Knocking on giant's doors:

The evolution of the dust-to-stellar mass ratio in distant galaxies

Darko Donevski, SISSA, Trieste

Collaborators:

A. Lapi, L. Pantoni (SISSA, Trieste)
R. Davé, K. Kraljic (ROE, Edinburgh)
D. Narayanan, Q. Li (Uni. Florida)
K. Malek, W. Pearson (NCBJ, Warsaw)
D. Liu (MPIA, Heidelberg)
C. Gomez-Guijarro (CEA, Saclay, Paris)
A. Man (Dunlap, Uni. Of Toronto)
A. Feltre (INAF, Bologna)
S. Fujimoto (DAWN, Copenhagen)
I. Damjanov (SMU, Halifax)

Online seminar, INAF, IASF, Milan 12/05/2021

Outline of the talk:

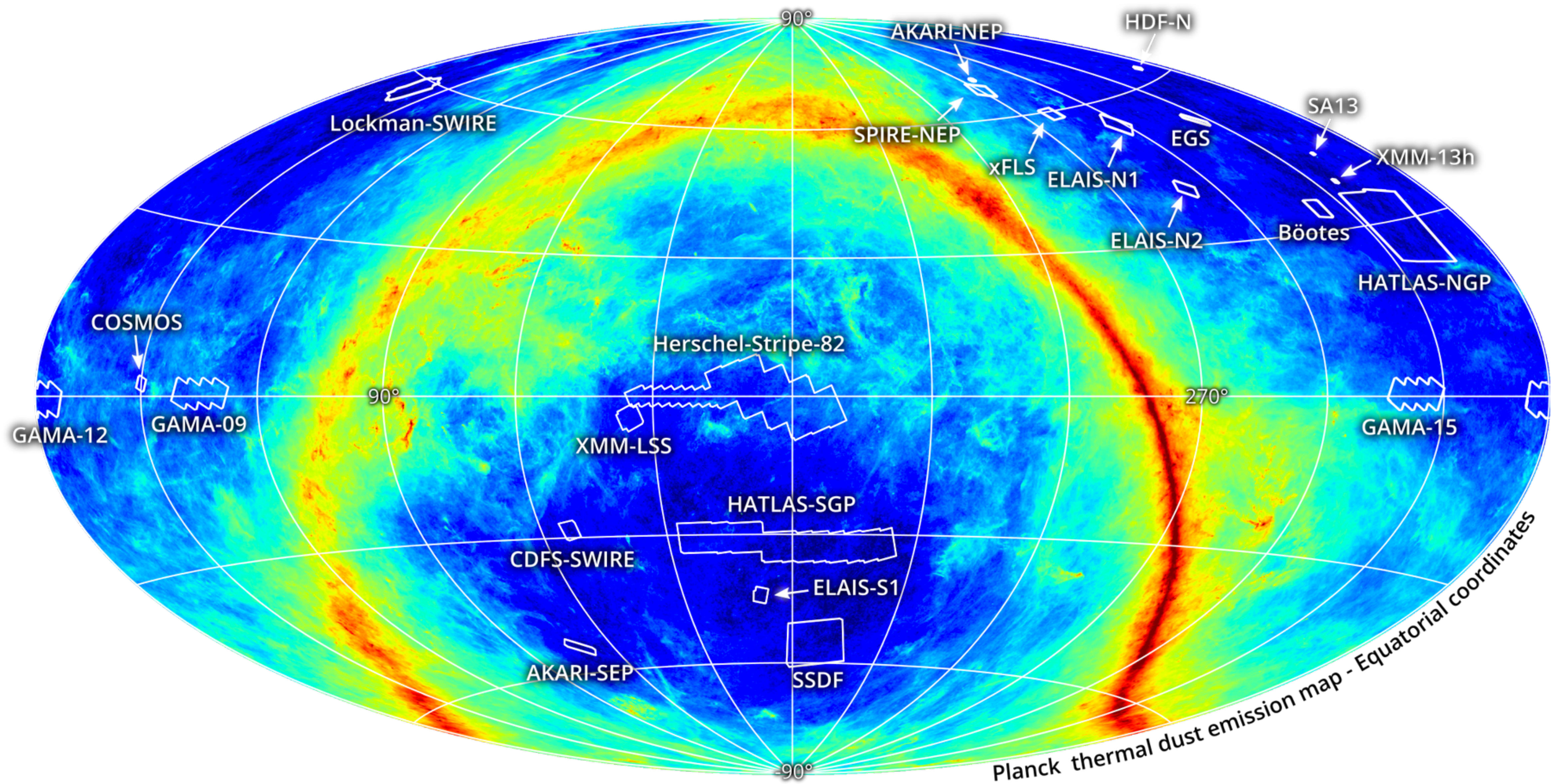
1. **Introduction:**
   Importance of studying the dust-to-stellar mass ratio in dusty star-forming galaxies (DSFGs)

2. **The observed evolution of the dust-to-stellar mass ratio**
   (Insight from ALMA observations)

3. **The modelled evolution of the dust-to-stellar mass ratio in simulations**
   (The observed evolution withing the cosmological framework)

Summary and future prospects

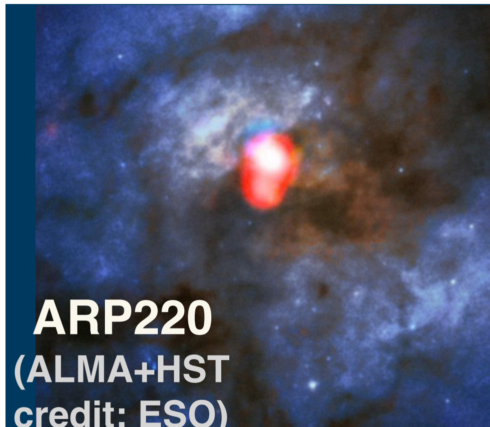
How do we know about hidden "giants" in the Universe ?



Credit: HELP collaboration

Herschel (far-IR) observed more than 1000 sq.degrees of the sky
+ in COSMOS field only there are ~1000 galaxies detected with ALMA

What did we learn from existing studies of DSFGs?



ARP220
(ALMA+HST
credit: ESO)

0 2 7

Redshift *(z)*

Dusty Star-forming Galaxy
(DSFG) at low-z

What did we learn from existing studies of DSFGs?

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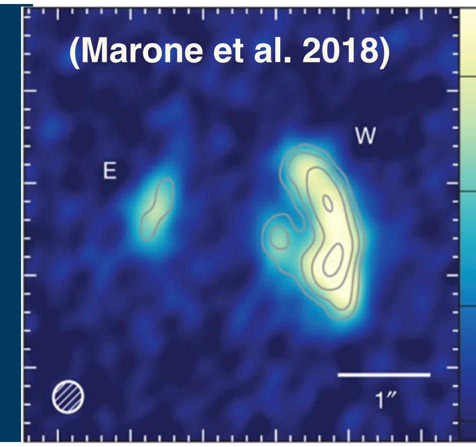

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2

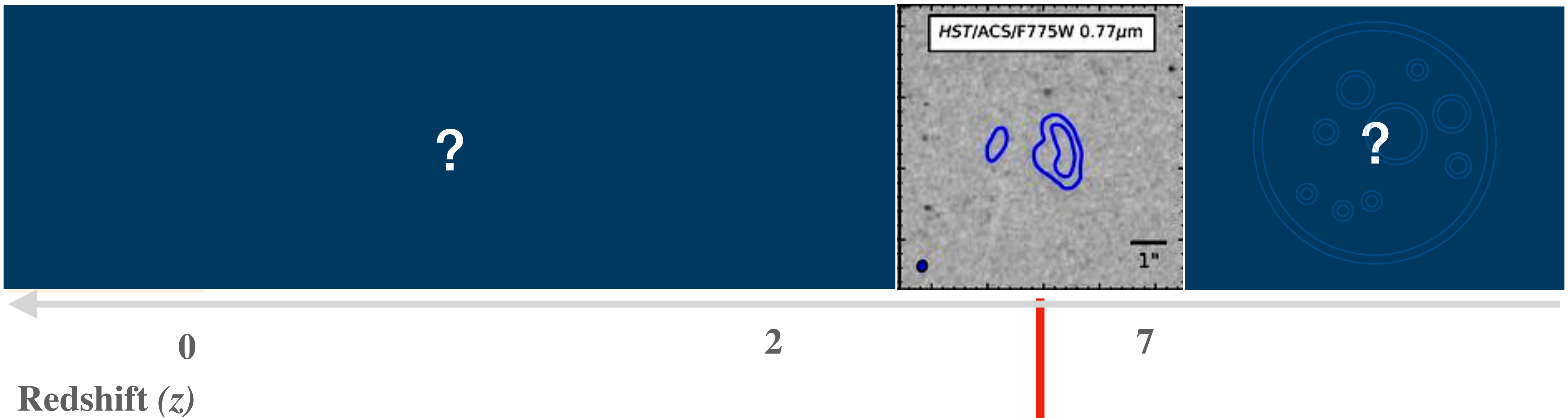
7

Redshift (*z*)

Dusty Star-forming Galaxies (DSFGs) at high-z

- **The highest star-formation rate in the Universe** (SFR > 500-2000 $M_\odot$/yr)
- **Most extreme tail of the galaxy stellar and dust mass function** ($M_\star > 10^{10}\ M_\odot$, Bethermin+ 2017)
- DSFGs confirmed even at $z{\sim}7$ (Harikane+ 2019, Strandet+ 2017, Riechers+ 2013) and show **tight connection to overdensities** (e.g. Miller+ 2018, Harikane+ 2019)

What did we learn from existing studies of DSFGs?



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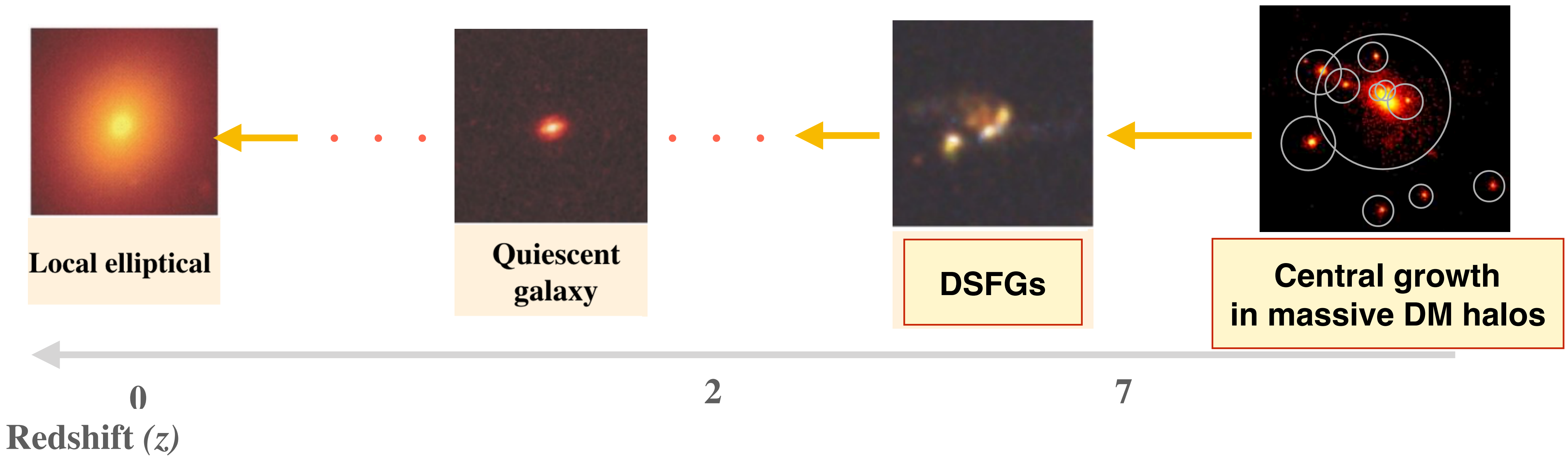
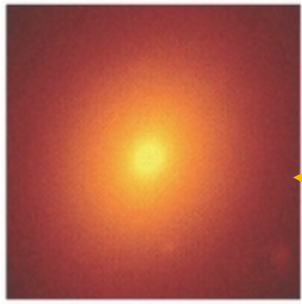
DSFGs - importance for galaxy formation & evolution



Dusty, star-forming galaxies are crucial to understand:

- The growth and evolution of early massive structures !
- Conditions for extreme star-formation and dust production in the distant Universe !

