Scaling relations involving cold gas in high-z galaxies

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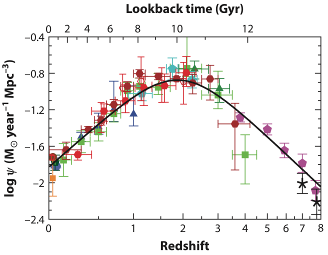
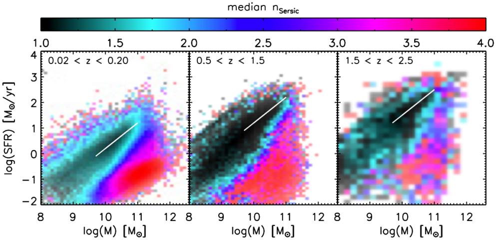
Star formation across cosmic time



Madau & Dickinson (2014)



Wuyts et al. (2011)

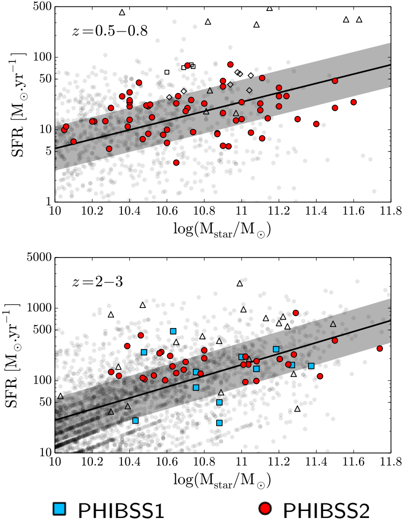
PHIBSS/PHIBSS2⋆: How does star formation depend on the available cold molecular gas and its evolution?

- A statistical samples of more than 170 MS galaxies at different redshifts
- Well-studied parent samples (CANDELS, 3D-HST, COSMOS,...)
- CO molecular gas observations at the IRAM Plateau de Bure/NOEMA interferometer
- High-resolution follow-ups

PHIBSS (2010-2013): Tacconi et al. 2010, 2013, Genzel et al. 2010, 2012, 2013, Freundlich et al. 2013
PHIBSS2 (2013-2017): Genzel et al. 2015, Tacconi et al. 2017, Freundlich et al. 2017 in prep.

⋆ Plateau de Bure High-z Blue Sequence Survey

The PHIBSS/PHIBSS2 samples



Sample selection:

- Cover the winding-down, peak and build-up of massive galaxy formation
- Well-understood parent samples (in the GOODS-N, COSMOS, AEGIS fields)
- Homogeneous coverage of the MS and its scatter
- No morphological selection

Scaling relations for $t_{\rm depl} = M_{\rm gas}/SFR$ and $\mu_{\rm gas} = M_{gas}/M_{\rm star}$

Genzel et al. 2015, Tacconi et al. 2017:

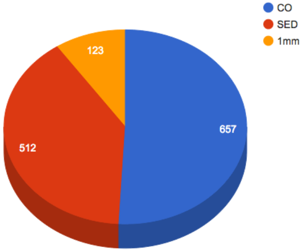
$$\log(t_{\rm depl}) = A + B\log(1+z) + C\log(\delta MS) + D\log(\delta M) + E\log(\delta R)$$
$$\log(\mu_{\rm gas}) = A + B\,(\log(1+z) - F)^{\beta} + C\log(\delta MS) + D\log(\delta M) + E\log(\delta R)$$

