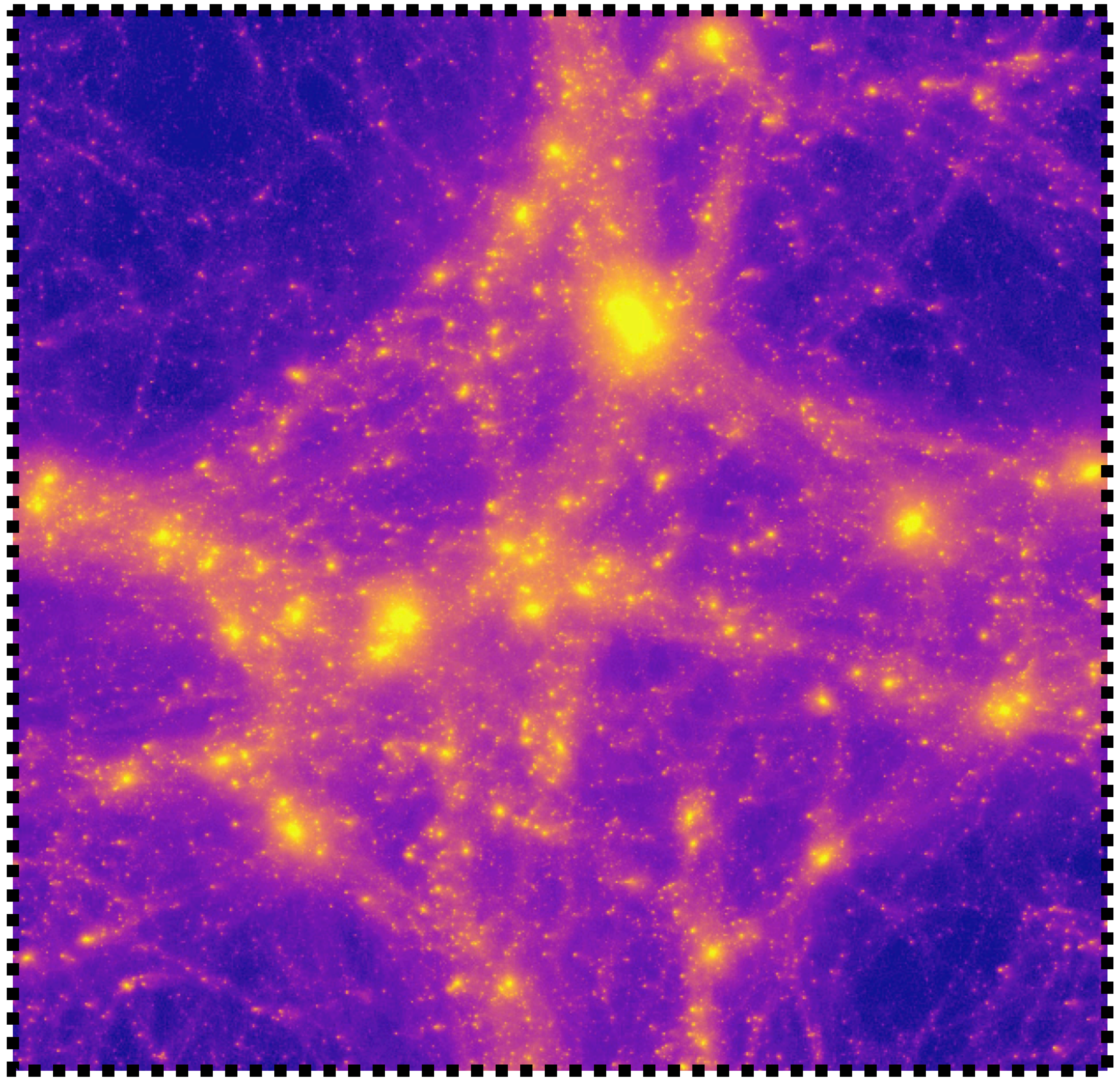
Rapid evolution of dusty interstellar medium in massive galaxies:

Observations, SIMBA & the role of cosmic web



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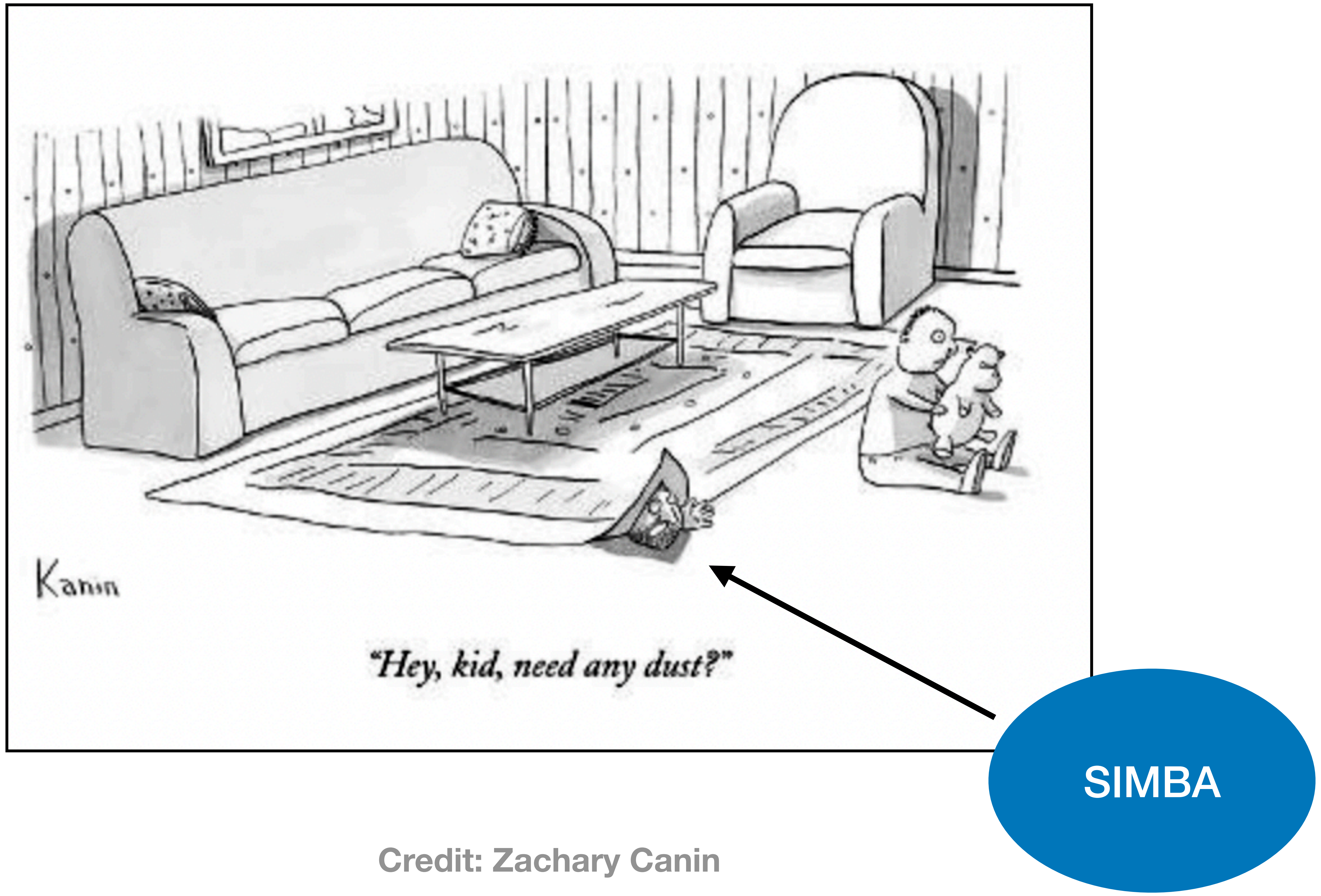
SIMBA Workshop, Flatiron, NewYork, May 01-04/2023

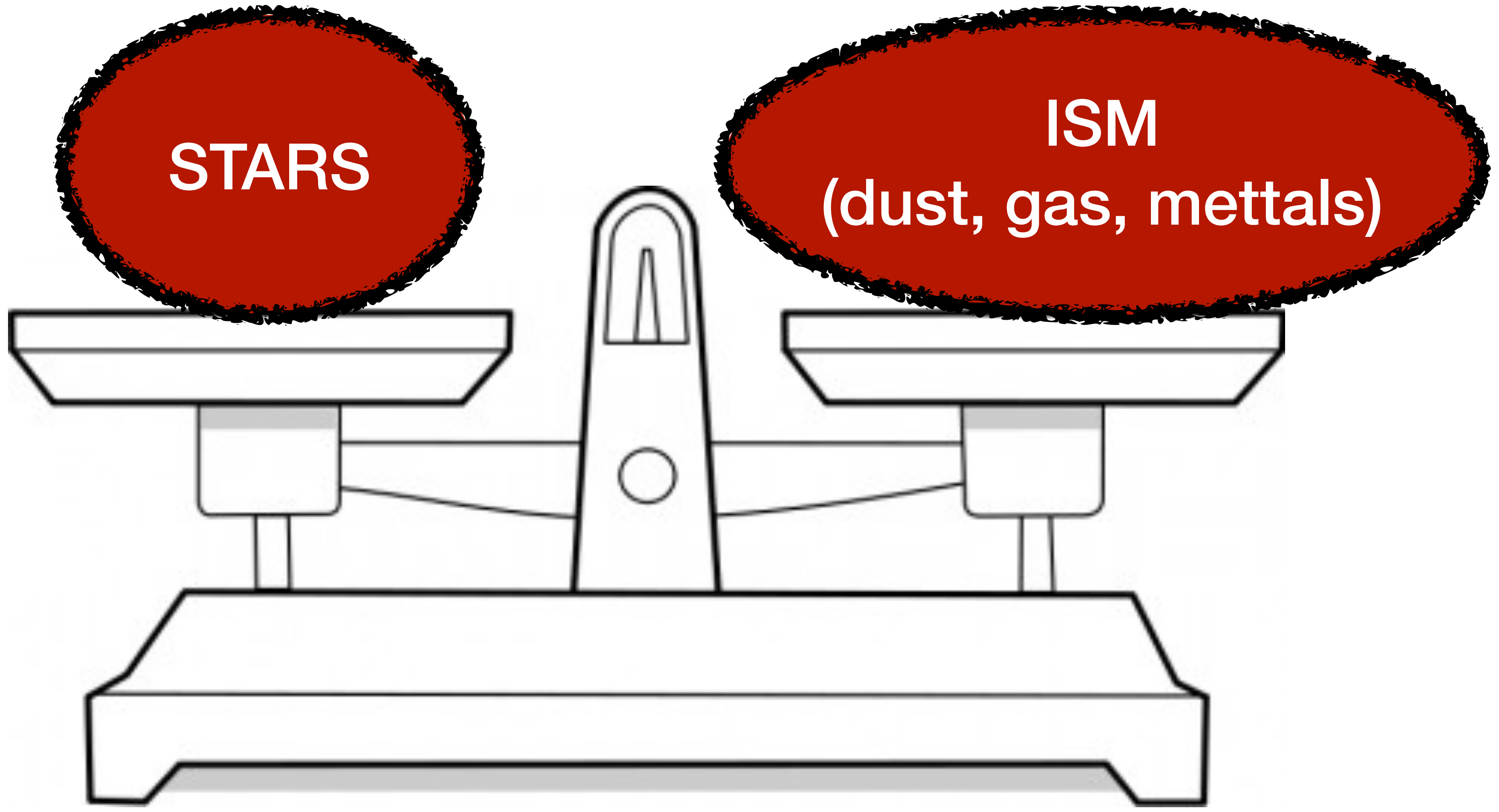
Problem with dust: even in The New Yorker cartoons…



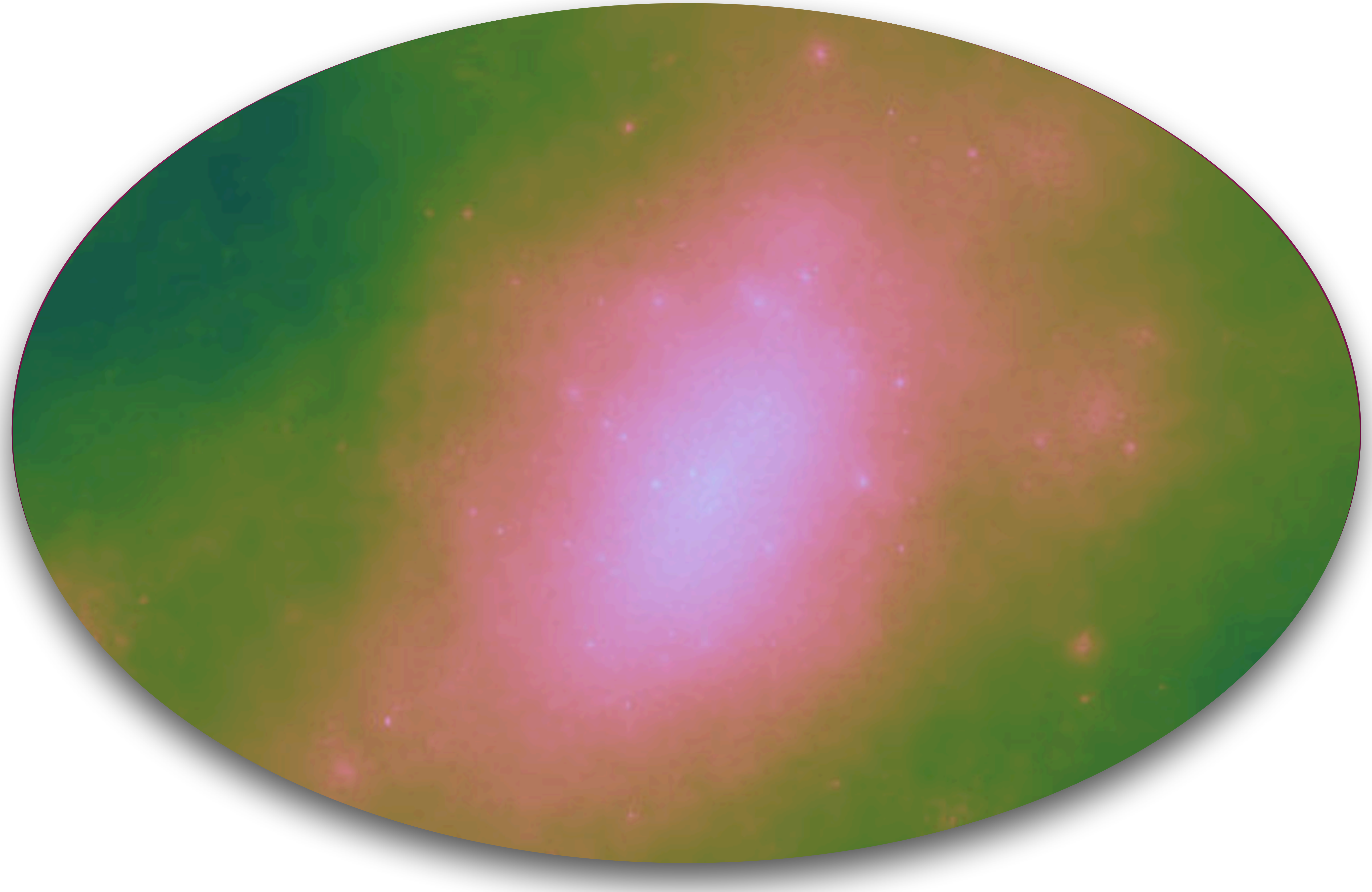
Credit: Zachary Canin

Problem

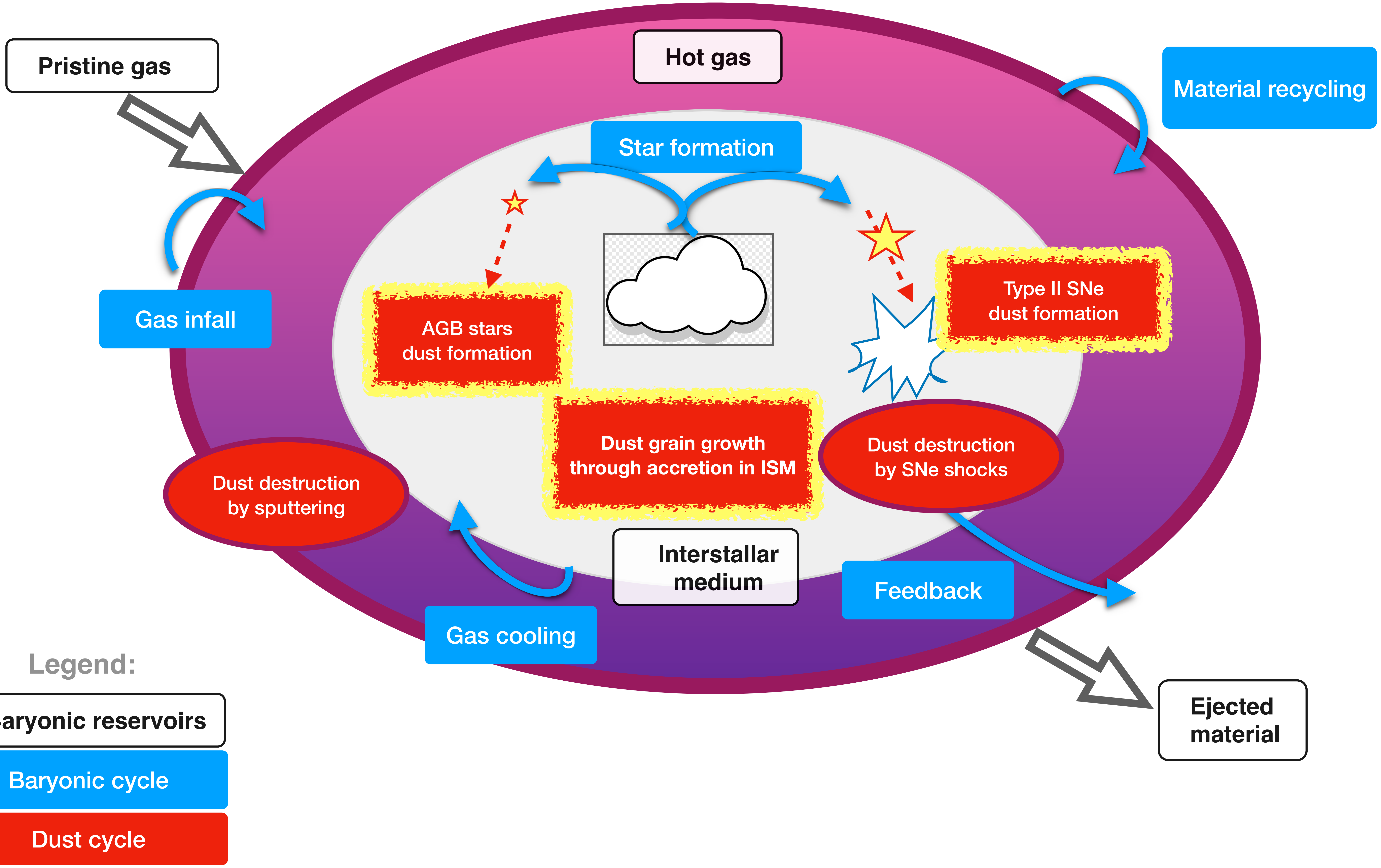
Quantifying changes in the interstellar medium as galaxies evolve



