Florent Renaud
Strasbourg Observatory

Bends of the River(s) of Galaxy Formation

Artist rendition
by Nic Risinger

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by Nic Risinger

PLEASE REWIND

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Strasbourg

PLEASE REWIND

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younger

PLEASE REWIND

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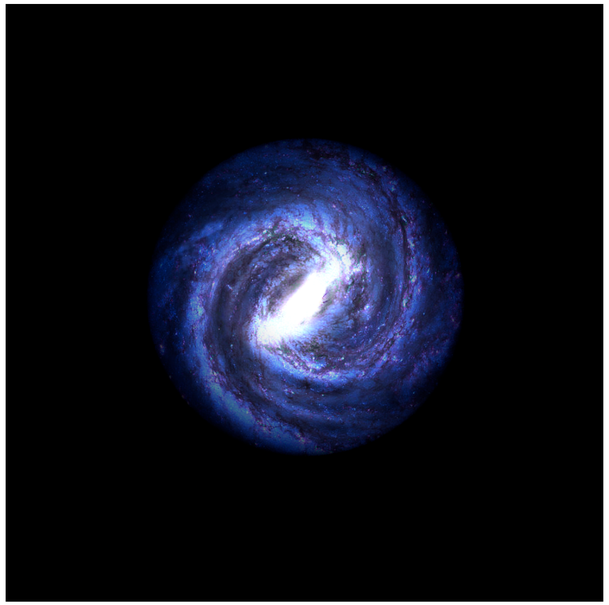
Strasbourg

younger

smaller



PLEASE REWIND

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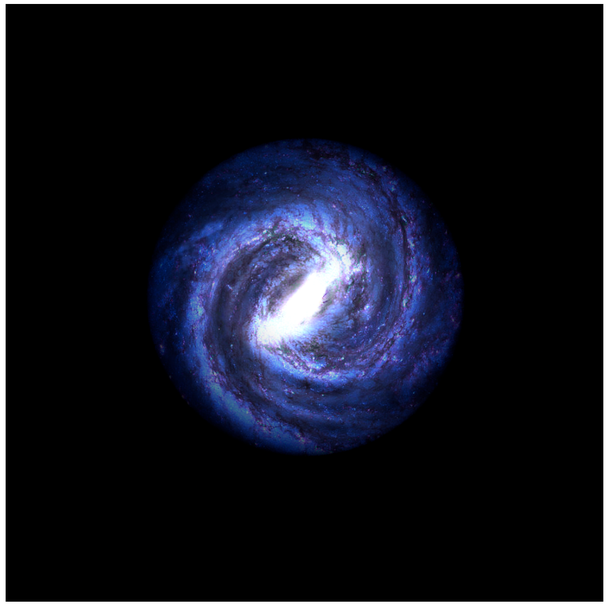
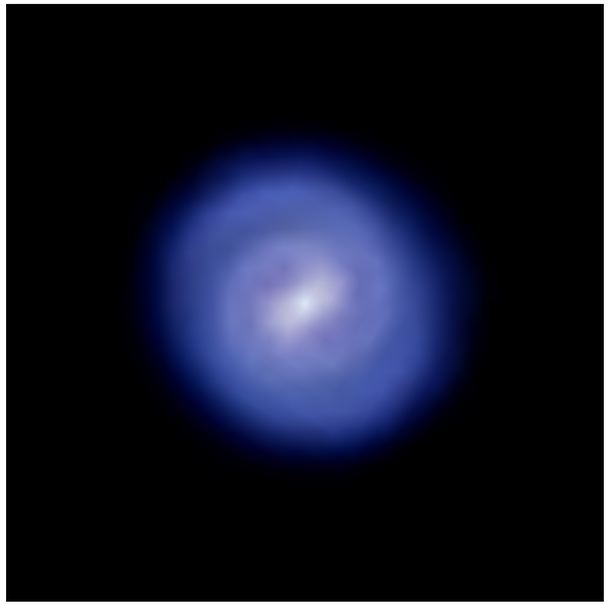
younger → smaller → less resolved



NOT SO FAST ...

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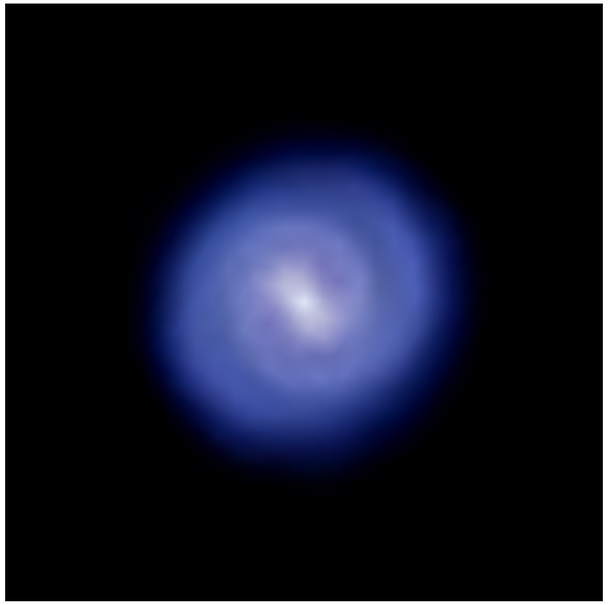

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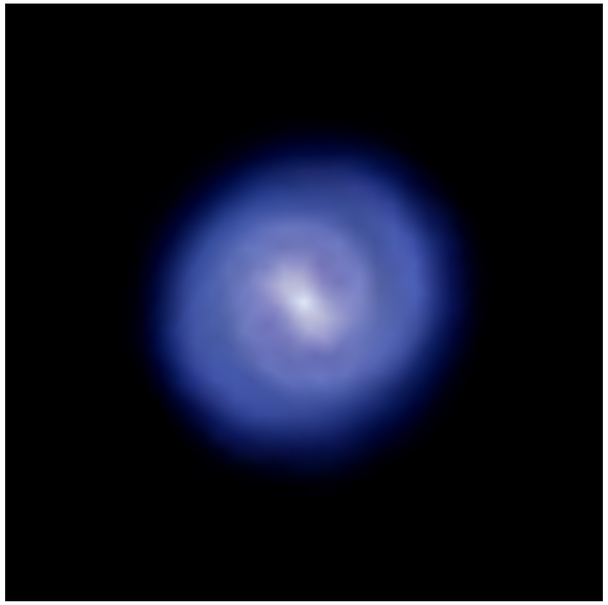

Elmegreen et al. (2009)

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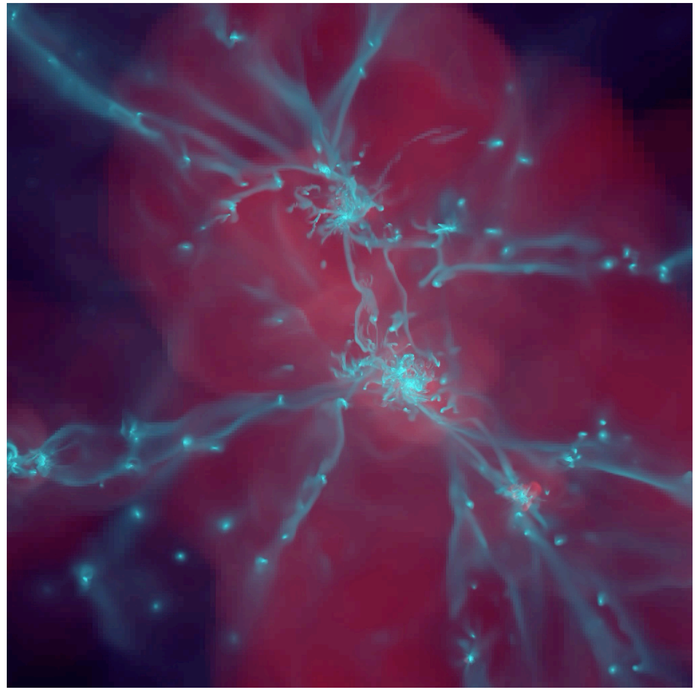

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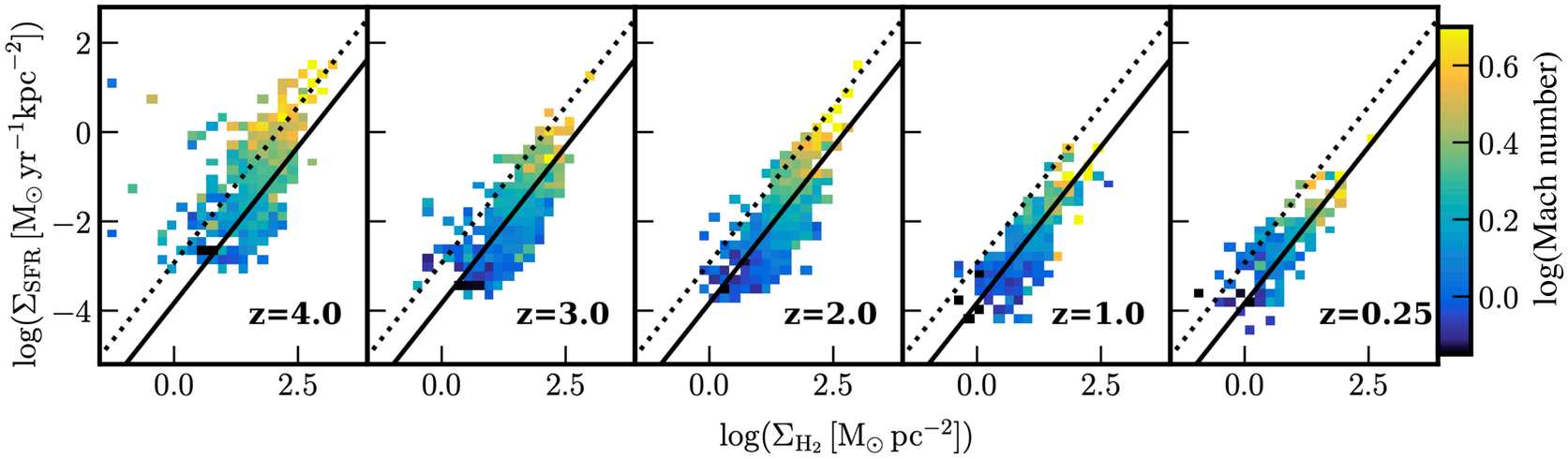

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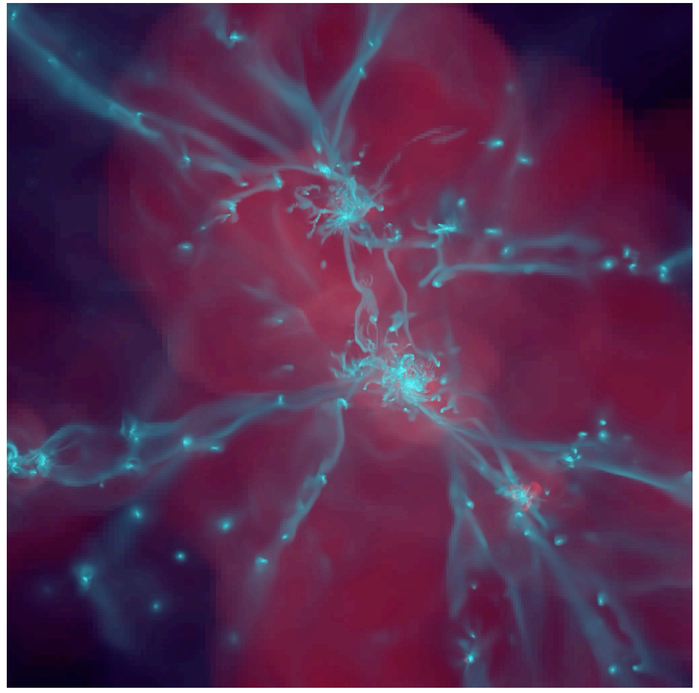

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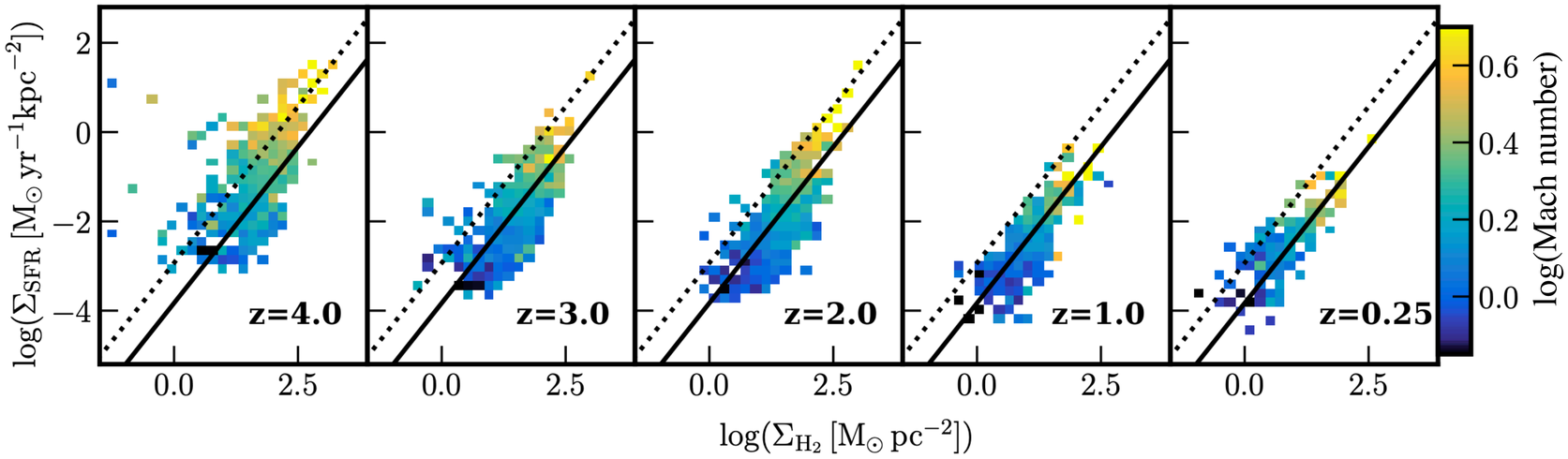

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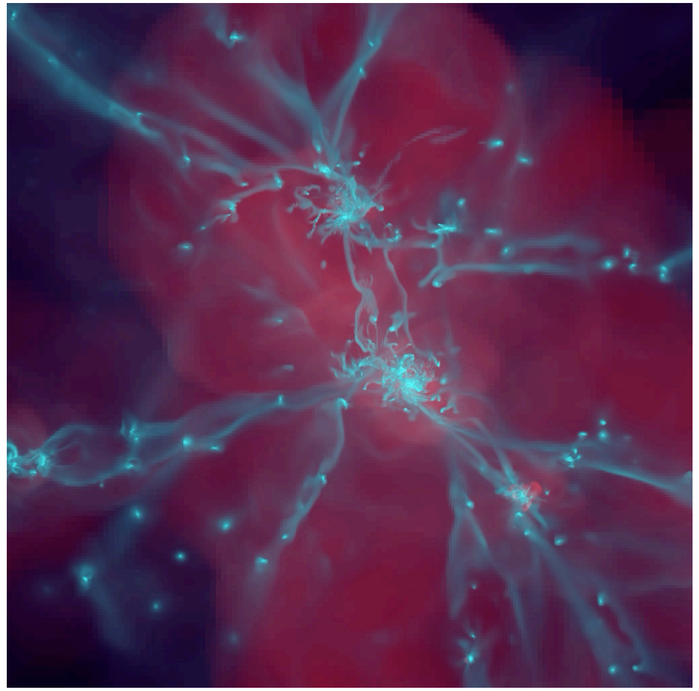

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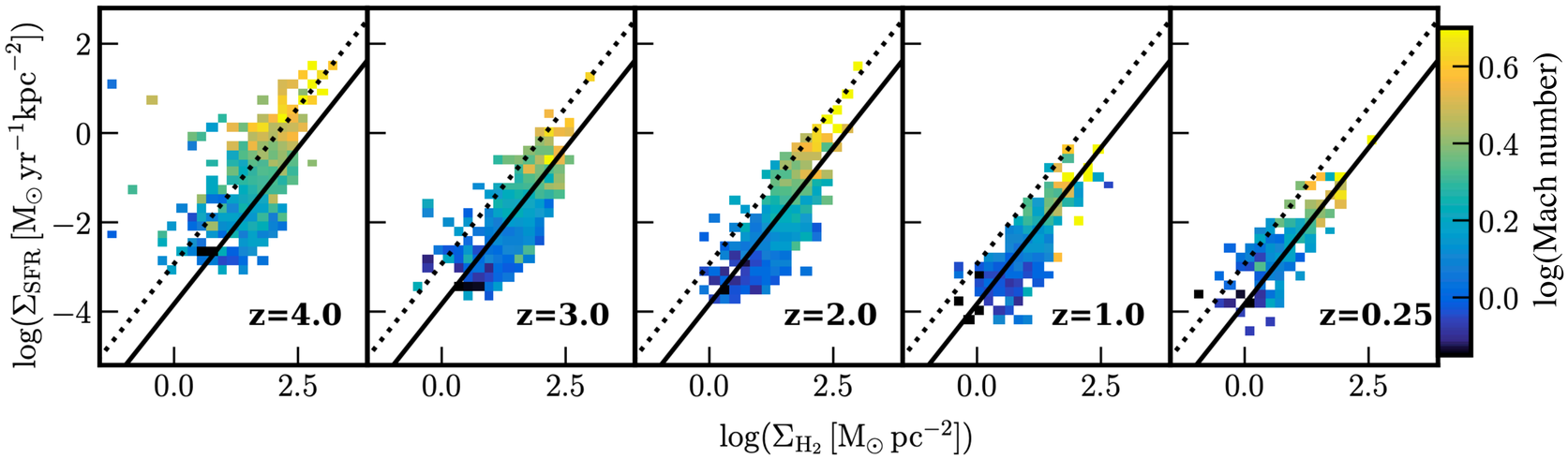

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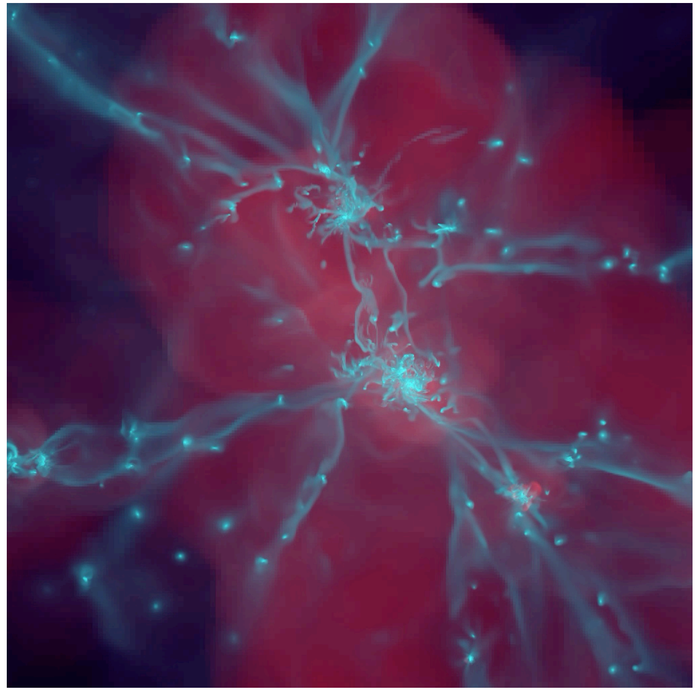

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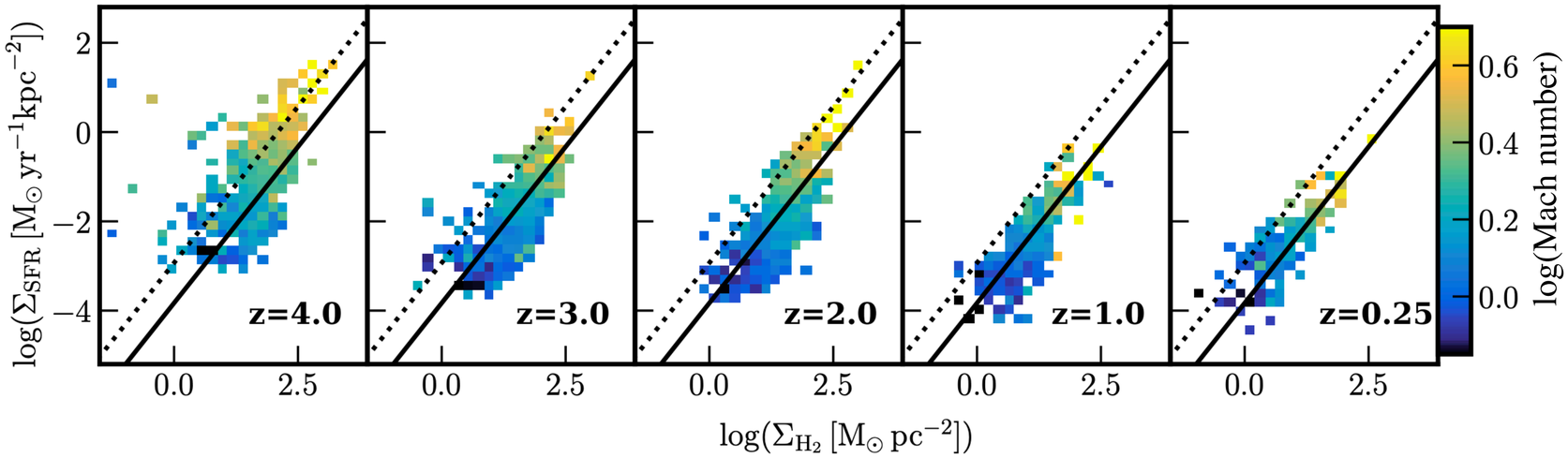

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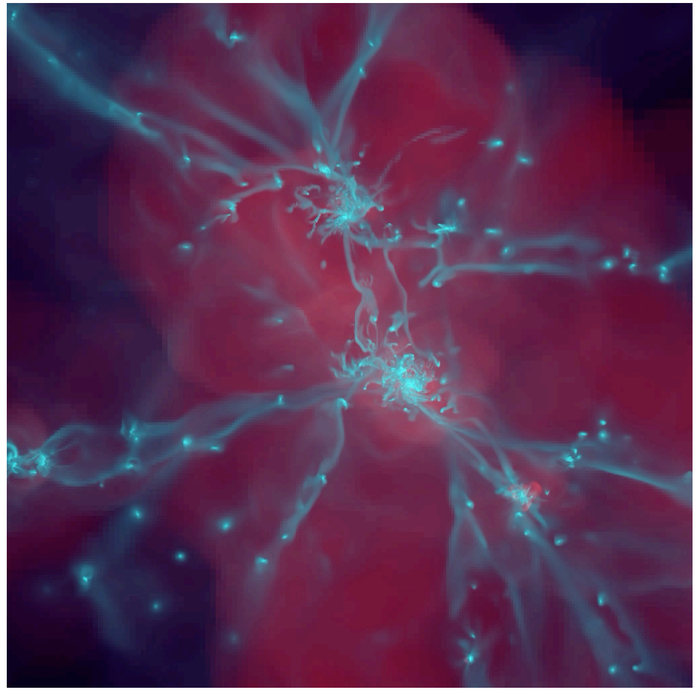

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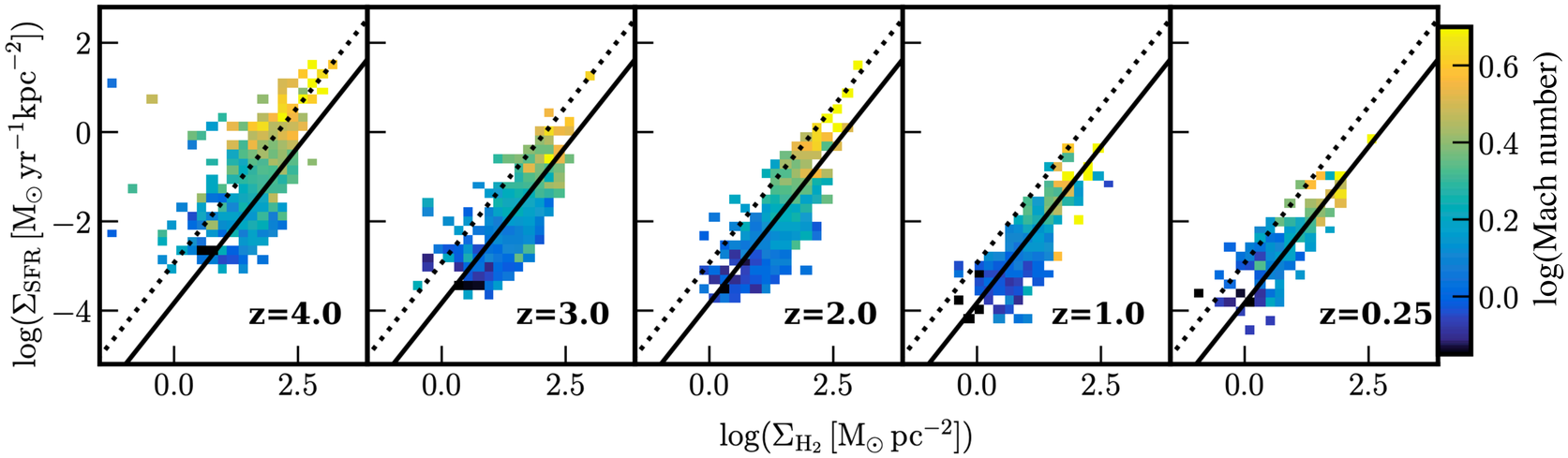

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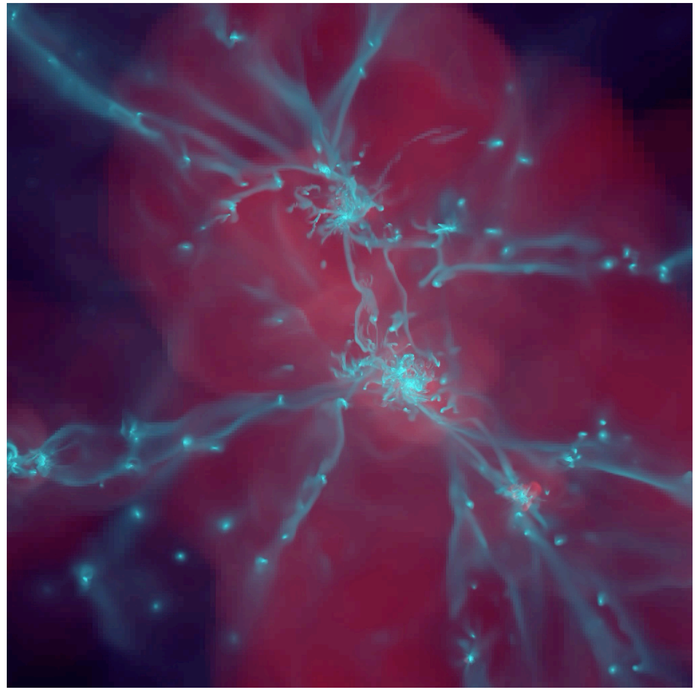

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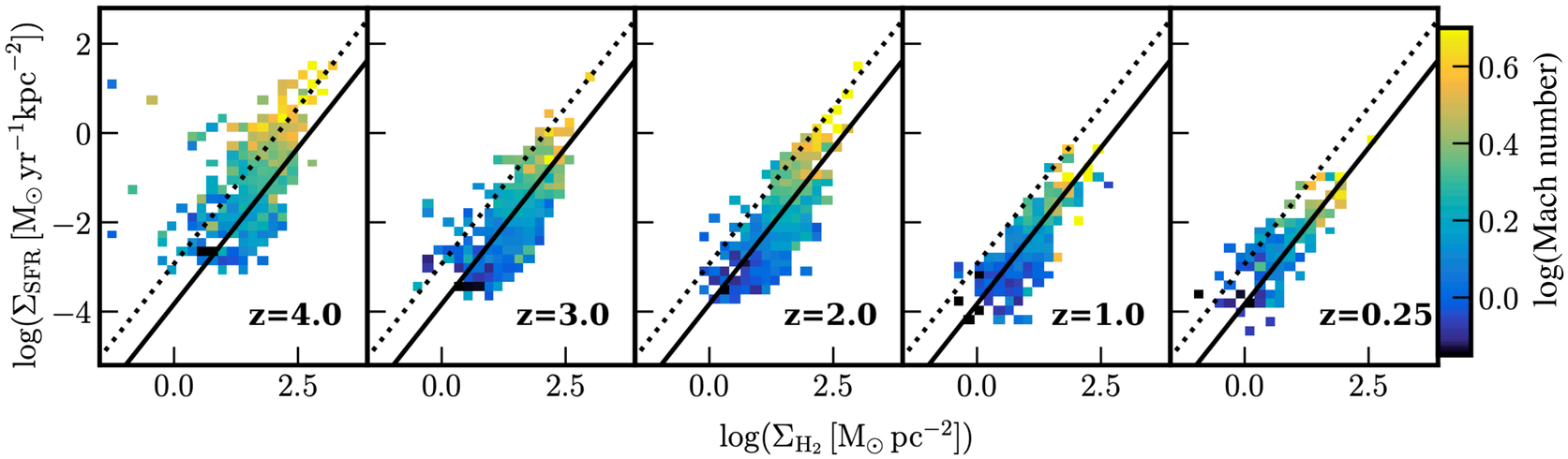

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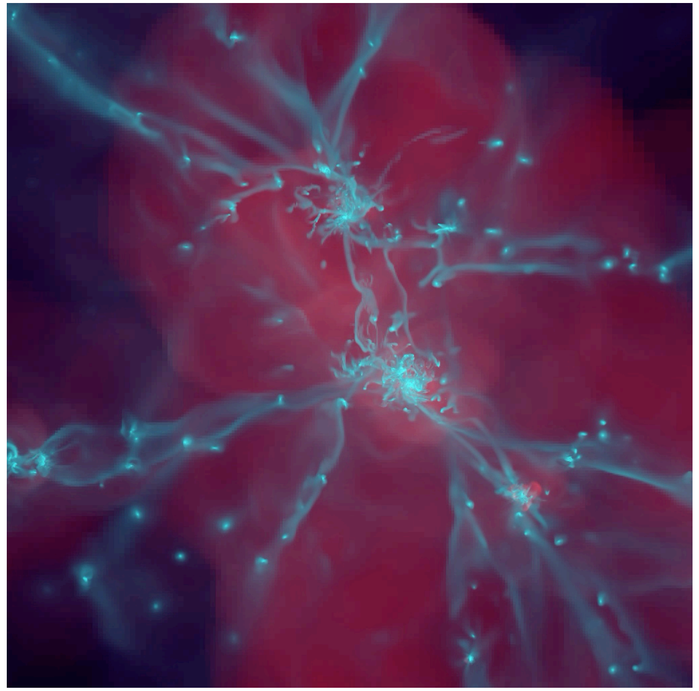

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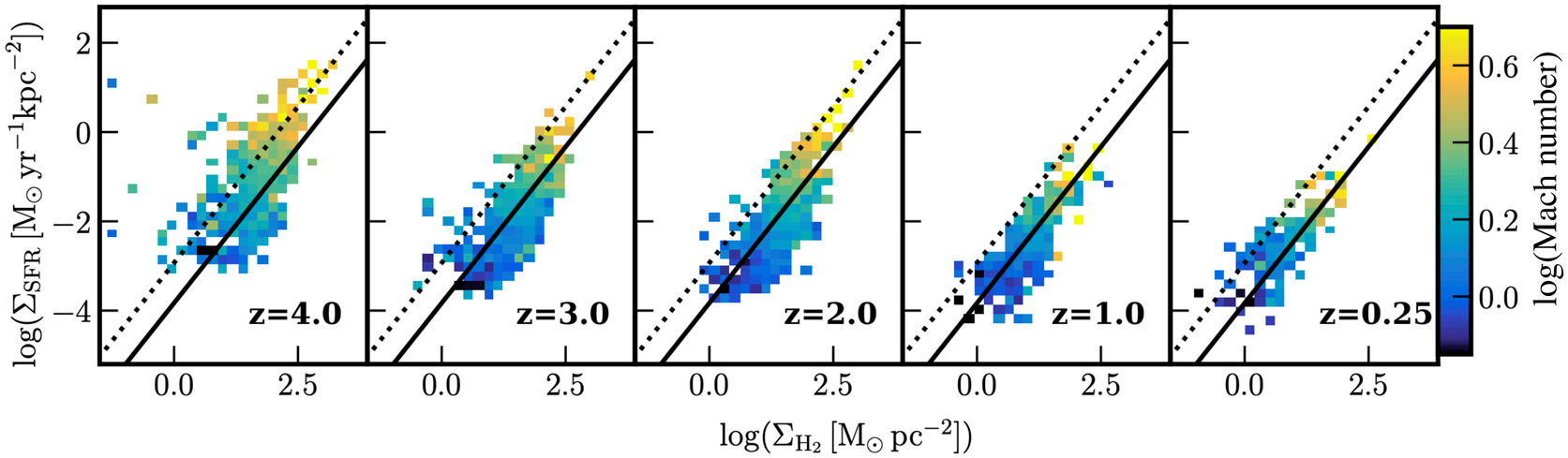