where

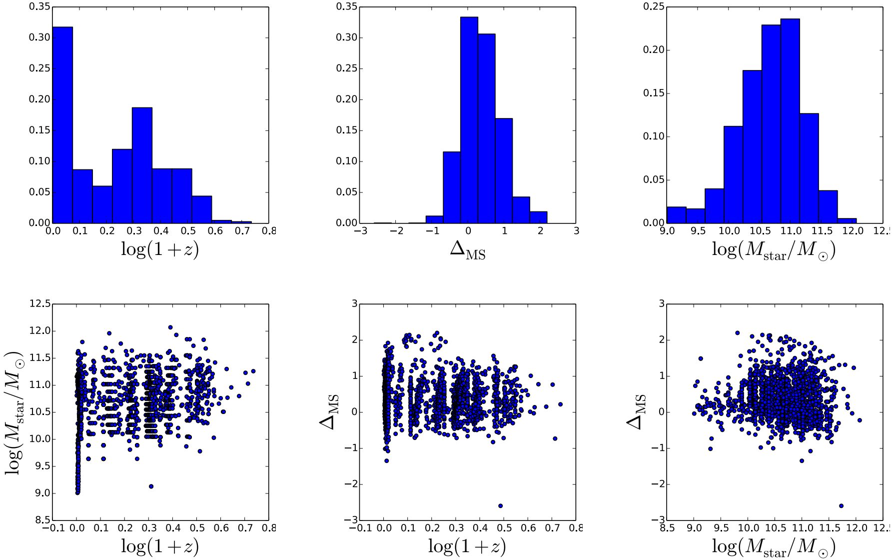
- A, B, C, D, E, (F, β) are assumed not to depend on redshift
- $\delta MS = \mathrm{SSFR}/\mathrm{SSFR}_{\rm MS}$ with $\mathrm{SSFR}_{\rm MS}$ the mean SSFR on the MS (Speagle et al. 2014)
- $\delta M = M_{\rm star}/5.10^{10} M_{\odot}$,
- $\delta R = R_{\rm d}/R_{\rm MS}$ with $R_{\rm MS}$ the mean half-light radius on the MS (Van der Wel et al. 2014)

A compilation of observations beyond the PHIBSS/PHIBSS2 samples:

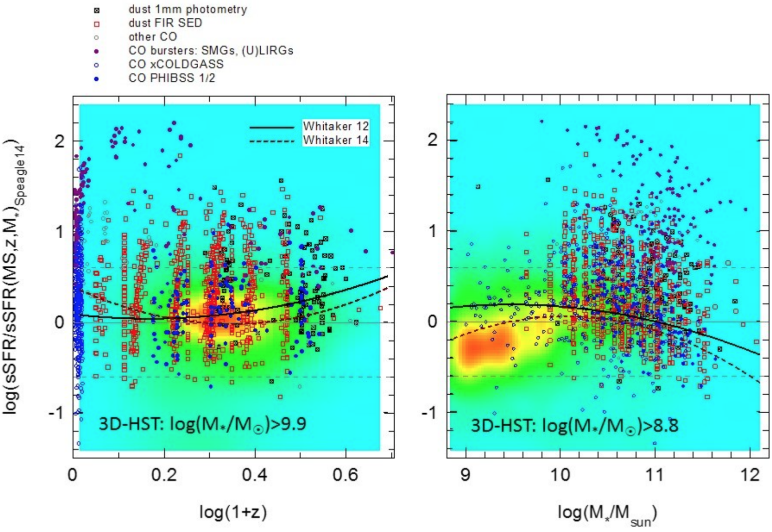
– 1285 galaxies
– $z = 0 - 4.4$, $\log(M_{\rm star}/M_{\odot}) = 9 - 11.9$ and $|\log(\delta MS)| \leq 2$
– 657 from CO molecular gas
– 512 from dust FIR SED and dust emissivity models
– 123 from dust 1mm emission in the Rayleigh-Jeans domain



Characteristics of the full sample



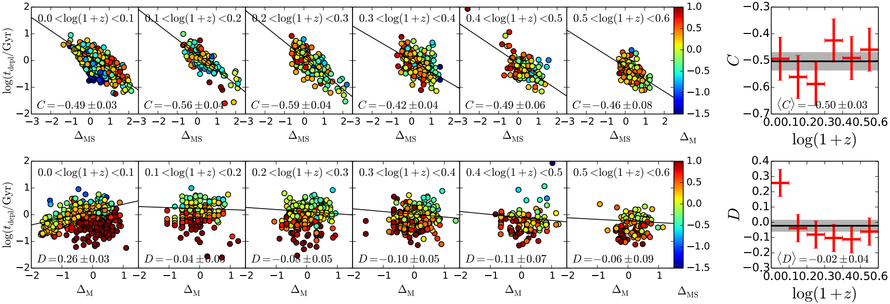
Comparison with the CANDELS/3D-HST parent sample



Tacconi et al. 2017

Method

1/ Provisional fit of the depletion time $t_{\rm depl}$ with δMS and δM to project it on the MS line ($\delta MS = 0$) at a specific stellar mass ($\delta M = 0$)



Method

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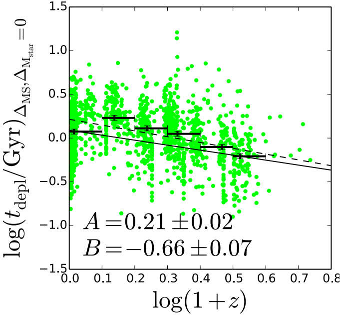
2/ Redshift dependence of the projected $\log(t_{\rm depl}) - \langle C \rangle \log(\delta MS) - \langle D \rangle \log(\delta M)$