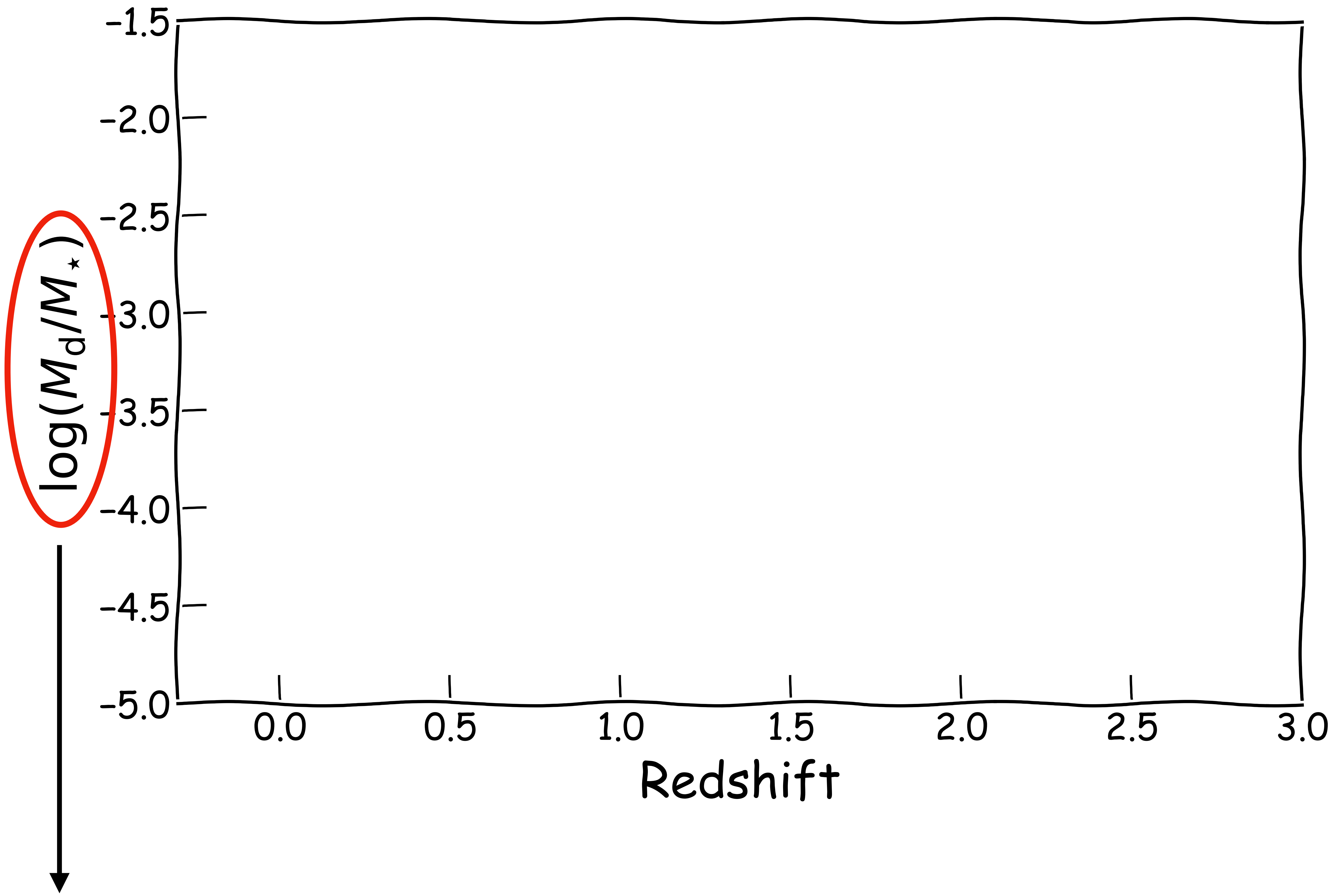
1. Inside the halo: interplay of metals, gas, stars and dust in galaxy evolution



1. Interplay of metals, gas, stars and dust in galaxy evolution

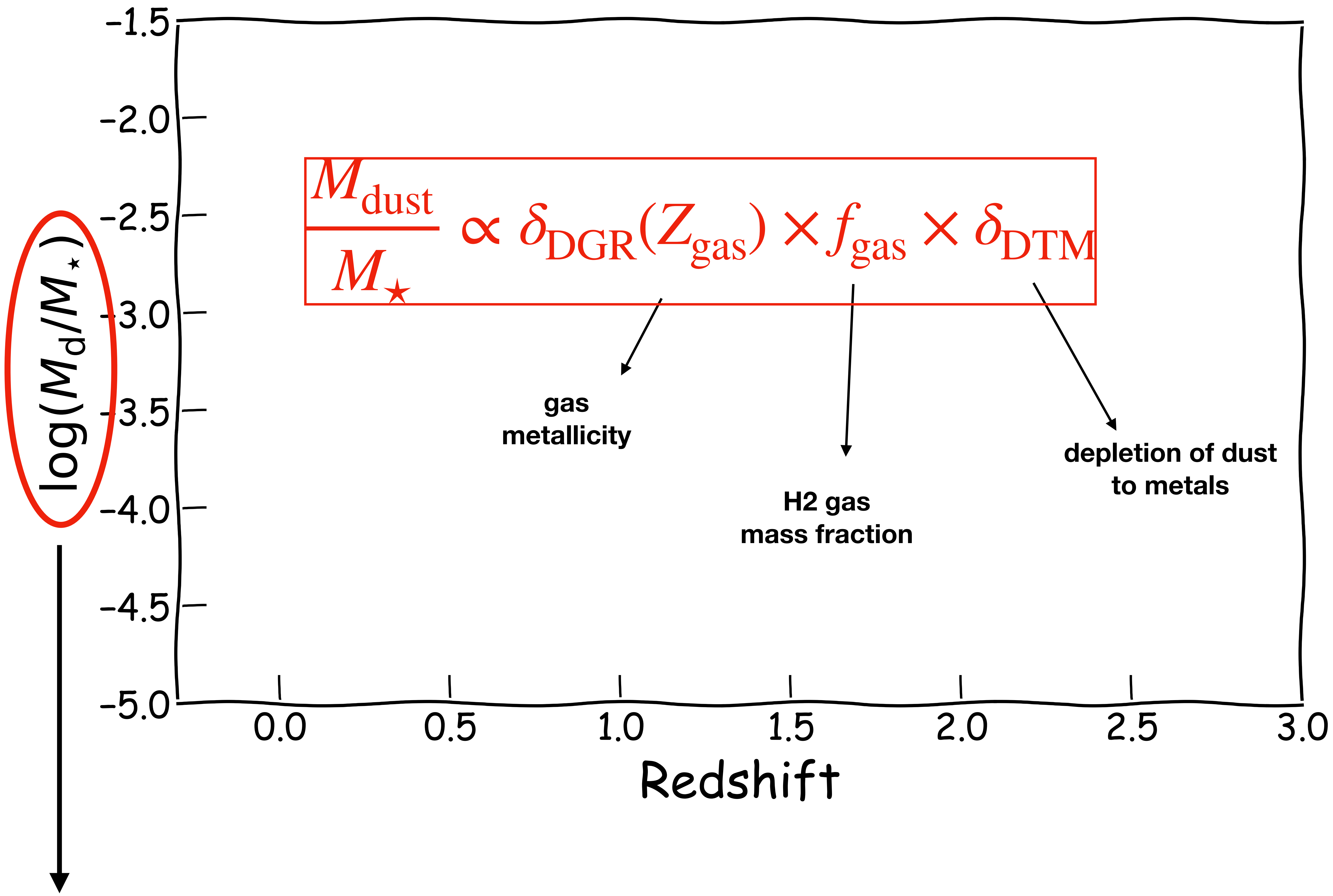


2.1 Evolution of specific dust mass: what are driving mechanisms?



Specific dust mass is realistic to measure by combining e.g. HST, JWST + ALMA, NOEMA, Herschel…

2.1 Evolution of specific dust mass: what are driving mechanisms?



$$\frac{M_{\rm dust}}{M_\star} \propto \delta_{\rm DGR}(Z_{\rm gas}) \times f_{\rm gas} \times \delta_{\rm DTM}$$

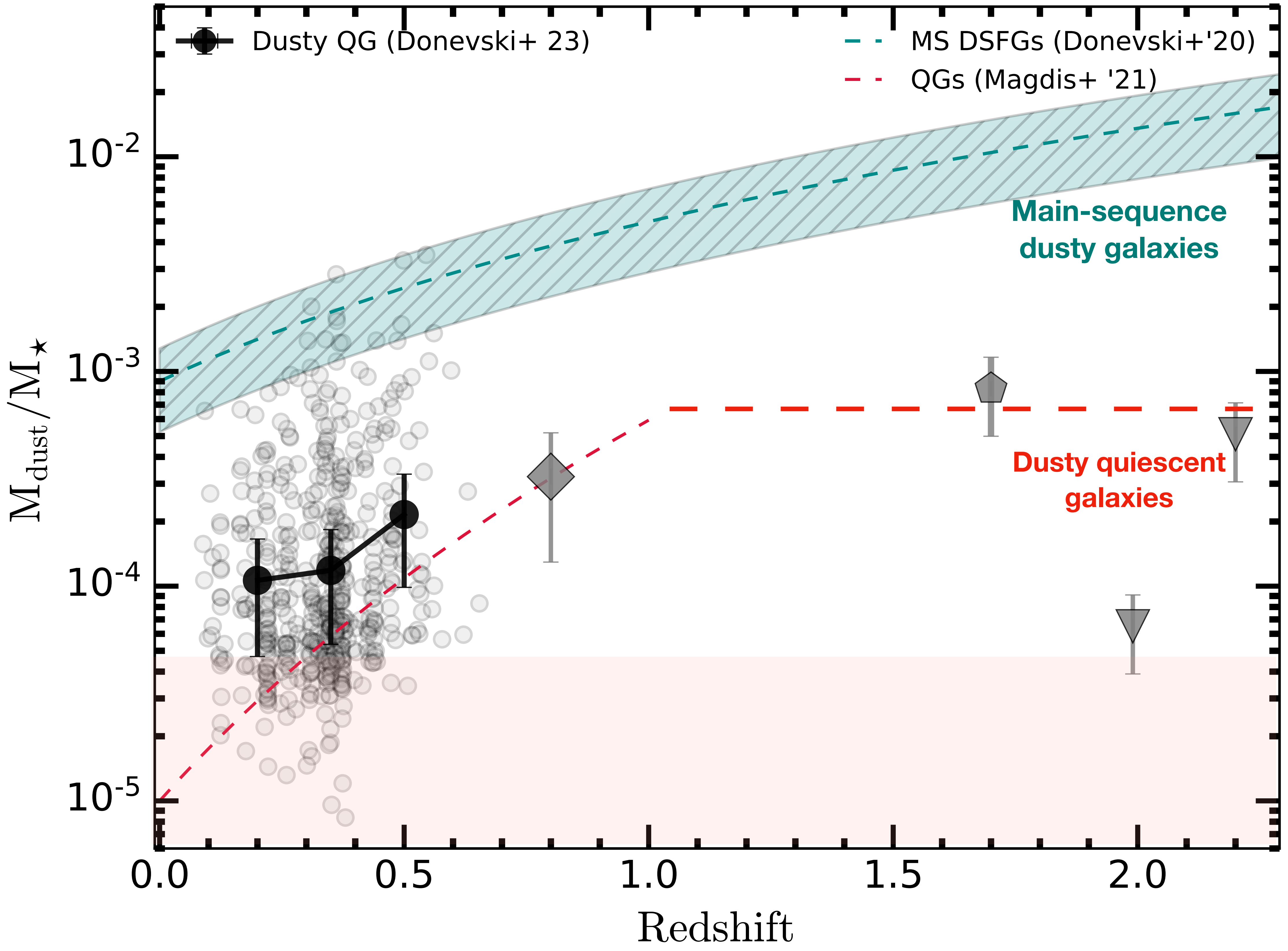
gas metallicity

H2 gas mass fraction

depletion of dust to metals

Specific dust mass is realistic to measure by combining e.g. HST, JWST + ALMA, NOEMA, Herschel…

2.1 Evolution of specific dust mass: observational status & challenges



MS galaxies observed with ALMA

Dust emission bright, but compact!

Stellar masses tricky to measure

(Bethermin+ 15, Donevski+ 20, Kokorev+ 21)

Dusty QG:

hardly observed, IR faint, Zgas difficult to get

Stacks & low-statistics studies:

Gobat+ 18, Magdis+ 21, Whitaker+ 21, Morashito+ 22 etc.

Large statistics studies: Donevski+ 23

Unexplored area !!!

- **Specific dust mass evolves with redshift, stellar mass, gas fraction, galaxy size…**
- In z>2 MS galaxies, higher dust mass reflects higher gas fraction and is partly due to rapid metal enrichment in massive halos.
- At z<2 QG, specific dust mass evolves in a similarly complex way

2.1 Evolution of specific dust mass: what are driving mechanisms?

Donevski et al. 2023; arXiv:2304.05842
500 Quiescent & dusty galaxies in the COSMOS field (z<0.6)

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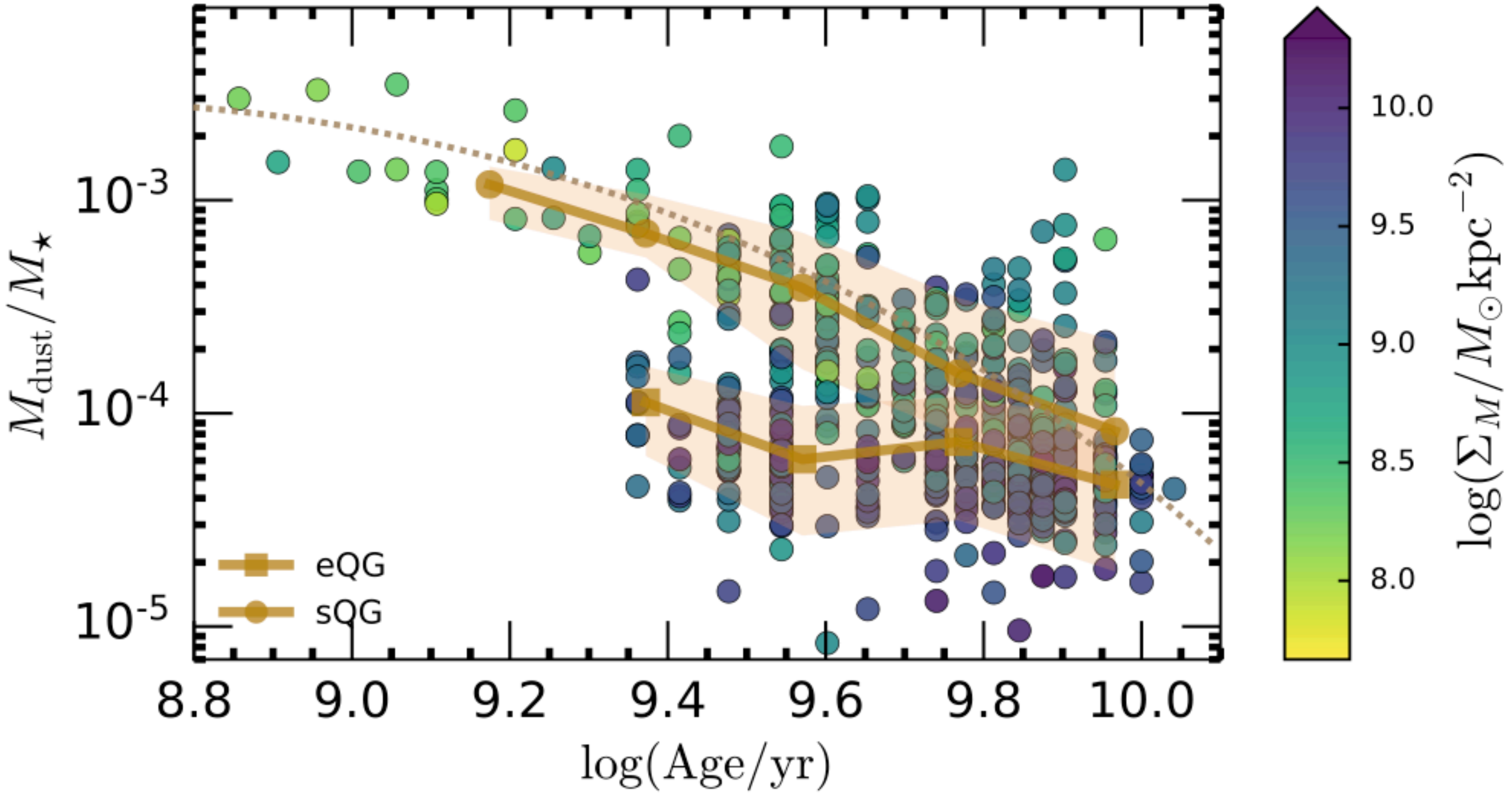


- **Large scatter in specific dust mass of QGs** —> non-uniform ISM conditions (e.g., various dust temperatures)
- **Impact of past SFH & morphology:** higher specific dust content in **extended QG** than in **compact QGs**
- **Long dust removal timescales (>2.5 Gyr)**

