Molecular gas, stellar and dust content in typical L* galaxies at z ~ 1–3

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IMMEDIATE OBJECTIVE

Achieve molecular gas measurements in z~1–3 SFGs characterized by

SFR < 40 $M_\odot$ yr^{-1} and $M_* < 2.5\times10^{10}$ $M_\odot$

an objective achievable only with the help of gravitational lensing

TARGET SELECTION FROM THE HERSCHEL LENSING SURVEY

Herschel/PACS+SPIRE Open Time Key project (PI: E. Egami): observations of 44 massive galaxy clusters to discover lensed, high-redshift background sources

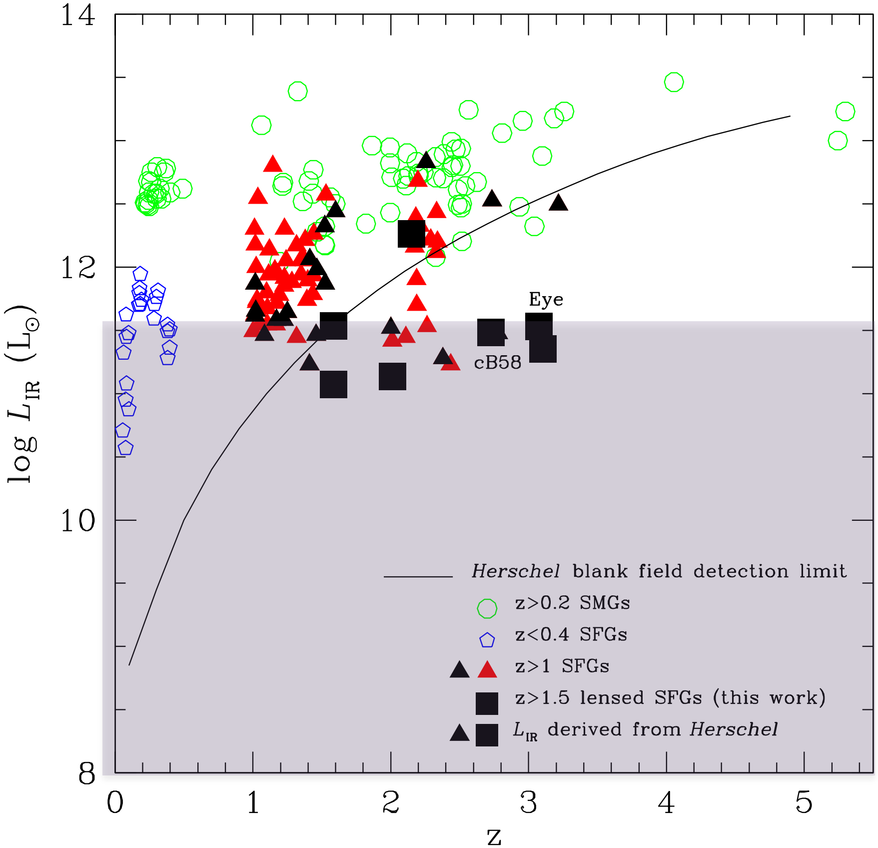
Selection criteria for CO follow-up studies:

1. high magnification factors (ideally >10)
2. spectroscopic redshifts z~1-3
3. delensed $L_{IR} < 4\times10^{11}$ $L_\odot$
4. well-sampled SEDs from optical, near-IR to IR to have good constraints on stellar SFR and M_*
5. available high-resolution HST images for the morphological information

