MOLECULAR GAS, STELLAR AND DUST CONTENT IN TYPICAL L★ GALAXIES AT Z ~ 1.5–3

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Dessauges-Zavadsky et al.
A&A submitted, arXiv:1408.0816

IMMEDIATE OBJECTIVE

Achieve molecular gas and dust measurements in *main-sequence* star-forming galaxies (SFGs) at z~1–3 characterized by

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

➔➔➔ in order to reach the $L^{\star}$ to sub-$L^{\star}$ domain

Objective only achievable with the help of gravitational lensing, thus current samples of CO-detected galaxies are still biased toward the high-SFR and high-$M_{\star}$ end of z ~2 SFGs

TARGET SELECTION FROM THE *HERSCHEL* LENSING SURVEY

Herschel/PACS+SPIRE Open Time Key project (PI: E. Egami) – talk by T. Rawle – observations of 54 massive galaxy clusters to discover lensed, high-redshift background sources

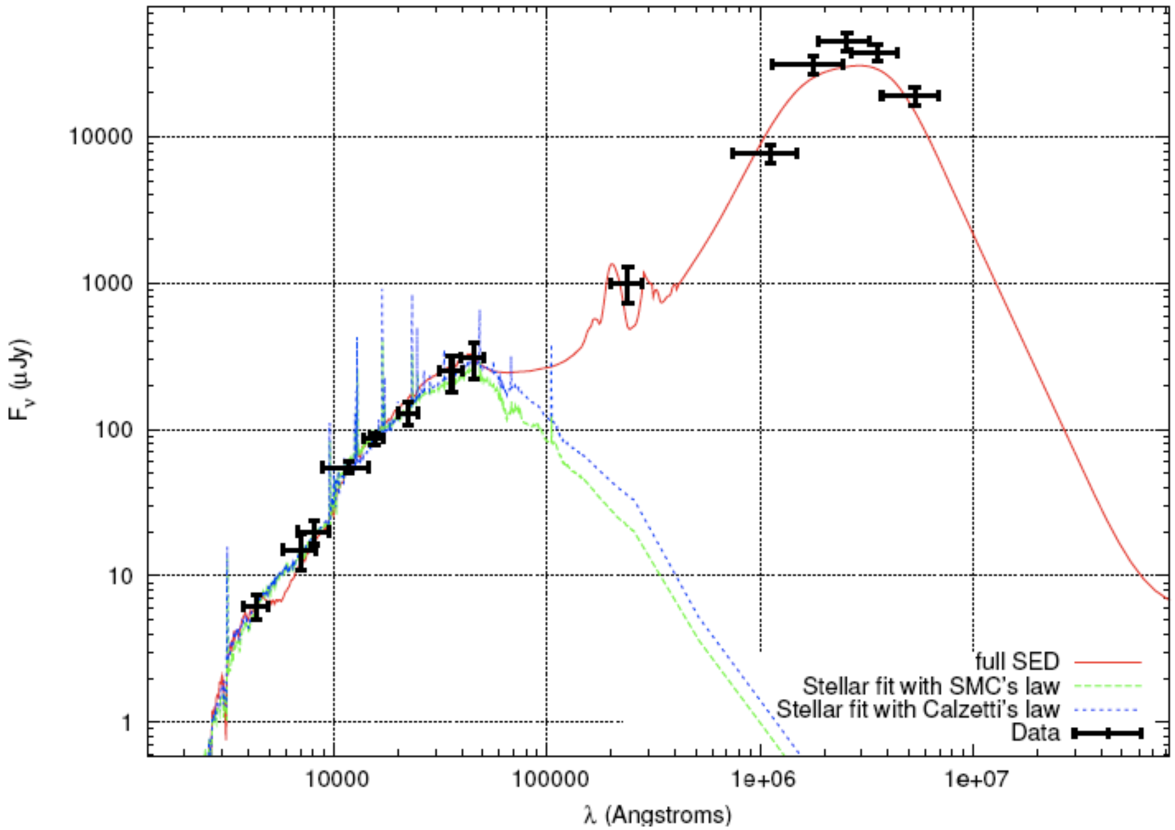
Selection criteria for our CO follow-up studies:

1. high magnification factors (ideally >10)
2. spectroscopic redshifts z~1-3
3. delensed $L_{IR} < 4\times10^{11}\ L_{\odot}$ (as measured from *Herschel* images)
4. complete photometry (from optical, NIR, IR to FIR) obtained with HST, Spitzer, and Herschel
5. high-resolution HST images for the morphological information

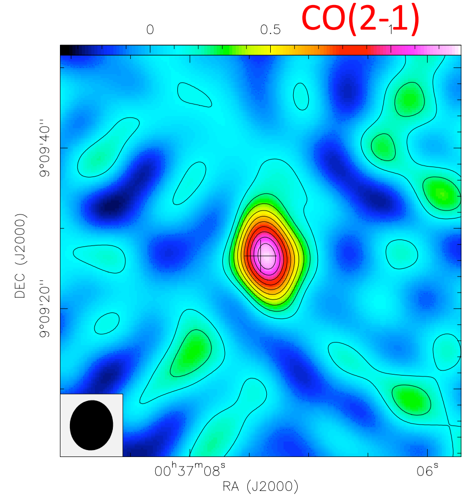
➔ Selection of 5 targets for new IRAM PdBI and 30m observations + MS1512-cB58 and Cosmic Eye

EXAMPLE OF ONE OF OUR 7 TARGETS: A68-C0 AT Z~1.6

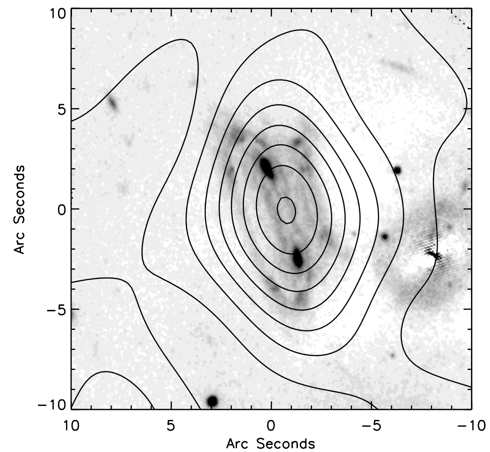
- poster by P. Sklias (4.09) -



CO(2-1)



F110W+CO(2-1)



Observables: L_{UV}, L_{bol} stars

↓

Optical/NIR SED fitting with new prescriptions:
- A_V extinction fixed at the observed L_{IR}/L_{UV}
- nebular emission taken into account (Schaerer+ 13; Sklias+ 14)