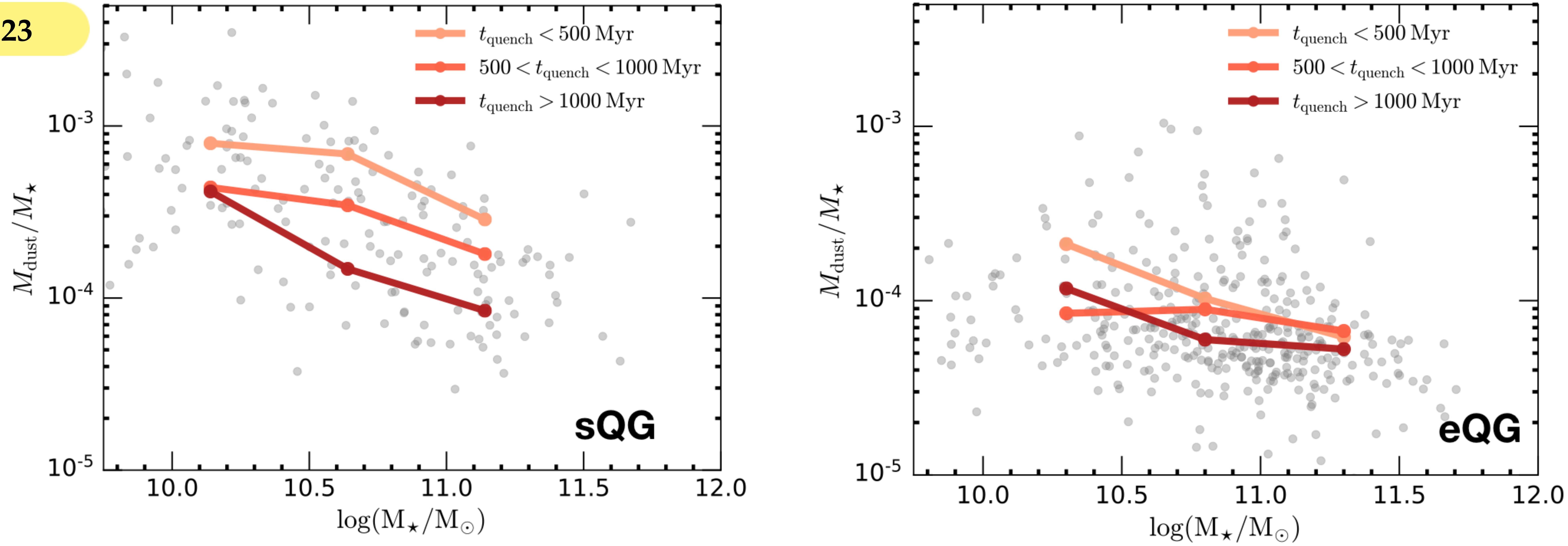
(in line with proposed lifetimes of re-formed Si grains, e.g., Hirashita+ 17)

➔ Different timescales for dust growth/removal in the metal-rich ISM ?

➔ Accretion of dust-rich satellites? Other environmental effects?

2.2 How to connect the dust evolution (formation & removal) & quenching processes?

Donevski et al. 2023



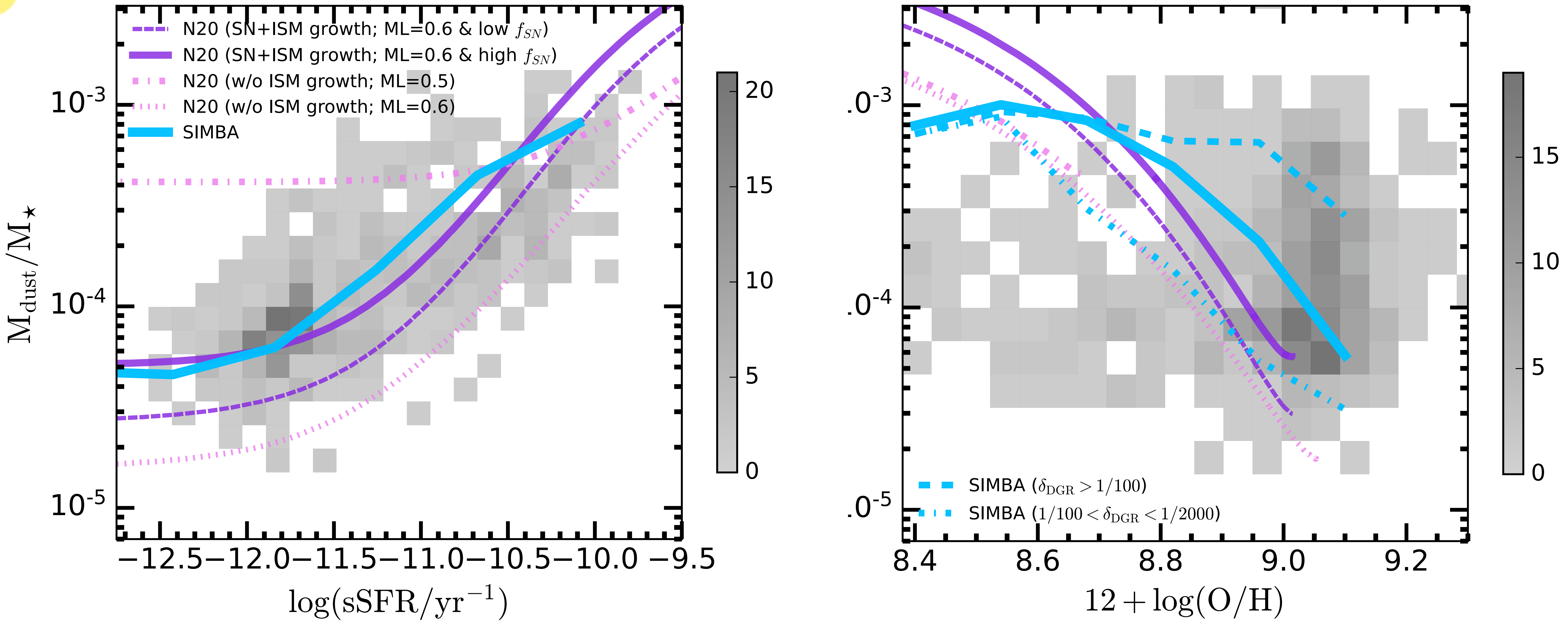
- **Long dust survival timescales (>2.5 Gyr) & shallow decline with Mstar**

- Rapid thermal sputtering due to hot gas ($t_{\rm destr}^{\rm hot} \sim 10-100$ Myr) ❌
- Lack of AGB stars ❌
- Strong AGN feedback ❌
- Fast environmental quenching (e.g. ISM gas removal due to stripping) **?**
- Slow environmental quenching (e.g., strangulation) ✅
  ($\sim$ 2 – 4 Gyr, e.g. Trussler+ '18)
- Morphological quenching ✅
  (e.g., Martig+ 09, Lin+ '19)

Implications for quenching mechanisms

2.3 Comparison with SIMBA

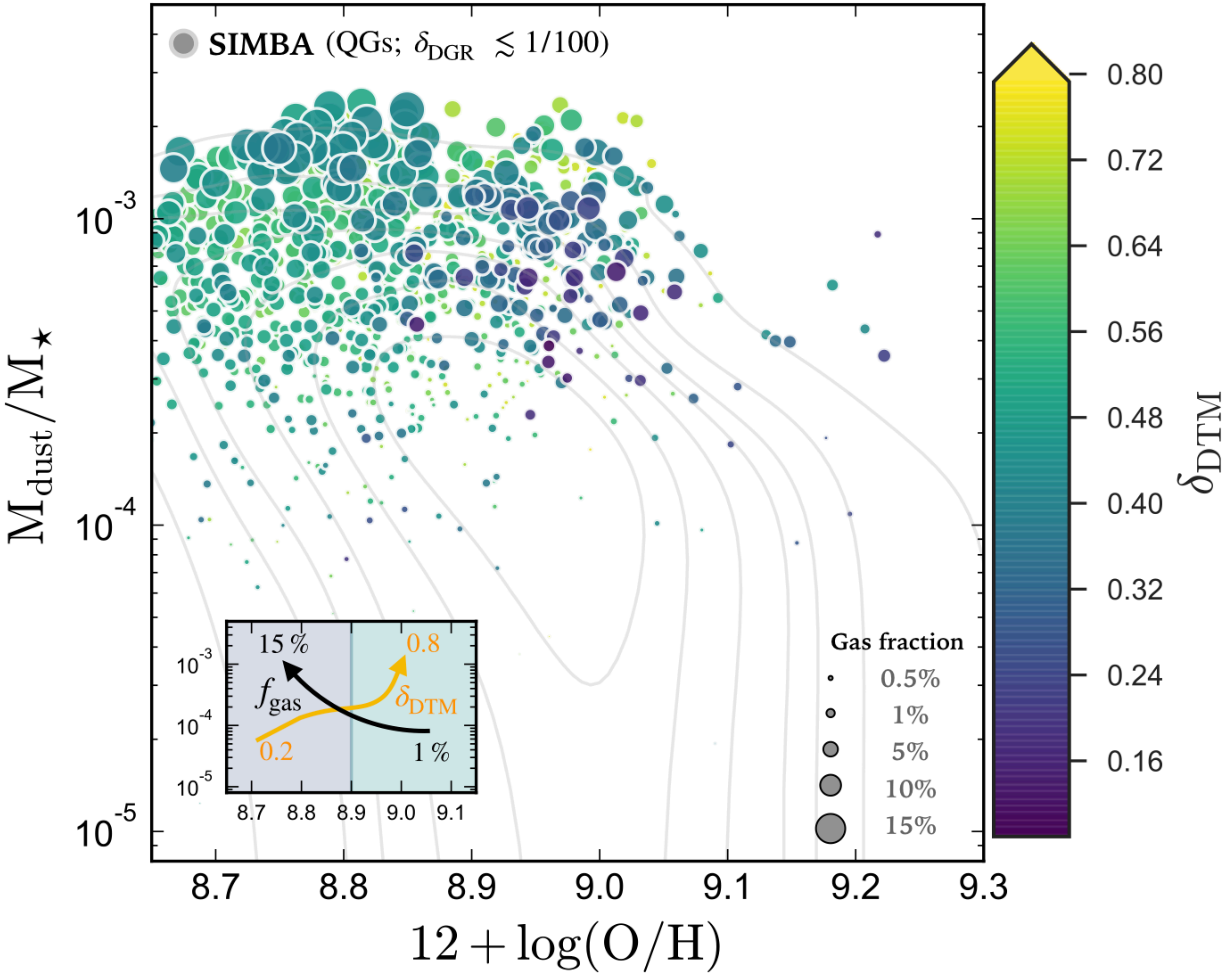
Donevski et al. 2023



SIMBA has a nice match with the data!!
What do models need to reproduce the data?

- Higher dust condensation efficiency in SNe ❌
- Strong stellar feedback ❌
- Fast dust-metal accretion timescales ✅
- Minor mergers / Dust-rich satellites in moderately massive $(> 10^{12.5} M_\odot)$halos ✅

2.4 Prolonged dust growth or "just" enough cold gas? Or both?



Donevski et al. 2023

- Cosmological simulation SIMBA predicts complex dust re-formation & removal in evolved systems.
- This is very similar to what we see in observations at z<1.
- ISM dust growth preserved at higher Zgas ✅

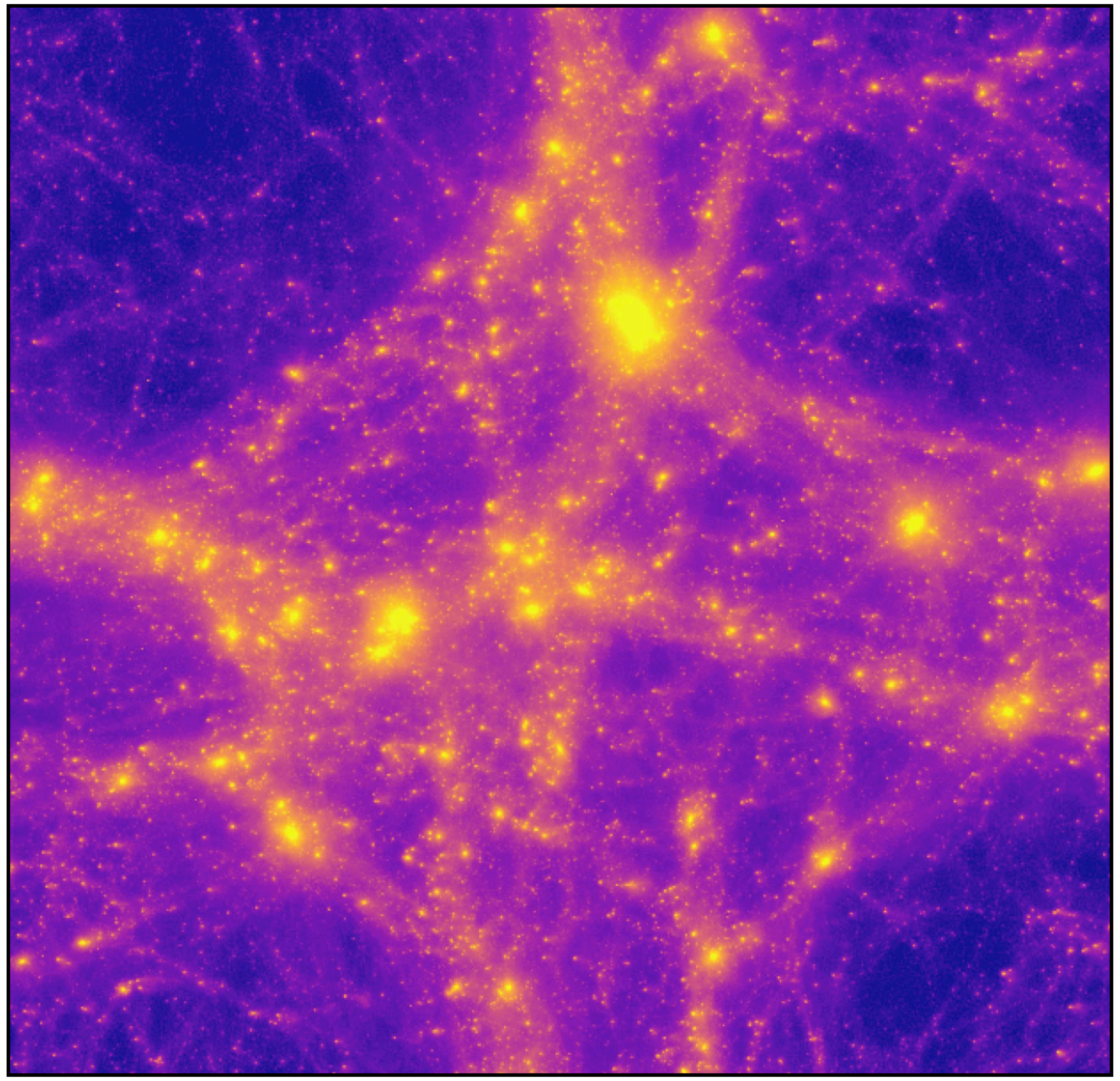
QUESTION:

Environments may affect both gas and metals…

… should we care about large-scales as well?

Part II

How does the dusty ISM evolve within the metric of cosmic web?



Credit: K. Lisiecki, NCBJ

Donevski & Kraljic, in prep.

3.1 Goal / method

Goal:

Connection between the dusty ISM & cosmic web features

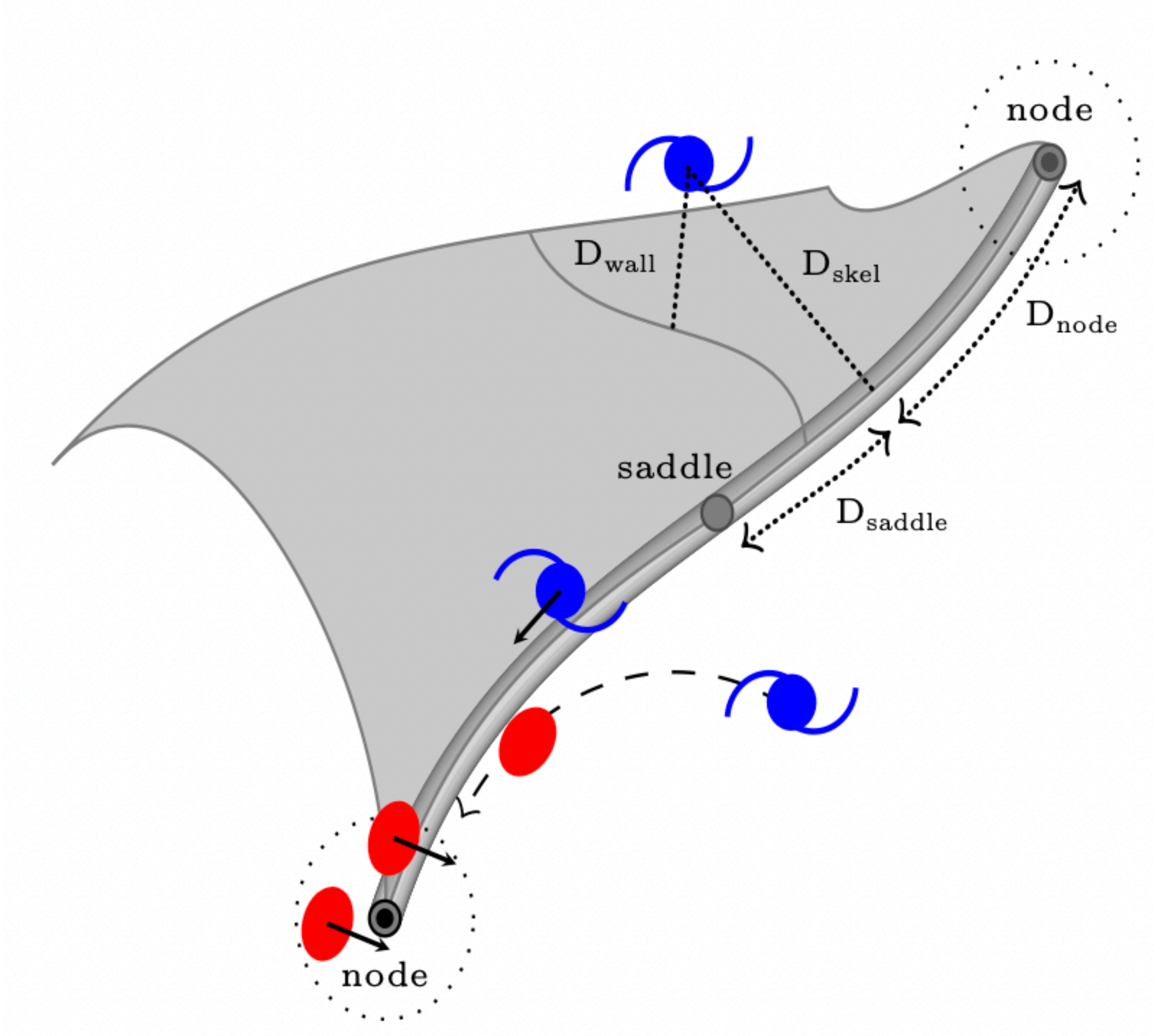
(i.e., distance to cosmic filaments)

