The ALPINE-ALMA [CII] Survey

Unveiling the baryon cycle in z ~ 5 star-forming galaxies

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Main collaborators: dr. hab. Ambra Nanni, dr. Michael Romano

NCBJ ŚWIERK

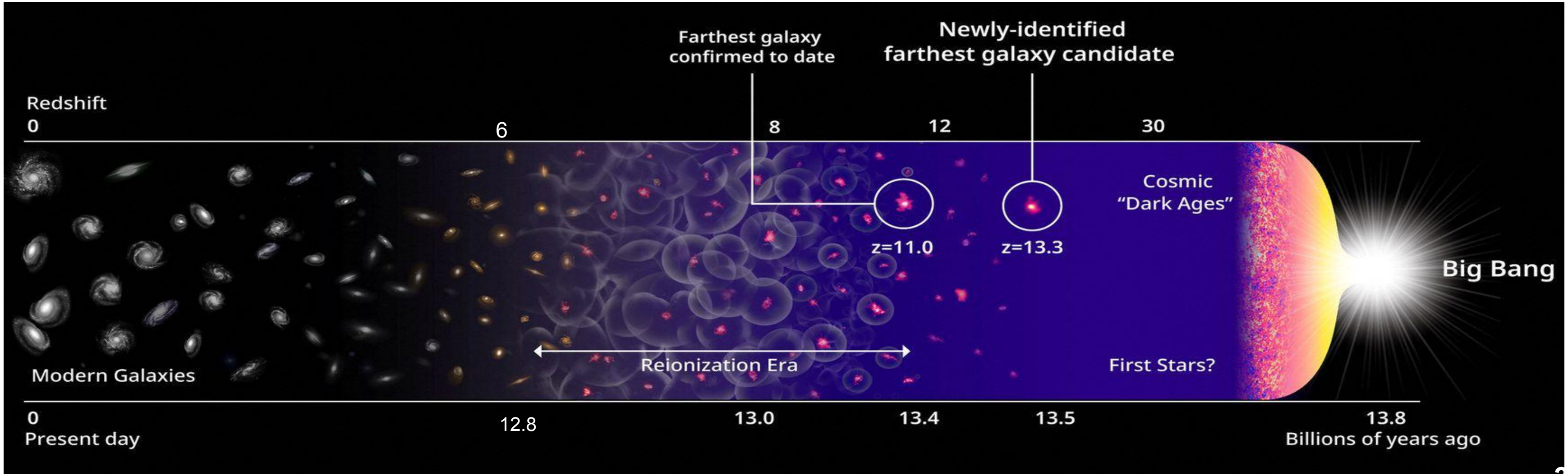
Narodowe Centrum Nauki

Graduate Seminar

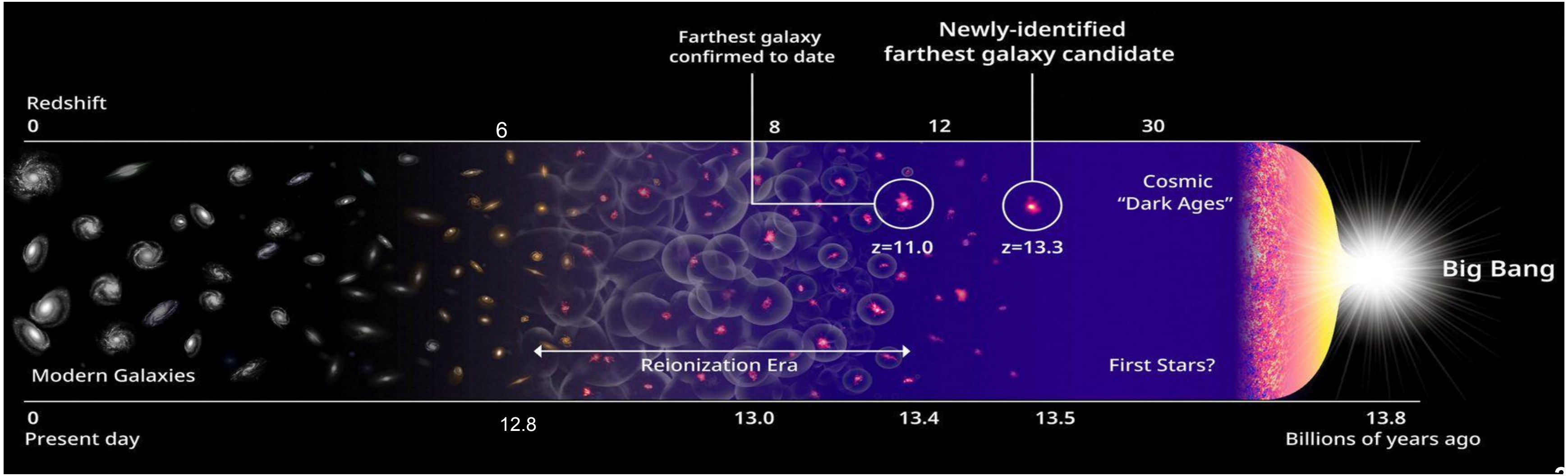
16 May 2024

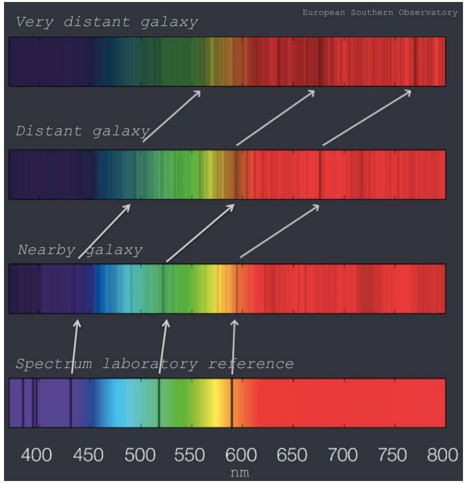
z = 5?

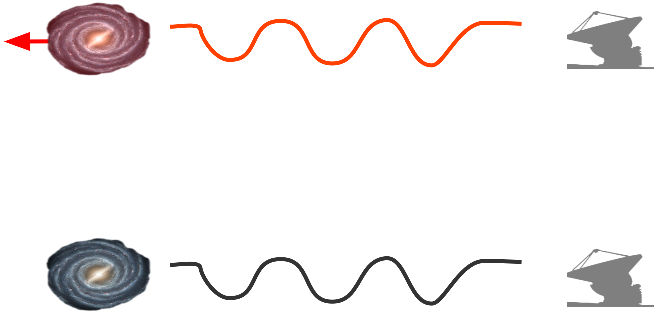
Looking back in time…



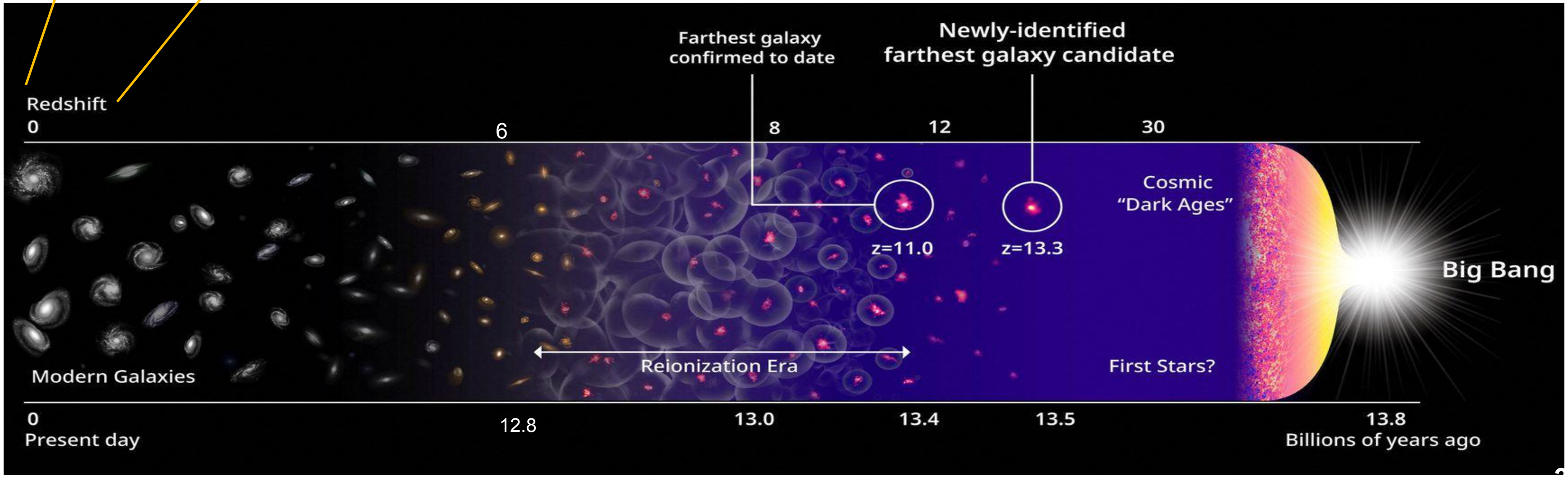
A long time ago in a galaxy far, far away….

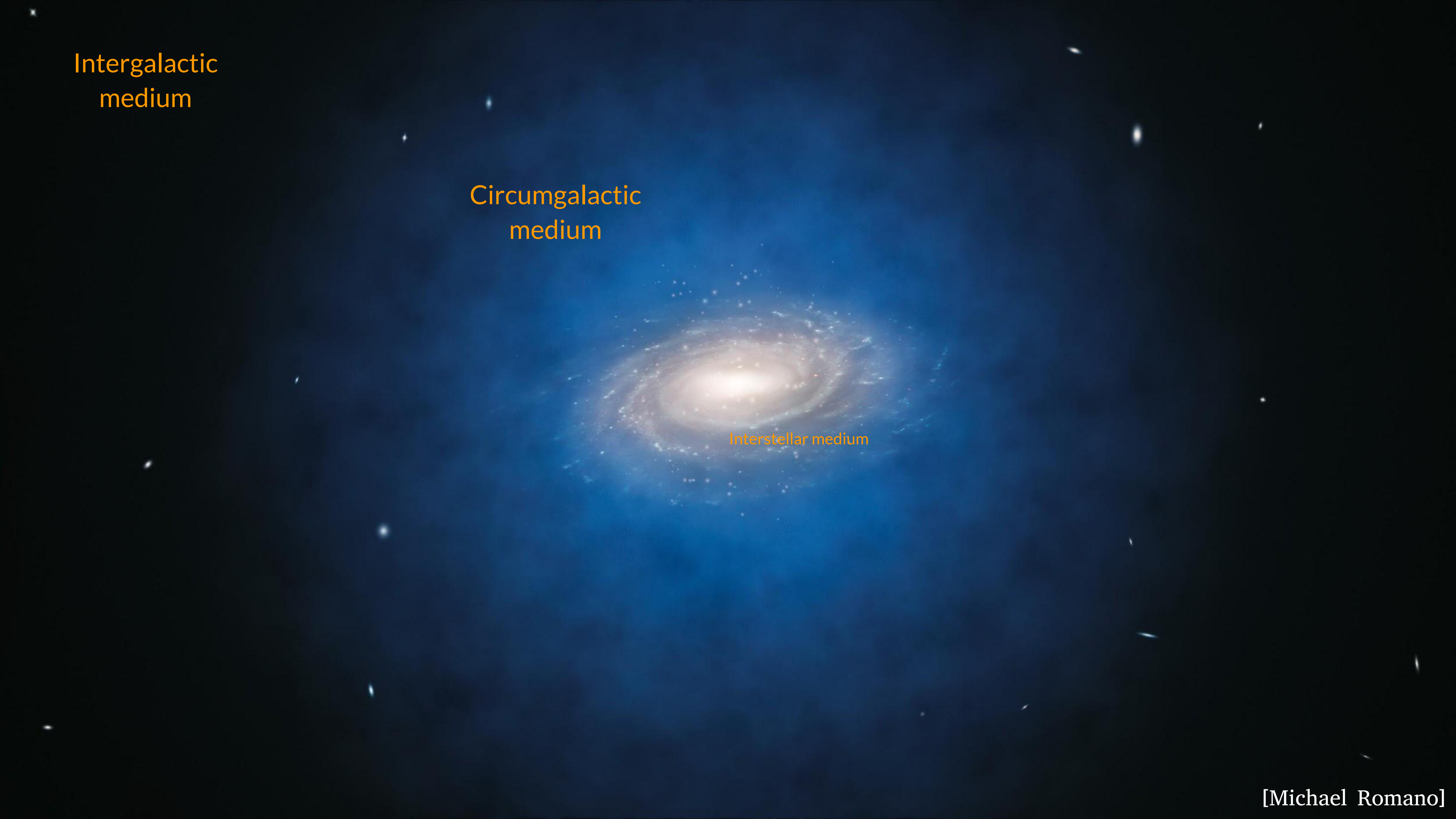


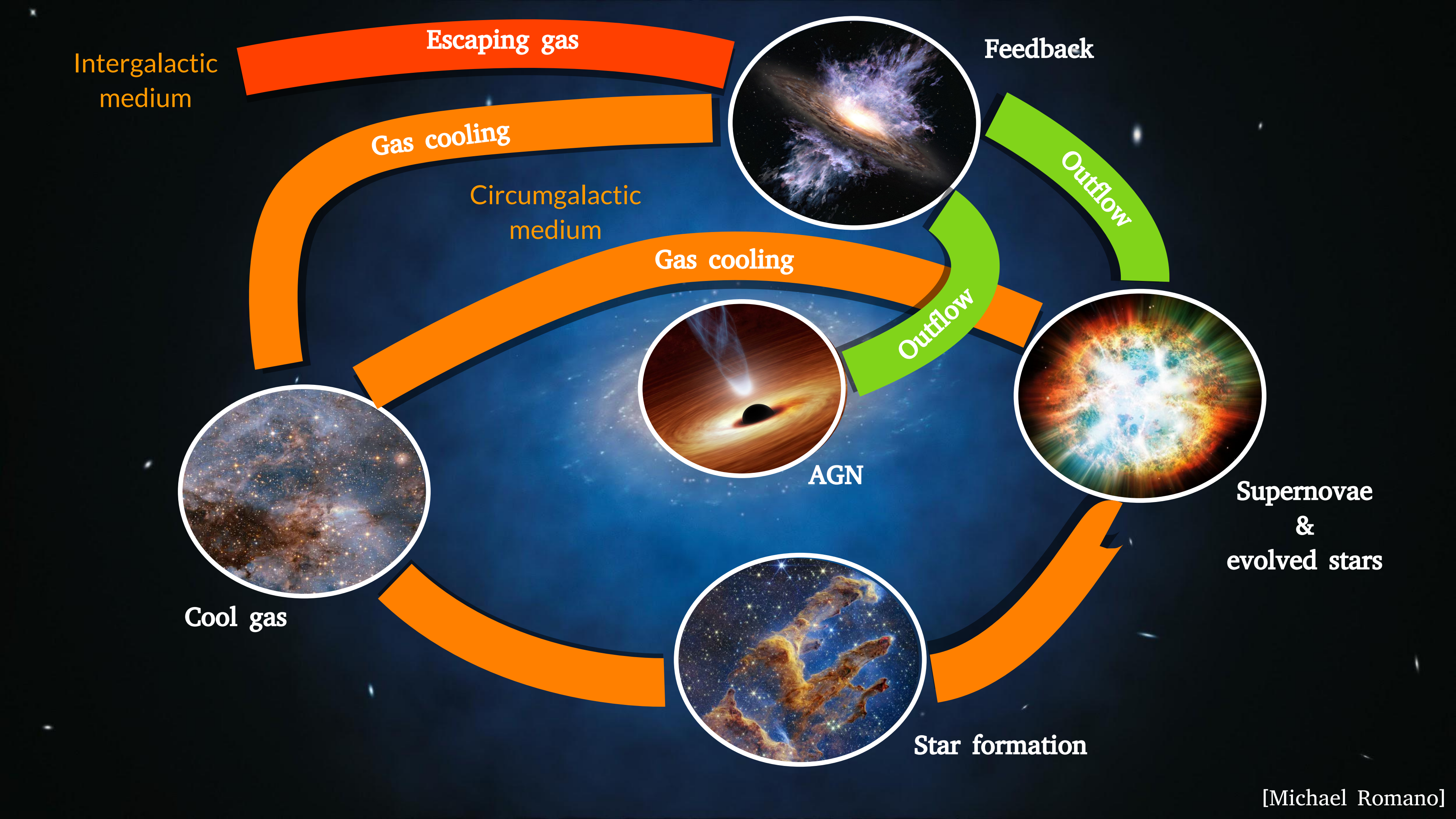


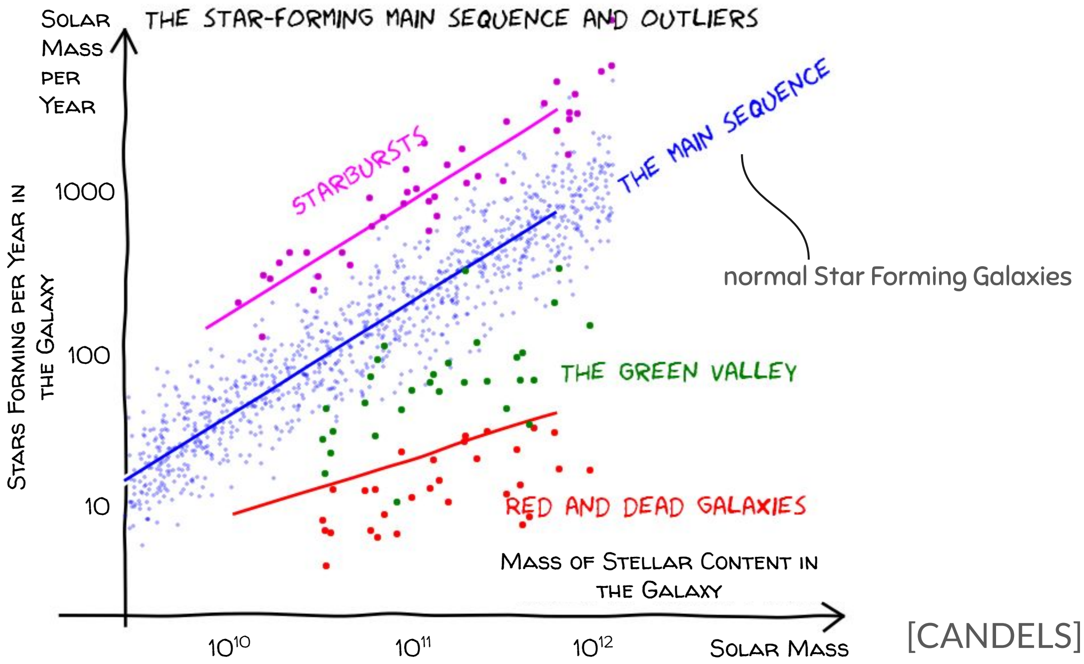


$$z = \frac{\Delta\lambda}{\lambda_{rest}} = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{v}{c}$$