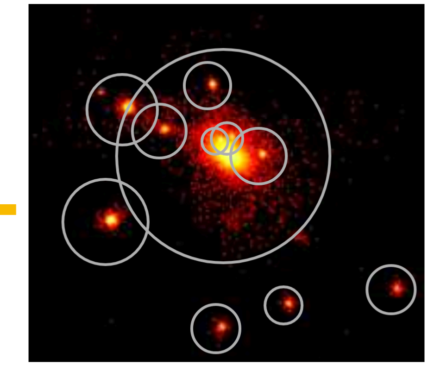
DSFGs - importance for galaxy formation & evolution



Local elliptical

Quiescent galaxy

DSFGs



Central growth in massive DM halos

0 2 7

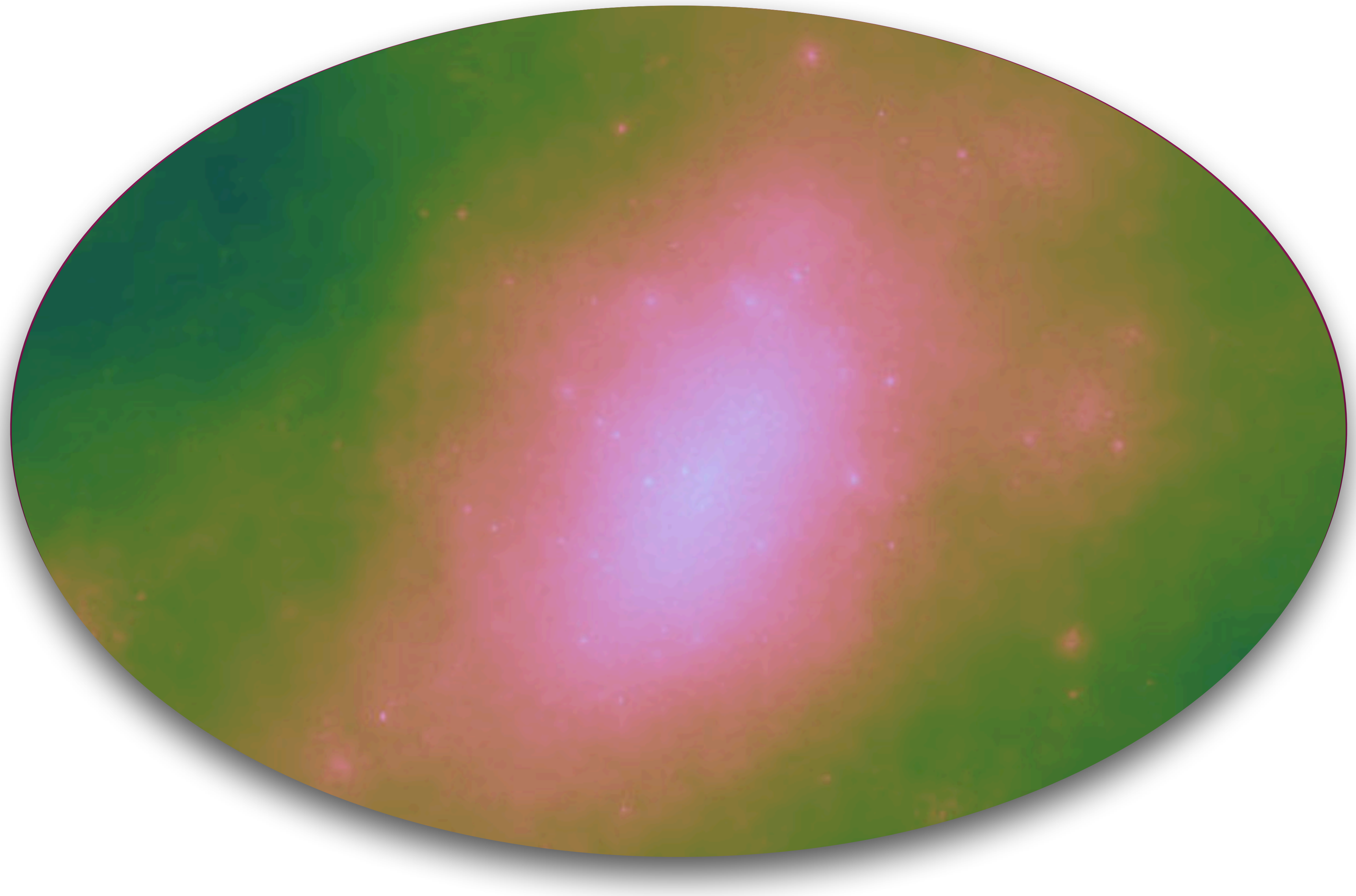
Redshift *(z)*

Q1: How these dusty “GIANTS” grow so fast?

Q2: How ther dust/stellar/gas content changed over cosmic times?

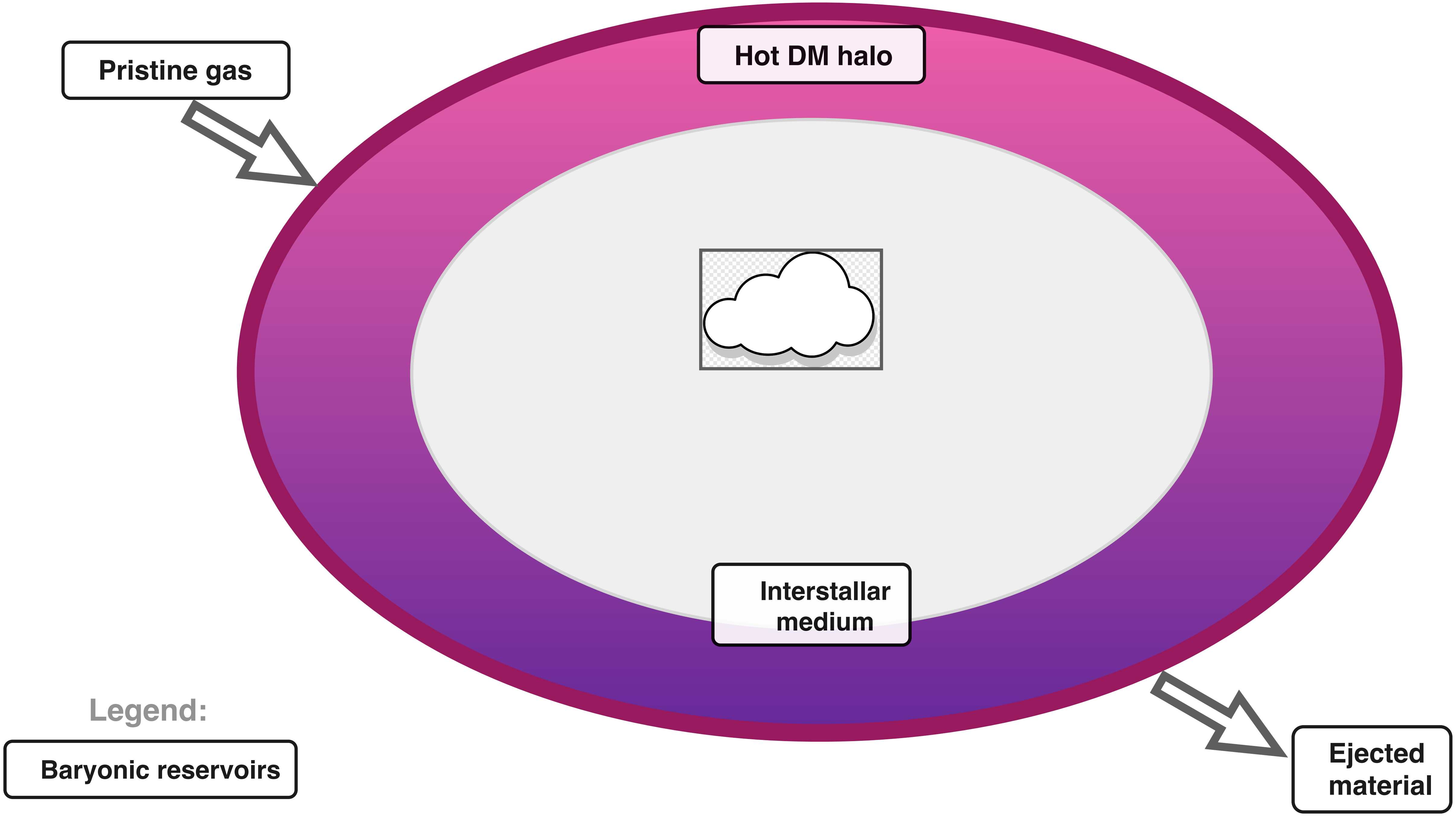
Q3: Are all quiescent and massive galaxies devoid of dust?

1.1 Modelling the evolution of dust/stars/gas in galaxy evolution



➡ Importance of dust modelling within the galaxy evolution framework

1.1 Modelling the evolution of dust/stars/gas in galaxy evolution



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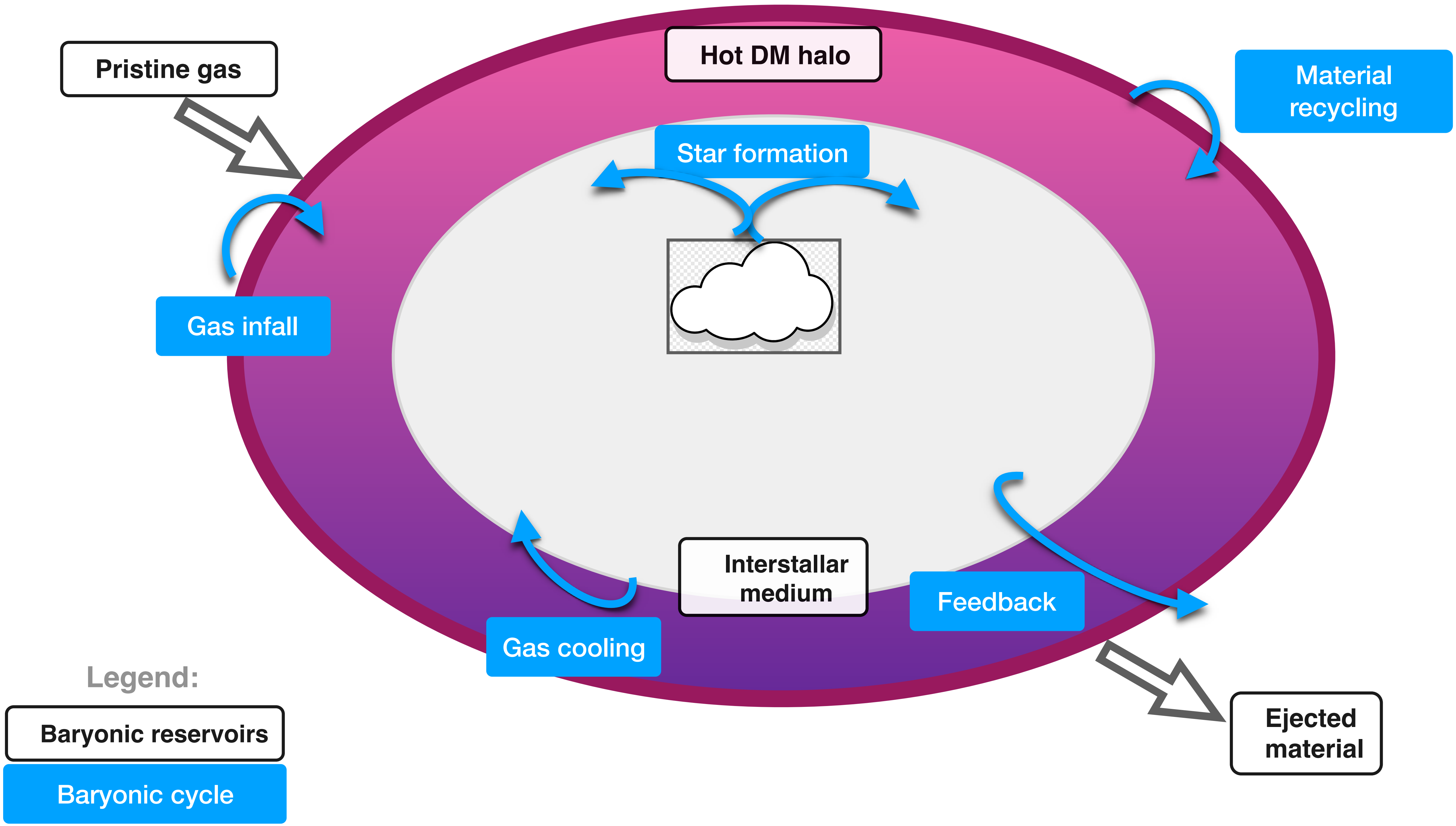

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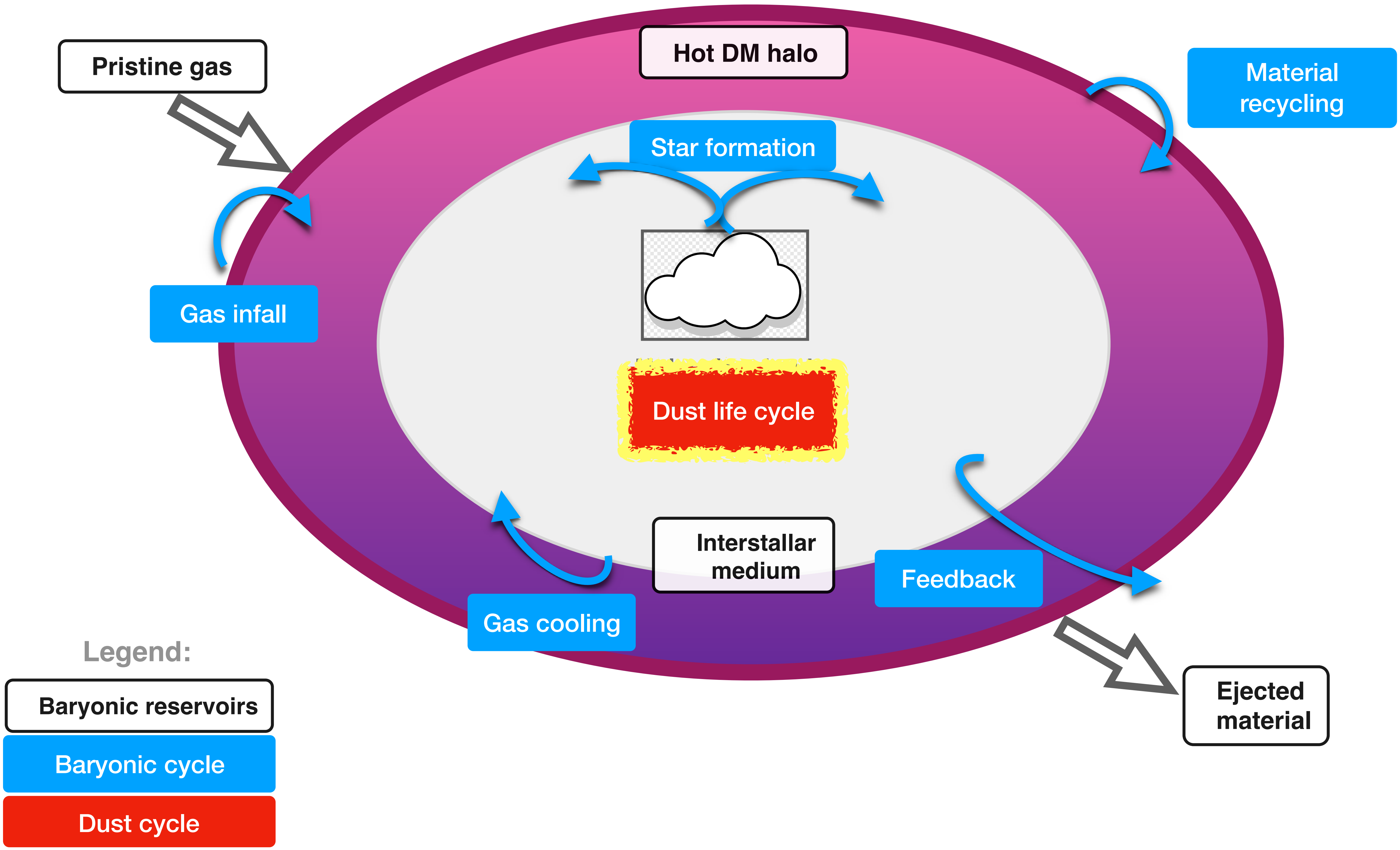