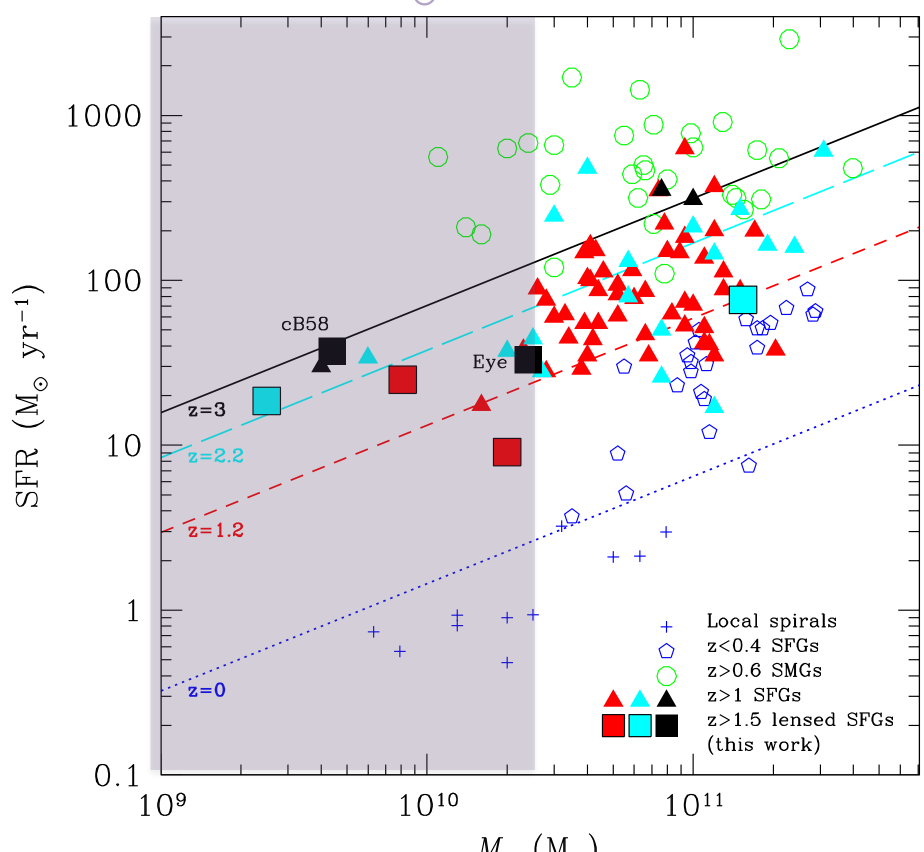
OUR TARGETS VERSUS CO-DETECTED GALAXIES FROM THE LITERATURE

Probe a new regime of lower SFR and M_*,
reaching the L* to sub-L* domain with CO measurements