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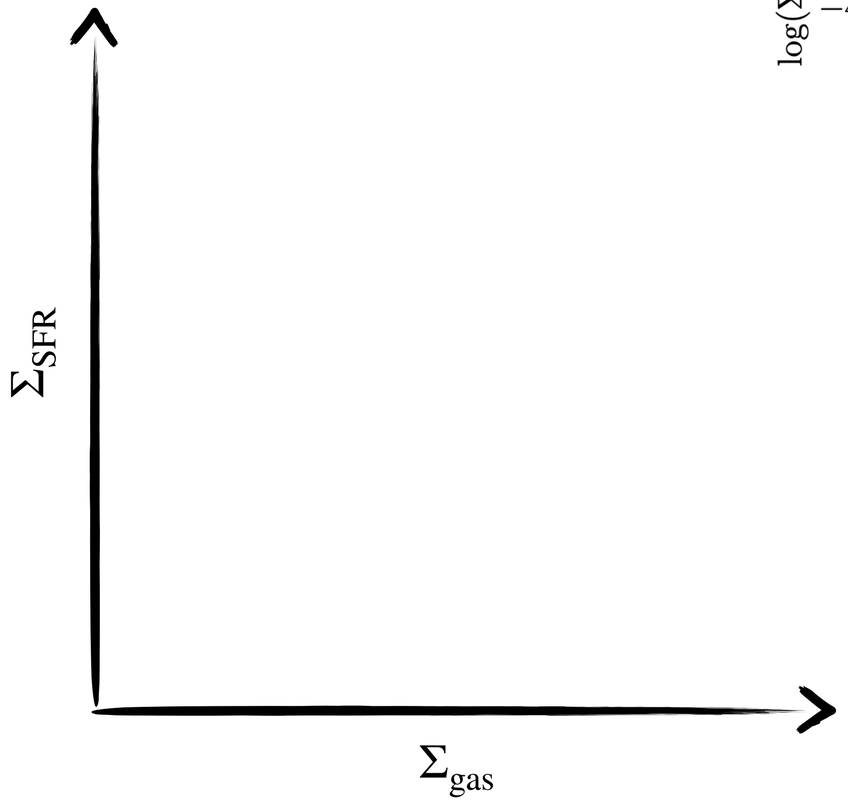

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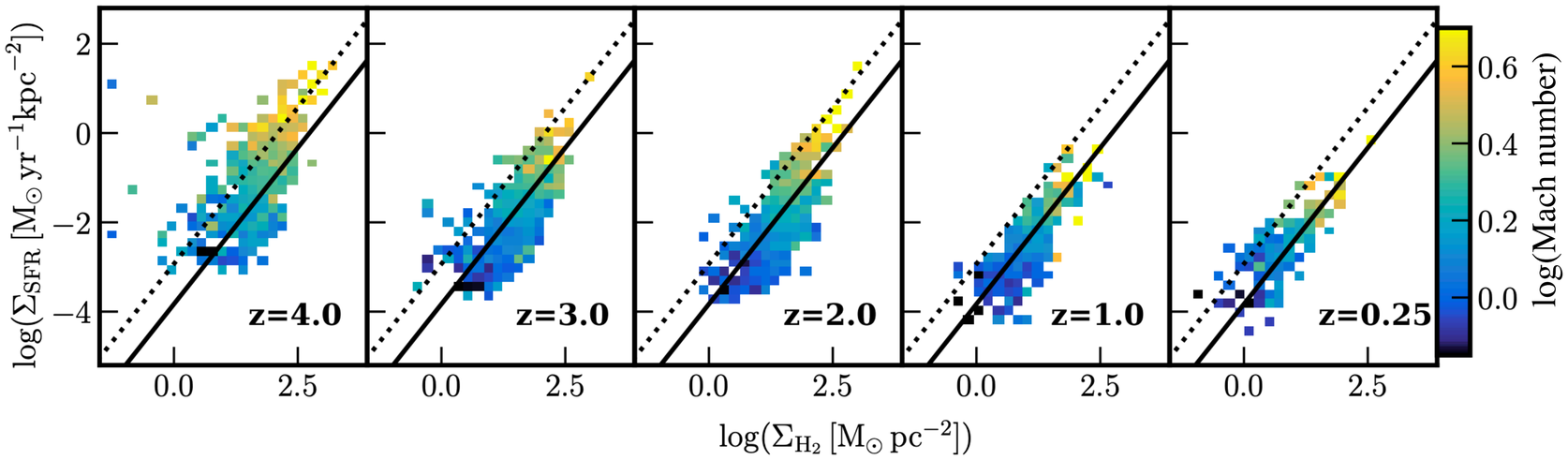

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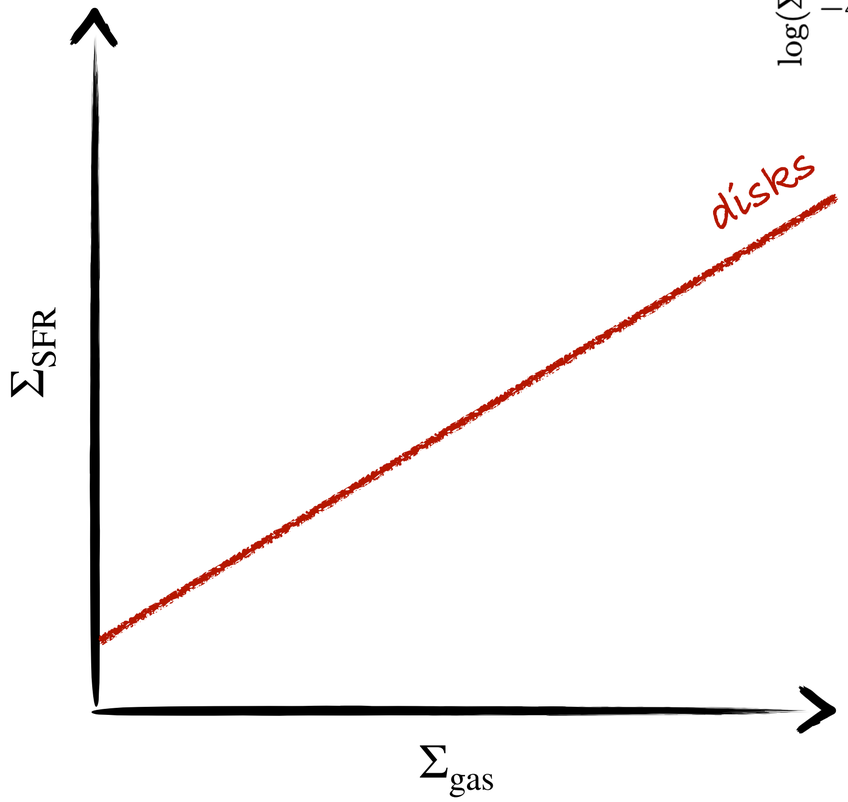

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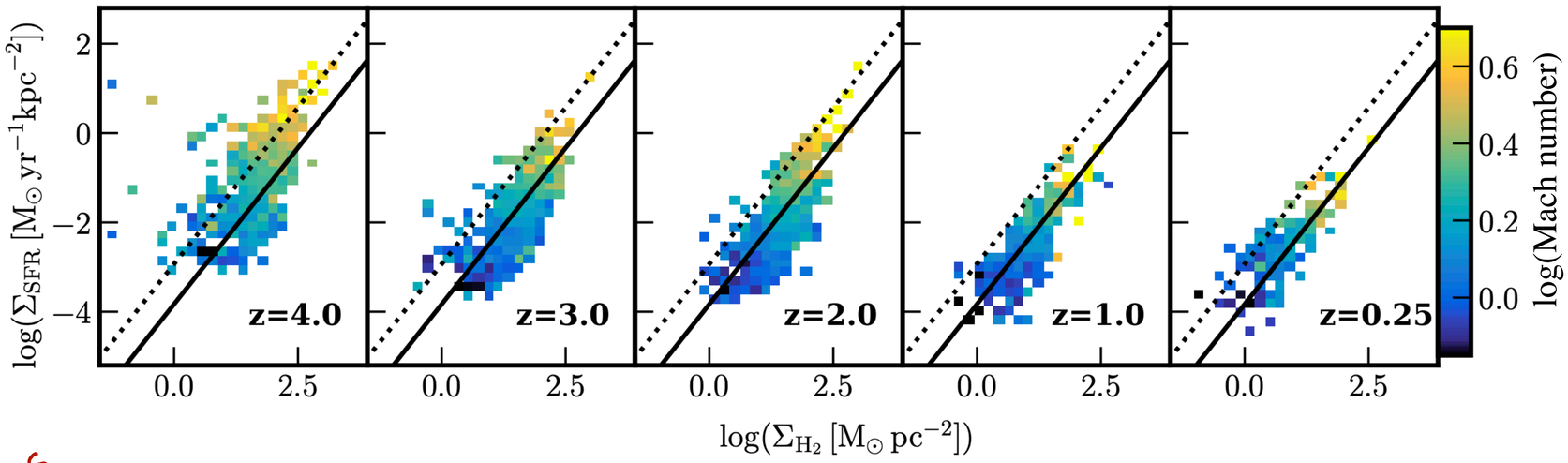

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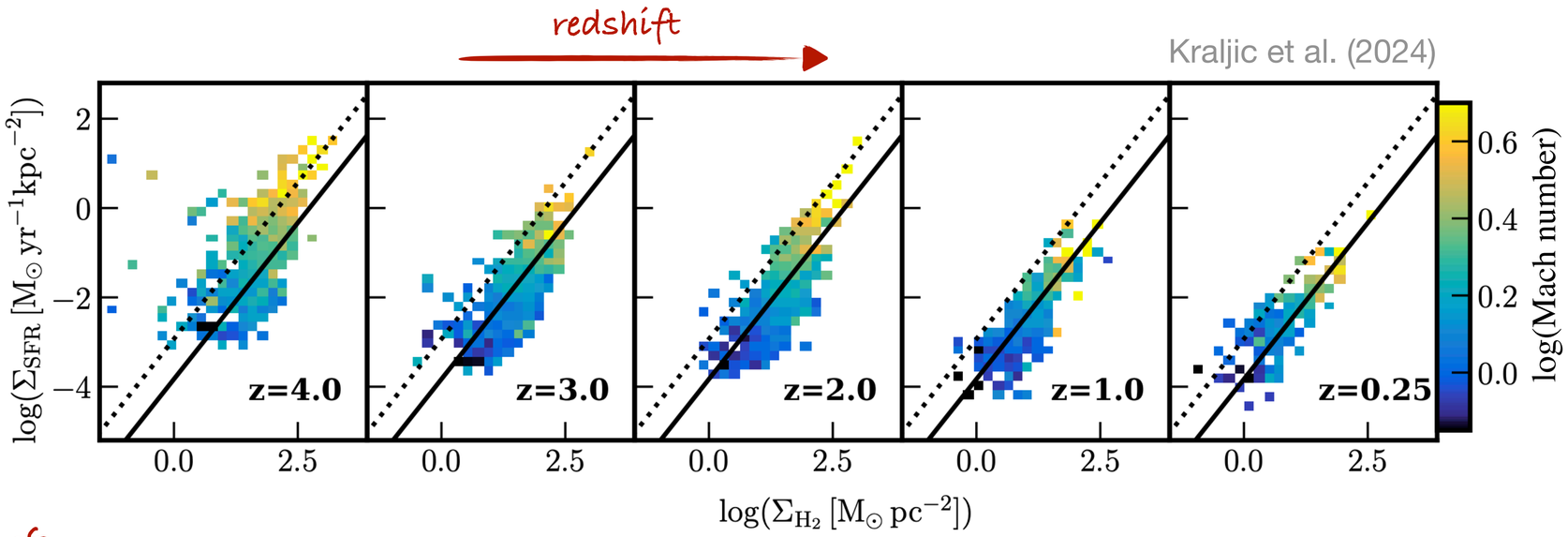

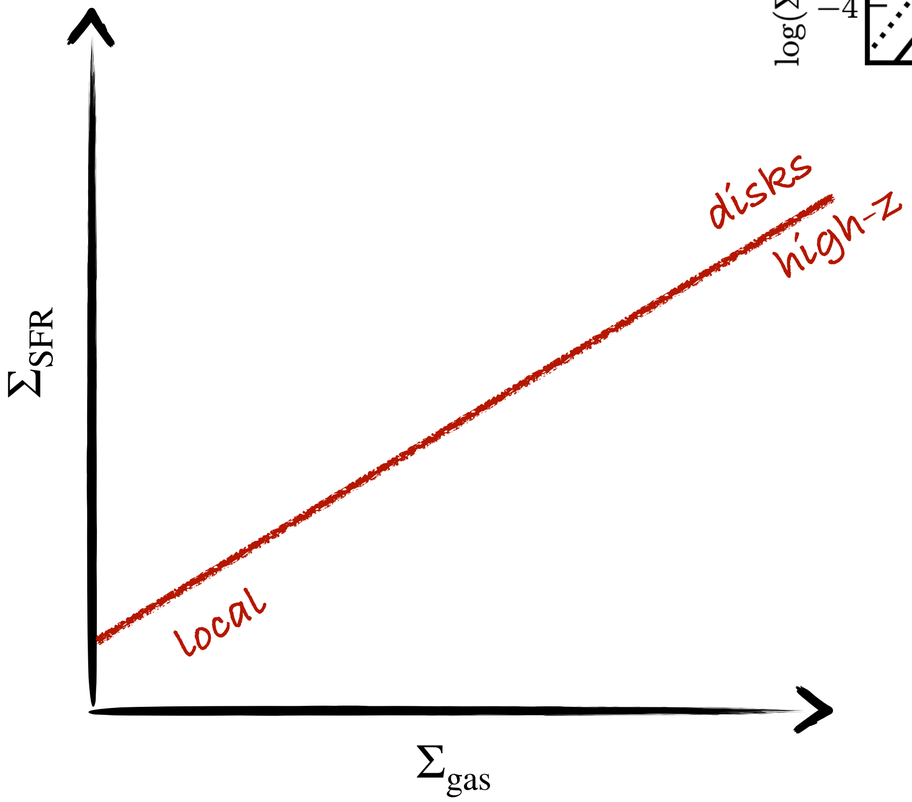

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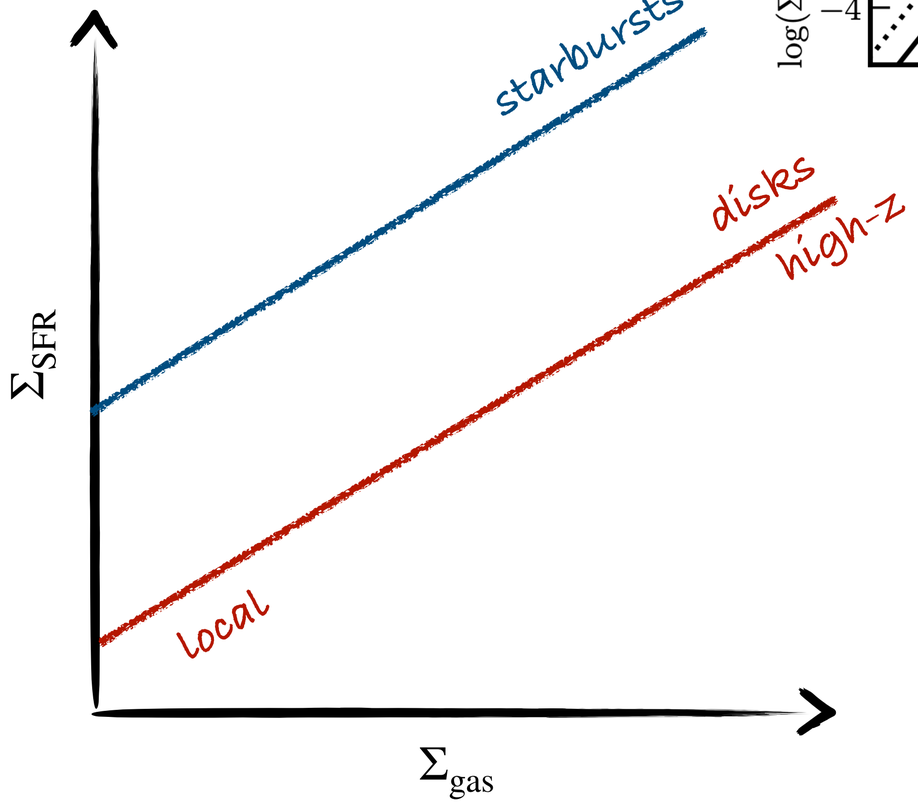

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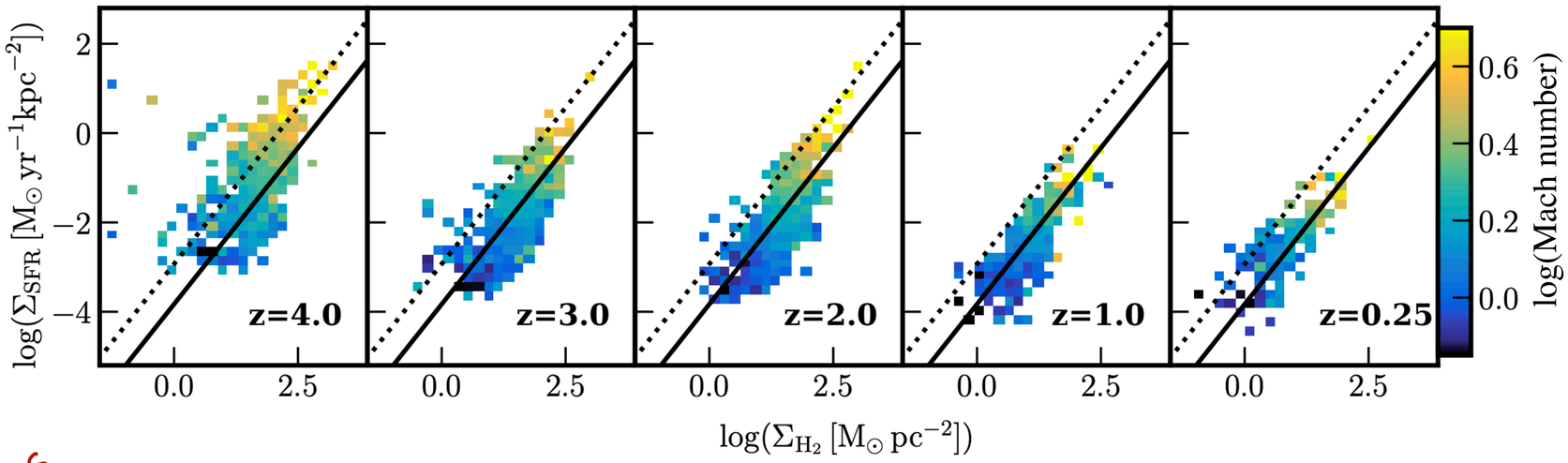

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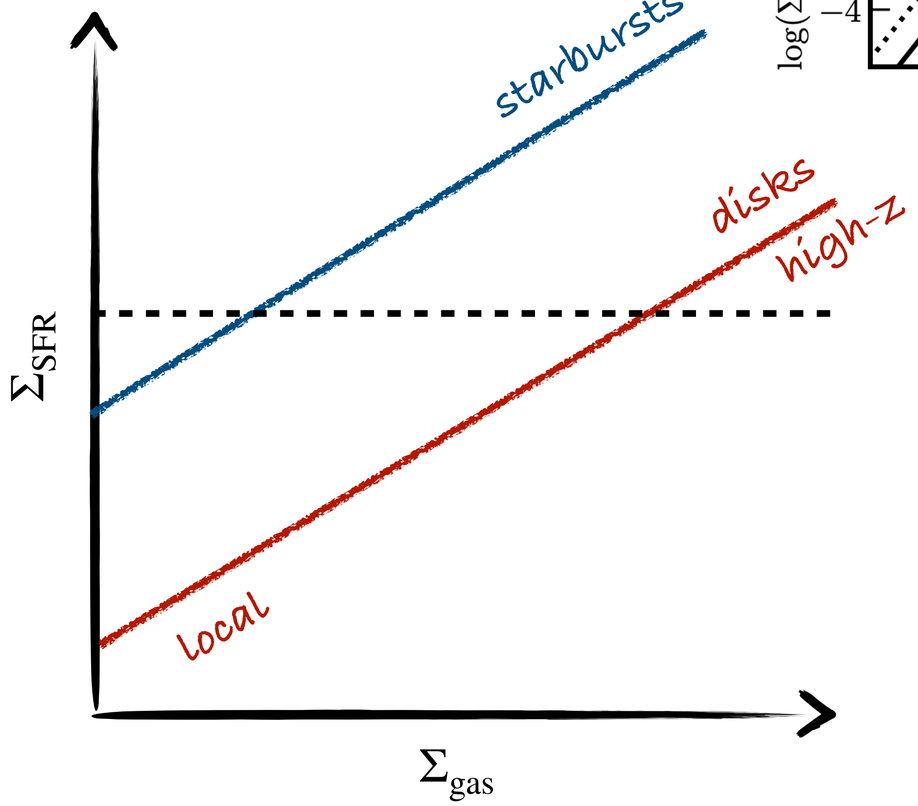

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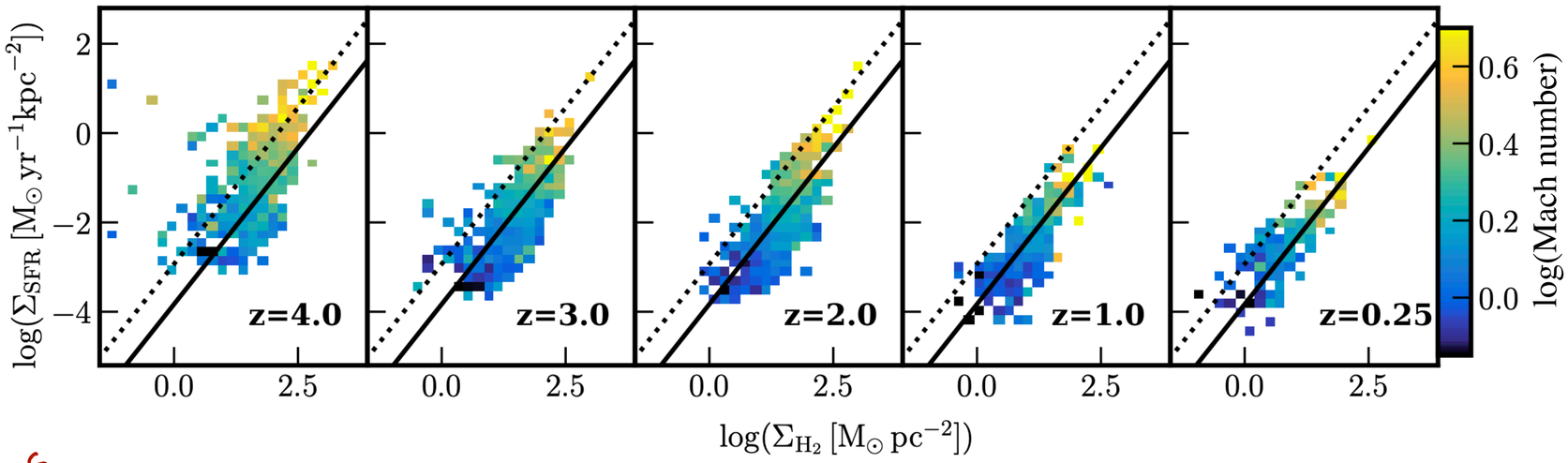

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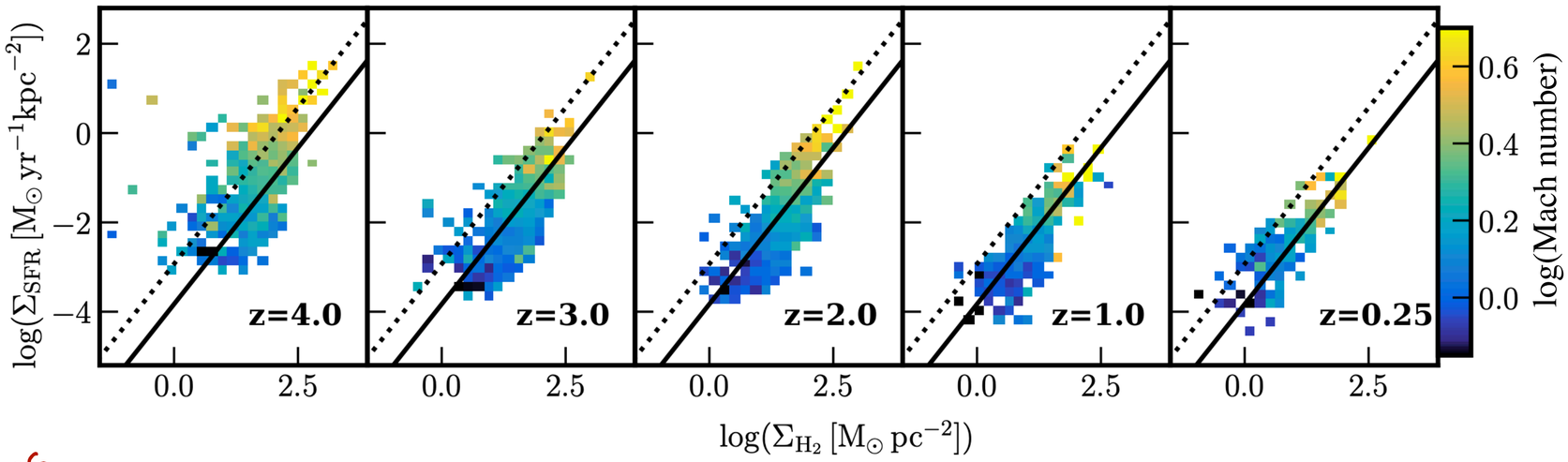

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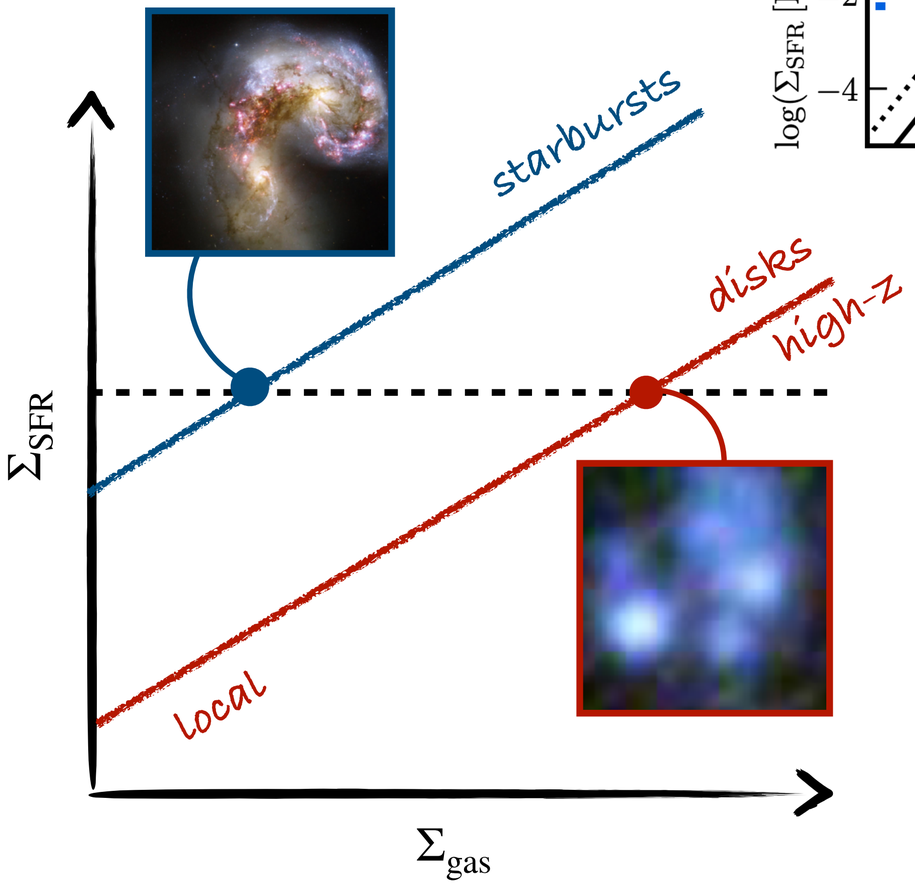

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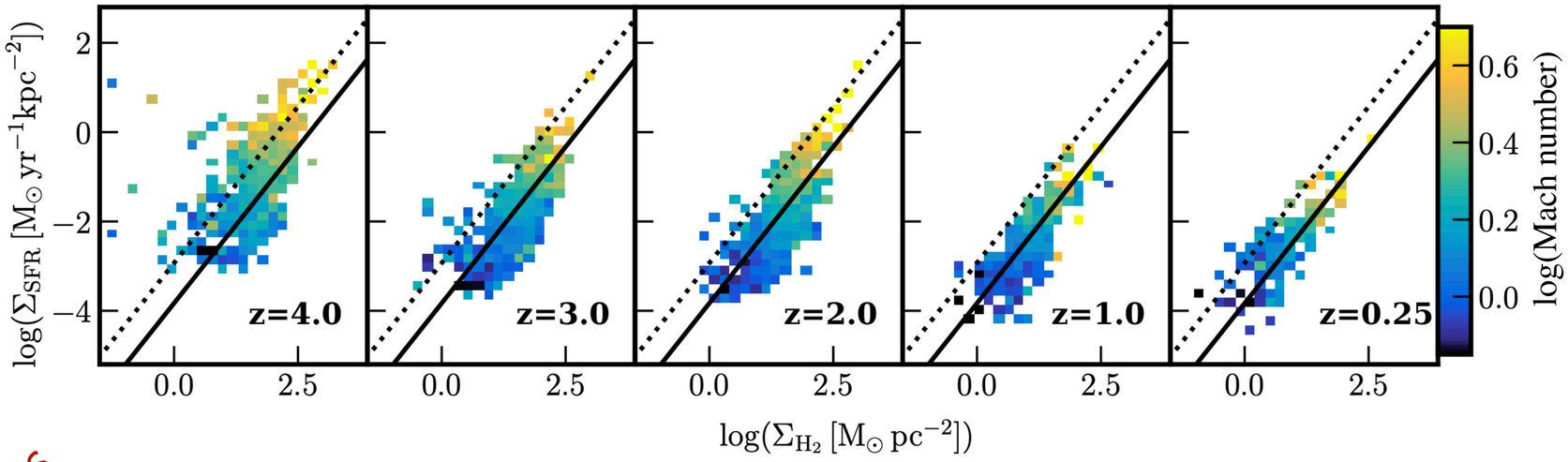

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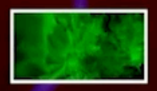
MILKY WAY
IRON
STARS
GAS
DARK MATTER
Z = 6
12.9 GYR AGO

VINTERGATAN

Agertz, Renaud et al. (2021)
Renaud, Agertz et al. (2021a,b)

MILKY WAY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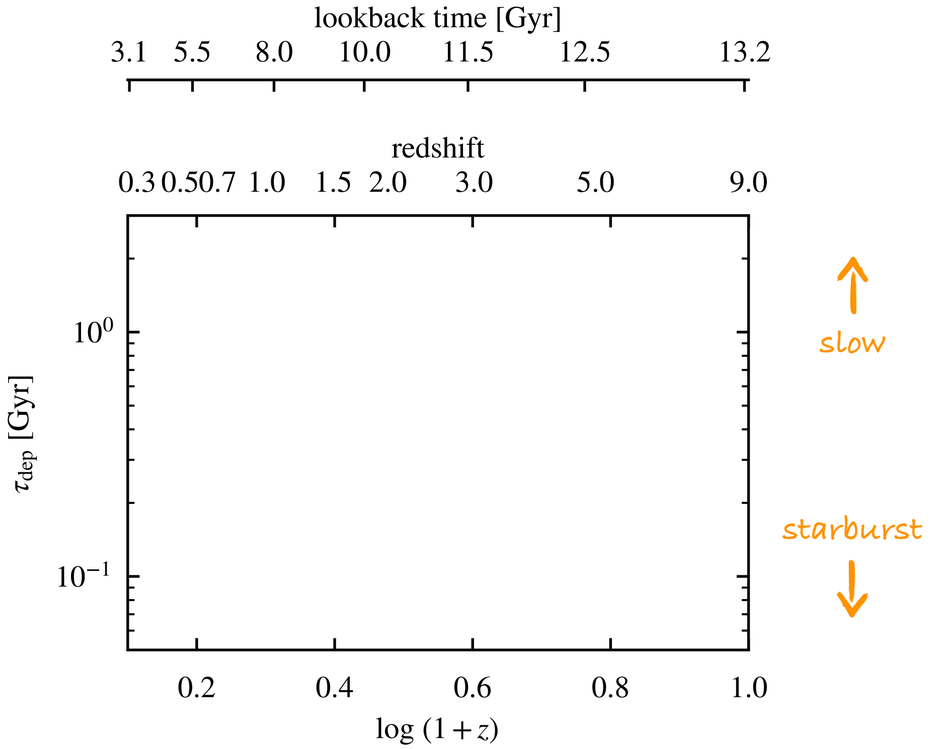

