ASSESSING THE MOLECULAR GAS CONTENT OF GALAXIES TOWARDS THE COSMIC REIONIZATION EPOCH

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A2C2S | ALMA ALPINE [CII] Survey

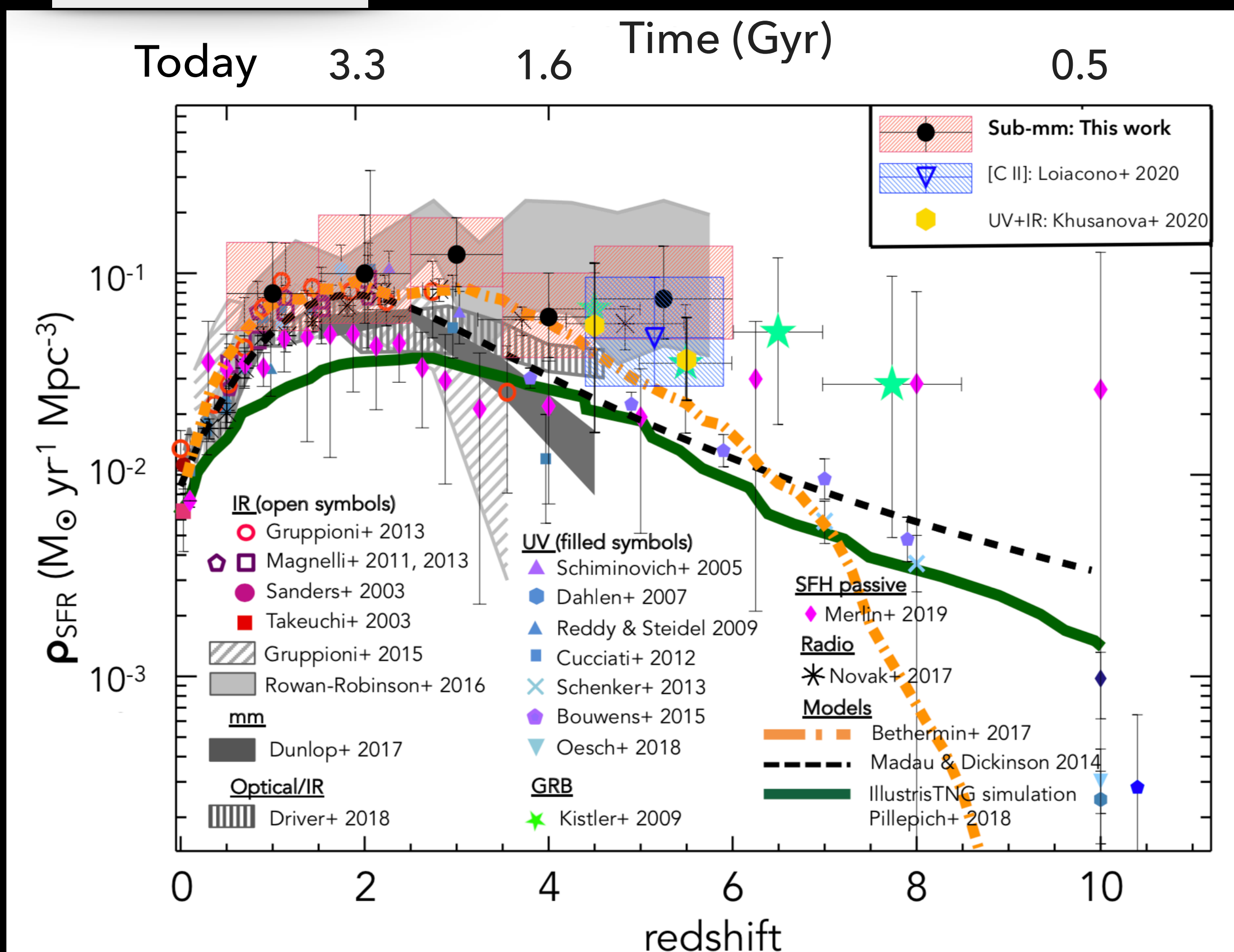
TWO FUNDAMENTAL PILLARS

TO UNDERSTAND THE GALAXY EVOLUTION

1 High star formation rates (SFR)

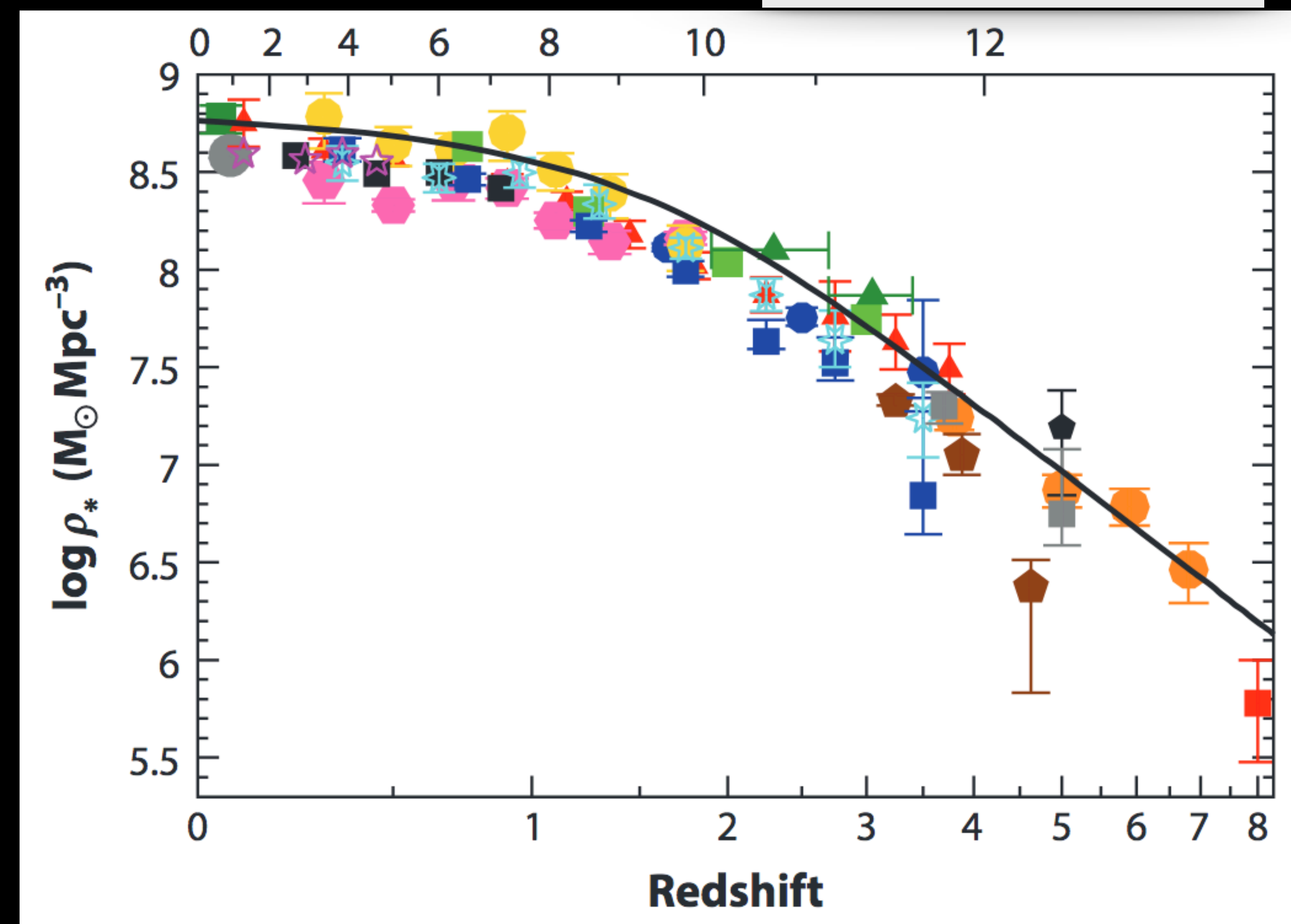
Galaxies at z~2 were experiencing much higher SFR than now.

SFR density



Gruppioni/w DZ+20

Stellar mass density



Madau&Dickinson+14

About half of all stellar mass is observed to be formed by z~1

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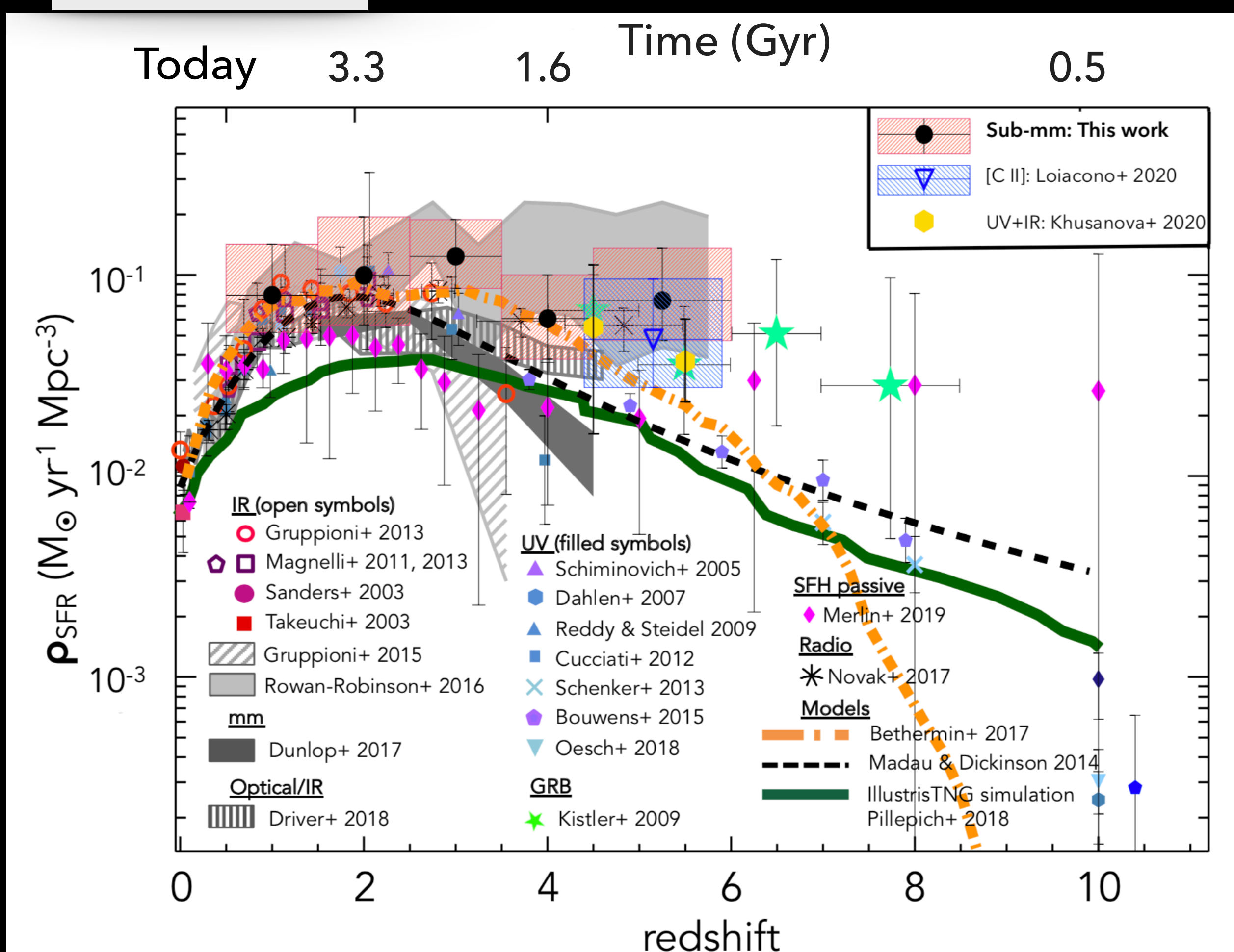
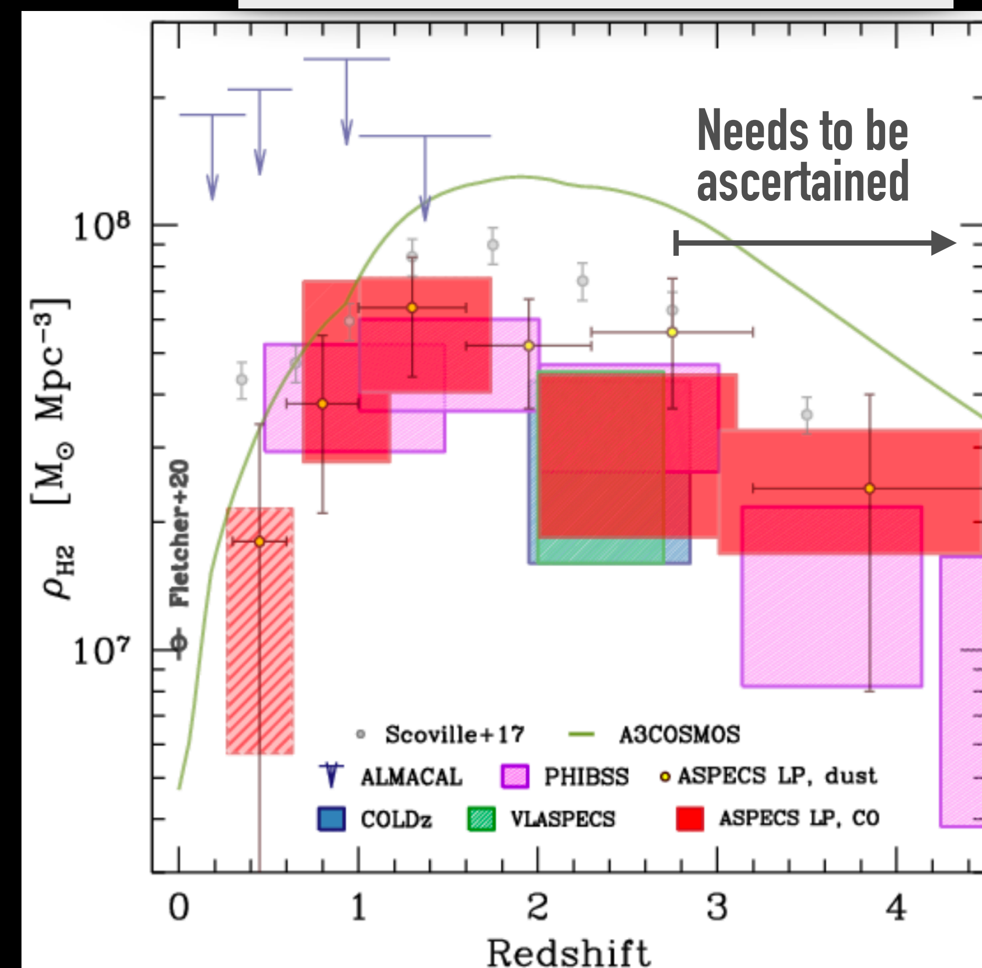


Gruppioni/w DZ+20

② Large molecular gas contents (M_{molgas})

The M_{molgas} density follows the SFR density evolution.