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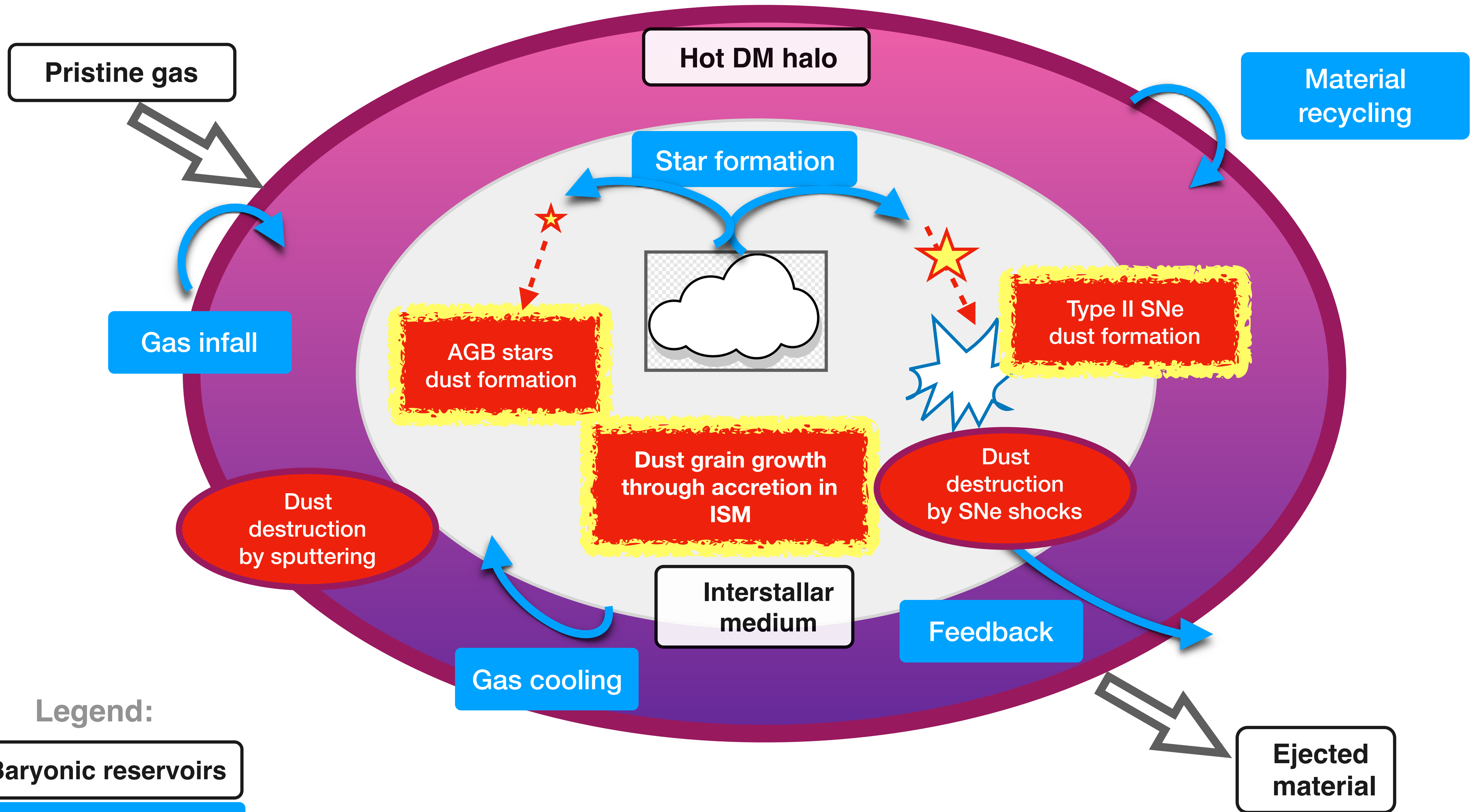


Legend:

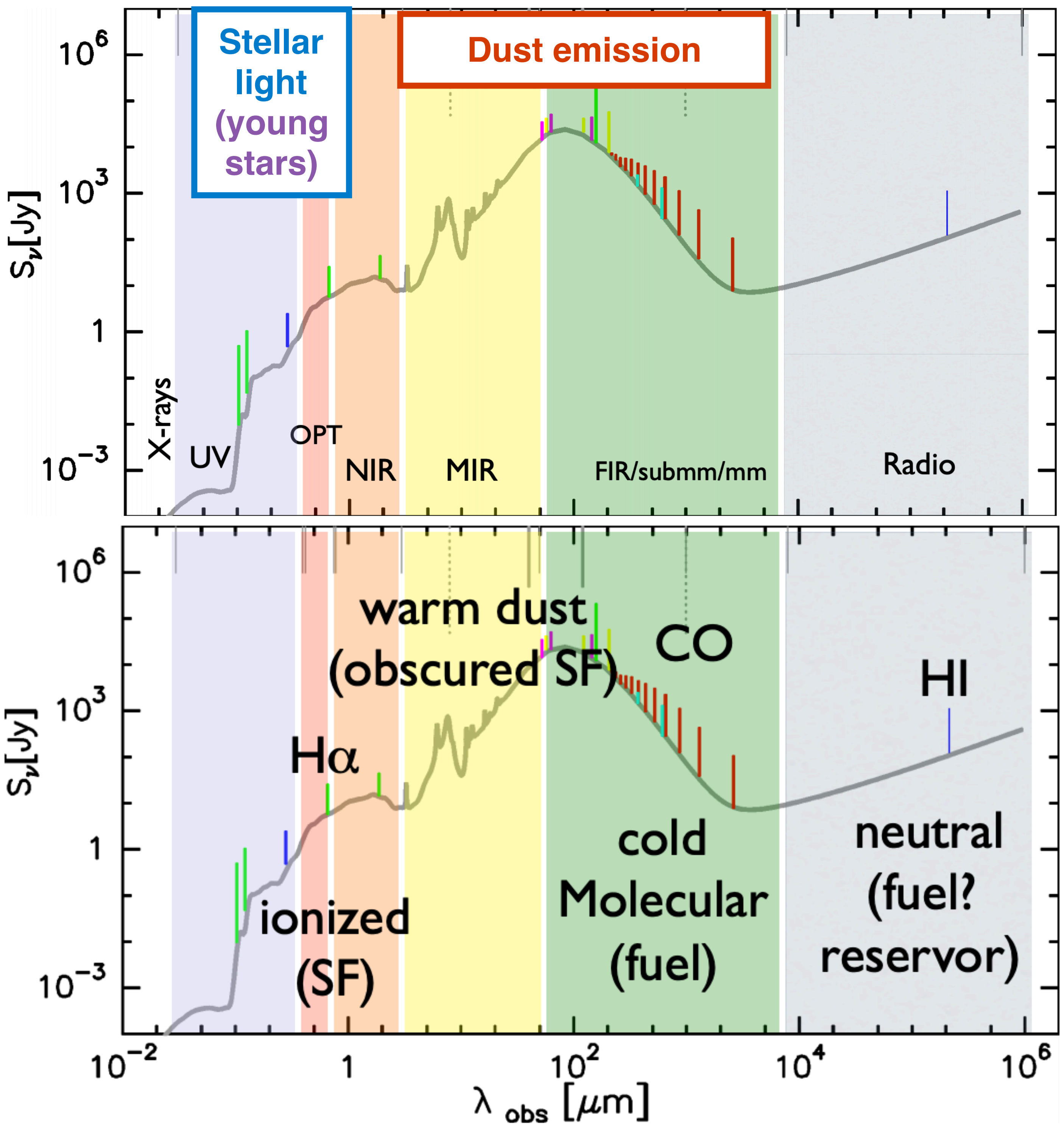
- Baryonic reservoirs
- Baryonic cycle
- Dust cycle

(I) Complex link of gas, stars & dust in galaxy evolution !

(II) Measure of different dust production/destruction processes !

1.2 Inferring physical properties of dusty galaxies

Full Spectral Energy Distribution (SED) of galaxies



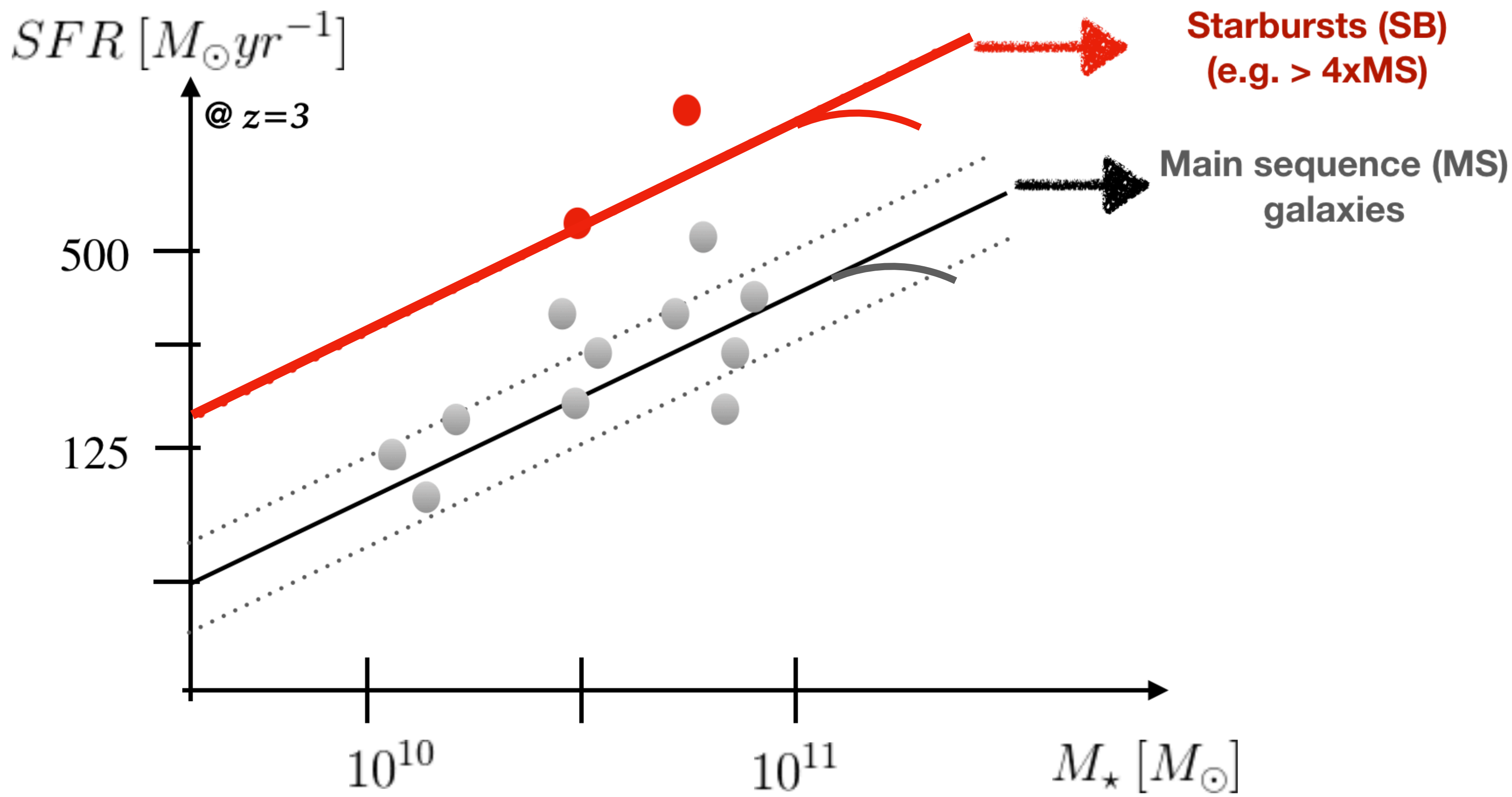
1. Full SED allows us to estimate:

- SFR (total) = SFR (UV) + SFR (IR)
- Stellar mass
- Dust mass

2. Dust mass can be applied as a **tracer of molecular gas mass** in massive galaxies !

➡ Studying the evolution of **ISM through observed SEDs** of dusty galaxies!

Main sequence of galaxies



(e.g. Elbaz+ '11, Rodighiero+ '11, Speagle+ '14, Whitaker+ '15, Schreiber+ '15, Pearson+ '18)

➡ **Investigating the conditions for star-formation in diverse SF populations !**

(e.g. MS and SB DSFGs)

Theoretical challenge

(Semi-)Analitic Models (SAMs)	Cosmological simulations	Phenomenological models
DURHAM (Lacey+ ’10, Lacey+ ‘16) L-GALAXIES (Vijayan+ ‘19) G.A.S (Causin+ ‘19) Popping+ ’17 SHARK (Lagos+ ’19) Pantoni+ ’19	Shimizu+ ’12 Illustris (McKinnon+ ‘17) Dusty-Gadget (Graziani+ ’19) SIMBA (Davé+ ’19, Li+ ’19)	Schreiber+ ’16 Casey ’18 Bethermin+ ’17

(+) Simultaneously explain the redshift distribution & SMF
(—) Disagree about merger contribution, metallicity, IMF, dust mass function etc.

Main questions & challenges addressed in our work:

- How the dust-to-stellar mass ratio evolves with cosmic time, and position of the galaxy with respect to the main-sequence in disty star-forming galaxies (DSFGs) ?

Observational

- How the cosmic evolution of the dust-to-stellar mass ratio can be understood within the framework of galaxy formation?

Theoretical

Challenges:

- Limited depth/beamsize of FIR surveys
- Lack of exquisite OPT+nearIR+dust SEDs
- Accounting for the AGN-contribution to estimated dust luminosity

- Dust life cycle modelled in a self-consistant way

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- How the dust-to-stellar mass ratio evolves with cosmic time, and position of the galaxy with respect to the main-sequence in disty star-forming galaxies (DSFGs) ?

Observational

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Theoretical

Our work:

- Dust-to-stellar mass ratio as a function of z, sSFR, Mstar & dust size for >300 ALMA galaxies with full SED.