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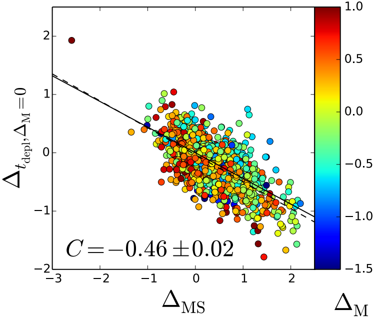
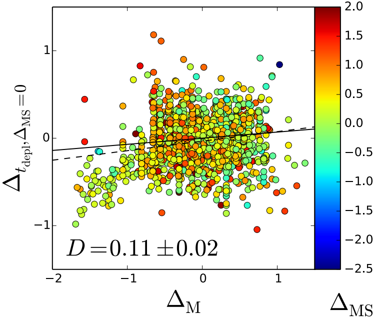
3/ Fit with δMS and δM of $\log(\delta t_{\rm depl}) = \log(t_{\rm depl}) - A - B \log(1+z)$





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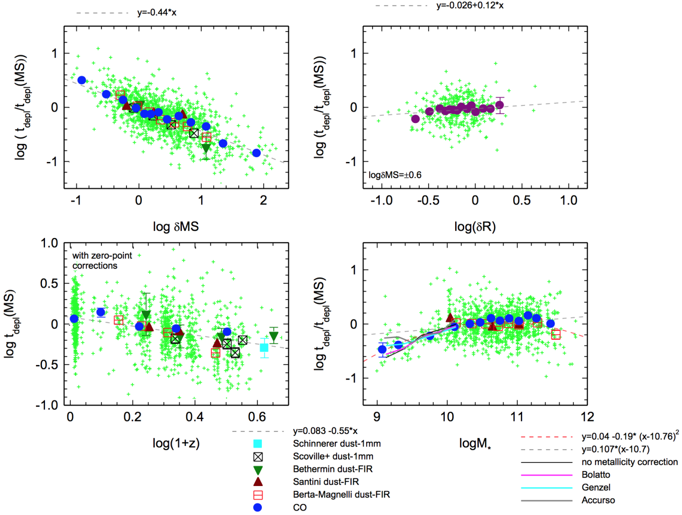
2/ Redshift dependence of the projected $\log(t_{\rm depl}) - \langle C \rangle \log(\delta MS) - \langle D \rangle \log(\delta M)$

3/ Fit with δMS and δM of $\log(\delta t_{\rm depl}) = \log(t_{\rm depl}) - A - B \log(1+z)$

4/ Fit of the residual $\log(t_{\rm depl}) - A - B \log(1+z) - C \log(\delta MS) - D \log(\delta M)$ with radius through δR

Scaling relations for the depletion time

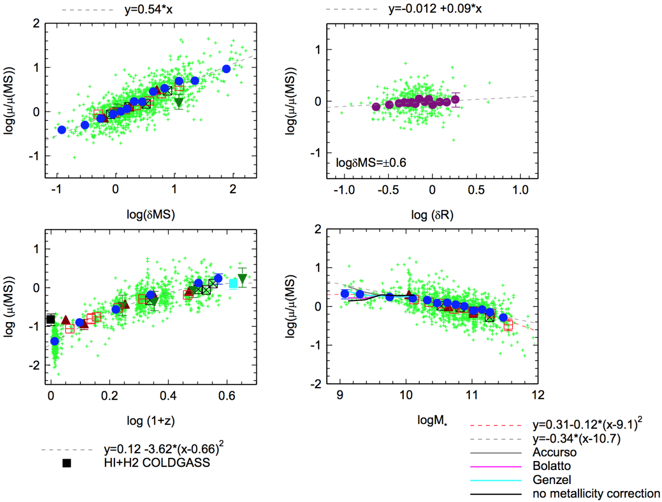
$$t_{\rm depl} \propto (1+z)^{-0.57} \left(\frac{SSFR}{SSFR_{\rm MS}}\right)^{-0.44} \left(\frac{M_{\rm star}}{5.10^{10} M_\odot}\right)^{+0.07} \left(\frac{R}{R_{\rm MS}}\right)^{+0.12}$$



Tacconi et al. (2017)