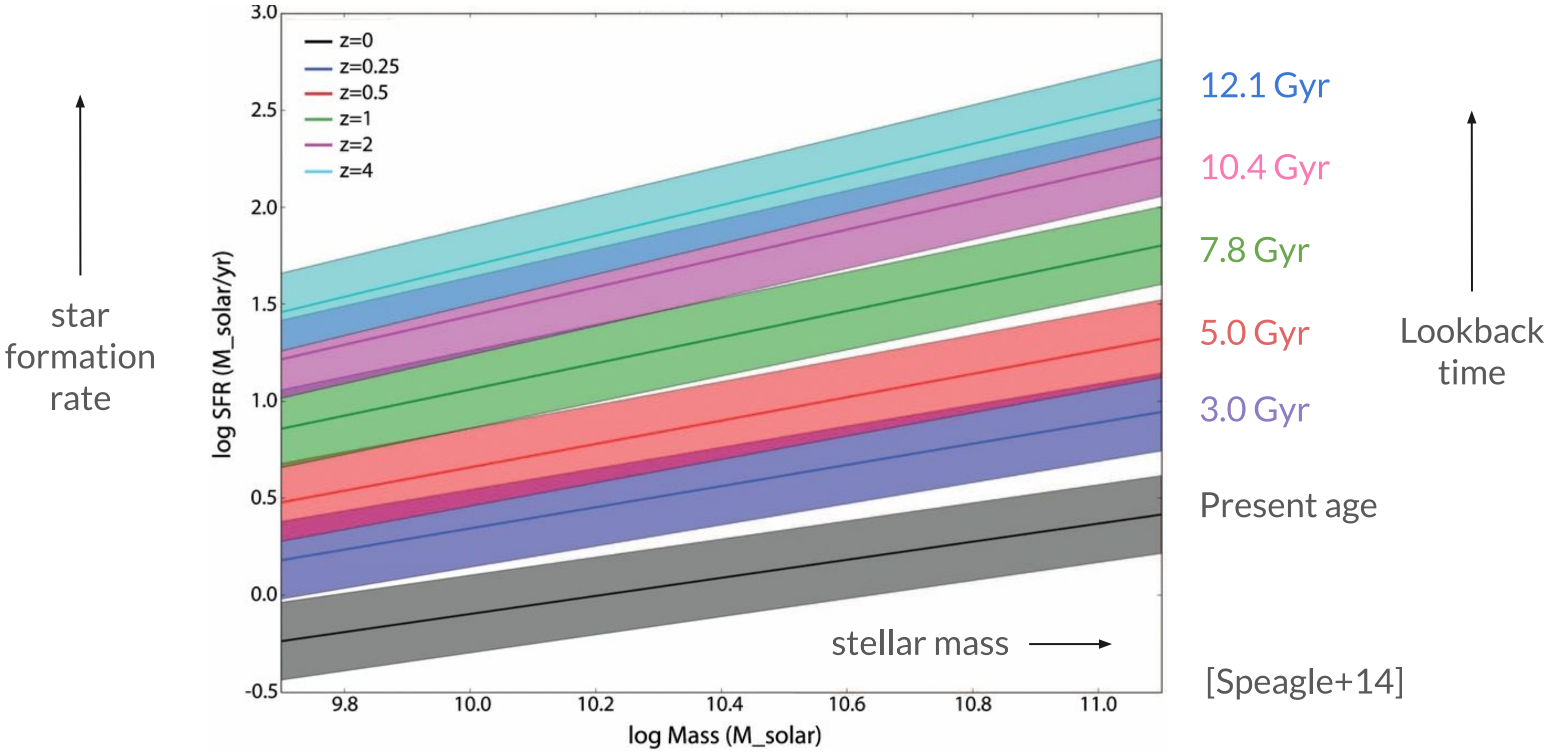

Intergalactic medium
Circumgalactic medium
Interstellar medium
[Michael Romano]


Escaping gas
Intergalactic medium
Feedback
Gas cooling
Circumgalactic medium
Outflow
Gas cooling
Outflow
AGN
Supernovae & evolved stars
Cool gas
Star formation
[Michael Romano]

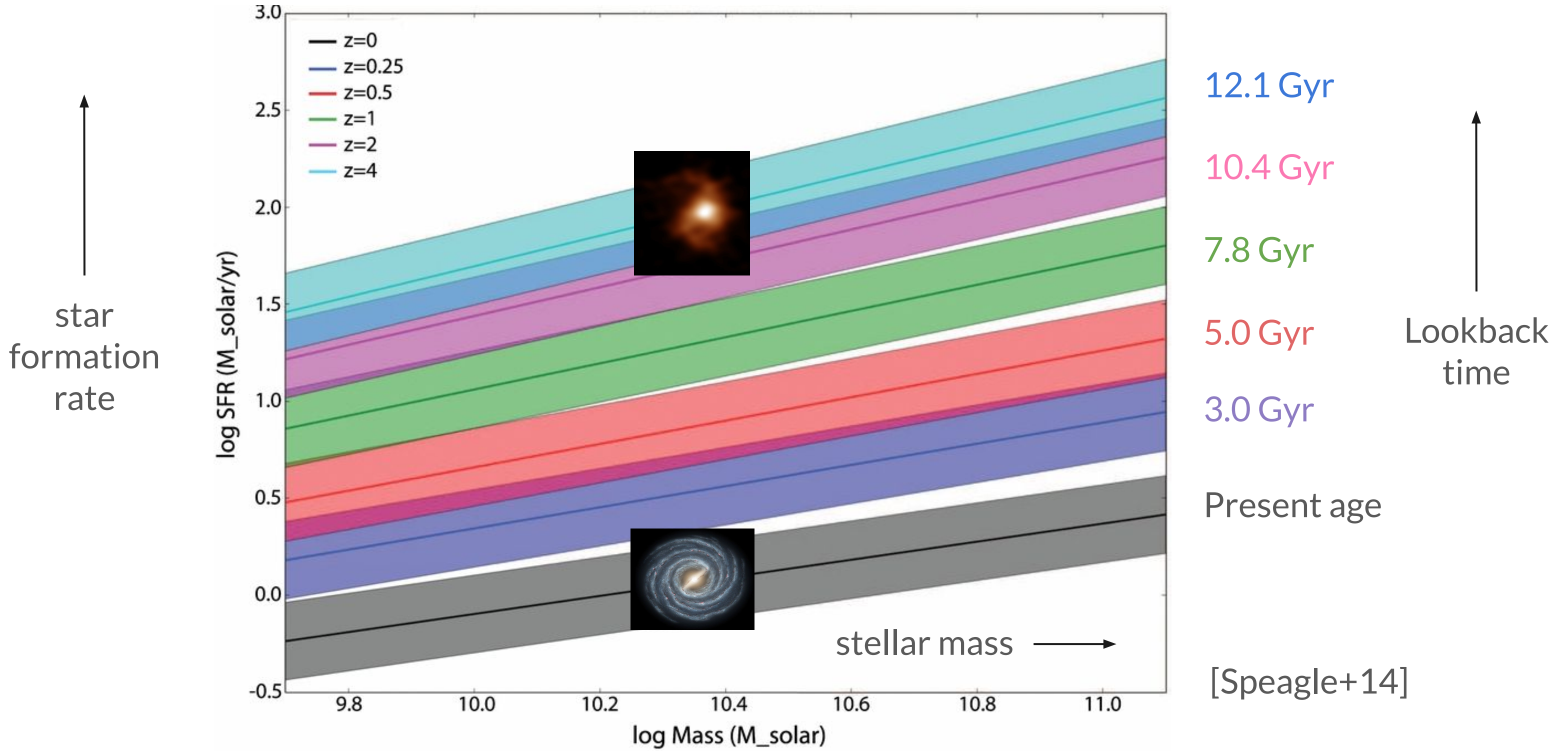


[CANDELS]

Existence of a "main-sequence" of galaxies.

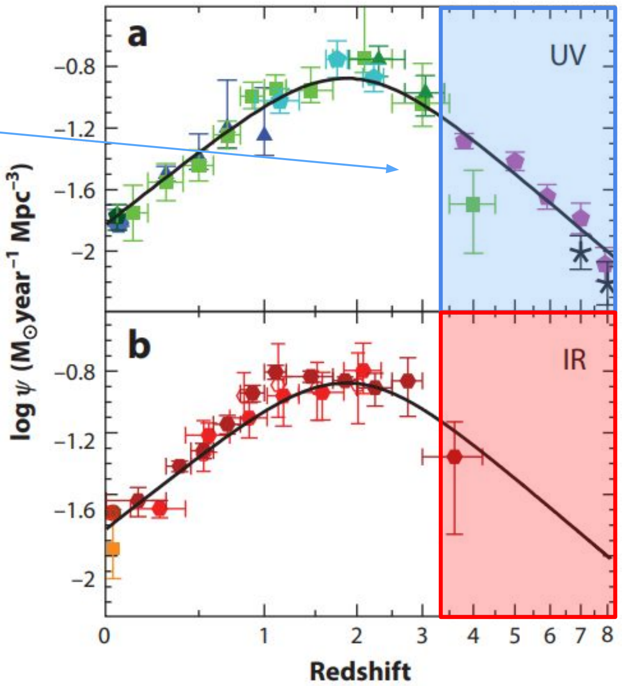


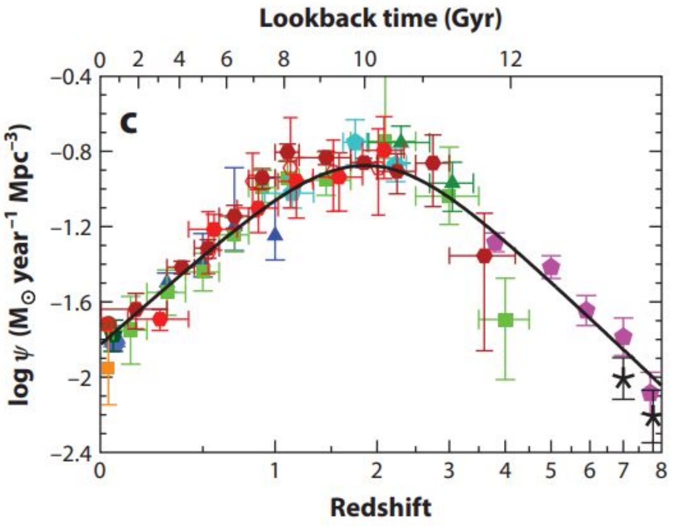
Evolution in the Nature with cosmic time



Evolution in the Nature with cosmic time

Data at redshift > 4 are based on UV measurements.

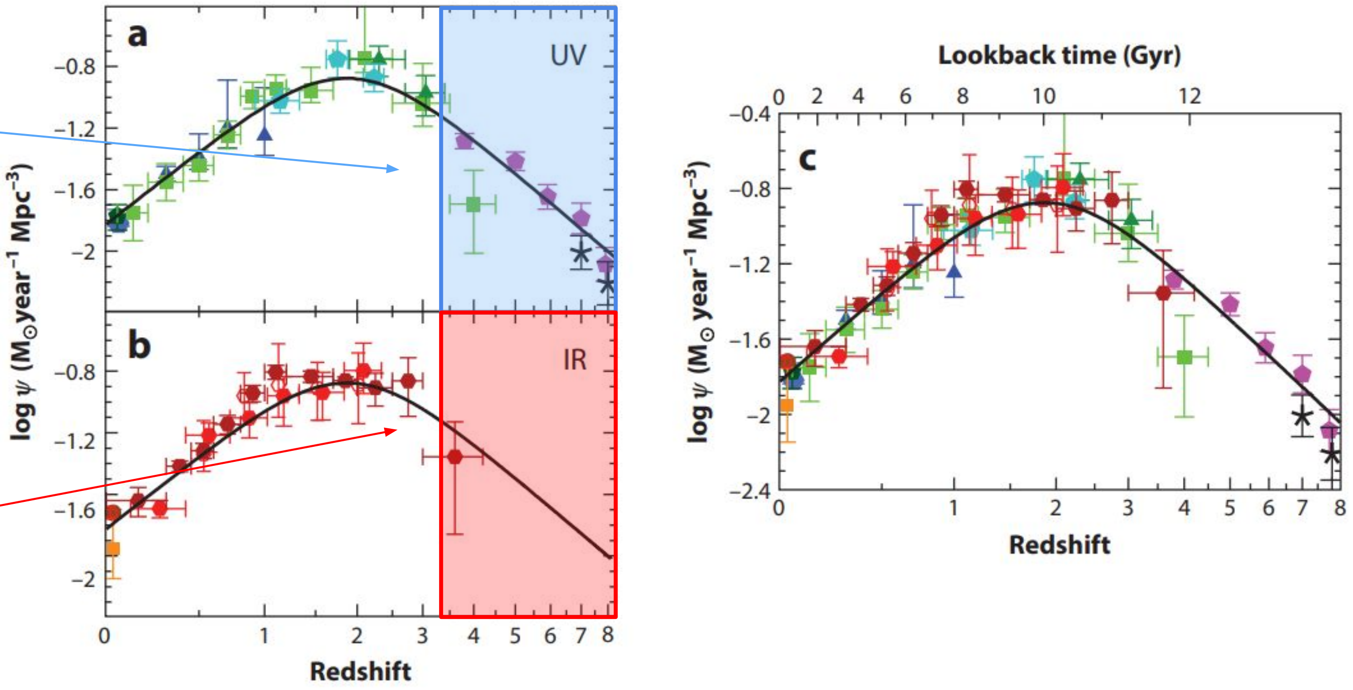




[Madau & Dickinson14]

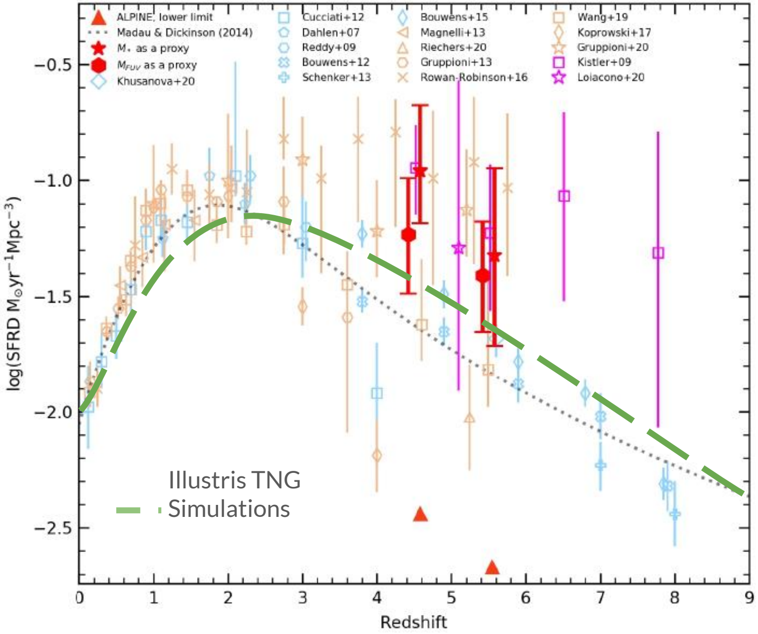
Data at redshift > 4 are based on UV measurements.