➔ SFR, $M_\star$, age, and star formation history

Observable: L_{IR} dust

↓

FIR SED fitting:

➔ M_{dust} , T_{dust}

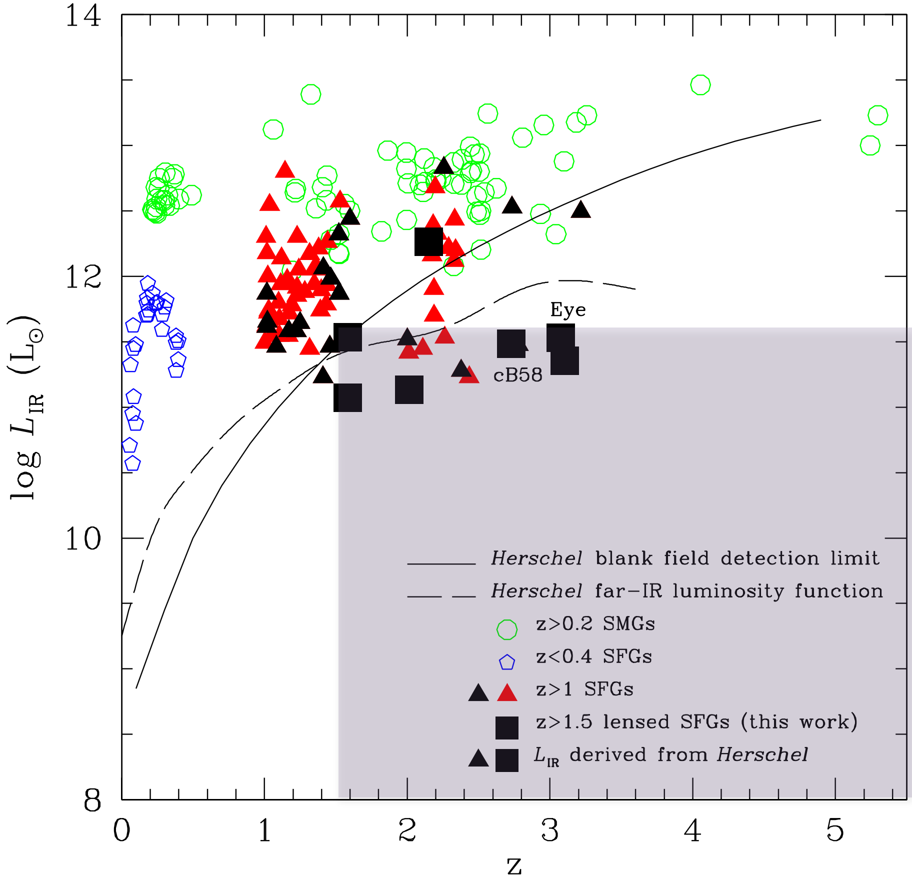
Observable: L_{CO} gas

↓

➔ M_{gas}
(Dessauges-Z.+ 14)