Method:

- **Full SIMBA run** (140 Mpc/h)
- **Cosmic Web environments reconstructed with DisPerSE** (Sousbie+ 11, Kraljic+ 18)

- **16 snapshots (0<z<4)** /~ 400k galaxies
- **Local densities** quantified with DTE & smoothed kernel density
- Remove all galaxies that are too close to nodes

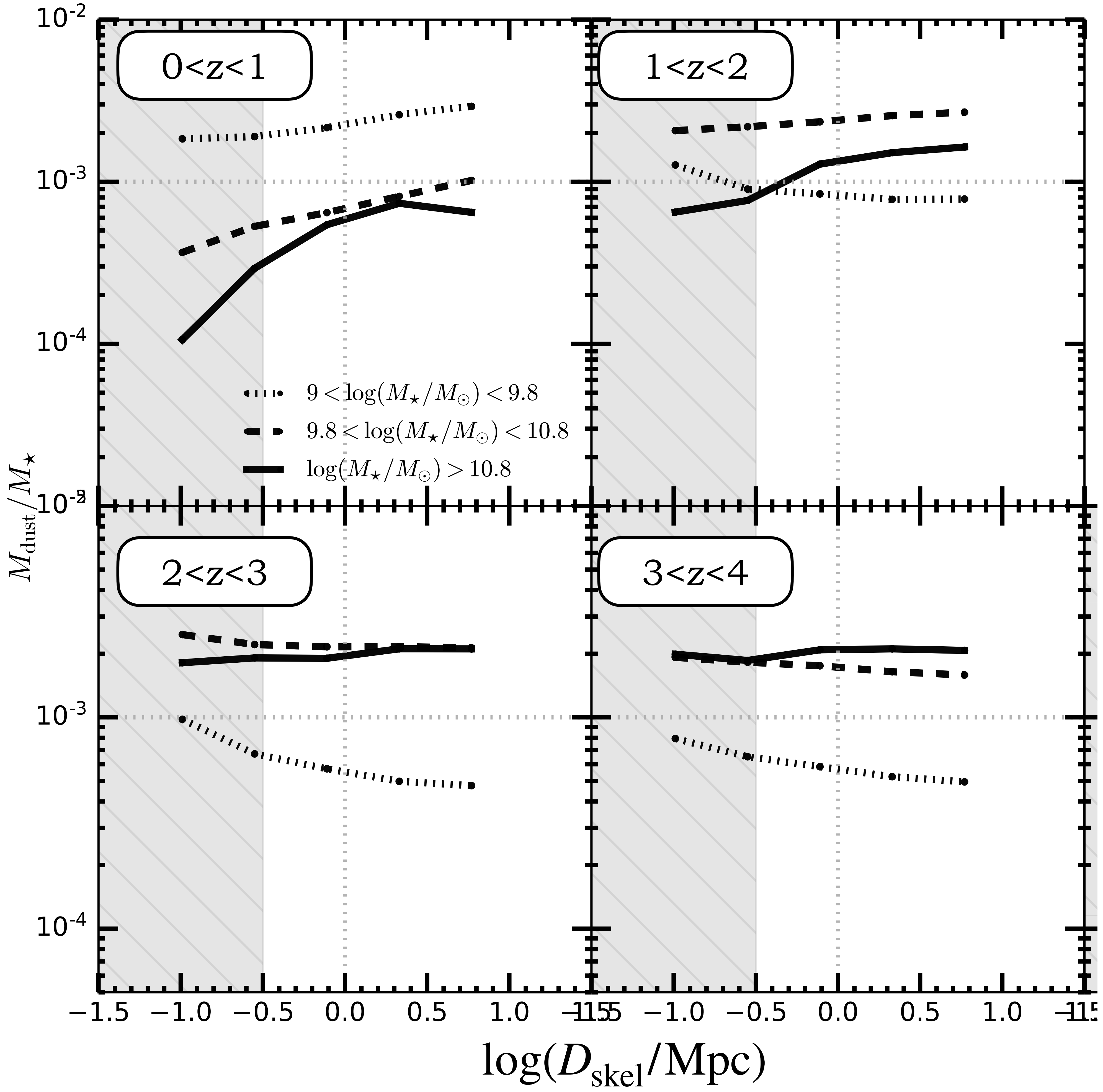
➡ **Reveal the evolution of dusty ISM (specific dust mass, dust-to-gas ratio, dust-to-metal ratio) with galaxies' distances to filaments**



Cosmic Web metric

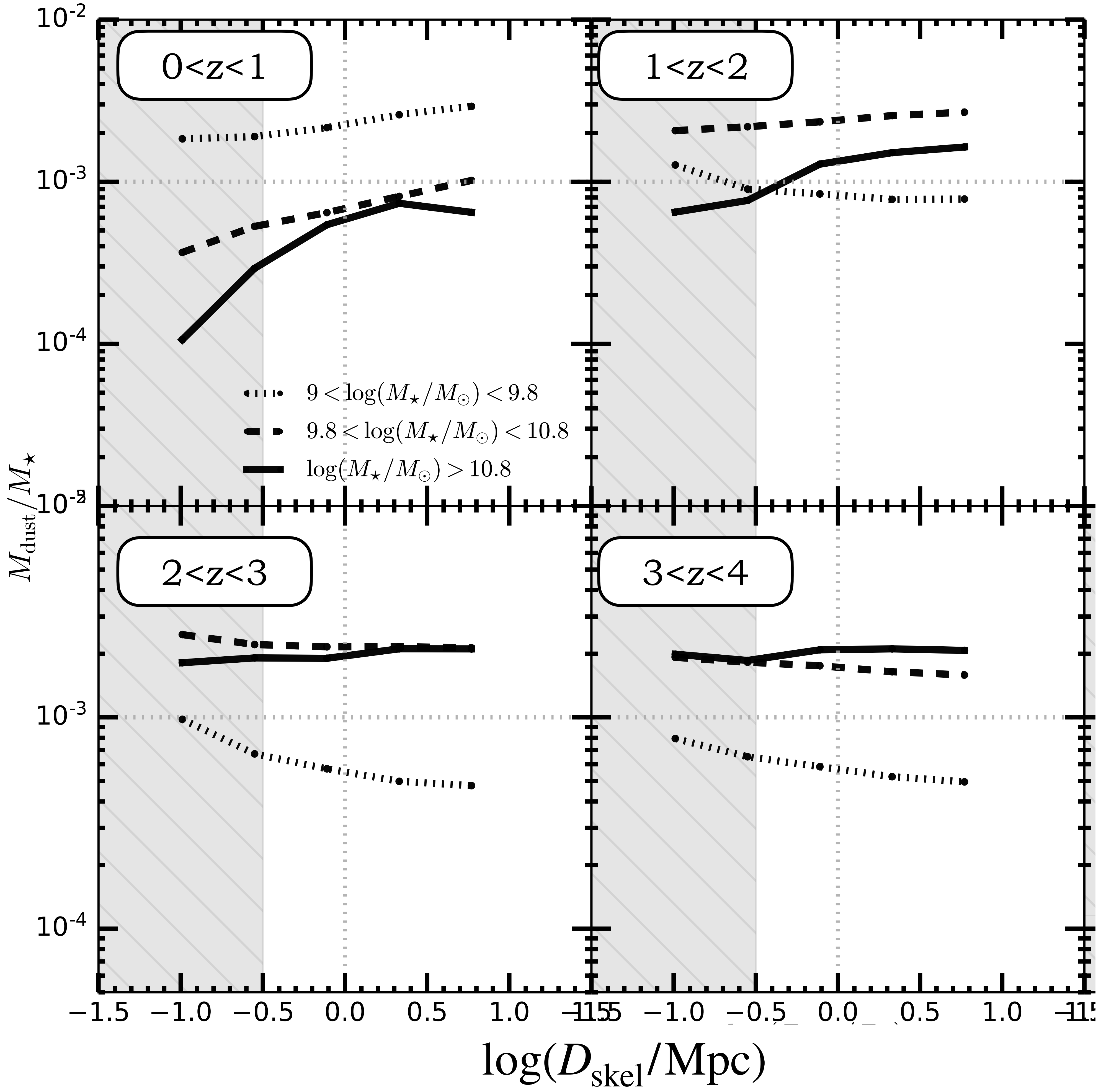
Credit: K. Kraljic, OAS, Strasbourg

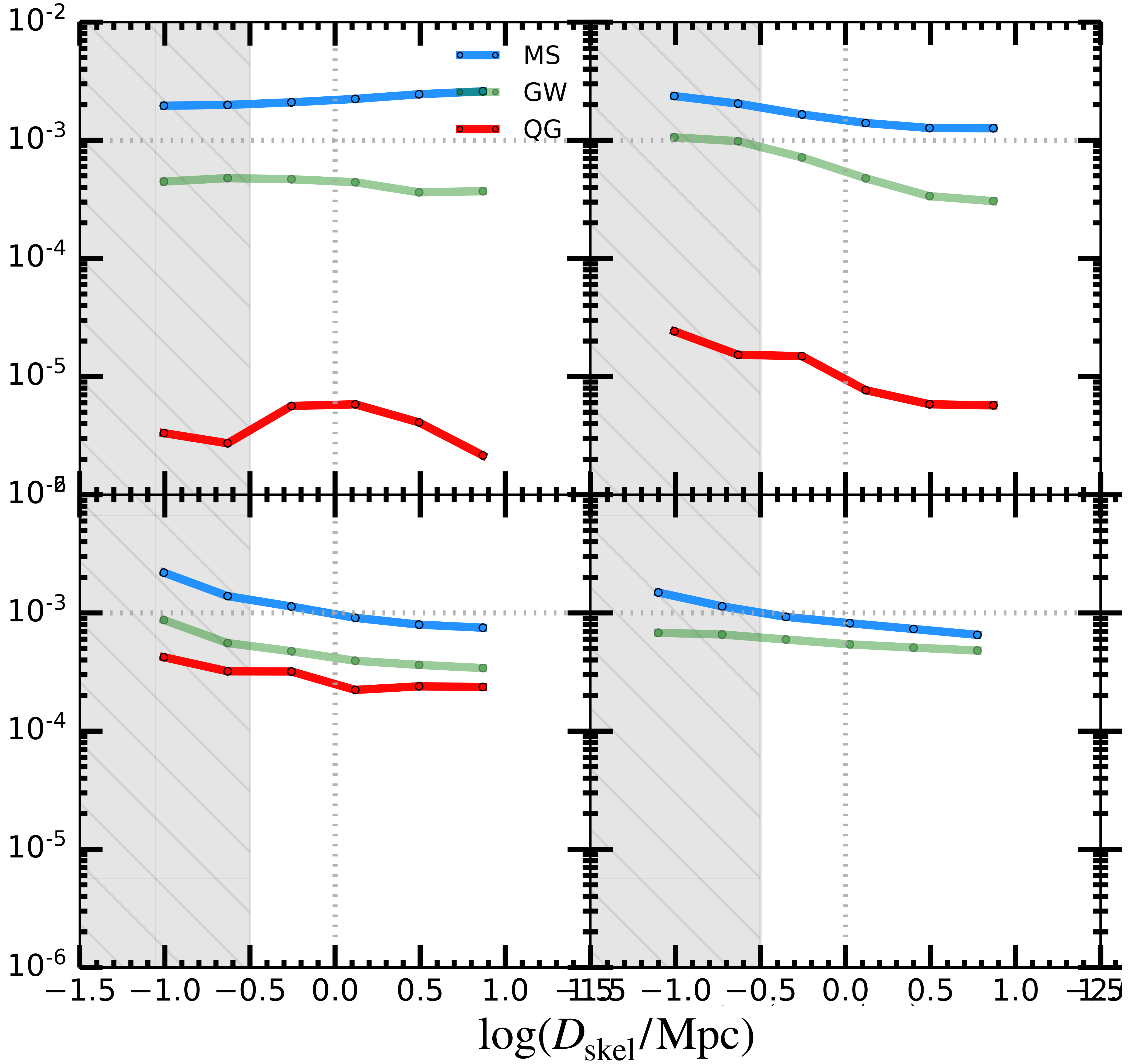
3.2 Evolution of specific dust mass with $D_{\rm skel}$



- Imprint of CW on specific dust mass is the strongest in the most massive galaxies at z<2
- Filaments are very "**supportive**" to ISM of lower-mass galaxies

3.2 Evolution of specific dust mass with $D_{\rm skel}$

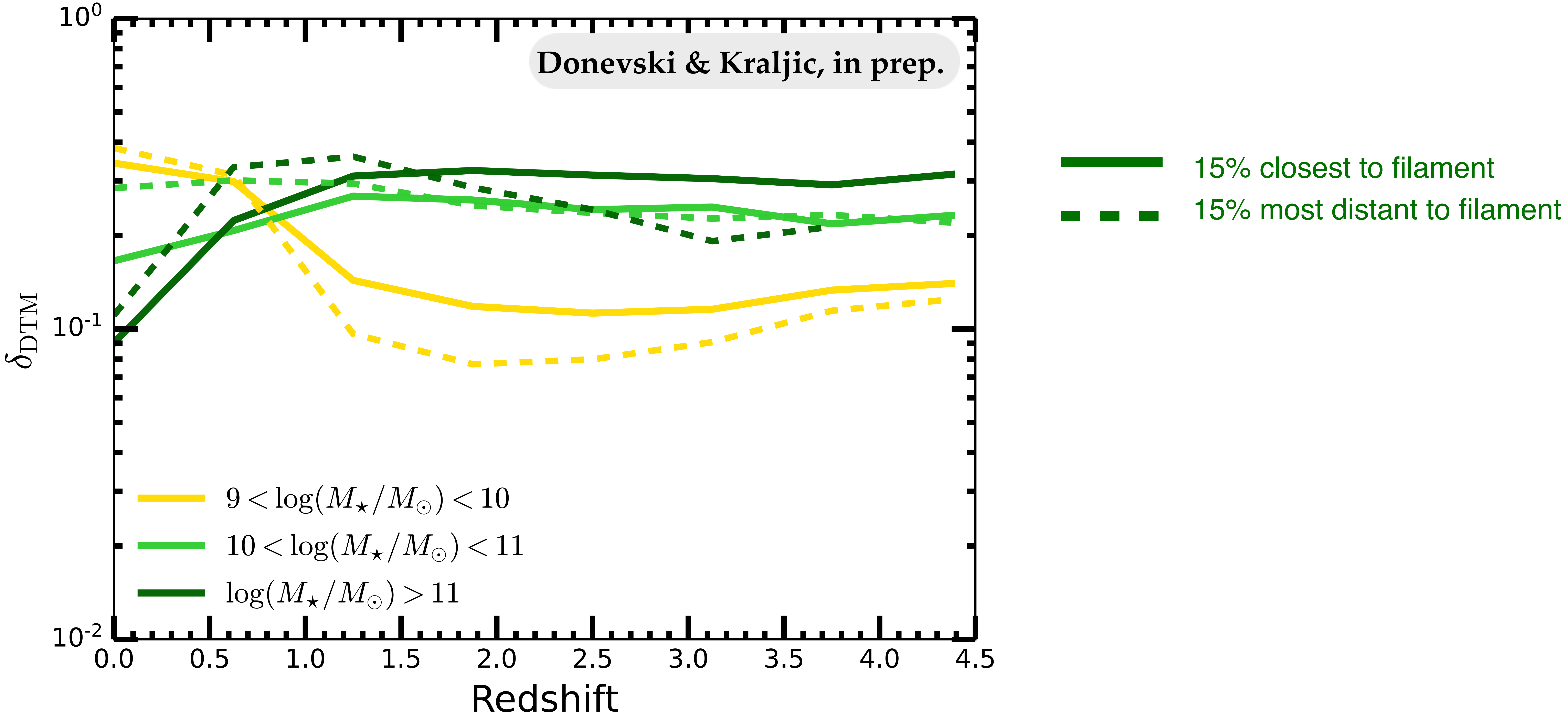




- Imprint of CW on specific dust mass is the strongest in the <u>most massive galaxies at z<2</u>
- Filaments are very “**supportive**” to ISM of lower-mass galaxies

- The CW effect is more complex in GW, and especially QG galaxies
- QGs have more specific dust if they reside closer to filaments, than further away - ***slower quenching or accretion of fresh ISM?***

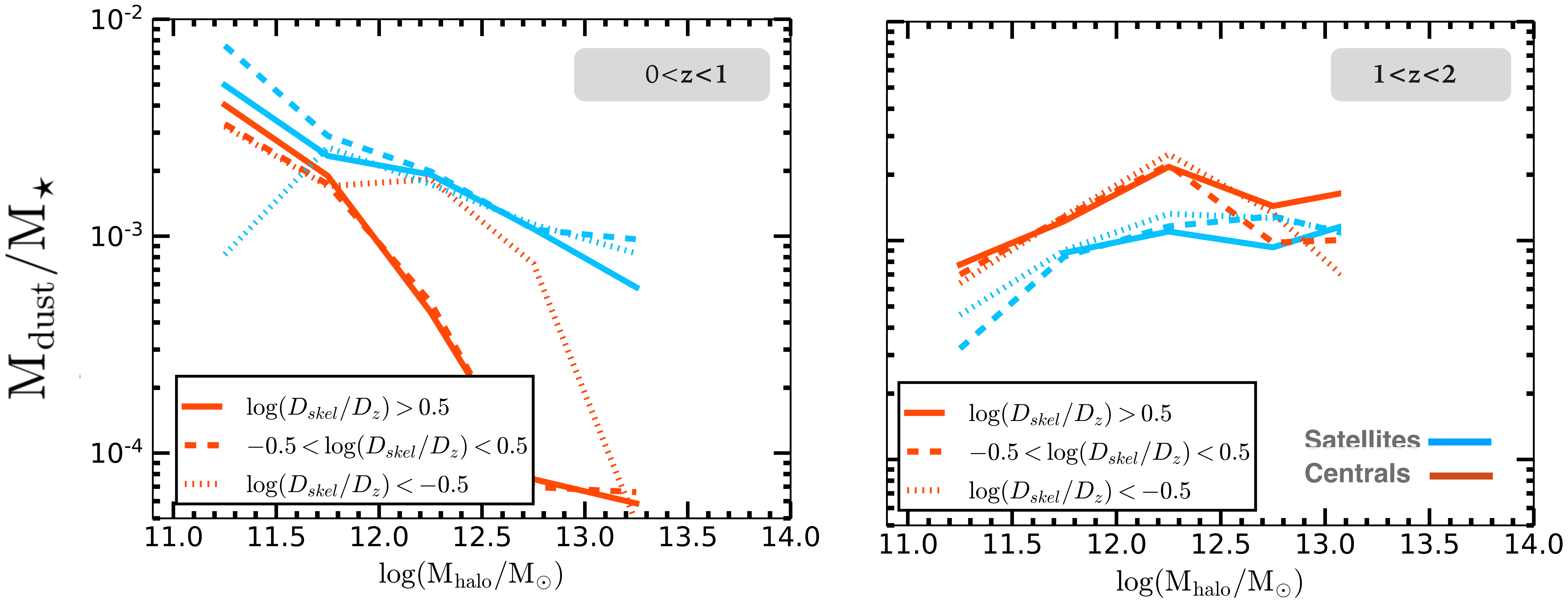
3.3 Is production of dust more efficient in certain CW environment?