Molecular gas mass density



Decarli+19,20 (see also *Riechers+19*)

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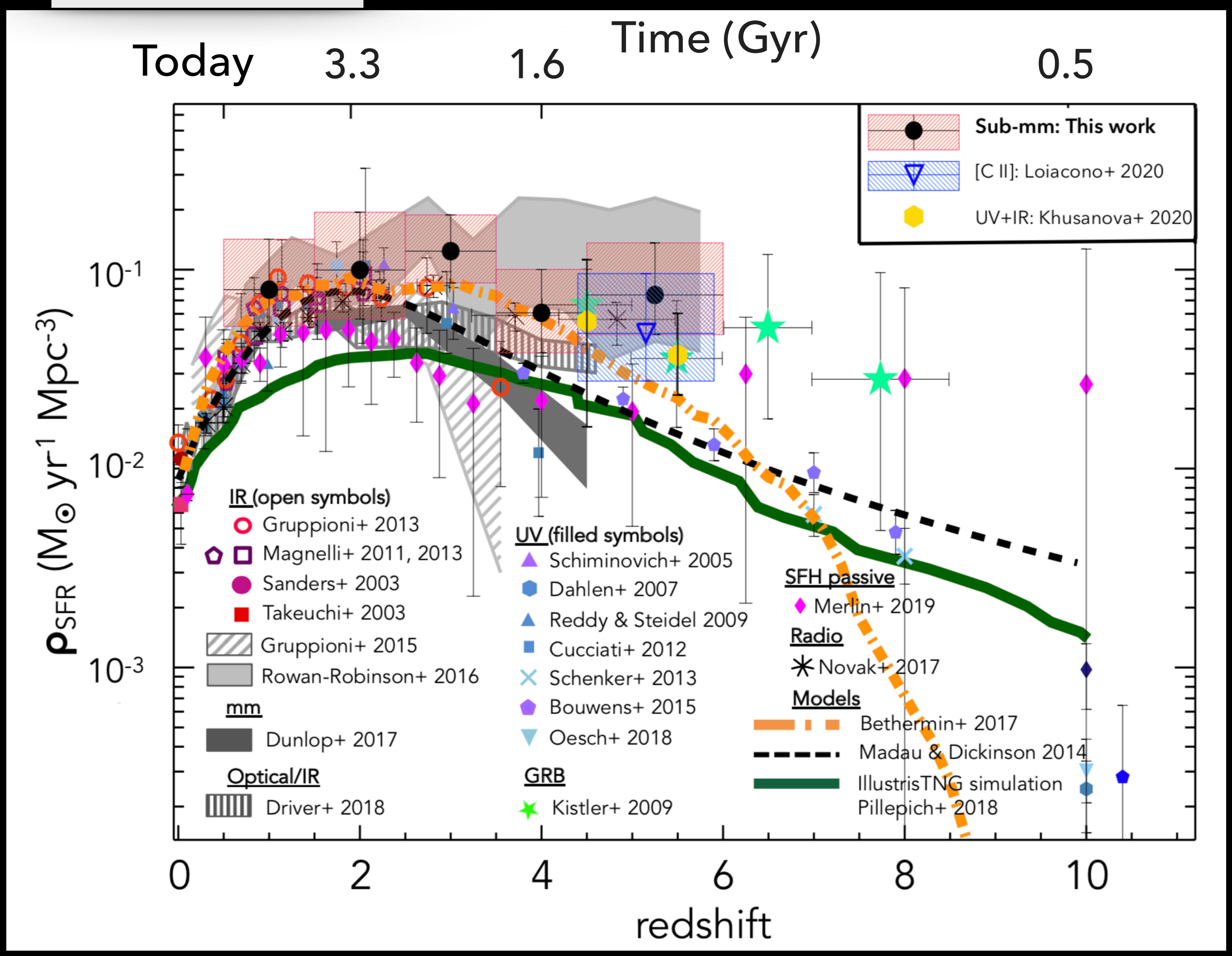

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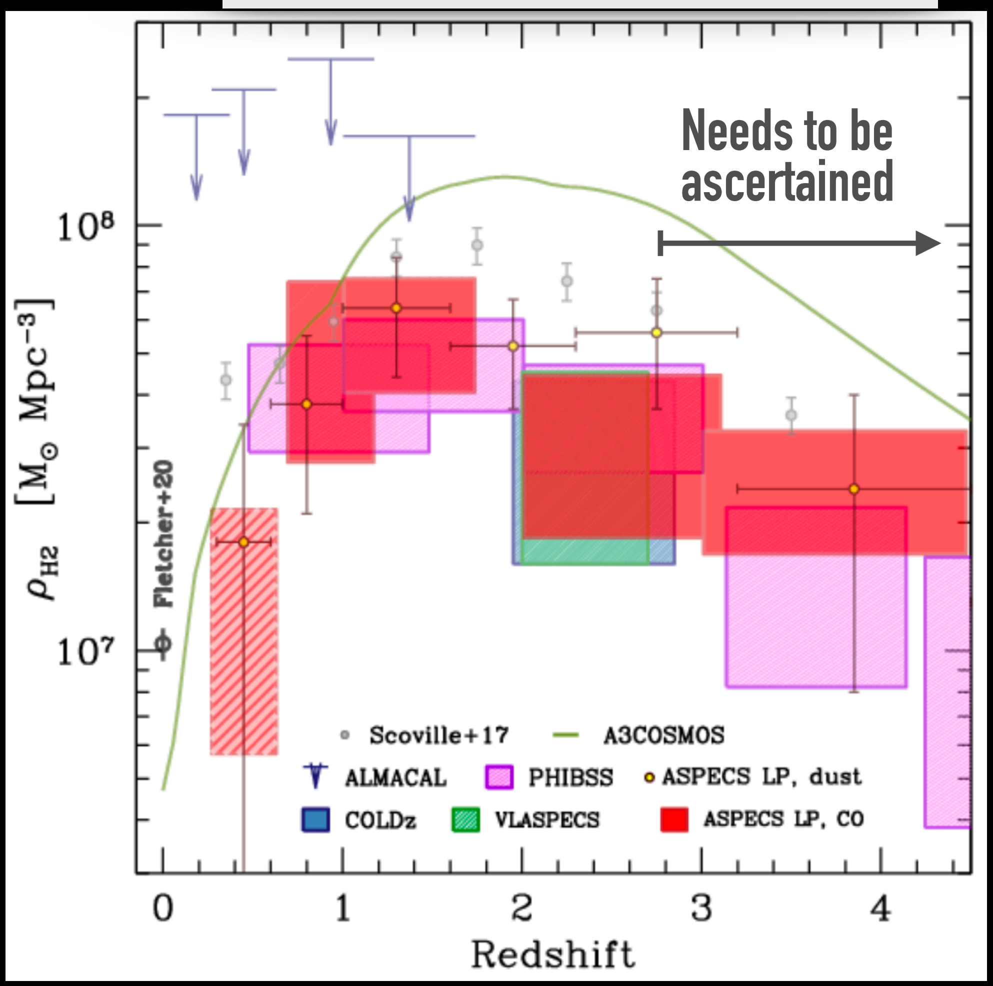


Decarli+19,20 (see also *Riechers+19*)

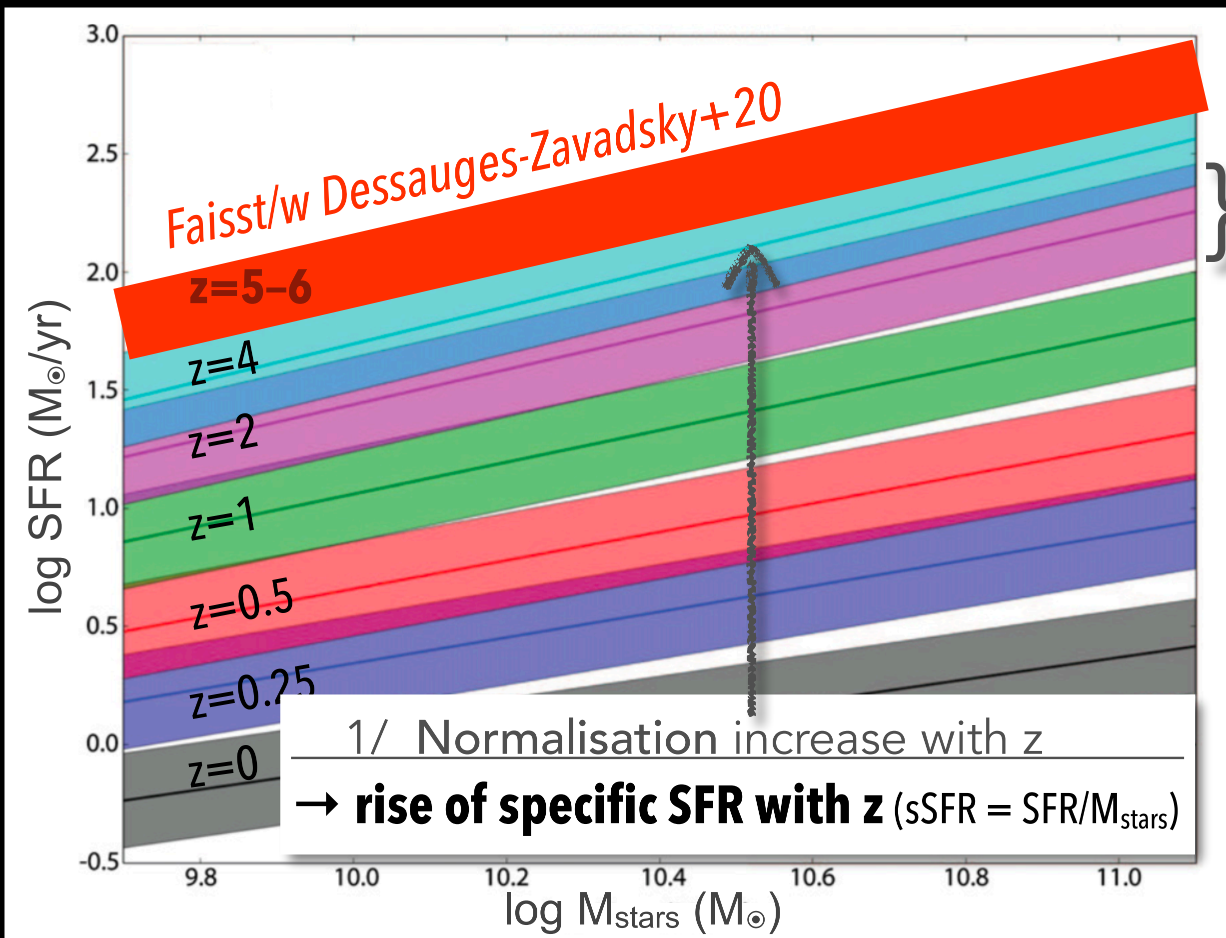
How galaxies assembled to acquire large gas reservoirs and induce high SFRs?