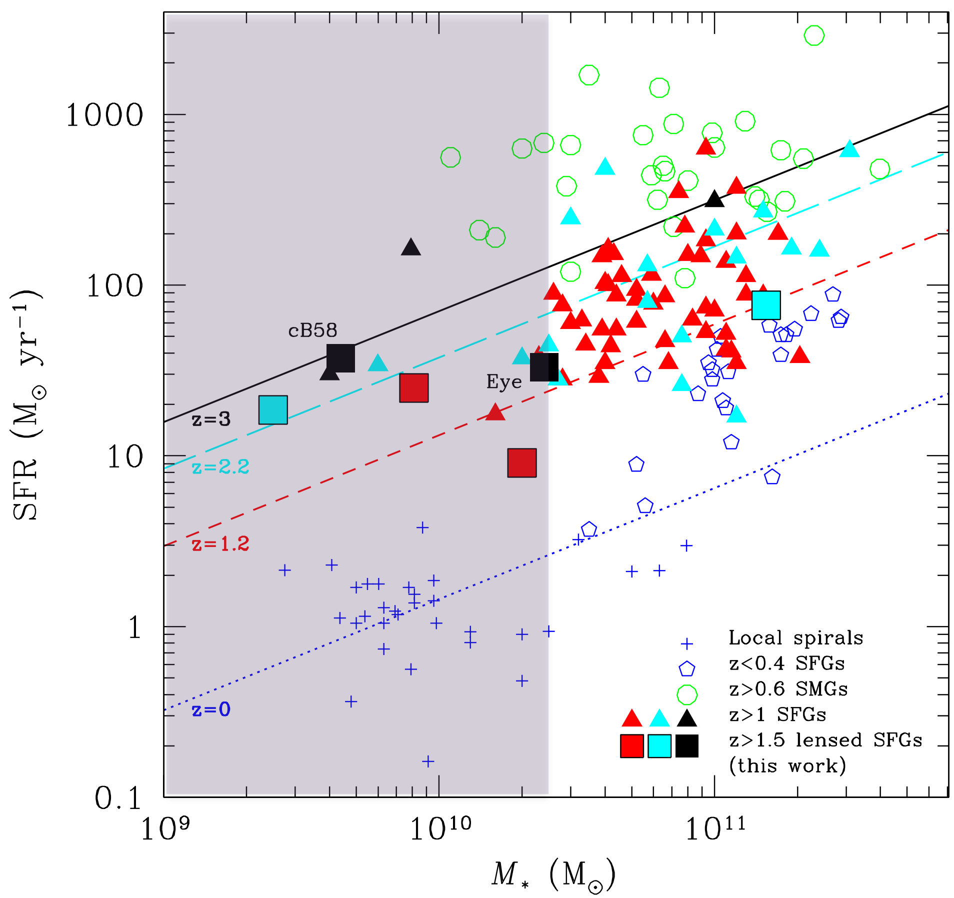
COMPARISON OF OUR TARGETS WITH CO-DETECTED GALAXIES FROM THE LITERATURE

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



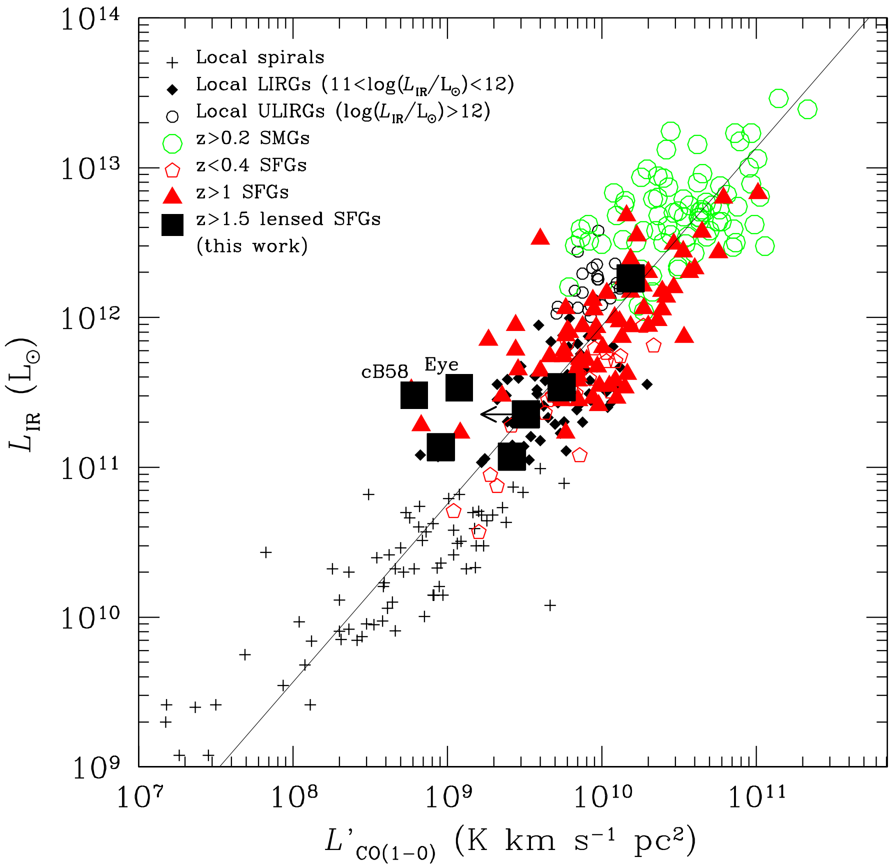
Our selected SFGs populate the regime with the lower L_{IR} at z>1.5 and even fall below the *Herschel* blank field detection limit (Elbaz+ 11)

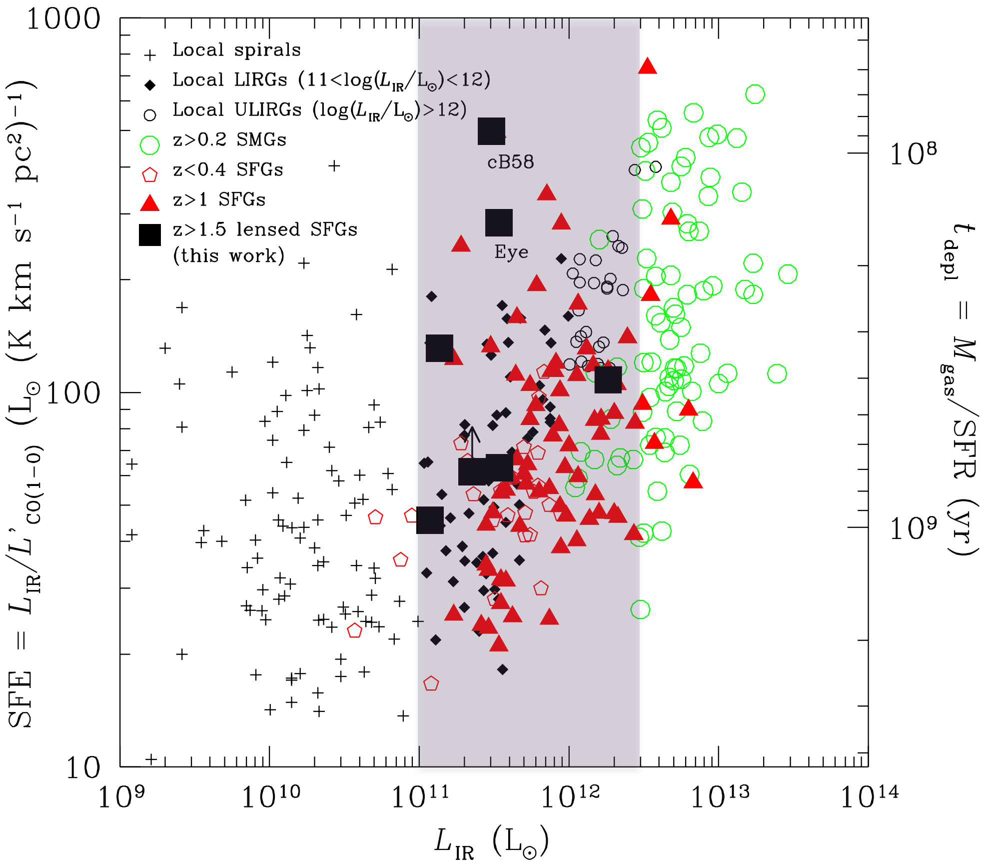
$M_\star < 2.5\times10^{10}\ M_\odot$



Our selected SFGs follow the *main-sequence* of z=1.2, 2.2, and 3 galaxies and probe one order of magnitude smaller $M_\star$.

COMPARISON OF OUR TARGETS WITH CO-DETECTED GALAXIES FROM THE LITERATURE





- Our selected SFGs nicely extend the L_{IR}-$L'_{CO(1-0)}$ distribution of z>1 SFGs
- 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
(SFE not confined to local spirals any more)