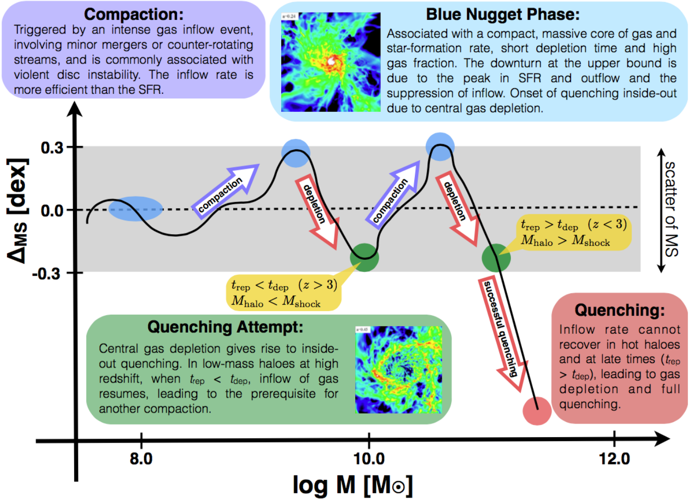
Scaling relations for the gas-to-stellar mass ratio

$$\mu_{\rm gas} \propto (1+z)^{+2.60} \left(\frac{SSFR}{SSFR_{\rm MS}}\right)^{+0.54} \left(\frac{M_{\rm star}}{5.10^{10}\,M_\odot}\right)^{-0.33} \left(\frac{R}{R_{\rm MS}}\right)^{+0.09}$$



Tacconi et al. (2017)

Interpretation of the δMS trend: compaction and replenishment



cf. Sandro's talk

Tacchella et al. (2016)

Why does $t_{\mathrm{depl}} \propto (1+z)^{-0.6}$ evolve so slowly?

Toy model:

- $SFR = \epsilon_{ff} M_{\mathrm{gas}}/t_{ff}$ with a constant $\epsilon_{ff} \sim 0.01$, so that $t_{\mathrm{depl}} \propto t_{ff}$
- $t_{ff} \propto t_{dyn}$, i.e., clump and galaxy densities and sizes are proportional
- $t_{dyn} = \lambda t_{dyn,halo}$ with a halo spin parameter λ
- $t_{dyn,halo} \propto t_{Hubble}$ by definition, as $\rho_{halo} \equiv 200\rho_{crit}$
- $t_{Hubble} \propto (1+z)^{-3/2}$ in a matter-dominated Universe

Hence, we would expect $t_{\mathrm{depl}} \propto (1+z)^{-1.5}$

Possible origins of the discrepancy

- Compaction, increasing the star formation efficiency locally and slowing down the increase of t_{depl}
- $t_{Hubble} \propto (\Omega_\Lambda + \Omega_m (1+z)^3)^{1/2} \propto (1+z)^{-1}$ between $z = 0-2.5$ in a ΛCDM Universe (Genzel et al. 2015)
- Star-forming clumps are not in the Toomre regime
- λ not constant with time...

Comparison with simulations

- VELA simulations: cf. talk by Daniel Ceverino
- NIHAO simulations: lower resolution, stronger density threshold for star formation, stronger feedback, cf. talk by Fangzhou Jiang

t_{depl}

	Tacconi-mock	Tacconi-real	VELA-mock	VELA-real	NIHAO-mock	NIHAO-real
$A \pm dA$	0.15 ± 0.02	0.21 ± 0.02	0.01 ± 0.06	0.61 ± 0.06	0.15 ± 0.02	0.95 ± 0.02
$B \pm dB$	-0.78 ± 0.07	-0.67 ± 0.07	-0.29 ± 0.10	-2.48 ± 0.10	-0.73 ± 0.04	-1.13 ± 0.04
$C \pm dC$	-0.44 ± 0.02	-0.44 ± 0.02	-0.41 ± 0.03	-0.52 ± 0.03	-0.46 ± 0.01	-0.60 ± 0.01
$D \pm dD$	0.09 ± 0.02	0.11 ± 0.02	0.13 ± 0.01	-0.42 ± 0.01	0.06 ± 0.00	-0.08 ± 0.00