(1) **Donevski et al.**, A&A 644, A144 **(2020)**; arXiv:2008.09995

(2) **Donevski et al.**, to be submitted

II Cosmic evolution of dust-to-stellar mass ratio in DSFGs

Donevski et al., A&A 644, A144 (2020)
arXiv:2008.09995

2.1 Data selection and SED modelling workflow

Initial data: HELP (Shirley et al. 2019)
Field: COSMOS

↓

ALMA+ MIPS/PACS/ SPIRE photometry de-blended with deep IRAC1 priors
(tool: XID+, Hurley et al. 2017)

↓

Final catalogue:

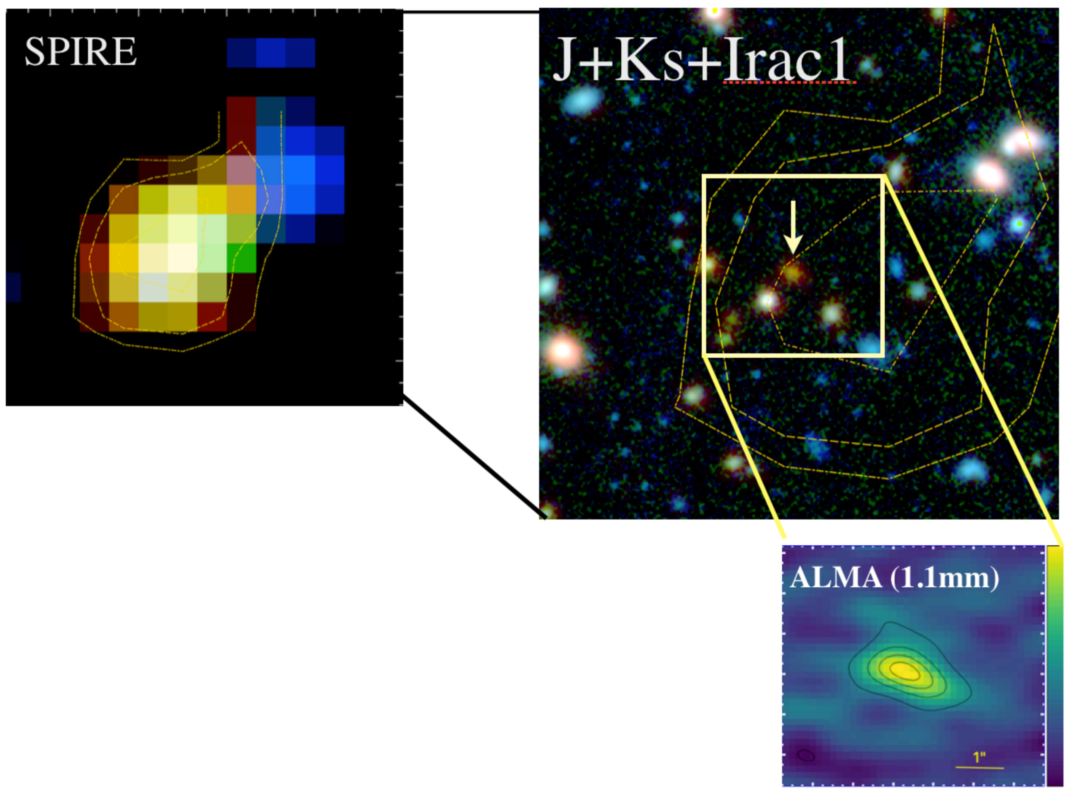
- **300 SF galaxies at $0 < z < 5$**
- **Panchromatic SED:** 10+ bands in **opt-NIR** and 5+ bands in **IR-submm**
- **IR sizes** estimated from ALMA band 6,7

I Data Selection Flow

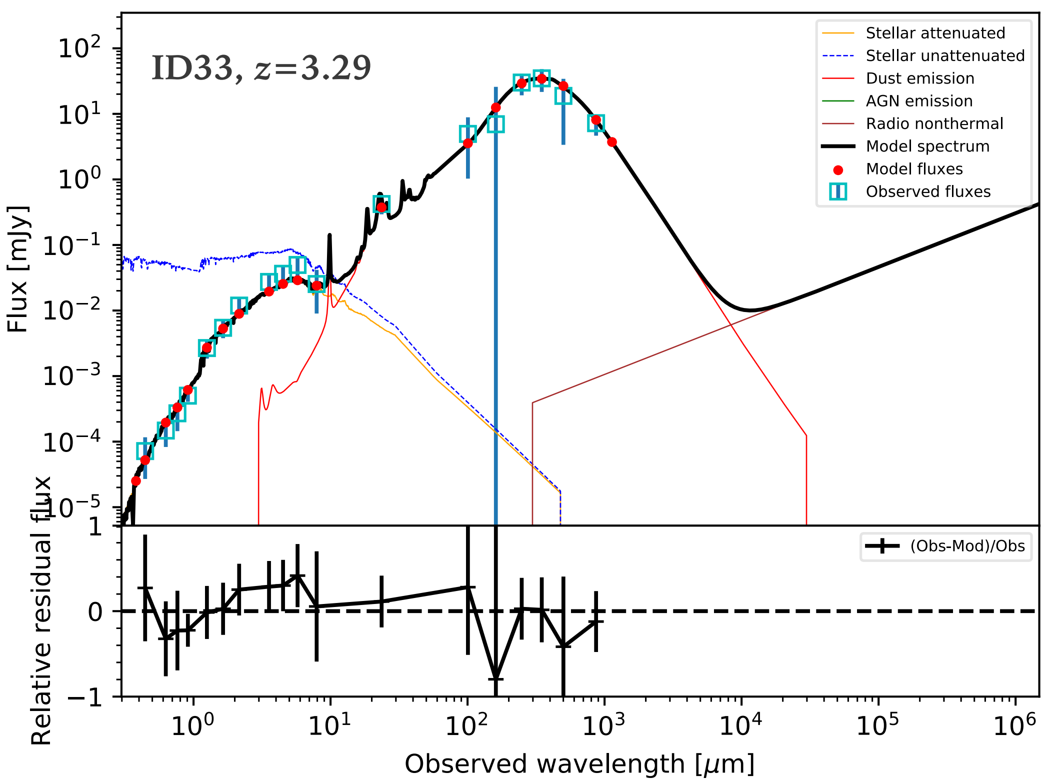
SED modelling
tool: CIGALE (Boquien et al. 2019)

- **modified-CF attenuation law**
- **SFH —> delayed+burst**
- **AGN fraction** derived to dissect AGN and SF
- **Physical dust model** (Draine & Li, 2014)
- **Systematics in** $M_{\rm dust}/M_{\star}$ are corrected with realistic mock simulations.

II Data Analysis



Source 2D cutout



UV-submm SED

(Donevski+ '20)

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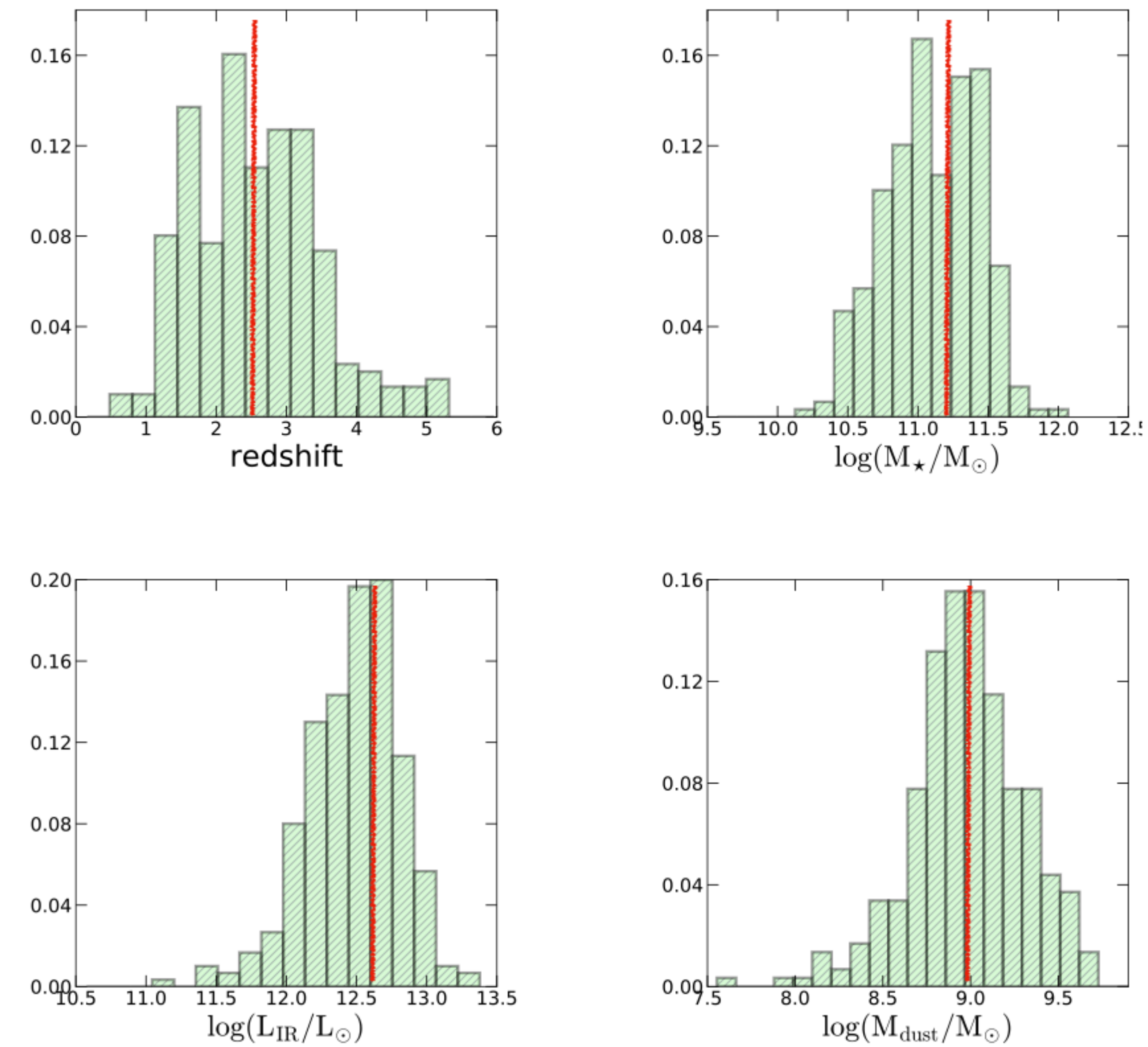
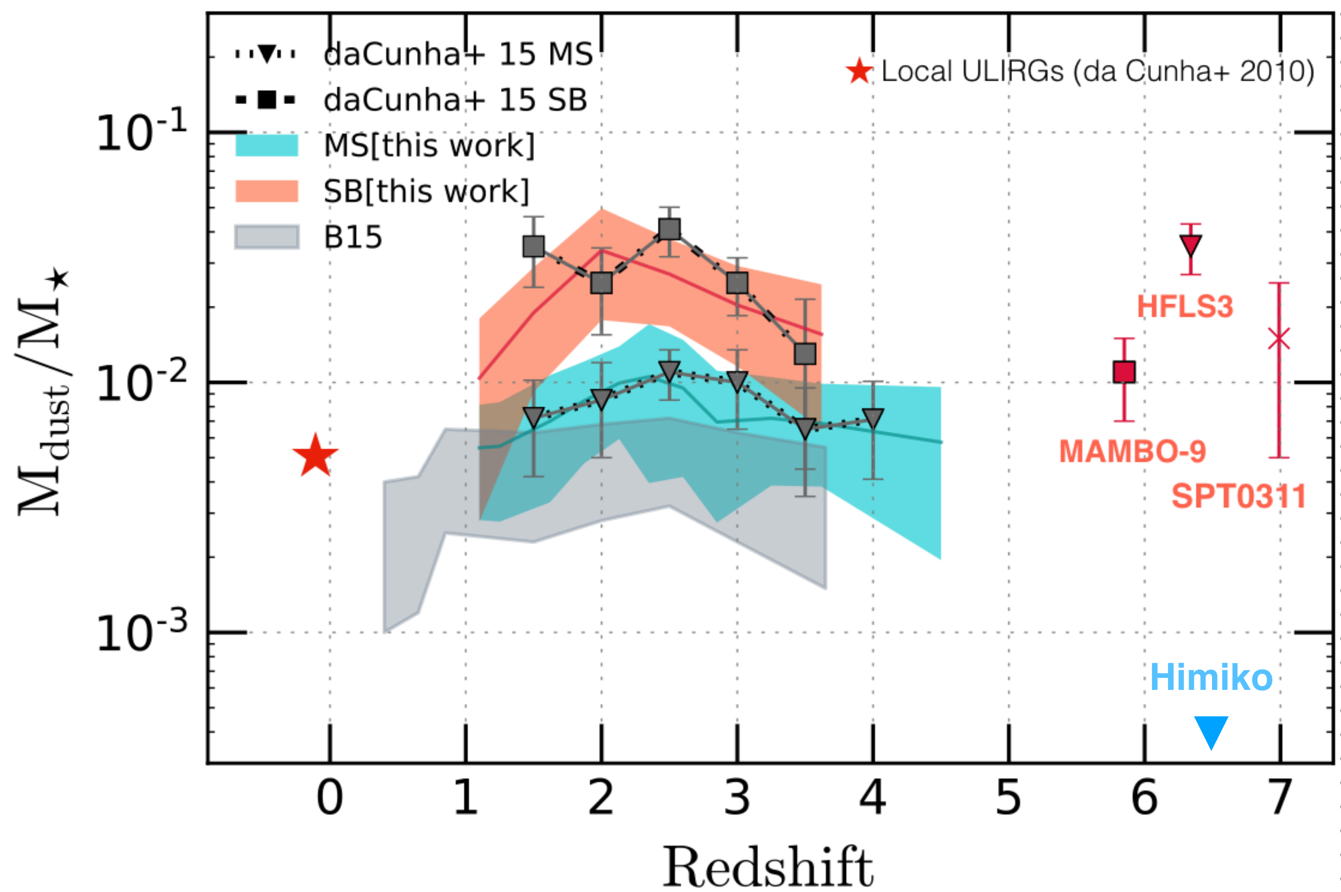