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

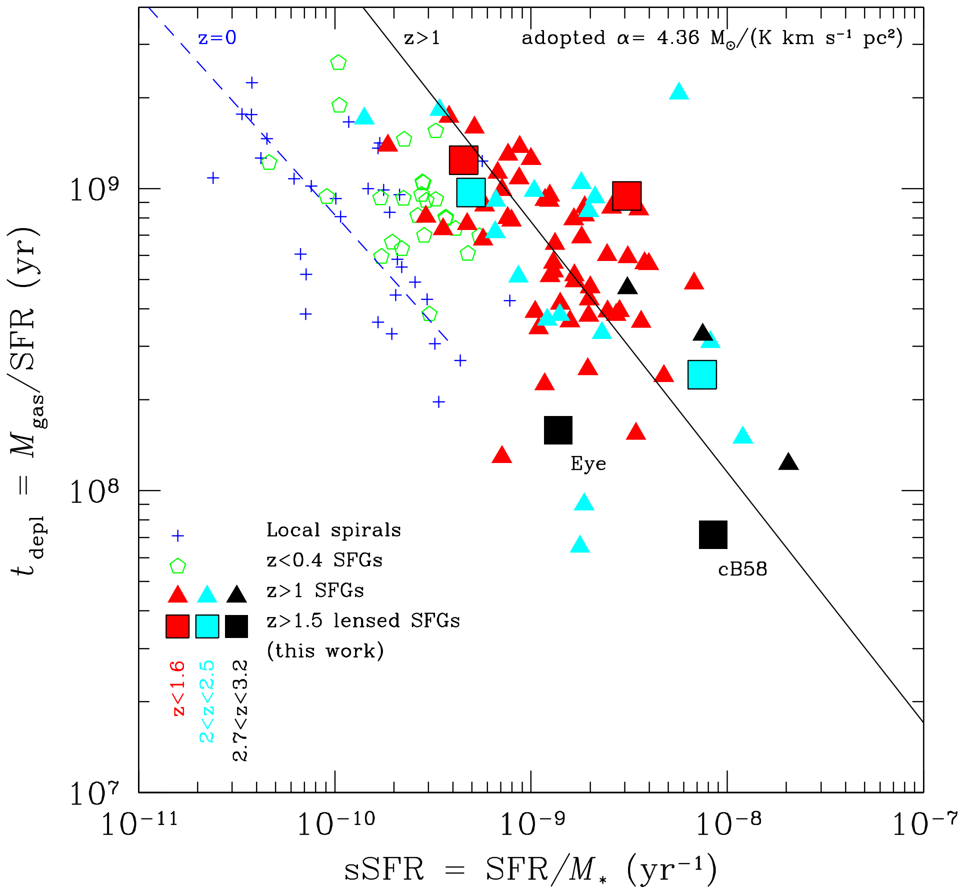
We investigate the dependence of SFE or t_{depl} on several physical parameters:

1. the specific star formation rate (sSFR)
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, $M_{\star}$, 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

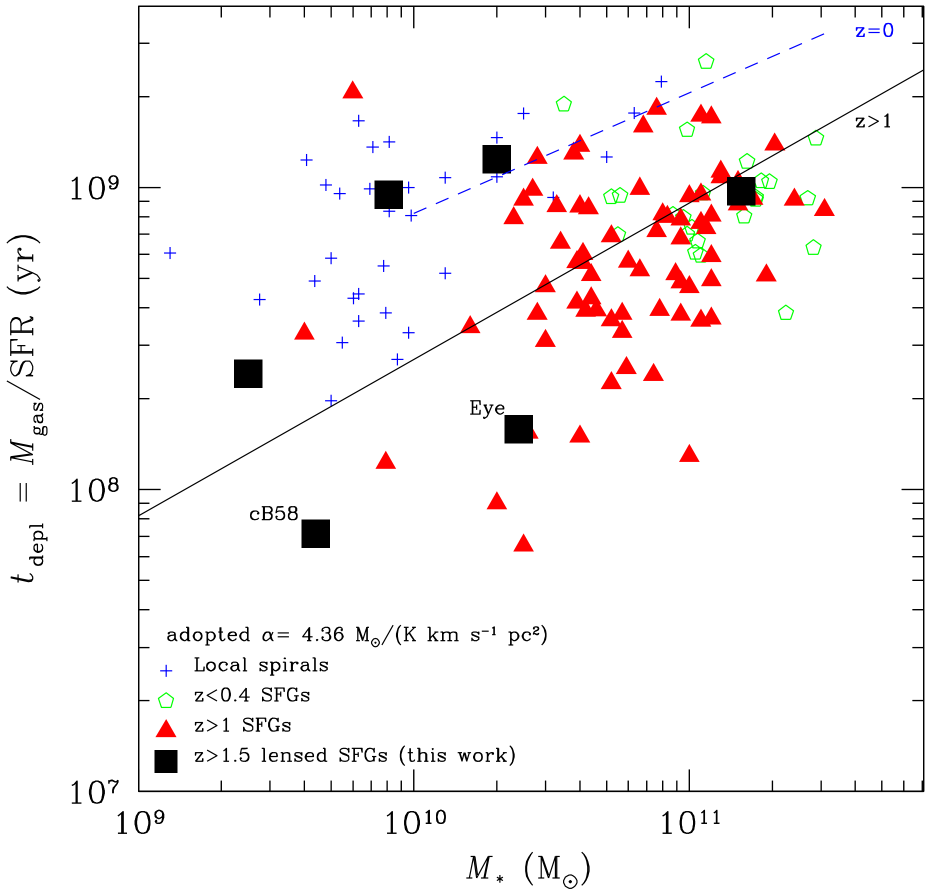
Good t_{depl}–sSFR anti-correlation with a shift toward longer t_{depl} by 0.75 dex at the same sSFR (see also Saintonge+ 11; Combes+ 13)

➔ 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, which increases the shift between local and z>1 galaxies

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 $10^{10} < M_\star/M_\odot < 10^{11.5}$ (COLD GASS survey by Saintonge+ 11)

Recently confirmed down to $M_\star \sim 10^9\ M_\odot$ (ALLSMOG survey by Bothwell+ 14)