$L_{IR} < 4\times10^{11}\ L_\odot$

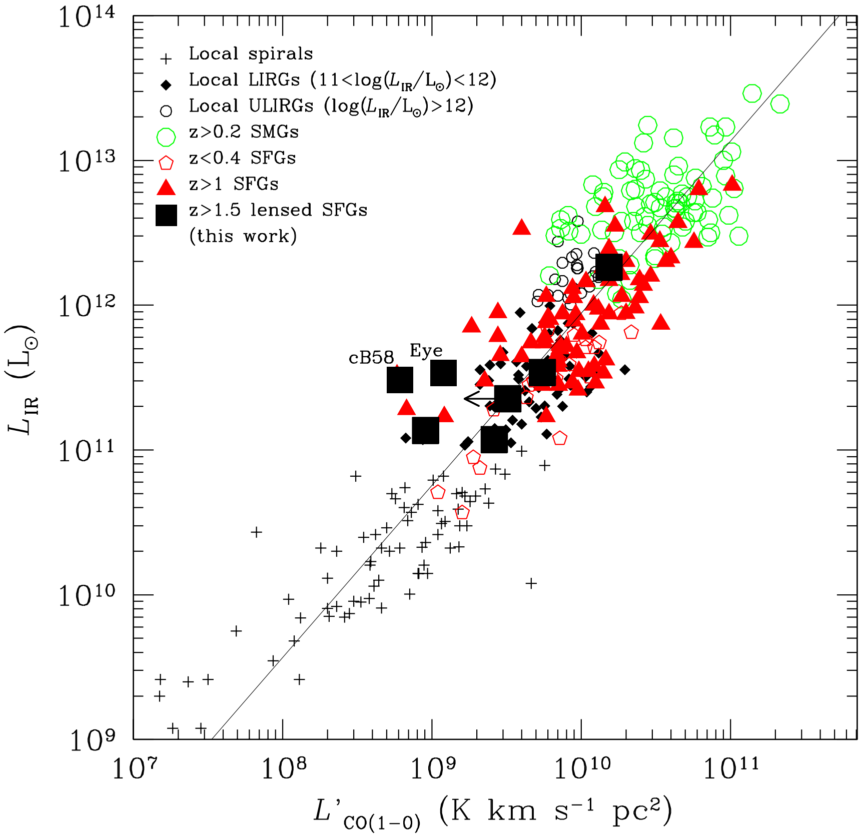


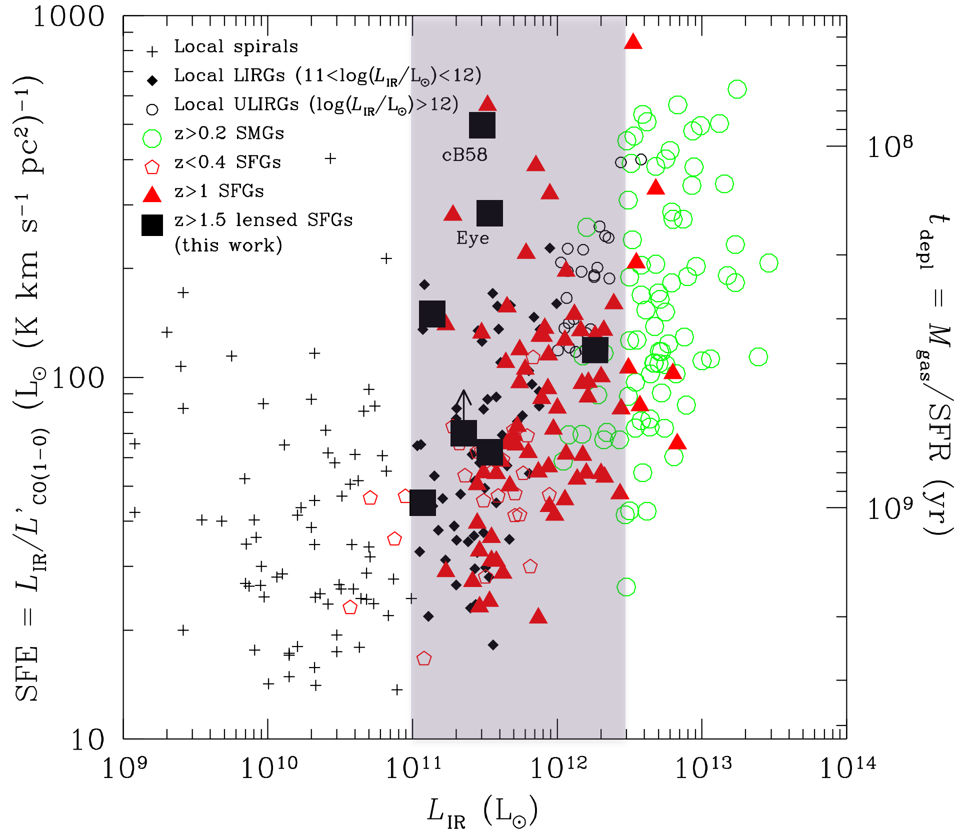
$M_* < 2.5\times10^{10}\ M_\odot$



see also Sklias+ 14

OUR TARGETS VERSUS CO-DETECTED GALAXIES FROM THE LITERATURE





- Evidence for a *single* linear relation (slope~1.2)
- The bimodal behaviour between the sequences of `disks’ and `starbursts’ has vanished (Daddi+ 10; Genzel+ 10; Sargent+ 13)