	This work	ALESS da Cunha et al. (2015)	AS2UDS Dudzevičiūtė et al. (2020)
$\langle z \rangle$	$2.39^{+0.92}_{-0.73}$	$2.7^{+1.39}_{-1.1}$	$2.61^{+0.79}_{-0.81}$
$\langle L_{IR} \rangle$	$2.93^{+2.17}_{-1.31} \times 10^{12}\ L_\odot$	$3.24^{+2.4}_{-1.8} \times 10^{12}\ L_\odot$	$2.88^{+2.52}_{-1.3} \times 10^{12}\ L_\odot$
$\langle \mathrm{SFR} \rangle$	$270^{+255}_{-170}\ M_\odot\ \mathrm{yr}^{-1}$	$281^{+420}_{-190}\ M_\odot\ \mathrm{yr}^{-1}$	$236^{+240}_{-150}\ M_\odot\ \mathrm{yr}^{-1}$
$\langle M_\star \rangle$	$1.02^{+0.7}_{-0.4} \times 10^{11}\ M_\odot$	$0.89^{+0.7}_{-0.4} \times 10^{11}\ M_\odot$	$1.26^{+0.5}_{-0.5} \times 10^{11}\ M_\odot$
$\langle M_{\rm dust} \rangle$	$7.33^{+5.2}_{-3.4} \times 10^{8}\ M_\odot$	$6.01^{+5.6}_{-3.8} \times 10^{8}\ M_\odot$	$6.8^{+5.1}_{-3.6} \times 10^{8}\ M_\odot$

(Donevski+ '20)

2.2 The observed evolution of the dust-to-stellar mass ratio

Evolution with redshift



(Donevski+ '20)

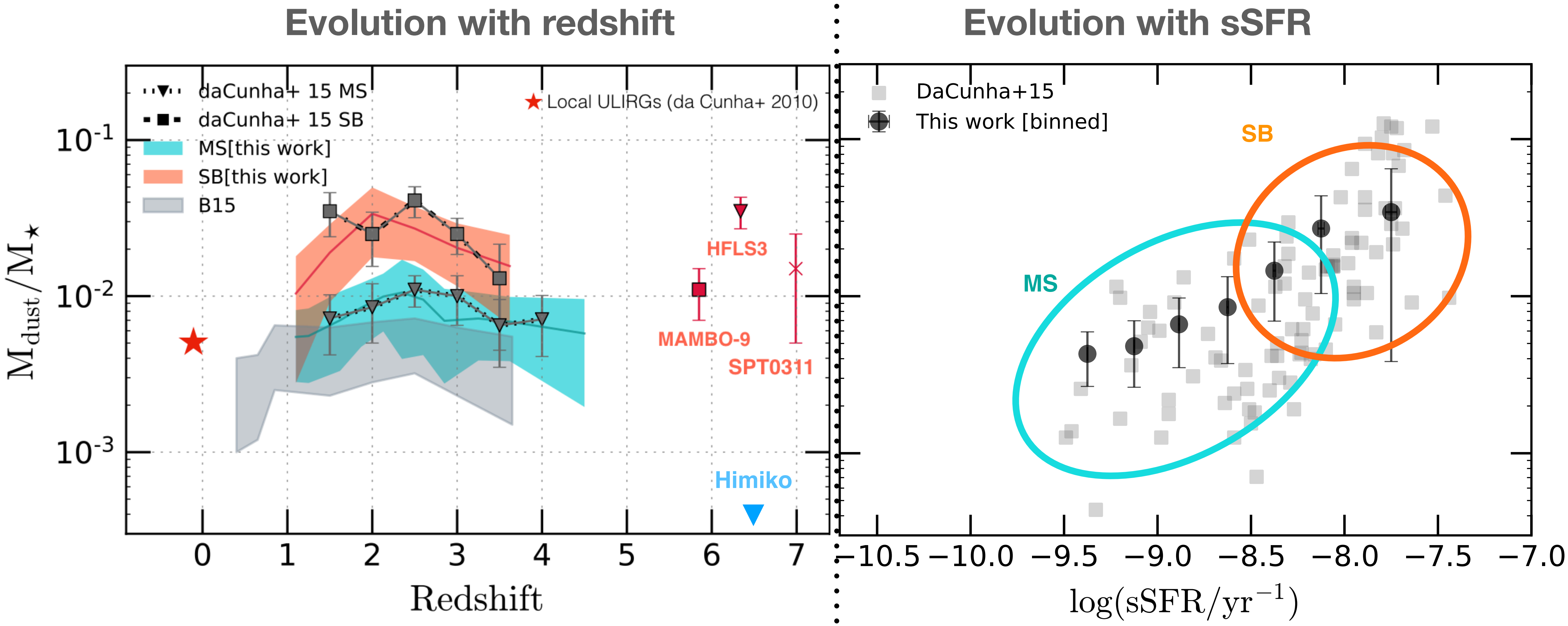
Message 2: The cosmic evolution

- MS vs SB separation based on Speagle+ 14
- Growth of dust-to-stellar mass ratio peaks @ z~2 and is **different for MS and SB galaxies** (in line with Tan+ '14, Bethermin+ '15)

➡ **Great diagnostics to pre-select MS and SB DSFGs @1<z<5 !**

➡ **Different ISM conditions in distant massive galaxies**

2.2 The observed evolution of the dust-to-stellar mass ratio



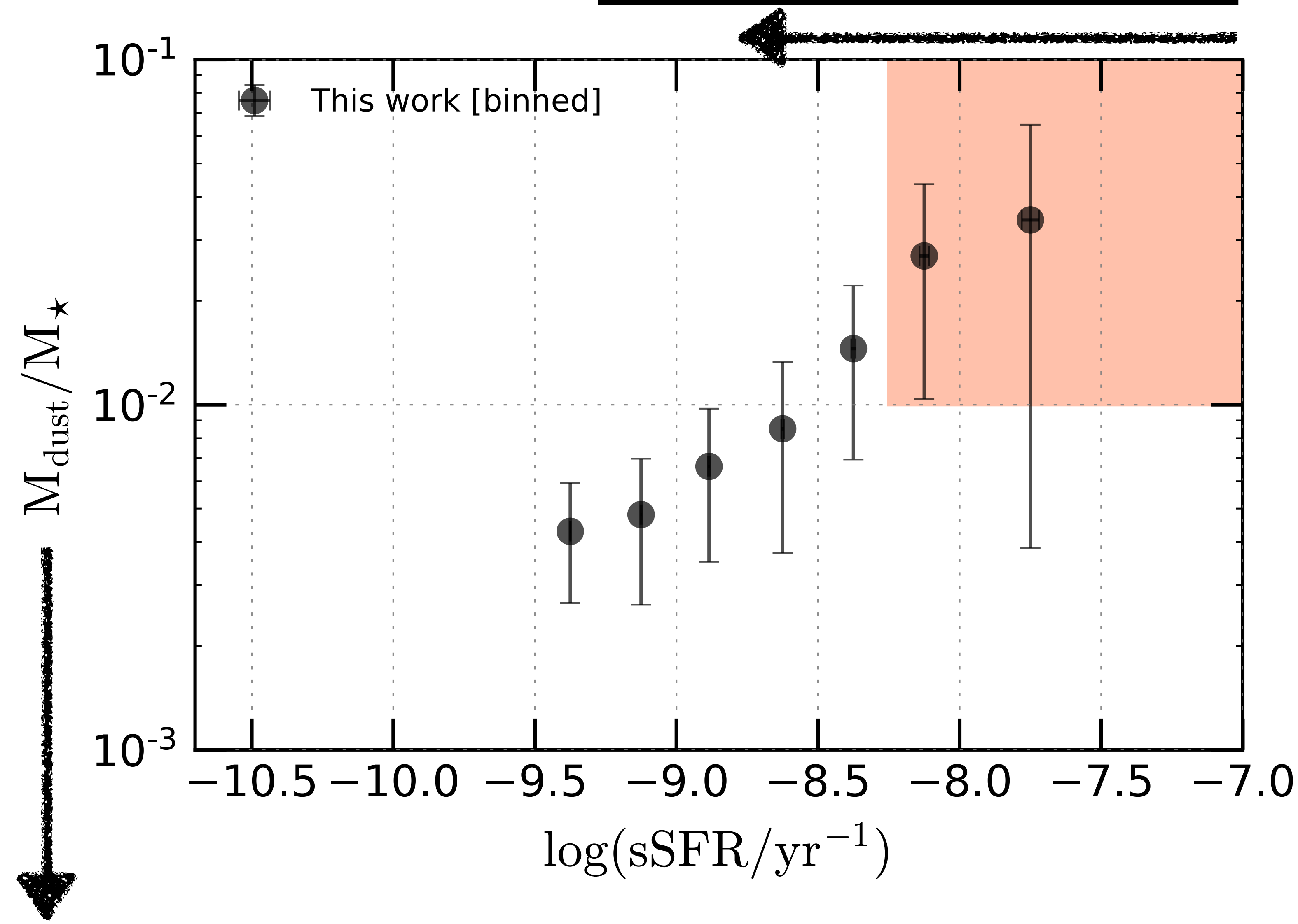
(Donevski+ '20)

Message 3: The evolution with sSFR

- The evolution of dust-to-stellar mass ratio **strongly correlates with sSFR**
  —> age-evolutionary sequence (Calura+ '17, Nanni+'20)

Question: What producess excess dust masses in high-z DSFGs?