Coefficients in mock:

$$A = 0.09$$
$$B = -0.57$$
$$C = -0.44$$
$$D = 0.07$$

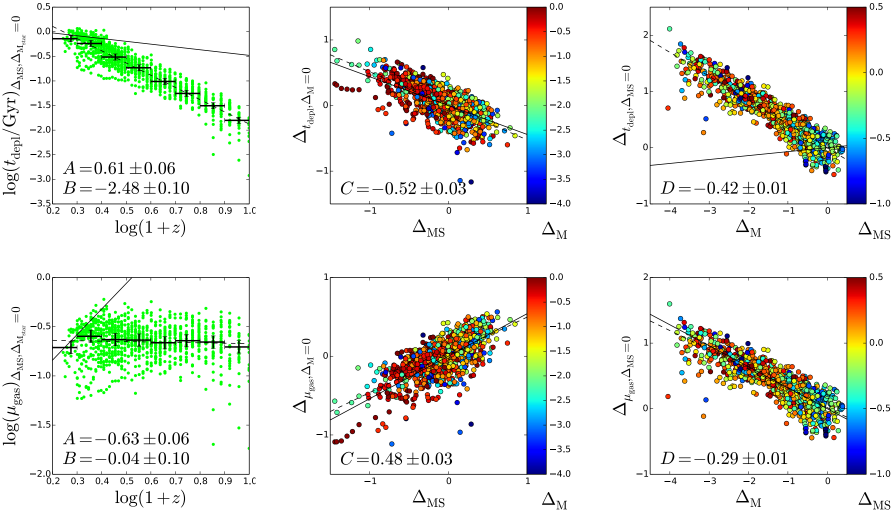
μ_{gas}

	Tacconi-mock	Tacconi-real	VELA-mock	VELA-real	NIHAO-mock	NIHAO-real
$A \pm dA$	-1.32 ± 0.02	-1.14 ± 0.02	-1.32 ± 0.06	-0.63 ± 0.06	-1.39 ± 0.02	-0.05 ± 0.02
$B \pm dB$	2.43 ± 0.07	2.54 ± 0.07	2.53 ± 0.10	-0.04 ± 0.10	2.44 ± 0.04	1.33 ± 0.04
$C \pm dC$	0.52 ± 0.02	0.52 ± 0.02	0.61 ± 0.03	0.48 ± 0.03	0.55 ± 0.01	0.40 ± 0.01
$D \pm dD$	-0.30 ± 0.02	-0.26 ± 0.02	-0.33 ± 0.01	-0.29 ± 0.01	-0.35 ± 0.00	0.05 ± 0.00

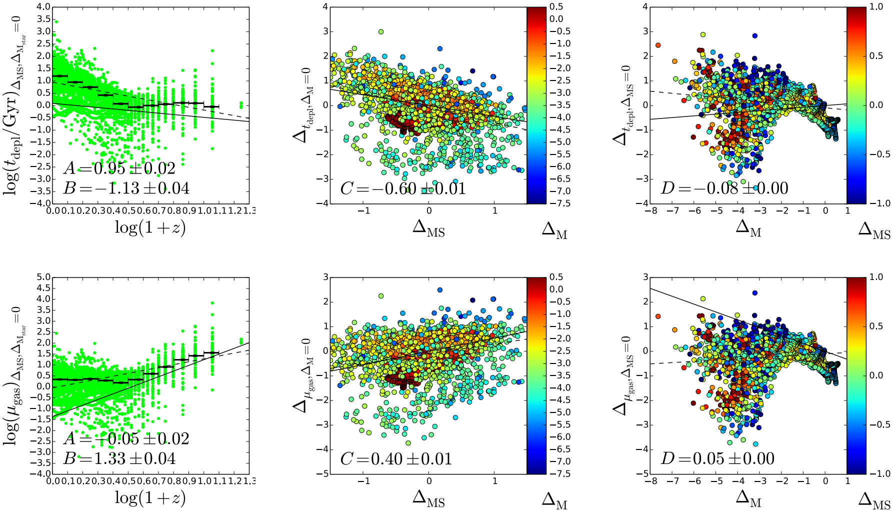
Coefficients in mock:

$$A = -1.36$$
$$B = 2.6$$
$$C = 0.54$$
$$D = -0.32$$

VELA simulations



NIHAO simulations



Conclusions

- The PHIBSS and PHIBSS2 surveys provide a census of the molecular gas in a statistically meaningful subsample of the CANDELS/3D-HST sample
- Genzel et al. (2015) and Tacconi et al. (2017): strong constraints on the dependencies of $t_{\rm depl}$ and $\mu_{\rm gas}$ with z, δMS and δM.
- Do we understand these relations theoretically?
- Simulations do not seem to reproduce the redshift evolution

Molecular gas and morphology > my talk on Monday
More about scaling relations > Linda's talk on Friday

Atacama Large Millimeter Array (ALMA), Chile