z>1 SFGs

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

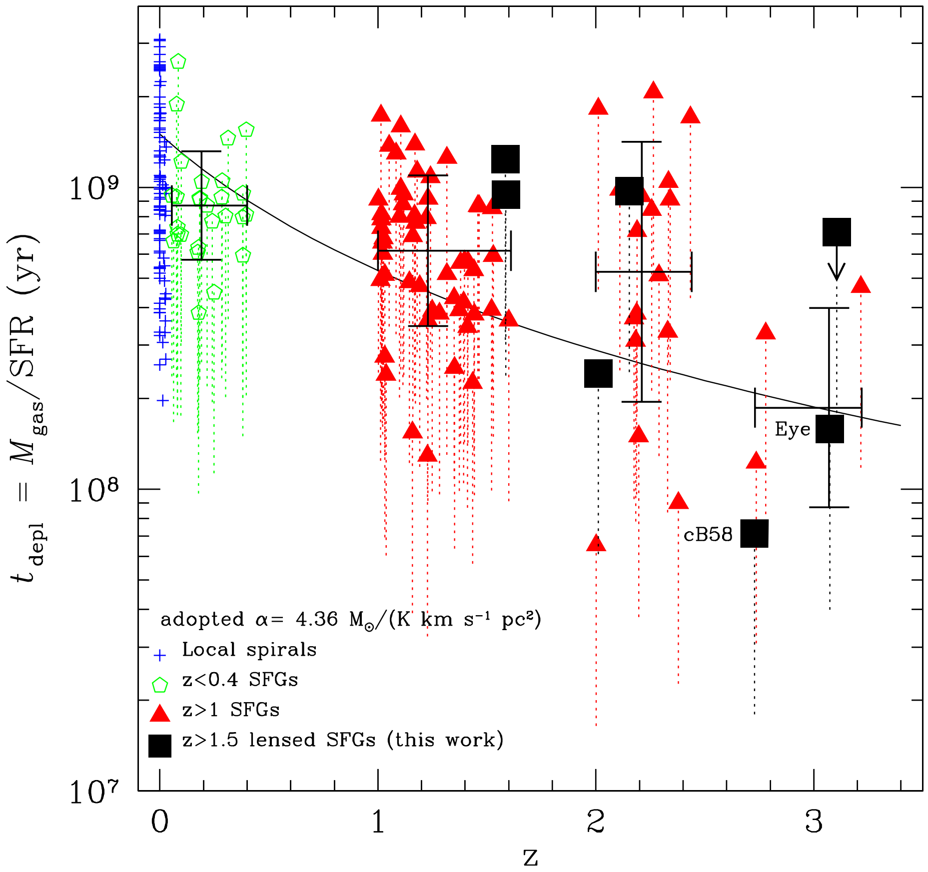
➔ the few data points at the low-$M_\star$ end seem to trigger the t_{depl}–$M_\star$ correlation

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 ($\Sigma_{SFR} \propto \Sigma_{H2\ gas}^N$ with N ≠1)

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

3. THE REDSHIFT



The cosmic evolution of t_{depl} is expected:

SFR ∝ M_{gas}/t_{dyn} => t_{depl} ∝ t_{dyn}

which in a canonical disk model scales as $(1+z)^{-1.5}$ (Hopkins & Beacom 06; Davé+ 11,12; Bouché+ 10)

z>1 SFGs

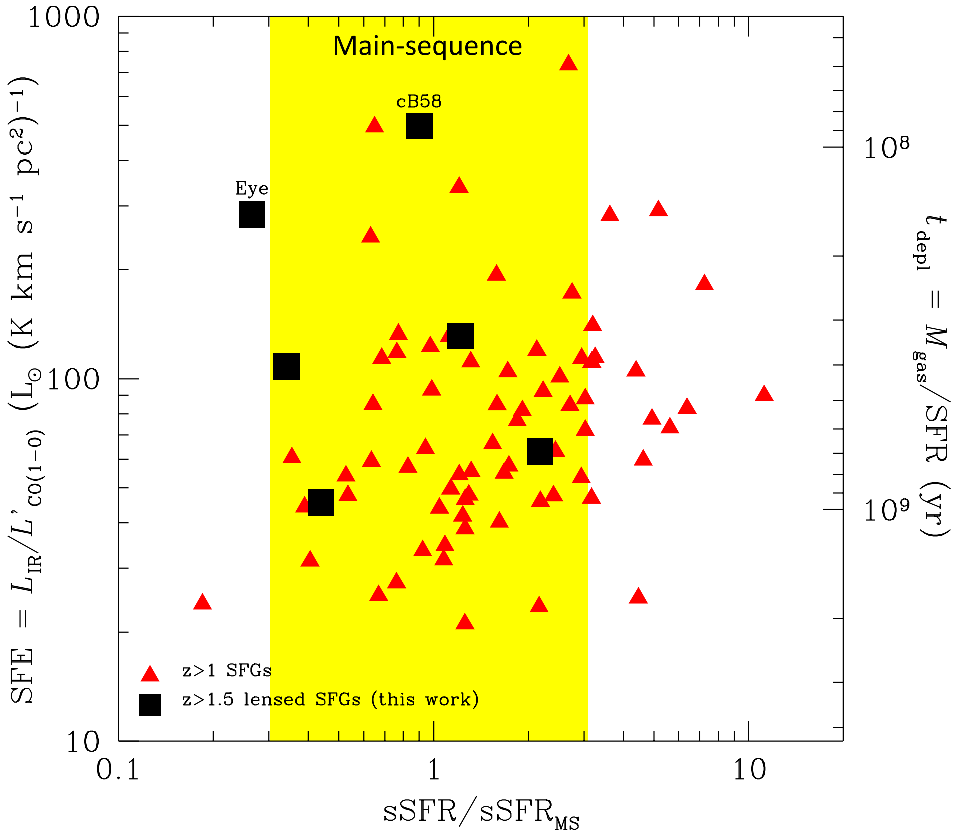
Observationally, the t_{depl} decrease with redshift is confirmed, such as $(1+z)^{-1.5}$ (also Combes+ 13; Tacconi+ 13; Saintonge+ 13; Santini+ 14) – talk by P. Santini –

➔ 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}–$M_\star$ relations: galaxies with the higher sSFR and smaller $M_\star$ have the shorter t_{depl}

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

4. 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

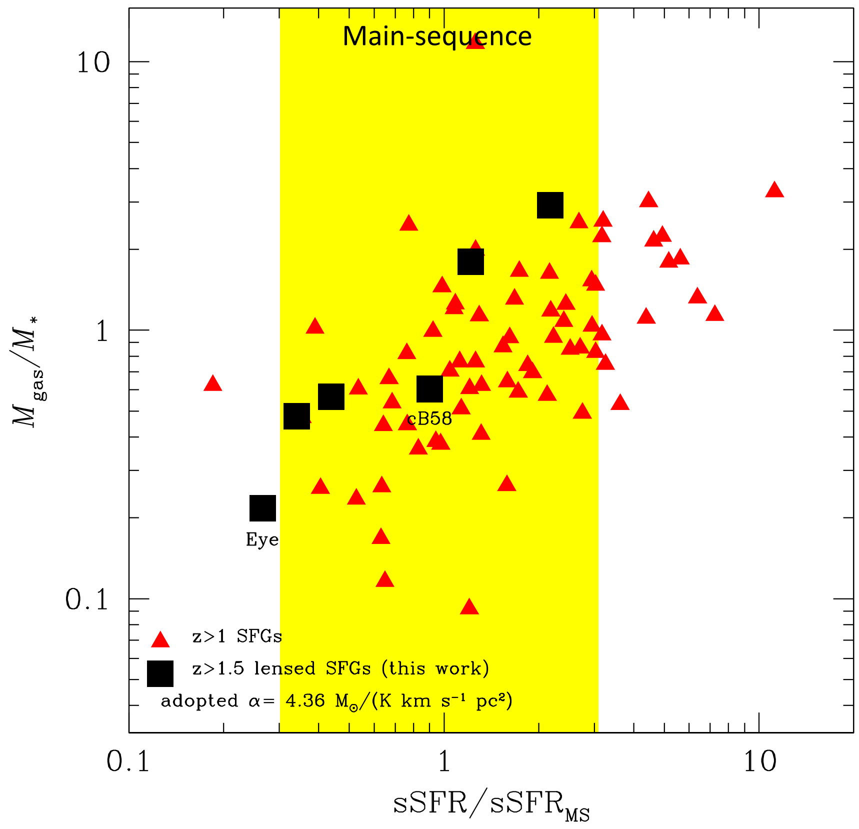
- The general trend of higher SFE for galaxies with larger offsets from the MS is confirmed