Donevski & Kraljic, in prep.

- Galaxies of <u>lower masses</u> dominate specific dust mass at z<1-2

➡ **Enhanced dust-to-metal ratio** (a.k.a. <u>dust grains are growing!</u>)

3.4 Dusty satellites vs. dusty centrals



Donevski & Kraljic, in prep.

- **Turn in central vs. satellite prevalence @z<2**

➡ **SIMBA predicts significant numbers of dust-rich satellites at z<2**

➡In the most massive halos at z<0.5:

(a) fast decrease in ISM abundance mostly in centrals

(b) dust-rich satellites undergo slow quenching and are effectively “shielded” by the rapid destruction due to hot gas

Longer thermal sputtering timescales (>0.5 Gyr-1Gyr) are possible if (i) gas is of lower density $n_{\rm H} \sim 10^{-4} cm^{-1}$, or (ii) if ISM dust growth is accelerated

Remarks

- Dusty galaxies (both SF and QG) show signs of non-uniform ISM and exhibit complex evolution with redshift, size, stellar age & metallicity.

- SIMBA predicts that large-scale environments (e.g., CW filaments) may also be important secondary effect on the dust/gas/metal interplay

- Prolonged dust production/survival timescales (>1-3Gyr) in dust-rich satellites suggest "slower" quenching modes and enhanced growth of dust on metals in gas-phase

  —> *AGN & X-ray feedbacks not so effective in dusty satellites? Still available cold gas in CGM?*

  —-> *CW affects dust ISM not only through gas-fraction, but through dust-to-metal ratio*

Future tasks

- **Quantifying the effect of CW against the local density**

Observational prospects

- Reconstructing the wide environments —> **task for *Euclid***
- Grain growth and mid-IR emission (e.g. via PAH) in smaller dusty galaxies —> **task for JWST**

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Future prospects

Euclid

- Environmental impact (e.g. densities, distance to CW features, dark-matter halo masses) to:
  - *(1) Fraction between dusty and non-dusty QGs@ redshifts* $z<2$
  - *(2) Galaxy scalling relations that include dust*
  - *(3) The role of centrals vs. satellites*
- Measurements of D4000, age, metallicity in quiescent populations up to $z\sim2$

Possible synergies

JWST

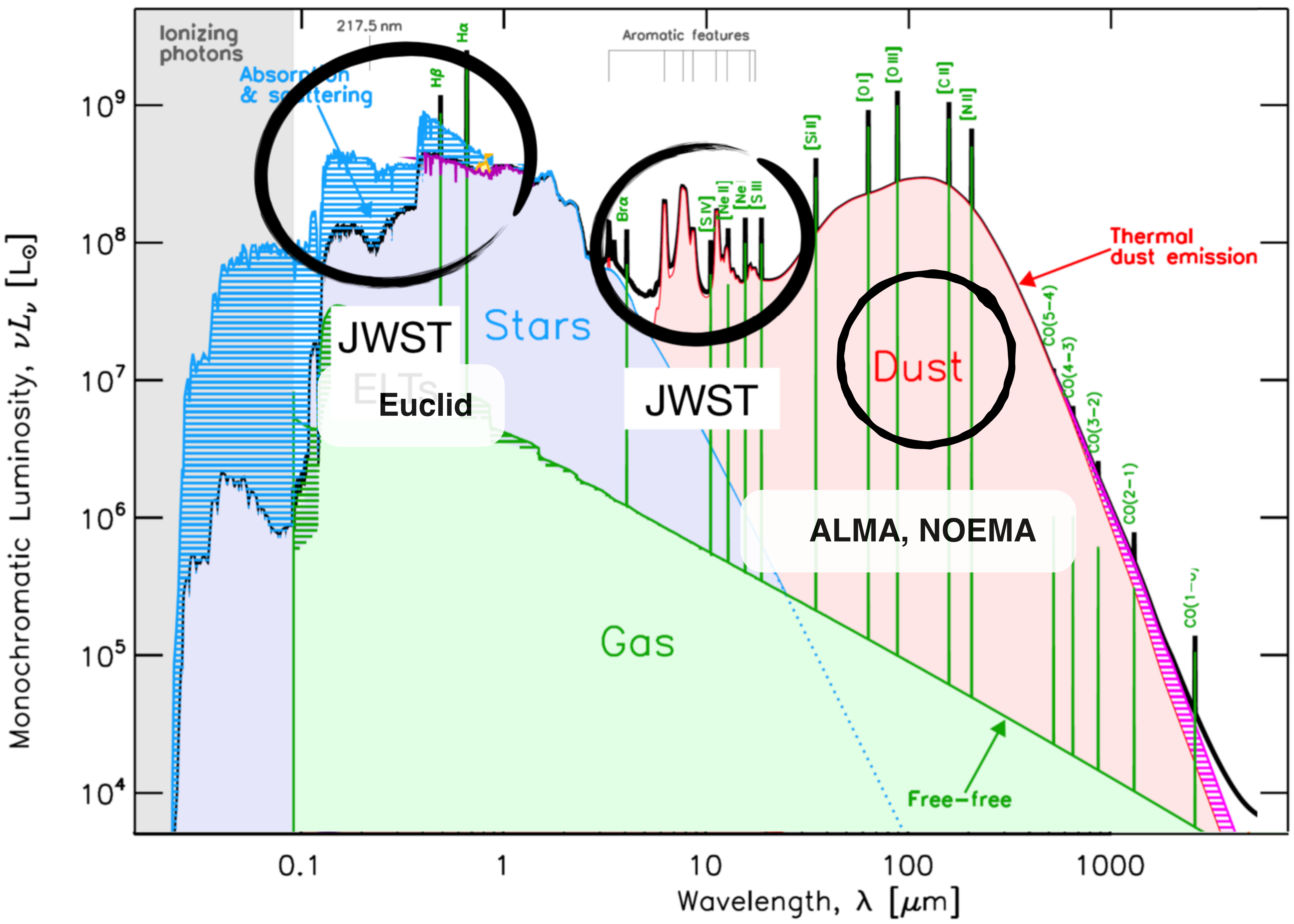
- MIRI spectra to confirm presence of silicate features (direct model output!)
- Metallicity (both through near-IR and mid-IR lines) of fainter dusty QGs
- Better constrain on AGN presence

Millimetric telescopes

- ALMA/NOEMA (cold-gas fraction)

Additional slides

Future synergies



☑ **NIR/MIR spectroscopy with JWST + cold gas estimates from ALMA**
☑ **NIR photometry with Euclid & LSST**

2.1 hCOSMOS: Data analysis/SED modelling workflow

Initial data: hCOSMOS (Damjanov+ 19)
(magnitude complete 17< r< 22 mag)
Instrument: MMT Hectospec
Selection criteria: Dn4000>1.5

Final catalogue:

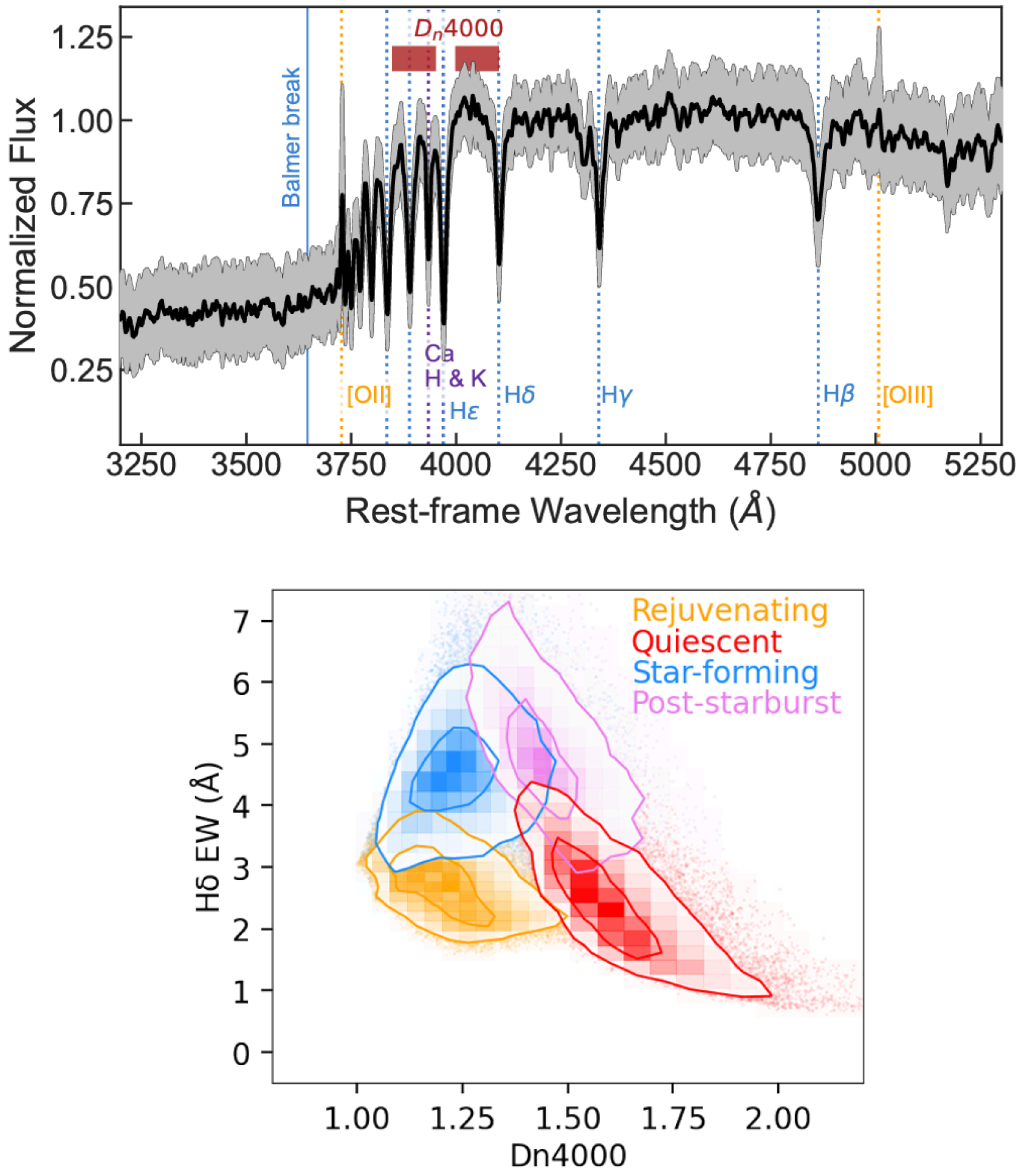
- **550 dusty quiescent galaxies @ $z < 0.7$** (25% of the full sample)
- **Panchromatic SED:** 10+ bands in **opt-NIR** and 4+ bands in **IR-submm** (XID+ on opt. priors)
- **Independent estimates of Dn4000 & gas-metallicity** (Sohn+ in prep.)

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

I Data processing workflow

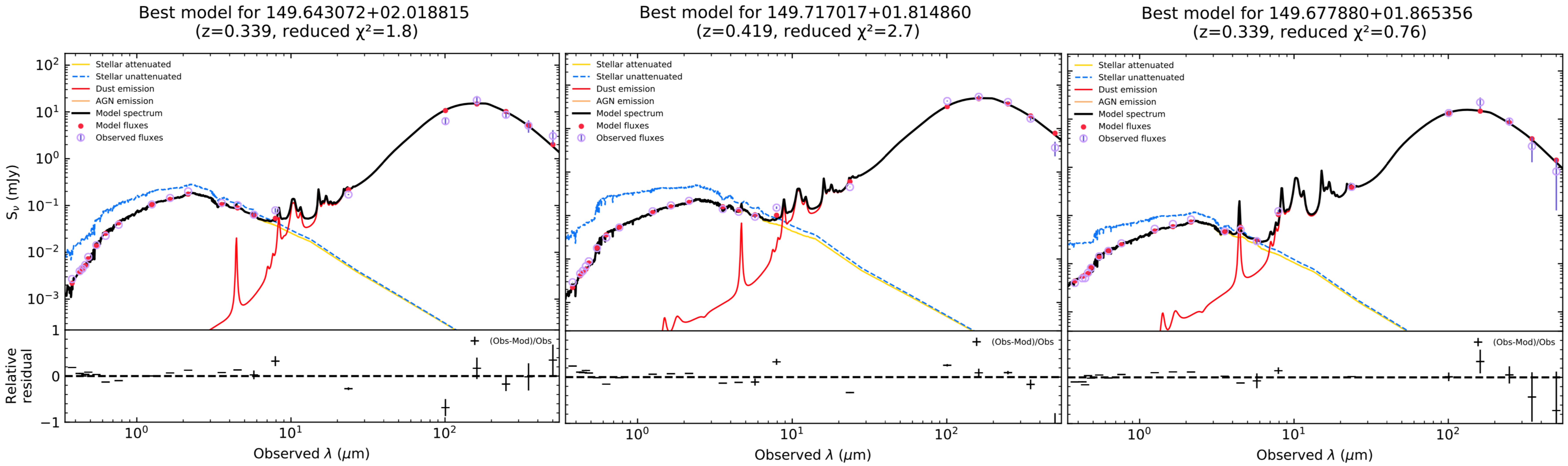
II Data Analysis

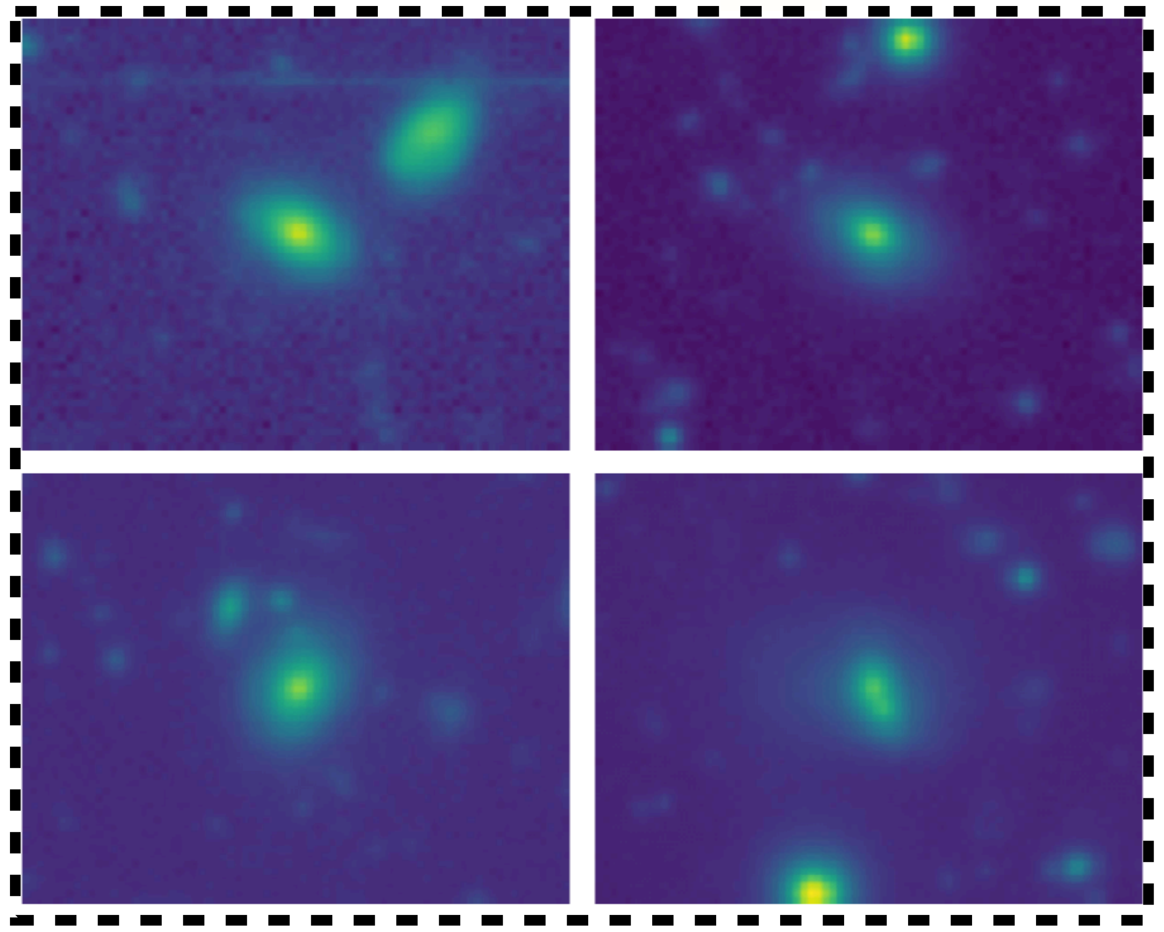
Why selecting QG based on D4000 break?