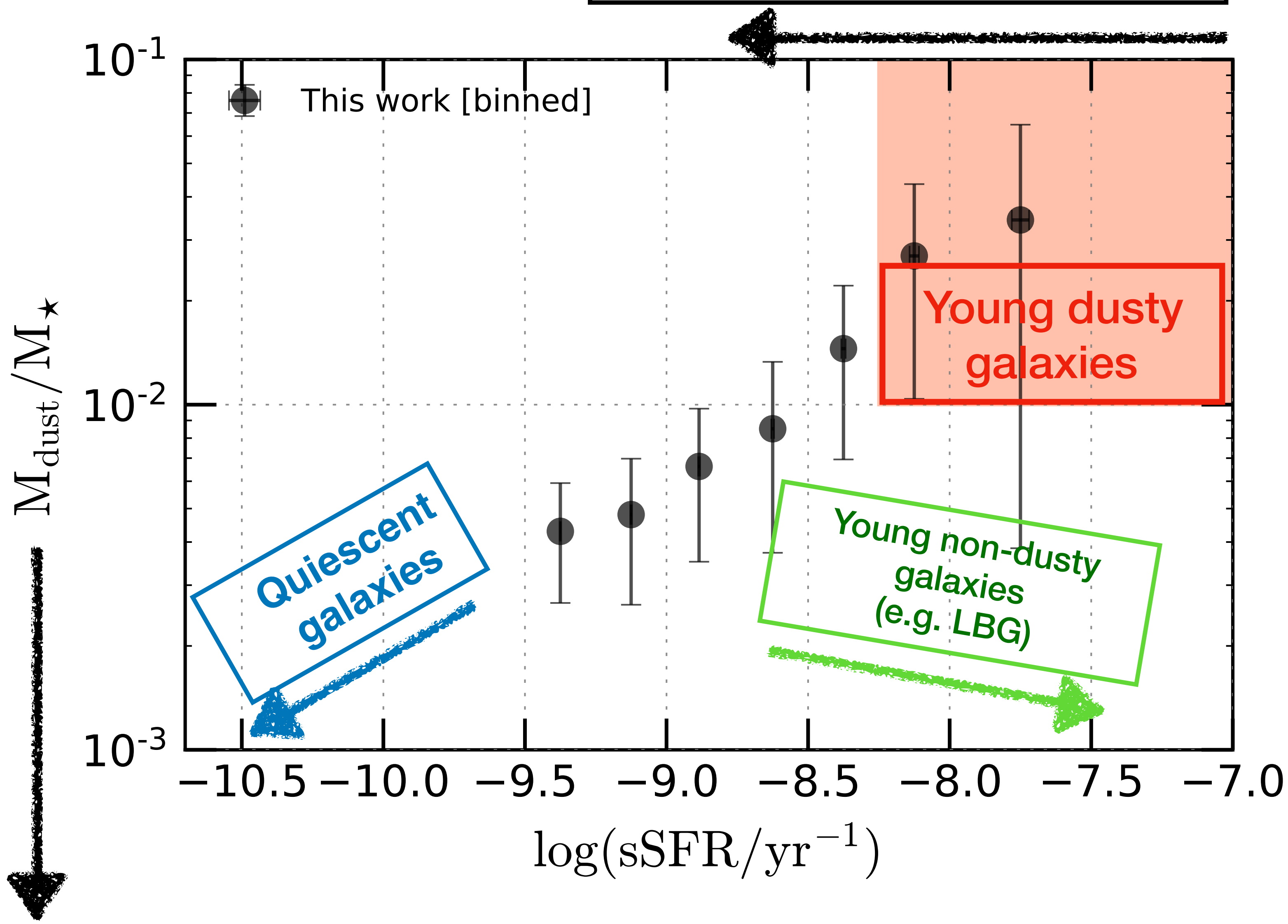
Age-evolutionary sequence



Dust production vs. dust destruction

2.2 The observed evolution of the dust-to-stellar mass ratio

Age-evolutionary sequence



Dust production vs. dust destruction

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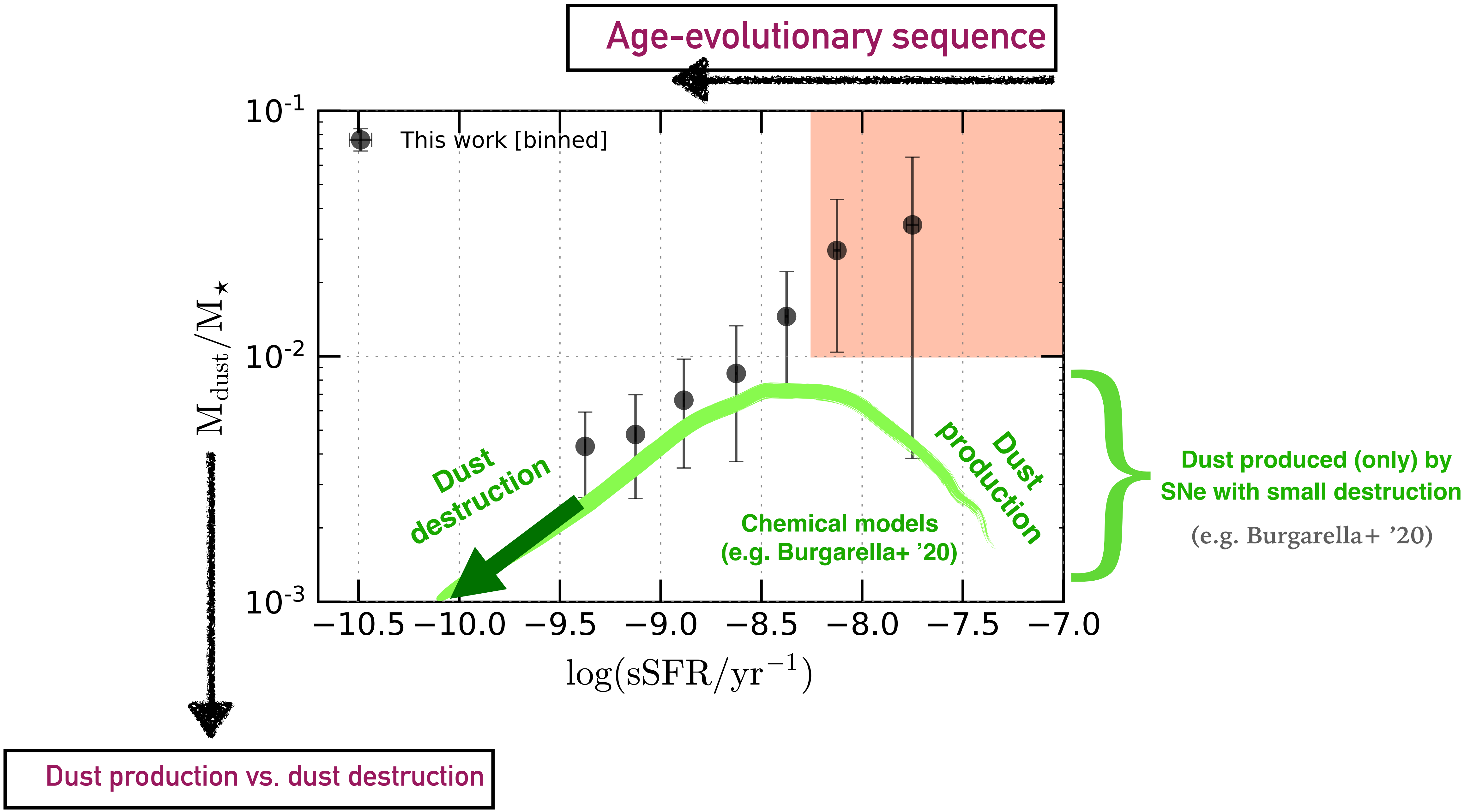
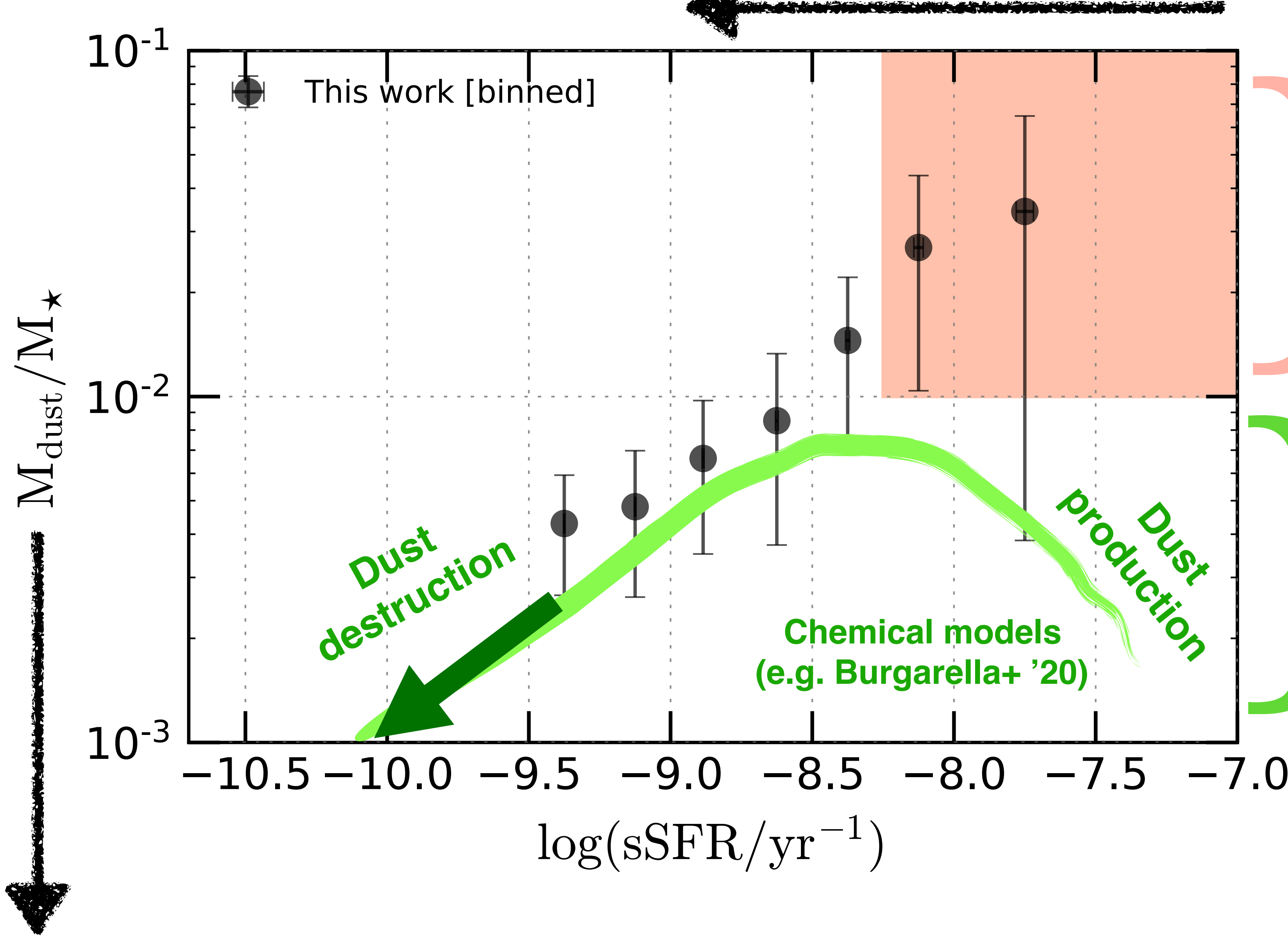


PROBLEM 1: SNe need to be maximaly efficient, with no destruction in order to explain observed dust masses in DSFGs (Gall+ '18)

2.2 The observed evolution of the dust-to-stellar mass ratio

Age-evolutionary sequence



(a) Top heavy IMF? (Lacey+ '16, Nanni+ '20)
or
(b) Dust grain growth in ISM ? (Asano+ '13, Popping+ '17, Li+ '19, Pantoni+'19, Triani +'20)

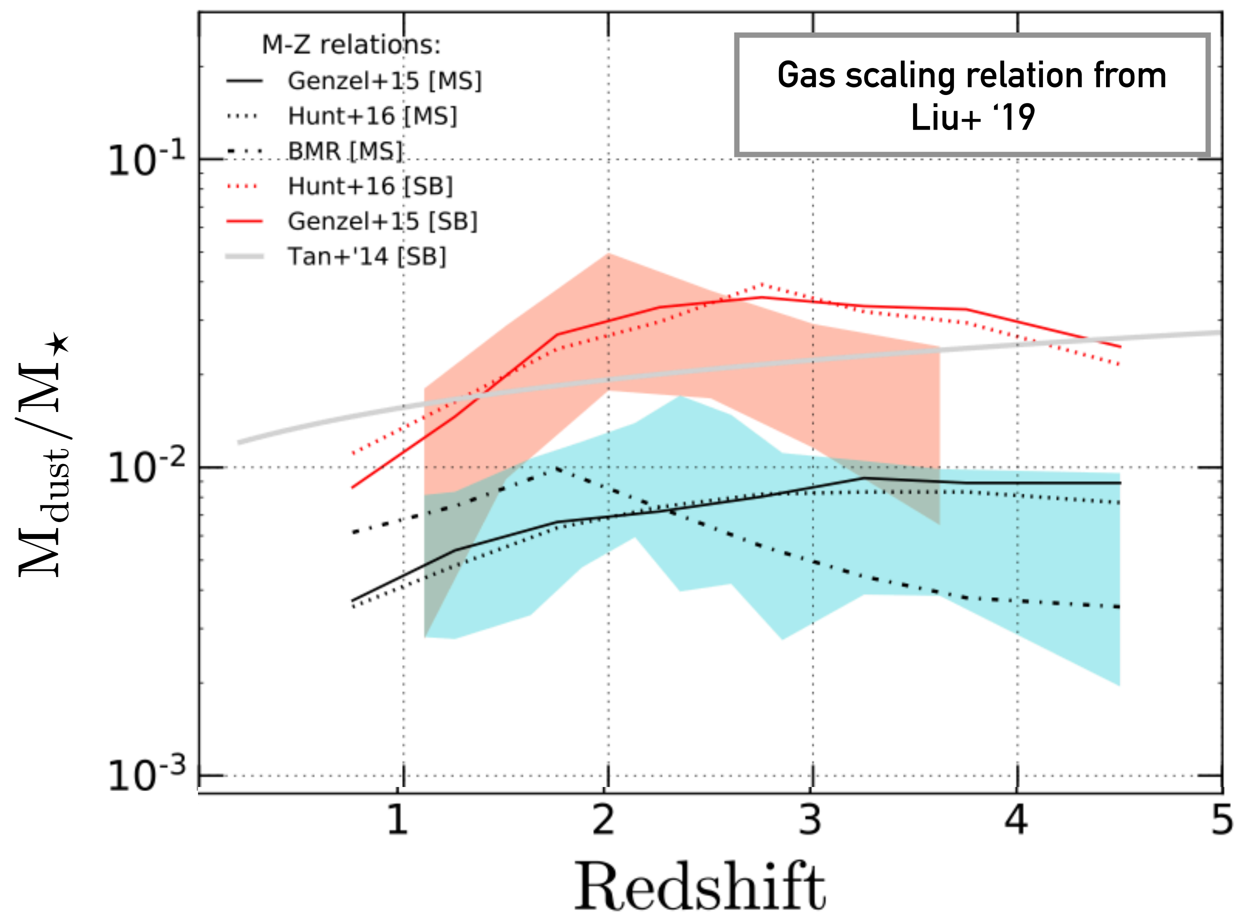
Dust produced (only) by SNe with small destruction (e.g. Burgarella+ '20)

Dust production vs. dust destruction

- **Top-heavy IMF cannot produce high enough Mdust** (McKinnon+ '18, ILLUSTRIS)
- Dust growth is plausible solution, but galaxies need to be metal rich!

2.3 The cosmic evolution of the dust-to-stellar mass ratio: empirical modelling

- **Cosmic evolution of the dust-to-stellar mass ratio:** $\frac{M_{\rm dust}}{M_\star}(z) \propto \frac{M_{\rm gas}}{M_\star}(z) \times Z_{\rm gas}(z)$



- **Slowly evolving MZR + gas-scaling relations** by Liu+ '19 and Tacconi+ '18 **supports the data.**
- **Average (modelled) Zgas:** 12+log(O/H)=8.63 **(for MS)** & 12+log(O/H)=8.5 **(for SB)**;

Conditions for dominant grain growth in ISM (e.g. Triani+ '20):

12+log(O/H)>8.49 & $M_{\rm gas} > 10^{10}\ [M_\odot]$

Fullfilled in ~80% of our ALMA galaxies!

2.3 The cosmic evolution of the dust-to-stellar mass ratio: empirical modelling

- **Dust-to-stellar mass ratio depends on metallicity and gas ratio**

$$\boxed{\frac{M_{\rm dust}}{M_\star}(z) \propto \frac{M_{\rm gas}}{M_\star}(z) \times Z_{\rm gas}(z)}$$

Gas metallicity

(from empirical mass-metallicity relations, MZR
e.g. Remy-Ruyer+ '14, Bethermin+ '15, Genzel+ '15, Hunt+ 16, Curti+ '19)

$$\boxed{Z_{\rm gas} = f(z, M_\star, {\rm SFR})}$$

Molecular gas ratio

(from empirical gas scaling relations;
e.g Scoville+ '17, Tacconi+ '18, Liu+ '19)

$$\boxed{\frac{M_{\rm gas}}{M_\star} = f(z, M_\star, {\rm SFR}, \Delta_{\rm MS})}$$

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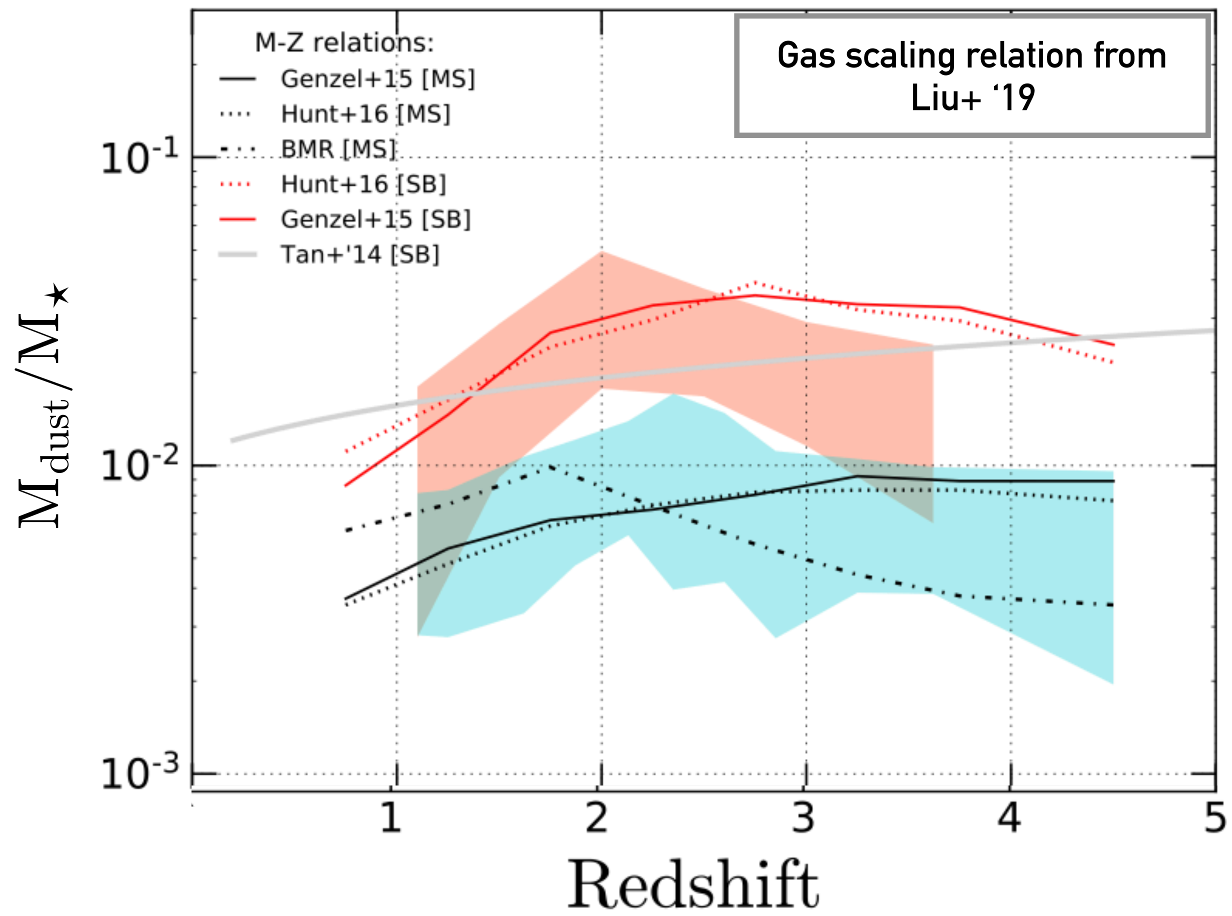


Message 4

Our work offers the first statistical evidence that the dust growth in ISM is dominant dust mass producer in DSFG at *z* >2-5

Caution:

If dust emission is strongly affected by opacity effects (i.e., emission is optically thick in most of SB galaxies), the model will return 2-4x lower Mdust !

