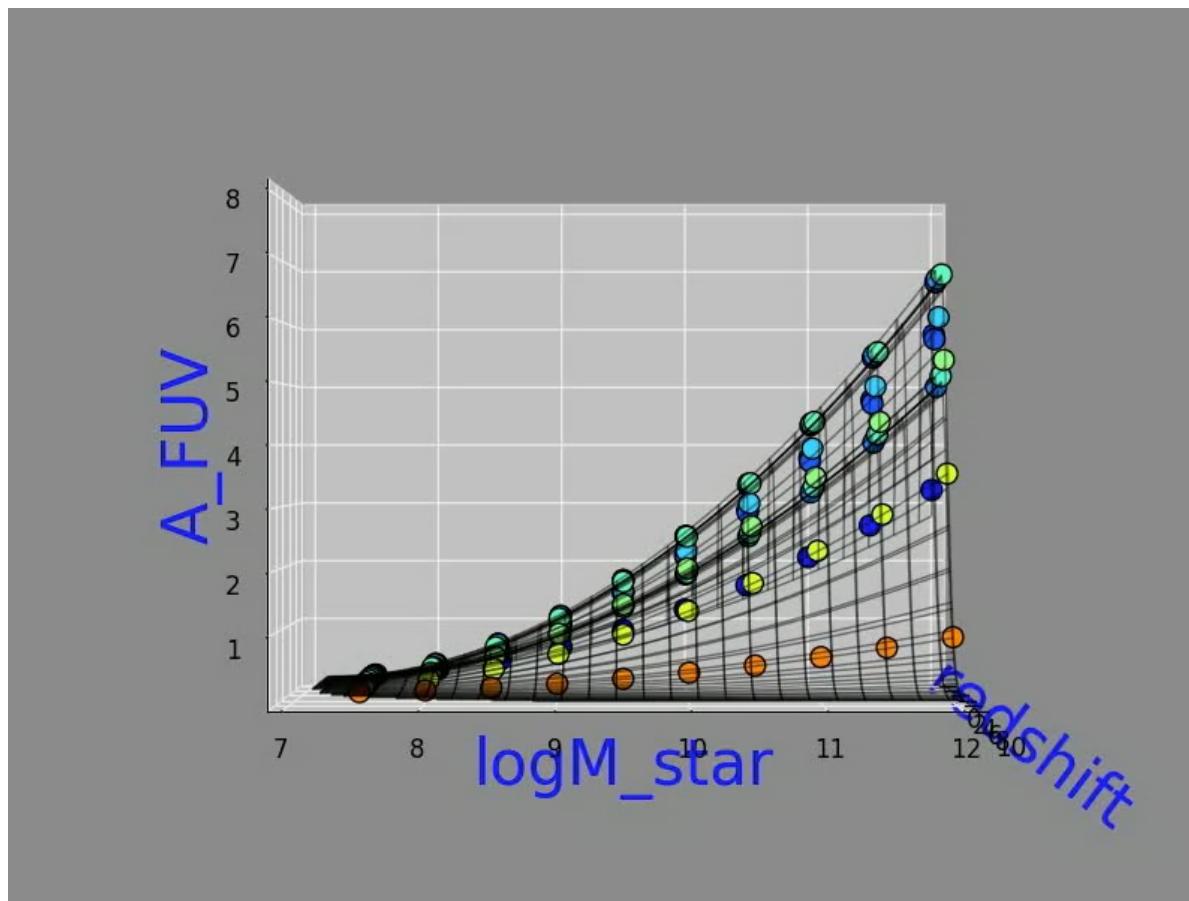


Burgarella & Bogdanoska (2020)



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Conclusions and perspectives

- We have constrained the **very first phases of dust formation and destruction / removal in the universe** and probably the first dust grains formed in the universe.
- We developed a model consistent with UV and IR observations that assumes **no grain growth in the ISM**.
- This model **should be implemented in galaxy evolution models** to provide a better agreement with observations.
- We showed that the M_{star} vs A_{FUV} relation evolves in redshift.
- More information from JWST (approved CEERS and Cycle 1) + ALMA/NOEMA data (?)
- More modelling...