Infrared observations were needed



[Madau & Dickinson14]

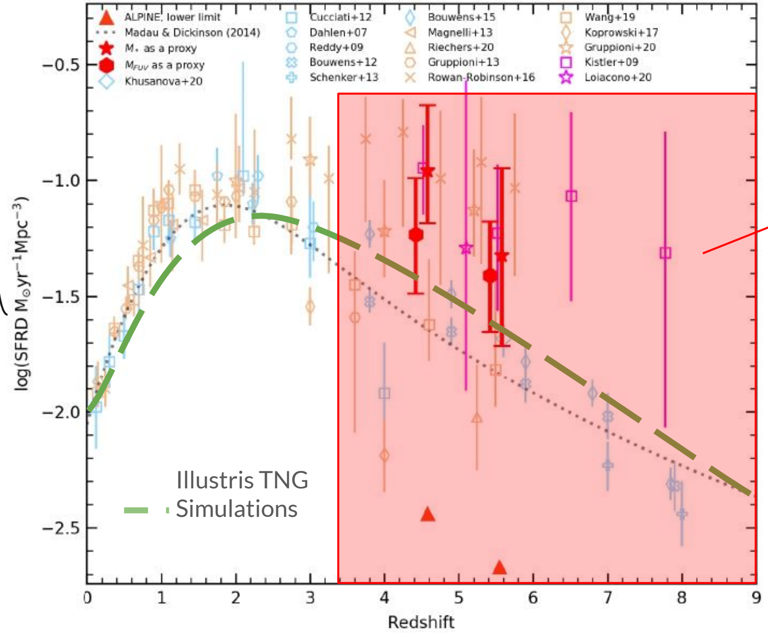
star formation rate per unit volume



age of the Universe

[Khusanova+21]

star formation rate per unit volume



age of the Universe

[Khusanova+21]

Newly discovered dust-obscured galaxies in high redshift Universe.

Dusty star forming galaxies contribute to the SFRD.

Models struggle to reproduce observed number counts and inferred physical properties.

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unit
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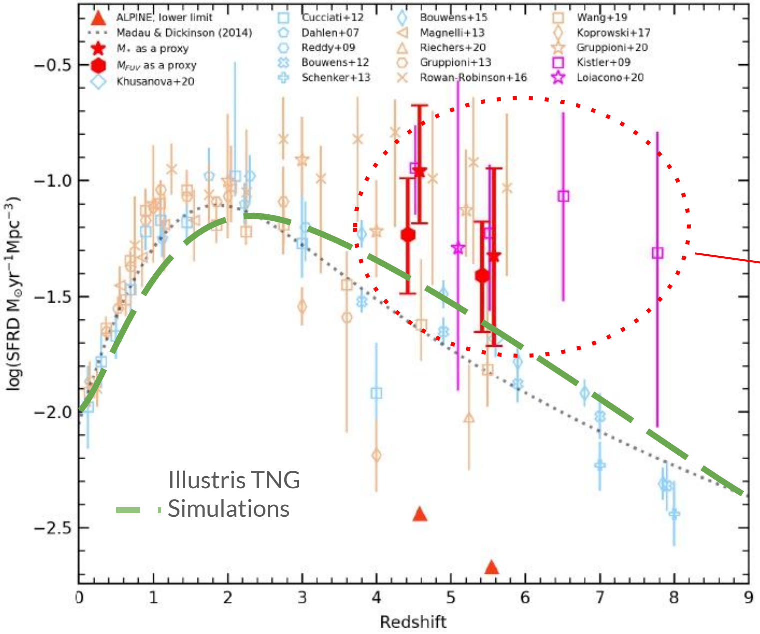

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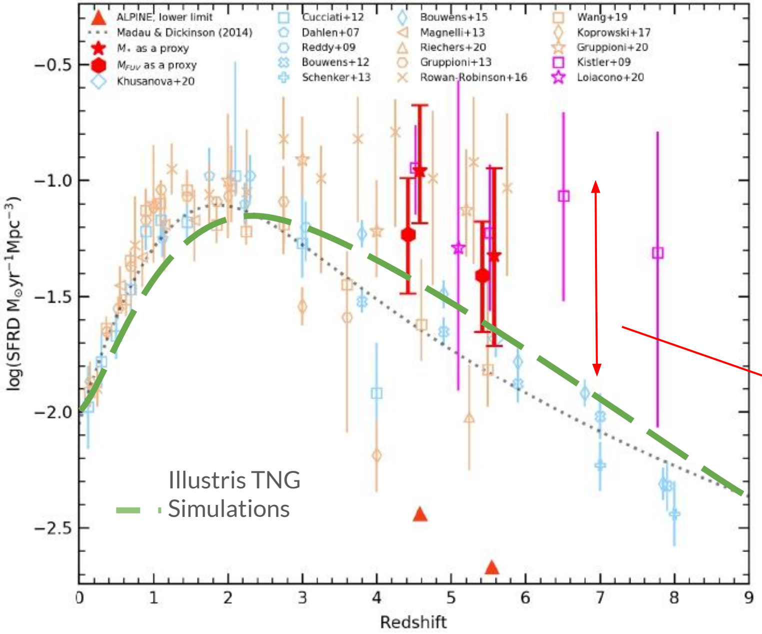

age of the Universe

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Dusty star forming galaxies contribute to the SFRD.

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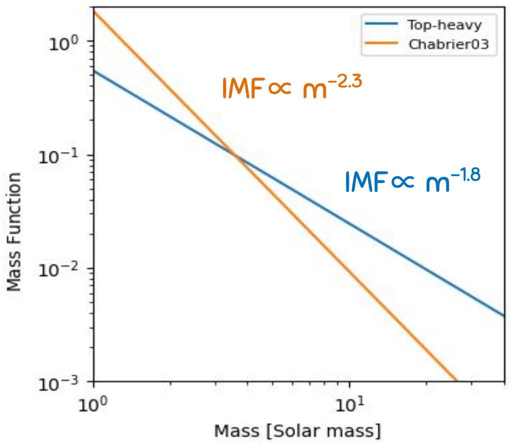
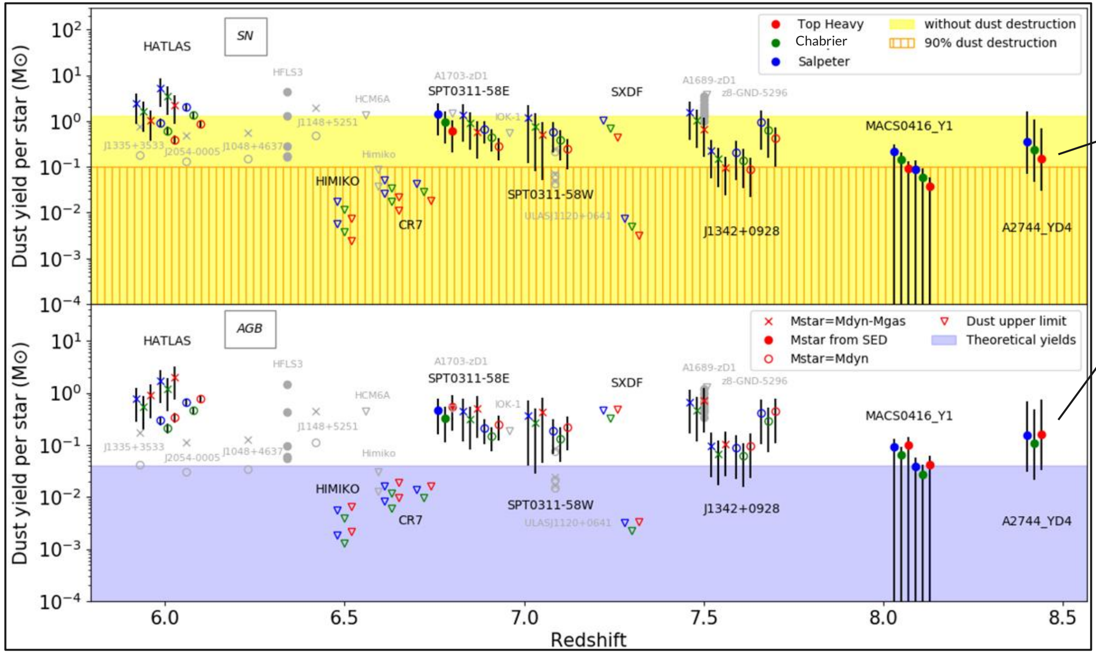
Initial Mass Function

- Initial mass function: Quantifies the distribution of stellar mass in the stellar population of a galaxy.
- Determines the chemical evolution of the galaxy and how the baryonic content changes.



mass of dust produced per star in a galaxy



galaxies

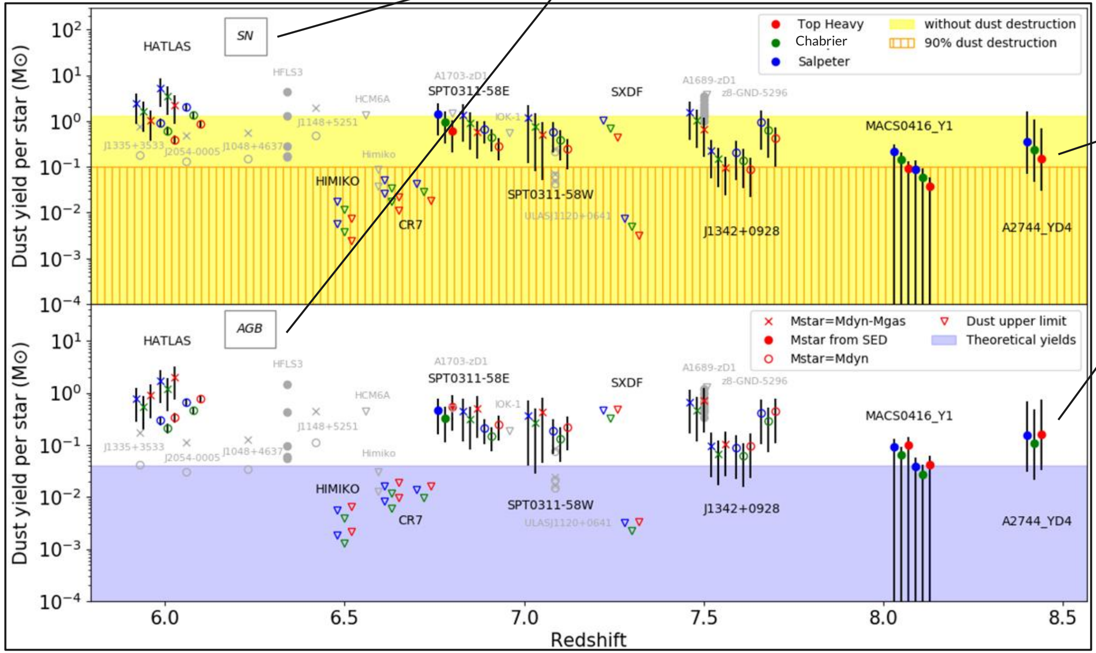
models

[adapted from Leśniewska & Michałowski+19]

Large amount of dust in high-z Universe.

different mechanisms of dust production

mass of dust produced per star in a galaxy



galaxies

models

[adapted from Leśniewska & Michałowski+19]

Large amount of dust in high-z Universe.

Dust be like:

galaxies

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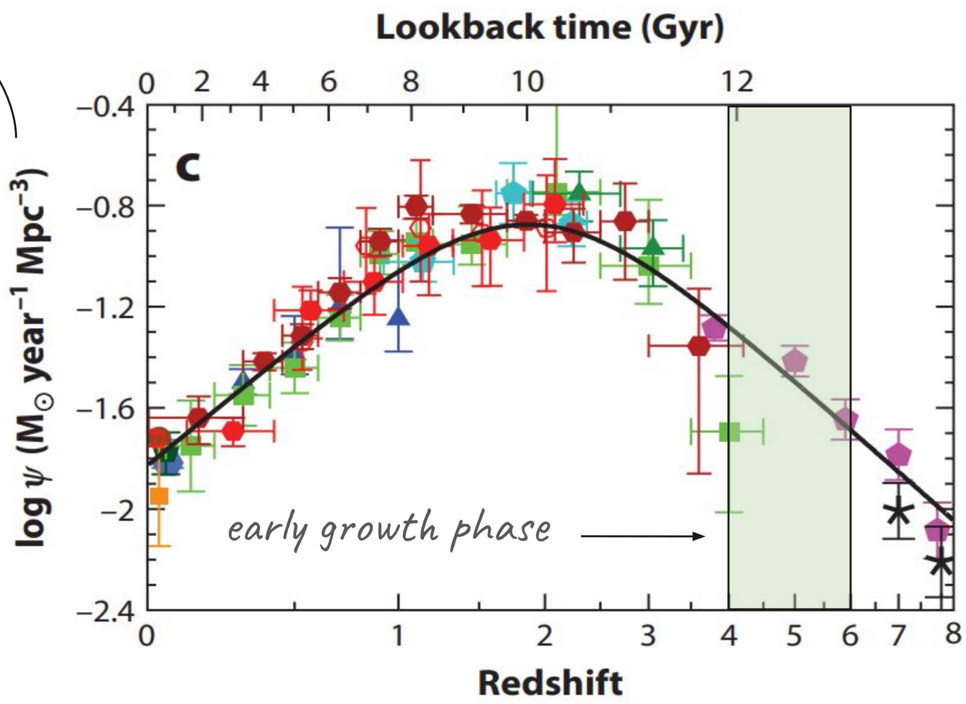
Large amount of dust in high-z Universe.

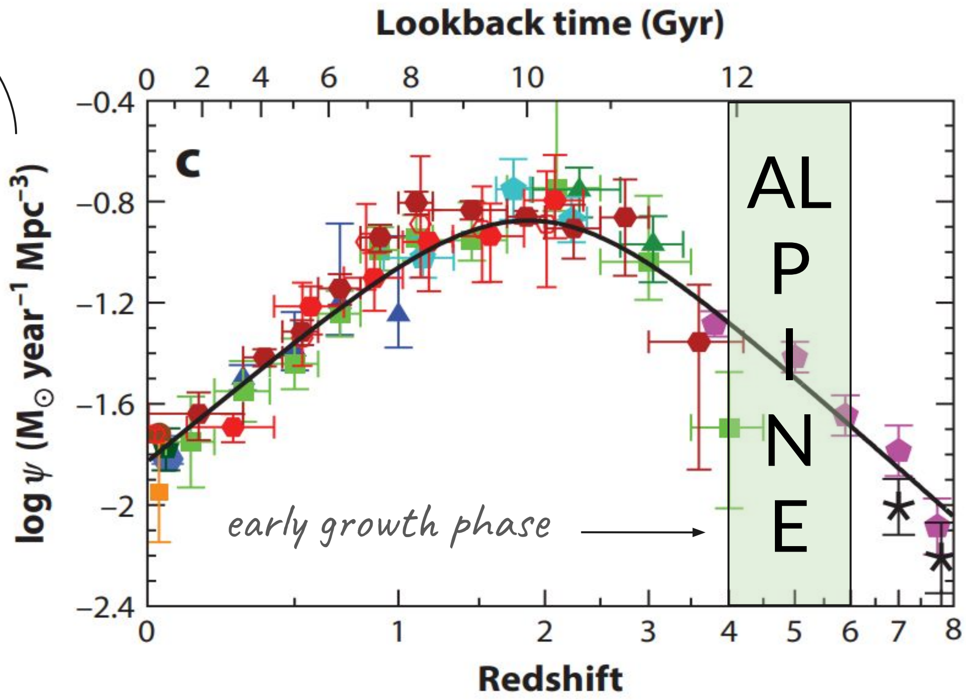
star formation rate per unit volume



[Madau & Dickinson+14]

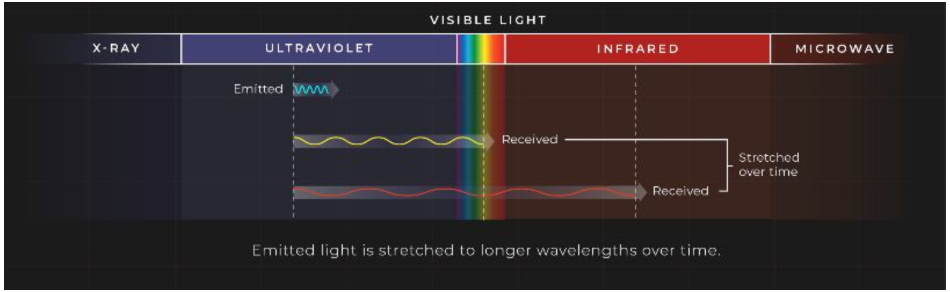
A transitional phase between primordial galactic formation and the onset of the peak of cosmic star formation rate density.