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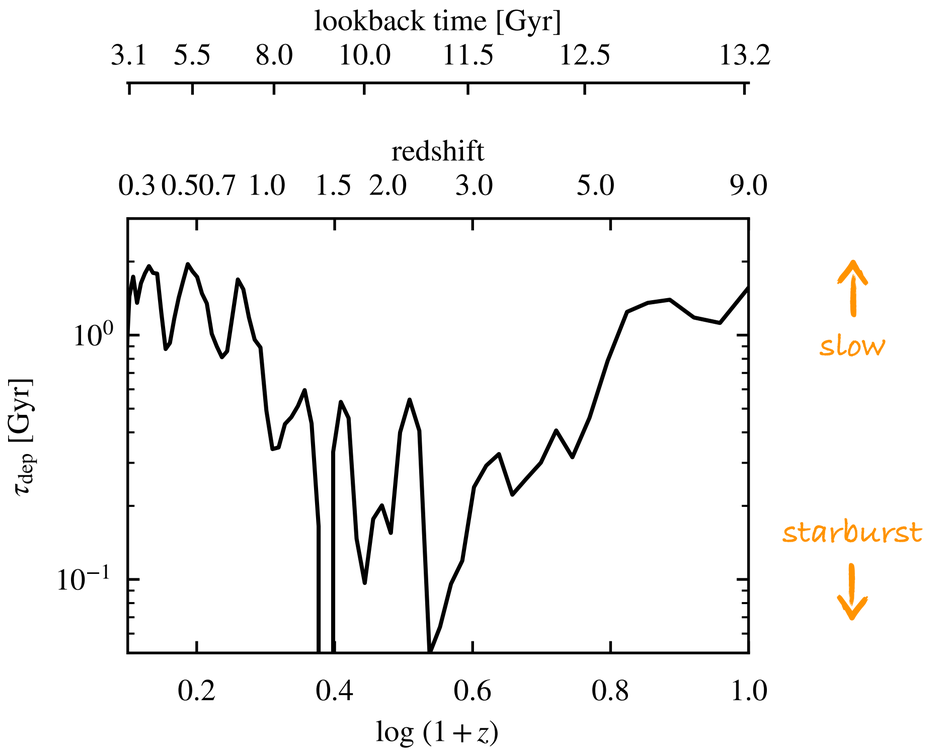

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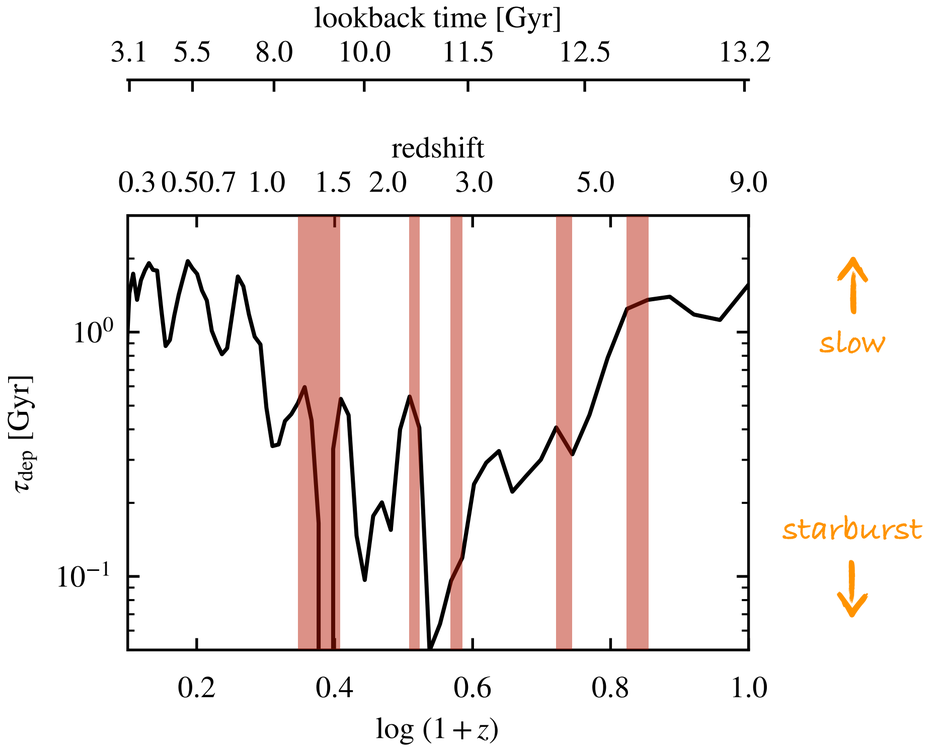

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Major mergers trigger starbursts
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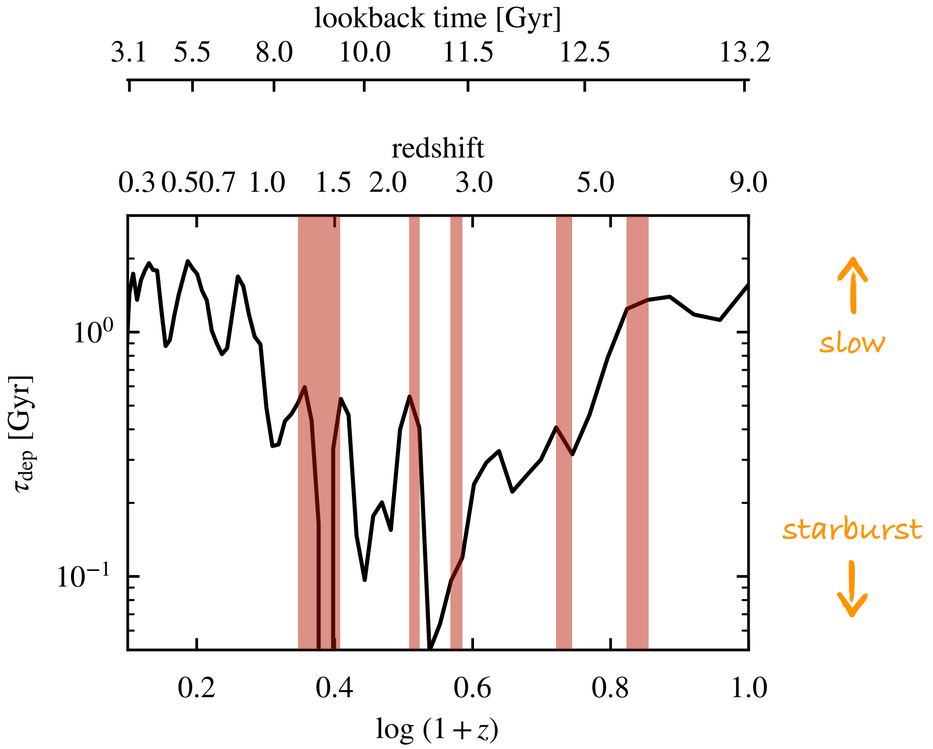

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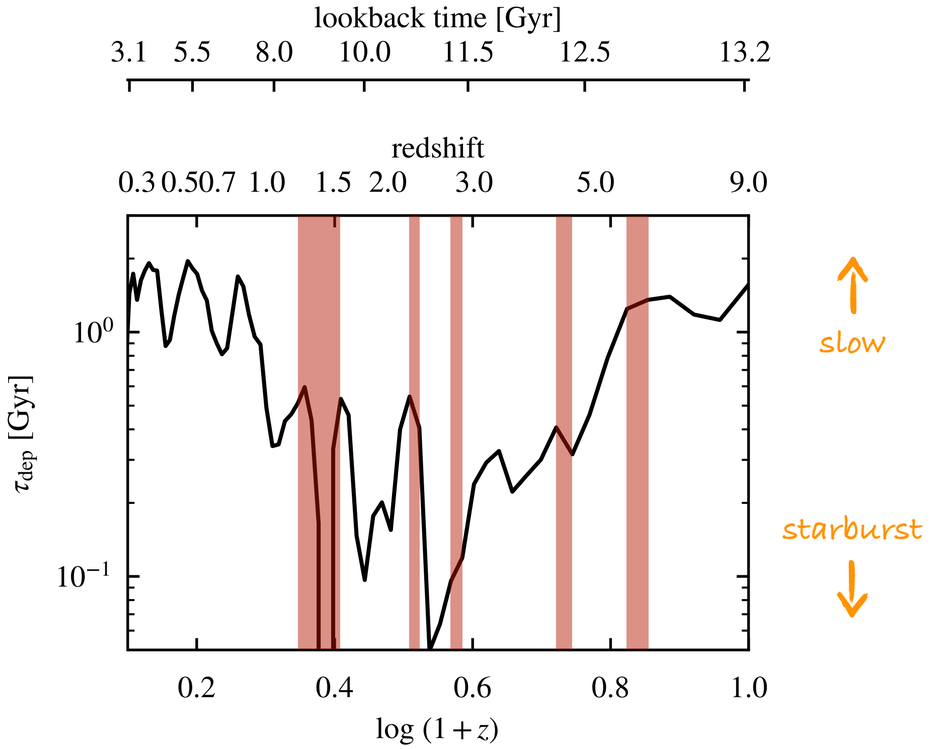

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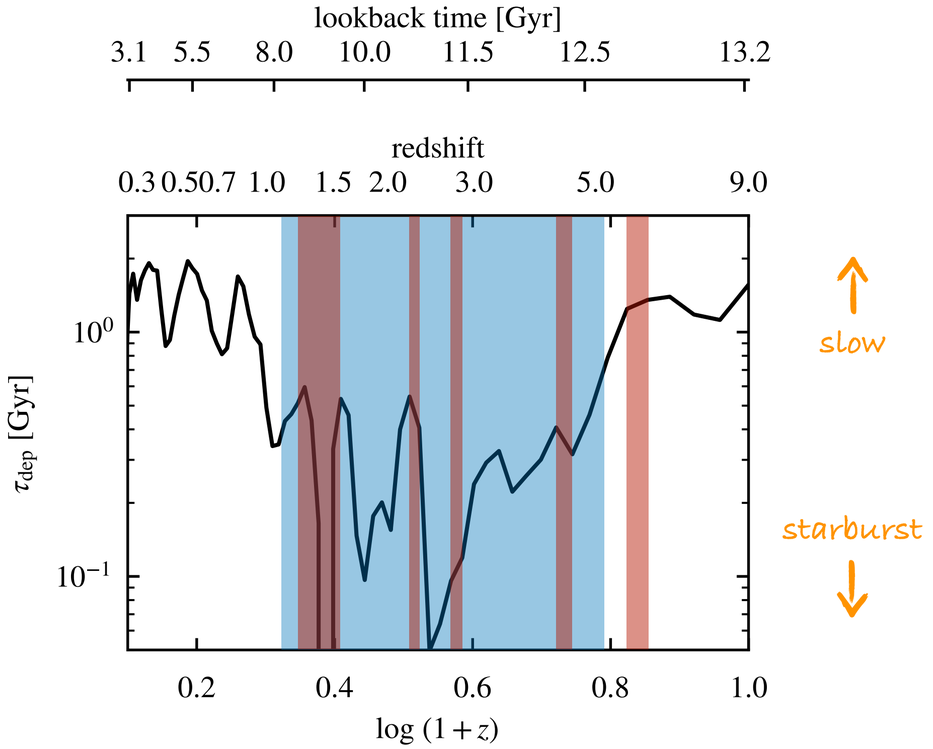

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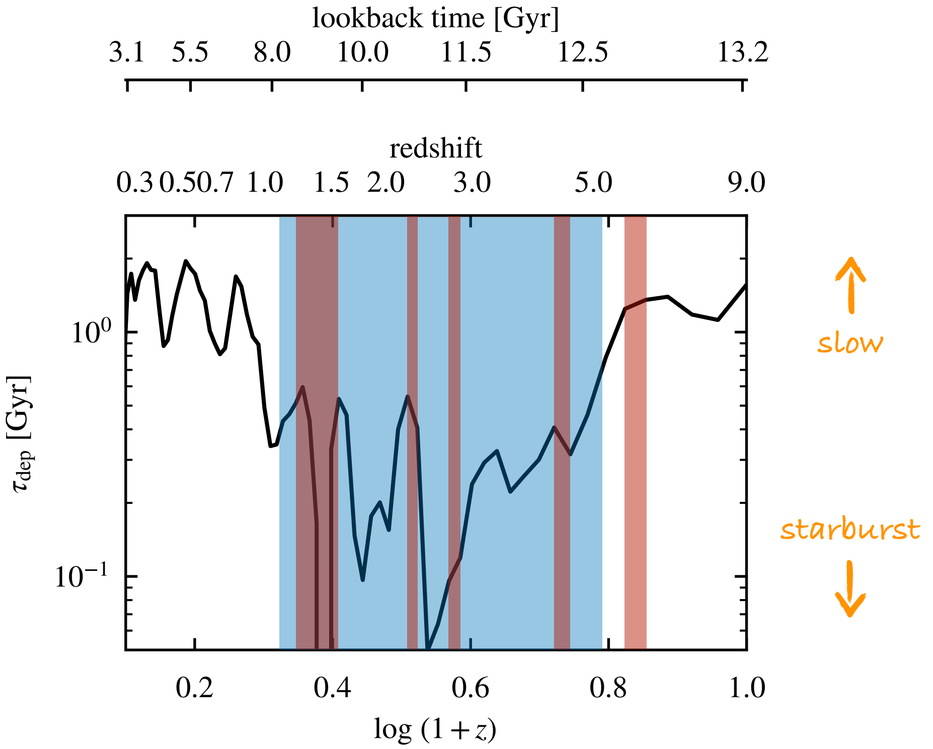

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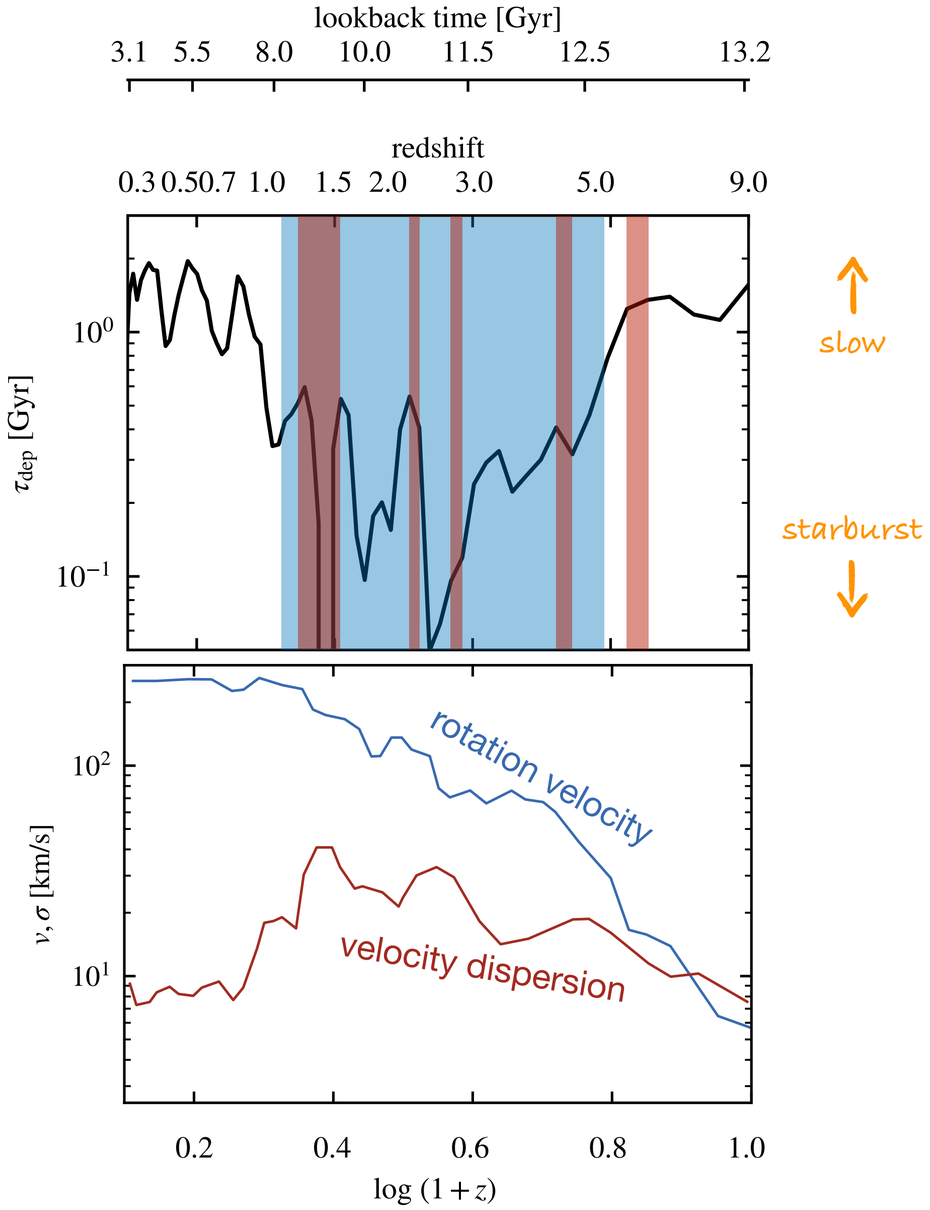

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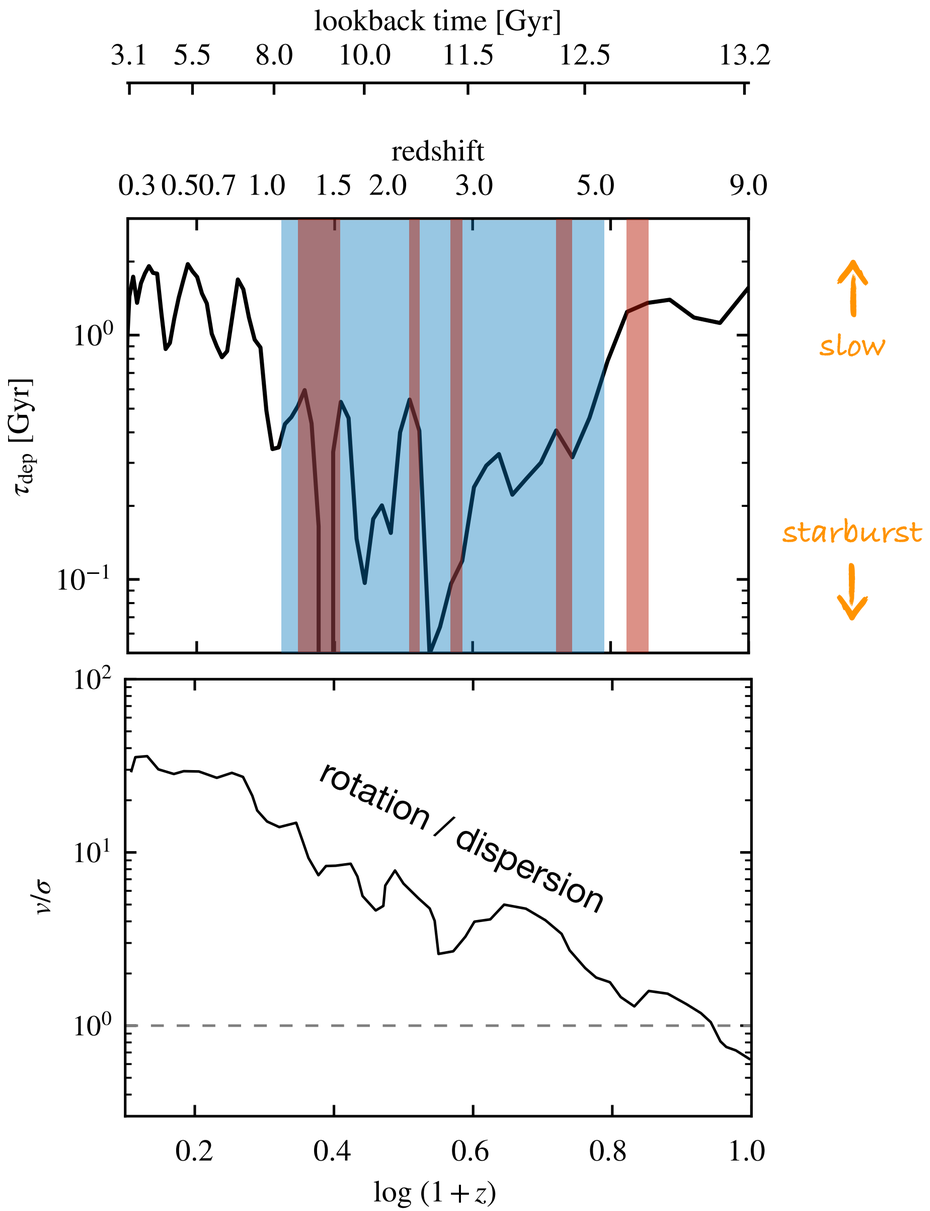


MERGERS DO NOT ALWAYS-INDUCE STARBURSTS

Florent Renaud
Strasbourg

Segovia Otero et al. (2022)

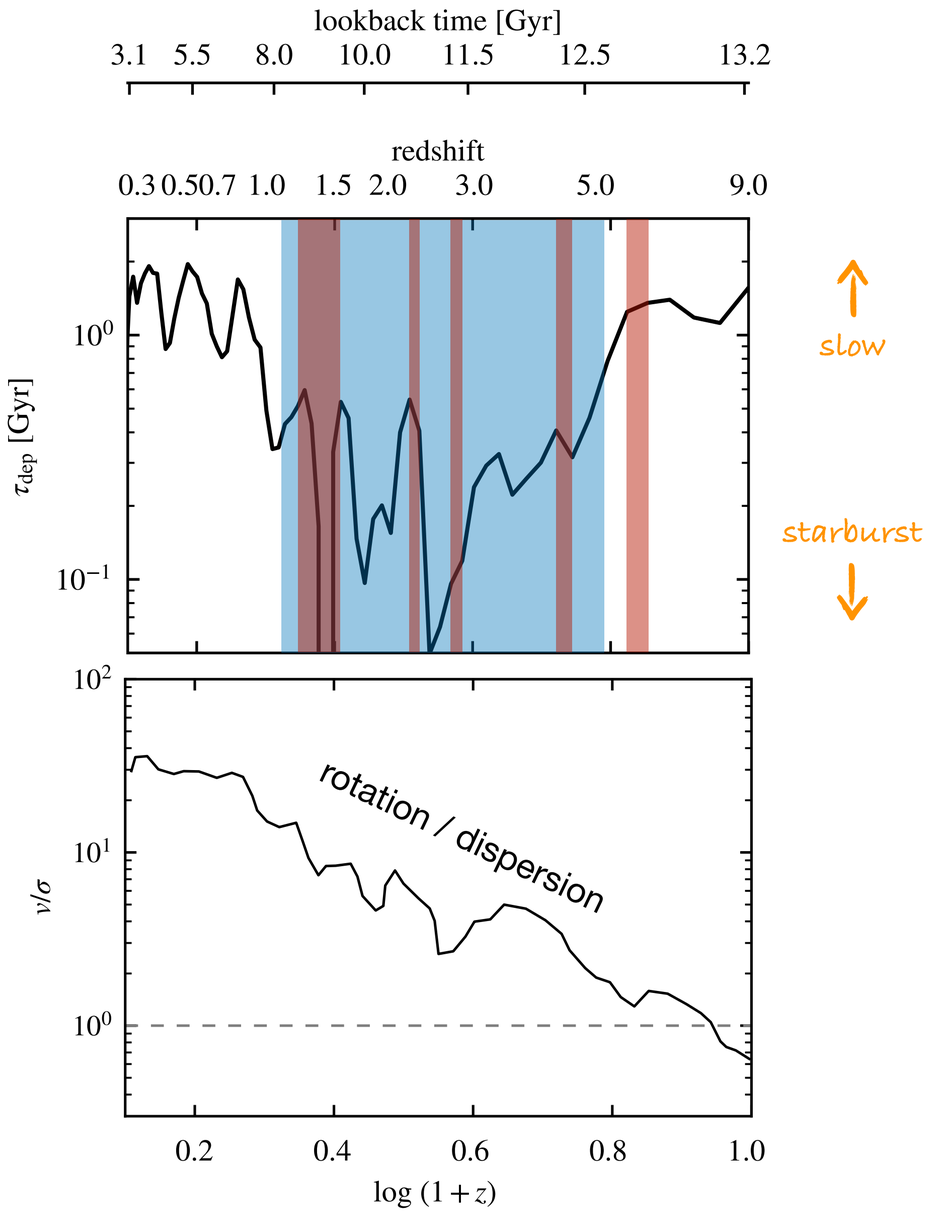
Major mergers trigger starbursts
(= short depletion time)

- Tidal + turbulent compression
- shocks, cloud-cloud collisions
- nuclear inflows

see Renaud et al. (2019) at low redshift

But not at very high redshift...

Before organized motions are in place:
no coherent response to interactions



RAPID CHEMICAL ENRICHMENT

Florent Renaud
Strasbourg

Starburst = short timescale of star formation

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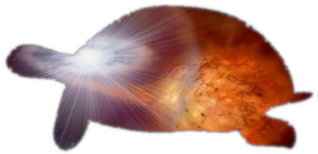
Starburst = short timescale of star formation

Faster than the enrichment in Fe

from type-Ia SNe



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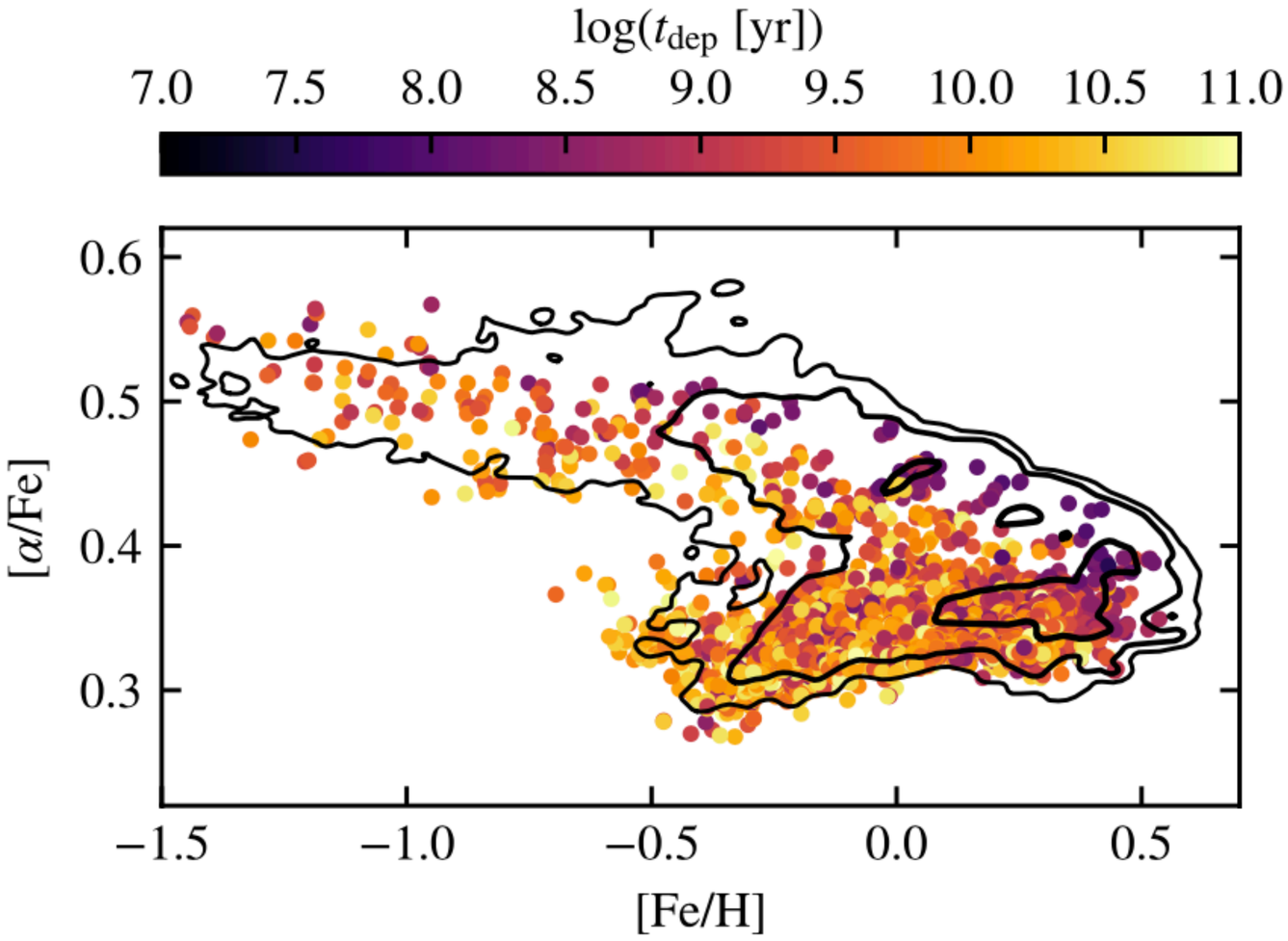

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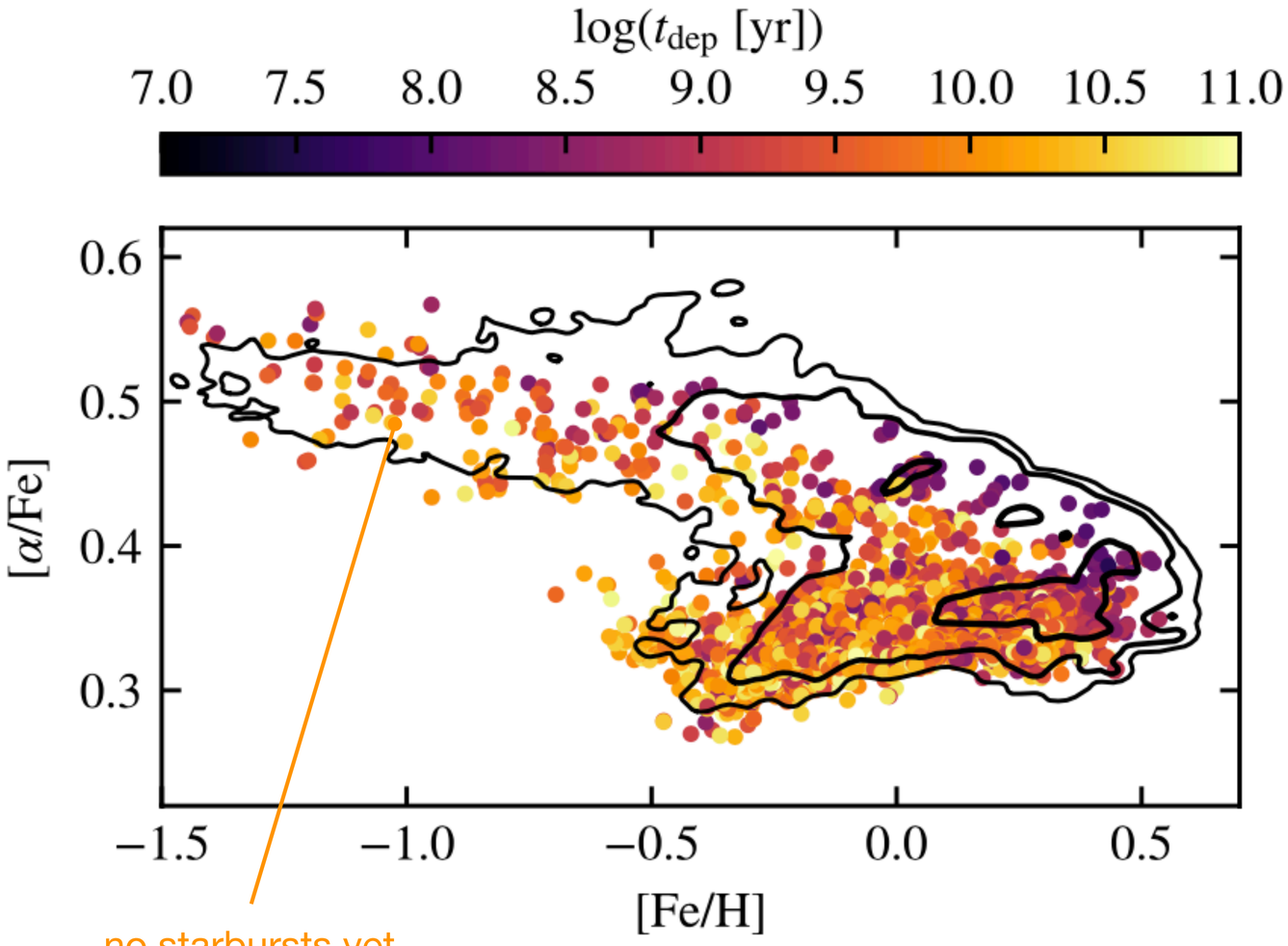

no starbursts yet
(Segovia Otero et al, 2022)