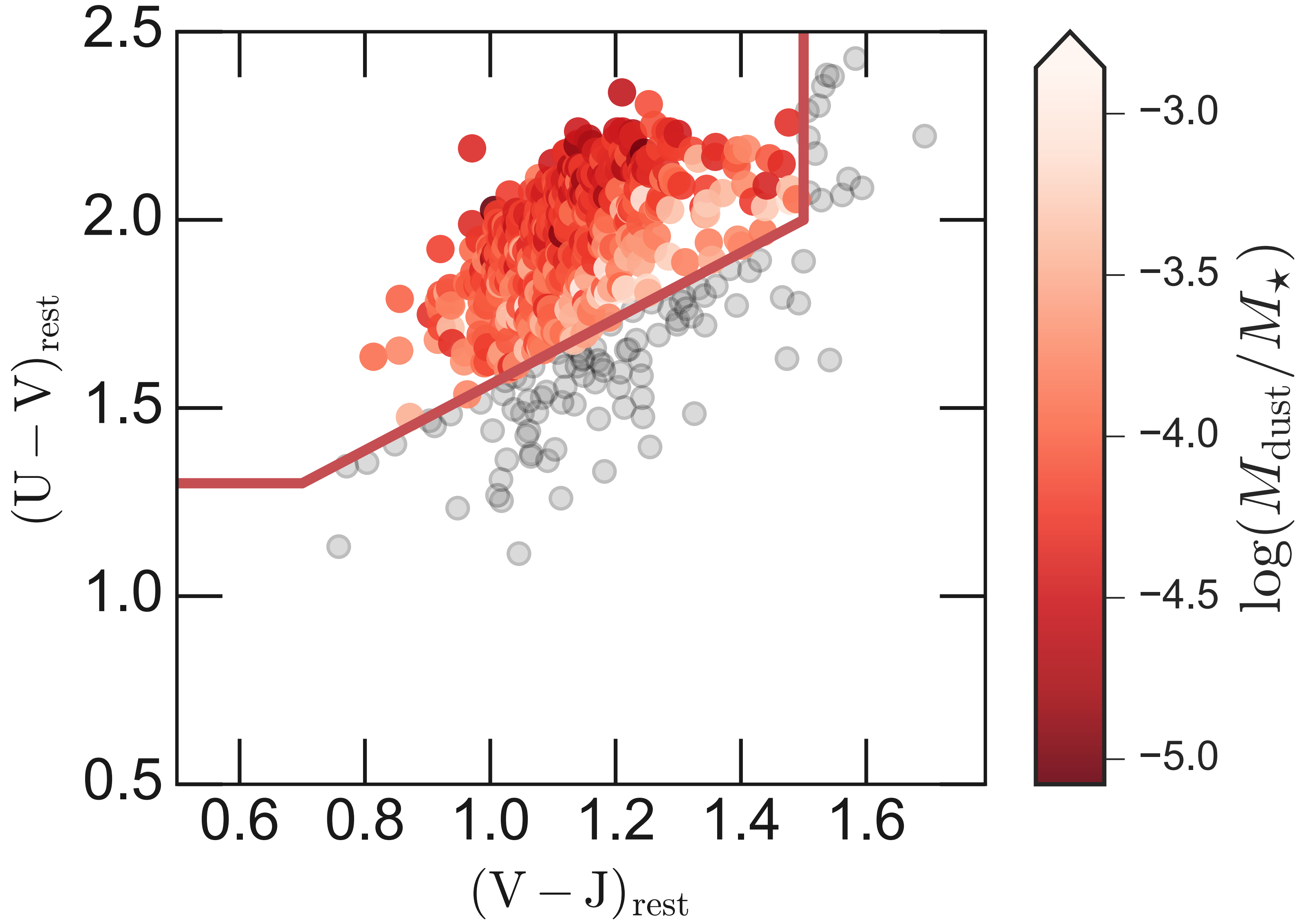
(Zhang, Leja & Whitaker 2022)

2.1 hCOSMOS: Data analysis/SED modelling workflow

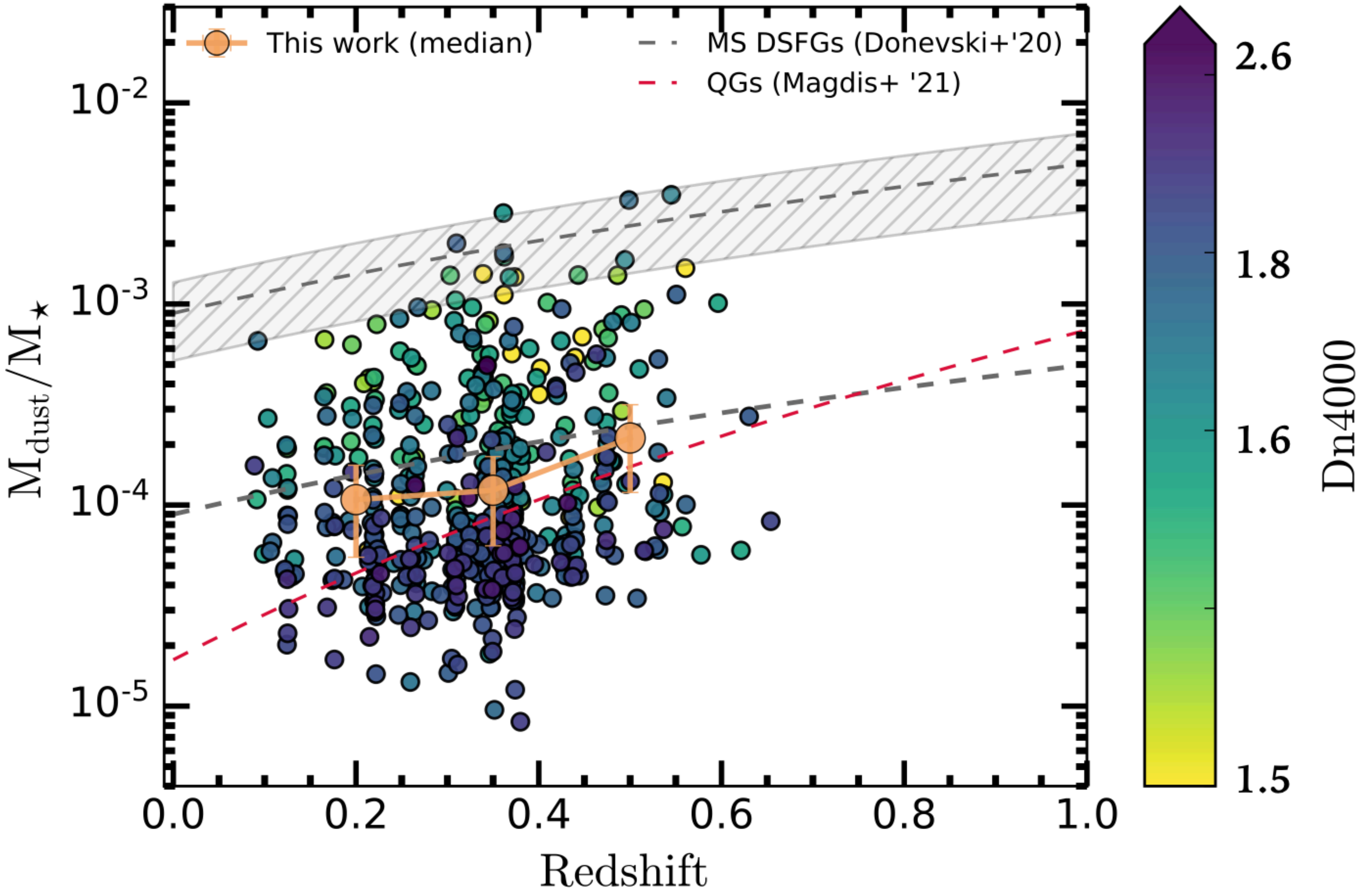




i-band HSC

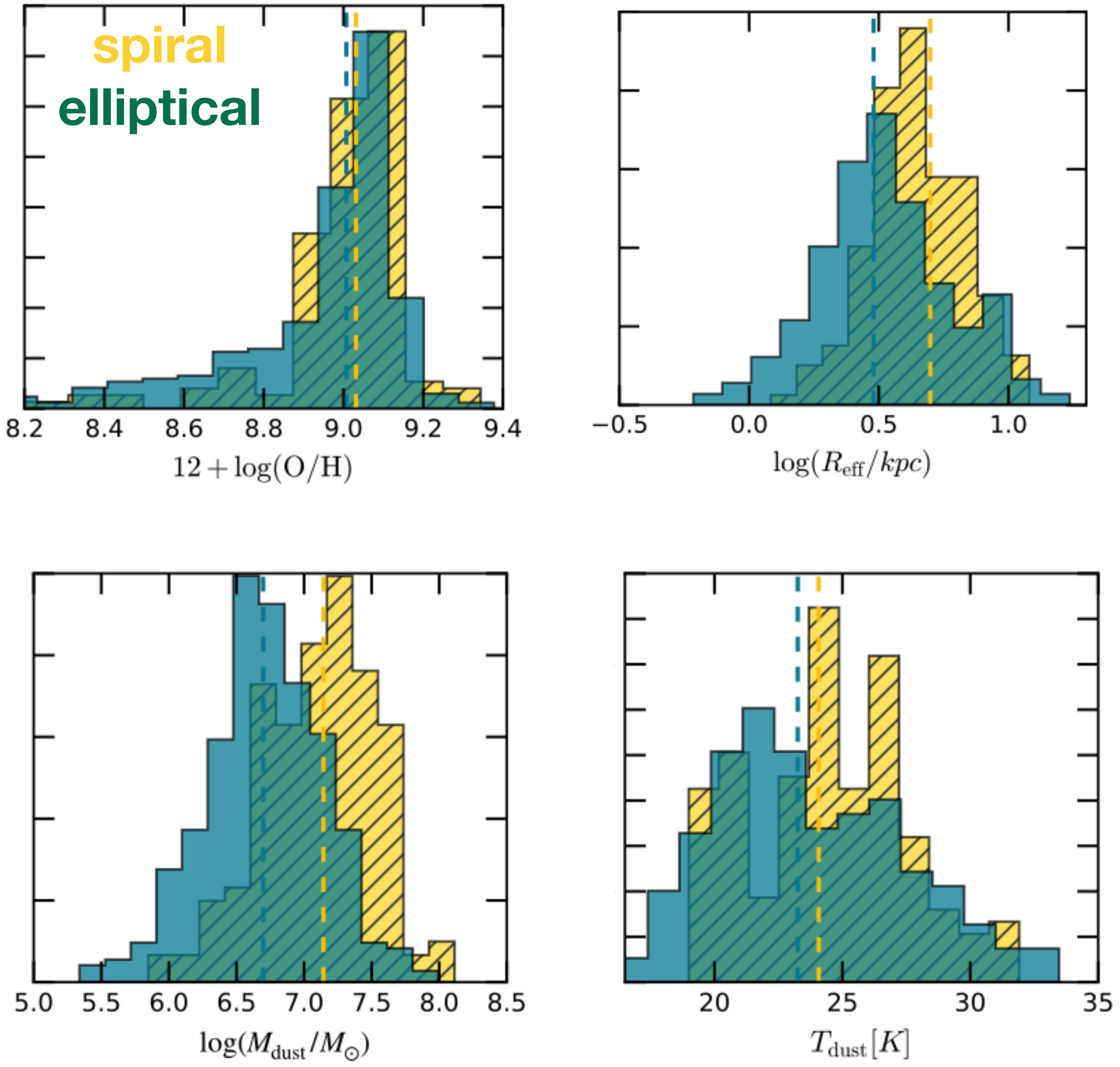


2.1 Cosmic evolution of specific dust mass in QGs



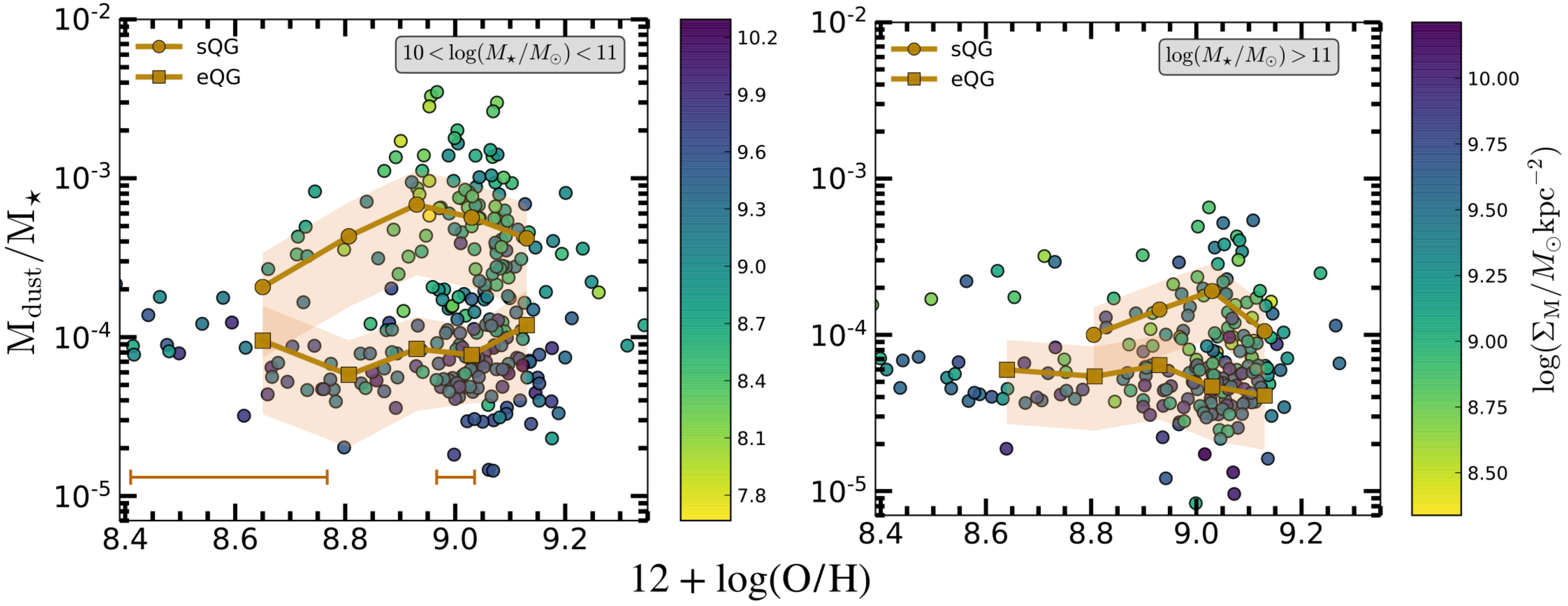
- Evolution of specific dust mass in 548 dusty QGs
- Shallow at $0.1<z<0.7$
- Tension with stacking analysis results (Magdis+ 20)

2.2 Morphological impact on specific dust



- Morphology plays role in driving the scatter in dust parameters
- Various Td and Zgas —> non-uniform ISM conditions!