star formation rate per unit volume

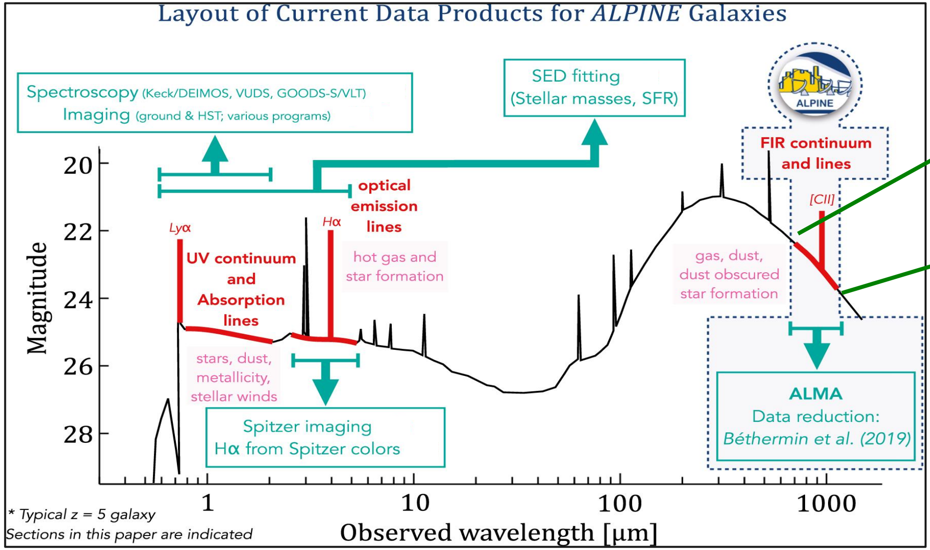


[Madau & Dickinson+14]

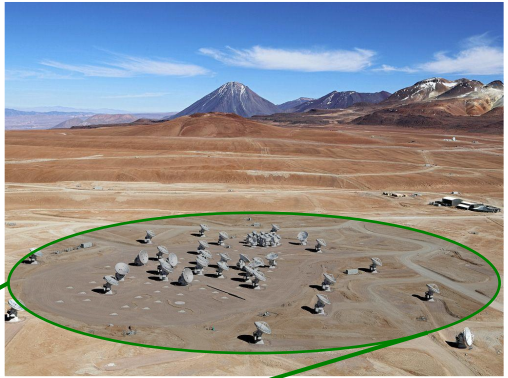
We look towards ALPINE - ALMA survey for the following reasons:



[GSFC]



[Faisst+20]

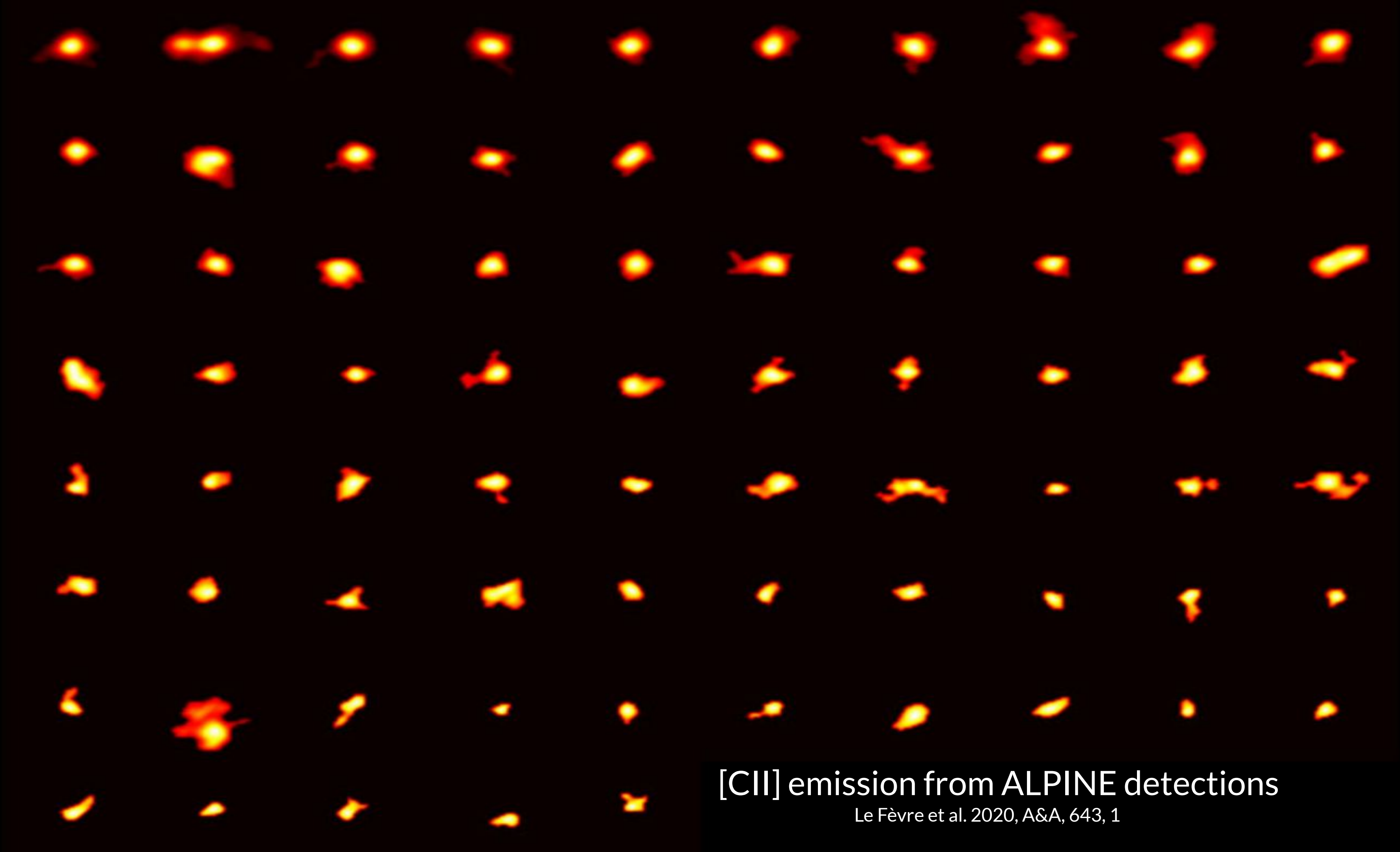


[Clem & Adri Bacri-Normier]

[CII] line @ 158 μm rest-frame:

- one of the strongest FIR line;
- mainly excited in photodissociation regions (PDRs);
- poorly affected by dust;
- near the peak of FIR emission

ALPINE: the ALMA Large Program to INvestigate [CII] at Early times



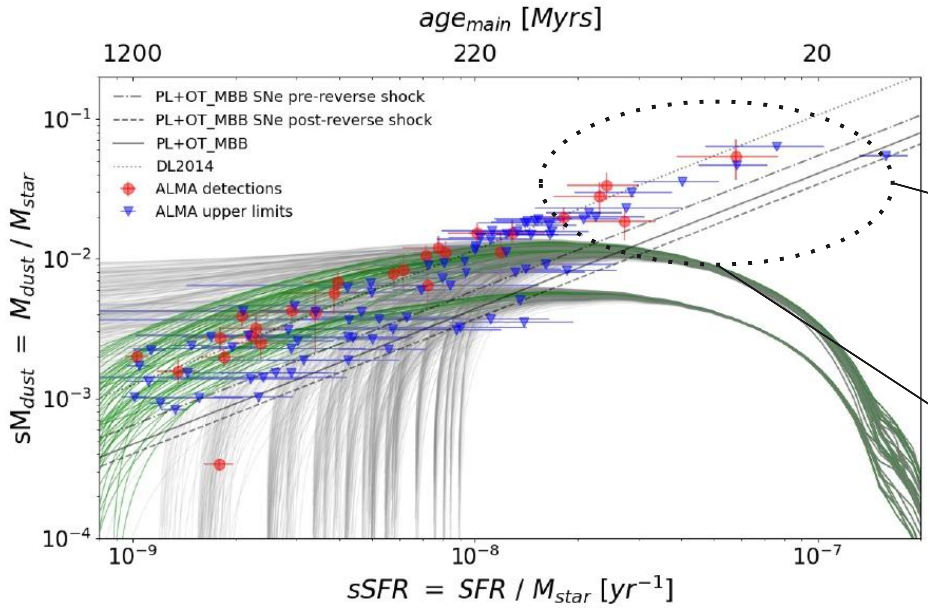
[CII] emission from ALPINE detections

Le Fèvre et al. 2020, A&A, 643, 1

Until now...

- ALMA Large Program to INvestigate [CII] at Early times (ALPINE) survey.
- Representative sample of 118 star-forming galaxies at the end of the HI reionization era at redshift ($4 < z < 6$).
- With stellar masses ~ $10^{8.4}$ - 10^{11} [MSun] and SFR ~ 3 - 270 [MSun/Yr].
- We have:
  - SED fitting and derivation of physical parameters: Faisst+20, Béthermin+20, Burgarella+22
  - Gas, Metal and Dust content: Dessauges-Zavadsky+20, Gruppioni+20, Pozzi+21, Vanderhoof+22
  - Baryonic cycle mechanisms: Fujimoto+20, Ginolfi+20a, b
  - Morphology and kinematical studies: Romano+21, Jones+22, Devereaux+23, Pozzi+24

The problem?



[Burgarella+22]

Tension with the models

High amount of dust observed in short timescales

Moving ahead…

Observations

1.

Estimating stellar mass, star formation rate, dust and gas mass from ancillary data.

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Observations

2.

Employing chemical models to reproduce gas and dust content in the galaxies.

Predictions

1.

Estimating stellar mass, star formation rate, dust and gas mass from ancillary data.

Observations

2.

Employing chemical models to reproduce gas and dust content in the galaxies.

Predictions

3.

Analyzing the impact of variational initial mass function (IMF) on our predictions.

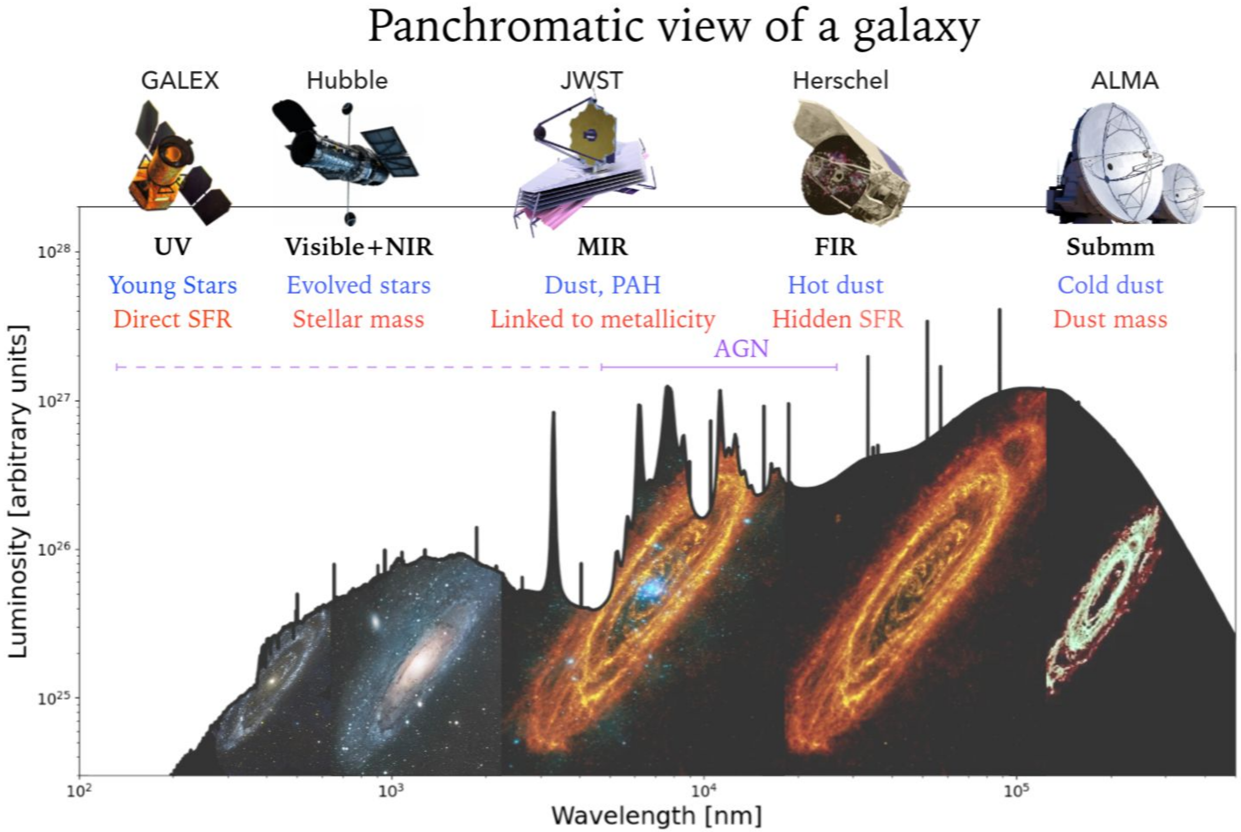
Solution?

Observations

1.

Estimating stellar mass, star formation rate, dust and gas mass from ancillary data.

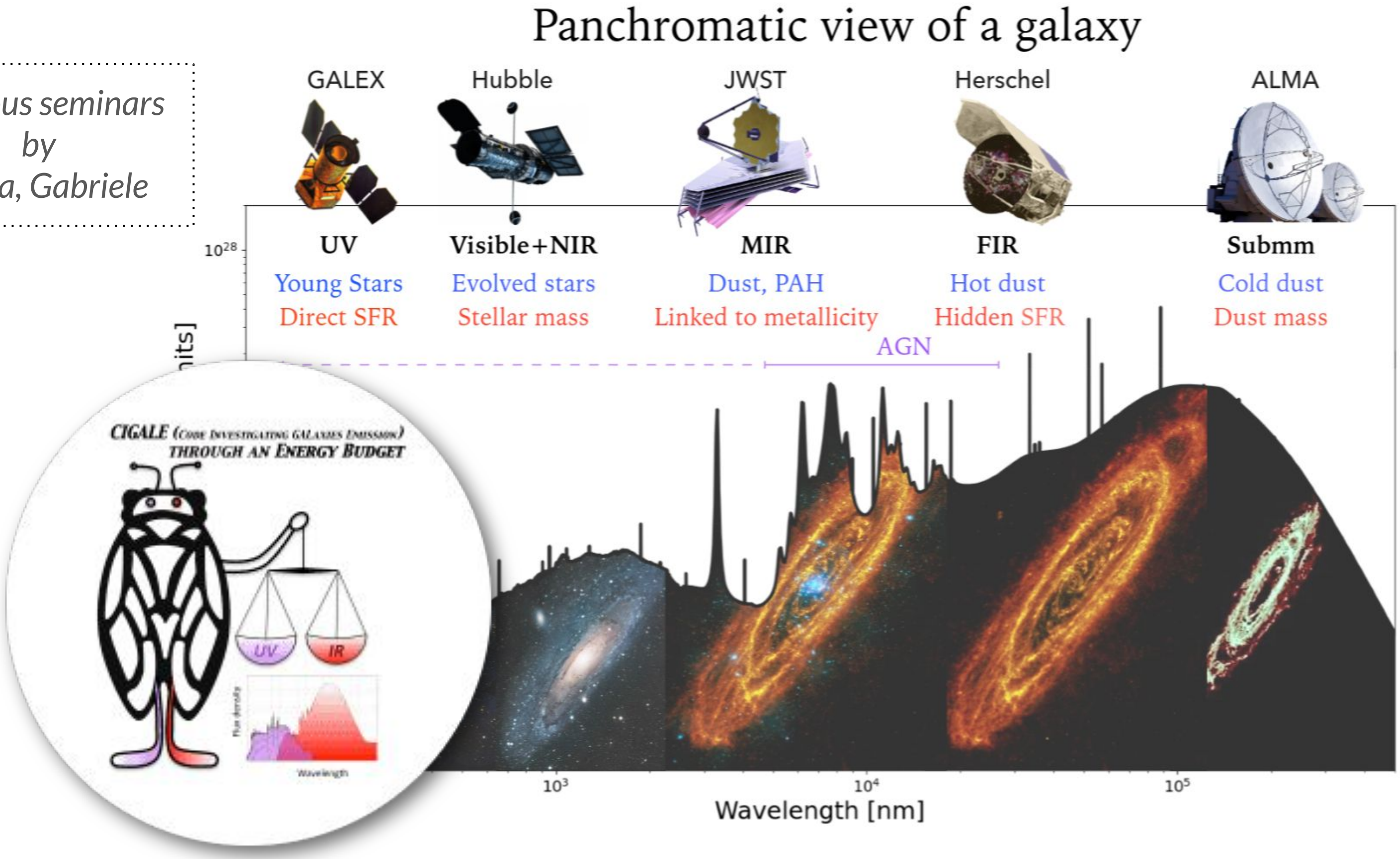
- Employ CIGALE to estimate stellar mass, star formation rate and dust mass following the description mentioned in Burgarella+22.



[M. Hamed]

Spectral Energy Distribution of a galaxy

Previous seminars by Misha, Gabriele



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Spectral Energy Distribution of a galaxy

Observations

1.

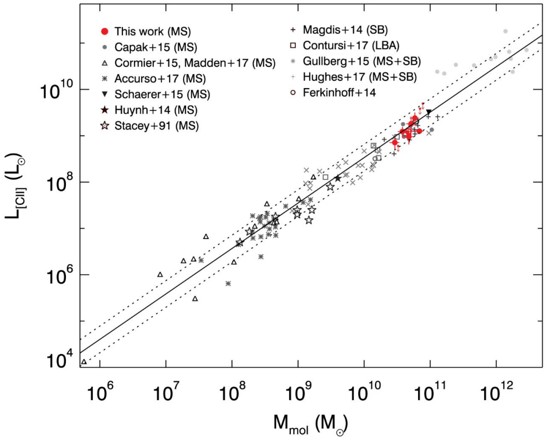
Estimating stellar mass, star formation rate, dust and gas mass from ancillary data.