Why so ???

Another way to represent the L_{IR}-$L_{CO(1-0)}$ relation is through the star formation efficiency:

$$SFE = SFR / M_{gas} = 1 / t_{depl}$$

z>1 SFGs show an enlarged spread and dispersion similar to that of z>1 SMGs

WHAT DRIVES THE LARGE SFE SPREAD OF Z>1 SFGS ?

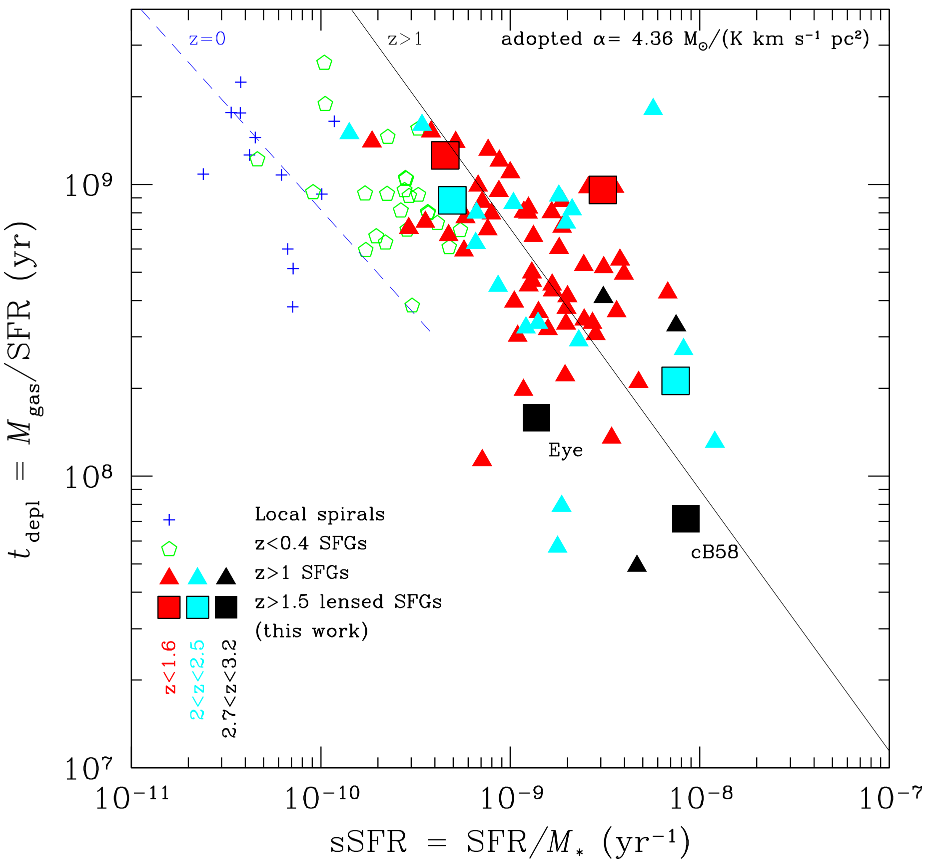
We investigate the dependence of SFE or t_{depl} on several physical parameters:

1. the specific star formation rate
2. the stellar mass
3. the redshift
4. the offset from the main-sequence
5. the compactness of the starburst

➔ SFE spread of z>1 SFGs triggered by the combination of sSFR, M_* and z

WHAT DRIVES THE LARGE SFE SPREAD OF Z>1 SFGS ?

1. THE SPECIFIC STAR FORMATION RATE



Local galaxies

Strongest dependence of t_{depl} on the sSFR (COLD GASS survey by Saintonge+ 11)

z>1 SFGs

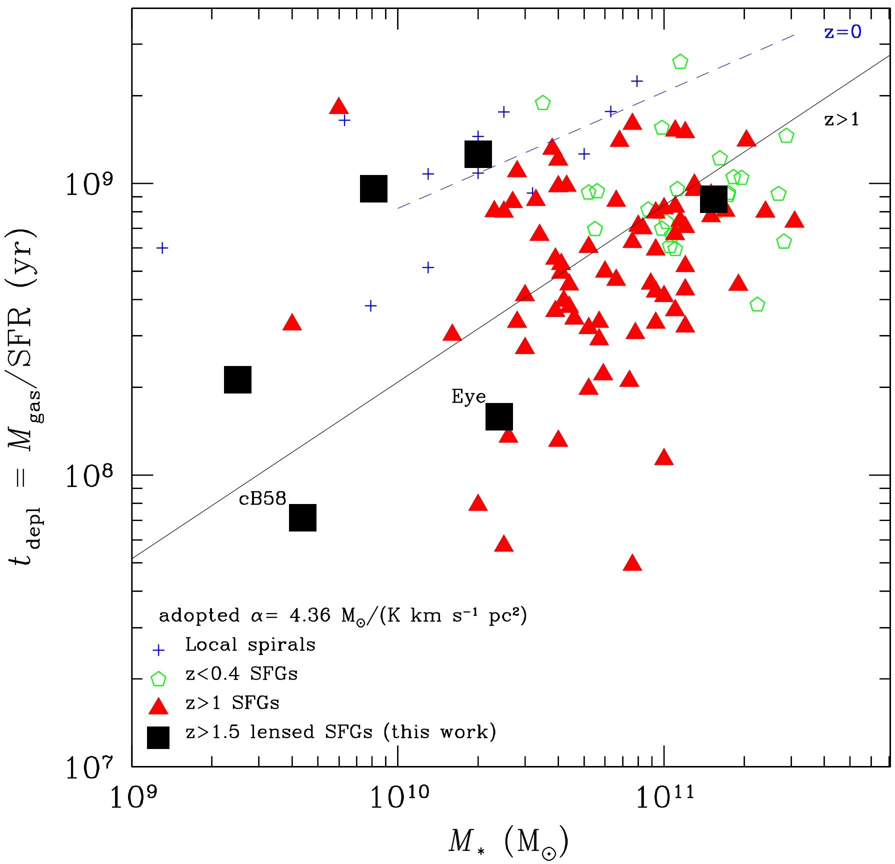
Good t_{depl}-sSFR correlation with a displacement toward longer t_{depl} by 0.75 dex at the same sSFR (see also Saintonge+ 11; Combes+ 13)

➔ due to larger molecular gas fractions at z>1 that afford longer molecular gas depletion times at a given value of sSFR

➔ the sSFR of local galaxies are sealed on low values because of the accumulation of more and more old stars in their bulge at z=0

WHAT DRIVES THE LARGE SFE SPREAD OF Z>1 SFGS ?