2.2 Relation between specific dust mass & metallicity

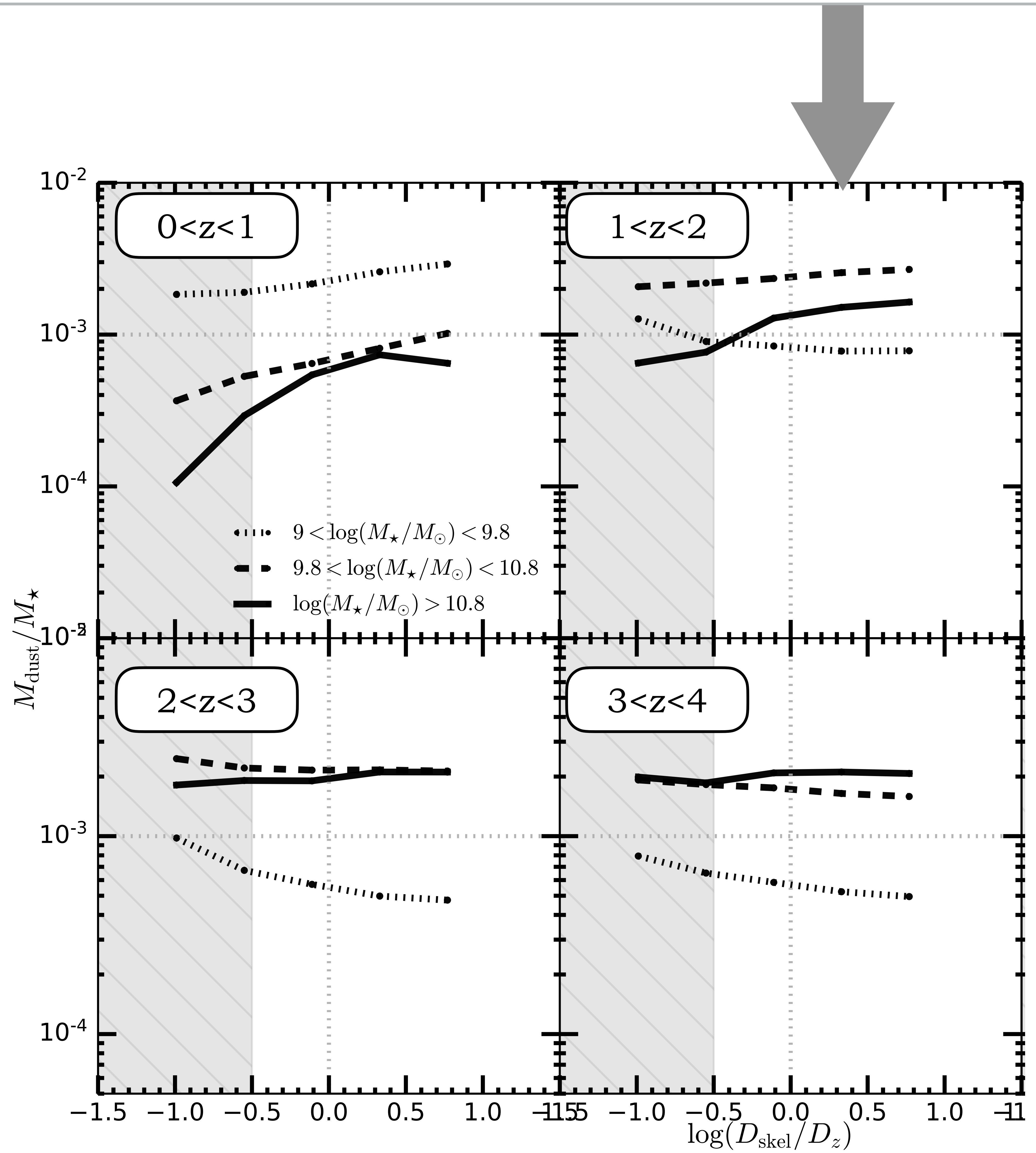


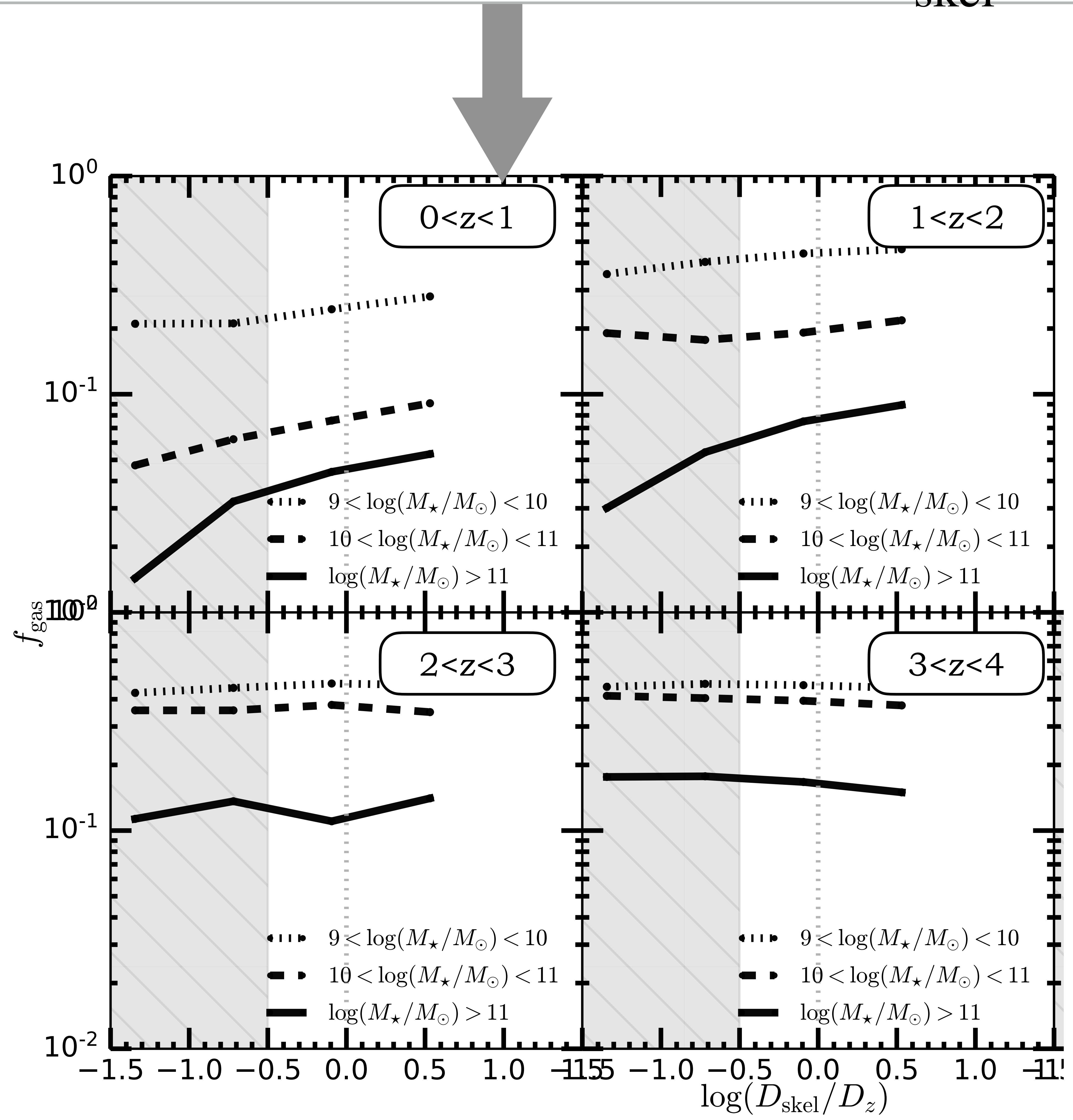
- **Large scatter** in specific dust mass of QGs.
- **Impact of morphology**: Higher specific dust content in **spirals QG** than in **elliptical QGs**

→ Different timescales for dust growth/removal in the metal-rich ISM ?

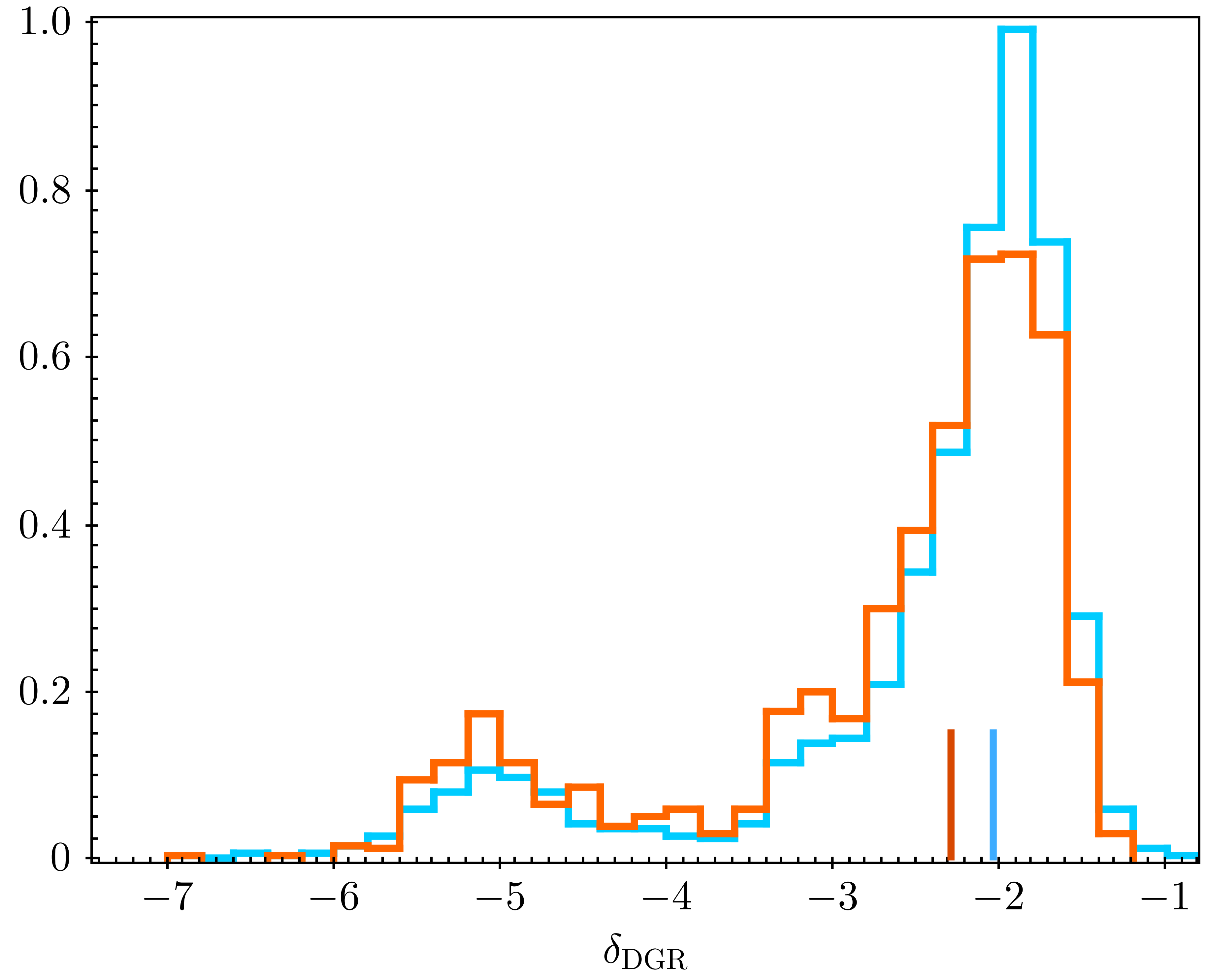
→ Accretion of dust-rich satellites? (e.g. Hirashita+ ’17; Calura+ ’17; Li+ ’19; Triani+’20)

2.2 Evolution of specific dust mass and gas-fraction with D_{skel}

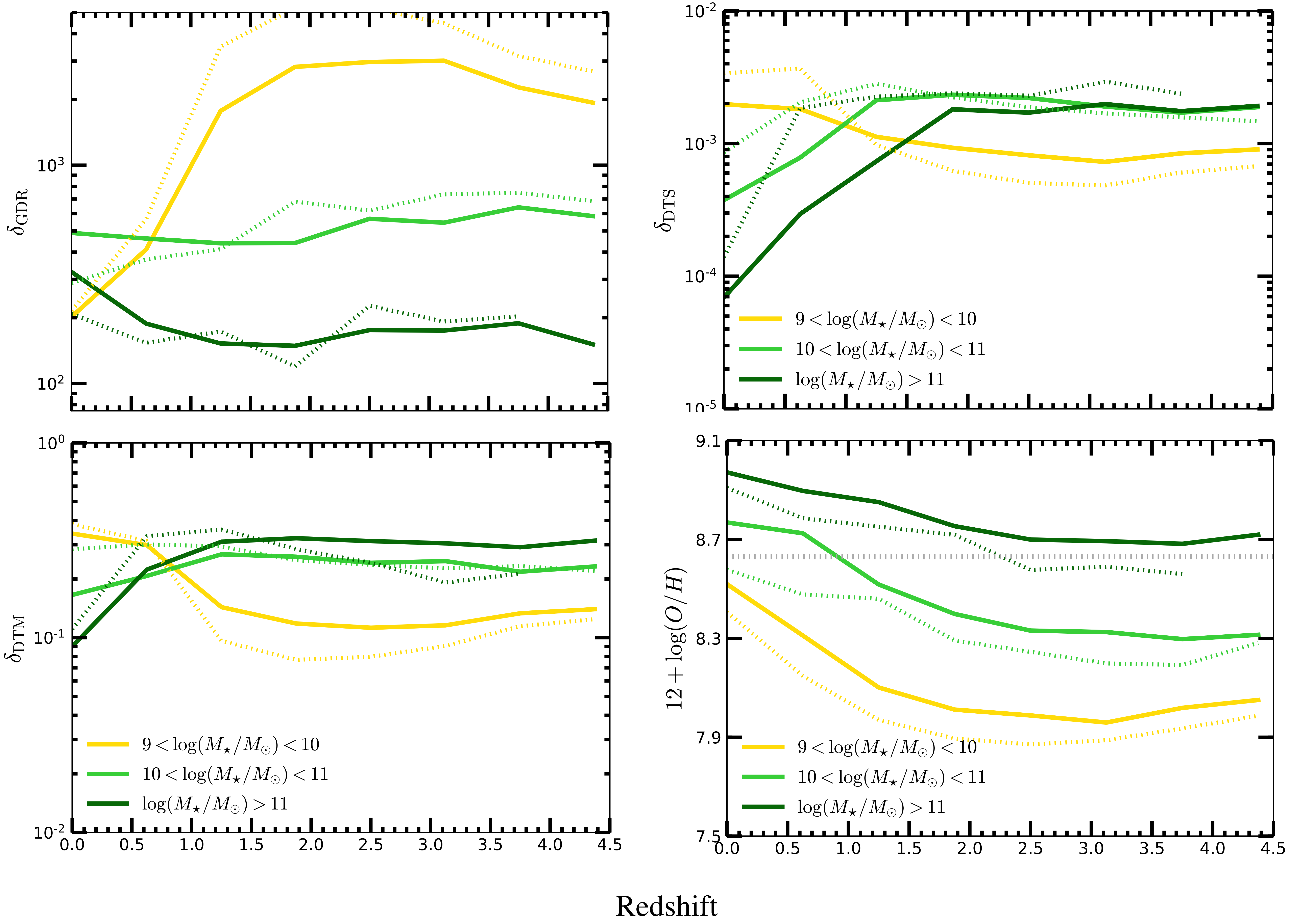


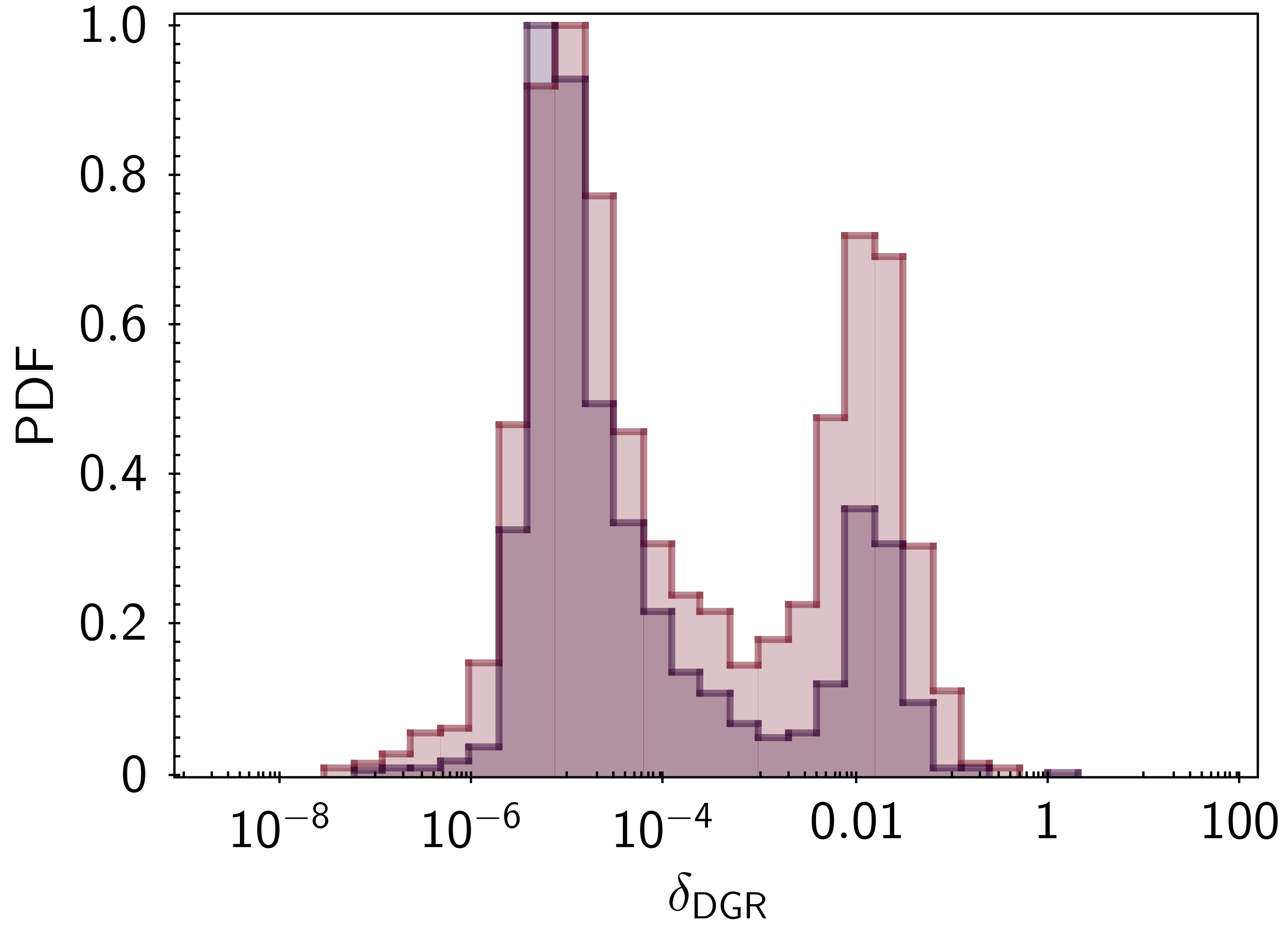


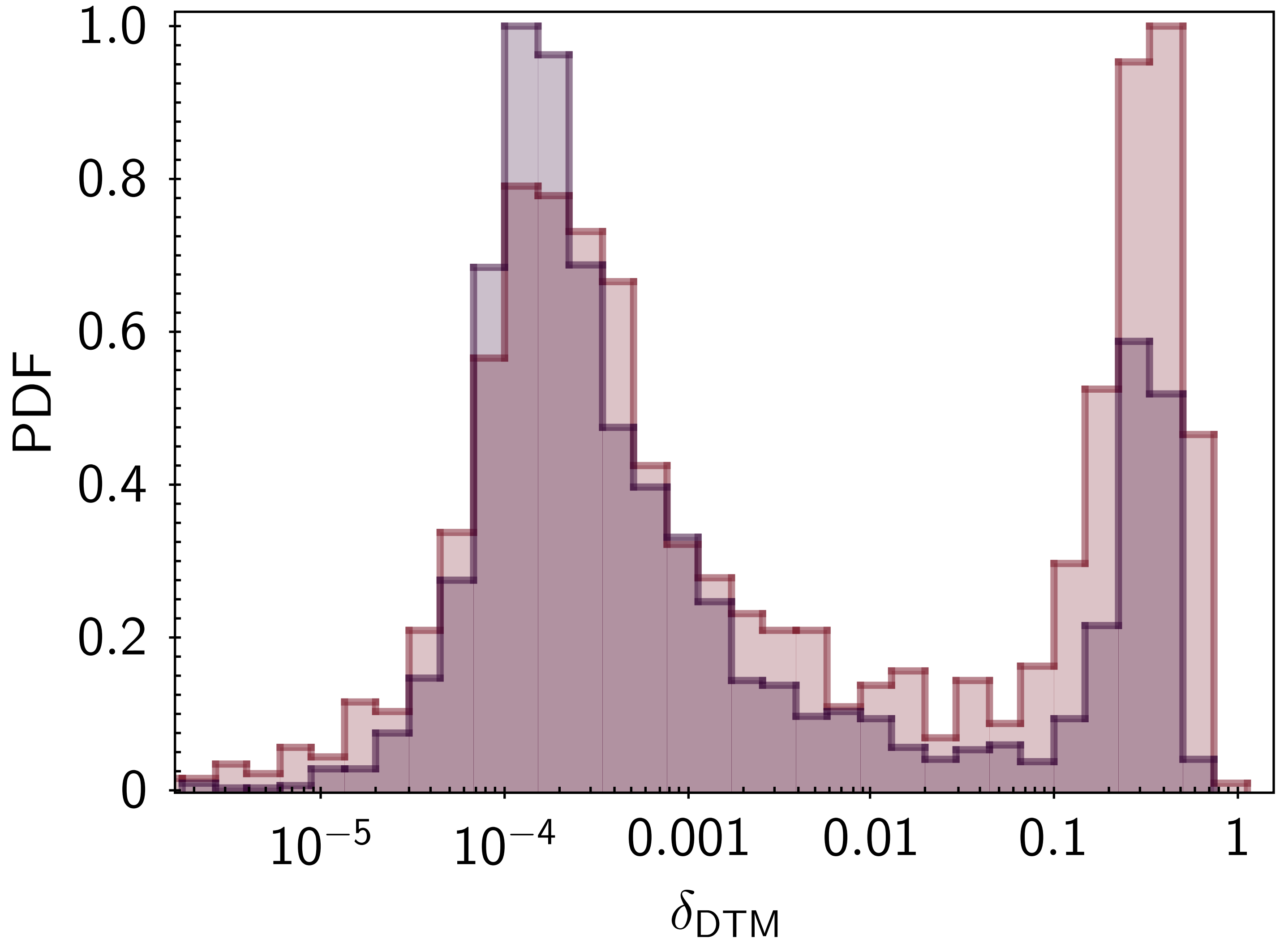
2.3 Dust-to-gas ratio in intermediate massive satellites vs centrals @ z<1