- Employ CIGALE to estimate stellar mass, star formation rate and dust mass following the description mentioned in Burgarella+22.
- Derive gas mass using [CII] luminosities using relation (Zanella+18):

$$\log_{10}(L_{[\mathrm{CII}]}/L_{\odot}) = (-1.28\pm0.21)+(0.98\pm0.02)\log_{10}(M_{\mathrm{gas}}/M_{\odot}),$$

Observations

[CII] luminosity



[Zanella+18]

Molecular gas content

$$\log_{10}(L_{[CII]}/L_\odot) = (-1.28\pm0.21)+(0.98\pm0.02)\log_{10}(M_{gas}/M_\odot),$$

[CII] is used as a tracer of molecular content of the galaxy

Observations

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$$\log_{10}(L_{[\mathrm{CII}]}/L_{\odot}) = (-1.28\pm0.21)+(0.98\pm0.02)\log_{10}(M_{\mathrm{gas}}/M_{\odot}),$$

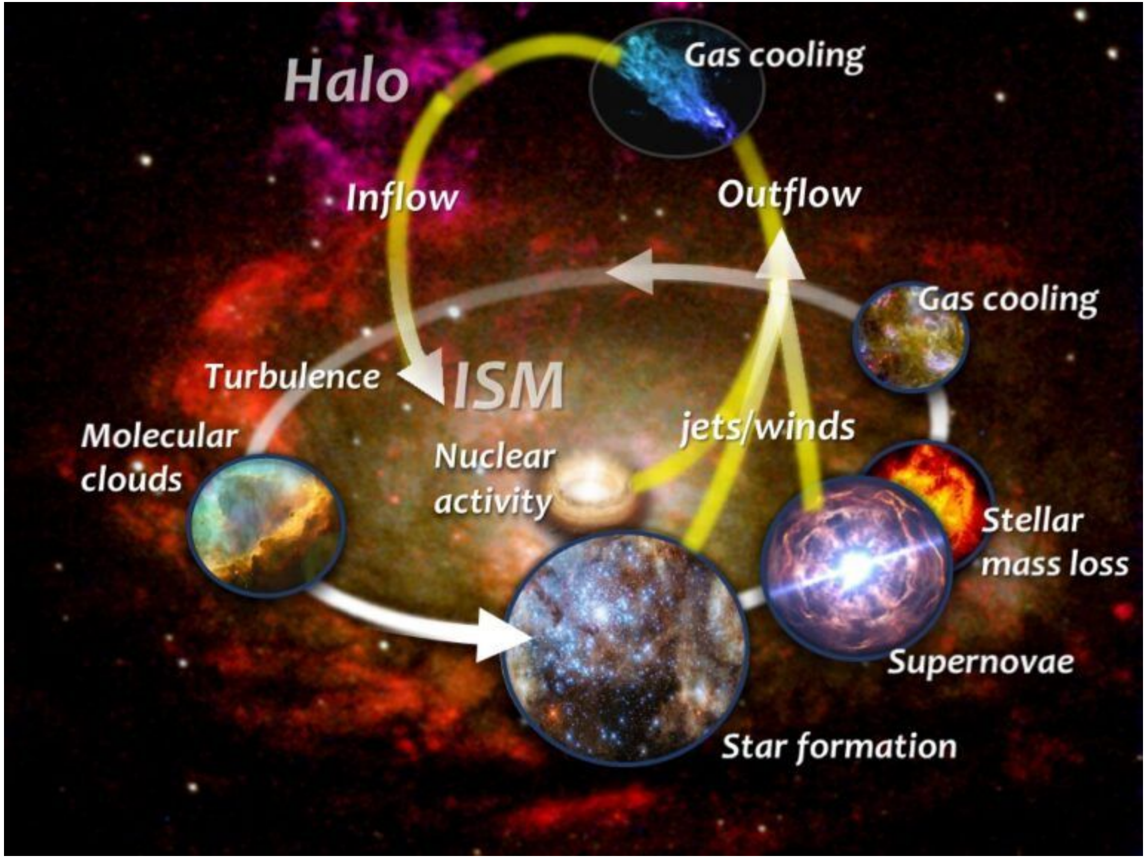
- Estimate sMGas = Gas Mass/Stellar Mass, sSFR = SFR/Stellar Mass and sMDust = Dust Mass/Stellar Mass

Predictions

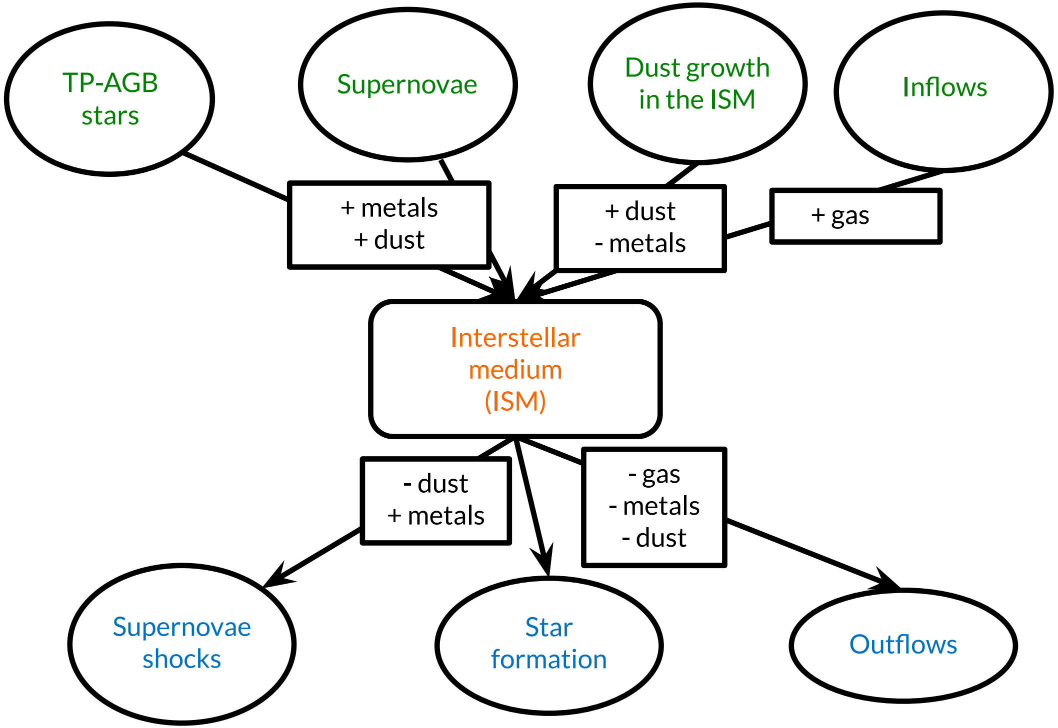
2.

Employing chemical models to reproduce gas and dust content in the galaxies.

- The description for baryonic evolution in these galaxies is adopted from **Nanni+20**.



Contributions to the baryonic content of the ISM



[A. Nanni]

Contributions to the baryonic content of the ISM

Predictions

2.

Employing chemical models to reproduce gas and dust content in the galaxies.

- The description for baryonic evolution in these galaxies is adopted from **Nanni+20**.
- What goes into the models:
  - Gas ejection by the stellar population.
  - Astration due to star formation
  - Galactic outflows/inflows
  - Dust:
    - Supernovae type Ia and II
    - AGB stars
    - Growth in ISM
  - Initial Mass Function (IMF)

[W.B]

Contributions to the baryonic content of the ISM

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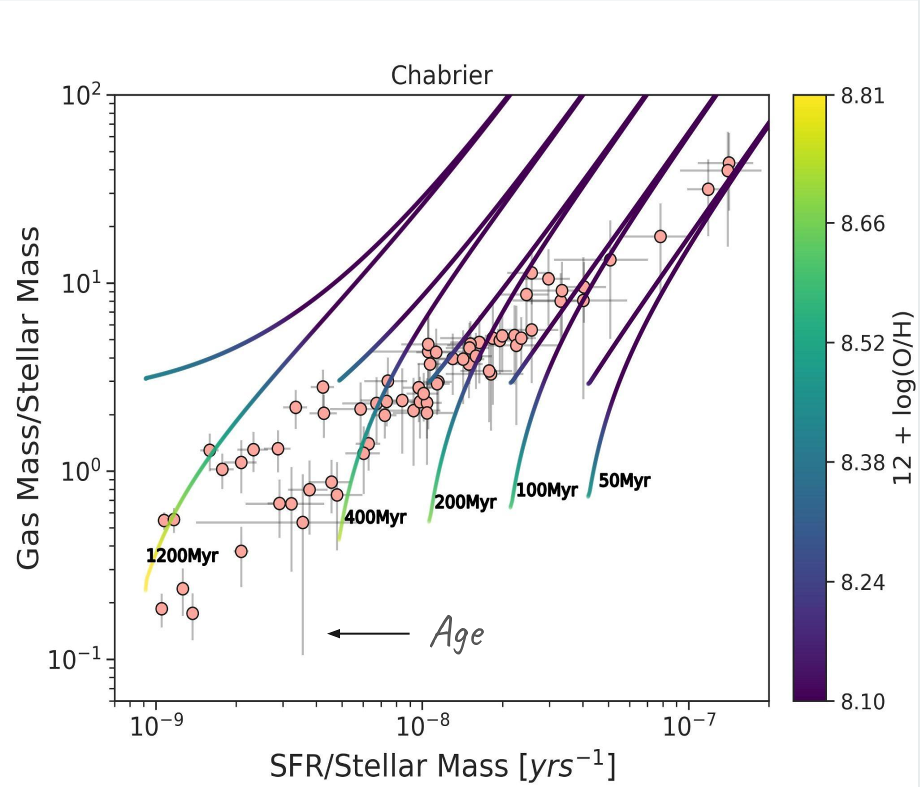
Table 1. List of parameters adopted in the simulations of metal and dust evolution described in Section 3. First tests are run in order to select the reference parameters adopted to run systematic calculations. The stellar mass produced by the end of the simulation is always normalised to 1 $M_\odot$.

Theoretical metal yields			
Stellar Source	**Data set and Denomination**	**Mass range in $M_\odot$**	
Type II SNe	Limongi & Chieffi (2018), Prantzos et al. (2018) - LC18	[13, 120]	Dust and metal yields
AGB	Cristallo et al. (2015) - C15	[1, 7]	
Pop III stars	Heger & Woosley (2010)	[10, 100]	
Type Ia SN	Iwamoto et al. (1999)	-	
Systematic Calculations			
τ [Myr]	500		Star formation history & stellar populations
IMF (Top-Heavy)	$\propto M^{-\alpha}$, $\alpha = 1.8$		
$M_{star,fin}$ [$M_\odot$]	1		
$M_{gas,ini}$ [$M_\odot$] (Chabrier)	(2 - 6) $\times M_{star,fin}$		Dictating the gas content
$M_{gas,ini}$ [$M_\odot$] (Top-heavy)	(2 - 6) $\times M_{star,fin}$		
ML	0-3 Ginolfi et al. (2020b)		
M_{in}	0 - 1		
M_{swept} [$M_\odot$]	$1535\, n_{SN}^{-0.202} [(Z/Z_\odot) + 0.039]^{-0.289}$		Dictating contributions by supernovae
ϵ	0.1, 0.5, 1.0		
SN condensation fraction	$f_{py} = 0.05$, $f_{ol} = 0$, $f_{ir} = 0.05$, $f_{car} = 0.05$ ($f_{cond} = 5\%$)		
	$f_{py} = 0.10$, $f_{ol} = 0$, $f_{ir} = 0.10$, $f_{car} = 0.10$ ($f_{cond} = 10\%$)		
	$f_{py} = 0.25$, $f_{ol} = 0$, $f_{ir} = 0.25$, $f_{car} = 0.25$ ($f_{cond} = 25\%$)		
	$f_{py} = 0.5$, $f_{ol} = 0$, $f_{ir} = 0.5$, $f_{car} = 0.5$ ($f_{cond} = 50\%$)		
	$f_{py} = 0.75$, $f_{ol} = 0$, $f_{ir} = 0.75$, $f_{car} = 0.5$ ($f_{cond} = 75\%$)		
	$f_{py} = 1$, $f_{ol} = 0$, $f_{ir} = 1$, $f_{car} = 0.5$ ($f_{cond} = 100\%$)		
AGB condensation fraction	$f_{py} = 0.3$, $f_{ol} = 0.3$, $f_{ir} = 0.01$, $f_{car} = 0.5$		→ Dictating contributions by AGB
Dust growth efficiency in the ISM	0.0, 0.5, 1		→ Dictating contributions by ISM growth

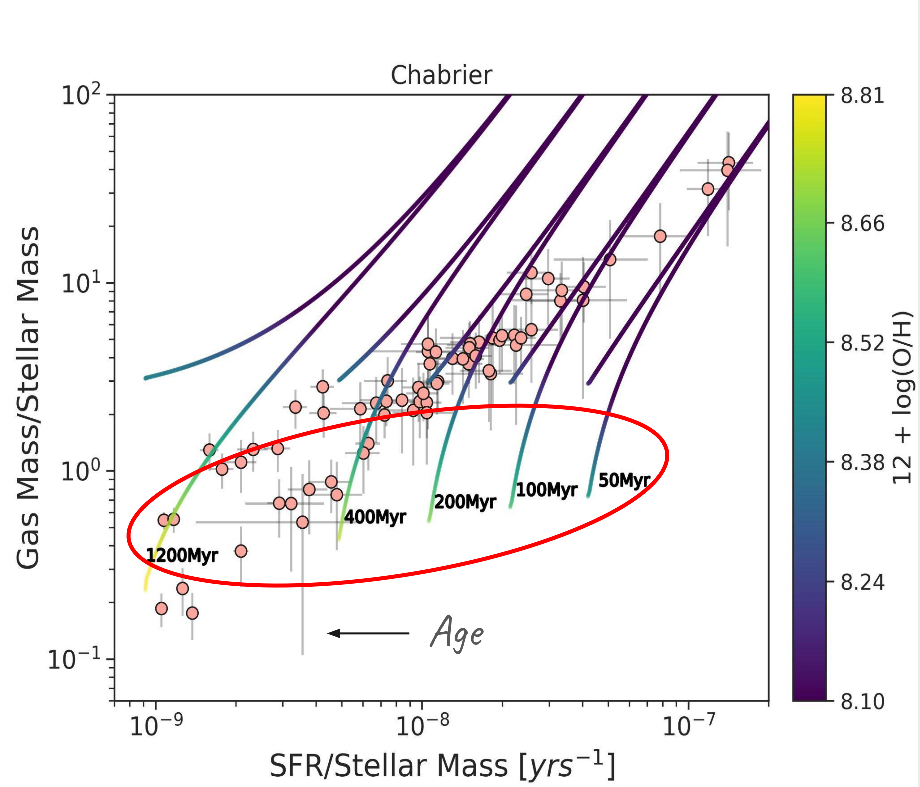
[Sawant+, submit. to collab]

Observations vs Predictions



[Sawant+, submit. to collab]

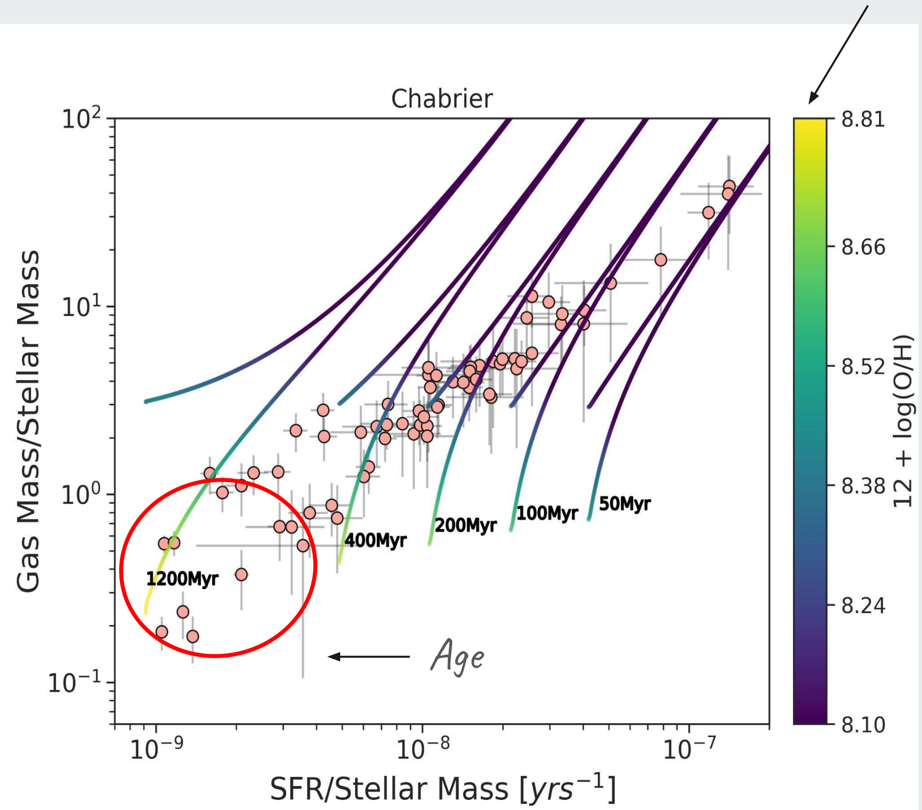
- Evolution of specific gas mass with age of the main stellar population.