III Evolution of the dust-to-stellar mass ratio in galaxy models

Can the observed evolution be understood within the dusty galaxy formation framework ?

3. Dusty galaxy formation models

(Semi-)Analitic Models (SAMs)	Cosmological simulations	Phenomenological models
DURHAM (Lacey+ '10, Lacey+ '16) L-GALAXIES (Vijayan+ '19) G.A.S (Causin+ '19) Popping+ '17 SHARK (Lagos+ '19) **Pantoni+ '19**	Shimizu+ '12 Illustris (McKinnon+ '17) Dusty-Gadget (Graziani+ '19) **SIMBA (Davé+ '19, Li+ '19)**	Schreiber+ '16 Casey '18 **Bethermin+ '17**

Main goal

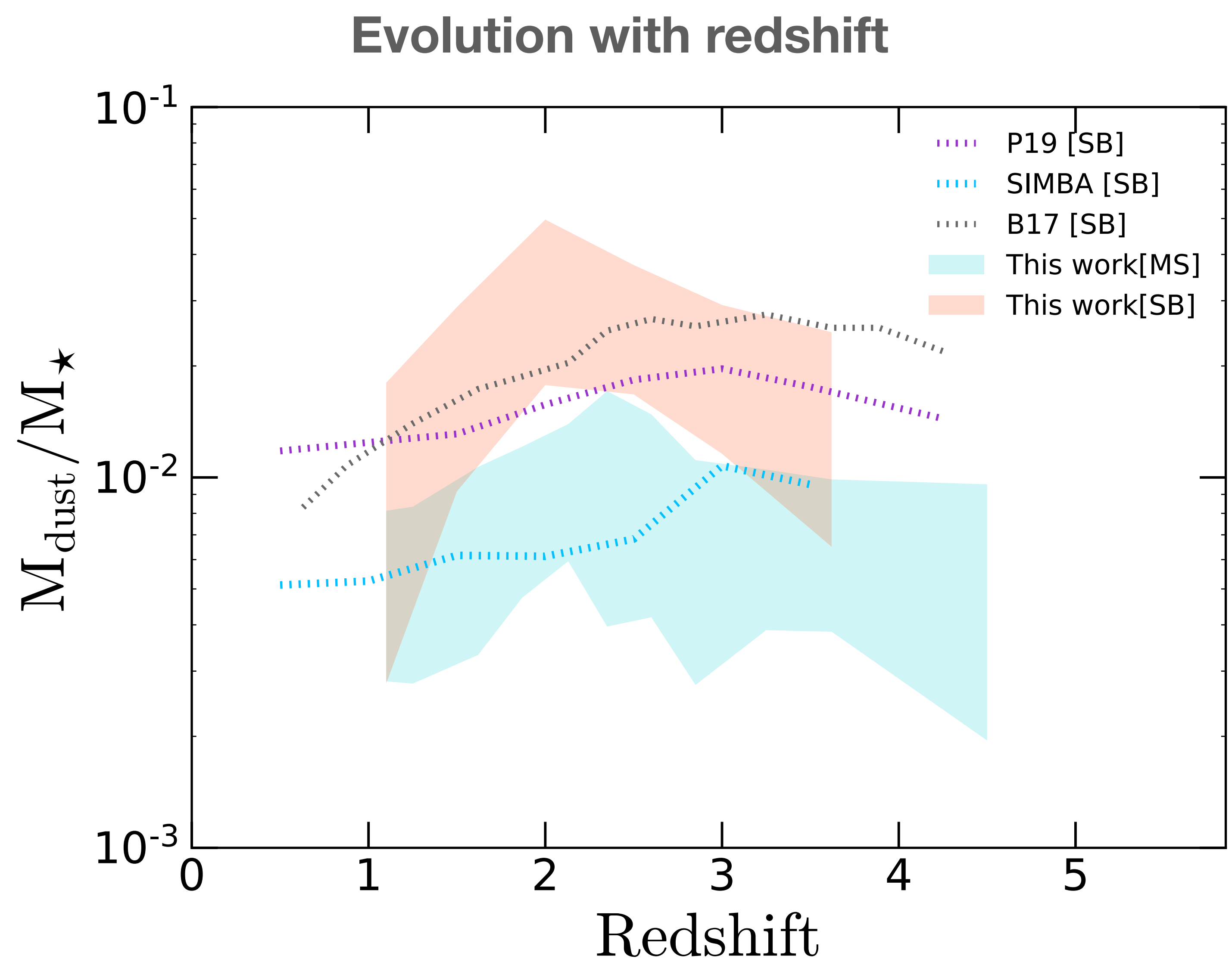
Interpreting the observed trends with models that include self-consistent dust life cycle of DSFGs.

$$\Sigma \dot{M}_{\rm dust} \propto \dot{M}_{\rm dust}^{\rm SNe} + \dot{M}_{\rm dust}^{\rm ISM} - \dot{M}_{\rm dust}^{\rm destr} - \dot{M}_{\rm dust}^{\rm SF} + \dot{M}_{\rm dust}^{\rm inf} - \dot{M}_{\rm dust}^{\rm out}$$

3.1 Modelled evolution of the dust-to-stellar mass ratio

- **Successes:**
  (1) Cosmological simulation **broadly consistant with** MS DSFGs.
  (2) Smooth evolution towards high-z in all models.

3.1 Modelled evolution of the dust-to-stellar mass ratio



- **Successes:**
  (1) Cosmological simulation **broadly consistant with MS DSFGs**.
  (2) Smooth evolution towards high-z in all models.
- **Problem:** Cosmological simulation cannot fully capture dust in **SB DSFGs**

3.1 Modelled evolution of the dust-to-stellar mass ratio

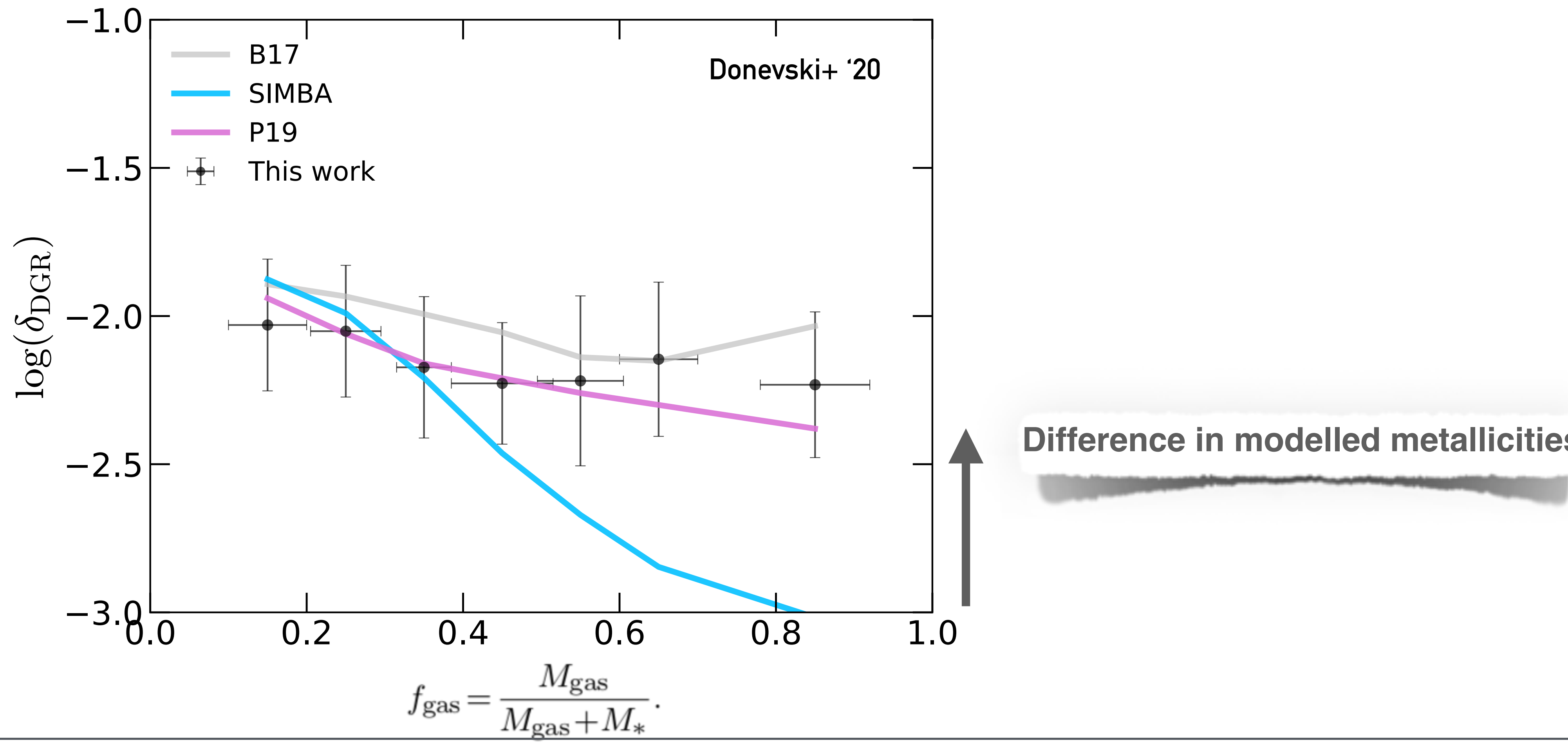
Relative missmatch for SB DSFGs:

- SIMBA seem to produce less metals (~2x below solar) relative to data in massive SB DSFGs with fgas>0.
- Metal production less rapid than in analytic solutions (e.g. Pantoni+ '19) (predicted timescale for which Zgas in cold ISM attains $Z_{\odot}/10$ is t<10 Myr).

$$\tau_{acc} = \tau_{acc,0} \times a^{-1} \times n_{H}^{-1} \times T_{gas}^{-1/2} \times Z_{gas}^{-1}$$

➡ Smaller Zgas —> longer accretion timescale

➡ Our data suggest $\tau_{acc,0} < 10^{6} yr$



3.1 Modelled evolution of the dust-to-stellar mass ratio

Relative missmatch for SB DSFGs:

- SIMBA seem to produce less metals (~2.5x below solar) relative to data in massive SB DSFGs with high f_gas (Mstar>10^10 Msol, f_gas>0.6) !

$$\tau_{\rm dust} = \frac{\tau_{\rm SN} M_{\rm ISM}}{M_g} = \frac{\Sigma_{\rm ISM}}{\mathcal{R}_{\rm SN} M_g}$$

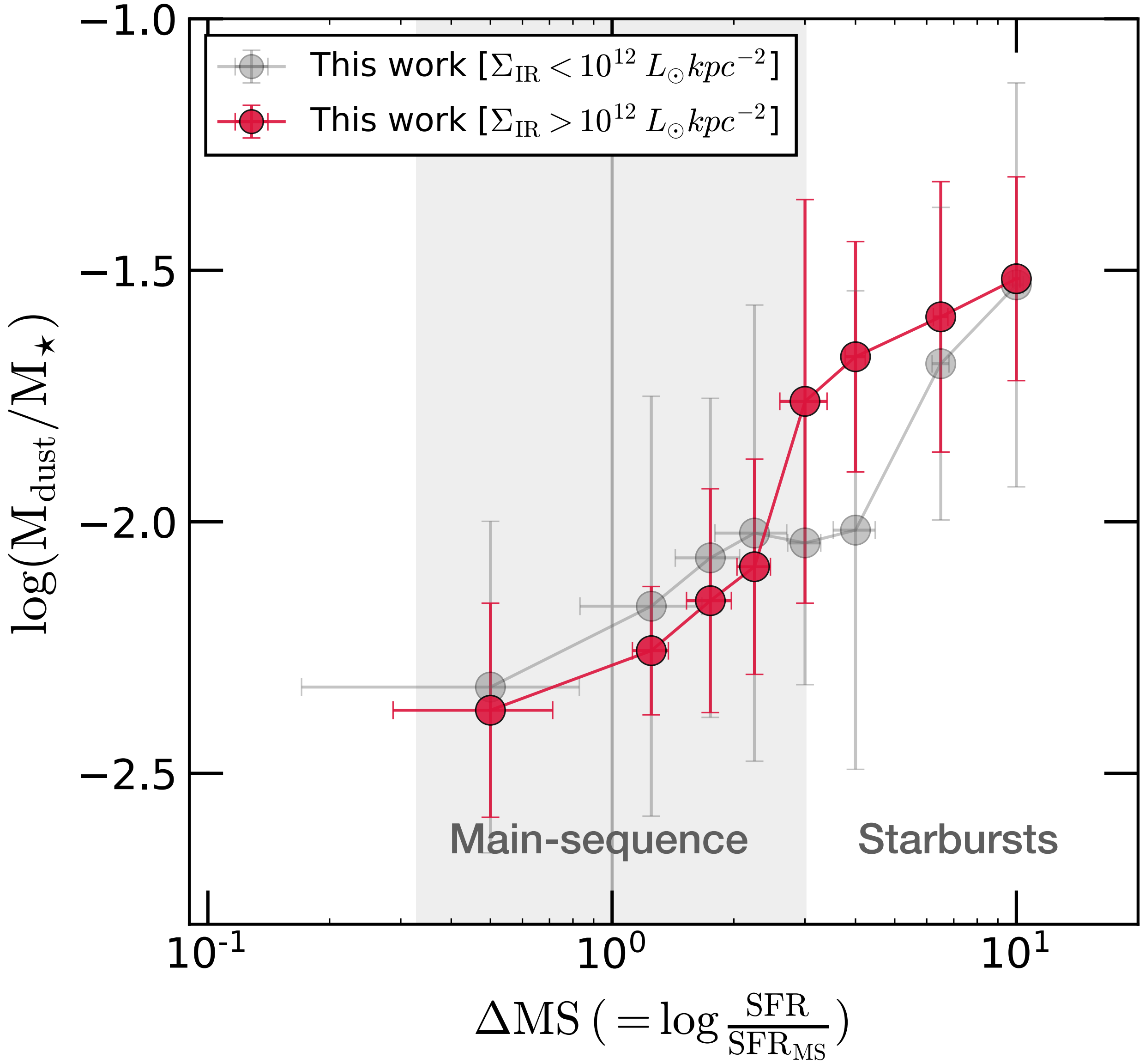
➡ Our data indicate longer (~ Gyr) destraction timescales!