2. THE STELLAR MASS



Local galaxies

t_{depl} increases by a factor of 6 over $10^{10} < M_*/M_\odot < 10^{11.5}$ (COLD GASS survey by Saintonge+ 11)

z>1 SFGs

t_{depl} increase by a factor of 15 over $10^{9.4} < M_*/M_\odot < 10^{11.5}$

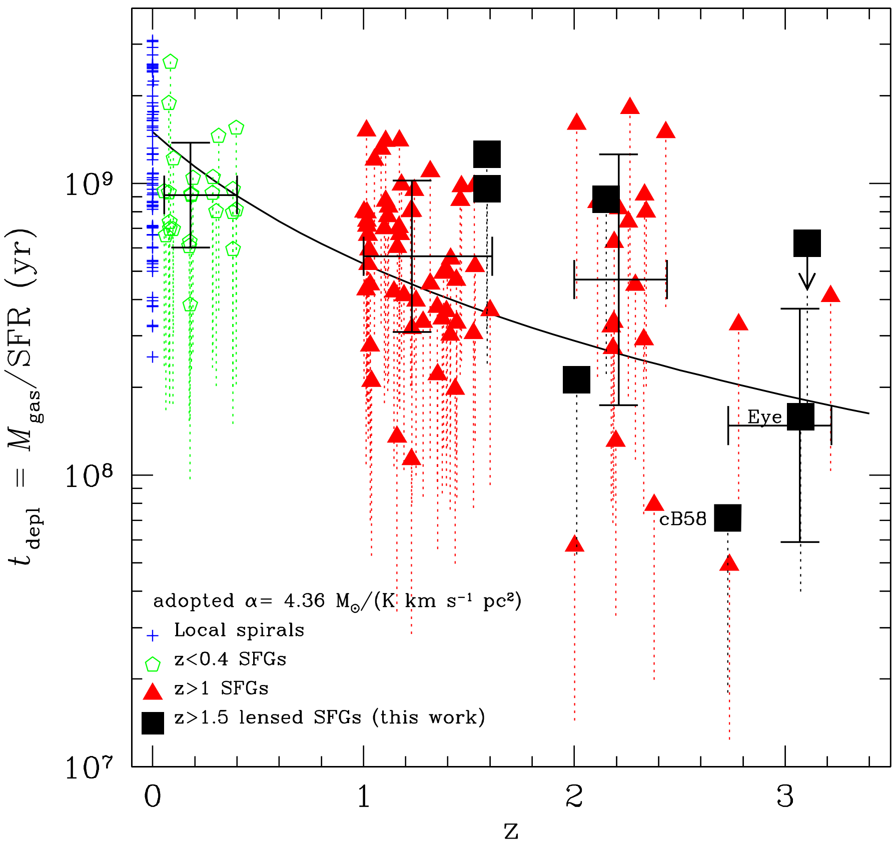
➔ the few data points at the low-M_* end seem to trigger the t_{depl}-M_* correlation

If true, this has several important implications:

1. questions the constant t_{depl} of 0.7 Gyr found by Tacconi+ 13
2. contradicts the ``bathtub'' model that assumes a constant t_{depl}
3. refutes the linearity of the Kennicutt-Schmidt relation

WHAT DRIVES THE LARGE SFE SPREAD OF Z>1 SFGS ?

3. THE REDSHIFT



The cosmic evolution of t_{depl} is expected (Hopkins & Beacom 06; Davé+ 11,12; Bouché+ 10)

z>1 SFGs

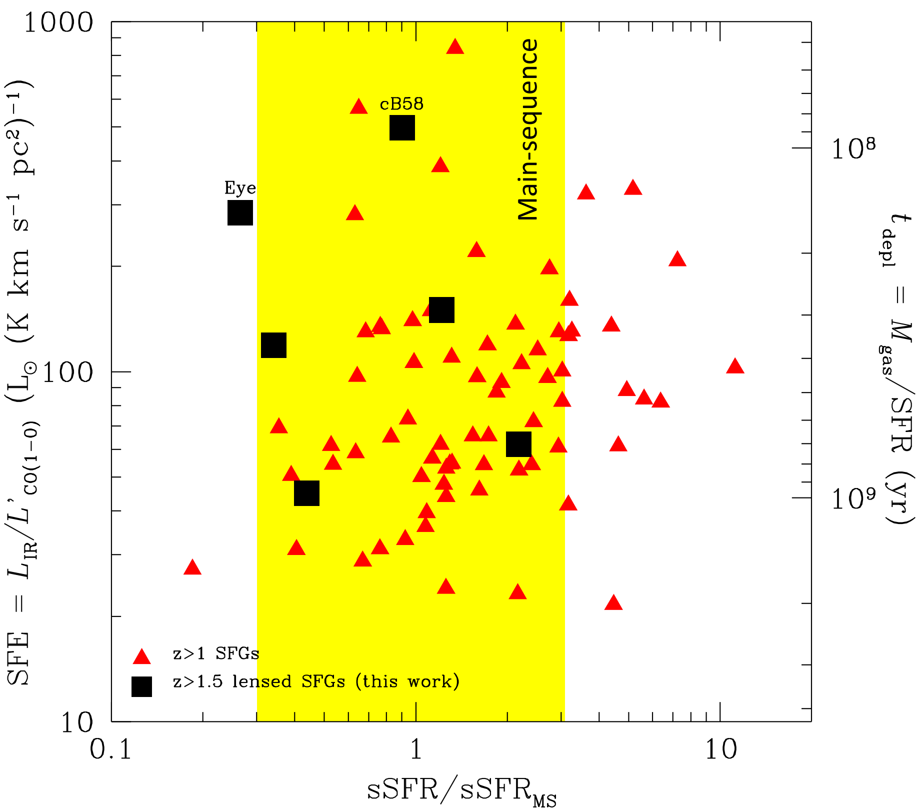
Observationally, the t_{depl} decrease with redshift is confirmed, such as $(1+z)^{-1.5}$
(see also Combes+ 13; Tacconi+ 13; Saintonge+ 13; Santini+ 14)