[Sawant+, submit. to collab]

Observations vs Predictions

- Evolution of specific gas mass with age of the main stellar population.
- Galactic outflows required to reproduce the observed gas mass.

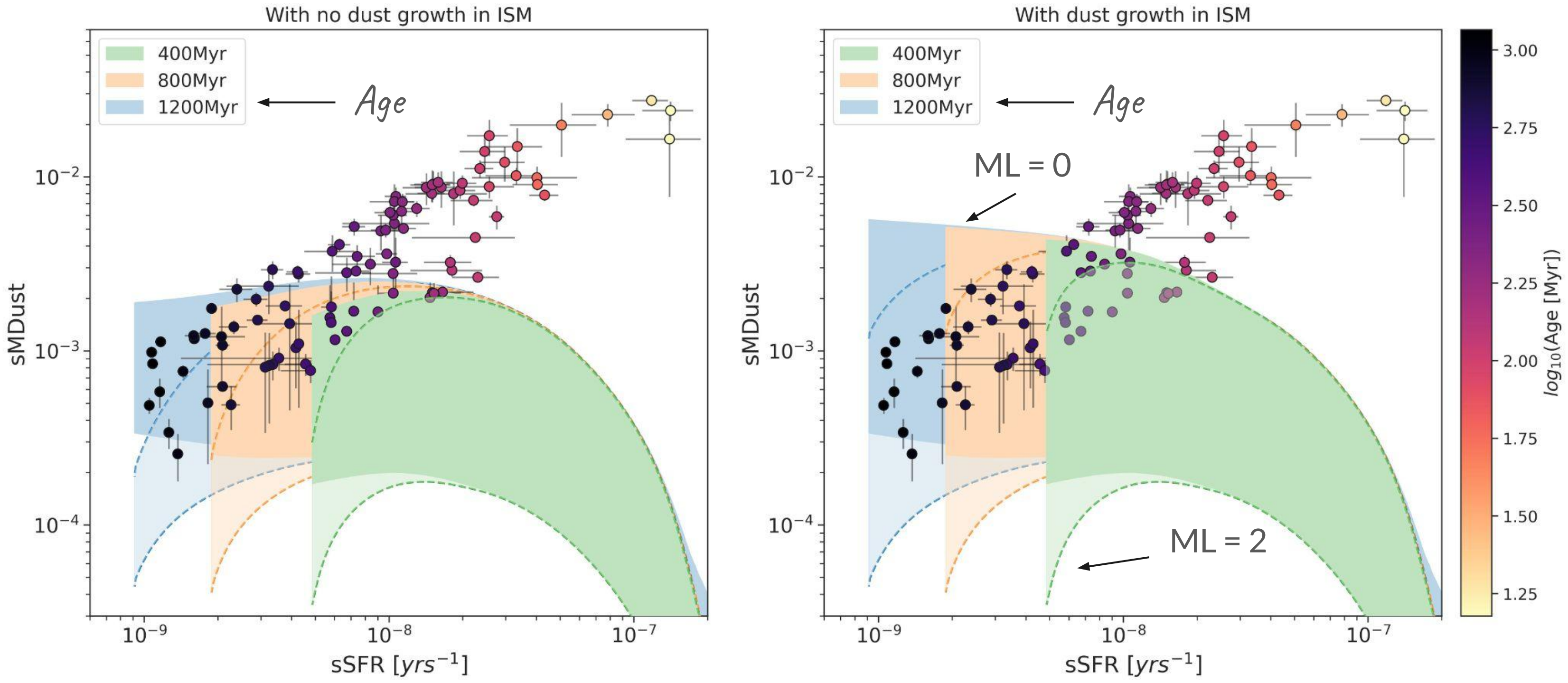


[Sawant+, submit. to collab]

Observations vs Predictions

- Evolution of specific gas mass with age of the main stellar population.
- Galactic outflows required to reproduce the observed gas mass.
- Higher metallicity required for older galaxies.

Observations vs Predictions



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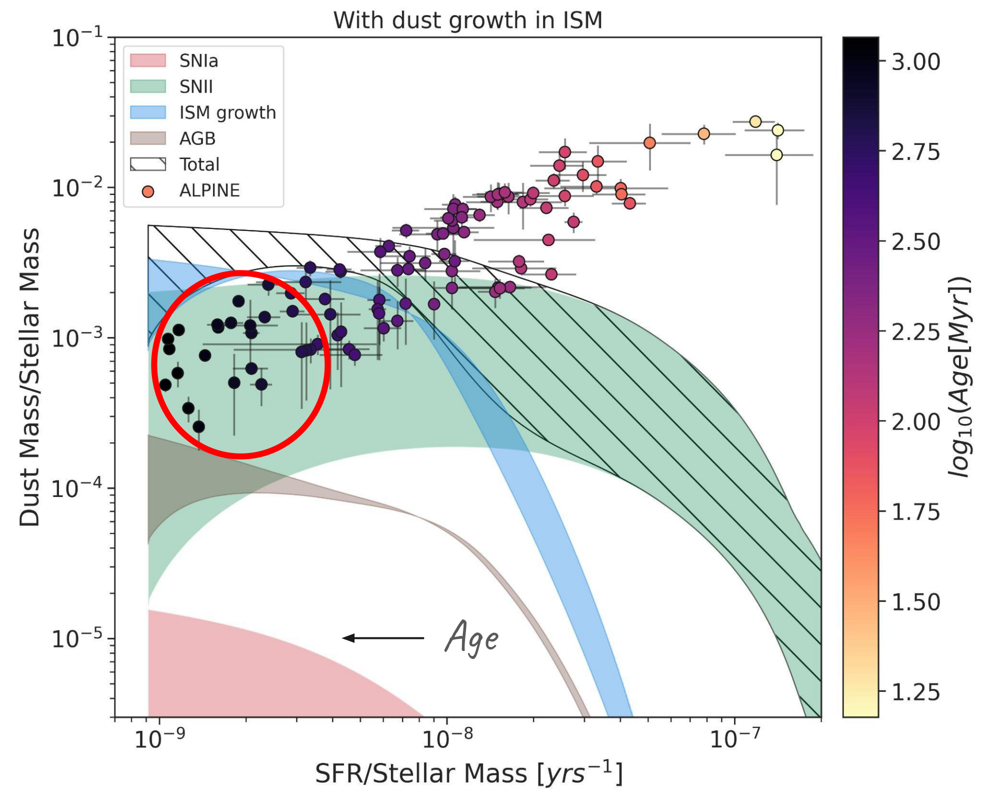
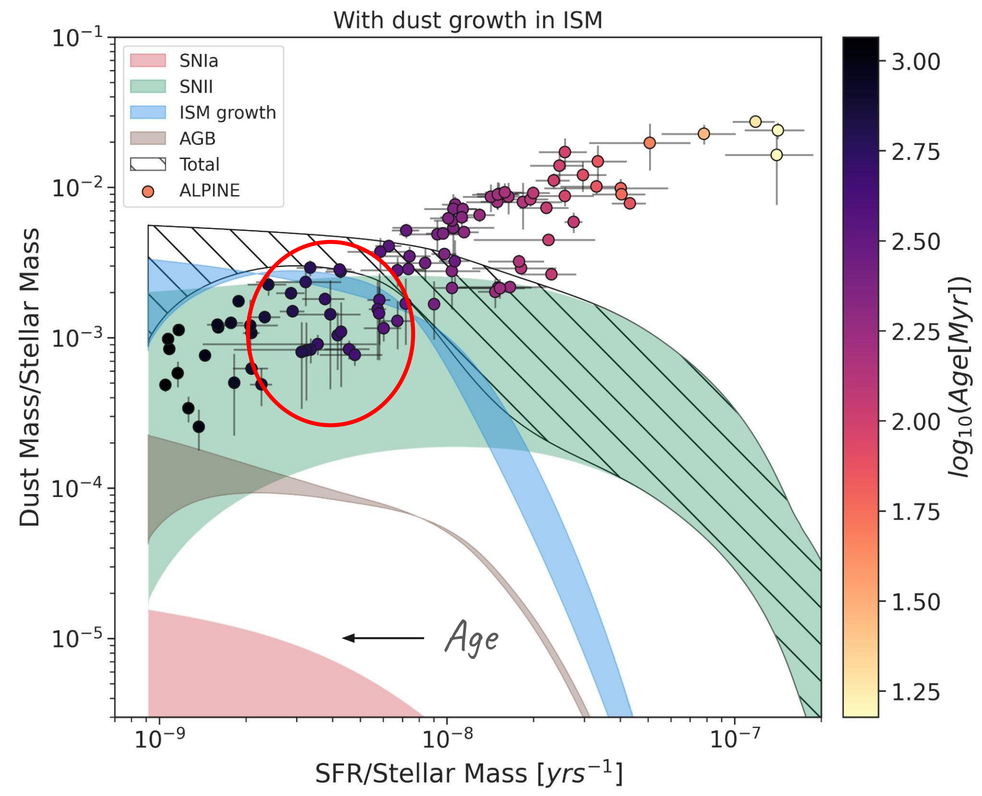


[Sawant+, submit. to collab]

- SNII and AGB - major contributors to the dust content for older galaxies (> 600 Myrs).

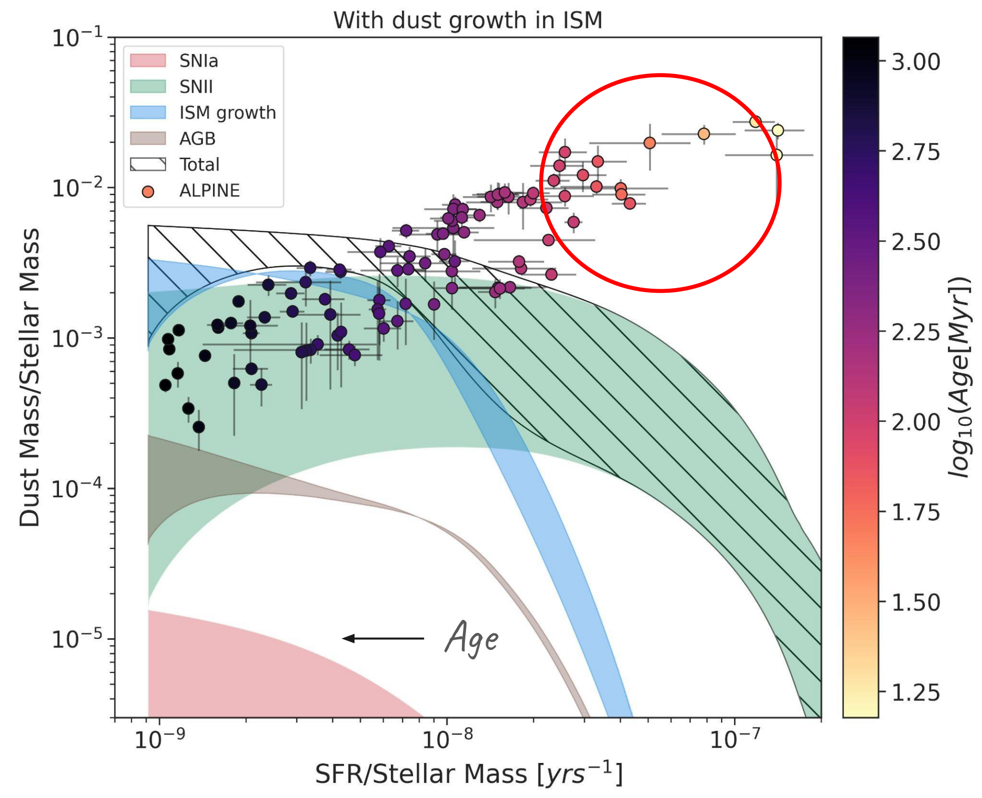


[Sawant+, submit. to collab]

Observations vs Predictions

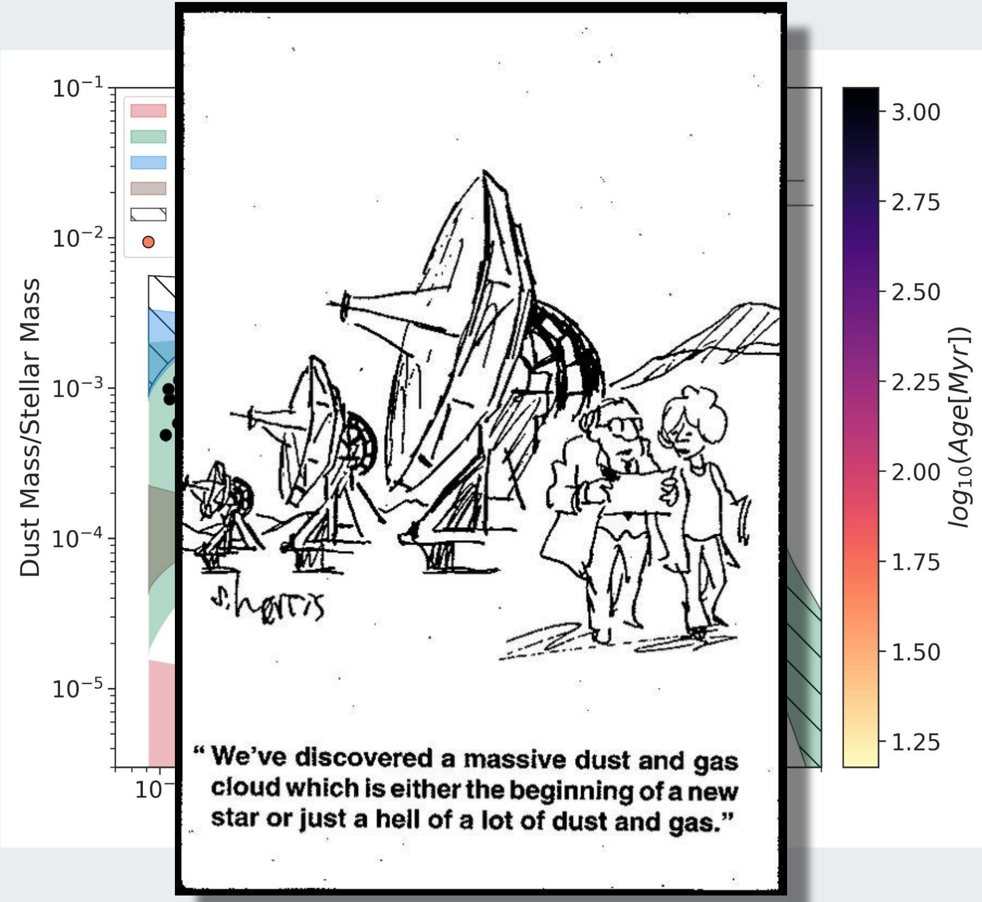
- SNII and AGB - major contributors to the dust content for older galaxies (> 600 Myrs).
- Dust growth in ISM required to reproduce galaxies with intermediate ages (300 - 600 Myrs).

Observations vs Predictions



[Sawant+, submit. to collab]

- SNII and AGB - major contributors to the dust content for older galaxies (> 600 Myrs).
- Dust growth in ISM required to reproduce galaxies with intermediate ages (300 - 600 Myrs).
- Younger galaxies with high dust masses are not reproduced.



Tensions?

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- Dust growth in ISM required to reproduce galaxies with intermediate ages (300 - 600 Myrs).
- Younger galaxies with high dust masses are not reproduced.