- *But* MS galaxies ($0.3 < \mathrm{sSFR}/\mathrm{sSFR_{MS}} < 3$) within the yellow area have roughly *constant* SFE with a large spread over 1.5 orders of magnitude

➔ The offset from the MS does not drive the large SFE spread of z>1 SFGs

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

4. THE OFFSET FROM THE MAIN-SEQUENCE



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What then drives the thickness of the MS ?
Essentially the molecular gas fraction !

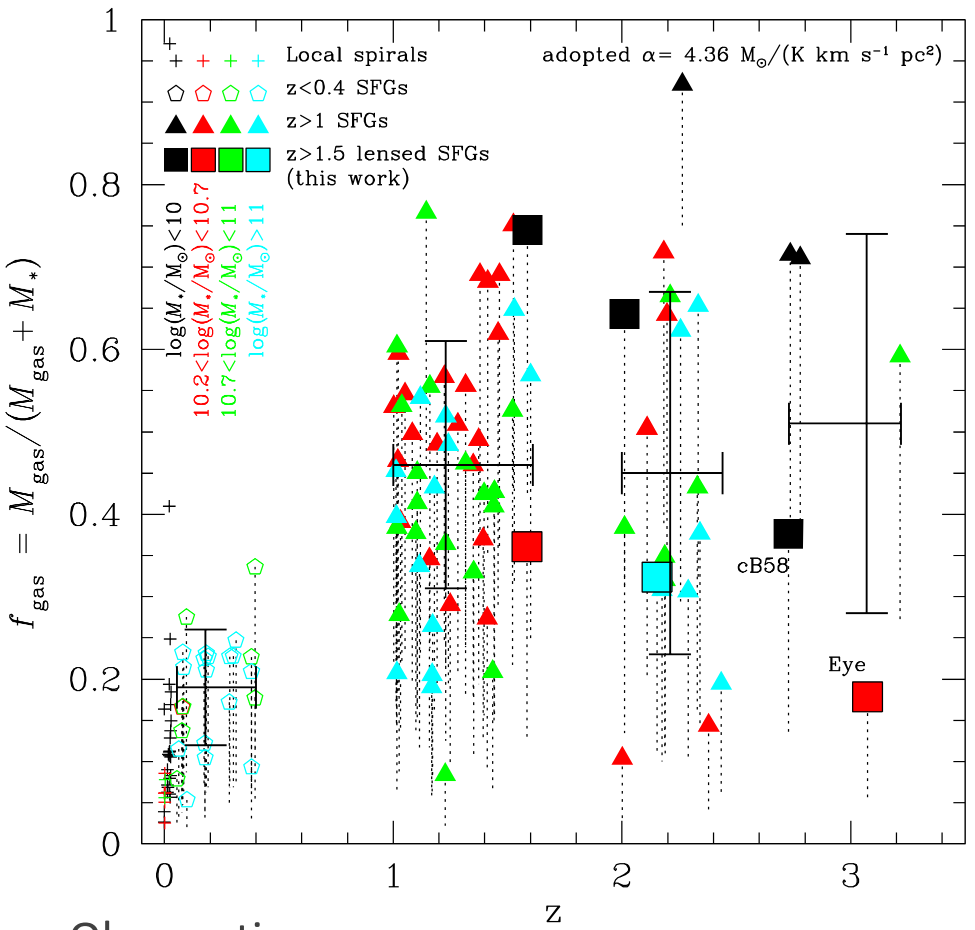
MOLECULAR GAS FRACTION

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 important tests of galaxy evolution models

We consider two main observables: redshift and $M_{\star}$

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:

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

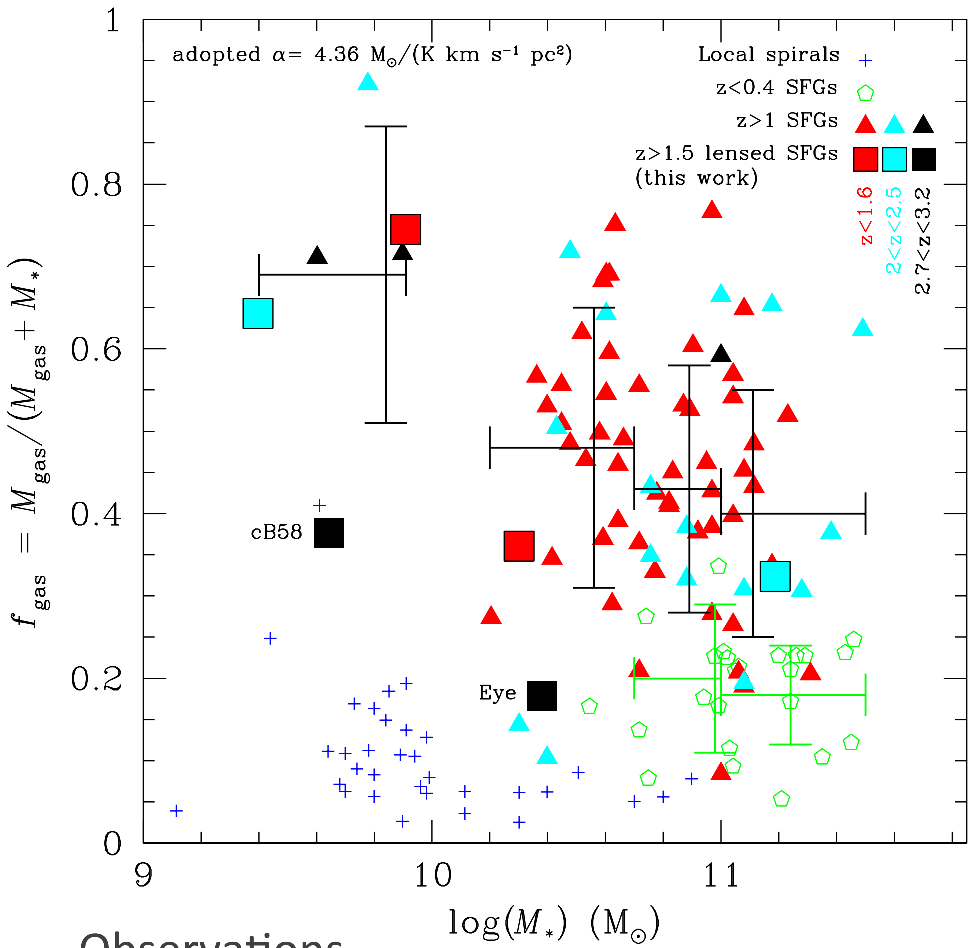
with $t_{depl} \propto (1+z)^{-1.5}$
and sSFR $\propto (1+z)^{\alpha}$ with α = 5/3 to 3