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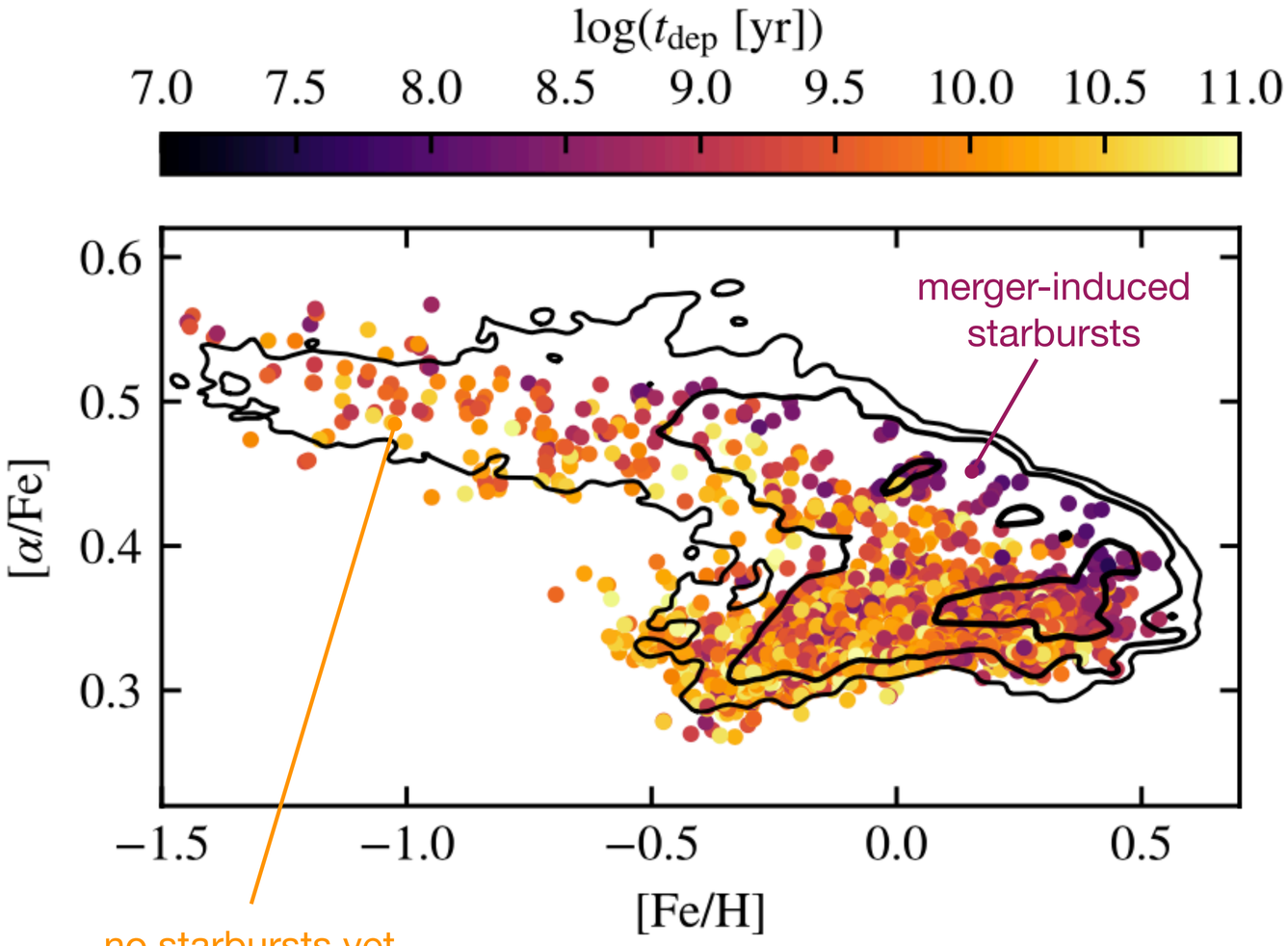

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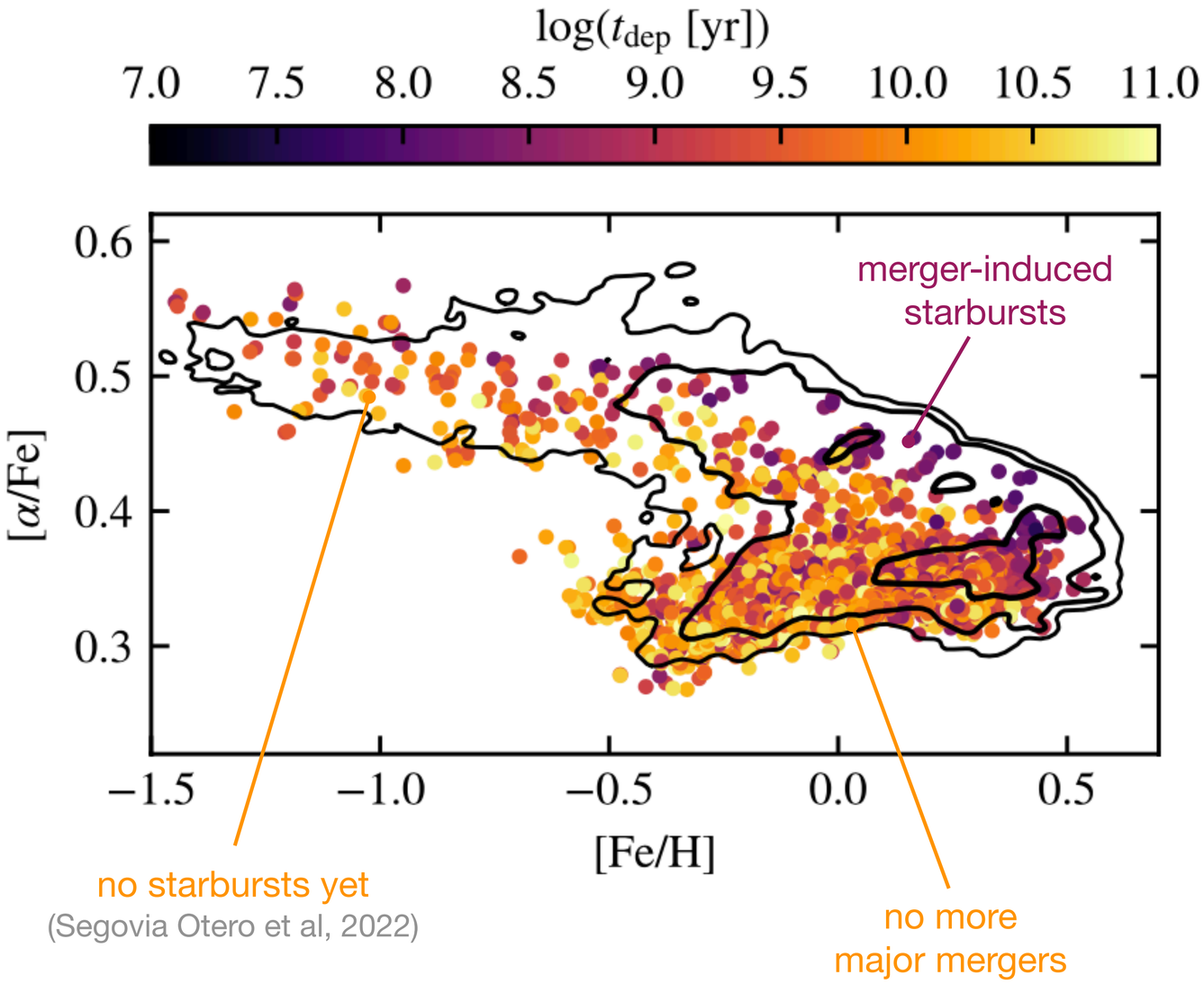

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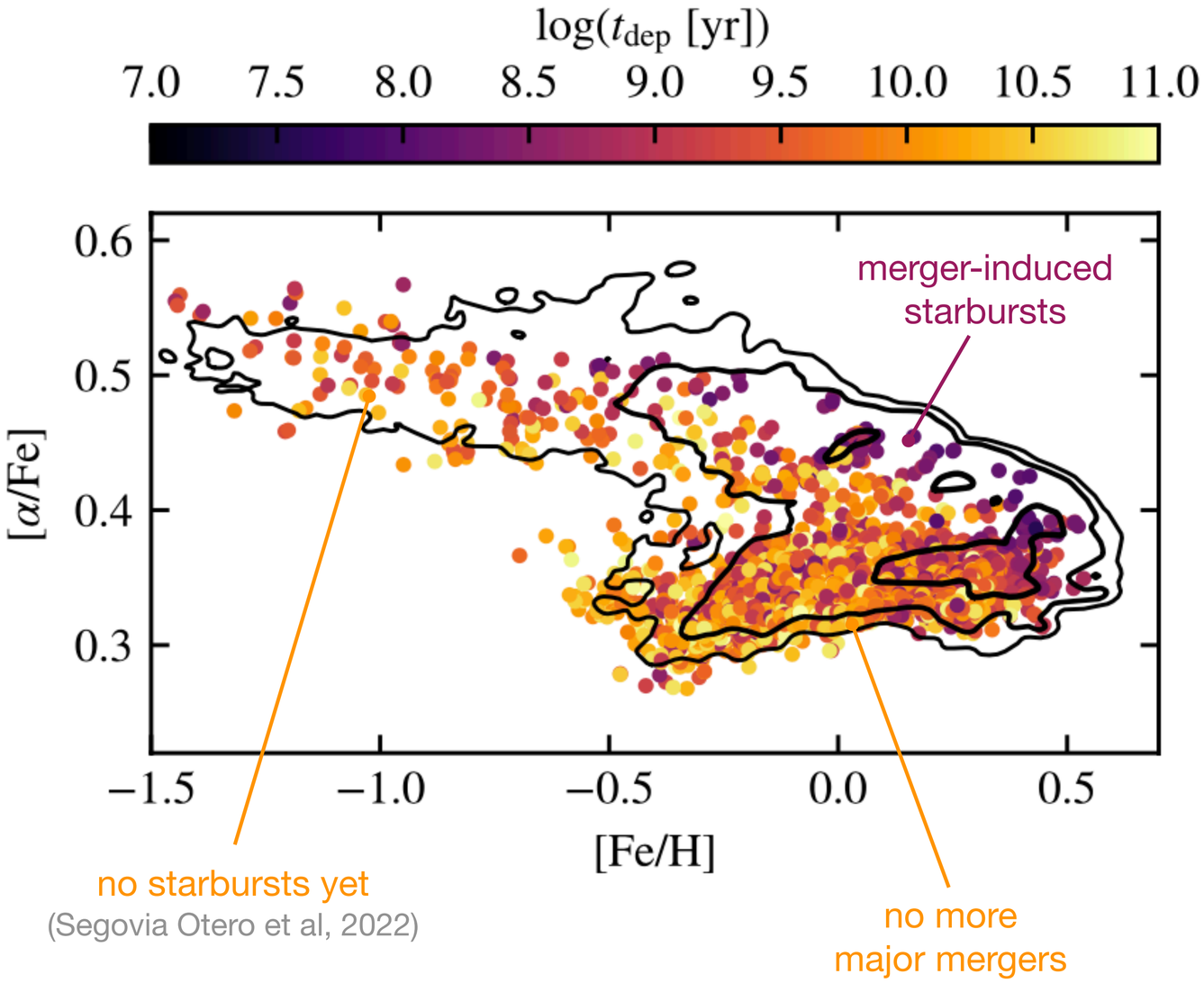
Transition after the last major merger (z~1)

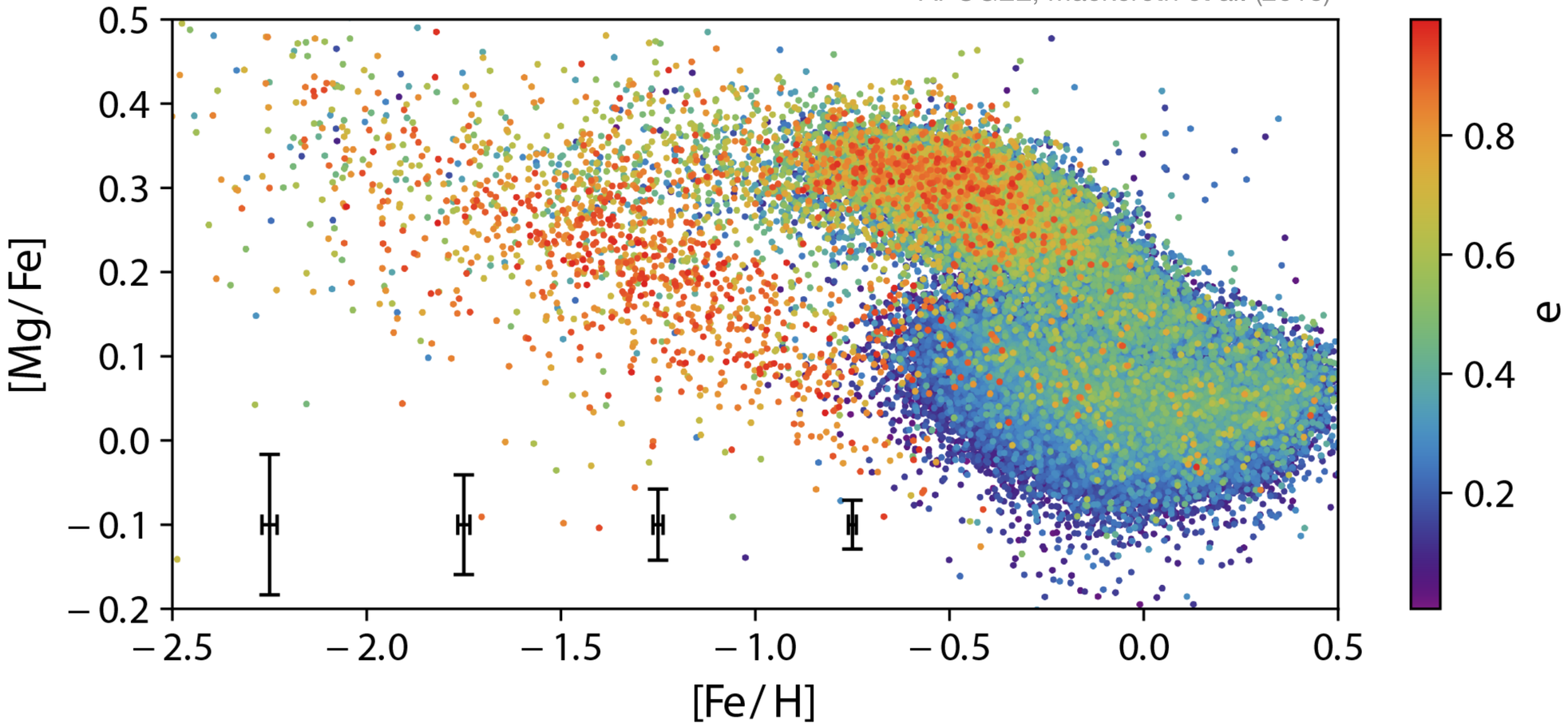
Renaud et al. (2021)



[α/Fe] BIMODALITY IN THE REAL MILKY WAY

Florent Renaud
Strasbourg

APOGEE, Mackereth et al. (2018)



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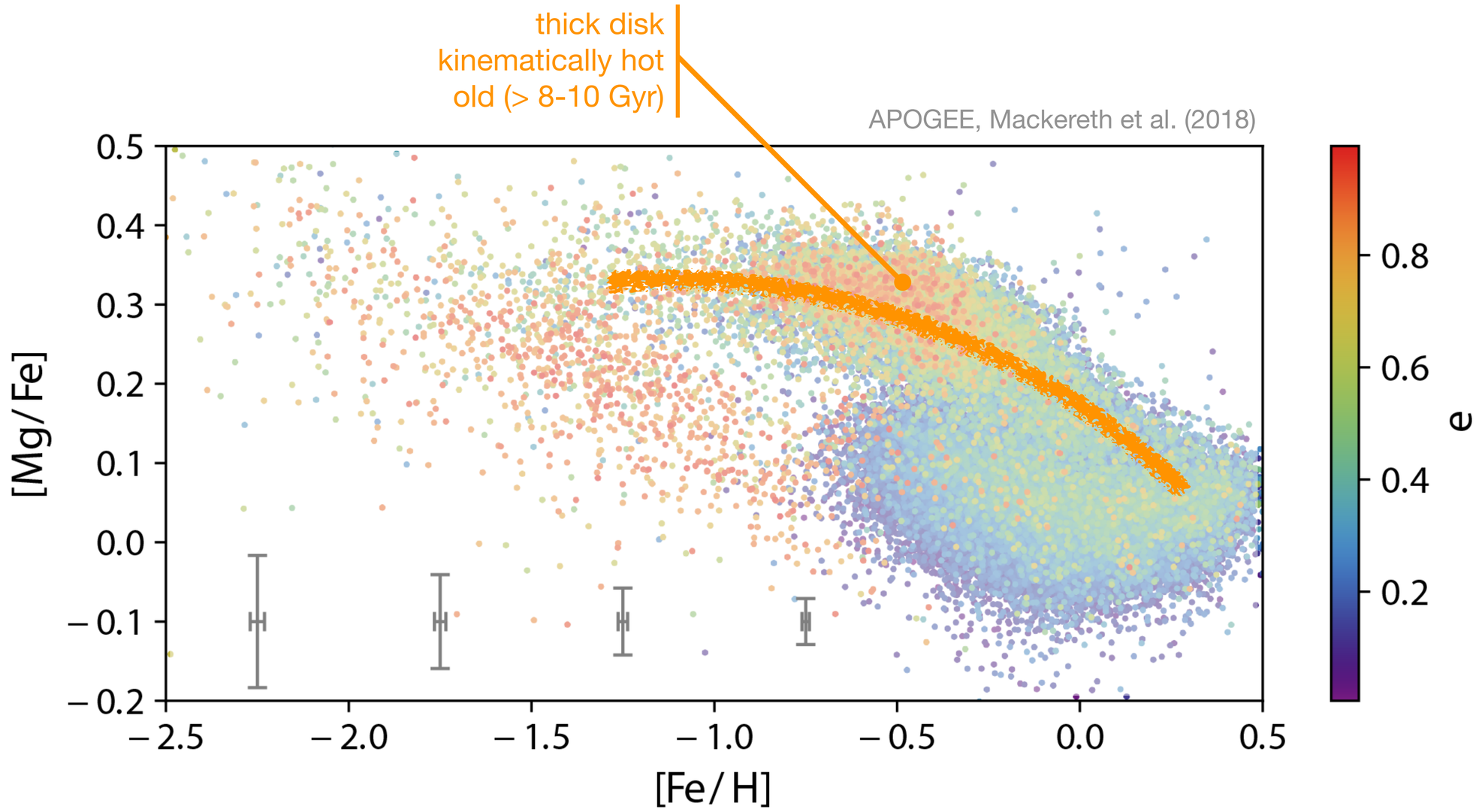

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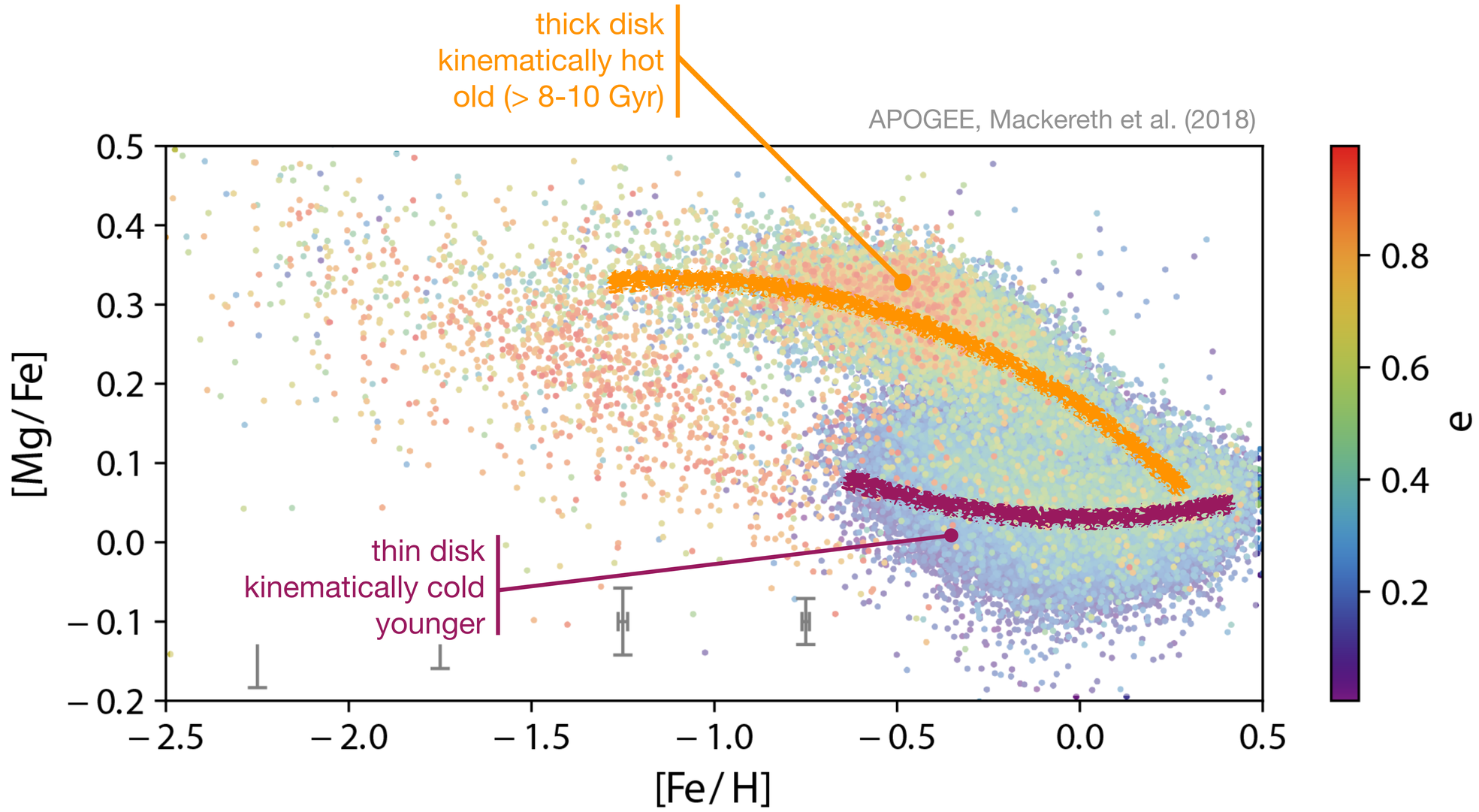

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NEW INSTABILITY REGIME IN GAS-RICH DISKS

Florent Renaud
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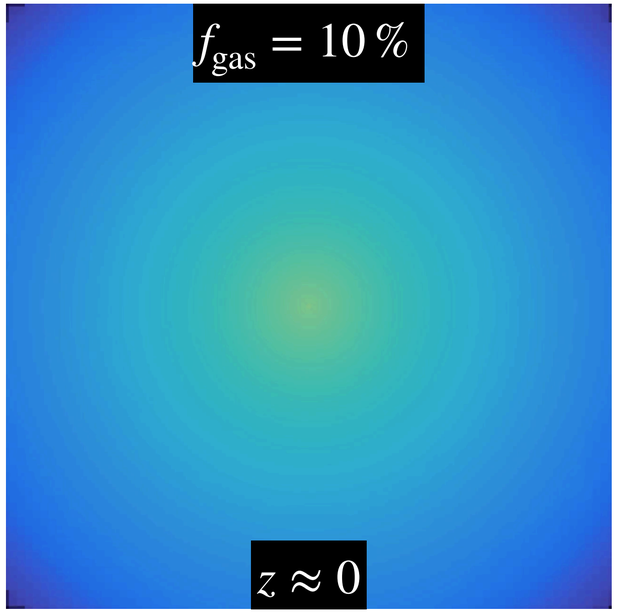
Renaud, Romeo & Agertz (2021)



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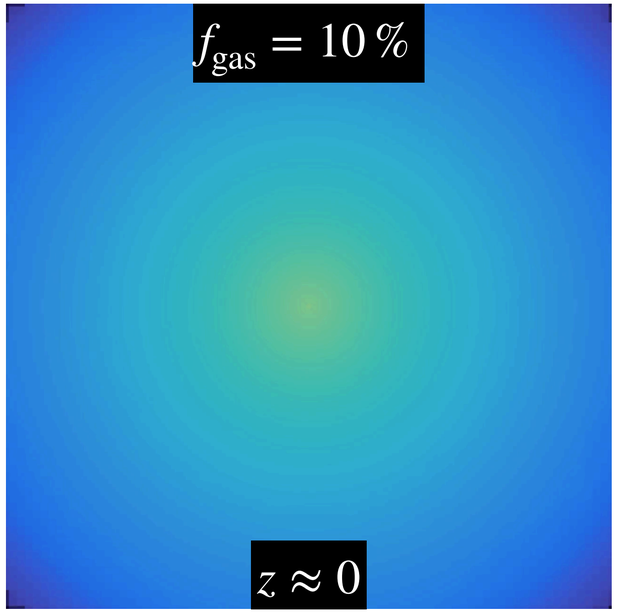

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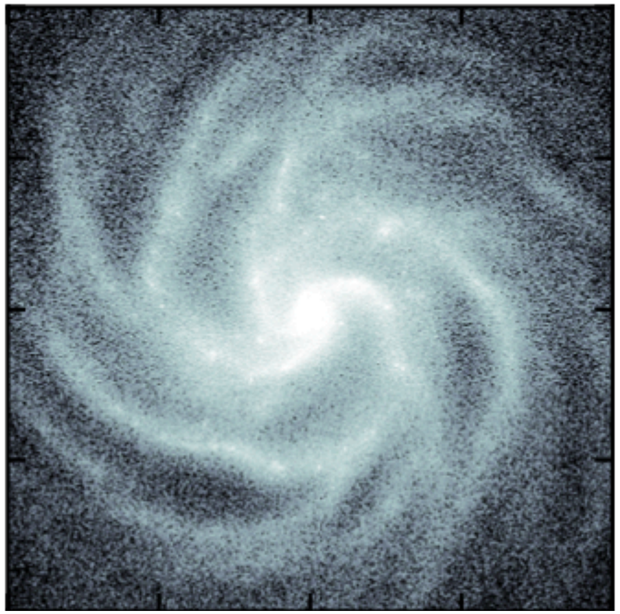

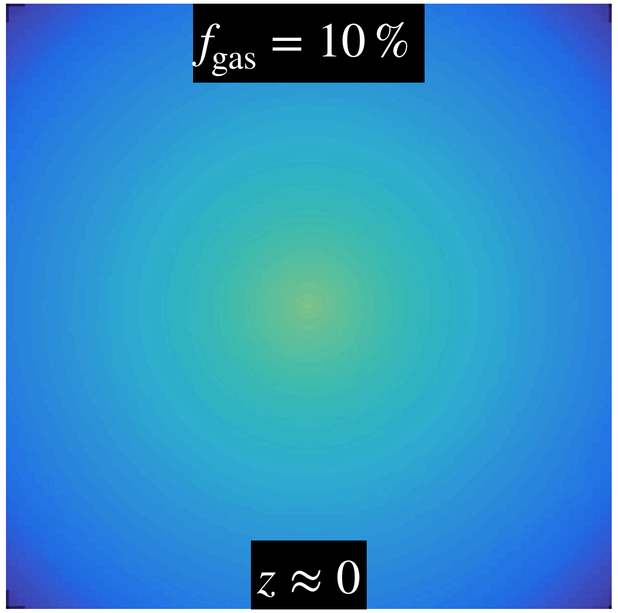

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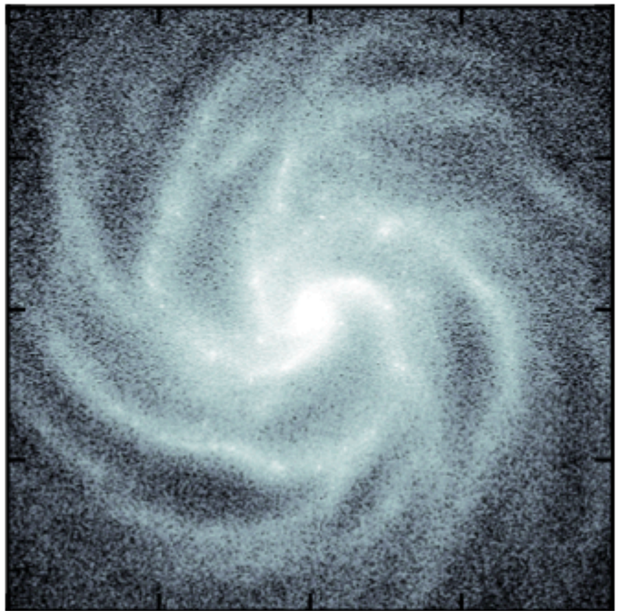
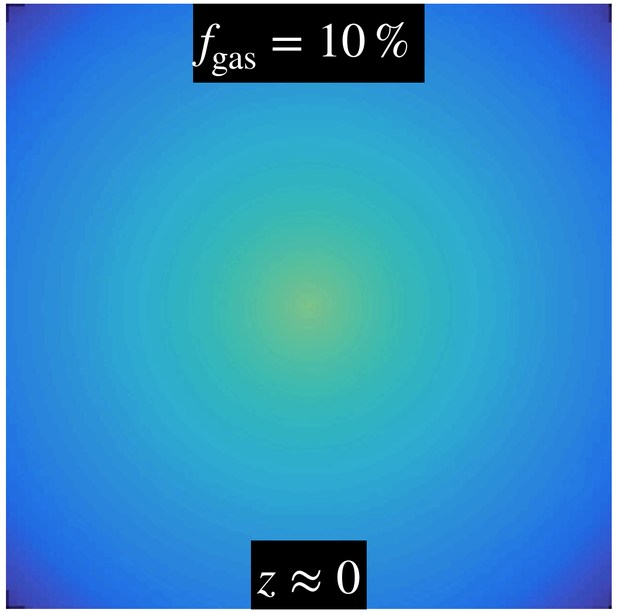
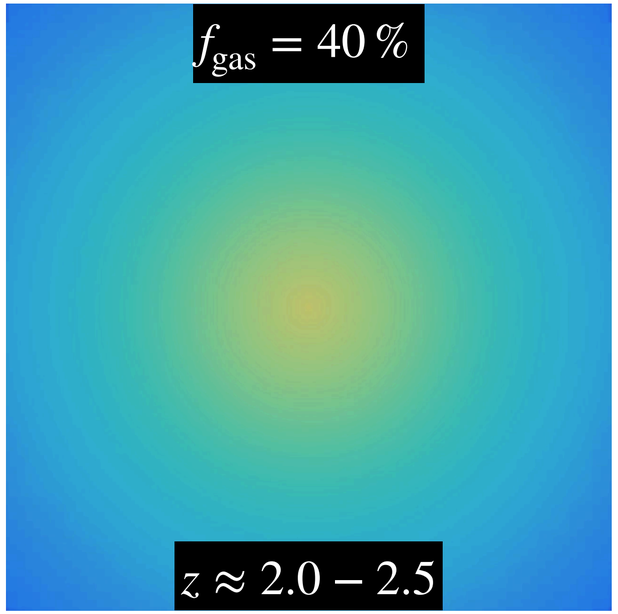
the molecular gas changes the instability regime







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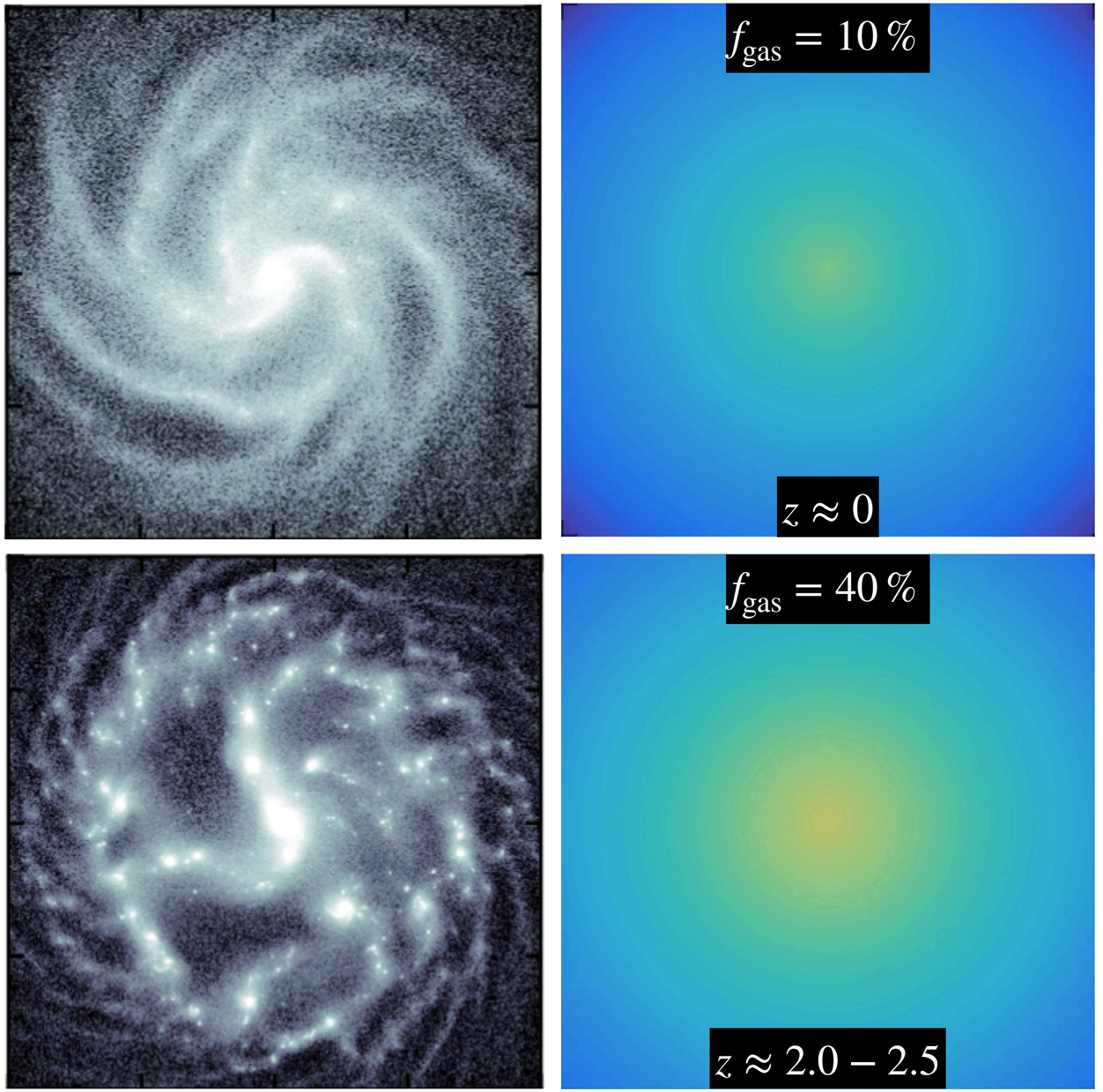
Transition clump-driven