- **a high merger rate at high redshift** could drive quiescent galaxies into burst of star formation (e.g., *Bluck+09; Hammer+09; Man+12*)
- **a high cold gas accretion rate from the cosmic web** could lead to high gas densities and SFR (e.g., *Kereš+05; Dekel+09; Conselice+13*)

IMPORTANCE OF THE MAIN SEQUENCE

GALAXIES CONTRIBUTING TO 90% OF THE COSMIC SFR DENSITY RESIDE ON THE STAR-FORMING MAIN SEQUENCE (MS)

(e.g., *Daddi+07; Rodighiero+11; Whitaker+14; Speagle+14; Schreiber+15; Tasca+15; Faisst+16,20*)



1/ Normalisation increase with z

→ **rise of specific SFR with z** (sSFR = SFR/M_{stars})

Speagle+14

2/ Tight MS relation with a 0.3 dex dispersion

→ **continuous supply of gas from the cosmic web** rather than merger-induced gas supply

The MS is often interpreted in terms of **the "gas-regulated" model.**

3/ MS in place up to z~6

as recently shown with the **ALPINE*** sample (*Faisst/w DZ+20*)

→ **similar processes regulate star formation in galaxies over Gyr** to keep them on the MS

* The **A**LMA **L**arge **P**rogram to **IN**vestigate [CII] at **E**arly times survey (*Le Fèvre/w DZ+20; Béthermin/w DZ+20*)

measured [CII] 158 μm and far-IR continuum emission in **118 galaxies at 4.5<z<6** with multi-wavelength observations

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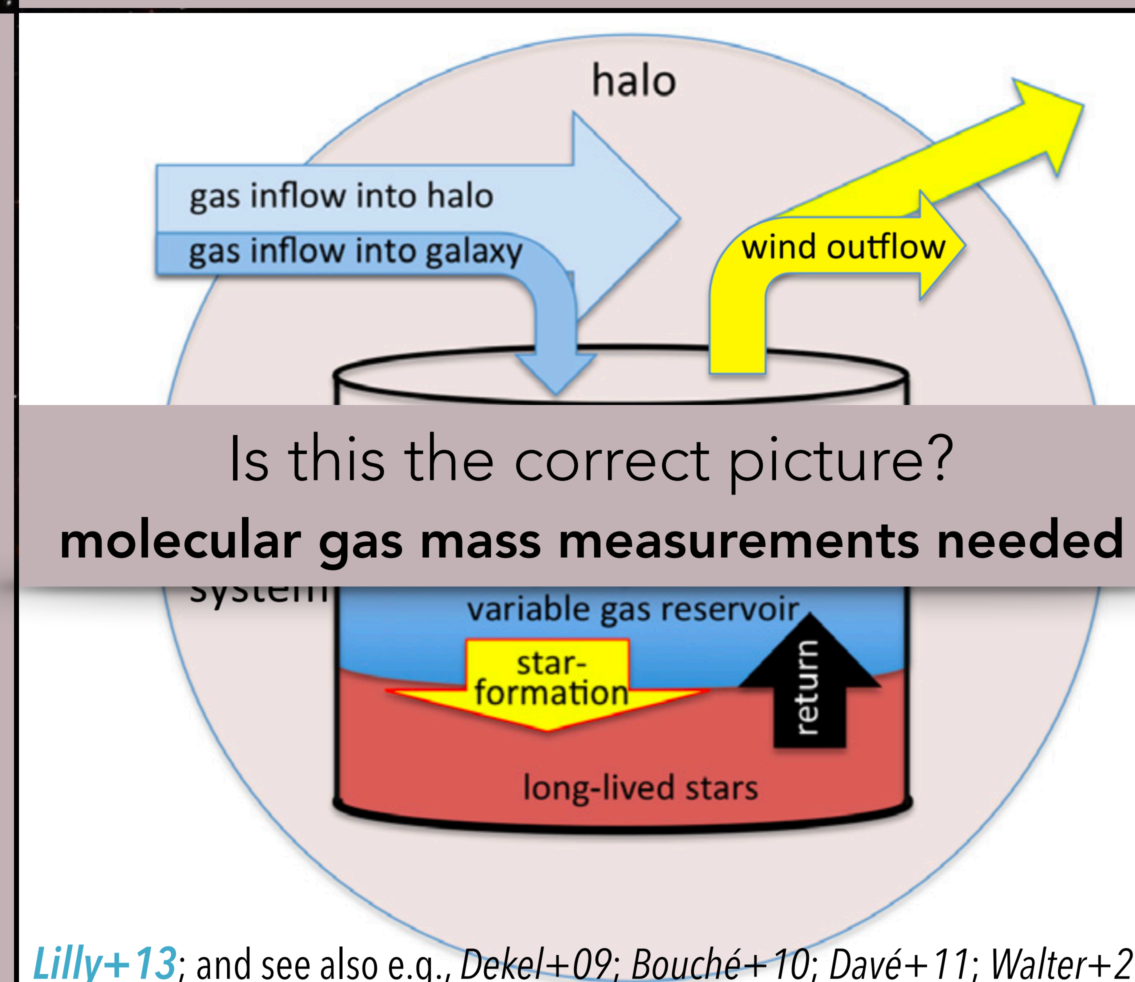
Credit: ESO/L. Calada/ESA/AOES Medialab

MS galaxies lie in a quasi-steady state equilibrium whereby star formation is **regulated by the available gas reservoir** replenished through gas accretion inflows.

GAS-REGULATED MODEL



Is this the correct picture?

molecular gas mass measurements needed

Lilly+13; and see also e.g., *Dekel+09*; *Bouché+10*; *Davé+11*; *Walter+20*

THE ROLE OF MOLECULAR GAS

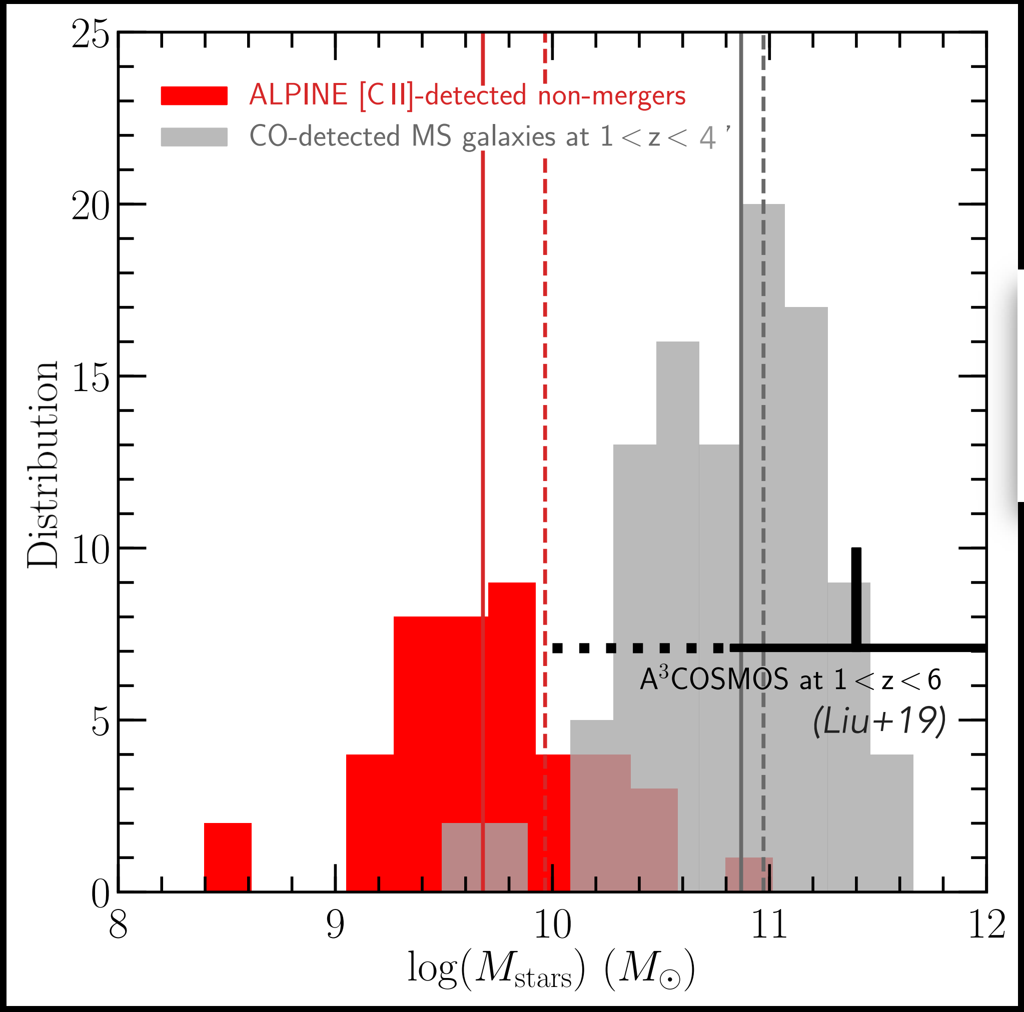
MOLECULAR GAS MASS CENSUS ACROSS COSMIC TIME

Three common tracers of **cold H_2 gas:**

✦ **CO rotational transitions at mm/submm** (*Bolatto+13*, references therein)
✦ **dust mass from the thermal FIR SED** (*Magdis+11*; *Santini+14*; *Kaasinen +19*)
✦ **cold dust emission in the Rayleigh-Jeans tail of the FIR SED** (*Scoville+14,16,17*)

PdBI/NOEMA + ALMA assembled the molecular gas mass census from z=0 to z~4-6
(e.g., *Daddi+10*; *Genzel+10,15*; *Tacconi+13,18*; *Saintonge+13,17*; *Dessauges-Zavadsky+15,17*; *Schinnerer+16*; *Scoville+16,17*; *Liu+19*)

Biased toward massive/luminous galaxies and against z>4 galaxies
because of surface brightness dimming as $(1+z)^4$, low-*J* CO transitions inaccessible at mm wavelengths, and lower metallicities making CO dark and dust rare



Dessauges-Zavadsky+20

CO-detected MS galaxies at 1<z<4: median $\log(M_{\rm stars}) = 10.9$ (*my literature compilation*)
Dust continuum-detected galaxies at 1<z<6: median $\log(M_{\rm stars}) = 11.5$ (*Liu+19*)
→ **At z>4.5:** very few molecular gas mass measurements for MS galaxies

To remedy to these biases:

44 MS galaxies at 4.5<z<6 with a median $\log(M_{\rm stars})=9.8$ from the ALPINE non-merger sample
using other H_2 gas tracers:

- fine-structure [CII] 158 μm line
  (*Hughes+17*; *Zanella+18*; *Madden+20*)
- dynamical masses (for resolved galaxies)

A2C2S | ALMA ALPINE [CII] Survey

PARENTHESIS: [CII] LUMINOSITY

AS A MOLECULAR GAS MASS TRACER

The [CII] emission is complex, different ISM phases – ionised, neutral, and molecular – are contributing to it.

CII may arise from PDR regions

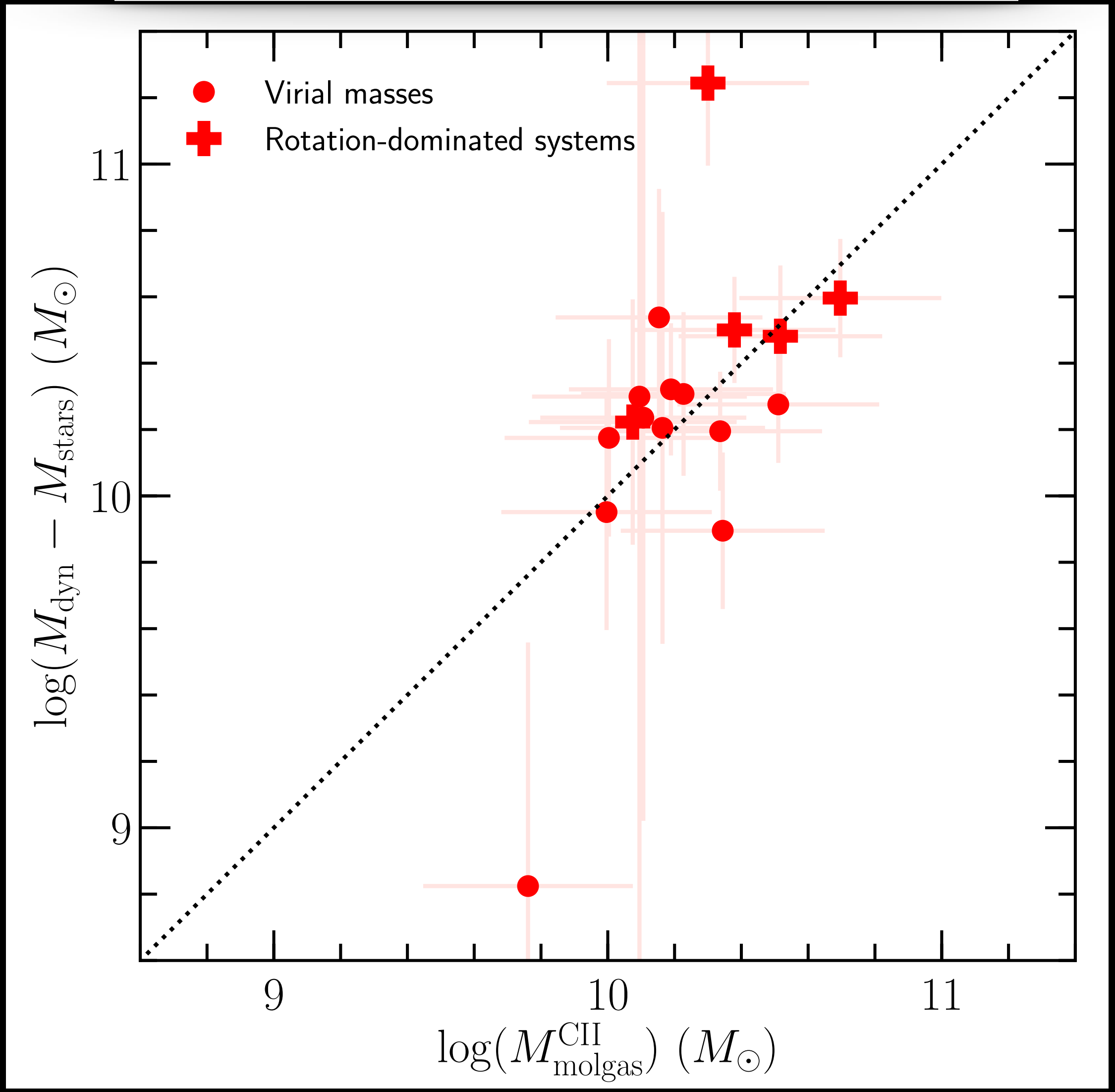
→ $L_{[CII]}$ extensively studied as an SFR tracer (e.g., *De Looze+11,14; Schaerer/w DZ+20*)