Residuals of the redshift evolution




1.0
0.8
0.6
0.4
0.2
0
PDF
10^{-8}
10^{-6}
10^{-4}
0.01
1
100
δ_{DGR}


1.0
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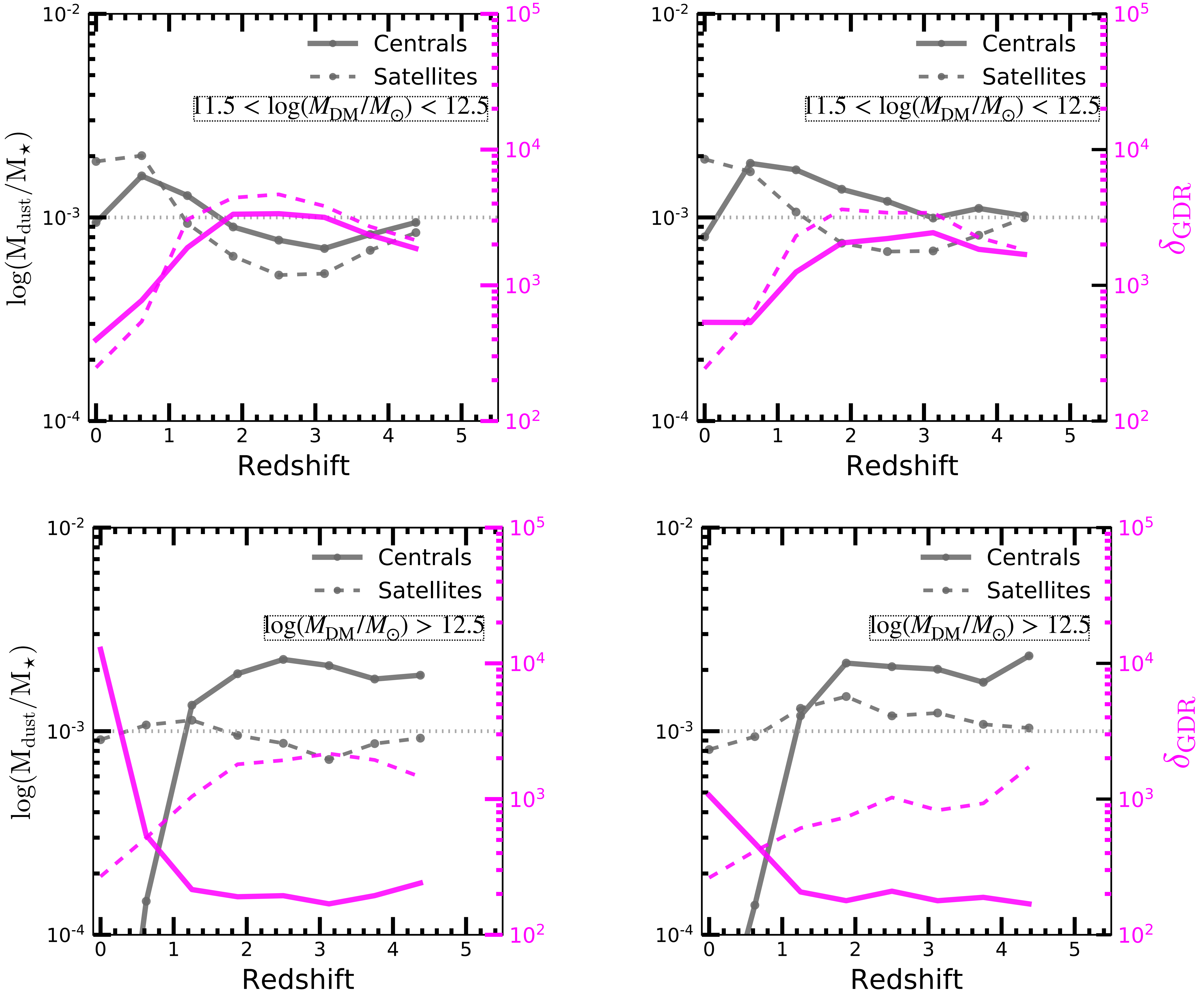
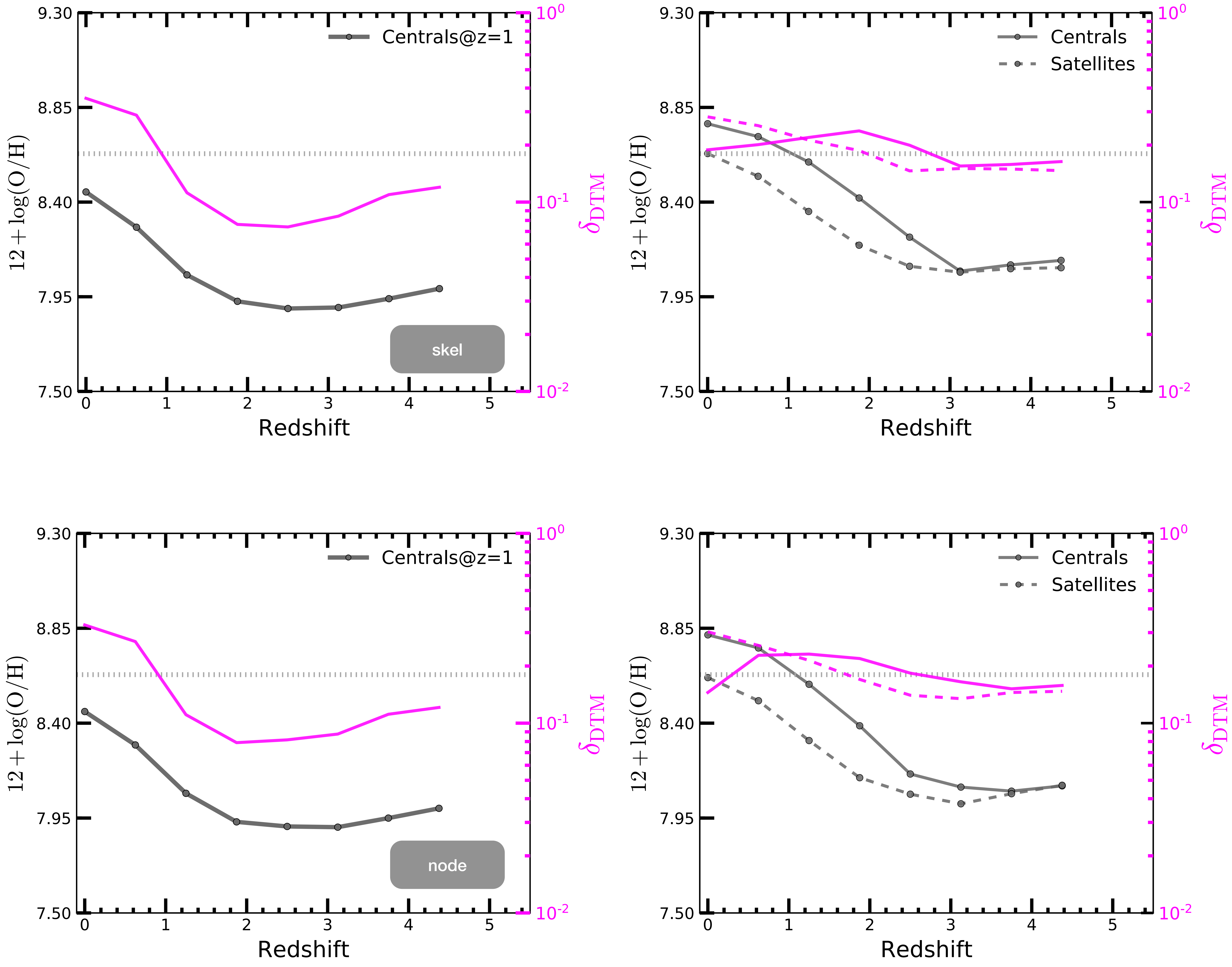
δ_{DTM}

Controlling for dark matter halos

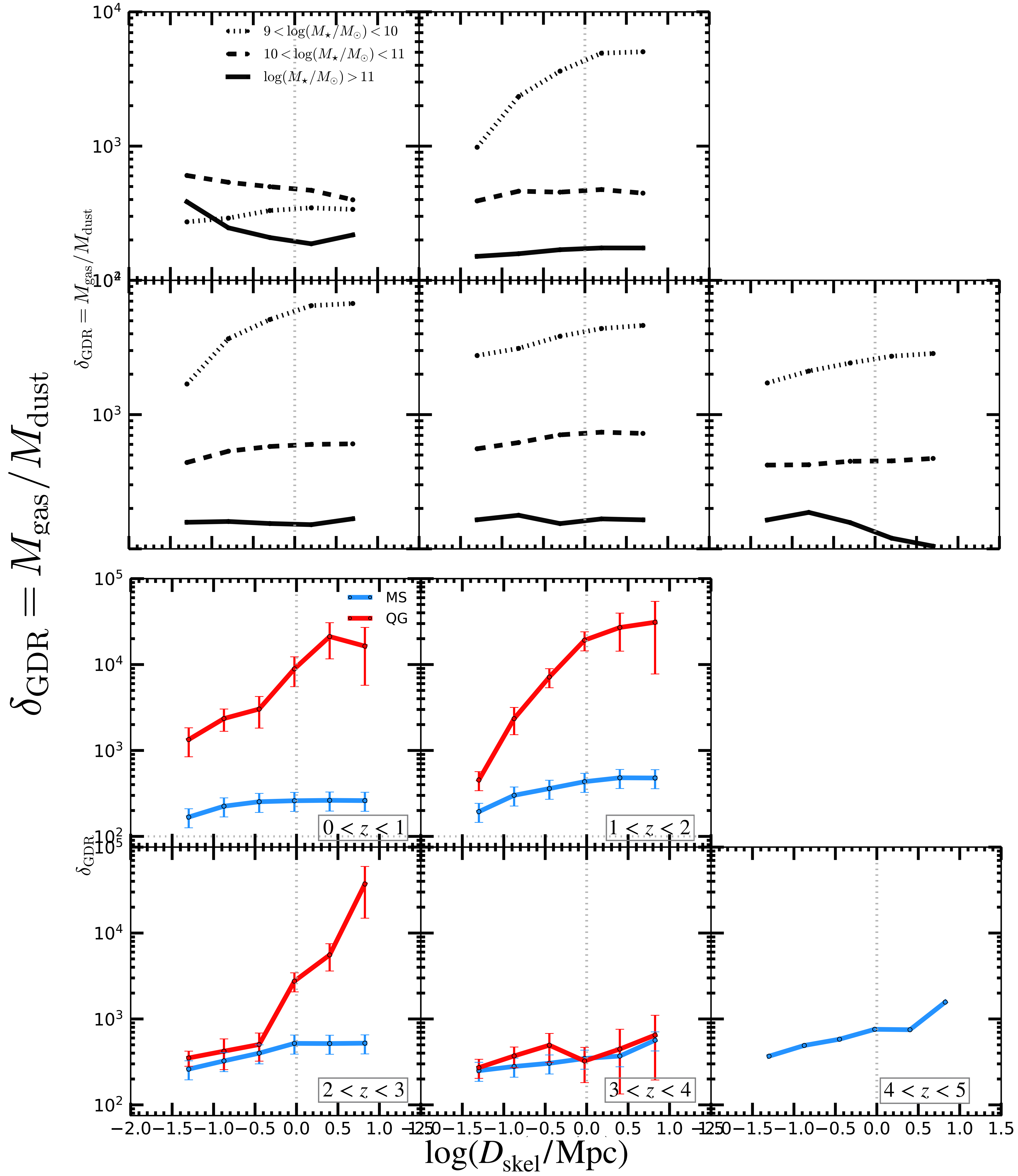


Comparison of cosmic evolution of dust abundance in the ISM for two separate halos.
Left columns denote the evolution of galaxies far from filaments, while the right columns represent those that reside close to filaments.

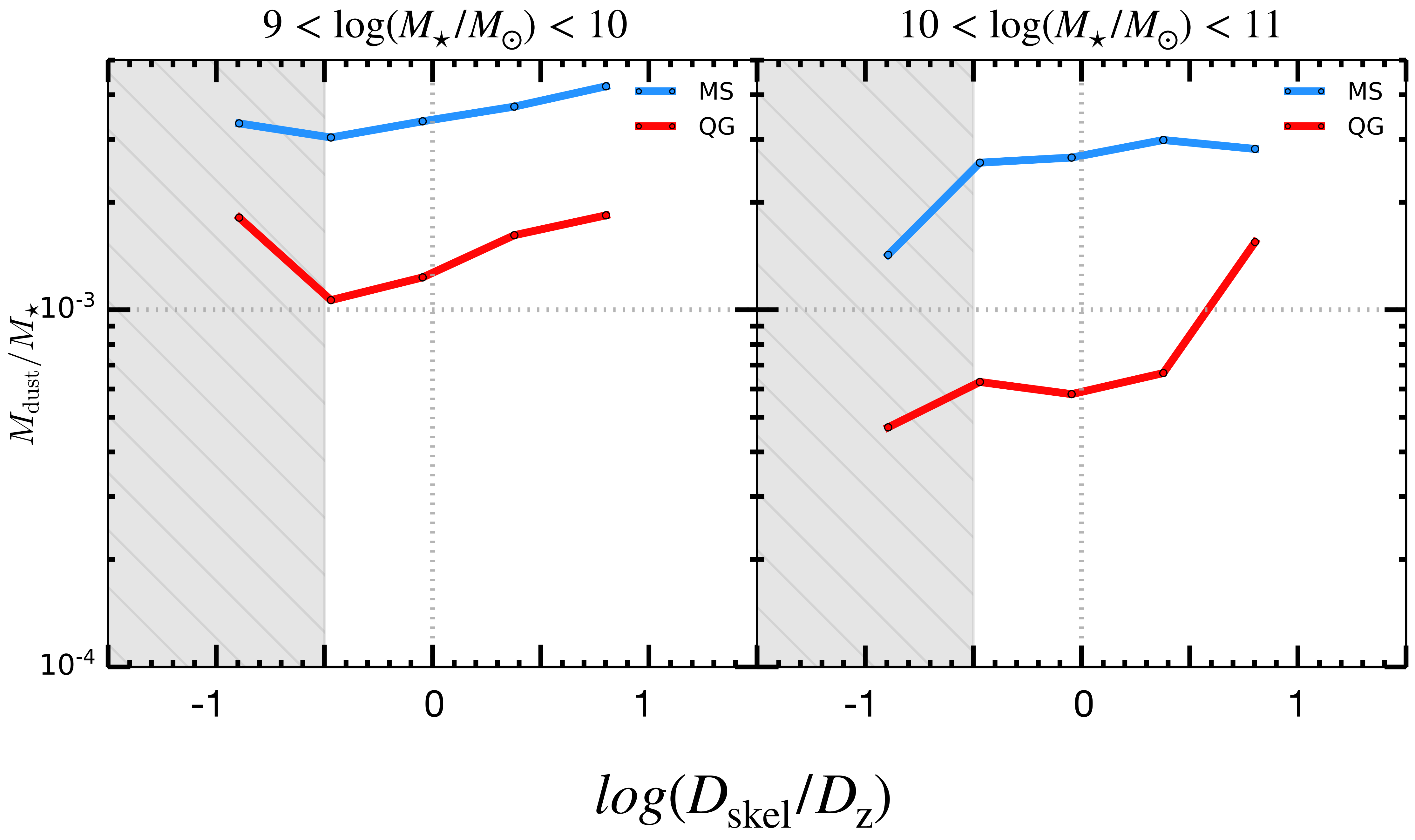
Controlling for dark matter halos



Gas-to-dust mass ratio



DUSTY GIANTS: clustered sources@z=0



Is dust-to-gas ratio within the CW affected differently in MS/QG galaxies?

- Lower mass galaxies within the node are fed by metals which increases/protects their dust content despite being affected by feedbacks and dense environments.
- In galaxies with higher stellar masses, feedback is the most important regulator of galaxy DGR, but CW plays important secondary role.