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

Observations

- net rise of f_{gas} from $\langle z = 0.2 \rangle$ to $\langle z = 1.2 \rangle$, followed by a mild increase 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 $M_\star$, such that galaxies with the smaller $M_\star$ have the larger f_{gas}

STELLAR MASS DEPENDENCE OF THE MOLECULAR GAS FRACTION



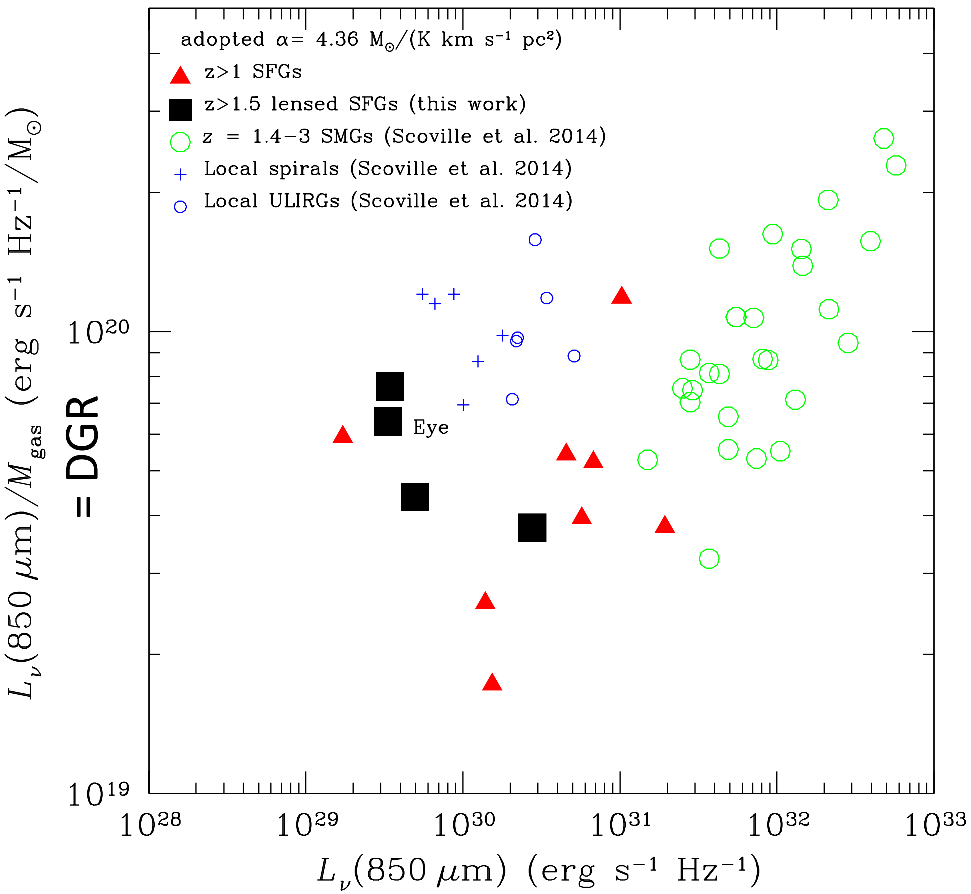
Models predict a drop in f_{gas} with increasing $M_\star$ and an upturn of f_{gas} at the low-$M_\star$ end (Bouché+ 10; Davé+ 11; Lagos+ 12)

The redshift increase of f_{gas} combined with the fact that it is even more substantial for low-$M_\star$ galaxies than for high-$M_\star$ galaxies is a direct output of ***downsizing***
(Bouché+ 10; Santini+ 14) :
massive galaxies consume their molecular gas more quickly because they form more rapidly
– talk by P. Santini –

Observations

- first insights on f_{gas} of z>1 SFGs at the low-$M_\star$ end between $10^{9.4} < M_\star/M_\odot < 10^{10}$, showing an upturn with $\langle f_{gas} \rangle = 0.69 \pm 0.18$
- mild decrease of f_{gas} with $M_\star$ for $M_\star/M_\odot > 10^{10.4}$
- large dispersion within $M_\star$ 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 (DGR) UNIVERSAL ?



DGR measurements from far-IR/sub-mm SED and CO luminosity are very uncertain, because of a number of assumptions:

1. dust mass estimates from SEDs tributary to the dust model, dust emissivity index, dust mass absorption cross section
2. CO-H_2 conversion factor
3. $M_{gas} \approx M_{H2} \gg M_{HI}$

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 DGRs in local galaxies and z>1.4 SMGs
– talk by N. Scoville –

Observations

- z>1 SFGs with near-solar metallicities ($Z/Z_\odot$>0.8) 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 0.33 dex at fixed metallicity

➔ *universal* DGR questionable ➔ direct CO measurements remain highly recommended
– talk by S. Madden –

CONCLUSIONS

New measures of the molecular gas, stellar, and dust content in typical $L^\star$ and sub-$L^\star$, strongly-lensed galaxies at $z \sim 1.5-3$:

- ➔ selected from the *Herschel* Lensing Survey with $L_{IR} < 4\times10^{11}\ L_\odot$
- ➔ sampling $SFR < 40\ M_\odot\ yr^{-1}$ and $M_\star < 2.5\times10^{10}\ M_\odot$
- ➔ put face-to-face with a comparison sample of CO-detected galaxies from the literature