CII may arise from the CO photodissociation into C and C+

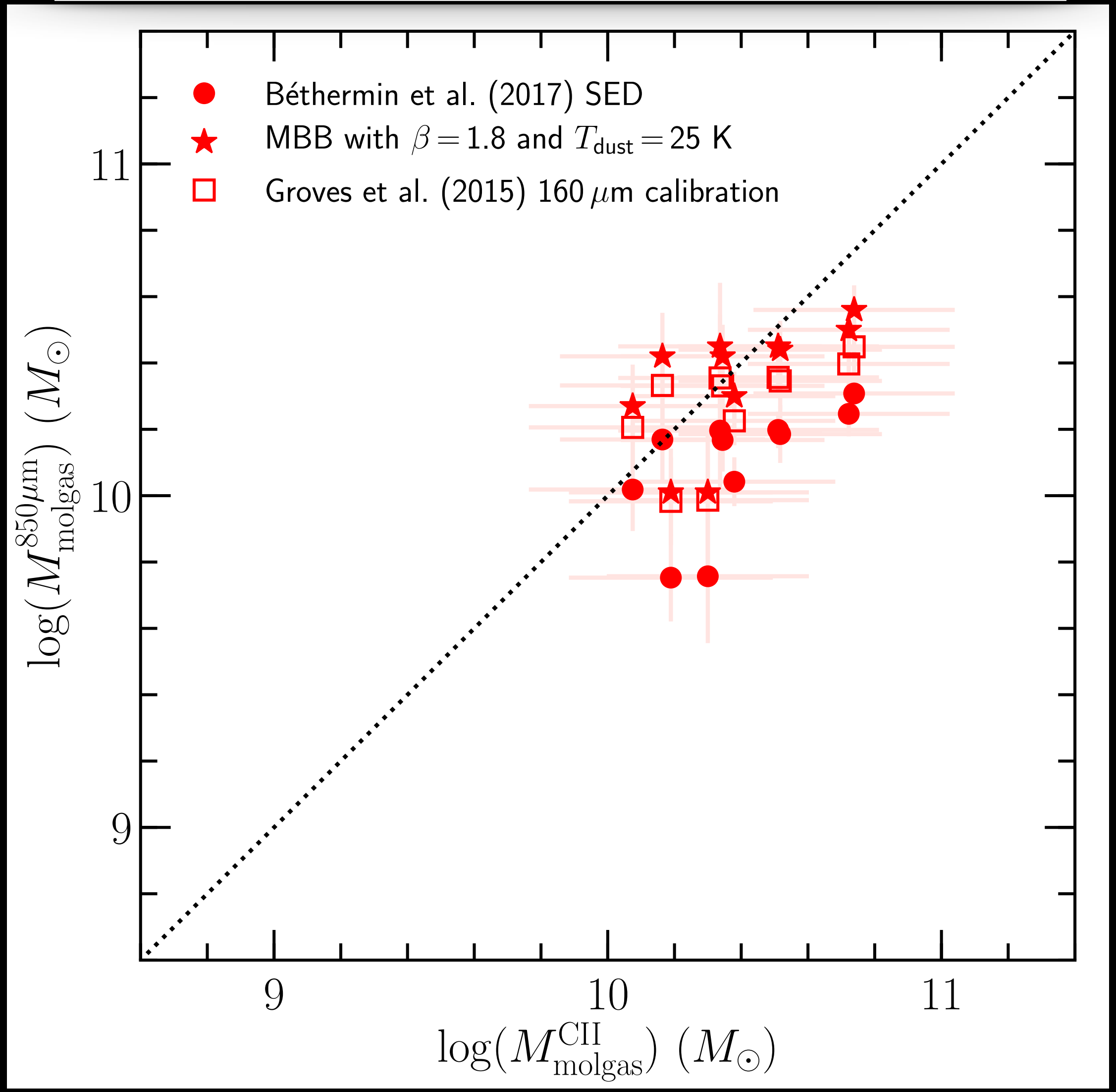
→ $L_{[CII]}$ examined as a molecular gas mass tracer (*Hughes+17; Zanella+18; Madden+20*)

For the ALPINE galaxies at 4.5<z<6:
we find **a good agreement** between molecular gas masses estimated with different H_2 tracers

$L_{[CII]}$ tracer vs dynamical mass tracer

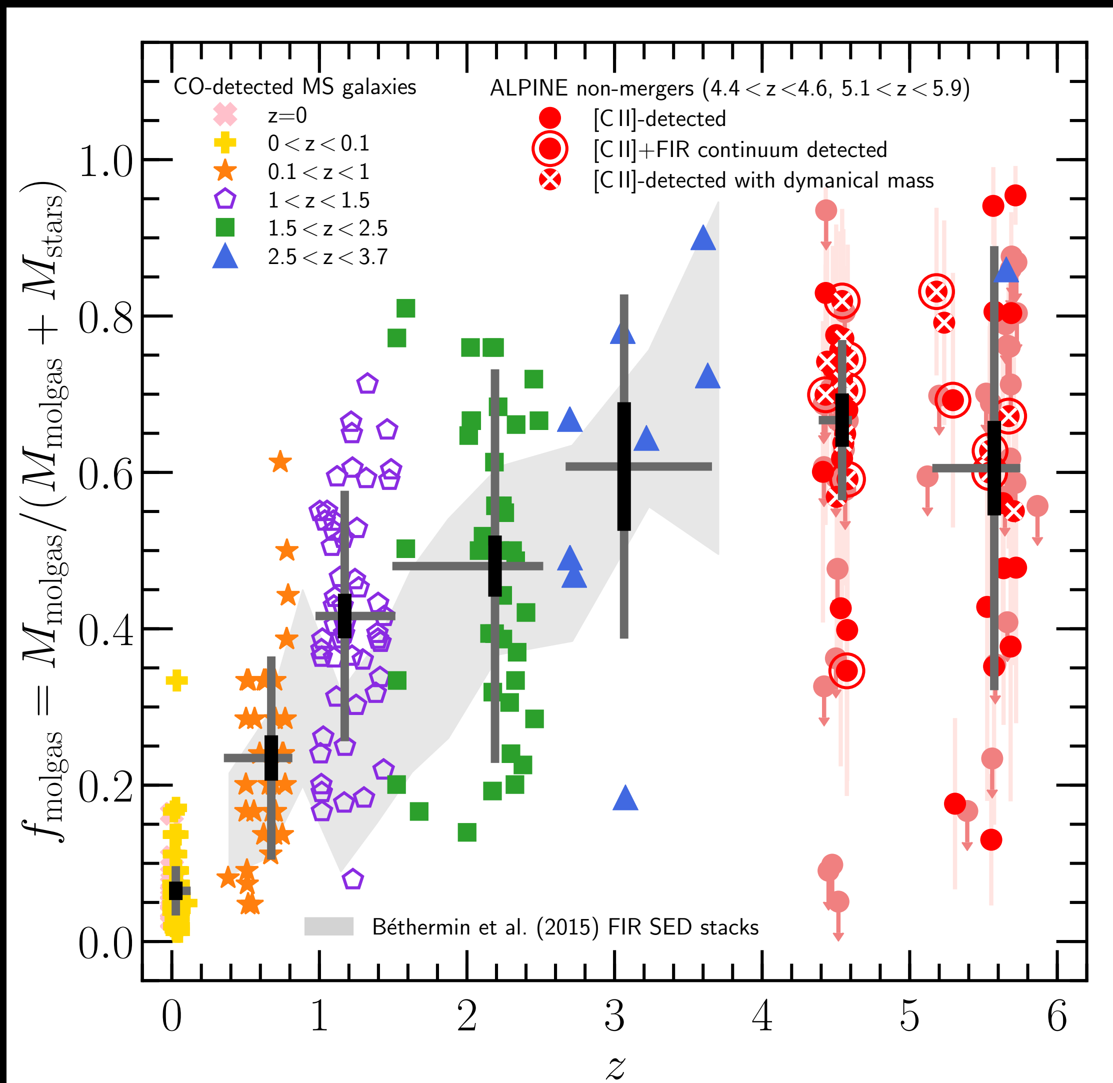


$L_{[CII]}$ tracer vs FIR dust continuum tracer



THE ROLE OF MOLECULAR GAS

MOLECULAR GAS FRACTION EVOLUTION ACROSS COSMIC TIME

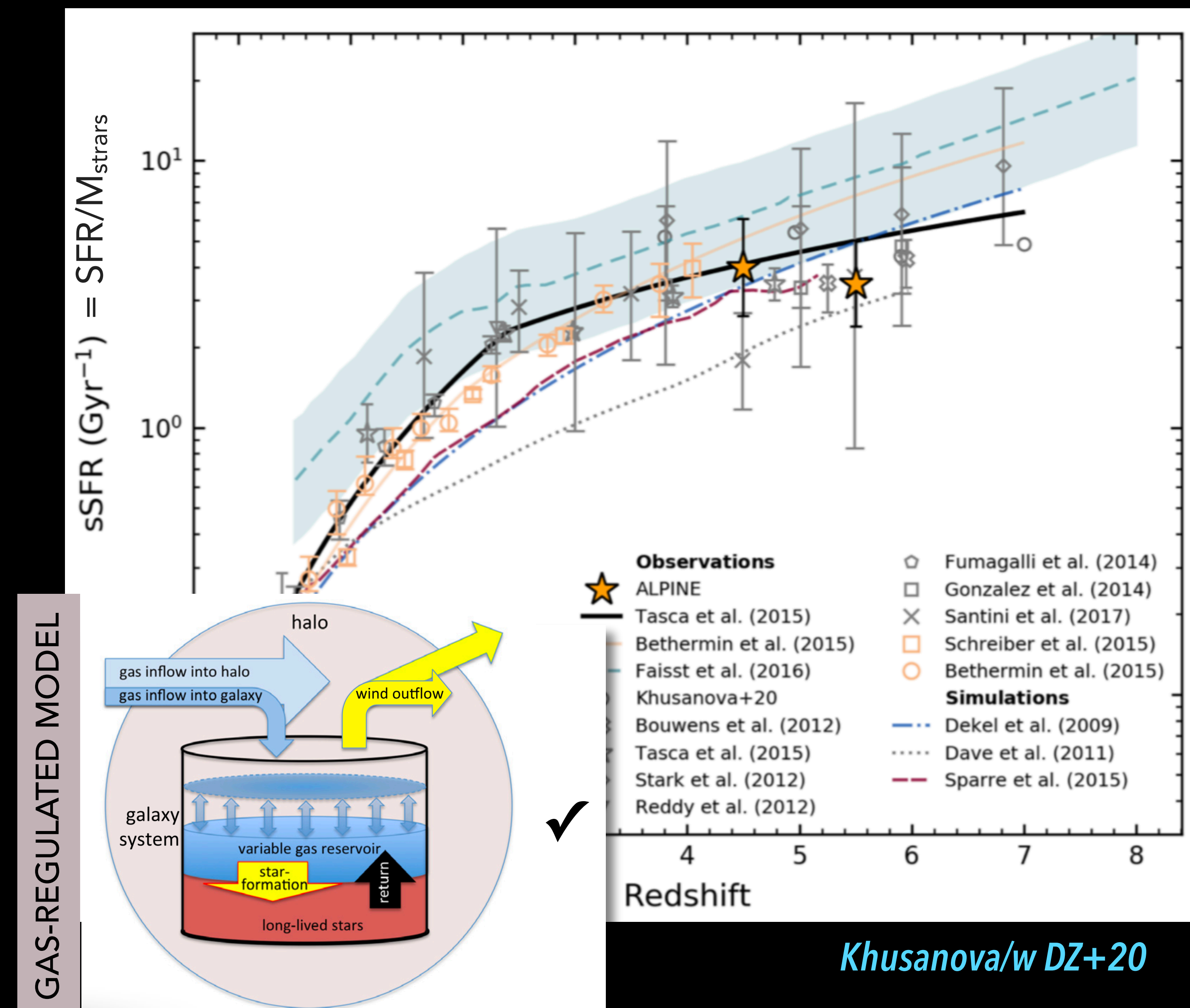


Dessauges-Zavadsky+20

The molecular gas fraction steeply rises with redshift to flatten off above *z*~3.5 and reach a mean value of **63% ± 3% at 4.5<z<6**.