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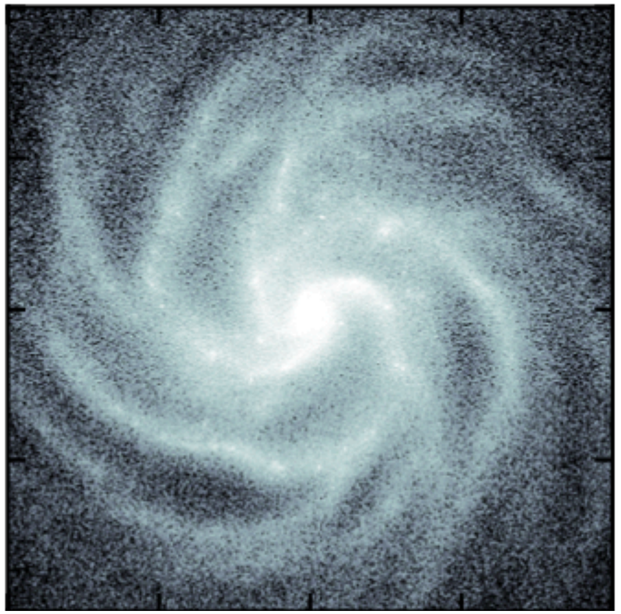

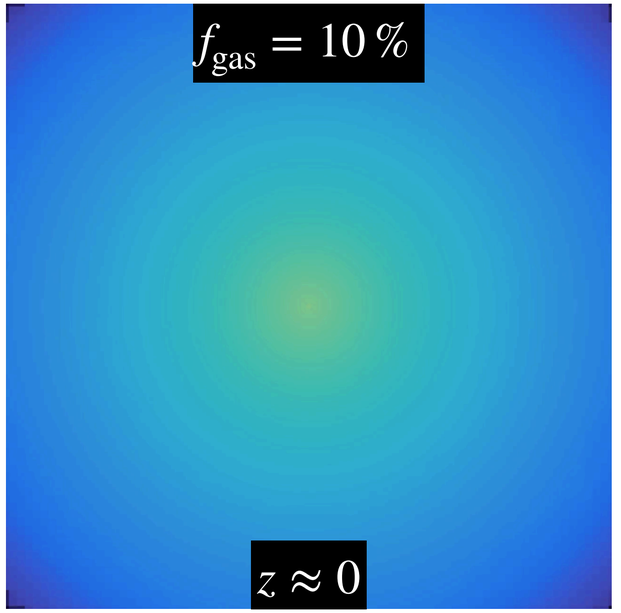

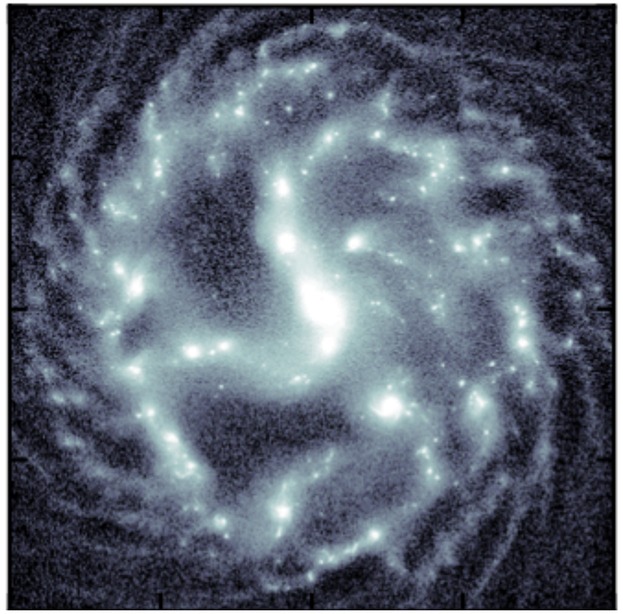

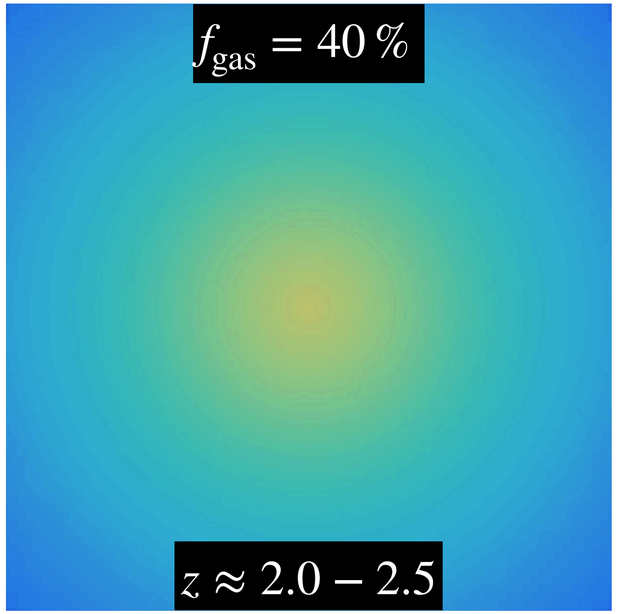

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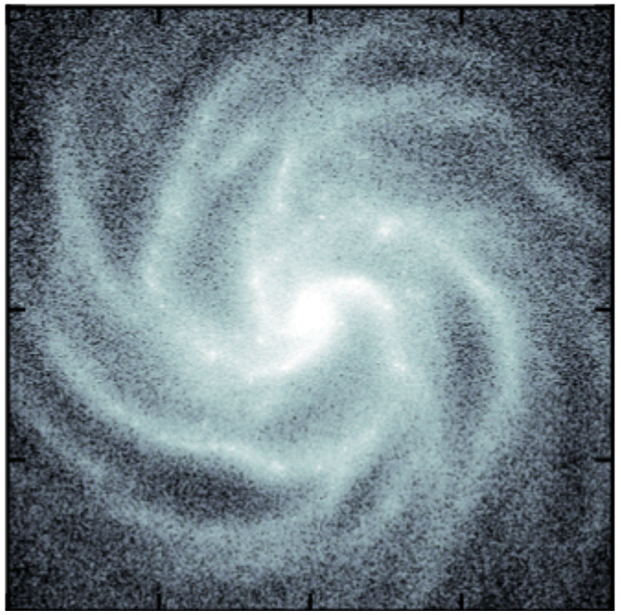

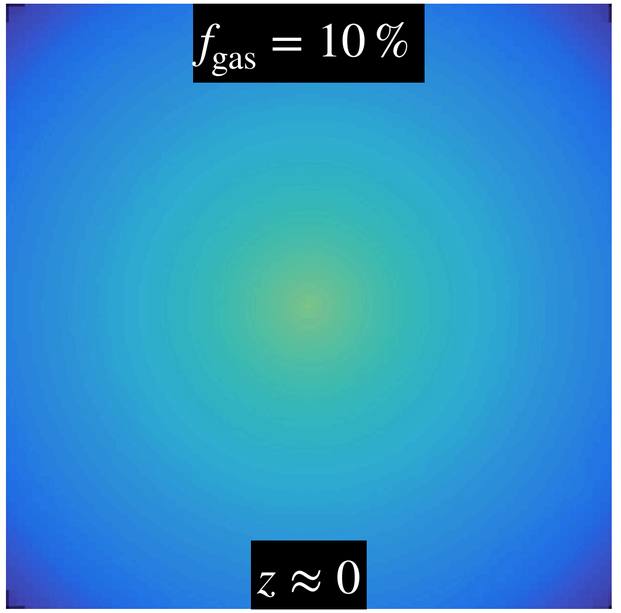

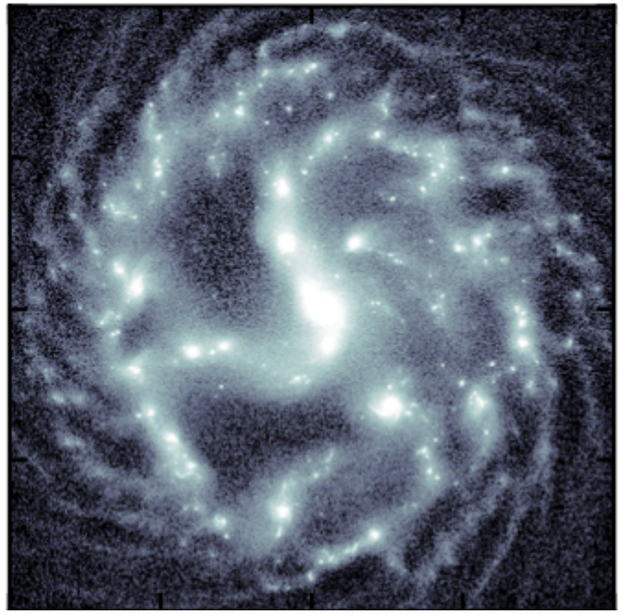

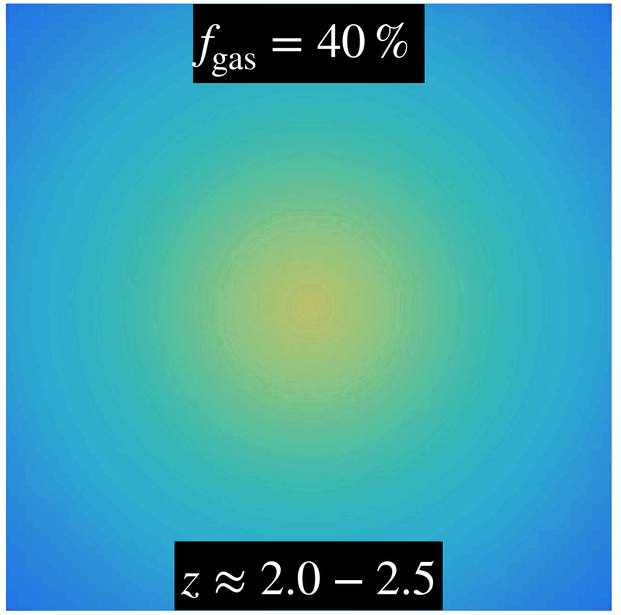

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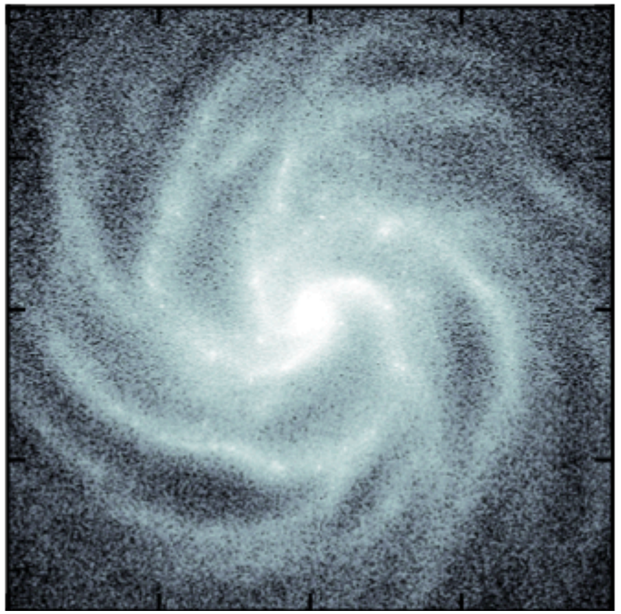
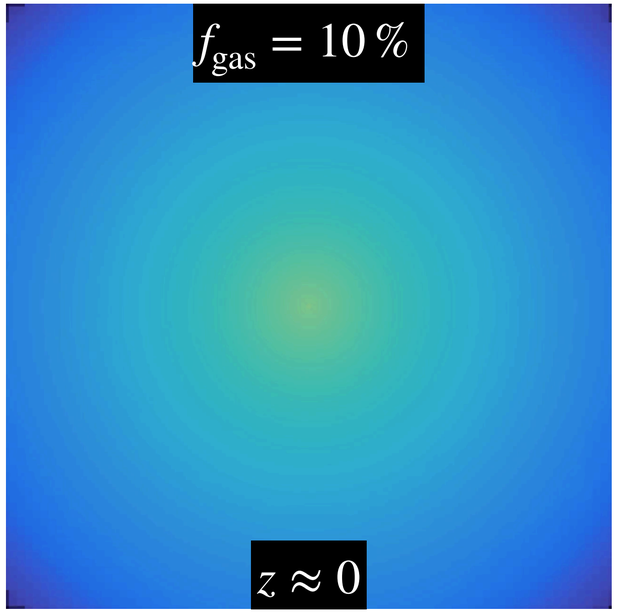
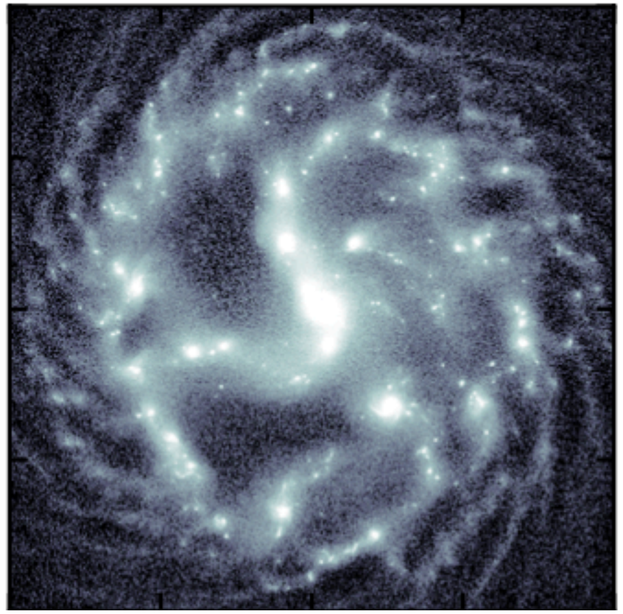
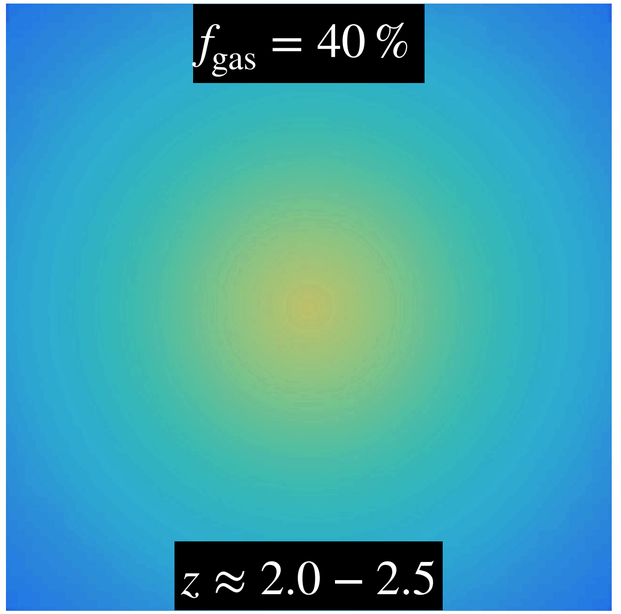
Rapid, vigorous star formation in clumps:
high $[\alpha/{\rm Fe}]$ stellar populations
Clarke et al. (2019), Khoperskov et al. (2021)









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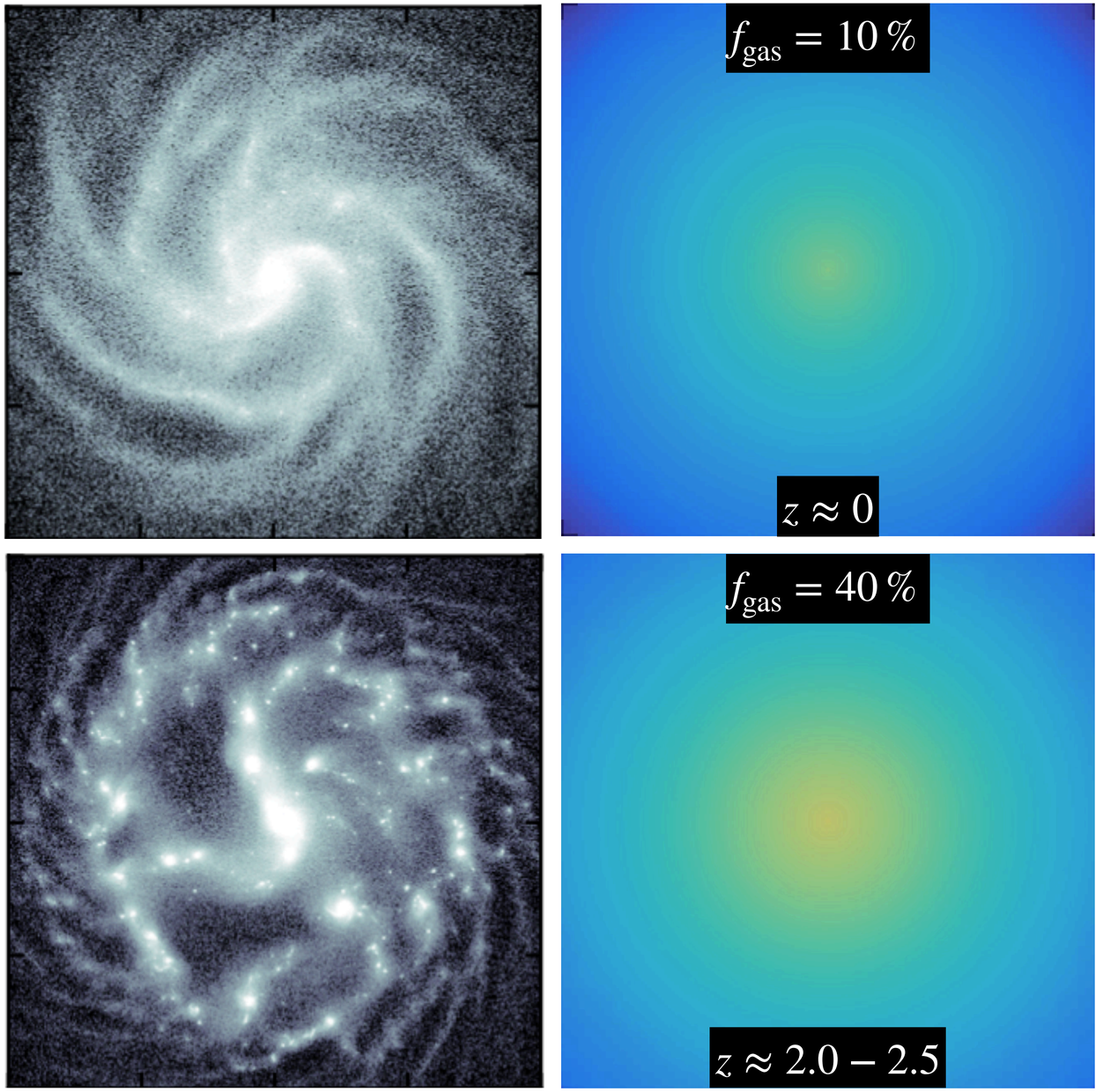
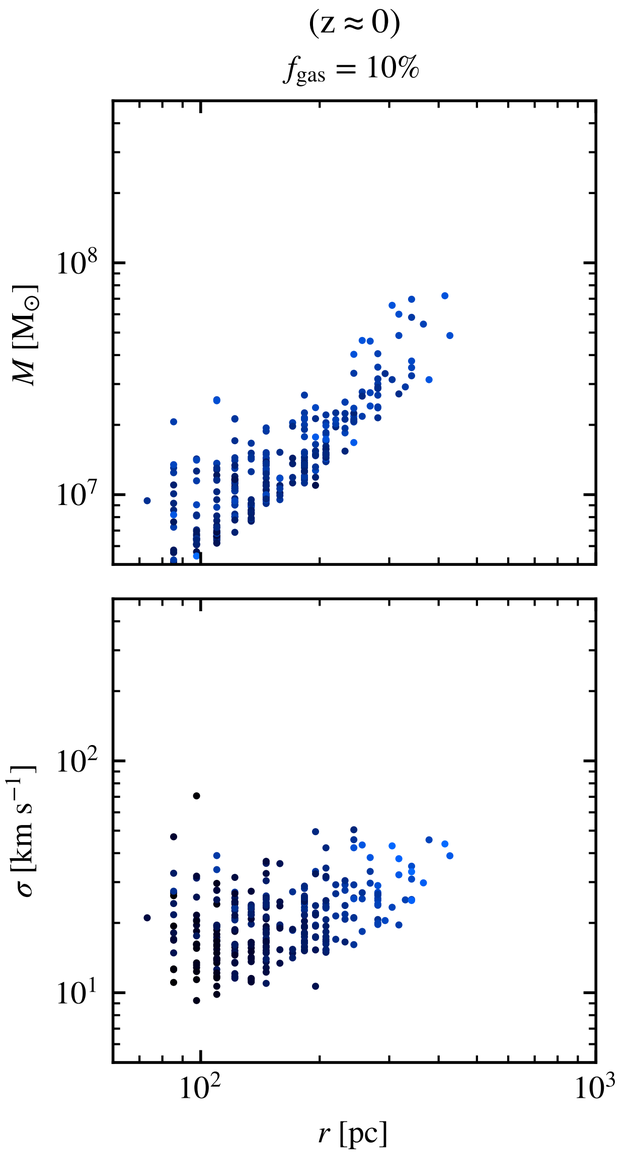
Similar signatures at major mergers ... conspiracy!

not really...



UNIVERSAL SCALING RELATIONS + OUTLIERS

Florent Renaud
Strasbourg



Renaud et al. (2024)

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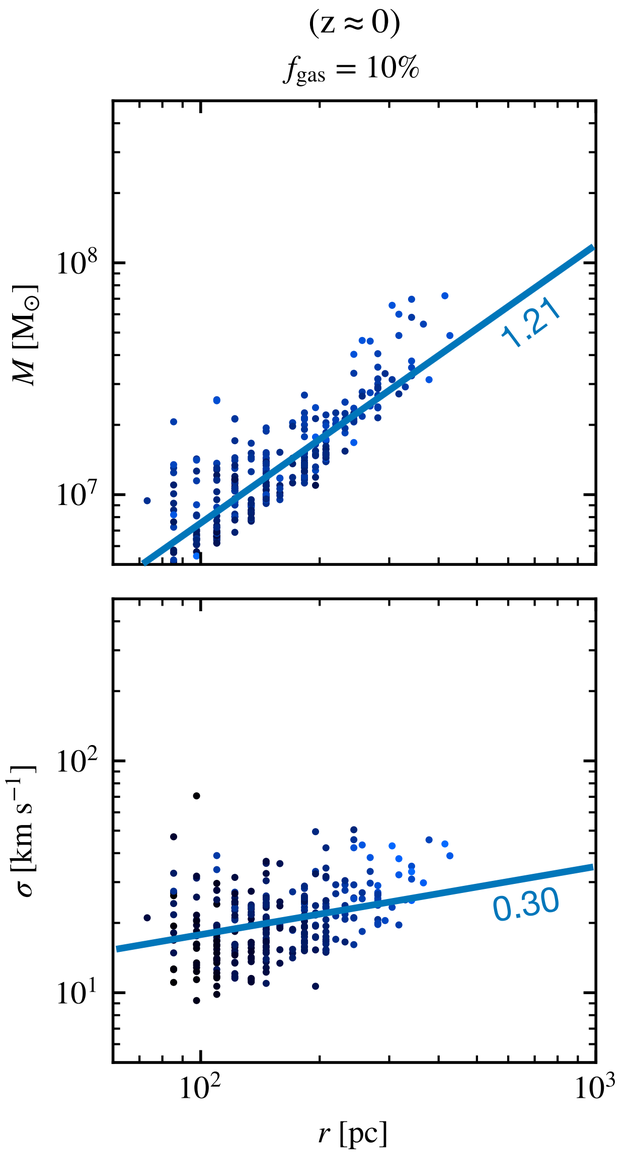

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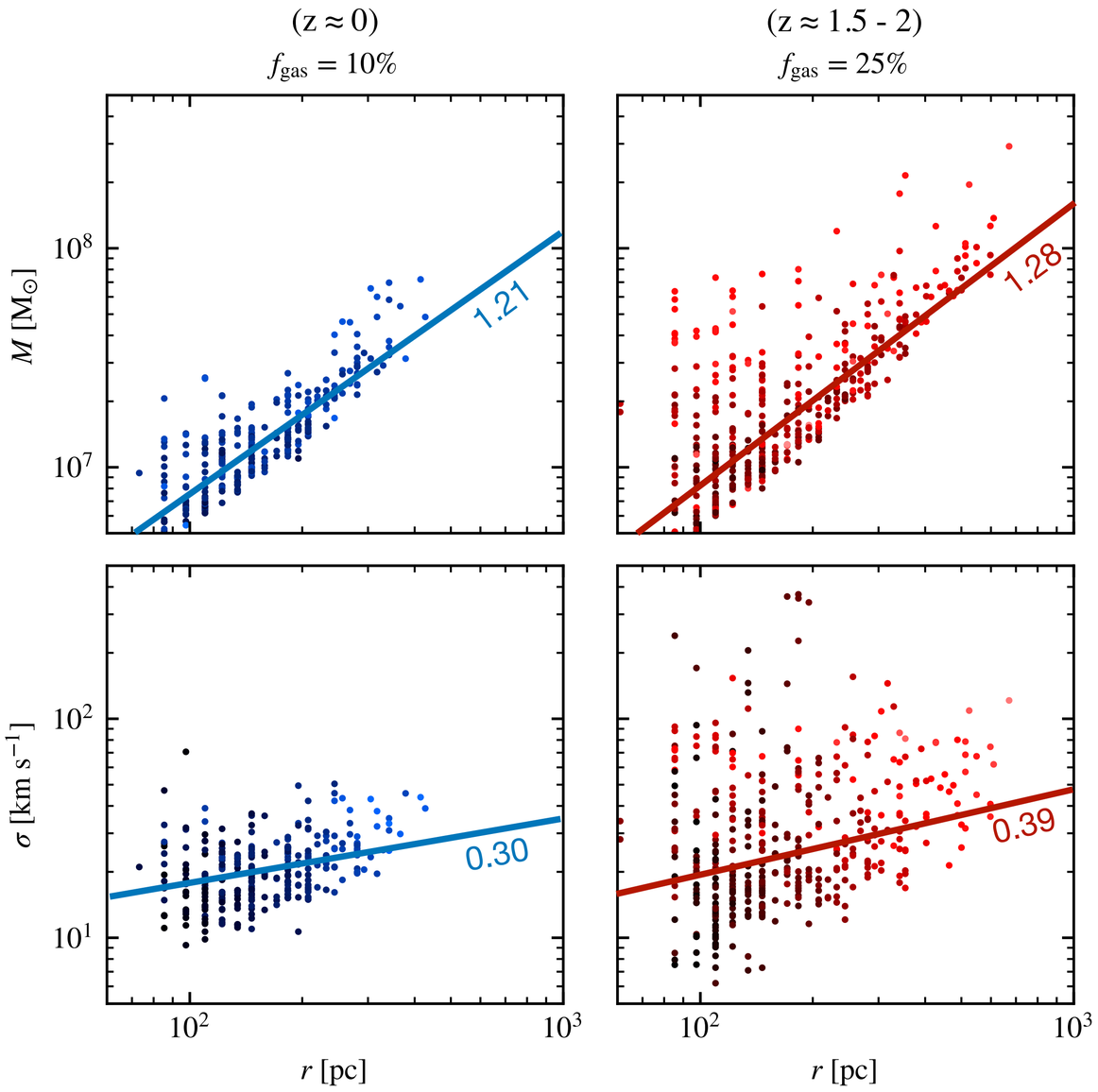

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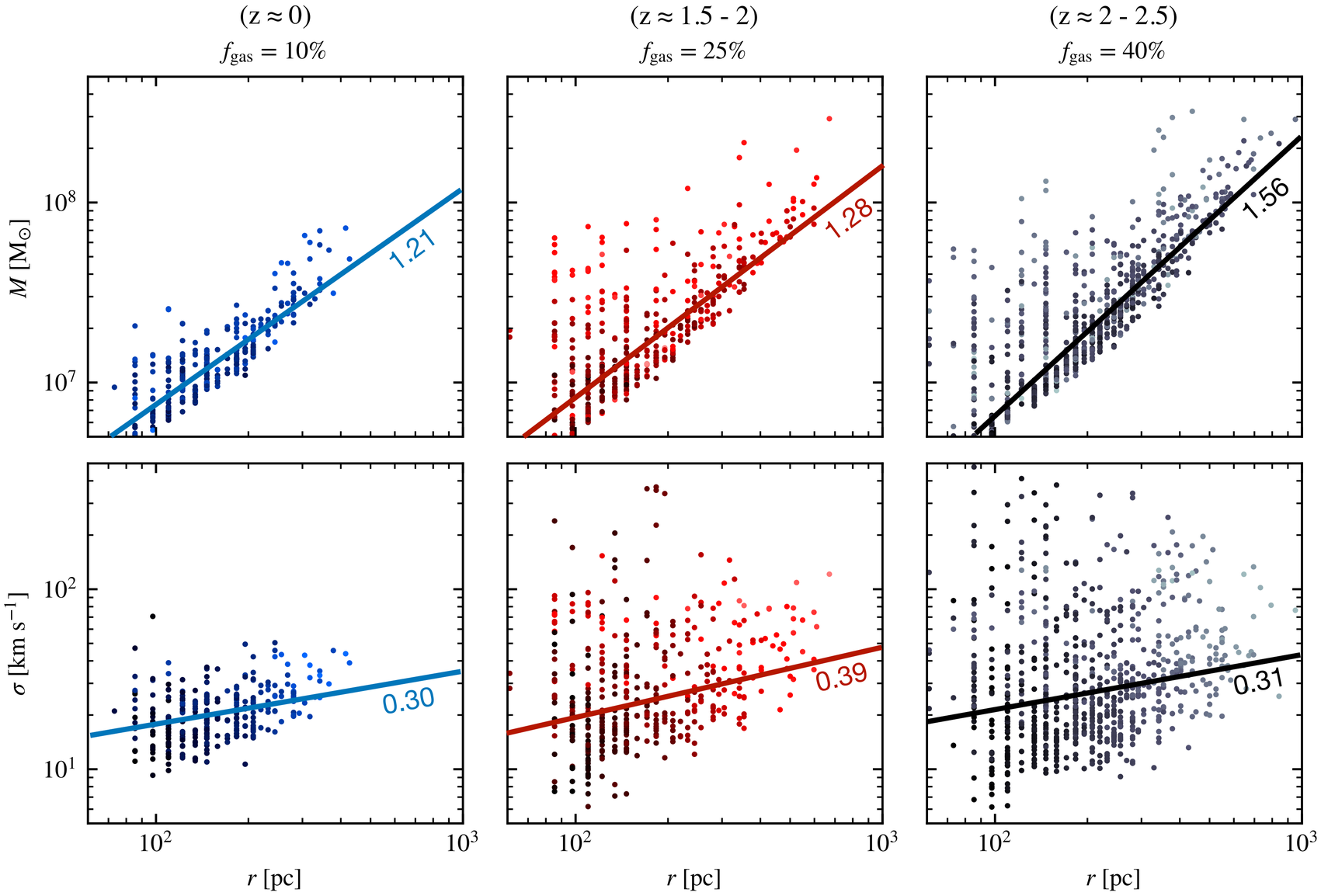