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- **NECO & IPhu**

Final note: CNRS International Research Network for Extragalactic astrophysics and Cosmology (NECO)

<https://collaborations.lam.fr/neco/>

Date	Name	Jp/F?	Short title
24 April 2020	BUAT, Veronique	■ ■	X-CIGALE
24 April 2020	BURGARELLA, Denis	■ ■	First dust grains at $5 < z < 10$
18 May 2020	COX, Pierre	■ ■	IRAM/NOEMA Large Program z-GAL
18 May 2020	TAKEUCHI, Tsutomu T.	■ ■	New SED model (chemical evolution + non-linear dust)
18 Jun 2020	OSATO, Ken	■ ■ / ■ ■	Perturbation theory challenge for Cosmology
18 Jun 2020	BARRET, Didier	■ ■	Athena X-IFU (current status)
22 July 2020	BAKX, Tom	■ ■	[CII] and warm dust in an LBG at $z = 8.31$
22 July 2020	YAMADA, Toru	■ ■	Deep Variability Survey by Subaru HSV
23 September 2020	BOGDANOSKA, Jana	■ ■	UV dust attenuation as a function of stellar mass and its evolution with redshift
23 September 2020	ZHOU, Yu	■ ■	Can Warm-hot IGM Account for the Spatial Fluctuation of the Soft Diffuse X-ray Background?
17 November 2020	DMYTRIEV, Anton	■ ■	Connecting steady emission and Very High Energy flaring states in blazars: the case of Mrk 421
17 November 2020	SAGA, Shohei	■ ■ / ■ ■	Relativistic effects on redshift-space distortions at quasi-linear scales
29 January 2021	MARIN, Frederic	■ ■	Probing Active Galactic Nuclei with X and gamma-ray polarimetry
29 January 2021	SUZUKI, Tomoko	■ ■	Dust, gas, and metal content in star-forming galaxies at $z=3.3$ revealed with ALMA and NIR spectroscopy
29 March 2021	INOUE, Akio	■ ■	Exploring the galaxy formation at $z>10$: Recent progresses and a future direction
29 March 2021	OI, Nagisa	■ ■	Dependence of AGN fraction for AKARI NEPW galaxies on redshift and infrared luminosity

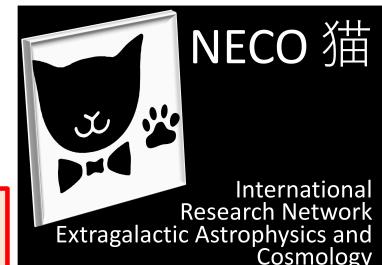
NECO teletalk #9: Late April 2021, France: 10h00 / Japan: 17h00

1) Jonathan Béteau, Paris-Saclay University, IJCLab, France: "Stellar Mass and Star Formation Rate within a Billion Light-Years"

2) Yusei KOYAMA, SUBARU Telescope, Japan: "Panoramic H-alpha views of early stages of galaxy cluster formation with Subaru"

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**Student (Master and PhD)
& researcher exchanges**

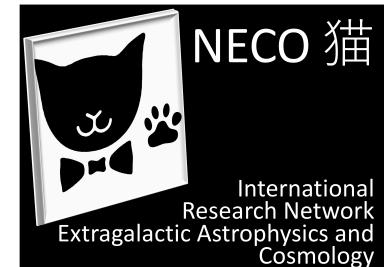


NECO organized (Dec. 2020) a workshop entitled: *Probing the Extragalactic Universe with High Energy and Very High Energy Sources*

SCIENTIFIC TOPICS: three main domains:

- AGN cycle and galaxy clusters: feedback from AGNs, UFO, extragalactic cosmic rays, galaxy clusters and related AGN physics, HITOMI/XRISM and Athena sciences
- Multi-messenger astrophysics: GRB host galaxies, UHECR and nearby extragalactic populations, short and long GRB and associated gravitational events, constraining stellar populations in galaxies and the Hubble constant, revealing the black hole population with gravitational waves
- Probing extragalactic lines of sight: Extragalactic background light, InterGalactic Magnetic Field, search for LIV signatures in signals from AGN and GRB, constraints deduced for cosmology and fundamental physics, CTA sciences

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From <https://www.univ-amu.fr/index.php/en/public/institute-physics-universe-iphu>:

IPhU is a leading collaborative scientific research and education environment, with a strong attractiveness and international influence, dedicated to the Physics of the Universe and associated technologies, from the infinitely small scales of particle physics to the infinitely large ones of cosmology, with high-energy astrophysics in between. Its goal is to provide answers to the key questions of the field that defy our imagination: which fundamental laws govern the Universe? What is it made of? How did it form and how does it evolve? Do we understand the Universe in its extreme states?

Questions:

1. **Are IPhU members (LAM but not only) interested to contribute?**
2. **How Can IPhU help funding NECO and its activities?**

Merci