→ **large gas reservoirs were present at z=6** to fuel the rapid increase in SFR and stellar build-up

The molecular gas fraction evolution perfectly matches the specific SFR (sSFR) evolution up to z~6.



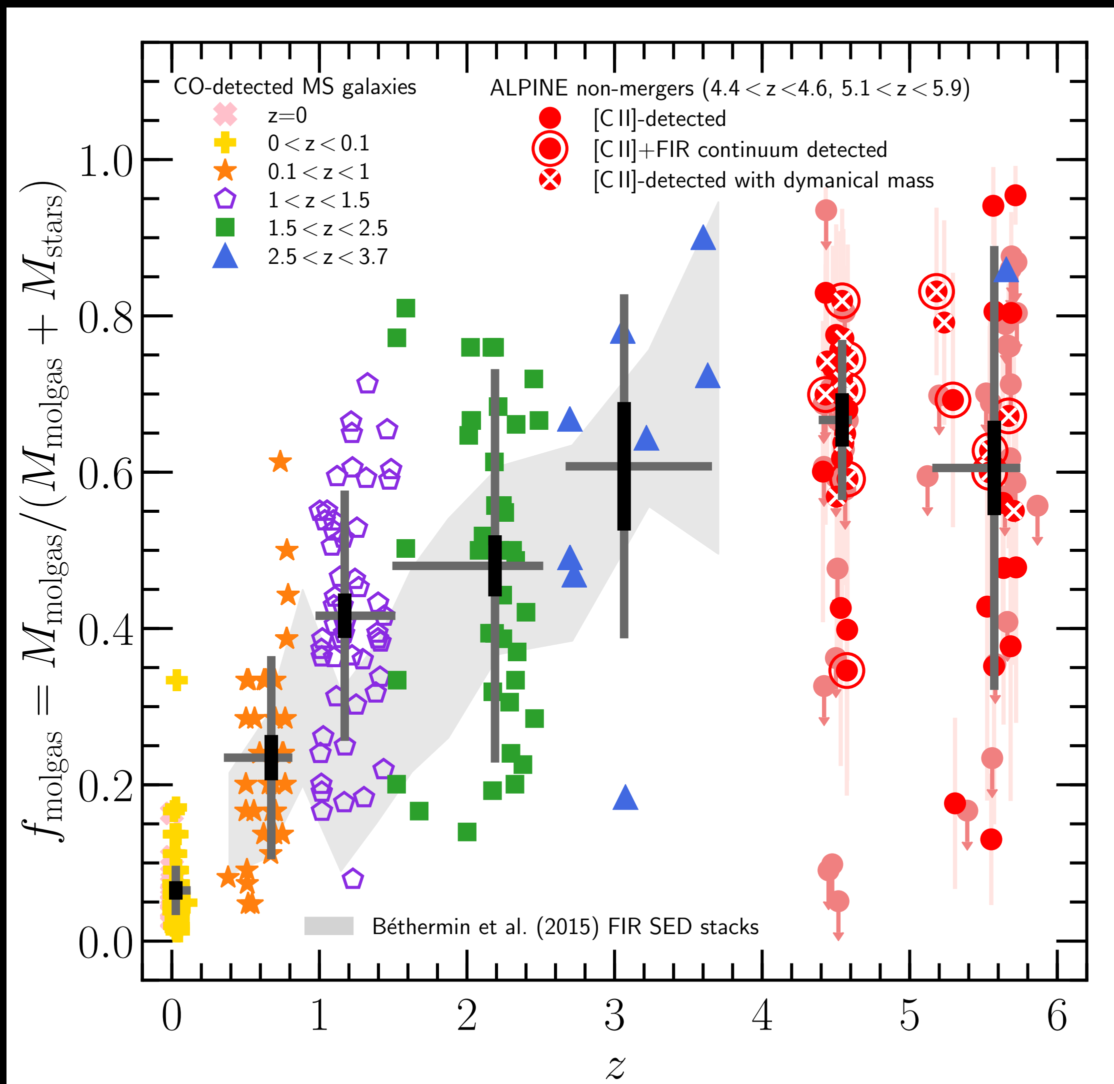
Khusanova/w DZ+20

The link between the gas fraction and sSFR evolutions results from **the interplay between cosmic inflow and gas consumption rates, modulo outflows**, as expected in the framework of the gas-regulated model.

Only when the molecular gas consumption rate catches up the inflow rate, the molecular gas fraction drops toward z=0.

THE ROLE OF MOLECULAR GAS

GAS CONSUMPTION RATE EVOLUTION ACROSS COSMIC TIME



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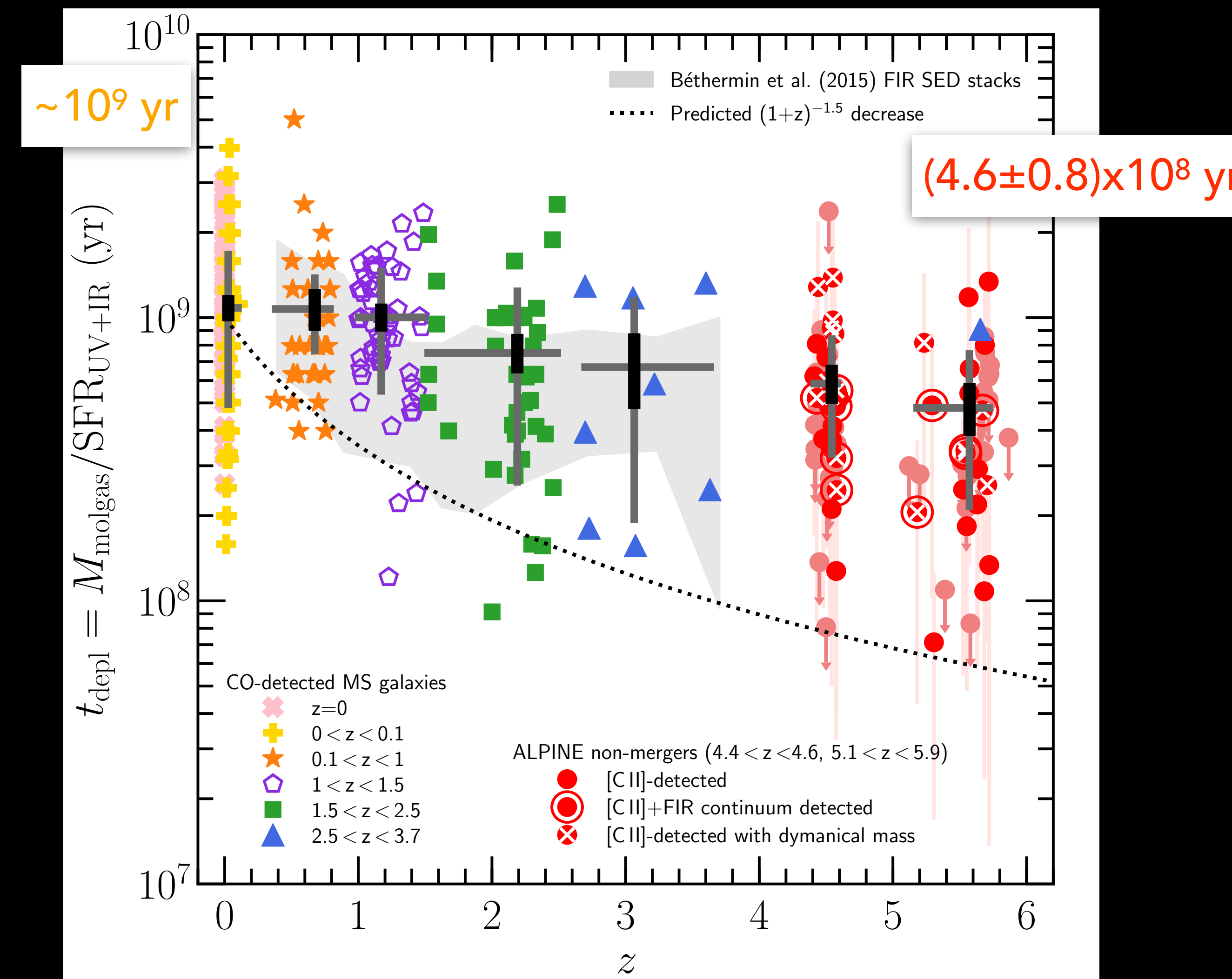

Shallow gas consumption timescale decrease with redshift, with **2–3x shorter values at 4.5<z<6** than in present-day galaxies.

→ **the star formation is inefficient (quiescent)**

→ MS galaxies are continuously supplied in gas to sustain the high SFR for several Gyr

→ the large $M_{\rm molgas}$ is the main driver of the sSFR increase with z

THE ROLE OF MOLECULAR GAS

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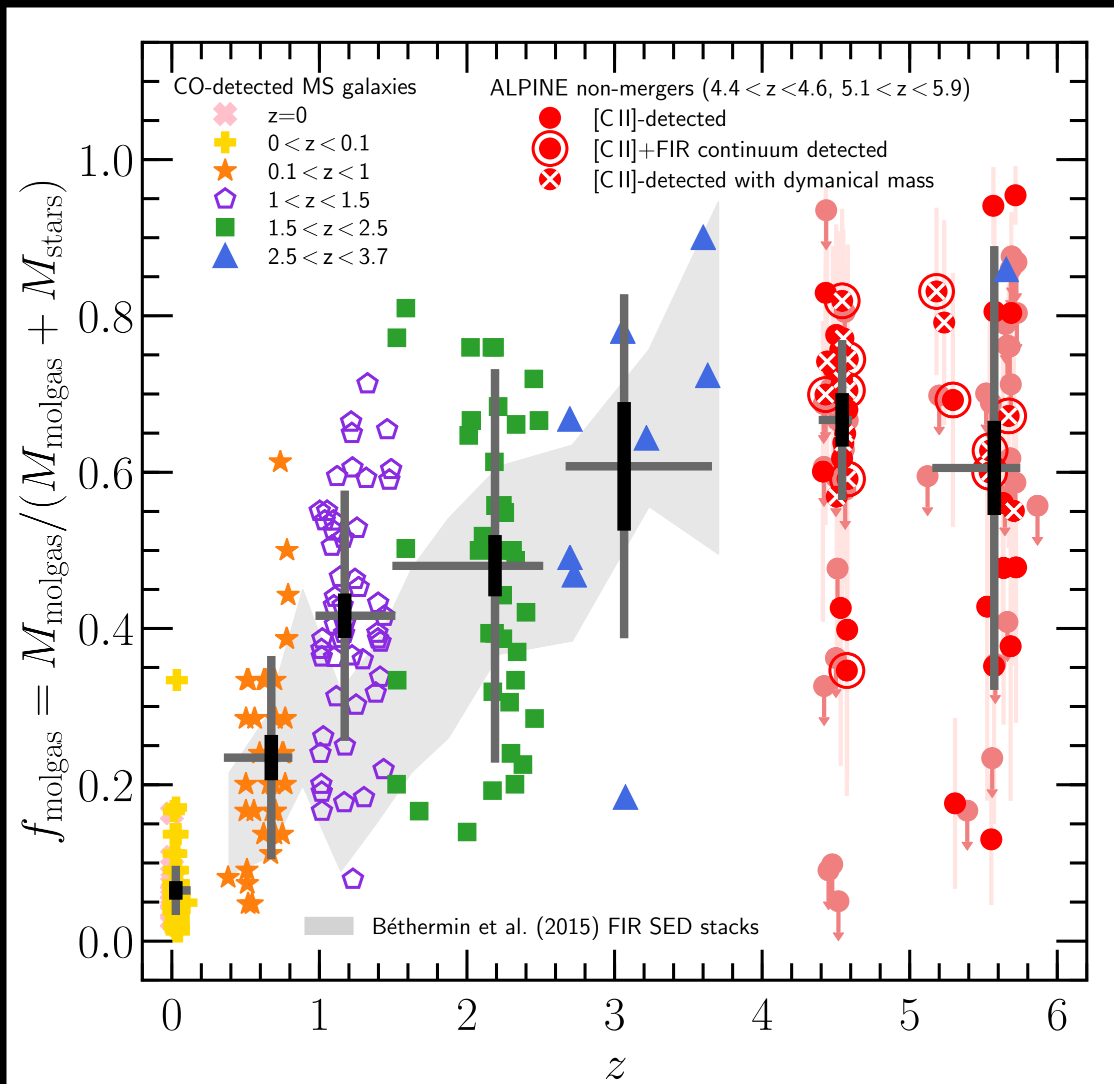