➔ z>1 SFGs form stars with a higher SFE, and consume molecular gas over a shorter timescale, than local galaxies

➔ large dispersion per z bin, due to the t_{depl}-sSFR and t_{depl}-M_* correlations: galaxies with the higher sSFR and smaller M_* have the shorter t_{depl}

WHAT DRIVES THE LARGE SFE SPREAD OF Z>1 SFGS ?

3. THE OFFSET FROM THE MAIN-SEQUENCE



Positive empirical correlation between SFE and the offset from the main-sequence (MS) found by Magdis+ 12, Saintonge+ 12, and Sargent+ 13

z>1 SFGs

- The general trend of higher SFE for galaxies with larger offsets from the MS is confirmed
- *But* MS galaxies ($0.3 < \mathrm{sSFR/sSFR_{MS}} < 3$) within the yellow area have roughly *constant* SFE with a large spread over 1.5 orders of magnitude

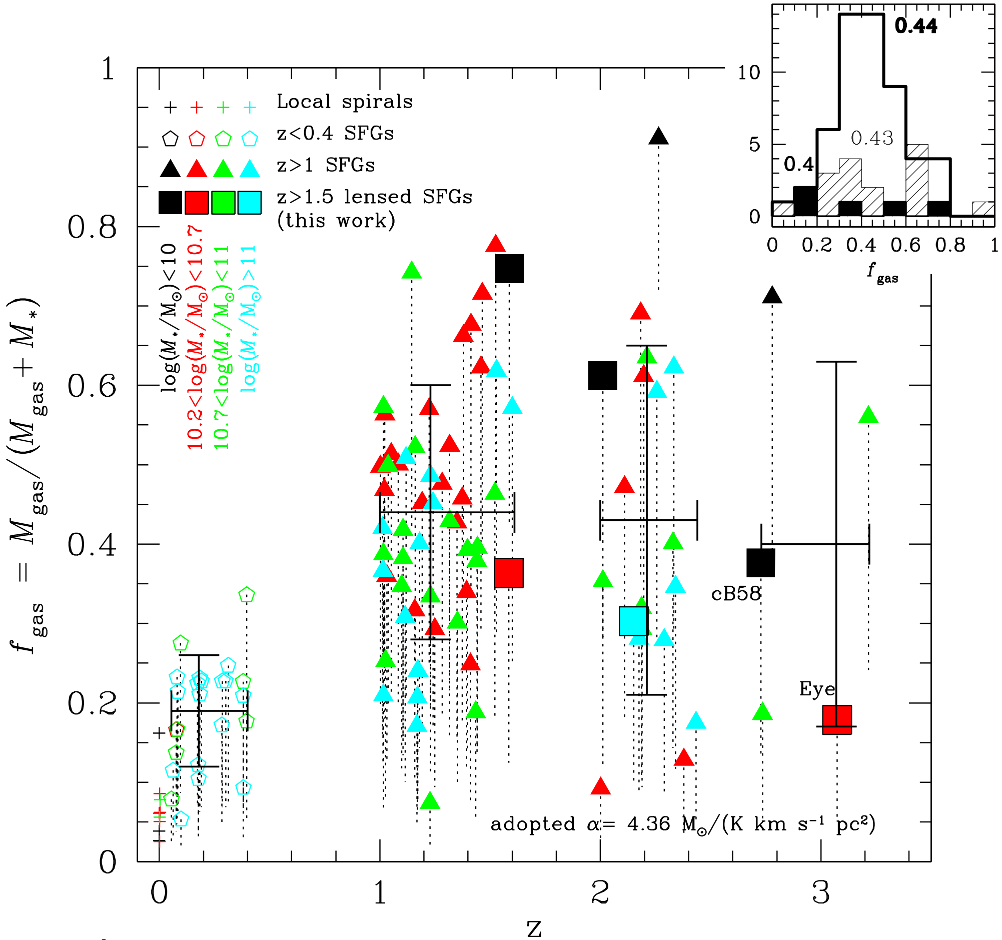
MOLECULAR GAS FRACTION

Various physical processes at play in the evolution of galaxies (accretion, star formation, and feedback) have direct impact on the molecular gas fraction

➔ f_{gas} provides tests of galaxy evolution models

We consider two main observables: redshift and stellar mass

REDSHIFT EVOLUTION OF THE MOLECULAR GAS FRACTION



The cosmic evolution of f_{gas} is a direct output of the expansion of the Universe (Mo+ 98; Obreschkow & Rawlings 09; Lagos+ 11,14; Stewart+ 13)

The molecular gas fraction can be expressed as:

$$f_{\rm gas} = \frac{1}{1 + (t_{\rm depl}{\rm sSFR})^{-1}}$$

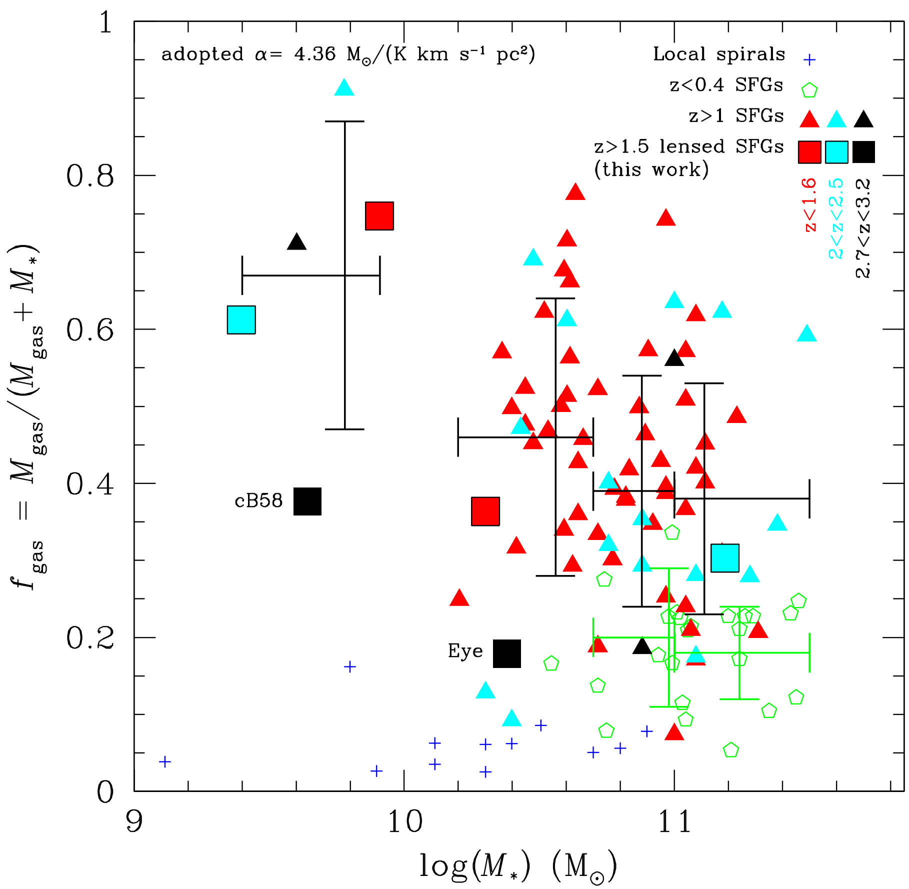
with $t_{depl} \propto (1+z)^{-1.5}$
and $sSFR \propto (1+z)^{\alpha}$ with α = 5/3 to 3

➔ *steady* increase of f_{gas} with redshift (Bouché+ 10; Davé+12; Lilly+ 13)

Observations

- Net increase of f_{gas} from ⟨z = 0.2⟩ to ⟨z = 1.2⟩, followed by a quasi non-evolution toward higher redshifts (see also Saintonge+ 13)
- large f_{gas} dispersion per redshift bin as expected, due to mainly the strong dependence of f_{gas} on M_*, such that galaxies with the smaller M_* have the larger f_{gas}