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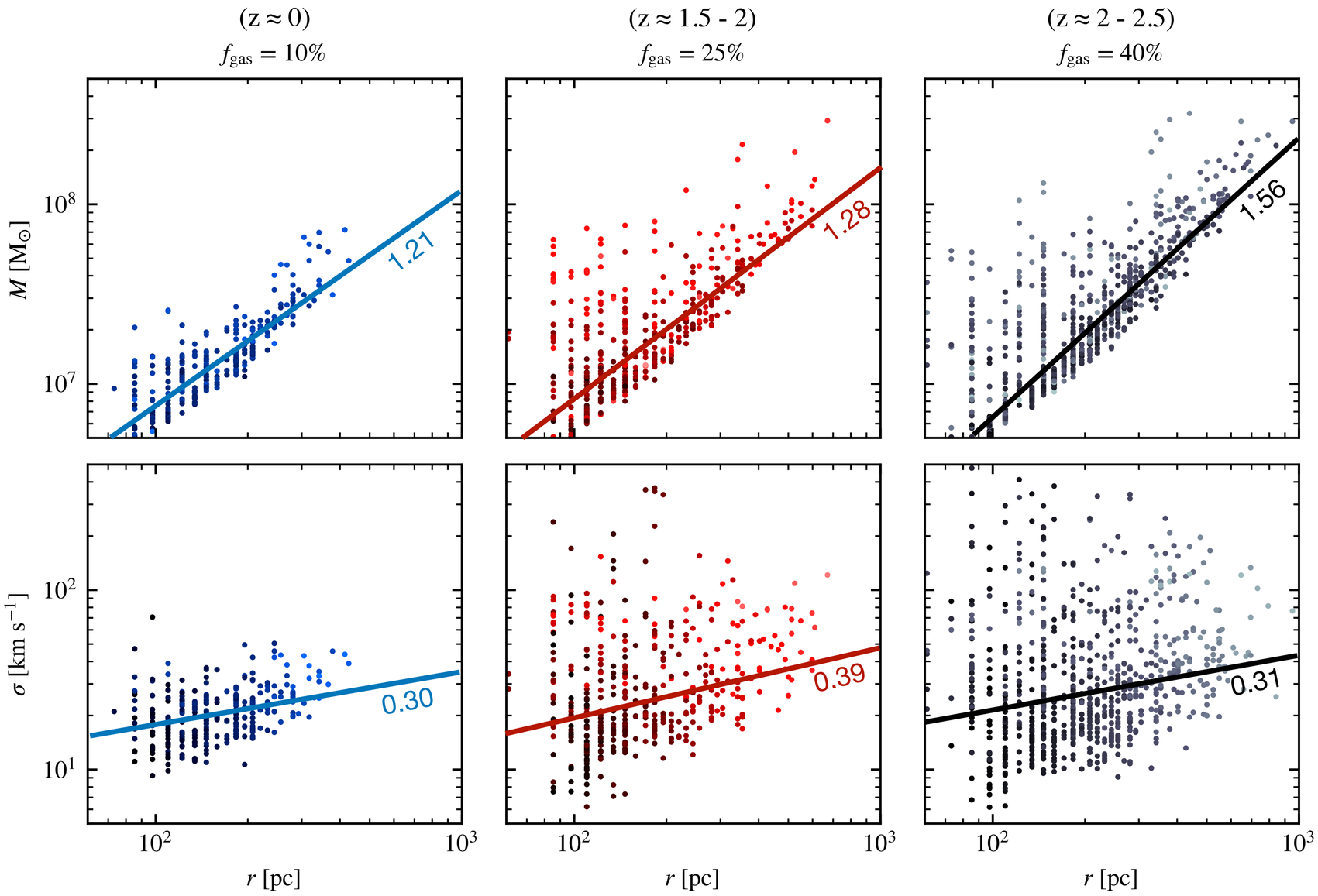

Clumps in gas-rich (high-z) disks follow Larson's-like scaling relations

Renaud et al. (2024)

UNIVERSAL SCALING RELATIONS + OUTLIERS

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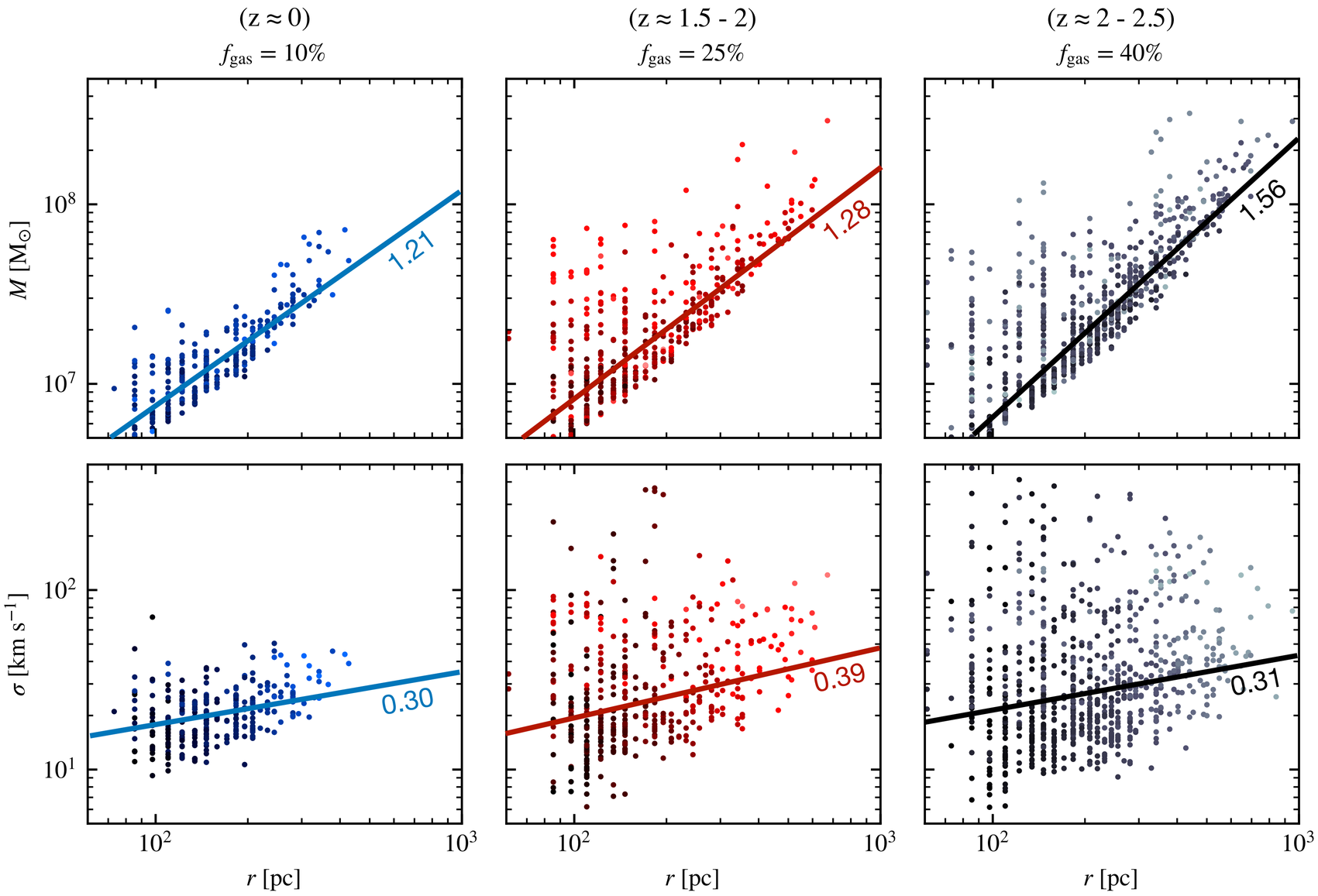
Strasbourg



Clumps in gas-rich (high-*z*) disks follow Larson's-like scaling relations

... but with increased range and scatter

Renaud et al. (2024)

UNIVERSAL SCALING RELATIONS + OUTLIERS

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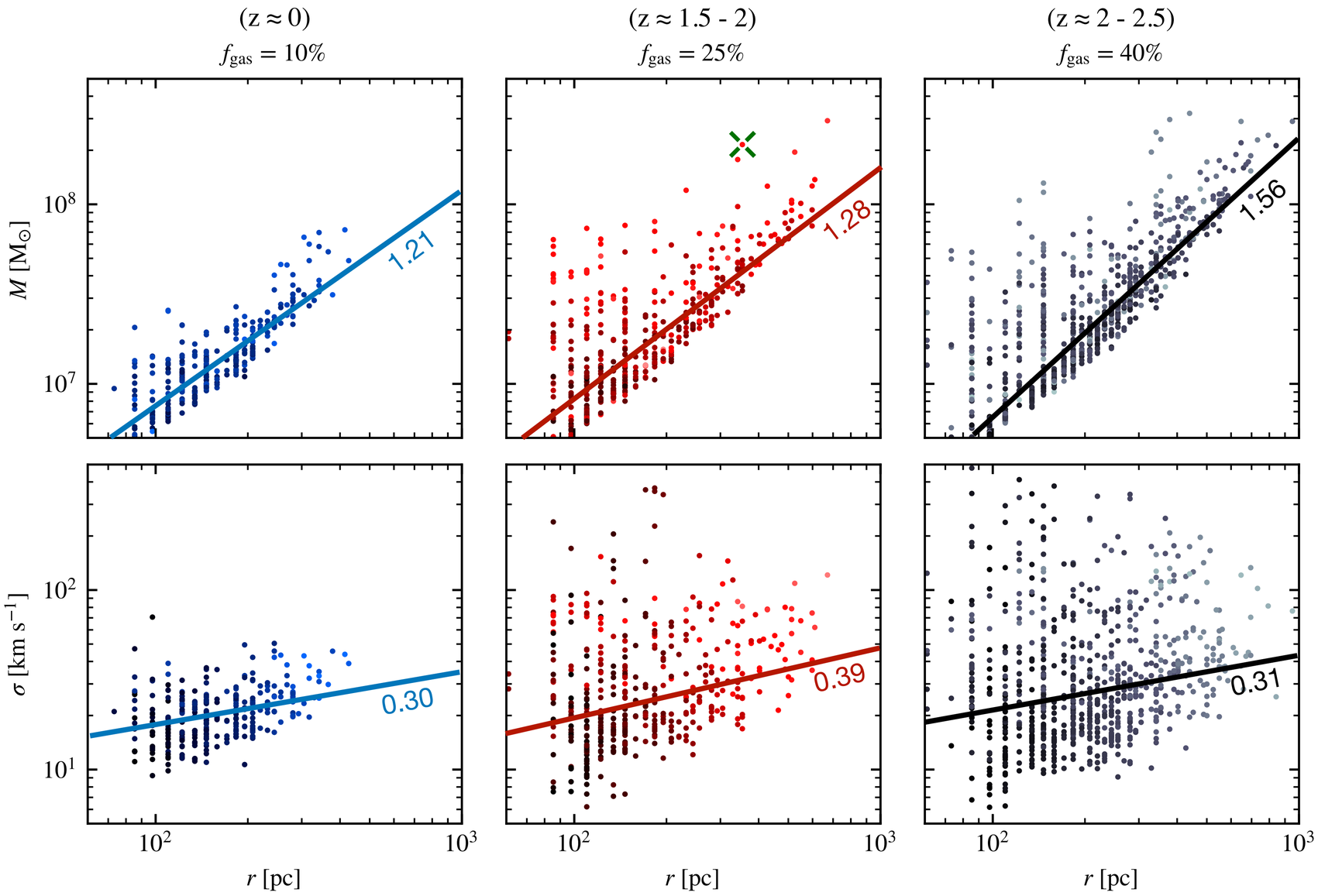
Strasbourg



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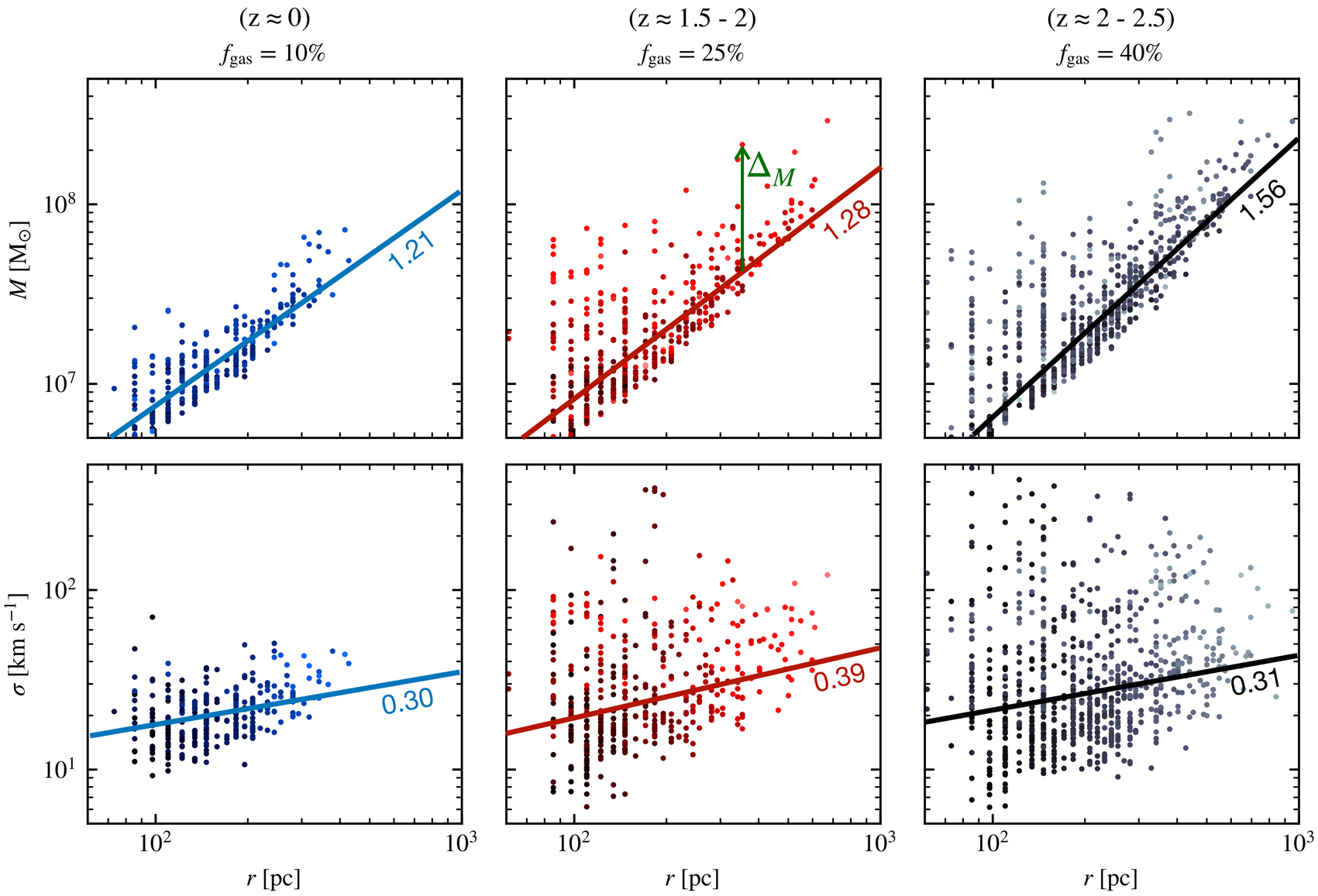

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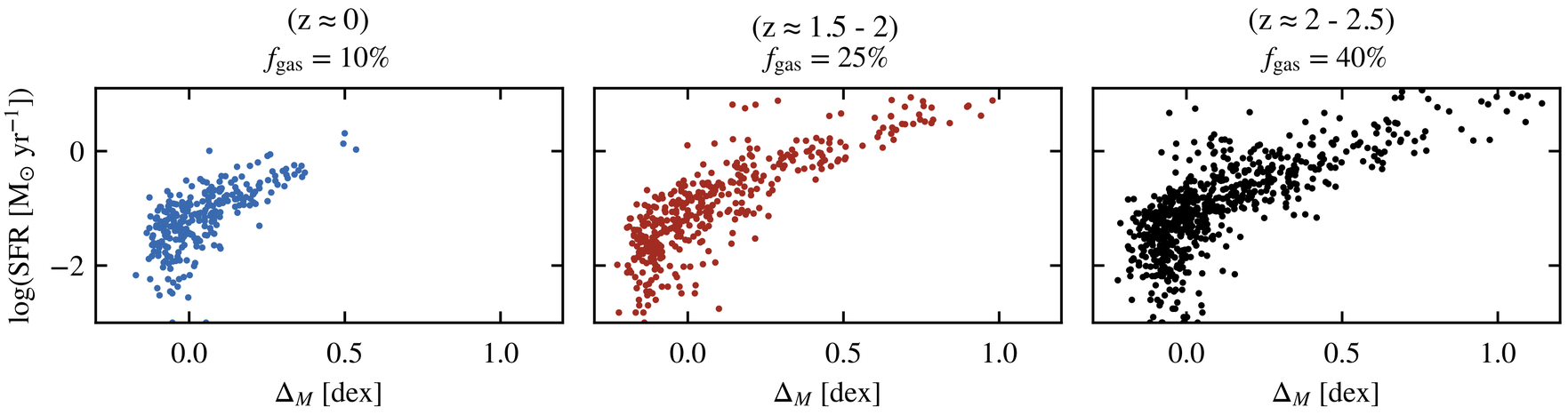
Renaud et al. (2024)

DIFFERENT REGIMES OF STAR FORMATION IN EXTREME CLUMPS

Florent Renaud
Strasbourg

rate



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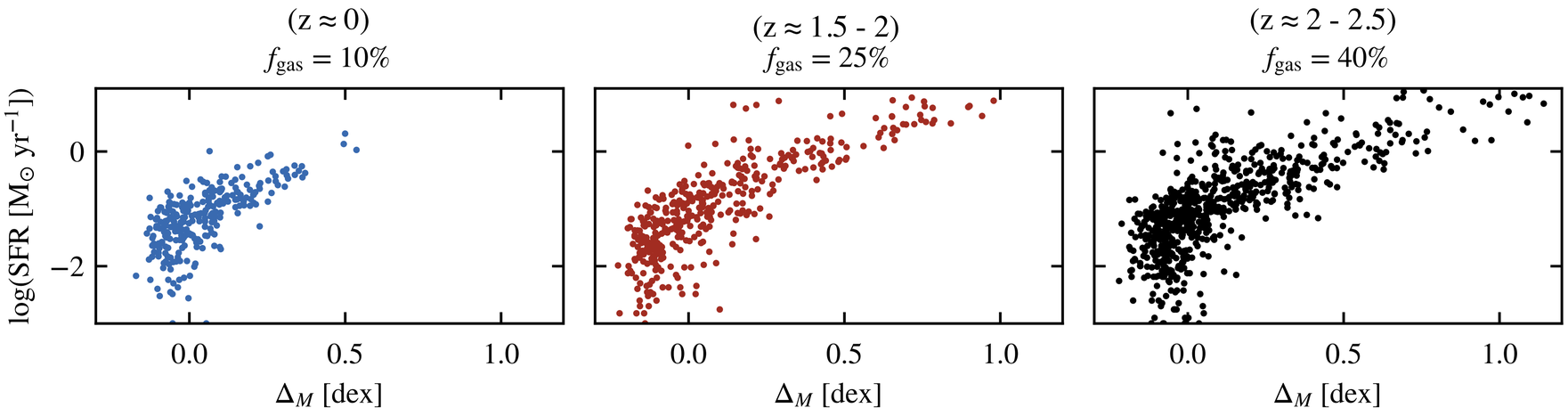
rate



Clumps with an *excess* of mass (for their size) have:

- high SFRs

Renaud et al. (2024)

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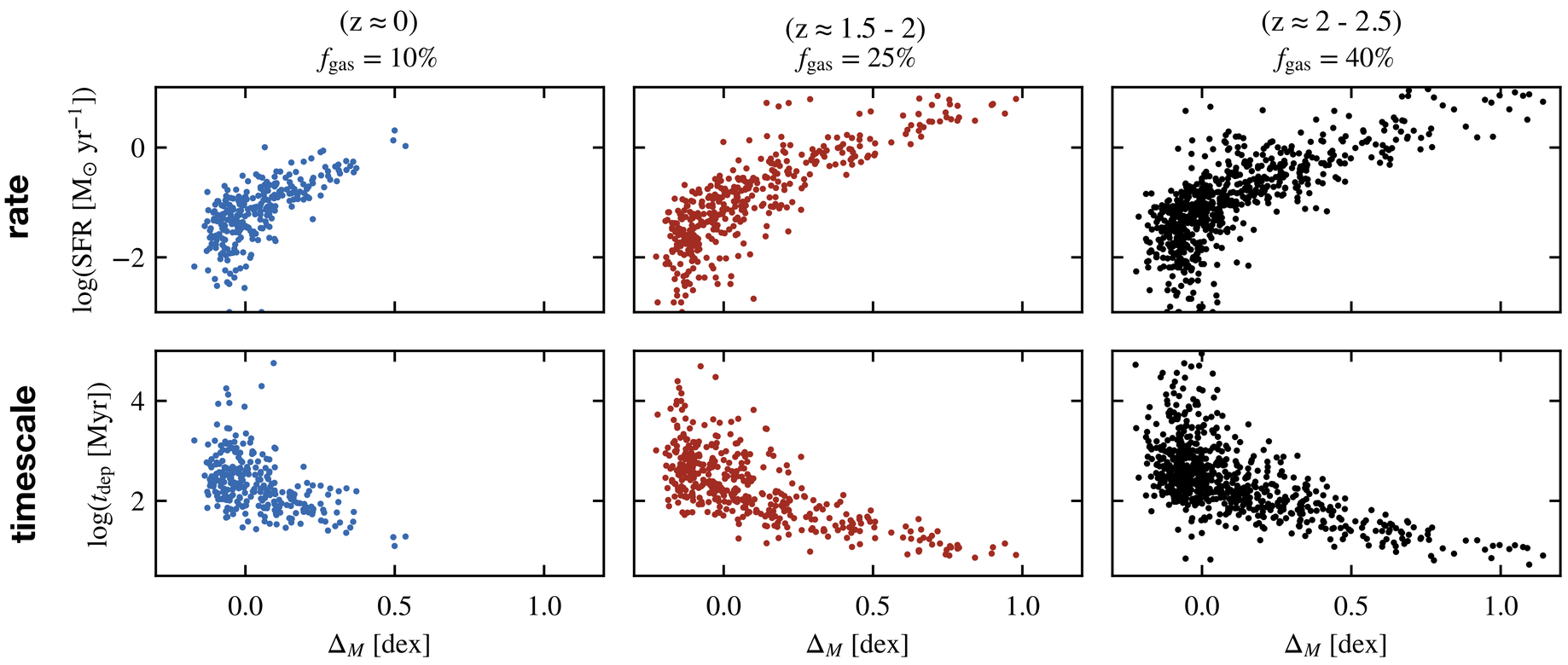


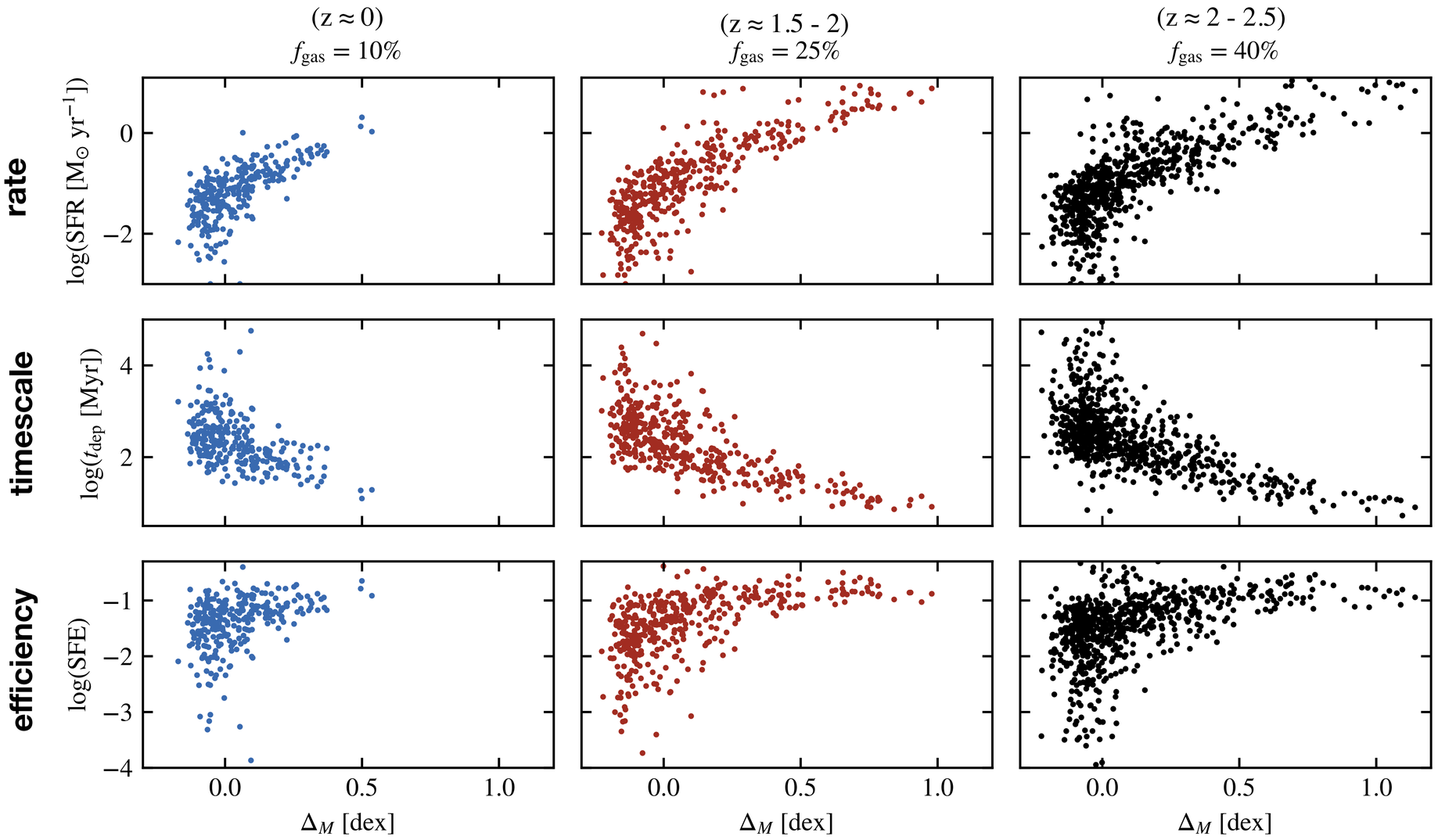
Clumps with an *excess* of mass (for their size) have:

- high SFRs
- short depletion times

Renaud et al. (2024)

DIFFERENT REGIMES OF STAR FORMATION IN EXTREME CLUMPS

Florent Renaud
Strasbourg



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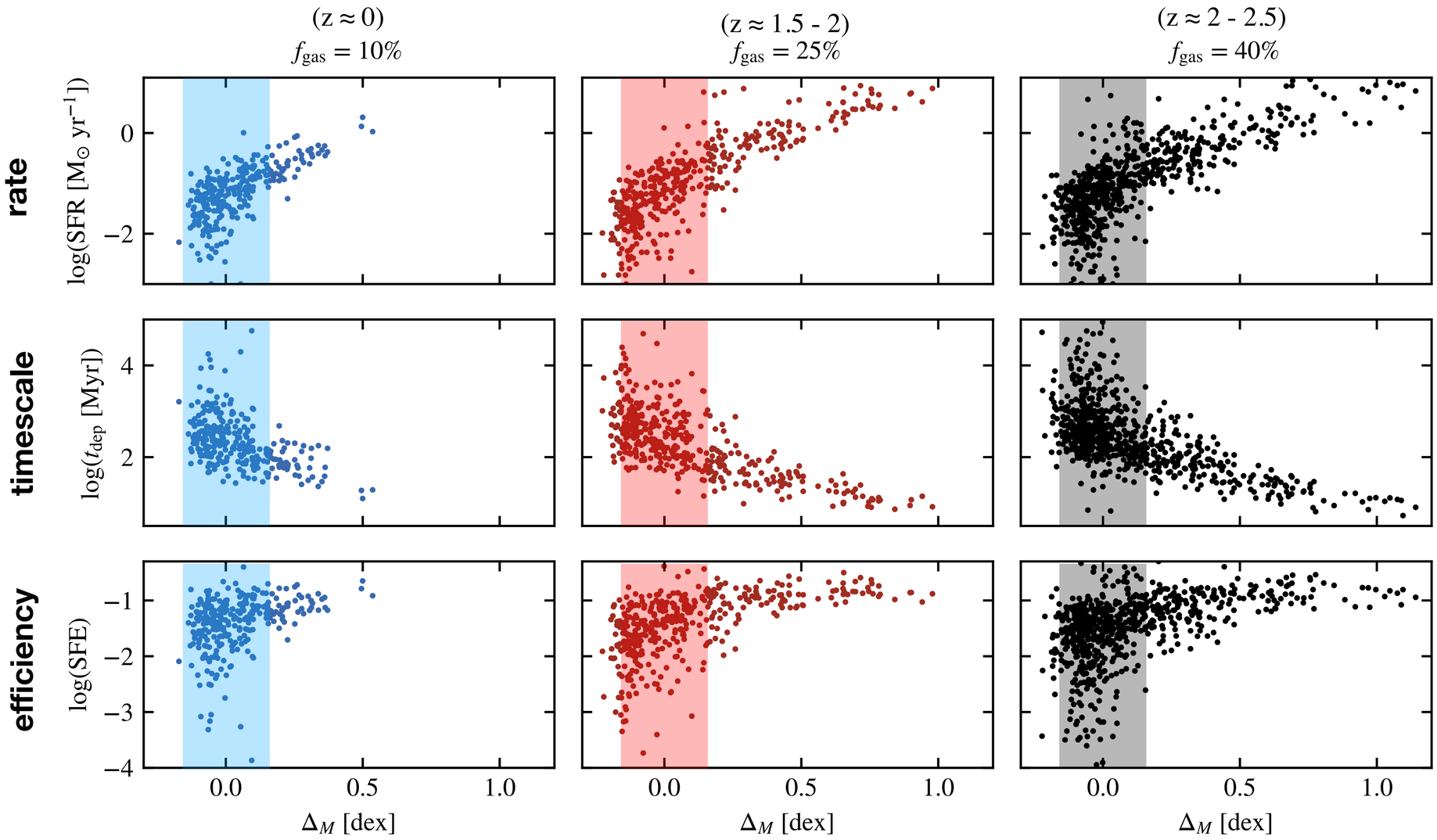

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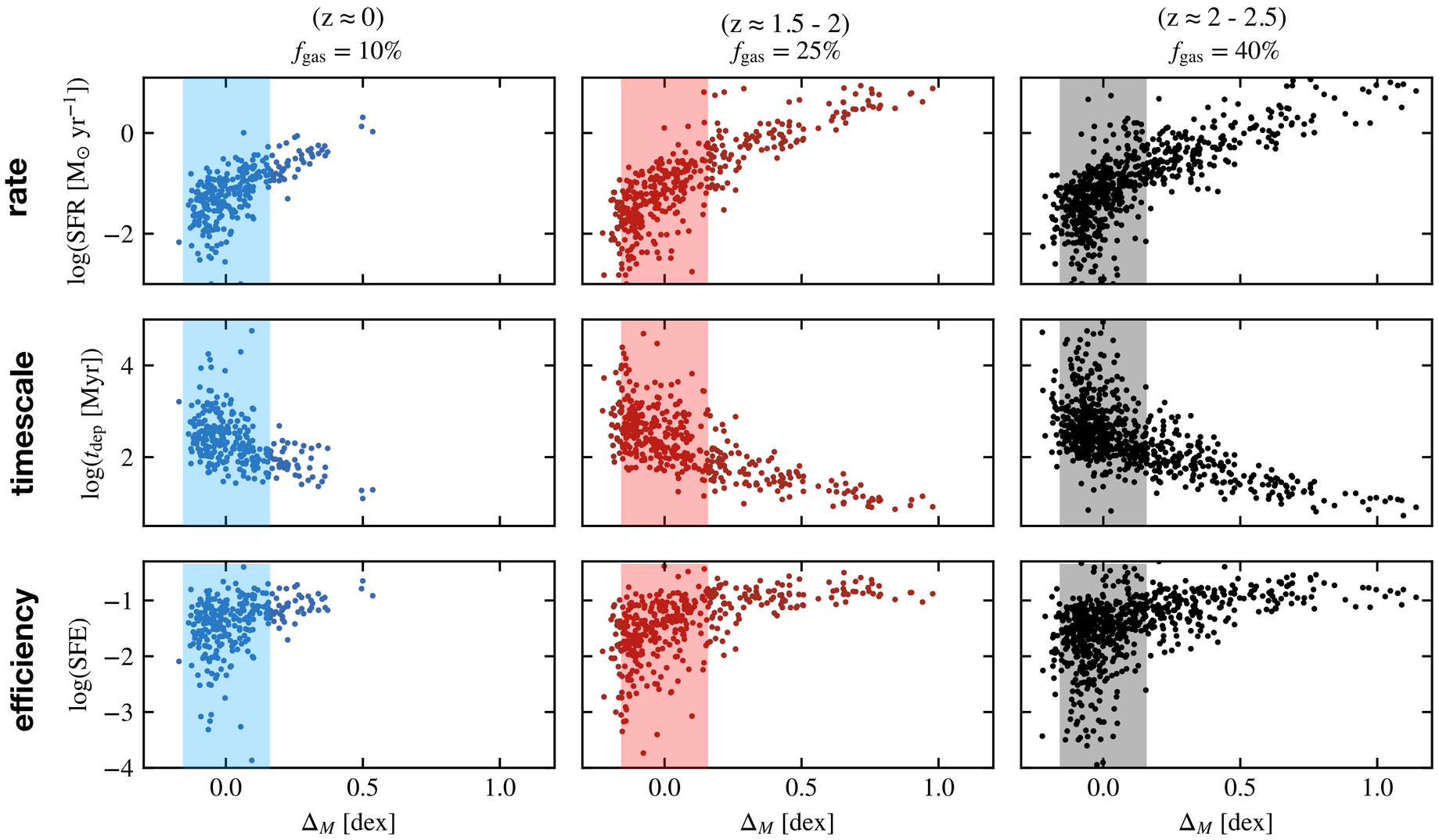