[W.B]

Contributions to the baryonic content of the ISM

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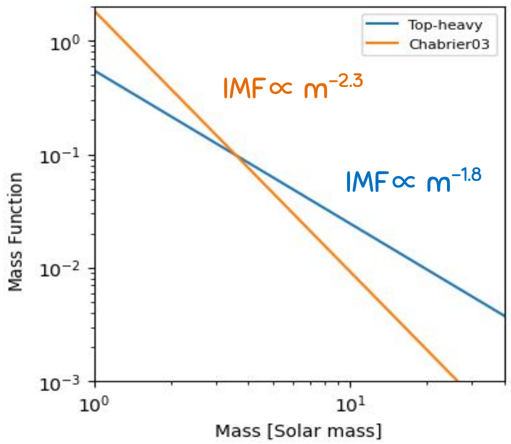
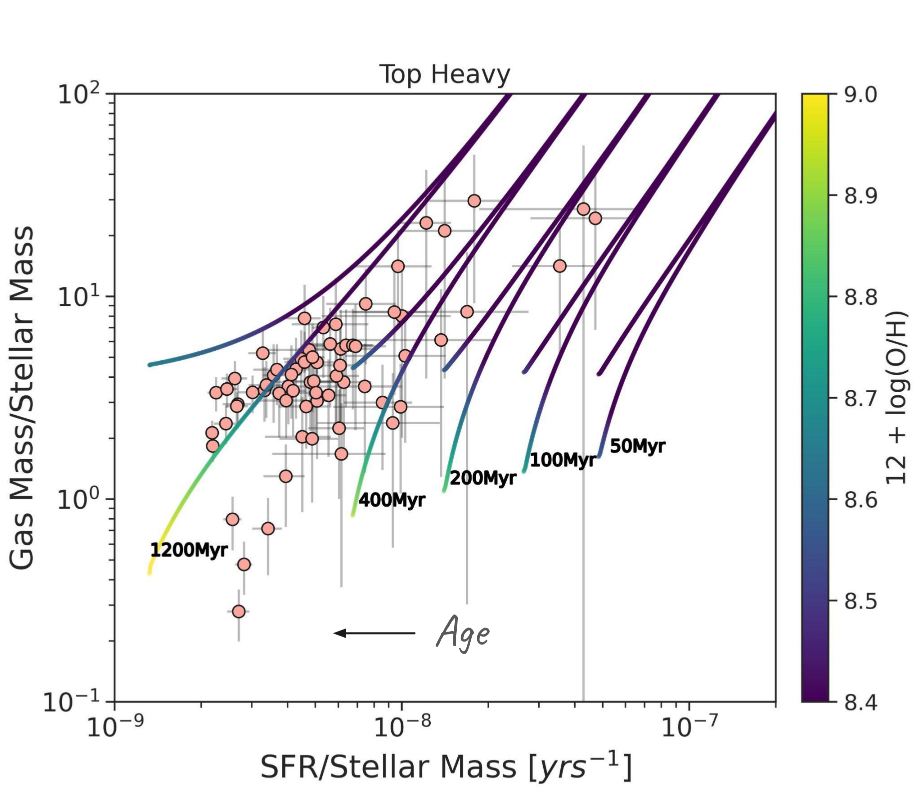
Hypothesis

A variational IMF

- Initial mass function: Quantifies the distribution of stellar mass in the stellar population of a galaxy.
- Determines the chemical evolution of the galaxy and how the baryonic content changes.
- Studies suggesting variational IMF:
    - Local universe: Dabringhausen+12, Geha+13, Marks+12, McWilliam+13, Sliwa+17, Brown & Wilson+19
    - High-z universe: Zhang+18, Sneppen+22, Bekki & Tsuijimoto+23, Steinhardt+22, 23, Sun+24
- Top-Heavy
- Chabrier+03



Let's try



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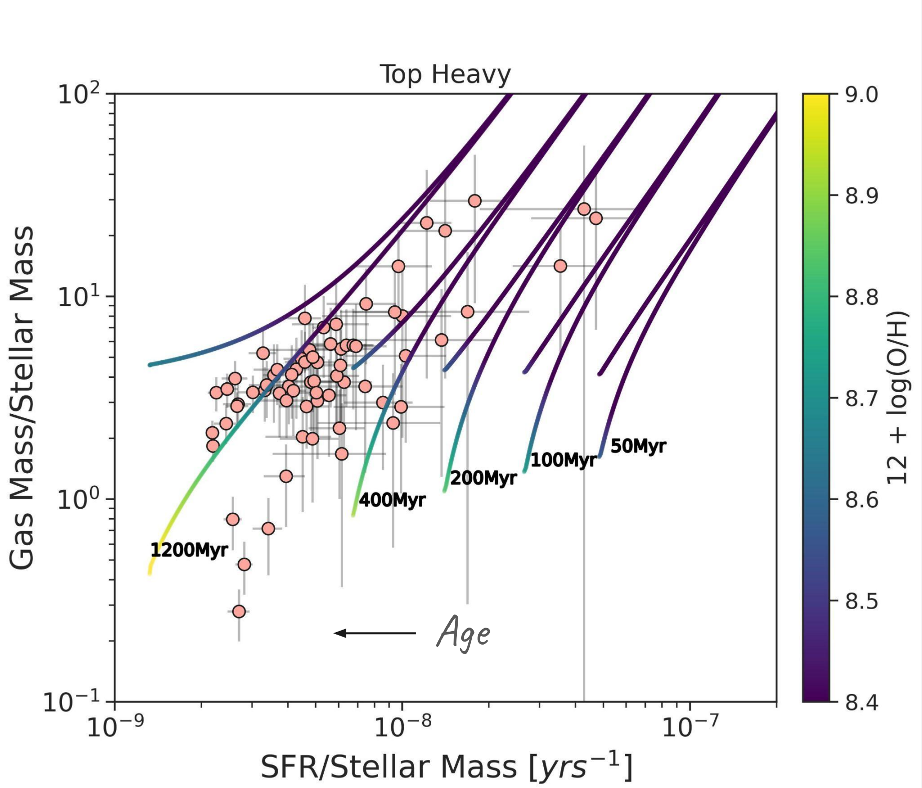
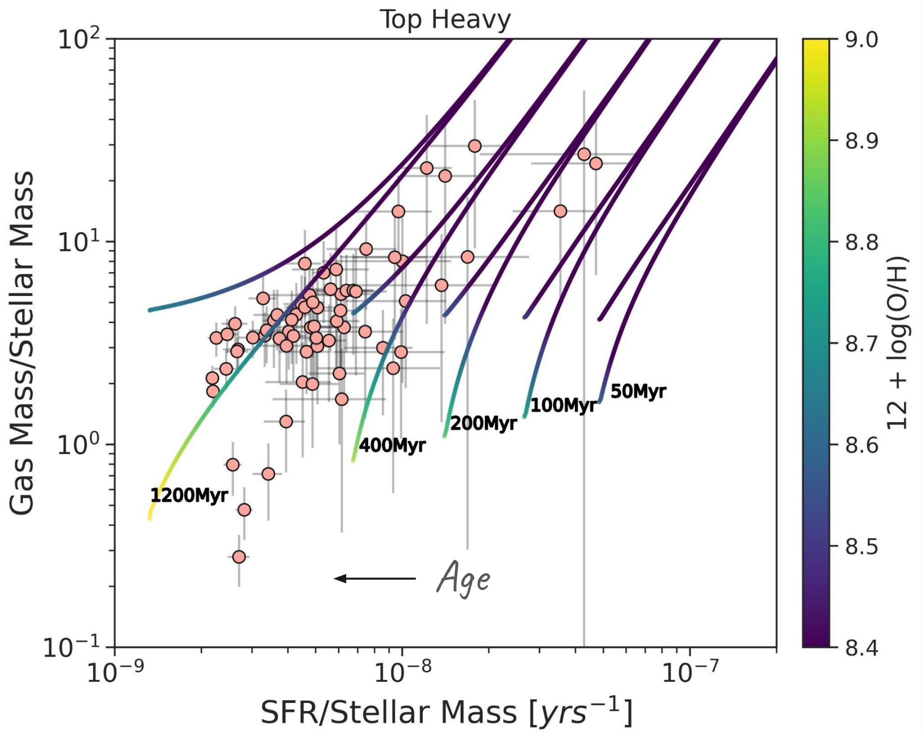


[Sawant+, submit. to collab]

Observations vs Predictions

- Older ages preferred through SED fitting.

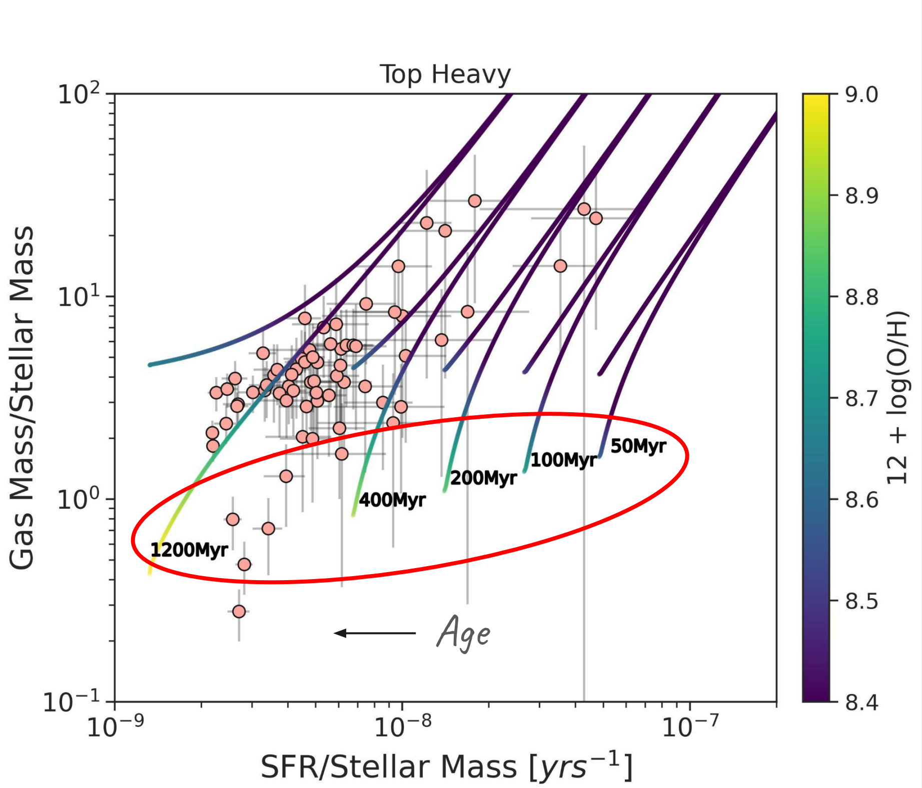


[Sawant+, submit. to collab]

Observations vs *Predictions*

- Older ages preferred through SED fitting.
- More gas required (Mgas, ini = 4.4) compared to Chabrier (Mgas, ini = 3.3).

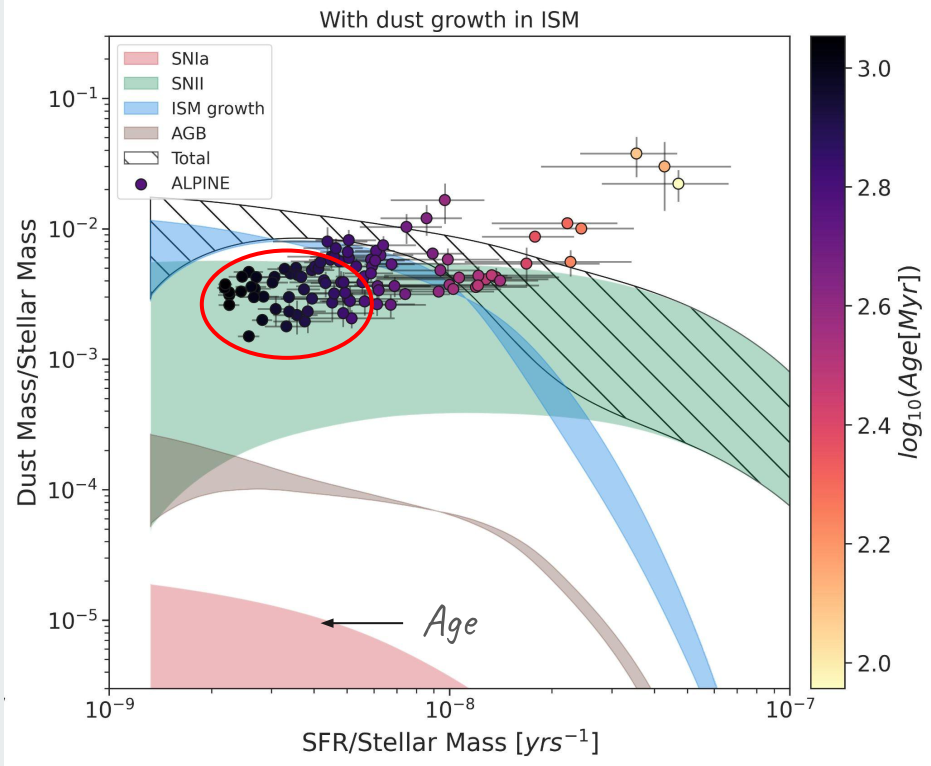
Observations vs Predictions



[Sawant+, submit. to collab]

- Older ages preferred through SED fitting.
- More gas required (Mgas, ini = 4.4) compared to Chabrier (Mgas, ini = 3.3).
- Galactic outflows are *required.*

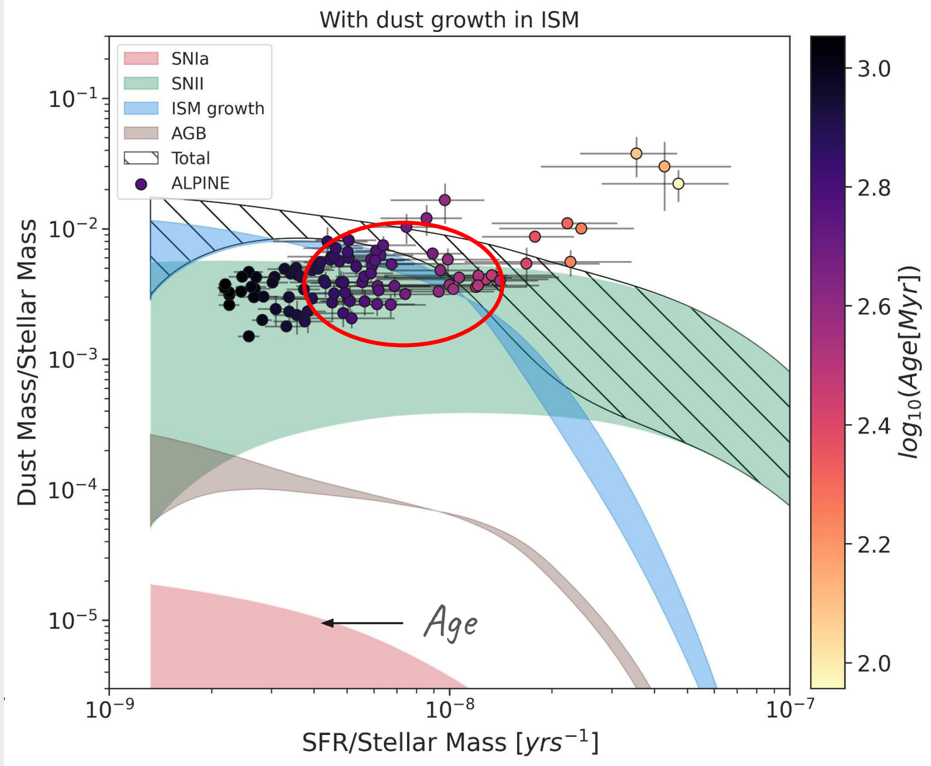
Observations vs Predictions



[Sawant+, submit. to collab]

- Older galaxies (> 800 Myrs) are reproduced assuming higher condensation fractions (60%) for SNII.

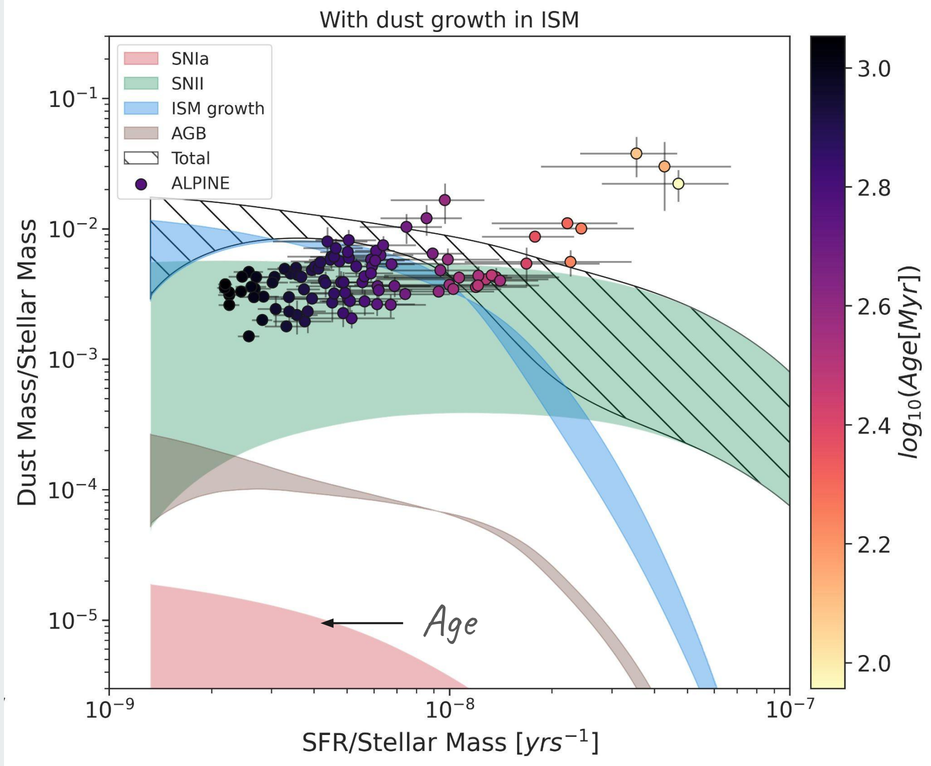
Observations vs Predictions



[Sawant+, submit. to collab]

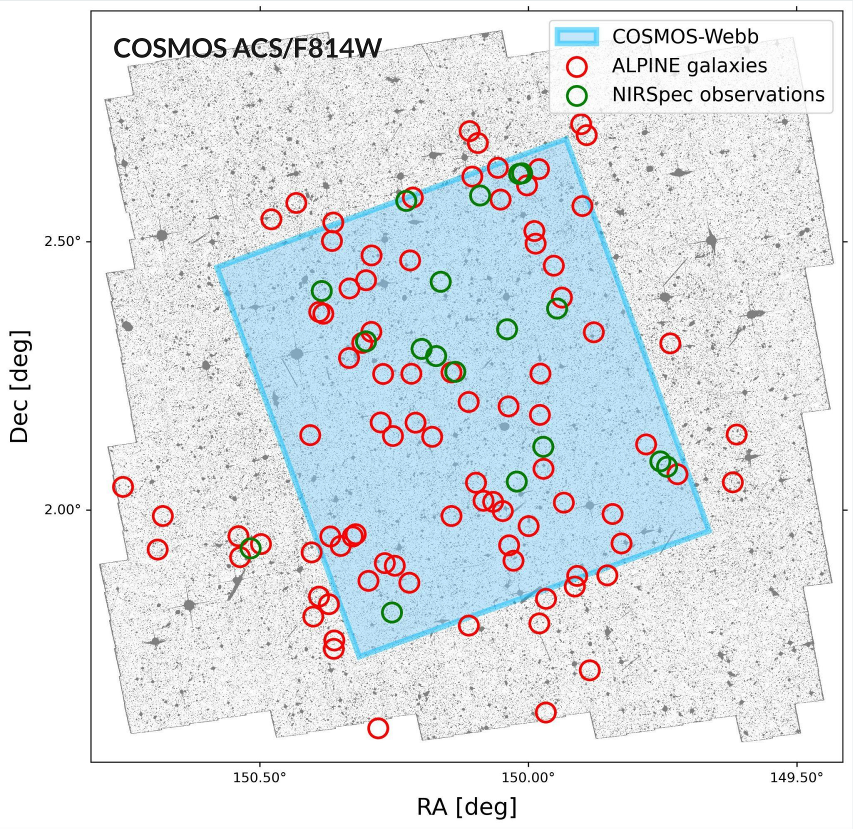
- Older galaxies (> 800 Myrs) are reproduced assuming higher condensation fractions (60%) for SNII.
- For younger galaxies (< 300 Myrs), dust growth in ISM is required, where SNII + AGB are insufficient.