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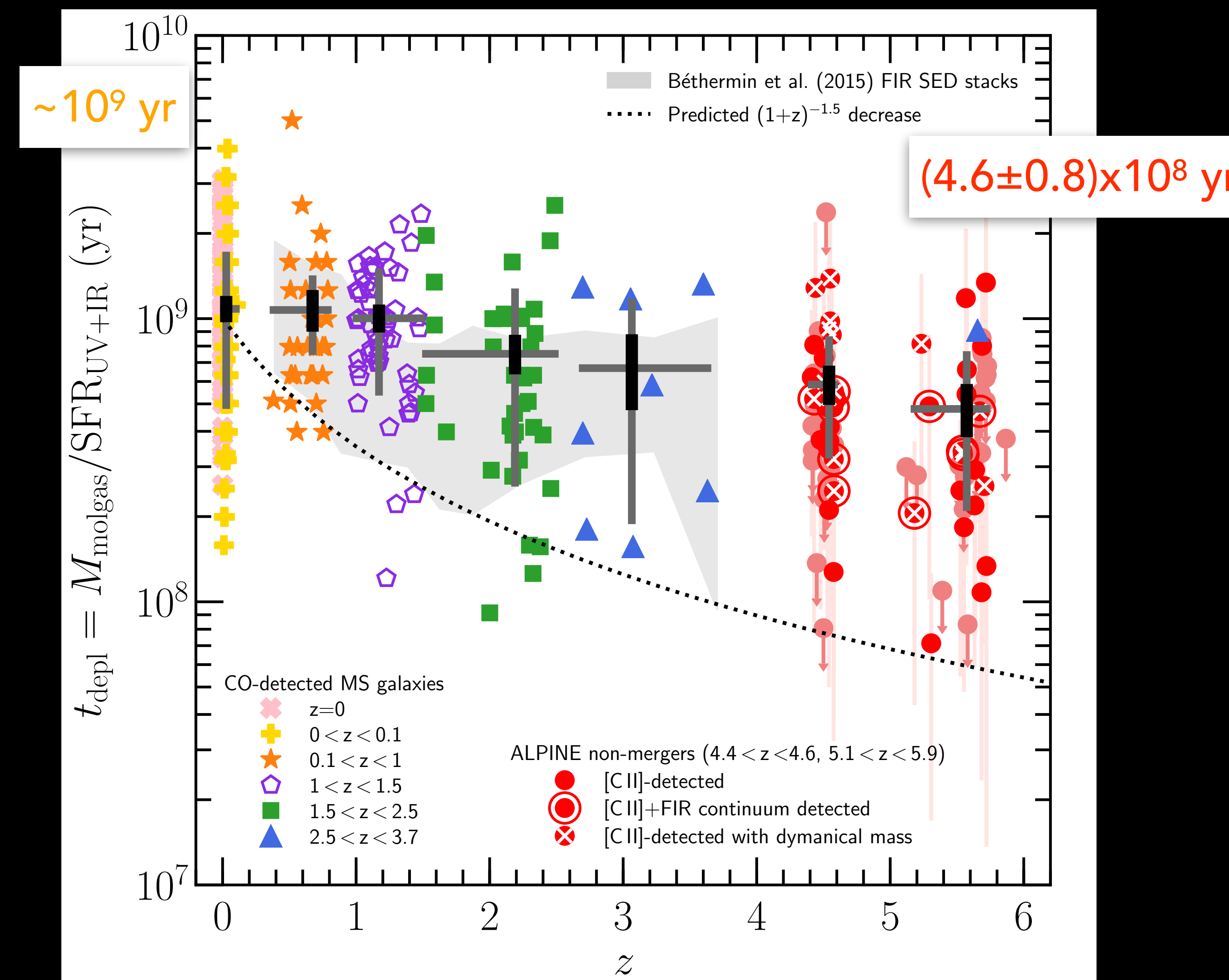

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The large scatter observed in both the molecular gas fraction and gas consumption rate at all redshifts results from the multi-functional dependence on the galaxy offset from MS, $M_{\rm stars}$, and SFR; and also from **the mix of evolutions of different galaxy populations**.

MOLECULAR GAS EVOLUTION

FOLLOWING SPECIFIC GALAXY POPULATIONS SELECTED WITH ABUNDANCE MATCHING

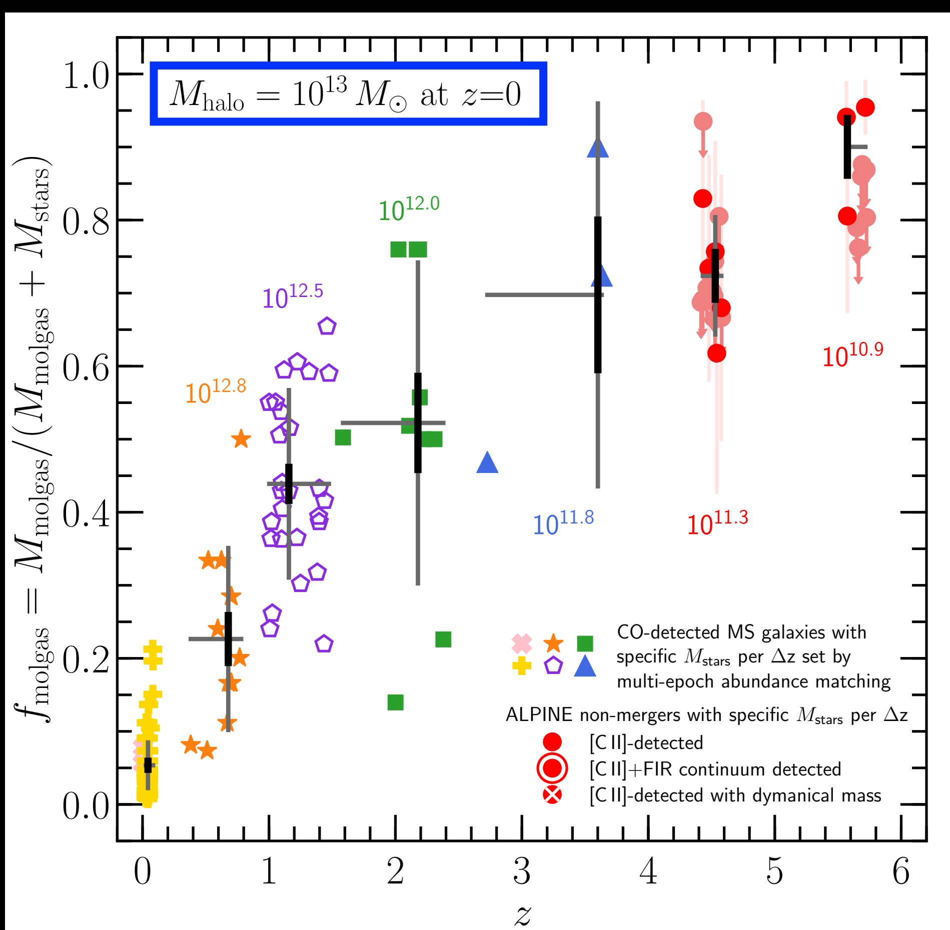
ALPINE galaxies appear to be the progenitors at 4.5<z<6 of

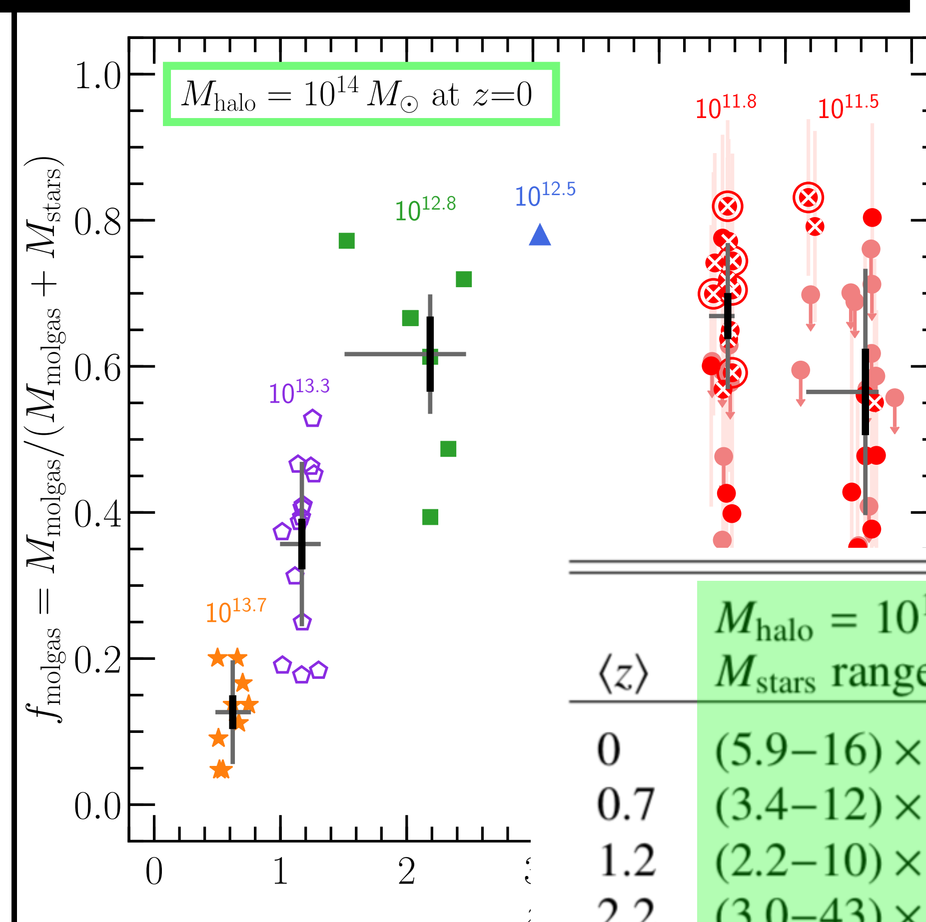
Milky Way-like galaxies in 10^{13} $M_\odot$ halos with $M_{stars} = 10^{7.5}$–$10^{9.1}$ $M_\odot$ at z=5.5

→ monotonic molecular gas fraction decrease with cosmic time

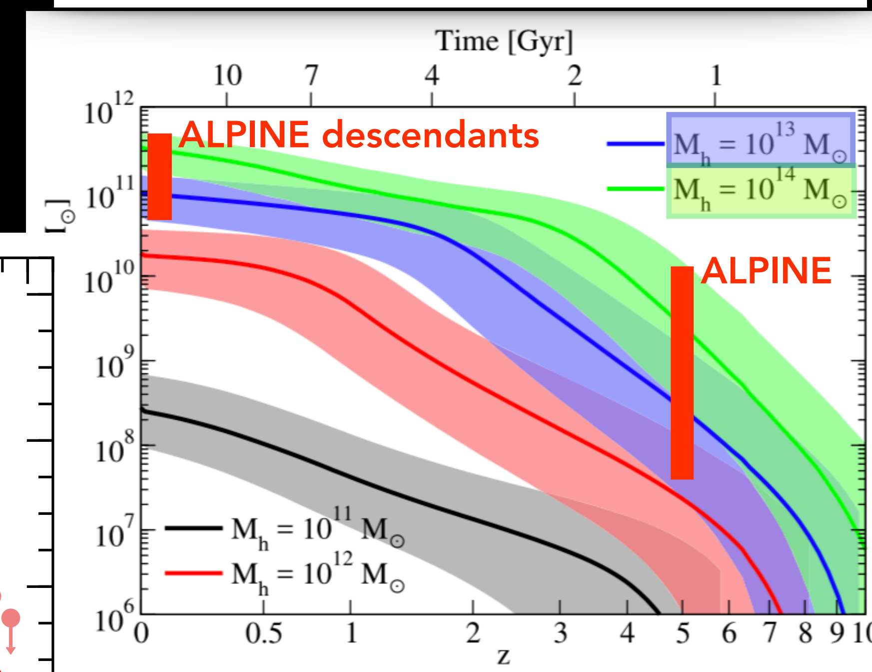
More massive galaxies in 10^{14} $M_\odot$ halos with $M_{stars} = 10^{9.1}$–$10^{9.9}$ $M_\odot$ at z=5.5

→ flat molecular gas fraction from z~6 to z~2–3 with a steep decrease at z≲3





Stellar mass history simulations



Monster+13; Behroozi+13,19

$\langle z \rangle$	$M_{halo} = 10^{13}\,M_\odot$ at $z=0$ M_{stars} range ($M_\odot$)	$M_{halo} = 10^{14}\,M_\odot$ at $z=0$ M_{stars} range ($M_\odot$)
0	$(5.9–16) \times 10^{10}$	$(2.5–5.0) \times 10^{11}$
0.7	$(3.4–12) \times 10^{10}$	$(1.2–2.7) \times 10^{11}$
1.2	$(2.2–10) \times 10^{10}$	$(1.0–1.8) \times 10^{11}$
2.2	$(3.0–43) \times 10^{9}$	$(4.3–10) \times 10^{10}$
3.0	$(8.0–180) \times 10^{8}$	$(1.8–8.0) \times 10^{10}$
4.5	$(1.0–29) \times 10^{8}$	$(2.9–27) \times 10^{9}$
5.5	$(3.2–130) \times 10^{7}$	$(1.3–8.0) \times 10^{9}$