1. SFGs at z>1 show an increased spread in SFE:
   SFE not confined to local spiral values any more, they overlap the distribution of z>1 SMGs

➔ What drives this large SFE spread ?
t_{depl}–sSFR anti-correlation, t_{depl}–$M_\star$ correlation, and $t_{depl} \propto (1+z)^{-1.5}$ evolution

2. The correlation of t_{depl} with $M_\star$ implies:
- constant t_{depl} assumed in the "bathtub" model not valid
- a non-linear Kennicutt-Schmidt relation ($\Sigma_{SFR} \propto \Sigma_{gas}^N$ with $N \neq 1$)

3. The molecular gas fraction provides tests of galaxy evolution models:
- net rise of f_{gas} from z~0 to z~1, followed by a very mild increase with z
- large f_{gas} dispersion per redshift bin: galaxies with the smaller $M_\star$ have the larger f_{gas}
- f_{gas} upturn at the low-$M_\star$ end
- mild decrease of f_{gas} with $M_\star$ for $M_\star/M_\odot > 10^{10.4}$

➔ betraying the *downsizing* effet

4. Evidence for a non-universal dust-to-gas ratio at fixed near-solar metallicity
   among high-z SFGs and SMGs, local spirals and ULIRGs

WHY CARING ABOUT MOLECULAR GAS, STARS, AND DUST ?

These are the main constituents of galaxies, which are interconnected. The molecular gas is the reservoir for star formation and stars feed the dust formation.

WHY STAR-FORMING GALAXIES AT Z~1.5–3 ?

Normal star-forming galaxies (SFGs) or *main-sequence* galaxies represent the bulk of galaxies near the peak of the cosmic galaxy formation activity at z~2.

WHY L★ AND EVEN SUB-L★ ?

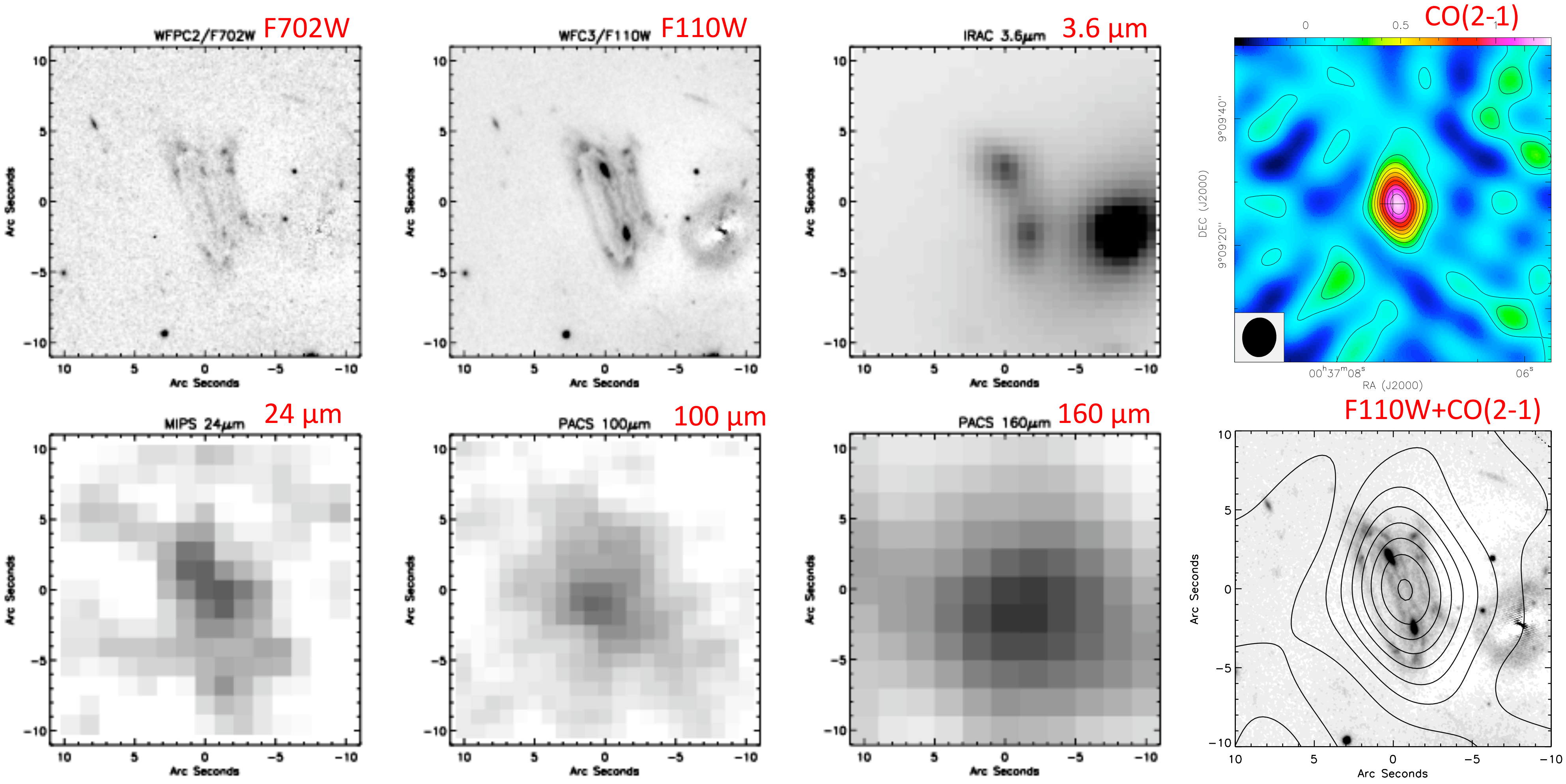
Despite large efforts dedicated to get the census of the molecular gas and dust content of SFGs, one is still biased toward the high-SFR and high-$M_\star$ end of SFGs at z~2. Molecular gas and dust measures in the faint, more numerous $L^\star$ and sub-$L^\star$ galaxies were not achieved (individually) yet.

(Daddi+ 10; Genzel+ 10; Tacconi+ 10,13; Magdis+ 12; Magnelli+ 12)

WHY STRONGLY-LENSED GALAXIES ?

Only with the gravitational lensing, we may detect CO and dust in $L^\star$ and sub-$L^\star$ galaxies.

EXAMPLE OF ONE OF OUR 7 TARGETS: A68-C0 AT Z~1.6



Complete photometry (optical, NIR, IR, FIR) obtained with HST, Spitzer, and Herschel

CO(2-1) emission from PdBI