Observations vs Predictions



[Sawant+, submit. to collab]

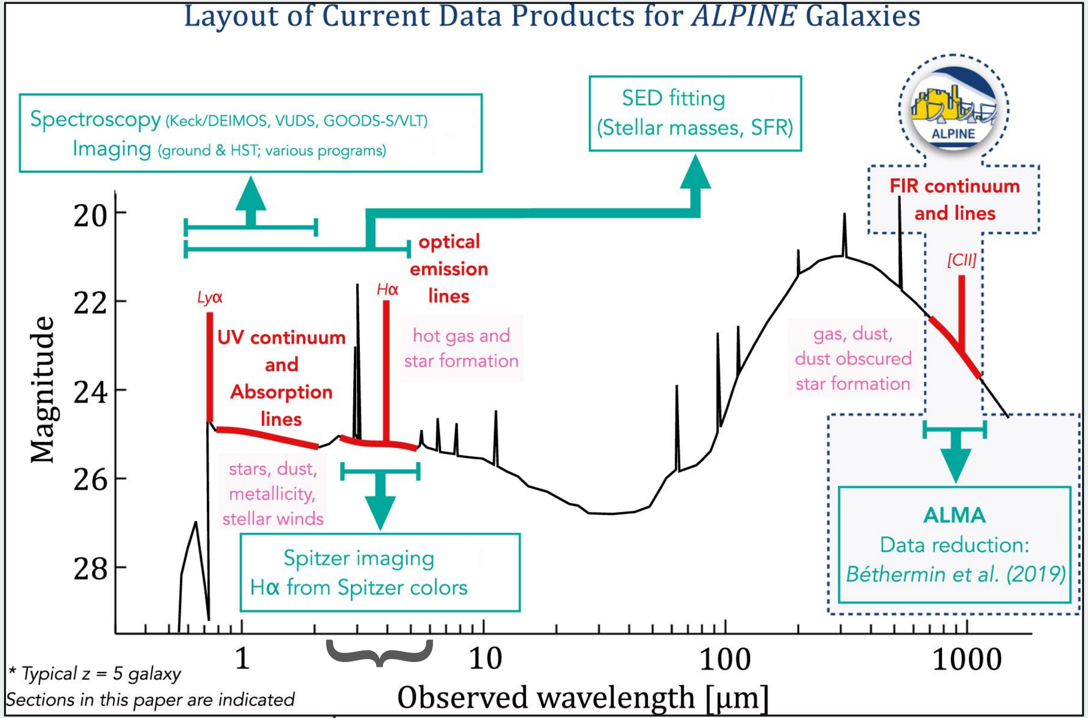
- Older galaxies (> 800 Myrs) are reproduced assuming higher condensation fractions (60%) for SNII.
- For younger galaxies (< 300 Myrs), dust growth in ISM is required, where SNII + AGB are insufficient.
- ~90% of galaxies are reproduced with top-heavy compared to ~60% with Chabrier.



[M. Romano]

The Future

- Observations from COSMOS-Webb and NIRSpec datasets.



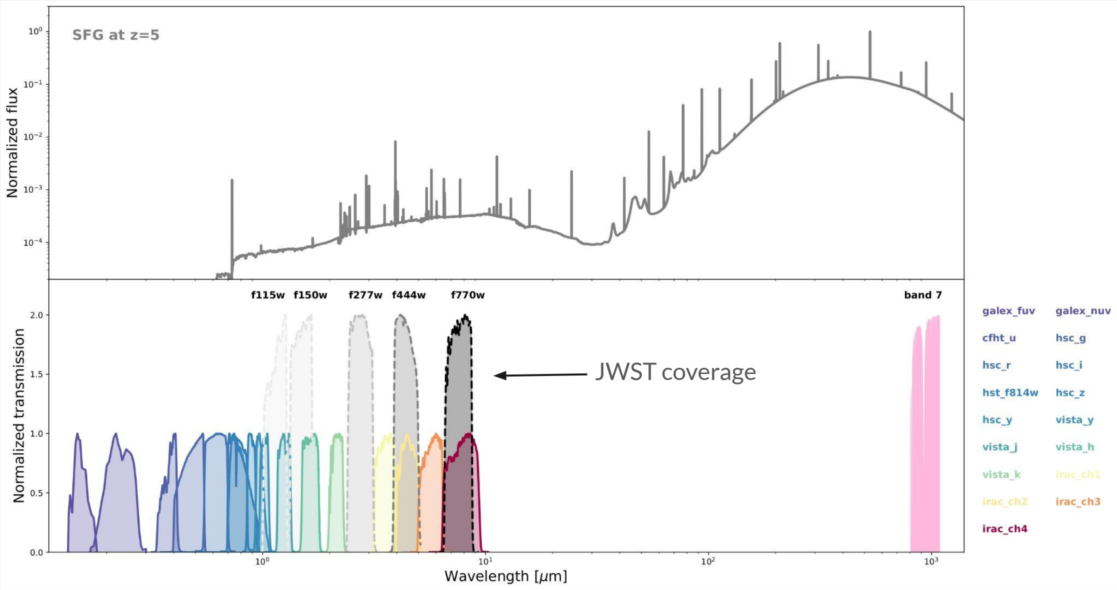
[Faisst+20]

Optical photometry from COSMOS-Webb & continuum with NIRSpec (A. Faisst, PID: 3045)

The Future

- Observations from COSMOS-Webb and NIRSpec datasets.
- Constraining the estimates of stellar mass and star formation rates.

The Future



[M. Romano]

- Observations from COSMOS-Webb and NIRSpec datasets.
- Constraining the estimates of stellar mass and star formation rates.
- Provide insights about SFHs, metallicities and various properties about ISM.

In short...

- Canonical descriptions of IMF can reproduce dust content in older galaxies but fails to reproduce observations in younger galaxies where rapid dust build-up is involved.

- Models show intermediate age galaxies with high dust content prefer a top-heavy IMF with dust growth in ISM as the primary contributor.

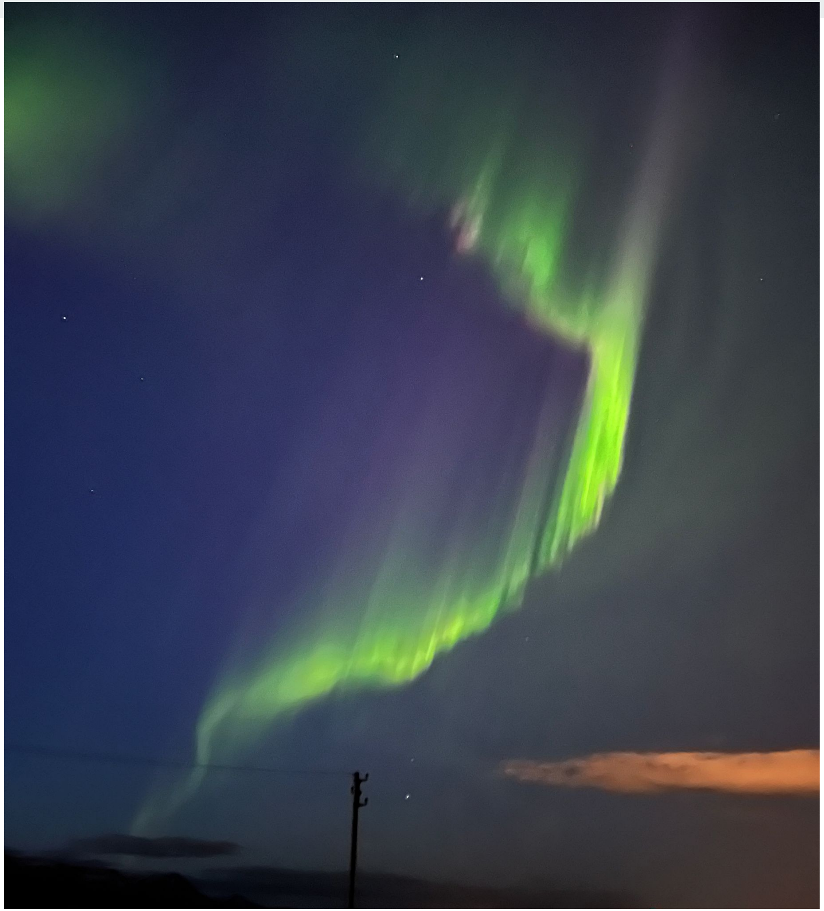
- Galaxies with higher dust content and younger ages are still in tension with models motivating further investigation with more constraints using the ever increasing observations.

Thank You

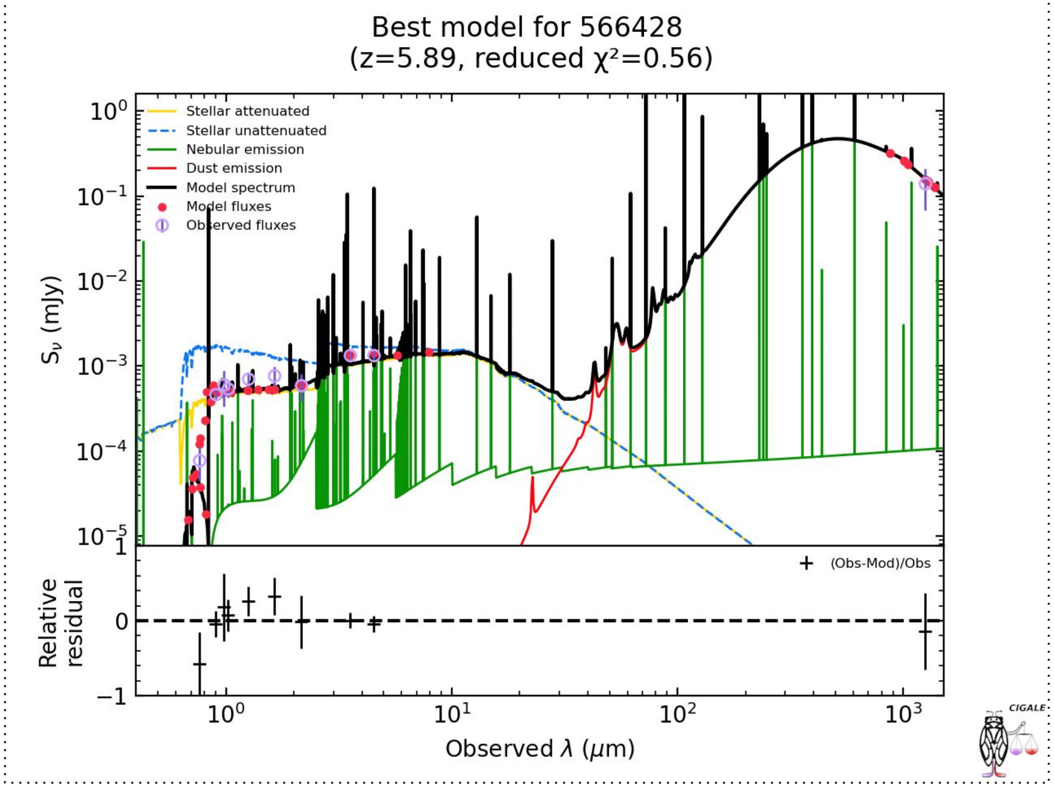
Questions, comments and criticism are welcome!

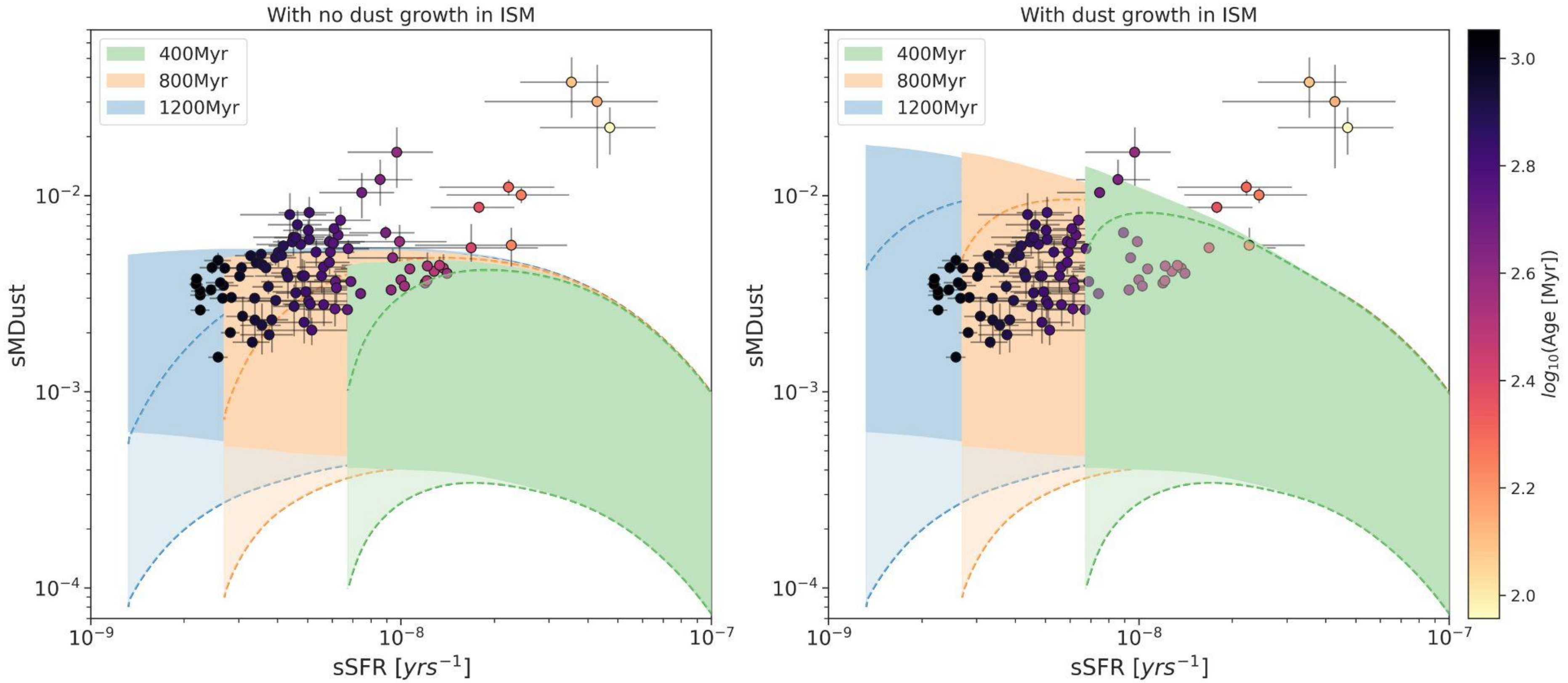
Or we can just move on to coffee.

[Iceland, 27th April]



SED fit of a galaxy





With no dust growth in ISM
400Myr
800Myr
1200Myr
sMDust
sSFR [yrs⁻¹]
With dust growth in ISM
400Myr
800Myr
1200Myr
sMDust
sSFR [yrs⁻¹]
log10(Age [Myr])