Dessauges-Zavadsky+20

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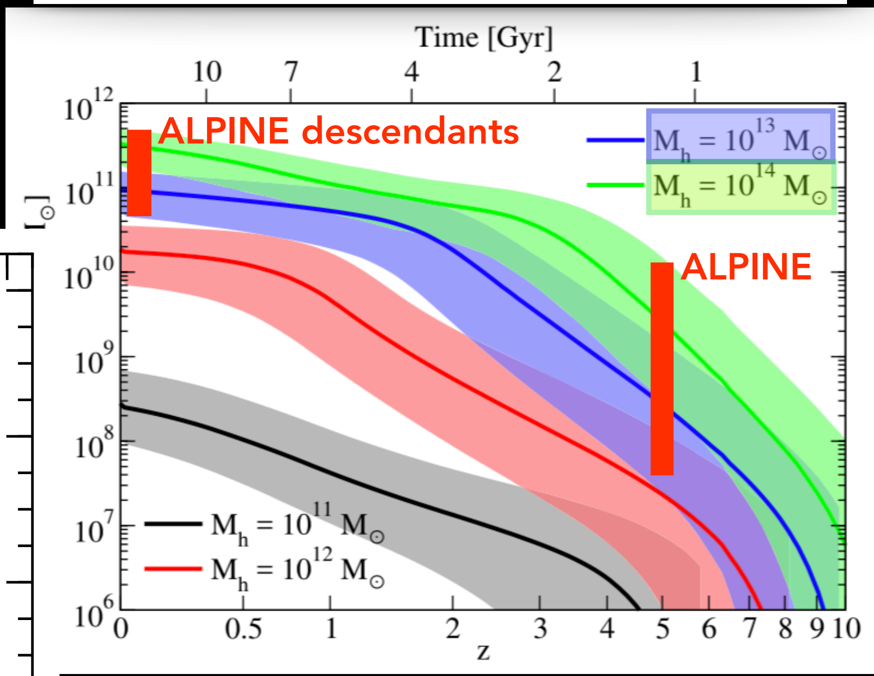

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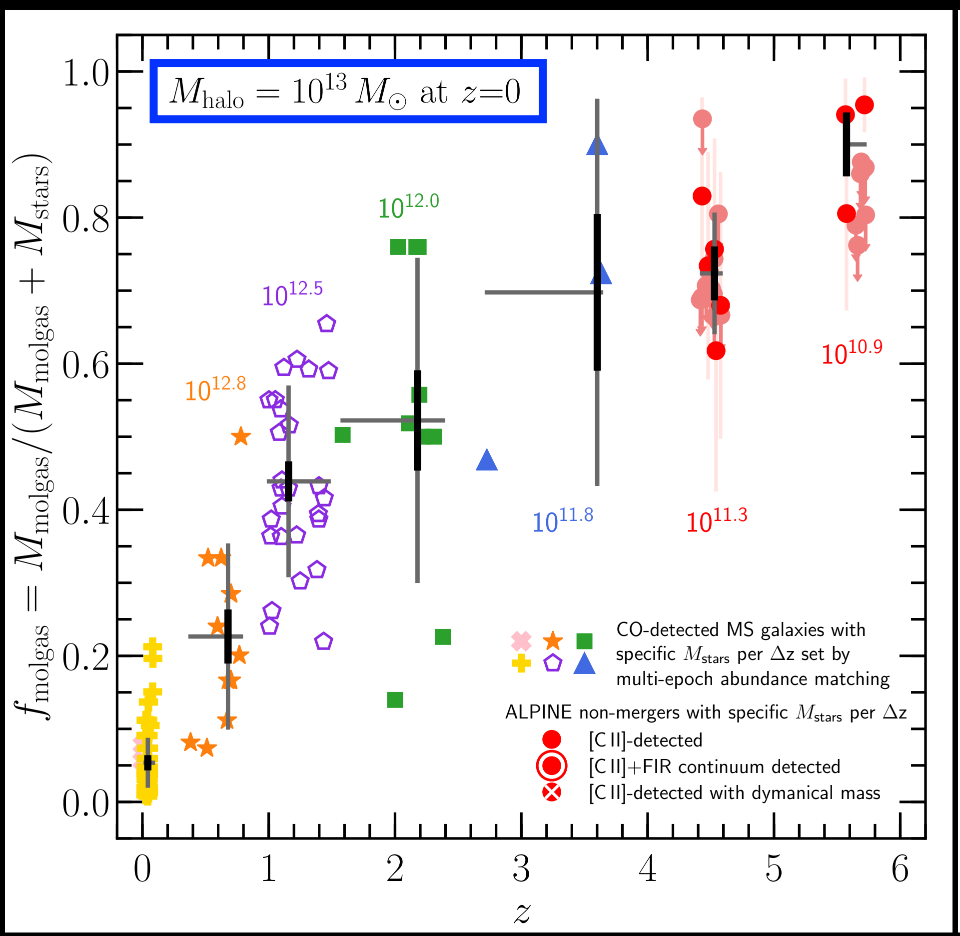

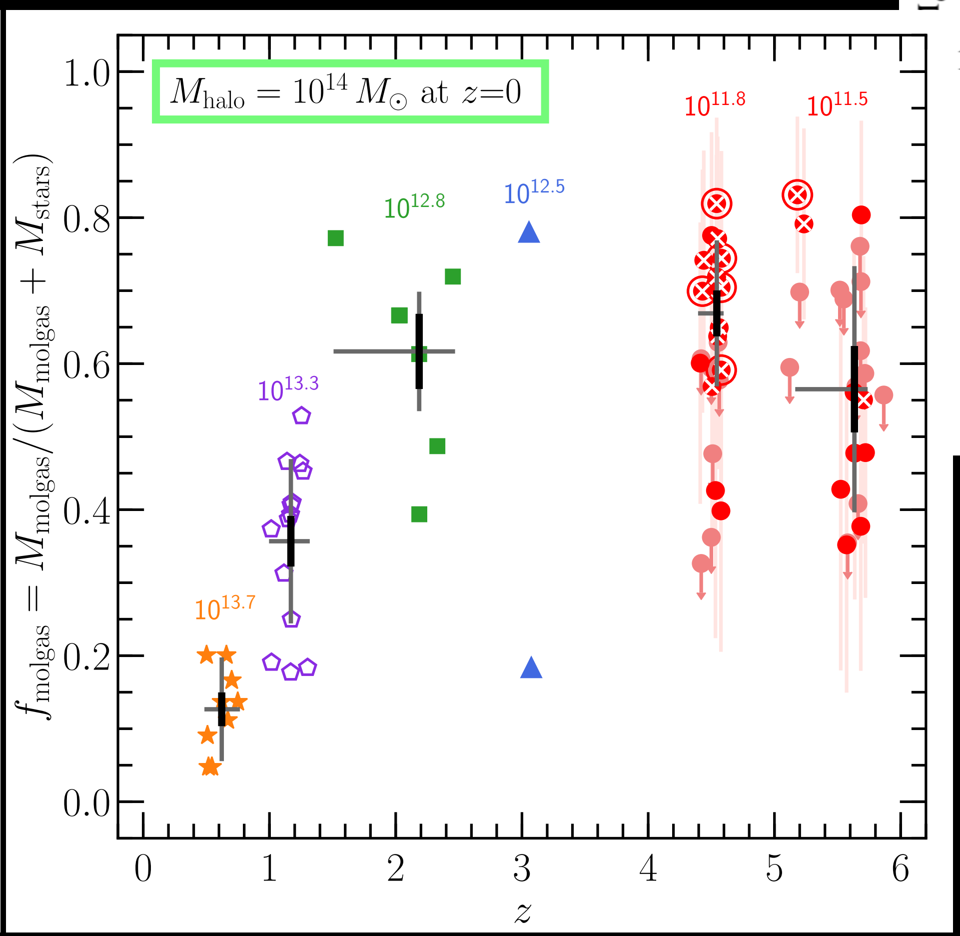

Dessauges-Zavadsky+20

The flat evolution may be attributed to…

- **efficient star formation** during early evolutionary phases
- **outflows** blowing part of the infalling gas and quenching star formation

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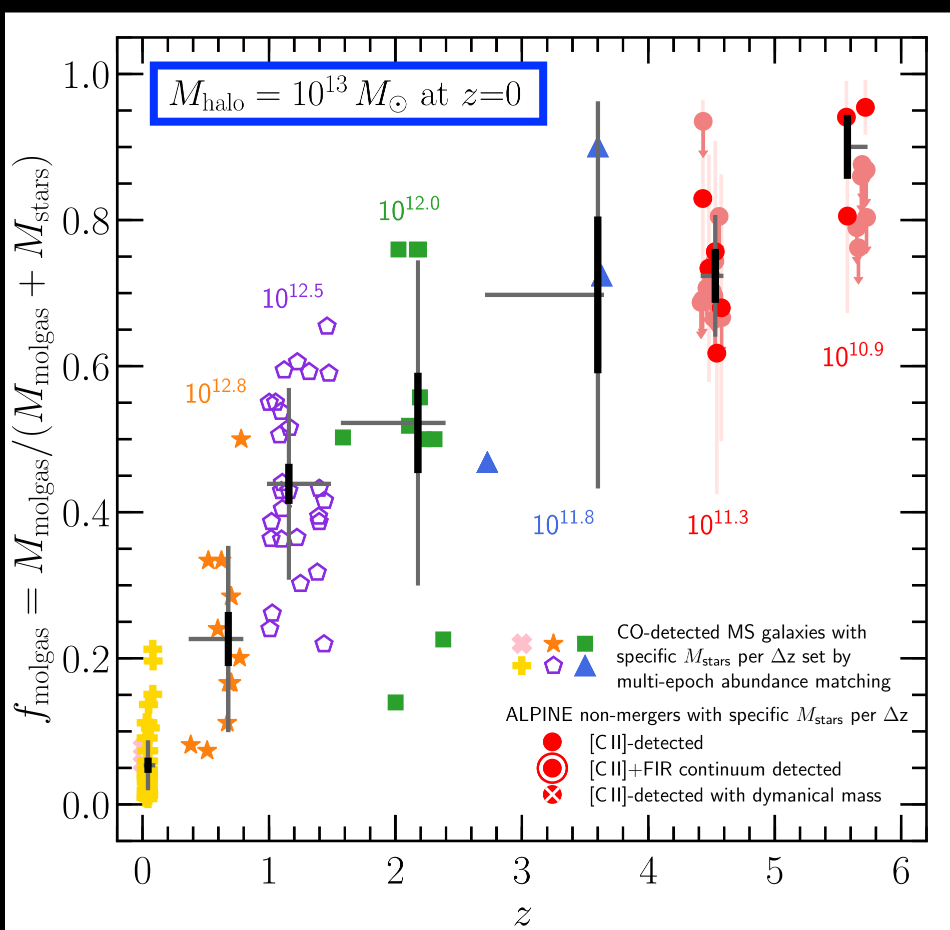

Dessauges-Zavadsky+20

More massive galaxies in 10^{14} $M_\odot$ halos with $M_{stars} = 10^{9.1}$–$10^{9.9}$ $M_\odot$ at z=5.5