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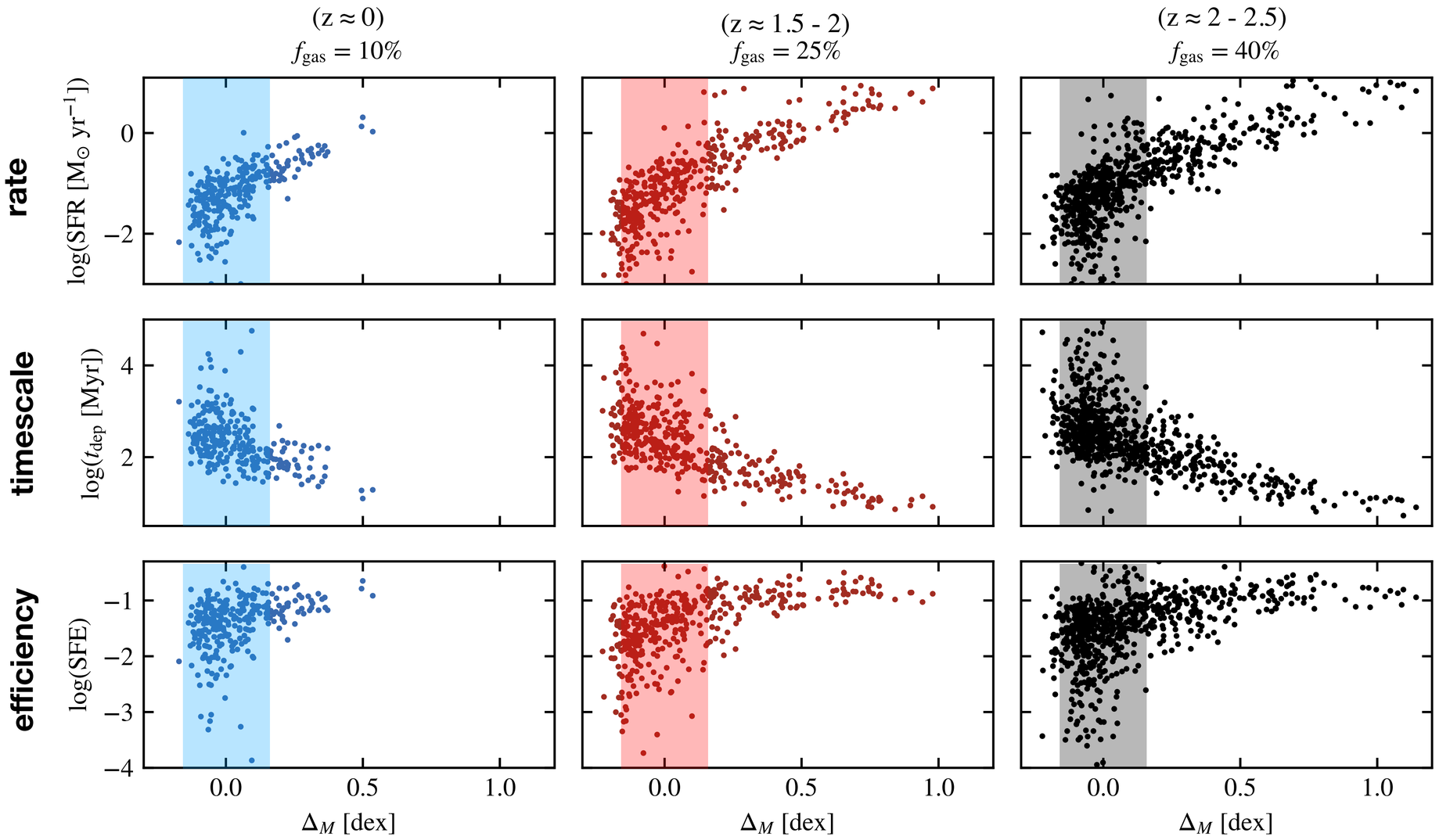

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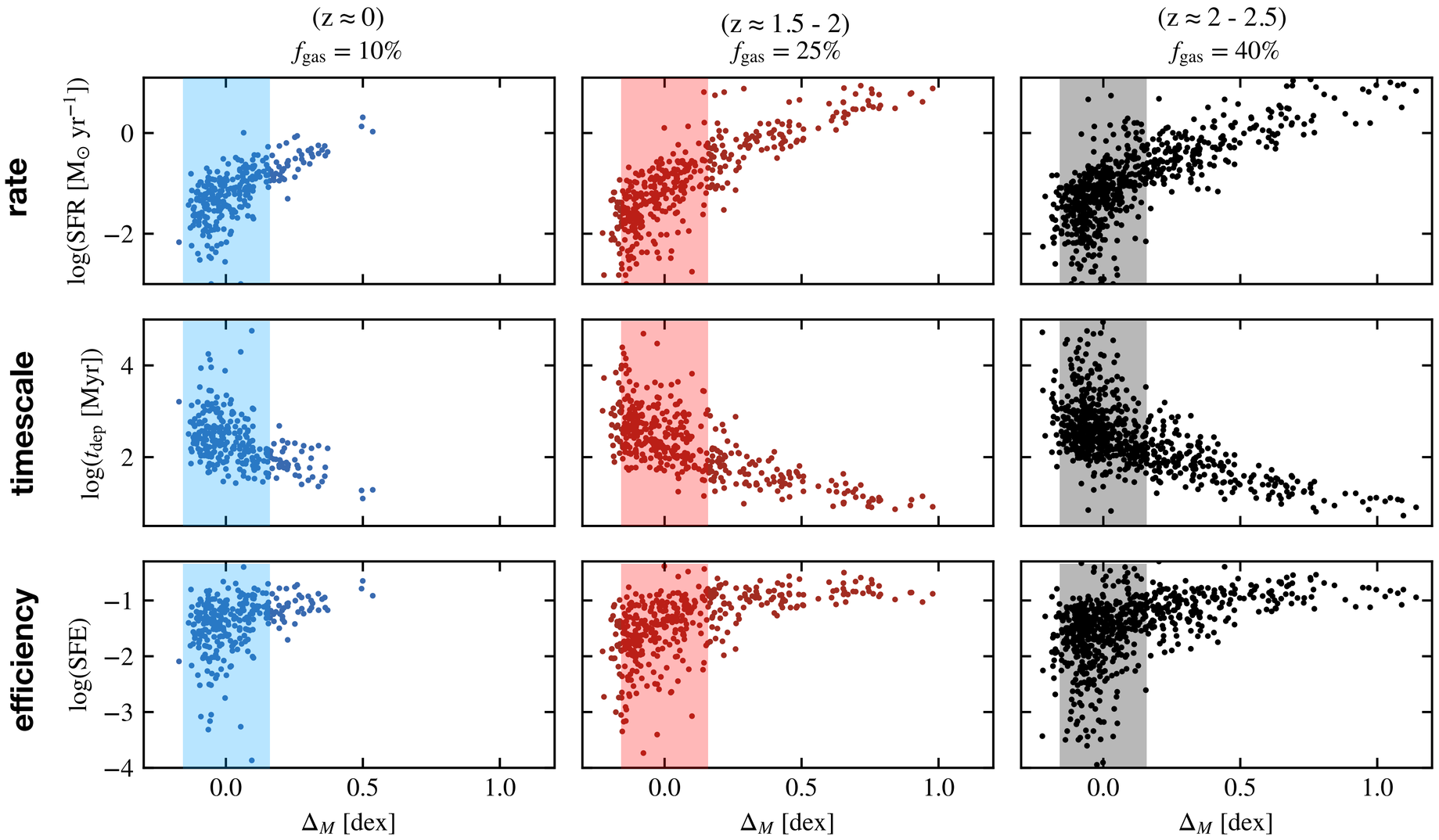

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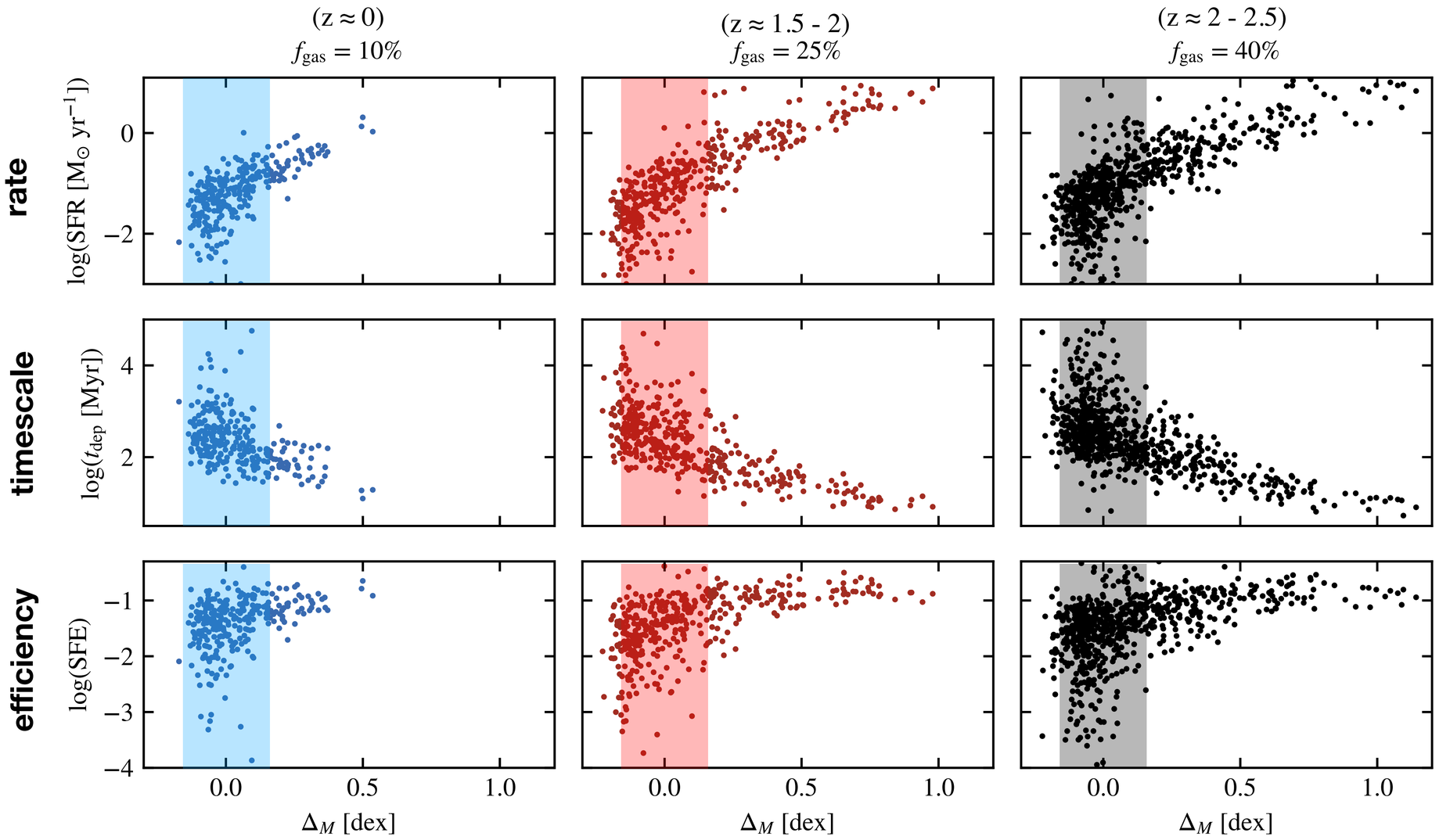

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Extreme clumps = formation sites of globular clusters?

Claeyssens et al. (2023, 2024)

THE CONUNDRUM OF BAR FORMATION

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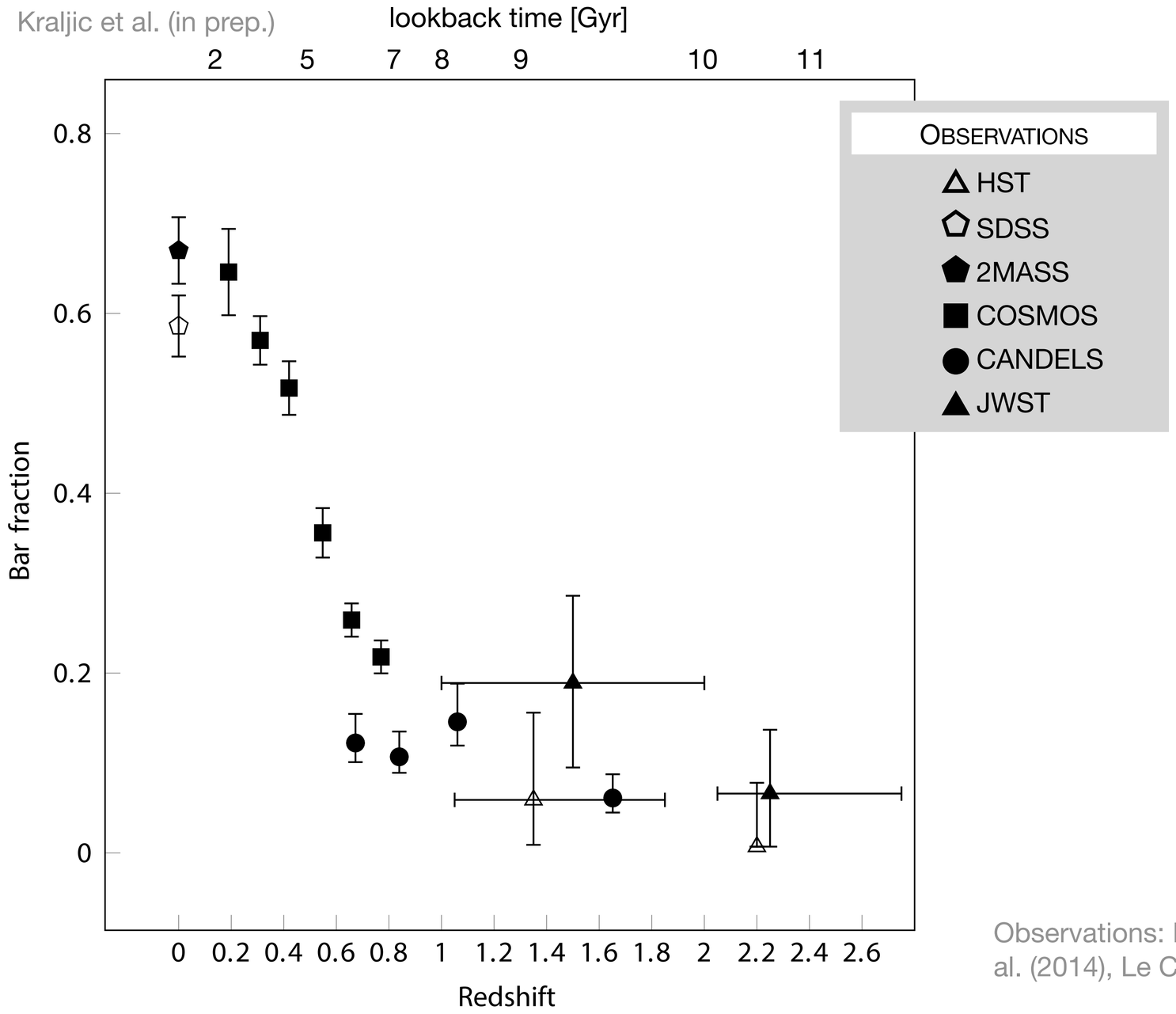
Kraljic et al. (in prep.)



Observations: Merendez-D. et al. (2007), Sheth et al. (2008), Simmons et al. (2014), Le Conte et al. (2023)

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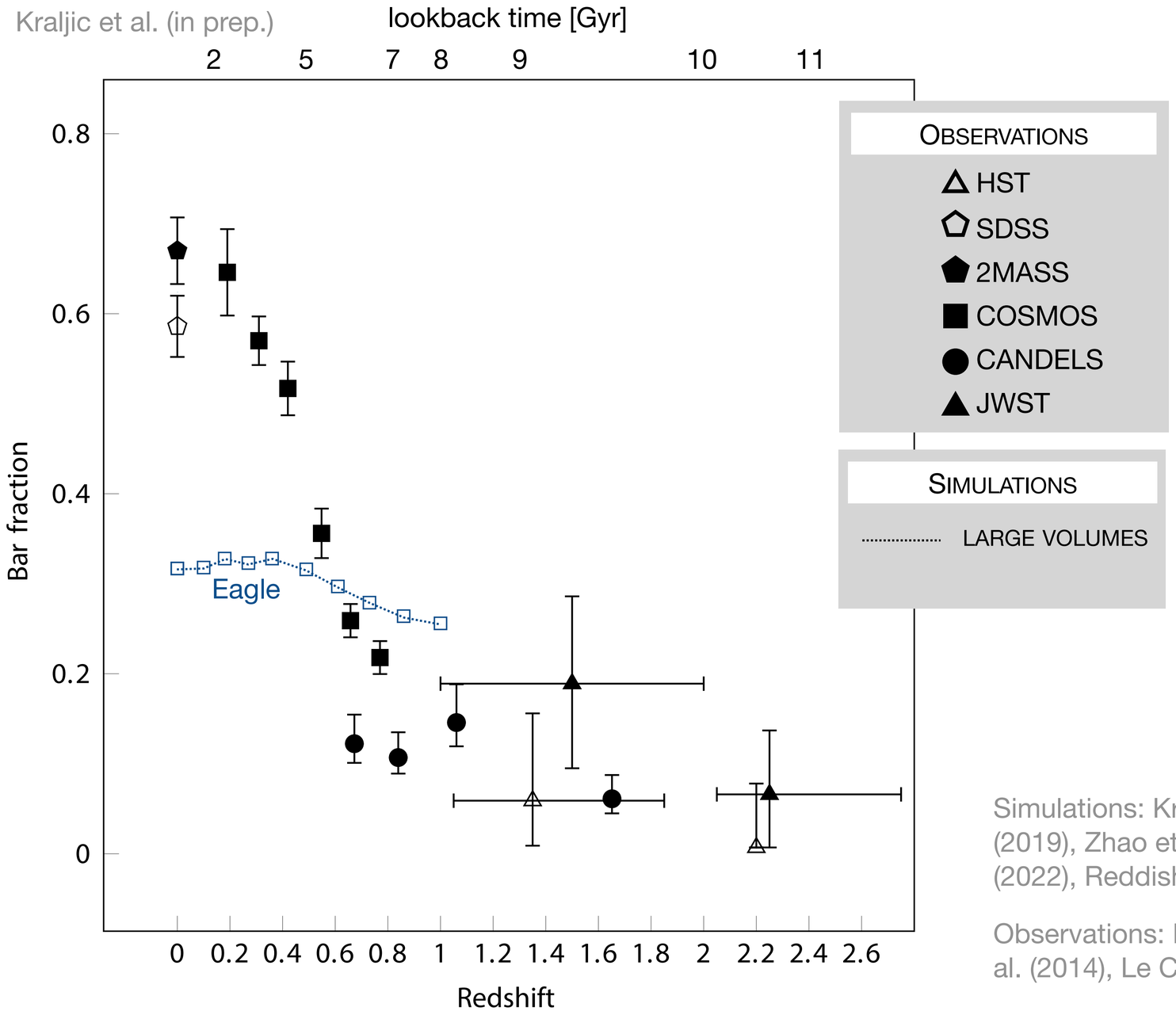

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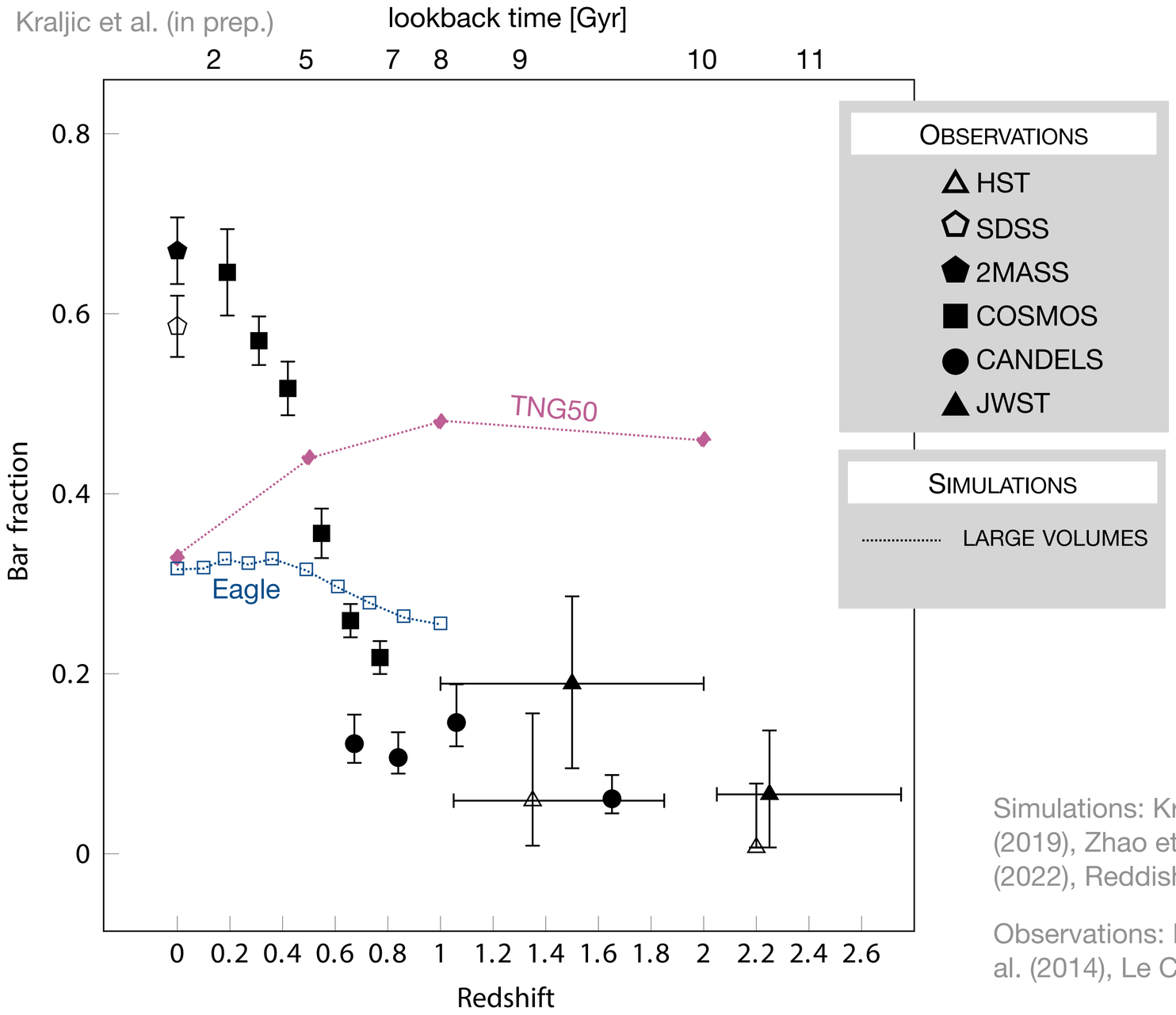

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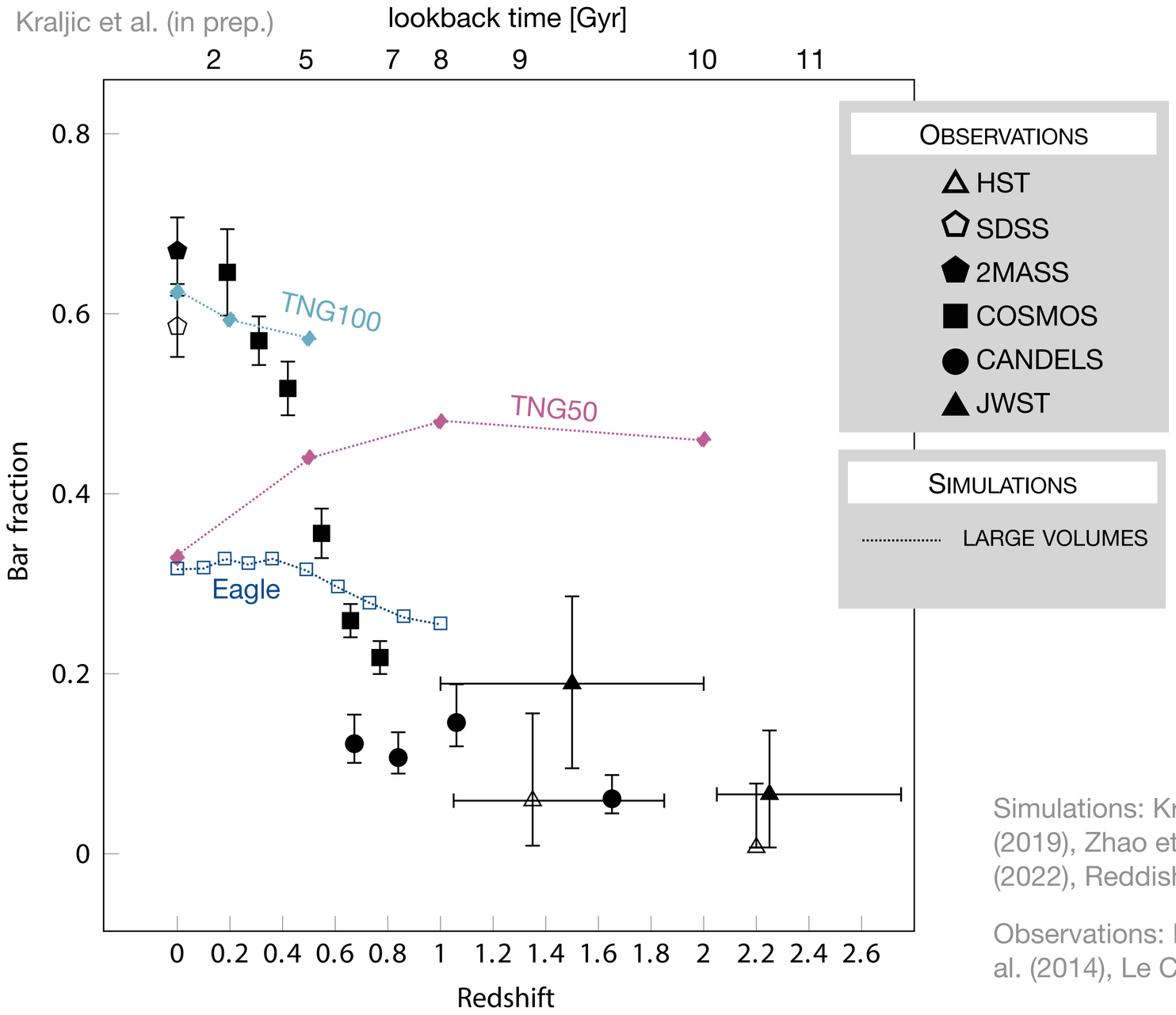

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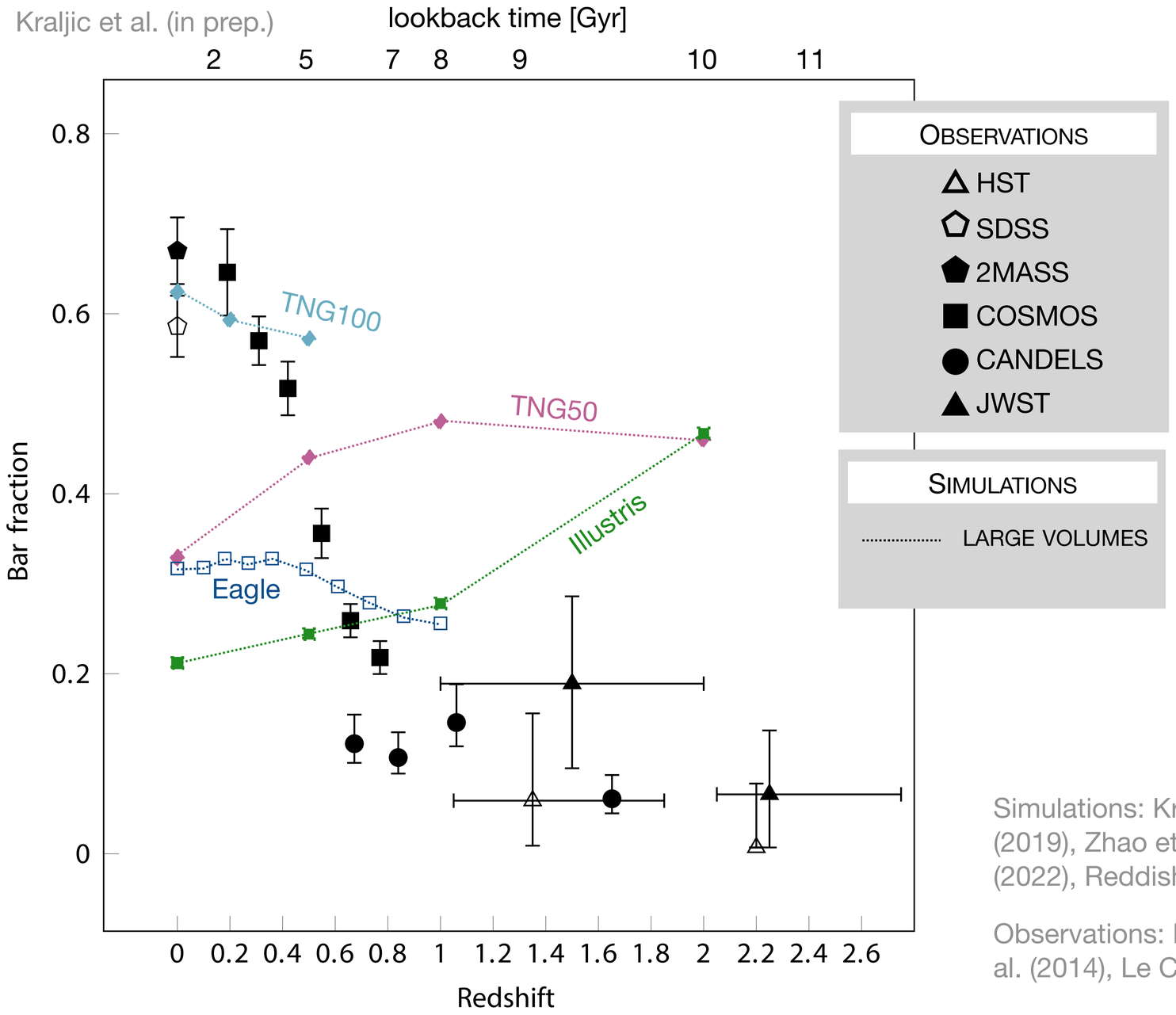

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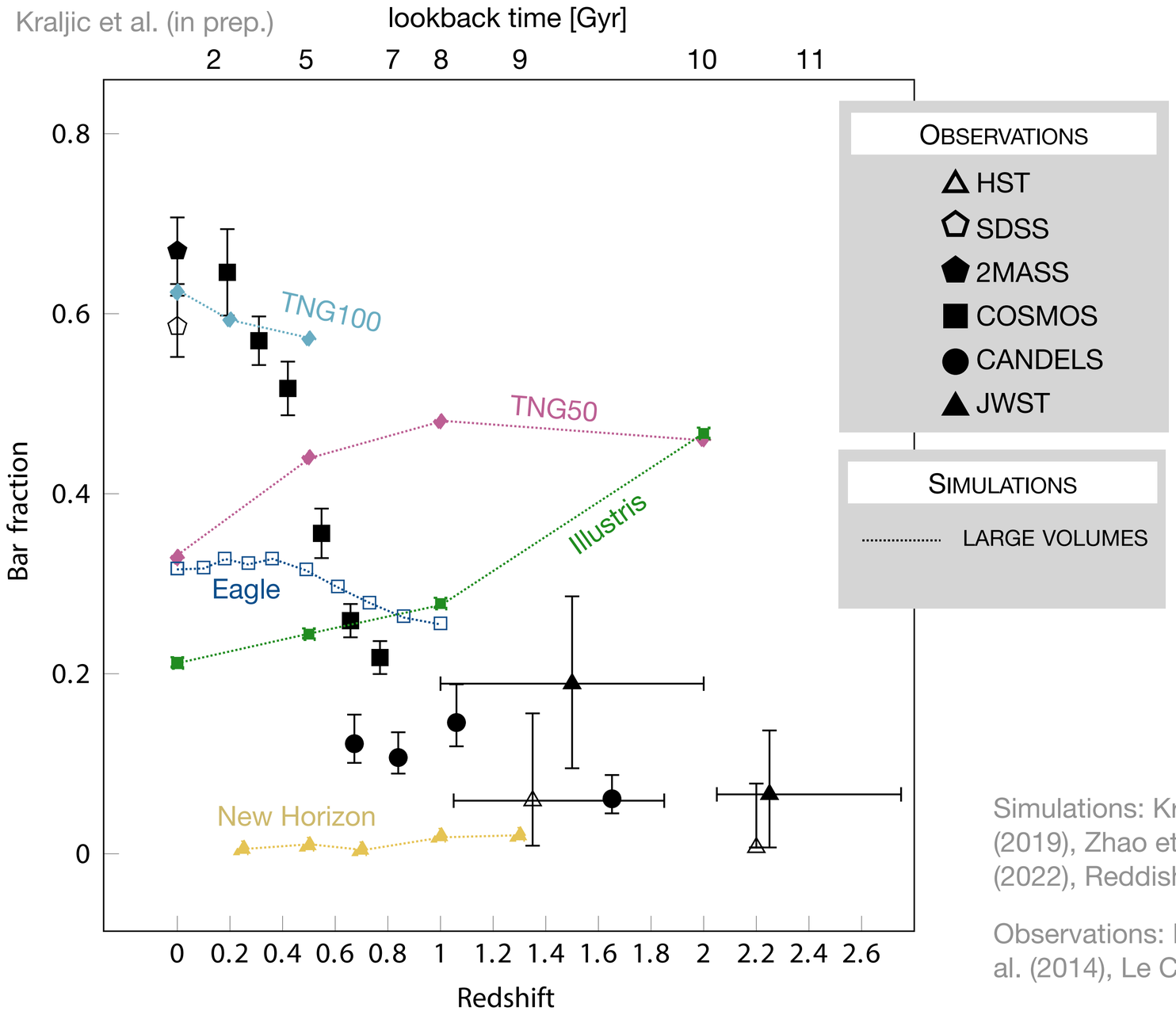