➡ For example: High ISM gas masses and metallicities in DSFGs ($M_{\rm gas} > 10^{10} M_\odot, Z_{\rm gas} \sim 0.8 - 0.9\ Z_\odot$) gives destruction timescales of ~ 1.1 Gyr for MS and 0.5 Gyr for SB galaxies! This is 2x longer than for very local systems with smaller gas density (Jones+ '11, Slavin+ '15, Aoyama+ '19).

➡ Survival grain capacity different at high-z ? (e.g Dwek+ '14)

➡ or: OBSERVATIONAL EFFECTS, i.e. Opacity effects affect the data (optically thick emission in SB —> higher Td —> smaller Md) ?

3.2 The role of compactness



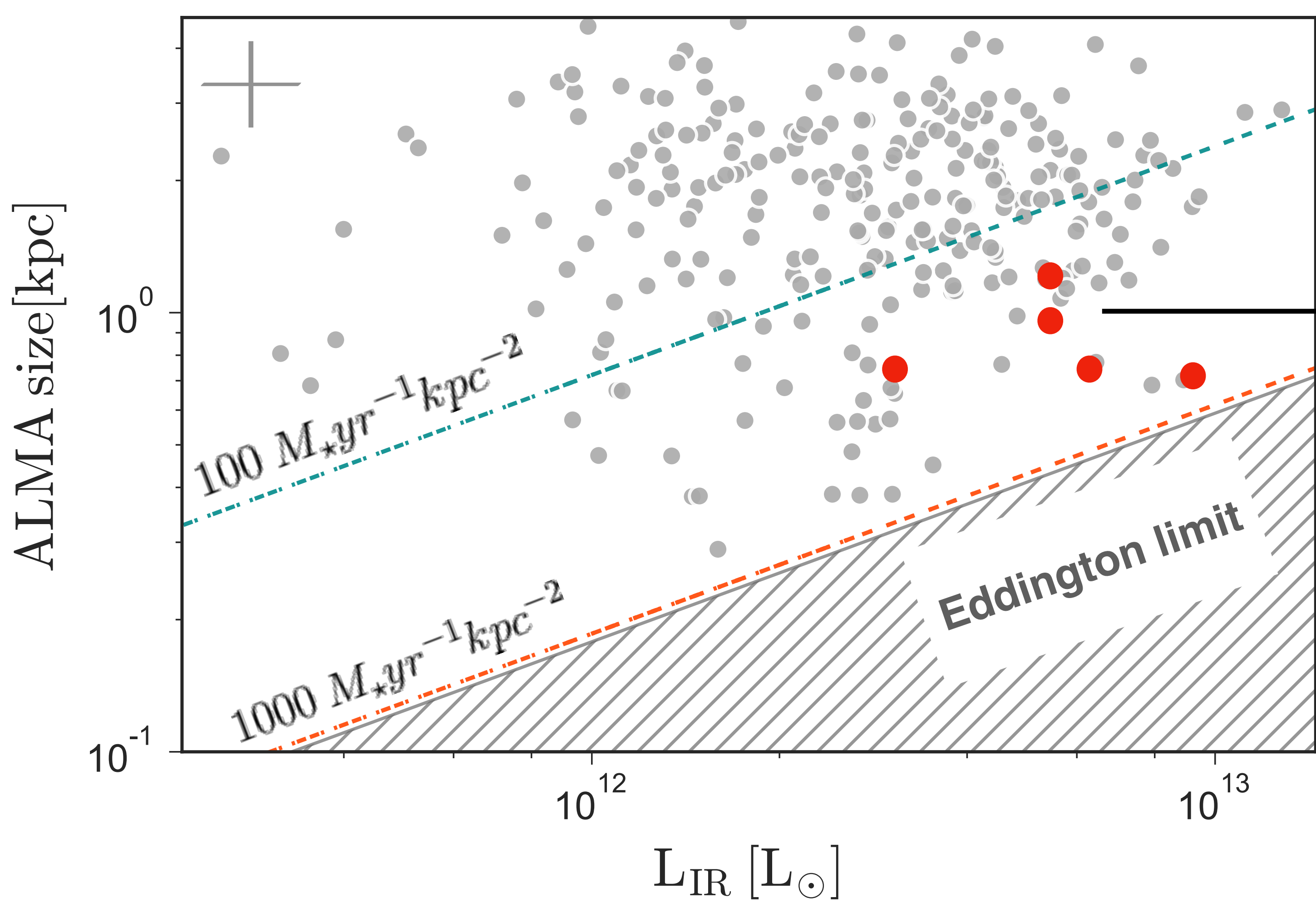
Message 5

- The dust-to-stellar mass ratio in **MS DSFG** similar, regardless of **Σ**LIR.
- The dust-to-stellar mass ratio in **SB DSFGs** slightly enhanced **in more compact objects !**
- **ΣLIR-to-ΔMS relation of SB DSFGs** maybe induced by **gas compression** or **rapid dust growth due to turbulent ISM** ? (e.g. Mattsson+'20)

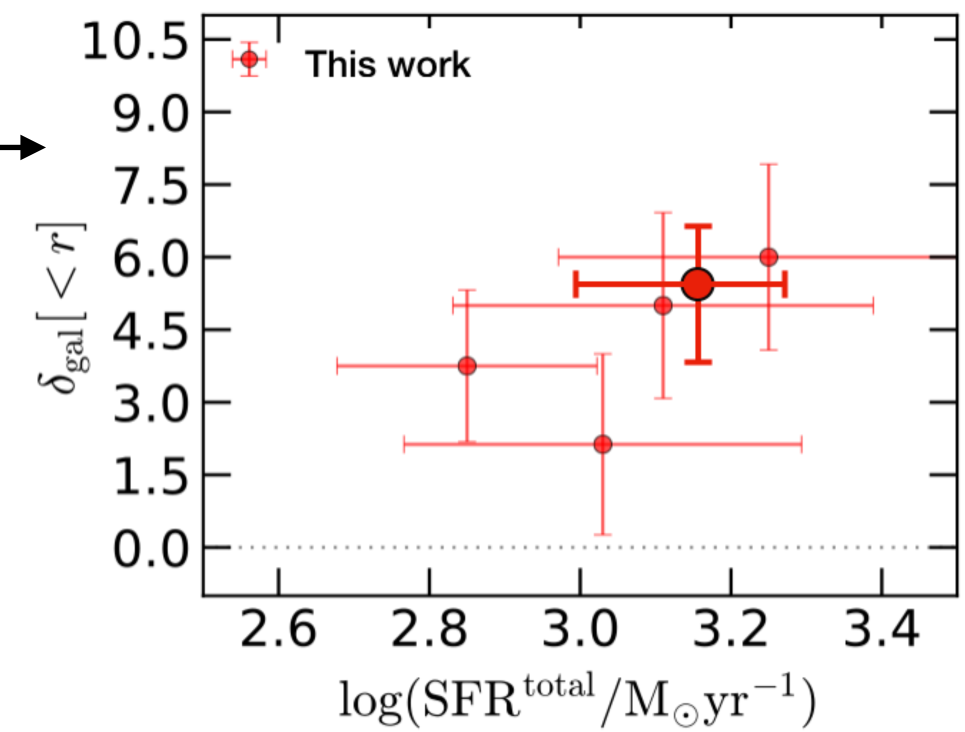
(1) **Donevski et al.**, A&A accepted ; arXiv:2008.09995
(2) **Donevski et al.**, to be submitted

3.3 The role of environments

- Connection between overdensities and compact DSFGs with enhenced dust mass



Very compact
and reside in very dense environments @z>2



(**Donevski et al.**, to be submitted)

- **Rapid dust growth linked to most massive DM halos (candidate protoclusters at z>3)**

Remarks

- The dust-to-stellar mass ratio evolves with z, sSFR, integrated dust size, but differently in MS DSFGs & SB DSFGs.
- Great diagnostic tool to separate the MS DSFGs & SB DSFGs, and unveil their evolutionary phases.

- <u>Our study first to provide strong evidence that large reservoirs of metal rich gas and rapid dust growth in ISM are common in many high-z DSFGs</u> ($M_{dust} = 8 \times 10^8 M_\odot$, $M_{gas} \approx 10^{11}\ M_\odot$, 12+log(O\H)=8.52).

- Phenomenological and analytical models broadly agree with observations.
- <u>SIMBA is able to reproduce MS DSFGs</u> (first such success for ALMA galaxies!) Less succesfull in most extreme SB DSFGs (e.g. longer accretion timescales due to lower Zgas and/or overefficient AGN feedback ?).

- Some of our <u>DSFGs have very high compact IR sizes</u> —> high ΣLIR —> need to understand which process drives enhanced dust-to-stellar mass ratio in such compact SB DSFGs !

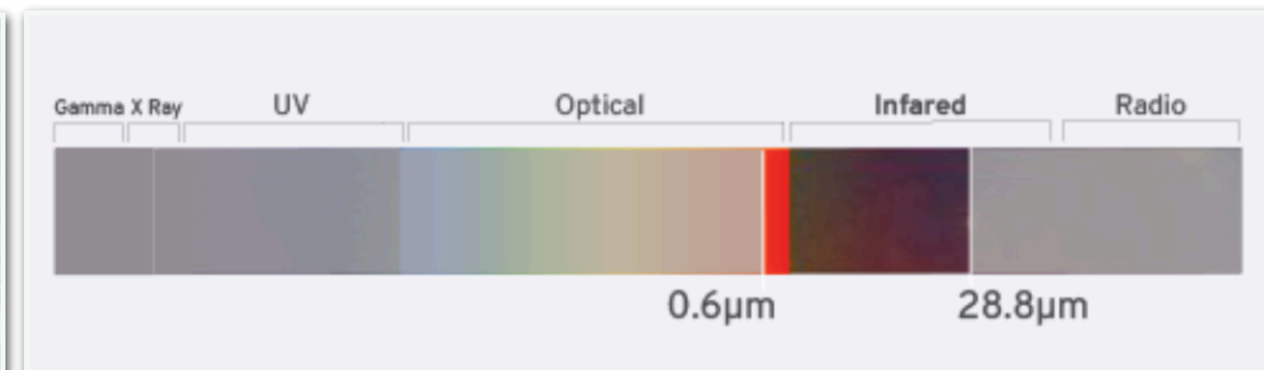
Darko Donevski, SISSA, Trieste, Italy

email: darko.donevski@sissa.it

- Future facilities

Future James Webb Space Telescope (JWST) data combined with larger ALMA samples + wide surveys (i.e. Euclid and NIKA2):

- More accurate AGN contribution to DSFGs
- Constraints on the Zgas from various lines (mid-IR lines up to z~3, optical up to z~8)
- Environmental dependence of dust life cycle.



Darko Donevski, SISSA, Trieste, Italy

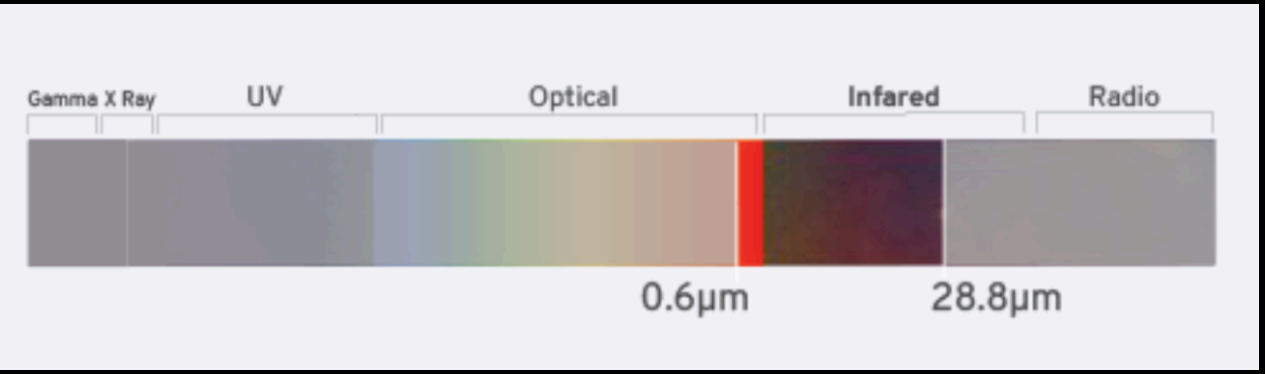
email: darko.donevski@sissa.it

Questions, comments…

Email: darko.donevski@sissa.it

@darkOenergy

James Webb Space Telescope



JWST-ALMA synergy

AGN characterisation	
ALMA	**JWST**
XDR tracers (HCN, HCO+)	Hot dust, broad lines (Pa-alpha)
Obscured star formation	
ALMA	**JWST**
Cold dust Molecular gas	PAH emission mid-IR lines
Kinematics	
ALMA	**JWST**
Cold molecular gas	Ionized gas Warm molecular gas