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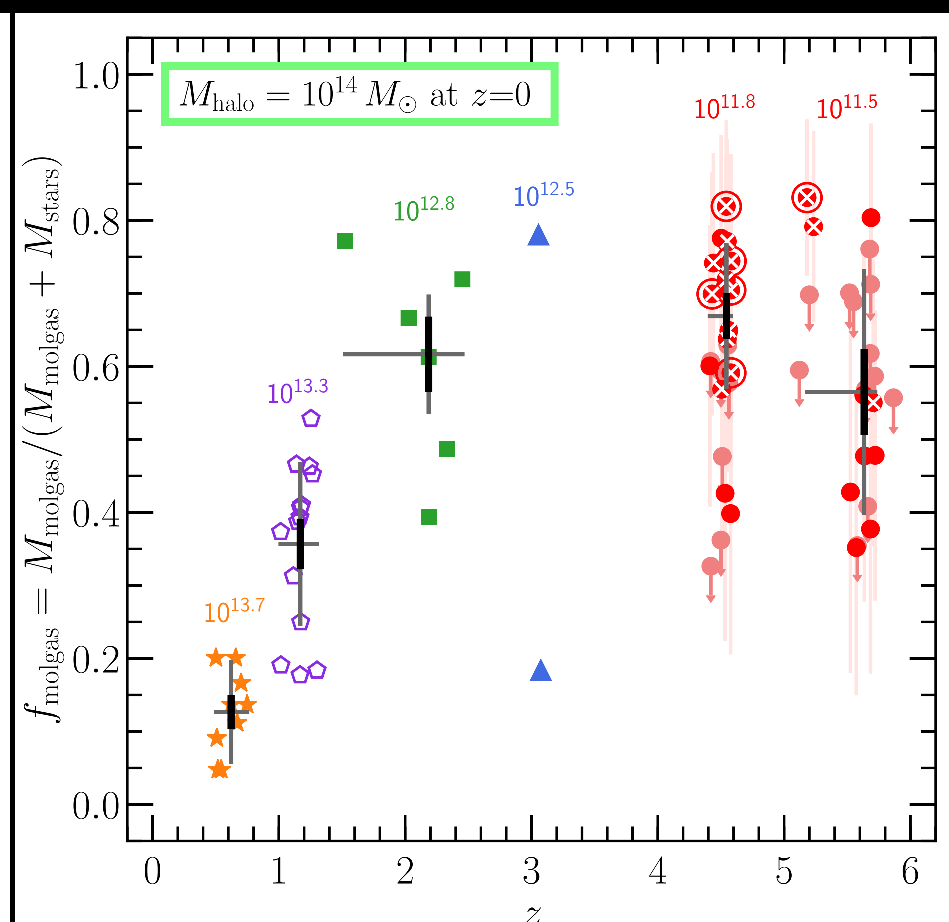
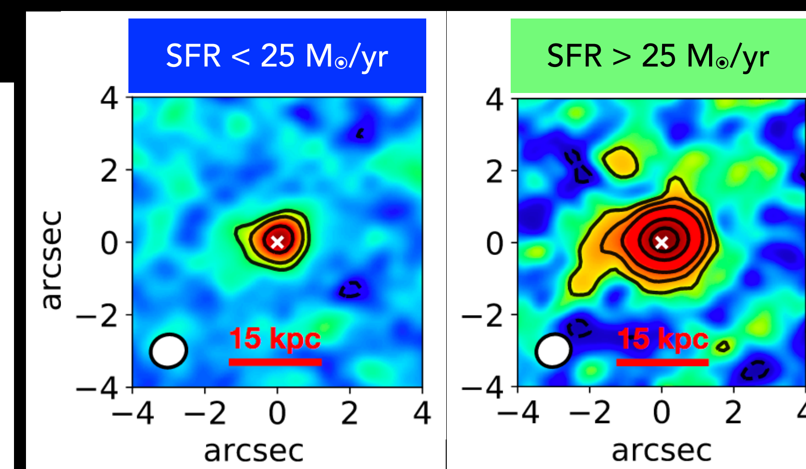
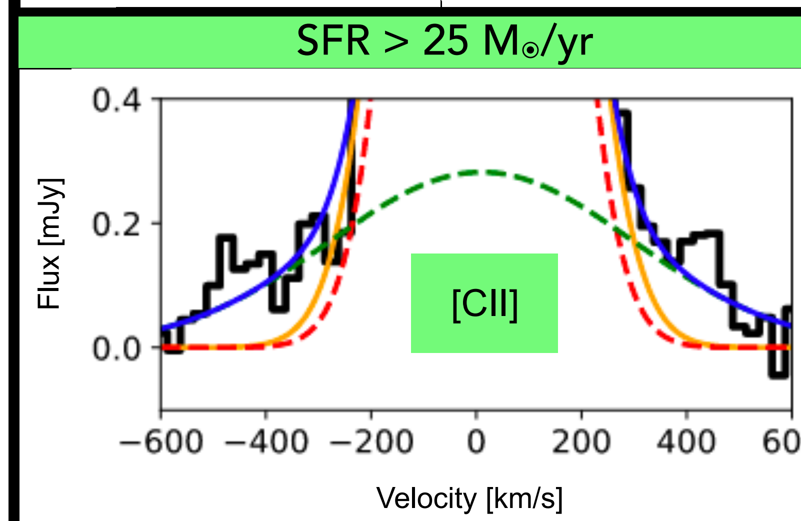


Evidence of **star formation-driven outflows** in the extended [CII] halos of **massive ALPINE galaxies**





Ginolfi/w DZ+20; Fujimoto/w DZ+20
(see also e.g., *Rubin+14*; *Talia+17*; *Fujimote+19*; *Sugahara+19*)

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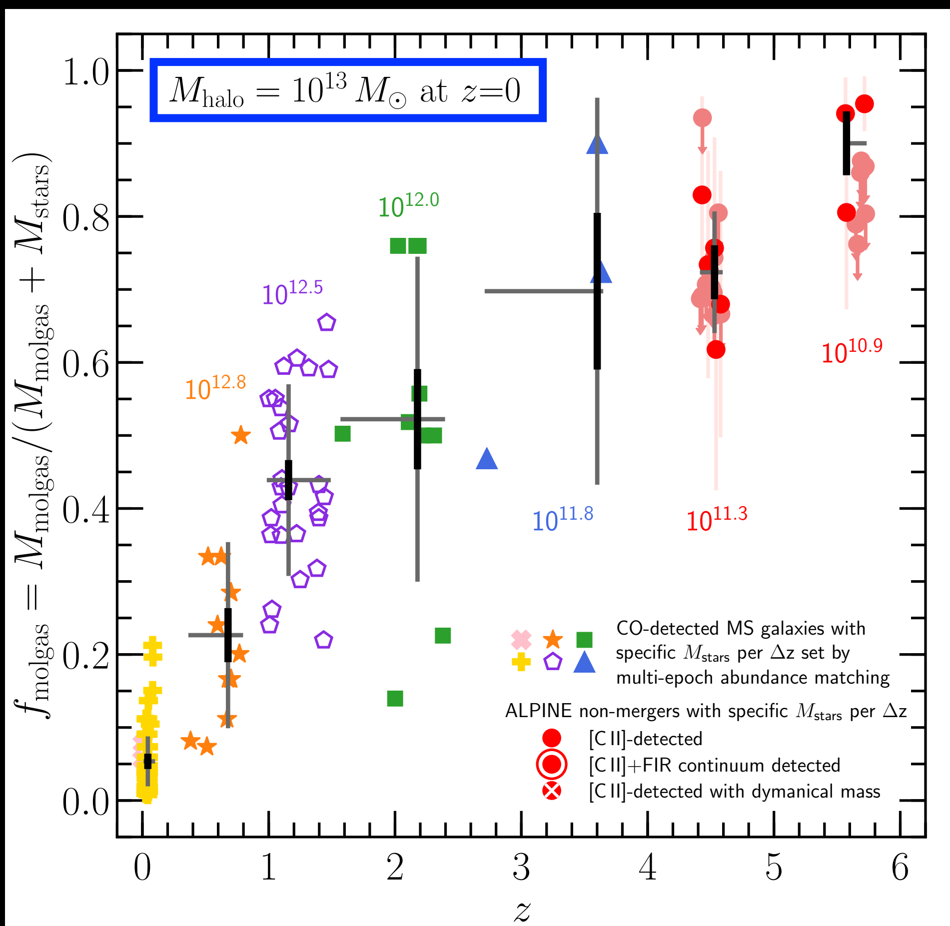
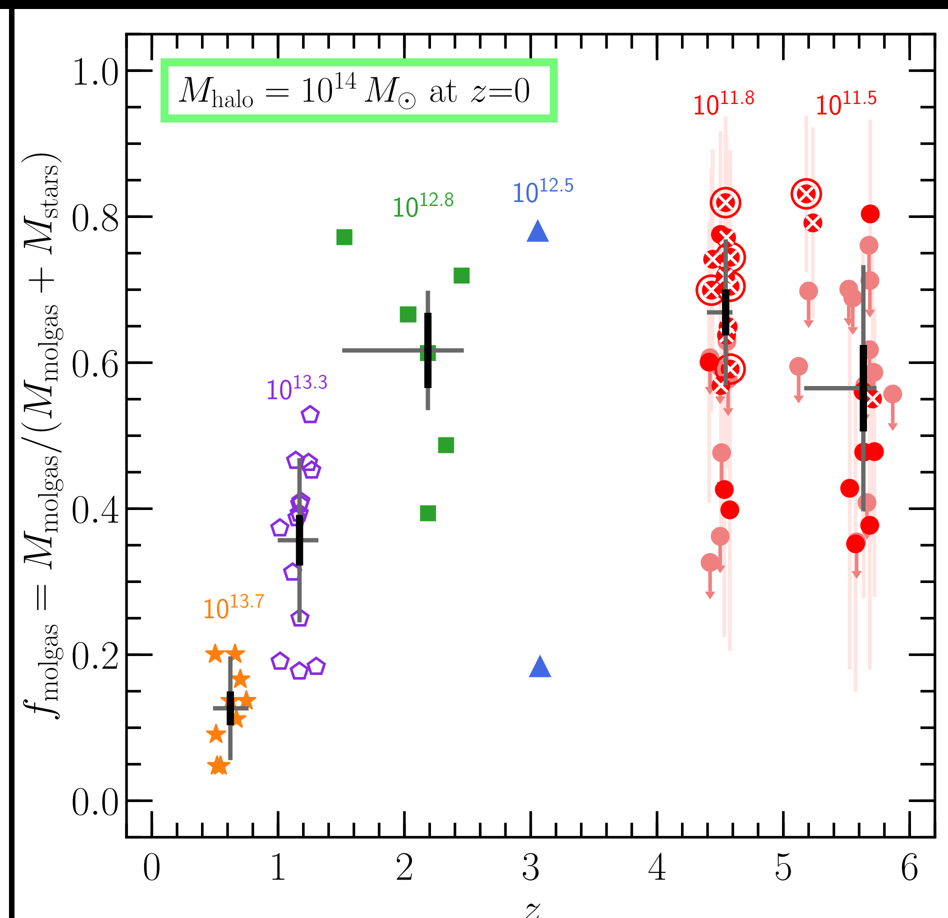
→ monotonic molecular gas fraction decrease with cosmic time	→ flat molecular gas fraction from z~6 to z~2–3 with a steep decrease at z≲3





Dessauges-Zavadsky+20

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- **efficient star formation** during early evolutionary phases
- **outflows** blowing part of the infalling gas and quenching star formation
- **halt of the gas supply** *(Dekel & Birnboim 06; Kereš+09; Bouché+10)*

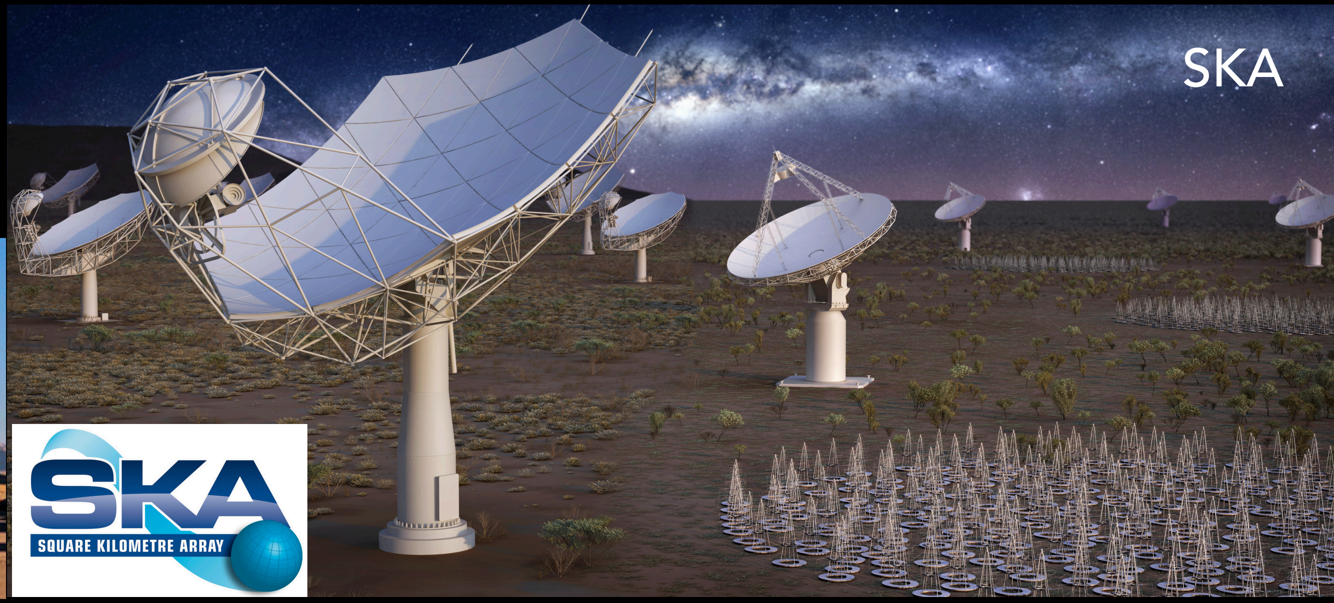
TAKE HOME MESSAGES

CONCLUSIONS

- ✦ The [CII] luminosity appears as a robust molecular gas mass tracer at z>4.5, as supported by the ALPINE MS galaxies with typical stellar masses.
- ✦ The molecular gas mass fraction steeply rises with redshift and flattens off at z>3.5 to reach a plateau at 63% between z=4.5 and z=6. This shows that large molecular gas reservoirs were present at z~6.
- ✦ The molecular gas consumption timescale shows a shallow monotonic decrease with z. This testifies of an inefficient star formation in distant galaxies, requiring a continuous supply in gas for several Gyr.
- ✦ The progenitors of massive present-day galaxies and Milky Way-like galaxies show different molecular gas fraction evolutions across cosmic time. This provides important constraints on the early evolutionary phases of galaxies during their rapid stellar mass build up.

PERSPECTIVES

ALMA AND SKA SYNERGY



Ascertain the molecular gas mass content of high-redshift galaxies:

at $z<9$ with CO(3-2) and at $z<5.5$ with CO(2-1) using ALMA Bands 1+2 (>35 GHz)

at $z>4$ with CO(1-0) using SKA2 mid-frequency (<24 GHz) [$z>6.6$ using SKA1]

modulo the CO molecule existence at these very high redshifts…

Determine the HI mass reservoir of high-redshift galaxies with the 21cm emission

Does this HI reservoir account for the large H_2 content we see with ALMA?

What is the connection between HI and H_2 in high-redshift galaxies?

Does HI fall onto galaxies via accretion flows as predicted by the gas-regulated model?