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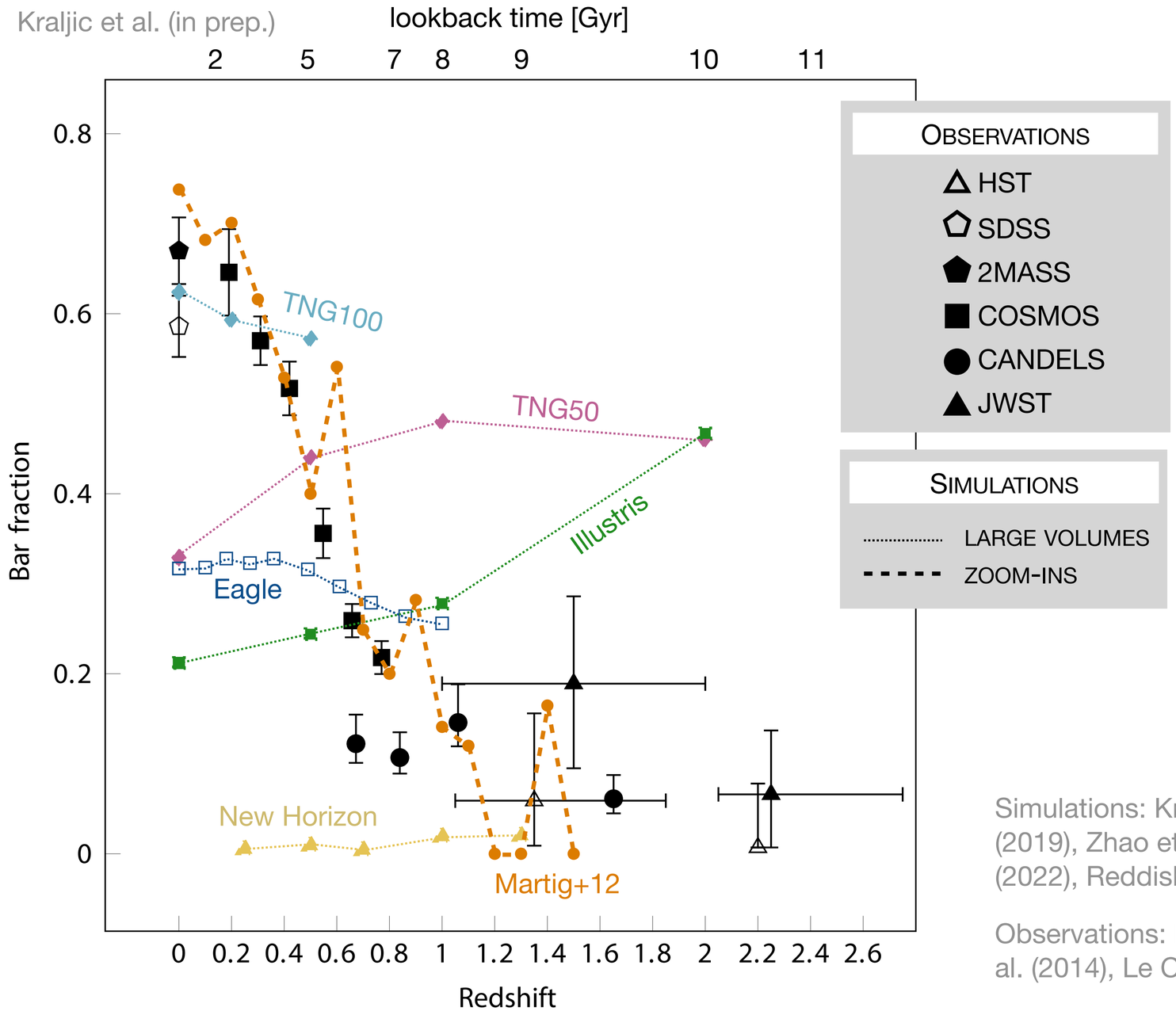

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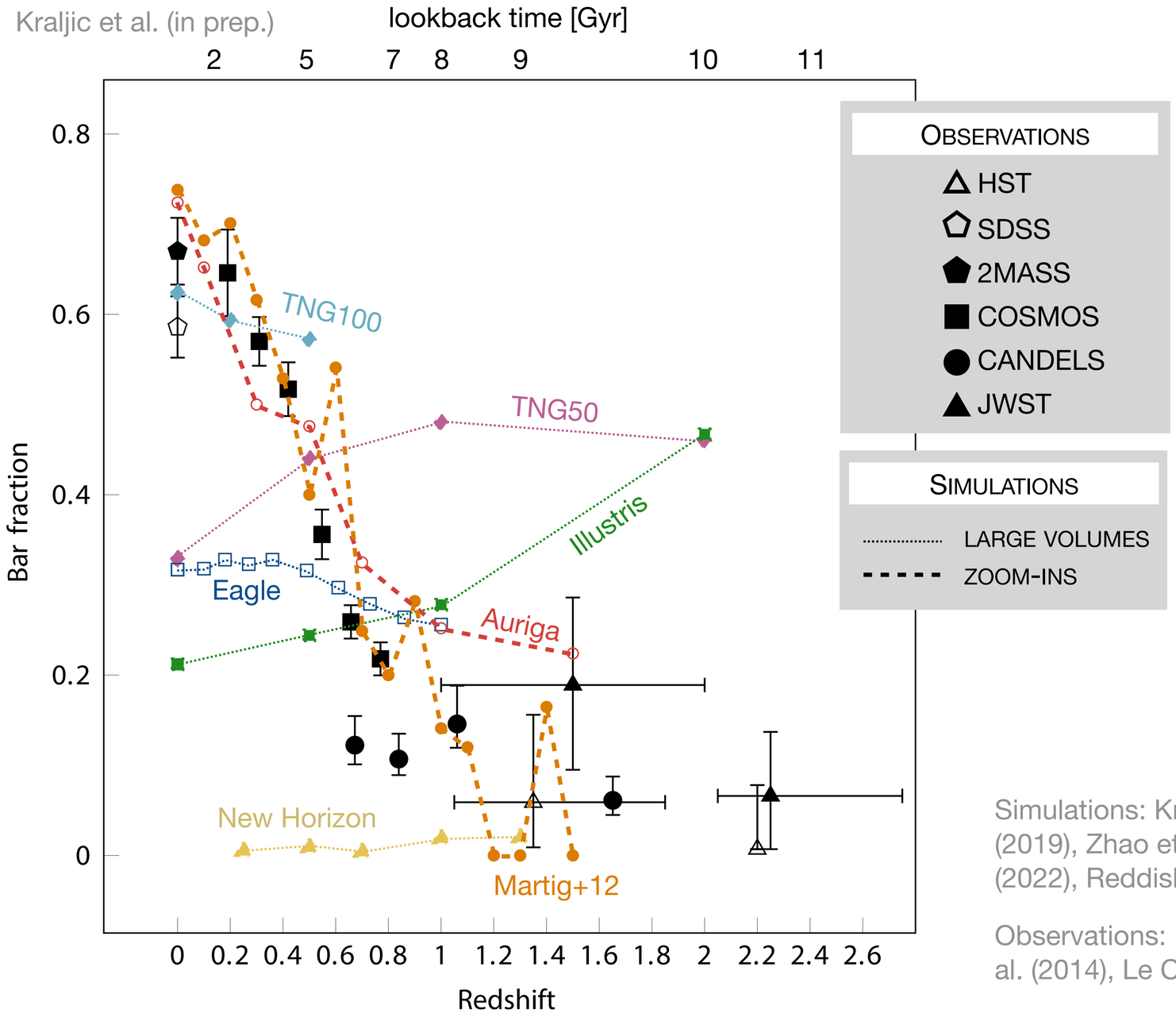

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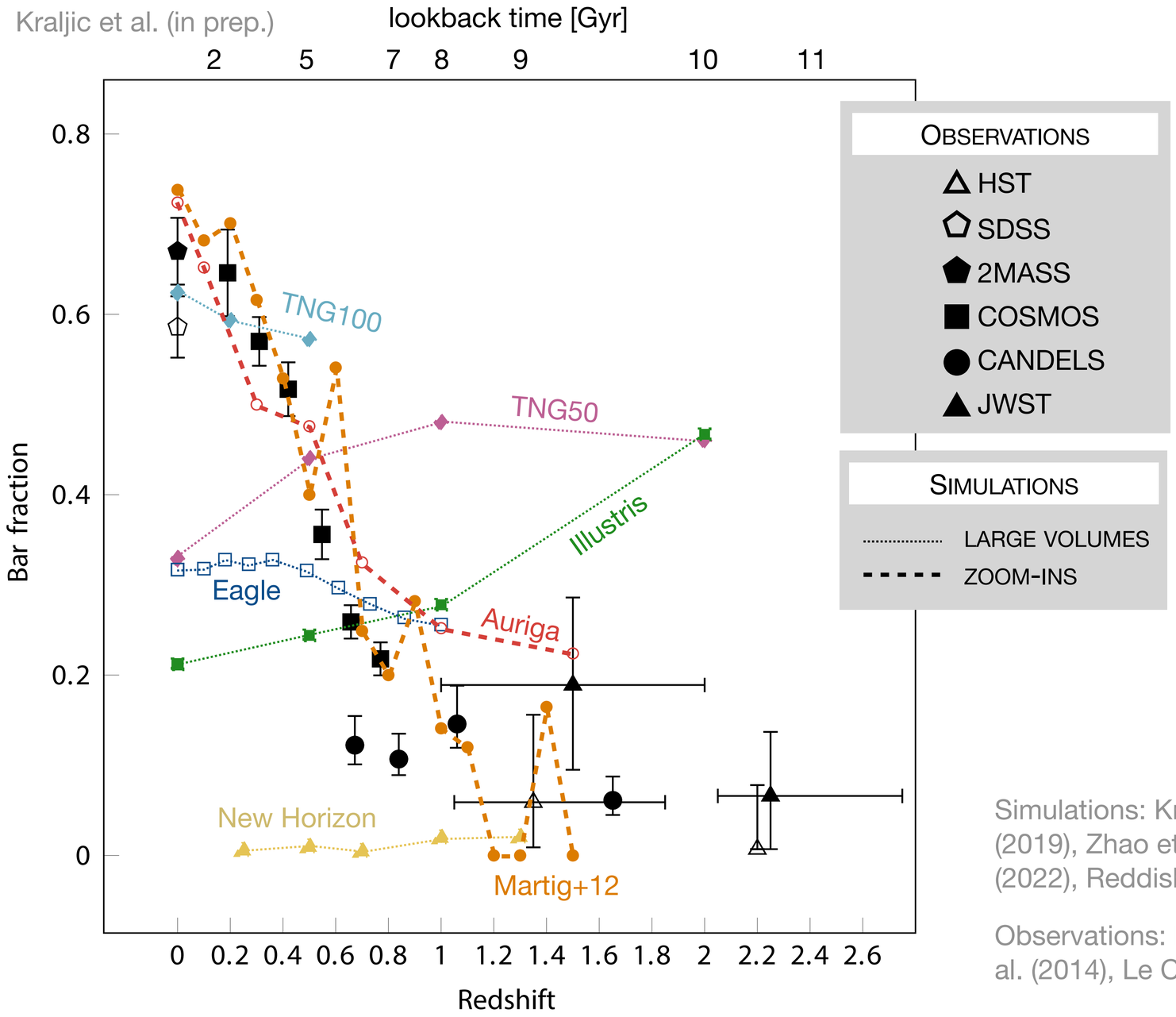

OBSERVATIONS
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- SDSS
- 2MASS
- COSMOS
- CANDELS
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SIMULATIONS
- LARGE VOLUMES
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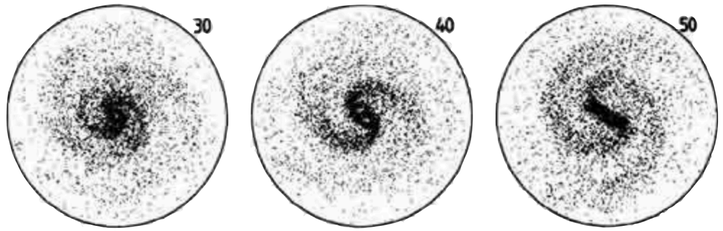

Sparke & Sellwood (1987)

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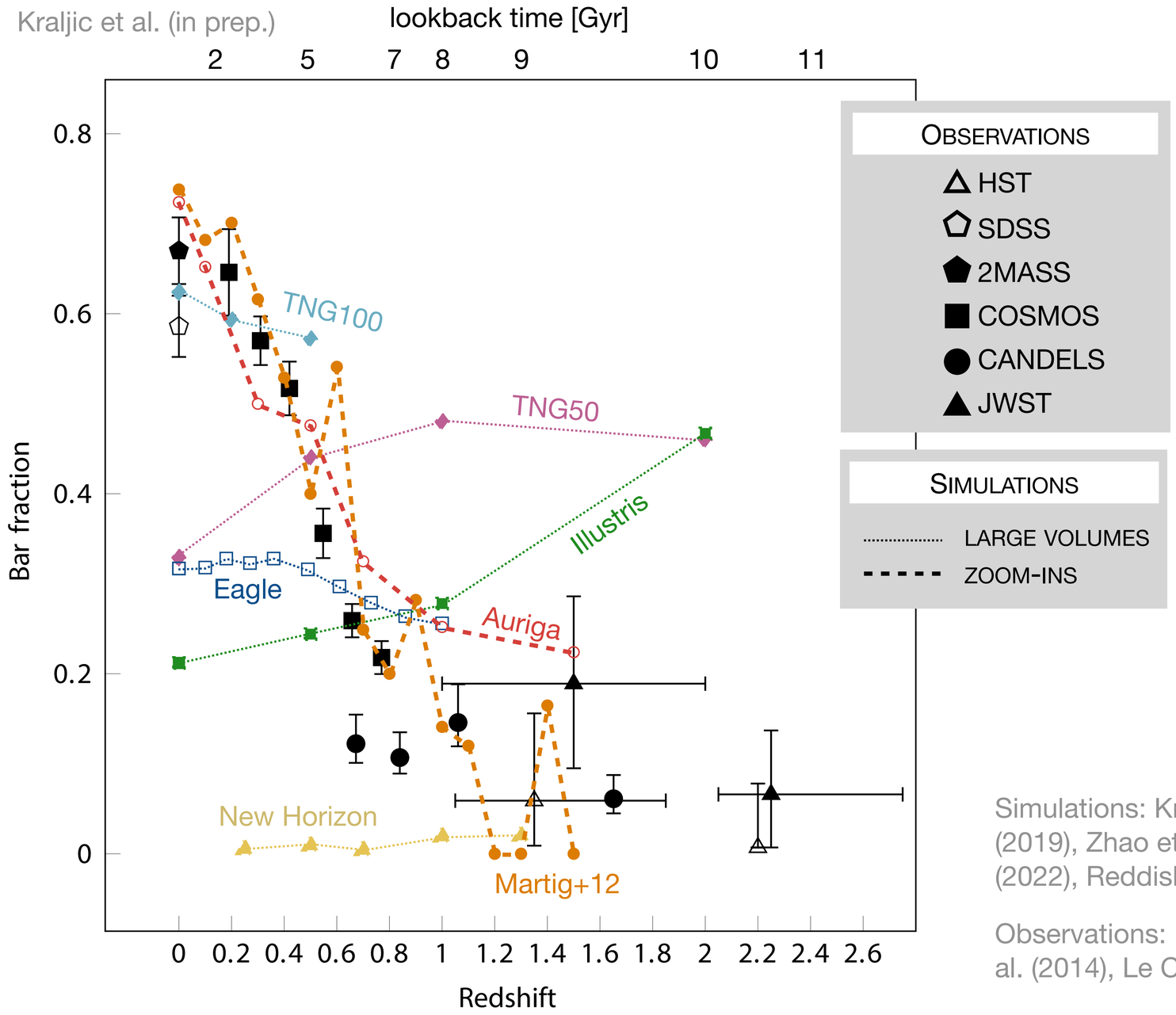

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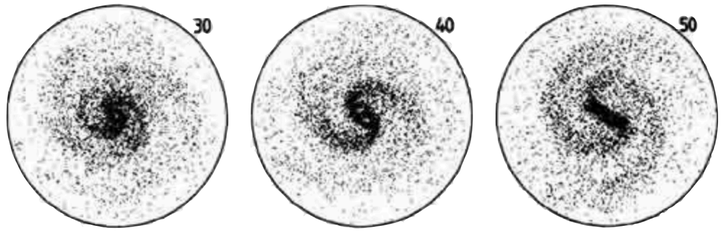

Sparke & Sellwood (1987)

Why do expensive cosmological simulations with complex physics fail at reproducing what the runs from the 80s did?

Simulations: Kraljic et al. (2012), Fragkoudi et al. (2020), Peschken et al. (2019), Zhao et al. (2020), Rosas-Guevara et al. (2022), Cavanagh et al. (2022), Reddish et al. (2022)

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DOES THE GAS FRACTION PLAY A ROLE?

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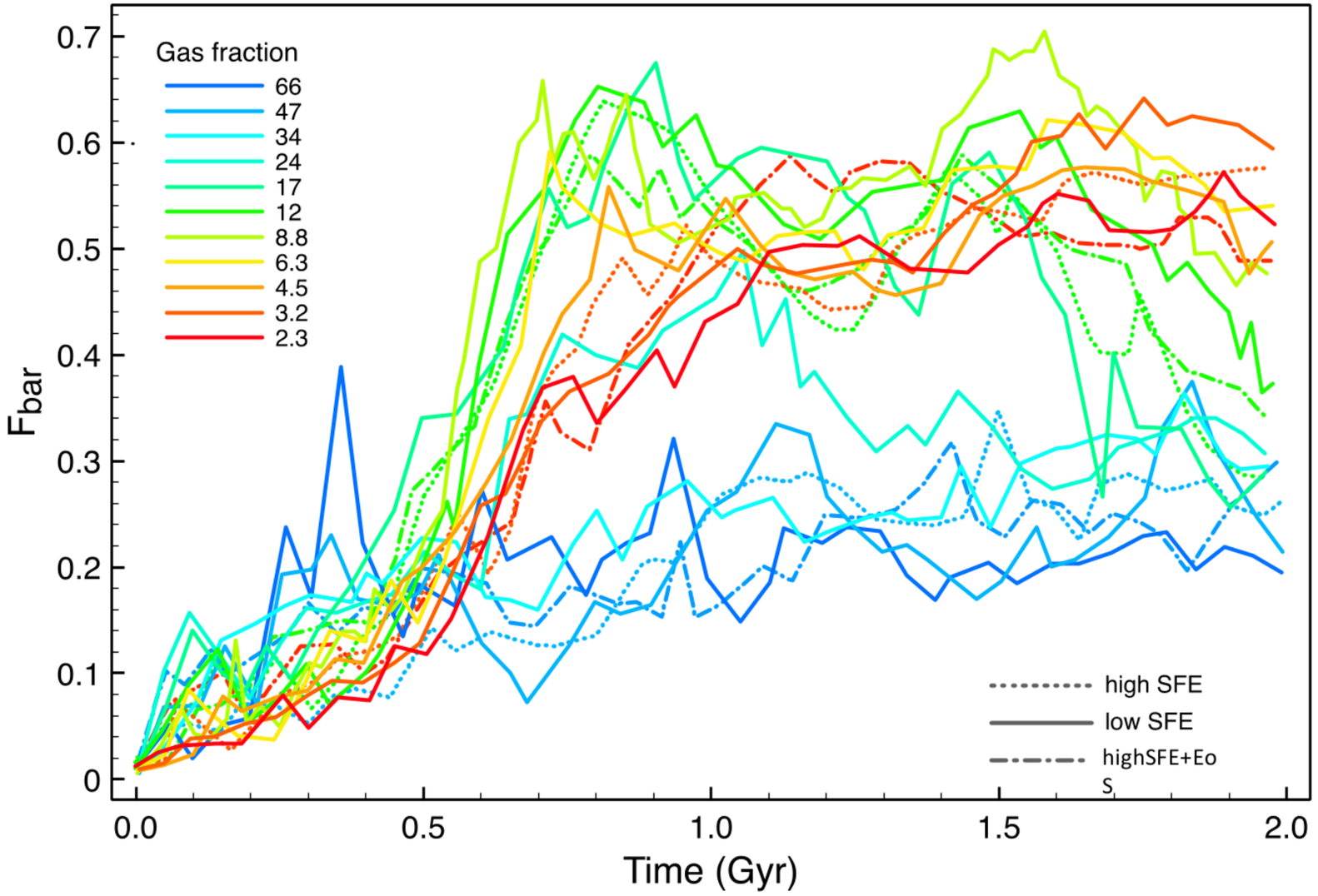
No continuous dependence on the gas fraction...

Bournaud (in prep.)



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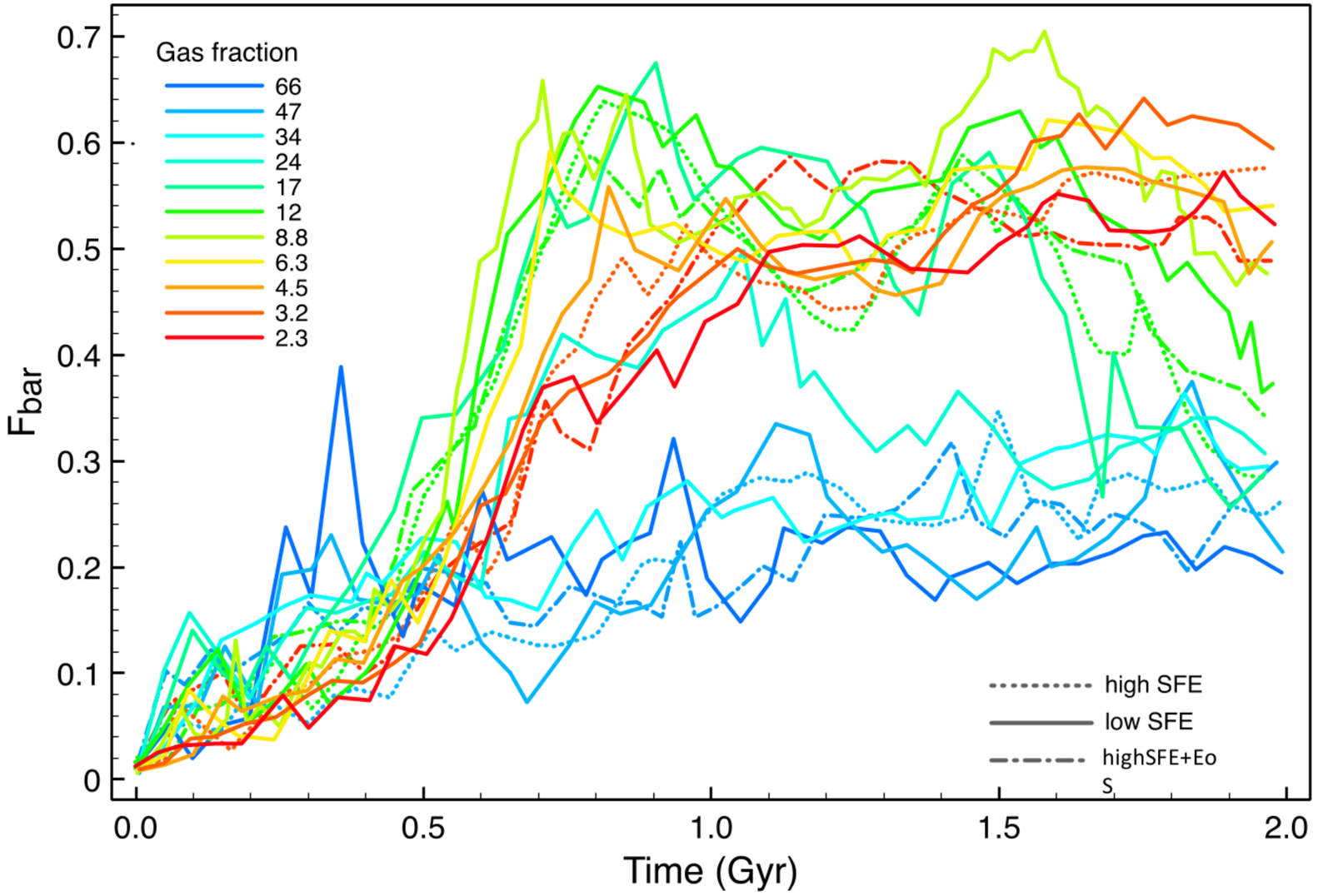

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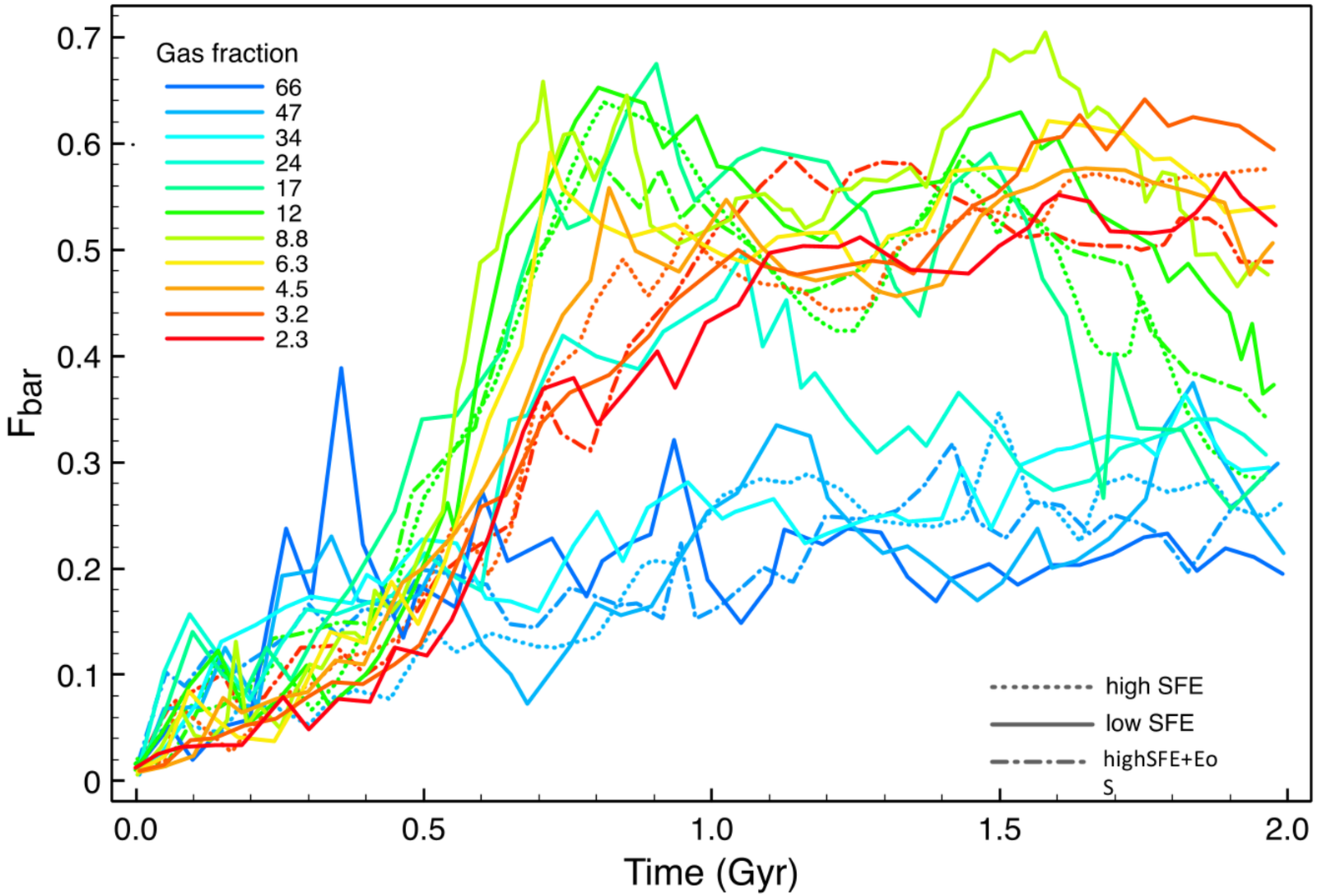

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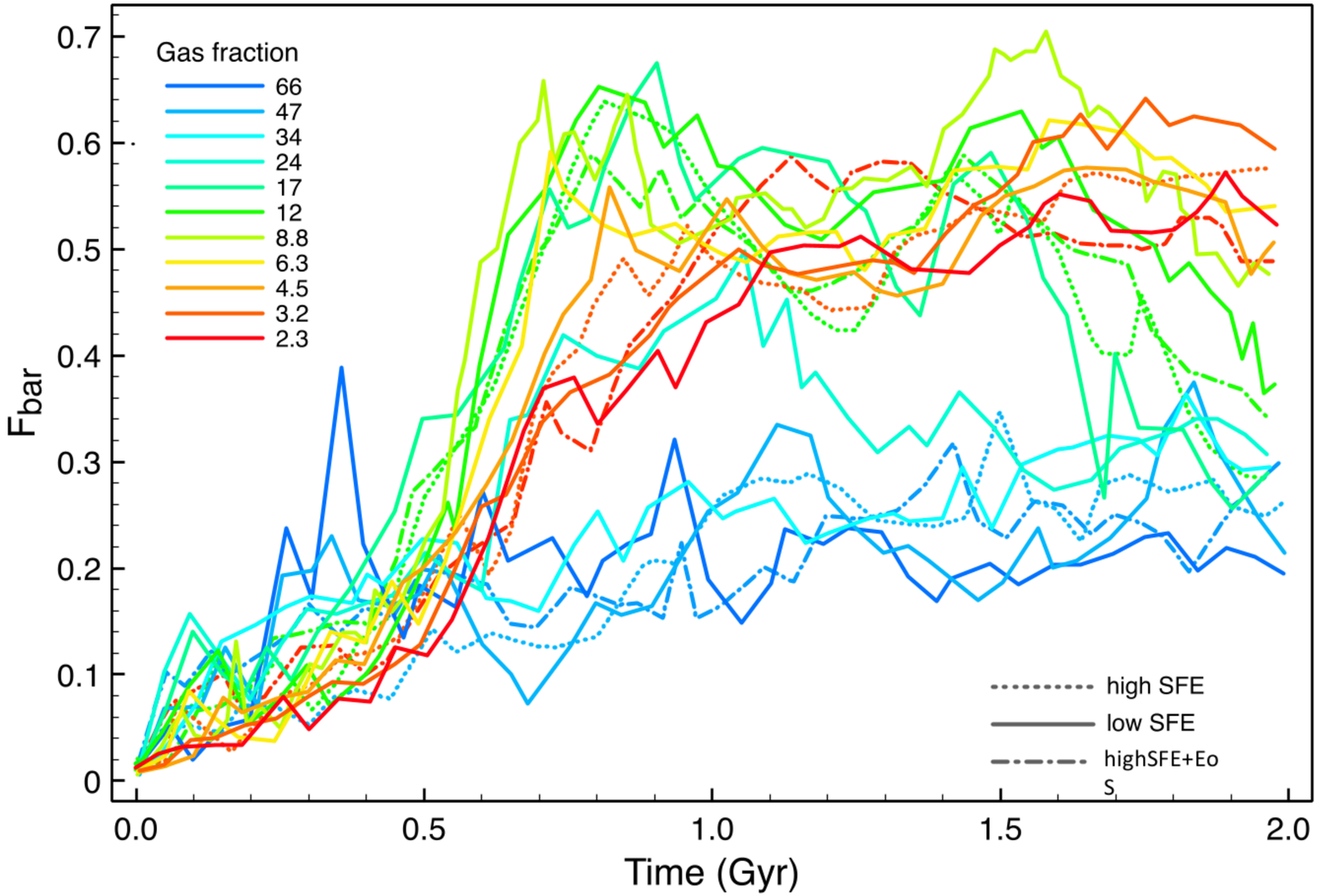
Role of internal dynamics
At which scale(s)?

Athanassoula et al. (2013), Verwilghen et al., (2024)

Bournaud (in prep.)



Conclusions

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Cosmic evolution of the "normal regime" of galaxy formation

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Star formation relations are driven by turbulence, which evolves with redshift

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Understanding bar formation is the next big challenge!