STELLAR MASS DEPENDENCE OF THE MOLECULAR GAS FRACTION



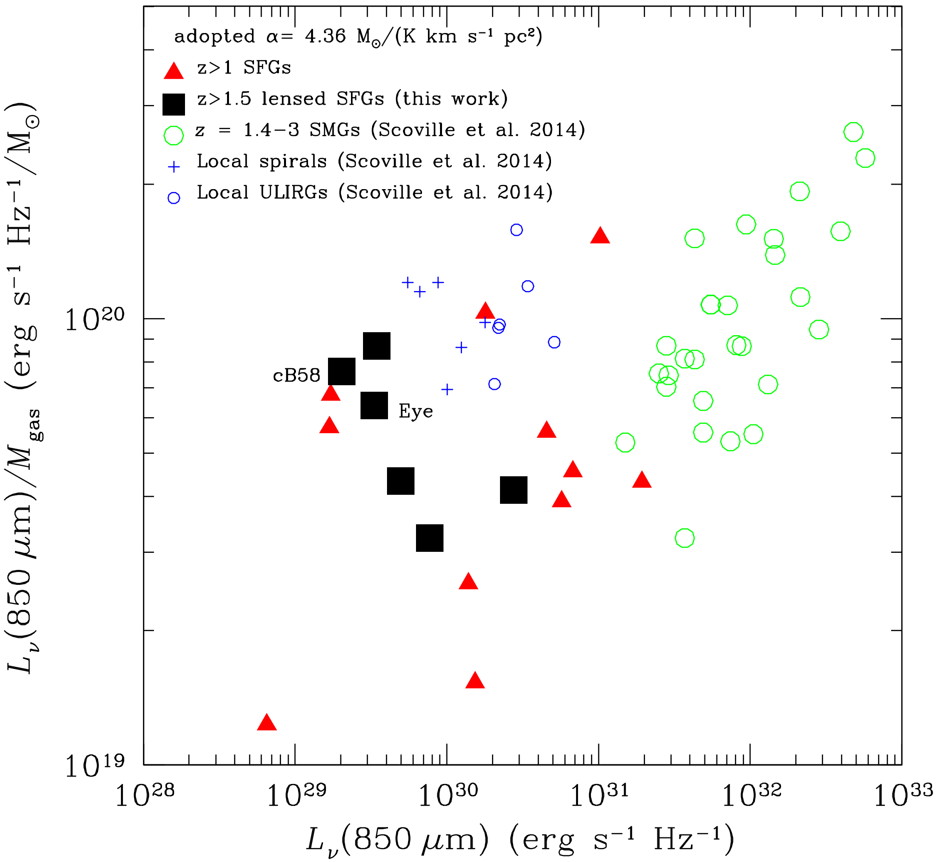
Models predict a drop in f_{gas} with increasing M_* and an upturn of f_{gas} at the low-M_* end (Bouché+ 10; Davé+ 11; Lagos+ 12)

The combined redshift increase of f_{gas} with its M_* increase, even more substantial for low-M_* galaxies than for high-M_* galaxies at z>1, is a direct result of *downsizing* (Bouché+ 10; Santini+ 14): massive galaxies consume their molecular gas more quickly because they form more rapidly

Observations

- first insights on f_{gas} of z>1 SFGs at the low-M_* end between $10^{9.4} < M_*/M_\odot < 10^{10}$, showing an upturn with $\langle f_{gas} \rangle = 0.67 \pm 0.20$
- mild decrease of f_{gas} with M_* for $M_*/M_\odot > 10^{10.2}$
- large dispersion within M_* bins due to the redshift evolution of f_{gas}
- a redshift evolution effect well highlighted by z<0.4 SFGs

IS THE DUST-TO-GAS RATIO UNIVERSAL ?



Dust-to-gas ratio measures from far-IR/sub-mm SED and CO luminosity are very uncertain

Scoville+14 considered the rest-frame 850 μm continuum as the dust mass tracer and derived in a homogeneous way (same CO-H_2 conversion factor and β-slope = 1.8) the dust-to-gas ratios in local galaxies and z>1.4 SMGs

Observations

- z>1 SFGs with solar metallicities added (our sample; Magdis+ 12; Saintonge+ 13)
- same $L_\nu(850\ \mu m)/M_{gas}$ means for local galaxies and high-redshift SMGs
- trend for a lower $L_\nu(850\ \mu m)/M_{gas}$ mean in z>1 SFGs by about 0.35 dex (see also Saintonge+ 13)

➔ *universal* dust-to-gas ratio questionable ➔ direct CO measures remain highly recommended